U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

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SMALL SYSTEM SCAN WITHIN A COMBINED COLOR GLASS CONDENSATE AND HYDRODYNAMIC MODEL

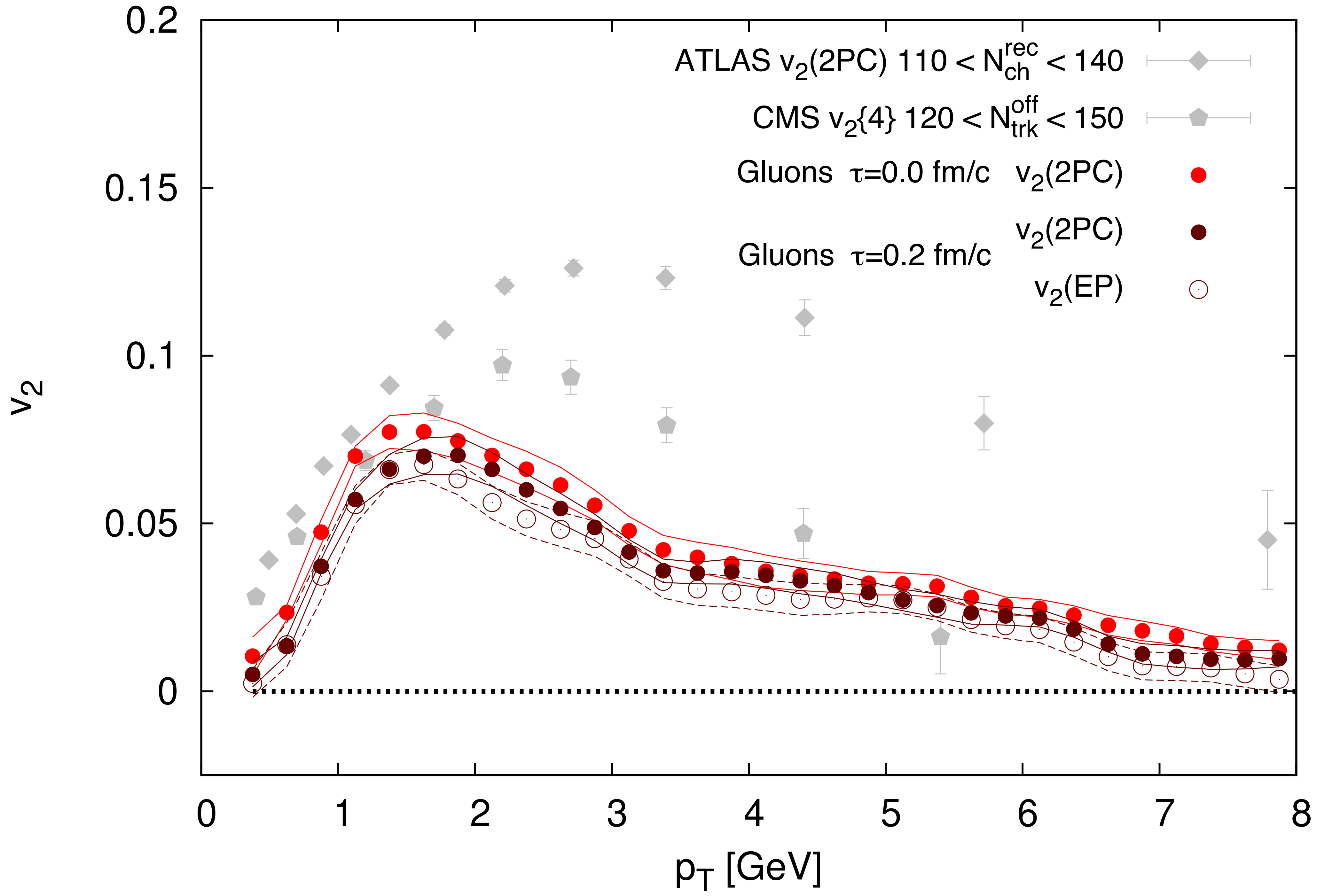
WITH C. SHEN AND P. TRIBEDY

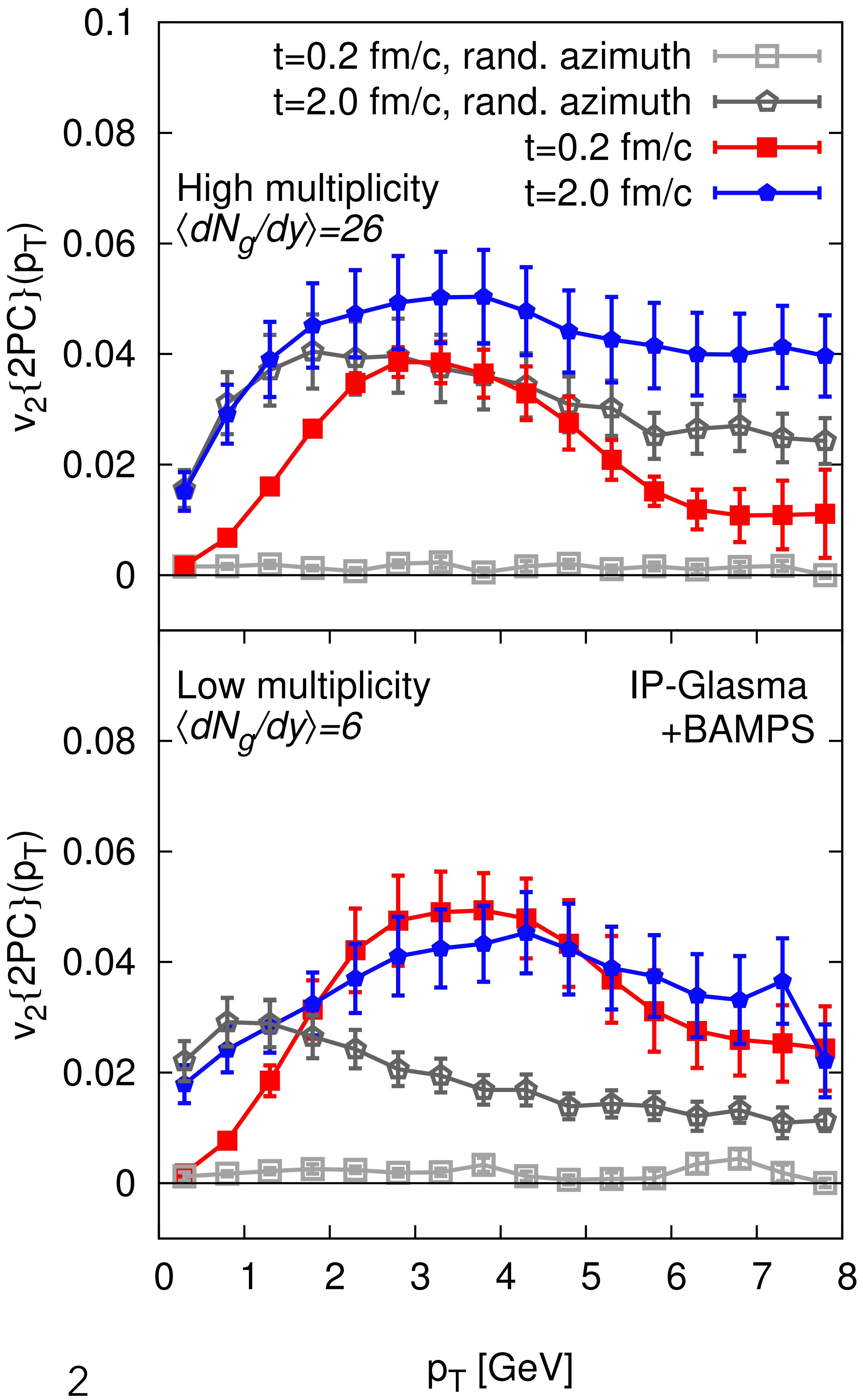
Quark Matter 2019
Wuhan - 11/06/2019

INITIAL MOMENTUM CORRELATIONS

B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett. B747 (2015) 76-82
M.Greif, C. Greiner, B.Schenke, S. Schlichting, Z. Xu, Phys.Rev. D96 (2017) 091504

- Initial ($\tau = 0$) momentum space correlations in Color Glass Condensate





- IP-Glasma + parton cascade (BAMPS)
- Initial anisotropy affects v_2 especially for low multiplicity and $p_T > 1.5\,\mathrm{GeV}$

Many more works.
For a review see e.g.:
S. Schlichting and P. Tribedy Adv.High Energy Phys. 2016 (2016) 8460349

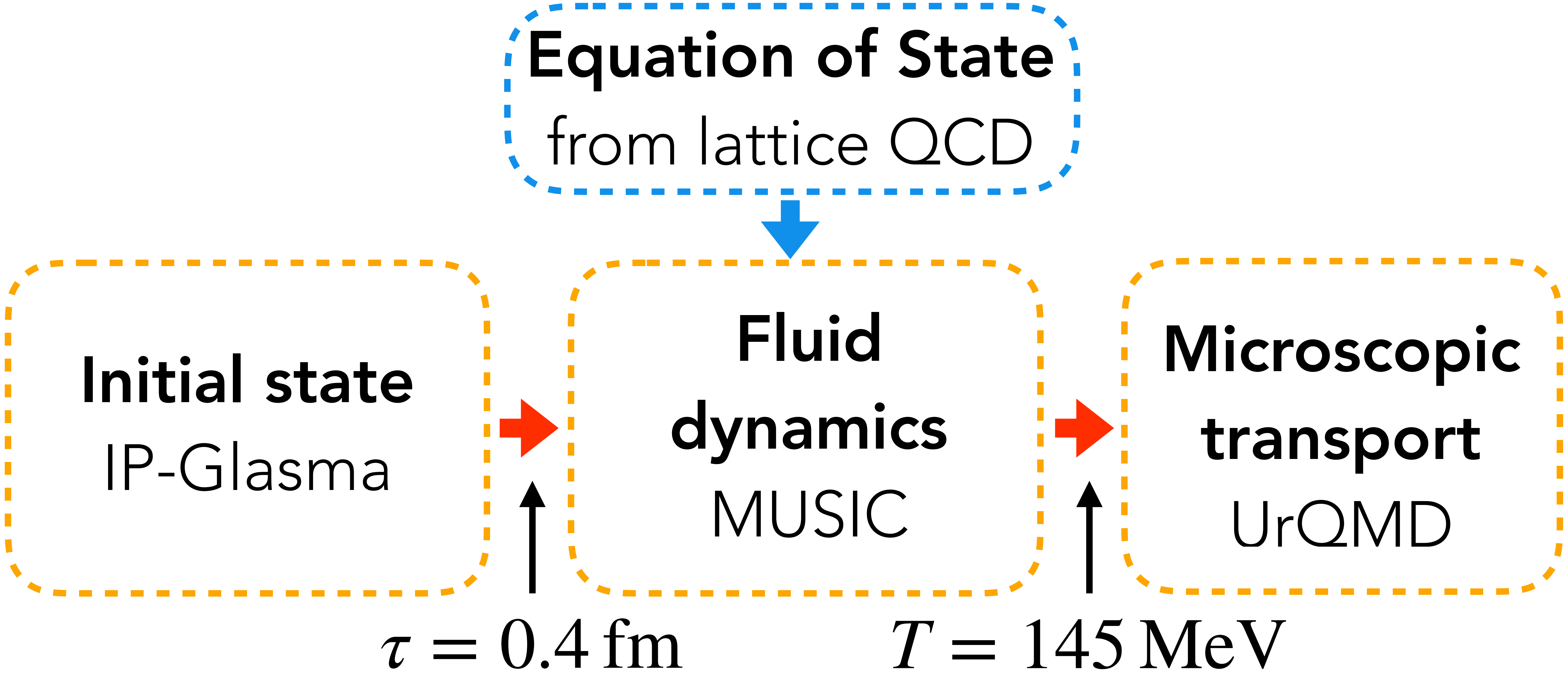
IP-GLASMA+MUSIC+URQMD

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

2 questions:

- How well do we describe small systems in our framework that is constrained to describe large systems (A+A)?
- How much can the initial momentum anisotropy affect final observables if the final state is described by hydrodynamics?

IP-GLASMA+MUSIC+URQMD



- Include sub-nucleonic fluctuations in IP-Glasma constrained by HERA data

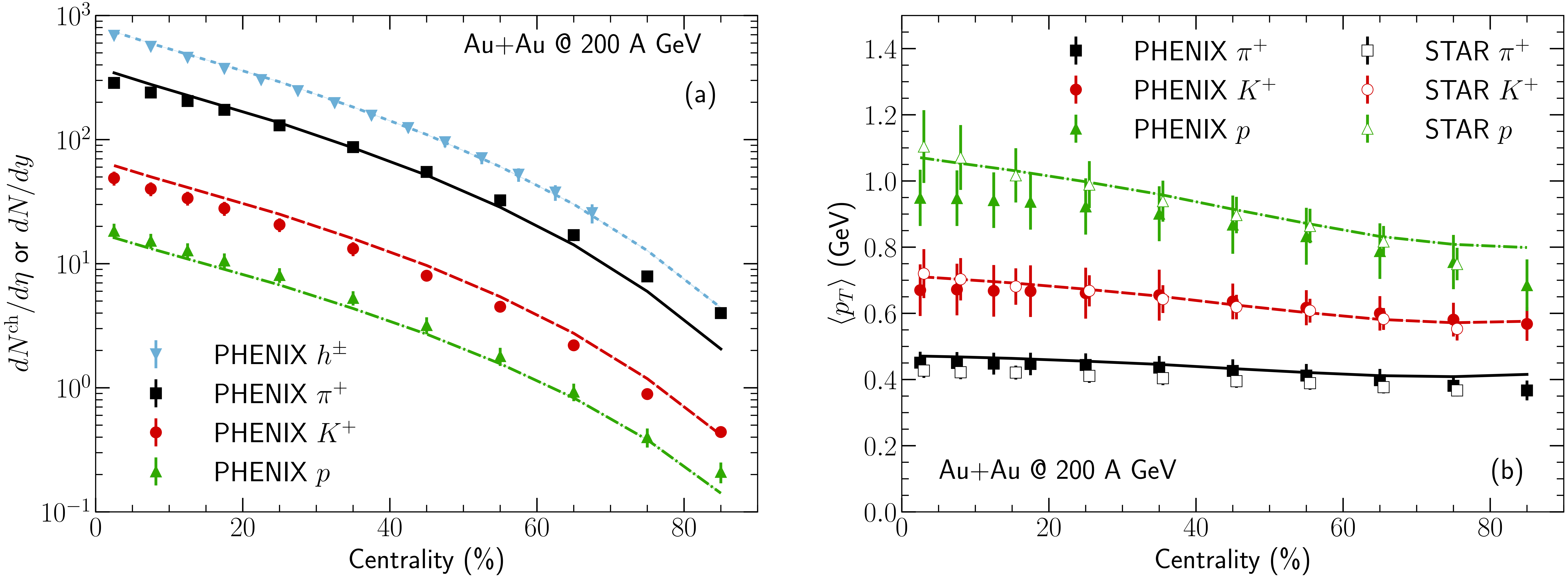
H. Mäntysaari, B. Schenke
Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042

- Exactly match $T^{\mu\nu}$ when switching from one part to the next
- Difference in EoS between IP-Glasma and lattice QCD absorbed in effective initial bulk Π (positive)

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)

HYDRO PARAMS. CONSTRAINED WITH AuAu DATA

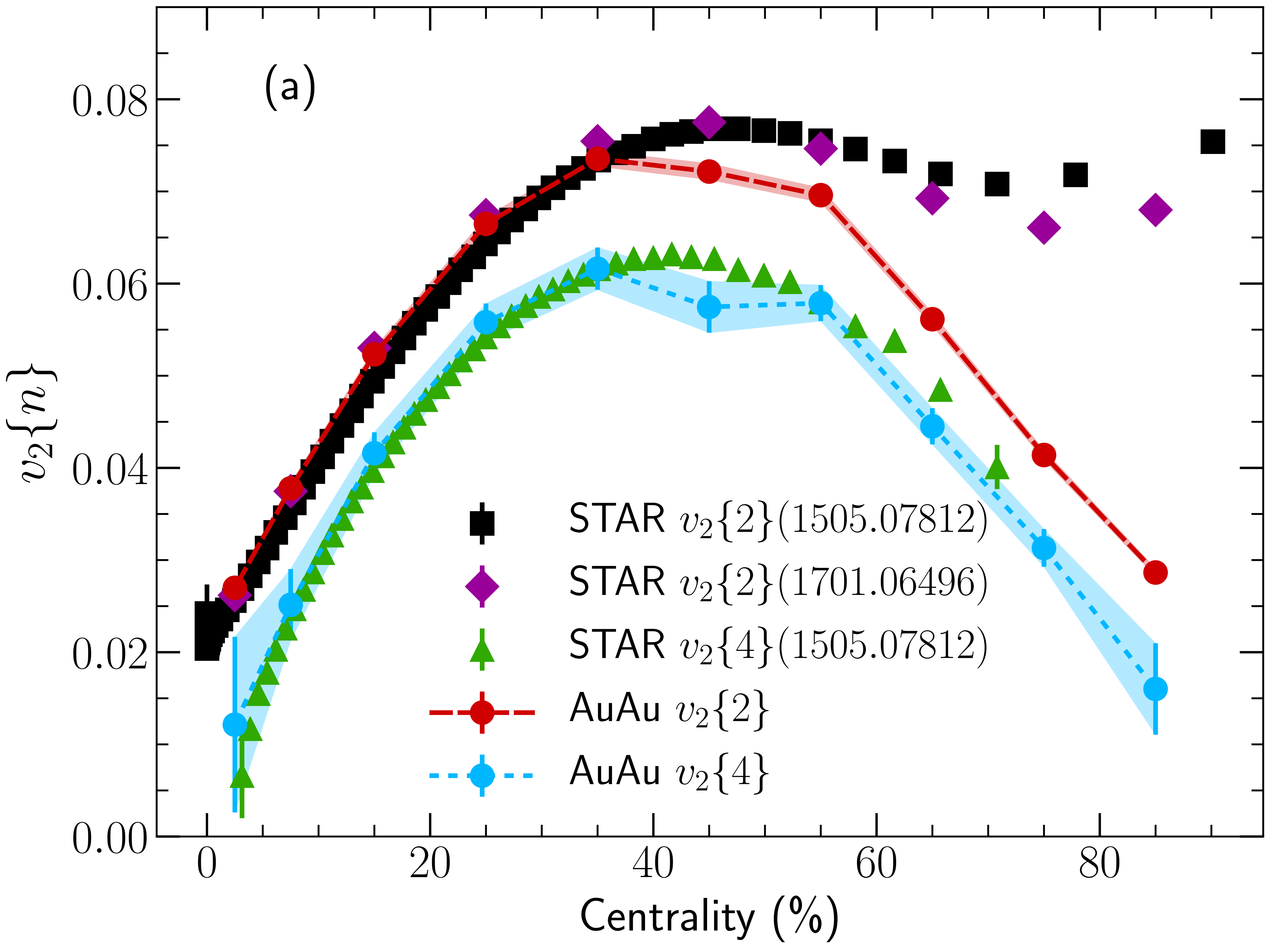
B. Schenke, C. Shen, P. Tribedy, Phys.Rev. C99 (2019) no.4, 044908

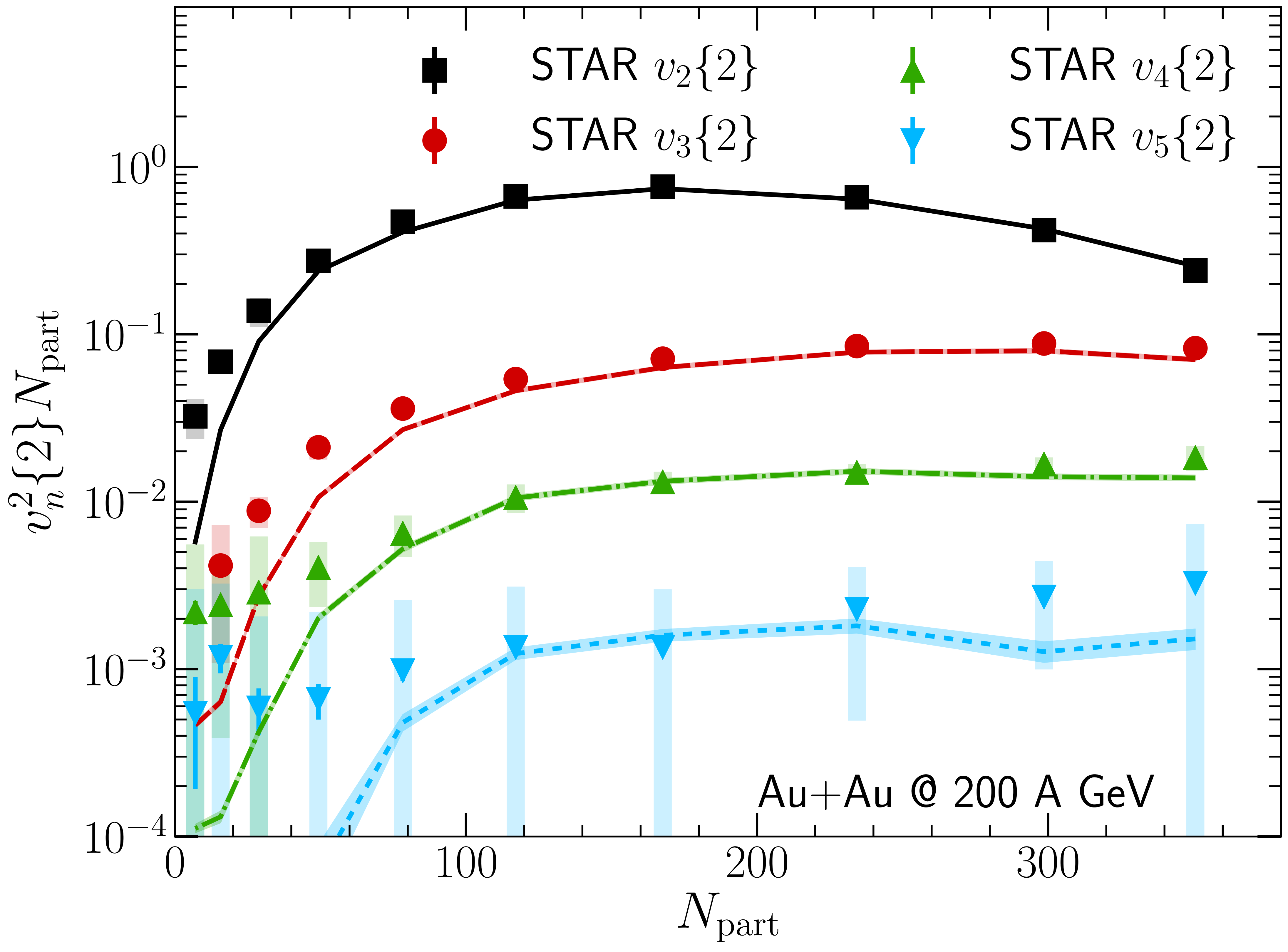


Experimental Data: S. S. Adler et al. (PHENIX), Phys. Rev. C69, 034909 (2004)
B. I. Abelev et al. (STAR), Phys. Rev. C79, 034909 (2009)

