
**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

Statistical Methods

2.1 Statistical methods: Confidence Limits

CHAPTER 3

Experimental setup

3.1 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 folds 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 3.1.

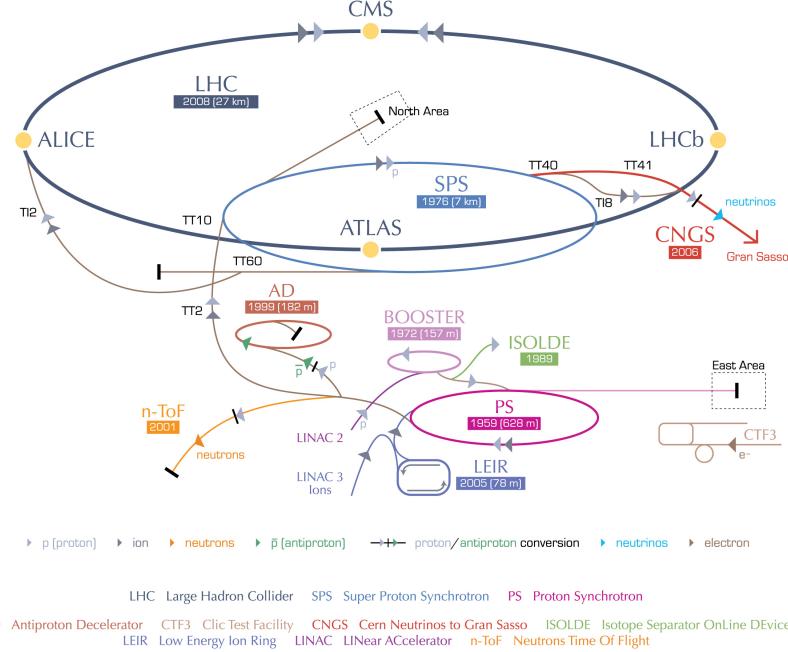


Figure 3.1: The Large Hadron Collider accelerator complex. The four collision points along the ring correspond to the location of the LHC particle detectors CMS, LHCb, ATLAS and ALICE [1].

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

$$\frac{dN_{events}}{dt} = \mathcal{L}\sigma. \quad (3.1)$$

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 barn = 10^{-28} 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

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi\epsilon_n\beta_*} F, \quad (3.2)$$

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 3.1: 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

$$\mathcal{L}_{int} = \int \mathcal{L} dt. \quad (3.3)$$

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 3.1

3.2 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 3.2. In the following, the different sub-detectors will be described in detail.

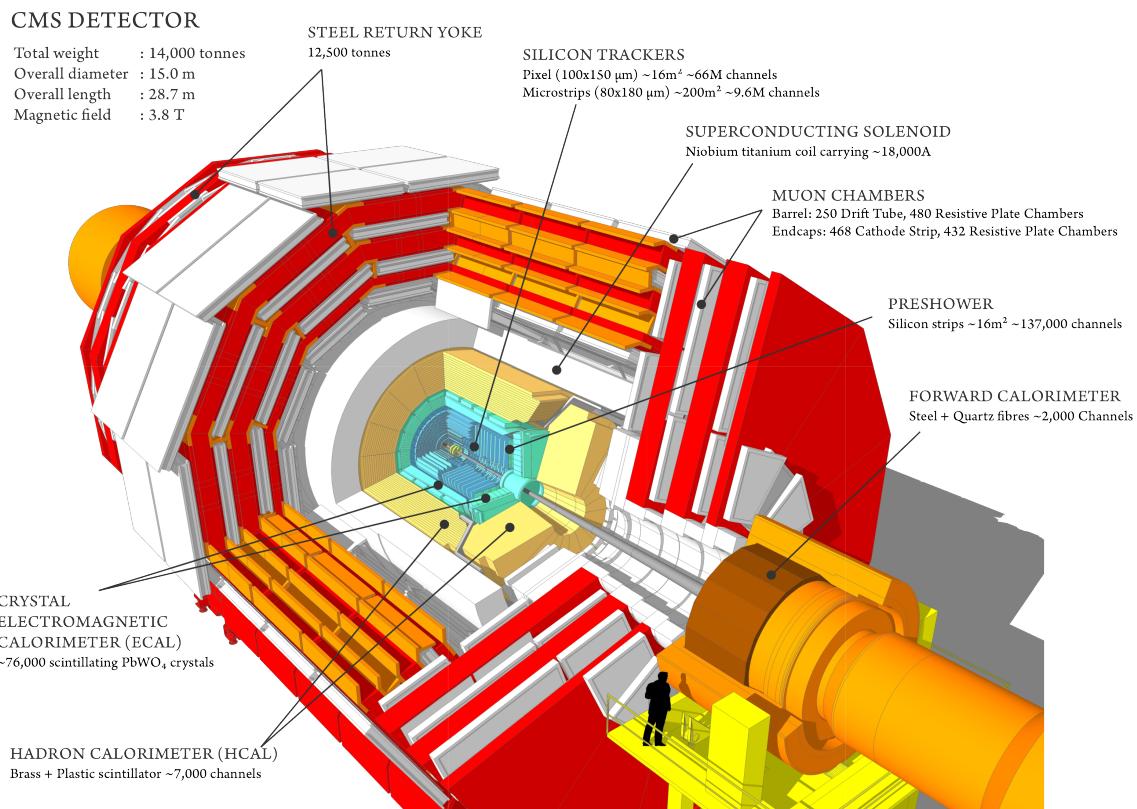


Figure 3.2: The CMS detector and its subsystems: The silicon tracker, electromagnetic and hadron calorimeters, the superconducting solenoid and the muon chambers inter-layered with the steel return yoke [2].

3.2.1 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 3.3.

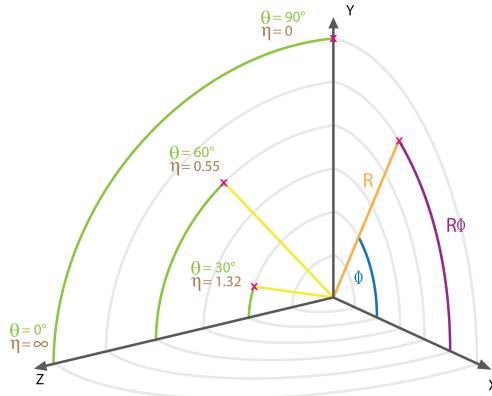


Figure 3.3: The CMS coordinate system [3]

3.2.2 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 3.4. 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.

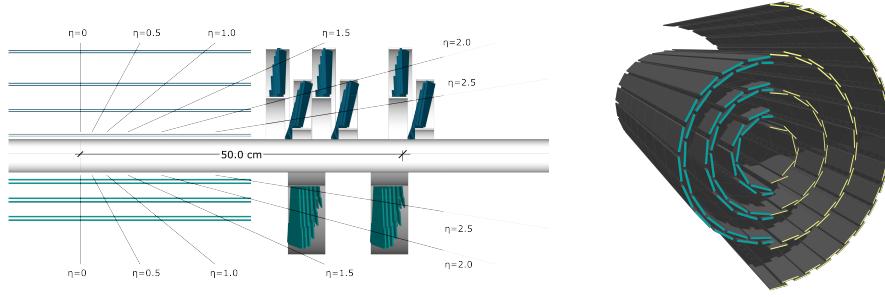


Figure 3.4: Left: The forward pixel detector layout before (bottom) and after (top) the Phase-I upgrade. Right: The barrel pixel detector before (left) and after (right) the Phase-I upgrade [4].

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 3.5. 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 $\sigma/p_T \approx 1.5 \times 10^{-5} p_T \oplus 0.005$.

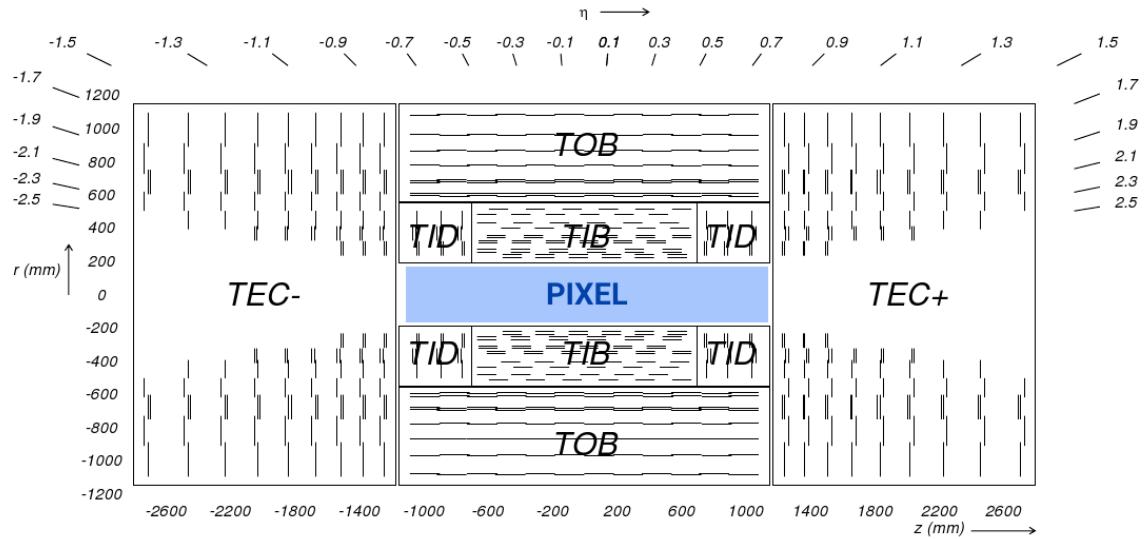


Figure 3.5: Schematic of the CMS silicon strip tracker and its four subsections: The inner barrel (TIB), inner endcaps (TID), the outer barrel (TOB) and the two endcaps (TEC) [5].

3.2.3 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 3.6.

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 3.7.

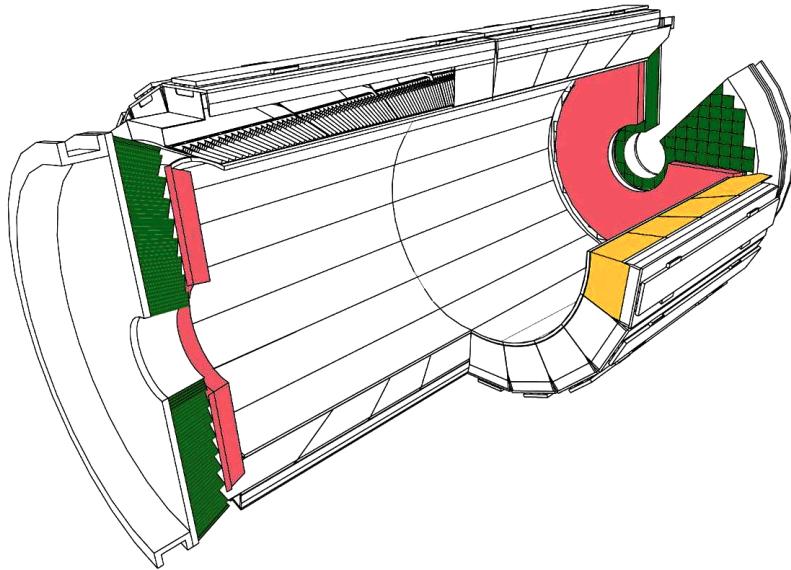


Figure 3.6: A schematic of the CMS electromagnetic calorimeter showing the barrel supermodules (yellow), the individual barrel crystals (black,top left), the endcap modules (green) and the pre-shower detectors (pink) [5].

3.2.4 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 3.8.

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 3.9.

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

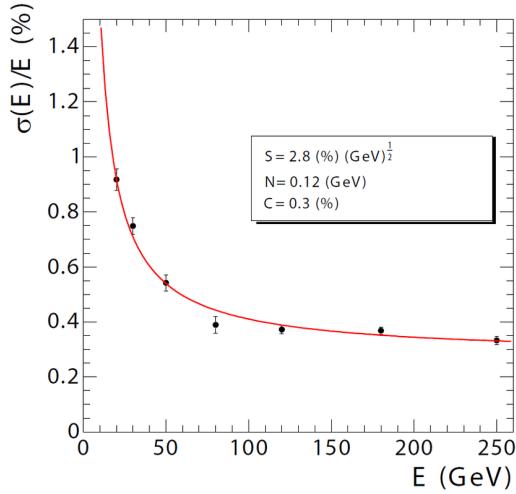


Figure 3.7: The ECAL energy resolution as a function of electron energy as measured in an electron test beam. [6]

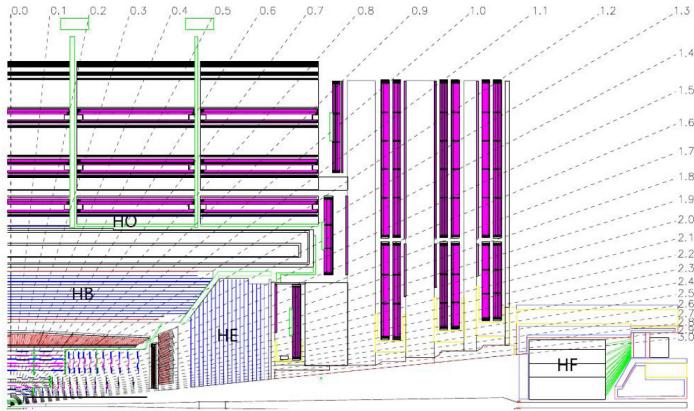


Figure 3.8: The four regions of the CMS hadron calorimeter: the inner (HB) and outer (HO) barrel, the endcap (HE) and the forward region (HF) [5]

(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 3.9: 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 3.10.

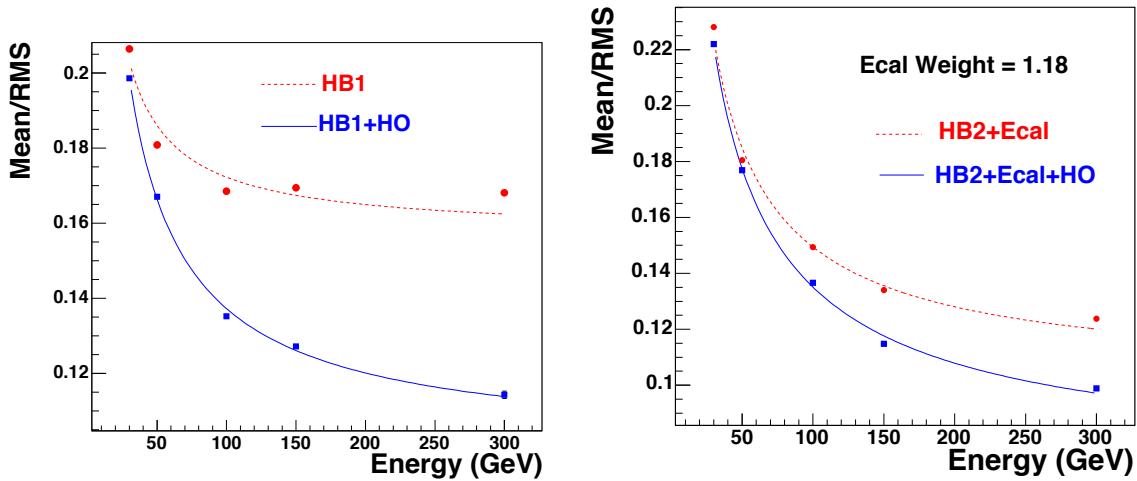


Figure 3.10: The calorimeter energy resolution as a function of pion energy using the HB only or HB+HO (left) and when adding ECal and HCAL measurements (right) [9].

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

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

3.2.5 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 3.11.

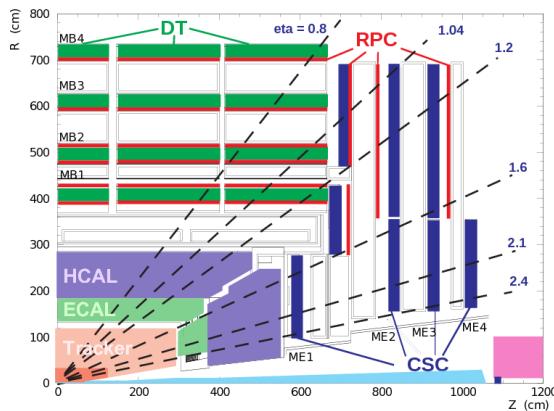


Figure 3.11: A schematic overview of the muon chambers: the DT chambers in the barrel, the CSCs in the endcaps and the redundant RPC system stretching out to $|\eta| < 1.6$ and used for triggering purposes [10].

3.3 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 4

Event reconstruction

4.1 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 4.1, with a combined average of 34 number of interactions per bunch crossing.

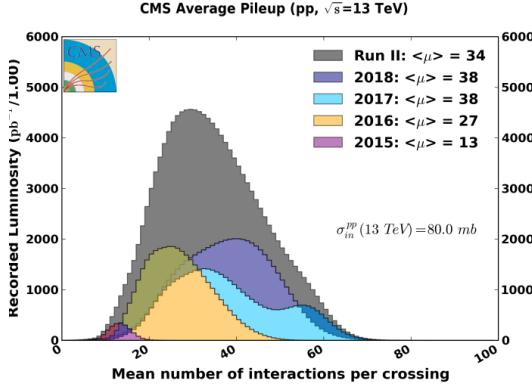


Figure 4.1: The average number of vertices per event in CMS during the Run 2 datataking [11].

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.

4.2 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 4.2.

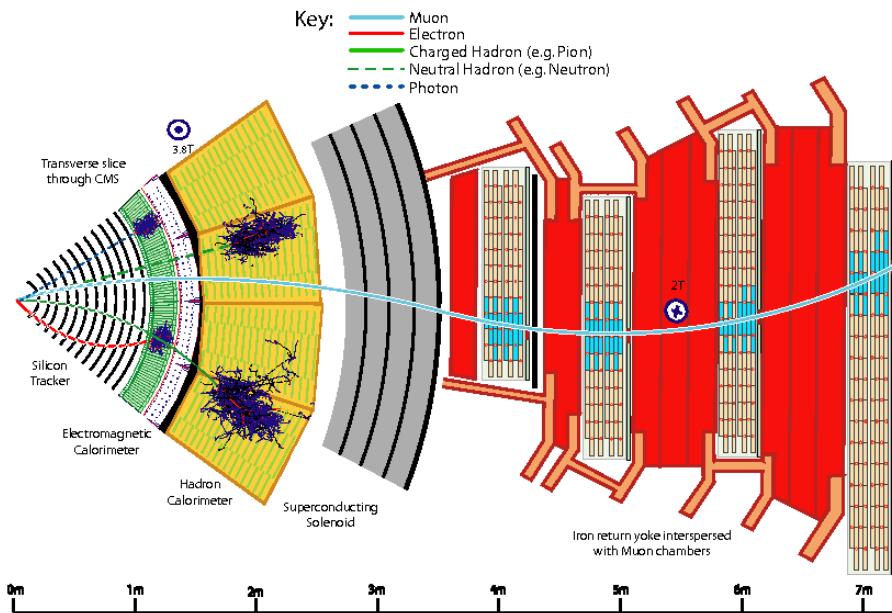


Figure 4.2: Particle interactions in the different subdetectors for a transverse slice through the CMS detector [13].

4.2.1 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 4.3, 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 4.3, 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.

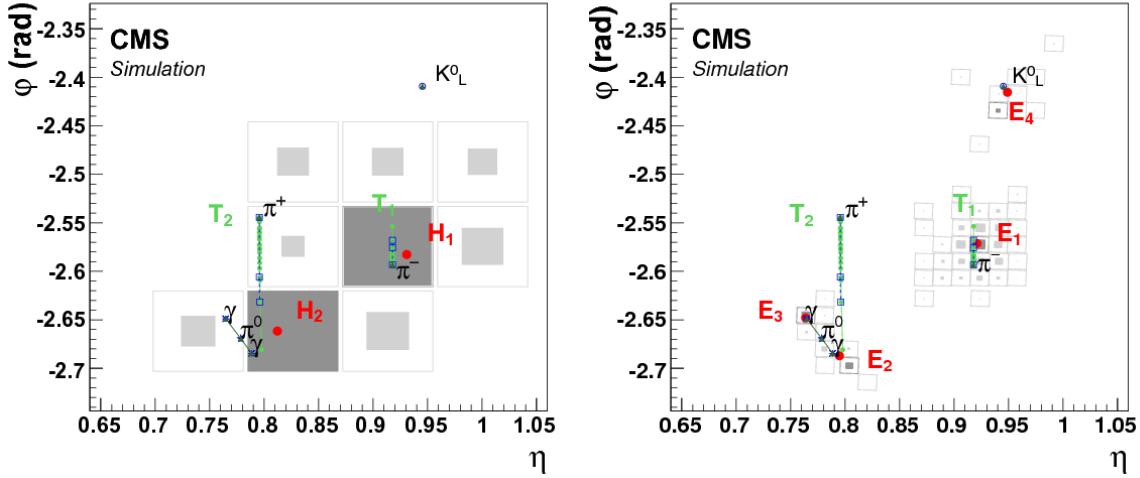


Figure 4.3: The $\eta - \phi$ vies of calorimeter clusters generated by a five-particle jet in the HCAL (left) and in the ECAL (right). The squares correspond to calorimeter cells, where the inner area is proportional to the logarithm of the cell energy. Cluster seeds are depicted in dark gray. The dotted blue lines correspond to the simulated particle trajectory, while the green lines correspond to charged tracks reconstructed in the tracker [13].

4.2.2 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 4.2.1

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.

Muons used in this thesis are required to pass an isolation requirement in order to suppress the background from QCD multijet events where jet constituents are identified as muons. For this, a cone of radius $\Delta R = 0.3$ is constructed around the muon direction. The isolation parameter is defined as the scalar sum of the transverse momenta of all additional reconstructed tracks within the cone, divided by the muon p_T . Muon candidates with an isolation parameter less than 0.1 are considered isolated and are used for further analysis. Further, the following selection criteria are applied:

- The χ^2 of the global muon track fit must be less than 10
- At least one muon-chamber hit is included in the global-muon track fit. The global muon track fit must include at least one muon chamber hit
- Muon segments in at least two of the muon stations must be matched to the muon tracker track
- The inner tracker track must be no more than 2 millimeters from the primary vertex in the xy plane and no more than 5 millimeters in the longitudinal direction
- At least one hit in the pixel detector.
- At least six layers of the inner tracker must contain hits.
- At least three matching track segments must be found in the muon detectors

Electrons

The electrons are seeded from a GSF track, as described in Section 4.2.1. 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.

Only electrons passing certain quality requirements, corresponding to the CMS electron HEEP ID, are used in this thesis. These requirements are listed in Table 4.1, with the following variable definitions:

- E_T : The supercluster energy $x \sin(\theta_{track})$ where θ_{track} is the electron track polar angle measured in the inner tracker layer and extrapolated to the interaction vertex.
- η^{sc} : η of the electron supercluster.
- **isEcalDriven**: Electron is found through ECAL requirements rather than through Particle Flow and the tracker.
- $\Delta\eta_{in}^{seed}$: η difference between the track position measured in the inner layer, extrapolated to the interaction vertex and to the calorimeter, and the η of the supercluster.
- $\Delta\phi_{in}$: ϕ difference between the track position measured in the inner layer, extrapolated to the interaction vertex and to the calorimeter, and the ϕ of the supercluster.
- **H/E**: Ratio of hadronic energy in the calorimeter towers within a cone of radius 0.15 centered at the electrons calorimeter position, to the electromagnetic energy of the supercluster.
- $\sigma_{in\eta}$: Measure of the energy spread in η in units of crystals of electron energy in a 5×5 block centered on the seed crystal.
- **ECAL Isolation**: The transverse electromagnetic energy of all reconstructed hits (with $E > 0.08$ GeV) in a cone of radius 0.3 centered at the electron calorimeter position, excluding those in an inner cone with a radius of 3 crystals and an η strip with a width of 3 crystals.
- **Hadronic Depth Isolation**: Defined as the transverse depth of the hadronic energy in the HCAL inside a cone of 0.3 centered on the electron calorimeter position, excluding towers in a cone of 0.15 radius.
- **Track p_T Isolation**: The sum p_T of the tracks in a ΔR cone of 0.04 to 0.3, excluding an η region of 0.015.
- d_{xy} : Transverse distance between the electron track and the primary vertex.

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, together with one charged hadron for each track within the cluster area.

Variable	Barrel	Endcap
E_T	$> 35 \text{ GeV}$	$> 35 \text{ GeV}$
η range	$ \eta_{sc} < 1.4442$	$1.566 < \eta_{sc} < 2.5$
isEcalDriven	yes	yes
$\Delta\eta_{lin}^{seed}$	< 0.004	< 0.006
$\Delta\phi_{in}$	< 0.06	< 0.06
H/E	$< 1/E + 0.05$	$< 5/E + 0.05$
full 5x5 $\sigma_{i\eta i\eta}$	n/a	< 0.03
full 5x5 E^{2x5}/E^{5x5}	$> 0.94 \text{ OR } E^{1x5}/E^{5x5} > 0.83$	n/a
EM+Had. Depth Iso.	$< 2 + 0.03 \times E_T + 0.28 \times \rho$	For $E_T < 50 \text{ GeV}$: $< 2.5 + 0.28 \times \rho$ else: $< 2.5 + 0.03 \times (E_T - 50) + 0.28 \times \rho$
Track p_T iso.	For $E_T < 100 \text{ GeV}$: $< 5 \text{ GeV} / < 5 + 1.5 \times \rho$ else: $< 5 + 1.5 \times \rho$	$< 5 + 0.5 \times \rho$
Inner Layer Lost Hits d_{xy}	≤ 1 < 0.02	≤ 1 < 0.05

Table 4.1: Summary of the electron requirements allied to all electrons used in this analysis.

Missing transverse energy

Neutrinos (and other predicted non-SM weakly interacting particles) do not interact in the detector and are instead inferred from the presence of a momentum imbalance in the detectors transverse plane. The missing transverse momentum is defined as the negative p_T vector sum of all reconstructed PF candidates in the event

$$\vec{p}_T^{\text{miss}} = - \sum_i^N \vec{p}_{T,i}. \quad (4.1)$$

and its magnitude, $|\vec{p}_T^{\text{miss}}|$, is denoted the missing transverse energy E_T^{miss} (which is used as a proxy for the neutrino p_T).

4.3 Pile-up removal

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

4.3.1 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).

4.3.2 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

$$\alpha_i = \log \sum_{\substack{j \in \text{Ch}_i, \text{PV} \\ j \neq i}} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2 \Theta(R_0 - \Delta R_{ij}), \quad (4.2)$$

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

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU})^2}{RMS_{PU}^2}, \quad (4.3)$$

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 4.4.

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.

4.4 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.

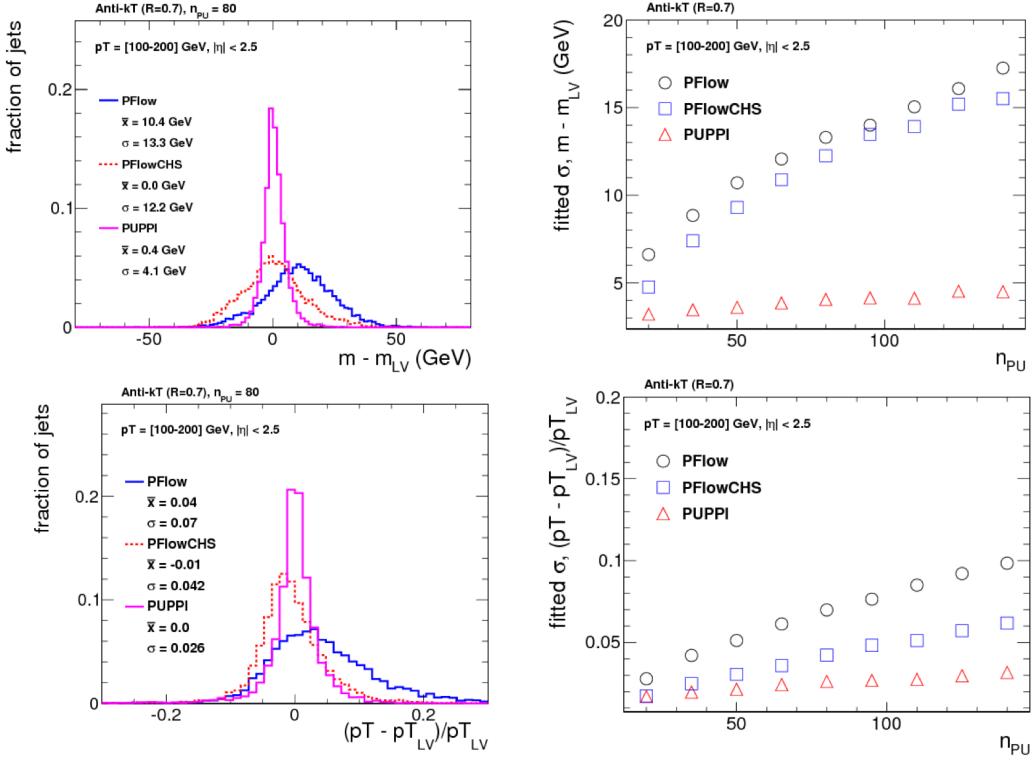


Figure 4.4: The mass (top) and p_T (bottom) resolution comparing PF only (blue), PF+CHS (red) and PUPPI (pink) jets. The absolute resolution (left) as well as the resolution as a function of the number of reconstructed primary vertices in the event (right) is shown [16].

4.4.1 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:

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

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \text{ with } \Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \quad (4.4)$$

$$d_{iB} = p_{ti}^{2p}, \quad (4.5)$$

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.

2. Find the minimum distance of d_{ij} and d_{iB} .
3. If this is d_{ij} , recombine particles i and j and return to step 1.

4. 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.
5. 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 4.5.

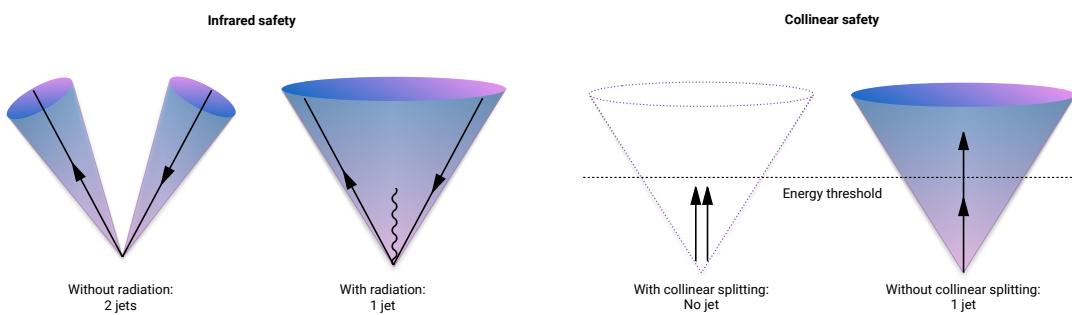


Figure 4.5: An illustration of what would happen for an infrared (left) and collinear (right) unsafe jet algorithm. If an algorithm is infrared unsafe, the presence of a soft emission changes the jet configuration. If an algorithm is collinear unsafe, then if a parton undergoes a collinear splitting 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 4.5, 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 4.5.

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 from 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 4.6. 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.

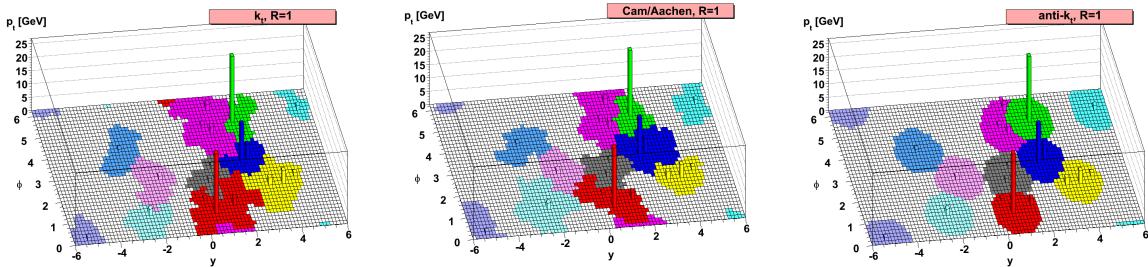


Figure 4.6: A comparison of the resulting jet cone area in the $\phi - \eta - p_T$ plane after clustering the same event with three different jet algorithms: k_T , C/A and anti- k_T . [19]

4.4.2 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 4.3.1), charged hadrons not associated to the primary vertex are discarded before clustering. If PUPPI is used (Section 4.3.2), 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.

These jets are further required to pass certain jet identification requirements provided by the JetMET POG [20], in order to distinguish them from fake jets. All jets used in this analysis are required to pass the *tight ID* requirements which are as follows:

- The jet must contain at least two PF constituents

- At least one of these constituents must be a charged hadron
- The fraction of jet energy coming from neutral hadrons must be < 0.90
- The fraction of jet energy coming from neutral electromagnetic energy must be < 0.90
- The fraction of jet energy coming from charged electromagnetic energy must be < 0.99

4.4.3 Jet energy corrections

All jets are further corrected for nonlinearities in p_T and rapidity using standard CMS jet energy corrections (JEC), as described in Ref. [21]. These are intended to bring the measured jet energy closer to the true jet energy by correcting the jet energy scale (JES) and jet energy resolution (JER). The energy corrections are derived in three steps:

- L1: Energy offset corrections intended to remove pileup and electronic noise, both for data and simulation
- L2L3: A relative (L2) and absolute (L3) correction to particle level jet response for simulation only
- Residual: A correction for data only meant to correct for residual differences between data and simulation

These are illustrated in Figure 4.7.

