U.S. DEPARTMENT OF ENERGY | Office of Science
Brookhaven National Laboratory

THEORETICAL DESCRIPTION OF MOMENTUM ANISOTROPIES IN SMALL SYSTEMS

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

NOVEMBER 18 2021
IV ALICE INDIA SCHOOL ON QUARK GLUON PLASMA, SPECIAL LECTURE

How to describe the mess that is a heavy ion collision:

Complex many-body systems are not well described by simple extrapolation from properties of a few particles

4 August 1972, Volume 177, Number 4047 **SCIENCE**

Need effective theories to describe emergent phenomena:

Phase transitions, critical phenomena, hydrodynamic behavior, gluon saturation, plasma instabilities, …

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

Color Glass Condensate (CGC): High energy effective theory of QCD

Includes gluon saturation at small longitudinal momentum fraction *x* and transverse momentum $p_T \lesssim Q_s(x)$, with the saturation scale $Q_s \gg \Lambda_{\rm QCD}$

→Use to compute initial conditions for heavy ion collisions

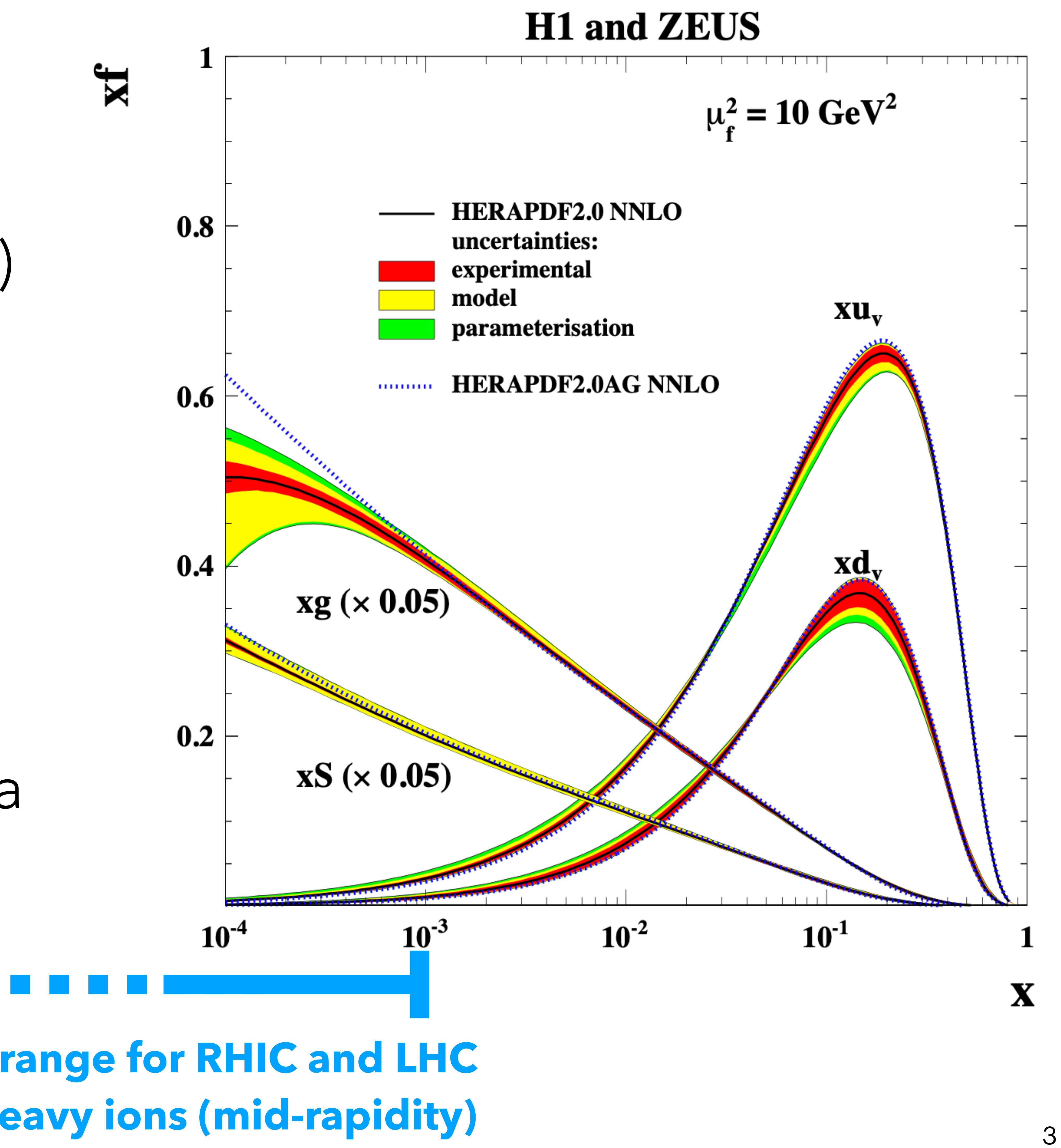
Relativistic Hydrodynamics

→Compute the final state evolution of heavy ion collisions

Initial state from an effective theory of QCD

- What is colliding? QCD tells us: mostly gluons
- High energy collisions probe small $x \sim p_T/\sqrt{s}$ (x is momentum fraction of the parton in nucleus)
- Gluon saturation for $p_T \lesssim Q_s(x)$ (Q_s is the saturation scale)
- Large occupation numbers → Classical description: Yang-Mills equations!
- Leading quantum corrections can be included via small-x evolution (BK, JIMWLK)

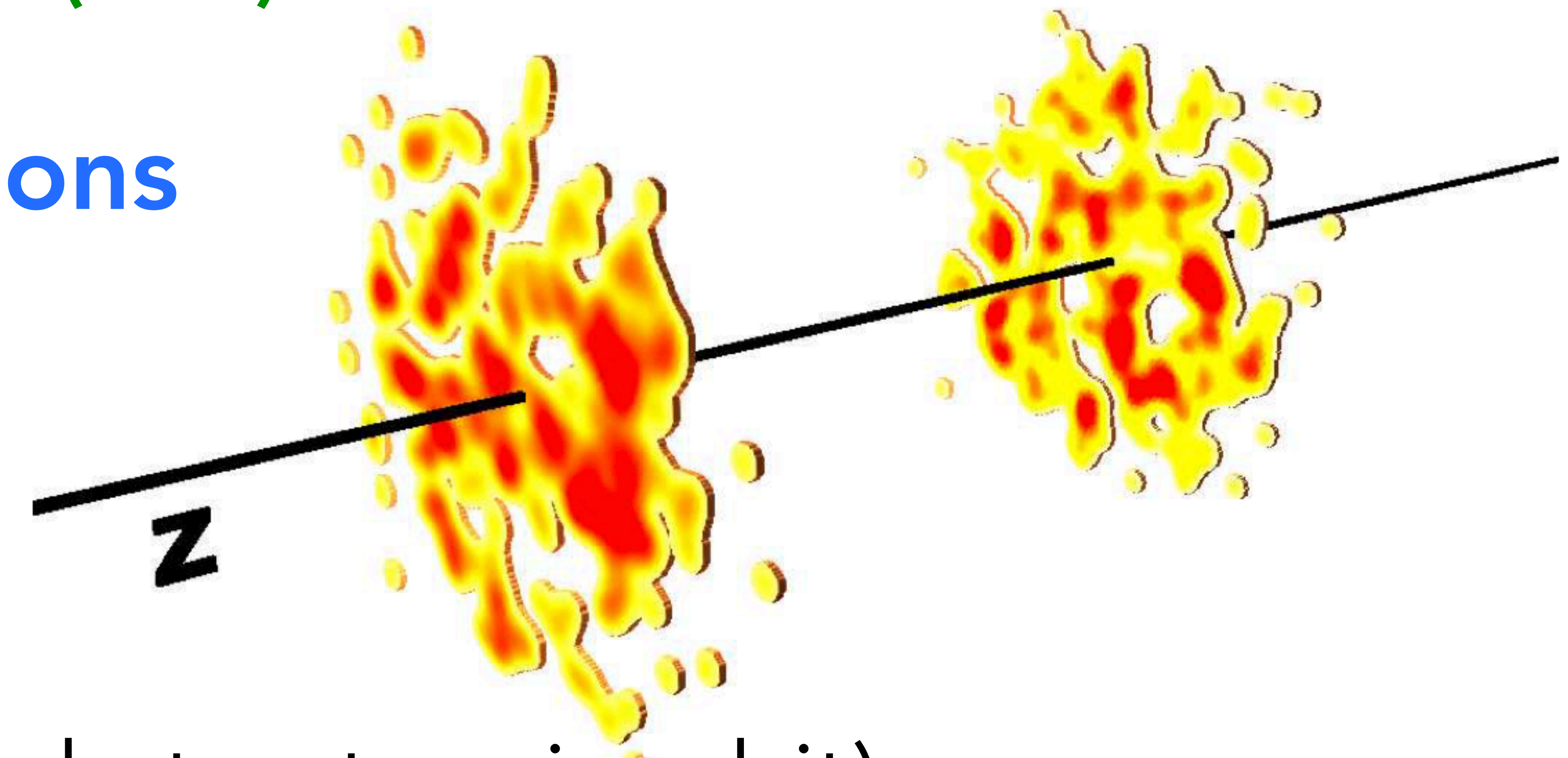
F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan
Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489



H1 and ZEUS, Eur.Phys.J. C75 (2015) no.12, 580

IP-Glasma: Colliding Color Glass Condensates

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



Particle production governed by **Yang Mills equations**

- Determine gluon fields inside fast moving nuclei:
  - Nucleon positions from nuclear wave function
  - Sample color charges in the nucleons (more on substructure in a bit)
    Their distribution is constrained from e+p scattering data from HERA (IPSat model)
    Kowalski, Teaney, Phys.Rev. D68 (2003) 114005
  - Then solve the Yang-Mills equations
    $[D_\mu, F^{\mu\nu}] = J^\nu$, where J^ν is constructed from color charges moving at speed of light
- Solve for the gluon fields after the collision
  Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
  Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

$$A^i = A^i_{(A)} + A^i_{(B)}\,,$$

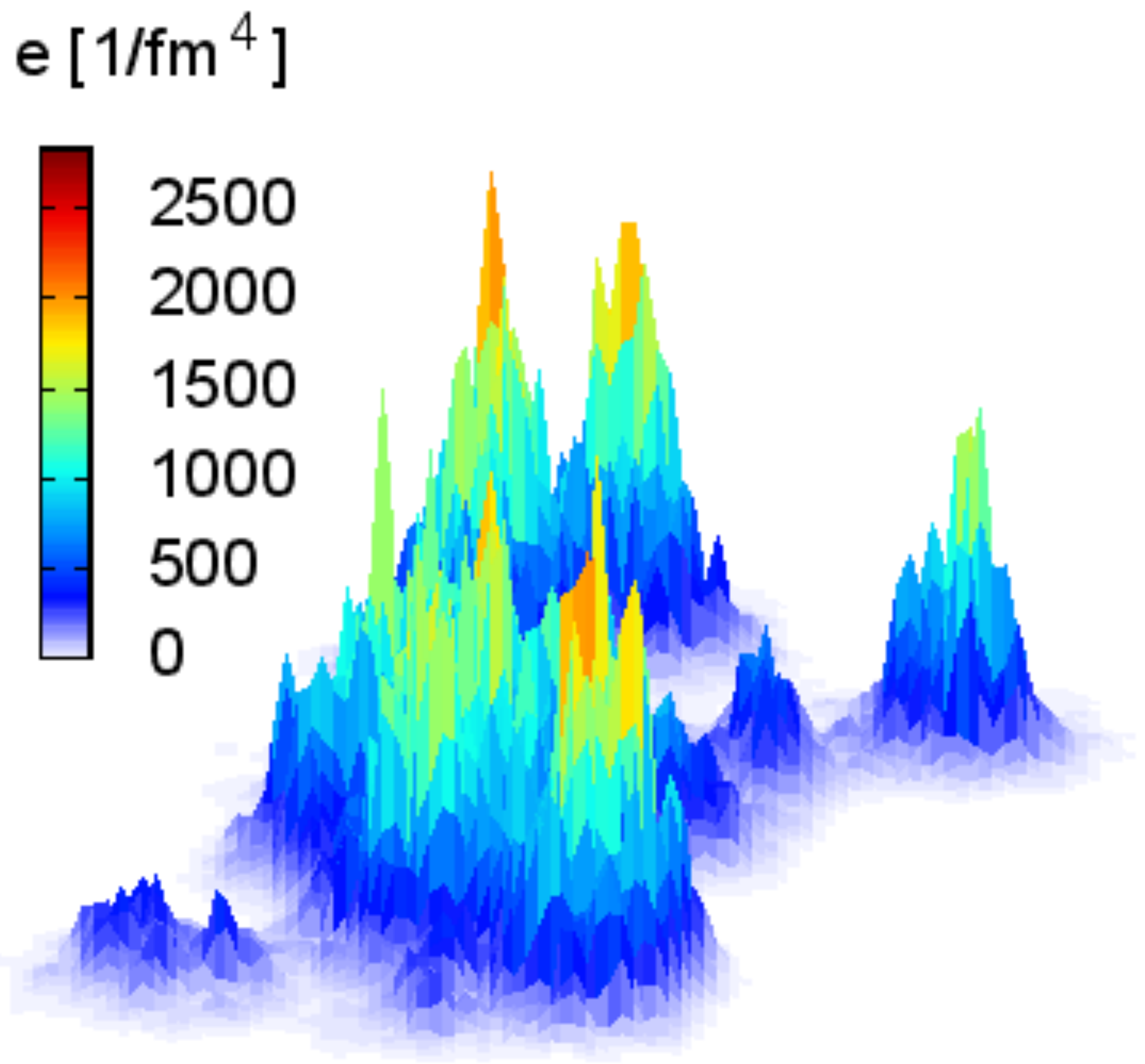
$$A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$

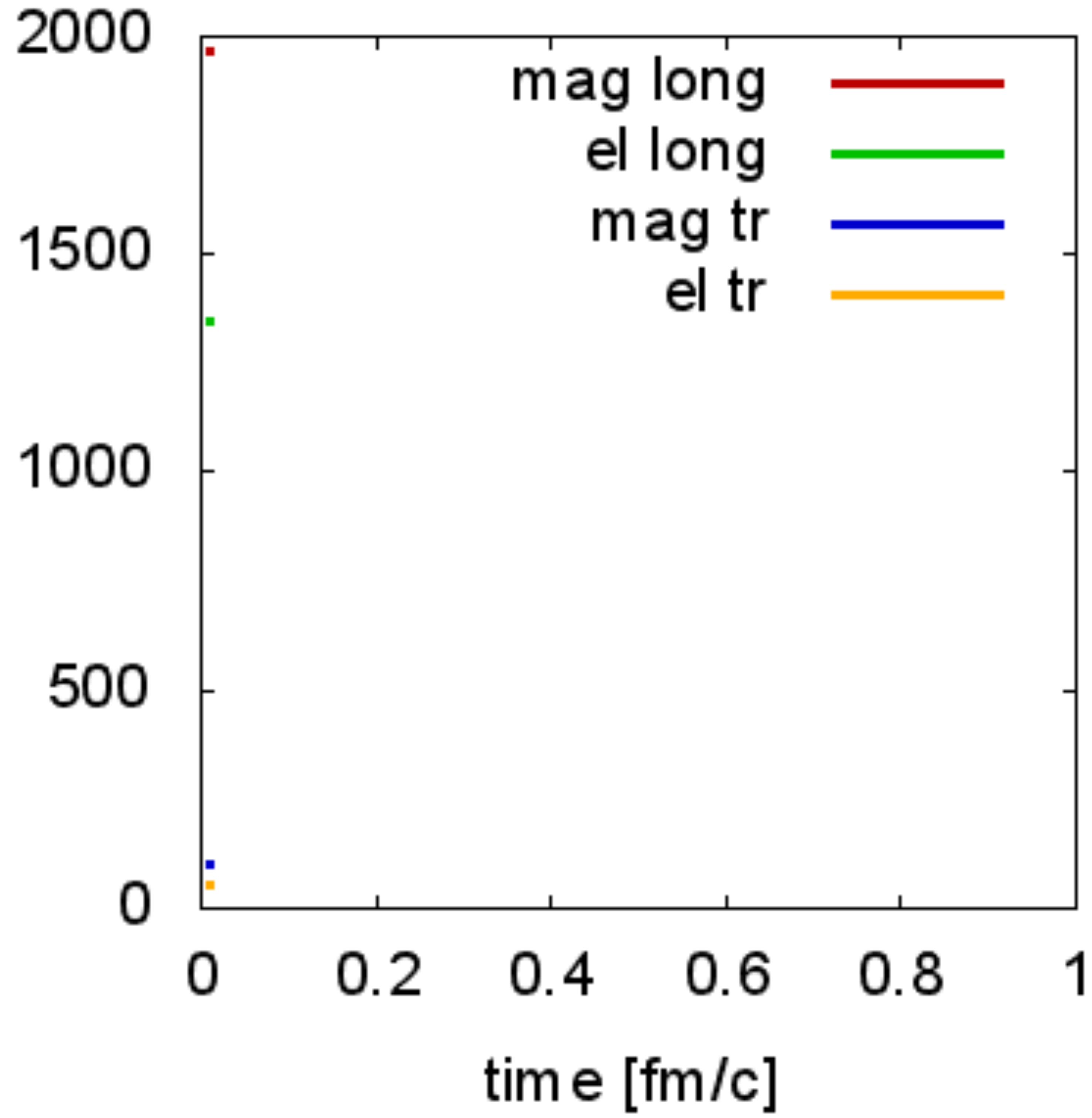
IP-Glasma: Colliding Color Glass Condensates

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

- Evolve produced fields in time using Yang Mills equations
- Compute energy-momentum tensor $T^{\mu\nu}(\vec{x})$ of the gluon fields

$$T^{\tau\tau} = \frac{1}{2}(E^\eta)^2 + \frac{1}{2\tau^2}[(E^x)^2 + (E^y)^2] + \frac{1}{2}F_{xy}F_{xy} + \frac{1}{2\tau^2}(F_{x\eta}^2 + F_{y\eta}^2)$$





Relativistic fluid dynamics

- Effective theory for the long wavelength modes, valid for a strongly interacting system

- Basic equations: **energy and momentum conservation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

energy density (ε), pressure (P), flow velocity (u^μ), viscous correction ($\Pi^{\mu\nu}$)

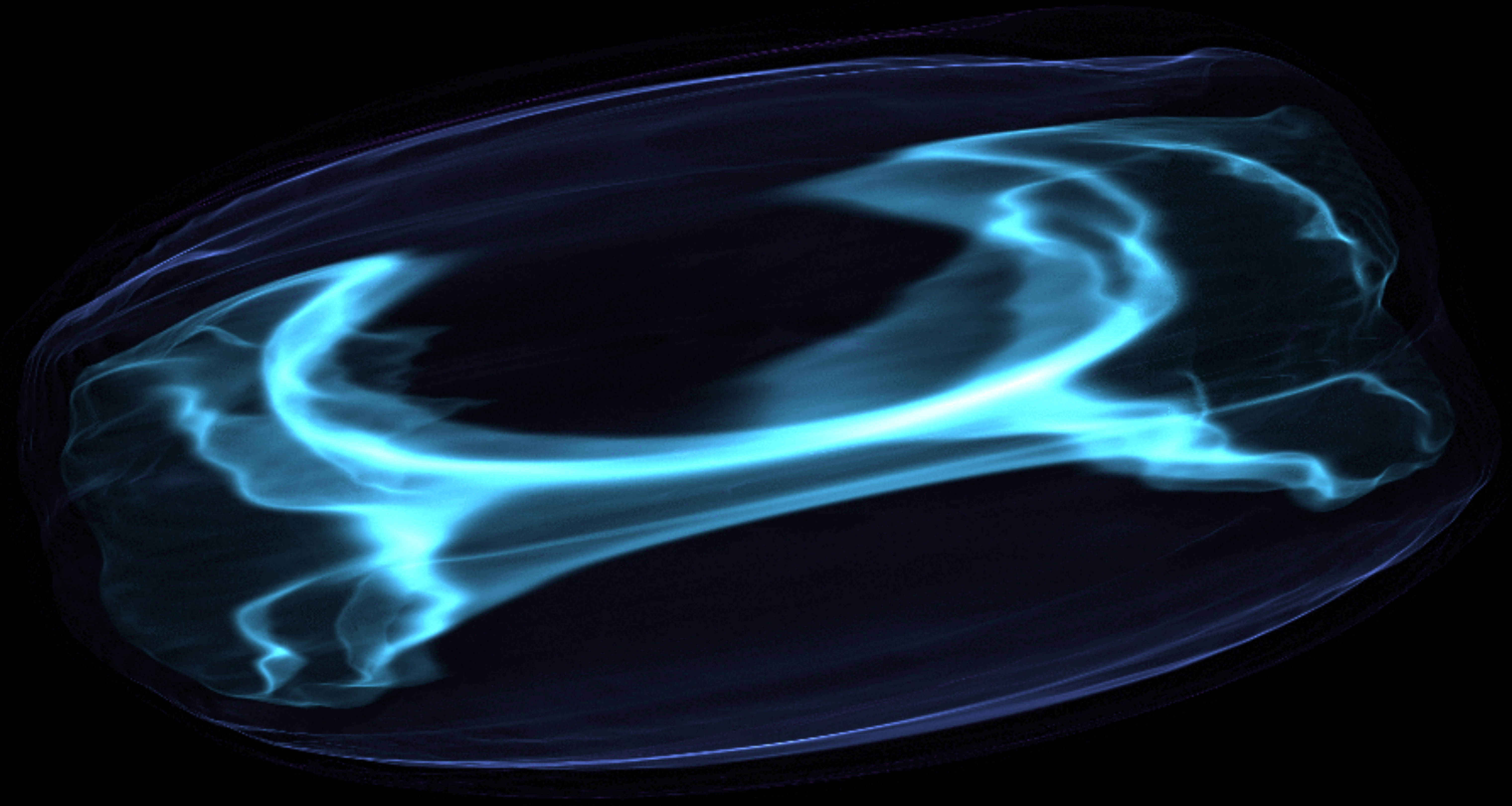
- + constituent equations for $\Pi^{\mu\nu}$ (contains shear viscosity η and bulk viscosity ζ, possibly heat conductivity and higher order transport coefficients)

- Equation of state *P*(ε) relates pressure to energy density (from lattice QCD)

Relativistic hydrodynamic evolution

MUSIC hydrodynamic simulation: Au+Au collision at top RHIC energy

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

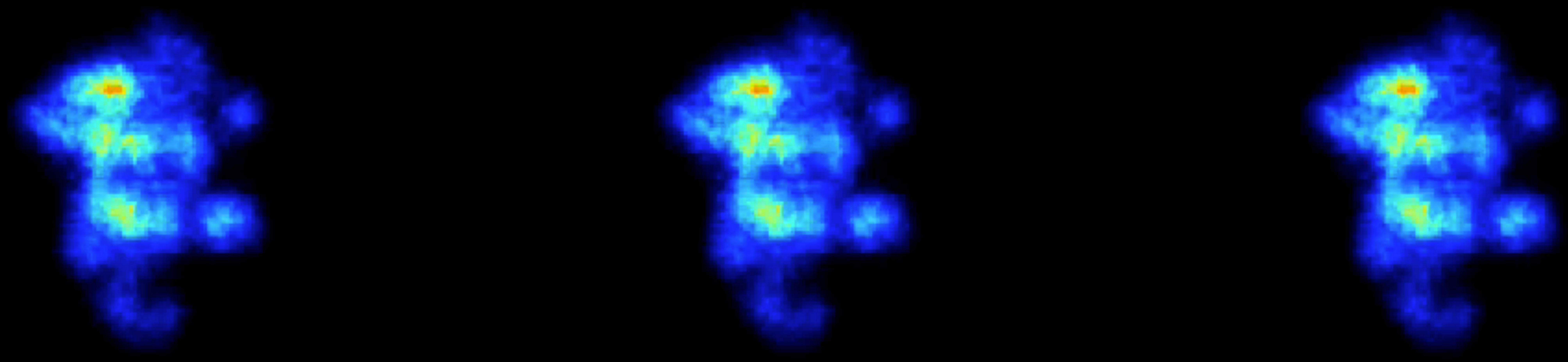


Duration ~10 fm/c ≈ 3 ×10^{-23} s, contours of constant temperature shown

Björn Schenke, BNL

Effect of shear viscosity

$\eta/s = 0$ $\eta/s = 0.1$ $\eta/s = 0.2$

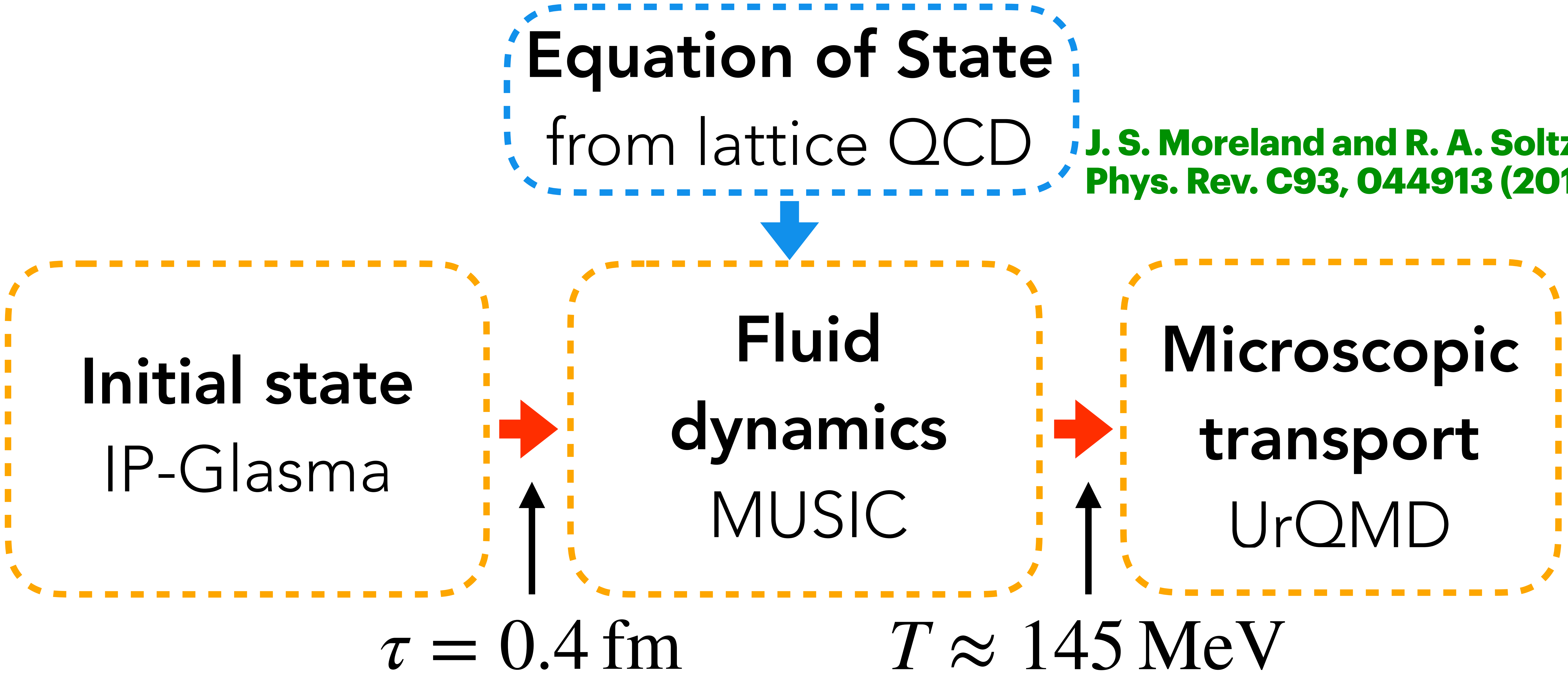


MUSIC hydrodynamic simulation

t = 0.40 fm

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

THE HYBRID FRAMEWORK



J. S. Moreland and R. A. Soltz Phys. Rev. C93, 044913 (2016)

Described in detail in

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

"Running the gamut of high energy nuclear collisions"

The term gamut was adopted from the field of **music**, where in middle age Latin "gamut" meant the entire range of musical notes of which musical melodies are composed

- **Exactly match $T^{\mu\nu}$ when switching from one part to the next**

B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)
B. Schenke, S. Jeon, and C. Gale, Phys. Rev. Lett. 106, 042301 (2011)
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998); M. Bleicher et al., J. Phys. G25, 1859 (1999)

INITIAL STATE GEOMETRY

Nucleus:

Sample nucleons from Woods Saxon distribution

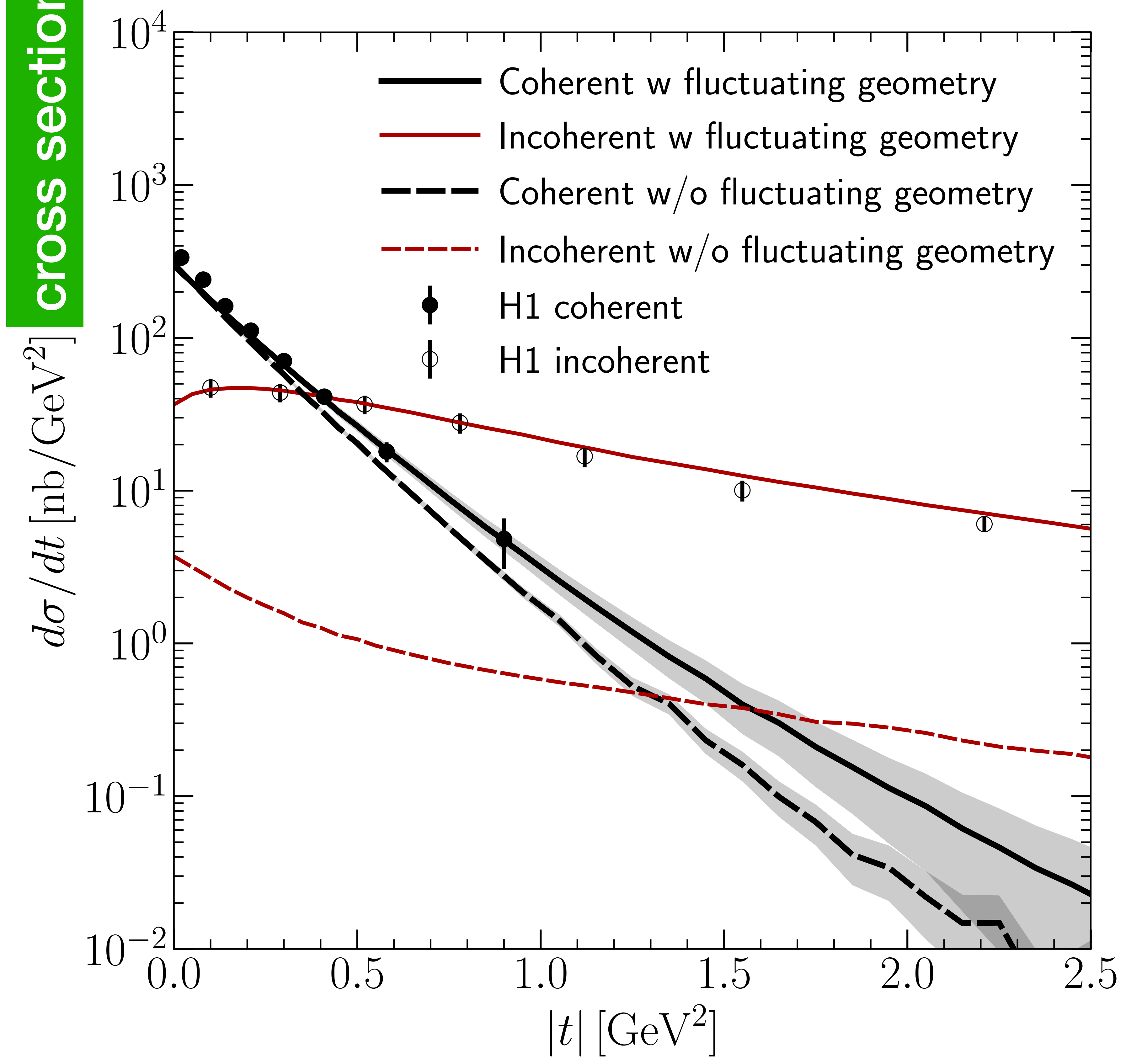
Nucleon:

- **consider substructure**
- **constrain parameters with HERA data**

Exclusive diffractive J/Ψ production in e+p:
Incoherent x-sec sensitive to fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042
also see:
S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319
H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

cross section



(transverse momentum transfer)^2

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

INITIAL STATE GEOMETRY

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Sample nucleons from Woods Saxon distribution

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- **consider substructure**
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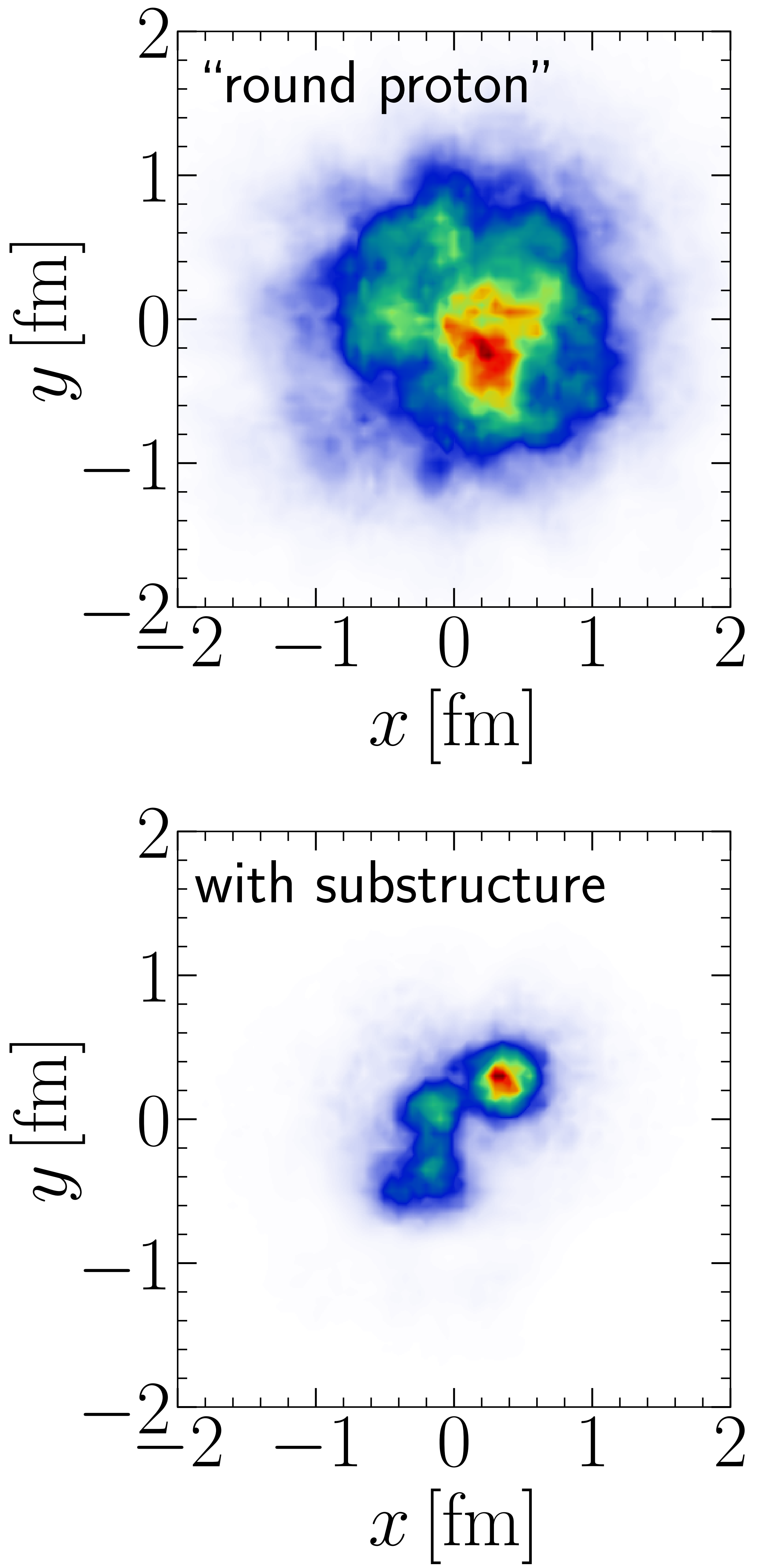

Exclusive diffractive J/Ψ production in e+p:
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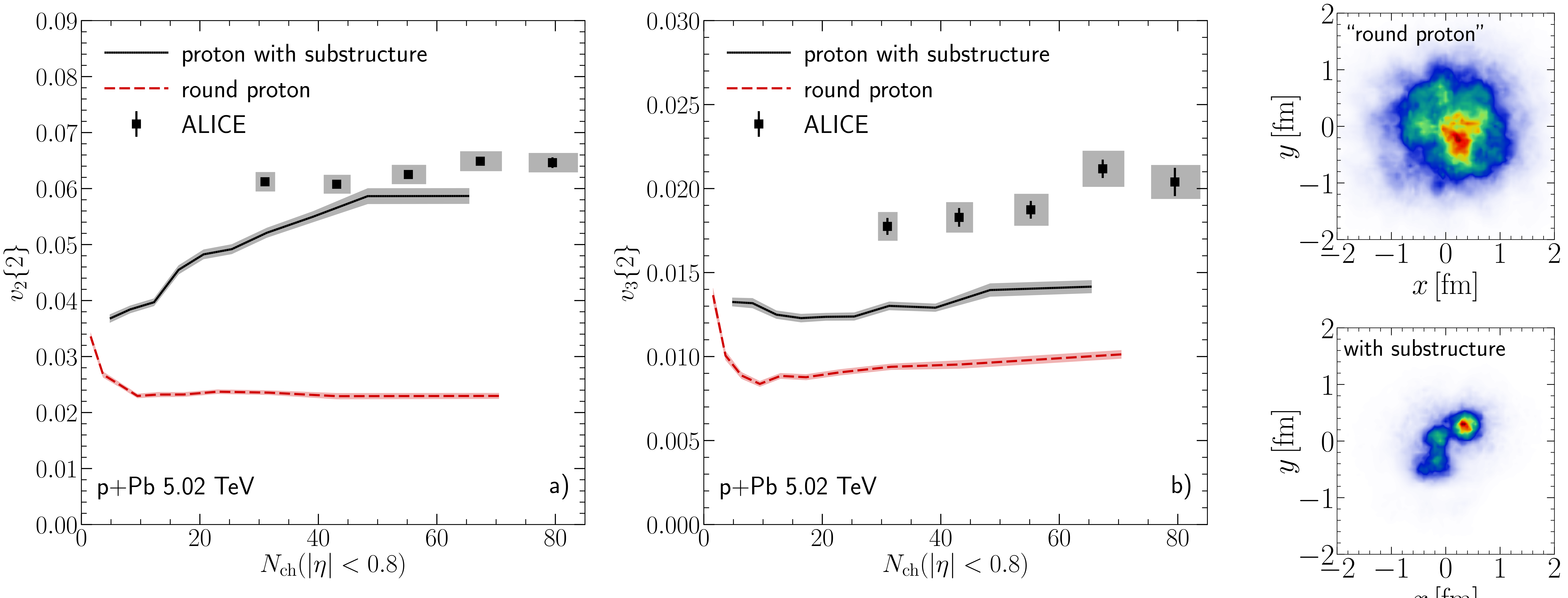
H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

NUCLEON SUBSTRUCTURE

Substructure is also needed to describe the anisotropic flow in p+A collisions with IP-Glasma



B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

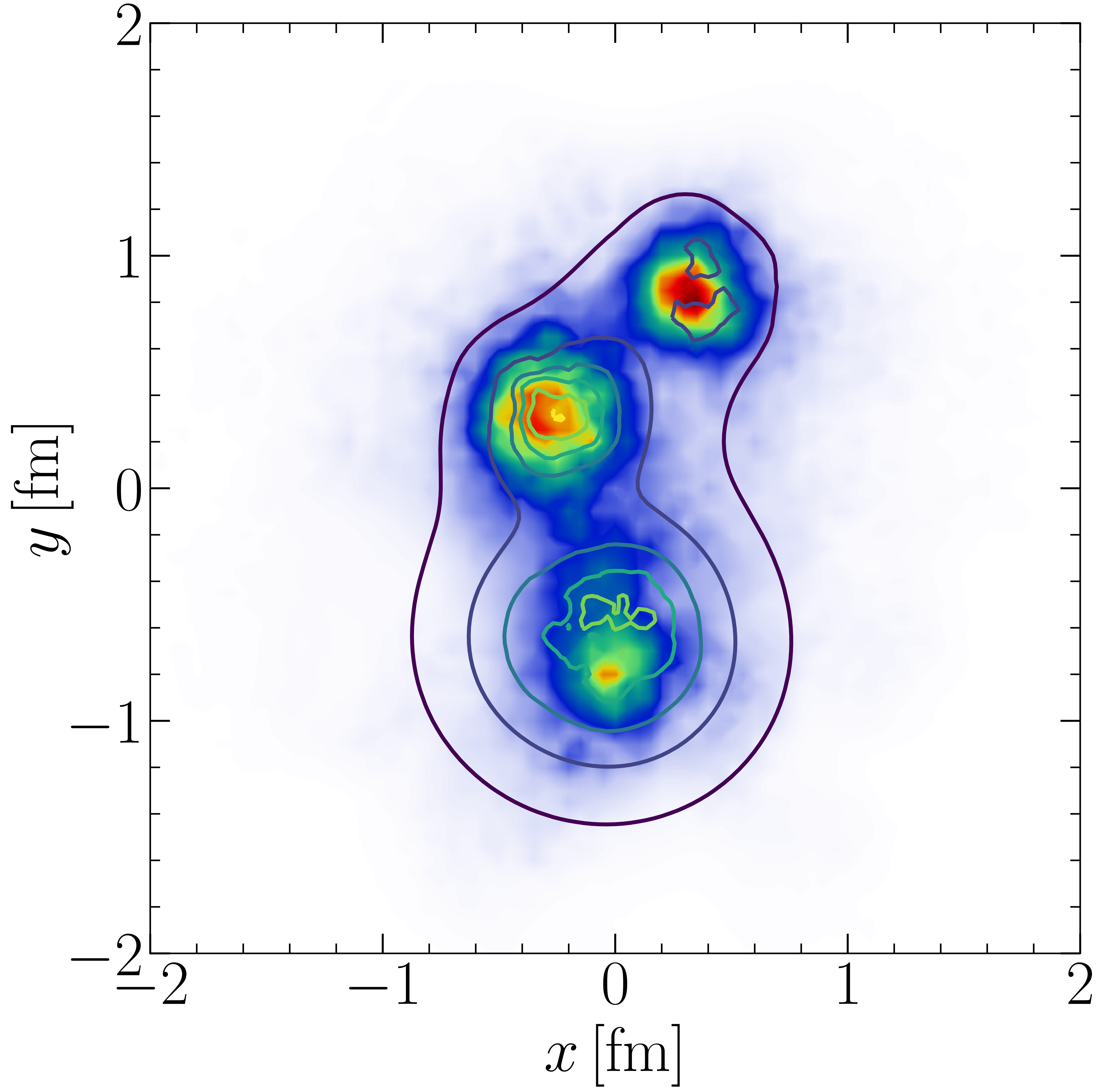
FIREBALL SHAPE ~ PROTON SHAPE

The shape of the overlap region in p+A collisions resembles the proton's shape

Color map: Energy density distribution (arbitrary units)

Contour lines: Shape of the projectile proton (quantified using a measure of the gluon density in the proton)

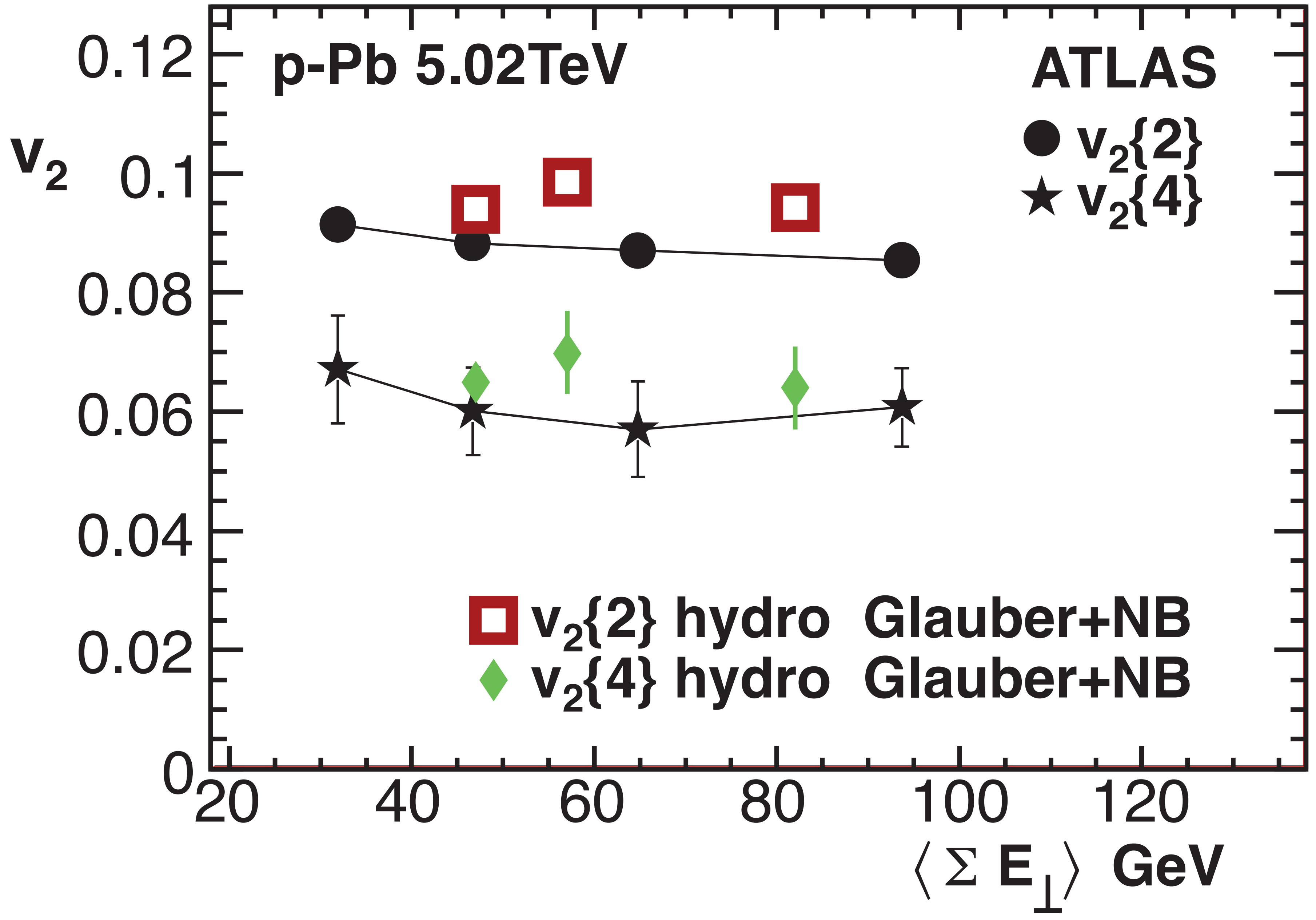
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)



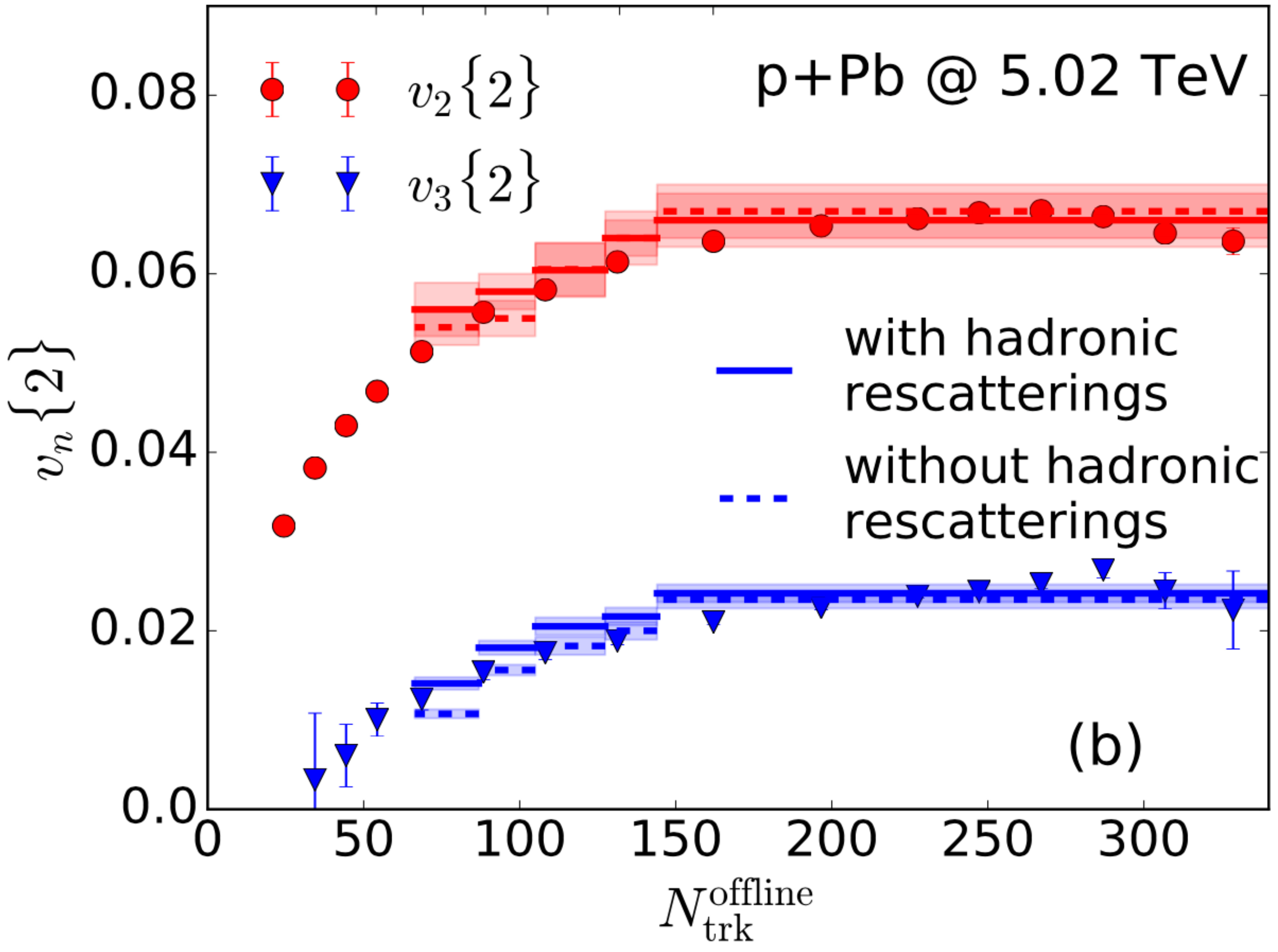
NUCLEON SUBSTRUCTURE

What about MC-Glauber (-like) models? They seem to get it right with just nucleons

ATLAS Coll. PLB725 (2013) 60-78



CMS Coll. PLB724, 213-240 (2013)



Bozek, Broniowski, PRC88 (2013) 014903

Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

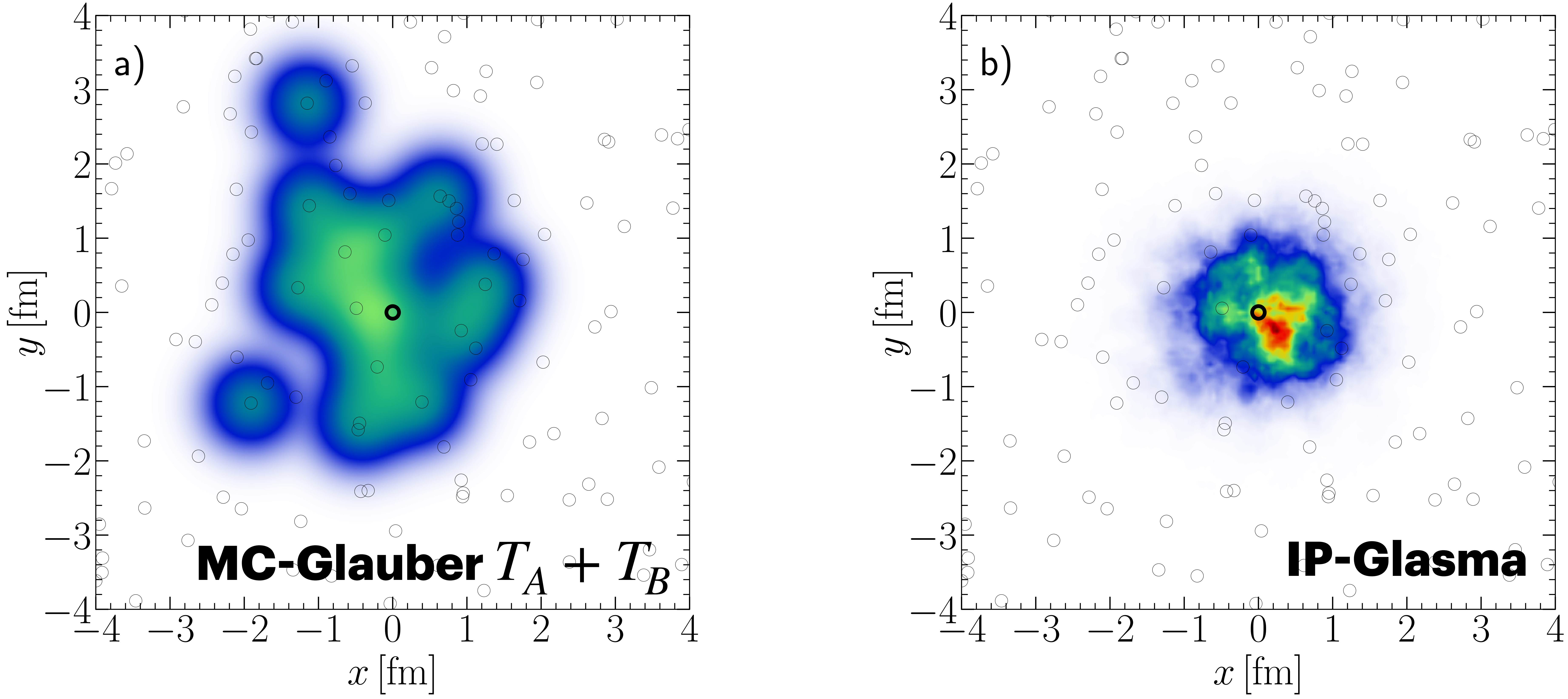
Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; …

MC-GLAUBER vs. IP-GLASMA

Proton position: thick circle; Nucleon positions in Pb: thin circles

Same configurations: Compare MC-Glauber $T_A + T_B$ to IP-Glasma with round nucleon

B. Schenke, Rep. Prog. Phys. 84 082301 (2021)



HOW SHOULD THE ENERGY DEPOSITION GO?

Energy (or entropy) deposition $\sim (T_A T_B)^q$ is preferred:

- **Bayesian analysis: Trento model prefers initial transverse entropy density to behave as $\sim \sqrt{T_A T_B}$ and also prefers a nucleon substructure**
  J.S. Moreland, J.E. Bernhard, and S.A. Bass, Phys. Rev. C 92 (2015) 011901
  G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021), Phys.Rev.C 103 (2021) 5, 054909
  JETSCAPE Collaboration, Phys.Rev.C 103 (2021) 5, 054904
- **AdS/CFT based calculations also result in such a relation**
  P. Romatschke, J.D. Hogg, JHEP 04 (2013) 048
- **IP-Glasma results in the initial energy density $\sim T_A T_B$**
- $T_A + T_B$ **disfavored by centrality dependence of v_2 in A+A** G. Giacalone, J. Noronha-Hostler, J.-Y. Ollitrault, Phys. Rev. C 95, 054910 (2017)

So, $T_A + T_B$ prescription with nucleons, that works for v_n in p+A, is generally disfavored

$\sim T_A T_B$ for round proton leads to too small fluctuations (eccentricities)

$\rightarrow$ subnucleon fluctuations required

DO WE AGREE ON THE NUCLEON SIZE?

We constrained the nucleon and hot spot size from e+p collisions at HERA.

