PROCEEDINGS OF SCIENCE

Summary: Jets and high-p_T

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In this paper, we give an overview of experimental measurements of jets and high-momentum particle production in heavy-ion collisions at the LHC and RHIC along with recent progress in model calculations of parton energy loss and medium response that were presented at the 10th Hard Probes conference. Several new observables which aim to improve our understanding of jet properties and inner workings of the QGP are discussed as well.

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Jets, collimated sprays of hadrons that originate from the evolution of highly virtual partons created in a hard scattering, are considered as one of the key probes of hot and dense medium created in heavy-ion collisions, the quark-gluon plasma (QGP). In this proceedings we summarize experimental results on jet and high-momentum particle production presented at the 10$^{\text{th}}$ Hard Probes conference along with relevant model comparisons, developments of new theoretical approaches and new observables which are expected to advance our understanding of jet quenching in the QGP and inner workings of the medium. As the number of talks and posters related to jets and particle production at high transverse momentum (p_{T}) presented at the conference including results shown for the first time in public, was very large, it was unfortunately not possible to include the wealth of results to the summary talk, neither to these proceedings. The interested reader is therefore kindly referred to the individual contributions posted at the conference webpage and included in the conference proceedings.

1. Jet R_{AA}

The bread and butter measurement, the nuclear modification factor R_{AA} of jets produced in heavy-ion collisions, is still attracting a lot of experimental and theoretical interest as we have witnessed at the conference. The measurements of the cone-size (R) dependence of the jet R_{AA} by CMS [1] displayed in Figure 1 as well as of ATLAS [2] show only a modest increase of the R_{AA} with jet radius. In fact, the R_{AA} never reaches unity even at jet transverse momenta p_{T} of the order of 1 TeV. To extend jet R_{AA} measurements to larger jet resolution parameters and lower transverse momenta, where the background contamination gets substantial, machine learning (ML) techniques are being recently explored as well. This was demonstrated by ALICE [3] which applied a shallow neural network (scikit-learn) to correct the jet p_{T} on a jet-by-jet basis using information about the jet constituents along with investigation of the potential fragmentation bias introduced by learning on

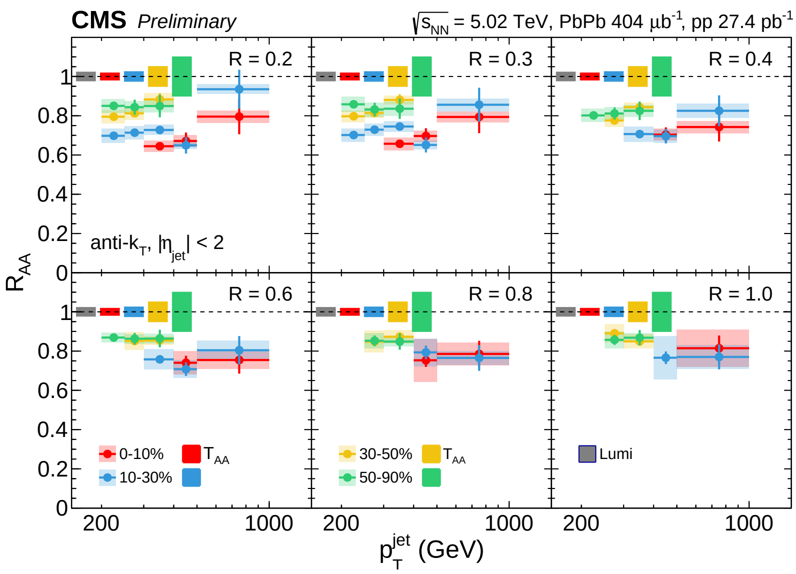

Figure 1: The jet R_{AA} for various R and centrality classes in Pb+Pb collisions at $\sqrt{s_{\text{NN}}}$ = 5.02 TeV by CMS. Figure from [1].

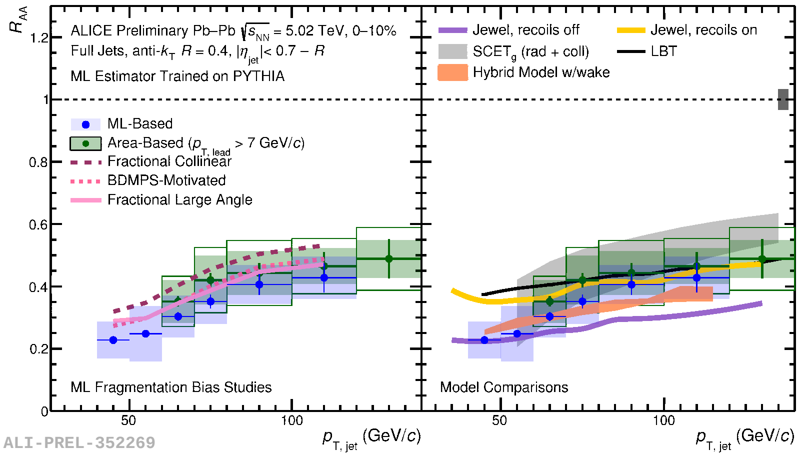

Figure 2: Jet R_{AA} with ML-based and area-based corrections for $R = 0.4$ jets in 0-10% Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by ALICE. The data are compared to the fragmenation bias curves for a toy model (left) and various models (right). Figure taken from [3].