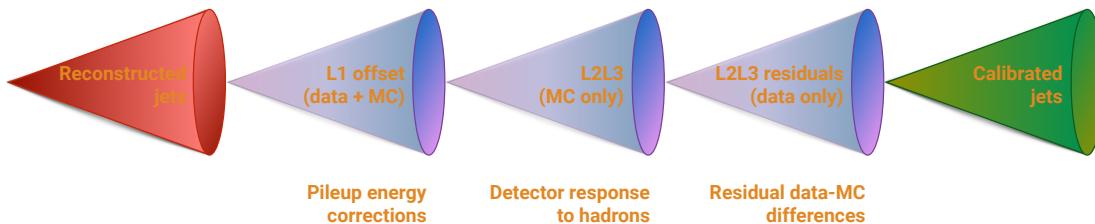


Figure 4.7: The CMS jet energy corrections are derived in three steps: A correction due to offset energy coming from pileup, applied to data and MC, a correction due to the particle level jet response, also applied to data and MC and finally a correction to account for residual differences between data and MC.

L1 offset correction

The largest correction is the L1 pileup offset correction, which are meant to subtract the additional energy in a jet due to pileup. This is done on an event-by-event basis through the *jet area method* which uses the jet effective area multiplied by the average event energy density to calculate the size of the offset energy to be subtracted from each jet. An additional p_T - and η -dependent term is added in order to account for different pileup densities in different parts of the detector and for different jet energies. For data, an additional scalefactor to account for data and simulation differences is computed. This is done by constructing a *Random Cone (RC)* centered at a given η, ϕ and dividing the energy density within that cone in data, evaluated in a dataset with no hard interactions (*Zero Bias*), by that of the true energy offset in simulation

L2 relative and L3 absolute corrections

After L1 corrections are applied, corrections to account for the detector response to hadrons are derived based on the true detector response in QCD MC. The simulated particle response is defined as the ratio

$$R_{\text{particle}} = \frac{p_{T,\text{reco}}}{p_{T,\text{particle}}} \quad (4.6)$$

These are derived in bins of particle level p_T and reconstructed η : The L2 relative corrections are intended to uniform the detector response and are derived as a function of η , while the L3 absolute corrections are derived as a function of jet p_T . These corrections are applied both to data and to MC.

Residual data corrections

After L1 and L2L3 corrections are applied, two additional corrections are derived for data only in order to account for any residual discrepancies between data and MC. This is done by looking at the transverse momentum balance between a jet which is to be calibrated, and some reference object (either another jet, a Z boson or a photon). If the jet energy scale is not equal to one, a p_T imbalance will be visible. The measurements are performed in a data dijet sample, where the statistical uncertainty is small but the energy of the reference object poorly measured, as well as in $Z(\mu\mu)+\text{jet}$, $Z(ee)+\text{jet}$ and $\gamma+\text{jet}$ samples, where the energy of the Z and γ is very well known but the statistics are small.

The ‘L2 relative’ residual correction is measured in dijet events by comparing the measured p_T of the reference jet, required to be central with $\eta < 1.3$, to that of the calibration jet, with an unconstrained η . This is done as a function of jet η , in bins of average jet p_T . The ‘L3 relative’ residual correction, is instead measured in $W/\gamma + \text{jet}$ events by comparing the measured jet p_T to the p_T of the precisely measured Z/γ , as a function of jet p_T . The response,

$$R_{\text{jet},p_T} = \frac{p_{T,\text{jet}}}{p_{T,\text{ref}}}$$

is then evaluated in data and in simulation. The ratio of the two, $R_{\text{data}}/R_{\text{MC}}$, defines the residual corrections.

The above description of jet energy corrections in CMS is meant as a rough, instructive summary only. A full description of the measurement techniques used in CMS, can be found in [21].

4.5 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

$$\Delta R = \frac{2M_V}{p_{T,V}}. \quad (4.7)$$

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 4.8. 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).

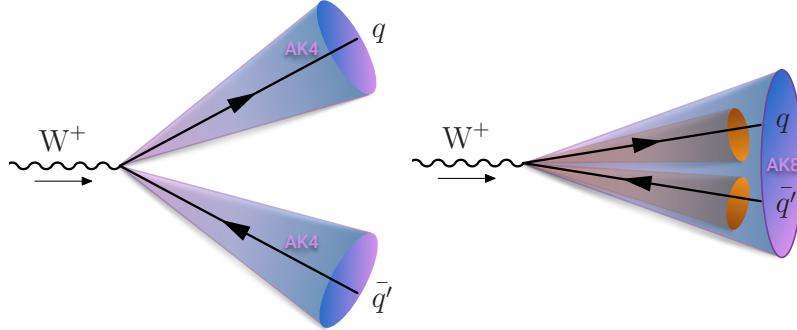


Figure 4.8: If the mass of the resonance is low enough, the quark decay products of each vector boson are well separated and clustered into distinguishable AK4 jets (left). If the transverse momentum of the vector boson is greater than 200 GeV, the vector boson decay products are merged into one single 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.

4.5.1 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 [22] 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 4.9. 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 $p_{T,frac} = 0.03$).

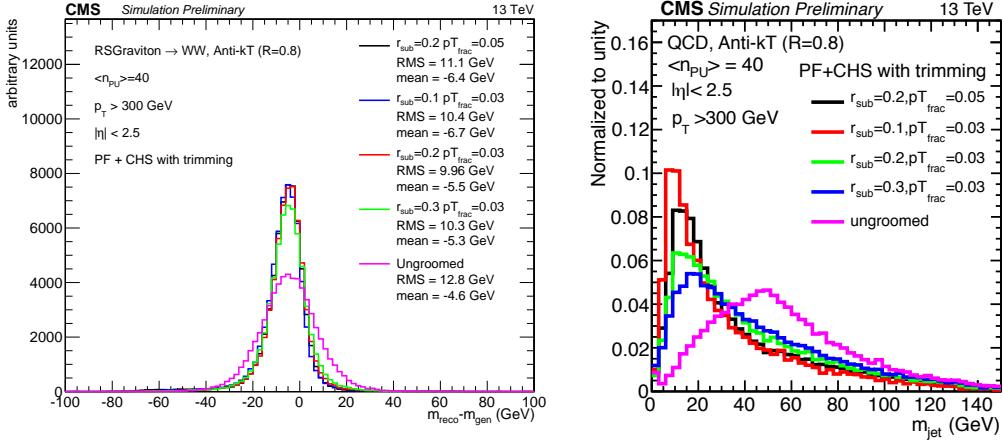


Figure 4.9: The effect of trimming on a signal jet (left) and a background jet (right) for different values of the tuned parameters r_{sub} and $p_{T,frac}$ [23].

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 4.10 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 $z_{cut} = 0.1$.

Modified Mass Drop Tagger and Soft Drop

The modified mass drop tagger (mMDT) [24] (a modified version of the originally suggested mass drop tagger [25]) 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

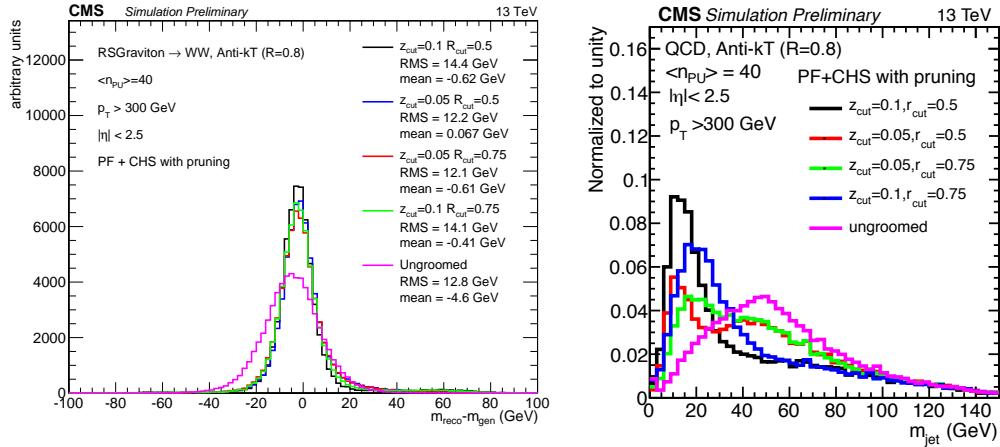


Figure 4.10: The effect of pruning on a signal jet (left) and a background jet (right) for different values of the tuned parameters z_{cut} and r_{cut} [23].

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 [26], simply called Soft Drop, which allows for different types of angular requirements to enter the condition. The Soft Drop condition is the following

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

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 4.11. The modified mass drop tagger (Softdrop with $\beta=0$) with $z_{\text{cut}} = 0.1$ is the default Soft Drop settings in CMS, due to it providing the best signal/background discrimination while maintaining an excellent signal mass resolution.

4.5.2 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 4.12.

The N-subjettiness algorithm [27] 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

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}) \quad (4.8)$$

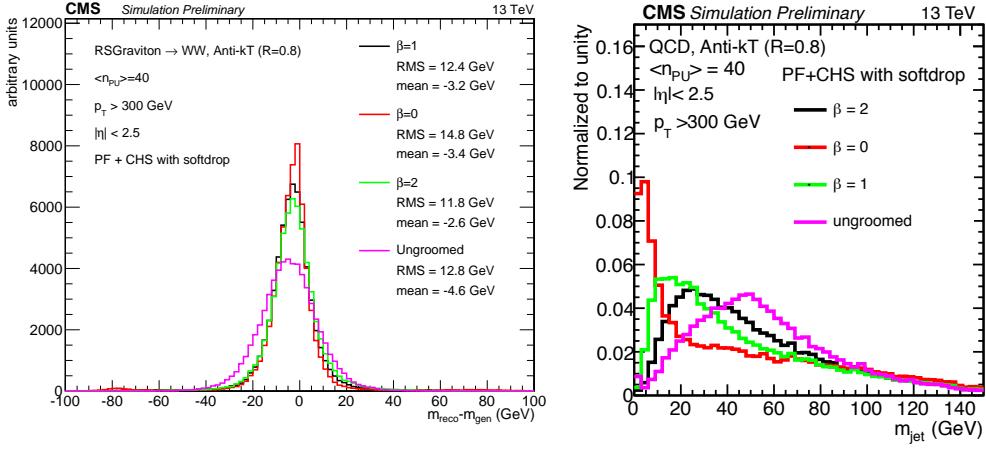


Figure 4.11: The effect of softdrop on a signal jet (left) and a background jet (right) for different values of the tuned parameters β . $\beta = 0$ corresponds to the Modified Mass Drop Tagger, which is the default Softdrop setting in CMS [23].

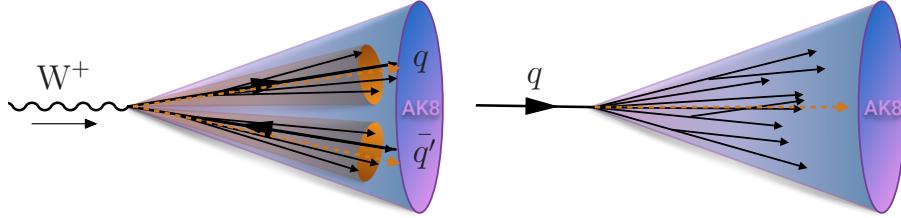


Figure 4.12: A jet stemming from the decay of a W will usually have two well-separated high- p_T subjets, while a jet with a single-prong origin consists of several large angle splittings.

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 [28]. The normalization factor in front is given as

$$d_0 = \sum_k p_{T,k} R_0 \quad (4.9)$$

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 [27], 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 4.13, where τ_{21} in combination with PF+PUPPI (green) yields a distribution most similar to the generated one (black).

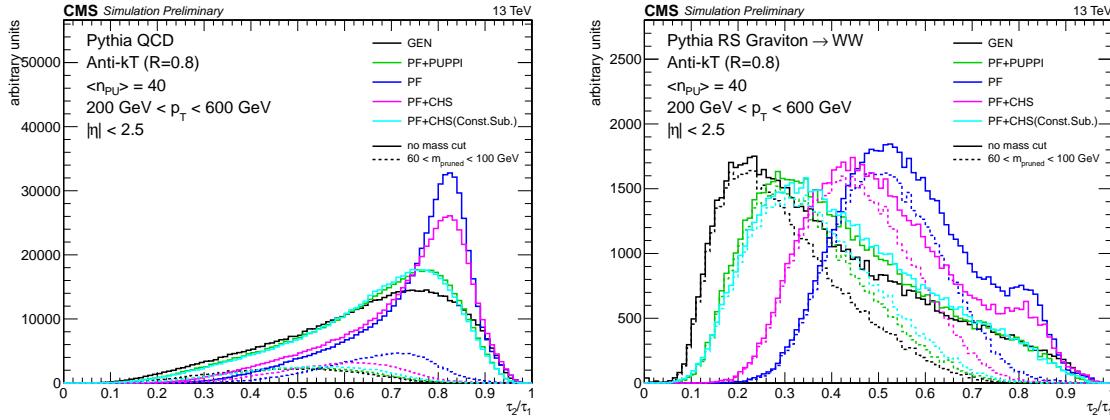


Figure 4.13: The distribution of the n-subjettiness ratio τ_{21} for signal jets (left) and background jets (right) with different combinations of pileup subtraction algorithms applied. The solid lines corresponds to the τ_{21} distribution with no mass cut applied, while the dotted lines are within a mass window of 60-100 GeV [23].

4.5.3 Vector boson tagging

In order to discriminate W and Z bosons from quark/gluon jets a combination of a groomer and shape-tagger (like n-subjettiness) is usually used. Typical values for a W-tagger are jet groomed mass between 60 and 100 GeV and $\tau_{21} < 0.5$. Which combination and which cuts to use is analysis dependent, and have been optimized for each search presented in this thesis. The details are thoroughly explained in each section.

Polarization effects

The vector boson polarization has a significant effect on the W-tagging efficiency. The helicity angle θ , defined as the angle between the outgoing quark daughters of the W in the W bosons rest frame relative to its direction of motion [29], is very different for longitudinally polarized vector bosons, W_L , and transversally polarized vector bosons W_T [30]. Figure 4.14 shows the $\cos \theta^*$ distribution for the outgoing quarks from a $W_L \rightarrow q\bar{q}$ (black) and $W_T \rightarrow q\bar{q}$ (red) decay, and it can be observed that transversely polarized W bosons decay with the quarks emitted closer to the vector boson direction of motion.

The consequence of this, is that there is a higher asymmetry in the transverse momenta of the two quarks from a W_T decay. This in turn makes grooming algorithms, designed to remove soft constituents of a jet, tend to reject particles coming from the softer quark, resulting in a lower jet mass and a drop in tagging efficiency. Figure 4.15 shows the W-jet tagging efficiency versus q/g jet mistagging rate for a selection on the jet pruned mass of $60 \text{ GeV} < m_{\text{pruned}} < 100 \text{ GeV}$, scanning τ_{21} cuts (here for CA R=0.8 jets).

The tagging efficiency for transversely polarized W bosons (green) is significantly lower than the tagging efficiency for longitudinally polarized bosons (red). This can be explained by looking at the $\cos \theta^*$ distribution on reconstructed level, using the C/A subjets, with a cut on the jet pruned mass of $60 \text{ GeV} < m_{\text{pruned}} < 100 \text{ GeV}$, shown in Figure 4.16. When comparing to the distribution at generator level with no groomed mass window applied, Figure 4.14, one can see that the W_T jets with $\cos \theta^* \approx 1$ are completely removed.

This is due to two effects: the p_T -asymmetry explained above and the fact that the ΔR distribution between the two quarks is much smaller in the case of W_L , making them more likely to be fully contained within a jet cone of $R=0.8$.

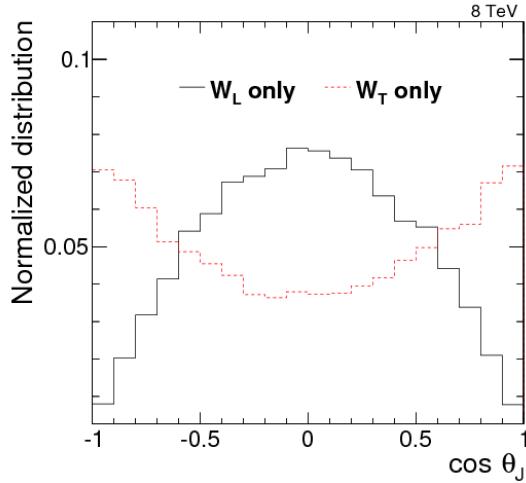


Figure 4.14: The helicity angle for generated quarks from $W_L \rightarrow q\bar{q}$ (black) and $W_T \rightarrow q\bar{q}$ (red) decays [30].

4.6 Monte Carlo Event Generators

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 ++ [31] and PYTHIA 8 [32], 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 [33]. 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 [34, 35] and POWHEG [36]. 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 [37], 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 [38]. Top quark pair

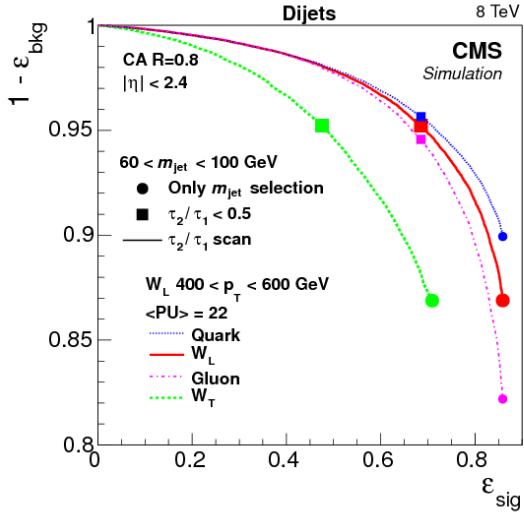


Figure 4.15: The helicity angle for generated quarks from $W_L \rightarrow q\bar{q}$ (black) and $W_T \rightarrow q\bar{q}$ (red) decays [30].

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.

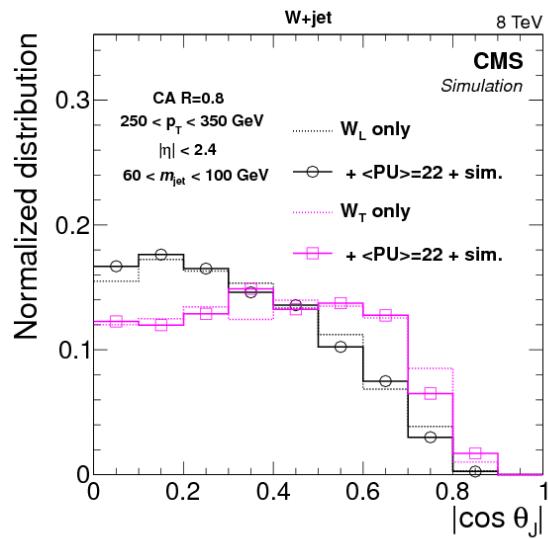


Figure 4.16: The helicity angle for subjets from $W_L \rightarrow q\bar{q}$ (black) and $W_T \rightarrow q\bar{q}$ (pink) decays. [30].

CHAPTER 5

Diboson resonance searches in CMS

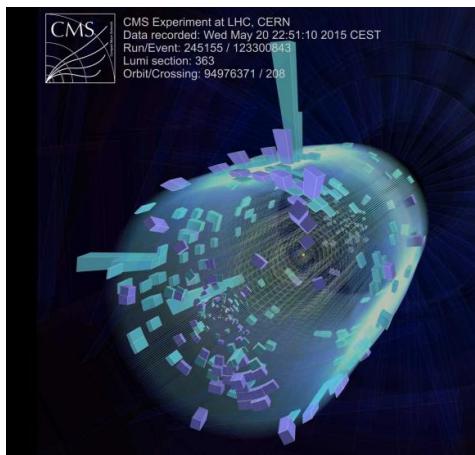
5.1 Search I: First search for diboson resonances at 13 TeV

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 Higgs boson for which the LHC was designed to find had been discovered at the end of the previous data taking era, leaving us with a Standard Model that we know is, in the best case, in need of extensions and, in the worst case, an effective theory valid only in a certain energy domain. The Run II search program 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 had to consider the following: 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’), would be manageable for a student with no previous analysis experience and would be robust enough incase there were issues with the never-before-validated 13 TeV Monte Carlo?

The attention of the high-energy physics community has in the past years been focused on certain ‘hot topics’: 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, attention was centered on 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 analysis.

This search became one of the first ‘boosted’ searches published with 13 TeV data as well as the first search to take advantage of dedicated ‘grooming’ (see Section 4.5.1) triggers.



5.1.1 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’ [33]. 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 [39]. Figure 5.1 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.

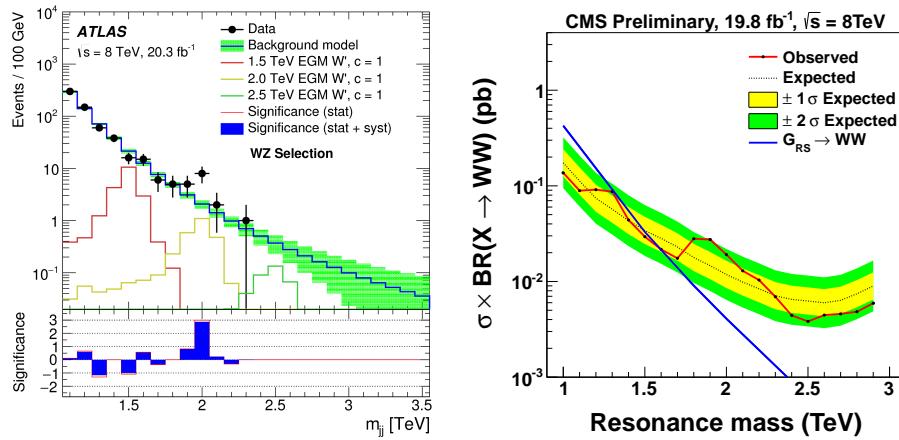


Figure 5.1: The mass (top) and p_T (bottom) resolution comparing PF only (blue), PF+CHS (red) and PUPPI (pink) jets. The absolute resolution (left) as well as the resolution as a function of the number of reconstructed primary vertices in the event (right) is shown [16].

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 [40]. Figure 5.2 show the obtained p-value of the ATLAS (red) and CMS (blue) search as well as their combination (black).

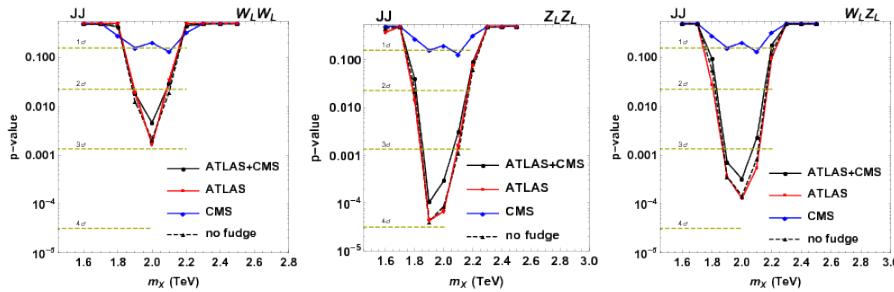


Figure 5.2: p-values as a function of resonance mass obtained with an emulation of the ATLAS (red) and CMS (blue) searches as well as the combination of the two (black). Here for a W W (left), W Z (middle) and Z Z (right) hypothesis [40].

The combination of the two excesses and the timing of the ATLAS paper, naturally lead to some excitement and in the coming weeks, the arXiv was flooded with theory papers seeking an explanation for the measurements.

In addition, one of the main benefits of increasing the LHC center-of-mass energy from 8 to 13 TeV, was that the partonic luminosity would increase. That meant that you could expect them same number of signal events as you would expect for the full 8 TeV dataset ($\sim 20 \text{ fb}^{-1}$), for a considerably smaller 13 TeV dataset. Figure 5.3 shows the system mass that can be probed with 3 fb^{-1} of 13 TeV data (y-axis), the expected 2015 integrated luminosity, as a function of the probe-able system mass with 20 fb^{-1} of 8 TeV data (x-axis) for different partonic channels. The probable 13 TeV mass is defined by finding the system mass which results in the same number of expected events at 8 TeV, if assuming cross sections scale with partonic luminosity and $1/m^2$. Three different partonic scattering channels are considered: qq, qg and gg. We see that, for instance for a resonance with a mass of 2000 GeV, the reach at 13 TeV is 2241(gg), 2091(qg), 1851(qq, one type) and 2046(qq, all types) GeV.

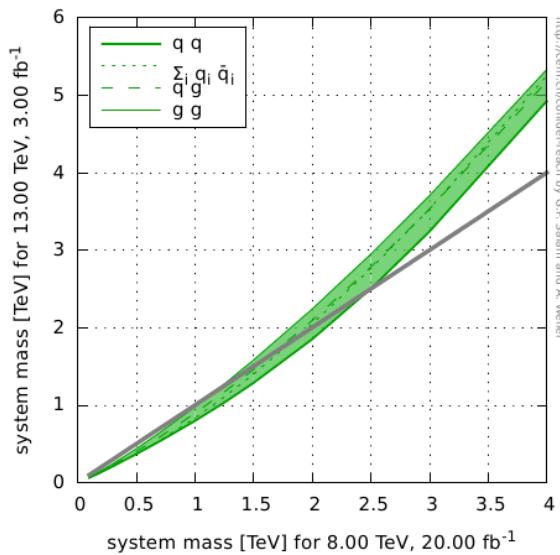


Figure 5.3: The system mass that can be probed with 3 fb^{-1} of 13 TeV data (y-axis) as a function of the probe-able system mass with 20 fb^{-1} of 8 TeV data (x-axis) for different partonic channels (Generated with [41]).

What this meant was that, if we saw hints of a 2 TeV G_{bulk} (mainly produced through gluon fusion, gg) with the 8 TeV dataset, we should be able to confirm it with nothing but the expected 3 fb^{-1} of data expected in 2015. The pressure on seeing early results with 13 TeV data in the VV all-hadronic final state was therefore extremely 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.

5.1.2 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 ($p_T \approx M_X/2 = 500 \text{ GeV}$, 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 4.5. 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 5.4.

The two jets are both expected to have a mass around the W or Z mass, and some intrinsic

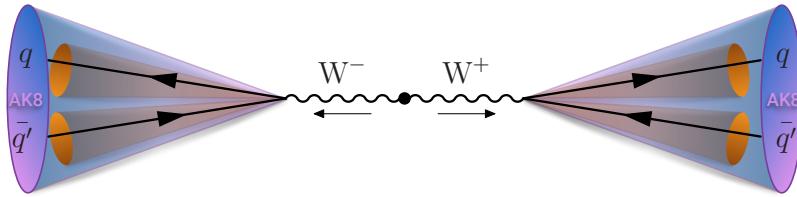


Figure 5.4: If a heavy (> 1 TeV) resonance decays into vector bosons, the transverse momentum of each boson will be large and its decay products are merged into one single large cone AK8 jet.

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 4.5, 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 5.1.5). 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 5.5.

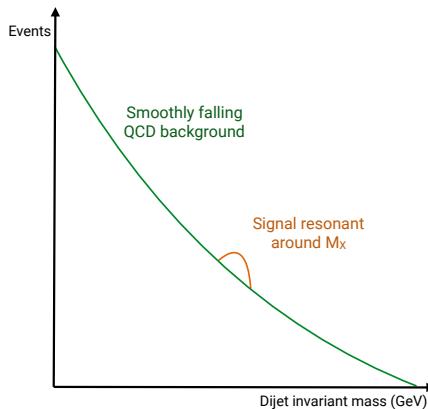


Figure 5.5: The search strategy consists of looking for signal ‘bumps’ in the dijet invariant mass on top of a smoothly falling QCD multijet background.

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.

5.1.3 Data and simulated samples

The data analyzed in this search correspond to a total integrated luminosity of 2.7 fb^{-1} collected at a center-of mass energy of 13 TeV between June and December 2015. The instantaneous luminosity of the LHC during this run was around half of the design luminosity ($0.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), with an average number of primary vertices per event of $\langle \mu \rangle = 13$.

The bulk graviton model (see Section 1.2.2) and the HVT model (W' and Z' , see Section 1.2.3) are used as benchmark signal processes. In these models, the vector gauge bosons are produced with a longitudinal polarization in more than 99% of the cases, which leads to a 24% higher acceptance per boson for reasons explained in Section 4.5.3. For the HVT model, a scenario (model B) with $g_V = 3$, $c_H = -0.976243$, and $c_F = 1.02433$ is chosen, where the heavy resonance predominantly couple to bosons and the coupling to fermions is suppressed. The bulk graviton samples were generated with $\tilde{k} = 0.5$. The resonance masses considered lie in the range 1.2 to 4 TeV and has a width of 0.1% of the resonance mass. The narrow width allows us to neglect detector effect as the natural width of the resonance is smaller than the detector resolution, making the modeling of detector effects on the signal shape independent of the model. All signal samples are generated at leading order with MADGRAPH5_AMC@NLO v2.2.2 [42].

Simulated samples of the production of QCD multijet events are generated to leading order using PYTHIA version 8.205 [43] with the CUETP8M1 tune [38].

5.1.4 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 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

where the two first triggers apply an additional cut on the $|\Delta\eta|$ between the two jets for reasons that will be explained below. In addition, two grooming triggers cutting on the jet trimmed mass (see Section 4.5.1) of 30 and 50 GeV are used

- HLT_AK8PFJet360_TrimMass30
- HLT_AK8PFHT700_TrimR0p1PT0p03Mass50.

The tuneable parameters for the trimming algorithm at HLT are $r_{sub} = 0.2$ 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

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

where $N_{\text{trigger+ref}}$ 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 5.6 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 (top 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 (top right). The real power of the grooming triggers become clear when adding them in OR with the H_T -based triggers. The bottom plot in Figure 5.6 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 4.5.1 and 4.5.1), for the grooming trigger with the lowest mass threshold (30 GeV). This is shown in Figure 5.7, 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 in data (as reference trigger for this study, the prescaled trigger `HLT_PFTJet320` was used).

Preselection

After trigger selections and the corresponding requirement of a dijet invariant mass above 1 TeV to ensure a smooth 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 4.4) to allow containment of the full vector boson decay products. 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 crosssection for QCD t-channel processes as a function of the opening angle with respect to the beam axis (θ^*), exhibit a

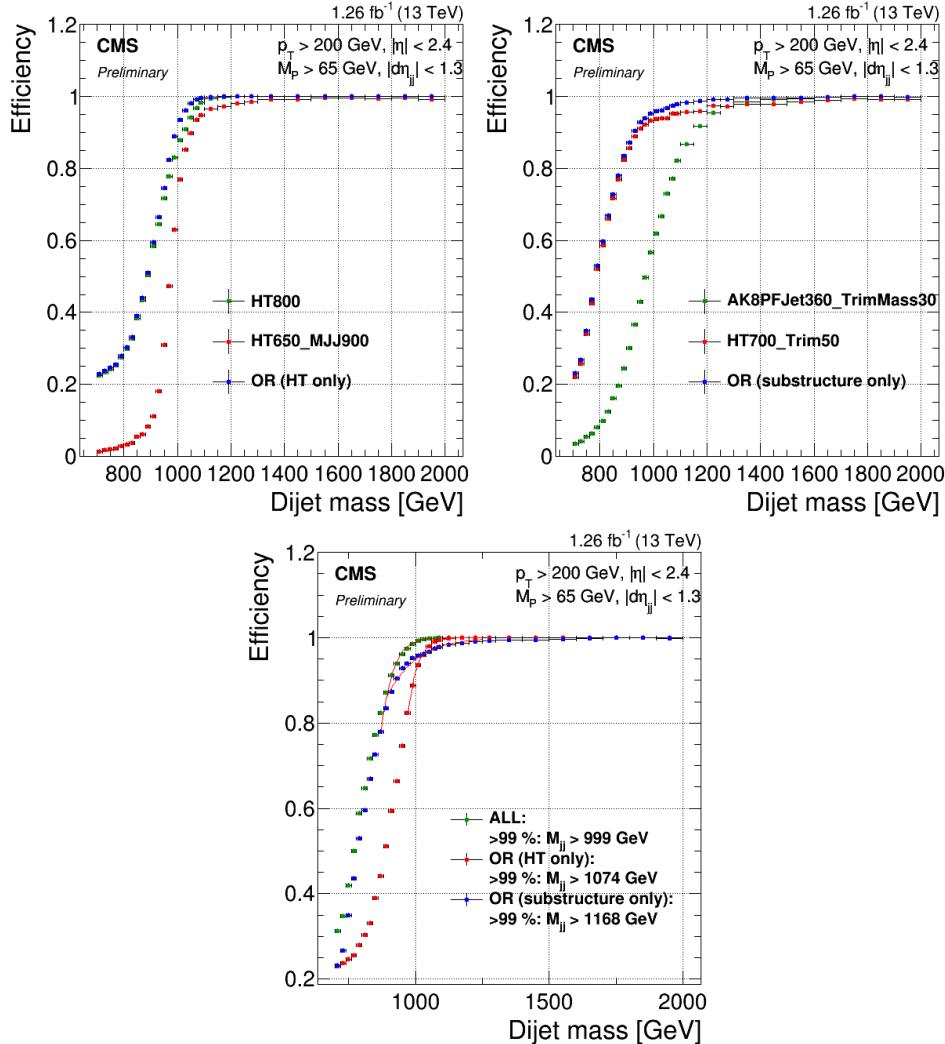


Figure 5.6: Top: Efficiency for the inclusive triggers (top left) and the grooming triggers (top right) as a function of dijet invariant mass for jet pairs where one jet has a pruned mass larger than 65 GeV. Bottom: Comparison of trigger efficiencies for jets passing one of the HT-triggers only (red), 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.

pole around $\cos\theta^* = 1$, meaning QCD t-channel jets are mostly forwardly produced, with an opening angle with respect to the beam axis close to zero. The signal jets on the other hand, produced through an s-channel process, 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 5.8

A cut of $|\Delta\eta|_{jj} < 1.3$ makes sure to remove the t-channel pole at $\cos\theta^* = 1$ and is in addition found to yield the best separation between signal and the QCD background.

