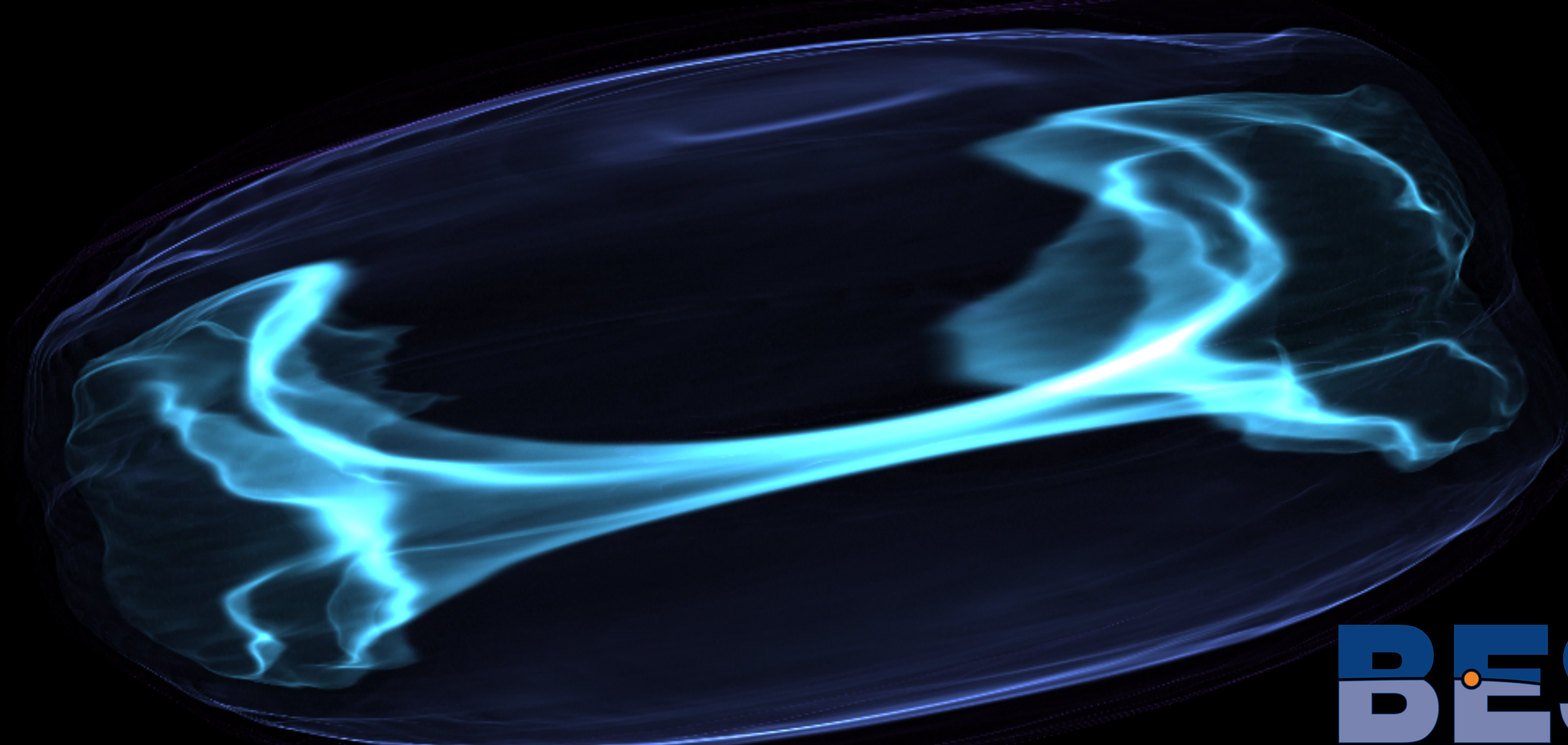
U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

MULTI-PARTICLE AZIMUTHAL CORRELATIONS AT THE RELATIVISTIC HEAVY-ION COLLIDER

BJÖRN SCHENKE - BROOKHAVEN NATIONAL LABORATORY
WORK WITH CHUN SHEN AND PRITHWISH TRIBEDY



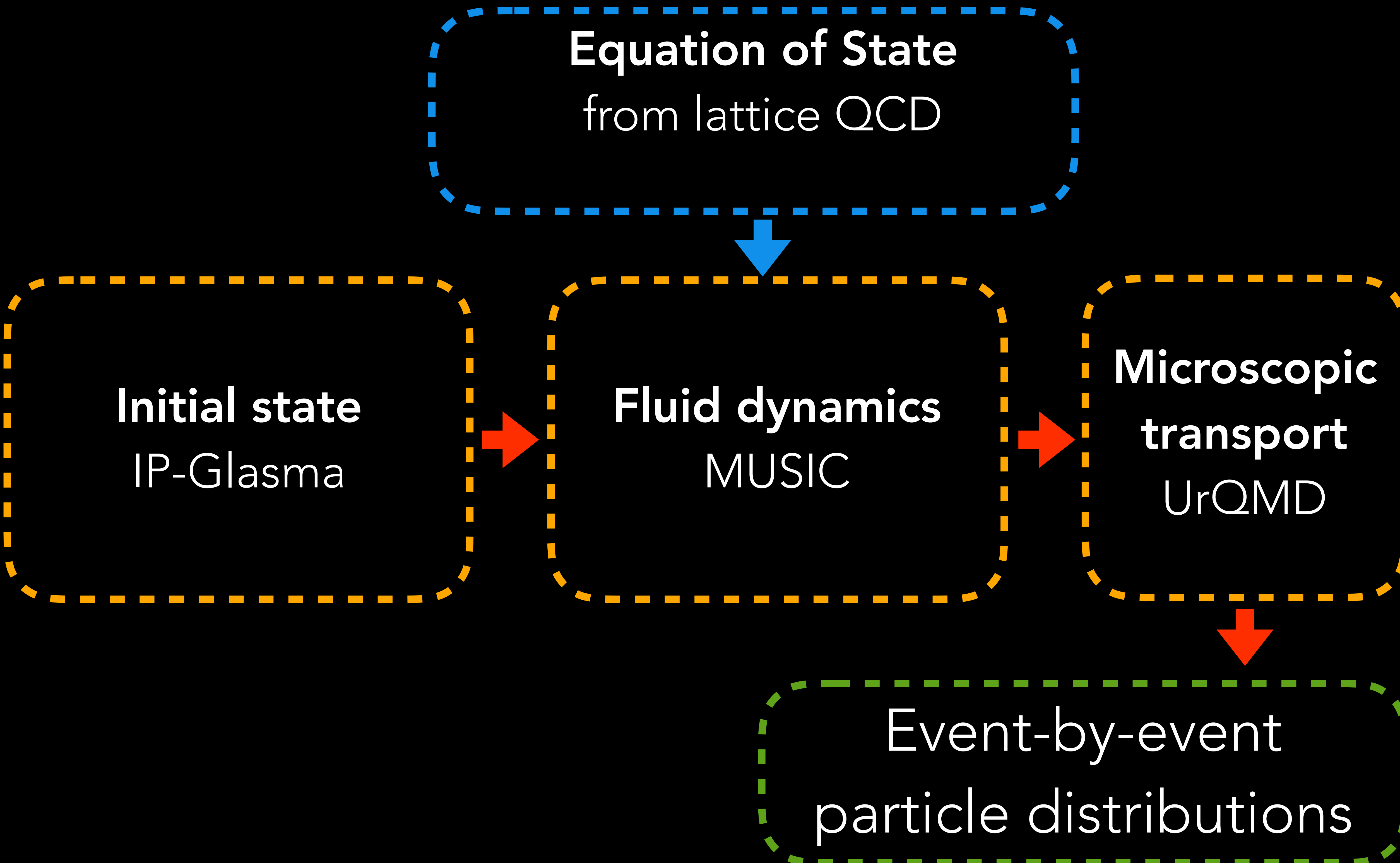
HIRSCHEGG, JANUARY 16 2019

BEST COLLABORATION

Strategy

- Establish precise calculations of multi-particle correlators in a comprehensive framework with hydrodynamics at its core
- Constrain transport coefficients with bulk observables
- Compute more complex three and four particle correlators and compare to new data from RHIC
- Including local charge conservation during particle sampling establish baseline for chiral magnetic effect search
- Given constrained parameters from heavy ion collisions, predict observables in small systems

Simulation Framework



Simulation Framework

Equation of State
from lattice QCD
github.com/morelandjs/eos-analysis

Initial state
IP-Glasma
github.com/schenke/ipglasma

Fluid dynamics
MUSIC
physics.mcgill.ca/music/

github.com/chunshen1987/iSS

Microscopic transport
UrQMD
urqmd.org

Event-by-event particle distributions

Initial state and pre-equilibrium: IP-Glasma

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Solve Yang-Mills equations with incoming color currents constrained with IPSat model fit to HERA data

Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)

Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

Color charge density constructed from nucleons (subnucleon structure possible, needed for p+A but also diffractive HERA data)

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301 and Phys.Rev. D94 (2016) 034042

Includes fluctuations of:

impact parameter, nucleon positions, (quark positions), color charge normalization, color charges

Matching to fluid dynamics

Extract energy density and flow velocity from fields' $T^{\mu\nu}_{\mathrm{CYM}}$

$$\varepsilon u^\nu = u_\mu T^{\mu\nu}$$

Initial shear viscous tensor is given by (here used P=ε/3)

$$\pi^{\mu\nu} = T^{\mu\nu}_{\mathrm{CYM}} \underbrace{- \frac{4}{3}\varepsilon u^\mu u^\nu + \frac{\varepsilon}{3} g^{\mu\nu}}_{\text{ideal part}}$$

Absorb the difference to the lattice EoS in a 'bulk' stress term (here, P_{lat} from the lattice EoS)

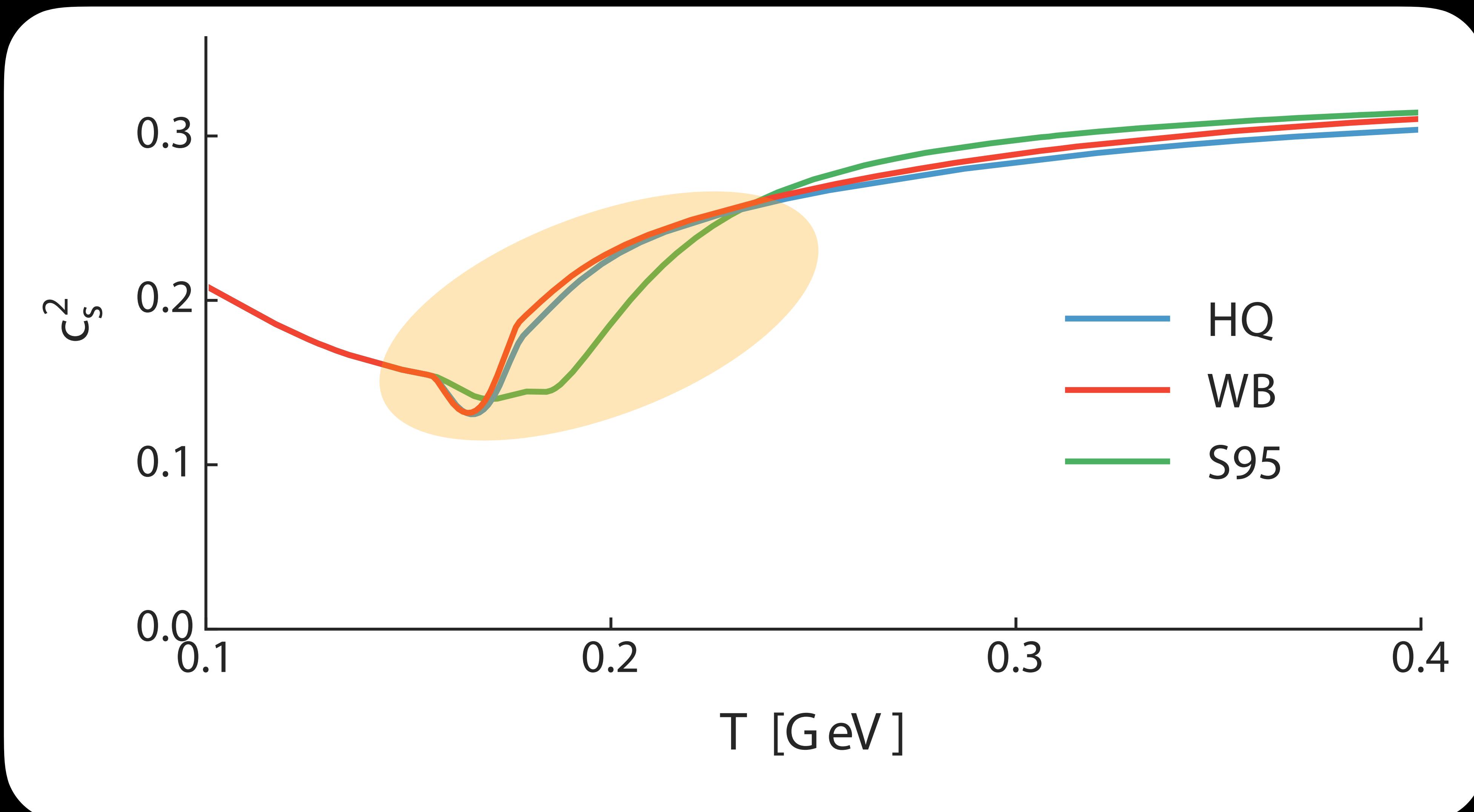
$$\Pi = \frac{\varepsilon}{3} - P_{\mathrm{lat}}$$

Björn Schenke, BNL

Equation of State

Use a new EoS constructed from HotQCD LQCD data

Larger speed of sound compared to s95p leads to more flow



Affects extraction of viscosities:

v_n change by 10%

η/s needs to change by ~50%

Figure from J.S. Moreland, R.A. Soltz, Phys.Rev. C93, 044913 (2016), also see P. Alba et al. arXiv:1711.05207

