
**Searching for diboson resonances in the
all-hadronic final state
and
a Lorentz invariance based deep neural network for
W-tagging**

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von
Thea Klaeboe Arrestad
aus
Norwegen

Promotionskommission:
Prof. Dr. Benjamin Kilminster
Prof. Dr. Florencia Canelli
Prof. Dr. Jesse Thaler
Dr. Andreas Hinzmann

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Abstract

Zusammenfassung

Die vorliegende Doktorarbeit stellt blabla.....

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Introduction

A short explanation of NP decaying to dibosons (Vprime, Gravition), jets in the boosted regime (substructure), the search strategy of 2015+2016 (1D) and 2017 (3D). Touch on triboson signatures to emphasise 3D

CHAPTER 1

The Standard Model and Beyond

1.1 The Standard Model Lagrangian

1.1.1 Particles and fields

1.1.2 Electroweak theory

1.1.3 The Higgs Mechanism

1.1.4 Quantum Chromodynamics

1.2 Beyond Standard Model Physics

1.2.1 The hierarchy problem and the gravitational force

1.2.2 Theories of New Physics

Warped extra dimensions

Compositeness

1.2.3 Heavy Vector Triplet formalism

CHAPTER 2

Experimental setup

2.1 The Large Hadron Collider

In March 1984, the European Organization for Nuclear Research (CERN) and the European Committee for Future Accelerators (ECFA) held a workshop in Lausanne entitled "Large Hadron Collider in the LEP Tunnel". This is history's first written mention of the Large Hadron Collider (LHC) and the topic under discussion was exactly how and where to build a new type of high-energy collider, capable of bringing hadrons to collide rather than leptons. The LHC would be housed in a tunnel which, at the time, was under excavation to host the Large Electron-Positron Collider (LEP) designed to collide leptons with center-of-mass energies up to around 200 GeV. LEP was a circular collider with a circumference of 27 km and the tunnel hosting it was located roughly 100 meters underground on the border between France and Switzerland, at the outskirts of Geneva. The justification for building a machine like the LHC, was that once LEP got to maximum reach, a new and more powerful collider would be needed in its place in order to probe higher energies. While collisions of electrons with positrons provided exceptionally clean and precise measurements due to them being point particles, their lightness prevent them from being accelerated to higher energies. Collisions of hadrons, however, would allow for center-of-mass energies two orders of magnitude higher than that of LEP. Therefore, after running a while at two times the W mass (160 GeV) and reaching a maximum center-of-mass energy of 209 GeV, LEP was dismantled in 2000 in order to make room for the LHC.

The Large Hadron Collider started up in September 2008 and, while having the same 27-kilometer radius as the LEP collider, is capable of accelerating protons up to a center-of-mass energy of around 14 TeV, 70 times that of LEP. The accelerator consists of two oppositely going proton beams, isolated from each other and under ultrahigh vacuum, which are accelerated up to speeds close to that of the speed of light through radio frequency (RF) cavities, before being brought to collide at four different interaction points along the ring. These four collision points correspond to the location of the four LHC particle detectors; ATLAS, CMS, LHCb and ALICE. While ATLAS and CMS are general-purpose detectors built in order to study a large range of different physics processes, LHCb and ALICE are built for dedicated purposes; LHCb for b-physics processes and ALICE for heavy ion collision. A proton's journey from gas to one of the LHC collision points is as follows: First, hydrogen nuclei are extracted from a small tank of compressed hydrogen gas and stripped of their electrons. The remaining protons are then injected into the LINAC2, a linear accelerator responsible for increasing the proton energy to about 50 MeV through RF cavities that push charged particles forward by switching from positive to negative electric fields. LINAC2 additionally divides the constant stream of particles into equally spaced "bunches" by careful tuning of the frequency of the field switch. The accelerated protons are then injected into the Proton Synchrotron Booster (PSB), where their energy is increased thirty-fold more, to an energy of roughly 1.4 GeV. The two final acceleration stages before the protons reach the LHC ring are the Proton Synchrotron and Super Proton Synchrotron, eventually leaving the protons with a total energy of 450 GeV. The protons are now ready for the final stage of their travel and are injected into the two beam pipes of the LHC in oppositely going direction. They are injected in trains of 144 bunches each (with an order of 10^{11} protons per bunch), where each bunch is roughly 7.5 meters apart (or 25 ns). There are some larger beam gaps present in each beam in order to give the beam dump and injection kickers sufficient time to reach full voltage, where the largest one, the beam abort gap, is roughly 3 ms or 900 m long. The ring is filled with proton bunches until these are equally distributed throughout the two rings, a process taking roughly 4 minutes. This is called a "fill". Here, the protons are accelerated to their maximum energy of 6.5 TeV, a process taking roughly 20 minutes, through eight

RF cavities. These RF cavities are also responsible of keeping the proton bunches tightly bunched, ensuring maximum luminosity at the four collision points. A complete sketch of the CERN accelerator complex is shown in Figure 2.1.

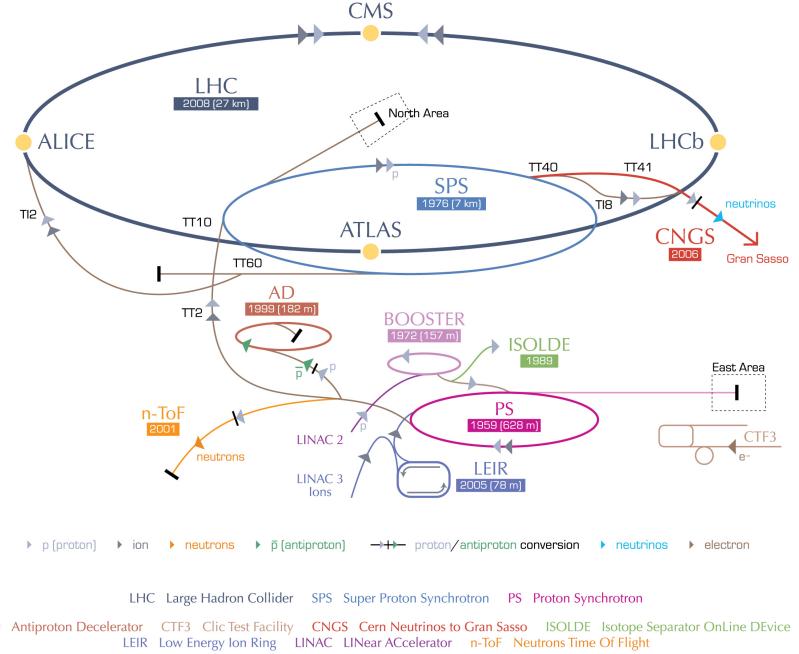


Figure 2.1: The Large Hadron Collider accelerator complex. The four collision points along the ring correspond to the location of the LHC particle detectors CMS, LHCb, ATLAS and ALICE [1].

After the beams have reached their maximum energy and are stably circulating in the LHC ring, they are brought to collide. The goal of such a collision, which occurs every 25 nano seconds, is that some of the protons will undergo an inelastic collision, allowing the quark/gluon constituents of each proton to interact with one another and produce new and interesting particles. The number of times such an interaction will take place inside a detector per area and time is quantified through the luminosity, \mathcal{L} , which is the proportionality factor between the number of observable events per second, and the cross section σ of the process you are interested in

$$\frac{dN_{events}}{dt} = \mathcal{L}\sigma. \quad (2.1)$$

The cross section is the probability that an event (like one which would produce new and interesting particles) will occur and is measured in barns, where $1 \text{ barn} = 10^{-28} \text{ m}^2$. This proportionality factor should therefore be as high as possible. It depends only on parameters of the detector and can, in the case of LHC, be defined through the following accelerator quantities

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta_*} F, \quad (2.2)$$

Parameter	Units	Nominal	2015	2016	2017
Energy	[TeV]	7.0	6.5	6.5	6.5
Bunch spacing	[ns]	25	25	25	25
Bunch intensity	$\times 10^{11}$ [protons/bunch]	1.15	1.15	1.15	1.2-1.45
Bunches per train		144	144	96	144
Total number of bunches		2808	2244	2220	2556
β^*	[cm]	55	80	40	27/25
Peak luminosity	$\times 10^{34}$ [cm $^{-2}$ s $^{-1}$]	1.0	0.5	1.4	2.0
Integrated luminosity			4.2	39.7	50.2

Table 2.1: Some key LHC detector parameters achieved during the first years of 13 TeV data taking

where N_b is the number of particles per bunch, n_b is the number of bunches, f_{rev} is their revolution frequency, γ_r is the relativistic gamma factor, ϵ_n is the transverse beam emittance (how confined the particles are in space and momentum), β^* is the beta function at the collision point (how narrow, or "squeezed", the beam is) and F is a reduction factor to account for a constellation where the beams do not collide heads-on but at slight crossing angles. From this, it becomes clear that the main goal of the LHC is to; maximize the number of particles (N_b, n_b), their frequency (f_{rev}) and their energy (γ_r), while at the same time ensuring the protons are packed together as tightly as possible (lower ϵ_n and β^*). Using the nominal values of the LHC, the peak luminosity is roughly $\mathcal{L} \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

The peak luminosity of the LHC by the end of Run 2 in 2018 was grazing around $2.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to 2 times the nominal design luminosity.

To quantify the size and statistical power of a given LHC dataset, the integrated luminosity is used. This is the integral of the instantaneous luminosity over time and is defined as

$$\mathcal{L}_{int} = \int \mathcal{L} dt. \quad (2.3)$$

It is usually defined in units of inverse cross section, b^{-1} .

Despite the LHC starting up in 2008, there would be another year before data taking began. In March 2010, the LHC saw its first collision with a center-of-mass energy of 7 TeV, and continued running at this energy collecting around 5 inverse femtobarns of data by the end of 2011. In 2012, the energy was increased to 8 TeV and the LHC continued running until a planned long shutdown scheduled to begin in February 2013, collecting a total of $\sim 20 \text{ fb}^{-1}$ and discovering the Higgs boson. This marked the end of Run 1 and the beginning of a two-year maintenance project intended to prepare the LHC for running at a center-of-mass energy of 13 TeV; Run 2.

Run 2, and where this thesis begins, started in June 2015. With the accelerator now running at 90% of its nominal energy, and with a peak luminosity between 1-2 times the design luminosity, the LHC managed to collect an impressive $\sim 160 \text{ fb}^{-1}$ at this energy until its planned shutdown at the end of 2018. Some key LHC accelerator parameters that were in use for the datasets analyzed in this thesis, are quoted in Table 2.1

2.2 The CMS detector

The Compact Muon Solenoid (CMS) detector is true to its name; with a diameter of 15 meters and a weight of 14000 tons, it is 60 % smaller but two times heavier than its general purpose counterpart, the ATLAS detector. Its large weight is due to the CMS housing the world's largest and most powerful solenoid: A superconducting niobium titanium coil

circulating 18500 Amps and capable of generating a magnetic field of 3.8 Tesla. Together with its corresponding iron return yoke, responsible for reflecting the escaping magnetic flux, it accounts for 90% of the total detector weight. The CMS detector is cylindrically symmetric and organized in the following way: closest to the beam pipe and at a radius of about 3 cm, the inner tracking system begins. It consists of an inner silicon pixel detector and an outer silicon strip tracker, stretching out to a radius of roughly 1.2 meters. Following the tracker are two calorimeter layers: the electromagnetic calorimeter (ECAL) consisting of lead tungstate scintillating crystals and responsible for measuring the energy of electromagnetically interacting particles, followed by the hermetic hadronic calorimeter (HCAL) measuring the energy of hadrons. Contrary to "standard" configurations for general purpose detectors, the CMS calorimeters are located inside the superconducting solenoid. This allows the detector to be rather compact, by reducing the necessary radius of the calorimeters, and additionally for the magnet to be strong enough (the magnetic field strength depends on the coil radius) to allow muon detectors to be located within the magnetic field so their momentum can be measured. The muon detectors are alternated with three layers of steel return yoke responsible for containing and reflecting the magnetic field and which only allows muons and weakly interacting particles to pass. A schematic overview of the CMS detector is shown in Figure 2.2. In the following, the different sub-detectors will be described in detail.

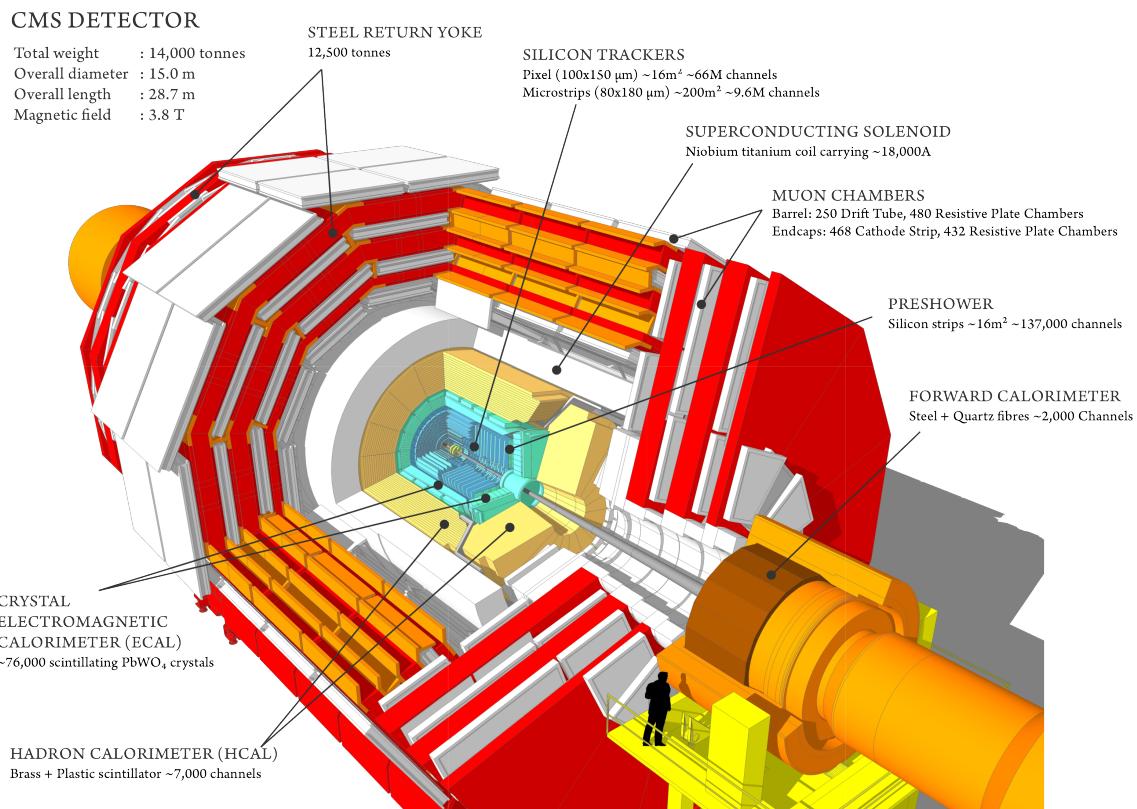


Figure 2.2: The CMS detector and its subsystems: The silicon tracker, electromagnetic and hadron calorimeters, the superconducting solenoid and the muon chambers inter-layered with the steel return yoke [2].