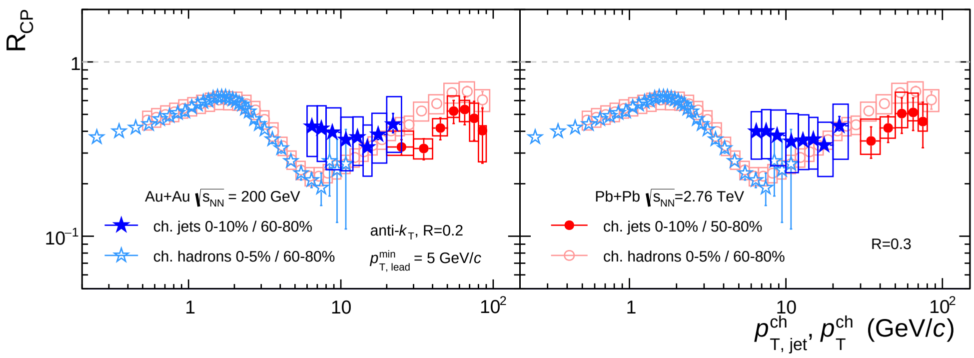

Figure 3: R_{CP} distributions of charged-particle jets compared to hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by STAR [5] for $R = 0.2$ (left) and $R = 0.3$ (right). The data are also compared with the data from Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Figure taken from [5].

constituents [4]. This approach allowed to extend inclusive jet R_{AA} measurements down to $p_T = 40$ GeV/c as demonstrated in Figure 2. Although jet-by-jet fluctuations were significantly narrowed, the ML training is affected by assumed fragmentation model and careful studies including quenched MC models are needed to fully understand the biases introduced by this method. Jet measurements pursued by ALICE at lower jet p_T are very important to constrain model predictions for the LHC energy but will also allow for comparison with data from RHIC where a large progress has been recently achieved by STAR. The first results on charged-particle jet R_{CP} and R_{AA} in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were presented at the conference [5, 6] together with encouraging expectations for high-statistics full jet measurements to appear soon. The charged-particle jet yield suppression at RHIC measured for $R = 0.2$–0.4 is consistent with inclusive hadron suppression and the amount of the suppression is similar to that observed at the LHC as demonstrated in Figure 3.

On theoretical side, several new predictions for R_{AA} were presented and due to space limitations only two of them are higlighted here. The first one from [7] and displayed in Figure 4 (left)

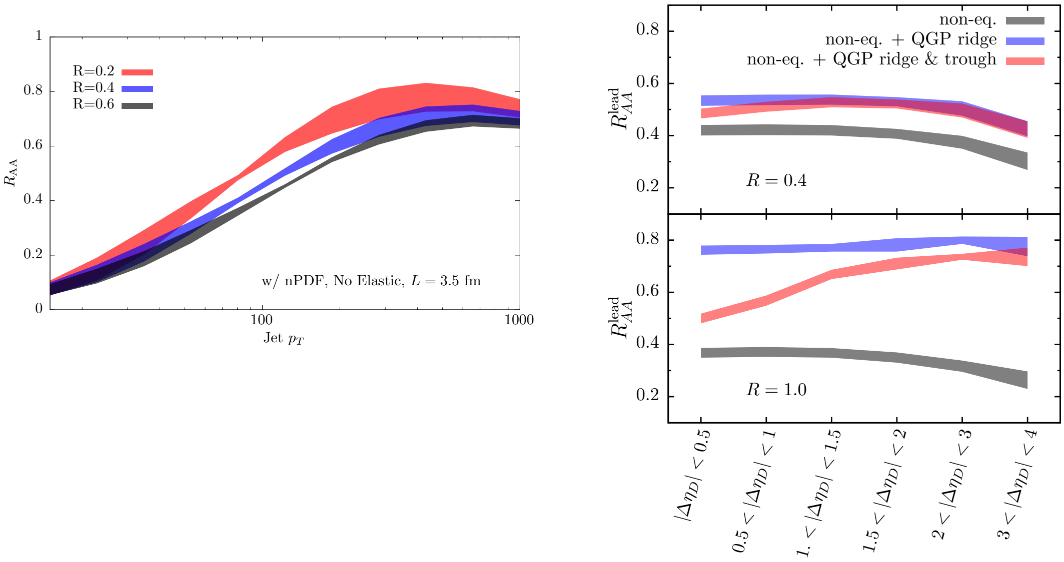

Figure 4: Left: The jet R_{AA} as a function of cone size for heavy-ion collisions at the LHC. Figure taken from [7]. Right: $R_{\rm AA}$ for leading jets above $p_{\rm T} > 250$ GeV/c as a function of the pseudorapidity separation with respect to the back-to-back subleading jet with $p_{\rm T} > 80$ GeV/c. Figure taken from [8, 9].

