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Exploring QCD dynamics using the jet invariant mass

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Systematic studies of jet substructure offer precision tests of quantum chromodynamics (QCD) in vacuum as well as at the large particle densities and high temperatures of the quark-gluon plasma (QGP) produced in heavy-ion collisions. The jet invariant mass is a canonical jet substructure observable which has been broadly studied for decades, both experimentally and theoretically, to qualify substructure of jets and to identify boosted particles. A proxy for the virtuality Q of the initiating parton, the jet invariant mass is a perturbatively calculable probe of an uncontrolled variable in scattering experiments, though it is also dominated by nonperturbative corrections at small values, presenting an excellent test of QCD dynamics across a broad range of Q^2. The jet invariant mass can be combined with jet grooming procedures such as soft drop to remove soft, wide-angle radiation, both enhancing the predictive strength of perturbative calculations and reducing experimental systematic uncertainties. First-principles calculations are essential to estimate QCD backgrounds in particle searches in combination with Monte Carlo generators, which have surprisingly produced jet mass distributions in tension with one another. The jet invariant mass has also presented mysteries in heavy-ion collisions, where observed quenching modifications are in apparent disagreement with those observed for theoretically related jet angularities.

These proceedings present an overview of recent jet invariant mass measurements from the Large Hadron Collider (LHC) in both pp and heavy-ion collisions. These measurements provide tests of QCD in vacuum and of jet quenching models, providing new critical information on nonperturbative effects and QCD medium evolution. These proceedings furthermore look forward to future precision measurements of the heavy-flavor tagged jet invariant mass, which will offer a unique frontier to disentangle the QCD dead cone from Casimir color effects, while also testing novel flavor tagging algorithms and perturbative QCD with a nonzero quark mass.

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1. Introduction

Collimated sprays of particles called "jets" are abundantly produced in high-energy particle collisions at modern synchrotron facilities such as the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These machines, which circulate both protons and heavy nuclei, produce jets via the hard scattering of quarks and gluons (partons) from colliding nuclei. These nuclear collisions are controlled experimentally by restricting properties of the colliding particle beams, such as the center-of-mass energy ($\sqrt{s}$) [1, 2]. Since hadronic beams are composed of particle bunches and therefore are impossible to experimentally control at the scale of individual nuclei ($\mathcal{O}$(fm)), collisions occur across a broad range of impact parameters and energy scales according to probability distributions theoretically prescribed by quantum chromodynamics (QCD). Scattered partons carry away some off-mass-shell virtuality $Q = \sqrt{E^2 - p^2}$ from the four-momentum exchanged in the interaction, the value of which is fundamentally unknown to an observer. However, in the parton shower picture, this excess virtuality is shed by the successive radiation of gluons, forming a jet. Studying the final-state jet substructure allows access to the radiation pattern of the scattered parton and therefore probes properties of that parton which initiated the jet.

Jets produced in heavy-ion collisions are modified by interactions with the hot, dense quark-gluon plasma (QGP), with modifications collectively referred to as jet quenching [3–5]. The origins of jet quenching have not yet been identified from first principles; however, the relative fraction of jets which originate from quarks versus gluons, as well as the structure of the parton shower, are generally expected to be modified in heavy-ion collisions and in the presence of the QGP, due to differences in the nuclear parton distribution functions (nPDFs) and extra gluon radiation induced by the presence of the medium, respectively [6].

