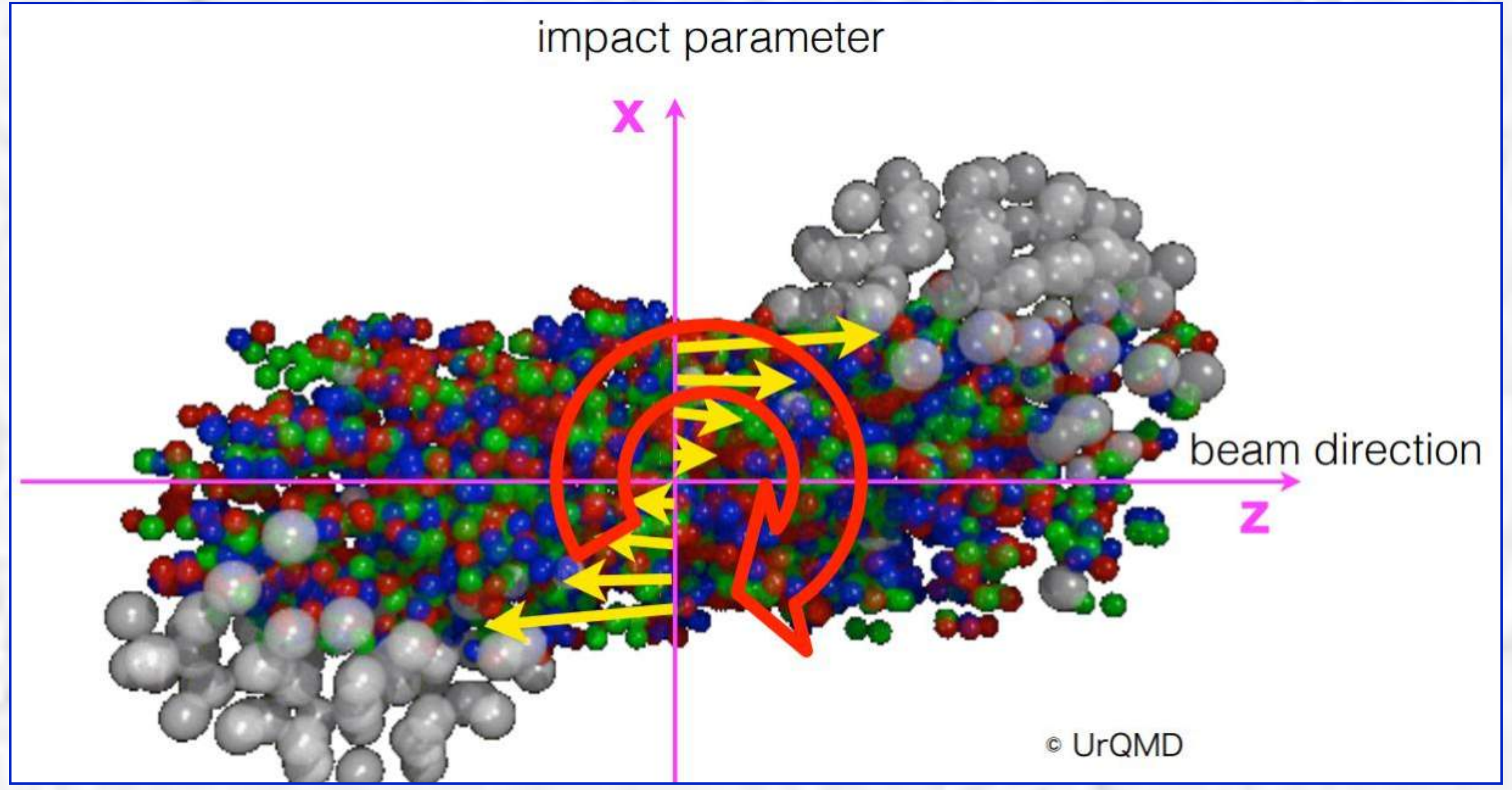
Polarization in relativistic nuclear collisions: recent measurements and open questions

Sergei A. Voloshin

Wayne State University



Outline:

- Introduction
- P_y: BES II, $\Lambda/\bar{\Lambda}$, ϕ_H dependence; average/global vs $P_{y,0}$
- P_z : BES II, LHC: higher harmonics, hydro, BW , SIP.
- BES II, LHC: Ω, Ξ

Discussion:

- P_ϕ, spin-spin correlations, hypertriton polarization
- Cooper Frye
- spin alignment - accounting for detector effects.

U.S. Department of Energy Office of Science

Recent review

International Journal of Modern Physics E
Vol. 33, No. 9 (2024) 2430010 (41 pages)

DOI: 10.1142/S0218301324300108

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Polarization phenomenon in heavy-ion collisions

Takafumi Niida *
Department of Physics, University of Tsukuba,
1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
niida.takafumi.fw@u.tsukuba.ac.jp

Sergei A. Voloshin
Department of Physics and Astronomy,
Wayne State University,
666 W. Hancock, Detroit, MI 48201, USA
sergei.voloshin@wayne.edu

Discussion of the physics at a qualitative level, include technical details of the measurements

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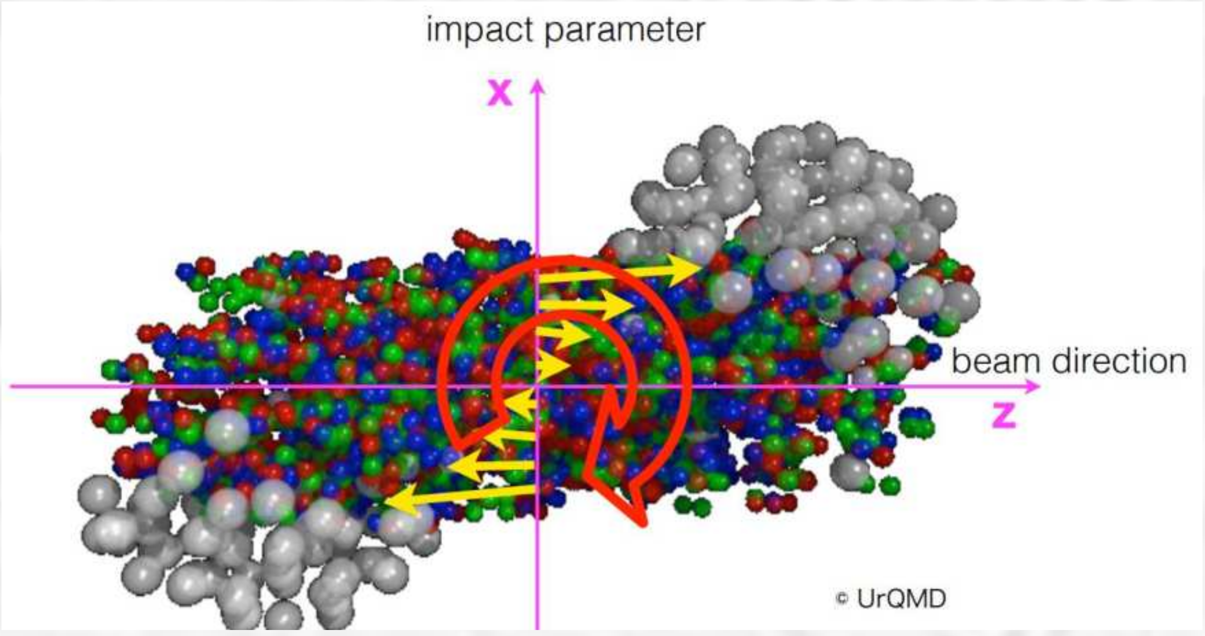
Brief history (~20 years in 60 seconds) part I



1987… +E 896, NA57

M. Jacob, J. Rafelski: Phys. Lett. 190 B (1987) 173
LONGITUDINAL $\bar{\Lambda}$ POLARIZATION, $\bar{\Xi}$ ABUNDANCE AND QUARK–GLUON PLASMA FORMATION

2003 first ideas/discussions
(STAR meeting in Prague)

2004 Idea goes "on-shell"
first publications

[nucl-th/0410079] Globally Polarized Quark-gluon Plasma in Non-central A+A Collisions
Authors: Zuo-Tang Liang (Shandong U), Xin-Nian Wang (LBNL)
(Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5))

prediction $P_H \sim 0.3$

[nucl-th/0410089] Polarized secondary particles in unpolarized high energy hadron-hadro...
Authors: Sergei A. Voloshin
(Submitted on 21 Oct 2004)

$\rho^0 \longrightarrow \pi^+\pi^-$ | $s_y = 1 \longrightarrow l_y = 1$

$\pi^+\pi^- \longrightarrow \rho^0$ | $l_y = 1 \longrightarrow s_y = 1$

- Spin alignment $\rightarrow v_2$
- Relation to single spin asymmetries?

2007 Fist measurements

B. I. Abelev *et al.* (STAR Collaboration), Global polarization measurement in Au+Au collisions, Phys. Rev. C **76**, 024915 (2007); **95**, 039906(E) (2017).

$$P_H = \frac{8}{\pi \alpha_H} \langle \sin(\Psi_{RP} - \phi_p) \rangle$$

I. Selyuzhenkov, S.V.

Λ global polarization < 2%

~10M events

B. I. Abelev and others (STAR Collaboration), "Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. C* **77**, 061902 (2008), arXiv:0801.1729.

First ideas on local vorticity

B. Betz, M. Gyulassy, and G. Torrieri, Polarization probes of vorticity in heavy ion collisions, Phys. Rev. C **76**, 044901 (2007).

2013 ALICE Physics Week in Padova
idea of thermodynamical equilibrium

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Relativistic distribution function for particles with spin at local thermodynamical equilibrium, Annals Phys. **338**, 32 (2013).

2017 STAR measurements in BES
first "non-zero" measurements

STAR Collaboration, L. Adamczyk *et al.*, "Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid", *Nature* **548** (2017) 62–65,

I. Upsal, M. Lisa, S.V.

Brief history (~20 years in 60 seconds) part II (as of summer 2024)

2017 - 2023

SQM: anisotropic flow -> polarization along the beam direction

Global polarization at different energies

Polarization of Ξ and Ω hyperons

Polarization due to anisotropic flow including higher harmonics

SQM 2017

S. A. Voloshin, "Vorticity and particle polarization in heavy ion collisions (experimental perspective)", *EPJ Web Conf.* **171** (2018) , arXiv:1710.08934

T. Niida, S.V,

STAR Collaboration, J. Adam *et al.*, "Global polarization of Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev. C* **98** (2018) , arXiv:1805.04400 [nucl-ex].

T. Niida, S.V.

STAR Collaboration, J. Adam *et al.*, "Polarization of Λ ($\bar{\Lambda}$) hyperons along the beam direction in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev. Lett.* **123** no. 13, (2019) , arXiv:1905.11917 [nucl-ex].

M. Konyushikhin, S.V.

ALICE Collaboration, S. Acharya *et al.*, "Global polarization of $\Lambda\bar{\Lambda}$ hyperons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV", *Phys. Rev. C* **101** no. 4, (2020) , arXiv:1909.01281 [nucl-ex].

T. Niida, S.V.

STAR Collaboration, J. Adam *et al.*, "Global polarization of Ξ and Ω hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev. Lett* **126** (4, 2021) , arXiv:2012.13601 [nucl-ex].

D. Sarkar, S.V

ALICE Collaboration, S. Acharya *et al.*, "Polarization of Λ and $\bar{\Lambda}$ Hyperons along the Beam Direction in Pb-Pb Collisions at $\sqrt{s_{NN}}$=5.02 TeV", *Phys. Rev. Lett.* **128**, no. 17, 172005 (2022), arXiv:2107.11183.

STAR Collaboration, M. S. Abdallah *et al.*, "Global $\bar{\Lambda}$-hyperon polarization in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV", *Phys. Rev. C* **104**, no. 6, L061901 (2021), arXiv:2108.00044.

STAR Collaboration, M. Abdulhamid *et al.*, "Hyperon Polarization along the Beam Direction Relative to the Second and Third Harmonic Event Planes in Isobar Collisions at sNN=200 GeV", *Phys. Rev. Lett.* **131**, no. 20, 202301 (2023),

T. Niida, S.V., & Shandong U. group

STAR Collaboration, M. Abdulhamid *et al.*, "Hyperon Polarization along the Beam Direction Relative to the Second and Third Harmonic Event Planes in Isobar Collisions at sNN=200 GeV", *Phys. Rev. Lett.* **131**, no. 20, 202301 (2023), arXiv:2303.09074.

Vector meson spin alignment measurements

ALICE Collaboration, S. Acharya *et al.*, "Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions", *Phys. Rev. Lett.* **125**, no. 1, 012301 (2020), arXiv:1910.14408.

STAR Collaboration, M. S. Abdallah *et al.*, "Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions", *Nature* **614**, no. 7947, 244–248 (2023),

ALICE Collaboration, S. Acharya *et al.*, "Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC", *Phys. Rev. Lett.* **131**, no. 4, 042303 (2023), arXiv:2204.10171.

ALICE Collaboration, S. Acharya *et al.*, "First measurement of prompt and non-prompt D*+ vector meson spin alignment in pp collisions at $\sqrt{s}$ = 13 TeV", *Phys. Lett. B* **846**, 137920 (2023), arXiv:2212.06588.

Statistical mechanics/thermodynamics

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431
Ren-hong Fang,[1] Long-gang Pang,[2] Qun Wang,[1] and Xin-nian Wang[3,4] arXiv:1604.04036v1

Spin s=1/2 !

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int d\Sigma_\lambda p^\lambda n_F(1-n_F)\partial^\rho \beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

$$\beta^\mu = u^\mu/T$$

$$\Pi_\mu = W_\mu/m = -\tfrac{1}{2}\varepsilon_{\mu\rho\sigma\tau} S^{\rho\sigma}\frac{p^\tau}{m}$$

W_μ – Pauli-Lubanski pseudovector

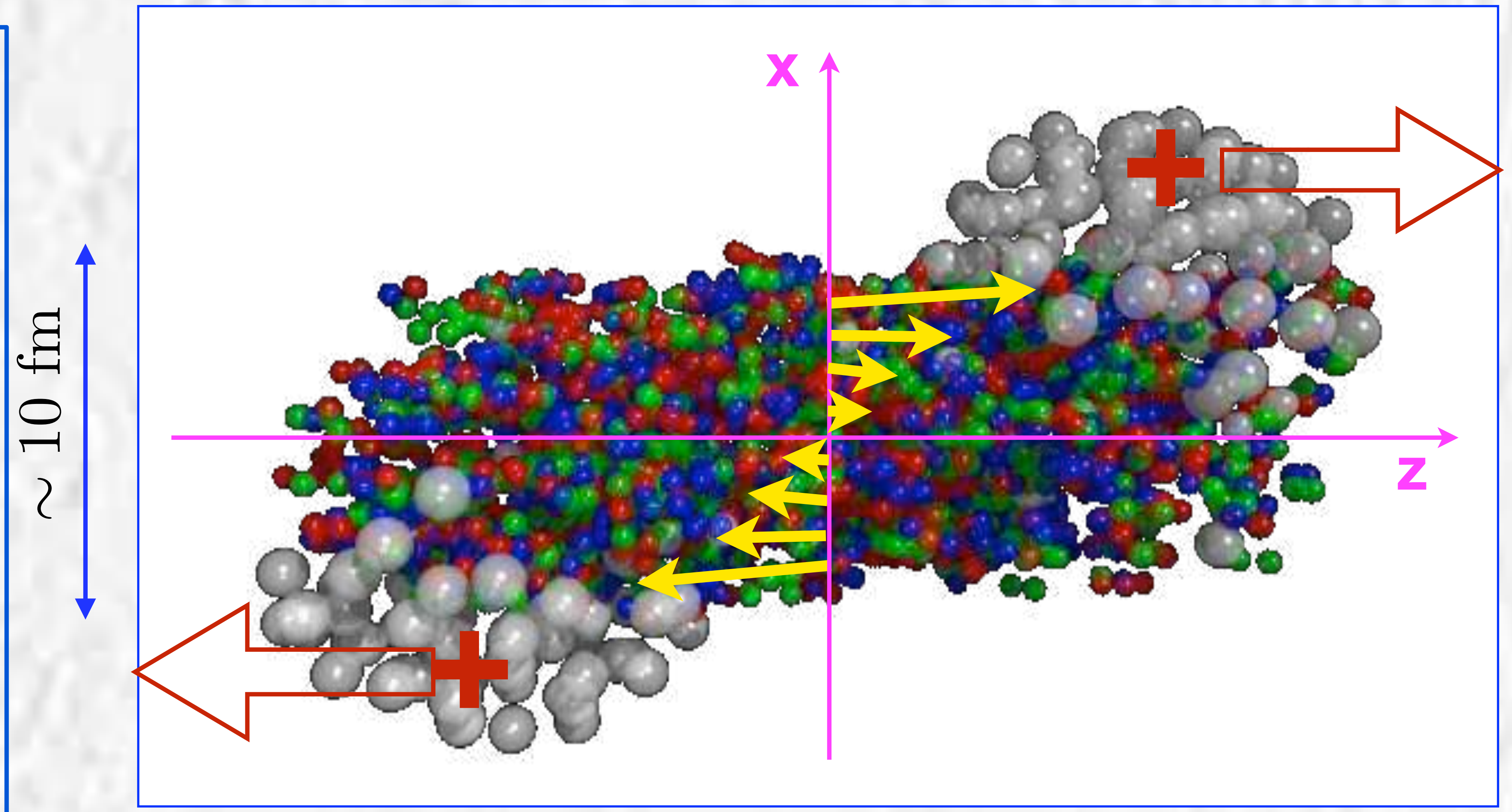
$$S^{\mu\nu} = \varepsilon^{\mu\nu\tau} S_\tau$$

Rest frame: $\Pi_\mu = (0, \mathbf{s})$

$$\omega_{\mu\nu} = \tfrac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

$$\tilde{\omega}_{\mu\nu} = \tfrac{1}{2}[\partial_\nu(u_\mu/T) - \partial_\mu(u_\nu/T)]$$

$$\omega^\alpha = \tfrac{1}{2}\varepsilon^{\alpha\mu\nu\sigma} u_\mu \omega_{\sigma\nu}$$



$$\boldsymbol{\omega} = \tfrac{1}{2}\nabla \times \mathbf{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, "Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down", *Phys. Rev.* **C95** no. 5, (2017) 054902, arXiv:1610.02506 [nucl-th].

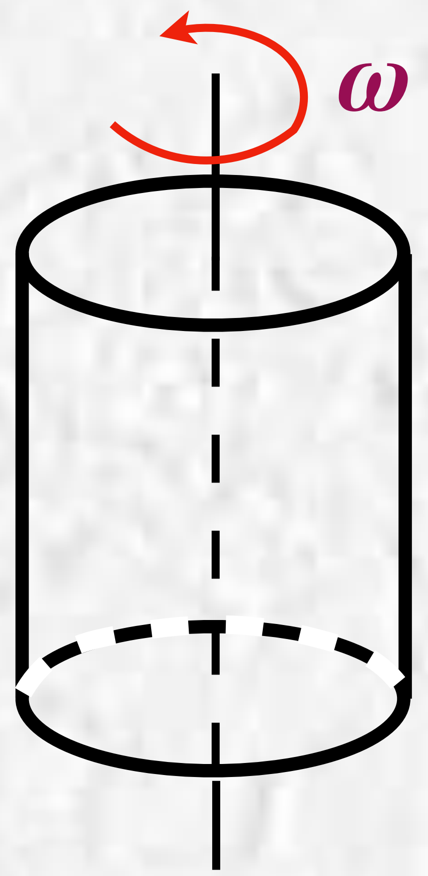
Nonrelativistic statistical mechanics (applicable for any spin)

$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu}\cdot\mathbf{B} + \boldsymbol{\omega}\cdot\mathbf{S})/T]$$

$$\mathbf{S} \approx \frac{S(S+1)}{3}\frac{\boldsymbol{\omega}}{T}$$

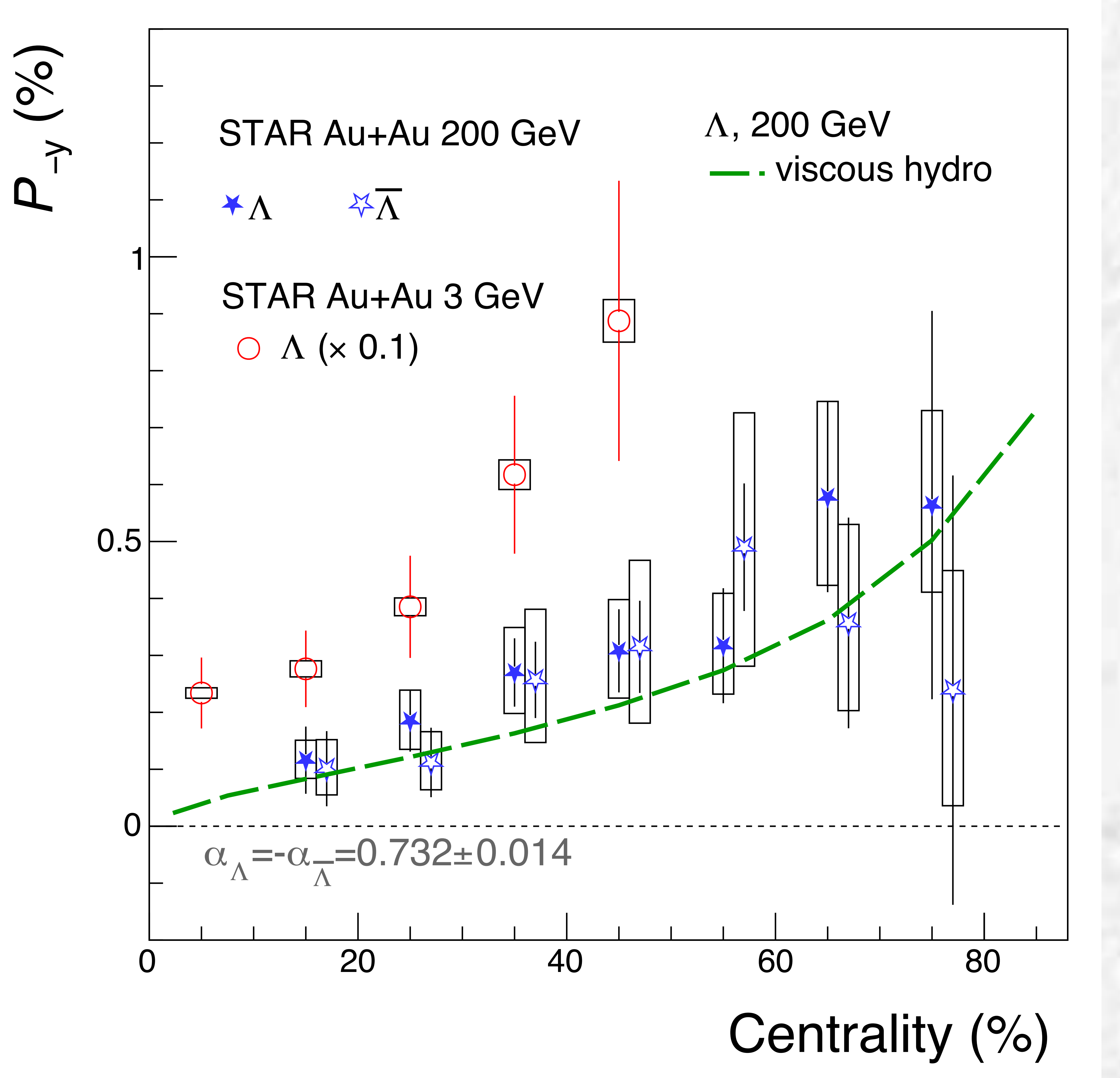
$$\mathbf{S} \approx \frac{\boldsymbol{\omega}}{4T} \text{ for s=1/2}$$

[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.
[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

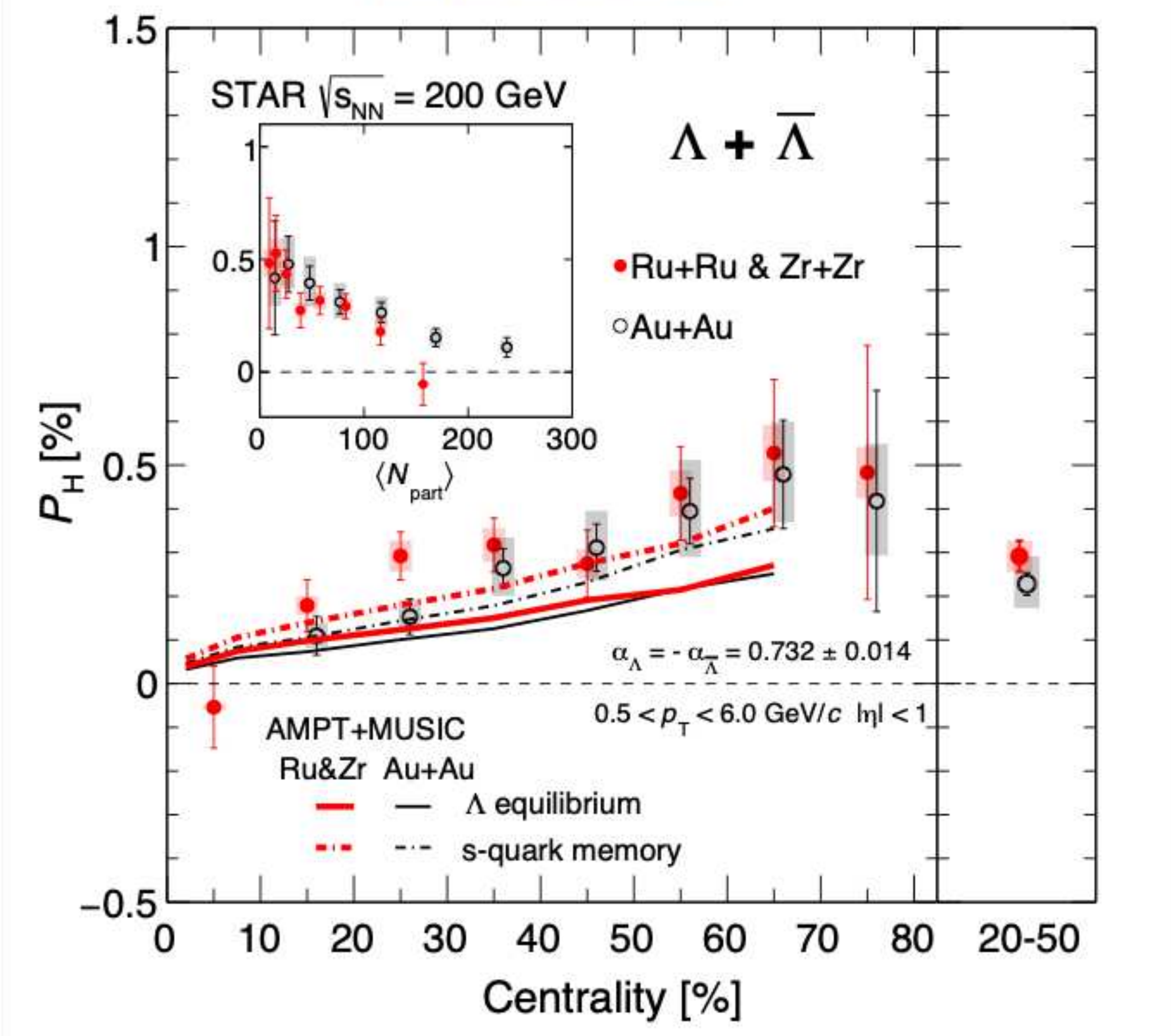


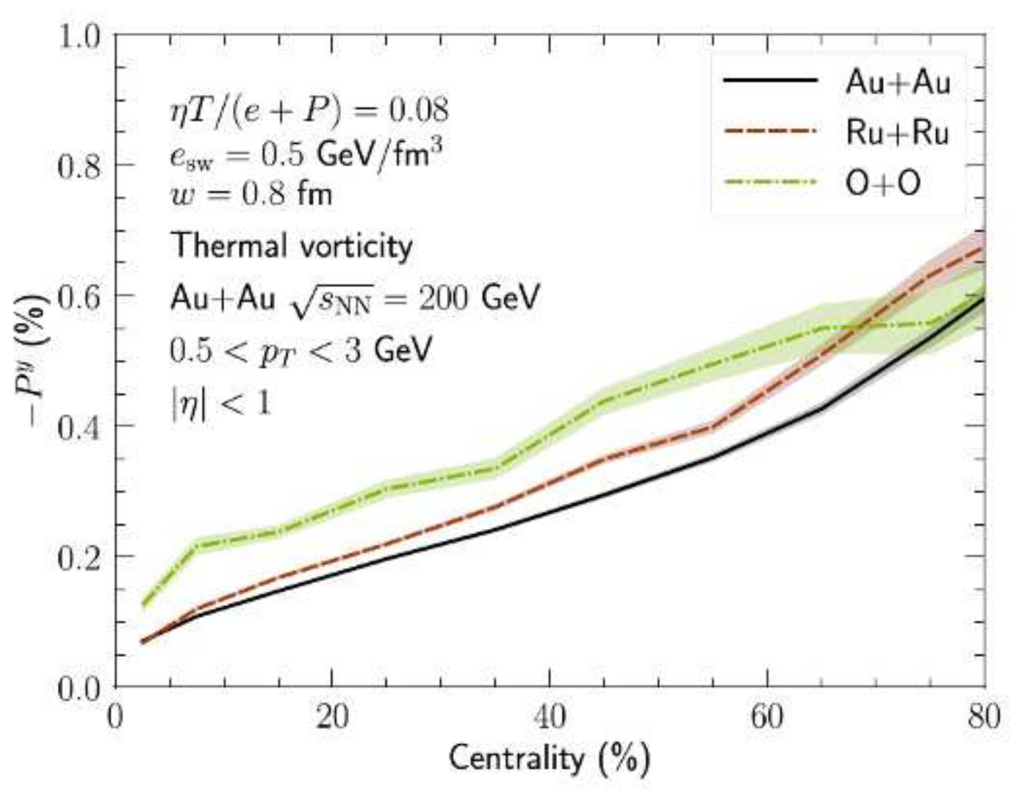
$$\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}$$

Global polarization: centrality, system size dependence



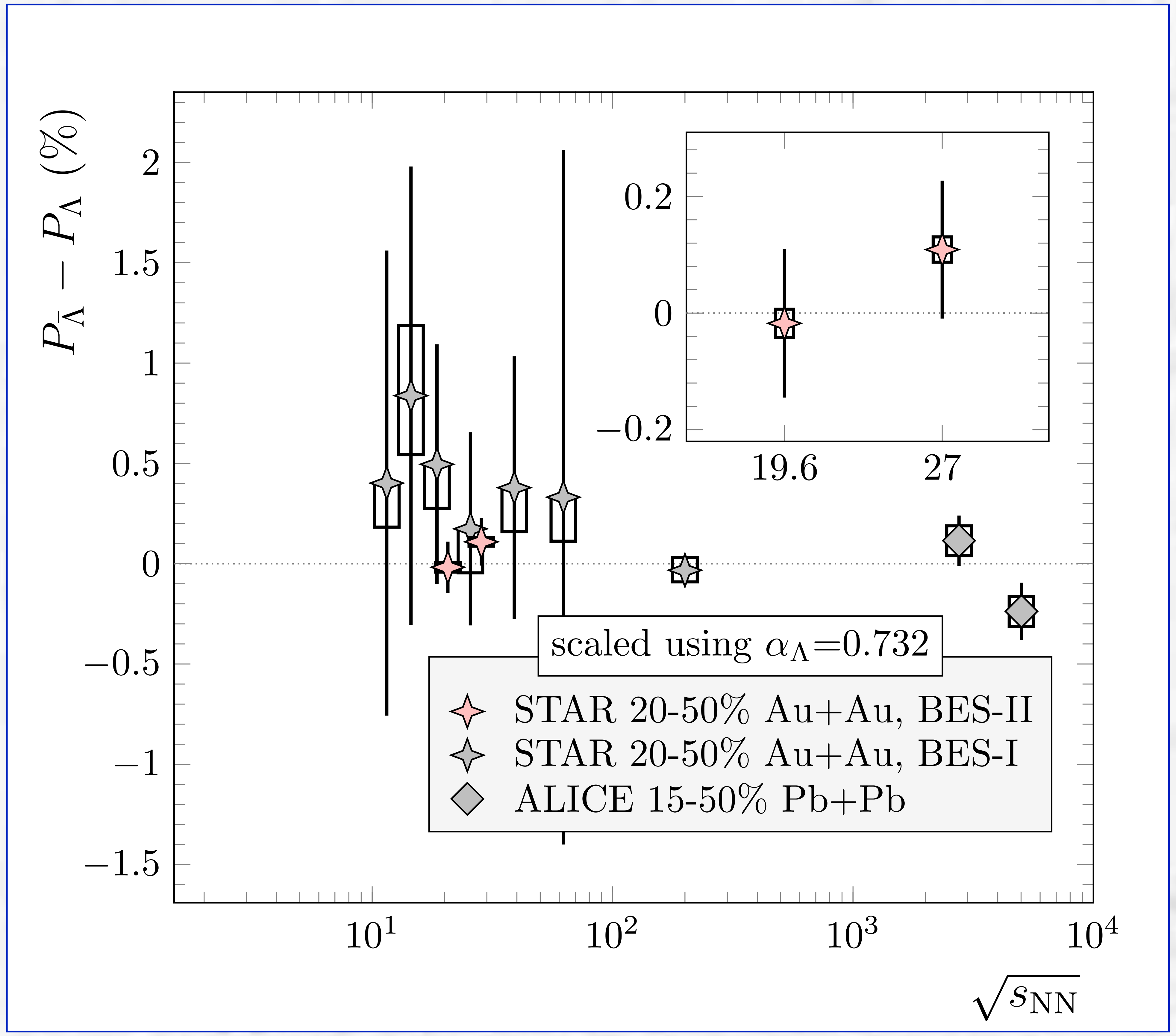
arXiv:2505.05046





$P^{\Lambda} - P^{\bar{\Lambda}}$: Magnetic field at freeze-out

!!! The splitting could be also due to other effects, e.g. baryon chemical potential



$$\Delta P_H = P_{\bar{\Lambda}} - P_{\Lambda} = \frac{2|\mu_{\Lambda}|B}{T}, \quad (57)$$

where $\mu_{\Lambda} = -\mu_{\bar{\Lambda}} = -0.613\mu_N$ with μ_N being the nuclear magneton. Thus, one arrives at the upper limit on the magnitude of the magnetic field $B \lesssim 10^{13}$ T assuming the temperature $T = 150$ MeV and ignoring the feed-down contributions

$$\frac{eB}{m_\pi^2} \approx \frac{T}{m_\pi}\frac{m_P}{0.613 m\pi}\Delta P_{\Lambda} \approx 10\,\Delta P_{\Lambda}$$

