Search for long-lived scenarios of dark matter and supersymmetry in final states with jets and missing energy in the CMS detector

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Abstract

The abstract.

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee. Say what I worked on.

Christian Laner

Acknowledgements

Of the many people who deserve thanks, some are particularly prominent, such as my supervisor…

Contents

Chapter 1.

Introduction

Fancy introduction to particle physics, DM, SUSY, LLPs.

Dark matter is a hypothetical form of matter which constitutes about 27% of the total energy content of the universe [1]. Its nature is unknown and its presence has so far only been inferred indirectly through its gravitational effects. Large efforts by the astrophysical and particle physics communities are being made on searches for the elusive dark matter.

Chapter 2 will describe the theoretical foundations and motivations for this search. Chapter 3 will do bla, etc.

Chapter 2.

Theory and motivation

Some introductory paragraph. We will begin by looking at the SM. Then bla and finally bla. I wouldnâĂŹt have so much SM math - brief intro to SM (each term in Lagrangian) and then move on to BSM (DM, SUSY, LL, simplified models, current limits). Theory and motivation (15%) (15 pages âĂŞ 2 pages per bullet below)

2.1. The standard model of particle physics

3 pages. Brief intro to SM - see Marco-Andrea two pages. If have time/space/botheredness, mention SM Lagrangian and SU3xSU2xU1. QED and QCD.

The Standard Model (SM) is a quantum field theory which describes the fundamental particles (quarks, leptons, gauge bosons and Higgs boson) and their interactions (electromagnetic, weak nuclear and strong nuclear). Fermions (half-integer spin, matter) and bosons (integer spin, force carriers).

SM particles summarised in Table. We will describe in the following subsections. Table summarising all SM particles with their mass and charge (Marco-Andrea, Adam, Nick).

2.1.1. Fundamental fermions

Quarks (6) and leptons (6), generations, charges, interactions.

2.1.2. Fundamental bosons

Quanta of gauge fields. Mediators of em, weak, strong interactions. Describe each interaction in turn. Gravity not included in SM. Ranges. Which particles feel each force.

Electroweak symmetry breaking. Higgs boson (scalar, spin 0). Discovered in 2012 (final piece of SM).

2.2. Beyond the standard model

1.5 pages. Problems with the standard model. Tapper slides. MA and AE.

The SM has been well tested experimentally and has been found to describe very accurately a wide range of physical phenomena. However, it does not incorporate the gravitational force, account for neutrino oscillations or explain the matter-antimatter asymmetry in the universe. There are also theoretical concerns about the lack of unification of forces at the Grand Unified Theory (GUT) scale as well as the hierarchy problem, whereby higher order loop corrections to the mass of the Higgs boson lead to a divergence in its mass unless a large amount of 'un-natural' fine tuning is introduced. Finally, and most relevant to this discussion, no particle in the SM is a viable candidate for dark matter. The SM is therefore thought to be an effective theory which is only valid at low energies and a more complete model at larger energy scales must exist. Gravitational force, Planck scale

Neutrino masses

Dark matter. Makes up large proportion of universe. Lots of evidence. No particle in SM is DM candidate. Discussed in more detail in Sec. 2.3. Or if chapter ends up being too long summarise and merge that section into here (maybe make a subsection)

Higgs mass/hierarchy problem

Gauge coupling unification

Matter-antimatter asymmetry

2.3. Dark matter

1-1.5 pages. More details on DM (evidence, WIMP miracle, cosmology) (borrow from my reports)

Evidence – see my report.

The most favoured DM candidate is a non-baryonic, weakly interacting massive particle (WIMP) which is stable and electrically neutral [8]. WIMPs fall into the category of cold dark matter, meaning that they were non-relativistic at the time of freeze-out and hence lead to the large scale structures observed in the universe today. Their weak interaction cross section also results in the correct relic abundance required to explain the present dark matter content of the universe (the “WIMP miracle”).

Searching for DM (report): DD, ID, collider (complimentary).

2.4. Supersymmetry

1.5-2 pages. SUSY theory (borrow from RA1/kostas theses and RA1 papers). MA and AE.

Poincare group, additional symmetry between bosons and fermions. Broken symmetry. Solves hierarchy problem, unification, DM.

MSSM is simplest version of SUSY (minimal particles). 105 parameters. Table of MSSM particles (MA). R-parity. Relationship with DM âĂŞ LSP/neutralino is DM candidate. stop naturalness?