Insomuch as the experimentally reconstructed jet is a proxy for the parton which initiated the shower, the jet invariant mass provides a proxy for the initiating parton's virtuality,

$$m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2} \sim Q_{\text{parton}}, \tag{1}$$

where E_{jet} is the jet energy and p_{jet} its total momentum. Measurements of the jet mass as a function of jet transverse momentum $p_{\text{T,jet}}$ therefore probe the dependence of partonic virtuality versus the hardness of the momentum scale of the initial hard scattering. Jets which are broader and contain more emissions will tend to have a higher mass; this angular- and momentum-dependent jet substructure can also be quantified by the so-called jet angularities [7–10],

$$\lambda_\alpha^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}} \right)^\kappa \left(\frac{\Delta R_i}{R} \right)^\alpha, \tag{2}$$

where i runs over jet constituents, p_{T} designates transverse momentum, R is the jet resolution parameter (radius), $\Delta R_i \equiv \sqrt{(y_{\text{jet}} - y_i)^2 + (\varphi_{\text{jet}} - \varphi_i)^2}$ gives the distance between constituent i and the jet axis in the rapidity (y) – azimuthal angle (φ) plane, and (κ, α) are continuous parameters which define the specific angularity observable. The jet mass is directly related theoretically to the jet angularities in the case $\kappa = 1$ and $\alpha = 2$, which is also called the jet thrust [11],

$$\lambda_2^1 = \left(\frac{m_{\text{jet}}}{p_{\text{T,jet}} R} \right)^2 + \mathcal{O}[(\lambda_2^1)^2], \tag{3}$$

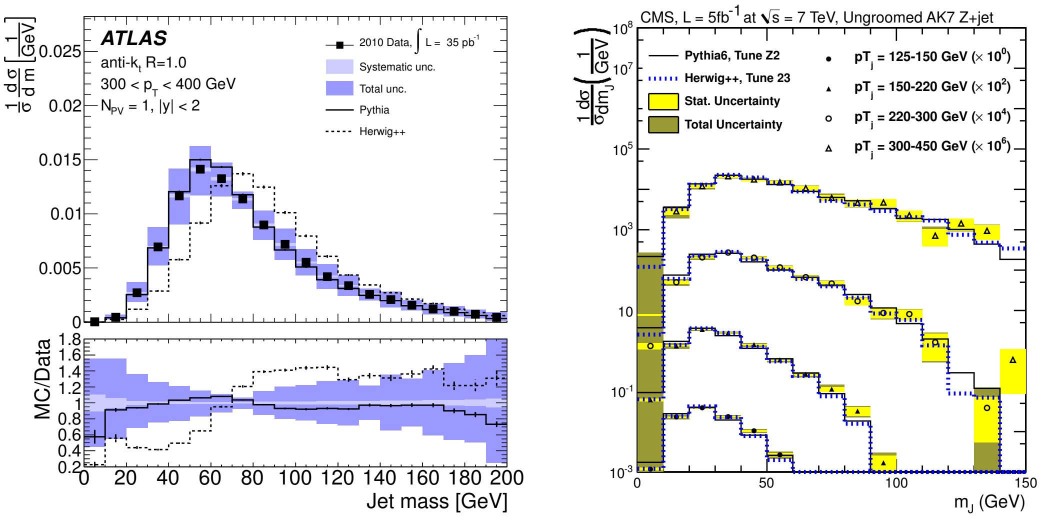

Figure 1: Early measurements of m_{jet} performed in central rapidity at the LHC. *Left:* m_{jet} as measured by the ATLAS Collaboration using $R = 1.0$ anti-k_{T} jets. Measurements were also performed using the Cambridge-Aachen algorithm with $R = 1.2$ as well as with grooming [13]. *Right:* m_{jet} as measured by the CMS Collaboration using $R = 0.7$ anti-k_{T} jets produced in association with a Z^0 boson. Measurements were also performed for dijets, using the Cambridge-Aachen algorithm and $R = 0.8$, as well as with grooming [14].

where the last term contains higher-order corrections in m_{jet} [12].

These proceedings present a selection of recent experimental measurements for the jet mass and angularities. These measurements are discussed for both pp and heavy-ion collisions in comparison to theoretical predictions. Finally, an outlook is given on studies of substructure for heavy-flavor jets using new flavor tagging algorithms which are calculable at high precision in QCD.

