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²A SEARCH FOR LONG-LIVED, CHARGED, SUPERSYMMETRIC PARTICLES
³USING IONIZATION WITH THE ATLAS DETECTOR

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BRADLEY AXEN

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⁸ Bradley Axen: *A Search for Long-Lived, Charged, Supersymmetric Particles using*
⁹ *Ionization with the ATLAS Detector*, Subtitle, © September 2016

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Usually a quotation.

11

Dedicated to.

₁₂ ABSTRACT

₁₃ How to write a good abstract:

₁₄ <https://plg.uwaterloo.ca/~migod/research/beck00PSLA.html>

₁₅ PUBLICATIONS

₁₆ Some ideas and figures have appeared previously in the following publications:

₁₇

₁₈ Put your publications from the thesis here. The packages `multibib` or `bibtopic`
₁₉ etc. can be used to handle multiple different bibliographies in your document.

²¹ ACKNOWLEDGEMENTS

²² Put your acknowledgements here.

²³

²⁴ And potentially a second round.

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585 ACRONYMS

- 586 SM Standard Model
587 CERN European Organization for Nuclear Research
588 SUSY Supersymmetry
589 LSP Lightest Supersymmetric Particle
590 LHC Large Hadron Collider
591 ATLAS A Toroidal LHC ApparatuS
592 CMS Compact Muon Solenoid
593 ALICE A Large Ion Collider Experiment
594 LHCb Large Hadron Collider beauty experiment
595 LEP the Large Electron Positron collider
596 PS Proton Synchrotron
597 PSB Proton Synchrotron Booster
598 SPS Super Proton Synchrotron
599 SCT silicon microstrip
600 TRT transition radiation tracker
601 LAr Liquid Argon
602 EM electromagnetic
603 RPC Resistive Plate Chamber
604 TGC Thin Gap Chamber
605 MDT Monitored Drift Tube
606 CSC Cathode Strip Chamber
607 ToT time over threshold
608 RoI Region of Interest
609 LCW local cluster weighted
610 MIP minimally ionizing particle
611 IP impact parameter

- 612 EPJC European Physical Journal C
613 JES jet energy scale
614 LLP Long-Lived Particle
615 CR Control Region
616 NLO next-to-leading order
617 NLL next-to-leading logarithmic
618 PDF parton distribution function
619 ISR initial state radiation
620 RMS root mean square
621 IBL Insertible B-Layer
622 CP Combined Performance
623 MDT Monitored Drift Tube
624 RF radiofrequency
625 HLT high level trigger
626 QCD quantum chromodynamics
627 BSM beyond the Standard Model

628

PART I

629

INTRODUCTION

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1

631

632 INTRODUCTION

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PART II

634

THEORETICAL CONTEXT

635

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2

636

637 STANDARD MODEL

638 The SM of particle physics seeks to explain the symmetries and interactions of
639 fundamental particles. The SM provides predictions in particle physics for in-
640 teractions up to the Planck scale (10^{15} - 10^{19} GeV). It has been tested by several
641 generations of experiments and has been remarkably successful; no significant
642 deviations from its predictions have been found.

643 The theory itself is a quantum field theory grown from an underlying sym-
644 metry, $SU(3) \times SU(2) \times U(1)$, that generates all of the interactions consistent
645 with experimental observations. These interactions are referred to as the Strong,
646 Weak, and Electromagnetic forces. Each postulated symmetry necessitates the
647 existence of an associated conserved charge, which appear as properties of the
648 observed particles in nature.

649 Although this model has been very predictive, the theory is incomplete; for
650 example, it is not able to describe gravity or astronomically observed dark mat-
651 ter. These limitations suggest a need for an extension or new theory to describe
652 physics at higher energies.

653 2.1 ACTION AND THE LAGRANGIAN

Originally, both action and the Lagrangian were constructed for an integral reformulation of the laws of classical mechanics, which is a purely mathematical step: any differential equation can be re-expressed in terms of an integral equation. The Lagrangian, \mathcal{L} , is classically given by the difference of kinetic energy and potential energy. The Lagrangian is defined this way so that the action, \mathcal{S} , given by

$$\mathcal{S}[\mathbf{q}(t)] = \int_{t_1}^{t_2} \mathcal{L}(\mathbf{q}, \dot{\mathbf{q}}, t) dt \quad (1)$$

654 returns the classical equations of motion when one requires it to be stationary
655 in the path, $\mathbf{q}(t)$. This formulation of classical mechanics is extremely useful in
656 calculations, and generalizes beautifully to cover all types of physics.

657 In particular, with the development of quantum mechanics in the twentieth
658 century, the concepts of action and the Lagrangian were found to generalize to
659 more complicated physics for which the classical laws do not hold. Quantum
660 mechanics and quantum field theory can be constructed from the action, using
661 the path integral formulation, by assuming that a particle undergoes all possible
662 paths $\mathbf{q}(t)$ with an imaginary phase given by $e^{i\mathcal{S}[\mathbf{q}(t)]/\hbar}$. This reduces to classical
663 mechanics in the limit as \hbar goes to zero, as all paths for which the action is not
664 stationary interfere with each other so as to cancel their contributions. Because
665 the wavefunction of a particle can be completely determined through the action

666 and the action depends only on the Lagrangian, the Lagrangian itself is sufficient
 667 to describe the physics governing the particle.

668 So, in both classical and quantum mechanics, the Lagrangian of a system con-
 669 tains everything there is to know about the system, apart from initial conditions.
 670 Thus, the most natural way to express that a system has a certain symmetry is to
 671 require that the Lagrangian is invariant under a corresponding symmetry trans-
 672 formation. This makes the Lagrangian the central piece of the discussion of
 673 gauge invariance; the mathematical representation of gauge invariance is that a
 674 gauge transformation on the appropriate components of the Lagrangian returns
 675 an identical Lagrangian. That is,

$$\mathcal{L}(\psi, D^\mu) = \mathcal{L}(U\psi, D'^\mu) \quad (2)$$

676 where ψ is the wavefunction and D^μ is the covariant derivative, both of which
 677 transform under a symmetry operation. There are a number of immediate and
 678 surprisingly powerful consequences of requiring that the Lagrangian is invariant
 679 under a symmetry operation.

680 2.2 GAUGE INVARIANCE AND FORCES

681 The simplest possible Lagrangian is the free Dirac Lagrangian, which describes
 682 a relativistic fermion in a vacuum.

$$\mathcal{L} = i\bar{\psi}\not{d}\psi - m\bar{\psi}\psi \quad (3)$$

683 A fermion denotes a particle with spin-1/2, and the kinematic term in the La-
 684 grangian correctly describes the free propagation of a fermionic particle with
 685 mass m . This equation is clearly invariant under a global $U(1)$ transformation,
 686 that is changing ψ by a complex phase has no effect. The derivative operator
 687 commutes with a constant phase factor, and wherever ψ appears its complex
 688 conjugate also appears so as to cancel out the change of phase. However, the La-
 689 grangian as written is not invariant under the local $U(1)$ symmetry postulated
 690 for the SM, which can be written as $U = e^{i\alpha(x)}$. The piece of the Lagrangian
 691 involving a derivative will return an extra term that will break the invariance of
 692 the Lagrangian under this transformation:

$$\begin{aligned} \mathcal{L}' &= i(\bar{\psi}U^\dagger)\not{d}(U\psi) - m(\bar{\psi}U^\dagger)(U\psi) \\ &= i(\bar{\psi}U^\dagger)U(\not{d} - \gamma^\mu\partial_\mu\alpha(x))\psi - m(\bar{\psi}U^\dagger)(U\psi) \\ &= i\bar{\psi}\not{d}\psi - m\bar{\psi}\psi - i\gamma^\mu\partial_\mu\alpha(x)\bar{\psi}\psi \\ &= \mathcal{L} - i\gamma^\mu\partial_\mu\alpha(x)\bar{\psi}\psi \\ &\neq \mathcal{L} \end{aligned}$$

693 So, in order to enforce the required symmetry, the typical approach is to con-
 694 struct a covariant derivative, that is to add a term to the derivative operator

so that the unwanted term in \mathcal{L}' is exactly canceled. A generic form for such a derivative is given by

$$D^\mu = \partial^\mu - iqA^\mu$$

where at this point A^μ is an arbitrary field that transforms under the $U(1)$ operator and q is a scaling factor. Adding this component to the above Lagrangian gives

$$\mathcal{L}' = i(\bar{\psi}U^\dagger)U(\not{d} - \gamma^\mu\partial_\mu\alpha(x) - iq\gamma^\mu A'_\mu)\psi - m(\bar{\psi}U^\dagger)(U\psi) \quad (4)$$

$$\mathcal{L}' = \mathcal{L} + \gamma^\mu(-i\partial_\mu\alpha(x) - iqA'_\mu + iqA_\mu)\bar{\psi}\psi \quad (5)$$

and because the transformation of A^μ is unspecified, $\mathcal{L} = \mathcal{L}'$ whenever

$$A'_\mu = A_\mu - \frac{1}{q}\partial_\mu\alpha(x)$$

The above procedure demonstrated that beginning with the Lagrangian for a free fermion and imposing a local $U(1)$ symmetry required the existence of a vector field A^μ , and specified its transformation under the $U(1)$ gauge group. The additional term in the derivative can be expanded to form a completely separate term in the Lagrangian,

$$\mathcal{L} = i\bar{\psi}\not{d}\psi - m\bar{\psi}\psi - (q\bar{\psi}\gamma^\mu\psi)A^\mu \quad (6)$$

and in this form it is clear that the A^μ term has the exact form of the electromagnetic interaction. That is, this is the Lagrangian which reproduces the relativistic form of Maxwell's equations for a particle interacting with an electromagnetic field. It is natural to also introduce a term to the Lagrangian at this point to describe the free propagation of the vector A field, where the propagation of a vector field has the form of

$$-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} \quad \text{with} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (7)$$

which then also describes the electromagnetic interactions in a vacuum and the propagation of a photon. The photon is an example of a gauge boson, a spin-0 particle required to exist by a gauge symmetry of the Lagrangian and one that corresponds to a force. In summary, requiring the $U(1)$ symmetry was enough to recover all of electromagnetism and to predict the existence of a photon in the SM.

The interaction term that was placed into the Lagrangian by this procedure can be conveniently summarized with Feynman diagrams, which diagrammatically represent a transition from an initial state to a final state. All diagrams that start with the same initial state and end with the same final state must be considered, but more complicated diagrams can be built by linking together the simplest versions. A diagram that corresponds to the above term, $(q\bar{\psi}\gamma^\mu\psi)A^\mu$, is shown in Figure 3, for an interaction with a generic fermion.

Figure 1: A Feynman diagram representing the interaction of the A field with a generic fermion, f .

725 2.2.1 $SU(2) \times U(1)$ AND THE ELECTROWEAK FORCE

726 The full picture of the electroweak section of the SM is more complicated than the
 727 simplified explanation of the electromagnetic piece described above. In practice,
 728 it is necessary to consider the entire $SU(2) \times U(1)$ symmetry together, but the
 729 procedure is the same. Enforcing the symmetry on the Lagrangian requires the
 730 introduction of a covariant derivative, this time with four total distinct terms,
 731 one for each of the generators of $SU(2) \times U(1)$. The result is a series of terms
 732 in the Lagrangian which describe the interaction of a fermion with four vector
 733 fields, the W_1 , W_2 , W_3 , and B fields. These fields can mix in the quantum sense,
 734 and linear combinations form the W^+ , W^- , Z , and A fields that are considered
 735 actual particles in the SM¹.

736 2.2.2 $SU(3)$ AND THE STRONG FORCE

737 The same procedure can be applied starting with the $SU(3)$ symmetry require-
 738 ment, where eight additional fields must be introduced, one for each of the gen-
 739 erators of $SU(3)$. The resulting Lagrangian describes quantum chromodynam-
 740 ics (QCD) and predicts the existence of eight gauge bosons known collectively as
 741 gluons.

742 2.3 NOETHER'S THEOREM, CHARGES, AND MATTER

743 Another direct consequence of the symmetries stipulated in the SM are a series
 744 of conserved quantities, Noether charges, named after the mathematician and
 745 physicist Emmy Noether. The charges arise as a direct consequence of Noether's
 746 theorem, which can be informally stated as

747 *For every symmetry of the Lagrangian, there exists a corresponding phys-
 748 ical quantity whose value is conserved in time.*

749 Or, stated another way, symmetries of the Lagrangian mathematically require
 750 the conservation of specific quantities taken from the Lagrangian. This rela-
 751 tionship can also be thought of as operating in the other direction, the exis-
 752 tence of a conserved charge can be shown to generate the symmetry in the La-
 753 grangian. This theorem is actually quite striking in a somewhat unexpected re-
 754 lation between simple geometric symmetries and physically observable conser-
 755 vation laws. For example, the theorem connects the translation invariance of
 756 the Lagrangian in space to the conservation of momentum and the translation
 757 invariance in time to the conservation of energy.

1 These states are the actual particles because they are mass eigenstates, but the full explanation of this will have to wait for the discussion of the Higgs mechanism.

In the context of the SM, the required symmetries of $U(1) \times SU(2) \times SU(3)$ correspond to the charges that are considered properties of all elementary particles. The most familiar of these properties is the electric charge, Q , which is one of the conserved quantities of $SU(2) \times U(1)$. The remaining pieces of $SU(2) \times U(1)$ correspond to weak isospin, T and T_3 , where T has only non-negative values and T_3 can be positive and negative. The $SU(3)$ symmetry is generated by the three colors of QCD, red, green, and blue, each with a corresponding opposite color, anti-red, anti-green, and anti-blue.

The matter in the observable universe consists of a collection of particles which carry these charges, in addition to spin and mass. The particles typically thought of as matter are all fermions: particles with spin-1/2. All of the fermions belong to one of two groups, quarks and leptons, and one of three generations. Each of the generations have similar properties but significantly different masses; the particles in consecutive generations have increasing mass. Quarks are distinguished from leptons in that they carry color charge, in addition to electric charge and weak isospin. The particles in the SM are summarized in Figure 2, and the matter particles are the twelve types of fermions displayed on the left side of the graphic.

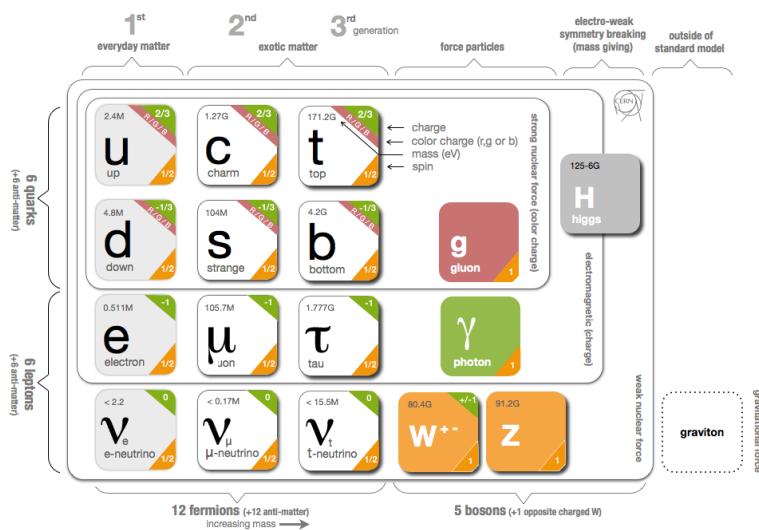


Figure 2: The particle content of the SM.

2.3.1 QUARKS

The three generations of quarks each have a particle with electric charge +2/3 and one with charge -1/3. They are referred to as up and down, charm and strange, and top and bottom respectively, and these are referred to as the quark flavors. Although Figure 2 only shows these six flavors, there is a unique particle for each combination of the three colors and flavor. And each quark has an anti-particle with the opposite electric and color charge values.

783 However, individual quarks are never observed in nature, but instead form
 784 color-neutral bound states. One way to form a color neutral combination is a
 785 bound state of three quarks with three different color charges, called a baryon.
 786 Baryons are the most common type of quark configuration in conventional mat-
 787 ter, and include protons and neutrons. The other common configuration is a
 788 bound state of a quark and an anti-quark, called a meson, where the two quarks
 789 have the same type but opposite colors. The conservation of the various charges
 790 carried by quarks, along with the requirement that quarks appear in color-neutral
 791 states, result in the observed conservation of baryon number, B , where baryons
 792 have $B = 1$ and mesons have $B = 0$.

793 2.3.2 LEPTONS

794 The remaining fermions, the leptons, do not carry color charge. Each generation
 795 contains an electrically charged lepton, the electron, muon, and tau, and an elec-
 796 trically neutral lepton called a neutrino. For the charged leptons, the flavors are
 797 mass eigenstates, with the masses listed in Figure 2. The flavors of the neutrinos,
 798 on the other hand, are not mass eigenstates: they propagate in mass eigenstates
 799 and so can oscillate between different flavors. The absolute masses of the neu-
 800 trinos are not currently known, but the phenomenon of oscillations shows that
 801 they have three different mass values. Although there is no direct conservation
 802 law resulting from the symmetries of the SM Lagrangian, no interactions have
 803 been observe which alter lepton number, L , the difference in the number of lep-
 804 tons and anti-leptons.

805 2.3.3 CHIRALITY

806 All of the fermions described above have two possible values of the magnitude
 807 of weak isospin, T , either 0 or $1/2$. The fermions with $T = 0$ are called right-
 808 handed, while those with $T = 1/2$ are called left-handed. For left-handed fermions,
 809 each of the quark and lepton generations have one particle with $T_3 = -1/2$ and
 810 one with $T_3 = +1/2$. The neutrinos have $T_3 = +1/2$, while the charged leptons
 811 have $T_3 = -1/2$. Similarly, the positively charged quarks have $T_3 = +1/2$ and the
 812 negatively charged quarks have $T_3 = -1/2$. Because the right-handed neutrinos
 813 would have no charge of any type, it is not clear if they exist at all.

814 2.4 HIGGS MECHANISM AND MASS

815 The description of the electroweak forces above left out an important part of the
 816 observed nature of the electroweak force. Many physical experiments observed
 817 phenomena corresponding to the interaction of the weak bosons that were best
 818 explained if they had significant masses. A large mass for the W and Z bosons
 819 would explain the relative weakness of their interactions compared to the elec-
 820 tromagnetic field. The Lagrangian's discussed above did not include a mass term
 821 for the gauge bosons, and in fact such a term would not be allowed by the require-

ment of gauge invariance. This was a significant problem for the SM, and the symmetry of the electroweak sector would have to be broken in order to allow for non zero masses for some of the gauge bosons.

One mechanism to allow for this spontaneous symmetry breaking is the Higgs mechanism, which posits the existence of an additional scalar field. It begins with a $SU(2) \times U(1)$ invariant Lagrangian of the form

$$\mathcal{L} = |D_\mu \phi|^2 - \frac{1}{2}\mu^2\phi^+\phi - \frac{1}{4}\lambda(\phi^+\phi)^2 \quad (8)$$

where ϕ is the new scalar field and, importantly, μ^2 is negative. This leads to a minimum value of the field at a non-zero value of ϕ , specifically where

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v = \frac{2\mu^2}{\lambda} \quad (9)$$

Expanding the original Lagrangian about its expectation value,

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (10)$$

gives potential terms in the Lagrangian like

$$\mathcal{L}_H = -\frac{1}{2}m_H^2H^2 - \sqrt{\frac{\lambda}{2}}m_HH^3 - \frac{1}{4}\lambda H^4 \quad (11)$$

where $m_H = \sqrt{2}\mu$. The form of this Lagrangian shows that the non-zero expectation value of the ϕ field has introduced a massive scalar field H with self interaction terms. It has an additional important consequence on the description of the gauge bosons, through the expansion of the term involving the covariant derivative:

$$|D_\mu \phi|^2 \supset \frac{1}{8} \left(g^2(W_{1\mu}W_1^\mu + W_{2\mu}W_2^\mu) + (g'B_\mu - gW_3\mu)^2 \right) \quad (12)$$

where the W_i and B fields are the original $SU(2) \times U(1)$ gauge fields mentioned previously. The above equation can be rearranged using linear combinations of the fields to from mass terms for the gauge bosons, and the mass eigenstates are exactly the W^\pm , Z , and A fields. Only the A field, corresponding to the photon, results in a zero mass, and the remaining three fields acquire masses. Because the originally introduced Lagrangian, written in terms of ϕ , was clearly gauge invariant, this resulting configuration must also be gauge invariant.

This is the Higgs mechanism, where the introduction of a gauge invariant scalar field with a non-zero expectation value can generate masses for the gauge bosons without violating the underlying symmetries. The particle that is associated with the perturbations of this field, H , is called the Higgs boson, and is

Figure 3: The Feynman diagrams representing the decays of the W and Z bosons to fermions. Here f indicates a generic fermion, \bar{f} its antiparticle, and f' the partner of that fermion in the same generation.

848 said to generate the masses of the remaining bosons. The resulting masses are
 849 listed in Figure 2. Because this mechanism was so successful in describing the
 850 observed properties of the W and Z bosons, it has been considered part of the
 851 SM for decades, although the actual Higgs boson was only recently observed in
 852 2012, confirming the theory.

853 The Higgs mechanism is also responsible for generating the masses of the
 854 fermions. The original mass terms that were listed in the Lagrangian for fermions
 855 are replaced with Yukawa coupling terms, which introduce interactions between
 856 the ϕ field and the fermions. Like with the gauge bosons, the non-zero expecta-
 857 tion value of the field yields mass terms, and the expansion about that value
 858 introduces interaction terms between the fermions and the Higgs boson. The
 859 masses are different between each fermion because each has a different Yukawa
 860 coupling, which results in the masses listed in Figure 2.

861 2.5 PHENOMENOLOGY

862 The SM Lagrangian described above contains all of the information necessary
 863 to describe particle physics through the path integral formulation. However, a
 864 tremendous amount of complexity emerges from that description because of the
 865 diverse allowed interactions between the ensemble of particles in the SM. A qual-
 866 itative understanding of the phenomenology produced by those interactions is
 867 immensely helpful in understanding the analysis of particle physics.

868 2.5.1 ELECTROWEAK PHYSICS

869 The masses of the W and Z bosons result in significantly different processes
 870 for the weak fields than the electromagnetic field, despite their interactions be-
 871 ing similar before symmetry breaking. The massless photon is stable, and can
 872 propagate in a vacuum, resulting in the familiar long range interactions of elec-
 873 tromagnetism. The W and Z bosons, however, are unstable, as they have large
 874 enough masses to decay to fermions, such as the decays shown in Figure ???. For
 875 this reason, photons can be observed directly, while the other bosons are suffi-
 876 ciently short-lived that they can only be measured from their decay products.

877 Because the W and Z bosons interact with both quarks and leptons, they are
 878 responsible for the production of leptons in proton-proton collisions. Z bosons
 879 produce pairs of opposite sign, same flavor leptons. W bosons, on the other hand,
 880 produce a single lepton and the corresponding neutrino.

881 2.5.2 STRONG PHYSICS

882 The phenomenology of the strong sector differs significantly from the weak sector
 883 because the gluons are massless but color charged. Because of this, gluons
 884 can interact with each other, and contributions from multiple gluon interactions
 885 lead to a significant growth in the strength of the field at low energies. The depen-
 886 dence of the field strength on the energy scale is described by renormalization,
 887 and in QCD the coupling is only small at high energies. Above around the GeV
 888 scale, the interactions of quarks become perturbative, similar to the electroweak
 889 fields; this phenomenon is known as asymptotic freedom.

890 At lower energies, however, the strength of the strong interaction is so signif-
 891 icant that the interactions of color-charged particles create additional particles
 892 until they form neutral bound-states. This process is known as hadronization,
 893 and explains why no quarks are observed isolated in nature: they all form bound
 894 states of hadrons like protons, neutrons, and pions. The hadronization process
 895 can produce a significant number of particles, so that a single energetic quark
 896 recoiling against another quark can generate a cascade of dozens of hadrons.
 897 Because of the initial boost of such an energetic configuration, the resulting
 898 hadrons are collimated, and conical spray of particles often referred to as a jet.

899 2.5.3 PROTON-PROTON COLLISIONS

900 Proton-proton collisions are a convenient way to generate high energy interac-
 901 tions to probe the SM and to search for new physics. At the energies that will be
 902 discussed in this analysis, the substructure of the protons is very important to the
 903 description of the resulting interactions. At lowest order, protons are composed
 904 of two up quarks and one down quark, but this description is incomplete. The
 905 actual bound state includes a chaotic sea of additional quarks and gluons, each of
 906 which carries a variable fraction of the proton's energy. When a proton-proton
 907 collision takes place, it is these constituents that interact with each other, result-
 908 ing in a highly variable collision energy even when the proton-proton energy is
 909 consistent.

910 The fraction of the energy carried by each constituent varies moment to mo-
 911 ment, but can be modelled probabilistically by PDFs. These are difficult to pre-
 912 dict theoretically, as the QCD calculations are extremely complex, and instead
 913 are measured in hard-scattering experiments. They are usually represented by
 914 how often a given type of particle carries a fraction x of the total proton energy.
 915 Those fraction change significantly with the scale of the interaction; the PDFs of
 916 proton-proton collisions at both $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$ are shown
 917 in Figure 4.

918 2.6 LIMITATIONS

919 Despite the great success of the relatively simple SM in describing such a broad
 920 range of emergent phenomena, it is clear that the picture it presents of the in-
 921 teractions of fundamental particles is incomplete. The SM contains concerning

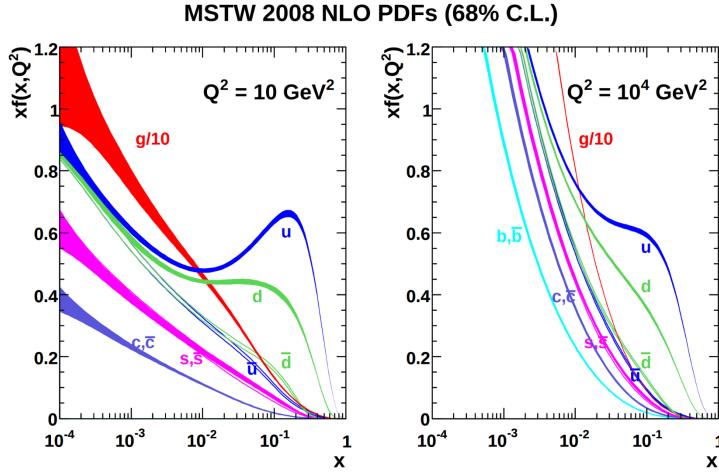


Figure 4: The PDFs for proton-proton collisions at $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$. Each shows the fraction of particles which carry a fraction x of the total proton energy at the specified scale [1].

922 coincidences that suggest a more ordered underlying substructure that is not ex-
 923 pressed in the current form. It also fails to explain a number of cosmological
 924 measurements of the nature of matter in the universe. These limitations suggest
 925 the need for new, beyond the Standard Model (BSM) physics that would provide
 926 a more complete description at higher energies.

927 2.6.1 THEORETICAL CONCERNs

928 There have been no successful integrations of the SM's description of the elec-
 929 troweak and strong forces with the description of gravity, and it is still unclear
 930 how to account for the effects of gravity at the Plank scale of approximately 10^{19}
 931 GeV, where it can no longer be ignored. The Plank scale is an important cutoff
 932 for the SM, as it is clear that the SM must break down somewhere between the
 933 current highest energy tests of the SM, around 1 TeV, and the Plank scale.

934 One example of this is the Higgs mass, which is determined in the SM by a
 935 sum of its bare mass and the interactions in the vacuum with all massive parti-
 936 cles. As their must be new physics at the Plank scale to describe gravity, some
 937 of those corrections would include contributions at a scale seventeen orders of
 938 magnitude above the mass of the Higgs. Either the bare mass of the Higgs boson
 939 precisely cancels those contributions to leave a remainder seventeen orders of
 940 magnitudes smaller, or a new theory exists at a lower scale the shields the Higgs
 941 mass from those terms. A theory where such a unlikely cancellation of free pa-
 942 rameters occurs is called fine-tuned, and one that is free from such cancellations
 943 is called natural. Theories where the mass of the Higgs is natural are usually
 944 preferred, as the suggest an underlying, coherent structure.

945 There is also a compelling argument that the $SU(3) \times SU(2) \times U(1)$ gauge
 946 structure of the SM might originate from a single, unified gauge theory. For ex-
 947 ample, it is possible to represent that gauge structure as a $SU(5)$ gauge group

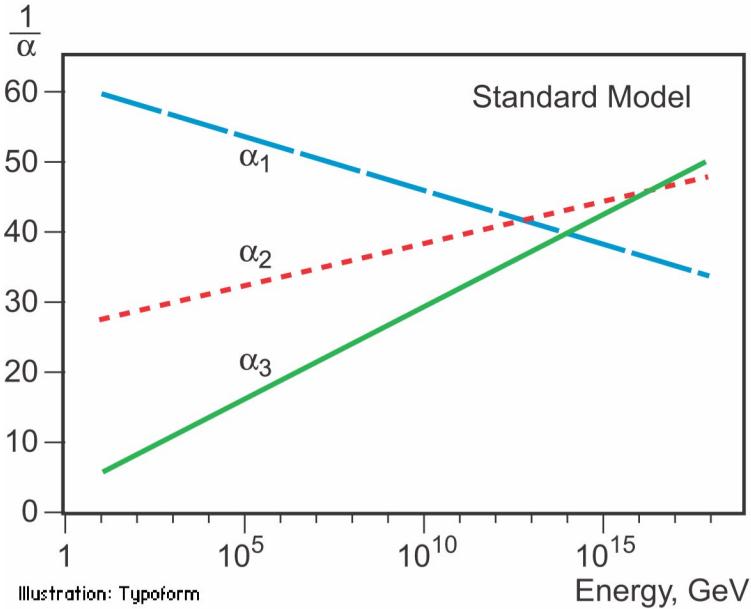


Figure 5: The running of the coupling constants in the SM up to the Planck scale.

948 with only a few inconsistencies with the current implementation. This unifica-
 949 tion is suggested by the scaling of the coupling constants for each of the forces
 950 under renormalization, they come close to converging to a single value at higher
 951 energies, as seen in Figure 6. An additional correction to the scaling of the cou-
 952 pling constants from new physics above the TeV scale could cause them to merge
 953 into a single value at high energies.

954 2.6.2 COSMOLOGICAL OBSERVATIONS

955 The SM contains a symmetry in the description of matter and antimatter that is
 956 not reflected in cosmological observations. The process of the standard model
 957 create or remove matter and antimatter in equal amounts, so a universe that be-
 958 gins with an equal quantity of each should result in a universe with an approxi-
 959 mate balance of matter and antimatter. However, cosmological observations of
 960 the relative amount of each type clearly show that the directly observable mass
 961 of the universe is overwhelmingly made of matter. As this difference is largely
 962 a difference in the generation of baryons and anti-baryons, this discrepancy is
 963 often referred to as the baryogenesis problem.

964 A number of astrophysical observations of large scale gravitational interac-
 965 tions suggest the presence of a significant amount of non-luminous matter that
 966 interacts with the normal matter only gravitationally. The first evidence of this
 967 came from the observation of galactic rotation curves, the velocities of stars as
 968 a function of the radius from the center of a galaxy. These can be directly pre-
 969 dicted from the amount of matter contained within the sphere up to the radius
 970 of the star. An estimate based only on the luminous matter in the galaxies would
 971 predict a dependence that falls off with the radius, but the observed curves show
 972 a mostly constant distribution of velocities [2], as seen in Figure ???. The higher

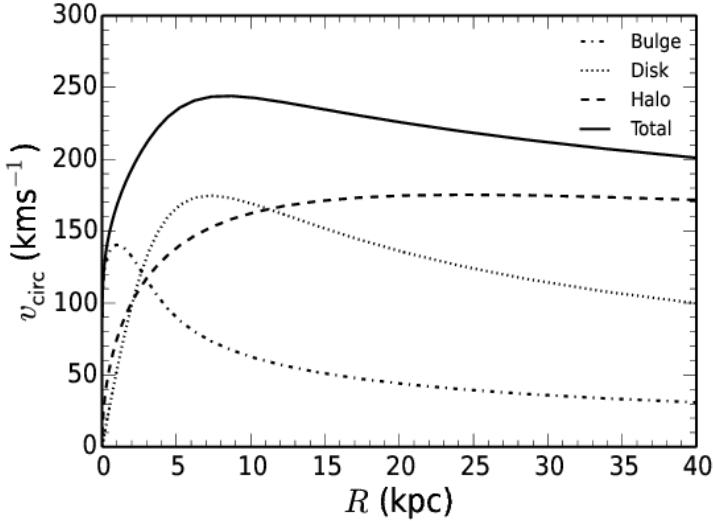


Figure 6: The distribution of velocities of stars as a function of the radius from the center of the galaxy. The contributions to the velocity from the various components of matter in the galaxy are shown [2].

973 velocities than predicted by the luminous matter can be explained by a halo of
 974 dark matter that extends significantly outside the galactic disk.

975 This dark matter accounts for a majority of the matter in the universe, and is
 976 incompatible with the matter particles predicted by the SM. Many observations
 977 support its existence, but there have been no direct detections of a particle which
 978 could account for the large quantity of gravitationally interacting dark matter.
 979 The SM would have to require a significant extension to include the particles
 980 needed to explain dark matter and the processes needed to explain the observed
 981 matter-antimatter asymmetry.

3

⁹⁸²

⁹⁸³ SUPERSYMMETRY

⁹⁸⁴ 3.1 MOTIVATION

⁹⁸⁵ 3.2 STRUCTURE

⁹⁸⁶ 3.3 PHENOMENOLOGY

4

987

988 LONG-LIVED PARTICLES

989 4.1 MECHANISMS

990 4.1.1 EXAMPLES IN SUPERSYMMETRY

991 4.2 PHENOMENOLOGY

992 4.2.1 DISIMILARITIES TO PROMPT DECAYS

993 4.2.2 CHARACTERISTIC SIGNATURES

994

PART III

995

EXPERIMENTAL STRUCTURE AND RECONSTRUCTION

996

You can put some informational part preamble text here.

997

998 THE LARGE HADRON COLLIDER

1000 The LHC, a two-ring superconducting hadron accelerator, provides high energy
 1001 proton-proton collisions for several large experiments at European Organization
 1002 for Nuclear Research (CERN) in Geneva, Switzerland [3, 4]. It is the largest,
 1003 highest-luminosity, and highest-energy proton collider ever built, and was con-
 1004 structed by a collaboration of more than 10,000 scientists from the more than
 1005 100 countries that contribute to CERN. The original design of the LHC focused on
 1006 providing collision energies of up to 14 TeV and generating enough collisions to
 1007 reveal physics beyond the SM which is predicted to exist at higher energy scales.

1008 The LHC was installed in an existing 27 km tunnel at CERN which was origi-
 1009 nally designed to house the Large Electron Positron collider (LEP). This allows
 1010 the collider to use existing accelerators at the same complex to provide the initial
 1011 acceleration of protons up to 450 GeV before injecting into LHC. The injected
 1012 hadrons are accelerated up to as much as 14 TeV while being focused into two
 1013 beams traveling in opposite directions. During this process the protons circulate
 1014 around the tunnel millions of times, while the beams are intermittently crossed
 1015 at the four locations of the experiments to provide collisions. These collision
 1016 points correspond to the four major LHC experiments: ATLAS, Compact Muon
 1017 Solenoid (CMS), Large Hadron Collider beauty experiment (LHCb), and A Large
 1018 Ion Collider Experiment (ALICE), and Figure 7 shows the layout of the exper-
 1019 iments both on the surface and below. ATLAS and CMS are both general pur-
 1020 pose, high-luminosity detectors which search for a wide range of new types of
 1021 physics [5, 6]. LHCb studies the interactions of b-hadrons to explore the asymme-
 1022 try between matter and antimatter [7]. ALICE focuses on the collisions of lead
 1023 ions, which the LHC also provides, in order to study the properties of quark-
 1024 gluon plasma [8].

1024 During the first five years of operation, after the LHC turned on in 2010, the
 1025 LHC has provided four major data collecting periods. In 2010 the LHC generated
 1026 collisions at several energies, starting at 900 GeV. It increased the energy from
 1027 900 GeV to 2.76 TeV and then subsequently to 7 TeV, with a peak luminos-
 1028 ity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, and a total delivered luminosity of 50 pb^{-1} . The next
 1029 run, during 2011, continued the operation at 7 TeV and provided an additional 5
 1030 fb^{-1} with a peak luminosity of $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The energy was then increased
 1031 to 8 TeV for the data collection during 2012, which provided 23 fb^{-1} with a peak
 1032 luminosity of $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. After the first long shutdown for 2013 and
 1033 2014, the LHC resumed operation and increased the energy to 13 TeV in 2015,
 1034 where it delivered 4.2 fb^{-1} with a peak luminosity of $5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The
 1035 LHC is currently providing additional 13 TeV collisions in 2016 with higher lu-
 1036 minosities than during any previous data collection periods. These running peri-
 1037 ods are summarized in Figure 8, which shows the total delivered luminosity over

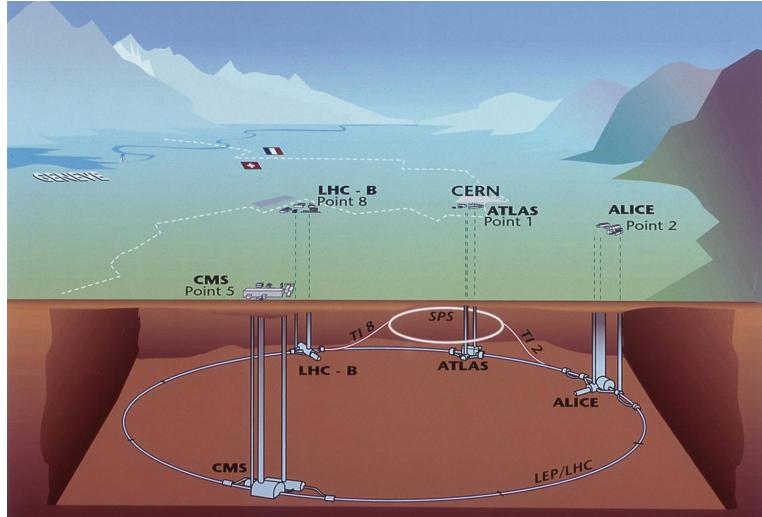


Figure 7: The four collision points and corresponding experiments of the [LHC](#). The image includes the location of the nearby city of Geneva as well as the border of France and Switzerland.

1038 time for the [ATLAS](#) experiment during each of the four years of data collection
 1039 since 2011.

1040 5.1 INJECTION CHAIN

1041 The [LHC](#) takes advantage of the presence of previously built accelerators at [CERN](#)
 1042 to work up to the target energy in consecutive stages. The series of accelerators
 1043 that feed into the [LHC](#) are known collectively as the injection chain, and together
 1044 with the [LHC](#) form the accelerator complex. The full complex is illustrated in
 1045 Figure 9, which details the complex series required to reach collisions of 13 or
 1046 14 TeV.

1047 Protons at the [LHC](#) begin as hydrogen atoms in the Linac 2, a linear accelerator
 1048 which replaced Linac 1 as the primary proton accelerator at CERN in 1978. In
 1049 Linac 2, the hydrogen atoms are stripped of their electrons by a strong magnetic
 1050 field, and the resulting protons are accelerated up to 50 MeV by cylindrical con-
 1051 ductors charged by radio frequency cavities. The protons are then transferred
 1052 to the Proton Synchrotron Booster ([PSB](#)), which uses a stack of four synchrotron
 1053 rings to accelerate the protons up to 1.4 GeV. Then the protons are injected
 1054 into the Proton Synchrotron ([PS](#)) which again uses synchrotron rings to bring
 1055 the energy up to 25 GeV. The intermediate step between Linac 2 and the [PS](#) is
 1056 not directly necessary, as the [PS](#) can accelerate protons starting from as low as
 1057 50 MeV. The inclusion of the [PSB](#) allows the [PS](#) to accept a higher intensity of
 1058 injection and so increases the deliverable luminosity in the [LHC](#). The penulti-
 1059 mate stage of acceleration is provided by the Super Proton Synchrotron ([SPS](#)), a
 1060 large synchrotron with a 7 km circumference that was commissioned at CERN
 1061 in 1976. During this step the protons increase in energy to 450 GeV, after which
 1062 they can be directly injected into the [LHC](#).

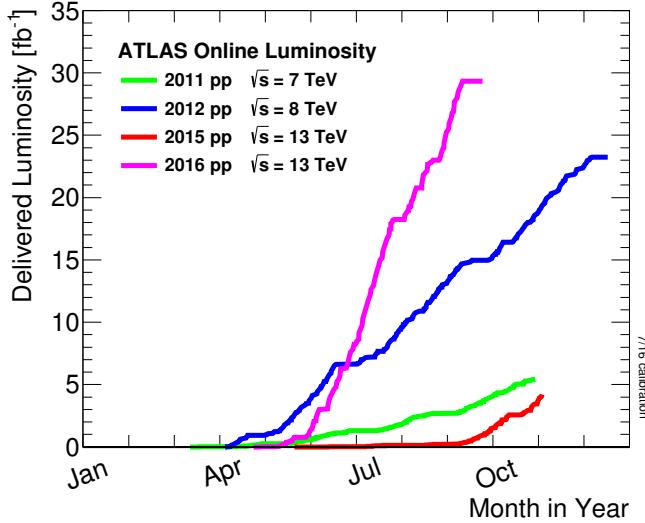


Figure 8: The cumulative luminosity over time delivered to the ATLAS experiment from high energy proton-proton collisions since 2011. The energies of the collisions are listed for each of the data-taking periods.

1063 The final step is the LHC itself, which receives protons from the SPS into two
 1064 separate beam pipes which circulate in opposite directions. The filling process
 1065 at this steps takes approximately 4 minutes, and the subsequent acceleration to
 1066 the final energy (6.5 TeV during 2015 and up to 7 TeV by design) takes approxi-
 1067 mately half an hour. At this point the protons circulate around the circumference
 1068 tens of thousands of times a second and continue for up to two hours.

1069 5.2 DESIGN

1070 5.2.1 LAYOUT

1071 Many of the aspects of the LHC design are driven by the use of the existing LEP
 1072 tunnel. This tunnel slopes gradually, with a 1.4% decline, with 90% of its length
 1073 built into molasse rock which is particularly well suited to the application. The
 1074 circumference is composed of eight 2987 meter arcs and eight 528 meter straight
 1075 sections which connect them; this configuration is illustrated in Figure 10. The
 1076 tunnel diameter is 3.7 m throughout its length.