A theoretically well motivated extension to the Standard Model is supersymmetry (SUSY) [6, 7], which introduces a new spacetime symmetry between fermions and bosons. Essentially, for every fundamental particle there exists a supersymmetric partner with spin differing by 12. Fermions and bosons enter the mass correction calculation of the Higgs boson with opposite signs, so if the mass difference between SM particles and their superpartners is not too large (ab 1 TeV), an incomplete cancellation between the two leads to the naturally small Higgs boson mass. Thus, supersymmetry can provide a solution to the hierarchy problem of the Standard Model. Furthermore, the strong, weak and electromagnetic couplings are found to converge at the GUT scale, thus providing a solution to the unification problem as well. Finally, most supersymmetric theories predict a particle candidate for dark matter, as explained in the next section.

R-parity is a quantity defined such that Standard Model and supersymmetric particles are assigned PR = +1 and PR = -1, respectively. If R-parity is conserved, the lightest supersymmetric particle (LSP) cannot decay and thus is stable. If it is neutral, this LSP satisfies the WIMP criteria. The LSP is usually assumed to be the neutralino, a superposition of the superpartners of the Higgs boson and gauge bosons. Other dark matter candidates include the axion and the lightest Kaluza-Klein particle (LKP) arising from solutions to the strong CP problem and theories of extra spatial dimensions, respectively.

2.5. Exotic long-lived particles

1 page.

Many BSM theories predict long-lived particles. There are examples in the SM (give examples). They travel some distance before decaying. Could be within or outside the detector. Decay length follows an exponential distribution (give pdf). Width is inverse of lifetime.

Briefly describe MSSM (NLSP), GMSB, hidden valleys, RPV SUSY.

2.5.1. Split supersymmetry

LLP thesis 4.2.4 and paper. SUSY borken near unification scale. Squarks decoupled to very high scale. Gluinos are long-lived. Coloured. Must decay via highly virtual squarks. Lifetime larger than hadronisation scale (ps?). Gluinos form R-hadrons (so-called because of non-trivial R-parity) (can be mesons, baryons or gluinoballs). Can change charge through nuclear interactions.

2.6. Simplified models

1.5 pages. Motivation for simplified models (see 3 reasons in OB LLDM, too many parameters in MSSM. CMSSM not model-independent).

These are the simplified models that are used in this thesis to interpret the results in this thesis.

The long-lived particle's lifetime is a parameter of the model. Consider life distances (lifetimes) from ctau = 1 um (tau = x ns) to 100 m (tau = y ns), plus prompt and stable.

2.6.1. Simplified models of supersymmetry

General SUSY signature at LHC: Pair production, strong interaction dominant at LHC (squarks and gluinos), decay to SM particles and LSP, large mass hence large MET (briefly describe MET - momentum imbalance due to LSP not being detected).

Only one decay considered, other particles at much higher scale.

T1qqqq and T1qqqqLL (split SUSY): here consider (long-lived) gluino pair production, each decays to two quarks and an LSP. As gluino lifetime goes to 0 recover prompt model. Interaction of R-hadron with detector material not simulated (won't have an effect on our analysis/not the purpose of our analysis – see paper). If necessary, describe cloud model, and percentages of gluinoball etc (and/or describe in simulation section).

Feynman diagram of T1qqqqLL (a) and dDM (need to make it myself?) (b) together.

2.6.2. Simplified models of dark matter

Buch. DMF, DMSimp?, dDM vector/axial

Run 2 DM searches interpreted using simplified "mono-X" models with V/A/S/P s-channel mediator pair decaying to Dirac fermion DM, with 4 parameters (two masses and couplings). (Lagrangians probably not necessary)

Extend these models to incorporate long-lived neutral particles. Kevin/me: instead of mediator decaying to stable DM, it decays intermediate chi2 that is long-lived and then chi2 decays to SM particles and stable DM. As chi2 lifetime goes to infinity recover stable model.

EFT description of chi2 decay. Lambda parameter can be swapped for lifetime parameter.

In this thesis consider model with vector mediator, couplings X and Y, and various masses and lifetimes.

2.7. Status of searches for dark matter, supersymmetry and long-lived particles

Current DM/SUSY limits (CMS/ATLAS and briefly compare to DD, mention X GeV limits on mediator/DM/gluino/LSP), very constrained hence look for LL signatures, we think weâĂŹve excluded X GeV gluinos but thatâĂŹs not true if theyâĂŹre LL. Mono-X but monojet strongest constraints.

Current LL limits (CMS/ATLAS). Many possible types of striking signatures – displaced leptons/photons/jets, disappearing/kinked tracks, stopped particles, etc. Not many with MET, first LL interpretation of prompt analysis (as long as decays within tracker can still reconstruct with standard algorithms, plus ISR), briefly mention complementarity (sensitive to whole range of lifetime, sub-cm and all mass splittings).

Chapter 3.

Experimental setup

20-25 pages. Intro to chapter.

