PROCEEDINGS OF SCIENCE

Jet substructure

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In this proceeding we emphasize the importance of jet substructure studies for testing theoretical approaches of understanding jet-medium interactions. We will review some established experimental measurements of infrared and collinear safe jet observables and the comparisons with theory calculations. The observables discussed here are the radial and longitudinal jet energy profiles, as well as the jet radius dependence of the jet suppression factor R_{AA} which is sensitive to the jet internal structure. We also highlight new and future directions in jet substructure studies, including hard probes using hadronic decaying electroweak bosons and top quarks, as well as tools for identifying relevant jet evolution phase space which may showcase signatures of jet-medium interactions. In the end we stress that in an era of precision jet substructure studies, significant improvement in controlling both theory and experiment uncertainties is required.

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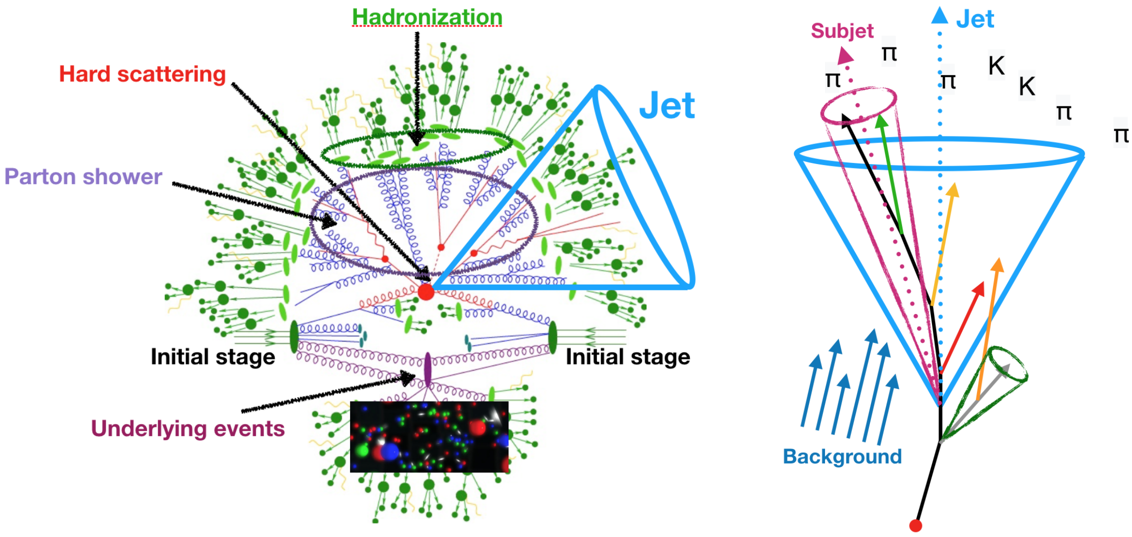

Figure 1: Left panel: Illustration of high energy ion-ion collision. Right panel: Sequential emissions of partons and fluctuating backgrounds affecting jet reconstruction and its substructure.

1. Introduction

Jet substructure studies have become a new paradigm beyond describing the jet quenching phenomenon with partonic energy loss picture. The initial stages of heavy ion collisions carry information about the ion structure. During the hard scattering, energetic quarks and gluons are produced, which then shower and produce more strongly interacting particles that are referred to as jets (Fig. 1). These collimated particles stand out as distinct objects in collider events and are identified using jet reconstruction algorithms. Hard kinematic information of jets, such as the transverse momentum and angular distribution, are basic jet observables. Jet substructure therefore refers to observables which can quantify detailed distributions of particles around energy flow directions. On the other hand, significant underlying event (UE) activities occur among spectator partons and nucleons. These interactions are responsible for producing the large number of final state soft particles, whose origin has been the central topic under investigation. Note that jets are therefore submerged in a huge and fluctuating UE background (Fig. 1). The soft particle distributions exhibit properties such as azimuthal angle flow modulations as well as long range correlations, and they can be described very well within hydrodynamic frameworks. Lattice QCD predictions also indicate a deconfined phase of quark gluon plasma (QGP) relevant in heavy ion collision. Thus we will refer to the hot and dense region early during heavy ion collisions as the medium in the rest of the discussion.

