"Imprints of fluctuating proton shapes on flow in proton–lead collisions at the LHC"

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Imprints of fluctuating proton shapes on flow in proton-lead collisions at the LHC

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Results for particle production in $\sqrt{s} = 5.02$ TeV p+Pb collisions at the Large Hadron Collider within a combined classical Yang-Mills and relativistic viscous hydrodynamic calculation are presented. We emphasize the importance of sub-nucleon scale fluctuations in the proton projectile to describe the experimentally observed azimuthal harmonic coefficients v_n, demonstrating their sensitivity to the proton shape. We stress that the proton shape and its fluctuations are not free parameters in our calculations. Instead, they have been constrained using experimental data from HERA on exclusive vector meson production. Including temperature dependent shear and bulk viscosities, as well as UrQMD for the low temperature regime, we present results for mean transverse momenta, harmonic flow coefficients for charged hadrons and identified particles, as well as Hanbury-Brown-Twiss radii.

Introduction

- In heavy ion collisions
  - Strong final state interaction produce azimuthaly anisotropic particle distributions that are strongly correlated with the initial event geometry.
- In collisions of protons with heavy ions
  - Observation of similar azimuthal anisotropies.
  - Origin of these anisotropies - the hydrodynamic response of the produced medium to the initial shape of the interaction region in the transverse plane.

Introduction

- The initial state and early time evolution is described with IP-Glasma model.
- The field energy-momentum tensor from IP-Glasma model provides the initialization for the relativistic viscous hydrodynamics simulation MUSIC.
- Spatial and momentum distributions of all particles are determined and fed into the hadronic cascade UrQMD.

Introduction

- Hydrodynamic evolution of IP-Glasma initial states in small systems has been explored before: $\rightarrow$ Measured harmonic flow coefficients in p+Pb collisions were significantly underestimated. $\rightarrow$ The reason: Underestimation of subnucleonic fluctuations in the IP-Glasma model.
- Yang-Mills framework - the interaction region follows closely the shape of the small projectile.
- DIS data from HERA were used to constrain parameters of IP-Glasma model
- Data from HERA on diffractive J/ψ production constrain the degree of fluctuations of the gluon distribution in the proton. $\rightarrow$ Model using three gluonic hot spots.

Fluctuating proton in the IP-Glasma initial state

- The original IP-Glasma model - 2D-Gaussian spatial shape for all nucleons lead to underestimation $\rightarrow$ Three gluonic hotspots:
  - Positions in transverse plane - Gaussian distributed
  - Density of each hot spot in transverse plane - Gaussian
- Because of the shorter lifetime in small systems, the initial viscous stress tensor from the classical Yang-Mills simulation plays more important role than in heavy-ion collisions.

$$\pi^{\mu\nu} = T^{\mu\nu}_{\mathrm{CYM}} - \frac{4}{3}\varepsilon u^\mu u^\nu + \frac{\varepsilon}{3} g^{\mu\nu} \,.$$

- The full energy-momentum tensor is included.

Hydrodynamics and hadronic cascade

- In the hydrodynamic simulation a temperature dependent shear viscosity to entropy ratio is employed:

$$(\eta/s)(T) = (\eta/s)_{\min} + a(T_c - T)\theta(T_c - T) + b(T - T_c)\theta(T - T_c)\,, \qquad (2)$$

where $a = 15\,\mathrm{GeV}^{-1}$, $b = 1\,\mathrm{GeV}^{-1}$, and $(\eta/s)_{\min} = 0.08$ at a temperature of 166 MeV. We note that both the

- Larger viscosity values were needed:
    - Different initial state model is used.
    - The parameters for the initial proton shape were determined at $x \approx 10^{-3}$, typically $x \approx 2 \cdot 10^{-4}$.
- Effective shear viscosity η/s =0.2.
- The bulk viscosity ζ/s is essential to reproduce $\langle p_T \rangle$ in small systems.
- Particles are sampled at $T_{switch} = 155$ MeV.

Results

- Without bulk viscosity, the pion $\langle p_T \rangle$ is overestimated the most by $\sim 50\%$.

