Next-Generation Multi-Fluid Hydrodynamics for RHIC BES

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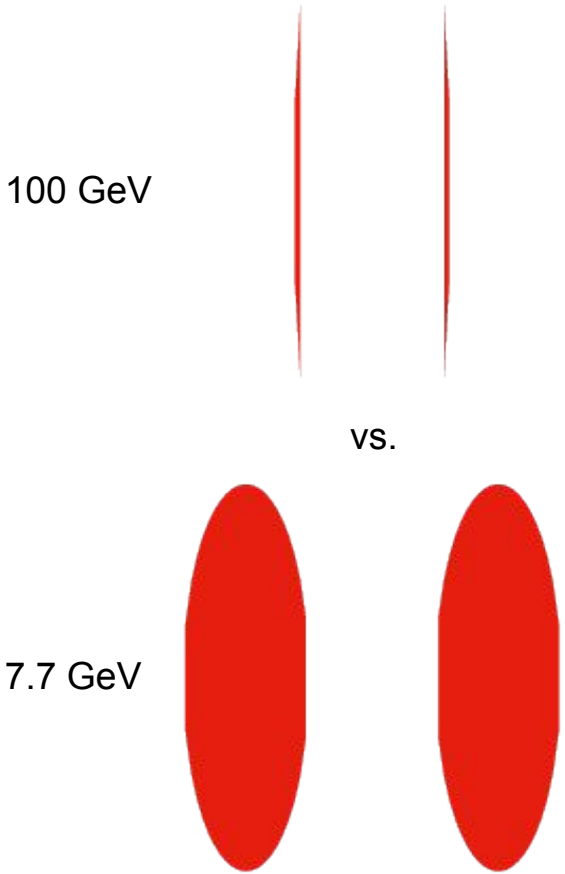
Motivation

- **Critical point** of the QCD phase diagram is assumed to be located at RHIC BES energy range
- Increasing number of heavy-ion experiments operating at energies from few to few tens of GeV
- Most current hydrodynamic models are not suitable for energies lower than 10 GeV

Challenges

- Non-zero baryon density
- No boost-invariant longitudinal expansion
- Weaker Lorentz contraction ⇒ longer inter-penetration (comparable with the lifetime of the fluid stage)

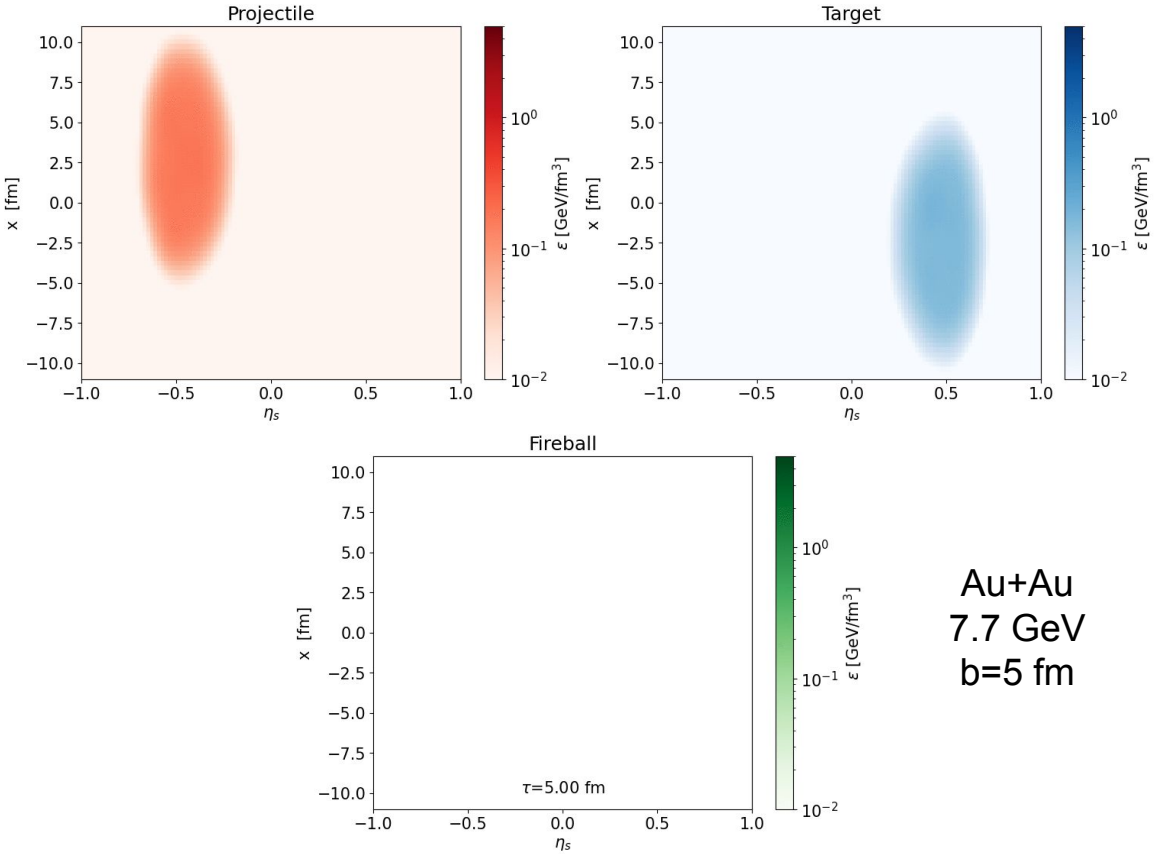


Multi-fluid Approach

- The initial stage is where the nuclear compression is happening
- Conventional hybrid models apply hydrodynamics only later, therefore there is less sensitivity to the EoS of dense baryon medium in a simulation
- Multi-fluid addresses this issue by applying an opposite assumption that the medium is in the fluid phase from the very beginning
- In the multi-fluid approach the initial non-equilibrium is represented as counter-flowing fluids