The p_T , η , dijet invariant mass and $|\Delta\eta|_{jj}$ distribution for the two leading jets in the event after the above preselections have been applied is shown in Figure 5.9.

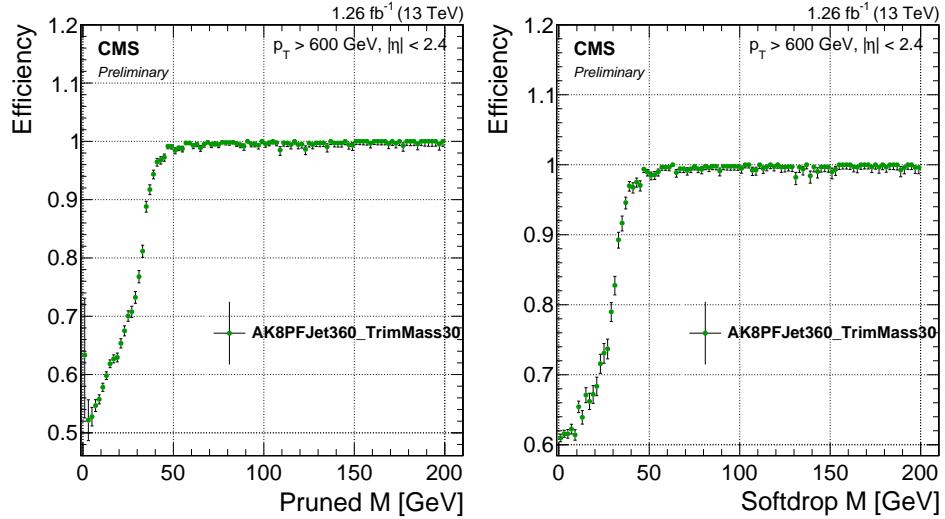


Figure 5.7: Efficiency for the lowest threshold grooming trigger as a function of pruned-jet (left) and softdrop-jet (right) mass for jets with $p_T > 600$ GeV.

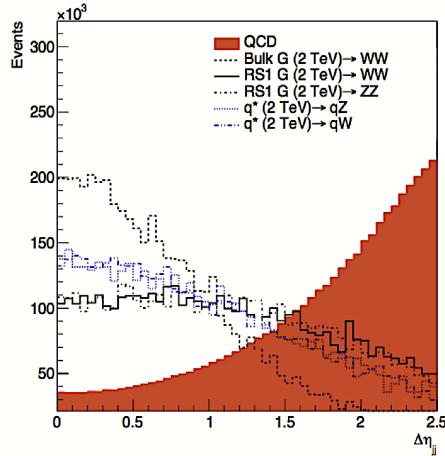


Figure 5.8: $|\Delta\eta|$ between the two highest- p_T jets for QCD jets and jets stemming from different signal scenarios.

Vector boson tagging

After preselections, we take advantage of the jet substructure algorithms described in Section 4.5 to further separate boosted W/Z jets from the QCD multijets background. In the 8 TeV analysis [39] published the previous year, the pruning algorithm was the groomer of choice. However, recent progress had been made in the development of alternative groomers which had favorable properties from a theoretical point of view (see Sections 4.5.1 and 5.2.5). We therefore studied two different grooming algorithms: pruning and softdrop (with $\beta = 0$ and $z_{cut} = 0.1$). A comparison of the softdrop (dotted lines) and pruned (solid lines) jet mass for W, Z and H jets is shown in Figure 5.10.

One of the first observations we made comparing the two groomers, was that there appeared to be a strong dependence of softdrop mass on the jet p_T . Figure 5.11 shows the pruned (left) and softdrop (right) mass distributions for W jets coming from the decay of a G_{bulk} with a resonance mass of $0.8 \text{ TeV} < M_X < 4 \text{ TeV}$. While the pruned jet mass mean appeared stable as the jet transverse momenta of the jet increased ($p_T \sim M_X/2$), the softdrop

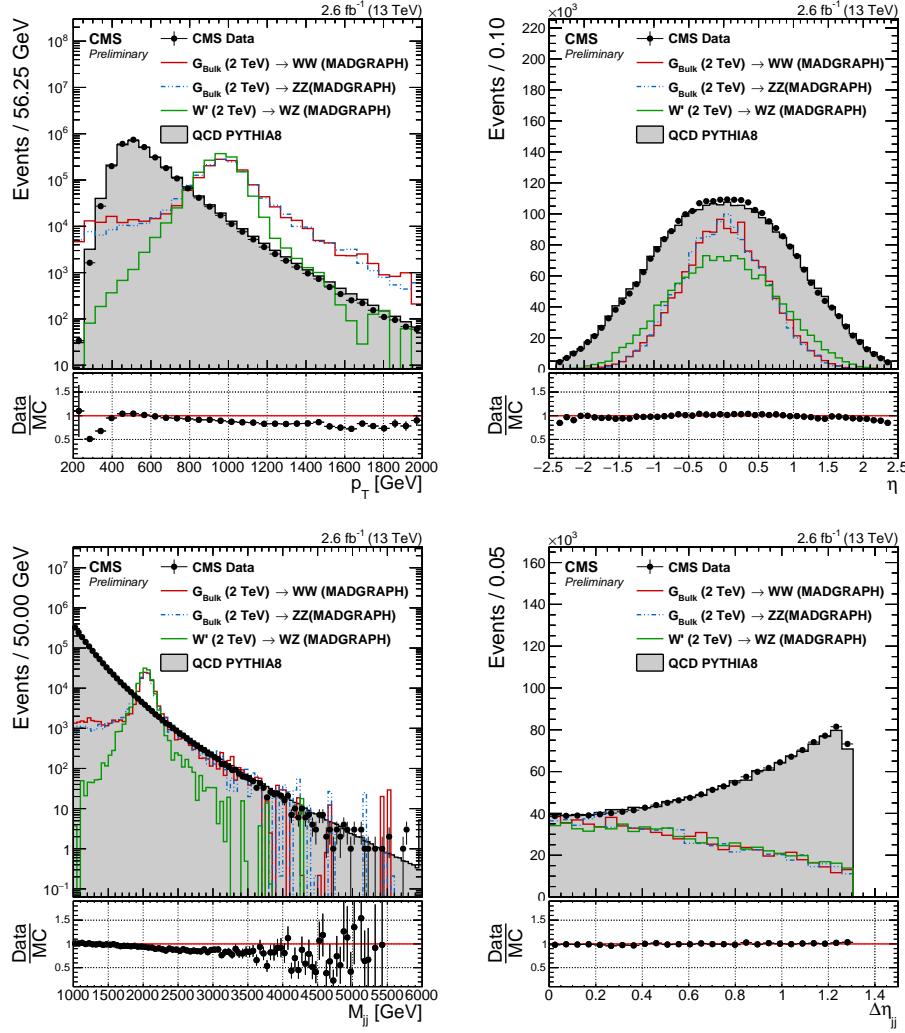


Figure 5.9: Jet p_T (top left), η (top right), dijet invariant mass (bottom left) and $|\Delta\eta|_{jj}$ (bottom right) distribution for the two leading jets in the event after loose preselections are applied. The signal is scaled by an arbitrary number.

jet mass mean shifted towards lower values as jet p_T increased.

In order to investigate whether this was a reconstruction effect or an algorithmic effect, we additionally looked at the pruned and softdrop mass for generator level jets (jets clustered with generator level particles before they are passed through the detector simulation). Figure 5.12 shows the reconstructed (solid line) and generator level (dotted line) jet mass distributions after pruning (left) or softdrop (right) have been applied. Again, the distributions are compared for jets with very different p_T profiles, here for W jets coming from a $G_{\text{bulk}} \rightarrow WW$ of mass $M_X = 0.8 \text{ TeV}$ (red), roughly $p_T \sim 400 \text{ GeV}$, and $M_X = 2.0 \text{ TeV}$ (blue), $p_T \sim 1 \text{ TeV}$. Interestingly, we observe a p_T -dependent mass shift already for generator level softdrop jets (comparing the dotted lines in the right plot); an effect further enhanced at reconstruction level. This effect is not present for pruned jets, neither at generator level nor reconstruction level.

The observed softdrop mass p_T -dependence was problematic, due to the fact that it would require a p_T dependent mass window. This would again require several different measurements of data to simulation tagging efficiency scale factors, for the respective mass windows, or a

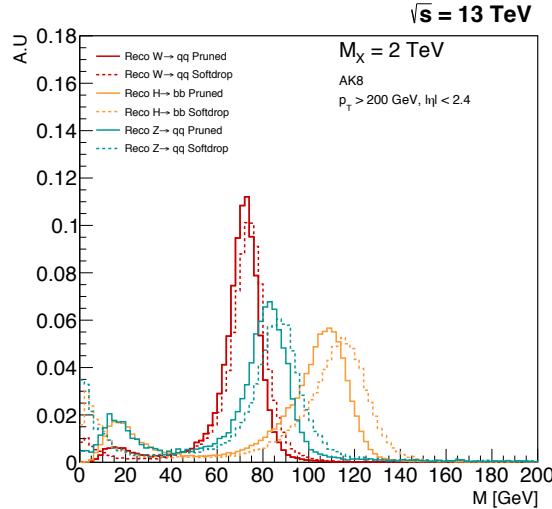


Figure 5.10: The softdrop (dotted lines) and the pruned (solid lines) jet mass for W, Z and H jets.

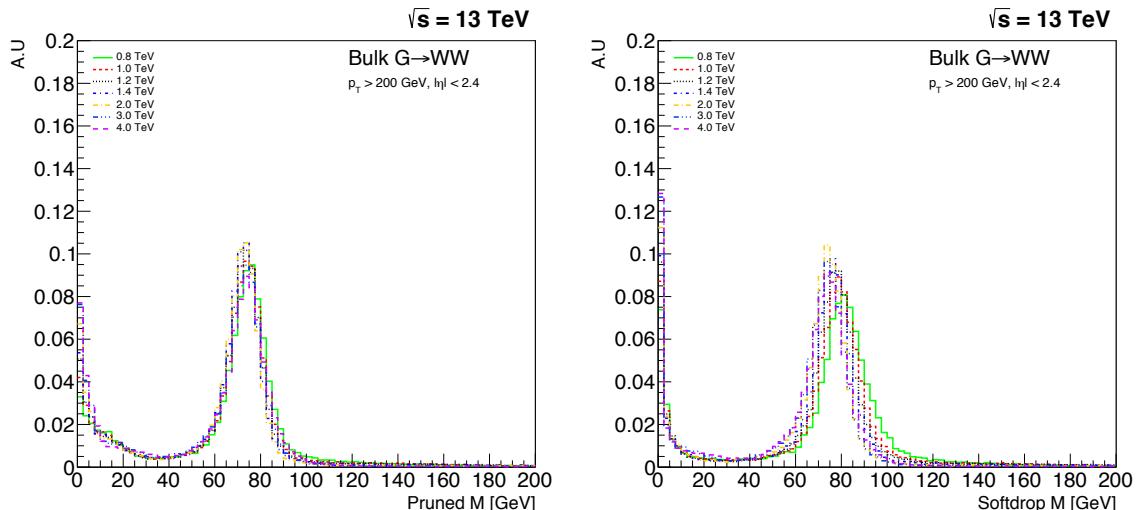


Figure 5.11: The jet mass distribution for W jets coming from a G_{bulk} of masses in the range $0.8 \text{ TeV} < M_X < 4 \text{ TeV}$ decaying to WW, here with pruning applied (left) and softdrop (right). A strong shift in the jet mass mean as a function of $p_T (\sim M_X/2)$, is observed for jets groomed with the softdrop algorithm. Charge hadron subtraction is applied to all jets before clustering.

significantly higher uncertainty on the signal yield. Due to these observations, the grooming algorithm of choice for this analysis is pruning, with $65 \text{ GeV} < m_{\text{pruned}} < 105 \text{ GeV}$. However, this would be a study we would return to in Search II (Section 5.2).

The shape tagger we chose for this analysis was the n-subjettiness ratio τ_{21} . τ_{21} is strongly correlated to the pruned jet mass, and the discriminating power of the variable is reduced when applying a pruned mass cut. The τ_{21} distribution for the QCD background and W jets from a signal decay before (left) and after (right) a pruned mass cut of $65 \text{ GeV} < m_{\text{pruned}} < 105 \text{ GeV}$ have been applied, is shown in Figure 5.13.

We therefore perform a cut optimization on τ_{21} after all analysis selections, including a

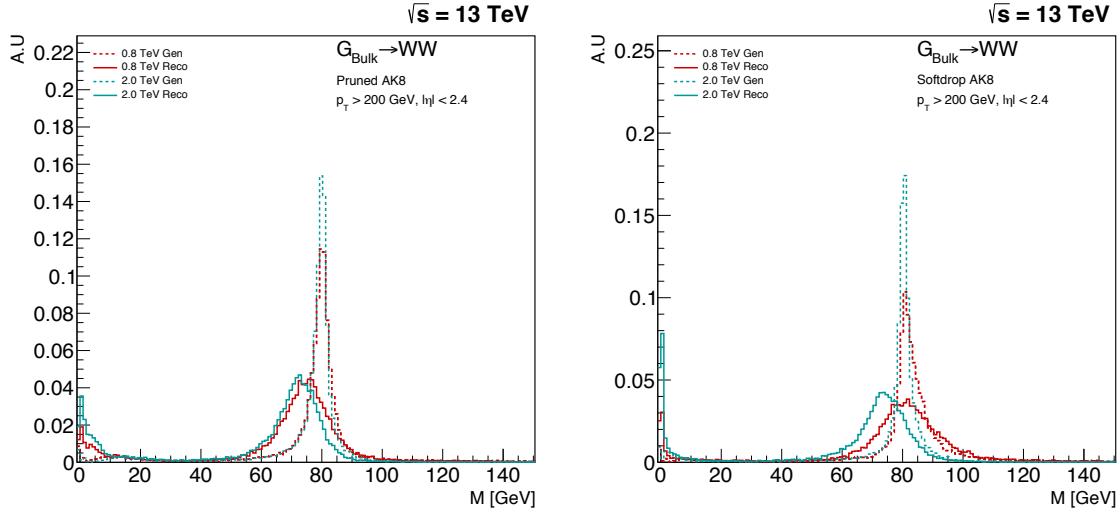


Figure 5.12: The reconstructed (solid line) and generator level (dotted line) jet mass distribution for W jets coming from a $G_{\text{bulk}} \rightarrow WW$ of mass $M_X = 0.8 \text{ TeV}$ (red), roughly $p_T \sim 400 \text{ GeV}$, and $M_X = 2.0 \text{ TeV}$ (blue), $p_T \sim 1 \text{ TeV}$. Here for the pruned (left) and softdrop (right) jet mass.

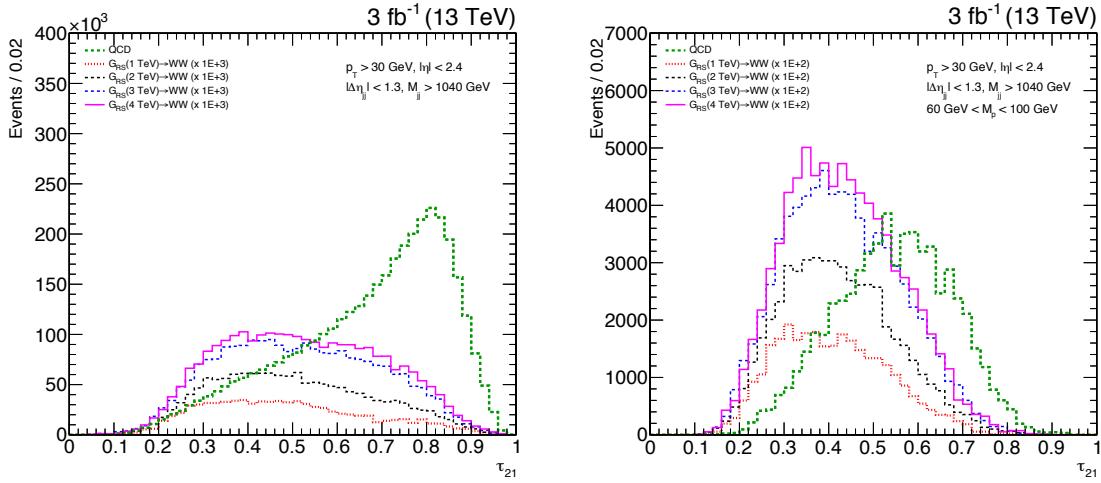


Figure 5.13: The τ_{21} distribution for QCD background and signal jets before (left) and after (right) a pruned mass window is applied. The discriminating power of τ_{21} is strongly reduced after grooming.

pruned mass window of $65 \text{ GeV} < m_{\text{pruned}} < 105 \text{ GeV}$, have been applied. This is done by scanning the τ_{21} cut, and for each cut computing the Punzi significance [44] defined as

$$S = \frac{\epsilon_S}{1 + \sqrt{B}}$$

where ϵ_S is the signal efficiency and B is the total background. The cut with the highest significance is defined as the optimal cut value. The signals under consideration are W jets coming from the decay of a G_{bulk} with $M_X = 1 - 4 \text{ TeV}$, against a background of light flavored QCD jets. Only jets with a dijet invariant mass in a 20% window around the resonance mass are considered. The Punzi significance as a function of the upper cut value on τ_{21} is shown on the left in Figure 5.14.

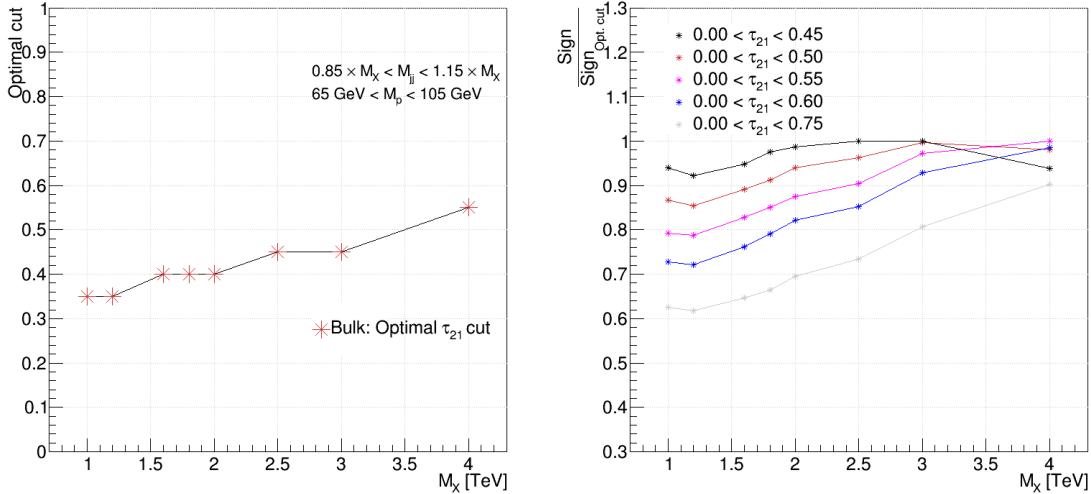


Figure 5.14: Optimal upper cut on τ_{21} as a function of G_{bulk} mass (left). The optimal τ_{21} selection for W' (HTV model) resembles the Bulk graviton selection.

The optimal cut gets looser as the dijet invariant mass increases, something which can be understood when looking at the QCD dijet invariant mass spectrum in Figure 5.9. The number of QCD jets falls off exponentially with m_{jj} , meaning that the background at 4 TeV is considerably lower than at 1 TeV. This allows for a looser cut on τ_{21} as m_{jj} increases. In order to choose a single cut which works reasonably well for all masspoints, we look at the ratio of a given τ_{21} cut over the significance of the best cut at that mass points. This is shown in the right plot of Figure 5.14. The cut $\tau_{21} < 0.45$ has the most stable performance out of the investigated cut values and is due to that, and due to the desire of keeping the background as low as possible at low m_{jj} , chosen as the nominal cut. In order to account for the fact that background is lower at high- m_{jj} , we add an additional analysis category, $0.45 < \tau_{21} < 0.75$, which contains $> 95\%$ of the signal and enhances the analysis sensitivity where the background is low. These categories are hereafter referred to as the ‘high purity’ (HP) category, for jets with $0 < \tau_{21} \leq 0.45$, and the low purity (LP) category, for jets with $0.45 < \tau_{21} \leq 0.75$.

The W -tagging efficiency and QCD light-flavored jet mistagging rate for a W -tagger consisting of $0 < \tau_{21} \leq 0.45$ and $65 \text{ GeV} < m_{\text{pruned}} < 105 \text{ GeV}$ is shown in Figure 5.15, both as a function of jet p_T and as a function of number of primary vertices in the event.

The signal efficiency for a pruned jet mass cut only, is around 80 % with a mistag rate of $\sim 15\%$. After adding a τ_{21} cut, the signal efficiency drops to around 55% and the mistagging rate to $\sim 2\%$. Another interesting feature is the dependence of τ_{21} on p_T on pileup, compared to the resilience of the groomed mass as a function of the same variables. This will be another feature we explore in Search II (Section 5.2).

Figure 5.1.7 shows the pruned-jet mass (left) and the n-subjettiness τ_{21} distribution (right) for signal and background Monte Carlo, as well as the distributions measured in data.

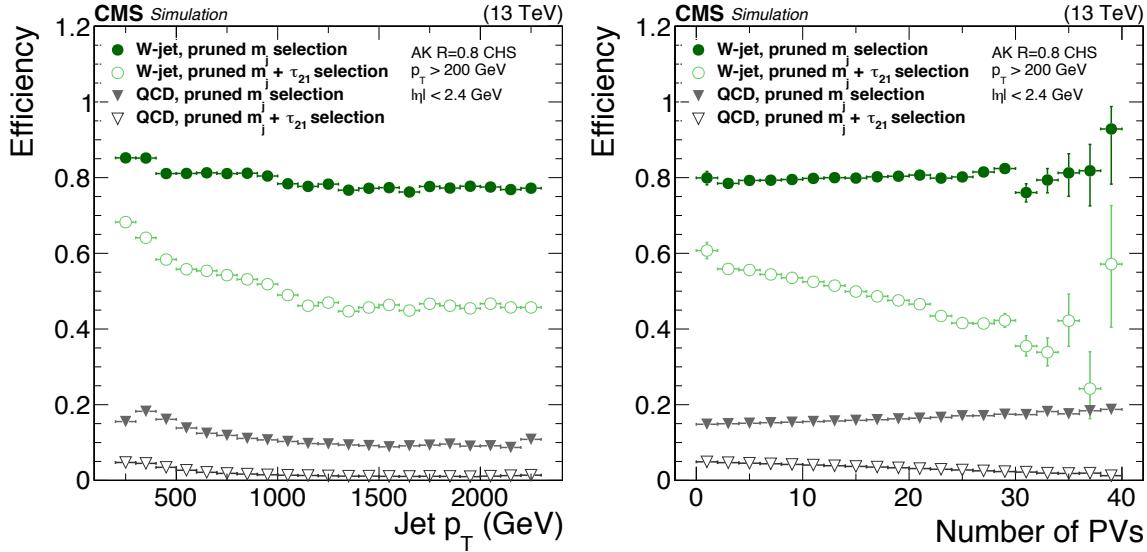


Figure 5.15: The W-tagging efficiency (green) and light jet mistag rate (grey) for a pruned jet mass cut only and pruned jet mass + τ_{21} cut as a function of p_T (left) and number of primary vertices (right).

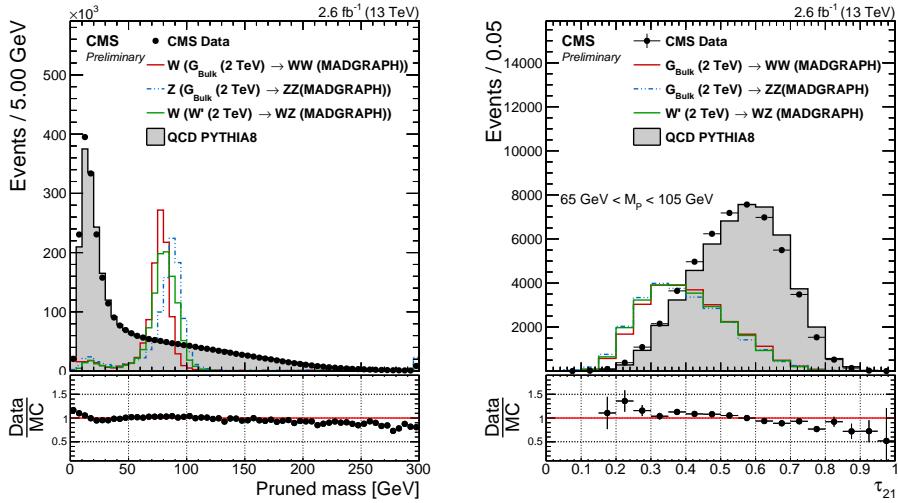


Figure 5.16: Pruned jet mass distribution (left) and n-subjettiness τ_{21} (right) distribution for data and simulated samples. Simulated samples are scaled to match the distribution in data. The τ_{21} distribution is shown for jets after a cut of $65 \text{ GeV} < M_p < 105 \text{ GeV}$ has been applied.

Analysis categorization

As the analysis requires two W/Z-tags, we always require one HP tagged jet and then divide into LP and HP categories depending on whether the other jet is of high or low purity. In addition, in order to further enhance the analysis sensitivity, we further split the pruned jet mass window into a W and a Z boson window where the W window is defined as $65 \text{ GeV} < m_{\text{pruned}} < 85 \text{ GeV}$ and the Z boson window as $85 \text{ GeV} < m_{\text{pruned}} < 105 \text{ GeV}$. This has the added benefit of allowing us to make a discrimination between a G_{bulk} decaying to WW or ZZ, and a W' decaying into WZ through counting events in each category. We, for instance, expect a higher signal yield in WZ category for a W' decaying to a W and Z boson

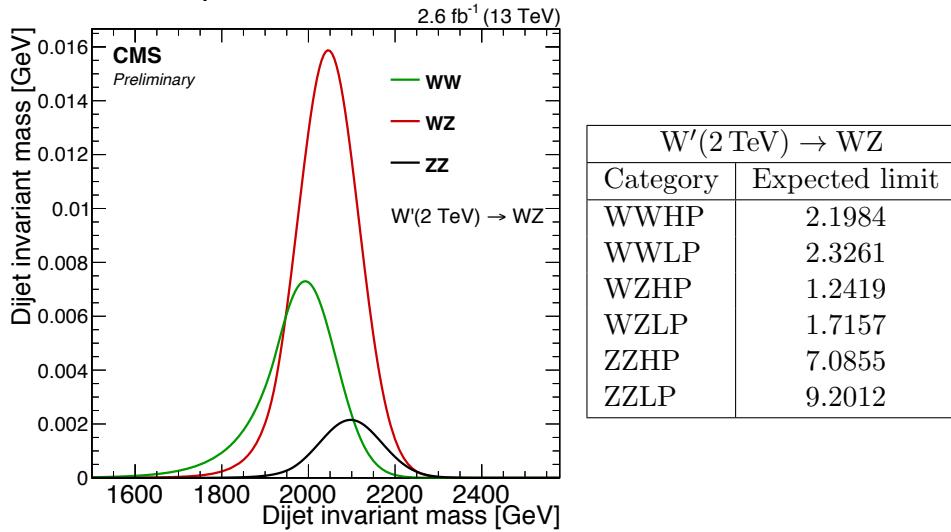


Figure 5.17: The expected signal yield per mass category for W' (2 TeV) decaying to a W and Z (left) together with the expected limit per mass category for the same signal (right).

then for a G_{bulk} decaying to WW or ZZ . Figure 5.17 shows the relative expected signal yield (left) and expected limits (left) in the different mass categories for a 2 TeV W' .

All categories are combined in the end, leading to the same or better sensitivity than when using the whole pruned mass window.

Figure 5.18 shows the expected 95% CL upper limits on the production cross section of a W' decaying to WZ (left) and a G_{bulk} decaying to WW (right) as function of the resonance mass in the HP category. The blue line corresponds to the expected limits obtained when not splitting into mass categories and the red line corresponds to the limit using the combination of two categories. The dotted and solid black lines are the limits in the W and Z categories, respectively. The combination of two mass categories leads to a slightly better (10%) or to the same sensitivity as when using one large mass window.

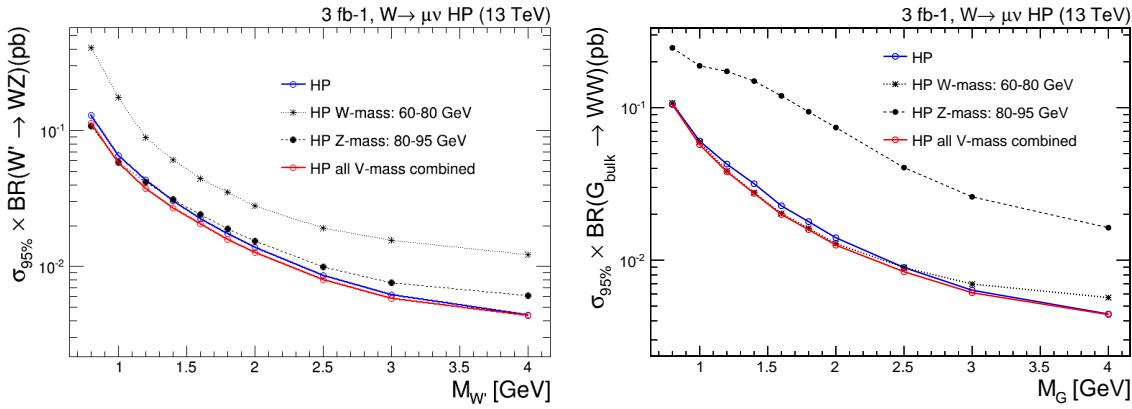


Figure 5.18: Expected 95% CL upper limits on the production cross section of a W' (left) and G_{bulk} (right) signal as function of the resonance mass for the different mass categories for events passing the high-purity τ_{21} selections.

The real benefit of splitting into mass categories becomes obvious when defining a test statistics based on the likelihood ratios of each signal hypothesis, $q = -2 \ln(L_{G_{\text{bulk}}}/L_{W'})$, shown in Figure 5.19. For a signal with a signal strength corresponding to a $3-4\sigma$ excess, the

test statistics for each signal hypothesis are well separated ($\sim 3.5\sigma$), allowing us to make a statement of how G_{bulk} or W' like a possible signal is.

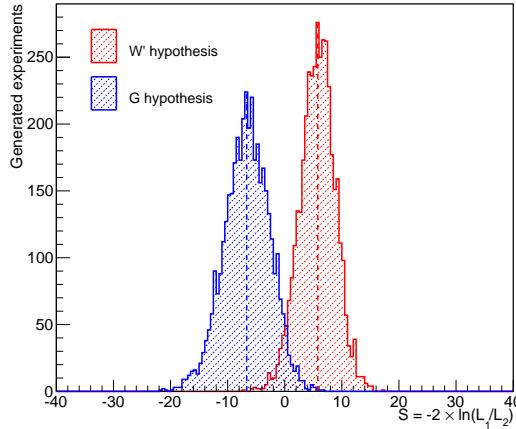


Figure 5.19: Distribution of the test statistic $q = -2 \ln(L_{G_{\text{bulk}}} / L_{W'})$ for a G_{bulk} (blue) and W' signal hypothesis.

With the high-purity and low-purity categories as defined above for each mass window combination, this leaves us with six different signal categories. They are as follows:

- High-purity, 3 mass categories: WW, ZZ and WZ
- Low-purity , 3 mass categories: WW, ZZ and WZ

In parallel to the mass-category based analysis, we perform an analysis without categorization in mass (similar to the 8 TeV analysis) as a cross-check. These studies can be found in the Appendix ??.