We assumed a 2D Gaussian:

$$\frac{1}{2\pi w^2} e^{-\frac{x^2+y^2}{2w^2}}$$

We found a width $w = 0.4\,\mathrm{fm}$ (we also use subnucleon hot spots with width $w_q = 0.11\,\mathrm{fm}$)

Similar values for w used in the past to describe heavy ion collisions

see e.g. B. Schenke, S. Jeon, C. Gale, Phys.Rev.C 85 (2012) 024901

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C 94, no.2, 024907 (2016)

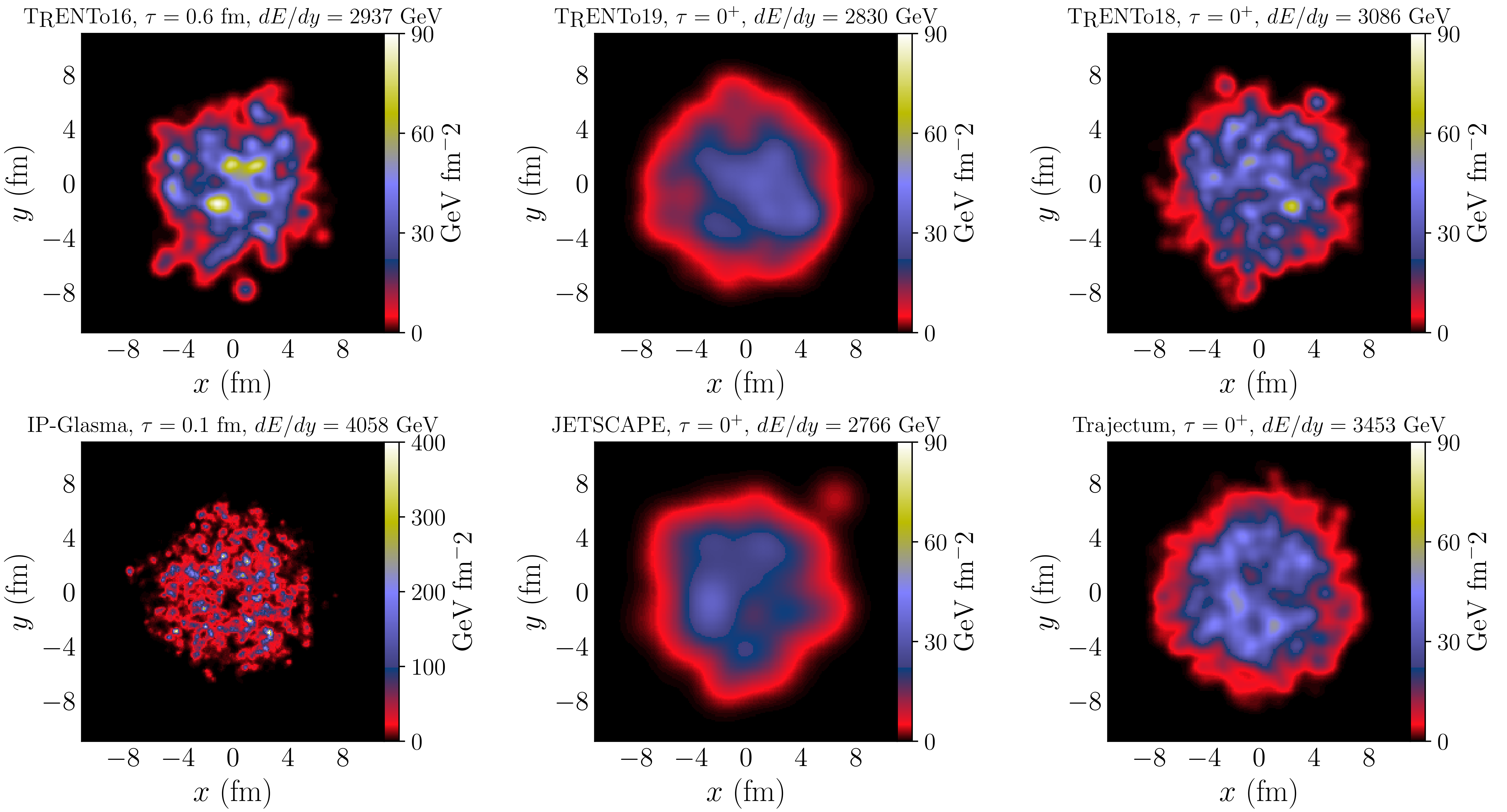
But some newer Bayesian analyses of heavy ion data find much larger values

J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, no.11, 1113-1117 (2019) $w = 0.96\,\mathrm{fm}$

D. Everett et al. [JETSCAPE], Phys. Rev. Lett. 126, no.24, 242301 (2021) $w = 0.9 - 1.1\,\mathrm{fm}$

G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021) 20, 202301 $w \approx 0.94\,\mathrm{fm}$

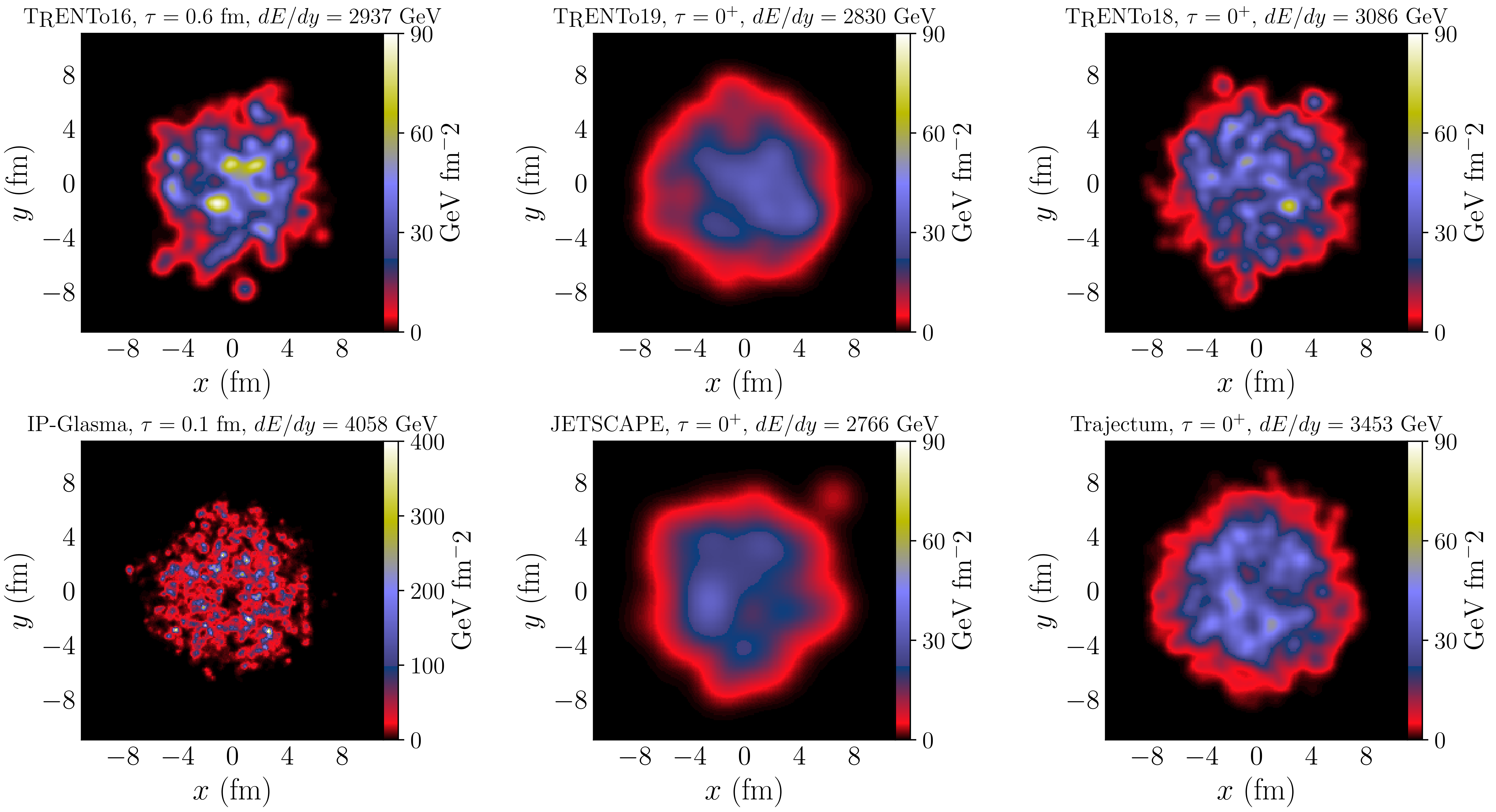
DO WE AGREE ON THE NUCLEON SIZE? NO



Trento16
[Bass, Bernhard, Moreland 1605.03954]
Trento18
[Bass, Bernhard, Moreland 1808.02106]
Trento19
[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]
IP-Glasma
[Schenke, Shen, Tribedy 2005.14682]
JETSCAPE
[JETSCAPE Collaboration 2011.01430, 2010.03928]
Trajectum
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

Figure by G. Giacalone

DO WE AGREE ON THE NUCLEON SIZE? NO



The fits trade a large w for smaller viscosities (especially bulk)

Can we pin down w and viscosities individually?

Figure by G. Giacalone

CORRELATION OF $[p_T]$ WITH v_2

P. Bozek, Phys. Rev. C 93, 044908 (2016); B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

The correlation of $[p_T]$ and v_n fluctuations can help!

Define $\hat{\rho}(v_n^2, [p_T]) = \dfrac{\langle \hat{\delta} v_n^2 \, \hat{\delta}[p_T] \rangle}{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}$

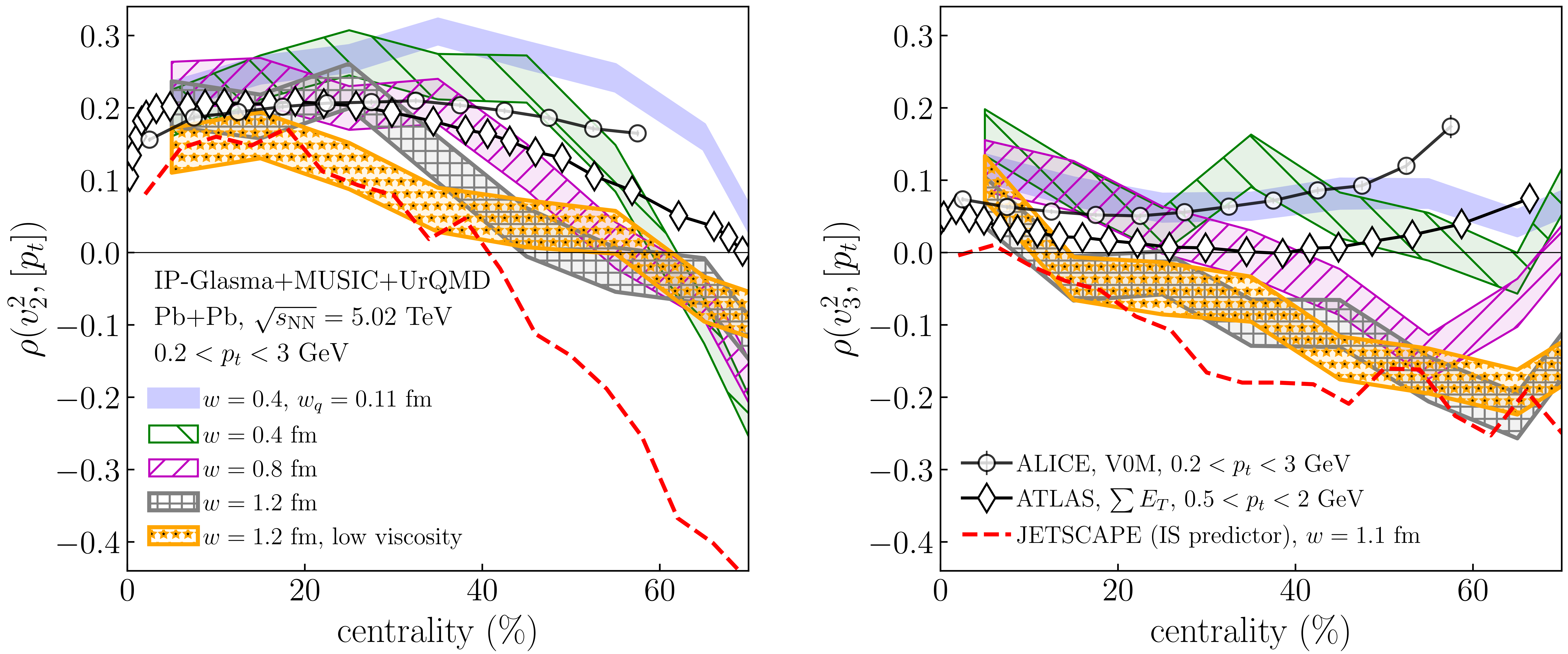
$$\delta O \equiv O - \langle O \rangle$$

$\hat{\delta} O \equiv \delta O - \dfrac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$ **is the variation of O at fixed multiplicity**

A. Olszewski, W. Broniowski, Phys. Rev. C96, 054903 (2017)

DEPENDENCE OF ρ CORRELATOR ON w

G. Giacalone, B. Schenke, C. Shen, arXiv:2111.02908; ALICE Collaboration, arXiv:2111.06106
ATLAS-CONF-2021- 001. https://cds.cern.ch/record/2748818?ln=en



TRANSPORT COEFFICIENTS

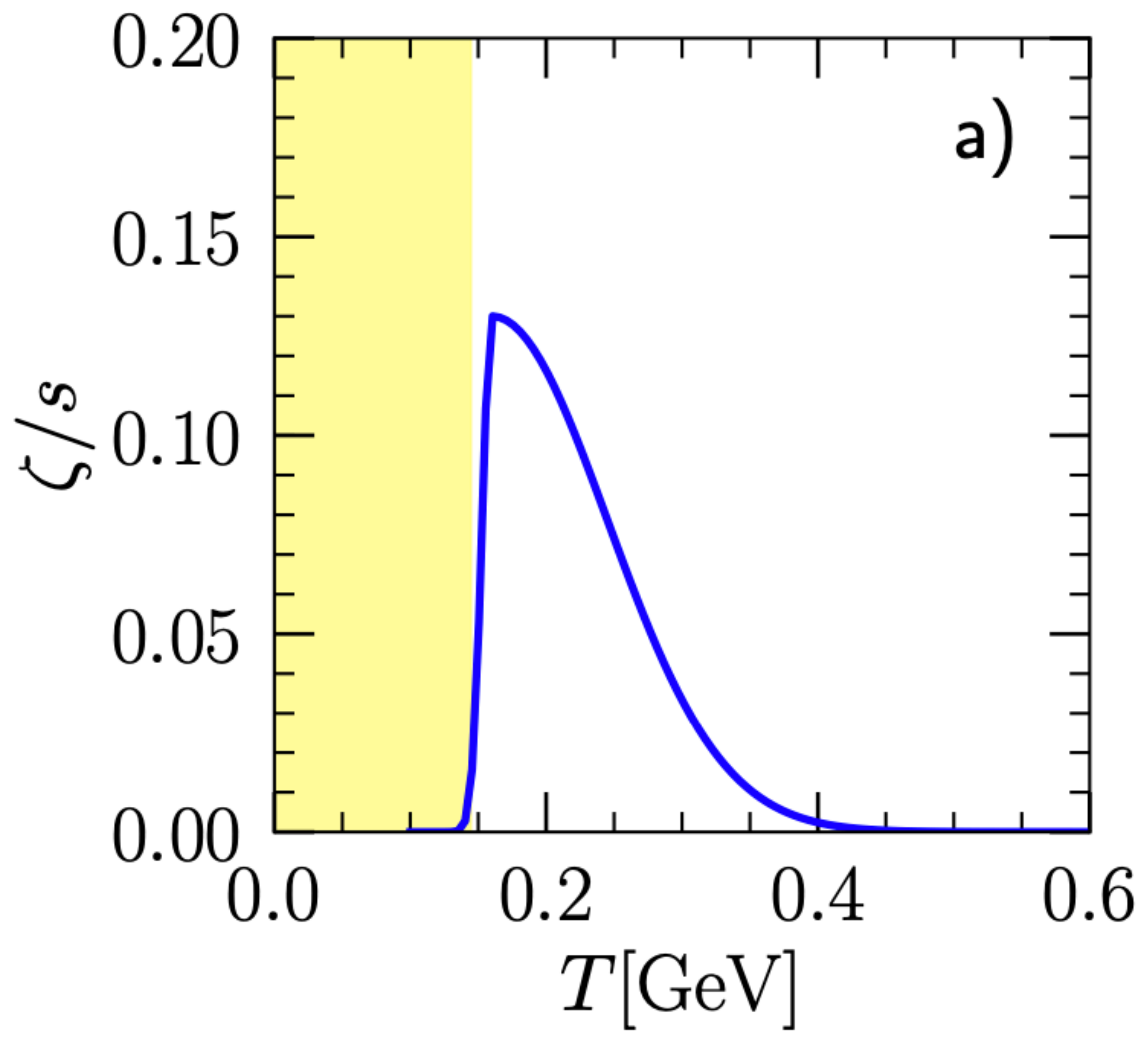
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

Transport coefficients:

Shear viscosity:

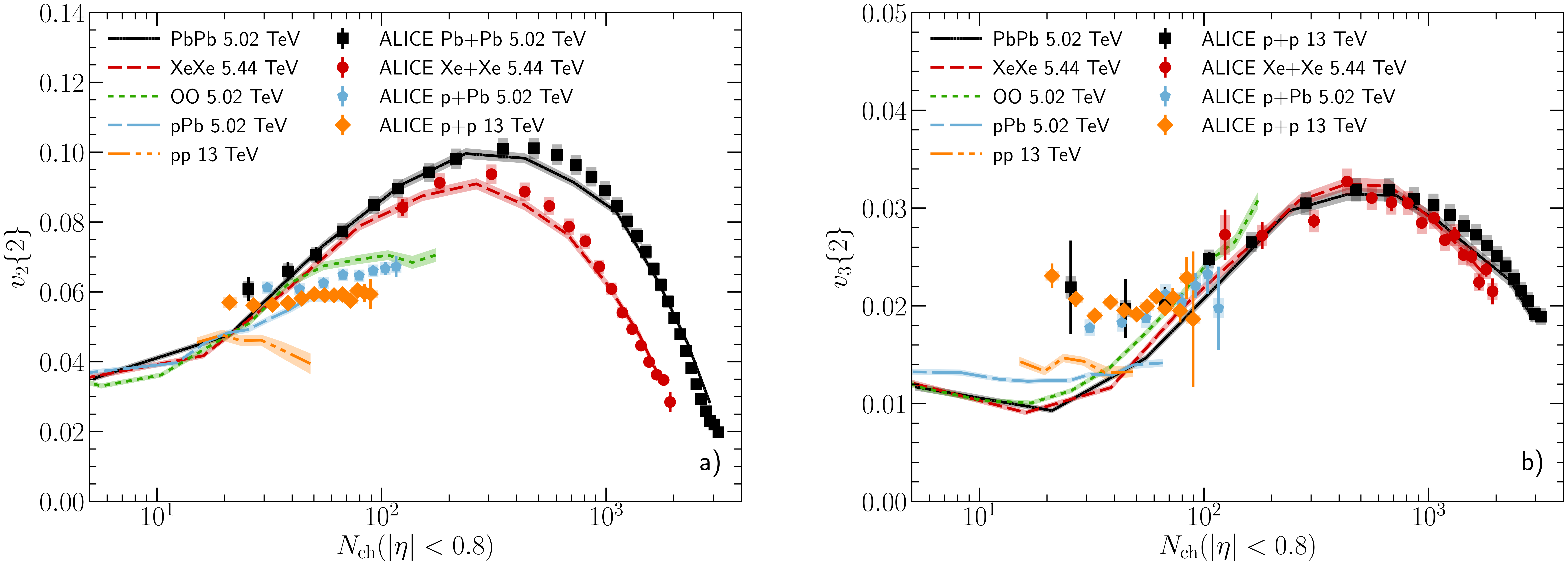
$$\eta/s = 0.12$$

Bulk viscosity:



SOME HYBRID MODEL RESULTS

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

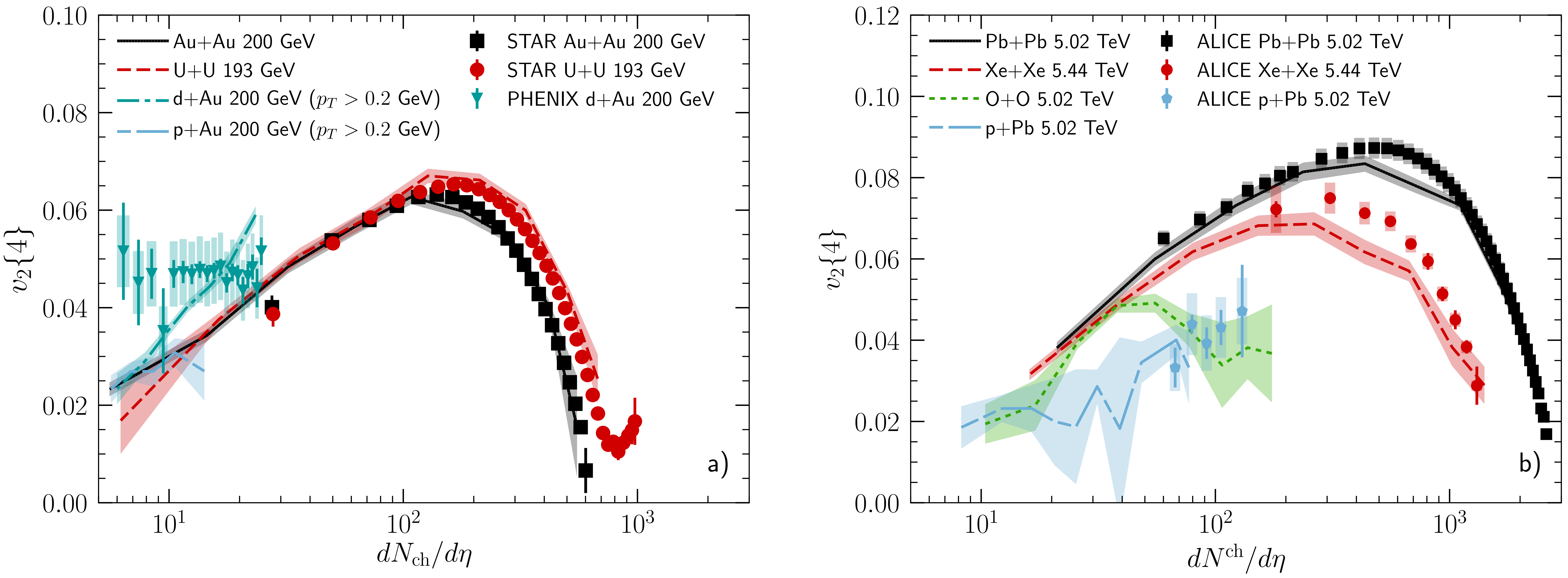


Parameters constrained only by HERA data (proton shape) and Au+Au data at RHIC

Underestimate v_n in p+p and v_3 in p+Pb

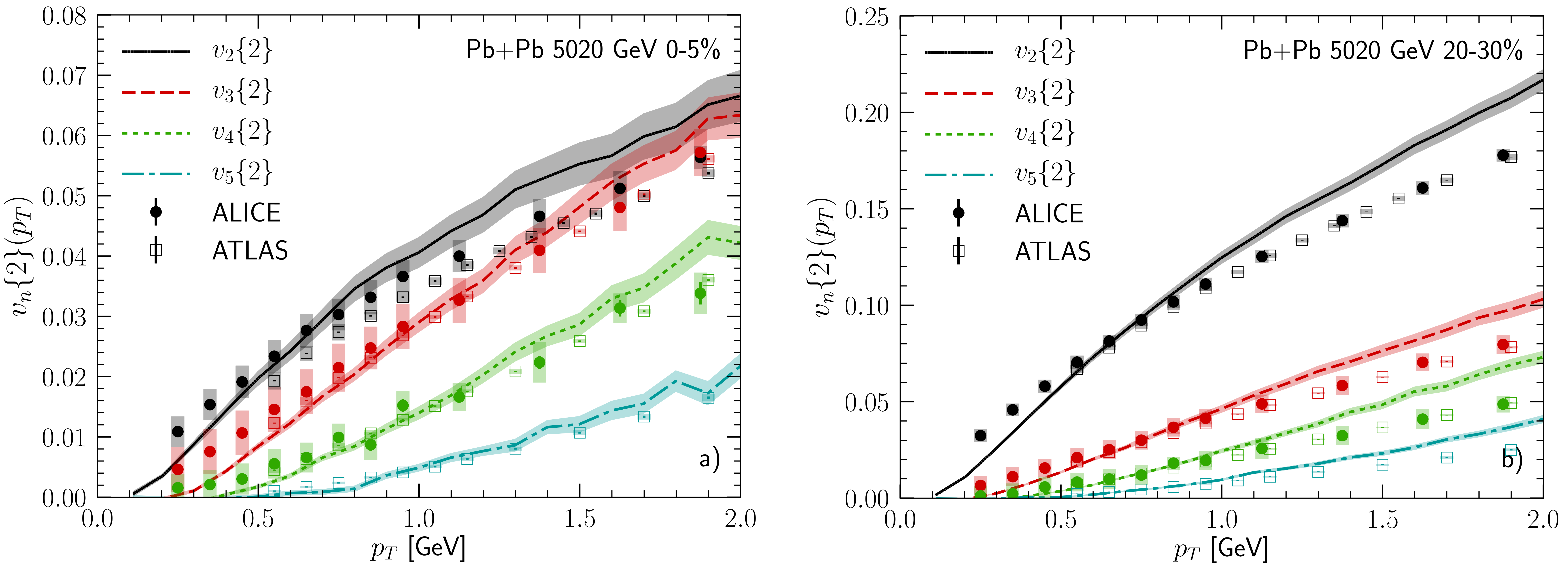
4-PARTICLE CUMULANTS

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



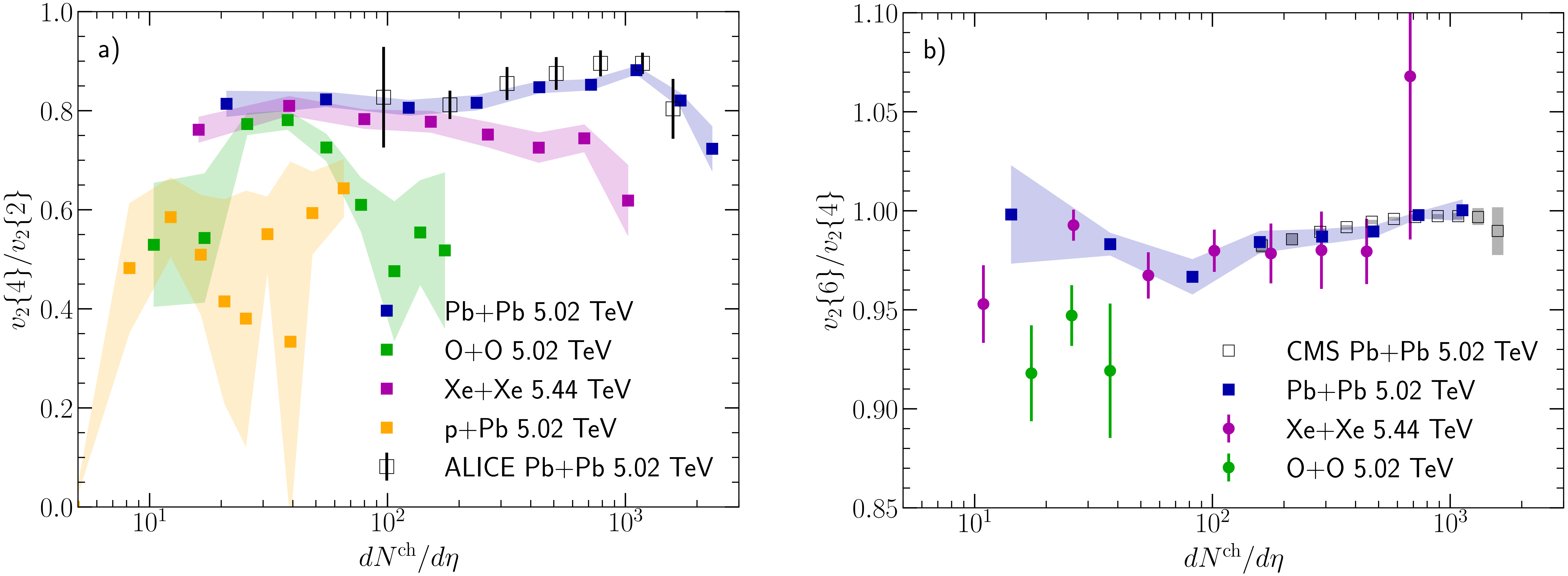
TRANSVERSE MOMENTUM DEPENDENCE

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



CUMULANT RATIOS

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

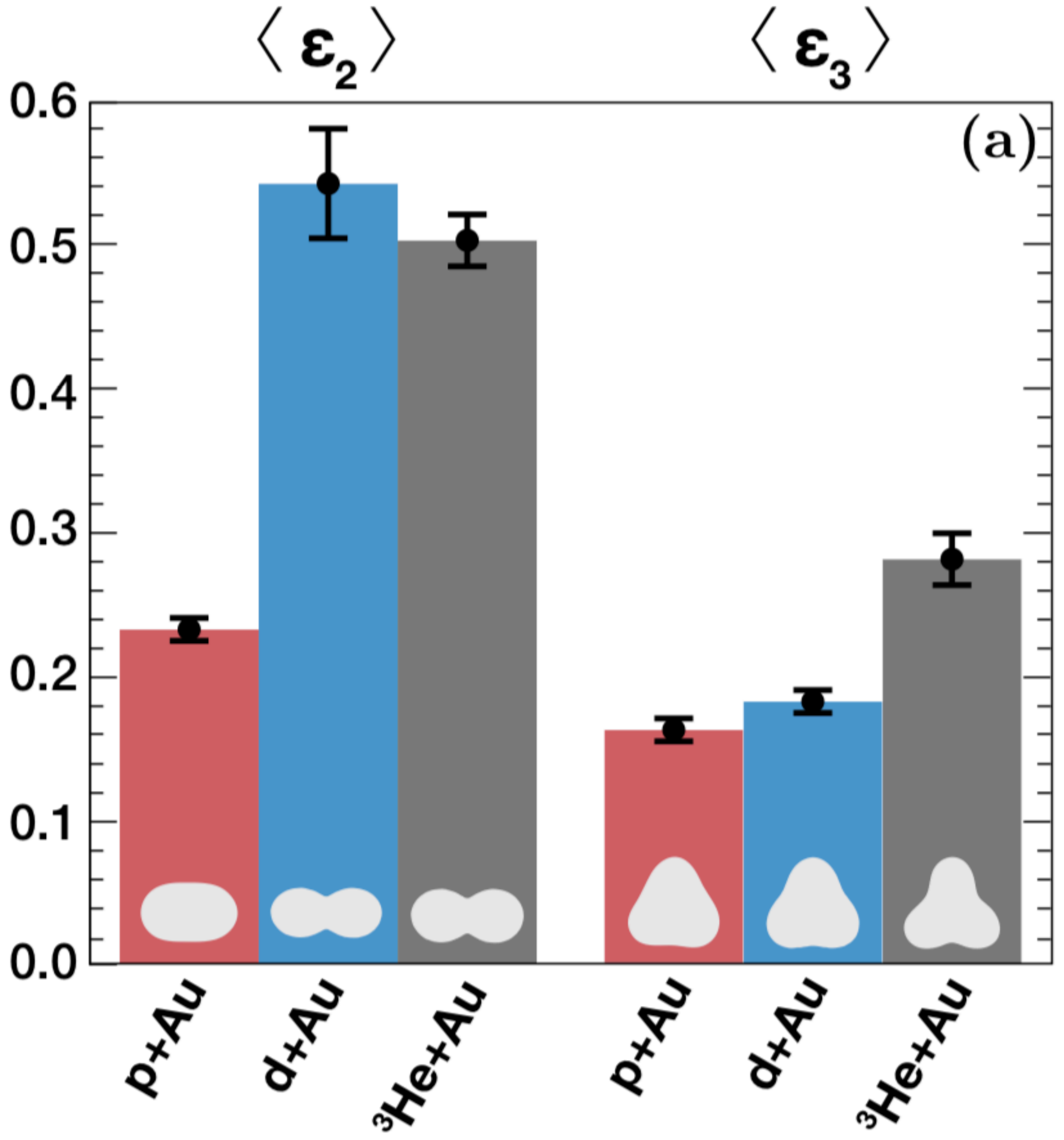


RHIC SYSTEM SCAN

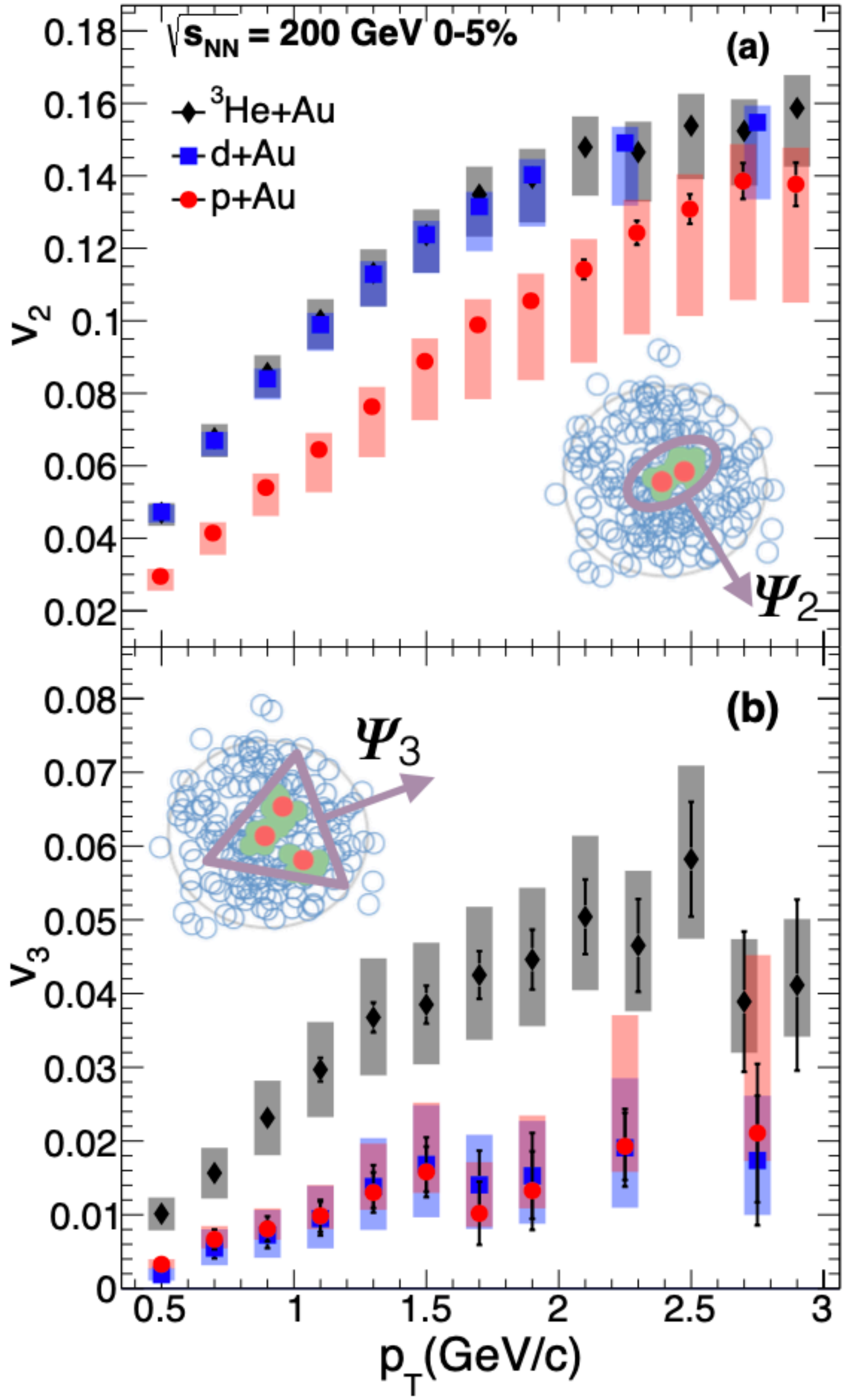
PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220

Idea: Engineer the geometry using different projectiles: p, d, ^{3}He

Simple model expectation: (using nucleon degrees of freedom)



Results confirmed expectation:

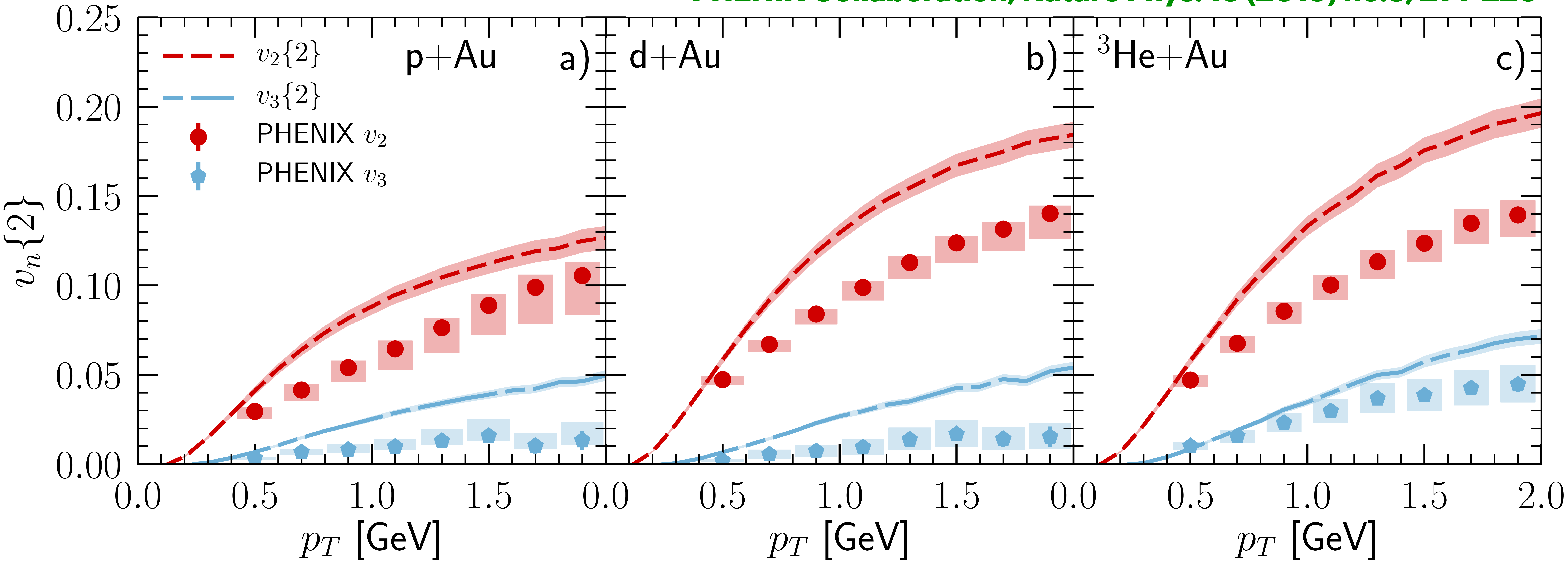


RHIC SYSTEM SCAN

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

Model results. No fine tuning after fitting Au+Au data

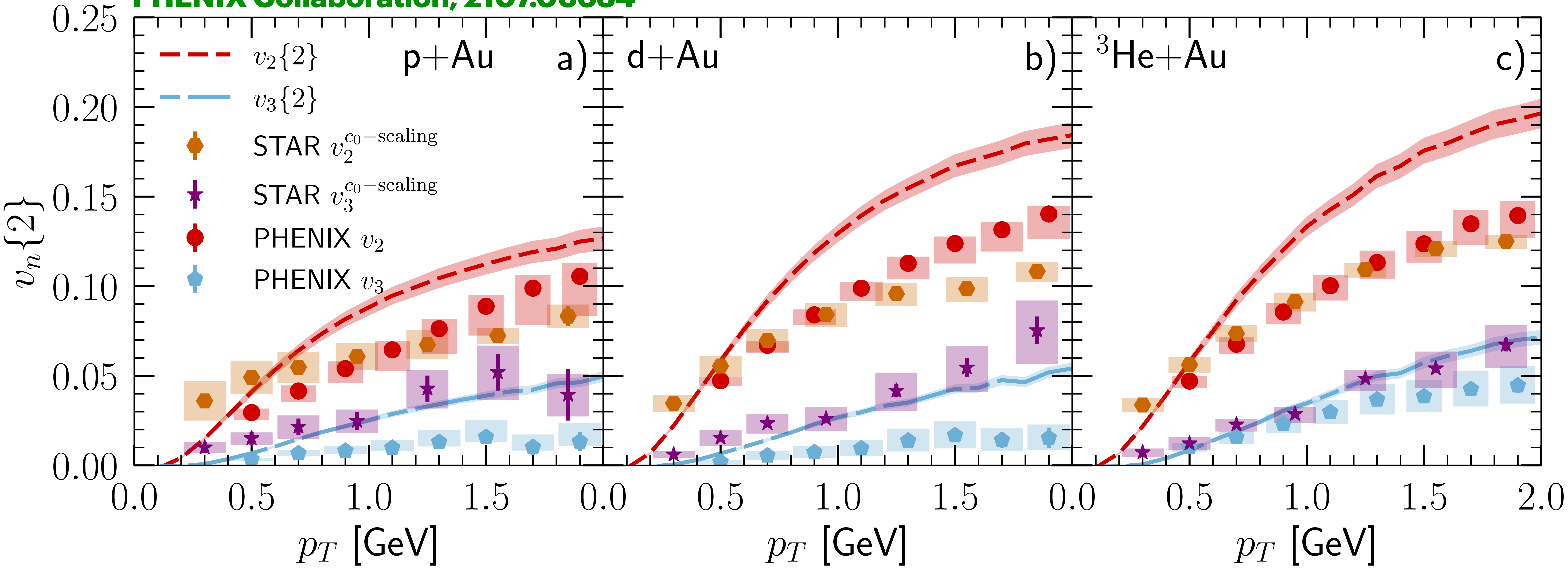
PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220



PHENIX VS. STAR

- Task force issued a report on the origin of the differences
  https://indico.bnl.gov/event/11308/contributions/47820/attachments/35369/57704/Dunlop_PAC_2021.pdf
- PHENIX sees large changes in v_3 when changing η

PHENIX Collaboration, 2107.06634



PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220,
STAR data: New at QM2019, Shengli Huang IS 2021

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

STAR vs. PHENIX: Slide from P. Tribedy

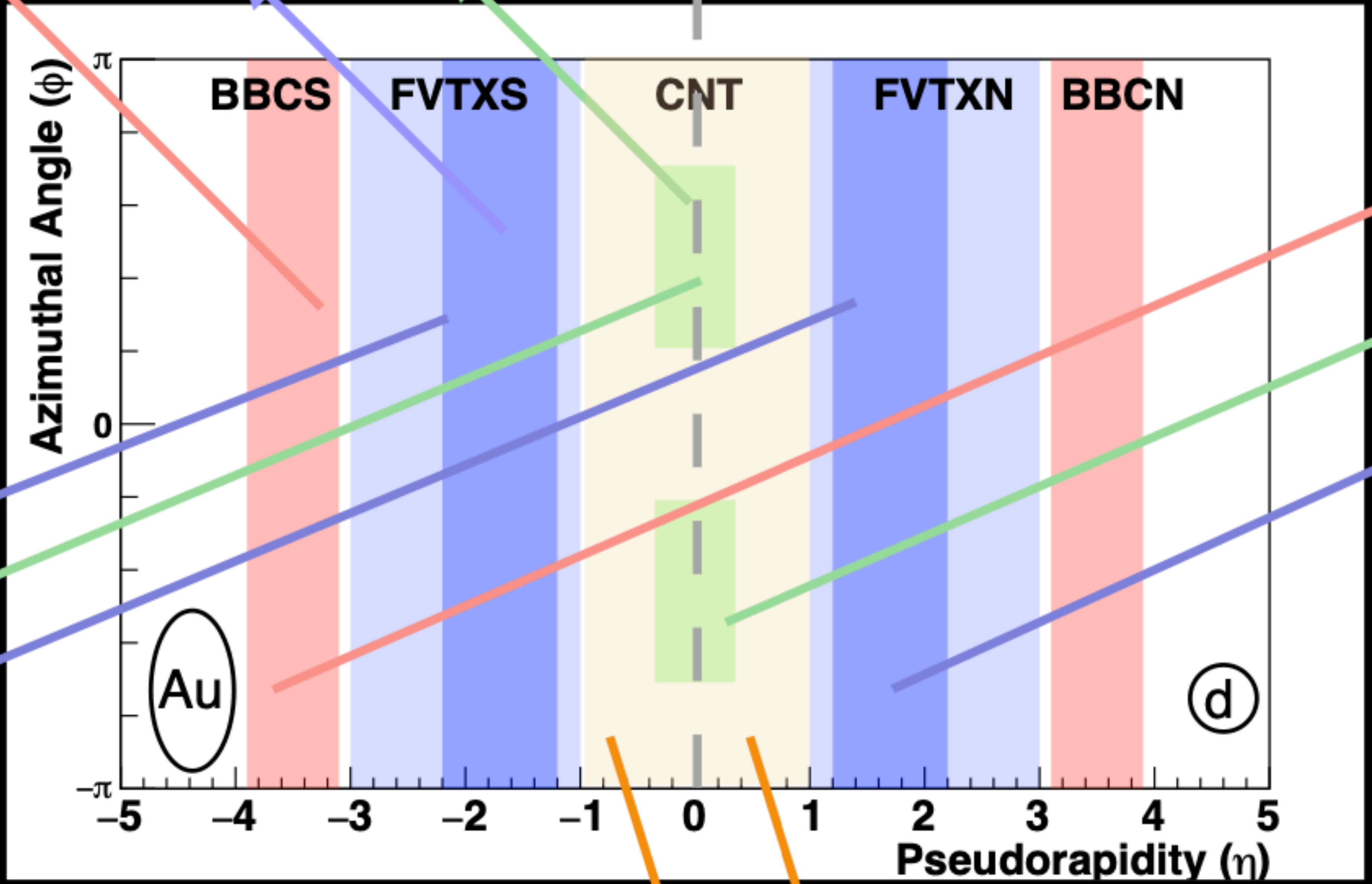
Strong acceptance dependence of (raw) harmonic coefficients

PHENIX (3x2PC,EP)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) > v_3(d+Au) \sim v_3(p+Au)$ ☺

PHENIX collab, Nature Phys. 15, 214–220 (2019)

CGC+Hydro (Boost invariant)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$ ☹

Schenke, Shen, PT, Phys.Lett.B 803 (2020) 135322



PHENIX (3x2PC)
$v_2(p+Au) \geq v_2(d+Au) \geq v_2(^3He+Au)$ ☹

$v_3(^3He+Au) > 0$
$v_3(d+Au) = ?$
$v_3(p+Au) = ?$ ☹

PHENIX collab., arXiv: 2107.06634v1,
Nagle et. al, arXiv:2107.07287

PHENIX (3x2PC)
$v_2(p+Au) \geq v_2(d+Au) \geq v_2(^3He+Au)$ ☹

$v_3(^3He+Au) > 0$
$v_3(d+Au) = ?$
$v_3(p+Au) = ?$ ☹

PHENIX collab., arXiv: 2107.06634v1
Nagle et. al, arXiv:2107.07287

STAR TPC (2PC)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$ ☹

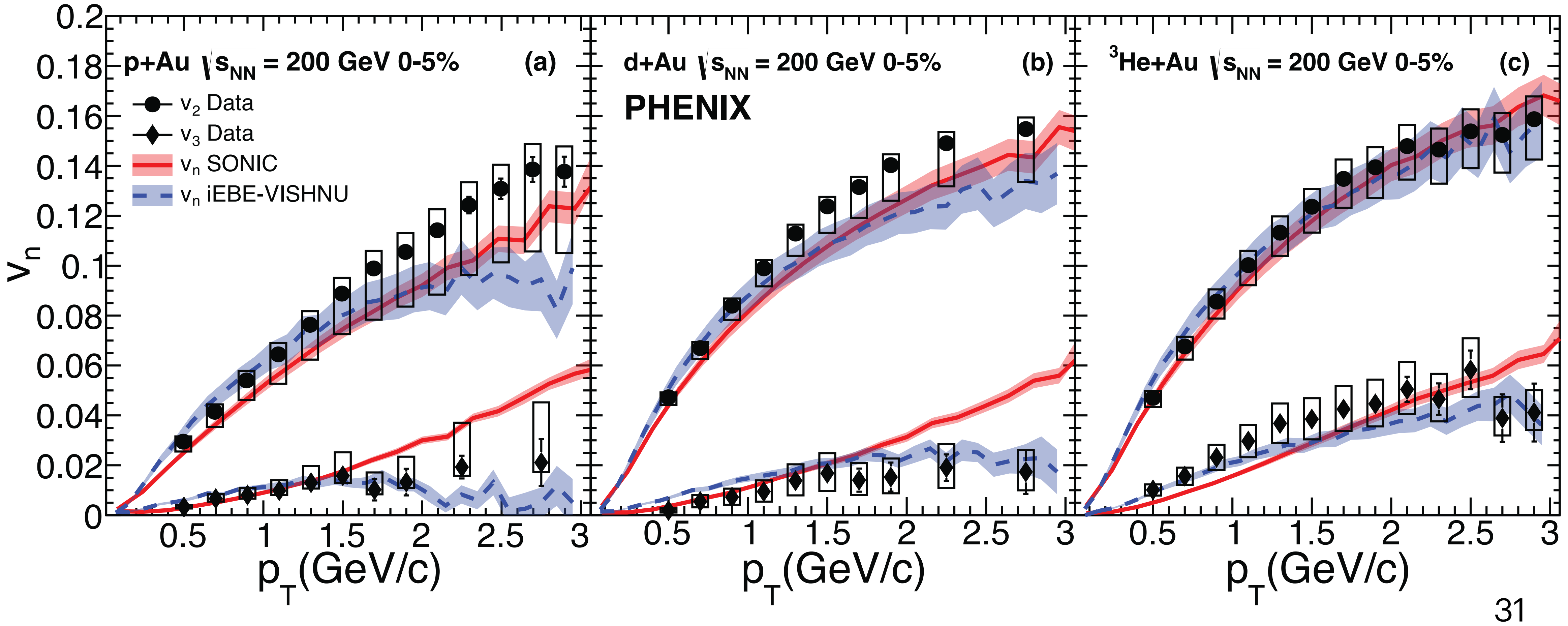
Shengli Huang, IS 2021

☺ Shape engineering works
☹ Doesn't work (or can't be checked)

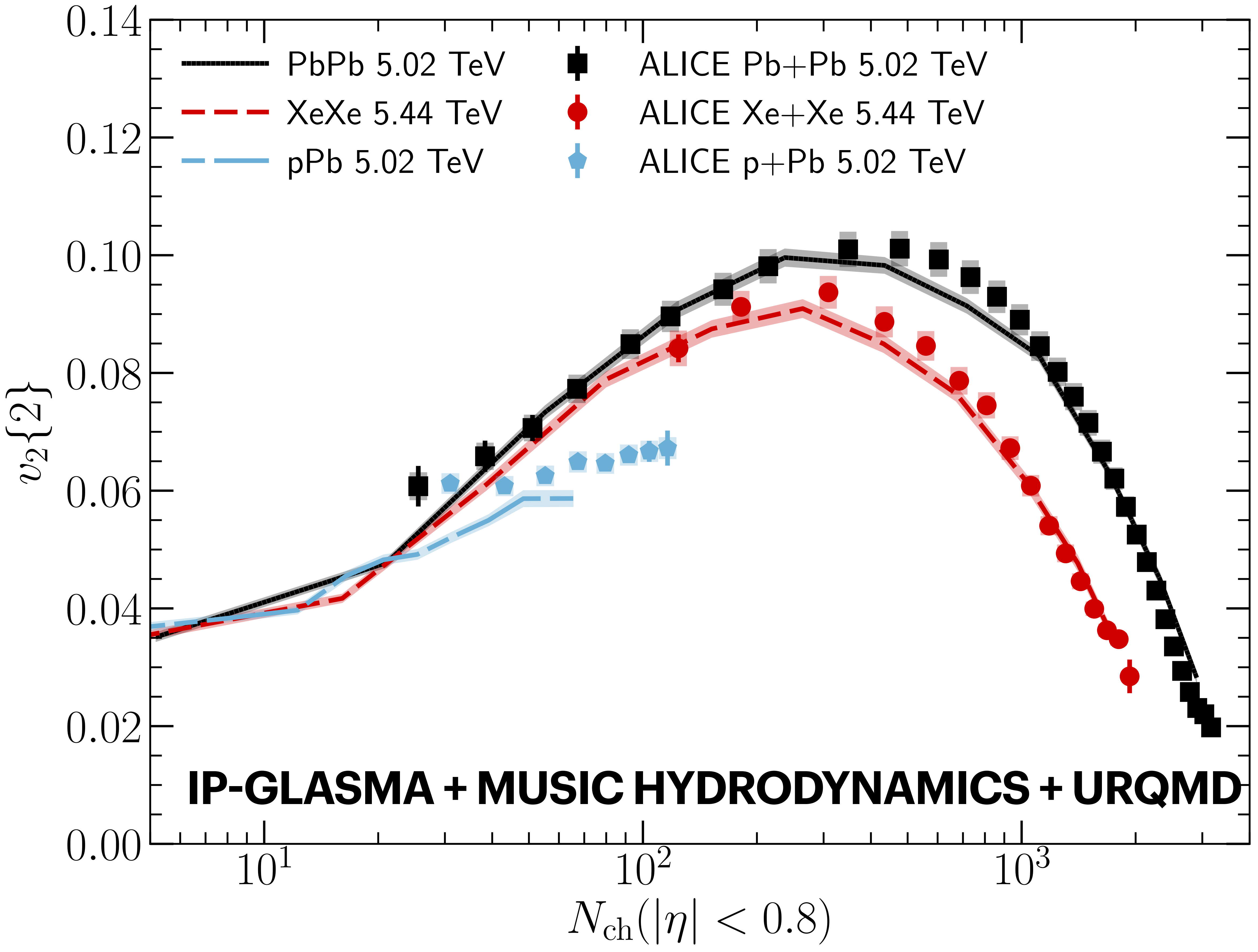
RAPIDITY DEPENDENCE

- Task force issued a report on the origin of the differences
  https://indico.bnl.gov/event/11308/contributions/47820/attachments/35369/57704/Dunlop_PAC_2021.pdf
- PHENIX sees large changes in v_3 when changing η
- Indication that boost invariant calculations **cannot** be compared to the PHENIX data **PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220,**
- That includes ours **B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905**
  B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322
- But also SONIC
  and iEbE-VISHNU results

M. Habich, J.L. Nagle, P. Romatschke
Eur. Phys. J. C 75, 15 (2015)
C. Shen, J.-F.,Paquet, G. S. Denicol, S. Jeon, S., C. Gale
Phys. Rev. C 95, 014906 (2017).



ORIGINS OF MOMENTUM ANISOTROPY



Anisotropic flow in heavy ion and high multiplicity small system collisions is driven by final state response to the initial geometry

B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

ORIGINS OF MOMENTUM ANISOTROPY

The initial momentum distribution is already anisotropic

The Color Glass Condensate predicts anisotropic particle production because of

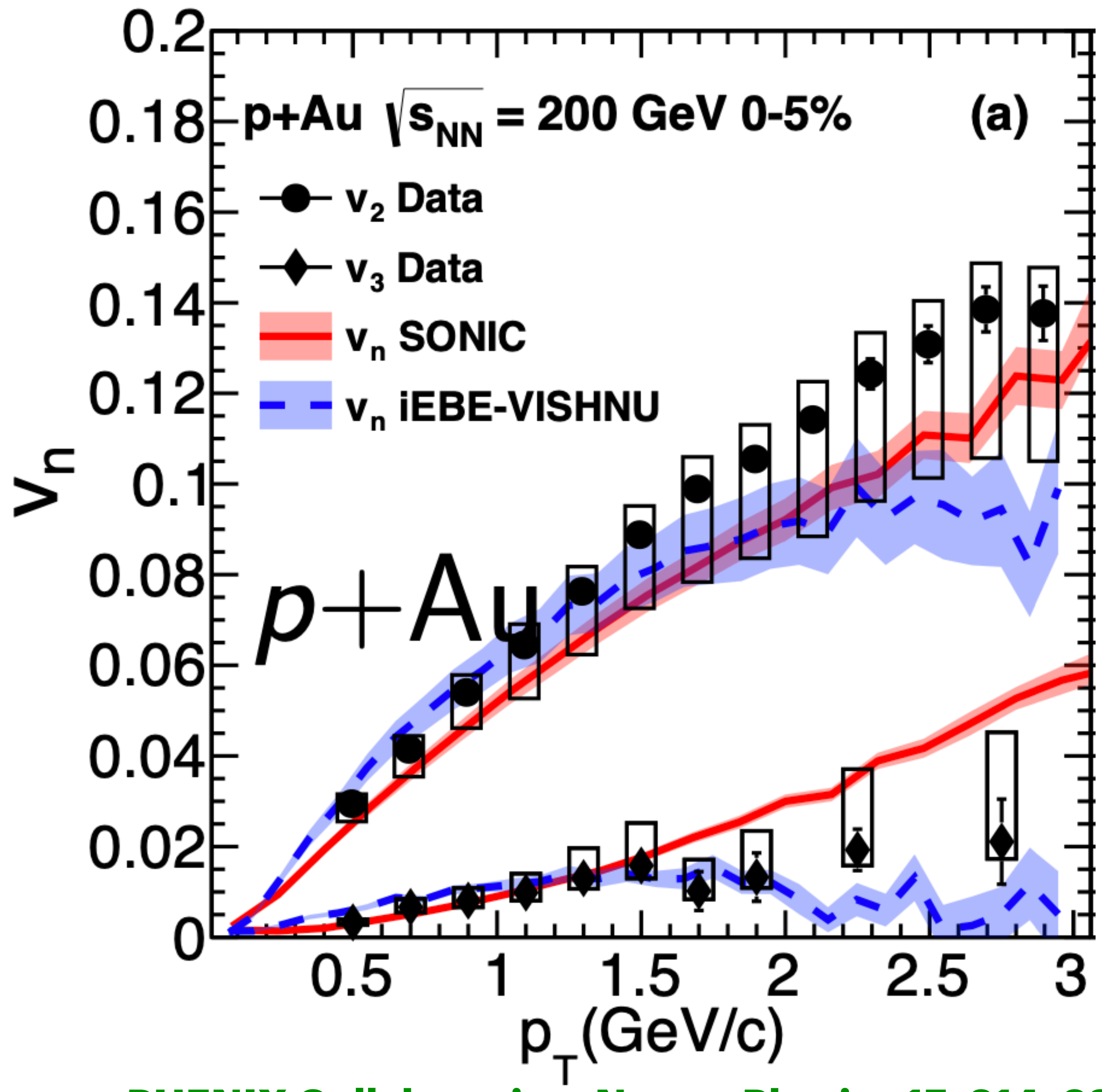
1. Local anisotropies in the color fields
2. Local density gradients
3. Quantum interference effects

Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009)
Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008)
Dumitru, Jalilian-Marian PRD 81 094015 (2010)
Dusling, Venugopalan PRD 87 (2013)
A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212
V. Skokov. Phys.Rev.D91 (2015) 054014
T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061
Kovner, Skokov, Phys.Rev. D98 (2018) no.1, 014004
...