Physics Assumption of 3-fluid Hydrodynamics

- Incoming nuclei are represented by two blobs of liquid
- Third fluid is created from the friction of the incoming fluids
- The fluids co-exist in the same coordinate space



Au+Au
7.7 GeV
b=5 fm

Technical Description of the Model

- To account for event-by-event fluctuations, coordinates of nucleons inside the nuclei are sampled using Woods-Saxon formula
- Baryon stopping is modelled via mutual friction of the baryon fluids
- The energy-momentum from the friction is transferred to a third, net baryon-free fluid
- Hydrodynamic evolution via *vHLLE*
- Particlization via Cooper-Frye formula and particle sampling via *smash-hadron-sampler*
- Final-state interactions via transport code *SMASH*

$$\rho(x, y, z) = \frac{\rho_0}{1 + \exp\left(\frac{\sqrt{x^2+y^2+z^2}-R}{a}\right)}$$

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$$F_\alpha^\nu = \vartheta^2 \rho_{\mathrm{p}}^\xi \rho_{\mathrm{t}}^\xi m_N V_{\mathrm{rel}}^{\mathrm{pt}} \left[(u_\alpha^\nu - u_{\overline{\alpha}}^\nu)\sigma_P(s_{\mathrm{pt}}) + (u_{\mathrm{p}}^\nu + u_{\mathrm{t}}^\nu)\sigma_E(s_{\mathrm{pt}}) \right]$$

$$F_{\mathrm{f}\alpha}^\nu = \rho_\alpha^b \xi_{\mathrm{f}\alpha}(s_{\mathrm{f}\alpha}) V_{\mathrm{rel}}^{\mathrm{f}\alpha} \frac{T_{\mathrm{f}(eq)}^{0\nu}}{u_{\mathrm{f}}^0} \sigma_{tot}^{N\pi \to R}(s_{\mathrm{f}\alpha})$$

Friction in the quark-gluon phase is included!

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evolution of 3 fluids is solved in parallel using a modified vHLLE code

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We chose to have single particlization surface to avoid issue of treating mixture of fluid and particles

$$N = \int \frac{\mathrm{d}^3 p}{E_p} \int \mathrm{d}\Sigma_\mu(x) p^\mu f(p, T(x), \mu_i(x))$$