2.2.1 Coordinate system

To describe locations within the CMS detector, a Euclidian space coordinate system is used. Here, the positive z axis points along the beam pipe towards the west, the positive x axis points towards the center of the LHC ring, and the positive y axis upw towards the earths surface. Due to the cylindrical symmetry of the detector, polar coordinates are more convenient and most frequently encountered. In this scheme, the azimuthal angle ϕ is measured in the xy-plane, where $\phi = 0$ correspond to the positive x axis and $\phi = \pi/2$ correspond to the positive y axis. The polar angle θ is measured with respect to the z axis, $\theta = 0$ aligning with the positive and $\theta = \pi$ with the negative z axis. To define a particles angle with respect to the beam line, the pseudorapidity $\eta = -\ln \tan(\theta/2)$ is preferred over θ . This is due to the fact that particle production is approximately constant as a function of pseudorapidity and, more importantly, because differences in pseudorapidity are Lorentz invariant under boosts along the z-axis when assuming massless particles. To measure angular difference between particles in the detector, the variable $R = \sqrt{\eta^2 + \phi^2}$ is used, again Lorentz invariant under longitudinal boosts. A summary of the CMS coordinate system together with some example values are shown in Figure 2.3.

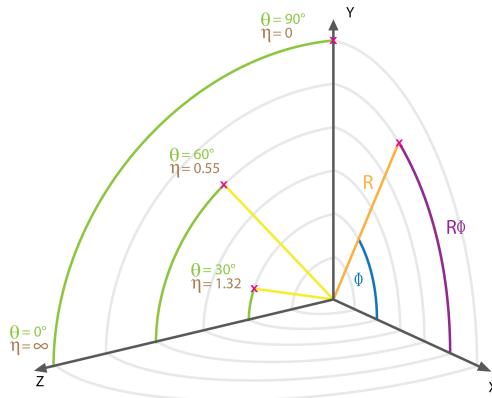


Figure 2.3: The CMS coordinate system [3]

2.2.2 Tracking detectors

The CMS tracker is responsible for accurately reconstructing the momentum of charged particles and consists of two sub-detectors. Closest to the interaction point, and where the particle intensity is the highest, the silicon pixel detector is located. Upgraded in 2017, from the so-called Phase-0 to the Phase-1 layout, it is structured in four cylindrical barrel layers at radii 2.9, 6.8, 10.9 and 16.0 cm (the barrel pixel) and three disks in each of the forward regions placed at a distance from the nominal interaction point of 29.1, 39.6 and 51.6 cm (the forward pixel). A sketch of the current Phase-I pixel detector compared to the Phase-0 detector is shown in Figure 2.4. The sensors located closest to the beam pipe are subject to hit intensities of $\mathcal{O}(\text{MHz}/\text{mm}^2)$ which puts strict constraints on the maximum sensor size in order to minimize occupancy in the detector. The pixel sensors are $100 \mu\text{m} \times 150 \mu\text{m}$ with a thickness of $285 \mu\text{m}$, and when counting both barrel and pixel sensors, sum up to a total of 79 million. The pixel sensors are mounted on detector modules with 16 read-out chips each, where the type of read-out chip depends on how close the module is to the beam pipe: the inner layer uses read-out chips with a rate capability of 600 MHz/cm^2 while for the outer layers, read-out chips with a rate capability of up to 200 MHz/cm^2 are sufficient.

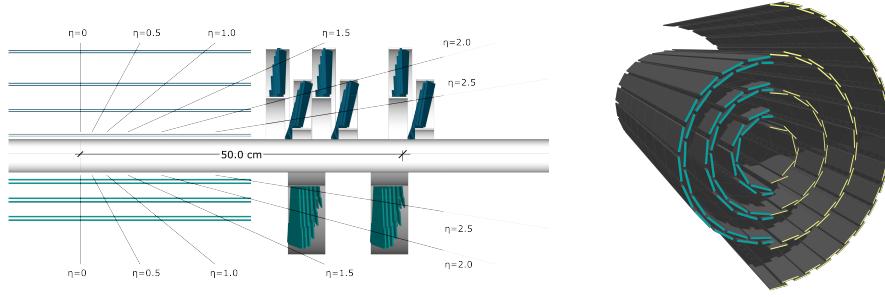


Figure 2.4: Left: The forward pixel detector layout before (bottom) and after (top) the Phase-I upgrade. Right: The barrel pixel detector before (left) and after (right) the Phase-I upgrade [4].

As the hit intensity reduces as you go further away from the beam pipe, the pixel sensors are replaced by silicon strip sensors, making up the second of the two tracker sub-systems, the silicon strip tracker. There are ten strip layers in total, stretching out to a radius of roughly 130 cm. These are divided into four sections: The inner barrel (TIB) with four strip layers, the two inner endcaps (TID) consisting of three disks each, the outer barrel (TOB) consisting of 6 cylindrical layers and the two endcaps (TEC) with 9 strip layers each. A schematic overview of the strip tracker layout is shown in Figure 2.5. The strips in the TIB and TID are 10 cm long, with a width of 80 μm and a thickness of 320 μm . The TOB and TEC sections consist of slightly larger strips of 25 cm x 180 μm and a thickness of 500 μm . The strip tracker has a total of 10 million detector strips and covers an area of $\sim 200 \text{ m}^2$. To prolong the silicon detector lifetime, the entire tracker (pixel and strip) is kept at a temperature of -20°C through a liquid cooling system. The tracker has a coverage up to $|\eta| < 2.6$ and a resolution of roughly $\sigma/p_T \approx 1.5 \times 10^{-5} p_T + 0.005$.

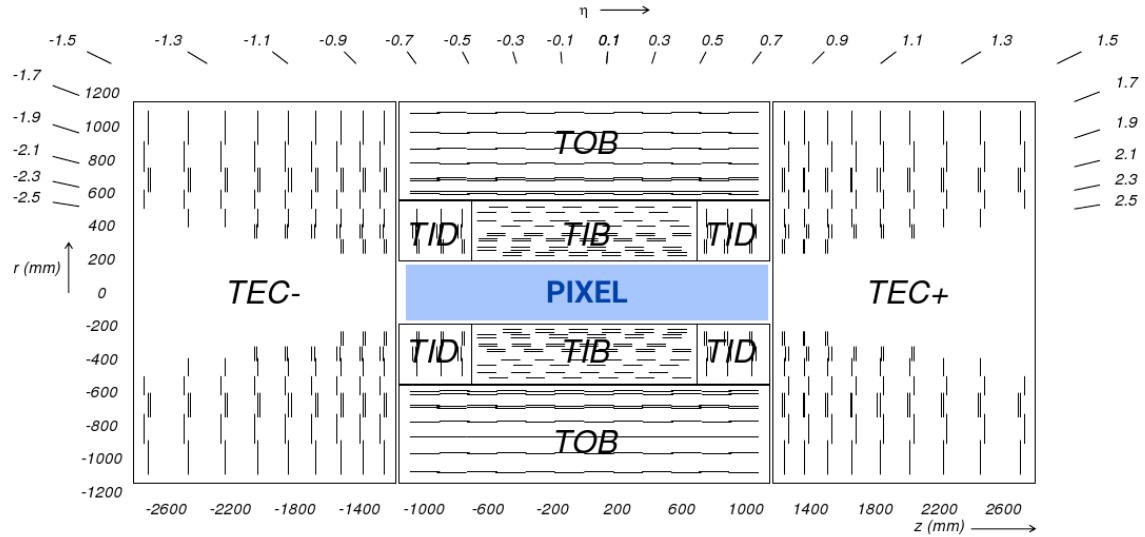


Figure 2.5: Schematic of the CMS silicon strip tracker and its four subsections: The inner barrel (TIB), inner endcaps (TID), the outer barrel (TOB) and the two endcaps (TEC) [5].

2.2.3 Electromagnetic calorimeter

Following the tracking detectors is the electromagnetic crystal calorimeter (ECAL). Consisting of 75 848 laterally segmented scintillating lead tungstate (PbWO_4) crystals, it was designed

to have the highest possible photon energy and position resolution in order to resolve a Higgs boson decaying into two photons, the cleanest of the Higgs discovery channels. With a goal of a photon/electron energy resolution of 0.5% above 100 GeV, the choice of detector material for the ECAL has been its most crucial design feature. In order to withstand the high doses of radiation and the high magnetic field present within the detector, while at the same time generating well-defined signal responses within the 25 nanoseconds between particle collisions, an extremely dense and transparent material capable of producing fast and clean photon bursts when hit, is required. The choice eventually fell on metal-heavy lead tungstate crystals, each taking roughly two days to artificially grow (and a total of about ten years to grow all of them). With a density of $\delta = 8.28 \text{ g/cm}^3$ (slightly higher than for stainless steel), the crystals are compact enough to yield excellent performance without taking up too much volume, allowing the ECAL to sit within the CMS superconducting solenoid. The homogeneous medium allows for a better energy resolution as it minimizes sampling fluctuation effects and it additionally contains enough oxygen in crystalline form to make it highly transparent to their entire scintillation emission spectrum. With an extremely short radiation length and small Moli  re radius ($X_0 = 0.85 \text{ cm}$,

$$R_M = 2.19$$

cm), the required homogeneity, granularity and compactness is obtained while at the same time emitting 80% of generated light within the 25 ns timeframe required. The largest drawbacks with a lead tungstate detector is the low light yield (100 γ per MeV), requiring dedicated avalanche photodiodes to increase the gain, as well as a light yield which strongly depends on the temperature. The detector response to an incident electron changes by $3.8 \pm 0.4 \%$ per degree Celsius which requires the ECAL temperature to be kept stable around $18.0(5)^\circ\text{C}$, obtained through an intricate water cooling system. The ECAL is completely hermetic and sorted into a barrel part (EB), covering pseudorapidities up to $|\eta| < 1.48$, and two endcap parts (EE) extending the total coverage to $|\eta| < 3.0$ in order to match the tracker coverage of $|\eta| < 2.5$. In order to improve the γ/π_0 separation power, a pre-shower detector (ES) using lead absorbers and silicon sensors covers the forward region between $1.65 < |\eta| < 2.6$. The crystals in the barrel are organized into supermodules, each consisting of about 1700 crystals, while the endcap is divided into two half disks consisting of 3662 crystals each (so-called "Dees"). Each PbWO₄ crystal weighs around 1.5 kilogram and has a slightly tapered shape with a front face of $2.2 \times 2.2 \text{ cm}^2$ in the barrel and $2.86 \times 2.86 \text{ cm}^2$ in the endcaps. The crystals are 2.3 and 2.2 cm long in the barrel and endcaps, respectively. The total volume of the calorimeter including barrel and endcaps is 11 m^2 and weighs a total of 92 tons. The ECAL detector layout is illustrated in Figure 2.6.

Having no longitudinal segmentation, the ECAL relies on an accurate reconstruction of the event primary vertex, provided by the tracker, in order to reconstruct the photon angle correctly.

The obtained energy resolution of the ECAL can be parametrized in three parts: a stochastic, a noise and a constant term [6]. It is given as

$$\frac{\sigma E}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128 \text{ GeV}}{E} \oplus 0.3\%$$

where the constant values were estimated in an electron test beam. The constant term of 0.3% is dominated by the non-uniformity in longitudinal light collection [7], and one of the main goals of the detector design was to get this term below 1%. The energy resolution as a function of electron energy is shown in Figure 2.7.