2. Experimental results

First analyses of m_{jet} at the LHC were performed using Run 1 data from the ATLAS and CMS collaborations [13, 14]. Example distributions are shown in Fig. 1. Jets were reconstructed using the anti-k_{T} [15] and Cambridge-Aachen [16, 17] algorithms, sequential recombination algorithms which offer both theoretical calculability as well as efficient runtime implementations via the FastJet software package [18]. At the high $p_{\text{T,jet}}$ studied in these measurements ($\geq$ 125 GeV/c), the peak position of the m_{jet} distributions was found to scale with $p_{\text{T,jet}}$ and generally occurred at around 20% of $p_{\text{T,jet}}$ for each bin, with a tail skewed towards higher m_{jet} values. This was true for both dijets and those produced in association with an electroweak boson. This is reasonably understood as harder interactions (signaled by higher $p_{\text{T,jet}}$) opening up a larger phase space for high-virtuality partons to be produced (signaled by larger m_{jet}).

Experimental results were compared to Pythia 6 [19] and Herwig++ [20] Monte Carlo (MC) simulations. These MC generators combine leading-order QCD matrix elements with parton showers and phenomenological hadronization models (the Lund string and cluster models, respectively), and are tuned to fit experimental results. MC predictions generally reproduced the shape of the data, though the m_{jet} scale in ATLAS data was better described by Pythia 6 than Herwig++. A measurement of m_{jet} performed by the STAR Collaboration at RHIC, using data recorded at much

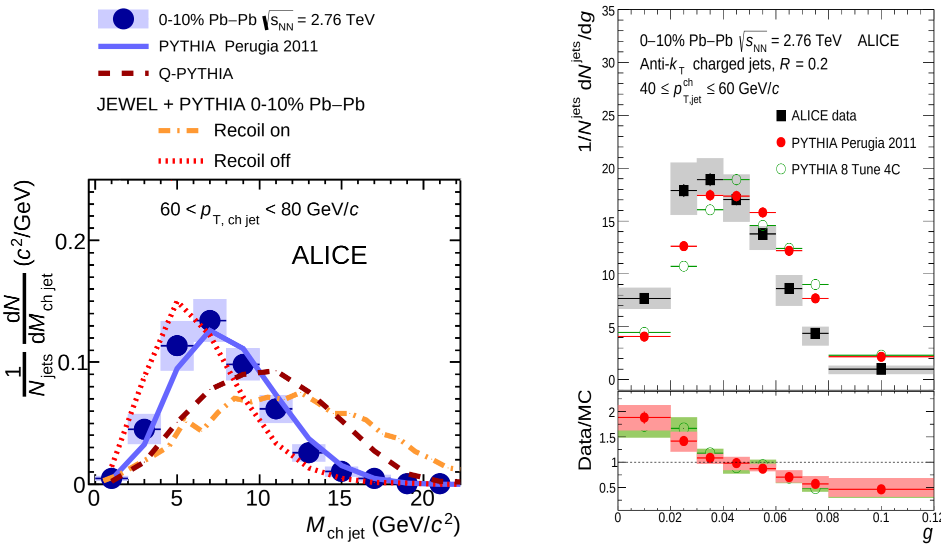

Figure 2: The jet invariant mass m_{jet} (left) [23] and the jet girth $g = \lambda_1^1 * R$ (right) [24] in Pb–Pb data compared with MC models, as measured by the ALICE Collaboration during Run 1. These measurements were performed at identical $\sqrt{s_{\text{NN}}} = 2.76$ TeV, but differed in both R (0.4 for m_{jet}, 0.2 for g) and $p_{\text{T,jet}}$ ranges.

lower $\sqrt{s} = 200$ GeV, also found better agreement with Pythia 6 (STAR tune) than with Pythia 8 or Herwig 7 (LHC tunes) [21]. When soft radiation was reduced by use of various jet grooming algorithms, the agreement between data and MC improved [13, 14], as well as agreement between data and perturbative calculations [21]. This can be understood as soft, nonperturbative effects being generally less well-described than the perturbative effects in MC models.

