Jet Modification in the QGP and the Hadronic Phases with SUBA-Jet Framework

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Abstract

We study jet production and modification in lead-lead collisions at the LHC energies within a recently introduced **SUBA-Jet** framework. The core of the framework is a time-like parton shower that starts with a seed parton with high Q^2, as well as realistic fluid dynamic evolution of the medium, simulated using the **vHLLE** code. The initial parton seeds are produced by **PYTHIA**, whereas the initial state for the medium is modeled with **TRENTo** model. At particlization, the medium decouples into hadrons, with final-state hadronic rescatterings simulated using the **SMASH** hadronic transport. The jet partons lose energy in the medium and hadronize. The ingredients above allow to simulate a complete event containing both soft and hard hadrons. This complete framework is called **J-PHASE-Generator**.

We benchmark the jet energy loss in lead-lead collisions at 5.02 TeV LHC energy in this framework, and, in particular, we examine the influence of hadronic phase on the jet properties. Traditionally, jet modification is assumed to happen solely in the QGP phase, based on arguments of formation time of jet hadrons and low jet transport coefficient in hadronic phase. We argue that the validity of those arguments depends on hadron p_{T}, and as a result the complete jet object can have a visible modification in the hadronic phase, as quantified by different observables.

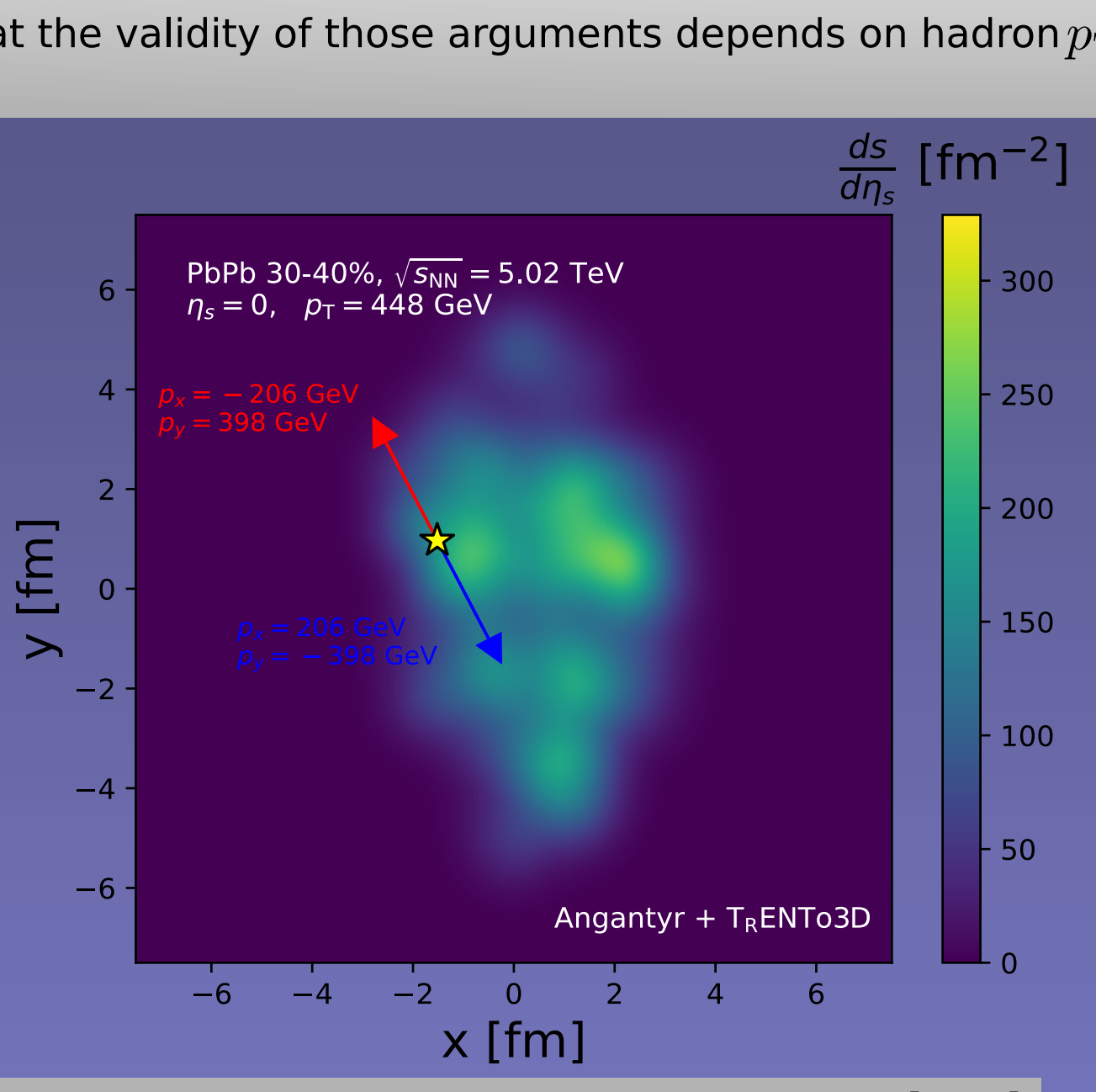
Description of the Jet Evolution

PYTHIA/Angantyr (Jet seed) [arXiv:1806.10820]