HYDRO PARAMS. CONSTRAINED WITH AuAu DATA

B. Schenke, C. Shen, P. Tribedy, Phys.Rev. C99 (2019) no.4, 044908

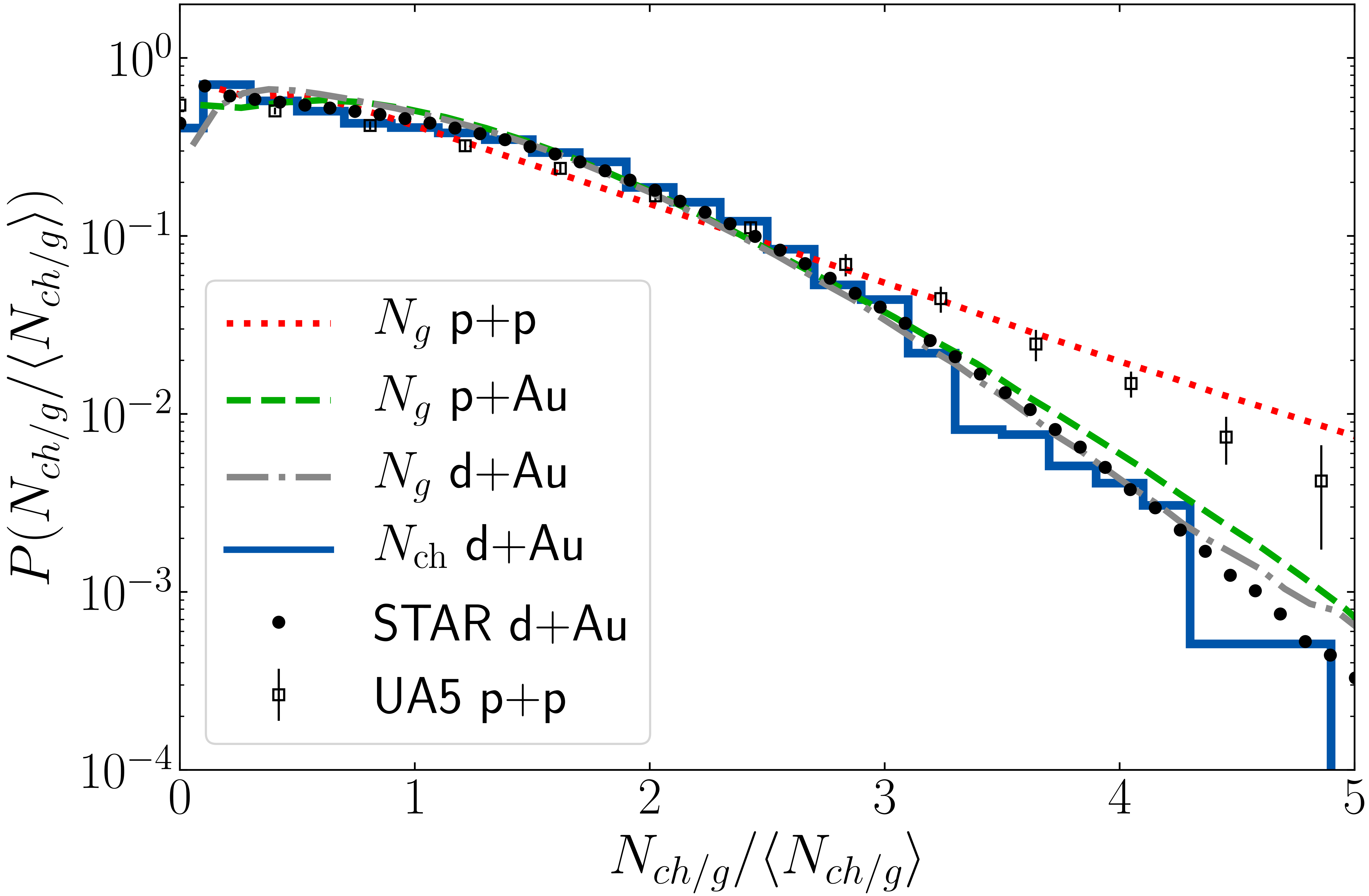




Experimental Data: L. Adamczyk et al. (STAR), Phys. Rev. C98, 034918 (2018);
L. Adamczyk et al. (STAR), Phys. Rev. Lett. 116, 112302 (2016); L. Adamczyk et al. (STAR), Phys. Rev. Lett. 115, 222301 (2015)

RESULTS: MULTIPLICITY DISTRIBUTIONS

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



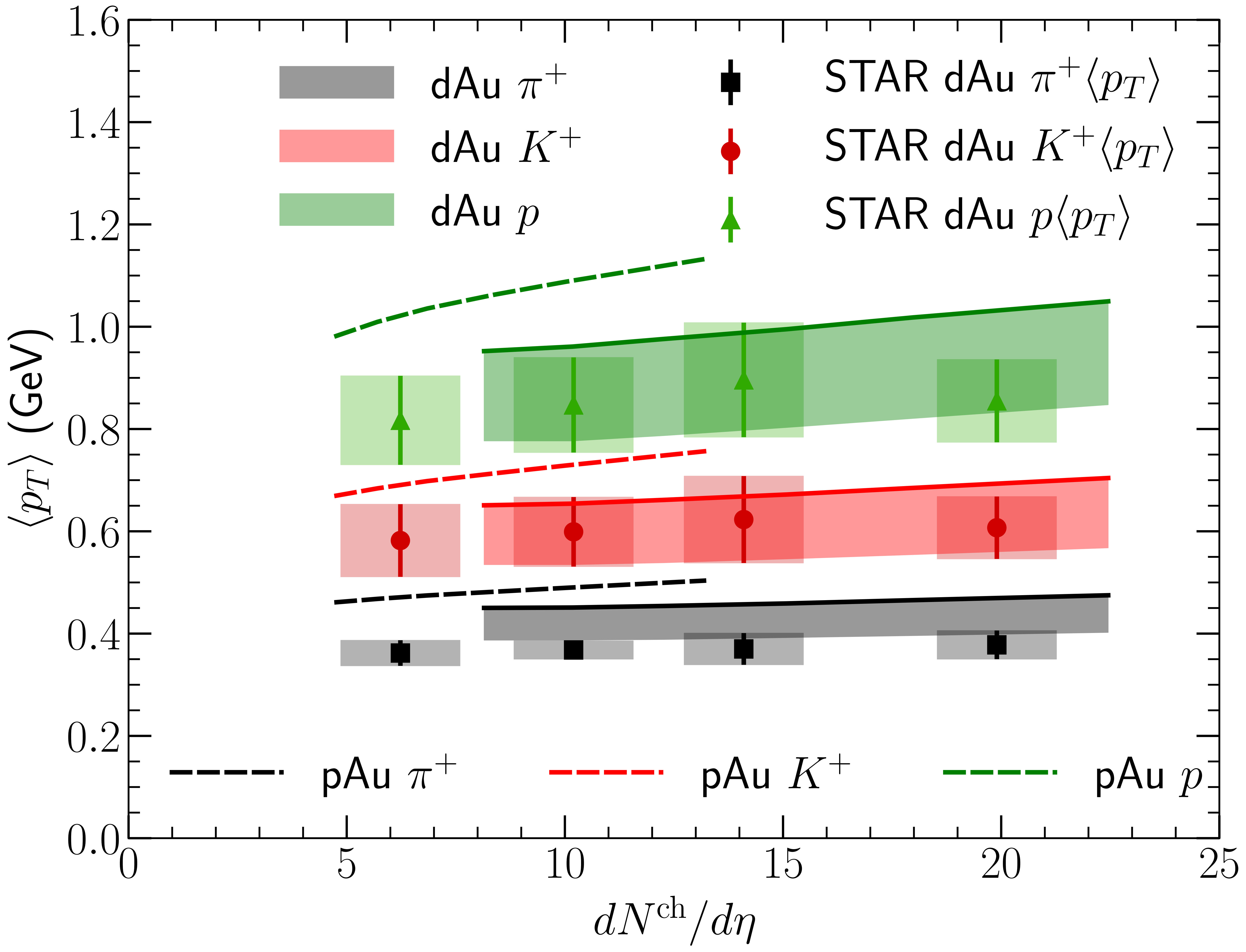
Experimental Data: B. I. Abelev et al. (STAR), Phys. Rev. C79, 034909 (2009)

R. Ansorge et al. (UA5 Collaboration), Zeitschrift für Physik C, Particles and Fields 43, 357 (1989)

RESULTS: MEAN TRANSVERSE MOMENTUM

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

Experimental Data: B. I. Abelev et al. (STAR), Phys. Rev. C79, 034909 (2009)

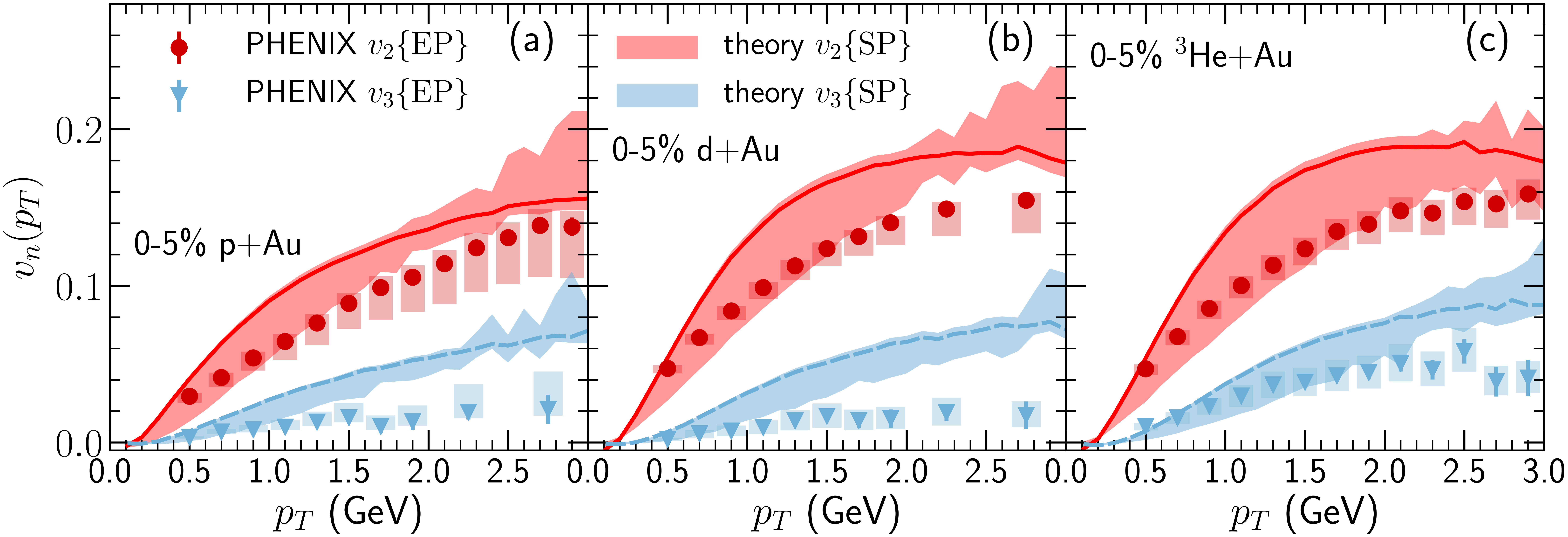


- Solid lines: dAu results constrained using AuAu data
- Bands: systematic uncertainty (different matching of EoS and removal of 2nd order transp. coefficients)
- Dashed lines: pAu results

RESULTS: MOMENTUM ANISOTROPIES

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

Experimental Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019)

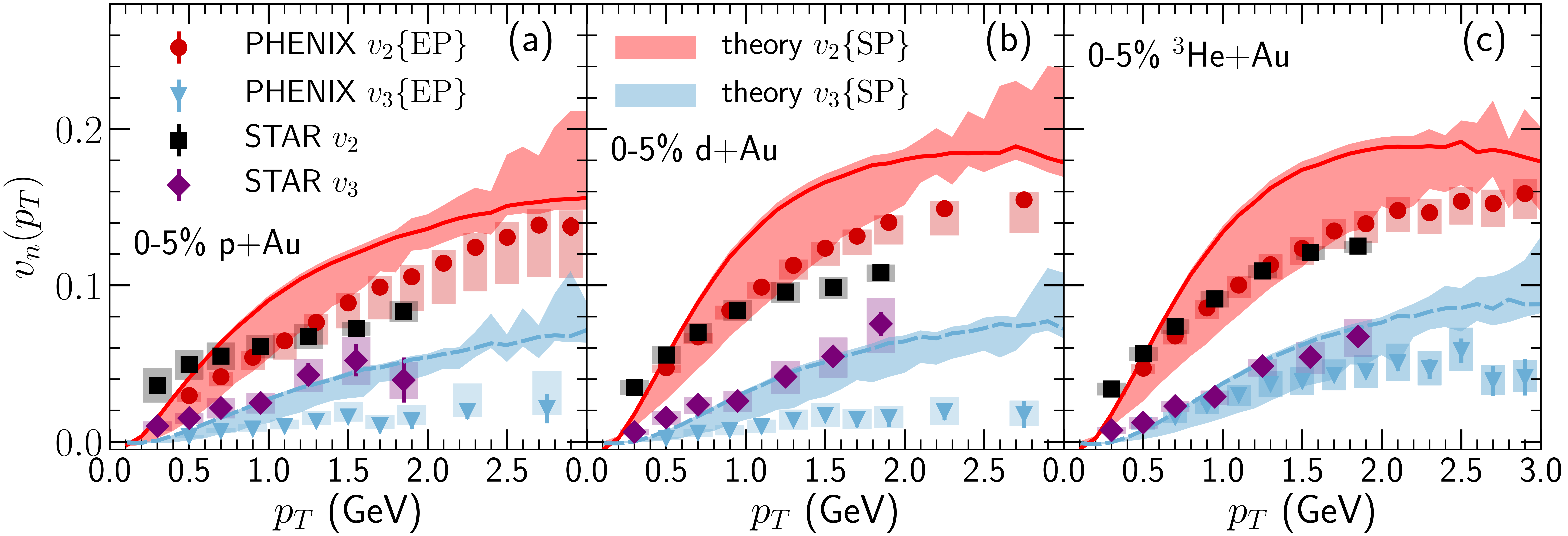


- Solid lines: v_2 result constrained by AuAu (band as before)
- Dashed lines: v_3 result constrained by AuAu (band as before)

RESULTS: MOMENTUM ANISOTROPIES

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

Experimental Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019); STAR, NEW AT QUARK MATTER 2019

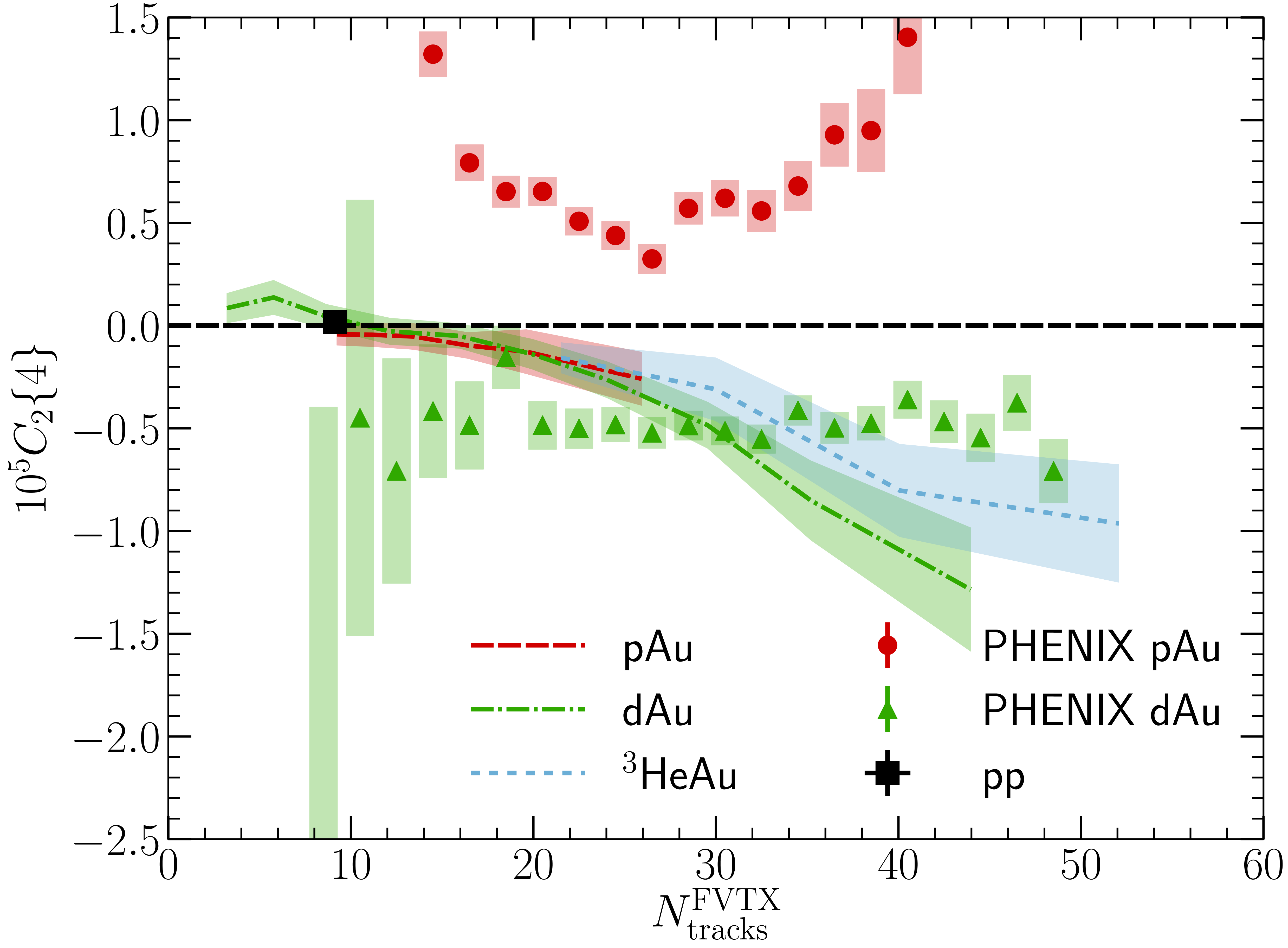


- v_2 similar between STAR and PHENIX (STAR: 0-2% pAu, 0-10% d/HeAu)
- Large difference in v_3 needs to be understood

RESULTS: MULTI-PARTICLE CORRELATIONS

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

Experimental Data: C. Aidala et al. (PHENIX), Phys. Rev. Lett. 120, 062302 (2018)

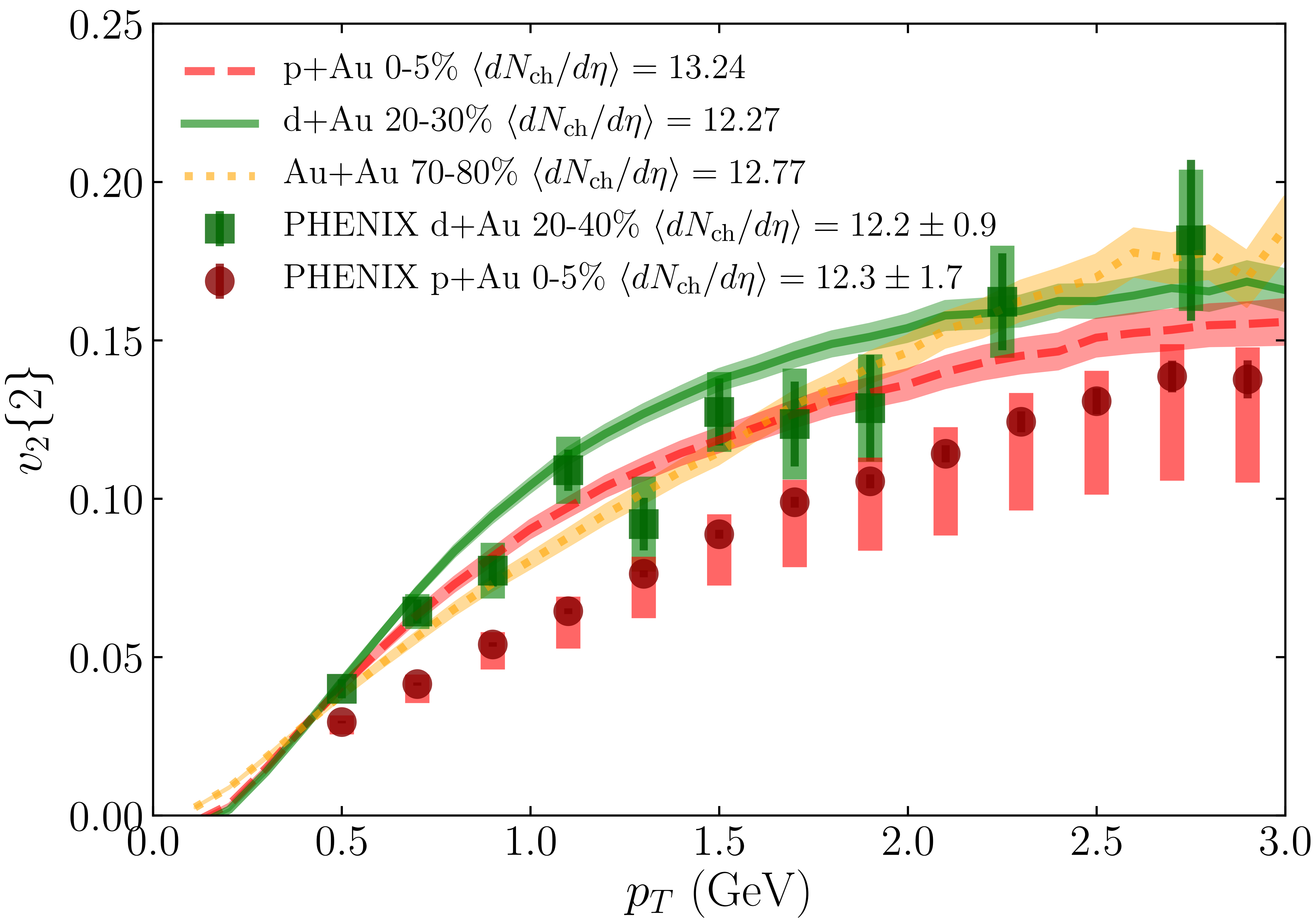


- No difference between $c_2\{4\}$ in pAu and dAu at the same multiplicity
- Sign of $c_2\{4\}$ in pAu opposite to the experimental data
- Stronger multiplicity dependence than in the data

RESULTS: p_T DEPENDENT ANISOTROPY

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

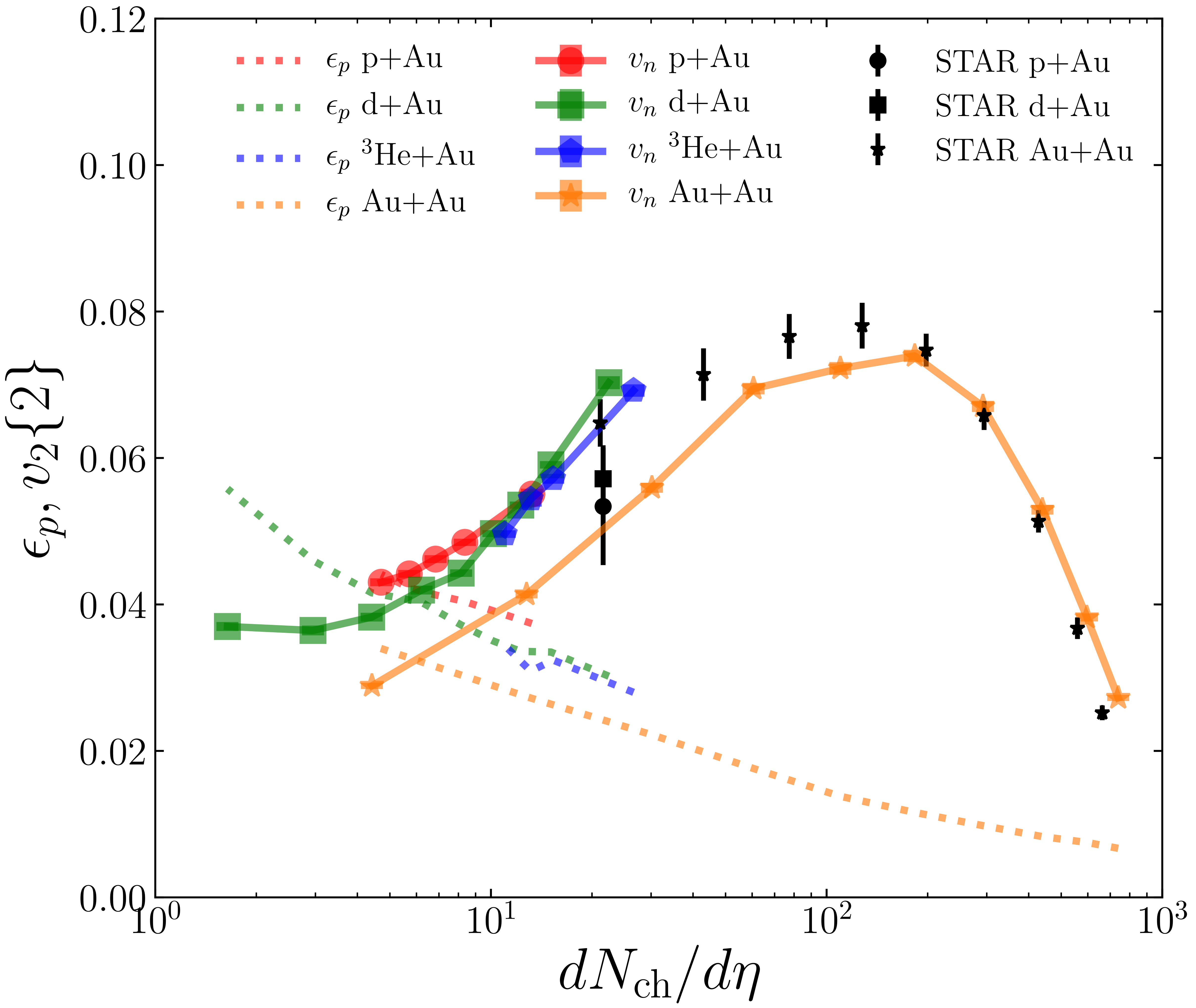
Experimental Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019)



- ~same multiplicity
- $v_2^{dAu} > v_2^{pAu}$ for $p_T > 0.5$ GeV
- Integrated v_2 is ~same Reason: $\langle p_T \rangle$ difference
- $v_2^{dAu} > v_2^{AuAu}$ for 0.5 GeV $< p_T <$ 2 GeV

