

Anisotropic hydrodynamic modeling of heavy-ion collisions at LHC and RHIC

Mubarak Alqahtani

Imam Abdulrahman Bin Faisal University

Collaborators

D. Almaalol, M. Nopoush, R. Ryblewski, and M. Strickland

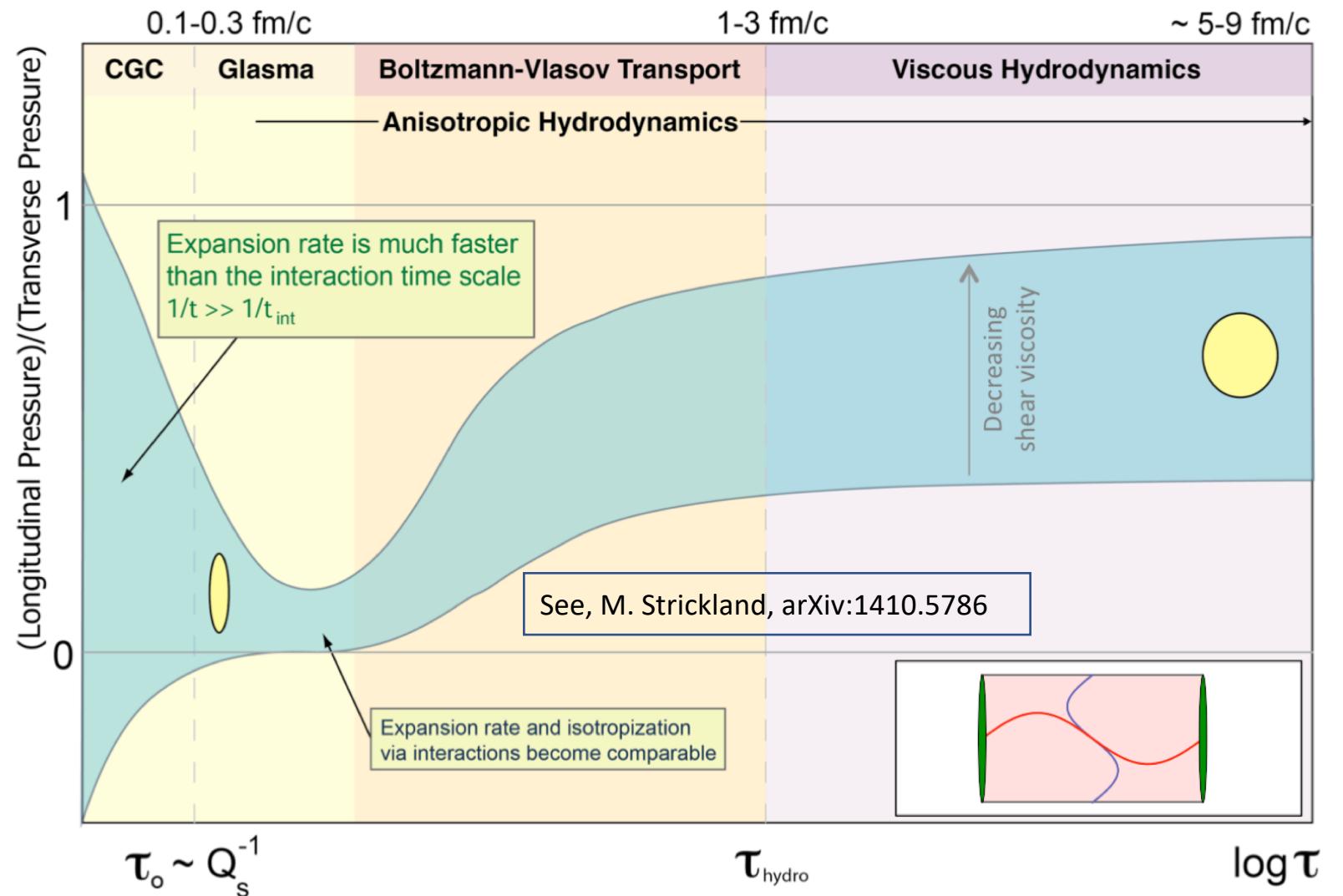
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Outline

- Motivation
- Brief introduction to anisotropic hydrodynamics (aHydro)
- Dynamical equations of quasiparticle anisotropic hydrodynamics (aHydroQP) (see our last review, arXiv:1712.03282)
- Phenomenological comparisons at:
 - LHC energies (2.76 TeV Pb-Pb collisions)
 - RHIC highest energies (200 GeV Au-Au collisions)
- Conclusions and outlook

QGP momentum anisotropy



The **QGP** is born into a state of rapid longitudinal expansion which drives the system **out of kinetic equilibrium**

Motivation of anisotropic hydrodynamics

- Viscous hydrodynamics is derived by linearization around an isotropic equilibrium distribution function

$$f(x, p) = f_{\text{eq}} \left(\frac{p^\mu u_\mu}{T} \right) [1 + \delta f(x, p)]$$

- However, QGP in the local rest frame is a highly anisotropic plasma.
- To take this into account in anisotropic hydrodynamics (aHydro), momentum-space anisotropies are included from the beginning (W. Florkowski and R. Ryblewski, arXiv:1007.0130 and M. Martinez and M. Strickland, arXiv:1007.0889)

$$f(x, p) = f_{\text{eq}} \left(\frac{\sqrt{p^\mu \Xi_{\mu\nu}(x) p^\nu}}{\lambda(x)} \right) + \delta f(x, p)$$

$$\Xi^{\mu\nu} = u^\mu u^\nu + \xi^{\mu\nu} - \Delta^{\mu\nu} \Phi$$

u^μ LRF four velocity

$\xi^{\mu\nu}$ the traceless anisotropy tensor

$\Delta^{\mu\nu}$ the transverse projector

Φ the degree of freedom associated with bulk

The dynamical equations for aHydroQP

- The dynamical equations can be found by taking moments of the Boltzmann equation

$$p^\mu \partial_\mu f + \frac{1}{2} \partial_i m^2 \partial_{(p)}^i f = -\mathcal{C}[f]$$

- A background field is introduced to guarantee thermodynamic consistency when including thermal mass $m(T)$, i.e., $S = \frac{\partial P}{\partial T}$.

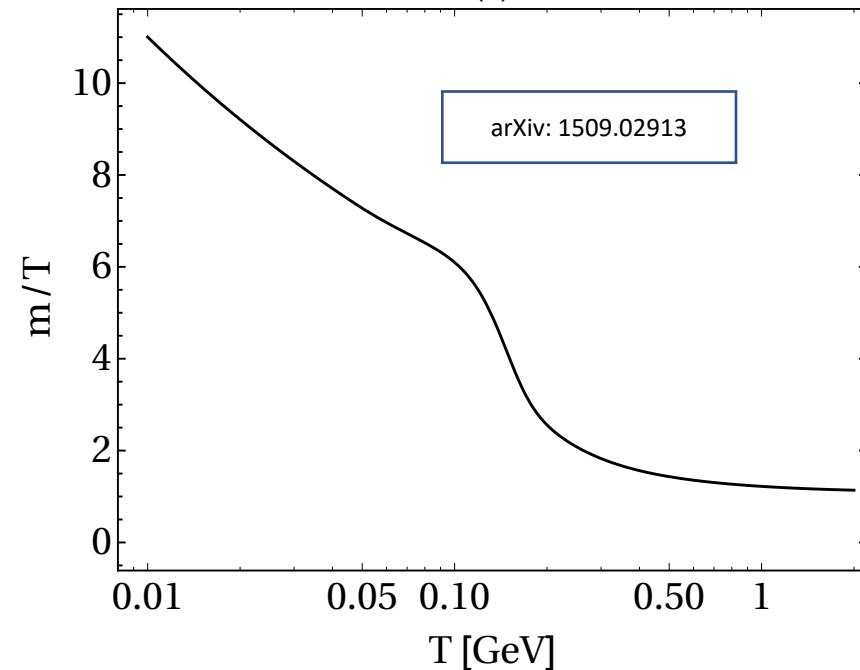
$$T^{\mu\nu} = T_{\text{kinetic}}^{\mu\nu} + g^{\mu\nu} B$$
$$\partial_\mu B = -\frac{1}{2} \partial_\mu m^2 \int dP f(x, p)$$

- Includes both shear and bulk viscosity.

- From lattice results $m(T)$ can be obtained

$$\mathcal{S}_{\text{eq}} = 4\pi \tilde{N} m^3 K_3(m/T)$$

(a)



Wuppertal-Budapest collaboration, arXiv:1007.2580

3+1d aHydroQP equations of motion

- In leading-order aHydro, we have eight degrees of freedom $\alpha_x, \alpha_y, \alpha_z, u_x, u_y, u_z, \lambda$, and T .
- We use 7 equations from the first and second moment and the matching condition to determine the effective temperature.

- First moment equations:

$$D_u \mathcal{E} + \mathcal{E} \theta_u + \mathcal{P}_x u_\mu D_x X^\mu + \mathcal{P}_y u_\mu D_y Y^\mu + \mathcal{P}_z u_\mu D_z Z^\mu = 0$$

$$D_x \mathcal{P}_x + \mathcal{P}_x \theta_x - \mathcal{E} X_\mu D_u u^\mu - \mathcal{P}_y X_\mu D_y Y^\mu - \mathcal{P}_z X_\mu D_z Z^\mu = 0$$

$$D_y \mathcal{P}_y + \mathcal{P}_y \theta_y - \mathcal{E} Y_\mu D_u u^\mu - \mathcal{P}_x Y_\mu D_x X^\mu - \mathcal{P}_z Y_\mu D_z Z^\mu = 0$$

$$D_z \mathcal{P}_z + \mathcal{P}_z \theta_z - \mathcal{E} Z_\mu D_u u^\mu - \mathcal{P}_x Z_\mu D_x X^\mu - \mathcal{P}_y Z_\mu D_y Y^\mu = 0$$

- Second moment equations:

$$D_u \mathcal{I}_x + \mathcal{I}_x (\theta_u + 2u_\mu D_x X^\mu) = \frac{1}{\tau_{\text{eq}}} [\mathcal{I}_{\text{eq}}(T, m) - \mathcal{I}_x]$$

$$D_u \mathcal{I}_y + \mathcal{I}_y (\theta_u + 2u_\mu D_y Y^\mu) = \frac{1}{\tau_{\text{eq}}} [\mathcal{I}_{\text{eq}}(T, m) - \mathcal{I}_y]$$

$$D_u \mathcal{I}_z + \mathcal{I}_z (\theta_u + 2u_\mu D_z Z^\mu) = \frac{1}{\tau_{\text{eq}}} [\mathcal{I}_{\text{eq}}(T, m) - \mathcal{I}_z]$$