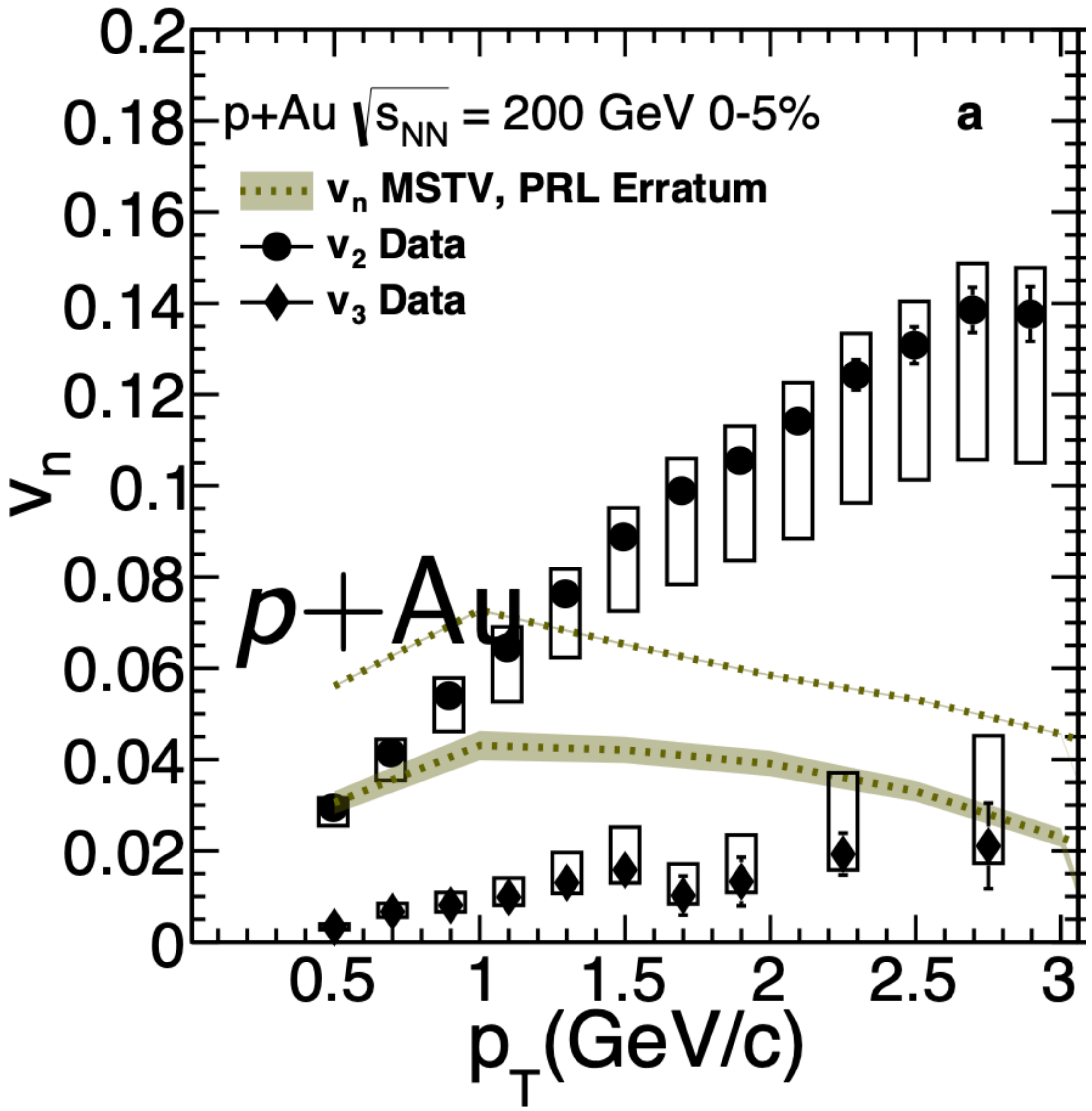
FINAL STATE EFFECTS ARE NEEDED

Qualitative features of the data are not well described by initial state anisotropy *alone*

GEOMETRY RESPONSE ONLY



INITIAL MOMENTUM ANISOTROPY ONLY



R. Belmont at the 2020 RHIC & AGS Users' Meeting

PHENIX Collaboration, Nature Physics 15, 214–220 (2019)
M. Mace, V. V. Skokov, P. Tribedy, R. Venugopalan , Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

BUT INITIAL STATE EFFECTS ARE THERE

Our calculation using the IP-Glasma initial state and hydrodynamics includes both effects

Initial state anisotropies are significant and can affect the final result at low multiplicity

$$Q_\varepsilon = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

CORRELATION OF THE FINAL ELLIPTIC FLOW V_2

WITH

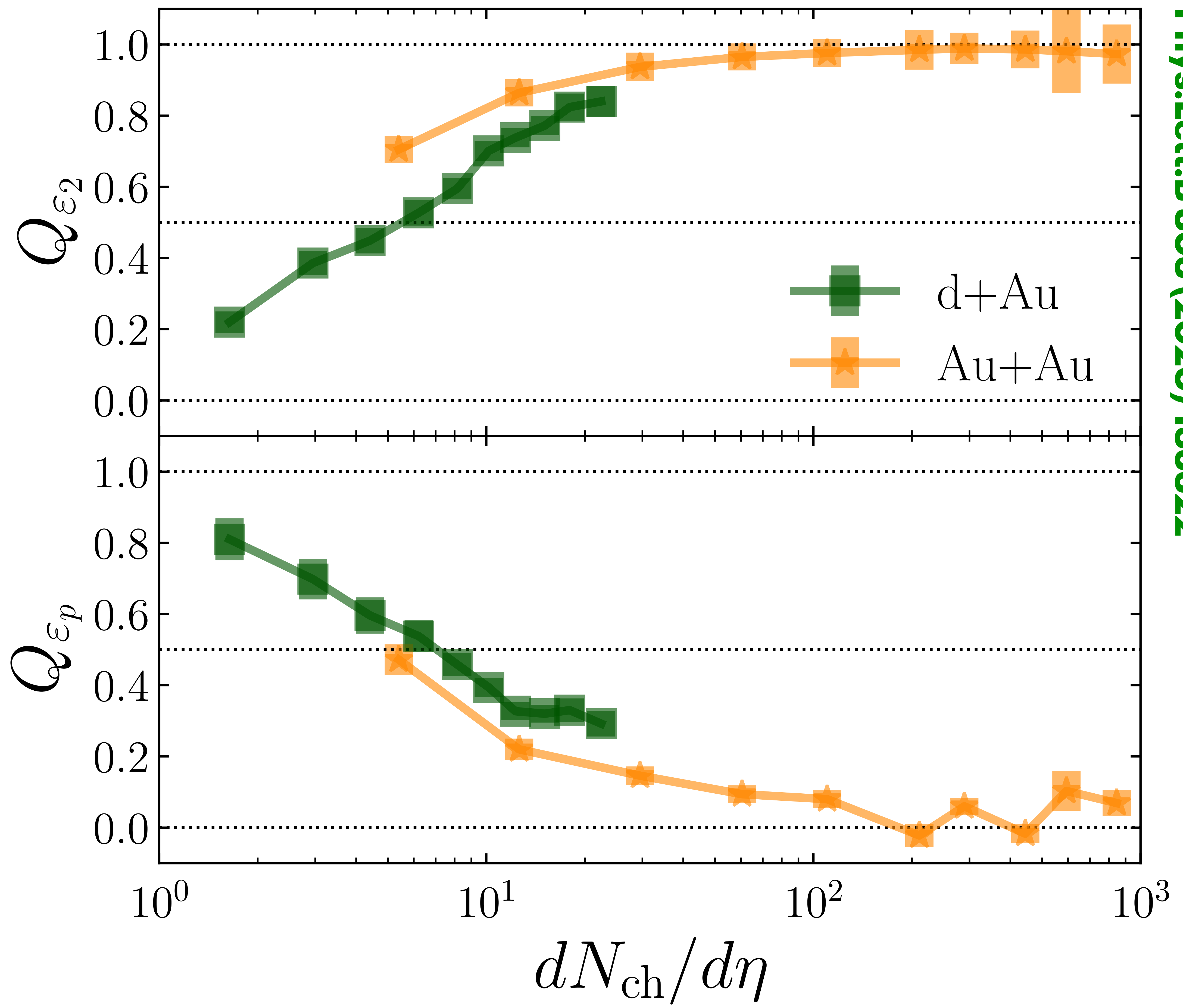
THE GEOMETRIC ELLIPTICITY

$$\mathcal{E}_2 = \varepsilon_2 e^{i2\psi_2} = \frac{\langle x^2 - y^2 \rangle + i\langle 2xy \rangle}{\langle x^2 + y^2 \rangle}$$

AND

THE INITIAL MOMENTUM ANISOTROPY

$$\mathcal{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy} \rangle + i\langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



B. Schenke, C. Shen, P. Tribedy
Phys.Lett.B 803 (2020) 135322

HOW TO DISTINGUISH THE SOURCE OF ANISOTROPY

P. Bozek, Phys. Rev. C 93, 044908 (2016); B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)
G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

Again, use the correlation of mean transverse momentum $[p_T]$ and v_2^2 at fixed multiplicity:

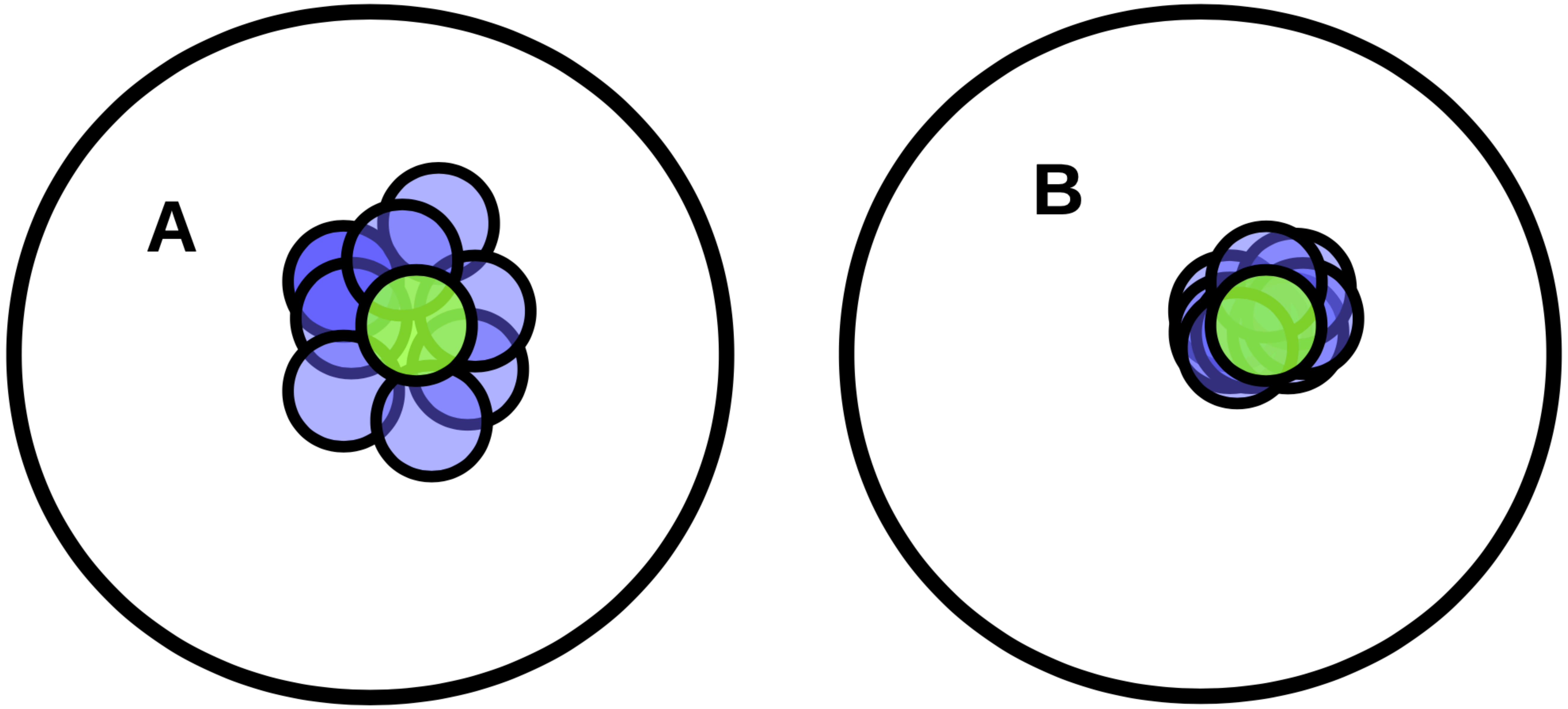
$$\hat{\rho}(v_n^2, [p_T]) = \frac{\langle \hat{\delta} v_n^2 \, \hat{\delta}[p_T] \rangle}{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}$$

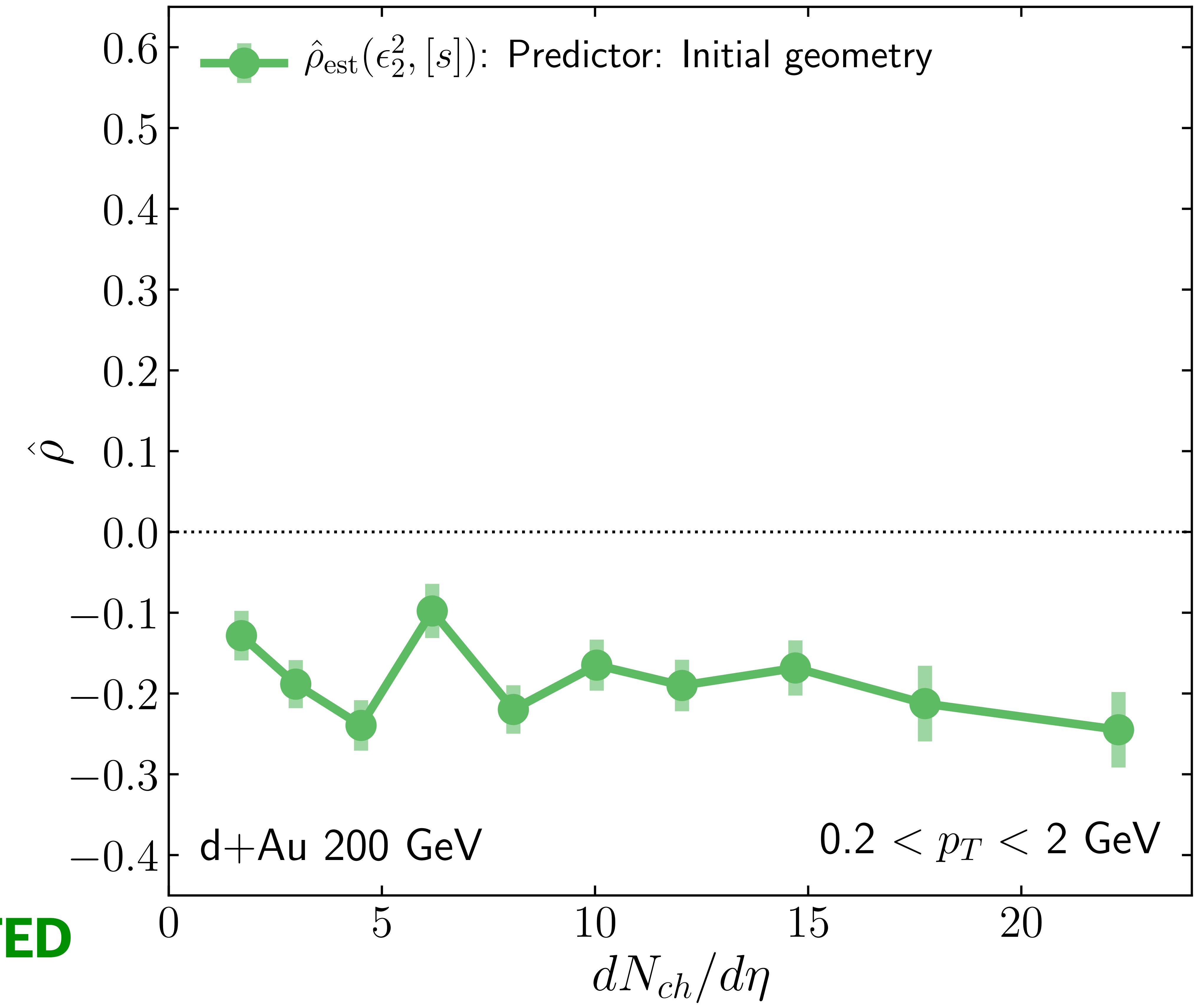
It can help to identify the source of the azimuthal anisotropy in the experimental data

The two origins of v_2 have very distinct predictions for this correlator

SMALL SYSTEMS: CORRELATION FROM GEOMETRY

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301





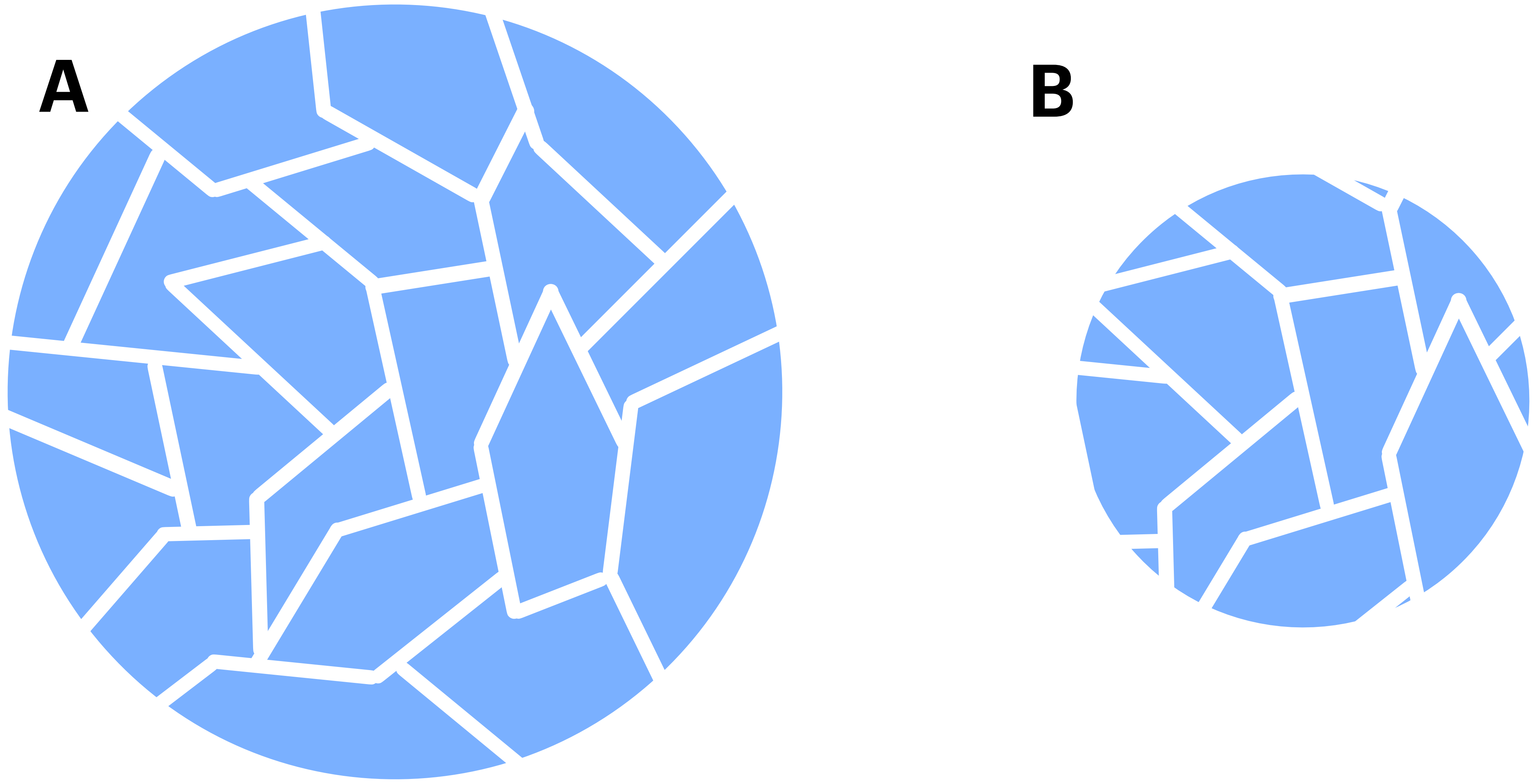
$$R(A) > R(B)$$
$$\langle p_T \rangle(A) < \langle p_T \rangle(B)$$
$$\varepsilon_2(A) > \varepsilon_2(B)$$

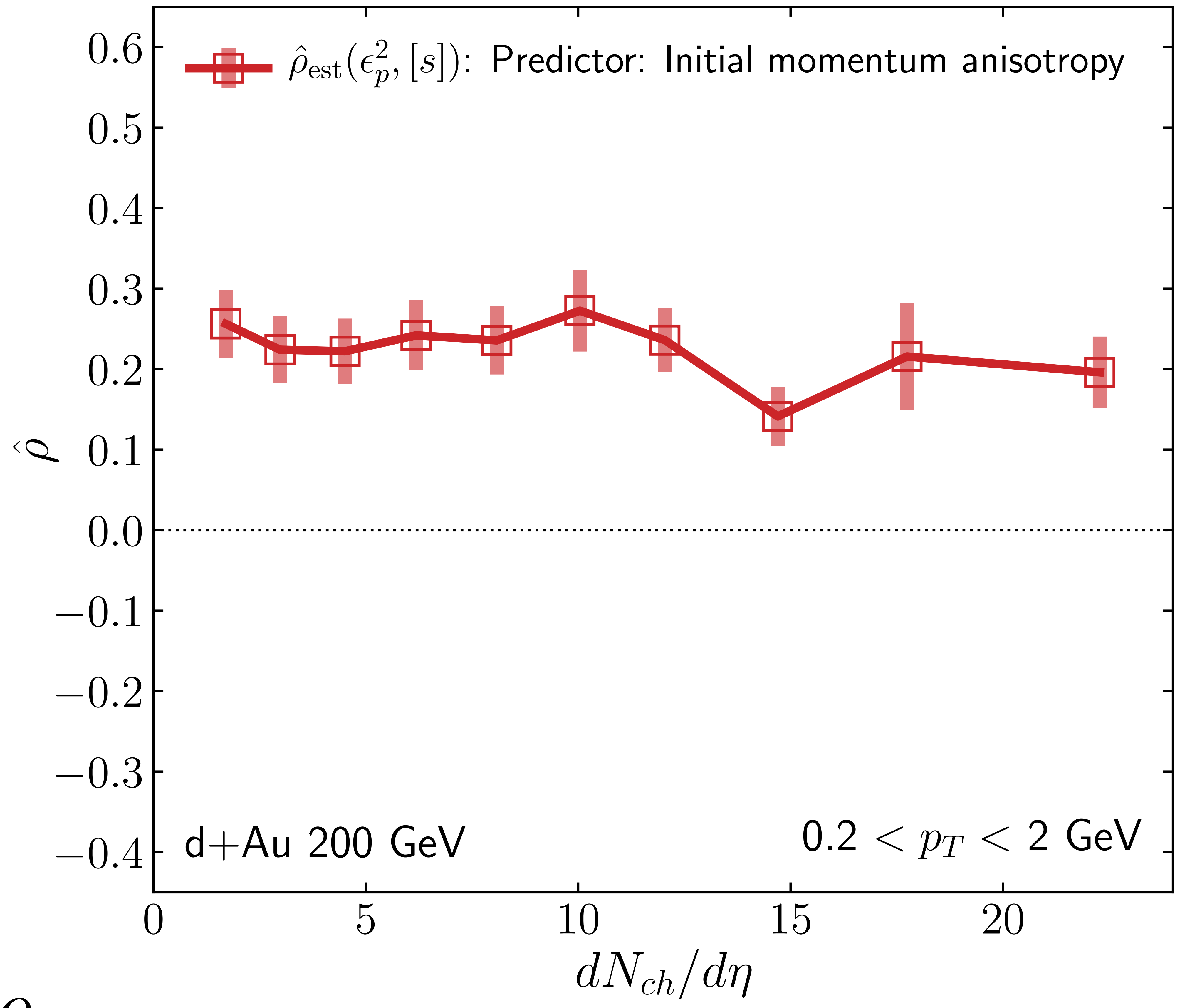
} v_2 AND $\langle p_T \rangle$ ARE ANTI-CORRELATED

CORRELATION FROM INITIAL MOMENTUM ANISOTROPY

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

COLOR DOMAIN CARTOON (PARTICLES PRODUCED FROM ONE DOMAIN ARE CORRELATED):





$$R(A) > R(B)$$

$$\langle p_T \rangle(A) < \langle p_T \rangle(B)$$

$$\varepsilon_p(A) < \varepsilon_p(B)$$

v_2 **AND** $\langle p_T \rangle$ **ARE CORRELATED**

BECAUSE A HAS MORE DOMAINS

NOTE: Multiplicity is dominated by projectile Q_s
At fixed multiplicity, for the target: $Q_s(A) \approx Q_s(B) \rightarrow$ **domain sizes** $1/Q_s$ **are the same**
$\langle p_T \rangle$ **assumed to be still driven by the geometry**

WHICH ONE SURVIVES?

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

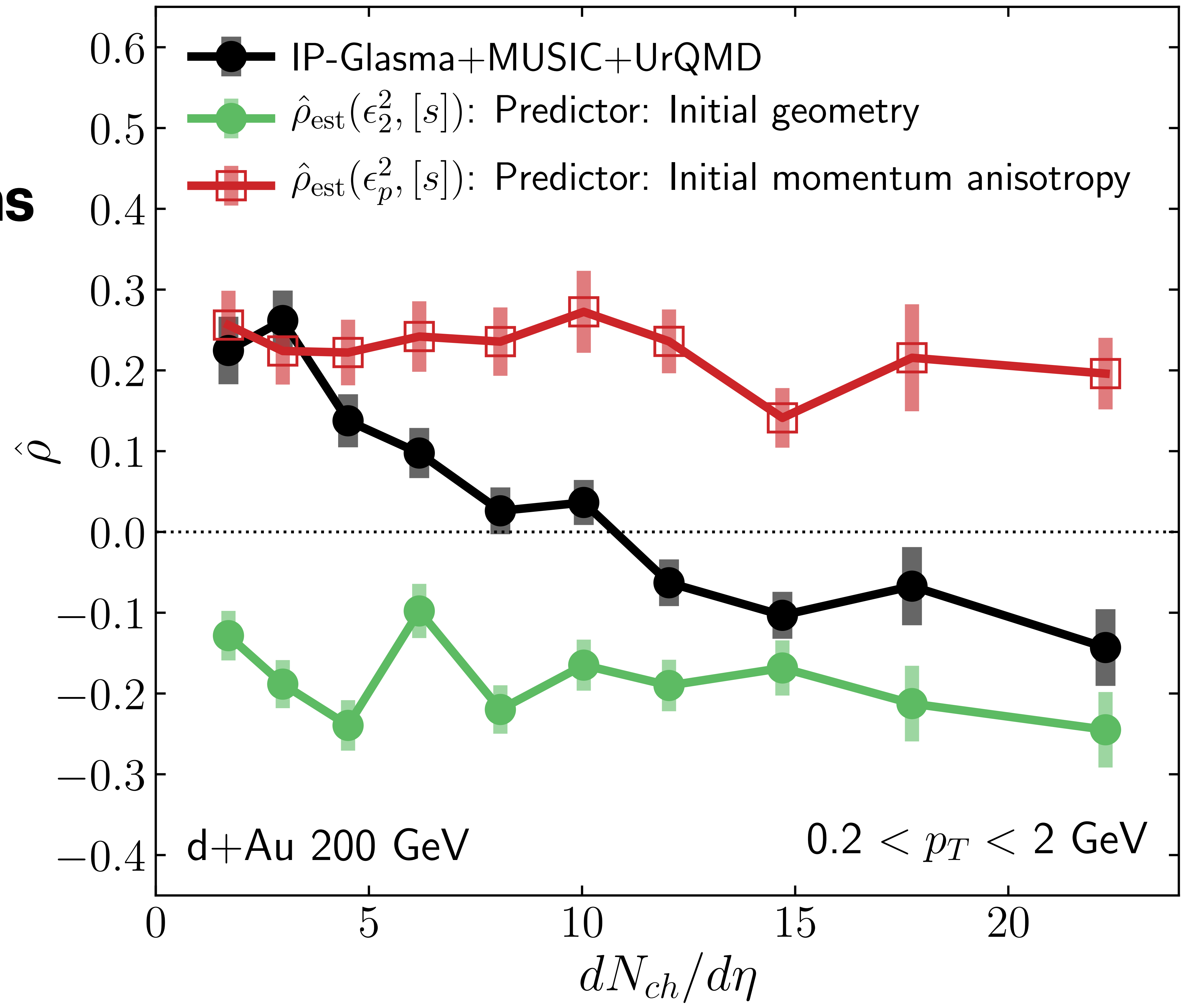
IT DEPENDS ON MULTIPLICITY

We predict a sign change of the ρ correlator with multiplicity in p/d+Au collisions at RHIC and p+Pb collisions at LHC around $dN_{\rm ch}/d\eta \approx 10$

Below $dN_{\rm ch}/d\eta \approx 10$
initial momentum anisotropy dominates

Above $dN_{\rm ch}/d\eta \approx 10$
final state response to the initial geometry dominates

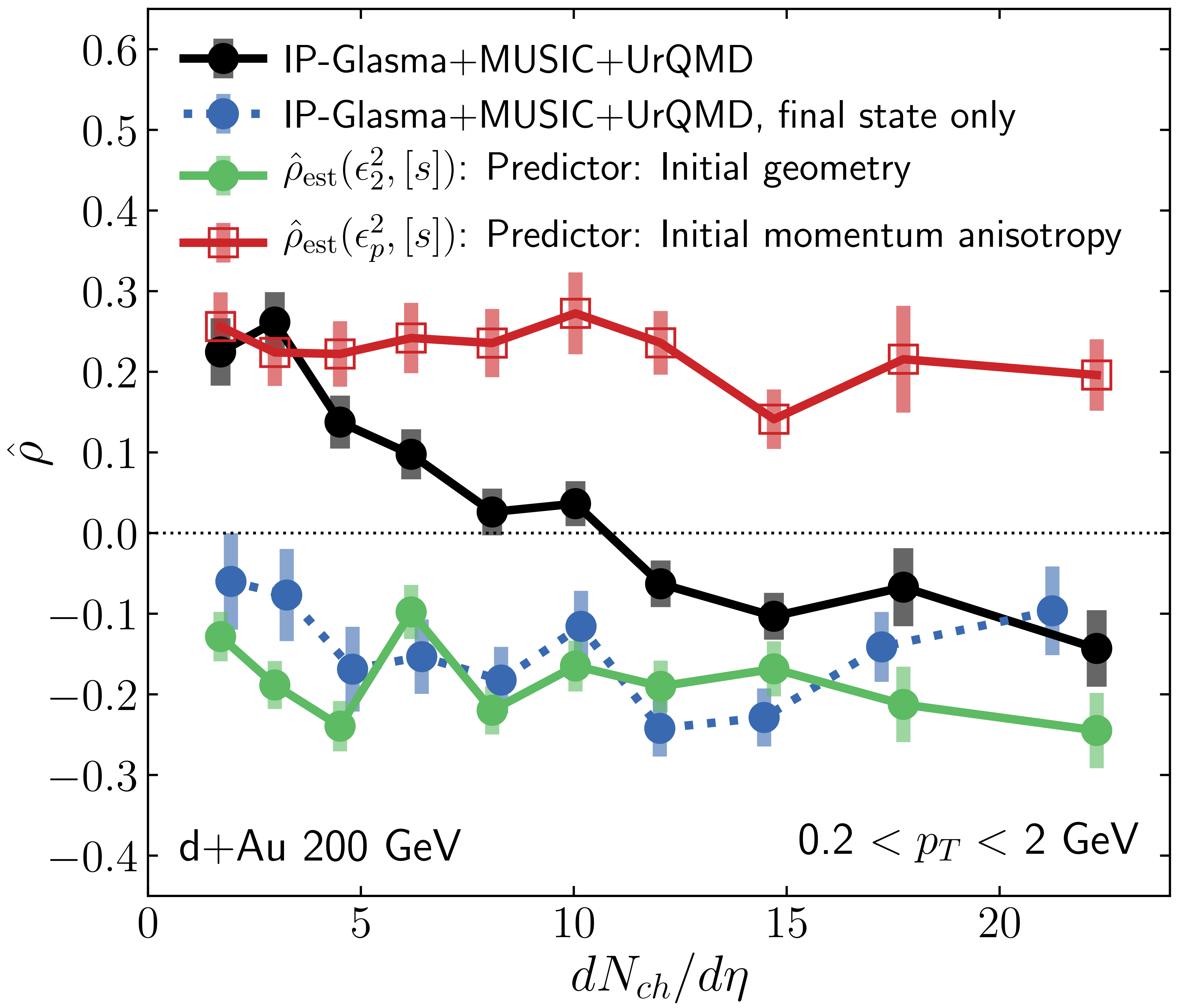
The observable moves from one predictor to the other



CHECK: REMOVE THE INITIAL STATE MOMENTUM ANISOTROPY

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

With no initial momentum anisotropy, our result follows the geometry predictor for all $dN_{\rm ch}/d\eta$ as expected



CHECK: REMOVE THE INITIAL STATE MOMENTUM ANISOTROPY

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

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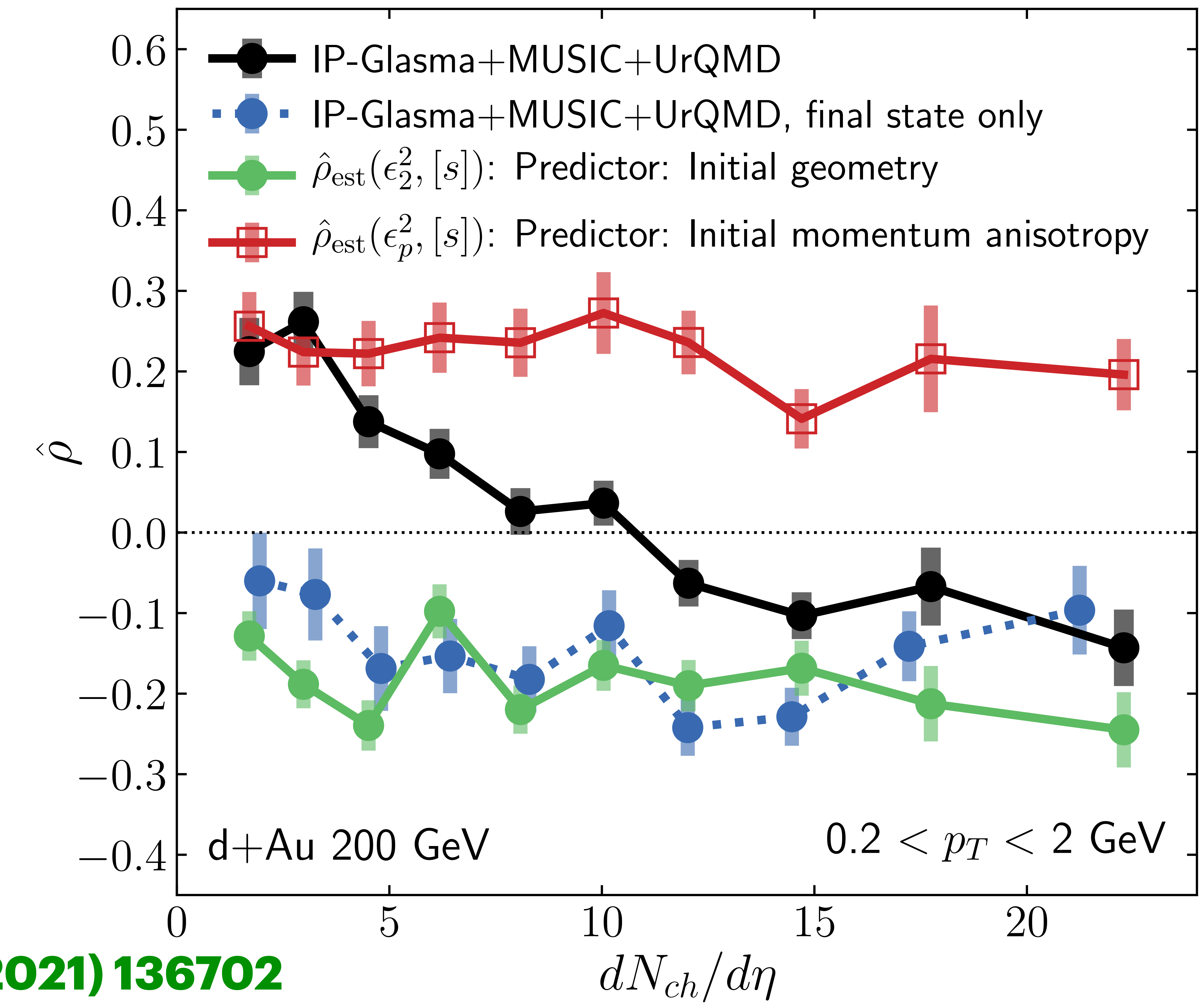


Is it detectable?

Very low multiplicity

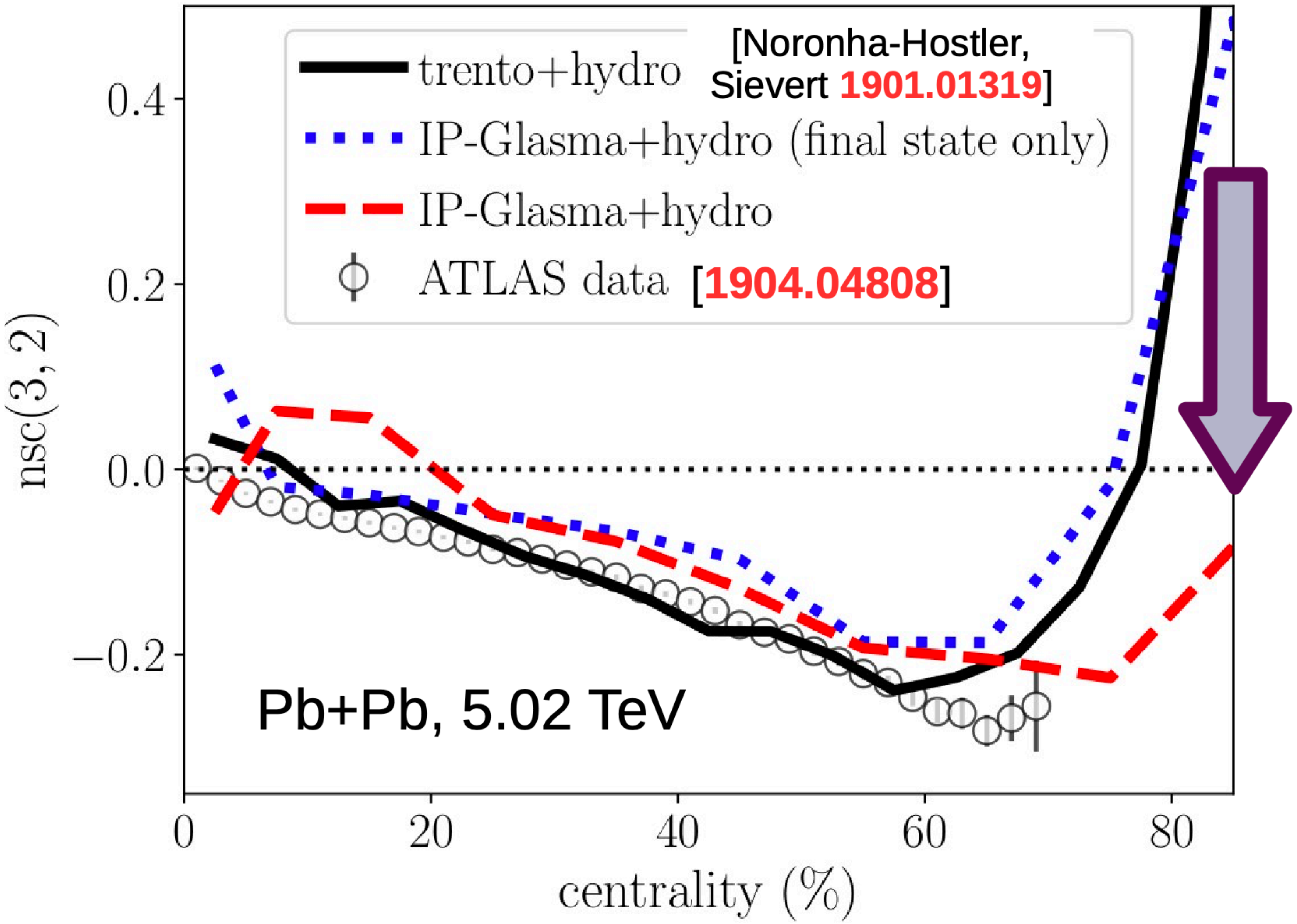
Non-flow can mimic the signal

C. Zhang, A. Behera, S. Bhatta, J. Jia, Phys.Lett.B 822 (2021) 136702

S. H. Lim, J. L. Nagle, Phys.Rev.C 103 (2021) 6, 064906

CORRELATION BETWEEN v_2^2 AND v_3^2

G. Giacalone, B. Schenke, C. Shen, in preparation



BEYOND BOOST-INVARIANCE

What is the rapidity dependence of the initial momentum space anisotropy?

Does it survive the experimentally applied gap?

PART II: GOING BEYOND BOOST INVARIANCE

- Use the CGC including JIMWLK evolution
- Do not assume boost invariance

BEYOND BOOST-INVARIANCE

work in progress with Pragya Singh and Sören Schlichting

Employ JIMWLK small-x evolution to the proton and nucleus

as in B. Schenke, S. Schlichting, Phys.Lett.B 739 (2014) 313-319 and Phys.Rev.C 94 (2016) 4, 044907

Functional Langevin equation

$$V_{\mathbf{x}_\perp}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}_\perp} K_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\left(V_{\mathbf{z}_\perp}\boldsymbol{\xi}_{\mathbf{z}_\perp}V^\dagger_{\mathbf{z}_\perp}\right)\right\} \times V_{\mathbf{x}_\perp}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}_\perp} K_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\boldsymbol{\xi}_{\mathbf{z}_\perp}\right\}, \quad (7)$$

IR regularized JIMWLK Kernel

$$K_{\mathbf{x}_\perp-\mathbf{z}_\perp} = m|\mathbf{x}_\perp-\mathbf{z}_\perp|\; K_1(m|\mathbf{x}_\perp-\mathbf{z}_\perp|)\,\frac{\mathbf{x}_\perp-\mathbf{z}_\perp}{(\mathbf{x}_\perp-\mathbf{z}_\perp)^2}$$

Compute the energy momentum tensor in different rapidity bins after Yang-Mills evolution

Study the correlation function of the geometry and initial momentum anisotropy as a function of rapidity

EVOLUTION OF THE PROTON

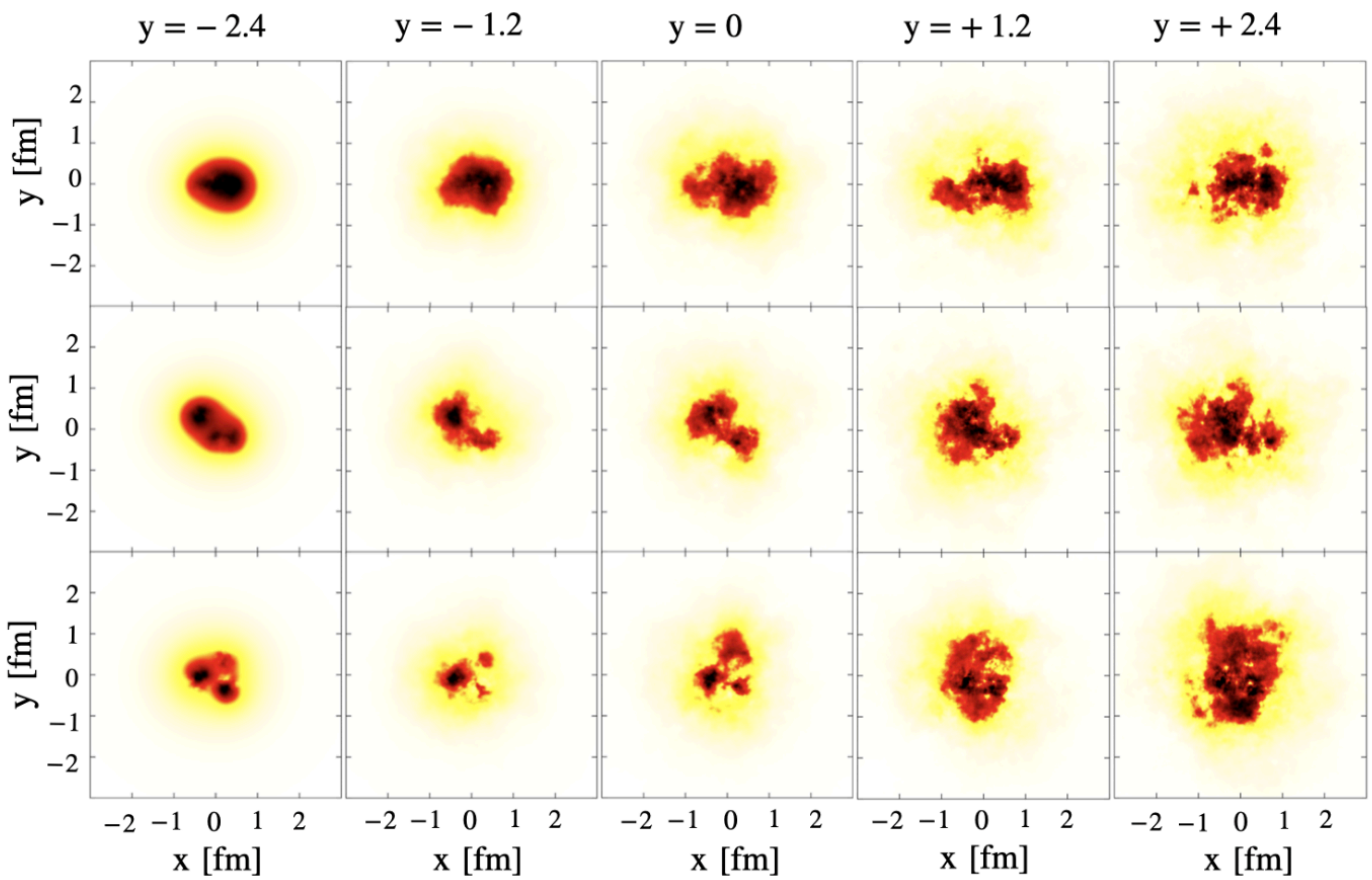
work in progress with Pragya Singh and Sören Schlichting

3 EXAMPLES

PROTON 1

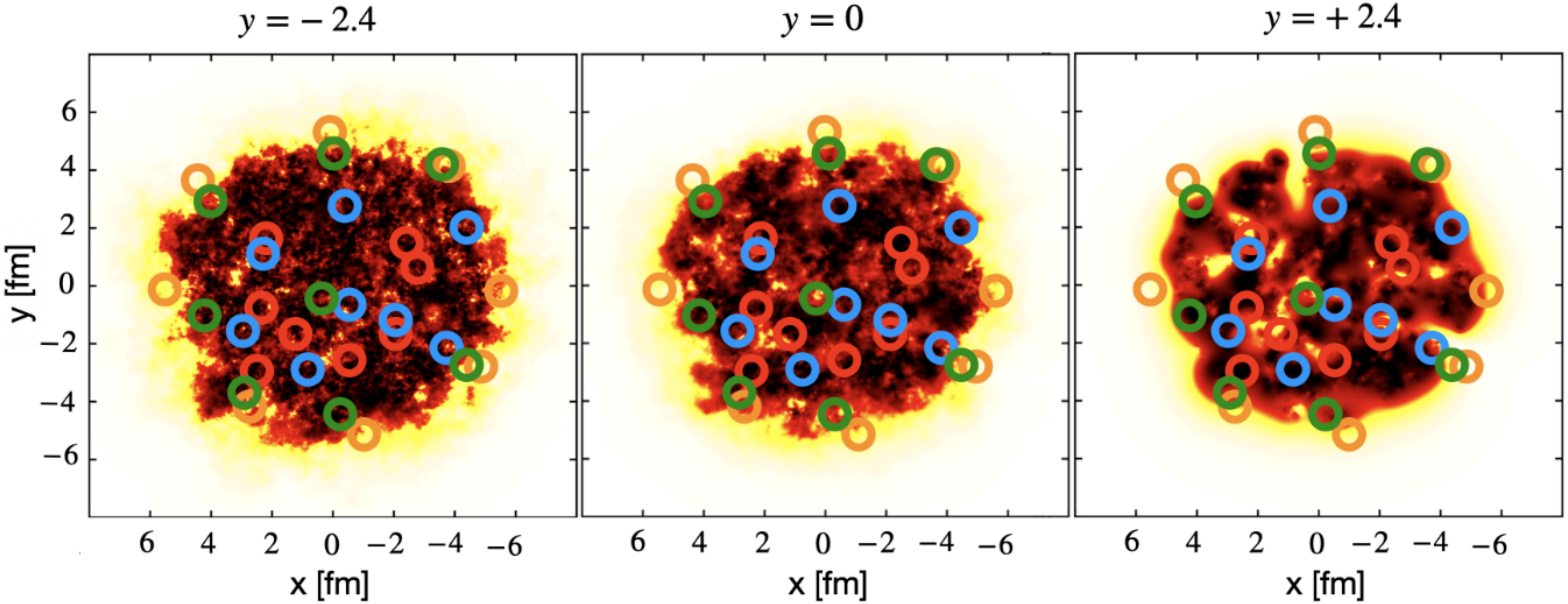
PROTON 2

PROTON 3



EVOLUTION OF THE NUCLEUS

work in progress with Pragya Singh and Sören Schlichting

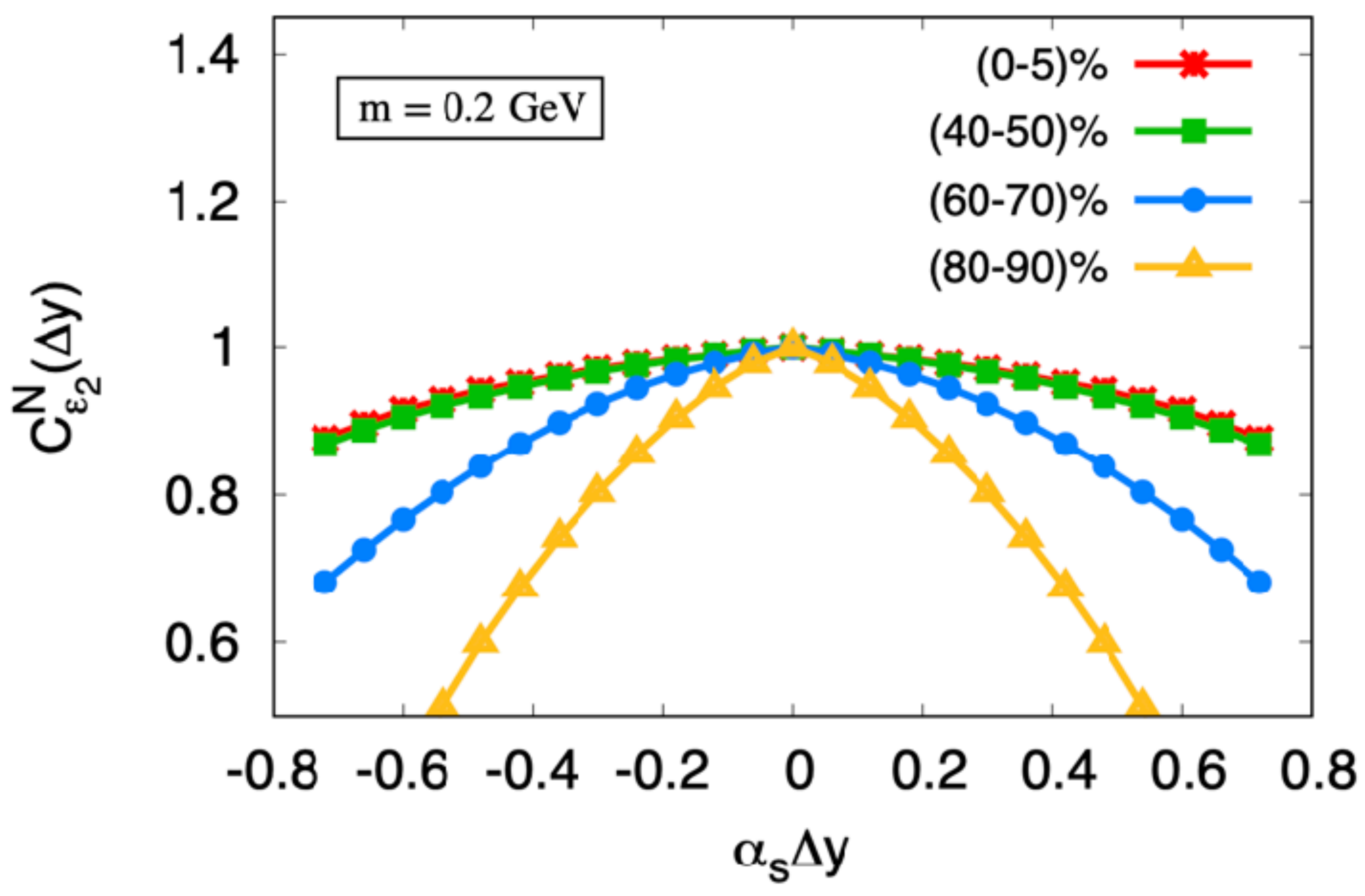


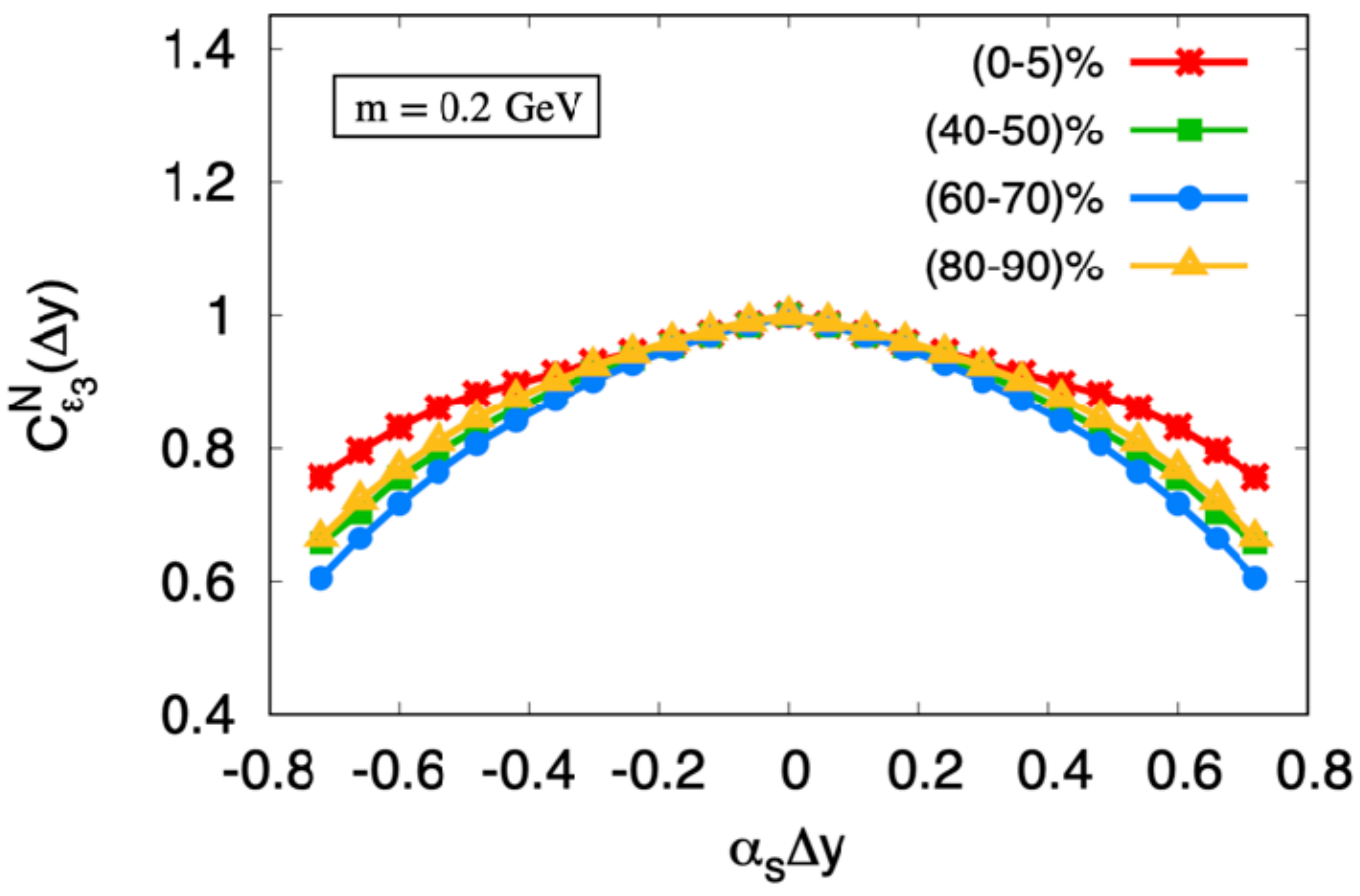
Dots indicate places where the proton hit in a given event in centrality class 0-5% (blue), 40-50% (blue), 60-70% (green), 80-90% (orange)