L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190

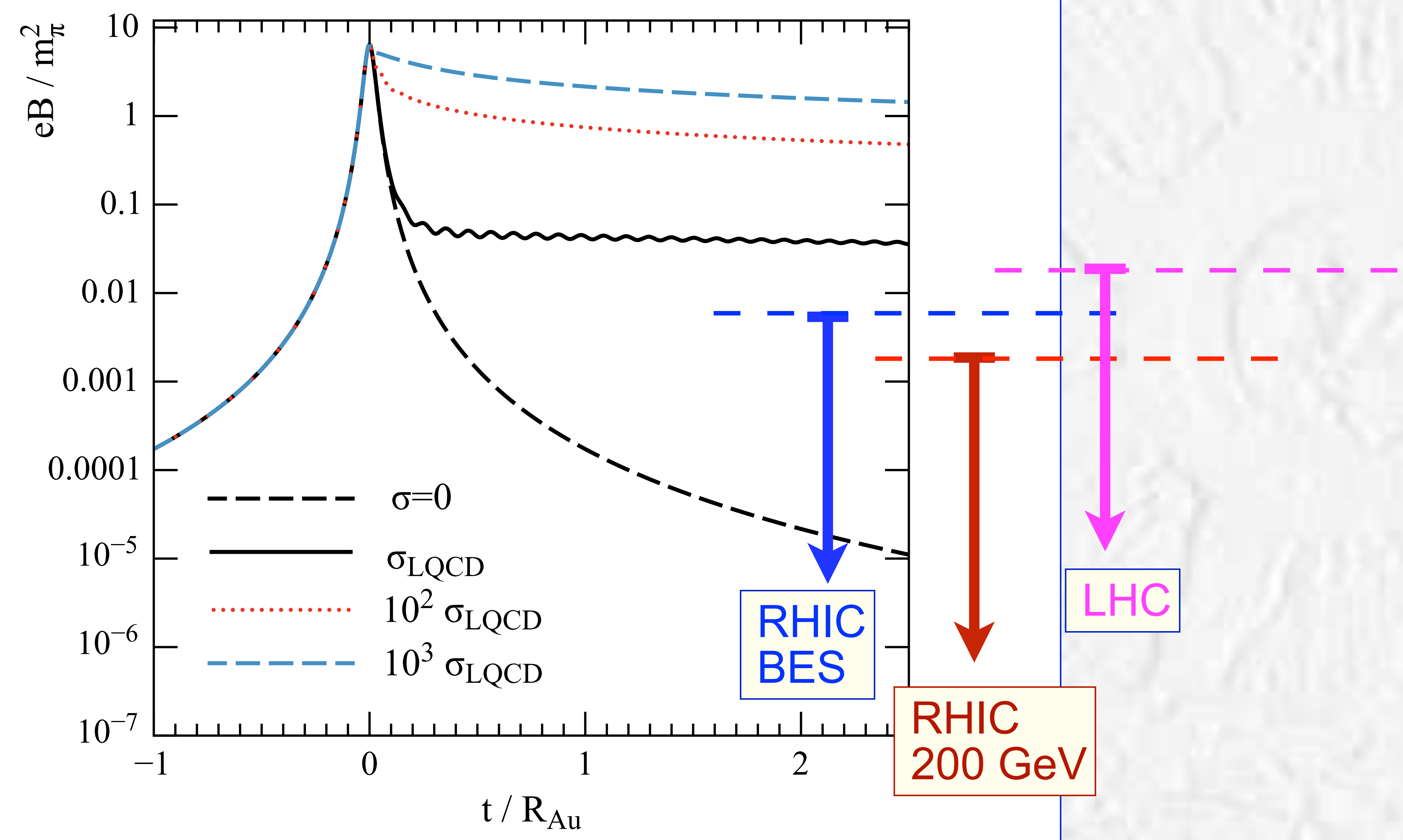
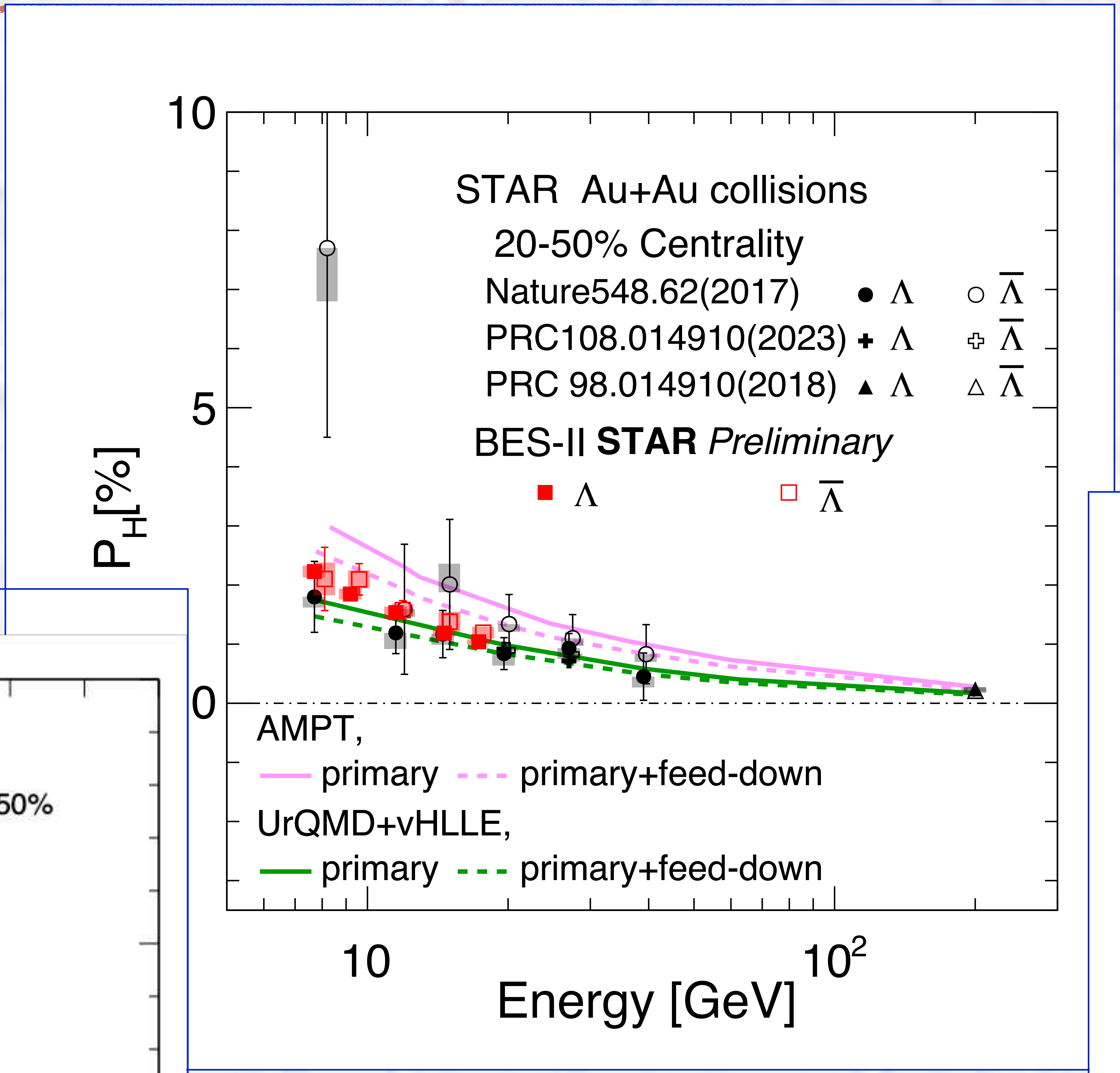
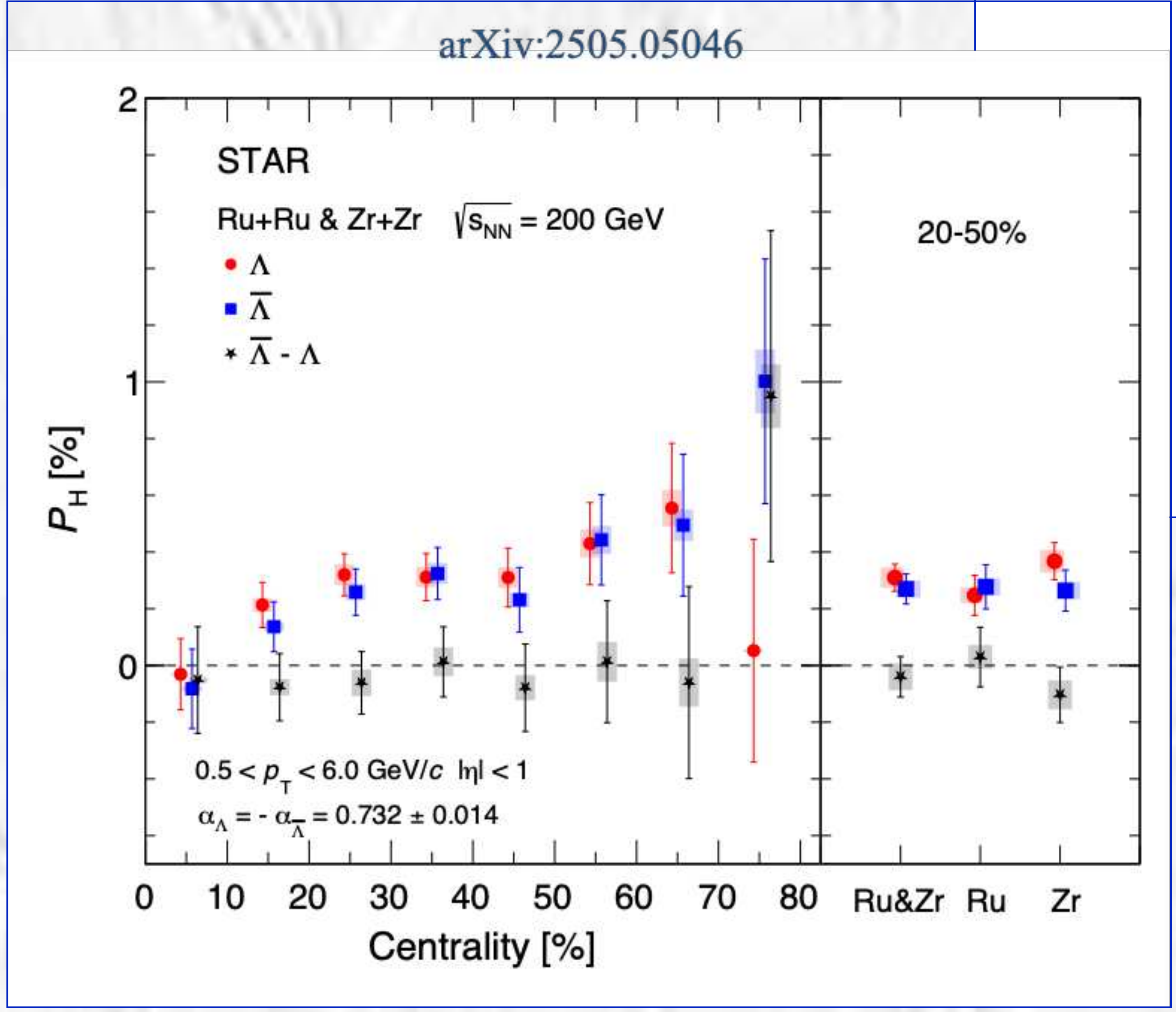


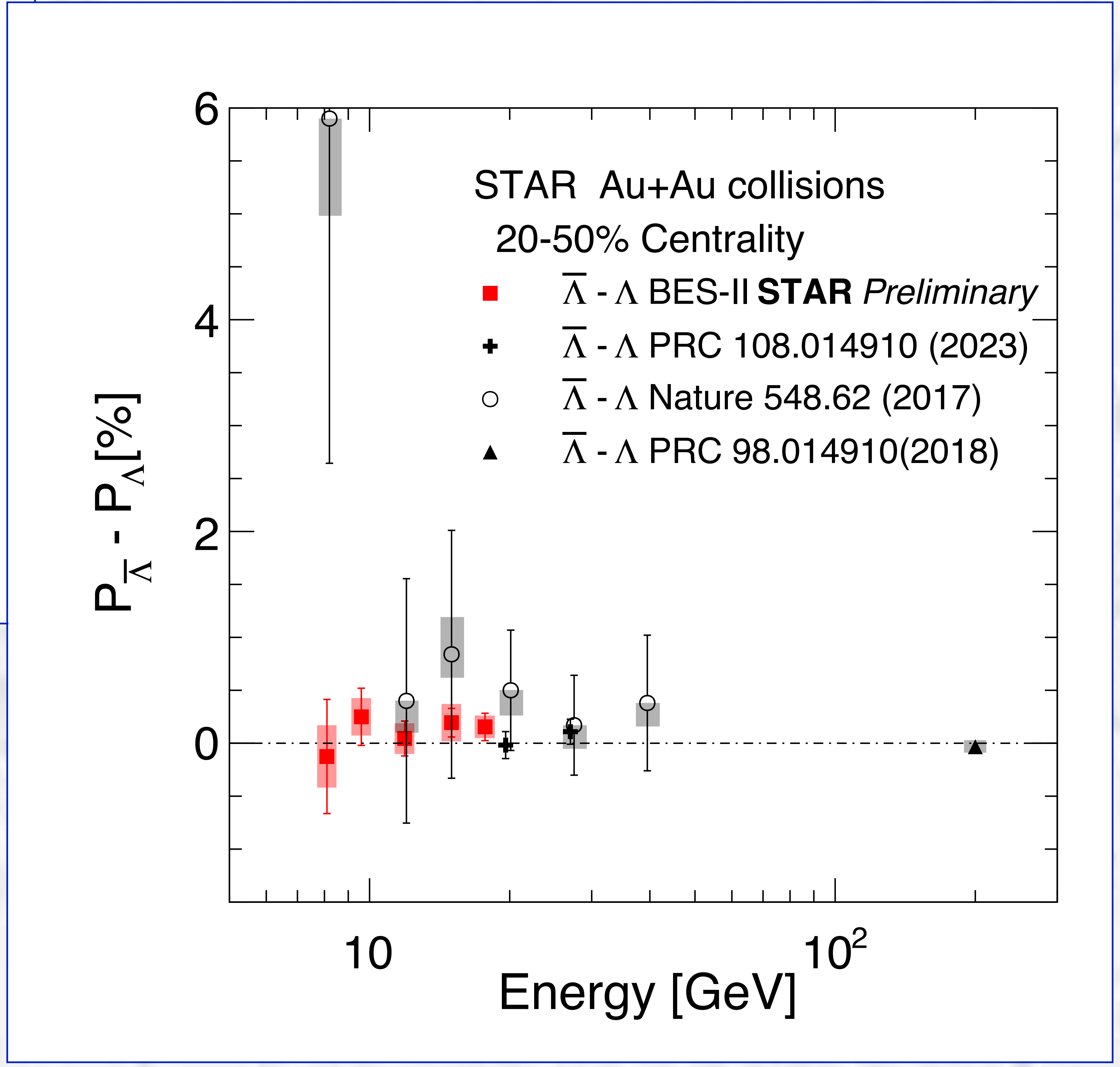
Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

Significant limits on the magnetic field at freeze-out (time ~ 10 - 15 fm?)

$P^{\Lambda} - P^{\bar{\Lambda}}$: isobars, BES II





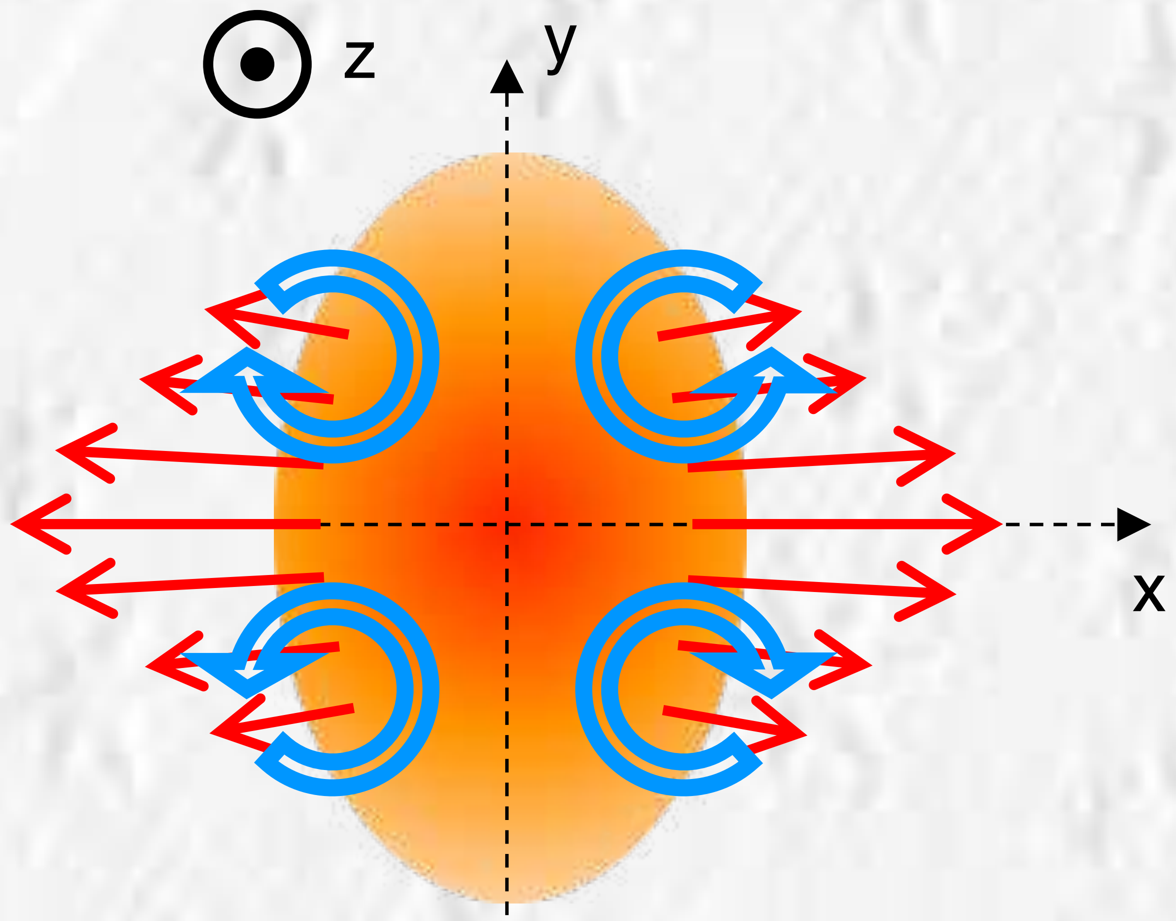


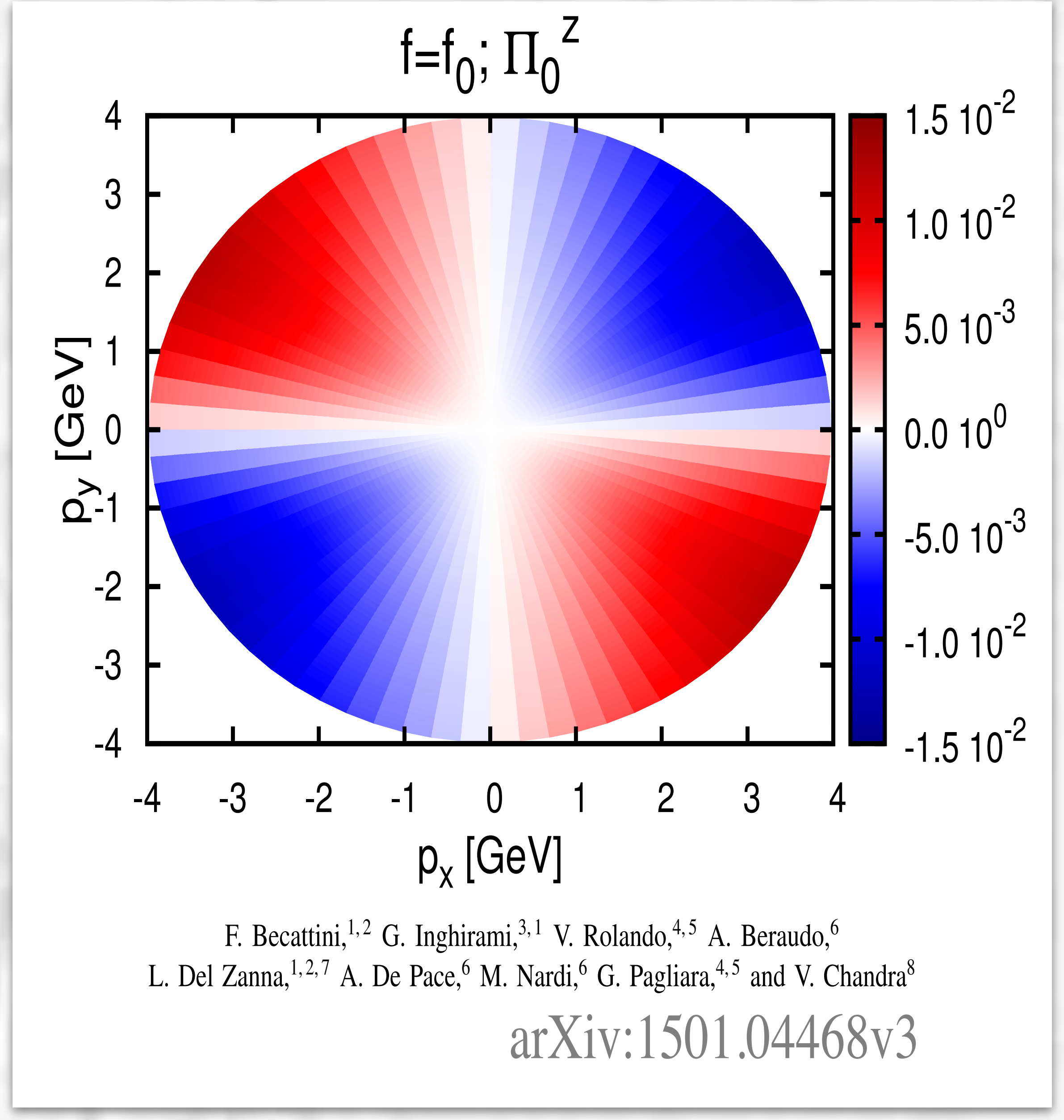
P_z

SQM2017

S. A. Voloshin, "Vorticity and particle polarization in heavy ion collisions (experimental perspective)", `arXiv:1710.08934 [nucl-ex]`. [EPJ Web Conf.17,10700(2018)].

Anisotropic flow $\Rightarrow \omega_z$

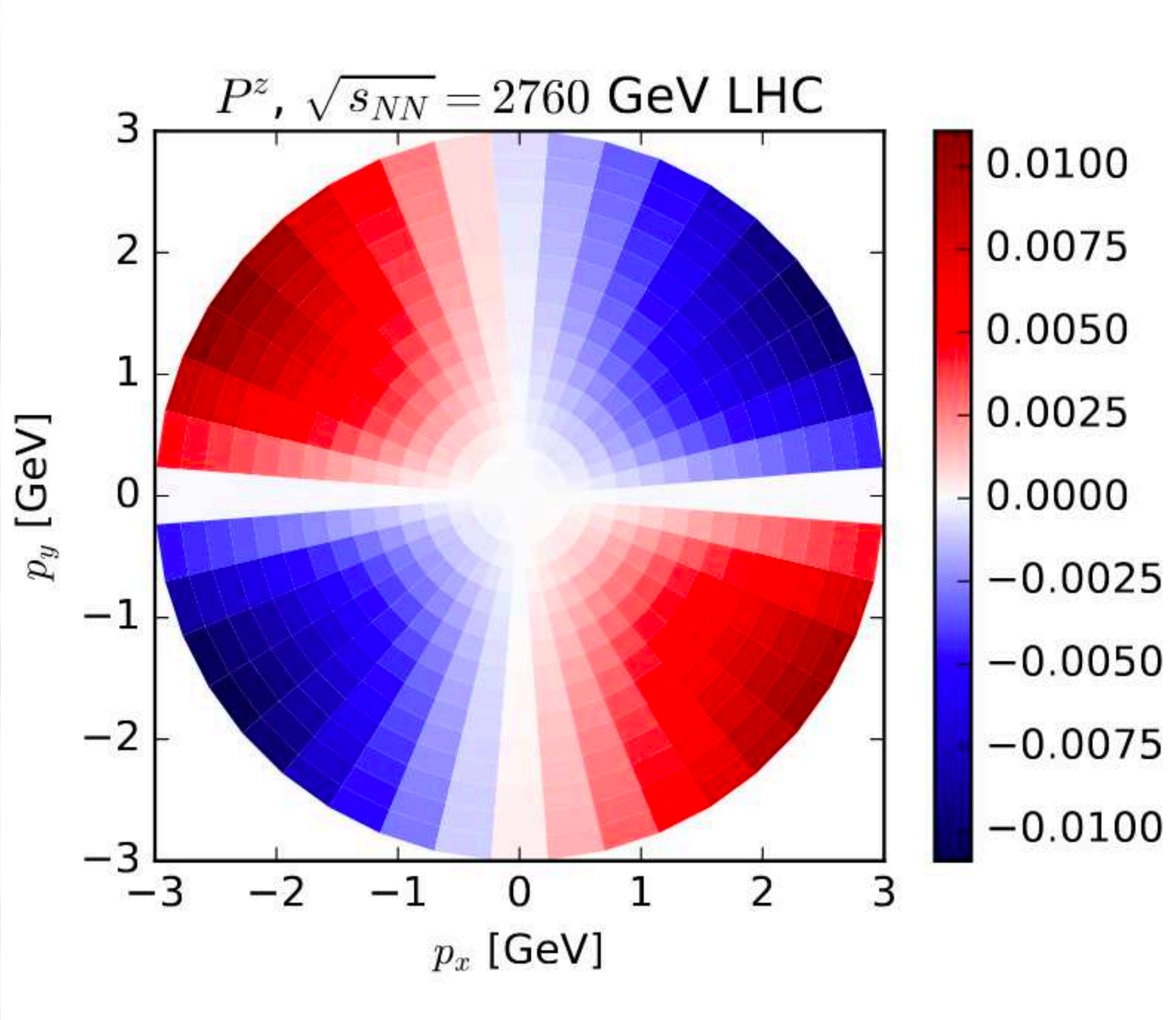




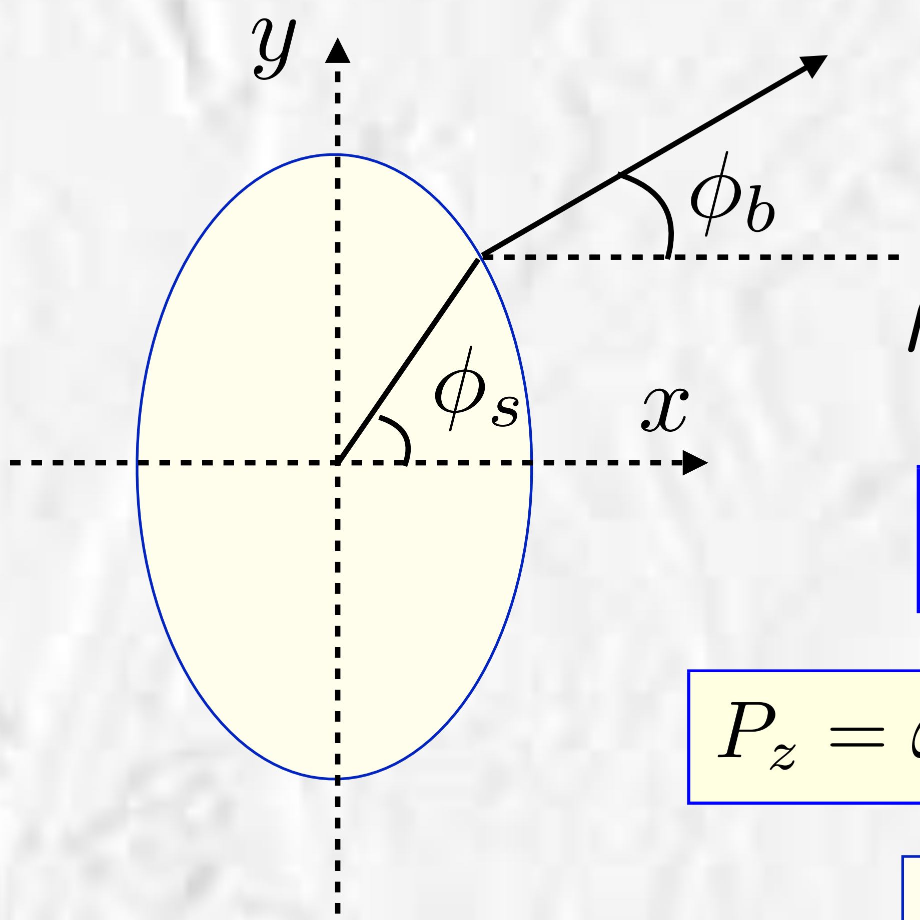
Plot not included in the orig. paper. Updated in 2018

Eur. Phys. J. C (2018) 78:354

F. Becattini and I. Karpenko, "Collective Longitudinal Polarization in Relativistic Heavy-Ion Collisions at Very High Energy", *Phys. Rev. Lett.* **120** no. 1, (2018) 012302, `arXiv:1707.07984`



Blast Wave:



$$r_{max} = R(1 - a\cos(2\phi_s))$$

$$\rho \approx \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s)]$$

$$\omega_z \approx (\rho_{t,max}/R)\sin(n\phi_s)[b_n - a_n]$$

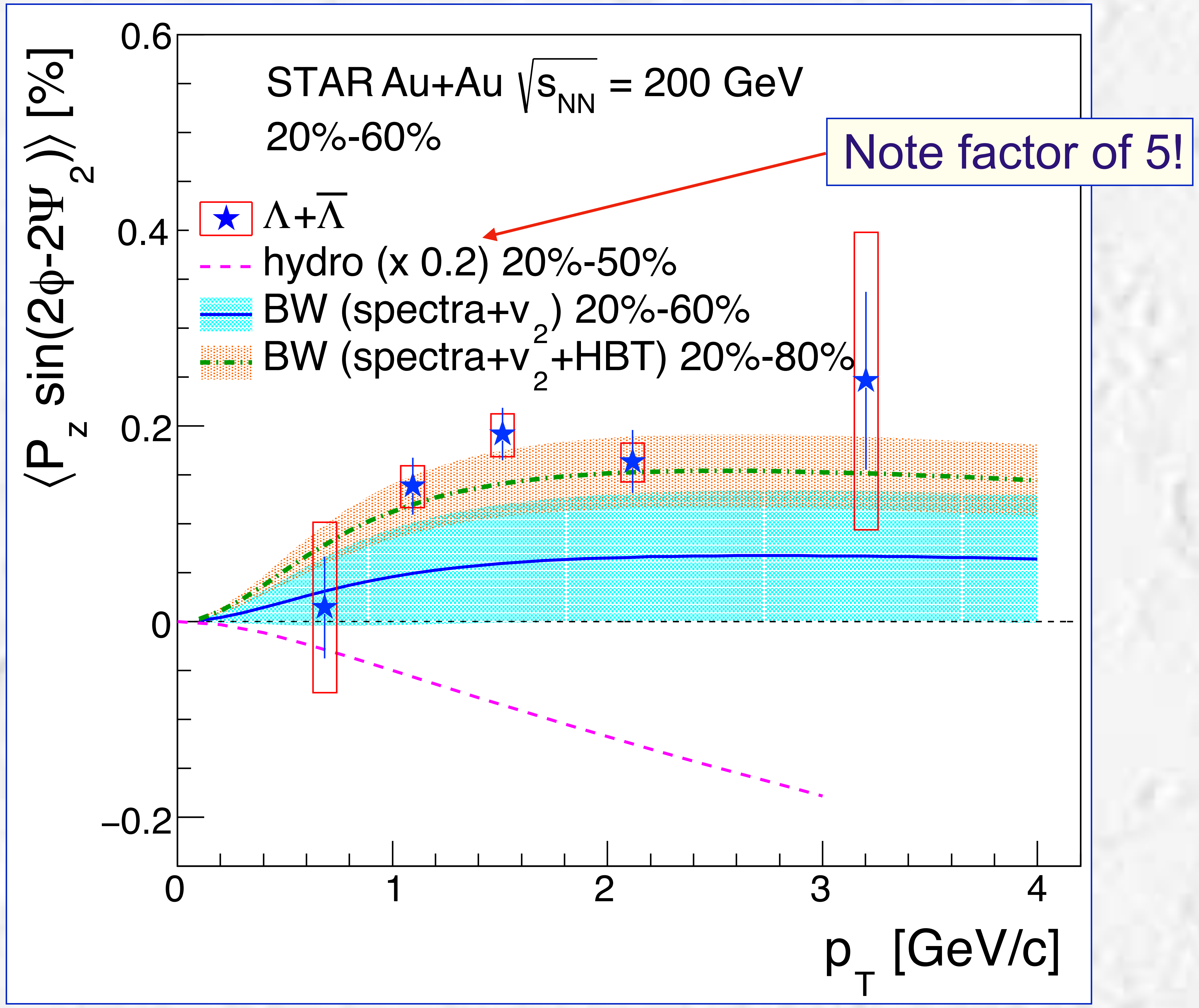
$$P_z = \omega_z/(2T) \approx 0.1\sin(n\phi_s)[b_n - a_n]$$

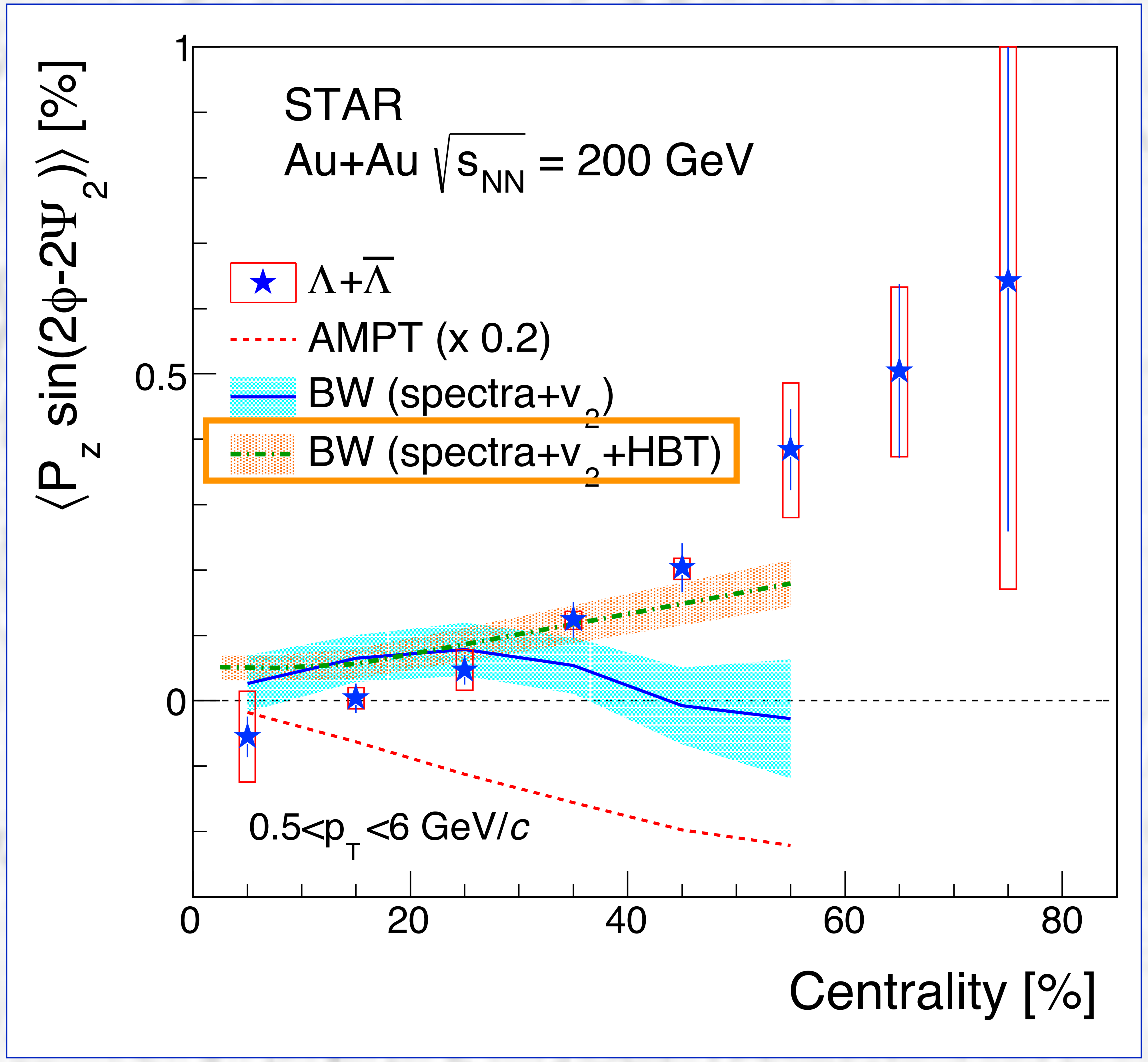
R≈10 fm, T≈100 MeV

$a_n,\ b_n$ of the order of a few percent

$\langle P_z \sin[2(\phi_H - \Psi_n)]\rangle$ centrality and p_T dependence

STAR Collaboration, J. Adam *et al.*, "Polarization of Λ ($\bar{\Lambda}$) hyperons along the beam direction in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **123** no. 13, (2019) , arXiv:1905.11917 [nucl-ex].





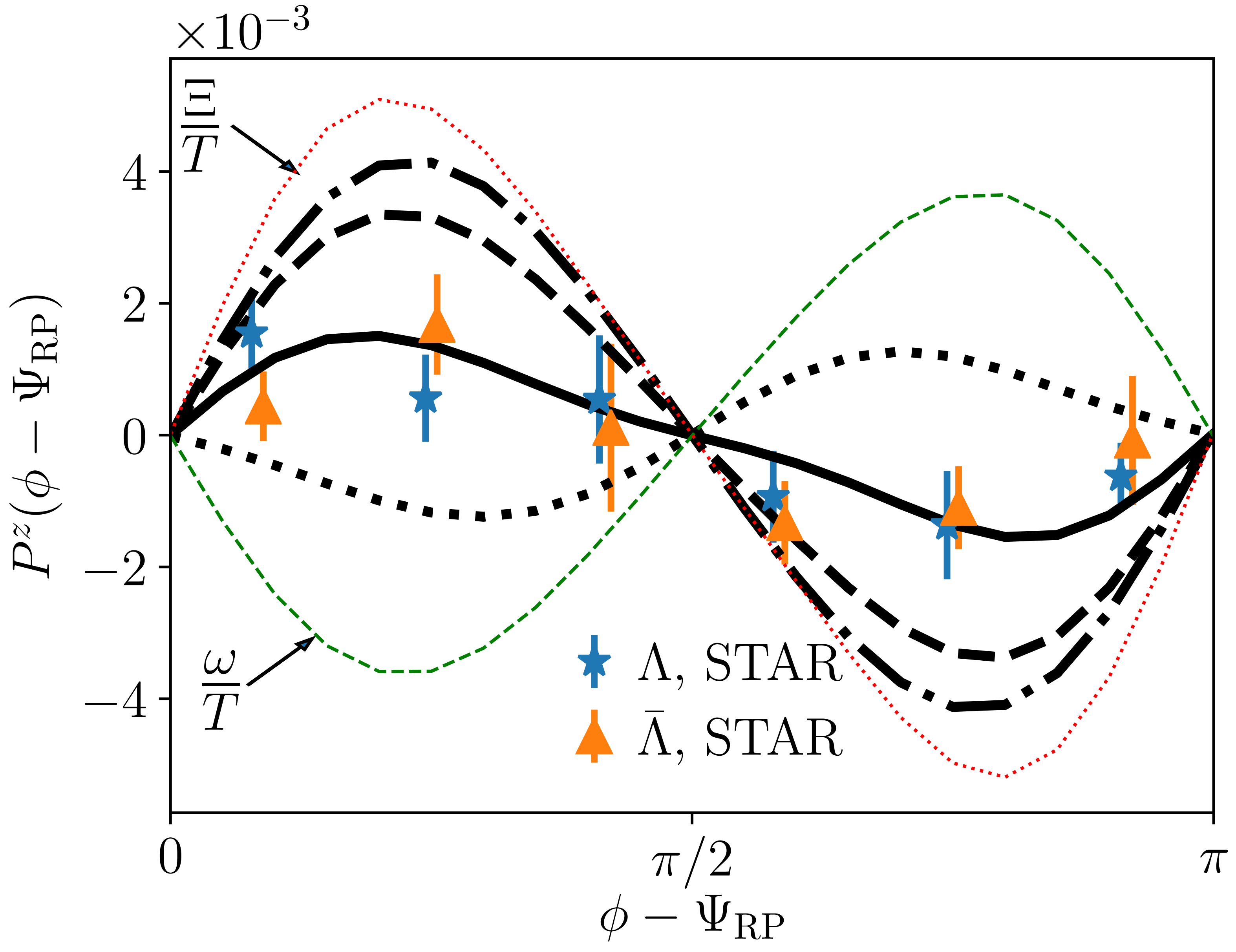
$$\langle \omega_z \sin(2\phi)\rangle = \frac{\int d\phi_s \int r dr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr\, I_0(\alpha_t) K_1(\beta_t)}$$

$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

BW parameters obtained with fits to spectra and HBT: STAR, PRC71.044906 (2005) !!!

