AZIMUTHAL ANISOTROPIES FROM COMBINED INITIAL+FINAL STATE FRAMEWORKS

WORK WITH CHUN SHEN AND PRITHWISH TRIBEDY

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INT 18-3, SEATTLE, NOVEMBER 15 2018

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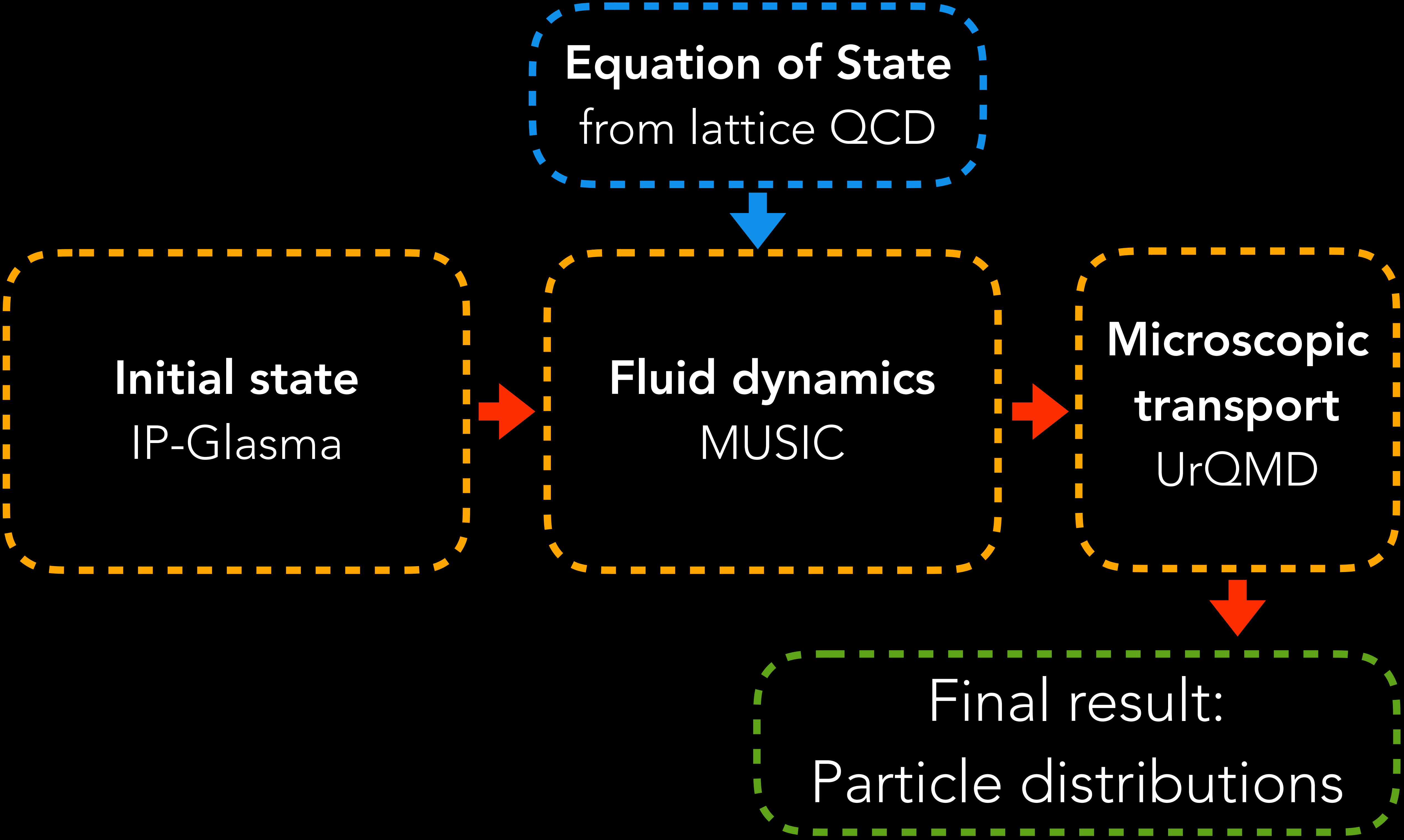
What is the dominant origin of azimuthal anisotropies in small systems?

- Initial momentum anisotropy from CGC (in IP-Glasma)
- Hydrodynamics with shear and bulk viscosities
- Include microscopic hadronic transport (UrQMD) at low *T*
- Fix parameters (e.g. transport parameters) in collisions of Pb+Pb, predict Xe+Xe and smaller systems
- Do the same for RHIC: fix parameters using AA (and HERA) and predict v_n in p+Au and d+Au collisions

- Determine origin of azimuthal anisotropy in small systems
- Lay out problems with viscous hydro in small systems

SIMULATION FRAMEWORK



Equation of State
from lattice QCD

Initial state
IP-Glasma

Fluid dynamics
MUSIC

Microscopic transport
UrQMD

Final result:
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 with three quark substructure (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

this is a place where EIC could help further constrain initial state

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)

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

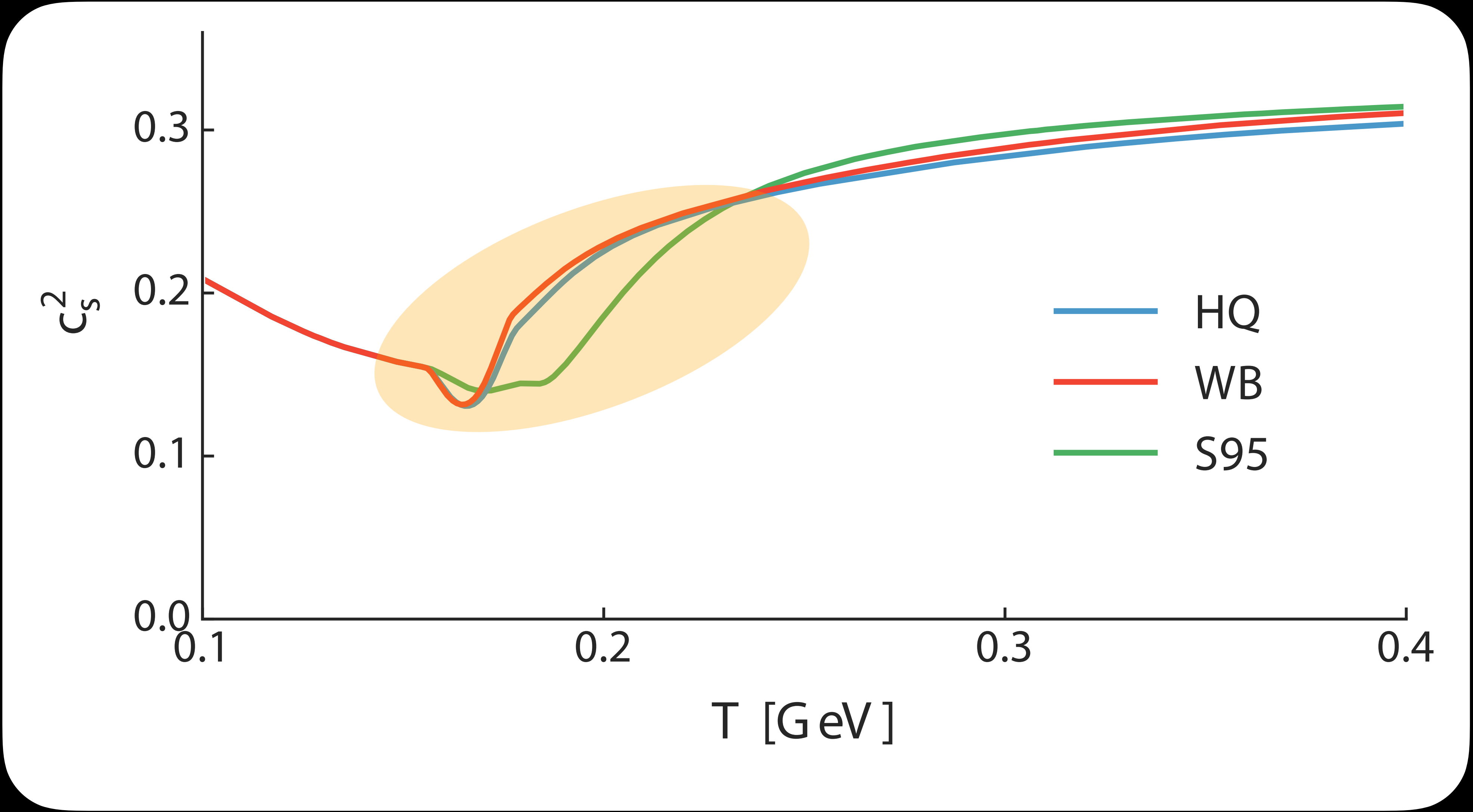
Absorb the difference to the lattice EoS in a 'bulk' stress term (here, *P* from the lattice EoS)

$$\Pi = \frac{\varepsilon}{3} - P$$

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

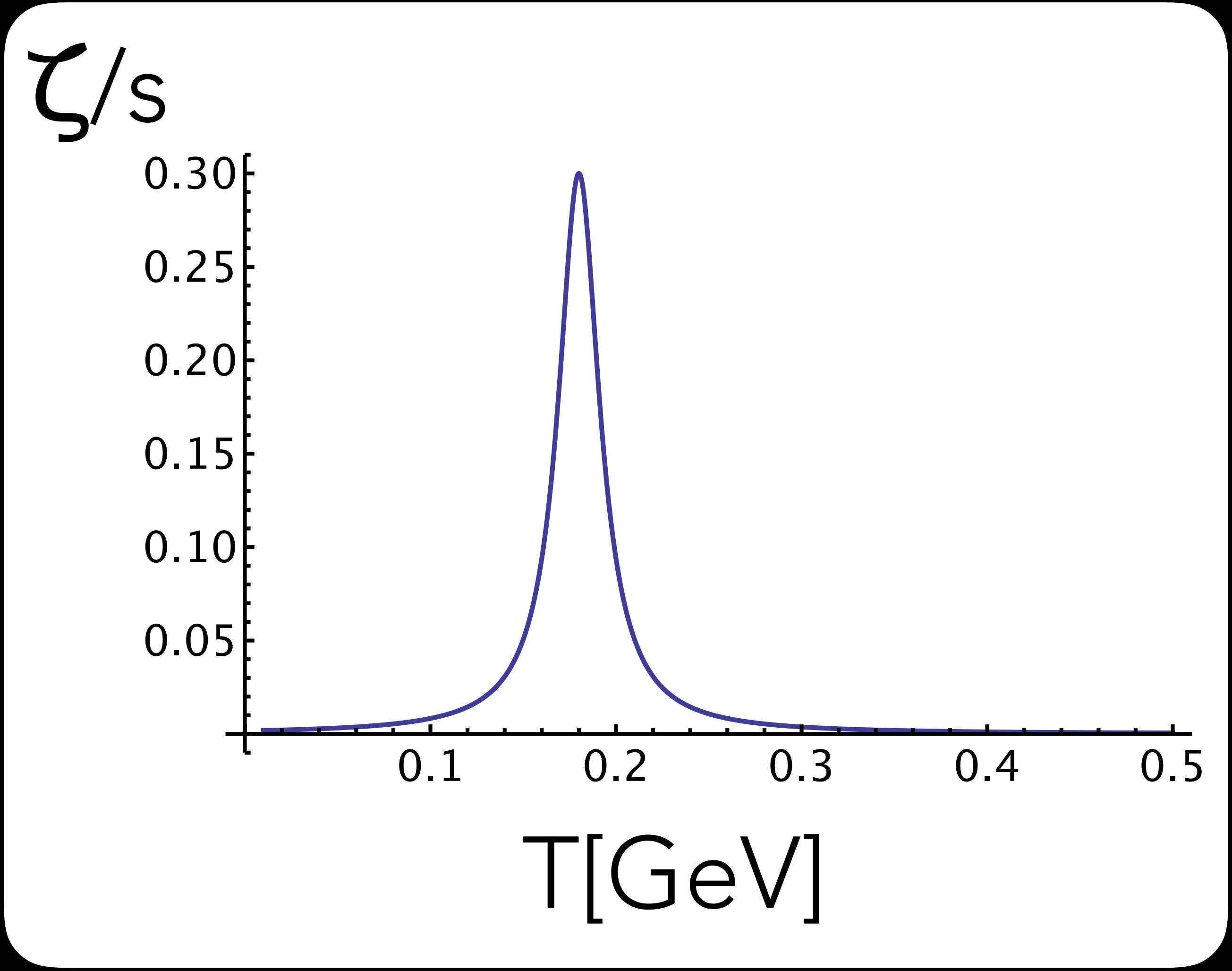
s95: P. Huovinen and P. Petreczky, Nucl. Phys. A837, 26–53 (2010)

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 - all parameters fit in AA

Constant **η**/s



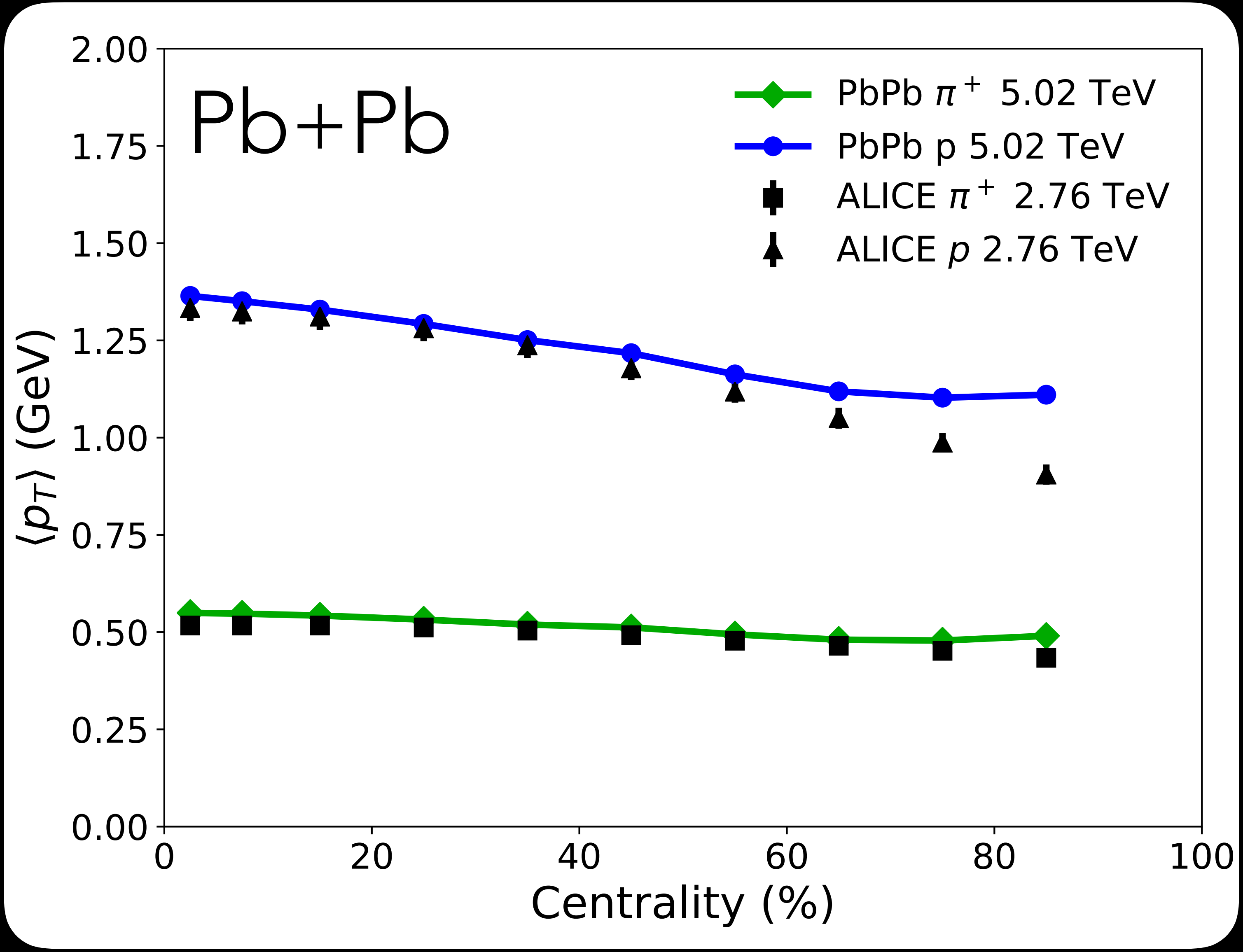
Bulk viscosity
peaks at 180 MeV

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)

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

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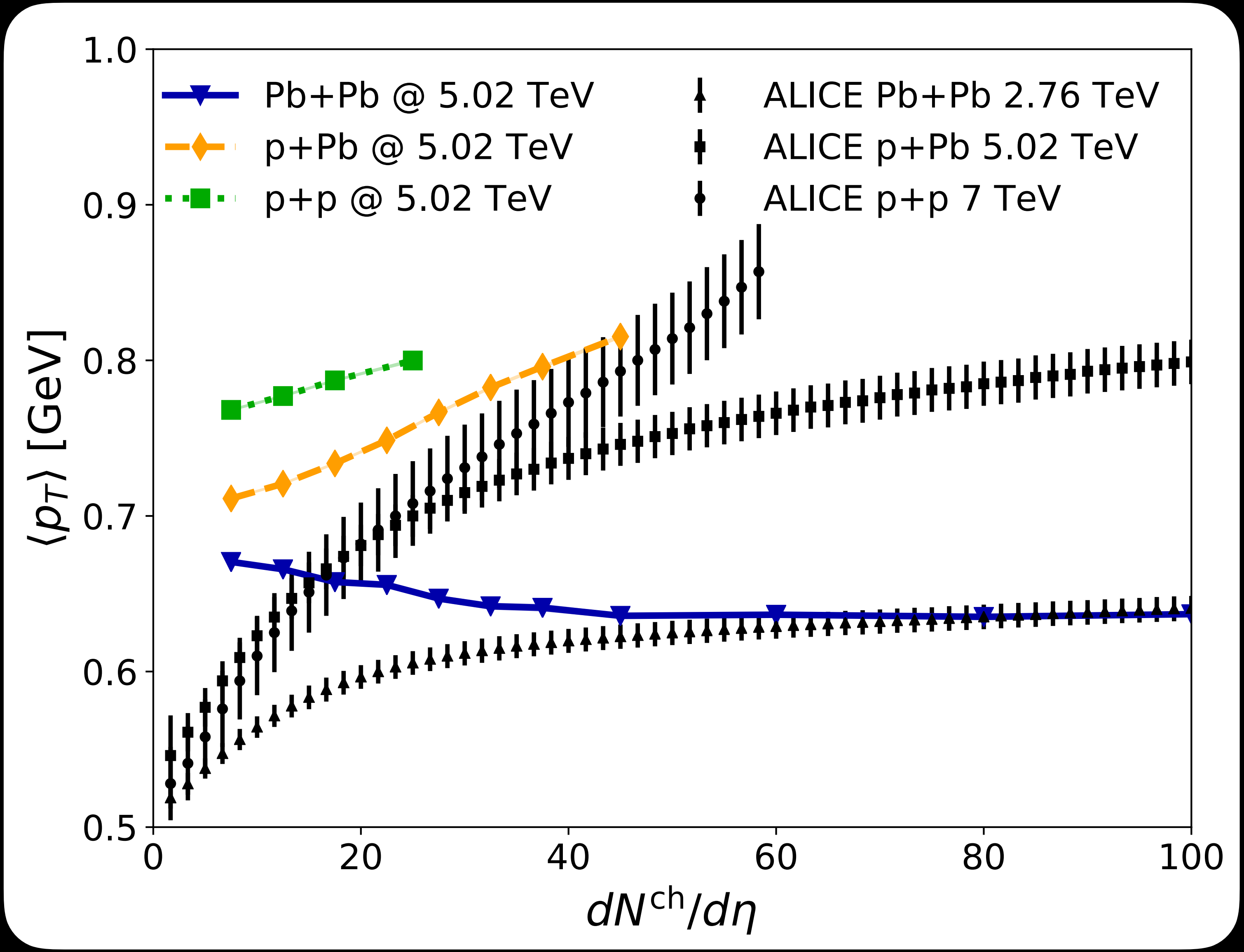


p+Pb $\langle p_T \rangle$ ~8% > than data

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

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

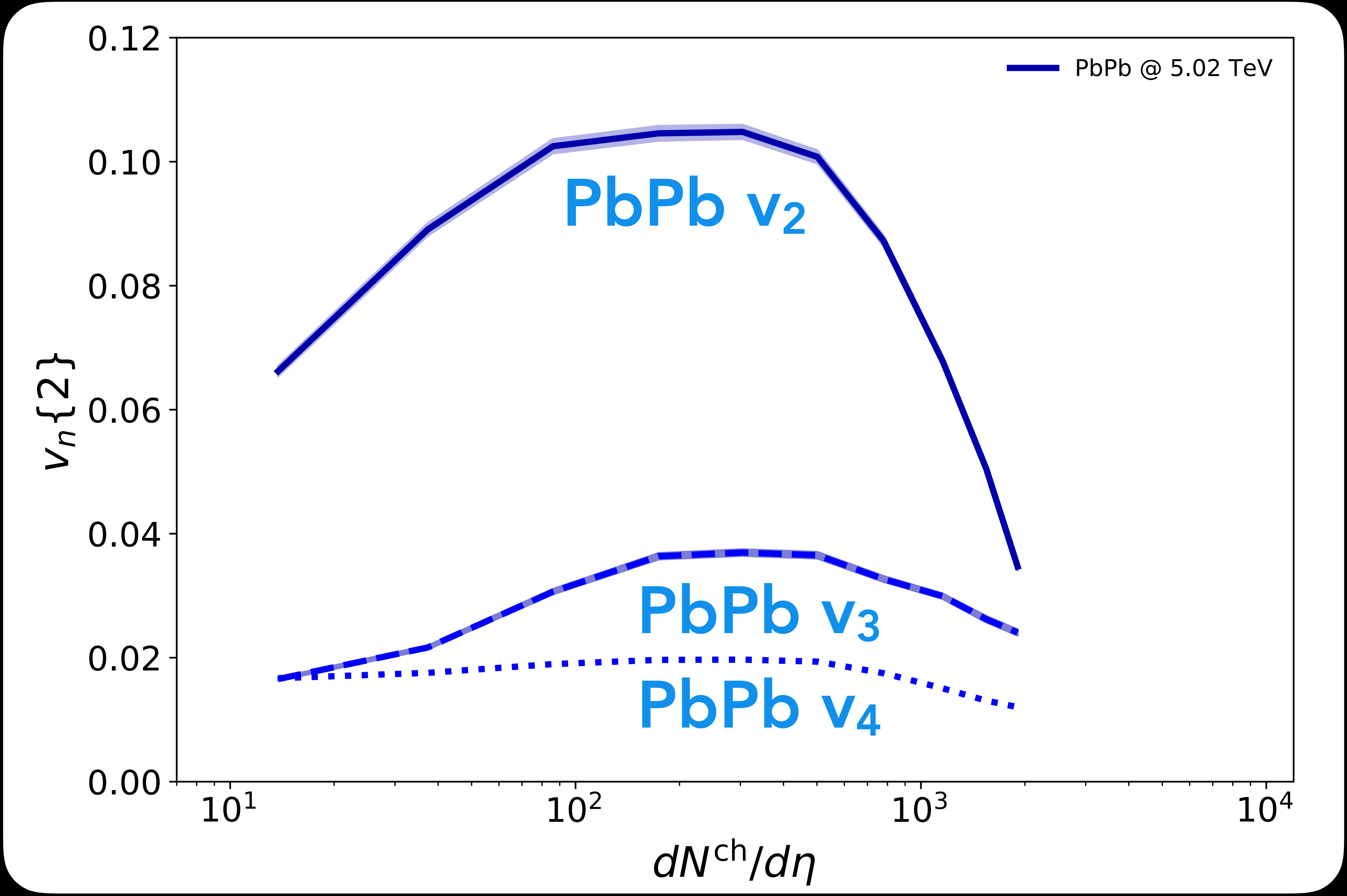
Bulk viscosity smaller at low T (low multiplicity)

UrQMD also may have too little bulk viscosity

Anisotropy vs. multiplicity

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

$\eta/s=0.13$



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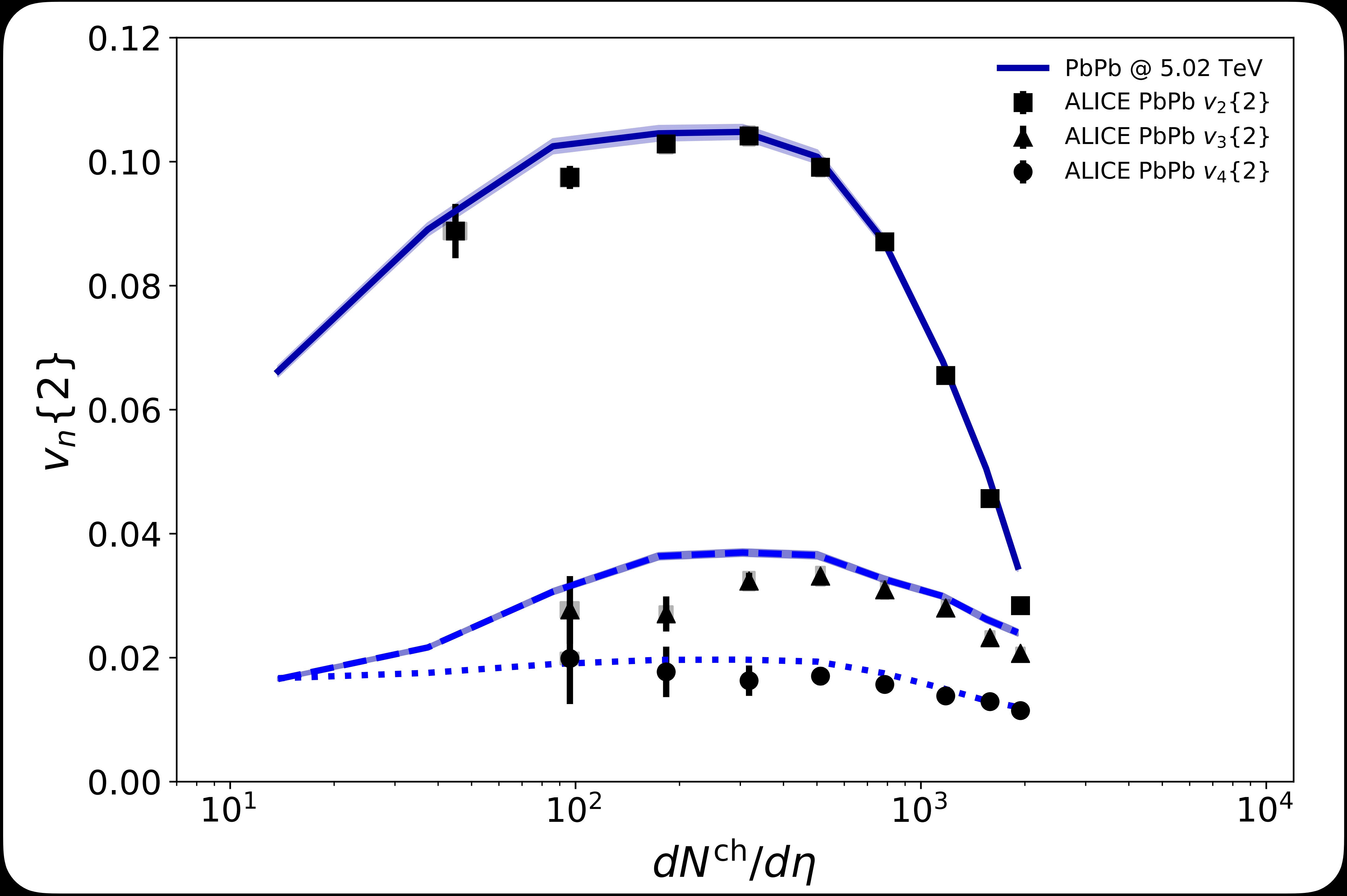

Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)

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

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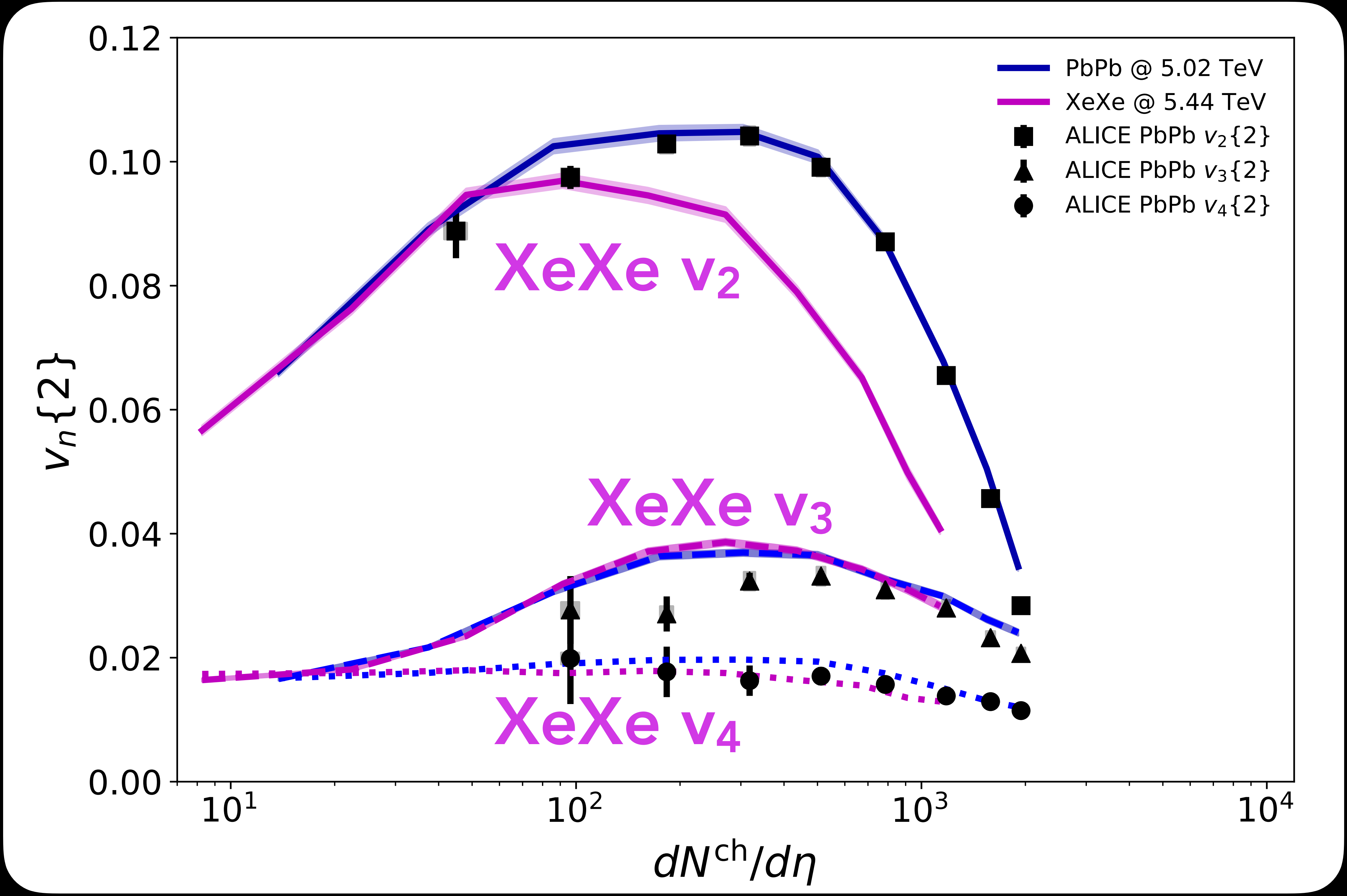

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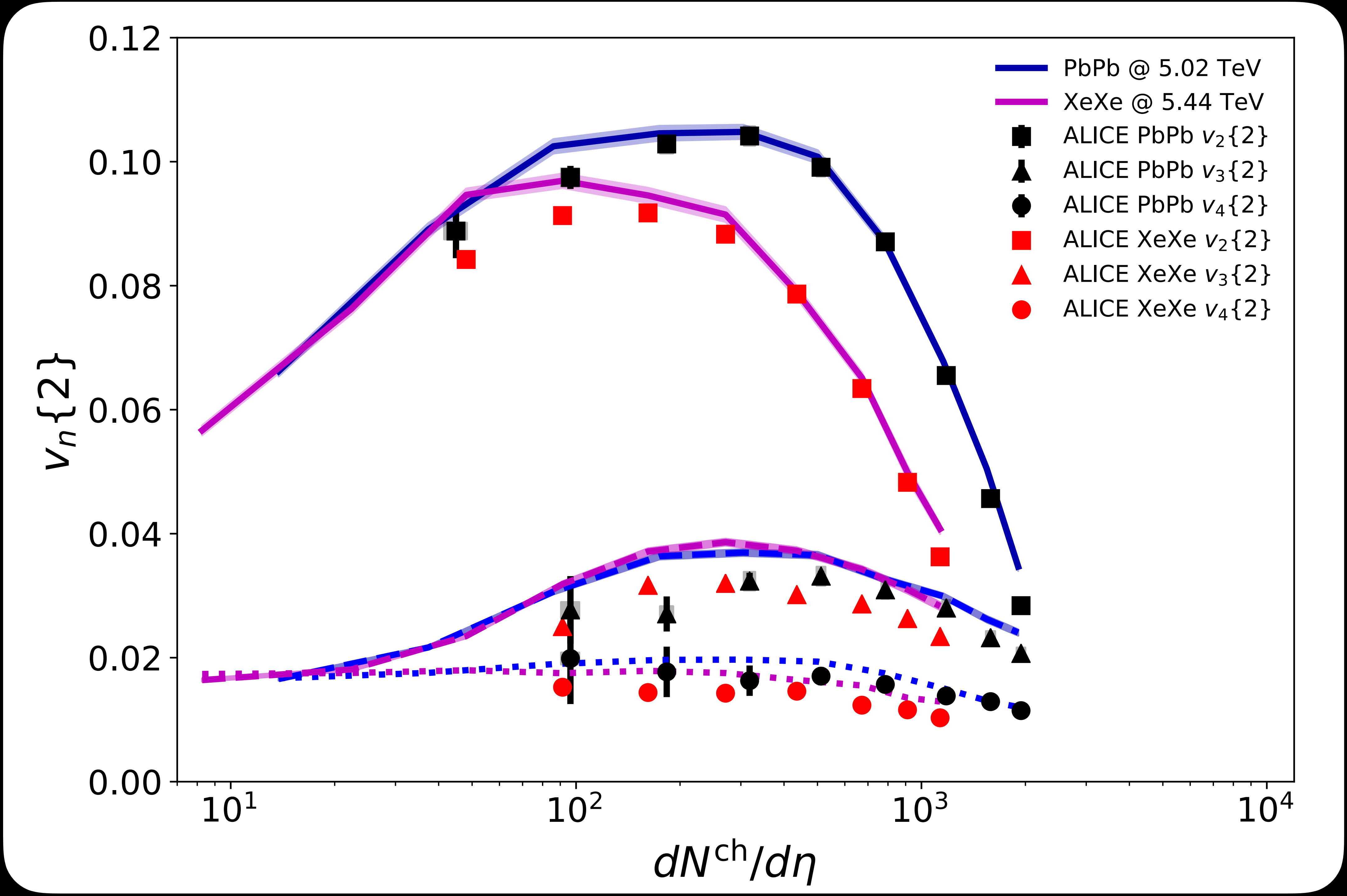

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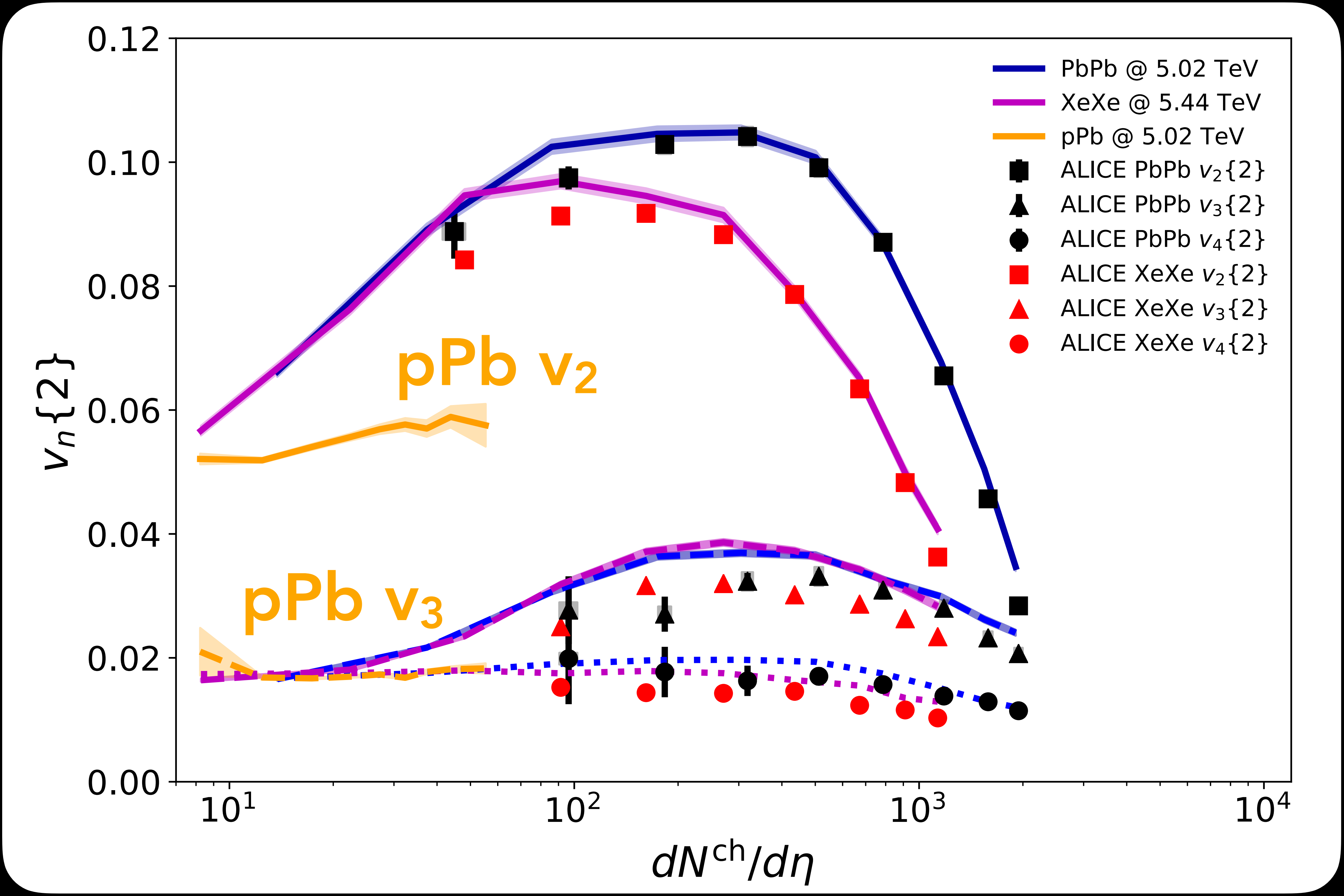