Centrality is determined at mid-rapidity

CORRELATION OF ECCENTRICITY

work in progress with Pragya Singh and Sören Schlichting





The geometry, quantified here with ε_2 and ε_3, decorrelates fairly slowly, at least for not too peripheral events

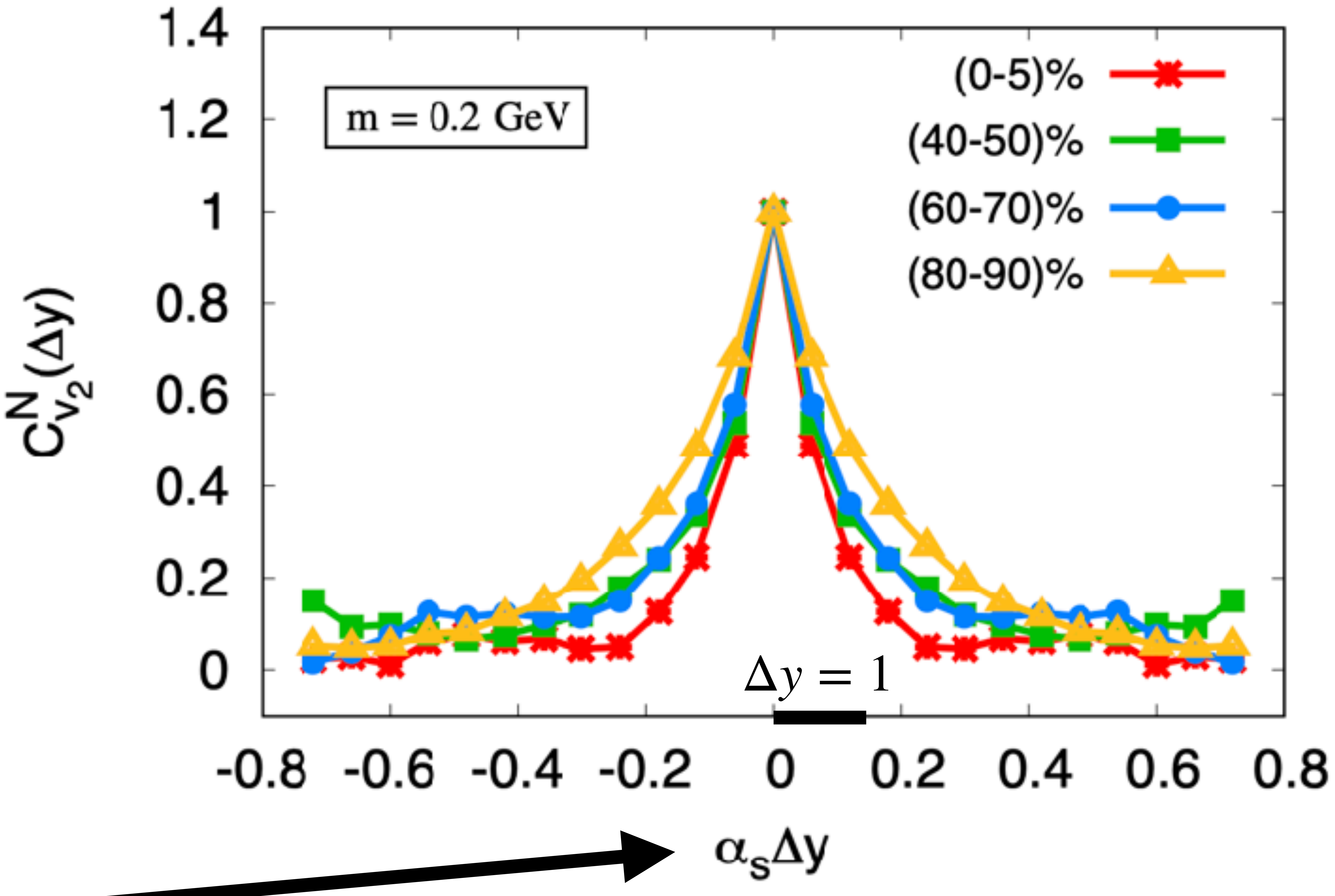
$$C^N_{\mathcal{O}}(\eta_1, \eta_2) = \frac{\left\langle \mathrm{Re}\left(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)\right)\right\rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2\rangle\langle |\mathcal{O}(\eta_2)|^2\rangle}}$$

CORRELATION OF INITIAL MOMENTUM ANISOTROPY

work in progress with Pragya Singh and Sören Schlichting

The initial momentum anisotropy, ε_p, or equivalently the initial anisotropy of the gluons, decorrelates comparatively quickly

Plug in $\alpha_s = 0.15$, which works well for the rapidity dependence of the charged hadron distribution

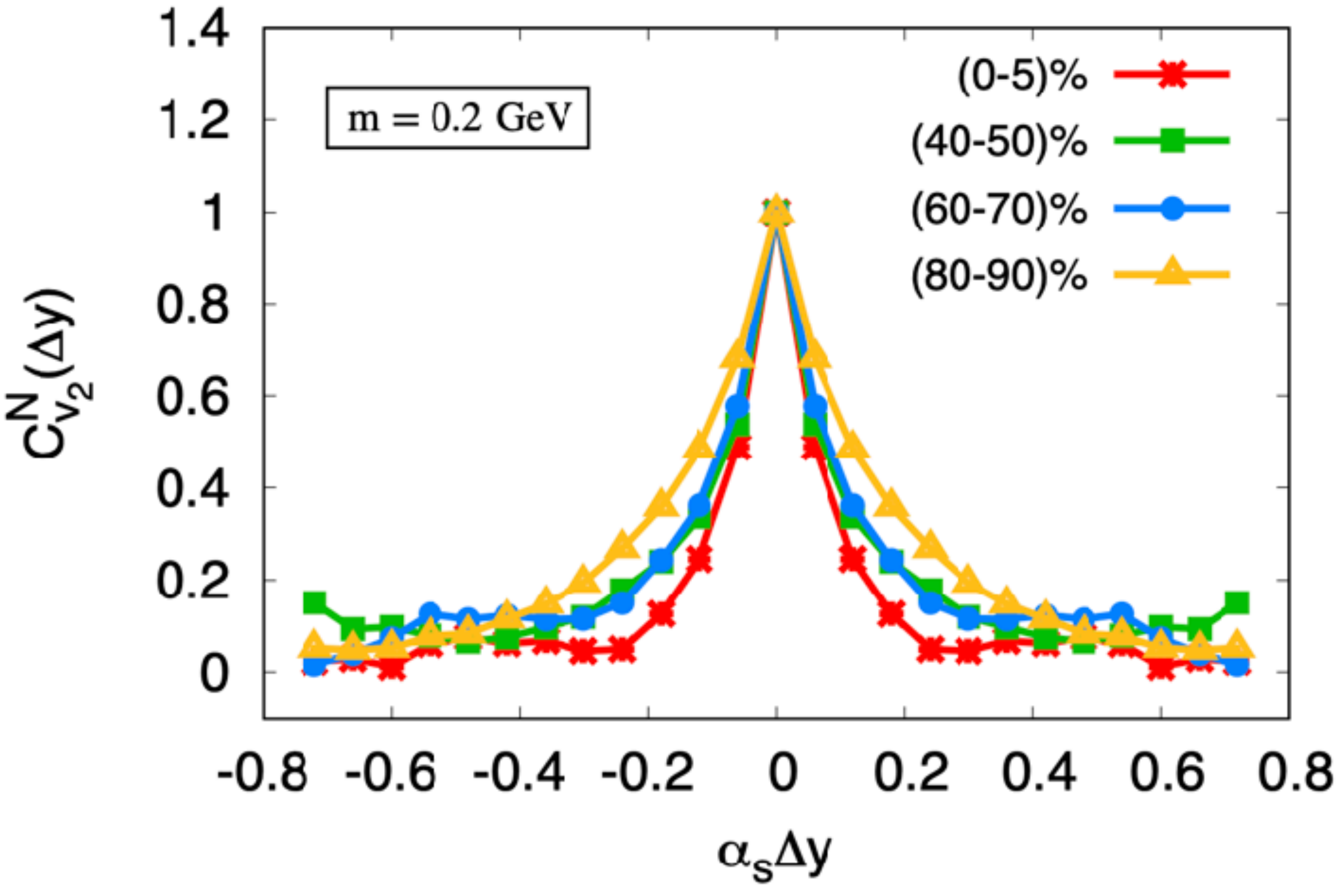


CORRELATION OF INITIAL MOMENTUM ANISOTROPY

work in progress with Pragya Singh and Sören Schlichting

So this is a bad sign for the initial momentum anisotropy

The ρ correlator is measured using different rapidity bins for $[p_T]$ and the two particles used for v_2 . Over the rapidity range used, the signal from initial state momentum anisotropy would have decayed significantly.



SUMMARY

- Boost-invariant hybrid model with IP-Glasma initial state and sub-nucleon fluctuations can describe bulk properties over a wide range of collision systems
- Models disagree on nucleon size. Including the correlation of mean transverse momentum and elliptic flow in Bayesian analyses should help to better constrain the models.
- Especially for small systems, observables that use large rapidity gaps cannot be compared to boost invariant calculations
- IP-Glasma+JIMWLK evolution: Geometry decorrelates with rapidity (faster for low multiplicity); initial state anisotropy decorrelates more quickly (faster for high multiplicity)
- Not covered: For fully 3D simulations an alternative initial state model using MC-Glauber + 3+1D string deceleration and feeding in of source terms into hydro can be used

CODES - ALL PUBLIC

- The iEBE-MUSIC framework integrates individual physical models which describe different stages of relativistic heavy-ion collisions. This work uses v1.0 of this framework, which can be downloaded from
  https://github.com/chunshen1987/iEBE-MUSIC/releases

- The official code repository of the IP-Glasma initial conditions is
  https://github.com/schenke/ipglasma . Here we used v1.0:
  https://github.com/schenke/ipglasma/releases

- MUSIC is the numerical implementation of (3+1)D relativistic viscous hydrodynamic simulations for high energy heavy-ion collisions. Its official website is
  http://www.physics.mcgill.ca/music . This work uses the version 3.0 of MUSIC, which can be downloaded from
  https://github.com/MUSIC-fluid/MUSIC/releases

- The iSS code package is an open-source particle sampler based on the Cooper-Frye freeze-out prescription. It converts fluid cells to particle samples. This work uses v1.0 of the iSS, which can be downloaded from
  https://github.com/chunshen1987/iSS/releases

- We use the official UrQMD v3.4 and set it up to run as the afterburner mode
  https://bitbucket.org/Chunshen1987/urqmd_afterburner/src/master/

- The hadronic afterburner toolkit is a code package which performs analysis of particle spectra, flow observables, and their correlations using the outputs from hadronic transport models. This work uses v1.0 of the code which can be downloaded from
  https://github.com/chunshen1987/hadronic_afterburner_toolkit/releases

- The NEOS equation of state v0.11:
  https://sites.google.com/view/qcdneos/

BACKUP

PART III: FULL 3+1D HYDRO FOR LOWER ENERGIES

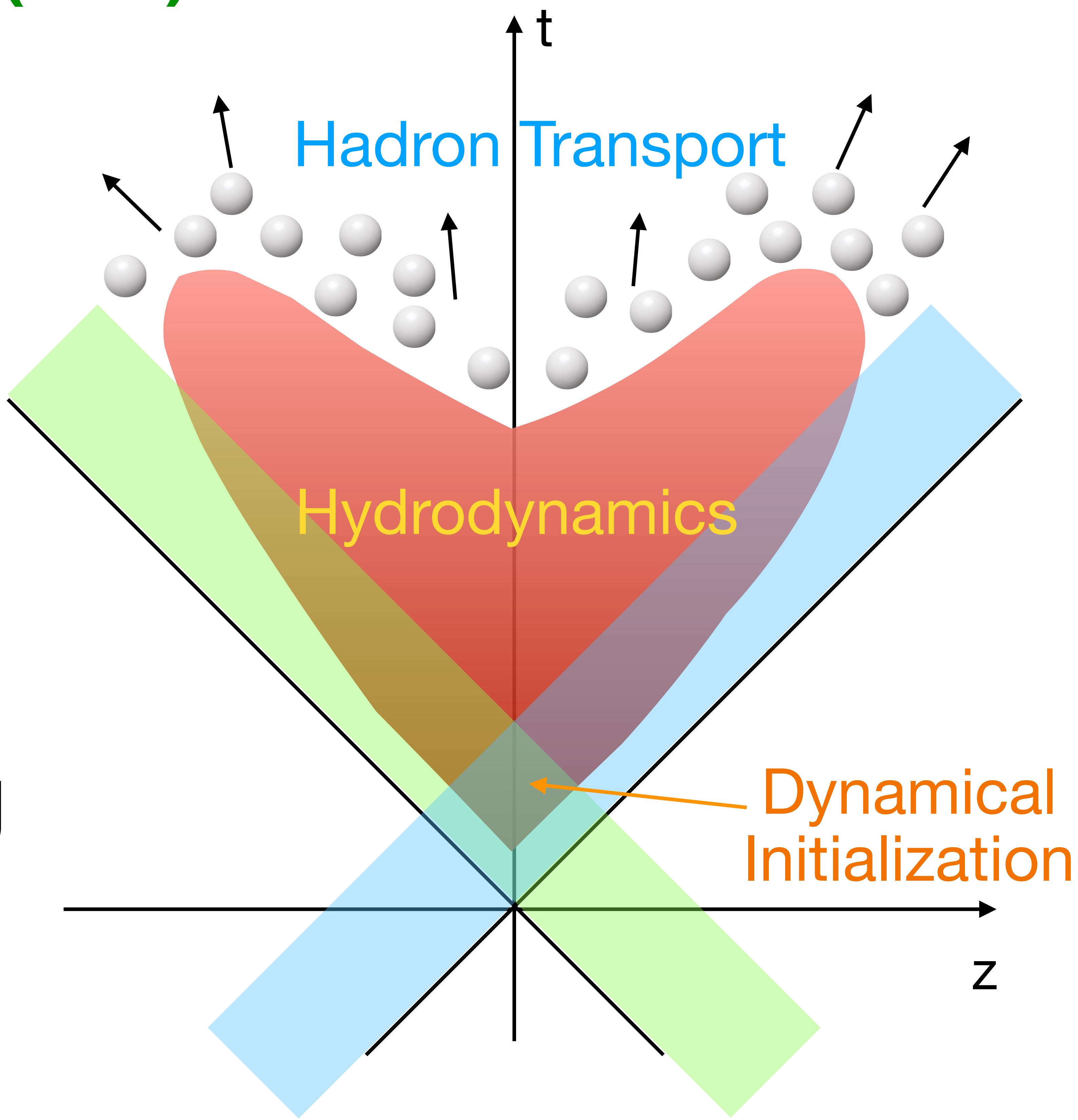
- Do not use CGC but dynamical MC-Glauber + string model
- Do full 3+1D hydrodynamic calculations

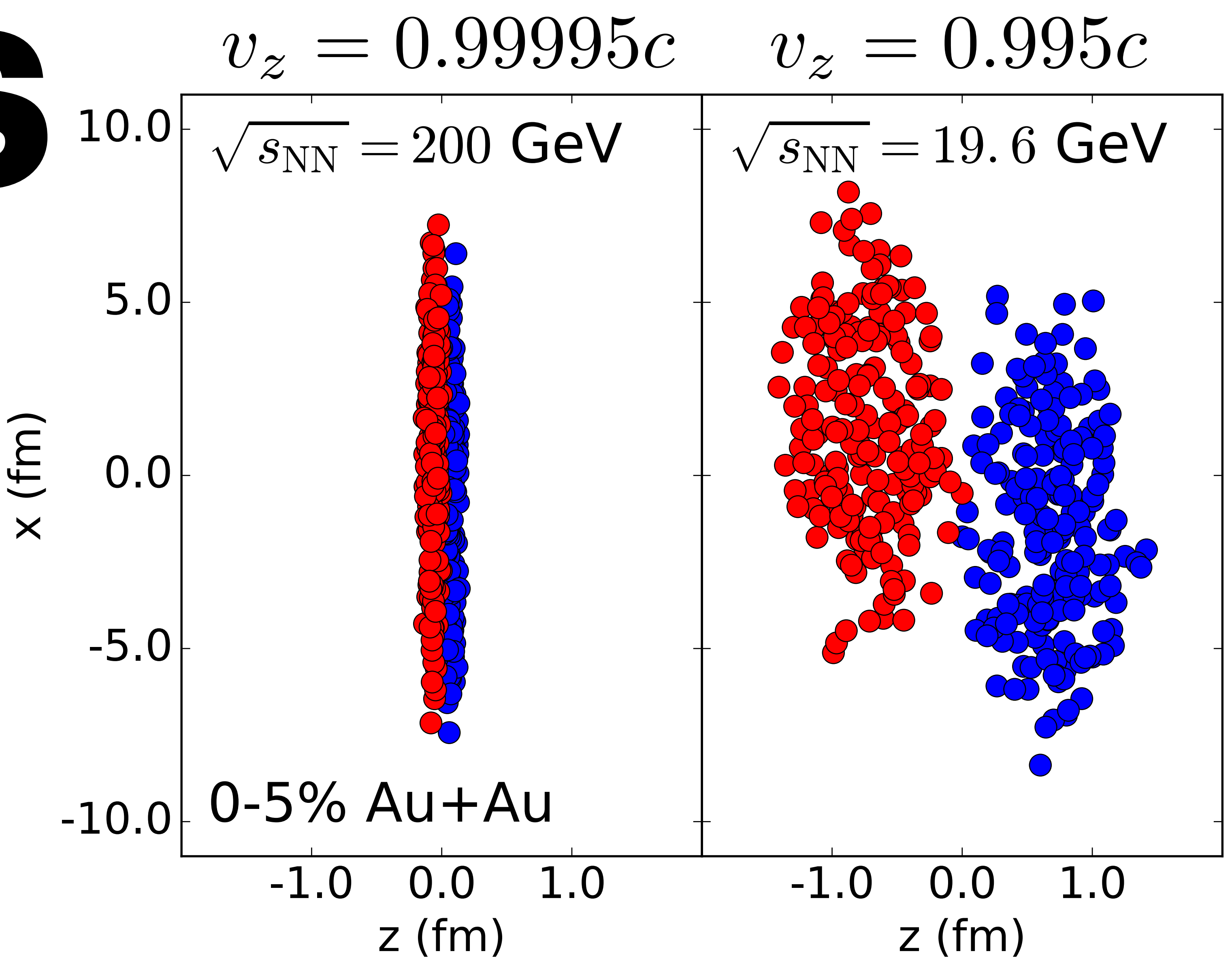
PART III: LOWER ENERGIES

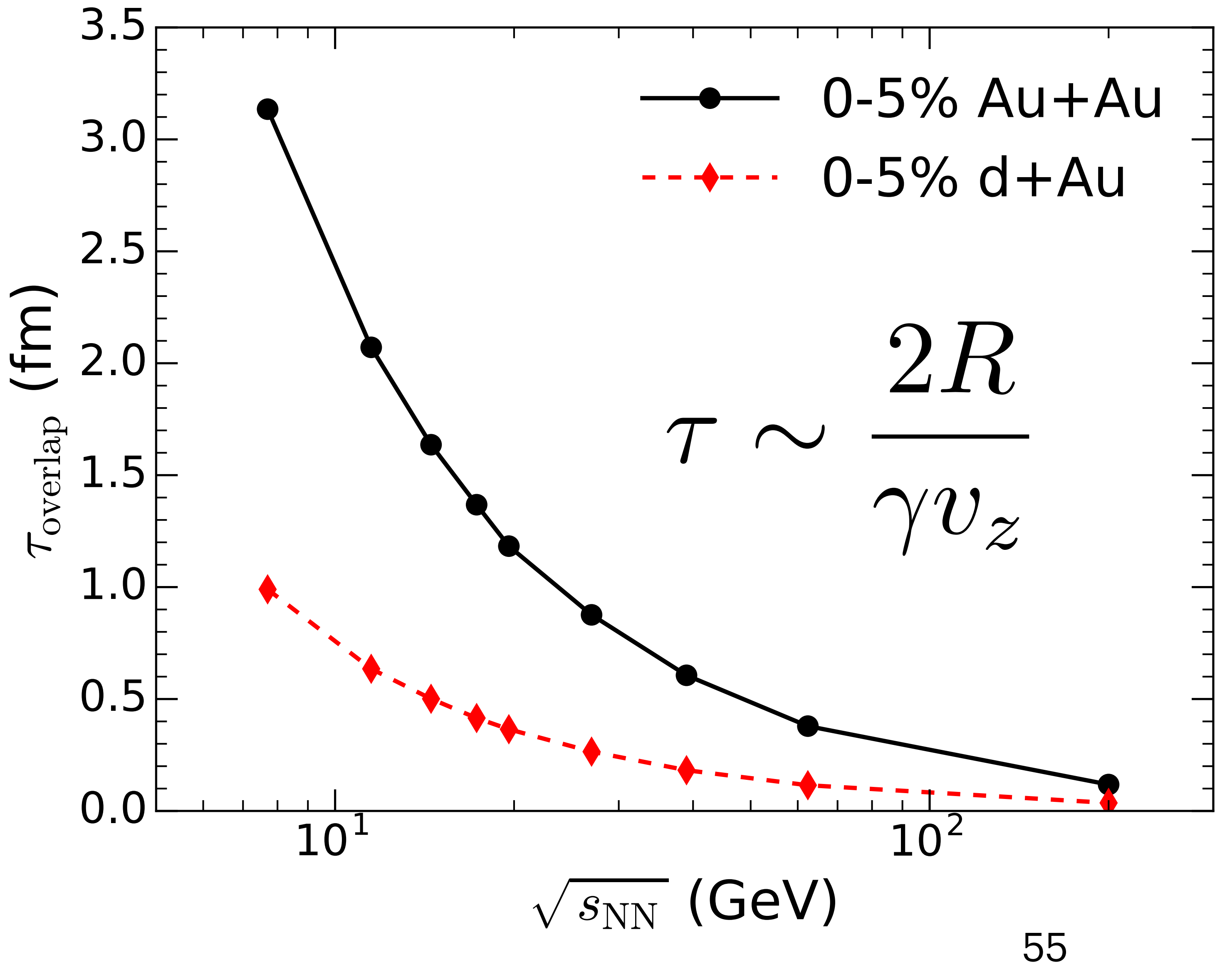
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

For lower energies, the CGC has very limited validity

Model the initial state within a dynamical string deceleration model

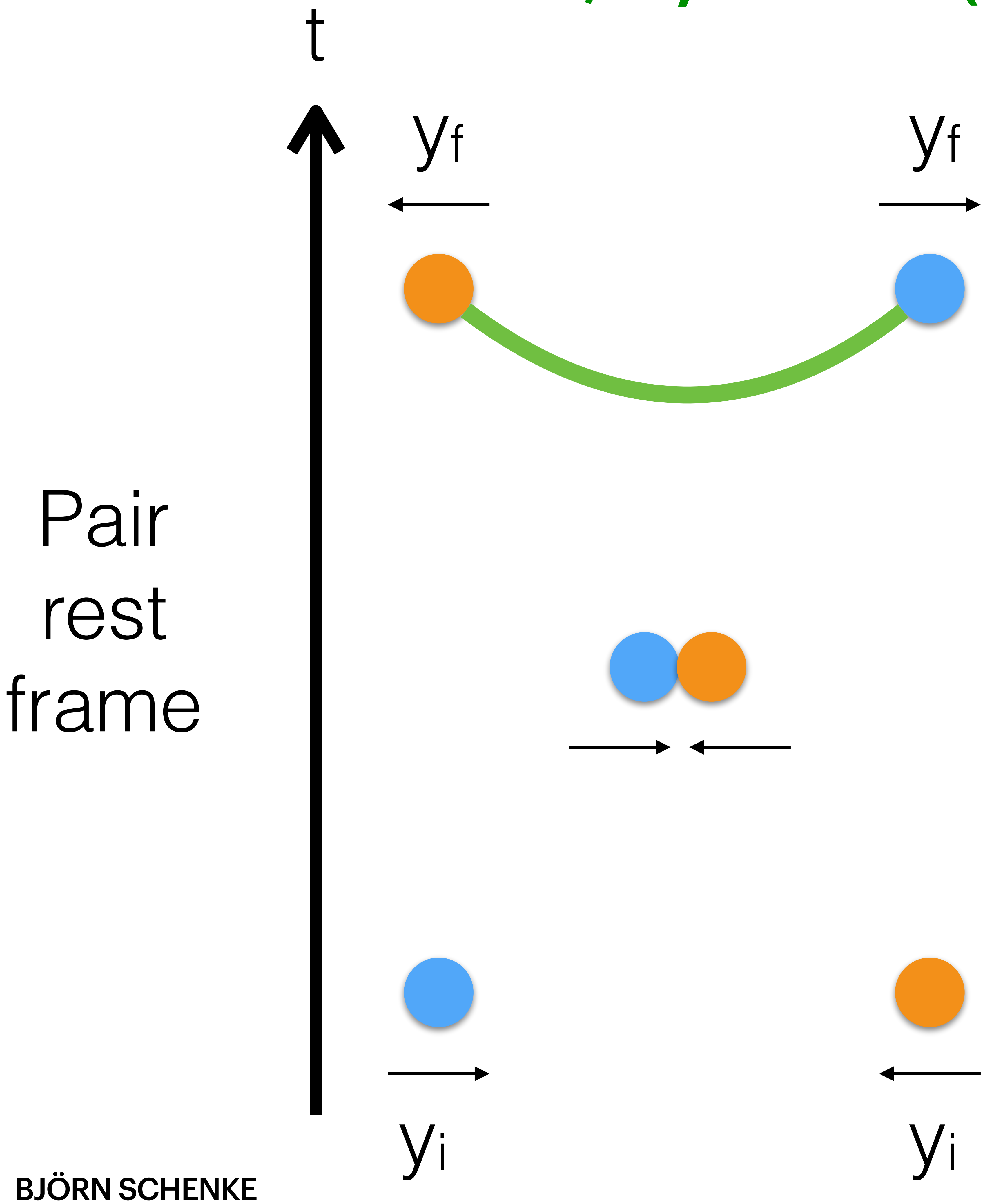






3D MC-GLAUBER + STRING MODEL

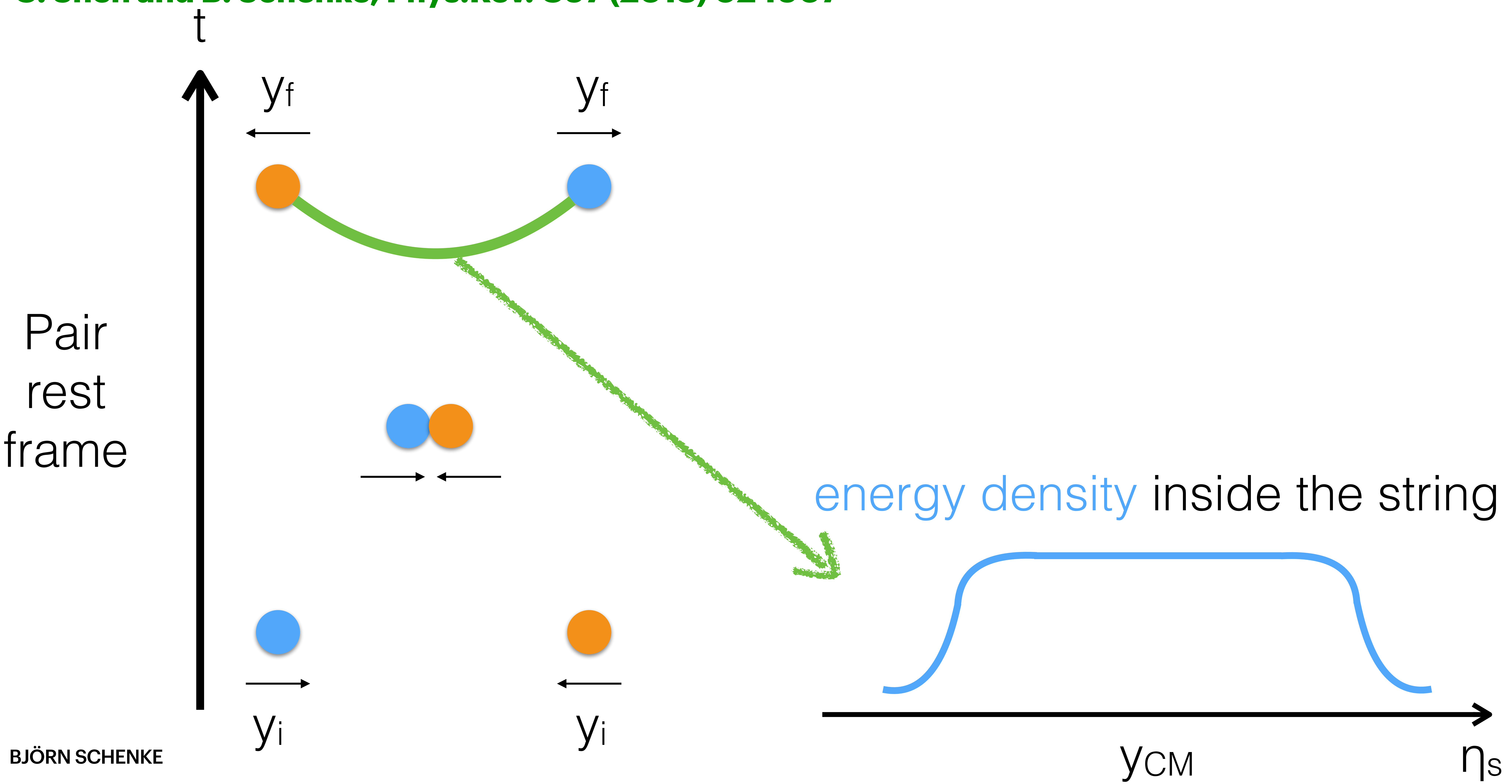
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



- Collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF and randomly picked to lose energy during a collision $\left(\sum_i x_i \leq 1\right)$
- Incoming quarks are decelerated with a classical string tension,

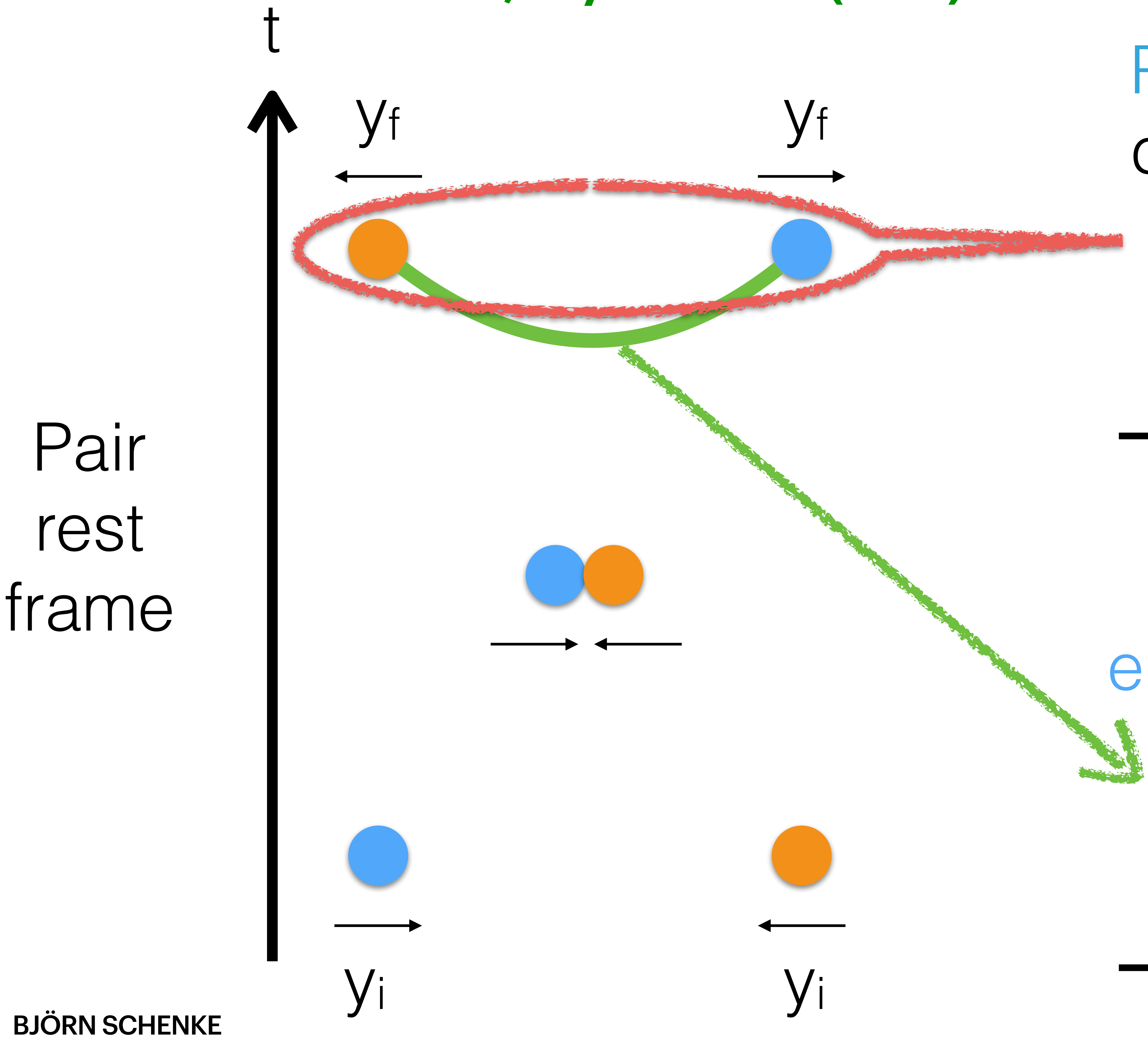
3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

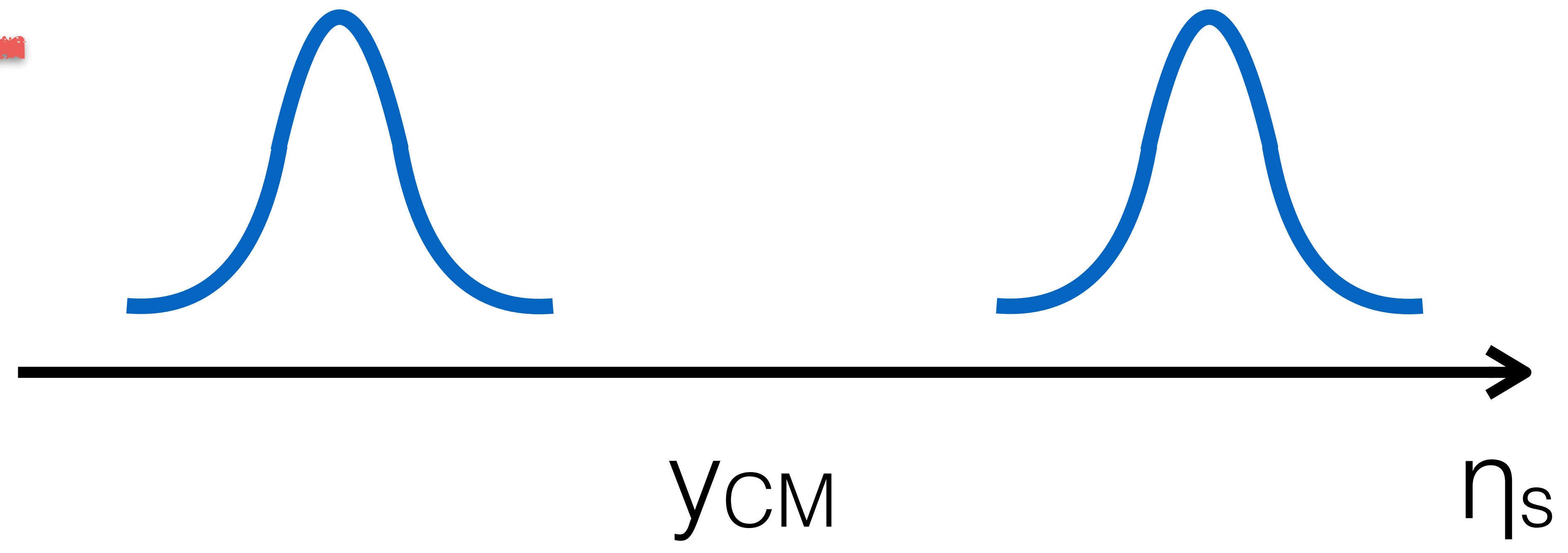


3D MC-GLAUBER + STRING MODEL

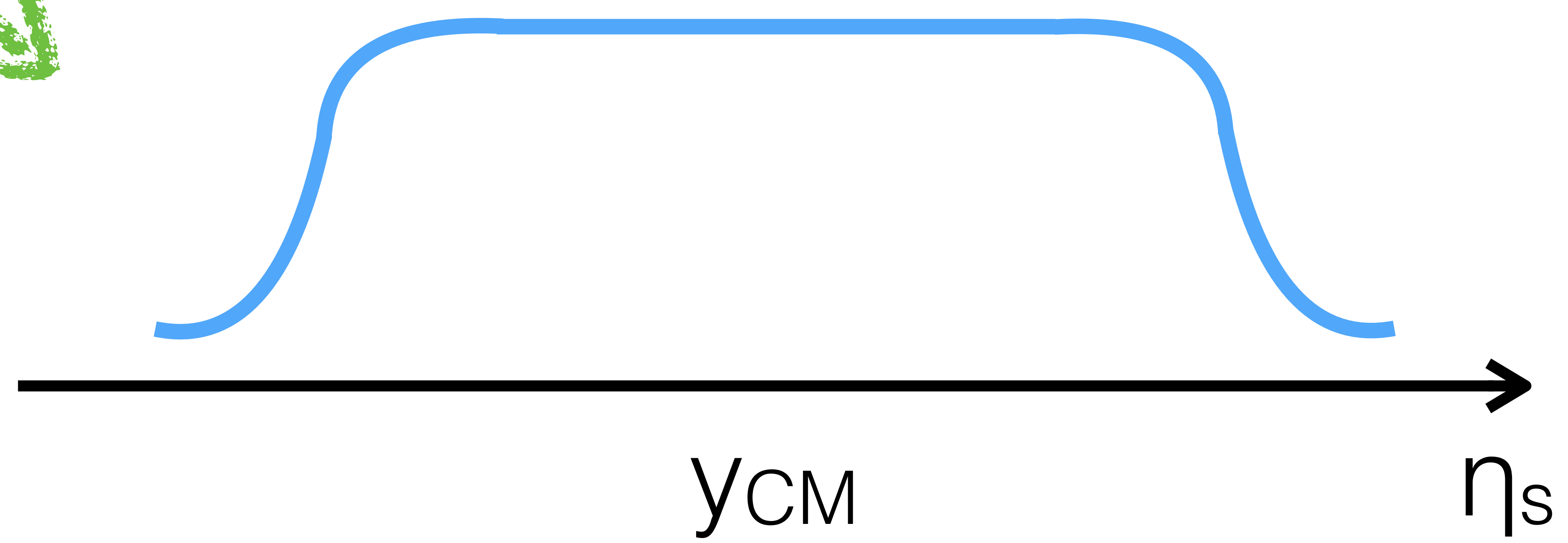
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



Partons' remaining energies are deposited at the string ends

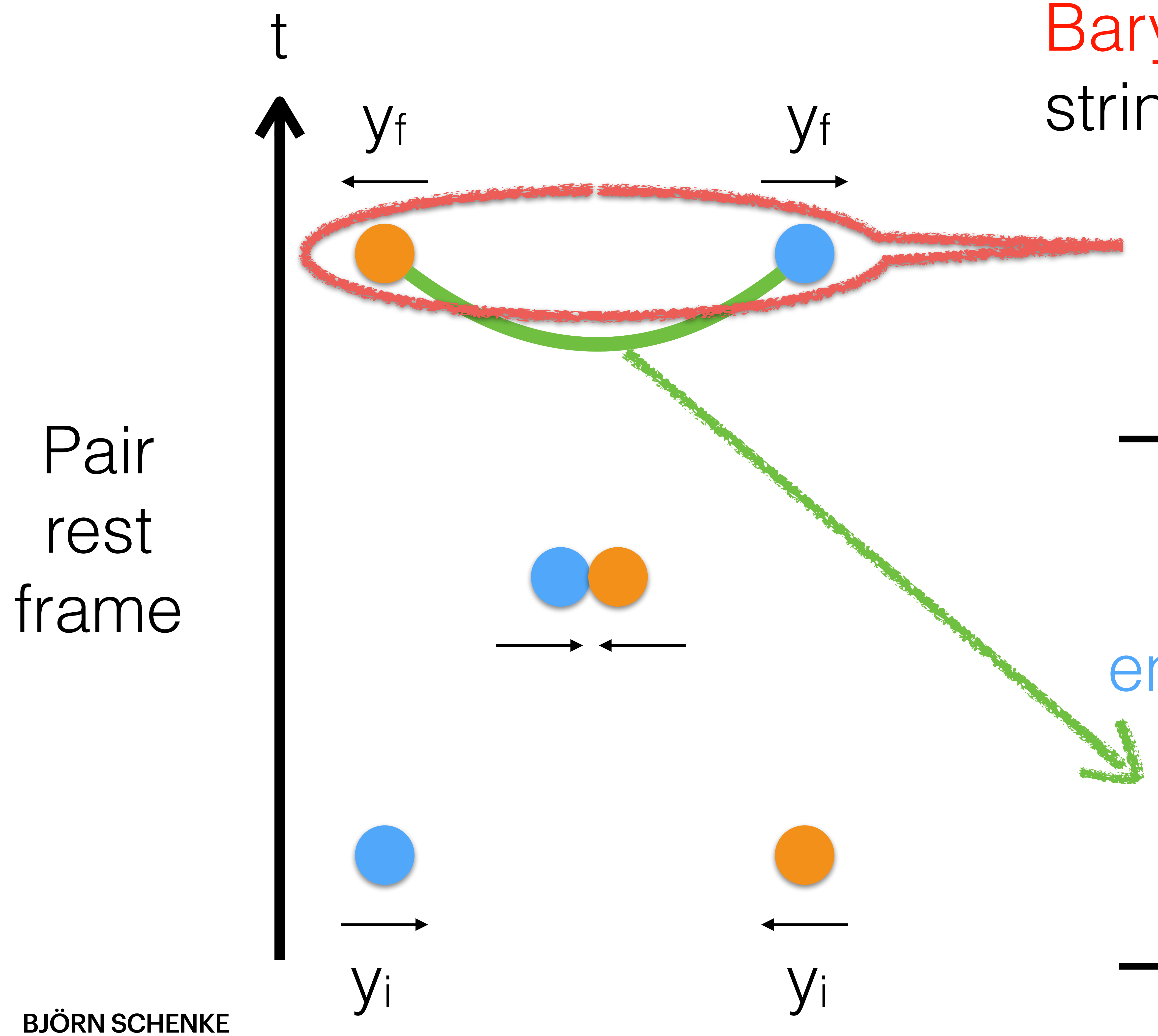


energy density inside the string

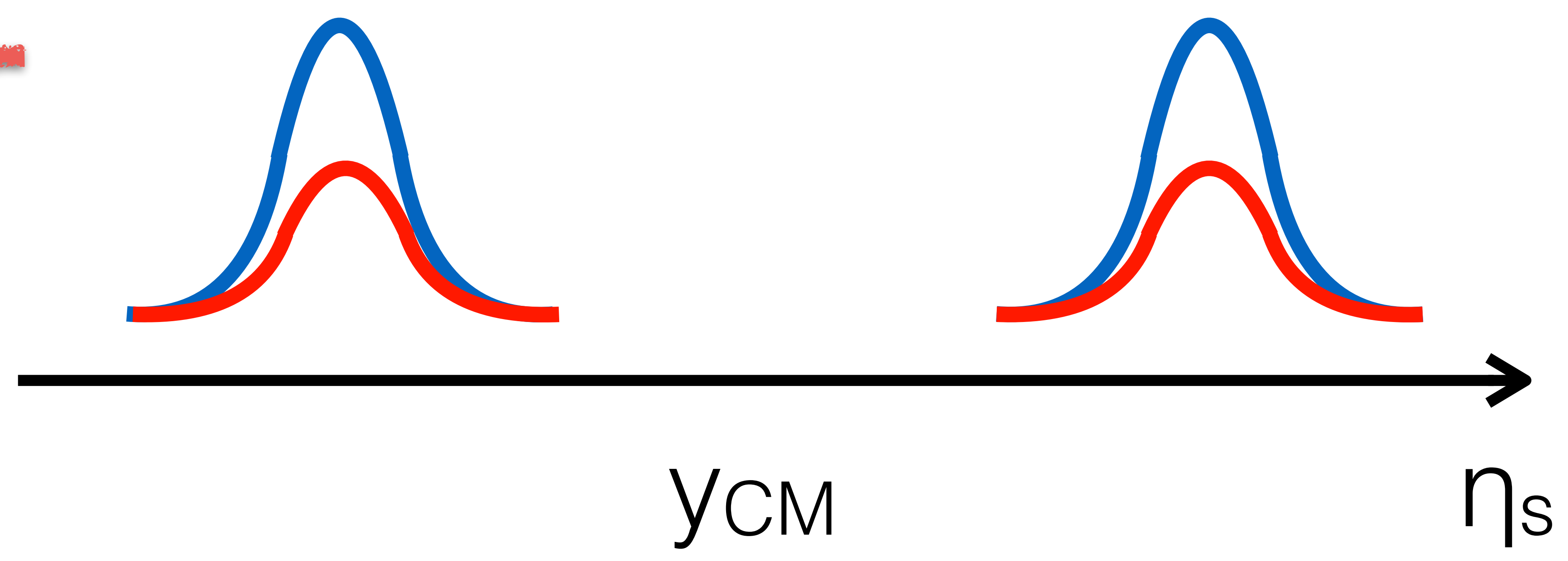


3D MC-GLAUBER + STRING MODEL

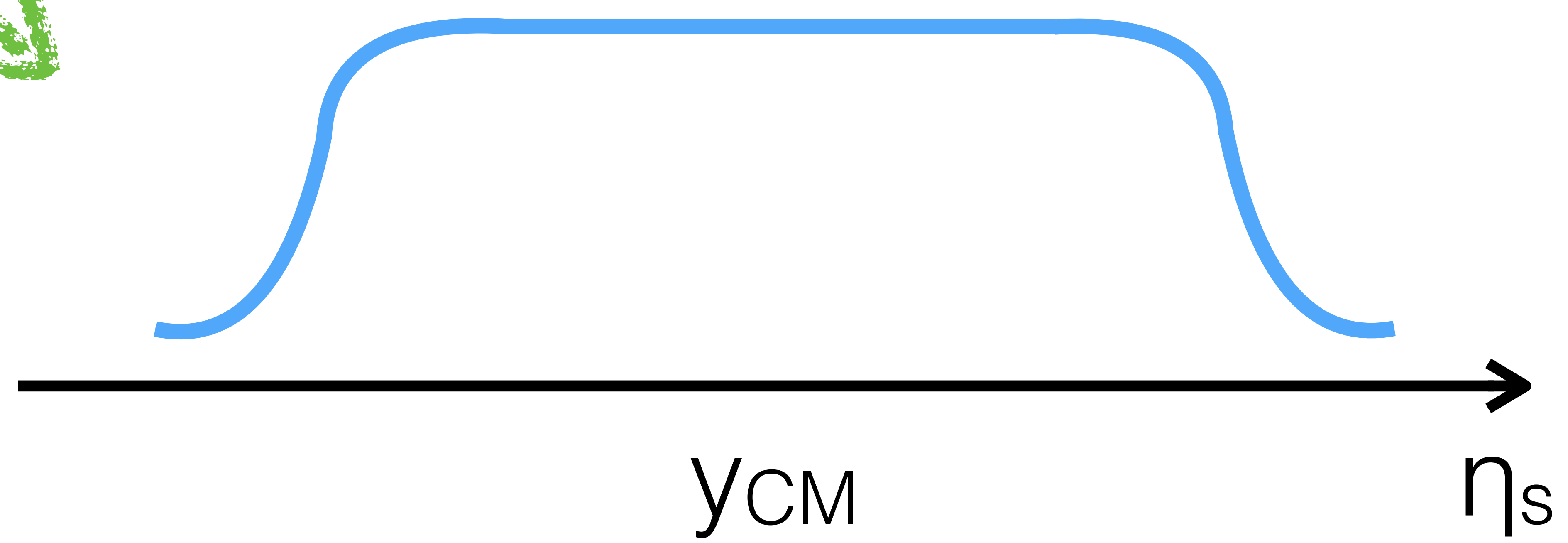
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



Baryon density is deposited at the string ends

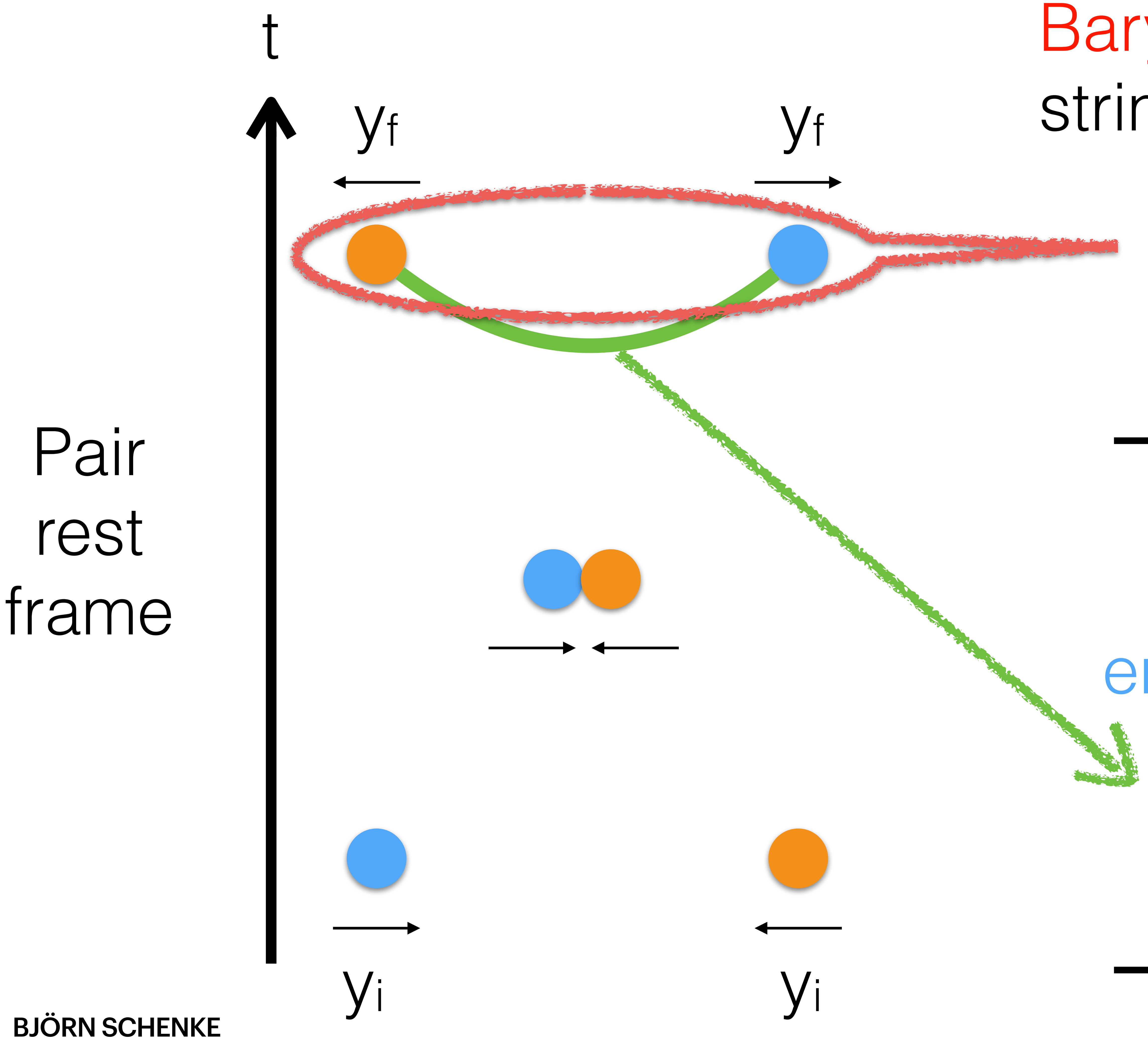


energy density inside the string



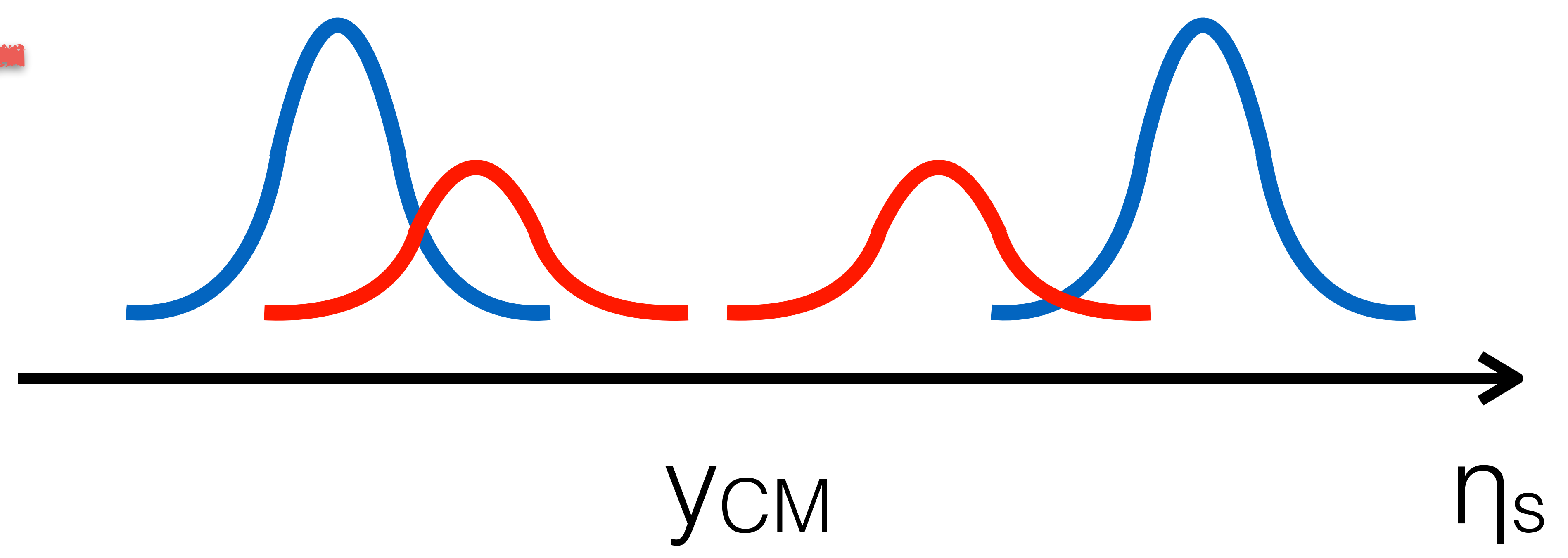
3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

