BROOKHAVEN NATIONAL LABORATORY

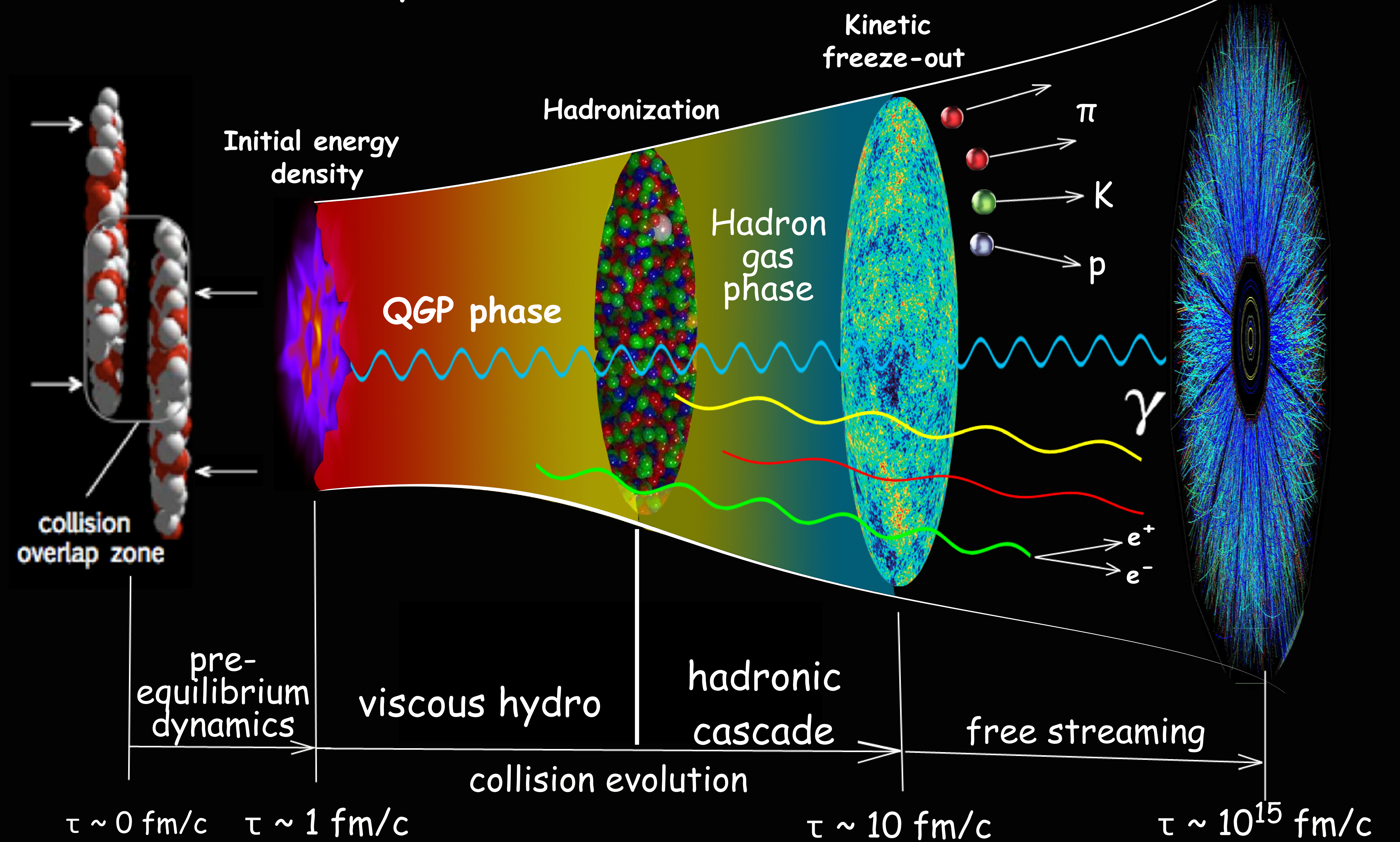
Collectivity and electromagnetic radiation in small collision systems

CHUN SHEN
Brookhaven National Lab

In collaboration with BJÖRN SCHENKE and PRITHWISH TRIBEDY

June 14, 2018 Wuhan China

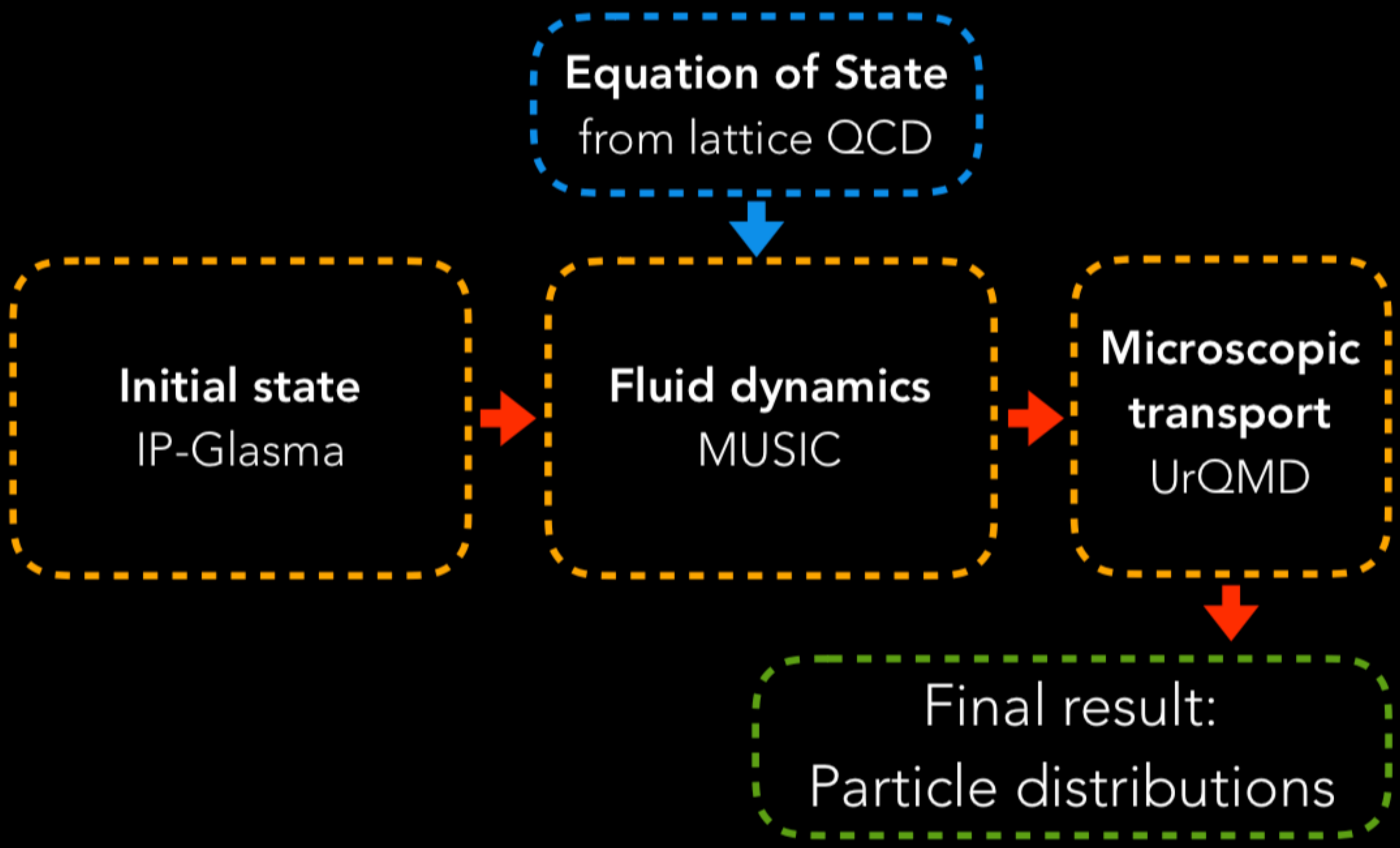
Relativistic Heavy-Ion Collisions



Can we describe a wide range of collision systems within a single framework?

- Study Pb+Pb, Xe+Xe, p+Pb, and p+p collisions

Concentrate on the same multiplicities



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 with three quark substructure (needed for p+Pb 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

Passing the system's full energy momentum tensor,

$$T^{\mu\nu}_{\mathrm{CYM}} = T^{\mu\nu}_{\mathrm{hydro}}$$

In the hydro phase, the energy momentum tensor can be decomposed as,

Landau Matching $$u_\mu T^{\mu\nu}_{\mathrm{hydro}} = e u^\nu$$

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

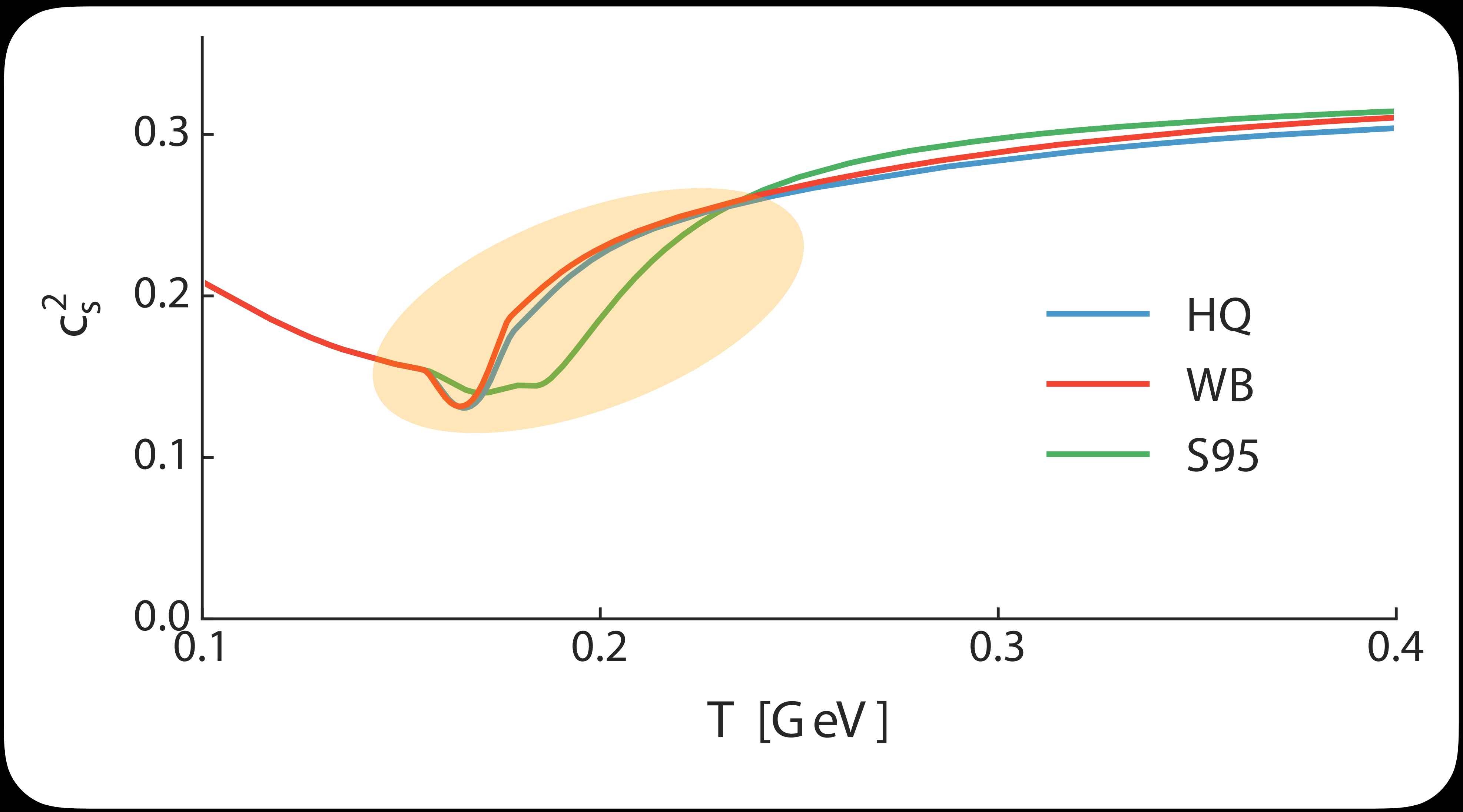
Bulk $$\Pi = \frac{e}{3} - P(e)$$

Lattice EoS

Equation of State

Use a new EoS constructed from (WB) 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)

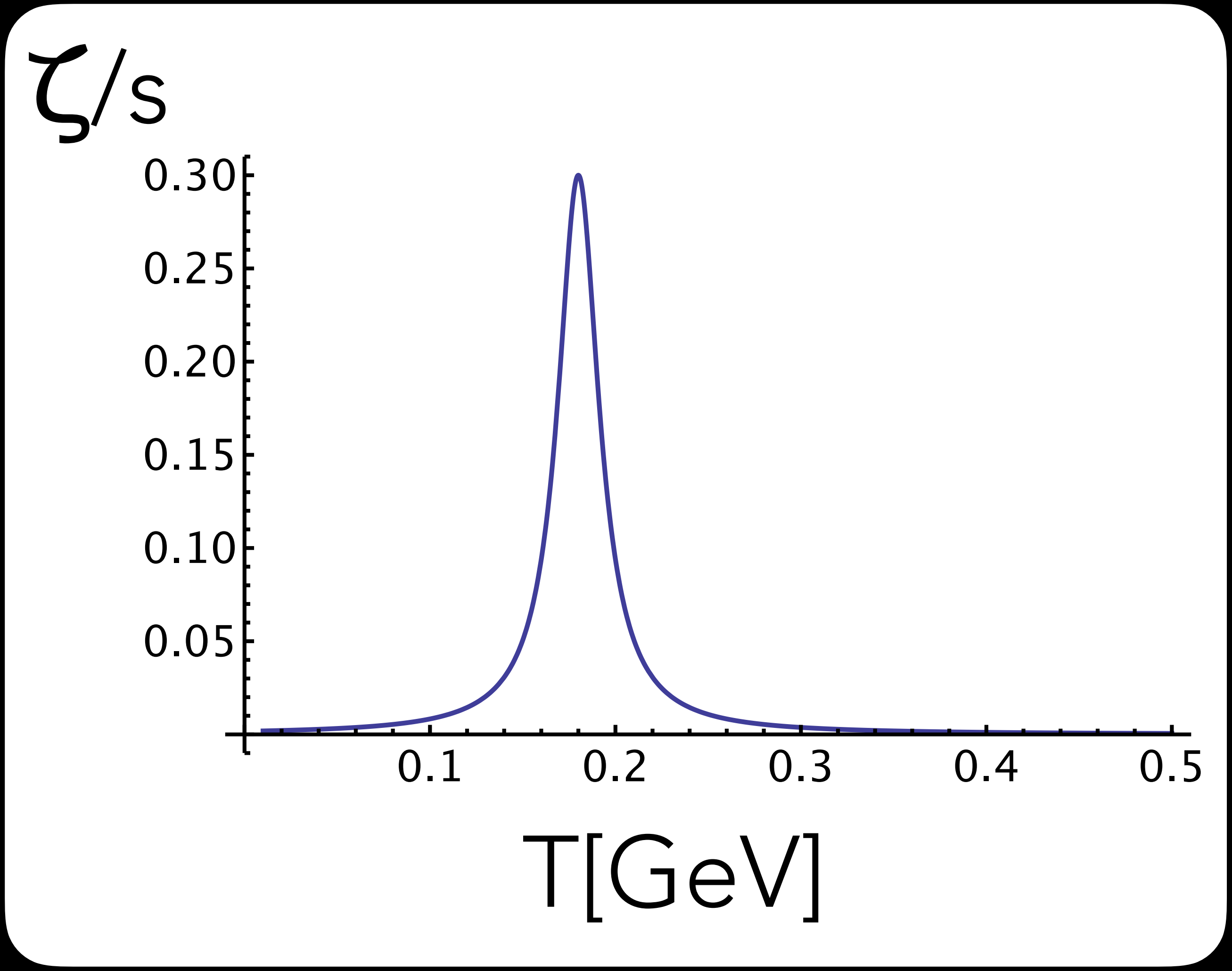
WB: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, K. K. Szabo, Phys. Lett. B730, 99–104 (2014)

Viscosities

Constant $\eta/s = 0.13$

(up from 0.095 used earlier because of change in EoS)