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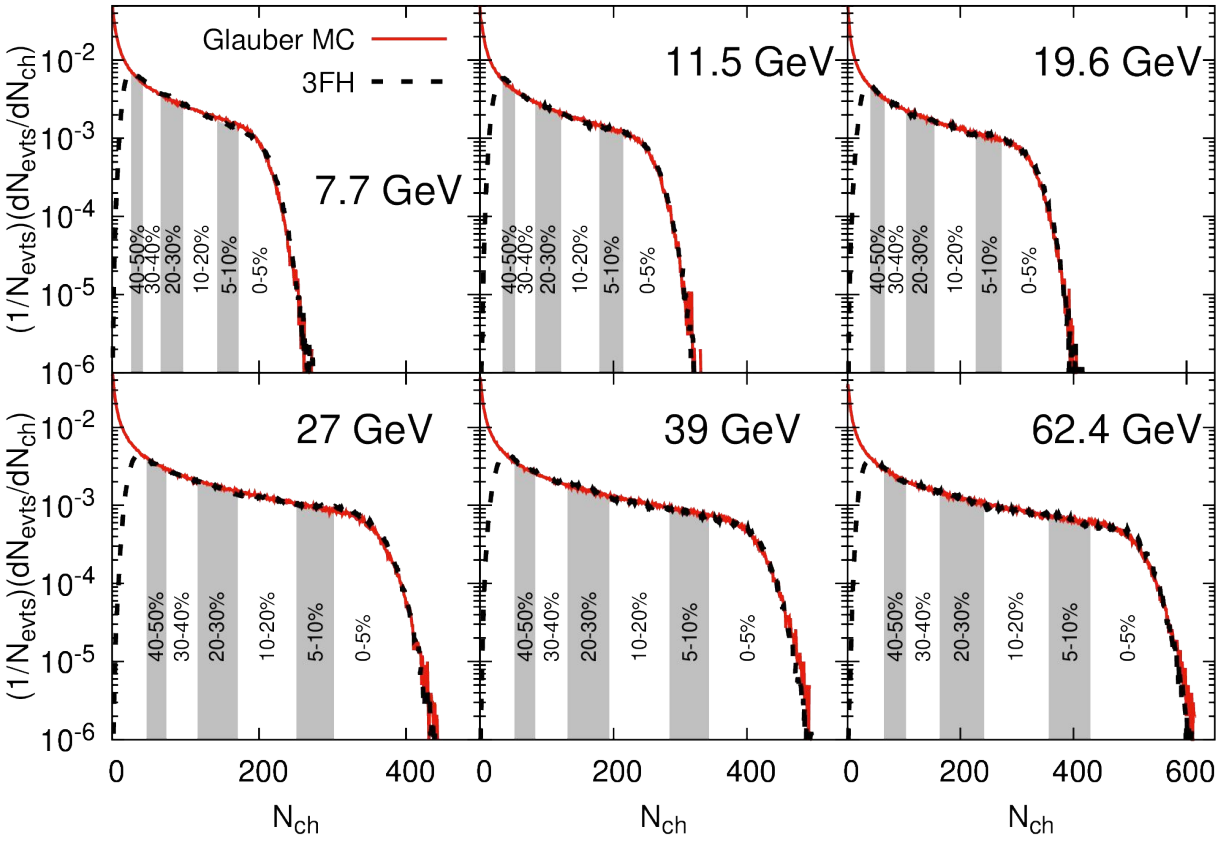
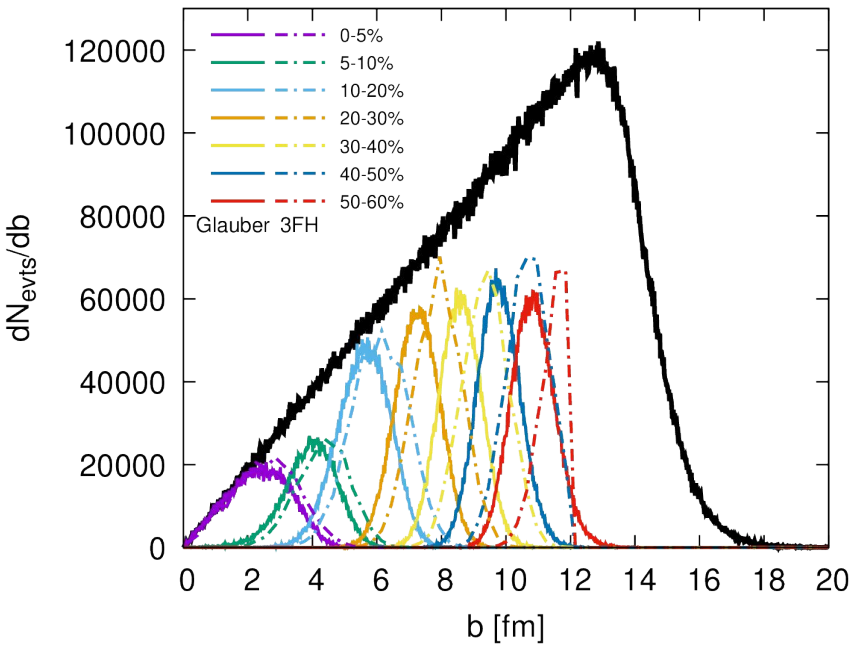
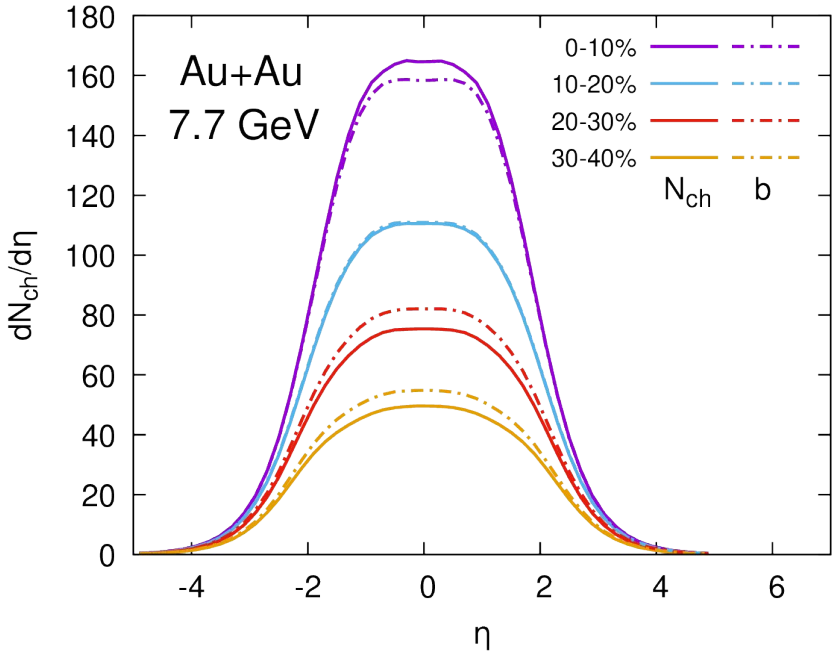
Centrality Determination

- Based on number of charged particles within |η|<0.5 (following STAR)
- Multiplicity distribution is fitted with Glauber Monte Carlo model to estimate missing peripheral collisions



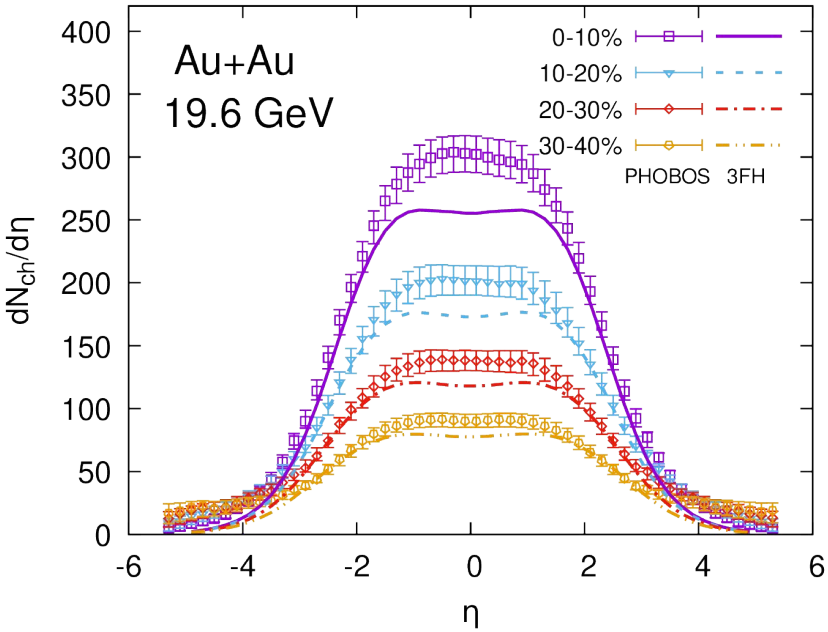
Centrality Determination - Impact Parameter from Glauber

