Study of the azimuthal asymmetry in heavy ion collisions combining initial state momentum orientation and final state collective effects

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Content

Main motivations

- Investigate particle production using high energy pQCD approaches;
- Experimental accuracy of measurements has shown a fantastic increasing due to largely improved statistics and detection techniques at the LHC;
- Investigate collective behavior due medium-induced effects which are especially pronounced in heavy-ion collisions;

Main observables to be adressed in the study

- Main goal: Describe both the nuclear modification factor R_{AA} and elliptic flow v_2 in nucleus-nucleus (AA) collisions..

Nuclear modification factor

$$R_{AA} = \frac{d^3 N_{AA}}{d\vec{p}^3} / \langle T_{AA} \rangle \frac{d^3 \sigma_{pp}}{d\vec{p}^3}$$

$\langle T_{AA} \rangle$ is the average value of the nuclear overlapping function

Collective flow coefficients

$$v_n(p_T) \equiv \frac{\int_0^{2\pi} d\phi \cos(n\phi) \frac{d^3\sigma(AA \to hX)}{dy d^2\vec{p}_T}}{\int_0^{2\pi} d\phi \frac{d^3\sigma(AA \to hX)}{dy d^2\vec{p}_T}}$$

Collective effects: Relaxation Time Approximation (RTA)

- RTA of the Boltzmann Transport Equation (BTE) is an effective model where the collisional term has the form $C[f] = -(f - f_{eq})/t_r$.
- The Boltzmann local equilibrium distribution, f_{eq}, for the distribution of particles, f, is typified by a freeze-out temperature T_{eq} and t_r is the relaxation time.
- t_r is the time for a non-equilibrium system to reach the equilibrium whereas t_f is the freeze-out time parameter.
- Given $C[f]$, the BTE is then solved with the following initial conditions, $f(t = 0) = f_{in}$ and $f(t = t_f) = f_{fin}$.

RTA approximation

$$f_{fin} = f_{eq} + (f_{in} - f_{eq})\, e^{-\frac{t_f}{t_r}}$$

Multiplicity of particles and the RTA

- The final p_{T_h}-spectrum can be obtained from RTA-BTE approach [with $\vec{p}_{T_h} = (\phi_p, p_{T_h})$] in the following way:

Particle multiplicity in the RTA

$$\frac{dN_{AA}}{p_{T_h} dp_{T_h} dy d\phi_p} = e^{-t_f/t_r} f_{in}(\phi_p) + (1 - e^{-t_f/t_r}) f_{eq}(\phi_p)$$

- The initial hard distribution f_{in} will be obtained from perturbative QCD and evolves until reach the equilibrium distribution f_{eq} obtained from Blast-Wave model.
- The ratio t_f/t_r is fitted for each centrality class.

Initial distribution of particles in high energy factorization

- Inclusive cross section for producing identified particles is given in terms of the convolution of the unintegrated gluon distribution (UGD), $\phi(x, k_T)$, for both target and projectile and the gluon-gluon sub-process cross section.

Gluon production cross section

$$E\frac{d^3N(b)}{dp^3}^{AB\to g+X} = \frac{2\alpha_s}{C_F}\frac{1}{p_T^2}\int d^2\vec{s}\, d^2\vec{k}_T\, \phi_A(x_A, k_T^2, \vec{s}) \times \phi_B(x_B, (\vec{p}_T - \vec{k}_T)^2, \vec{b} - \vec{s}).$$

- p_T is transverse momentum of the produced gluon and x_A and x_B are the momentum fraction in the nucleus A and B: $x_A = \frac{p_T}{\sqrt{s}}e^y$, $x_B = \frac{p_T}{\sqrt{s}}e^{-y}$.

Nuclear effects in the initial distribution

- The nuclear UGD may be obtained from the nucleon distribution by using the Glauber-Mueller approach for multiple scattering.
- The color dipole scattering matrix, S_{dA}, is obtained from the cross section for dipole scattering off a proton, σ_{dip} (many parametrizations available in literature).

Nuclear dipole scattering matrix

$$S_{dA}(x,r,b) = e^{-\frac{1}{2}T_A(b)\sigma_{dip}(x,r)}, \quad \int d^2b\, T_A(b) = A$$

- $T_A(b)$ is the nuclear thickness function (Woods-Saxon).

Phenomenology: MPM model for UGDs

- The nuclear UGD is obtained from a Fourier-Bessel transform of the nuclear dipole scattering amplitude.