Shear induced polarization (SIP)

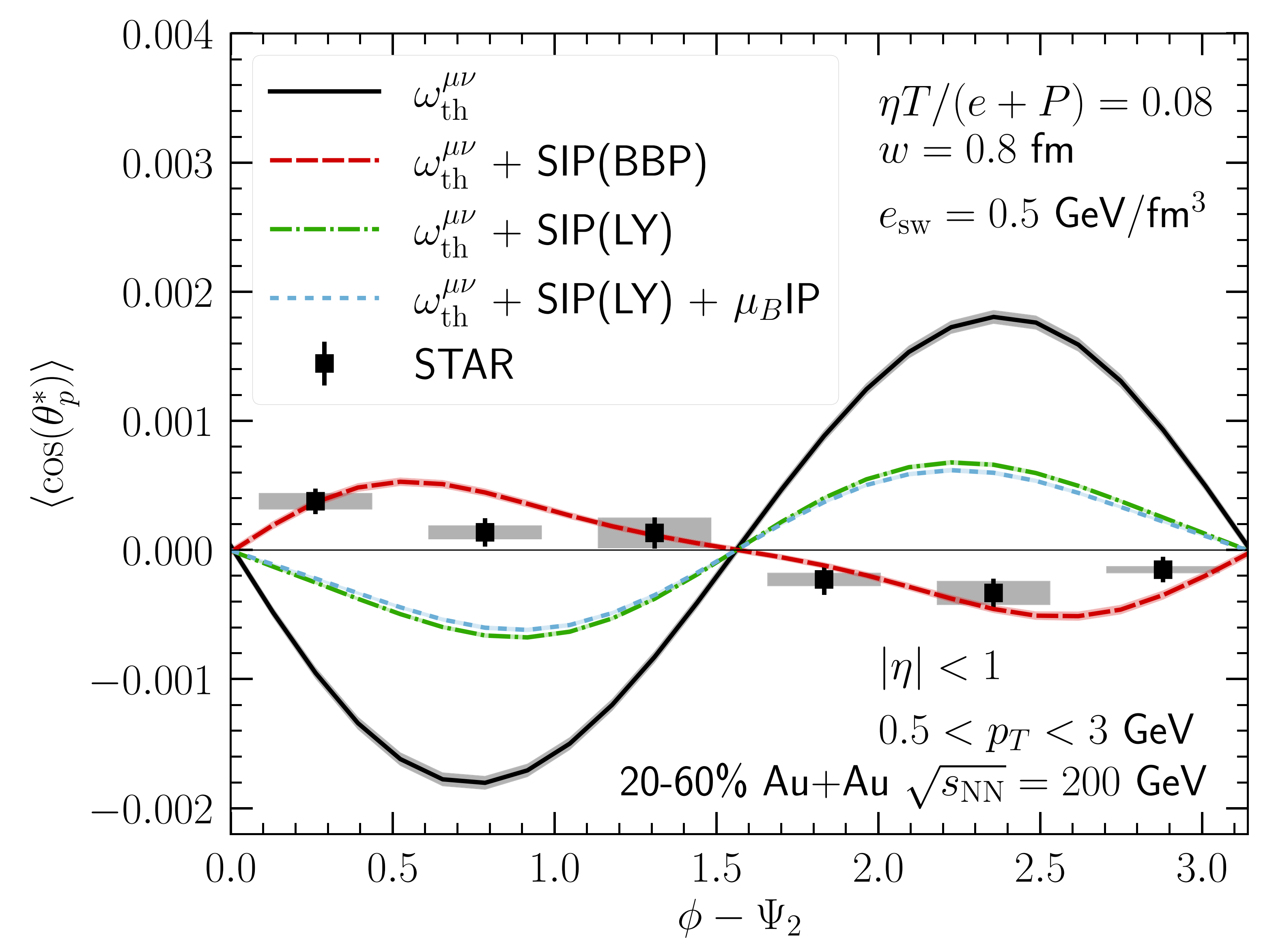
Neither sign nor magnitude of P_z could not be reproduced by models based on thermal vorticity - “spin sign puzzle”. SIP?



vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

S. Liu, Y. Yin, JHEP07(2021)188
B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PLB820(2021)136519
F. Becattini et al., PRL127, 272302 (2021)

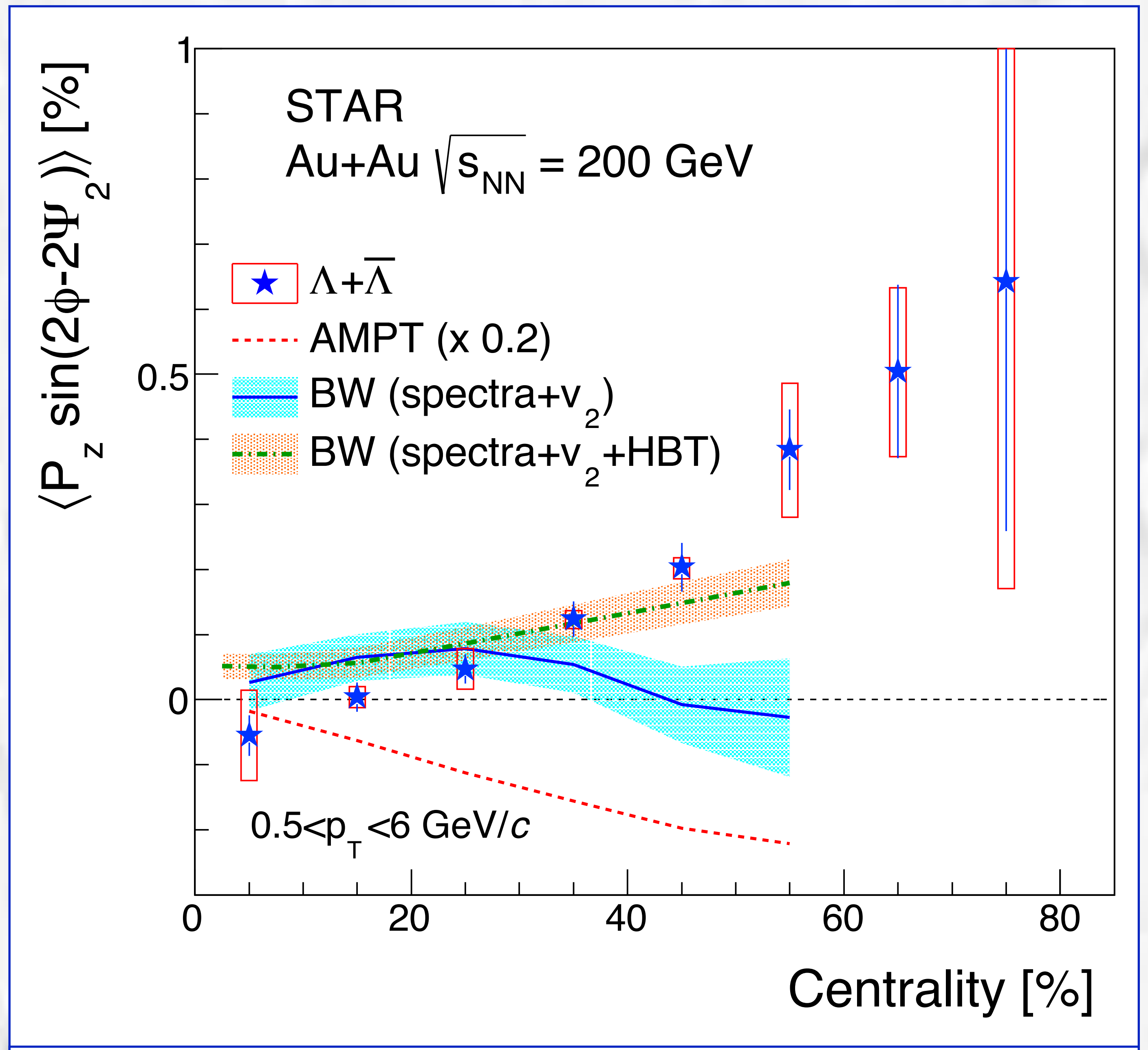


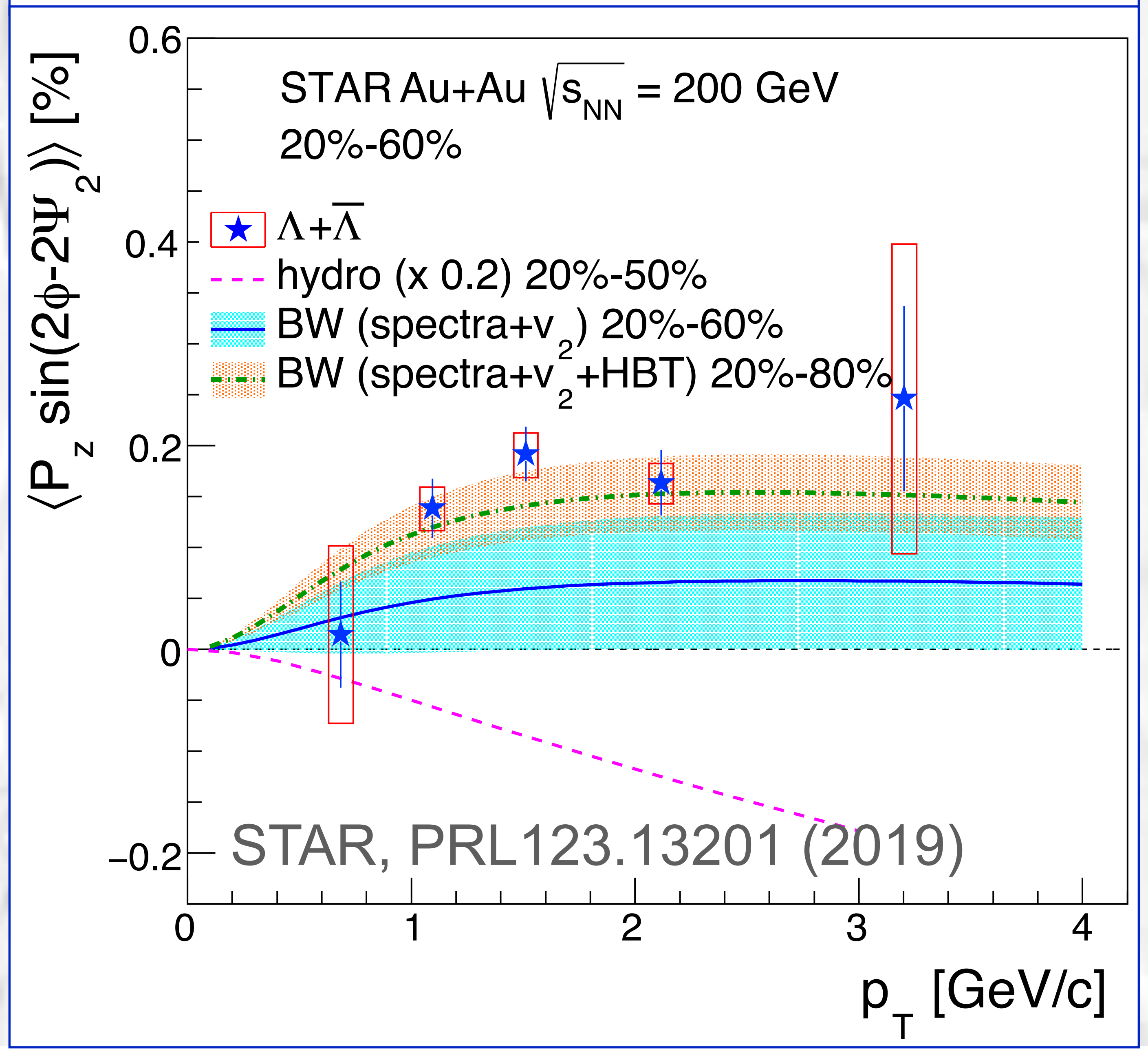
S. Alzhrani, S. Ryu, and C. Shen, “Λ spin polarization in event-by-event relativistic heavy-ion collisions”, *Phys. Rev. C* **106** no. 1, (2022) , arXiv:2203.15718 [nucl-th].

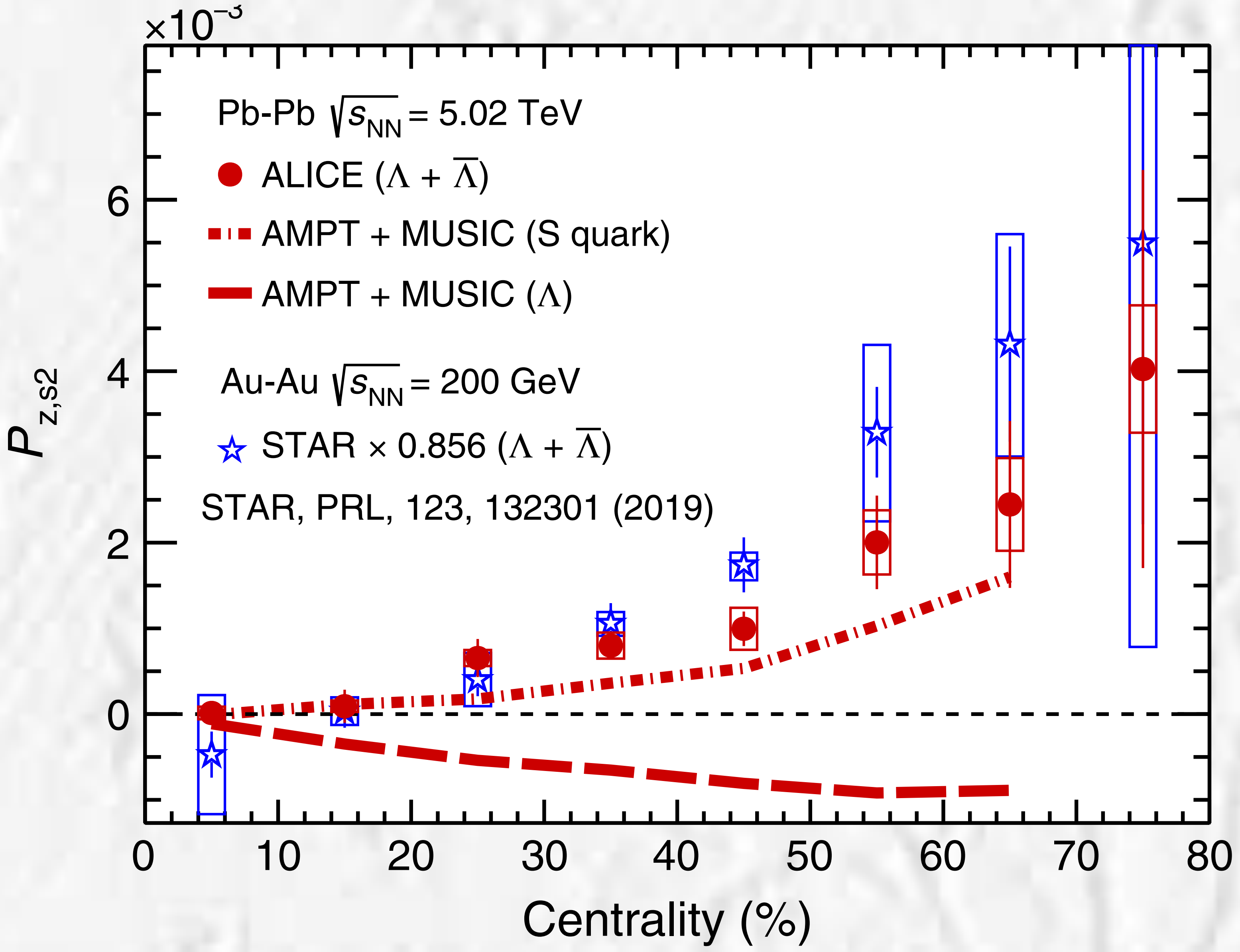
$$S_i^{\rm (shear)} \approx \frac{1}{4mTE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j v_m + \partial_m v_j)$$

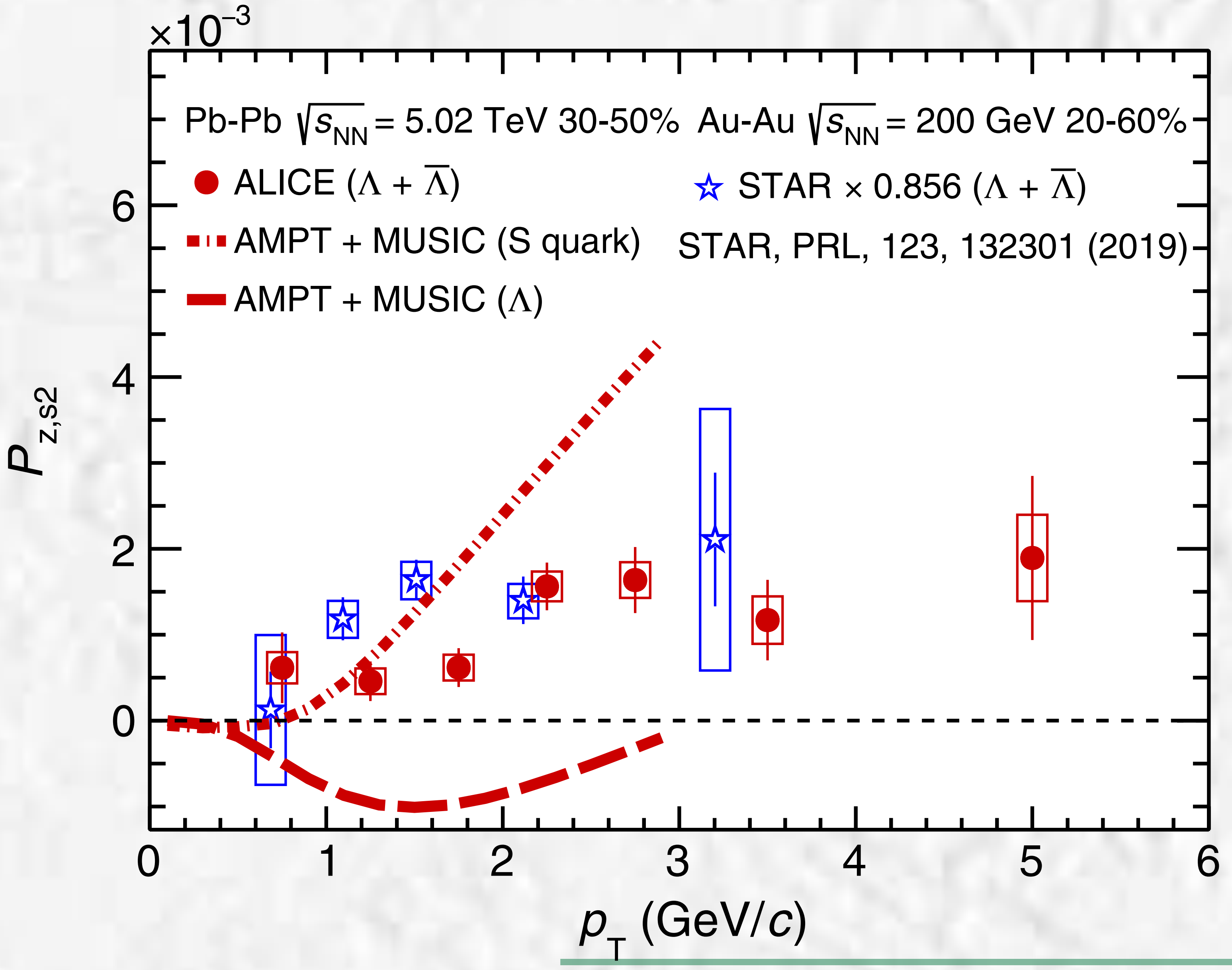
+ LHC measurements

ALICE Collaboration, S. Acharya *et al.*, "Polarization of Λ and $\overline{\Lambda}$ hyperons along the beam direction in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", arXiv:2107.11183









HYDRO, AMPT: It was noticed that the "kinematic non-relativistic vorticity" fits data well, but is (much) smaller than that including contributions from acceleration and temperature gradients

- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- X. Xia et al., PRC98.024905 (2018)
- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Y. Xie, D. Wang, and L. P. Csernai, Eur. Phys. J. C (2020) 80:39
- W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)
- H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)

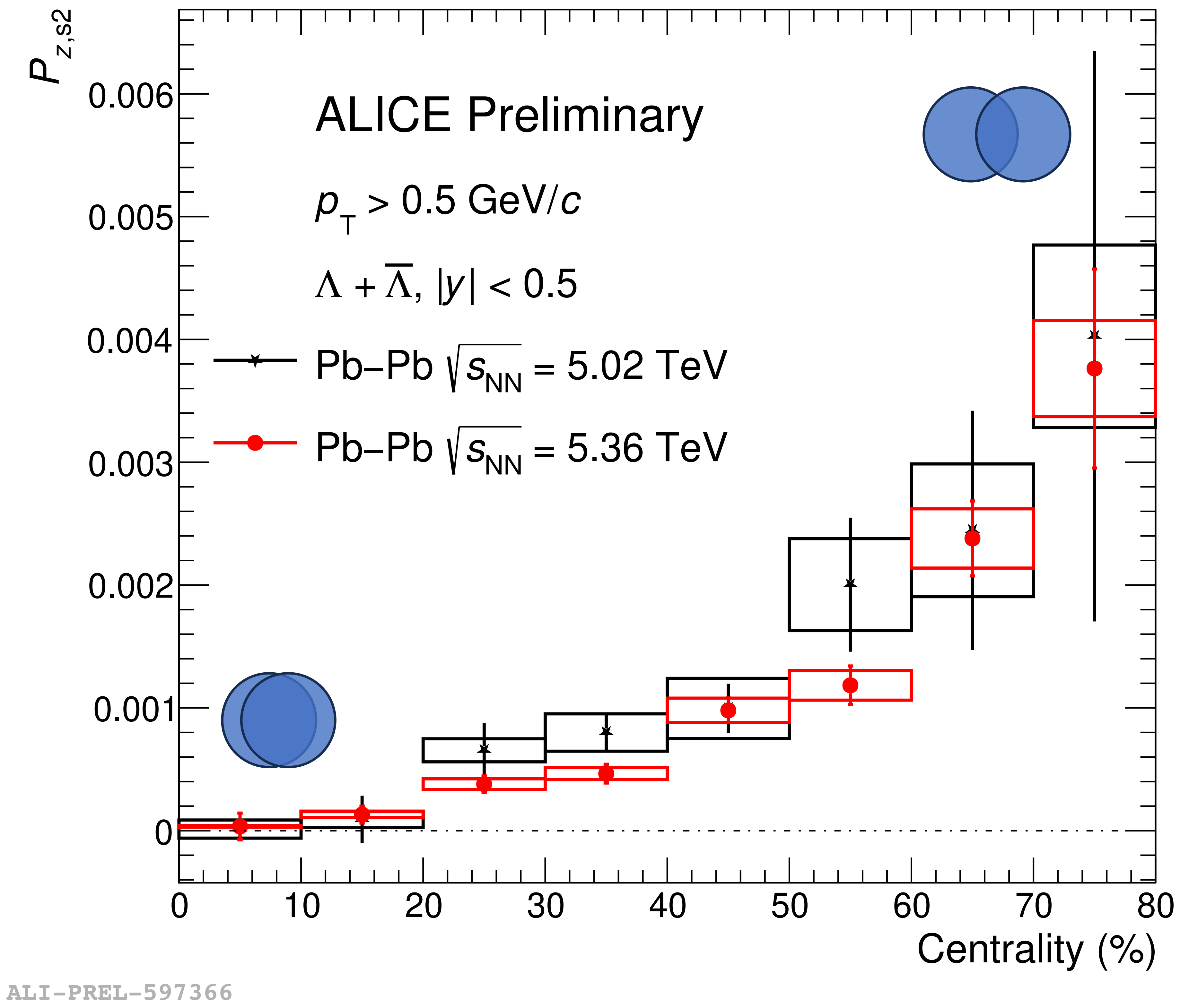
shear induced polarization?

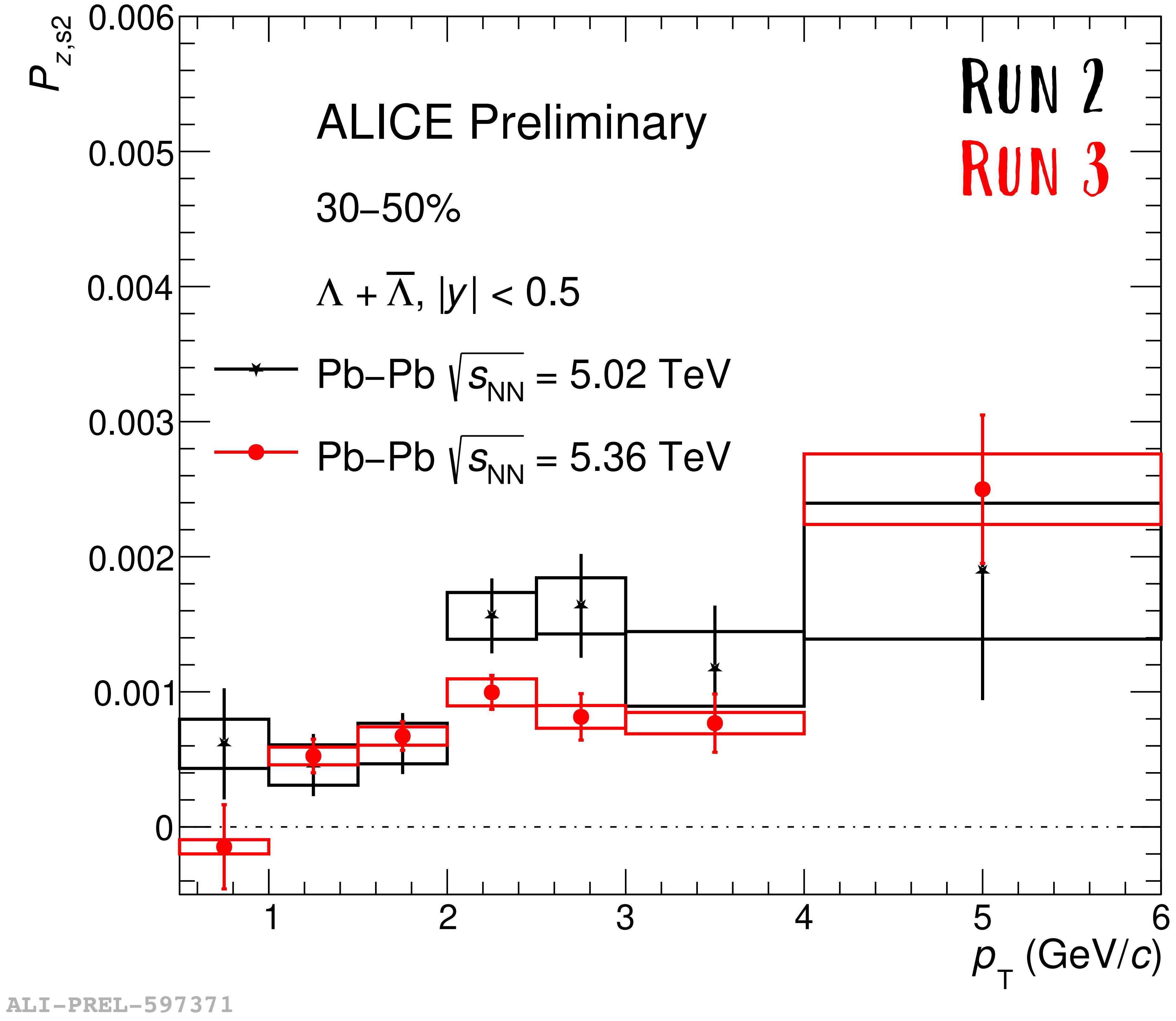
$$P_{z,s2} \equiv \langle P_z \sin[2(\phi_H - \Psi_n)] \rangle$$

ALICE (Run 3)

$P_{z,s2} \equiv \langle P_z \sin[2(\phi_H - \Psi_n)] \rangle$

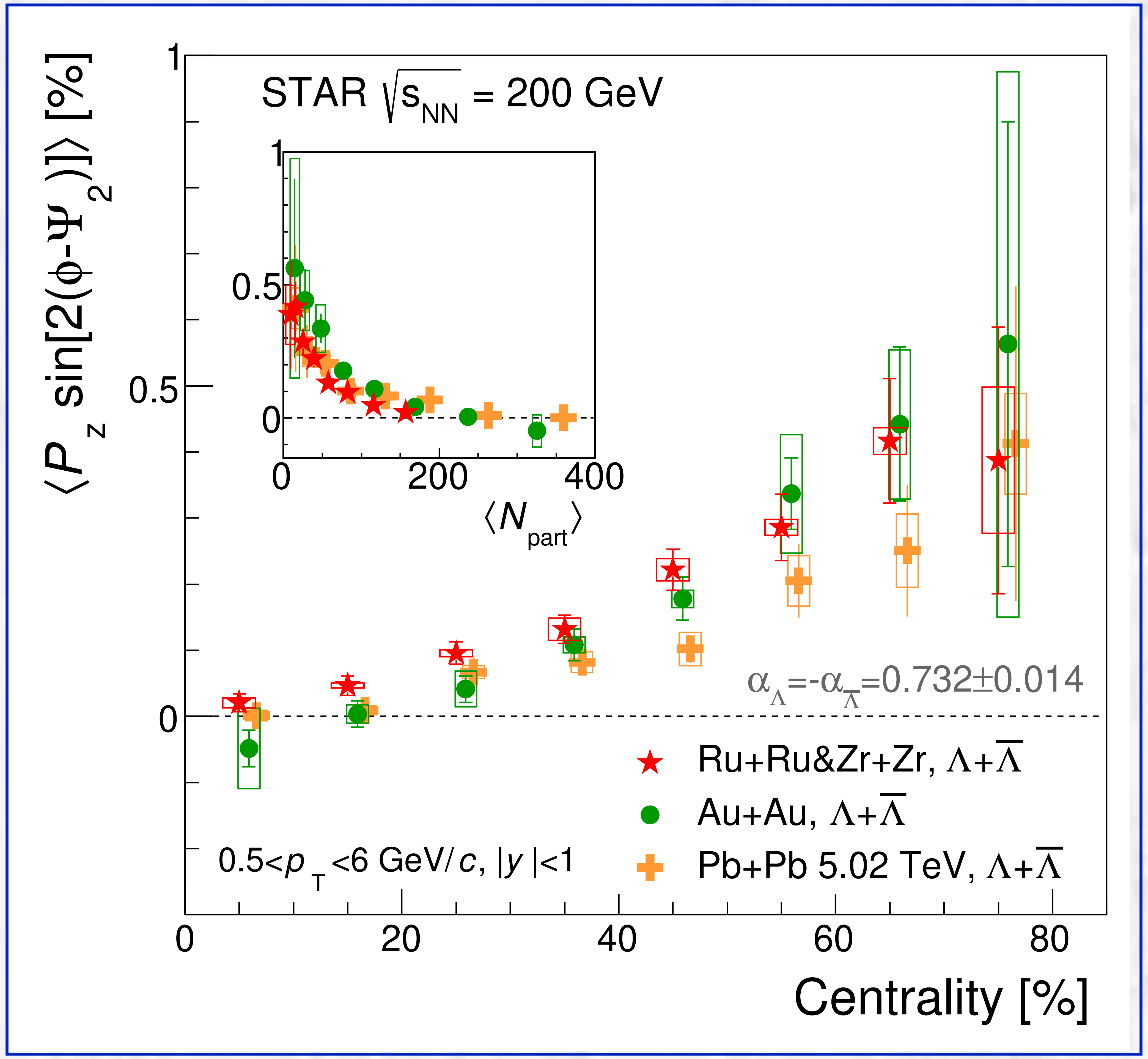
NEW!

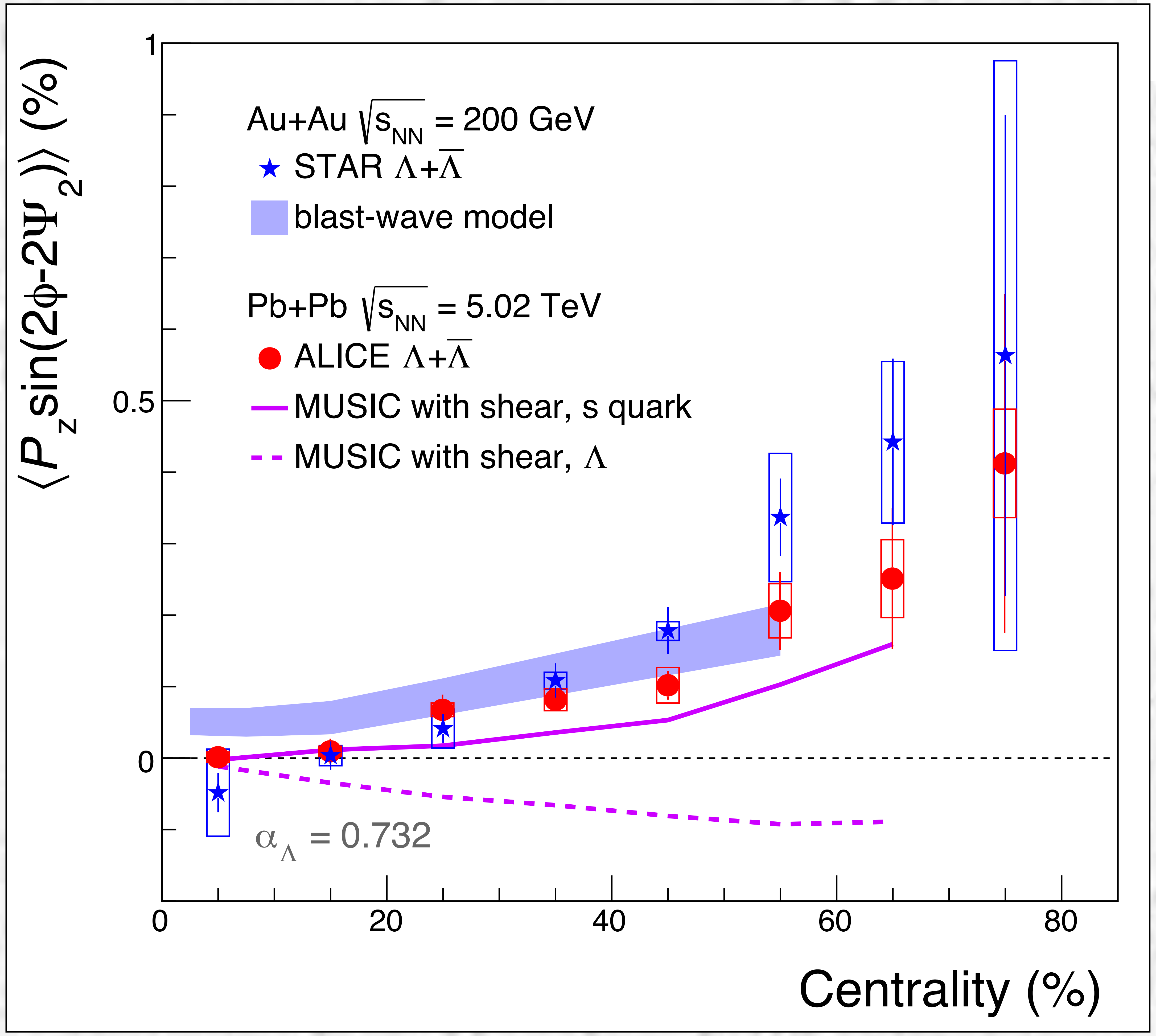


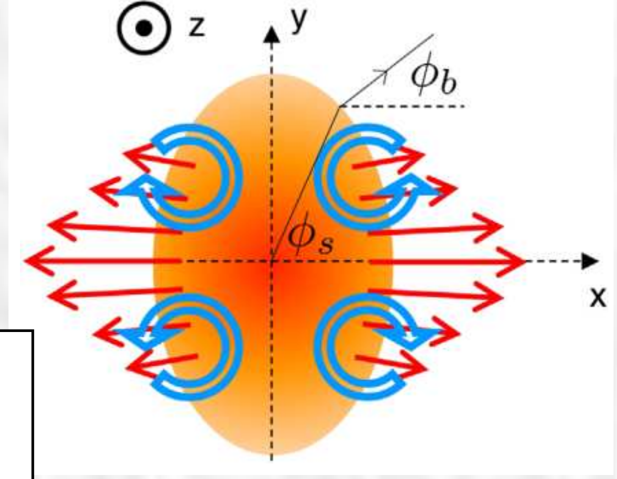


- $P_{z,s2}$ **increases with decreasing centrality** due to increasing system anisotropy, and mildly increases with increasing p_T
- **Run 3 results** are compatible with Run 2 ones and have **smaller statistical and systematic** uncertainties, thanks to the x20 size of the data sample ($\sim 6 \times 10^9$ collisions)