- The matching condition:

$$\mathcal{E}(\boldsymbol{\alpha}, \lambda) = \mathcal{E}_{\text{eq}}(T)$$

Phenomenological comparisons

First: Comparisons with ALICE data using aHydroQP

- M. Alqahtani, M. Nopoush, R. Ryblewski, and M. Strickland, arXiv:1703.05808 (PRL)
- M. Alqahtani, M. Nopoush, R. Ryblewski, and M. Strickland, arXiv:1705.10191 (PRC)

- We solve 3+1d quasiparticle anisotropic hydrodynamics.
- The system is assumed initially to be isotropic in momentum space.
- We used smooth Glauber initial conditions.
- We consider ALICE 2.76 TeV Pb-Pb collisions.
- We use anisotropic Cooper-Frye freeze-out to extract the freeze-out hypersurface.
- Then, we use THERMINATOR 2 to perform the hadronic production and decays.
- The parameters we obtained from our fit are

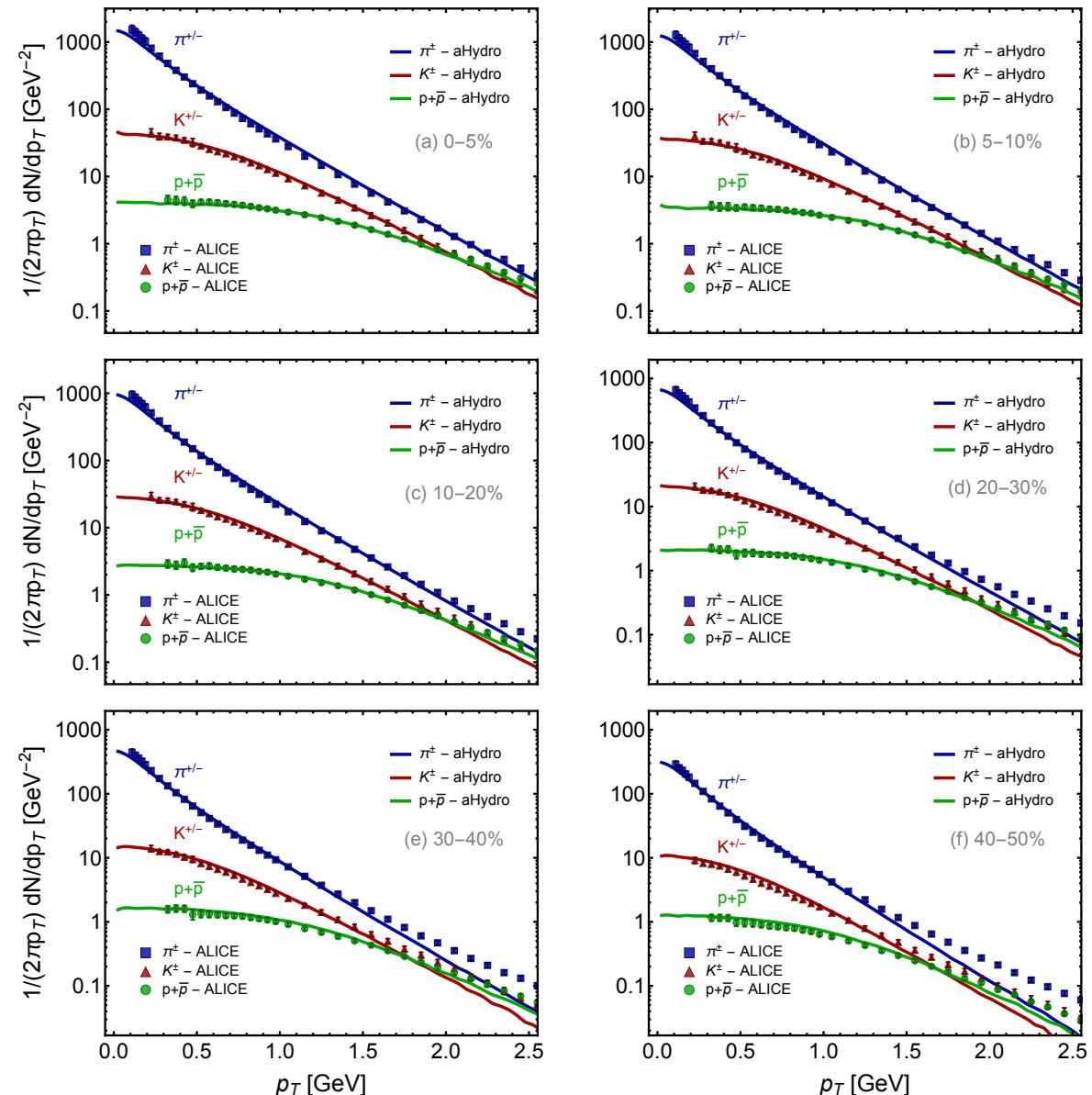
$$\tau_0 = 0.25 \text{ fm/c}$$

$$\begin{aligned}T_0 &= 600 \text{ MeV} \\ \frac{\eta}{s} &= 0.159 \\ T_{FO} &= 130 \text{ MeV}\end{aligned}$$

Pion, kaon, and proton spectra

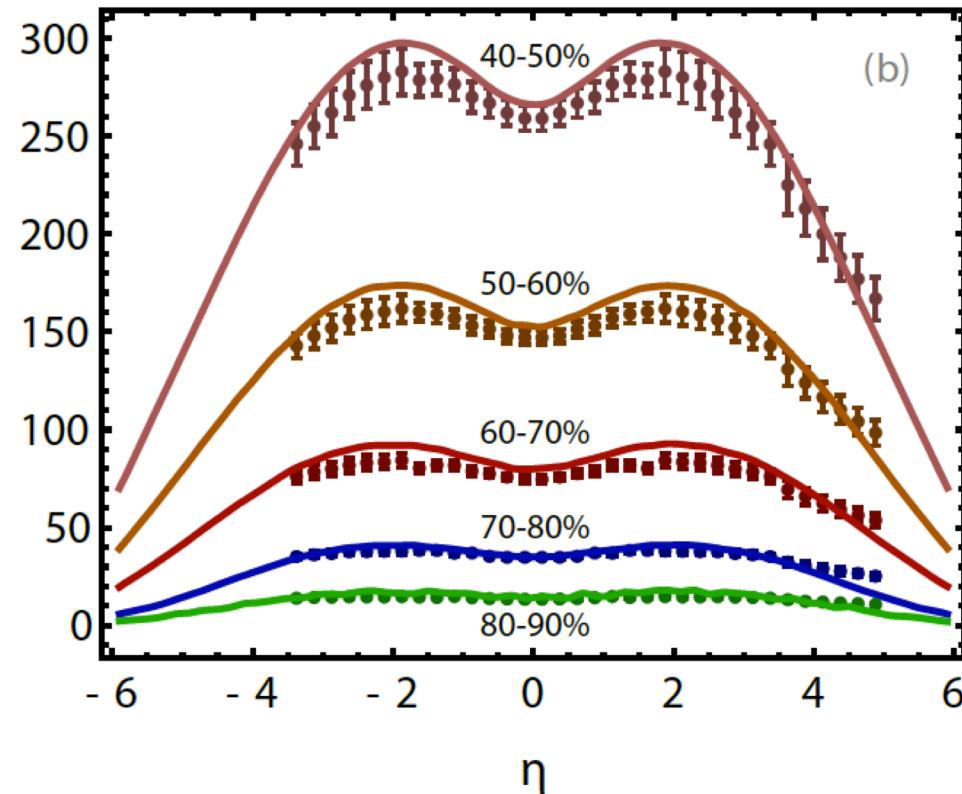
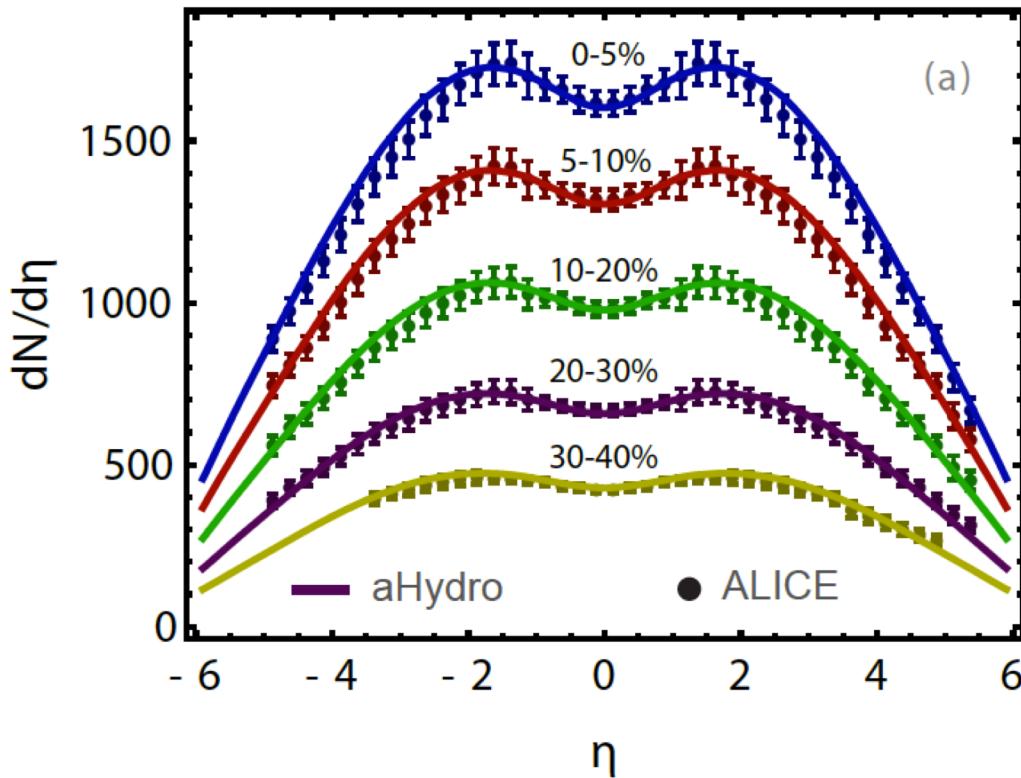
- To fix the free parameters we scanned over them and compared the theoretical predictions resulting from this scan with experimental data for the differential spectra of pions, kaons, and protons in both the 0-5% and 30-40% centrality classes.
- Our fits to the data show very good agreement including the mass splitting between different hadrons (pion, kaon, protons).
- The largest differences appear at relatively high centrality classes, e.g., our model shows good agreement only up to $p_T \gtrsim 1.5$ GeV in 40-50%, where in 0-5% up to $p_T \gtrsim 2.5$ GeV.