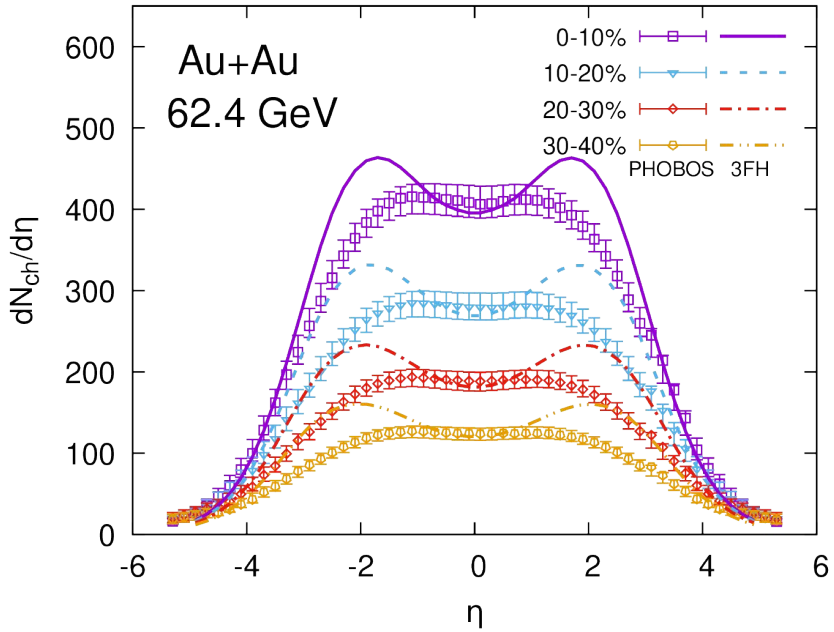




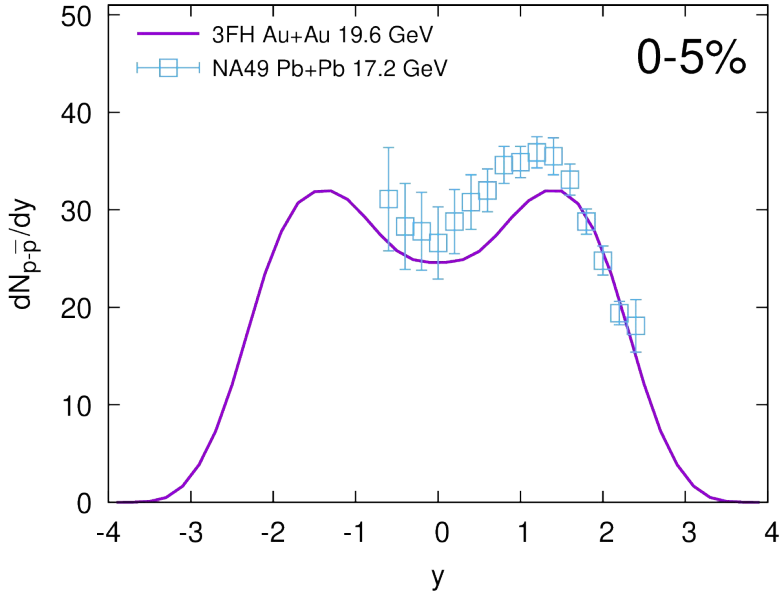
- Glauber model is used as standard for extracting impact parameter in experiments, however, our model predicts quite different impact parameter intervals