- The incoming partons are described by nuclear parton distribution functions (nPDFs) obtained from experimental data.
- Hard parton-parton interactions is calculated using perturbative QCD.
- Then, the QCD factorization theorem was applied to obtain the cross-section of the jet's initial parton in a heavy-ion collision.

$$\sigma^{\mathrm{Hard}} = \sum_r \sum_{ijkl} f_{i/A}\left(Q^2\right) \star f_{j/B}\left(Q^2\right) \star \hat{\sigma}_r^{ij\to kl}(\hat{s},\hat{t},\hat{u})$$

- Position of the vertex is determined according to Glauber-based model.

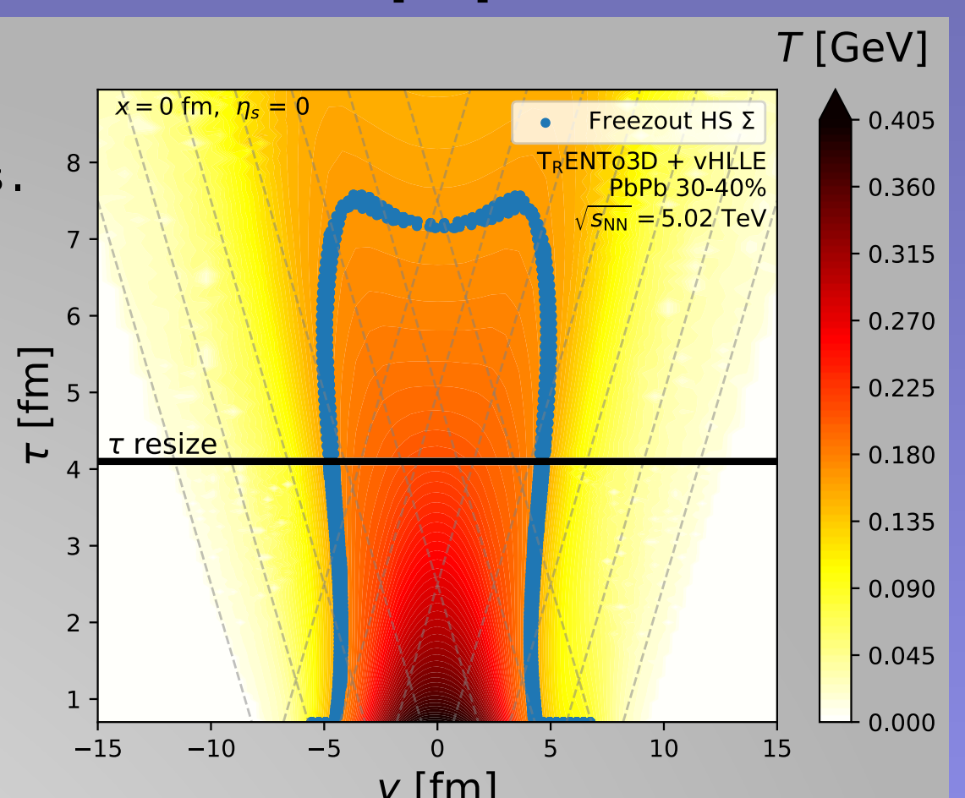


SUBA-Jet [arXiv:2404.14579]

- In SUBA-Jet, high-virtuality evolution in vacuum is governed by the DGLAP equations.
- Inside the medium, high-virtuality evolution is modified by a local, continuous increase in virtuality.

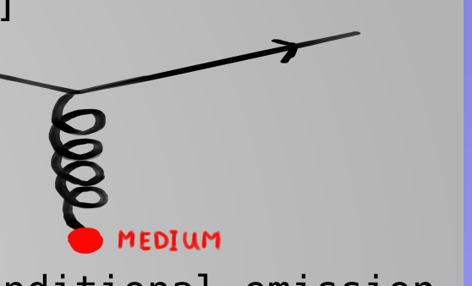
$$S_a\left(Q_{a\uparrow}, Q_a\right) = \exp\left(-\sum_{a\to b,c}\int_{Q_a^2}^{Q_{a\uparrow}^2}\frac{\mathrm{d}Q^2}{Q^2}\int_{x^-}^{x^+}\mathrm{d}x\,\frac{\alpha_s\left(x(1-x)Q^2\right)}{2\pi}P_{a\to b,c}(x)\right)$$

$$\frac{\mathrm{d}Q^2}{\mathrm{d}t} = \hat{q}(T,p)$$



- Low-virtuality component involves both elastic and inelastic collisions in medium interactions.
- Elastic collisions follow the parton-medium differential elastic rate, derived from pQCD cross-sections.