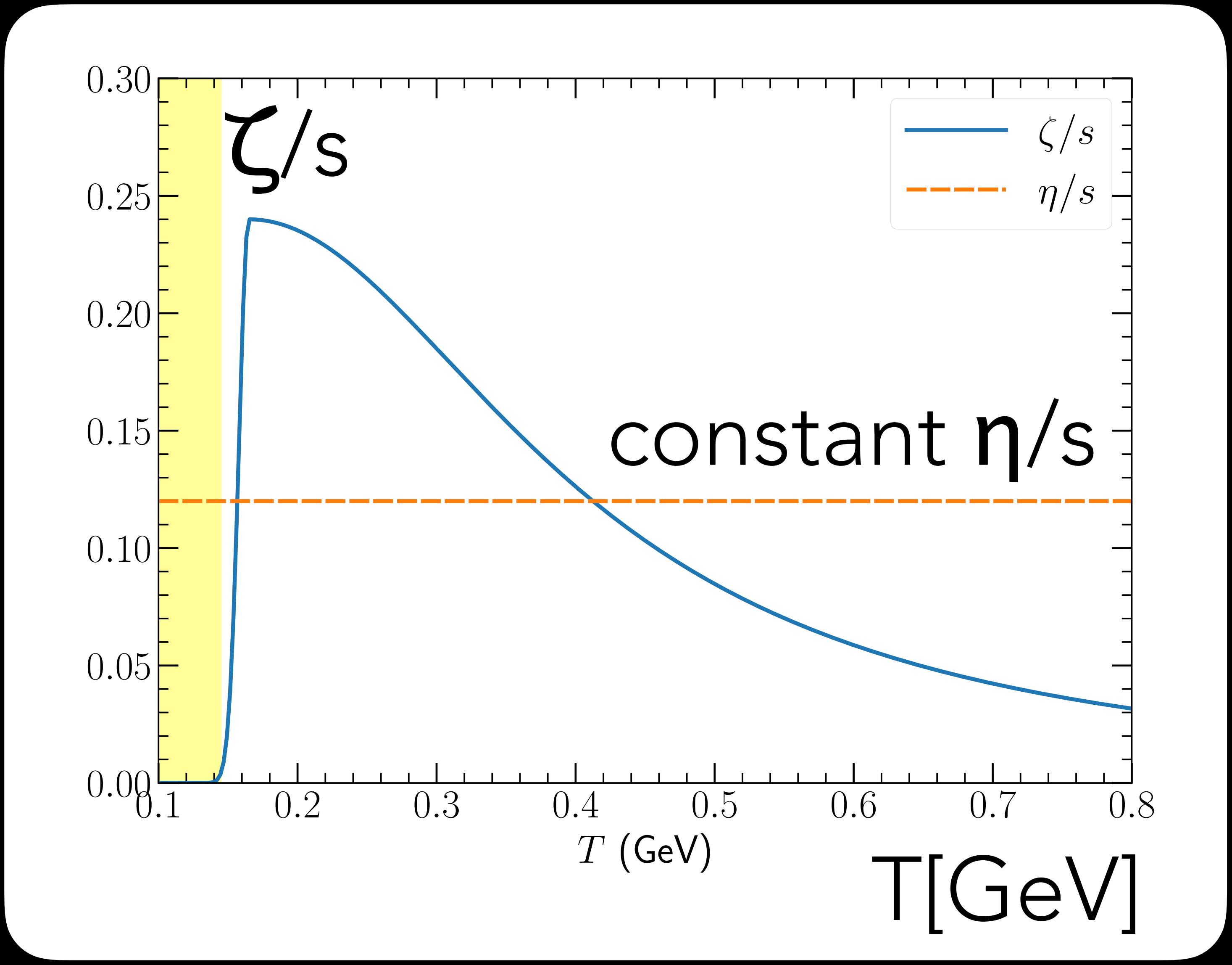
s95: P. Huovinen and P. Petreczky, Nucl. Phys. A837, 26–53 (2010)

HQ: A. Bazavov et al. (HotQCD), Phys. Rev. D90, 094503 (2014)

WB: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, K. K. Szabo, Phys. Lett. B730, 99–104 (2014)

Viscosities - all parameters fit in Au+Au

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378



Bulk viscosity peaks at 165 MeV

Width, height, and position are free parameters

S. Ryu, J.-F. Paquet, C. Shen, G. Denicol, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C97, 034910, (2018)

MUSIC → UrQMD

Sample particles on the freeze-out surface (surface of constant energy density) according to

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\Delta^3\Sigma_\mu p^\mu(f_i^{(0)} + \delta f_i)$$

then feed particles into UrQMD

S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255–369 (1998)
M. Bleicher et al., J. Phys. G25, 1859–1896 (1999)

which performs resonance decays and scattering according to hadronic cross sections

Exact conservation laws should be fulfilled when converting to particles…

Local charge conservation

Implement simple model that respects local charge conservation P. Bozek, W. Broniowski, PRL 109 062301 (2012)

- For each sampled particle sample its anti-particle in the same surface cell
- The common boost will introduce a correlation between the two opposite sign particles in momentum space

Implemented in sampler iSS available at: https://github.com/chunshen1987/iSS

Global momentum conservation

- Ideally implement local momentum conservation
- But it is not trivial and left for future work
- We will concentrate on observables where the effect of local momentum conservation cancels
- For now: global momentum conservation
  - Compute net momentum of the system $\langle \vec{p} \rangle = \sum_i \vec{p}_i$
  - Then we correct every particle's momentum by

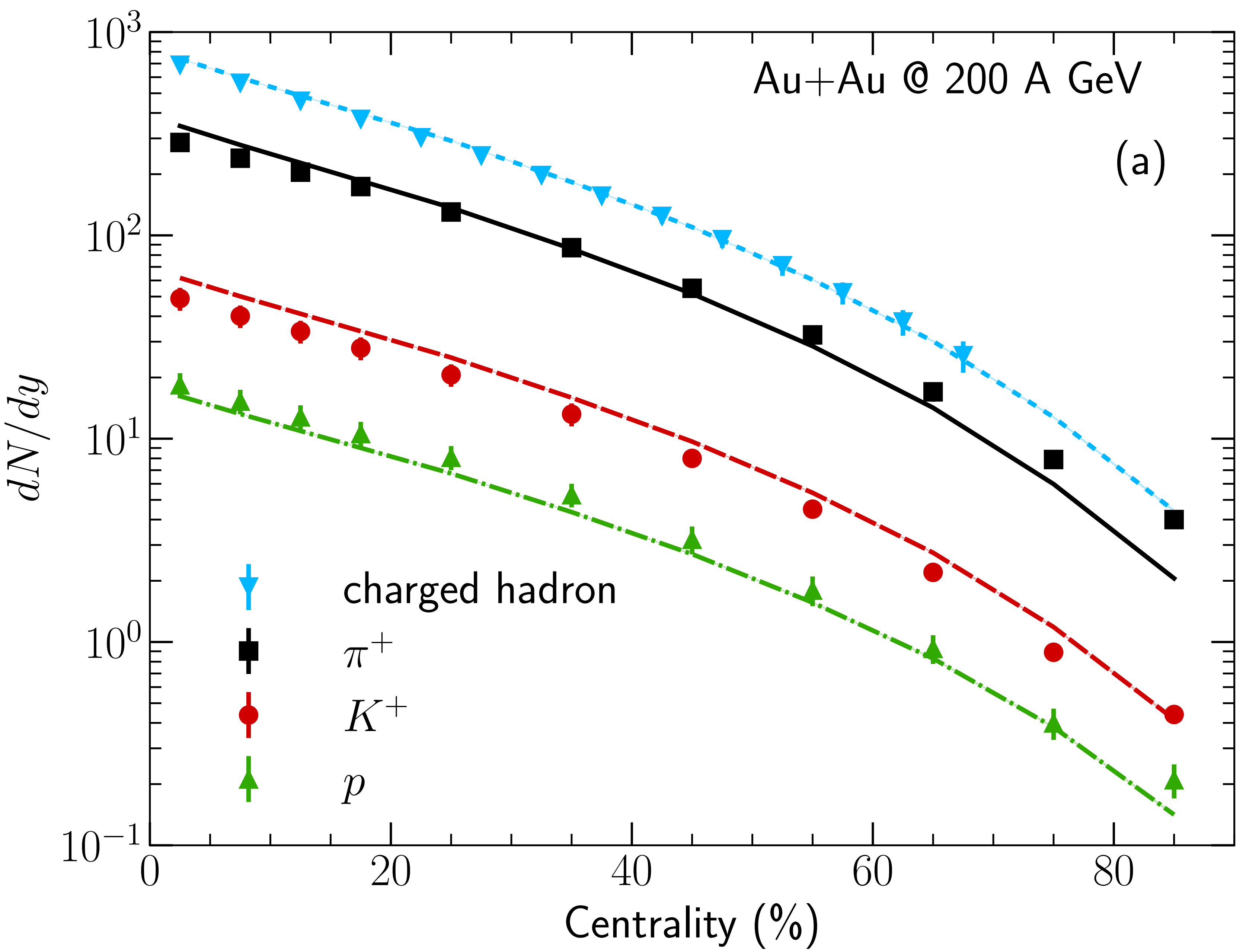
$$\vec{p}\,'_i = \vec{p}_i - \frac{p^2_{T,i}}{\langle p^2_T \rangle} \langle \vec{p} \rangle$$

  - Correction to each particle's momentum is order *1/N* where *N* is the total number of particles in the sampled event

Implemented in sampler iSS available at: `https://github.com/chunshen1987/iSS`

Identified particles

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

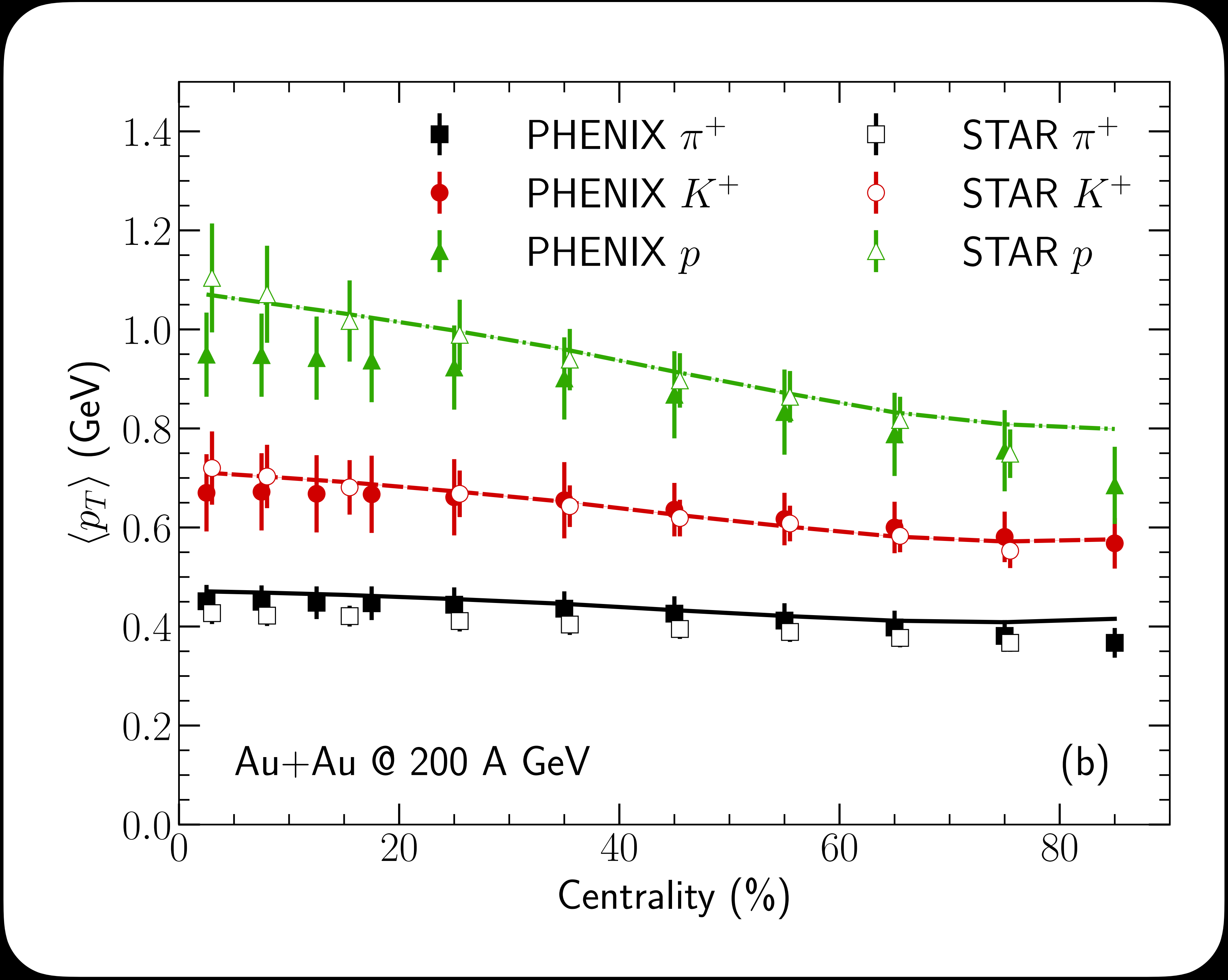


$\eta/s=0.12$

Experimental data: PHENIX Collaboration, Phys. Rev. C 69, 034909 (2004)

Mean transverse momentum

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

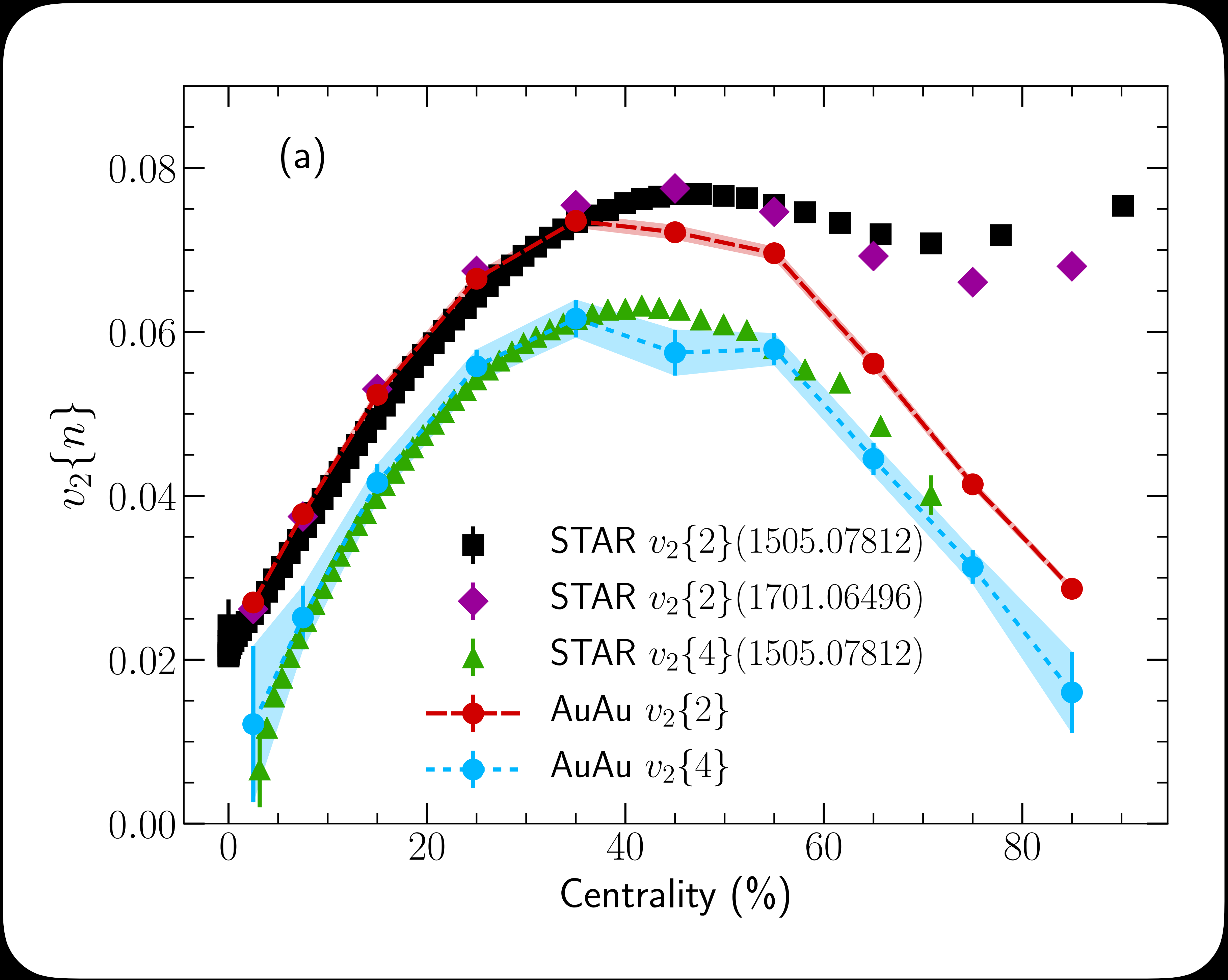


$\eta/s=0.12$

Experimental data: PHENIX Collaboration, Phys. Rev. C 69, 034909 (2004)
STAR Collaboration, Phys. Rev. C 79, 034909 (2009)