1077 The design energy is directly limited by the size of this tunnel, with its radius
 1078 of curvature of 2804 m. A significant magnetic field is required to curve the
 1079 protons around that radius of curvature; the relationship is given by

$$p \simeq 0.3BR \quad (13)$$

1080 where p is the momentum of the particle in GeV, B is the magnetic field in Tesla,
 1081 and R is the radius of curvature in meters. From the target design energy of
 1082 14 TeV, or 7 TeV of momentum for protons in each beam, the required mag-
 1083 netic field is 8.33 Tesla. This is too large a field strength to be practical with

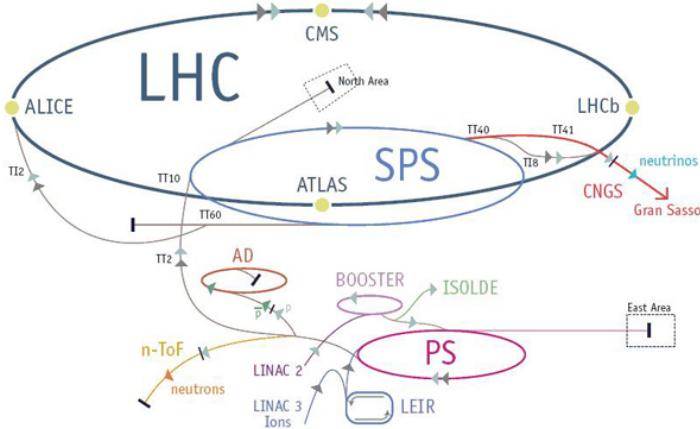


Figure 9: The accelerator complex that builds up to the full design energies at the [LHC](#). The protons are passed in order to Linac 2, the [PSB](#), the [PS](#), the [SPS](#) and then the [LHC](#).

iron electromagnets, because of the enormous power required and the resulting requirements for cooling. Because of these constraints, the [LHC](#) uses superconducting magnets which can maintain that field strength with significantly less power consumption.

5.2.2 MAGNETS

Specifically the magnets chosen were Niobium and Titanium (NbTi) which allow for field strengths as high as 10 Tesla when cooled down to 1.9 K. Reaching the target temperature of 1.9 K for all of the magnets requires superfluid helium and a large cryogenic system along the entire length of the tunnel. During normal operation, the [LHC](#) uses 120 tonnes of helium within the magnets, and the entire system is cooled by eight cryogenic helium refrigerators. The temperature increase that occurs during transit from the refrigerator along the beam necessitates that the refrigerators cool the helium down to 1.8 K. Any significant increase above this temperature range can remove the superconductive properties of the magnets, which in turn generates drastically larger heat losses from the current within the magnets and causes a rapid rise in temperature called a quench.

In all there are approximately 8000 superconducting magnets distributed around the [LHC](#). The 1232 bending magnets, which keep the protons curving along the length of the beam, are twin bore cryodipoles, which allow both proton beams to be accommodated by one magnet and all of the associated cooling structure. Figure 11 shows the cross section of the design for these dipoles. The magnets are very large, 16.5 m long with a diameter of 0.57 meters and a total weight of 28 tonnes. They are slightly curved, with an angle of 5.1 mrad, in order to carefully match the beam path. The twin bore accommodates both magnets inside the two 5 cm diameter holes which are surrounded by the superconducting coils. The coils require 12 kA of current in order to produce the required mag-

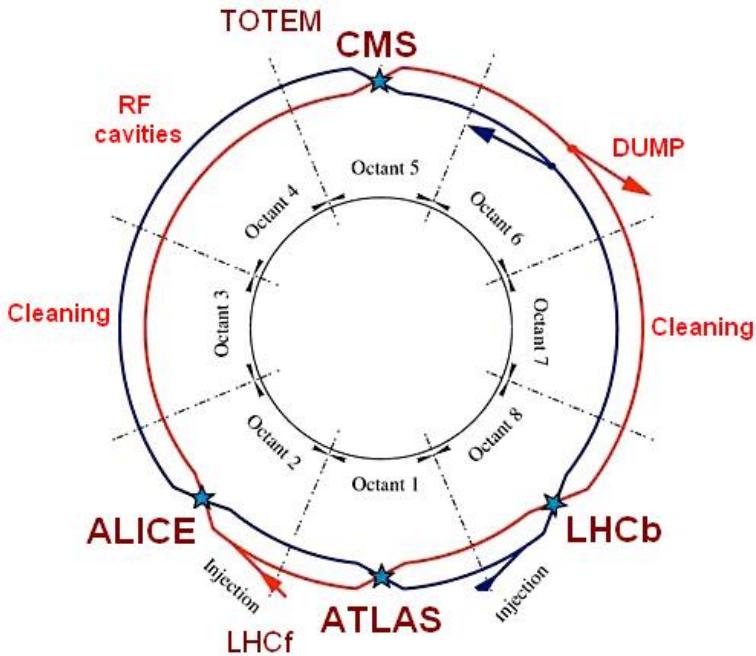


Figure 10: A schematic of the layout of the LHC, not to scale. The arched and straight sections are illustrated at the bottom of the schematic, and all four crossing sites are indicated with their respective experiments.

111 netic field. These coils are comprised of NbTi cable wound in two layers; the
 112 wire in the inner layer has a diameter of 1.065 mm while the wire in the outer
 113 layer has a diameter of 0.825 mm.

114 The large currents in the wires, along with the magnetic field produced, result
 115 in forces on the magnets which would tend to push them apart with over 10,000
 116 Newtons per meter. Constraining the magnets requires a significant amount of
 117 structure including non-magnetic stainless steel collars. Both the presence of
 118 these electromagnetic forces and the varying thermal contraction coefficient of
 119 the pieces of the magnet produce significant forces on the cold mass structure.
 1120 The cold mass is carefully engineered to so that these stresses do not significantly
 1121 alter the magnetic field shape, which must be maintained between magnets to a
 1122 precision of approximately 10^{-4} for successful operation.

1123 The remaining 6800 magnets are a variety of quadrupole, sextapole, octopole,
 1124 and single bore dipole magnets. These are used to damp oscillations, correct
 1125 beam trajectories, focus the beams during circulation, and to squeeze the beams
 1126 before collisions.

1127 5.2.3 RF CAVITIES

1128 Sixteen RF cavities produce the actual acceleration of the proton beam up to the
 1129 design energy. These RF cavities are tuned to operate at 400 MHz, and are pow-
 1130 ered by high-powered electron beams modulated at the same frequency, called
 1131 klystrons. The resonance within the cavity with the oscillating electric field
 1132 establishes a voltage differential of 2 MV per cavity. The sixteen cavities are

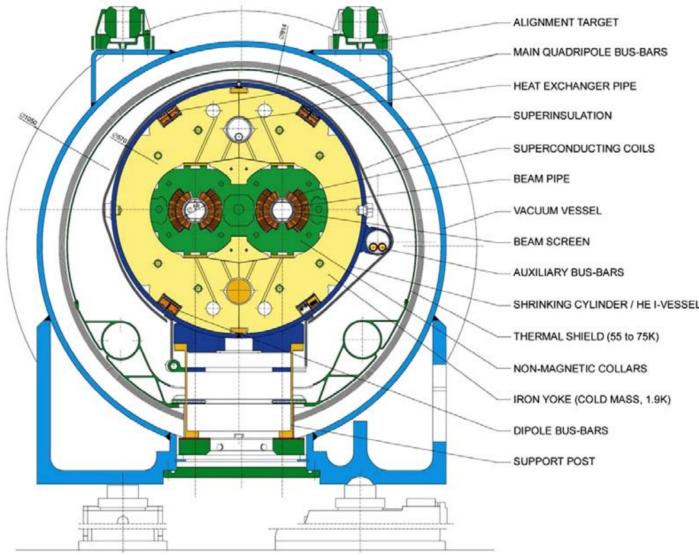


Figure 11: A cross section of the cryodipole magnets which bend the flight path of protons around the circumference of the LHC. The diagram includes both the superconducting coils which produce the magnetic field and the structural elements which keep the magnets precisely aligned.

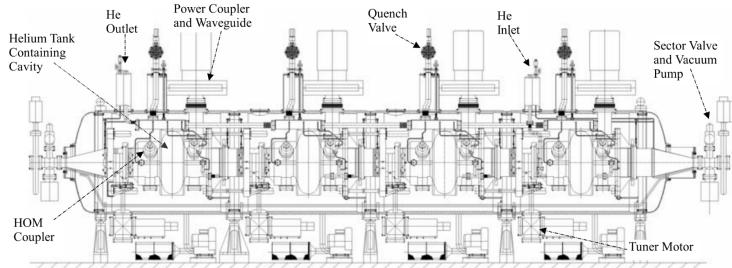


Figure 12: The arrangement of four RF cavities within a cryomodule.

split between the two beams, so combined the cavities provide 16 MV per beam, which accelerate the protons on each consecutive pass through the cavity. This acceleration is also necessary during circulation even after the target energy has been reached in order to compensate for losses from synchrotron radiation.

The cavities are arranged in cryomodules which contain four cavities, with two cryomodules per beam; this arrangement is illustrated in Figure 12. These cryomodules are necessary to maintain the superconducting state of the cavities, which are also constructed from niobium. The RF cavities use niobium along with copper to allow for low power losses in the superconductors. The copper provides a reduced susceptibility to quenching, as it rapidly conducts away heat generated by imperfections in the niobium, as well as natural shielding from the earth's magnetic field which can interfere with the RF system.

The nature of the radio frequency oscillations tends to group protons together into buckets. A proton traveling exactly in phase with the RF oscillations will not be displaced at all during a single circulation, and those slightly ahead or behind

1148 of that phase will slightly decelerate or accelerate, respectively. This produces
 1149 separate clusters of protons which arrive in phase to the cavities every 2.5 ns,
 1150 corresponding to the 400 MHz frequency.

1151 5.2.4 BEAM

1152 The beams of protons circulate within 54 km of 5 cm diameter beam pipe. This
 1153 entire structure is kept under vacuum at 1.9 K to prevent interactions between
 1154 the beam pipe and the magnets as well as to prevent any interactions between the
 1155 circulating protons and gas in the pipe. The vacuum within the pipe establishes
 1156 a pressure as low as 10^{-9} mbar before the protons are introduced.

1157 Because of the very high energies of the circulating protons, synchrotron ra-
 1158 diation is not negligible in the bending regions. The protons are expected to
 1159 radiate 3.9 kW per beam at 14 TeV, with 0.22 W/m, which is enough power to
 1160 heat the liquid helium and cause a quench were it absorbed by the magnets. To
 1161 prevent this, a copper screen is placed within the vacuum tube that absorb the
 1162 emitted photons. This screen is kept between 5 and 20 K by the liquid helium
 1163 cooling system.

1164 5.3 LUMINOSITY PARAMETERS

1165 In addition to the high energy of the collisions, the rate of collisions is extremely
 1166 important to enabling the discovery of new physics. Many measurements and
 1167 searches require a large number of events in order to be able to make statistically
 1168 significant conclusions. The rate of collisions is measured using luminosity, the
 1169 number of collisions per unit time and unit cross section for the proton-proton
 1170 collisions. From the beam parameters, luminosity is given by

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F \quad (14)$$

1171 where N_b is the number of protons per bunch, n_b is the number of bunches per
 1172 beam, f_{rev} is the frequency of revolution, γ is the Lorentz factor for the protons
 1173 at the circulating energy, ϵ_n is the emittance, β^* is the amplitude function at the
 1174 collision point, and F is a geometric factor that accounts for the crossing angle of
 1175 the beams at the collision point. The emittance measures the average spread of
 1176 particles in both position and momentum space, while the amplitude function
 1177 is a beam parameter which measures how much the beam has been squeezed.
 1178 Together ϵ_n and β^* give the size of the beam in the transverse direction, $\sigma = \sqrt{\epsilon \beta^*}$. β
 1179 changes over the length of the beam as the accessory magnets shape the
 1180 distribution of protons, but only the value at the point of collisions, β^* , affects
 1181 the luminosity.

1182 The luminosity is maximized to the extent possible by tuning the parameters
 1183 in Equation 14. A number of these are constrained by the design decisions. The
 1184 revolution frequency is determined entirely by the length of the tunnel, as the

Parameter	Unit	Injection	Nominal
Beam Energy	TeV	0.450	7
Peak Instantaneous Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	-	10^{34}
Bunch Spacing	ns	25	25
Number of Filled Bunches	-	2808	2808
Normalized Transverse Emittance	μm	3.75	3.75
Frequency	MHz	400.789	400.790
RF Voltage/Beam	MV	8	16
Stored Energy	MJ	-	362
Magnetic Field	T	0.54	8.33
Operating Temperature	K	1.9	1.9

Table 1: The design parameters of the [LHC](#) beam that determines the energy of collisions and the luminosity, for both the injection of protons and at the nominal circulation.

1185 protons travel at very close to the speed of light. The geometric factor F is de-
 1186 determined by the crossing angle of the beams at the collision points, again a com-
 1187 ponent of the tunnel design; this angle is already very small at $285 \mu\text{rad}$, which
 1188 helps to maximize the geometric factor.

1189 The major pieces that can be adjusted are the number of protons per bunch,
 1190 N_b , the number of bunches in the beam, n_b , and the amplitude function β . In-
 1191 creasing either N_b or n_b increases the amount of energy stored in the beam,
 1192 which presents a danger if control of the beam is lost. At design specifications,
 1193 the beam stores 362 MJ, which is enough energy to damage the detectors or ac-
 1194 celerator if the beam were to wander out of the beam pipe. So, the luminosity
 1195 is primarily controlled at the [LHC](#) by adjusting β^* , where lowering β^* increases
 1196 the luminosity. β^* is tuned to provide the various values of luminosity used at
 1197 the [LHC](#) which can be raised to as much as 10^{34} .

1198 The nominal bunch structure consists of 3654 bunches, each holding 10^{11} pro-
 1199 tons, which cross a collision point in 25 ns. These are further subdivided into the
 1200 buckets mentioned in Section 5.2.3 by the clustering properties of the [RF](#) cavities.
 1201 The bunches are further grouped into trains of 72 bunches which are separated
 1202 by a gap which would otherwise hold 12 bunches. At nominal operation 2808
 1203 of the bunches will actually be filled with protons, while the remainder are left
 1204 empty to form an abort gap that can be used in case the beam needs to be dumped.

1205 The various beam parameters are summarized in Table 1 for the designed op-
 1206 eration. In practice the beam has operated at lower energies and lower luminosi-
 1207 ties than the design values, but the [LHC](#) is expected to operate at the full design
 1208 values during Run 2.

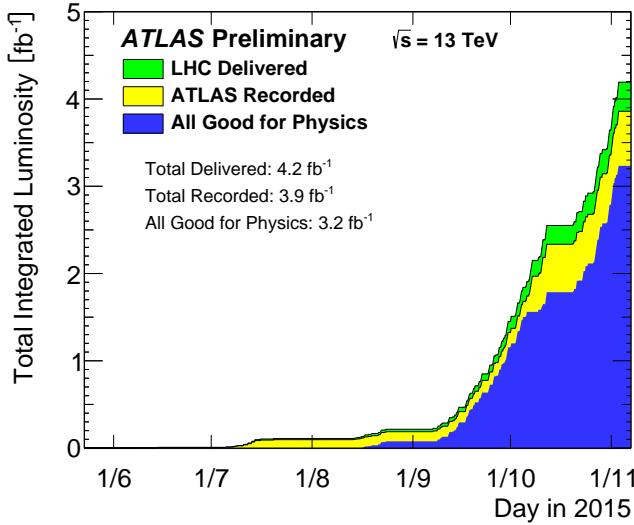


Figure 13: The cumulative luminosity versus time delivered to ATLAS (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams for pp collisions at 13 TeV in 2015.

1209 5.4 DELIVERED LUMINOSITY

During the data collection of 2015, the [LHC](#) operated at luminosities as large as 5×10^{33} . It is convenient to refer to the integrated luminosity, the integral of the instantaneous luminosity, which corresponds directly to the number of delivered events for a given process.

$$N = \sigma \times \int \mathcal{L}(t) dt$$

1210 where σ is the cross section for the process of interest. The integrated luminosity over time is shown in Figure 13. This includes the luminosity delivered by
 1211 the [LHC](#) as well as the luminosity that was recorded by [ATLAS](#). Some of the de-
 1212 livered luminosity is not recorded because [ATLAS](#) is placed in standby until the
 1213 [LHC](#) reports that the beam conditions are stable, and only then does [ATLAS](#) begin
 1214 recording. The figure also includes the amount of luminosity marked as good for
 1215 physics, which includes additional requirements on the operation of the detector
 1216 during data collection that are necessary for precise measurements.
 1217

1218 In addition to the instantaneous luminosity, the beam conditions also influ-
 1219 ence the number of collisions that occur within a single bunch crossing. The
 1220 multiple interactions at each crossing are referred to as pileup, often denoted μ ,
 1221 and each of these interactions are present in a single measured event. Figure 14
 1222 shows the luminosity-weighted distribution of the mean number of interactions
 1223 for events collected in 2015. The presence of as many as 20 events in a single
 1224 collision provides a significant challenge in reconstructing events and isolating
 1225 the targeted physical processes.

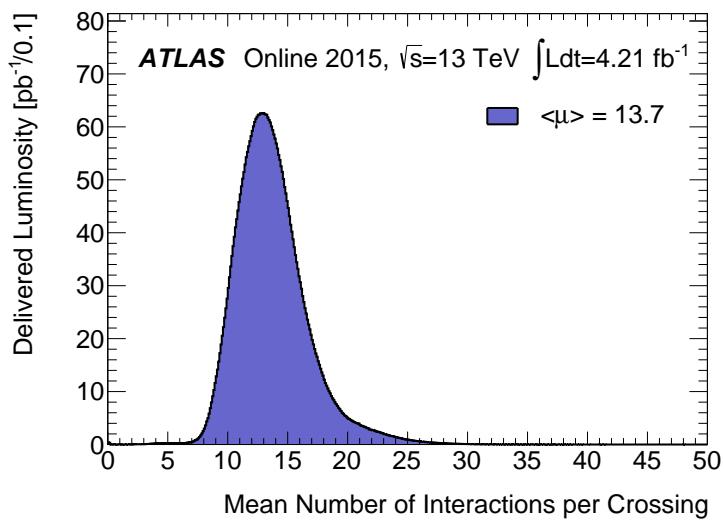


Figure 14: The luminosity-weighted distribution of the mean number of interactions per crossing for the 2015 pp collision data at 13 TeV.

1226

1227 THE ATLAS DETECTOR

1228 The four major LHC experiments at CERN seek to use the never before matched
1229 energies and luminosities of the new collider to explore the boundaries of par-
1230 ticle physics and to gain insight into the fundamental forces of nature. Two of
1231 these experiments, ATLAS and CMS, are general purpose detectors that seek to
1232 measure a variety of processes in the up to 14 TeV proton-proton collisions that
1233 occur as much as 40 million times per second at the LHC at the design luminosity
1234 of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. ATLAS employs a hermetic detector design, one which encloses
1235 the particle collisions as completely as possible with detecting elements, that al-
1236 lows it to study a wide range of physics from SM and Higgs measurements to
1237 searches for new physics in models like Supersymmetry [5].

1238 Accommodating this wide variety of goals is a challenge for the design of
1239 the detector. The wide range of energies involved requires high measurement
1240 precision over several orders of magnitude and the ability to measure a vari-
1241 ety of particle types. At the time of the construction of ATLAS, the Higgs bo-
1242 son had yet to be discovered, but the diphoton decay mode was (correctly) ex-
1243 pected to be important and necessitated a high resolution photon measurement.
1244 The potential for decays of new heavy gauge bosons, W' and Z' , required a simi-
1245 larly high momentum resolution for leptons with momentum up to several TeV.
1246 Hadronic decay modes of several possible new high energy particles could re-
1247 sult in very energetic jets, again up to several TeV, and reconstructing the decay
1248 resonances would again require good energy resolution. Several models, such
1249 as Supersymmetry (SUSY) or Extra Dimensions, predict the existence of particles
1250 which would not interact with traditional detecting elements. However these
1251 particles can still be observed in a hermetic detector by accurately measuring
1252 the remaining event constituents to observe an imbalance in energy called miss-
1253 ing energy or E_T^{miss} . Measuring E_T^{miss} implicitly requires a good resolution on all
1254 SM particles that can be produced. And at the lower end of the energy spectrum,
1255 precision SM measurements would require good resolution of a variety of parti-
1256 cle types at energies as low as a few GeV, so the design needs to accommodate
1257 roughly three orders of magnitude.

1258 This broad spectrum of measurements requires a variety of detector systems
1259 working together to form a cohesive picture of each collision. Two large magnet
1260 systems provide magnetic fields that provide a curvature to the propagation of
1261 charged particles and allows for precision momentum measurements by other
1262 systems. The inner detector uses a combination of tracking technologies to re-
1263 construct particle trajectories and vertices for charged particles. A variety of
1264 calorimeters measure the energies of hadrons, electrons, and photons over a
1265 large solid angle. A large muon spectrometer identifies muons and uses the sec-
1266 ond magnet system to provide an independent measurement of their momentum

1267 from the inner detector and improve the resolution. The layout of all of these
 1268 systems is shown in Figure 15.

1269 The performance goals needed to achieve the various targeted measurements
 1270 and searches discussed above can be summarized as resolution and coverage re-
 1271 quirements on each of these systems. Those requirements are listed in Table 2.

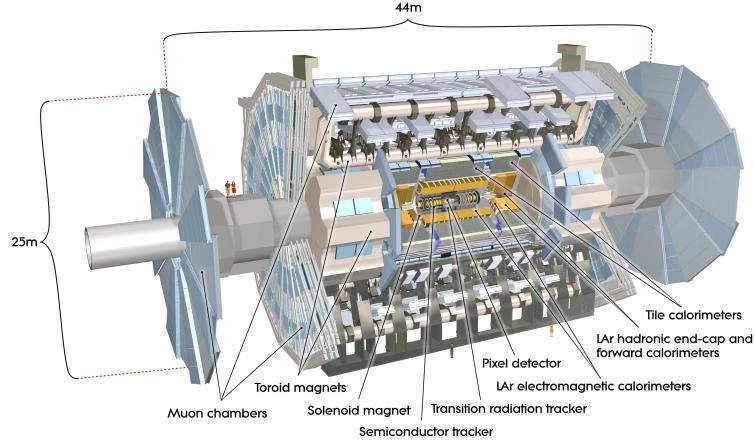


Figure 15: A cut-away schematic of the layout of the [ATLAS](#) detector. Each of the major subsystems is indicated.

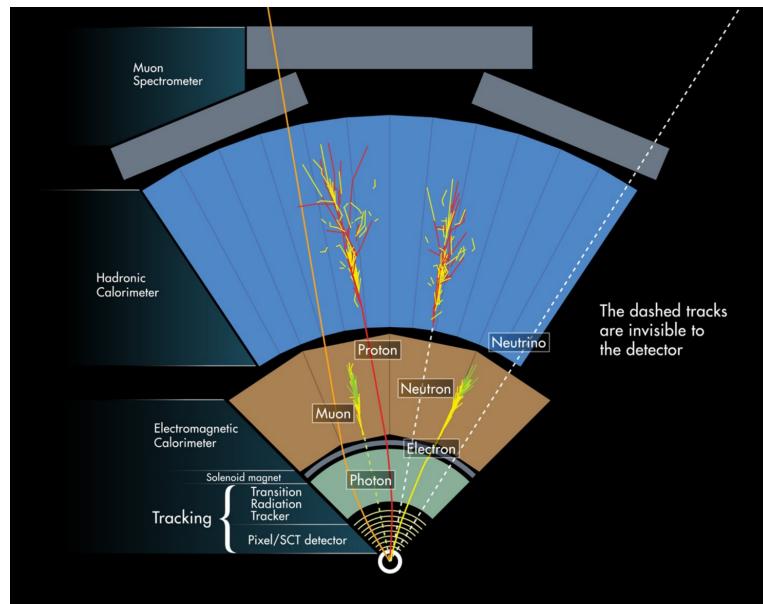


Figure 16: A cross-sectional slice of the [ATLAS](#) experiment which illustrates how the various SM particles interact with the detector systems.

1272 Incorporating these various pieces into a single detector is a significant tech-
 1273 nical challenge. The resulting detector has a diameter of 22 m, is 46 m long,
 1274 and weighs 7,000 tons; it is the largest volume particle detector ever constructed.
 1275 The various detector elements need to be constructed and assembled with pre-
 1276 cision as low as micrometers. These systems all need to function well even after
 1277 exposure to the significant radiation dose from the collisions. Designing, con-

Detector Component	Required Resolution	$ \eta $ Coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T + 1\%$	2.5	-
EM Calorimetry	$\sigma_E/E = 10\%/\sqrt{E} + 0.7\%$	3.2	2.5
Hadronic Calorimetry			
Barrel and Endcap	$\sigma_E/E = 50\%/\sqrt{E} + 3\%$	3.2	3.2
Forward	$\sigma_E/E = 100\%/\sqrt{E} + 10\%$	3.1 – 4.9	3.1 – 4.9
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\% \text{ at } p_T = 1 \text{ TeV}$	2.7	2.4

Table 2: The performance goals for each of the subsystems of the [ATLAS](#) detector. The $|\eta|$ coverage specifies the range where the subsystem needs to be able to provide measurements with the specified resolution. The resolutions include a p_T or E dependence that is added in quadrature with a p_T/E independent piece.

1278 structing, and installing the detector took the combined effort of more than 3000
 1279 scientists from 38 countries over almost two decades.

1280 6.1 COORDINATE SYSTEM

1281 The coordinate system defined for the [ATLAS](#) detector is used throughout all of
 1282 the sections of this thesis. The choice of coordinate system reflects the cylindri-
 1283 cal symmetry of the [ATLAS](#) detector, and is oriented by the direction of the
 1284 beamline which defines the z -direction. The positive z side of the detector is
 1285 commonly referred to as the A -side, and the negative z side is referred to as
 1286 the C -side. The $x - y$ plane is then the plane transverse to the beam direction,
 1287 with the x direction defined as pointing from the interaction point to the center
 1288 of the [LHC](#) ring and the y direction defined as pointing upwards. The nominal
 1289 interaction point is the origin of this system.

1290 It is more convenient in practice to use a cylindrical coordinate system. The
 1291 angle from the z -axis is θ . The azimuthal angle uses the usual definition, with ϕ
 1292 running around the z -axis and $\phi = 0$ corresponding to the x -axis. Many aspects
 1293 of the detector are independent of the this coordinate to first order. The re-
 1294 maining direction is typically specified using rapidity or pseudorapidity, where
 1295 rapidity is defined as

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (15)$$

1296 Rapidity is particularly useful to indicate the component along the z direction
 1297 because differences in rapidity are invariant to boosts along the z -direction. A
 1298 similar quantity which depends only the θ is pseudorapidity,

$$\eta = -\ln \tan \frac{\theta}{2} \quad (16)$$

1299 which is the same as rapidity when the particle is massless and in the limit where
 1300 the energy is much larger than the particle's mass. It is often useful to refer to
 1301 differences in solid angle using the pseudorapidity and the azimuthal angle:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad (17)$$

1302 The pseudorapidity is also invariant to boosts along the z -axis for high mo-
 1303 mentum particles, and is preferable to rapidity because it does not depend on
 1304 the specific choice of particle. Pseudorapidity is also preferable to θ because
 1305 of the aforementioned boost-invariance and also because particle production is
 1306 roughly uniform in equal-width intervals of η up to about $\eta = 5.0$. A particle
 1307 traveling along the beampipe has $\eta = \text{inf}$ and a particle traveling perpendicular
 1308 to the beampipe has $\eta = 0$. The extent of the tracker, $|\eta| < 2.5$, corresponds
 1309 to approximately $0.05\pi < \theta[\text{rad}] < 0.95\pi$ and the extent of the calorimeters,
 1310 $|\eta| < 4.9$ corresponds to approximately $0.005\pi < \theta[\text{rad}] < 0.995\pi$. Many de-
 1311 tector components are broken into multiple subsystems to provide coverage at
 1312 greater $|\eta|$. The lower $|\eta|$ region is referred to as the barrel, typically with $|\eta| \lesssim 2$,
 1313 and the greater $|\eta|$ region is often referred to as the endcap.

1314 The initial energy and momentum of a proton-proton collision along the z di-
 1315 rection is unknown in hadron colliders because different energies and momenta
 1316 can be carried by the partons. Along the transverse plane, however, the vector
 1317 sum of momentum will be zero. For this reason, many physical quantities are
 1318 quantified in terms of their projection onto the transverse plan, such as p_T or
 1319 E_T . In addition, p_T alone determines the amount of curvature in the magnetic
 1320 field, and can be measured independently by measuring the curvature of a parti-
 1321 cle's propagation.

1322 6.2 MAGNETIC FIELD

1323 The magnet system used in [ATLAS](#) is designed to provide a substantial magnetic
 1324 field in the two regions where the trajectory of particles is measured, the inner
 1325 detector and the muon spectrometer. The magnetic field provides a curvature
 1326 to the trajectory of charged particles and allows the precision tracking measure-
 1327 ments to make high resolutions measurements of p_T . To provide a magnetic field
 1328 in these regions, [ATLAS](#) uses a hybrid system with four separate, superconduct-
 1329 ing magnets. A single solenoid provides a 2 T axial magnetic field for the inner
 1330 detector, while a barrel toroid and two endcap toroids produce a magnetic field
 1331 of 0.5 and 1 T, respectively, for the muon detectors. This geometry is illustrated
 1332 in Figure 17, and the parameters of the three magnet systems are summarized in
 1333 Table 3.

1334 The central solenoid uses a single-layer coil with a current of 7.730 kA to gen-
 1335 erate the 2 T axial field at the center of the magnet. The single-layer coil design
 1336 enables a minimal amount of material to be used in the solenoid's construction,
 1337 which is important because the solenoid is placed between the inner detector
 1338 and the calorimeters. At normal incidence the magnet has only 0.66 radiation
 1339 lengths worth of material, where one radiation length is the mean distance over

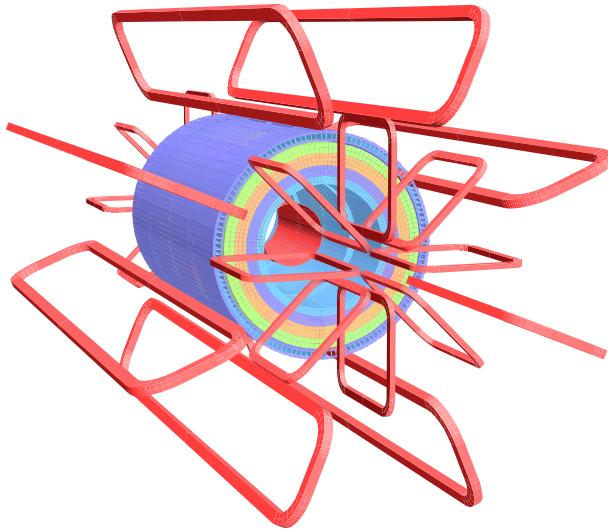


Figure 17: The layout of the four superconducting magnets in the [ATLAS](#) detector.

Parameter	Unit	Solenoid	Barrel Toroid	Endcap Toroids
Inner Diameter	m	2.4	9.4	1.7
Outer Diameter	m	2.6	20.1	10.7
Axial Length	m	5.3	25.3	5.0
Weight	tons	5.7	830	239
Conductor Size	mm ²	30×4.25	57×12	41×4.25
Peak Field	T	2.6	3.9	4.1
Heat Load	W	130	990	330
Current	kA	7.7	20.5	20.0
Stored Energy	MJ	38	1080	206

Table 3: A summary of the parameters of each of the three magnet systems on [ATLAS](#).

1340 which a high-energy electron loses all but $1/e$ of its energy through material in-
 1341 teractions [9]. The coil is made of a high-strength aluminum stabilized NbTi
 1342 superconductor which was optimized to achieve a high field with minimal thick-
 1343 ness. The axial magnetic field produced by the solenoid bends charged particles
 1344 in the ϕ direction.

1345 The barrel toroid consists of eight coils which generate a 0.5 T magnetic field
 1346 in the cylindrical region around the calorimeters with an approximately 20 kA
 1347 current. The coils are separated only by air to reduce the scattering of muons as
 1348 they propagate through the region. The coils are made of an aluminum stabilized
 1349 NbTiCu superconductor and each is separately housed in a vacuum and cold
 1350 chamber. This magnetic configuration produces a field in the ϕ and so curves
 1351 muons traversing the volume primarily in the η direction.

1352 The endcap toroids follow a similar design to the barrel toroid, with eight
 1353 separate NbTiCu coils, but in this case all eight are housed within a single cold
 1354 mass. This extra structure is necessary to withstand the Lorentz forces exerted
 1355 by the magnets. These magnets are rotated 22.5% relative to the barrel toroid to
 1356 provide a uniform field in the transition between the two systems. The endcap
 1357 toroids also produce a field in the ϕ direction and curve muons primarily in the
 1358 η direction.

1359 6.3 INNER DETECTOR

1360 The [ATLAS](#) inner detector provides excellent momentum resolution as well as
 1361 accurate primary and secondary vertex measurements through robust pattern
 1362 recognition that identifies tracks left by charged particles. These tracks fulfill
 1363 a number of important roles in the [ATLAS](#) measurement system: they measure
 1364 the momentum of charged particles including electrons and muons, they can
 1365 identify electrons or photon conversions, they assign various particles and jets
 1366 to different vertices, and they provide a correction to E_T^{miss} measurements from
 1367 low energy particles. The system has to be accurate enough to separate tracks
 1368 from dozens of vertices and to resolve each vertex individually, as well as accu-
 1369 rate enough to measure the p_T of very high momentum tracks which curve very
 1370 little even in the large magnetic field. This is accomplished by several indepen-
 1371 dent layers of tracking systems. Closest to the interaction point is the very high
 1372 granularity Pixel detector, which is followed by the [SCT](#) layers. These subdetec-
 1373 tors both use discrete space-points to reconstruct track patterns. The final layer,
 1374 the transition radiation tracker ([TRT](#)), uses many layers of straw tube elements
 1375 interleaved with transition radiation material to provide continuous tracking.
 1376 The arrangement of these subdetectors is shown in Figure 18. To provide the
 1377 desired hermetic coverage, the subdetectors are divided into barrel and endcap
 1378 geometries. Figure 19 shows the layout of the subdetectors in more detail, and
 1379 illustrates how tracks at various pseudorapidities can traverse the subdetectors;
 1380 tracks with $\eta > 1.1$ begin to traverse the endcap subdetectors rather than those
 1381 in the barrel, and tracks with $\eta > 1.7$ use primarily endcap elements. The [IBL](#)
 1382 was not present during the original commissioning of the inner detector and is
 1383 not shown in this figure.

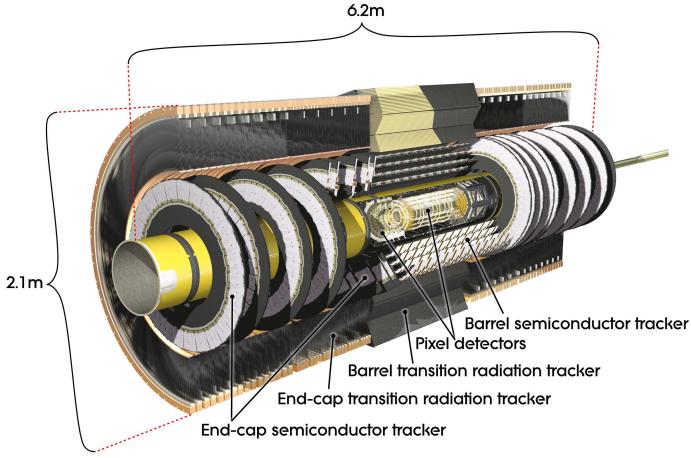


Figure 18: The arrangement of the subdetectors of the ATLAS inner detector. Each of the subdetectors is labeled in the cut-away view of the system.

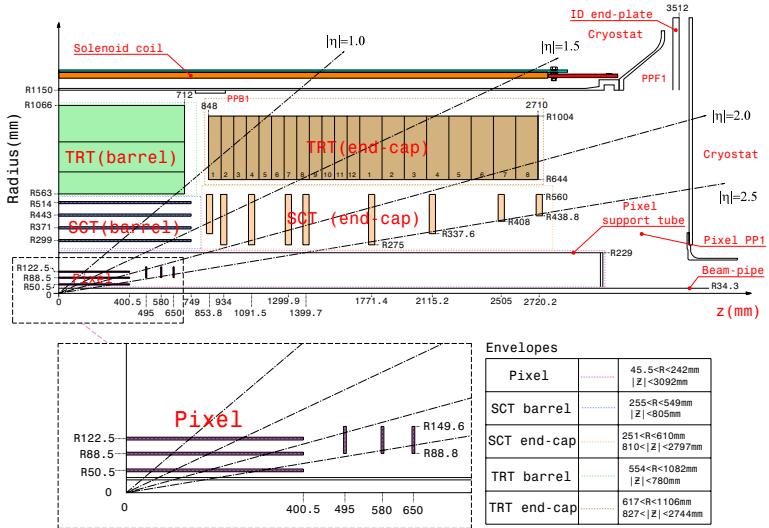


Figure 19: A quarter section of the ATLAS inner detector which shows the layout of each of the subdetectors in detail. The lower panel shows an enlarged view of the pixel detector. Example trajectories for a particle with $\eta = 1.0, 1.5, 2.0, 2.5$ are shown. The IBL, which was added after the original detector commissioning, is not shown.

1384 Figure 20 shows a computer generated three-dimensional view of the inner
 1385 detector along the beam axis, which emphasizes the straw tube structure of the
 1386 **TRT** as well as the overlapping geometry of the **SCT**. This figure also includes
 1387 the **IBL**, which was added during the long shutdown and provides an additional
 1388 measurement layer in the Pixel detector as of the beginning of Run 2. Figure 21
 1389 shows an alternative computer generated three-dimensional view transverse to
 1390 the beam axis which emphasizes the endcap structures of the **SCT** and **TRT**.

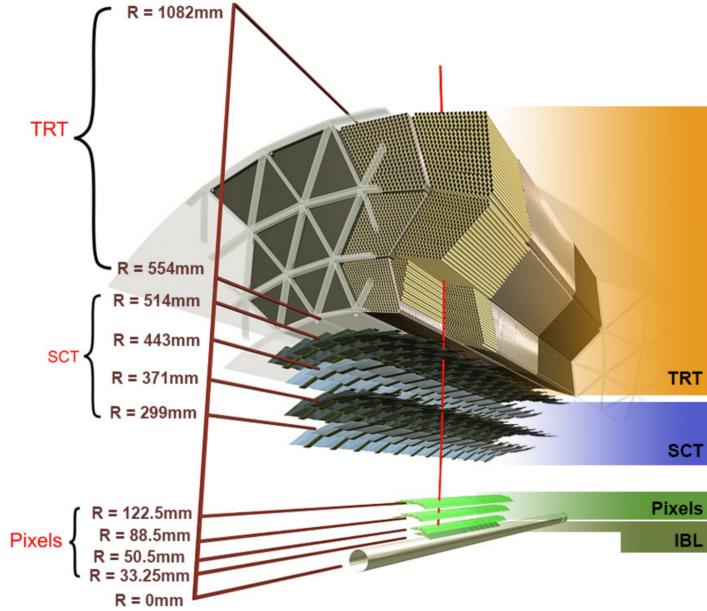


Figure 20: A computer generated three-dimensional view of the inner detector along the line of the beam axis. The subdetectors and their positions are labeled.

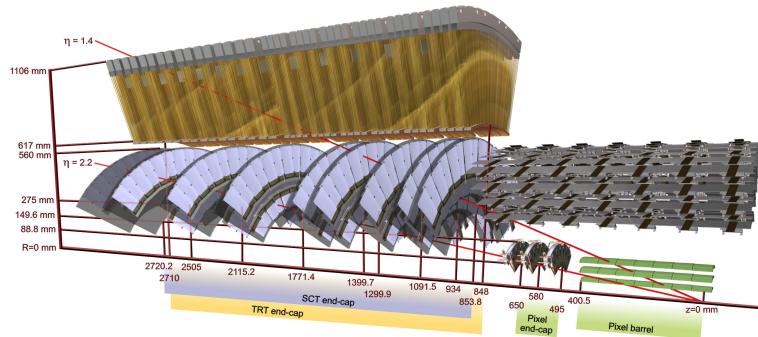


Figure 21: An alternative computer generated three-dimensional view of the inner detector transverse to the beam axis. The subdetectors and their positions are labeled.

1391 As the closest system to the interaction point, it is crucial for the inner de-
 1392 tector to use as little material as possible to avoid scattering of charged parti-
 1393 cles or photon conversions before they reach the remaining subdetectors. The
 1394 various components, including the readout electronics, cooling infrastructure,
 1395 gas volumes, and support structures, were designed to use as little material as

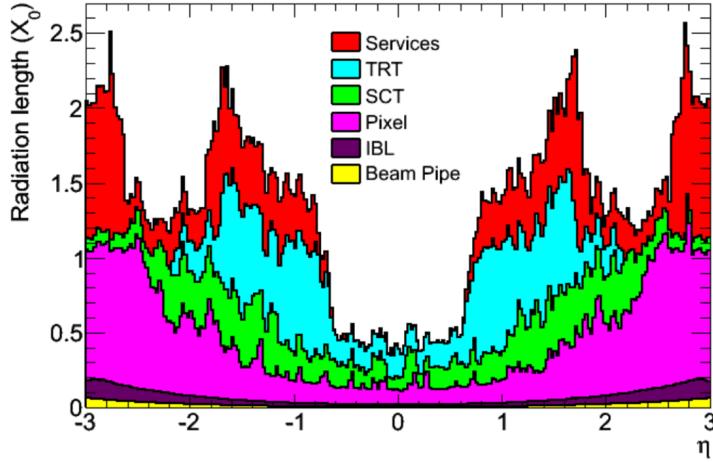


Figure 22: The integrated radiation lengths traversed by a straight track at the exit of the ID envelope, including the services and thermal enclosures. The distribution is shown as a function of $|\eta|$ and averaged over ϕ . The breakdown indicates the contributions of individual sub-detectors, including services in their active volume.

possible. Even with these optimizations, the combination of stringent performance requirements and the harsh radiation environment in the inner detector requires a significant amount of material. This material causes many electrons to lose most of their energy before reaching the electromagnetic calorimeter and approximately 40% of photons convert into an electron-positron pair while traversing the inner detector. Figure 22 shows the integrated radiation lengths traversed by a straight track in the inner detector as a function of η , grouped by subdetector. There is a large increase in the amount of material for support structures around $|\eta| = 1.7$, where the inner detector transitions from barrel to endcap.

The inner detector is designed to work as a cohesive unit to provide complete tracking information for charged particulars, and the subdetectors are complementary. Table 4 summarizes the parameters of each of the subdetectors as well as the parameters of the combined inner detector. Table 5 summarizes the expected performance that can be achieved by the inner detector as a whole.

6.3.1 PIXEL DETECTOR

The Pixel detector is the closest detector to the interaction point and therefore is designed to provide extremely high granularity while simultaneously handling a very large dose of radiation from collisions. It consists of four layers of silicon pixel modules, each of which provides a precision measurement on the trajectory of any charged particle. In the barrel region, the four layers are located at radial distances of 31 mm, 51 mm, 89 mm, and 123 mm. The three outer layers also include endcap elements, illustrated in Figure 19, which are located at 495 mm, 580 mm, and 650 mm away from the interaction point.