Interestingly, medium signatures in final states persist in proton-ion (pA) and proton-proton (pp) collision events with large particle multiplicities. On one hand, the validity of hydrodynamic descriptions for a "small" system of the size of the proton calls for better understanding. On the other hand, standard high energy physics simulations of proton-proton collisions have not yet fully captured such signatures in underlying event particle contributions. Recently, progress has been made in extending the Pythia multi parton interaction model for describing UE to the Angantyr

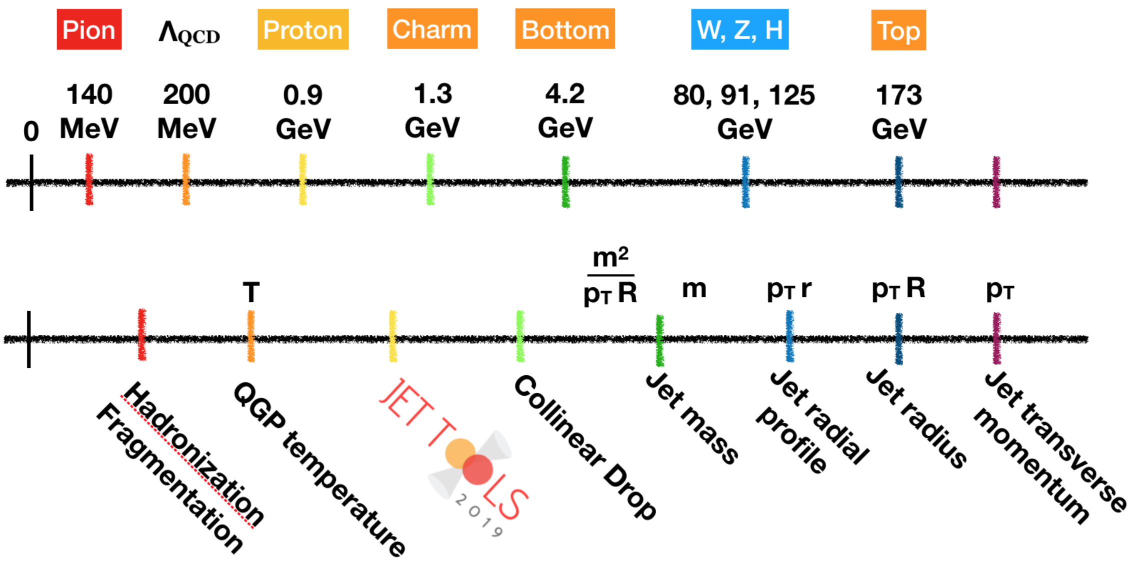

Figure 2: The energy and jet substructure observable spectra across RHIC and the LHC energies.

model with string shoving effects [1, 2]. Such a string based model gives an alternative and qualitatively different picture of the medium. The relation and a consistent understanding with the hydrodynamics description may give us insights on a more fundamental description of the medium.

2. Jet substructure as multi scale probes

Since jets represent dynamical and complex states which evolve from the highest energy scale of the collision down to the confinement scale Λ_{QCD} (Fig. 2), jet substructure encodes information about the whole parton shower and hadronization history. The suppression of hadron and jet cross sections indicates that jets can be affected by the presence of the medium at any stage of the jet evolution. This gives the excellent opportunity of probing the medium properties through jet-medium interactions. Indeed, physical parameters such as the jet quenching parameter $\hat{q}$ and similarly the jet-medium coupling have been extracted. The physical scales and phase space constraints of the system characterize the interaction and determine the parton energy loss pattern. While it is natural to incorporate the spacetime evolution of the medium into the interaction, a momentum space representation of the in-medium parton shower [3, 4] can give a complementary picture of the role of medium properties in jet substructure studies. With the complexity in the evolution of jets and the medium, efficient and accurate Monte Carlo simulations [5] are essential tools for moving forward. Note that medium responses to jets [6] correspond to correlated medium excitations and can contribute to the energy flows around jets.