is an analytical calculation in collinear factorization with nuclear PDF and medium effects on resummation. In particular, the calculation includes the multi-prong structure of jets that interact with the plasma and their fluctuations and models energy transfer from the leading particle to large angles where thermalization occurs. The predicted weak R-dependence of the jet $R_{\rm AA}$ in this approach is a consequence of color coherence due to which only splittings occuring at angles larger than a certain scale are resolved. The jet energy loss is therefore not only sensitive to the parton energy loss mechanisms as such but also depends on how jets as coherent quantum states interact with the surrounding thermal environment. The second calculation we highlight here is the hybrid strong/weak coupling model from [8, 9]: while parton splittings can be well described by pQCD, the interaction of the jet constituents with the QGP is assumed to be dominated by non-perturbative processes. In this approach, jets with larger cone are more susceptible to the contribution from the QGP trough coming from the wake originated by the recoiling jet. At LHC energies, there is enough phase space for dijet systems with a large rapidity ($\Delta\eta$) gap which in turn provides suitable conditions to study differentially the QGP trough effect, while at RHIC, there is almost no phase space left as demonstrated in [9]. This calculation thus motivates a new observable to be explored at the LHC to unravel the fluid nature of quenched energy, namely the study of suppression of the leading jet as a function of the $\Delta\eta$ between the dijet system as shown in Figure 4 (right).

2. Semi-inclusive recoil jet studies

Semi-inclusive measurements of jets recoiling from high-momentum hadron, π^0 or direct photon (γ) have been extensively explored in past both at RHIC and the LHC. We would like to point the interested reader to new studies of semi-inclusive recoil jet distributions in small systems, in particular high-multiplicity pp collisions in ALICE [10] and p+Au collisions in STAR [11] presented at this conference which aim to search for possible jet quenching effects in small systems. Here, we higlight two new measurements in heavy-ion collisions.

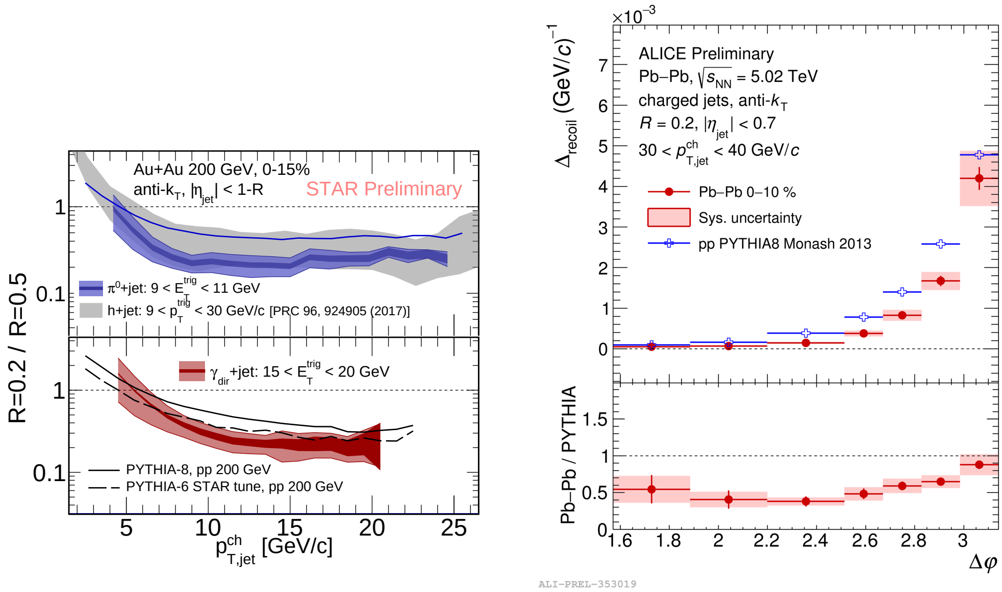

Figure 5: Left: Ratio of recoil jet yields for R = 0.2 and 0.5 as a function jet p_T for h+jet and π^0+jet (top) and γ_{dir}+jet (bottom). Figure taken from [12]. Right: Azimuthal distribution of recoiling charged-particle jets with p_T = 30–40 GeV/c in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV from ALICE. Figure taken from [15].

STAR reported measurements of jets recoiling from π^0 and direct γ in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV up to jet cone-size of R = 0.5 [12]. Similar suppression in central Au+Au collisions relative to PYTHIA pp reference is observed for both π^0 and γ-triggered jet distributions with no significant dependence on the transverse energy (E_T) of the trigger particle. However, a dependence on the jet radius is observed, the measured suppression in central collisions is smaller for R = 0.5 than for R = 0.2 jets. Figure 5 (left) displays the respective ratio of recoil jet yields for R = 0.2 and 0.5 which is sensitive to the jet transverse profile. The γ-triggered ratio is consistent with a calculation based on PYTHIA6 tuned to RHIC energy, which would indicate no significant in-medium broadening of recoil jets. However, a notable difference is observed relative to the PYTHIA8 reference which overpredicts the measured ratio. This clearly calls for extracting the pp reference from the data in order to reach a definite conclusion on possible medium jet transverse profile modification.