Parameter	Inner Detector	Pixel	SCT	TRT
Inner Radius	3.1 cm	3.1 cm	30 cm	56 cm
$ \eta $ Coverage	-	2.5	2.5	2.0
Cell Width	-	50 μm	80 μm	4 mm
Cell Length	-	400 μm	12 cm	70 cm
Material at $ \eta = 0.0$	0.3 X/X_0			
Material at $ \eta = 1.7$	1.2 X/X_0			
Material at $ \eta = 2.5$	0.5 X/X_0			
Number of Hits	48	4	8	36
Channels	99 M	92 M	6.3 M	350 k

Table 4: A summary of the parameters of the inner detector and each of the subdetectors [5].

1420 The pixel sensor technology uses a p-n junction of n-type bulk that contains
 1421 both p⁺ and n⁺ impurities. This combination is crucial in maintaining perfor-
 1422 mance after a significant radiation dose, as the n⁺ implants allow the sensor to
 1423 continue function after the n-type bulk has been converted to a p-type bulk by
 1424 the accumulation of radiation.

1425 The size of the pixels in the original three layers are 50 $\mu\text{m} \times$ 400 μm in the
 1426 $r - \phi$ and z directions, respectively. Those pixels are bump-bonded to front-end
 1427 readout chips, the FE-I3, which contains a total of 2880 pixels per chip. In the
 1428 three original pixel layers, the chips are grouped into modules composed of 16
 1429 chips each with 46,080 pixels per module and a total size of 20 mm x 60 mm
 1430 x 250 μm . The modules are further arranged into long rectangular structures
 1431 that run parallel to the beamline called staves. By tiling several staves with an
 1432 offset of 20°, the stave geometry provides full azimuthal coverage in the barrel
 1433 region while accommodating the readout and cable systems. The endcap regions
 1434 are instead arranged into petals and then into wheels. This arrangement can be
 1435 seen in Figure 23 which shows a computer-generated, cut-away image of the
 1436 outer three layers of the pixel detector. Together these three layers contain 1744
 1437 modules between the barrel and two endcap sections.

1438 The innermost layer, the IBL, was added during the long shutdown before Run
 1439 2, and provides the fourth track measurement. It was inserted directly into the
 1440 existing pixel detector by removing the existing beam pipe and replacing it with
 1441 a significantly smaller version. This insertion can be seen in action in Figure 24,
 1442 which emphasizes the extreme precision required to place the the 70 cm long
 1443 layer with only 2 mm of clearance. The IBL was commissioned to provide con-
 1444 tinued tracking robustness and high precision in the higher luminosity environ-
 1445 ment of Run 2 [11]. The proximity of this layer to the collisions necessitated an
 1446 even higher granularity and better radiation hardness than the other pixel lay-
 1447 ers. And the strict space requirements to add an active sensing layer so close to
 1448 the interaction point required a sensor chip with a much higher active area and
 1449 a larger overall area per chip. These requirements led to the development of a

Parameter	Particle	Value
Reconstruction Efficiency	Muon, $p_T = 1 \text{ GeV}$	96.8%
	Pion, $p_T = 1 \text{ GeV}$	84.0%
	Electron, $p_T = 5 \text{ GeV}$	90.0%
Momentum Resolution	$p_T = 1 \text{ GeV}, \eta \approx 0$	1.3%
	$p_T = 1 \text{ GeV}, \eta \approx 2.5$	2.0%
	$p_T = 100 \text{ GeV}, \eta \approx 0$	3.8%
	$p_T = 100 \text{ GeV}, \eta \approx 2.5$	11%
Transverse IP Resolution	$p_T = 1 \text{ GeV}, \eta \approx 0$	$75 \mu\text{m}\%$
	$p_T = 1 \text{ GeV}, \eta \approx 2.5$	$200 \mu\text{m}$
	$p_T = 1000 \text{ GeV}, \eta \approx 0$	$11 \mu\text{m}$
	$p_T = 1000 \text{ GeV}, \eta \approx 2.5$	$11 \mu\text{m}$
Longitudinal IP Resolution	$p_T = 1 \text{ GeV}, \eta \approx 0$	$150 \mu\text{m}\%$
	$p_T = 1 \text{ GeV}, \eta \approx 2.5$	$900 \mu\text{m}$
	$p_T = 1000 \text{ GeV}, \eta \approx 0$	$90 \mu\text{m}$
	$p_T = 1000 \text{ GeV}, \eta \approx 2.5$	$190 \mu\text{m}$

Table 5: A summary of the expected performance of the combined inner detector [10]. Included are the reconstruction efficiencies for multiple particle types as well as the momentum and IP resolution for various momenta.

1450 new chip type, the FE-I4 (compared to the FE-I3 chips used in the original pixel
 1451 detector) with improved radiation hardness and a larger active footprint of 90%.
 1452 The IBL is comprised of 448 of these individual chips arranged in 14 staves, with
 1453 26,880 pixels per chip and a chip size of 18.5 mm x 41.3 mm x 200 μm . The
 1454 staves, like in the other layers of the pixel detector, are offset by 14° to provide
 1455 full azimuthal coverage. This arrangement can be seen in Figure 25, which shows
 1456 two computer-generated images of the IBL geometry and includes the some of
 1457 the remaining pixel layers.

1458 6.3.2 SEMICONDUCTOR TRACKER

1459 The SCT, the subdetector which immediately surrounds the Pixel detector, pro-
 1460 vides additional discrete measurements of the trajectory of a charged particle.
 1461 Because the SCT is further away from the interaction point, the spatial resolution
 1462 does not need to be as high as in the pixel detector, and so the SCT uses micro-
 1463 strips instead of pixels. Although pixels provide a more accurate measurement,
 1464 the number of pixels and readout channels required to cover the cylindrical area
 1465 at the radius of the SCT layers would be prohibitively complicated and expensive.
 1466 Each individual silicon strip sensor contains 768 individual readout strips
 1467 with a total area of 6.36 cm x 6.40 cm and a pitch of 80 μm . Pairs of these sen-
 1468 sors are then bonded together to form a combined strip with a length of 12.8 cm.
 1469 Two of these combined strips are then placed back to back with a relative tilt

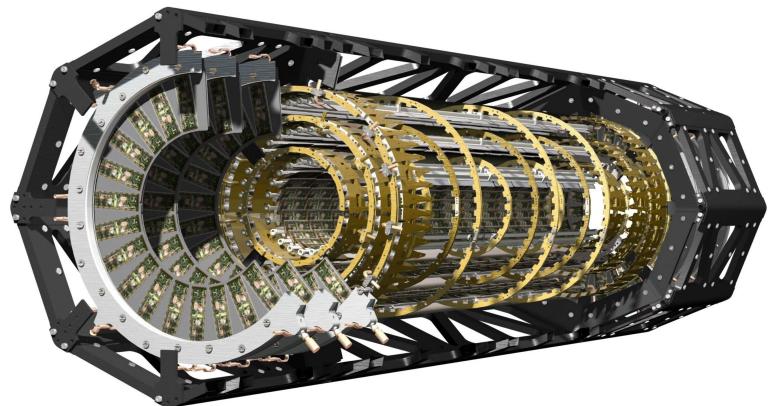


Figure 23



Figure 24: An image of the insertion of the [IBL](#) into the current pixel detector.

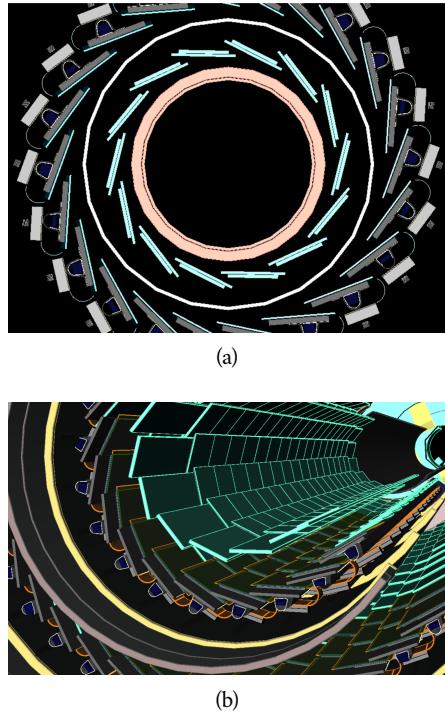


Figure 25: A three-dimensional computer-generated image of the geometry of the [IBL](#) with a view (a) mostly transverse to the beam pipe (b) mostly parallel to the beam pipe.

of 40 mrad. This geometry is illustrated in an exploded-out view in Figure 26. The purpose of angular offset of the consecutive layers is to allow the strip sensor areas to more accurately measure the position of a particle by comparing the overlap of the two strips which were traversed by a track.

Four of these double layers are placed in the barrel region, with radii of 284 mm, 355 mm, 427 mm, and 498 mm. Together these layers provide eight additional measurements for each track that traverses the central $|\eta|$ region. In the endcap region, the layers are arranged in wheels, with the double layers similarly offset to provide improved resolution. With these configurations, the [SCT](#) achieves a spatial resolution of $17 \mu\text{m}$ in the $r - \phi$ direction and $580 \mu\text{m}$ in the z direction.

6.3.3 TRANSITION RADIATION TRACKER

The final component of the inner detector, the [TRT](#), provides continuous tracking using straw drift tubes. The tubes are made of Kapton and aluminum with a diameter of 4 mm and are filled with a gas mixture of 70% Xe, 27% CO₂, and 3% O₂. At the center of each tube is a gold-plated anode tungsten wire $30 \mu\text{m}$ in diameter. When a charged particle passes through these tubes, it ionizes the gas within. The ions produced drift in the electric field established between the wire and the tube wall, and the large electric field near the wire produces avalanche multiplication and results in an electric current on the wire that is read out by the electronics and provides a track measurement. The time it takes the ioniza-

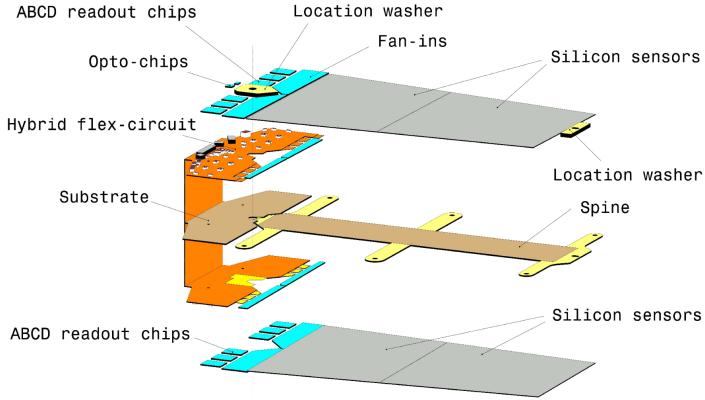


Figure 26: An exploded view of the geometry of the [SCT](#) double layers in the barrel region.

tion to drift to the wire can be used to estimate the distance from the wire that the particle passed through the tube; this gives a resolution on the distance of approximately $130\mu\text{m}$. Combining several such measurements between consecutive hits in the [TRT](#) tubes allows the trajectory of the particle to be reconstructed.

In addition to the continuous tracking, the detector can use transition radiation produced when a particle passes between the layers to distinguish between electrons and heavier charged particles. The space between the tubes is filled with CO_2 , and so has a different dielectric constant than the gas within the tubes which contains Xe. At the transition between those media, a relativistic particle emits radiation proportional to γ , so inversely proportional to mass at a fixed momentum. The photons produced in this transition then produces an ionization cascade which is significantly larger than the signal for the minimally-ionizing charged particles. To distinguish between these two cases, the [TRT](#) defines two signal thresholds, a low threshold for the typical signal produced by a minimally ionizing particle ([MIP](#)) and a high threshold for the the signal produced by transition radiation. A high momentum electron is expected to produce approximately 7 to 10 high threshold hits as it traverses the [TRT](#), and thus these hits provide a way to distinguish electrons from other charged particles.

The [TRT](#) contains 351,000 tubes in total, divided between the barrel and endcap regions. In the barrel region, the tubes are 144 cm long and arranged in 73 layers parallel to the beampipe. In the endcap region, the tubes are 37 cm long and arranged in 160 layers transverse to the beampipe. These configurations can be seen in Figure 20 and Figure 21. With this geometry the [TRT](#) achieves a resolution of $130\mu\text{m}$ in the $r - \phi$ direction.

6.4 CALORIMETRY

The combination of calorimeter systems used in [ATLAS](#) can measure the energy of electrons, photons, hadrons, and hadronic jets with complete coverage up to $|\eta| < 4.9$ and across ϕ . Unlike the inner detector, the calorimeters are capable of measuring neutral particles. To accomplish precision measurements of these

1520 particle types, the [ATLAS](#) calorimeter system uses four individual calorimeters,
 1521 a [LAr](#) electromagnetic calorimeter in the barrel region, a tile hadronic calorime-
 1522 ter in the barrel region, a [LAr](#) hadronic endcap calorimeter, and a [LAr](#) forward
 1523 calorimeter. Together these provide hermetic coverage for the [ATLAS](#) detector.
 1524 The configuration of these calorimeters is illustrated in Figure 27. **Note: I could
 1525 make this section much longer. It might be nice to include a more com-
 1526 plete description of showers for example. I will extend this section if their
 1527 is space at the end.**

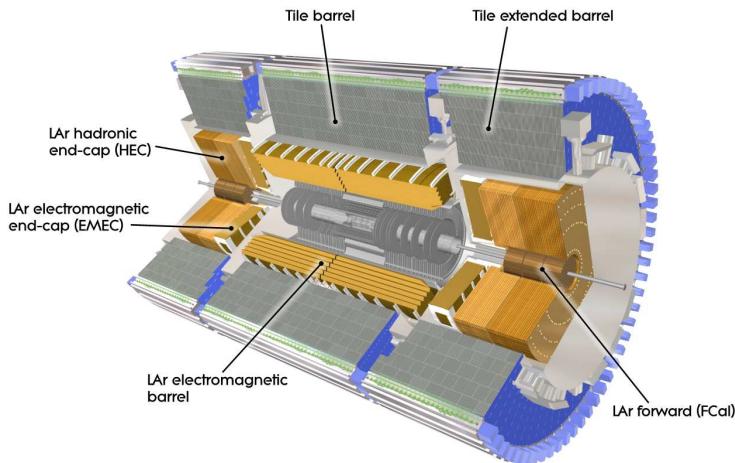


Figure 27

1528 The calorimeters are designed to absorb and measure the energy carried by
 1529 a particle, and completely stop the particle's propagation in the process. This
 1530 requires a significant amount of material to provide interactions. These interac-
 1531 tions then produce secondary particles, which can produce secondary particles
 1532 in turn, and thus form a cascade of particles called an electromagnetic ([EM](#)) or
 1533 hadronic shower, depending on the governing mechanism. Electromagnetic and
 1534 hadronic showers have very different properties and require different technolo-
 1535 gies to measure them accurately. All of the calorimeters in the [ATLAS](#) calorimeter
 1536 system are sampling calorimeters, that is they use alternating layers of absorbing
 1537 and active material. The dense absorbing layers initiate the showers while the ac-
 1538 tive layers measure the energy of the produced particles. A fraction of the energy
 1539 is lost in the inactive layers, so the energy measurement from the active layers
 1540 has to be corrected to estimate the actual energy of the particle.

1541 The [EM](#) calorimeter provides around 20 radiation lengths (X_0) while the hadronic
 1542 calorimeter provides around 10 interaction lengths (λ_0). As mentioned previ-
 1543 ously, radiation lengths measure the distance over which an electromagnetically
 1544 interacting particle loses a characteristic fraction of its energy. Interaction lengths,
 1545 on the other hand, measure the mean distance traveled by a hadronic particle be-
 1546 fore undergoing a nuclear interaction [9]. Figure 28 show the radiation lengths
 1547 in the layers of the [EM](#) calorimeter in the barrel region as well as the interaction
 1548 lengths for all calorimeters.

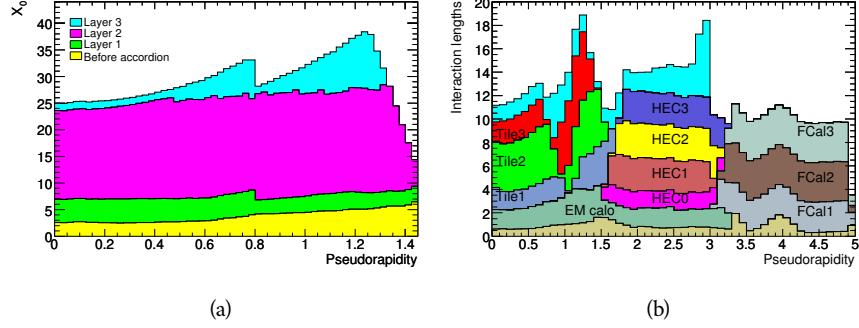


Figure 28: The depth of (a) the electromagnetic barrel calorimeter in radiation lengths and (b) all calorimeters in interaction lengths as a function of pseudorapidity.

1549 6.4.1 ELECTROMAGNETIC CALORIMETER

1550 The electromagnetic calorimeters use alternating layers of Liquid Argon
 1551 and lead in an accordion shape. The accordion shape allows a construction that pro-
 1552 vides complete coverage in the ϕ direction while also providing many alterna-
 1553 ting layers for the a particle to pass through. The configuration is detailed in
 1554 Figure 29. When an electron or photon passes through the lead, it produces an
 1555 electromagnetic shower. The particles produced in those showers then pass into
 1556 and ionize the Liquid Argon; the ions produced can then be collected by an elec-
 1557 trode in the Liquid Argon layer to provide the actual energy measurement.

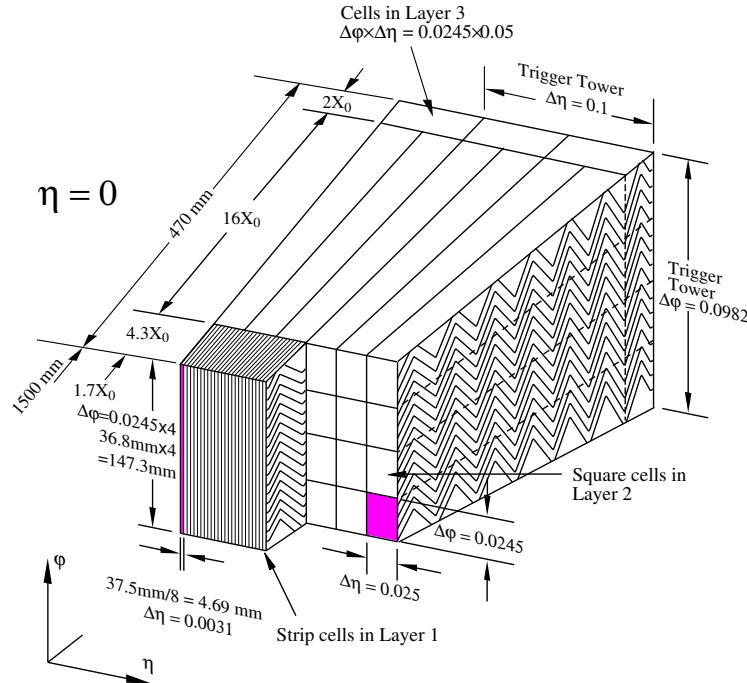


Figure 29: A schematic of the [LAr](#) calorimeter in the barrel region, highlighting the accordian structure.

1558 The barrel region is covered by a presampler and three separate sampling layers
 1559 with decreasing segmentation. The presampler is just a thin layer of Liquid
 1560 Argon which measures the energy of any electromagnetic showers which are
 1561 initiated before the particle reaches the calorimeter due to interactions with the
 1562 detector material. The first layer is the strip layer, which has fine segmentation
 1563 in η to enhance the identification of shower shapes and to provide a precise η
 1564 measurement for reconstructing photons and electrons. The strip layer has only
 1565 4 radiation lengths worth of material, and has a segmentation of $\Delta\eta = 0.003$
 1566 and $\Delta\phi = 0.1$. The second layer is also finely segmented, with a segmentation
 1567 of $\Delta\eta = 0.025$ and $\Delta\phi = 0.025$, and a thickness of $16 X_0$. This layer is designed
 1568 to contain an electromagnetic shower and to measure the majority of the energy
 1569 for photons and electrons. The third layer is only $2 X_0$ thick and measures the
 1570 energy of electromagnetic showers which leak out of the second layer, and helps
 1571 to separate electromagnetic showers from hadronic showers. The structure of
 1572 the LAr endcap calorimeter is similar except that the layers are arranged parallel
 1573 to the beampipe to measure energy deposits from high η particles.

1574 6.4.2 HADRONIC CALORIMETERS

1575 The hadronic calorimeters use a few different technologies to satisfy the resolu-
 1576 tion demands in the different areas of the detector, and together they cover the
 1577 region $|\eta| < 2.7$. In the barrel region, for $|\eta| < 1.7$, the hadronic calorimeters
 1578 are constructed of alternating tiles of steel and plastic scintillator. Like in the
 1579 electromagnetic calorimeter, the dense layer initiates a shower (in this case the
 1580 dense layer is the steel and the shower is hadronic) of particles which pass into
 1581 and ionize the following layer. The ionization in the plastic scintillator instead
 1582 produces a light signal proportional to the amount of ionization produced by the
 1583 shower, and this signal is measured using photomultipliers and provides the ac-
 1584 tual energy measurement. The construction of a tile in the calorimeter is shown
 1585 Figure 30, which highlights the alternating layers of steel and scintillator.

1586 This tile calorimeter, as well as the remaining hadronic calorimeters, have a
 1587 much coarser granularity than the electromagnetic calorimeters. The high gran-
 1588 ularity is not needed for an accurate energy measurement, and the hadronic
 1589 calorimeters are not designed to distinguish particle types like the electromag-
 1590 netic calorimeters. The tile granularity is approximately $\Delta\eta = 0.1$ and $\Delta\phi = 0.1$,
 1591 and the segmentation in depth and η is shown in Figure 31.

1592 The remaining hadronic calorimeters all use the same alternating, sampling
 1593 structure but with different active and inactive materials. The hadronic endcap
 1594 calorimeter covers the range of $1.5 < |\eta| < 3.2$ and uses an inactive layer of
 1595 copper and an active layer of Liquid Argon. The forward calorimeter covers the
 1596 range of $3.1 < |\eta| < 4.9$ and uses a dense matrix of copper and tungsten filled
 1597 with Liquid Argon.

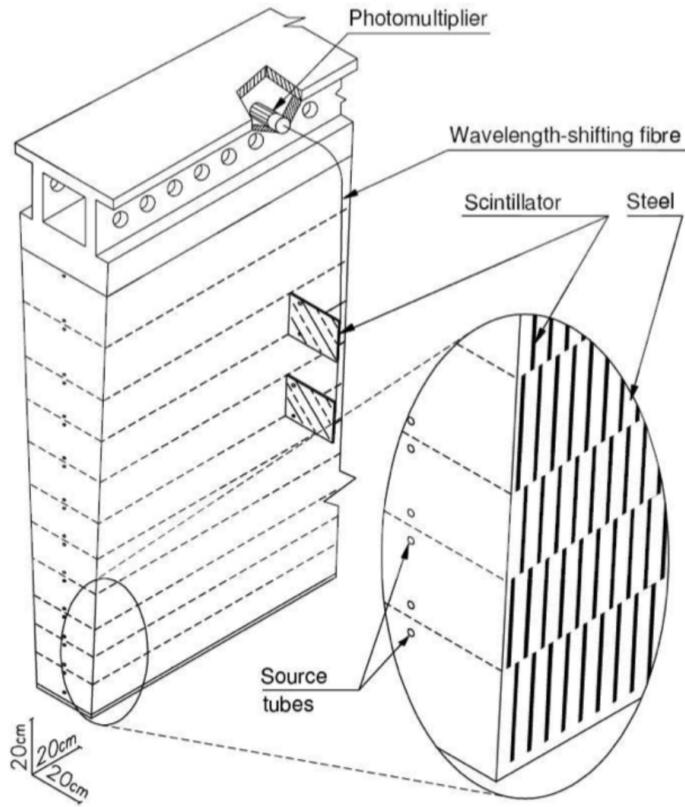


Figure 30: A schematic of a hadronic tile module which shows the alternating layers of steel and plastic scintillator.

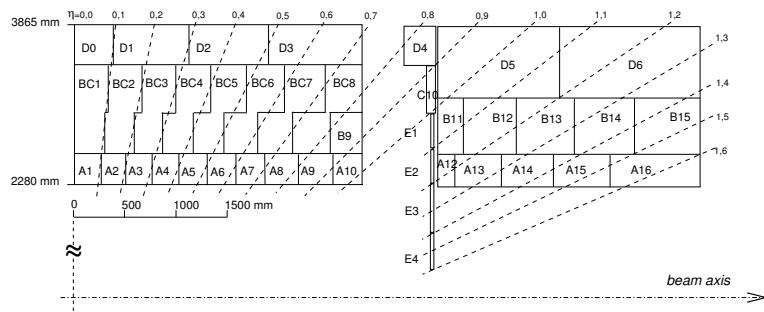


Figure 31: The segmentation in depth and η of the tile-calorimeter modules in the central (left) and extended (right) barrels.

1598 6.5 MUON SPECTROMETER

1600 Among SM particles, only muons and neutrinos consistently pass through the
 1601 calorimeters. Because the neutrinos are also electrically neutral, there is no fea-
 1602 sible option to measure them directly in ATLAS. The muons, on the other hand,
 1603 are charged and are thus already measured as a track in the inner detector. The
 1604 muon spectrometer provides a way to consistently identify muon tracks and also
 1605 a way to provide an additional measurement of their momentum.

1606 The muon spectrometer contains four subdetectors that cover the barrel and
 1607 endcap regions. In the barrel region, the muon spectrometer uses a combination
 1608 of Resistive Plate Chambers (RPCs) and MDTs to provide both a coarse, fast mea-
 1609 surement for triggering and a precise momentum measurement for offline event
 1610 reconstruction. Similarly, in the endcap region, the TGCs, MDTs, and CSCs allow
 1611 for both triggering and precise measurements. The CSCs are used only in the in-
 1612 nermost layer of the endcap region between $2.0 < |\eta| < 2.7$ where the particle
 1613 flux is too large for the MDTs to provide accurate measurements. The overall
 1614 layout of the muon systems are shown in the cut-away diagram in Figure 32,
 1615 and Figure 33 shows a precise schematic of the layout of each of the detecting
 1616 elements. The geometric arrangement shown provides consistent coverage for
 1617 muons produced up to $|\eta| < 2.7$, and takes full advantage of the bending of the
 1618 muons in the toroidal magnetic field, described in Section 6.2, to measure their
 1619 momentum. Figure 34 shows a cross-section of the arrangement of the muon
 1620 spectrometer in the barrel; the layers are divided into eight small and eight large
 chambers that are overlapped to provide complete coverage in ϕ .

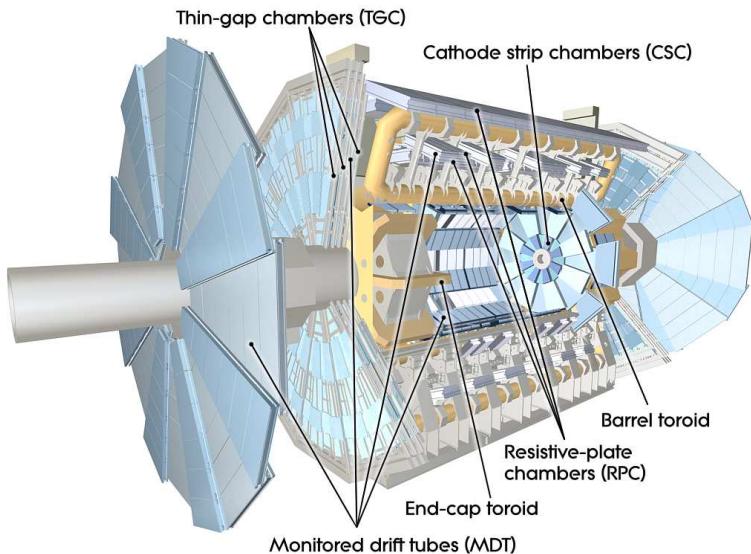


Figure 32: A cut-away diagram of the muon systems on ATLAS.

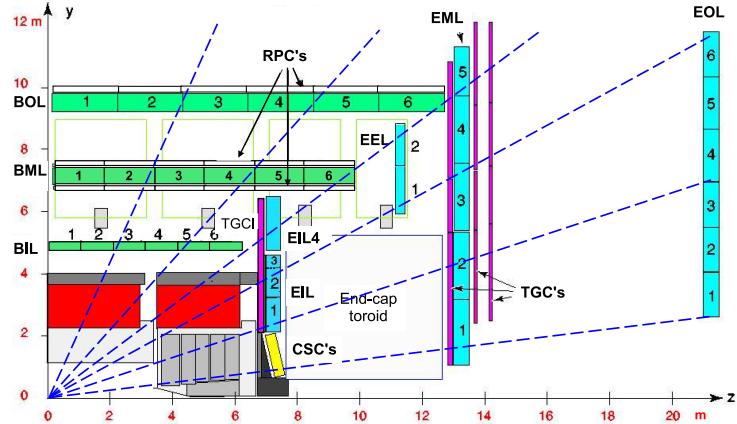


Figure 33: A quarter view of the muon spectrometer which highlights the layout of each of the detecting elements. The BOL, BML, BIL, EOL, EML, and EIL are all MDT elements, where the acronyms encode their positions.

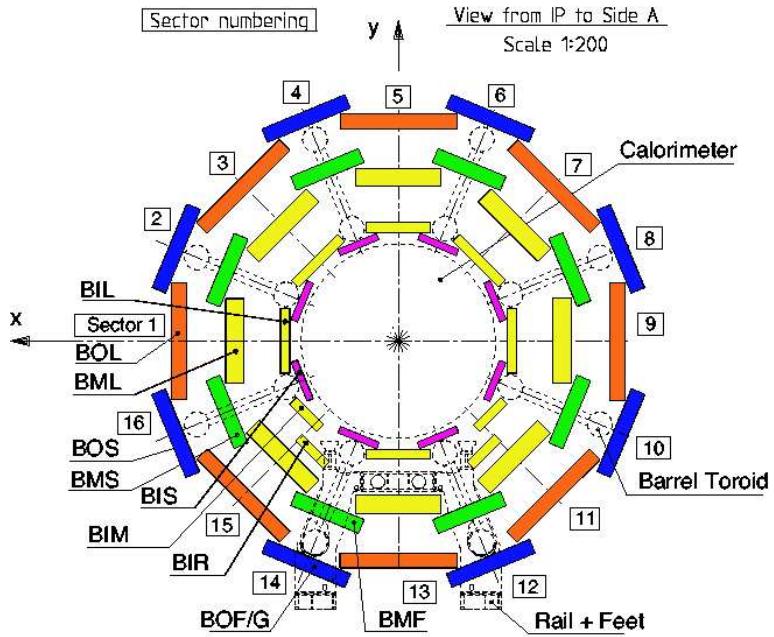


Figure 34: A schematic of the cross-section of the muon spectrometer in the barrel region.

1621 6.5.1 MONITORED DRIFT TUBE

1622 The momentum measurements in the barrel region are provided by three con-
 1623 secutive layers of MDT elements, located at approximately 5 m, 7 m, and 9 m from
 1624 the interaction point. Each of these layers is a composite of two multilayers of
 1625 drift tubes: two layers of three to four layers of tubes, as shown in Figure 35.
 1626 These aluminum tubes are 3 cm in diameter, with lengths between 0.9 and 6.2 m,
 1627 and are filled with a mixture of ArCO₂ kept at 3 bar absolute pressure. A central
 1628 tungsten-rhenium wire with a diameter of 50 μm runs along the length of the
 1629 tube, and is kept at a potential of 3080 V.

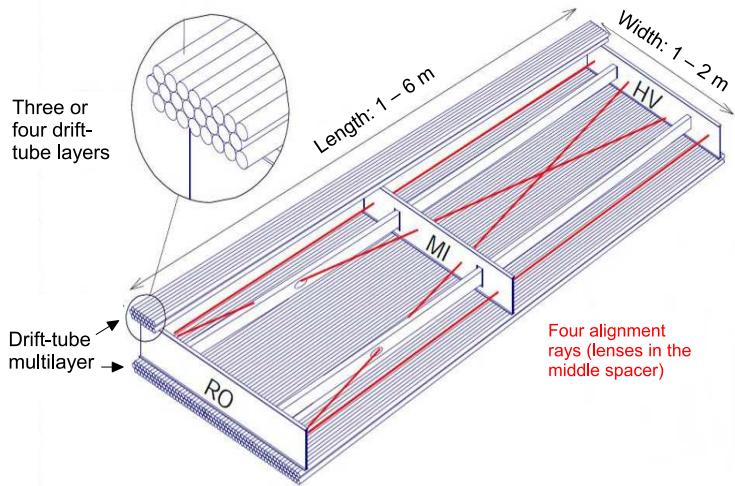


Figure 35: A schematic of a single MDT chamber, which shows the multilayers of drift tubes as well as the alignment system.

1630 A muon traversing these tubes ionizes the gas, and the ionization electrons
 1631 then drift in the electric field toward the central wire. Close to the wire, the
 1632 electric field is strong enough to cause the original ionization electrons to ion-
 1633 ize additional electrons, producing an avalanche that can be measured as a cur-
 1634 rent along the wire. The time of arrival of that current depends on how far the
 1635 muon entered from the wire, and can be used to achieve a position resolution of
 1636 80 μm in an individual tube. The combination of the measurements in the con-
 1637 secutive layers of tubes improves this position resolution to 35 μm .

1638 To achieve a good resolution over the entire length of a muon track, the rel-
 1639 ative positions of the tubes of the muon spectrometer must be known to an ac-
 1640 curacy of 30 μm . This is achieved by an optical laser alignment system placed in
 1641 each of the individual chambers and throughout the cavern. These monitor any
 1642 changes in position or alignment due to effects like gravitational sag, tempera-
 1643 ture shifts, and the magnetic field. The configuration of the alignment system
 1644 within an individual chamber is also shown in Figure 34.

1645 6.5.2 RESISTIVE PLATE CHAMBER

1646 The **RPC** is the outermost detecting layer in the muon spectrometer in the barrel
 1647 region, and provides a fast measurement of the ϕ position of muons for trig-
 1648 gering. The speed of the measurement, with a time resolution of just a few
 1649 nanoseconds, requires a poor spatial resolution of approximately 1 cm. There
 1650 are three **RPCs** layers in the muon spectrometer, two located on either side of
 1651 the central **MDT** layer and one located outside the final **MDT** layer, as shown in
 1652 Figure 33. The **RPCs** consist of two layers of parallel plates filled with a gas mix-
 1653 ture of $C_2H_2F_4$. A muon passing through these systems ionizes the gas, like in
 1654 the **MDT**, which causes an avalanche of ionization electrons in the electric field
 1655 maintained between the plates. Metal strips on the outside of the chamber ca-
 1656 pacitively couple to the accumulated charge, and are read out to measure the η
 1657 and ϕ positions of the muon track.

1658 6.5.3 CATHODE STRIP CHAMBER

1659 The majority of the momentum measurements in the endcap region are provided
 1660 by the **MDTs**. In the most forward region of the muon spectrometer, between
 1661 $2.0 < \eta < 2.7$, the particle flux is very high due to contributions from low energy
 1662 photons and neutrons. The **MDT** can only sustain a hit rate of approximately 150
 1663 Hz/cm² because of limitations in the drift times of the gas and the capacity of
 1664 the readout electronics. The **CSCs** were designed to handle higher hit rates, up to
 1665 1000 Hz/cm², and provide the necessary coverage in that high flux region.

1666 The **CSC** consists of several multiwire proportional chambers, where the wires
 1667 are oriented in the radial direction out from the beampipe. There are eight large
 1668 and eight small chambers, arranged to partially overlap in the ϕ direction, as
 1669 shown in Figure 36. Like in the **MDT**, a muon traversing the system produces
 1670 ionization in the gas; here, however, the ionization is collected on a number of
 1671 wires. These wires couple to cathodes on the chambers which are segmented
 1672 into strips in two directions. The relative amount of charge on each of the neigh-
 1673 boring strips can be used to interpolate to the position of the muon in both η
 1674 and ϕ .

1675 6.5.4 THIN GAP CHAMBER

1676 Like in the barrel region, a separate, fast detector is required to provide position
 1677 measurements of muons for trigger in the endcap region. This is provided by
 1678 the **TGC** which consists of seven layers in the middle station of the endcap, two
 1679 doublet layers and one triplet layer, and a single doublet layer in the inner endcap
 1680 station. Figure 37 shows the arrangement of the triple and doublet layers of the
 1681 **TGCs**.

1682 Like the **CSCss**, the **TGCs** are multiwire proportional chambers with a wire-to-
 1683 cathode distance of 1.4 mm and a wire-to-wire distance of 1.8 mm. Readout
 1684 strips on the outside of the chambers run perpendicular to the wires, and couple
 1685 to the charge collected on the wires to provide a position measurement in the η

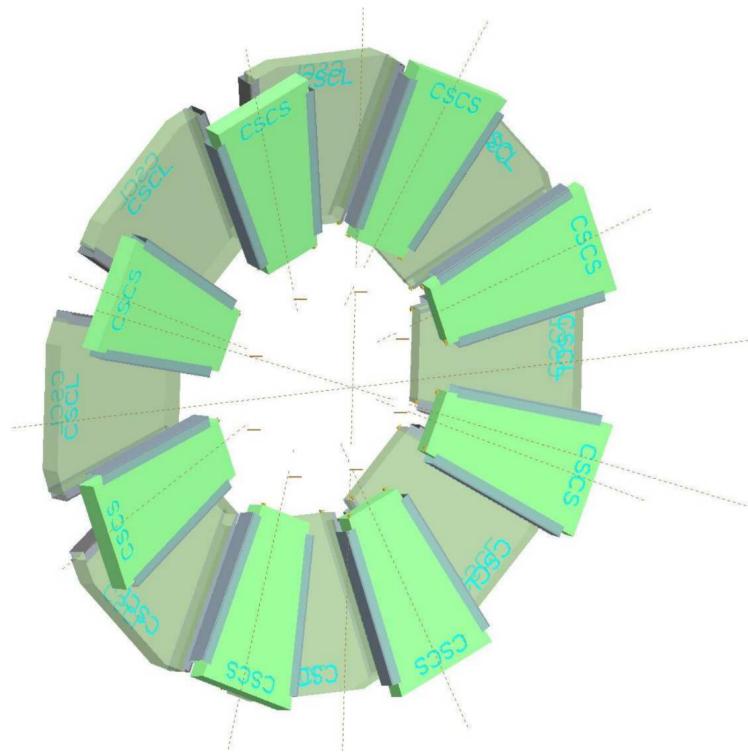


Figure 36: A schematic of the **CSC** endcap, showing the overlapping arrangement of the eight large and eight small chambers.

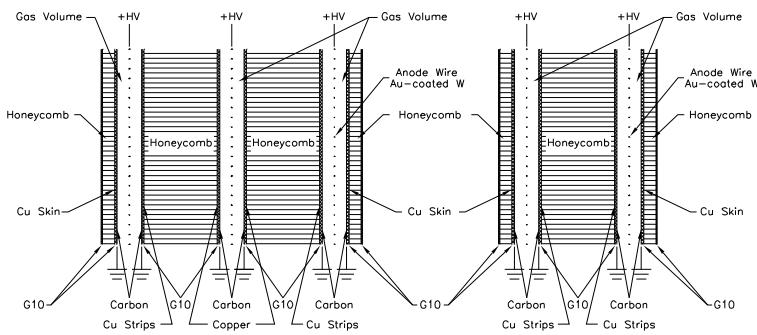


Figure 37: A schematic of the **TGC** doublet and triplet layers.

1686 direction. The current induced on the wires is also readout to provide a position
 1687 measurement in the ϕ direction. The high electric field and small wire-to-wire
 1688 distance give it the required good time resolution to be used for triggering events.

1689 6.6 TRIGGER

1690 It is not possible for the detector and the associated computing systems to record
 1691 the terabytes of data that the 40 MHz of proton-proton collisions produce every
 1692 second. Instead, a small fraction of these events are selected by the trigger sys-
 1693 tem to be recorded and later analyzed. Selecting interesting events at such a high
 1694 rate poses a significant challenge for the both the detector design and the imple-
 1695 mentation of a trigger decision and data acquisition system. The trigger must
 1696 balance the time needed to decide to keep an event, to avoid losing information,
 1697 with the filtering accuracy to consistently select a full menu of physics events
 1698 that can be used for the wide array of searches and measurements targeted by
 1699 [ATLAS](#).

1700 The [ATLAS](#) trigger system, as of Run 2, consists of two levels of decision mak-
 1701 ing. The first level, referred to as L1, is hardware based and uses inputs from
 1702 a subset of the detector elements to narrow the considered event rate from the
 1703 original 40 MHz down to 100 kHz. The 100 kHz rate is the maximal rate that
 1704 the event information can be transferred from the detector. The second level,
 1705 referred to as the [HLT](#), makes the final decisions on which events to keep for
 1706 analysis and selects a rate of around 1 kHz. The collection of selection criteria
 1707 used to make the L1 decisions feed into subsequent selection criteria in the [HLT](#),
 1708 and the set of these combinations of L1 and [HLT](#) criteria from the trigger menu
 1709 which defines exactly what events are recorded on [ATLAS](#). The entirety of the
 1710 trigger menu used for 2015 data collection is shown in Table 6, which summa-
 1711 rizes the selection requirements at both levels and additionally shows the peak
 1712 measured rates contributed by each.

1713 At L1, the trigger system uses information primarily from the calorimeters
 1714 and muon spectrometer to select high p_T jets, electrons, photons, and muons.
 1715 The electromagnetic calorimeter uses reduced granularity energy measurements
 1716 as well as isolation requirements to select electrons and photons. The hadronic
 1717 calorimeter also uses a combination of reduced granularity energy measurements
 1718 and isolation to select high momentum jets and hadronically decaying tau lept-
 1719 ons. The calorimeters are also used to provide triggers based on missing energy:
 1720 the coarse granularity energy measurements are used to calculate a directional
 1721 sum of energies and to trigger on a significant imbalance. Only the [RPCs](#) and [TGCs](#)
 1722 muon subdetectors contribute to the decision at L1, and are used to identify high
 1723 momentum muons. The contributions to the triggering rate of the various types
 1724 of L1 triggers are shown in Figure 38. The total rate is indicated in black and
 1725 is lower than the sum of individual rates because their is significant overlap be-
 1726 tween different trigger channels. The majority of the rate comes from lepton
 1727 and photon triggers.