$\langle P_z \sin[2(\phi_H - \Psi_n)]\rangle$ Centrality, size dependence







$$r_{max} = R(1 - a\cos(2\phi_s))$$

$$\rho \approx \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s)]$$

$$\omega_z \approx (\rho_{t,max}/R)\sin(n\phi_s)[b_n - a_n]$$

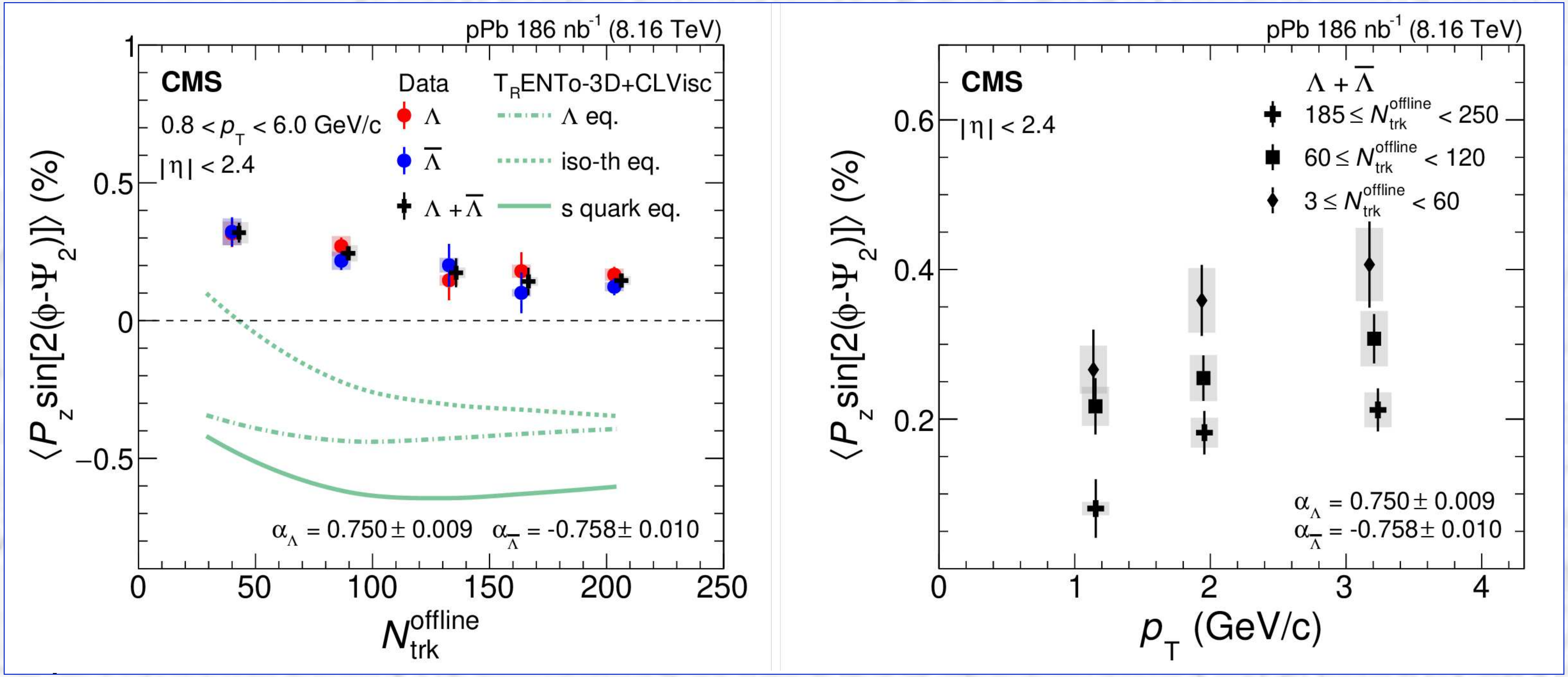
p-Pb

Available on the CERN CDS information server — CMS PAS HIN-24-002

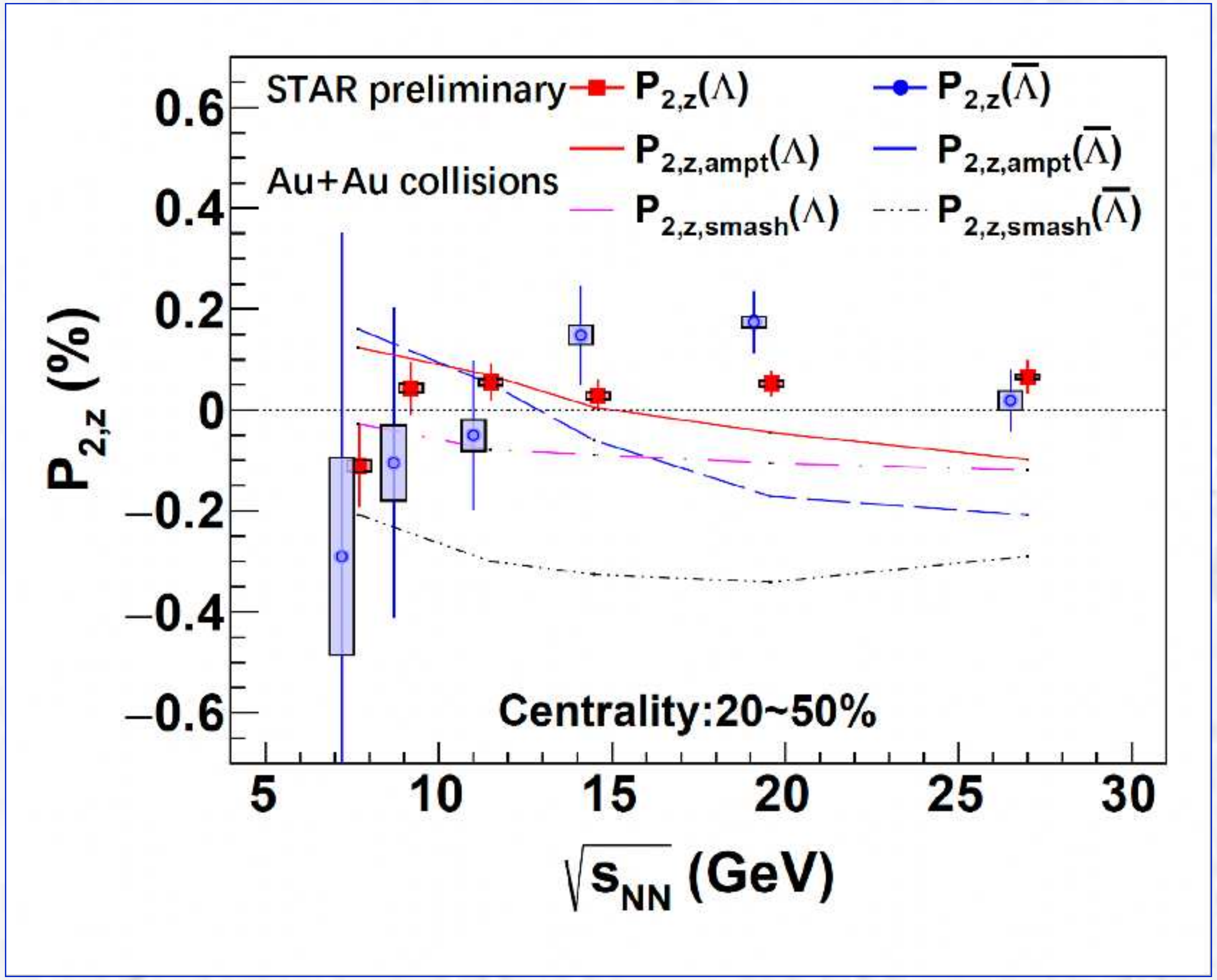
CMS Physics Analysis Summary

Contact: cms-pag-conveners-heavyions@cern.ch — 2024/06/02

Azimuthal dependence of hyperon polarization along the beam direction in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

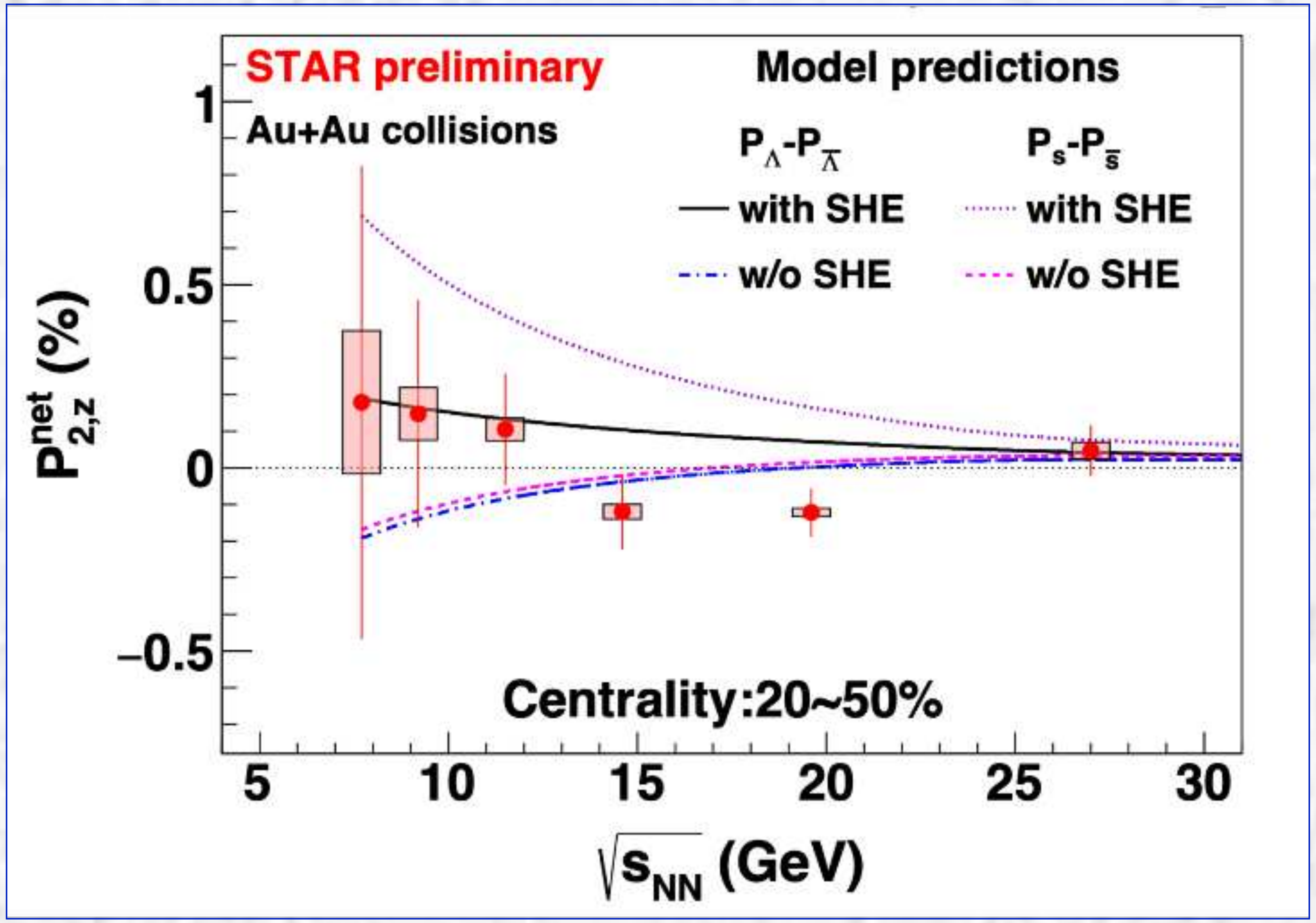


BES II: P_z



Spin Hall effect:

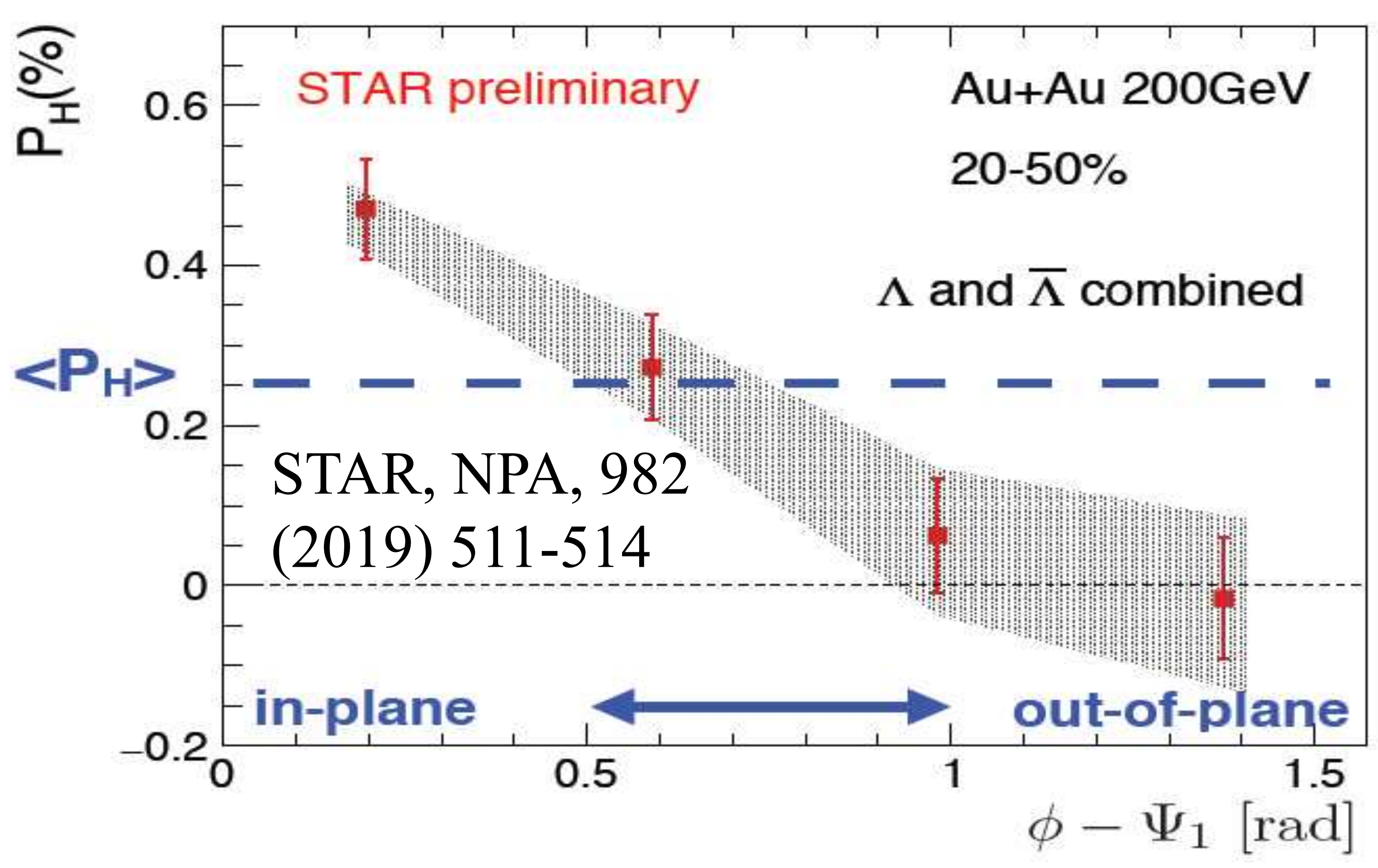
$$S_i^{(\mathrm{SHE})} \approx \frac{1}{4mE}\epsilon_{ikj}p_k\partial_j(\mu/T).$$

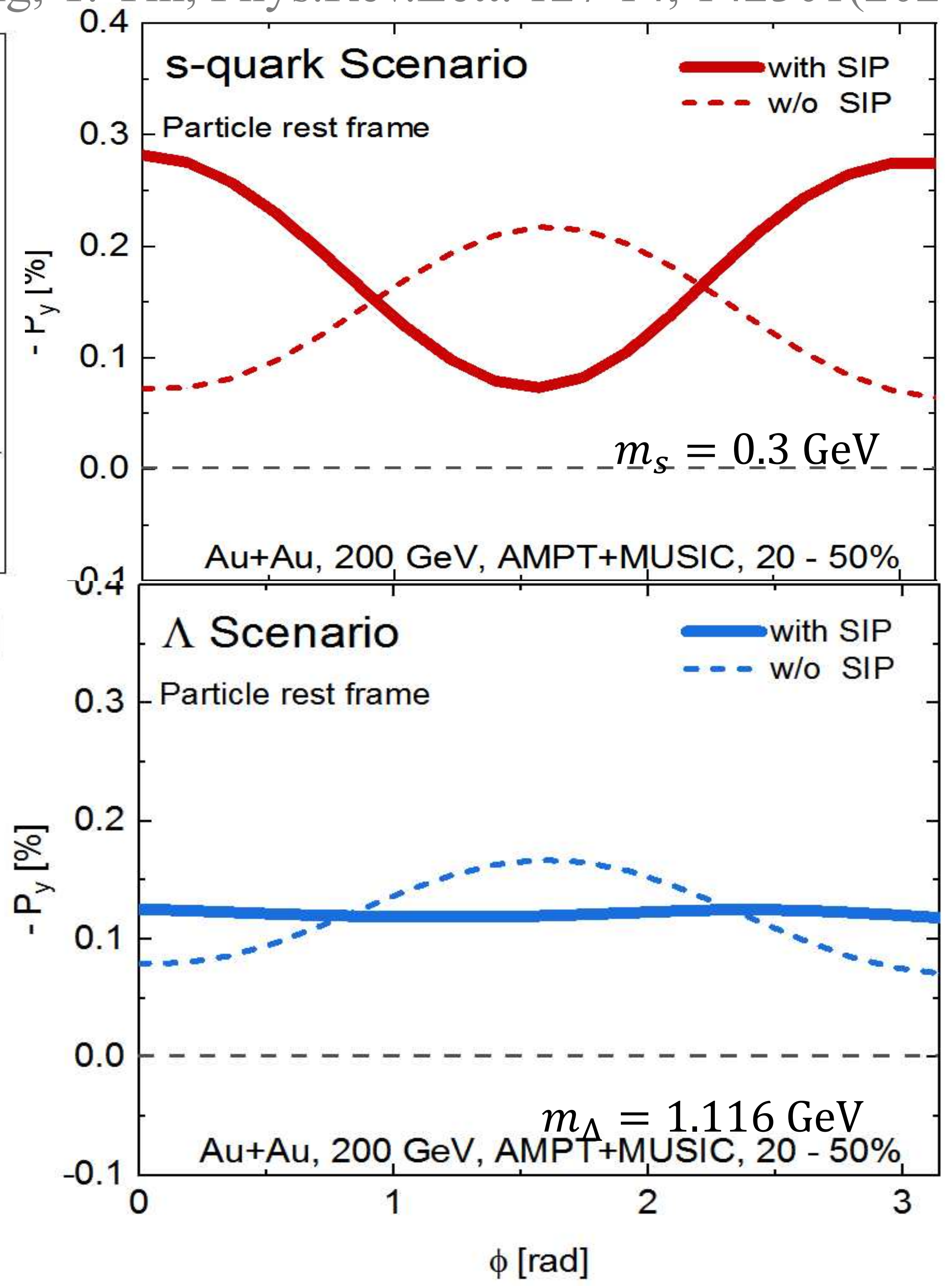


$P_y(\phi)$ SIP vs simple estimates

Compare with exp data: $P_y(\phi)$ with & without SIP

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021)



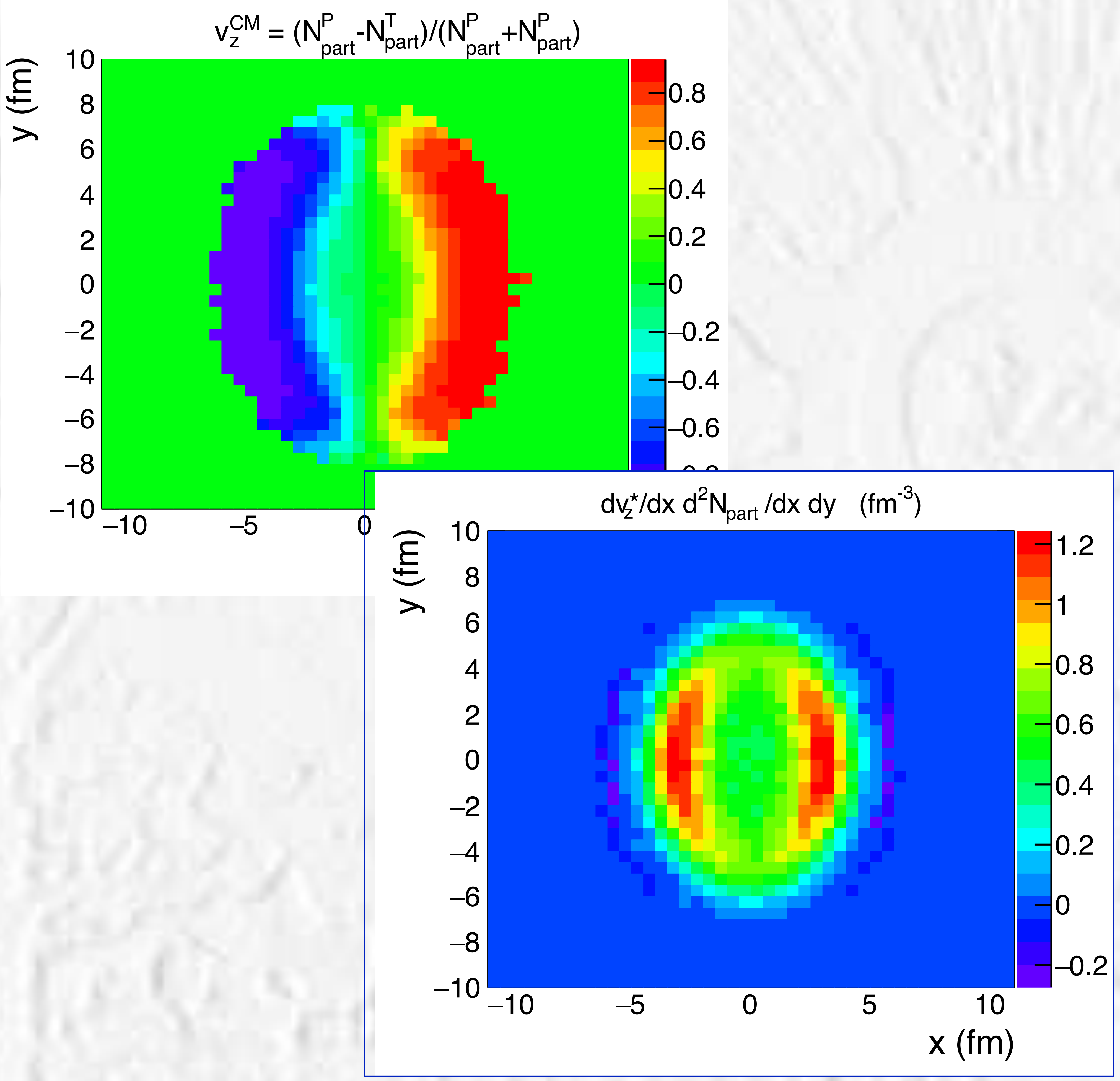


Total P^μ
=Thermal vorticity + Shear effects

-In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

$$S_i^{(\mathrm{shear})} \approx \frac{1}{4mTE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j v_m + \partial_m v_j)$$

Vorticity



It is not clear why hydro without SIP predicts larger polarization "out-of-plane" — which is at odds with expectation from the right plot

Vorticity

PHYSICAL REVIEW C **76**, 044901 (2007)

Polarization probes of vorticity in heavy ion collisions

Barbara Betz,[1,2] Miklos Gyulassy,[1,3,4] and Giorgio Torrieri[1,3]

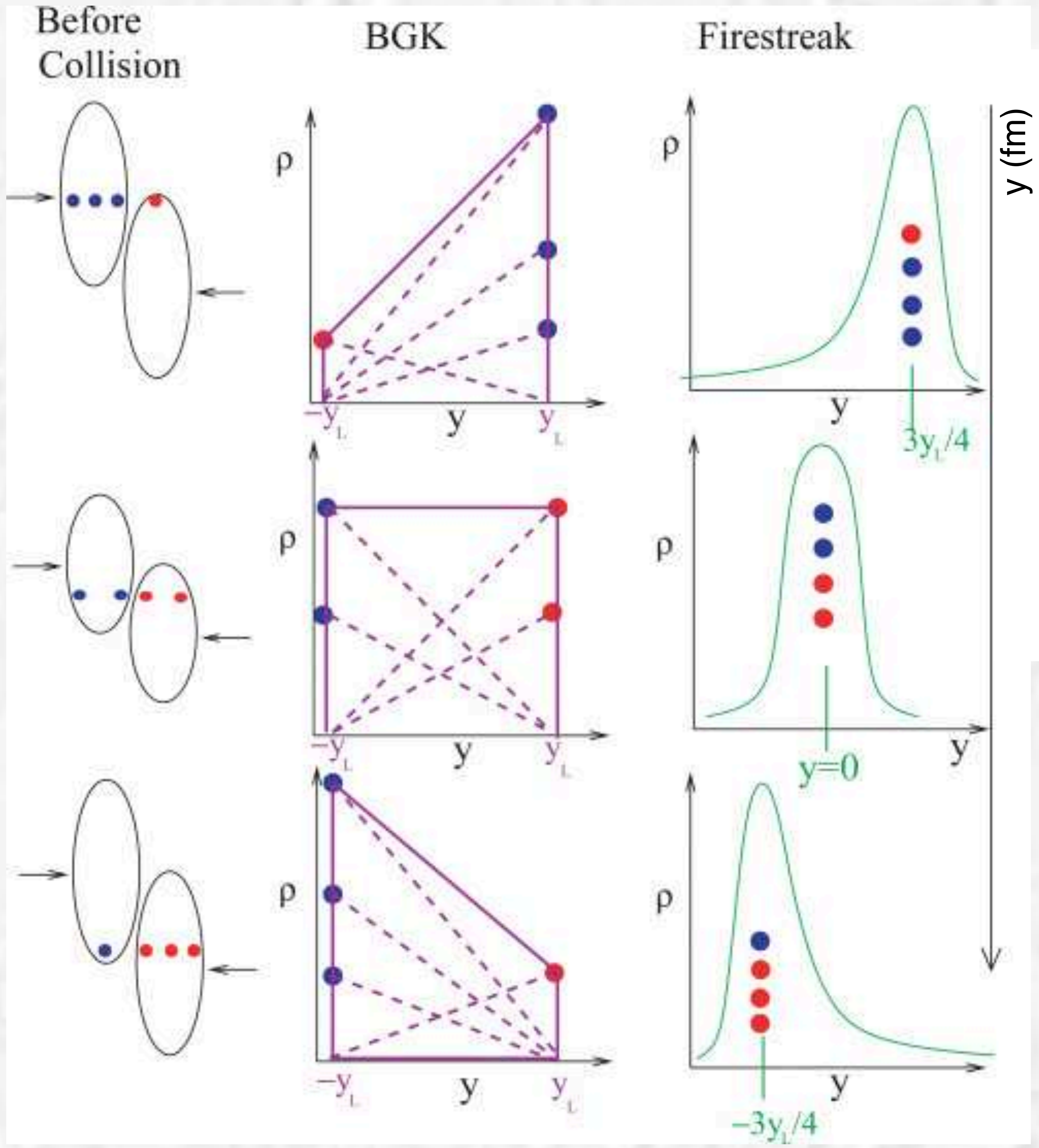
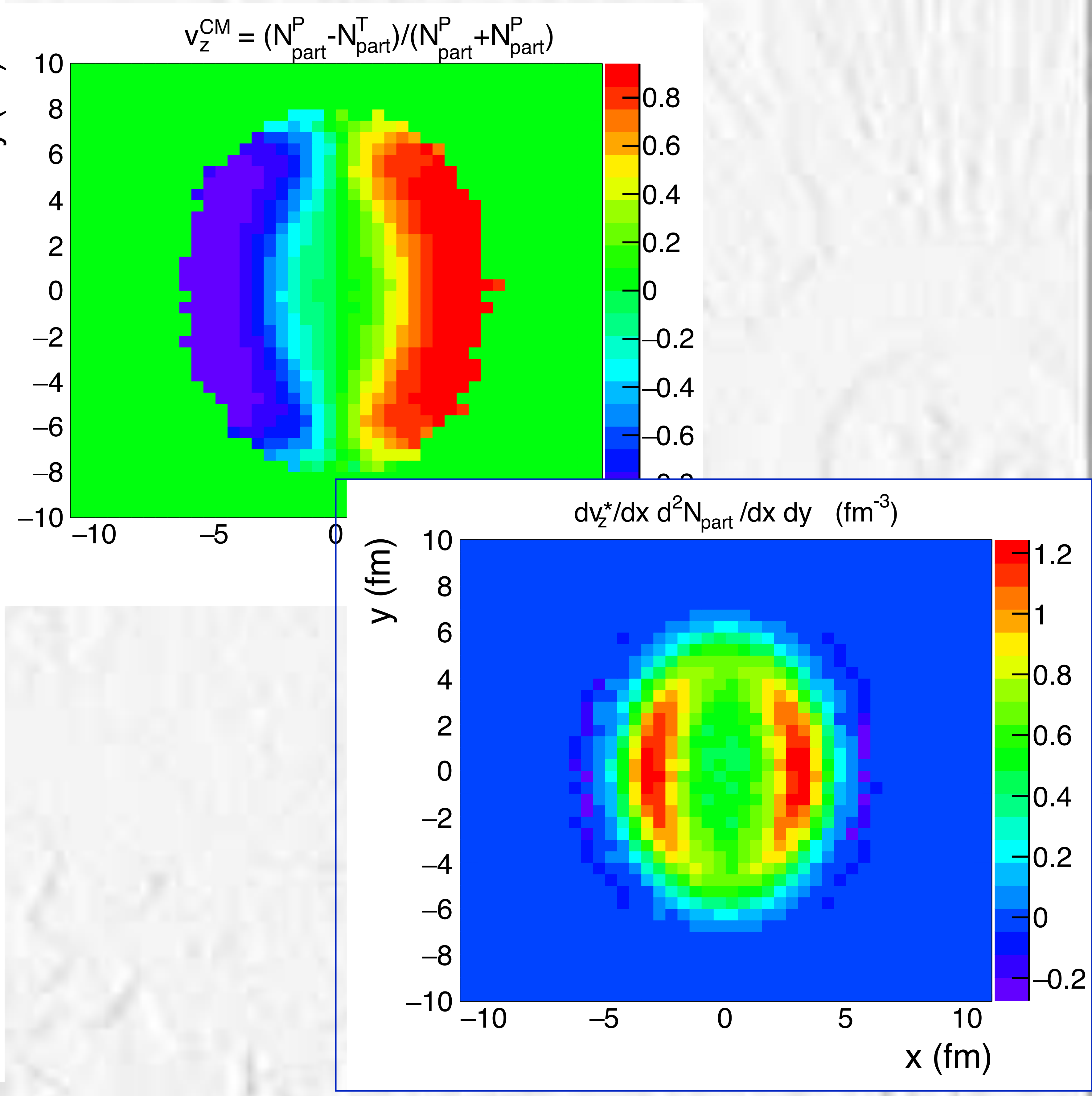


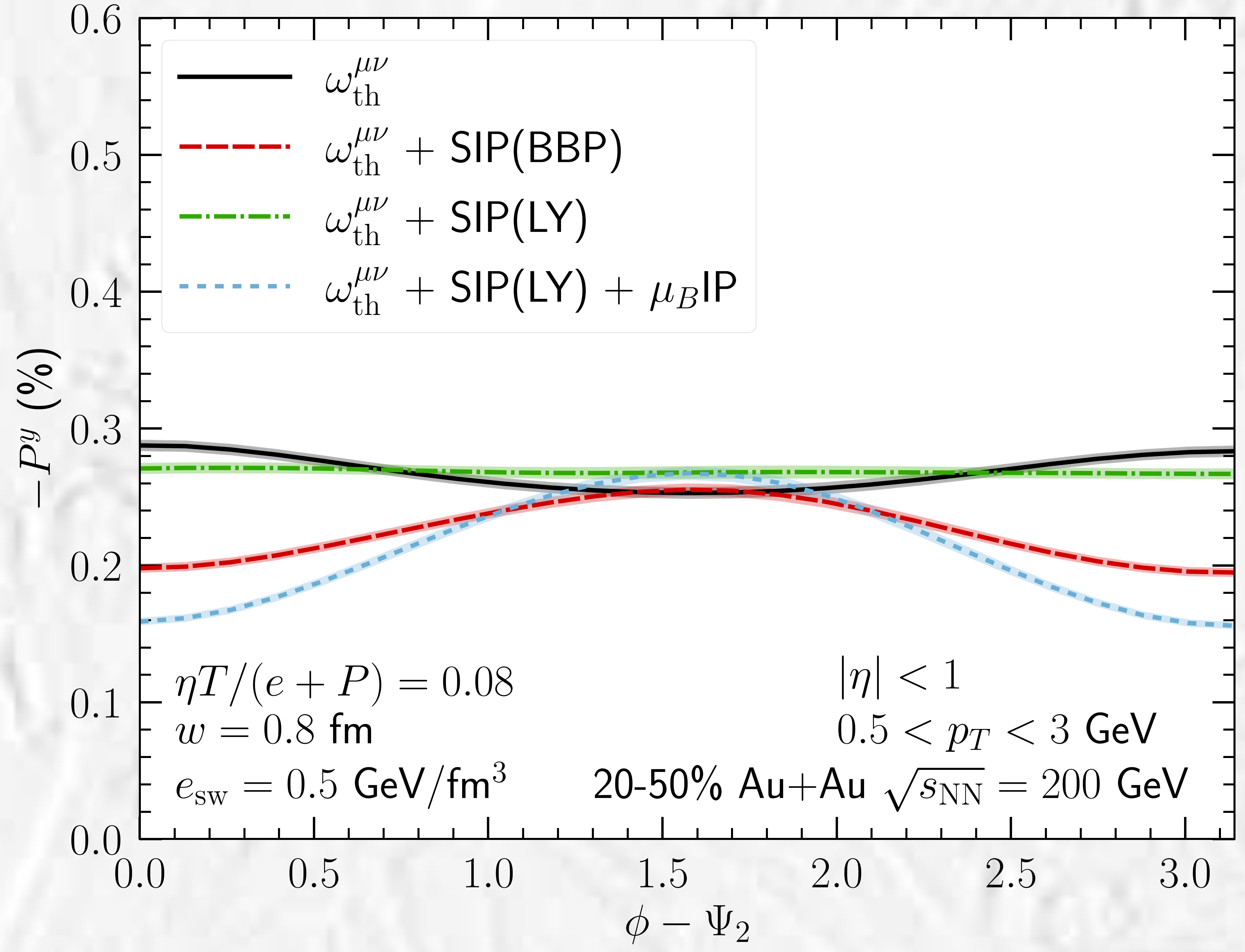
FIG. 2. (Color online) Initial densities in the BGK model (left
as well as the model used in Ref. [7] (right). In the BGK case, dashe
lines represent the rapidity extent of the "excited state" produced b
the individual nucleon, while solid lines correspond to the cumulativ
density. See text for model definitions and further explanation.