Nuclear UGD

$$\phi_A(x,k_T^2,b) = \frac{3}{4\pi^2\alpha_s} k_T^2 \nabla_k^2 \mathcal{H}_0 \left\{ \frac{1 - S_{dA}(x,r,b)}{r^2} \right\}$$

$$\mathcal{H}_0\{f(r)\} = \int r dr J_0(k_T r) f(r)$$

- $\mathcal{H}_0$ the Hankel transform of order zero.
- Here, we use Moriggi-Peccini-Machado (MPM) model with parameters from Ref. L. S. Moriggi, G. M. Peccini and M. V. T. Machado, Phys. Rev. D **102**, 034016 (2020), which presents geometric scaling property.

MPM model for proton target

- Here, UGD does not depend separately on $k_\perp$ and x but on the ratio $\tau = k_\perp^2/Q_s^2$, where Q_s is the saturation scale.

MPM parametrization for protons

$$\phi_{MPM}(x, k_\perp^2) = \frac{3\,\sigma_0}{4\pi^2}\tau\frac{(1+\delta n)}{(1+\tau)^{(2+\delta n)}}$$

- where $Q_s^2(x) = \left(\frac{x_0}{x}\right)^{0.33}\ GeV^2$ and $\delta n = a\tau^b$.
- Model describes simultaneously ep DIS data and spectra of charged particles in pp collisions.
- The corresponding dipole cross section for protons is $\sigma_{dip}(\tau_r) = \sigma_0\left(1 - \frac{2(\frac{\tau_r}{2})^{\xi}K_{\xi}(\tau_r)}{\Gamma(\xi)}\right)$ in which $\tau_r = rQ_s(x)$ is the scaling variable in the position space and $\xi = 1 + \delta n$.

Including dipole-orientation on σ_{dip}

- An azimuthal asymmetry in pp and pA can be generated if there is a dipole orientation[1] described by the transverse size $\vec{r}$ regarding the impact parameter $\vec{b}$ (the angle between them is denoted by ϕ_{rb}).
- The evaluation of the amplitude taking into account the dipole orientation is not an easy task (very few models).
- Simple way to incorporate this effect from a phenomenological perspective, by angular modulation: substitution $r^2 \to r^2\,[1 + a_r \cos(2\phi_{rb})]$ in the $S_A(x,r,b)$.
- The parameter a_r will be fitted from the experimental data of each centrality class.

[1] Edmond Iancu, Amir H. Rezaeian, Phys.Rev.D 95 (2017) 9, 094003

Initial particle distribution incorporating dipole orientation

- The cross section for inclusive gluon production with transverse momentum p_T in the high energy factorization formalism, can be described with the dipole scattering matrix $S_A(x,\vec{r},\vec{b})$ in the position space.
- Corresponding initial particle distribution is given by:

Initial distribution

$$
\begin{aligned}
f_{in}(\vec{p}_T,\phi_p) &= \frac{1}{p_T^2}\frac{2C_F}{(2\pi)^4\alpha_s}\int d^2b d^2r e^{i\vec{p}_T\cdot\vec{r}}\nabla_r^2 S_A(x_1,r,\vec{b}) \\
&\times \quad \nabla_r^2 S_A(x_2,r,\vec{b}'), \quad \vec{b}' = \vec{b}-\vec{B}
\end{aligned}
$$

- $x_{1,2} = p_T e^{\pm y}/\sqrt{s}$ and ∇_r^2 is the Laplacian with respect to r.

Equilibrium distribution from Boltzmann-Gibbs-Blast-Wave (BGBW) model

- BGBW is hydro-inspired (freeze-out) model describing collective flow and subsequent hydrodynamic expansion.
- Popular model of Schnedermann-Sollfrank-Heinz allows to obtain the rapidity and transverse-momentum distribution of the emitted particles in the form:

Equilibrium distribution within BGBW model

$$f_{eq}(\phi_p) \propto m_{T_h} \int_0^{R_0} r dr \int_0^{2\pi} d\phi_s K_1 \left(\frac{m_{T_h}}{T_{eq}} \cosh(\rho(\phi_s)) \right)$$

$$\exp\left(\frac{p_{T_h}}{T_{eq}} \sinh(\rho(\phi_s)) \cos(\phi_s - \phi_p) \right) [1 + 2 s_2 \cos(2\phi_s)]$$

Equilibrium distribution from BGBW model - defining quantities and parameters

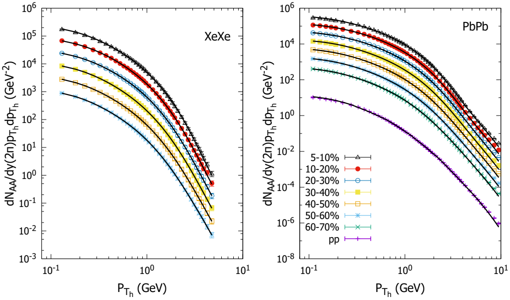
- The azimuthal asymmetry can be parameterized by modulation in the velocity profile $\rho = \rho(\phi_s)$, where ϕ_s is the azimuthal angle in relation to reaction plane.