1728 After an event is chosen by the L1 trigger, the detector measurements from the
 1729 bunch crossing which fired the trigger is read out from the front-end electronics

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$	
Single leptons	Single iso μ , $p_T > 21$ GeV	15	20	7	130
	Single e , $p_T > 25$ GeV	20	24	18	139
	Single μ , $p_T > 42$ GeV	20	40	5	33
	Single τ , $p_T > 90$ GeV	60	80	2	41
Two leptons	Two μ 's, each $p_T > 11$ GeV	2×10	2×10	0.8	19
	Two μ 's, $p_T > 19, 10$ GeV	15	18, 8	7	18
	Two loose e 's, each $p_T > 15$ GeV	2×10	2×12	10	5
	One e & one μ , $p_T > 10, 26$ GeV	$20 (\mu)$	7, 24	5	1
	One loose e & one μ , $p_T > 19, 15$ GeV	15, 10	17, 14	0.4	2
	Two τ 's, $p_T > 40, 30$ GeV	20, 12	35, 25	2	22
	One τ , one μ , $p_T > 30, 15$ GeV	12, 10 (+jets)	25, 14	0.5	10
Three leptons	One τ , one e , $p_T > 30, 19$ GeV	12, 15 (+jets)	25, 17	1	3.9
	Three loose e 's, $p_T > 19, 11, 11$ GeV	15, 2 \times 7	17, 2 \times 9	3	< 0.1
	Three μ 's, each $p_T > 8$ GeV	3 \times 6	3 \times 6	< 0.1	4
	Three μ 's, $p_T > 19, 2 \times 6$ GeV	15	18, 2 \times 4	7	2
One photon	Two loose γ 's, $p_T > 40, 30$ GeV	2×10	$2 \times 10 (\mu's)$	0.8	0.2
	Two tight γ 's, $p_T > 25, 25$ GeV	$2 \times 8, 10$	$2 \times 12, 10$	0.3	< 0.1
Two photons	one γ , $p_T > 125$ GeV	22	120	8	20
	Two loose γ 's, $p_T > 40, 30$ GeV	2×15	35, 25	1.5	12
Single jet	Two tight γ 's, $p_T > 25, 25$ GeV	2×15	2×20	1.5	7
	Jet ($R = 0.4$), $p_T > 400$ GeV	100	360	0.9	18
E_T^{miss}	Jet ($R = 1.0$), $p_T > 400$ GeV	100	360	0.9	23
	$E_T^{\text{miss}} > 180$ GeV	50	70	0.7	55
Multi-jets	Four jets, each $p_T > 95$ GeV	3×40	4×85	0.3	20
	Five jets, each $p_T > 70$ GeV	4×20	5×60	0.4	15
	Six jets, each $p_T > 55$ GeV	4×15	6×45	1.0	12
b -jets	One loose b , $p_T > 235$ GeV	100	225	0.9	35
	Two medium b 's, $p_T > 160, 60$ GeV	100	150, 50	0.9	9
	One b & three jets, each $p_T > 75$ GeV	3×25	4×65	0.9	11
	Two b & two jets, each $p_T > 45$ GeV	3×25	4×35	0.9	9
b -physics	Two μ 's, $p_T > 6, 4$ GeV plus dedicated b -physics selections	6, 4	6, 4	8	52
Total				70	1400

Table 6: The trigger menu for the 2015 data collection with $L = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Both the L1 and HLT selection requirements and their trigger rates are shown measured at the specified luminosity are shown. The typical offline selections represent a typical set of offline requirements imposed after the trigger in an analysis.

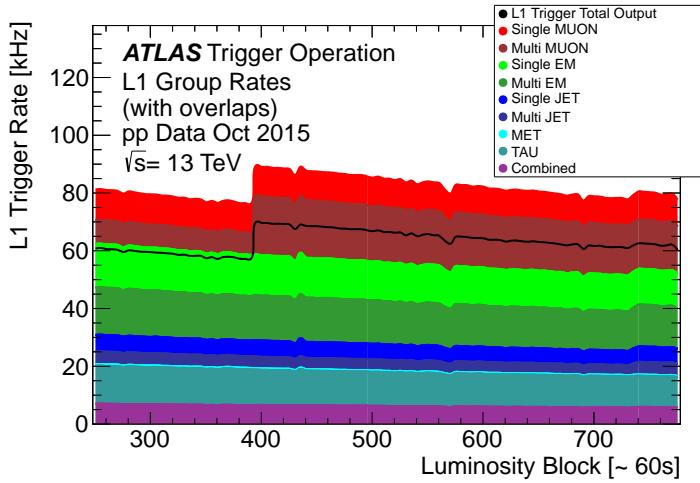


Figure 38: The L1 Trigger rate broken down into the types of triggers as a function of the luminosity block for the 2015 data collection period.

1730 and stored on read-out boards. This inclusive information is necessary to make
 1731 more the more precise event selections than is possible with the reduced infor-
 1732 mation at L1. The **HLT** then uses this information with software algorithms to
 1733 decide whether or not to permanently record the event. The L1 trigger also for-
 1734 wards which decision was made and Region of Interests (**RoIs**) to the **HLT**, which
 1735 allows the **HLT** to focus on particular algorithms and particular sections of the
 1736 detector to greatly improve the algorithmic selection speed. The additional in-
 1737 formation available to the **HLT** allows it to implement additional trigger targets,
 1738 such as identified jets from the decays of b-hadrons. The contributions to the
 1739 triggering rate of the various types of **HLT** triggers are shown in Figure 39.

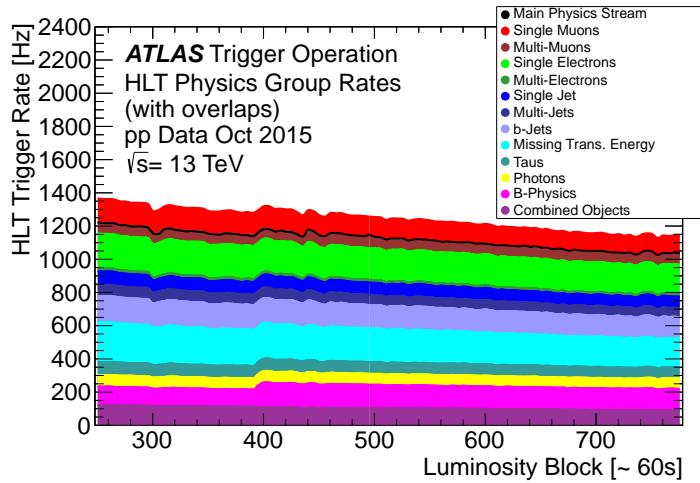


Figure 39: The HLT Trigger rate broken down into the types of triggers as a function of the luminosity block for the 2015 data collection period.

1740

1741 EVENT RECONSTRUCTION

1742 The ATLAS experiment combines measurements in the subdetectors to form a
 1743 cohesive picture of each physics event. The majority of particles that traverse
 1744 the detector leave behind some combination of ionization hits in the tracking
 1745 detectors or energy deposits in the calorimeters, and these measurements can
 1746 be used to reconstruct physical quantities like the particle's energy, momentum,
 1747 or trajectory. Even the type of the particle can be distinguished by comparing
 1748 the various ways that different species of stable particles interact with the subde-
 1749 tectors. Reconstruction is the process which takes the electronic outputs of the
 1750 detector and collects them into individual physics objects. The physics objects
 1751 summarize the properties of particles produced by the collision or subsequent
 1752 decays, either for individual isolated particles like leptons, or for a collection of
 1753 the cascade of products produced in the decay of an energetic hadron, called a
 1754 jet. These are the objects and quantities most often used in analysis to make
 1755 measurements of SM processes or to search for new physics.

1756 7.1 TRACKS AND VERTICES

1757 As described in Section 6.3, charged particles that traverse the inner detector
 1758 leave behind hits in the subdetectors. Each of these hits translates into a position
 1759 measurement along the trajectory of that particle, with position resolutions de-
 1760 pending on the subdetector that provided the measurement. Track reconstruc-
 1761 tion uses these position measurements to cluster hits in consecutive layers of
 1762 the detector into a trajectory consistent with a particle curving in a magnetic
 1763 field [12, 13]. The number of hits in the inner detector for each event makes
 1764 a combinatorial method completely infeasible: the algorithms that form tracks
 1765 must be significantly more intelligent so that event reconstruction does not ex-
 1766 haust computing resources.

1767 The first and primary algorithm employed in track reconstruction is called
 1768 the inside-out method, which begins with the assumption that the track orig-
 1769 inated from the interaction point. Its purpose is to identify primary particles,
 1770 those which originate in the proton-proton collisions and with a lifetime long
 1771 enough to reach the inner detector. Combinations of three space points are con-
 1772 sidered from measurements in the Pixel detector and the first layer of the SCT,
 1773 and form the seed for a track. The seed is then extrapolated into the SCT and
 1774 hits in each layer are considered to be added to the track using a combinatorial
 1775 Kalman filter [13]. After all of the SCT layers have been considered, tracks are
 1776 filtered to reduce ambiguities from other nearby tracks or from combinatorial
 1777 coincidences. Then the tracks are extended into the TRT in the same way. This
 1778 algorithm is how the hits are chosen to be incorporated into a single track. Once
 1779 the hits are collected, a fitting algorithm calculates the track parameters which

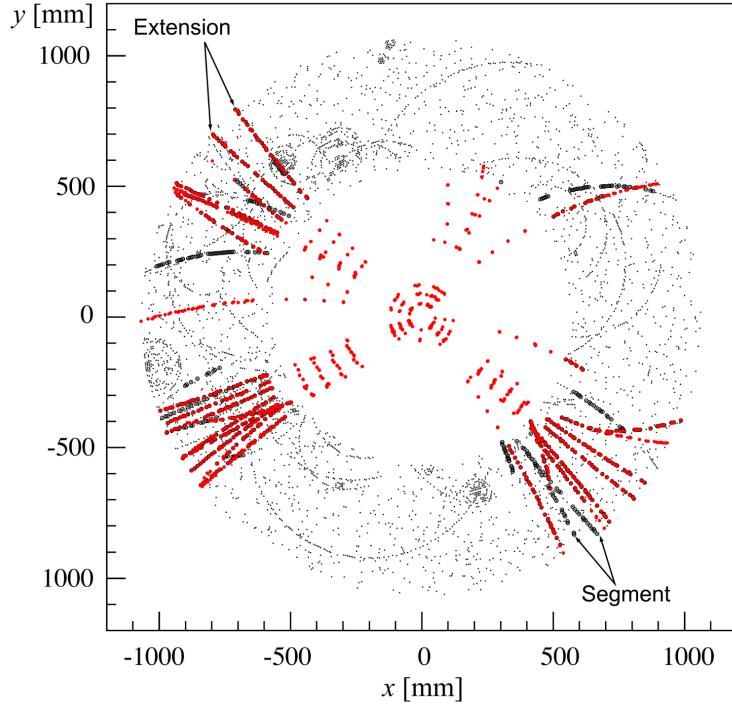


Figure 40: The x and y locations of the hits generated in a simulated $t\bar{t}$ event in the inner detector. The hits which belong to tracks formed using the inside-out algorithm are highlighted in red, while the hits which belong to tracks formed using the outside-in algorithm are circled in black.

best model the locations of the hits and their resolutions. Those parameters directly determine the direction and momentum of the particle which produced the track.

This inside-out algorithm is complemented by an outside-in algorithm, which is used to find tracks from secondary particles, those produced in the decays or interactions of the primary particles inside the detector. As the name indicates, the outside-in algorithm begins by seeding tracks in the outermost layers of the inner detector, in the TRT. The seed in this case is formed by a segment in the TRT, and the track is propagated backwards into the SCT before being refitted to use all the included points. Some tracks are found with TRT segments only, which can result from interactions with the detector following the SCT. Figure 40 shows an example of the geometry of tracks formed by both algorithms, where the hits belonging to tracks found using the inside-out algorithm are highlighted in red, and the hits belonging to the tracks found using the outside-in algorithm are circled in black. The figure highlights the presence of a large number of both primary and secondary tracks in a single event, as well as the overall large number of hits present in the inner detector.

The tracks resulting from these algorithms can be contaminated by nearby particles confusing the tracking algorithm in a high luminosity environment. For example, enough hits present in the inner detector can lead to fake tracks from combinations of hits from multiple individual tracks. Therefore, after the tracks are formed and fitted, additional quality requirements are imposed in

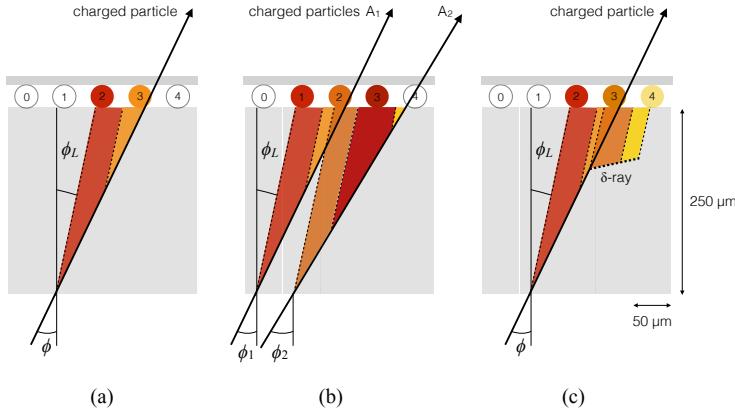


Figure 41: Examples of the clusters formed in a single layer of the pixel detector for (a) a single isolated particle, (b) two nearly-overlapping particles, and (c) a particle which emits a δ -ray [14].

order to reduce such backgrounds. Most tracking applications require at least seven silicon hits, that is, seven hits between the Pixel detector and [SCT](#). Then the tracks are required to have at most two holes in the Pixel detector, where holes are non-existing but expected measurements in a layer of the subdetector. If the missing hit corresponds to an inactive module, however, it is not counted as a hole but instead as a hit for tracking as the lack of a measurement is expected in that case.

7.1.1 PIXEL NEURAL NETWORK

The hits in the Pixel detector are not typically confined to a single pixel, but rather the charge is spread over several pixels per layer which are grouped together into clusters. The clustering of these pixels for isolated tracks is relatively straightforward, but complications can arise in the high track density environment where hits from multiple particles can overlap in a single cluster. Figure 41 shows examples of clusters generated by a single isolated particle, two nearly overlapping particles, and a particle which emits a δ -ray. A δ -ray is a secondary electron which is generated with enough energy to escape a significant distance away from the original particle and to generate additional ionization.

A series of neural-networks analyzes the shape of the clusters to determine how many particles produced the cluster and to find the positions of each of the particles within the cluster. These allow for an identification of clusters caused by more than one particle or by a particle that emits a δ -ray. In a high-density tracking environment, the multiple position outputs can be used as the locations of individual hits to allow reconstruction of tracks which almost overlap and with a much better separation than is possible without the splitting of individual clusters.

1827 7.1.2 PIXEL DE/DX

1828 A hit in the Pixel detector corresponds to the voltage generated from ionization
 1829 current rising above a threshold value that is tuned to consistently record the
 1830 passing of MIPs. A larger amount of charge deposited results in a larger voltage,
 1831 and a larger signal remains above the threshold for a longer period of time. The
 1832 time over threshold (`ToT`) is read out of the Pixel detector, and can be used to
 1833 provide a measurement of the charge deposited in each pixel. The charge mea-
 1834 surements from each of the pixels included in a pixel cluster are summed to form
 1835 one charge measurement per layer of the pixel detector. That charge measure-
 1836 ment, combined with the angle of incidence of the track and the known sizes of
 1837 each detector element, can be converted into a measurement of dE/dx , the ion-
 1838 ization energy deposited per unit distance, measured in $\text{MeVg}^{-1}\text{cm}^2$. The IBL
 1839 only has sixteen available values (4 bits) of `ToT` to readout, compared to the 256
 1840 available values (8 bits) in the remaining pixel layers. To help alleviate this lack
 1841 of range, the IBL also records if it is in overflow: when the ionization is sufficient
 1842 to generate a `ToT` above the largest value that can be recorded in the 4 bits.

1843 The measurements across multiple layers are combined to form an average
 1844 value of dE/dx for the track as a whole. To reduce the influence of the typical
 1845 long Landau tails of the distribution of dE/dx deposits [9], the average is calcu-
 1846 lated as a truncated mean. The value measured in the IBL is removed if it is in
 1847 overflow, as the measured value is not reliable in that case. If a track has five
 1848 measurements in the pixel detector, the two highest cluster values are removed.
 1849 If a track has two, three, or four measurements in the pixel detector, only the
 1850 single highest cluster value is removed. The remaining values are averaged to
 1851 form the pixel dE/dx .

1852 7.1.3 VERTEX RECONSTRUCTION

1853 A vertex represents the intersection of multiple tracks and corresponds to the
 1854 location of an interaction. If at least two charged particles result from the in-
 1855 teraction, the intersection of their resulting tracks reveals its position with high
 1856 precision. Vertices are divided into two groups, primary vertices which corre-
 1857 spond to the actual proton-proton collisions, and secondary vertices which cor-
 1858 respond to decays of short-lived particles or interactions with the detector. Pri-
 1859 mary vertices are particularly important, as they can provide a precise location
 1860 for the interaction which generated the observed particles. Understanding that
 1861 location is crucial in understanding the geometry of the event.

1862 Primary vertices are reconstructed by iteratively identifying seeds from re-
 1863 constructed tracks. Each track's extrapolated z position at the beamline forms a
 1864 seed, and nearby tracks are fitted using that position as a point along their trajec-
 1865 tory. The goodness of fit with that vertex is considered for each track, measured
 1866 in χ^2 . The final position of the vertex is determined by a fit to all of the con-
 1867 sidered tracks, where the contribution from each track is weighted according to
 1868 the χ^2 compatibility with that vertex. Any tracks from this procedure that are
 1869 displaced by more than 7σ from that vertex are removed from the fit and used

1870 to seed a new vertex. This procedure is iterated until no additional vertices can
 1871 be found.

1872 This procedure is typically performed twice. The first set of vertices is used
 1873 to fit a profile for the beamspot, which indicates the position of the intersection
 1874 of beams in that particular bunch crossing. The fitted beamspot then provides
 1875 a constraint for the second attempt to locate primary vertices, where both the
 1876 track fitting and seeding of vertices are required to be consistent with interac-
 1877 tions occurring within the beamspot.

1878 7.2 ELECTRONS AND PHOTONS

1879 Electrons are measured as both a charged particle track and energy deposits in
 1880 the electromagnetic calorimeter. Photons, on the other hand, leave energy de-
 1881 posits in the electromagnetic calorimeter but do not produce a corresponding
 1882 track. Because the electromagnetic interactions with the calorimeter of both
 1883 photons and electrons produces more photons and electrons, the behavior in the
 1884 calorimeter is very similar and there is significant overlap in the reconstruction
 1885 techniques for each.

1886 The reconstruction of a photon or an electron in the calorimeter is based on
 1887 clustering algorithms which identify groups of energy deposits [15]. For this
 1888 purpose, the entire electromagnetic calorimeter is subdivided into a grid of 200
 1889 by 256 towers in the η and ϕ directions, respectively, where the individual grid
 1890 units have a size of $\Delta\eta = 0.025$ and $\Delta\phi = 0.025$. These towers correspond to
 1891 individual cells in the middle, coarsest layer of the EM calorimeter, and in the
 1892 remaining layers the cells are grouped together cover the same area in $\eta - \phi$
 1893 space. The clustering begins by finding seeds with a sliding-window algorithm
 1894 based on the towers: a window of 3 by 5 towers is formed and translated until
 1895 the sum of the energy within the window is maximized. If that energy is above
 1896 2.5 GeV, then that region becomes a seed. The choice of 2.5 GeV was chosen to
 1897 compromise between maximizing reconstruction efficiency while minimizing
 1898 fake electron seeds from electronic noise or pileup. The seeds are rejected if the
 1899 energy measured in the hadronic calorimeter behind the seed is large, as this
 1900 typically indicates a hadron rather than an electron or photon.

1901 Next, the inner detector tracks within a cone of $\Delta R = 0.3$ are compared to
 1902 the location and energy of the seed. Tracks are matched to the cluster if the ex-
 1903 trapolation of the track to the energy-weighted center in the middle layer of the
 1904 EM calorimeter falls within $\Delta\phi < 0.2$ in the direction of the curvature of the
 1905 track or $\Delta\phi < 0.05$ in the direction opposite of the curvature of the track. If the
 1906 seed matches with a track that originated from a primary vertex, the combina-
 1907 tion of track and electromagnetic cluster is reconstructed as an electron. If the
 1908 seed matches with a track that did not originate from a primary vertex, then the
 1909 electromagnetic cluster is reconstructed as a converted photon. And if there is
 1910 no corresponding track in the inner detector, then the cluster is reconstructed
 1911 as a photon.

1912 After classification, the final clustering of the energy in the EM calorimeter
 1913 calorimeter is performed. The classification must be done first, as the expected

1914 size of the energy deposits in the calorimeter are different for electrons and pho-
 1915 tons. In the barrel region, the final clusters for electrons are formed in rectangles
 1916 of 3 towers in the η -direction and 7 towers in the ϕ -direction. This asymmetric
 1917 window accounts for the curving of the produced charged particles only in the
 1918 ϕ direction. For photons, the size of the rectangle is 3 towers by 5 towers. In the
 1919 endcap region, all object types are clustered in rectangles of 5 towers by 5 tow-
 1920 ers, as the effect of the magnetic field curvature is less pronounced in this region.
 1921 The sum of the energies in these clusters provide the final energy measurement
 1922 for the electron or photon.

1923 7.2.1 PHOTON IDENTIFICATION

1924 The original requirement for constructing a photon cluster, a significant energy
 1925 deposit in the electromagnetic calorimeter without a corresponding track or en-
 1926 ergy deposits in the hadronic calorimeter, is already effective in identifying pho-
 1927 tons. However, there is a significant background for prompt photon production
 1928 from the decays of pions, $\pi^0 \rightarrow \gamma\gamma$. These can be identified using the shape of
 1929 the cluster in the narrow η granularity in the first layer of the [EM](#) calorimeter.

1930 7.2.2 ELECTRON IDENTIFICATION

1931 Prompt electrons have a number of backgrounds, such as secondary electrons
 1932 from hadron decays or misidentified hadronic jets, that can be rejected using ad-
 1933 ditional information from the [EM](#) calorimeter and the inner detector. The most
 1934 basic level of electron identification, referred to as Loose, makes requirements
 1935 on the shower shapes in the high granularity first layer of the [EM](#) calorimeter
 1936 as well as the quality of the inner detector track. It also requires a good match
 1937 between the track and the calorimeter energy deposits and a small fraction of
 1938 energy in the hadronic calorimeter behind the electromagnetic cluster. [ATLAS](#)
 1939 defines several additional working points, including Medium and Tight, which
 1940 provide progressively lower background rates for electrons by imposing addi-
 1941 tionally strict requirements on the above variables as well as new requirements
 1942 like the impact parameter of the inner detector track or the comparison of the
 1943 cluster energy to the momentum in the inner detector.

1944 7.3 MUONS

1945 Muons produced in [ATLAS](#) first traverse the inner detector and leave behind a
 1946 track as described in Section 7.1. The muon then passes through the calorimeter,
 1947 leaving behind a small, characteristic amount of energy, and then passes through
 1948 the muon spectrometer where it produces hits in the [MDTs](#) or [CSCs](#). Muon tracks
 1949 are formed from local segments of hits in each layer of the [MDTs](#) or [CSCs](#), and
 1950 then the final muon spectrometer track is formed by combining the two local
 1951 segments. When a track is reconstructed in both the inner detector and the muon
 1952 spectrometer, they are combined to form a combined muon.

1953 In a few regions of the detector, a muon may fail to leave behind both a com-
 1954 plete inner detector and muon system track. For a very small fraction of the
 1955 acceptance of the muon system, there is only one layer of muon chambers and a
 1956 global muon system track is not formed. In this case, as long as the track in the
 1957 inner detector exists and geometrically matches to a segment, a segment-tagged
 1958 muon is formed using momentum measurements from the inner detector. In
 1959 the region where the muon system has coverage but the inner detector does not,
 1960 $2.5 < |\eta| < 2.7$, a stand-alone muon is formed which uses only information
 1961 from the muon system. And for muons produced within one of the few holes in
 1962 the muon system, including $|\eta| < 0.1$, the characteristic energy deposits in the
 1963 calorimeter can be used to tag an inner detector track as a calo-tag muon. These
 1964 additional categories are used to achieve high efficiency over a larger range of
 1965 acceptance, but the combined muons are the most reliable.

1966 7.3.1 MUON IDENTIFICATION

1967 The various types of muons are incorporated into three working points: Loose,
 1968 Medium, and Tight, which reflect the increasing muon purity for each of the
 1969 selections definitions. Tight muons include only combined muons with a good
 1970 track fit quality and momentum resolution and at least two hits in a precision
 1971 muon system layer. Medium muons include those in tight as well as combined
 1972 muons with one precision hit and one precision hole, where hole is defined in
 1973 the same way as in Section 7.1. The medium working point also includes stand-
 1974 alone muons with $|\eta| > 2.5$ and at least two hits in precision layers. And finally
 1975 the loose working point includes both medium and tight muons, but additional
 1976 includes segment-tagged and calo-tagged muons in the region $|\eta| < 0.1$.

1977 7.4 JETS

1978 A jet does not directly correspond to a physical particle, unlike all of the recon-
 1979 structed objects described above, but instead tries to capture the conical cascade
 1980 of particles produced in the hadronization of a quark or gluon from the proton-
 1981 proton collision. The hadronization process creates a very large number of col-
 1982 limated particles, with a high enough density that individually reconstructing all
 1983 of the produced particles in the calorimeter is not possible within ATLAS. How-
 1984 ever most analyses are interested only in the kinematics of the particle which
 1985 produced the cascade, rather than the individual products. Therefore, jets are
 1986 a useful tool to measure the combined energy and direction of the ensemble of
 1987 products and thus represents the kinematics of the original. Jet algorithms are
 1988 very generic and can be used to group together a number of types of objects to
 1989 form aggregate representations. For example, truth particles in simulation can
 1990 be grouped in truth jets, or tracks from the inner detector can be grouped to-
 1991 gether to form track jets. This section, however, will focus on calorimeter jets
 1992 which take topoclusters of energy deposits in the calorimeter as inputs and pro-
 1993 duce a combined object which represents the energy measured by the calorime-
 1994 ter and the location where it was deposited.

1995 74.1 TOPOLOGICAL CLUSTERING

1996 Hadrons often deposit their energy into multiple individual cells in both the elec-
 1997 tromagnetic and hadronic calorimeters. The purpose of topological clustering is
 1998 to group cells in all three dimensions into clusters that represent a single energy
 1999 deposit. The procedure must be robust enough to reject noise fluctuations in
 2000 the cell energy measurements that can come from both electronic noise and ad-
 2001 ditional low energy particles produced in pileup activity. The background level
 2002 of calorimeter noise is called σ_{noise} , and is an important component of the topo-
 2003 logical clustering.

2004 The topological clusters are formed in a three step process called the 4-2-0
 2005 threshold scheme, which uses three energy thresholds to build up a cluster from
 2006 cells. First, any cells with a measured energy above $4\sigma_{\text{noise}}$ are identified as seed
 2007 cells. The cells adjacent to the seed cells with a measured energy above $2\sigma_{\text{noise}}$ are
 2008 called secondary cells. All of the cells which are adjacent to a secondary cell
 2009 with $E_{\text{cell}} > 2\sigma_{\text{noise}}$ are also labelled secondary cells. Tertiary cells are those
 2010 immediately adjacent to a seed or secondary cell with a measured energy above
 2011 zero. Adjacency in this sense is defined in three dimensions, cells are adjacent if
 2012 they are neighbors within a layer but also if they have the same $\eta - \phi$ coordinates
 2013 but are in adjacent layers or even in an adjacent layer in another calorimeter.

2014 From these definitions, clusters are built by resolving the seeds in order of
 2015 significance, the ratio $E_{\text{cell}}/\sigma_{\text{noise}}$. All adjacent secondary cells to the highest
 2016 significance seed are added to that seed's topocluster, and any of those cells which
 2017 would also have qualified as seeds are removed from the list of seeds. Once all
 2018 of the secondary cells have been added, the tertiary cells are then added to that
 2019 cluster as well. This procedure is then iterated until no seeds remain, forming
 2020 the first round of topoclusters.

2021 It is also useful to split topoclusters into multiples if local maxima are present
 2022 within the topocluster, as clusters produced by multiple nearby particles can
 2023 merge. The splitting process begins by finding local maxima cells in the middle
 2024 layer of the calorimeters with a minimum energy of 500 MeV and at least four
 2025 neighboring secondary cells. These requirements reduce the likelihood to split
 2026 a cluster due to random fluctuations, as the middle layers provide the most reli-
 2027 able energy measurements. Cells between two local maxima can then be shared
 2028 between two clusters to account for overlapping contributions from two parti-
 2029 cles. The energy sharing is weighted by the energy of each cluster as well as the
 2030 distance of the cell to the centroid of that cluster.

2031 The energies of all the cells in the cluster are then summed together to form
 2032 the energy of that cluster. The energy needs to be corrected for the various losses
 2033 expected in the calorimeter, as described in Section 6.4. The simplest correction,
 2034 scaling the measured energy by the sampling fraction, brings the cluster energies
 2035 to the EM scale. It is called the EM scale because it accurately describes the energy
 2036 of electromagnetic showers.

2037 Another scale is defined to improve accuracy for hadronic processes, the local
 2038 cluster weighted (LCW) scale, that helps to correct for the expected variations in
 2039 hadronic energy deposits. The LCW correction first determines if the shower is

hadronic or electromagnetic, based on the depth of the shower and the cluster energy density. For hadronic showers, the energy is corrected for calorimeter non-compensation, an effect which reduces the measured energy of hadronic showers because some of the energy goes into invisible processes like the break up of nuclei. All clusters are then corrected for energy that may be deposited in uninstrumented regions in that cluster's location in the calorimeter, and they are also corrected with an estimate of how much energy falls outside the extent of the cluster based on its shape and the deposit type.

7.4.2 JET ALGORITHMS

Using the topological clusters as inputs, a jet algorithm groups them together into a collection of adjacent energy deposits that is intended to correspond to a single process. Jet algorithms need a few key characteristics to be usable for physics analysis. First, the jets produced by the algorithm should have little dependence on the addition of soft particles to the event (infrared safety), as a negligible addition of energy should not significantly modify the event topology. Similarly, the jets produced by the algorithm should also not significantly depend on mostly collinear splitting of an input particle (collinear safety); that is, a single quark splitting into two nearly parallel quarks should not change the resulting jets, which are intended to capture only the properties of the aggregate and not those of individual particles. And finally the algorithm needs to be sufficiently simple and fast to be used for the large rate of collected proton-proton collisions on [ATLAS](#).

The most commonly used algorithm on [ATLAS](#) that satisfies these requirements is called the anti- k_t algorithm, and is discussed in further detail in Reference [16]. The anti- k_t , in brief, relies on iteratively combining the input objects that are closest together, where closest is defined by a particular distance metric, d_{ij} . The combinations stop when the closest remaining object is the beam itself, where the distance to the beam is called $d_{i,B}$. An entire class of algorithms follows this procedure with the following distance metrics

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (18)$$

$$d_{i,B} = k_{ti}^{2p} \quad (19)$$

where $\Delta_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, k_{ti} is the transverse momentum of the object, y is the rapidity, and p is a parameter of the algorithm. Anti- k_t is the particular case where $p = -1$, and is a choice that results in an algorithm that is both infrared and collinear safe.

The algorithm is repeated until there are no input objects remaining, which results in a series of jets. Each jet has a complete four momentum from the combination of its input clusters. The jet energies then need to be calibrated to attempt to match the energy of the object which produced the jet.

2077 74.3 JET ENERGY SCALE

2078 Though the [LCW](#) scheme attempts to correct the topoclusters to reflect the true
 2079 deposited energy, the correction does not fully account for energy lost within
 2080 the calorimeters. Because of these effects, the original reconstructed jet energy
 2081 does not reflect the true energy of the particle which initiated the jet. Therefore
 2082 it is necessary to additionally correct the reconstructed jet itself, in addition to
 2083 the corrections on the inputs. This correction is referred to as the [JES](#), which
 2084 combines several individual steps of calibration.

2085 The first calibration step corrections the direction of the jet to ensure that it
 2086 points back to the primary vertex. Next, the energy of the jet is corrected for
 2087 pileup by subtracting the expected contribution from pileup (measured in simu-
 2088 lation) based on the momentum, η , and area of the jet as well as the number of
 2089 reconstructed vertices and expected number of interactions per crossing. The
 2090 largest single correction is the absolute η and [JES](#) correction, where the jet energy
 2091 and pseudorapidity is corrected to attempt to match the energy and pseudorapid-
 2092 ity of the parton which produced it. This correction is measured in simulation
 2093 by comparing the reconstructed jet energies to the energy of the truth particle
 2094 which produced it. However the simulation is not relied on alone to estimate
 2095 this correction, and an additional step applies an additional energy correction
 2096 based on in-situ measurements in data. These corrections come from various
 2097 techniques which measure jet energies indirectly by balancing them with other,
 2098 well-measured objects. In the central region ($|\eta| < 1.2$), jets are balanced against
 2099 photons and the leptonic decays of Z bosons and high momentum jets ($p_T > 210$
 2100 GeV) are also balanced against multiple smaller jets in multijet events. Jets at
 2101 larger pseudorapidities, above $|\eta| = 1.2$, are calibrated by balancing with lower
 2102 pseudorapidity jets.

2103 These steps introduce a number of systematic uncertainties, referred to as
 2104 the [JES](#) uncertainty. The largest of these comes from the in-situ measurements,
 2105 which are statistically limited in measuring high momentum and high pseudora-
 2106 pidity jets. The total, fractional [JES](#) uncertainty is shown as a function of p_T in
 2107 Figure 42. The uncertainty falls to a minimum value of just over 1.0% around a
 2108 few hundred GeV, and rises again at high momentum because of the difficulty of
 2109 measuring jet balance in data above 2-3 TeV. The uncertainty is also minimized
 2110 at low $|\eta|$, and grows at large $|\eta|$ again where making in-situ measurements is
 2111 difficult. This technique does not actually provide a measurement of the uncer-
 2112 tainty for the highest energy jets, above 3 TeV, because there are not enough
 2113 measured data events to provide them. An alternative method for deriving the
 2114 [JES](#) and [JES](#) uncertainty that can be used even for very high p_T jets will be dis-
 2115 cussed in Chapter 9.

2116 7.5 MISSING TRANSVERSE ENERGY

2117 Among [SM](#) particles, only the neutrino cannot be directly measured in the [ATLAS](#)
 2118 detector. Because the neutrino carries neither electric nor color charge, it is very
 2119 unlikely to interact with the tracking detectors or the calorimeters, and instead

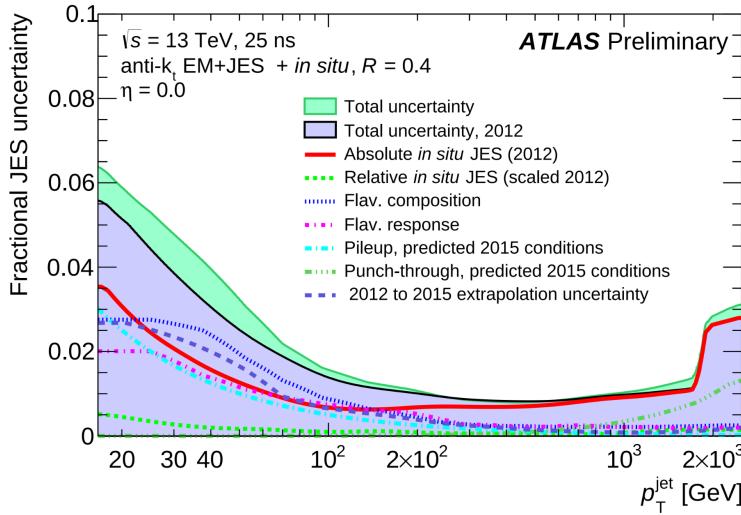


Figure 42: The total, fractional JES uncertainties estimated for 2015 data as a function of jet p_T .

passes through the detector completely unobserved. Some particles which have been conjectured to exist, like the LSP in many SUSY models, would also have the same behavior. Therefore, it is important for ATLAS to provide some way to assess the momentum carried away by a neutral, colorless particle. This can be accomplished through a measurement of missing energy in the transverse direction, or E_T^{miss} , which quantifies the momentum imbalance of the observed particles. From the conservation of momentum and the lack of the initial momentum in the transverse plane in the proton-proton collisions, any imbalance of momentum can be inferred to be carried away by an unmeasured particle.

E_T^{miss} is more precisely defined as the magnitude of the vector sum of the (p_x, p_y) components of each observed object's momentum. The definition is simple, but there can be significant complexity in defining the inputs. As of Run 2, ATLAS uses a common algorithmic approach to carefully calculate missing energy, but each analysis is free to define its own inputs. For the analysis discussed throughout this thesis, the missing energy inputs consist of the electrons, photons, muons, and jets discussed in the previous sections, in addition to a track-based soft term.

To produce the most precise measurement of E_T^{miss} , it is important to use the best representation of the momentum of each of the input objects, which can often be reconstructed as multiple different types in a single event. For example, an electron can be reconstructed separately as an electron (Section 7.2) and a jet (Section 7.4), but the electron representation has the highest precision for reconstructing the true electron momentum. To ensure no duplications in the E_T^{miss} definition, the inputs are collectively considered for overlap removal. Only the most precise object type is kept for objects that fall within a cone of $\Delta R < 0.2$ for pairs of electrons and jets and a cone of $\Delta R < 0.4$ for other pair types.

The fully reconstructed objects do not include all of the energy within the events, as some clusters do not enter into a jet and some tracks are not classified as electrons or muons. These momentum carried by these objects is accounted

2149 for in a soft-term, which tallies all of the energy carried by the particles too soft
2150 to form separate objects. The track soft term uses only tracking information to
2151 estimate the contribution of soft objects, and does so by vectorially summing the
2152 momentum of all well-reconstructed tracks with momentum above 400 MeV.

2153 All of these contributions together give a single E_T^{miss} value for a given event.
2154 The direction of that missing energy is taken as opposite the vector sum of all the
2155 constituents, to correspond to the momentum an invisible particle would have to
2156 have to make the event balanced. Depending on the context, this missing energy
2157 can be considered the energy of a neutrino or an LSP, with a large missing energy
2158 being a common signal criteria for searches for new physics.

2159

PART IV

2160

CALORIMETER RESPONSE

2161

You can put some informational part preamble text here.

8

2162

2163 RESPONSE MEASUREMENT WITH SINGLE HADRONS

2164 As discussed in Section 7.4, colored particles produced in collisions hadronize
2165 into jets of multiple hadrons. One approach to understanding jet energy mea-
2166 surements in the ATLAS calorimeters is to evaluate the calorimeter response to
2167 those individual hadrons; measurements of individual hadrons can be used to
2168 build up an understanding of the jets that they form. The redundancy of the
2169 momentum provided by the tracking system and the energy provided by the
2170 calorimeter provides an opportunity to study calorimeter response using real
2171 collisions, as described further in Section 8.2.

2172 Calorimeter response includes a number of physical effects that can be ex-
2173 tracted to provide insight into many aspects of jet modeling. First, many charged
2174 hadrons interact with the material of the detector prior to reaching the calorime-
2175 ters and thus do not deposit any energy. Comparing this effect in data and simu-
2176 lation is a powerful tool in validating the interactions of particles with the mate-
2177 rial of the detector and the model of the detector geometry in simulation, see Sec-
2178 tion 8.2.2. The particles which do reach the calorimeter deposit their energy into
2179 several adjacent cells, which are then clustered together. The energy of the clus-
2180 ter is then the total energy deposited by that particle. Comparing the response of
2181 hadrons in data to that of simulated hadrons provides a direct evaluation of the
2182 showering of hadronic particles and the energy deposited by particles in matter
2183 (Section 8.2.4).

2184 The above studies all use an inclusive selection of charged particles, which are
2185 comprised predominantly of pions, kaons, and (anti)protons. It is also possible to
2186 measure the response to various identified particle types separately to evaluate
2187 the simulated interactions of each particle, particularly at low energies where
2188 differences between species are very relevant. Pions and (anti)protons can be
2189 identified through decays of long-lived particles, in particular Λ , $\bar{\Lambda}$, and K_S^0 , and
2190 then used to measure response as described above. This is discussed in detail in
2191 Section 8.3.

2192 The results in this chapter use data collected at 7 and 8 TeV collected in 2010
2193 and 2012, respectively. Both are included as the calorimeter was repaired and
2194 recalibrated between those two data-taking periods. Both sets of data are com-
2195 pared to an updated simulation that includes new physics models provided by
2196 Geant4 [17] and improvements in the detector description [18, 19]. The present
2197 results are published in European Physical Journal C (EPJC) [20] and can be com-
2198 compared to a similar measurement performed in 2009 and 2010 [21], which used
2199 the previous version of the simulation framework [22].

2200 8.1 DATASET AND SIMULATION

2201 8.1.1 DATA SAMPLES

2202 The two datasets used in this chapter are taken from dedicated low-pileup runs
 2203 where the fraction of events with multiple interactions was negligible. These
 2204 datasets are used rather than those containing full-pileup events to facilitate mea-
 2205 surement of isolated hadrons. The 2012 dataset at $\sqrt{s} = 8$ TeV contains 8 mil-
 2206 lion events and corresponds to an integrated luminosity of 0.1 nb^{-1} . The 2010
 2207 dataset at $\sqrt{s} = 7$ TeV contains 3 million events and corresponds to an inte-
 2208 grated luminosity of 3.2 nb^{-1} . The latter dataset was also used for the 2010 re-
 2209 sults [21], but it has since been reanalyzed with an updated reconstruction in-
 2210 cluding the final, best understanding of the detector description for the material
 2211 and alignment from Run 1.

2212 8.1.2 SIMULATED SAMPLES

2213 The two datasets above are compared to simulated single-, double-, and non-
 2214 diffractive events generated with Pythia8 [23] using the A2 configuration of
 2215 hadronization [24] and the MSTW 2008 parton-distribution function set [25,
 2216 26]. The admixture of the single-, double-, and non-diffractive events uses the
 2217 default relative contributions from Pythia8. The conditions and energies for
 2218 the two simulations are chosen so that they match those of the corresponding
 2219 dataset.

2220 To evaluate the interaction of hadrons with detector material, the simulation
 2221 uses two different collections of hadronic physics models, called physics lists, in
 2222 Geant4 9.4 [27]. The first, QGSP_BERT, combines the Bertini intra-nuclear
 2223 cascade [28–30] below 9.9 GeV, a parametrized proton inelastic model from 9.5
 2224 to 25 GeV [31], and a quark-gluon string model above 12 GeV [32–36]. The
 2225 second, FTFP_BERT, combines the Bertini intra-nuclear cascade [28–30] below
 2226 5 GeV and the Fritiof model [37–40] above 4 GeV. In either list, Geant4 en-
 2227 forces a smooth transition between models where multiple models overlap.

2228 8.1.3 EVENT SELECTION

2229 The event selection for this study is minimal, as the only requirement is selecting
 2230 good-quality events with an isolated track. Such events are triggered by requir-
 2231 ing at least two hits in the minimum-bias trigger scintillators. After trigger, each
 2232 event is required to have exactly one reconstructed vertex, and that vertex is re-
 2233 quired to have four or more associated tracks.

2234 The particles which are selected for the response measurements are first iden-
 2235 tified as tracks in the inner detector. The tracks are required to have at least 500
 2236 MeV of transverse momentum. To ensure a reliable momentum measurement,
 2237 these tracks are required to have at least one hit in the pixel detector, six hits in
 2238 the SCT, and small longitudinal and transverse impact parameters with respect
 2239 to the primary vertex [21]. For the majority of the measurements in this chapter,

the track is additionally required to have 20 hits in the TRT, which significantly reduces the contribution from tracks which undergo nuclear interactions. This requirement and its effect is discussed in more detail in Section 8.2.5. In addition, tracks are rejected if there is any other reconstructed track which extrapolates to the calorimeter within a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$. This requirement guarantees that the contamination of energy from nearby charged particles is negligible [21].