arXiv:1703.05808 & arXiv:1705.10191



Charged-hadron multiplicity

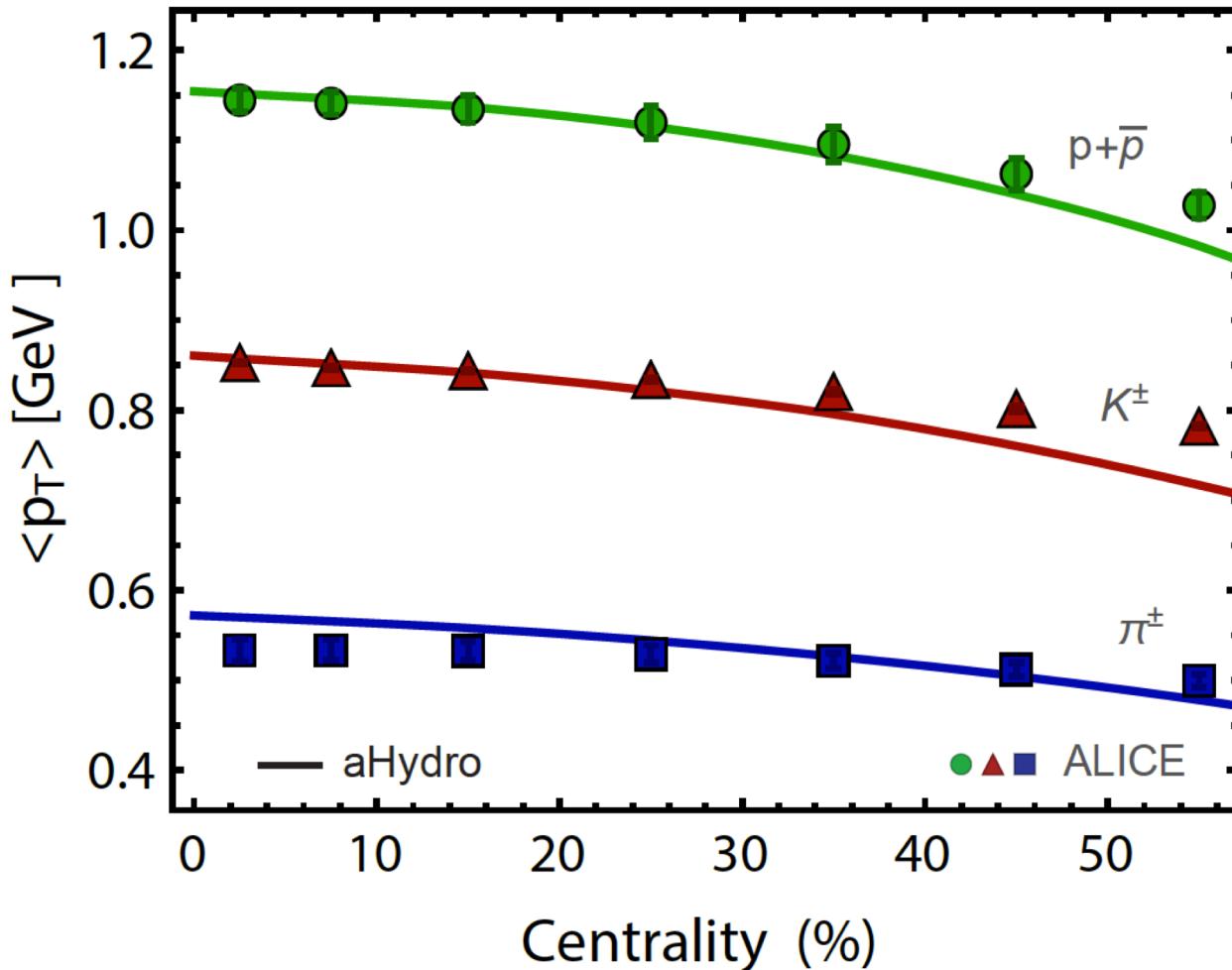
arXiv:1703.05808 & arXiv:1705.10191



Our model shows good agreement with data for the charged hadron multiplicity as a function of pseudorapidity in many different centrality classes.

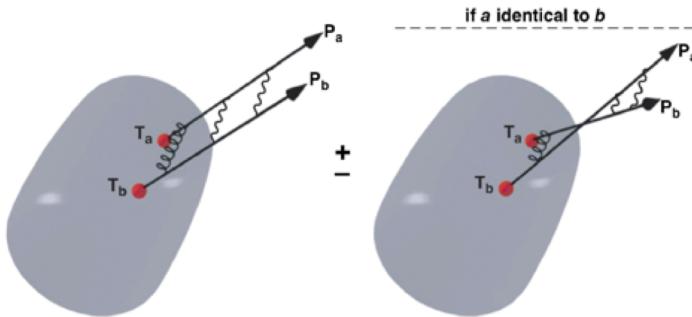
The average transverse momentum

arXiv:1703.05808 & arXiv:1705.10191



- Other studies found that inclusion of the bulk viscosity is important to obtain agreement with the experimentally observed average transverse momentum.
- aHydroQP incorporates bulk viscosity automatically; no fine tuning necessary.

