Jet energy loss in hadronic re-scattering of Pb+Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV at the LHC

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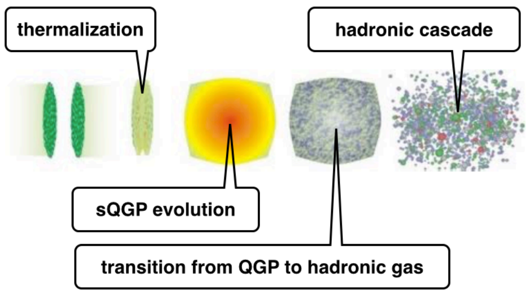
Introduction

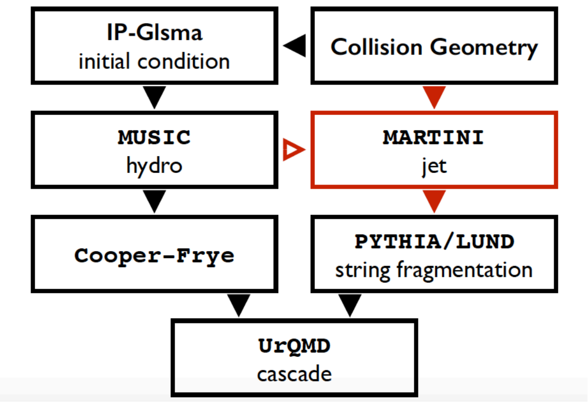
Extend the state-of-art hybrid with jets!

Relativistic heavy ion collision at a glance



What do we need to improve our understanding?
realistic dynamical description

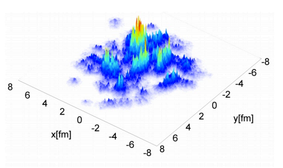
Overview



Full event generator : includes **fluctuations in every stage**

IP-Glasma pre-thermalization dynamics

nucleon + partonic fluctuations



In the IP-Glasma picture [1, 2], partons with high x provide color sources for classical Yang-Mills fields. The color gauge field in terms of the path-orderd Wilson line is given by

$$A^i(\mathbf{x}_\perp) = \frac{i}{g} V(\mathbf{x}_\perp)\partial_i V^\dagger(\mathbf{x}_\perp) \quad (1)$$

$$V(\mathbf{x}_\perp) = P \exp\left[-ig\int dx^- \frac{\rho(x^-,\mathbf{x}_\perp)}{\nabla_T^2 - m^2}\right] \quad (2)$$

The fluctuation of color charges carried by high-x partons in nuclei are described as

$$\langle \rho^a(x^-,\mathbf{x}_\perp)\rho^b(y^-,\mathbf{y}_\perp)\rangle = g^2\mu_A^2(\mathbf{x}_\perp)\delta^{ab}\delta(x^- - y^-)\,\delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp) \quad (3)$$

where $g^2\mu$ depends on the transverse position inside the nucleus. These fluctuations are not present in the MC-Glauber model.

MUSIC Hydrodynamics

Second-order viscous hydrodynamics

MUSIC [3] solves 3 + 1D hydrodynamic conservation equations $\partial_\mu T^{\mu\nu}(t,\mathbf{x}) = 0$, along with the equations for the dissipative currents

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\,\theta - \delta_{\Pi\Pi}\Pi\,\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \quad (4)$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\,\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\,\sigma^{\mu\nu}. \quad (5)$$

The transport coefficients are determined using the relaxation time and 14-moment approximation [4].

Cooper-Frye particlization

Switching from hydro to particles

Hadrons are sampled on the freeze-out hypersurface Σ according to the Cooper-Frye formula [5].

$$\left.\frac{dN}{d^3\mathbf{p}}\right|_{\text{1-cell}} = \begin{cases} \frac{d}{(2\pi)^3}\left[f_0(x,\mathbf{p}) + \delta f_{\text{shear}}(x,\mathbf{p}) + \delta f_{\text{bulk}}(x,\mathbf{p})\right]\frac{p^\mu\Delta\Sigma_\mu}{E_\mathbf{p}} \\ \quad \text{if} \quad f_0 + \delta f_{\text{shear}} + \delta f_{\text{bulk}} > 0 \quad \text{and} \quad p^\mu\Delta\Sigma_\mu > 0 \\ 0 \quad \text{otherwise} \end{cases} \quad (6)$$

where f_0 is the local equilibrium distribution function and the bulk [6] and shear [7] viscous corrections are given by

$$\delta f_{\text{shear}} = f_0(1 \pm f_0)\frac{\pi_{\mu\nu}p^\mu p^\nu}{2(\epsilon_0 + P_0)T^2} \quad (7)$$

$$\delta f_{\text{bulk}} = -f_0(1 \pm f_0)\frac{C_{\text{bulk}}}{T}\left[\frac{m^2}{3(p\cdot u)} - \left(\frac{1}{3} - c_s^2\right)(p\cdot u)\right]\Pi \quad (8)$$

We assume a grand canonical ensemble where particles on each fluid cell are sampled independently.