ALICE presented in [15] an extension of its pioneering Run-1 study of azimuthal hadron+jet distributions in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [13]. The presence of medium could lead to an additional deflection of the away-side jet via multiple soft scatterings. What is, however, even more interesting are investigations of the tail of these azimuthal correlations which are expected to be sensitive to Molière scatterings off quasi-particles in the QGP [14]. The Run-1 analysis showed no evidence of jet broadening with respect to the vacuum expectation within experimental uncertainties and no sign of quasi-particles. The high-statistics Run-2 preliminary results presented in [15] and displayed in Figure 5 (right) for 30–40 GeV/c jets measured in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV show that the recoil jet yield in central collisions is suppressed with respect to the PYTHIA pp reference, inline with quenching effects. At the same time, the $\Delta\phi$-distribution is narrower in central Pb+Pb relative to pp collisions. Also for this analysis, future measurements using high statistics measured pp data in combination with an extension to larger R and jet p_T values will provide definite conclusion on presence of quasi-particles in hot and dense matter at the LHC.

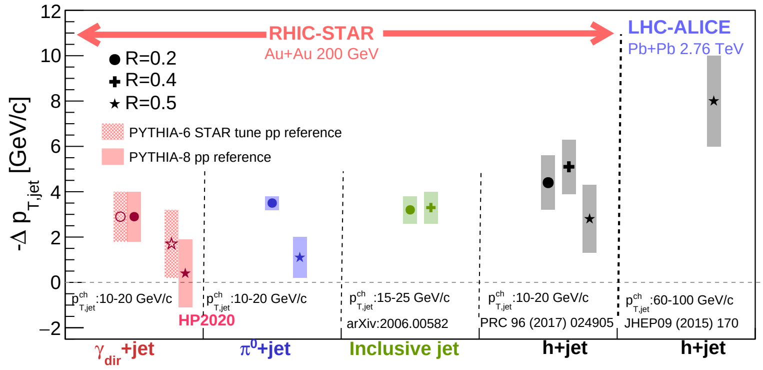

Figure 6: The p_T shift for γ_{dir}+jet, π^0+jet, inclusive jet, h+jet measurements at RHIC, and h+jet at the LHC. Note the different jet p_T ranges. Figure taken from [12].

The available LHC and RHIC measurements of recoil jet suppresion and inclusive jet R_{AA} measurements can be used to estimate the size of out-of-cone energy loss at RHIC and the LHC. For this purpose the transverse momentum shift ($-\Delta p_T$) corresponding to yield suppression in p_T was calculated in [12] and the results are displayed in Figure 6. This comparison indicates that there is a smaller out-of-cone energy loss at RHIC than at the LHC.

3. Path-length effects on jet production

The parton energy loss depends on the length of the QGP that the parton travels through. The geometry of the non-central heavy-ion collision leads to shorter average path lengths if the jet is oriented along the direction of the impact parameter than if it is oriented in the perpendicular direction. This should lead to an observable dependence of the jet yield on the azimuthal angle. The first measurements by ATLAS [16] and ALICE [17] in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV yielded positive ($\approx$ few percent) values of the second Fourier coefficient (v_2) for jets with some tension between the two experiments. The new analysis presented by ATLAS in [18] extends the measurement of jet v_2 to higher p_T and energy $\sqrt{s_{NN}}$ = 5.02 TeV and is displayed in Figure 7 (left).

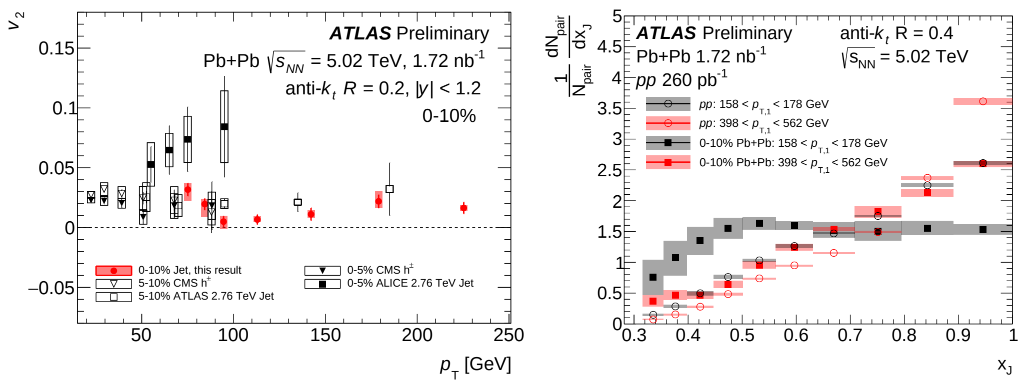

Figure 7: Left: The p_T dependence of jet v_2 in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared with other experiments. Right: The x_J distribution in 0–10% central Pb+Pb and pp collisions for different p_T selections of the leading jet. Figures are taken from [18, 19].