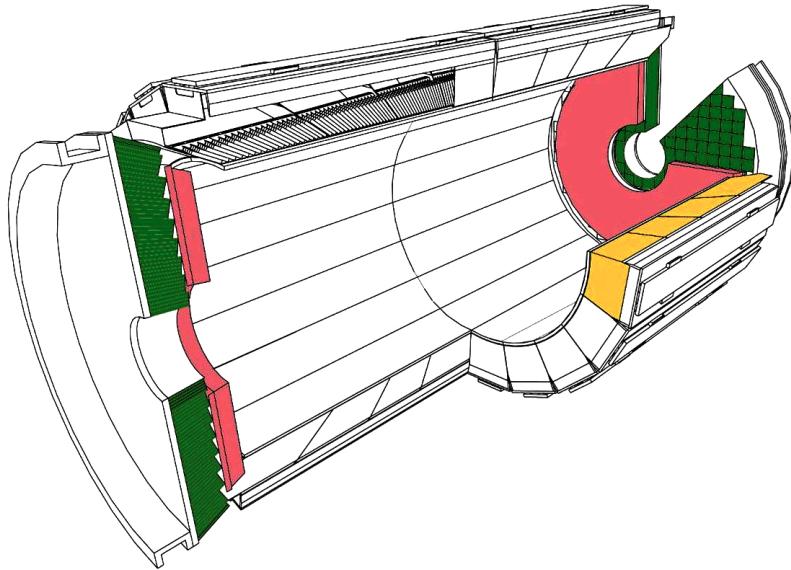


Figure 2.6: A schematic of the CMS electromagnetic calorimeter showing the barrel supermodules (yellow), the individual barrel crystals (black,top left), the endcap modules (green) and the pre-shower detectors (pink) [5].

2.2.4 Hadron calorimeter

Outside the crystal calorimeter is the hadron calorimeter (HCAL). It is the combined response of the ECAL and the HCAL that are responsible for measuring the energy of quarks, gluons and neutrinos through the reconstruction of particle jet energy and missing transverse energy. The HCAL is a sampling calorimeter, meaning it consists of alternating layers of dense brass absorber material and plastic scintillators. When a particle hits an absorber plate, it interacts with the absorber material and generates a shower of secondary particles which themselves generate new particle showers. These particles then generate light in the scintillating material which is proportional to their energy, and summing up the total amount of generated light over consecutive layers within a region, called a "tower", is representative of the initial particles energy. The hadron calorimeter is split into four regions: the inner (HB) and outer (HO) barrel, the endcap (HE) and the forward region (HF). A schematic of the CMS HCAL is shown in Figure 2.8.

The inner barrel lies within the superconducting solenoid volume and covers the pseudorapidity range $|\eta| < 1.3$. It consists of 36 identical wedges, each of which weighing 26 tonnes, split into two half barrels (HB+ and HB-). A photograph of the wedges taken during installation is shown in Figure 2.9.

The wedges are made up of flat brass absorber plates oriented parallel to the beam axis. These plates consist of a 4 cm thick front steel plate followed by eight 5 cm thick brass plates, six 5.6 cm thick brass plates and ending with a 7.5 cm thick steel back plate. The absorber plates are then alternated by 4 mm thick plastic scintillator tiles, the detectors active medium, which are read out using wavelength-shifting plastic fibers. The effective thickness of the barrel hadron calorimeter in terms of interaction lengths increases with the polar angle θ , starting out at about $5.8 \lambda_I$ at an angle of 90 degrees, and increases to $10.6 \lambda_I$ at $|\eta| < 1.3$. As the energy resolution of the calorimeter depends on how much of the particles shower can be absorbed by the calorimeter, the quality of the energy measurement depends on its thickness. Due to the CMS design, the HB is confined to the volume between the ECAL

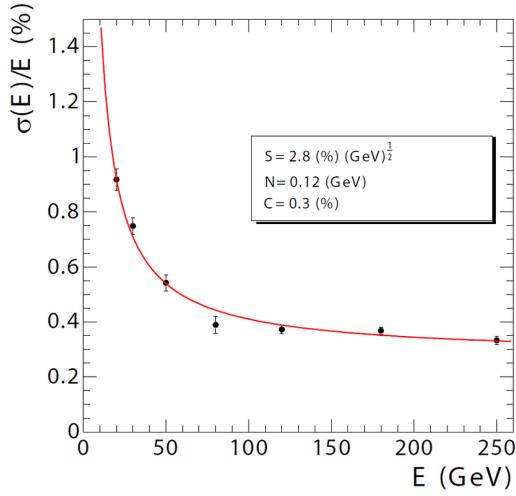


Figure 2.7: The ECAL energy resolution as a function of electron energy as measured in an electron test beam. [6]



Figure 2.8: The four regions of the CMS hadron calorimeter: the inner (HB) and outer (HO) barrel, the endcap (HE) and the forward region (HF) [5]

(ending at a radius of 1.77 m) and the magnetic coil (starting at a radius of 2.95 m). In the central η region, the combined ECAL and HCAL interaction length is too small to sufficiently contain hadron showers. In order to ensure adequate sampling, especially of late starting showers, an additional layer of scintillator has therefore been added outside of the solenoid coil. This is the outer barrel (HO). It uses the coil itself as absorbing material and increases the total barrel calorimeter interaction length to $11.8 \lambda_I$. The hadron calorimeter endcaps (HE) are located in the forward region close to the beam pipe and covers the pseudorapidity range $1.3 < |\eta| < 3.0$, a region containing about 35 % of the particles produced in collisions. Due to its close proximity to the beam pipe, the endcaps need to handle extremely high rates as well as have a high radiation tolerance. As the resolution in the endcap region anyways is limited by pile-up and magnetic field effects, the hadron calorimeter endcaps were designed to minimize the cracks between HB and HE rather than having the best single-particle resolution (as is the case for the barrel). The absorber plates in the endcaps are mounted in a staggered geometry rather than on top of each other as is done in the barrel, in order to contain no dead material and provide a hermetic self-supporting construction. The HCAL is read out in individual towers with a size $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ in the barrel, and 0.17×0.17 at larger pseudorapidities. In order to obtain a completely hermetic calorimeter, an additional



Figure 2.9: The installation of the barrel HCAL wedges consisting of alternating layers of brass absorber plates and plastic scintillator, each weighing roughly 26 tonnes [8].

hadron forward calorimeter (HF) is added in the very forward region. Stretching out to a pseudorapidity of $|\eta| = 5.2$, this detector is located so close to the beam pipe that the particle rate exceeds 10^{11} per cm^2 , receiving roughly 760 GeV per proton-proton collision compared to an average of 100 GeV for the rest of the detector. It consists of a cylindrical steel structure with an outer radius of 130 cm and inner radius of 12.5 cm, located 11.2 meters from the interaction points. Also a sampling calorimeter, it consists of grooved 5 mm thick steel absorber plates, where the quartz fiber active medium is inserted into these grooves. The energy resolution of the CMS ECAL and HCAL for pions is measured in a test beam as a function of energy and is shown in Figure 2.10.

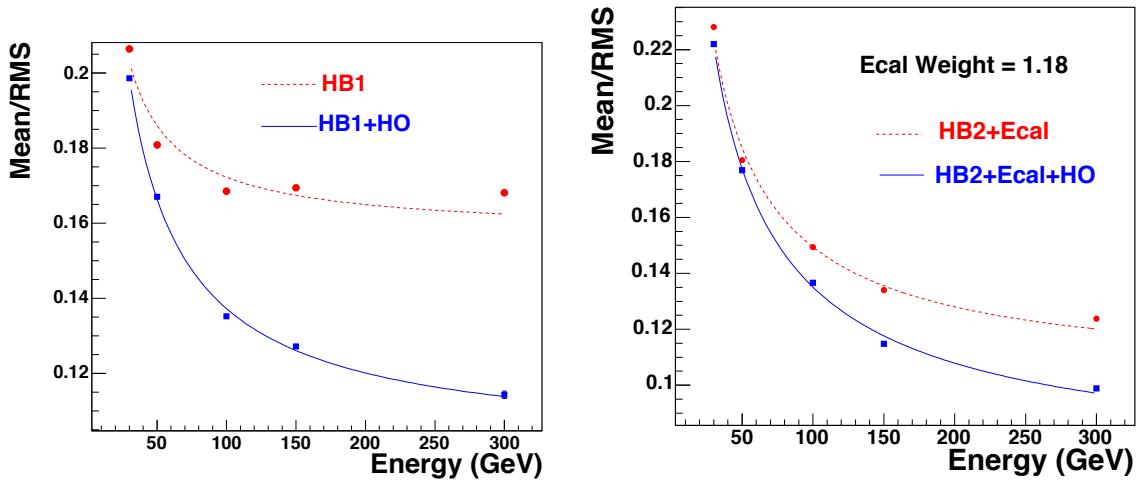


Figure 2.10: The calorimeter energy resolution as a function of pion energy using the HB only or HB+HO (left) and when adding ECal and HCAL measurements (right) [9].

The typical HCAL electronics noise is measured to be 200 MeV per tower. The inclusion of the HO increases the resolution by 10 % for a pion energy of 300 GeV. The final energy resolution parametrization when using ECal+HB+HO is given by a stochastic and a constant

term, as for ECAL, and is

$$\frac{\sigma E}{E} = \frac{84.7\%}{\sqrt{E}} \oplus 7.4\%.$$

2.2.5 Muon chambers

The outer part of the CMS detector is dedicated to performing muon identification, momentum measurement and triggering. In order to do so, the muon system is made up of three types of gaseous particle detectors: drift tube (DT) chambers, cathode strip chambers (CSCs) and resistive plate chambers (RPCs), all integrated into the magnetic return yoke structure. In the barrel region, where particle rates are low and the magnetic field uniform, DT chambers are used and cover the pseudorapidity region $|\eta| < 1.2$. In the endcap regions, however, the muon rates and background levels are considerably higher and the magnetic field itself is large and non-uniform. Here, faster, finer segmented and more radiation hard CSCs are used, covering the region $0.9 < |\eta| < 2.4$. To ensure accurate muon triggering, a complimentary dedicated muon triggering system has been added both in the barrel and in the endcaps. Made out of RPCs, they provide an excellent time resolution at a sharp p_T threshold and cover the region $|\eta| < 1.6$. These chambers also assist in resolving ambiguities if multiple hits are present within a DT/CS chamber. A schematic overview of the muon system is shown in Figure 2.11.

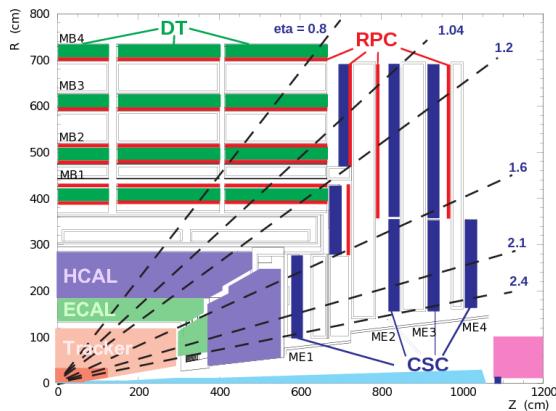


Figure 2.11: A schematic overview of the muon chambers: the DT chambers in the barrel, the CSCs in the endcaps and the redundant RPC system stretching out to $|\eta| < 1.6$ and used for triggering purposes [10].

2.3 Trigger system: From collision to disk

With protons in CMS colliding at a rate of 40 MHz, there are only 25 nanoseconds between collisions available to process event data. One billion collisions take place every second, and with an event size of roughly 1 MB, it is impossible for all of these events to be read out and stored to disk. The CMS triggering system is therefore designed to make ultra fast high-quality decisions of which events are interesting and which events are not. The first stage of triggering, called Level 1 (L1), is designed to reduce the event rate to a maximum of 100 kHz through custom-designed hardware. It uses coarse data from the muons system and calorimeters in order to make a decision on whether the event should be recorded or not, a decision that needs to happen within 3.2 micro seconds. In the mean time, the full granularity data is stored in detector front-end electronics awaiting the L1 decision. The information

used by L1 is gathered in three steps. First, trigger primitives are created. For the muon system, these consist of track segments from each of the three types of muon detectors. For the calorimeter, trigger primitives are generated by calculating the transverse energy of a trigger tower (energy deposits with an $\eta - \phi$ coverage of 0.087×0.087) and assigning it to the correct bunch crossing. Trigger primitives from the calorimeter information is then passed on to a regional trigger which defines electron, muon and jet candidates. Some of this information is passed to the muon trigger (is particle a minimum ionizing particle?). The muon trigger combines the track information with the calorimeter information and selects a maximum of four muon candidates and calculates their momentum, position, charge and quality. This is done in the global muon trigger. The output from the regional calorimeter trigger is also passed to a global calorimeter trigger which provides information about the jets, total transverse energy and missing energy in the event. Combining the information from the global muon trigger and the global calorimeter trigger, the L1 decides whether to keep the event or not by combining several decisions by simple logic operations (AND/OR/NOT) to form up to 128 algorithms.

If the events is accepted, the full event information is read out at a rate of 100 kHz and passed to the so-called "event filter farm", a single processor farm made out of commodity computers. Here, the full precision of the detector data is used on order to take decisions based on offline-quality reconstruction algorithms. The goal of the HLT is to eventually reduce the event rate to an average rate of 400 Hz for offline event storage.

CHAPTER 3

Event reconstruction

3.1 Track and primary vertex reconstruction

The CMS tracker gets traversed by \mathcal{O} 1000 charged particles at each bunch crossing, produced by an average of roughly 34 proton-proton interactions happening simultaneously. This makes track reconstructions extremely challenging, and is the reason why a high granularity of the tracker is vital. The average number of vertices per event for the whole Run 2 is shown in Figure 3.1, with a combined average of 34 number of interactions per bunch crossing.

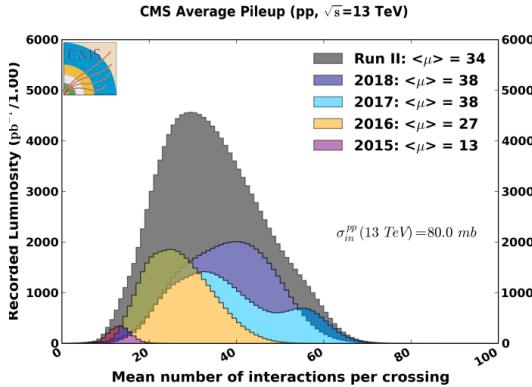


Figure 3.1: The average number of vertices per event in CMS during the Run 2 datataking [11].