UrQMD Cascade

Transport approach for dilute hadronic matter

UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [8] is a transport model dealing with the Boltzmann's transport equation

$$p^\mu \frac{\partial f_i}{\partial x^\mu}(t,\mathbf{x},\mathbf{p}) = \mathcal{C}_i[f] \quad (9)$$

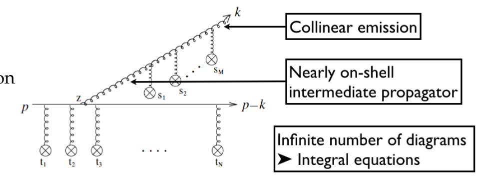
by performing scattering (and decay) in an N-body system.

- 55 baryon species and 32 meson species with masses up to 2.25 GeV.
- Cross sections and decay rates based on the experimental data.

McGill-AMY Formalism in MARTINI

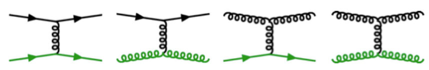
Radiative Energy Loss

Photon and gluon emmision with the LPM effect [9].



Collisional Energy Loss

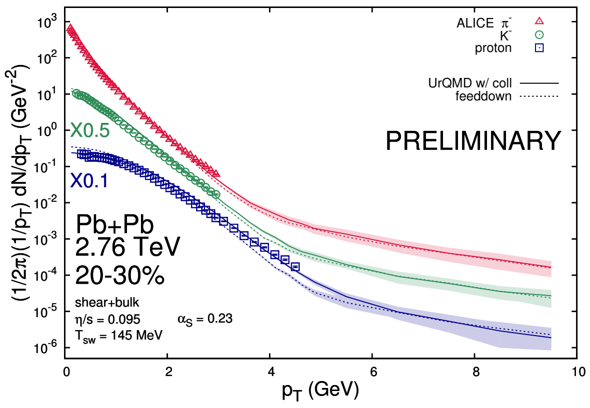
$2 \to 2$ elastic processes between hard and thermal partons [10, 11].

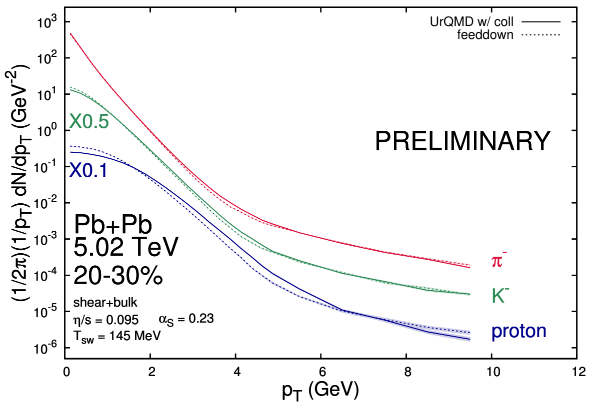


$$\left.\frac{dE}{dt}\right|_{ab} = C_{ab}\pi\alpha_s^2 T^2\left[\ln\frac{ET}{m_g^2} + D_{ab}\right] \quad (10)$$

where C_{ab} and D_{ab} are constants that depend on which kind of partons are interacting.

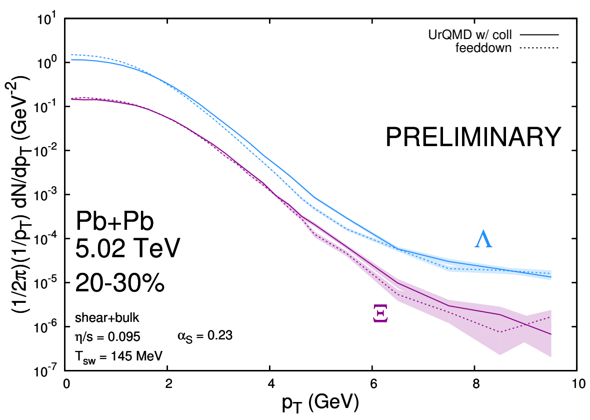
p_T spectra (PID)





Hybrid approach can be extended toward **higher p_T with jets**.

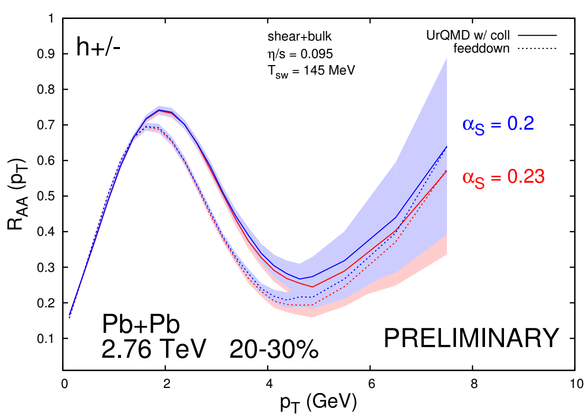
Even though effects on pions and kaons are not significant, **protons are largely affected** by hadronic re-scattering.