HBT radii

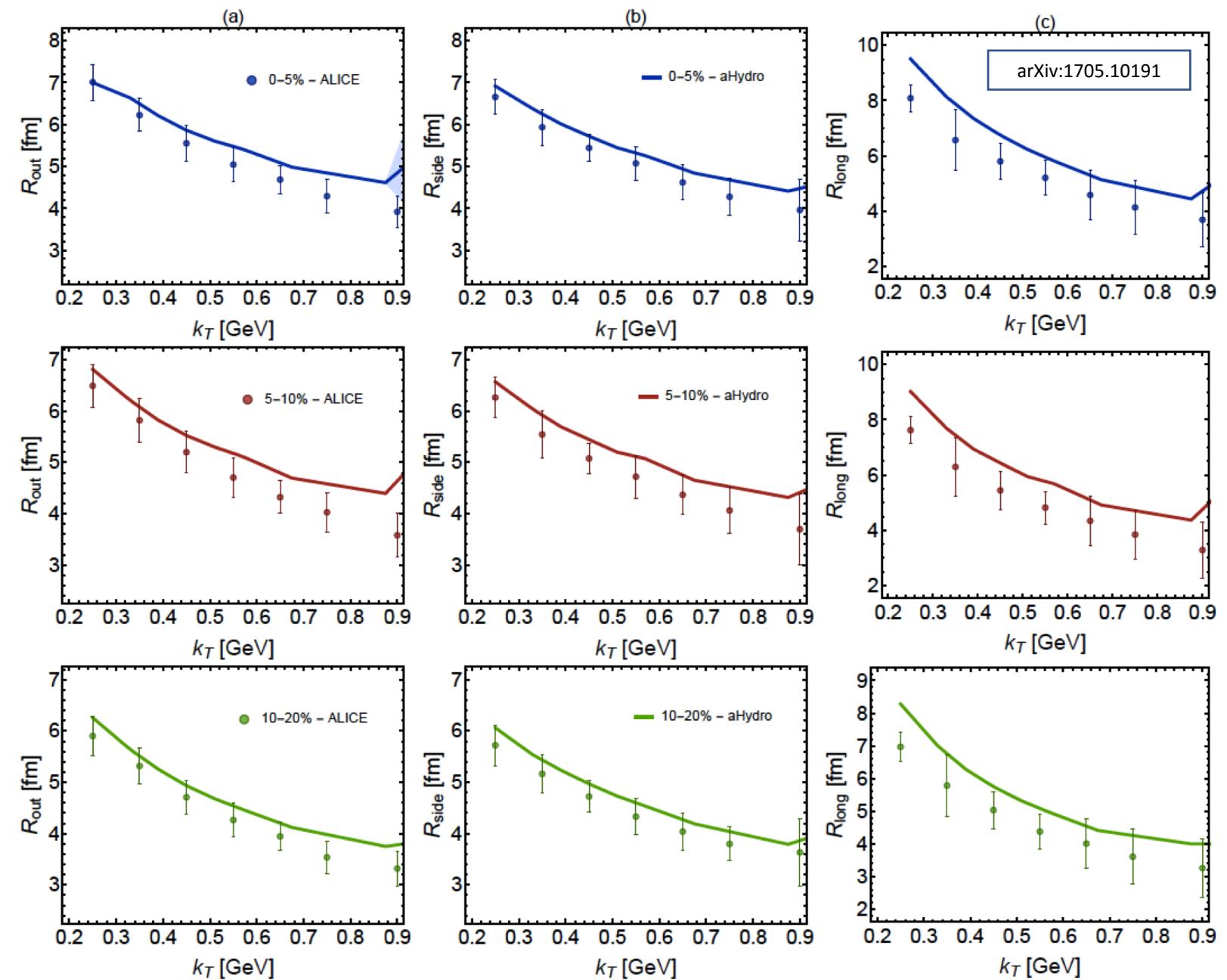


$$R_{\text{out}} \parallel \mathbf{k}_T$$

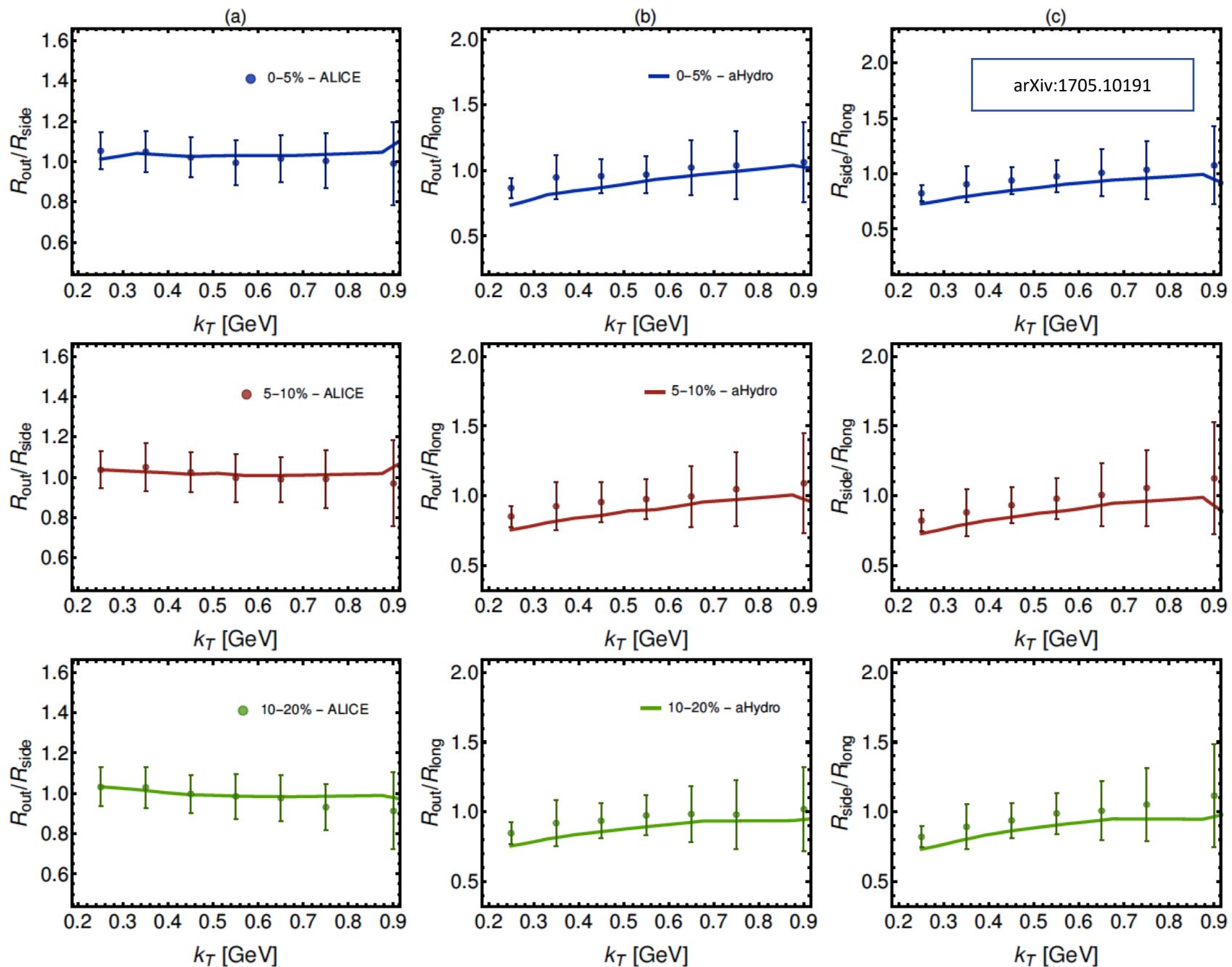
$$R_{\text{side}} \perp \mathbf{k}_T$$

R_{long} along the beam line

$$\mathbf{k}_T = \frac{1}{2}(\mathbf{p}_{T,1} + \mathbf{p}_{T,2})$$

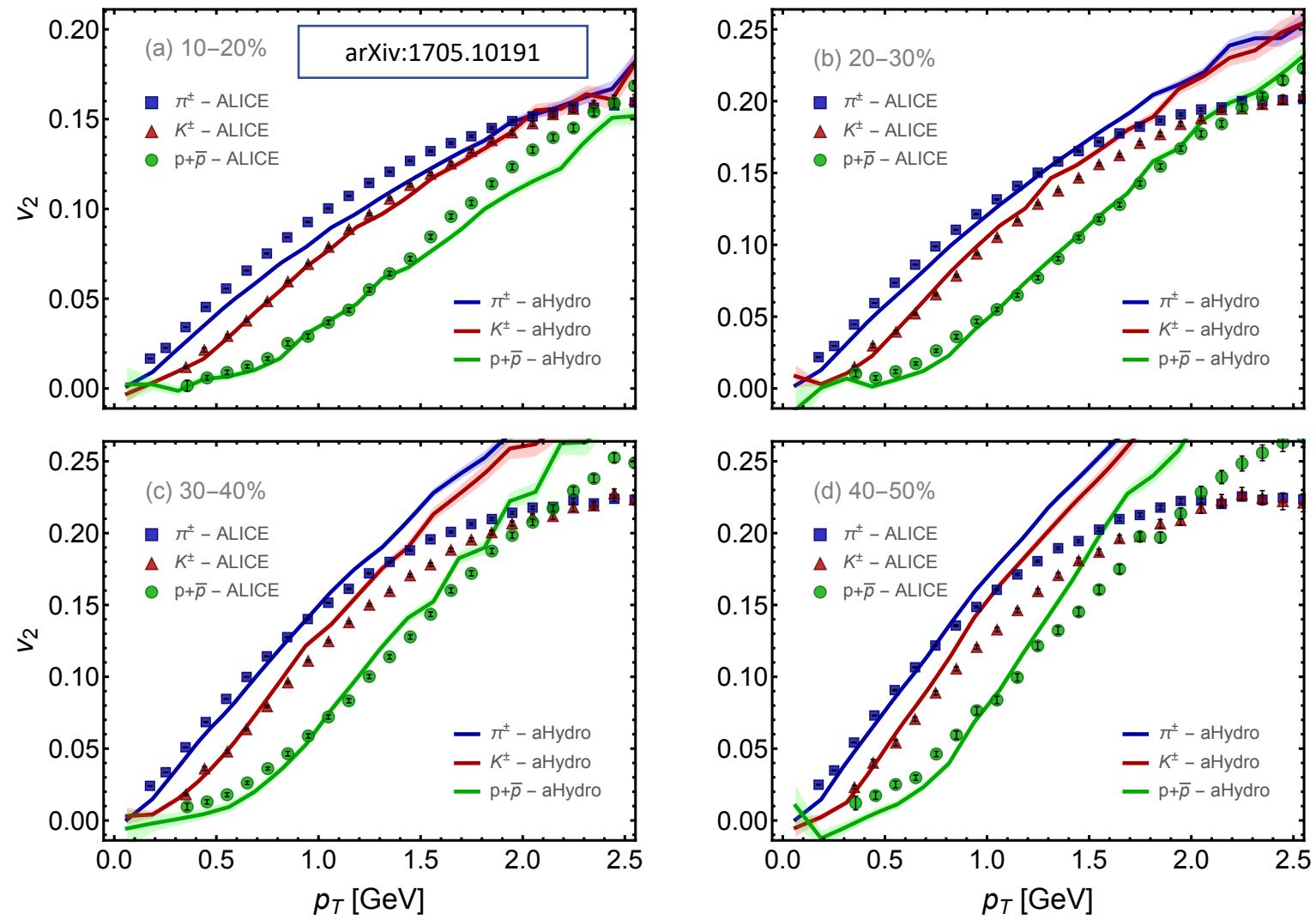


HBT radii ratios



V_2 for identified hadrons as a function of p_T

- Overall, our model shows a quite reasonable description of the data.
- In panels (b) and (c), the agreement is quite good, our model reproduces the data for pion, kaon, and proton out to $p_T \sim 1.5, 1.5$, and 2.5 GeV.
- In panel (a) and (d), the agreement is less.
- This difference can be related to using smooth Glauber initial conditions and/or constant η/s .



Second: Comparisons with RHIC data using aHydroQP

D. Almaalol, M. Alqahtani, and M. Strickland, forthcoming

- We solve 3+1d quasiparticle anisotropic hydrodynamics.
- The system is assumed initially to be isotropic in momentum space.
- We used smooth Glauber initial conditions.
- We consider RHIC 200 GeV Au-Au collisions.
- We use anisotropic Cooper-Frye freeze-out to extract the freeze-out hypersurface.
- Then, we use THERMINATOR 2 to perform the hadronic production and decays.
- The parameters we obtained from our fit are

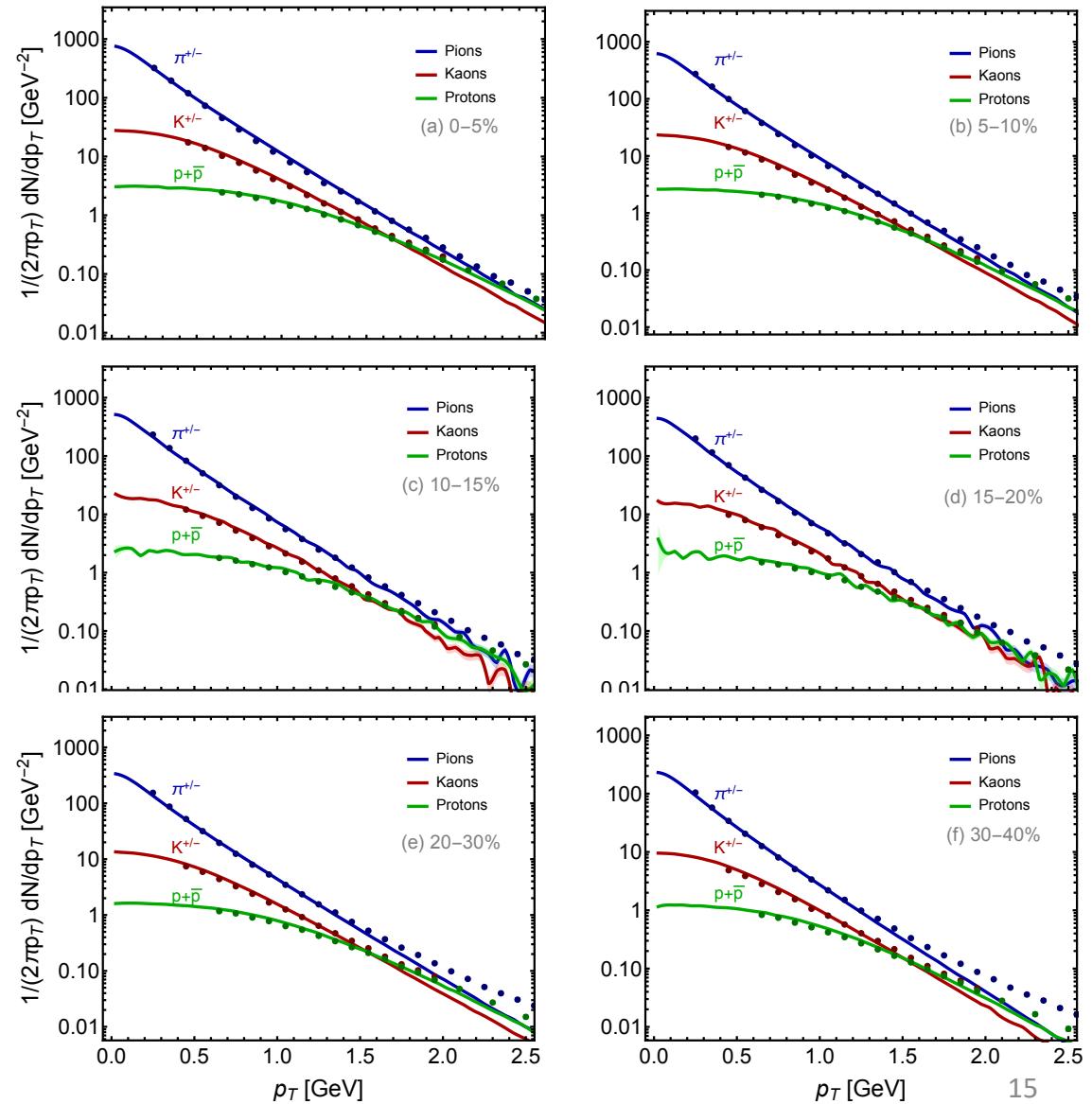
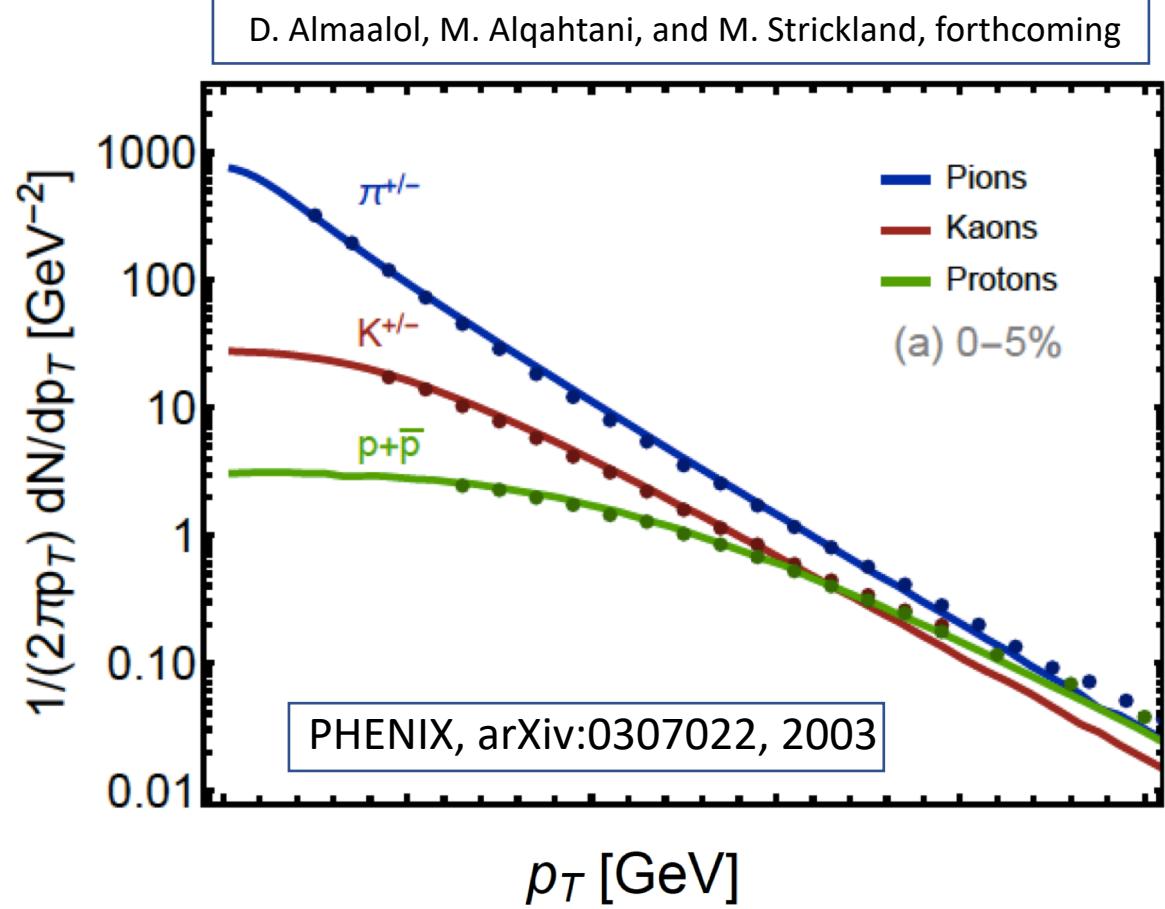
$$\tau_0 = 0.25 \text{ fm/c}$$