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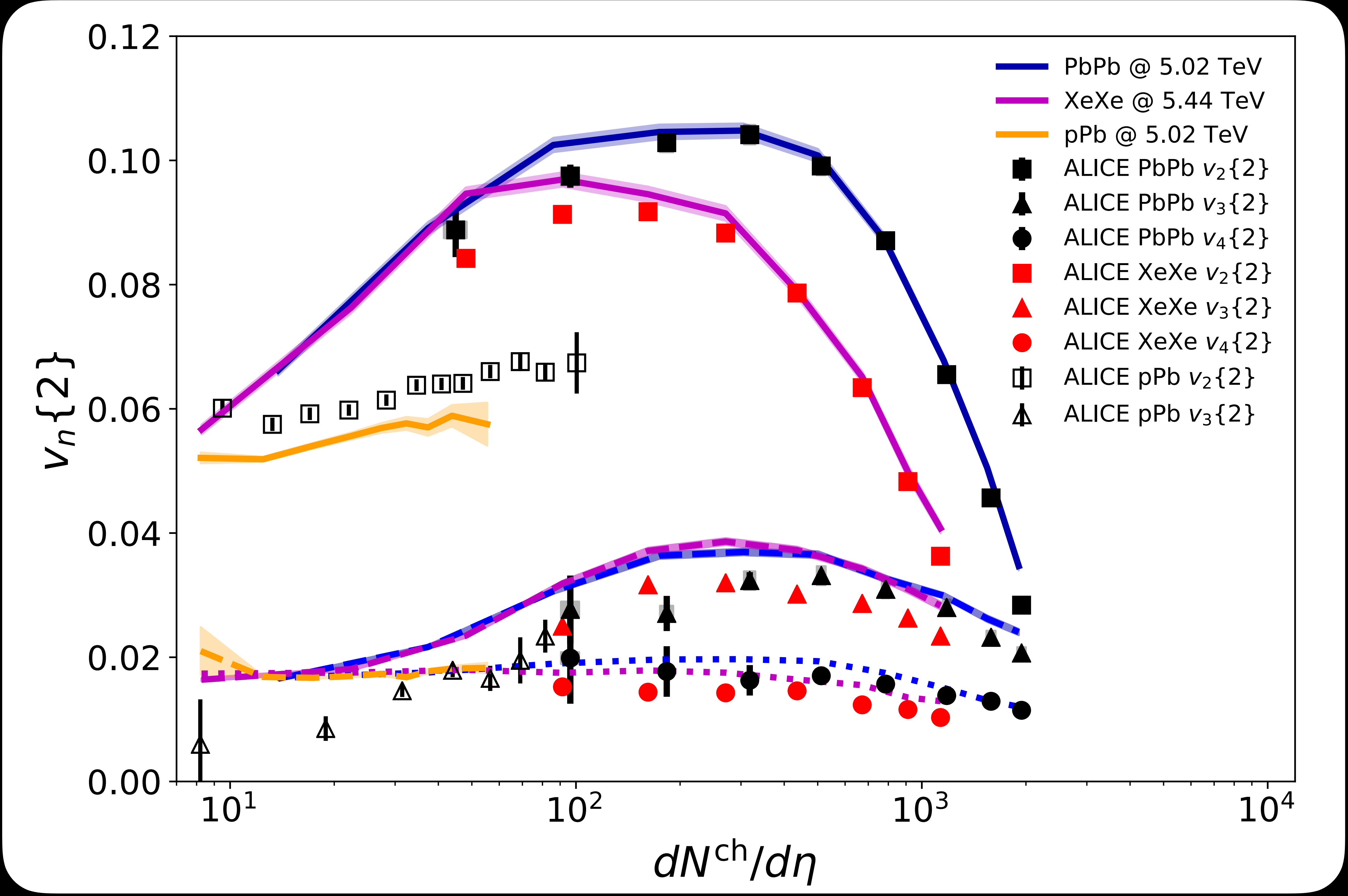

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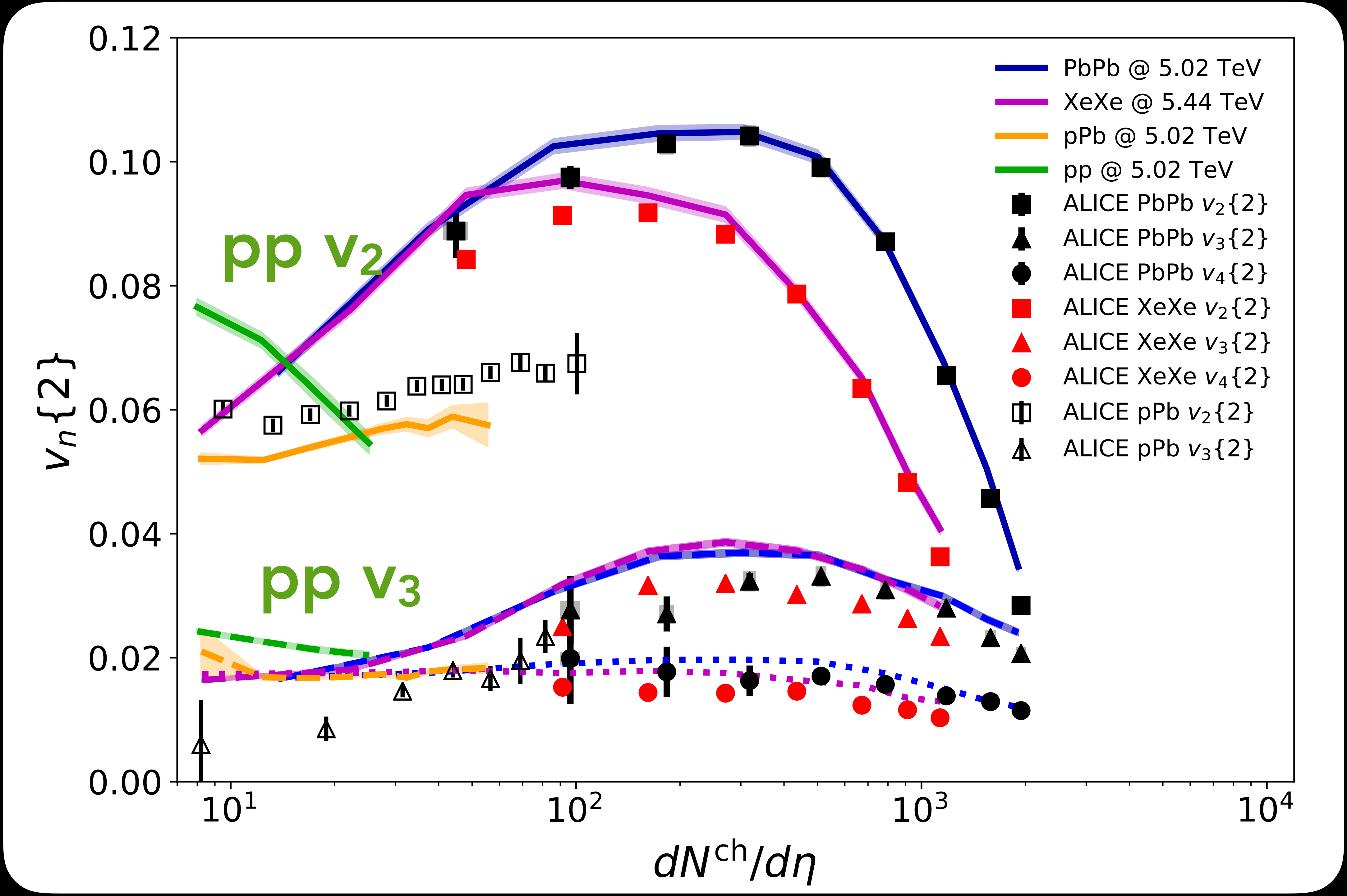

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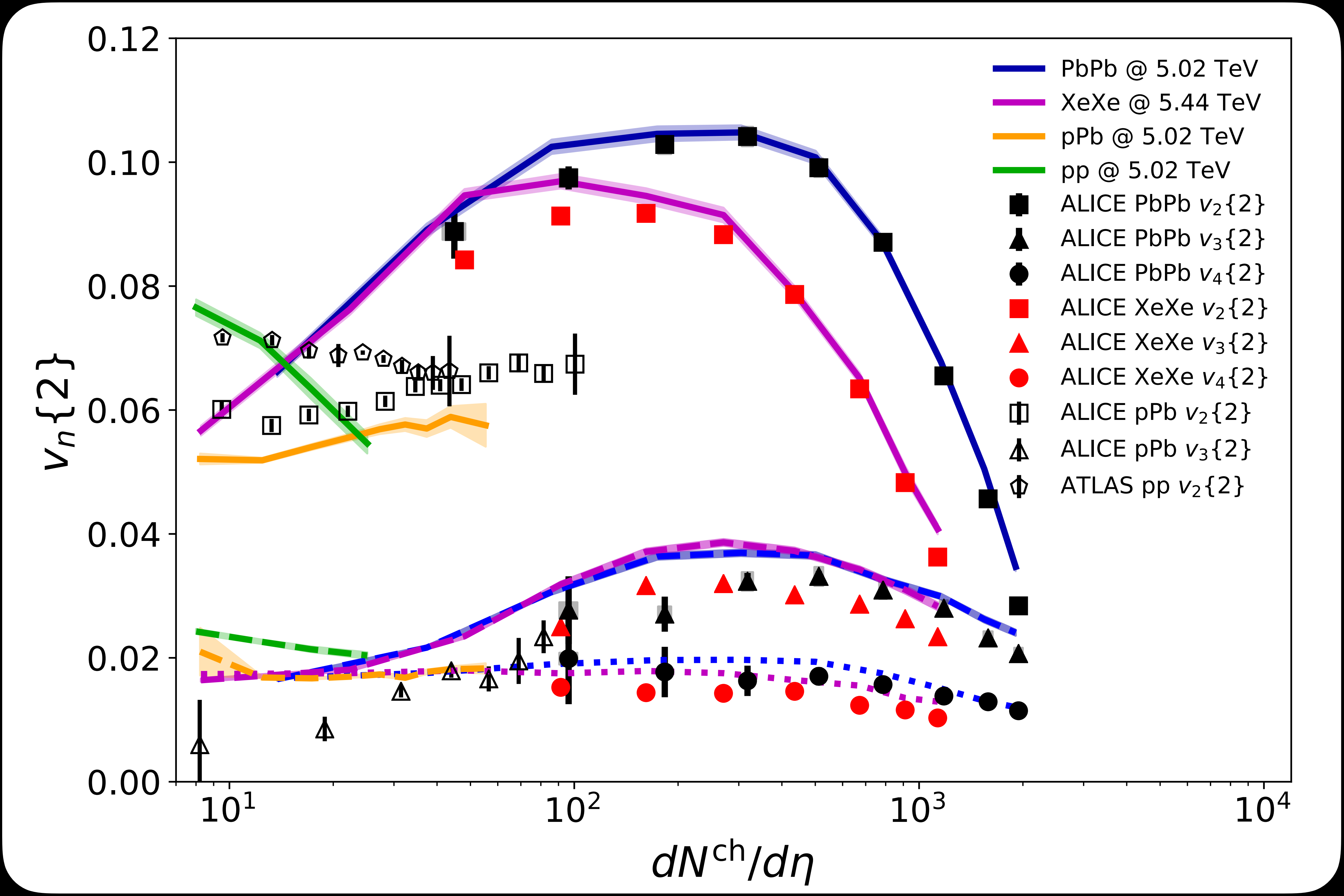

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ATLAS Collaboration, Eur. Phys. J. C (2017) 77:428

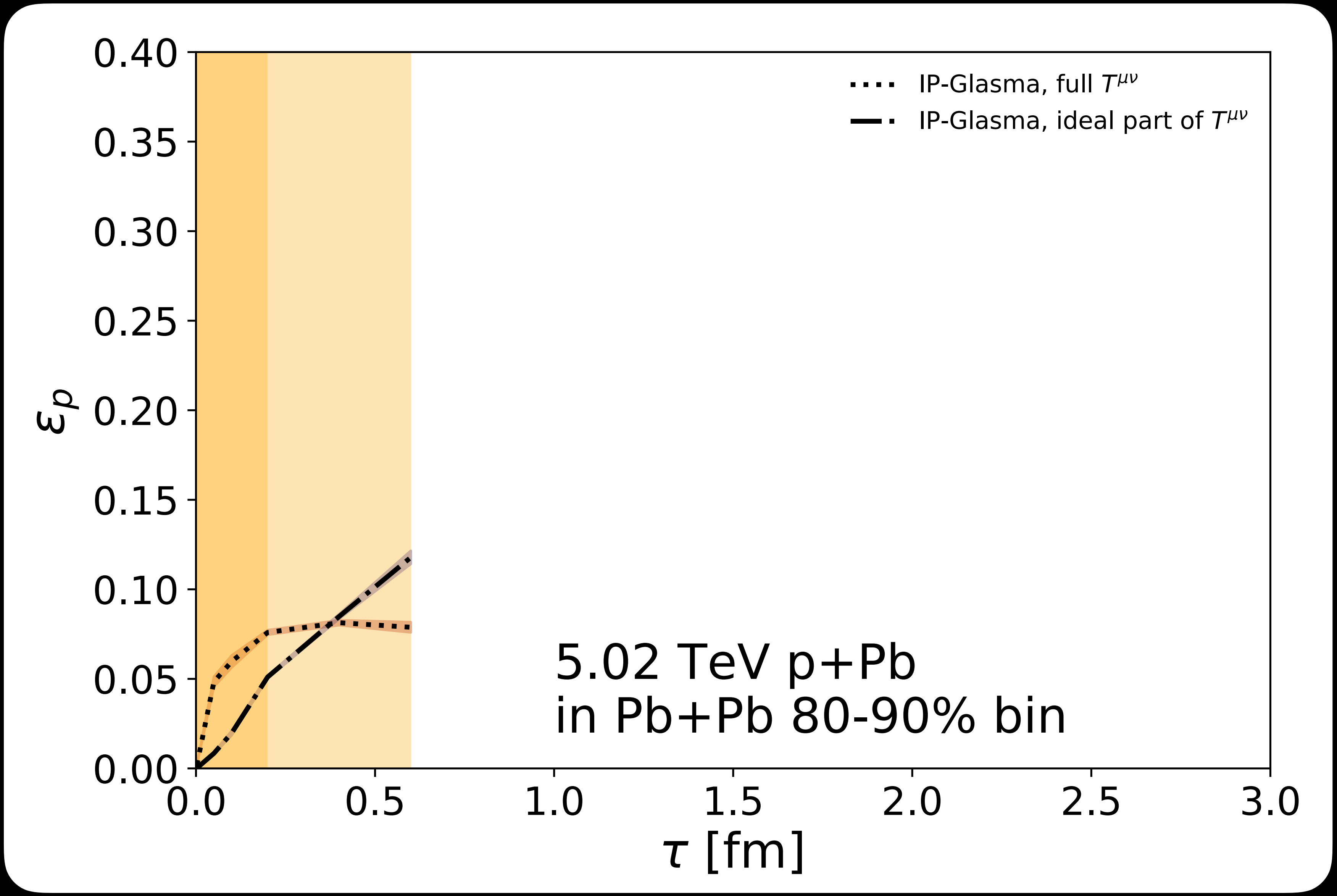
When is momentum anisotropy generated in p+Pb?

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

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

averages over space
(weighted with energy density)

IP-Glasma



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

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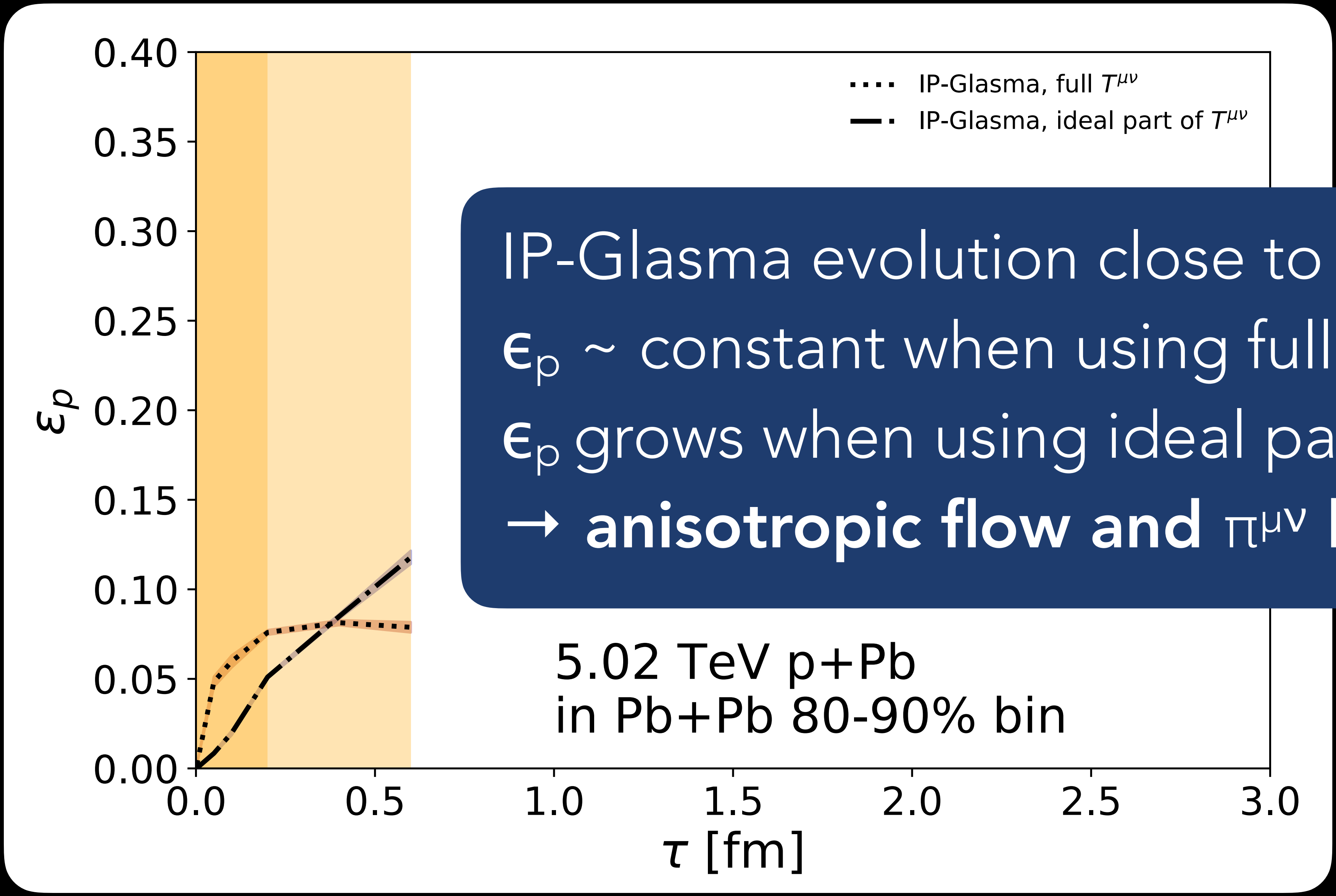

IP-Glasma evolution close to free streaming

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

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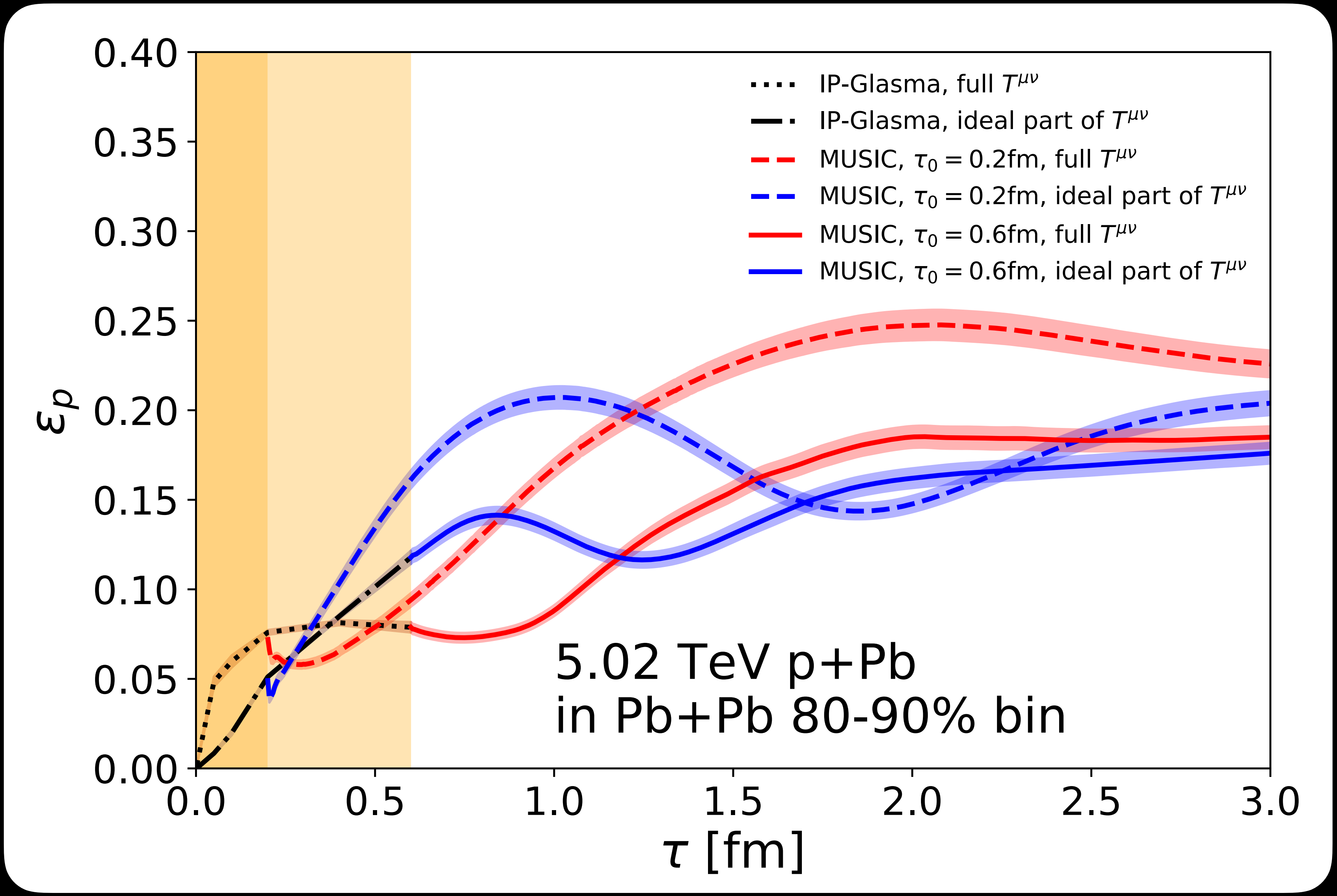
IP-Glasma Hydrodynamics



Switching at τ=0.6fm:
(full lines)
initial ϵ_p with full $T^{\mu\nu}$
~45% of final value

Switching at τ=0.2fm:
(dashed lines)
initial ϵ_p with full $T^{\mu\nu}$
~35% of final value

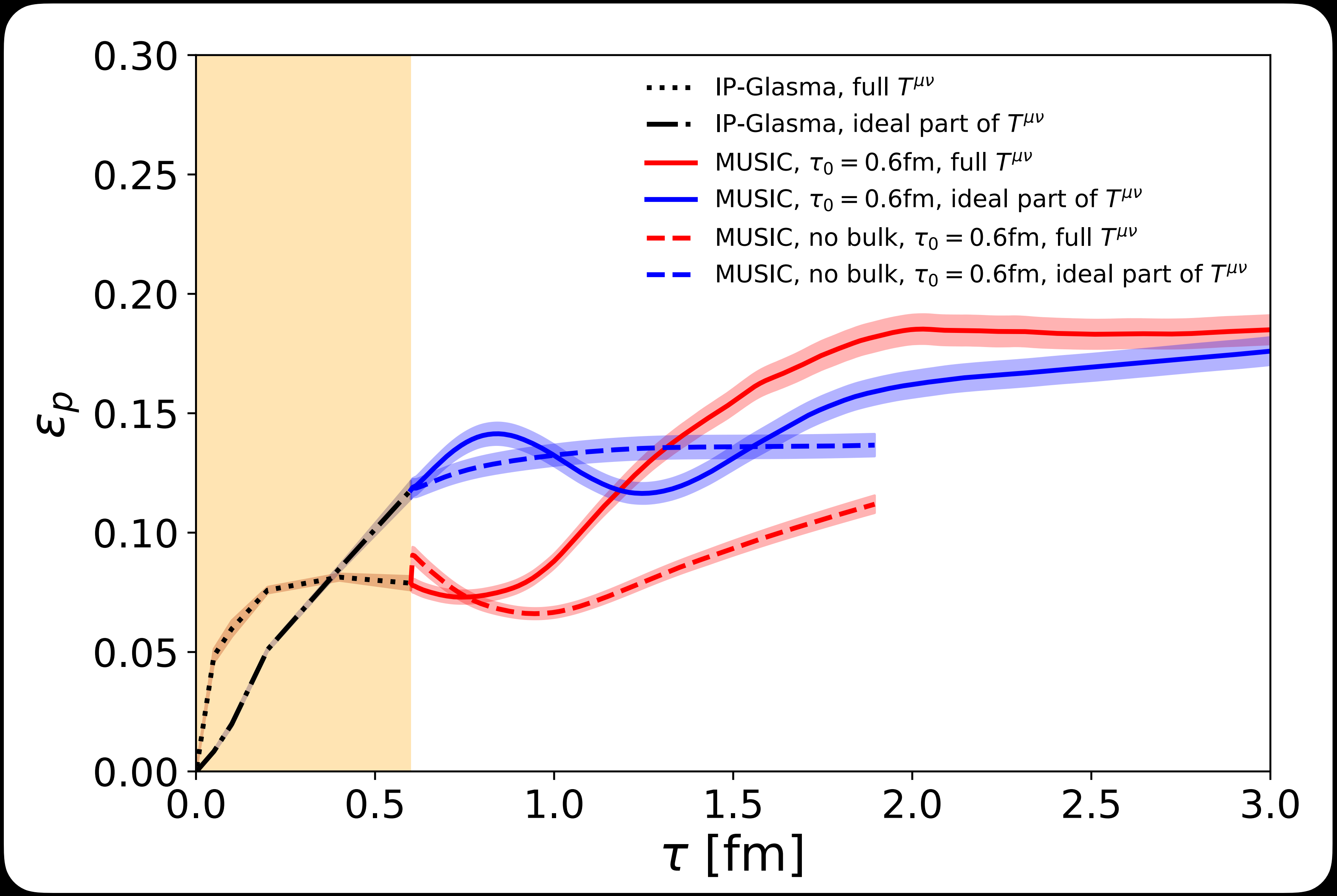
B. Schenke, C. Shen, P. Tribedy, in preparation

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



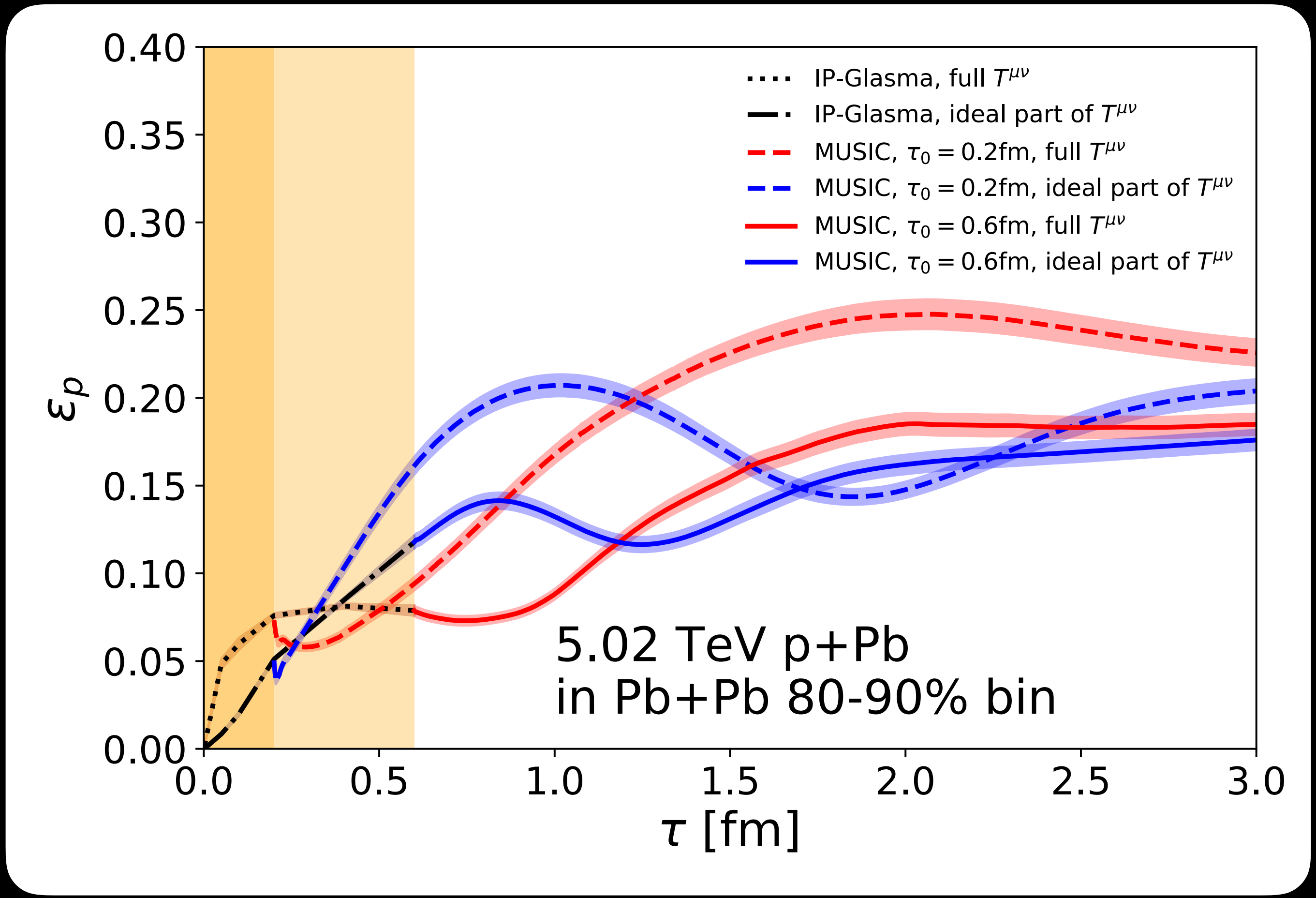
With bulk viscosity (full lines)

initial ϵ_p with full $T^{\mu\nu}$ ~45% of final value

w/o bulk viscosity (dashed lines)

initial ϵ_p with full $T^{\mu\nu}$ ~70% of final value

When is momentum anisotropy generated in p+Pb?



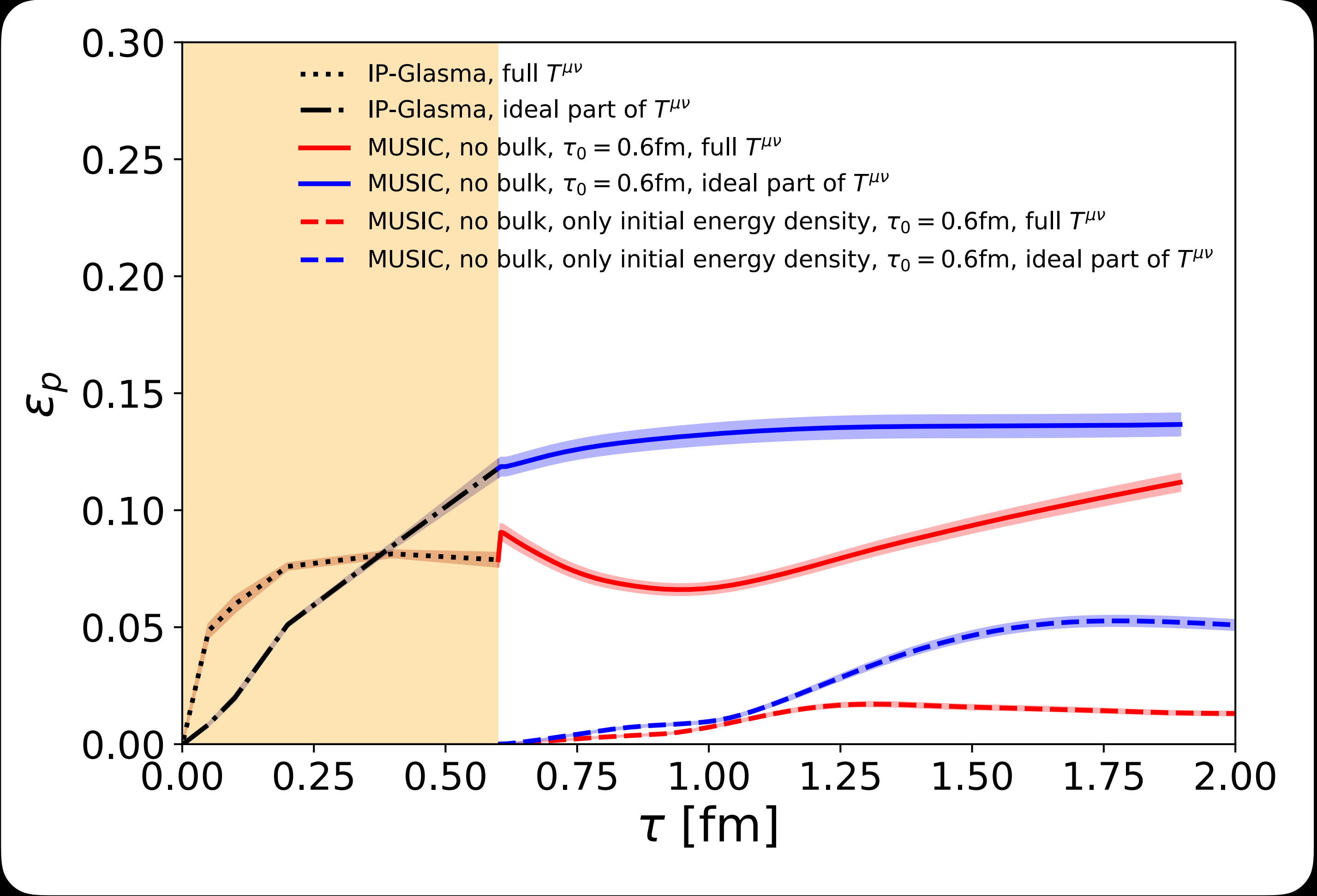
$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

- 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**

When is momentum anisotropy generated in p+Pb?

No bulk, with and w/o initial flow



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

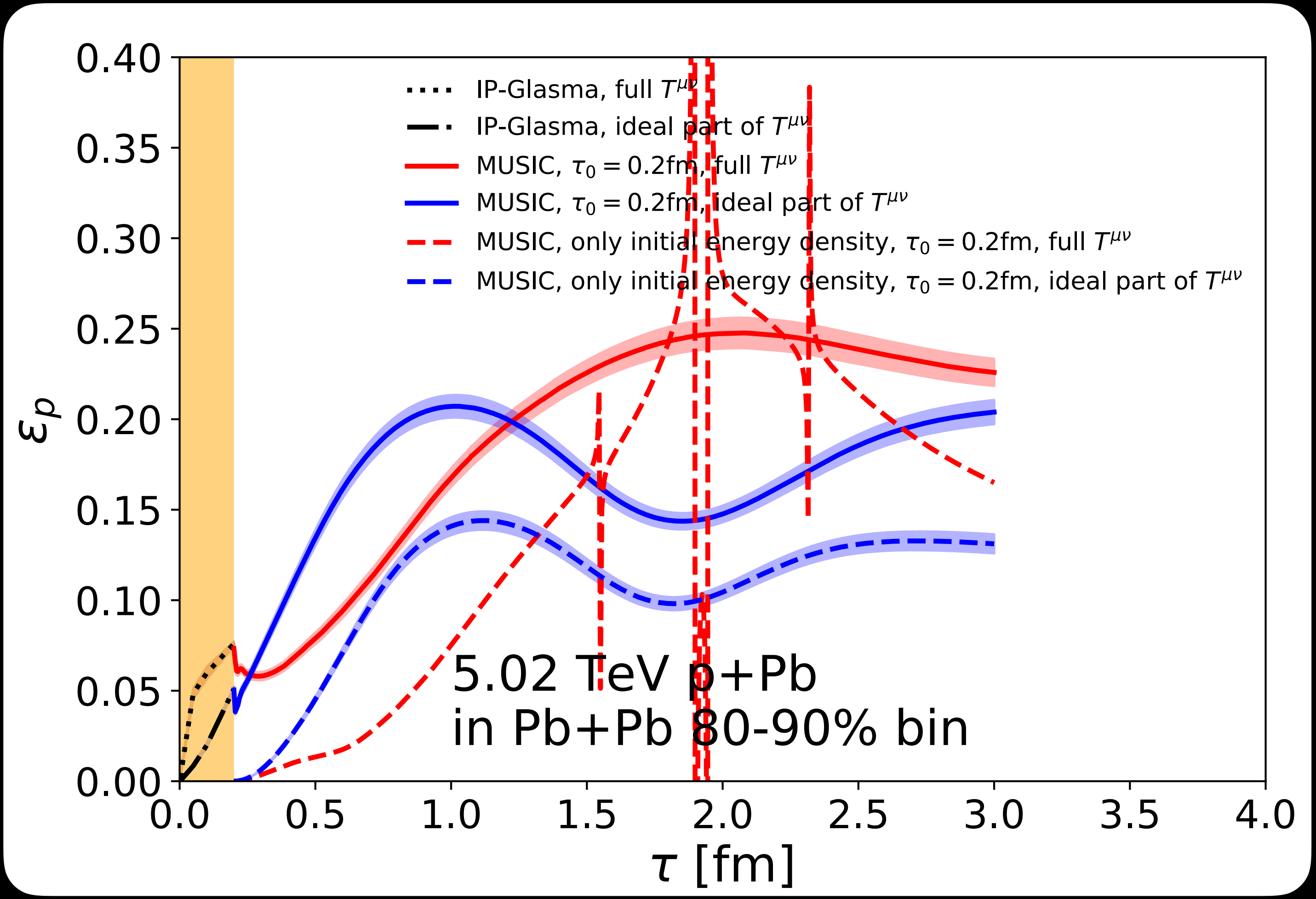
Turning off initial flow when switching at **τ**=0.6fm

almost no anisotropic flow is built up

This is also reflected in v_n values

When is momentum anisotropy generated in p+Pb?