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

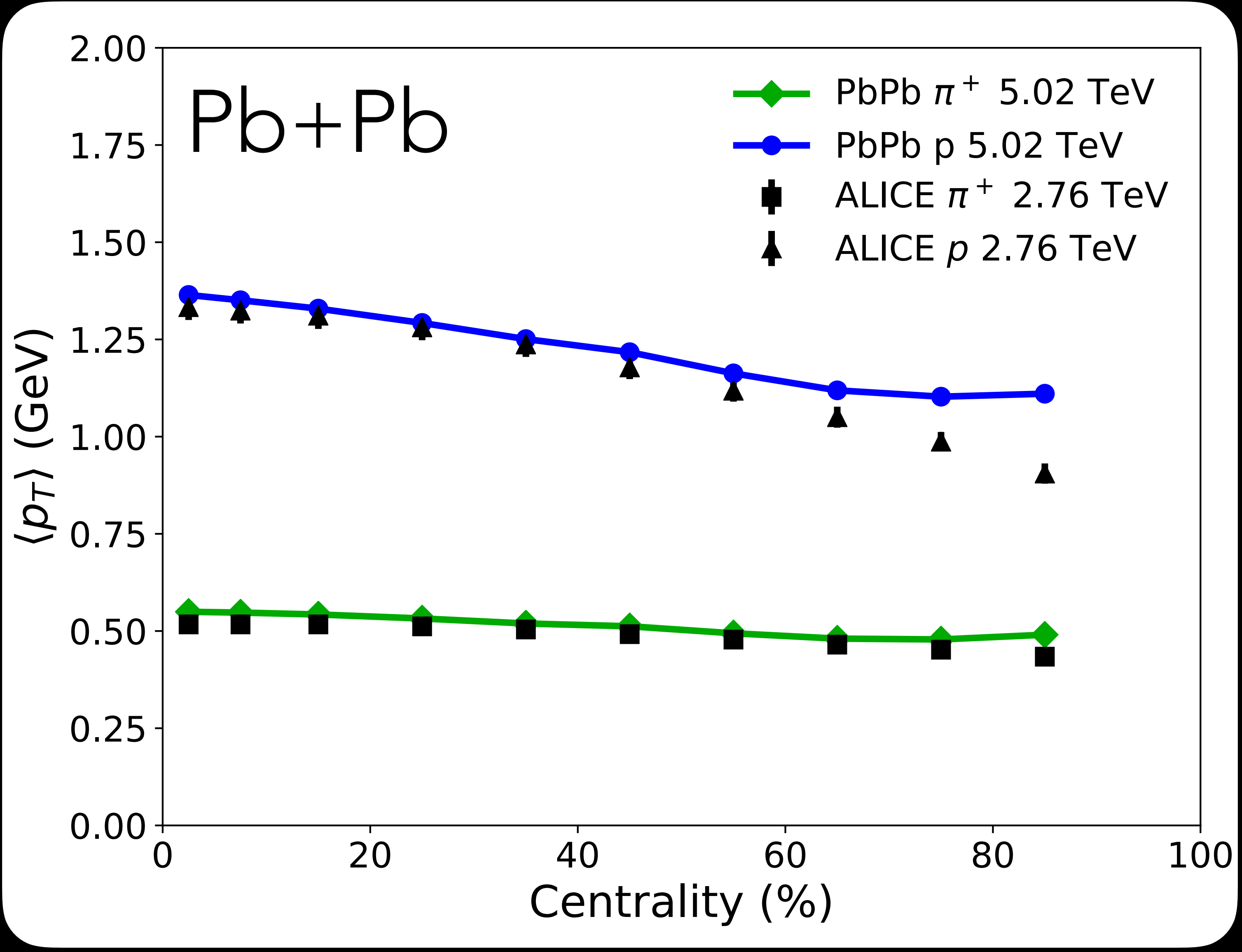


Bulk viscosity peaks at 180 MeV

Width, height, and position are free parameters

Mean transverse momentum

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

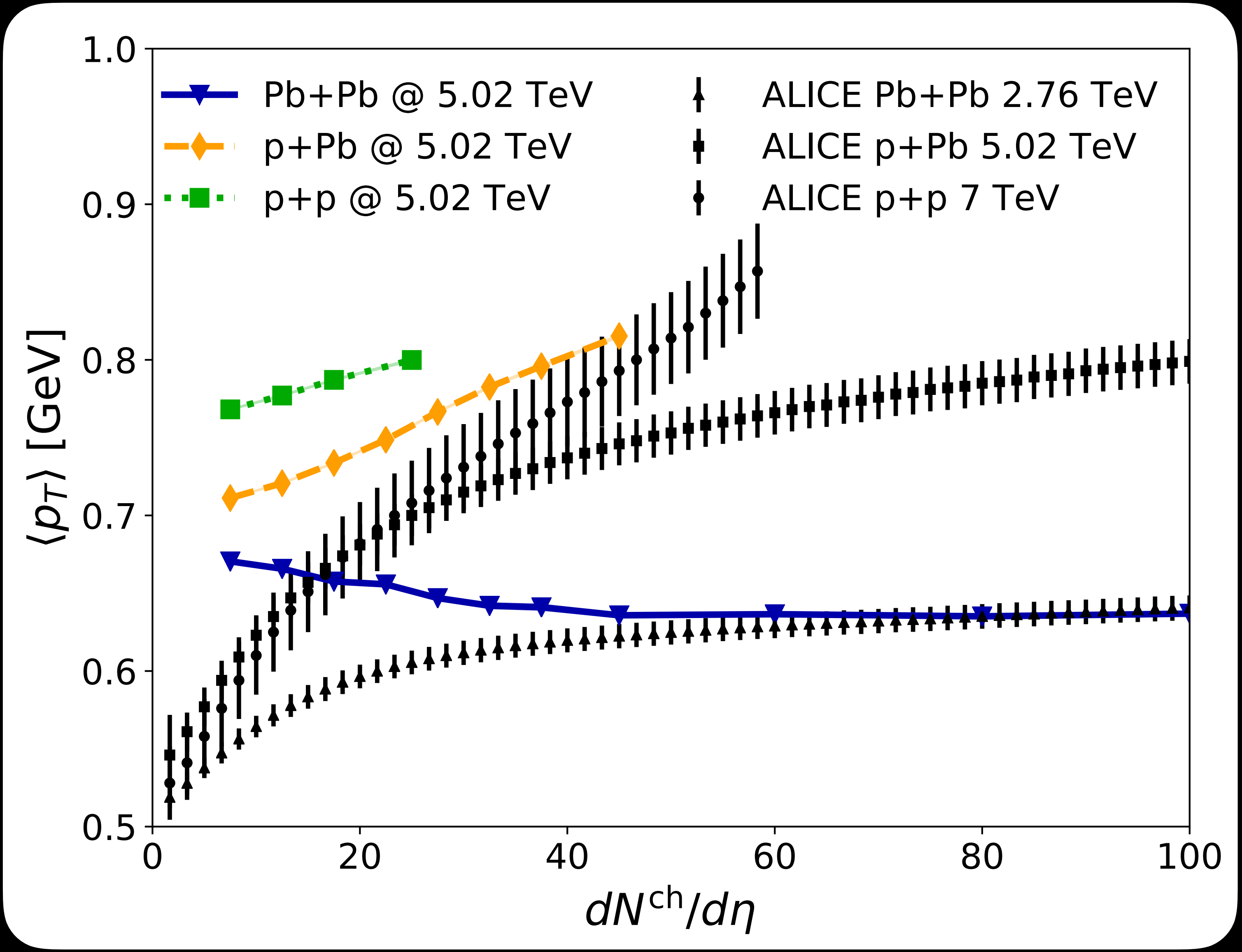


Bulk viscosity smaller at low T (low multiplicity)

UrQMD also may have too little bulk viscosity

Mean transverse momentum

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



p+Pb $\langle p_T \rangle$ ~8% > than data

p+p $\langle p_T \rangle$ ~12% > data

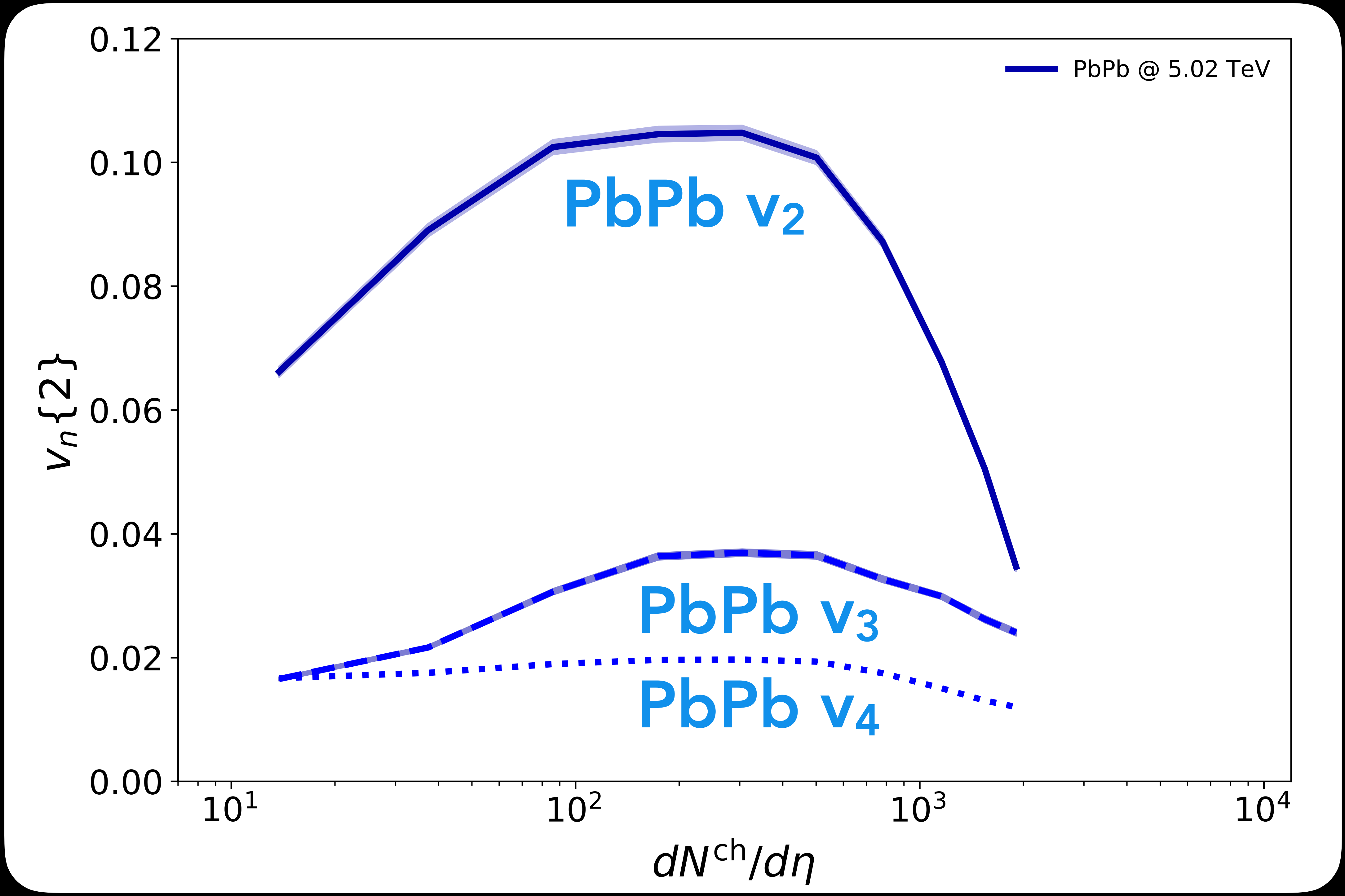
Pb+Pb $\langle p_T \rangle$ over-estimated at $N_{ch} < 60$

Bulk viscosity smaller at low T (low multiplicity)

UrQMD also may have too little bulk viscosity

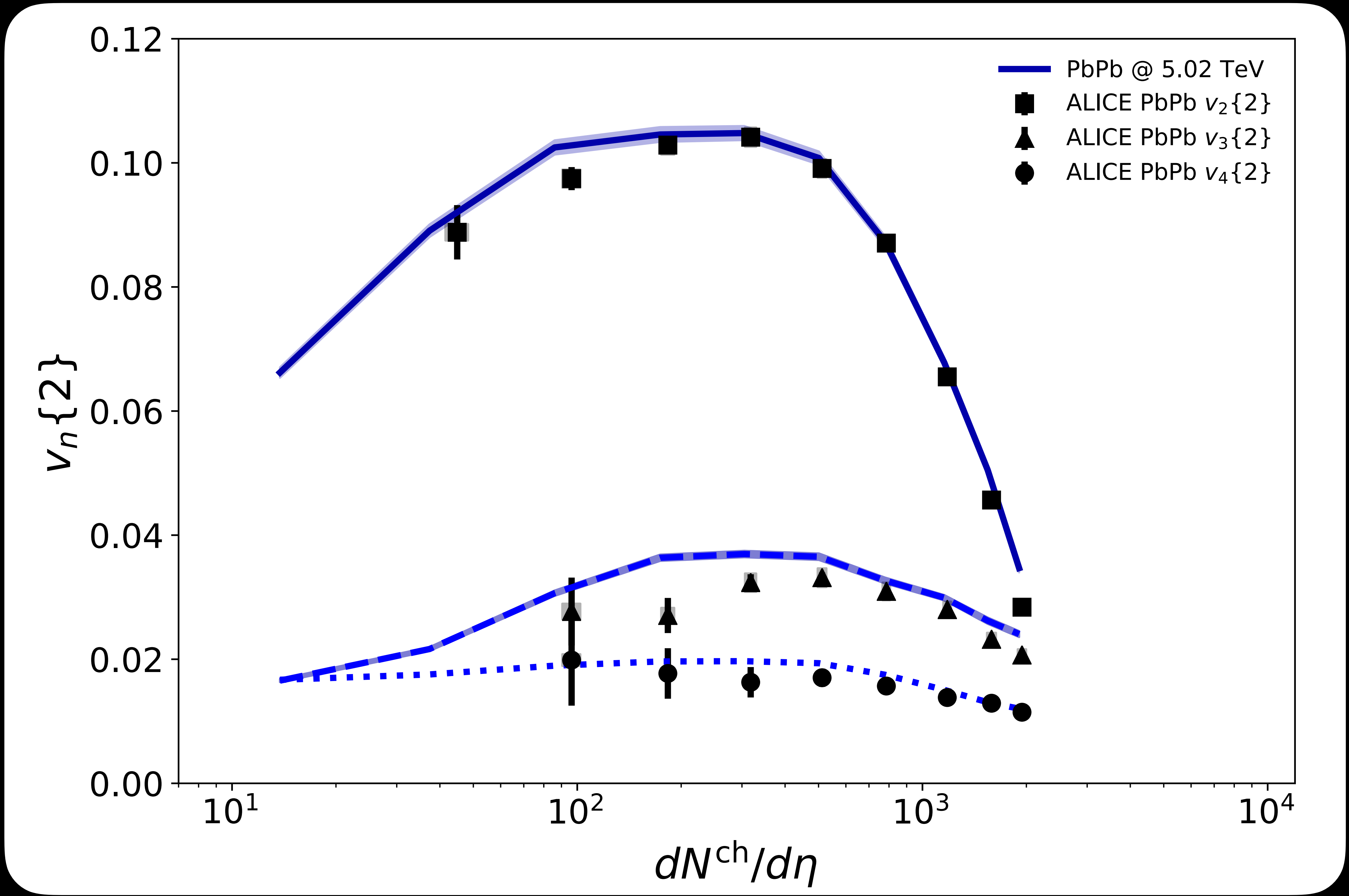
Anisotropy vs. multiplicity

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



Anisotropy vs. multiplicity

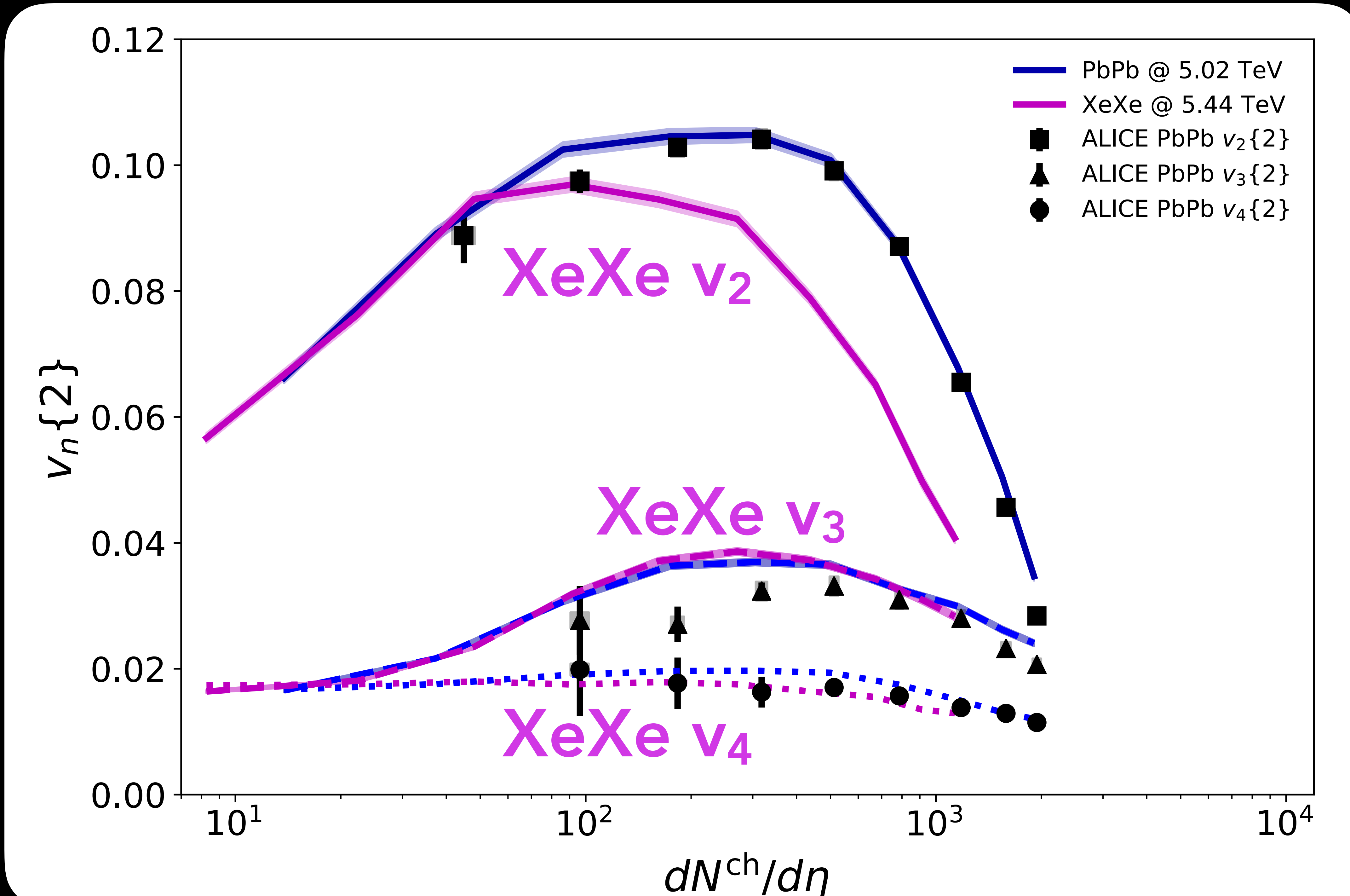
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014)