8.2 INCLUSIVE HADRON RESPONSE

The calorimeter response is more precisely defined as the ratio of the measured calorimeter energy to the true energy carried by the particle, although this true energy is unknown. For charged particles, however, the inner detector provides a very precise measurement of momentum (with uncertainty less than 1%) that can be used as a proxy for true energy. The ratio of the energy deposited by the charged particle in the calorimeter, E , to its momentum measured in the inner detector p , forms the calorimeter response measure called E/p . Though the distribution of E/p contains a number of physical features, this study focuses on the trends in two aggregated quantities: $\langle E/p \rangle$, the average of E/p for the selected tracks, and the zero fraction, the fraction of tracks with no associated energy in the calorimeter for those tracks.

The calorimeter energy assigned to a track is defined using clusters. The clusters are formed using a 4–2–0 algorithm [41] that begins with seeds requiring at least 4 times the average calorimeter cell noise. The neighboring cells with at least twice that noise threshold are then added to the cluster, and all bounding cells are then added with no requirement. This algorithm minimizes noise contributions through its seeding process, and including the bounding cells improves the energy resolution [42]. The clusters are associated to a given track if they fall within a cone of $\Delta R = 0.2$ of the extrapolated position of the track, which includes about 90% of the energy on average [21]. This construction is illustrated in Figure 43.

8.2.1 E/P DISTRIBUTION

The E/p distributions measured in both data and simulation are shown in Figure 44 for two example bins of track momentum and for tracks in the central region of the detector. These distributions show several important features of the E/p observable. The large content in the bin at $E = 0$ comes from tracks that have no associated cluster, which occurs due to interactions with detector material prior to reaching the calorimeter or the energy deposit being insufficiently large to generate a seed, and are discussed in Section 8.2.2. The small negative tail also comes from tracks that do not deposit any energy in the calorimeter but are randomly associated to a cluster with an energy below the noise threshold. The long positive tail above 1.0 comes from the contribution of neutral particles. Nearby neutral particles deposit (sometimes large) additional energy in the calorimeter but do not produce tracks in the inner detector, so they cannot be

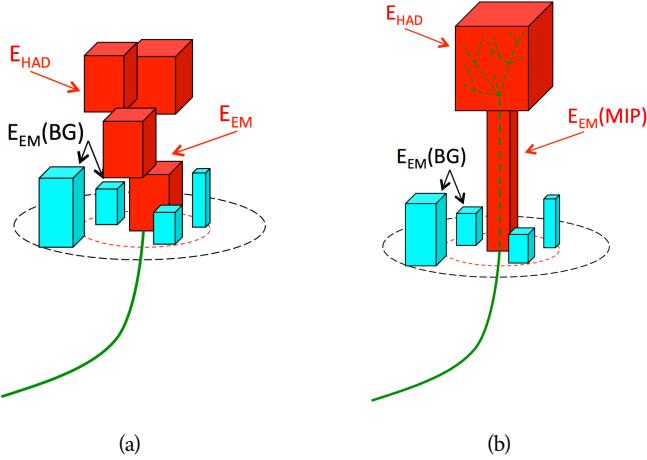


Figure 43: An illustration (a) of the E/p variable used throughout this paper. The red energy deposits come from the charged particle targeted for measurement, while the blue energy deposits are from nearby neutral particles and must be subtracted. The same diagram (b) for the neutral-background selection, described in Section 8.2.3.

2282 rejected by the track isolation requirement. Additionally the peak and mean of
 2283 the distribution falls below 1.0 because of the loss of energy not found within
 2284 the cone as well as the non-compensation of the calorimeter.

2285 The data and simulation share the same features, but the high and low tails
 2286 are significantly different. The simulated events tend to overestimate the con-
 2287 tribution of neutral particles to the long tail, an effect which can be isolated and
 2288 removed as discussed in Section 8.2.3. Additionally, the simulated clusters have
 2289 less noise on average, although this is a small effect on the overall response.

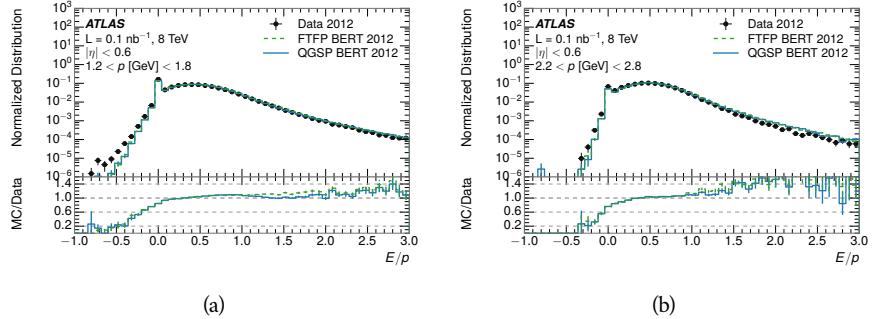


Figure 44: The E/p distribution and ratio of simulation to data for isolated tracks with
 (a) $|\eta| < 0.6$ and $1.2 < p/\text{GeV} < 1.8$ and (b) $|\eta| < 0.6$ and $2.2 < p/\text{GeV} < 2.8$.

2290 8.2.2 ZERO FRACTION

2291 The fraction of particles with no associated clusters, or similarly those with $E \leq$
 2292 0, reflects the modeling of both the detector geometry and hadronic interactions.

2293 The zero fraction is expected to rise as the amount of material a particle traverses
 2294 increases, while it is expected to decrease as the particle energy increases. This
 2295 dependence can be seen in Figure 45, where the zero fraction in data and simulation
 2296 is shown as a function of momentum and the amount of material measured
 2297 in interaction lengths. The trends are similar between 2010 and 2012 and for
 2298 positively and negatively charged particles. The zero fraction decreases with
 2299 energy as expected. The absolute discrepancy in zero fraction decreases with
 2300 momentum from 5% to less than 1%, but this becomes more pronounced in the
 2301 ratio as the zero fraction shrinks quickly with increasing momentum. There is
 2302 a small constant difference between the data and simulation in both interaction
 2303 models that becomes more pronounced. The amount of material in the detector
 2304 increases with η , which is used to obtain results for interaction lengths ranging
 2305 between 0.1 and 0.65 λ . As the data and simulation have significant disagree-
 2306 ment in the zero fraction over a number of interaction lengths, the difference
 2307 must be primarily from the modeling of hadronic interactions with detector ma-
 2308 terial and not just the detector geometry. Although two different hadronic in-
 2309 teraction models are shown in the figure, they have very similar discrepancies to
 2310 data because both use the same description (the BERT model) at low momentum.

2311 8.2.3 NEUTRAL BACKGROUND SUBTRACTION

2312 The isolation requirement on hadrons is only effective in removing an energy
 2313 contribution from nearby charged particles. Nearby neutral particles, predomi-
 2314 nantly photons from π^0 decays, also add their energy to the calorimeter clusters,
 2315 but mostly in the electromagnetic calorimeter. It is possible to measure this con-
 2316 tribution, on average, using late-showering hadrons that minimally ionize in the
 2317 electromagnetic calorimeter. Such particles are selected by requiring that they
 2318 deposit less than 1.1 GeV in the EM calorimeter within a cone of $\Delta R < 0.1$
 2319 around the track. To ensure that these particles are well measured, they are addi-
 2320 tionally required to deposit between 40% and 90% of their energy in the hadronic
 2321 calorimeter within the same cone.

2322 These particles provide a clean sample to measure the nearby neutral back-
 2323 ground because they do not deposit energy in the area immediately surrounding
 2324 them in the EM calorimeter, as shown in Figure 43. So, the energy deposits in the
 2325 region $0.1 < \Delta R < 0.2$ can be attributed to neutral particles alone. To estimate
 2326 the contribution to the whole cone considered for the response measurement,
 2327 that energy is scaled by a geometric factor of $4/3$. This quantity, $\langle E/p \rangle_{BG}$, mea-
 2328 sured in aggregate over a number of particles, gives the contribution to $\langle E/p \rangle$
 2329 from neutral particles in the EM calorimeter. Similar techniques were used in
 2330 the individual layers of the hadronic calorimeters to show that the background
 2331 from neutrals is negligible in those layers [21].

2332 The distribution of this background estimate is shown in Figure 46 for data
 2333 and simulation with the two different physics lists. The contribution from neu-
 2334 tral particles falls from 0.1 at low momentum to around 0.03 for particles above
 2335 7 GeV. Although the simulation captures the overall trend, it significantly over-
 2336 estimates the neutral contribution for tracks with momentum between 2 and 8

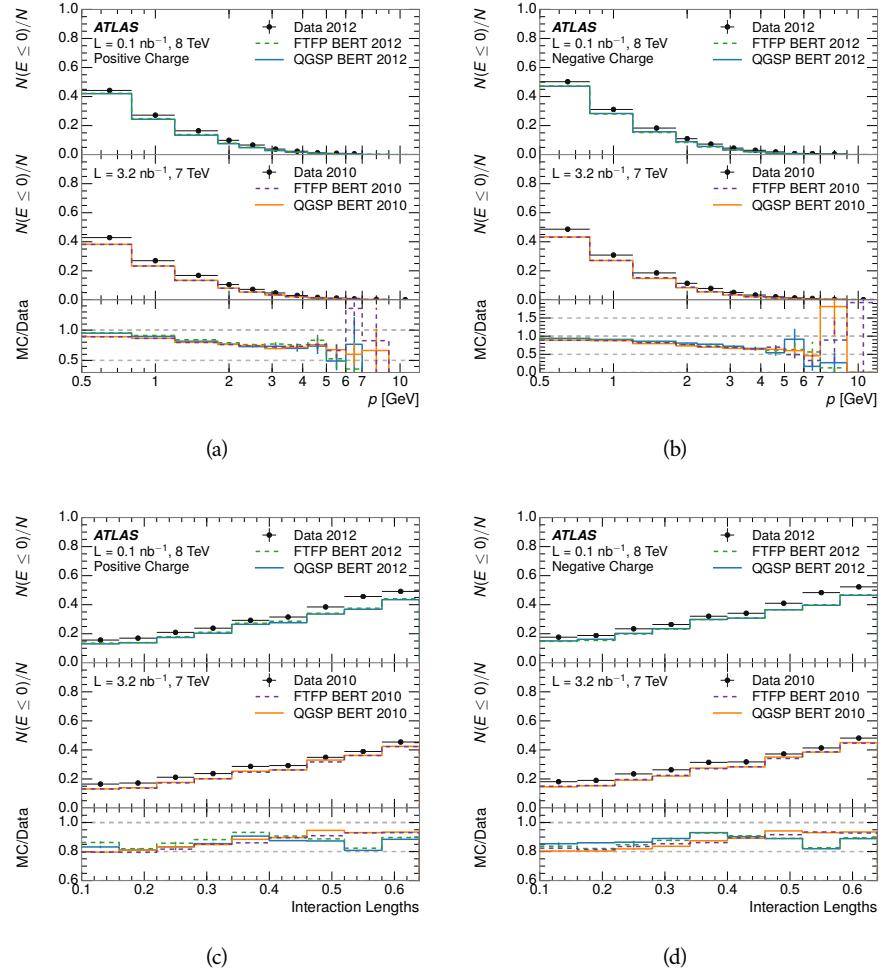


Figure 45: The fraction of tracks as a function (a, b) of momentum, (c, d) of interaction lengths with $E \leq 0$ for tracks with positive (on the left) and negative (on the right) charge.

2337 GeV. This effect was also seen in the tails of the E/p distributions in Figure 44.
 2338 This difference is likely due to modeling of coherent neutral particle radiation
 2339 in Pythia8 that overestimates the production of π^0 near the production of the
 2340 charged particles. The discrepancy does not depend on η and thus is unlikely to
 2341 be a mismodeling of the detector. This difference can be subtracted to form a
 2342 corrected average E/p , as in Section 8.2.4.

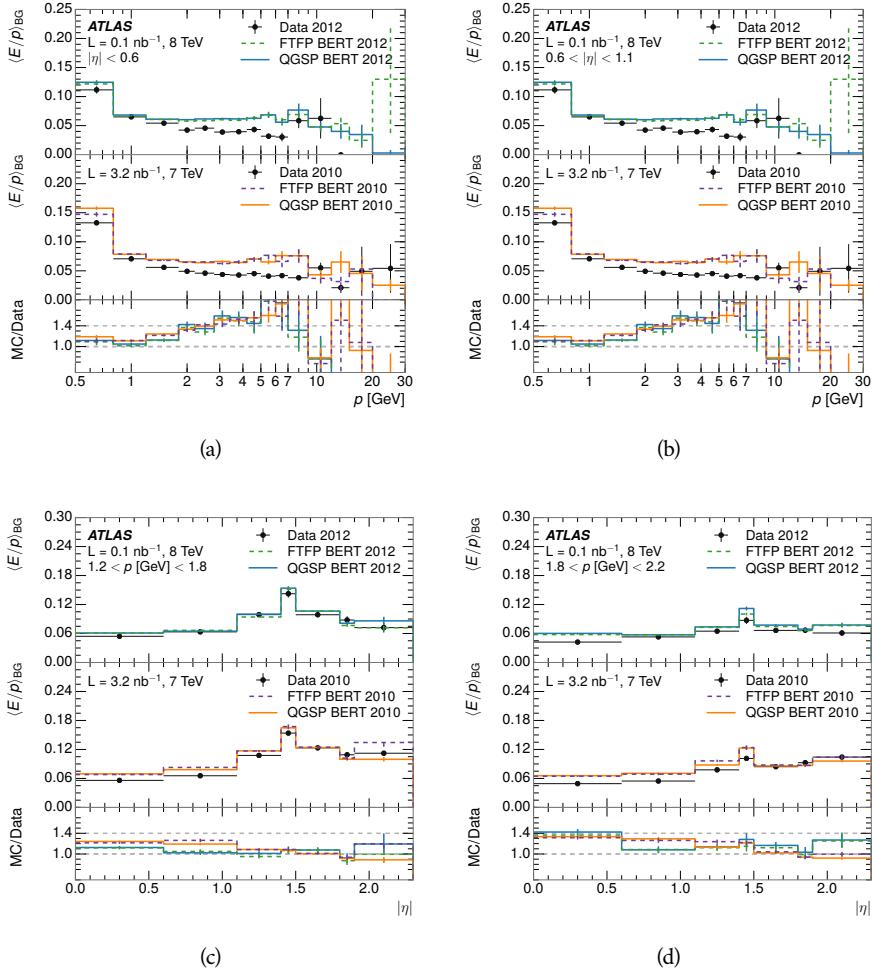


Figure 46: $\langle E/p \rangle_{BG}$ as a function of the track momentum for tracks with (a) $|\eta| < 0.6$,
 (b) $0.6 < |\eta| < 1.1$, and as a function of the track pseudorapidity for tracks
 with (c) $1.2 < p/\text{GeV} < 1.8$, (d) $1.8 < p/\text{GeV} < 2.2$.

2343 8.2.4 CORRECTED RESPONSE

2344 Figure 47 shows $\langle E/p \rangle_{COR}$ as a function of momentum for several bins of pseudo-
 2345 rapidity. This corrected $\langle E/p \rangle_{COR} \equiv \langle E/p \rangle - \langle E/p \rangle_{BG}$ measures the average
 2346 calorimeter response without the contamination of neutral particles. It is the
 2347 most direct measurement of calorimeter response in that it is the energy mea-
 2348 sured for fully isolated hadrons. The correction is performed separately in data
 2349 and simulation, so that the mismodeling of the neutral background in simulation

is removed from the comparison of response. The simulation overestimates the response at low momentum by about 5%, an effect that can be mostly attributed to the underestimation of the zero fraction mentioned previously. For $|\eta| < 0.6$, the data-simulation agreement has a larger discrepancy by about 5% for 2010 than 2012, although this is not reproduced in at higher pseudorapidity.

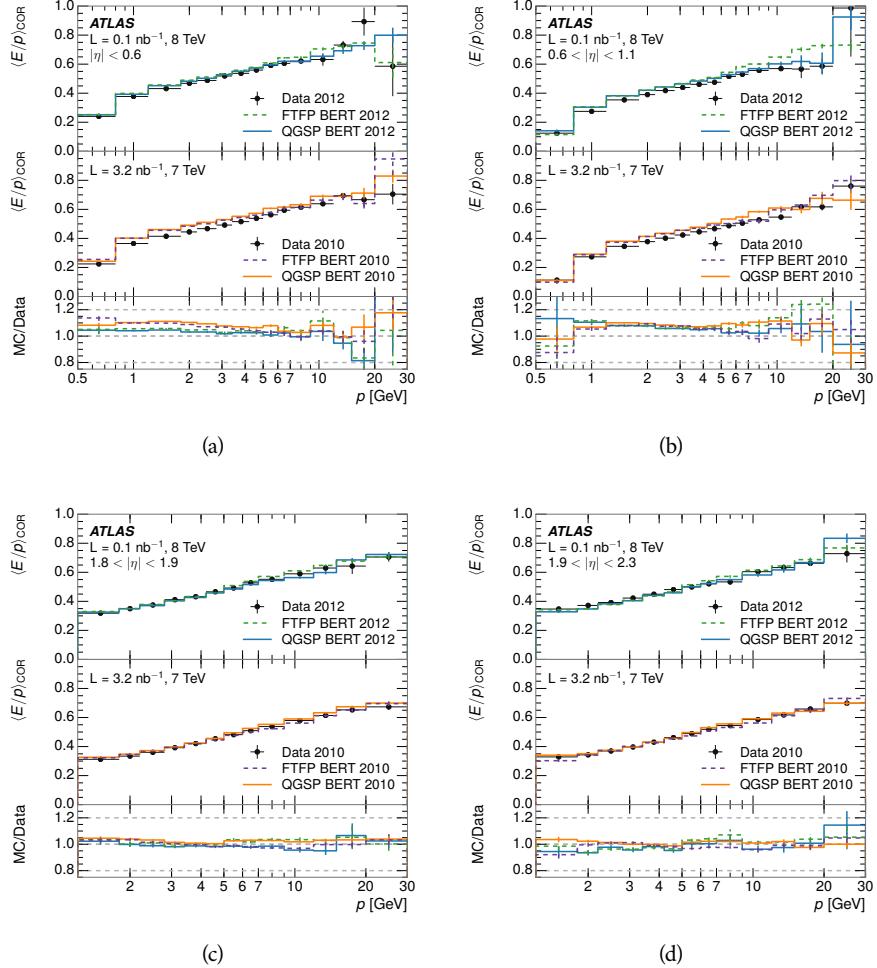


Figure 47: $\langle E/p \rangle_{\text{COR}}$ as a function of track momentum, for tracks with (a) $|\eta| < 0.6$, (b) $0.6 < |\eta| < 1.1$, (c) $1.8 < |\eta| < 1.9$, and (d) $1.9 < |\eta| < 2.3$.

The response measurement above used topological clustering at the EM scale, that is clusters were formed to measure energy but no corrections were applied to correct for expected effects like energy lost outside of the cluster or in uninstrumented material. It is also interesting to measure $\langle E/p \rangle_{\text{COR}}$ using LCW energies, which accounts for those effects by calibrating the energy based on the properties of the cluster such as energy density and depth in the calorimeter. Figure 48 shows these distributions for tracks with zero or more clusters and separately for tracks with one or more clusters. The calibration moves the mean value of $\langle E/p \rangle_{\text{COR}}$ significantly closer to 1.0 as desired. The agreement between data and simulation improves noticeably when at least one cluster is required, as this removes the contribution from the mismodeling of the zero fraction. The

good agreement in that case again demonstrates that the difference in $\langle E/p \rangle_{\text{COR}}$ between data and simulation is caused predominantly by the difference in zero fraction.

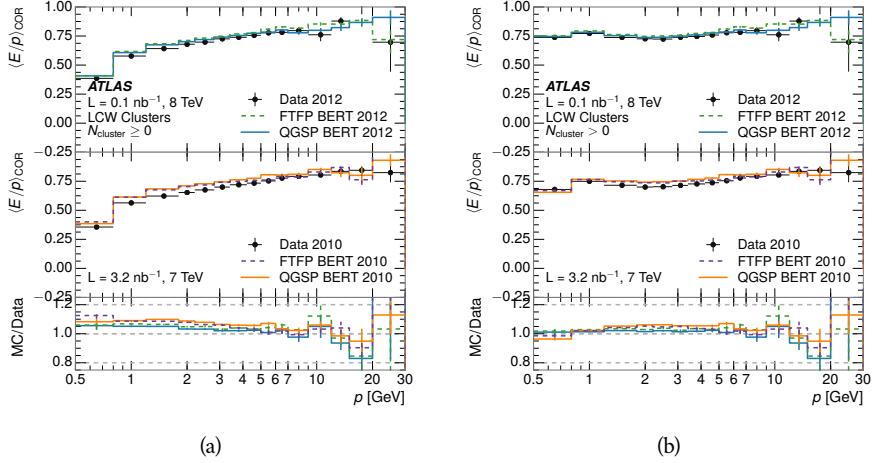


Figure 48: $\langle E/p \rangle_{\text{COR}}$ calculated using LCW-calibrated topological clusters as a function of track momentum for tracks with (a) zero or more associated topological clusters or (b) one or more associated topological clusters.

8.2.5 ADDITIONAL STUDIES

As has been seen in several measurements in previous sections, the simulation does not correctly model the chance of a low momentum hadron to reach the calorimeter. Because of the consistent discrepancy across pseudorapidity and interaction lengths, this can be best explained by incomplete understanding of hadronic interactions with the detector [20]. For example, a hadron that scatters off of a nucleus in the inner detector can be deflected through a significant angle and not reach the expected location in the calorimeter. In addition, these interactions can produce secondary particles that are difficult to model.

The requirement used throughout the previous sections on the number of hits in the TRT reduces these effects by preferentially selecting tracks that do not undergo nuclear interactions. It is interesting to check how well the simulation models tracks with low numbers of TRT hits, which selects tracks that are more likely to have undergone a hadronic interaction. Figure 49 compares the distributions with $N_{\text{TRT}} < 20$ to $N_{\text{TRT}} > 20$ for real and simulated particles. As expected, the tracks with fewer hits are poorly modeled in the simulation as $\langle E/p \rangle_{\text{COR}}$ differs by as much as 25% at low momentum.

Another interesting aspect of the simulation is the description of antiprotons at low momentum, where QGSP_BERT and FTFP_BERT have significant differences. This can be seen to have an effect in the inclusive response measurement when separated into positive and negative charge. The $\langle E/p \rangle_{\text{COR}}$ distributions for positive and negative particles are shown in Figure 50, where a small difference between QGSP_BERT and FTFP_BERT can be seen in the distribution for

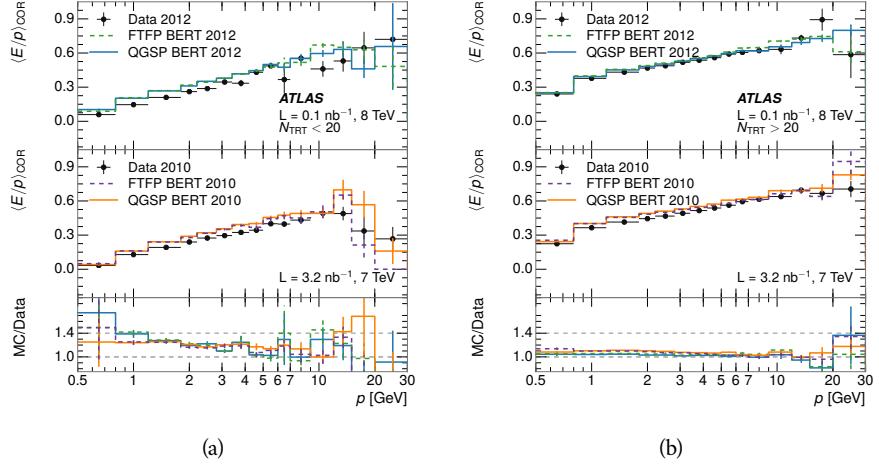


Figure 49: Comparison of the $\langle E/p \rangle_{\text{COR}}$ for tracks with (a) less than and (b) greater than 20 hits in the TRT.

negative tracks. This is demonstrated more clearly in Figure 51, which shows the E/p distribution in the two simulations separated by charge. There is a clear difference around $E/p > 1.0$, which can be explained by the additional energy deposited by the annihilation of the antiproton in the calorimeter that is modeled well only in FTFP_BERT. This is also explored with data using identified antiprotons in Section 8.3.

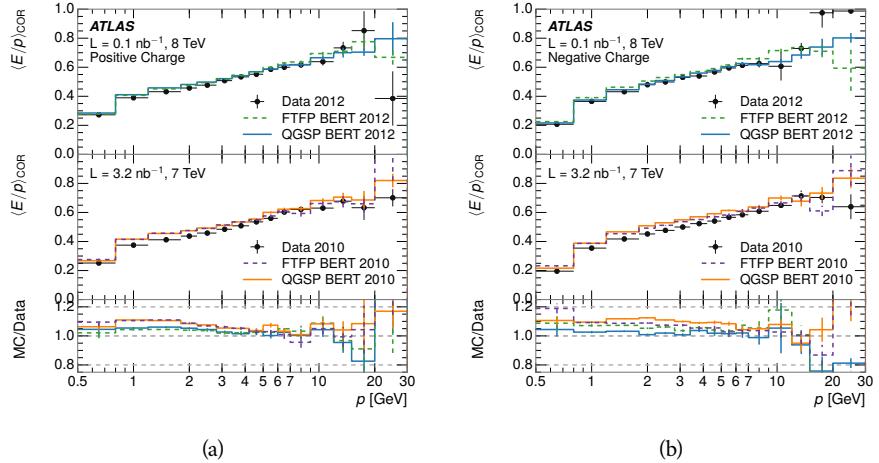


Figure 50: Comparison of the $\langle E/p \rangle_{\text{COR}}$ for (a) positive and (b) negative tracks as a function of track momentum for tracks with $|\eta| < 0.6$.

The $\langle E/p \rangle$ results in previous sections have considered the electromagnetic and hadronic calorimeters together as a single energy measurement, to emphasize the total energy deposited for a given particle. However, the deposits in each calorimeter are available separately and $\langle E/p \rangle$ can be constructed for each layer. As the layers are composed of different materials and are modeled separately in the detector geometry, confirmation that the simulation matches the data well

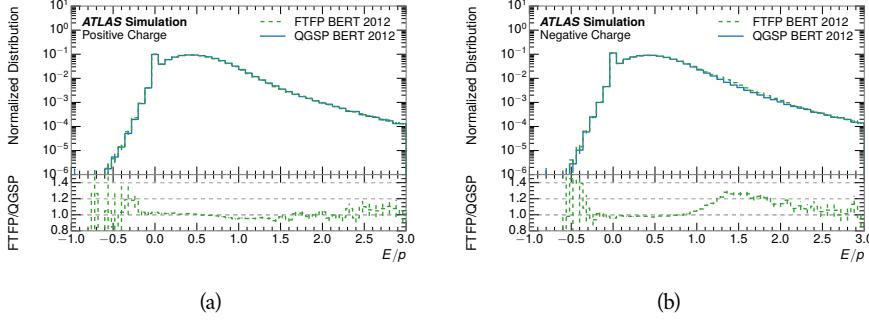


Figure 51: Comparison of the E/p distributions for (a) positive and (b) negative tracks with $0.8 < p/\text{GeV} < 1.2$ and $|\eta| < 0.6$, in simulation with the FTFP_BERT and QGSP_BERT physics lists.

in each layer adds confidence in both the description of hadronic interactions with the two different materials and also the geometric description of each.

The technique discussed in Section 8.2.3 for selecting MIPs in the electromagnetic calorimeter is also useful in studying deposits in the hadronic calorimeter. Those MIPs deposit almost all of their energy exclusively in the hadronic calorimeter. Figure 52 shows $\langle E/p \rangle_{\text{RAW}}^{\text{Had}}$, where RAW indicates that no correction has been applied for neutral backgrounds and Had indicates that only clusters for the hadronic calorimeter are included. The RAW and COR versions of $\langle E/p \rangle$ in this case are the same, as the neutral background is negligible in that calorimeter layer. The distributions are shown both for the original EM scale calibration and after LCW calibration. The data and simulation agree very well in this comparison, except in the lowest momentum bin which has 5% discrepancy that has already been seen in similar measurements.

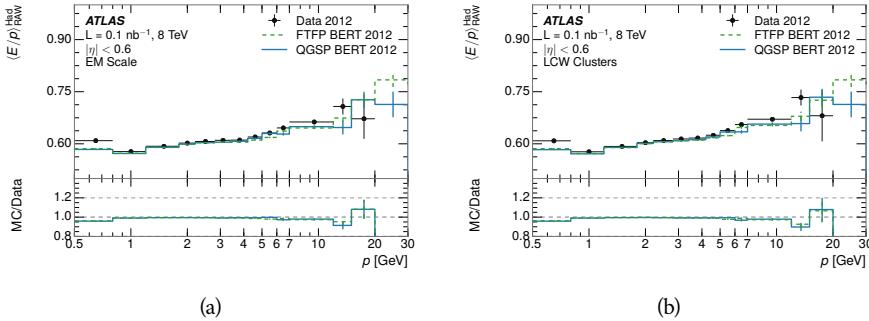


Figure 52: Comparison of the response of the hadronic calorimeter as a function of track momentum (a) at the EM-scale and (b) after the LCW calibration.

A similar comparison can be made in the electromagnetic calorimeter by selecting particles which have no associated energy in the hadronic calorimeter. These results are measured in terms of $\langle E/p \rangle_{\text{COR}}^{\text{EM}}$, where EM designates that only clusters in the electromagnetic calorimeter are included and COR designates that the neutral background is subtracted as the neutral background is present in this case. Figure 53 shows the analogous comparisons to Figure 52 in

2423 the electromagnetic calorimeter. In this case the disagreement between data and
 2424 simulation is more pronounced, with discrepancies as high as 5% over a larger
 2425 range of momenta. This level of discrepancy indicates that the description of
 2426 the electromagnetic calorimeter is actually the dominant source of discrepancy
 2427 in the combined distributions in Section 8.2.4.

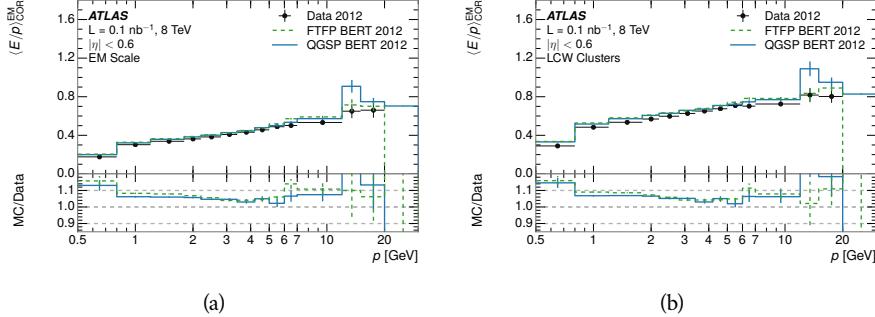


Figure 53: Comparison of the response of the EM calorimeter as a function of track momentum (a) at the EM-scale and (b) with the LCW calibration.

2428 **NOTE: There are more studies that I skipped for brevity that could be in-**
 2429 **cluded if interesting. E/p at different cluster threshold settings, E/p with**
 2430 **pileup, E/p with cells. I also left out a lot of eta bins that appear in the**
 2431 **paper so that this section didn't turn into 20 pages of plots.**

2432 8.3 IDENTIFIED PARTICLE RESPONSE

2433 The inclusive response measurement for hadrons can be augmented by measur-
 2434 ing the response for specific particle species. The simulation models each parti-
 2435 cle type separately, and understanding the properties of each is important in con-
 2436 straining the uncertainty on jets. In order to select and measure specific hadrons,
 2437 this section relies on the displaced decays of long-lived particles. Such decays
 2438 can be identified by reconstructing secondary vertices with a requirement on
 2439 mass. In particular, Λ , $\bar{\Lambda}$, and K_S^0 can be used to select a pure sample of protons,
 2440 antiprotons, and pions, respectively.

2441 8.3.1 DECAY RECONSTRUCTION

2442 The measurement of response for identified particles uses the same selection as
 2443 for inclusive particles (Section 8.1.3) with a few additions. Each event used is
 2444 required to have at least one secondary vertex, and the tracks are required to
 2445 match to that vertex rather than the primary vertex. Pions are selected from
 2446 decays of $K_S^0 \rightarrow \pi^+ \pi^-$, which is the dominant decay for K_S^0 to charged particles.
 2447 Protons are selected from decays of $\Lambda \rightarrow \pi^- p$ and antiprotons from $\bar{\Lambda} \rightarrow \pi^+ \bar{p}$,
 2448 which are similarly the dominant decays of Λ and $\bar{\Lambda}$ to charged particles. The
 2449 species of parent hadron in these decays is determined by reconstructing the
 2450 mass of the tracks associated to the secondary vertex. The sign of the higher

momentum decay particle can distinguish between Λ and $\bar{\Lambda}$, which of course have the same mass, as the proton or antiproton is kinematically favored to have higher momentum. Examples of the reconstructed masses used to select these decays are shown in Figure 54.

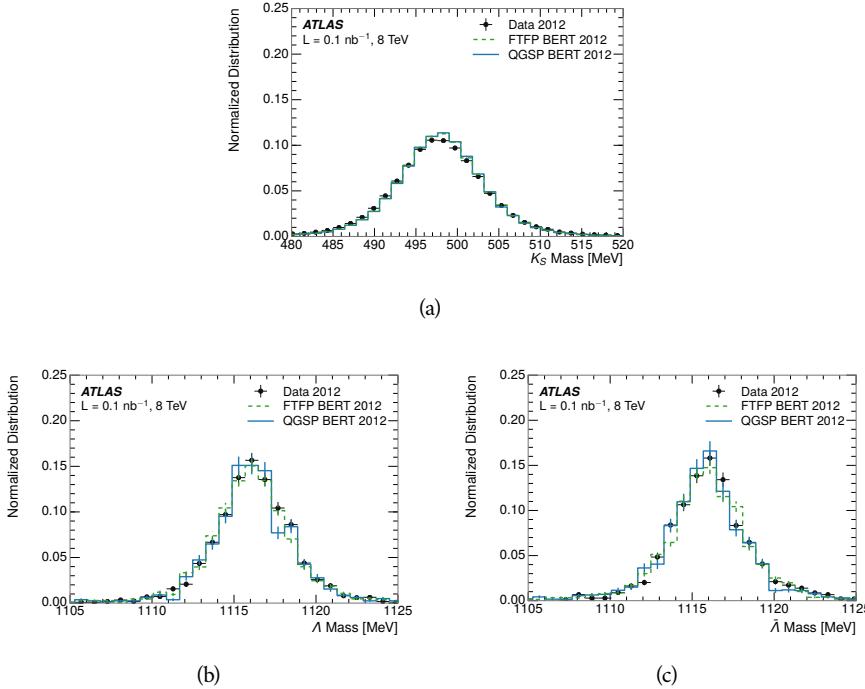


Figure 54: The reconstructed mass peaks of (a) K_S^0 , (b) Λ , and (c) $\bar{\Lambda}$ candidates.

The dominant backgrounds for the identified particle decays are nuclear interactions and combinatoric sources. These are suppressed by the kinematic requirements on the tracks as well as an additional veto which removes candidates that are consistent with both a Λ or $\bar{\Lambda}$ and a K_S^0 hypothesis, which is possible because of the different assumptions on particle mass in each case [21]. After these requirements, the backgrounds are found to be negligible compared to the statistical errors on these measurements.

8.3.2 IDENTIFIED RESPONSE

With these techniques the E/p distributions are extracted in data and simulation for each particle species and shown in Figure 55. These distributions are shown for a particular bin of E_a ($2.2 < E_a/\text{GeV} < 2.8$), rather than p . E_a is the energy available to be deposited in the calorimeter: for pions $E_a = \sqrt{p^2 + m^2}$, for protons $E_a = \sqrt{p^2 + m^2} - m$, and for antiprotons $E_a = \sqrt{p^2 + m^2} + m$. The features of the E/p distributions are similar to the inclusive case. There is a small negative tail from noise and a large fraction of tracks with zero energy from particles which do not reach the calorimeter. The long positive tail is noticeably more pronounced for antiprotons because of the additional energy generated by the annihilation in addition to the neutral background.

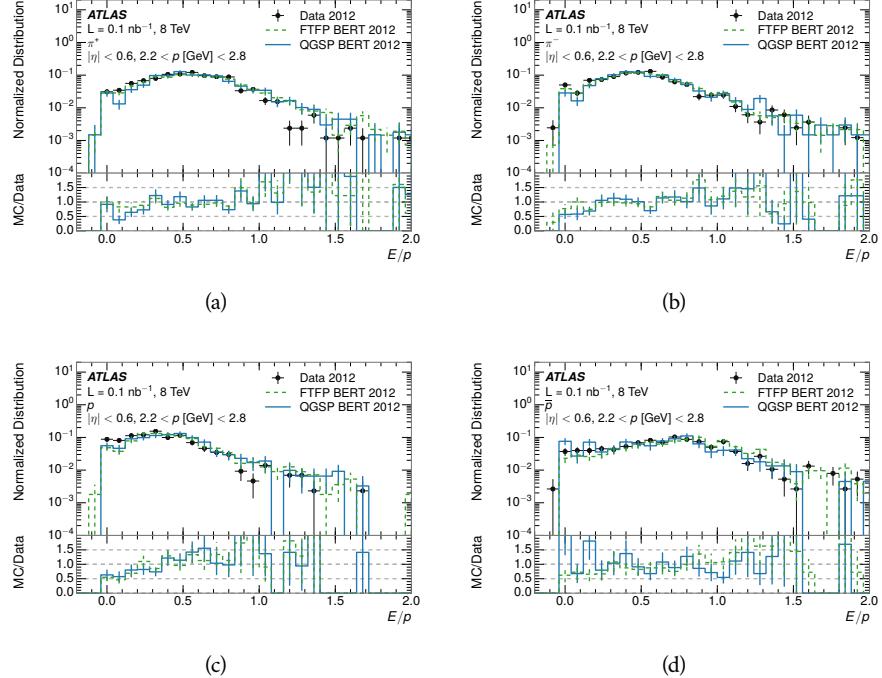


Figure 55: The E/p distribution for isolated (a) π^+ , (b) π^- , (c) proton, and (d) anti-proton tracks.

2473 The zero fraction is further explored in Figure 56 for pions and protons in data
 2474 and simulation. The simulation consistently underestimates the zero fraction
 2475 independent of particle species, which implies that this discrepancy is not caused
 2476 by the model of a particular species but rather a feature common to all.

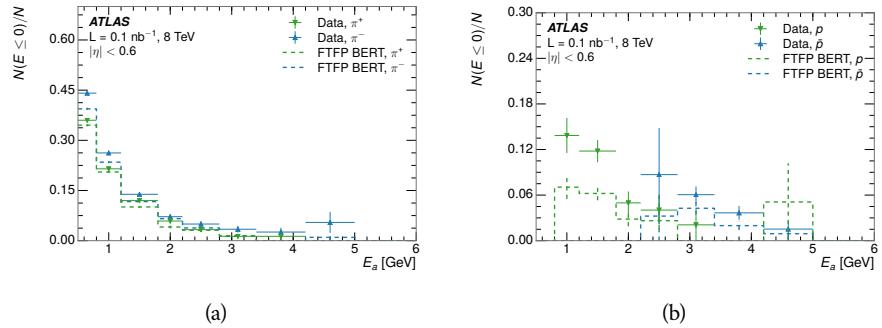


Figure 56: The fraction of tracks with $E \leq 0$ for identified (a) π^+ and π^- , and (b) proton and anti-proton tracks

2477 It is also interesting to compare the response between the different particle
 2478 species. One approach to do this is to measure the difference in $\langle E/p \rangle$ between
 2479 two types, which has the advantage of removing the neutral background. These
 2480 differences are shown in various combinations in Figure 57. The response for
 2481 π^+ is greater on average than the response to π^- because of a charge-exchange
 2482 effect which causes the production of additional neutral pions in the showers of

2483 π^+ [43]. The response for π^+ is also greater on average than the response to p ,
 2484 because a large fraction of the energy of π^+ hadrons is converted to an electro-
 2485 magnetic shower [44, 45]. However, the \bar{p} response is significantly higher than
 2486 the response to π^- because of the annihilation of the antiproton. FTFP_BERT
 2487 does a better job of modeling this effect than QGSP_BERT because of their differ-
 2488 ent descriptions of \bar{p} interactions with material.

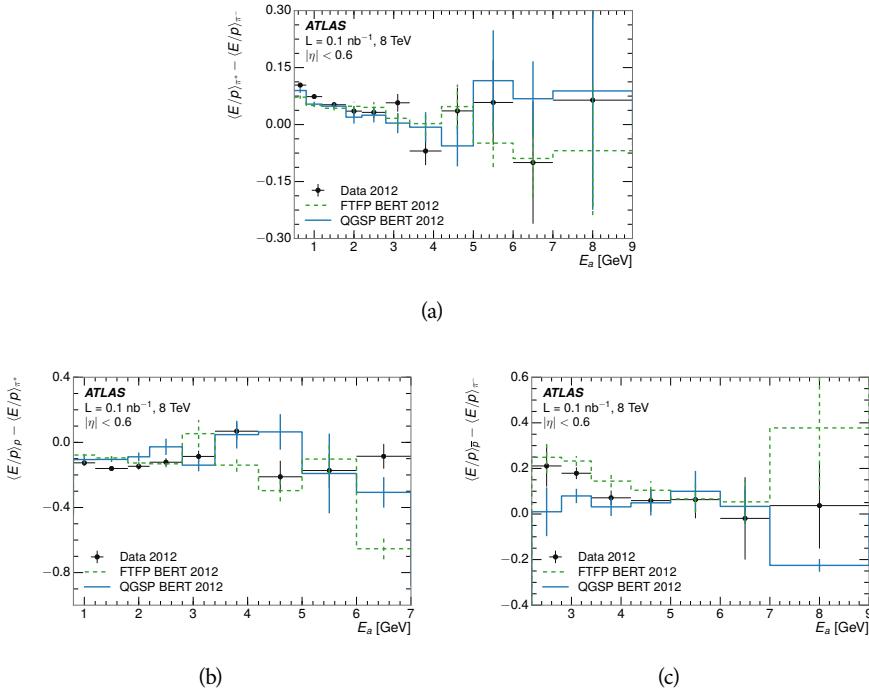


Figure 57: The difference in $\langle E/p \rangle$ between (a) π^+ and π^- (b) p and π^+ , and (c) \bar{p} and π^- .

2489 It is also possible to remove the neutral background from these response dis-
 2490 tributions using the same technique as in Section 8.2.3. The technique is largely
 2491 independent of the particle species and so can be directly applied to $\langle E/p \rangle$ for
 2492 pions. The $\langle E/p \rangle_{\text{COR}}$ distributions for pions are shown in Figure 58, which are
 2493 very similar to the inclusive results. The inclusive hadrons are comprised mostly
 2494 of pions, so this similarity is not surprising. It is also possible to see the small
 2495 differences between π^+ and π^- response here, where $\langle E/p \rangle_{\text{COR}}$ is higher on av-
 2496 erage for π^+ . The agreement between data and simulation is significantly worse
 2497 for the π^- distributions than for the π^+ , with a discrepancy greater than 10%
 2498 below 2-3 GeV.