ANALYSIS:
EFFECT OF INITIAL STATE MOMENTUM ANISOTROPY

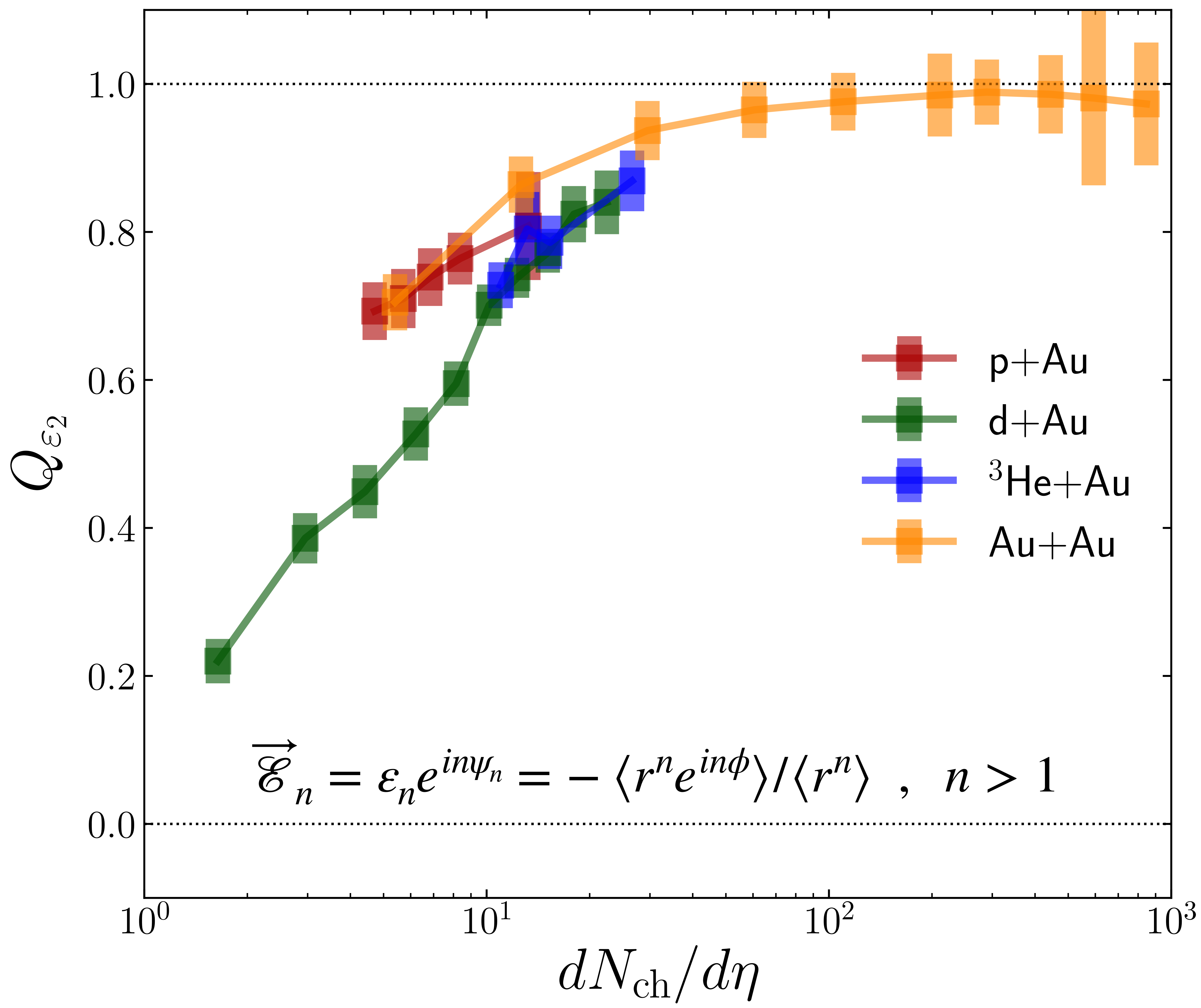
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212
Experimental Data: J. Adam et al. (STAR), Phys. Rev. Lett. 122, 172301 (2019)



- Initial state momentum anisotropy
  $$\overrightarrow{\mathcal{E}}_p = \varepsilon_p e^{2i\psi_2^p} = \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$
- ε_p decreases with multiplicity
- Opposite to $v_2\{2\}$
- System ordering opposite to data at $dN_{ch}/d\eta \approx 20$ ($v_2^{dAu} > v_2^{AuAu}$ in calculation)

CORRELATION OF FLOW VECTOR WITH GEOMETRY

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



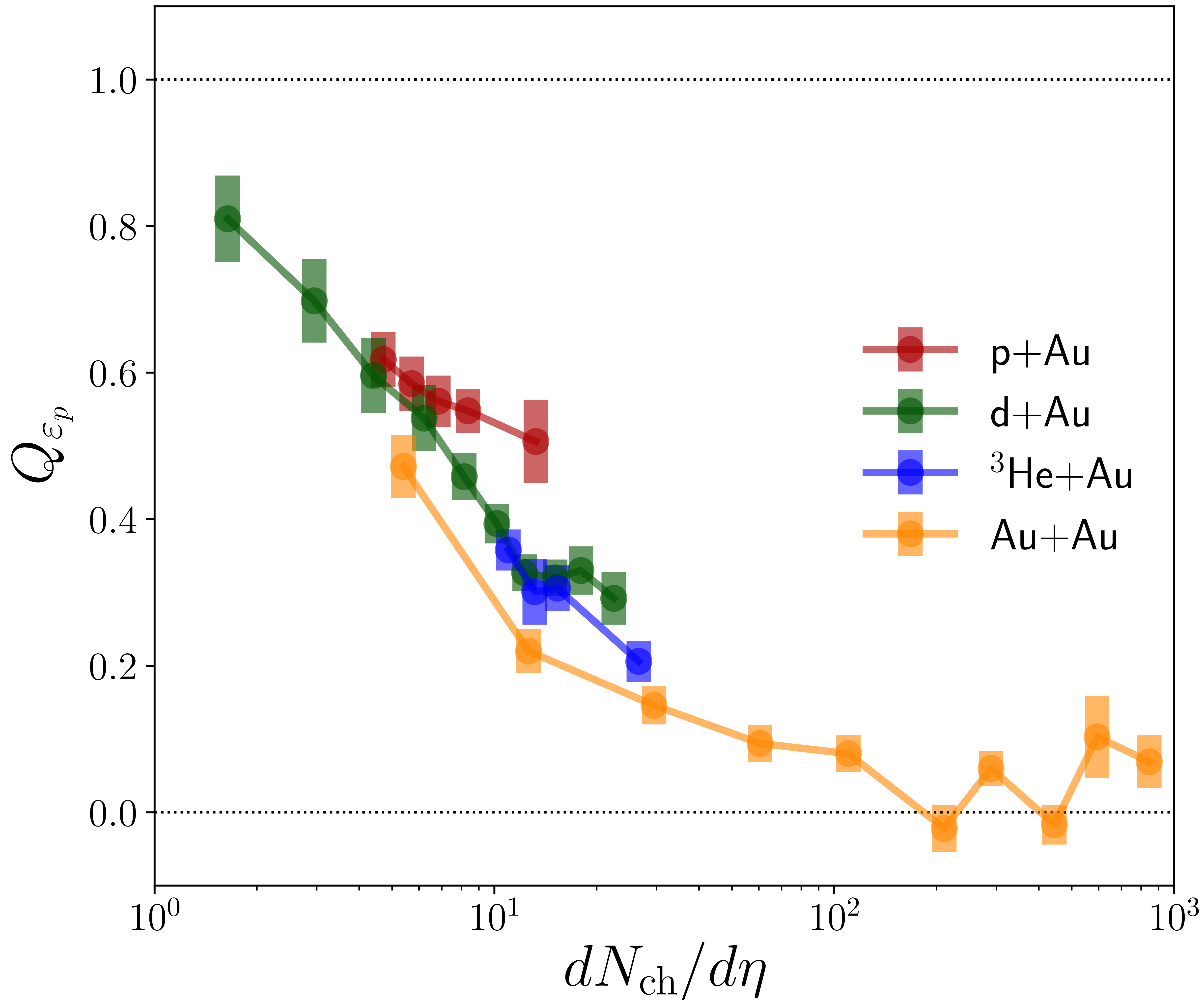
- Pearson coefficient

$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \overrightarrow{\mathscr{E}}_2 \cdot \overrightarrow{V}_2^* \rangle}{\sqrt{\langle |\overrightarrow{\mathscr{E}}_2|^2\rangle \langle |\overrightarrow{V}_2|^2\rangle}}$$

- Correlation of v_2 vector with the geometry (ε_2) vector decreases towards low multiplicity

CORRELATION OF FLOW VECTOR WITH INITIAL MOMENTUM ANISOTROPY

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



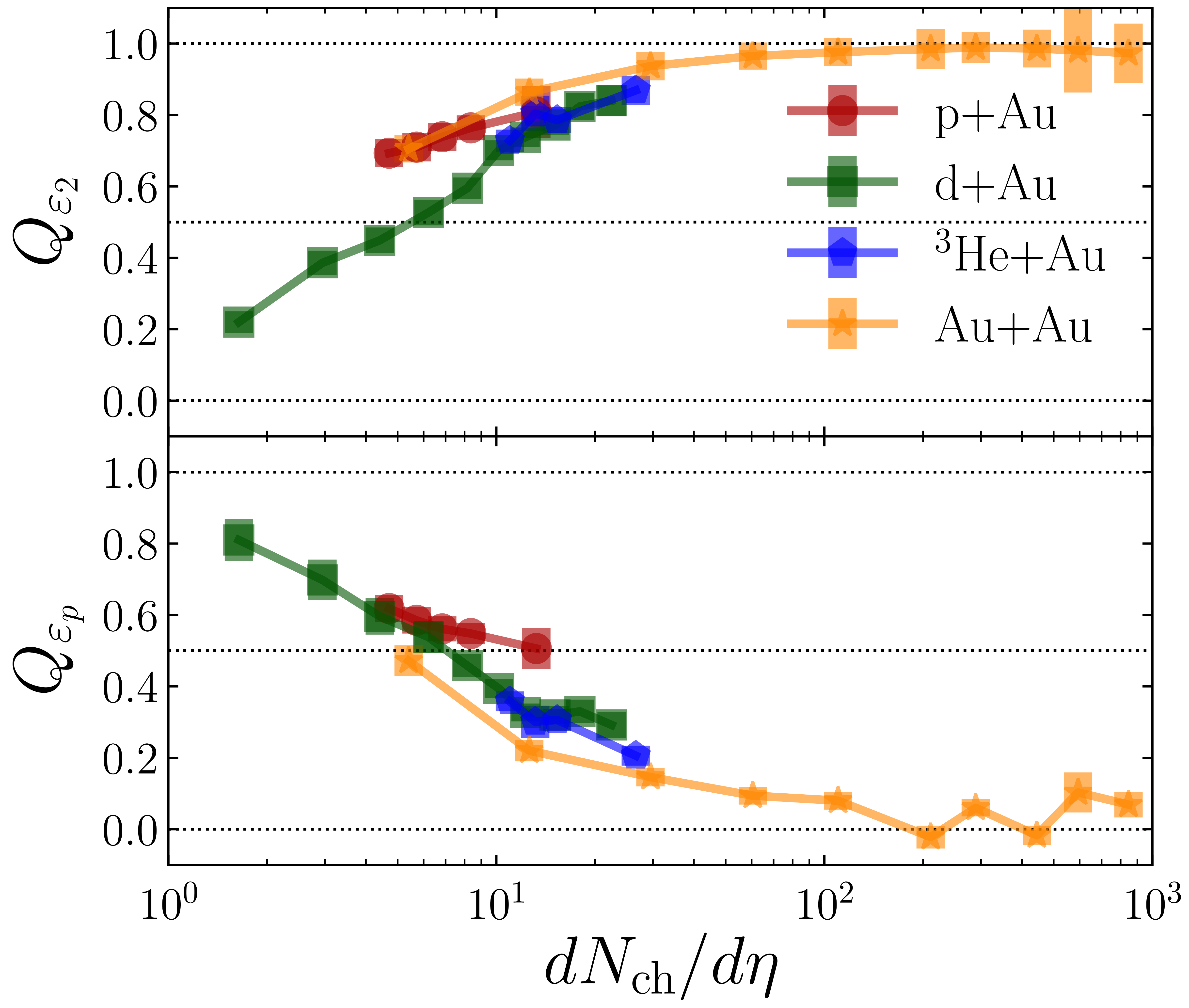
- Pearson coefficient

$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_p \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_p|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

- Reversely, correlation of v_2 with the initial momentum anisotropy ε_p increases towards low multiplicity for all systems

WHAT DRIVES THE FLOW IN SMALL SYSTEMS?

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



- Below $dN_{\mathrm{ch}}/d\eta \approx 10$ the initial momentum anisotropy contributes strongly to the final charged hadron elliptic anisotropy
- Only above $dN_{\mathrm{ch}}/d\eta \approx 100$ (only AuAu here) everything is geometry driven

CONCLUSION ON RHIC SMALL SYSTEM SCAN

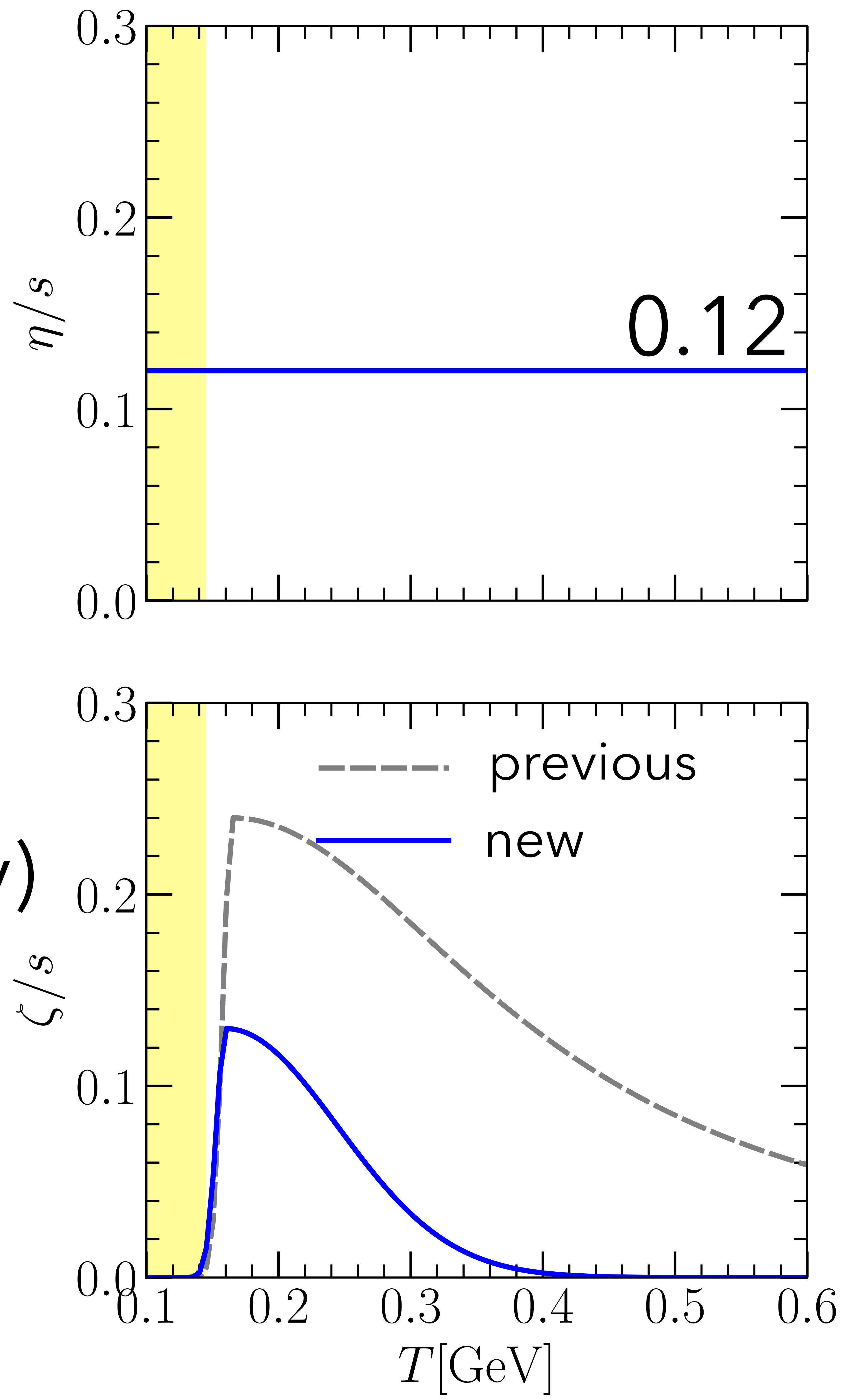
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

- Qualitative description of v_n data seems to require dominance of final state interactions for $dN_{\mathrm{ch}}/d\eta \gtrsim 10$
- Even if final state is described by realistic hydrodynamics, the initial momentum anisotropy can affect final observables at low multiplicity
- We find $v_3(p_T)$ to be very similar for all three systems in their respective 0-5% central bins

MANY MORE SYSTEMS SCAN

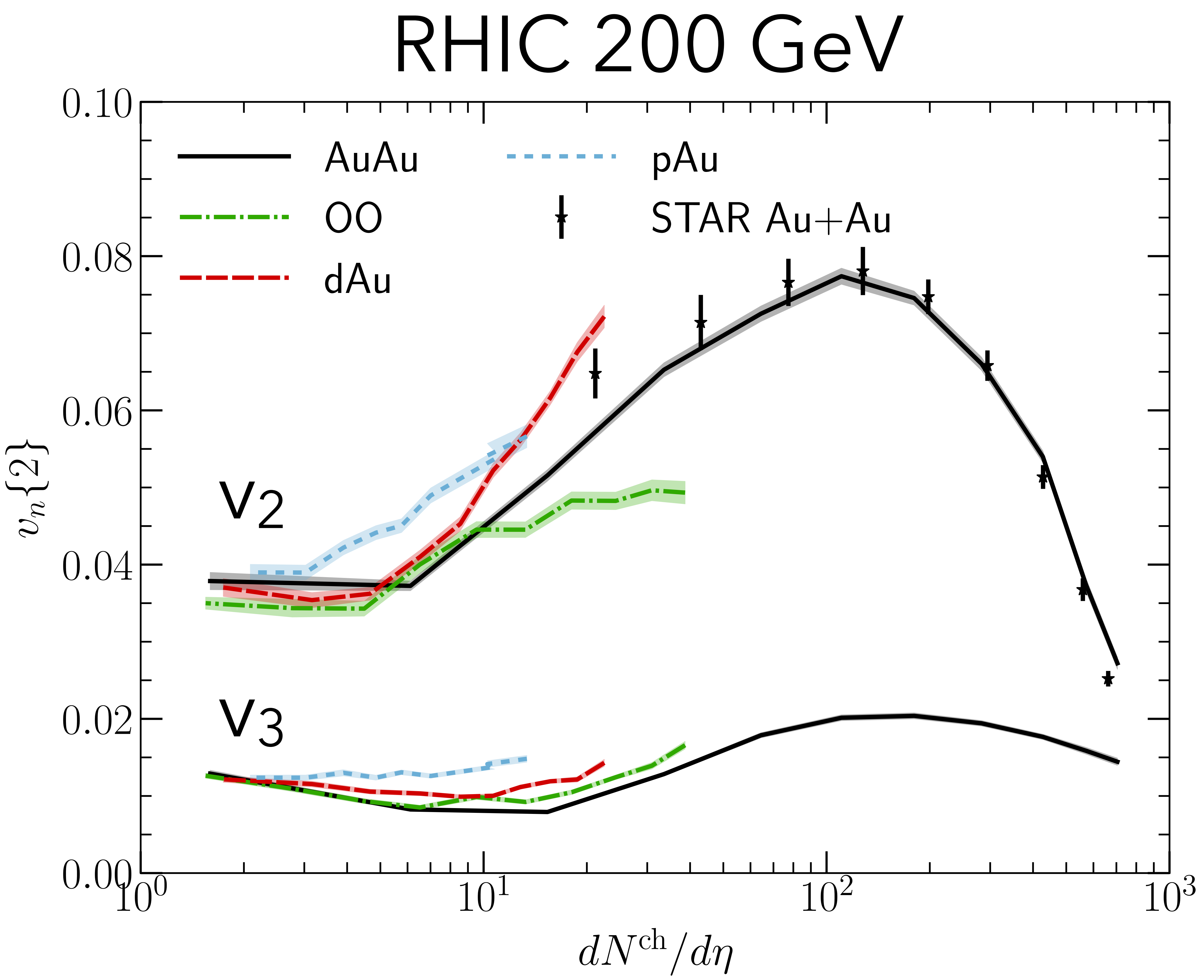
B. Schenke, C. Shen, P. Tribedy, in preparation

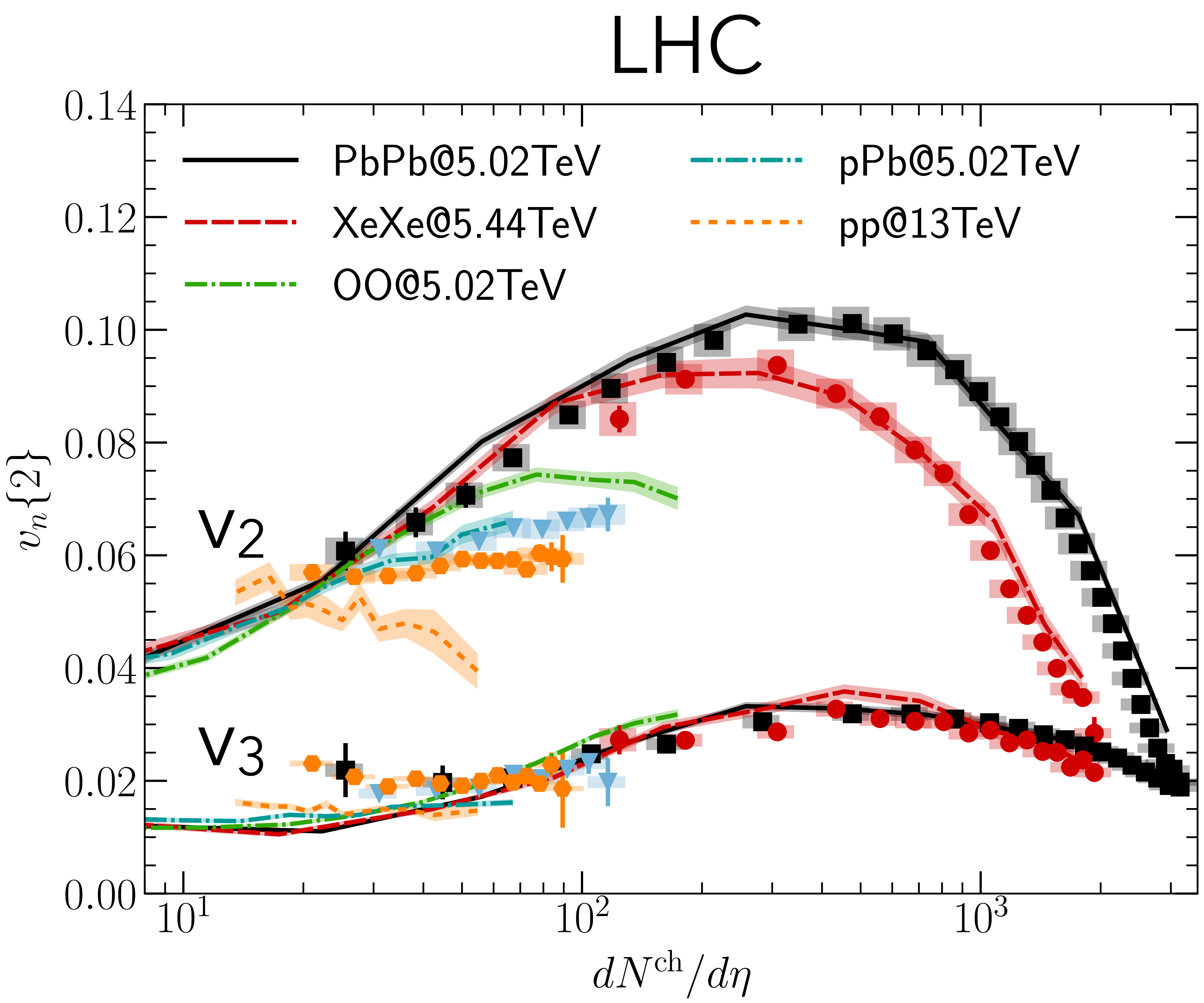
- New parametrization of bulk viscosity
  (smaller τ_Π at high temperature)
- pp, pAu, dAu, [3]HeAu, pPb, OO, XeXe, AuAu, PbPb
- All with the same parameters
  (we only change system and collision energy)
- Conclusions in previous slides remain unchanged with new parameters



MANY MORE SYSTEMS SCAN

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

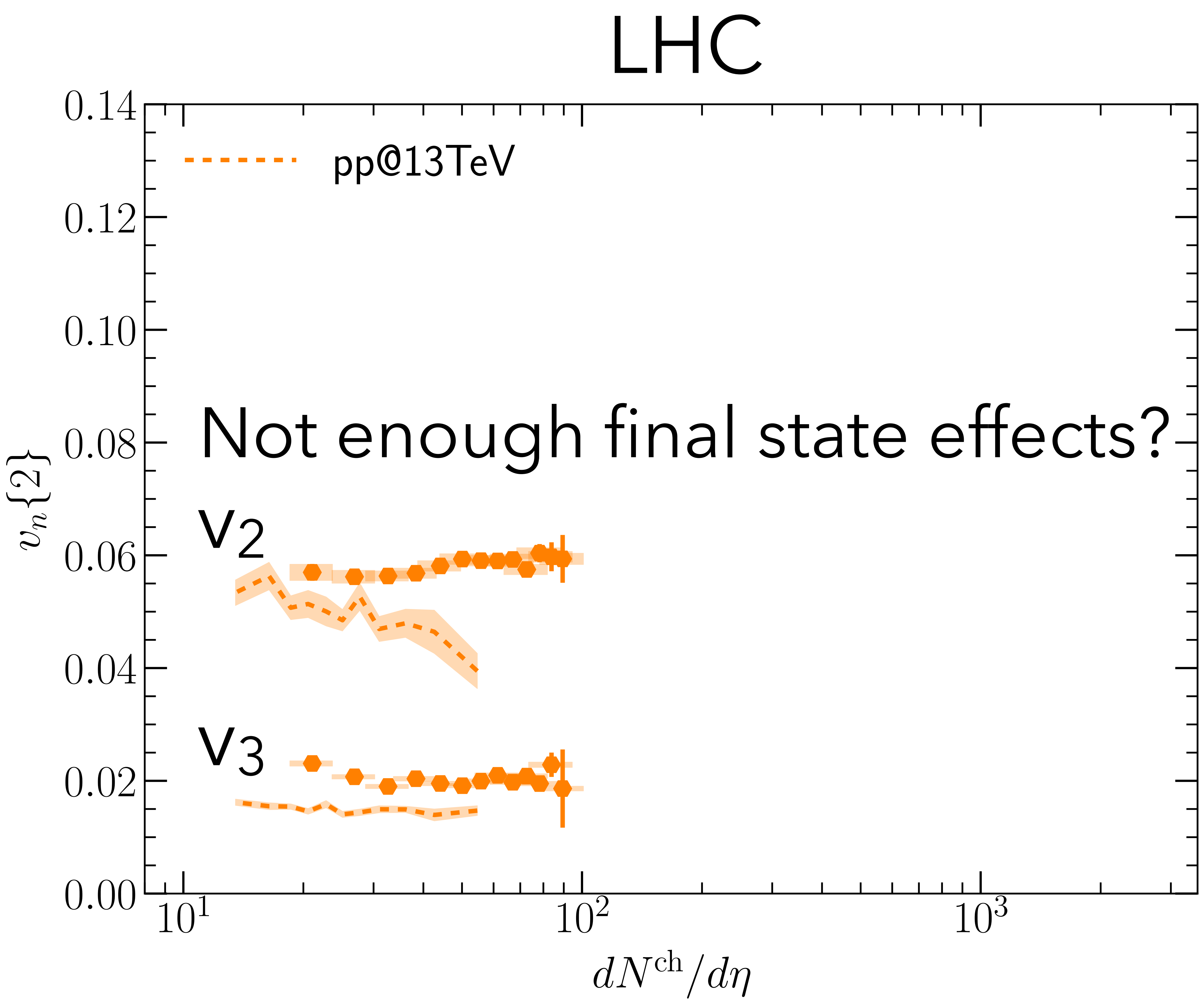




more comparisons to experimental data in the backup slides…

WHAT ABOUT pp COLLISIONS?