P_y : SIP vs vorticity

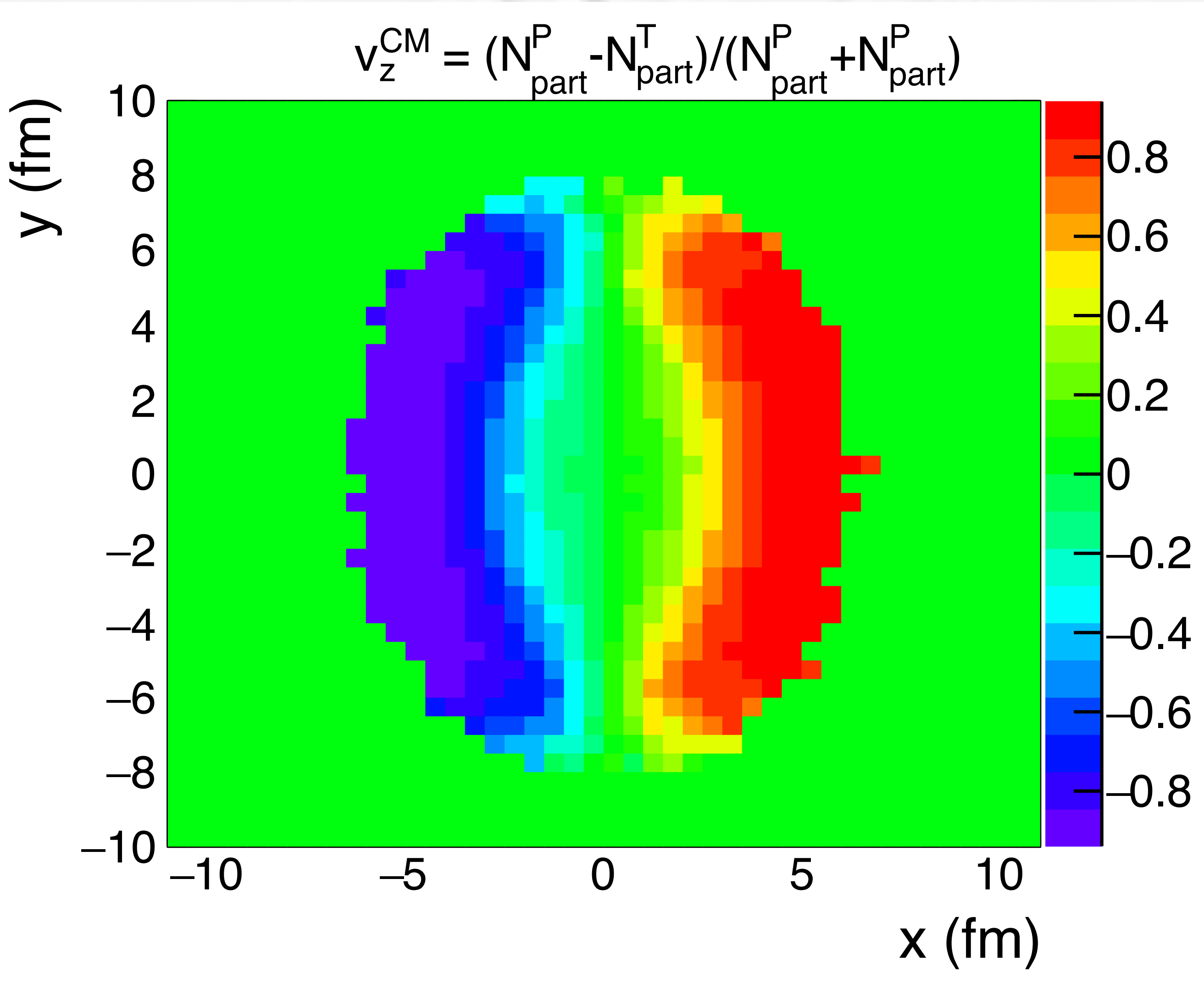
SIP:

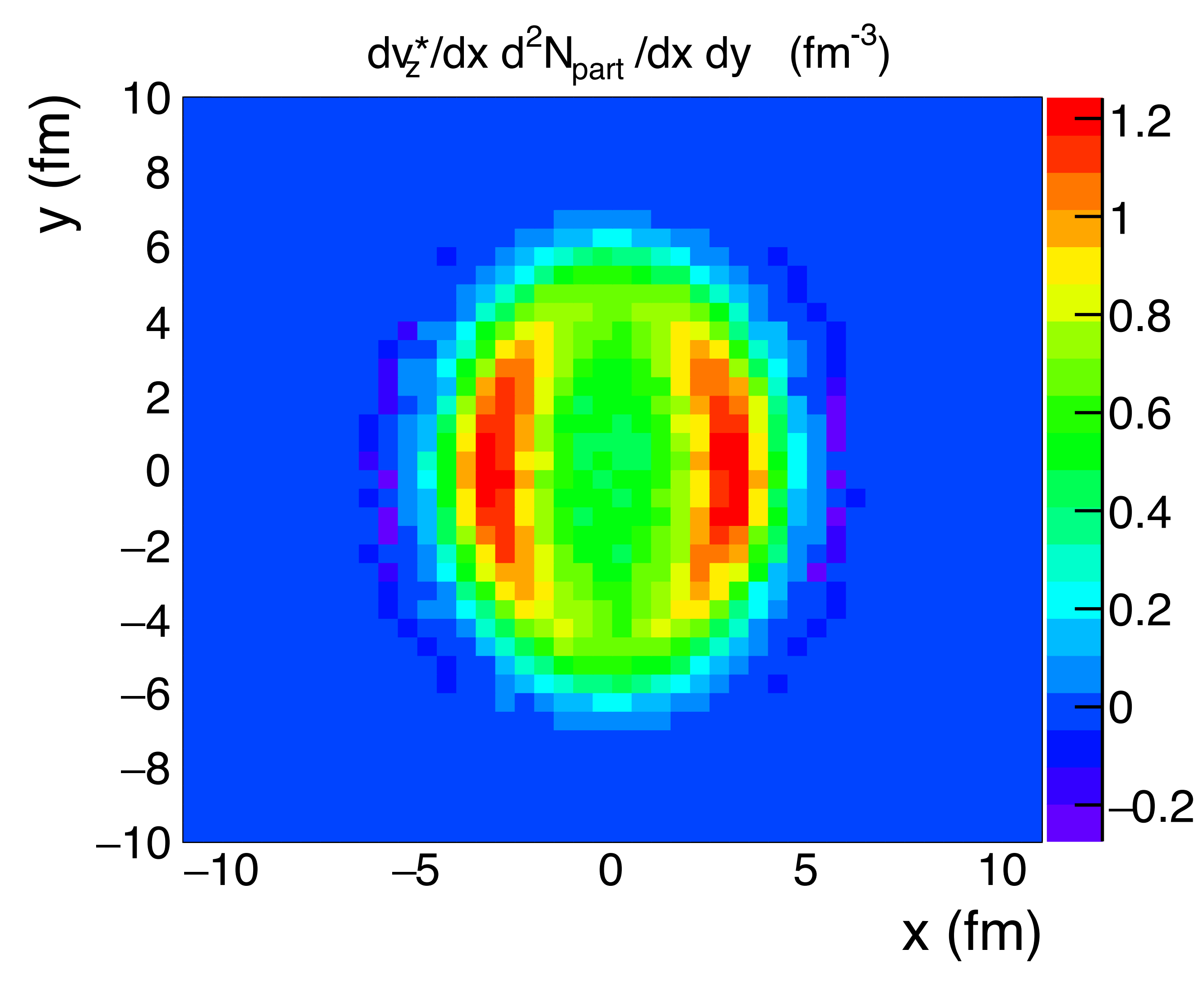
SAHR ALZHRANI, SANGWOOK RYU, AND CHUN SHEN



Results from different calculations under the same conditions differ!

Vorticity

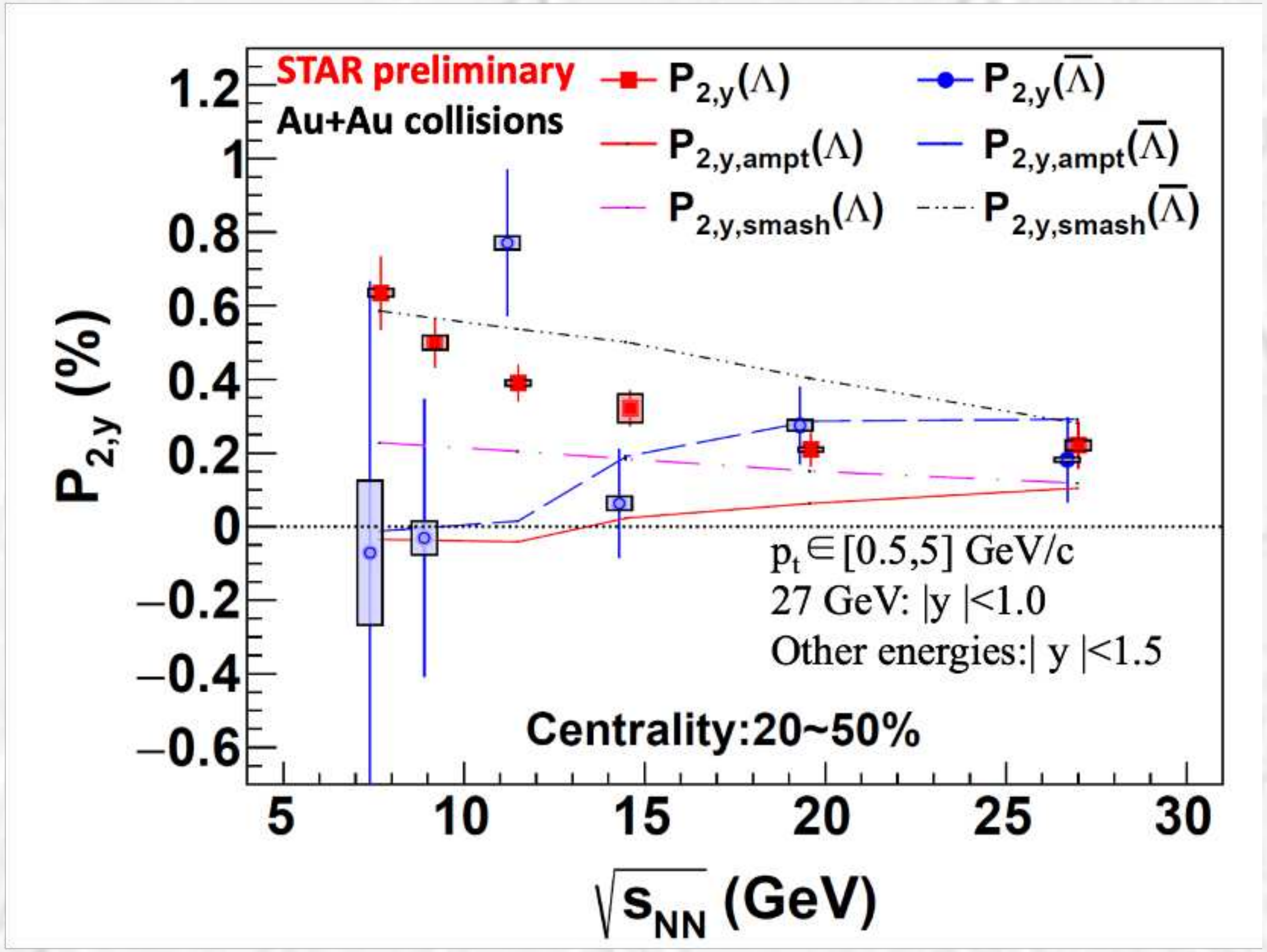




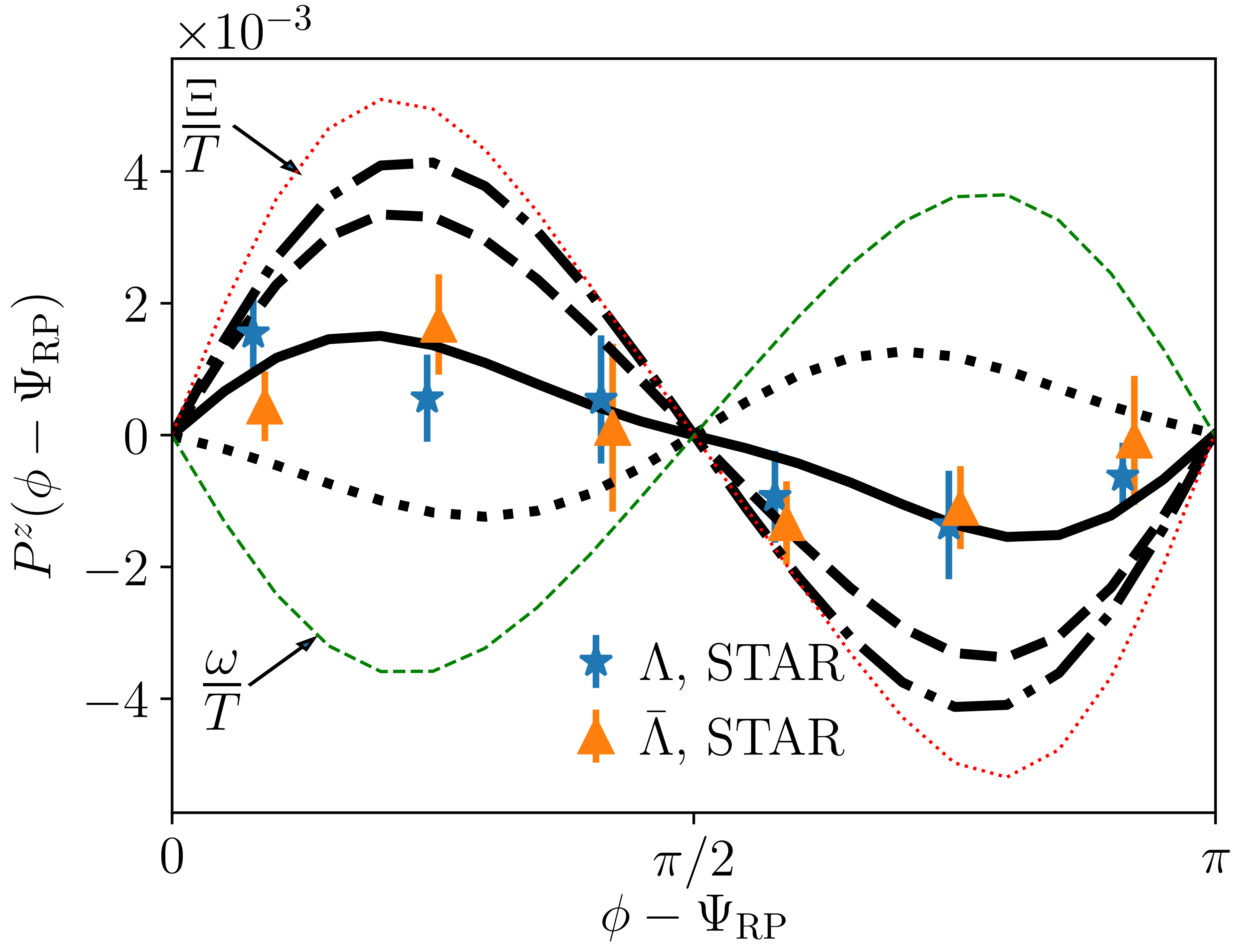
Will be difficult to separate the two contributions

BES II: $P_y(\phi)$

$$P_H\left(\phi_H - \Psi_{\mathrm{RP}}, p_t^H, \eta^H\right) = P_0\left(p_t^H, \eta^H\right) + 2P_2\left(p_t^H, \eta^H\right)\cos\{2[\phi_H - \Psi_{\mathrm{RP}}]\}$$



Shear induced polarization (SIP)



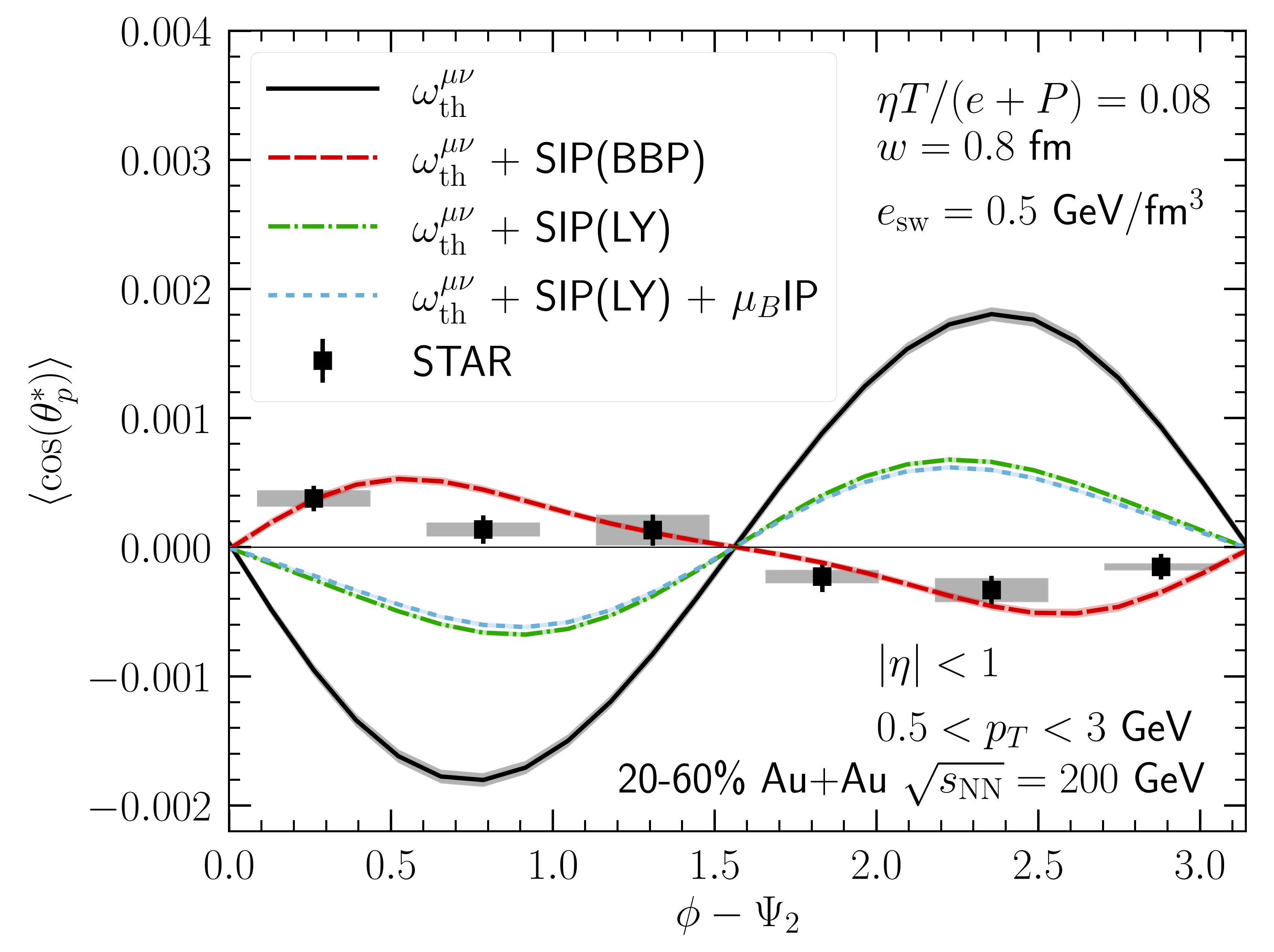
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

S. Liu, Y. Yin, JHEP07(2021)188
B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PLB820(2021)136519
F. Becattini et al., PRL127, 272302 (2021)

$$S_i^{(\mathrm{shear})} \approx \frac{1}{4mTE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j v_m + \partial_m v_j)$$

Neither sign nor magnitude of P_z could not be reproduced by models based on thermal vorticity - "spin sign puzzle"



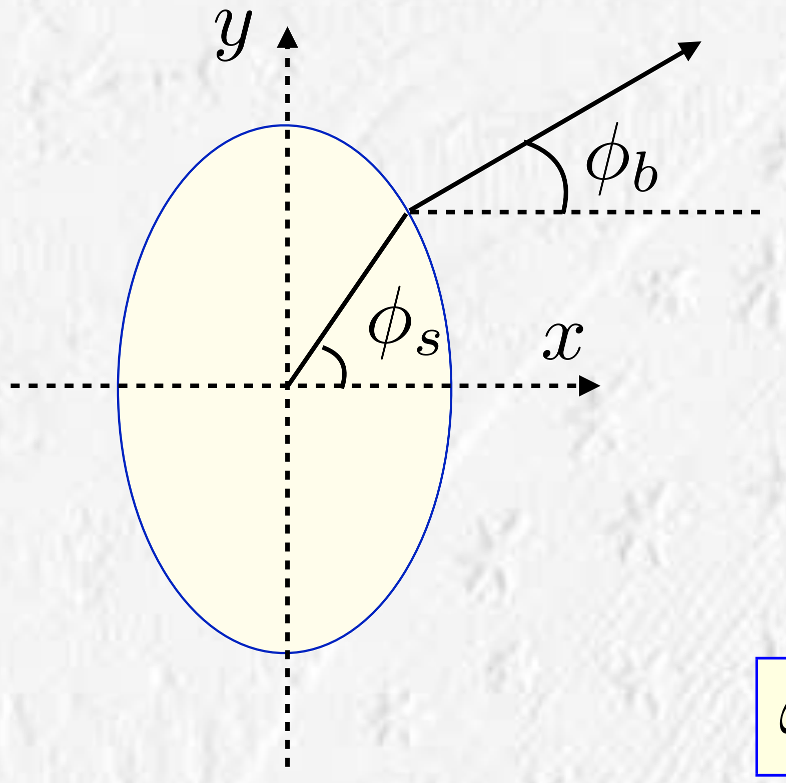
Would higher harmonics measurements help to observe the SIP contribution?

Note that SIP contribution comes mostly (?) from dv_z/dx

S. Alzhrani, S. Ryu, and C. Shen, "Λ spin polarization in event-by-event relativistic heavy-ion collisions", *Phys. Rev. C* **106** no. 1, (2022) , arXiv:2203.15718 [nucl-th].

$$P_{z,sn} = \langle P_z \sin[n(\phi - \Psi_n)] \rangle$$

Blast wave parameterization



Number of emitting “sources”:

$$\propto [1 + 2s_2 \cos(2\phi_b)]$$

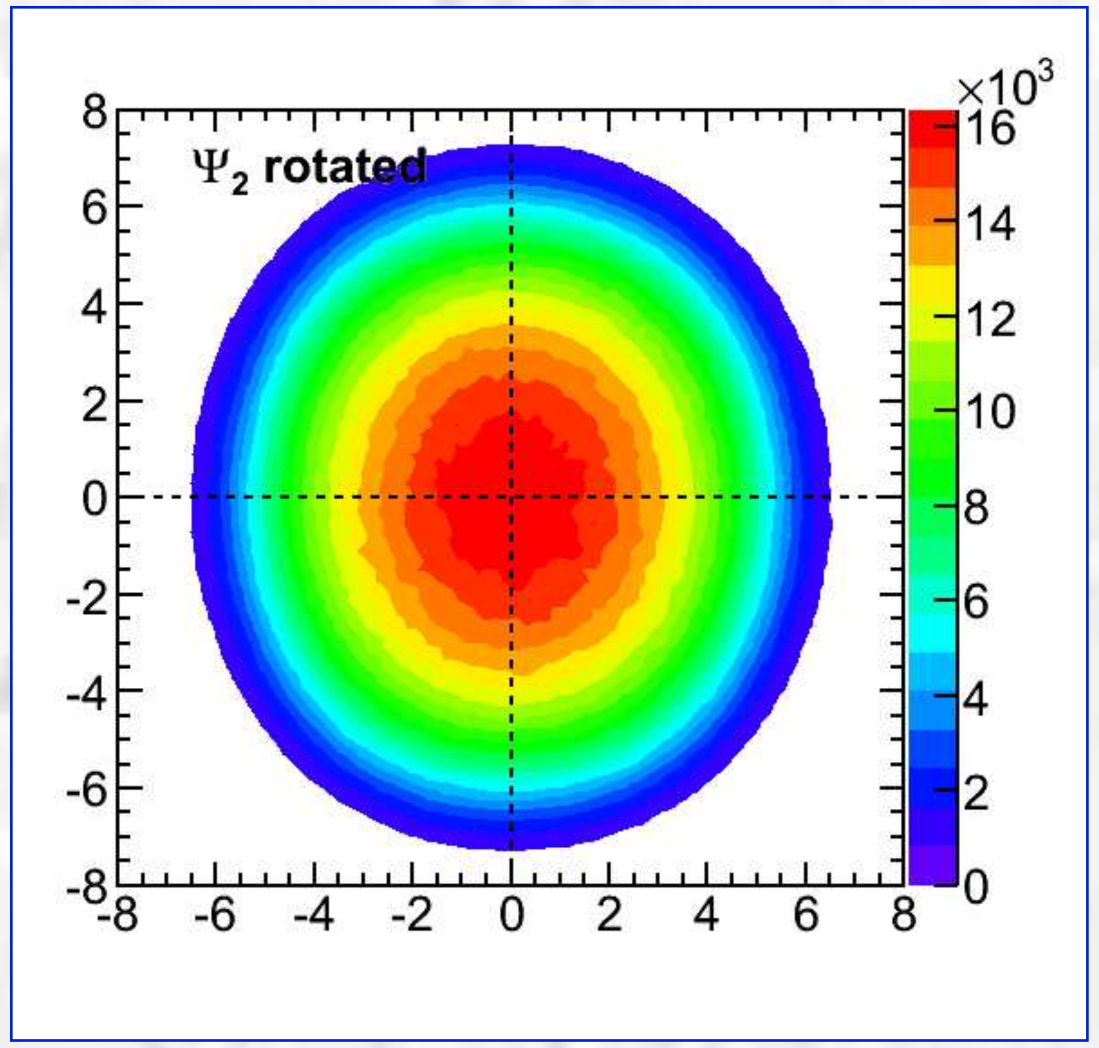
Transverse rapidity (boost):

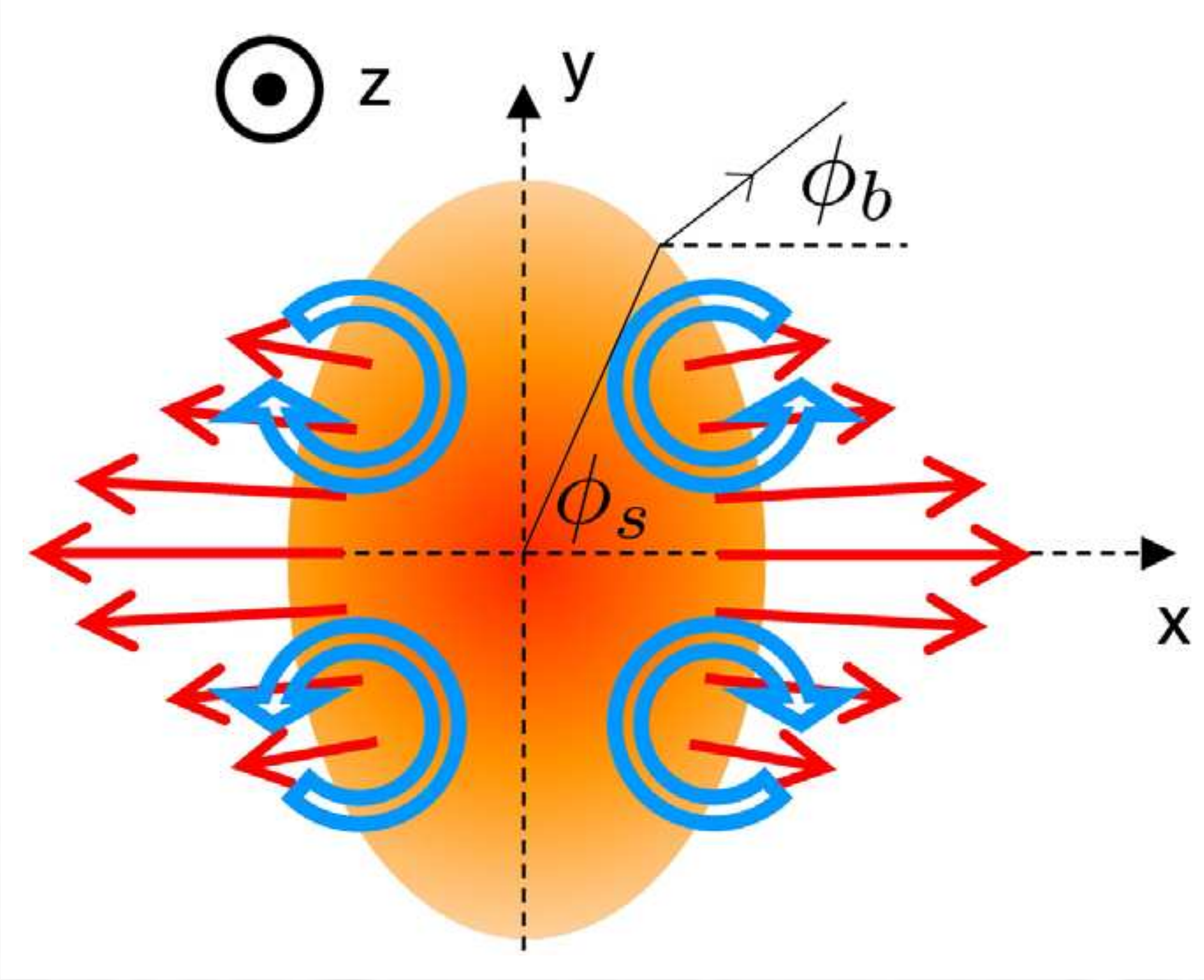
$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + a_2 \cos(2\phi_s)]$$

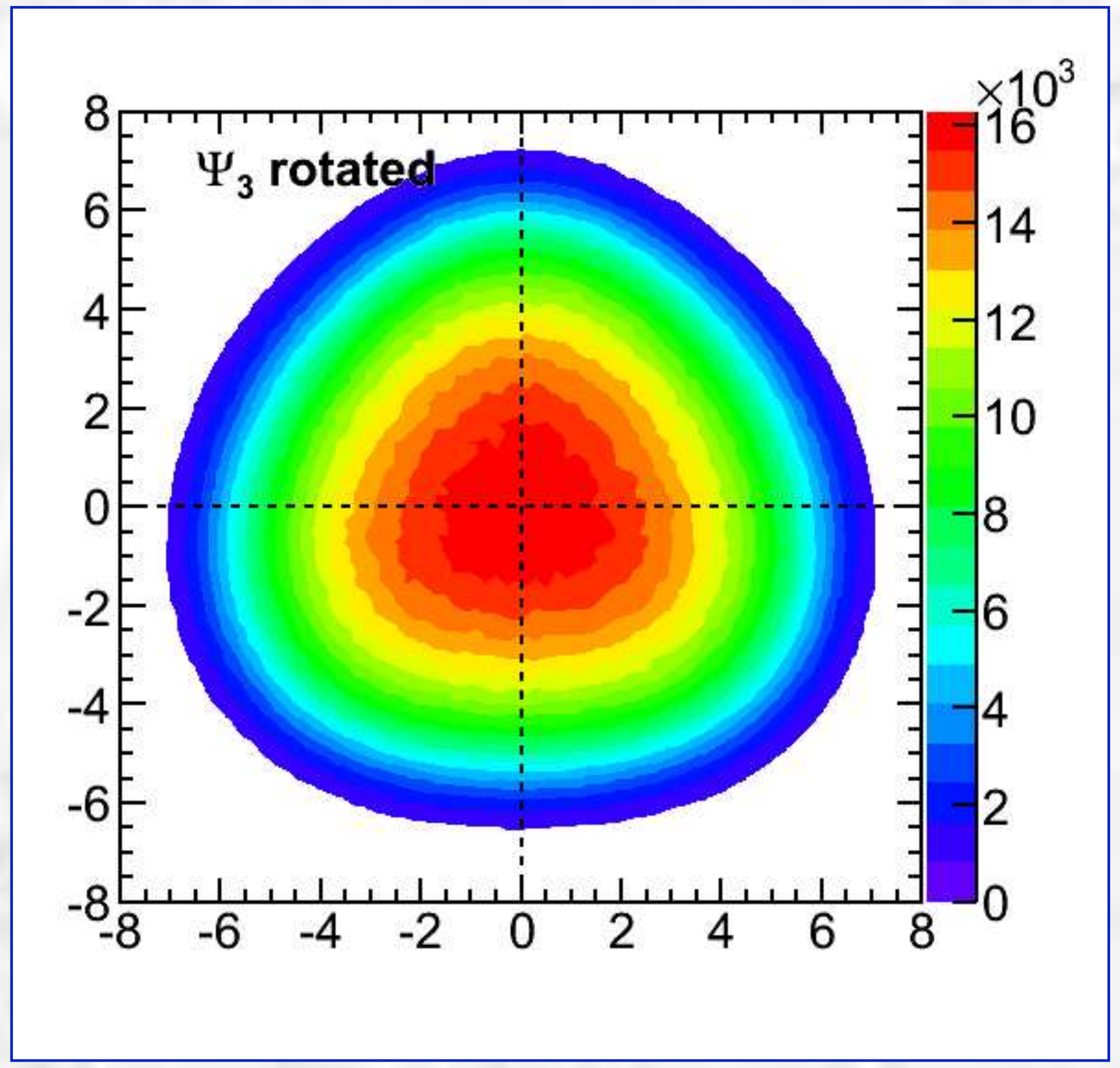
$$\omega_z \approx \rho_{t,max} \sin(n\phi_s)[a_n - 2s_n]$$

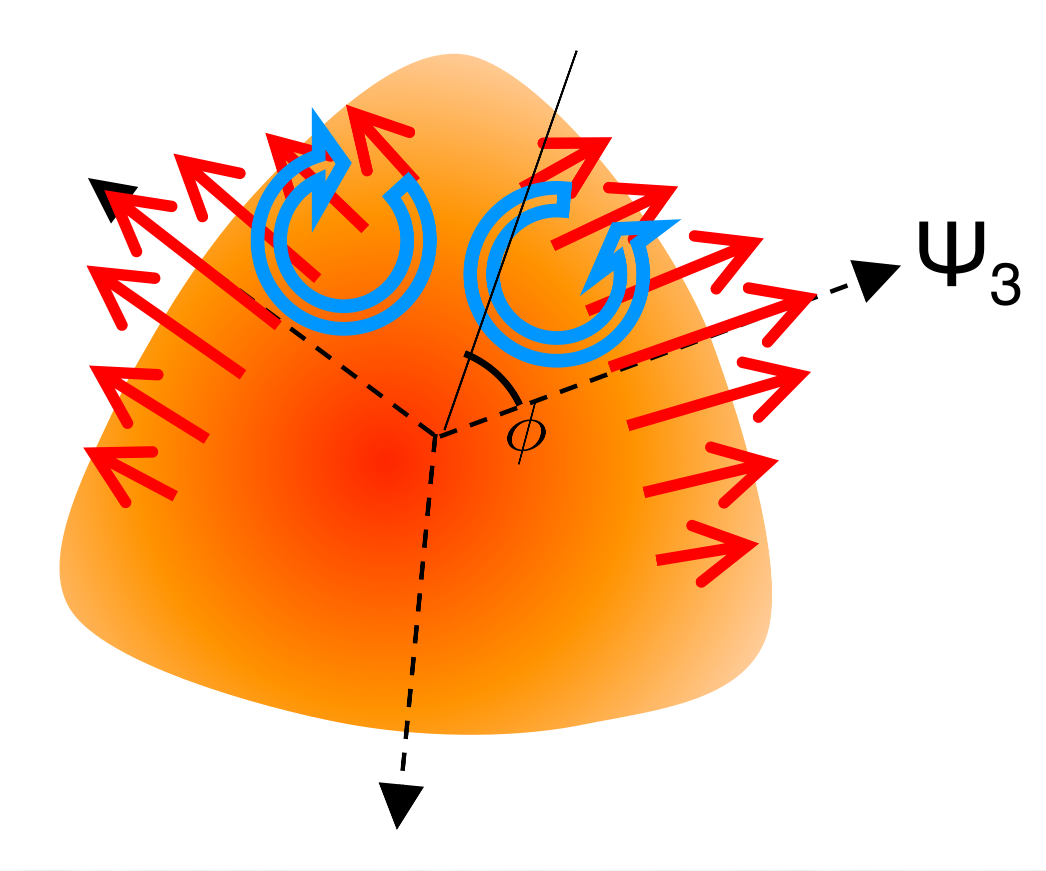
The effects should be present also at higher harmonics, e.g. for triangular flow.

