

Jet substructure measurements at CMS

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In these proceedings, we present recent jet substructure measurements with the CMS experiment, namely the primary Lund jet plane and the energy-energy correlators. The data are compared with perturbative QCD calculations and various MC event generators. These jet substructure measurements highlight different aspects of physics modelling. The sensitivity of jet substructure to the strong coupling will also be discussed.

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1. Introduction

We present measurements of jet substructure in proton-proton collisions performed with the CMS experiment [1]. Studies of jets provide information on the strong interaction, described by quantum chromodynamics (QCD). In recent years, jet substructure has been widely studied at the LHC [2]. The comparison of high precision measurements of jet substructure observables with perturbative QCD calculations and Monte Carlo (MC) simulations improve our understanding of QCD. In addition, studies of jet substructure can be used to determine the strong coupling α_s [3].

2. Measurement of the primary Lund jet plane density

The Lund plane is a two-dimensional representation of the phase space of $1 \rightarrow 2$ partonic splitting. The kinematics of a splitting are described with the splitting angle of the branching ΔR , and the transverse momentum k_T of the emission relative to its emitter. Since partons are emitted uniformly as a function of $\ln(k_T/\text{GeV})$ and $\ln(1/\Delta R)$, the logarithm of k_T and the logarithm of $1/\Delta R$ are used for the vertical and horizontal axes of the Lund plane. The internal structure of the jet can be represented in the Lund plane by using the iterative jet declustering done by the Cambridge-Aachen (CA) algorithm [4]. The constituent of a jet are reclustered using by the CA algorithm. In each step of the declustering, the jet j is declustered into the two subjects $j \rightarrow j_1 + j_2$, where j_1 and j_2 are the harder and softer subjects, respectively.

The measurement [5] performed by the CMS Collaboration focuses on the primary Lund jet plane, which corresponds to the Lund jet plane obtained by following the harder subject at each step of the declustering. The primary Lund jet plane can provide detailed information about the radiation pattern of the jet as different regions are affected by different mechanisms. The multiple-parton interactions, the underlying event activity and the initial-state radiation affect wide-angle radiation. These effects are located in the region of low $\ln(1/\Delta R)$. The hadronization affects the low $\ln(k_T/\text{GeV})$ region. Hard and soft collinear parton splitting affect the rest of the plane. The measurement is based on an event sample of proton-proton collisions at $\sqrt{s} = 13$ TeV collected by CMS during Run 2 (2016-2018), corresponding to an integrated luminosity of 138fb^{-1} . The analysis uses the hadronic jets clustered with the anti- k_T algorithm [6] with a resolution parameter of 0.4 and 0.8, respectively. In contrast to the 0.4 value, the value of 0.8 allows us to study more phase-space with the wide-angle, hard emissions. The jets are required to have $p_T > 700$ GeV and $|y| < 1.7$. Only the charged particles of the jet are used to construct the primary Lund jet plane. The measured detector-level distributions are corrected to particle level. The regularized matrix inversion implemented in RooUnfold [7] package was used in this measurement.

Figure 1 shows two-dimensional distributions of the charged-particle primary Lund jet plane corrected to particle for AK4 jets (left plot) and AK8 jets (right plot). The diagonal line in the plots represents the kinematic limit. Figure 2 (right plot) shows the vertical slide of the primary Lund jet plane for fixed $\ln(R/\Delta R)$ and spans the full range in $\ln(k_T/\text{GeV})$. The horizontal slice of the primary Lund jet plane for fixed $\ln(k_T/\text{GeV})$ and for low k_T splitting is shown in Figure 2 (right plot). This slice populates mostly wide-angle radiation. The unfolded data are compared with the MC predictions based on PYTHIA8 with the Monash, CP2, CP5, CUETP8M1 tunes. In general,

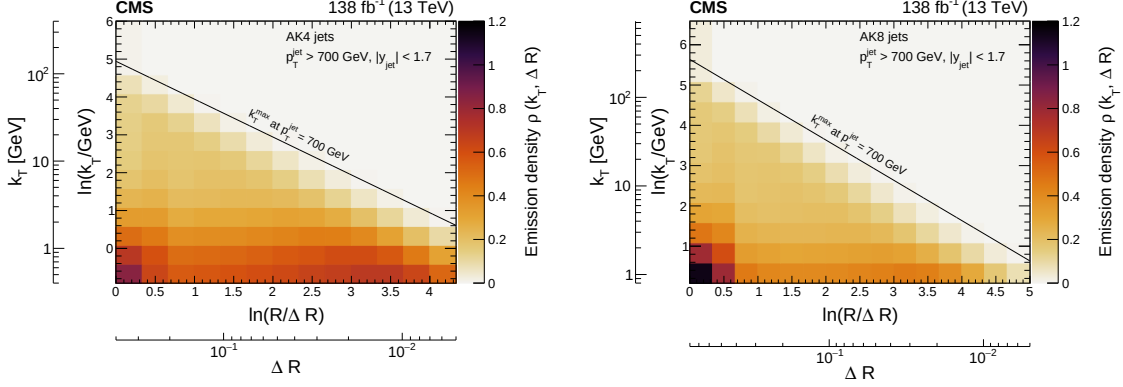


Figure 1: Unfolded two-dimensional distribution of the charged-particle primary Lund jet plane for AK4 jets (left plot) and AK8 jets (right plot). Taken from [5].