Elliptic anisotropy - Au+Au

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378



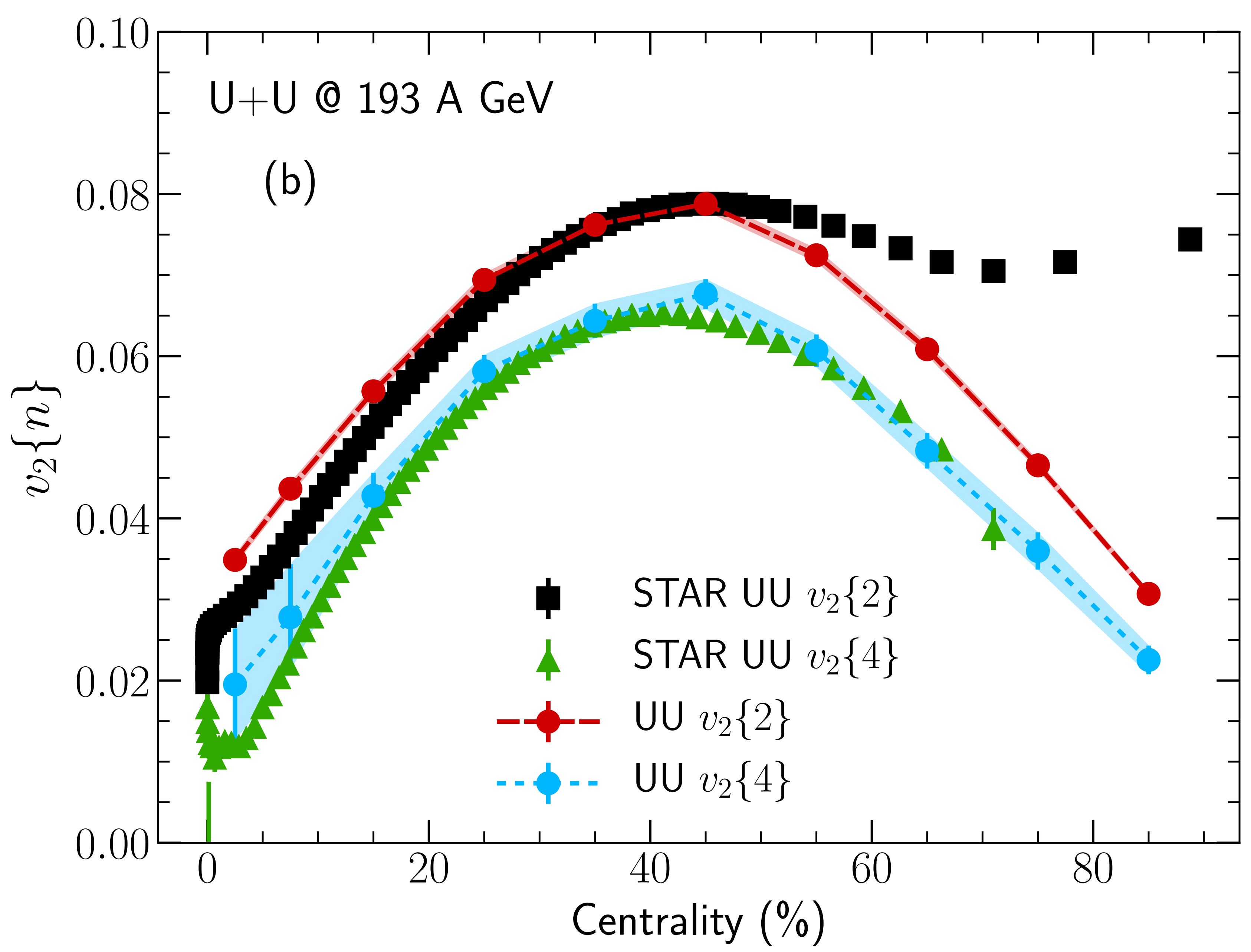
η/s=0.12

Experimental data: STAR Collaboration, Phys. Rev. Lett. 115, 222301 (2015)

Phys. Rev. C 98, 034918 (2018)

Elliptic anisotropy - U+U

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

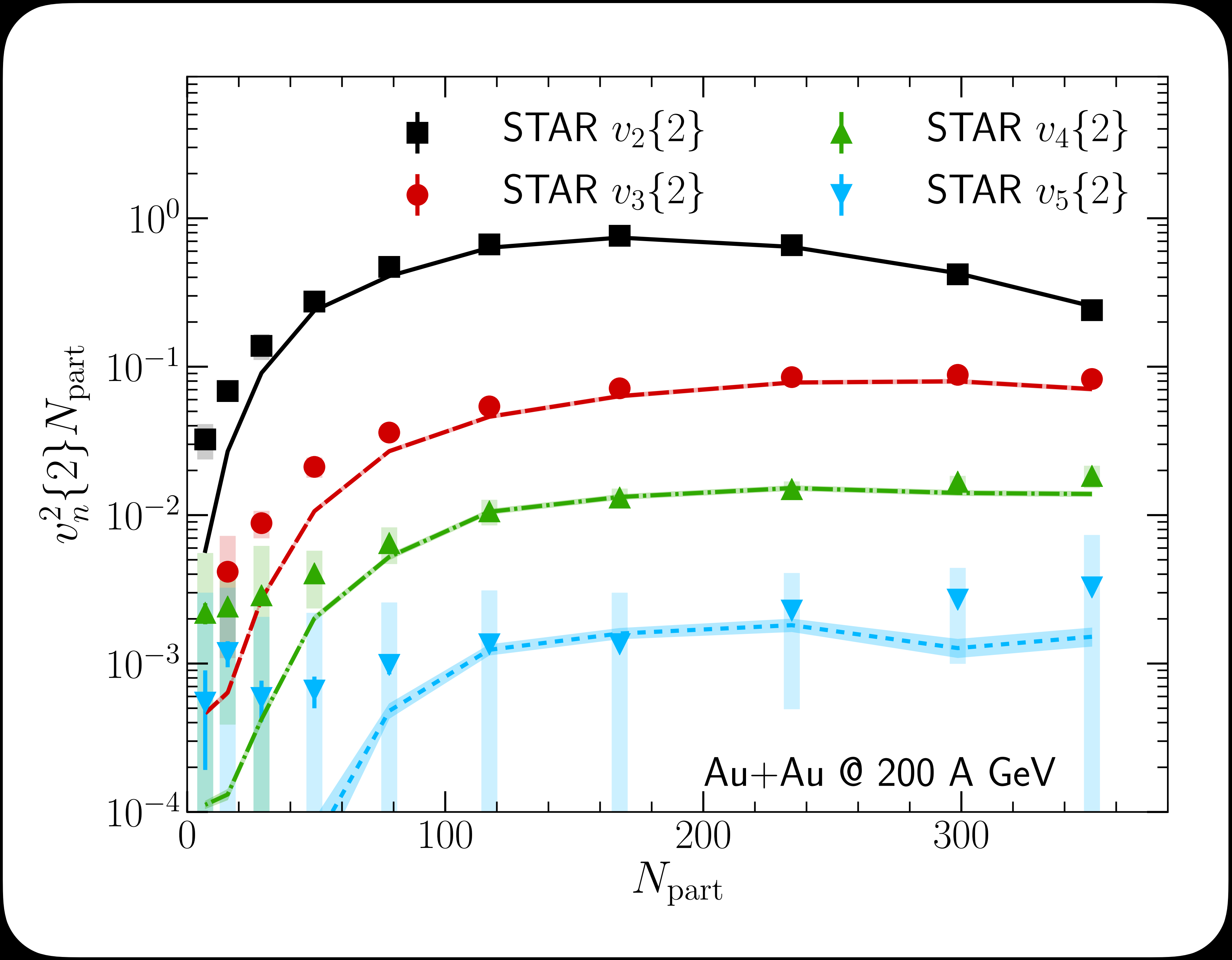


η/s=0.12

Experimental data: STAR Collaboration, Phys. Rev. Lett. 115, 222301 (2015)
Phys. Rev. C 98, 034918 (2018)

Higher harmonics (Au+Au)

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378



Experimental data: STAR Collaboration, Phys. Rev. Lett. 116, 112302 (2016), Phys. Rev. C 98, 034918 (2018)

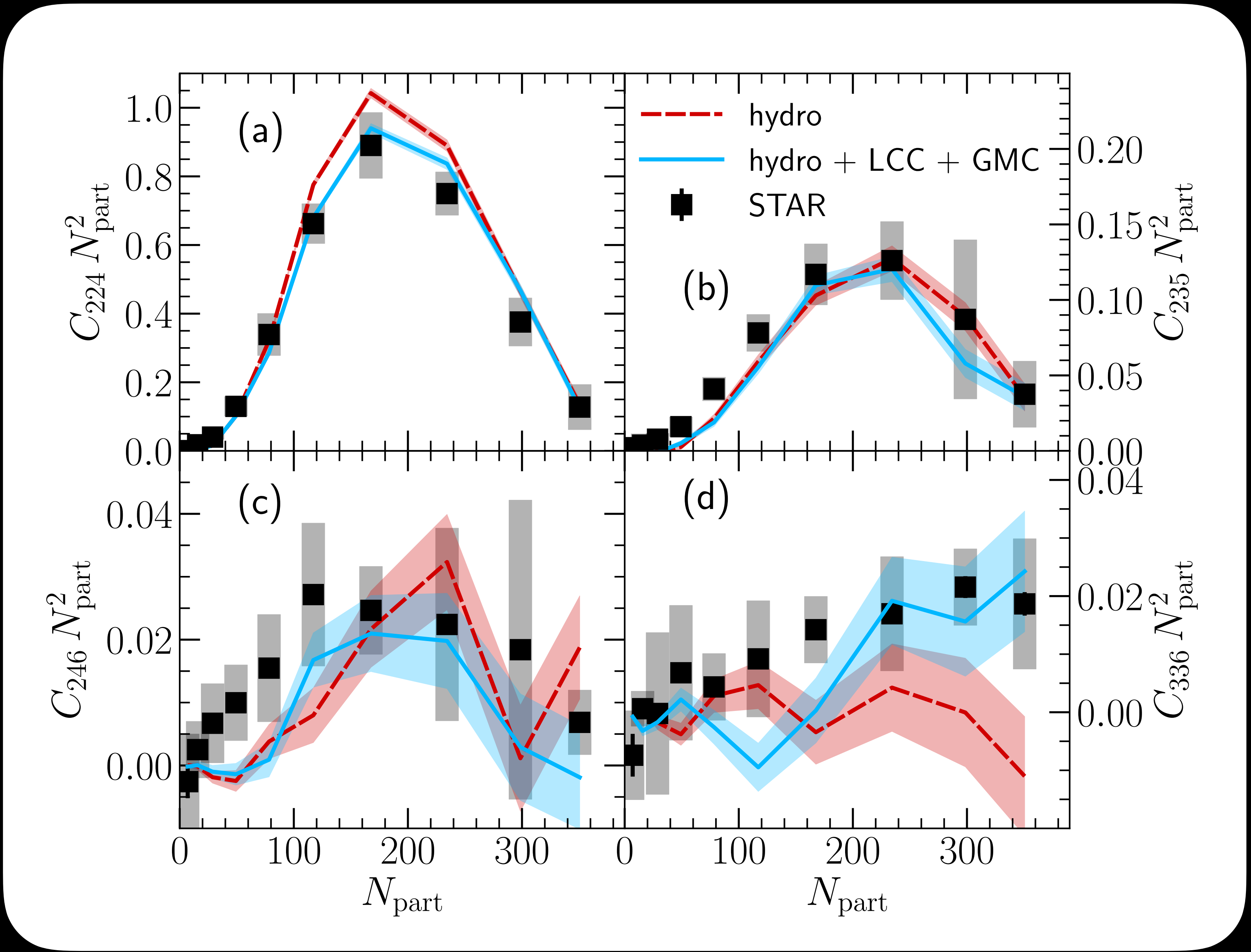
$\eta/s=0.12$

Charge inclusive 3-particle correlations

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

$$C_{mnk} = \langle \cos(m\phi_1 + n\phi_2 - k\phi_3) \rangle$$

Measures correlation between different harmonics

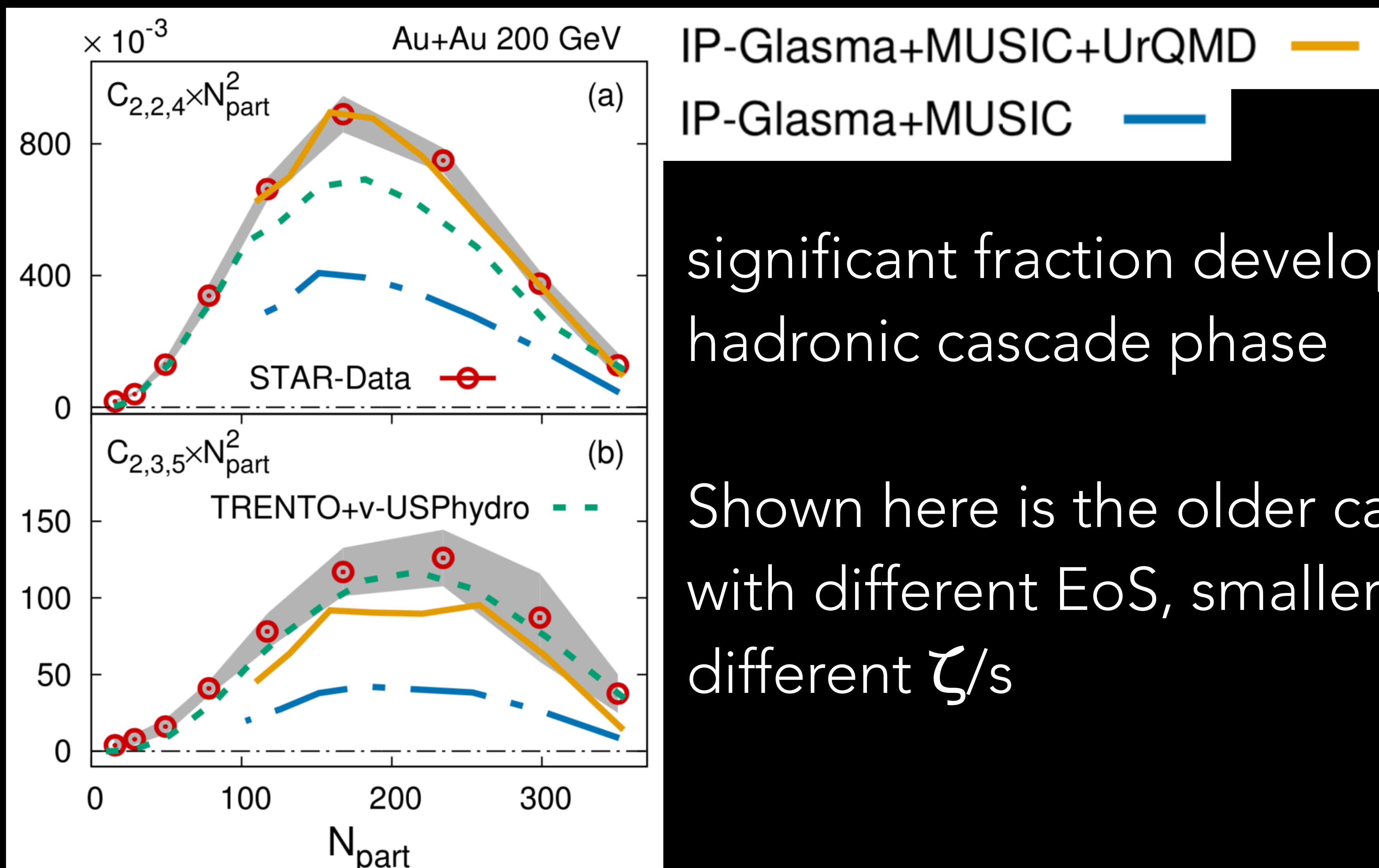


significant fraction developed in the hadronic cascade phase

Experimental data: STAR Collaboration, Phys. Rev. C 98, 034918 (2018)