The final tagging efficiency for different signal hypothesis (top) together with the QCD mistag rate (bottom) in the different signal categories is shown in Figure 5.20. The solid lines represent the tagging efficiency in the full mass window ($65 \text{ GeV} < M_p < 105 \text{ GeV}$) before splitting into mass categories. A lower signal efficiency the ZZ mass category is observed in all cases. This can be explained from the pruned jet mass distribution on the left in Figure 5.1.7, where a cut at 85 GeV leaves a large fraction of the Z peak in the W mass window. As the main benchmark models under consideration preferably decays to W bosons (in the Bulk Graviton model the branching ratio $\text{BR}(G_{\text{Bulk}} \rightarrow W W) = 2 * \text{BR}(G_{\text{Bulk}} \rightarrow ZZ)$, and in the HVT model $W'/Z' \rightarrow WZ/WW$ (but not ZZ)), a high tagging efficiency for the W boson is preferred. In the limit-setting procedure all the categories are combined and the overall signal efficiency is conserved. For the combined mass-categories (solid line) the signal efficiency is between 16 and 23 % in the double-tag categories, and between 20 and 34 % in the single-V tag categories. The mistagging rate in the double-V tag categories is below 1 % in the high-purity category.

The full analysis selections and final categories are listed in Table ??.

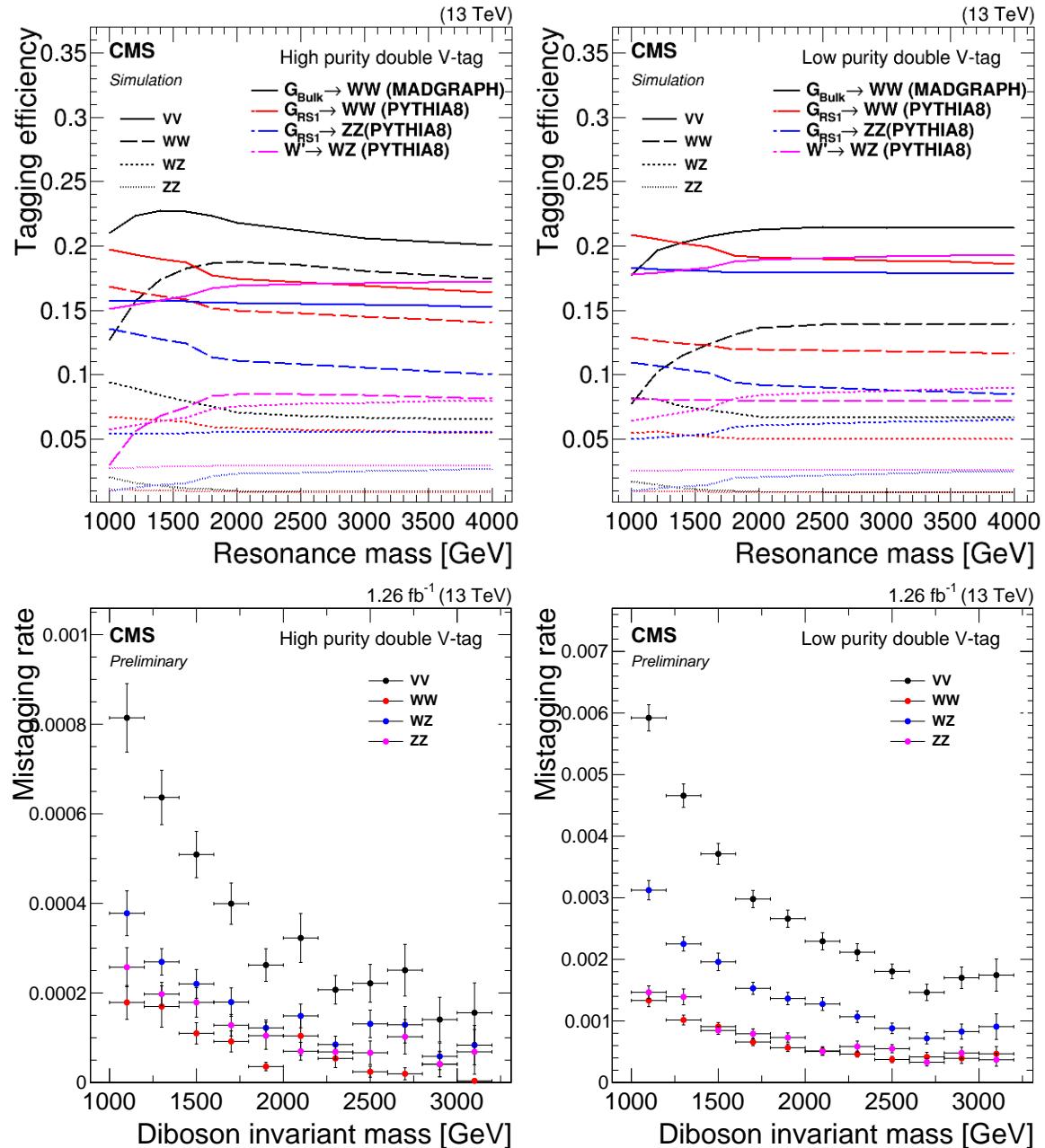


Figure 5.20: Tagging efficiency (top) and mistagging rate (bottom) in the different pruned mass categories in the high-purity category (left) and in the low-purity category (right)

Selection	Value
Boson selections	
V → q̄q (2 AK8 jets)	$p_T > 200 \text{ GeV}$ $ \eta < 2.4$
Pruned jet mass	$65 < m_{\text{jet}_1}, m_{\text{jet}_2} < 105 \text{ GeV}$
Topology	$ \Delta\eta_{jj} < 1.3$
Dijet invariant mass	$m_{jj} > 1 \text{ TeV}$
2- to 1-subjettiness ratio	$\tau_{21} < 0.75$
m_{jet} categories	
WW	$65 < m_{\text{jet}_1} < 85 \text{ GeV}, 65 < m_{\text{jet}_2} < 85 \text{ GeV}$
WZ	$65 < m_{\text{jet}_1} < 85 \text{ GeV}, 85 < m_{\text{jet}_2} < 105 \text{ GeV}$
ZZ	$85 < m_{\text{jet}_1} < 105 \text{ GeV}, 85 < m_{\text{jet}_2} < 105 \text{ GeV}$
τ_{21} categories	
High-purity	$\tau_{21,\text{jet}1} < 0.45, \tau_{21,\text{jet}2} < 0.45$
Low-purity	$\tau_{21,\text{jet}1} < 0.45, 0.45 < \tau_{21,\text{jet}2} < 0.75$

Table 5.1: The full analysis selections, mass and τ_{21} categories.

5.1.5 Background modeling

The background modeling in this analysis is based on a smoothness test performed directly on unblinded data, similar to what is done in previous CMS analyses looking for bumps in the dijet invariant mass spectrum [45, 46]. We assume that the QCD multijet background in the different analysis categories can be described by smooth, monotonically decreasing functions of 2 or 3 parameters

$$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_2}} \quad \text{and} \quad \frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}, \quad (5.1)$$

where m is the dijet invariant mass, \sqrt{s} the centre of mass energy and P_0 is a normalization parameter for the probability density function and P_1 and P_2 describe the shape. The number of fit parameters is decided through a Fishers F-test [47]. In this test, we start from the 2 parameter function and compare the goodness of fit (χ^2 divided by degrees of freedom) when fitting the data signal region with a 2, 3, 4 and 5 parameter function. We then check at 10% confidence level (CL) if additional parameters are needed to model the background distribution. The 4 and 5 parameter functions are

$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2+P_3 \times \log(m_{jj}/\sqrt{s})}} \quad (5.2)$$

$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2+P_3 \times \log(m_{jj}/\sqrt{s})+P_4 \times \log(m_{jj}/\sqrt{s})^2}} \quad (5.3)$$

where P_3 and P_4 are additional free parameters. As an additional cross check, an alternative fit function is also tested:

$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s} + P_3(m_{jj}/\sqrt{s})^2)^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}. \quad (5.4)$$

The fit range is chosen such that it starts where the trigger efficiency has reached its plateau to avoid bias from trigger inefficiency, and extends to the bin after the highest m_{VV} mass point. The binning chosen for the fit follows the detector resolution as in [45, 46]. Before unblinding the signal region, we check that the QCD dijet invariant mass spectrum is expected to be smooth from the distribution in QCD MC as well as exercise the F-test in QCD MC and in a data sideband.

The fits to data in the signal region using the different fit functions, are shown in Figure 5.22, and the corresponding F-test output are given in Table 5.2 through Table 5.4. The findings can be summarized as follows: for the WW enriched category a 2 parameter fit is sufficient to describe the data in both the high- and low-purity categories. In the WZ category, a two parameter fit is sufficient in the high-purity category, while three parameters are needed for the low-purity category. For the ZZ category, a 3 parameter fit is needed for both purity categories. The 2 and 3 parameters fit functions as defined in Equation 5.2 will therefore be used to model the background component in the simultaneous signal and background fit.

WW enriched, HP				WW enriched, LP			
Function	Residuals	χ^2	ndof	Function	Residuals	χ^2	ndof
2 par	0.034	9.279	11	2 par	0.270	13.462	17
3 par	0.034	9.160	10	3 par	0.300	13.819	16
4 par	0.040	8.030	9	4 par	0.324	13.680	15
Fishers23	-0.053	CL	1.0	Fishers23	-1.723	CL	1.0
Fishers34	-1.456	CL	1.0	Fishers34	-1.191	CL	1.0

Table 5.2: Residuals, χ^2 , and degrees of freedom for the WW enriched HP and LP categories. A 2 parameter fit is needed to describe the data in both categories.

WZ enriched, HP				WZ enriched, LP			
Function	Residuals	χ^2	ndof	Function	Residuals	χ^2	ndof
2 par	0.039	9.105	16	2 par	1.016	17.602	20
3 par	0.047	7.915	15	3 par	0.270	11.424	19
4 par	0.048	8.370	14	4 par	0.269	11.421	18
Fishers23	-2.598	CL	1.0	Fishers23	55.258	CL	0.0
Fishers34	-0.491	CL	1.0	Fishers34	0.078	CL	0.783

Table 5.3: Residuals, χ^2 , and degrees of freedom for the WZ enriched HP (left) and LP (right) categories. A 2 parameter fit is sufficient to describe the data in the high-purity category, while three parameters are needed for the low-purity category.

ZZ enriched, HP				ZZ enriched, LP			
Function	Residuals	χ^2	ndof	Function	Residuals	χ^2	ndof
2 par	0.220	9.901	11	2 par	0.448	18.832	15
3 par	0.140	9.511	10	3 par	0.121	17.463	14
4 par	0.124	9.781	9	4 par	0.118	17.394	13
Fishers23	6.302	CL	0.029	Fishers23	40.438	CL	0.0
Fishers34	1.246	CL	0.290	Fishers34	0.356	CL	0.56

Table 5.4: Residuals, χ^2 , and degrees of freedom for the ZZ enriched LP and HP categories. A 3 parameter fit is sufficient to describe the data in both categories.

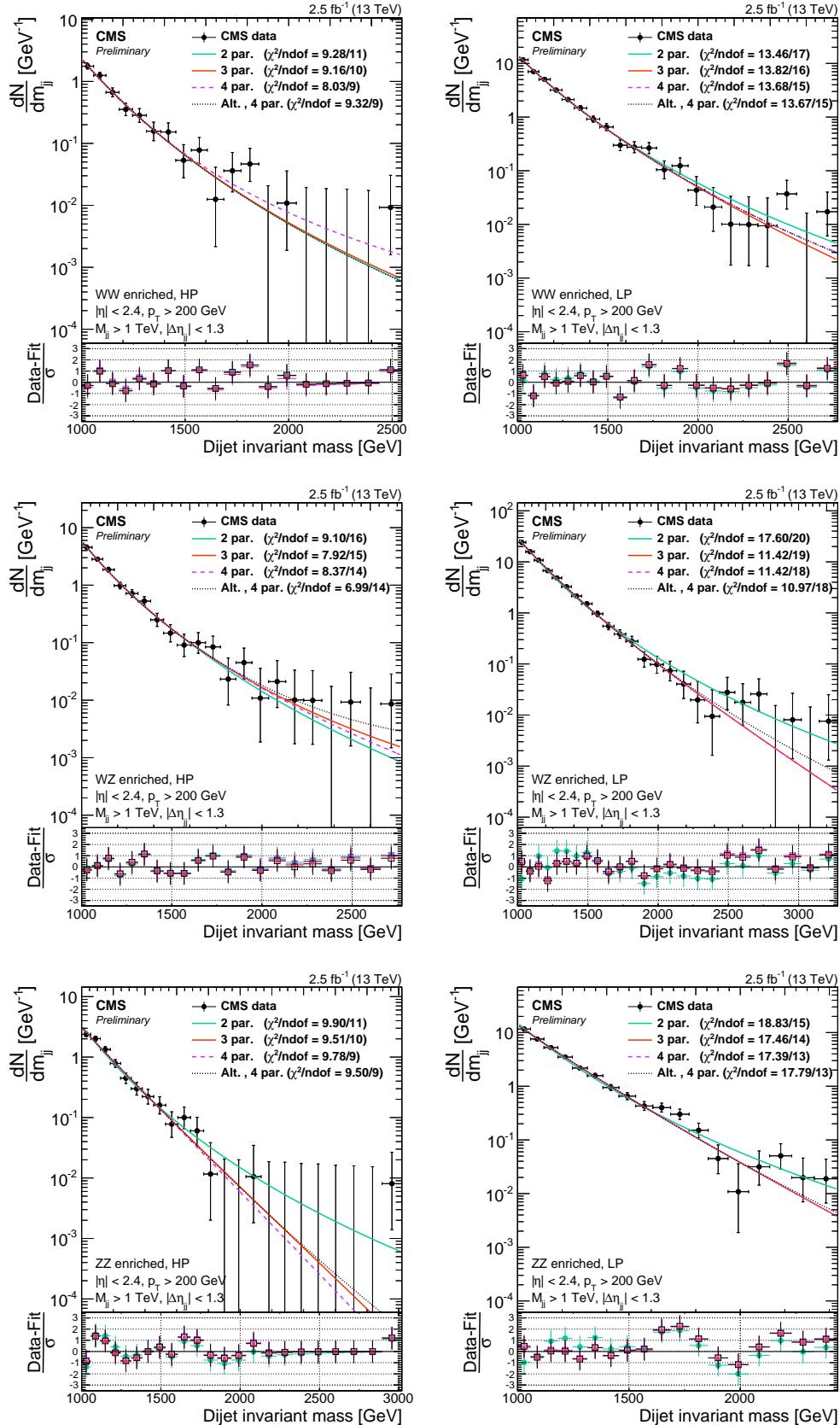


Figure 5.21: Fitted dijet mass spectrum in the different mass and purity categories in data for the double V-tag category. A 2 parameter fit is sufficient to describe the data for the WW (HP and LP) and WZ (LP) enriched categories. For the ZZ enriched (HP and LP) and WZ (HP) categories, a 3 parameter fit is needed.

5.1.6 Signal modeling

The signal shape is extracted from signal MC with masses in the range from 1 to 4 TeV. A linear interpolation provides shapes for the mass points in between in steps of 100 GeV. From these shapes, pdf models are constructed as composite models with a Gaussian core due to detector resolution and an exponential tail to account for parton distribution function effects. Parametric shape uncertainties due to jet energy scale and resolution uncertainties are inserted by variations of the Gaussian peak position and width. The dijet invariant mass shape for different benchmark model signals are shown in Figure ???. The signal and background components are then simultaneously fitted to the data points.

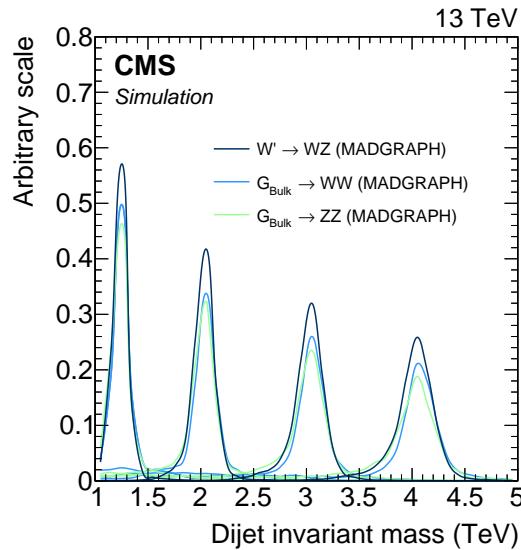


Figure 5.22: Dijet invariant mass from signal MC used to extract the signal shape. Here for 1.2, 2, 3 and 4 TeV resonances.

5.1.7 V-tagging scale factors

As seen in Figure , some discrepancy is observed in the τ_{21} distribution between data and MC. This can lead to a bias in the signal efficiency estimation and we therefore measure the real data signal efficiency in an orthogonal data sample. The W-tagging efficiency is measured using real boosted W-jets in a semi-leptonic $t\bar{t}$ enriched data sample. This region is mainly quark-enriched, as opposed to the QCD gluon-enriched region we saw previously, and substructure variables are better described here. The sample is obtained through requiring a final state compatible with two b-jets and two W bosons, where one of the bosons decay leptonically and the other one hadronically. There are several good reasons to use this channel: Top quark pair production events are plentifully produced at the LHC, we can ensure a high purity of the sample through high-energy lepton, b-tag and missing energy requirements and lastly we can ensure that the W jets are boosted by requiring the leptonic leg, together with the hadronic W candidate, to have high transverse momentum. The final state is illustrated in Figure 5.23, with the object of interest being the AK R=0.8 jet containing the two quark daughters of the hadronically decaying W.

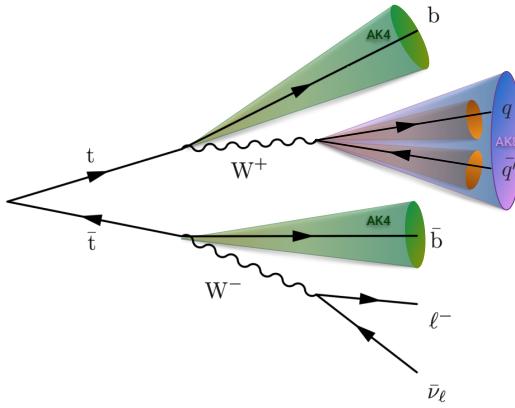


Figure 5.23: A top quark pair decaying into two b quarks and two W bosons, one of which decays leptonically and one on which decays hadronically

5.1.8 Event selection

The W can decay either to an electron or a muon, both final states ('channels') are used in the analysis. We select events through triggering and selections on the leptonic leg. First, we require a high-energy lepton at trigger level, with an online p_T above 45 GeV for the muon and 135 GeV for the electron. This requires an offline muon(electron) p_T threshold of 53(120) GeV. The leptons are further required to pass the lepton requirements defined in Section 4.2.2 and Section 4.2.2, and events containing additional leptons (passing the same ID requirements, but looser cuts as defined in Table 5.5) are vetoed. Offline, we further require a high missing energy of 40(80) GeV in the muon(electron) channel. To insure a high signal (boosted hadronic W) purity, the leptonic W four-vector is reconstructed such that we can put tight momentum requirements on the leptonic leg (ensuring that both tops, and therefore vector bosons, have a high momentum). The leptonic W is reconstructed in two steps: First, the unknown z component of the neutrino momentum must be solved for through a second order equation assuming the real W mass

$$M_W^2 = m_\ell^2 + 2(E_\ell E_\nu - p_{x_\ell} p_{x_\nu} - p_{y_\ell} p_{y_\nu} - p_{z_\ell} p_{z_\nu}) = (80.4)^2.$$

This results in a completely defined neutrino four-vector, which is then added to the lepton four-vector. The sum of the two defines the leptonic W and its momentum is required to be greater than 200 GeV.

Further, we require at least one AK R=0.4 jet to be b-tagged with the Combined Secondary Vertex (CSV) algorithm [56, 57]. This algorithm exploits the relatively long lifetime of b quarks leading to the presence of a displaced vertex, in order to distinguish between jets originating from b quarks to those originating from light flavor quarks. More information on the CSV algorithm can be found in [56, 57]. The reason for requiring only one b-tagged jet is to ensure a high selection efficiency.

Finally, we require at least one AK R=0.8 jet in the event with a momentum greater than 200 GeV which will be the hadronic W candidate. Its pruned jet mass is required to be between 40 GeV and 150 GeV. After reconstructing and selecting all our objects, a set of angular selections are applied to ensure a diboson like topology. These are the following:

- $\Delta R(l, W_{AK8}) > \pi/2$
- $\Delta\phi(W_{AK8}, E_T^{\text{miss}}) > 2$

- $\Delta\phi(W_{AK8}, W_{lep}) > 2$

With these requirements, we have a nearly pure sample of $t\bar{t}$ events, with a small contamination from single top, $W+jets$ and VV events. A summary of the final selection criteria is presented in Table 5.5. The pruned jet mass and τ_{21} variables in data and in MC are shown in Figure 5.24.

Selection	Value	Comments
Tight Lepton selection		
Electron p_T	$p_T > 120 \text{ GeV}$	
Muon p_T	$p_T > 53 \text{ GeV}$	
Electron η	$ \eta _{\text{SC}} < 2.5$ except [1.4442, 1.566]	Veto ECAL barrel-endcap transition.
Muon η	$ \eta < 2.1$	
Loose Lepton selection		
Electron p_T	$p_T > 35 \text{ GeV}$	
Muon p_T	$p_T > 20 \text{ GeV}$	
Electron η	$ \eta _{\text{SC}} < 2.5$ except [1.4442, 1.566]	Veto ECAL barrel-endcap transition.
Muon η	$ \eta < 2.4$	
AK8 jet selections		
Jet p_T	$p_T > 200 \text{ GeV}$	
Jet η	$ \eta < 2.4$	For hadronic W reconstruction
AK4 jet selections		
Jet p_T	$p_T > 30 \text{ GeV}$	Used for b-tag
Jet η	$ \eta < 2.4$	jet selection
E_T^{miss} selections		
E_T^{miss} (electron channel)	$E_T^{\text{miss}} > 80 \text{ GeV}$	
E_T^{miss} (muon channel)	$E_T^{\text{miss}} > 40 \text{ GeV}$	
Boson selections		
Pruned jet mass	$40 < m_p < 150 \text{ GeV}$	
Leptonic W p_T	$p_T > 200 \text{ GeV}$	
Hadronic W p_T	$p_T > 200 \text{ GeV}$	
Veto		
Number of loose electrons	0	
Number of loose muons	0	
Number of b-tagged jets	> 0	CSV medium working point
Angular selections		
$\Delta R(l, W_{AK8})$	$> \pi/2$	
$\Delta\phi(W_{AK8}, E_T^{\text{miss}})$	> 2	
$\Delta\phi(W_{AK8}, W_{lep})$	> 2	

Table 5.5: Summary of the final semi-leptonic $t\bar{t}$ selections.

Fitting procedure

For this measurement, what we are interested in is to extract and compare the W-tagging efficiency of the combined jet mass and τ_{21} selection in data and in MC. We are additionally interested in the difference in jet mass scale (mean of the W jet mass peak) and jet mass resolution (width of W jet mass peak), as this also affects the signal jet mass shape and therefore efficiency. In order to study these variables, we look at the pruned jet mass spectrum between 40 and 150 GeV in two regions:

- Pass region: $0 < \tau_{21} \leq 0.45 \sim \text{high purity}$
- Fail region: $0.45 < \tau_{21} \leq 0.75 \sim \text{low purity}$

Our goal is to understand what the real fraction of merged W jets is in the pass category and in the fail category, assuming that the sum of the two correspond to a 100% selection

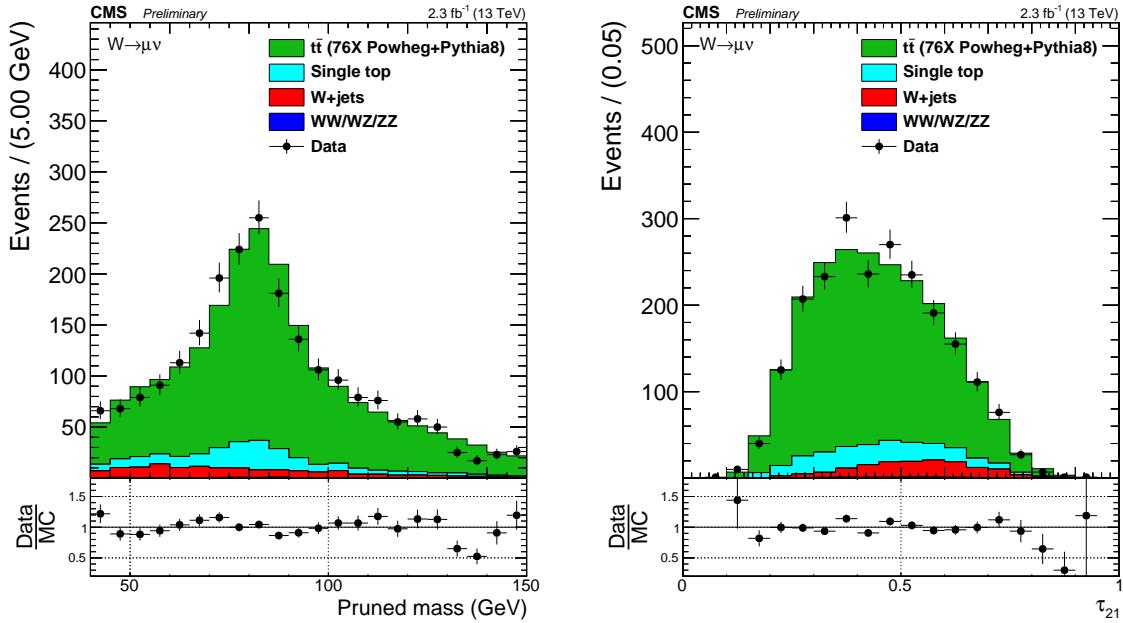


Figure 5.24: Distribution of pruned jet mass (left) and n-subjettiness (right) in the $t\bar{t}$ control sample.

efficiency (the amount of W jets falling outside of this region is negligible). The strategy is the following: We first derive probability density functions (PDFs) which describe the distribution of fully merged W jets and non-W jets in $t\bar{t}$, both in the pass and in the fail region. The PDFs describing real W jets and non-W jets are added with a fraction which is left floating: the fit decides what the fraction of real W to non-W jets is in the pass and in the fail region. As simultaneous fit of pass and fail is then performed (using the two composite W +non-W PDFs), where the fraction of real W jets in both pass and fail is constrained such that, if the signal efficiency in pass is ϵ_S , the signal efficiency in fail is $(1 - \epsilon_S)$. This is done by letting the normalization of the PDF describing real W jets in the pass category, be defined as the *total* real W yield in pass and fail combined multiplied by some fraction, ϵ_S . The normalization of the PDF describing real W jets in the fail category is then the total real W yield multiplied by $(1 - \epsilon_S)$.

To understand which part of the $t\bar{t}$ jet mass distribution contains “real” merged Ws and which are only pure combinatorial background, non-PWs, we start from $t\bar{t}$ MC. By matching the AK8 jet with quarks coming from the hadronic W at generator level, in a cone of $\Delta R < 0.8$, we can access the real merged W and non-merged W shapes. The real W and non-W PDFs for jets that pass and fail the N-subjettiness selection $\tau_{21} < 0.45$, are found to be well described by the following functions:

$$f_{\text{bkg}}(m_j) = F_{\text{ExpErf}} = e^{c_0 m_j} \cdot \frac{1 + \text{Erf}((m_j - a)/b)}{2} \quad \sim \text{for non-W jets in both pass and fail}$$

$$f^{\text{sig}}(m_j) = F_{\text{Gaus}}(m_j) + F_{\text{ExpErf}}(m_j) \quad \sim \text{for real W jets in both pass and fail}$$

Figure 5.25 shows the fitted PUPPI softdrop mass spectrum for $t\bar{t}$ real W (top) and non-W (bottom) distributions for jets that passed (left) and failed (right column) the N-subjettiness selection PUPPI $\tau_{21} < 0.4$. The corresponding plots for the jet pruned mass can be found in Figure B.

These shapes constitute the fit functions used for the simultaneous fit. As can be seen from the fit to real W jets in the pass region, the distribution is not purely Gaussian and have

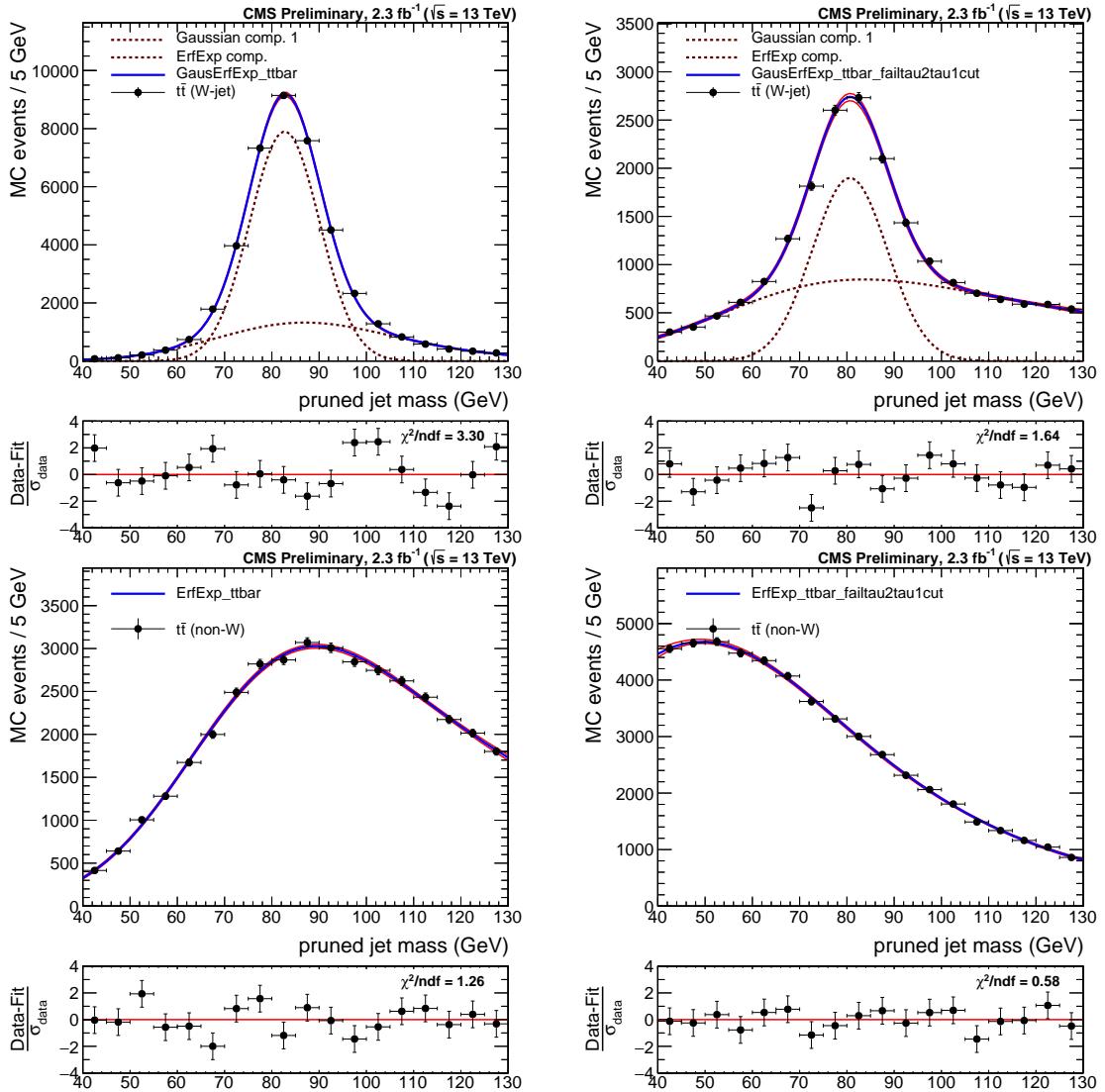


Figure 5.25: Fit to the real W (top) and non-W (bottom) pruned jet mass distribution for jets that pass (left) and fail (right) the cut on $\tau_{21} < 0.45$.