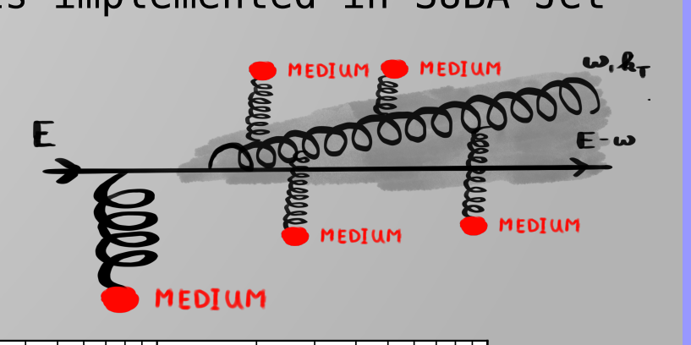
$$\frac{\mathrm{d}^2\Gamma_{\mathrm{el}}^{\mathrm{q}}}{\mathrm{d}^2 q_{\mathrm{T}}} = n_{\mathrm{q}}(T)\frac{\mathrm{d}^2\sigma_{\mathrm{el}}^{\mathrm{qq}}}{\mathrm{d}^2 q_{\mathrm{T}}} + n_{\mathrm{g}}(T)\frac{\mathrm{d}^2\sigma_{\mathrm{el}}^{\mathrm{qg}}}{\mathrm{d}^2 q_{\mathrm{T}}} \qquad \frac{\mathrm{d}^2\sigma_{\mathrm{el}}^{\mathrm{qq}}}{\mathrm{d}^2 q_{\mathrm{T}}} = \frac{2C_{\mathrm{F}}}{N_{\mathrm{c}}}\frac{\alpha_s^2}{\left(q_{\mathrm{T}}^2+\mu^2\right)^2} \qquad \frac{\mathrm{d}^2\sigma_{\mathrm{el}}^{\mathrm{qg}}}{\mathrm{d}^2 q_{\mathrm{T}}} = \frac{2C_{\mathrm{A}}}{N_{\mathrm{c}}}\frac{\alpha_s^2}{\left(q_{\mathrm{T}}^2+\mu^2\right)^2}$$

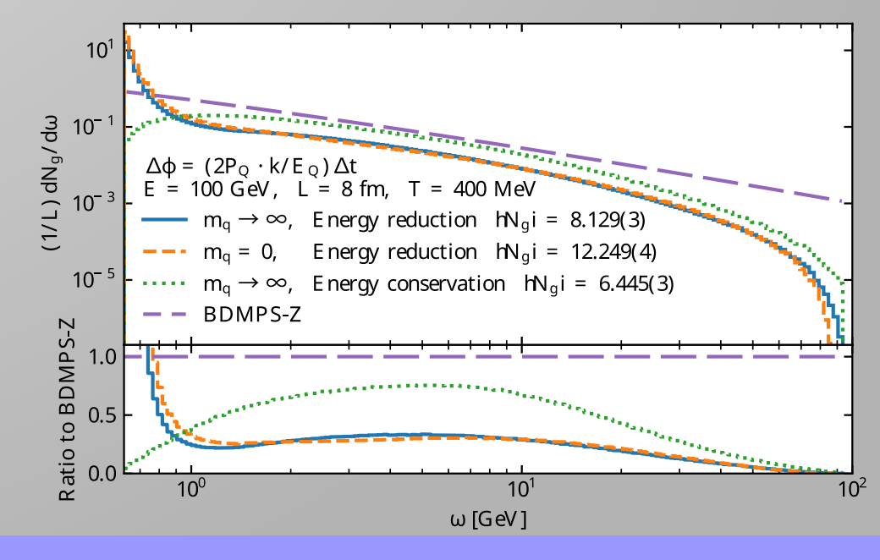


- Inelastic collisions in SUBA-Jet follow the Gunion-Bertsch cross-section, combining matrix elements, conditional emission probability, and phase space constraints.

$$\frac{\mathrm{d}^5\sigma_{\mathrm{rad}}}{\left(\mathrm{d}x\,\mathrm{d}^2 l_\perp \mathrm{d}^2 k_\perp\right)} \sim \left|\mathcal{M}_{\mathrm{el}}\right|^2 \times P_g \times \Theta$$

- Coherent gluon radiation as QCD analog of LPM effect is implemented in SUBA-Jet with the help of formation time of trial-radiated gluons.