The new jet v_2 data are consistent with the previous ATLAS measurements at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and lower than the ALICE results. We note here, that better precision of jet v_2 measurements by ALICE is desirable to resolve the discrepancy. ATLAS also presented for the first time higher-order Fourier harmonics (v_3 and v_4) for jets, which are within uncertainties consistent with zero [18].

Next, we discuss the new ATLAS measurement of dijet asymmetry [19] in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. Already at $\sqrt{s_{\rm NN}}$ = 2.76 TeV dijets have been found to be momentum-imbalanced in central Pb+Pb compared to *pp* collisions which is commonly interpreted as the unequal energy loss that the jets suffer due to different path lengths traversed through the QGP. Figure 7 (right) displays the new data which reach to $p_{\rm T}$ = 562 GeV/c and manifest even at this very large jet $p_{\rm T}$ still significant momentum imbalance in central Pb+Pb collisions relative to *pp* data.

4. Jet fragmentation

It is well established that fragmentation functions are modified in central heavy-ion collisions at the LHC as well as RHIC energies where high-$p_{\rm T}$ (high-z) fragment suppression is compensated by an enhanced production of low-$p_{\rm T}$ (low-z) fragments distributed at large angles relative to the jet axis. Especially interesting is to explore γ-jet and Z-jet fragmentation as γ and Z offer a calibrated probe of the transverse momentum of the away-side jet. Here we highlight several measurements presented at the conference, γ-jet fragmentation by PHENIX [20, 21] and CMS [22] displayed in Figure 8 and Z-jet fragmentation from CMS [23] in Figure 9. Both at the LHC and at RHIC, these data corroborate earlier findings of the excess of low $p_{\rm T}$-particles and depletion at high $p_{\rm T}$ in central heavy-ion collisions. The data are qualitatively well described by the CoLBT-hydro [24, 25] and SCET$_G$ [26] models, where the lost energy is redistributed into soft hadrons by multiple scattering, gluon radiation and medium excitation from jet. The Hybrid model even with the back reaction of the medium underpredicts the measured fragmentation distributions at intermediate $p_{\rm T}$. This discrepancy gets even more pronounced in azimuthal distributions of associated particle tracks in Z-tagged correlations in Figure 9 and clearly calls for improved description of medium response.

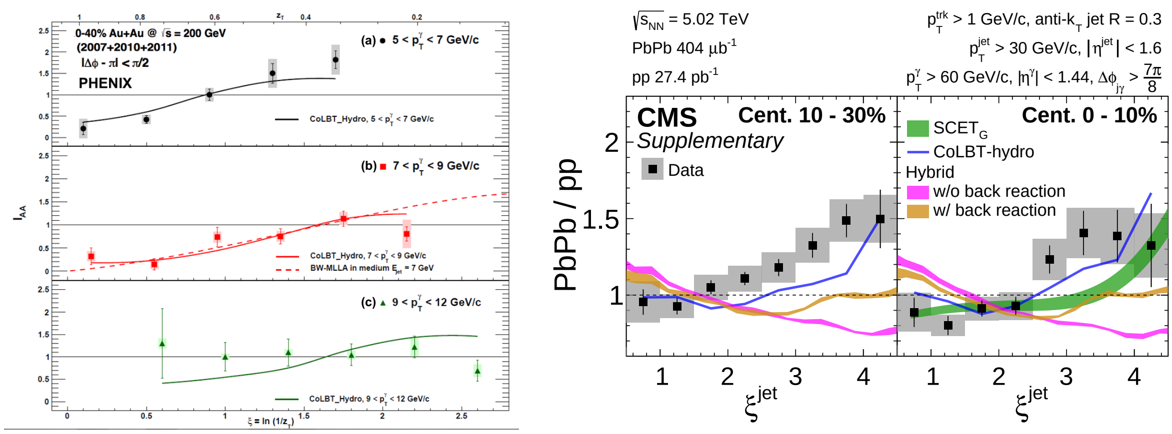

Figure 8: Left: Nuclear modification factor I_{AA} for γ-hadron correlations in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV as a function of ξ. Figure taken from [20, 21]. Right: I_{AA} for γ-jet fragmentation in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV from CMS. Figure taken from [22]. The data are compared with theoretical models (see legend).