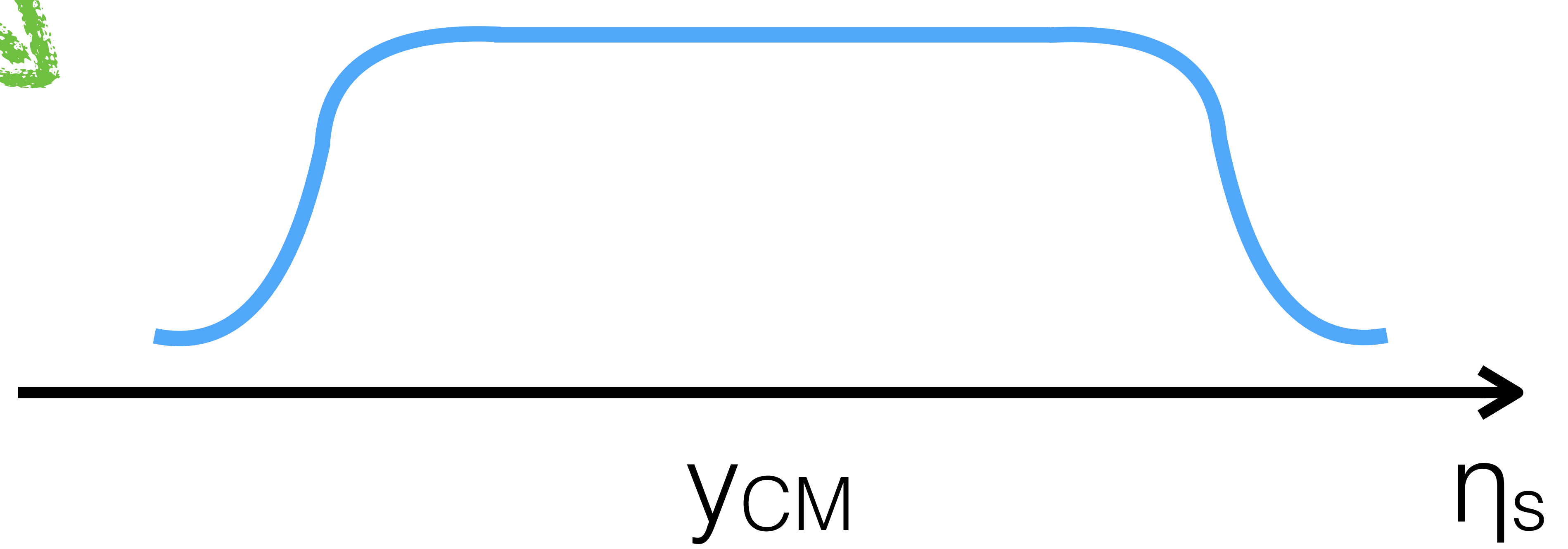


Baryon density is deposited at the string ends or string junctions

D. Kharzeev, Phys. Lett. B 378, 238 (1996)

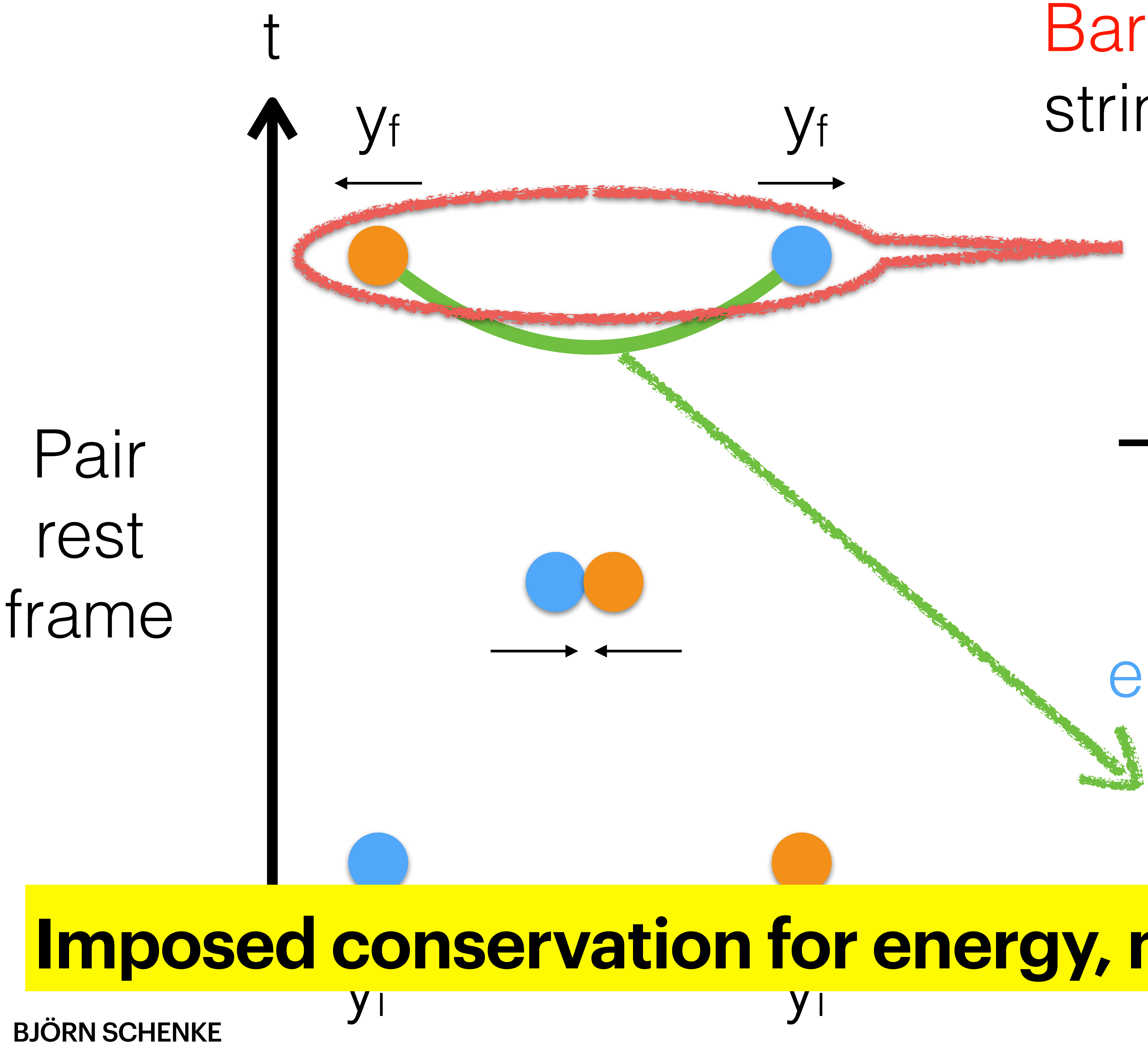


energy density inside the string



3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



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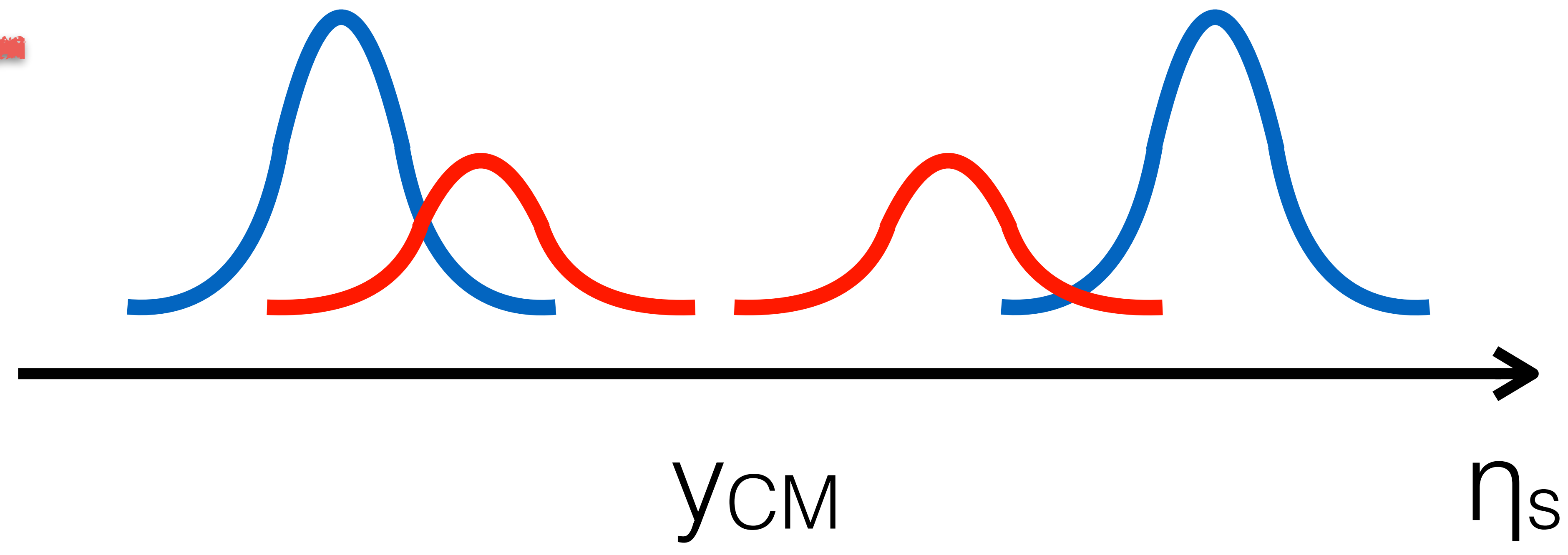
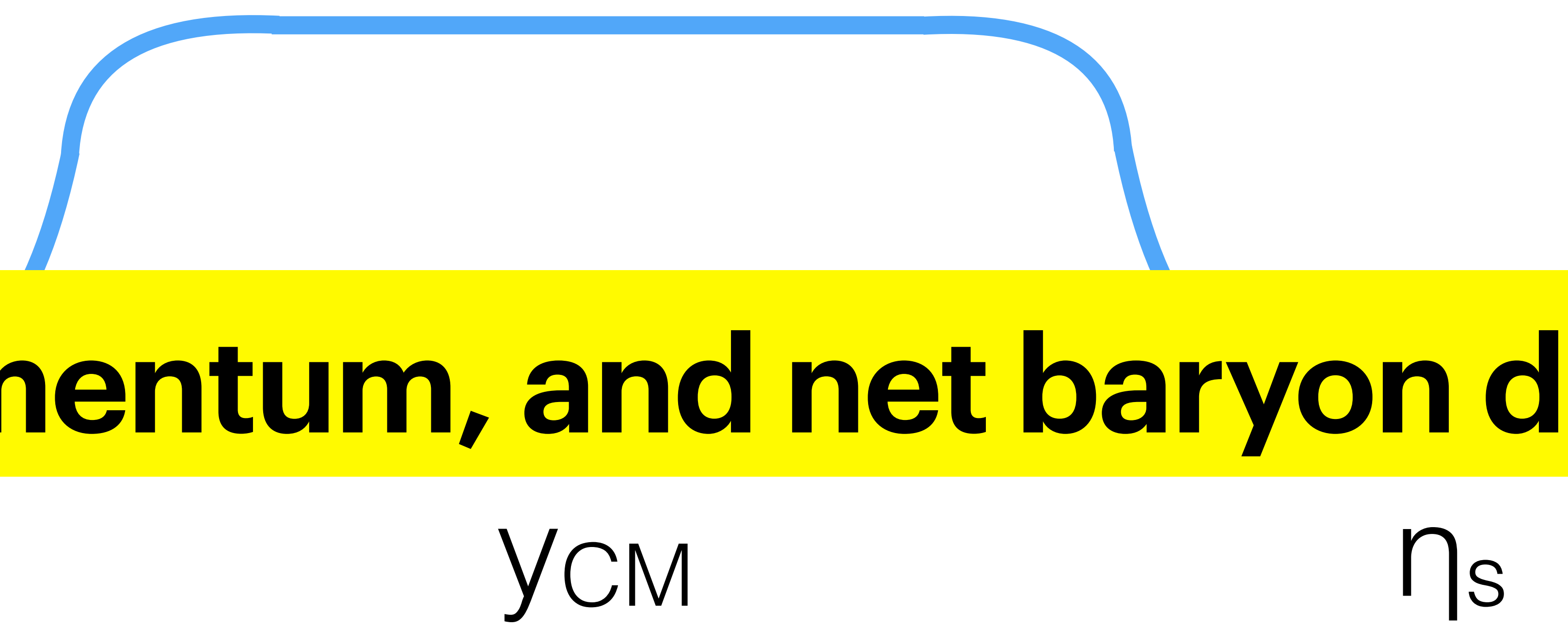
D. Kharzeev, Phys. Lett. B 378, 238 (1996)



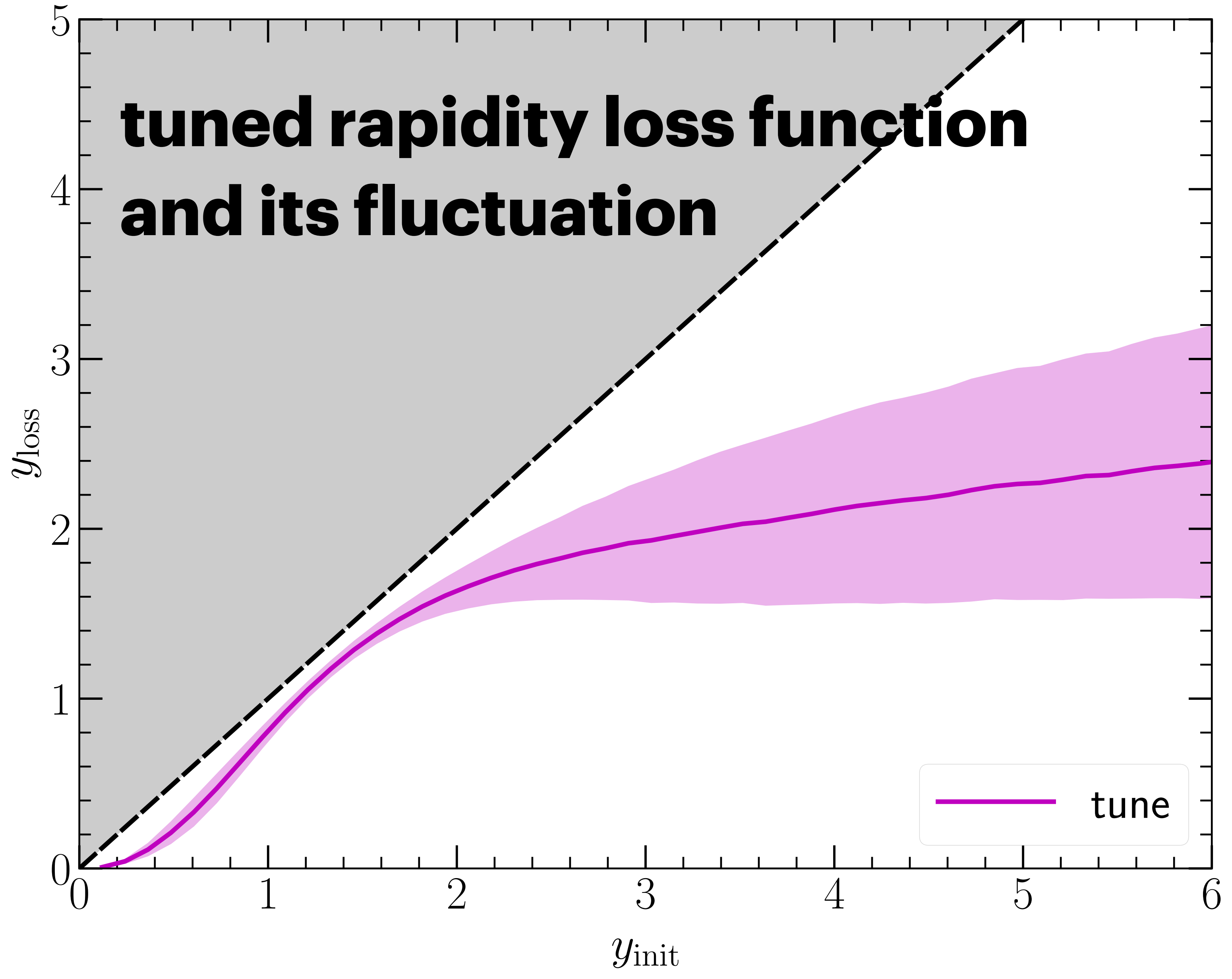
energy density inside the string

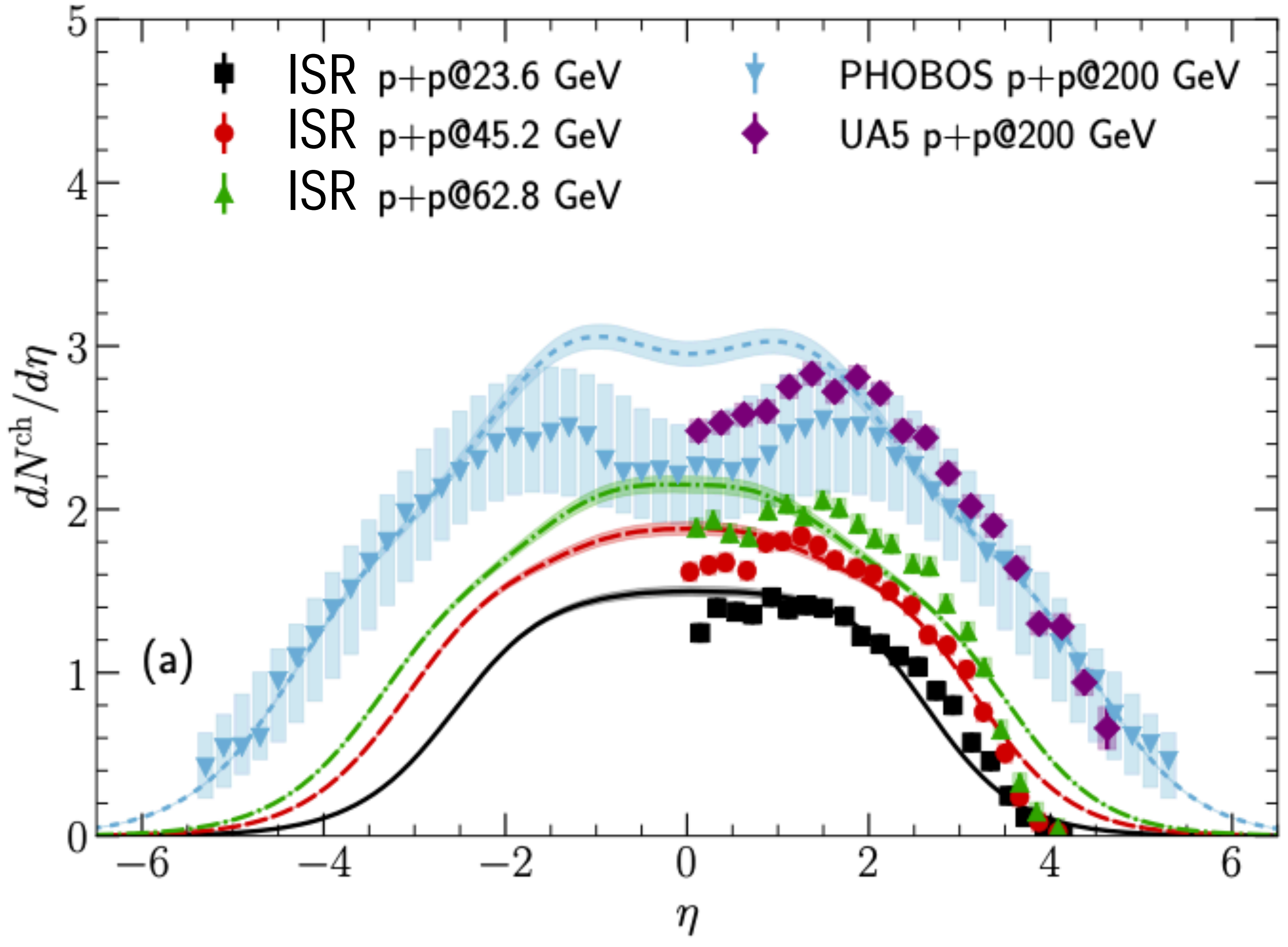


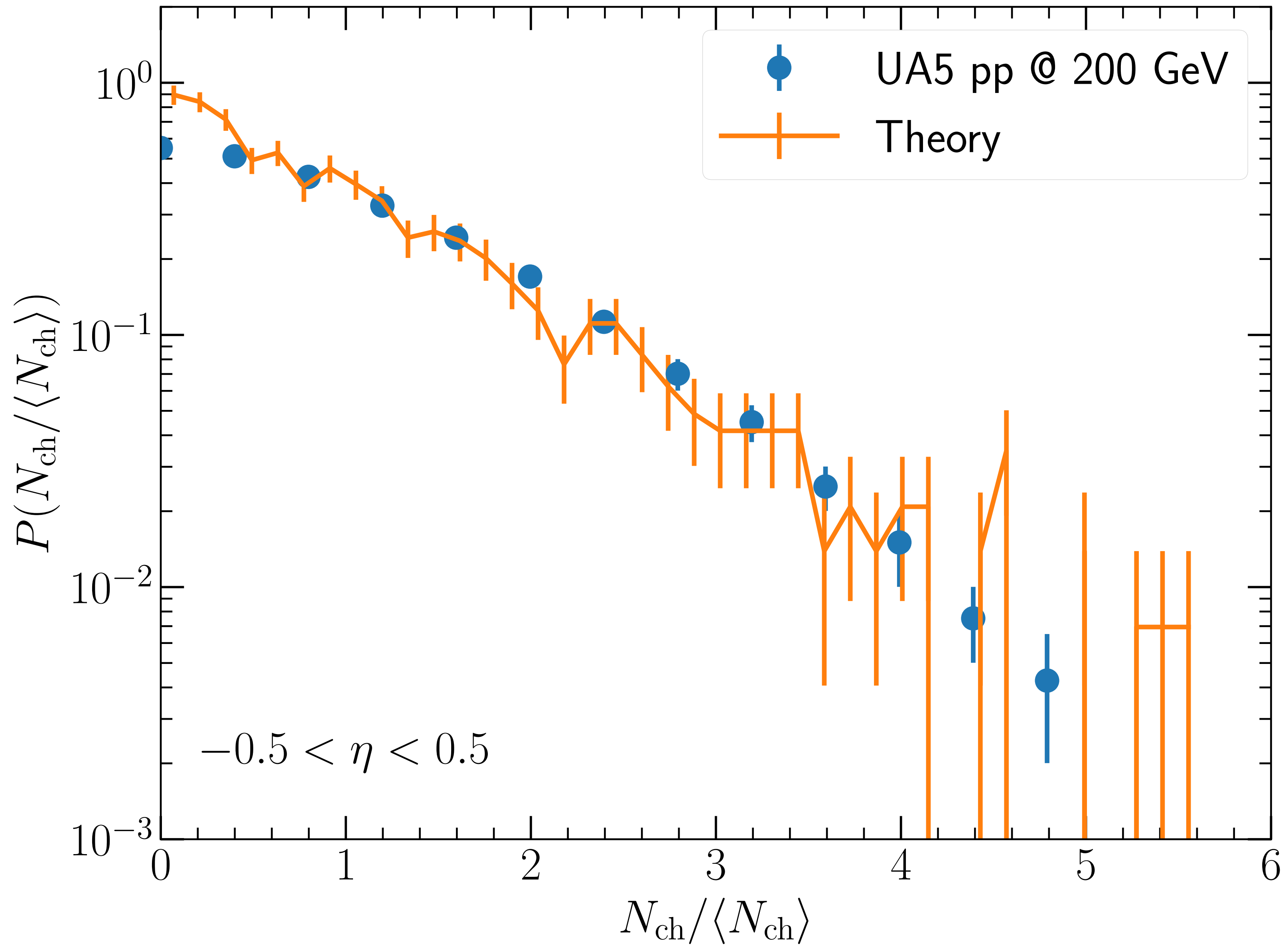
Imposed conservation for energy, momentum, and net baryon density

3D MC-GLAUBER + STRING MODEL+MUSIC

C. Shen and B. Schenke, in preparation







- **Feed energy and momentum of the strings dynamically into hydrodynamics via source terms**
- **Calibrated with minimum bias pp measurements at mid-rapidity and their multiplicity distributions**

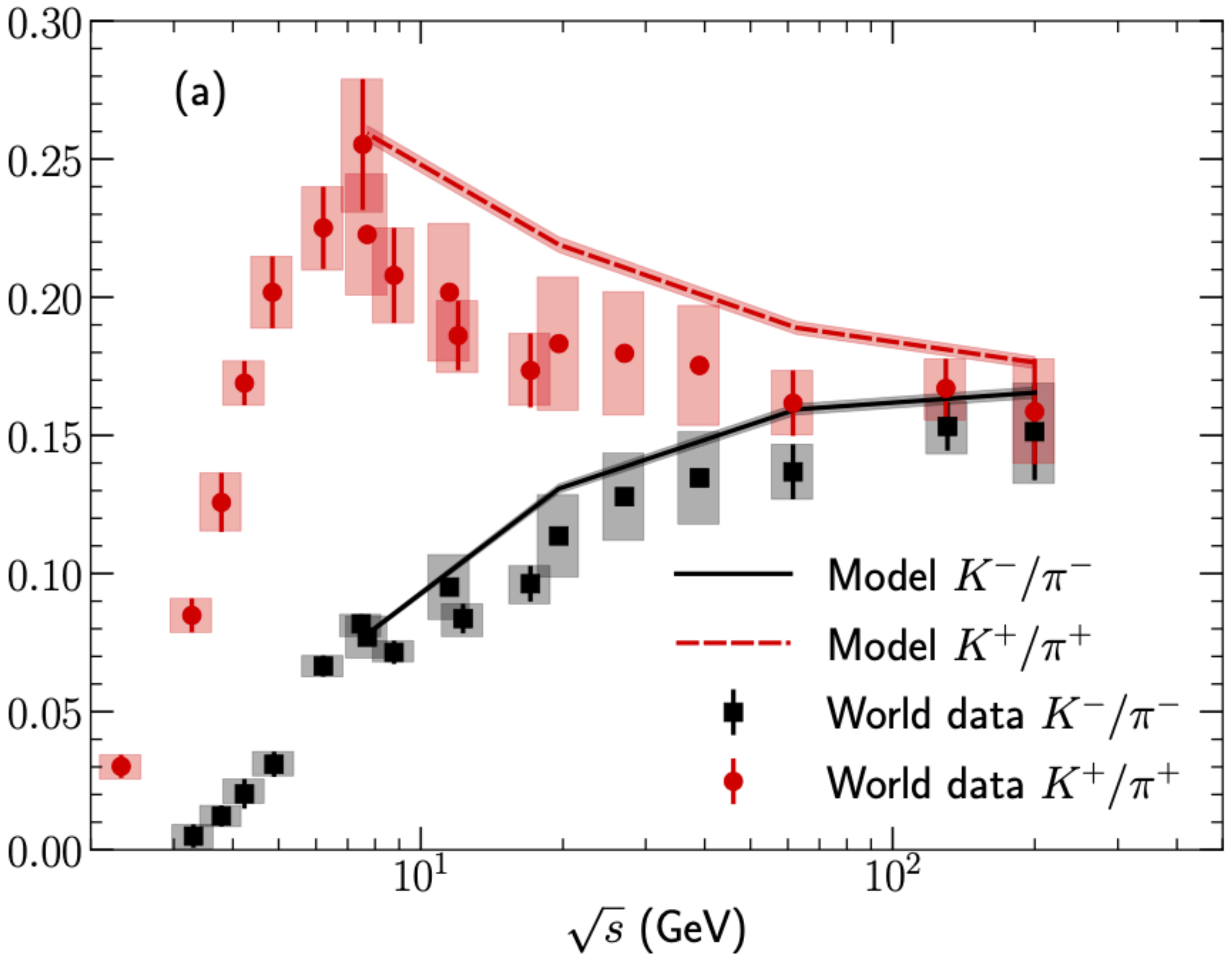
HYDRODYNAMICS AND EOS

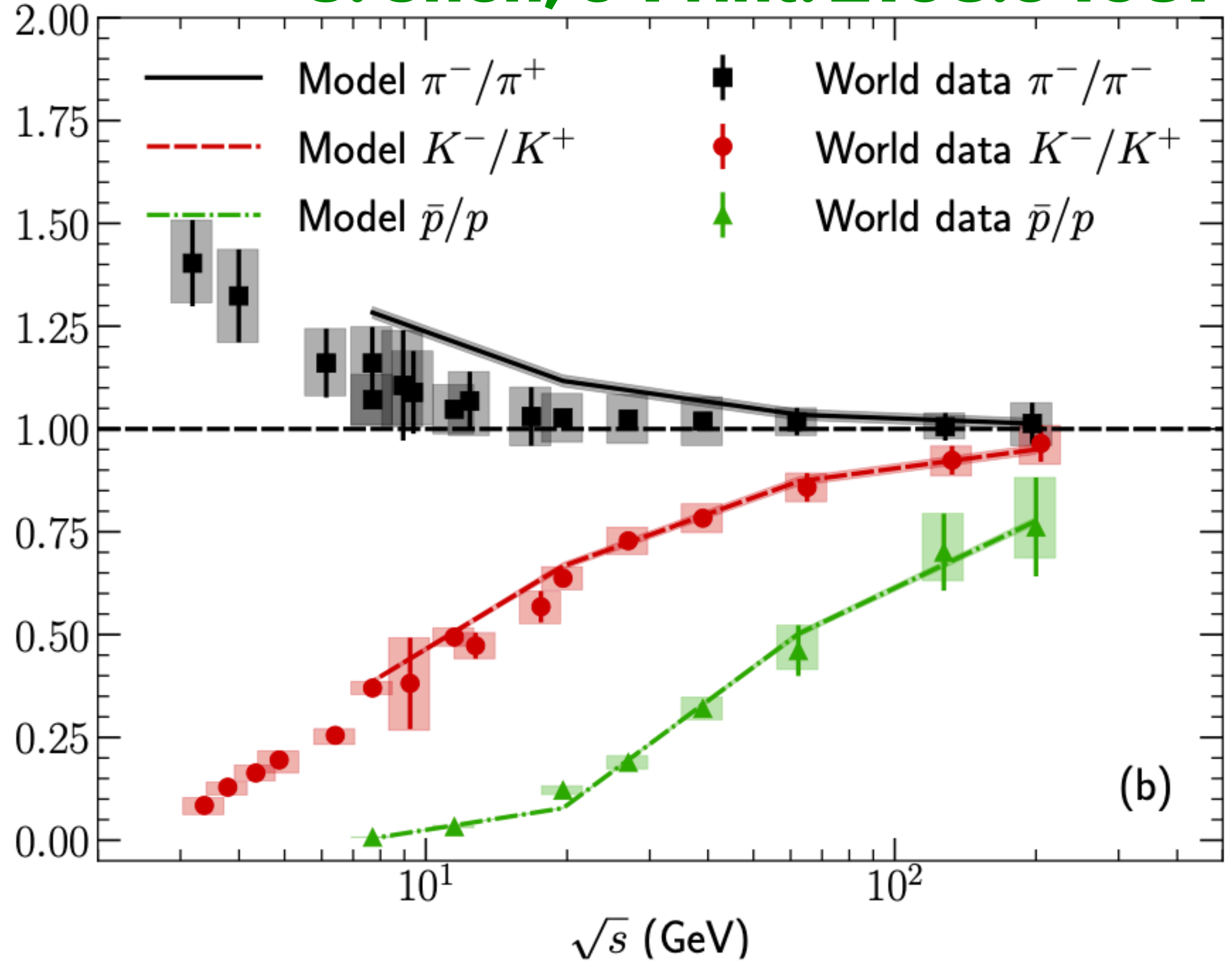
- **For the equation of state we use NEOS with finite μ_B, μ_S, μ_Q**

  A. Monnai, B. Schenke, C. Shen, Phys. Rev. C 100, 024907 (2019)
  A. Monnai, B. Schenke, C. Shen, Int.J.Mod.Phys.A 36 (2021) 07, 2130007

And choose $n_S = 0$ and $n_Q = 0.4 n_B$ for Au+Au collisions:

C. Shen, e-Print: 2108.04987

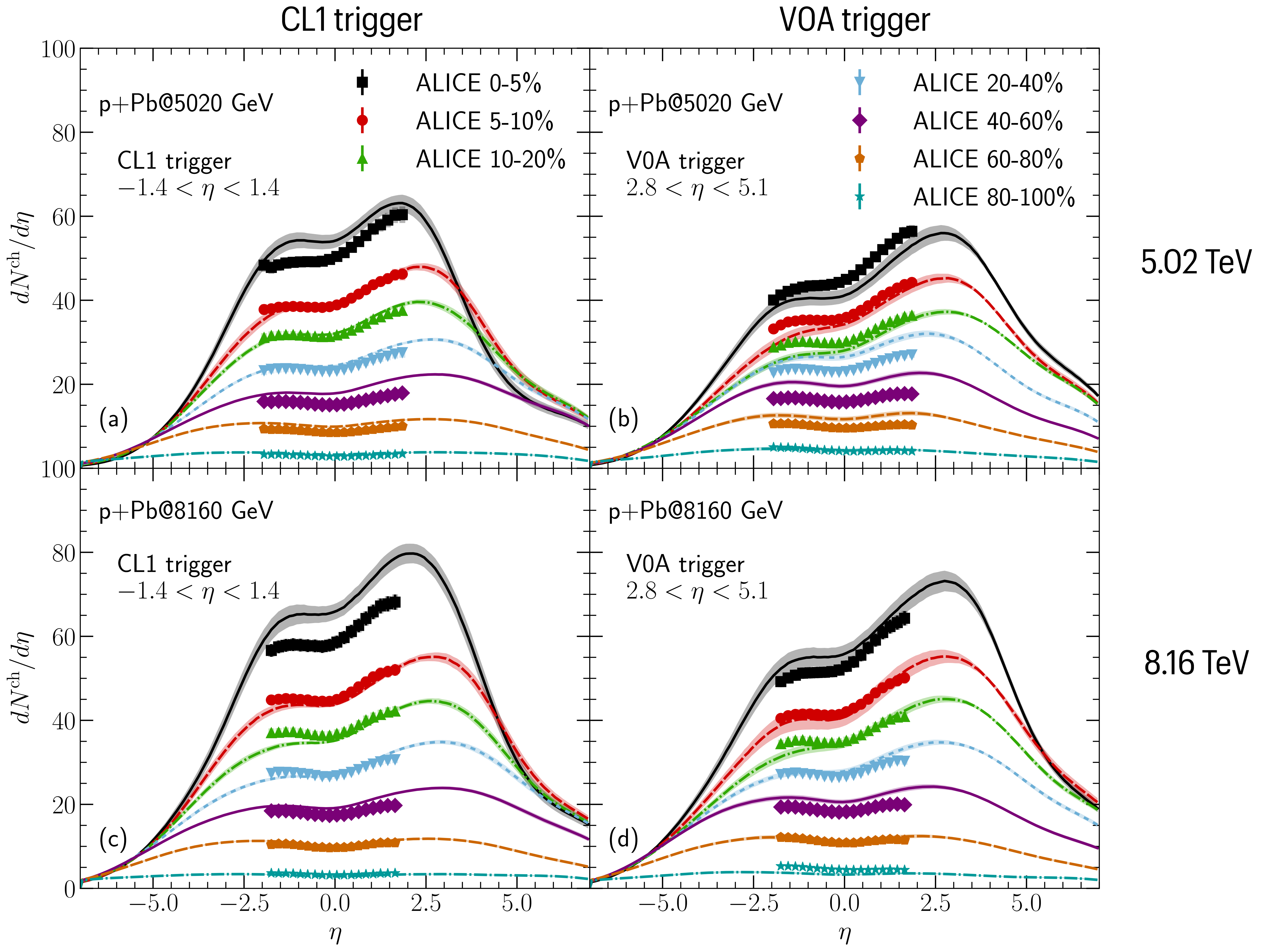




CENTRALITY DEFINITION

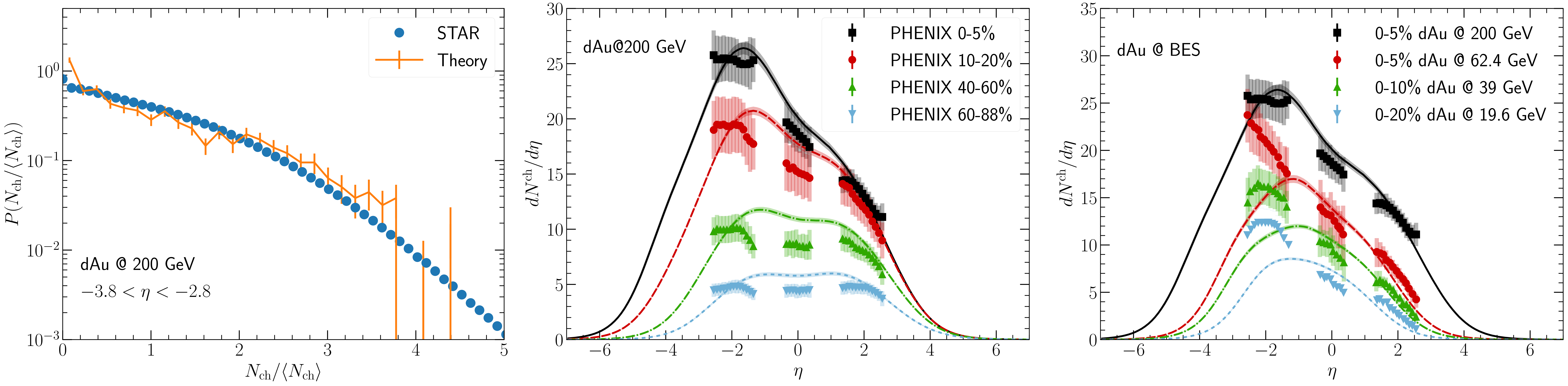
C. Shen and B. Schenke, in preparation

- **We can now determine centrality in the same rapidity bins as the experiments**
- **It does make a difference for the shape of the rapidity distribution**



MULTIPLICITY DISTRIBUTIONS

C. Shen and B. Schenke, in preparation

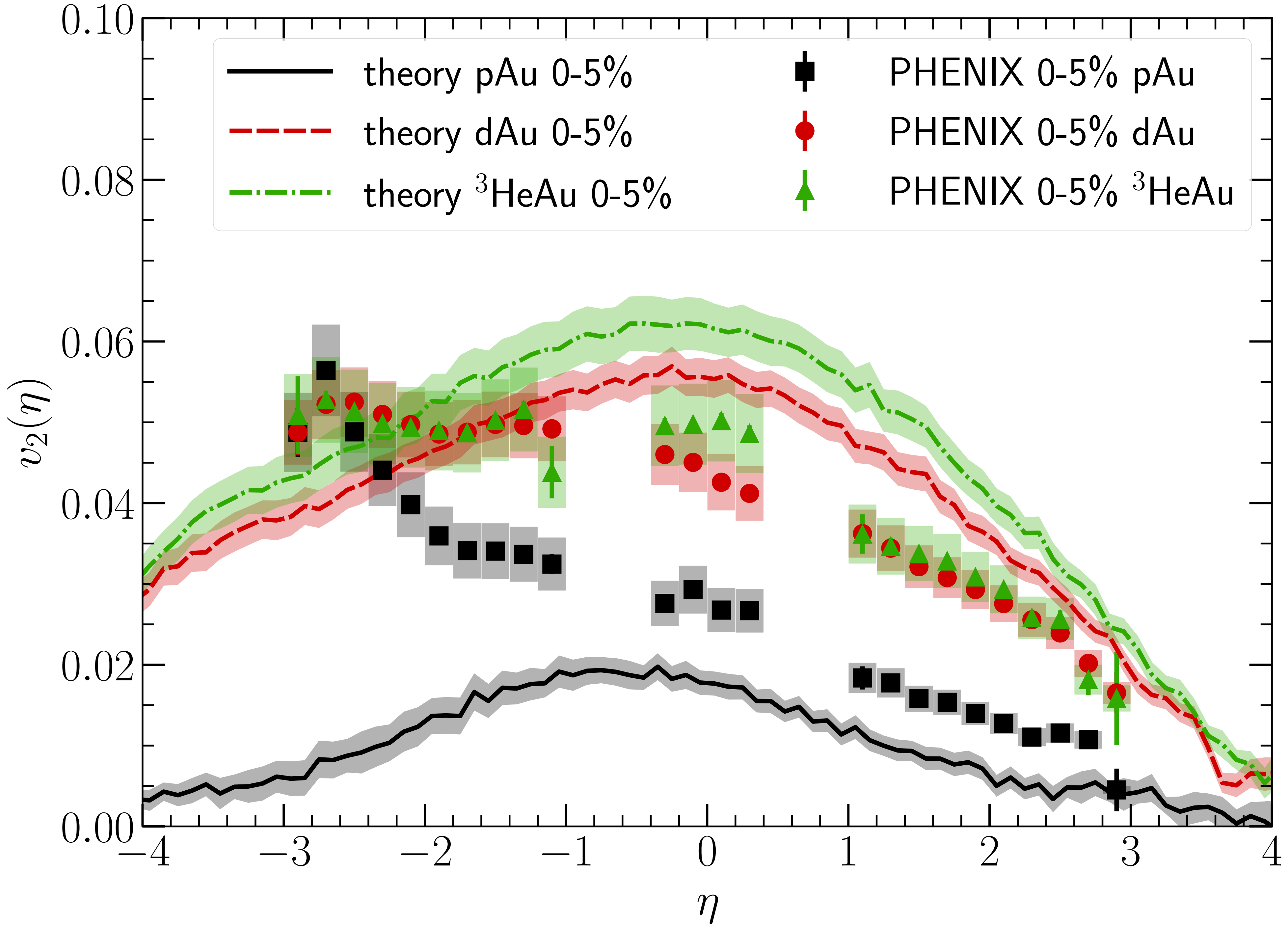


- **Model reproduces the STAR multiplicity distribution in d+Au collisions at 200 GeV**
- **The predicted charged hadron rapidity distribution agrees well with the PHENIX measurements from central to peripheral collisions**
- **The role of spectators at forward rapidity needs further investigation**

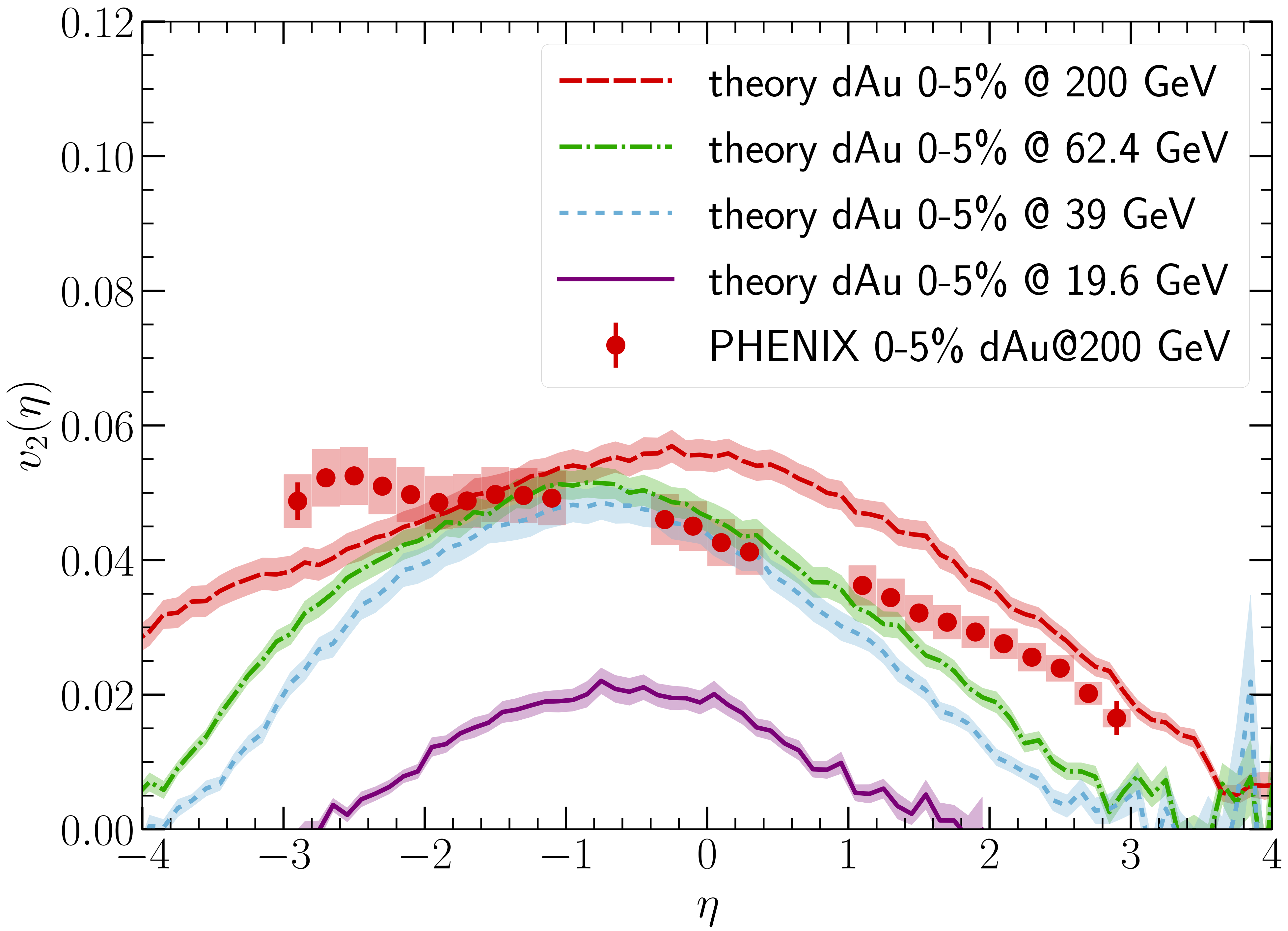
ANISOTROPIC FLOW

C. Shen and B. Schenke, in preparation

System dependence



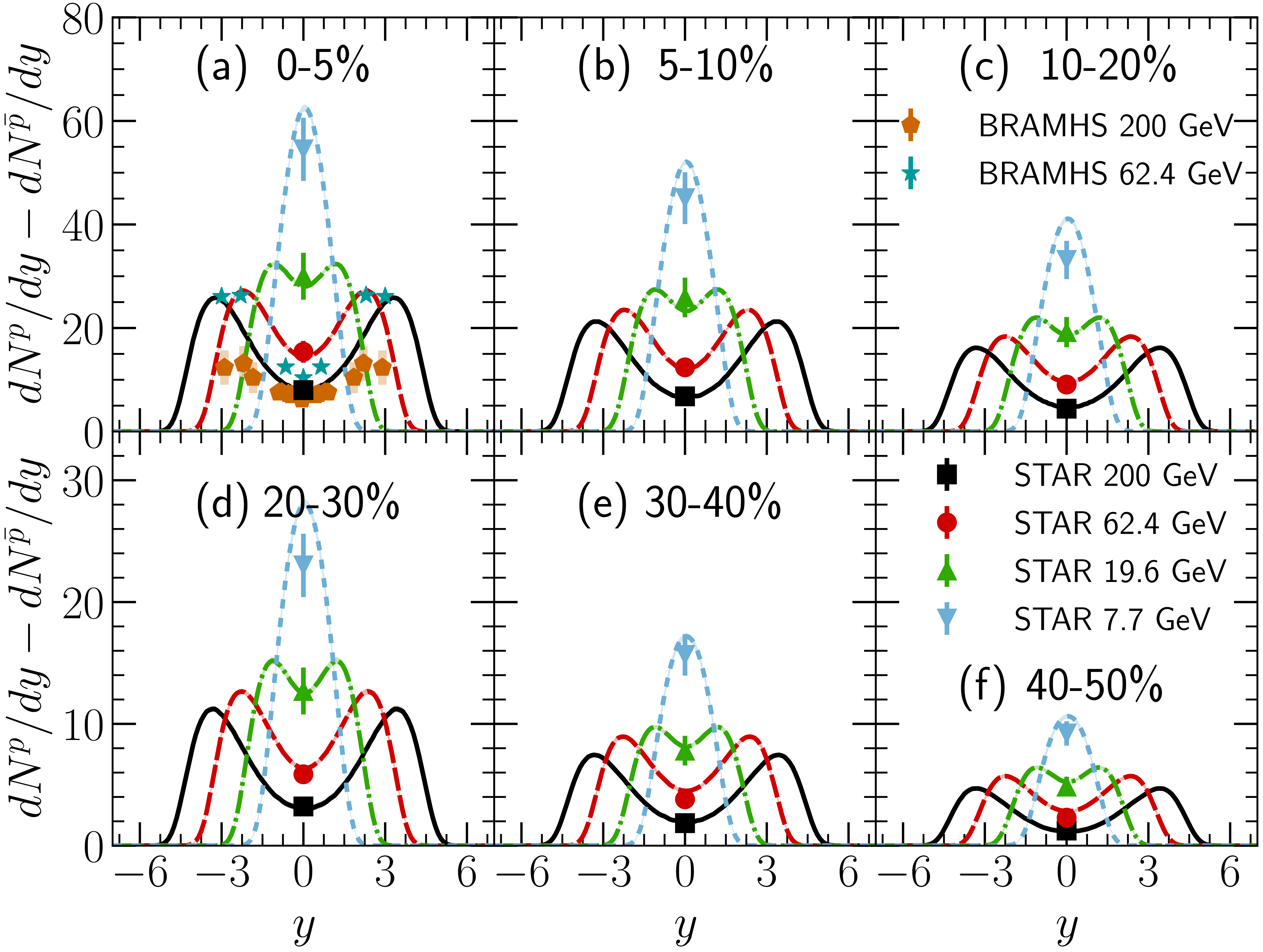
Energy dependence



- **Discrepancies could come from different method being used in the experiment**
- **Biggest deviation from the data in p+Au in the Au going direction (non-flow?)**
- **PHENIX event plane method with event plane at *y* in [-3.9, -3.1]**

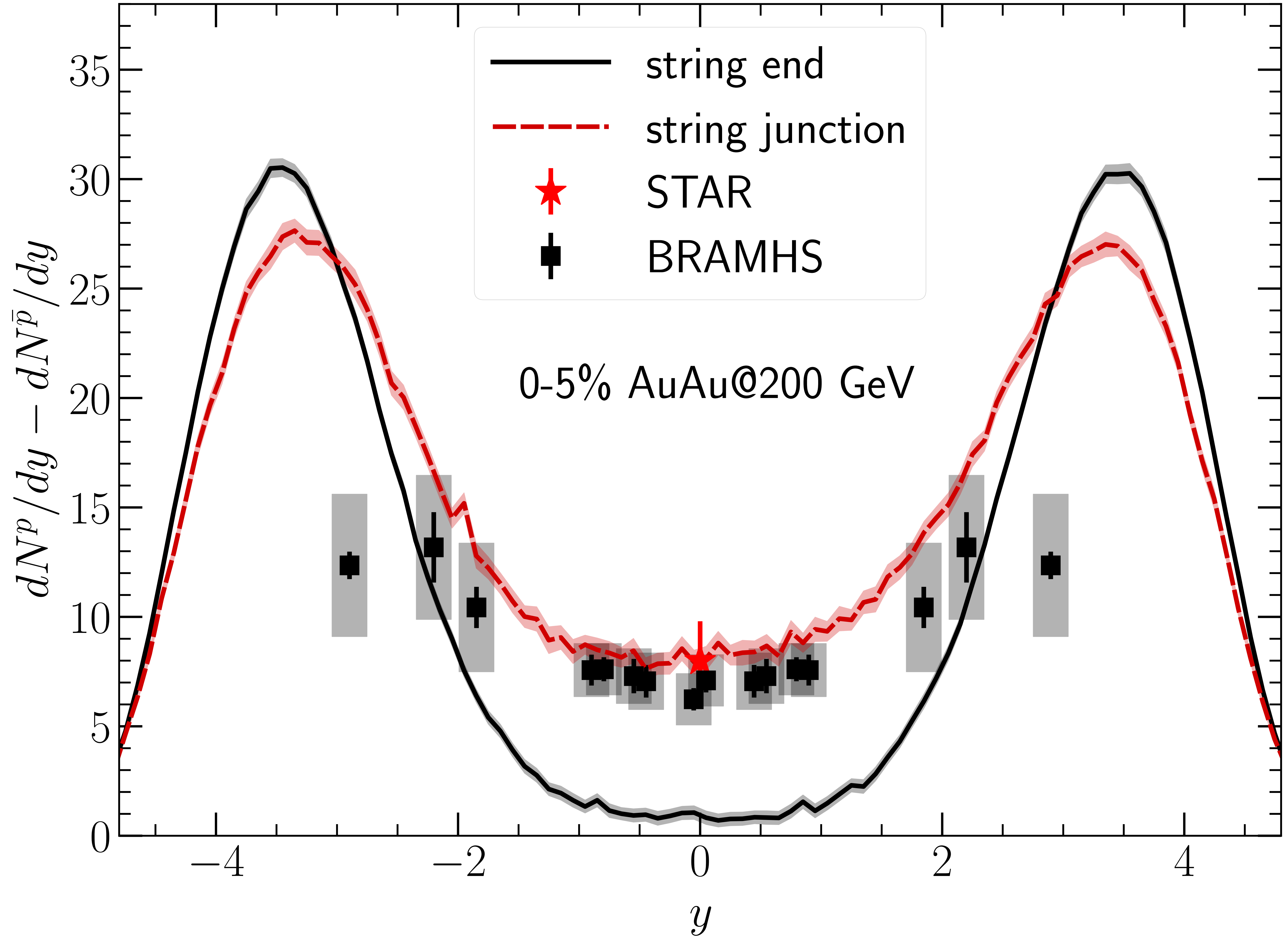
NET-BARYON DISTRIBUTIONS

C. Shen and B. Schenke, in preparation

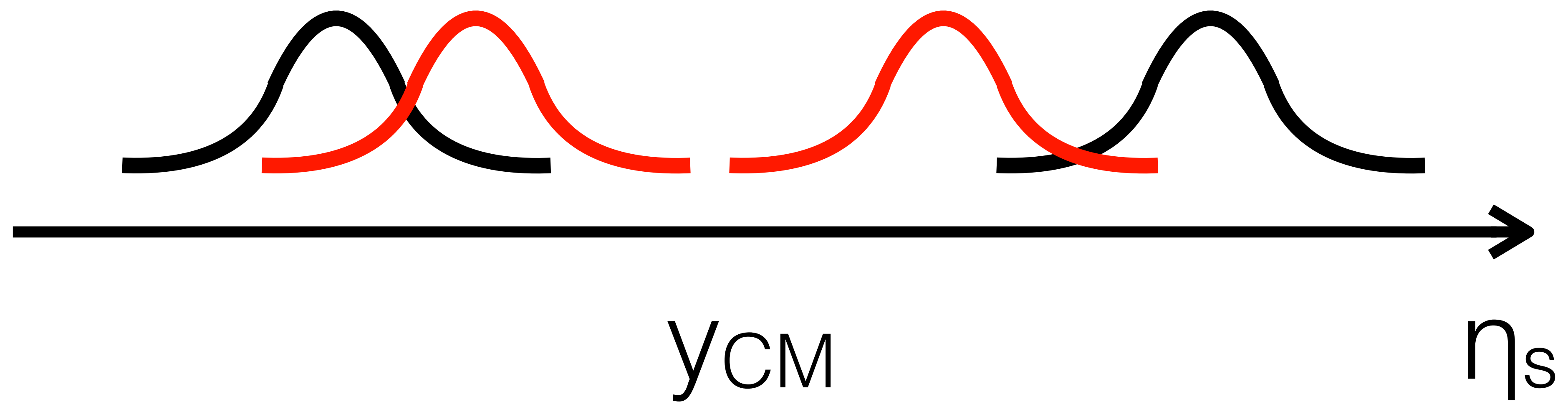


NET-BARYON DISTRIBUTIONS

C. Shen and B. Schenke, in preparation



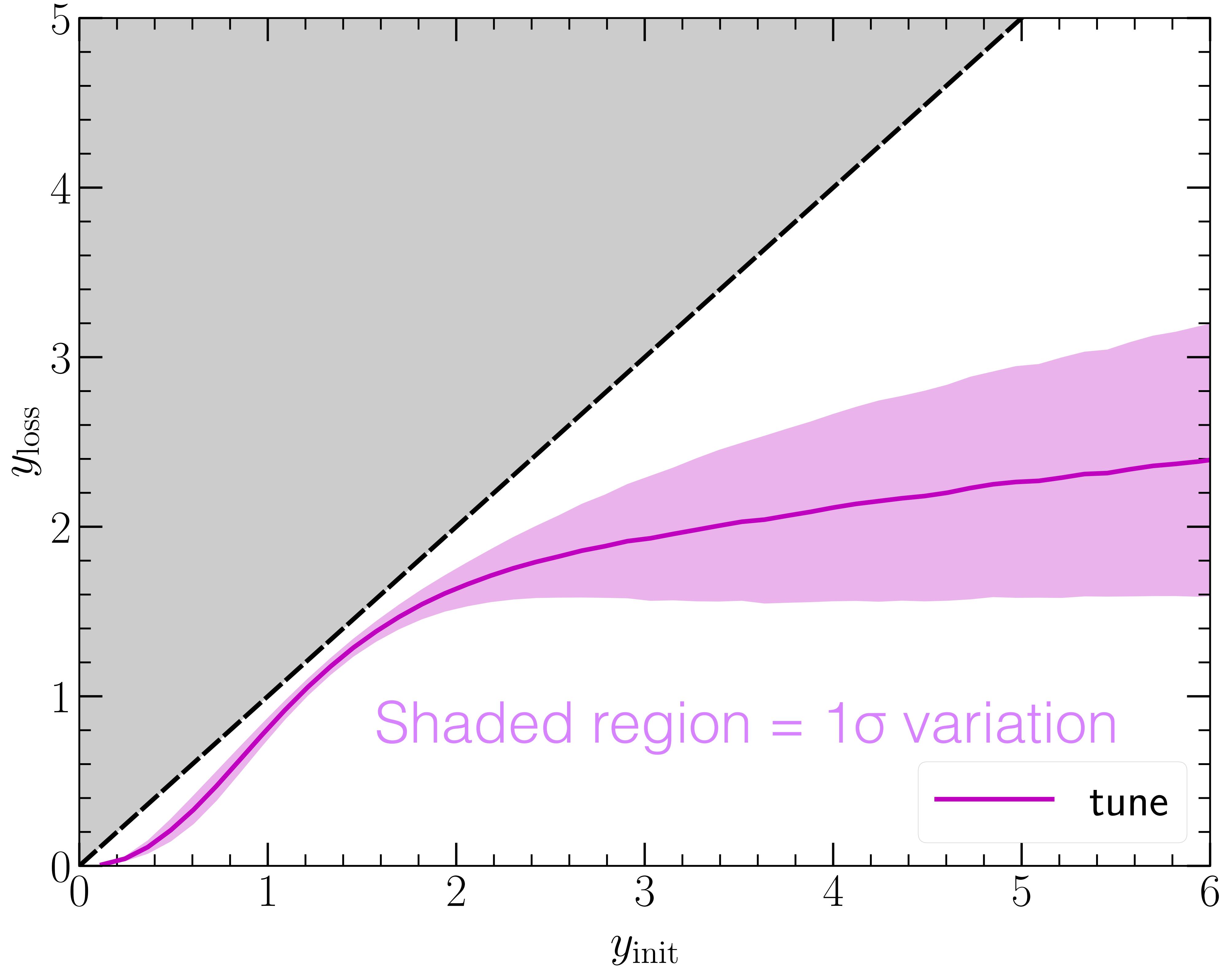
Effect of baryon junctions



3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, in preparation

Parametrize the valence quark energy loss



$$\langle y_{\rm loss}\rangle = A y_{\rm init}^{\alpha_2}[\tanh(y_{\rm init})]^{\alpha_1-\alpha_2}$$

- A: the slope
- At small y: $\langle y_{\rm loss}\rangle \propto y_{\rm init}^{\alpha_1}$
- At large y: $\langle y_{\rm loss}\rangle \propto y_{\rm init}^{\alpha_2}$
- Std of $y_{\rm loss}$ fluctuations: σ_y ($y_{\rm loss} \in [0, y_{\rm init}]$)

...motivated by the baryon stopping extracted by the BRAHMS Collaboration

I. C. Arsene et al. (BRAHMS), Phys. Lett. B677, 267–271 (2009)

THE MODEL: IP-GLASMA

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

$$\rho(r,\theta) = \frac{\rho_0}{1+\exp[(r-R'(\theta))/a]},$$

with $R'(\theta) = R[1+\beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$, and ρ_0 the nuclear density at the center of the nucleus. R is the radius parameter, a the skin depth.