PYTHIA (Hadronisation) [arXiv:1808.04619, arXiv:2203.11601]

- In the Lund string hadronisation model implemented in Pythia, partons form a color string, which stretches and breaks into hadrons.
- String tension (around 0.9 GeV/fm) represents the energy needed to break the string.

$$\left|\frac{\mathrm{d}p_{z,\mathrm{q}/\bar{\mathrm{q}}}}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_{z,\mathrm{q}/\bar{\mathrm{q}}}}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E_{\mathrm{q}/\bar{\mathrm{q}}}}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}E_{\mathrm{q}/\bar{\mathrm{q}}}}{\mathrm{d}z}\right| = \kappa$$

- String breaks via tunneling process, leading to a Gaussian suppression factor in the production probability.

$$\mathcal{P}\left(m_{\mathrm{q}}^2, p_\perp^2\right) \propto \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right)\exp\left(-\frac{\pi p_\perp^2}{\kappa}\right)$$

- A consequence of the Gaussian mass suppression is that heavy quarks are not produced during fragmentation hadronisation.

$$\mathrm{u\bar{u}} : \mathrm{d\bar{d}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1:1:0.3:10^{-11}$$

Description of the Medium Evolution

TRENTo [arXiv:1412.4708]

- TRENTo is a non-dynamical initial state model for high-energy nuclear collisions.
- The projectile can be represented by the participant thickness, which is the projection of the nuclear matter density participating in inelastic collisions onto the transverse plane.

$$T_A(x,y) \equiv \int \mathrm{d}z\rho_A^{\mathrm{part}}(x,y,z)$$

- A scale-invariant reduced thickness function can be constructed as a generalized mean. Reduced thickness function is proportional to the entropy density deposited at mid-spatial pseudorapidity at the hydrodynamic thermalization time.

$$T_{\mathrm{R}}\left(p;T_A,T_B\right) \equiv \left(\frac{T_A^p+T_B^p}{2}\right)^{1/p} \qquad T_{\mathrm{R}}\left(p;T_A,T_B\right) \propto \left.\frac{\mathrm{d}s}{\mathrm{d}\eta_s}\right|_{\substack{\tau=\tau_0\\ \eta_s=0}} \qquad T_{\mathrm{R}}\left(0;T_A,T_B\right) = \sqrt{T_A T_B}$$

- Geometric mean is prefered by multiple Baysian analysis studies.
- Boost-invariant transverse plane initial conditions are extended into nonzero spatial pseudorapidity.

vHLLE [arXiv:1312.4160]

- vHLLE is a second-order relativistic hydrodynamics code designed to simulate the evolution of quark-gluon plasma (QGP) in heavy-ion collisions, with the inclusion of bulk and shear viscous effects.
- In addition to the equation of state and first-order conservation equations, vHLLE incorporates two second-order constitutive hydrodynamic equations, using the Israel-Stewart formalism.

$$u^\mu\partial_\mu\Pi = \frac{-\zeta\partial_\mu u^\mu - \Pi}{\tau_\Pi} - \frac{\delta_{\Pi\Pi}}{\tau_\Pi}\Pi\partial_\mu u^\mu + \frac{\lambda_{\Pi\pi}}{\tau_\Pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$
$$u^\alpha\partial_\alpha\pi^{\langle\mu\nu\rangle} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\partial_\mu u^\mu + \frac{\phi_7}{\tau_\pi}\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \frac{\lambda_{\pi\Pi}}{\tau_\pi}\Pi\sigma^{\mu\nu}$$

- The Israel-Stewart equations include shear and bulk viscosities (first-order transport coefficients), parameterized by temperature-dependent viscosity-to-entropy density ratios.