3.1. The Large Hadron Collider

CERN and LHC. Franco-Swiss border. 26 km. x km underground. Largest and most powerful. Collider physics. Luminosity (instantaneous/integrated) and cross section formulas (Marco-Andrea/Pesaresi). Used to search for new physics and discover Higgs boson. Need very high energy to produce high mass particles and search for new physics (cf xs vs com). (Compare to ep collider and fixed target). Proton-proton (and ion) collisions. Bunch spacing, number of bunches, number of protons per bunch (Marco-Andrea table). ATLAS, CMS, LHCb, ALICE. Accelerator complex: hydrogen, LINAC, PS, SPS, etc (show diagram). Centre of mass energy. Pileup (formula/estimate using inelastic xs?).

Diagram of accelerator complex.

History of Run1, shutdown, Run 2. Amount of data delivered.

3.2. The Compact Muon Solenoid

One of two multipurpose detectors. Used to search for new physics and discover Higgs boson.

Hermetic coverage. Overview of subdetectors. Magnet strength.

Diagram.

Coordinate system. Pseudorapidity.

3.2.1. Tracker

How tracker works, ie electron-hole pairs (see Adam and MSci report). High radiation environment. Little material.

Pixel tracker.

Silicon strip tracker.

TOB, TEC, etc. Their positions/extents.

Diagram of layout.

Momentum resolution, tracking efficiency, spatial resolution.

3.2.2. Electromagnetic calorimeter

Designed to detect electrons and photons. Lead tungstate crystals.

EB. EE. Preshower.

Diagram of layout.

How ECAL works (ECAL shower, bremmstrahlung and pair production - see Adam and APP MSci course.)

Resolution formula (a+b+c).

3.2.3. Hadronic calorimeter

Designed to detect hadrons/jets. Brass and scintillating plastic. Photodiodes. HF. Fibres.

HB. HE. HO. HF

Diagram of layout.

How HCAL works (hadronic showers produce scintillation light - see Adam and APP MSci course.)

Resolution formula.

3.2.4. Muon system

Adam: As muons are heavier than electrons, they are minimally ionising and lose little energy through bremsstrahlung. They therefore mostly pass through the ECAL and HCAL. As muons are a key component of many electroweak decays, CMS has a dedicated muon system interleaved with the iron return yoke surrounding the solenoid.

DT (MB), CSC (ME), RPC.

Diagram of layout.

Momentum resolution 1%.

3.2.5. Magnet

Just one or two short paragraphs. See Marco-Andrea, Citron, Baber.

3.2.6. Trigger and data acquisition

40 MHz.

L1 trigger.

HLT.

Computing tiers.

L1 trigger upgrade and my service work?

Not sure yet. Look at Adam, Matt, Jad.

3.3. Event reconstruction

Intro: need to put together the things observed in the detector to reconstruct the objects.

Object reconstruction/identification (requires revision). Tag and probe. vertexing/tracking, btagging, PF, antikt. PU subtraction, isolation, cross-cleaning. MC corrections (JECs, PU, btagging, lepton ID, etc.).

Mention objects/working points used in analysis as you go along. Maybe summary table like Matt. Actually maybe include this in analysis chapter (see Adam).

3.3.1. Tracks and vertices

Combinatorial track finder (CTF), Kalman filter.

Primary vertex. PU vertices. Secondary/displaced vertices (b quarks) found in subsequent levels of reconstruction.

Efficiencies.

Isolated tracks? (when talking about analysis objects).

3.3.2. Electrons and photons

3.3.3. Muons

Global and tracker muons.

Define relative and mini-isolation. Define pileup subtraction - effective rho area, delta beta? (have a dedicate section like adam)

rho*Aeff, where rho is the median of the transverse energy density per unit area in the event [26] and Aeff is the area of the isolation region weighted by a factor that takes into account the dependence of the pileup transverse energy density on pseudorapidity. The effective areas have been determined in gamma + jet events.

3.3.4. Particle flow algorithm

Need to decide where to put this. Not clear on the connection between object reconstruction and particle flow. Resources: Particle Flow paper, Particle Flow summary.

The tracks are extrapolated through the calorimeters, if they fall within the boundaries of one or several clusters, the clusters are associated to the track. The set of track and cluster(s) constitute a charged hadron and the building bricks are not considered anymore in the rest of the algorithm. The muons are identified beforehand so that their track does not give rise to a charged hadron. The electrons are more difficult to deal with. Indeed, due to the frequent Bremsstrahlung photon emission, a specific track reconstruction [3] is needed as well as a dedicated treatment to properly attach the photon clusters to the electron and avoid energy double counting. Once all the tracks are treated, the remaining clusters result in photons in case of the electromagnetic calorimeter (ECAL) and neutral hadrons in the hadron calorimeter (HCAL). Once all the deposits

3.3.5. Jets

Briefly describe what a jet is (hadronisation, tight cone of particles [MA]). antikt algorithm. Infrared and collinear safe. Inputs are PF candidates. Pileup subtraction (not just here but for all objects).