Nucleus	R [fm]	a [fm]	β_2	β_4
^{238}U	6.81	0.55	0.28	0.093
^{208}Pb	6.62	0.546	0	0
^{197}Au	6.37	0.535	-0.13	-0.03
^{129}Xe	5.42	0.57	0.162	-0.003
^{96}Ru	5.085	0.46	0.158	0
^{96}Zr	5.02	0.46	0	0

Sample nucleons, determine thickness functions, then compute $x = x(\mathbf{b}_\perp) = Q_s(x, \mathbf{b}_\perp)/\sqrt{s_{\rm NN}}$

Using $g^2\mu_i(x,\mathbf{b}_\perp) = cQ_s^i(x,\mathbf{b}_\perp)$ sample color charges with zero mean and variance: $\langle \rho_i^a(\mathbf{b}_\perp)\rho_i^b(\mathbf{x}_\perp)\rangle = g^2\mu_i^2(x,\mathbf{b}_\perp)\delta^{ab}\delta^{(2)}(\mathbf{b}_\perp - \mathbf{x}_\perp)$

Sampled color charges yield currents moving on the light cone $J_i^\nu = \delta^{\nu\pm}\rho_i(x^\mp, \mathbf{x}_\perp) = \delta^{\nu\pm}\rho_i^a(x^\mp,\mathbf{x}_\perp)t^a$

which are sources in the Yang-Mills equations $[D_\mu, F^{\mu\nu}] = J^\nu$

THE MODEL: IP-GLASMA

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

Yang-Mills equations $[D_\mu, F^{\mu\nu}] = J^\nu$

are solved in Lorenz gauge to yield $A_i^{\pm} = -\frac{\rho_i(x^{\mp}, \mathbf{x}_\perp)}{\boldsymbol{\nabla}_\perp^2 - m^2}$ with m=0.2 GeV

The field from both nuclei in Fock-Schwinger gauge reads

$$A^j(\mathbf{x}_\perp) = \theta(x^-)\theta(-x^+)\frac{i}{g}V_P(\mathbf{x}_\perp)\partial^j V_P^\dagger(\mathbf{x}_\perp) + \theta(x^+)\theta(-x^-)\frac{i}{g}V_T(\mathbf{x}_\perp)\partial^j V_T^\dagger(\mathbf{x}_\perp)$$

where $V_i(\mathbf{x}_\perp) = P\exp\left(-ig\int dx^{\mp}\frac{\rho_i(x^{\mp}, \mathbf{x}_\perp)}{\boldsymbol{\nabla}_\perp^2 - m^2}\right)$

The fields in the forward light-cone are then

$$A^j = A_P^j + A_T^j\,,$$
$$A^\eta = -\frac{ig}{2}\left[A_{Pj}, A_T^j\right],$$
$$\partial_\tau A^j = 0\,,$$
$$\partial_\tau A^\eta = 0\,.$$

THE MODEL: IP-GLASMA

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

Yang-Mills evolution in the forward light cone is given by the discretized equations of motion ($\pi = E^\eta$, $\phi = A_\eta$)

$$\dot{U}_j = i\frac{g^2}{\tau}E^j U_j \quad \text{(no sum over } j\text{)} \tag{29}$$

$$\dot{\phi} = \tau\pi \tag{30}$$

$$\dot{E}^1 = \frac{i\tau}{2g^2}[U_{(1,2)} + U_{(1,-2)} - U^\dagger_{(1,2)} - U^\dagger_{(1,-2)} - T_1] + \frac{i}{\tau}[\tilde{\phi}_1, \phi] \tag{31}$$

$$\dot{E}^2 = \frac{i\tau}{2g^2}[U_{(2,1)} + U_{(2,-1)} - U^\dagger_{(2,1)} - U^\dagger_{(2,-1)} - T_2] + \frac{i}{\tau}[\tilde{\phi}_2, \phi] \tag{32}$$

$$\dot{\pi} = \frac{1}{\tau}\sum_j \left[\tilde{\phi}_j + \tilde{\phi}_{-j} - 2\phi\right], \tag{33}$$

One can then compute $T^{\mu\nu}$. The $\tau\tau$ component for example reads

$$\begin{aligned} T^{\tau\tau}(s) = {} & \frac{g^2}{2\tau^2}\mathrm{Tr}[(E^1)^2(s) + (E^1)^2(s+\hat{e}_2) \\ & + (E^2)^2(s) + (E^2)^2(s+\hat{e}_1)] \\ & + \frac{1}{2\tau^2}\mathrm{Tr}\Big[\big(\phi(s) - \tilde{\phi}_1(s)\big)^2 \\ & + \big(\phi(s+\hat{e}_2) - \tilde{\phi}_1(s+\hat{e}_2)\big)^2 \\ & + \big(\phi(s) - \tilde{\phi}_2(s)\big)^2 \\ & + \big(\phi(s+\hat{e}_1) - \tilde{\phi}_2(s+\hat{e}_1)\big)^2\Big] \\ & + \frac{1}{4}\mathrm{Tr}\big[\pi^2(s) + \pi^2(s+\hat{e}_1) \\ & + \pi^2(s+\hat{e}_2) + \pi^2(s+\hat{e}_1+\hat{e}_2)\big] \\ & + \frac{2}{g^2}\Big(N_c - \mathrm{ReTr}[U_{(1,2)}(s)]\Big). \end{aligned}$$

THE MODEL: MUSIC

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

$T^{\mu\nu}$ is matched to hydrodynamics, which solves $\partial_\mu T^{\mu\nu} = 0$

We decompose $T^{\mu\nu} = eu^\mu u^\nu - (P+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$

We use the DNMR formalism that has constitutive relations

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\,\theta - \delta_{\Pi\Pi}\Pi\,\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$
$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\,\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\,\sigma^{\mu\nu}\,,$$

G. S. Denicol, H. Niemi, E. Molnar, and D. H. Rischke, Phys. Rev. **D85**, 114047 (2012), [Erratum: Phys. Rev.D91,no.3,039902(2015)], arXiv:1202.4551 [nucl-th].
G. S. Denicol, S. Jeon, and C. Gale, Phys. Rev. **C90**, 024912 (2014), arXiv:1403.0962 [nucl-th].

$$\sigma^{\mu\nu} = \frac{1}{2}\left[\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}(\nabla_\alpha u^\alpha)\right]$$

$$\tau_\pi = \frac{5\,\eta}{e+P}\,,$$

$$\tau_\Pi = \frac{\zeta}{15\,\left(\frac{1}{3} - c_s^2\right)^2 (e+P)}$$

$\tau_{\pi\pi}[\tau_\pi]$	$\delta_{\pi\pi}[\tau_\pi]$	$\varphi_7 P$	$\lambda_{\pi\Pi}[\tau_\pi]$	$\lambda_{\Pi\pi}[\tau_\Pi]$	$\delta_{\Pi\Pi}[\tau_\Pi]$
$10/7$	$4/3$	$9/70$	$6/5$	$8(1/3 - c_s^2)/5$	$2/3$

THE MODEL: PARTICLE SAMPLING

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

When converting to particles, we use viscous corrections

$$\delta f^i_{\mathrm{shear}}(x^\mu, p^\mu) = f^i_0(1 \pm f^i_0)\frac{\pi^{\mu\nu}p_\mu p_\nu}{2T^2(e+P)},$$

and

$$\delta f^i_{\mathrm{bulk}}(x^\mu, p^\mu) = f^i_0(1 \pm f^i_0)\left(-\frac{\Pi}{\hat{\zeta}}\right)\frac{(p\cdot u)}{T} \times \left[\frac{m_i^2}{3(p\cdot u)^2} - \left(\frac{1}{3} - c_s^2\right)\right]$$

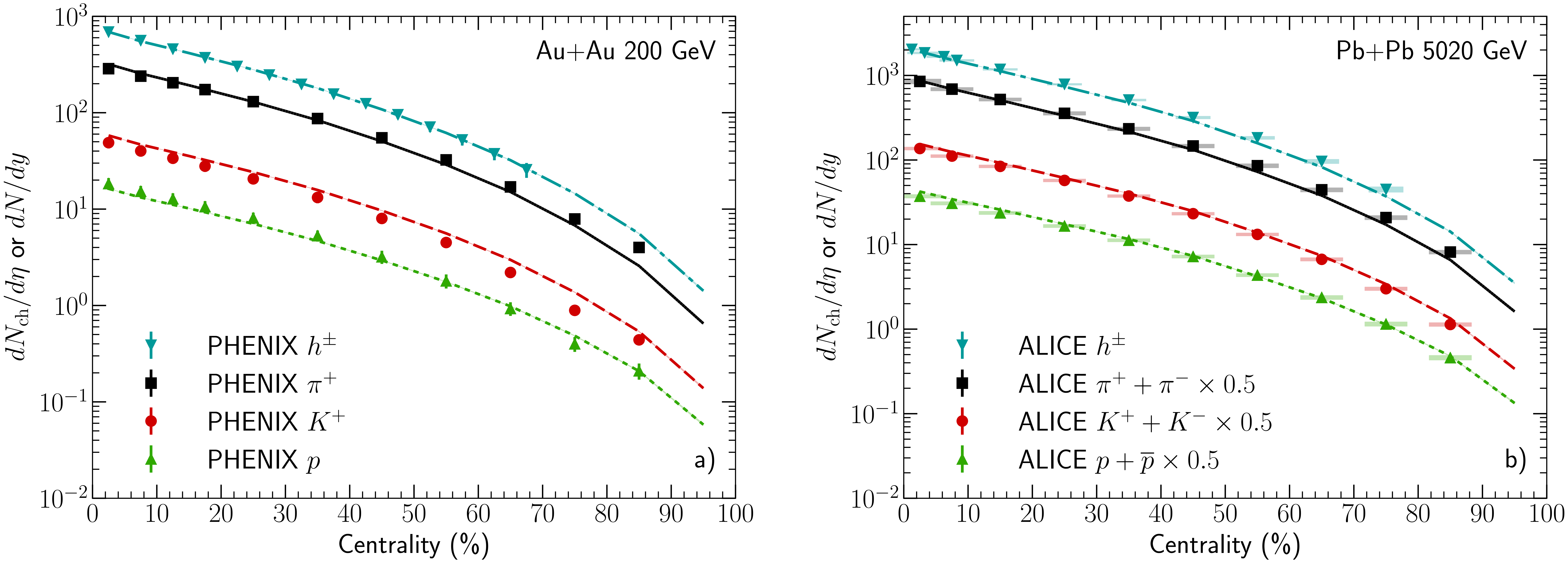
where

$$\hat{\zeta} = \frac{1}{3T}\sum_i \frac{g_i}{(2\pi)^3} m_i^2 \int \frac{d^3k}{E} f^i_0(1 \pm f^i_0) \times E\left[\frac{m_i^2}{3E^2} - \left(\frac{1}{3} - c_s^2\right)\right]$$

Should the value of any δf be larger than that of the equilibrium distribution, we set the distribution to zero,

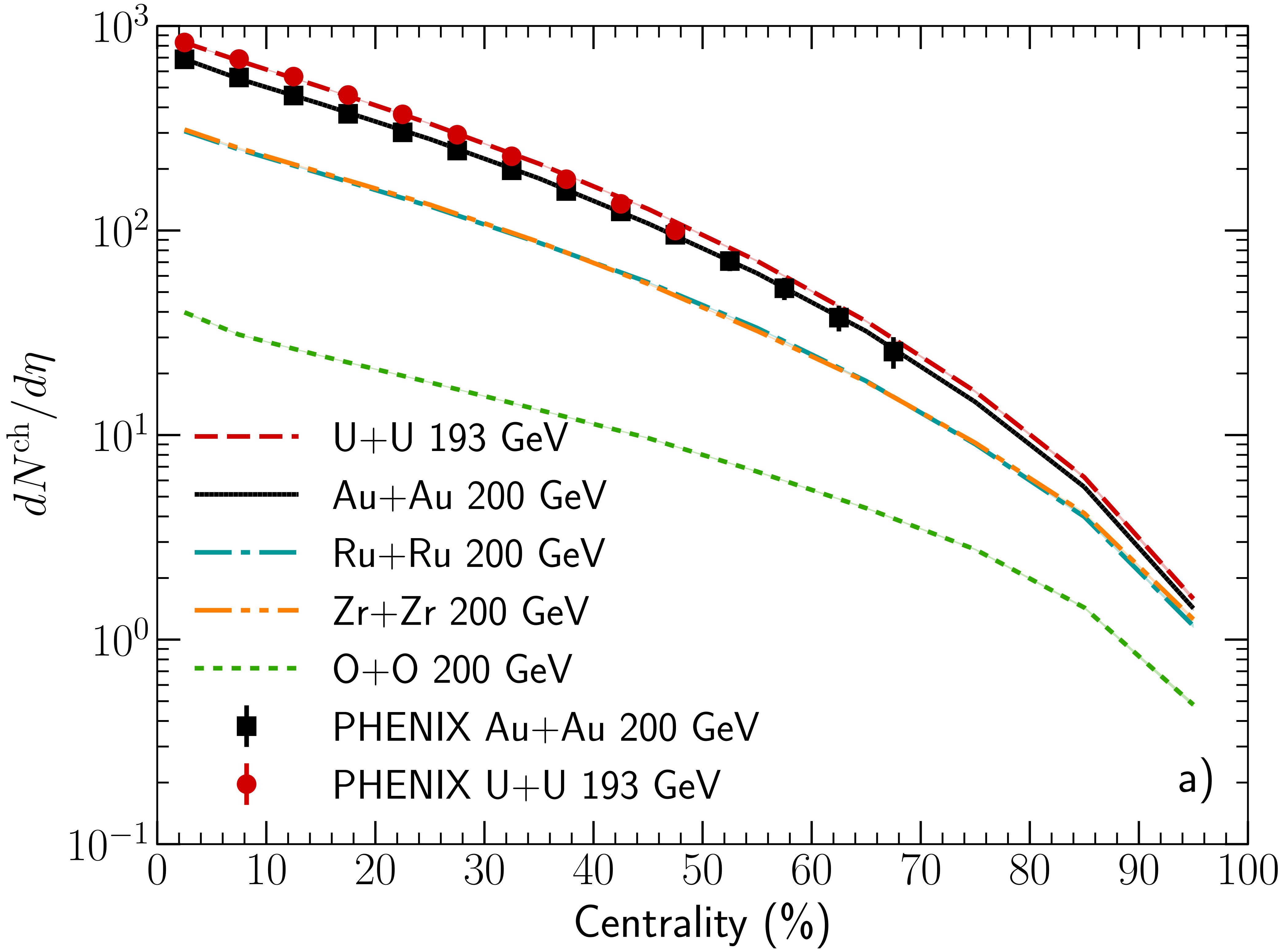
BACKUP: Model validation

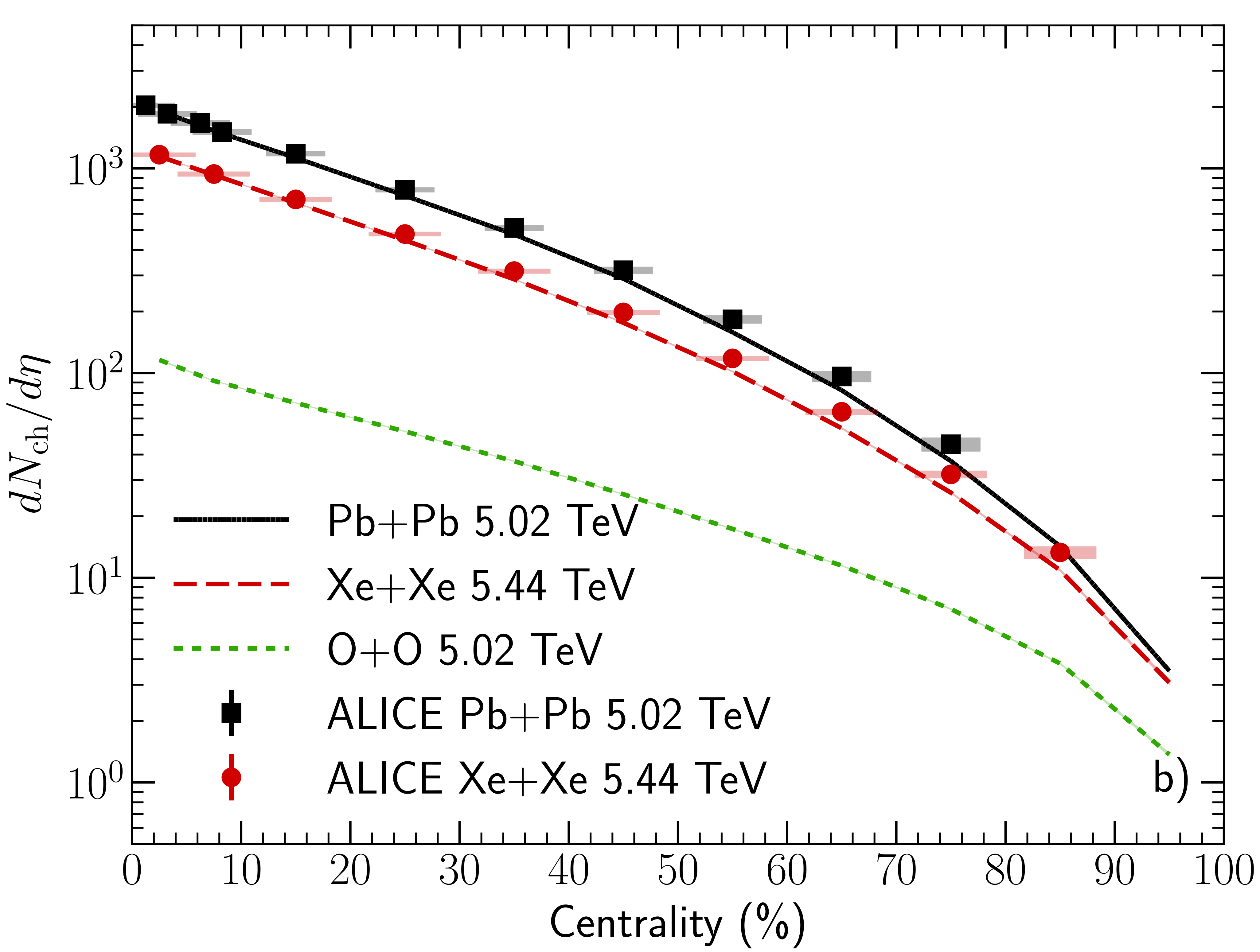
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



BACKUP: Model validation

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905





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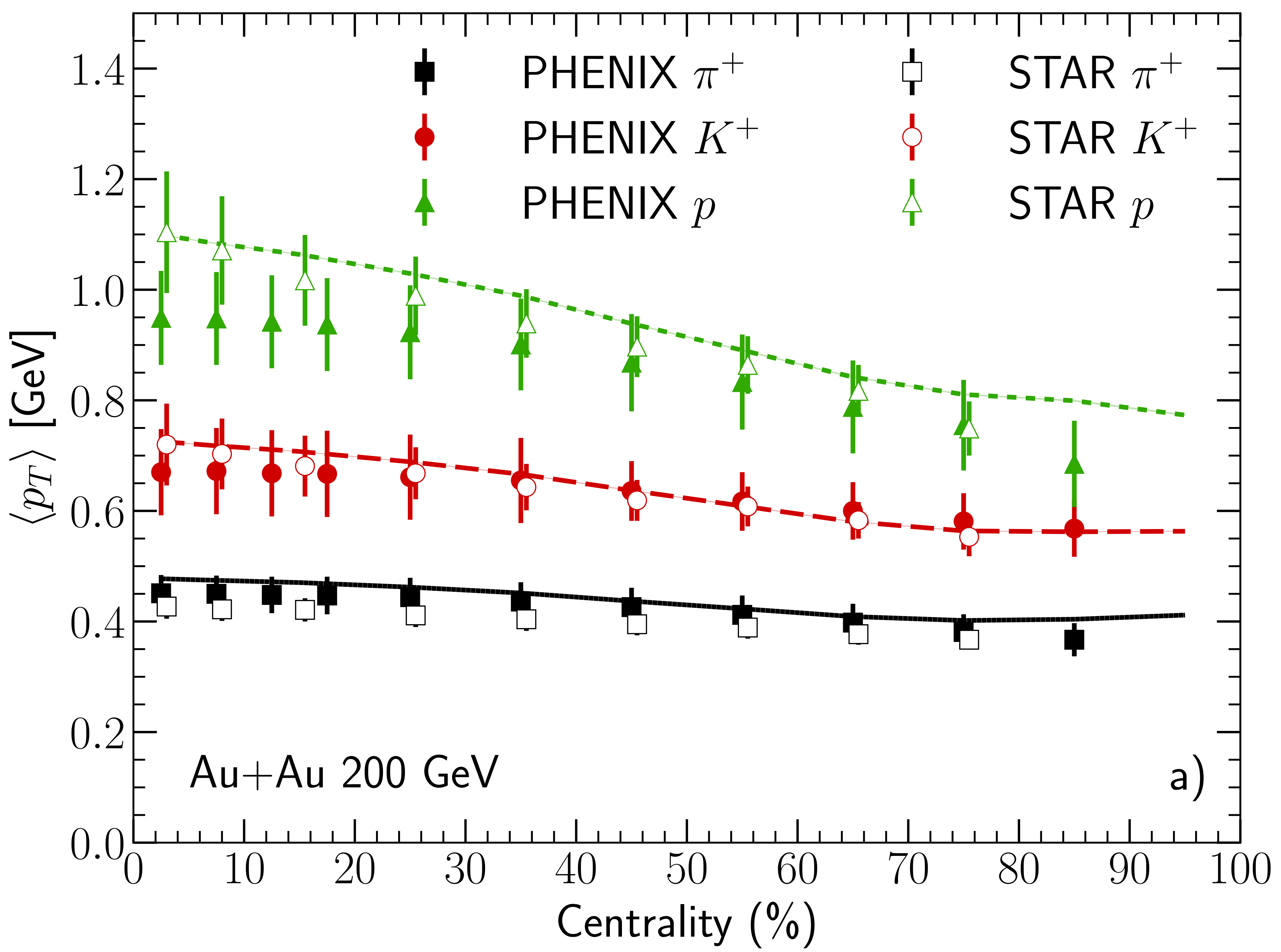
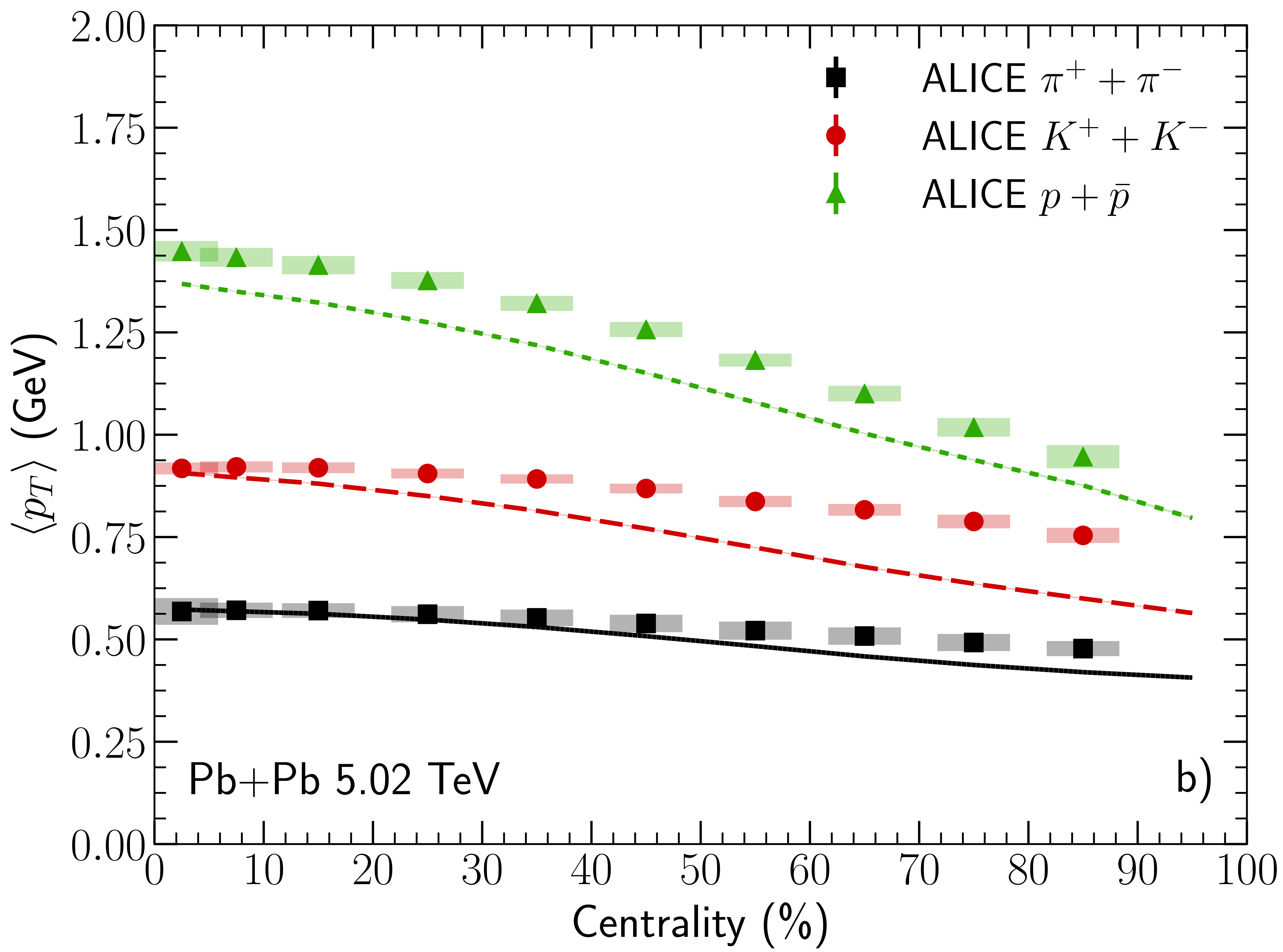
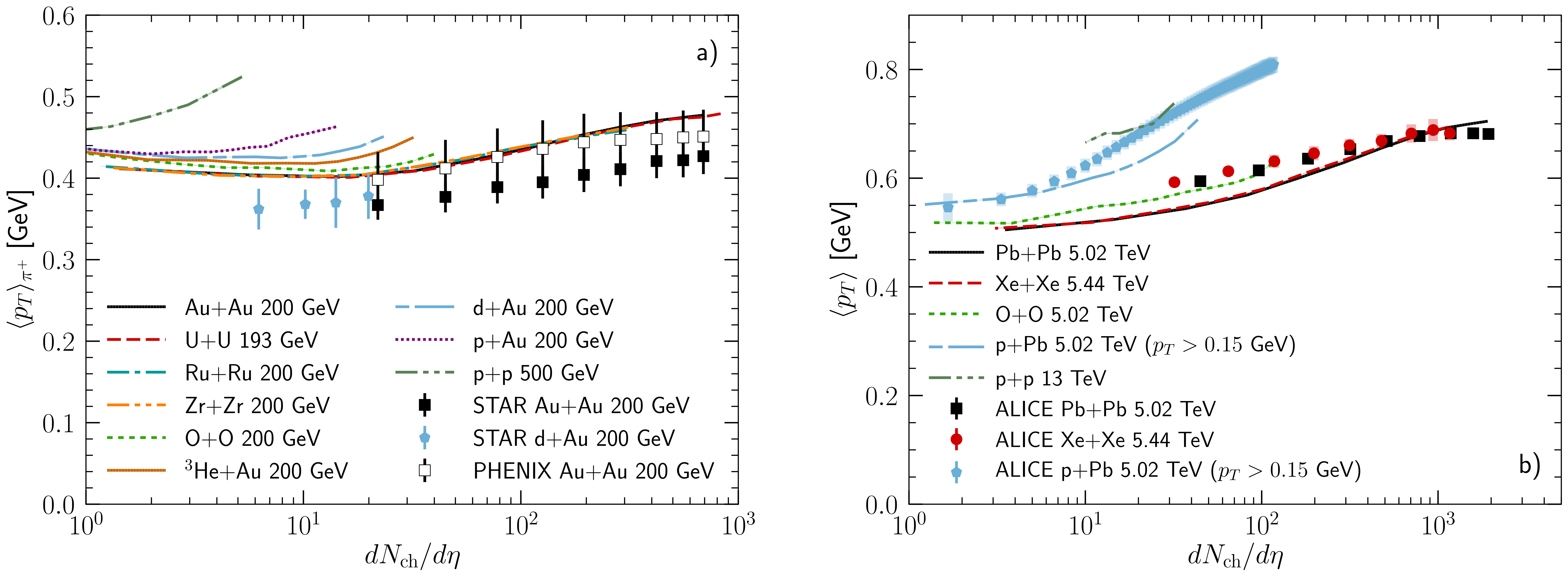
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905





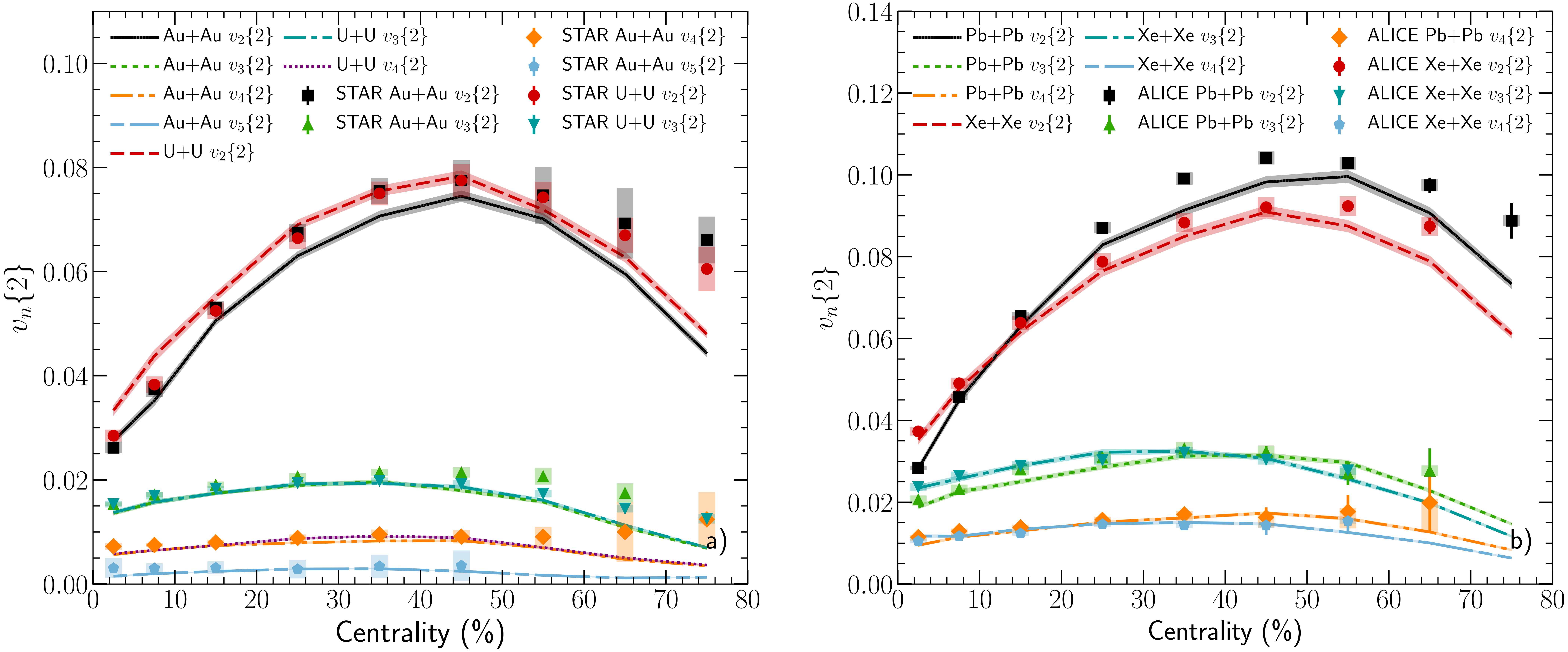
BACKUP: Model validation

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



BACKUP: Model validation

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



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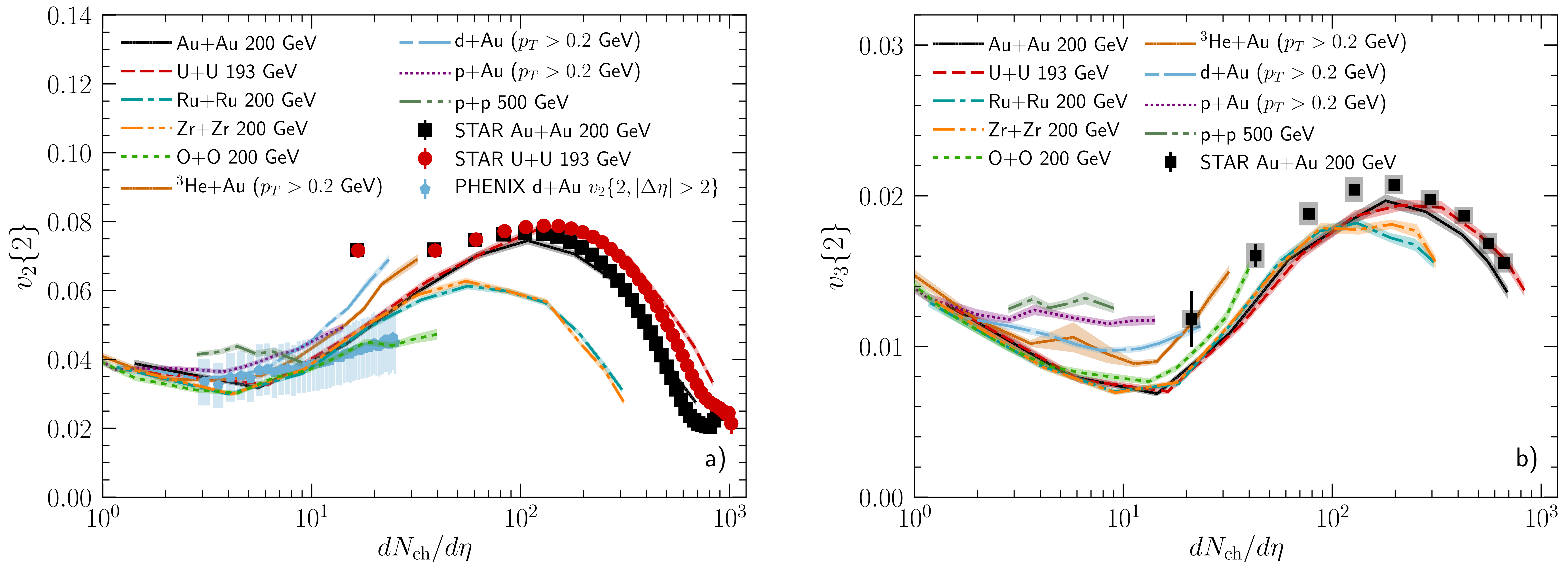
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



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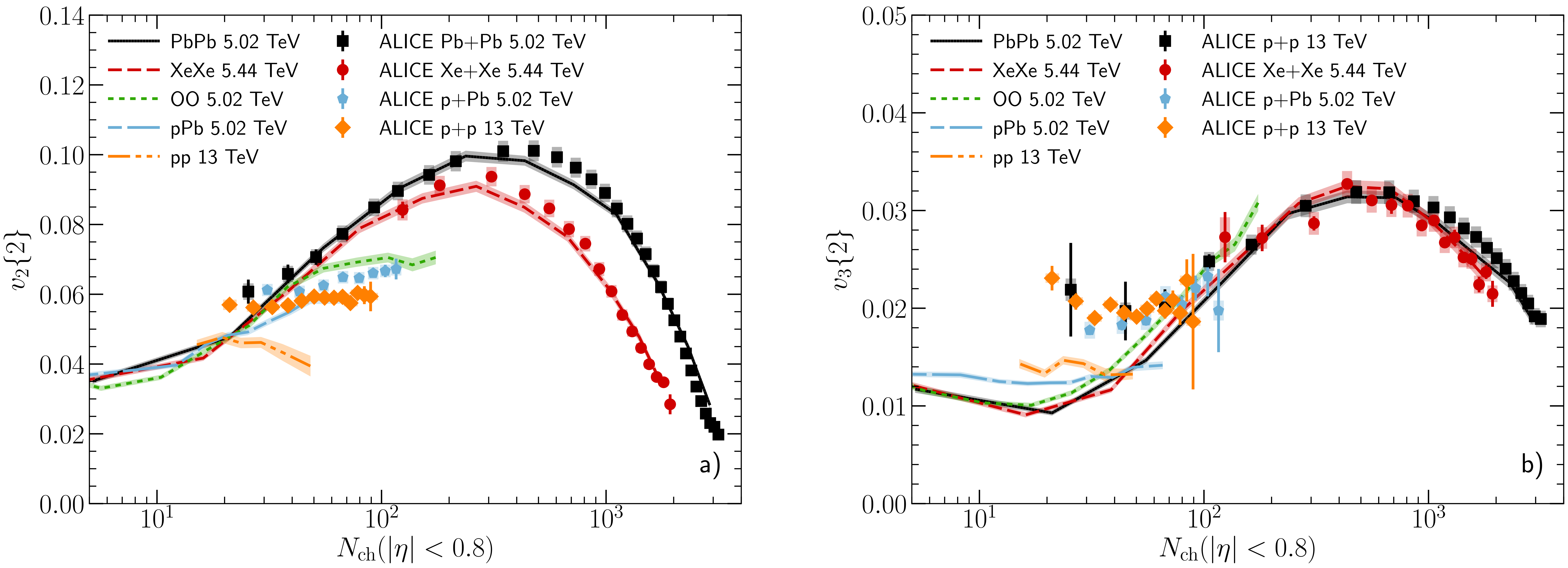
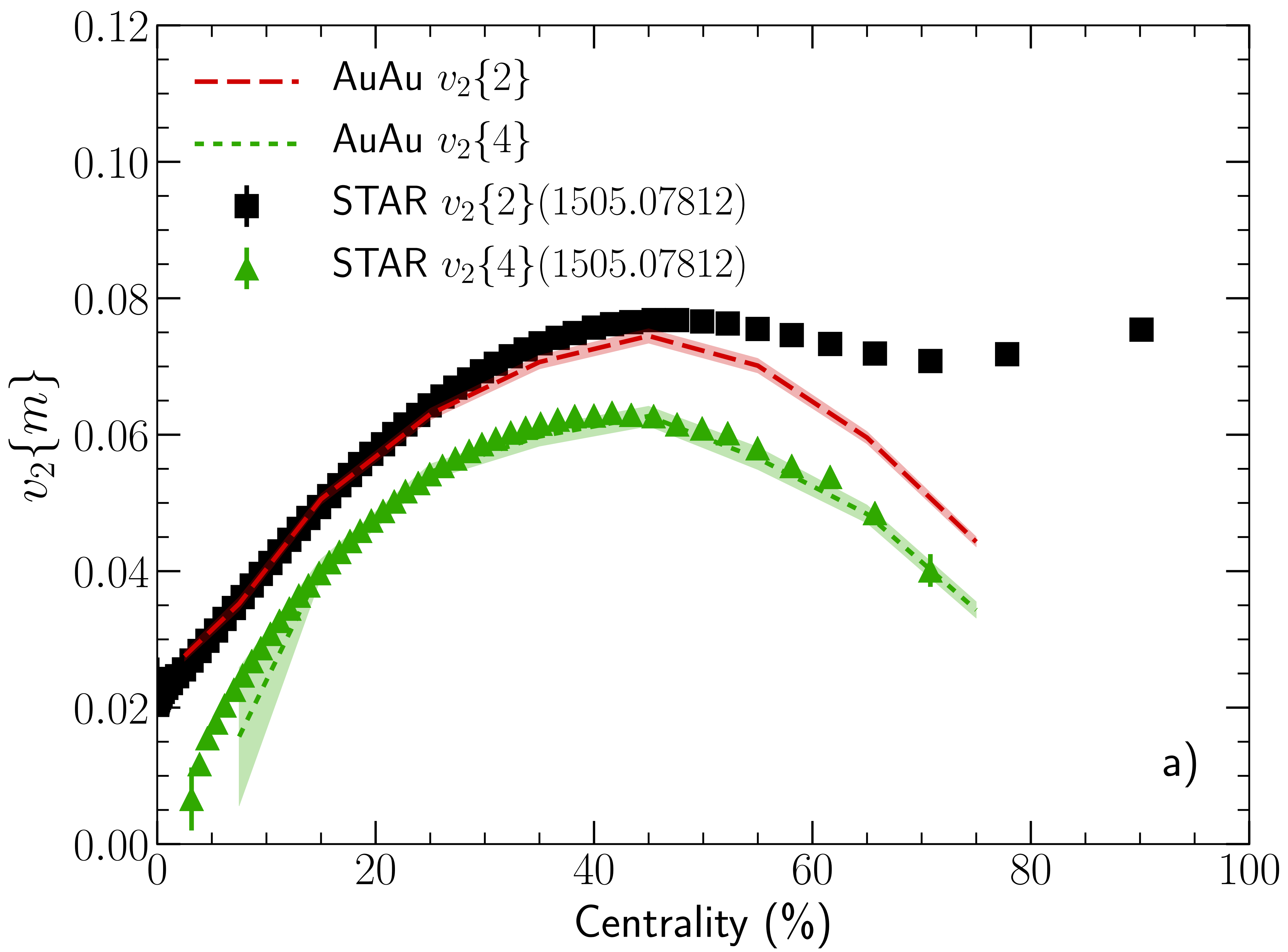
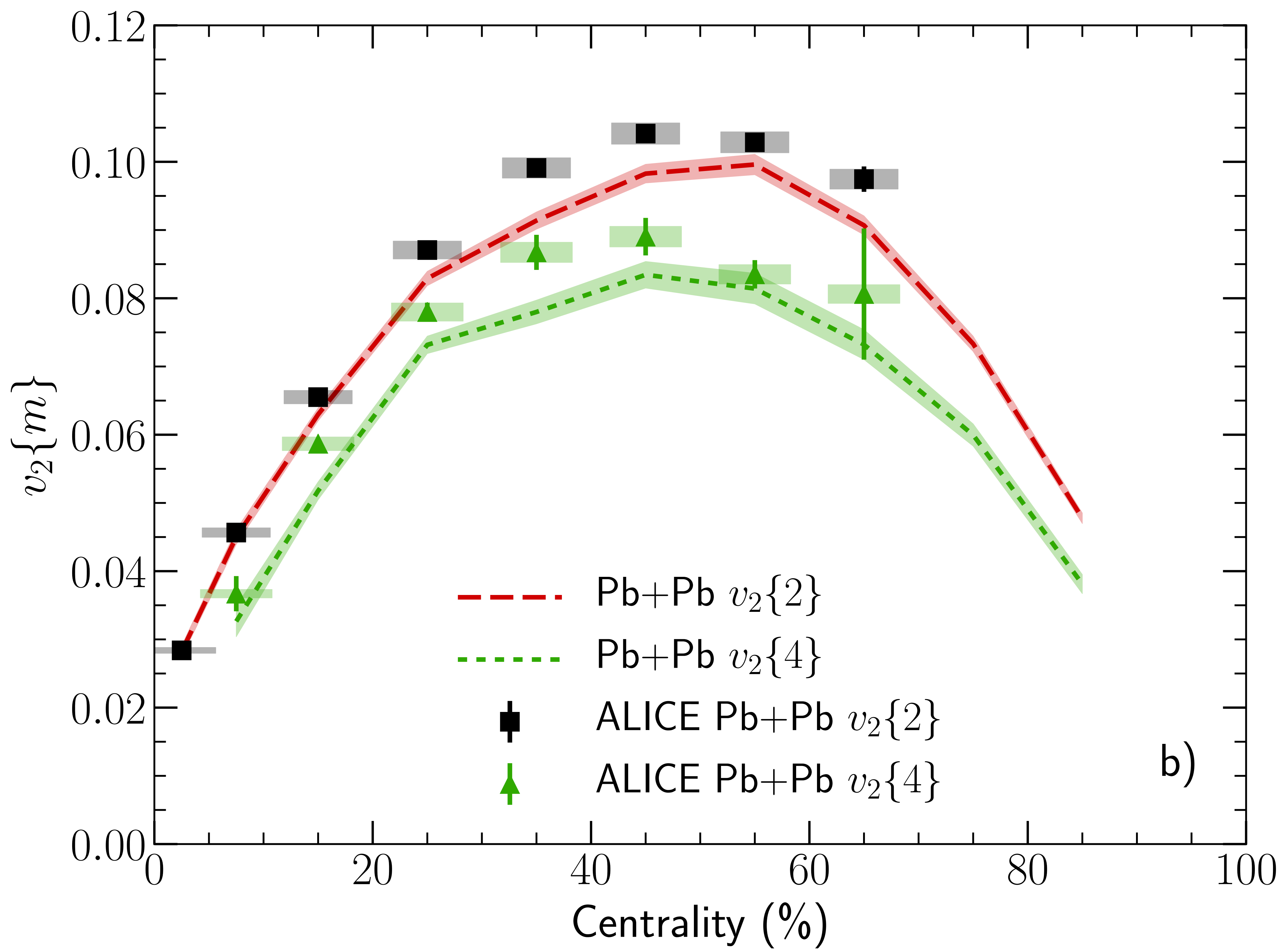
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



BACKUP: Model validation

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905





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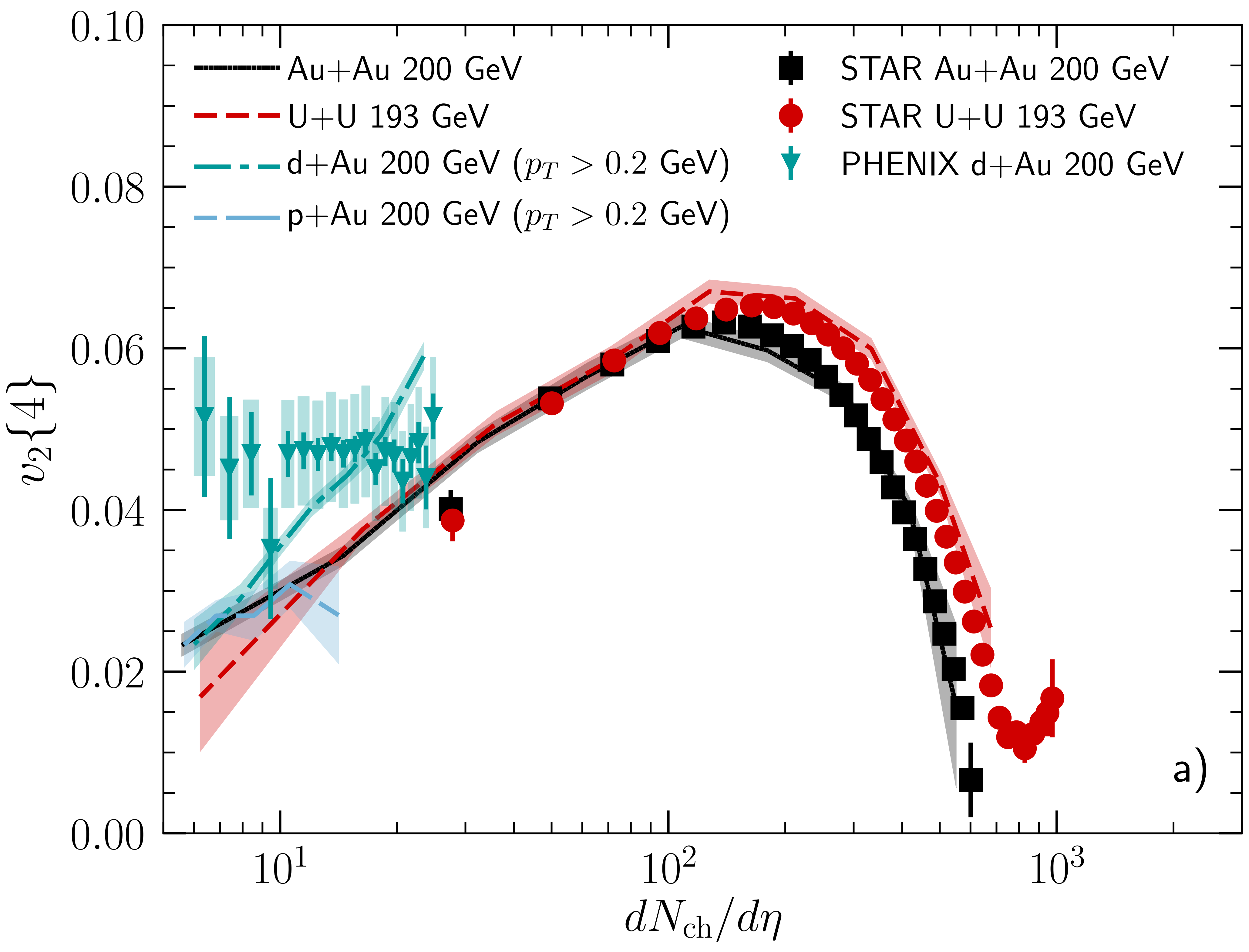
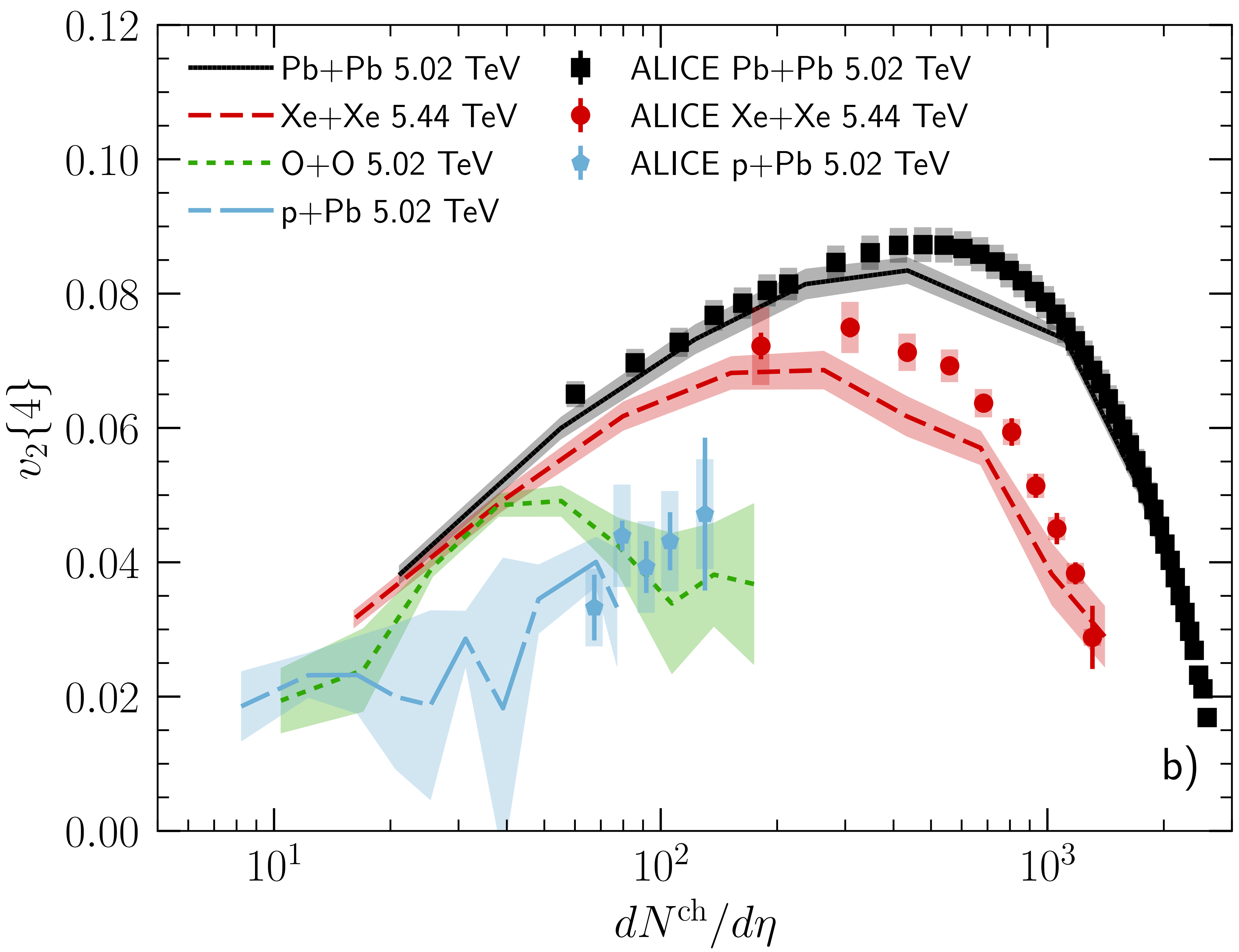
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905