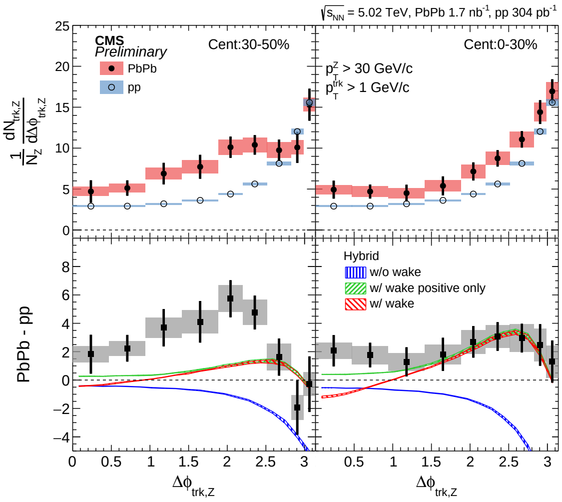

Figure 9: Azimuthal distributions of tracks ($\Delta\phi_{trk}$) in Z-tagged correlations in pp and Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and their respective difference. Figure taken from [23].

Progress in this direction within the linearized hydrodynamics has been presented at the conference and the reader is kindly referred for more details to [27].

Moving to RHIC energy, STAR has reported the first semi-inclusive FF for the population of recoil jets with respect to a high-p_T trigger particle in semi-central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [28]. The results depicted in Figure 10 (left) do not manifest any modification of jet fragmentation relative to the PYTHIA reference. It will be crucial to perform these studies relative to the measured pp reference and for more central collisions to quantify possible medium modification of FF at RHIC energy.

We finish this section with new theoretical development for FF. The standard fragmentation functions discussed above are sensitive to hadronization corrections and/or the unphysical cut-off parameter $k_{\perp,min}$ regulating the collinear divergence in the calculation. At the conference a new IRC safe FF for subjets was discussed in [29]. The subjets originate from declustering jets using the Cambridge/Aachen algorithm and only jets with a p_T with respect to the hard branch larger than

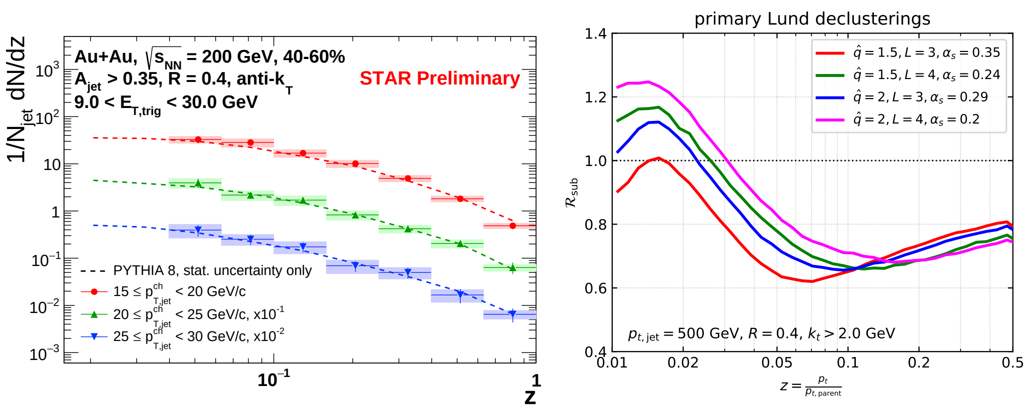

Figure 10: Left: Semi-inclusive jet fragmentation functions measured by STAR in 40–60% Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, compared to PYTHIA. Figure taken from [28]. Right: Nuclear modification factor $\mathcal{R}_{sub}(z)$ of subjets. Figure taken from [29].

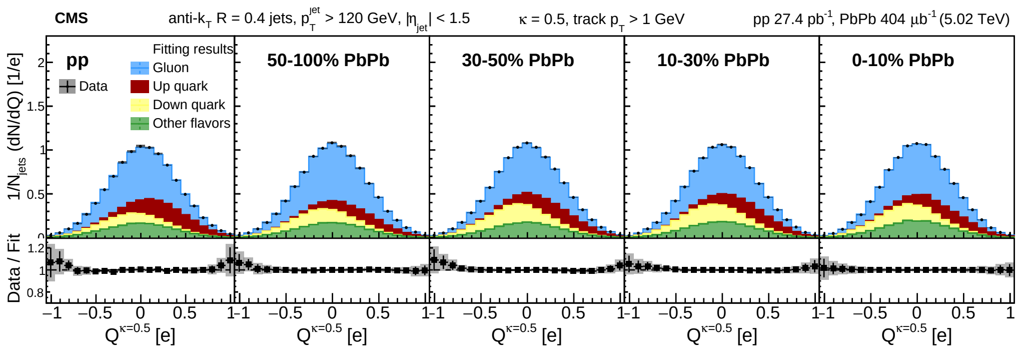

Figure 11: Jet charge measurements in pp and Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV for κ = 0.5 and track p_{T} > 1 GeV/c along with the extracted fractions of u, d, gluon and other flavor jets. The lower panel shows the ratio to the results of template fits. Figure taken from [31].

$k_{\perp,cut}$, chosen much larger than the Λ_{QCD}, are kept. This new observable is sensitive to the same medium effects as standard FF while being resilient to non-perturbative physics. Figure 10 (right) shows the nuclear modification factor of this sub-jet FF, $\mathcal{R}_{\mathrm{sub}}(z)$, which could be confronted with future experimental measurements at the LHC.