a tail at higher groomed masses. This tail depends on the matching requirements used to define real merged W jets and is unphysical. We therefore assume that the distribution of real W-jets can be described by a Gaussian only, allowing the exponential error function used to describe non W-jets to cover the contribution from the tails, hereby taking the number of real W-jets as the integral of the Gaussian shape only. This eliminates two additional fit functions, corresponding to six free parameters from the fit. In older estimations of the W-tagging scale factor based on the same procedure [51]), the functions used to describe the tail of the real W-jet distributions were also taken into account as contributing to the real W-jet tagging efficiency. These two calculations tests two extremes: The new method assumes a Gaussian peak, absorbing the tails into the background function making the fit more robust, while the old method assumes a Gaussian peak with tails estimated from matched MC. The latter uses a more precise definition of real W jets, but a less robust fit. Both methods were investigated and we found that the absorption of tails into the background function resulted in a decrease in the relative uncertainty on the final scale factor of 50 % and an overall improvement on the fit quality, reducing the fit χ^2 by 15 %. The fit parameters of the functions used to describe non W-jets in both the pass and in the fail region, are further constrained using the values obtained from matched $t\bar{t}$ MC. The W-tagging scale factors (SF_{HP}), for the high purity selection ($\tau_{21} < 0.45$), are then extracted estimating the cut efficiency (ϵ_{HP}) on both data and simulated samples fitting, simultaneously, pass and fail samples:

$$L_{\text{pass}} = \prod_i^{N_{\text{evt}}^{\text{pass}}} \left[N_W \cdot \epsilon_{HP} \cdot f_{\text{pass}}^{\text{sig}}(m_j) + N_2 \cdot f_{\text{pass}}^{\text{bkg}}(m_j) + \sum_{j=\text{ST,VV,WJet}} N_{\text{pass}}^j \cdot f_{\text{pass}}^j \right]$$

$$L_{\text{fail}} = \prod_i^{N_{\text{evt}}^{\text{fail}}} \left[N_W \cdot (1 - \epsilon_{HP}) \cdot f_{\text{fail}}^{\text{sig}}(m_j) + N_3 \cdot f_{\text{fail}}^{\text{bkg}}(m_j) + \sum_{j=\text{ST,VV,WJet}} N_{\text{fail}}^j \cdot f_{\text{fail}}^j \right]$$

where N_W is the number of real W jets, N_2 and N_3 are the number of combinatorial background events passing and failing the τ_{21} cut respectively. N_j and f_j , with $j = \text{ST, VV, WJet}$, are the normalizations and shapes of the minor backgrounds (single top, VV, W+jets) which are fixed from simulation. The fit functions used are

$$f_{\text{pass}}^{\text{sTop}} = F_{\text{ErfExpGaus}}(x) = \frac{1 + \text{Erf}((x - a)/b)}{2} \cdot e^{-(x - x_0)^2/2\sigma^2}$$

$$f_{\text{fail}}^{\text{sTop}} = F_{\text{ExpGaus}}(x) = e^{ax} \cdot e^{-(x-b)^2/2s^2}$$

$$f_{\text{pass}}^{\text{VV}} = F_{\text{ExpGaus}}(x) = e^{ax} \cdot e^{-(x-b)^2/2s^2}$$

$$f_{\text{fail}}^{\text{VV}} = F_{\text{ExpGaus}}(x) = e^{ax} \cdot e^{-(x-b)^2/2s^2}$$

$$f_{\text{pass}}^{\text{wjet}} = F_{\text{ErfExp}}(x) = e^{c_0 x} \cdot \frac{1 + \text{Erf}((x - a)/b)}{2}$$

$$f_{\text{fail}}^{\text{wjet}} = F_{\text{ErfExp}}(x) = e^{c_0 x} \cdot \frac{1 + \text{Erf}((x - a)/b)}{2}$$

with the corresponding distributions shown in Figure 5.26. The floating parameters of the fit (besides the PDF shape parameters themselves) are the rates N_W , N_2 and N_3 , and the mean and sigma of the W-mass distribution defined in $f_{\text{pass}}^{\text{sig}}(m_j)$ and $f_{\text{fail}}^{\text{sig}}(m_j)$. The ratio between data and simulation efficiencies are then taken as the W-tagging scale factor:

$$SF_{HP} = \frac{\epsilon_{HP}(\text{data})}{\epsilon_{HP}(\text{sim})} \quad (5.5)$$

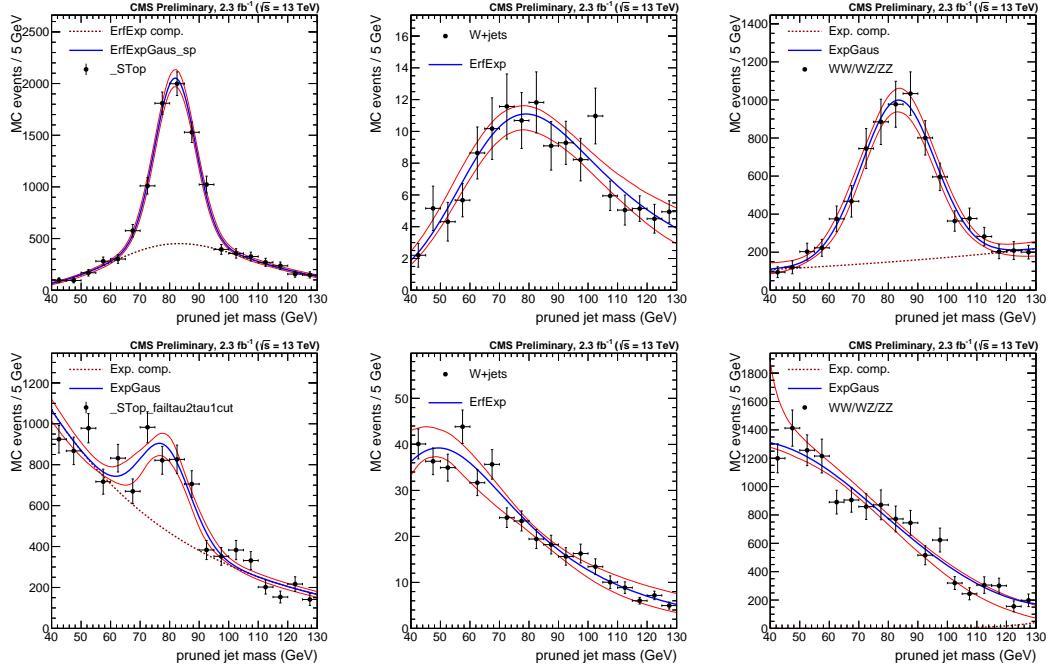


Figure 5.26: Fits to the pruned jet mass spectrum for the non-dominant backgrounds (Single top, W+jets and VV respectively) in the pass (top) and fail (bottom) regions.

Considering that, both for data and simulation, $\epsilon_{HP} + \epsilon_{LP} + \epsilon_{fail} = 1$, the scale factor for low purity category can be defined as:

$$SF_{LP} = \frac{1 - \epsilon_{HP}(\text{data}) - \epsilon_{fail}(\text{data})}{1 - \epsilon_{HP}(\text{sim}) - \epsilon_{fail}(\text{sim})}$$

where ϵ_{fail} is the ratio between the number of events with $\tau_2/\tau_1 > 0.75$ and the total number of events. As mentioned previously, the number of real W jets with $\tau_2/\tau_1 > 0.75$ is negligible and the definition of the low purity scale factor simplifies to

$$SF_{LP} = \frac{1 - \epsilon_{HP}(\text{data})}{1 - \epsilon_{HP}(\text{sim})} \quad (5.6)$$

Systematic uncertainties

As systematic uncertainties, we consider effects due to differences in $t\bar{t}$ simulation as well as effects due to choice of fit method. The former is evaluated by comparing the extracted scale factor when using $t\bar{t}$ MC samples produced with different matrix element (ME) and shower generators: POWHEG (NLO) interfaced with PYTHIA8, MADGRAPH (LO) QCD interfaced with HERWIG++ and POWHEG interfaced with HERWIG++. The uncertainty due to different ME generators (POWHEG versus MADGRAPH) correspond to 3(13)% and are listed in Table ?? as the first quoted systematic uncertainty. The uncertainty due to parton showering (PYTHIA8 versus HERWIG++) is 8.6%, but are not relevant for analyses where no HERWIG++ based simulation is used, as is the case for the search presented in this chapter. For the systematic uncertainty accounting for effects due to choice of fit method, we compare the estimated extracted efficiency in $t\bar{t}$ MC using the two different fit models described above: The new model, where the signal is modeled by a Gaussian peak and the tails of the distribution are absorbed in the background fit model, and the old model, including the tails when calculating

the fraction of real W jets. Figure 5.27 shows the fits obtained in the pass and fail regions using the two different models. With the new model only the Gaussian component of the fit contributes to the W-tagging efficiency while, with the old model, a Chebyshev component is additionally contributing to the total W-tagging efficiency. The estimated efficiencies

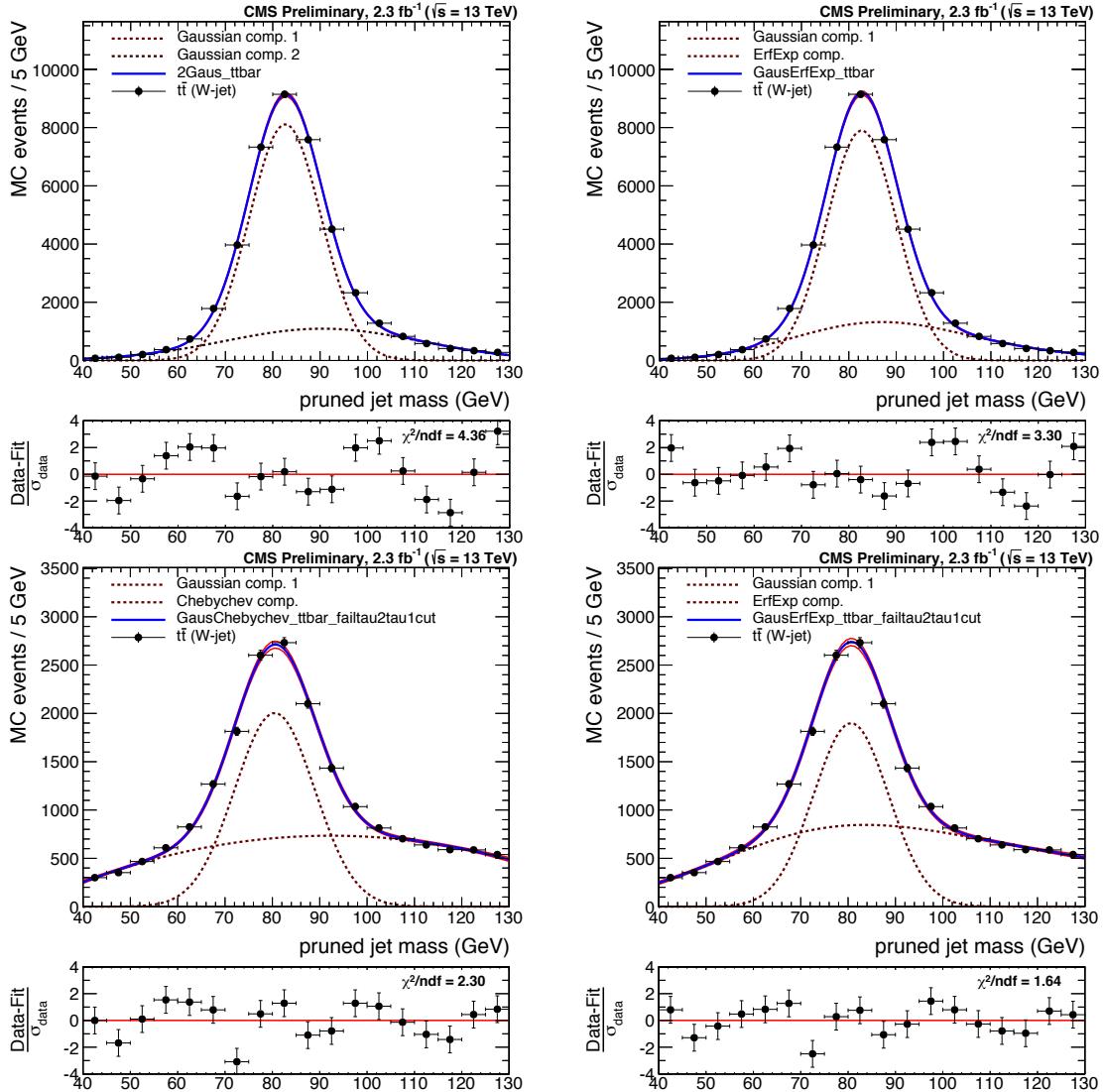


Figure 5.27: Fits obtained in the pass (top) and fail (bottom) regions using two different models: An alternative model with tails (top and bottom, left) where the tail component is contributing to the total W-tagging efficiency. When using the default model (top and bottom, right), only the Gaussian component of the fit contributes to the W-tagging efficiency.

obtained using both methods, after being corrected for the fraction of W jets in the tails, agree within 0.3(0.8)% and are listed as systematic uncertainty in Table ??.

One additional uncertainty is added. As the W-tagging scale factor is evaluated in a $t\bar{t}$ sample, the transverse momentum range is rather limited. When the W p_T reaches ~ 400 GeV, the AK8 jet becomes a fully merged top jet with a mass of 170 GeV and a scale factor measurement becomes impossible. However, the jets used in the analyses presented in this thesis have very high transverse momenta, up to 2-3 TeV, and we therefore need an estimate of how the uncertainty on the W-tagging scalefactor changes as a function of p_T . This is estimated by comparing the difference in tagging between $G_{\text{bulk}} \rightarrow WW$ signal MC showered

by PYTHIA8 and HERWIG++ as a function of p_T , relative to the difference in tagging efficiency between the two at a $p_T \sim 200$ GeV. This measurement was performed by a separate analysis team, and found to be $5.90\% \times \ln(p_T/200\text{ GeV})$.

Systematic uncertainties from other sources (lepton identification, b tagging etc.) are less than 0.5% and therefore negligible.

Results

The simultaneous fit as described above is then performed both for data and for simulation, where we take the ratio of data and MC efficiencies as efficiency scale factors. The corresponding fits are shown in Figure 5.28, with the corresponding extracted efficiencies and scale factors summarized in Table ??.

Category	Working point	Eff. data	Eff. simulation	Scale factor
High-purity Pruning	$(\tau_2/\tau_1 < 0.45)$	0.775 ± 0.041	0.822 ± 0.033	$0.94 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (sys)}$
Low-purity Pruning	$(0.45 < \tau_2/\tau_1 < 0.75)$	0.225 ± 0.041	0.178 ± 0.033	$1.27 \pm 0.25 \text{ (stat)} \pm 0.13 \text{ (sys)}$

Table 5.6: Efficiencies in data and in MC together with the corresponding W-tagging scale factors for the high purity and low purity categories.

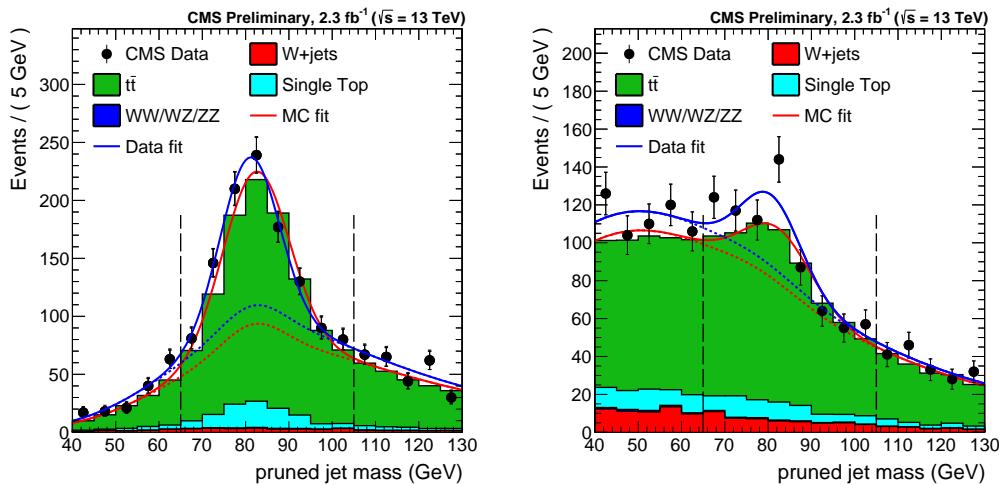


Figure 5.28: Pruned jet mass distribution that pass (left) and fail (right) the $\tau_2/\tau_1 < 0.45$ selection. Results of both the fit to data (blue) and simulation (red) are shown. The background components of the fit are shown as short-dashed lines.

We additionally extract the jet mass scale and jet mass resolution, used to scale and smear the jet mass signal shape in the limit setting procedure. These values are taken from the mean $\langle m \rangle$ and width σ of the Gaussian component of the simultaneous fit in the pass region and are summarized in Table 5.7. Both the jet mass scale as well as the jet mass resolution is larger in data than in simulation with a relative difference of 2 and 10%, respectively.

Impact on search variables

The obtained W-tagging scale factors are used as a scale of the signal yield. As we require two W-tagged jets, either HPHP or HPLP, the actual scale factors for the high-purity signal yield is $SF_{HP} \times SF_{HP}$ and for the low-purity category $SF_{HP} \times SF_{LP}$. The actual signal yields

Parameter	Data	Simulation	Data/Simulation
Pruning $\langle m \rangle$	80.9 ± 0.6 GeV	82.5 ± 0.1 GeV	0.980 ± 0.007
Pruning σ	6.7 ± 0.7 GeV	7.5 ± 0.3 GeV	0.89 ± 0.10

Table 5.7: Jet mass scale and resolution in data and in simulation together with the relevant data-simulation scale factors.

are then

$$N_S^{HP} = N_{\text{HPTot.yield}} \times \text{SF}_{HP} \times \text{SF}_{HP}$$

$$N_S^{LP} = N_{\text{LPTot.yield}} \times \text{SF}_{HP} \times \text{SF}_{LP}$$

The uncertainties on the scale factors are again multiplied, and considered as anti-correlated between the HP and the LP categories.

5.1.9 Systematic uncertainties

The uncertainty on the background parametrization is statistical only and is taken as the covariance matrix of the dijet fit function. As demonstrated in the F-test, we study different background parameterizations and we have found these to be well within the fit uncertainty of the nominal fit. The remaining uncertainties concern the signal shape and yield and are listed in Table 5.8. Jet reconstruction uncertainties affect both the signal yield and the signal shape. These are evaluated by rescaling the jet four-momenta according to uncertainties on the jet energy scale and resolution and recomputing the signal efficiency. The difference in efficiency with and without smearing/scaling is taken as systematic uncertainties. The jet mass/energy scale and resolution also affect the signal shape, and are added as uncertainties in the peak position and width of the Gaussian component of the signal PDFs.

Source	Relevant quantity	HP uncertainty (%)	LP uncertainty (%)
Jet energy scale	Resonance shape	2	2
Jet energy resolution	Resonance shape	10	10
Jet energy and m_{jet} scale	Signal yield	0.1–4	
Jet energy and m_{jet} resolution	Signal yield	0.1–1.4	
Pileup	Signal yield	2	
Integrated luminosity	Signal yield	2	
PDFs (W')	Signal yield	4–19	
PDFs (Z')	Signal yield	4–13	
PDFs (G_{bulk})	Signal yield	9–77	
Scales (W')	Signal yield	1–14	
Scales (Z')	Signal yield	1–13	
Scales (G_{bulk})	Signal yield	8–22	
Jet energy and m_{jet} scale	Migration	1–50	
V tagging τ_{21}	Migration	14	21
V tagging p_T -dependence	Migration	7–14	5–11

Table 5.8: Summary of systematic uncertainties and the quantities they affect. Migration uncertainties result in events switching between the purity/mass categories and changes the efficiency in each category, but do not affect the total signal efficiency.

5.1.10 Results

The background fits for each analysis category in the data signal region are shown in Figure 5.29. Here a background only fit is performed while, as described above, a simultaneous fit is used for the limit setting procedure. The filled area correspond to the 1 sigma error band of the background fit, obtained using linear error propagation.

We proceed by setting limits on the cross section of the process $X \rightarrow VV$, using the asymptotic CL_s method as described in Section 2.1. The binned likelihood is defined as

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} \quad (5.7)$$

with

$$\mu_i = \sigma \cdot N_i(S) + N_i(B) \quad (5.8)$$

Here σ is the signal strength scaling the expected number of signal events in the i -th dijet invariant mass bin $N_i(S)$, $N_i(B)$ is the expected number of background events in dijet invariant mass bin i and n_i is the observed number of events in the i th dijet invariant mass bin. The background per bin $N_i(B)$ is estimated from the background component of the best signal+background fit to the data points with the signal cross section set to zero. The number of signal events in the i -th dijet invariant mass bin, $N_i(S)$, is then estimated from the signal templates, where only a dijet invariant mass in a 20% window around the resonance mass is considered, containing most of the signal contribution while making sure to keep a good description of the core.

5.1.11 Limits: All-hadronic analysis

As mentioned in Section 5.1.3, we set limits on three different signal scenarios: $G_{\text{bulk}} \rightarrow WW$, $G_{\text{bulk}} \rightarrow ZZ$ and $W' \rightarrow WZ$, with a $\tilde{k} = 0.5$ for the G_{bulk} . Figure 5.30 shows the asymptotic limits at 95 % confidence level on signal cross section as a function of the resonance mass obtained with 2.7 fb^{-1} of 13 TeV CMS data after combining all mass and purity categories (top). The corresponding p-values are shown in the bottom panel.

The statistics are too low to exclude the excess around 2 TeV observed in the corresponding Run 1 analysis and in addition an under-fluctuation in data is present in this region. The largest excess is observed for a $G_{\text{bulk}} \rightarrow ZZ$ hypothesis at a resonance mass of 2.8-3 TeV, around 2.3σ . This is driven by the ZZ high-purity category, the category with the lowest statistics, where one event at 3 TeV yields a local significance of 2.8σ . A 3 parameter fit is the default background fit function for this category, however, a 2 parameter fit could also be used to describe these data. In Figure 5.31 we compare the limits and p-values obtained using a 2 parameter and a 3 parameter fit to describe the background in this category. The significance at 3 TeV is reduced from 2.8 to 1.5σ with a 2 parameter fit, reflecting the fact that the fit is poorly constrained in the high mass tail due to low statistics. The fit to data using both a 2 and 3 parameter fit in the ZZHP category is shown in Figure 5.32 and we in addition see that the 2 parameter fit lies within the fit uncertainties of the nominal fit.

The lack of constraint on the fit in the dijet invariant mass tail when statistics are very low, is a drawback of a method relying fully on a parametric fit and reduces the analysis sensitivity in the high- m_{jj} region. In Search II (Section 5.2) we will keep taking advantage of the dijet fit, however, the integrated luminosity is ~ 15 times higher, resulting in more datapoints in the m_{jj} tail which further constrains the fit. In Search III (Section 5.4), we will

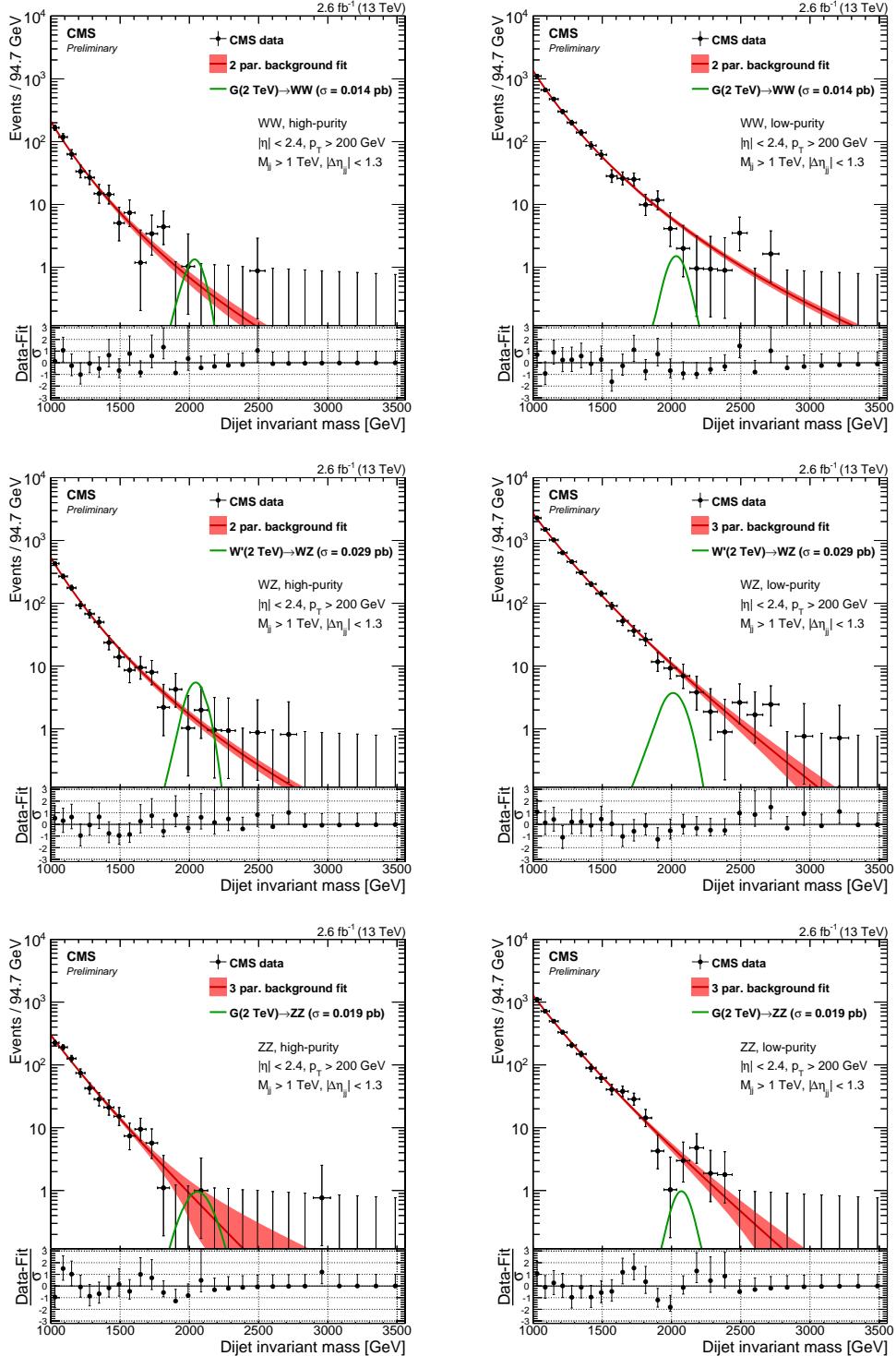


Figure 5.29: Fit to data in the signal region using the background fit only for the different mass and purity categories. The filled red area correspond to the 1 sigma statistical error of the fit.

explore alternate methods which allow more control over the background shape across the full mass spectrum.

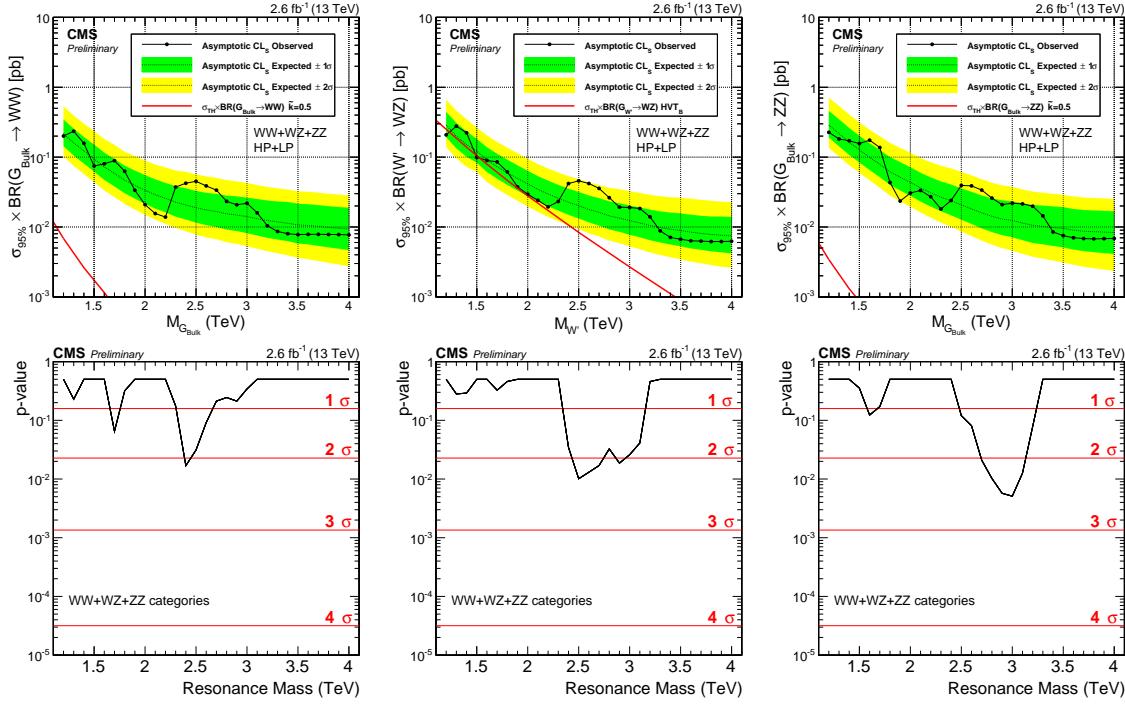


Figure 5.30: Expected and observed limits with corresponding p-values obtained using 2.6 fb^{-1} of CMS data after combining all mass and purity categories. Here for a Bulk $G \rightarrow WW$ (left), $W' \rightarrow WZ$ (middle) and $G \rightarrow ZZ$ (right) signal.

5.1.12 Limits: Semi-leptonic and all-hadronic combination

To maximize the search sensitivity, we combine the results obtained above with those of the corresponding semi-leptonic analysis. We assume the uncertainties on luminosity, V-tagging efficiency, jet mass scale and resolution to be fully correlated.

The obtained exclusion limits are shown in Figure 5.33 shows the resulting expected and observed exclusion limits. As before, we consider a scenario where only either a W' or Z' resonance is expected, called the singlet hypothesis (upper two plots). In addition, we set limits on the triplet hypothesis, assuming the W' and Z' bosons to be degenerate in mass (bottom left plot). Due to larger branching fraction, the all-hadronic analysis sets stronger upper limits than the semi-leptonic analysis above 1.7 TeV for Z' and $> 1.3 \text{ TeV}$ for W' ($\mathcal{B}(WW \rightarrow q\bar{q}q\bar{q}) = 44\%$, $\mathcal{B}(WW \rightarrow \ell\nu q\bar{q}) = 31\%$, $\mathcal{B}(WZ \rightarrow q\bar{q}q\bar{q}) = 46\%$, and $\mathcal{B}(WZ \rightarrow \ell\nu q\bar{q}) = 16\%$). The analysis sensitivity for G_{bulk} is too weak to set limits, but cross sections between 3–1200 fb are excluded. For the HVT model A and B, W' is excluded below < 2.0 and 2.2 TeV , respectively. Z' resonances are excluded below < 1.6 (1.7 TeV) for HVT model B(A). If assuming a HVT Model A(B) triplet hypothesis, resonances below $< 2.3 (< 2.4) \text{ TeV}$ are excluded.

The combined results would therefore just exclude a W' with a mass around 2 TeV, the favored candidate to explain the 8 TeV diboson excess. However, Bulk Graviton signals were still far from excluded and, with the expected ten times increase in luminosity in 2016, we were excited to keep on searching.

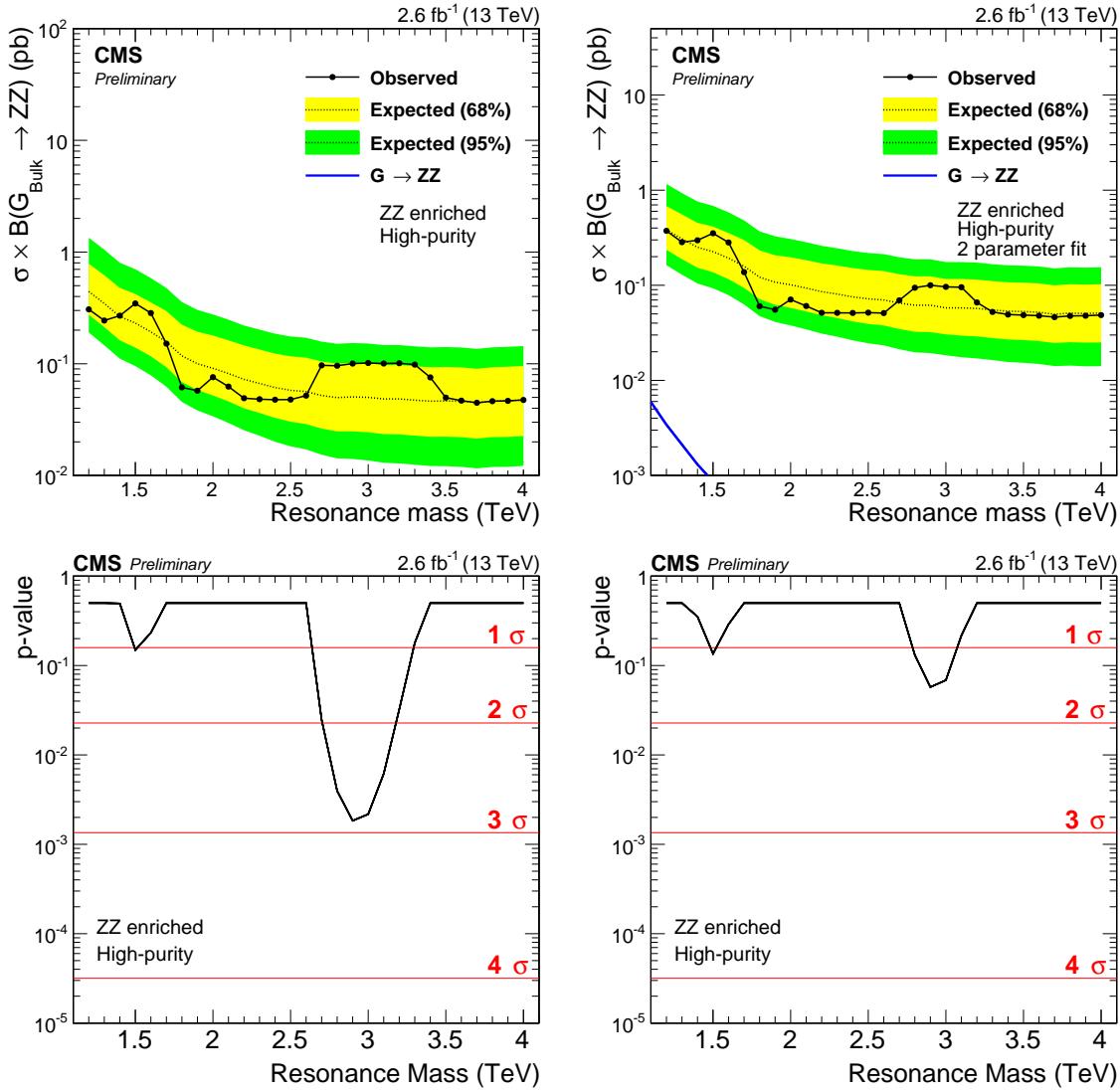


Figure 5.31: Expected/observed limits and corresponding p-values obtained in the ZZHP category using a 3 (left) and two (right) parameter fit to describe the background. The significance at 3 TeV is reduced from 2.8 to 1.5 σ .