It can be applied for **hyperons with higher p_T** as well.

The hadronic re-scattering also has **a relevant effects for the intermediate p_T range**.

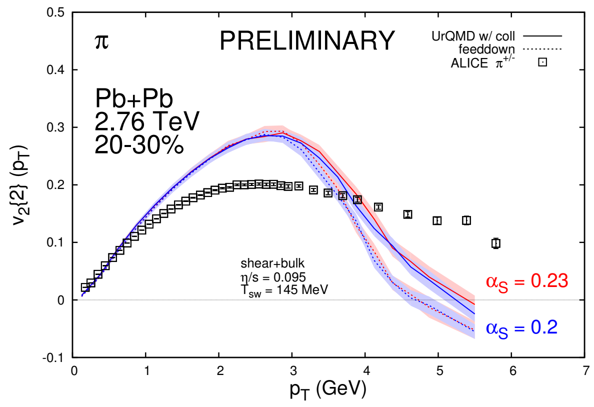
Nuclear modification factor

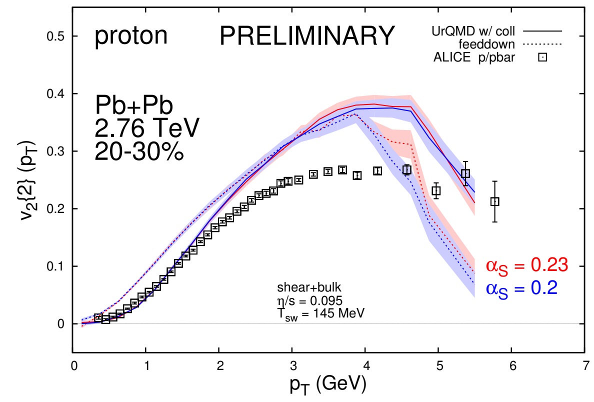


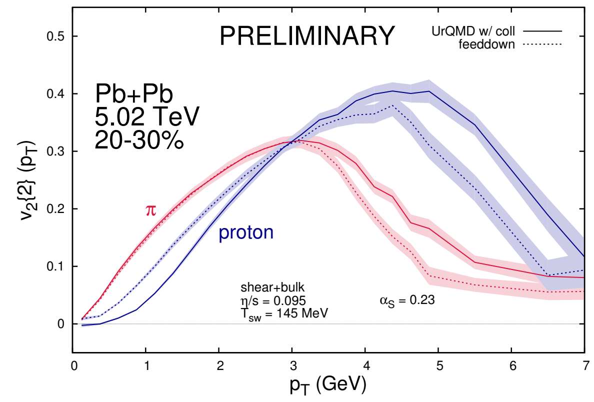
QGP energy loss and hadronic re-scattering have **different effects** on the particle yields.

While R_{AA} significantly depends on the strong coupling α_S for higher p_T, **the hadronic re-scattering has the larger effects in the intermediate p_T range** where contributions from the thermal hadrons and minijets are comparable.

Elliptic flow (PID)

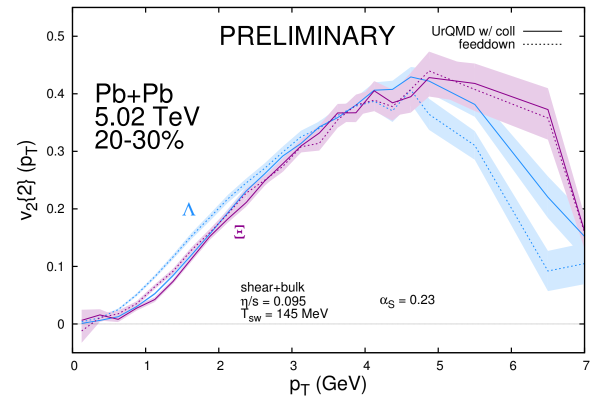






The hadronic re-scattering has **significant effects on the elliptic flow** in the intermediate p_T range.

The hadronic re-scattering **increases** $v_2(p_T)$ **of identified hadrons** in the intermediate p_T range. This can affect the determination of jet-medium interaction in the QGP phase.



Hadronic re-scattering has also **relevant effects on the hyperon v_2**.

Conclusion

1. By combining production and energy-loss of jets in heavy ion collisions, dynamical modelling can be extended to higher p_T.
2. Our hybrid approach is applied for Pb+Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV at the LHC.
3. The final state spectra at the intermediate p_T largely depend on the hadronic re-scattering.
   → **Energy loss in the hadronic phase needs to be taken into account for understanding of jet-medium interaction.**

References

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