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LONGITUDINAL DYNAMICS OF HEAVY-ION COLLISIONS AT BEAM ENERGY SCAN

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QCD PHASE DIAGRAM TRAJECTORIES

- **Starting points:** initial baryon density
- **Trajectory:** hydrodynamic evolution
- **Endpoints:** final baryon density
The measurements indicate longitudinal inhomogeneity at the beam energy scan; it’s essential to study the longitudinal dynamics;

Rapidity-dependent measurements are essential for constraining theoretical models: Charged particle multiplicity $\rightarrow$ entropy/energy density; net-proton yields $\rightarrow$ baryon density

LONGITUDINAL DYNAMICS

- initial energy deposition
- initial baryon stopping
- longitudinal pressure gradient \(\rightarrow\) longitudinal flow & expansion
- baryon density gradient \(\rightarrow\) baryon diffusion (hydro transport)
- rapidity-dependent particle distributions
Boost invariance is strongly broken, especially at forward-/backward rapidities;

- Particles produced at forward rapidities may be boosted from a smaller $\eta_s$. 

From the nucleon deceleration picture, the baryon density gets two peaks, naturally giving the double-humped net proton yields;

Both initial baryon stopping and diffusive transport can influence rapidity-dependent yields; probing initial baryon distribution is essential for constraining baryon diffusion.

Denicol et al, PRC 98, 034916 (2018)
\( \nu_1(y) \) of baryons is mainly driven by the asymmetric distribution of baryon density with respect to beam axis + transverse expansion;

The widely used baryon-stopping picture results in \( \nu_1(y) \) strongly overshooting the experimental measurements for protons at all beam energies.
A rapidity-independent “plateau” component in initial baryon profile & tilted baryon peaks describing the varying baryon stopping in the transverse plane
To explain the rapidity distributions of net proton yield and proton’s directed flow simultaneously, the plateau is favored;

- It helps to reduce baryons’ $v_1(y)$ while giving enough net proton yields around midrapidity.
At high beam energies with large beam rapidity, the plateau dominates and strongly reduces baryons’ $v_1(y)$.

Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018)

Initial baryon distribution: central plateau + tilted peaks

Transverse expansion + asymmetric distribution of baryon density along $x$ $\implies$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV
Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV

- Initial baryon distribution: central plateau + tilted peaks

- Transverse expansion + asymmetric distribution of baryon density along $x \implies$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV
Baryons get distributed in rapidity by deceleration of the incoming nucleons

Baryons get distributed in rapidity through string junction breaking

- Profound impact on understanding initial baryon distribution and energy loss
- How to differentiate “baryon deceleration” and “string junction breaking” in the initial baryon distribution?
TOTAL BARYON CHARGE AND TOTAL ENERGY

- Number of participants vs. total net baryon charge (obtained by fitting the net proton yields)
- The energy carried by incoming participant nucleons vs. total energy deposited in the fireball (obtained by fitting the charged particle multiplicity)
- Differentiate deflected spectators and hadrons emitted from the fireball; EPD can help!
Statistical thermal models have been applied to hadron yields for extracting freeze-out parameters around midrapidity [Andronic, Braun-Munzinger, Stachel and Winn, PLB 718 (2012) 80]
Extracting rapidity-dependent freeze-out parameters of boost-non-invariant inhomogeneous systems at beam energy scan

SUMMARY AND OUTLOOK

- Longitudinal pressure gradients drive flows faster than the Bjorken flow. Boost invariance is strongly broken at beam energy scan, especially at forward-/backward rapidities;

- A central plateau component in the initial baryon distribution is essential for simultaneously explaining characteristic features of $v_1(y)$ at various beam energies and net proton yields.

- Baryon distributions from incoming nucleon deceleration and string junction breaking correspond to different energy losses. Probing the total energy deposited in the fireball helps differentiate these two mechanisms.
THANK YOU!
**DIRECTED FLOW OF MESONS**

- $v_1(y)$ of mesons with **negative slope** at all beam energies; slope increases when beam energy decreases.

- Slight shift of energy density along $x$ (tilted structure) generates **sideward pressure gradient**

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**Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV**

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Starting from the same $T(\eta_s), \mu_B(\eta_s)$ profiles, the distributions get stretched in with a larger longitudinal flow $y$, which is more strongly for heavier species.
A smaller system size in $\eta_s$ can be compensated by a more considerable longitudinal boost and a larger volume.