At RHIC and the LHC we have been using high transverse momentum jets and hadrons, including those associated with heavy quarks such as charm and bottom quarks, to probe the medium. With increased integrated luminosity in the future we will be able to utilize hadronic decaying heavy electroweak bosons and top quarks [7] as new probes of the medium. The quantitative studies of

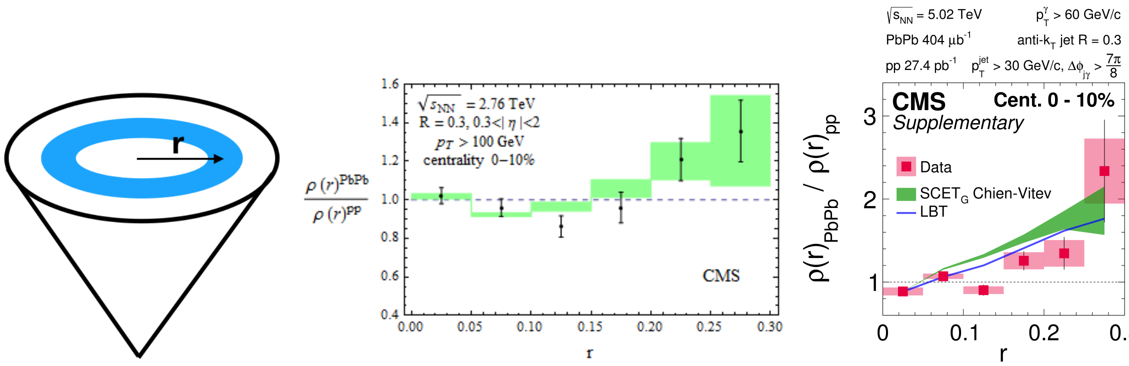

Figure 3: Left panel: Illustration of the radial energy profile as a function of the angle r to the jet direction. Middle panel: The first measurement of the nuclear modification factor $\rho(r)^{\text{PbPb}}/\rho(r)^{\text{pp}}$ for inclusive jets. Right panel: Measurement of $\rho(r)^{\text{PbPb}}/\rho(r)^{\text{pp}}$ for photon-tagged jets.

these processes require significant integrated luminosity at the LHC, and such requirement may influence plans for future LHC heavy ion runs.

The hard probes produced at high energy carry distinct quantum numbers. The subsequent jet evolution inherits partonic origins therefore constitutes independent probes of the medium. Since parton shower populates diverse partonic states, jet substructure observables can be designed to search for specific features in such high dimensional phase space. In order to extract concrete and robust information contained in jet substructure, it is important to improve the sensitivity and precision in theory calculations and experiment measurements. While perturbative precision continues to be improved at fixed orders, there has been significant progress in using soft-collinear effective theory (SCET), an effective field theory suitable for describing jet processes, for precision calculations of jet substructure observables. The factorization of kinematic phase space identifies characteristic, physical scales relevant to specific jet observables, which can be mapped on the energy spectrum. Note that a characteristic medium scale, labelled as the QGP temperature (Fig. 2), is expected to be above and close to the nonperturbative scale. Therefore developments of jet substructure tools [8–11] which help enhance the sensitivity to physics at such low scale are essential for determining the inner working of the medium.