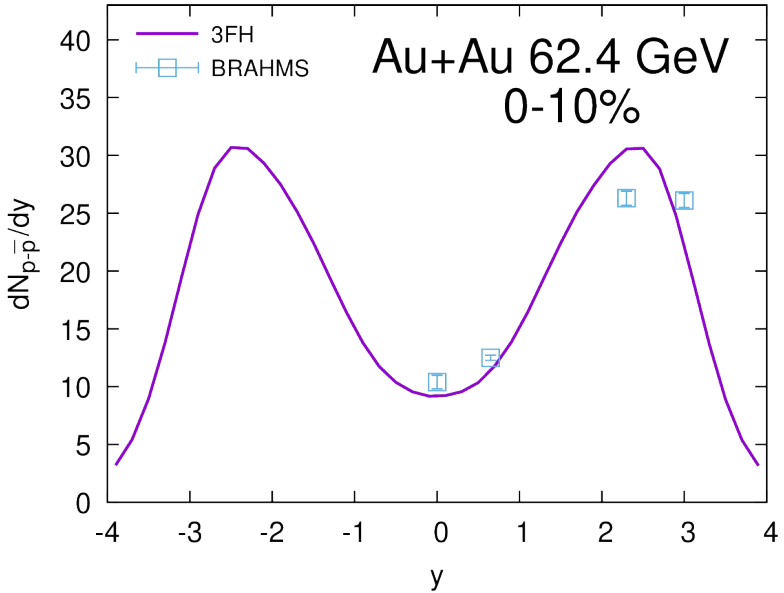
Pseudorapidity Distributions





Rapidity Distributions of Net-Protons

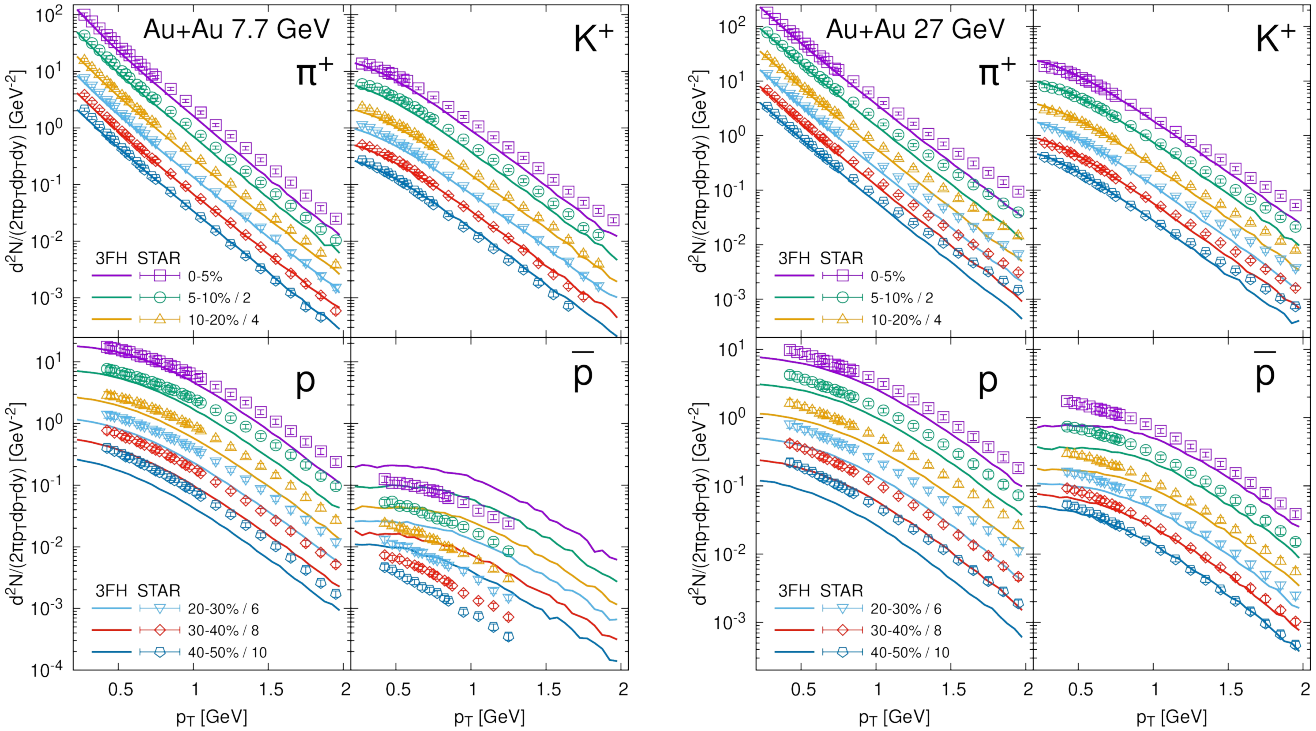




- Small difference due to comparison to different system and energy at 19.6GeV, otherwise good agreement with data ⇒ 3FH model yields correct baryon stopping

Transverse Momentum Spectra

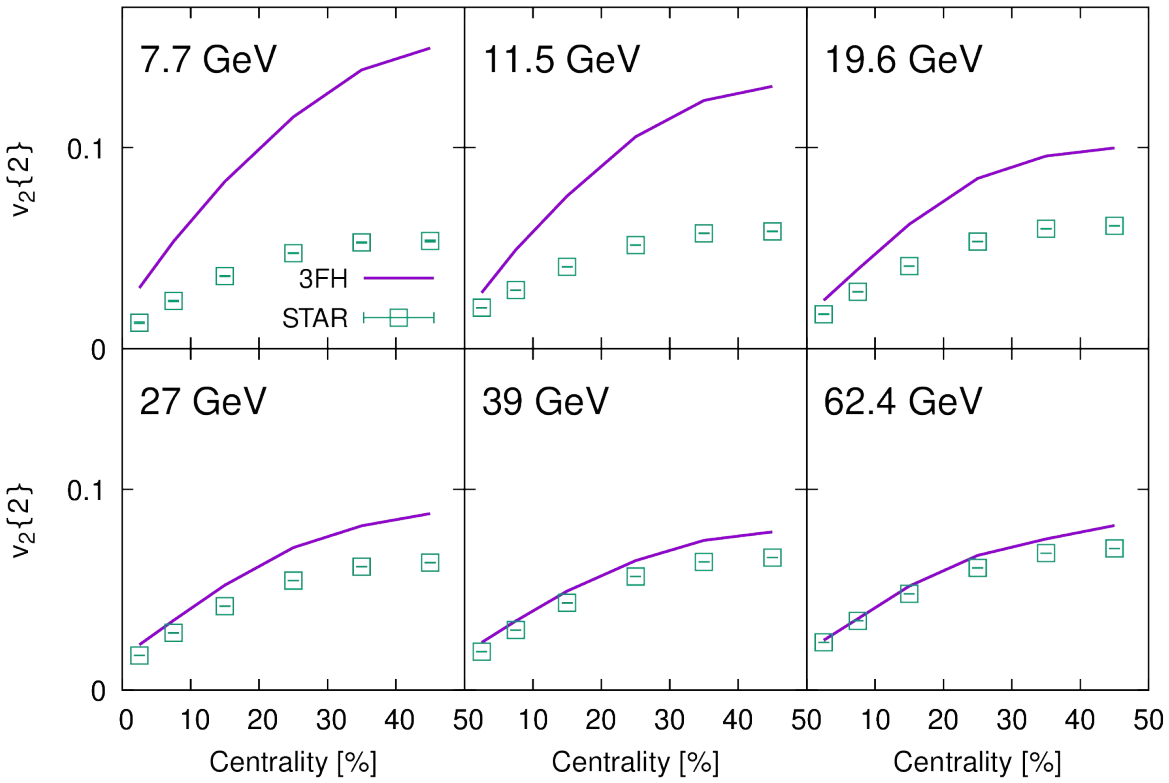
Although not all spectra reproduce data perfectly, the slope of the spectra is generally quite well reproduced ⇒ 3FH model yields correct strength of the transverse expansion