$$T_0 = 0.455 \text{ MeV}$$

$$\frac{\eta}{s} = 0.175$$

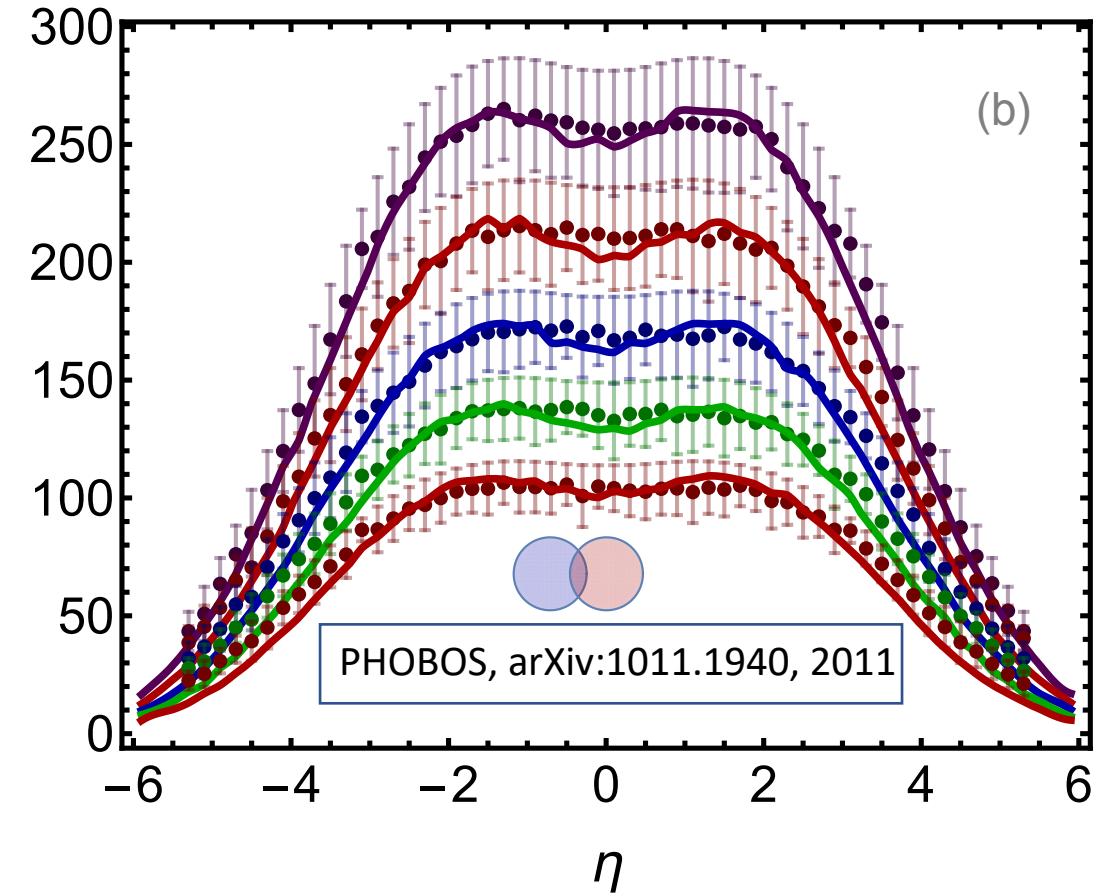
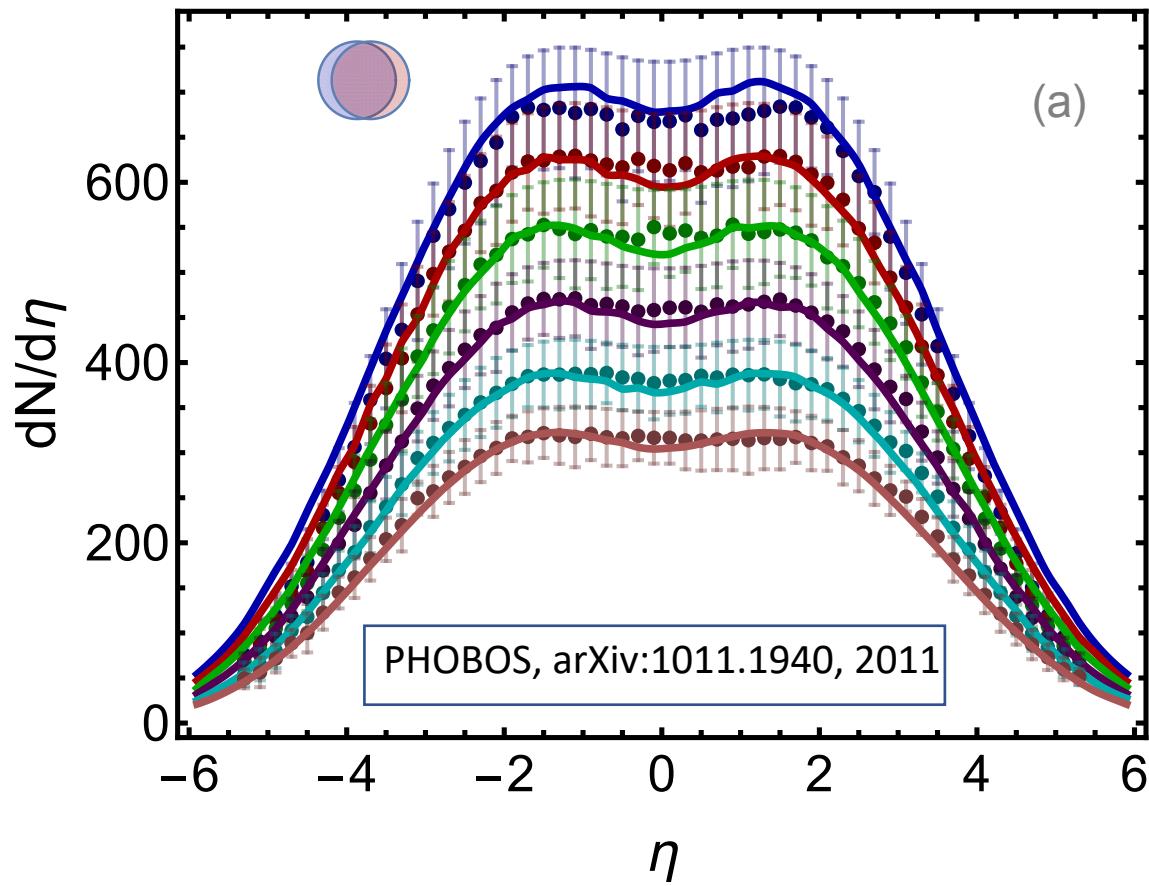
$$T_{FO} = 130 \text{ MeV}$$

Spectra (preliminary results)



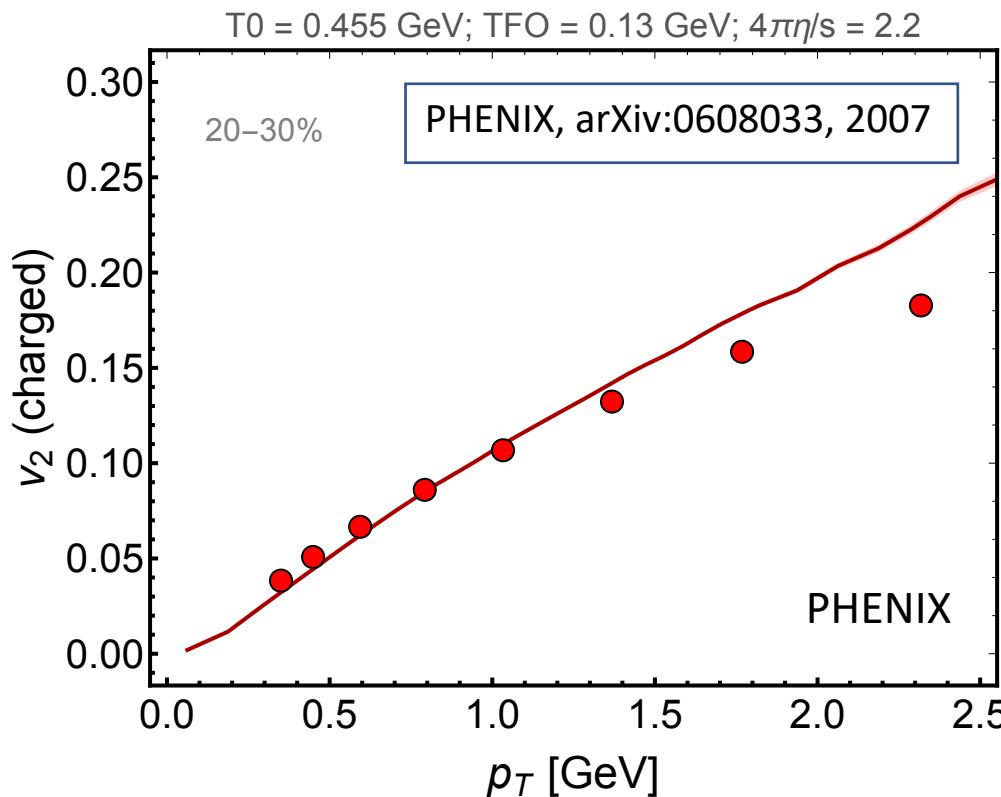
Charged-hadron Multiplicity (preliminary results)