With bulk, with and w/o initial flow

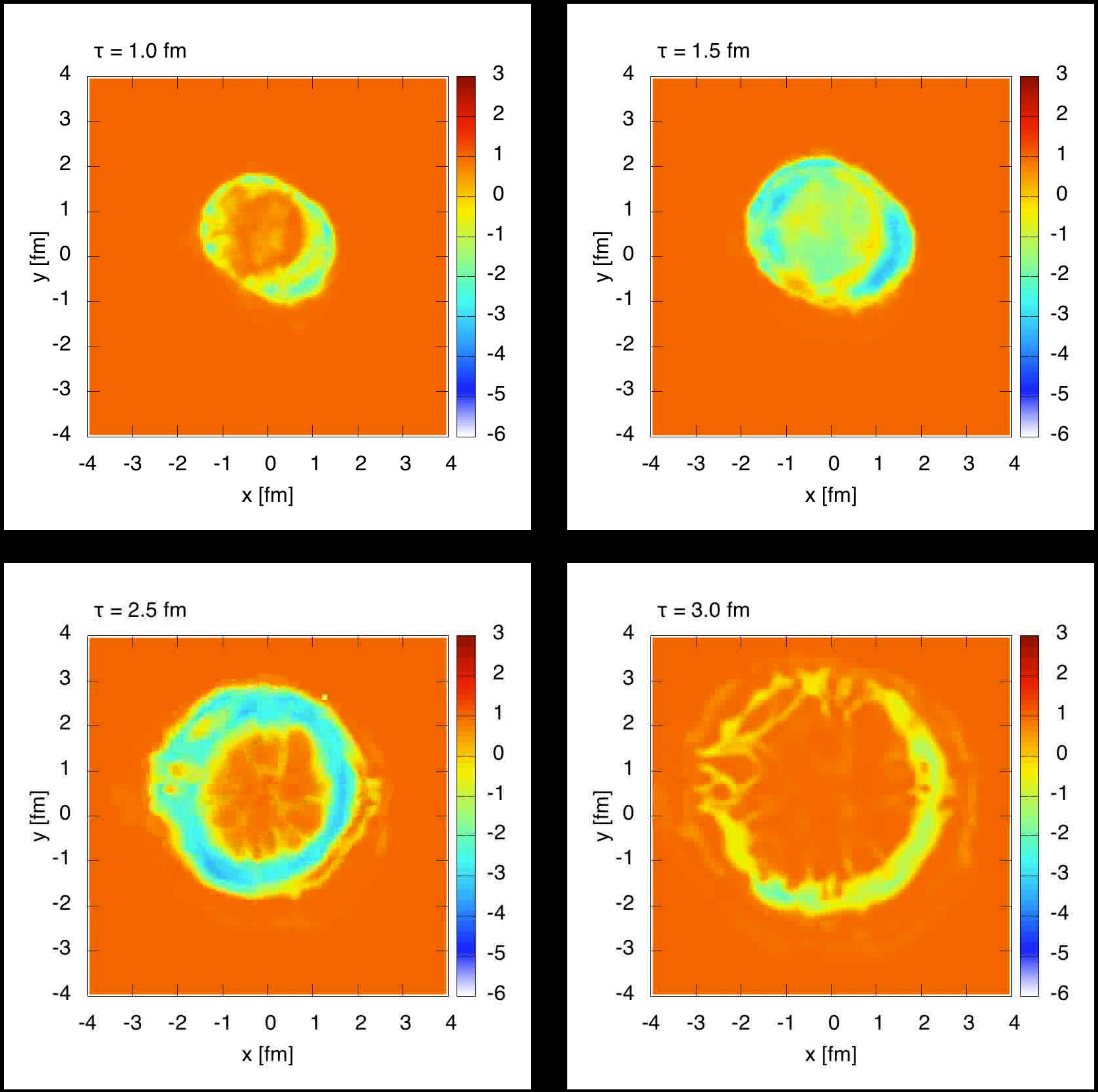


$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

Things go crazy when denominator goes through zero

Happens because of bulk correction ~ - ideal pressure

Large bulk viscosity → negative pressure

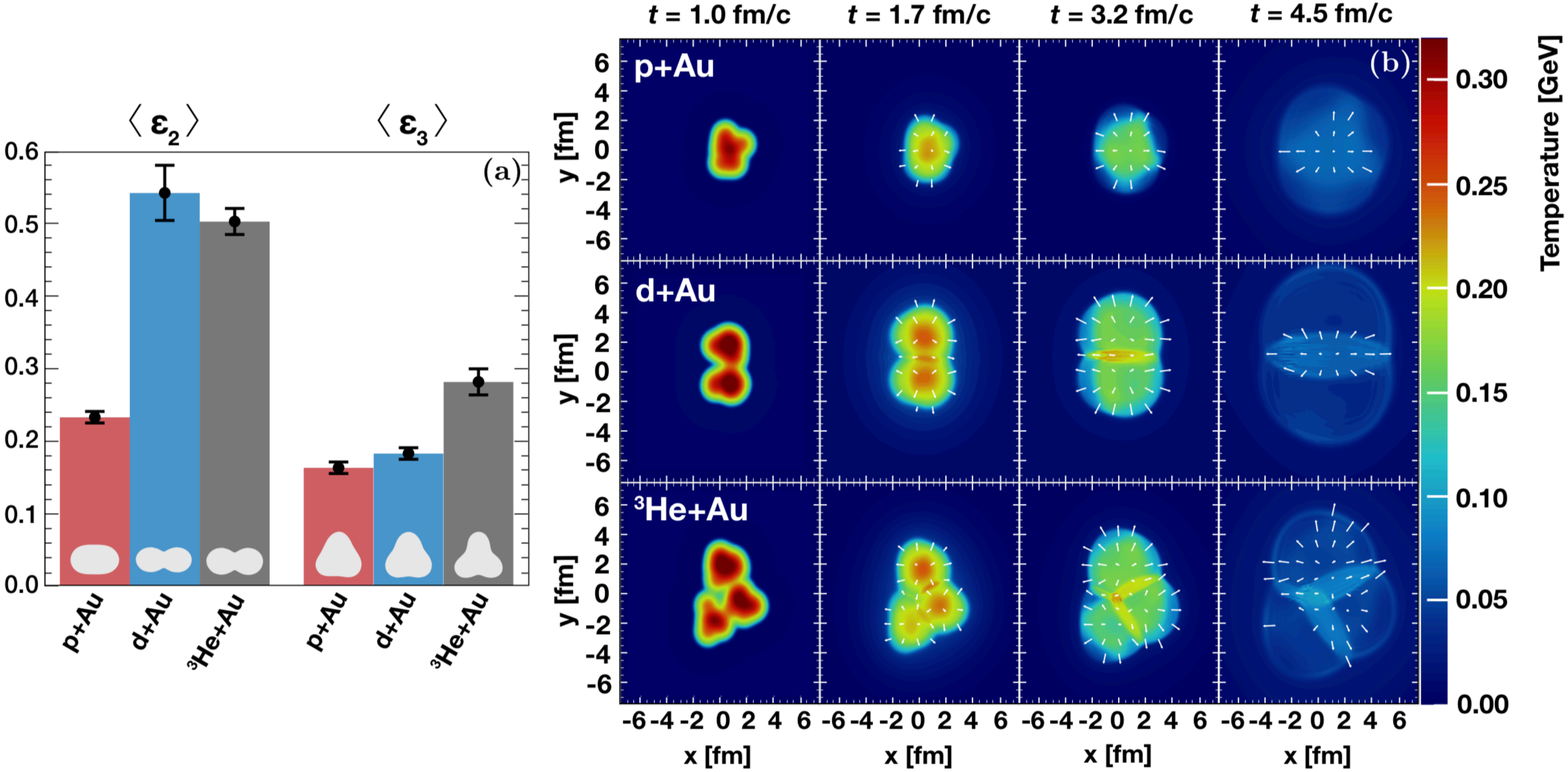


1+Π/P

in a p+Pb collision

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

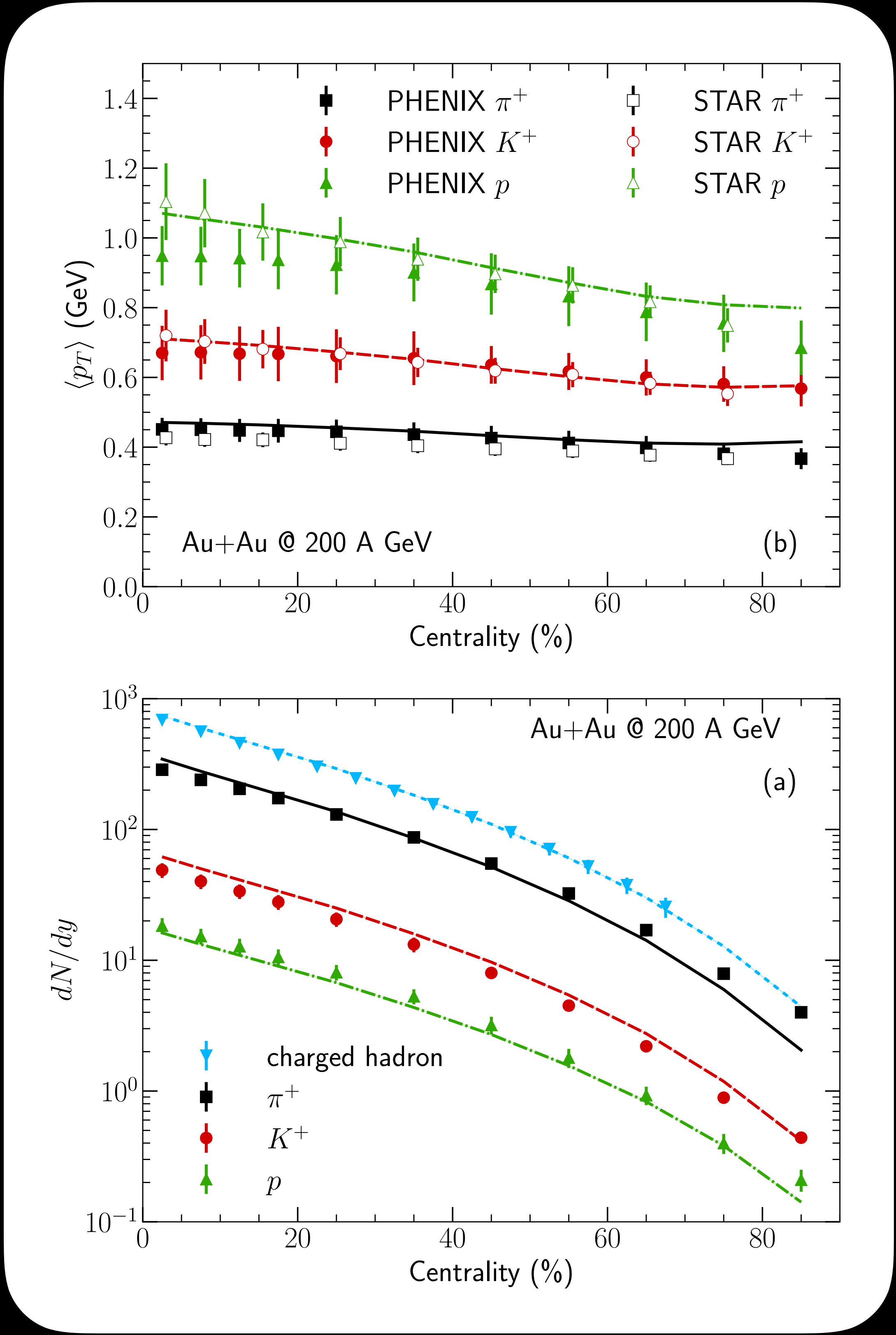
PHENIX Collaboration, arXiv:1805.02973v2

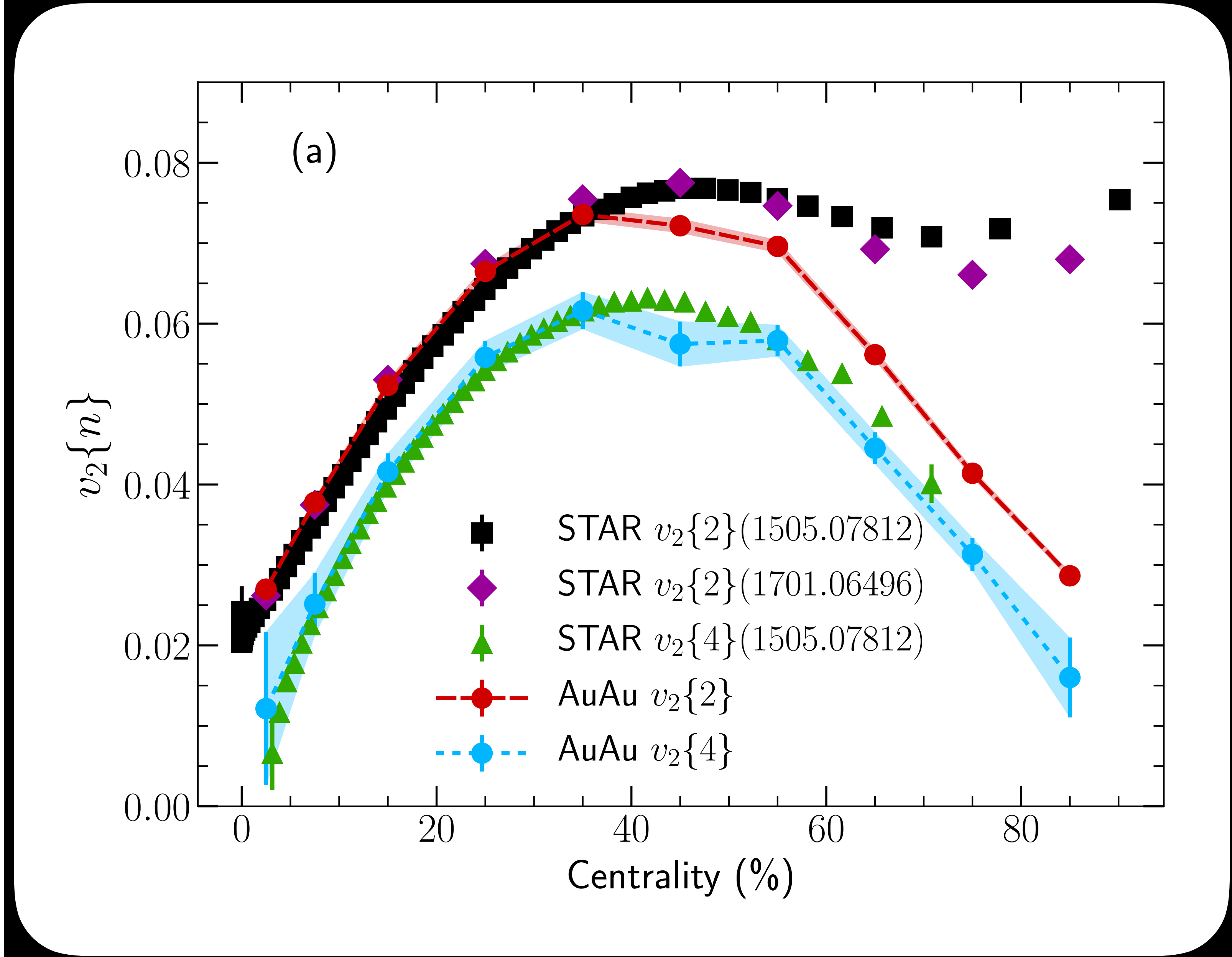


Fix parameters in Au+Au

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

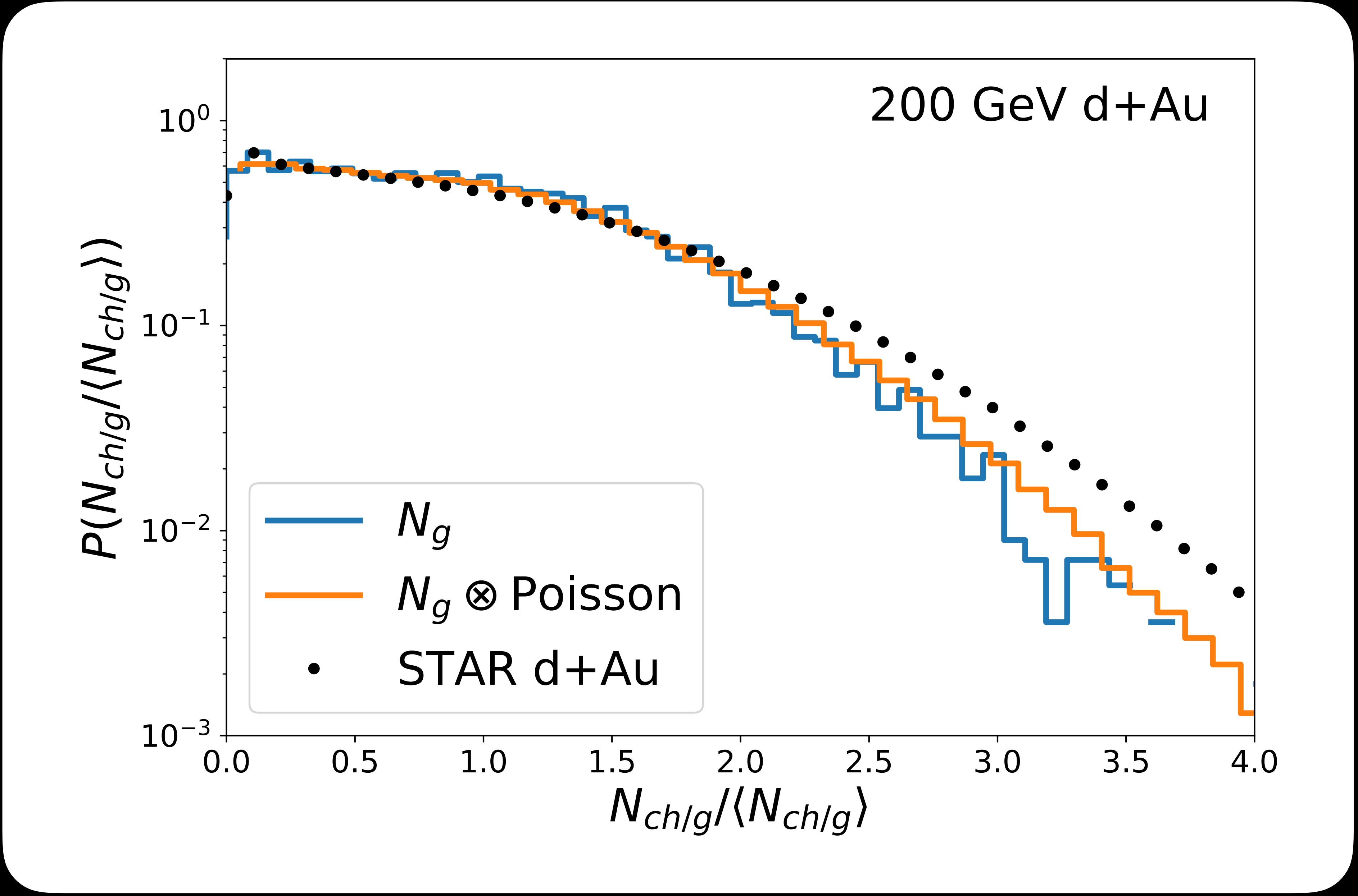
η/s=0.12





RHIC system scan

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

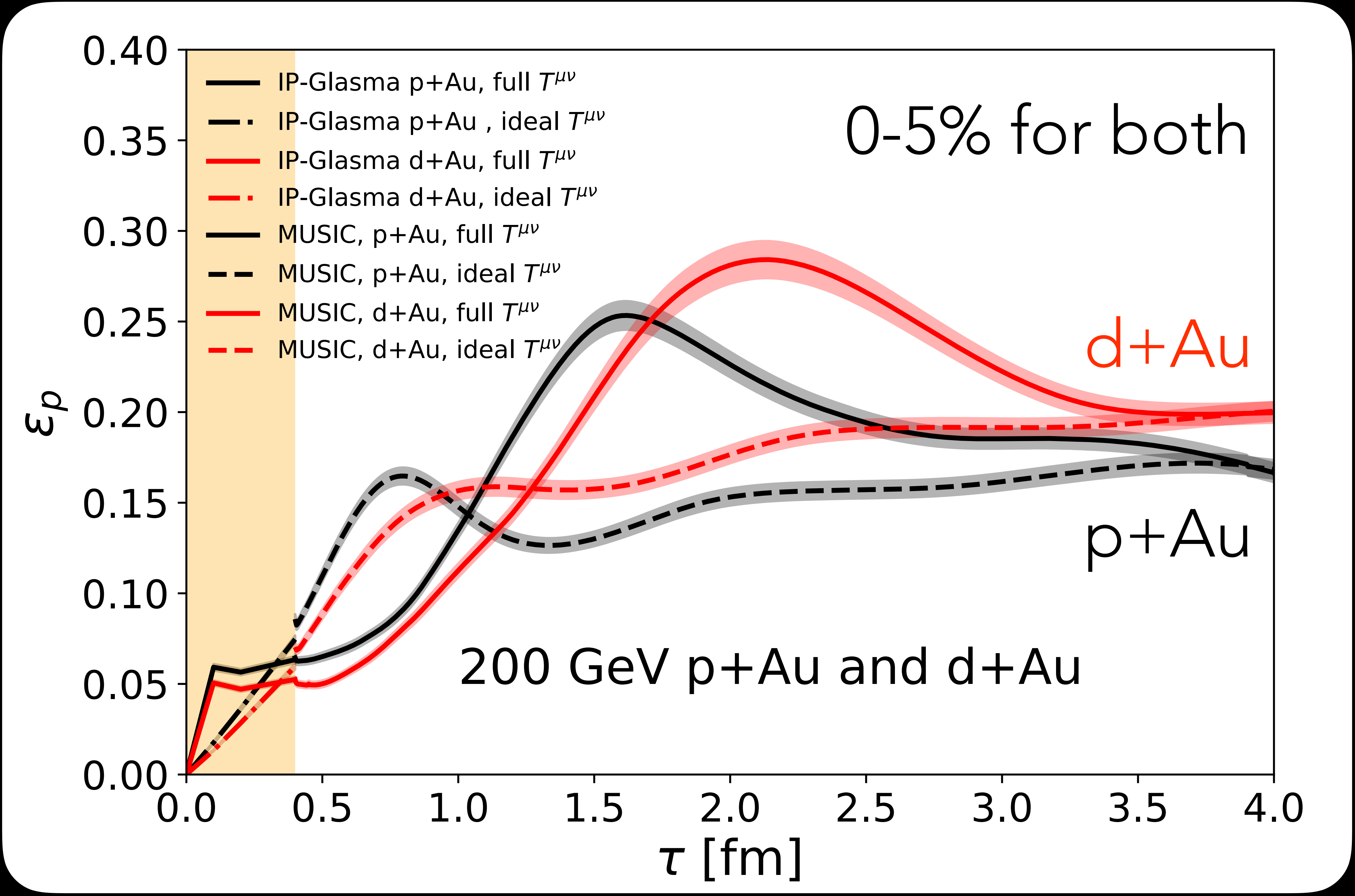


Multiplicity distribution: d+Au 200 GeV

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



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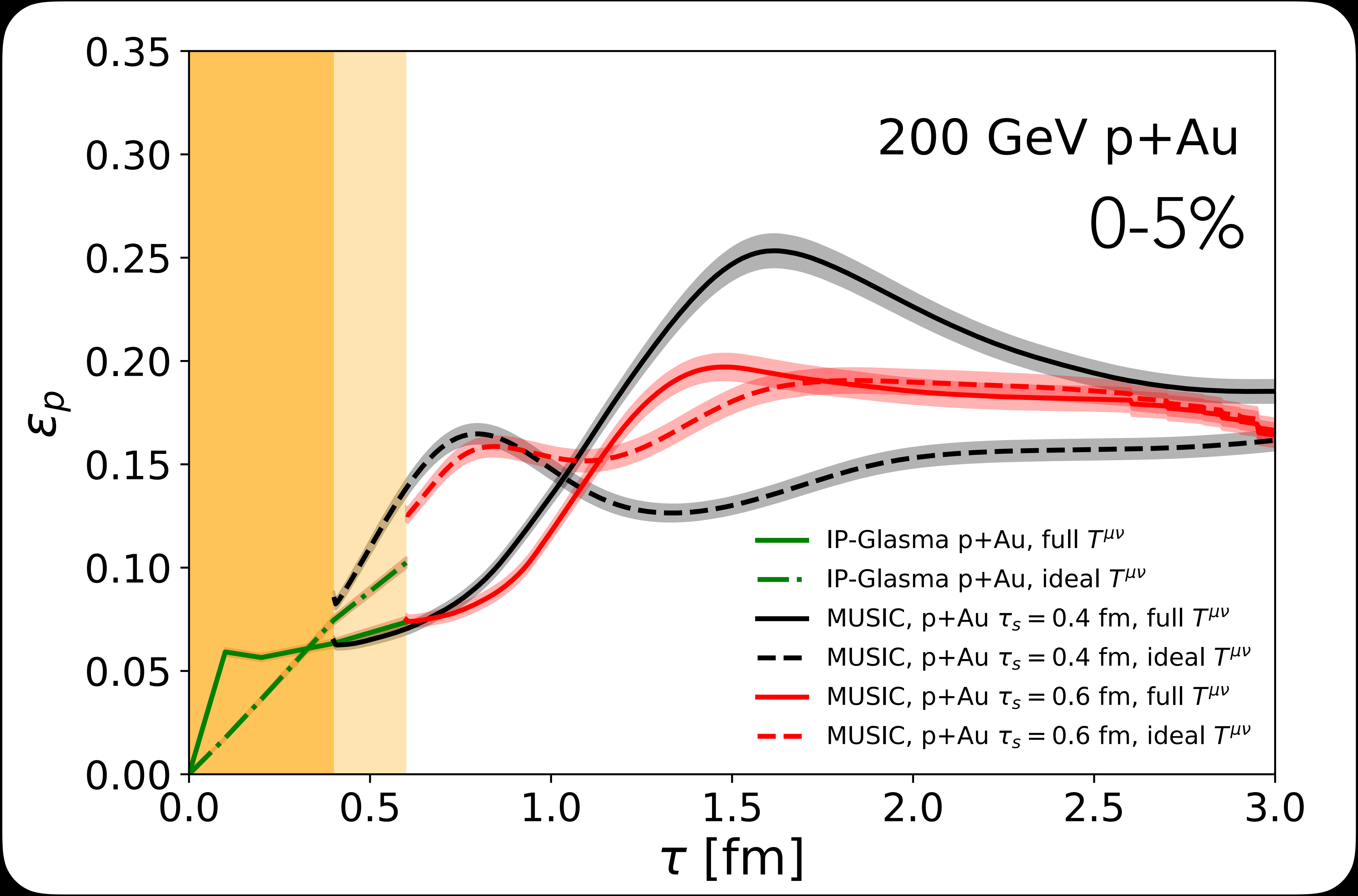

jump in ideal part from difference in P (EoS)

RHIC system scan

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

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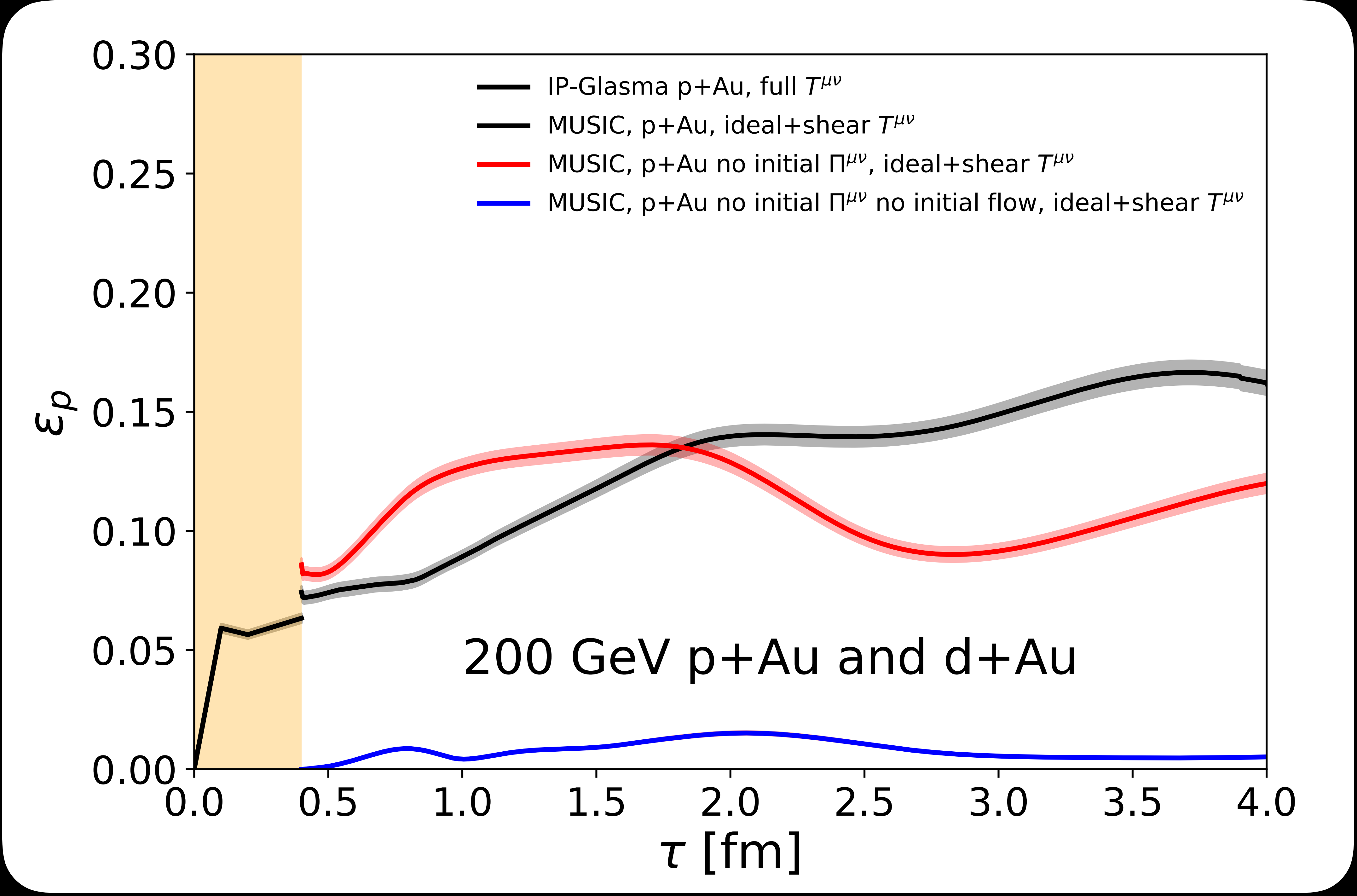

RHIC system scan

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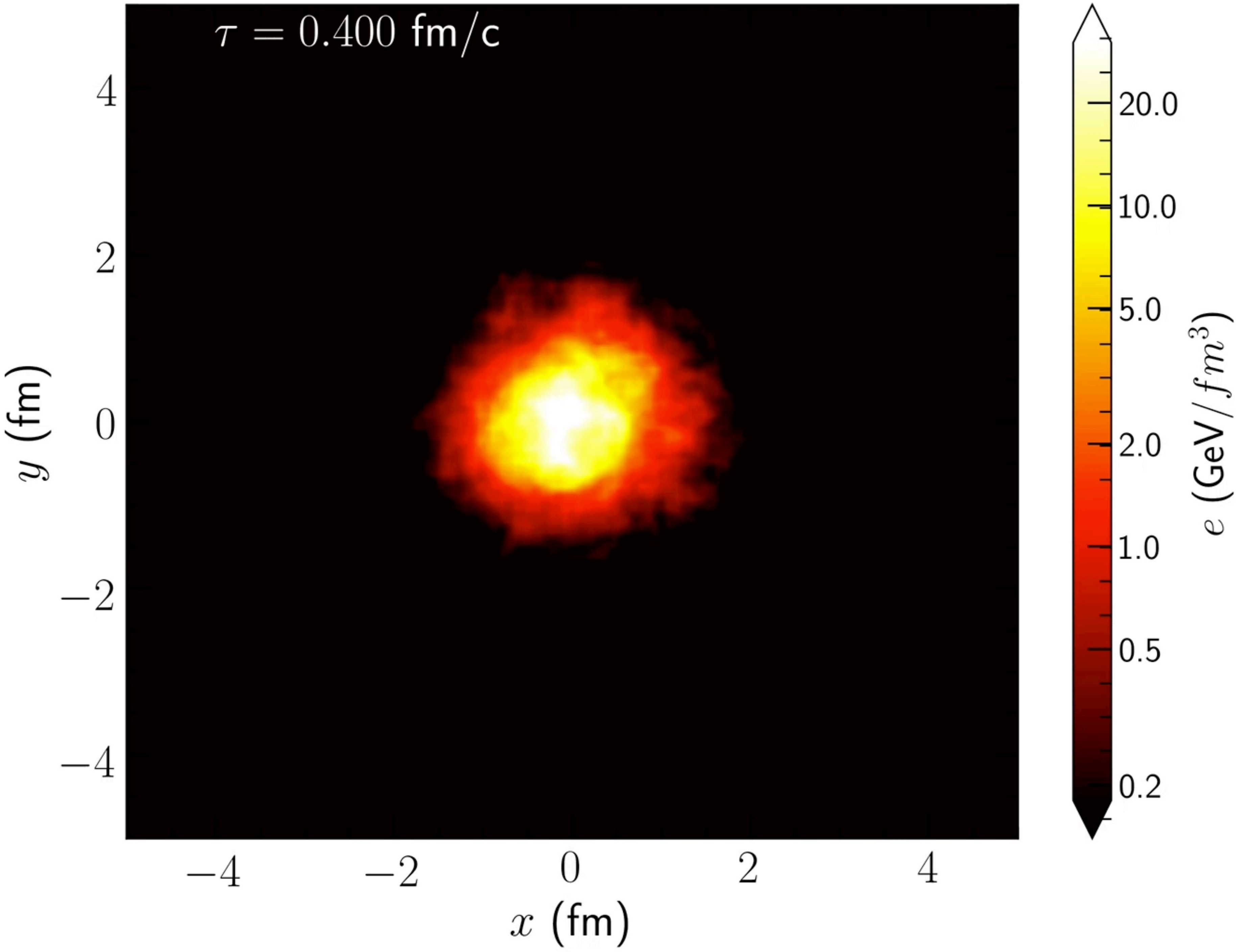

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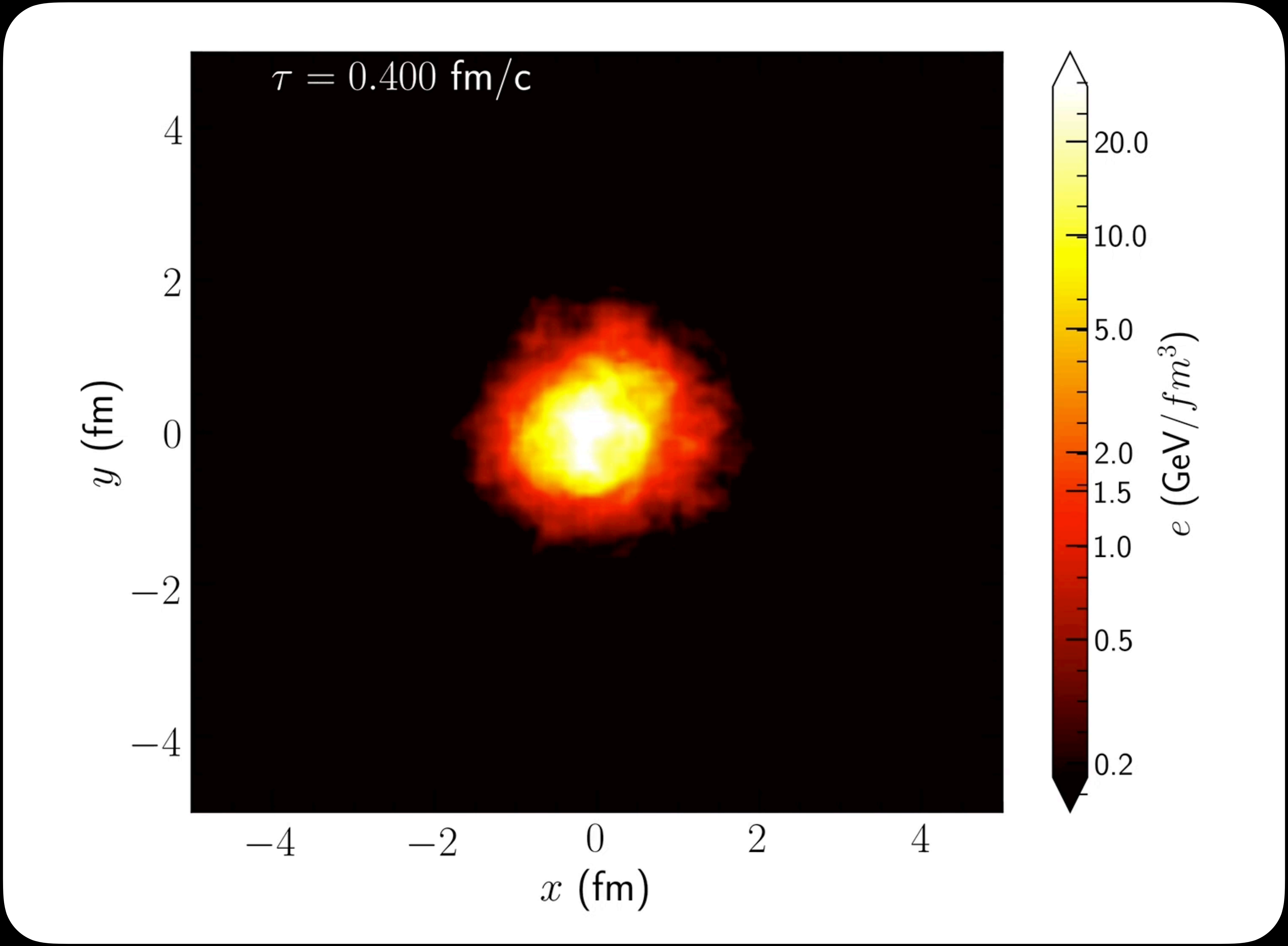
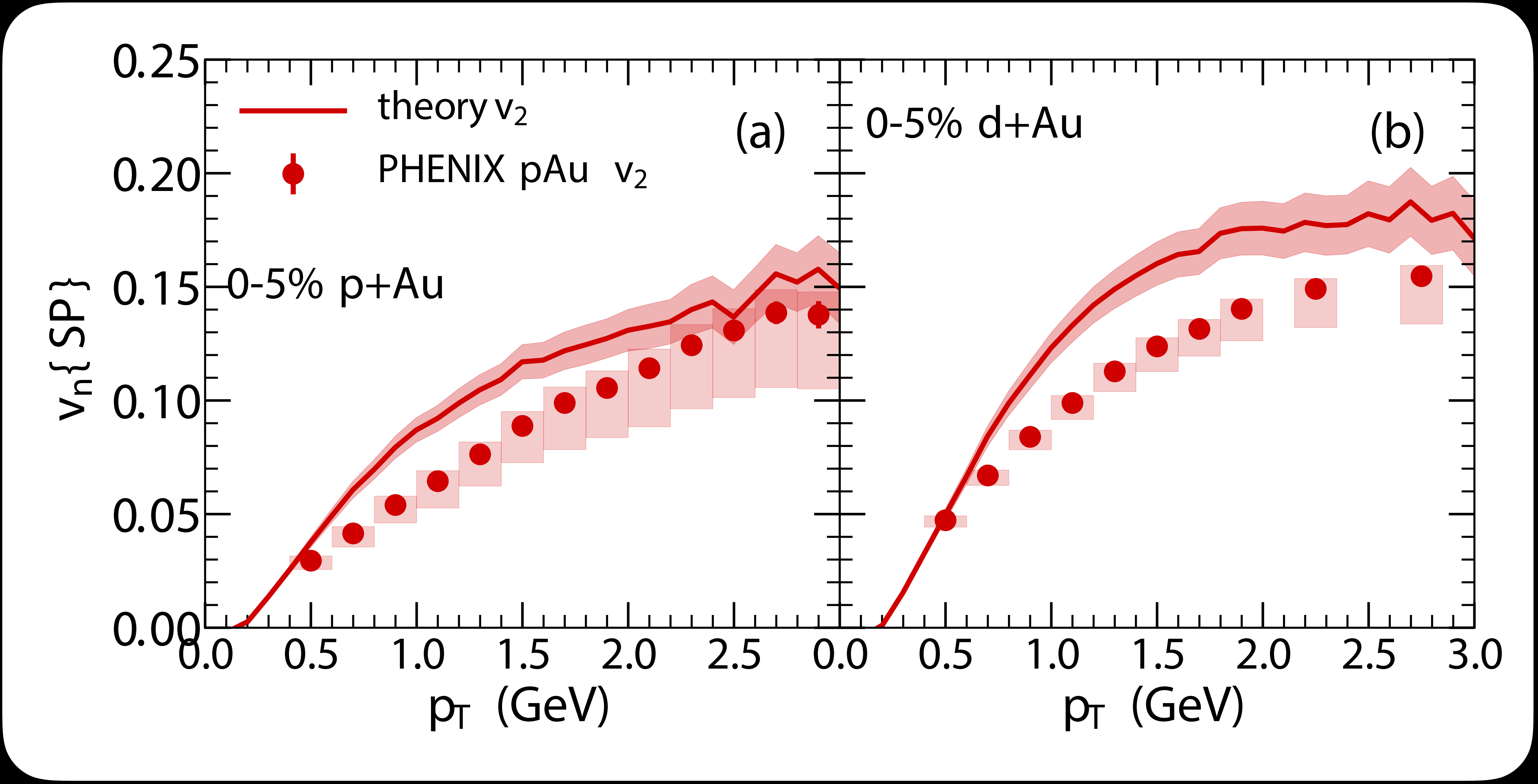