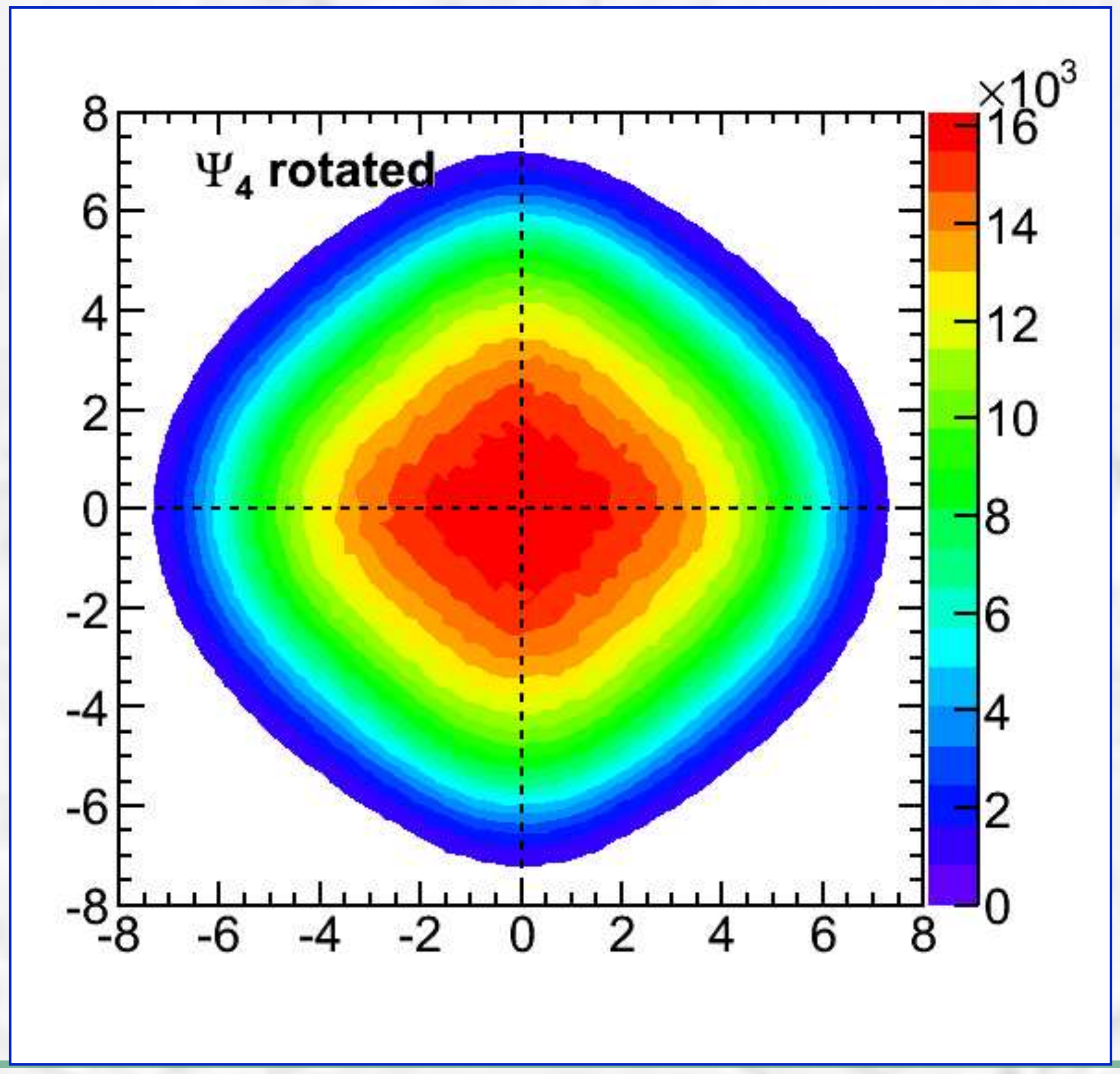
Provides connection to $v_n(p_t)$ and azFemto measurements







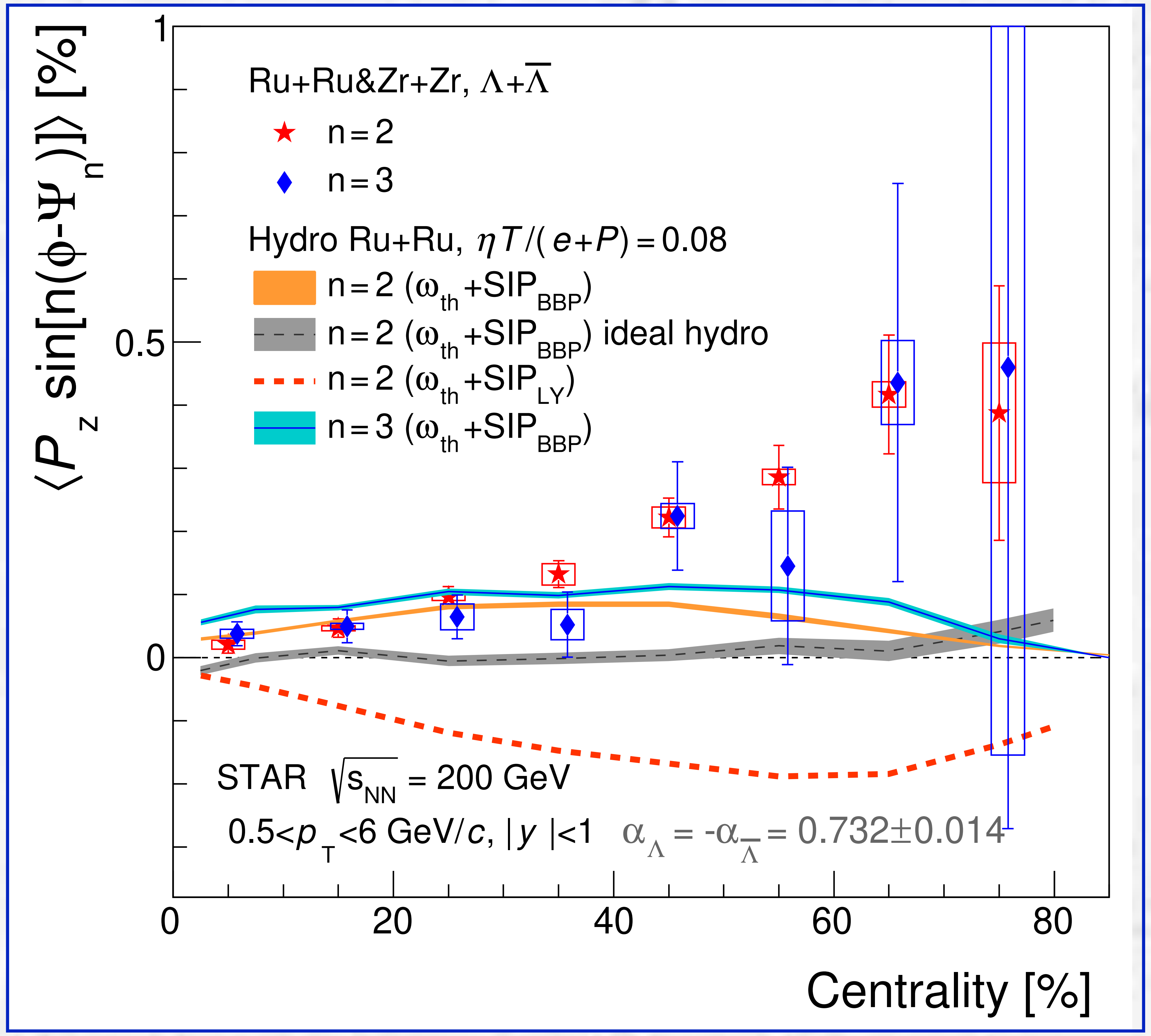


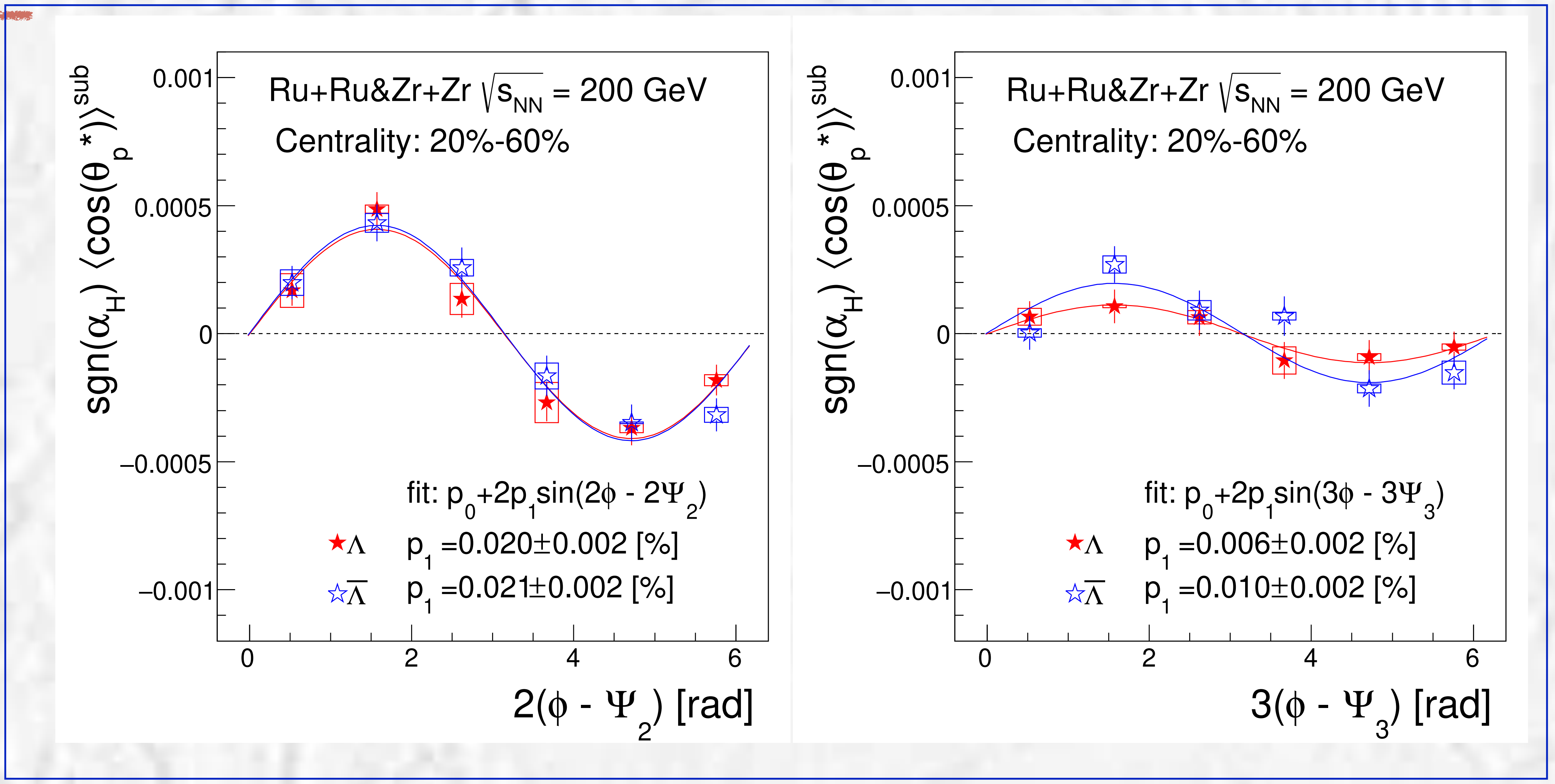


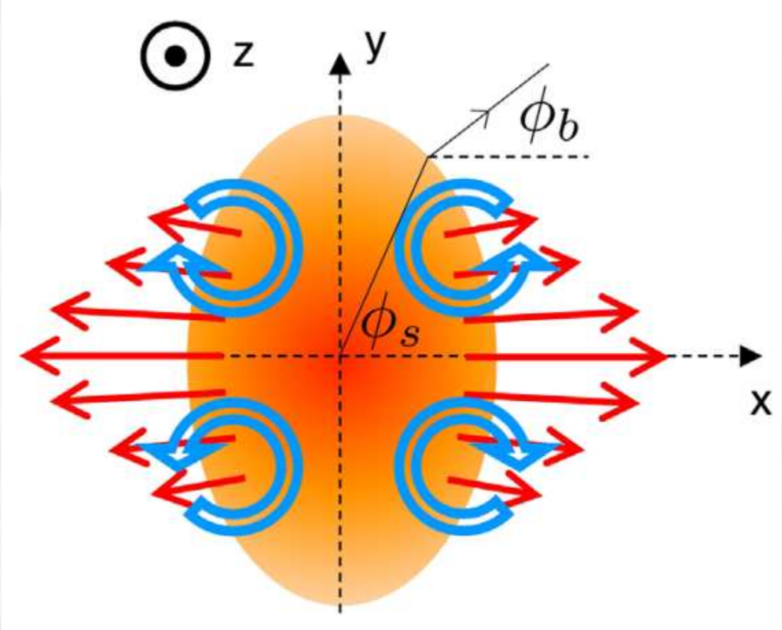
P_z in isobar collisions, + third harmonic

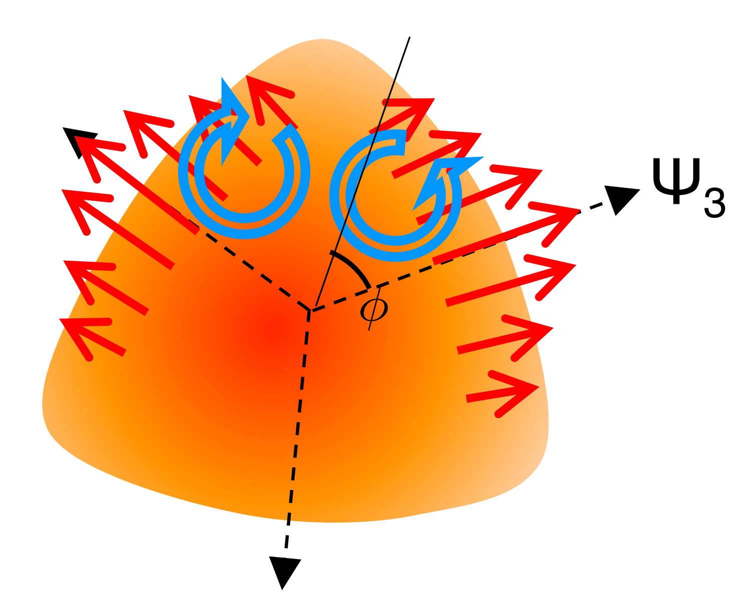
STAR Collaboration, "Hyperon polarization along the beam direction relative to the second and third harmonic event planes in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV", arXiv:2303.09074 [nucl-ex].

~4B events





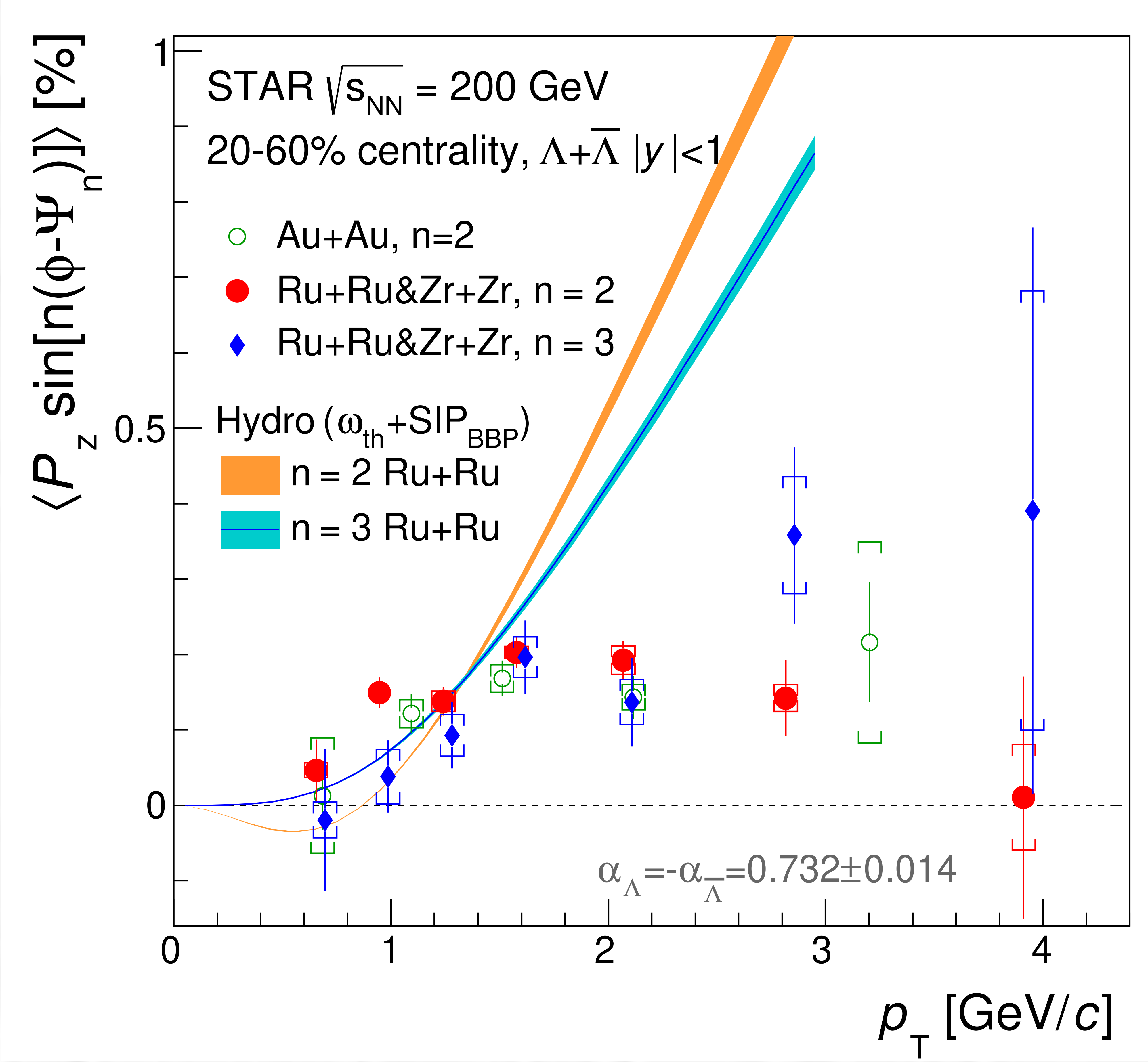




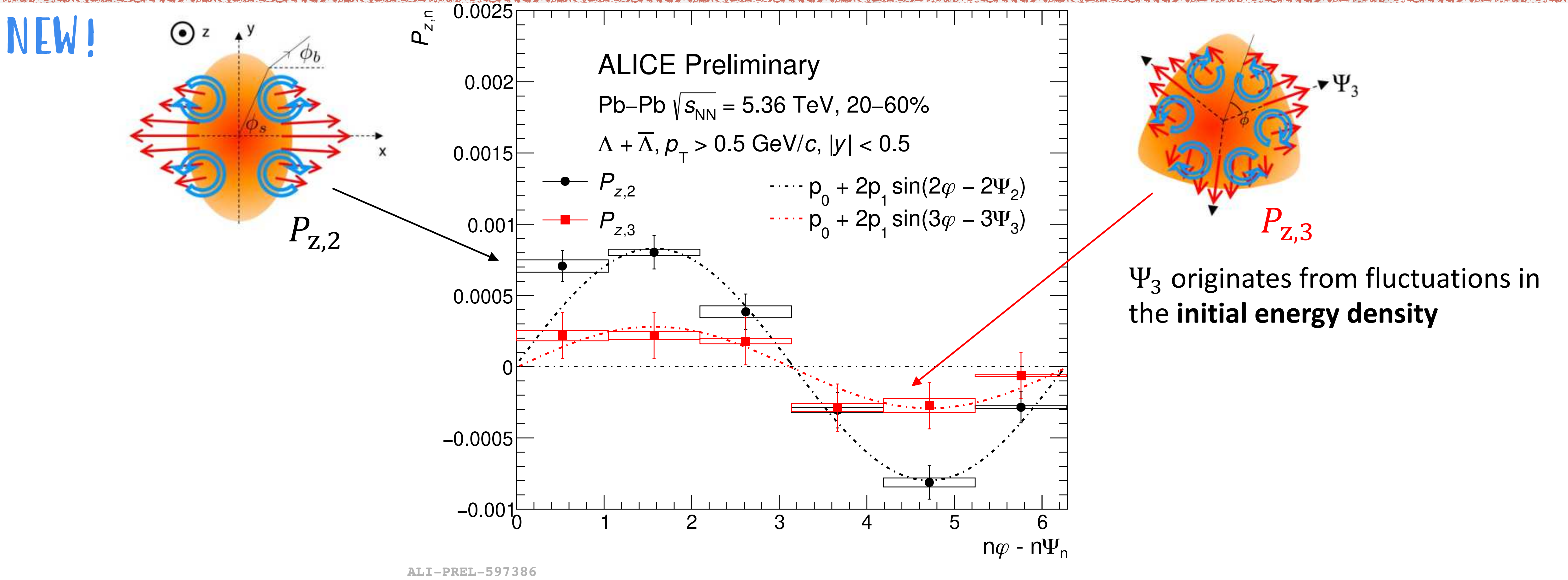
Model calc's:

S. Alzhrani, S. Ryu, and C. Shen, "Λ spin polarization in event-by-event relativistic heavy-ion collisions", *Phys. Rev. C* **106** no. 1, (2022) , arXiv:2203.15718 [nucl-th].

p_T dependece, + fourth harmonic



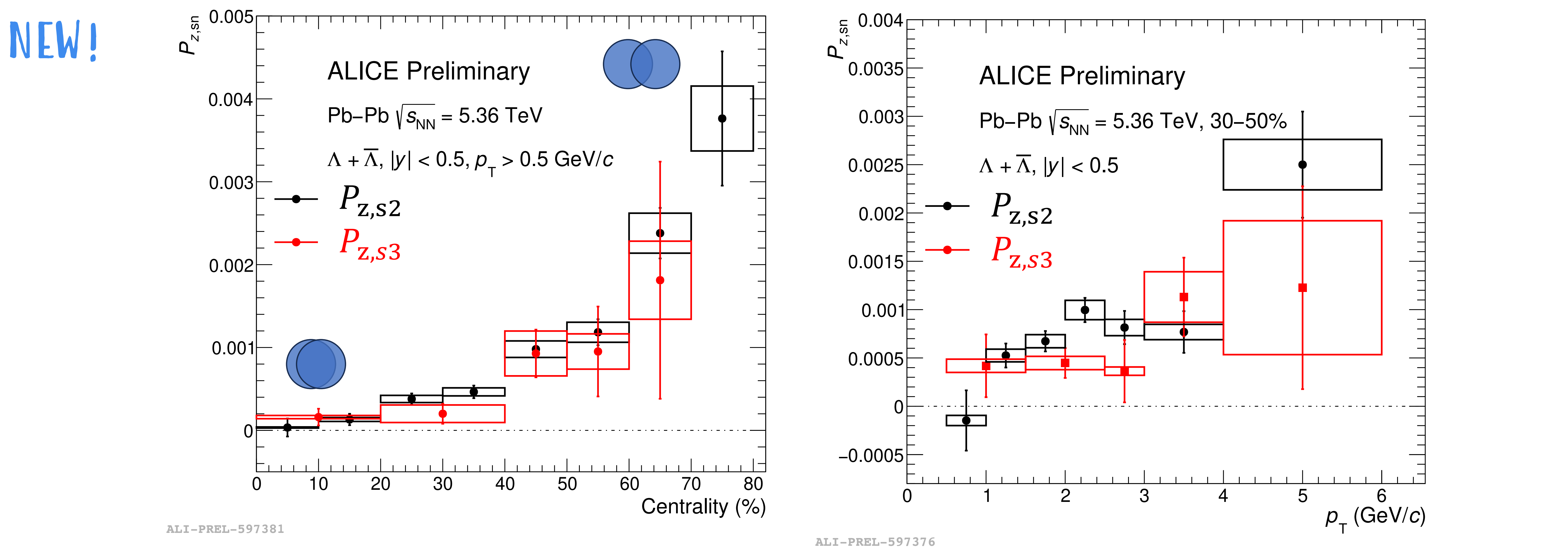
ALICE, Run 3



- The polarization induced by the **triangular flow** is measured for the first time at the LHC energies

→ it helps **identify the contribution from SIP**, which is expected to be different for different harmonics

07/07/2025 Chiara De Martin – EPS 2025 11/14



- The third-order polarization $P_{z,s3}$ is **compatible** with the second-order polarization, despite the **triangular flow being smaller than the elliptic flow** → comparison to model predictions needed to interpret these results
- With 2024 and 2025 data, the measurement of polarization induced by **higher harmonic flow** will be possible

07/07/2025 Chiara De Martin – EPS 2025 12/14

Measuring Ξ and Ω polarization

P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

	Mass (GeV/c²)	cτ (cm)	decay mode	decay parameter α_H	magnetic moment (μ_N)	spin
Λ (uds)	1.115683	7.89	Λ->πp (63.9%)	0.732±0.014	−0.613	1/2
Ξ^- (dss)	1.32171	4.91	Ξ^-->Λπ^- (99.887%)	−0.401±0.010	−0.6507	1/2
Ω^- (sss)	1.67245	2.46	Ω^-->ΛK^- (67.8%)	0.0157±0.002	-2.02	3/2

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

Smaller α, more difficult to measure P

- Different spin, magnetic moments, quark structure
- Less feed-down in Ξ and Ω compared to Λ
- Freeze-out at different time?

$\alpha_\Omega \approx 0.02$ make it impractical to measure the polarization of Ω via $\Omega \to \Lambda + K^-$ decay

T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}_\Lambda^* = \frac{(\alpha_\Xi + \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*)\hat{\boldsymbol{p}}_\Lambda^* + \beta_\Xi \mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^* + \gamma_\Xi \hat{\boldsymbol{p}}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^*)}{1 + \alpha_\Xi \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

α : P-violation

β : CP violation

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda}\mathbf{P}_\Xi^* = \tfrac{1}{3}\left(1 + 2\gamma_\Xi\right)\mathbf{P}_\Xi^*$$

$$C_{\Xi^-\Lambda} = \tfrac{1}{3}\left(2 \times 0.89 + 1\right) = +0.927$$

Ξ, spin 1/2

$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda}\mathbf{P}_\Omega^* = \tfrac{1}{5}\left(1 + 4\gamma_\Omega\right)\mathbf{P}_\Omega^*$$

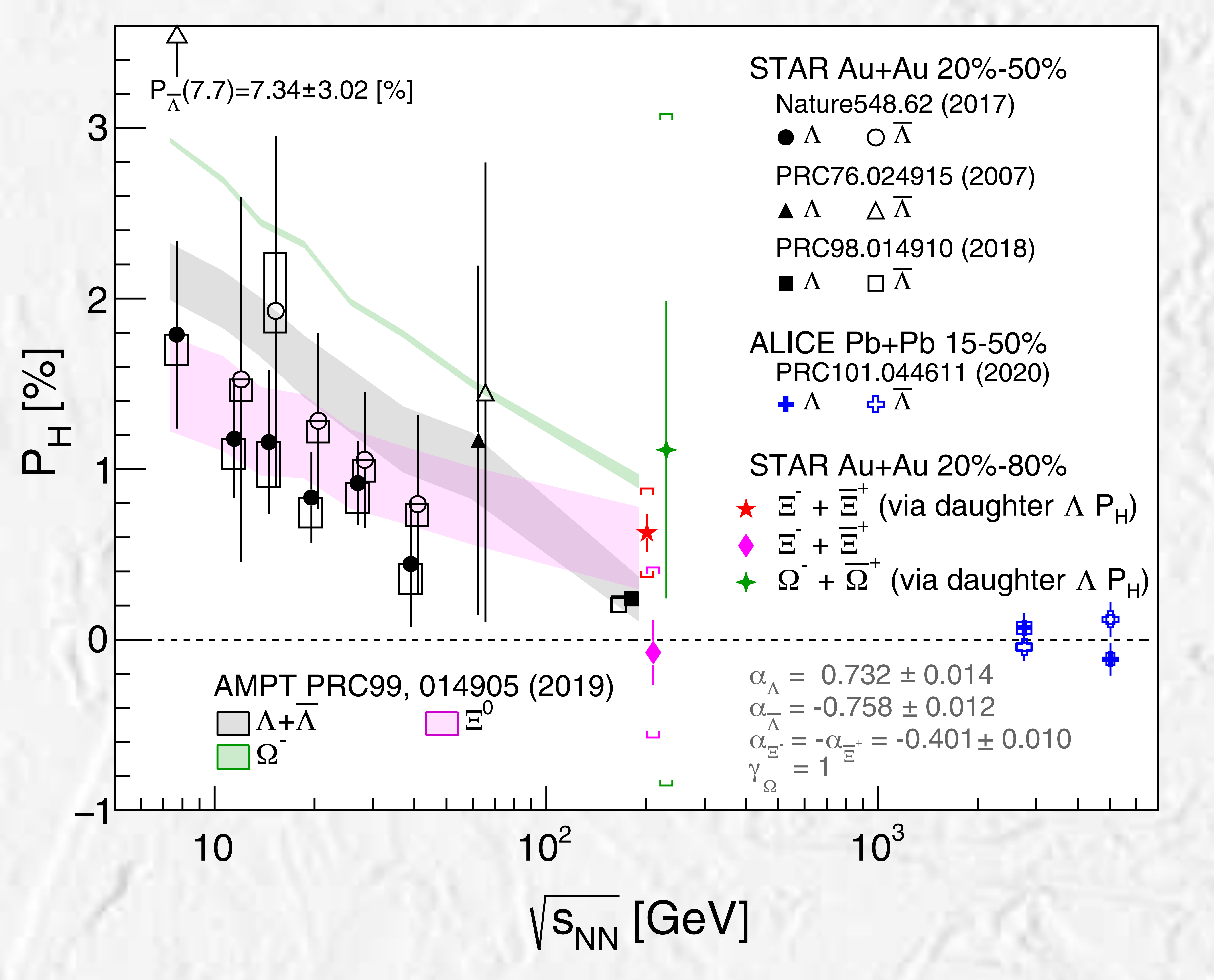
$$C_{\Omega^-\Lambda} \approx 1 \text{ or } C_{\Omega^-\Lambda} \approx -0.6$$

Ω, spin 3/2, γ not known

$\gamma_\Omega \approx \pm 1$

Possibility to determine γ_Ω under assumption of the global polarization

Ξ and Ω global polarization



$$\mathbf{P}^*_\Lambda = \frac{(\alpha_\Xi + \mathbf{P}^*_\Xi \cdot \hat{\boldsymbol{p}}^*_\Lambda)\hat{\boldsymbol{p}}^*_\Lambda + \beta_\Xi \mathbf{P}^*_\Xi \times \hat{\boldsymbol{p}}^*_\Lambda + \gamma_\Xi \hat{\boldsymbol{p}}^*_\Lambda \times (\mathbf{P}^*_\Xi \times \hat{\boldsymbol{p}}^*_\Lambda)}{1 + \alpha_\Xi \mathbf{P}^*_\Xi \cdot \hat{\boldsymbol{p}}^*_\Lambda}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$\mathbf{P}^*_\Lambda = C_{\Omega^- \Lambda} \mathbf{P}^*_\Omega = \frac{1}{5}(1 + 4\gamma_\Omega)\mathbf{P}^*_\Omega.$$

A way to measure the decay parameter γ_Ω !

Ξ, spin 1/2

Ω, spin 3/2, γ not known $\gamma_\Omega \approx \pm 1$

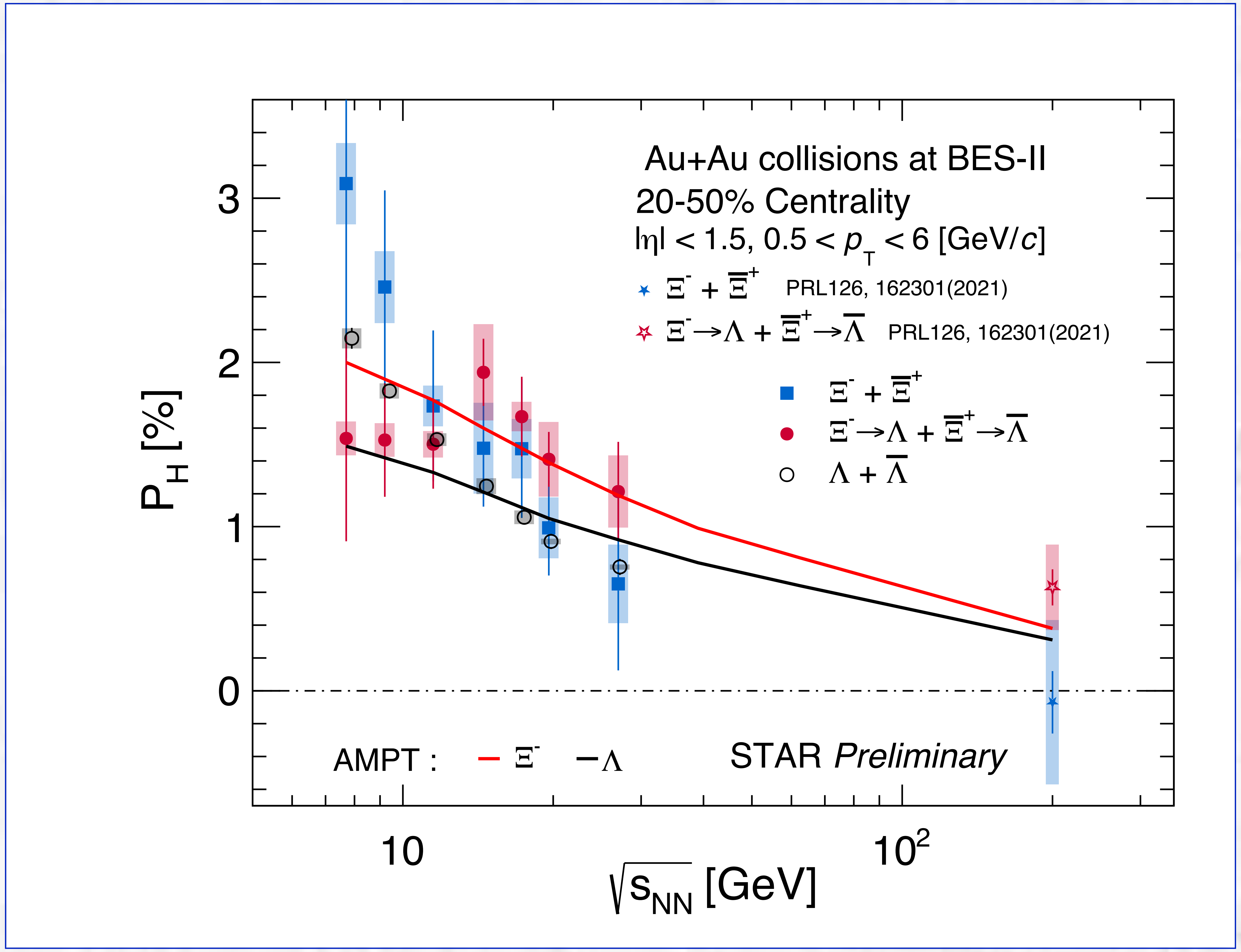
Ξ polarization might be slightly larger than that of Λ

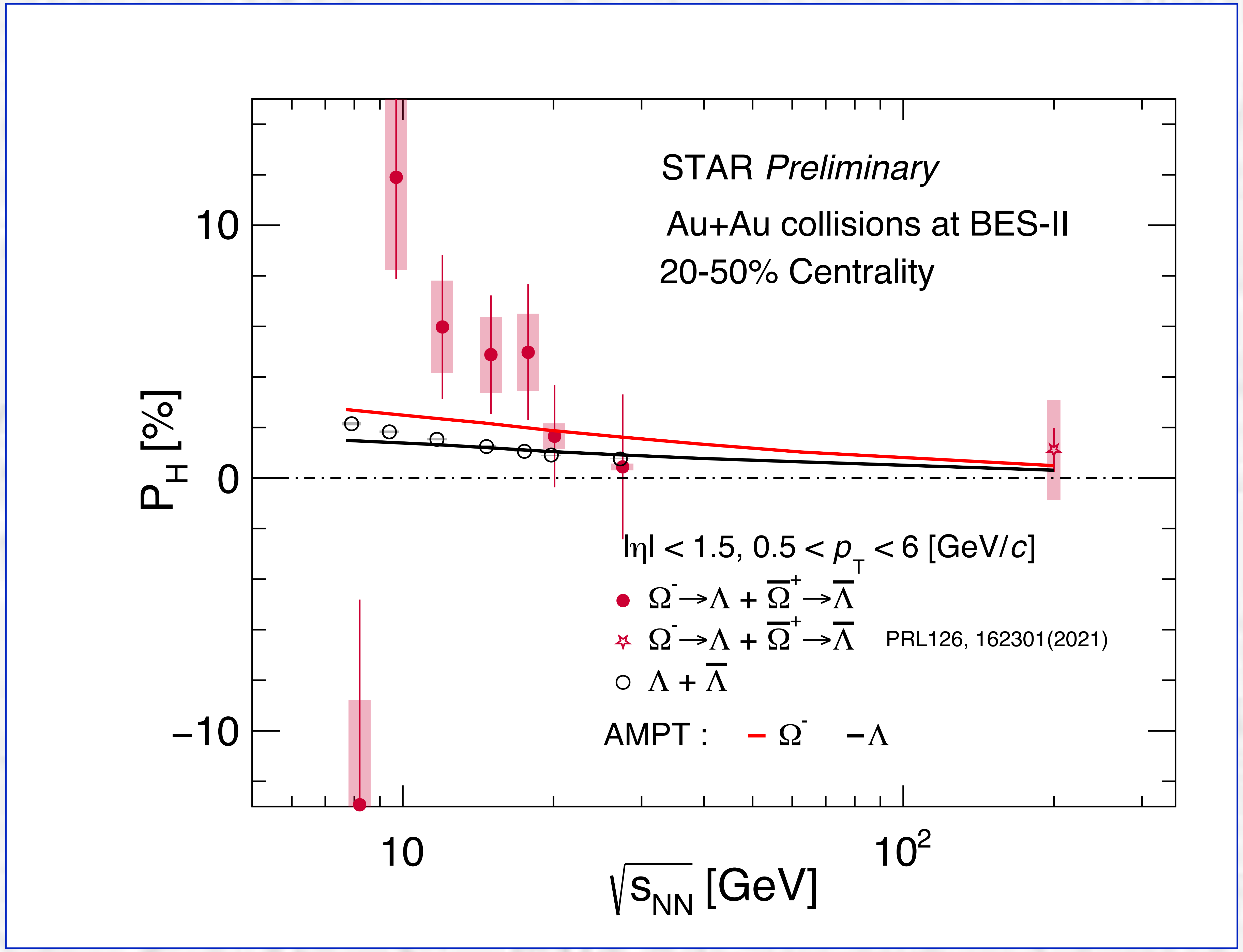
Ω polarization results favor $\gamma_\Omega = +1$

Expectation $P_\Omega \approx \frac{5}{3} P_\Lambda$

STAR Collaboration, J. Adam *et al.*, "Global polarization of Ξ and Ω hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett* **126** (4, 2021) , arXiv:2012.13601 [nucl-ex].

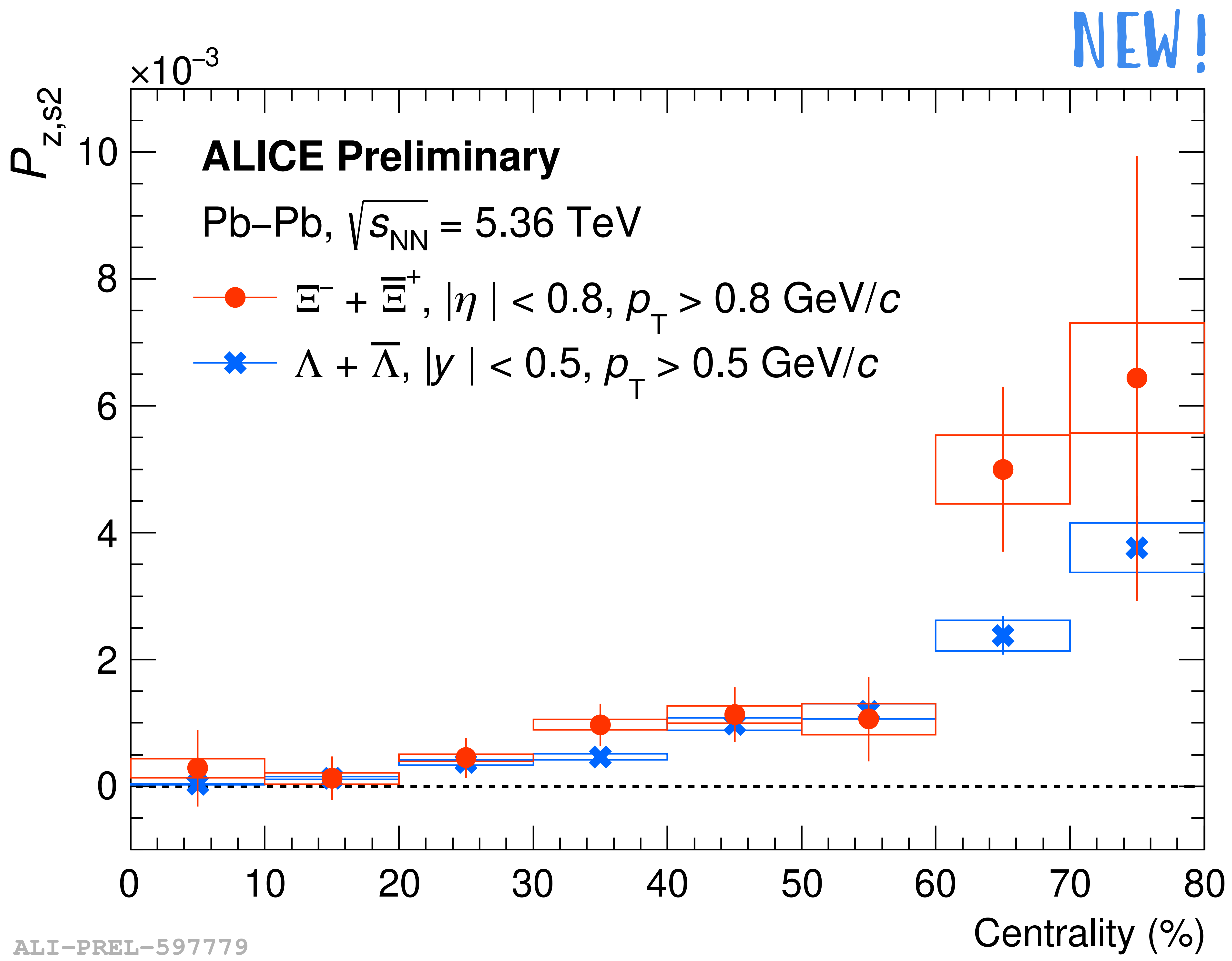
BES II: Ξ, Ω





Model calculation:
H. Li, X. Xia et al Phys. Lett. B 827, 136971 (2022)

ALICE: P_z^{Ξ}



The **first measurement of Ξ longitudinal polarization** in Pb–Pb collisions was performed using a sample of $\sim 6 \times 10^9$ Pb–Pb collisions collected during the LHC Run 3 in 2023

The **Ξ longitudinal polarization** shows a **hint of increase with decreasing centrality** and is compatible with **Λ** one, confirming the **spin hierarchy** $(s_\Lambda = s_\Xi = 1/2)$

Contributions to polarization

fluid rest frame $u^\mu = (1,0,0,0) \quad \omega^\mu = (0, \boldsymbol{\omega})$

$$S^0(x,p) = \frac{1}{8m}(1-n_F)\,\frac{\boldsymbol{\omega}\cdot\mathbf{p}}{T},$$

$$\mathbf{S}(x,p) = \frac{1}{8m}(1-n_F)\left(-\frac{\mathbf{p}\times\boldsymbol{\nabla}T}{T^2} + 2\,\frac{E\,\boldsymbol{\omega}}{T} + \frac{\mathbf{p}\times\mathbf{A}}{T}\right)$$

$$\mathbf{S}^* = \mathbf{S} - \frac{\mathbf{p}\cdot\mathbf{S}}{E(E+m)}\mathbf{p}.$$

Contributions due to ∇T and A should be small in nonrelativistic limit!