2499 8.3.3 ADDITIONAL SPECIES IN SIMULATION

2500 The techniques above provide a method to measure the response separately for
 2501 only pions and protons. However the hadrons which forms jets include a num-
 2502 ber of additional species such as kaons and neutrons. The charged kaons are
 2503 an important component of the inclusive charged hadron distribution, which is
 2504 comprised of roughly 60-70% pions, 15-20% kaons, and 5-15% protons. These

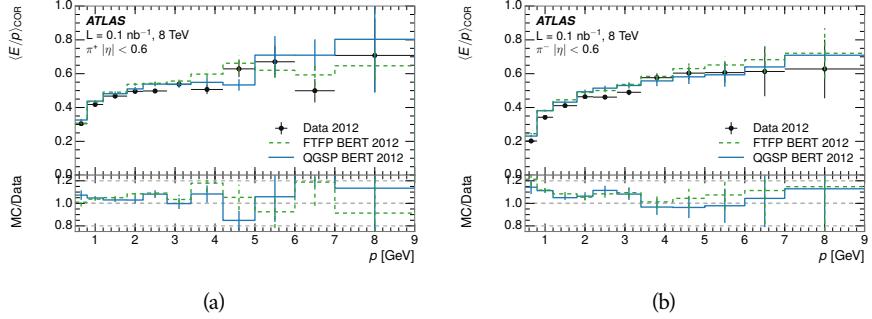


Figure 58: $\langle E/p \rangle_{\text{COR}}$ as a function of track momentum for (a) π^+ tracks and (b) π^- tracks.

are difficult to measure in data at the ATLAS detector, although a template subtraction technique has been proposed which may be effective with larger sample sizes [20]. The simulation of these particles includes noticeable differences in response at low energies, which are shown in Figure 59 for FTFP_BERT. The significant differences in response between low energy protons and antiprotons are accounted for above in the definitions of E_a .

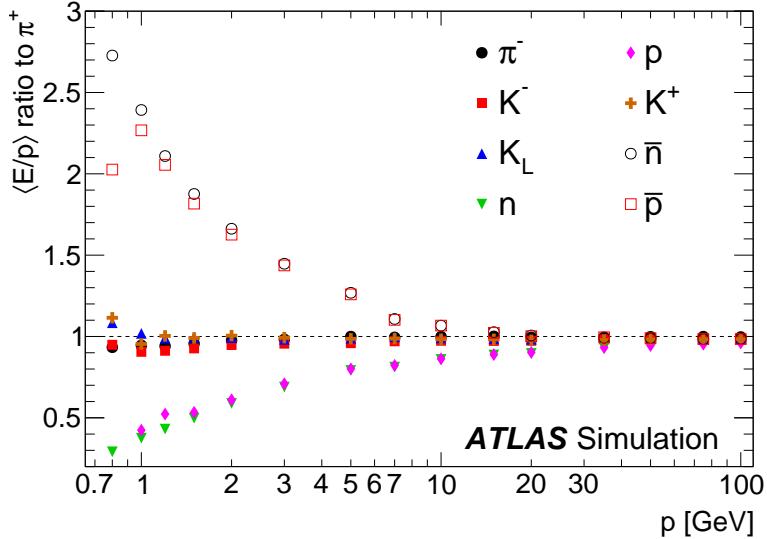


Figure 59: The ratio of the calorimeter response to single particles of various species to the calorimeter response to π^+ with the physics list FTFP_BERT.

2511 8.4 SUMMARY

2512 These various measurements of calorimeter response shown above for data and
 2513 simulation illuminate the accuracy of the simulation of hadronic interactions at
 2514 the ATLAS detector. The results were done using 2010 and 2012 data at 7 and 8
 2515 TeV, but reflect the most current understanding of the detector alignment and
 2516 geometry. A number of measurements focusing on a comparison between pro-

2517 tons and antiprotons suggest that FTFP_BERT models those interaction more
2518 accurately than QGSP_BERT. These measurements, among others, were the moti-
2519 vation to switch the default Geant4 simulation from FTFP_BERT to QGSP_BERT
2520 for all ATLAS samples.

2521 Even with these updates, there are a number of small, approximately 5%, dis-
2522 crepancies in response between the data and simulation at low energies. At
2523 higher energies the simulation of hadronic interactions is very consistent with
2524 data. Chapter 9 discusses how to use these observed differences to constrain the
2525 jet energy scale and its associated uncertainties.

2526

2527 JET ENERGY RESPONSE AND UNCERTAINTY

2528 9.1 MOTIVATION

2529 As jets form a major component of many physics analyses at ATLAS, it is crucial
 2530 to carefully calibrate the measurement of jet energies and to derive an uncer-
 2531 tainty on that measurement. These uncertainties have often been the dominant
 2532 systematic uncertainty in high-energy analyses at the LHC. Dijet and multijet
 2533 balance techniques provide a method to constrain the JES and its uncertainty in
 2534 data, and provide the default values used for ATLAS jet measurements at most
 2535 energies [46]. These techniques are limited by their reliance on measuring jets
 2536 in data, so they are statistically limited in estimating the jet energy scale at the
 2537 highest jet energies. This chapter presents another method for estimating the jet
 2538 energy scale and its uncertainty which builds up a jet from its components and
 2539 thus can be naturally extended to high jet momentum. Throughout this chapter
 2540 the jets studied are simulated using Pythia8 with the CT10 parton distribution
 2541 set [47] and the AU2 tune [24], and corrections are taken from the studies includ-
 2542 ing data and simulation in Chapter 8.

2543 As described in Section 7.4, jets are formed from topological clusters of energy
 2544 in the calorimeters using the anti- k_t algorithm. These clusters originate from a
 2545 diverse spectrum of particles, in terms of both species and momentum, leading to
 2546 significantly varied jet properties and response between jets of similar produced
 2547 momentum. Figure 60 shows the simulated distribution of particles within jets
 2548 at a few examples energies. The E/p measurements provide a thorough under-
 2549 standing of the dominant particle content of jets, the charged hadrons.

2550 9.2 UNCERTAINTY ESTIMATE

2551 Simulated jets are not necessarily expected to correctly model the energy de-
 2552 posits in the calorimeters, because of the various discrepancies discussed in Chap-
 2553 ter 8. To evaluate a jet energy response, the simulated jet energies are compared
 2554 to a corrected jet built up at the particle level. Each cluster in a jet is associated
 2555 to the truth particle which deposited it, and the energy in that cluster is then
 2556 corrected for a number of effects based on measurements in data. The primary
 2557 corrections come from the single hadron response measurements in addition to
 2558 response measured using the combined test beam which covers higher momen-
 2559 tum particles [48]. These corrections include both a shift (Δ), in order to make
 2560 the simulation match the average response in data, and an uncertainty (σ) asso-
 2561 ciated with the ability to constrain the difference between data and simulation.
 2562 Some of the dominant sources of uncertainty are itemized in Table 7 with typi-
 2563 cal values, and the full list considered is described in detail in the associated pa-

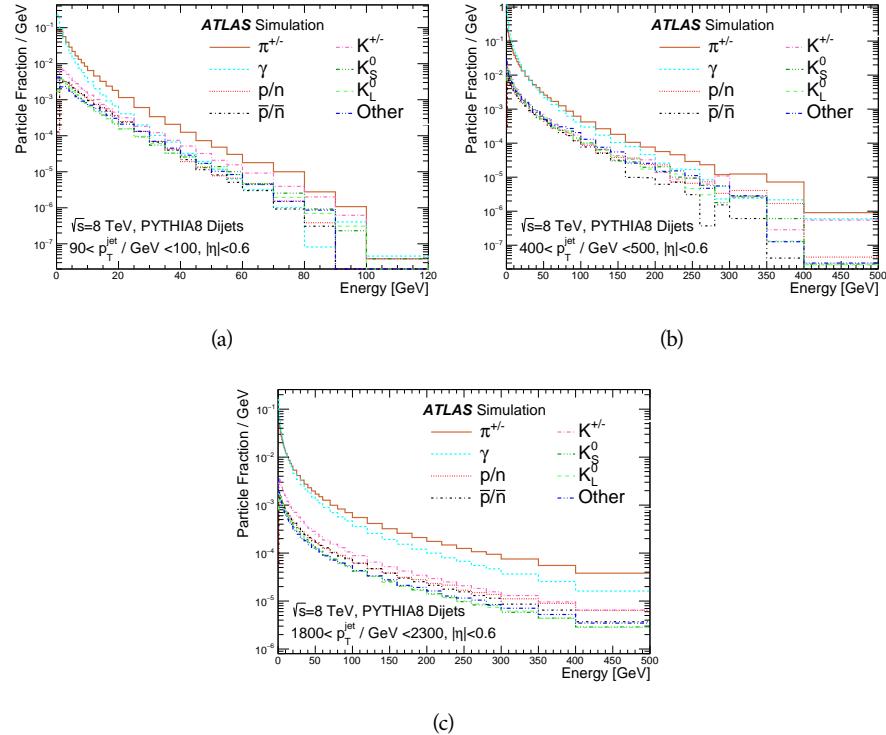


Figure 60: The spectra of true particles inside anti- k_t , $R = 0.4$ jets with (a) $90 < p_T/\text{GeV} < 100$, (b) $400 < p_T/\text{GeV} < 500$, and (c) $1800 < p_T/\text{GeV} < 2300$.

2564 per [20]. These uncertainties cover differences between the data and simulation
 2565 in the modeling of calorimeter response to a given particle. No uncertainties are
 2566 added for the difference between particle composition of jets in data and simu-
 2567 lation.

2568 From these terms, the jet energy scale and uncertainty is built up from indi-
 2569 vidual energy deposits in simulation. Each uncertainty term is treated indepen-
 2570 dently, and are taken to be gaussian distributed. The resulting scale and uncer-
 2571 tainty is shown in Figure 61, where the mean response is measured relative to
 2572 the calibrated energy reported by simulation. The dominant uncertainties come
 2573 from the statistical uncertainties on the E/p measurements at lower energies and
 2574 the additional uncertainty for out of range measurements at higher energies. The
 2575 total uncertainty from this method at intermediate jet energies is comparable to
 2576 other simulation-based methods [49] and is about twice as large as in-situ meth-
 2577 ods using data [46]. This method is the only one which provides an estimation
 2578 above 1.8 TeV, however, and so is still a crucial technique in analyses that search
 2579 for very energetic jets.

2580 These techniques can also be used to measure the correlation between bins of
 2581 average reconstructed jet momentum across a range of p_T and $|\eta|$, where cor-
 2582 relations are expected because of a similarity in particle composition at similar
 2583 energies. Figure 62 shows these correlations, where the uncertainties on jets in
 2584 neighboring bins are typically between 30% and 60% correlated. The uncertainty
 2585 on all jets becomes significantly correlated at high energies and larger pseudora-

Abbrev.	Description	Δ (%)	σ (%)
In situ E/p	The comparison of $\langle E/p \rangle_{\text{COR}}$ as described in Chapter 8 with statistical uncertainties from 500 MeV to 20 GeV.	0-3	1-5
CTB	The main $\langle E/p \rangle$ comparison uncertainties, binned in p and $ \eta $, as derived from the combined test beam results, from 20 to 350 GeV [48].	0-3	1-5
E/p Zero Fraction	The difference in the zero-fraction between data and MC simulation from 500 MeV to 20 GeV.	5-25	1-5
E/p Threshold	The uncertainty in the EM calorimeter response from the potential mismodeling of threshold effects in topological clustering.	0	0-10
Neutral	The uncertainty in the calorimeter response to neutral hadrons based on studies of physics model variations.	0	5-10
K_L	An additional uncertainty in the response to neutral K_L in the calorimeter based on studies of physics model variations.	0	20
E/p Misalignment	The uncertainty in the p measurement from misalignment of the ID.	0	1
Hadrons, $p > 350$ GeV	A flat uncertainty for all particles above the energy range or outside the longitudinal range probed with the combined test beam.	0	10

Table 7: The dominant sources of corrections and systematic uncertainties in the [JES](#) estimation technique, including typical values for the correcting shift (Δ) and the associated uncertainty (σ).

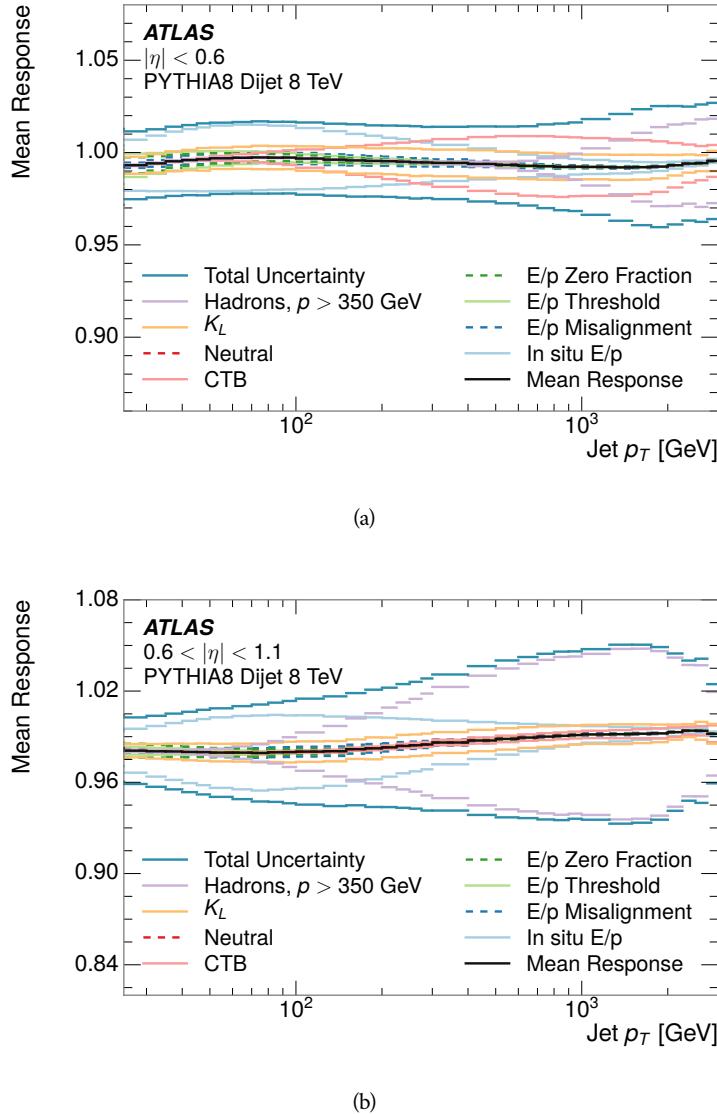


Figure 61: The [JES](#) uncertainty contributions, as well as the total [JES](#) uncertainty, as a function of jet p_T for (a) $|\eta| < 0.6$ and (b) $0.6 < |\eta| < 1.1$.

2586 pidities, when the uncertainty becomes dominated by the single term reflecting
 2587 out of range particles.

2588 9.3 SUMMARY

2589 The technique described above provides a jet energy scale and uncertainty by
 2590 building up jet corrections from the energy deposits of constituent particles. The
 2591 E/p measurements are crucial in providing corrections for the majority of parti-
 2592 cles in the jets. The uncertainty derived this way is between 2 and 5% and is about
 2593 twice as large at corresponding momentum than jet balance methods. However
 2594 this is the only uncertainty available for very energetic jets using 2012 data and
 2595 simulation, and repeating this method with Run 2 data and simulation will be

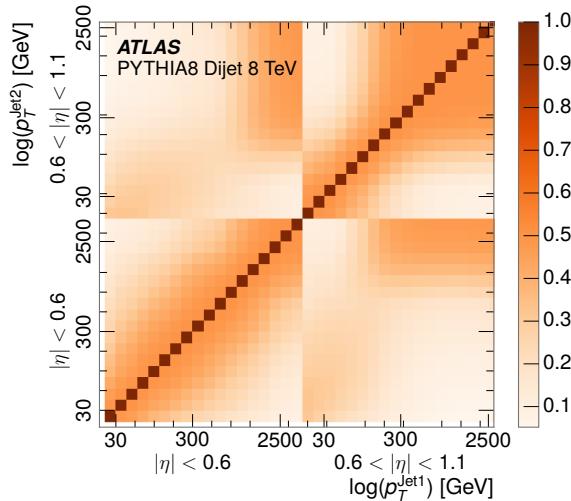


Figure 62: The **JES** correlations as a function of jet p_T and $|\eta|$ for jets in the central region of the detector.

2596 important in providing an uncertainty for the most energetic jets in 13 TeV col-
2597 lisions.

2598

PART V

2599

SEARCH FOR LONG-LIVED PARTICLES

2600

You can put some informational part preamble text here.

2601

2602 LONG-LIVED PARTICLES IN ATLAS

2603 As discussed in Section ??, various limitations in the SM suggest a need for new
 2604 particles at the TeV scale. A wide range of extensions to the Standard Model
 2605 predict that these new particles can have lifetimes greater than approximately
 2606 one-hundredth of a nanosecond. These include theories with universal extra-
 2607 dimensions [50, 51], with new fermions [52], and with leptoquarks [53]. Many
 2608 SUSY theories also produce these Long-Lived Particles (LLPs), in both R-Parity
 2609 violating [54–56] and R-Parity conserving [57–60] formulations. Split super-
 2610 symmetry [61, 62], for example, predicts long-lived gluinos with O(TeV) masses.
 2611 This search focuses specifically on the SUSY case, but many of the results are
 2612 generic to any model with LLPs.

2613 Long-lived gluinos or squarks carry color-charge and will thus hadronize into
 2614 color neutral bound states called R-Hadrons. These are composit particles like
 2615 the usual hadrons but with one supersymmetric constituent, for example $\tilde{g}q\bar{q}$
 2616 and $\tilde{q}\bar{q}$. Through this hadronization process, the neutral gluino can acquire a
 2617 charge. Gluino pair production, $pp \rightarrow \tilde{g}\tilde{g}$ has the largest cross sectional increase
 2618 with the increase in energy to 13 TeV, and so this search focuses on gluino R-
 2619 Hadrons. Planned future updates will extend the case to explicitly include squark
 2620 and chargino models, but the method covers any long-lived, charged, massive
 2621 particle.

2622 10.1 EVENT TOPOLOGY

2623 The majority of SUSY models predict that gluinos will be produced in pairs at
 2624 the LHC, through processes like $pp \rightarrow q\bar{q} \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow gg \rightarrow \tilde{g}\tilde{g}$, where the
 2625 gluon mode dominates for the collision energy and gluino masses considered
 2626 for this search. During their production, the long-lived gluinos hadronize into
 2627 color singlet bound states including $\tilde{g}q\bar{q}$, $\tilde{g}qqq$, and even $\tilde{g}g$ [63]. The probability
 2628 to form the gluon-only bound states is a free parameter usually taken to be 0.1,
 2629 while the meson states are favored among the R-Hadrons [64]. The charged and
 2630 neutral states are approximately equally likely for mesons, so the R-Hadrons will
 2631 be charged roughly 50% of the time.

2632 These channels produce R-Hadrons with large p_T , comparable to their mass,
 2633 so that they typically propagate with $0.2 < \beta < 0.9$ [64]. The fragmentation that
 2634 produces these hadrons is very hard, so the jet structure around the R-Hadron
 2635 is minimal, with less than 5 GeV of summed particle momentum expected in a
 2636 cone of $\Delta R < 0.25$ around the R-Hadron [64]. After hadronization, depending
 2637 on the gluino lifetime, the R-Hadrons then decay into hadrons and a LSP [63].

2638 In summary, the expected event for pair-produced long-lived gluinos is very
 2639 simple: two isolated, high-momentum R-Hadrons that propagate through the
 2640 detector before decaying into jets. The observable features of such events depend

2641 strongly on the interaction of the R-Hadron with the material of the detector and
 2642 also its lifetime. Section 10.1.1 describes the interactions of R-Hadrons which
 2643 reach the various detector elements in ATLAS and Section 10.1.2 provides a sum-
 2644 mary of the observable event descriptions for R-Hadrons of various lifetimes.

2645 10.11 DETECTOR INTERACTIONS

2646 After approximately 0.2 ns, the R-Hadron reaches the pixel detector. If charged,
 2647 it deposits energy into the material through repeated single collisions that result
 2648 in ionization of the silicon substrate [9]. Because of its comparatively low β , the
 2649 ionization energy can be significantly greater than expected for SM particles be-
 2650 cause the most-probable energy loss grows significantly as β decreases [9]. This
 2651 large ionization can be measured through the ToT read out from the pixel detec-
 2652 tor as described in Section 7.1.2. Large ionization in the inner detector is one of
 2653 the major characteristic features of LLPs.

2654 Throughout the next few nanoseconds, the R-Hadron propagates through the
 2655 remainder of the inner detector. A charged R-Hadron will provide hits in each
 2656 of these systems as would any other charged particle, and can be reconstructed
 2657 as a track. The track reconstruction provides a measurement of its trajectory
 2658 and thus its momentum as described in Section 7.1. The large momentum is
 2659 another characteristic feature of massive particles produced at the LHC. **Note: At**
 2660 **this point I am failing to mention that the TRT provides a possible dE/dx**
 2661 **measurement, because no one uses it as far as I know.**

2662 As of roughly 20 ns, the R-Hadron enters the calorimeter where it interacts
 2663 hadronically with the material. Because of its large mass and momentum, the
 2664 R-Hadron does not typically stop in the calorimeter, but rather deposits a small
 2665 fraction of its energy through repeated interactions with nucleons. The proba-
 2666 bility of interaction between the gluino itself and a nucleon is low because the
 2667 cross section drops off with the inverse square of its mass, so the interactions are
 2668 primarily governed by the light constituents [65]. Each of these interactions can
 2669 potentially change that quark content and thus change the sign of the R-Hadron,
 2670 so that the charge at exit is typically uncorrelated with the charge at entry [64].
 2671 The total energy deposited in the calorimeters during the propagation is small
 2672 compared to the kinetic energy of the R-Hadron, around 20-40 GeV, so that
 2673 E/p is typically less than 0.1 [64].

2674 Then, 30 ns after the collision, it reaches the muon system, where it again
 2675 ionizes in the material if charged and can be reconstructed as a muon track. Be-
 2676 cause of the charge-flipping interactions in the calorimeter, this track may have
 2677 the opposite sign of the track reconstructed in the inner detector, or there may
 2678 be a track present when there was none in the inner detector and vice-versa. The
 2679 propagation time at the typically lower β results in a significant delay compared
 2680 to muons, and that delay can be assessed in terms of a time-of-flight measure-
 2681 ment. Because of the probability of charge-flip and late arrival, there is a signif-
 2682 icant chance that an R-Hadron which was produced with a charge will not be
 2683 identified as a muon. The long time-of-flight is another characteristic feature of
 2684 R-Hadrons which are reconstructed as muons.

2685 10.1.2 LIFETIME DEPENDENCE

2686 The above description assumed a lifetime long enough for the R-Hadron to exit
 2687 the detector, which through this search is referred to as “stable”, even though
 2688 the particle may decay after exiting the detector. There are several unique sig-
 2689 natures at shorter lifetimes where the R-Hadron decays in various parts of the
 2690 inner detector; these lifetimes are referred to as “metastable”.

2691 The shortest case where the R-Hadron is considered metastable is for life-
 2692 times around 0.01 ns, where the particle decays before reaching any of the de-
 2693 tector elements. Although the R-Hadrons are produced opposite each other in
 2694 the transverse plane, each R-Hadron decays to a jet and an [LSP](#). The [LSPs](#) are not
 2695 measured, so the produced jets can be significantly imbalanced in the transverse
 2696 plane which results in large missing energy. That missing energy can be used
 2697 to trigger candidate events, and provides the most efficient trigger option for
 2698 shorter lifetimes. Additionally, the precision of the tracking system allows the
 2699 displaced vertex of the R-Hadron decay to be reconstructed from the charged
 2700 particles in the jet. The distance of that vertex from the interaction point can
 2701 be used to distinguish R-Hadron decays from other processes. Figure 63 shows
 2702 a schematic diagram of an example R-Hadron event with such a lifetime. The
 2703 diagram is not to scale, but instead illustrates the detector interactions in the
 2704 pixel detector, calorimeters, and muon system. It includes a representation of
 2705 the charged R-Hadron and the neutral R-Hadron, as well as the [LSPs](#) and jets
 2706 (shown as charged hadrons) produced in the decay. Neutral hadrons may also
 2707 be produced in the decay but are not depicted. Previous searches on [ATLAS](#) have
 2708 used the displaced vertex to target [LLP](#) decays [66].

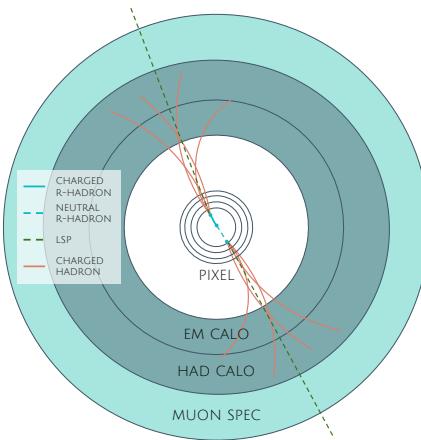


Figure 63: A schematic diagram of an R-Hadron event with a lifetime around 0.01 ns.
 The diagram includes one charged R-Hadron (solid blue), one neutral R-Hadron (dashed blue), [LSPs](#) (dashed green) and charged hadrons (solid orange).
 The pixel detector, calorimeters, and muon system are illustrated but not to scale.

2709 The next distinguishable case occurs at lifetimes greater than 0.1 ns, where
 2710 the R-Hadron forms a partial track in the inner detector. If the decay products
 2711 are sufficiently soft, they may not be reconstructed, and this forms a unique sig-

2712 nature of a disappearing track. An example of such an event is illustrated in
 2713 Figure 64, which shows the short track in the inner detector and the undetected
 2714 soft charged hadron and LSP that are produced. A dedicated search on ATLAS used
 2715 the disappearing track signature to search for LLP in Run 1 [67]. **zNote: might**
 2716 **not be worth mentioning the disappearing track here since it is actually a**
 2717 **chargino search, the soft pion is pretty unique to charginos.**

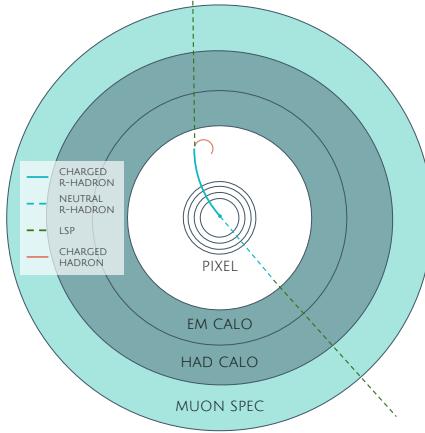


Figure 64: A schematic diagram of an R-Hadron event with a lifetime around 4 ns. The diagram includes one charged R-Hadron (solid blue), one neutral R-Hadron (dashed blue), LSPs (dashed green) and a charged hadron (solid orange). The pixel detector, calorimeters, and muon system are illustrated but not to scale.

2718 If the decay products are not soft, the R-Hadron daughters form jets, resulting
 2719 in an event-level signature of up to two high-momentum tracks, jets, and signif-
 2720 icant missing energy. The missing energy has the same origin as in the case of
 2721 0.01 ns lifetimes, from the decay to unmeasured particles, and again can be large.
 2722 The high-momentum tracks will also have the characteristically high-ionization
 2723 of massive, long-lived particles in the inner detector. Figure 65 illustrates an ex-
 2724 ample event with one charged R-Hadron which decays after approximately 10 ns,
 2725 and shows how the jets from the decay can still be reconstructed in the calorime-
 2726 ter. Several previous searches on ATLAS from Run 1 have used this signature to
 2727 search for R-Hadrons [68, 69], including a dedicated search for metastable parti-
 2728 cles [70].

2729 If the lifetime is longer than several nanoseconds, in the range of 15-30 ns,
 2730 the R-Hadron decay can occur in or after the calorimeters, but prior to reaching
 2731 the muon system. This case is similar to the above, although the jets may not be
 2732 reconstructed, and is covered by many of the same search strategies. The events
 2733 still often have large missing energy, although it is generated through different
 2734 mechanisms. The R-Hadrons do not deposit much energy in the calorimeters, so
 2735 a neutral R-Hadron will not enter into the missing energy calculation. A charged
 2736 R-Hadron opposite a neutral R-Hadron will thus generate significant missing en-
 2737 ergy, and close to 50% of pair-produced R-Hadron events fall into this category.
 2738 If both R-Hadrons are neutral then the missing energy will be low because nei-
 2739 ther is detected. Two charged R-Hadrons will also result in low missing energy
 2740 because both are reconstructed as tracks and will balance each other in the trans-

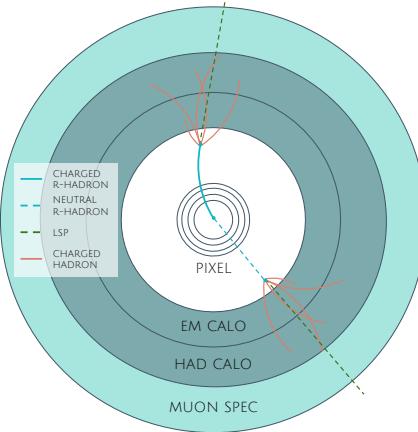


Figure 65: A schematic diagram of an R-Hadron event with a lifetime around 5 ns. The diagram includes one charged R-Hadron (solid blue), one neutral R-Hadron (dashed blue), LSPs (dashed green) and charged hadrons (solid orange). The pixel detector, calorimeters, and muon system are illustrated but not to scale.

2741 verse plane. A small fraction of the time, one of the charged R-Hadron tracks may
 2742 fail quality requirements and thus be excluded from the missing energy calcula-
 2743 tion and again result in significant missing energy. Figure 66 illustrates another
 2744 example event with one charged R-Hadron which decays after approximately 20
 2745 ns, and shows how the jets from the decay might not be reconstructed.

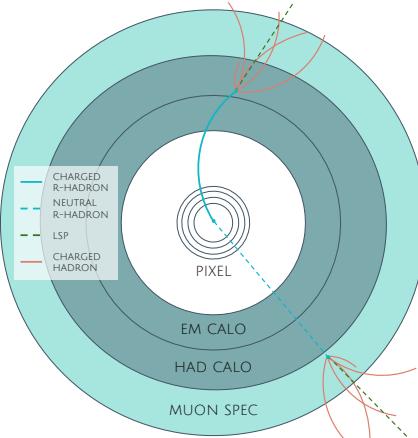


Figure 66: A schematic diagram of an R-Hadron event with a lifetime around 20 ns. The diagram includes one charged R-Hadron (solid blue), one neutral R-Hadron (dashed blue), LSPs (dashed green) and charged hadrons (solid orange). The pixel detector, calorimeters, and muon system are illustrated but not to scale.

2746 The longest lifetimes, the stable case, has all of the features of the 30-50 ns case
 2747 but with the addition of muon tracks for any R-Hadrons that exit the calorimeter
 2748 with a charge. That muon track can provide additional information from time-
 2749 of-flight measurements to help identify LSPs. An example of the event topology
 2750 for one charged and one neutral stable R-Hadron is shown in Figure 67. Some
 2751 searches on ATLAS have included this information to improve the search reach
 2752 for stable particles [69, 71].

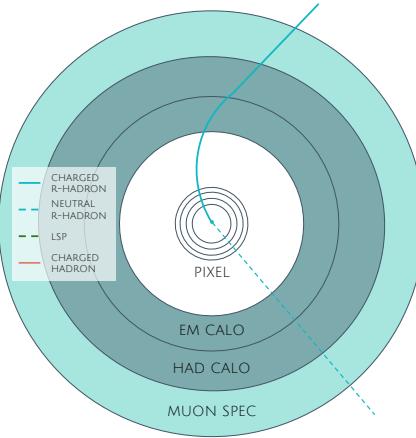


Figure 67: A schematic diagram of an R-Hadron event with a lifetime around 20 ns. The diagram includes one charged R-Hadron (solid blue) and one neutral R-Hadron (dashed blue). The pixel detector, calorimeters, and muon system are illustrated but not to scale.

2753 10.2 SIMULATION

2754 All of the event topologies discussed above are explored by simulations of R-
 2755 Hadron events in the [ATLAS](#) detector. A large number of such samples are gen-
 2756 erated to determine signal efficiencies, to measure expected yields, and to esti-
 2757 mate uncertainties. The primary interaction, pair production of gluinos with
 2758 masses between 400 and 3000 GeV, is simulated using [Pythia 6.4.27](#) [72]
 2759 with the AUET2B [73] set of tuned parameters for the underlying event and the
 2760 [CTEQ6L1](#) [47] PDF set. The simulated interactions include a modeling of pileup
 2761 by adding secondary, minimum bias interactions from both the same (in-time
 2762 pileup) and nearby (out-of-time pileup) bunch crossings. This event generation
 2763 is then augmented with a dedicated hadronization routine to hadronize the long-
 2764 lived gluinos into final states with R-Hadrons [74], with the probability to form
 2765 a gluon-gluino bound set at 10% [75].

2766 The cross sections used for these processes are calculated at next-to-leading
 2767 order ([NLO](#)) in the strong coupling constant with a resummation of soft-gluon
 2768 emmission at next-to-leading logarithmic ([NLL](#)) [76–80]. The nominal predic-
 2769 tions and the uncertainties for each mass point are taken from an envelope of
 2770 cross-section predictions using different PDF sets and factorization and renor-
 2771 malization scales [81].

2772 The R-Hadrons then undergo a full detector simulation [], where the interac-
 2773 tions of the R-Hadrons with the material of the detector are described by dedi-
 2774 cated [Geant4](#) [17] routines. These routines model the interactions described in
 2775 Section 10.1.1, including the ionizing interactions in the silicon modules of the
 2776 inner detector and the R-Hadron-nucleon interactions in the calorimeters [82,
 2777 83]. The specific routine chosen to describe the interactions of the R-Hadrons
 2778 with nucleons, the “generic model”, uses a pragmatic approach where the scatter-
 2779 ing cross section is taken to be a constant 12 mb per light quark. In this model

2780 the gluino itself does not interact at all except through its role as a reservoir of
 2781 kinetic energy.

2782 The lifetimes of these R-Hadrons are then simulated at several working points,
 2783 $\tau = 0.1, 1.0, 3.0, 10, 30, 50$ and detector stable, where the particle is required to
 2784 decay after propagating for a time compatible with its lifetime. Only one decay
 2785 mode is simulated for these samples, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ with the neutralino mass set to
 2786 100 GeV, which is chosen because it has the highest sensitivity among all of the
 2787 modes studied in previous searches [70]. Heavier neutralinos have similar results
 2788 but generate less missing energy which reduces the efficiency of triggering.

2789 All of the simulated events are then reconstructed using the same software
 2790 used for collision data. The fully reconstructed events are then reweighted to
 2791 match the distribution of initial state radiation in an alternative sample of events,
 2792 generated with MG5_aMC@NLO [84], which has a more accurate description of ra-
 2793 diate effects than Pythia6. This reweighting provides a more accurate descrip-
 2794 tion of the momentum of the gluino-gluino system and is important in modeling
 2795 the efficiency of triggering and offline event selection.

2796

2797 EVENT SELECTION

2798 The [LLPs](#) targeted by this search differ in their interactions with the detector from
 2799 [SM](#) particles primarily because of their large mass. When produced at the ener-
 2800 gies available at the [LHC](#), that large mass results in a low β (typically $0.2 < \beta <$
 2801 0.9). Such slow-moving particles heavily ionize in detector material. Each layer
 2802 of the pixel detector provides a measurement of that ionization, through [ToT](#), as
 2803 discussed in Section 7.1.2. The ionization in the pixel detector, quantified in
 2804 terms of dE/dx , provides the major focus for this search technique, along with
 2805 the momentum measured in the entire inner detector. It is effective both for its
 2806 discriminating power and its use in reconstructing a particle's mass, and it can
 2807 be used for a wide range of masses and lifetimes as discussed in Section 10.1.2.
 2808 However dE/dx needs to be augmented with a few additional selection require-
 2809 ments to provide a mechanism for triggering and to further reduce backgrounds.

2810 Ionization itself is not currently accessible for triggering, so this search in-
 2811 stead relies on E_T^{miss} to trigger signal events. Although triggering on E_T^{miss} can
 2812 be inefficient, E_T^{miss} is often large for many production mechanisms of [LLPs](#), as
 2813 discussed in Section 10.1.

2814 The use of ionization to reject [SM](#) backgrounds relies on well-measured, high-
 2815 momentum tracks, so some basic requirements on quality and kinematics are
 2816 placed on the tracks considered in this search. These quality requirements have
 2817 been significantly enhanced in Run 2 by a newly introduced tracking variable
 2818 that is very effective in removing highly-ionizing backgrounds caused by over-
 2819 lapping tracks. A few additional requirements are placed on the tracks consid-
 2820 ered for [LLP](#) candidates that increase background rejection by targeting specific
 2821 types of [SM](#) particles. These techniques provide a significant analysis improve-
 2822 ment over previous iterations of ionization-based searches on ATLAS by provid-
 2823 ing additional background rejection with minimal loss in signal efficiency.

2824 The ionization measurement with the Pixel detector can be calibrated to pro-
 2825 vide an estimator of $\beta\gamma$. That estimate, together with the momentum measure-
 2826 ment provided by tracking, can be used to reconstruct a mass for each track
 2827 which traverses the pixel detector. That mass variable will be peaked at the [LLP](#)
 2828 mass for any signal, and provides an additional tool to search for an excess. In
 2829 addition to an explicit requirement on ionization, this search constructs a mass-
 2830 window for each targeted signal mass in order to evaluate any excess of events
 2831 and to set limits.

2832 The strategy discussed here is optimized for lifetimes of $O(1) - O(10)$ ns.
 2833 Pixel ionization is especially useful in this regime as particles only need to prop-
 2834 agate through the first seven layers of the inner detector, about 37 cm from the
 2835 beam axis. The search is still competitive with other searches for [LLPs](#) at longer
 2836 lifetimes, because the primary discriminating variables are still applicable even
 2837 for particles that do not decay within the detector [71]. Although the majority of

2838 the requirements will be the same for all lifetimes, two signal regions are defined
 2839 to optimize separately for intermediate and long lifetime particles.

2840 11.1 TRIGGER

2841 Triggering remains a significant difficulty in defining an event selection with
 2842 high signal efficiency in a search for LLPs. There are no triggers available in
 2843 the current ATLAS system that can fire directly from a high momentum track
 2844 with large ionization (Section 6.6). Although in some configurations a charged
 2845 LLP can fire muon triggers, this requirement introduces significant model depen-
 2846 dence on both the allowed lifetimes and the interactions in the calorimeter [64],
 2847 as discussed in Section 10.1.1.

2848 For a search targeting particles which may decay prior to reaching the muon
 2849 system, the most efficient available trigger is based on missing energy [64]. As
 2850 discussed in Section 10.1, signal events can produce significant E_T^{miss} by a few
 2851 mechanisms. At the trigger level however, the missing energy is only calculated
 2852 using the calorimeters (Section 6.6) where the R-Hadrons deposit little energy.
 2853 So, at short lifetimes, E_T^{miss} measured in the calorimeter is generated by an im-
 2854 balance between the jets and undetected LSPs produced in R-Hadron decays. At
 2855 longer lifetimes, without the decay products, missing energy is only produced in
 2856 the calorimeters when the R-Hadrons recoil against an initial state radiation (ISR)
 2857 jet.

2858 These features are highlighted in Figure 68, which shows the E_T^{miss} distribu-
 2859 tions for simulated short lifetime (3 ns) and stable R-Hadron events. The figure
 2860 includes both the offline E_T^{miss} , the missing energy calculated with all available
 2861 information, and Calorimeter E_T^{miss} , the missing energy calculated using only
 2862 information available at the calorimeter which approximates the missing energy
 2863 available at the trigger. The short lifetime sample has significantly greater E_T^{miss}
 2864 and Calorimeter E_T^{miss} than the stable sample as expected. For the stable sam-
 2865 ple, a small fraction of events with very large E_T^{miss} (about 5%) migrate into the
 2866 bin with very small Calorimeter E_T^{miss} because the E_T^{miss} produced by a charged
 2867 R-Hadron track opposite a neutral R-Hadron track does not contribute any miss-
 2868 ing energy in the calorimeters.

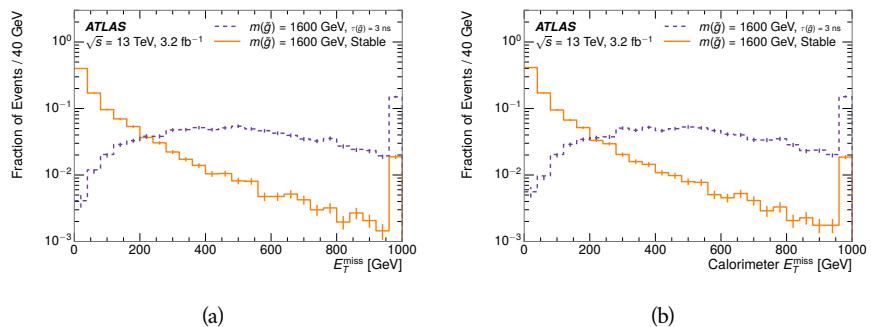


Figure 68: The distribution of (a) E_T^{miss} and (b) Calorimeter E_T^{miss} for simulated signal events before the trigger requirement.

2869 So, either case to some extent relies on kinematic degrees of freedom to pro-
 2870 duce missing energy, as the pair-produced LLPs tend to balance each other in
 2871 the transverse plain. That balance results in a relatively low efficiency for long-
 2872 lifetime particles, roughly 40%, and efficiencies between 65% and 95% for shorter
 2873 lifetimes depending on both the mass and the lifetime. For long lifetimes in par-
 2874 ticular, the presence of ISR is important in providing an imbalance in the trans-
 2875 verse plane, and is an important aspect of modeling the selection efficiency for
 2876 R-Hadron events.

2877 The missing energy trigger with the lowest threshold available is chosen for
 2878 this selection in order to maximize the trigger efficiency. During 2015 data col-
 2879 lection this was the HLT_xe70 trigger, which used a 50 GeV threshold on miss-
 2880 ing energy at LVL1 and a 70 GeV threshold on missing energy at the HLT. These
 2881 formation of the trigger decision for missing energy was discussed in more detail
 2882 in Section 6.6.

2883 11.2 KINEMATICS AND ISOLATION

2884 After the trigger requirement, each event is required to have a primary vertex
 2885 reconstructed from at least two well-measured tracks in the inner detector, each
 2886 with $p_T > 400$ MeV. If more than one such vertex exists, the primary vertex
 2887 is taken to be the one with the largest summed track momentum for all tracks
 2888 associated to that vertex. The offline reconstructed E_T^{miss} is required to be above
 2889 130 GeV to additionally reject SM backgrounds. The transverse missing energy
 2890 is calculated using fully reconstructed and calibrated offline objects, as described
 2891 in Section 7.5. In particular the E_T^{miss} definition in this selection uses jets recon-
 2892 structed with the anti- k_t algorithm with radius $R = 0.4$ from clusters of energy
 2893 in the calorimeter (Section 7.4) and with $p_T > 20$ GeV, as well as reconstructed
 2894 muons, electrons, and tracks not identified as another object type.