3. Recent progress in jet substructure

Since the observation of jet quenching explained by the partonic energy loss picture, the quantitative studies of how energies are redistributed by jet-medium interactions have been the main focus in jet quenching phenomenology. We will review some recent jet substructure measurements which are established by multiple experimental collaborations and comparisons to theoretical calculations based on different underlying model assumptions. In some cases jets produced in different hard scattering processes are used to gain sensitivity to the difference between quark jet and gluon jet quenching. It is expected that hadronization can also be affected by the presence of the medium. We will focus on discussing infrared and collinear safe observables which can be calculated perturbatively with power suppressed hadronization corrections.

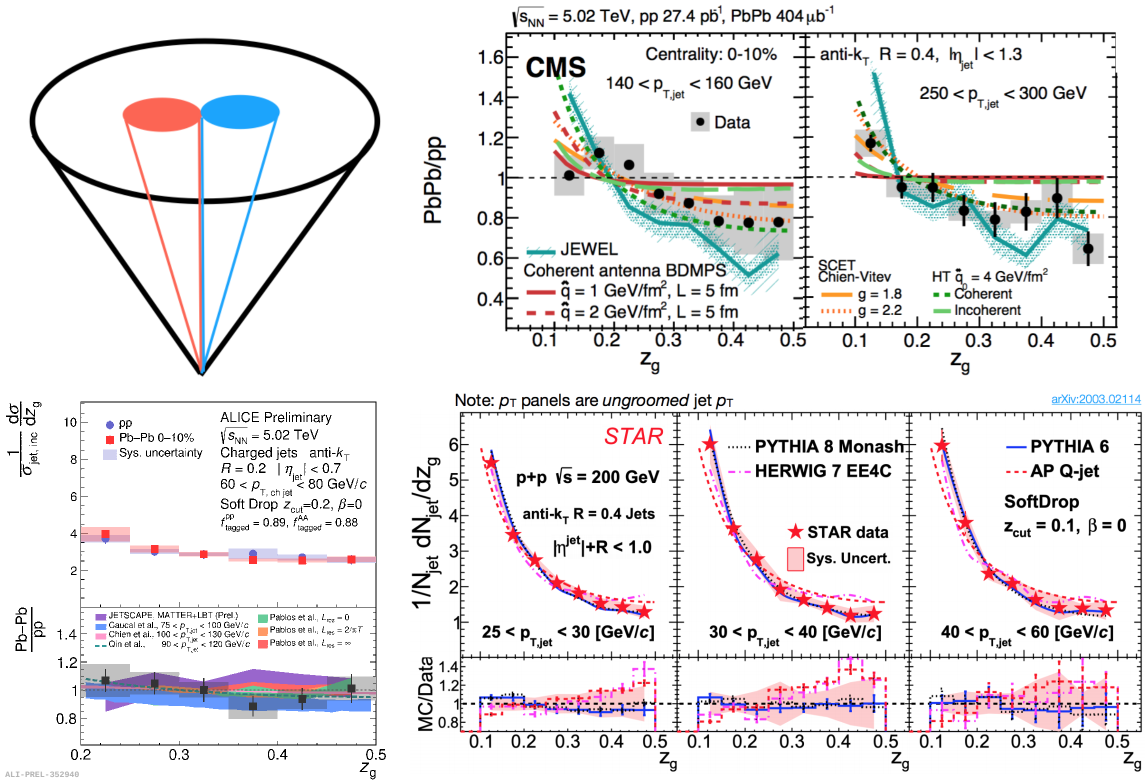

Figure 4: Top left panel: Illustration of the longitudinal energy profile z_g as the momentum fraction carried by the soft subjet determined in the soft-drop grooming procedure. Top right panel: The first measurement of the z_g distribution for inclusive jets. New measurements of the z_g distribution by the ALICE (lower left panel) and the STAR (lower right panel) collaborations.