Track reconstruction describes the process of taking hits from the pixel and strip detectors, combining them and estimating the momentum and flight direction of the charged particle responsible for producing the hits. It is an extremely computationally heavy process and is based on what is called a combinatorial Kalman filter [12]. A Kalman filter is an algorithm that uses time-dependent observations in order to estimate unknown variables, by proceeding progressively from one measurement to the next, improving the knowledge of the trajectory with each new measurement. The track reconstruction software in CMS (called the Combinatorial Track Finder (CTF)) constructs its collection of tracks by iteratively looping over the hits and reconstructing tracks, then removing those which are already used as inputs for a previous track. It starts from a seed in the inner most tracker layers, usually two or three hits, and then extrapolates the seed trajectories searching for additional hits to associate to that candidate. It then disregards tracks that fail certain criteria based on a χ^2 calculation taking both hit and trajectory uncertainties into account, as well as the number of missing hits. The track reconstruction algorithm is effective over the full tracker coverage range up to $|\eta| < 2.5$ and can reconstruct particles with momenta as low as 0.1 GeV or particles which are produced up to 60 cm from the beam line. In the central region, particles with a momentum of 100 GeV have a p_T -resolution of roughly 2.8 %, a transverse impact parameter resolution of 10 μm and a longitudinal impact parameter of 30 μm .

In order to define the location and uncertainty of every proton-proton interaction in an event, primary-vertex reconstruction is performed. Primary vertices lie within a radius of a few millimeters of the beam axis and are defined as the common origin of groups of tracks. The reconstruction algorithm takes as input the reconstructed tracks from the previous step which pass certain selection criteria, clusters the tracks that share a common origin and then fit for the position of each vertex. Each track must have at least 2 hits in the pixel layers and no less than 5 hits in the pixel+strip as well as a $\chi^2 < 20$ from a fit to the particle trajectory to be considered as input for the vertex finder. The primary vertex resolution is around 12 μm in x and 10 μm in z for vertices with at least 50 tracks.

Offline, all events are required to have at least one primary vertex reconstructed within a

24 cm window along the beam axis, with a transverse distance from the nominal interaction region of less than 2 cm. The reconstructed vertex with the largest value of summed physics object p_T^2 is selected as the primary interaction vertex where the hard scattering process occurred.

3.2 The Particle Flow Algorithm

After track reconstruction, what remains is an incoherent collection of tracks, calorimeter clusters and hits in the muon chambers. In order to connect these, CMS uses an algorithm called Particle Flow (PF) [13] to combine the information obtained from all sub-detectors in order to infer which particles were actually produced in the event. The reconstructed physics object in the order of which they are reconstructed are

- Muons, through hits in the tracker and in the muon chambers
- Charged hadrons, through hits in the tracker and energy deposits in the calorimeters
- Neutral hadrons, through energy deposits in the calorimeters but no hits in the tracker
- Photons, through energy deposits in the ECAL but not in the HCAL and no hits in the tracker
- Electrons, through hits in the tracker and energy deposits in the ECAL

How these different particles propagate through the CMS detector is illustrated in Figure 3.2.

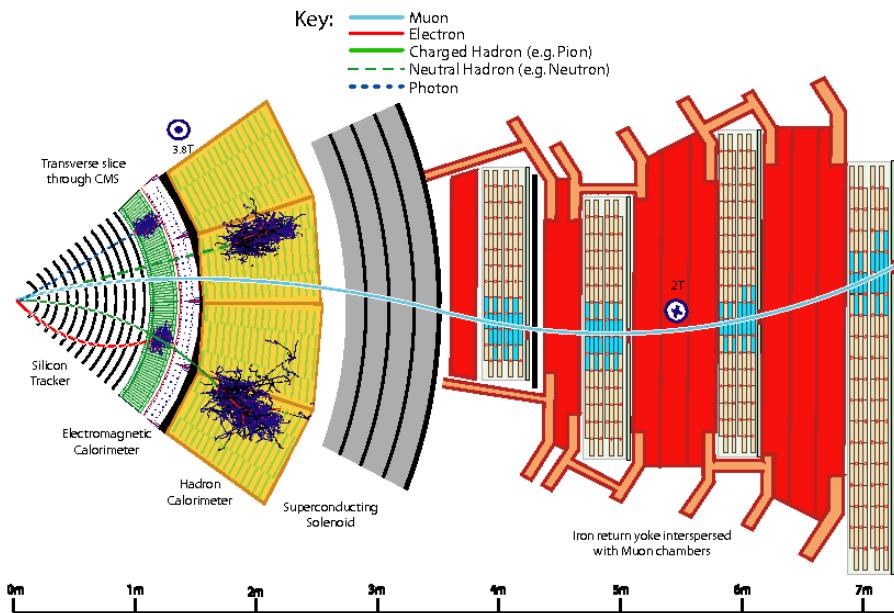


Figure 3.2: Particle interactions in the different subdetectors for a transverse slice through the CMS detector [13].

3.2.1 Reconstruction of the Particle Flow inputs

Electron tracking

Electron seeding is done in two different ways: ECAL-based or tracker-based electron seeding. In the ECAL-based method, electrons are seeded from ECAL clusters with $E_T > 4 \text{ GeV}$, where the position of the cluster is used to infer which hits in the inner tracker belongs to a given electron or positron. As a large fraction of the electron/positron energy is emitted through bremsstrahlung before even reaching the ECAL, ECAL superclusters covering a small window in η and a larger window in ϕ are defined in order to fully contain the electron as well as its bremsstrahlung photons. As these superclusters are prone to contamination, tight isolation requirements need to be applied, leading to reconstruction inefficiencies. Therefore, an additional tracker-based seeding approach has been developed. All tracks with $p_T > 2 \text{ GeV}$ are used as potential electron seeds. These tracks are then extrapolated to the ECAL and matched to the closest ECAL cluster. The ratio of the cluster energy to the track momentum is required to be 1. The electron candidates are then fit with a Gaussian-sum filter (GSF) [14] and required to pass certain criteria based on the score of a boosted-decision-tree (BDT) which combines the number of tracker hits, the χ^2 of the GSF track, the energy loss along the track, and the distance between the extrapolated track to the closest ECAL cluster.

Muon tracking

Muon tracking consists of two part: the muon spectrometer allows muons to be identified with high efficiency over the full pseudorapidity range, while maintaining a low background due to the absorbing calorimeter layers upstream. The inner tracker on the other hand, provides an accurate measurement of the muon momentum. Three muon quality flags are defined

- Standalone muon: Muon tracks based on hits in the DT or CSC only
- Global muon: A standalone muon track matched to a track in the tracker if the track parameters of the two are compatible
- Tracker muon: An inner track with $p_T > 0.5 \text{ GeV}$, a total momentum greater than 2.5 GeV and at least one muon segment matching the extrapolated inner track

Around 99% of muons produced within $|\eta| < 2.4$ are reconstructed as a global muon or a tracker muon, and very often as both. If the global and tracker muon share the same inner tracker segment, the two are combined.

Calorimeter clusters

The calorimeter clustering is performed separately for each calorimeter subdetector (ECAL barrel and endcaps, HCAL barrel and endcaps and the preshower layers). The first step is to define cluster seeds from cells with an energy exceeding some predefined threshold and in addition is larger than the energy in its neighboring cells. Topological clusters are then formed by adding cells to the seed which has at least one corner in common with a cell already in the cluster, and that has an energy which is at least twice the noise level of the detector. In Figure 3.3, an example of calorimeter clustering for a five-particle jet is shown for the HCAL (left) and ECAL (right). In the HCAL (left), two seeds have been identified (gray filled areas) inside a topological cluster consisting of 9 cells. These are then defined as two HCAL clusters, with a position as indicated by the red circles. The green solid lines

correspond to charged tracks reconstructed in the tracker, both pointing to the center of the HCAL cluster seeds. The observed deposits left by the same particles are shown on the right in Figure 3.3, where the K^0_L , π^- and the two photons from the decay of a π^0 leave distinct clusters in the ECAL. The π^+ leaves no energy deposit in this case.

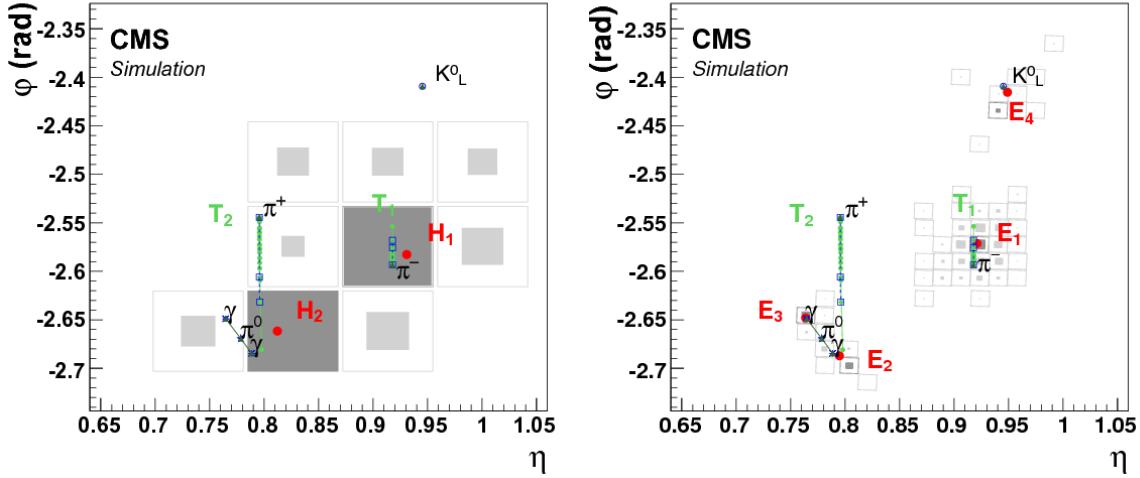


Figure 3.3: The $\eta - \phi$ vies of calorimeter clusters generated by a five-particle jet in the HCAL (left) and in the ECAL (right). The squares correspond to calorimeter cells, where the inner area is proportional to the logarithm of the cell energy. Cluster seeds are depicted in dark gray. The dotted blue lines correspond to the simulated particle trajectory, while the green lines correspond to charged tracks reconstructed in the tracker [13].

3.2.2 Particle Flow identification

The link algorithm

The link algorithm is the algorithm responsible for combining the particle flow elements from different subdetectors. It can test any pair of elements in the event based on specific requirements depending on the nature of the element, but is restricted to the nearest neighbors in the $\eta - \phi$ plane. The outputs of the link algorithm are so-called *PF blocks* of linked elements, either directly linked or linked through having common elements.

- **Inner track - calorimeter cluster link:** The track is interpolated from its last hit, through the preshower layers, the ECAL and ending in the HCAL at an interaction length depth of 1. A link is made if the track is within the cluster area, where the areas is enlarged by up to a cell in each direction to account for detector gaps. In case several ECAL/HCAL clusters are linked to the same track, only the one with the smallest distance in $\eta - \phi$ is kept.
- **Calorimeter cluster - cluster link:** A link between ECAL and HCAL clusters as well as between ECAL and preshower clusters is made when the cluster position of the more granular calorimeter is within the cluster envelope in the less granular calorimeter. Also here, if there is link overlap, only the link with the smallest distance is kept
- **Inner tracker -muon chamber link:** As described in Section 3.2.1

For each PF block, the reconstruction proceeds in the following order. First, muons are reconstructed and their corresponding PF elements removed from the PF block. Then the electrons are reconstructed, with the hopes of removing their corresponding bremsstrahlung photons from the list of PF elements. Energetic photons are reconstructed in the same step. Finally, neutral and charged hadrons are reconstructed.

Muons

First, isolated global muons are selected by requiring the sum of track p_T and calorimeter energy deposits within a cone of $\Delta R = 0.3$ not belonging to the muon track, to be smaller than 10 % of the muon p_T . If the muons are non-isolated, they are required to pass the tight muon requirement [15] and have at least three matching track segments in the muon detector or have matched calorimeter deposits compatible with being a minimum ionizing particle. Muons failing both the requirements above are kept if the standalone muon track is of high quality and have a lot of hits in the muon detectors, otherwise they are discarded. The muon momentum is defined from the inner tracker measurement if the muon p_T is less than 200 GeV. Otherwise, its chosen according to the track fit with the smallest χ^2 probability.

Electrons

The electrons are seeded from a GSF track, as described in Section 3.2.1. To differentiate electrons from charged hadrons, the energy deposit in the HCAL within a distance of 0.15 in the $\eta - \phi$ plane of the supercluster , is required to be less than 10 % of that of the supercluster. The electron candidate must further pass a requirement on the output of a dedicated electron-identification BDT, using inputs such as track-cluster distance, track χ^2 and number of hits as input. In this step, isolated photons are also reconstructed, seeded from ECAL superclusters with $|E_T > 10 \text{ GeV}|$ and no link to a GSF track. All the tracks and calorimeter deposits used to reconstruct electrons and isolated photons are further removed from the list of PF blocks.

Hadrons

Finally, after the removal of muons and electrons, the remaining hadrons and non-isolated photons are identified. HCAL clusters with no track link are defined as neutral hadrons, while ECAL clusters with no track link are defined as photons (photons are exclusively associated to the ECAL deposits as neutral hadrons leave only 3 % of their energy in the ECAL). The remaining HCAL clusters are then linked to one or more tracks from the inner tracker. In order to determine the particle content within a cluster, the sum of track momenta and the calorimeter energy is compared.If the calorimeter energy is compatible with the sum of track momenta, a particle for each track is inferred, with its corresponding energy taken from the track momentum. If the calorimeter energy is larger than the sum of track momenta, a photon or a neutral hadron is added, togehter with one charged hadron for each track within the cluster area.