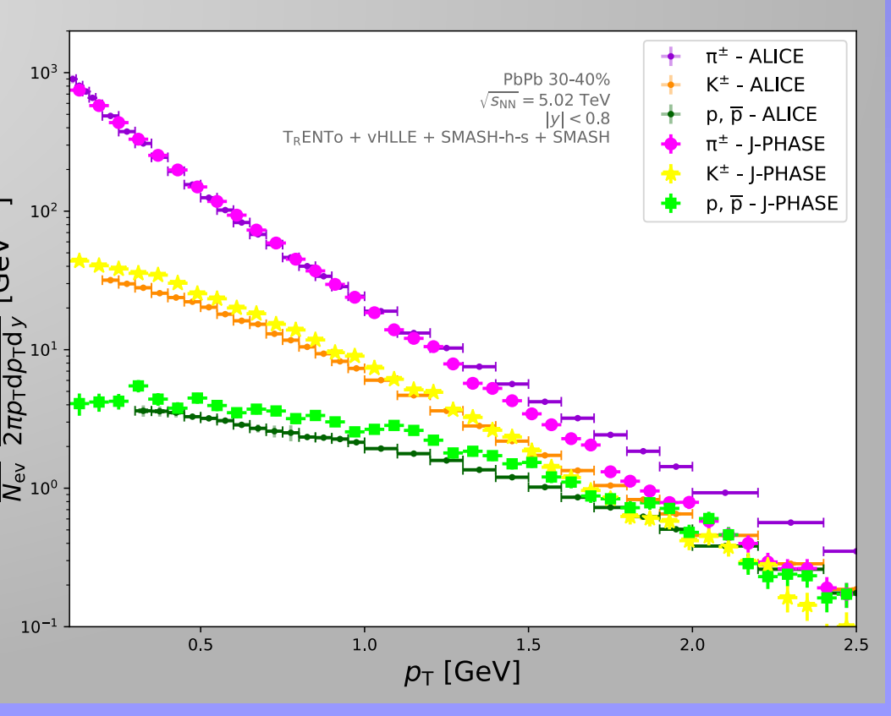
$$\frac{\eta}{s}(T), \quad \frac{\zeta}{s}(T)$$

- Second order transport coefficients.

$$\frac{\delta_{\Pi\Pi}}{\tau_\Pi} = \frac{2}{3}, \quad \frac{\lambda_{\Pi\pi}}{\tau_\Pi} = \frac{8}{5}\left(\frac{1}{3}-c_s^2\right), \quad \frac{\delta_{\pi\pi}}{\tau_\pi} = \frac{4}{3}, \quad \phi_7 = \frac{9}{70p}, \quad \frac{\tau_{\pi\pi}}{\tau_\pi} = \frac{10}{7}, \quad \frac{\lambda_{\pi\Pi}}{\tau_\pi} = \frac{6}{5}$$

- Relaxation times.

$$\tau_\pi = \frac{5\eta}{sT}, \quad \tau_\Pi = \frac{\zeta}{15\left(\frac{1}{3}-c_s^2\right)^2 sT}$$



SMASH-hadron-sampler [arXiv:1502.01978, arXiv:2112.08724]

- The SMASH-hadron-sampler facilitates the transition from the quark-gluon plasma (QGP) to hadronic degrees of freedom at the isothermal freeze-out hypersurface, employing the Cooper-Frye formalism with viscosity corrections for out-of-equilibrium effects to the local thermal equilibrium distribution function.

$$\frac{\mathrm{d}N^i}{p_{\mathrm{T}}\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}\mathrm{d}\phi_p} = \frac{g}{(2\pi)^3}\int_\Sigma \mathrm{d}^3\sigma_\mu p^\mu\left(f_0^i(x,p)+\delta f^i(x,p)\right)$$

SMASH [arXiv:1606.06642]