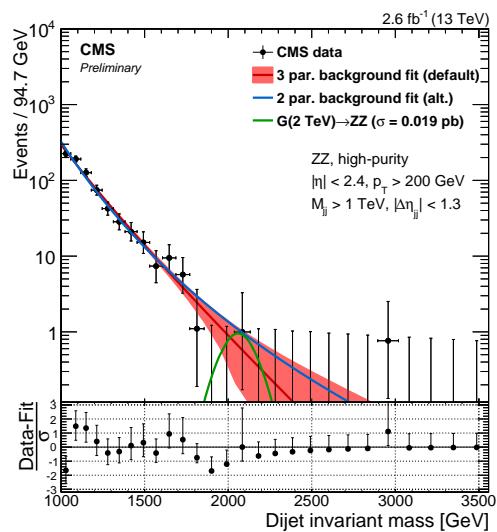


Figure 5.32: Background fit to data in the ZZHP category using the default 3 (red) and an alternate 2 (blue) parameter fit to describe the background.

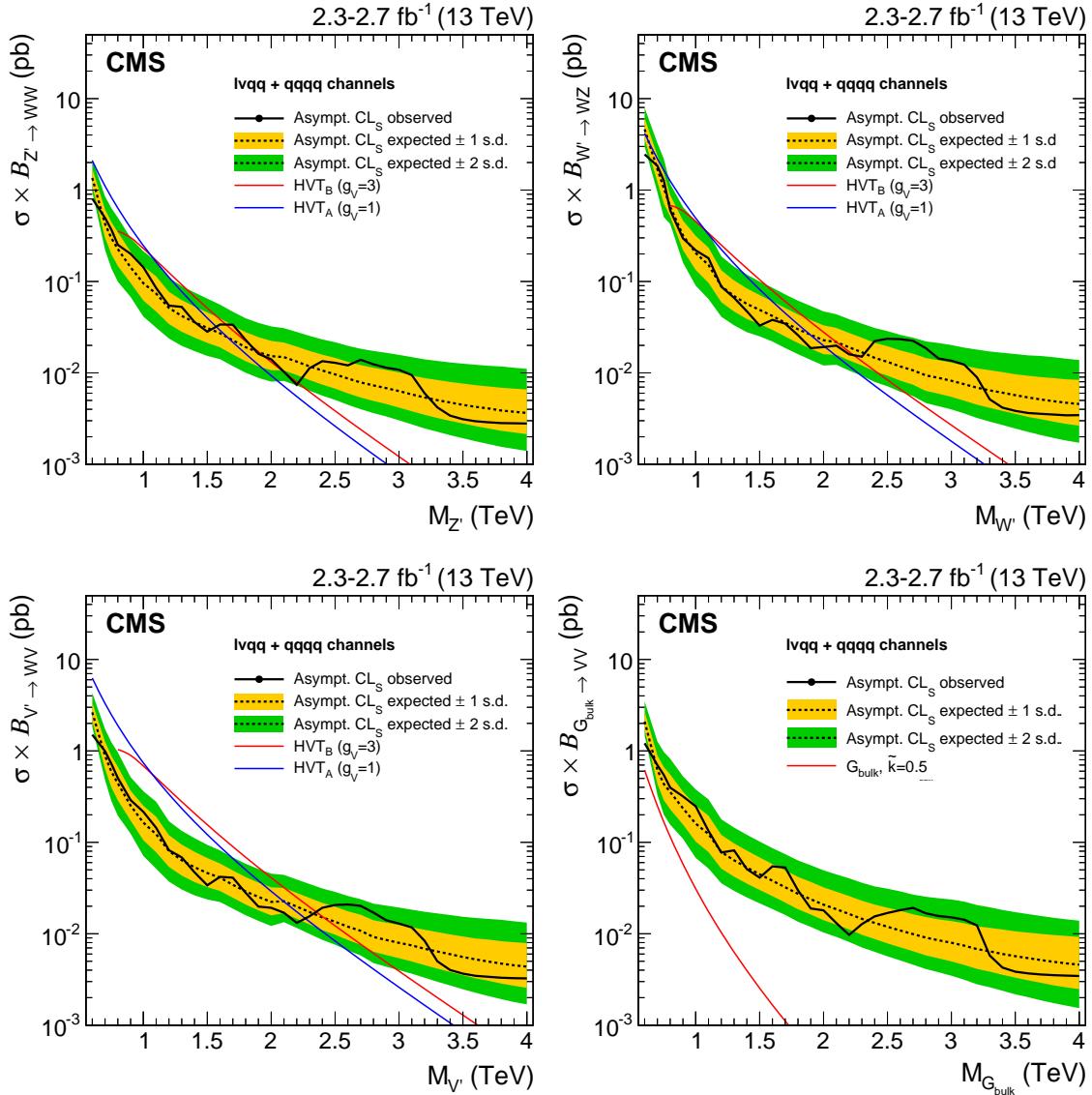


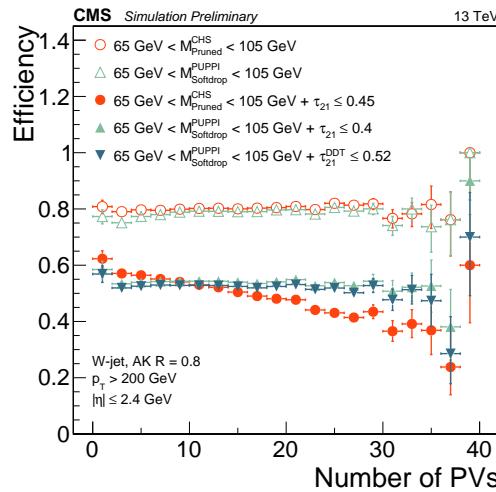
Figure 5.33: Observed (black solid) and expected (black dashed) 95% CL upper limits on the production of a narrow-width resonance decaying to a pair of vector bosons for different signal hypotheses. In the upper plots, limits are set in the context of a spin-1 neutral Z' (left) and charged W' (right) resonances, and compared with the prediction of the HVT Models A and B. In the lower left plot, limits are set in the same model under the triplet hypothesis (W' and Z'). In the lower right plot, limits are set in the context of a bulk graviton with $\tilde{k}=0.5$ and compared with the prediction.

5.2 Search II: A new pileup resistant and perturbative safe tagger

With the first 13 TeV diboson resonance search published, we could conclude that more data would be needed in order to fully exclude the observed Run 1 excess. Luckily, 2016 was right around the corner and, with the LHC planning to reduce β^* from 80 cm to 40, the machine was expected to deliver an instantaneous luminosity three times that of the 2015 peak luminosity. Higher instantaneous luminosity, however, meant double the pileup.

We knew that a novel pileup subtraction algorithm had been developed, which provided far better pileup and underlying event rejection than the current default (CHS). We also knew that there had been made progress on the theory side in the development of a groomer which was insensitive to the soft divergences of QCD and allowed to accomplish jet grooming in a theoretically calculable way, SoftDrop (mMDT). With more time at hand than in 2015, I therefore decided to pursue a novel W-tagger for this second search. This included work like optimization, development of dedicated jet mass corrections (in use today and recommended by the jet physics object group) as well as validation of the new tagger. The tagger, together with the mass corrections, afterwards became the default W-tagging algorithm in CMS.

Search II became the first published analysis to use the novel PUPPI+softdrop algorithm, now default for W-tagging in CMS. Through this search, the tagger was optimized, commissioned and validated, making it available for several analysis to come. In addition, the search was extended to setting limits on three additional signal hypothesis. Two of these were in a final state never before explored at 13 TeV, the $q^* \rightarrow qV$ single V-tag analyses.



5.2.1 Towards robust boosted jet tagging

When we first studied W-tagging at 13 TeV in context with the analysis of the 2015 dataset, Section 5.2.5, two interesting correlations were observed:

- 1) A strong dependence of the AK8 CHS softdrop ($\beta = 0$) jet mass on jet p_T and
- 2) a strong dependence of the AK8 CHS τ_{21} cut efficiency on pileup.

The reason we studied the softdrop algorithm as an alternative to pruning in 2015 was, besides the possibility it would result in a higher signal efficiency, that we knew it had certain favorable qualities compared to other groomers: Softdrop removes all sensitivity to the soft divergences of QCD, by removing all soft emission, more specifically the non-global logarithmic terms (NGLs) in the jet mass [24]. These arise from constellations where, for instance, a soft gluon is radiated into the jet cone, as illustrated in Figure 5.34. The consequence of

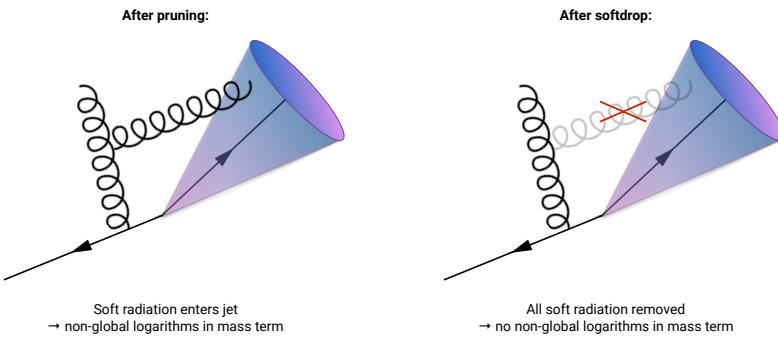


Figure 5.34: The pruning algorithm does not remove all soft emission and therefore has non-global logarithmic terms in the jet mass. Softdrop ($\beta = 0$) completely removes soft emissions and is therefore free of non-global logarithms.

this is that you can calculate the softdrop jet mass to way higher precision than what is possible for other grooming algorithms or for the plain jet mass (NGLs are the main reason a full resummation of the plain jet mass beyond NLL (considering e.g multiple-emission effects) accuracy does not exist). Despite this not being a precision measurement analysis, we had theoretically well-motivated reasons for wanting the baseline CMS V-tagger to be softdrop-based. However, despite being less sensitive to soft radiation for QCD jets, signal jets groomed with softdrop were found to be far more sensitive to the underlying event than pruned jets [48]. Figure 5.35 shows the signal efficiency for pruning (left) and softdrop (right) as a function of jet transverse momenta when including FSR only, FSR+ISR, hadronization and hadronization + underlying event. On parton level, as well as after hadronization, the two algorithms perform very similar as a function of p_T . However, once UE contamination is added, the softdrop tagging efficiency is severely affected. This can be explained by the larger effective radius considered by the softdrop algorithm ($\propto m_V/p_T \sqrt{z_{cut}(1-z_{cut})}$) in comparison to pruning ($\propto m_V/p_T$). This observation corresponds very well with the shift in jet mass we observed for softdrop as a function of p_T in Section 5.2.5: As the jet p_T decreases the softdrop effective radius increases and the jet mass mean shifts to higher values, due to absorbing more background radiation. If softdrop would be our new default tagger, a better rejection of pileup and UE contamination would be needed. In parallel to the ongoing theoretical work on groomers, a novel pileup removal algorithm had been proposed: Pileup per particle identification (PUPPI) [16]. Described in detail in Section 4.3.2, PUPPI considers not only charged pileup but rather reweights each particle in the jet with its probability of arising from pileup. PUPPI had proven it self far superior to the current CHS algorithm in

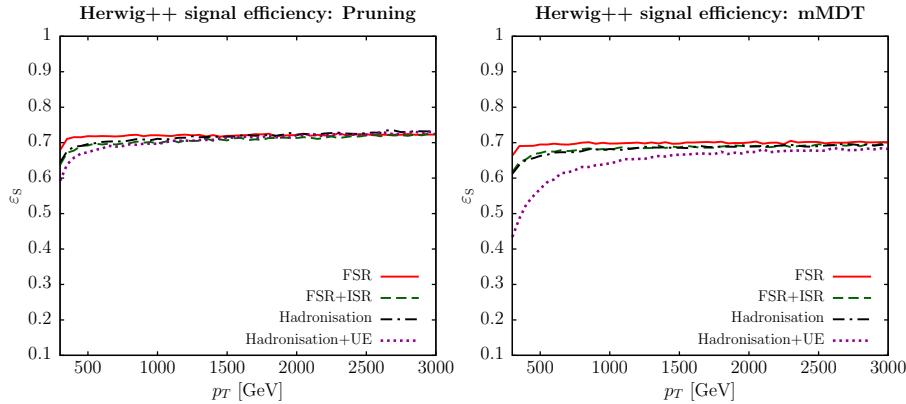


Figure 5.35: The signal efficiency for pruning (left) and softdrop (right) as a function of jet p_T when adding FSR, ISR, hadronization and UE. The UE has a severe impact on the softdrop efficiency for signal jets [48].

terms of jet observables for large radius jets, and therefore seemed like the obvious choice to address both issues listed above: The sensitivity of softdrop regarding UE contamination and the strong pileup dependence of τ_{21} . The focus of Search II would therefore be on the commissioning of a novel W-tagger. There are interesting changes and inclusions in the analysis strategy as well: The inclusion of a $Z' \rightarrow WW$ signal hypothesis and the addition of a completely new analysis, the single V-tag analysis.

5.2.2 Analysis strategy

The analysis strategy for this search is conceptually the same as for Search I. In addition, we'll take advantage of the n-subjettiness categorization and do an additional analysis in parallel: A search for excited quark resonances q^* [49, 50] decaying to qW or qZ . We call this the single V-tag analysis, and the analysis selection only differs in that one jet is not required to pass the V-tag selection (groomed mass and n-subjettiness). The VV analysis is hereby referred to as the double V-tag analysis. The difference between the two analyses is illustrated in Figure 5.36. In addition, limits are set on a $Z' \rightarrow WW$ signal hypothesis in the

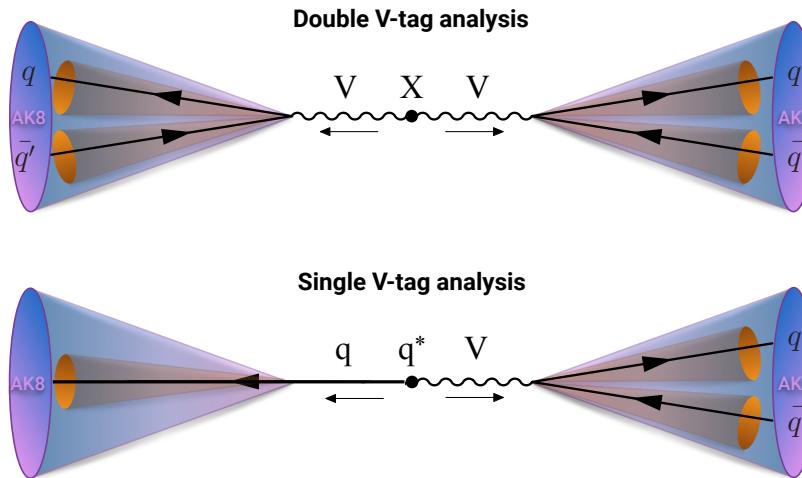


Figure 5.36: The double (top) and single (bottom) W/Z-tag analysis.

double V-tag analysis, another 13 TeV first.

This analysis was published in two steps: An early Physics Analysis Summary (PAS) based on 12.9 fb^{-1} of 2016 data [51], describing the new PUPPI+softdrop based V-tagger as well as the single V-tag analysis, and a second analysis topping up with the full 2016 data [52]. The commissioning of the new W Z-tagger has also been documented in a jet performance Physics Analysis Summary [53]. As the new V-tagger was developed and commissioned in the context of the early analysis, which was also where the single V-tag analysis was first published with 13 TeV data, the main emphasis will be on the work presented in CMS-PAS-B2G-16-021 [51]. The second part of the results chapter, Section 5.3, includes the results obtained using the full 2016 dataset of 35.9 fb^{-1} .

5.2.3 Data and simulated samples

As mentioned above, the analysis of the 2016 dataset was done in two steps: One analysis based on 12.9 fb^{-1} of early 2016 data, describing the new W-tagger and single V-tag category, and a second paper topping up with the full 2016 dataset, corresponding to 35.9 fb^{-1} .

The G_{bulk} and HVT signal samples are modeled in precisely the same way as in 2015. For the single V-tag q^* samples, we simulate unpolarized boson with a compositeness scale Λ set equal to the resonance mass. These are generated to leading order using PYTHIA version 8.212 [43].

The background Standard Model processes; QCD, W+jets and Z+jets are all simulated to leading order. V+jets is simulated with MADGRAPH5_AMC@NLO [42, 54], while three different combinations of matrix element and shower generators are used for QCD as these predictions are known to differ: PYTHIA only, the leading order mode of MADGRAPH5_AMC@NLO matched with PYTHIA, and HERWIG++ 2.7.1 [31] with tune CUETHS1 [38].

5.2.4 Event selection

Triggering

The triggers used in this analysis are the same ones as in 2015 (see Section 5.1.4), however, due to the new single V-tag analysis, the trigger turn-ons have this time been re-evaluated separately requiring either one or two jets to have an offline softdrop jet mass above 65 GeV.

Figure 5.37 shows 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. The turn-on curves are shown for all jet pairs passing loose selections as described in Section 5.1.4. Zero, one or two of the two jets is further required to have a softdrop mass larger than 65 GeV.

Including grooming triggers lowers the 99% trigger efficiency threshold by around 50(80) GeV in the single (double) tag category once substructure is requested on the analysis level. Using the or of all triggers, we are safely on the trigger plateau for dijet invariant masses above 955(986) GeV in the double (single) tag category, setting the analysis threshold at a dijet invariant mass of 955 GeV for the double tag analysis and 990 GeV for the single tag analysis. For controlplots, where no groomed mass window is applied, a trigger threshold of 1020 GeV is used.

Trigger efficiencies as a function of the offline softdrop-jet mass for the `HLT_AK8PFJet360_TrimMass30` trigger are shown in Figure 5.38. Here the jet transverse momentum of one of the jets is required to be at least 600 GeV and no other mass cut is applied. This trigger requires one jet to have a trimmed mass above 30 GeV at HLT level

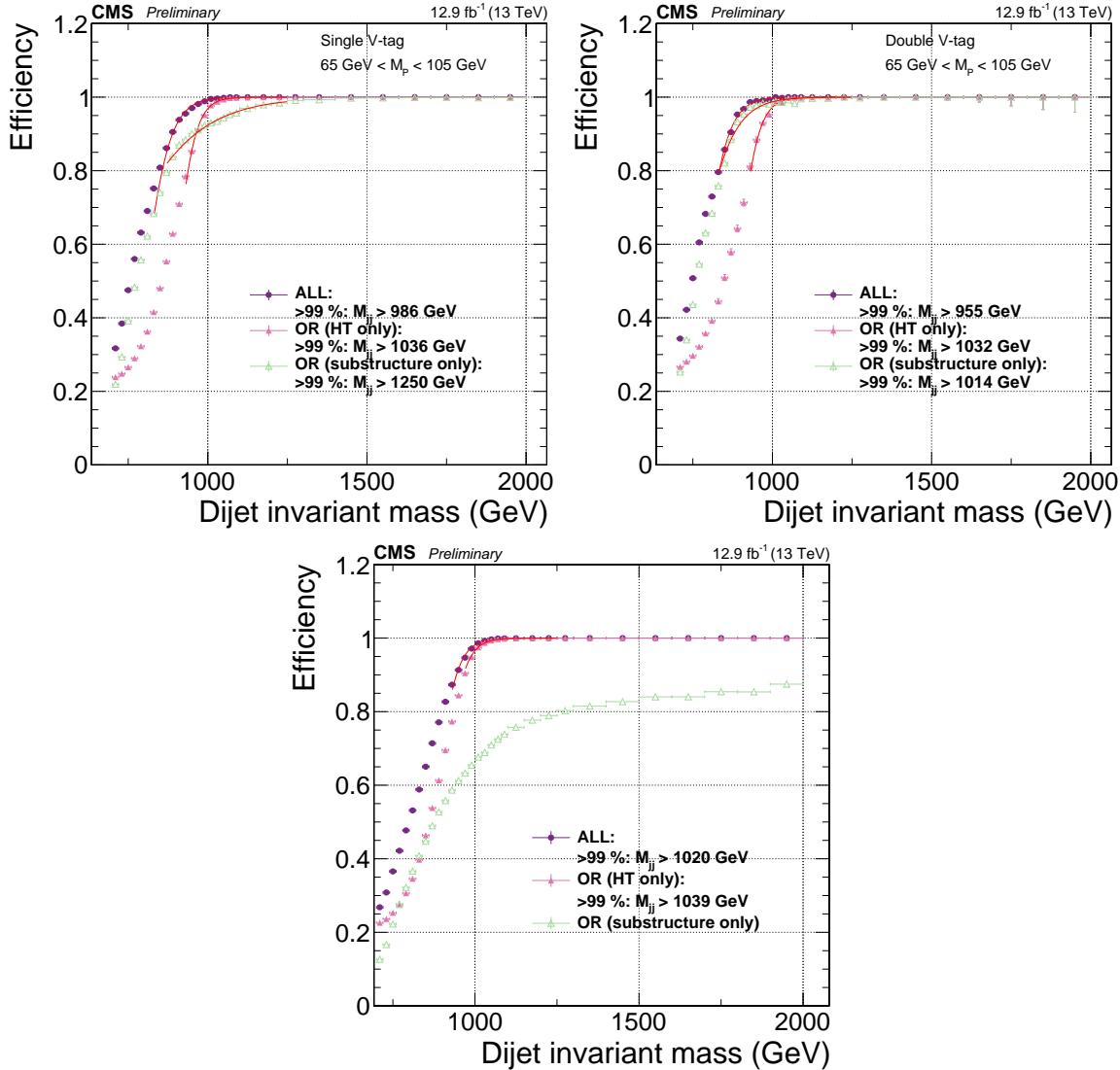


Figure 5.37: Comparison of trigger efficiencies for jets passing one of the HT-triggers only (pink), for jets passing one of the grooming-triggers only (green) and for jets passing one of the HT-triggers or one of the grooming triggers (purple). Here as a function of dijet invariant mass for all jet pairs passing loose selections and where one jet has a softdrop mass larger than 65 GeV (top left), both jets have a softdrop mass larger than 65 GeV (top right) and where no mass cut is applied (bottom).

and reaches the trigger plateau for groomed-jet masses around 50 GeV. As reference trigger, the prescaled trigger HLT_PFTJet320 is used.

Preselection

The same preselections as in Search I, described in , have been applied: We require two AK R=0.8 jets with CHS applied pre-clustering, required to pass the tight jet ID requirement, $p_T > 200 \text{ GeV}$ and $|\eta| < 2.5$. The same QCD t-channel suppressing cut of $|\Delta\eta| < 1.3$ is required together with the following trigger thresholds on the dijet invariant mass: $m_{jj} > 955 \text{ GeV}$ for the double V-tag and 990 GeV for the single V-tag analysis. The jet p_T (top left), η (top right), $\Delta\eta_{jj}$ and dijet invariant mass (bottom left) for the two leading jets in the event after loose preselections are applied is shown in Figure 5.39. A large difference in slope in the

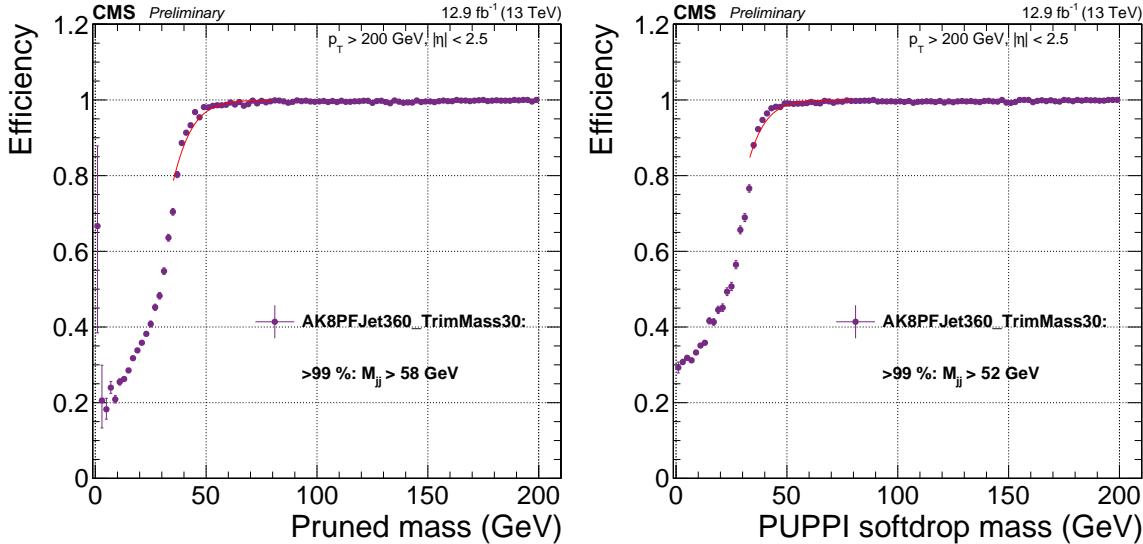


Figure 5.38: Efficiency for the HLT_AK8PFJet360_TrimMass30 trigger as a function of pruned-jet (left) and softdrop-jet (right) mass for jets with $p_T > 600 \text{ GeV}$.

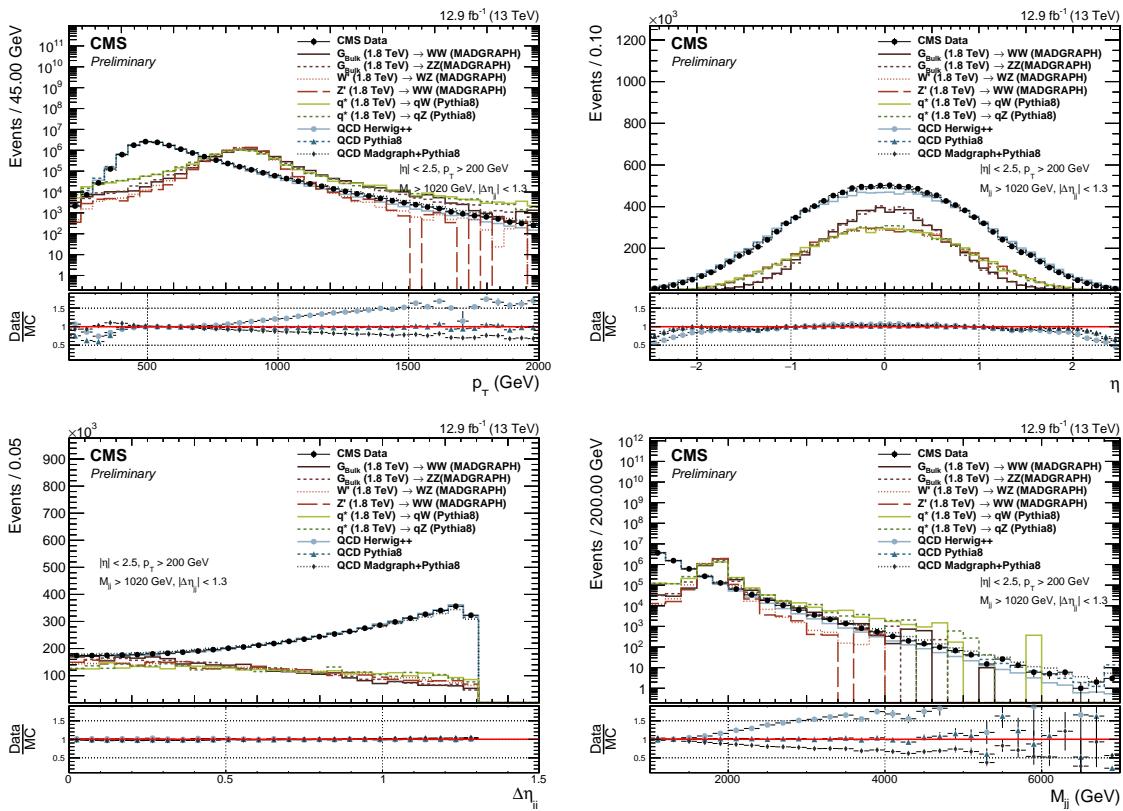


Figure 5.39: Jet p_T (top left), η (top right), $\Delta\eta_{jj}$ and dijet invariant mass (bottom left) for the two leading jets in the event after loose preselections are applied. The signal is scaled by an arbitrary number.

jet p_T and dijet invariant mass spectrum depending on the QCD matrix element or shower generator is observed. Pure PYTHIA QCD MC describes the data best, while HERWIG++ and MADGRAPH5_AMC@NLO+PYTHIA tend to under- or over-estimate the number of high p_T/m_{jj}

jets, respectively. Pure PYTHIA QCD MC is therefore used for all background checks in this analysis.

5.2.5 Developing a new W-tagger

As mentioned in the introduction to this chapter, early studies had shown that the PUPPI pileup subtraction algorithm yielded superior resolution on large-cone jet observables like the jet mass. We therefore wanted to check whether the softdrop jet mass, and its observed sensitivity to the Underlying Event and pileup, would be improved if a better pileup subtraction algorithm was applied pre-clustering.

Two interesting observations were made. Softdrop used together with PUPPI pileup subtraction displayed a much smaller p_T -dependent shift than CHS+Softdrop, as hoped. Figure 5.40 shows the PUPPI softdrop mass for W-jets from a 1 TeV ($p_T \sim 500$ GeV) and 4 TeV ($p_T \sim 2$ TeV) resonance, exhibiting the desired reduced p_T dependence in jet mass scale. However, when applying centrally provided L2 and L3 jet energy corrections (see Section 4.4.3)

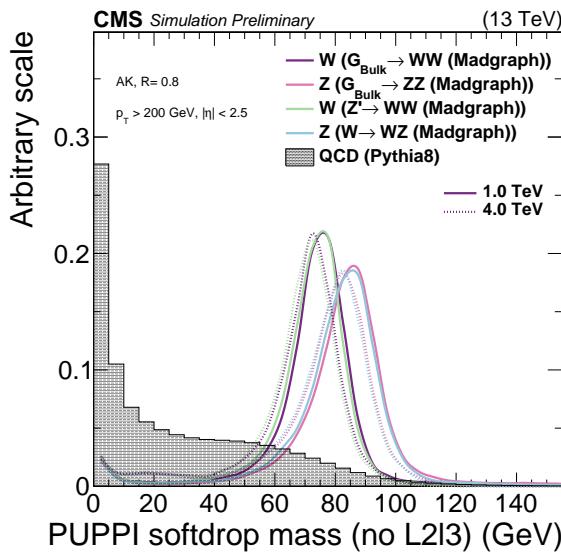


Figure 5.40: The PUPPI softdrop jet mass distribution with no jet energy corrections applied

to the jet groomed mass, as is recommended, a strong p_T dependence is re-introduced. This effect is not present for the pruned jet mass. Figure 5.41 show the softdrop (top left) and pruned (top right) jet mass distribution with recommended L2L3 corrections applied. Here, the PUPPI+softdrop jet mass shift is significantly increased with respect to what was observed for the uncorrected mass, while CHS+pruned jet mass is stable. This points to the PUPPI jet energy corrections not being optimal for scalar jet mass variables, while they may be good for correcting jet 4-vectors. The jet energy corrections derived for CHS and PUPPI jets as a function of jet p_T is shown in the bottom plot in Figure 5.41 . A significant slope in JEC as a function of p_T is measured for PUPPI, while not present for CHS.