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



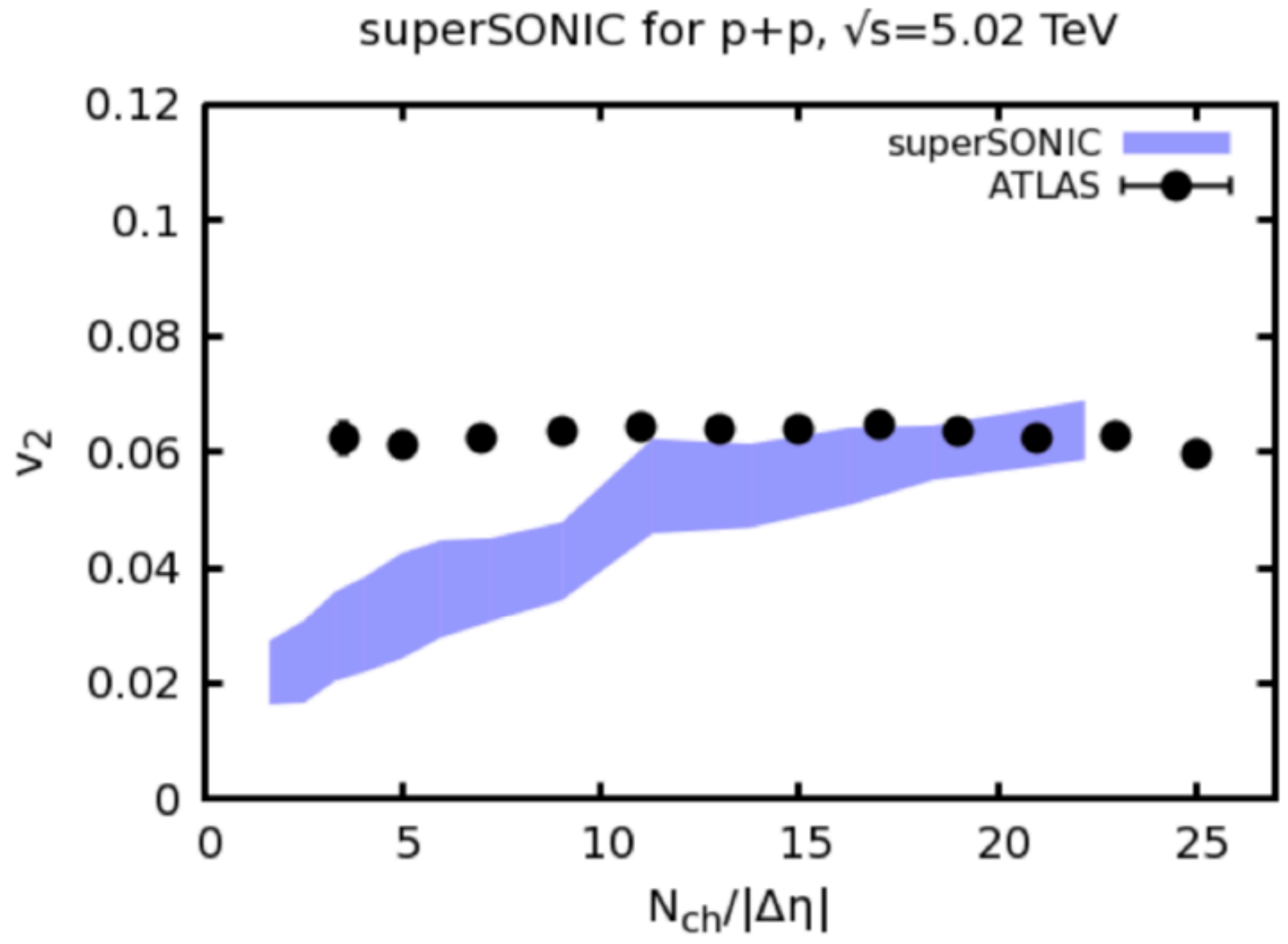
WHAT ABOUT pp COLLISIONS?

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

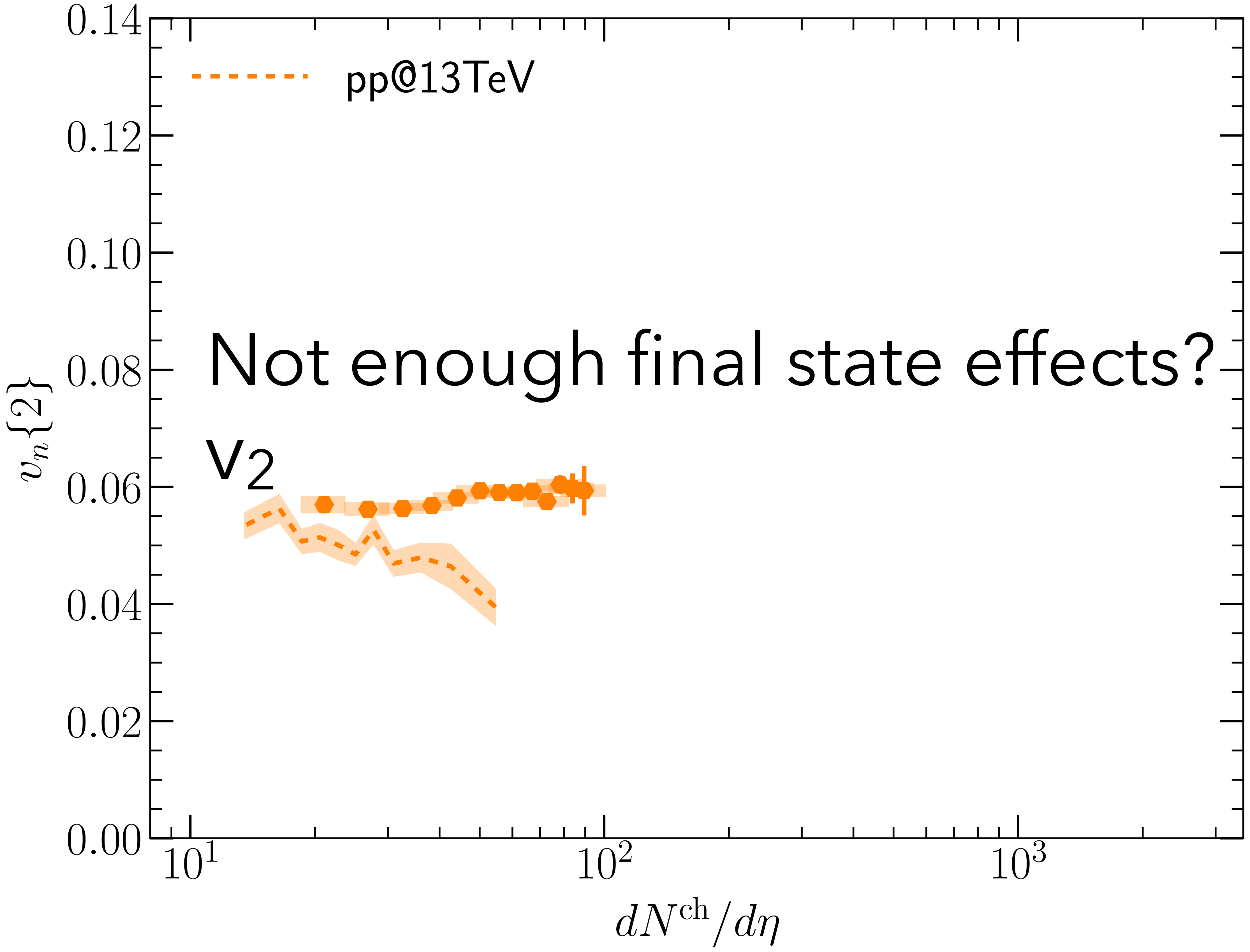
R.D. Weller, P. Romatschke, Phys.Lett. B774 (2017) 351-35

Pure hydro: Opposite trend

Too much final state effects?



LHC



Not enough final state effects?

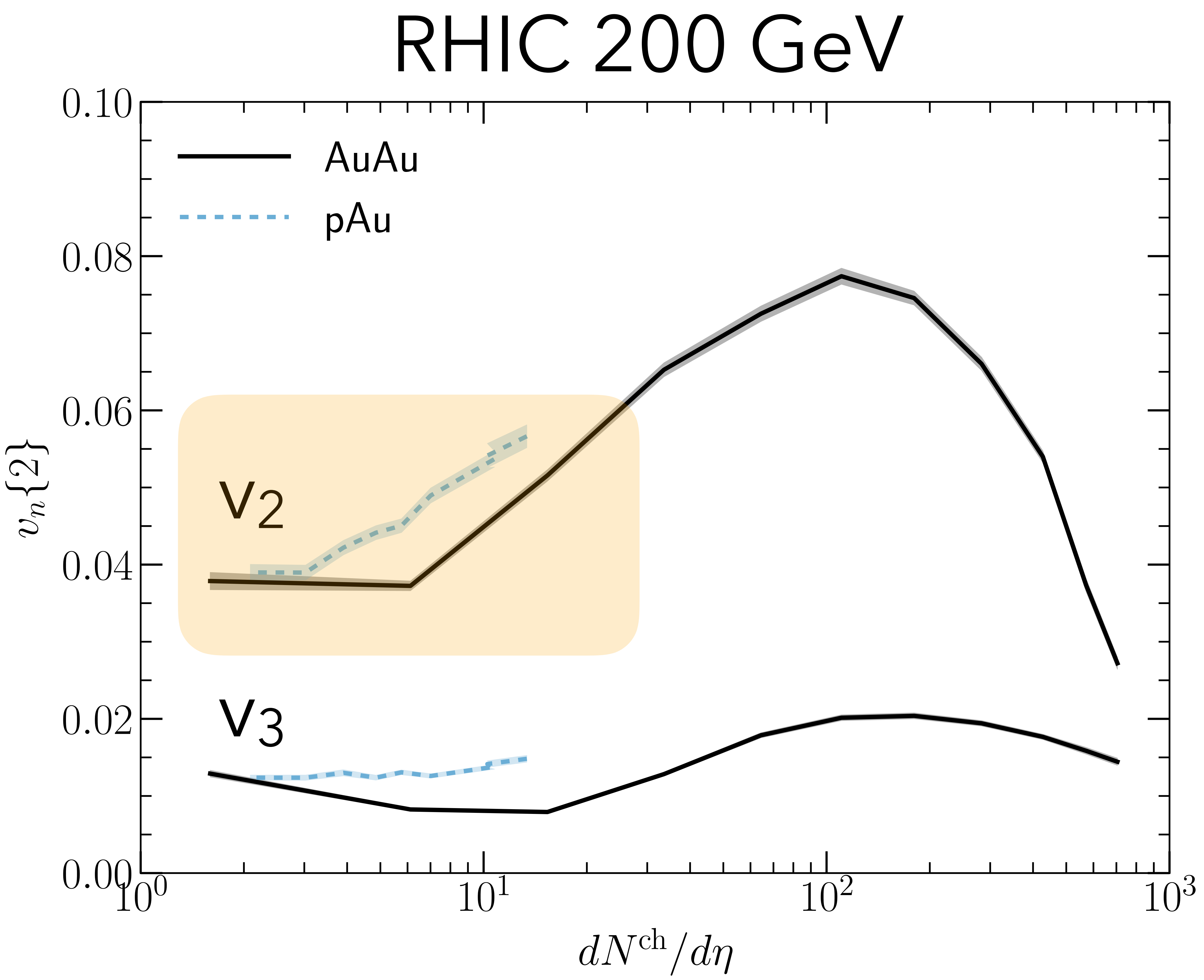
v_2

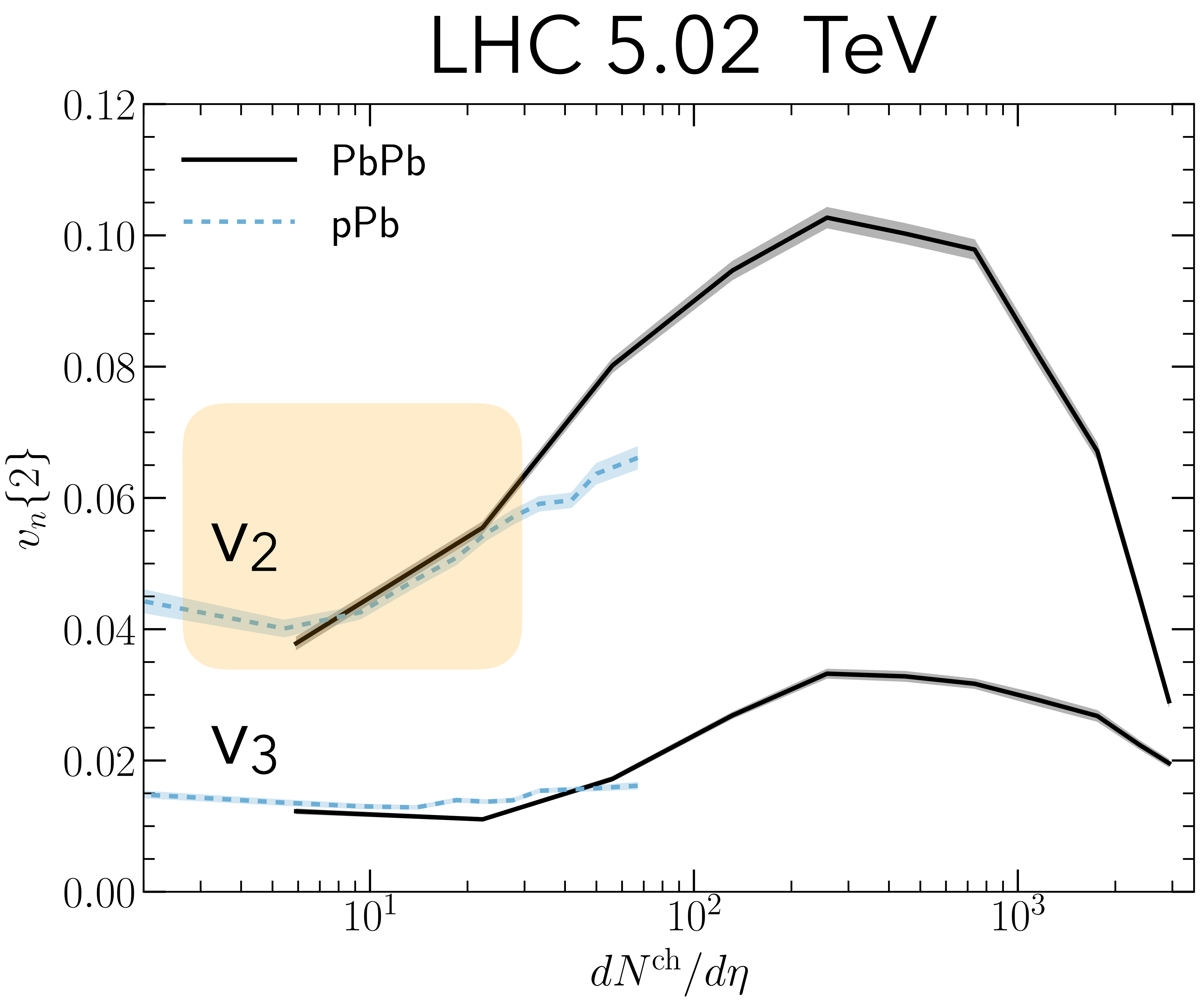
A delicate balance?

Other effects?

pA vs. AA AT DIFFERENT ENERGIES

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





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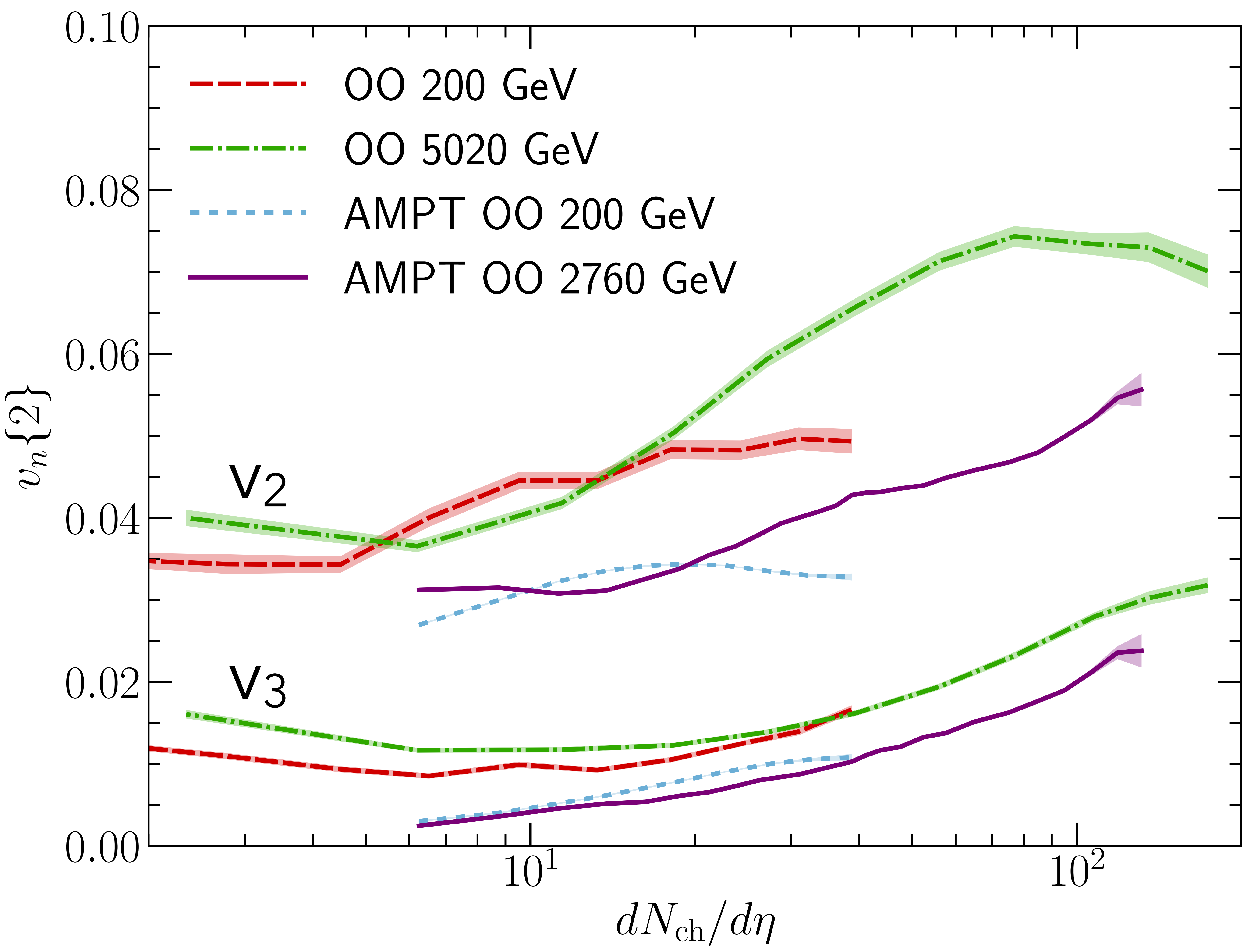
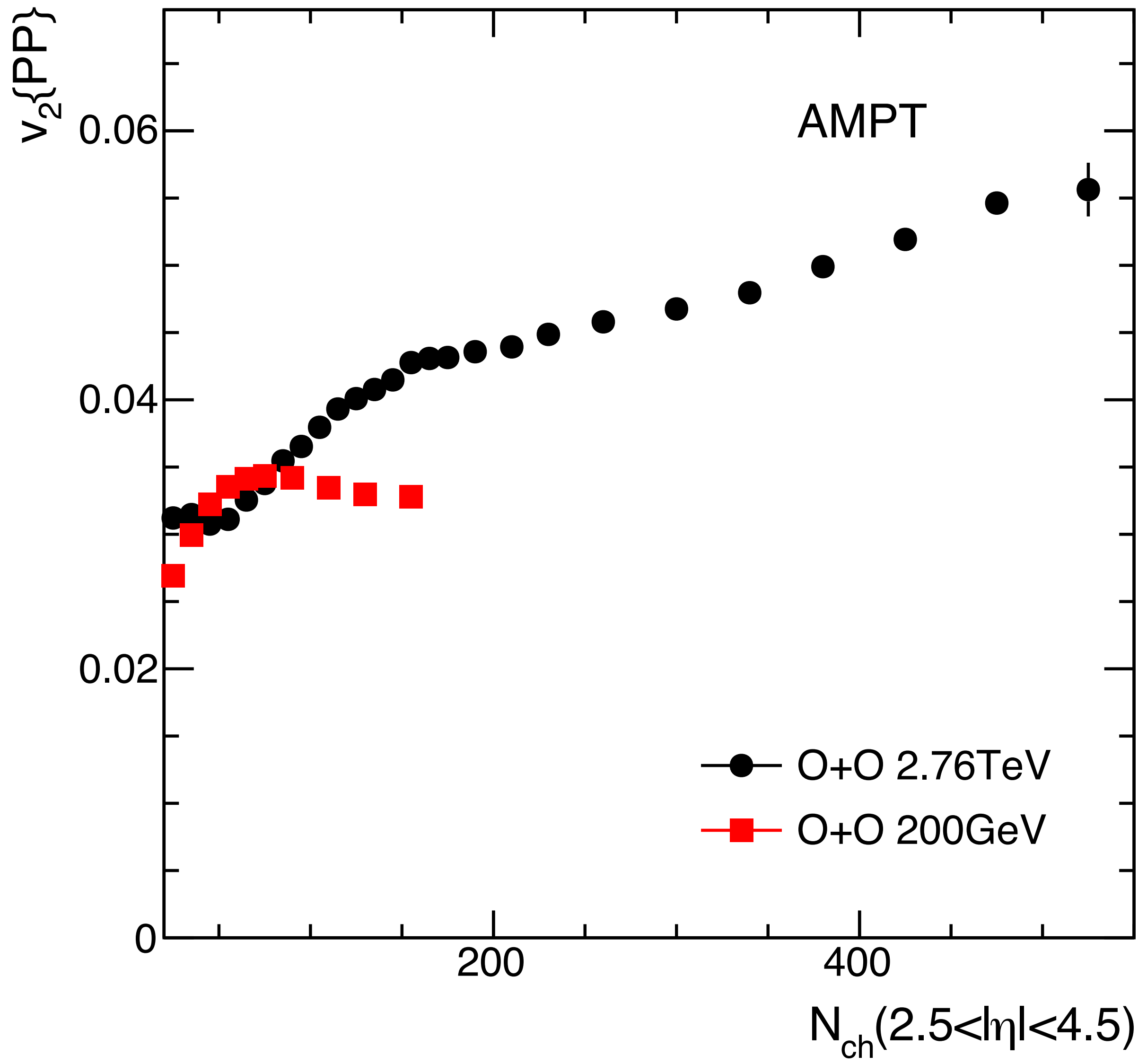
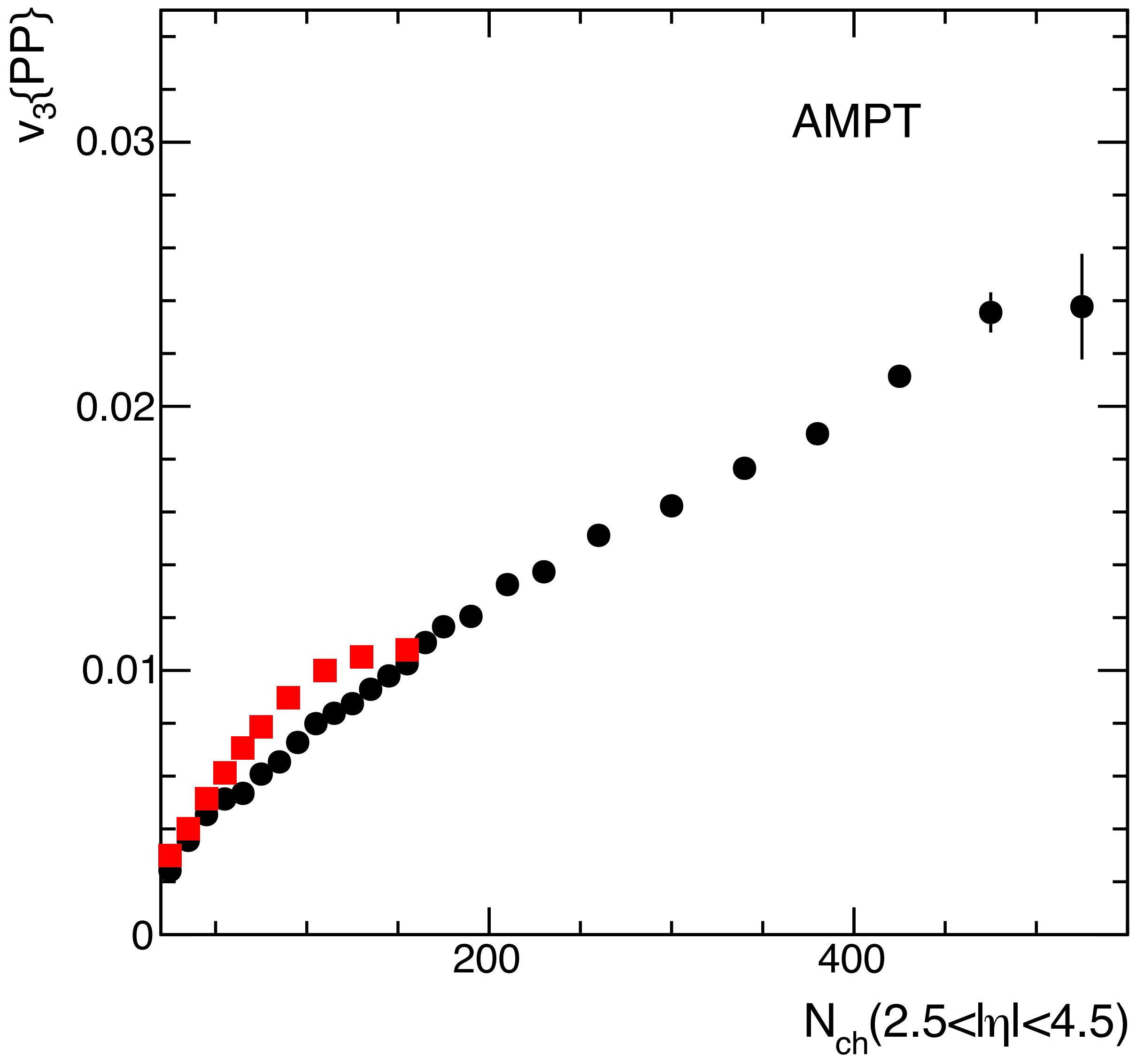
B. Schenke, C. Shen, P. Tribedy, in preparation
AMPT results: S. Huang, Z. Chen, J. Jia, W. Li, e-Print: arXiv:1904.10415