3.3 Pile-up removal

Particles originating from proton-proton interactions not associated with the hardest primary vertex, are denoted pileup events. These distorts observables of interest from the hard scattering event and must be mitigated through dedicated pileup removal techniques

3.3.1 Charged Hadron Subtraction

As mentioned previously, primary vertices are reconstructed using tracks from charged hadrons. If a primary vertex does not correspond to the hard scattering vertex of the event, the charged hadrons (as reconstructed through Particle Flow) associated to this vertex (called pileup vertex) are removed from the event collection of particles and will not participate in any further object reconstruction. This method is denoted charged hadron subtraction (CHS).

3.3.2 Pile up per particle identification (PUPPI)

CHS was the default pileup removal algorithm in CMS until very recently. In 2014, a new pileup removal algorithm with improved performance was proposed; the pileup per particle identification (PUPPI) [16] algorithm. PUPPI uses a combination of local shape information, event pileup properties and tracking information to compute a weight describing the degree of "pileup-likeness" of a given particle. First, a variable denoted α is computed based on the difference between soft radiation coming from pileup and the harder collinear QCD pattern. The shape of α for charged particles is then used as a proxy for all pileup particles and is used on an event-by-event basis to calculate a weight for each particle. This weight in turn describes the degree to which particles are pileup-like and are used to rescale the particle four-momenta.

The shape variable for a given particle i is defined as

$$\alpha_i = \log \sum_{\substack{j \in \text{Ch,PV} \\ j \neq i}} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2 \Theta(R_0 - \Delta R_{ij}), \quad (3.1)$$

where Θ is the step function and j refers to the neighboring charged particles from the primary vertex within a cone of radius $R_0 = 0.4$. Charged particles are defined as coming from the primary vertex if they are associated to the leading vertex of the event or are within a distance of $d_z < 0.3$ cm from the leading vertex.

In order to determine the probability that a particle comes from pileup, a χ^2 calculation is performed. The probability is defined as

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU})^2}{RMS_{PU}^2}, \quad (3.2)$$

where $\bar{\alpha}_{PU}$ is the median value of the α_i distribution for pileup particles in the given event and RMS_{PU} is its RMS.

Each particle (neutral and charged) is then assigned a weight $w_i = F_{\chi^2, NDF=1}(\chi_i^2)$, where $F_{\chi^2, NDF=1}$ is the cumulative distribution function of the χ^2 distribution with one degree of freedom. Particles with $w_i < 0.01$ are rejected. In addition, a cut on the weighted p_T of neutral particles of $w_i \cdot p_{T,i} > (A + B \cdot N_{PV})$ GeV is applied, where N_{PV} correspond to the number of reconstructed vertices in the event and A and B are tunable parameters.

The performance of the PUPPI algorithm compared to CHS for jet observables is shown in Figure 3.4.

The top row shows the absolute mass resolution (left) as well as the mass resolution as a function of N_{PV} for CHS jets (red) and PUPPI (pink) jets. The bottom row shows the corresponding quantities but for jet transverse momentum. A significantly better resolution on jet observables can be achieved using PUPPI compared to CHS.

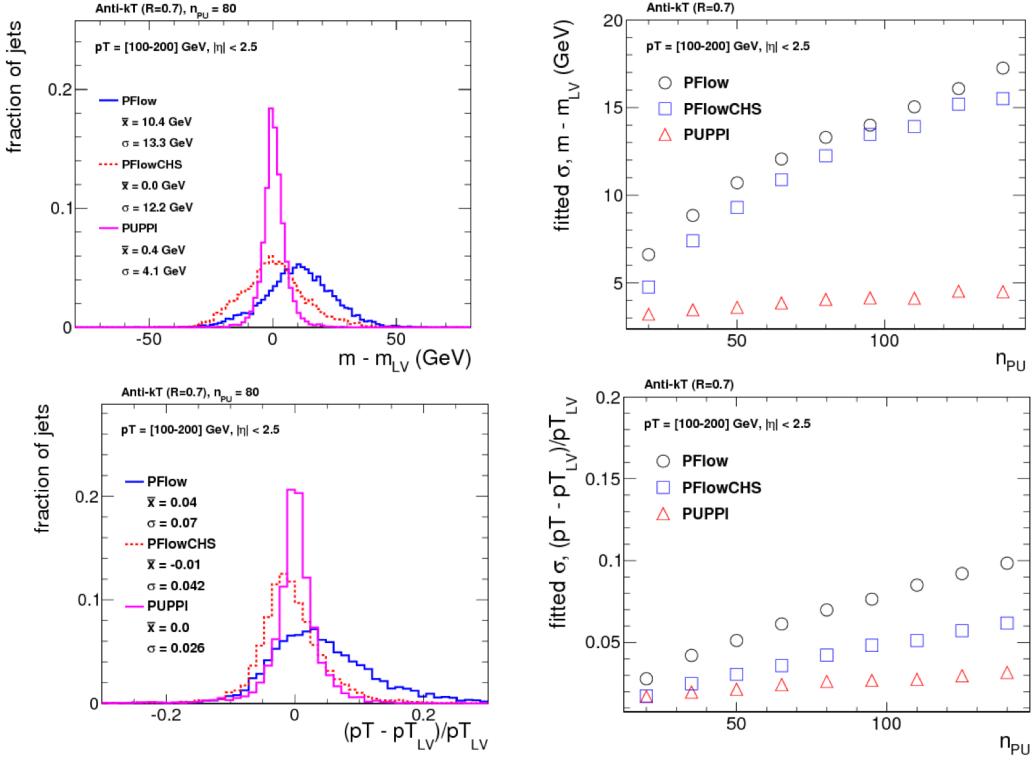


Figure 3.4: The mass (top) and p_T (bottom) resolution comparing PF only (blue), PF+CHS (red) and PUPPI (pink) jets. The absolute resolution (left) as well as the resolution as a function of the number of reconstructed primary vertices in the event (right) is shown [16].

3.4 Jet reconstruction

As explained in Section 1.1.4, quarks and gluons are never themselves visible in a detector. Within 10^{-23} seconds, the timescale of the strong interactions, they fragment and hadronize into a collimated spray of hadrons, a so-called jet. In order to infer the properties of the original parton generating the jet, the properties of the full particle spray needs to be evaluated. Combining these particles algorithmically is non-trivial, and several algorithms designed to do, called jet clustering algorithms, exist. These provide a set of rules for grouping particles together into jets and are usually based on certain distance requirements between particles as well as rules for how to recombine their momenta. Thanks to Particle Flow, objects like charged hadrons, neutral hadrons and photons together with their estimated energy and direction are already defined, and jet clustering in CMS therefore consists of associating these particles to one common origin.

3.4.1 Jet clustering

The most common jet clustering algorithms used in hadron colliders are the Cambridge/Aachen algorithm [17], the k_T algorithm [18] and the anti- k_T algorithm [19]. These are all sequential recombination algorithms, meaning they systematically go through each particle pair in the event and recombines them into one particle if the combination satisfies certain criteria. The rules, shared by all three algorithms, are as follows:

- For each pair of particles i and j , compute the longitudinally invariant distances

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \text{ with } \Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \quad (3.3)$$

$$d_{iB} = p_{ti}^{2p}, \quad (3.4)$$

where d_{ij} is a measure of the relative transverse momenta between the particles, ΔR_{ij}^2 is the distance between them in the $\eta - \phi$ plane (which can be roughly translated into a jet radius), ΔR^2 corresponds to a distance parameter which controls the extension of the jet and d_{iB} is the distance between the particle and the beam. The parameter p is what separates the three algorithms from one another and controls the relative power of energy versus geometrical scales. For the anti- k_T algorithm, it is defined as $p = -1$, for the k_T algorithm $p = 1$ and in the case of the C/A algorithm, $p = 0$. The consequences of these choices are explained in detail below.

- Find the minimum distance of d_{ij} and d_{iB} .
- If this is d_{ij} , recombine particles i and j and return to step 1.
- If it is d_{iB} , the particle is defined to be a final state jet, and is removed from the list of particles. The algorithms proceeds back to step 1.
- Repeat until no particles remain.

Infrared and collinear safety

There are two requirements that are extremely important when defining jet algorithms: They must be 1) *infrared* (IR) and 2) *collinear* (C) safe. *Infrared* safety corresponds to the requirement that if the final state particles are modified by the presence of a soft emission, and there are always soft emission in QCD events (both perturbative and non-perturbative), then the set of hard jets should remain unchanged. This is illustrated by the two left figures in Figure 3.5.

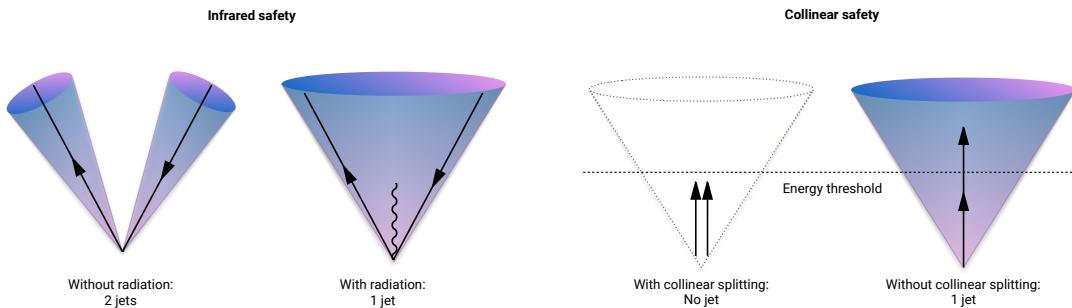


Figure 3.5: An illustration of what would happen for an infrared (left) and collinear (right) unsafe jet algorithm. If an algorithm is infrared unsafe, the presence of a soft emission changes the jet configuration. If an algorithm is collinear unsafe, then if a parton undergoes a collinear splitting this will change the configuration of the jet

Here, the algorithm is infrared unsafe: the presence of an additional soft gluon changes the jet configuration from 2 to 1 jets. If an algorithm is *collinear* unsafe, it means that the jet configuration would change if the hard parton undergoes collinear splitting (which a hard parton often does as part of the fragmentation process and which are also part of non-perturbative dynamics, like the decay of highly energetic hadrons). This is shown in the

two left figures of Figure 3.5, where a hard parton undergoing collinear splitting fails to be reconstructed due to its daughters being below the energy threshold of the algorithm.

All sequential recombination algorithms are trivially infrared safe.

The k_T algorithm

The k_T algorithm is the oldest of the sequential recombination algorithms and, due to its $p = 1$ definition in the distance measures, follows the QCD branching structure in both p_T and in angle (in reverse). Soft particles are clustered together first, and the final step is the clustering of the two hardest particles. A consequence of this definition is that there is nothing that keeps arbitrarily soft particles from being defined as jets, and a minimum cut on the jet p_T should be introduced. Despite several favorable qualities, the k_T algorithm is not the algorithm of choice in most hadron collider experiments due to the irregular jets it produces, a consequence of clustering soft particles first.

The Cambridge/Aachen algorithm

The Cambridge/Aachen algorithm, with $p = 0$ in the distance measures, follows the QCD branching structure only in angle as the clustering order is based solely on spatial separation. The simplest of the algorithms, it recombines all pairs close in ΔR until $\Delta R_{ij} > R$. The benefits of this is that the clustering history contains information about the presence of any geometrical substructure within a jet, a feature that will become important in Section 3.5.

The anti- k_T algorithm

The default jet clustering algorithm in CMS is the anti- k_T algorithm [19], which follows the rules and distance measures above with $p = -1$. The algorithm favors the clustering of high- p_T - high- p_T and high- p_T – low- p_T particles first, disfavoring clustering between soft particles. That means the algorithm grows around a hard core, yielding jets with a well-defined cone shaped area. Together with being IRC-safe and insensitive to the underlying event (any event not arising the primary hard scattering process) and pileup, makes it the main jet algorithm in CMS.

A comparison of the resulting jet area in the $\phi - \eta$ plane after clustering with either k_T , C/A and anti- k_T , is shown in Figure 3.6. The z-axis correspond to the parton p_T . One can clearly see that when clustering with the anti- k_T algorithm, the produced jets are circular, with a radius set by R , around the hardest parton.

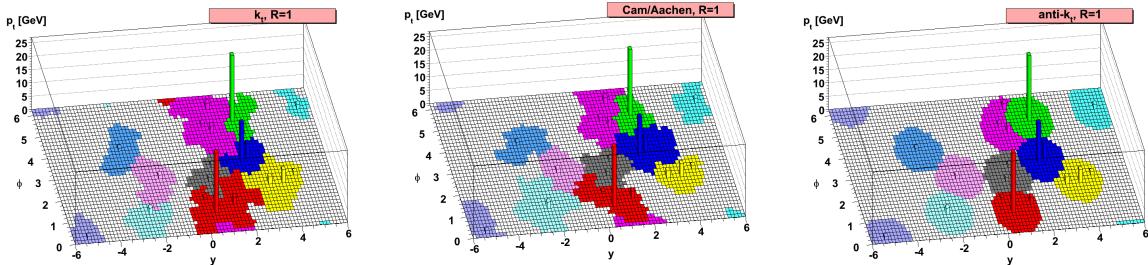


Figure 3.6: A comparison of the resulting jet cone area in the $\phi - \eta - p_T$ plane after clustering the same event with three different jet algorithms: k_T , C/A and anti- k_T . [19]

3.4.2 PF jets in CMS

Jet algorithms in CMS mainly use PF candidate four-vectors as input and a pileup removal algorithm is usually applied before clustering occurs. If using CHS (Section 3.3.1), charged hadrons not associated to the primary vertex are discarded before clustering. If PUPPI is used (Section 3.3.2), all the PF candidates are reweighted based on how likely they are to have originated from pileup. For the anti- k_T algorithm, CMS by default uses two jet cone sizes: R=0.4 and R=0.8. Jets with R=0.4, called PFAK4, are used for single-prong jets while the larger R=0.8 jets, PFAK8, are more often used when looking for jets containing multiple hard quarks/gluons in order to contain all the hadronization products.