Charge inclusive 3-particle correlations

$$C_{mnk} = \langle \cos(m\phi_1 + n\phi_2 - k\phi_3) \rangle$$



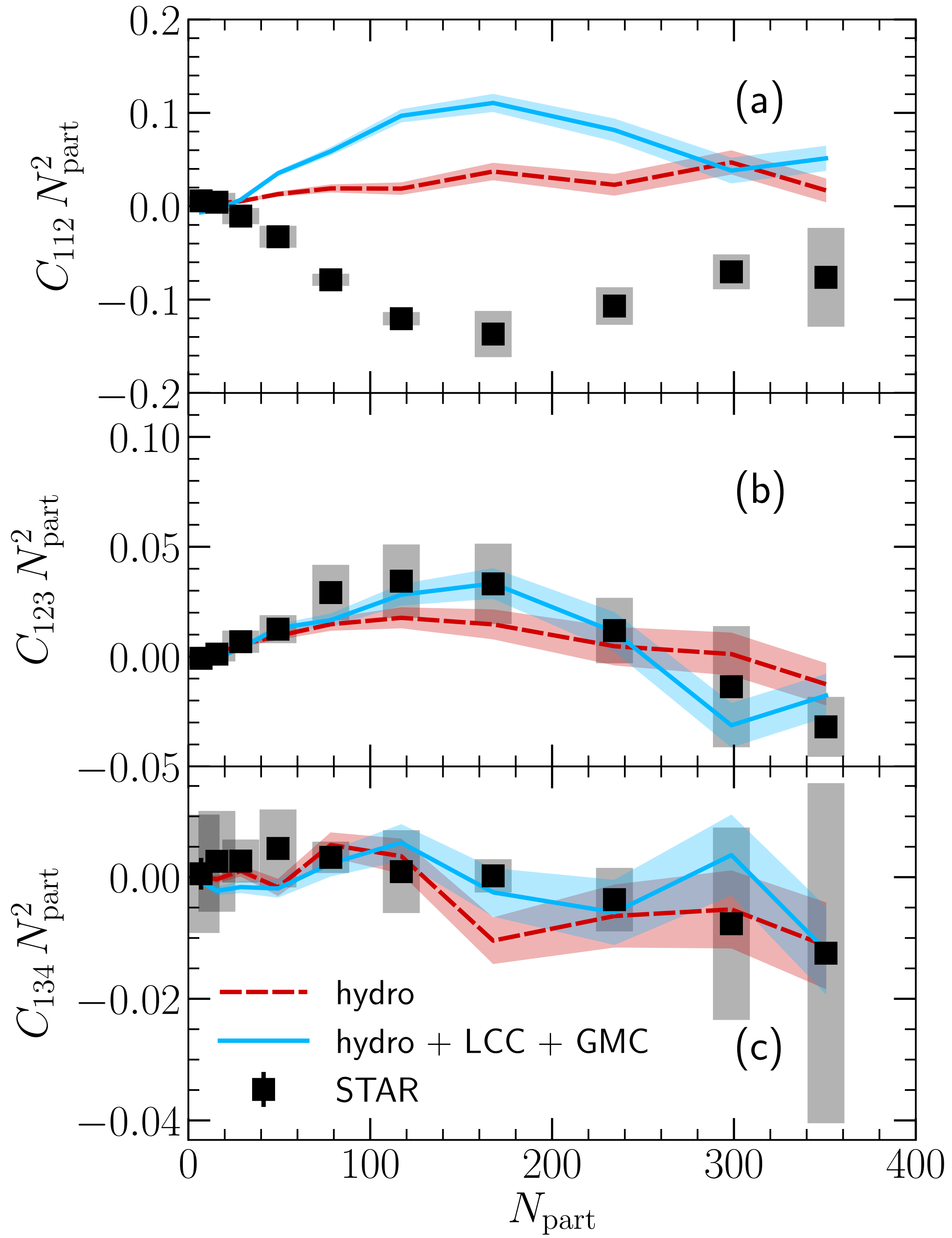
significant fraction developed in the hadronic cascade phase

Shown here is the older calculation with different EoS, smaller **η**/s, different ζ/s

Experimental data: STAR Collaboration, Phys. Rev. C 98, 034918 (2018)

Charge inclusive 3-particle correlations

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378



Correlators involving v_1 are sensitive to momentum conservation

Implementation of local momentum conservation in the sampling process will likely improve agreement with C_{112} from STAR

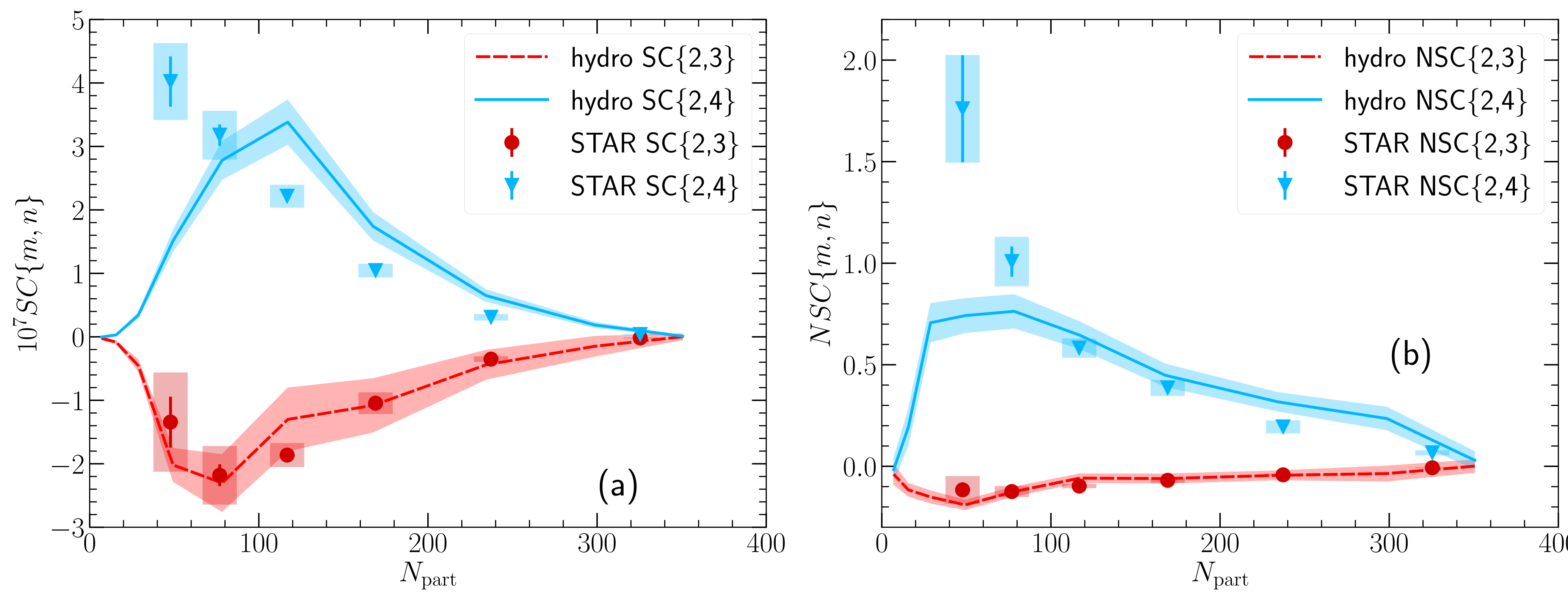
Experimental data:
STAR Collaboration, Phys. Rev. C 98, 034918 (2018)

4-particle symmetric cumulants

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

$$SC\{m,n\} = \frac{\langle Q_n Q_n^* Q_m Q_m^* \rangle_{\rm ev}}{\langle M(M-1)(M-2)(M-3)\rangle_{\rm ev}} - \frac{\langle Q_n Q_n^* \rangle}{\langle M(M-1)\rangle_{\rm ev}} \frac{\langle Q_m Q_m^* \rangle}{\langle M(M-1)\rangle_{\rm ev}}$$

A. Bilandzic et al, Phys. Rev. C 89, 064904 (2014)



$$Q_n = \sum_{j=1}^{M} e^{in\phi_j}$$

Effect of hadronic afterburner is strong:

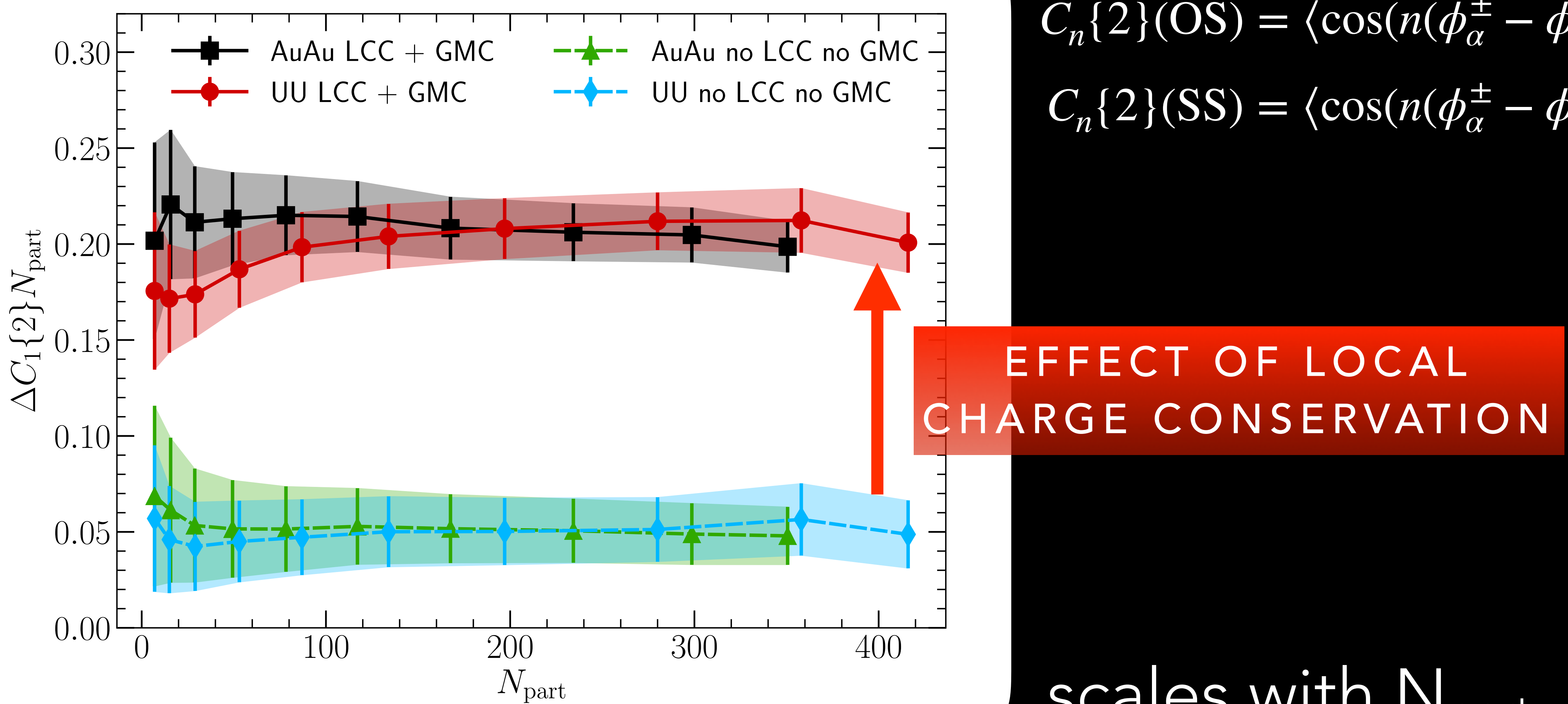
20-30%	10^7 SC{2,3}	10^7 SC{2,4}
DECAY ONLY	-0.3(4)	0.9(1)
URQMD	-1.1(4)	1.7(2)

Experimental data:
STAR Collaboration, arXiv:1803.03876

Charge dependent correlators

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

$$\Delta C_n\{2\} = C_n\{2\}(\mathrm{OS}) - C_n\{2\}(\mathrm{SS})$$



$$C_n\{2\}(\mathrm{OS}) = \langle \cos(n(\phi_\alpha^{\pm} - \phi_\beta^{\mp}))\rangle$$

$$C_n\{2\}(\mathrm{SS}) = \langle \cos(n(\phi_\alpha^{\pm} - \phi_\beta^{\pm}))\rangle$$