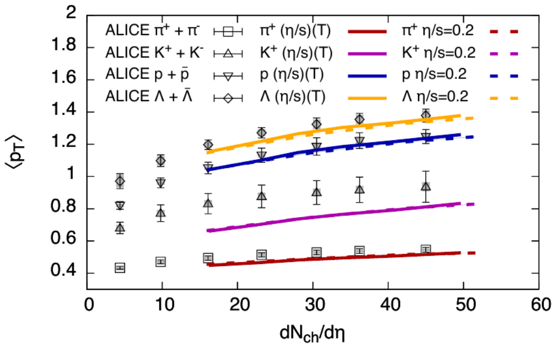

Figure: The mean transverse momentum $< p_T >$ of identified particles as a function of number of charged hadrons per pseudo-rapidity interval around mid-rapidity compared to experimental data from the ALICE collaboration.

Results

Having established the agreement with measured transverse momentum spectra, which is almost entirely determined by $\langle p_T \rangle$, we now present results for v_n from two-particle correlations. To compute $v_n\{2\}$ using particle samples from UrQMD, we first construct the flow vector $Q_n = \sum_i w_i e^{in\phi_i}$, where the sum i runs over all particles of interest with $0.3\,\text{GeV} < p_T < 3\,\text{GeV}$ (when comparing to CMS results), and the weights are set to $w_i = 1$. The two particle cumulant $v_n\{2\}$ is then computed as

$$\boxed{v_n\{2\} = \frac{1}{\langle N(N-1)\rangle_{\text{ev}}} \left(\langle \text{Re}\{Q_n Q_n^*\} - N\rangle_{\text{ev}}\right),} \quad (3)$$

where N is the number of particles included in the calculation of Q_n and $\langle\cdot\rangle_{\text{ev}}$ is the average over events. In practice, we sample the hypersurface from each hydrodynamic event 5000 times and run UrQMD for each of these particle configurations. For the evaluation of $v_n\{2\}$ we combine the UrQMD output of all 5000 runs to collect enough statistics and suppress short range correlations from e.g. resonance decays. The latter effect is desired because the measurement uses a large pseudo-rapidity gap of $|\Delta\eta| > 2$ between the two particles, also eliminating short range correlations.

Results

- Including subnucleonic fluctuations increases flow harmonics in p+Pb collisions by a factor of ∼5 compared to previous calculations using round nucleons.
- Earlier switching to hydrodynamics leads to an increased anisotropic flow.
- For lower multiplicities, initial state momentum correlations are expected.

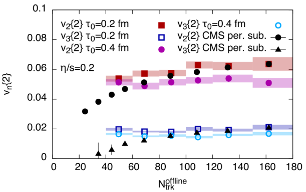

Figure: The $v_2\{2\}$ and $v_3\{2\}$ of charged hadrons as a function of the number of tracks for $\eta/s(T)$ using $\tau_0 = 0.2$ fm and $\tau_0 = 0.4$ fm, compared to experimetal data from CMS Collaboration with peripheral events subtracted.

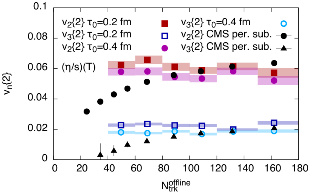

Figure: The $v_2\{2\}$ and $v_3\{2\}$ of charged hadrons as a function of the number of tracks for $\eta/s = 0.2$ using $\tau_0 = 0.2$ fm and $\tau_0 = 0.4$ fm, compared to experimetal data from CMS Collaboration with peripheral events subtracted.

Results

- Reference bin for the second particle is $1 < p_T < 3$ GeV

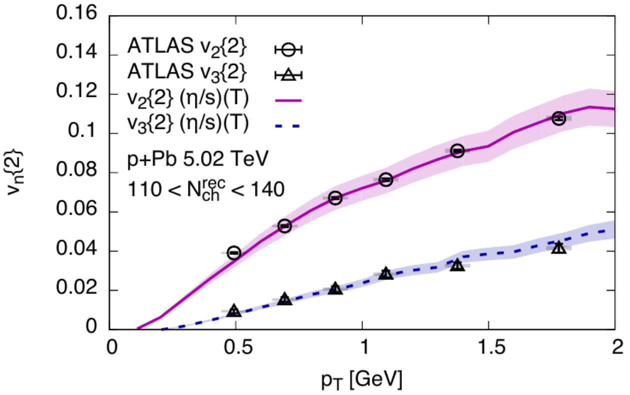

Figure: The $v_2\{2\}$ and $v_3\{2\}$ of charged hadrons as a function of transverse momentum p_T in ine centrality class corresponding to $110 \leq N_{ch}^{rec} < 140$ for $\eta/s(T)$, compared to data from ATLAS Collaboration.