CONCLUSIONS

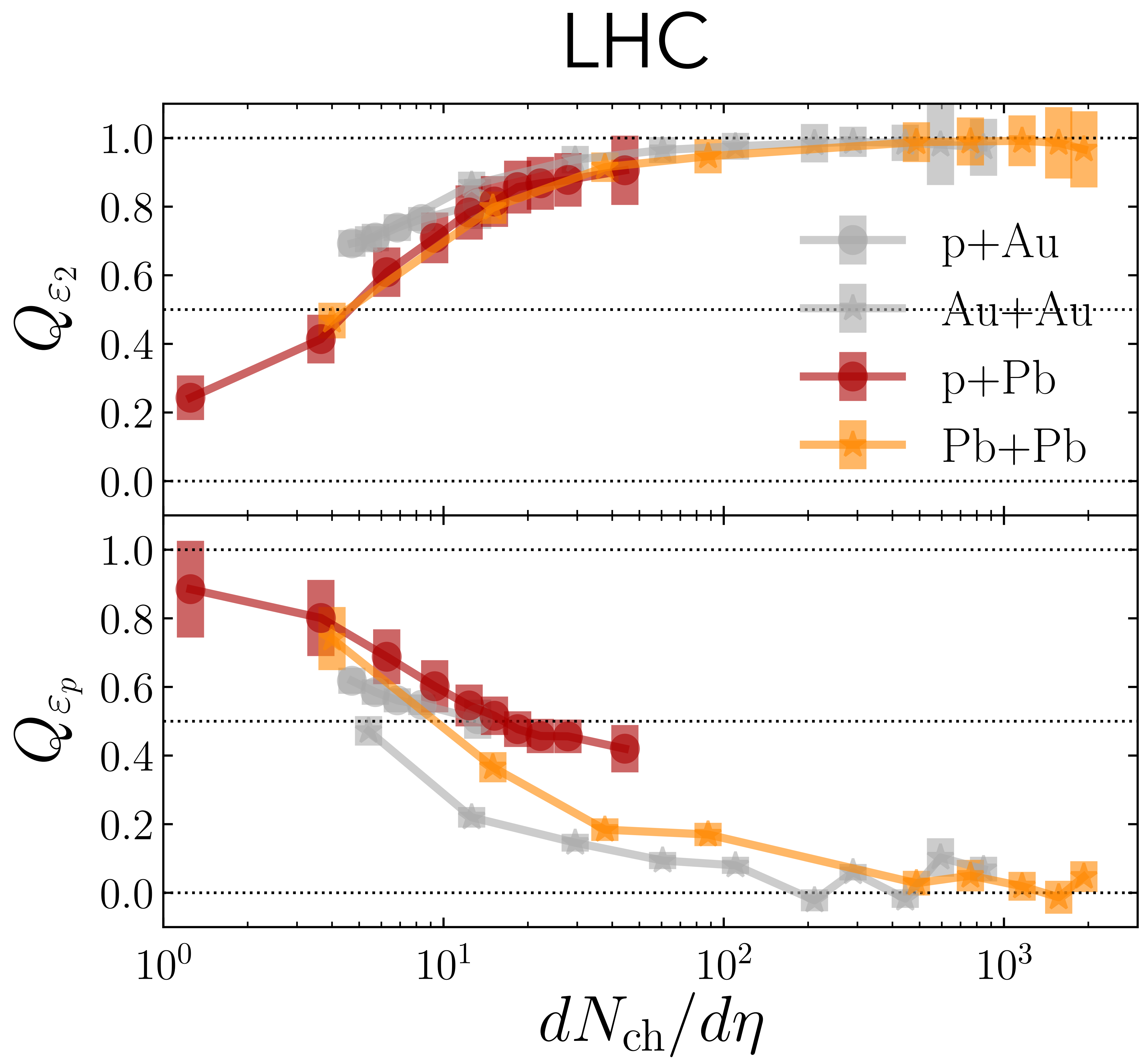
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212

- Qualitative description of v_n data seems to require dominance of final state interactions for $dN_{\rm ch}/d\eta \gtrsim 10$
- Even if final state is described by realistic hydrodynamics, the initial momentum anisotropy can affect final observables
- With one set of parameters, we describe a wide range of data for different systems at RHIC & LHC
- A delicate balance between initial and final state effects in pp? Could help constrain model, but one needs to be careful: Other effects like hydro-fluctuations, conservation laws at particle sampling, etc. can be very important here

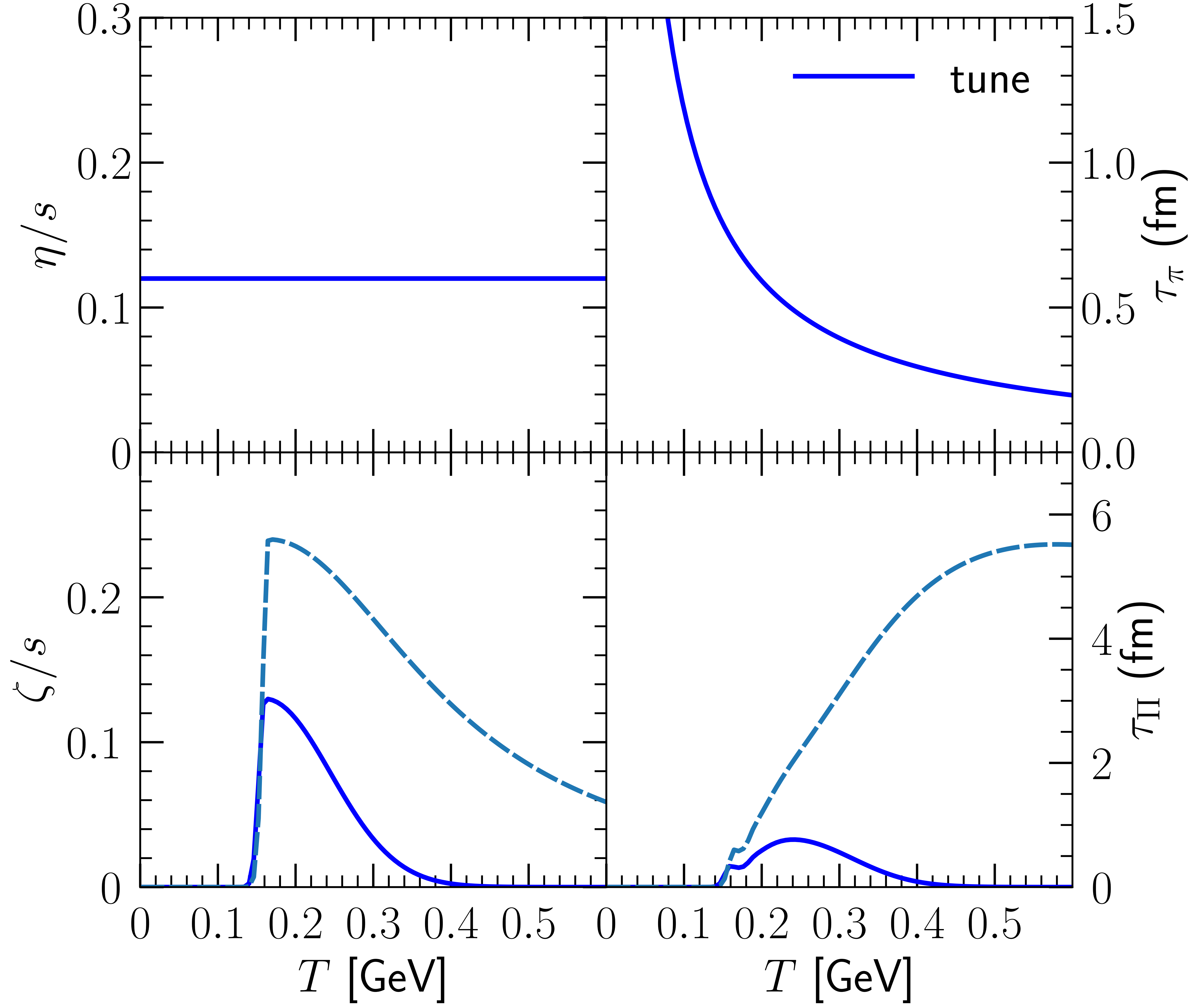
BACKUP

ROLE OF INITIAL MOMENTUM ANISOTROPY AT LHC

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



OLD VS. NEW TRANSPORT COEFFICIENTS

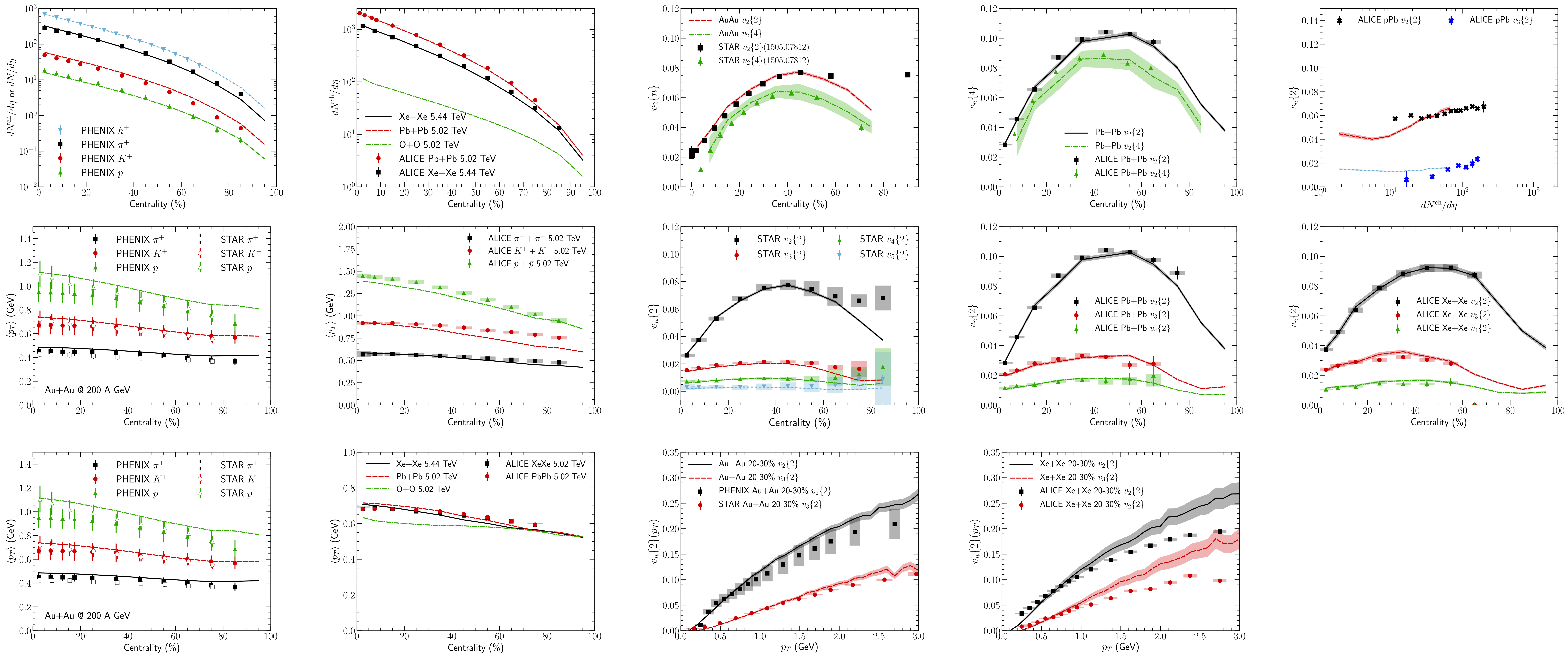


- Previous parametrization lead to very large bulk relaxation times in high temperature regime
- This lead to enhanced effect of initial positive bulk pressure that was put in to match the EoS between YM and lattice QCD

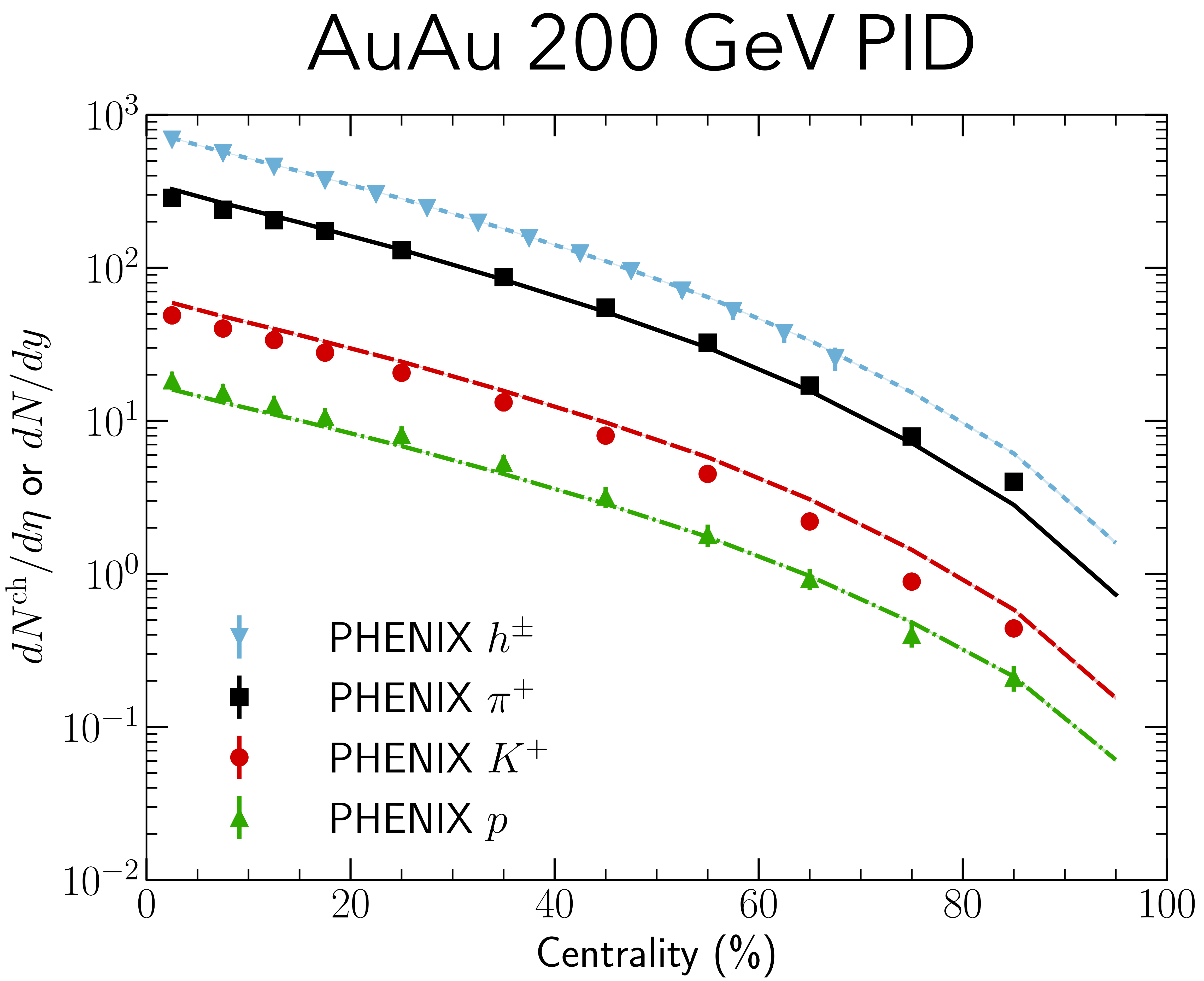
Our conclusions are unchanged by using the new parameters

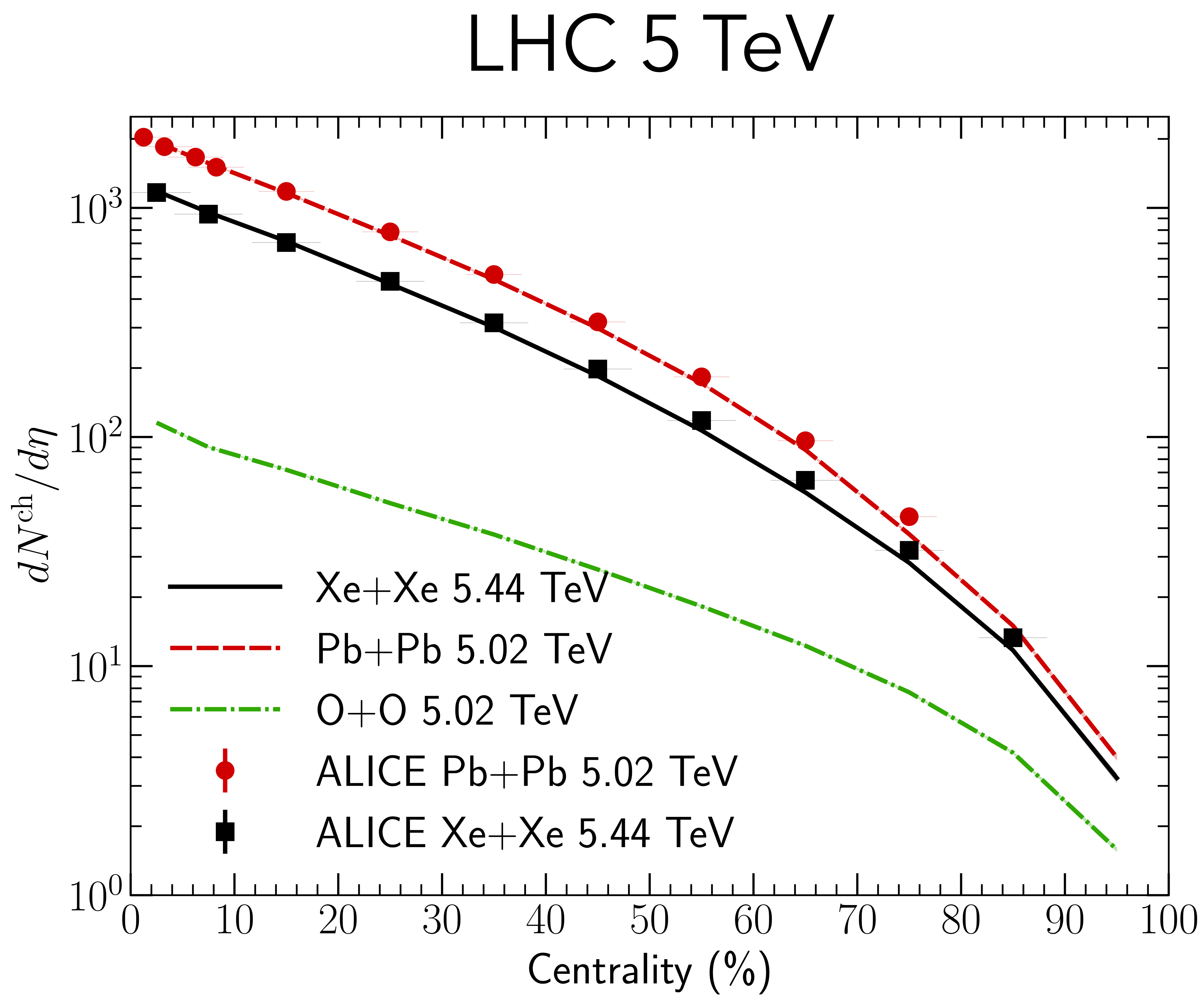
MANY MORE SYSTEMS SCAN

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



OTHER NEW RESULTS: $dN_{\mathrm{ch}}/d\eta$



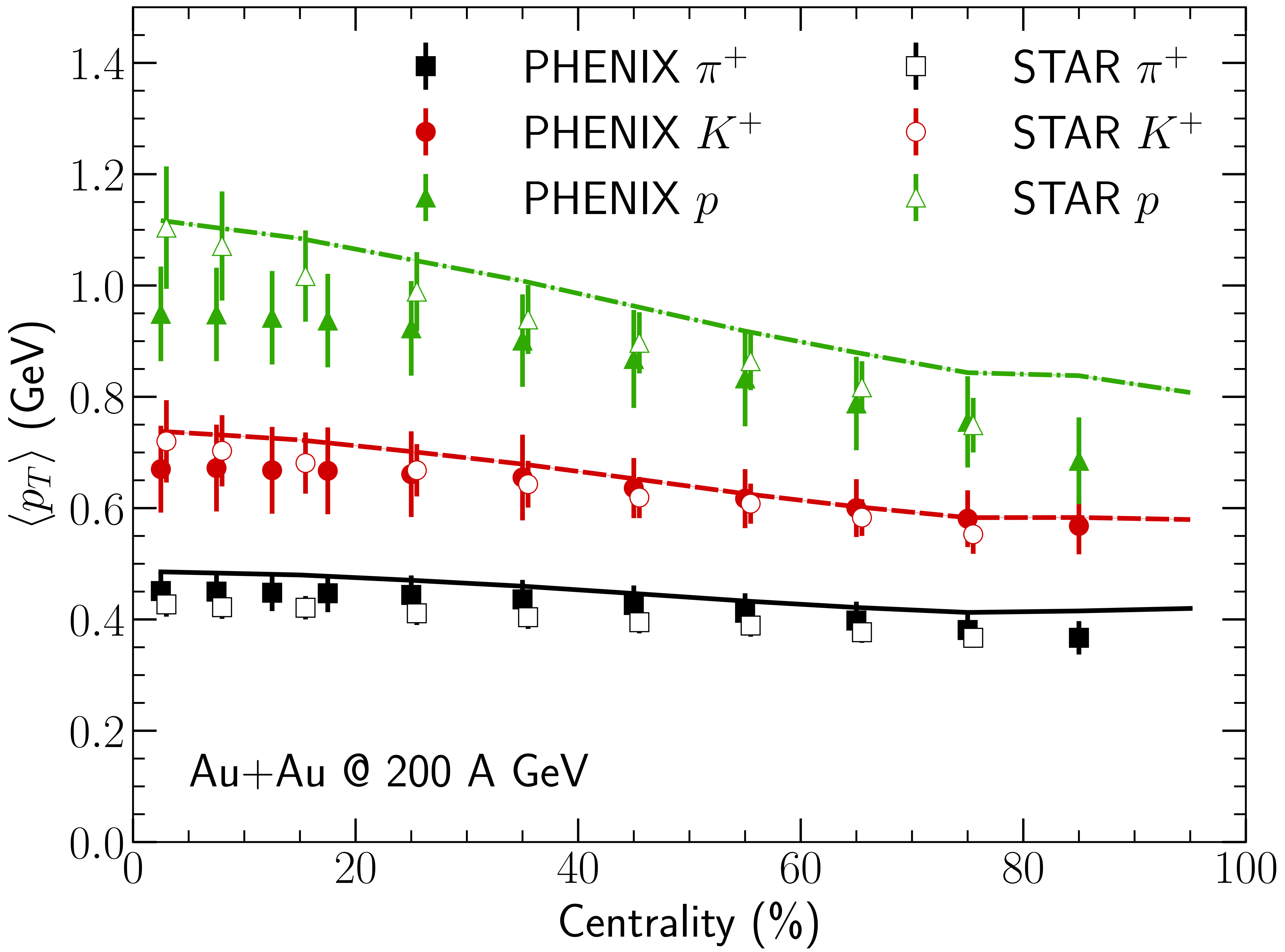


Experimental Data: S. S. Adler et al. (PHENIX), Phys. Rev. C69, 034909 (2004)
ALICE Collaboration, Phys.Rev.Lett. 116 (2016) no.22, 222302; Phys.Lett. B790 (2019) 35-48