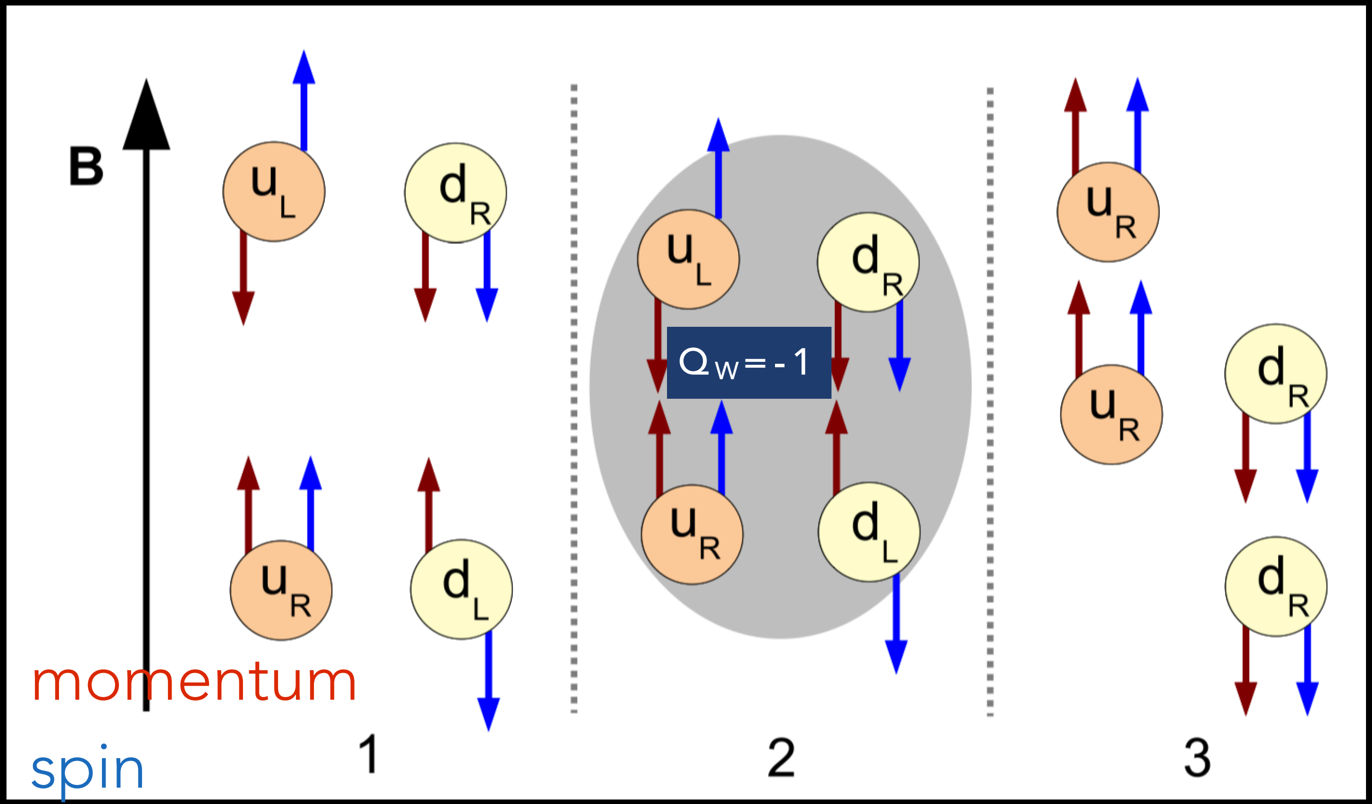
scales with N_{part}

One slide of Chiral Magnetic Effect

see D. Kharzeev, L.D. McLerran, H.J. Warringa, Nucl.Phys.A803 : 227-253 (2008)

- QCD has topologically non-trivial configurations of gauge fields characterized by Chern-Simons topological charge
- Sphaleron configurations dominate at high temperature
- Configurations with positive topological charge convert right-handed fermions into left-handed ones $(N_L^f - N_R^f) = 2Q_w$
- Large magnetic field suppresses spin flip, so momenta change

- In the example a net chirality is induced by the gauge field, then a net charge separation is generated by the current along the magnetic field



Correlators sensitive to charge separation

S. Voloshin, PRC 70, 057901 (2004)

- Measure difference in correlations along the x and y axes:

$$C_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$$

  Correlations that do not depend on the orientation with respect to the reaction plane cancel out
- In case of the CME:
  - α=+/- and β=+/- (same sign): negative C_{112}
  - α=+/- and β=-/+ (opposite sign): positive C_{112}

- Generally consider the difference

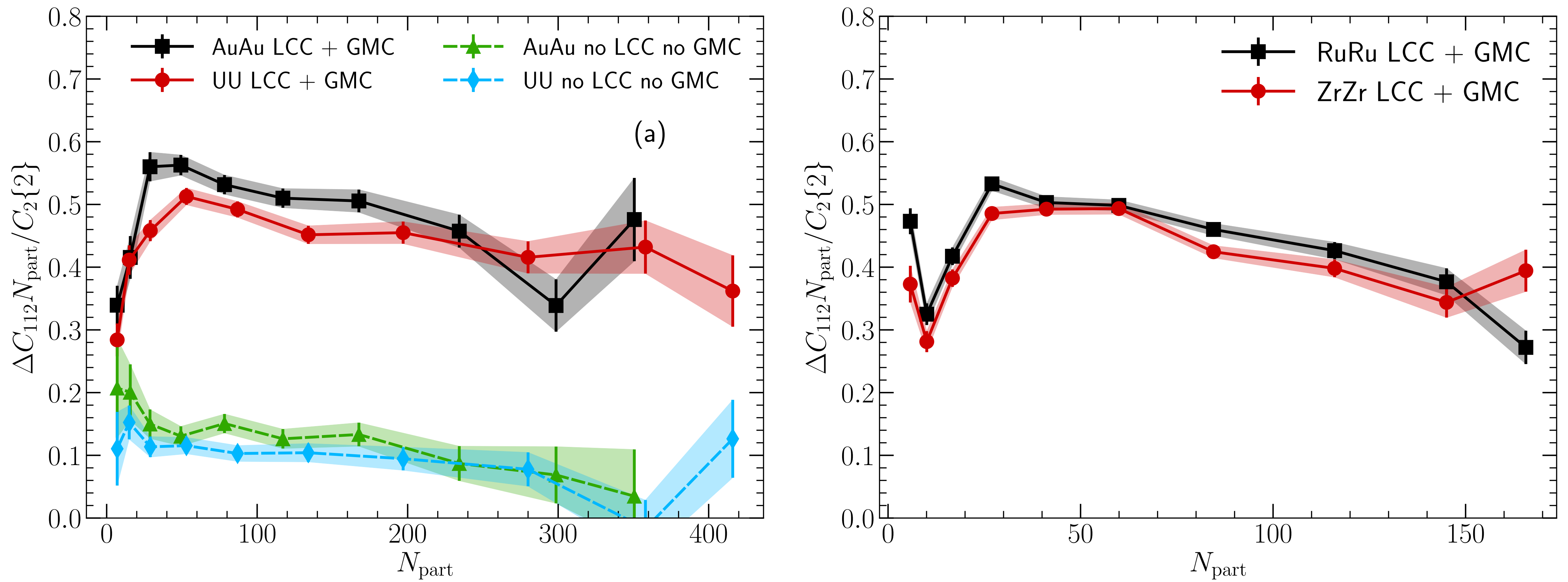
$$\Delta C_{mnk} = C_{mnk}(\mathrm{OS}) - C_{mnk}(\mathrm{SS})$$

  here we also cancel effects of local momentum conservation

Baseline for the CME search

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

Au+Au and U+U   RHIC Isobar run

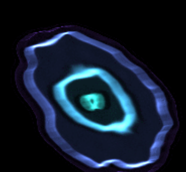


Difference in magnetic field between Ru and Zr expected to lead to ~10-15% larger ΔC_{112} for Ru from CME

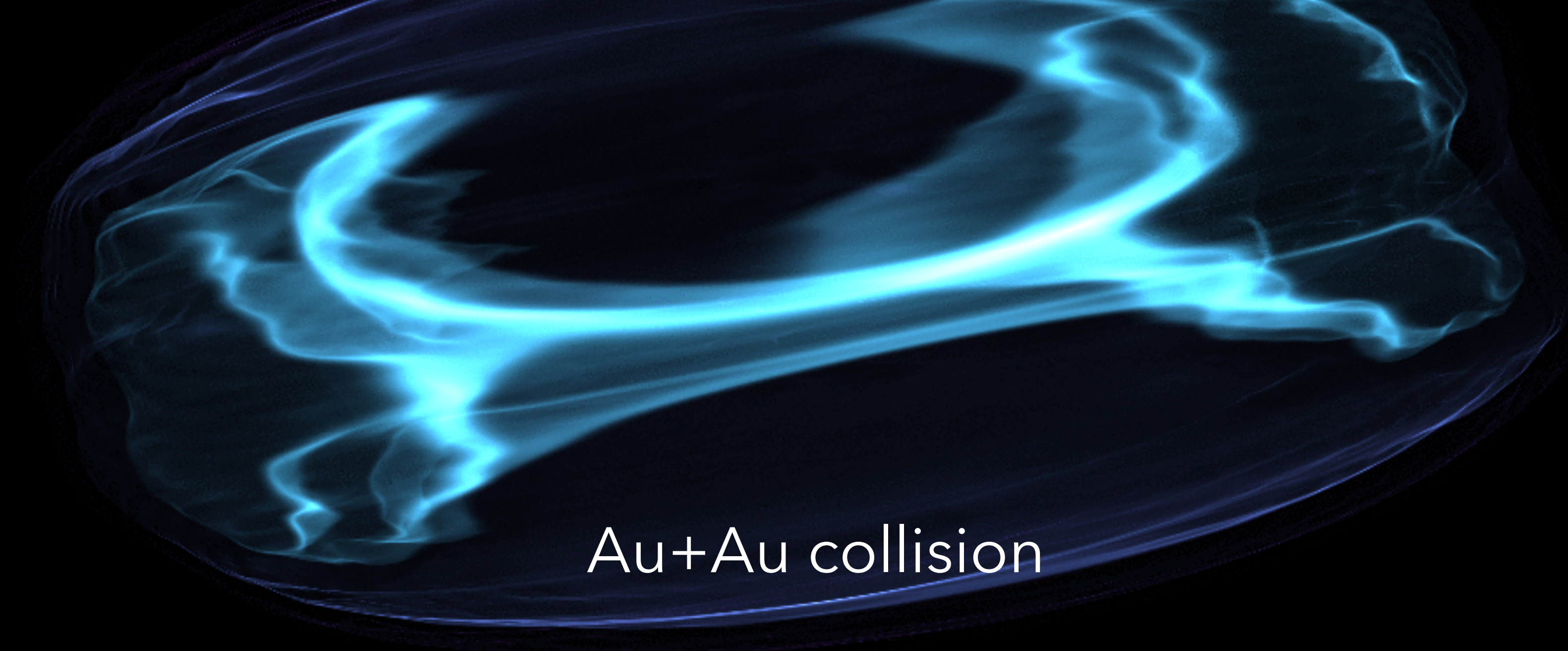
Deng, Huang, Ma, Wang, Phys. Rev. C 97, 044901 (2018); Shi, Jiang, Lilleskov, Liao, Annals of Physics 394 (2018) 50-72; Sun, Ko, Phys. Rev. C 98, 014911 (2018)

Going smaller: What is the dominant origin of azimuthal anisotropies in small systems?

- Initial momentum anisotropy from CGC (in IP-Glasma)
- Hydrodynamics with shear and bulk viscosities
- Parameters fixed using shown AA calculations (and HERA)
  - add 3 hotspot substructure
- Predict v_n in p+Au and d+Au collisions ^{3}He+Au to come