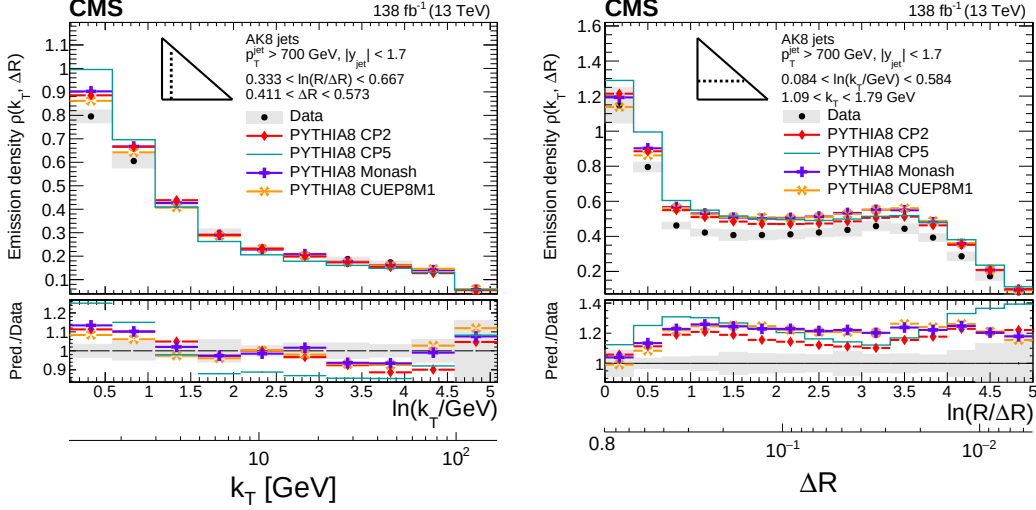


Figure 2: Unfolded two-dimensional distribution of the charged-particle primary Lund jet plane for AK8 jets (left plot). The horizontal slice of the charged-particle primary Lund jet plane for AK8 jets compared with the predictions by PYTHIA8 using CP2, CP5, Monash, and CUETP8M1 tunes. Taken from [5].

the predictions obtained by MC event generators with tunes with the larger value of strong coupling used for final-state radiation (FSR), α_s^{FSR} , agree better with the data.

3. Measurement of energy correlations inside jets

Recently, new observables have been proposed to describe multiparticle energy correlations within jets [8]. The two- and three-particle energy correlators (E2C and E3C, respectively) describe energy-weighted distance between two or three particles in a hadronic jet. They are derived from energy-flow operators and are collinear- and infrared-safe. E2C and E3C provide distributions because each jet has many particles and, hence, many pairs and triplets. These distributions depend on x_L , defined as the angular distance between the two particles of the E2C pair, $\sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$, where $\Delta\eta$ and $\Delta\phi$ are the distances in pseudorapidity and azimuthal angle of the particles, respec-

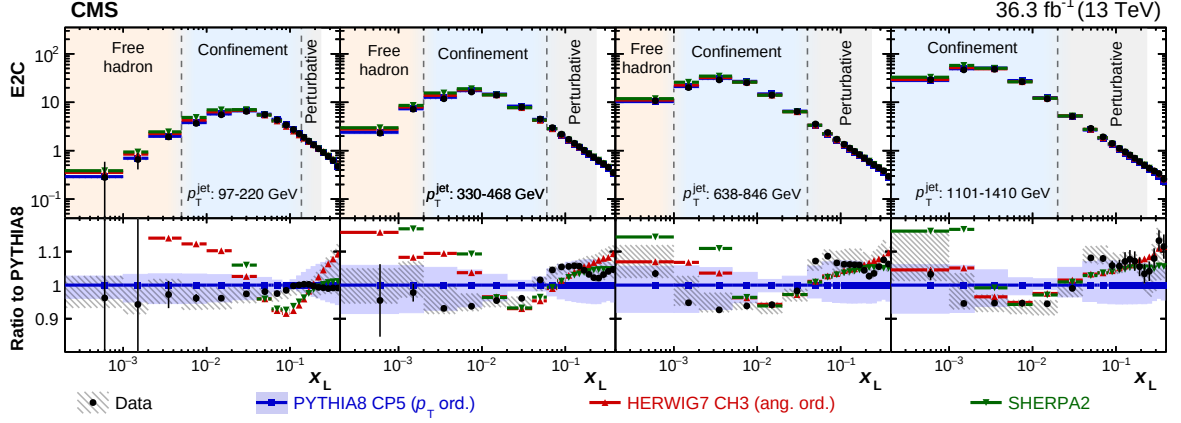


Figure 3: Measured (unfolded) and simulated E2C x_L distribution, in four p_T bins. The lower panels show the ratios to the PYTHIA8 reference. The data statistical (bars) and systematic (boxes) uncertainties are also shown, as is the PYTHIA8 uncertainty (blue band). Taken from [9].

tively, or as the largest angular distance among the three pair combinations of an E3C triplet. Each jet has many particles and, hence a jet with n particles contributes n^2 entries to the E2C distribution, with weights $E_i E_j / E^2$, where the indices represent the two particles in the pair. Similarly, a jet contributes n^3 entries to the E3C distribution.