v_2 in pAu and dAu at 0-5%

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

$\eta/s=0.12$

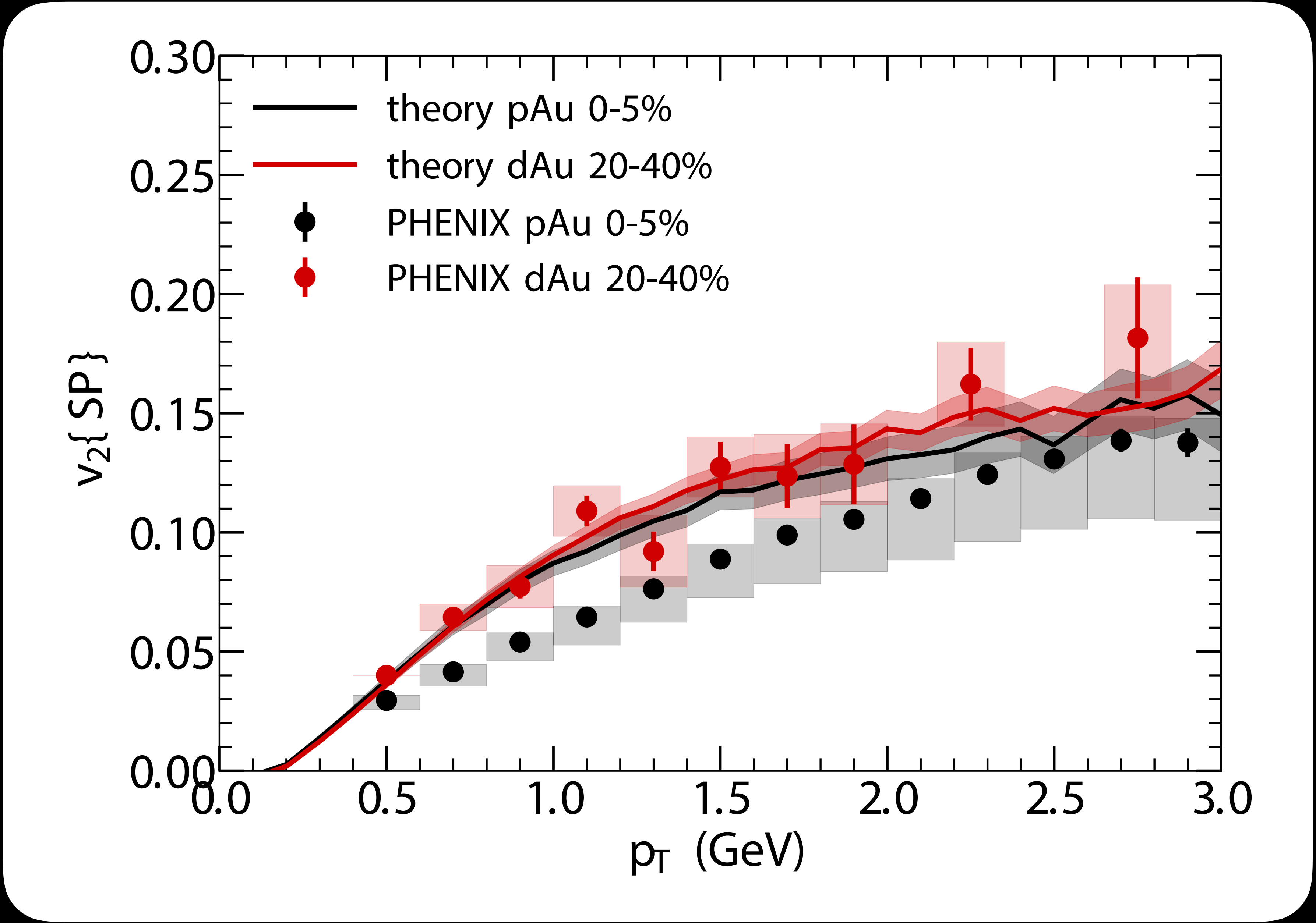


PHENIX Collaboration, e-Print: arXiv:1805.02973

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



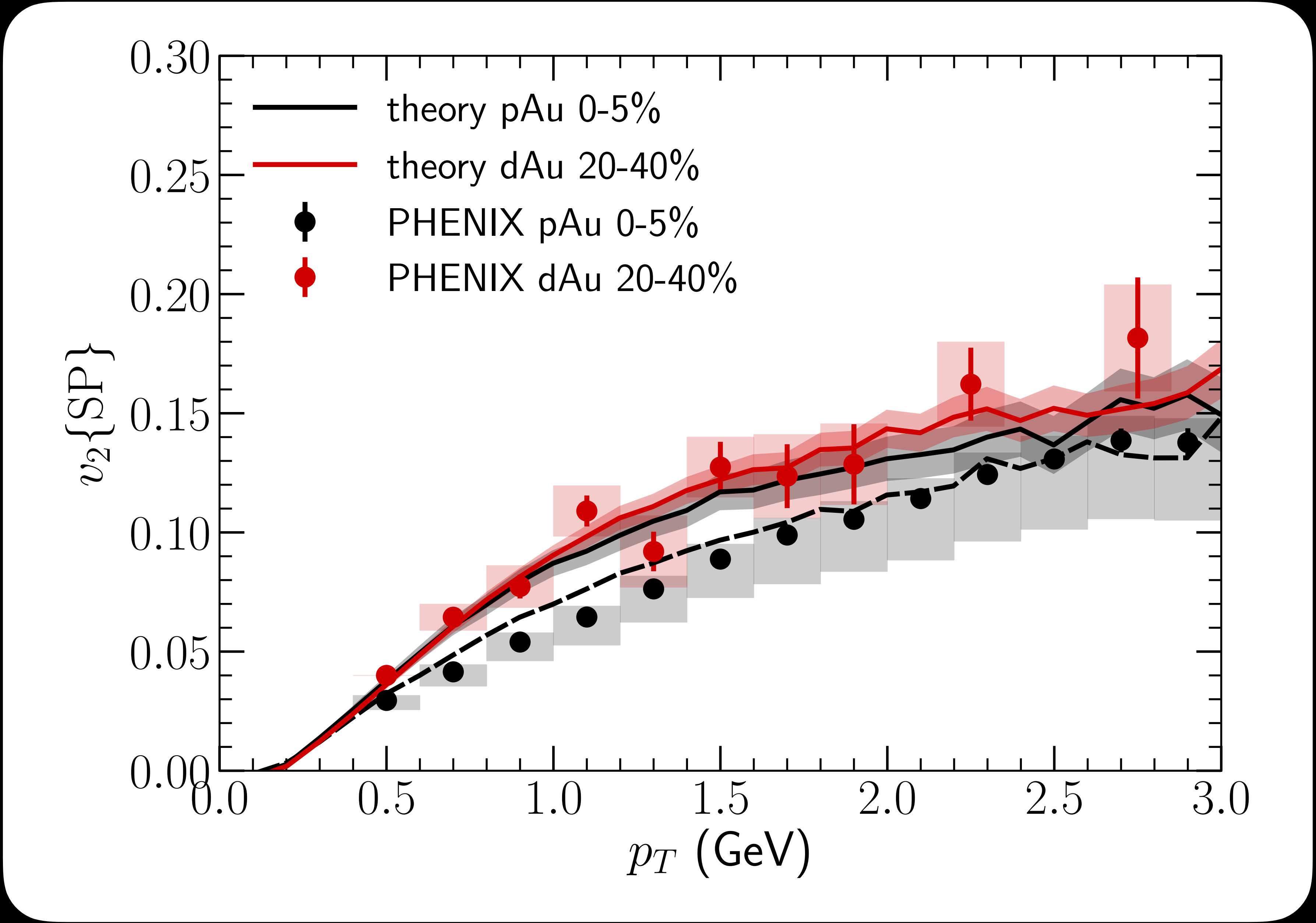
$\eta/s=0.12$

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



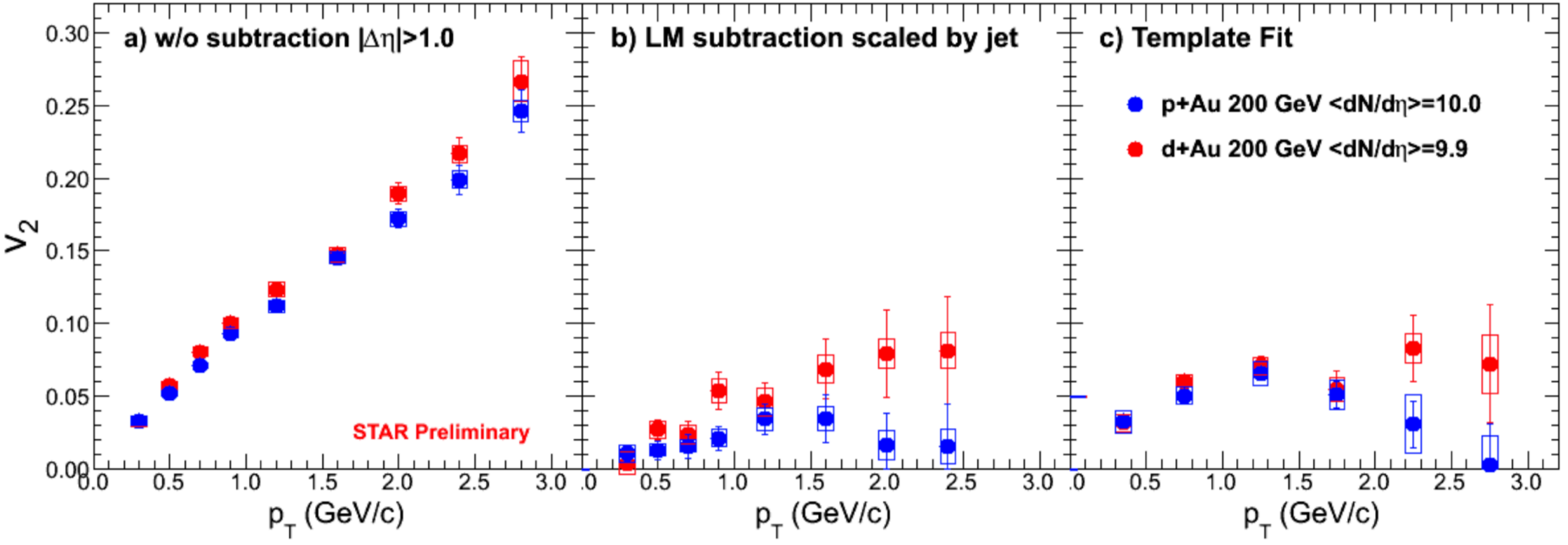
dashed line: different parameters for fluctuating proton

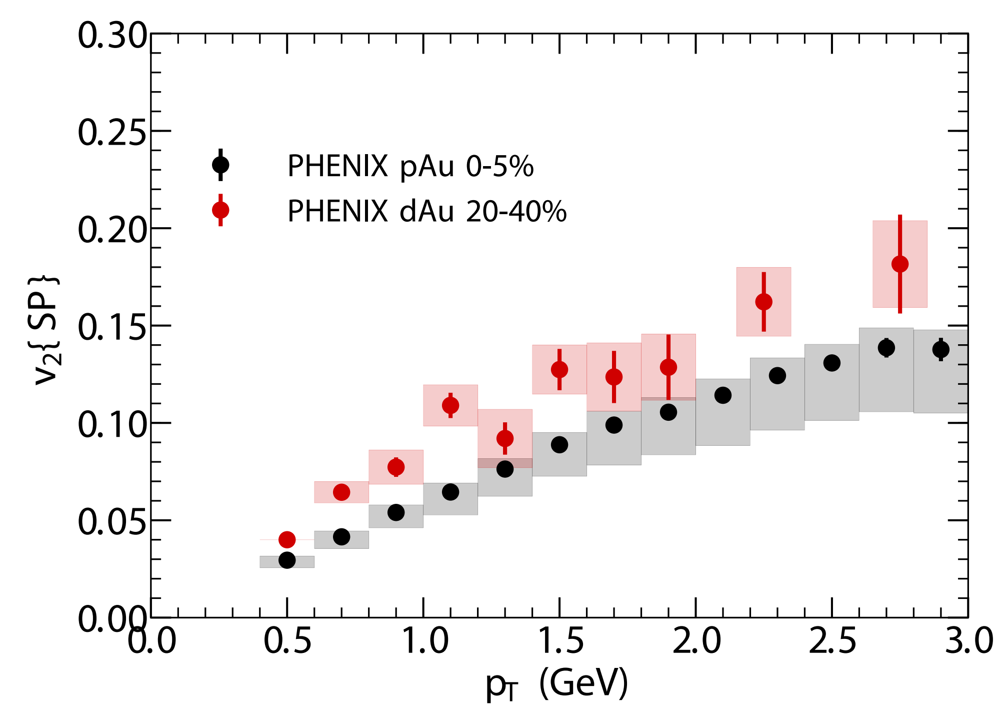
dAu
little affected

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}

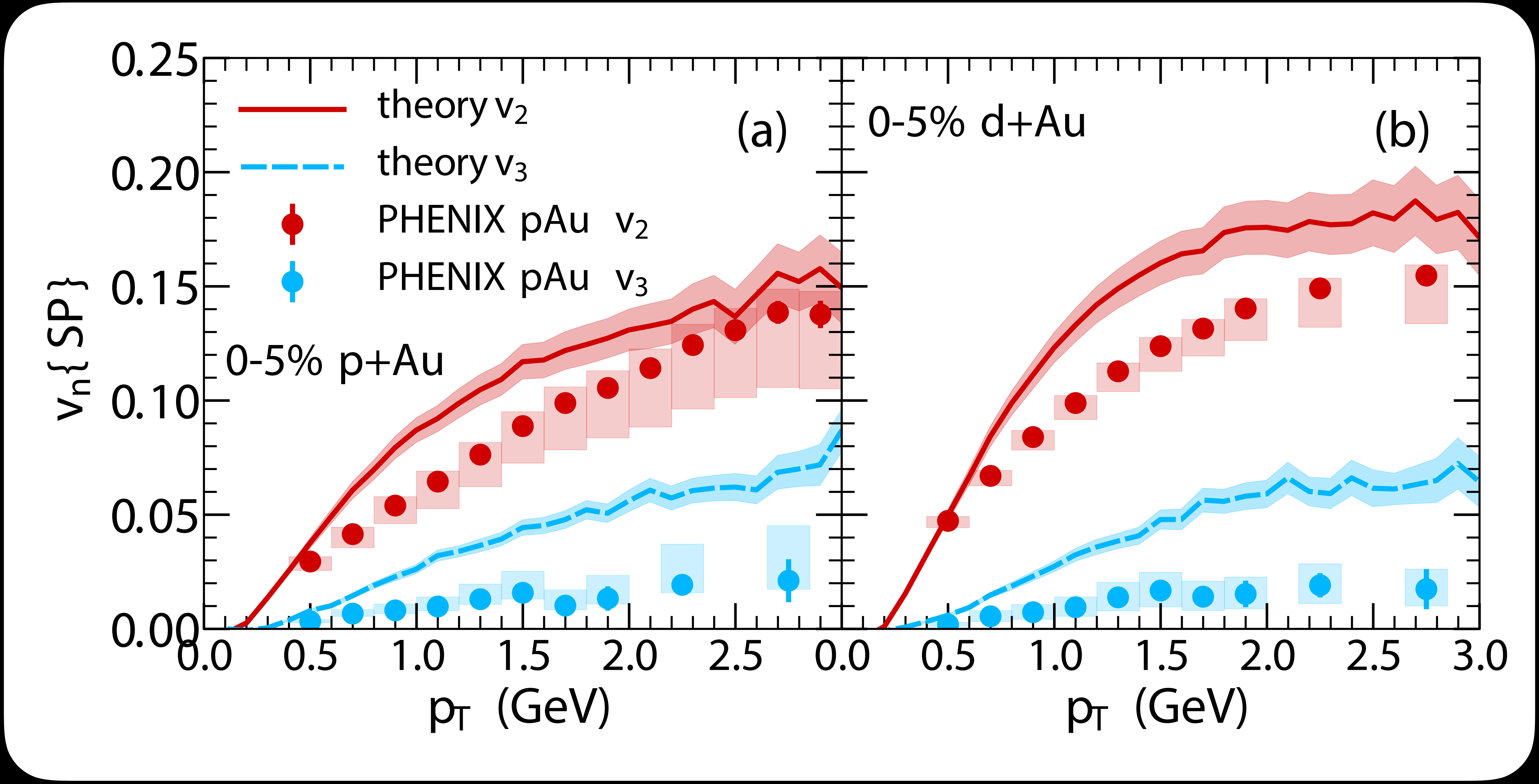




STAR Collaboration, talk by Shengli Huang, QM2018
PHENIX Collaboration, e-Print: arXiv:1805.02973

v_3 in pAu and dAu - too large...

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

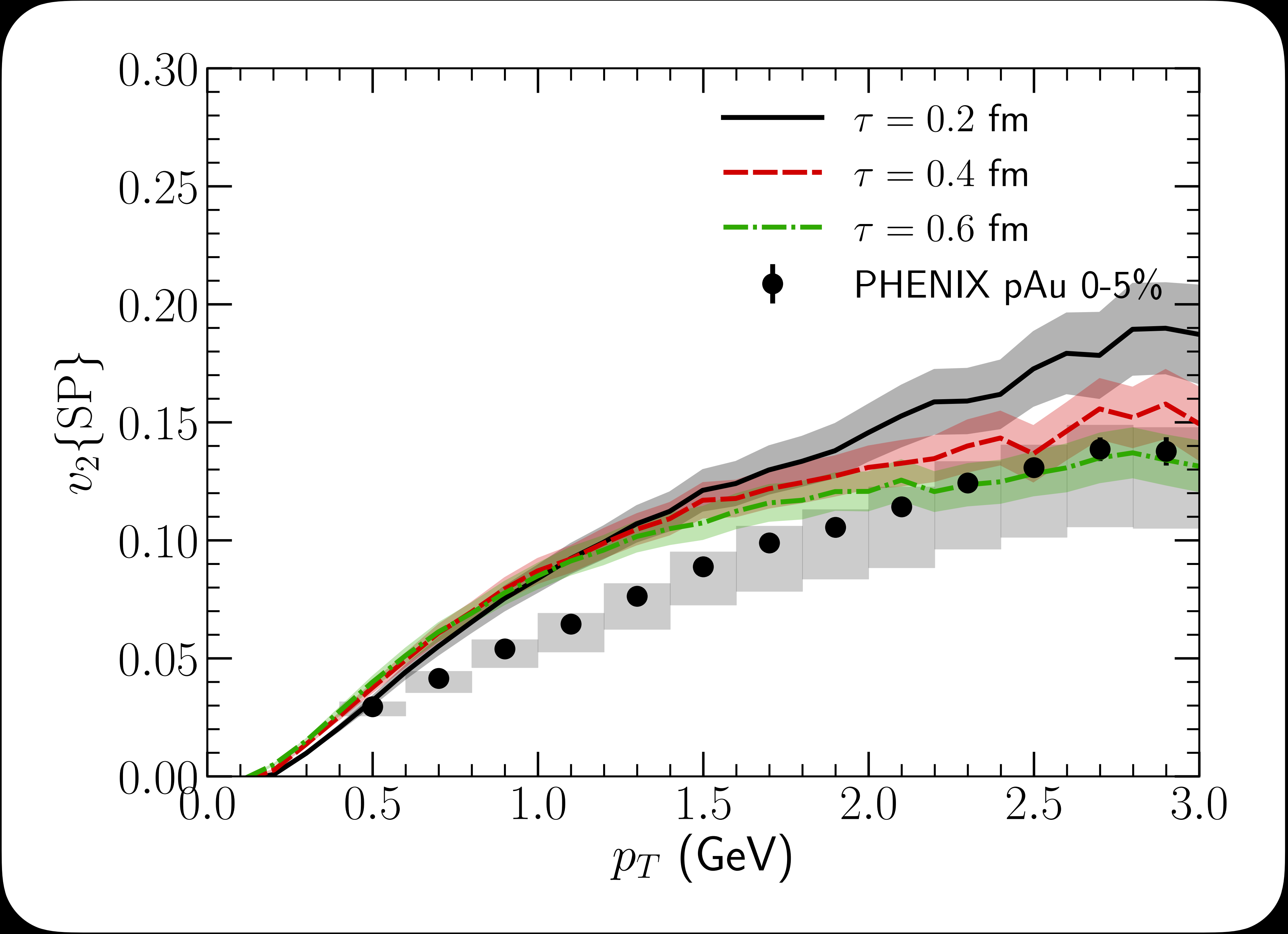


PHENIX Collaboration, e-Print: arXiv:1805.02973

Calculation: dN/dη = 19.6 for dAu, 11.3 for pAu

Effect of switching time on v_2

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



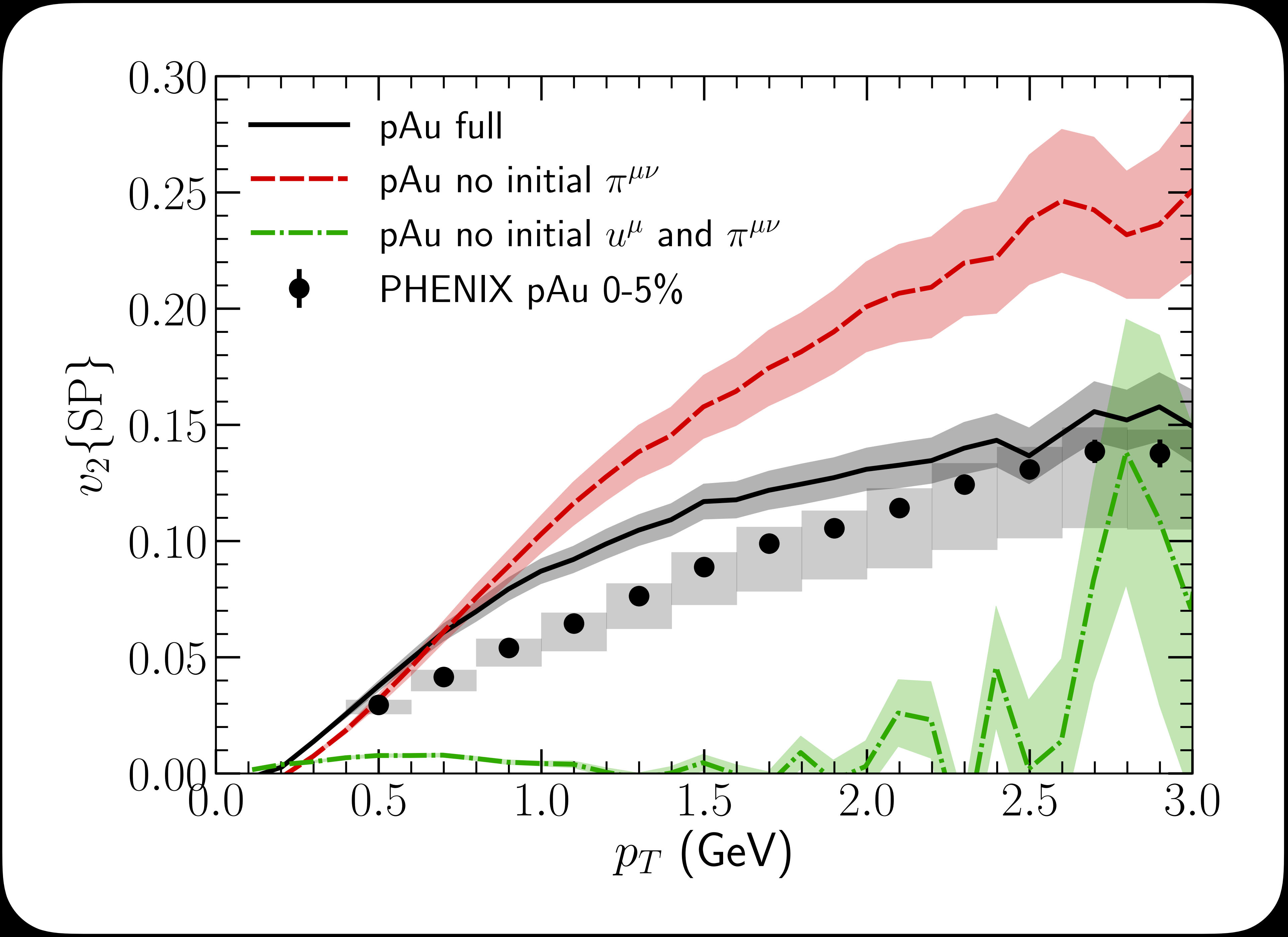
larger initial $\pi^{\mu\nu}$ for later switching time: reduction of v_2 at high p_T

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



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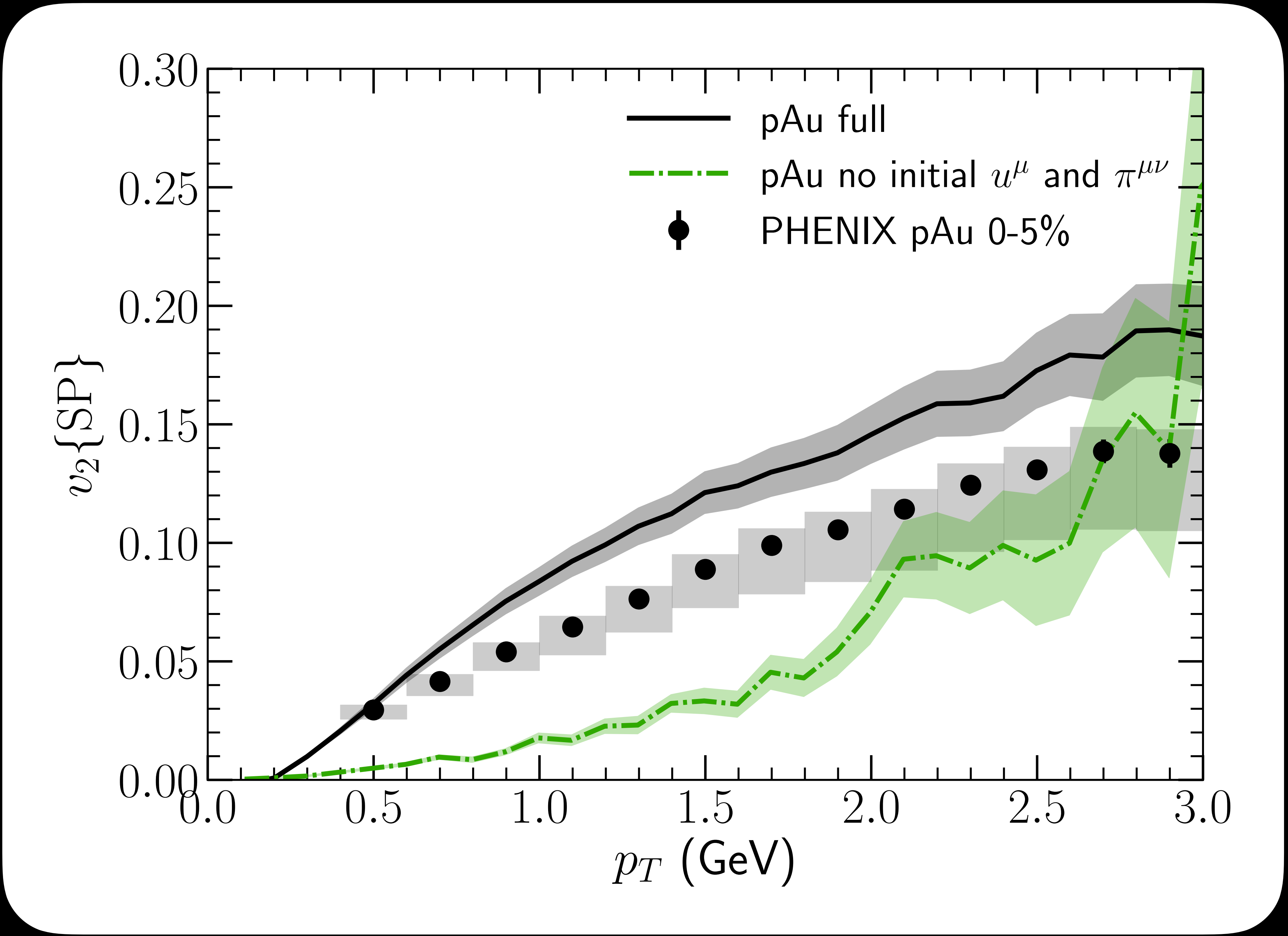
Effect of initial flow

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

τ_0=0.2fm



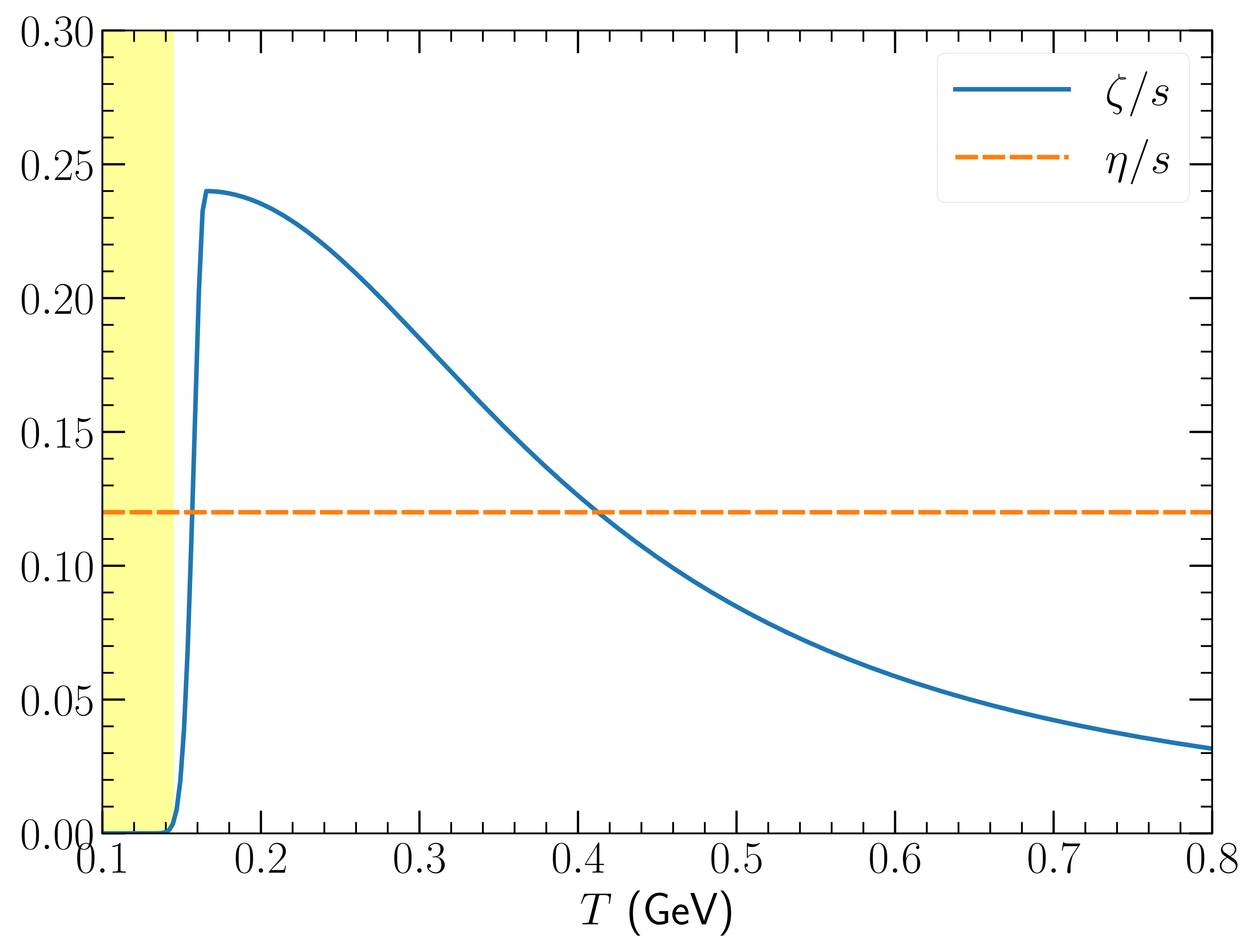
PHENIX Collaboration, e-Print: arXiv:1805.02973

Conclusions

- Heavy ions well described by hydrodynamics for range of >2 orders of magnitude in multiplicity
- Initial state contributes to the final anisotropy in p+A depending on switching time and transport params.
- Large bulk viscosity is a problem: causes negative pressures and large δf-corrections - seems to dominate evolution in small systems
- High sensitivity to initial flow, viscous tensor, in small systems at RHIC - can we trust hydro there?

Backup

MODIFIED BULK VISCOSITY



For RHIC we used broader bulk viscosity with lower peak and more extreme drop above the switching temperature

Will redo LHC calculations with this too

PROTON SHAPE FLUCTUATIONS

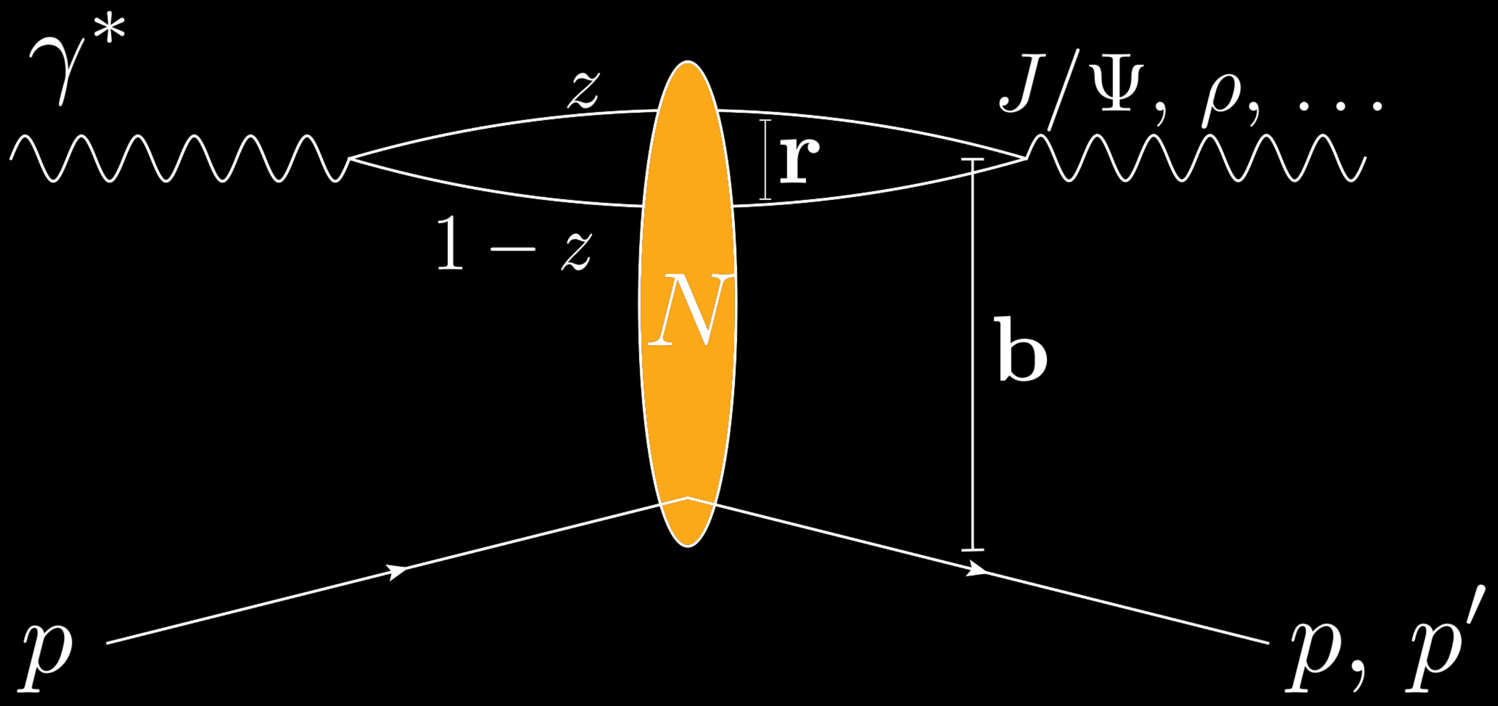
Do not only sample nucleon positions
but also gluonic hot spots inside a nucleon
(e.g. around 3 valence quarks)

Will mostly make a difference for the geometry in p+A and p+p collisions

Next:
Constrain the size and distribution of these hot spots using data from e+p collisions

Diffractive J/Ψ production

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



No exchange of color charge
→Large rapidity gap

Coherent diffraction:

Proton remains intact, Sensitive to average gluon distribution in the proton

Incoherent diffraction:

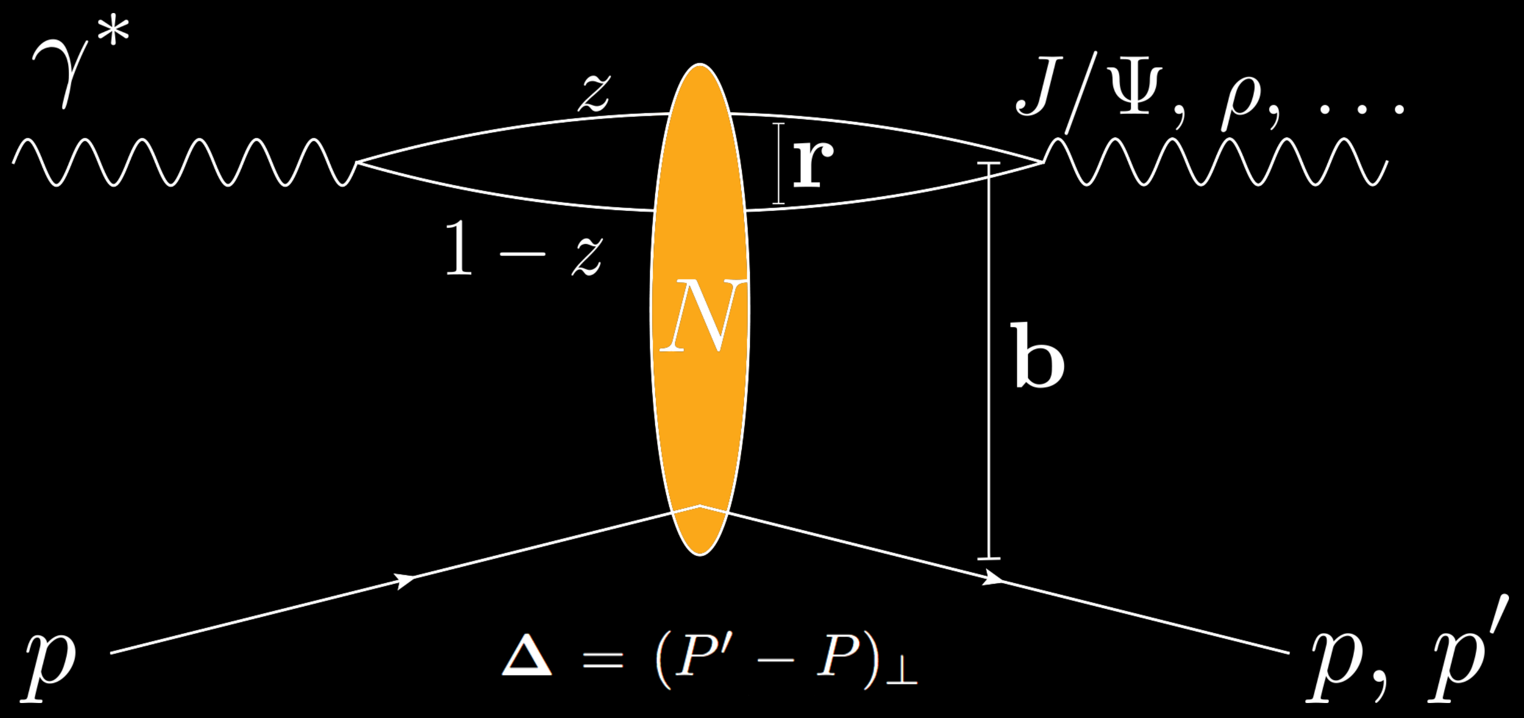
Proton breaks up, Sensitive to shape fluctuations

CGC Framework J/Ψ production

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

Diffractive eigenstates are color dipoles at fixed r_T and b_T

see
M. L. Good and W. D. Walker
Phys. Rev. 120 (1960) 1857.



Scattering amplitude

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

Dipole amplitude *N* determined in IPsat or IP-Glasma

Averaging over the target

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

COHERENT DIFFRACTION:

TARGET STAYS INTACT

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle\right|^2$$

INCOHERENT DIFFRACTION:

TARGET BREAKS UP

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp^*}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle\left|\mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\right|^2\right\rangle - \left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle\right|^2\right)$$

SENSITIVE TO FLUCTUATIONS!