Dedicated PUPPI softdrop mass corrections

In order to minimize p_T dependence in the PUPPI softdrop jet mass, all jet energy corrections to the softdrop jet mass are removed. However, this still leaves a residual p_T dependence and, in addition, the uncorrected mass does not peak at the correct W-mass of 80.4 GeV. Figure 5.42 shows the mean of a Gaussian fit to the uncorrected PUPPI softdrop mass as

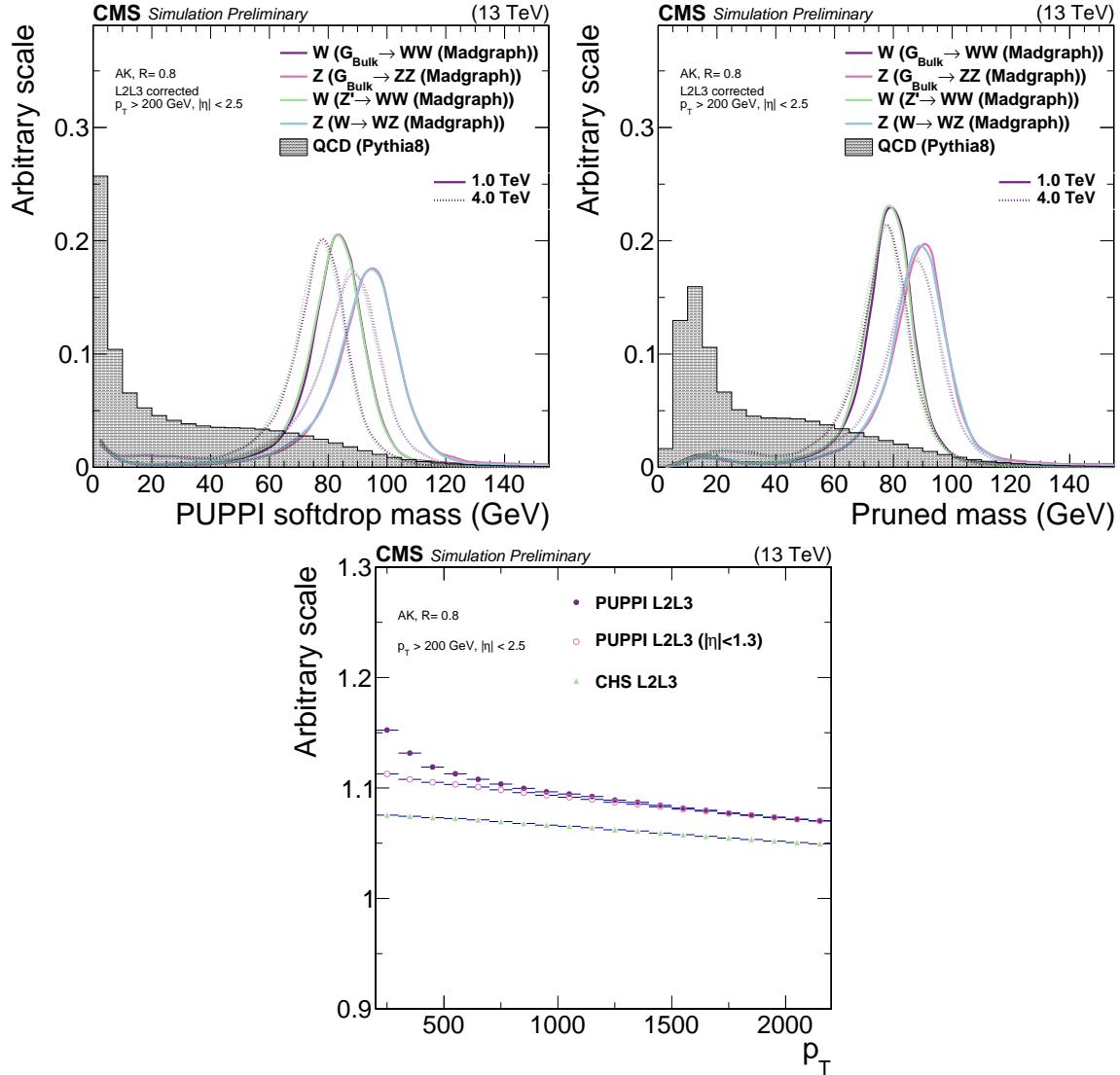


Figure 5.41: Top: PUPPI softdrop mass distribution (top left) and pruned jet mass distribution (top right) with L2 and L3 corrections applied. Bottom: The projection of CHS and PUPPI jet energy corrections versus jet p_T .

a function of jet p_T in two different η bins (smaller or greater than $|\eta| = 1.3$) for W-jets coming from a Bulk Graviton signal sample. A mass shift both as a function of η and p_T is observed, together with an average mean significantly lower than the W-mass. In order to use PUPPI+softdrop for W-tagging, we therefore derive dedicated jet mass corrections to compensate for two factors: A generator level p_T -dependence, as first observed in , and a reconstruction level p_T - and η -dependence, most likely caused by UE effects and the growing effective softdrop radius at low jet p_T . Figure 5.43 shows the mean of the generated softdrop mass (left) and the normalized difference in reconstructed and generated softdrop mass (right) as a function of jet p_T . The shift in generated softdrop mass at lower p_T is of the order of 2-3% while the difference between reconstructed and generated softdrop mass is a 5-10% effect. The mass shift introduced at generator level is corrected by a fit to $M_{\text{PDG}}/M_{\text{GEN}}$ as a function of jet p_T , where $M_{\text{PDG}} = 80.4$ GeV and M_{GEN} is the fitted mean of the generator level mass as shown in the left plot in Figure 5.43. To correct for the residual shift between generated and reconstructed softdrop mass, a fit to $(M_{\text{RECO}} - M_{\text{GEN}})/M_{\text{RECO}}$, where M_{RECO}

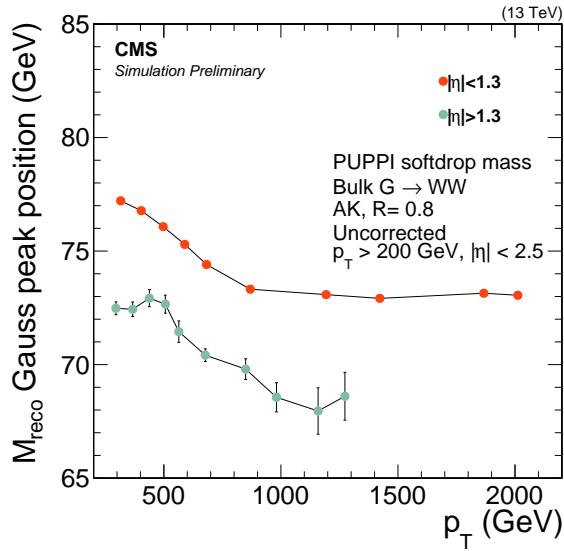


Figure 5.42: The mean of a Gaussian fit to the W-jet PUPPI softdrop mass peak as a function of jet p_T in two different η bins (smaller or greater than $|\eta| = 1.3$). No corrections have been applied to the softdrop mass.

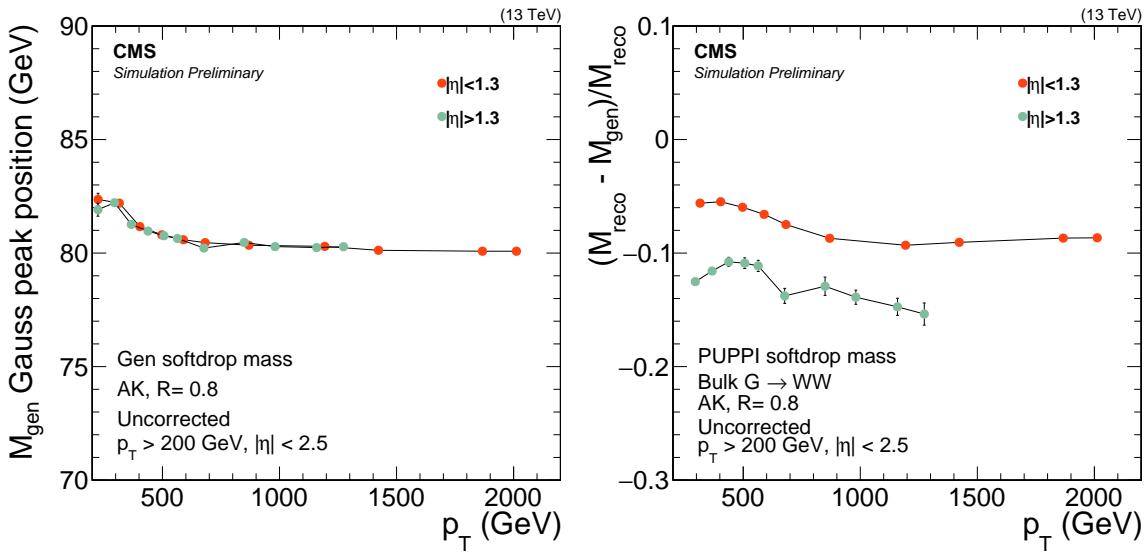


Figure 5.43: The mean of the fitted generator level W-jet softdrop mass distribution as a function of jet p_T (left) and the normalized difference in reconstructed and generated softdrop mass (right).

is the reconstructed mass shown in the right plot in Figure 5.43 and M_{GEN} is as defined above, as a function of jet p_T in two η bins (smaller or greater than $|\eta| = 1.3$) is performed. Polynomial fit functions of the following forms are used

$$\begin{aligned} w(p_T) &= A + B(x^2)^{-C} && \sim \text{"gen correction"} \\ w(p_T) &= A + Bx + Cx^2 + Dx^3 + Ex^4 + Fx^5 && \sim \text{"reco correction"} \end{aligned}$$

The distribution and corresponding fits for the two weights is shown in Figure 5.44 for the ‘gen correction’ (left) and ‘reco correction’ (right). The two corrections are then applied to

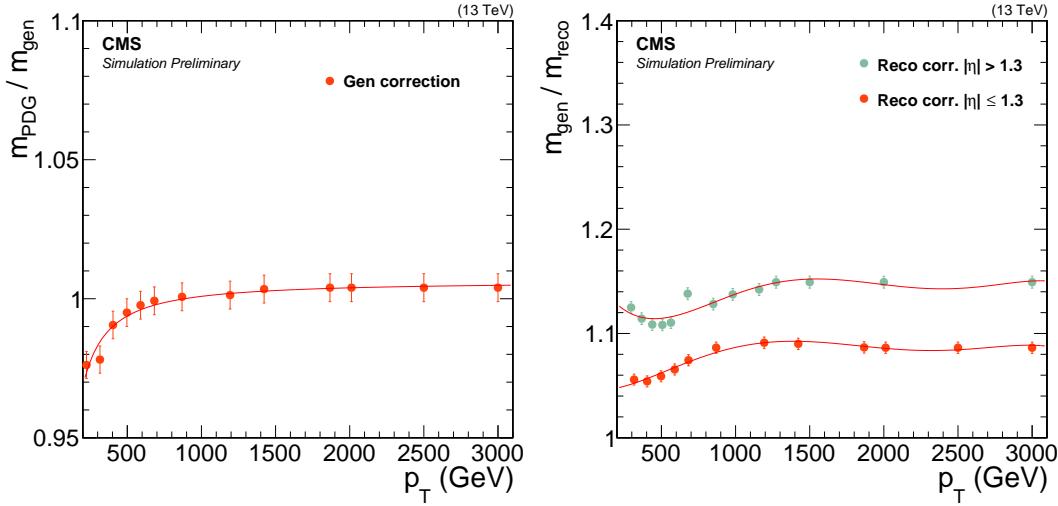


Figure 5.44: Fit to $M_{\text{PDG}}/M_{\text{GEN}}$ as a function of jet p_T (left), where $M_{\text{PDG}} = 80.4$ GeV and M_{GEN} is the fitted mean of the generator level mass and a fit to $(M_{\text{RECO}} - M_{\text{GEN}})/M_{\text{RECO}}$ (right), where M_{RECO} is the reconstructed softdrop mass, as a function of jet p_T in two η bins.

the uncorrected PUPPI softdrop mass both in data and in MC as

$$M_{SD} = M_{\text{SD,uncorr}} \times w_{\text{GEN}} \times w_{\text{RECO}} \quad (5.9)$$

where w_{GEN} and w_{RECO} correspond to the gen and reco corrections respectively and $M_{\text{SD,uncorr}}$ is the uncorrected PUPPI softdrop mass.

Finally, a closure test is performed in order to check that the corrected PUPPI+softdrop W-jet mass peaks at 80.4 GeV and is stable with p_T and η . The fitted mean of the corrected PUPPI softdrop mass peak as a function of jet p_T in two different η bins is shown in Figure 5.45. Good closure is observed, with the corrected mass peaking around 80 GeV independent of the jet p_T and η . The PUPPI softdrop jet mass peak for W/Z-jets from different signal samples after jet mass corrections have been applied is shown in Figure 5.46, for resonances with a mass of 1 and 4 TeV. The corrections applied to Z-jets yield a mass stable with p_T , peaking around the Z mass.

W-tagging performance

The new PUPPI+softdrop based W/Z-tagger uses a mass window of $65 \text{ GeV} < m_{SD} < 105 \text{ GeV}$ in combination with a cut of PUPPI $\tau_{21} < 0.4$. We compare its performance to that of the CHS+pruning based tagger used in Search I as well as to that of a ‘DDT-transformed’ τ_{21} based tagger [55]. The τ_{21}^{DDT} variable is a linear transformation of τ_{21} given as

$$\tau_{21}^{DDT} = \tau_{21} + M \times \log \left(\frac{m^2}{p_T \times 1 \text{ GeV}} \right) \quad (5.10)$$

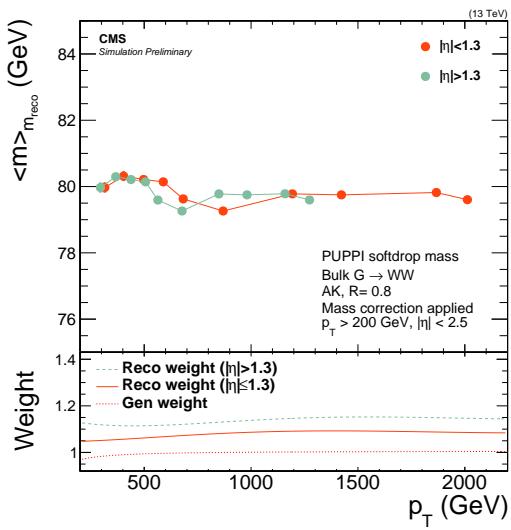


Figure 5.45: The mean of the fitted W-jet corrected PUPPI softdrop mass peak as a function of jet p_T in two different η bins.

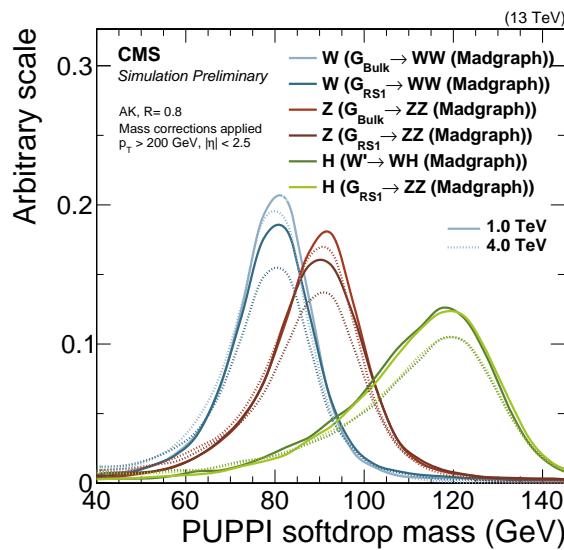


Figure 5.46: The W/Z/H-jet corrected PUPPI softdrop mass peak for jets from different signal samples with masses of 1 and 4 TeV.

where $M = -0.063$ is obtained from a fit of τ_{21} against the variable $\rho' = \log(m^2/p_T/\mu)$, where $\mu = 1 \text{ GeV}$. The purpose of this is to decorrelate τ_{21} from the softdrop mass and p_T , yielding a mass and dijet invariant mass spectrum minimally sculpted by a cut on the τ_{21}^{DDT} tagging variable. This is tagger that will be further explored and explained in detail in the context of Search III, Section 5.4.4.

The background rejection efficiency for QCD light flavor jets as a function of W-jet signal efficiency is shown in Figure 5.47. The efficiency is measured requiring a fixed jet mass window of $65\text{-}105 \text{ GeV}$, while scanning the cut on τ_2/τ_1 . The general performance of each tagger

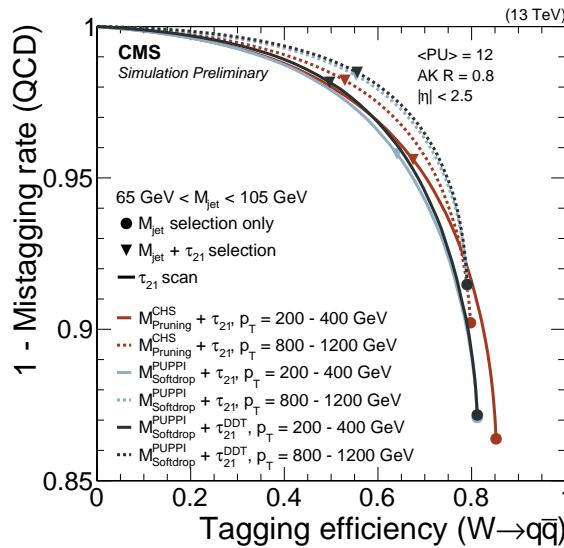


Figure 5.47: The background rejection efficiency for QCD light flavor jets as a function of W-jet signal efficiency. A cut on CHS pruned or PUPPI softdrop jet mass of $65 < m_{\text{jet}} < 105 \text{ GeV}$ is applied while scanning the cut on τ_{21} . The cuts corresponding to $\tau_2/\tau_1 < 0.45$ for CHS+pruning, PUPPI $\tau_2/\tau_1 < 0.4$ for PUPPI+softdrop or $\tau_{21}^{DDT} < 0.52$ are indicated with triangles, while the solid circles represent the efficiency and mistag rate for a mass cut only.

is very similar, with the PUPPI+softdrop based taggers displaying a slightly higher signal efficiency for a given mistag rate at high p_T and CHS+pruning slightly better at low p_T . To better understand the difference between each tagger, we look at the tagging performance as a function of jet p_T as well as pileup, shown in Figure 5.48 and 5.49.

Starting with the tagger p_T -dependence in Figure 5.48, we observe that the signal efficiency of a PUPPI+softdrop of CHS+pruned jet mass cut is flat as a function of p_T , at around 80%. The QCD mistag rate drops for both groomers, with a 1-3% lower mistag rate using PUPPI+softdrop than CHS+pruning. Once applying an n-subjettiness cut, the signal efficiency as well as the mistag rate for the PUPPI τ_{21} and CHS τ_{21} taggers drops as a function of p_T , with an average signal efficiency of around 50% for a $\sim 2\%$ mistag rate. An interesting behavior is observed for the τ_{21}^{DDT} tagger: While the mistag rate is flat as a function of p_T , as is the purpose of decorrelated taggers, the signal efficiency improves as the p_T increases, outperforming the other taggers above 1 TeV.

Turning to the tagger pileup dependence, shown in Figure 5.49, the expected benefit from using the PUPPI algorithm is observed: The tagging efficiency for the CHS+pruning (red solid circles) based tagger falls off steeply versus the number of primary vertices in the event, while the PUPPI+softdrop based taggers (light and dark blue solid circles) are more or less insensitive to pileup. Based on general performance, tagging stability versus pileup and due to theoretical considerations, PUPPI softdrop mass with dedicated mass corrections applied

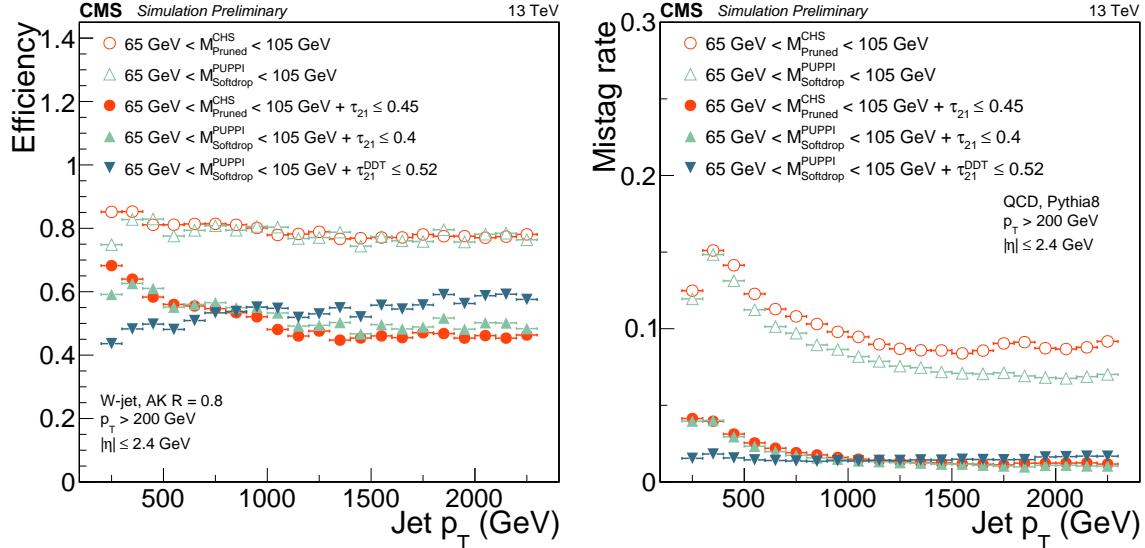


Figure 5.48: W-jet efficiency (left) and QCD light jet mistag rate (right) for a PUPPI+softdrop or CHS+pruned jet mass selection only (hollow circles) and the combined $m_{\text{jet}} + (\text{PUPPI}) \tau_2/\tau_1$ (DDT) selection (solid circles) as a function of jet p_T .

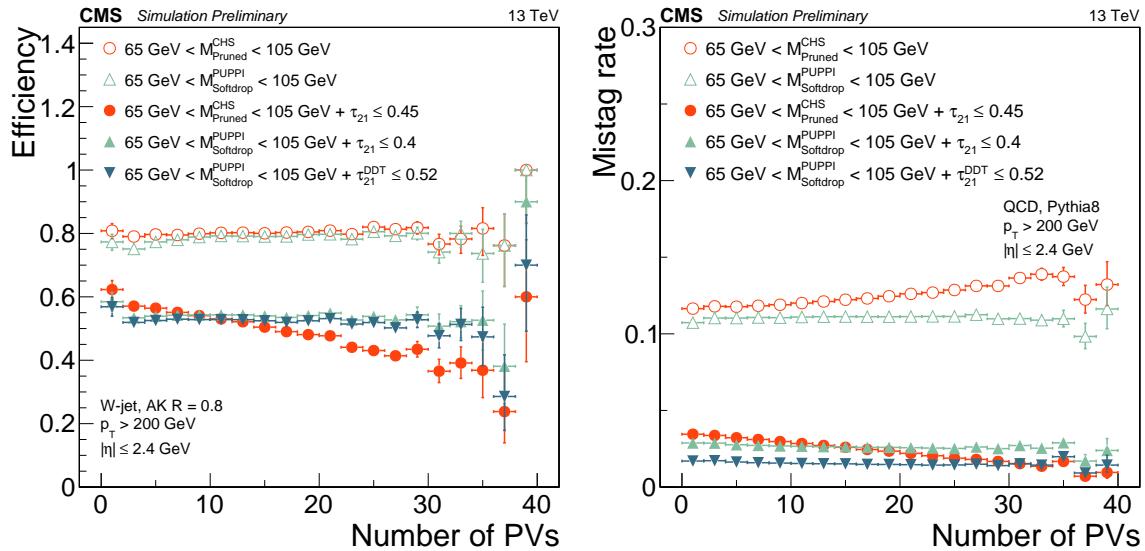


Figure 5.49: W-jet efficiency (left) and QCD light jet mistag rate (right) for a PUPPI+softdrop or CHS+pruned jet mass selection only (hollow circles) and the combined $m_{\text{jet}} + (\text{PUPPI}) \tau_2/\tau_1$ (DDT) selection (solid circles) as a function of jet pileup.

together with PUPPI τ_{21} is chosen as this analysis W-tagger. The per-jet efficiency is around 50-55% for a 1-2% mistag rate.

The PUPPI softdrop jet mass and PUPPI τ_{21} distribution in data is shown in Figure 5.50. We see some disagreement between data and MC, especially in the high-purity region ($\text{PUPPI } \tau_{21}^{\text{DDT}} < 0.4$). In order to have an accurate estimate of the signal efficiency when applying this W-tagger, a good measurement of the difference in tagging efficiency between data and MC is crucial and is what we will focus on next.

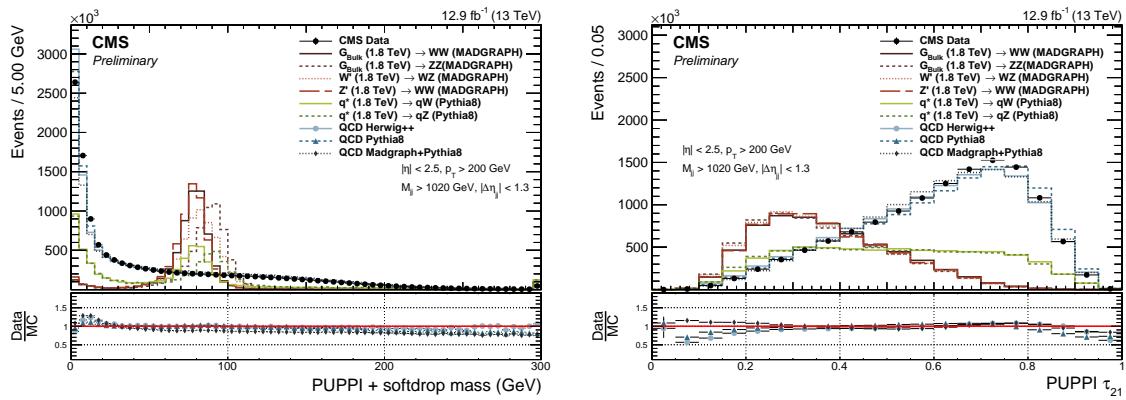


Figure 5.50: PUPPI softdrop jet mass distribution (left) and PUPPI n-subjettiness τ_{21} (right) distribution for data and simulated samples. Simulated samples are scaled to match the distribution in data.

Efficiency scale factors and mass scale/resolution measurement

In order to measure the W-tagging efficiency, jet mass scale and resolution for the new PUPPI+softdrop based tagger, we use the same procedure as outlined in Section 5.1.7. We first did an early measurement of the efficiency using 2.3 fb^{-1} of data collected in 2015, which was published in a jet algorithms performance note [53] and became the first commissioning of the new tagger. We then redid the measurement with 12.9 and 35.9 fb^{-1} of 2016 data, respectively, for the two analyses presented in this chapter (the latter measurement performed by a separate analysis team). The results shown in the following will be those obtained during the commissioning of the tagger as well as those eventually used in the two analyses (summarized in Section 5.2.7). In order to better understand the differences between the CHS+pruning and PUPPI+softdrop based taggers, the first measurement was done in parallel for both algorithms, requiring either a softdrop or a pruned jet mass between 40 GeV and 150 GeV. The softdrop mass is computed after PUPPI and the jet mass corrections as described in Section 5.2.5 are applied, while the pruned mass is corrected with L2L3 jet energy corrections.

5.2.6 W-tagging mistagging rate measurement

We additionally measure the W-tagging fake rate in data in a QCD dijet enriched region and compare this to the prediction from QCD MC using the three different combination of generators described above (HERWIG++, PYTHIA and MADGRAPH +PYTHIA). Figure 5.51 shows the mistag rate as a function of p_T

5.2.7 Efficiency scale factors for 12.9 and 35.9 fb^{-1}

5.3 Results for the full 2016 dataset

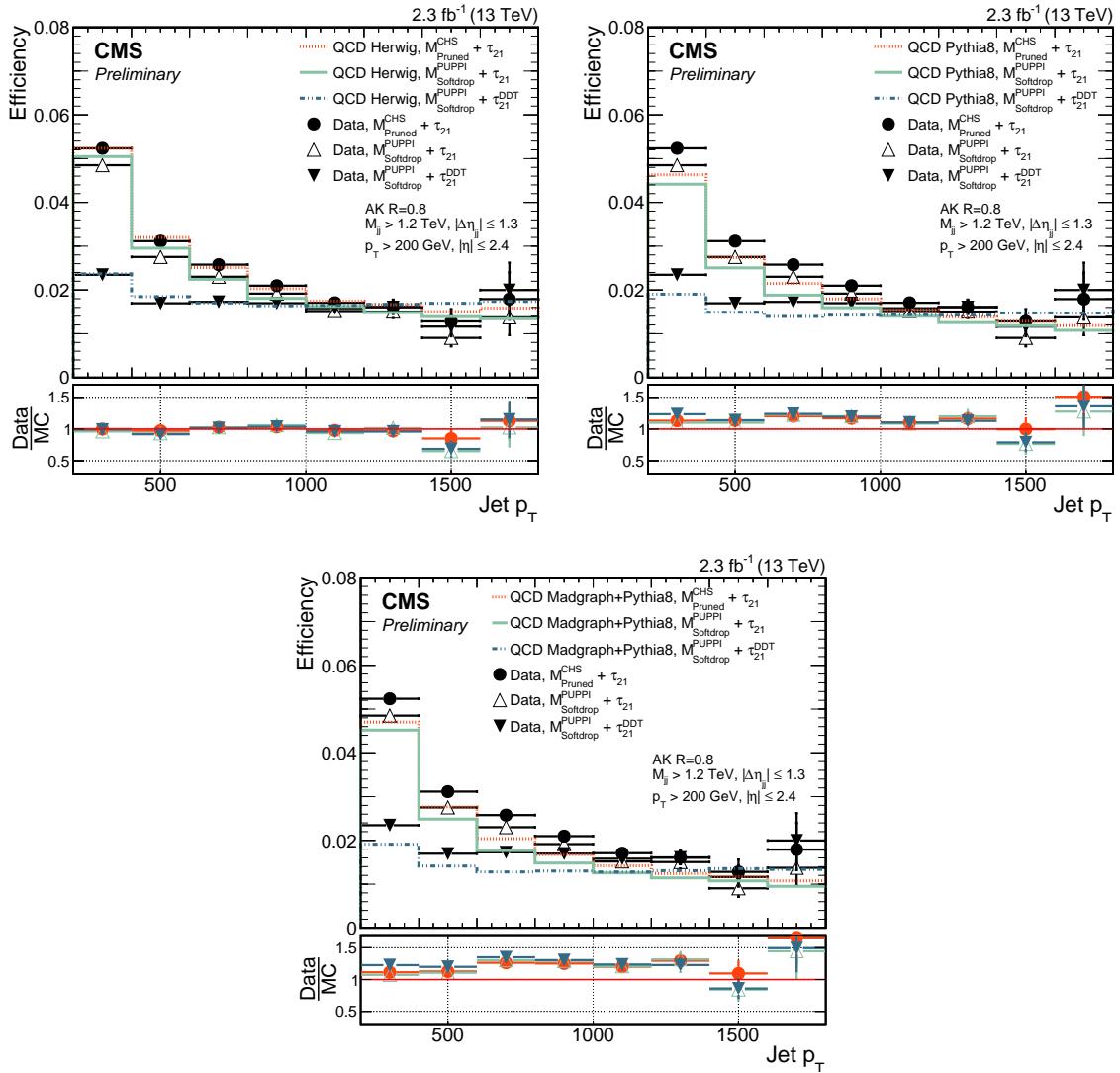
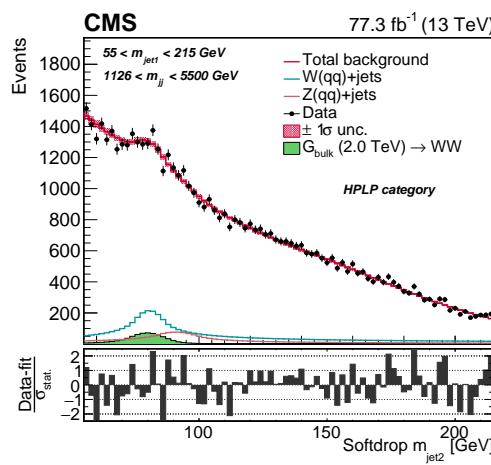


Figure 5.51: Fraction of jets passing the m_{jet} and τ_2/τ_1 selections in a dijet data sample and in simulation as a function of p_T , comparing (a) HERWIG++, (b) PYTHIA8 and (c) PYTHIA8 with MADGRAPH as matrix-element generator. The data over simulation ratio is shown for the combination of the m_{jet} and τ_2/τ_1 selections.

5.4 Search III: A novel framework for multi-dimensional searches

After two successful analyses of 13 TeV data, no excess had been observed in the all-hadronic VV channels. The available phase space for New Physics to hide out was shrinking and we saw two ways forward: Either look for deviations from the Standard Model through precision measurements that would allow searching for resonances currently out of LHC reach, or deplete the number of places New Physics could be hiding as efficiently and completely as possible. With a solid background in searches with boosted final states, we decided for the latter. Our idea was the following: What if the small excesses observed in VV final states were due to us catching the tail of another type of boson with a mass slightly different from that of a W or a Z boson? And what if we were seeing cascade decays, where the jets in questions were actually four-prong like rather than two?.....TODO

Completing the Run 2 VV search program is Search III: A novel framework for multi-dimensional searches.