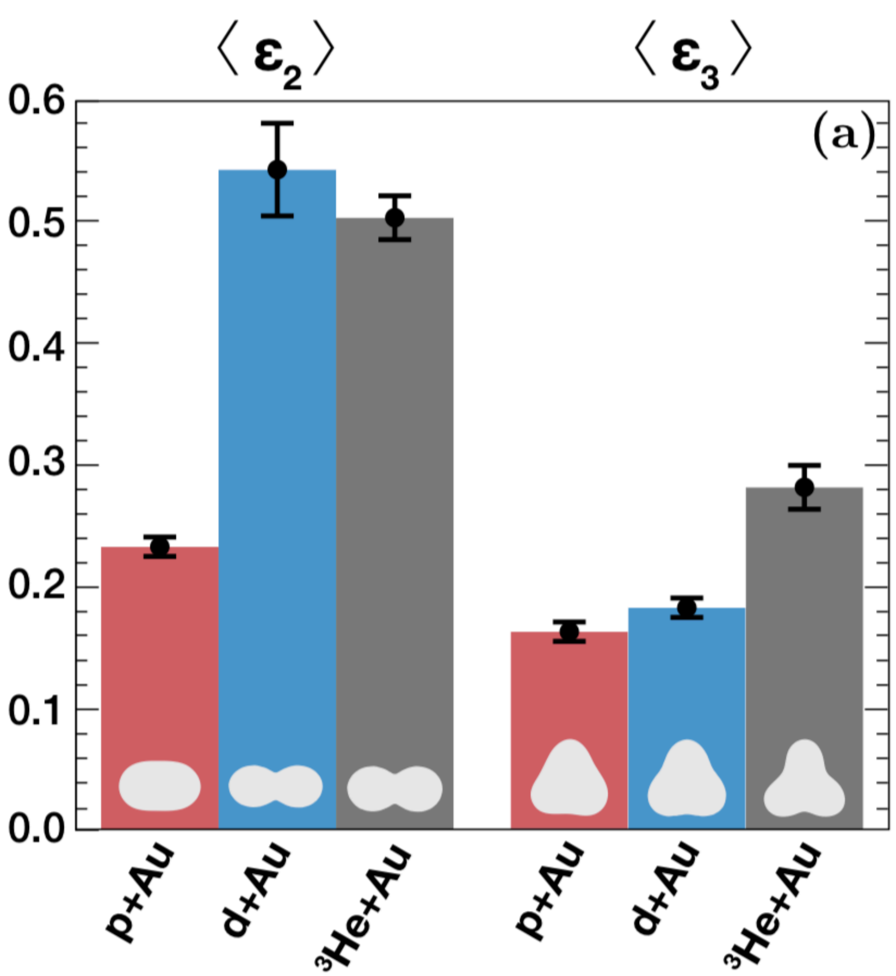
p+Au collision

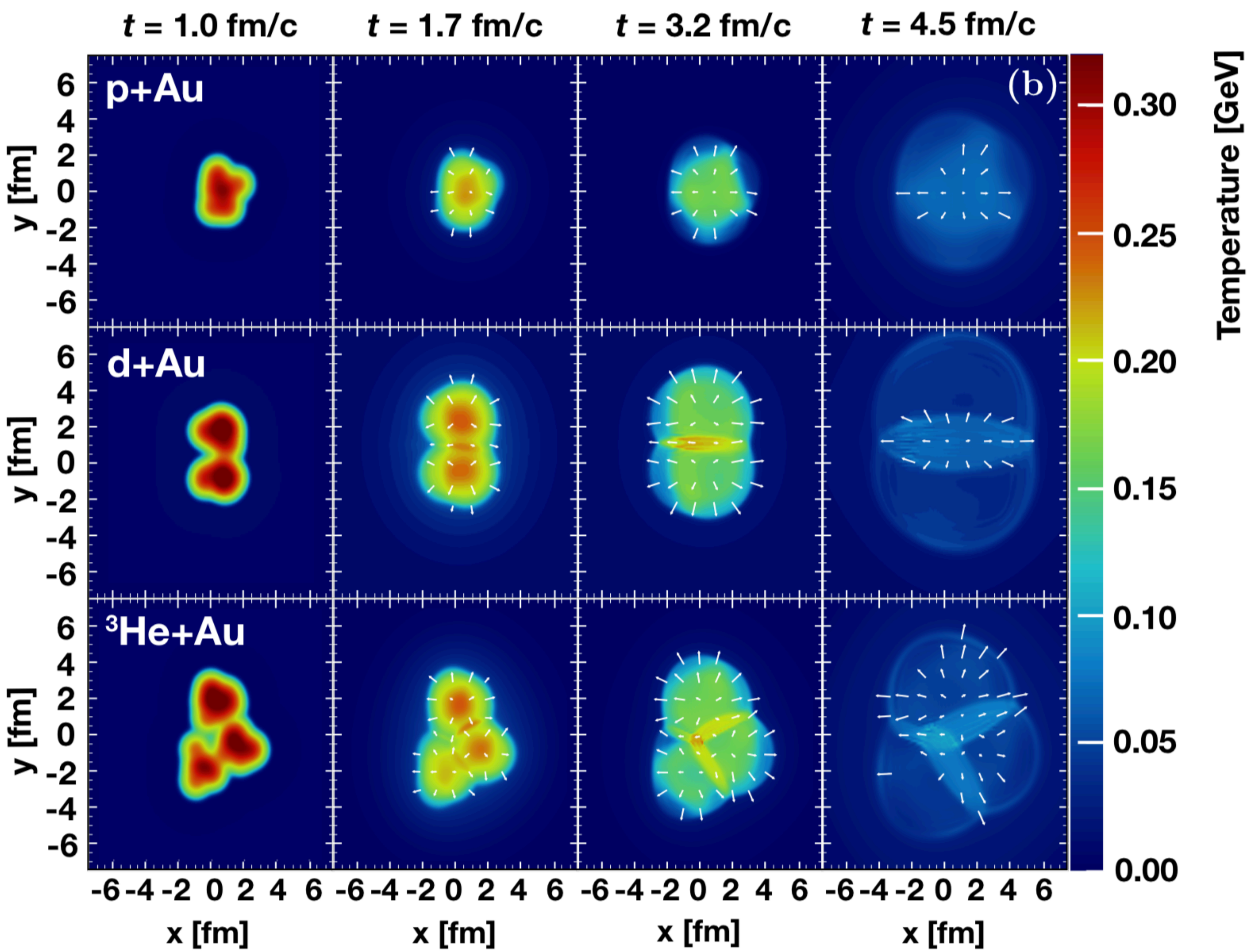


Au+Au collision

RHIC system scan: pAu, dAu, ^{3}HeAu

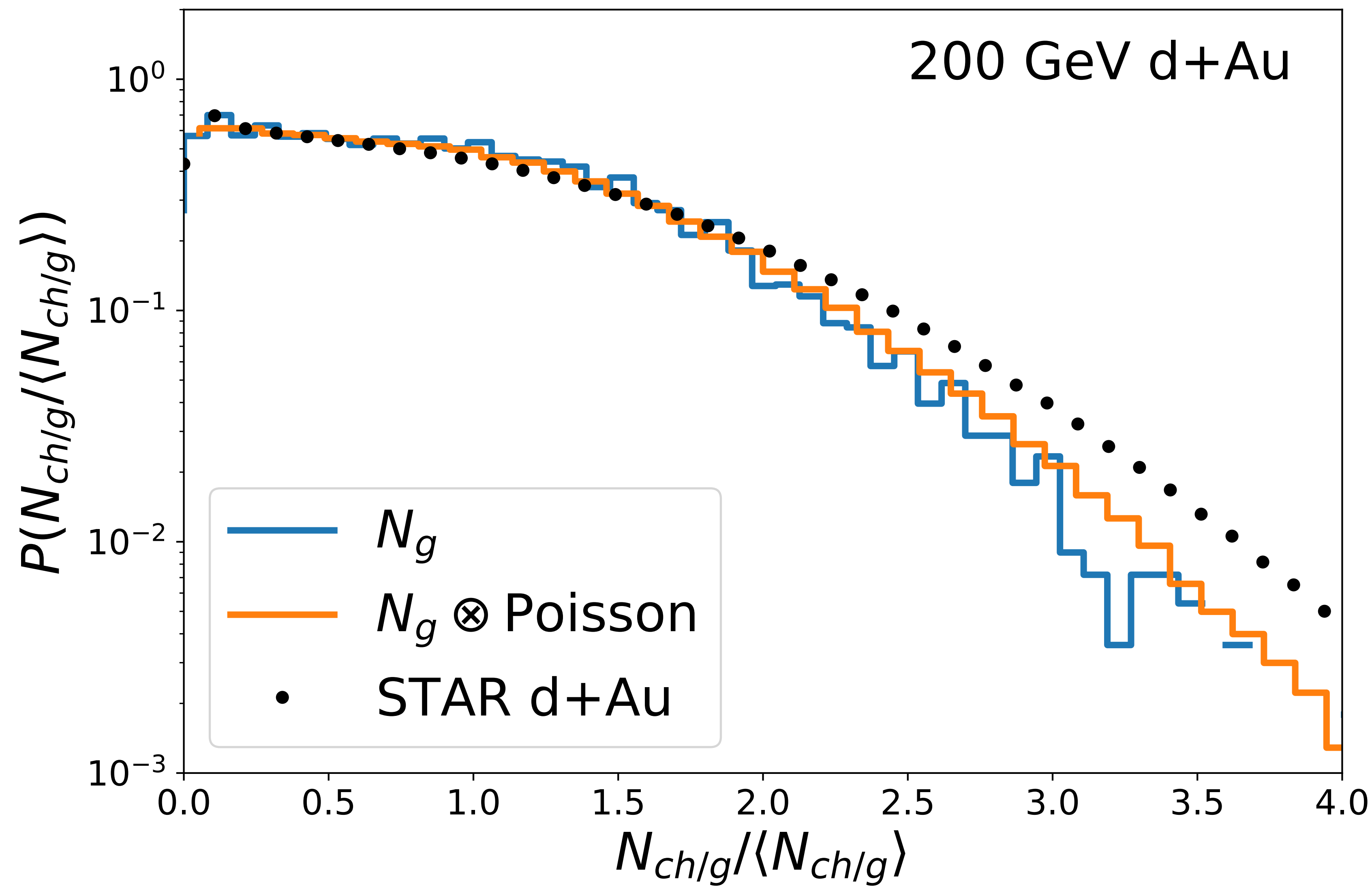
PHENIX Collaboration, arXiv:1805.02973v2





RHIC system scan

B. Schenke, C. Shen, P. Tribedy, in preparation

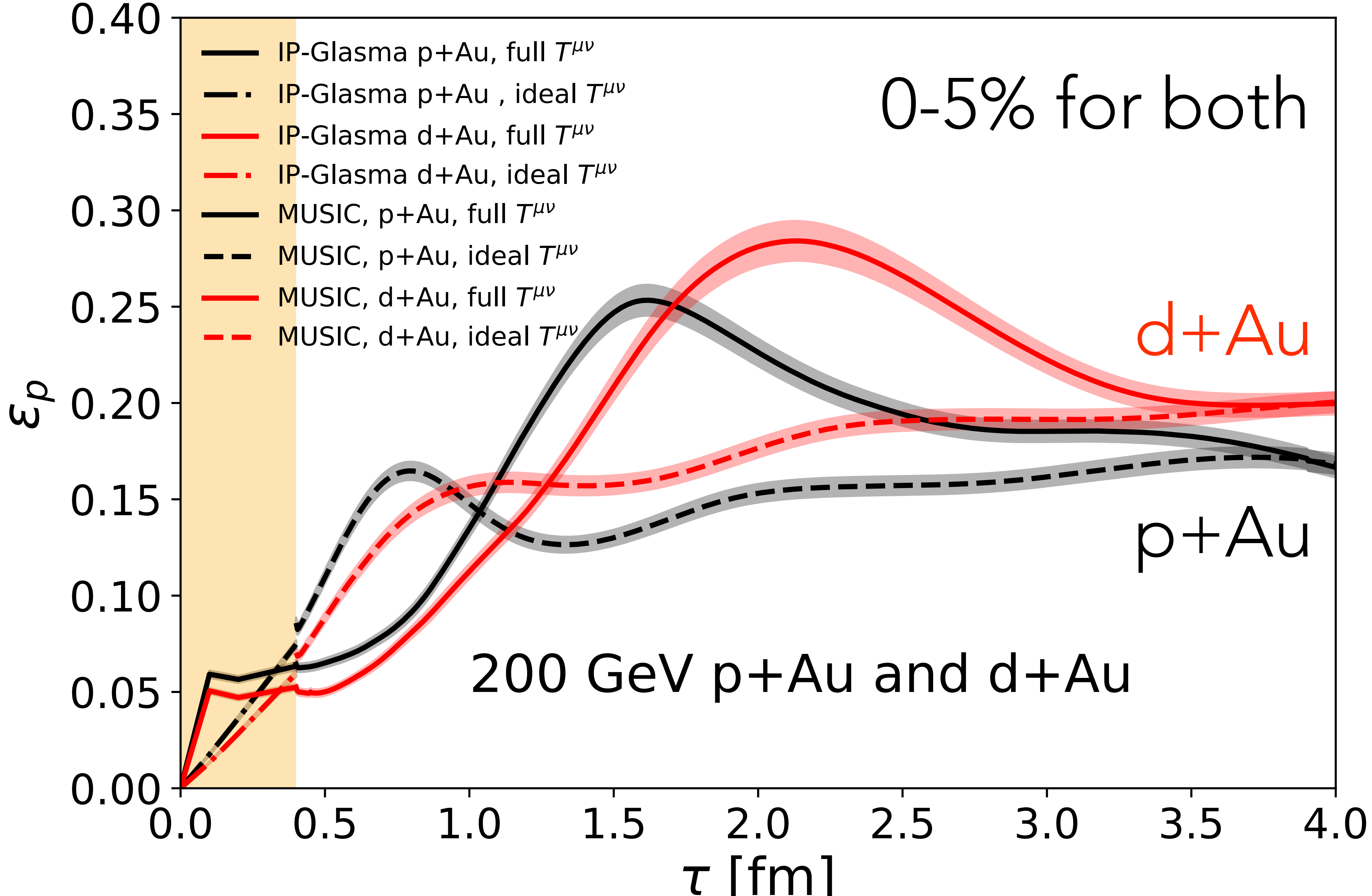


Multiplicity distribution: d+Au 200 GeV

RHIC system scan

$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

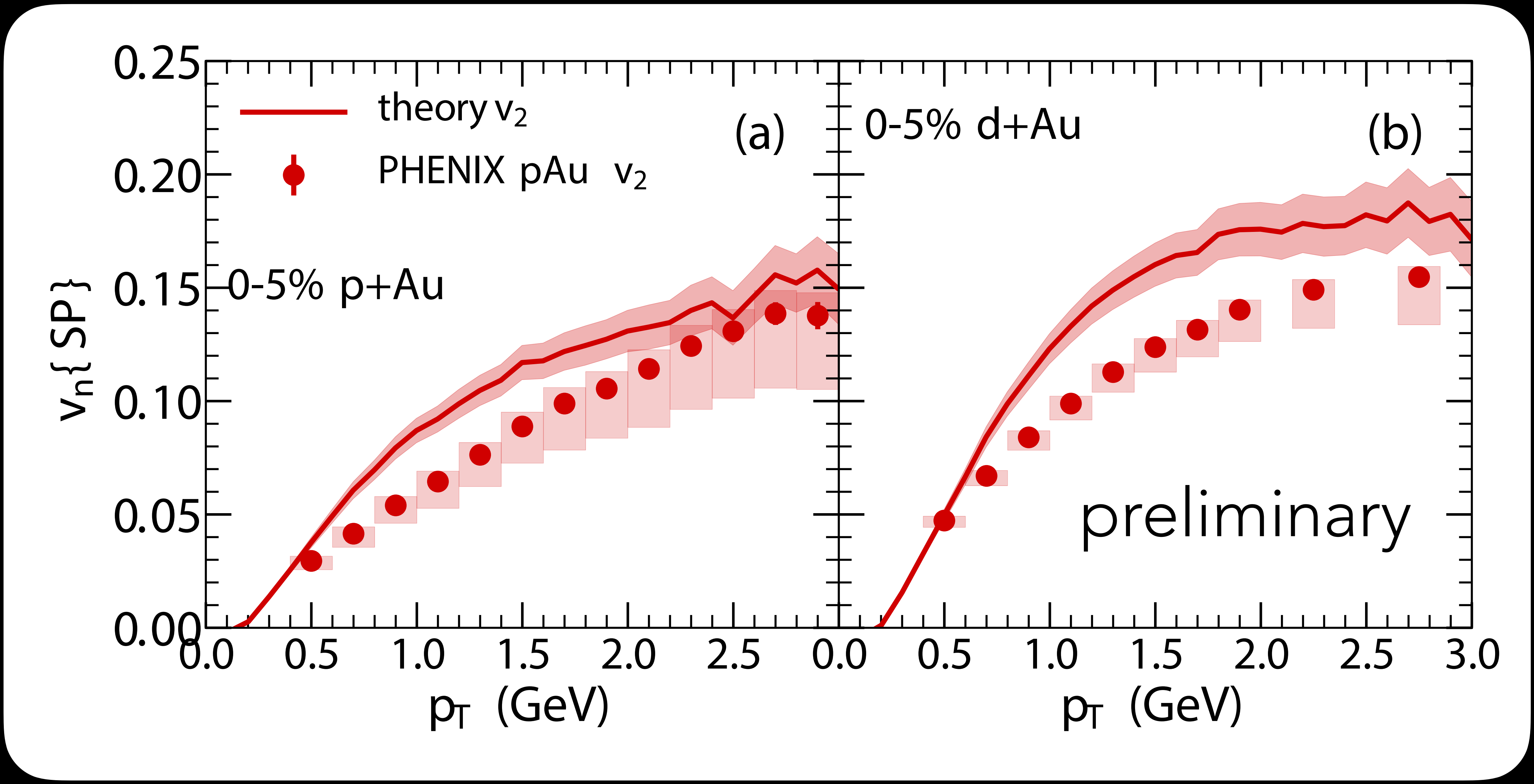
B. Schenke, C. Shen, P. Tribedy, in preparation