The ALICE Collaboration performed the first measurement of the jet mass in heavy-ion collisions along with the related jet angularity λ_1^1, also called the jet girth g [22], using LHC Run 1 data from Pb–Pb collisions [23, 24]. Figure 2 shows these results, including comparisons to vacuum MC simulations, as no pp dataset at the equivalent $\sqrt{s}$ was available. While both observables fundamentally probe the radial profile of the jet momentum, Pythia MC agreed with Pb–Pb data for m_{jet}, but significantly disagreed with that for g, signifying a difference in observed quenching behavior between the two measurements. It was not clear what underlying physics caused this difference, as the measurements differed in the observable definitions, R, and $p_{\text{T,jet}}$.

This girth–mass inconsistency was recently resolved by the ALICE Collaboration by performing a systematic study of m_{jet} and λ_α^κ using Run 2 data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [25], where an equivalent pp baseline was available [26]. The mass m_{jet} and thrust λ_2^1 distributions, which are directly related by Eq. 3, are shown in Fig. 3. Despite using identical R and $p_{\text{T,jet}}$ bins, differing agreement between data and MC persisted for the two observables. Since the distributions are positive definite, large corrections to Eq. 3 must apply. These could include hadronization effects as well as higher-order correction terms, which both grow at low $p_{\text{T,jet}}$ where the strong coupling α_{S} is large.

3. Future outlook

With the recent availability of fixed-order jet substructure calculations up to next-to-next-to-leading order (N^{2}LO) including resummation of large logarithms up to next-to-next-to-next-

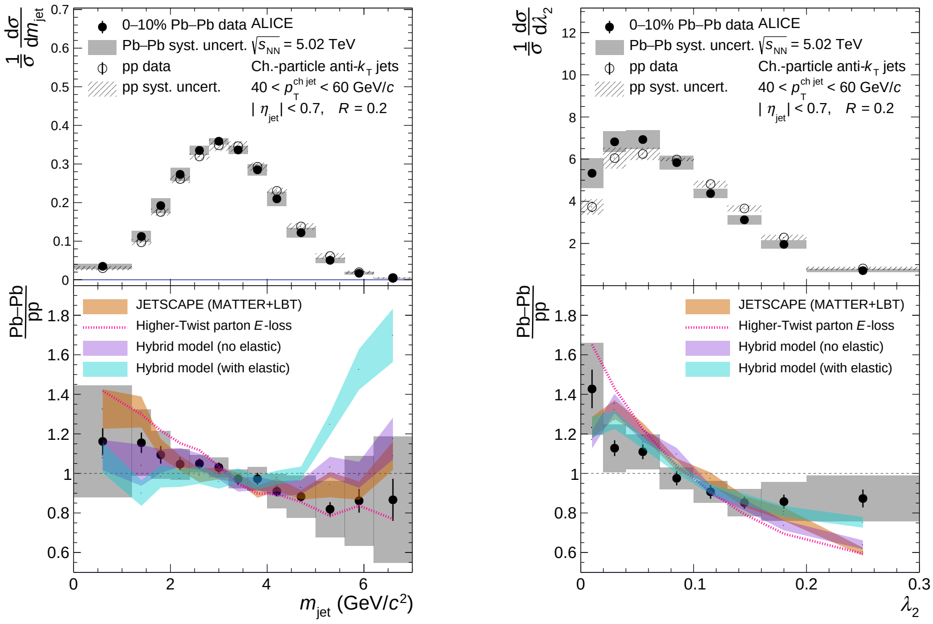

Figure 3: The jet invariant mass m_{jet} (left) and the jet thrust λ_2^1 (right) in Pb–Pb data compared with MC models, as measured by the ALICE Collaboration during Run 2 data taking at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [25].

to-leading logarithmic accuracy (N^{3}LL) [27], and with enhanced precision of experimental measurements from increased data volumes (reducing statistical uncertainties) and improved analysis methods (reducing systematic uncertainties), there is an unparalleled opportunity to study QCD at unprecedented precision using observables like m_{jet}. There has additionally been a growing interest in measuring such observables for jets containing a hadron with a heavy valence quark, such as charm or bottom. These jets can be useful for several studies, including searches for an intrinsic valence-like charm component of the proton wavefunction [28] or studies of heavy quark fragmentation functions [29].