Correcting the energy of jets

b-tagging

Identification of jets originating from bottom quarks.

3.3.6. Energy sums and missing energy

Define HT, MHT and MET. At some point (maybe near the beginning) explain why we use the transverse plane (initial momentum is zero, whereas it isn't in the longitudinal plane).

Neutrinos do not interact in particle detectors, and therefore escape undetected. Their presence can be inferred by the momentum imbalance of the visible particles in an event. (this should be mentioned in overview of analysis in intro chapter).

Type-1 corrections.

3.4. Data sets

See Nick. MA has this in the analysis chapter. We use data collected by the CMS during certain runs, plus simulated data of background and signal processes.

3.4.1. Collected data

35.9 fb-1. 2016. (This would be mentioned in the intro anyway). Show lumi delivered/collected vs time. Triggers/Primary Datasets. SR and Muon CRs.

Maybe keep this chapter general, just have section on MC simulation, and mention which specific data and MC samples elsewhere.

3.4.2. Monte Carlo simulation

Description of madgraph, pythia, GEANT.

MC simulation data sets. (Grid of masses and ctau, couplings used) - no need to specify grid, couplings mentioned in simplified models section. See paper.

Describe weights and xs/lumi normalisation?

Chapter 4.

Search strategy

This chapter describes the analysis strategy of a search for physics beyond the standard model in proton-proton collisions at a centre of mass energy of 13 TeV. The search is performed in final states containing missing transverse momentum and at least one jet.

The search is designed to have sensitivity to a wide range of new physics models that involve the production of a weakly interacting particle (WIMP), such as dark matter or the lightest supersymmetric particle. The search has been optimised for signatures in which the WIMP is produced from prompt decays at the primary collision vertex. However, as will be discussed in Chap. 5, the search is also sensitive to signatures in which the WIMP is produced at a displaced vertex following the decay of a long-lived particle.

In the proton-proton collisions, the net momentum of the colliding partons in the plane transverse to the beam direction is effectively zero, whereas the longitudinal momentum is not necessarily so. In order to conserve momentum, the outgoing particles produced in the collision must therefore have an overall transverse momentum of zero. As WIMPs do not interact with the detector material, the measured net transverse momentum in the event will be non-zero. This non-zero "missing transverse momentum" is the key signature of such particles. In addition, at a hadron collider such as the LHC, the dominant production is via the strong interaction, and hence jets are readily produced either in association with the WIMP, or as initial or final state radiation (ISR, FSR). For these two reasons the search is performed in final states containing jets and missing energy. The requirement of at least one jet is needed for the missing momentum to be defined and for the event to be triggered. A hadronic final state is ensured by vetoing events containing leptons or photons.

A missing energy signature is not unique to WIMPs, however, and is also present in certain standard model processes. Neutrinos (produced in the decays of Z and W bosons, for example) are also weakly interacting and undetectable at CMS. It is also possible for particles to be over or under-measured, thereby introducing a "fake" momentum imbalance. This type of background arising from energy mismeasurements is suppressed as much as possible (to lt1% of the total background) using the variables described in Sec. X. The remaining standard model background (that involving neutrinos) must be estimated as precisely as possible, using a combination of theory calculations, simulation, and calibrations in data. This is described in Sec. X. One can then look for a statistically significant excess in the data above the expected amount of standard model background that would be an indication of the observation of physics beyond the standard model. The statistical analysis is covered in Chap. 5.

In order to maximise the sensitivity to a wide range of SUSY and DM scenarios, all of which may manifest themselves in topologically slightly different ways in the detector, the candidate signal events (which form part of the *signal region*) are categorised according to four variables (the total jet energy, the missing jet energy, the number of jets, and the number of b-tagged jets) as detailed in Sec. X. Two *control regions* are defined, labelled μ + jets and $\mu\mu$ + jets, that are analogous to the signal region but are enriched by selection of muons in the W and Z background processes, respectively, and are employed in the background estimations as described in Sec. X.

Similar searches for supersymmetry have been performed in Runs 1 and 2 of the LHC, at centre of mass energies of 8 and 13 TeV, and for a range of integrated luminosities. These can be found in Refs. [1,2,3,4,5]. These searches are used as a basis for the analysis described in this thesis. A series of developments and optimisations have been made in order to adapt the analysis for the higher centre of mass energy and larger amount of data collected. In addition, the interpretations in dark matter and long-lived particles described in Chap. X are a novelty to this search.

Dataset used is 36.9 pm x fb-1 and corresponds to the p-p run of 2016.