v_2 in pAu and dAu at 0-5%

B. Schenke, C. Shen, P. Tribedy, in preparation

$\eta/s=0.12$

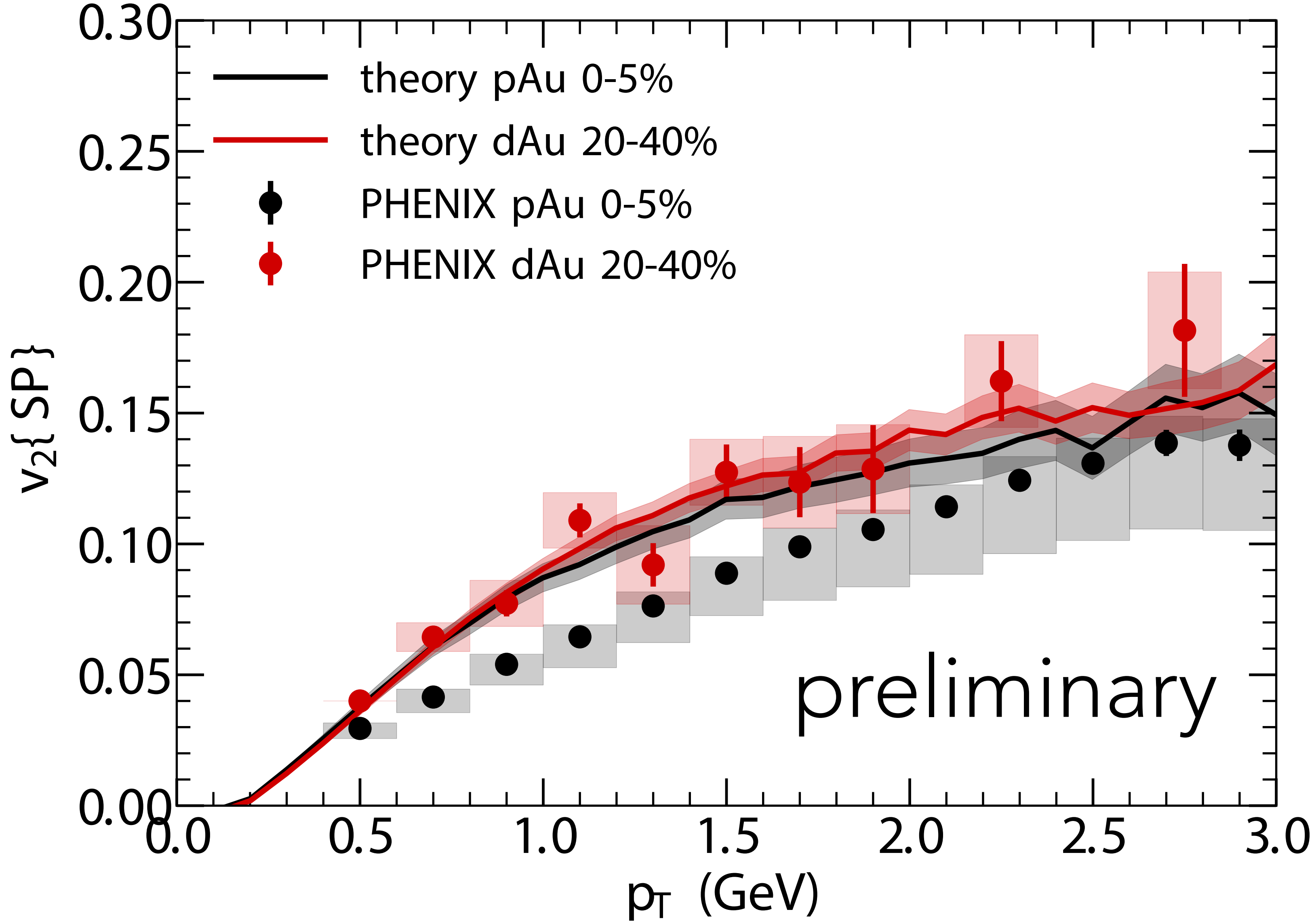


PHENIX Collaboration, e-Print: arXiv:1805.02973

Calculation: $dN/d\eta$ = 19.6 for dAu, 11.3 for pAu

v_2 in pAu and dAu at ~same N_{ch}

B. Schenke, C. Shen, P. Tribedy, in preparation



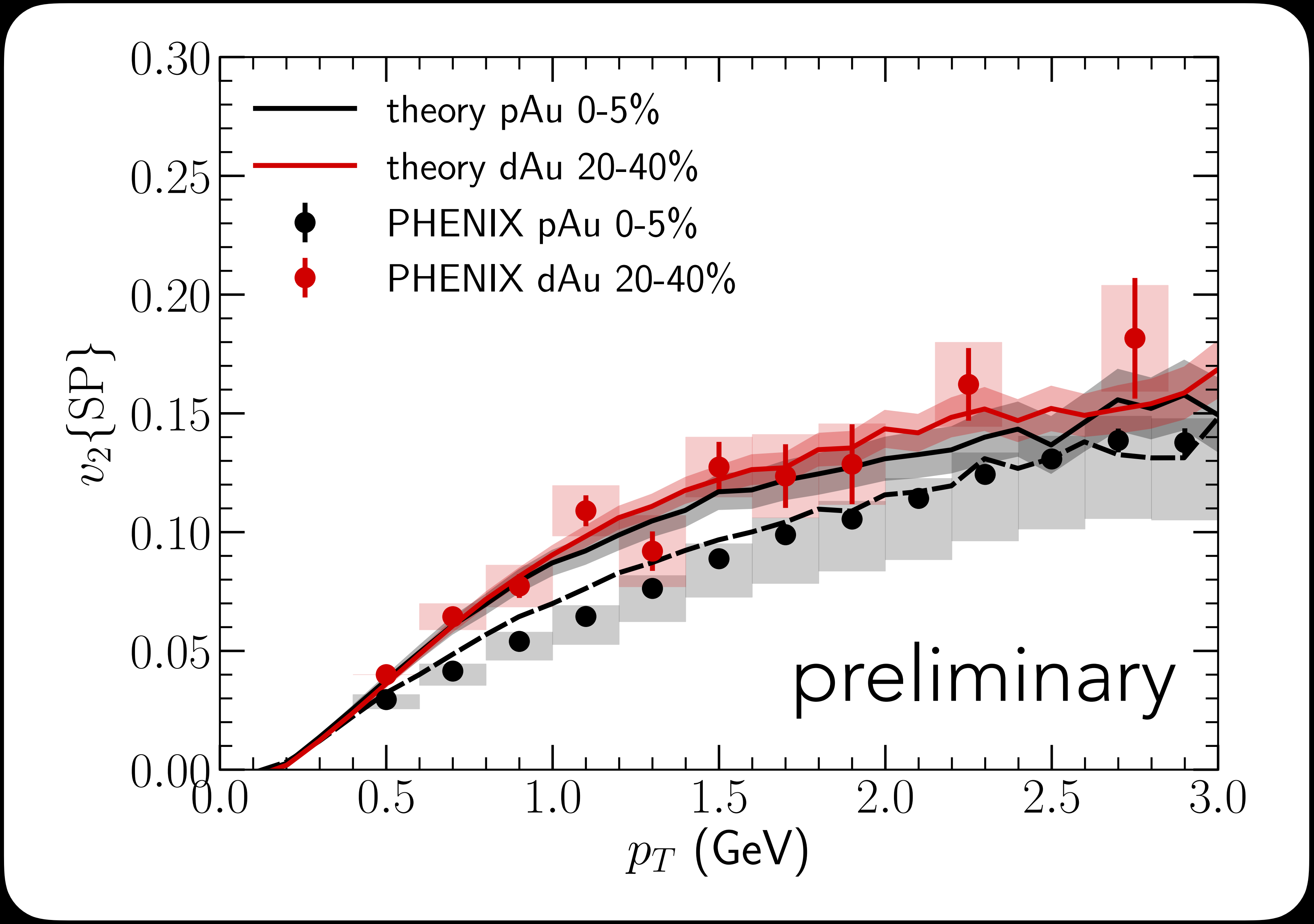
$\eta/s=0.12$

PHENIX Collaboration, e-Print: arXiv:1805.02973

Calculation: $dN/d\eta$ = 9.8 for dAu, 11.3 for pAu

v_2 in pAu and dAu at ~same N_{ch}

B. Schenke, C. Shen, P. Tribedy, in preparation



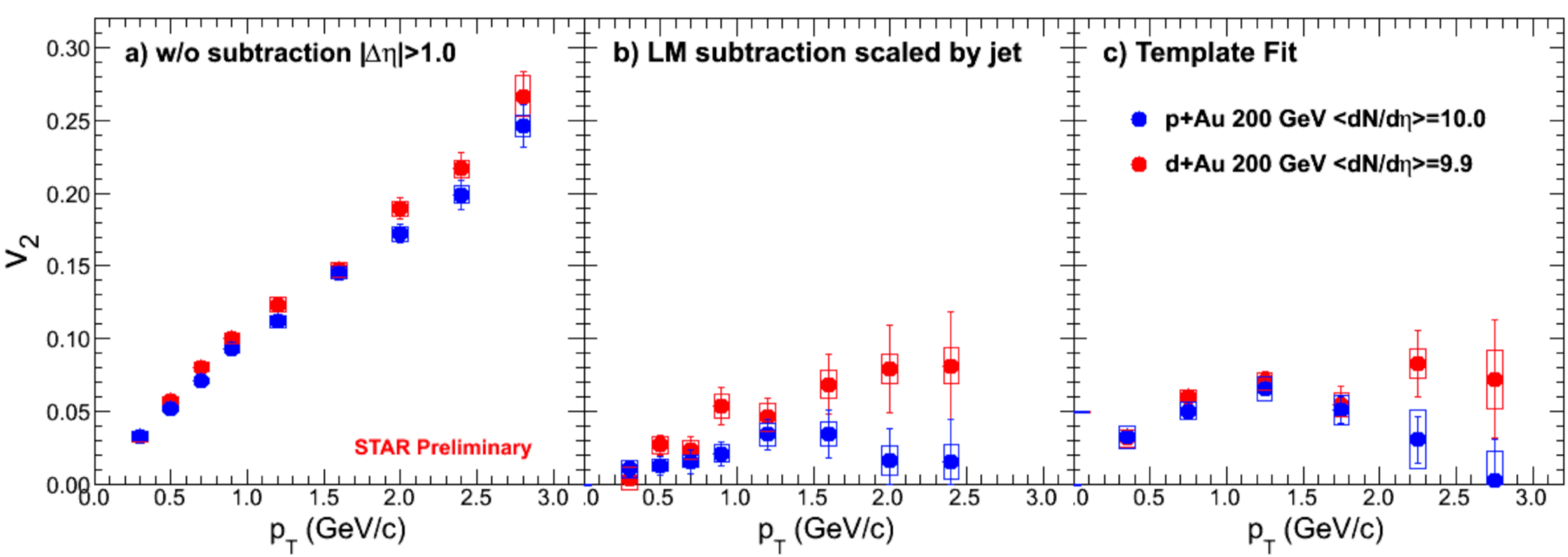
dashed line: different parameters for fluctuating proton

dAu little affected

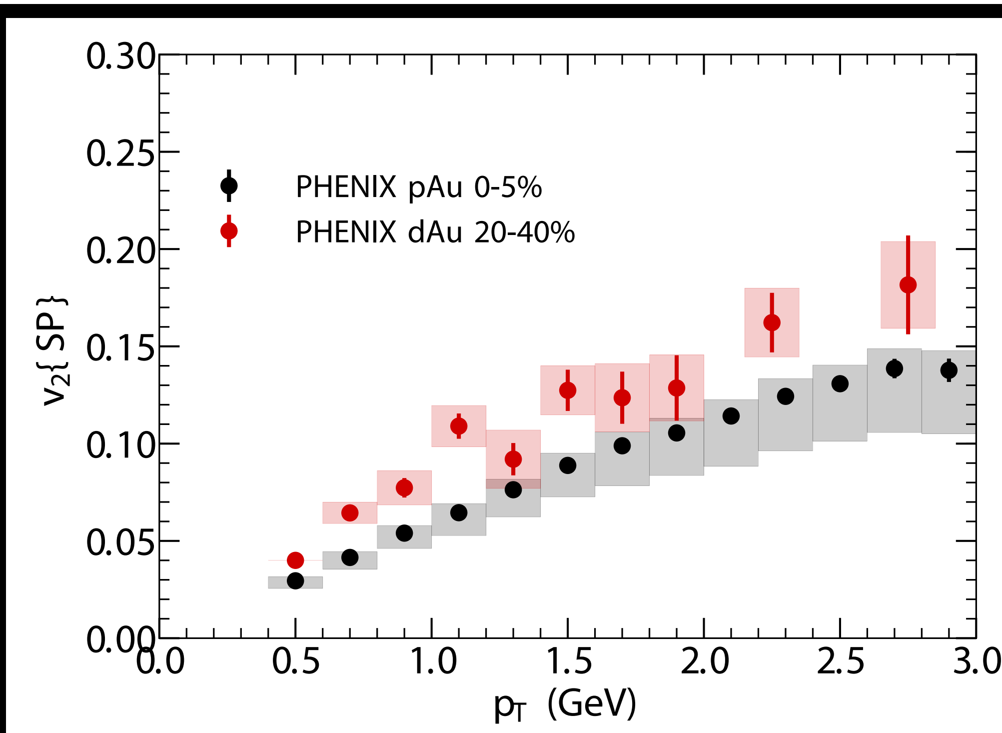
PHENIX Collaboration, e-Print: arXiv:1805.02973