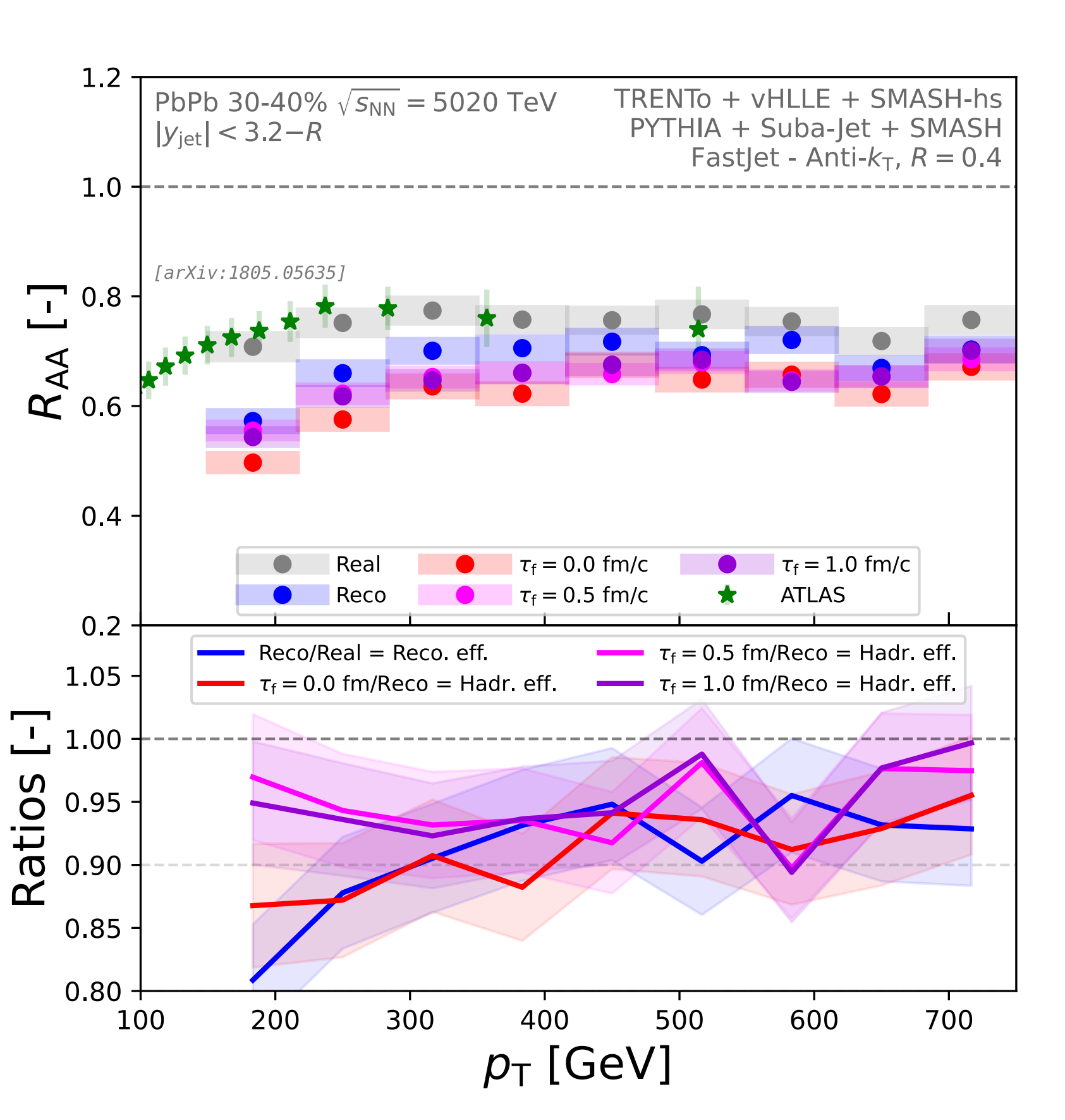
- SMASH is a relativistic hadronic transport model designed to simulate non-equilibrium hadronic dynamics. All well-established hadrons with mass up to ~2 GeV are included as degrees of freedom.
- SMASH constitutes an effective solution of the relativistic Boltzmann transport equation, where the evolution of the phase-space distribution of particles is governed by the collision integral on the right-hand side. Effective solution is obtained with the test particle method by increasing the number of particles and proportionally reducing the cross-sections, preserving the overall dynamics.

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\cdot\nabla_{\vec{x}}f + \vec{F}\cdot\frac{\partial f}{\partial\vec{p}} = \mathcal{C}[f] \qquad N \mapsto NN_{\mathrm{test}} \qquad \sigma \mapsto \sigma N_{\mathrm{test}}^{-1}$$