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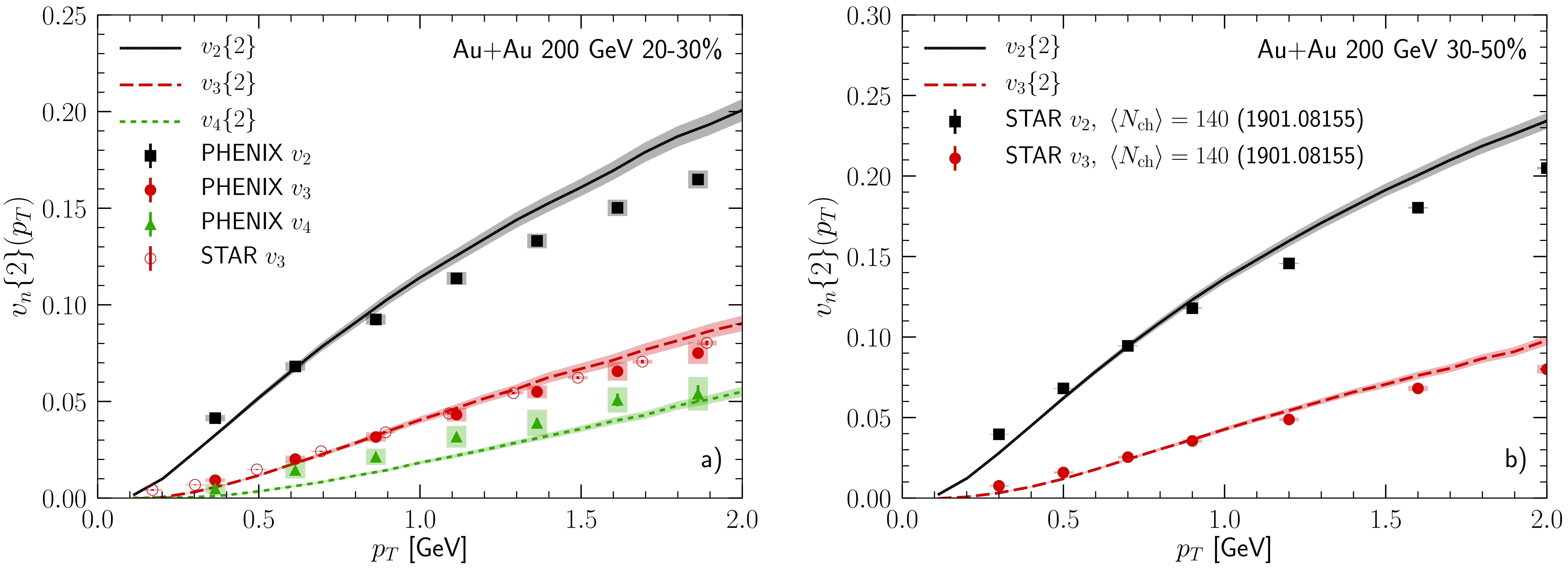
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



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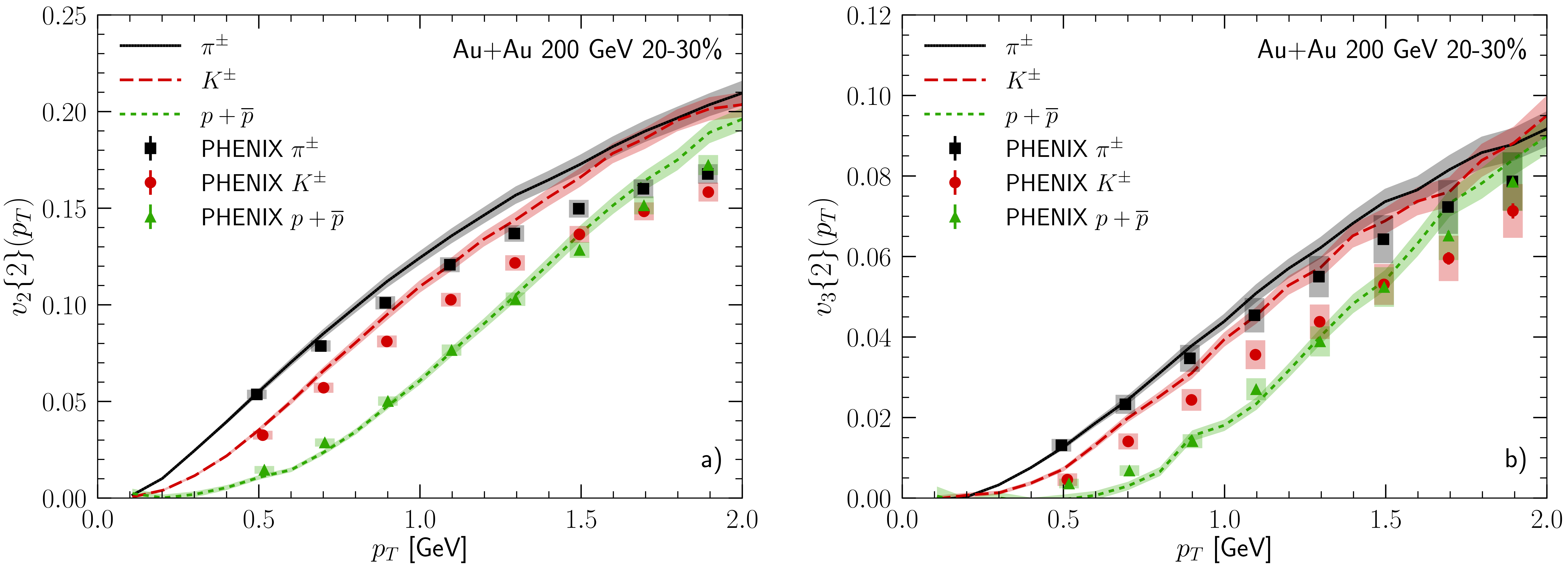

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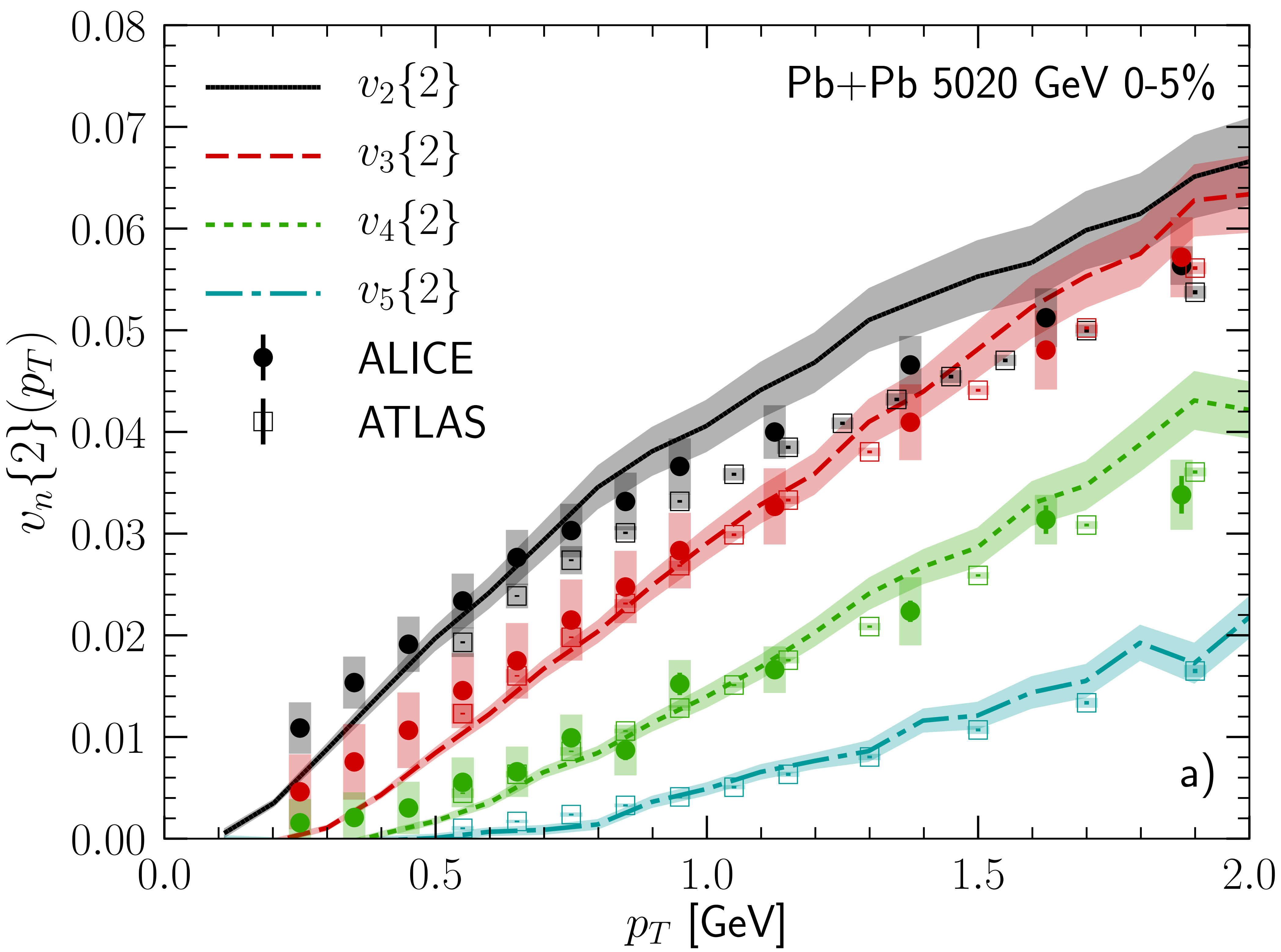

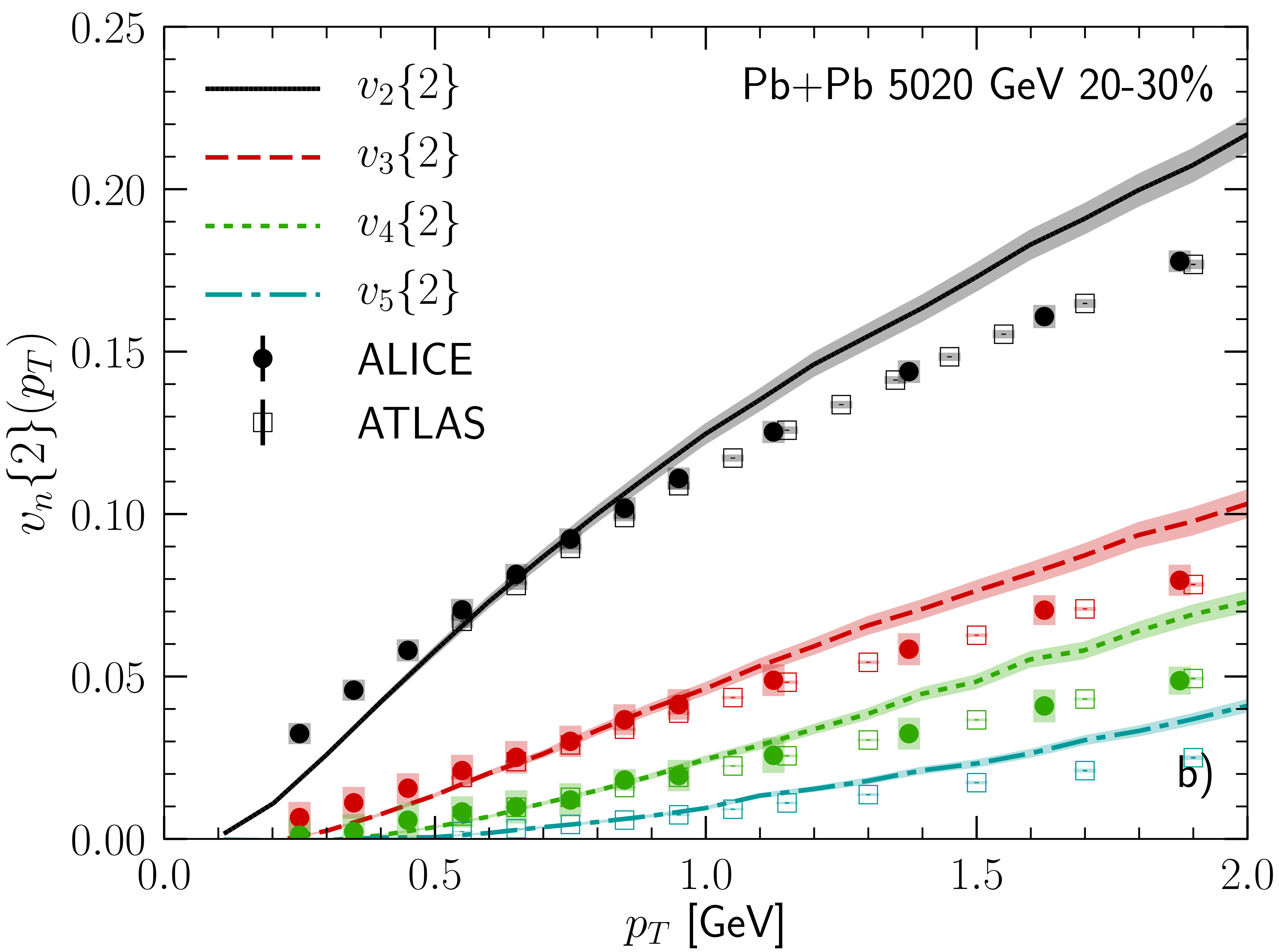

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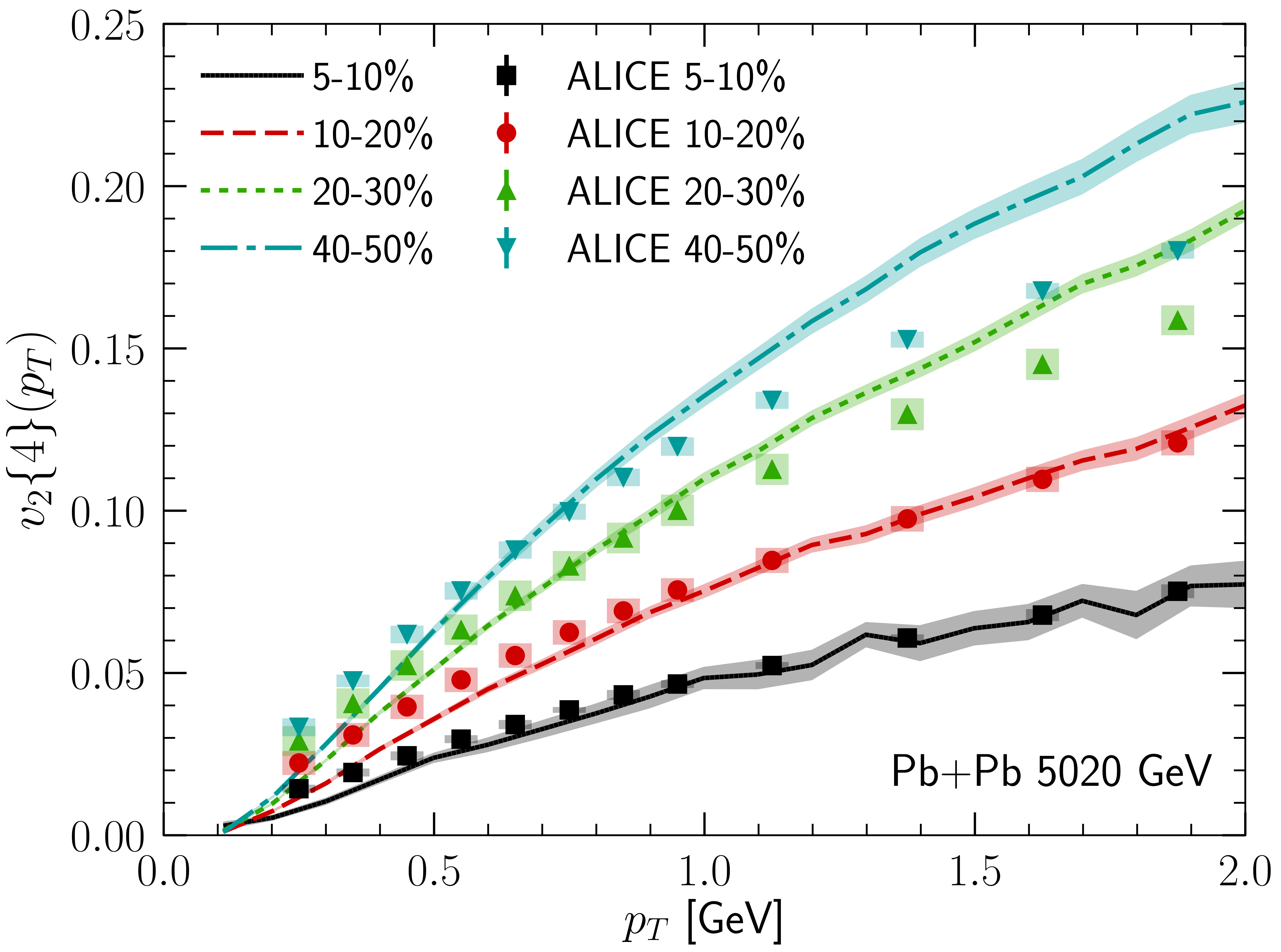
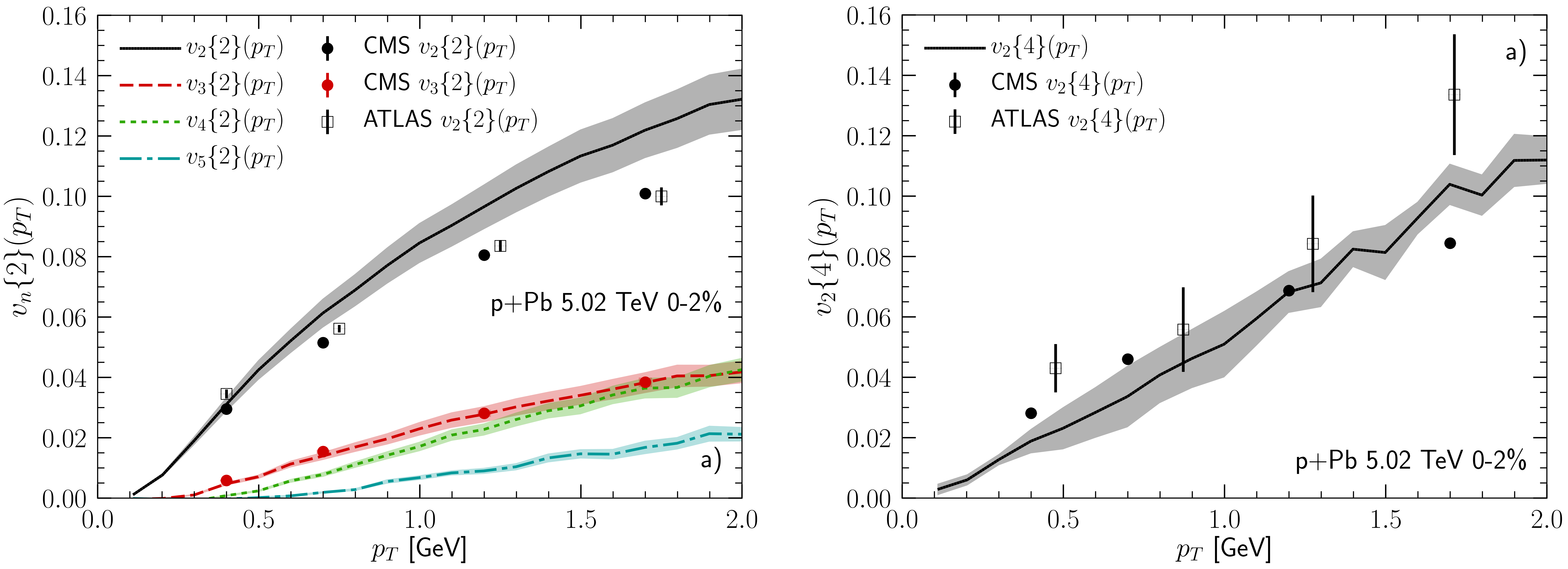
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



BACKUP: Model validation

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



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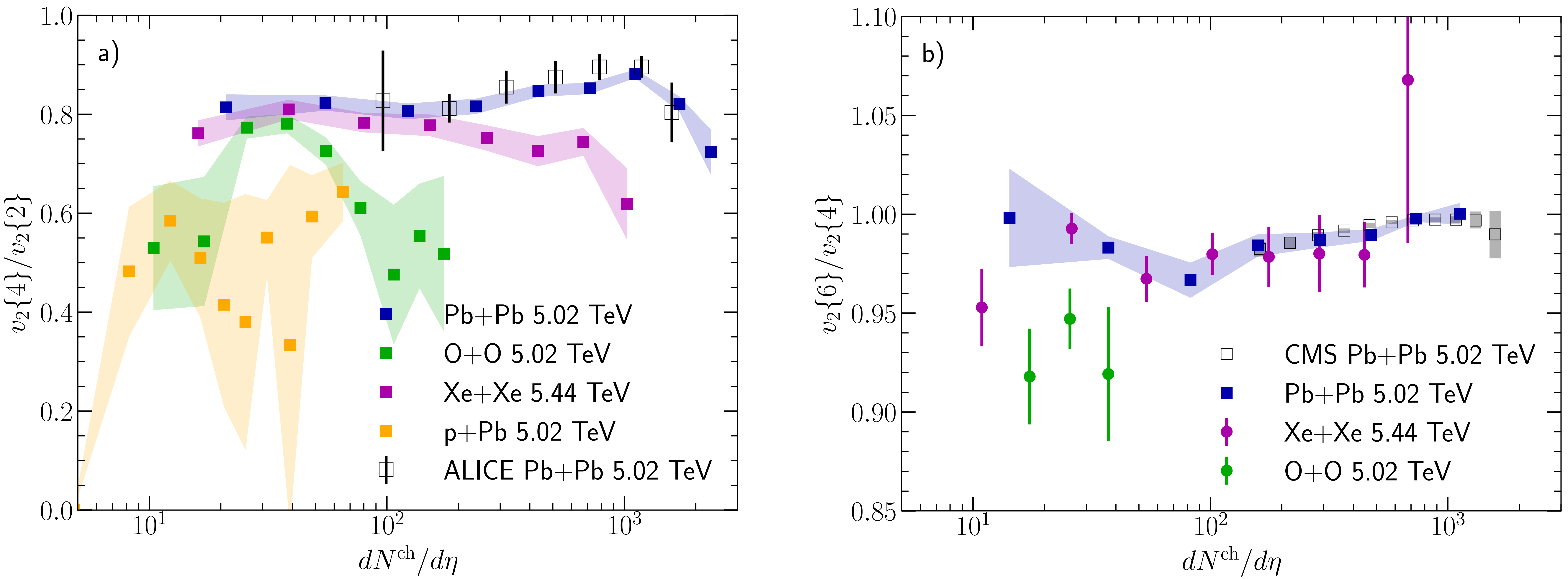
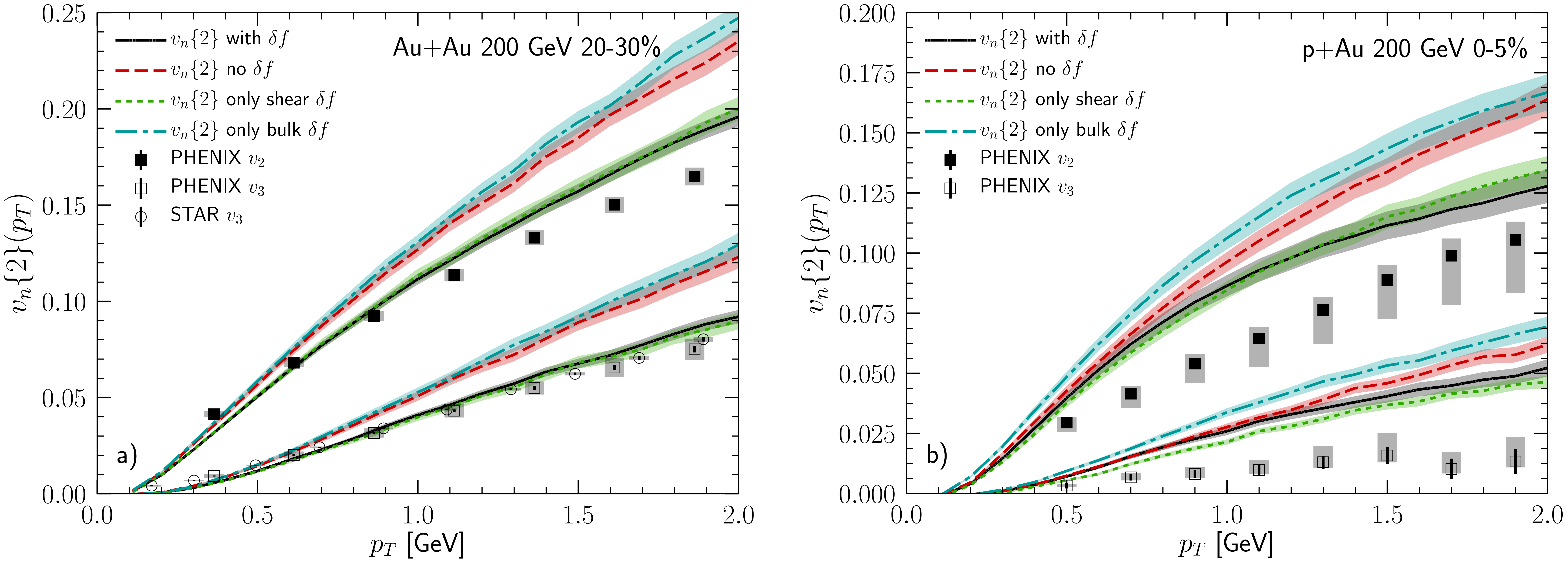
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



BACKUP: Effects of δf

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905



MEAN TRANSVERSE MOMENTUM

Fluctuations of the mean transverse momentum have not quite received the same amount of care: e.g. typically no rapidity gap

(except in a principal component analysis in CMS Collaboration, Phys. Rev. C96, 064902 (2017))

Origin of fluctuations in $[p_T]$: Event-by-event fluctuations in the radius of the fireball (at fixed multiplicity), that drive *radial* flow

We use $[\,\cdot\,]$ to indicate the average in a single event,

and $\langle\,\cdot\,\rangle$ for event averages

Important observable, sensitive to bulk visc., EoS, and initial size

MEAN TRANSVERSE MOMENTUM FLUCTUATIONS: v_0

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

We define a measure of $[p_T]$ fluctuations in analogy to the v_n

First event-by-event deviation: $\delta O \equiv O - \langle O \rangle$

and at fixed multiplicity: $\hat{\delta} O \equiv \delta O - \frac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$

The corresponding variance: $\hat{\sigma}_O^2 = \langle (\hat{\delta} O)^2 \rangle$

A. Olszewski, W. Broniowski, Phys. Rev. C96, 054903 (2017)

MEAN TRANSVERSE MOMENTUM FLUCTUATIONS: v_0

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

E-by-e spectra: $\mathcal{N}(p_T) = \dfrac{dN}{dp_T}$ **and multiplicity:** $N = \displaystyle\int_0^\infty dp_T\, \mathcal{N}(p_T)$

Fluctuations of spectra at fixed multiplicity:

$$\hat{\delta}\mathcal{N}(p_T) = \delta\mathcal{N}(p_T) - \frac{\langle \delta\mathcal{N}(p_T)\delta N\rangle}{\sigma_N^2}\delta N$$

Integrated p_T and its fluctuations at fixed multiplicity:

$$P_T \equiv \int_0^\infty dp_T p_T \mathcal{N}(p_T) \quad \text{and} \quad \hat{\delta}P_T = \int_0^\infty dp_T\, p_T\, \hat{\delta}\mathcal{N}(p_T)$$

MEAN TRANSVERSE MOMENTUM FLUCTUATIONS: v_0

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

Now define $v_0^2 = \dfrac{\hat{\sigma}_{P_T}^2}{\langle P_T \rangle^2}$ **and** $v_0(p_T) = \dfrac{1}{\langle \mathcal{N}(p_T) \rangle} \dfrac{\langle \hat{\delta} \mathcal{N}(p_T)\, \hat{\delta} P_T \rangle}{\hat{\sigma}_{P_T}}$

The two are related by $v_0 \equiv \dfrac{\int_0^\infty dp_T\, p_T \langle \mathcal{N}(p_T) \rangle\, v_0(p_T)}{\int_0^\infty dp_T\, p_T \langle \mathcal{N}(p_T) \rangle}$

Assuming factorization, v_0 **can be obtained from two-particle correlations:**

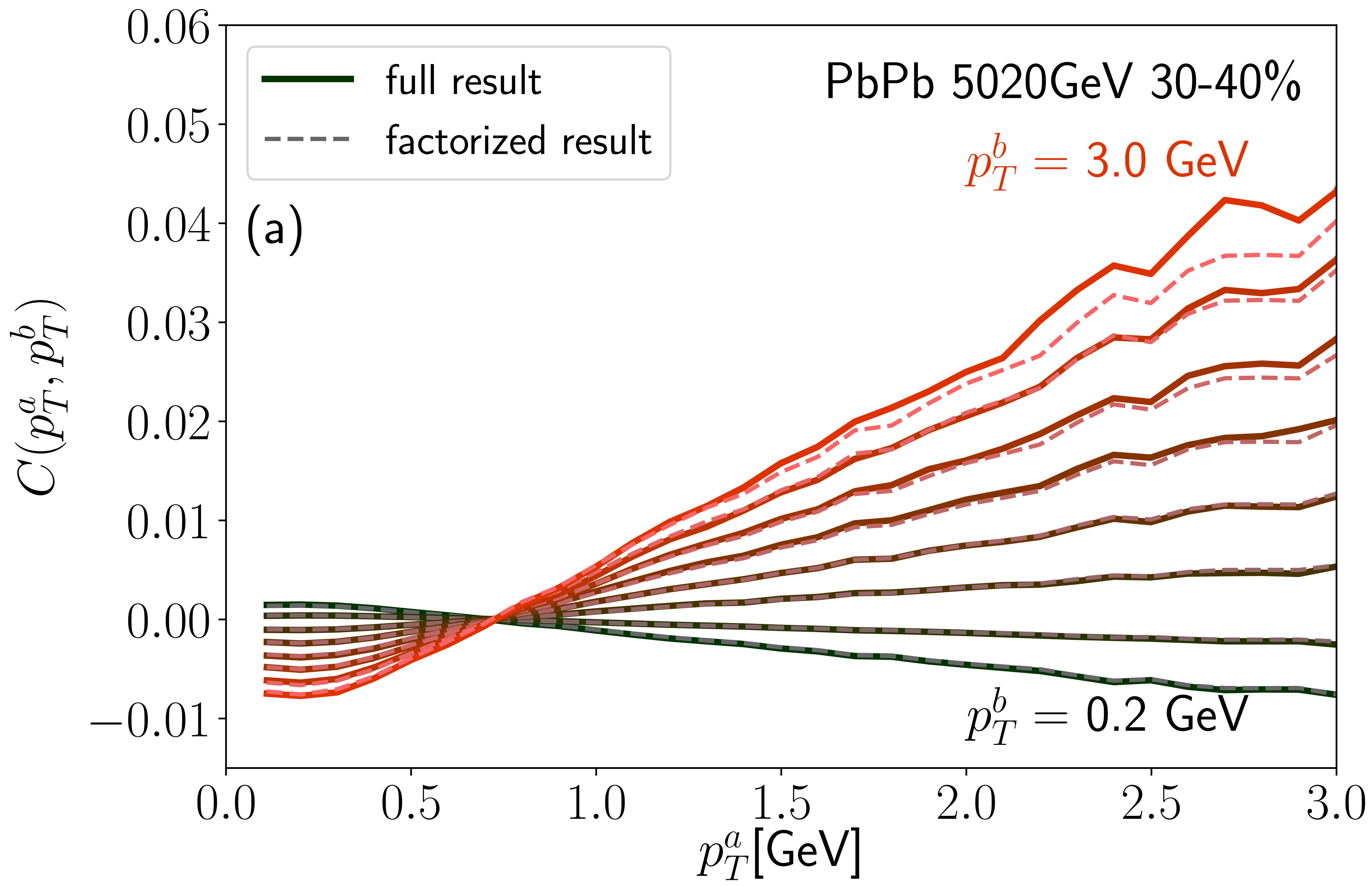
$$C(p^a, p^b) = \frac{\langle \hat{\delta} \mathcal{N}(p^a) \hat{\delta} \mathcal{N}(p^b) \rangle}{\langle \mathcal{N}(p^a) \rangle \langle \mathcal{N}(p^b) \rangle} \approx v_0(p^a) v_0(p^b)$$

CHECK FACTORIZATION

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

$$C(p^a, p^b) = \frac{\langle \hat{\delta}\mathcal{N}(p^a)\hat{\delta}\mathcal{N}(p^b)\rangle}{\langle \mathcal{N}(p^a)\rangle \langle \mathcal{N}(p^b)\rangle} \approx v_0(p^a)v_0(p^b)$$

Model calculation using
IP-Glasma initial state
MUSIC hydrodynamics
UrQMD hadronic rescattering



SIMPLE MODEL COMPARISON

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)
F. G. Gardim et al., Phys. Rev. C100, 054905 (2019)

Write spectrum as $\mathcal{N}(p_T) = (2\pi p_T) N \frac{e^{-2p_T/[p_T]}}{\pi[p_T]^2}$

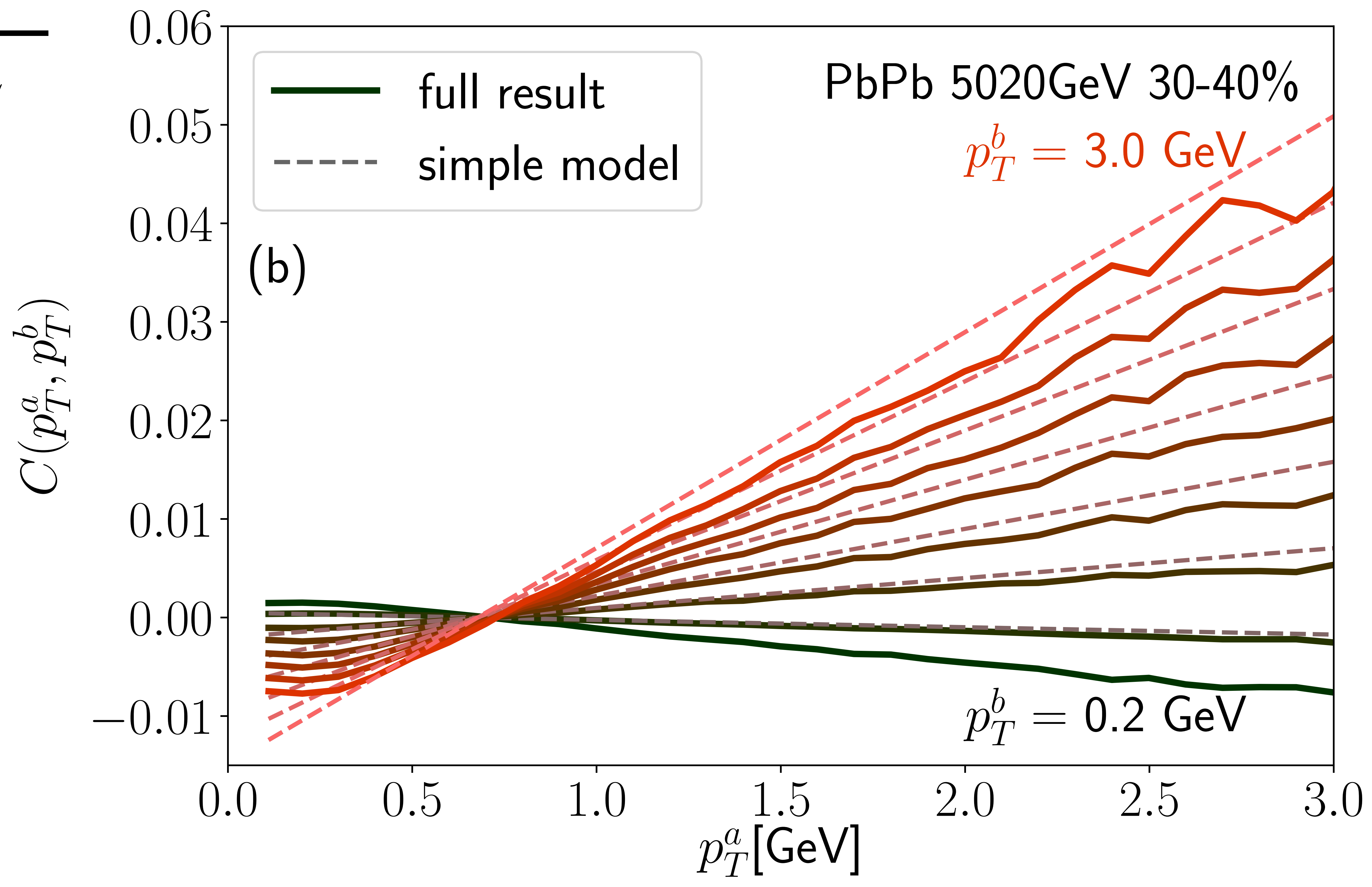
When N **and** $[p_T]$ **fluctuate, the spectrum fluctuates as**

$$\frac{\delta\mathcal{N}(p_T)}{\langle\mathcal{N}(p_T)\rangle} = \frac{\delta N}{\langle N\rangle} - \frac{2\delta[p_T]}{\langle[p_T]\rangle} + 2\frac{p_T\delta[p_T]}{\langle[p_T]\rangle^2}$$

and one finds

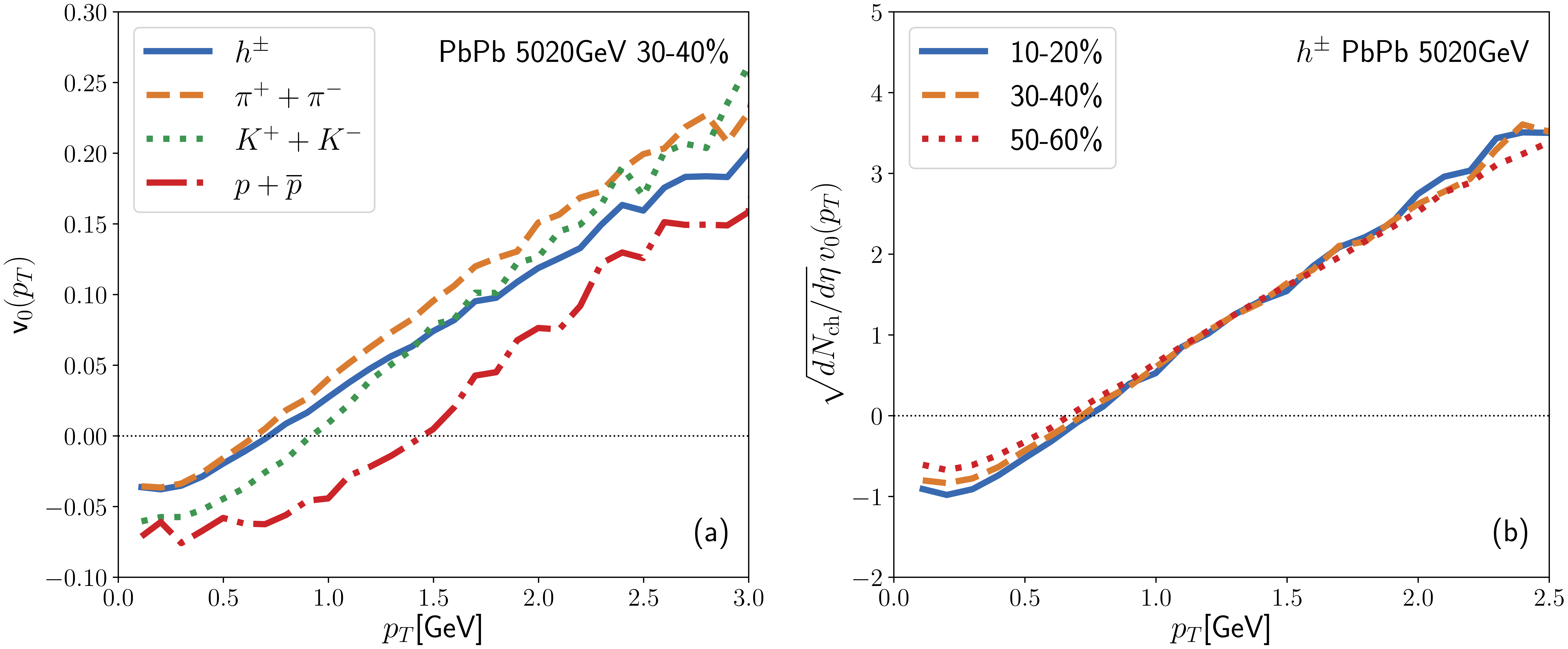
$$C(p_T^a, p_T^b) = \frac{\hat{\sigma}^2_{[p_T]}}{\langle[p_T]\rangle^2}\left(\frac{2p_T^a}{\langle[p_T]\rangle} - 2\right)\left(\frac{2p_T^b}{\langle[p_T]\rangle} - 2\right)$$

(at fixed multiplicity)



$v_0(p_T)$ RESULTS FOR Pb+Pb COLLISIONS

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)



RELATION TO ALICE MEAN-p_T FLUCTUATION MEASURE

Relation to C_m used in **ALICE Collaboration, Eur. Phys. J. C74, 3077 (2014)**

$$C_m = \frac{\langle \Delta P_T \Delta P_T \rangle}{\langle N^2 \rangle}, \quad \text{where} \quad \Delta P_T = \delta P_T - \frac{\langle P_T \rangle}{\langle N \rangle}\delta N = P_T - \frac{\langle P_T \rangle}{\langle N \rangle} N$$

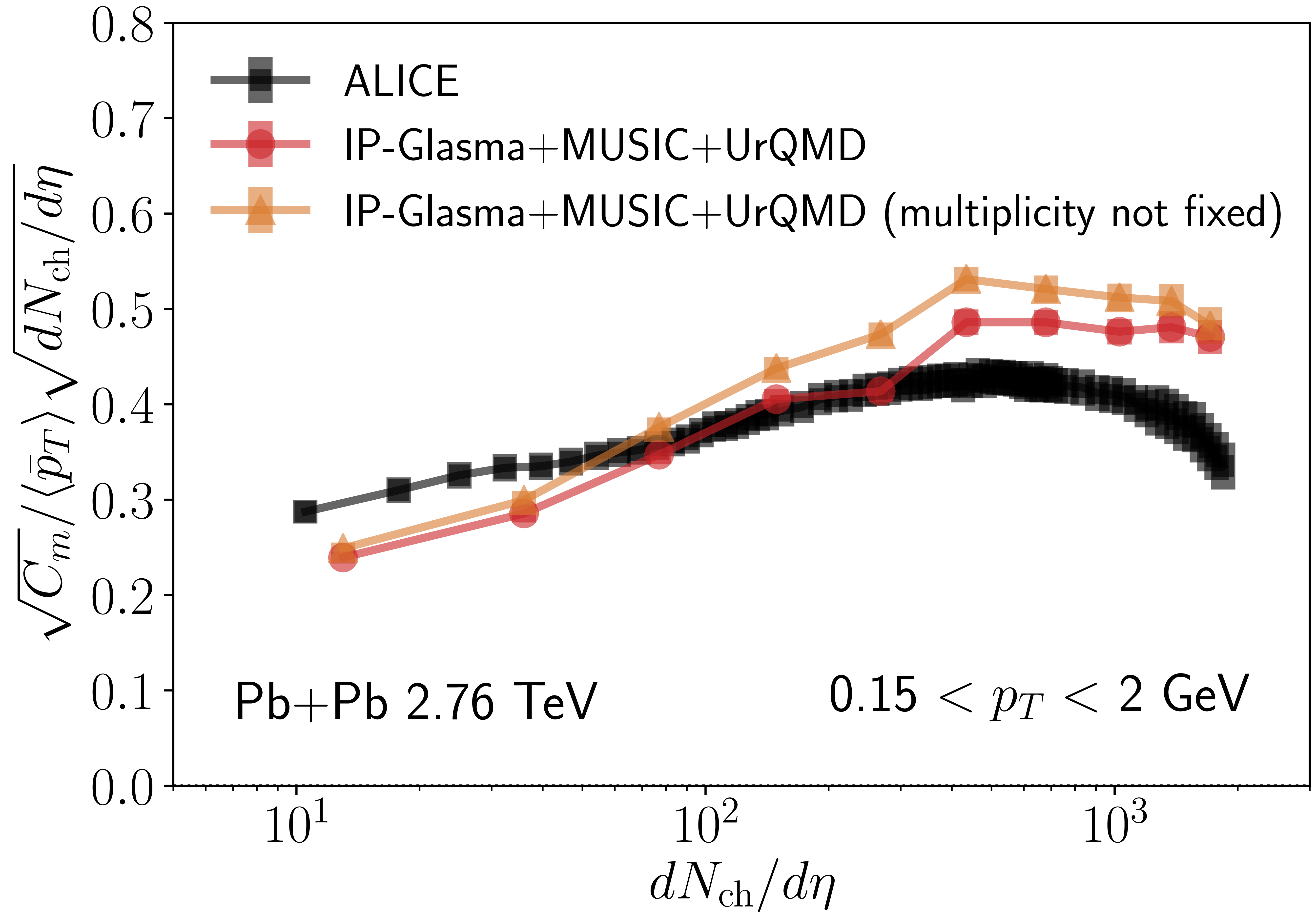
Also, they use $M(P_T) = \langle P_T \rangle / \langle N \rangle$ and measure

$$\frac{C_m}{M^2(P_T)} = \frac{\sigma^2_{P_T}\langle N^2 \rangle + (\delta N)^2(\langle P_T \rangle^2 - \sigma^2_{P_T})}{\langle P_T \rangle^2 \langle N^2 \rangle} \approx \frac{\sigma^2_{P_T}}{\langle P_T \rangle^2}$$ **if multiplicity fluctuations are small**

Compare this to $v_0^2 = \frac{\hat{\sigma}^2_{P_T}}{\langle P_T \rangle^2} = \frac{\sigma^2_{P_T}}{\langle P_T \rangle^2} - \frac{\langle \delta P_T \delta N \rangle^2}{\sigma^2_N \langle P_T \rangle^2}$ **where the last term is small if multiplicity bins are very narrow as in the ALICE measurement**

COMPARISON OF C_m TO ALICE DATA

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)
ALICE Collaboration, Eur. Phys. J. C74, 3077 (2014)



ESTIMATORS

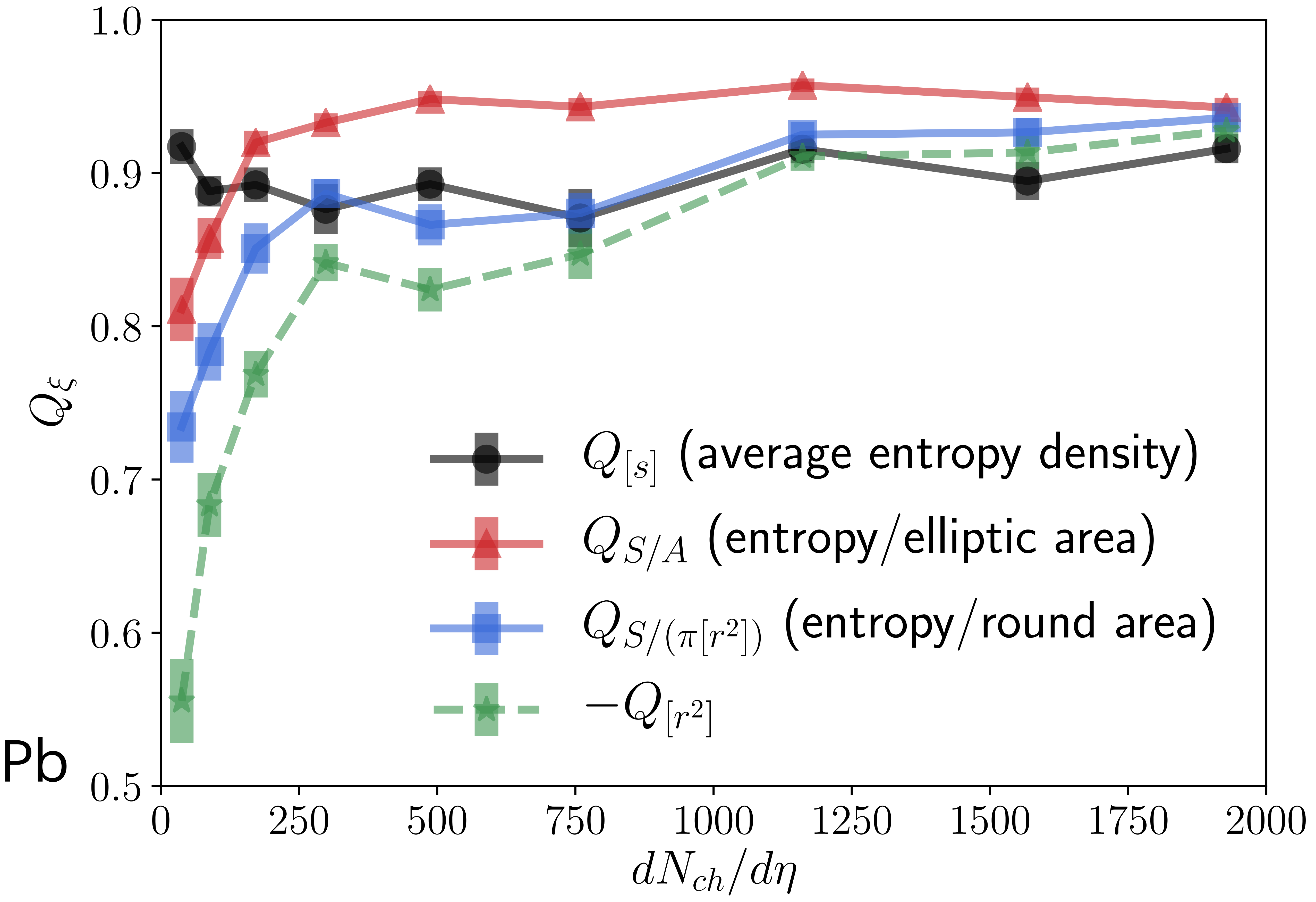
B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

Test different estimators for transverse momentum fluctuations:

Pearson coefficients:

$$Q_\xi = \frac{\langle \hat{\delta} P_T \hat{\delta} \xi \rangle}{\sqrt{\langle \hat{\delta} P_T^2 \rangle \langle \hat{\delta} \xi^2 \rangle}}$$

5.02 TeV Pb+Pb

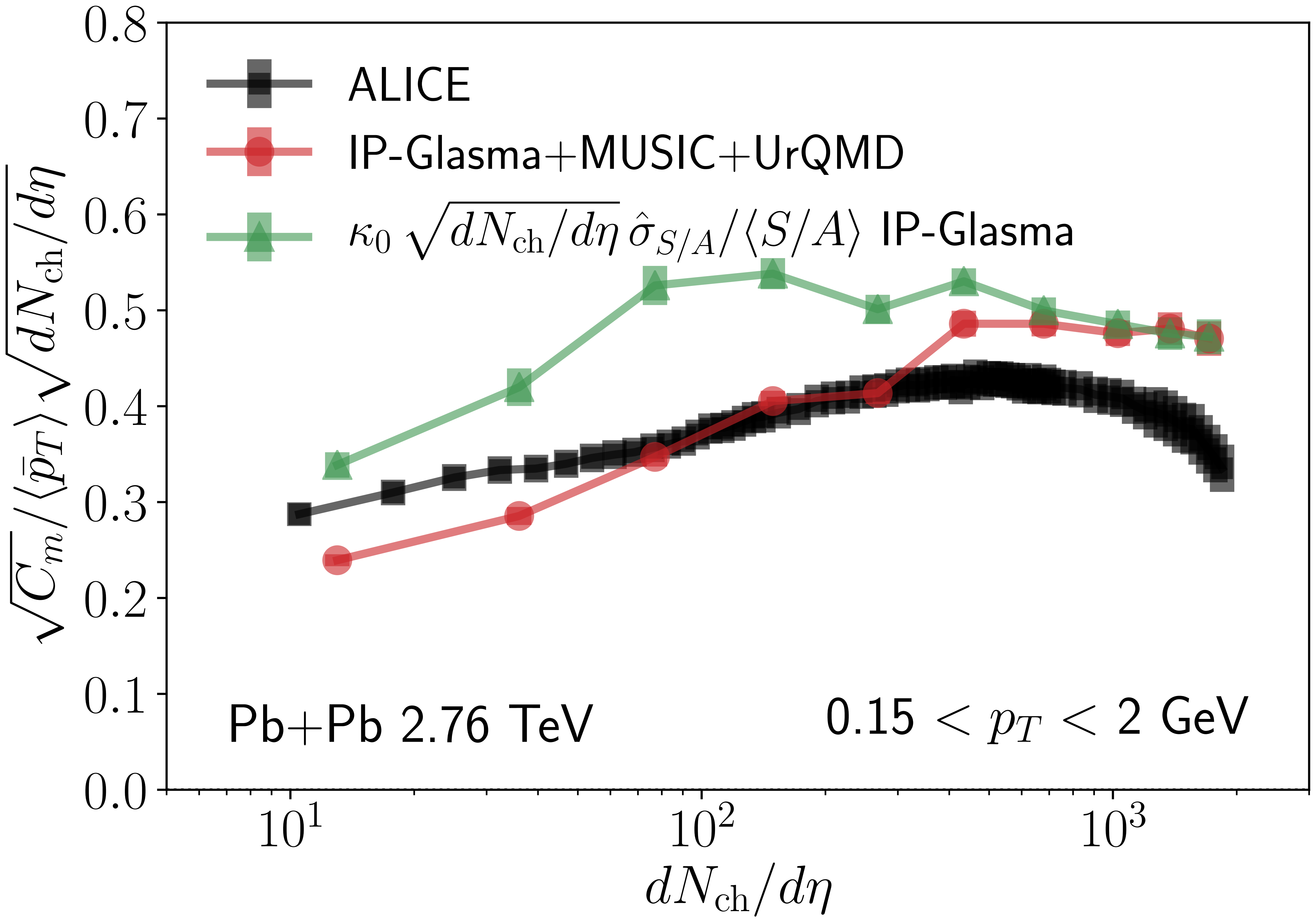


ESTIMATOR - ENTROPY PER AREA

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

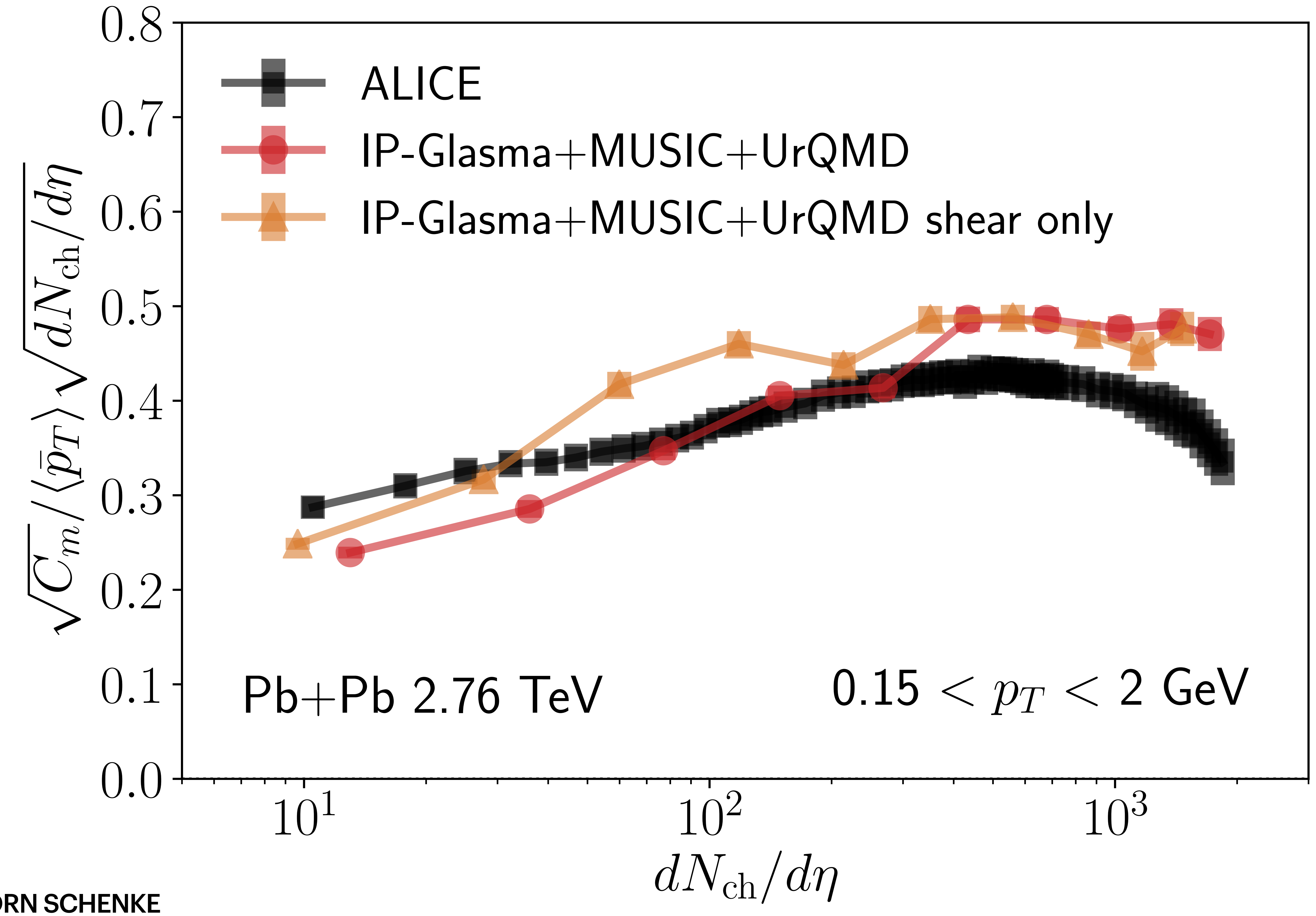
Estimator S/A works perfectly in central collisions (up to 30% central)

The response coefficient κ is assumed to be constant but should depend on centrality



EFFECT OF BULK VISCOSITY

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)
ALICE Collaboration, Eur. Phys. J. C74, 3077 (2014)



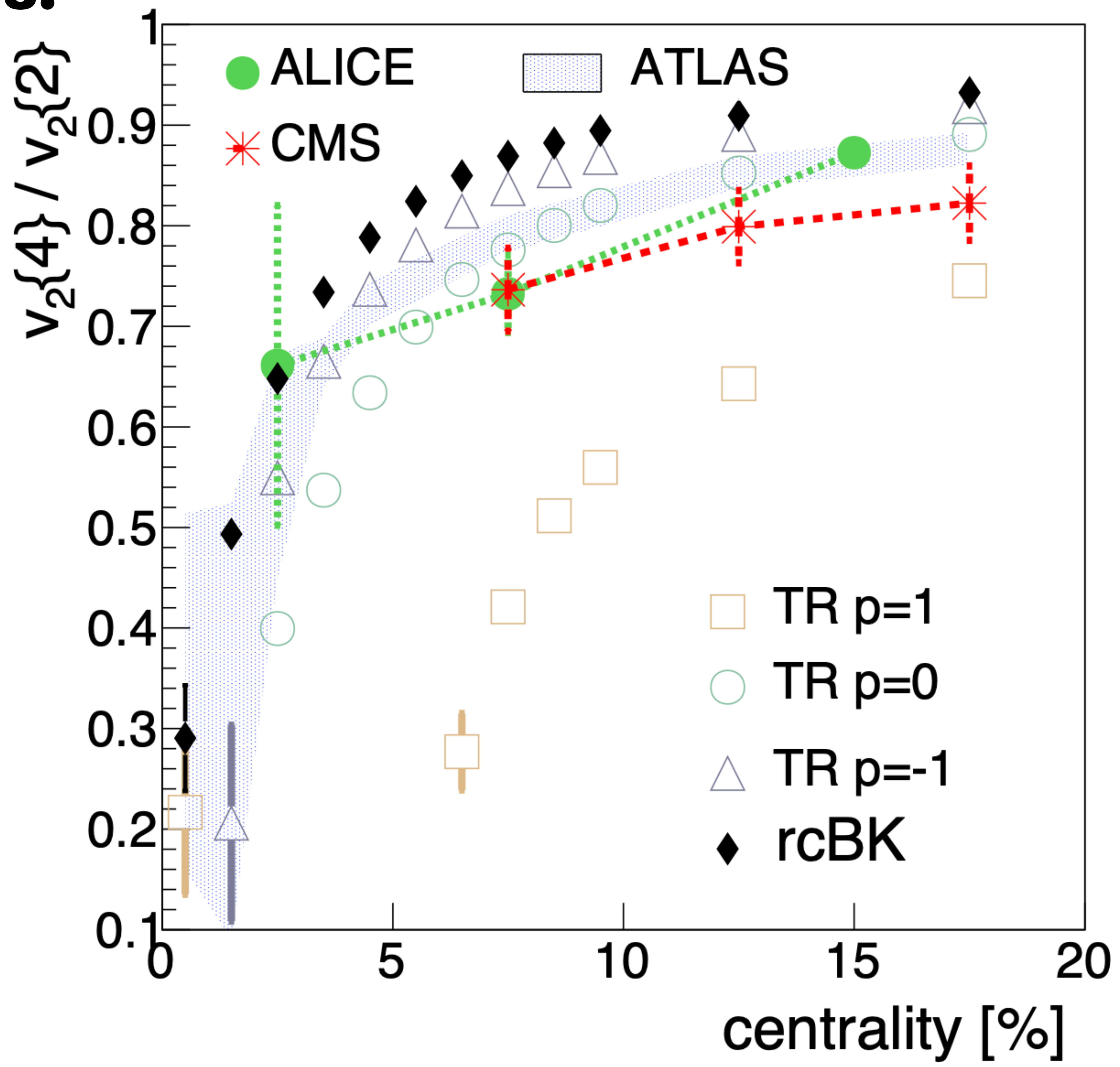
Shape is modified for different details of the medium

$[p_T]$ fluctuations should be included when constraining model parameters

HOW SHOULD THE ENERGY DEPOSITION GO?