Anisotropy vs. multiplicity

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

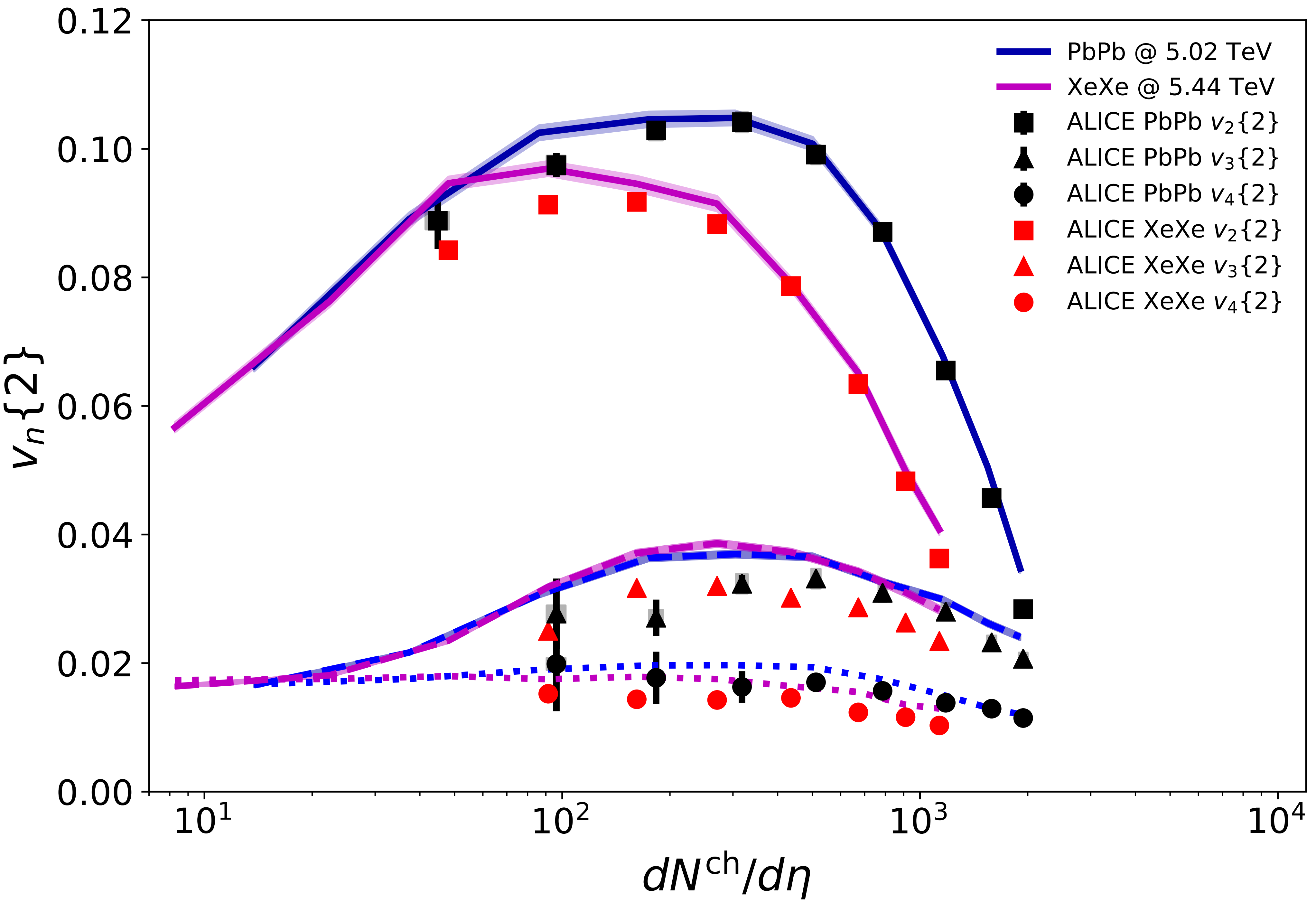


Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)

B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014)

Anisotropy vs. multiplicity

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

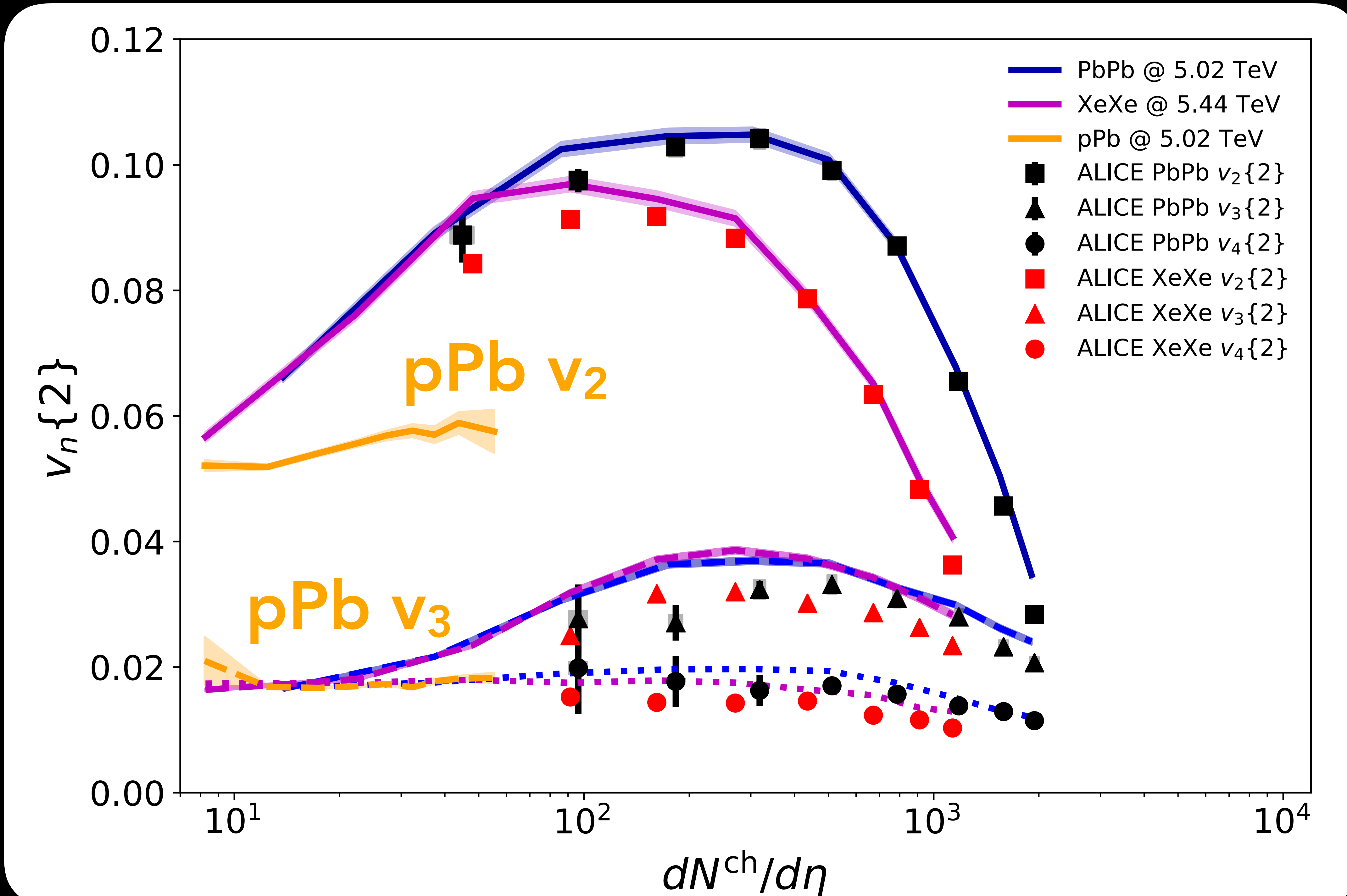


Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)

B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Anisotropy vs. multiplicity

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

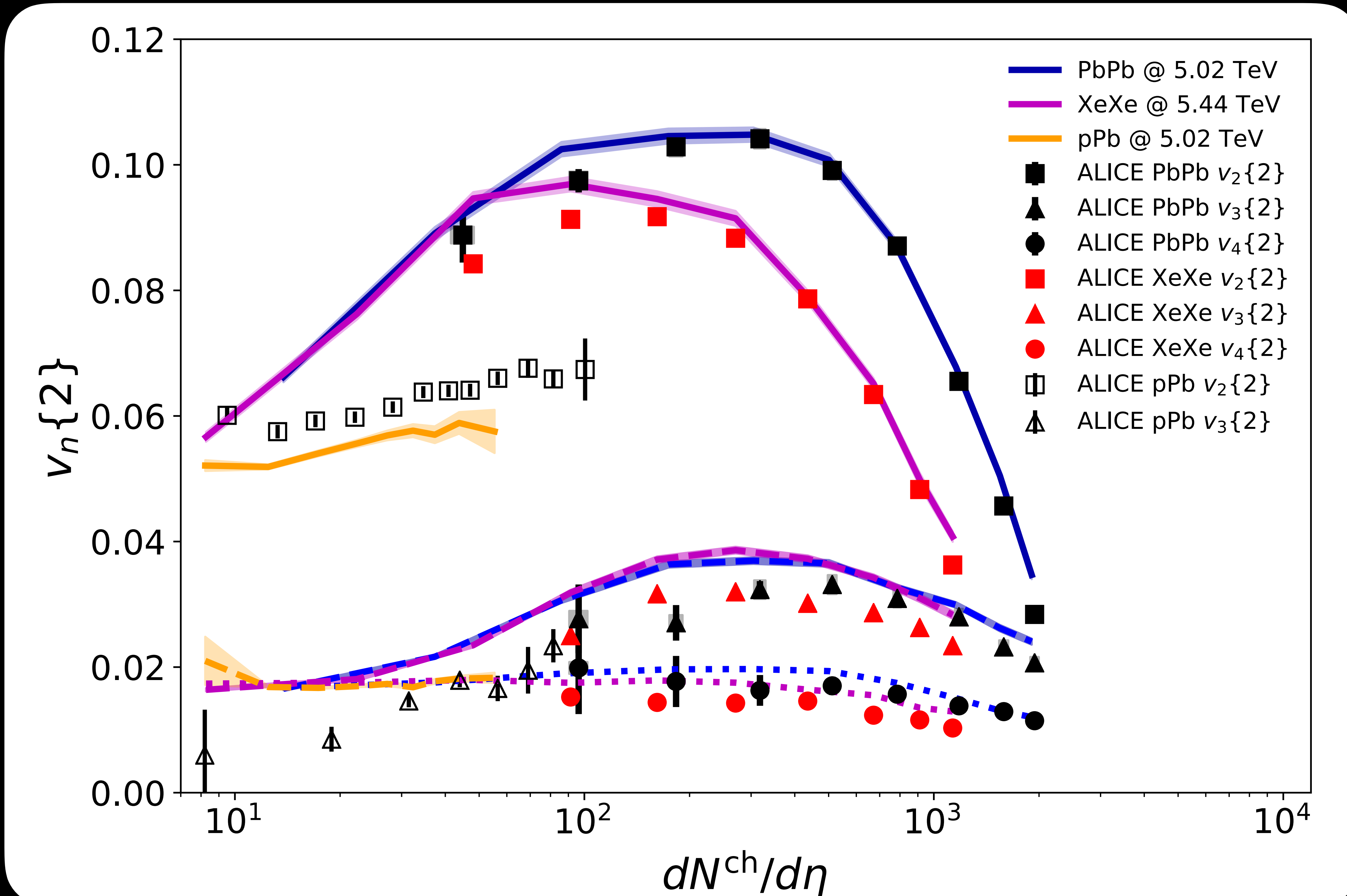


Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)

B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Anisotropy vs. multiplicity

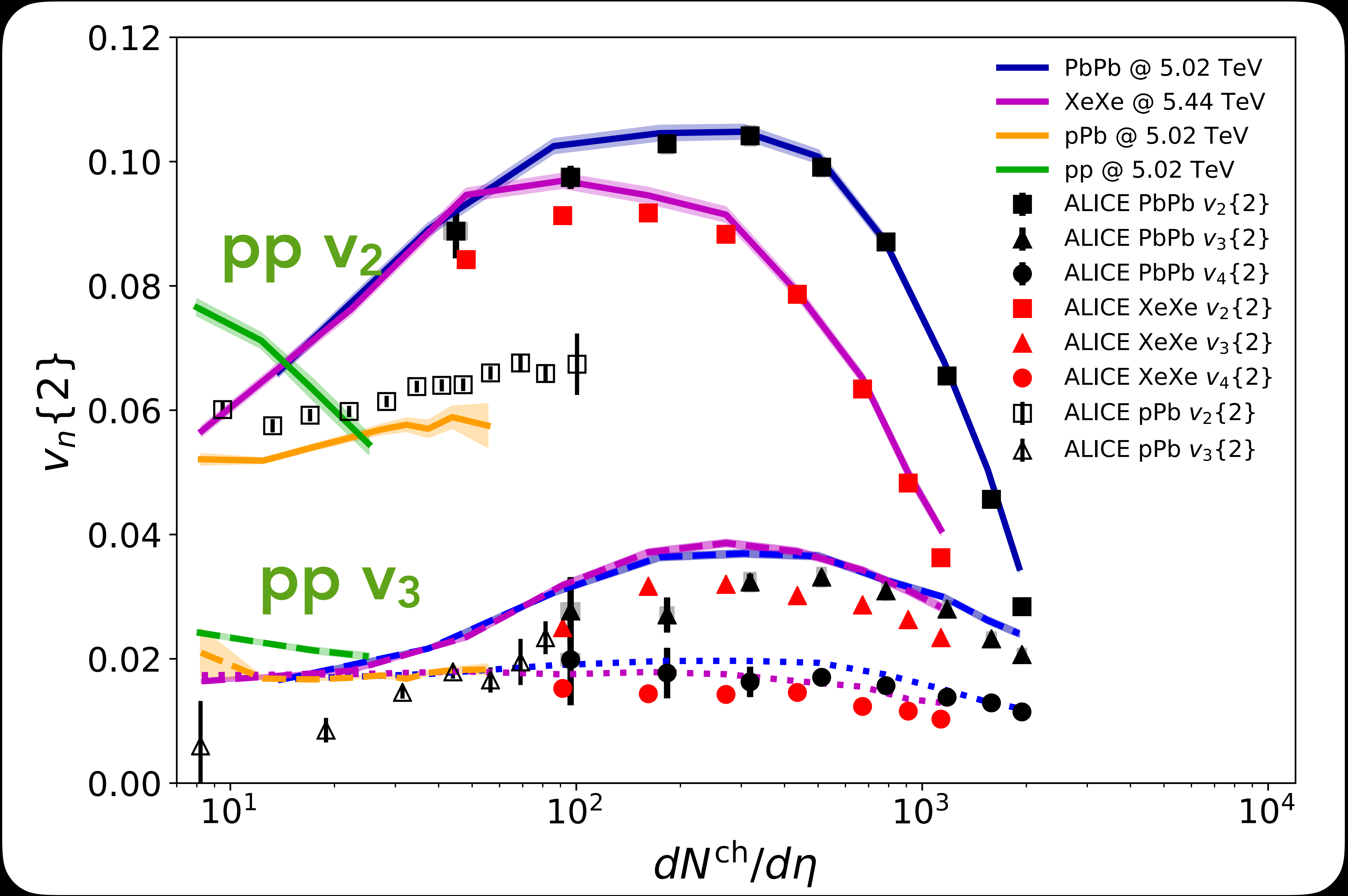
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Anisotropy vs. multiplicity

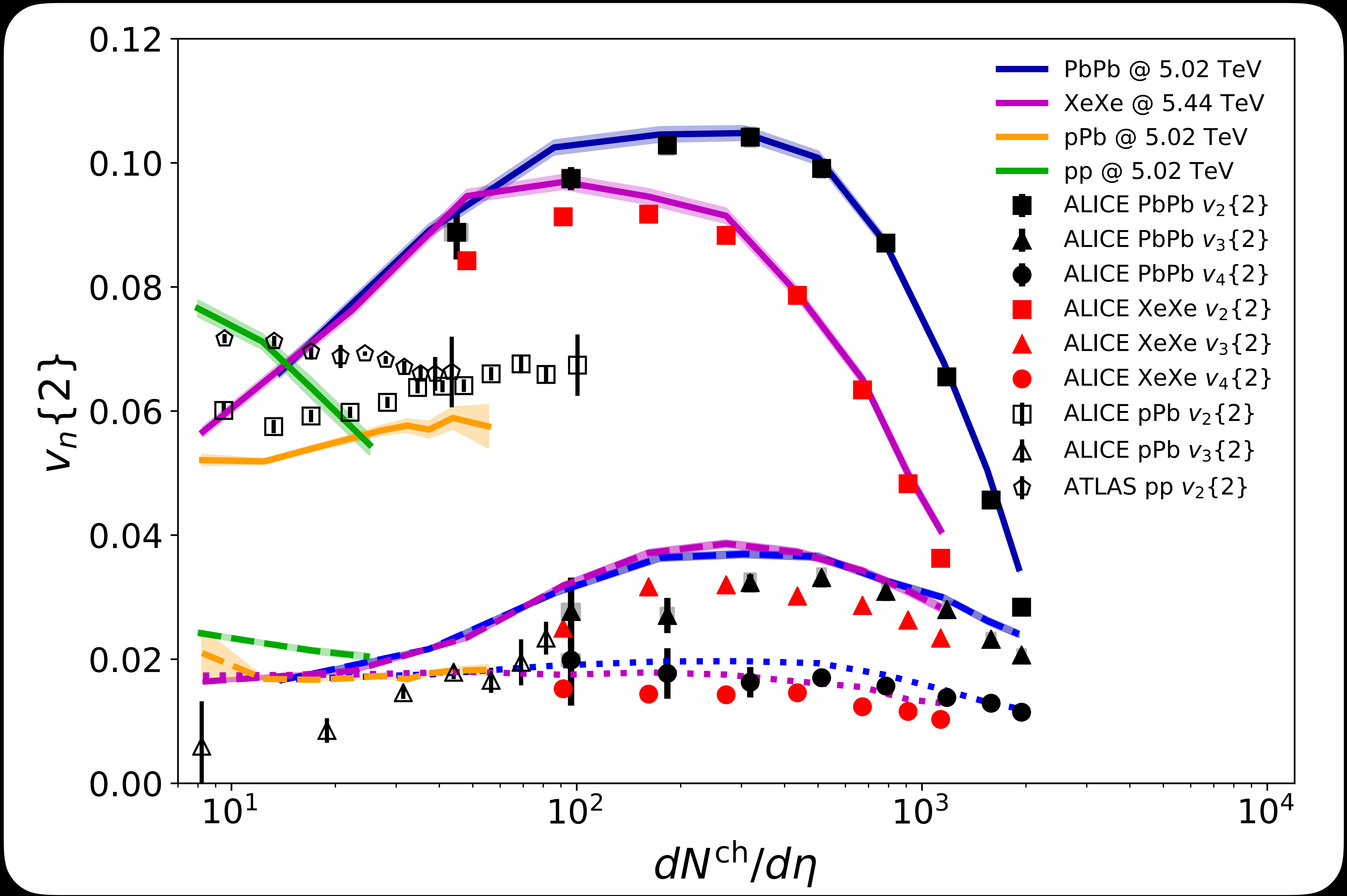
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Anisotropy vs. multiplicity