4.1. Physics objects

This section describes the definitions of the various physics objects employed in the search. Each object is reconstructed using the algorithms described in Chap. 3, and each algorithm has parameters that can be tuned in order to provide a desired balance between identification efficiency and fake rate. Jets and energy sums form a key component in the search and are required in both the signal and control regions. Electrons, photons and isolated tracks are vetoed in the signal region. Muons are vetoed in the signal region and are required in the control regions.

Jets

Jets are constructed by clustering Particle Flow candidates using the anti-k_T algorithm with a distance parameter of 0.4. Charged PF candidates that originate from pileup vertices are not included. The four-momentum of a jet is defined to be the vector sum of the four-momenta of all clustered constituents. Corrections to the energies of the resulting jets are applied as described in Sec. Detector.

Several loose requirements on the jet constituents are imposed in order to avoid spurious jets originating from noise in the calorimeters. These requirements include a minimum number of charged constituents and a minimum fraction of the jet energy attributed to charged hadrons, as well as an upper bound on neutral hadron, photon, and electron contributions. The requirements are summarised in Tab. 4.1.

Table 4.1.: Table: jet ID requirements (have 3 columns for each eta region, merge columns if applies to more than one, dash if not applied). Do similar ID table for other objects? Ideally not (I haven't worked on it), but yes if you need to fill up space.

Variable	cut	notes
$-3.0 < \eta_{\text{jet}} < 3.0$		
Neutral Hadron Fraction	< 0.99	-
Neutral Electromagnetic Fraction	< 0.99	-
Number of constituents	> 1	-
Charged Hadron Fraction	> 0	only for $\lvert\eta_{\text{jet}}\rvert < 2.4$
Charged Multiplicity	> 0	only for $\lvert\eta_{\text{jet}}\rvert < 2.4$
Charged Electromagnetic Fraction	< 0.99	only for $\lvert\eta_{\text{jet}}\rvert < 2.4$
$\lvert\eta_{\text{jet}}\rvert > 3.0$		
Neutral Electromagnetic Fraction	< 0.90	-
Number of Neutral Particles	> 10	-

Jets in the event are assigned a probability of having originated from a bottom quark by the CSV algorithm described in Sec. X. A jet in the analysis is considered to be b-tagged if its probability is larger than 0.8484. This value results in a b-tagging efficiency of $\sim$60%, as well as a mis-tagging rate of $\sim$10% for charm quarks and $\sim$1% for up, down, strange, and gluon quarks.

The jets employed in the analysis have pt 40 and eta 2.4 to select jets originating from the hard scatter, avoid pileup jets. Mention pt and eta cuts of the other objects here or in event selection?

Muons

The muons considered for event vetoing in the signal region are required to be reconstructed as either global or tracker muons. The efficiency for this is $\sim$ 98%. The contribution to the muon energy from pileup tracks is subtracted using the effective area correction. A mini-isolation requirement of $I^{\text{rel}}_{\text{mini}} < 0.2$ is imposed that aids in identifying muons from the decays of boosted top quarks.

In the control regions, global muons are selected. Additional quality criteria are required in order to enhance the purity of prompt W and Z boson decays. These include a minimum goodness of fit of the corresponding track, and a minimum number of hits in the muon chambers – this helps to suppress fake muons resulting from *hadron punch-through*, that is high energy hadron shower remnants that penetrate the calorimeters and reach the muon chambers. A minimum number of hits in the tracker is required to provide an accurate measurement of the momentum. The muon track is also required to be compatible with having originated from the primary vertex – this suppresses the potential background from cosmic muons and muons produced at a pileup vertex. The effective area pileup correction is applied. The relative isolation quantity is required to be $I^{\text{rel}} < 0.15$. The mini-isolation algorithm is not employed in the control regions because of QCD and trigger efficiency???

pt 10, eta 2.5 in SR veto. pt 30, eta 2.1 in CR selection.

Photons

Events containing photons are vetoed in both the signal and control regions. The isolation of a photon is measured with respect to charged hadrons, neutral hadrons, and other photons within a $\Delta\eta - \Delta\phi$ cone of size 0.3. These three isolation variables are required to be below certain thresholds. An upper bound is also imposed on the ratio of the photon's energy deposited in the HCAL and the ECAL, which can be non-zero in the case of leakage of the electromagnetic shower. The shape of the shower as measured by the distribution of energy deposits in the ECAL crystals is used as a further discriminator. **What is sigmaietaieta!!** The photon identification efficiency following these requirements is $\sim 71\%$. The effects of pileup are mitigated using the effective area corrections.