D. Almaalol, M. Alqahtani, and M. Strickland, forthcoming

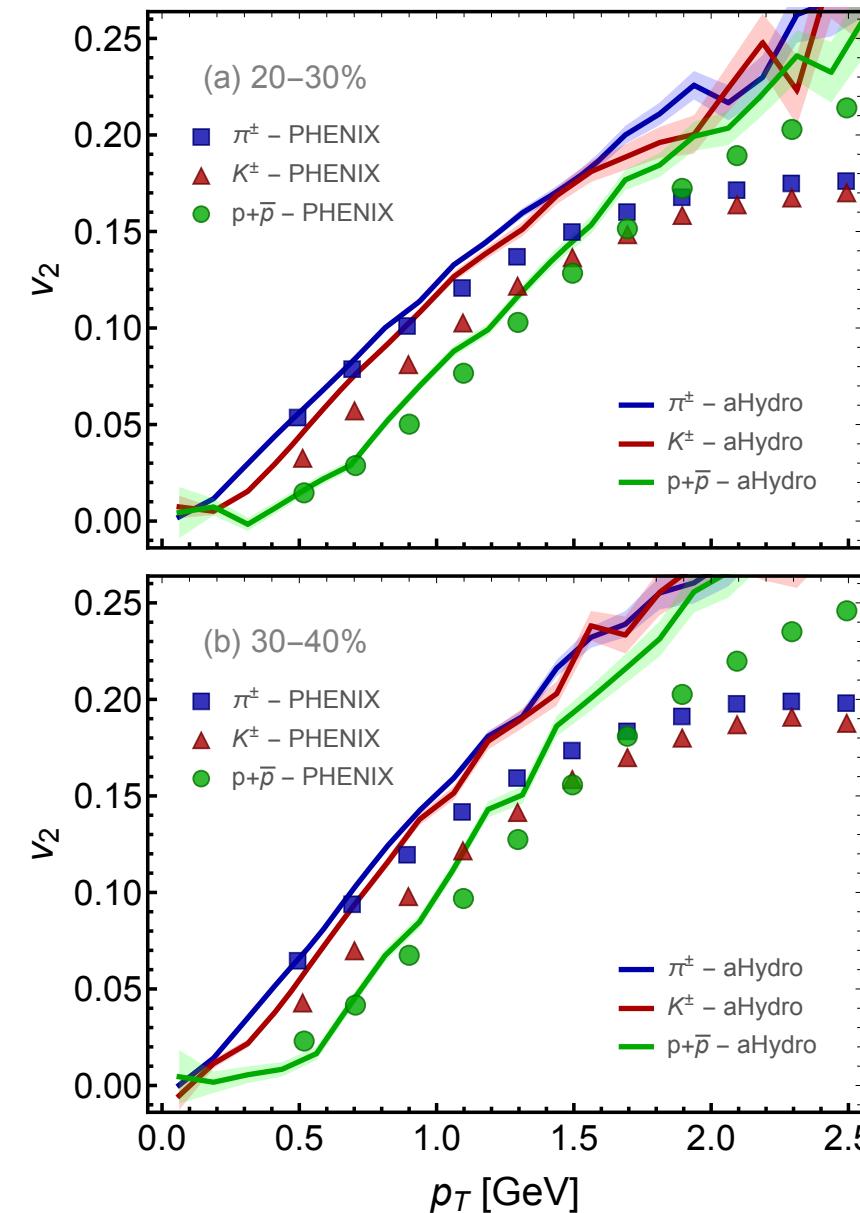


Elliptic flow (preliminary results)

- Quite good description of elliptic flow at low p_T
- Our model curves overestimate elliptic flow at high p_T