5. Jet charge

Jet charge, the momentum-weighted sum of the electric charges of particles inside a jet, is sensitive to the electric charge of the quark or gluon that initiates the parton shower. The jet charge was for the first time measured by CMS both in *pp* and Pb+Pb collisions using jet constituents with p_{T} > 1 GeV/c and jets above 120 GeV/c [30, 31]. The widths of the jet charge distributions are in good agreement with PYTHIA and independent of Pb+Pb collision centrality. The gluon-like jet fractions extracted from the template fits based on quark- and gluon-initiated jets in PYTHIA are found to be similar in both *pp* and Pb+Pb data. The data thus do not shown any evidence for a significant modification of quark- and gluon-like abundance in the studied jet sample and do not support recent interpretations of modified q/g fraction caused by color-charge dependent jet quenching. It should be noted, that this analysis relies on PYTHIA template fitting and in future it will be important to use data driven methods.

Figure 12 (left) displays the in-medium modification of jet charge calculated in the framework of soft-collinear effective theory [32, 33]. The effects of in-medium evolution become pronounced at jet p_{T} < 200 GeV/c, however uncertainty bands corresponding to the variation of the coupling g between the jet and the medium don not allow to cleanly isolate the medium contribution. Therefore the study of modification of individual flavor jet charge has been proposed in [32, 33] and is demonstrated on the u-quark jet charge in the right panel of Figure 12.

6. Jet substructure studies

Jets are rich objects and studies of their inner structure provide a multi-scale probe of QCD. Although jet substructure is of primary interest to particle physics, recently is also beeing explored in p+A (d+A) and A+A collisions both at RHIC and LHC energies to help improve understanding of hadronization mechanisms and the nature of jet quenching. To rigorously define the jet

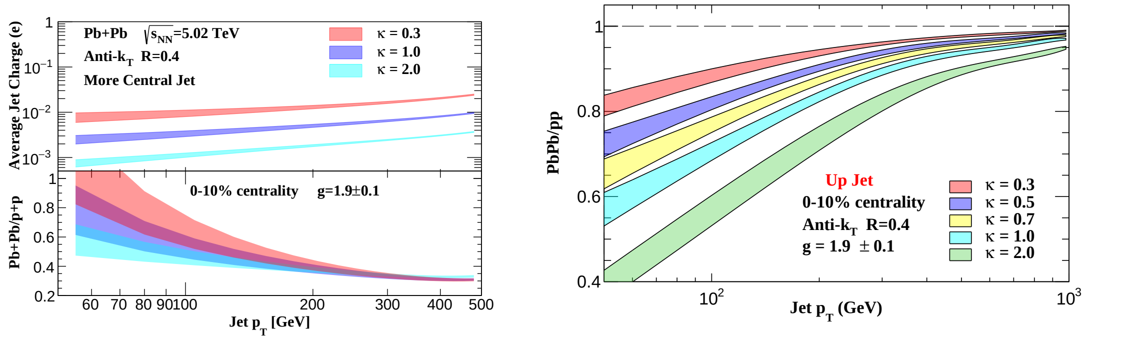

Figure 12: Left: The average jet charge in central Pb+Pb collisions and its modification relative to *pp* collisions at $\sqrt{s_{NN}}$ = 5.02 TeV calculated in SCET$_G$. Right: In-medium modification of the u-quark jet charge. Figures taken from [33].

substructure and allow for controlled comparisons with pQCD, grooming techniques must be applied on reconstructed jets (such as SoftDrop) to reduce non-perturbative effects by removing soft large-angle radiation. At the conference a new family of so-called 'dynamical groomers' has been presented [34] which reduces the number of unconstrained parameters in traditional grooming techniques. Using the primary Lund plane, the 'hardest' emission inside the jet defines a fluctuating grooming condition that is self-generated on a jet-by-jet basis. This new grooming method has been proved to be robust in *pp* collisions and could offer a larger discriminating power than SoftDrop in heavy-ion collisions, where the underlying bacgkround and its fluctuations make the reconstruction of groomed jet observables challenging. The first results in this direction presented in Figure 13 look promising.