pt 25 eta 2.5

Electrons

The electrons considered for vetoing in the signal region are identified according to requirements on the shape of the electromagnetic shower, the ratio of energy deposits in the HCAL and ECAL, the number of hits in the tracker, and the track's impact parameter. These requirements provide an identification efficiency of $\sim 90\%$, and are effective at avoiding spurious electrons (such as jets misidentified as electrons) and electrons produced from photon conversions. Effective area pileup corrections and a mini-isolation requirement of $I^{\mathrm{rel}}_{\mathrm{mini}} < 0.1$ are applied.

pt 10 eta 2.5

Isolated tracks

Events containing isolated tracks are vetoed in the signal and control regions as discussed in Sec. EventSelectionSITV. An isolated track is defined to be a charged PF candidate that originates from the primary vertex and has a relative isolation (computed with respect to other charged PF candidates within a cone of size $\Delta R = 0.3$) of $I^{\mathrm{rel}} < 0.1$.

pt 10, eta? Yes and then in event selection say "veto muons" where muons are defined as in this section.

Energy sums

The H_{T} and $\not{H}_{\mathrm{T}}$ variables are defined, respectively, as the scalar sum and the magnitude of the negative vector sum of the transverse energy of all jets in the event satisfying $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.4$.

The missing transverse energy $\not{E}_{\mathrm{T}}$ is computed as the magnitude of the negative vector sum of the transverse energy/momentum of all PF candidates in the event. The jet energy corrections described in Sec.X are progagated as a correction to the $\not{E}_{\mathrm{T}}$ value [FIXME]. This variable is used in the definition of the M_{T} and $\not{H}_{\mathrm{T}}/\not{E}_{\mathrm{T}}$ variables as described in Sec.EventSelection.

4.2. Baseline selection

This section describes a set of baseline selections and filters that are used to ensure a final state with significant hadronic activity and genuine missing energy that is typical of the SUSY and DM processes being searched for.

Events containing muons or electrons are vetoed. This mainly suppresses the W+jets background process in which the W boson decays semileptonically, resulting in missing energy and a lepton in the final state. In case the lepton is not identified as such but its track is reconstructed, events are vetoed if they contain an isolated track. This veto also helps to reject single prong decays of tau leptons. As a final requirement to ensure an all-jet final state, events containing photons are also vetoed.

At least one jet in the event is required to have a transverse momentum $p_{\mathrm{T}} >$ 100 GeV. The jet energy sums must satisfy $H_{\mathrm{T}} > 200$ GeV and $\not{H}_{\mathrm{T}} > 200$. These two thresholds are chosen to be as low as possible in order to maximise the acceptance of the search across a wide range of the SUSY and DM mass parameter space, while simultaneously maintaining a reasonable trigger rate and efficiency. The trigger strategy will be discussed further in Sec. 4.7.

Primary vertex selection? MC and AE have it in MET filter section. See vertex skimmer in heppy - "good vertex".

Missing energy is not only caused by undetectable or misreconstructed particles produced in the proton-proton collisions. Spurious $\not{E}_{\mathrm{T}}$ can also be induced by effects related to detector malfunctions and beam dynamics. These effects include spurious energy in the HCAL due to electronics noise and particle interactions with the instrumentation, missed energy in the ECAL due to dead cells, anomalous high amplitude pulses in certain ECAL endcap supercrystals, and beam halo particles. Beam halo refers to the showers of particles, including pions, neutrons and muons, that are produced when beam protons collide with residual gas particles in the LHC vacuum chambers or with the beam collimators. These beam halo particles can deposit energy in the calorimeters and CSCs of the muon system along lines parallel to the beam direction. Events affected by these spurious $\not{E}_{\mathrm{T}}$ sources are identified and vetoed using dedicated algorithms as described in Ref. [**?**]. These algorithms take advantage of various features related to geometrical patterns, pulse shapes and timing information. The impact of these filters on signal acceptance is negligible.

The beam halo filter, however, only targets halo muons, and is ineffective against calorimeter deposits from halo hadrons. These types of events are straightforwardly recognised, as shown in Fig. 4.1. The highest p_{T} jet in the event usually appears at ϕ values of 0 and π as this corresponds to the plane of the LHC ring in which the proton beams are steered, and will have a contribution from charged hadrons close to zero because of the lack of tracker hits. To suppress these beam halo events, events are rejected if the leading jet has a charged hadron energy fraction $f_{\mathrm{CH}} < 0.1$.

As a further safeguard against noise and misreconstruction effects, events that contain a jet that fails the identification requirements outlined in Sec. 4.1 are not considered.

Finally within the set of baseline selections, events are vetoed if there are any jets with pseudorapidity direction $|\eta| > 2.4$. This corresponds to the extent of the tracker and hence ensures well reconstructed jets and a better resolution of the energy sums. This requirement also has the added benefit of rejecting a larger proportion of background, particularly QCD processes, compared to signal processes, which tend to produce more central jets.