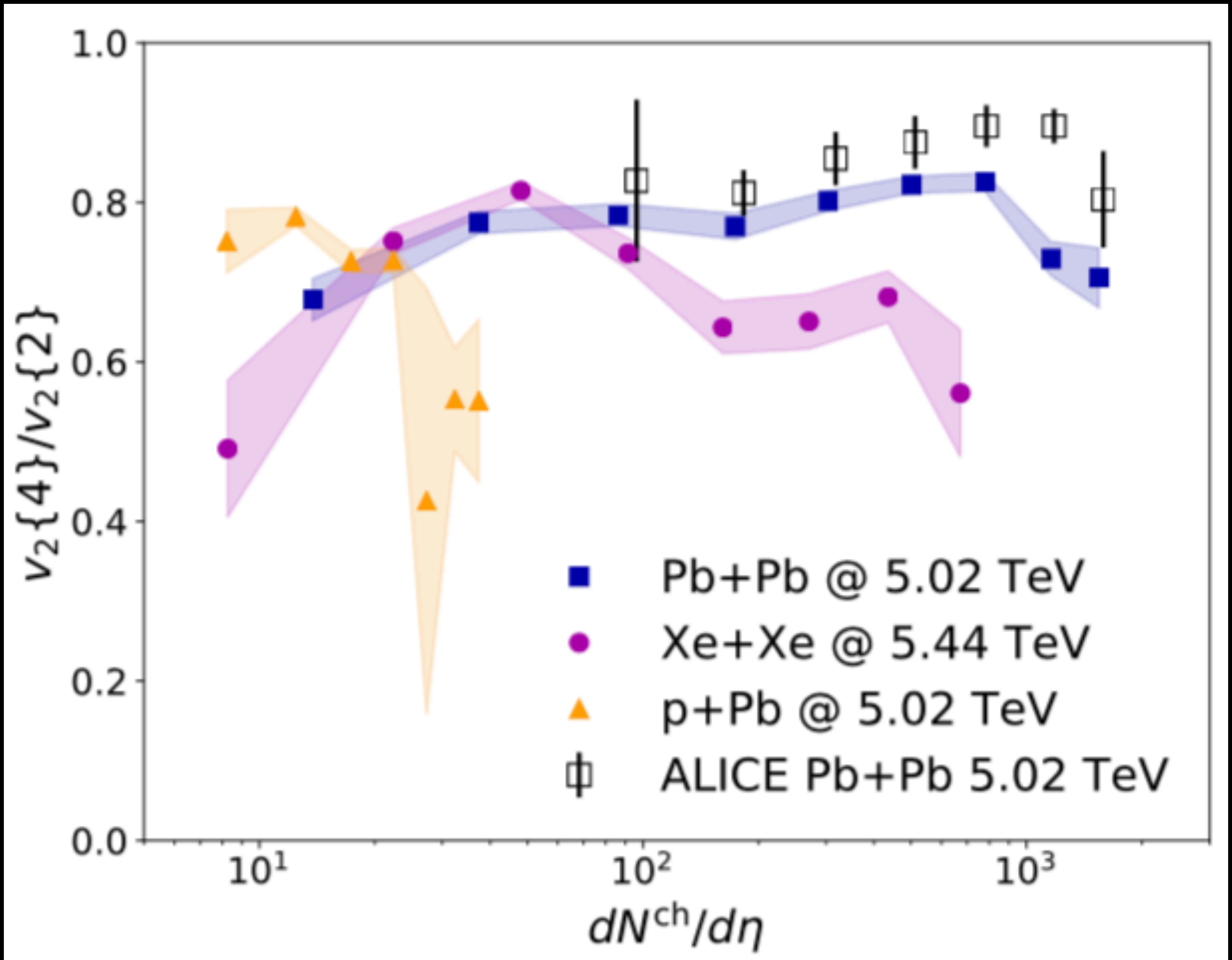
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Higher order cumulants

Bjoern Schenke, Chun Shen, and Prithwish Tribedy, in preparation

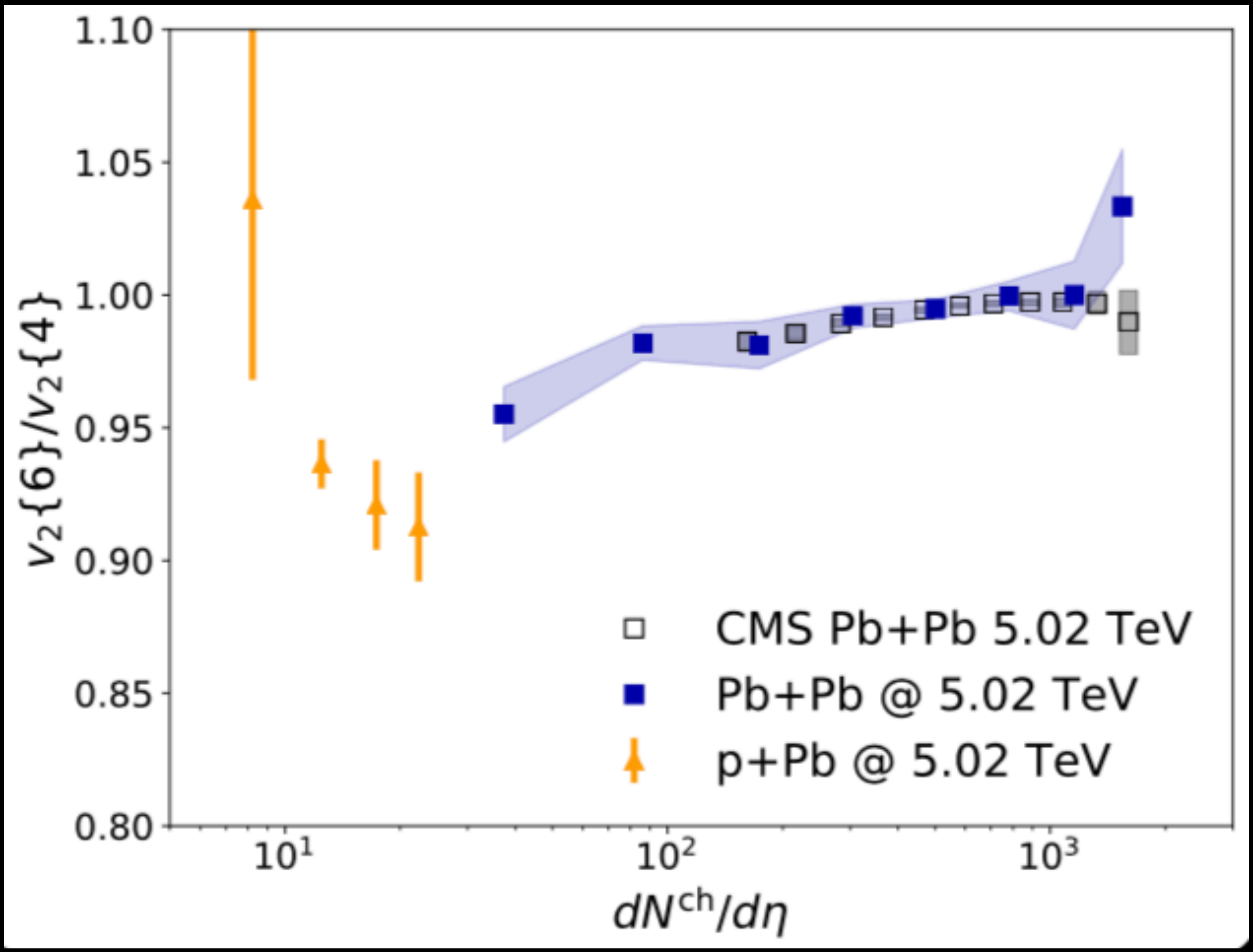


$$\frac{v_2\{4\}}{v_2\{2\}} \rightarrow \sqrt{\frac{1-(\sigma^2/\bar{v}_2^2)}{1+(\sigma^2/\bar{v}_2^2)}}$$

- The IP-Glasma initial condition captures the v_2 fluctuations from central to peripheral centralities

Higher order cumulants

Bjoern Schenke, Chun Shen, and Prithwish Tribedy, in preparation

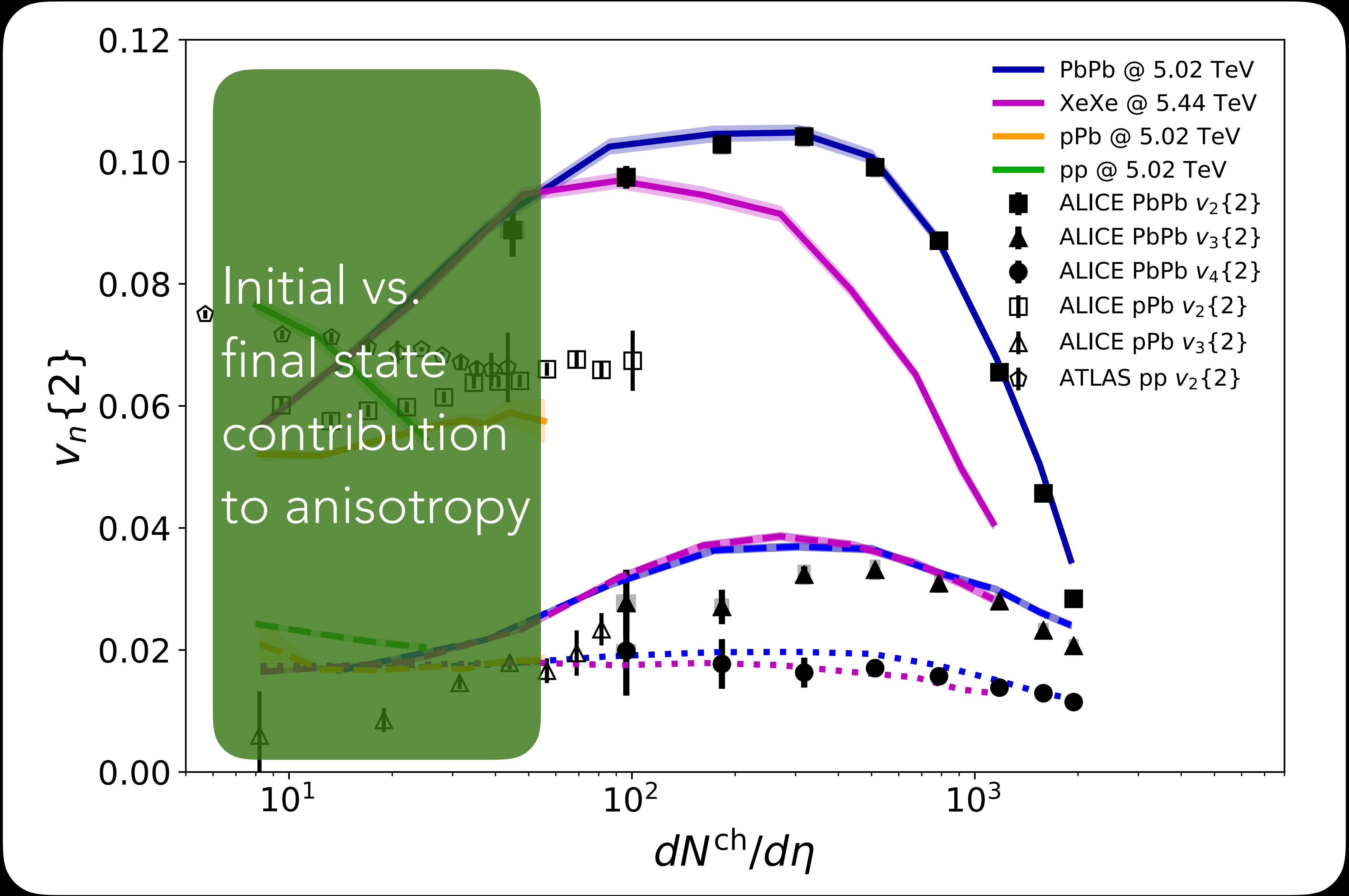


The ratio of $\frac{v_2\{6\}}{v_2\{4\}}$ away from 1 reflects the non-Gaussianity of v_n fluctuations

The IP-Glasma + hydrodynamics framework reproduces the $v_2\{6\}/v_2\{4\}$ ratio for PbPb collisions

Initial or final state effects?

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



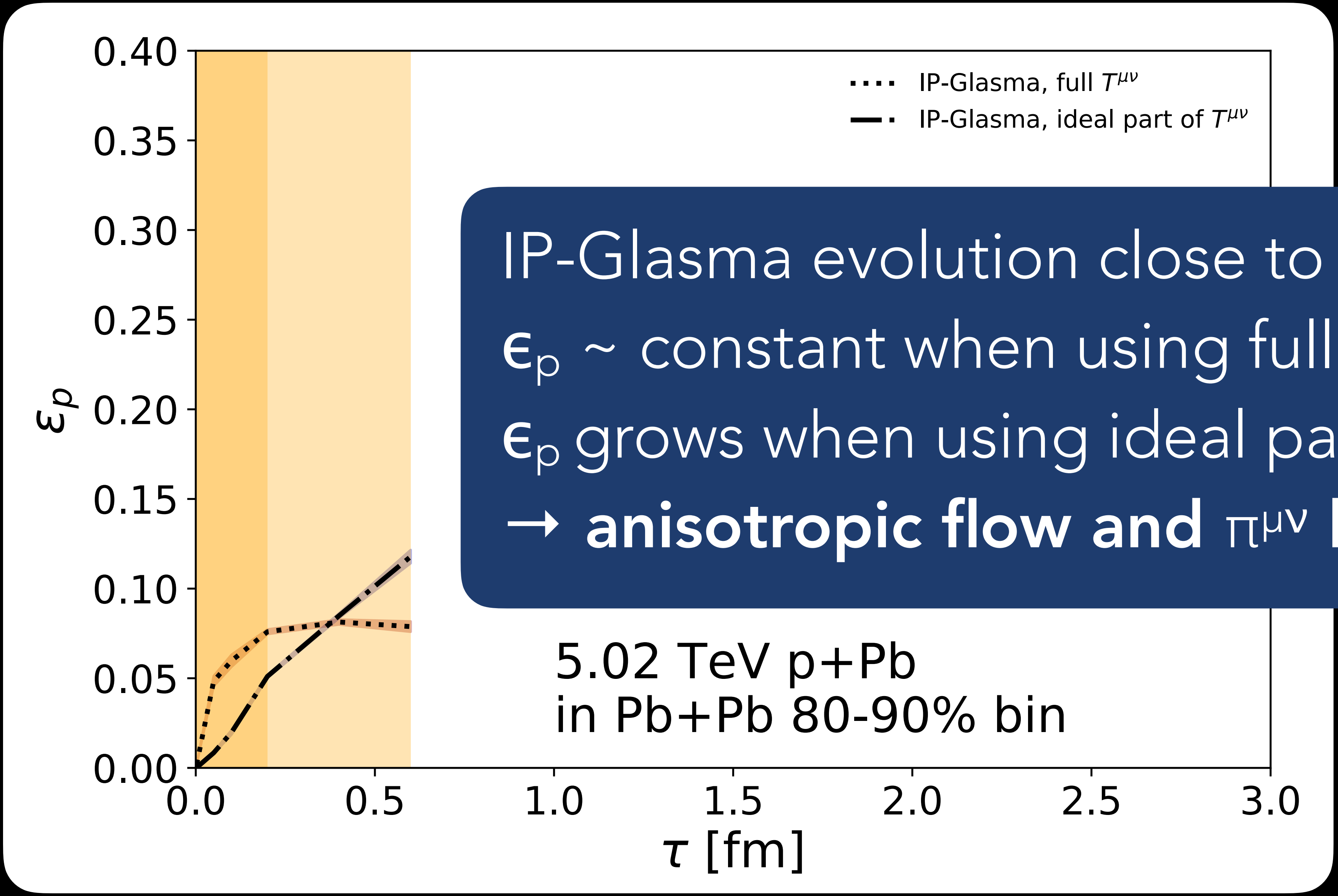
Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ATLAS Collaboration, Eur. Phys. J. C (2017) 77:428

When is momentum anisotropy generated in p+Pb?

p+Pb events in 80-90% Pb+Pb class

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

IP-Glasma



IP-Glasma evolution close to free streaming

ϵ_p ~ constant when using full $T^{\mu\nu}$

ϵ_p grows when using ideal part of $T^{\mu\nu}$

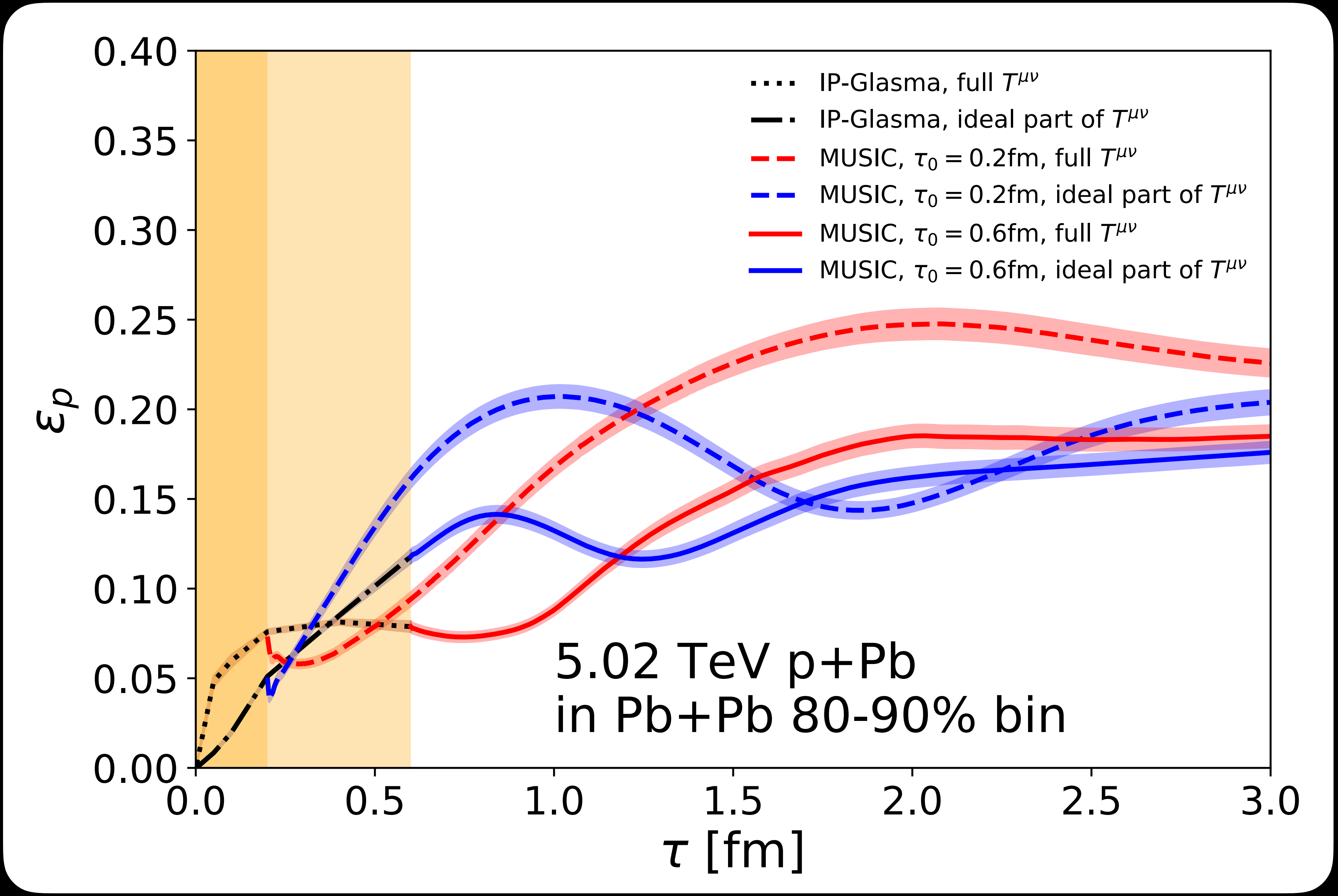
→ **anisotropic flow and $\pi^{\mu\nu}$ both grow**

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

When is momentum anisotropy generated in p+Pb?