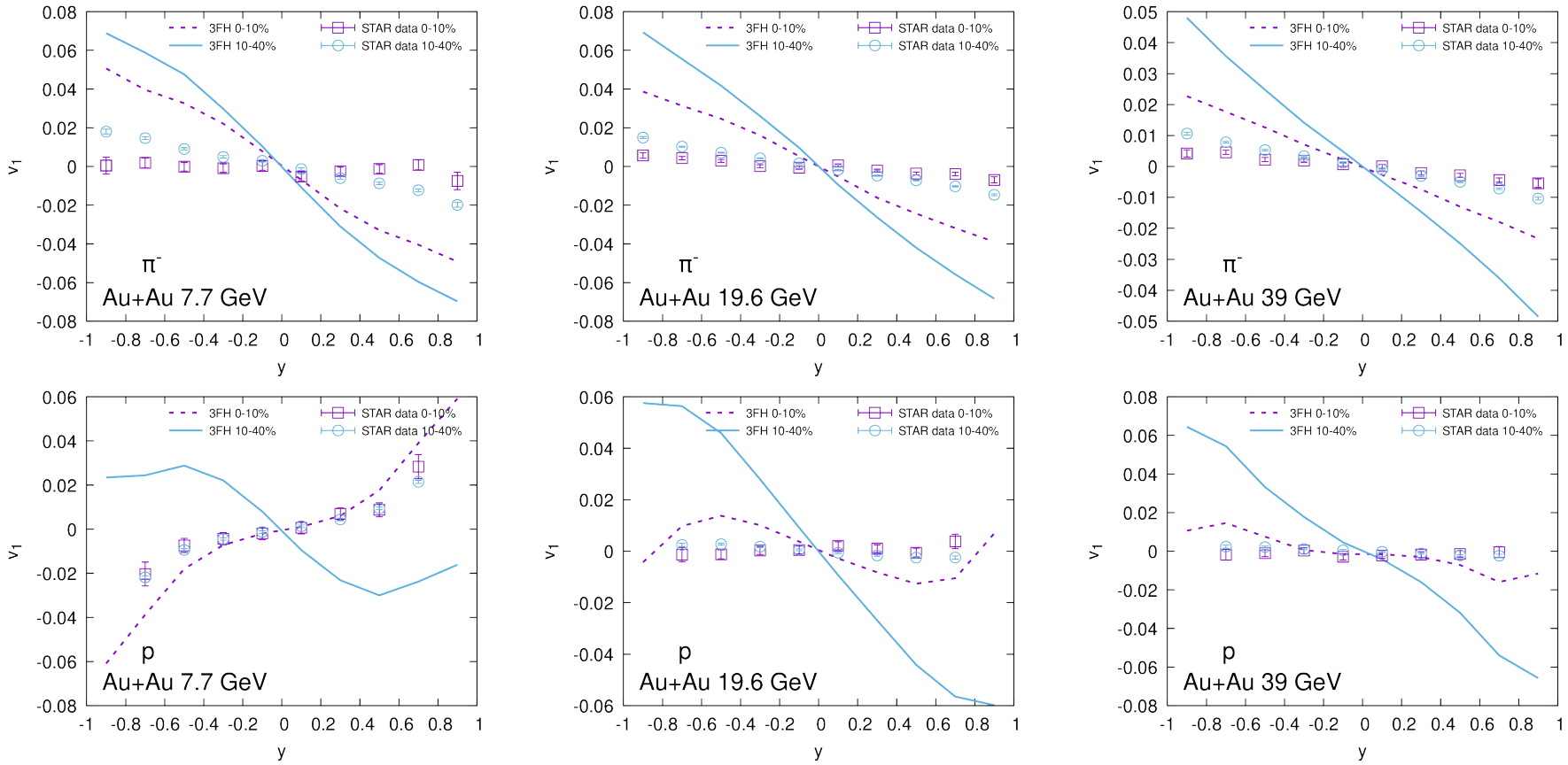
Elliptic Flow

- Flow is quite overestimated at the lowest energy, gets closer to data at higher energies