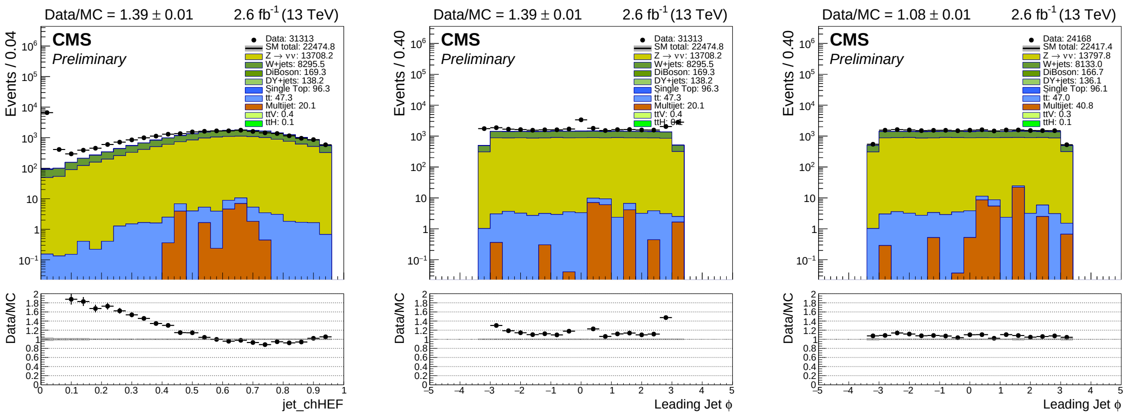

Figure 4.1.: The leading jet's charged hadron energy fraction (Left) and ϕ direction before (Centre) and after (Right) applying a requirement of $f_{\mathrm{CH}} > 0.1$. The large excess in data at f_{CH} values close to zero and $\phi = 0$ and π is consistent with beam halo effects, and is effectively suppressed by the f_{CH} requirement.

4.3. Standard model backgrounds

2-3 pages

After these requirements, still left with significant SM backgrounds from electroweak and QCD processes.

4.3.1. Electroweak processes

Dominant are Z and W.

Z is irreducible. Neutrinos.

W/ttbar is when lepton lost - not reconstructed or out of acceptance.

Plus minor/residual backgrounds - single top, diboson, Higgs, etc.

4.3.2. QCD processes

Different QCD mechanisms (bullet list plus my studies) - detector effects, fake MET, mismeasurement, below threshold, heavy flavour.

4.4. QCD background rejection

2-3 pages.

Various ways of killing it: alphat, bdphi, mht/met. Propaganda plots.

4.4.1. alphaT

4.4.2. bdphi

4.4.3. missing energy ratio MHT/MET

4.5. Event selection

2-3 pages

Now define the cuts to suppress the QCD, the definition of the signal region where we expect the signal, and the definition of the control regions that are used to estimate the SM backgrounds.

Big summary table of all selections/regions/objects (see paper).

define mono sym asym somewhere.

4.5.1. Signal region

alphat (summarise HT-dependent cuts in table), bdphi, mht/met cuts. Anything else?

4.5.2. Control regions

Enriched in background they want to estimate. No overlap with SR events. Ignored lepton in sums to mimic/proxy the SR. Exactly the same cuts as SR except for inversion of muon veto to selection, plus some other differences described in the following.

Background estimation described in Sec X (EWK) and Y (QCD).

mujets

Exactly one muon that passes requirements mentioned before. DeltaR. MT. No alphat or bdphi.

mumujets

Exactly two muons opposite charge. DeltaR. Mll.

QCD sidebands

bdphi and MHT/MET sidebands. Enriched in QCD.

4.6. Event categorisation

2 pages.

See AN.

Signal region binning in njet, nb, ht, mht. Jet pt (mono sym asym).

Same bins in single mu as SR. Slightly different in double mu - only two nb bins. Explain why? Higher stats. Show nb extrapolation validation (AN) or just summarise briefly in couple of sentences (similar to MHT validation).

Table of bins.

4.7. Triggers

5 pages.

See Mark. List of SR and CR triggers. Efficiencies.

4.8. Simulation samples

0.5 pages. Maybe put here the "datasets" section of data and MC samples (see Matt).

4.9. Corrections to simulation

3-5 pages

Simulation modelling is not perfect. Need to correct it using scale factors by comparing data and MC. These corrections introduce systematic uncertainties in the background estimation, that will be described later in Sec X.

4.9.1. Pileup

4.9.2. b-tagging efficiency

Reweighting formula.

4.9.3. Trigger efficiency

4.9.4. Lepton and photon reconstruction, identification, isolation and triggering efficiency

Tag and probe.