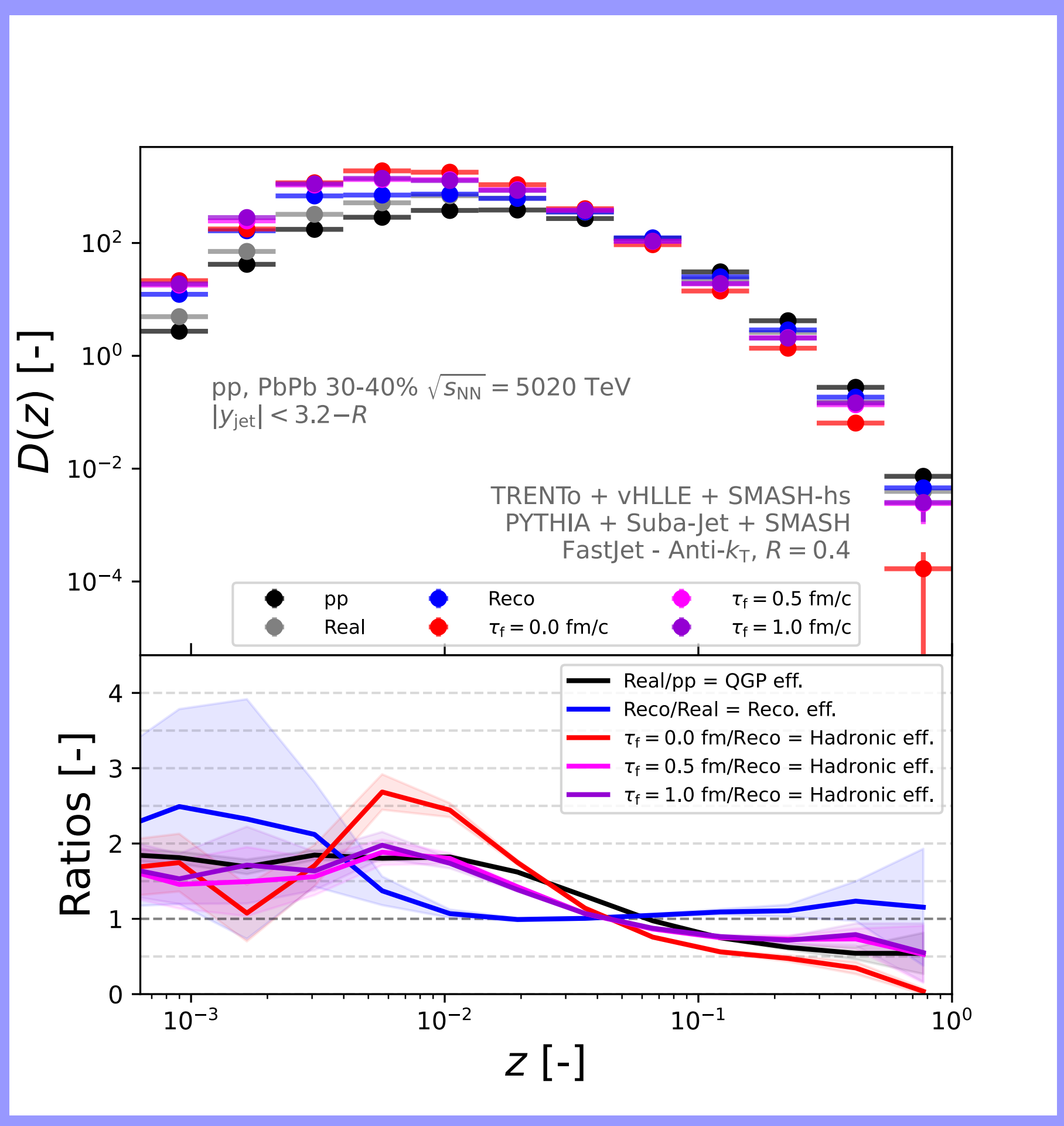
- The collision integral accounts for 2 → 2 elastic and inelastic scatterings, 2 → 1 processes, and 1 → 2 decays. For high center-of-mass energies (above ~3 GeV), the Lund string fragmentation model is applied.

Results

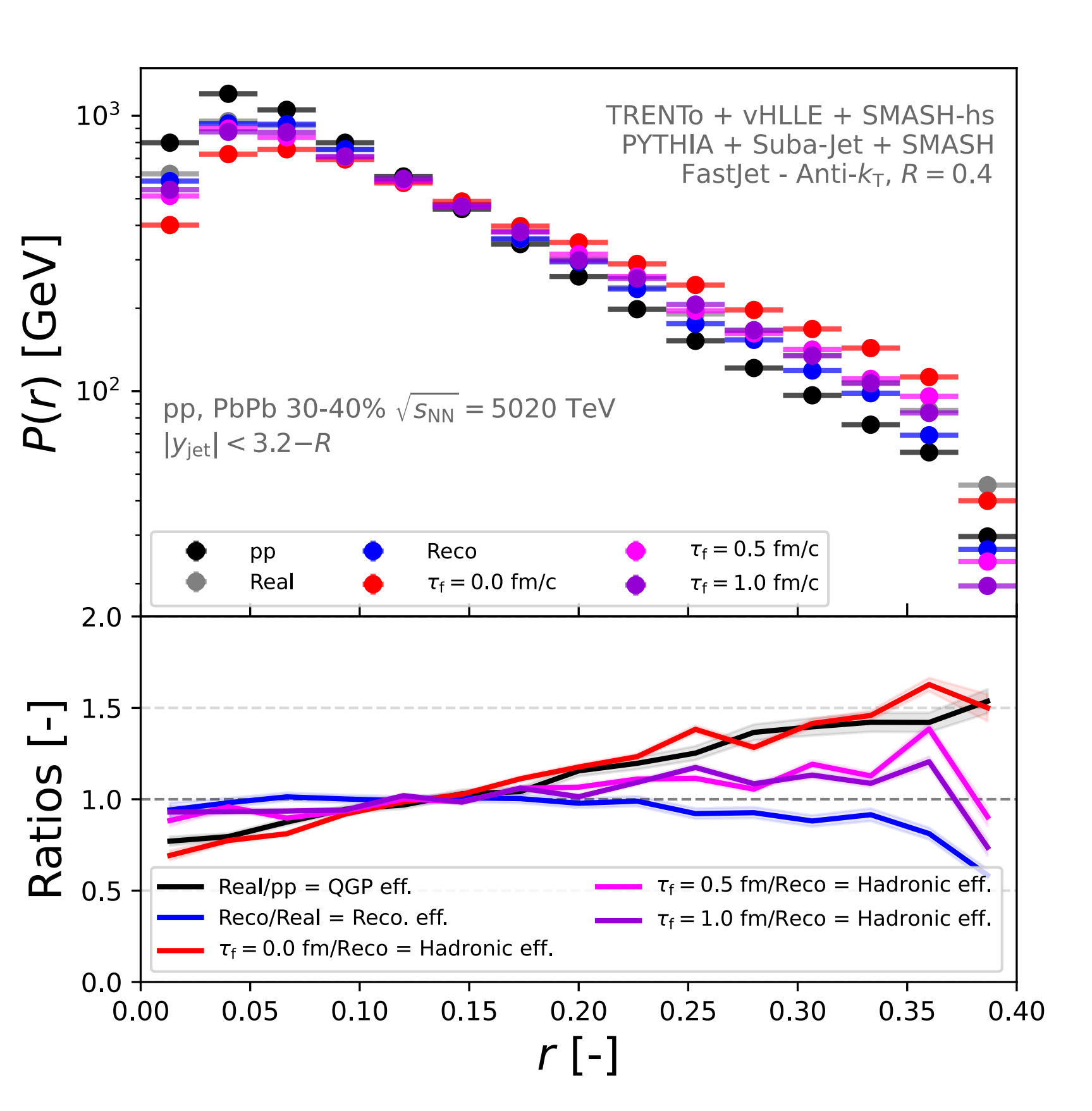
"Real" - Hadronised parton shower without background, followed by simple reconstruction.
"Reco" - Jets and soft hadrons are combined (without interaction), followed by jet reconstruction with background subtraction
"$\tau_F = x$" - Jet hadrons interact with soft hadrons after a formation proper time, followed by the same reconstruction as in "Reco"