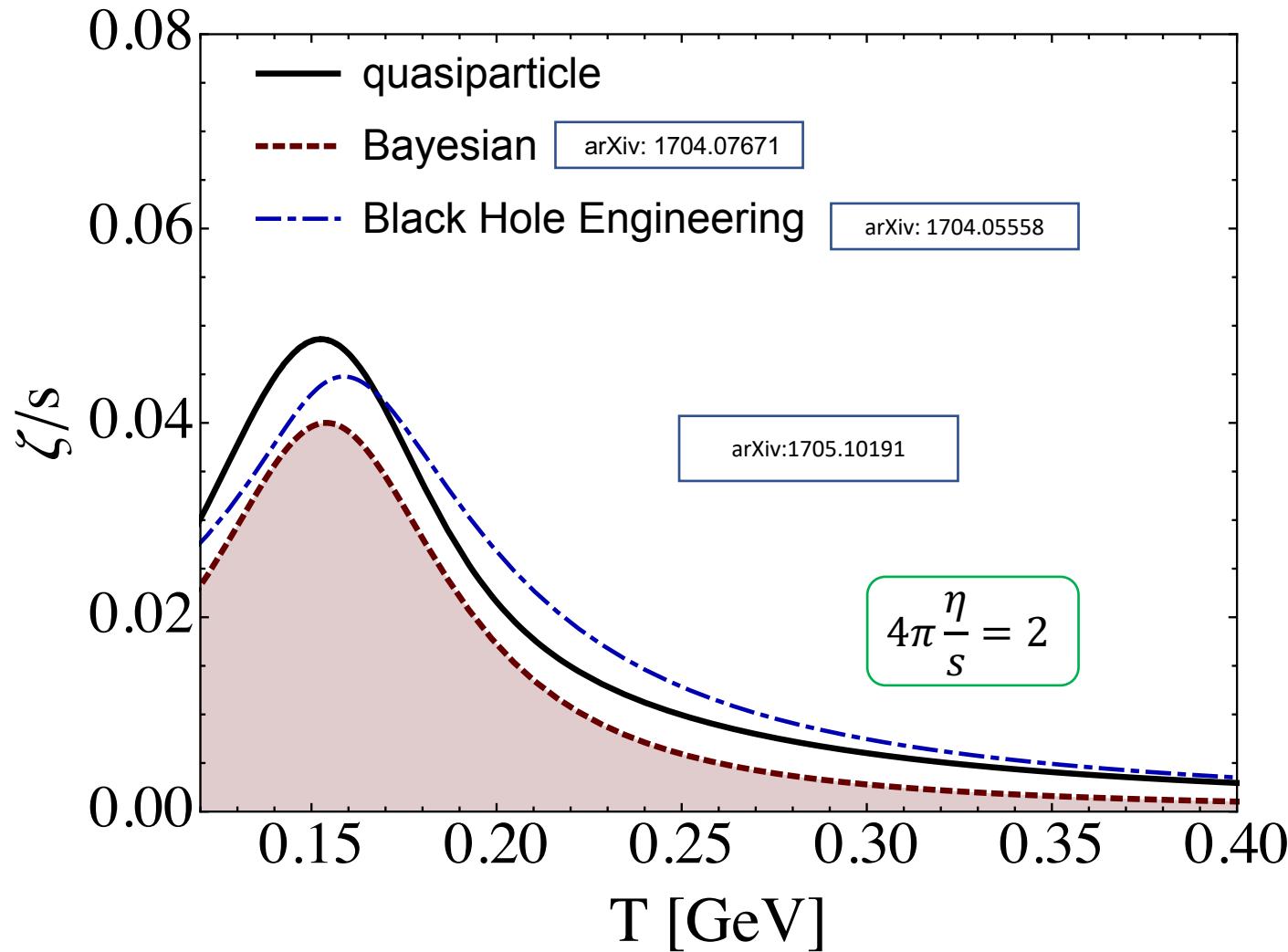


D. Almaalol, M. Alqahtani, and M. Strickland, forthcoming



PHENIX, arXiv:1412.1038, 2016

The bulk viscosity

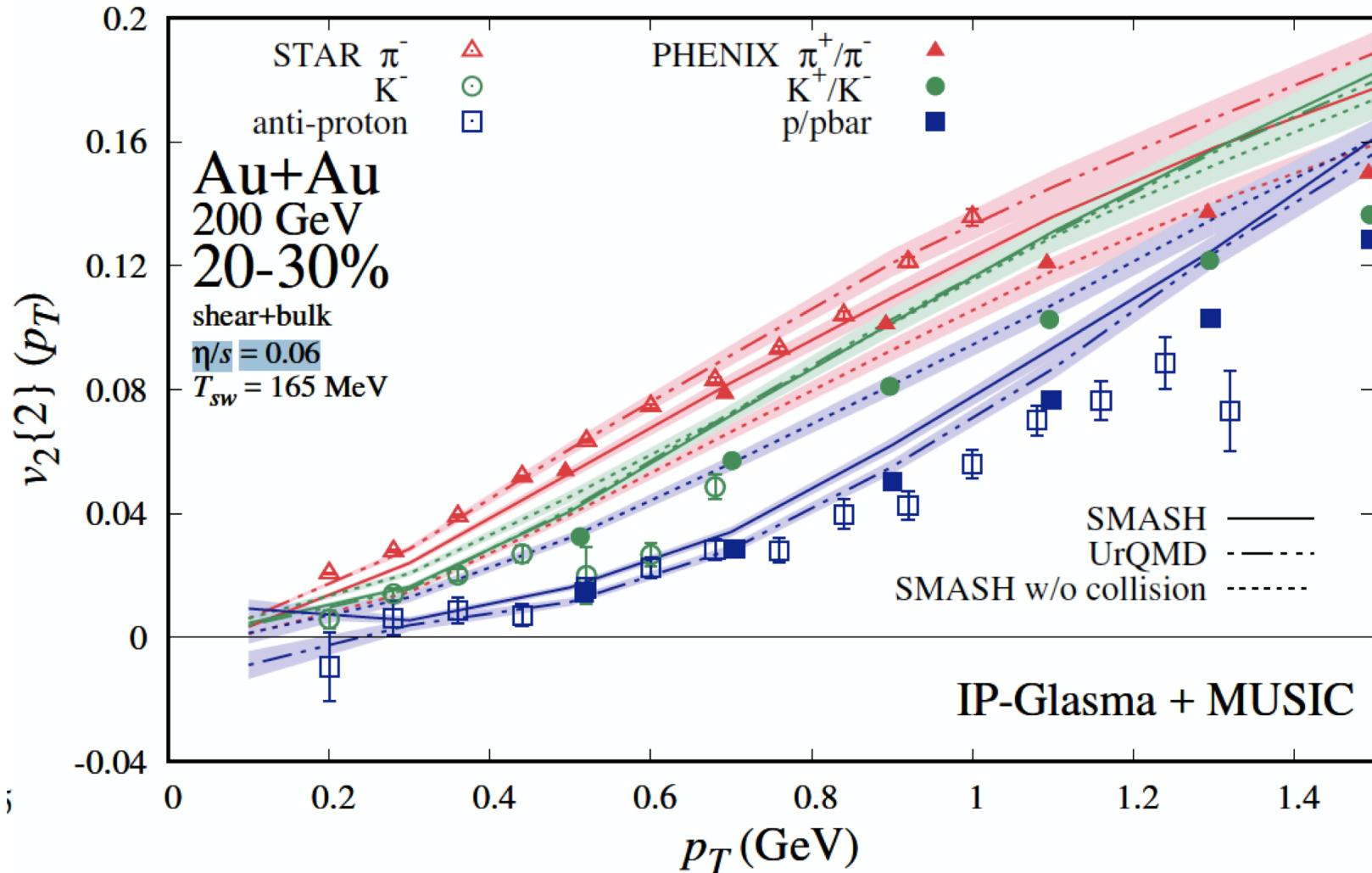


Conclusions and outlook

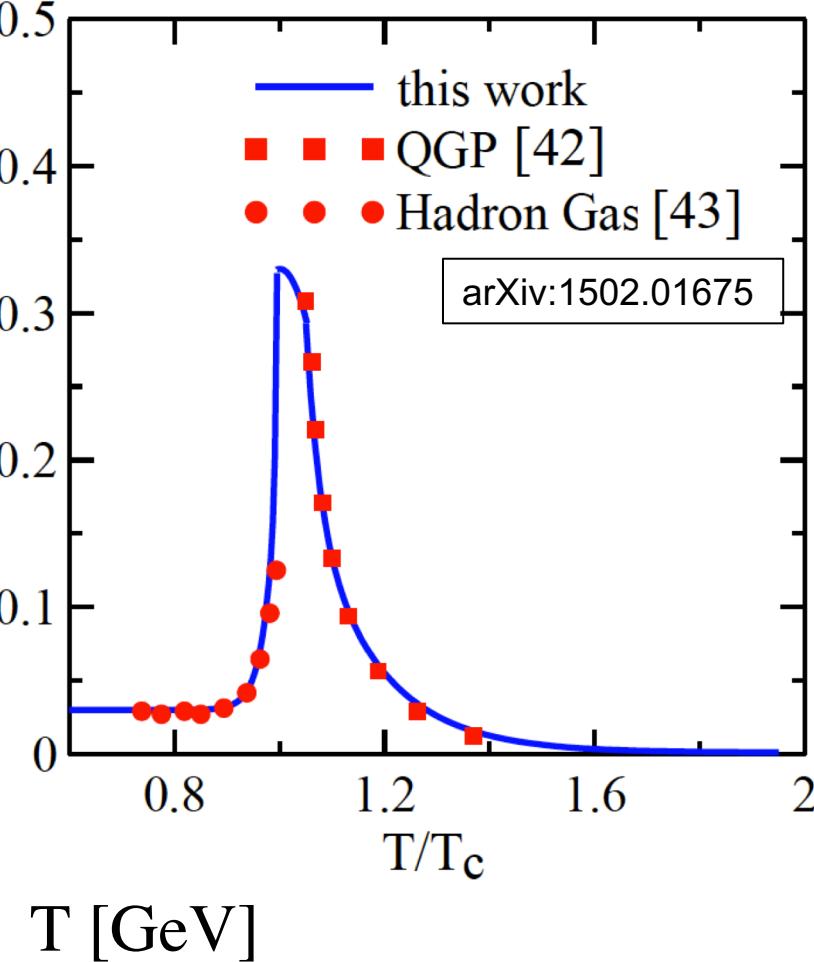
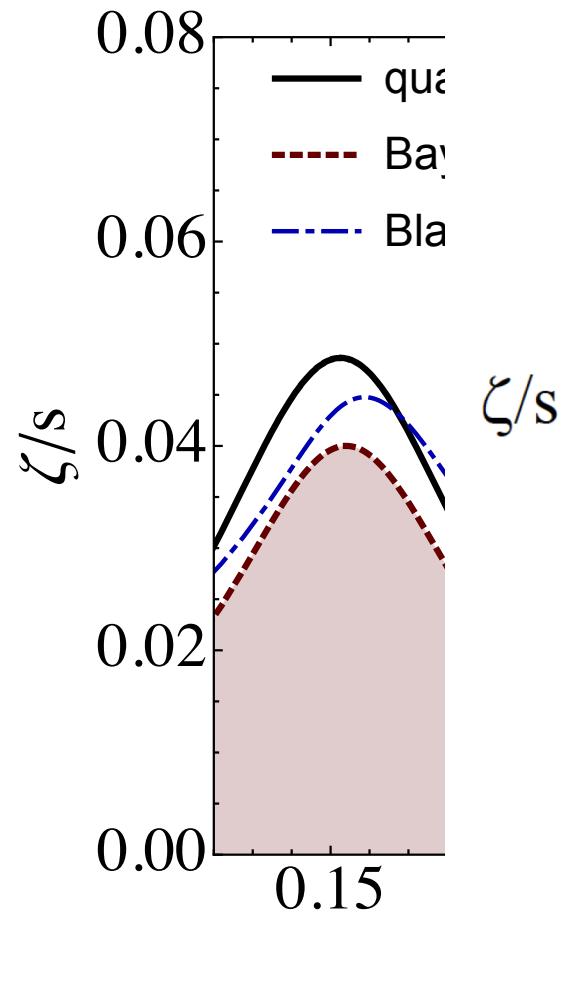
- Anisotropic hydrodynamics takes into account momentum-space anisotropies of the QGP from the beginning.
- Quasiparticle anisotropic hydrodynamics more self-consistently treats the non-conformality of the QGP than prior approaches.
- Using aHydroQP, we were able to fit both ALICE 2.76 TeV Pb-Pb and RHIC 200 GeV Au-Au (preliminary results) collisions quite well.
- Our model predicts for ALICE experiments $\frac{\eta}{s} = 0.159$, $T_0 = 600 \text{ MeV}$ at $\tau_0 = 0.25 \text{ fm/c}$, $T_{FO} = 130 \text{ MeV}$.
- However, for RHIC experiments $\frac{\eta}{s} = 0.175$, $T_0 = 455 \text{ MeV}$ at $\tau_0 = 0.25 \text{ fm/c}$, $T_{FO} = 130 \text{ MeV}$.
- The peak value of $\zeta/s \sim 0.05$ which is smaller than what other viscous studies (arXiv:1502.01675) found ~ 0.3 at LHC energies (2.76 TeV).
- Looking to future, we are working on improving our code in many ways
 - Going from LO aHydro to NLO aHydro.
 - Including fluctuating initial conditions.
 - Including temperature dependence of $\frac{\eta}{s}$
 - Realistic collisional kernels instead of relaxation time approximation (RTA).
 - Including elastic hadronic collisions using some available codes on the market like URQMD or SMASH.
 - Including finite chemical potential which is important for RHIC lower energies.