3.5 Jet substructure reconstruction

In analyses looking for highly energetic ("boosted") vector bosons like, a main theme of this thesis, the opening angle between the vector boson quark decay products become so small that the highly boosted boson appears as a single large jet instead of two well-separated smaller jets. The distance between the two quarks, in the case of an hadronic decay, depends on the mass of the vector boson and its p_T and goes as

$$\Delta R = \frac{2M_V}{p_{T,V}}. \quad (3.5)$$

Above a W boson p_T of 200 GeV, the two quarks are therefore merged into a single large cone jet of size R = 0.8. A sketch of the two different situation is shown in Figure 3.7. If the W p_T is well below 200 GeV, its decay products are well-defined jets in their own right (left). However, once the W transverse momenta starts exceeding 200 GeV, both the quarks are completely contained within a single jet (right).

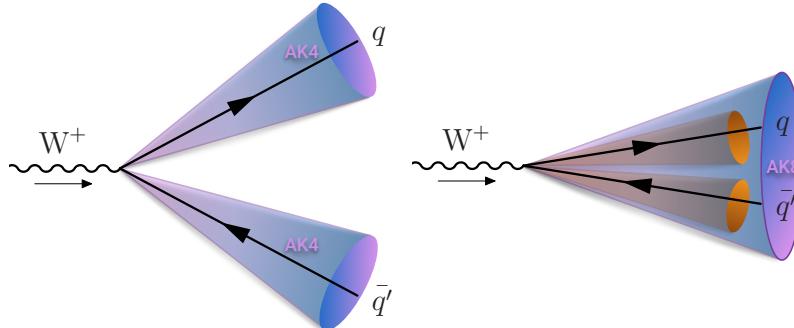


Figure 3.7: If the mass of the resonance is low enough, the quark decay products of each vector boson are well separated and clustered into distinguishable AK4 jets (left). If the transverse momentum of the vector boson is greater than 200 GeV, the vector boson decay products are merged into one single large cone AK8 jet.

In order to distinguish hadronically decaying vector boson from QCD quark/gluon jets, the jet mass would in principle be a good discriminant as we know the W has a mass of around 80 GeV while the quark/gluon mass is close to zero. At very high transverse momenta, however, the width (and therefore the mass) of QCD jets may become equally large. In addition, diffuse radiation caused by the Underlying Event and pileup give rise to a significant number of additional particles in the event contributing to the total jet mass. Therefore, being able to accurately and efficiently separate highly boosted QCD jets from highly boosted

vector bosons, requires other methods. In order to get rid of UE and pileup, algorithms like PUPPI and CHS can be used. Then, to improve the mass resolution further, dedicated grooming algorithms must be applied.

3.5.1 Grooming

Grooming was introduced as a tool to improve the signal, most often W/Z/, mass resolution without significantly changing the background and signal event numbers. It consists of removing the softest parts of a jet in order to resolve its "true" mass, by means of reclustering and identifying soft particles within the jet which then are removed.

Trimming

The trimming algorithm [20] is a grooming algorithm mostly used at trigger level in CMS (also where it is used in this thesis) due to it being less aggressive than other grooming algorithms. It works in the following way: Starting from a large jet clustered with either anti- k_T or C/A (in the case of CMS), it reclusters the jet using the k_T algorithm in order to create subjets of some size R_{sub} . It then proceeds to check whether each subjet has a momentum fraction above a certain threshold,

$$p_{T,i}/p_{T,jet} > p_{T,frac}.$$

If the subjet fails this requirement, it is removed. The remaining subjets are then assembled into a new "trimmed" jet. The effect of trimming on real W jets and QCD quark/gluon jets for different values of r_{sub} and $p_{T,frac}$ is shown in Figure 3.8. The best signal mass resolution is obtained with $r_{sub} = 0.2$ and $p_{T,frac} = 0.03$, which is also the parameter setting that provides the best signal and background discrimination by pushing the QCD jet mass closer to zero. These are the default values of the tuned parameters of the trimming algorithm in CMS ($r_{sub} = 0.2$ and $p_{T,frac} = 0.03$).

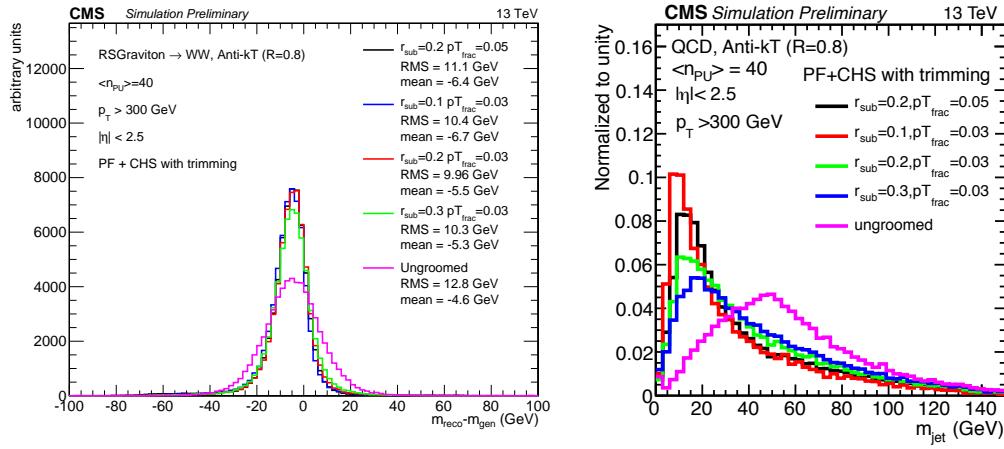


Figure 3.8: The effect of trimming on a signal jet (left) and a background jet (right) for different values of the tuned parameters r_{sub} and $p_{T,frac}$ [21].

Pruning

The pruning algorithm, in addition to removing soft particles, has an additional requirement on the distance between any recombination that are at wide angle. It proceeds by reclustering

the jet with the C/A algorithm, requiring at each step that

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,P}} > z_{cut} \quad \text{and} \quad \Delta R_{i,j} < D_{cut} = \frac{2r_{cut}m_{jet}}{p_T}.$$

The first requirement is a requirement on the hardness of the combination. $p_{T,i}$ and $p_{T,j}$ correspond to the transverse momenta of each protojet (single particle or group of particles already combined in a previous step) and $p_{T,P}$ is the combined p_T of the two. The protojet with the lowest transverse momenta is removed if its hardness is below z_{cut} , or if it forms an angle wider than D_{cut} relative to the axis of the recombination of the two protojets. In CMS, the tuned parameters are set to $r_{cut} = 0.5$ and where $z_{cut} = 0.1$. Figure 3.9 shows the ungroomed as well as the pruned jet mass distribution for signal (left) and background jets. The highest amount of signal and background separation in CMS, is achieved with $r_{cut} = 0.5$ and $z_{cut} = 0.1$.

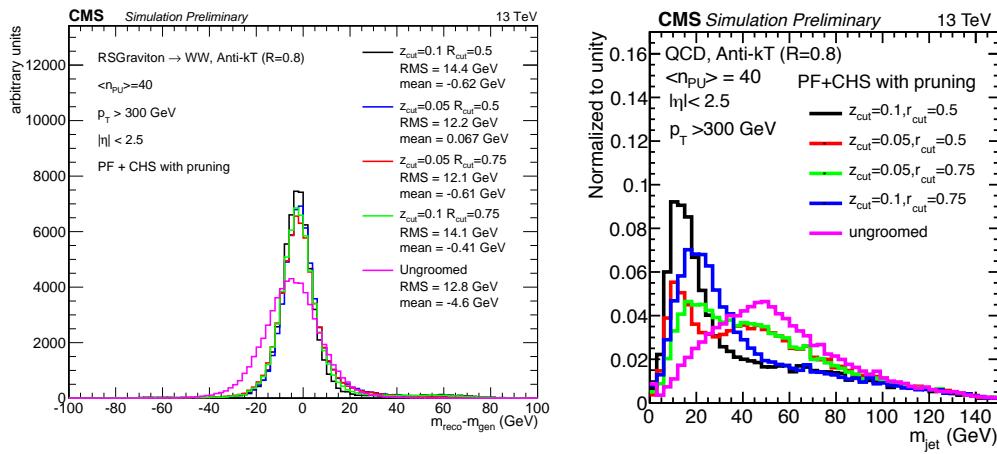


Figure 3.9: The effect of pruning on a signal jet (left) and a background jet (right) for different values of the tuned parameters z_{cut} and r_{cut} [21].

Modified Mass Drop Tagger and Soft Drop

The modified mass drop tagger (mMDT) [22] (a modified version of the originally suggested mass drop tagger [23]) is based on the idea that a W/Z jet is formed by two quark subjets and that, therefore, the mass of each subjet is much smaller than their combined mass (and much smaller than the mass of the boson itself). A QCD jet is, on the other hand, formed by continuous soft radiation, meaning that its heaviest subjet should be close to the mass of the jet itself. The mMDT tagger therefore starts from an already clustered jet, reclusters it with the C/A algorithm and then declusters it again defining subjets s_1 and s_2 . It then looks for a significant mass drop going from total jet mass to the mass of each subjet, and checks that the splitting is not too asymmetric. The modified mass drop condition is generalized through the soft drop declustering method [24], simply called Soft Drop, which allows for different types of angular requirements to enter the condition. The Soft Drop condition is the following

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \frac{\Delta R_{12}^\beta}{R_0}.$$

If no significant mass drop occurred and the splitting is not too asymmetric, the condition is met and the full jet is deemed the softdrop jet. Otherwise only the highest- p_T subjet is kept

and the declustering continues. If the jet can not be declustered any further, it can either be removed from consideration, so-called "tagging"-mode, or deemed the final soft-dropped jet, "grooming"-mode. A $\beta = 0$ corresponds to the modified mass drop tagger and removes all soft emission from the jet. For $\beta > 0$, soft radiation is removed, but some fraction of soft-collinear radiation is kept. Lastly, with $\beta < 0$, Soft Drop can remove soft as well as collinear radiation. The performance of Soft Drop on W jets and QCD quark/gluon jets for different values of β is shown in Figure 3.10. The modified mass drop tagger (Softdrop with $\beta=0$) is the default Soft Drop settings in CMS, due to it providing the best signal/background discrimination while maintaining an excellent signal mass resolution.

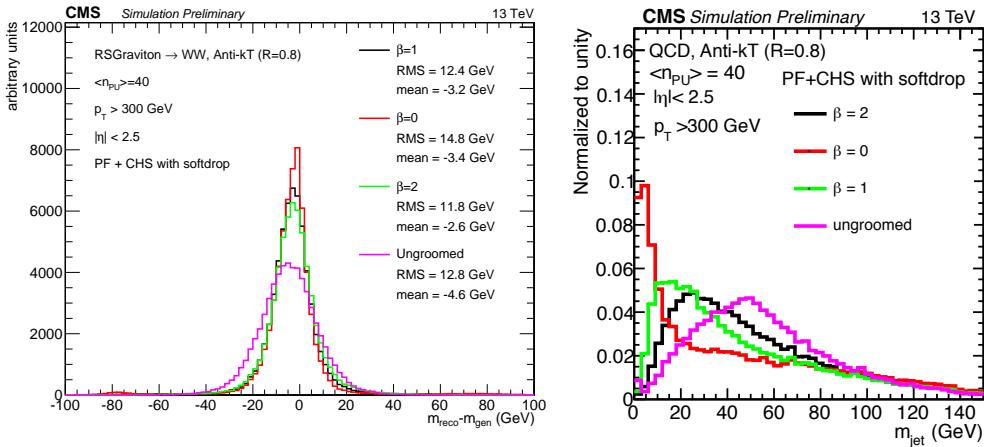


Figure 3.10: The effect of softdrop on a signal jet (left) and a background jet (right) for different values of the tuned parameters β . $\beta = 0$ corresponds to the Modified Mass Drop Tagger, which is the default Softdrop setting in CMS [21].

3.5.2 N-subjettiness

After hopefully having resolved the particle mass with one of the grooming algorithms above, there is still discriminating information to be gathered from the jet structure itself. A W or Z jet consists of two well-defined high- p_T subjets. A quark/gluon jet on the other hand, made from a single parton, consists of several large angle, asymmetric splittings, as illustrated in Figure 3.11

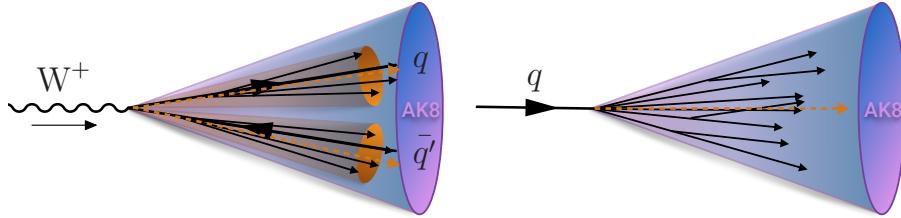


Figure 3.11: A jet stemming from the decay of a W will usually have two well-separated high- p_T subjets, while a jet with a single-prong origin consists of several large angle splittings.