Nuclear modification fuctor



Jet fragmentation function



Jet shape

Simulated data of pp and PbPb (30-40% centrality) collisions at a center-of-mass nucleon-pair energy of 5.02 TeV are presented. Simulations of PbPb collisions are divided into five cases. The "Real" case considers jet hadrons after medium evolution, without any additional soft background or rescattering. The "Reco" case, compared to "Real," combines the jet hadrons with the soft background, followed by reconstruction with background subtraction. Additionally, three cases that consider different formation proper times, after which jet hadrons undergo evolution in a soft hadronic gas.

Nuclear modification fuctor (left)

- The nuclear modification factor is compared with ATLAS experiment results and tuned to account for QGP effects. Reconstruction effects are observed across the entire range of transverse momenta. Formation time does not have strong influence on the nuclear modification factor but hadronic rescatterings account for roughly 5-10% change.

Jet fragmentation function (mid)

- The jet fragmentation function is modified by the QGP, showing suppression at high values of the fraction of jets momentum (between 0.1 and 1) and enhancement at small values (<0.04). A similar effect is observed from hadronic rescattering with non-zero formation time. For zero formation time enhancement peaks around ~0.01. Reconstruction effects are relatively small across a wide range (>0.1).

Jet shape (right)

- Both QGP and hadronic interactions suppress the hard jet core and spread its momentum distribution to the outer regions, resulting in an enhancement at larger radii. The point where suppression transitions into enhancement occurs around 0.1. A non-zero formation time reduces the effects on the jet shape.

Conclusion

- A comprehensive framework for heavy-ion collisions, called **J-PHASE-Generator** (**J**et **P**articles evolved in **H**ydrodynamic and **A**fterburner **S**tages **E**vent **Generator**), was constructed.
  - Low-transverse-momenta observables were obtained from the **TRENTo** + **vHLLE** + **SMASH-hadron-sampler** + **SMASH** simulation chain.
  - Jet observables were obtained either from **PYTHIA/Angantyr** (initial seed) + **SUBA-jet** + **PYTHIA** (hadronisation) alongside hydrodynamic medium evolutionton to isolate the effects of the QGP or complete framework incorporating **SMASH** hadronic rescattering.

- We studied the impact of the hadronic phase on jet observables in PbPb 30-40% central collisions at 5.02 TeV LHC.
  - We explored three scenarios for the formation proper time of jet hadrons (1.0, 0.5, and 0.0 fm/c), assuming the jet hadrons travel freely.
  - A visible effect on the jet nuclear modification factor is observed for all formation proper time values.
  - The hadronic phase is sufficiently long to produce a 10% enhancement of the jet shape at large distances from the jet axis.
  - In the extreme scenario of zero formation proper time for jet hadrons, the modification of the jet shape in the hadronic phase becomes comparable to that in the QGP phase.

- The results underscore the importance that existing paradigm of neglecting interactions in the hadronic phase based on formation proper time argument may not be entirely accurate.
- An analysis of hadronic effects on the jet observables in different centrality bins (~multiplicity) and the intrajet multiplicity is planned.

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