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

IP-Glasma   Hydrodynamics



Switching at τ=0.6fm: (full lines)

ϵ_p with full $T^{\mu\nu}$ ~45% from initial flow

Switching at τ=0.2fm: (dashed lines)

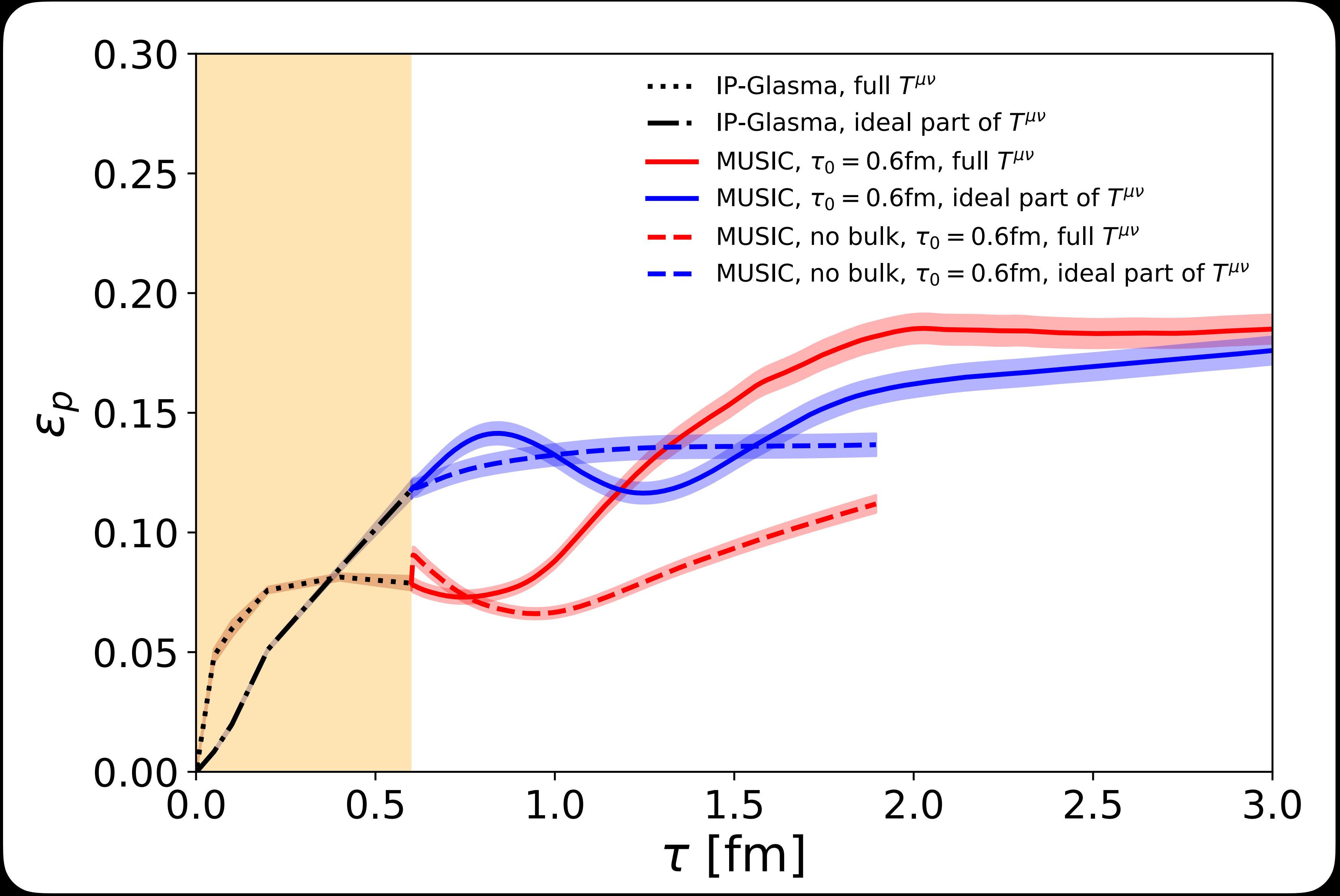
ϵ_p with full $T^{\mu\nu}$ ~35% from initial flow

When is momentum anisotropy generated in p+Pb?

Effect of bulk viscosity

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

IP-Glasma Hydrodynamics



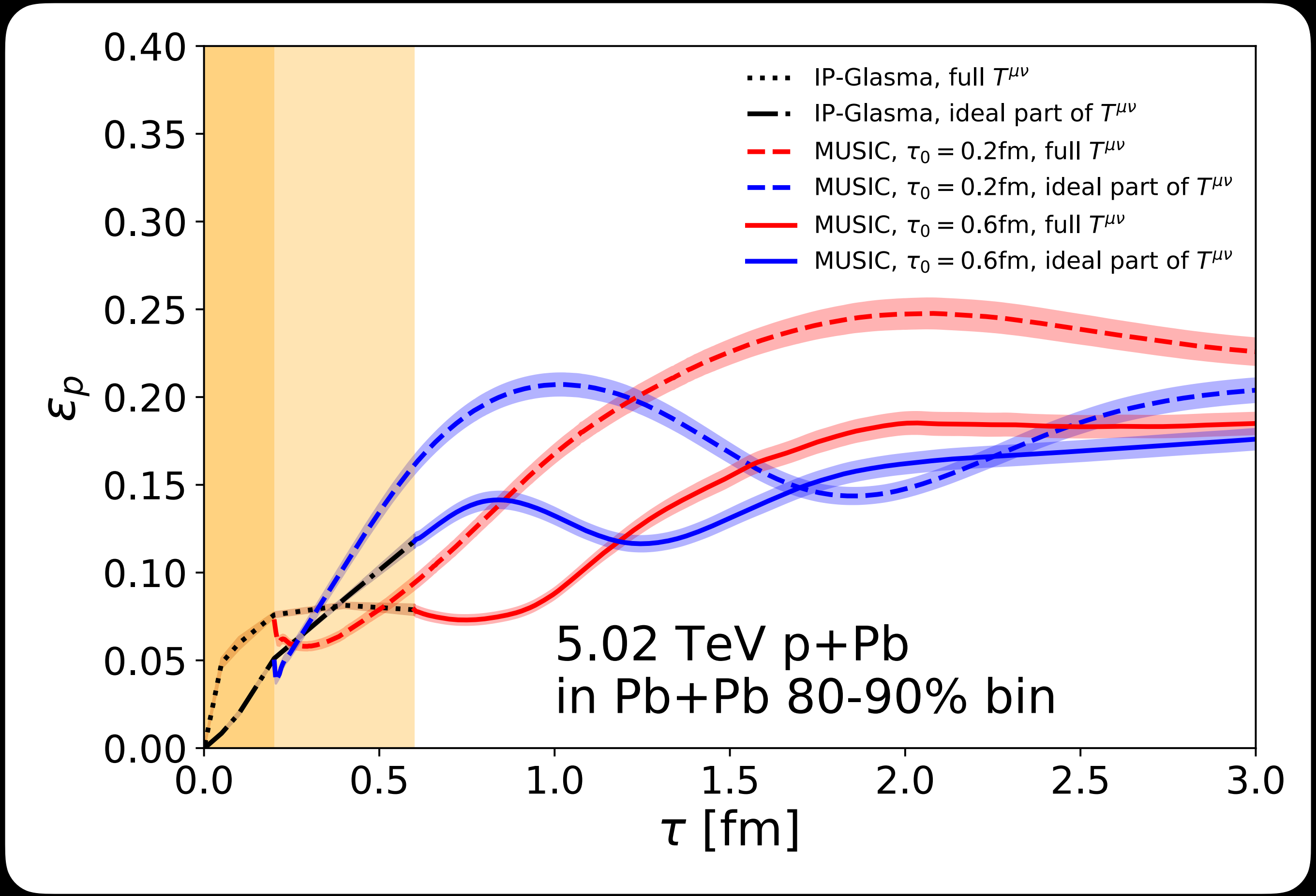
With bulk viscosity (full lines)

ϵ_p with full $T^{\mu\nu}$ ~45% from initial flow

w/o bulk viscosity (dashed lines)

ϵ_p with full $T^{\mu\nu}$ ~70% from initial flow

When is momentum anisotropy generated in p+Pb?

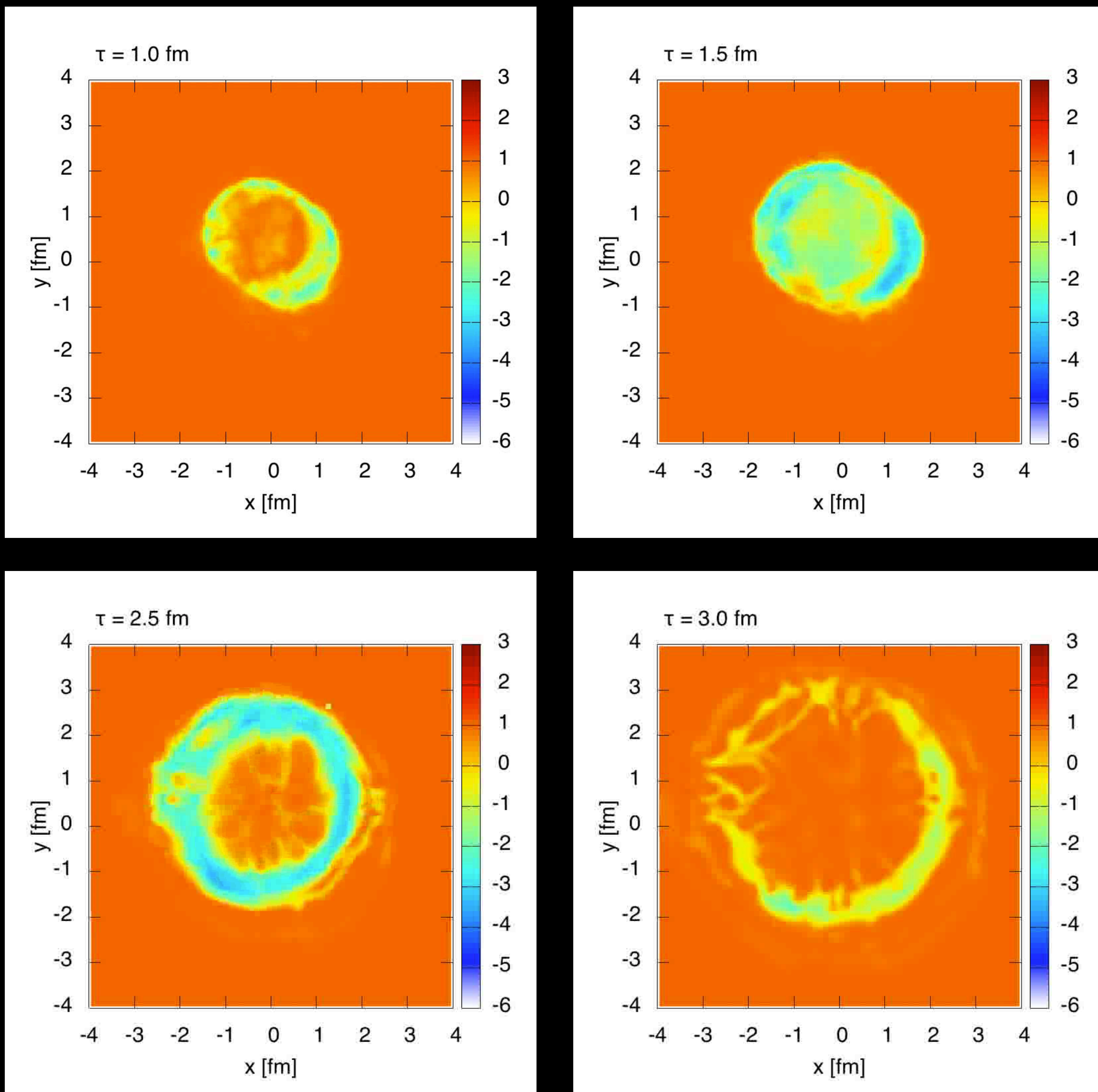


$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

- Initial state color glass v_2 encoded in initial $T^{\mu\nu}$
- Free streaming makes (ideal) flow anisotropy and $\pi^{\mu\nu}$ grow
- Role of hydrodynamics is to dynamically reduce the initial $\pi^{\mu\nu}$ and possibly generate more anisotropy
- Tricky questions about artifacts of matching arise…

Possible improvement: **A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, D. Teaney, arXiv:1805.01604**

Large bulk viscosity → negative pressure

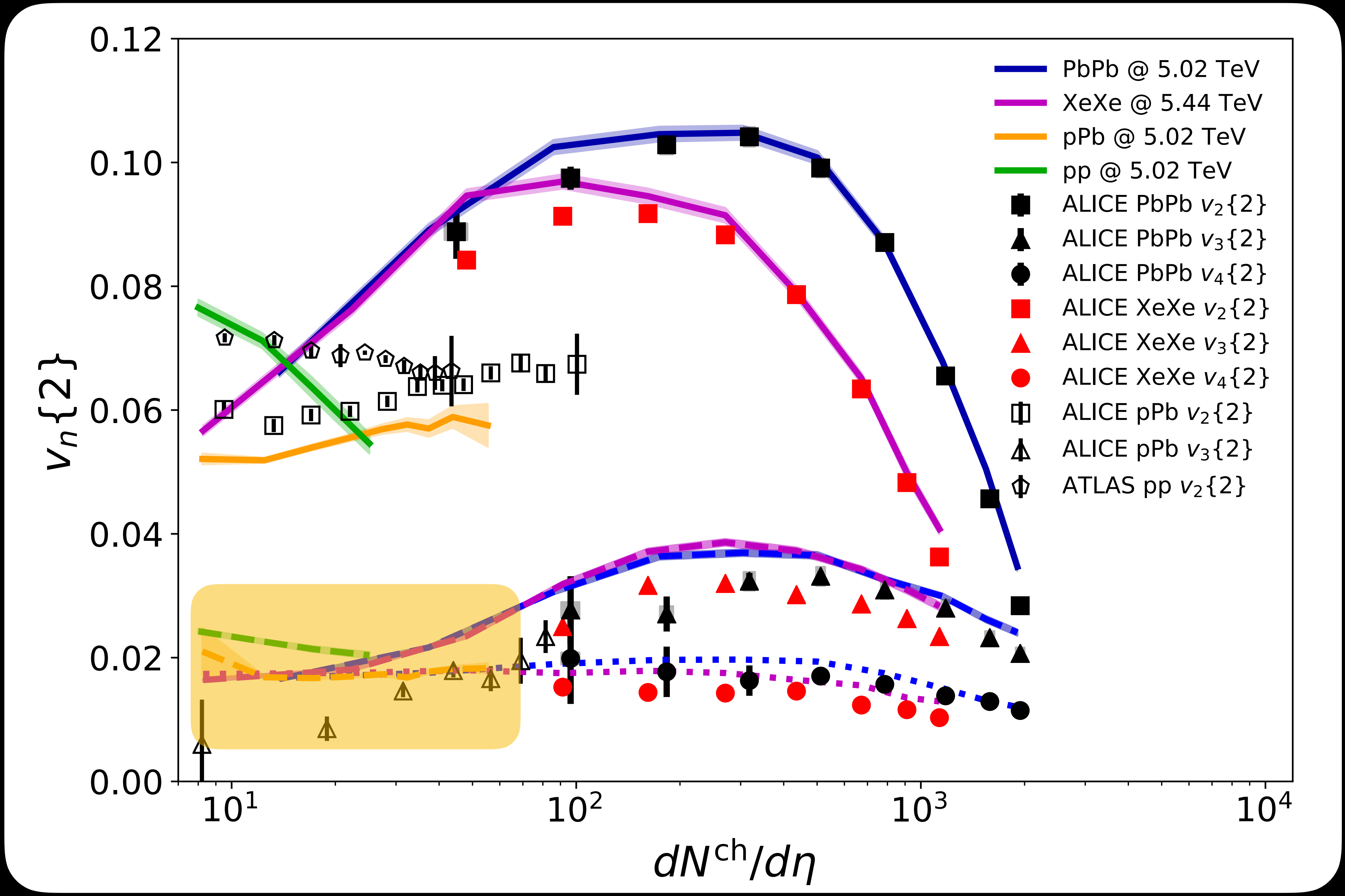


1+Π/P

in a p+Pb collision

Anisotropy vs. multiplicity

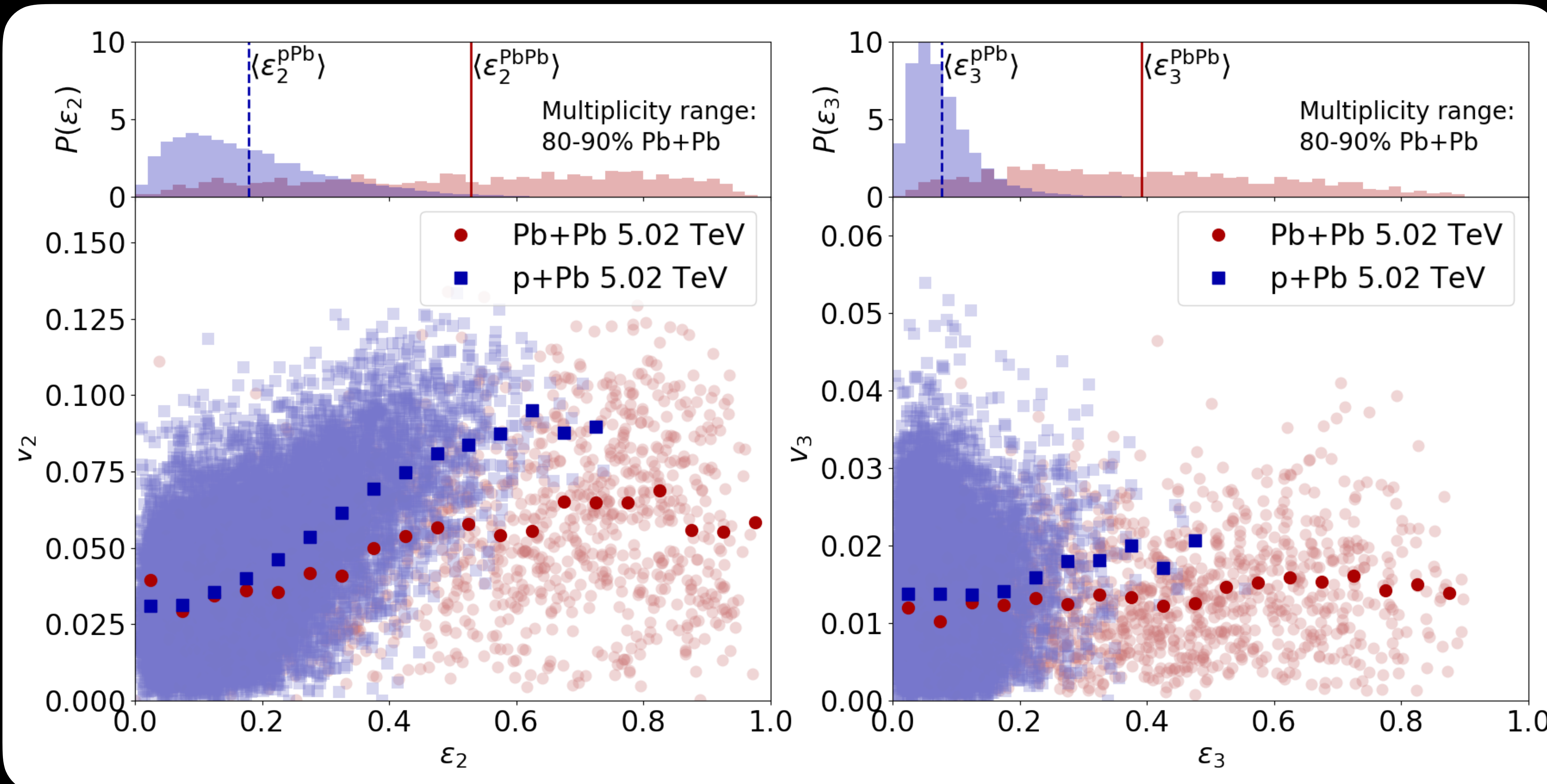
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), ALICE Collaboration, arXiv:1805.01832