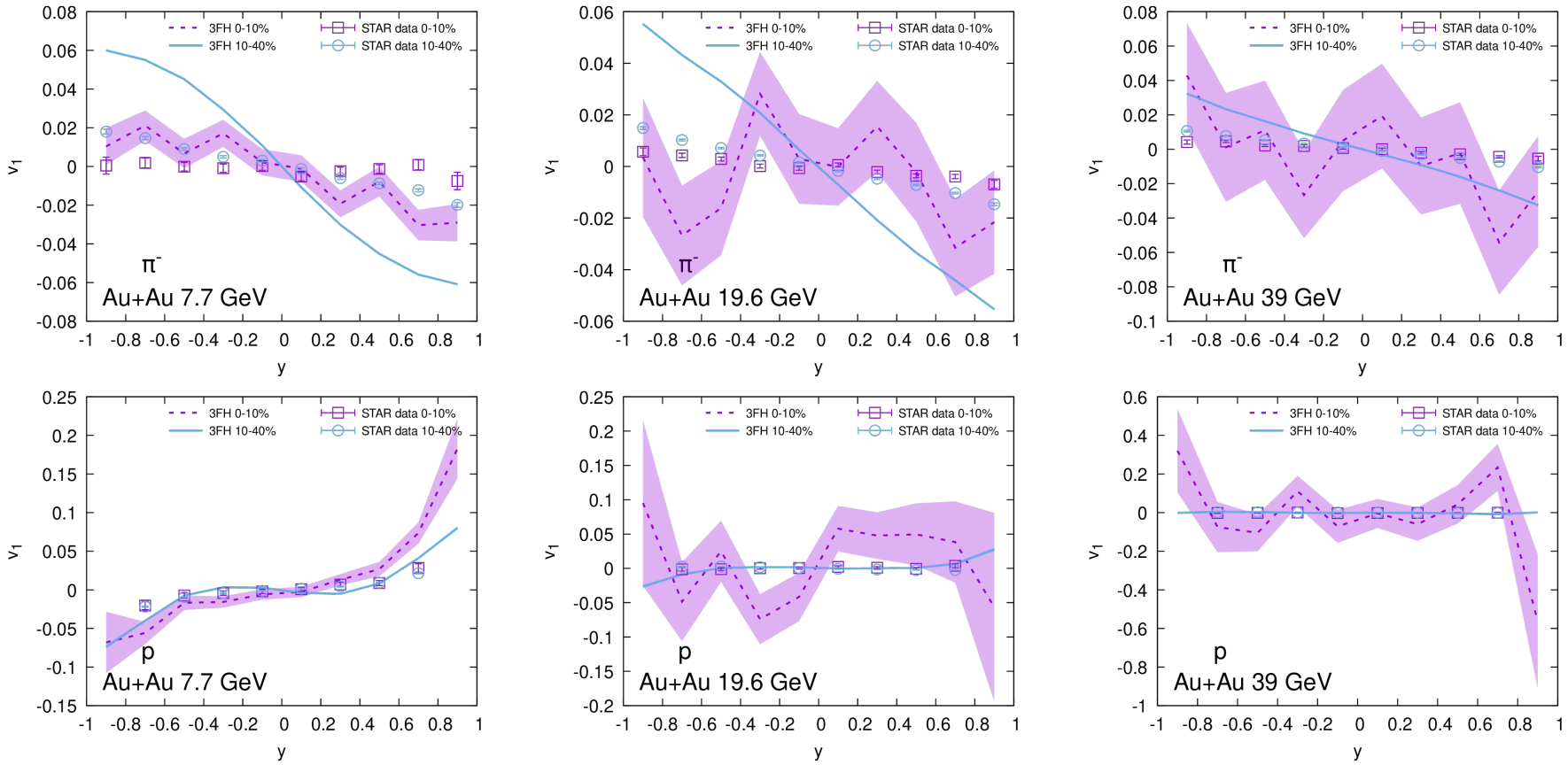
- This demonstrate missing viscosity in the model, which decreases elliptic flow, and it grows towards lower energies



Directed Flow



Directed Flow before Hadronic Rescatterings



Summary

- We developed a novel hybrid model designed for BES energies with:
  - 3-fluid hydrodynamics (in Milne coordinates)
  - fluctuating initial state
  - final-state hadronic cascade: SMASH
- Tuning parameters do not depend on collision energies
- Rapidity distributions and momentum spectra are well reproduced
- Flow is overestimated, indicating that the model lacks viscosity
- Future plans:
  - adding viscous corrections to the model
  - studying various equations of state within the model