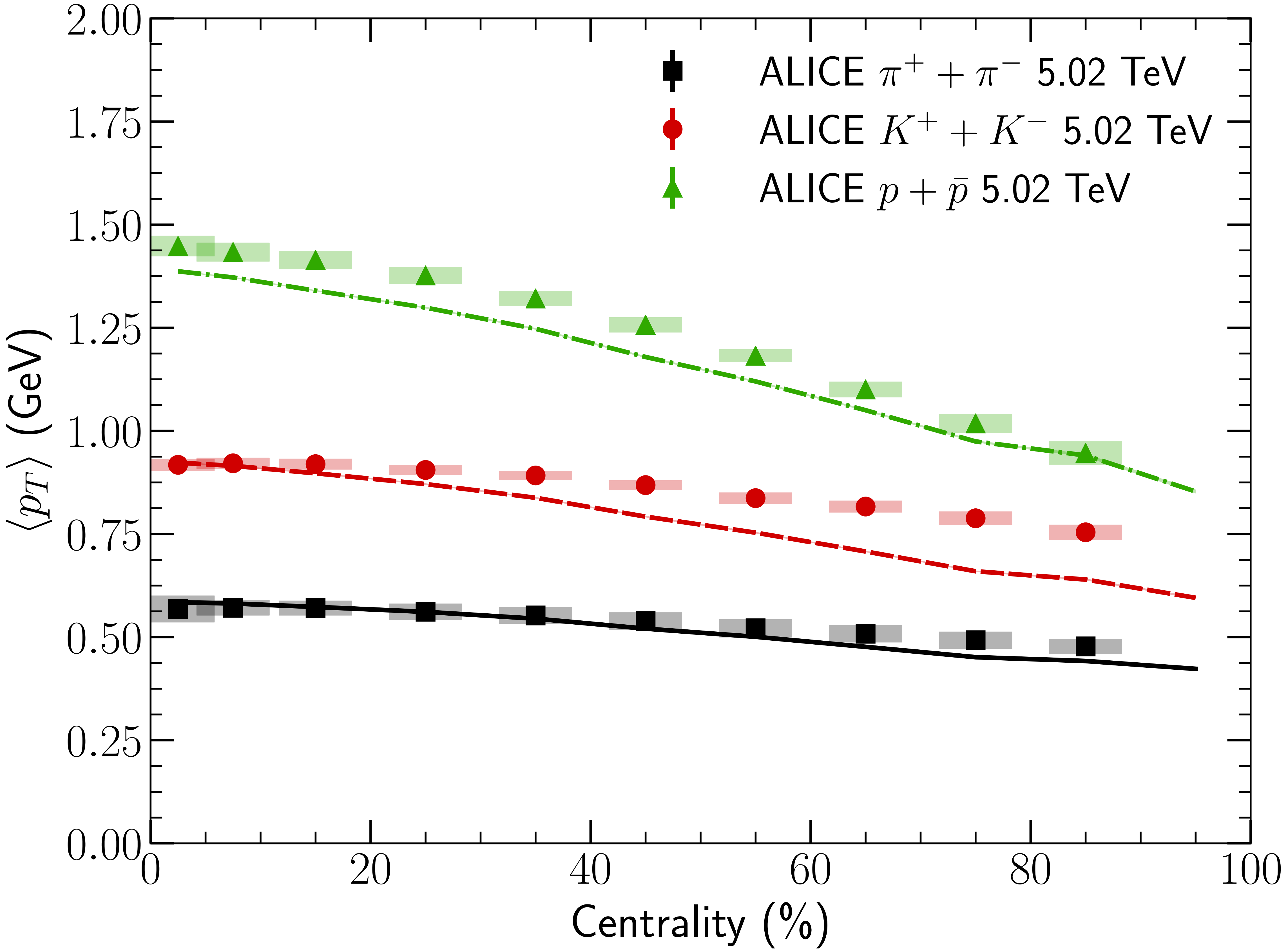
OTHER NEW RESULTS: $\langle p_T \rangle$

STAR Collaboration, Phys.Rev. C79 (2009) 034909
PHENIX Collaboration, Phys.Rev. C69 (2004) 034909
ALICE Collaboration, e-Print: arXiv:1910.07678

AuAu 200 GeV PID



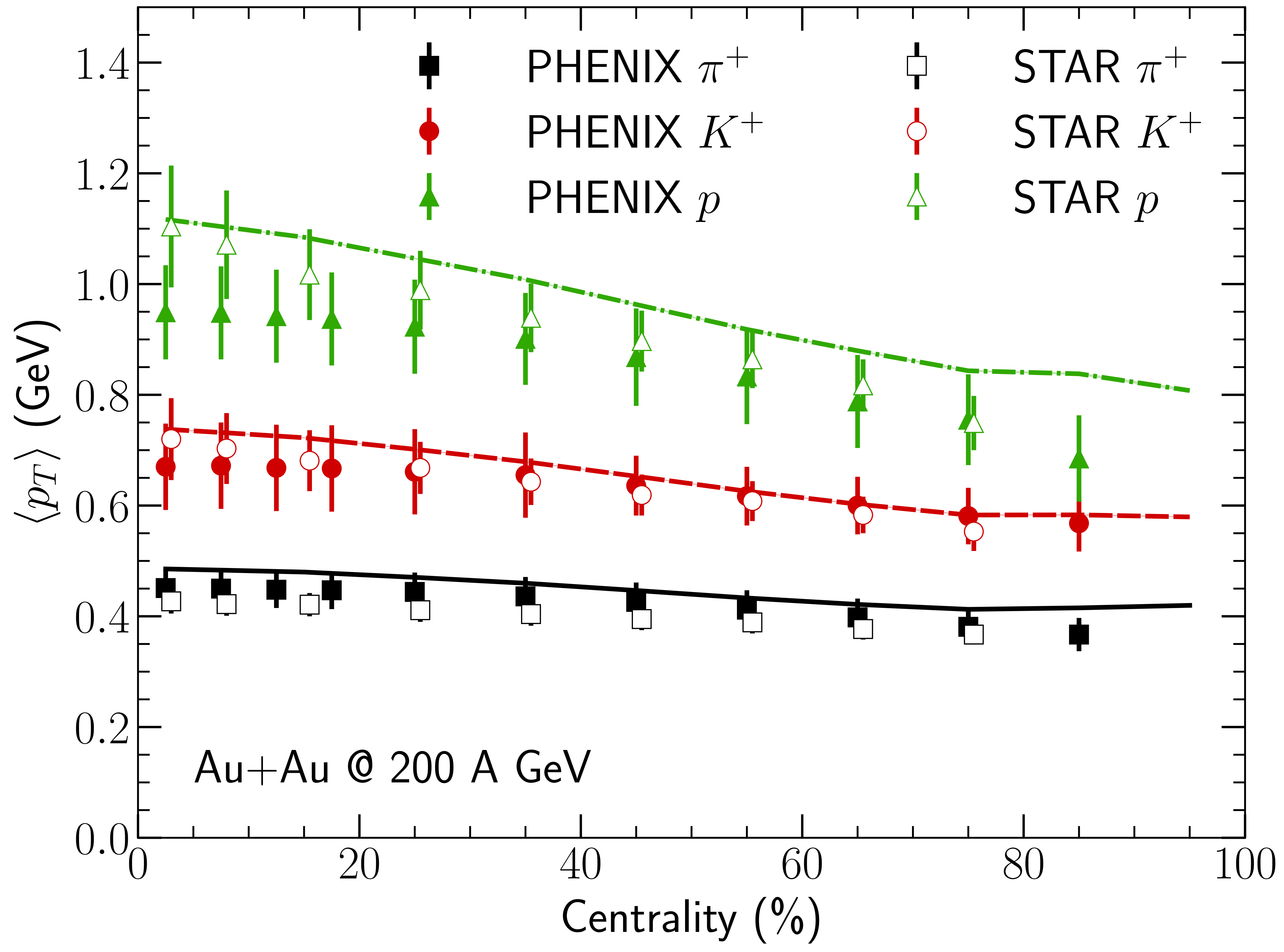
LHC 5 TeV PID



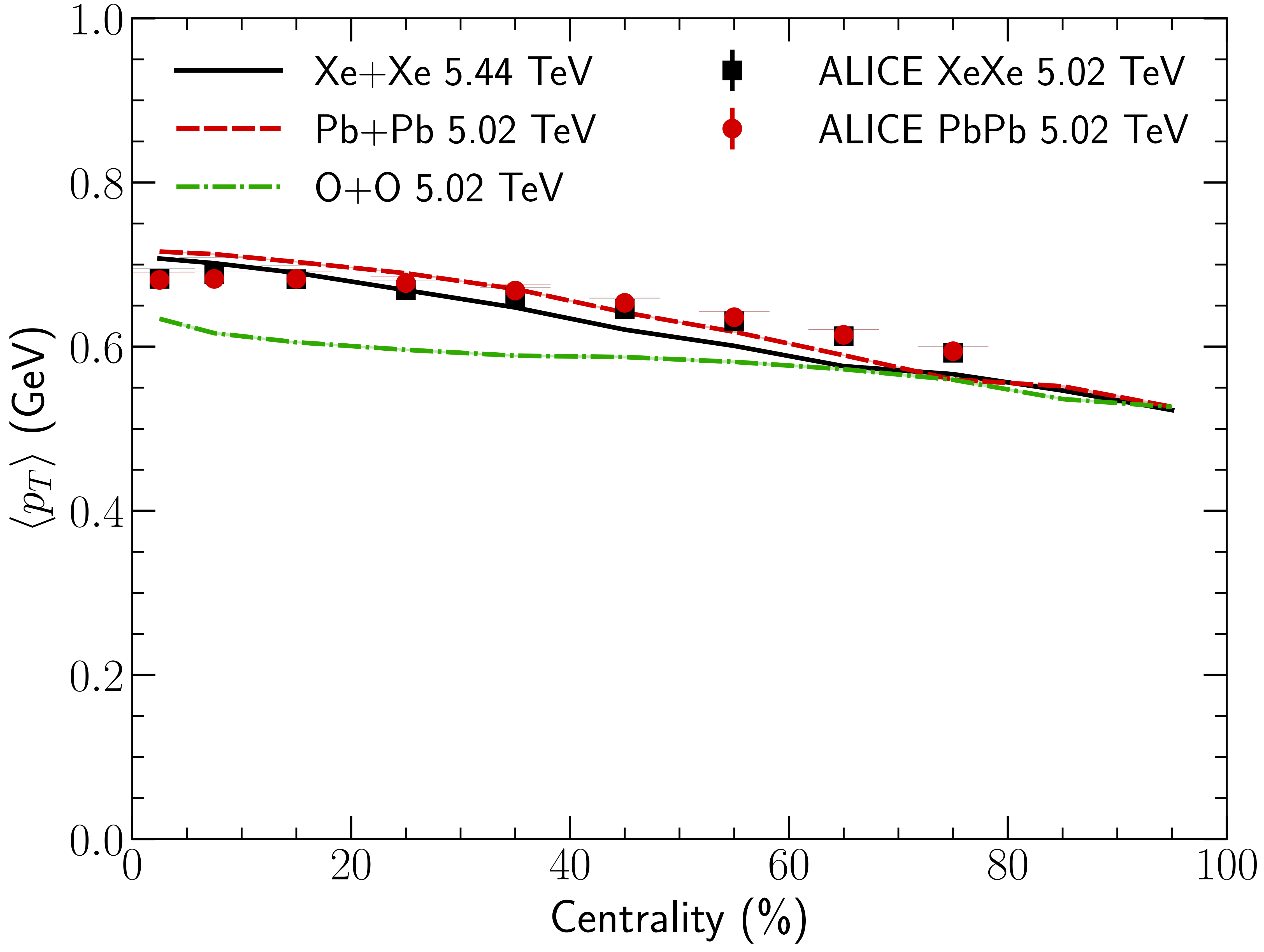
OTHER NEW RESULTS: $\langle p_T \rangle$

PHENIX Collaboration, Phys.Rev. C69 (2004) 034909
ALICE Collaboration, Phys.Lett. B788 (2019) 166-179

AuAu 200 GeV PID

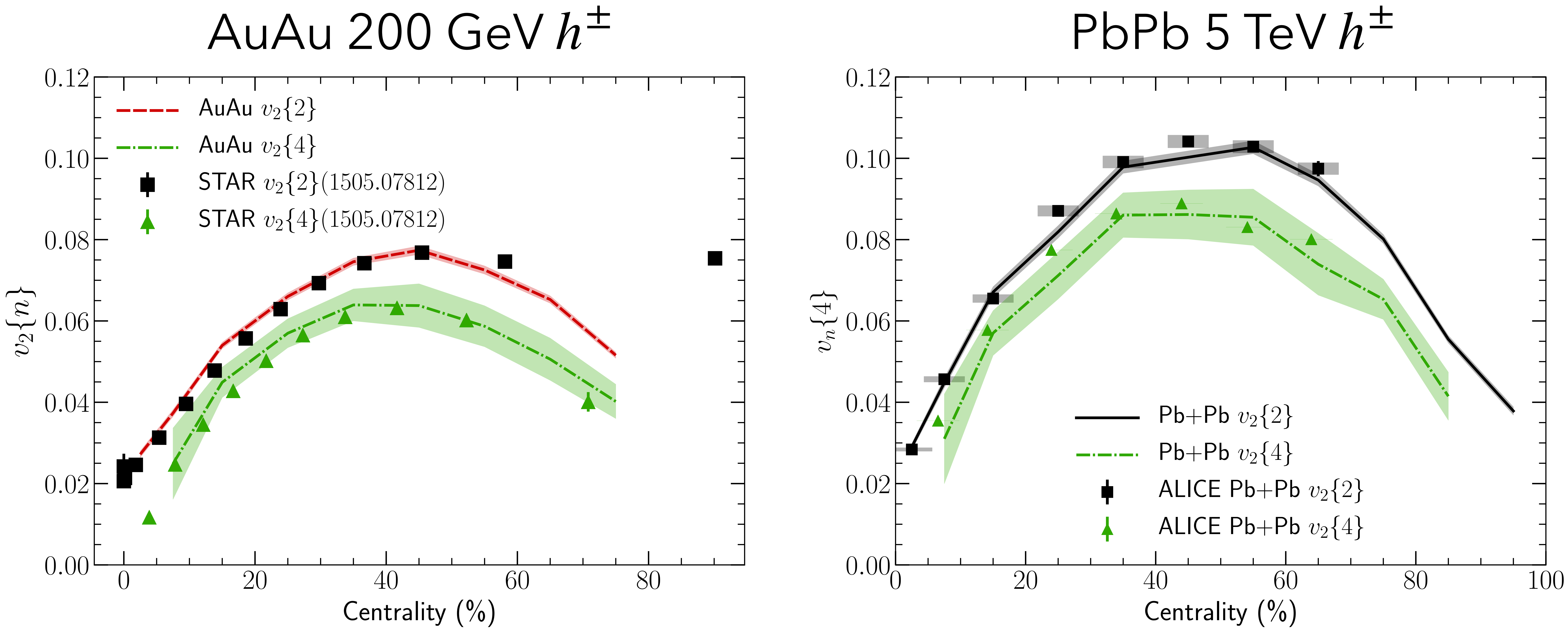


LHC 5 TeV $h^\pm$



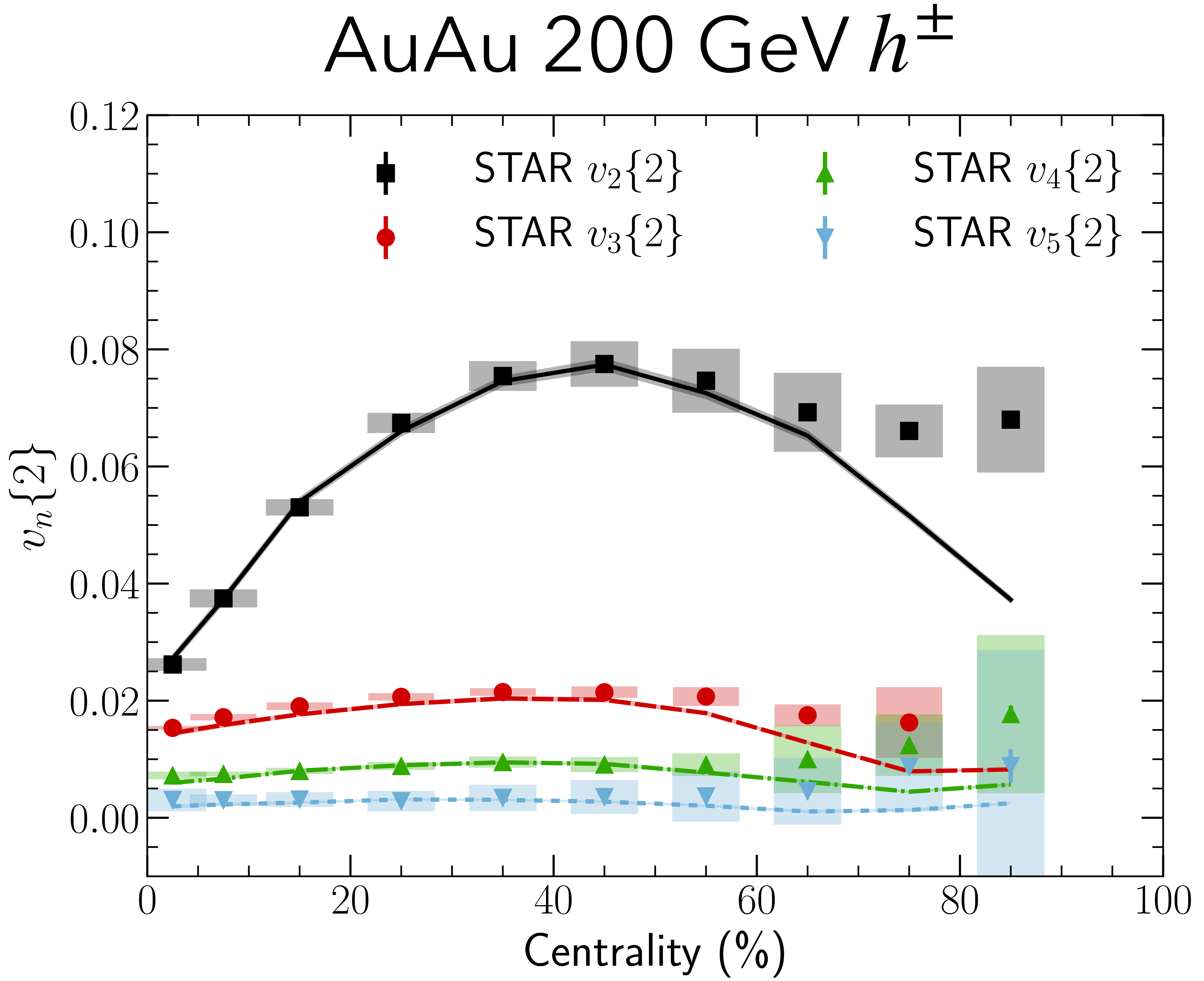
OTHER NEW RESULTS: $v_2\{m\}$

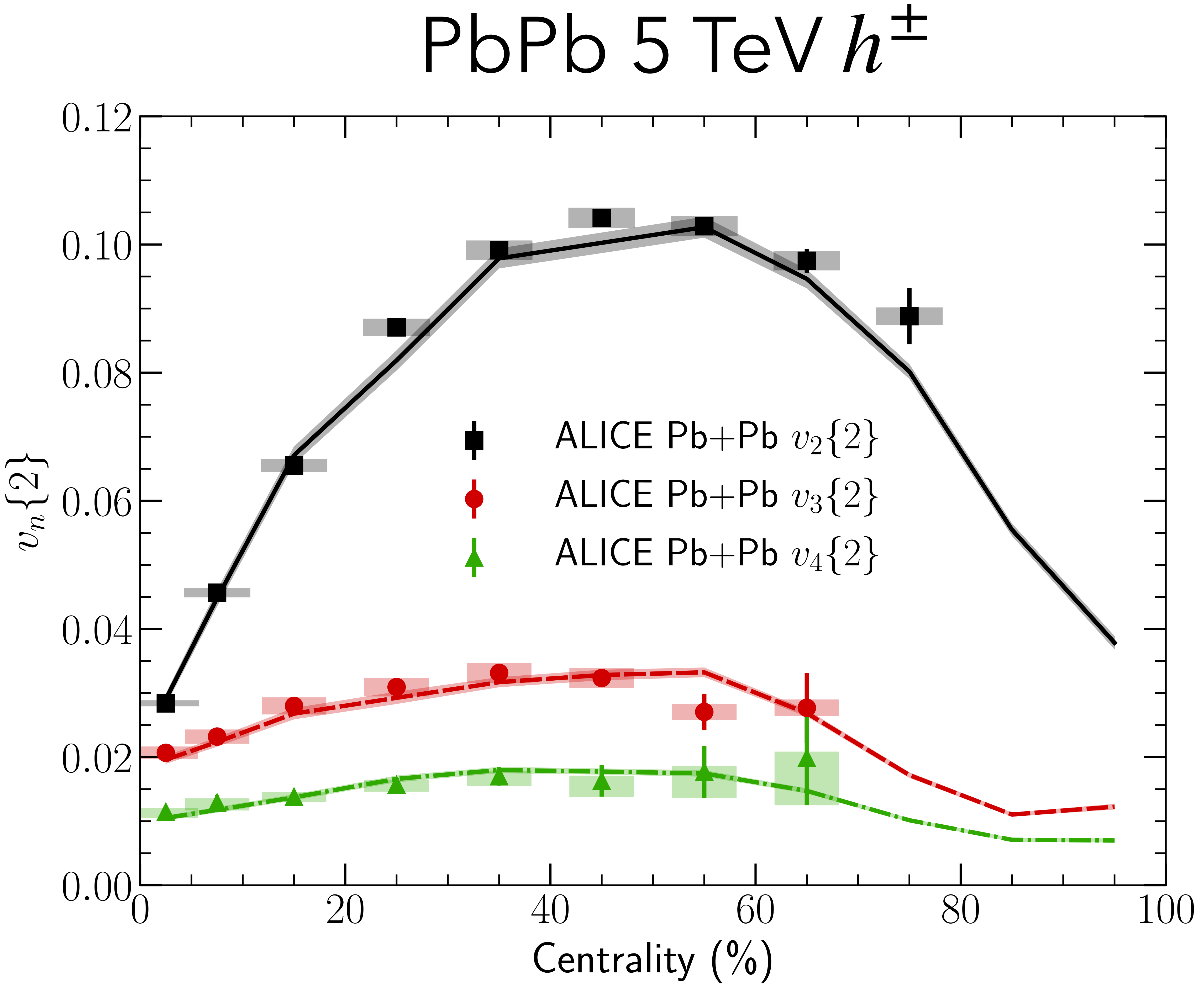
STAR Collaboration, Phys.Rev.Lett. 115 (2015) 222301
ALICE Collaboration, Phys.Rev.Lett. 116 (2016) 132302