Results

- The results demonstrate the mass ordering of v_2 is quantitatively reproduced.

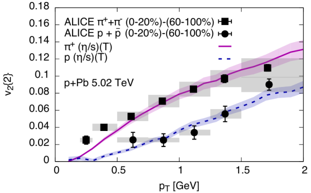

Figure: The $v_2\{2\}$ of protons and pions as a function of transverse momentum p_T for 0–20% central events corresponding to $dN_{ch}/d\eta > 2\langle dN_{ch}/d\eta\rangle$, compared to data from ALICE Collaboration.

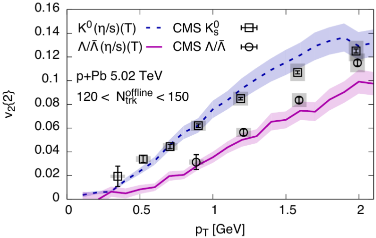

Figure: The $v_2\{2\}$ of Λ baryons and K_S^0 as a function of transverse momentum p_T for $120 < N_{trk}^{offline} < 150$, compared to data from CMS Collaboration.

Results–HBT radii

- UrQMD results that include hadronic rescattering and independent of UrQMD that includes only resonance decays are used.
- For $k_T = (p_T^1 + p_T^2)/2$: two-particle correlation function:

$$\boxed{C(\mathbf{q}) = 1 + \frac{\frac{1}{\langle N_{\rm pair}\rangle}\langle\sum_{ij}\cos(q_{ij}\cdot x_{ij})\rangle}{\frac{1}{\langle N_{\rm mixpair}\rangle}\langle N_{\rm mixpair}(q)\rangle},} \qquad (4)$$

where ij runs over all particle pairs (i,j) within the $k_T = |\mathbf{k}_T|$ bin, and $q_{ij}^\mu = p_i^\mu - p_j^\mu$ and $x_{ij}^\mu = x_i^\mu - x_j^\mu$, with x_i^μ the space-time four vector of the last interaction point of particle i. $\langle N_{\rm pair}\rangle$ is the average total number of all pairs from single events, $\langle N_{\rm mixpair}\rangle$ the average total number of pairs from different (hydrodynamic) events, and $\langle N_{\rm mixpair}(q)\rangle$ is the average number of pairs from different events in the considered q-range. For this analysis we also perform many UrQMD runs for a single hydrodynamic event. This results in values of $\langle N_{\rm pair}\rangle$ and $\langle N_{\rm mixpair}\rangle$ of the order of 10^8 per k_T bin.

- The two-pion HBT correlation function is fitted to the Pratt-Bertsch parametrization in LCMS.

Results–HBT radii

- Non-Gaussianity results in different HBT radii depending on the fit range.

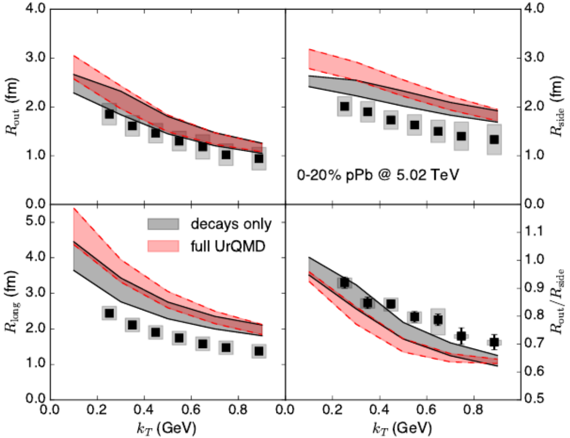

Figure: HBT radii extracted using a Gaussian fit to the correlation function in the case of resonance only and UrQMD with interactions, compared to data from ALICE Collaboration.

Thank you for your attention!