Backup slides

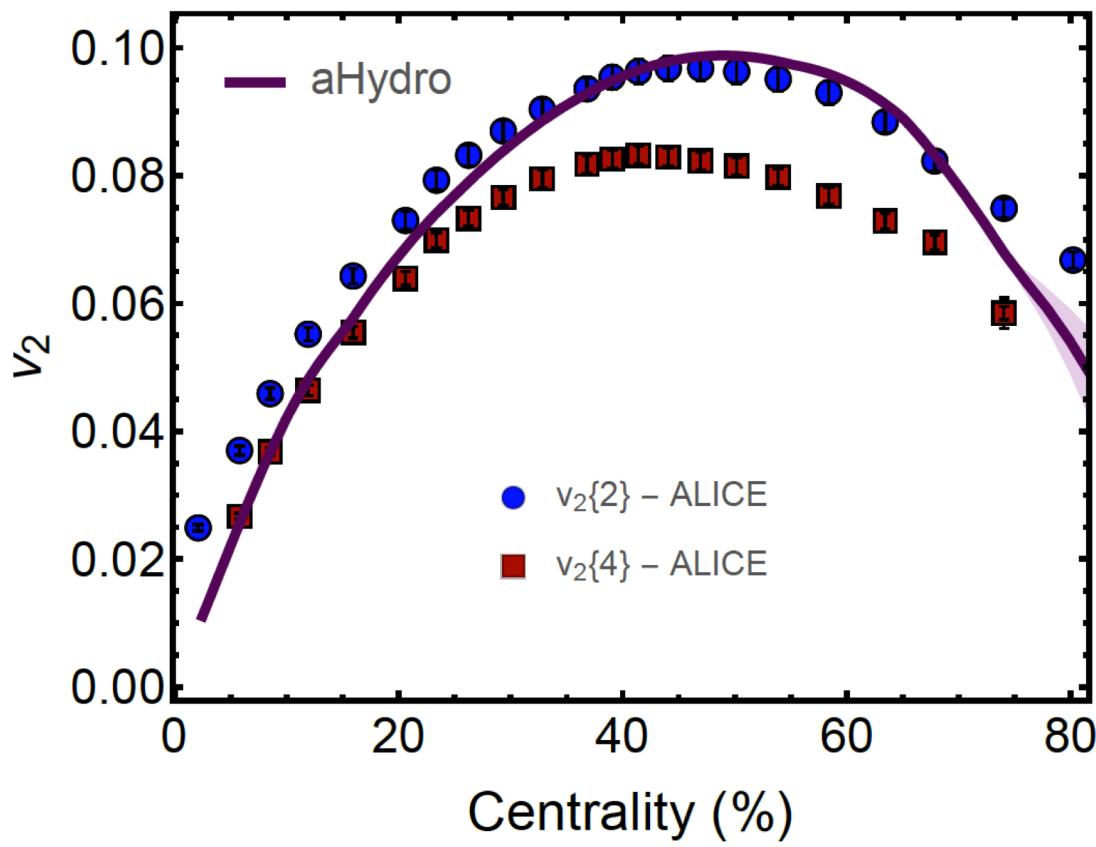
Hannah Petersen yesterday talk



The bulk viscosity

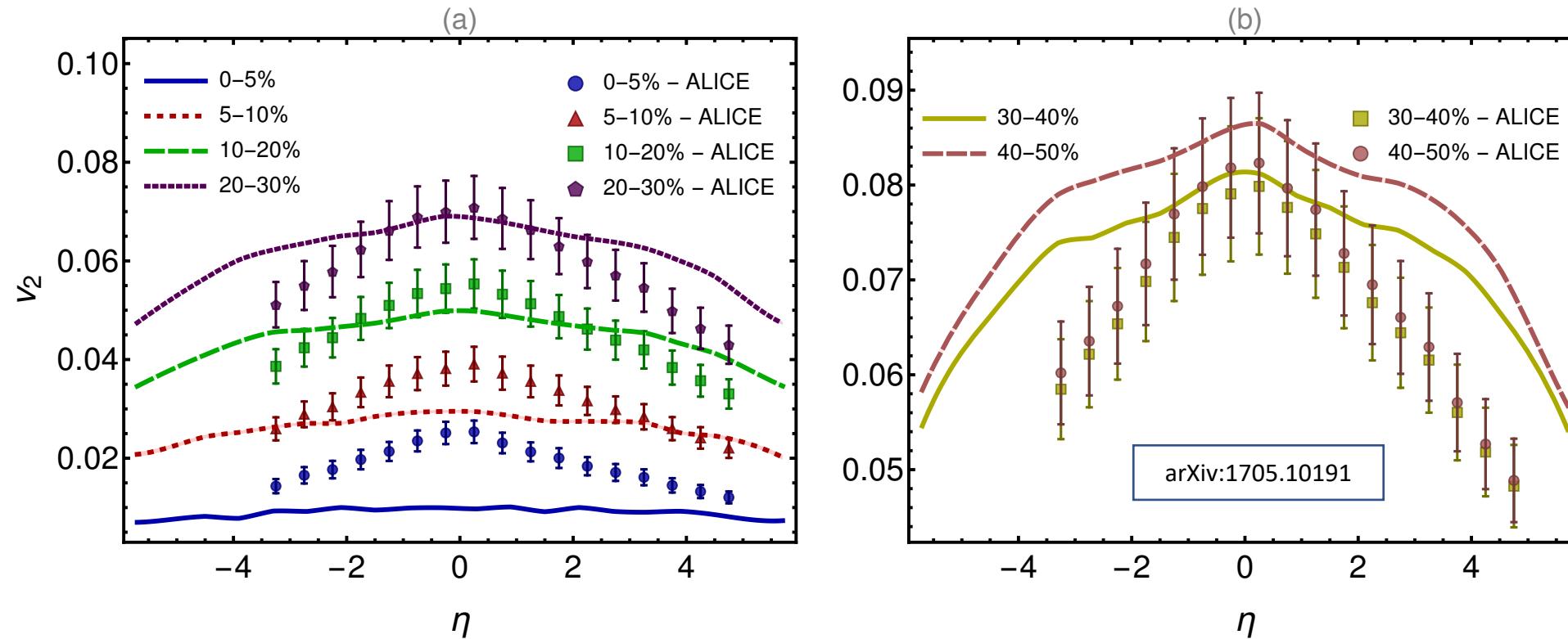


v_2 as a function of centrality



arXiv:1703.05808 & arXiv:1705.10191

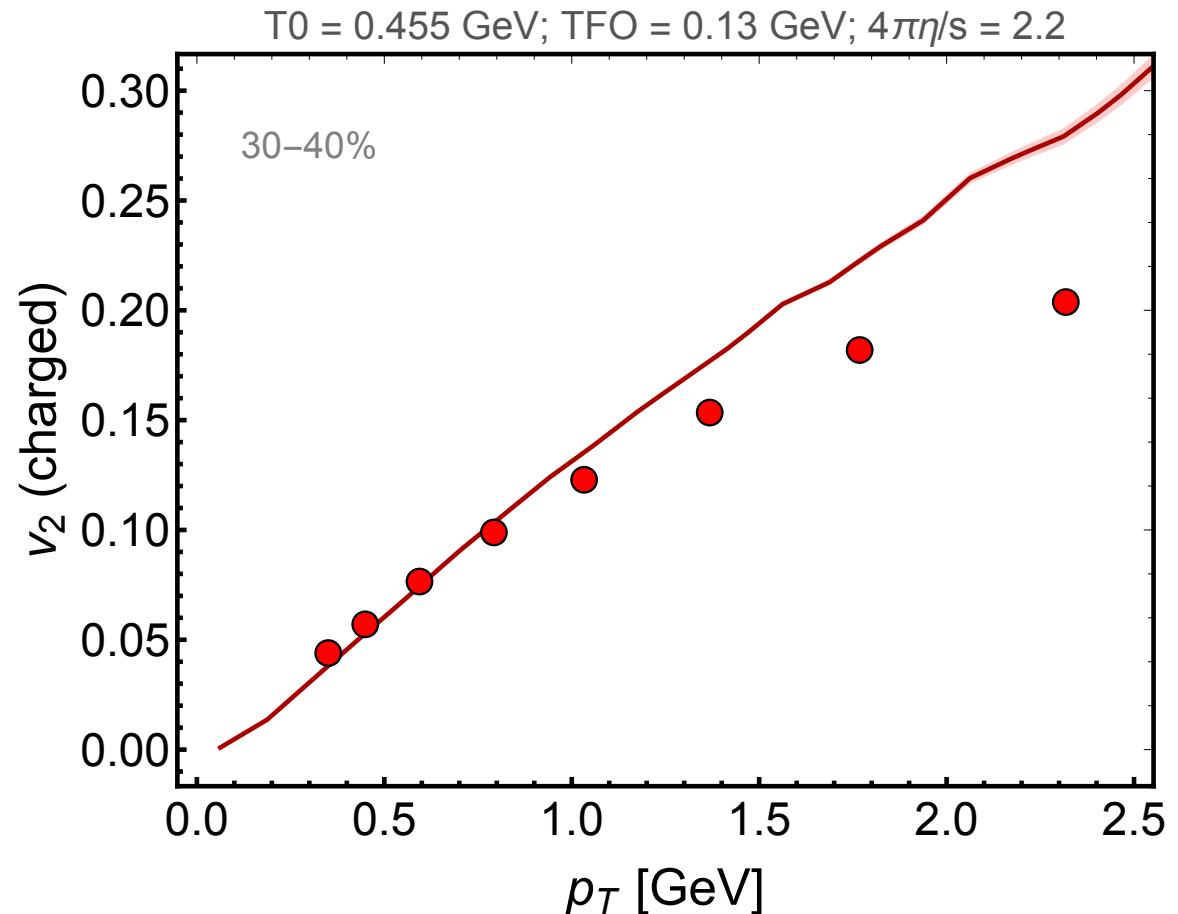
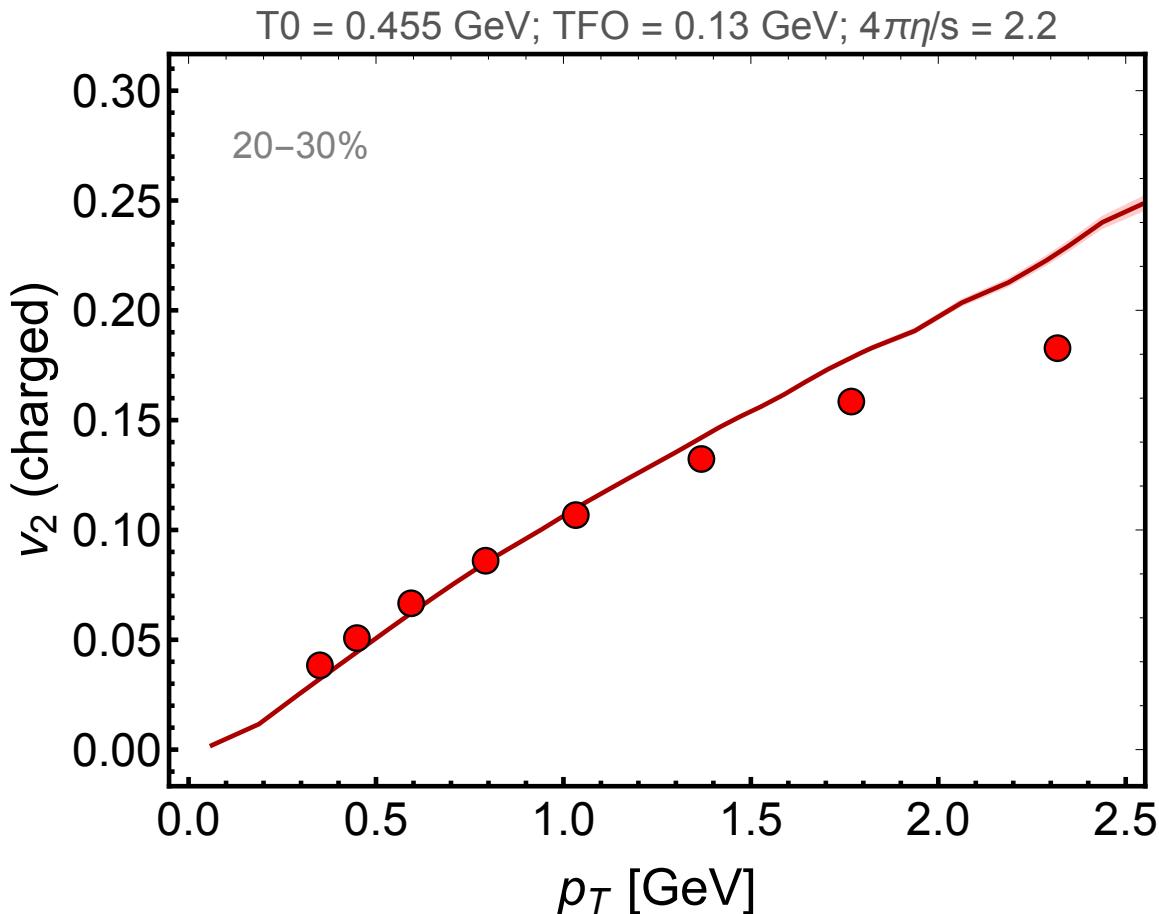
The pseudorapidity dependence of v_2



- We show the pseudorapidity dependence of v_2 for different centrality classes.
- At large pseudorapidity, our model results do not fall fast enough compared with experimental data.

Elliptic flow at RHIC (preliminary results)

D. Almaalol, M. Alqahtani, and M. Strickland, forthcoming



HBT radii

- This method is introduced by Hanbury Brown and Twiss.
- Very powerful tool to study the source space-time extension in heavy ion collisions.
- The HBT radii calculations is based on studying the two-particle correlation functions for any pair of identical particles.
- In this study, we use the pair $\pi^+\pi^+$.
- The average pair transverse momentum is defined by

$$k_T = \frac{1}{2}(\mathbf{p}_{T,1} + \mathbf{p}_{T,2})$$