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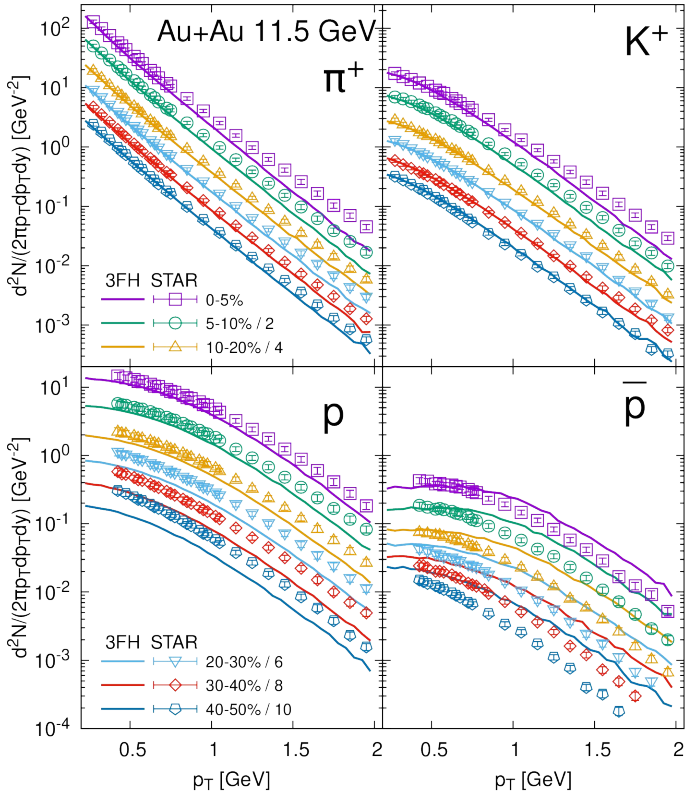
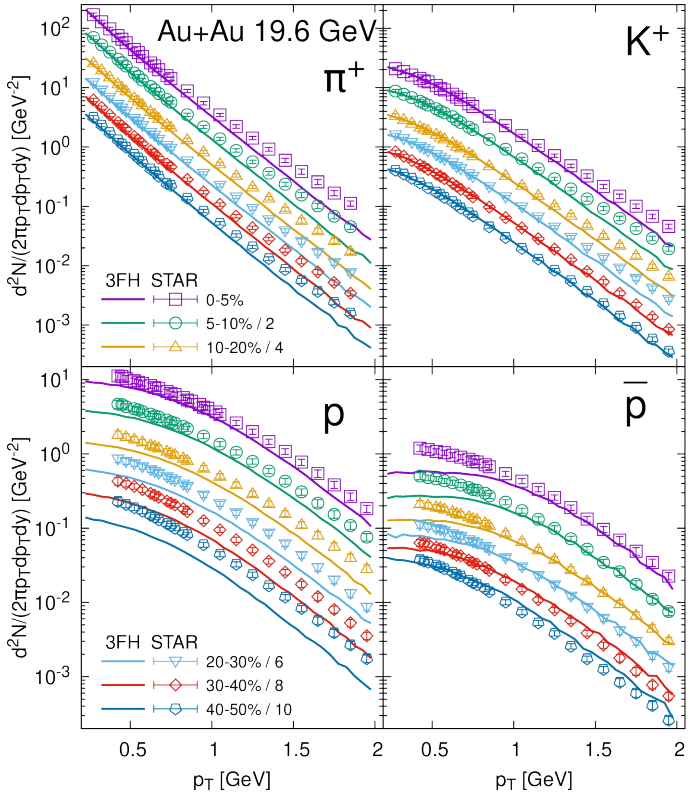
Backup slides

Transverse Momentum Spectra





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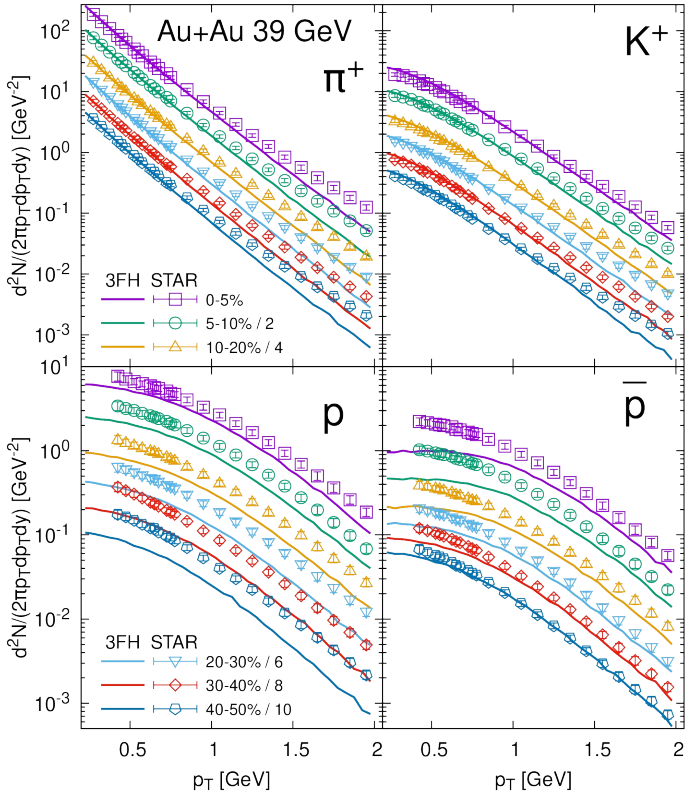

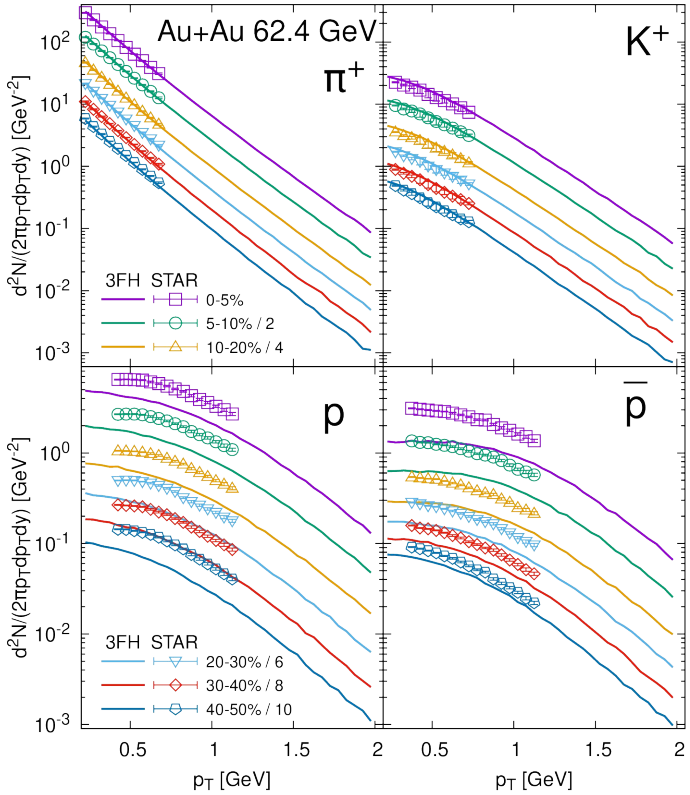

Elliptic Flow