Calculation: $dN/d\eta$ = 9.8 for dAu, 11.3 for pAu

Data: v_2 in pAu and dAu at ~same N_{ch}

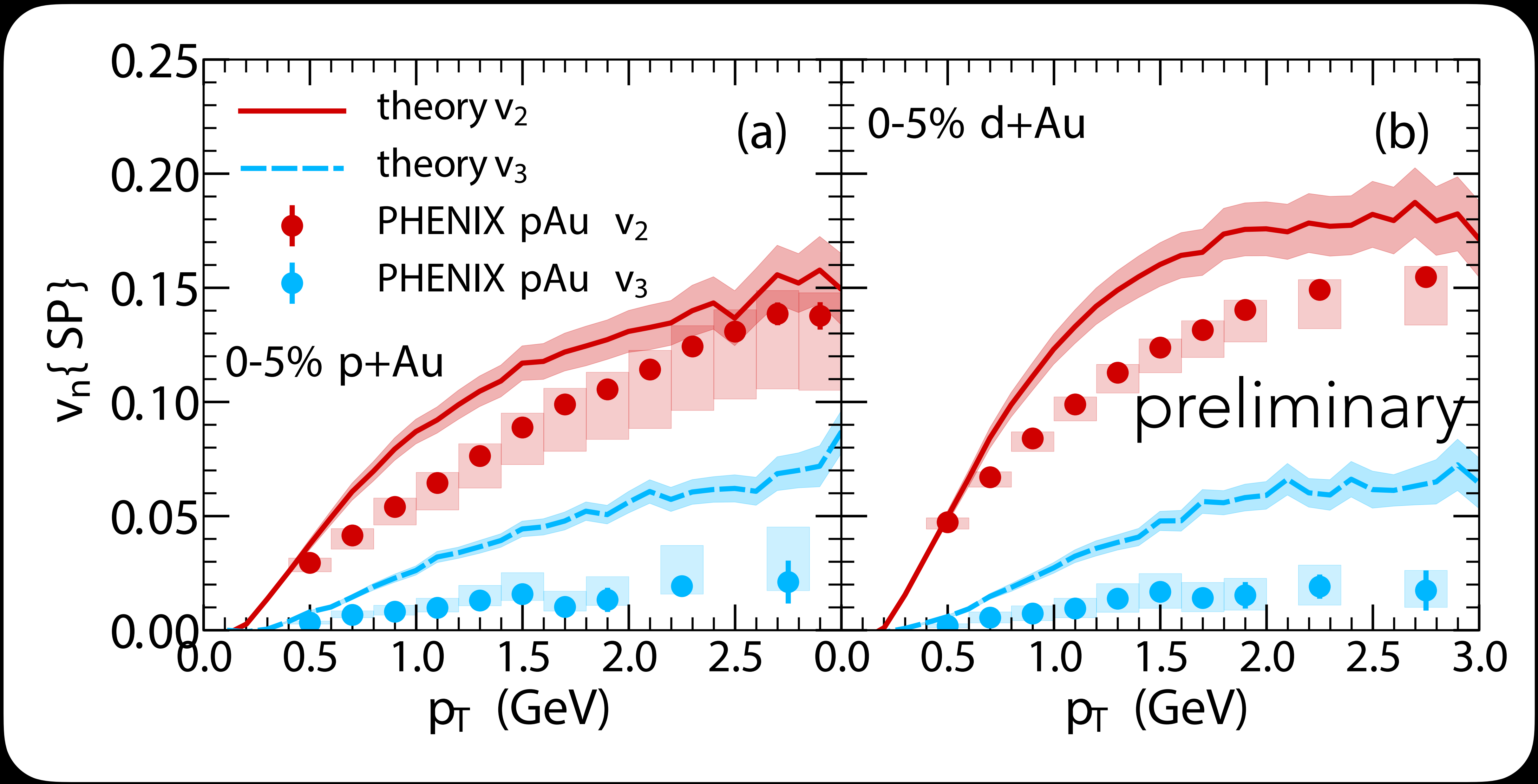


STAR Collaboration, talk by Shengli Huang, QM2018
PHENIX Collaboration, e-Print: arXiv:1805.02973



v_3 in pAu and dAu - too large…

B. Schenke, C. Shen, P. Tribedy, in preparation

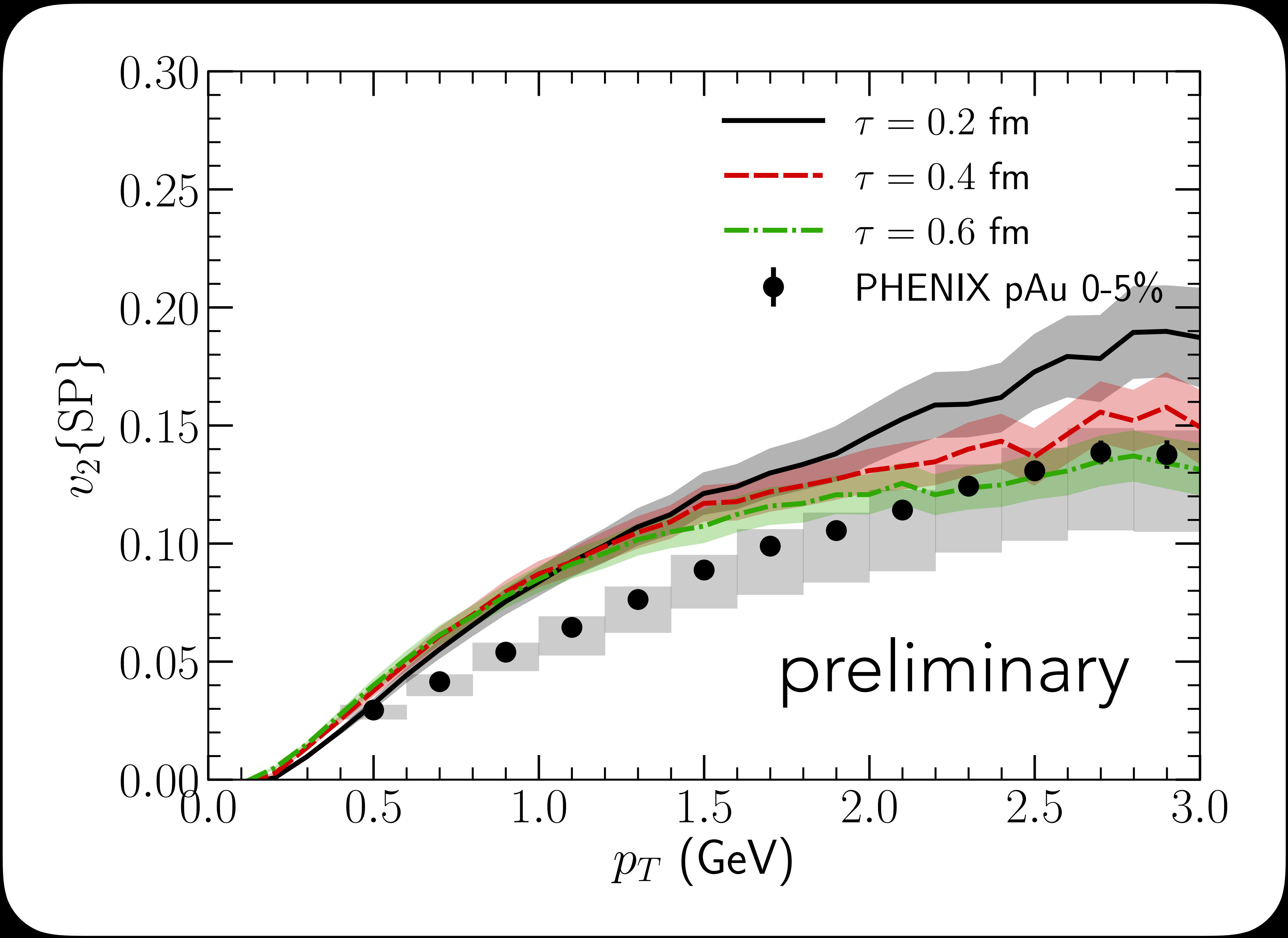


PHENIX Collaboration, e-Print: arXiv:1805.02973

Calculation: $dN/d\eta$ = 19.6 for dAu, 11.3 for pAu

Effect of switching time on v_2

B. Schenke, C. Shen, P. Tribedy, in preparation



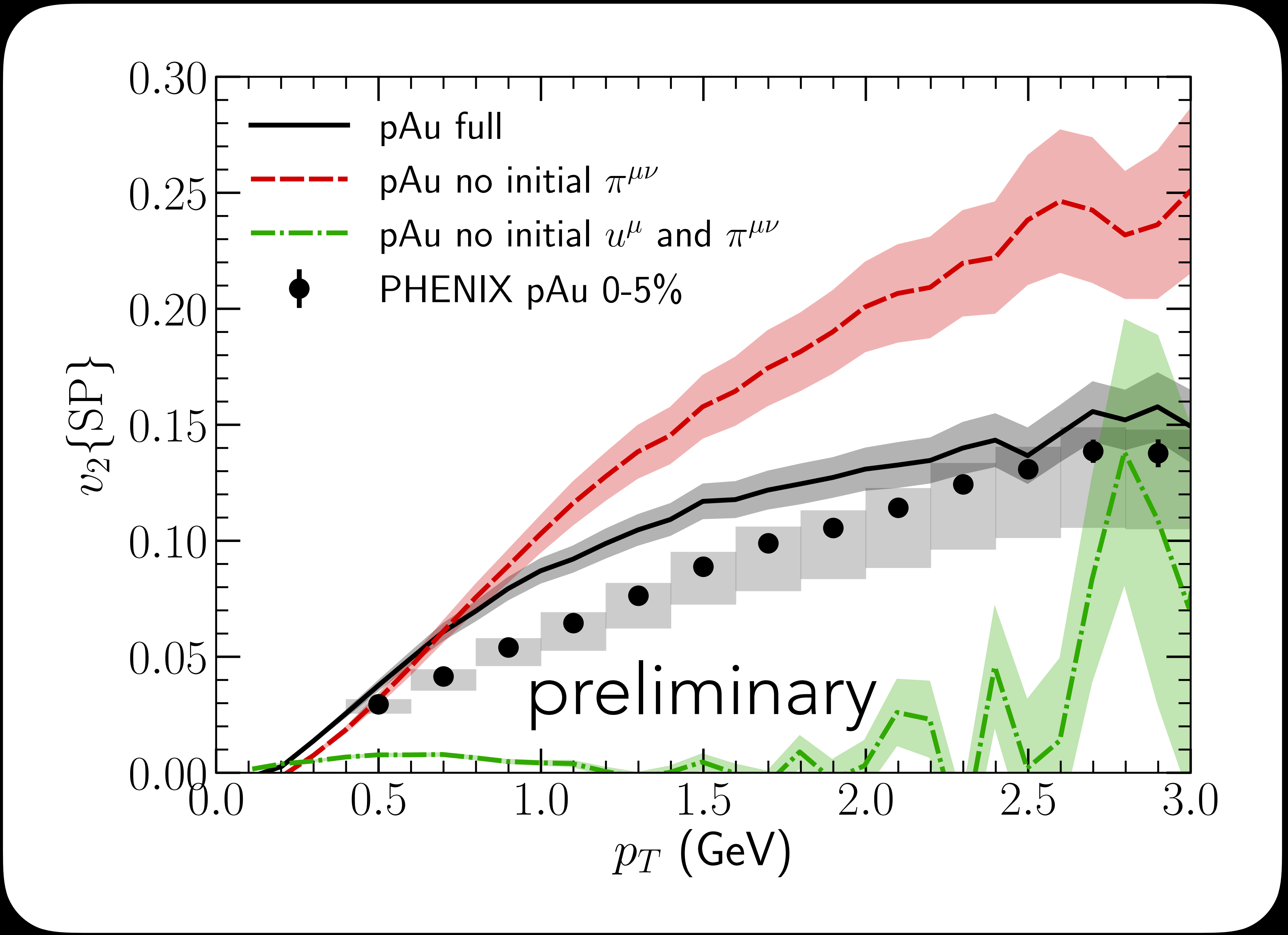
larger initial $\pi^{\mu\nu}$ for later switching time: reduction of v_2 at high p_T

PHENIX Collaboration, e-Print: arXiv:1805.02973

Effect of initial flow and viscous tensor

B. Schenke, C. Shen, P. Tribedy, in preparation

τ_0=0.4fm

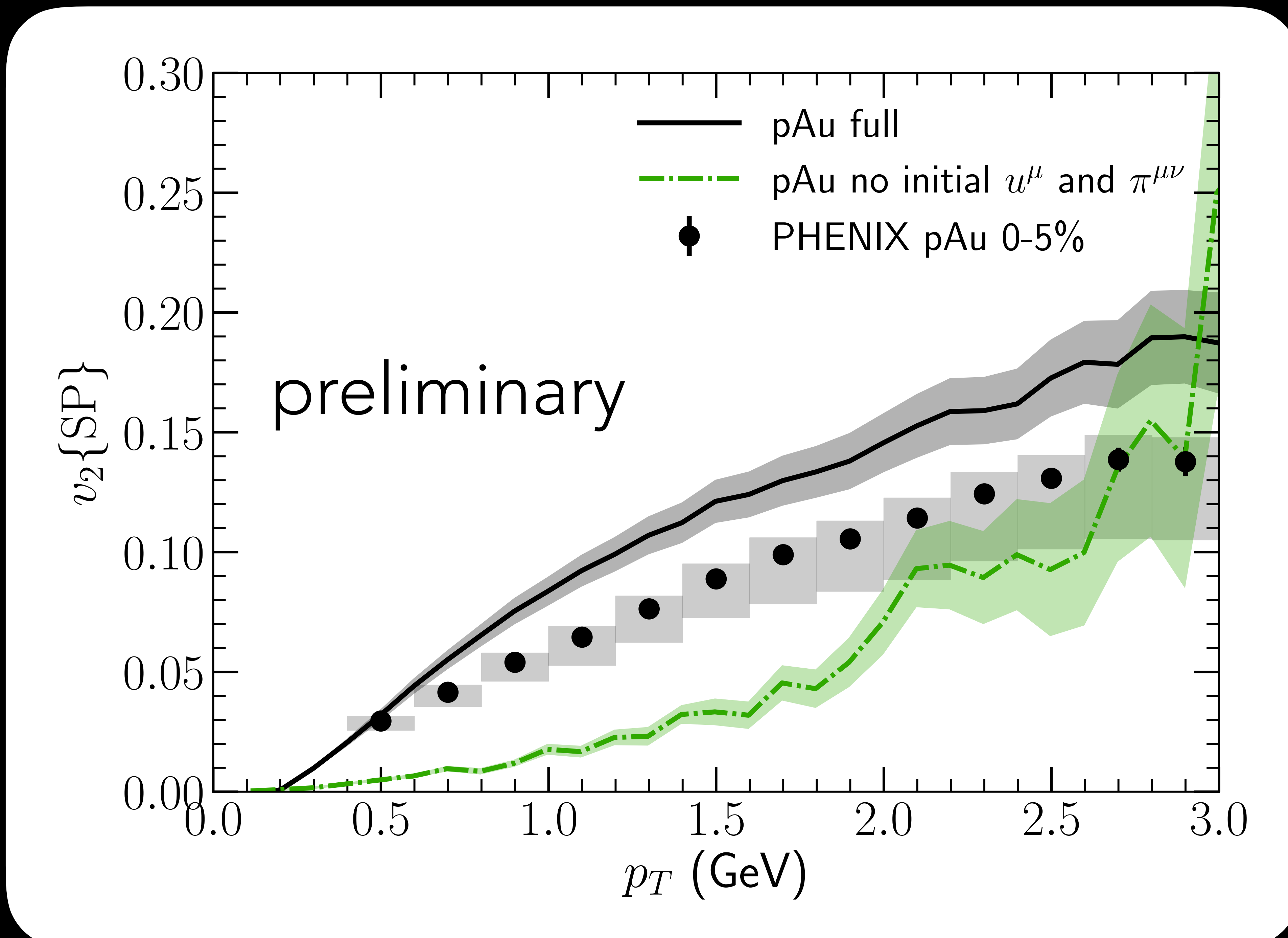


PHENIX Collaboration, e-Print: arXiv:1805.02973

Effect of initial flow

B. Schenke, C. Shen, P. Tribedy, in preparation

τ_0=0.2fm



PHENIX Collaboration, e-Print: arXiv:1805.02973

Conclusions

- Hybrid model (IP-Glasma+MUSIC+UrQMD) provides good description of bulk observables in heavy ion collisions
- Inclusion of local charge conservation when sampling allows for predictions of CME-sensitive correlators
- We make predictions for RHIC isobar run
- Small systems not perfectly well described when all parameters are fixed to describe heavy ion collisions
- Initial flow and viscous tensor have large effect on final flow observables

Backup