Geometry - flow correlations

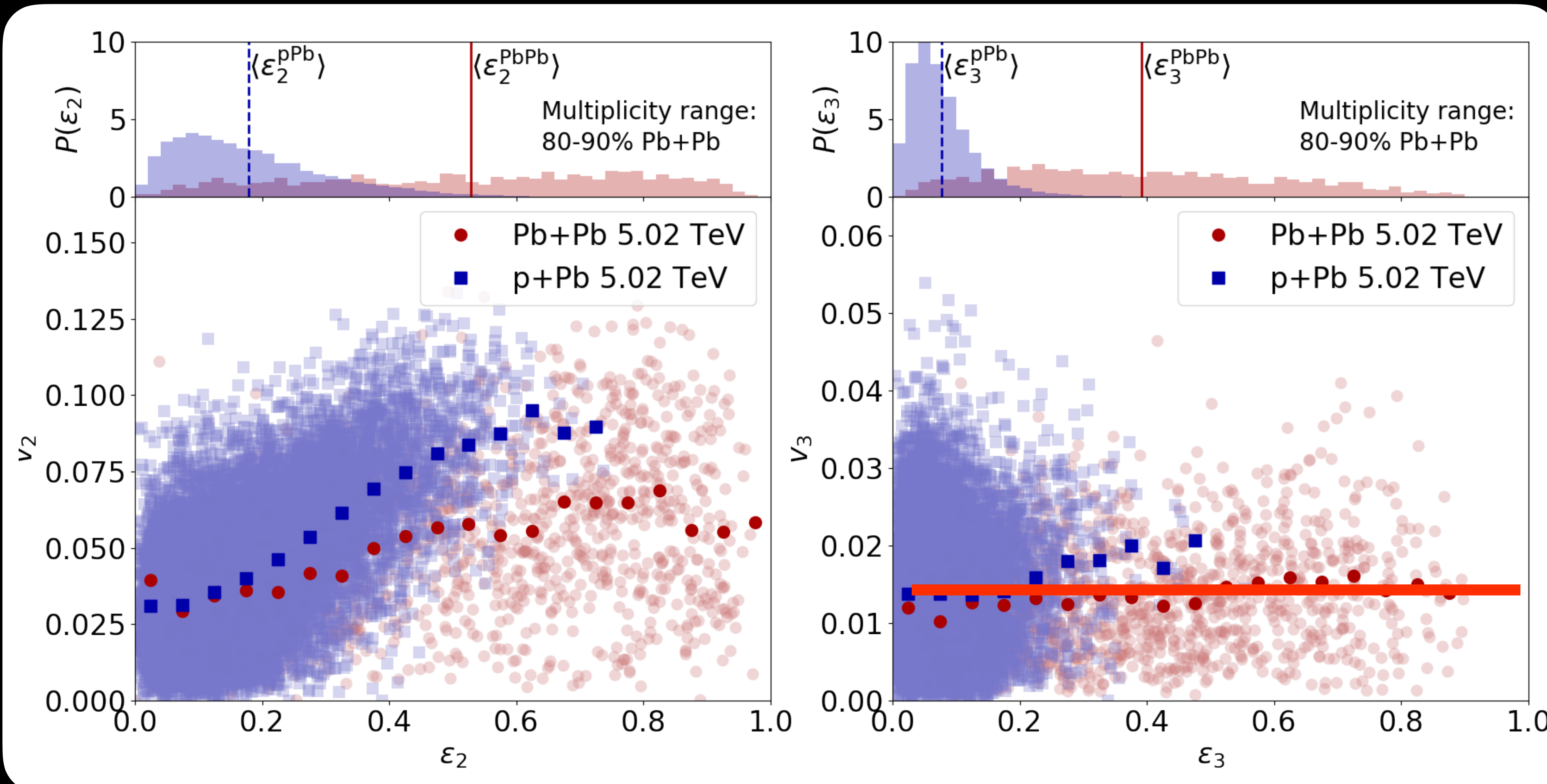
First: Eccentricity distributions are indeed different



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

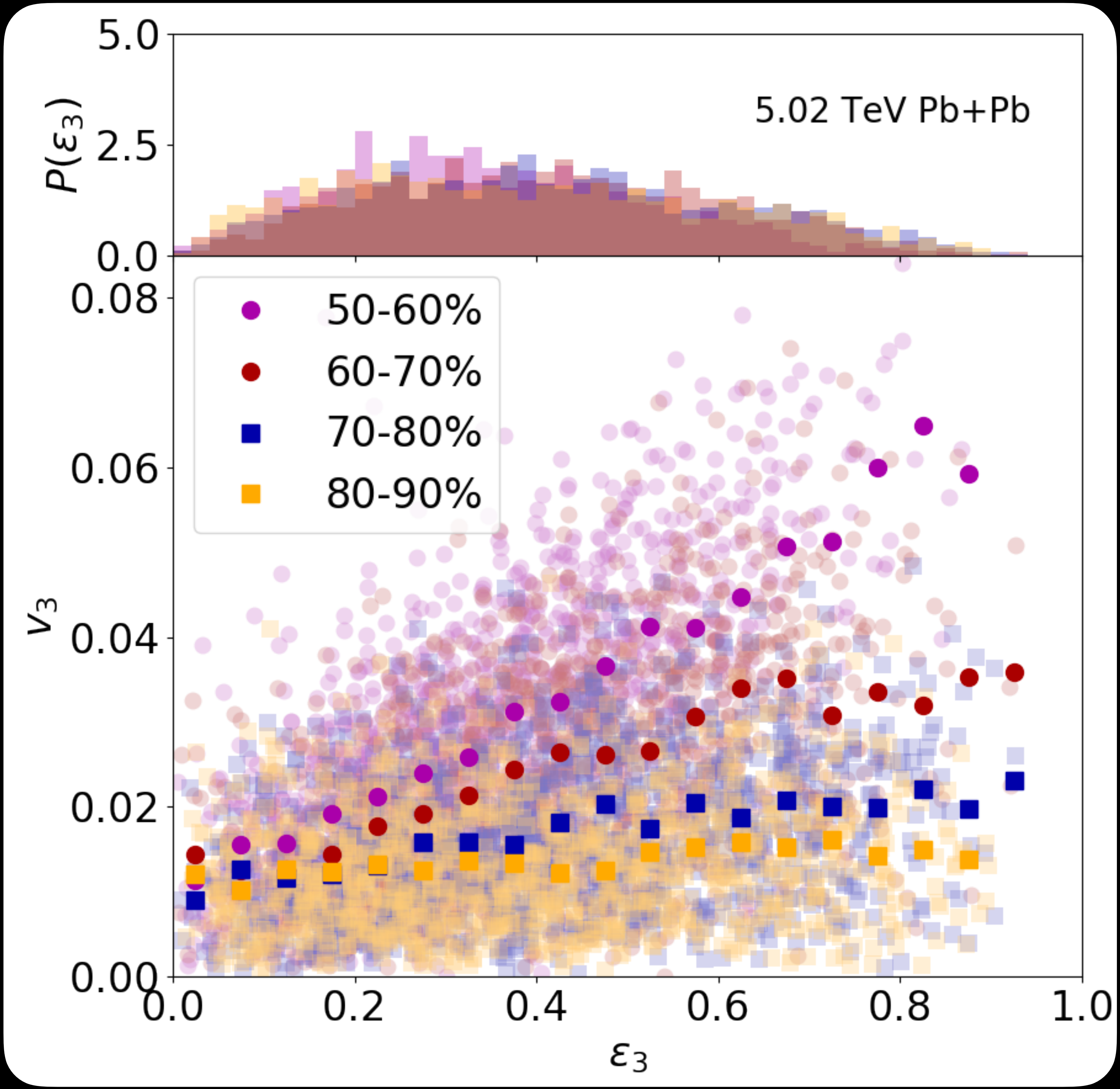
Geometry - flow correlations

First: Eccentricity distributions are indeed different



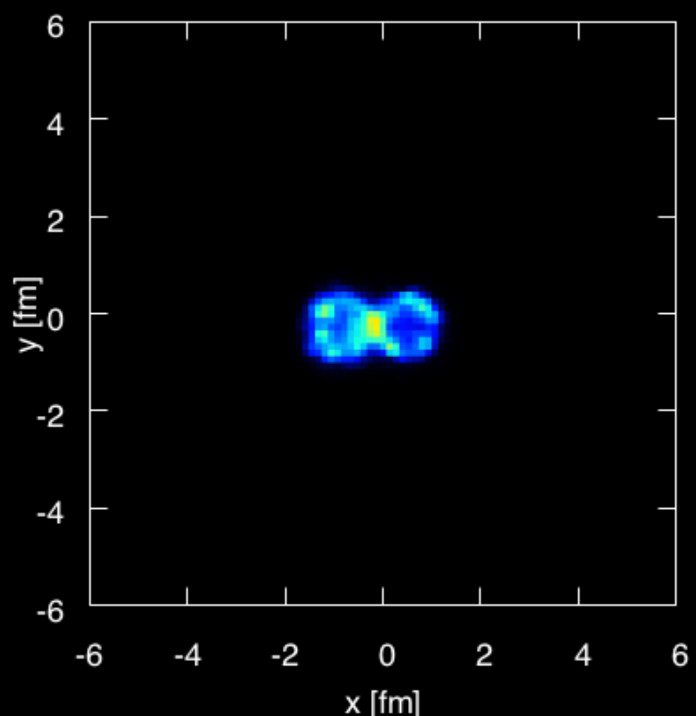
But: In very peripheral Pb+Pb no correlation with v_3

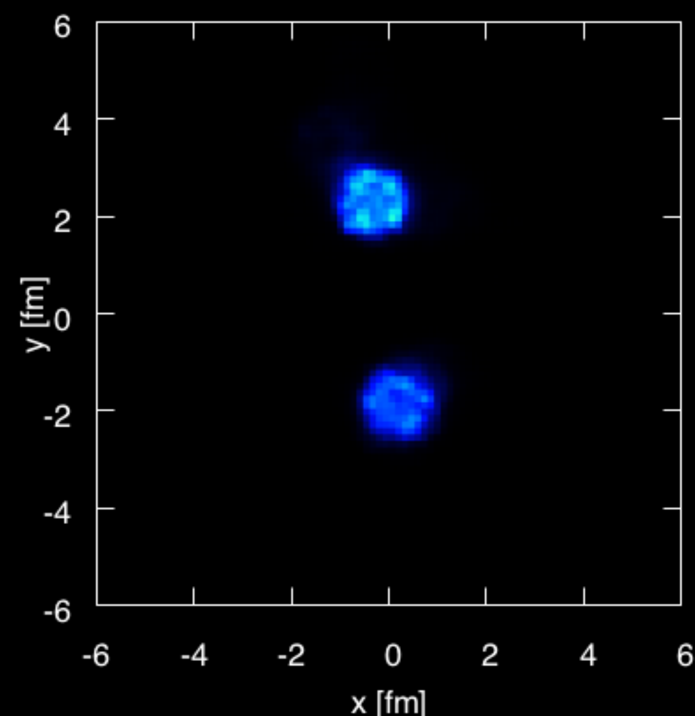
Correlation gradually vanishes



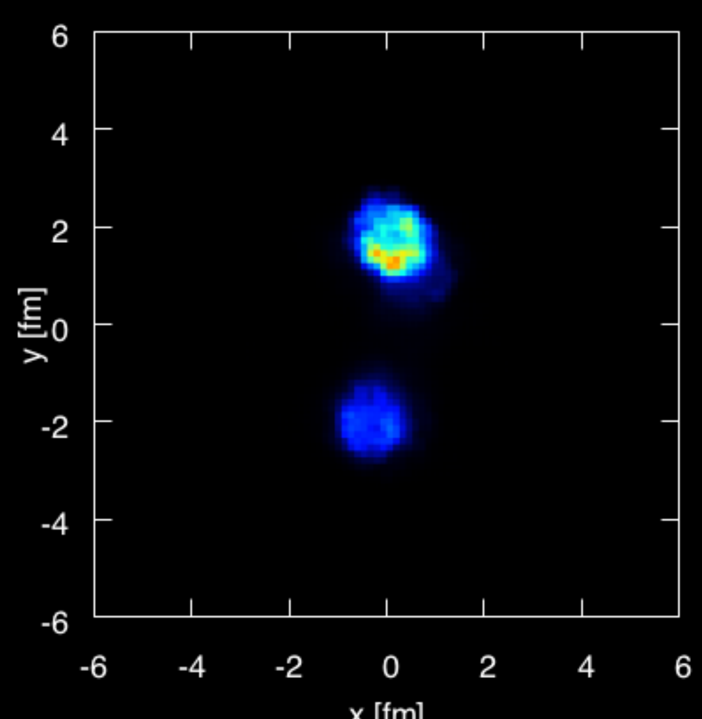
the more peripheral we go

Correlation vanishes in peripheral PbPb





Initial energy densities



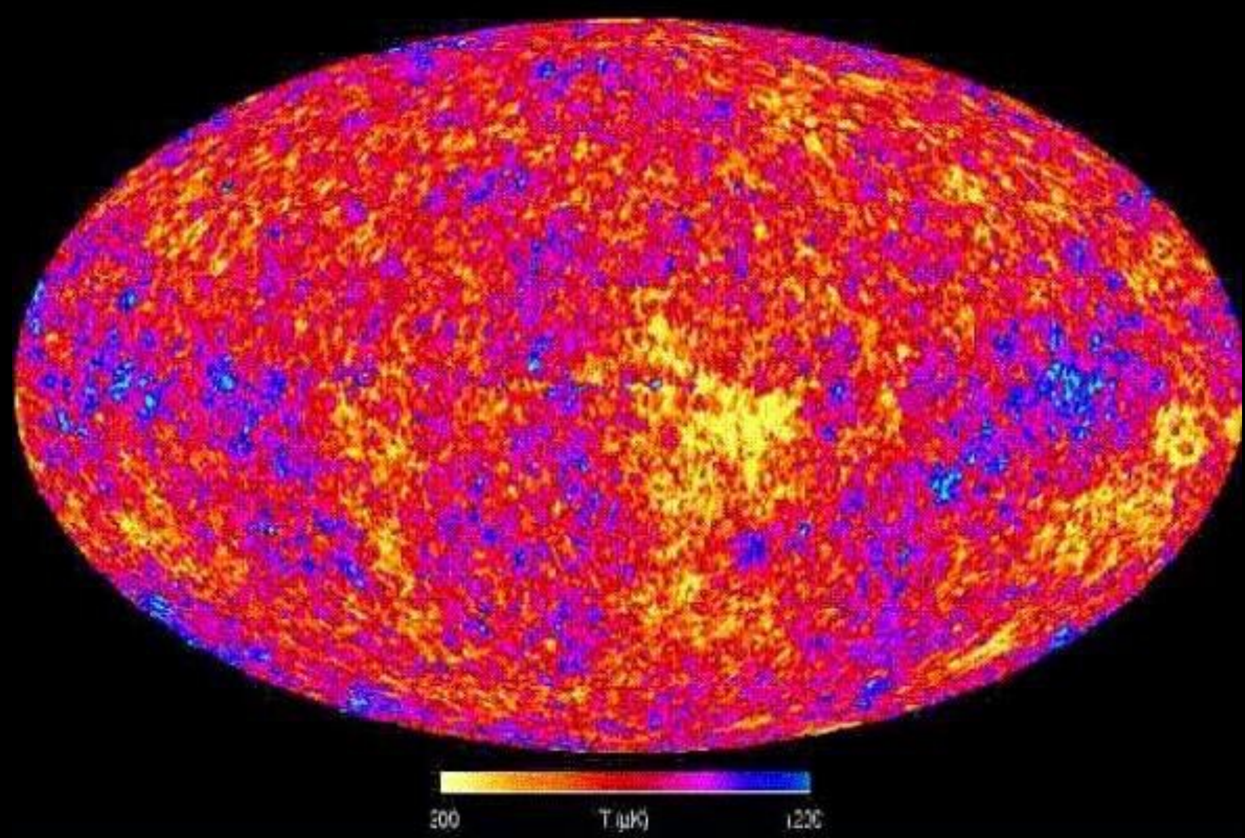
Many peripheral PbPb events consist of separated blobs that barely interact with one another