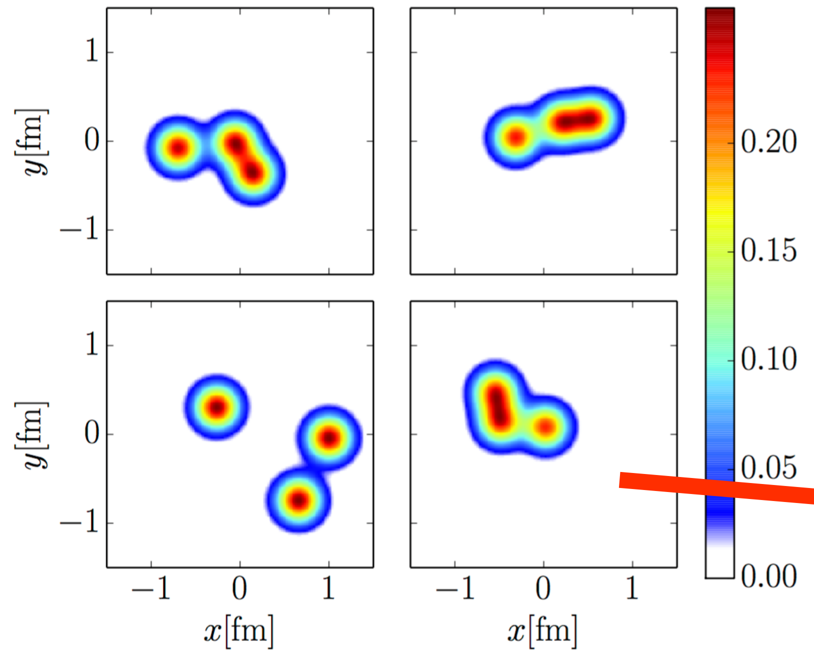
SEE
H. I. MIETTINEN
AND J. PUMPLIN
PHYS. REV. D18 (1978) 1696

Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

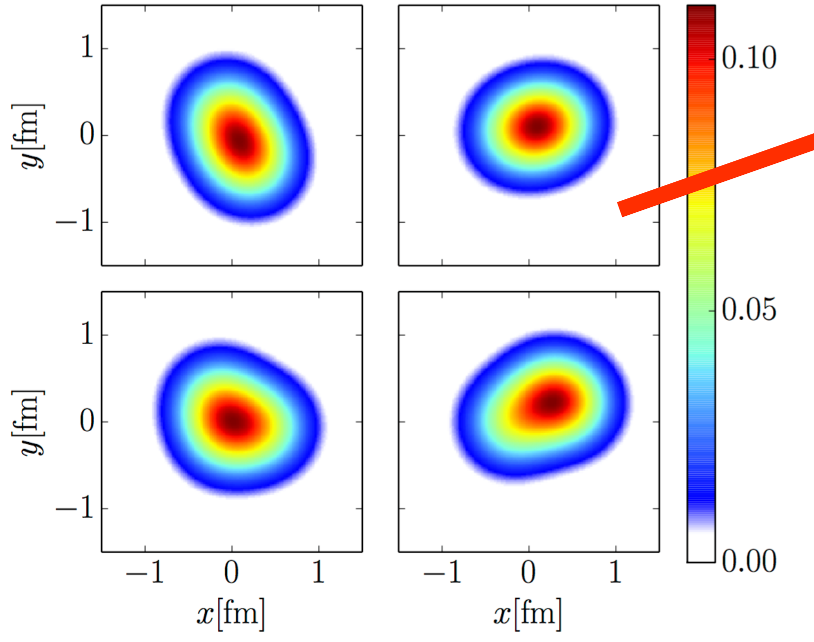
A. KOVNER AND
U. A. WIEDEMANN
PHYS. REV. D64 (2001) 114002

Introduce geometric fluctuations

Assume 3 valence quark-like hot spots

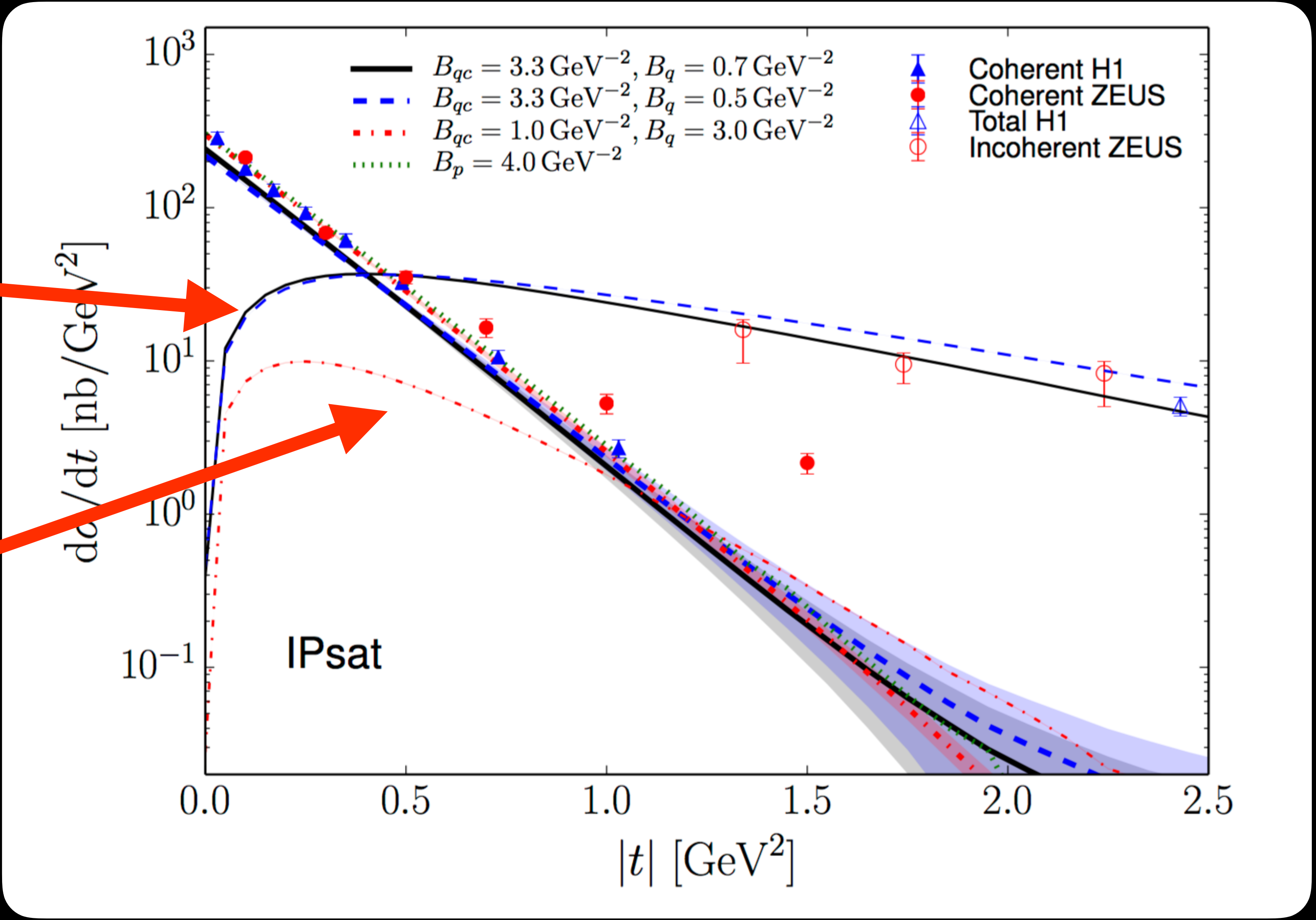


(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$



(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

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



H1 collaboration, Eur. Phys. J. C46 (2006) 585,
Phys. Lett. B568 (2003) 205
ZEUS collaboration, Eur. Phys. J. C24 (2002) 345
Eur. Phys. J. C26 (2003) 389

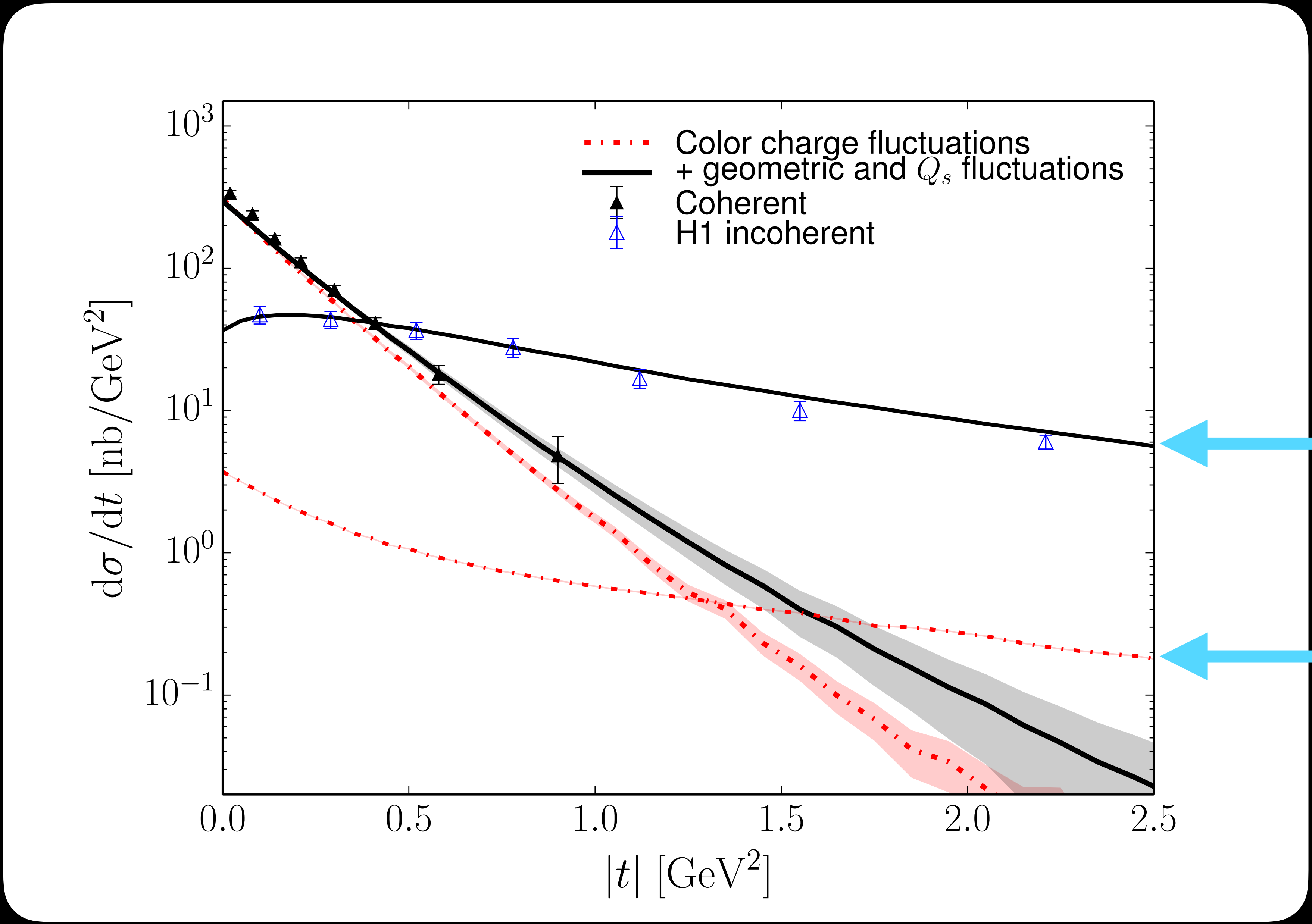
IP-Glasma calculation

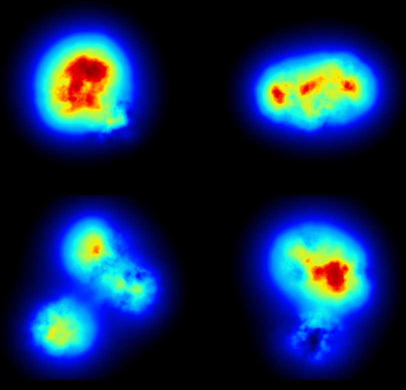
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

Geometric + color charge fluctuations

Wilson lines

Dipole amp.: $N(\vec{r}, x_{\mathbb{P}}, \vec{b}) = N(\vec{x}-\vec{y}, x_{\mathbb{P}}, (\vec{x}+\vec{y})/2) = 1 - \mathrm{Tr}\,V(\vec{x})V^{\dagger}(\vec{y})/N_c$





tuned shape fluctuations

round proton

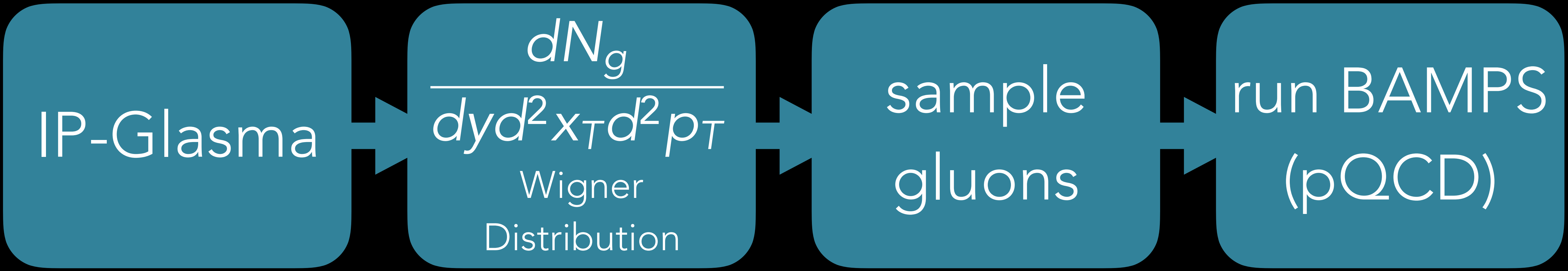
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

IP-Glasma + parton cascade

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)

To study how final state interactions affect the initial state correlations, we use a microscopic final state model, the parton cascade BAMPS

Z.Xu, C. Greiner, PRC71, 064901 (2005)



IP-Glasma

$$\frac{dN_g}{dyd^2x_Td^2p_T}$$

Wigner Distribution

sample gluons

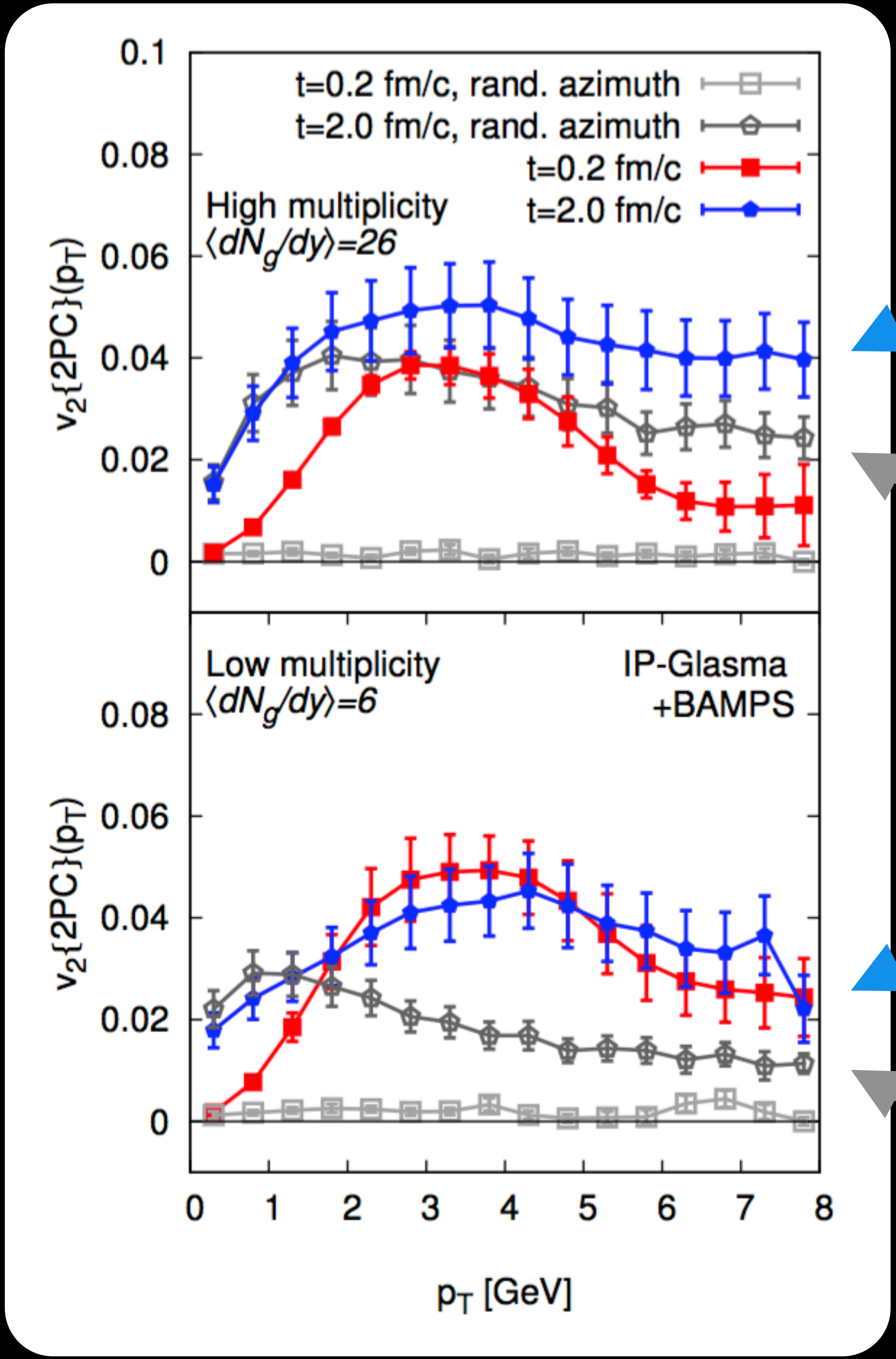
run BAMPS (pQCD)

smear → Husimi Distribution

→ study momentum anisotropy as function of time

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)



high multiplicity

with initial corr.

without initial corr.

low multiplicity

with initial corr.

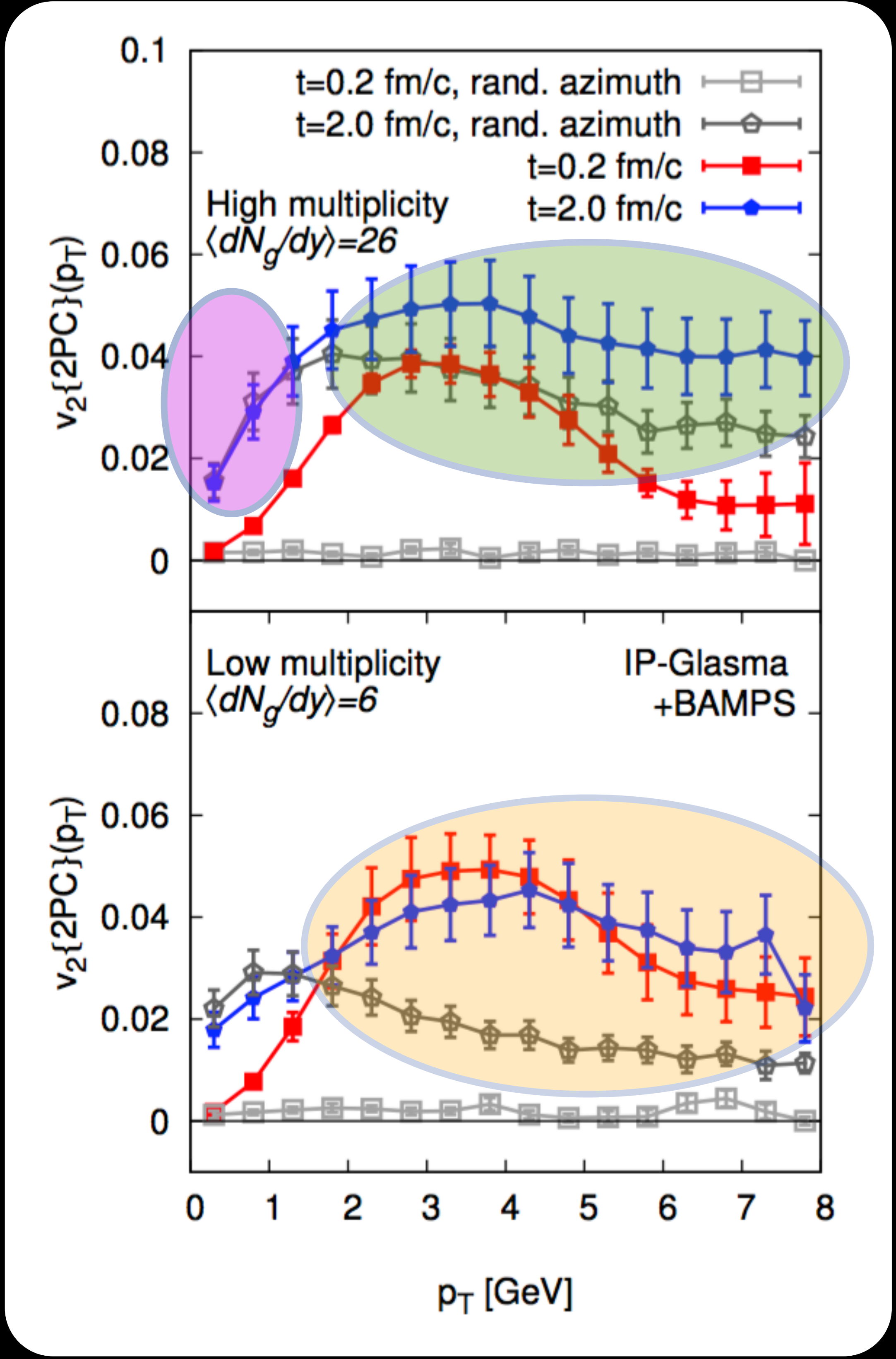
without initial corr.

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)

high multiplicity

low multiplicity

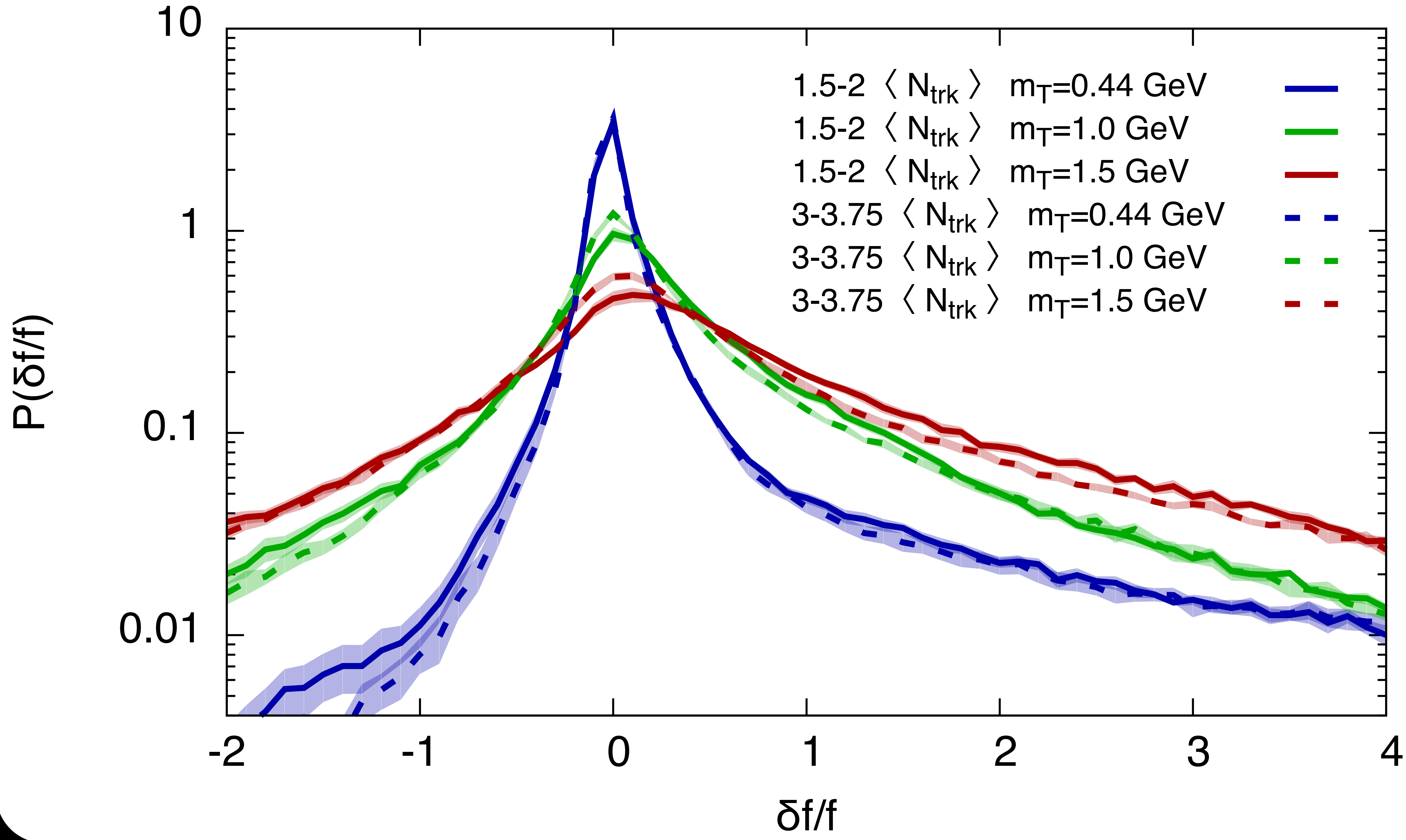


🟣 negligible effect at small p_T and high multiplicity

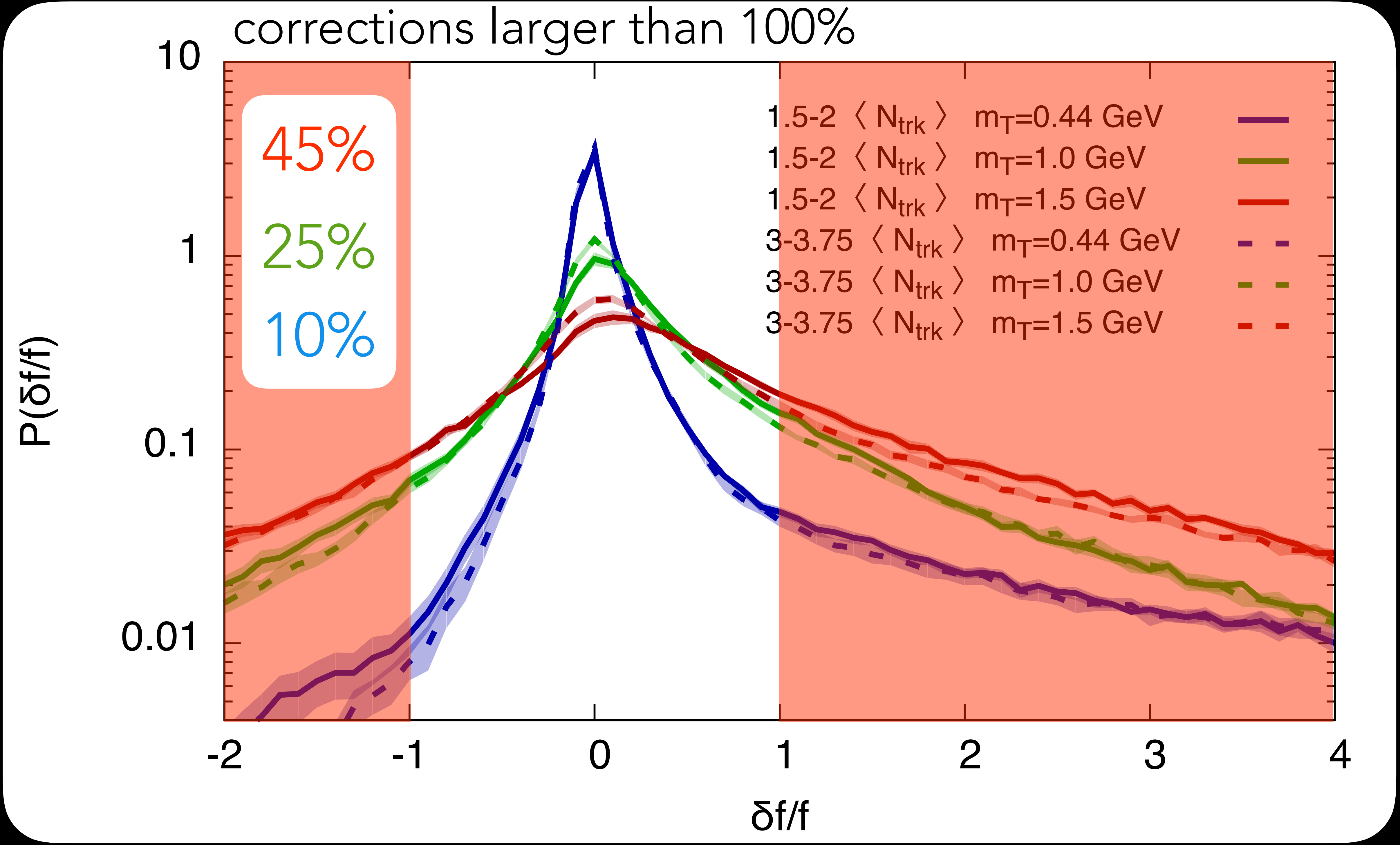
🟠 significant effect at p_T >2 GeV and low multiplicity

🟢 visible effect at p_T >3 GeV and high multiplicity

Histogram of δf/f on the switching surface

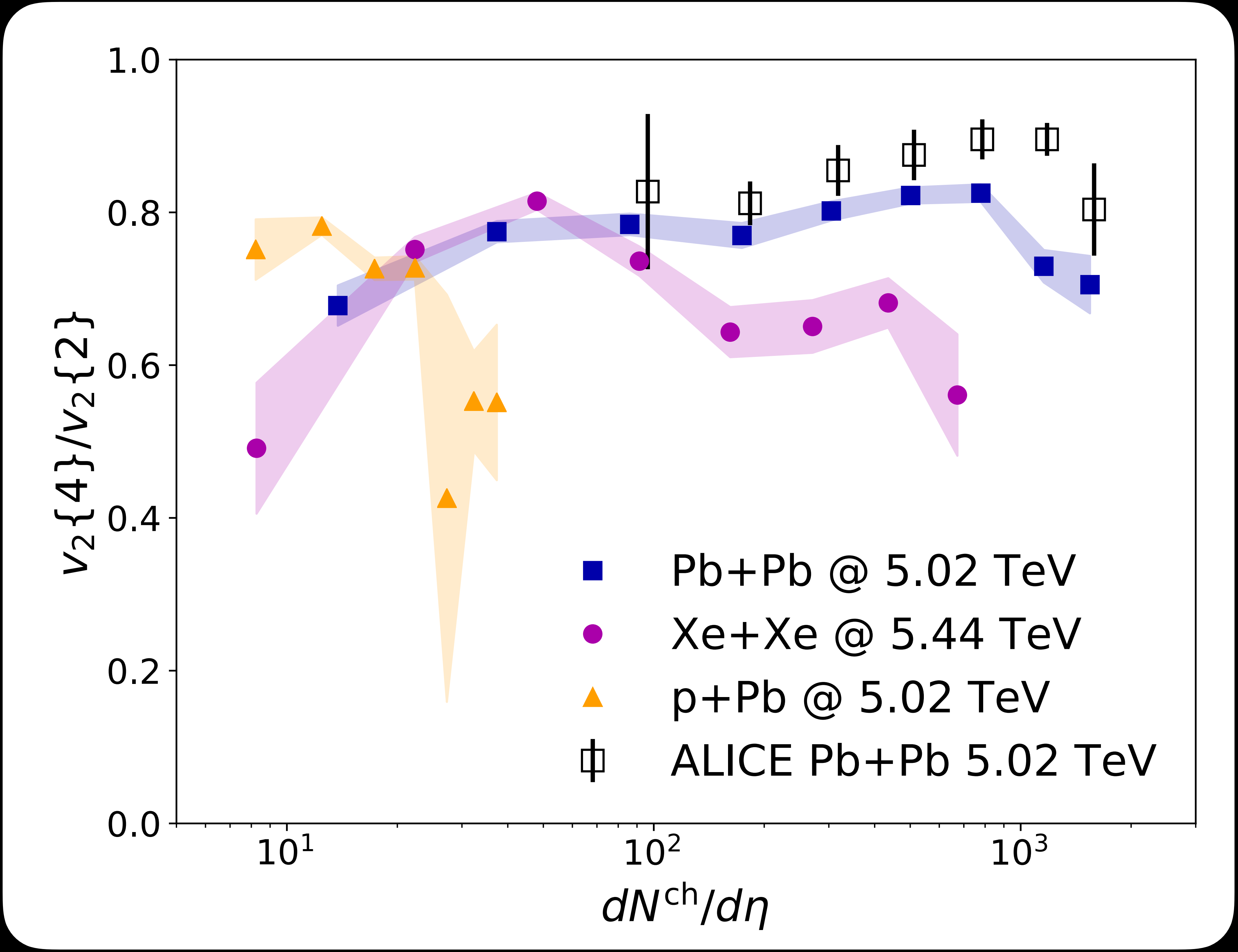


Histogram of δf/f on the switching surface



Cumulant ratios

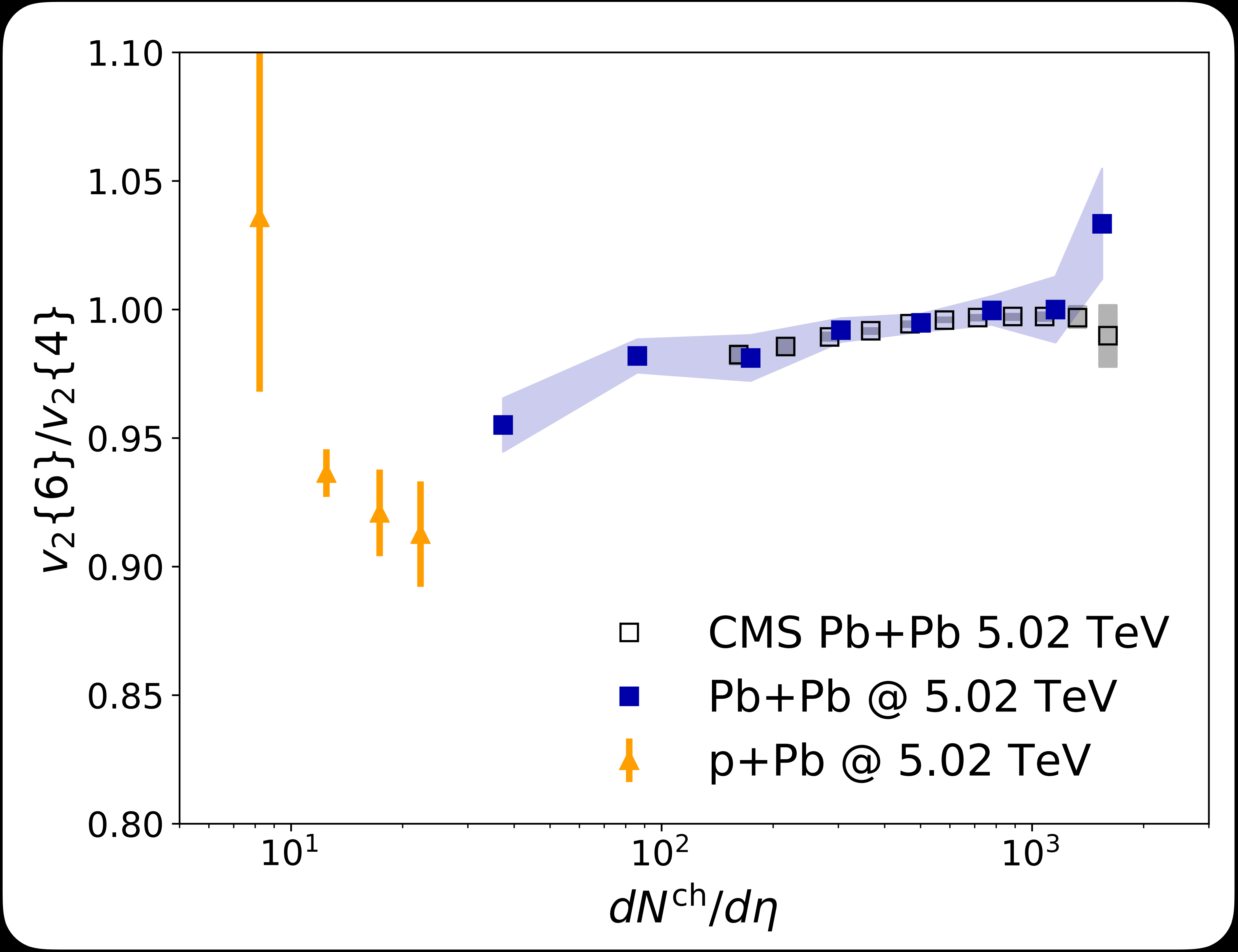
B. Schenke, C. Shen, P. Tribedy, in preparation



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

Cumulant ratios

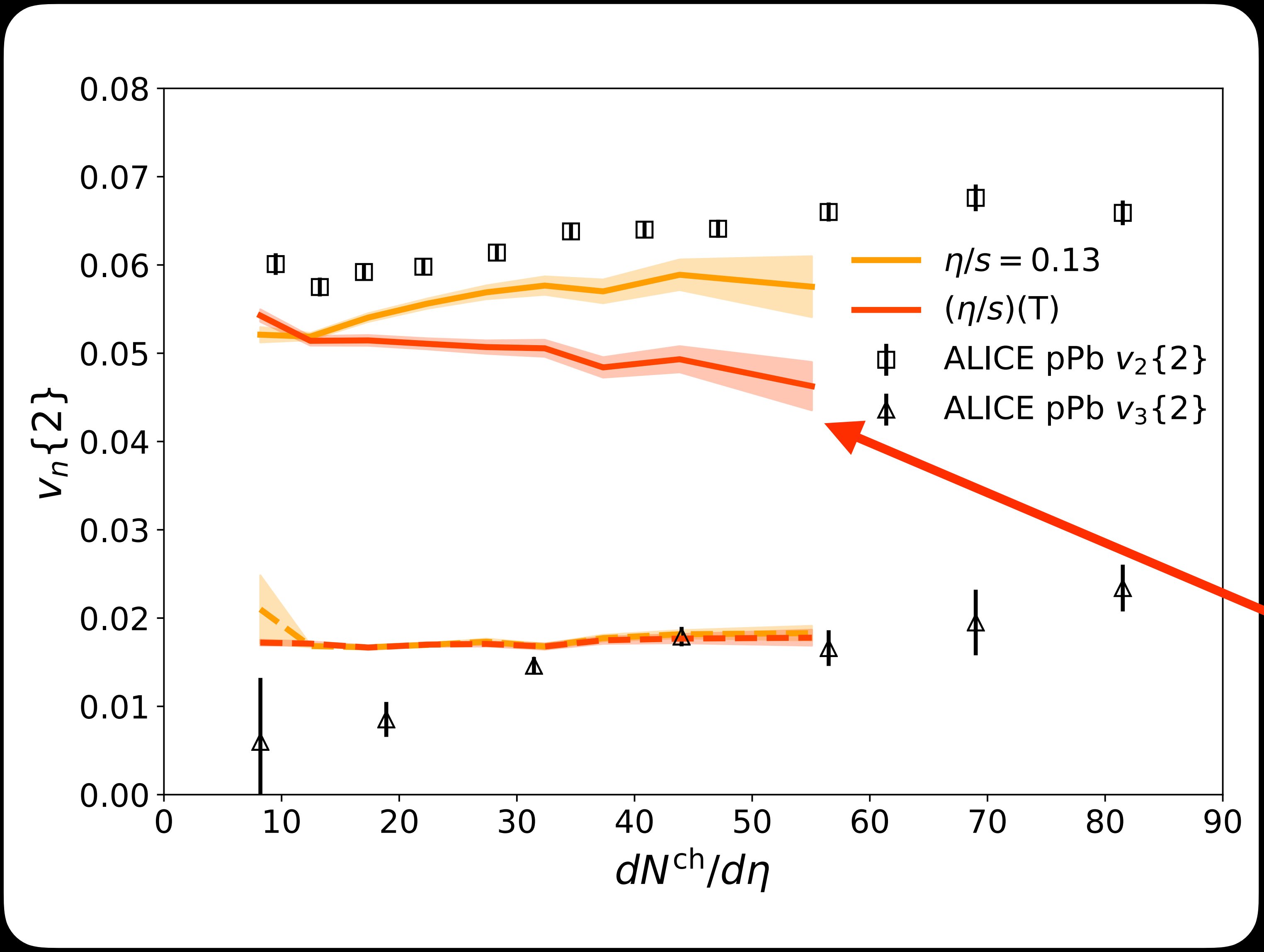
B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: A. M. Sirunyan et al. (CMS), (2017), arXiv:1711.05594