The N-subjettiness algorithm [25] takes advantage of this fact by attempting to count the number of hard subelements within a jet. This is quantified through the n-subjettiness variable, τ_N , defined as

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}) \quad (3.6)$$

where k runs over all the jet constituents, $p_{T,k}$ is the constituent transverse momentum and $\Delta R_{i,k}$ is the distance between the constituent and candidate subjet axes. These subjet axes are obtained through a one-pass optimization procedure which minimizes N-subjettiness [26]. The normalization factor in front is given as

$$d_0 = \sum_k p_{T,k} R_0 \quad (3.7)$$

where R_0 corresponds to the cone size of the initial jet. With this definition, jets with $\tau_N = 0$ have most of its constituents aligned along the subjet axes. However, if $\tau_N \gg 0$, a large fraction of the energy is radiated away from the subjet directions and are more likely to have more than N subjets. In CMS, and as recommended by the authors in [25], the ratio τ_2/τ_1 is used to discriminate W jets from QCD jets. The reason for this is that, while signal jets are expected to have a large τ_1 , quark/gluon can similarly have large τ_1 due to the diffuse radiation present. However, QCD jets with a large τ_1 tend to have an equally large τ_2 , while signal jets do not, hence the ratio of the two provides greater separation power. In CMS, the n-subjettiness algorithm is by default applied to ungroomed jets. The distribution of τ_{21} for signal and background jets with different pileup subtraction algorithms applied are shown in Figure 3.12, where τ_{21} in combination with PF+PUPPI (green) yields a distribution most similar to the generated one (black).

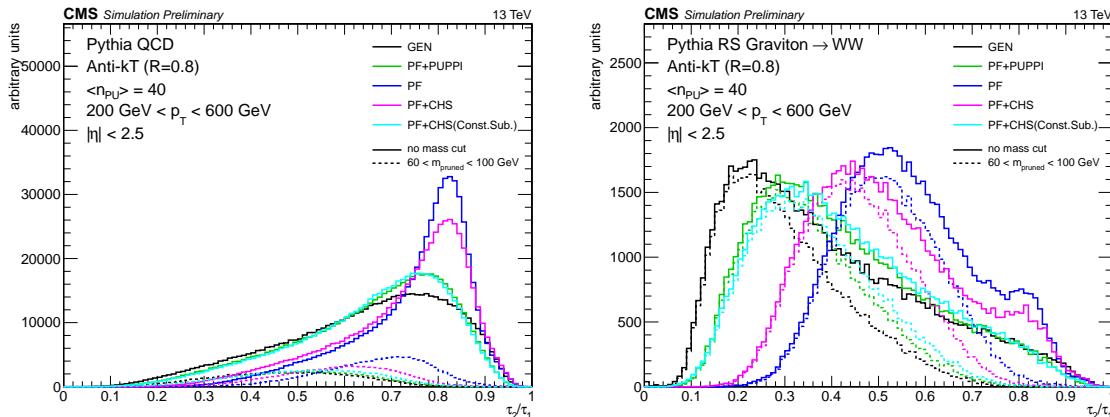


Figure 3.12: The distribution of the n-subjettiness ratio τ_{21} for signal jets (left) and background jets (right) with different combinations of pileup subtraction algorithms applied. The solid lines correspond to the τ_{21} distribution with no mass cut applied, while the dotted lines are within a mass window of 60-100 GeV [21].

3.6 Monte Carlo Simulation

Monte Carlo event generators offer a realistic estimate of high-energy collisions on an event-by-event basis, allowing us to estimate signal and background processes accurately. Simulated events are usually produced in three steps, describing a process from very short timescales up until hadronization and decay. First, a matrix element generator simulates the hard scattering process and subsequent decays. Secondly, the showering and hadronization of

unstable particles is performed and, lastly, the final state particles are passed through a full detector simulation in order to reproduce a range of experimental effects.

General-purpose Monte Carlo (GPMC) generators, like HERWIG ++ [27] and PYTHIA 8 [28], deal with both perturbative as well as hadronization phenomena, simulating an event all the way up until detector simulation. In HERWIG ++ and PYTHIA 8, the hardest processes are only simulated at the lowest order of perturbative expansion, meaning $2 \rightarrow 2$ or $2 \rightarrow 3$ scatterings. In order to have tree-level matrix elements with an arbitrary final-state multiplicity, they can be combined with programs used to generate parton-level events at higher accuracy, which are then processed through showering and hadronization with the GPMC generators. One popular program for generating matrix elements is MADGRAPH [29]. This, however, still correspond to a tree-level (leading order) approach. To go to next-to-leading-order (NLO), meaning the inclusion of virtual corrections, two methods exist: MC@NLO [30, 31] and POWHEG [32]. These combine the full next-to-leading-order prediction for inclusive processes with the subsequent parton showers, either by a subtraction method regularizing the real contributions, or by a matrix-element correction of the parton shower branching probability. After hadronization, all final state particles are passed through a full simulation of the CMS detector. This is done with GEANT4 [33], where experimental effects like object reconstruction and detector resolution are accounted for.

For the work presented in this thesis, simulated samples of the Standard Model background processes are used to optimize the analysis and in some cases provide flexible background templates. QCD multijet production is simulated with four generator configurations: 1. PYTHIA standalone, 2. the LO mode of MADGRAPH matched with PYTHIA, 3. POWHEG matched with PYTHIA and 4. HERWIG++ 2.7.1 with tune CUETHS1 [34]. Top quark pair production is modeled with POWHEG and showered with PYTHIA unless otherwise stated. W+jets and Z+jets production are simulated with the leading-order (LO) mode of MADGRAPH matched with PYTHIA. Signal samples are generated with standalone PYTHIA.

All samples are processed through a GEANT4-based simulation of the CMS detector. To simulate the effect of additional proton-proton collisions within the same or adjacent bunch crossings (pileup), additional inelastic events are generated using PYTHIA and superimposed on the hard-scattering events. The MC simulated events are finally weighted to reproduce the distribution of the number of pileup interactions observed in data.

CHAPTER 4

Diboson resonance searches in CMS

4.1 Search I: First search for diboson resonances at 13 TeV

When the LHC started its Run II data taking period in summer 2015, it would be the first time ever for a particle collider to produce collisions with center-of-mass energies of 13 TeV. The high-energy physics community was at cross roads. The Higgs boson for which the LHC was designed to find, had been discovered at the end of the previous data taking era. We were stuck with a Standard Model that we knew was, in the best case, in need of extensions and in the worst case an effective theory valid only in a certain region of phenomena phase space. The search program in Run II would therefore be oriented around two main efforts: Precision measurements of the newly discovered Higgs boson and searches for Beyond Standard Model physics.

I started my PhD four months before the first 13 TeV collisions took place and was faced with the following questions: What was the most interesting search that could be done on a short time scale (to be presented 6 months after first collisions, at the CERN end-of-year Jamboree), that would be manageable for a student with no experience to perform alone and that would be robust enough incase the never-before-validated 13 TeV Monte Carlo would fail?

Every year in high-energy physics has its hot topic: In 2018, this was most certainly leptoquarks (driven by a dimuon excess around 30 GeV), in 2016 and 2017 it was diphoton resonances (with $> 3\sigma$ excesses observed both in ATLAS and in CMS). And in 2015 during the 13 TeV LHC start-up, it was centered around diboson resonances in the all-hadronic final state.

The choice was therefore clear: My first analysis would be a search for diboson resonances in the boosted dijet final state. With a background model based on a smooth fit to data in the signal region, eliminating the need for accurate QCD MC predictions, this was a simple one-background only (QCD) analysis, feasible for a first-year PhD student to finalize within a year. Despite its straightforwardness, due to observed 8 TeV excesses, it was in addition considered a high-profile, high-impact analysis.

It became one of the first "boosted" searches published with 13 TeV data as well as the first search to take advantage of dedicated grooming triggers. This introduces Search I: First search for diboson resonances at 13 TeV.

4.1.1 A small bump

On June 2nd 2015, the day before CMS recorded its first ever 13 TeV event, a pre-print appeared on the arXiv "Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector" [29]. It was an analysis of the full ATLAS Run 1 dataset, corresponding to 20.3 fb^{-1} , searching for heavy resonances decaying to vector bosons in the all-hadronic state. The analysis documented a 3.4σ excess for a heavy resonance decaying to W Z around 2 TeV. The corresponding CMS analysis, published the previous year, had a 1.3σ excess at roughly the same resonance mass, but mostly compatible with a W W final state hypothesis [35]. Figure 4.1 shows the corresponding dijet invariant mass spectrum as seen by ATLAS (left) and the upper limit on the production times the cross section for a G_{Bulk} decaying to W W (right) as documented by CMS.

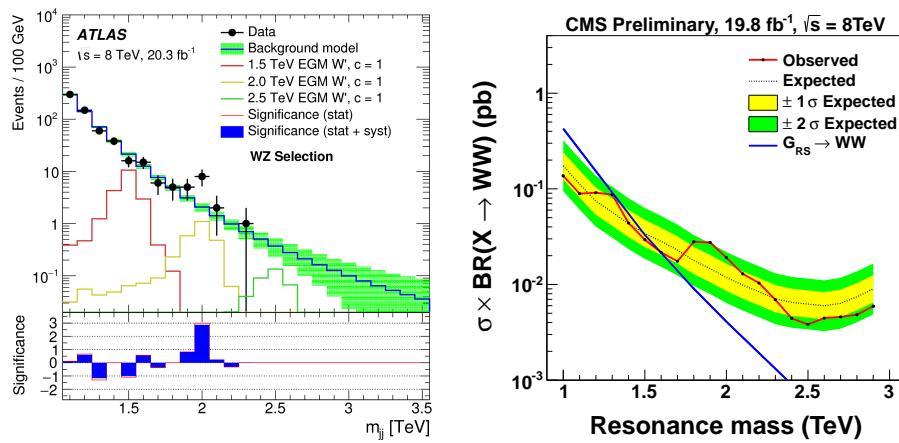


Figure 4.1: The mass (top) and p_T (bottom) resolution comparing PF only (blue), PF+CHS (red) and PUPPI (pink) jets. The absolute resolution (left) as well as the resolution as a function of the number of reconstructed primary vertices in the event (right) is shown [16].

The two measurements were found to be compatible, favoring a heavy resonance with a production cross section of around 5 fb^{-1} and a mass between 1.9 and 2.0 TeV decaying to either W W, W Z or Z Z [36]. Figure 4.2 show the obtained p-value of the ATLAS (red) and CMS (blue) search as well as their combination (black).

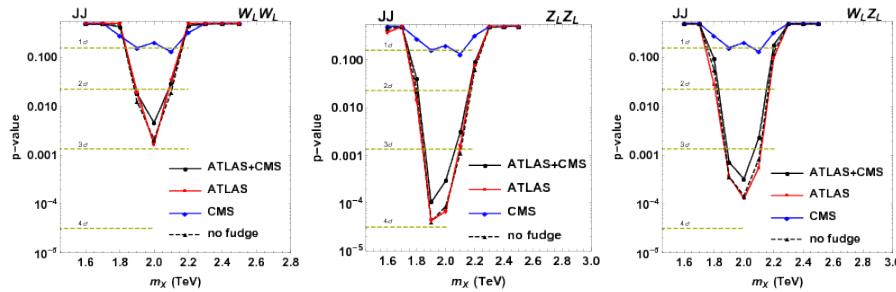


Figure 4.2: p-values as a function of resonance mass obtained with an emulation of the ATLAS (red) and CMS (blue) searches as well as the combination of the two (black). Here for a W W (left), W Z (middle) and Z Z (right) hypothesis [36].

The combination of the two excesses and the timing of the ATLAS paper, naturally lead to quite a commotion. And in the coming weeks, the arXiv was flooded with theory papers seeking an explanation for the measurements. The pressure on seeing early results with 13

TeV data in the VV all-hadronic final state was high, and it was agreed with CMS Physics Coordination that a preliminary analysis would be ready in December that same year, only 6 months after the first 13 TeV collision.

4.1.2 Analysis strategy

When a resonance X with a mass above 1 TeV decays into a vector boson pair, the bosons have a very high energy ($\tilde{p}_T = M_X/2 = 500 \text{ GeV}$, assuming X is produced at rest). The boson is co-called "boosted". The decay products of a hadronically decaying boosted vector boson, will therefore not appear as back-to-back in the lab frame but rather be very collimated, as described in Section 3.5. This results in a final state with two large high- p_T jets, where an AK R=0.8 jet is expected to fully contain the two quarks coming from the vector boson decay. This is illustrated in Figure 4.3.

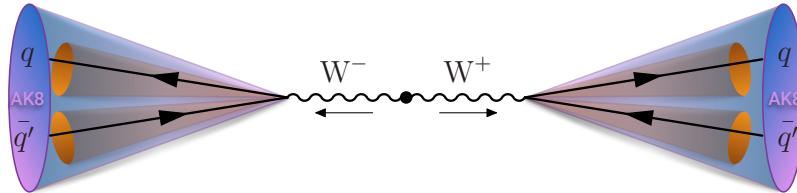


Figure 4.3: If a heavy ($> 1 \text{ TeV}$) resonance decays into vector bosons, the transverse momentum of each boson will be large and its decay products are merged into one single large cone AK8 jet.

The two jets are both expected to have a mass around the W or Z mass, and some intrinsic substructure stemming from their two-prong origin. The invariant mass of the dijet system, m_{jj} , should be roughly equal to the resonance mass M_X . This dijet system is the final state under scrutiny and the dijet invariant mass is the parameter of interest. Both WW and ZZ, as well as WZ final states are of interest.