v_n driven by geometry of single blob

Like separate p+Pb collisions

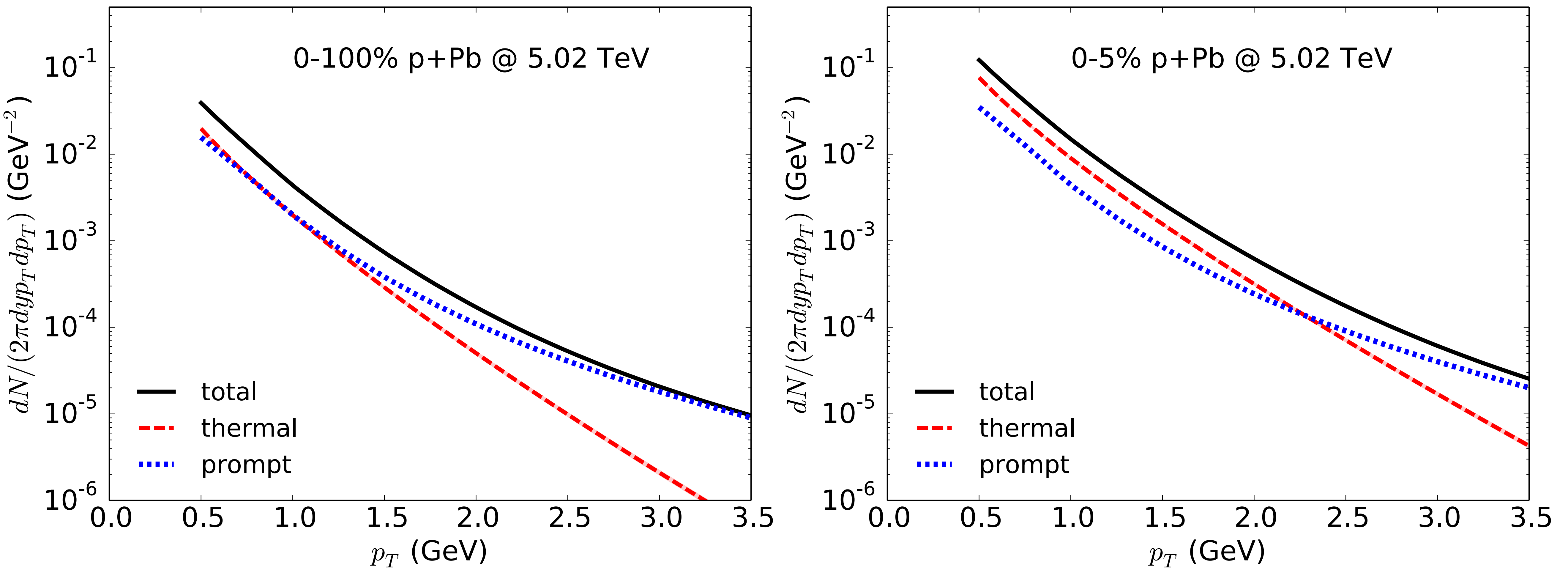
Probes for Quark Gluon Plasma

- Electromagnetic radiation



Thermal radiation in small systems

C. Shen, J-F. Paquet, G. Denicol, S. Jeon and C. Gale, Phys. Rev. C 95, 014906 (2017)

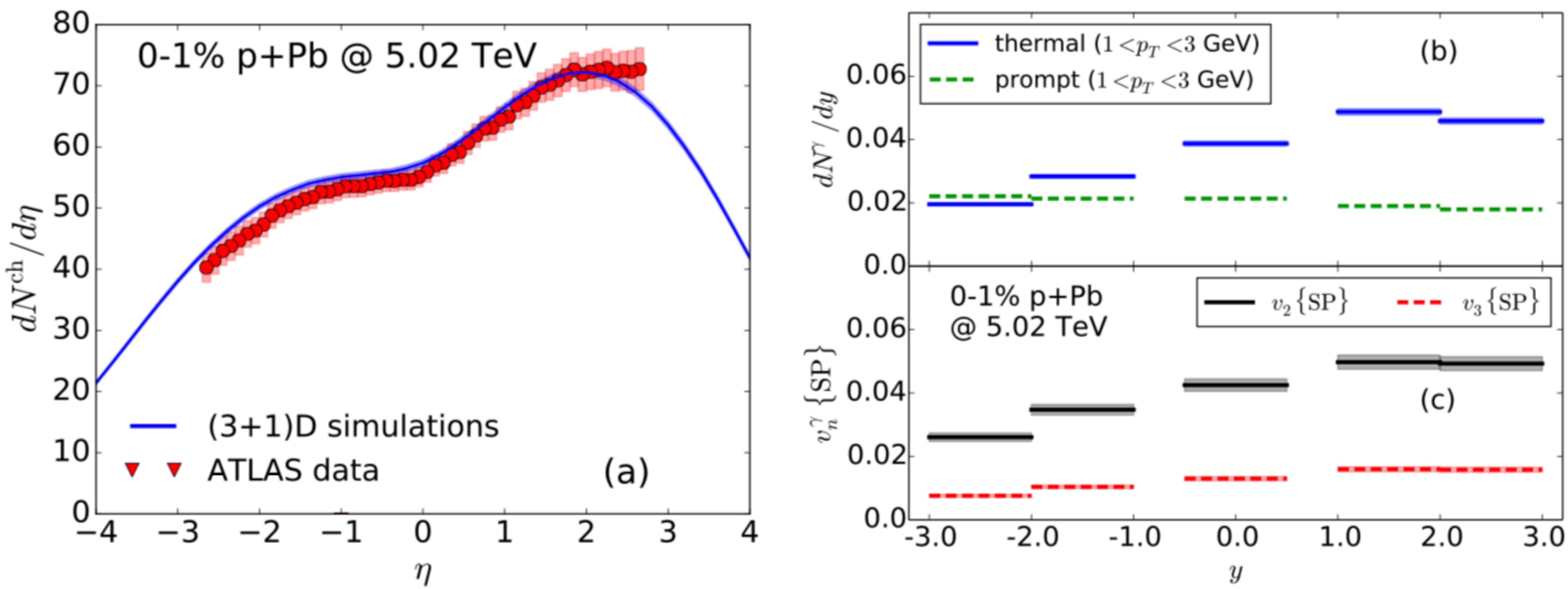


- In 0-5% p+Pb collisions, thermal photon can out-shine prompt photons

Signature of a nearly thermalized medium in small systems

Thermal radiation in small systems

C. Shen, J-F. Paquet, G. Denicol, S. Jeon and C. Gale, Nucl. Part. Phys. Proc. 289-290, 161 (2017)

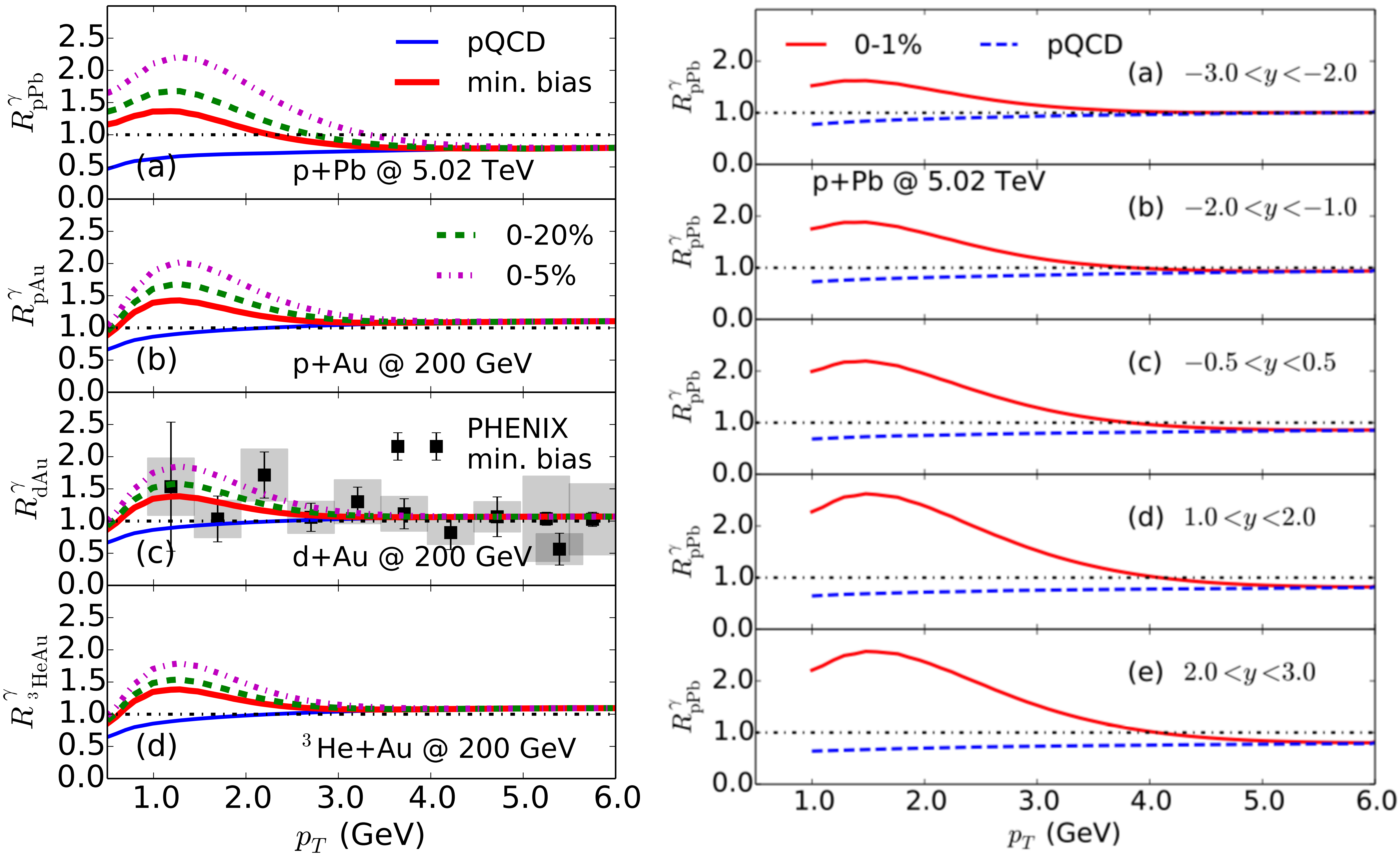


- Thermal and prompt photons show opposite rapidity dependence

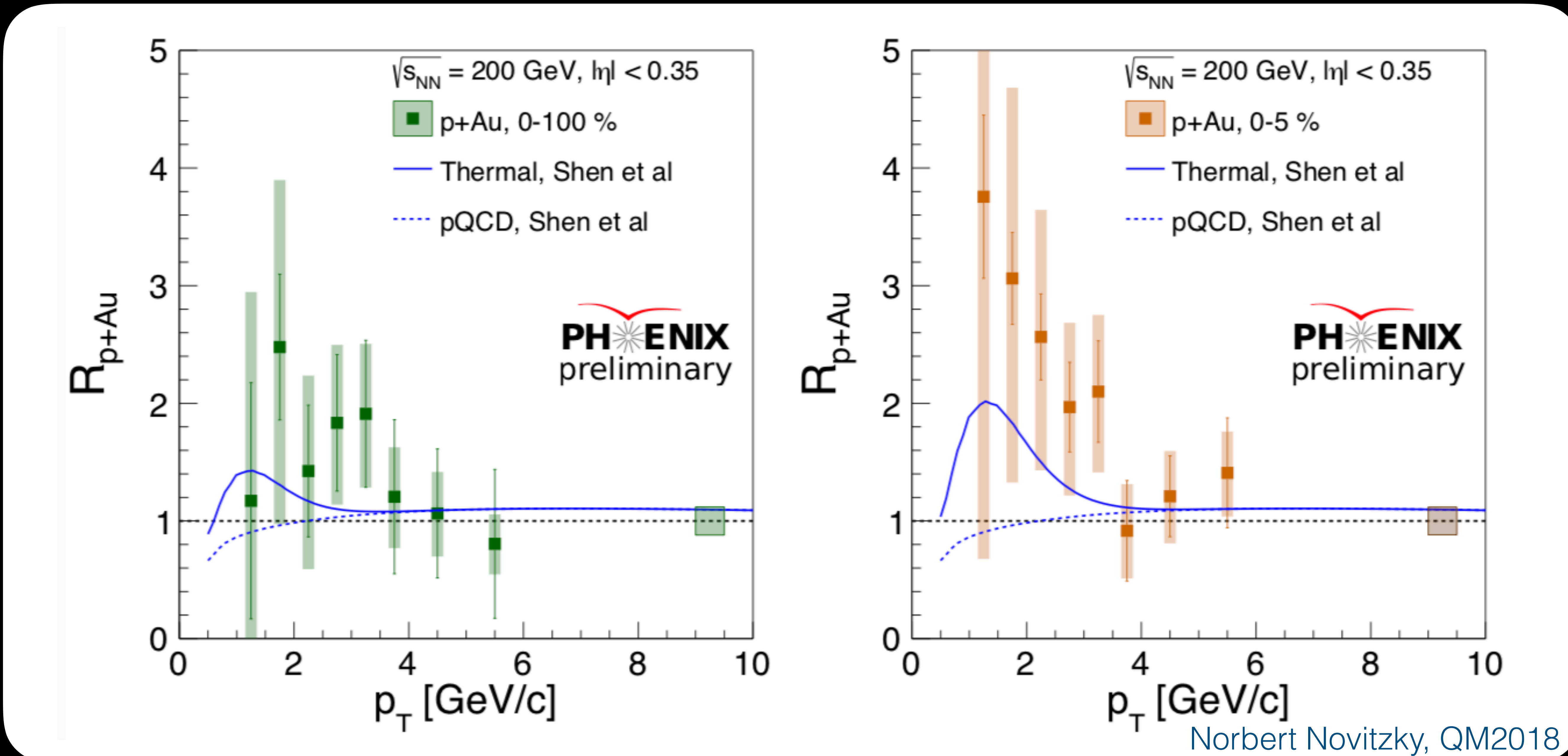
Large medium coming with large shadowing effect

Thermal radiation in small systems

C. Shen, J-F. Paquet, G. Denicol, S. Jeon and C. Gale, Phys. Rev. C 95, 014906 (2017)



Thermal radiation in small systems



- The latest PHENIX measurements show hints of thermal radiations in central p+Au collisions

Conclusions

- The hydrodynamic framework can well describe the bulk dynamics of heavy-ion collisions for range of > 2 orders of magnitude in particle multiplicity

- Initial state contributes ~50% of the momentum anisotropy in p+Pb collisions

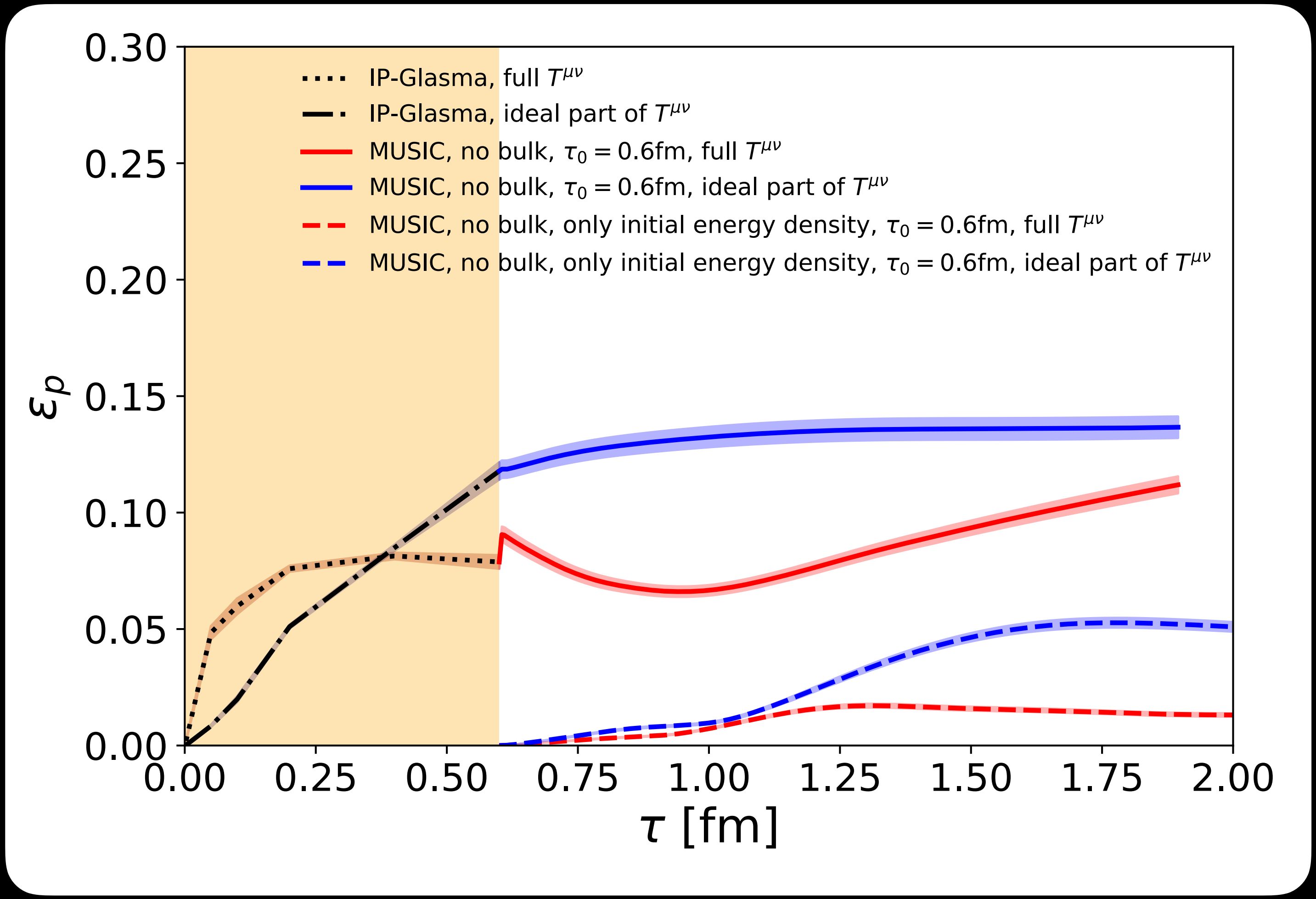
- Large bulk viscosity is a problem: causes negative pressures and large δf-corrections

- Direct photons provide us with an independent tool to study the nature and dynamics of the QCD matter created in small systems


BACKUP

When is momentum anisotropy generated in p+Pb?