Not much room for T-dependent η/s

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

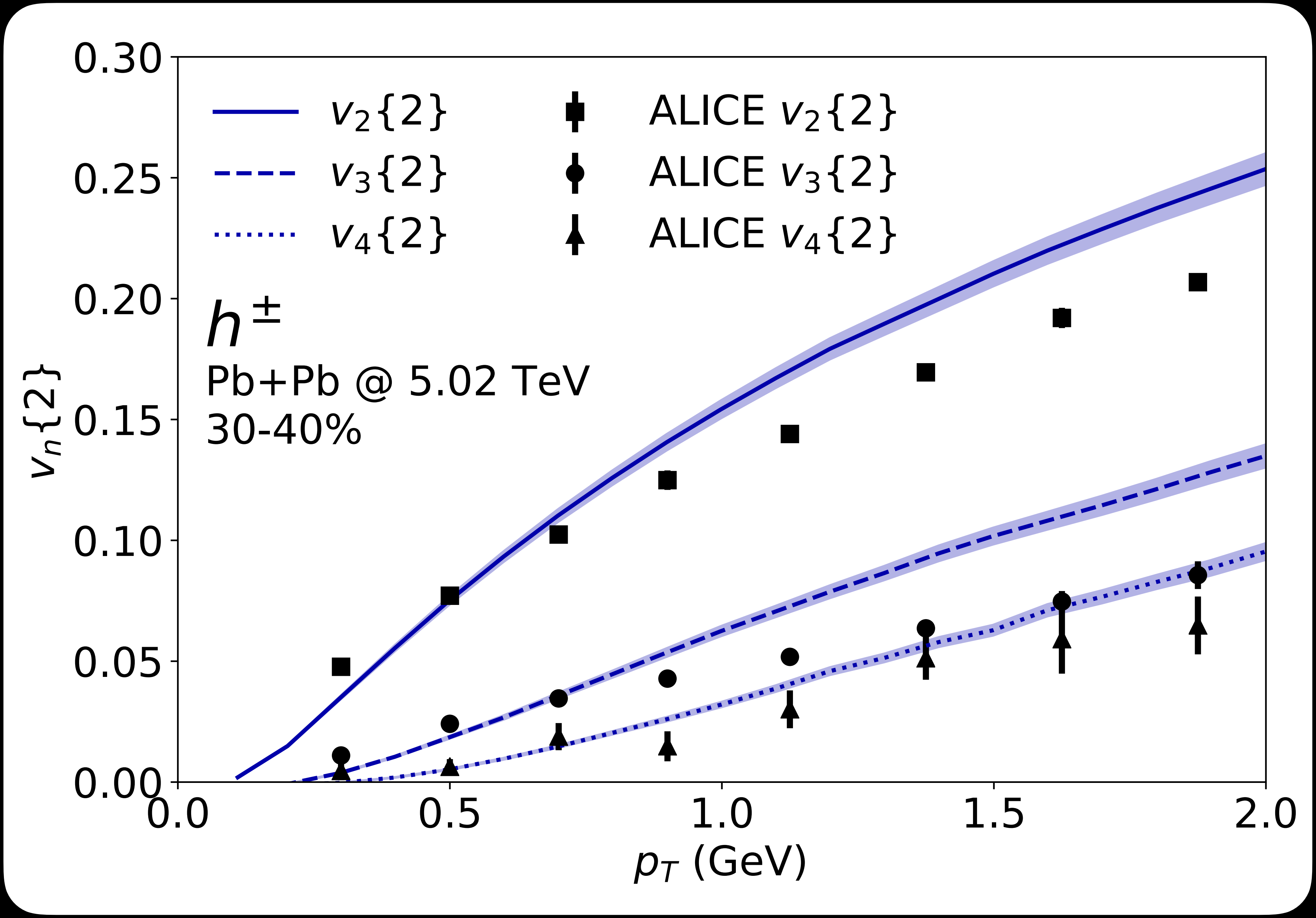


Rising **η**/s with increasing T leads to dropping v_2 for p+Pb

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

Differential v_n

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

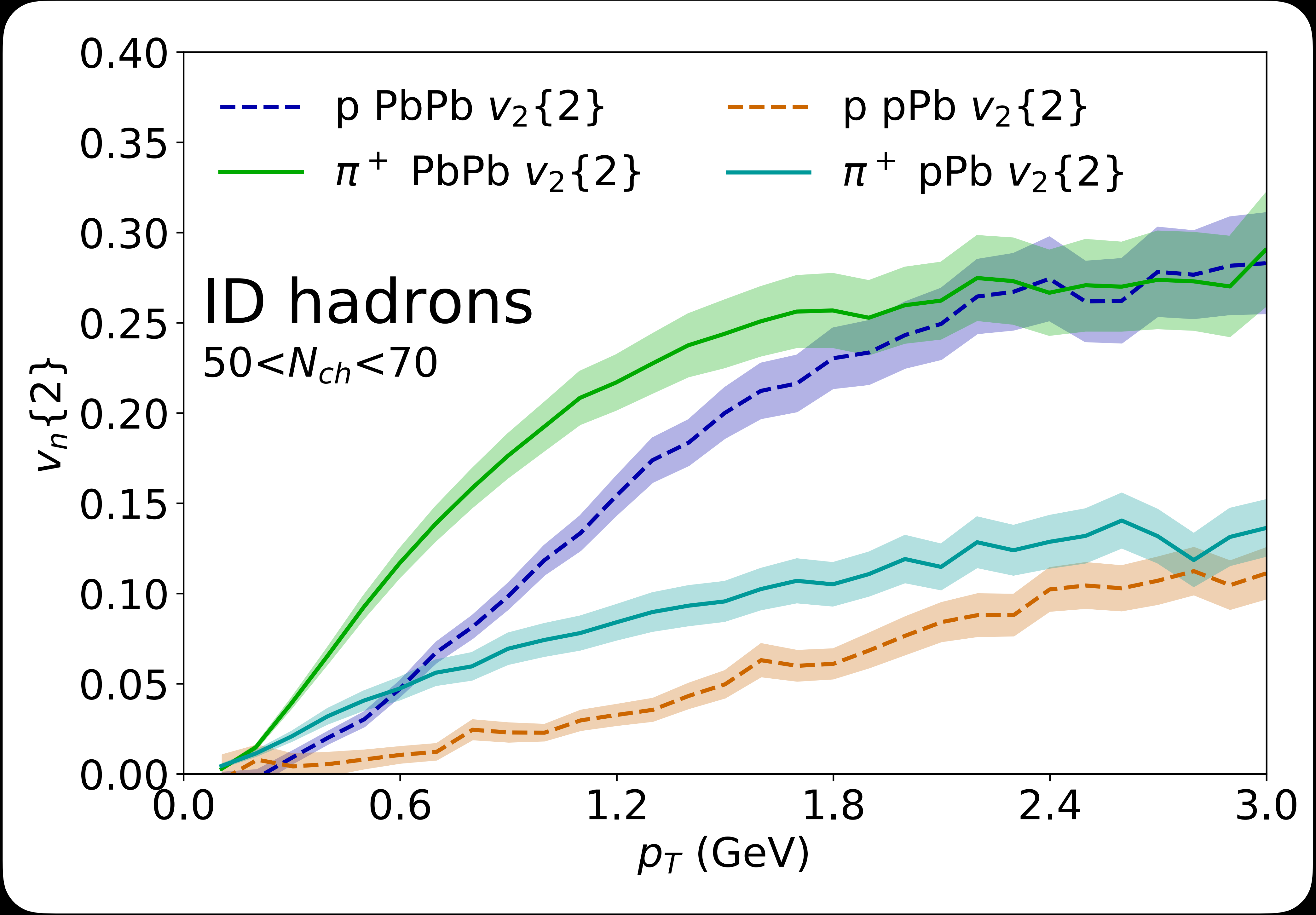


New EoS and inclusion of bulk viscosity makes agreement worse

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

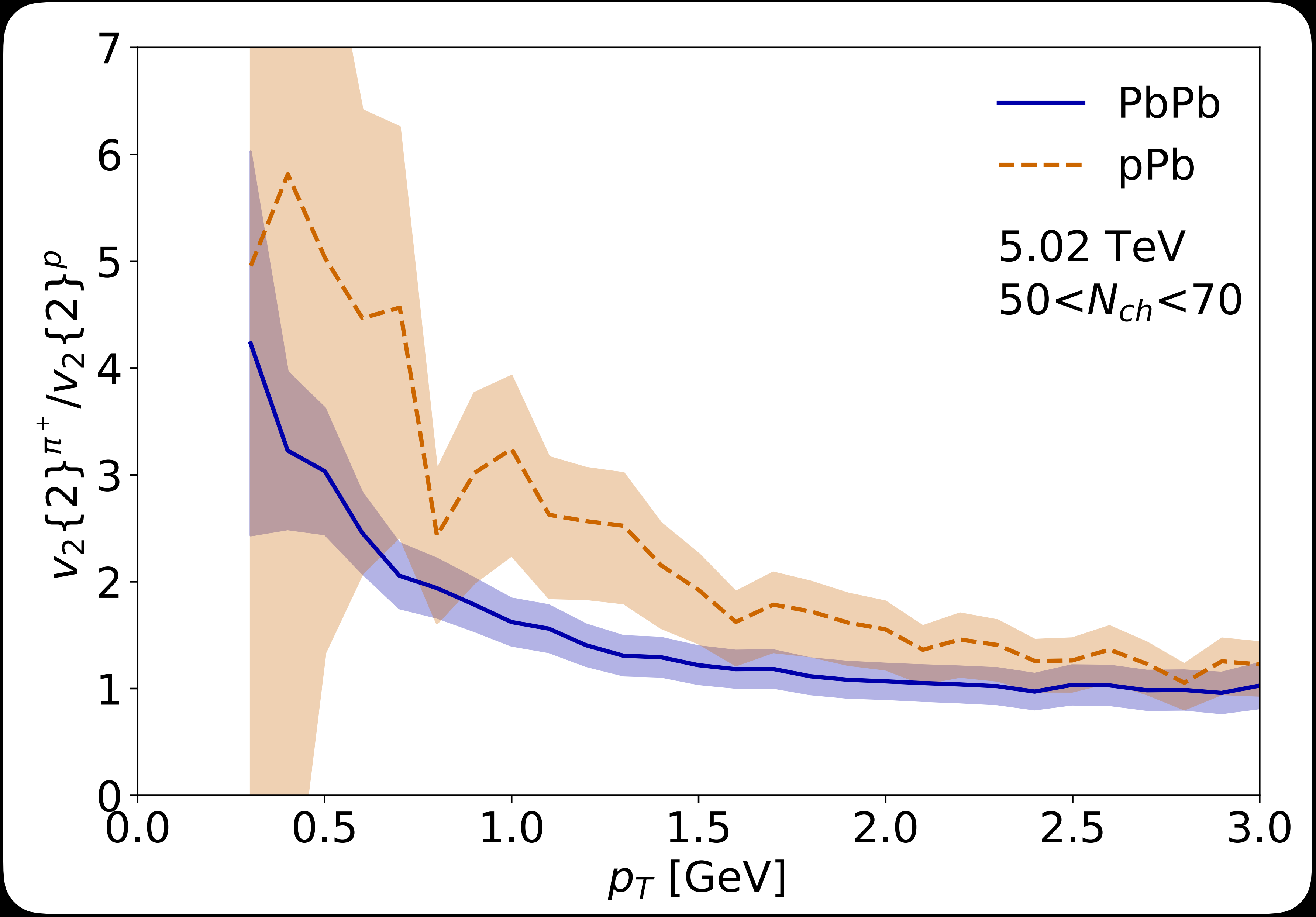
Mass splitting

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

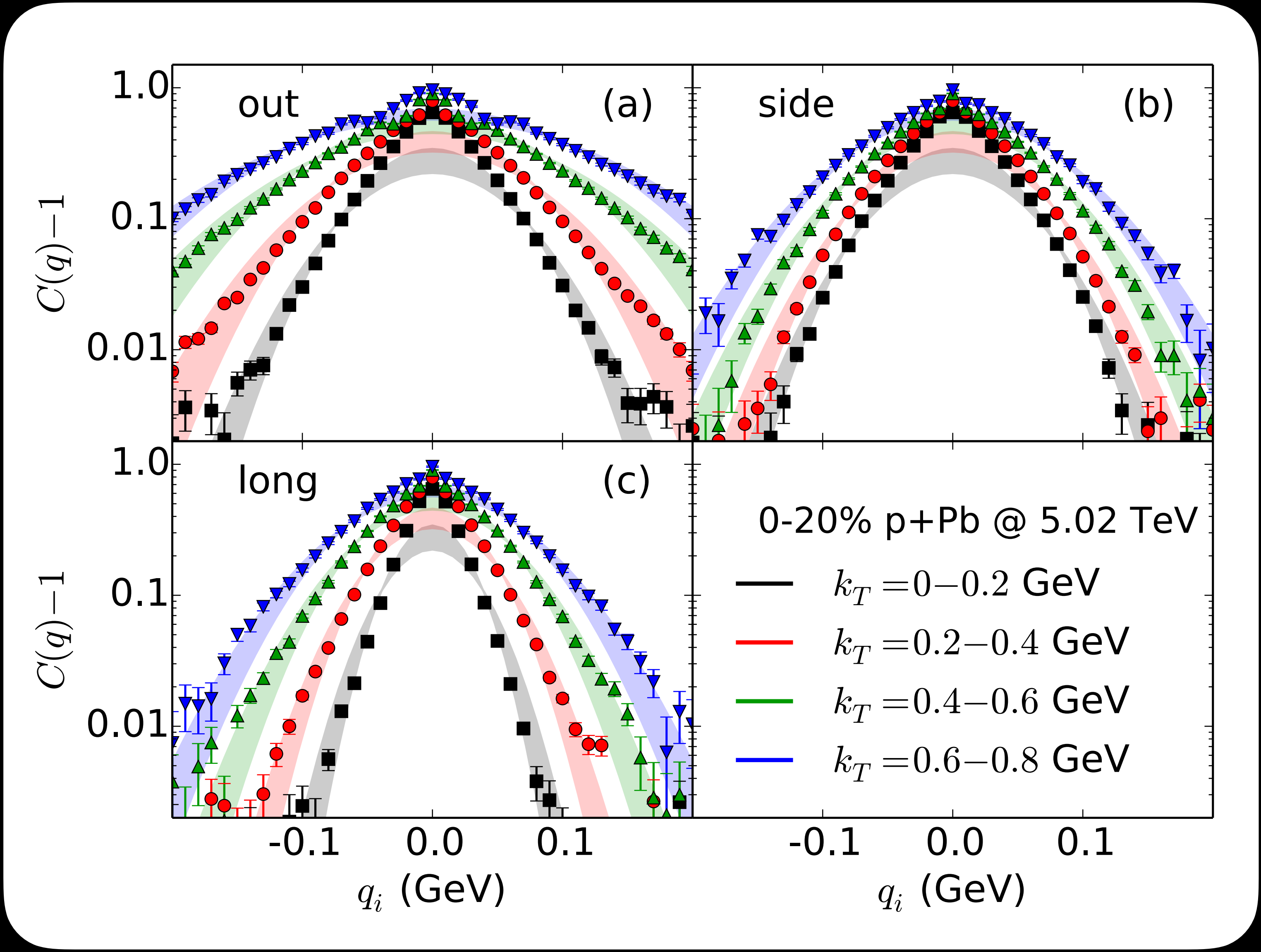
HBT radii

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

$$C(\mathbf{q}) = 1 + \frac{\frac{1}{\langle N_{\mathrm{pair}}\rangle}\langle\sum_{ij}\cos(q_{ij}\cdot x_{ij})\rangle}{\frac{1}{\langle N_{\mathrm{mix\,pair}}\rangle}\langle N_{\mathrm{mix\,pair}}(q)\rangle}$$

M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. 55, 357 (2005)

R. Hanbury Brown and R. Q. Twiss Nature 178, 1046 (1956)



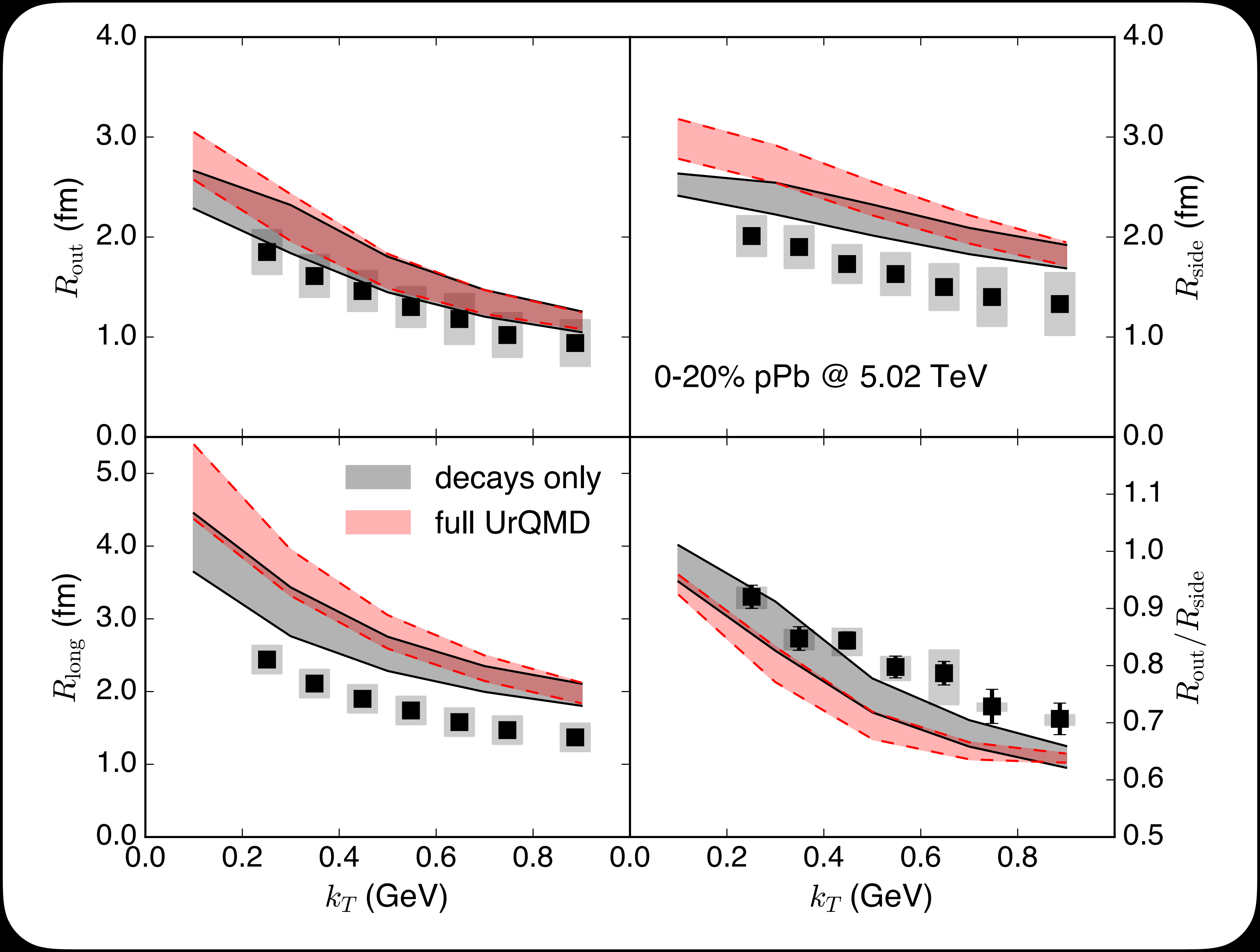
Fit to the Pratt-Bertsch parameterization in the longitudinally co-moving system

S. Pratt, Phys. Rev. D33, 1314 (1986)
G. Bertsch, M. Gong, and M. Tohyama Phys. Rev. C37, 1896 (1988).

HBT radii

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

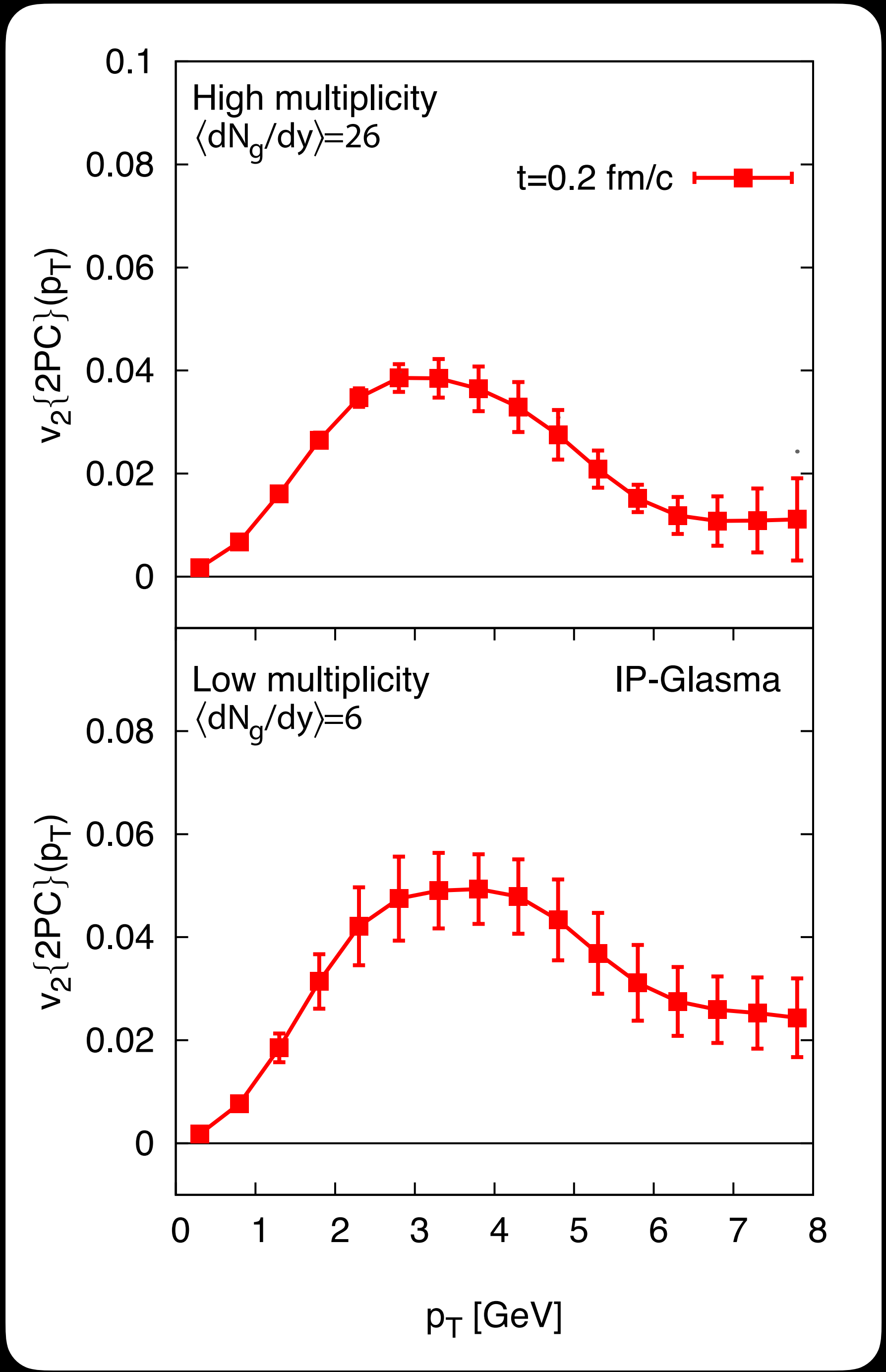
Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)

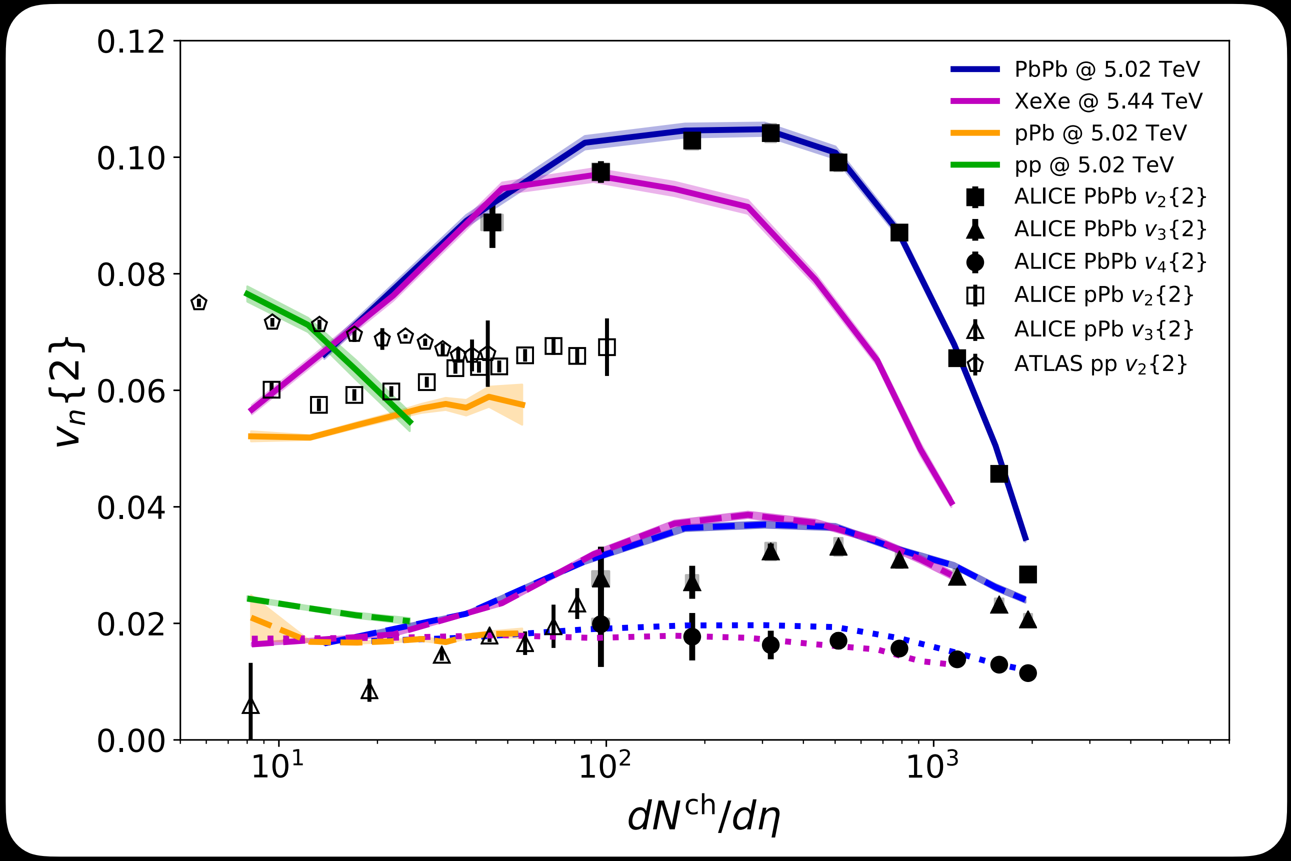


τ_0=0.4 fm (η/s)(T)

p+p v_n drop with multiplicity

…so do the initial state anisotropies (shown for pPb):





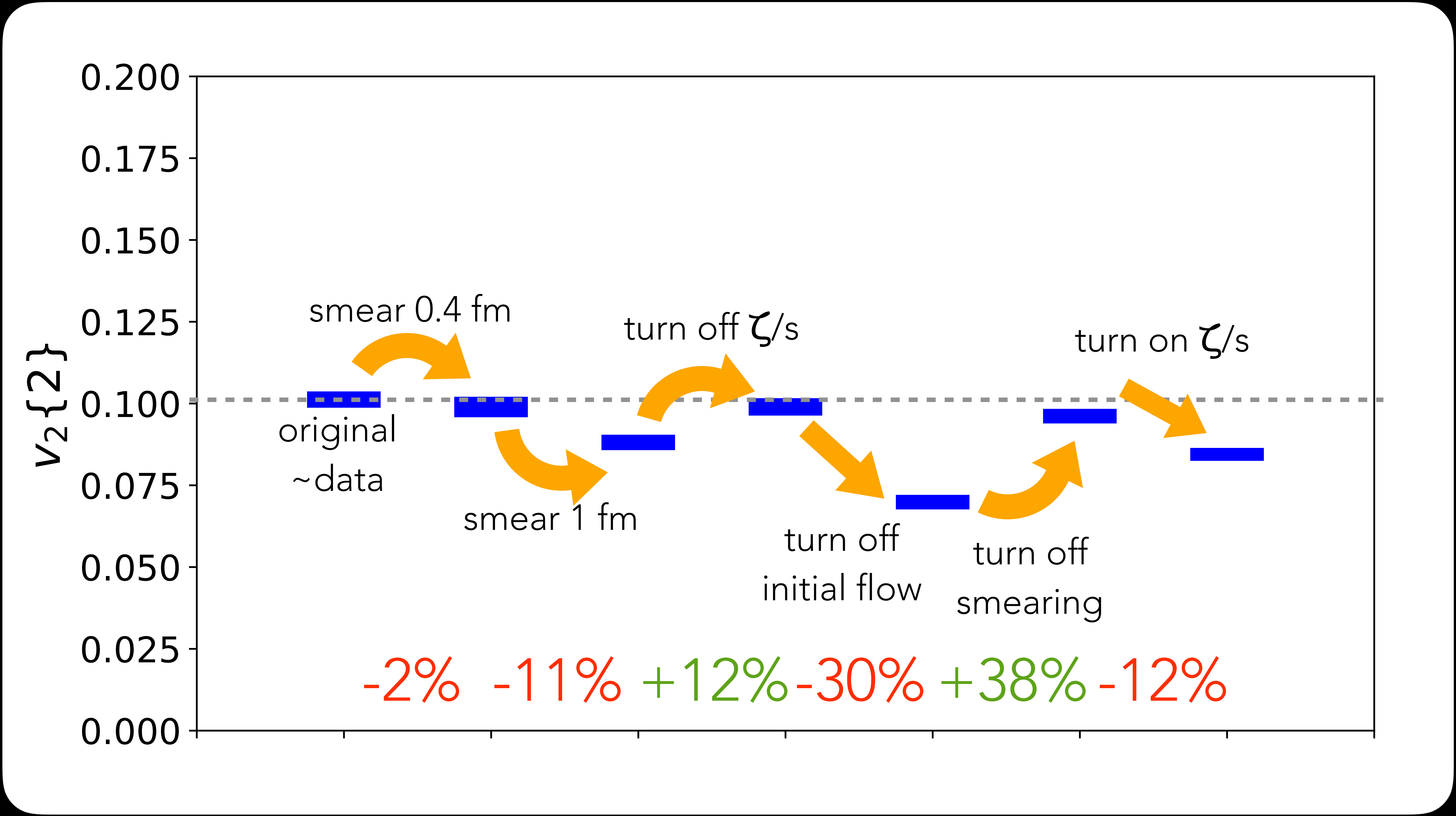
When switching at τ=0.6fm, a large part of the anisotropy is from the initial state

Warning: Removing dijet contribution by subtracting peripheral events may remove some real long range physics …

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu
Phys.Rev. D96 (2017), 091504

Effects of initial flow and smearing on v_2

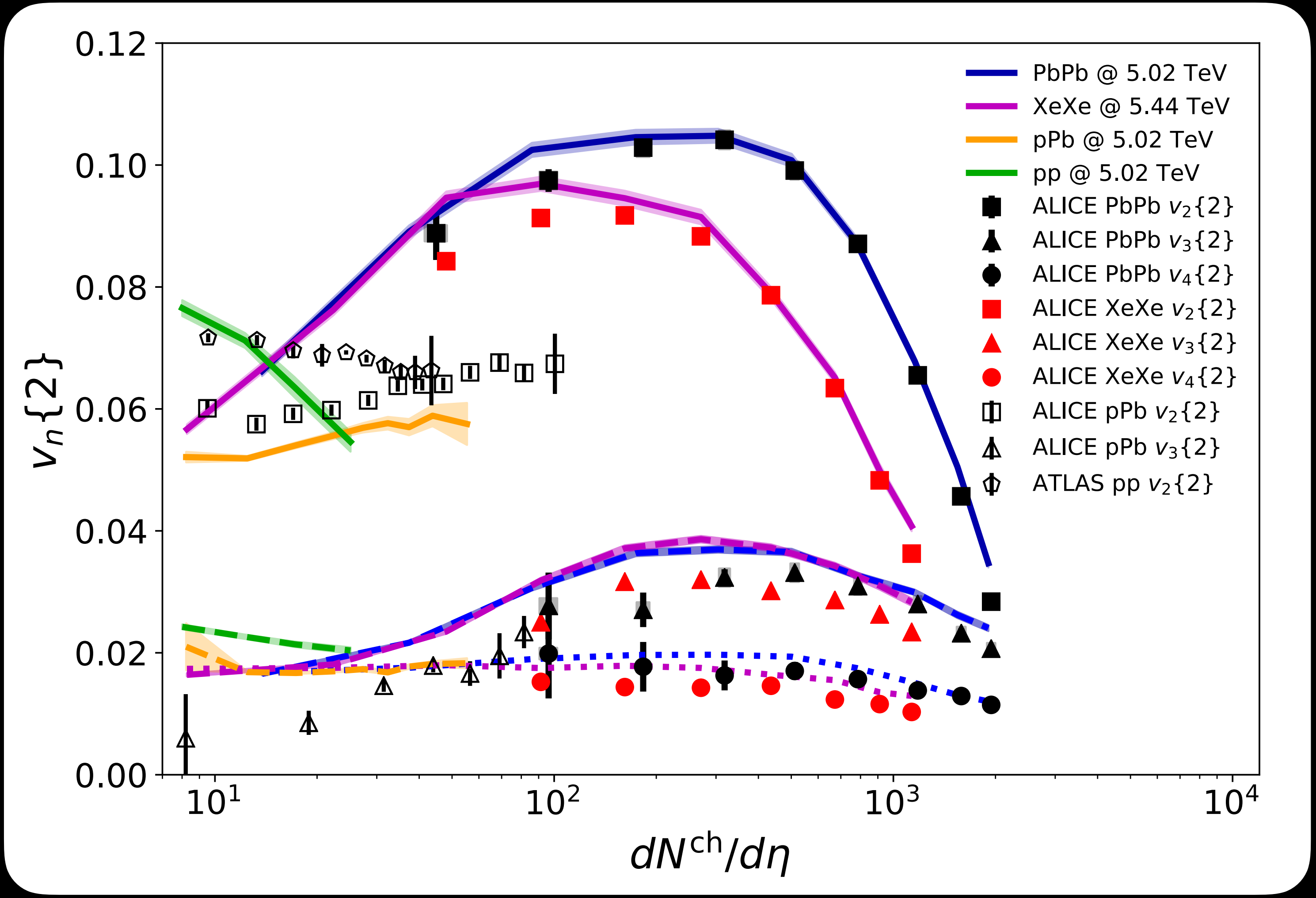
B. Schenke, C. Shen, P. Tribedy, in preparation



Also differences in bulk δf between calculations

Anisotropy vs. multiplicity

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

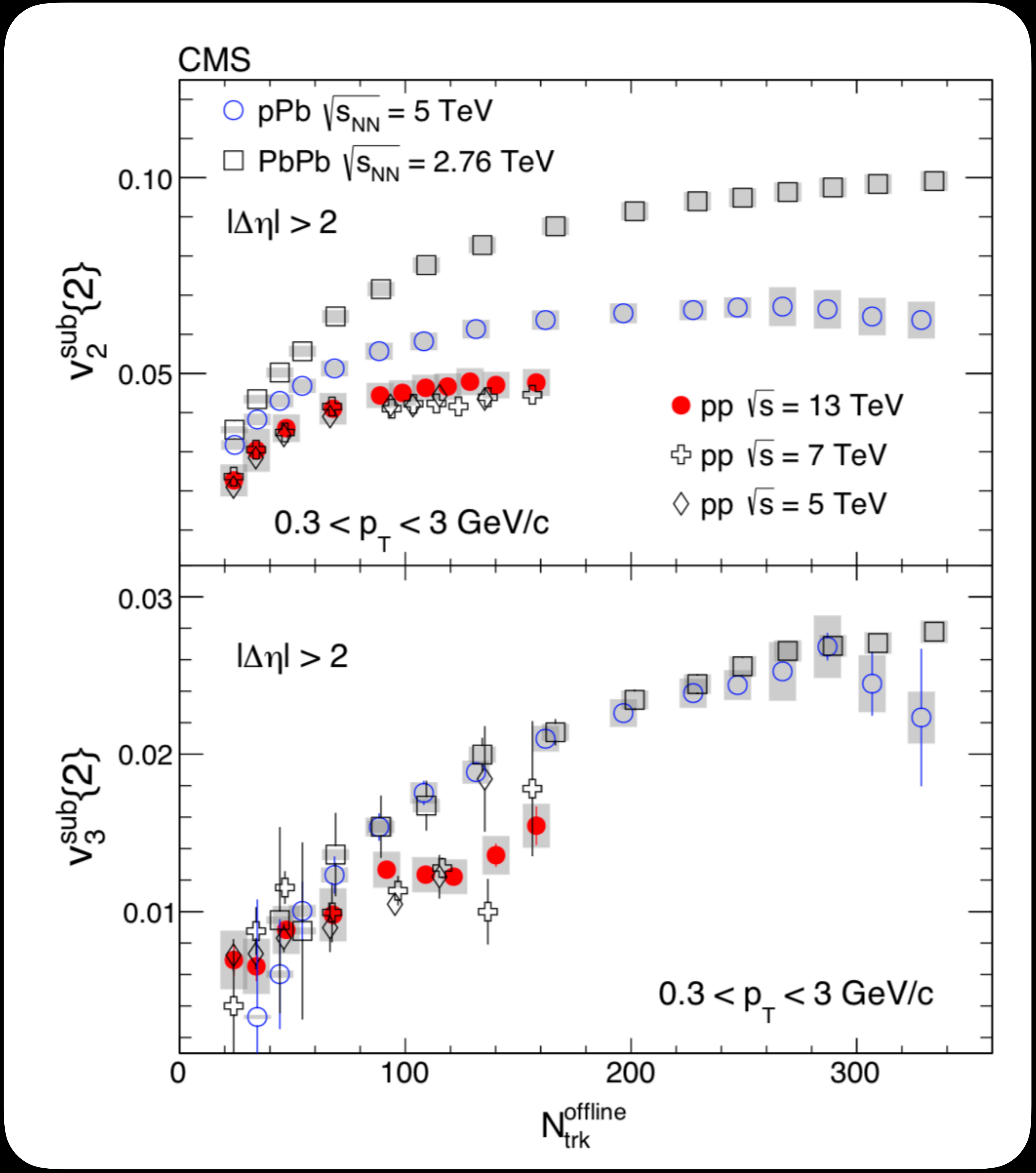


|η|<0.8 for ALICE

Results are boost invariant - comparison to ATLAS (CMS) difficult because there |η|<2.5 (2.4)

Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)
B. B. Abelev et al. (ALICE), Phys. Rev. C90, 054901 (2014), CMS Collaboration, Phys.Lett. B765 (2017) 193-220

Why is v_3 same in p+Pb and Pb+Pb?