The main background for such an analysis, is QCD multijet events. As mentioned in Section 3.5, quark/gluon jets can obtain a high mass due to diffuse radiation and QCD processes have such a large cross section that the number of QCD jets with a mass compatible with the W mass can be large. In order to discriminate between the two, we take advantage of three properties: 1. The groomed mass of signal and background jets should be very different, 2. signal jets should appear two-prong like, quark/gluon jets not, and 3. the dijet invariant mass for a signal process should peak around the resonance mass while the QCD spectrum is predicted to be smoothly falling (we will get back to why this assumption is justified in Section 4.1.4). The strategy therefore consists of performing a smoothness test on m_{jj} of the observed data, a so-called "bump-hunt", by assuming that the signal will appear as a bump on top of a smooth distribution. This is illustrated in Figure 4.4.

The benefit of such a method is that there is no need for any background simulation and the strategy is simple and robust. The disadvantage is that the analysis is intrinsically limited to regions where the dijet invariant mass spectrum is smooth, hence must avoid regions with continuities due to trigger turn-ons or kinematic selections.

4.1.3 Event selection

Triggering

The first selection to be confronted in any analysis, is the trigger selection. Due to an overwhelming QCD background in all-hadronic final states, the threshold for fully-hadronic

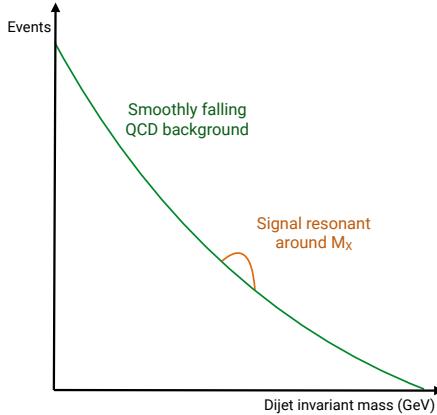


Figure 4.4: The search strategy consists of looking for signal "bumps" in the dijet invariant mass on top of a smoothly falling QCD multijet background.

triggers is very large in order to keep the trigger rate low (preferably around 10-30 Hertz). In this analysis, we therefore decided to take advantage of triggers that place requirements on the jet groomed mass in addition to the "standard" triggers based on the scalar sum of jet transverse energy H_T . These "boosted" triggers were never before tested in data, and this analysis was the first published result taking advantage of grooming at the trigger level in CMS. The following H_T -based triggers (called inclusive triggers in the following) are used

- HLT_PFHT650_WideJetMJJ900DEtaJJ1p5
- HLT_PFHT650_WideJetMJJ950DEtaJJ1p5
- HLT_PFHT800

as well as two grooming triggers cutting on the jet trimmed mass (see Section 3.5.1) of 30 and 50 GeV

- HLT_AK8PFJet360_TrimMass30
- HLT_AK8PFHT700_TrimR0p1PT0p03Mass50

The tuneable parameters for the trimming algorithm at HLT, were set to $r_{sub} = 0.2$ and $p_{T,frac} = 0.03$. The HLT_AK8PFJet360_TrimMass30 trigger is seeded by single-object Level 1 triggers with jet p_T thresholds of 176 or 200 GeV (L1_SingleJet176 or L1_SingleJet200), and the remaining triggers requires an online $H_T > 150$ or 175 GeV (L1_HTT150 or L1_HTT175).

In order to avoid any kinks in the dijet invariant mass spectrum due to the presence of a trigger turn-on, we need to define for which dijet invariant mass the analysis triggers are fully efficient ($> 99\%$), then cut away everything below that point.

In order to estimate the trigger efficiency, we use a lower threshold prescaled H_T trigger HLT_PFHT650 as reference trigger. This trigger has a prescale of 40, meaning it only stores information for every 40 events that trigger it, and is seeded by L1 triggers L1_HTT150 or L1_HTT175. We then define the efficiency as

$$\text{Efficiency} = \frac{N_{trigger+ref}}{N_{ref}}$$

where $N_{trigger+ref}$ corresponds to events passing the trigger under study as well as the reference trigger and N_{ref} corresponds to all events passing the reference trigger.

Figure 4.5 shows the trigger turn-on curves as a function of dijet invariant mass for jets where one of the jets is required to have a pruned mass larger than 65 GeV (in other words, compatible with a W jet). A sharp turn-on for the inclusive triggers (left) is observed, reaching the 100% efficiency plateau for dijet masses of around 1.0–1.1 TeV. The grooming triggers, however, turn on more slowly and are not fully efficient before dijet invariant masses of around 1.2 TeV (right).

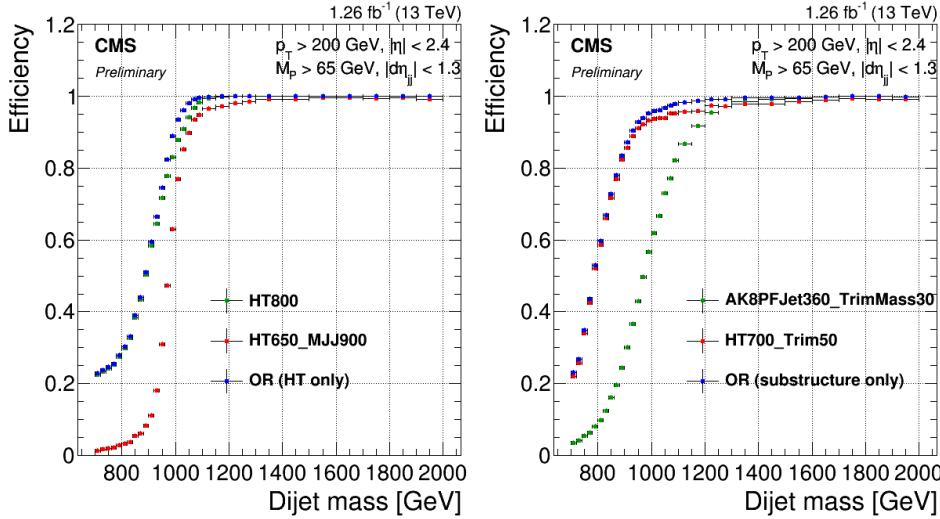


Figure 4.5: Efficiency for the inclusive triggers (left) and the grooming triggers (right) as a function of dijet invariant mass for jet pairs where one jet has a pruned mass larger than 65 GeV.

The real power of the grooming triggers become clear when adding them in OR with the H_T -based triggers. Figure 4.6 compares the trigger turn-on curves as a function of dijet invariant mass for jets passing one of the three inclusive triggers only, one of the grooming triggers only and when combining all of them. Here, one can see that the 99% efficiency threshold is lowered by 75 GeV when including the substructure triggers, once substructure is required at analysis level. This allowed for the analysis to start at a dijet invariant mass of 1 TeV.

As a measure of the performance of the grooming triggers, we have in addition looked at the trigger efficiencies as a function of the offline groomed mass (pruned and softdrop, see Sections 3.5.1 and 3.5.1), for the grooming trigger with the lowest mass threshold (30 GeV). This is shown in Figure 4.7, where an additional cut on the jet transverse momentum of one of the jets of 600 GeV is required and no other mass cut is applied. The trigger plateau is reached for offline groomed-jet masses around 50 GeV, an impressively sharp turn-on for a trigger paths first test i data (as reference trigger for this study, the prescaled trigger HLT_PFJet320 was used).

Preselection

After trigger selections and the corresponding requirement of a dijet invariant mass above 1 TeV to ensure a smoothly falling background, the process of maximizing the signal significance while keeping the background low can begin. This is done through a set of jet requirements. The jets used in this analysis are clustered with the anti- k_T jet clustering algorithm with a clustering parameter of $R = 0.8$ (see Section 3.4) to allow containment of the full vector boson decay products. These jets are further required to pass certain jet identification requirements

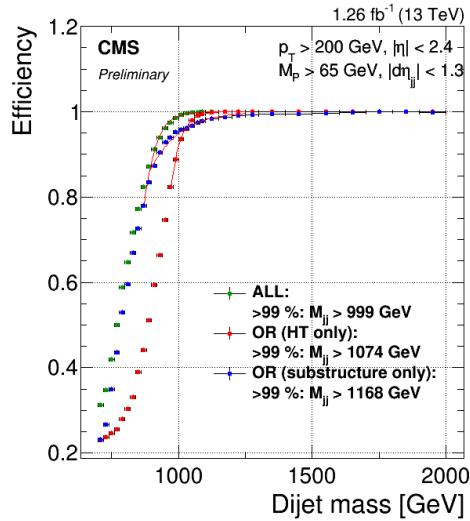


Figure 4.6: Comparison of trigger efficiencies for jets passing one of the HT-triggers only (red), for jets passing one of the grooming-triggers only (blue) and for jets passing one of the HT-triggers or one of the grooming triggers (green). Here as a function of dijet invariant mass for all jet pairs passing loose selections and where one jet has a pruned mass larger than 65 GeV. The 99% efficiency threshold is lowered by 75 GeV when including substructure taggers.

provided by the JetMET POG [37], in order to distinguish them from fake jets. These are as follows:

- Number of Constituents > 1 , for all jet η
- Neutral Hadron Energy Fraction < 0.90 , for all jet η
- Neutral EM Energy Fraction < 0.90 , for all jet η
- Charged Hadron Multiplicity > 0 , for jet $|\eta| < 3.0$
- Charged EM Energy Fraction < 0.99 , for jet $|\eta| < 3.0$

Jets are further corrected for nonlinearities in p_T and rapidity using standard jet energy corrections at CMS as described in Ref. [38] for $R=0.8$ anti- k_T jets. As we know that a minimum transverse of 200 GeV is required for the decay products of a W/Z to be fully contained within an $R=0.8$ jet, events are further selected by requiring at least two jets with $p_T > 200$ GeV. These are in addition required to be central, with an $|\eta| < 2.4$.

The two highest p_T jets in the event passing these criteria are selected as potential vector boson candidates. As our main background is QCD multijet events, we further take advantage of the fact that the angular distribution between these, mainly t-channel, processes are very different from the s-channel signal processes under study. The QCD t-channel jets are mostly forwardly produced, with an opening angle with respect to the beam axis close to zero, while the signal jets are concentrated in the barrel region. We therefore require the jets to have a separation of $|\Delta\eta| < 1.3$ in order to reduce the QCD multijets background. The distribution of $|\Delta\eta|$ between the two highest- p_T jets for QCD as well as for different signal scenarios, is shown in Figure 4.8

A summary of the applied preselections is as follows:

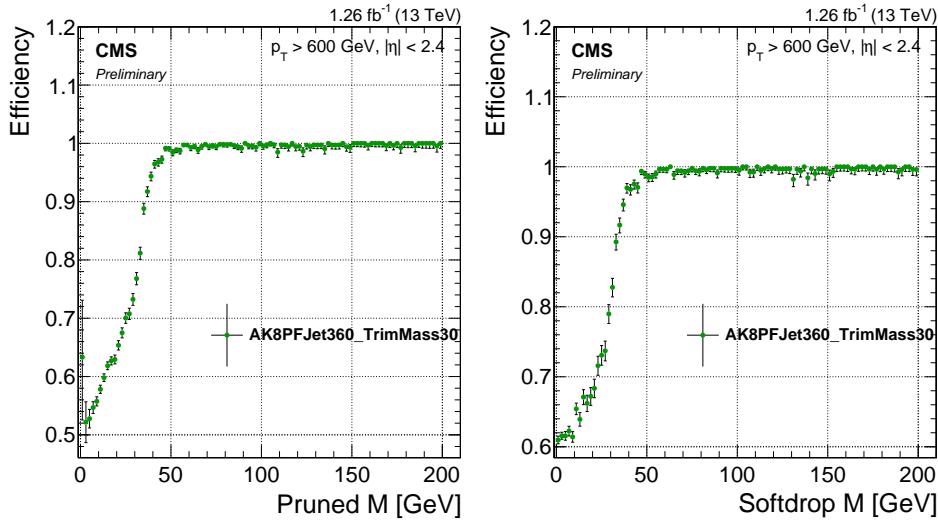


Figure 4.7: Efficiency for the lowest threshold grooming trigger as a function of pruned-jet (left) and softdrop-jet (right) mass for jets with $p_T > 600 \text{ GeV}$.

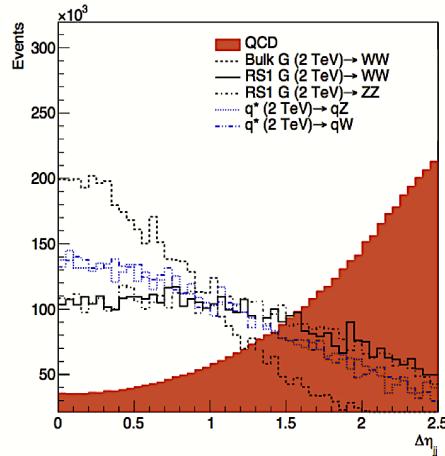


Figure 4.8: $|\Delta\eta|$ between the two highest- p_T jets for QCD jets and jets stemming from different signal scenarios.

Vector boson tagging

4.1.4 Background modeling

4.2 Search II: Developing a new pileup resistant and infrared safe tagger

With the first 13 TeV search for dibosons published and the awareness that the pileup in 2016 would double with respect to what was observed in 2015, the development of new and more robust taggers was the main focus of 2016.

4.3 Search III: A novel multi-dimensional search

After two successful analyses of 13 TeV data, no excess had been observed in the all-hadronic VV channels.

CHAPTER 5

LoLa: A novel Machine Learning W-tagger for future analyses

- 5.1 Machine Learning: The future of high-performance, low-latency taggers**
- 5.2 LoLa: A Lorentz Invariance Based Deep Neural Network for W-tagging**
 - 5.2.1 Inputs**
 - 5.2.2 The Combination Layer**
 - 5.2.3 The Lorentz Layer**
- 5.3 Decorrelating from mass and p_T**
- 5.4 Performance**

CHAPTER 6

Summary

.1 Data versus MC in 2015 data

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