No bulk, with and w/o initial flow



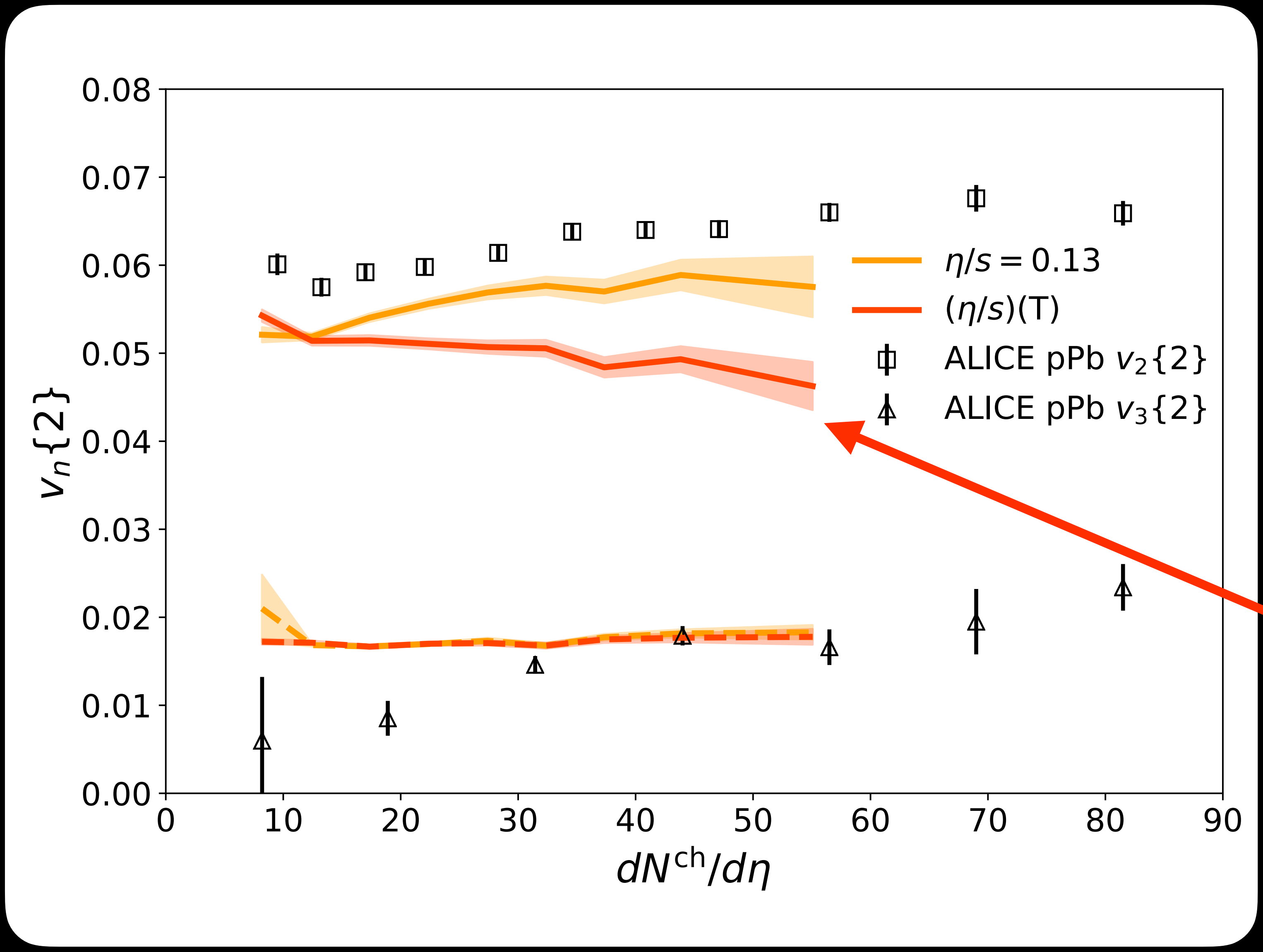
$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

Turning off initial flow when switching at τ=0.6fm almost no anisotropic flow is built up

This is also reflected in v_n values

Not much room for T-dependent η/s

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

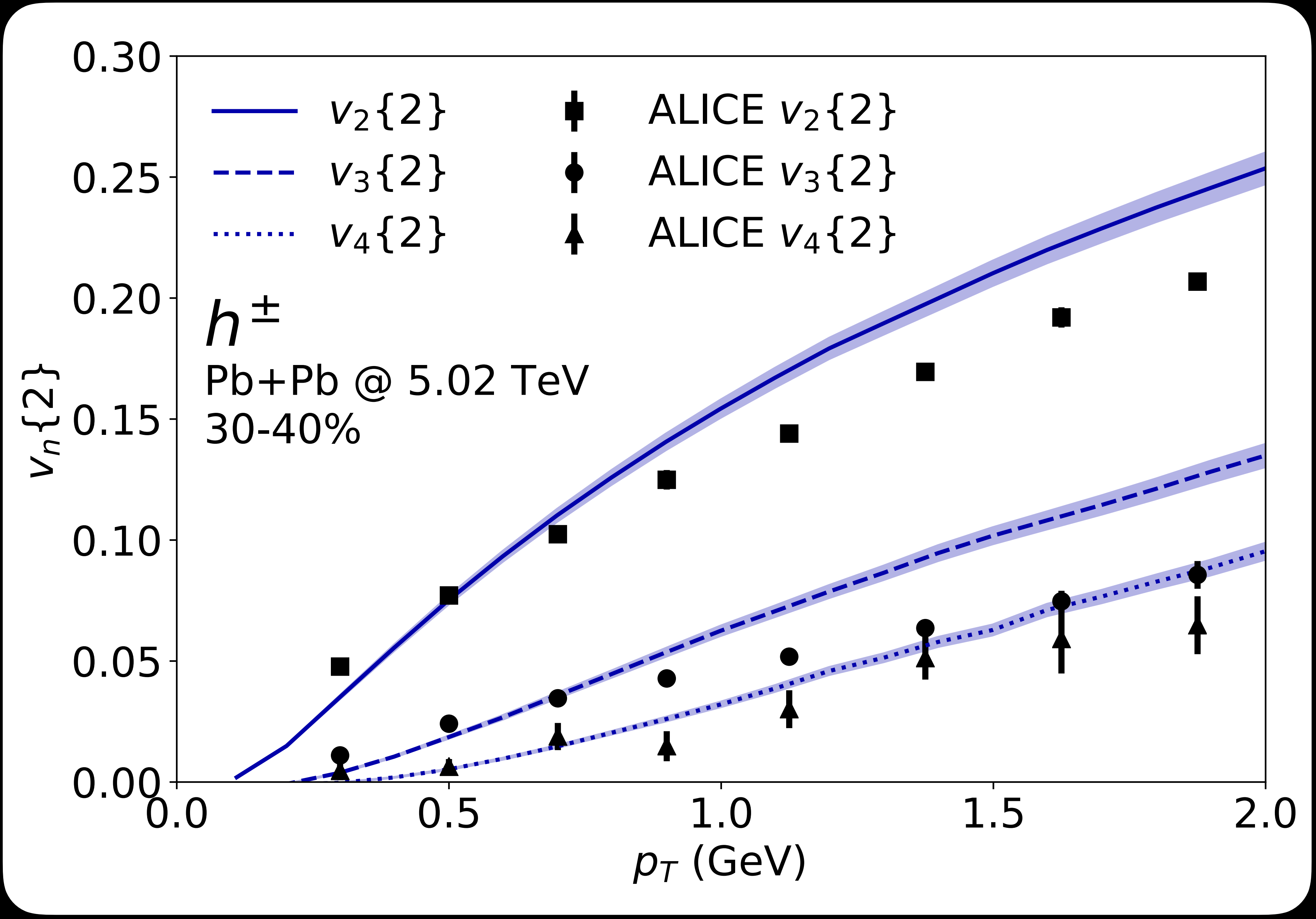


Rising η/s with increasing T leads to dropping v_2 for p+Pb

Experimental data: B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014)

Differential v_n

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

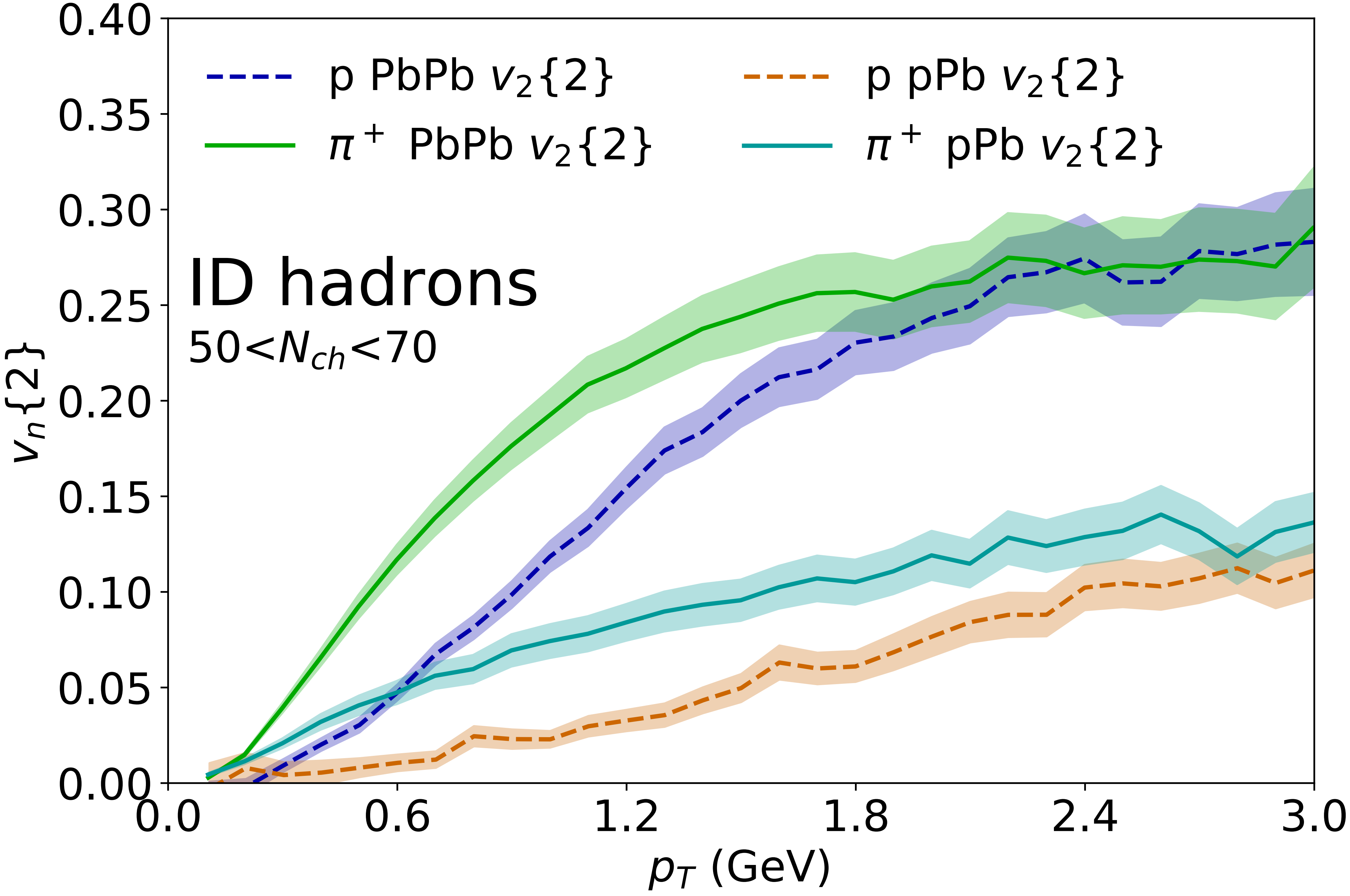


New EoS and inclusion of bulk viscosity makes agreement worse

Experimental data: ALICE Collaboration, Phys.Rev.Lett. 116, 132302 (2016)

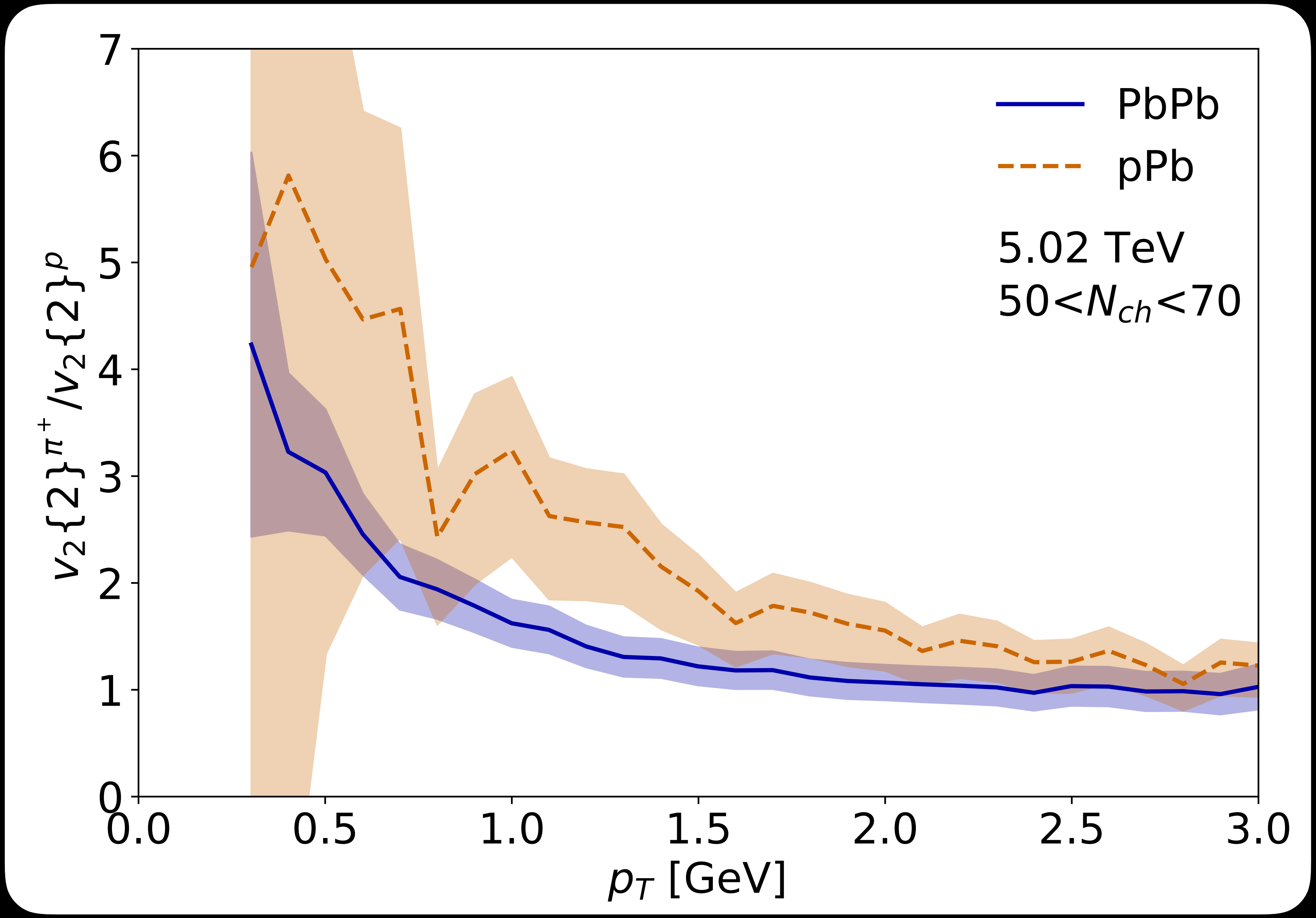
Mass splitting

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



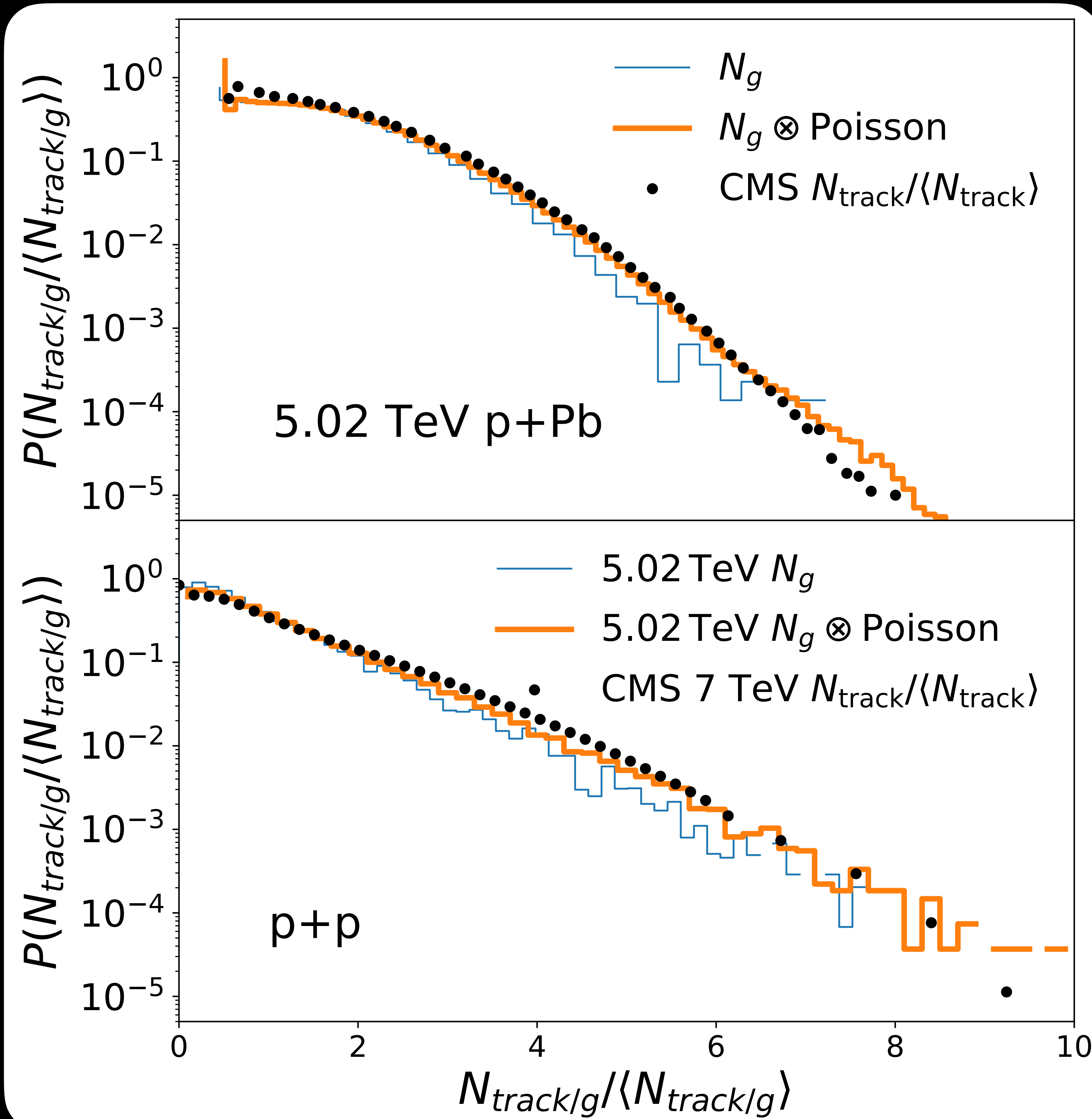
More mass splitting in p+Pb

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



as expected from larger mean transverse momentum

MULTIPLICITY DISTRIBUTIONS



Includes fluctuations of

- nucleon positions in Pb
- hot spot positions
- saturation scale normalization
- color charges
- Poisson fluctuations to estimate effect from hadronization