2895 The E_T^{miss} distributions are shown for data and a few simulated signals in Fig-
 2896 ure 69, after the trigger requirement. The cut placed at 130 GeV is 95% effi-
 2897 cient for metastable and 90% efficient for stable particles, after the trigger re-
 2898 quirement, because of the missing energy generating mechanisms discussed pre-
 2899 viously. The distribution of data in this figure and subsequent figures in this sec-
 2900 tion can be interpreted as the distribution of backgrounds, as any signal contam-
 2901 ination would be negligible if present at these early stages of the selection (prior
 2902 to the final requirement on ionization). The background falls rapidly with miss-
 2903 ing energy, motivating the direct requirement on E_T^{miss} for the signal region. Al-
 2904 though a tighter requirement than the specified value of 130 GeV would seem to
 2905 increase the search potential from these early distributions, other requirements
 2906 are more optimal when taken as a whole. The specific values for each require-
 2907 ment in signal region were optimized considering the increase in discovery reach
 2908 for tightening the requirement on each discriminating variable. **NOTE: If space**
2909 and time permit, I will add a whole section about signal region optimiza-
2910 tion..

2911 It is typically the practice for searches for new physics on ATLAS to place an
 2912 offline requirement on the triggering variable that is sufficiently tight to guar-

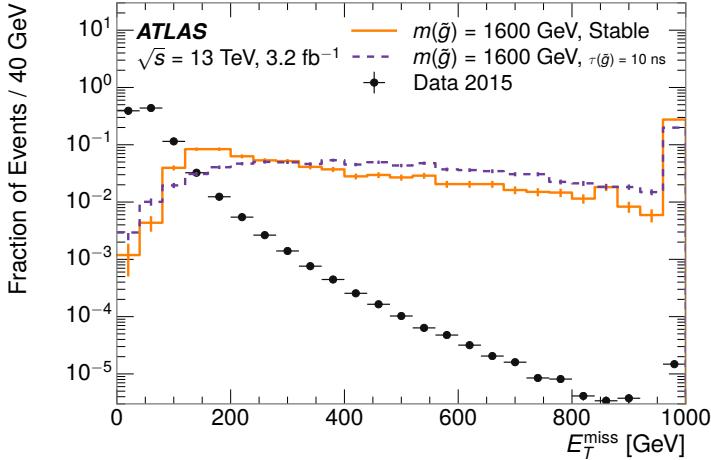


Figure 69: The distribution of E_T^{miss} for data and simulated signal events, after the trigger requirement.

2913 antee that the event would pass the trigger. Such a tight requirement makes the
 2914 uncertainty on the trigger efficiency of the simulation negligible, as modeling the
 2915 regime where the trigger is only partially efficient can be difficult. In this analy-
 2916 sis, however, because of the atypical interactions of R-Hadrons with the tracker
 2917 and the calorimeter, the offline requirement on E_T^{miss} is not sufficient to guar-
 2918 antee a 100% trigger efficiency even at large values, as can be seen in Figure 70.
 2919 This figure shows the efficiency for passing the HLT_xe70 trigger as a function
 2920 of the requirement on E_T^{miss} , which plateaus to roughly 85% even at large values.
 2921 This plateau does not reach 100% because events which have large offline miss-
 2922 ing energy from a neutral R-Hadron produced opposite of a charged R-Hadron
 2923 can have low missing energy in the calorimeters. The Calorimeter E_T^{miss} , on the
 2924 other hand, does not have this effect and reaches 100% efficiency at large values
 2925 because it is the quantity that directly corresponds to the trigger threshold. In
 2926 both cases the efficiency of triggering is greater for the short lifetime sample be-
 2927 cause the late decays to hadrons and LSPs produce an imbalance in the calorime-
 2928 ters even though they may not be reconstructed offline as tracks or jets. For this
 2929 reason, the requirement on E_T^{miss} is determined by optimizing the background
 2930 rejection even though it corresponds to a value of trigger efficiency significantly
 2931 below 1.0.

2932 Potential signal events are then required to have at least one candidate LLP
 2933 track. Although the LLPs are produced in pairs, many models do not consistently
 2934 yield two charged particles. For example, in the R-Hadron model highlighted
 2935 here, only 20% of events have two charged R-Hadrons while 47% of events have
 2936 just one. A signal region requiring two charged candidates could be a powerful
 2937 improvement in background rejection for a larger dataset, but it is not consid-
 2938 ered in this version of the analysis as it was found to be unnecessary to reject the
 2939 majority of backgrounds.

2940 For a track to be selected as a candidate, it must have $p_T > 50 \text{ GeV}$ and pass
 2941 basic quality requirements. The track must be associated to the primary vertex.

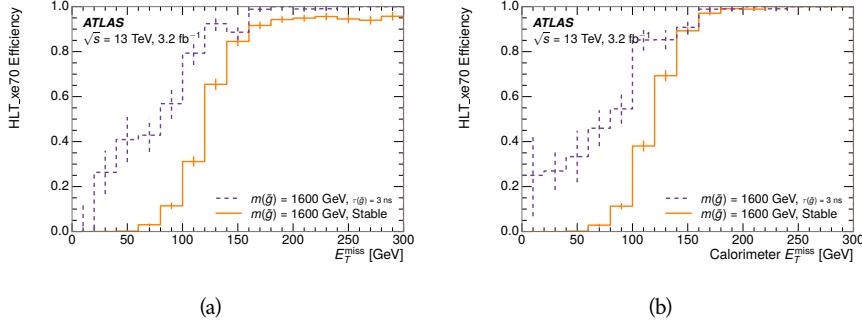


Figure 70: The trigger efficiency for the HLT_xe70 trigger requirement as a function of (a) E_T^{miss} and (b) Calorimeter E_T^{miss} for simulated signal events.

It must also have at least seven clusters in the silicon layers in the inner detector to ensure an accurate measurement of momentum. Those clusters must include one in the innermost layer if the extrapolated track is expected to pass through that layer. And to ensure a reliable measurement of ionization, the track is required to have at least two clusters in the pixel detector that provide a measurement of dE/dx .

At this point in the selection, there is a significant high-ionization background from multiple tracks that significantly overlap in the inner detector. Previous version of this analysis have rejected these overlaps by an explicit overlap rejection between pairs of fully reconstructed tracks, typically by requiring no additional tracks within a cone around the candidate. This technique, however, fails to remove the background from tracks that overlap so precisely that the tracks cannot be separately resolved, which can be produced in very collimated photon conversions or decays of pions.

A new method, added in Run 2, identifies cluster shapes that are likely formed by multiple particles based on a neural network classification algorithm. The number of clusters that are classified this way in the pixel detector for a given track is called N_{split} . As the shape of clusters requires significantly less spatial separation to identify overlaps than it does to reconstruct two fully resolved tracks, this variable is more effective at rejecting backgrounds from overlaps. Figure 71 shows the dependence of ionization on N_{split} ; as N_{split} increases the most probable value of dE/dx grows significantly up to twice the expected value when $N_{\text{split}} = 4$.

This requirement is very successful in reducing the long positive tail of the dE/dx distributions, as can be seen in Figure 72. Comparing the distribution for “baseline tracks”, tracks with only the above requirements on clusters applied and before the requirement on N_{split} , to the distribution with $N_{\text{split}} = 0$, it is clear that the fraction of tracks with large dE/dx is reduced by several orders of magnitude. The tracks without split hits are very close to the dE/dx distribution of identified muons, which are extremely well isolated on average. Figure 72 also includes the distribution of dE/dx in an example signal simulation to demonstrate how effective dE/dx is as a discriminating variable with this isolation applied. The background falls rapidly for $dE/dx > 1.8 \text{ MeVg}^{-1}\text{cm}^2$

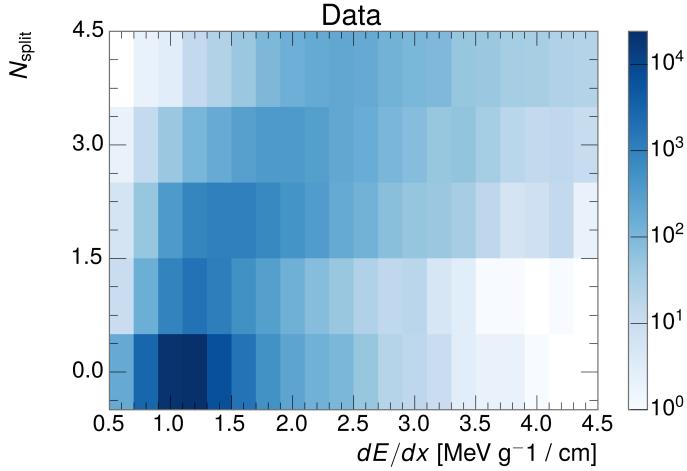


Figure 71: The dependence of dE/dx on N_{split} in data after basic track hit requirements have been applied.

2975 while the majority of the signal, approximately 90% depending on the mass, falls
 2976 above that threshold. Over 90% of [LLP](#) tracks in simulated signal events pass the
 2977 N_{split} -based isolation requirement.

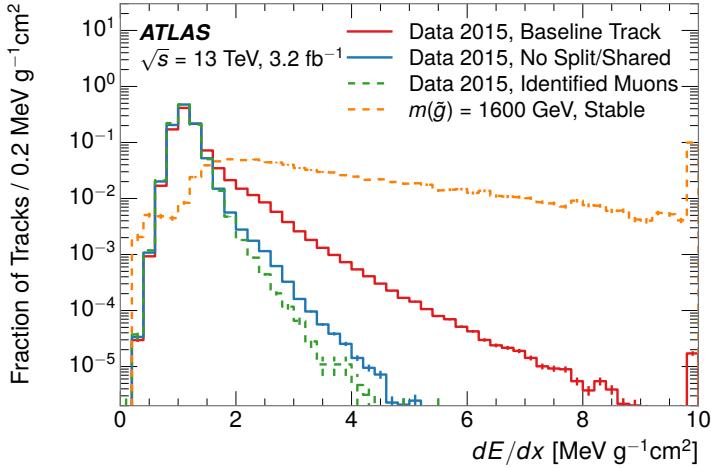


Figure 72: The distribution of dE/dx with various selections applied in data and simulated signal events.

2978 A few additional kinematic requirements are imposed to help reduce [SM](#) back-
 2979 grounds. The momentum of the candidate track must be at least 150 GeV, and
 2980 the uncertainty on that measurement must be less than 50%. The distribution of
 2981 momentum is shown in Figure 73 for tracks in data and simulated signal events
 2982 after the previously discussed requirements on clusters, transverse momentum,
 2983 and isolation have been imposed. The signal particles are much harder on aver-

age than their backgrounds because of the high energy interactions required to produce them. The transverse mass, M_T , defined as

$$M_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos(\Delta\phi(E_T^{\text{miss}}, \text{track})))} \quad (20)$$

estimates the mass of a decay of to a single charged particle and an undetected particle and is required to be greater than 130 GeV to reject contributions from the decay of W bosons. Figure 74 shows the distribution of M_T for data and simulated signal events. The signal is distributed over a wide range of M_T , with about 90% above the threshold value of 130 GeV. The data shows a dual-peaked structure, where the first peak comes from W boson decays and the second peak is a kinematic shaping from the requirements on E_T^{miss} and the track p_T in dijet events.

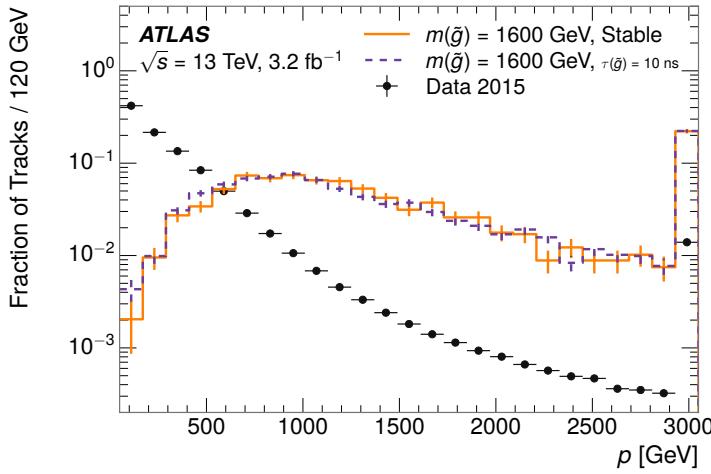


Figure 73: The distribution of track momentum for data and simulated signal events, after previous selection requirements have been applied.

11.3 PARTICLE SPECIES REJECTION

The amount of ionization deposited by particles with low mass and high momentum has a large positive tail [9], so backgrounds can be formed by a wide variety of SM processes when various charged particles have a few randomly large deposits of energy in the pixel detector. Those backgrounds can be additionally reduced by targeting other interactions with the detector where they are expected to have different behavior than R-Hadrons. The interactions with the detector depend on the types of particles produced rather than the processes which produce them, so this search forms a series of rejections to remove backgrounds from individual particle species. These rejections focus on using additional features of the event, other than the kinematics of the candidate track, as they can provide a powerful source of background rejection with very high signal efficiency. However, the lifetime of an R-Hadron can significantly change its

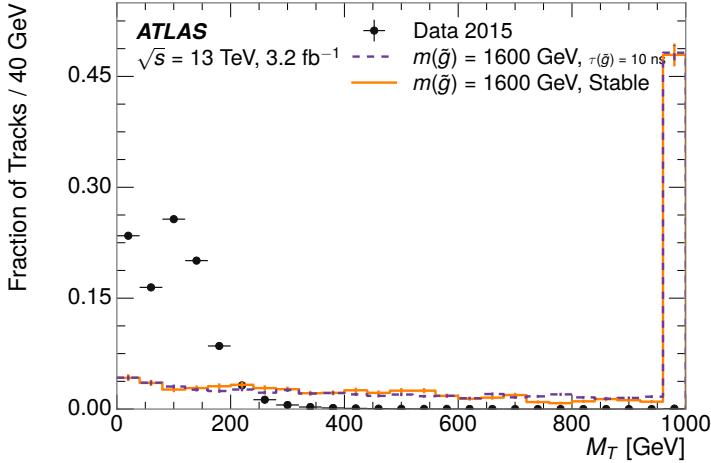


Figure 74: The distribution of M_T for data and simulated signal events, after previous selection requirements have been applied.

3007 detector characteristics, as discussed in Section 10.1.2. To accommodate these
 3008 differences, the SM rejections defined in this section are split to form two signal
 3009 regions, one for long-lifetimes particles, the stable region ($50 \leq \tau[\text{ns}] < \infty \text{ ns}$),
 3010 and one for intermediate lifetime particles, the metastable region ($0.4 < \tau[\text{ns}] <$
 3011 50).

3012 Jets can be very effectively rejected by considering the larger-scale isolation of
 3013 the candidate track. In this case the isolation focuses on the production of nearby
 3014 particles as a jet-veto, rather than the isolation from overlapping tracks based on
 3015 N_{split} that was used to reduce high-ionization backgrounds. As explained in Sec-
 3016 tion 10.1, the fragmentation process which produces an R-Hadron is very hard
 3017 and thus is not expected to produce additional particles with a summed momen-
 3018 tum of more than 5 GeV. The jet-veto uses the summed momentum of tracks
 3019 with a cone of $\Delta R < 0.25$, referred to as p_T^{Cone} , which is shown in Figure 75 for
 3020 data and simulated signal events. In the data this value has a peak at zero from
 3021 isolated tracks such as leptons, and a long tail from jets which contains as much
 3022 as 80% of the background above 20 GeV at this stage of the selection. In signal
 3023 events p_T^{Cone} is strongly peaked at zero and significantly less than 1% of signal
 3024 events have p_T^{Cone} above 20 GeV. This makes a requirement of $p_T^{\text{Cone}} < 20 \text{ GeV}$
 3025 a very effective method to reject background without losing signal efficiency.
 3026 For the stable signal region, this cut is further tightened to $p_T^{\text{Cone}} < 5 \text{ GeV}$ as
 3027 it is the most effective variable remaining to extend the search reach for long
 3028 lifetimes.

3029 Even for fully isolated particles, there are additional methods to reject each
 3030 type of particle using information in the muon system and calorimeters. Muons
 3031 can be identified very reliably using the tracks in the muon system, as described
 3032 in Section 7.3. For intermediate lifetimes the LLPs do not survive long enough
 3033 to reach the muon system, and so muons are vetoed by rejecting tracks that as-
 3034 sociate to a muon with medium muon identification requirements (Section 7.3).
 3035 For longer lifetimes, this rejection is not applied because LLPs which reach the

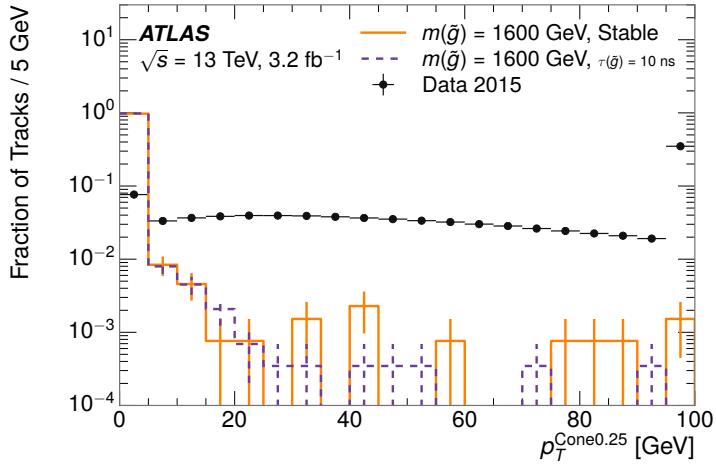


Figure 75: The distribution of summed tracked momentum within a cone of $\Delta R < 0.25$ around the candidate track for data and simulated signal events, after previous selection requirements have been applied.

3036 muon system can be identified as muons as often as 30% of the time in simulated
 3037 samples.

3038 Calorimeter-based particle rejection relies on the expected small deposits of
 3039 energy from LLPs. When the lifetime is long enough to reach the calorimeter, a
 3040 LLP deposits little of its energy as it traverses the material, as discussed in Sec-
 3041 tion 10.1. Even when the particle does decay before the calorimeter, the major-
 3042 ity of its energy is carried away by the LSP and not deposited in the calorimeter.
 3043 In both cases the energy is expected to be distributed across the layers of the
 3044 calorimeters and not peaked in just one layer. This can be quantified in terms
 3045 of E/p , the ratio of calorimeter energy of a nearby jet to the track momentum,
 3046 and f_{EM} , the fraction of energy in that jet within the electromagnetic calorime-
 3047 ter. When no jets fall within a cone of 0.05 of the particle, E/p and f_{EM} are both
 3048 defined as zero. E/p is expected to be above 1.0 for typical SM particles because
 3049 of calibration and the contributions from other nearby particles, as discussed in
 3050 Chapter 8. At these momenta there is no significant zero fraction due to inter-
 3051 actions with the detector or insufficient energy deposits (see Section 8.2.2). f_{EM}
 3052 is peaked close to 1.0 for electrons, and distributed between 10% and 90% for
 3053 hadrons.

3054 These trends can be seen in the two dimensional distribution for signal in
 3055 Figure 76 for stable and metastable (10 ns) events. The majority of R-Hadrons
 3056 in both samples fall into the bin for $E/p = 0$ and $f_{\text{EM}} = 0$ because the majority
 3057 of the time there is no associated jet. In the stable sample, when there often is
 3058 an associated jet, E/p is typically still below 0.1, and the f_{EM} is predominantly
 3059 under 0.8. In the metastable sample, on the other hand, E/p is larger but still
 3060 typically below 0.1 because of actual jets produced during the decay. The f_{EM} is
 3061 much lower on average in this case, below 0.1, because the 10 ns lifetime particles
 3062 rarely decay before passing through the electromagnetic calorimeter. Figure 76
 3063 also includes simulated Z decays to electrons or tau leptons. From the decays

3064 to electrons it is clear that the majority of electrons have f_{EM} above 0.9. The
 3065 tau decays include a variety of products. Muons can be seen in the bin where
 3066 $E/p = 0$ and $f_{\text{EM}} = 0$ because they do not have an associated jet. Electrons fall
 3067 into the range where $E/p > 1$ and $f_{\text{EM}} > 0.9$. Hadronic tau decays are the most
 3068 common, and fall in the range of $0.1 < f_{\text{EM}} < 0.9$ and $E/p > 1.0$.

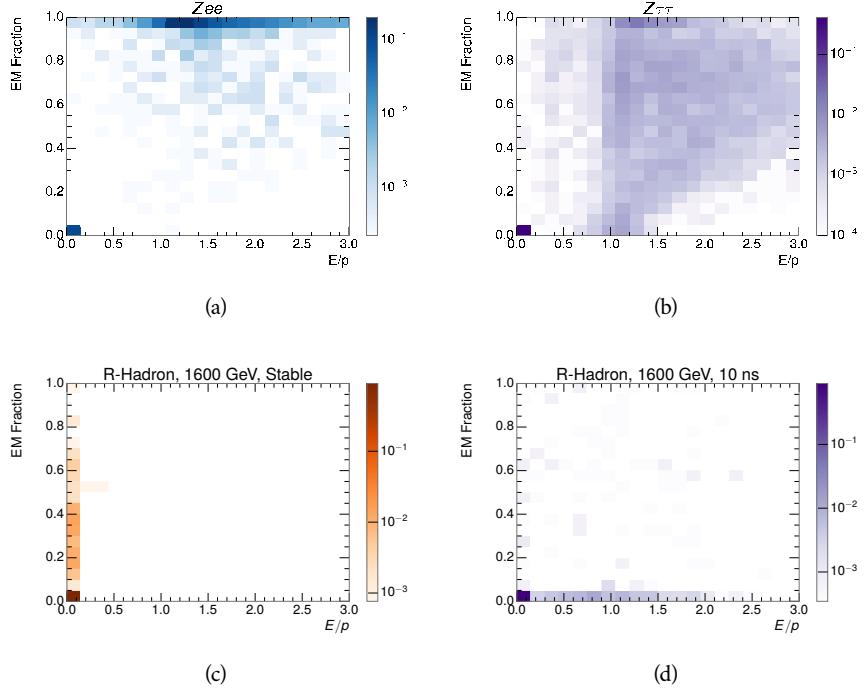


Figure 76: The normalized, two-dimensional distribution of E/p and f_{EM} for simulated
 3070 (a) $Z \rightarrow ee$, (b) $Z \rightarrow \tau\tau$, (c) 1200 GeV Stable R-Hadron events, and (d) 1200
 3071 GeV, 10 ns R-Hadron events.

3069 These differences motivate an electron rejection by requiring an f_{EM} below
 3070 0.9. Similarly, isolated hadrons are rejected by requiring $E/p < 1.0$. These re-
 3071 quirements combine to remove the majority of isolated electrons and hadrons
 3072 but retain over 95% of the simulated signal across a range of masses and lifetimes.

3073 11.4 IONIZATION

3074 The final requirement on the candidate track is the primary discriminating vari-
 3075 able, the ionization in the pixel detector. That ionization is measured in terms
 3076 of dE/dx , which was shown for data and simulated signal events in Figure 72.
 3077 dE/dx is dramatically greater for the high mass signal particles than the back-
 3078 grounds, which start to fall immediately after the minimally ionizing peak at 1.1
 3079 $\text{MeV g}^{-1} \text{cm}^2$. The dE/dx for candidate tracks must be greater than a pseudorapidity-
 3080 dependent threshold, specifically $1.80 - 0.11|\eta| + 0.17\eta^2 - 0.05\eta^3 \text{ MeV g}^{-1} \text{ cm}^{-2}$,
 3081 in order to correct for an approximately 5% dependence of the MIP peak on η .
 3082 The requirement was chosen as part of the signal region optimization, and man-

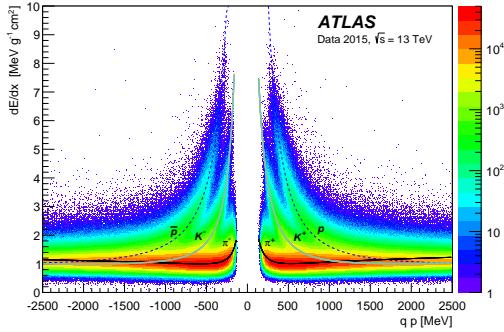


Figure 77: Two-dimensional distribution of dE/dx versus charge signed momentum (qp) for minimum-bias tracks. The fitted distributions of the most probable values for pions, kaons and protons are superimposed.

ages to reduce the backgrounds by a factor of 100 while remaining 70-90% efficient for simulated signal events depending on the mass.

11.4.1 MASS ESTIMATION

The mean value of ionization in silicon is governed by the Bethe equation and the most probable value follows a Landau-Vavilov distribution [9]. Those forms inspire a parametric description of dE/dx in terms of $\beta\gamma$,

$$(dE/dx)_{MPV}(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln(1 + [p_2 \beta\gamma]^{p_5}) - p_4 \quad (21)$$

which performs well in the range $0.3 < \beta\gamma < 1.5$. This range includes the expected range of $\beta\gamma$ for the particles targeted for this search, with $\beta\gamma \approx 2.0$ for lower mass particles ($O(100 \text{ GeV})$) and up to $\beta\gamma \approx 0.5$ for higher mass particles ($O(1000 \text{ GeV})$). The parameters, p_i , are fit using a 2015 data sample of low-momentum pions, kaons, and protons as described in Ref. [85]. Figure 77 shows the two-dimensional distribution of dE/dx and momentum along with the above fitted values for $(dE/dx)_{MPV}$.

The above equation (21) is then numerically inverted to estimate $\beta\gamma$ and the mass for each candidate track. In simulated signal events, the mean of this mass value reproduces the generated mass up to around 1800 GeV to within 3%, and 3% shift is applied to correct for this difference. The mass distributions prior to this correction are shown for a few stable mass points in Figure 78. The large widths of these distributions come from the high variability in energy deposits in the pixel detector as well as the uncertainty on momentum measurements at high momentum, but the means converge to the expected values.

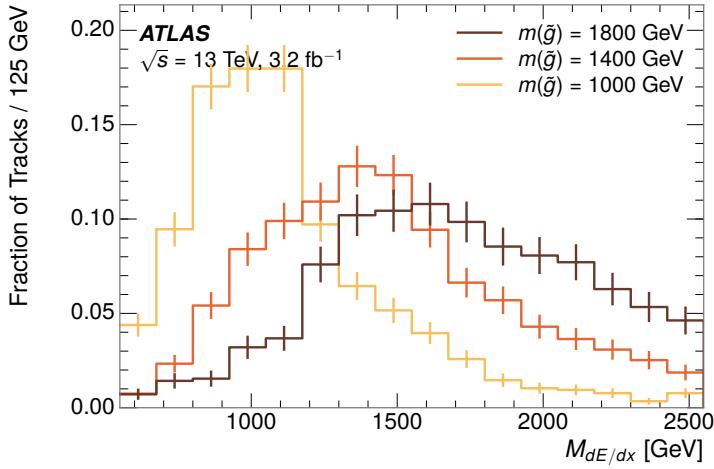


Figure 78: The distribution of mass estimated using dE/dx for simulated stable R-Hadrons with masses between 1000 and 1600 GeV.

This analysis evaluates expected yields and the resulting cross sectional limits using windows in this mass variable. The windows are formed by fitting mass distributions in simulated signal events like those in Figure 78 to Gaussian distributions and taking all events that fall within $\pm 1.4\sigma$ of the mean. As can be seen in Figure 78, typical values for this width are $\sigma \approx 300 - 500$ GeV depending on the generated mass.

11.5 EFFICIENCY

The numbers of events passing each requirement through ionization are shown in Table 8 for the full 2015 dataset and a simulated 1600 GeV, 10 ns lifetime R-Hadron sample. The table highlights the overall acceptance \times efficiency for signal events, which for this example is 19%. Between SM rejection and ionization, this signal region reduces the background of tracks which pass the kinematic requirements down by an additional factor of almost 2000.

There is a strong dependence of this efficiency on lifetime and mass, with efficiencies dropping to under 1% at low lifetimes. Figure 79 shows the dependence on both mass and lifetime for all signal samples considered in this search. The dependence on mass is relatively slight and comes predominantly from the increasing fraction of R-Hadrons which pass the ionization cut with increasing mass. The trigger and E_T^{miss} requirements are most efficient for particles that decay before reaching the calorimeters. However, the chance of a particle to be reconstructed as a high-quality track decreases significantly at low lifetimes as the particle does not propagate sufficiently through the inner detector. These effects lead to a maximum in the selection efficiency for lifetimes around 10-30 ns.

The inefficiency of this signal region at short lifetimes comes almost exclusively from an acceptance effect, in that the particles do not reach the necessary

Selection	Exp. Signal Events	Observed Events in 3.2 fb^{-1}
Generated	26.0 ± 0.3	
E_T^{miss} Trigger	24.8 ± 0.3 (95%)	
$E_T^{\text{miss}} > 130 \text{ GeV}$	23.9 ± 0.3 (92%)	
Track Quality and $p_T > 50$	10.7 ± 0.2 (41%)	368324
Isolation Requirement	9.0 ± 0.2 (35%)	108079
Track $p > 150 \text{ GeV}$	6.6 ± 0.2 (25%)	47463
$M_T > 130 \text{ GeV}$	5.8 ± 0.2 (22%)	18746
Electron and Hadron Veto	5.5 ± 0.2 (21%)	3612
Muon Veto	5.5 ± 0.2 (21%)	1668
Ionization Requirement	5.0 ± 0.1 (19%)	11

Table 8: The expected number of events at each level of the selection for metastable $1600 \text{ GeV}, 10 \text{ ns}$ R-Hadrons, along with the number of events observed in data, for 3.2 fb^{-1} . The simulated yields are shown with statistical uncertainties only. The total efficiency \times acceptance is also shown for the signal.

3130 layers of the SCT. This can be seen more clearly by defining a fiducial region
 3131 which includes events with at least one R-Hadron that is produced with non-
 3132 zero charge, $p_T > 50 \text{ GeV}$, $p > 150 \text{ GeV}$, $|\eta| < 2.5$, and a decay distance greater
 3133 than 37 cm in the transverse plane. At short (1 ns) lifetimes, the acceptance into
 3134 this region is as low as 4%. Once this acceptance is accounted for, the selection
 3135 efficiency ranges from 25% at lifetimes of 1 ns up to 45% at lifetimes of 10 ns.

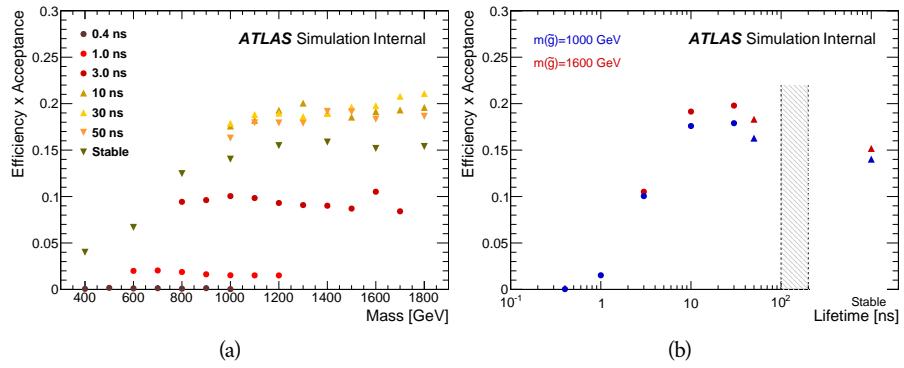


Figure 79: The acceptance \times efficiency as a function of R-Hadron (a) mass and (b) lifetime. (a) shows all of the combinations of mass and lifetime considered in this search, and (b) highlights the lifetime dependence for 1000 GeV and 1600 GeV R-Hadrons.

3136

3137 BACKGROUND ESTIMATION

3138 The event selection discussed in the previous section focuses on detector signa-
 3139 tures, emphasizing a single high-momentum, highly-ionizing track. That track
 3140 is then required to be in some way inconsistent with the expected properties
 3141 of SM particles, with various requirements designed to reject jets, hadrons,
 3142 electrons, and muons (Section 11.3). Therefore the background for this search comes
 3143 entirely from reducible backgrounds that are outliers of various distributions in-
 3144 cluding dE/dx , f_{EM} , and p_T^{Cone} . The simulation can be tuned in various ways to
 3145 do an excellent job of modeling the average properties of each particle type [86],
 3146 but it is not necessarily expected to accurately reproduce outliers. For this rea-
 3147 sons, the background estimation used for this search is estimated entirely using
 3148 data.

3149 12.1 BACKGROUND SOURCES

3150 SM charged particles with lifetimes long enough to form tracks in the inner de-
 3151 tector can be grouped into three major categories based on their detector inter-
 3152 actions: hadrons, electrons, and muons. Every particle that enters into the back-
 3153 ground for this search belongs to one of these types. Relatively pure samples of
 3154 tracks from each of these types can be formed in data by inverting the various
 3155 rejection techniques in Section 11.3. Specifically, muons are selected requiring
 3156 medium muon identification, electrons requiring $E/p > 1.0$ and $f_{\text{EM}} > 0.95$,
 3157 and hadrons requiring $E/p > 1.0$ and $f_{\text{EM}} < 0.95$.

3158 Figure 80 shows the distributions of momentum and dE/dx for these cate-
 3159 gories in data, after requiring the event level selection as well as the track re-
 3160 quirements on p_T , hits, and N_{split} , as discussed in Section 11.2. Simulated signal
 3161 events are included for reference. These distribution are only illustrative of the
 3162 differences between types, as the rejection requirements could alter their shape.
 3163 This is especially significant for momentum which enters directly into E/p and
 3164 can indirectly affect muon identification. However the various types show clear
 3165 differences in both distributions. The distributions of momentum are not nec-
 3166 cessarily expected to match between the various types because the production
 3167 mechanisms for each type result in different kinematic distributions. dE/dx is
 3168 also different between types because of incomplete isolation; although the re-
 3169 quirement on N_{split} helps to reduce the contribution of nearby particles it does
 3170 not completely remove the effect of overlaps. Muons are better isolated because
 3171 they do not have the additional particle from hadronization present for hadrons
 3172 and they are significantly less likely do interact with the detector and produce
 3173 secondary particles compared to hadrons and electrons. Thus muons have the
 3174 smallest fraction of dE/dx above the threshold of $1.8 \text{ MeVg}^{-1}\text{cm}^2$; hadrons and
 3175 electrons have a larger fraction above this threshold.

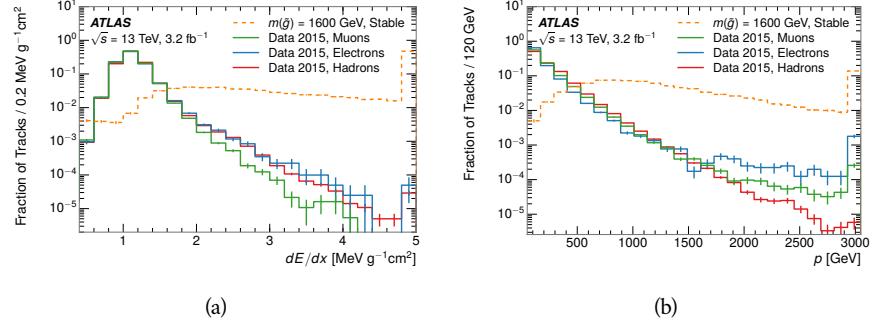


Figure 80: The distribution of (a) dE/dx and (b) momentum for tracks in data and simulated signal after requiring the event level selection and the track selection on p_T , hits, and N_{split} . Each sub-figure shows the normalized distributions for tracks classified as hadrons, electrons, and muons in data and R-Hadrons in the simulated signal.

3176 It is difficult to determine what fraction of each particle type enters into the fi-
 3177 nal signal region. The background method will not have significant dependence
 3178 on the relative contributions of each species, but it is useful to understand the
 3179 differences between each when considering the various tests of the method.

3180 12.2 PREDICTION METHOD

3181 The data-driven background estimation relies on the independence between ion-
 3182 ization and other kinematic variables in the event. For standard model particles
 3183 with momenta above 50 GeV, dE/dx is not correlated with momentum; though
 3184 there is a slight relativistic rise as momentum increases, the effect is small com-
 3185 pared to the width of the distribution of ionization energy deposits.. So, the
 3186 proposed method to estimate the mass distribution of the signal region is to use
 3187 momentum from a track with low dE/dx (below the threshold value) and to com-
 3188 bine it with a random dE/dx value from a dE/dx template. The resulting track is
 3189 just as likely as the original, so a number of such random generations provide the
 3190 expected distributions of momentum and ionization. These are then combined
 3191 using the parametrization described in Section 11.4.1 to form a distribution of
 3192 mass for the signal region.

3193 Algorithmically this method is implemented by forming two distinct Control
 3194 Regions (**CR**s). The first **CR**, CR1, is formed by applying the entire event selec-
 3195 tion from Chapter 11 up to the dE/dx and mass requirements. The dE/dx re-
 3196 quirement is instead inverted for this region. Because of the independence of
 3197 dE/dx , the tracks in this control region have the same kinematic distribution
 3198 as the tracks in the signal region, and are used to measure a two-dimensional
 3199 template of p and η . The second **CR**, CR2, is formed from the event selection
 3200 through the dE/dx requirement, but with an inverted E_T^{miss} requirement. The
 3201 tracks in this control region are expected to have similar dE/dx distributions to
 3202 the signal region before the ionization requirement, and so this region is used to
 3203 measure a two-dimensional template of dE/dx and η .

3204 The contribution of any signal to the control regions is minimized by the in-
 3205 verted selection requirements. Only less than 10% of simulated signal events
 3206 have either dE/dx or E_T^{miss} below the threshold values in the original signal re-
 3207 gion, while the backgrounds are significantly enhanced by inverting those re-
 3208 quirements. The signal contamination is less than 1% in both control regions
 3209 for all of the simulated masses and lifetimes considered in this analysis.

3210 With those measured templates, the shape of the mass estimation is generated
 3211 by first selecting a random (p, η) combination from CR1. This momentum
 3212 value is combined with a dE/dx value taken from the appropriate distribution
 3213 of dE/dx for the selected η from CR2. The use of η in both random samplings
 3214 controls for any correlation between p , dE/dx , and η . Those values are then
 3215 used to calculate a mass in the same way that is done for regular tracks in data,
 3216 see Section 11.4.1. As this procedure includes all dE/dx values, the cut at 1.8
 3217 MeVg $^{-1}$ cm 2 is then enforced to fully model the signal region. The generated
 3218 mass distribution is then normalized by scaling the background estimate to the
 3219 data in the region $M < 160$ GeV, where signals of this type have already been
 3220 excluded [70]. This normalization uses the distributions of mass generated with-
 3221 out the ionization requirement.

3222 The statistical uncertainties on these background distributions are calculated
 3223 by independently fluctuating each bin of the input templates according to their
 3224 Poisson uncertainties. These fluctuations are repeated a large number of times,
 3225 and the uncertainty on the resulting distribution is taken as the root mean square
 3226 (RMS) deviation of the fluctuations from the average. As the procedure uses one
 3227 million random combinations to generate the distributions, The statistical un-
 3228 certainty from the actual random generations is negligible compared to the un-
 3229 certainty from measuring the templates.

3230 12.3 VALIDATION

3231 The validity of the background estimation technique can be evaluated in both
 3232 data and simulation. The underlying assumption that random combinations of
 3233 dE/dx and momentum can predict a mass distribution in an orthogonal region
 3234 can be tested using simulated samples where concerns like multiple particle types
 3235 can be controlled. Using the same technique in another set of signal-depleted
 3236 regions in data then extends this confidence to the more complicated case where
 3237 several particle species are inherently included.

3238 12.3.1 CLOSURE IN SIMULATION

3239 The first test of the procedure is done using a simulated sample of $W \rightarrow \mu\nu$
 3240 decays. These types of events provide the ingredients required to test the back-
 3241 ground estimate, E_T^{miss} and isolated tracks, with high statistics. In this example
 3242 there is no signal, so simulated events in the orthogonal CRs are used to estimate
 3243 the shape of the mass distribution of the simulated events in the signal region. To
 3244 reflect the different topology for W boson decays, the CRs use slightly modified
 3245 definitions. In all CRs, the requirement of $p > 150$ GeV and the SM rejection

3246 requirements are removed. Additionally, for the signal region the requirement
 3247 on E_T^{miss} is relaxed to 30 GeV and the corresponding inverted requirement on
 3248 CR2 is also set at 30 GeV.

3249 With these modified selections, the simulated and randomly generated distri-
 3250 butions of $M_{dE/dx}$ are shown in Figure 81. This figure includes the mass distri-
 3251 butions before and after the requirement on dE/dx , which significantly shapes
 3252 the distributions. In both cases the background estimation technique repro-
 3253 duces the shape of $M_{dE/dx}$ in the signal region. There is a small difference in the pos-
 3254 itive tail of the mass distribution prior to the ionization cut, where the random
 3255 events underestimate the fraction of tracks with mass above 150 GeV by about
 3256 20%. After the ionization requirement, however, this discrepancy is not present
 3257 and the two distributions agree to within statistical uncertainties.

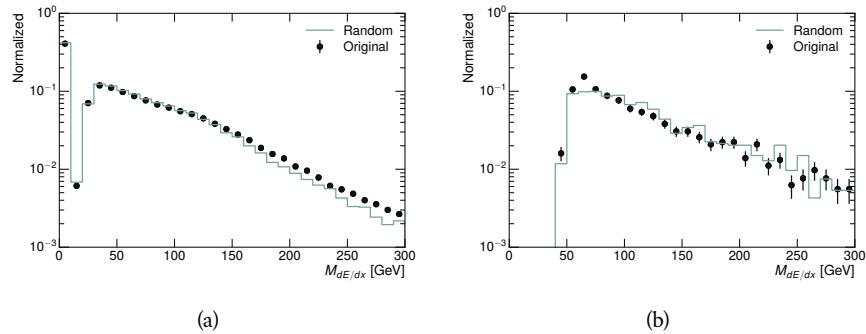


Figure 81: The distribution of $M_{dE/dx}$ (a) before and (b) after the ionization requirement for tracks in simulated W boson decays and for the randomly generated back-
 ground estimate.

3258 This ability to reproduce the shape of the mass distribution in simulated events
 3259 shows that the technique works as expected. No significant biases are acquired
 3260 in using low dE/dx events to select kinematic templates or in using low E_T^{miss}
 3261 events to select ionization templates, as either would result in a mismodeling of
 3262 the shape of the mass distribution. The simulated events contain only one par-
 3263 ticle type, however, so this test only establishes that the technique works well
 3264 when the the CRs are populated by exactly the same species.