Using the dynamical grooming ALICE has presented in [35] the groomed jet radius θ_g and momentum fraction z_g in *pp* collisions at $\sqrt{s_{NN}}$ = 5.02 TeV extending earlier studies of SoftDrop groomed observables. Figure 14 (left) shows the θ_g for several values of the grooming parameter a. For small a values, symmetric splittings are preferred as reflected in small θ_g values while large a values lead to splittings with large angular separation. ALICE also showed at the conference for the first time SoftDrop groomed θ_g and z_g in Pb+Pb collisions applying stronger grooming conditions than in *pp*. While the z_g distributions in Pb+Pb collisions are consistent with *pp* data, a significant narrowing of the θ_g distributions is observed relative to *pp* as demonstrated in Figure 14 (right). The observed θ_g narrowing effect is consistent with models based on medium-modified q/g fractions with coherent energy loss as well as calculations based on incoherent interaction of the jet

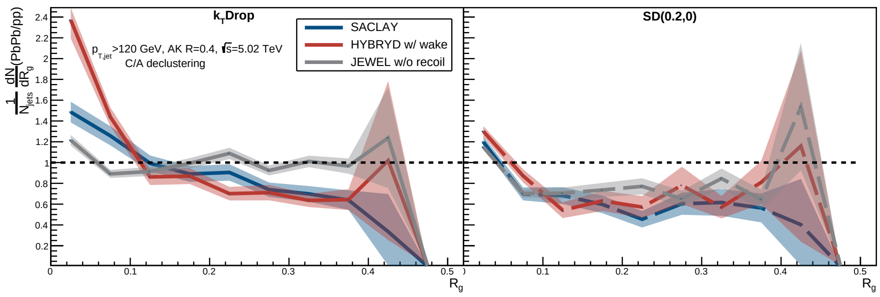

Figure 13: The PbPb/pp ratio of the R_g distribution obtained with Dynamical Grooming (left) and SoftDrop (right) for different jet quenching Monte-Carlo models (see legend). Figure taken from [34].

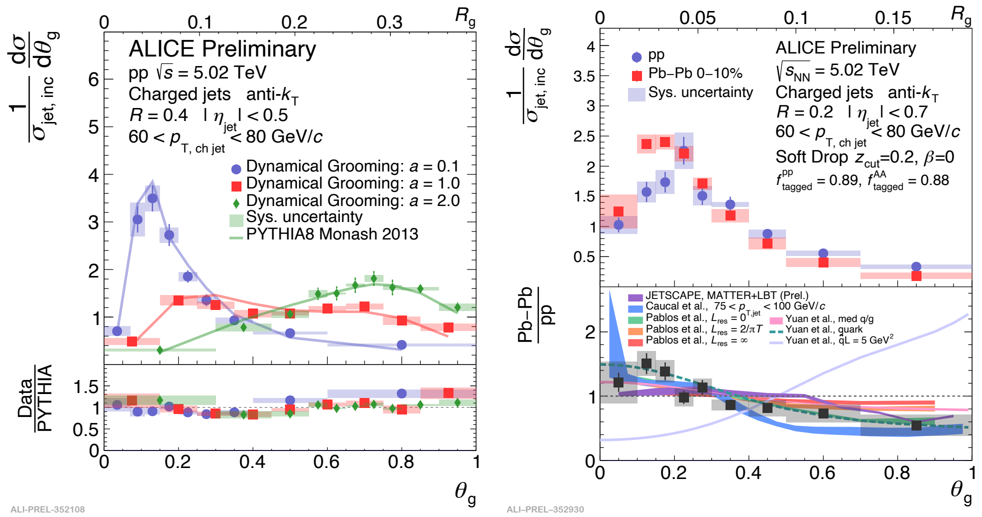

Figure 14: Left: Dynamically groomed θ_g distribution in pp collisions at $\sqrt{s}$ = 5.02 TeV for different values of the grooming parameter a compared to PYTHIA. Right: SoftDrop groomed θ_g in 0–10% central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to pp and theoretical models. Figure adopted from [35].

constituents with the medium and further studies are needed to discriminate between them.

7. Instead of the summary

This Hard Probes conference was the 10th edition and it is therefore a good moment to look back and see what our understanding of jet and high-p_T particle production was in 2004 when Hard Probes were born. At that time, jets were only studied via R_{AA} of inclusive particles and di-hadron correlations at high p_T. We should also remind that at the 1st Hard Probes, a new unexpected phenomenon, the long-range rapidity correlation, the *ridge*, in Au+Au collisions was reported for the first time. In the summary talk on high-p_T and jets [36] it was concluded "... that measurements in the near future at RHIC and the LHC will push the kinematic boundaries of jet studies significantly outward and provide strong constraints on the physics underlying partonic energy loss..." and that "... it remains to be seen whether the intermediate p_T region at the LHC will exhibit similar interplay as at RHIC between perturbative and non-perturbative processes, but it is reasonable to expect that this region will remain interesting even for fragments of the highest energy jets at RHIC II and the LHC ...". In the last fifteen years we have witnessed what was expected in 2004: without any doubts, we are in the high-precision era of jet studies using fully reconstructed jets and the intermediate p_T region at the LHC brought a new surprise: the discovery of the ridge in small-systems which triggered intensive searches for QGP-like behavior in small systems. A big advances were achieved on theoretical side as well toward implementations of parton energy loss formalism and jet-medium interaction in great detail. What was perhaps not expected is that experimentalists and theorists will form common collaborations such as the JETSCAPE Collaboration [37] to develop a comprehensive computational framework aiming to provide a systematic and rigorous approach to simulate the complex environment of heavy-ion collisions.

Acknowledgements

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