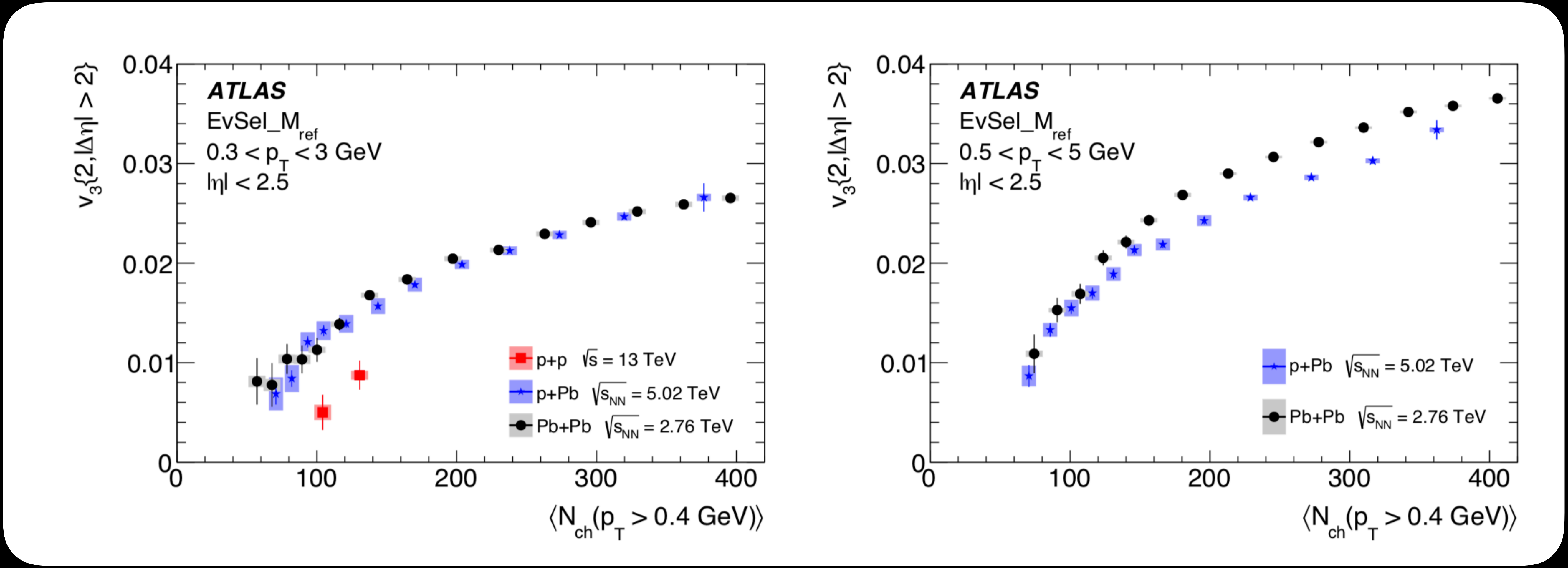


We expect vastly different eccentricity distributions for the two systems

Why is $v_3^{pPb} \approx v_3^{PbPb}$?

CMS Collaboration, Phys.Lett. B765 (2017) 193-220

Equality depends on p_T cut



ATLAS Collaboration, Eur.Phys.J. C77 (2017) no.6, 428

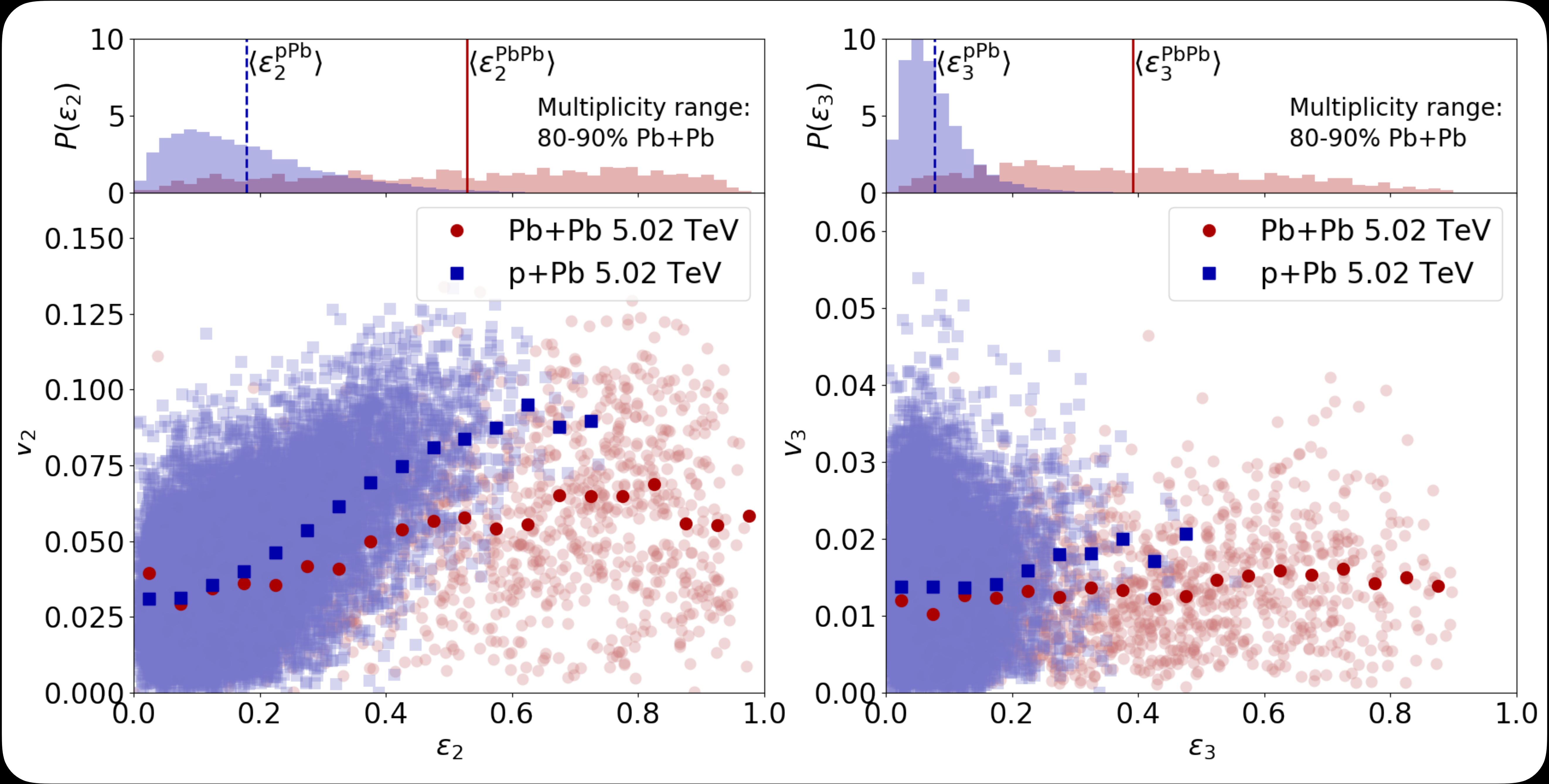
Energies different, but v_3^{PbPb} only ~5% larger at 5.02 TeV

ALICE, Phys. Rev. Lett. 116 (2016) 132302

Some level of coincidence, but there is some physics…

Geometry - flow correlations

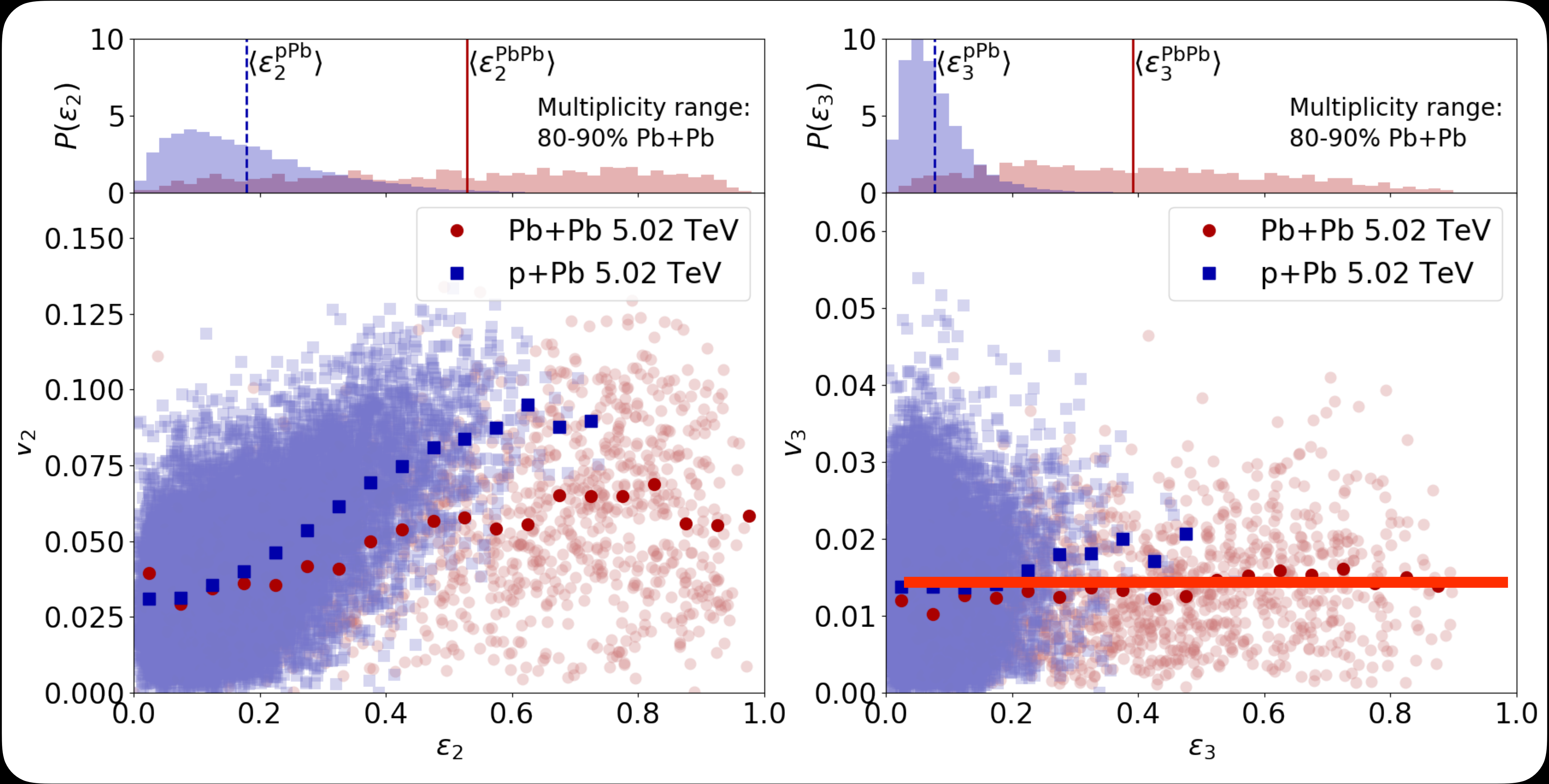
First: Eccentricity distributions are indeed different



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

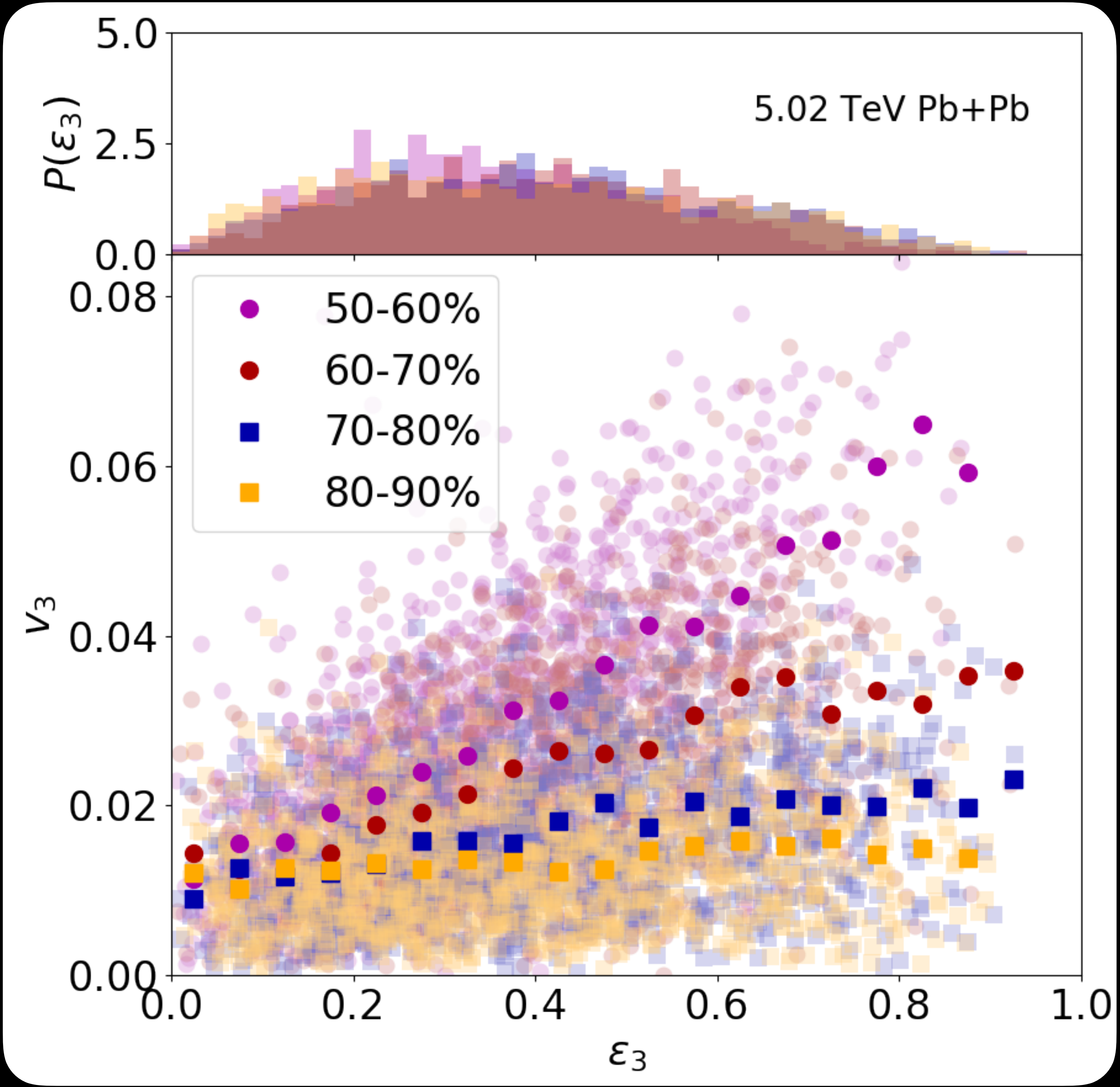
Geometry - flow correlations

First: Eccentricity distributions are indeed different



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

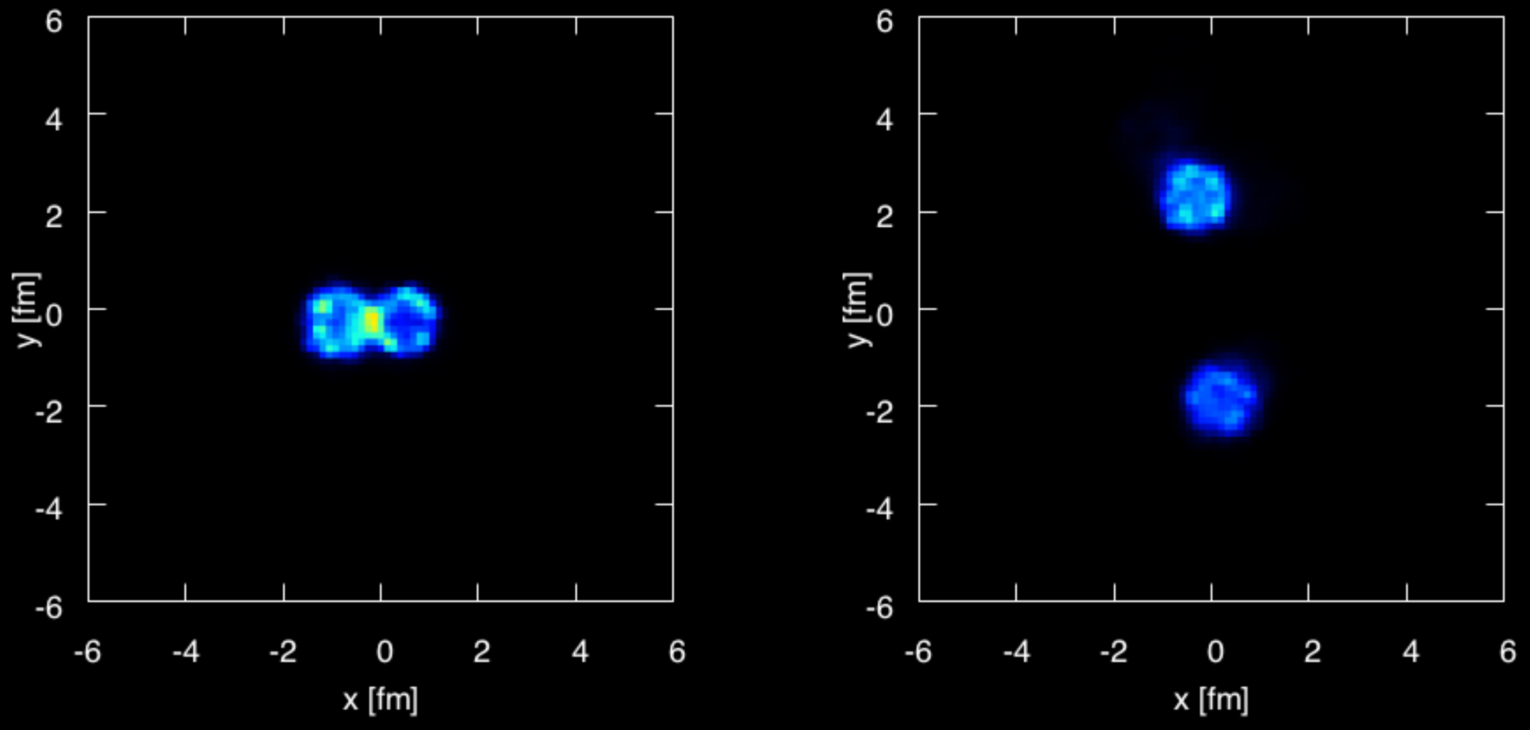
Correlation gradually vanishes



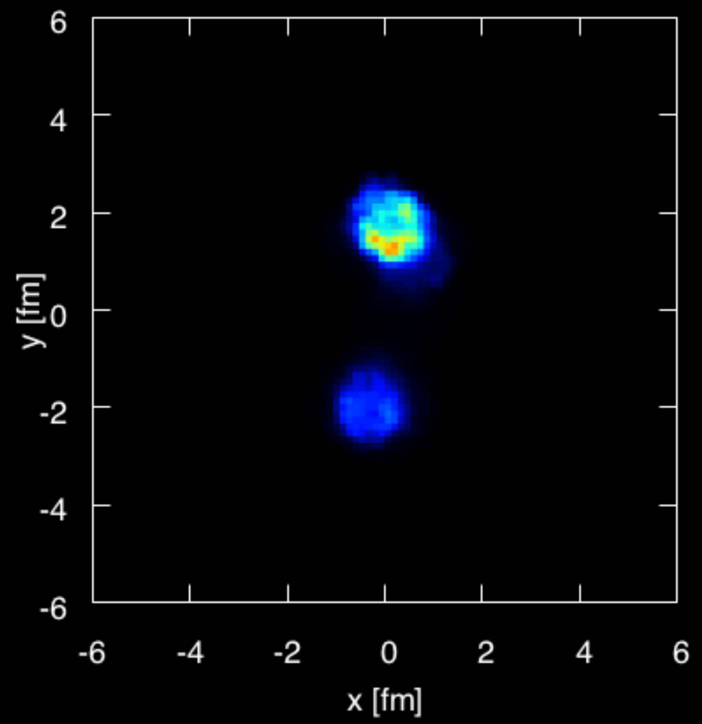
the more peripheral we go

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

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

Situation in IP-Glasma

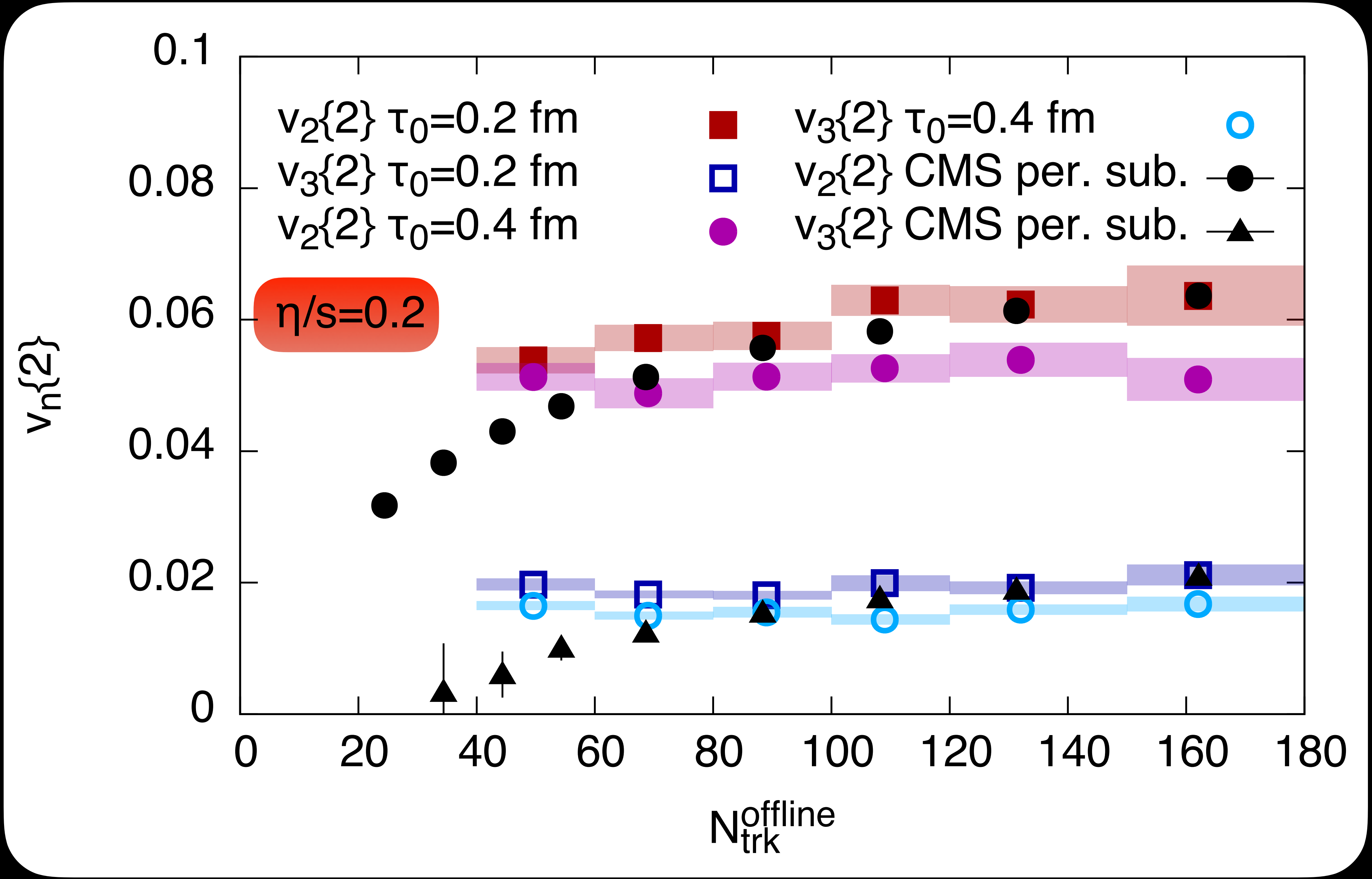
This leads to smaller v_n compared to pPb at the same multiplicity, because
1) geometry of separate blobs not aligned
2) energy density in blobs lower than in 1 pPb blob

Finite interaction between blobs must compensate for that

But in fact in the calculation v_3 are only same at very low multiplicity (data shows same value to higher multiplicity)

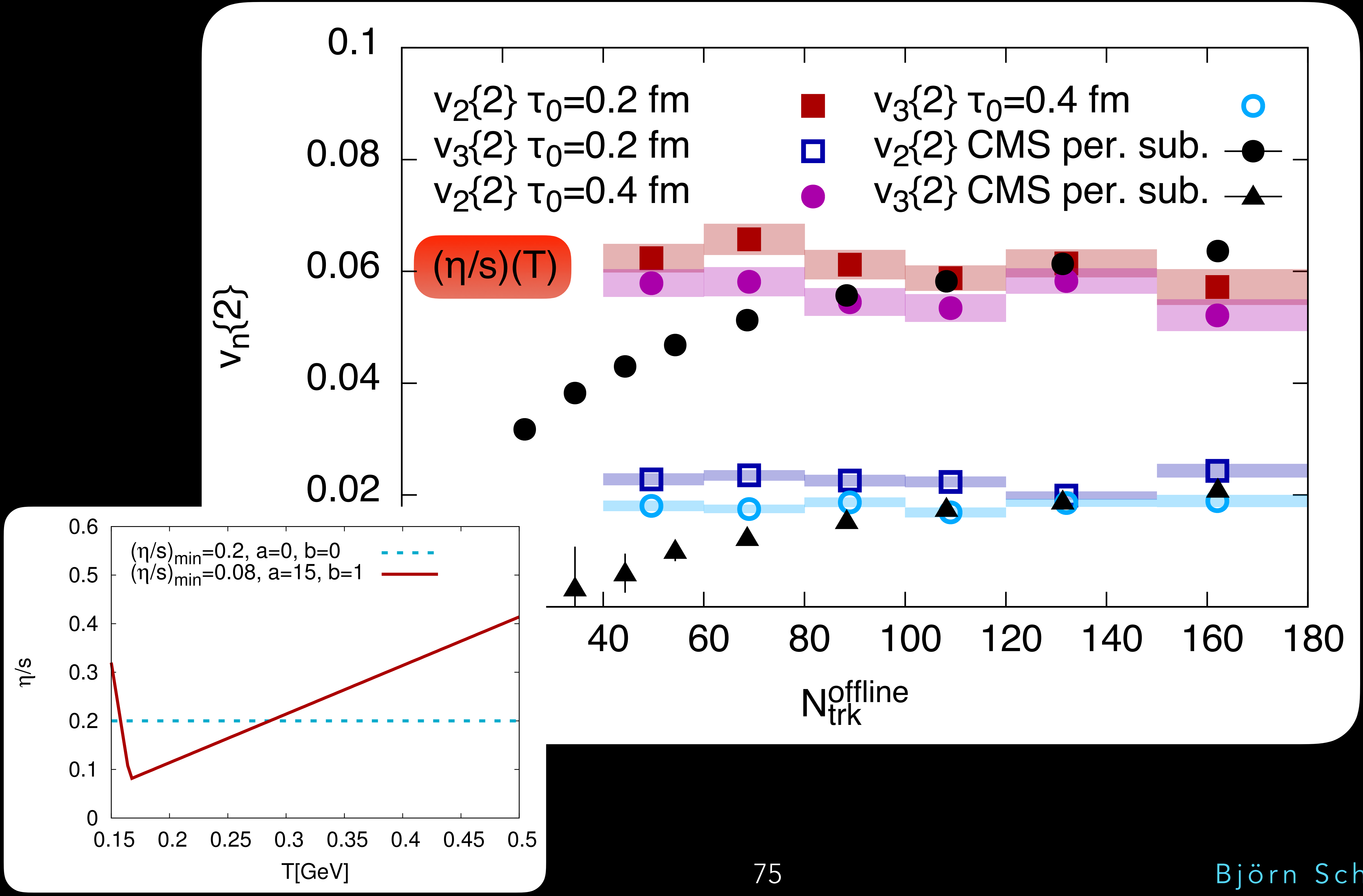
Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

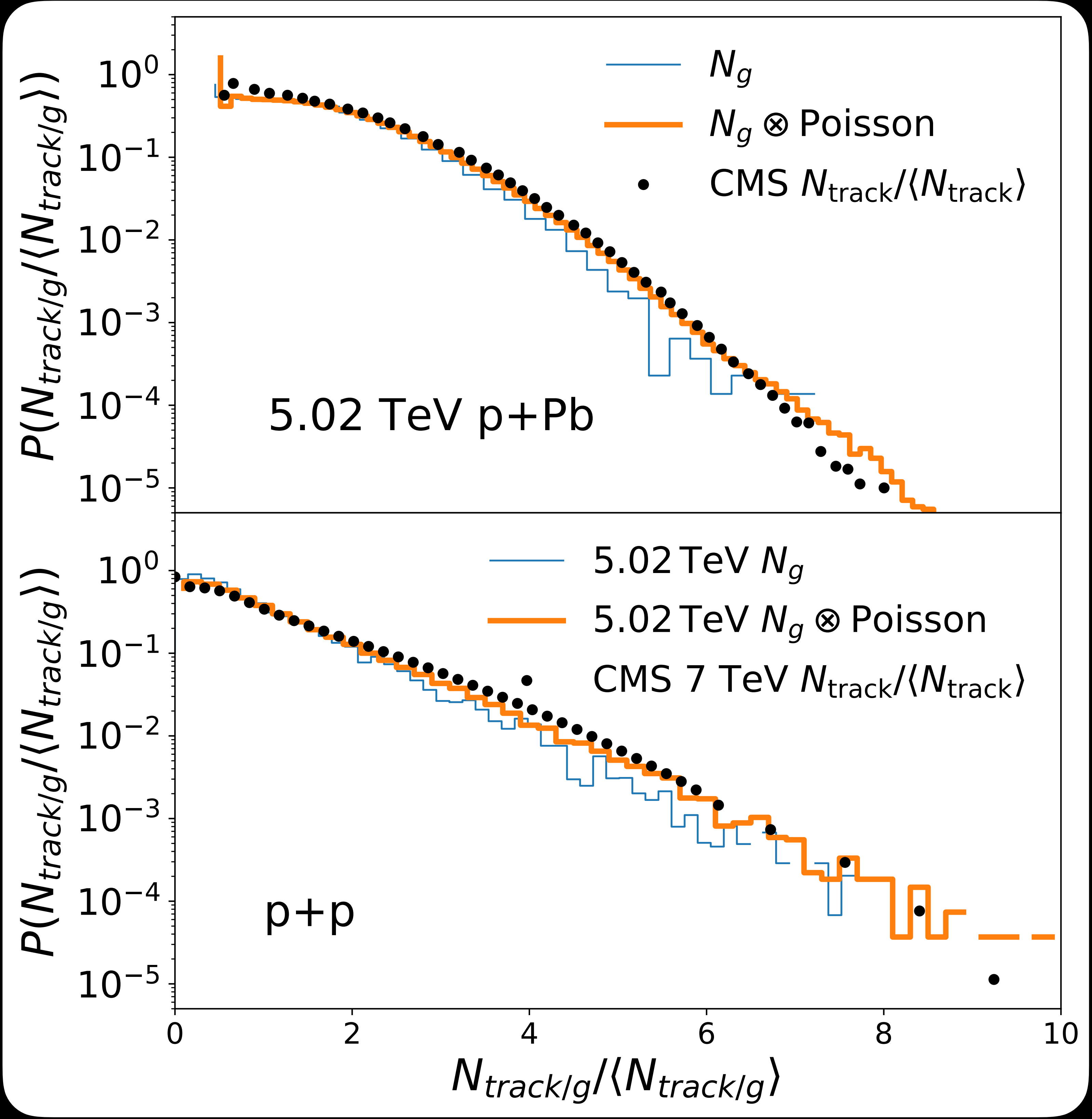


Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



MULTIPLICITY DISTRIBUTIONS



Includes fluctuations of

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

VISCOUS FLUID DYNAMICS

Energy momentum conservation: $\partial_\mu T^{\mu\nu} = 0$

with $T^{\mu\nu} = \varepsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$

Navier-Stokes limit:

$\Pi = -\zeta \nabla_\alpha u^\alpha$ (bulk viscous pressure)

$\pi^{\mu\nu} = \eta \nabla^{\langle\mu} u^{\nu\rangle} = \eta[\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}(\nabla_\alpha u^\alpha)]$ (shear)

Implementing this is numerically unstable. Need to go to higher order in gradients → evolution equations for Π and $\pi^{\mu\nu}$ involving relaxation times τ_Π and τ_π

$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

VISCOUS FLUID DYNAMICS

Second order equations derived by Israel and Stewart

W. Israel and J. M. Stewart, Phys. Lett. 58A, 213 (1976); Ann. Phys. (N.Y.) 118, 341 (1979)

New method involving systematic power-counting in Knudsen and inverse Reynolds number

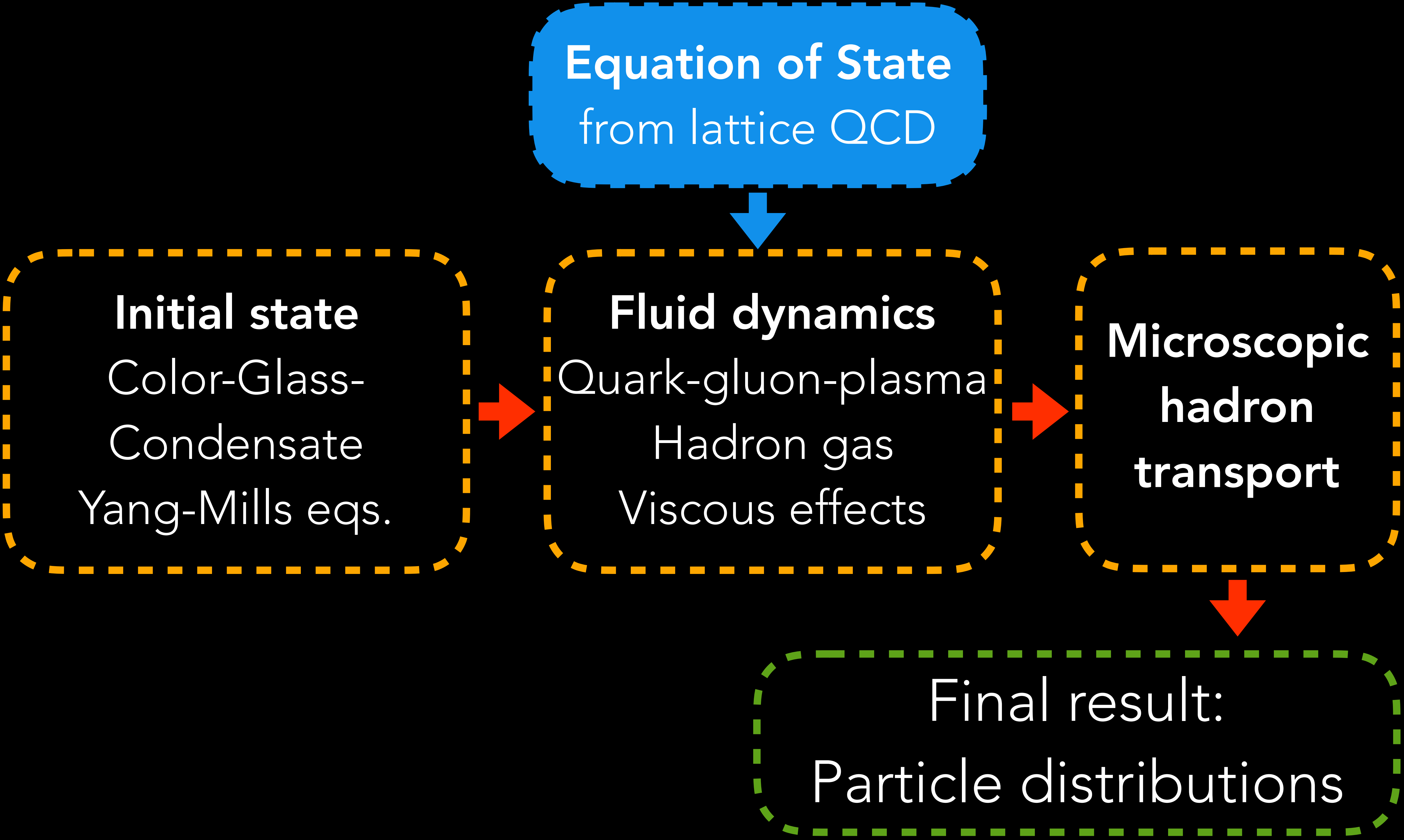
G. S. Denicol, H. Niemi, E. Molnar, D. H. Rischke, Phys.Rev. D85, 114047 (2012)

All transport coefficients are determined within this scheme once values for η and ζ are chosen

G. S. Denicol, H. Niemi, E. Molnar, D. H. Rischke, Phys.Rev. D85, 114047 (2012)
G. S. Denicol, S. Jeon, and C. Gale, Phys.Rev. C90, 024912 (2014)

$$\tau_\pi = 5\frac{\eta}{\varepsilon + P} \qquad \tau_\Pi = \frac{1}{15(\frac{1}{3} - c_s^2)^2}\frac{\zeta}{\varepsilon + P}$$

SIMULATION FRAMEWORK



Equation of State
from lattice QCD

Initial state
Color-Glass-Condensate
Yang-Mills eqs.