3265 12.3.2 VALIDATION REGION IN DATA

3266 The second test of the background estimate is performed using data in an or-
 3267 thogonal validation region. The validation region, and the corresponding CRs,
 3268 are formed using the same selection requirements as in the nominal method but
 3269 with a modified requirement on momentum, $50 < p[\text{GeV}] < 150$. This allows
 3270 the technique to be checked in a region with very similar properties but where
 3271 the signal is depleted, as the majority of the signal has momentum above 150
 3272 GeV while the backgrounds are enhanced below that threshold. Any biases on
 3273 the particle composition of the CRs for the signal region will be reflected in the
 3274 CRs used to estimate the mass distribution in the validation region.

Figure 82 shows the measured and randomly generated mass distributions for data before and after the ionization requirement. The background estimate does an excellent job of modeling the actual background before the ionization requirement, with good agreement to within the statistical uncertainties out to the limit of the mass distribution. There are very few events in the validation region after the ionization requirement, but the few observed events are consistent with the background prediction. The good agreement in this validation region provides a confirmation that the technique works even in the full-complexity case with multiple particle types entering the distributions. Any bias from changes in particle composition between regions is small compared to statistical uncertainties.

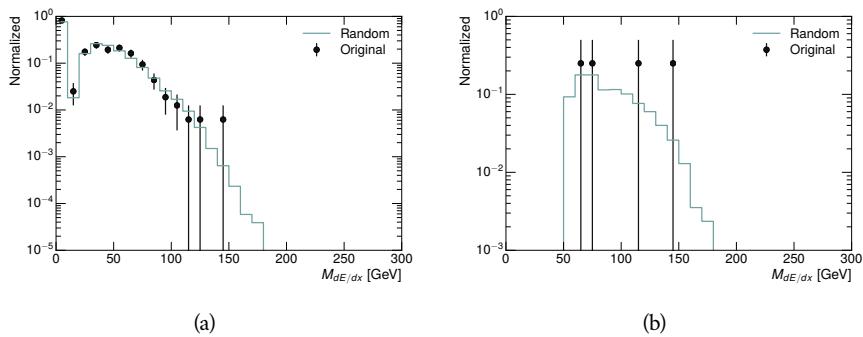


Figure 82: The distribution of $M_{dE/dx}$ (a) before and (b) after the ionization requirement for tracks in the validation region and for the randomly generated background estimate.

3285

3286 SYSTEMATIC UNCERTAINTIES AND RESULTS

3287 13.1 SYSTEMATIC UNCERTAINTIES

3288 A number of systematic uncertainties affect the interpretation of the results of
 3289 the search. These uncertainties can broken down into two major categories,
 3290 those which affect the estimate of the background using data and those which
 3291 affect the measurement of the signal yield estimated with simulated events. The
 3292 total measured systematic uncertainties are 7% for the background estimation
 3293 and approximately 32% for the signal yield depending on lifetime. These system-
 3294atic uncertainties are expected to be small compared to the statistical fluctuations
 3295 of the measured yields so that measured cross-sectional limits will be dominated
 3296 by statistical uncertainties. The following sections describe each source of sys-
 3297 tematic uncertainty for each of the two types.

3298 13.1.1 BACKGROUND ESTIMATE

3299 The systematic uncertainties on the background estimate come primarily from
 3300 considering alternative methods for generating the background distributions.
 3301 These uncertainties are small compared to the statistical uncertainties on the
 3302 background estimate which come from the limited statistics in measuring the
 3303 template distributions, as described in Section 12.2. They are summarized in
 3304 Table 9.

Source of Uncertainty:	Value [%]
Analytic Description of dE/dx	4.0
Muon Fraction (Stable Region only)	3.0
IBL Ionization Correction	3.8
Normalization	3.0
Total (Metastable Region):	6.3
Total (Stable Region):	7.0

Table 9: A summary of the sources of systematic uncertainty for the data-driven background in the signal region. If the uncertainty depends on the mass, the maximum values are reported.

3305 13.1.1.1 ANALYTIC DESCRIPTION OF DE/DX

3306 The background estimate uses a binned template distribution to estimate the
 3307 dE/dx of tracks in the signal region, as described in Section 12.2. It is also possi-

ble to fit that measured distribution to a functional form to help smooth the distribution in the tails of dE/dx where the template is driven by a small number of tracks. Both Landau convolved with a Gaussian and Crystal Ball functions are considered as the functional form and used to re-estimate the background distribution. The deviations compared to the nominal method are found to be 4%, and this is taken as a systematic uncertainty to cover the inability carefully predict the contribution from the long tail of dE/dx where there are few measurements available in data.

3316 13.1.1.2 MUON FRACTION

3317 The stable region of the analysis explicitly includes tracks identified as muons,
 3318 which have a known difference in their dE/dx distributions compared to non-
 3319 muon tracks (Section 12.1). To account for a difference in muon fraction be-
 3320 tween the background region and the signal region for this selection, the dE/dx
 3321 templates for muons and non-muons are measured separately and then the rel-
 3322 ative fraction of each is varied in the random generation. The muon fraction
 3323 is varied by its statistical uncertainty and the resulting difference of 3% in back-
 3324 ground yield is taken as the systematic uncertainty.

3325 13.1.1.3 IBL CORRECTIONS

3326 The IBL, described in Section 6.3.1, received a significant dose of radiation during
 3327 the data collection in 2015. The irradiation can cause a drift in the frontend
 3328 electronics and thus alter the dE/dx measurement which includes the ToT output
 3329 by the IBL. These effects are corrected for in the nominal analysis by scaling the
 3330 dE/dx measurements by a constant factor derived for each run to match the
 3331 average dE/dx value to a reference run where the IBL was known to be stable
 3332 to this effect. However, this corrective factor does not account for inter-run
 3333 variations. To account for this potential drift of dE/dx , the correction procedure
 3334 is repeated by varying the corrections up and down by the maximal run-to-run
 3335 variation from the full data-taking period, which results in an uncertainty of
 3336 3.8%.

3337 13.1.1.4 NORMALIZATION

3338 As described in Section 12.2, the generated distribution of masses is normalized
 3339 in a shoulder region ($M < 160$ GeV) where signals have been excluded by pre-
 3340 vious analyses. That normalization factor is varied by its statistical uncertainty
 3341 and the resulting fluctuation in the mass distribution of 3% is taken as a system-
 3342 atic uncertainty on the background estimate.

3343 13.1.2 SIGNAL YIELD

3344 The systematic uncertainties on the signal yield can be divided into three cate-
 3345 gories; those on the simulation process, those on the modeling of the detector
 3346 efficiency or calibration, and those affecting the overall signal yield. They are
 3347 summarized in Table 9. The largest uncertainty comes from the uncertainty on

3348 the production cross section for gluinos, which is the dominant systematic un-
 3349 certainty in this analysis.

Source of Uncertainty	-[%]	+[%]
ISR Modeling (Metastable Region)	1.5	1.5
ISR Modeling (Stable Region)	14	14
Pile-up Reweighting	1.1	1.1
Trigger Efficiency Reweighting	0.9	0.9
E_T^{miss} Scale	1.1	2.2
Ionization Parametrization	7.1	0
Momentum Parametrization	0.3	0.0
Electron Rejection	0.0	0.0
Hadron Rejection	0.0	0.0
μ Identification	4.3	4.3
Luminosity	5	5
Signal size uncertainty	28	28
Total (Metastable Region)	30	29
Total (Stable Region)	33	32

Table 10: A summary of the sources of systematic uncertainty for the simulated signal yield. The uncertainty depends on the mass and lifetime, and the maximum negative and positive values are reported in the table.

3350 13.1.2.1 ISR MODELING

3351 As discussed in Section 10.2, MadGraph is expected to reproduce the distribution
 3352 of ISR in signal events more accurately than the nominal Pythia samples. The
 3353 analysis reweights the distribution of ISR in the simulated signal events to match
 3354 the distribution found in generated MadGraph samples. This has an effect on the
 3355 selection efficiency in the signal samples, where ISR contributes to the generation
 3356 of E_T^{miss} . To account for the potential inaccuracy on the simulation of ISR at high
 3357 energies, half of the difference between the signal efficiency with the reweighted
 3358 distribution and the original distribution is taken as a systematic uncertainty.

3359 13.1.2.2 PILEUP REWEIGHTING

3360 The simulated events were generated prior to data collection with an estimate of
 3361 the average number of interactions per bunch crossing. This estimate does not
 3362 match the value of pileup during actual data collection, but a large fraction of the
 3363 simulated events would be discarded in order to match the distribution in data.
 3364 Therefore the simulated signal events are not reweighted for pileup by default
 3365 in the analysis. The effect of the pileup on signal efficiency is not expected to
 3366 depend on the mass or lifetime of the generated signal events, which allows all

3367 of the generated signal events to be used together to assess the pileup dependence.
 3368 To account for the potential effect of the difference in the number of interactions
 3369 per bunch crossing between data and simulation, the difference in yield between
 3370 the nominal signal events and the reweighted events averaged over all masses
 3371 and lifetimes is taken as a systematic uncertainty on the yield for each mass and
 3372 lifetime (1.1%).

3373 13.1.2.3 TRIGGER EFFICIENCY REWEIGHTING

3374 As described in Section 11.2, the selection for this analysis does not require a suf-
 3375 ficiently large value of E_T^{miss} to be above the plateau of trigger efficiency. There-
 3376 fore, some signal events which would otherwise pass the event selection can be
 3377 excluded because of the trigger requirement. These effects can be difficult to es-
 3378 timate in simulation, and thus are constrained by comparing data and simulated
 3379 events in an alternative W boson region which uses decays to muons to find a rel-
 3380 atively pure sample of events with missing energy. The trigger efficiency for data
 3381 and simulated W events are shown in Figure 83. The comparison between data
 3382 and MC in this region constrains the simulation of the trigger efficiency. The
 3383 simulated signal events are reweighted by the ratio of data to simulation in the
 3384 W boson decays, while the difference between the data and simulation in those
 3385 decays is taken as a systematic uncertainty. This results in an uncertainty of only
 3386 0.9% as the majority of events are well above the plateau and the disagreement
 3387 between data and simulation is small even below that plateau.

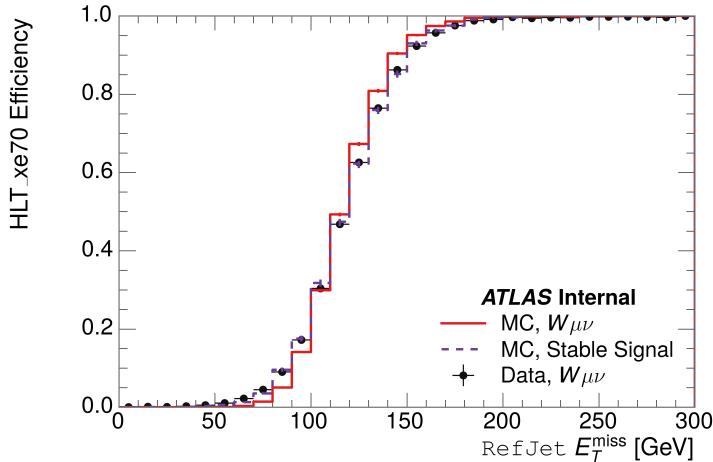


Figure 83: The trigger efficiency for the HLT_xe70 trigger requirement as a function of Calorimeter E_T^{miss} for simulated data events with a W boson selection. Simulated signal events and simulated W boson events are also included.

3388 13.1.2.4 MISSING TRANSVERSE MOMENTUM SCALE

3389 The ATLAS Combined Performance (CP) group provides a default recommenda-
 3390 tion for systematic variations of jets and missing energy (**note: I'm not quite**
 3391 **sure what to cite for this - I don't see any papers from the jet/met group**

Systematic Variation	-[%]	+[%]
JET_GroupedNP_1	-0.7	1.3
JET_GroupedNP_2	-0.7	1.2
JET_GroupedNP_3	-0.5	1.3

Table 11: Example of the contributing systematic variations to the total systematic for the E_T^{miss} Scale, as measured in a 1200 GeV, Stable R-Hadron signal sample.

after this was implemented). These variations enter into this analysis only in the requirement on E_T^{miss} . The effect of the measured scale of E_T^{miss} is evaluated by varying the E_T^{miss} scale according to the one sigma variations provided by all CP recommendations on objects affecting event kinematics in simulated signal events. Missing energy is reconstructed from fully reconstructed objects so any systematic uncertainties affecting jets, muons, electrons, or the E_T^{miss} soft terms are included. The only non-negligible contributions found using this method are itemized in Table 11 for an example signal sample (1200 GeV, Stable R-Hadron), where the systematic is measured as the relative difference in the final signal efficiency after applying the associated variation through the CP tools. The only variations that are significant are the grouped jet systematic variations, which combine recommended jet systematic uncertainties into linearly independent variations.

As the peak of the reconstructed E_T^{miss} distribution in the signal is significantly above the current threshold for events which pass the trigger requirement, the effect of scale variation is expected to be small, which is consistent with the measured systematic of approximately 2%. Events which do not pass the trigger requirement usually fail because there are no ISR jets in the event to balance the R -hadrons' transverse momentum, so the reconstructed E_T^{miss} is low and therefore also expected to be not very sensitive to scale changes.

13.1.2.5 MOMENTUM PARAMETRIZATION

The uncertainty on the signal efficiency from track momentum is calculated using the CP group recommendations for tracks. In particular, only one recommended systematic variation affects track momentum, the sagitta bias for q/P . This uncertainty is propagated to the final selection efficiency by varying the track momentum by the recommended one sigma variation, and the associated uncertainty is found to be negligible (0.3%).

13.1.2.6 IONIZATION REQUIREMENT

The dE/dx distributions in data and simulated events have different most probable values, which is due in part to radiation effects in the detector that are not fully accounted for in the simulation. The difference does not affect the mass measurement used in this analysis, as independent calibrations are done in simulation and in data. However, it does affect the efficiency of the high dE/dx selection requirement. To calculate the size of the effect on the signal efficiency,

3426 the dE/dx distribution in signal simulation is scaled by a scale factor obtained
 3427 from comparing the dE/dx distribution of inclusive tracks in data and in sim-
 3428 ulation. The difference in efficiency for this sample with a scaled dE/dx dis-
 3429 tribution, relative to the nominal case, is taken as a systematic uncertainty on
 3430 signal efficiency. The uncertainty is as large as 7% for low masses and falls to a
 3431 negligible effect for large masses.

3432 13.1.2.7 ELECTRON AND JET REJECTION

3433 The systematic uncertainty on the electron rejection is measured by varying the
 3434 EM fraction requirement significantly, from 0.95 to 0.9. This is found to have
 3435 a less than 0.04% effect on signal acceptance, on average, and so is completely
 3436 negligible. Similarly, the uncertainty on jet rejection is measured by tightening
 3437 the E/p requirement from 0.5 to 0.4. This is found to have no effect on signal
 3438 acceptance, so again the systematic is again negligible.

3439 13.1.2.8 MUON VETO

3440 The metastable signal region requires that the candidate tracks are not identi-
 3441 fied as medium muons because the majority of R-Hadrons in the lifetime range
 3442 included in that region do not reach the muon spectrometers before they de-
 3443 cay. However, the exponential tail of the R-Hadron lifetime distribution results
 3444 in some R-Hadrons traversing the muon spectrometer. These can still fail the
 3445 muon medium identification because they can fail on the requirement on the
 3446 number of precision hits required to pass the loose selection because they ar-
 3447 rive late to the muon spectrometer. This can be seen in Figure 84, which shows
 3448 the efficiency of the muon veto as a function of $1/\beta$, for two simulated stable
 3449 R-Hadron samples.

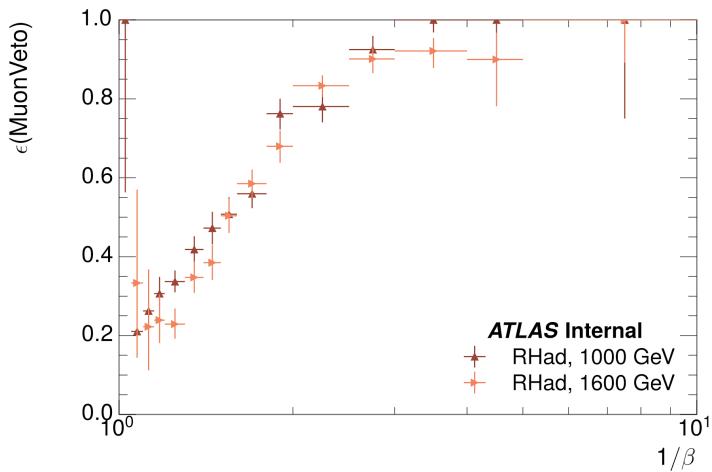
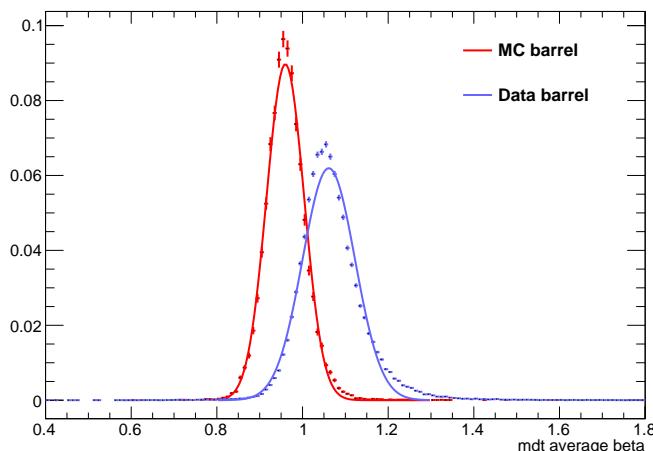


Figure 84: The efficiency of the muon veto for R -hadrons of two different masses, as a function of $1/\beta$ for simulated R-Hadron tracks.

3450 Thus, the efficiency of the muon veto depends on the timing resolution of
 3451 the spectrometer, so an uncertainty is applied to the signal efficiency to cover

3452 differences in timing resolution between data and simulation. First, a sample of
 3453 $Z \rightarrow \mu\mu$ events is selected in data in which one of the muons has a late arrival
 3454 time measured in the MDT. Then the reconstructed β distribution is compared
 3455 to the distribution in simulated $Z \rightarrow \mu\mu$ events; the difference between these
 3456 two distributions reflects the difference in timing resolution between data and
 3457 simulation. To emulate this difference in simulated signal events, the magnitude
 3458 of the difference is used to scale and shift the true β distribution of R-Hadrons in
 3459 simulation. Signal events are then reweighted based on this varied β distribution,
 3460 and the difference in the efficiency of the muon veto selection is compared with
 3461 the nominal and reweighted true β distributions. The difference in muon veto
 3462 efficiency is taken as a systematic uncertainty of the muon veto.

3463 The comparison of reconstructed β between data and simulation is performed
 3464 separately in the barrel, transition, and endcap regions of the spectrometer, and
 3465 the reweighting of the true β distribution in signal is done per region. The com-
 3466 parison of average reconstructed MDT β between data and simulation for the
 3467 barrel region is shown in Figure 85 for $Z \rightarrow \mu\mu$ events. As expected, The uncer-
 3468 tainty is found to be negligible for R-hadrons with short lifetimes, and is only
 3469 significant for lifetimes above 30 ns.



3470 Figure 85: The average reconstructed MDT β distribution for $Z \rightarrow \mu\mu$ events in which
 3471 one of the muons is reconstructed as a slow muon, for both data and simula-
 3472 tion. A gaussian fit is superimposed.

3470 13.1.2.9 LUMINOSITY

3471 The luminosity uncertainty is provided by a luminosity measurement on ATLAS
 3472 and was measured to be 5% at the time of the publication of this analysis.

3473 13.1.2.10 SIGNAL SIZE

3474 As discussed in Section 10.2, the signal cross sections are calculated at NLO in the
 3475 strong coupling constant with a resummation of soft-gluon emission at NLL. The
 3476 uncertainties on those cross sections are between 14% to 28% for the R-Hadrons

Selection Region	Expected Background	Data
Stable	$17.2 \pm 2.6 \pm 1.2$	16
Metastable	$11.1 \pm 1.7 \pm 0.7$	11

Table 12: The estimated number of background events and the number of observed events in data for the specified selection regions prior to the requirement on mass. The background estimates show statistical and systematic uncertainties.

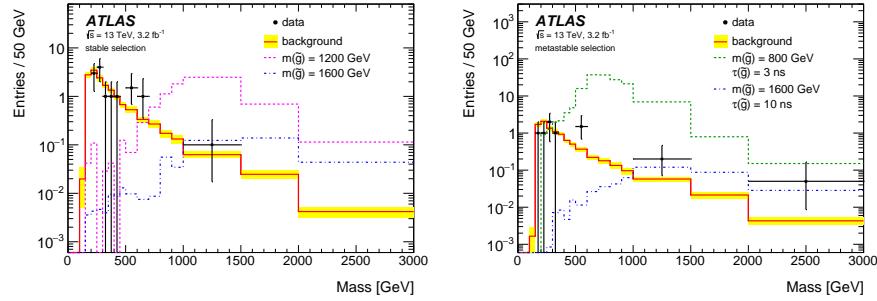


Figure 86: The observed mass distribution of events in data and the generated background distribution in (a) the stable and (b) the metastable signal region. A few example simulated signal distributions are superimposed.

3477 in the range of 400 to 1800 GeV [82, 83], where the uncertainty increases with
3478 the mass.

3479 13.2 FINAL YIELDS

3480 This full analysis was performed using the 3.2 fb^{-1} from the 2015 data-taking.
3481 Using the selections discussed in Chapter 11, sixteen events were observed in
3482 the stable signal region and eleven events were observed in the metastable signal
3483 region, prior to requirements on the candidate track mass. The background esti-
3484 mate discussed in Chapter 12 predicts $17 \pm 2.6(\text{stat}) \pm 1.2(\text{syst})$ events for the
3485 stable region and $11.1 \pm 1.7(\text{stat}) \pm 0.7(\text{syst})$ events for the metastable region.
3486 These counts are summarized in Table 12.

3487 The mass estimated using dE/dx (Section 11.4.1) provides the final discrimi-
3488 nating variable, where the signal would be expected as an excess in the falling ex-
3489 ponential tail of the expected background. The observed distribution of masses
3490 is shown in Figure 86, along with the predicted distribution from the background
3491 estimate for each signal region. Both include a few example simulated signal dis-
3492 tributions, which show the scale of an excess were the R-Hadron signals present.
3493 There is no statistically significant evidence of an excess in the data over the back-
3494 ground estimation. From this distribution it is clearly possible to rule out signals
3495 with lower masses, around 1200 GeV, which have larger cross sections.

3496 13.3 CROSS SECTIONAL LIMITS

3497 Because there is no observed significant excess of events in the signal region, this
 3498 analysis sets upper limits on the allowed cross section for R-Hadron production.
 3499 These limits are set for each mass point by counting the observed events in data,
 3500 along with the expected background and simulated signal events, in windows of
 3501 mass. The mass windows are formed by fitting the distribution of signal events to
 3502 a Gaussian distribution, and the window is then $\pm 1.4\sigma$ around the center of that
 3503 Gaussian. Two examples of the windows formed by this procedure are shown
 3504 in Tables 13-14, for the stable and 10 ns working points. The corresponding
 3505 counts of observed data, expected background, and simulated signal for those
 3506 same working points are shown in Tables 15-16. Appendix B includes the mass
 3507 windows and counts for all of the considered signal points.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
1000	655	1349
1100	734	1455
1200	712	1631
1300	792	1737
1400	717	1926
1500	815	2117
1600	824	2122
1700	900	2274
1800	919	2344

Table 13: The left and right extremum of the mass window for each generated mass point with a 10 ns lifetime.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
800	627	1053
1000	726	1277
1200	857	1584
1400	924	1937
1600	993	2308
1800	1004	2554

Table 14: The left and right extremum of the mass window used for each generated stable mass point.

3508 The 95% confidence level upper limits on the cross sections for a large grid of
 3509 masses (between 800 and 1800 GeV) and lifetimes (between 0.4 and stable) are
 3510 extracted from these counts with the CL_S method using the profile likelihood

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
800	462.83 ± 14.86	1.764 ± 0.080	2.0
1000	108.73 ± 3.38	1.458 ± 0.070	1.0
1200	31.74 ± 0.95	1.137 ± 0.060	1.0
1400	10.22 ± 0.29	1.058 ± 0.058	1.0
1600	3.07 ± 0.09	0.947 ± 0.054	1.0
1800	1.08 ± 0.05	0.940 ± 0.054	1.0

Table 15: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated stable mass point

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
1000	144.48 ± 5.14	1.499 ± 0.069	2.0
1100	73.19 ± 2.61	1.260 ± 0.060	2.0
1200	41.54 ± 1.41	1.456 ± 0.067	2.0
1300	22.58 ± 0.77	1.201 ± 0.058	2.0
1400	12.70 ± 0.42	1.558 ± 0.071	2.0
1500	6.73 ± 0.24	1.237 ± 0.060	2.0
1600	3.90 ± 0.13	1.201 ± 0.058	2.0
1700	2.27 ± 0.07	1.027 ± 0.052	2.0
1800	1.34 ± 0.04	1.019 ± 0.052	2.0

Table 16: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 10 ns.

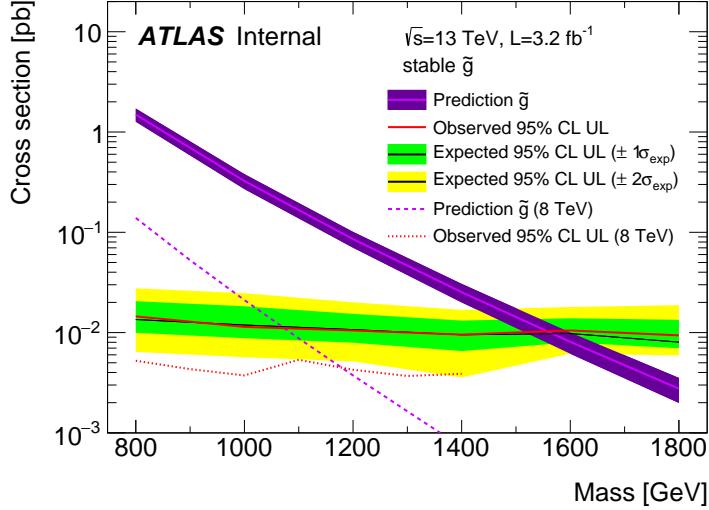


Figure 87: The observed and expected cross section limits as a function of mass for the stable simulated signal. The predicted cross section values for the corresponding signals are included.

ratio as a test statistic [87]. For this procedure, the systematic uncertainties estimated for the signal and background yields are treated as Gaussian-distributed nuisance parameters. The uncertainty on the normalization of the expected background distribution is included in the expected background events. At this point the expected cross section limit is calculated for both the metastable and stable signal region for each lifetime point, and the region with the best expected limit is selected for each lifetime. Using that procedure, the metastable region is used for lifetimes up to and including 30 ns, and the stable region for lifetimes above it.

The resulting cross-sectional upper limits are shown as a function of mass in Figure 87 and Figure 88 for each lifetime considered. The limits are interpolated linearly between each mass point, and the dependence of the limit on the mass is small as the efficiency is relatively constant for large R-Hadron masses. There is however a strong dependence on lifetime, as discussed in Section 11.5, where the probability to form a fully reconstructed track and the kinematic freedom to produce E_T^{miss} result in a local maximum in the limit at 10–30 ns. The figures also include the expected cross section for pair-produced gluino R-Hadrons for reference. For the 10 ns and stable cross section limits, both the observed limit and expected cross section for the Run 1, 8 TeV version of this analysis are included. There the cross sectional limits are lower because of the increased available luminosity, while the signal cross sections were also much lower because of the lower collision energy.

13.4 MASS LIMITS

The cross-sectional limits can then be used to derive a lower mass limit for gluino R-Hadrons by comparing them to the theoretically predicted production cross

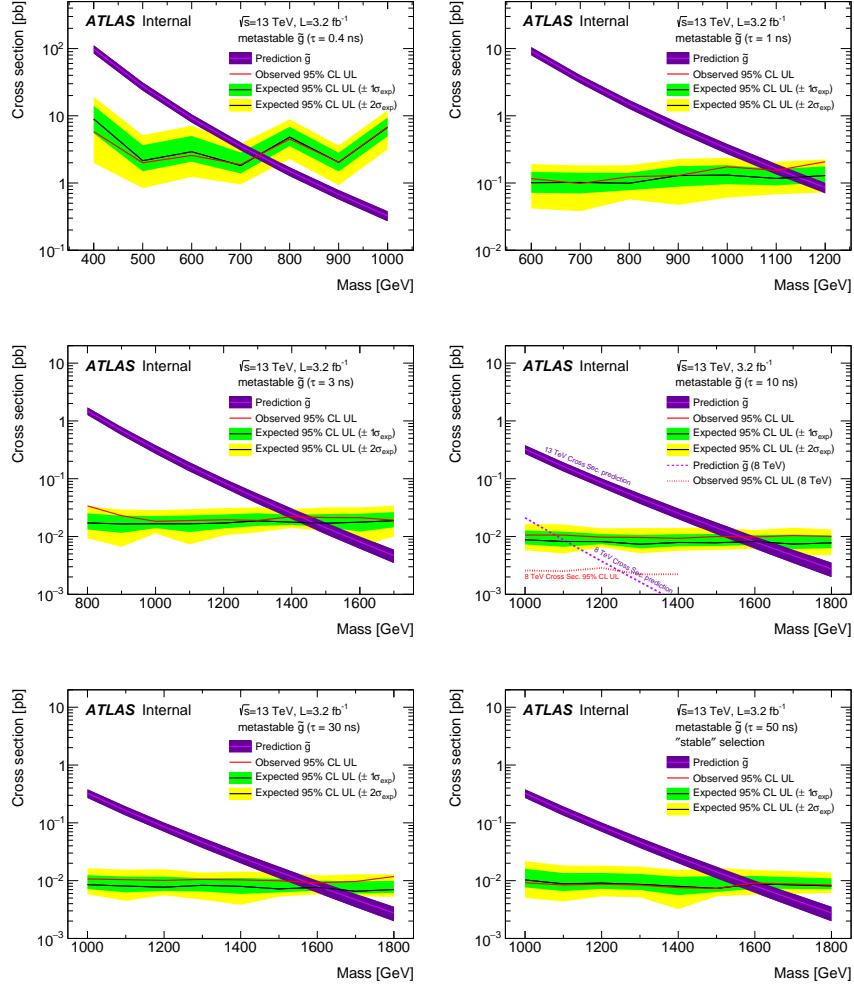


Figure 88: The observed and expected cross section limits as a function of mass for each generated lifetime. The predicted cross section values for the corresponding signals are included.

sections. These mass limits range from only 740 GeV at the lowest lifetimes considered, where the selection efficiency is very low, to up to 1580 GeV at 30 ns where the selection efficiency is maximized. The observed and expected mass limits for each lifetime point are detailed in Table 17, which also lists which selection region was used for each lifetime. These excluded range of masses as a function of lifetime is also shown in Figure 89. The Run 1 limits are included for comparison; the limits have increased by about 200 GeV on average. The search has also improved since the previous incarnation from Run 1 in optimizing the region between 30 GeV and detector-stable lifetimes by introducing the second signal region. The definition of the stable region prevents the significant drop in mass limit that occurred above 30 GeV in the Run 1 analysis.

Selection	τ [ns]	$M_{\text{obs}} > [\text{GeV}]$	$M_{\text{exp}} > [\text{GeV}]$
Metastable	0.4	740	730
"	1.0	1110	1150
"	3.0	1430	1470
"	10	1570	1600
"	30	1580	1620
Stable	50	1590	1590
"	stable	1570	1580

Table 17: The observed and expected 95% CL lower limit on mass for gluino R-Hadrons for each considered lifetime.

13.5 CONTEXT FOR LONG-LIVED SEARCHES

This search plays an important role in the current, combined ATLAS search for long lived particles. The mass limits provided by various ATLAS searches for long-lived gluino R-Hadrons can be seen in Figure 90. This search provides the most competitive limit for lifetimes between 3 ns up through very long lifetimes, where it is still competitive with dedicated searches for stable particles. The limits placed on gluino production are very similar to the limits on promptly decaying models.

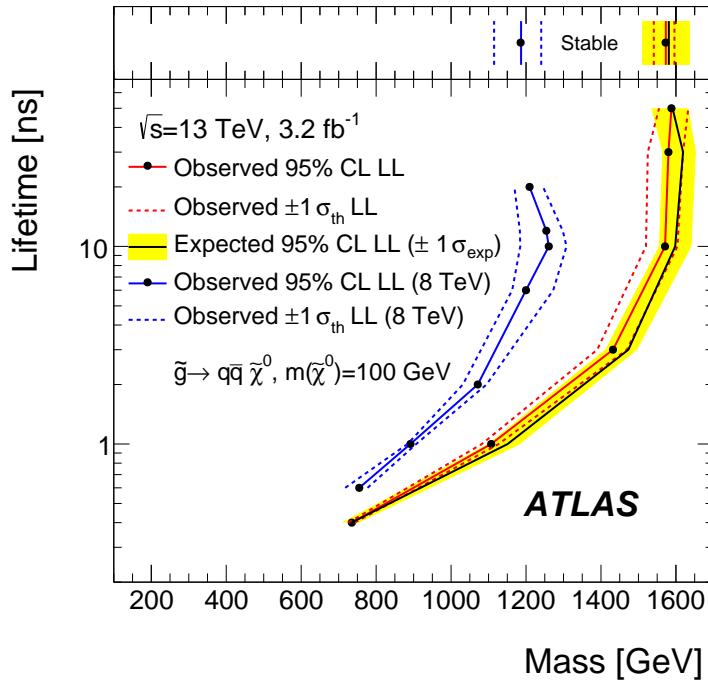


Figure 89: The excluded range of masses as a function of gluino lifetime. The expected lower limit (LL), with its experimental $\pm 1\sigma$ band, is given with respect to the nominal theoretical cross-section. The observed 95% LL obtained at $\sqrt{s} = 8 \text{ TeV}$ [70] is also shown for comparison.

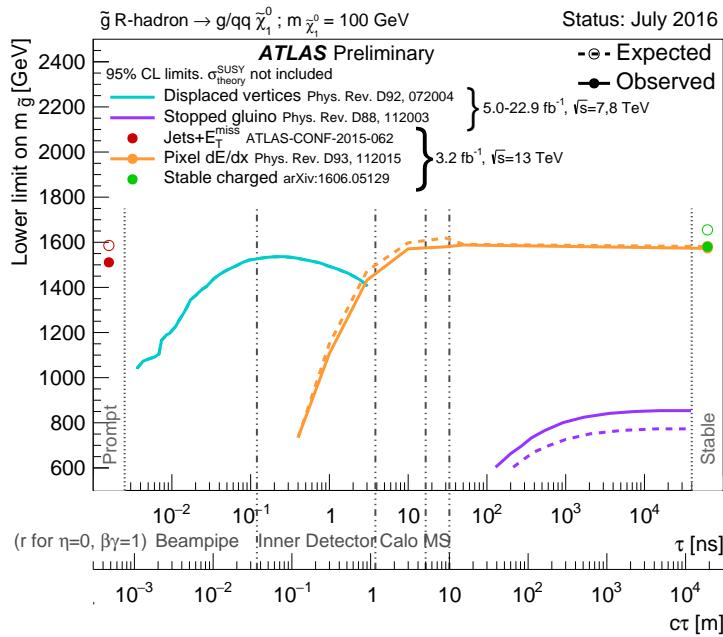


Figure 90: The constraints on the gluino mass as a function of lifetime for a split-supersymmetry model with the gluino R-Hadrons decaying into a gluon or light quarks and a neutralino with mass of 100 GeV. The solid lines indicate the observed limits, while the dashed lines indicate the expected limits. The area below the curves is excluded. The dots represent results for which the particle is assumed to be prompt or stable.

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PART VI

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CONCLUSIONS

3557

You can put some informational part preamble text here.

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3558

3559 SUMMARY AND OUTLOOK

3560 14.1 SUMMARY

3561 14.2 OUTLOOK

3562

PART VII

3563

APPENDIX

3564

A

3565

3566 INELASTIC CROSS SECTION

B

3567

3568 EXPANDED R-HADRON YIELDS AND LIMITS

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
1000	682	1387
1100	763	1478
1200	801	1606
1300	809	1841
1400	861	2011
1500	920	2032
1600	952	2173
1800	1017	2422

Table 18: The left and right extremum of the mass window for each generated mass point with a 50 ns lifetime.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
1000	689	1321
1100	746	1513
1200	788	1670
1300	860	1734
1400	833	1925
1500	852	2048
1600	833	2283
1700	946	2379
1800	869	2505

Table 19: The left and right extremum of the mass window for each generated mass point with a 30 ns lifetime.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
1000	655	1349
1100	734	1455
1200	712	1631
1300	792	1737
1400	717	1926
1500	815	2117
1600	824	2122
1700	900	2274
1800	919	2344

Table 20: The left and right extremum of the mass window for each generated mass point with a 10 ns lifetime.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
800	531	1065
900	576	1165
1000	610	1345
1100	635	1432
1200	663	1563
1300	620	1667
1400	742	1727
1500	761	1937
1600	573	2000
1700	621	2182

Table 21: The left and right extremum of the mass window used for each generated mass point with a lifetime of 3 ns.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
600	411	758
700	385	876
800	486	970
900	406	987
1000	408	1136
1100	555	1196
1200	516	1378

Table 22: The left and right extremum of the mass window used for each mass point with a lifetime of 1 ns.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
400	204	510
500	295	639
600	288	702
700	323	701
800	190	771
900	277	677
1000	249	688

Table 23: The left and right extremum of the mass window for each generated mass point with a lifetime of 0.4 ns.

$m(\tilde{g})$ [GeV]	Left Extremum [GeV]	Right Extremum [GeV]
800	627	1053
1000	726	1277
1200	857	1584
1400	924	1937
1600	993	2308
1800	1004	2554

Table 24: The left and right extremum of the mass window used for each generated stable mass point.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
1000	131.18 ± 6.35	1.803 ± 0.081	1.0 ± 1.0
1100	71.11 ± 3.35	1.409 ± 0.069	1.0 ± 1.0
1200	37.18 ± 1.75	1.310 ± 0.066	1.0 ± 1.0
1300	20.76 ± 0.95	1.431 ± 0.069	1.0 ± 1.0
1400	12.63 ± 0.57	1.273 ± 0.065	1.0 ± 1.0
1500	6.57 ± 0.29	1.115 ± 0.059	1.0 ± 1.0
1600	3.56 ± 0.16	1.041 ± 0.057	1.0 ± 1.0
1800	1.27 ± 0.05	0.918 ± 0.053	1.0 ± 1.0

Table 25: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 50 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
1000	144.65 ± 6.34	1.328 ± 0.063	2.0 ± 1.4
1100	75.28 ± 3.27	1.255 ± 0.060	2.0 ± 1.4
1200	40.51 ± 1.75	1.193 ± 0.058	2.0 ± 1.4
1300	20.91 ± 0.93	0.997 ± 0.051	2.0 ± 1.4
1400	11.97 ± 0.51	1.131 ± 0.056	2.0 ± 1.4
1500	6.81 ± 0.28	1.111 ± 0.055	2.0 ± 1.4
1600	4.19 ± 0.16	1.193 ± 0.058	2.0 ± 1.4
1700	2.42 ± 0.09	0.963 ± 0.050	2.0 ± 1.4
1800	1.46 ± 0.05	1.138 ± 0.056	3.0 ± 1.7

Table 26: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 30 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
1000	144.48 ± 5.14	1.499 ± 0.069	2.0 ± 1.4
1100	73.19 ± 2.61	1.260 ± 0.060	2.0 ± 1.4
1200	41.54 ± 1.41	1.456 ± 0.067	2.0 ± 1.4
1300	22.58 ± 0.77	1.201 ± 0.058	2.0 ± 1.4
1400	12.70 ± 0.42	1.558 ± 0.071	2.0 ± 1.4
1500	6.73 ± 0.24	1.237 ± 0.060	2.0 ± 1.4
1600	3.90 ± 0.13	1.201 ± 0.058	2.0 ± 1.4
1700	2.27 ± 0.07	1.027 ± 0.052	2.0 ± 1.4
1800	1.34 ± 0.04	1.019 ± 0.052	2.0 ± 1.4

Table 27: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 10 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
800	362.97 ± 14.68	1.841 ± 0.080	5.0 ± 2.2
900	169.20 ± 6.69	1.710 ± 0.076	3.0 ± 1.7
1000	84.78 ± 3.23	1.727 ± 0.076	2.0 ± 1.4
1100	40.06 ± 1.60	1.679 ± 0.075	2.0 ± 1.4
1200	20.06 ± 0.81	1.598 ± 0.072	2.0 ± 1.4
1300	10.76 ± 0.43	1.851 ± 0.080	2.0 ± 1.4
1400	5.52 ± 0.22	1.374 ± 0.064	2.0 ± 1.4
1500	3.16 ± 0.13	1.355 ± 0.064	2.0 ± 1.4
1600	2.13 ± 0.11	2.235 ± 0.093	3.0 ± 1.7
1700	1.10 ± 0.06	1.995 ± 0.085	2.0 ± 1.4

Table 28: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 3 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
600	431.80 ± 36.60	2.418 ± 0.099	3.0 ± 1.7
700	192.77 ± 15.28	3.267 ± 0.126	3.0 ± 1.7
800	69.63 ± 5.90	2.125 ± 0.089	3.0 ± 1.7
900	28.91 ± 2.59	3.114 ± 0.121	3.0 ± 1.7
1000	13.64 ± 1.22	3.359 ± 0.129	5.0 ± 2.2
1100	6.13 ± 0.57	1.879 ± 0.081	3.0 ± 1.7
1200	3.24 ± 0.30	2.387 ± 0.098	5.0 ± 2.2

Table 29: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of 1 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
400	181.71 ± 75.59	6.780 ± 0.238	4.0 ± 2.0
500	103.88 ± 30.05	4.310 ± 0.160	4.0 ± 2.0
600	28.34 ± 9.34	4.868 ± 0.177	4.0 ± 2.0
700	13.62 ± 4.00	3.908 ± 0.147	4.0 ± 2.0
800	2.75 ± 1.15	9.001 ± 0.308	8.0 ± 2.8
900	2.25 ± 0.71	5.045 ± 0.183	5.0 ± 2.2
1000	0.34 ± 0.19	6.026 ± 0.214	6.0 ± 2.4

Table 30: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated mass point with a lifetime of p4 ns.

$m(\tilde{g})$ [GeV]	Expected Signal	Expected Background	Observed Data
800	462.83 ± 14.86	1.764 ± 0.080	2.0 ± 1.4
1000	108.73 ± 3.38	1.458 ± 0.070	1.0 ± 1.0
1200	31.74 ± 0.95	1.137 ± 0.060	1.0 ± 1.0
1400	10.22 ± 0.29	1.058 ± 0.058	1.0 ± 1.0
1600	3.07 ± 0.09	0.947 ± 0.054	1.0 ± 1.0
1800	1.08 ± 0.05	0.940 ± 0.054	1.0 ± 1.0

Table 31: The expected number of signal events, the expected number of background events, and the observed number of events in data with their respective statistical errors within the respective mass window for each generated stable mass point

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3853 DECLARATION

3854 Put your declaration here.

3855 *Berkeley, CA, September 2016*

3856

Bradley Axen

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3858 COLOPHON

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Not sure that this is necessary.