3.1 Jet radial energy profile

The suppression of not only hadron cross sections but also jet cross sections suggests that energies are transported away from dominant energy flow directions at an angular scale larger than the jet radius R. The radial energy profile – commonly referred to as the jet shape and denoted as $\rho(r)$ – is the average differential jet energy distribution as a function of the angle r to the jet direction (left panel of Fig. 3). Its modification, first measured by the CMS collaboration [12], shows a nontrivial pattern that attenuates at intermediate angles and enhances at large angles (middle panel of Fig. 3). The later can be explained by most model calculations and is consistent with the observed jet quenching, while the attenuation can be understood as caused by the decrease of gluon jet fraction [13]. For inclusive jets, there is a significant fraction of gluon jets whose suppression is expected to be larger compared to quark jets. This implies that for photon tagged jets which are more dominantly quark jets, the attenuation should be less significant. Indeed, it was observed to be the case in the experimental data (right panel of Fig. 3) [14] . It remains to determine the quark gluon jet fraction consistent in multiple measurements in order to test this effect. Note that in certain model calculations the medium response contributions may play a significant role in the modification of the radial energy profile.

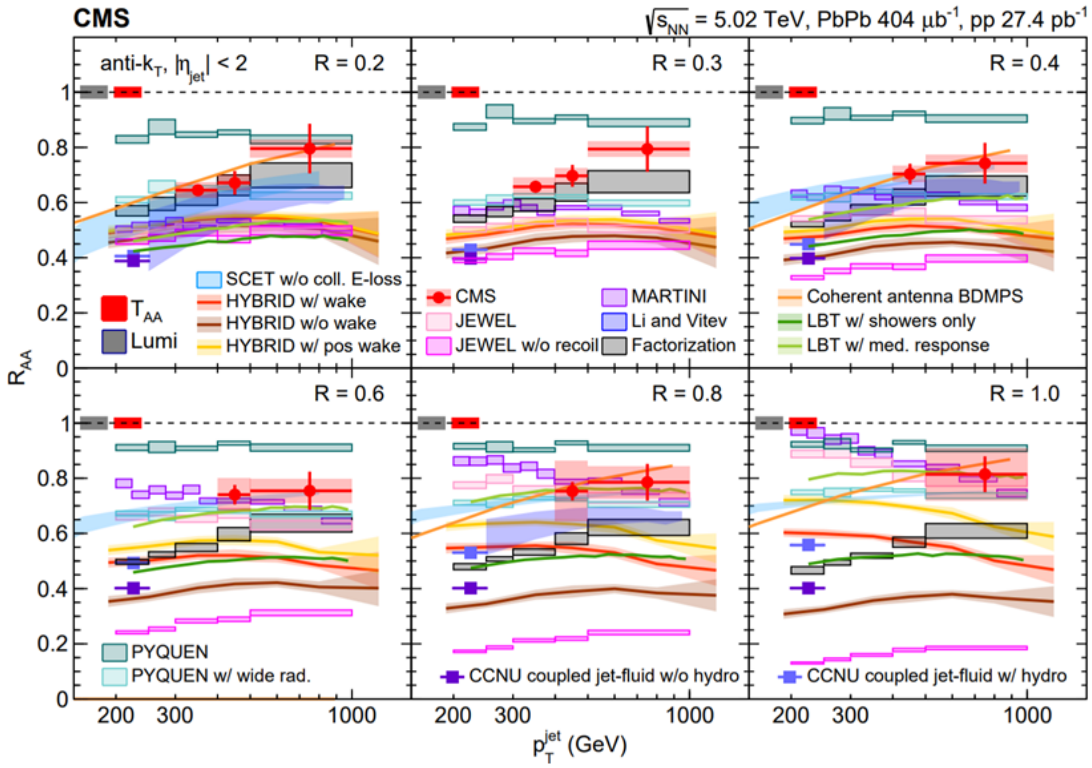

Figure 5: Nuclear modification factor R_{AA} for jets with different radii and comparisons to a variety of theoretical calculations.