Similarly for SIP

$$S_i^{(\mathrm{vort})} \approx \frac{E}{8mT}\,\epsilon_{ikj}\frac{1}{2}(\partial_k v_j - \partial_j v_k)$$

$$S_i^{(\mathrm{shear})} \approx \frac{1}{4mTE}\,\epsilon_{ikj}p_k p_m\,\frac{1}{2}(\partial_j v_m + \partial_m v_j)$$

Contribution from dv_z/dx:

$$S_x \propto p_x p_y \propto \sin(2\phi)$$

$$S_y \propto p_z^2 - p_x^2 \propto \sim 1 + \cos(2\phi)$$

$$S_z \propto p_y p_z \propto \sin(2\theta)\ \sin(\phi)$$

Momentum in the rest frame of the fluid - averaging over the production volume should further suppress such contributions.

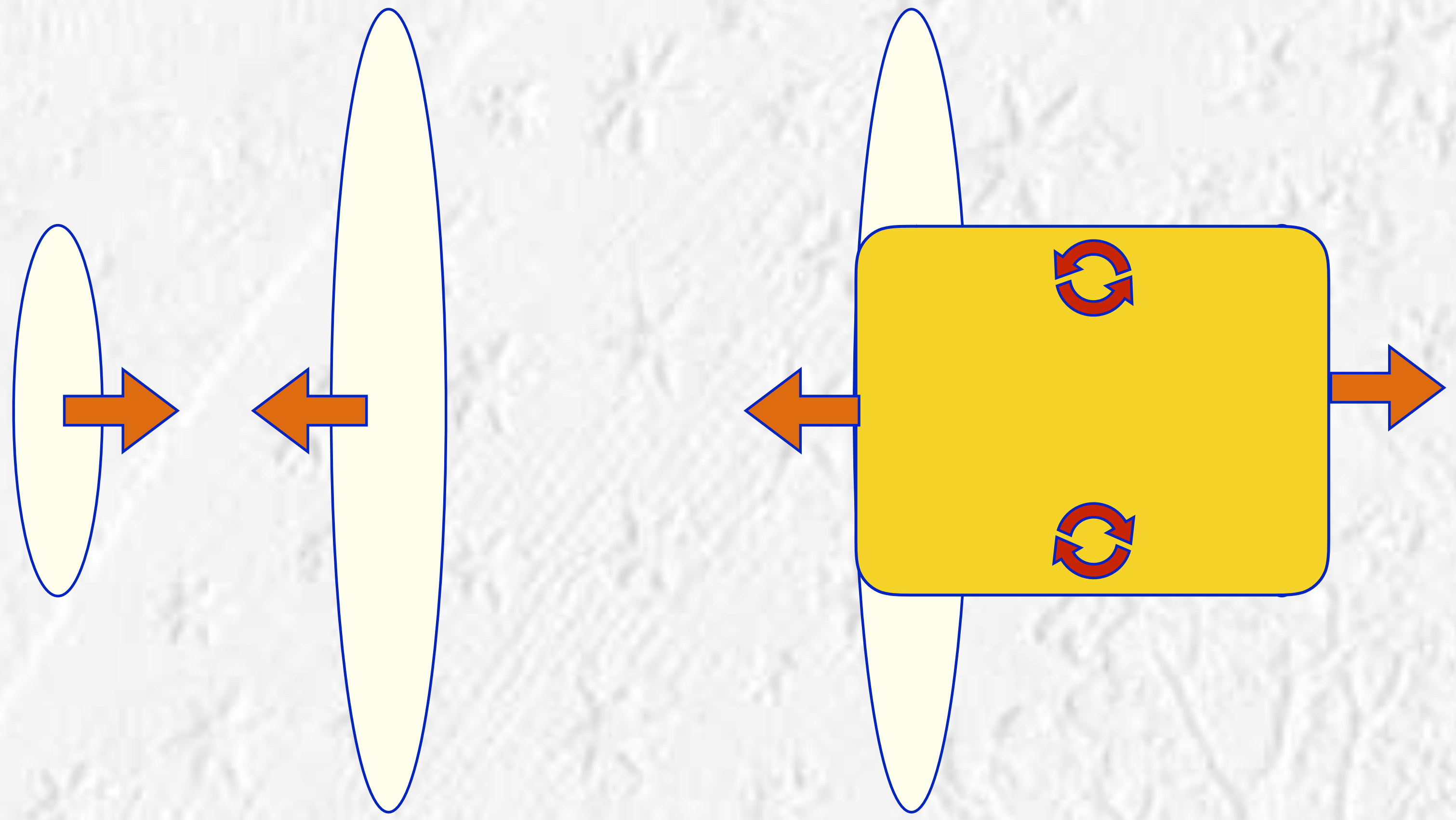
P_ϕ in asymmetric collisions

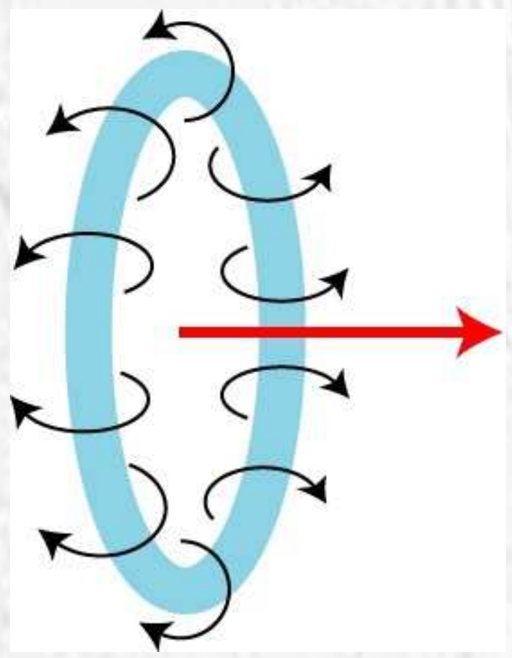
Global/local polarization and…

… and asymmetric collisions (CuAu, dAu, pPb,…) => ω_ϕ

… and radial flow+longitudinal(y) => ω_ϕ

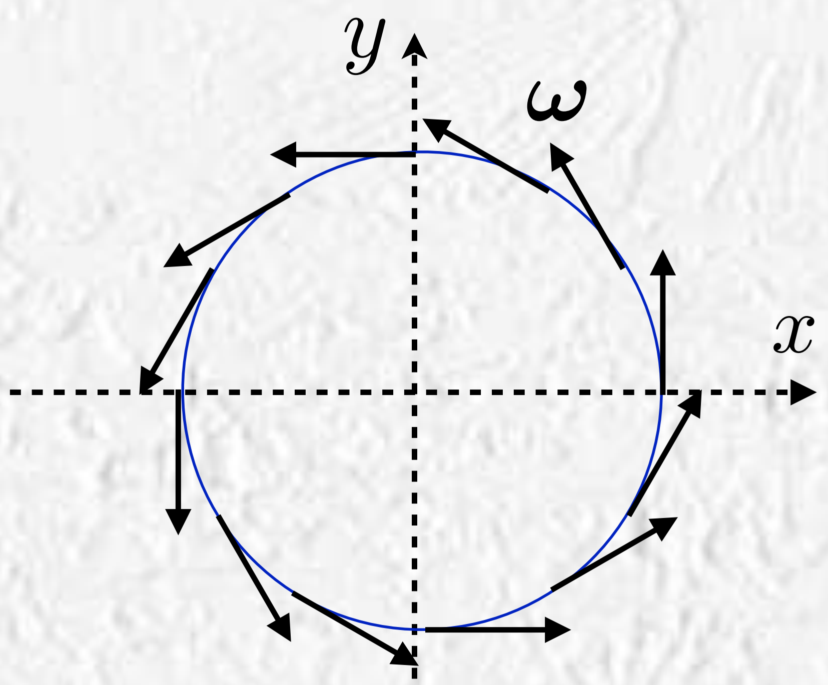
+ anisotropic flow => $\omega_\phi(\phi)$





z-direction — Cu beam

$\omega \propto \hat{\phi}$



Small off-center (impact parameter) will lead to "circular" vorticity *on average*

dAu, pPb, etc…

EPJ Web of Conferences **171**, 07002 (2018) https://doi.org/10.1051/epjconf/201817107002
SQM 2017

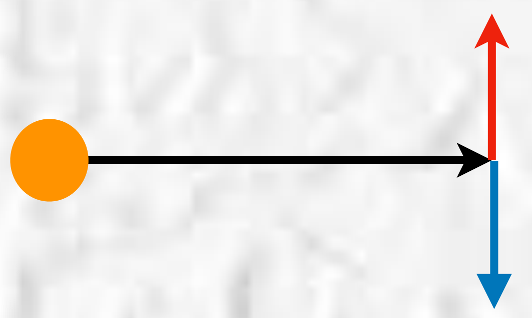
Vorticity and particle polarization in heavy ion collisions (experimental perspective)

Sergei A. Voloshin[1,⋆]

Finally, we mention another very interesting possibility for vorticity studies in asymmetric nuclear collisions such as Cu+Au. For relatively central collisions, when during the collision a smaller nucleus is fully "absorbed" by the larger one (e.g. such collisions can be selected by requiring no signal in the zero degree calorimeter in the lighter nucleus beam direction), one can easily imagine a configuration with toroidal velocity field, and as a consequence, a vorticity field in the form of a circle. The direction of the polarization in such a case would be given by $\hat{\mathbf{p}}_T \times \hat{\mathbf{z}}$, where $\hat{\mathbf{p}}_T$ and $\hat{\mathbf{z}}$ are the unit vectors along the particle transverse momentum and the (lighter nucleus) beam direction.

One of the analyses, where the results *directly* depends on the correction: the effect — nonzero results — can be *faked* by "slightly off" acceptance/efficiency correction.

In that, it is very different from the global or P_z analyses, where "wrong correction", could lead only to a relatively small difference in the *magnitude* of the effect.



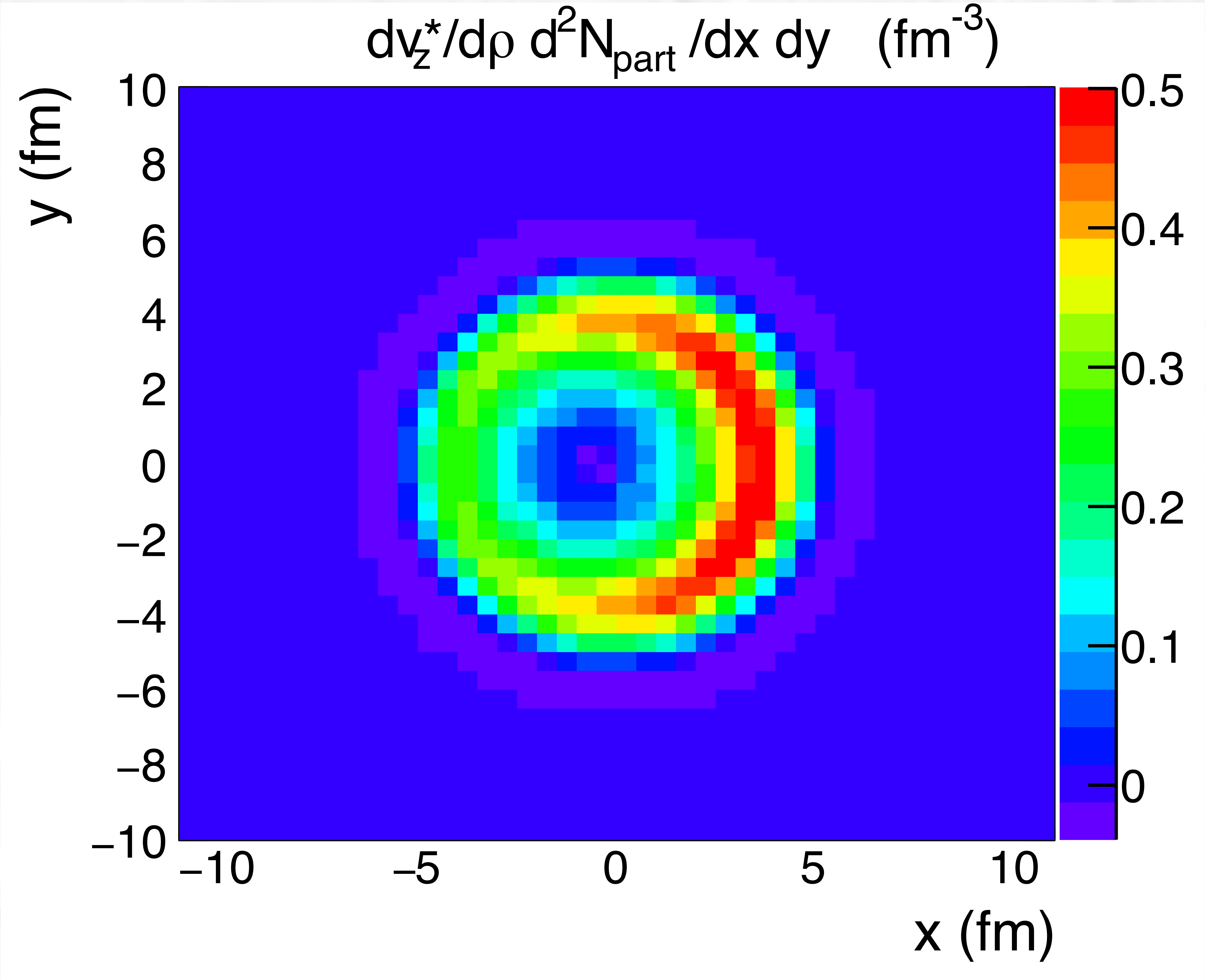
Probability to reconstruct decay on the left is different from that on the right

This is one of the reasons for many years Cu-Au analysis is still "in progress". Requires running with opposite polarity magnetic field

Calculations: M. A. Lisa, J. a. G. P. Barbon, D. D. Chinellato, W. M. Serenone, C. Shen, J. Takahashi, and G. Torrieri, "Vortex rings from high energy central p+A collisions", *Phys. Rev. C* **104**, no. 1, 011901 (2021), arXiv:2101.10872.

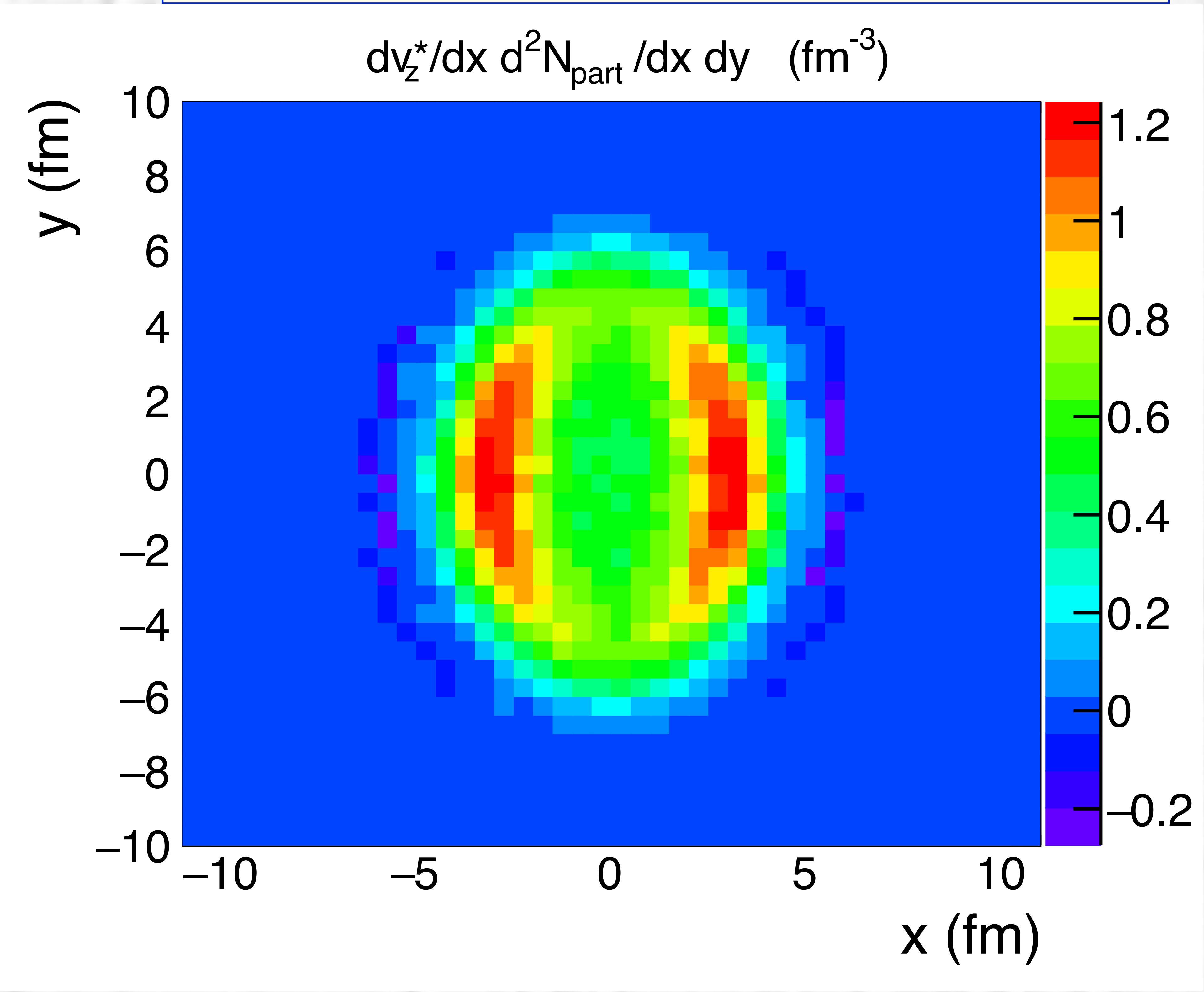
But fluctuations/correlations should be possible to measure!

Simle estimate of the effect



Cu+Au, b<1 fm, $\Psi_{RP} = 0$. NN center-of-mass

compare to “global” polarization in AuAu



Summary

Vorticity is an important piece in the picture of heavy ion collisions
Very rich and extremely interesting results and future

P_z measurements surprisingly (or not?) well agree with the BW expectations

It is not clear how/why $\nabla_\mu T$ and A_μ and SIP contributions appear to be large/significant

A specific predictions for SIP, SHE, etc. are needed

A tool to study hadron spin structure?

Is the "Cooper-Frye" prescription good for polarization calculations?

Spin alignment: a thorough review and understanding of the detector effects are needed

- Polarization splitting between particles and antiparticles, including particles with larger magnitude of the magnetic moment such as Ω. It will further constrain the magnetic field time evolution and its strength at freeze-out, and the electric conductivity of quark-gluon plasma.
- Precise measurements of multistrange hyperon polarization to study particle species dependence and confirm the vorticity-based picture of polarization. Measurement with Ω will also constrain unknown decay parameter γ_Ω.
- Precise differential measurements of the azimuthal angle and rapidity dependence of P_J $(P_{-\mathrm{y}})$.
- Detailed measurement of P_{z} induced by elliptic and higher harmonic flow. In particular this study could help to identify the contribution from SIP, which is expected to be different for different harmonics.
- Application of the event-shape-engineering technique[126] testing the relationship between anisotropic flow and polarization.
- Measuring P_{x} to complete all the components of polarization and compare the data to the Glauber estimates and full hydrodynamical calculations.
- Circular polarization P_ϕ to search for toroidal vortex structures
- The particle-antiparticle difference in the polarization dependence on azimuthal angle at lower collision energies testing the Spin-Hall Effect.
- Understanding of the vector meson spin alignment measurements including new results with corrections of different detector effects.
- Measurement of the hyperon polarization correlations to access the scale of vorticity fluctuations.
- Measurement of the hyperon polarization in pp collisions to establish/disprove possible relation to the single spin asymmetry effect.

T. Niida and S. A. Voloshin, Polarization phenomenon in heavy-ion collisions, (2024), arXiv:2404.11042 [nucl-ex].

EXTRA SLIDES

The Cooper-Frye prescription

PHYSICAL REVIEW D VOLUME 10, NUMBER 1 1 JULY 1974

Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production

Fred Cooper* and Graham Frye
Belfer Graduate School of Science, Yeshiva University, New York, New York 10033

In both models, one assumes that the collision process yields a distribution of collective motions. In Hagedorn's approach these collective motions are called fireballs; in Landau's approach the collective motions are that of the hadronic fluid

Milekhin's[6] version of Landau's model, in which dN/d^3v is proportional to the distribution of entropy in the fluid. In a notation explained below [see Eq. (18)], Milekhin's expression is

$$\frac{dN}{d^3v} = \bar{n}(\vec{v})u^\mu \frac{\partial\sigma_\mu}{\partial^3 v}. \qquad (4)$$

Equations (1) and (4) can be combined to give

$$E\frac{dN}{d^3p} \overset{?}{=} \int_\sigma g(\bar{E}, \bar{T}(\vec{v}))\bar{E}u^\mu d\sigma_\mu . \qquad (5)$$

Equation (5) yields the correct number of particles, but it is inconsistent with energy conservation [see Eq. (20)], so we are led to consider how one determines EdN/d^3p for the simplest system, an expanding ideal gas.

t if we choose $d\sigma_\mu = (d^3x, \vec{0})$. The invariant single-particle distribution in momentum space, of those particles on σ, is

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu . \qquad (9)$$

Equation (9) is to be compared with Eq. (5) under the assumption that the fluid is locally in thermodynamic equilibrium,

$$f(x,p) = g(\bar{E}(v(x)), T(x)). \qquad (10)$$

The contrast between Eqs. (5) and (9) is that p^μ has been replaced by $\bar{E}u^\mu$ in Eq. (5). To choose

Is the Blast Wave model "closer" to Milekhin's prescription?

Note that the polarization observables are sensitive to the *gradients* of the fields, unlike most (all?) of the observables used so far. This bring new important information to the picture of the freeze-out stage.

Spin alignment in vector meson decays

$$\Delta\rho = \rho_{00} - 1/3$$

$$\Delta\rho \approx (\omega/T)^2/3 \approx 4P_H^2/3$$ Thermal estimate

Strong decays of vector mesons into two (pseudo)scalar particles

$K^{*0} \to \pi + K$

$\phi \to K^- + K^+$

$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

$\rho_{00} = w_0$ - probability for $s_z = 0$

$$\frac{dN}{d\cos\theta^*} \propto w_0|Y_{1,0}|^2 + w_{+1}|Y_{1,1}|^2 + w_{-1}|Y_{1,-1}|^2 \propto w_0\cos^2\theta^* + (w_{+1}+w_{-1})\sin^2\theta^*/2$$

$$\Delta\rho = \frac{5}{2}\left(\langle\cos^2\theta^*\rangle - \frac{1}{3}\right)$$ Theta* method

$$\Delta\rho = -\frac{4}{3}\langle\cos[2(\phi^* - \Psi_{RP})]\rangle$$ Phi* method

$V \to l^+l^-$

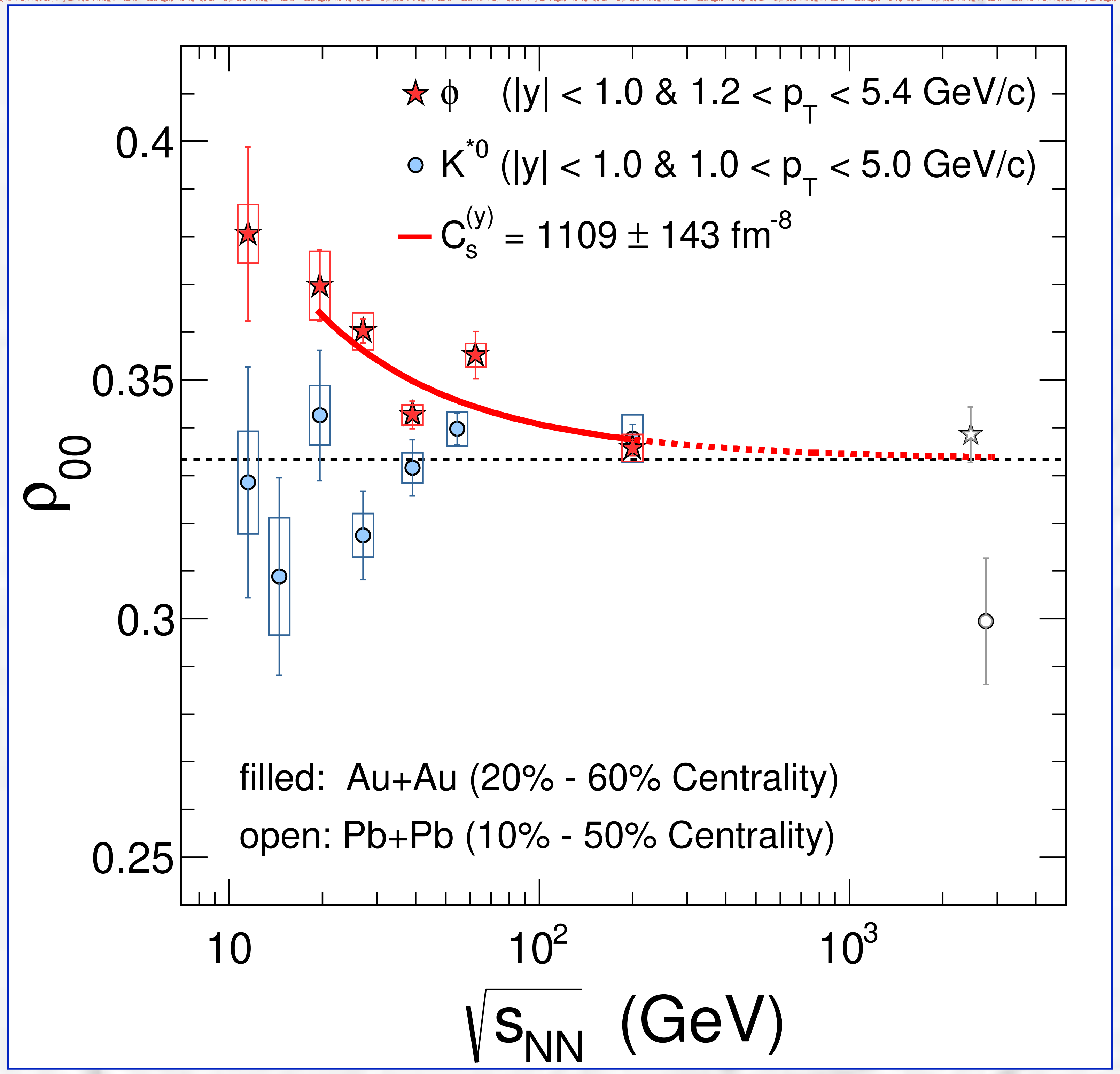
$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta + \lambda_\phi\sin^2\theta\cos 2\phi + \lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

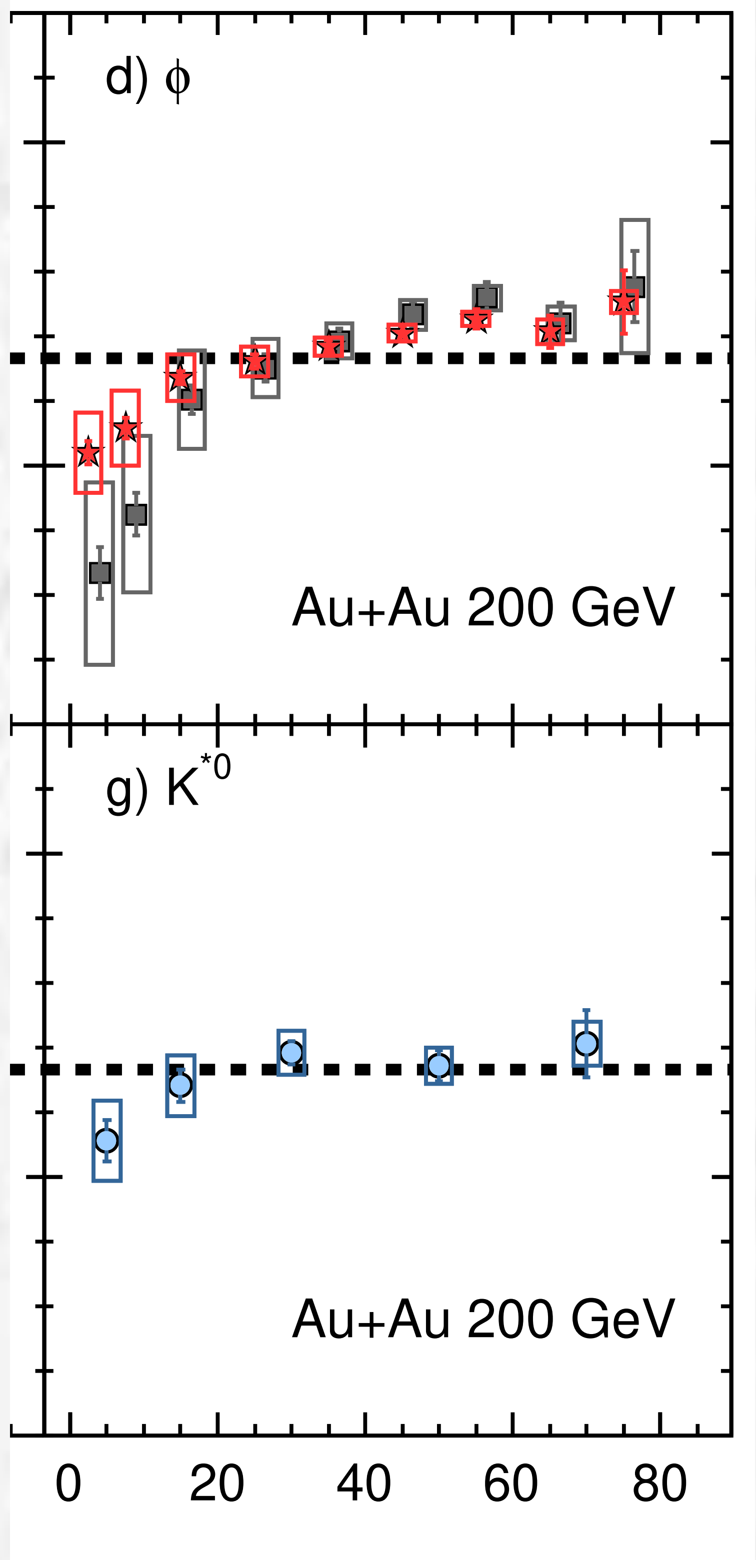
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

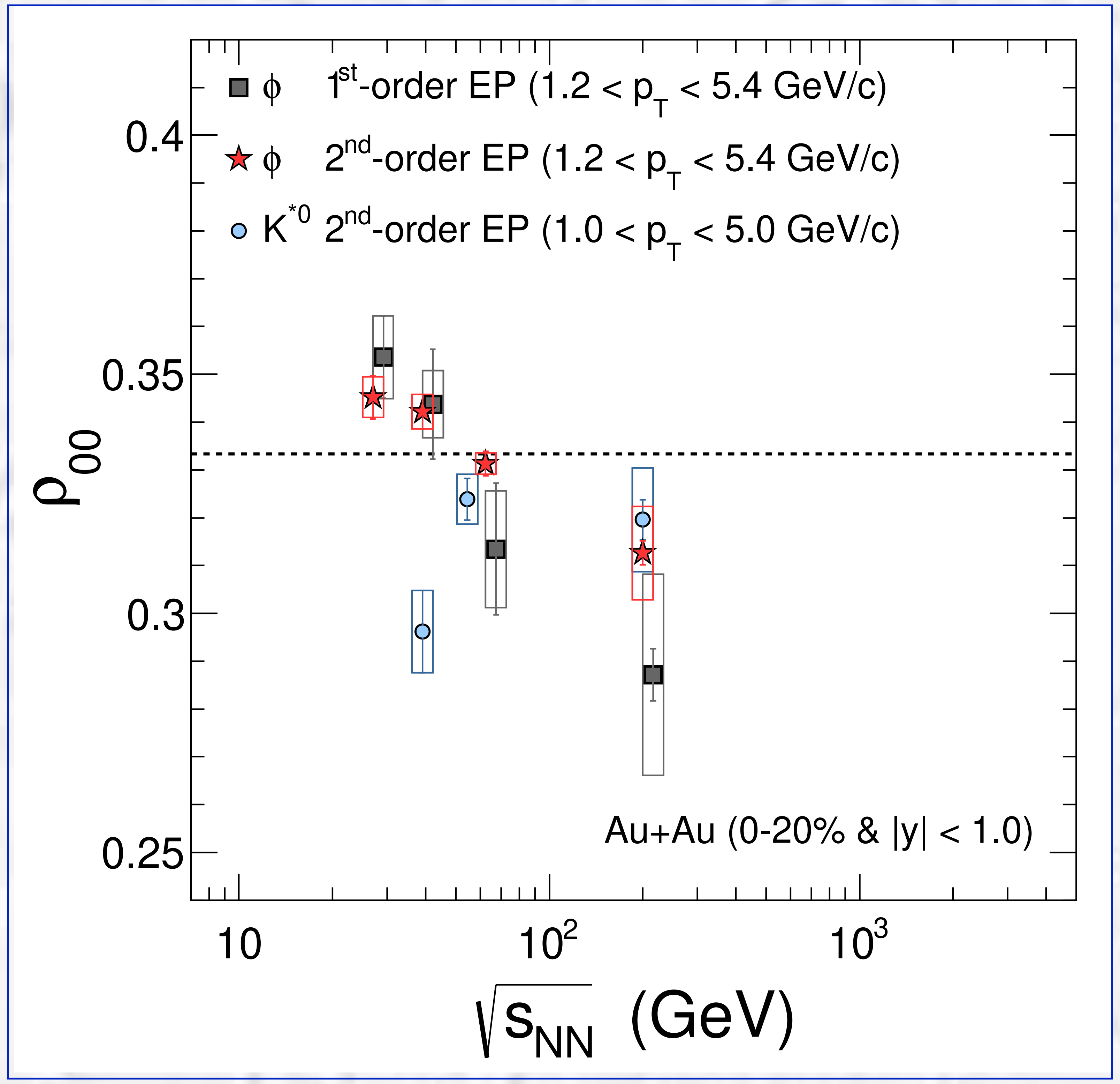
Unlike $K^{0*} \to K\pi$ and $\phi \to K^+K^-$, the daughters in $J/\psi \to l^+l^-$ have spin 1/2

Spin-alignment: STAR

Observation of Global Spin Alignment of ϕ and K^{*0} Vector Mesons in Nuclear Collisions (STAR Collaboration)







RHIC: Mean field of φ meson plays a role?
Does it change from RHIC to LHC?

One possibility for noticeable spin alignment might be strong, fluctuating in direction, polarization, e.g vorticity, (the mechanism discussed by B. Mueller).

This possibility might be checked with $\Lambda\Lambda$ correlations

X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)

X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

If it is related to the vorticity, it must depend on the direction. In mean field approach (as well as any others) -
what are the predictions for $\rho_{1,1}$ and $\rho_{-1,-1}$?