However, traditional flavor tagging, where a specific heavy-flavor hadron is simply required to be reconstructed inside an anti-k_{T} jet, is not theoretically safe past NLO [30]. Recently a variety of algorithms calculable beyond NLO have been proposed to tag jet flavor while maintaining anti-k_{T} kinematics [31–35]. Studies are underway to understand how these different algorithms behave in experimental kinematics with various event selection criteria.

Figure 4 shows example m_{jet} distributions generated using different flavor-tagging algorithms in comparison to traditional anti-k_{T} tagging for jets containing a charmed D^0 meson reconstructed in the K$^{\mp}\pi^{\pm}$ decay channel. Events were generated in Pythia 8 MC using all 2→2 hard QCD processes at LO, which enables both prompt and shower-induced production of heavy-flavor quarks, the latter proceeding via the gluon splitting process ($g \to q\bar{q}$). Two peaks are evident in the m_{jet} spectra, with the second (higher) peak occurring at the turn-on for di-charm in the jet. The new algorithms, which provide better theoretical control on gluon splitting, are observed to reduce the di-charm contribution at this higher mass peak in comparison to nominal anti-k_{T} flavor tagging. Experimental studies will provide stringent tests of these new theoretical predictions at high precision, offering strong constraints on perturbative QCD in a regime where quark mass effects are significant.

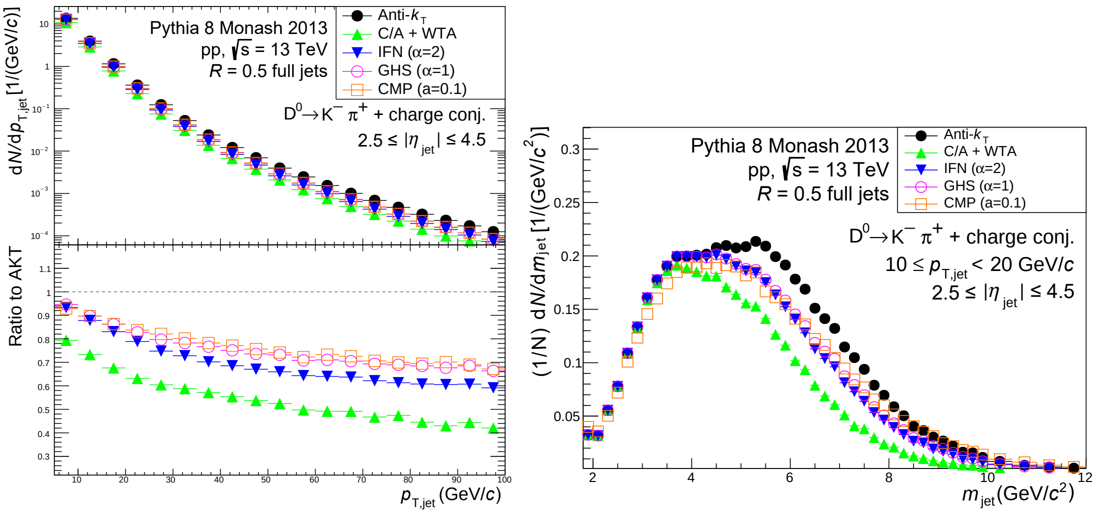

Figure 4: Pythia 8 MC simulations of the $R = 0.5$ jet mass $m_{\rm jet}$ and cross section for $\rm D^0$-tagged jets in approximate LHCb kinematics, using several different flavor tagging algorithms. The ratio panel (left) depicts the tagging fraction as compared to nominal anti-$k_{\rm T}$ flavor, which is theoretically unsafe beyond NLO.

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