Also, the $T_A + T_B$ prescription fails in A+A collisions:

G. Giacalone, J. Noronha-Hostler, J.-Y. Ollitrault
Phys. Rev. C 95, 054910 (2017)



CORRELATION OF $[p_T]$ WITH v_2

P. Bozek, Phys. Rev. C 93, 044908 (2016); B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

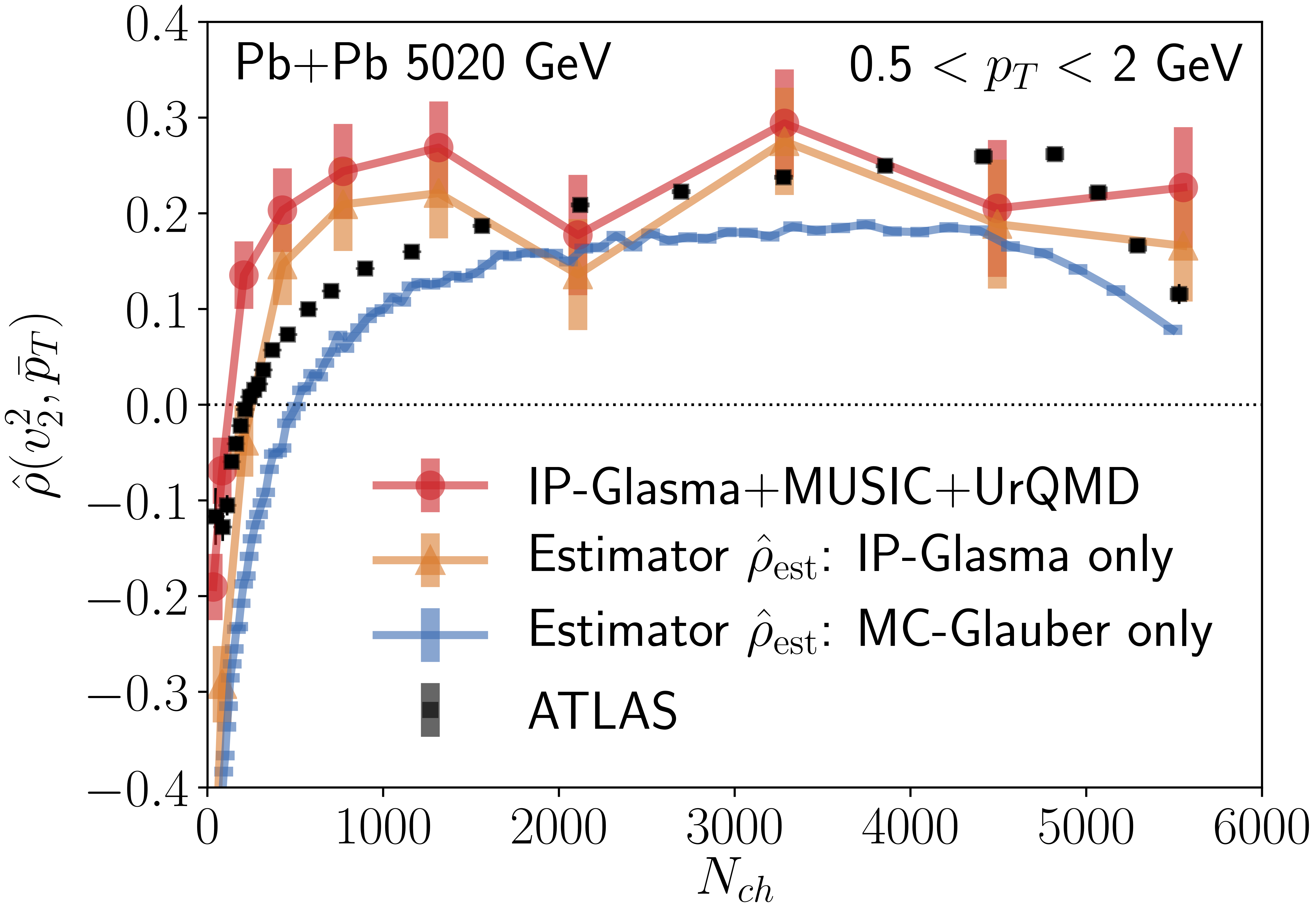
The correlation of $[p_T]$ and v_n fluctuations is quite powerful.

Define $\hat{\rho}(v_n^2,[p_T]) = \dfrac{\langle \hat{\delta} v_n^2\, \hat{\delta}[p_T]\rangle}{\langle(\hat{\delta} v_n^2)^2\rangle\langle(\hat{\delta}[p_T])^2\rangle}$

and the predictor $\hat{\rho}_{\mathrm{est}}(v_n^2,[p_T]) = \dfrac{\langle \hat{\delta}\varepsilon_n^2\, \hat{\delta}(S/A)\rangle}{\langle(\hat{\delta}\varepsilon_n^2)^2\rangle\langle(\hat{\delta}(S/A))^2\rangle}$

CORRELATION WITH v_2: RESULTS

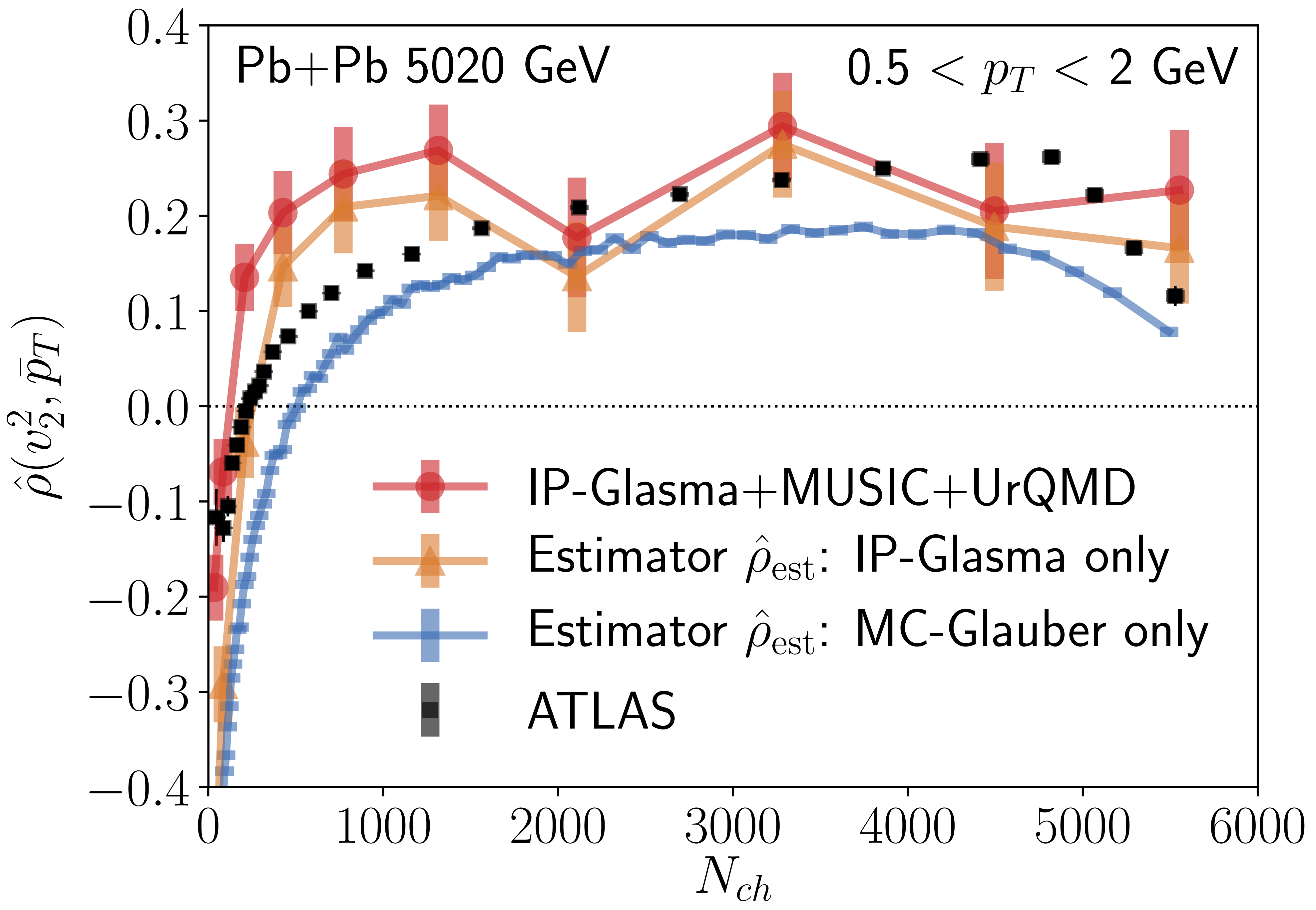
B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)



CORRELATION WITH v_2: INTERPRETATION

B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

Positive correlation at high, negative at low multiplicity. Driven by geometry:



High multiplicity:

Larger ε_2 means larger v_2 but and smaller elliptic area $A = \pi[r^2]\sqrt{1-\varepsilon_2^2}$ and hence larger $[p_T]$

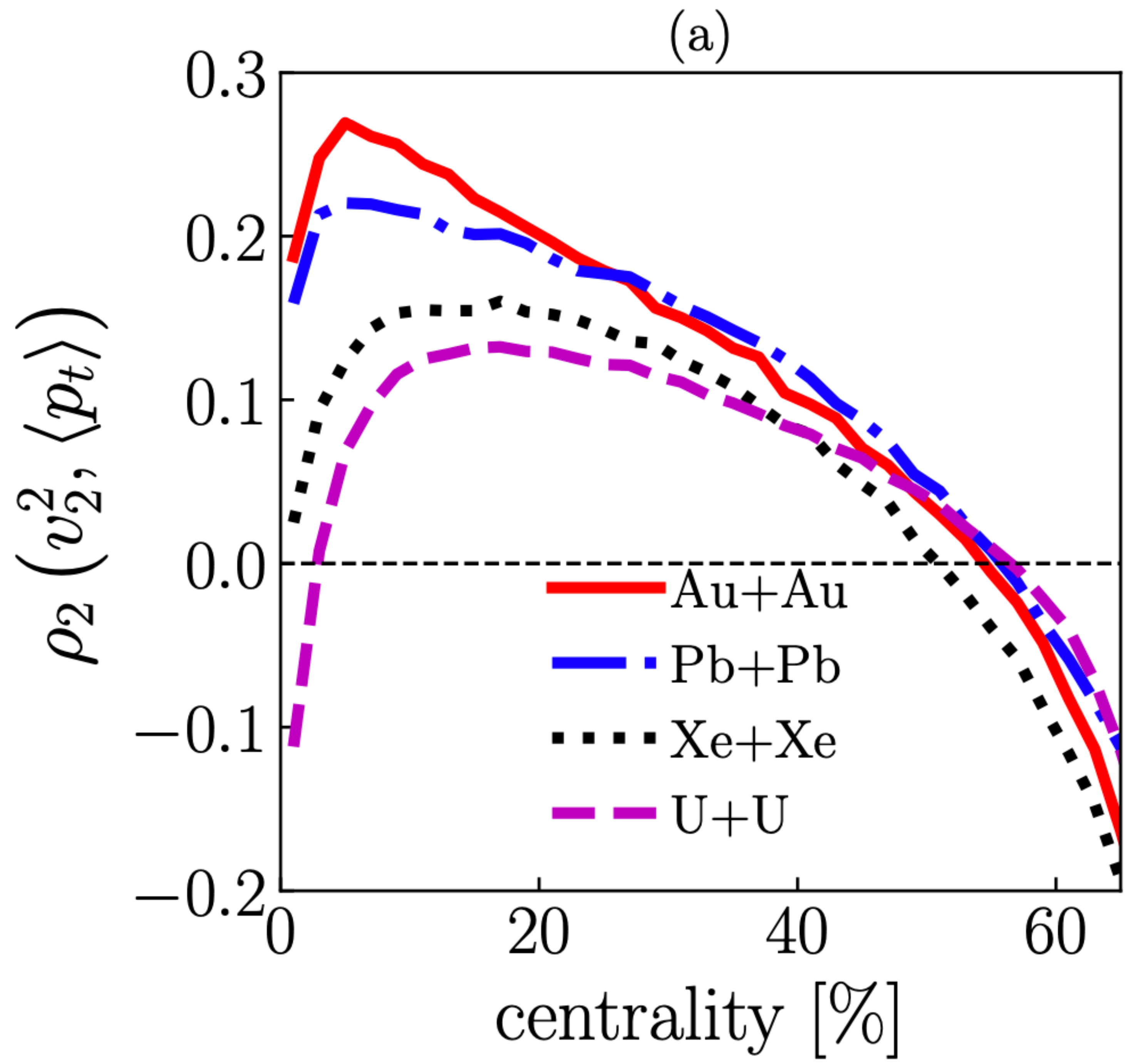
Low multiplicity:

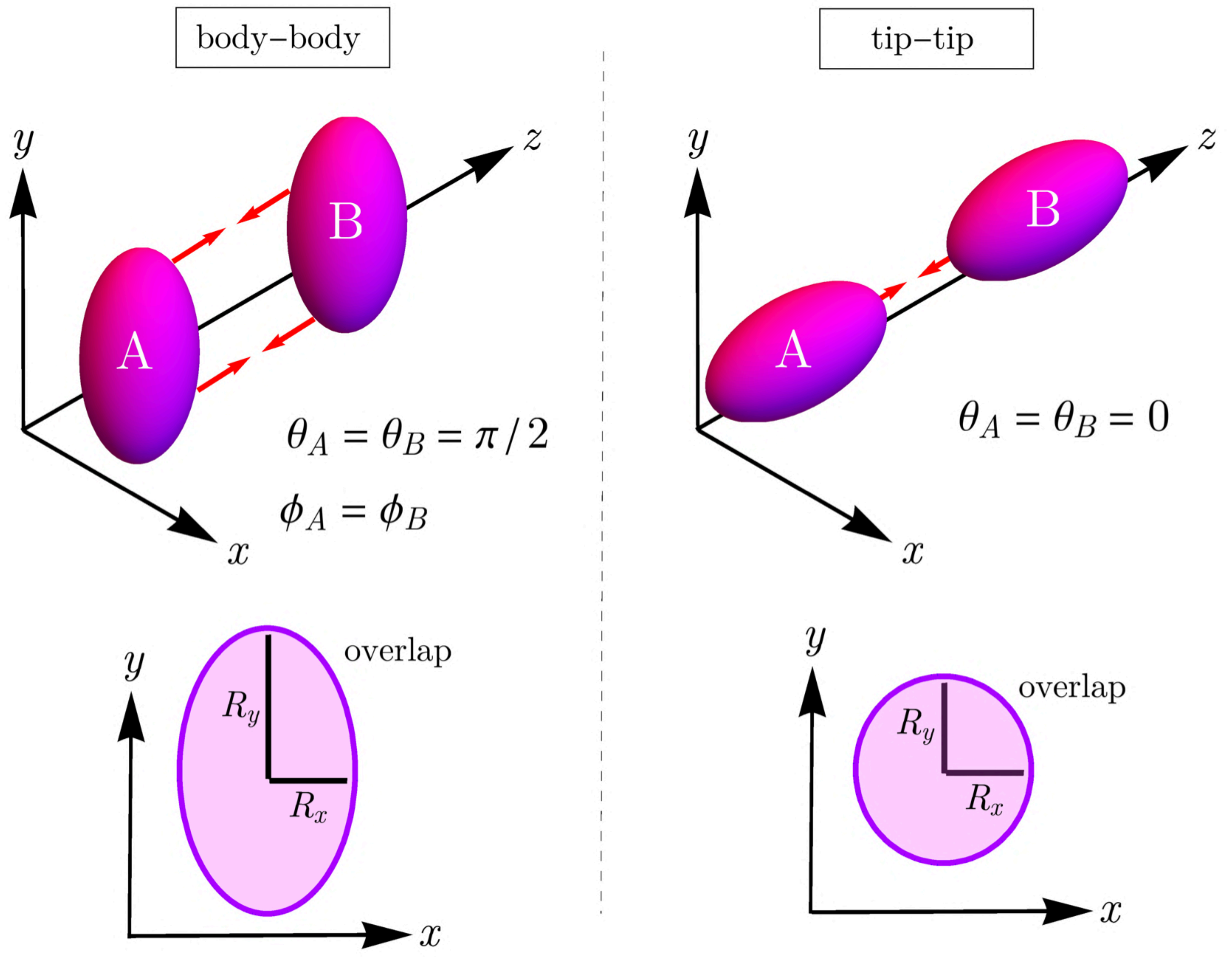
Smaller area obtained by clustering particles in single region. This region will be less elliptic than a more spread out distribution. Smaller A means larger $[p_T]$, smaller ε_2 means smaller v_2

SENSITIVE TO NUCLEAR DEFORMATION

G. Giacalone, Phys. Rev. C 102, 024901 (2020)

Central U+U collisions:
More prolate deformation means stronger anti-correlation of $[p_T]$ and v_2





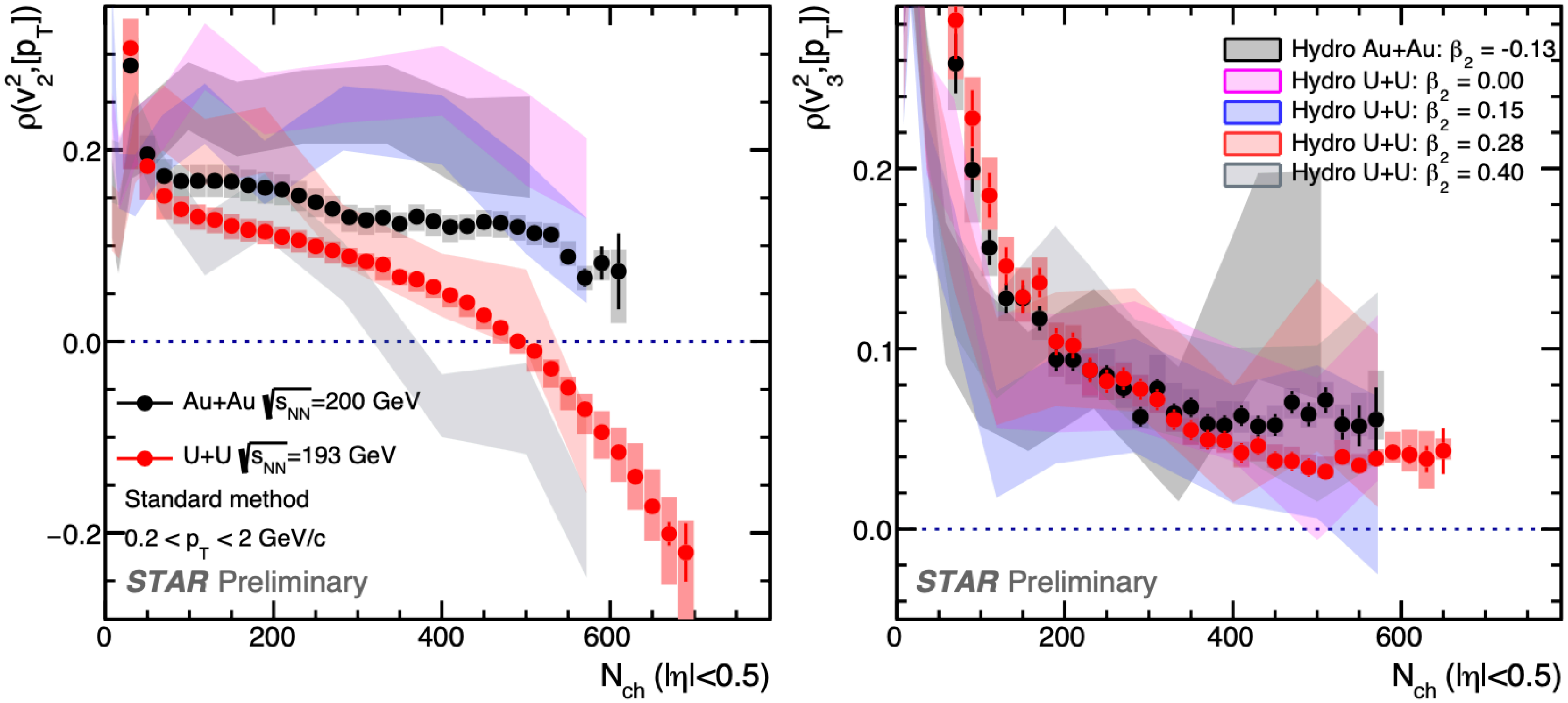
SENSITIVE TO NUCLEAR DEFORMATION

Poster at IS2021 by Chunjian Zhang (For the STAR Collaboration)

Comparing our model predictions to STAR data

$$\rho(r,\theta) = \frac{\rho_0}{1+\exp[(r-R'(\theta))/a]}$$

$$R'(\theta) = R[1+\beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

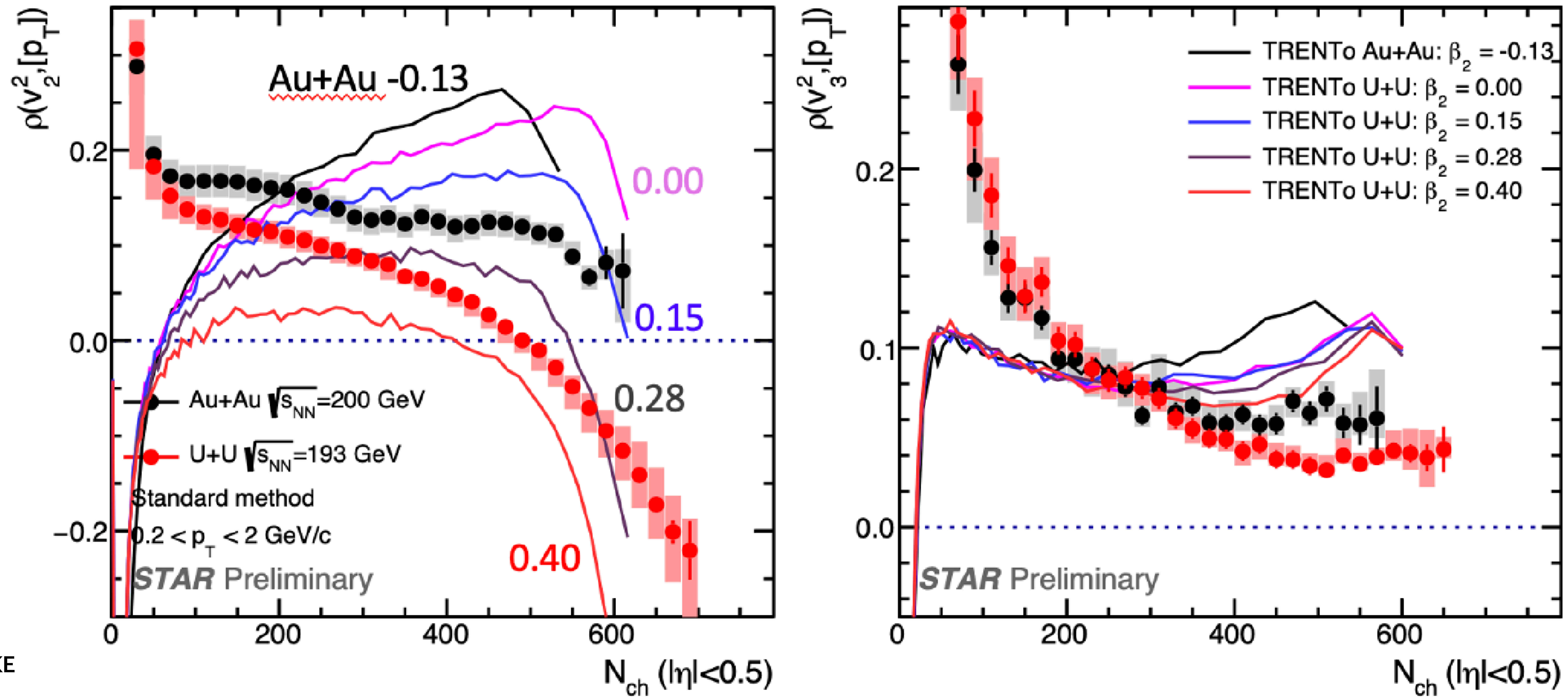


SENSITIVE TO NUCLEAR DEFORMATION

Poster at IS2021 by Chunjian Zhang (For the STAR Collaboration)

And now with Trento initial conditions...

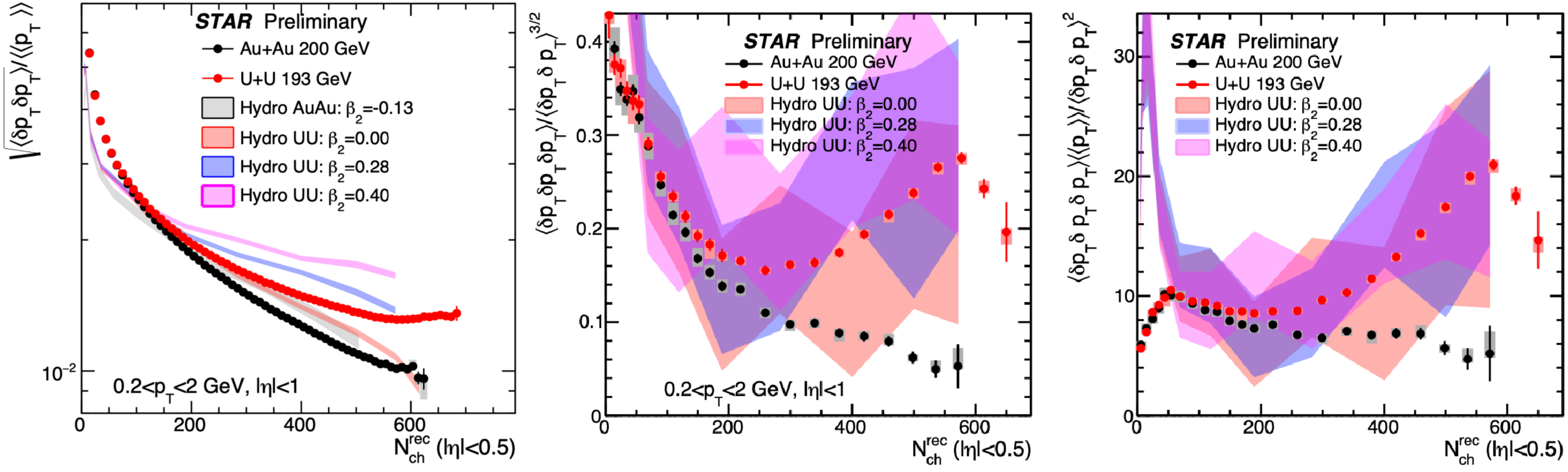
TRENTo: *G. Giacalone, PRC102, 104901(2020), PRL124,202301(2020)*



HIGHER ORDER $[p_T]$ FLUCTUATIONS

Poster at IS2021 by Chunjian Zhang (For the STAR Collaboration)

Variance, standard skewness, and intensive skewness



statistics is still limited

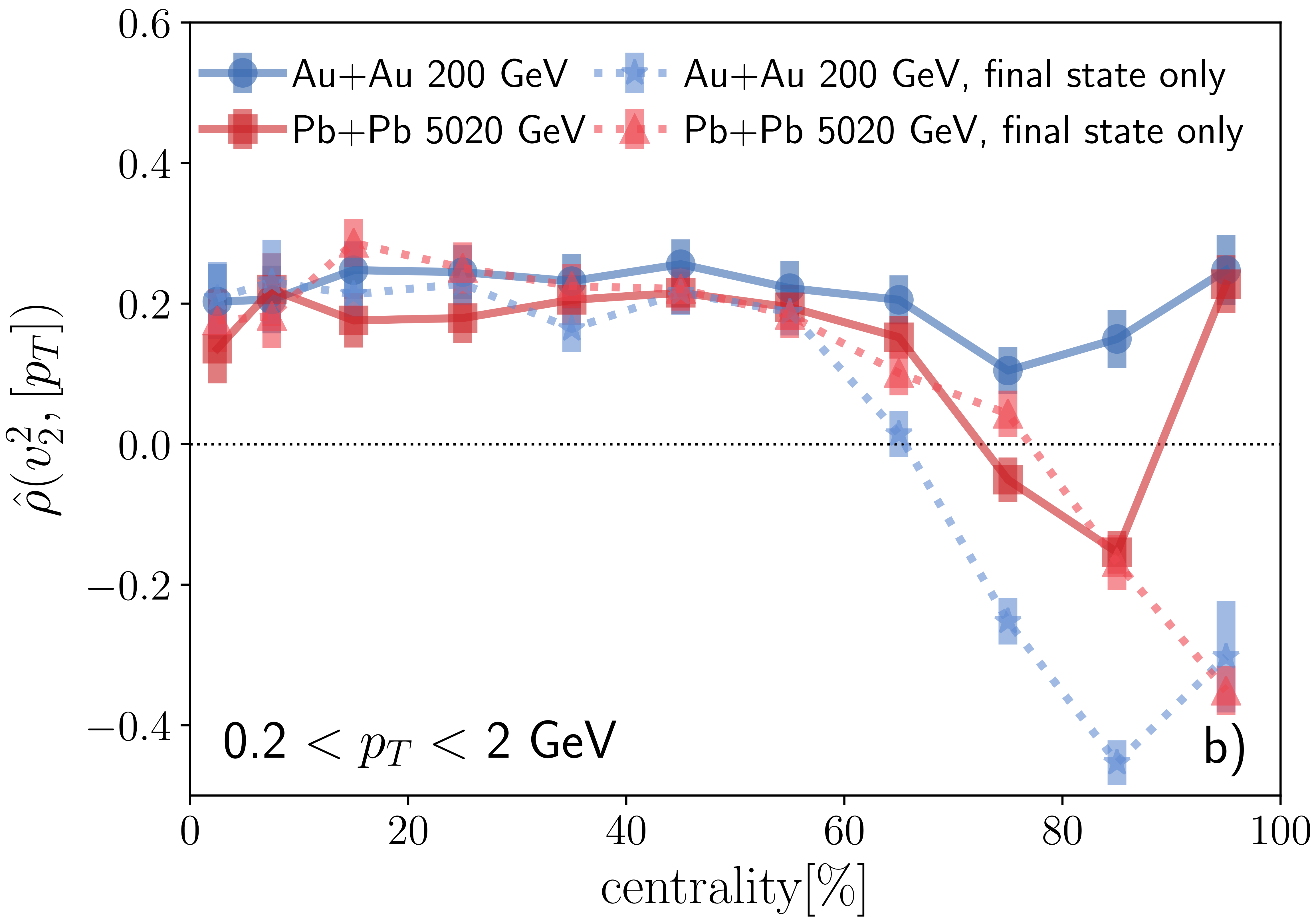
SMALL SYSTEMS

The $[p_T]$ - v_2 correlation can also give insight into the origin of azimuthal anisotropies in small systems, like p+A

BACK TO HEAVY ION COLLISIONS

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

Going to very peripheral events, we also expect to see an effect of the initial state momentum anisotropy



Geometry predictors change sign with centrality
Initial momentum anisotropy predictor is always positive

If final state effects always win, we will see a sign change
happens in 5.02 TeV Pb+Pb

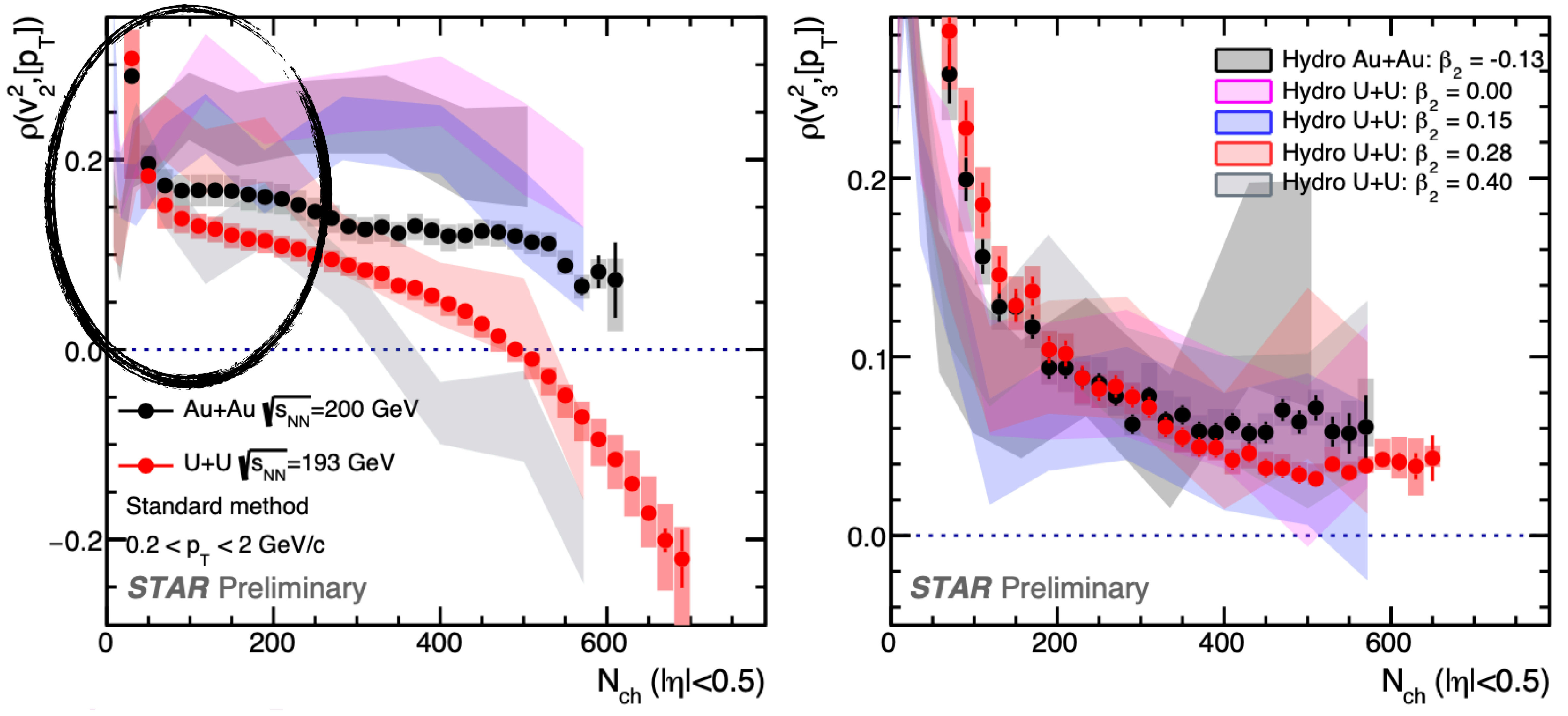
If final state effects are weaker, no sign change may be observed
happens in 200 GeV Au+Au

Consistent with data from ATLAS
G. Aad et al. (ATLAS), Eur. Phys. J. C79, 985 (2019)
and preliminary results from STAR shown earlier

WE HAVE SEEN THIS EFFECT BEFORE

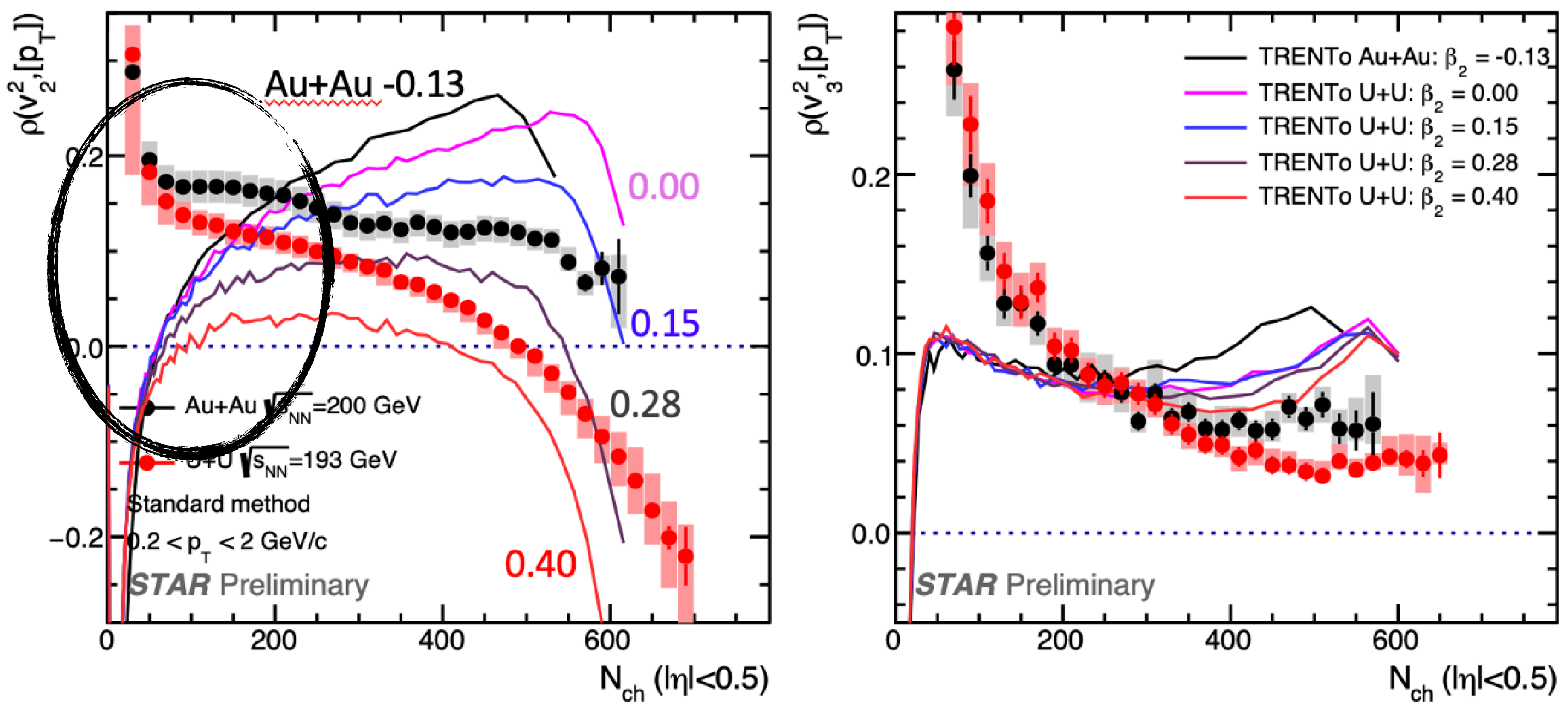
Poster at IS2021 by Chunjian Zhang (For the STAR Collaboration)

with initial momentum anisotropy



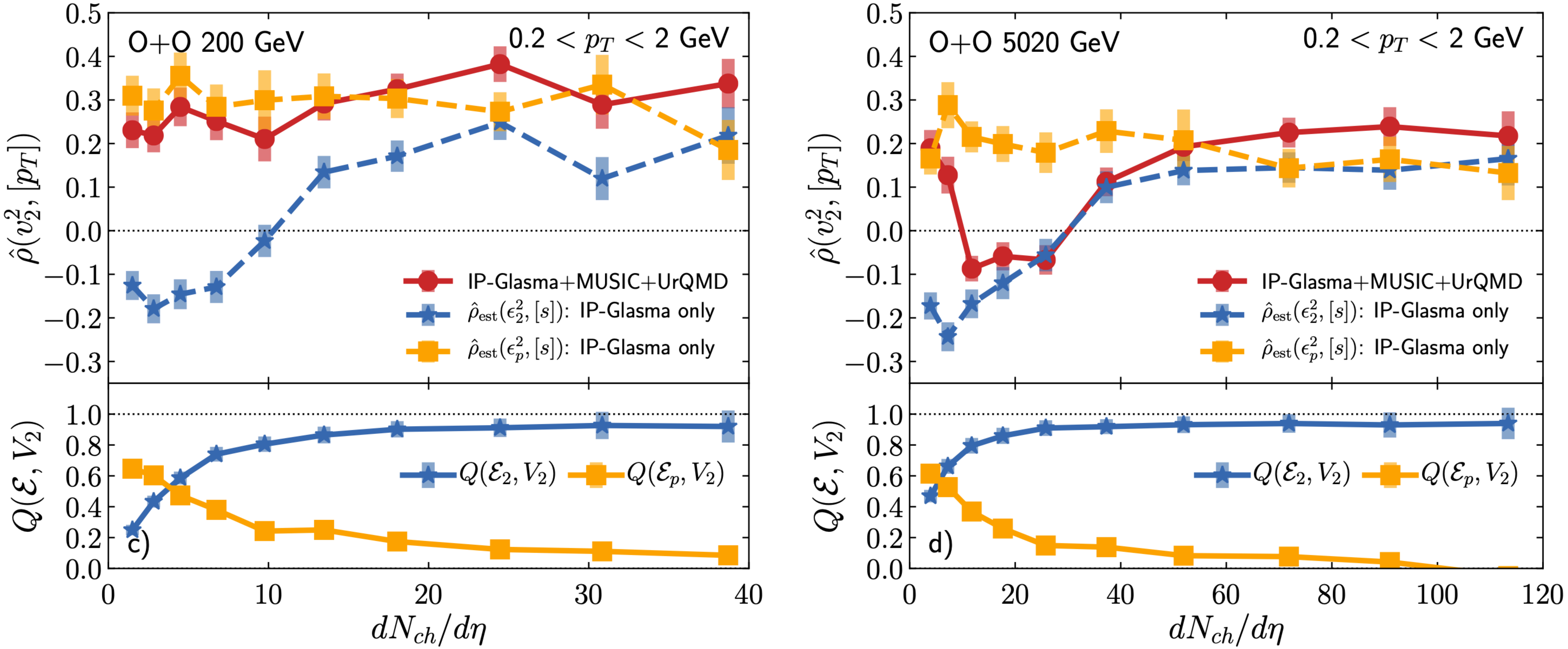
TRENTo: *G. Giacalone, PRC102, 104901(2020), PRL124,202301(2020)*

without initial momentum anisotropy



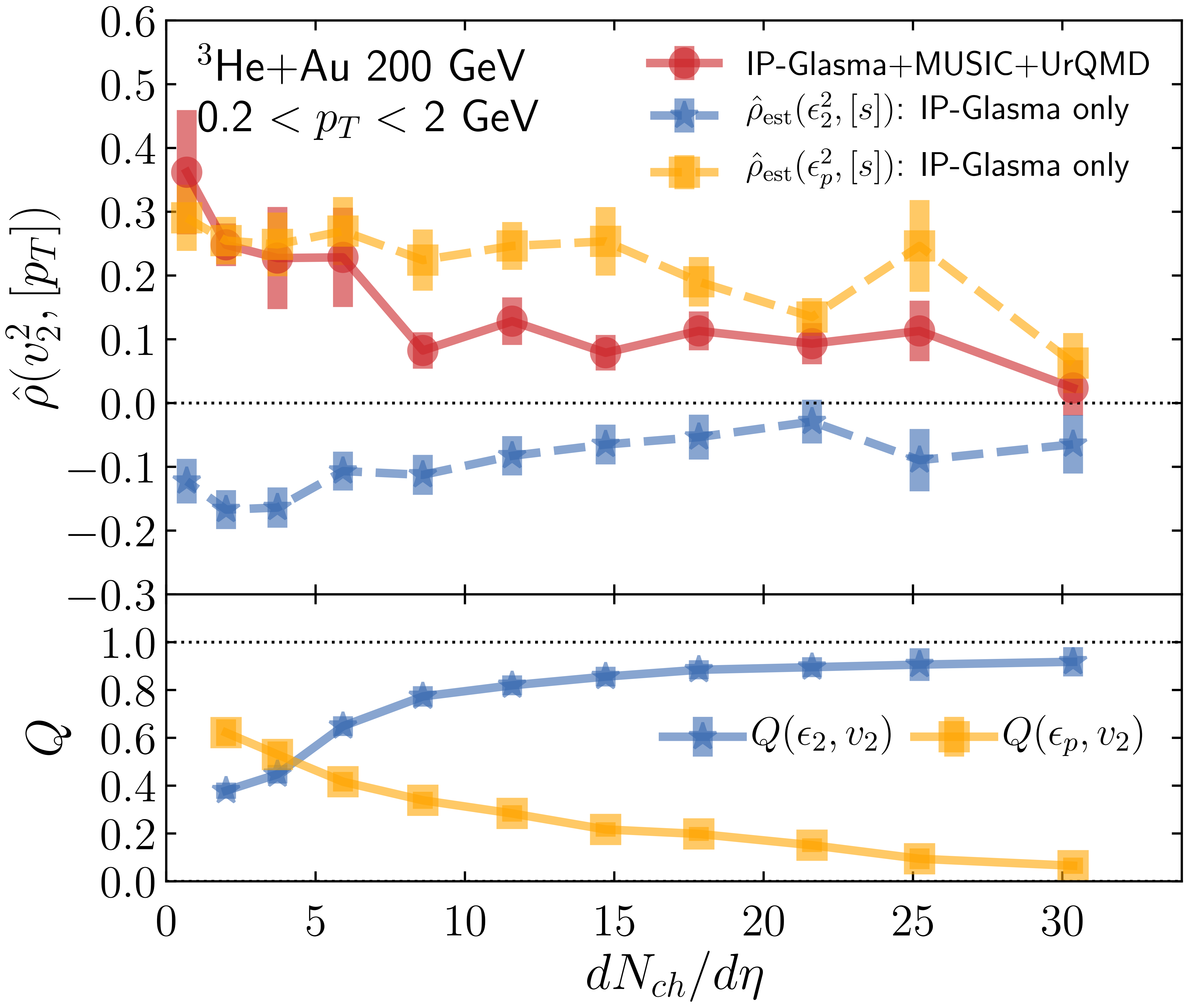
O+O PREDICTIONS

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301



INTERMEDIATE: ^{3}He+Au

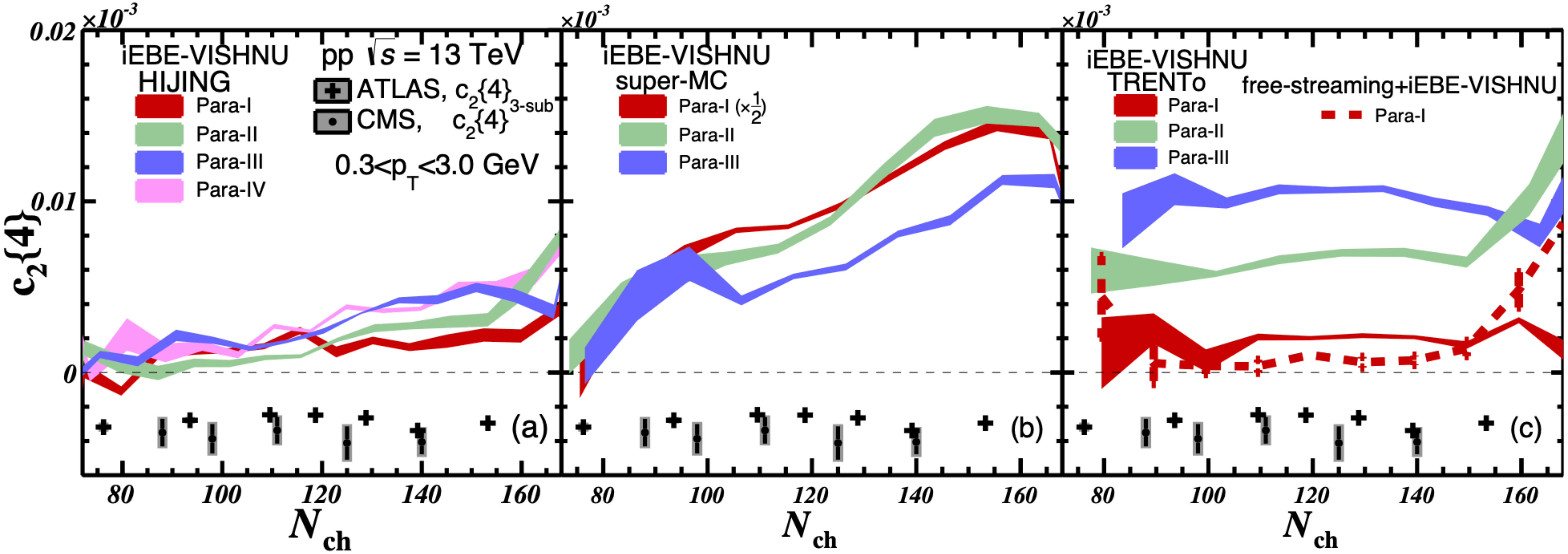
G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301



A WORD ON p+p

Multi-particle single and mixed harmonics cumulants can not be described by hydrodynamics with HIJING, super-MC or TRENTo initial conditions, even for the signs in a few cases

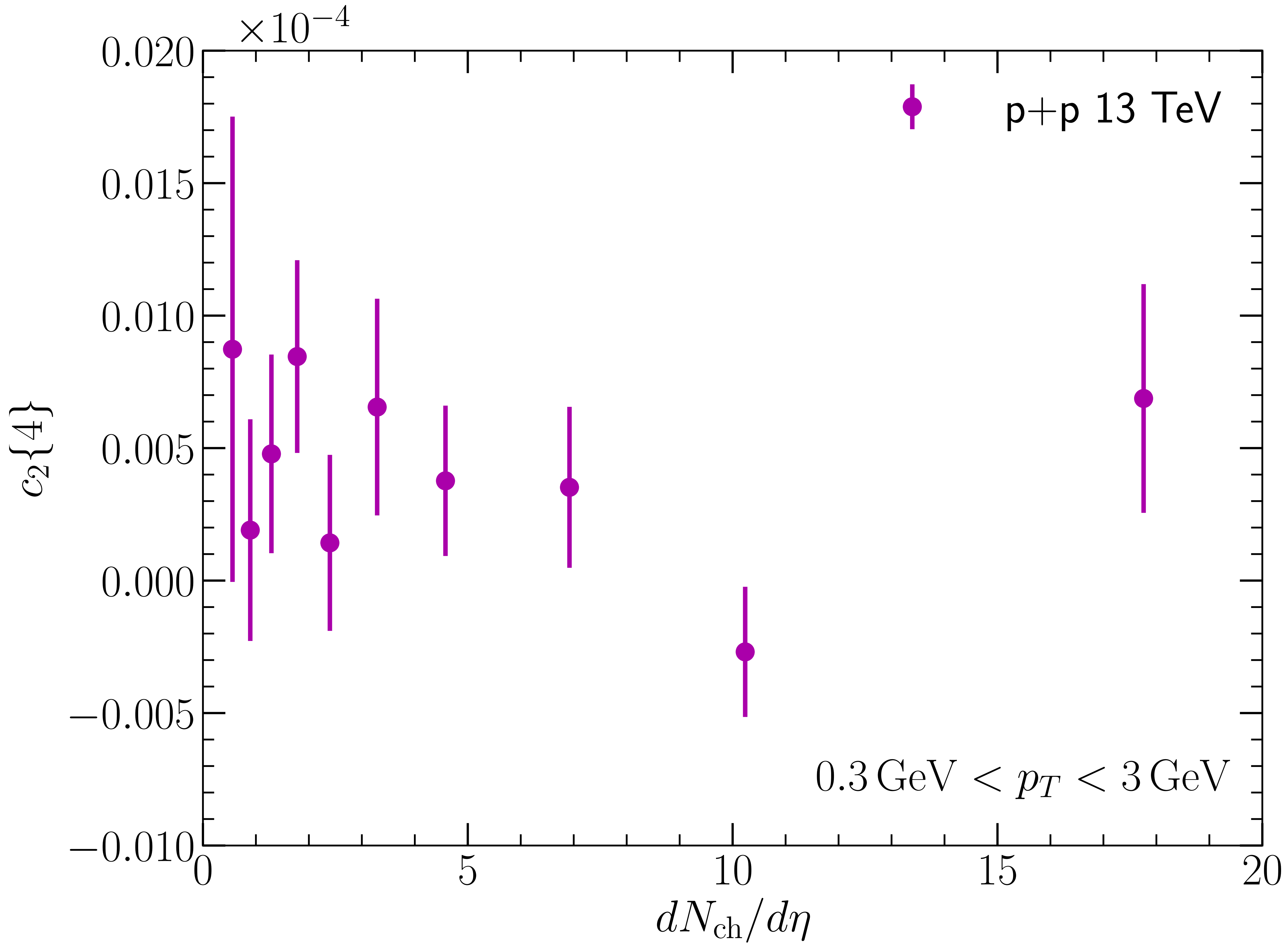
Y. Zhou, W. Zhao, K. Murase, H. Song, Nucl.Phys.A 1005 (2021) 121908



So, it is very hard to generate initial conditions that produce negative $c_2\{4\}$ in p+p collisions

A WORD ON p+p: IP-GLASMA + MUSIC + URQMD

preliminary



Errors still large, but looks positive as well. However, we do not have more central results yet. Need to “trigger” on even more high multiplicity events. Ongoing…