4.9.5. Top quark pT

4.9.6. Cross-sections

Sideband corrections. Summarise in table.

4.9.7. Plus more?

NLO, pdf/scale Signal (maybe later): nISR, gen met

4.10. b-tag formula method

1-2 pages.

See Burton. AN Sec 4.4. Relevant but be brief. How much improves limits? Just refer to T1bbbb as T1qqqqLL 1 mm is very similar.

Purpose: reduce stat uncertainty of simulation in higher nb bins (where signal can lie).

Method: show the formula and explain it.

Summarise in table/plot or one-two sentences how much the stat unc is reduced. Maybe also how much the limits are improved (Lucien did this).

Formula systematics.

4.11. Estimation of electroweak background processes

Predict normalisation using CRs (data-driven to reduce reliance on MC). Use MHT templates from MC.

4.11.1. nj, nb, ht dimensions

1 page

Transfer factor method.

4.11.2. MHT dimension

2 pages

Take templates because don't want to bin CRs too finely (lose statistical power - curse of dimensionality).

Validation: Check data MC ratio is flat in CRs. Assign syst as described later in Sec X.

4.12. Estimation of QCD background processes

2 pages

Method.

Validation.

Plot of estimated yields per bin.

4.13. Systematic uncertainties on background estimation

These are explained below and also summarised, with representative magnitudes, in the big summary table of systs.

4.13.1. MC-based

3-4 pages (maybe 2 pages just of plots).

Known theoretical and experimental uncertainties. Largely cancel out in the TF ratio.

Refer to Section of corrections to simulation. These are the associated uncertainties.

Pileup, JEC, b-tagging, lepton, photon, trigger, top pt, W/tt, NLO, ttbar nISR.

Example 2D plots of variations in the bins.

4.13.2. Closure tests

2-3 pages.

Probe additional sources of systematics.

Define method.

Go through each test (there's not many now) and describe what it's probing: extrapolation in alphat and bdphi, W polarisation, SITV.

Closure plots.

4.13.3. MHT templates

2 pages. See Matt and old ANs.

Derivation of uncertainties. Vs njet and ht.

Plot illustrating size of uncertainty in each bin.

Chapter 5.

Results and interpretation

All signal model studies and systematics go first.

First LL interpretation of prompt analysis. say why this is interesting/important (benchmark for future LL searches, see where sensitivity to LL currently lies - surprisingly already quite sensitive)

5.1. Systematic uncertainties on signal model simulation

1-2 pages.

Similar to backgrounds. Luminosity, trigger, MC stat, pileup, b-tagging, JEC, ISR, genmet.

Additional systs for LL. b-tagging, odd jet (chf, jet id), trigger.

Summarise in table or words typical size of systs for relevant models.

5.2. Statistical model

2-3 pages.

Model the bins and number of events and uncertainties and correlations between bins as a likelihood function (probability of observing the observed data given some model parameters). This will then be fitted/maximised/used to make the background estimations and perform statistical tests to determine limits.

Maybe describe how minimisation is done (gradient descent bla migrad bla).

5.3. Results under background-only hypothesis

3-5 pages.

CR fit ("predictions") and full fit (background-only).

Mountain range plots (2 pages).

Distributions of pulls.

Pulls on nuisances.

No excess observed hence set limits.

5.4. title

2-3 pages. Hypothesis testing, setting limits, asymptotic CLs See Nick.

5.5. Limits

Exclusion

Acceptance times efficiency. Most sensitive bins. Some LL studies - in results section?

DMLL: my presentations, raffaele, oliver exo workshop (future prospects). Take home message: (see presentation - lack of coverage for models with compressed (N2,N1) and small ctau). Prompt search retains some sensitivity for long (short) gluino (DM) lifetimes (and is the most sensitive sub-cm and lifetimes beyond the detector, hence continue with prompt search in future), although clearly could be improved with a dedicated search/tagger as shown by the b-tag effects. Also compressed DM can be much improved by removing dphi cut.

Chapter 6.

Conclusion

This is the conclusion.

Appendix A.

Transfer factors

Appendixes (or should that be "appendices"?) make you look really clever, 'cos it's like you had more clever stuff to say than could be fitted into the main bit of your thesis. Yeah. So everyone should have at least three of them...

A.1. Like, duh

Padding? What do you mean?

A.2. $y = \alpha x^2$

See, maths in titles automatically goes bold where it should (and check the table of contents: it *isn't* bold there!) Check the source: nothing needs to be specified to make this work. Thanks to Donald Arsenau for the teeny hack that makes this work.

Appendix B.

Systematics

Hi.

Bibliography

[1] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).

[2] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. **D2**, 1285 (1970).

[3] S. Willenbrock, (2004), hep-ph/0410370.

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