The CMS Collaboration performed the first measurement of E2C at a hadron collider, and the first ever measurement of E3C [9]. The measurement is based on an event sample of proton-proton collisions at $\sqrt{s} = 13$ TeV collected by CMS in 2016 and corresponding to an integrated luminosity of 36.3fb^{-1} [10]. The hadronic jets are clustered with the anti- k_T algorithm [6] with a resolution parameter of 0.4. This value is well suited for parton shower studies at relatively small angles. Only events with at least two jets, with $p_T > 97$ GeV and $|\eta| < 2.1$ are used. The two leading jets are required to be back-to-back in the transverse plane, with $|\phi| > 2$. The energy dependence of E2C and E3C was studied in eight p_T bins in the 97-1784 GeV range.

Figure 3 shows the measured(unfolded) E2C distribution as a function of x_L in four illustrative jet p_T bins. Various MC simulations like PYTHIA8 [11] with the CP3 tune, HERWIG7 [12] with the CH3 tune and SHERPA2 [13] were utilized in the comparison with the data. As shown in Figure 3, the shape of the x_L -differential E2C and E3C provides information on the time scale of hadron formation and the different x_L regions can probe the different stage of jet formation.

The ratio of multiparticle energy correlators was proposed for the precise α_s determination [8]. The E3C/E2C ratio is sensitive to α_s because E3C and E2C have different dependences on α_s . In addition, it improves the precision of the α_s determination as it reduces its dependence on the relative fraction of quark- and gluon-initiated jets. It was shown in Ref. [8] that the ratio is approximately linear in $\alpha_s \ln x_L$ for the calculation at leading logarithmic accuracy. So measuring its slope with the respect to $\ln x_L$, as a function of the jet p_T gives the dependency of α_s on the jet energy. Figure 4 shows the measured E3C/E2C ratio and their ratio to predictions at NLO+NNLL_{approx}. The strong coupling α_s can be then obtained by comparing the measured ratio with the theoretical predictions for various α_s values. In this measurement, the α_s at the Z boson mass is determined to be $\alpha_s(m_Z) = 0.1229^{+0.0014}_{-0.0012}(\text{stat})^{+0.0030}_{-0.0033}(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$, where stat, theo

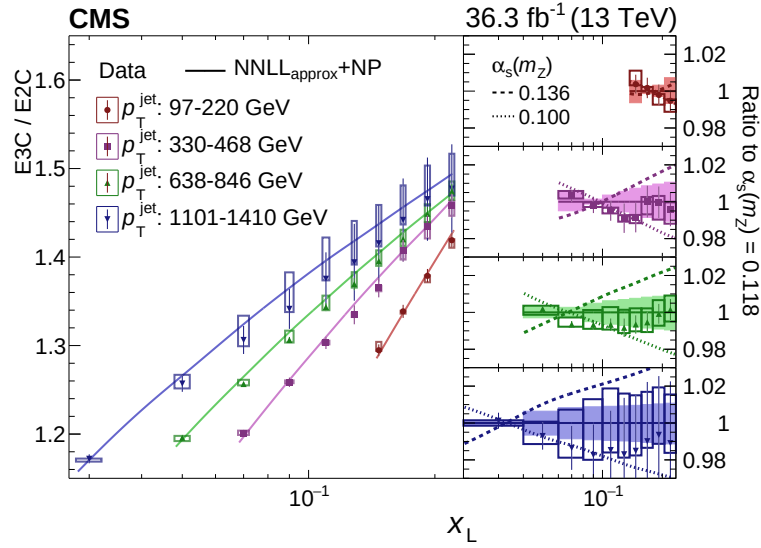


Figure 4: Measured E3C/E2C ratio (left) and their ratio to predictions (right) in the perturbative x_L region and four jet p_T bins. The statistical and experimental systematic uncertainties are shown with bars and boxes, respectively. Taken from [9].

and exp stand for statistical, theoretical and experimental systematic uncertainties, respectively. The result is consistent with the world average and it is the most precise determination of α_s using the jet substructure technique.

4. Conclusions

In these proceedings, we reported on two recent CMS measurements of jet substructure in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$. The data are compared with perturbative QCD calculations and various MC event generators. The measurements of jet substructure highlight different aspects of physics modelling. The sensitivity of jet substructure to the strong coupling was shown.

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