3.2 Jet longitudinal energy profile

Orthogonal information can be gained about jet-medium interactions through the longitudinal energy profile. For unpolarized jets with sequential one-to-two splittings in the jet evolution, the hard branching kinematics is determined by the longitudinal momentum fraction and the angle between the two branches. The precise procedure for identifying the hard branching is through the soft-drop grooming algorithm [15]. It is based on angular-ordered clustering with a criterium of selecting the widest hard branching by removing soft, wide angle radiation (top left panel of Fig. 4). The groomed momentum sharing observable z_g measures the momentum fraction of the soft branch, and it is directly related to the collinear splitting function of QCD. The first measurement was performed by the CMS collaboration showing significant enhancement of soft branchings and suppression of hard branchings (top right panel of Fig. 4). Such modification pattern can qualitatively be described by several model calculations of soft bremsstrahlung induced by jet-medium interactions. Quantitatively the z_g modification pattern suggests that the medium can induce hard splittings [16] and interact with the branches coherently. Incoherent energy loss of the two branches is not favored by the data. Note that medium response and underlying event fluctuation may also affect the soft branch identification. Lower panels of Fig. 4 show the new measurements performed by the ALICE (lower left) [17] and STAR (lower right) [18] collaborations.

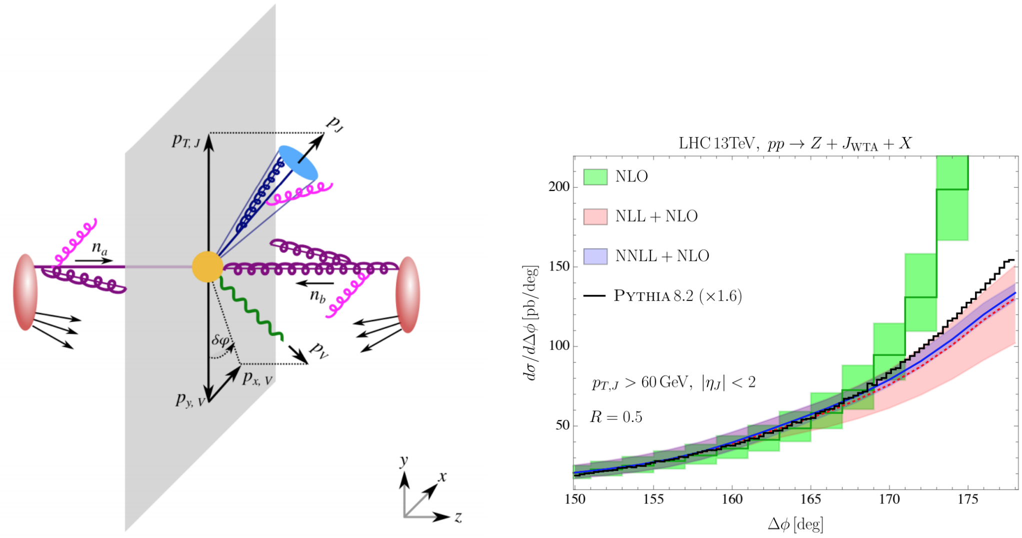

Figure 6: Left panel: Illustration of boson-jet correlation by measuring the azimuthal angle $\Delta\phi = \pi - \delta\phi$ between the boson (green) and the jet (blue). Right panel: The $\Delta\phi$ distribution at next-to-next-to-leading logarithmic accuracy matched to next-to-leading order calculation.

3.3 Jet suppression factor R_{AA}: radius dependence

We discuss the measurement of jet cross section suppression factor R_{AA} and in particular its dependence on the jet radius. Such detailed information about the nuclear modification factor depends on the energy distribution around jets and is complementary to the information contained in jet radial energy profile. Therefore precision studies of jet cross sections are closely connected to jet substructure. There are two categories of energy loss mechanisms at play. For jets with larger radii, more particles are included in jet reconstruction which may increase the chance of medium interacting with jet partons. If the resulting loss energy is transported away at an angular scale larger than the jet radius, large jets may lose more energy and be more suppressed. On the other hand, jets with larger radii have larger coverage area which therefore in general decreases the chance of energy being transported out of jets. A precise measurement of jet suppression with different jet radii will allow us to constrain the contributions in a wide variety of model calculations. Comparisons between theoretical calculations and the recent preliminary measurement performed by the CMS collaboration suggest that in-medium parton shower may be modified throughout the jet evolution. Also, multiple model calculations have significant medium response contributions. This gives the opportunity of identifying and constraining such component and quantifying its properties.