Fluid dynamics
Quark-gluon-plasma
Hadron gas
Viscous effects

Microscopic hadron transport

Final result:
Particle distributions

EQUATION OF STATE

Equation of State

To close the equations we need P(ε)

We use an EoS constructed from lattice QCD data

S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, K. K. Szabo, Phys. Lett. B730, 99–104 (2014)
S. Borsanyi, Z. Fodor, S. D. Katz, S. Krieg, C. Ratti, and K. Szabo, JHEP 01, 138 (2012)

$$\frac{P(T)}{T^4} = \frac{P(T_{\mathrm{low}})}{T_{\mathrm{low}}^4} + \int_{T_{\mathrm{low}}}^{T} \frac{dT'}{T'} \frac{\varepsilon - 3P}{T'^4}$$

measured trace anomaly

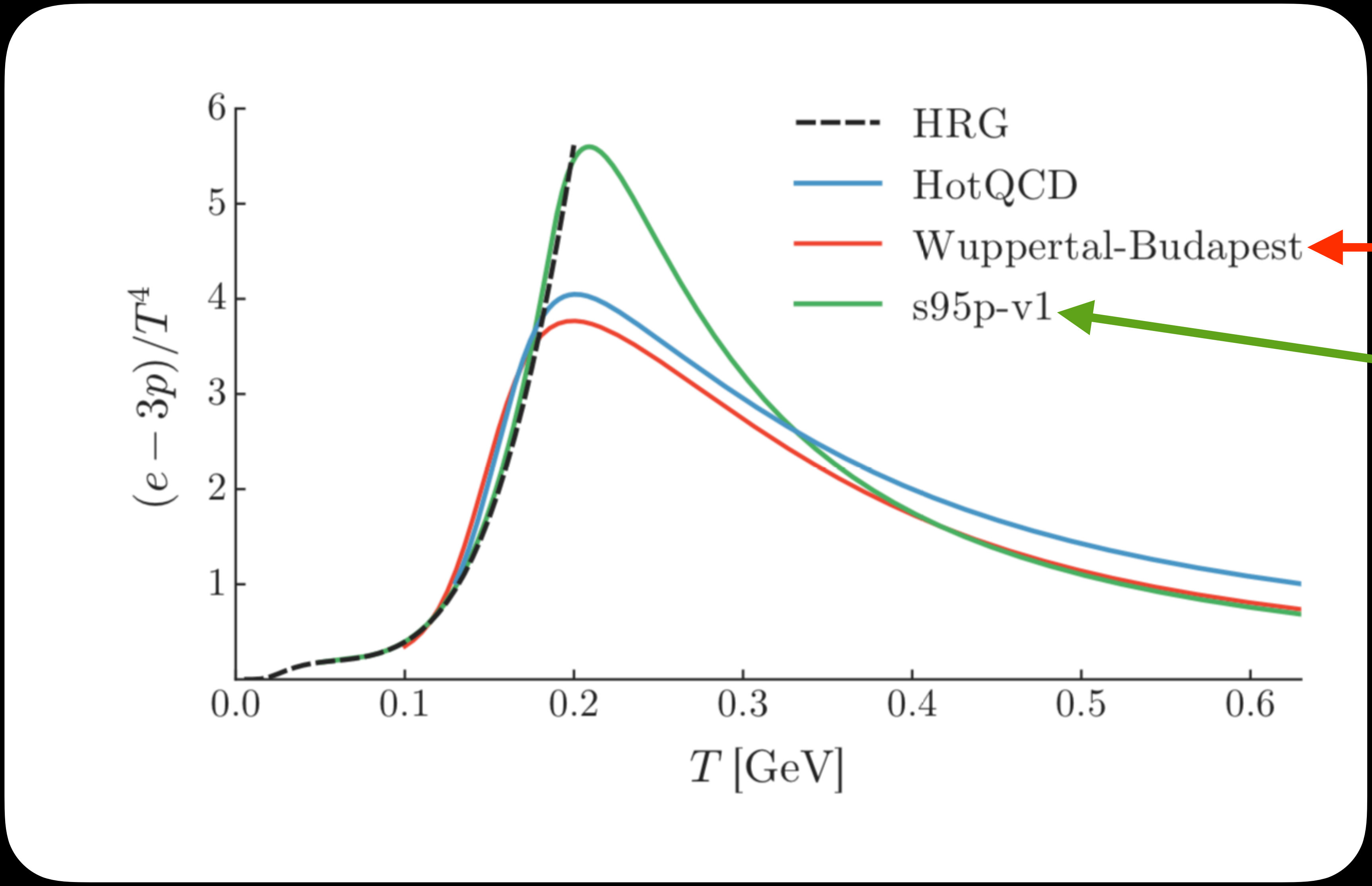
smoothly matched to a hadron resonance gas around $T_{\mathrm{match}} \approx 165$ MeV

The EoS is also constructed at non-zero μ_B which we do not need in this talk

EQUATION OF STATE

Equation of State

Different lattice results and constructions



what we use now

previously used

Figure from J.S. Moreland, R.A. Soltz, Phys.Rev. C93, 044913 (2016)
s95p-v1: P. Huovinen and P. Petreczky, Nucl. Phys. A837, 26–53 (2010)
HotQCD: 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)

MICROSCOPIC HADRON CASCADE

Microscopic hadron transport

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

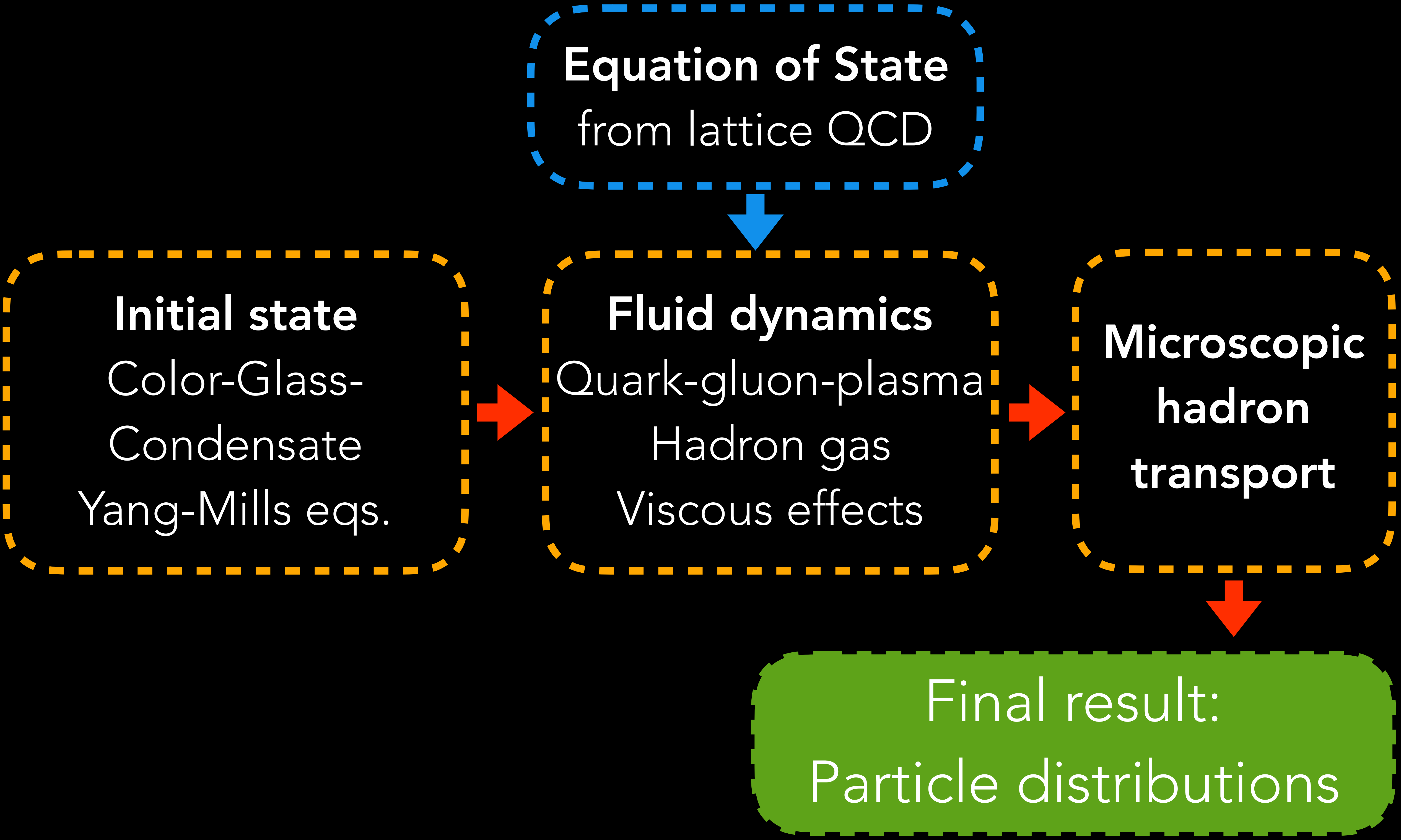
$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\Delta^3\Sigma_\mu p^\mu (f_i^{(0)} + \delta f_i)$$

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

SIMULATION FRAMEWORK



Equation of State
from lattice QCD

Initial state
Color-Glass-Condensate
Yang-Mills eqs.

Fluid dynamics
Quark-gluon-plasma
Hadron gas
Viscous effects

Microscopic hadron transport

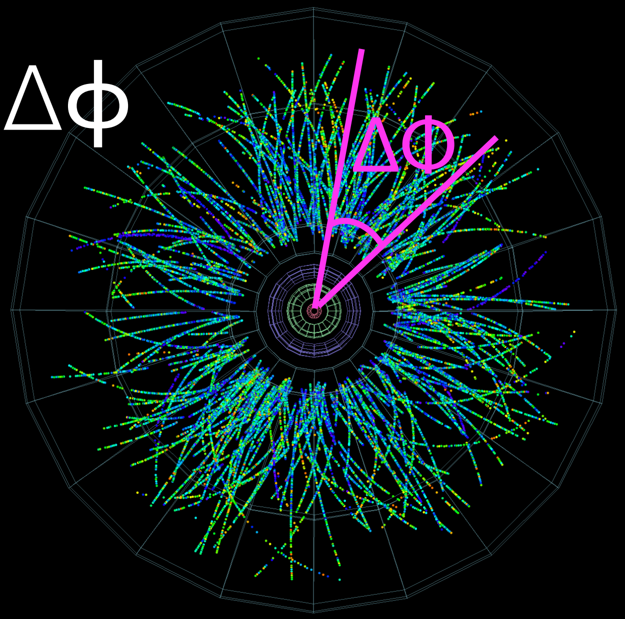
Final result:
Particle distributions

Introduction: Multi-particle correlations

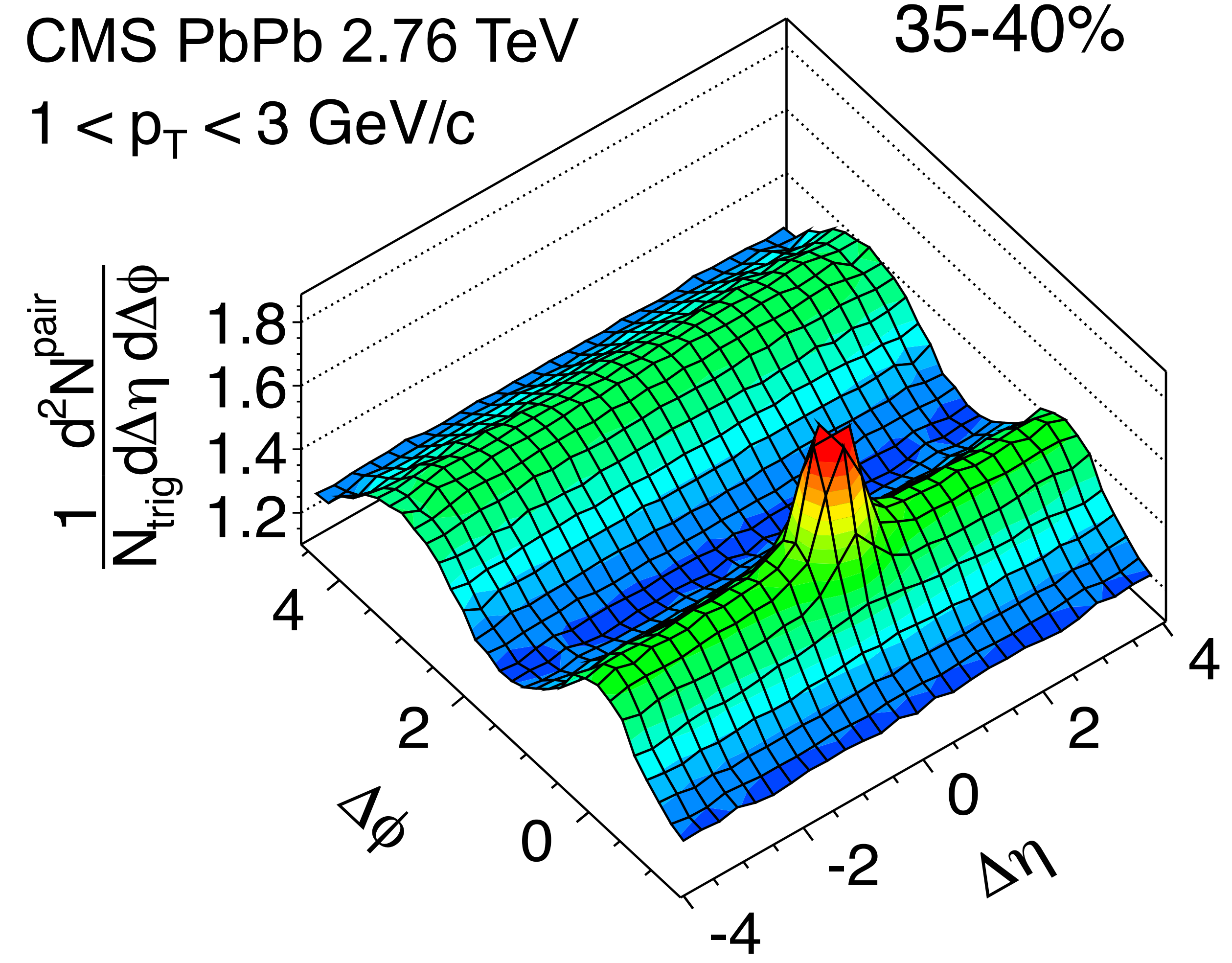
2-particle correlation as a function of Δη and Δϕ

ΔΗ: DIFFERENCE IN PSEUDO-RAPIDITY

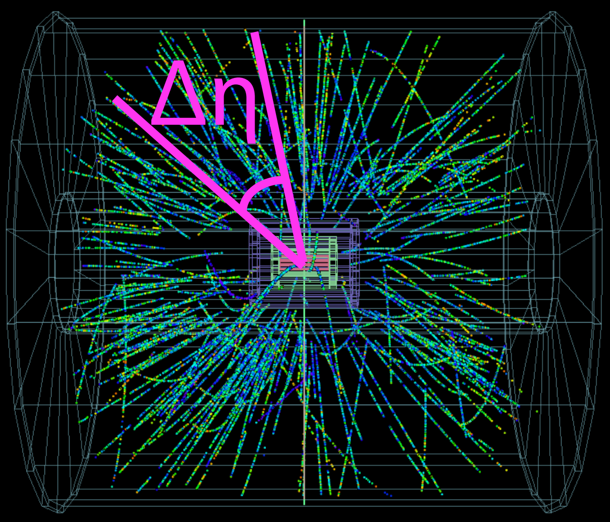
ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE



ΔΦ: DIFFERENCE
IN AZIMUTHAL ANGLE



CMS COLL., EUR. PHYS. J. C72 (2012)

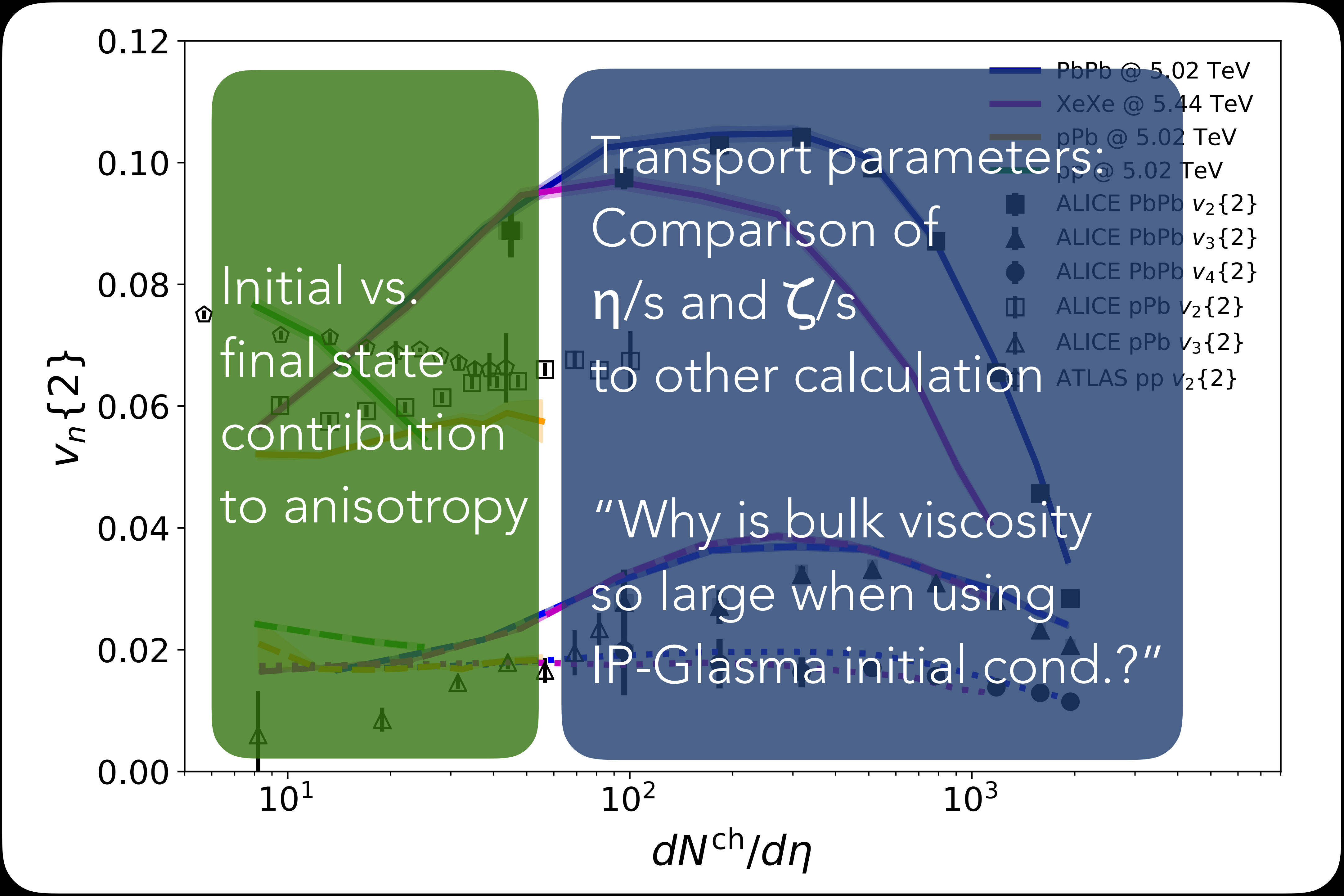


Δη: DIFFERENCE
IN PSEUDO-RAPIDITY

Event Displays: © 2012 CERN, ALICE

Important questions

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



Initial vs. final state contribution to anisotropy

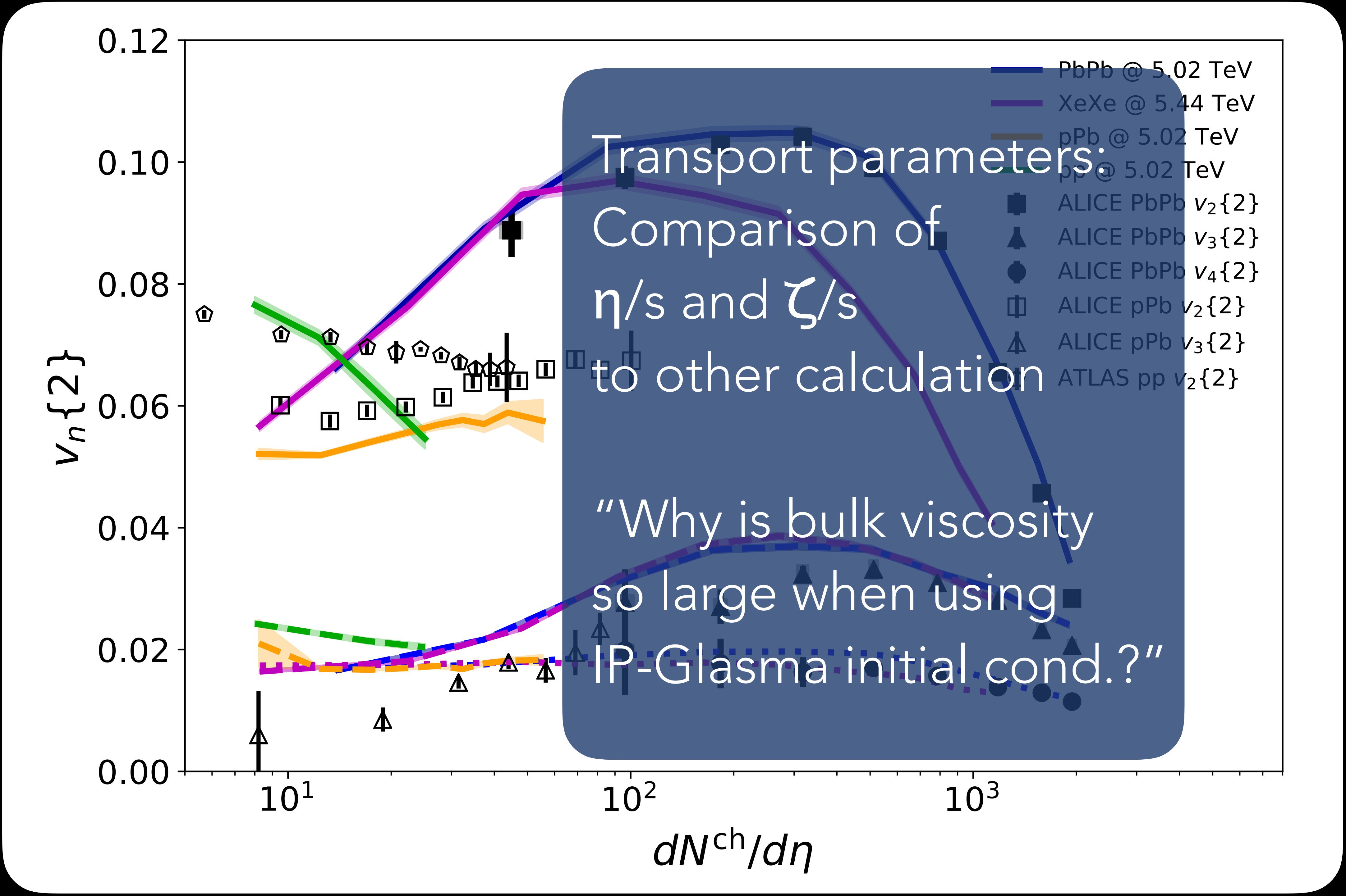
Transport parameters: Comparison of η/s and ζ/s to other calculation

"Why is bulk viscosity so large when using IP-Glasma initial cond.?"

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
ATLAS Collaboration, Eur. Phys. J. C (2017) 77:428

Why do we need a large ζ/s?

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



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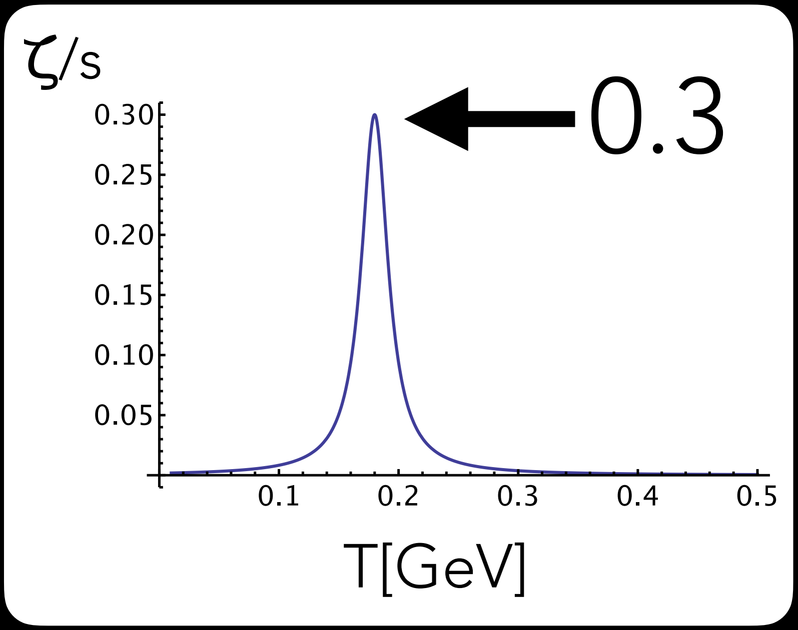
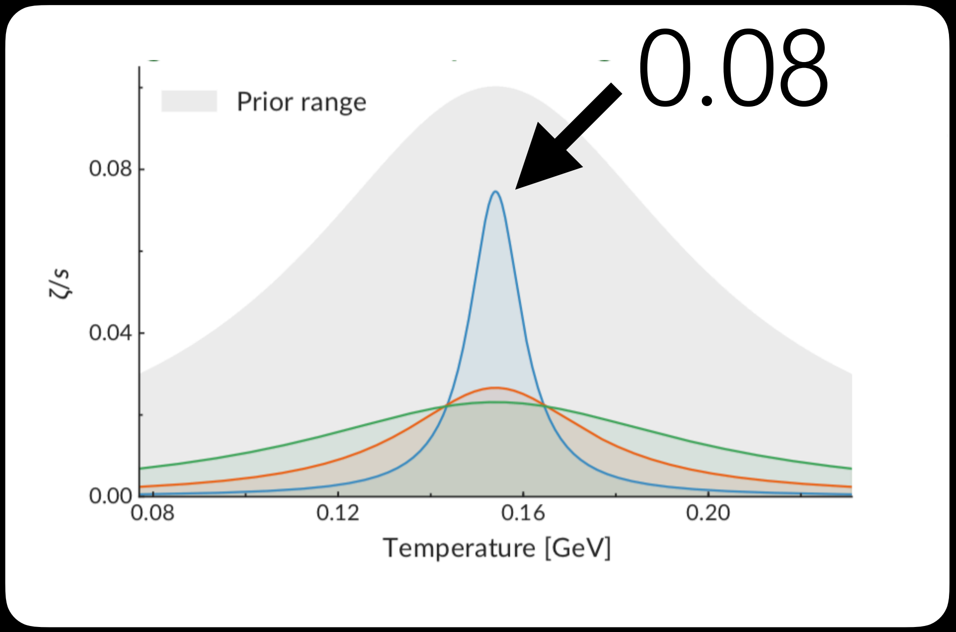
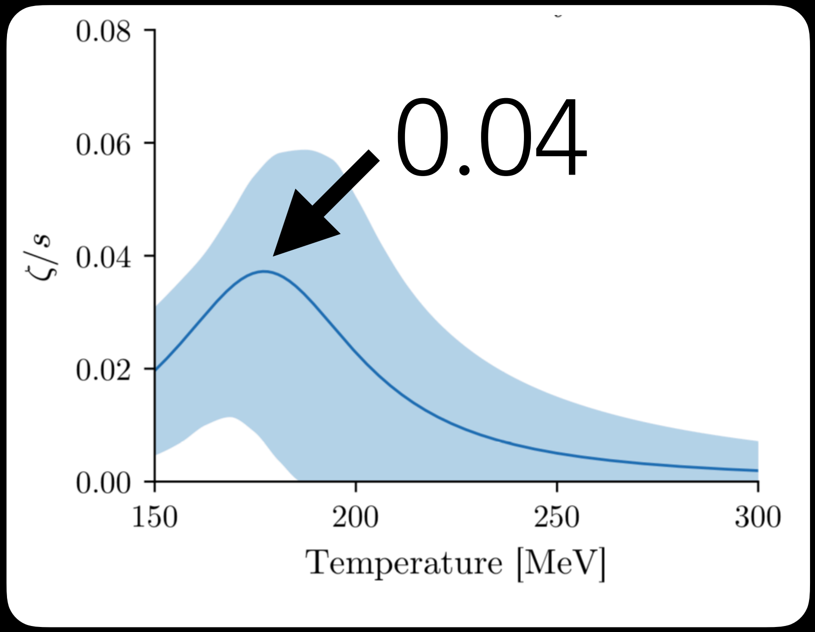


this work



S.A. Bass @ QM2017



J. E. Bernhard, arXiv:1804.06469

Also: $\zeta/s = 0.01$ in **R.D. Weller, P. Romatschke, Phys.Lett. B774 (2017) 351-356**

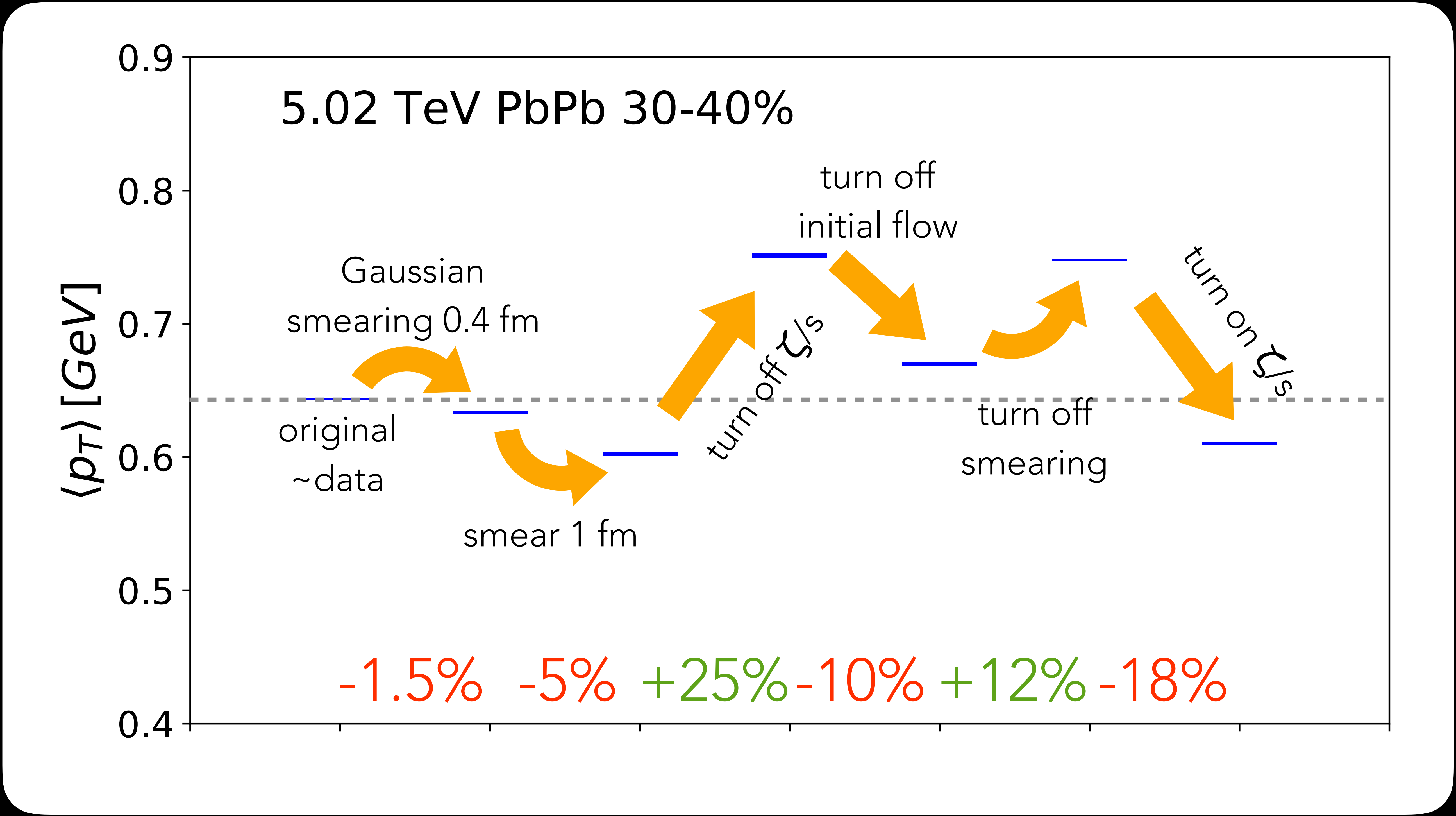
$\zeta/s = 0.04$ in **P. Bozek, Phys. Lett. B 699 (2011) 283**

IP-Glasma initial condition requires large bulk viscosity because it generates large $\langle p_T \rangle$. But why?

Possible answers: 1. Strong initial flow 2. Spiky/compact geometry

Effects of initial flow and smearing on $\langle p_T \rangle$

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



Also differences in bulk δf between calculations

SEE POSTER BY S.A. BASS

Answer: ~50% initial flow, ~50% size

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

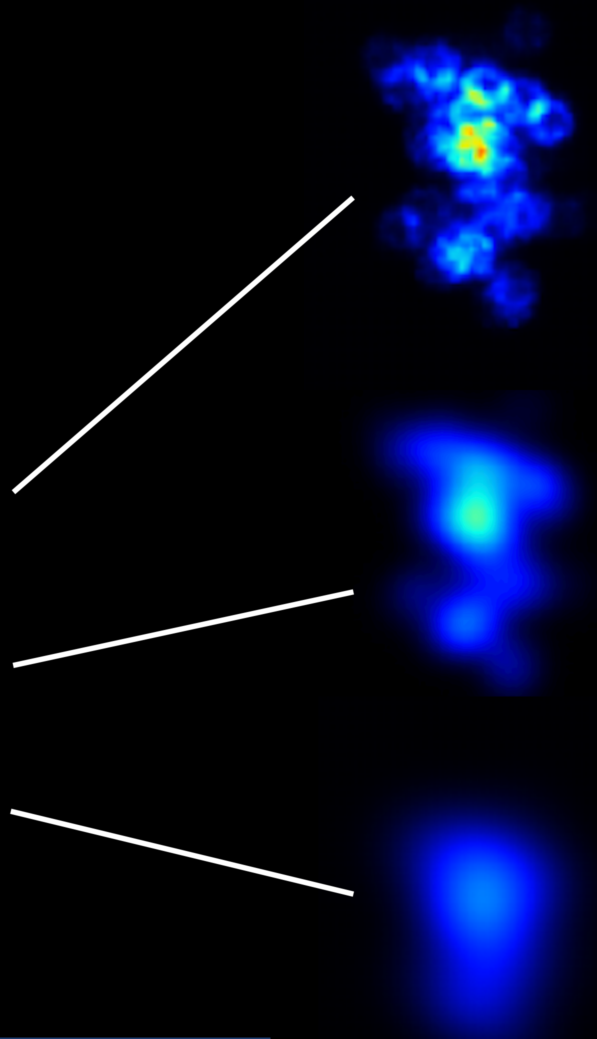
Substructure has little effect on v_n and $\langle p_T \rangle$

F. G. Gardim, F. Grassi, P. Ishida, M. Luzum, P. S. Magalhães, J. Noronha-Hostler, arXiv:1712.03912 [nucl-th]

Main effect of Gaussian smearing results from distributing energy over a larger area:

Average rms radii for 30-40% Pb+Pb:

	$\langle r^2 \rangle^{1/2}$ [fm]
IP-GLASMA	2.6
0.4fm SMEARED IP-GLASMA	2.69
1fm SMEARED IP-GLASMA	2.98
MC-GLAUBER σ=0.4fm	2.94



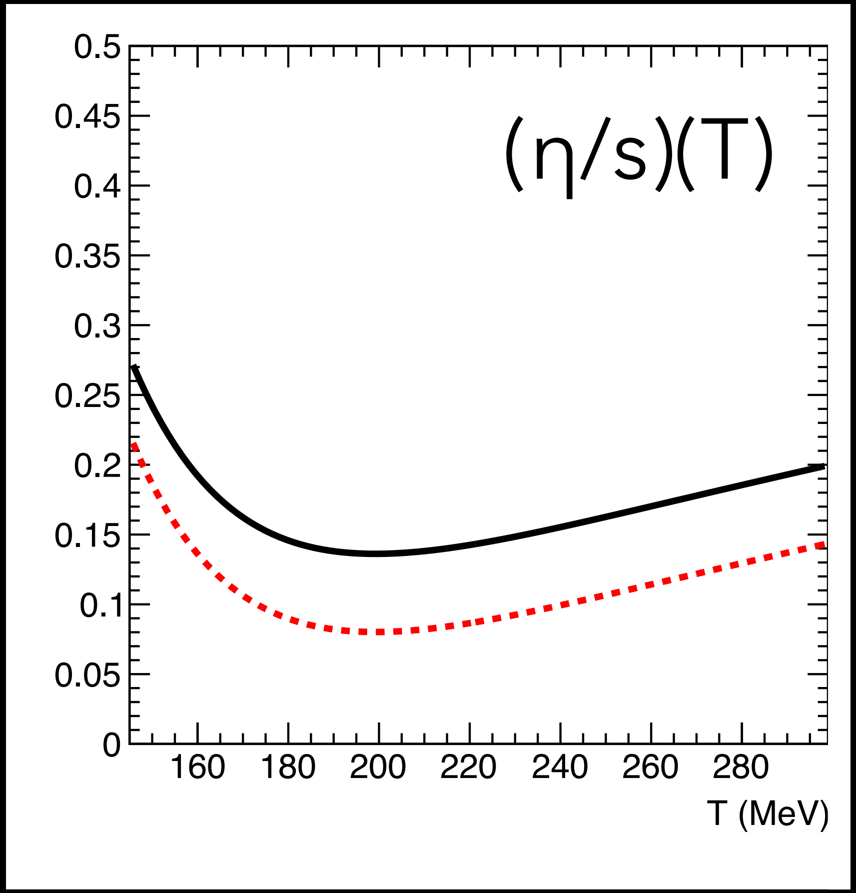
NOTE: JUST p=0 TRENTO DOES NOT MEAN IP-GLASMA

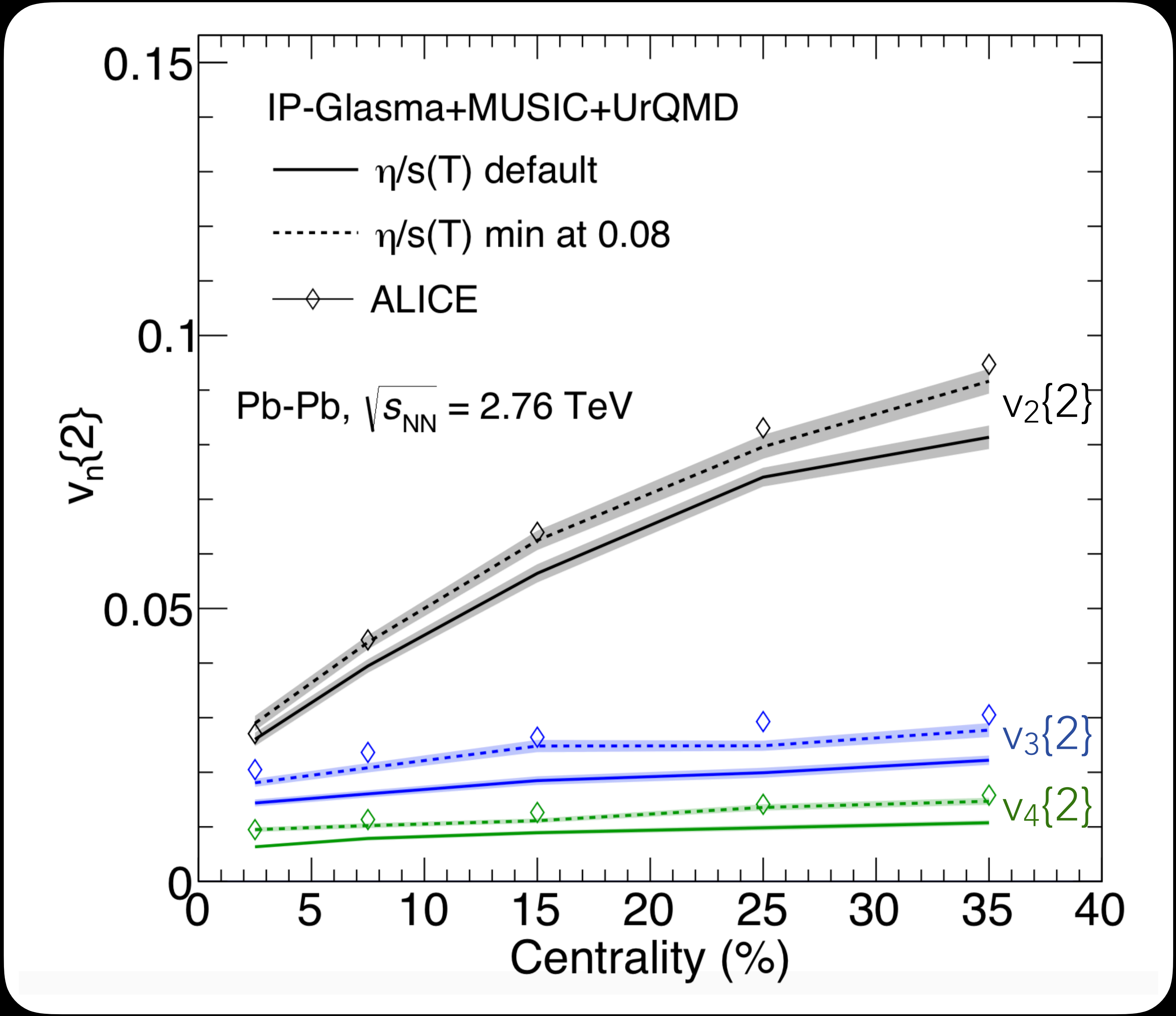
QCD based (η/s)(T)

SEE POSTER BY A. DUBLA

A. Dubla, S. Masciocchi, J. M. Pawlowski, B. Schenke, C. Shen, J. Stachel, arXiv:1805.02985

(η/s)(T) from a functional diagrammatical approach to QCD transport coefficients





M. Haas, L. Fister, and J. M. Pawlowski
Phys.Rev. D90, 091501 (2014)
N. Christiansen, M. Haas
J. M. Pawlowski, and N. Strodthoff
Phys. Rev. Lett. 115, 112002 (2015)