OTHER NEW RESULTS: $v_n\{2\}$

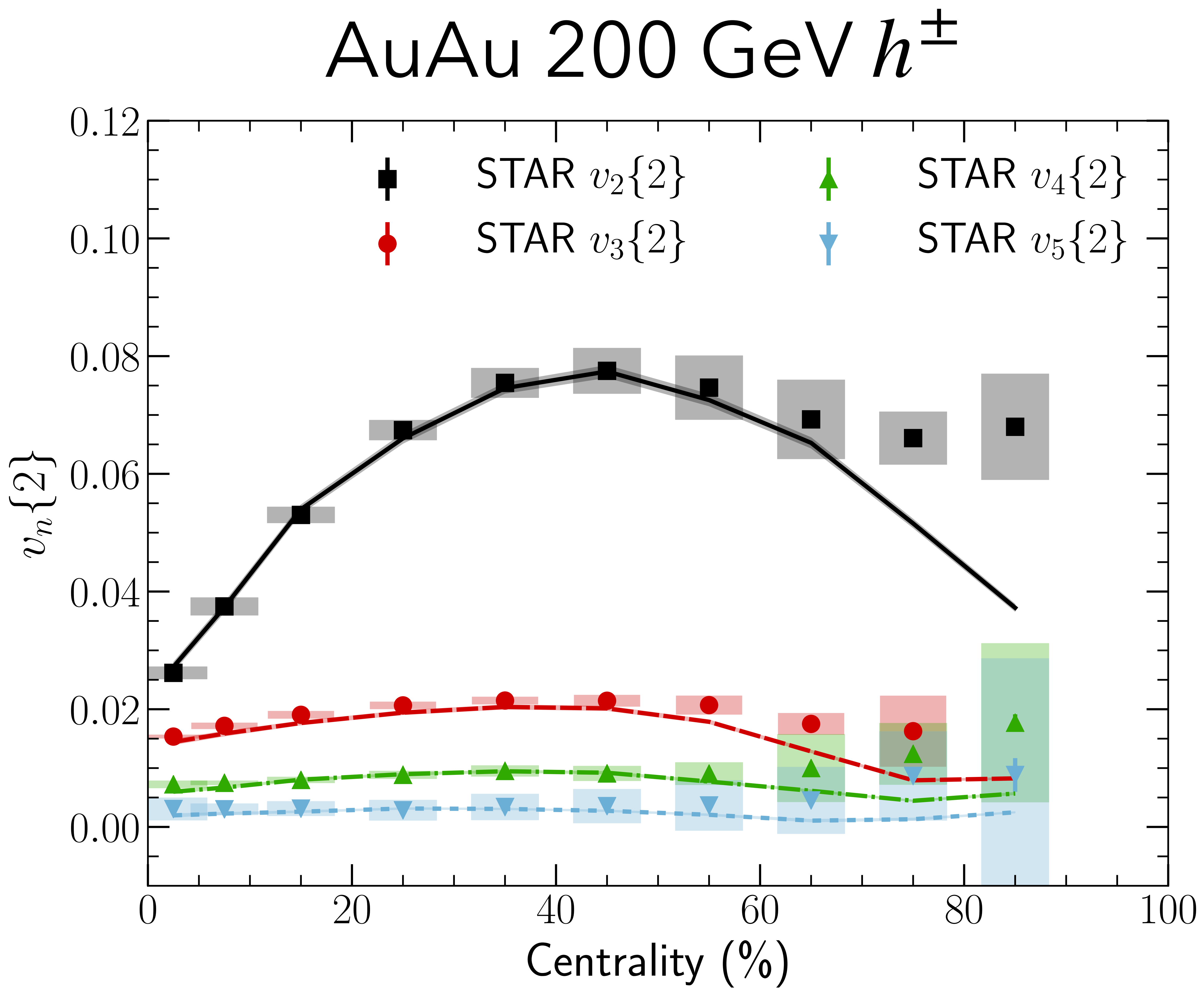
STAR Collaboration, Phys. Rev. C98, 034918 (2018)
STAR Collaboration, Phys. Rev. Lett. 116, 112302 (2016)
ALICE Collaboration, Phys.Rev.Lett. 116 (2016) 132302

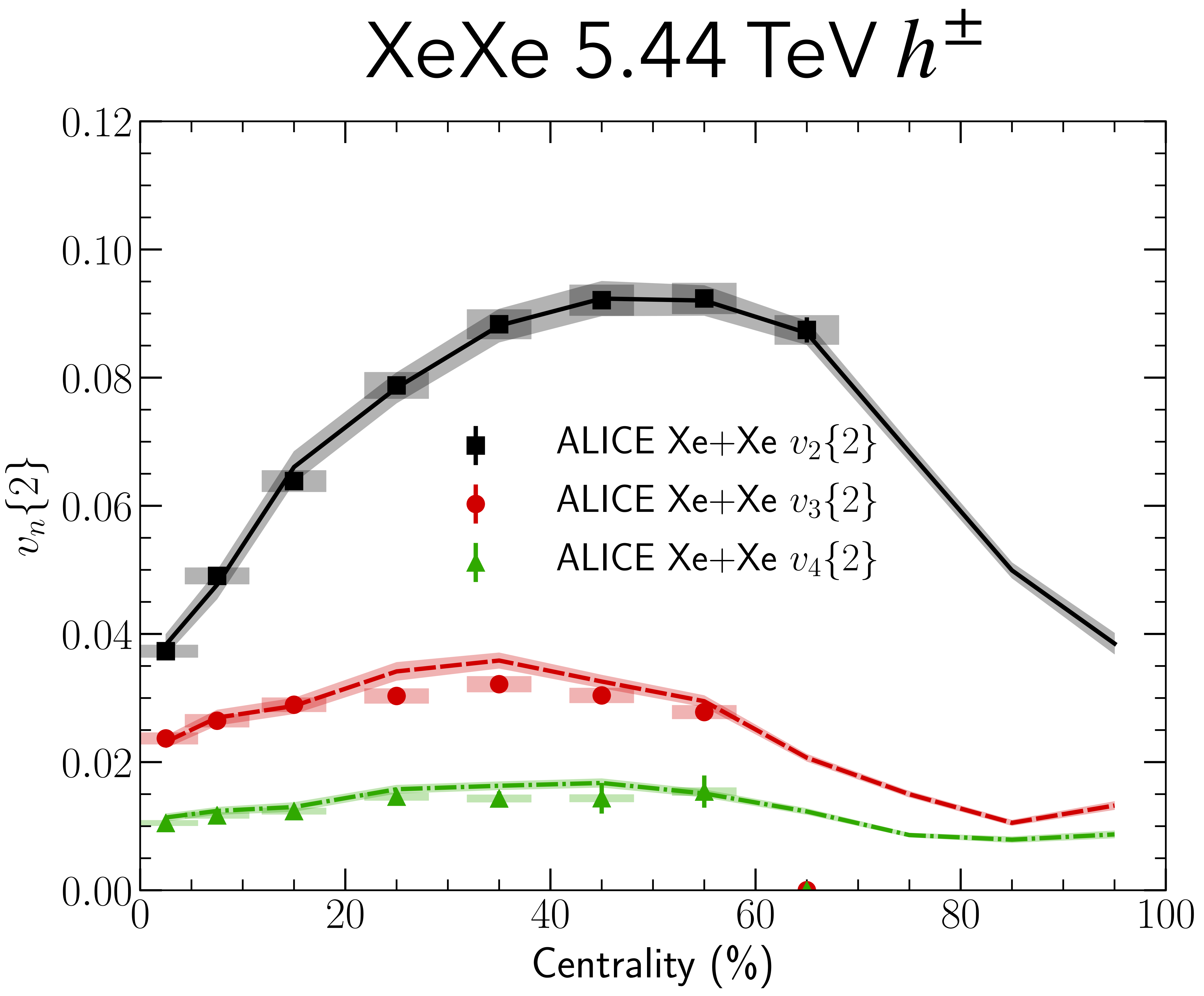




OTHER NEW RESULTS: $v_n\{2\}$

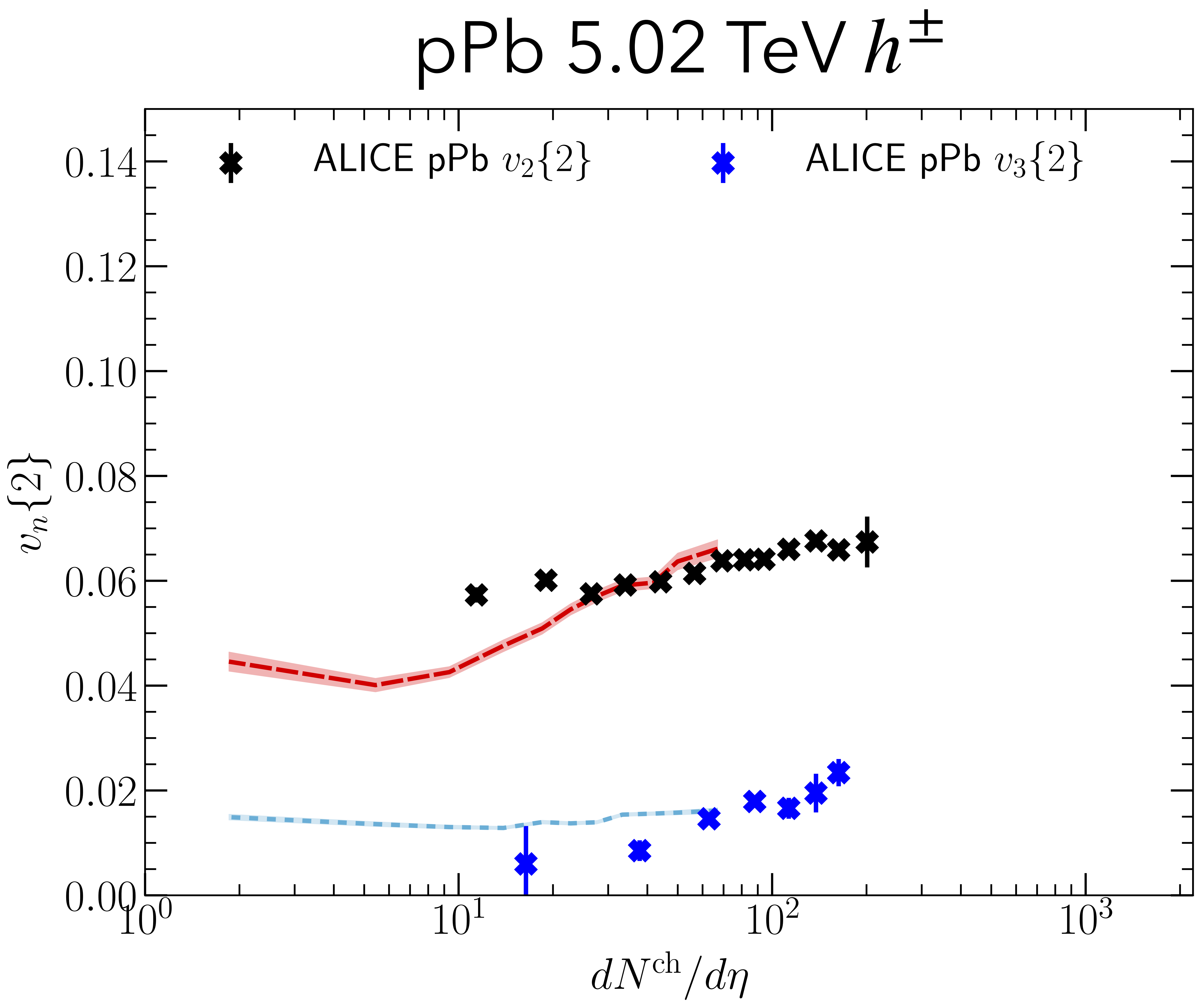
STAR Collaboration, Phys. Rev. C98, 034918 (2018)
STAR Collaboration, Phys. Rev. Lett. 116, 112302 (2016)
ALICE Collaboration, Phys.Lett. B784 (2018) 82-95





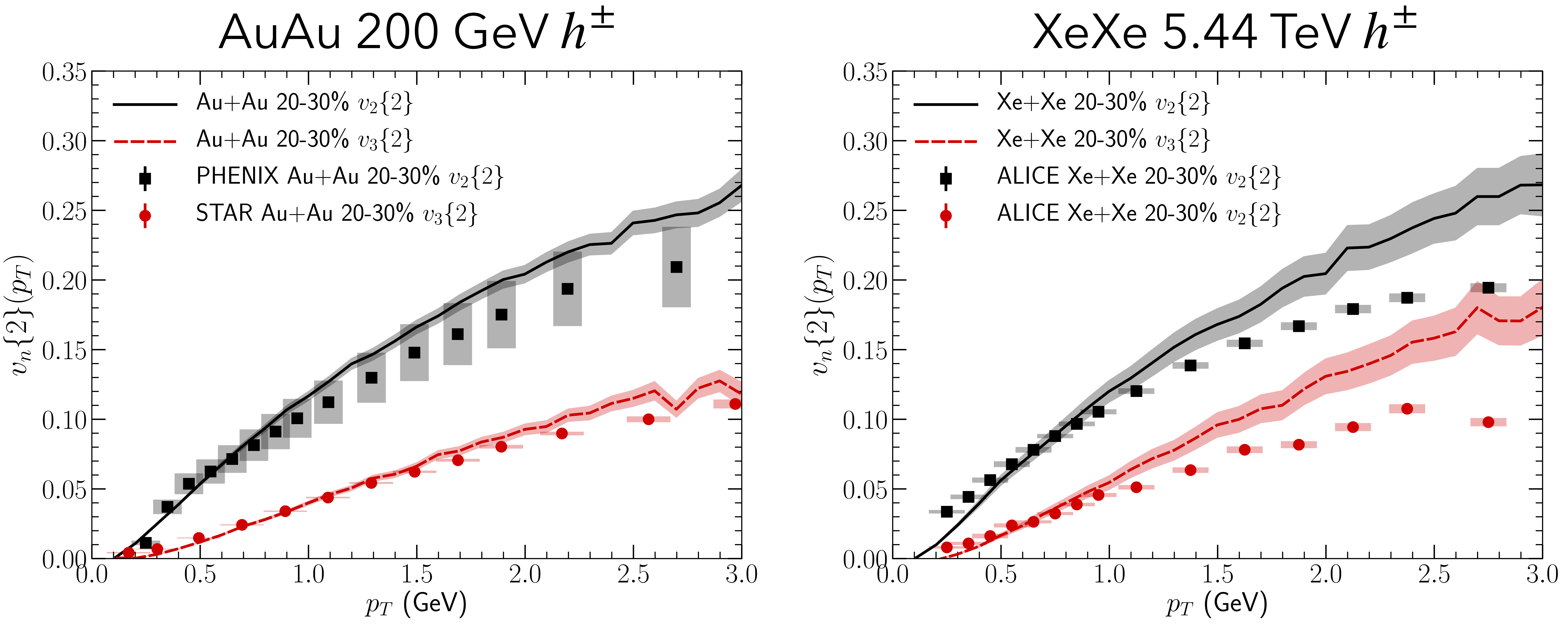
OTHER NEW RESULTS: $v_n\{2\}$

ALICE Collaboration, Phys.Rev. C90 (2014) 054901



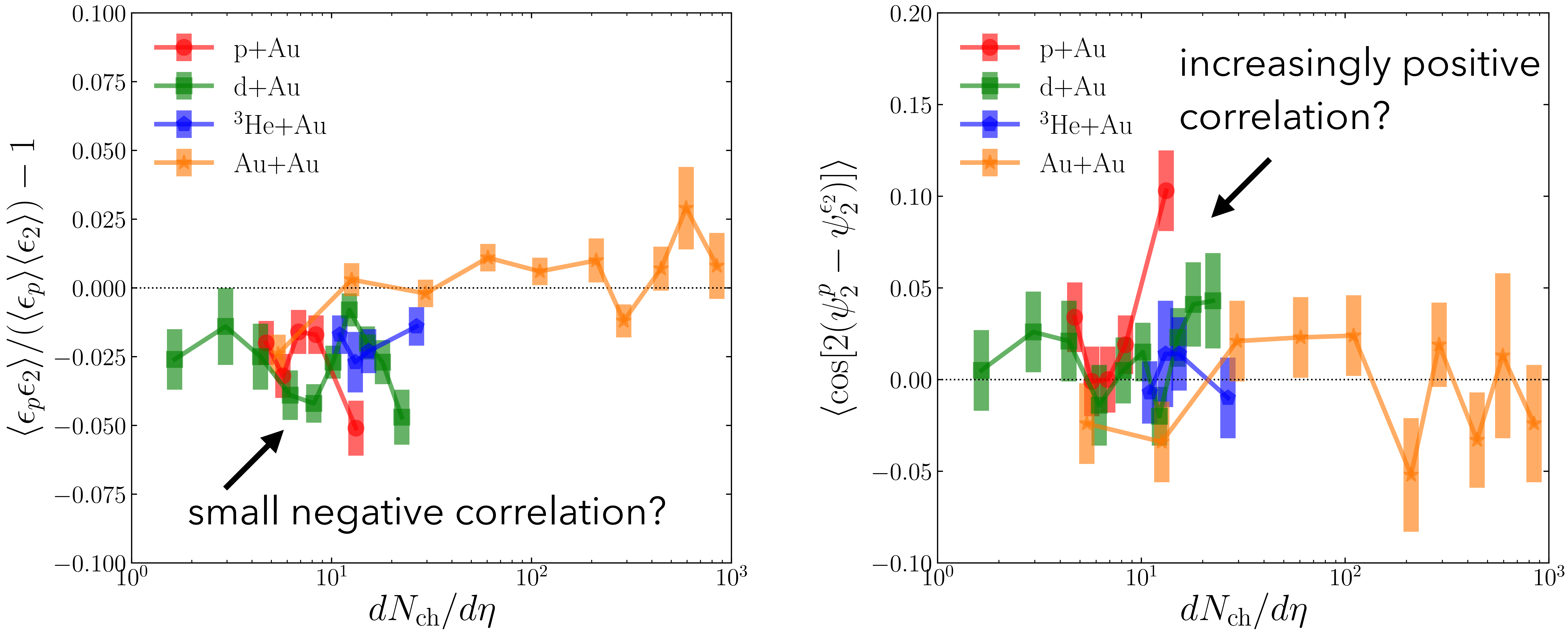
OTHER NEW RESULTS: $v_n\{2\}(p_T)$

STAR Collaboration, Phys.Rev. C88 (2013) 014904
PHENIX Collaboration, Phys. Rev. Lett. 107, 252301
ALICE Collaboration, Phys.Lett. B784 (2018) 82-95



INITIAL MOMENTUM ANISOTROPY AND GEOMETRY ARE MOSTLY UNCORRELATED

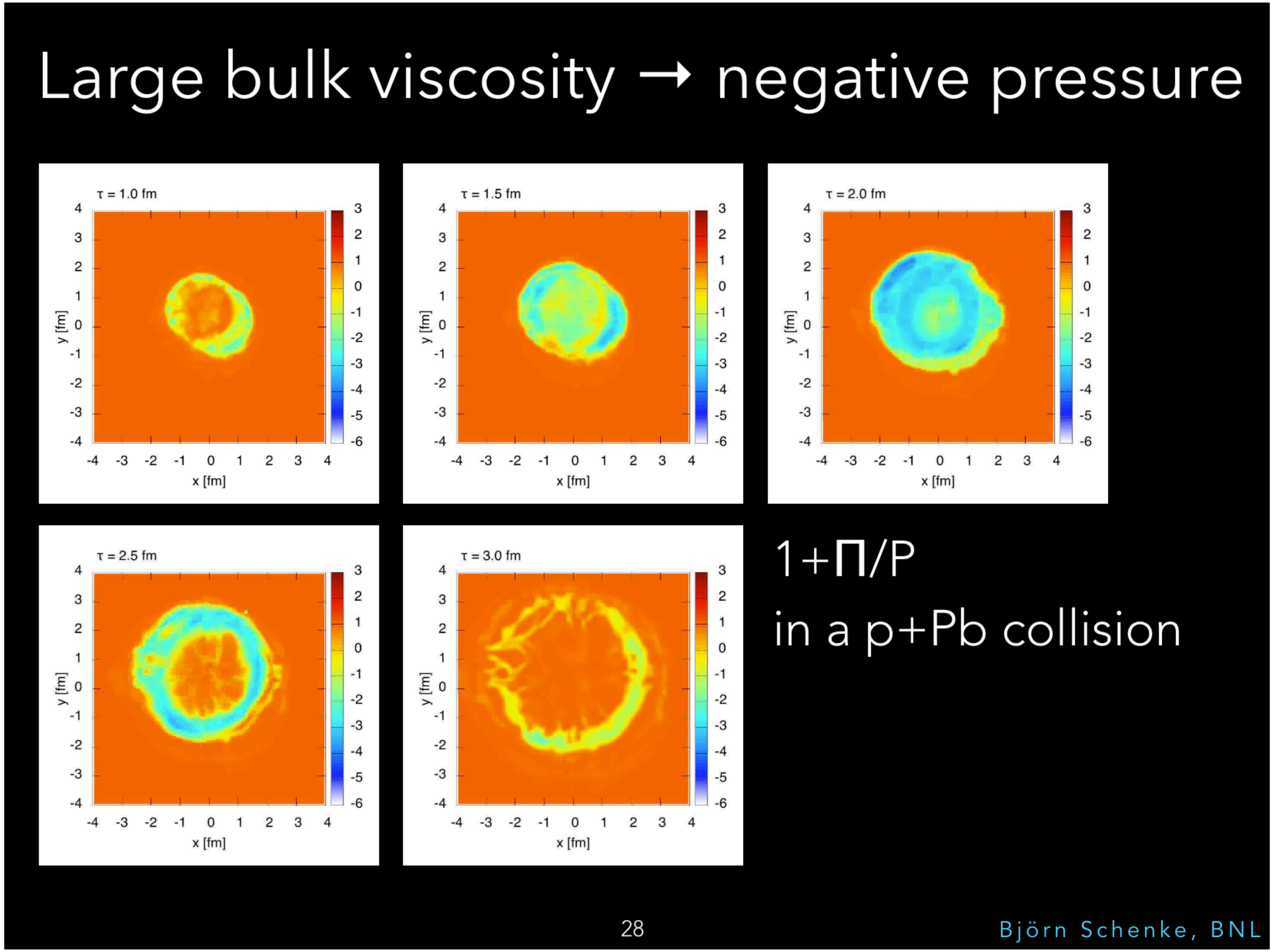
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