3.4 Precision boson-jet correlation using recoil-free axis

Lastly we discuss the classic observable of boson-jet correlation, and how its distribution can be calculated and measured at unprecedented precision facilitating a refined definition using jet substructure techniques. Conventionally the azimuthal angle decorrelation is measured between the boson and the jet axis (left panel of Fig. 6). While the boson direction can be determined in experiment very precisely, the jet axis direction is largely affected by the huge underlying event background. Since the conventional jet axis is defined as the direction along the total threemomentum of the jet, it can be significantly recoiled and smeared due to underlying event particles within the jet. With δp_t representing the transverse momentum of misidentified particles, the $\Delta\phi$ distribution is smeared at an angular scale of $O(\delta p_t/p_t^{\text{jet}})$, thereby limiting the sensitivity of identifying intrinsic properties of jet-medium interactions through the modification of the $\Delta\phi$ distribution. Such recoil effect is also not theoretically well understood, especially the local underlying event fluctuation and medium response. On the other hand, the perturbative precision of theoretical calculations for conventional boson-jet correlations is limited at next-to-leading-logarithmic (NLL) accuracy by the presence of non-global correlations between radiation inside and outside the jet, precisely due to the sensitivity to soft particles [22]. The NLL accuracy may be sufficient for qualitative understanding of the shapes of jet substructure distributions. However, in order to extract robust information from jet substructure modification we need a higher accuracy.

In order to suppress soft recoil from underlying event particles, a direction which is more sensitive to the energetic collinear particles should be adopted. By using the anti-k_t clustering algorithm [20] with Winner-Take-All (WTA) recombination scheme [21], energetic collinear particles determine the reference direction. Note that it will align with one of the jet particles taking into account local clustering in order to represent the dominant energy flow. Although by momentum conservation the WTA jet axis will recoil against soft emissions correlated with the hard scattering process, such contribution is perturbatively calculable without the presence of non-global correlation. This allows the perturbative precision to be improved to next-to-next-to-leading-logarithmic (NNLL) accuracy [23]. The right panel of Fig. 6 shows a comparison of the $\Delta\phi$ distribution at NNLL matched to NLO accuracy with significant shrinking of the theoretical uncertainty band. It is also shown that [23] the WTA jet axis is accurately represented by charged particles. Therefore by utilizing the excellent angular resolution of charged tracks a precise measurement of the $\Delta\phi$ distribution will be possible.

4. Conclusion

In the past few years we have seen significant developments in the studies of jet substructure modifications to test and refine the understanding of jet-medium interactions. These include more and more experimental measurements in different collision systems, at different center of mass energies, and using different hard probes. Certainly the field of jet substructure in heavy ion physics is a fast developing field and we encourage further progress and exploration. Along this direction, as we are entering the era of detailed jet substructure studies, sensitivity and precision are key considerations in order to make meaningful and robust progress. This poses a challenge as well as gives an opportunity to both theoretical calculations and experimental measurements to develop proper tools for searching and identifying unique signatures in jet substructure modifications. At the moment several measurements have been performed to study the average jet properties, including the radial energy profile and hadron fragmentation (however not covered here). A more precise and detailed jet suppression study is also ongoing. In the near future we hope to establish the quantification of these average jet observables. On the other hand, jet-by-jet fluctuation contains much more information about the dynamics of jet evolution, and we are beginning to probe them with theoretical and experimental rigor. This points toward the necessity of a unified treatment of the hard and soft components of heavy ion collision events.

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