5.4.1 Small bumps and tribosons

5.4.2 Analysis strategy

5.4.3 Event selection

5.4.4 A mass and p_T decorrelated tagger

5.4.5 The multidimensional fit

CHAPTER 6

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

- 6.1 Machine Learning: The future of high-performance, low-latency taggers**
- 6.2 LoLa: A Lorentz Invariance Based Deep Neural Network for W-tagging**
 - 6.2.1 Inputs**
 - 6.2.2 The Combination Layer**
 - 6.2.3 The Lorentz Layer**
- 6.3 Decorrelating from mass and p_T**
- 6.4 Performance**

CHAPTER 7

Summary

APPENDIX A

Search I: Limits per mass category

The asymptotic limits obtained with 2.6 fb^{-1} of 13 TeV CMS data per mass and purity category. The largest significance is found at 2.8-3 TeV in the ZZ high-purity category, where one event at 3 TeV yields a local significance of 2.8σ . A 3 parameter fit is the default background fit function for this category, however, a 2 parameter fit could also be used to describe these data. In Figure ?? we compare the limits and p-values obtained using a 2 parameter and a 3 parameter fit to describe the background in this category. The significance at 3 TeV is reduced from 2.8 to 1.5σ with a 2 parameter fit, reflecting the fact that the fit is poorly constrained in the high mass tail due to low statistics. The fit to data using both a 2 and 3 parameter fit is the ZZHP category is shown in Figure 5.32.

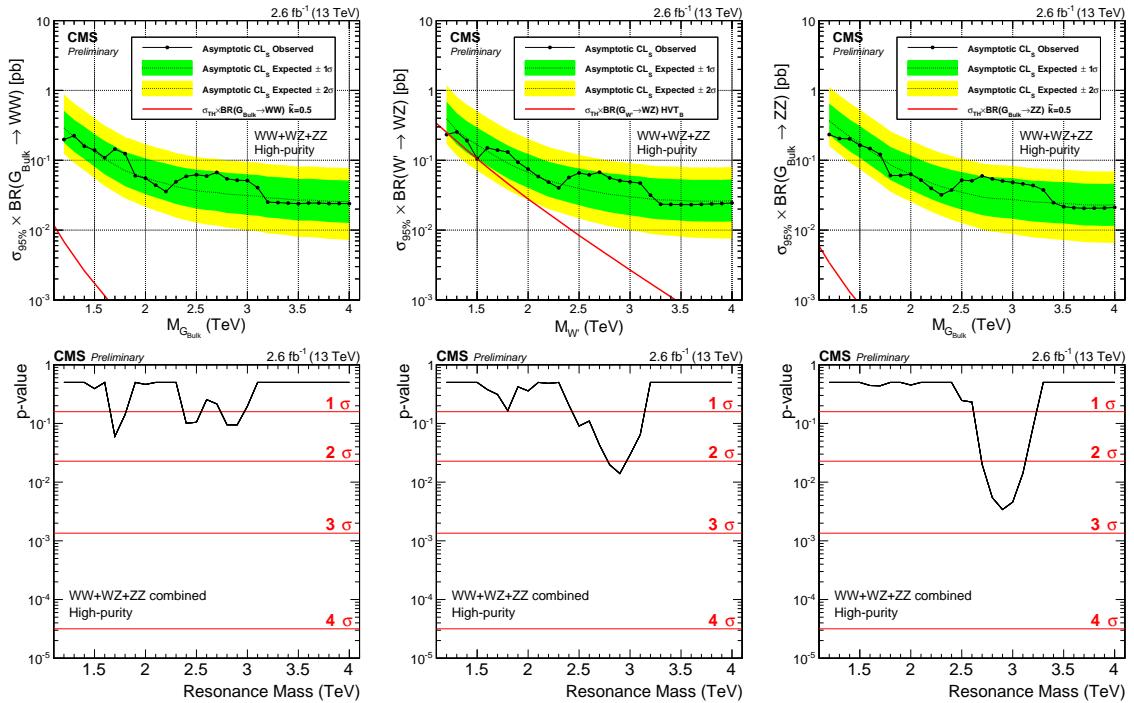


Figure A.1: Expected/observed limits and corresponding p-values obtained in the high purity category using 2.6 fb^{-1} of CMS data. Here for a Bulk $G \rightarrow WW$ (left), $W' \rightarrow WZ$ (middle) and $G \rightarrow ZZ$ (right) signal.

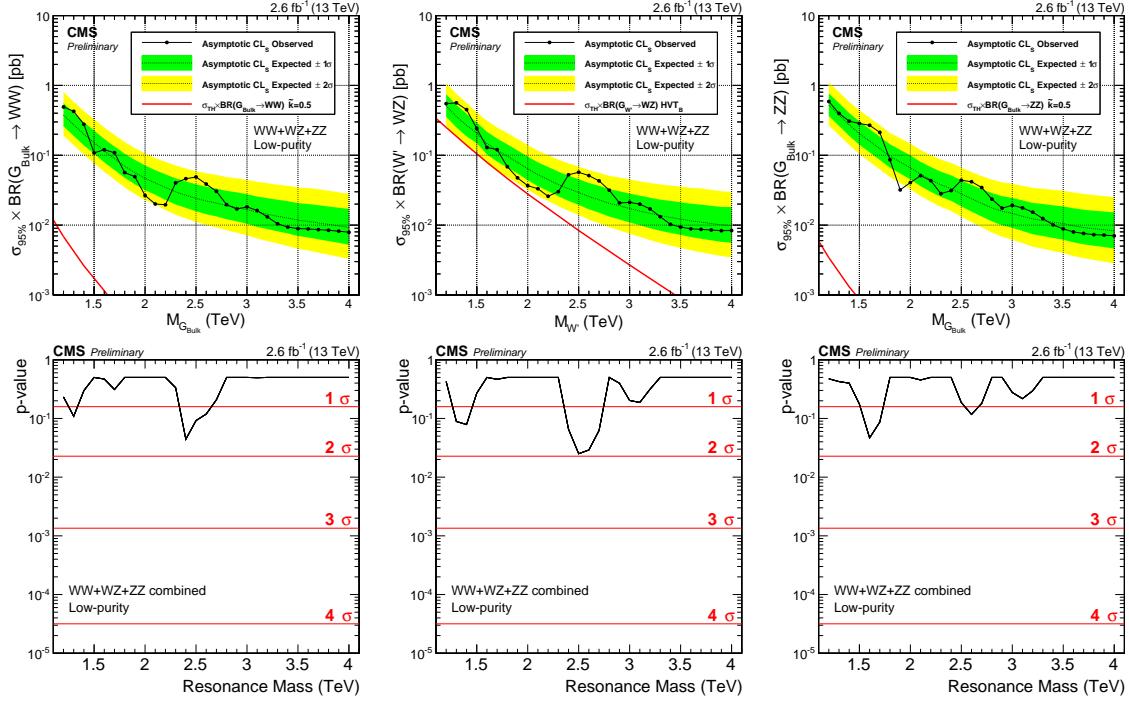


Figure A.2: Expected/observed limits and corresponding p-values obtained in the low purity category using 2.6 fb^{-1} of CMS data. Here for a Bulk $G \rightarrow WW$ (left), $W' \rightarrow WZ$ (middle) and $G \rightarrow ZZ$ (right) signal.

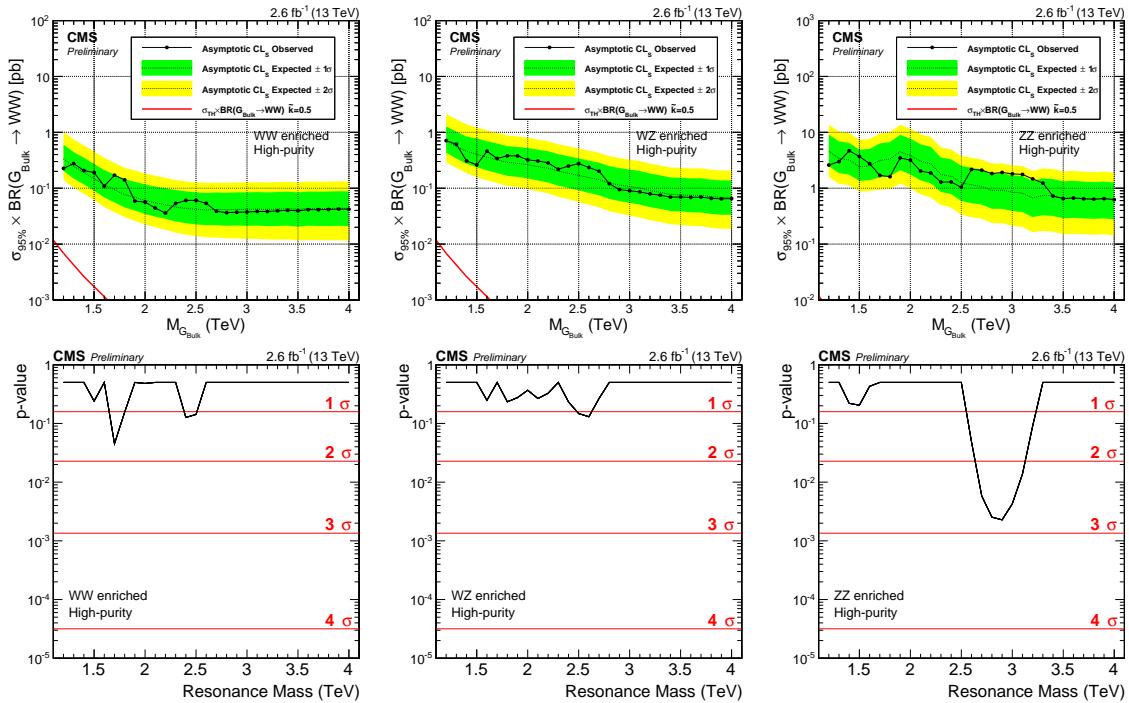


Figure A.3: Expected/observed limits and corresponding p-values obtained for the different mass categories using 2.6 fb^{-1} of CMS data. Here for a Bulk $G \rightarrow WW$ signal in the HP category

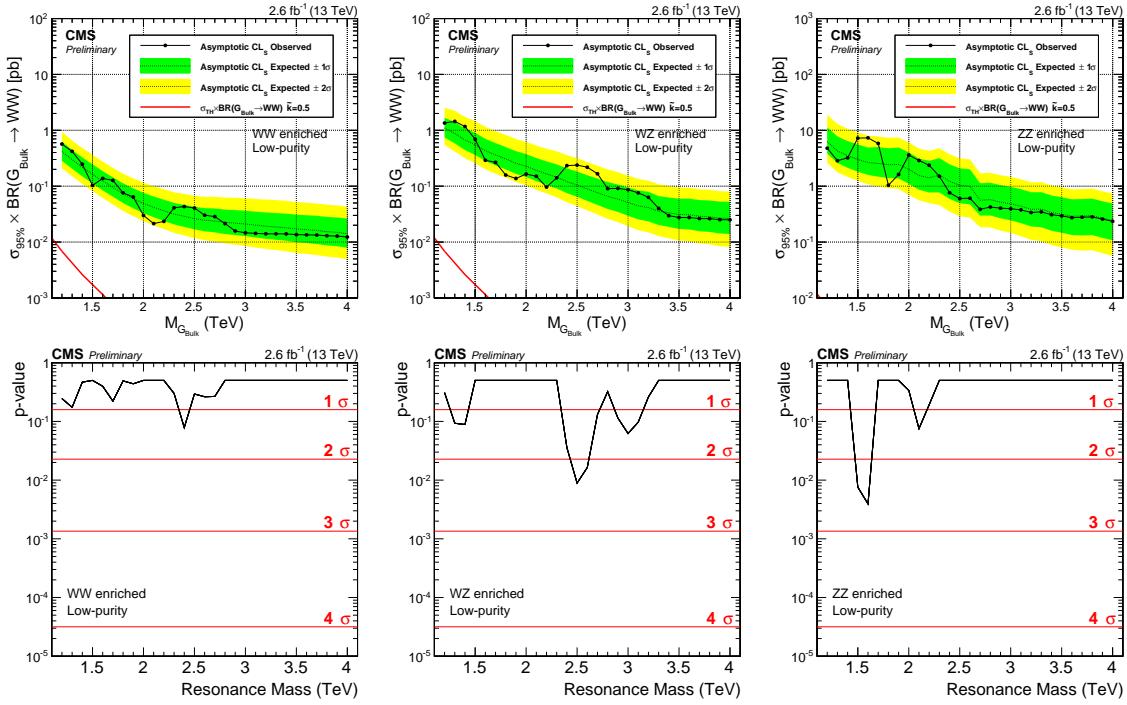


Figure A.4: Expected/observed limits and corresponding p-values obtained in the different mass categories using 2.6 fb^{-1} of CMS data. Here for a Bulk $G \rightarrow WW$ signal in the LP category.

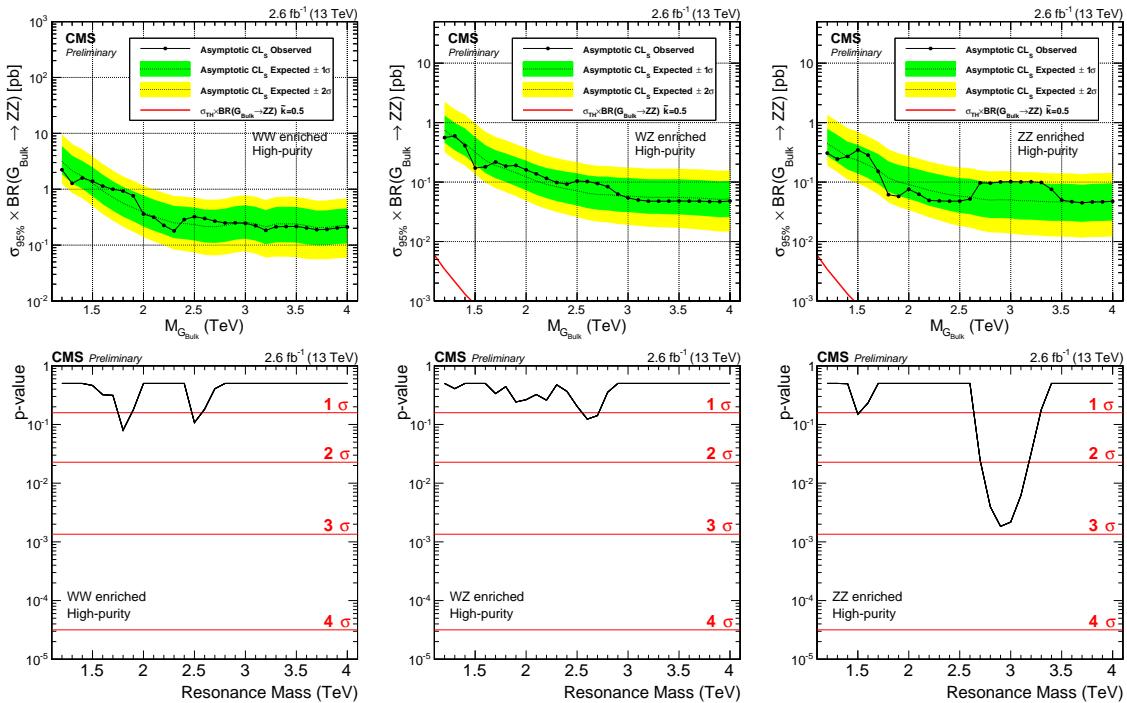


Figure A.5: Expected/observed limits and corresponding p-values obtained in the different mass categories. Here for a $G \rightarrow ZZ$ signal in the HP category.

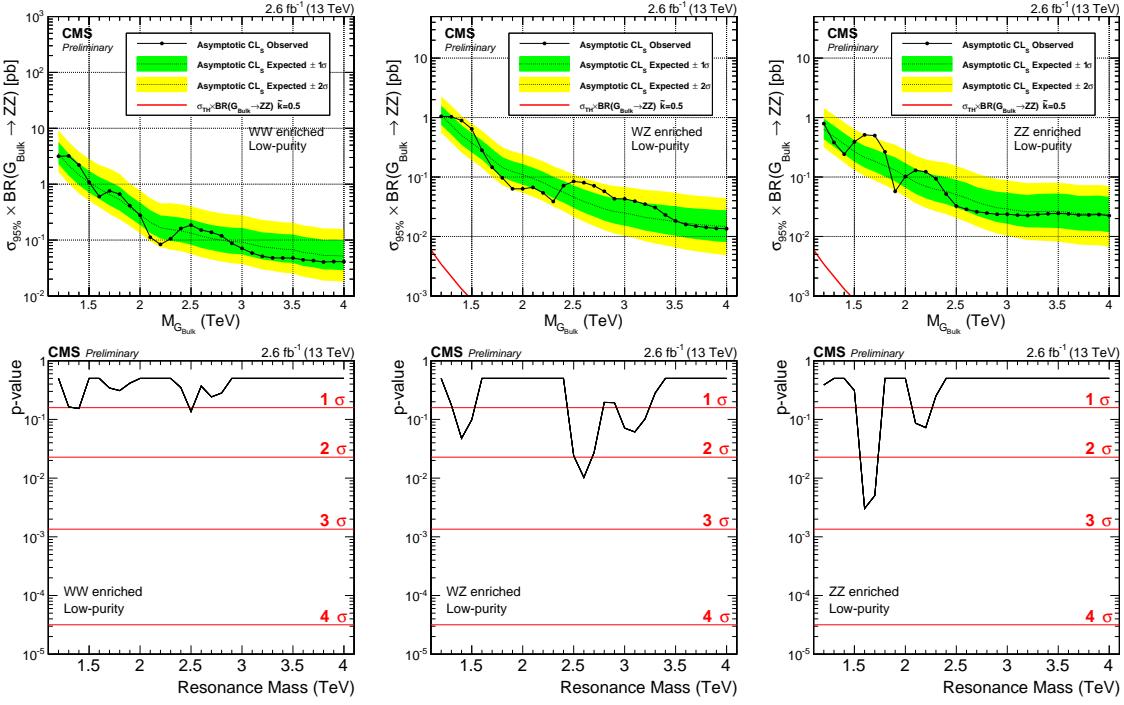


Figure A.6: Expected/observed limits and corresponding p-values obtained in the different mass categories. Here for a $G \rightarrow ZZ$ signal in the LP category.

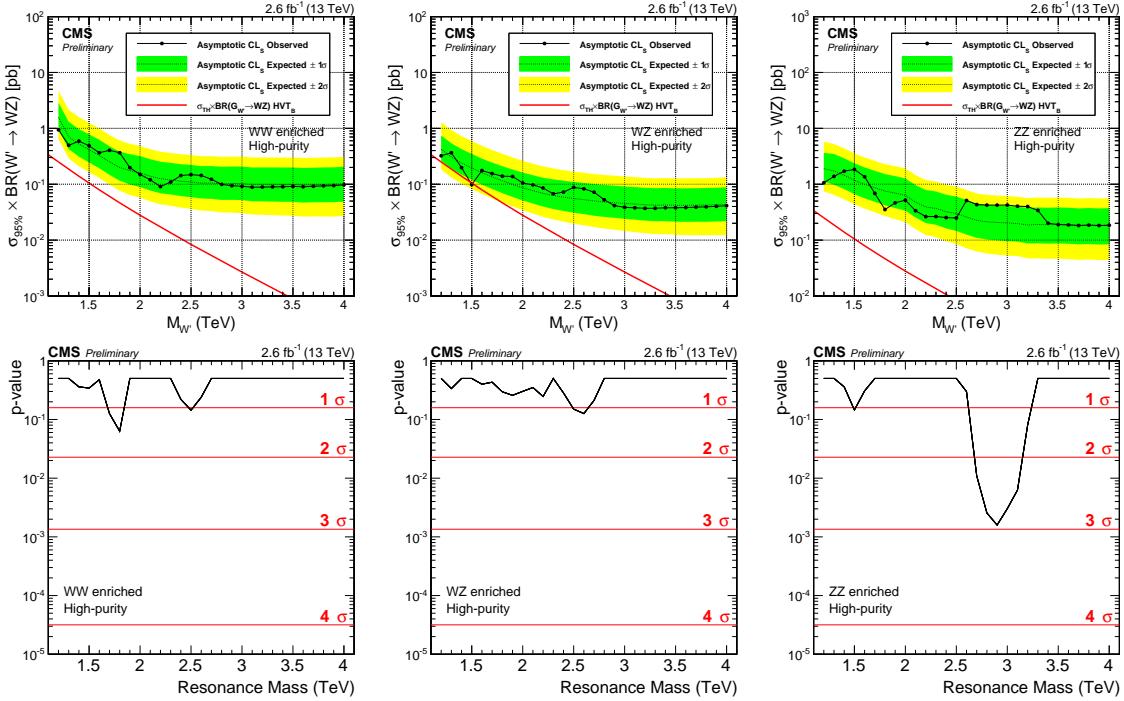


Figure A.7: Expected/observed limits and corresponding p-values obtained in the different mass categories. Here for a $W' \rightarrow WZ$ signal in the high-purity category.

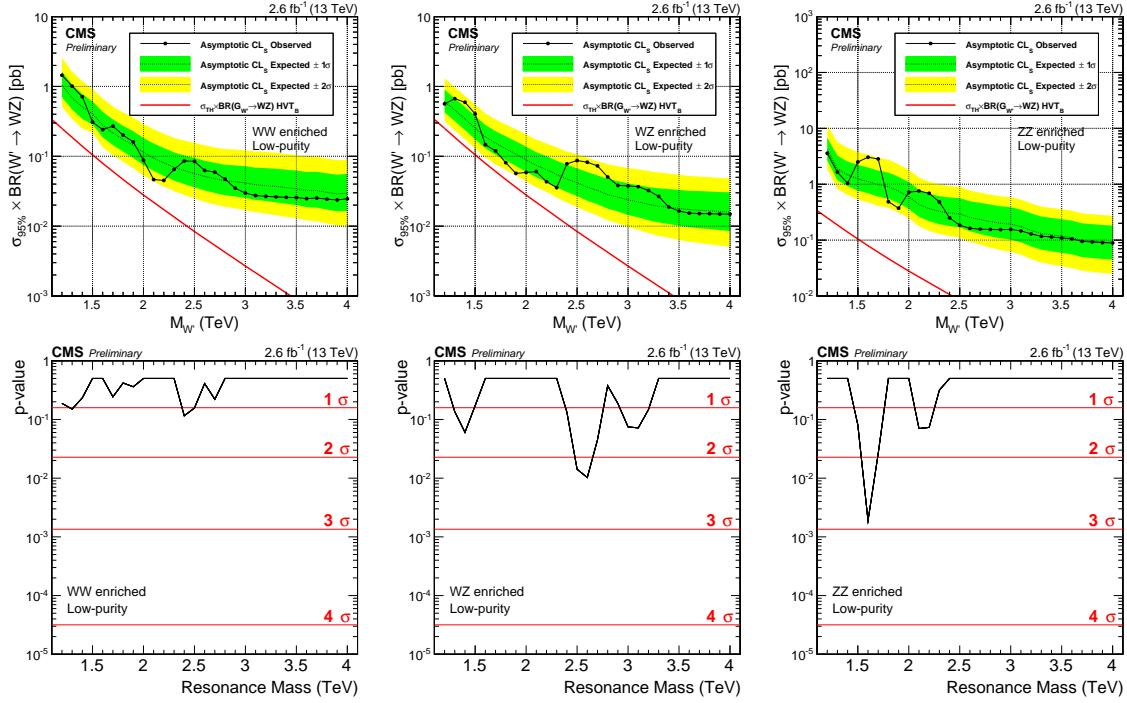


Figure A.8: Expected/observed limits and corresponding p-values obtained in the different mass categories. Here for a $W' \rightarrow WZ$ signal in the low purity category.

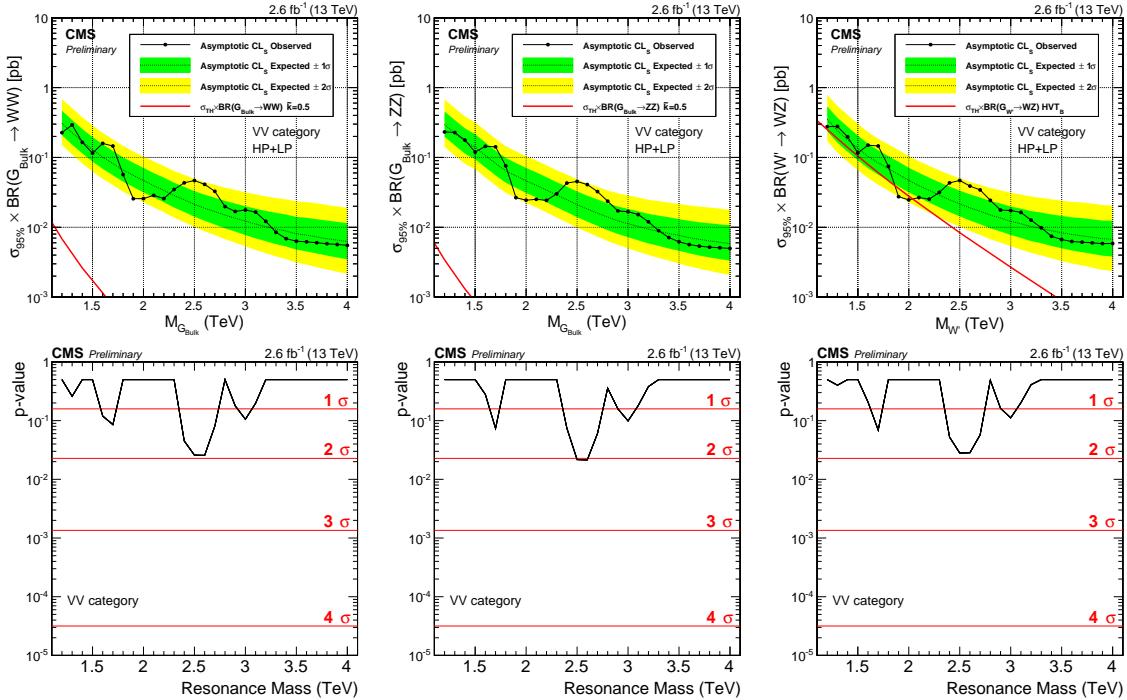


Figure A.9: Expected/observed limits and corresponding p-values obtained without splitting into mass categories. This analysis is performed as a cross check analysis and directly compares with the method used in the corresponding Run 1 analysis [?]. Here for a Bulk $G \rightarrow WW$ (left), $G \rightarrow ZZ$ (middle) and $W' \rightarrow WZ$ signal (right).

APPENDIX B

2016 W-tagging scalefactor measurement

Figures 5.25 show the $t\bar{t}$ real W (top) and non-W (bottom) distributions for jets that passed (left) and failed (right column) the N-subjettiness selections $\tau_{21} < 0.45$.

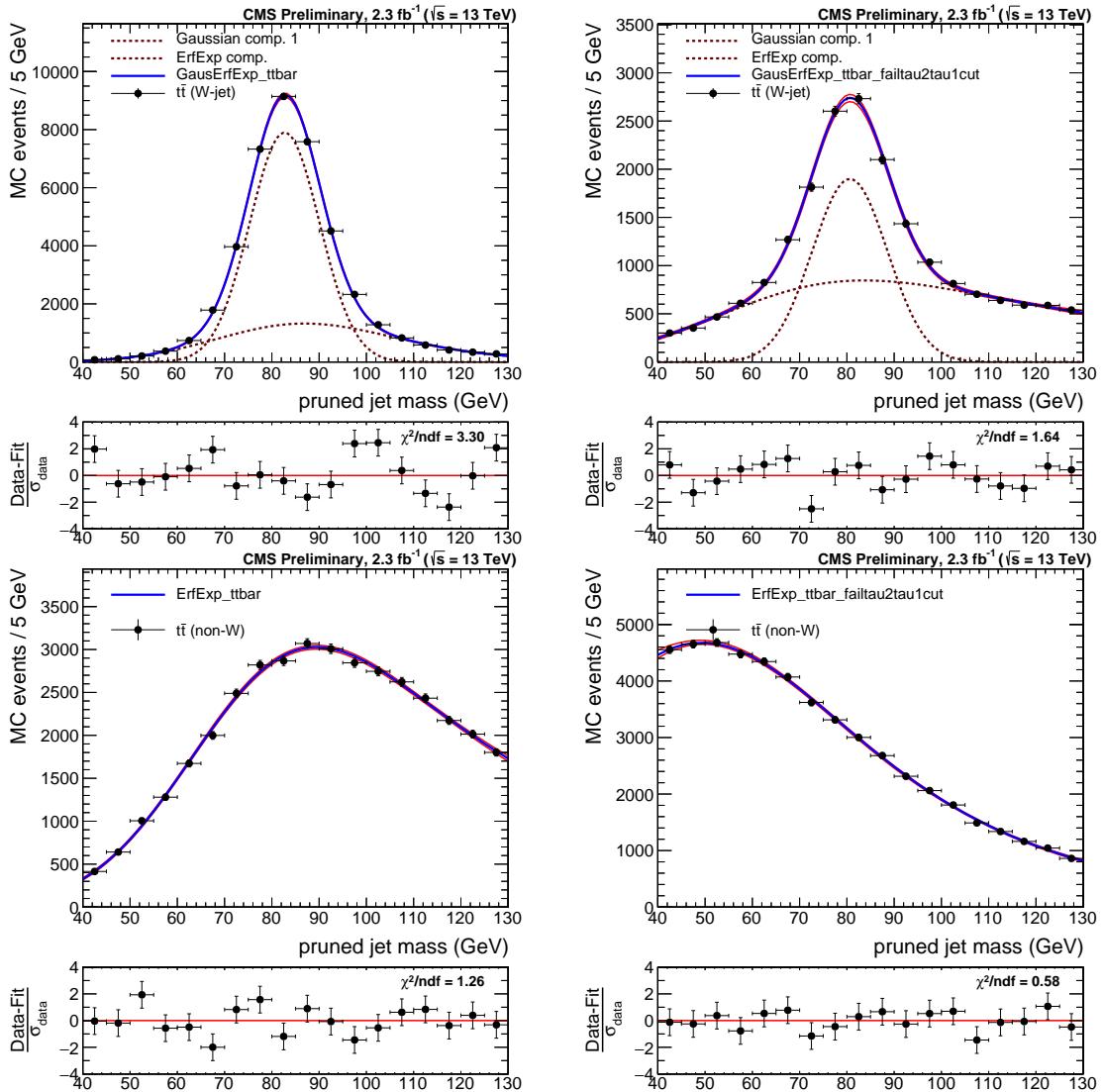


Figure B.1: Fit to the real W (top) and non-W (bottom) pruned jet mass distribution for jets that pass (left) and fail (right) the cut on $\tau_{21} < 0.45$.

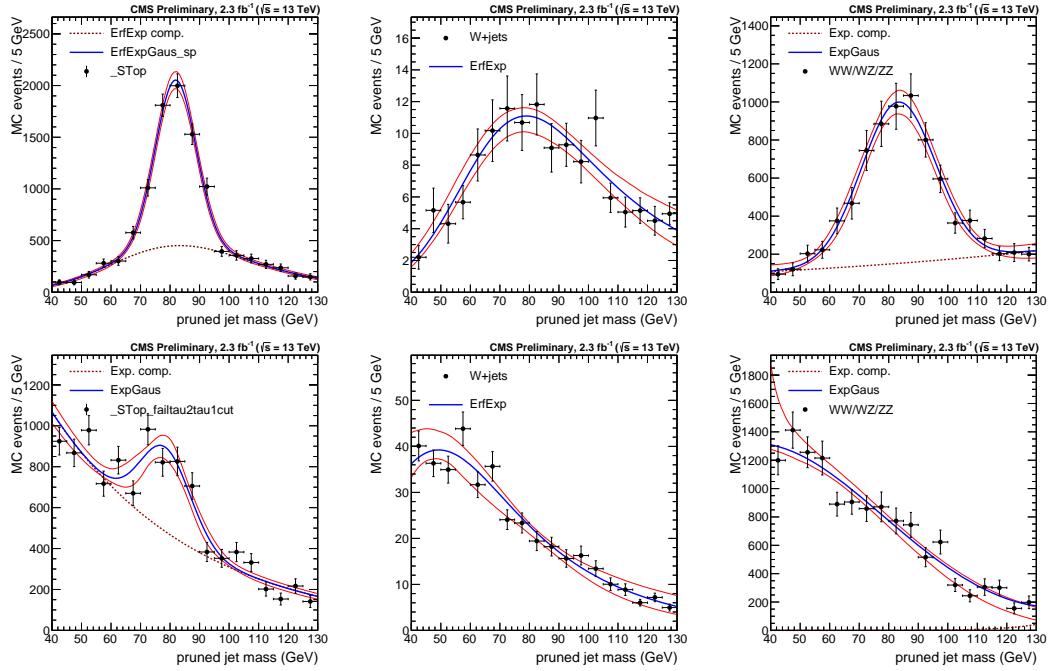


Figure B.2: Fits to the pruned jet mass spectrum for the non-dominant backgrounds (Single top, W+jets and VV respectively) in the pass (top) and fail (bottom) regions.

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