NEGATIVE PRESSURES FROM LARGE BULK VISCOSITY

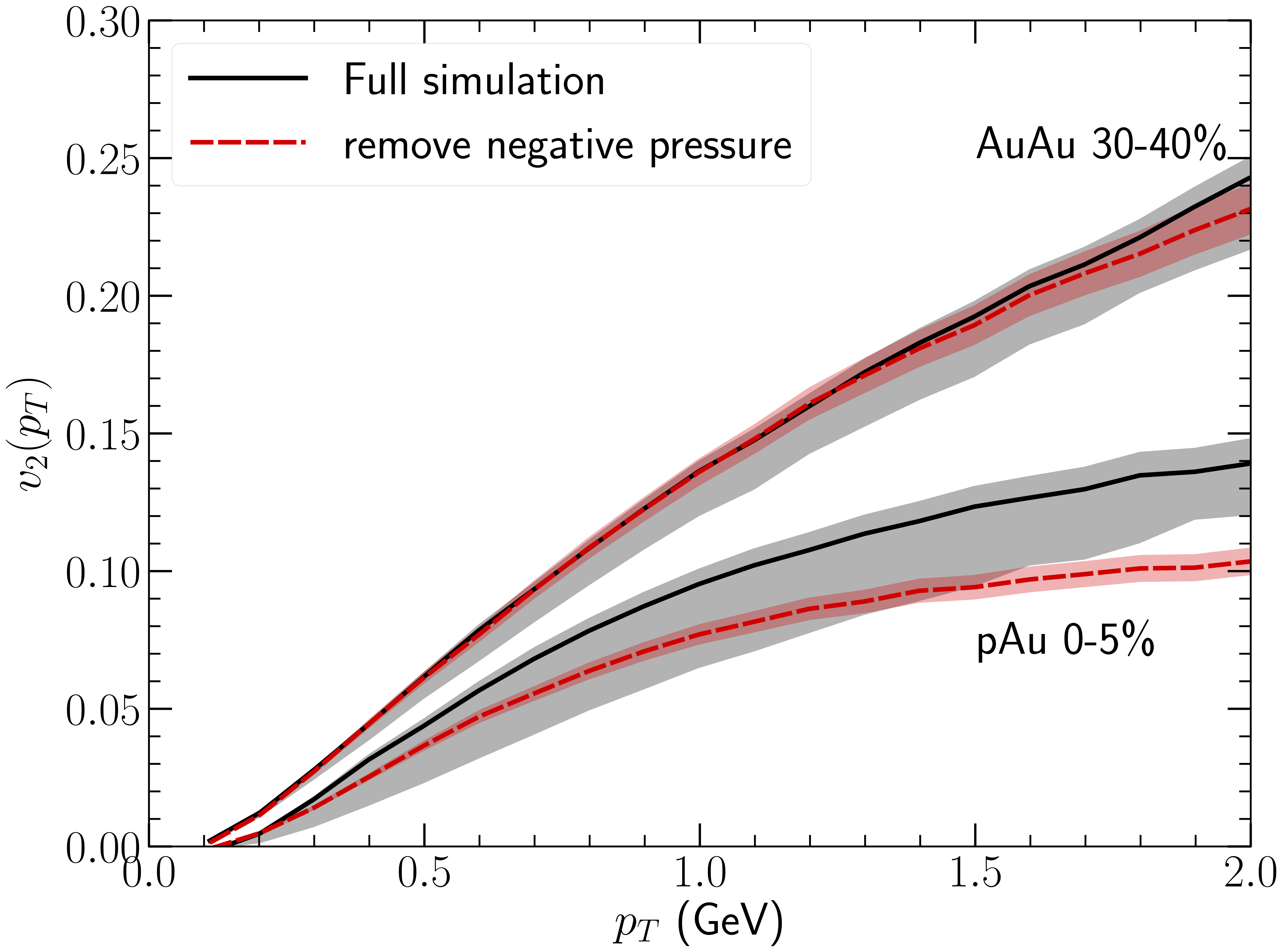
https://indico.cern.ch/event/656452/contributions/2869794/attachments/1650052/2638601/Schenke-QM2018-Venice.pdf

Slide from my QM2018 talk:

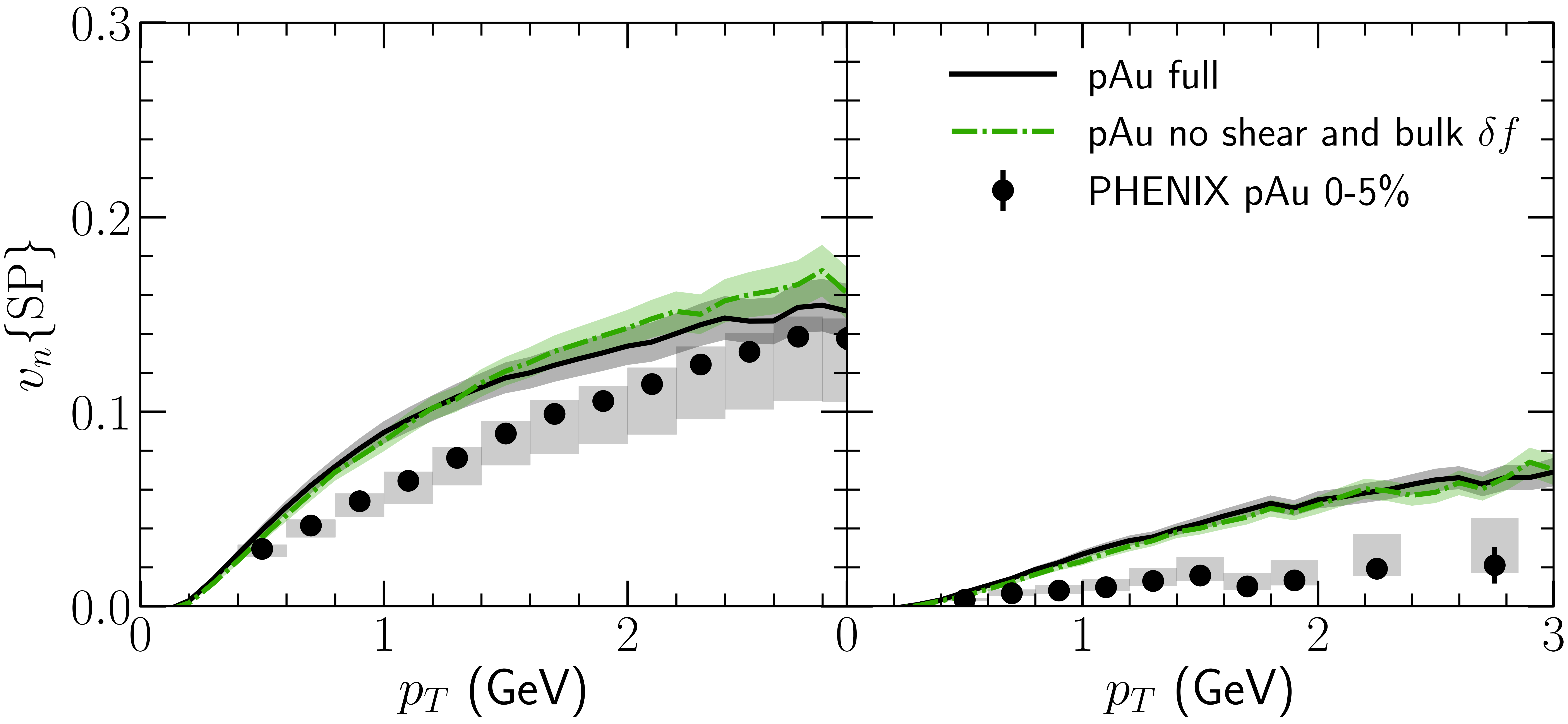


NEGATIVE PRESSURES FROM LARGE BULK VISCOSITY

Quick estimate of the uncertainty from negative pressures by setting negative values to zero in the evolution

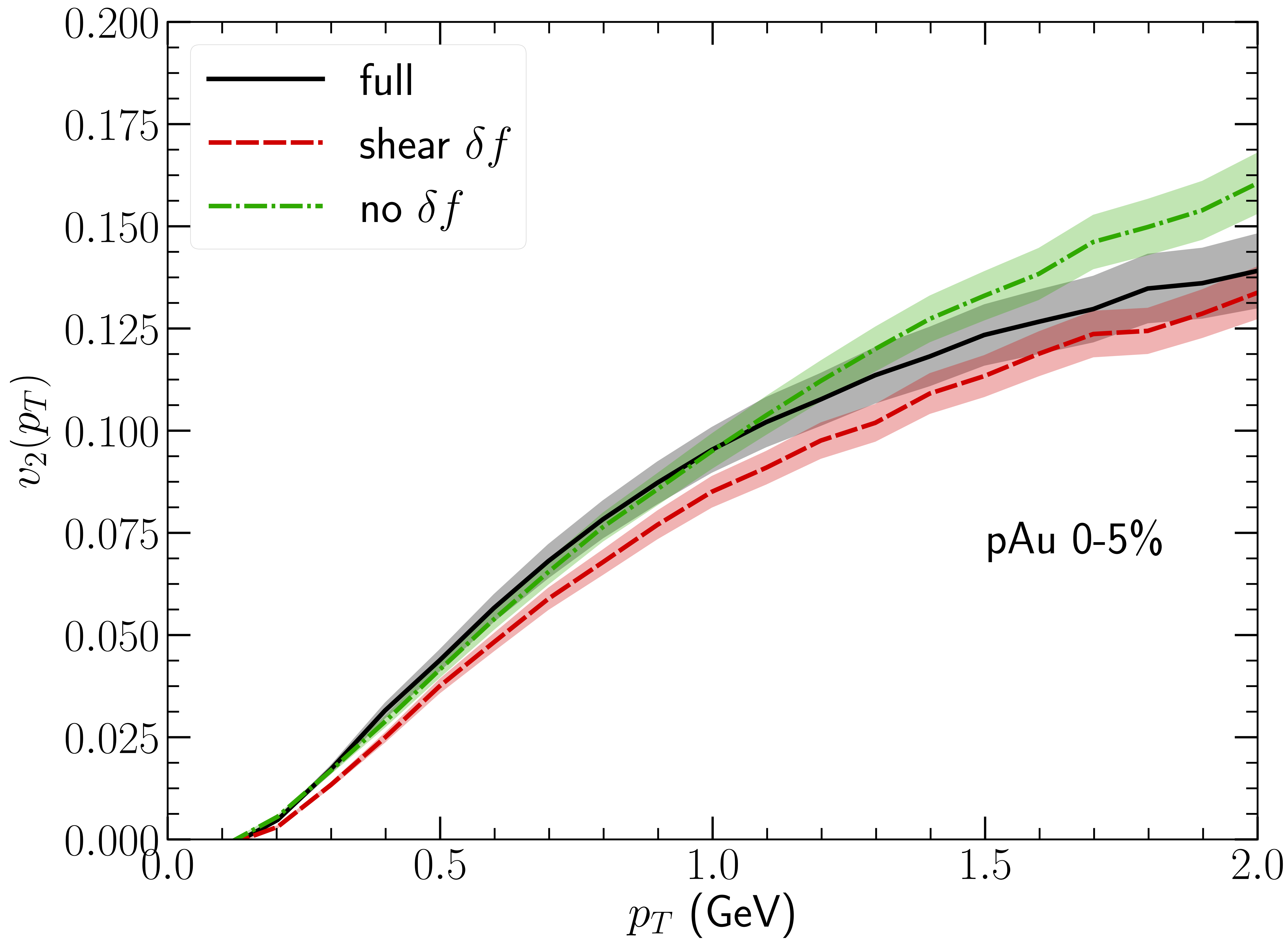


COMBINED EFFECT OF SHEAR AND BULK δf



Combined effect of bulk δf and shear δf is small in pAu collisions

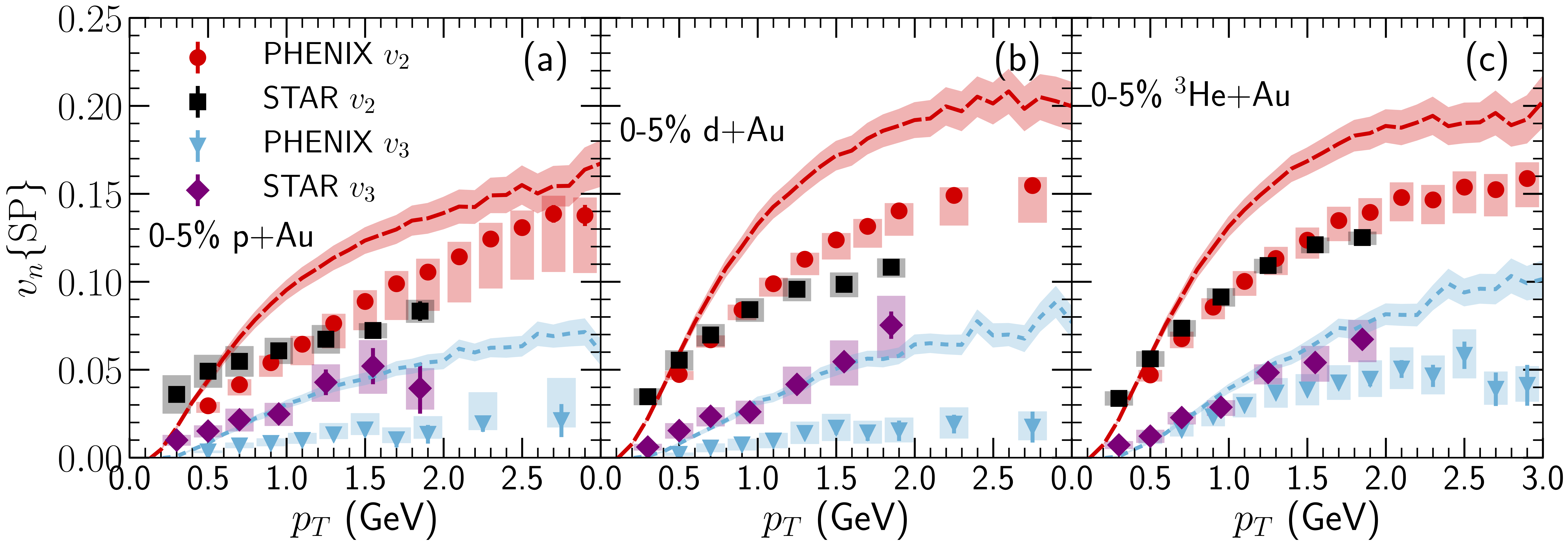
INDIVIDUAL EFFECTS OF SHEAR AND BULK δf



Individual effects of bulk δf and shear δf are not very large either

RHIC SYSTEM SCAN WITH NEW PARAMETERS

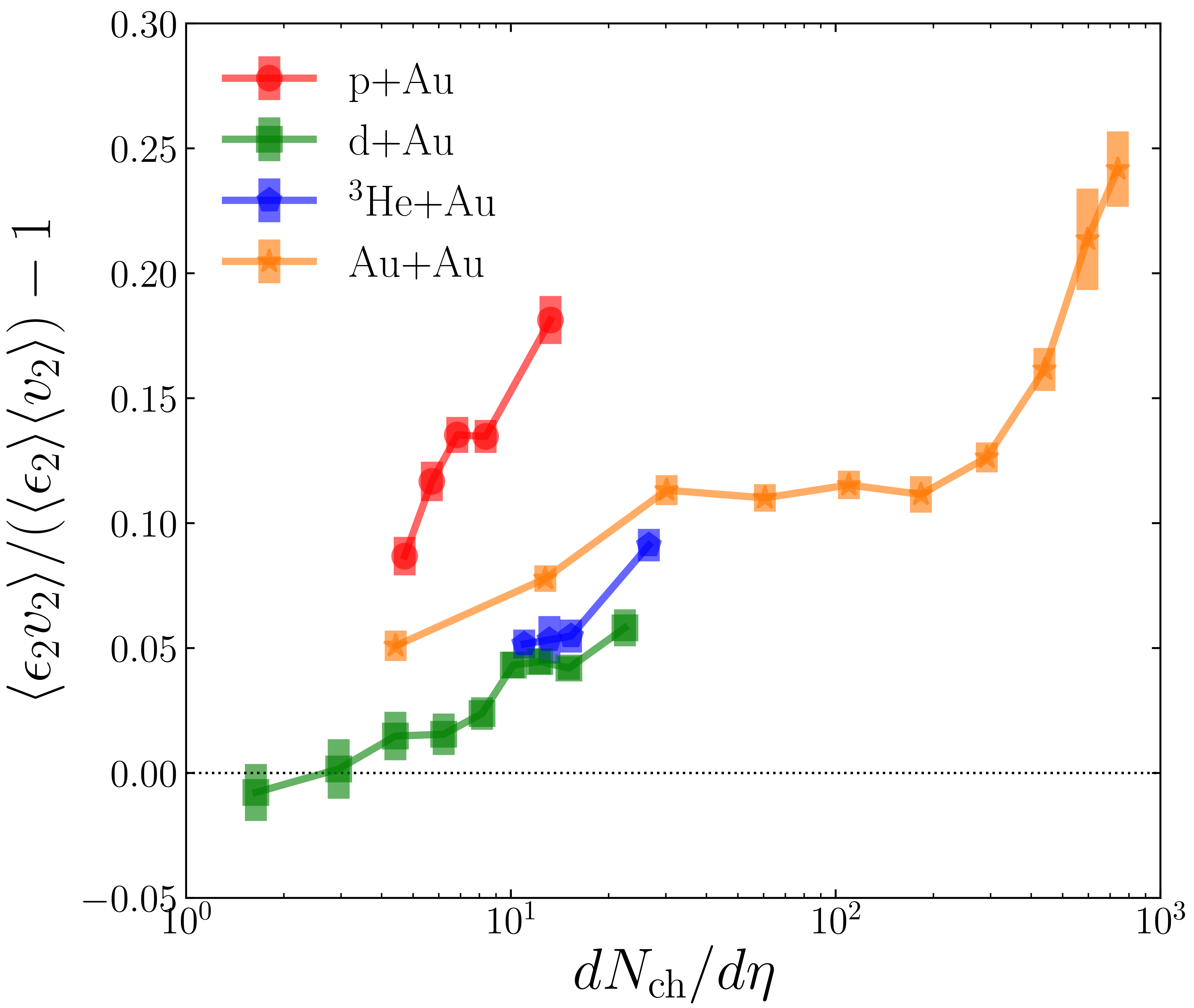
Experimental Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019); STAR, NEW AT QUARK MATTER 2019



Will T-dependent η/s help (rising below T_c)?

ANALYSIS: EFFECT OF INITIAL STATE MOMENTUM ANISOTROPY

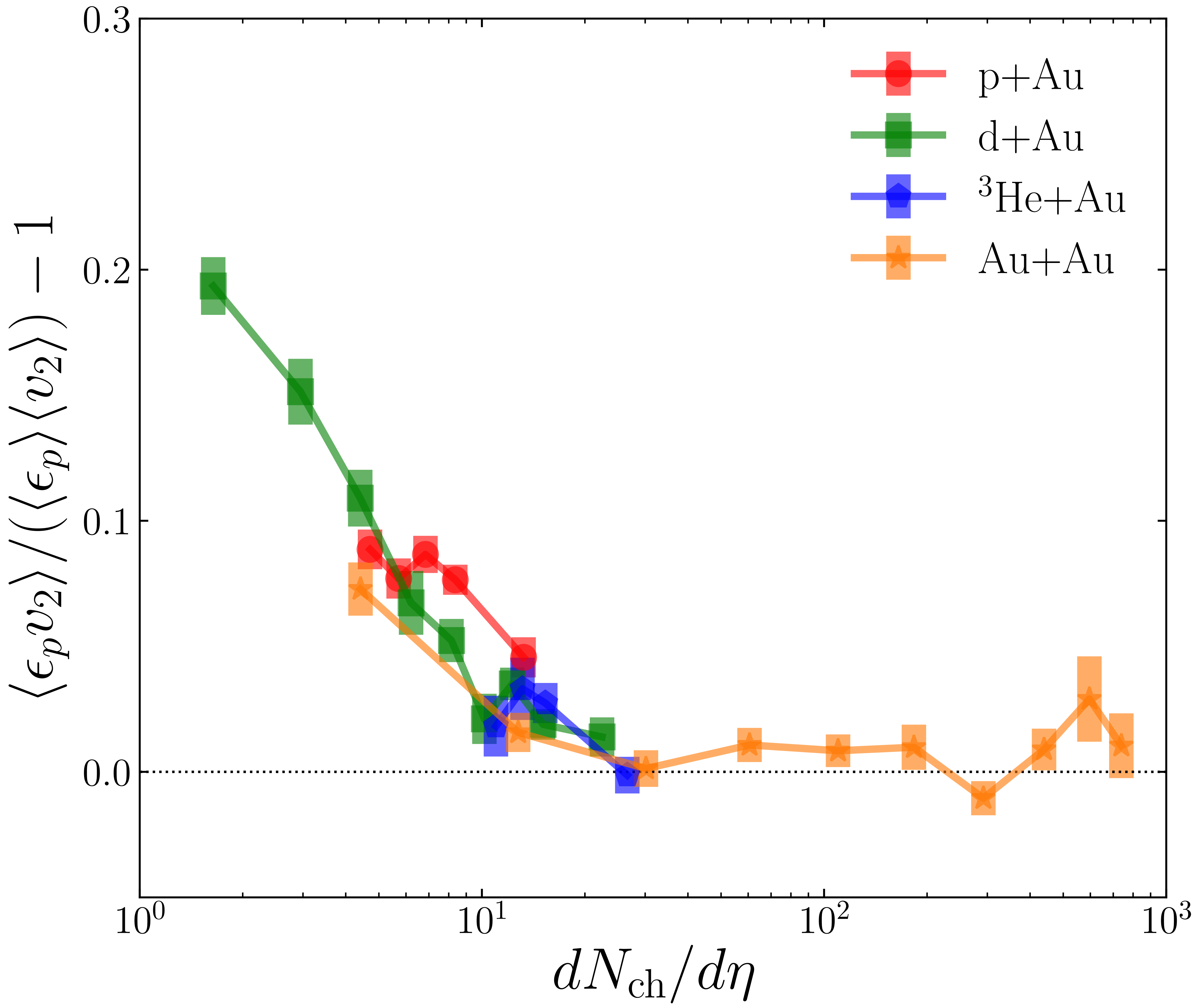
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



- Correlation of $v_2\{2\}$ with the geometry ε_2 decreases towards low multiplicity

ANALYSIS:
EFFECT OF INITIAL STATE MOMENTUM ANISOTROPY

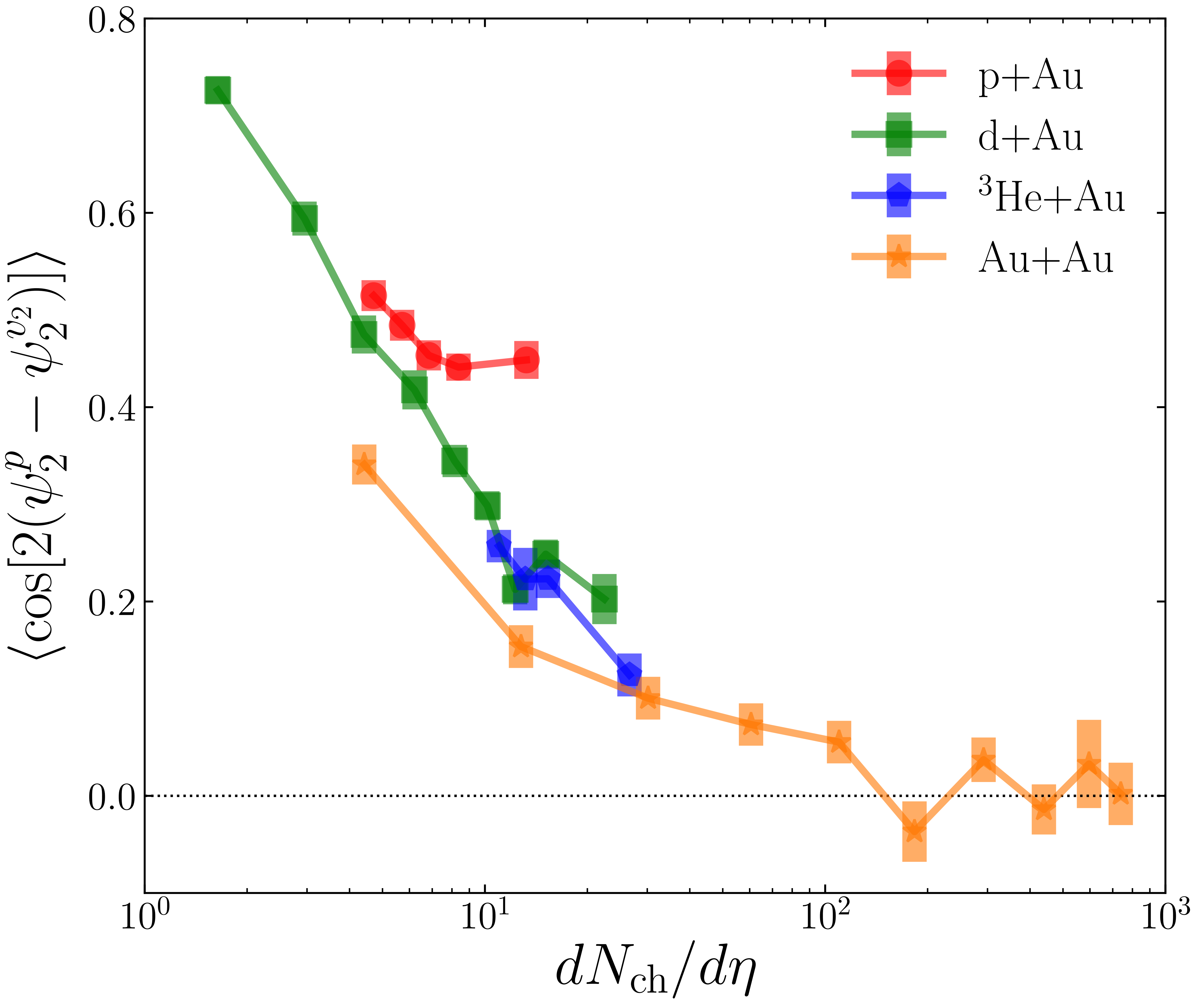
B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



- Reversely, correlation of $v_2\{2\}$ with the initial momentum anisotropy ε_p increases towards low multiplicity for all systems

ANALYSIS:
EFFECT OF INITIAL STATE MOMENTUM ANISOTROPY

B. Schenke, C. Shen, P. Tribedy, e-Print: arXiv:1908.06212



- Similarly, the orientation of $v_2\{2\}$ becomes more correlated with the orientation of the initial momentum anisotropy ε_p towards low multiplicity