Modulation in the velocity profile

$$\rho = \rho_0 + \rho_a \cos(2\phi_s)$$
$$\rho_a \Longrightarrow \text{anisotropy parameter in the flow}$$

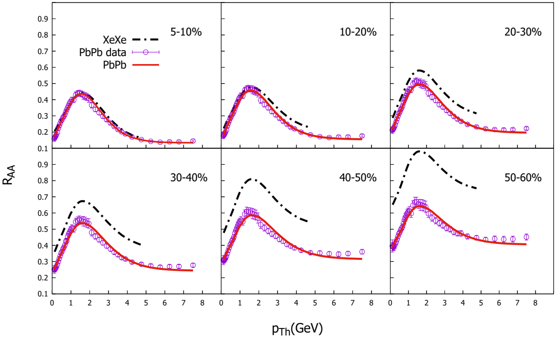
- Velocity profile $\rho_0 = tanh^{-1}(\beta_r)$, with $\beta_r = \beta_s(\xi)^n$, determined by the surface expansion velocity β_s.
- β_r is the radial flow with $\xi = r/R_0$ being the ratio between the radial distance of the transverse plane and the fireball radius R_0. It is assumed a linear velocity profile ($n = 1$).

Results - Multiplicity of $\pi^{\pm}$ produced in PbPb($\sqrt{s} = 5.02$ TeV) and XeXe collisions ($\sqrt{s} = 5.44$ TeV)



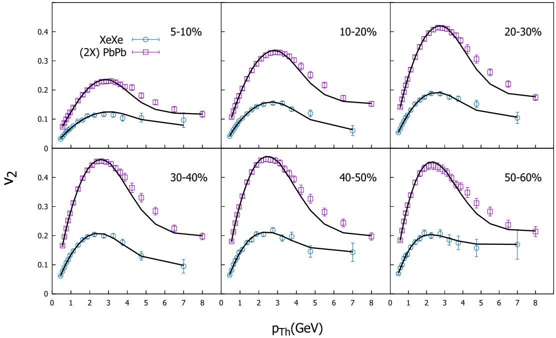
- Experimental data from Alice.
- Pion spectrum pp colisions.

Results - Nuclear modification factors for PbPb and XeXe collisions at the LHC



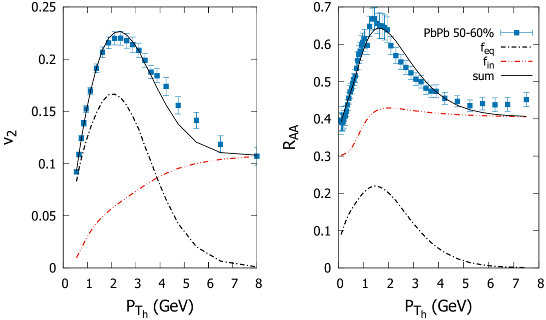
- Experimental data from Alice for $\pi^{\pm}$.
- For central collisions, $R_{AA}^{PbPb} \sim R_{AA}^{XeXe}$.
- The reason is that both uses same t_f/t_r ration, therefore both systems will develop in similar time.
- At peripheral collisions, this ration is very small for XeXe case.

Results - Elliptic flow coefficient $v_2(p_{T_h})$ for XeXe and PbPb collisions



- Experimental data from Alice.
- We have better experimental data agreement for v_2^{XeXe} than v_2^{PbPb}, due the smaller value of χ^2 for PbPb case.
- The value of v_2 is greater in peripheral collisions.
- For all classes, the p_T dependence is approximatelly linear at low values of transverse momentum.

Results - Analysis for the f_{in} and f_{eq} contributions for the final asymmetry v_2 and nuclear modification R_{AA}



- The contribuition distribuition terms $f_{in}(p_T) \times e^{-t_f/t_r}$ and $f_{eq} \times (1 - e^{t_f/t_r})$ is shown.
- Maximum at $p_{T_h} \sim 2$ GeV.
- After that, the curves decreases, indicating produced particles distribuition predominace in the collision inital stages.
- The momentum azimuthal assimetry produced by the inital collision is generated by large p_T hadrons, while equillibrium assimetry takes place in small p_T.

Main conclusions

- We make use of initial state production mechanism uses dipole scattering matrix in the position space, where an initial asymmetry has been added.
- Moreover, collective effects are described by BGBW distribution, leading to an increasing of the momentum asymmetry for small p_{T_h}.
- One advantage of the present parameterization is that it allow us to describe an interface between different mechanisms of hadron production providing a good description of both soft and hard contributions.

The end ...

Thank you!