Helicity conservation and heavy resonance decays into vector mesons?

rapidity dependence of ρ_{00}

Spin alignment of D^{*+} vector mesons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV   ALICE Collaboration

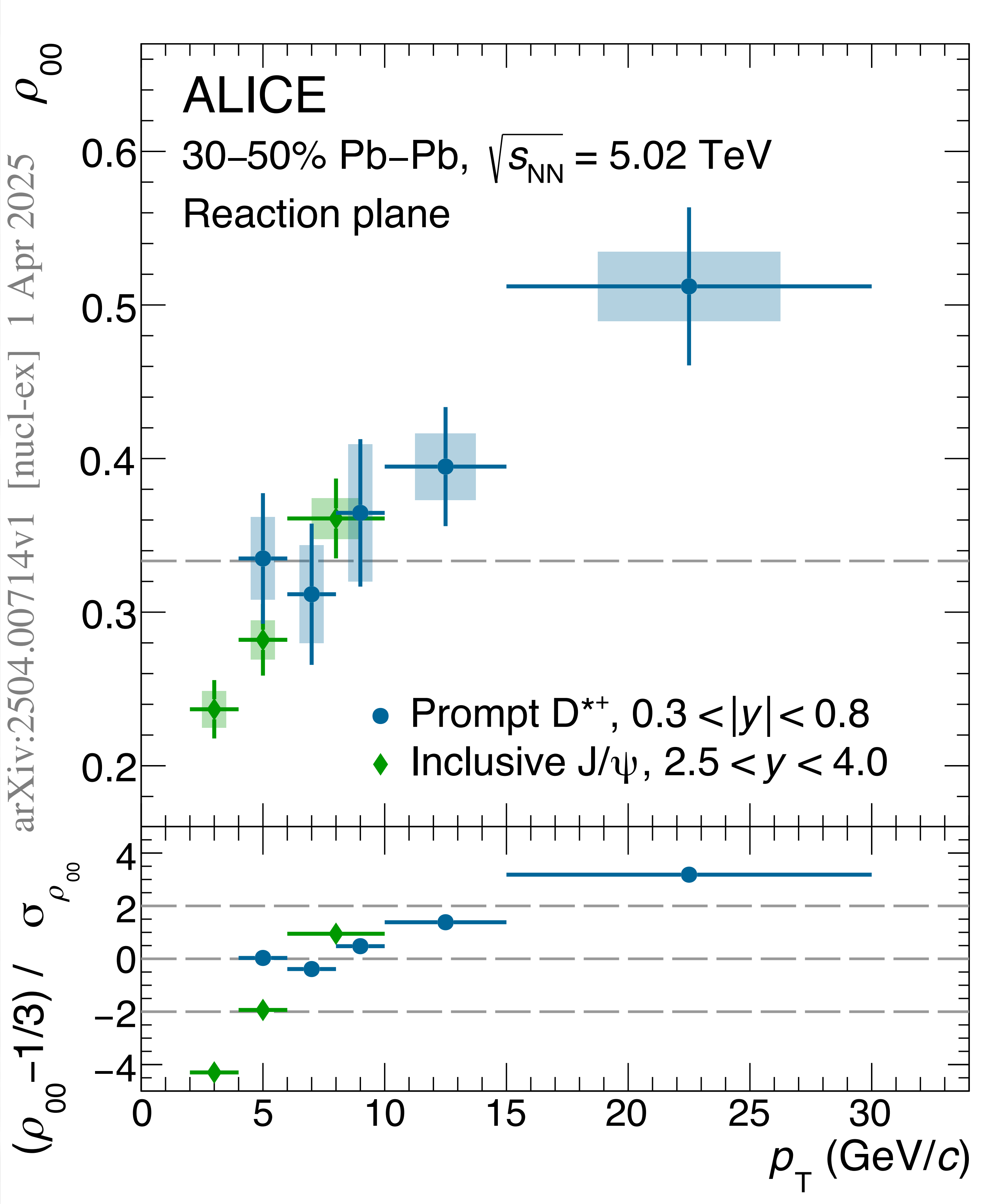


Fig. 5: The spin density matrix element ρ_{00} of prompt D^{*+} mesons as a function of p_T in the rapidity interval $0.3 < |y| < 0.8$ compared to that of inclusive J/ψ mesons in the rapidity interval $2.5 < y < 4$ measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 30–50% centrality class. The bottom panel shows the deviation of the measurements from the null hypothesis ($\rho_{00} = 1/3$) in units of the total uncertainties $\sigma_{\rho_{00}}$.

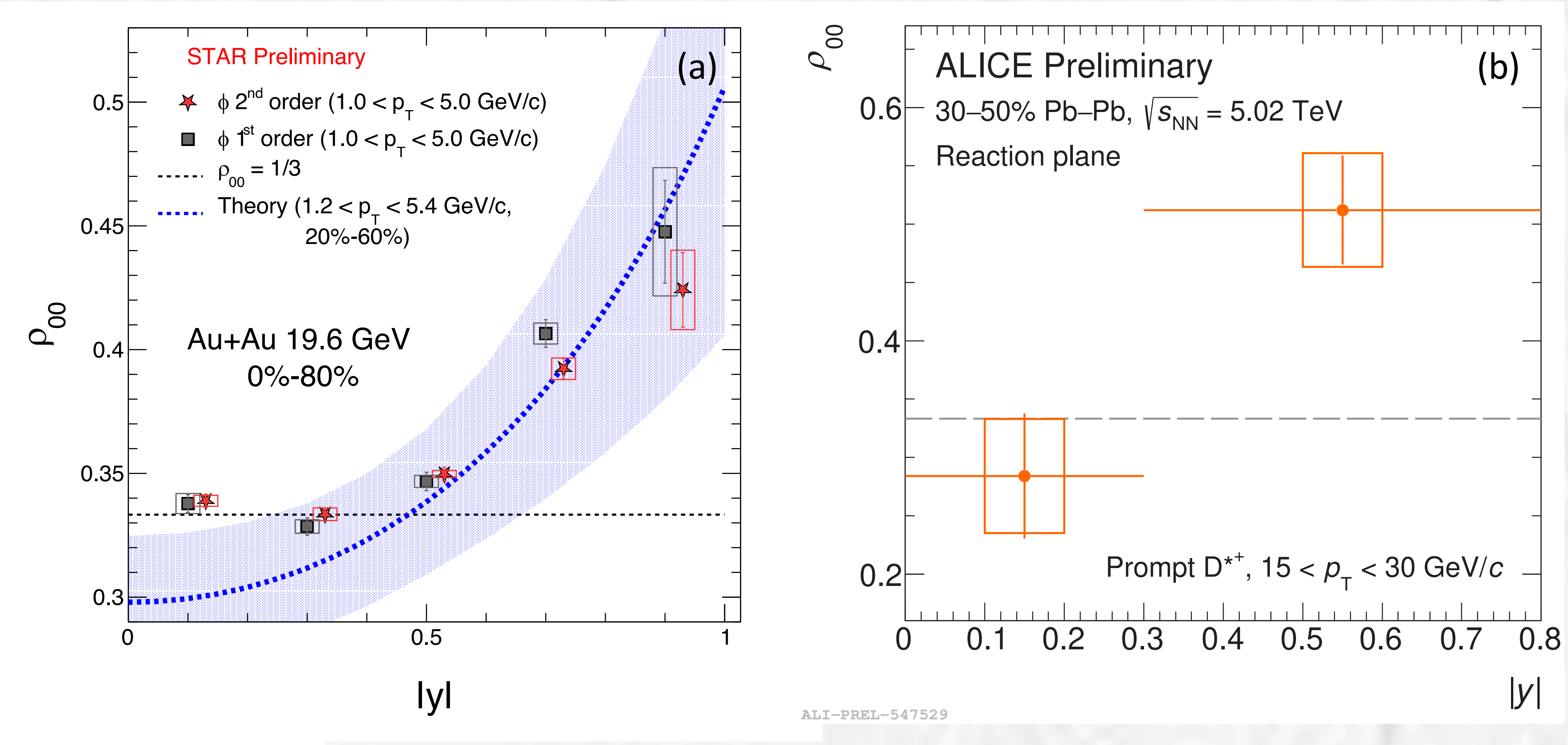


Figure 5. Rapidity dependenc of ρ_{00} measured by STAR [18] and ALICE [17].

EPJ Web of Conferences **296**, 01024 (2024) https://doi.org/10.1051/epjconf/202429601024
Quark Matter 2023

Aihong Tang[1,*]

[1]Brookhaven National Laboratory, Upton NY, USA

static medium calculations

PHYSICAL REVIEW D **110,** 056047 (2024)

Holographic spin alignment for vector mesons

Xin-Li Sheng[1,2,*] Yan-Qing Zhao[2,†] Si-Wen Li[3,‡] Francesco Becattini[4,§] and Defu Hou[2,∥]

PHYS. REV. D **110,** 056047 (2024)

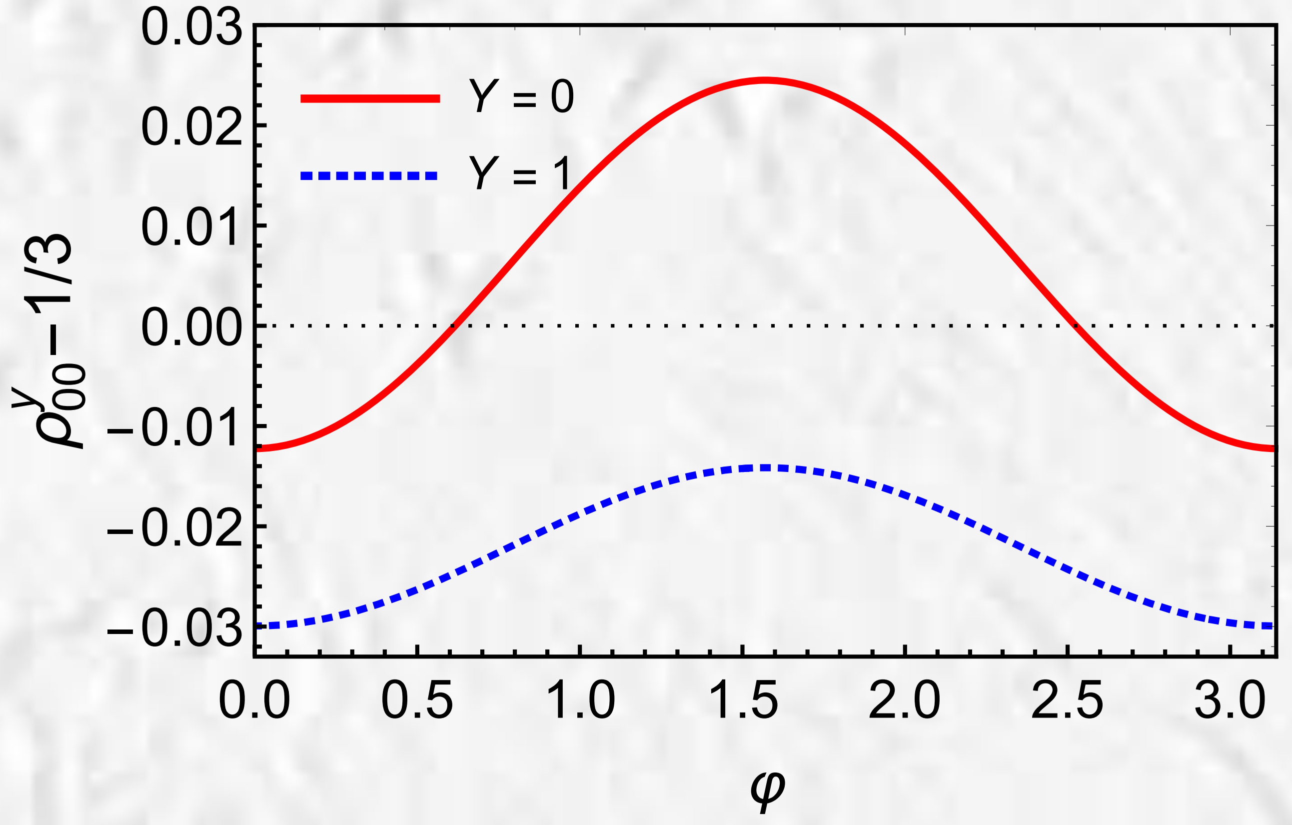


FIG. 3. The global spin alignment for J/ψ mesons with transverse momentum $p_T = 2$ GeV and rapidity $Y = 0$ (red solid line) or $Y = 1$ (blue dashed line), as functions of the meson's azimuthal angle φ.

where the superscripts h and y label different choices for ϵ_0. The global spin alignment is then calculated using Eqs. (11) and (12). It is straightforward to show that

$$\rho_{00}^{y}(x,\mathbf{p}) = \frac{1}{3} + \frac{3\rho_{00}^{h}(x,\mathbf{p})-1}{3|\mathbf{p}|^2}\left(p_y^2 - \frac{p_x^2+p_z^2}{2}\right), \quad (32)$$

which qualitatively agrees with the prediction of the quark coalescence model [19]. We plot in Fig. 3 ρ_{00}^{y} as functions of the meson's azimuthal angle, where the thermal background is assumed to be static while the meson's transverse momentum is fixed to $p_T = 2$ GeV and the longitudinal momentum is determined by the rapidity Y as $p_z = \sqrt{M^2 + p_T^2}\sinh(Y)$. We also fix the temperature as $T = 150$ MeV. For mesons at center rapidity $Y = 0$, the

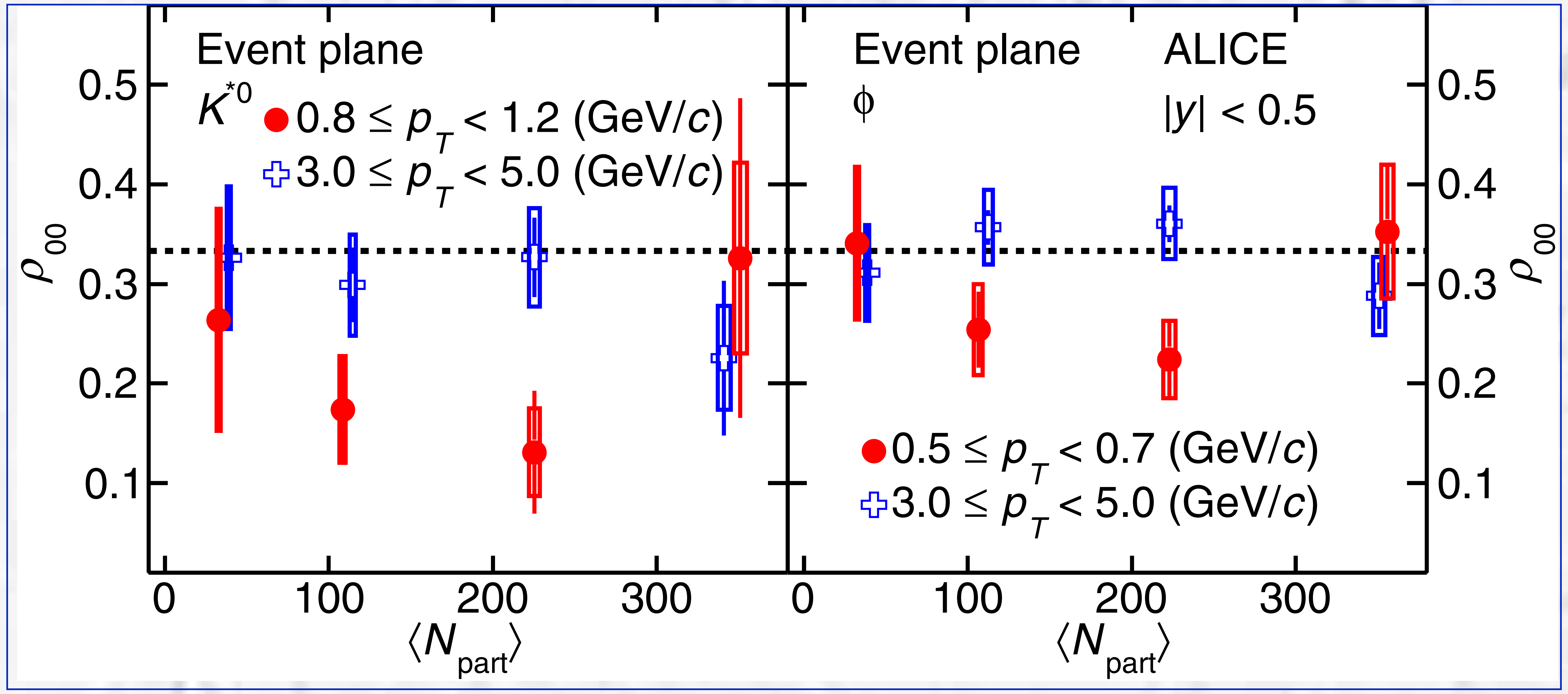
Spin-alignment: ALICE

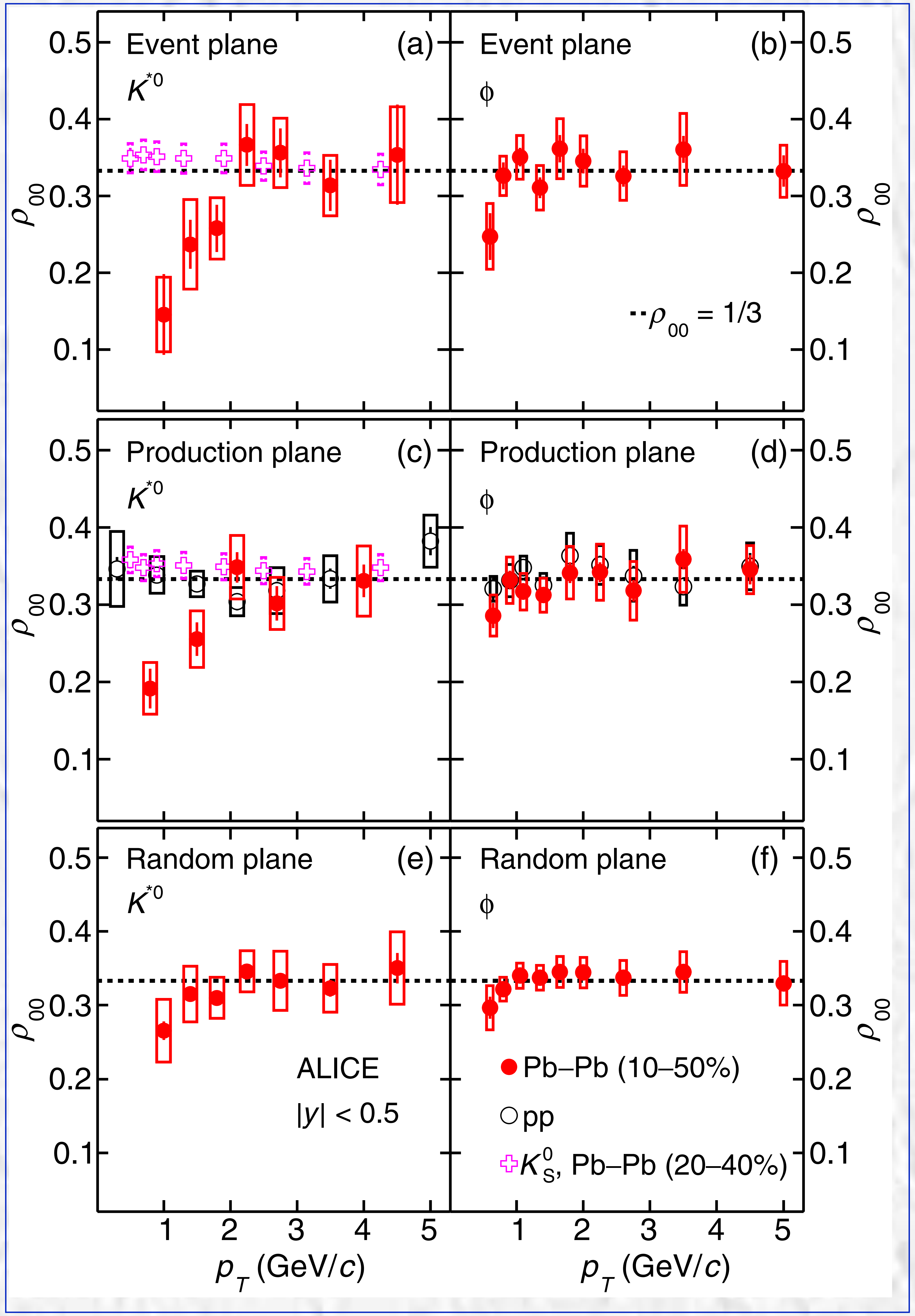
PHYSICAL REVIEW LETTERS **125,** 012301 (2020)

Editors' Suggestion

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

S. Acharya *et al.*[*]
(The ALICE Collaboration)





Thermal model:

$\rho_{00} = 0.15 \Rightarrow w(s_z = +1) = 0.82,$
$w(0) = 0.15, w(-1) = 0.03$

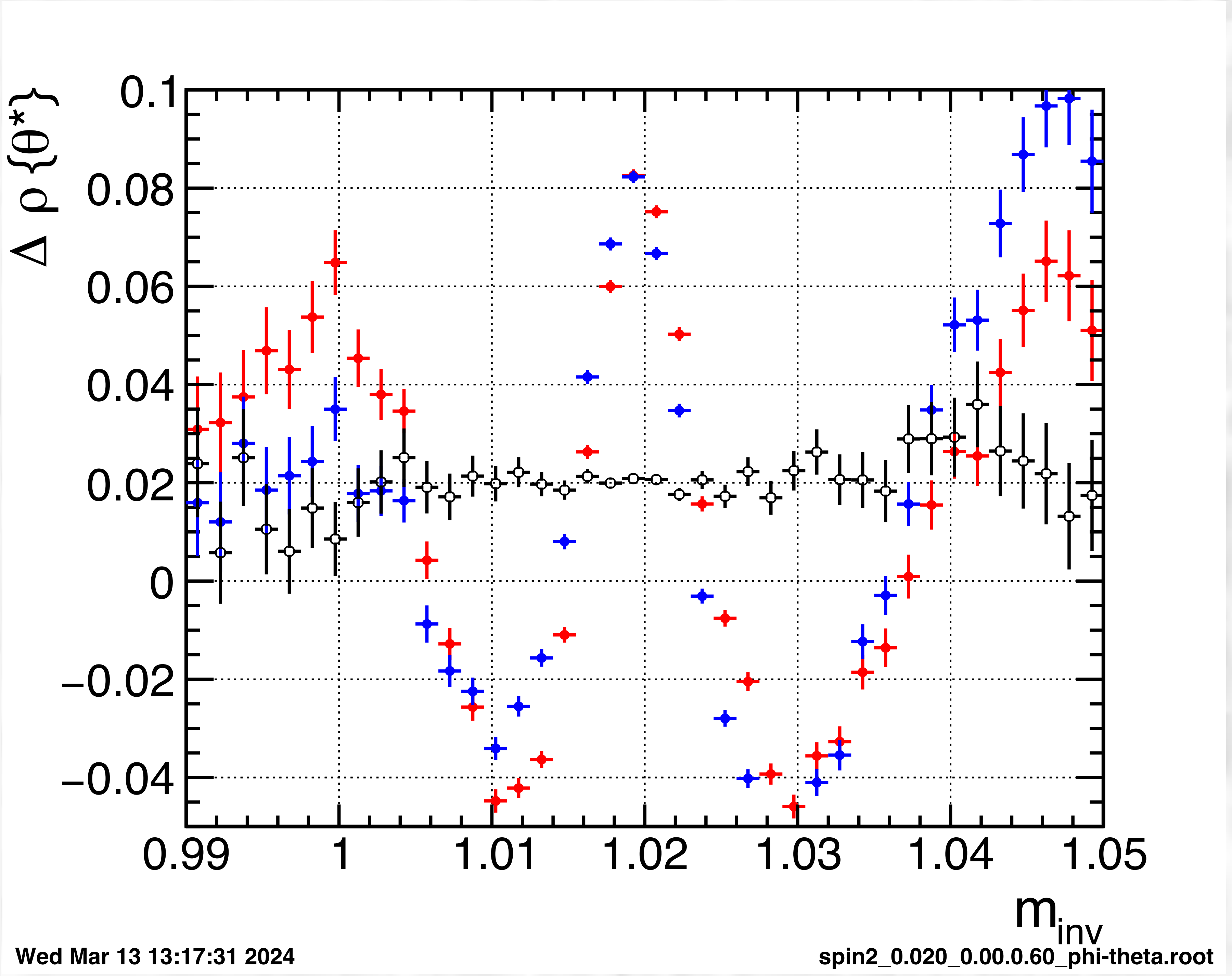
Spin alignment and efficiency, momentum resolution

Unlike the hyperon polarization case, the spin alignment non-zero result might be totally due "wrong" acceptance correction value.

Different approaches and methods and different correction procedures should lead to the same result.

Using theta* / using phi*
Invariant mass, / signal+background
Yield vs phi / moments of the distribution
Understanding momentum resolution effects
Efficiency from data / Monte-Carlo

spin alignment: momentum resolution effect



Impact of Tracking Resolutions on ϕ-Meson Spin Alignment Measurement

C.W. Robertson,[1] Yicheng Feng,[1] and Fuqiang Wang[1]

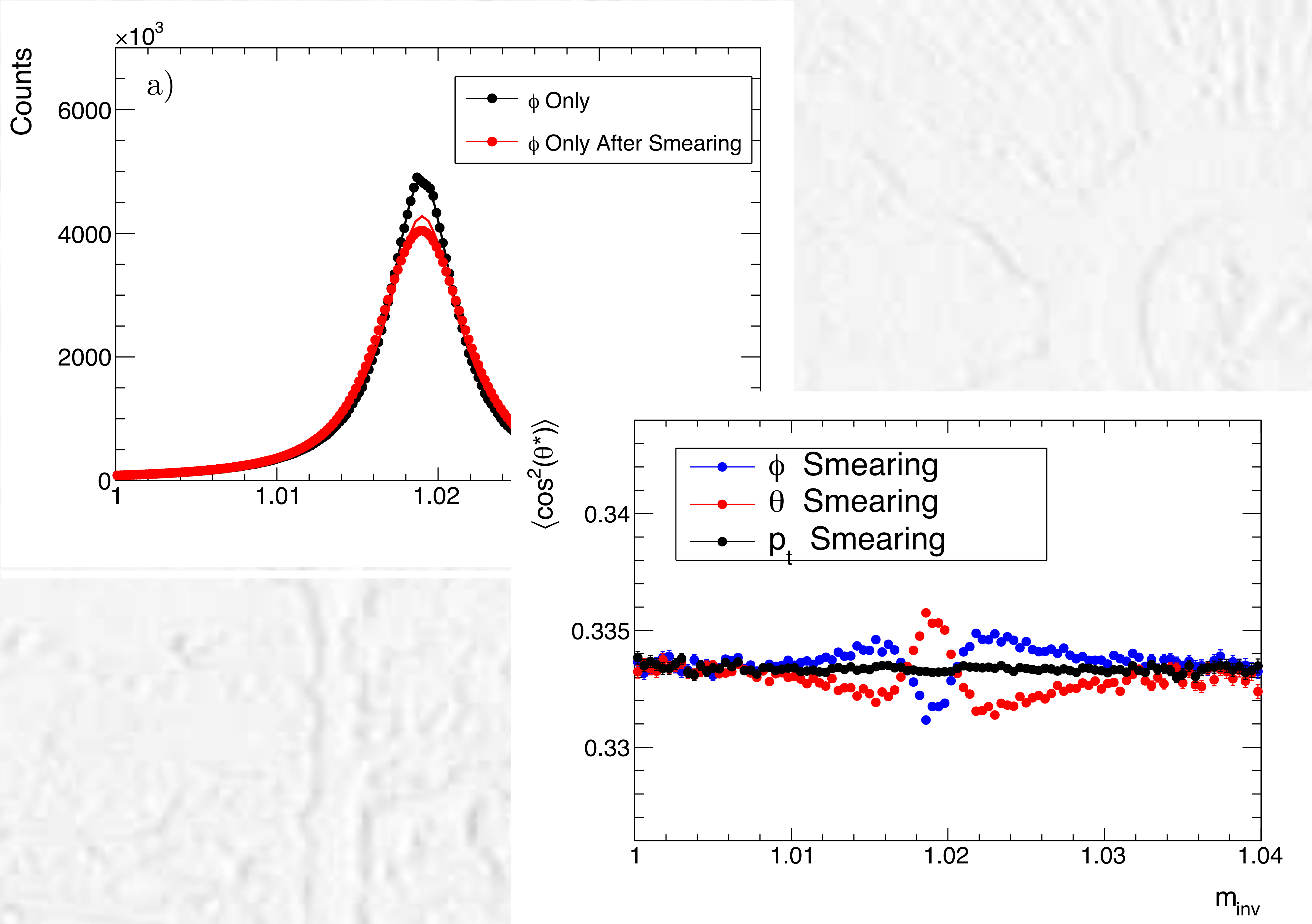


FIG. 3. (Color online) Effects of smearing for θ (red markers), ϕ (blue markers), and $p_\perp$ (black markers), separately, on $\langle\cos^2\theta^*\rangle$ for true ϕ-mesons. The effect of momentum smearing is insignificant compared to those of angular smearing.

Spin alignment and elliptic flow

[nucl-th/0410089] Polarized secondary particles in unpolarized high energy hadron-hadro...

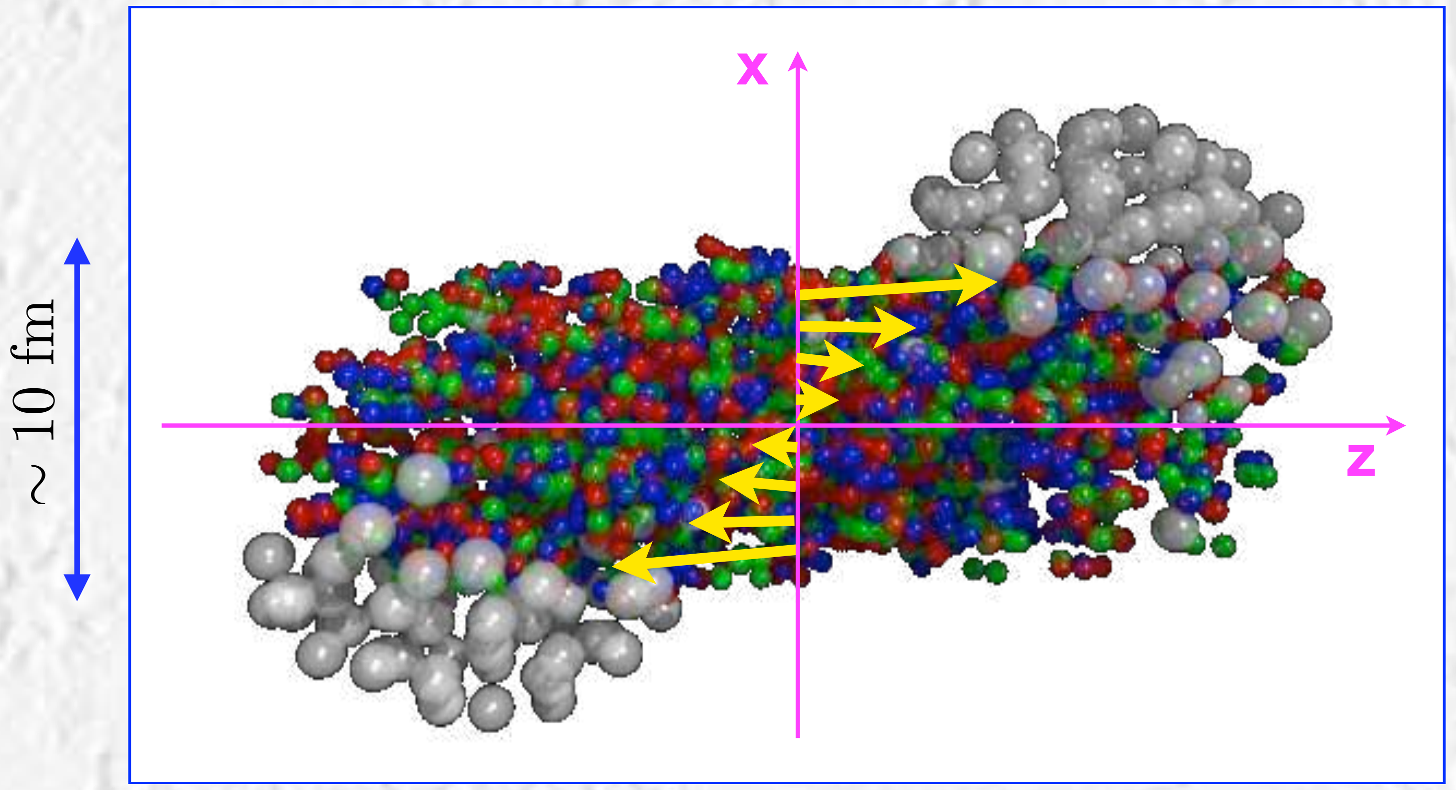
Authors: Sergei A. Voloshin

(Submitted on 21 Oct 2004)

$\rho^0 \longrightarrow \pi^+\pi^-$ $\quad s_y = 1 \longrightarrow l_y = 1$

$\Updownarrow$

$\pi^+\pi^- \longrightarrow \rho^0$ $\quad l_y = 1 \longrightarrow s_y = 1$



angular distribution $\propto \sin^2\theta$, where θ is the angle relative to the spin direction (in the resonance rest frame), and consequently $\propto \cos(2\phi)$, where the angle ϕ is now the azimuthal angle with respect to the reaction plane, and thus would contribute to the elliptic flow (modulo distortions due to transformation from the resonance rest frame). Such an additional contribution could probably explain the very strong elliptic flow observed at RHIC (recall, that in transverse momentum region, $p_t \sim 3$ GeV/c elliptic flow at RHIC can not be explained by any model [4]).

pion elliptic flow from rho decays

$$\frac{dN}{d\cos\theta^*} \propto w_0|Y_{1,0}|^2 + w_{+1}|Y_{1,1}|^2 + w_{-1}|Y_{1,-1}|^2 \propto w_0\cos^2\theta^* + (w_{+1} + w_{-1})\sin^2\theta^*/2$$

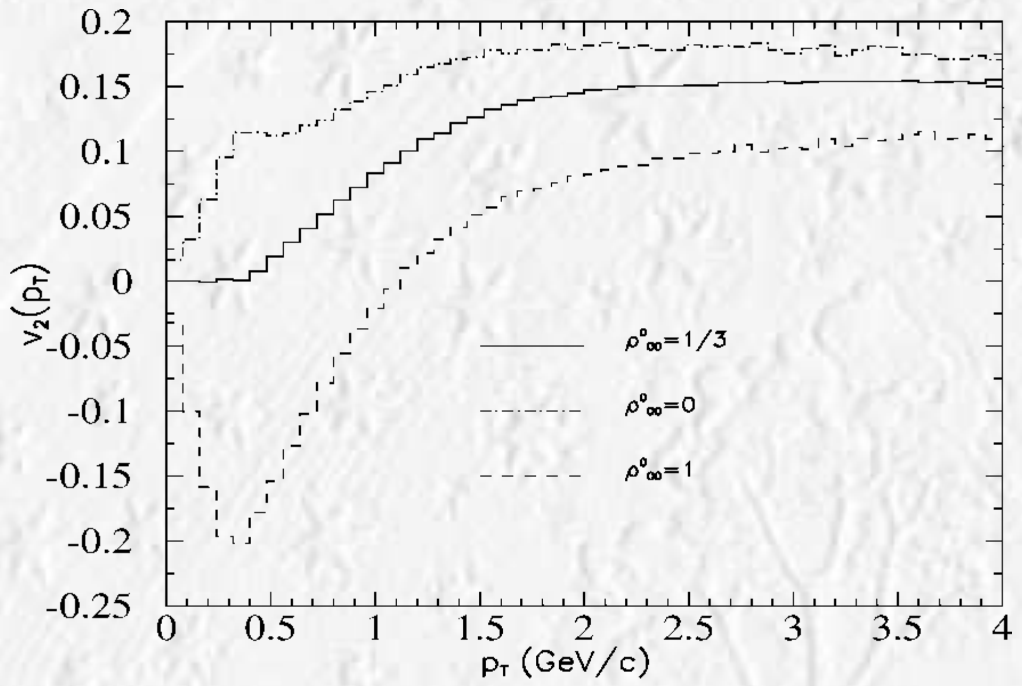


Fig. 1. Azimuthal anisotropy v_2 of pions from the decay of ρ vector mesons that have spin alignment according to Eq. (13) with $\rho^0_{00} = 1/3$ (solid line), 0 (dot-dashed line) and 1 (dashed line).

NSM: $\rho_{00} \approx \dfrac{1}{3 + (\omega/T)^2}$

$$\rho_{00}^{\rho\,(\mathrm{rec})} = \frac{1 - P_q^2}{3 + P_q^2},$$

$$\rho_{00}^{V\,(\mathrm{frag})} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}$$

Z.-T. Liang, X.-N. Wang / Physics Letters B 629 (2005) 20–26

v_2 of pions from 100% polarized rho decays is ~20%!

P_x : SIP vs vorticity

SIP:

$$S_i^{(\xi)} \approx \frac{1}{4T}\frac{1}{mE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j u_m + \partial_m u_j)$$

$$\propto \sin[2(\phi_h^* - \Psi_2)]$$

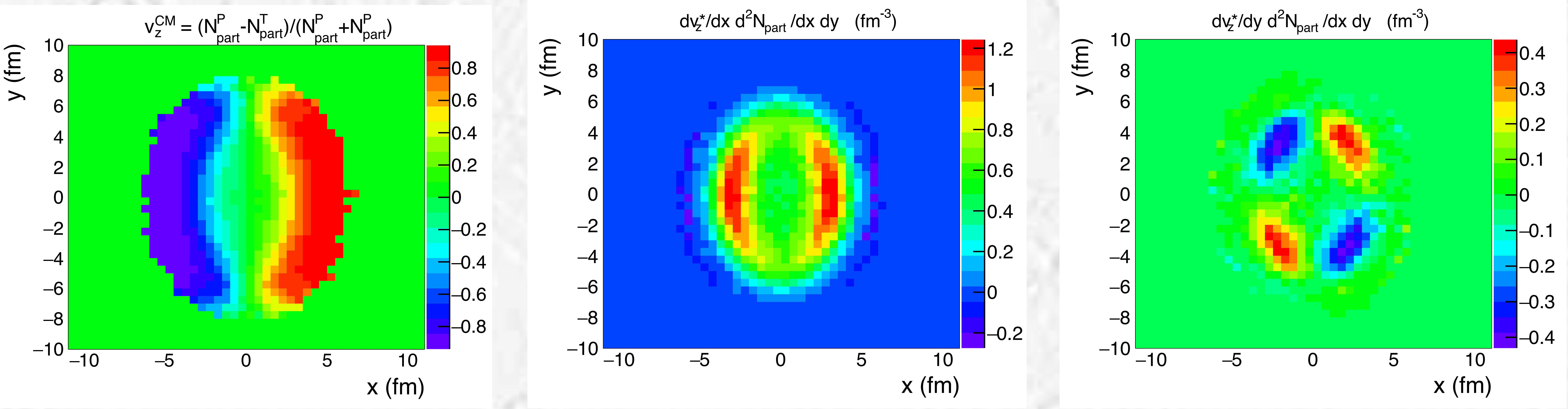
u_i - fluid velocity
Star denotes the value in the rest frame of fluid element

$$S_i^{(\omega)} \approx \frac{1}{8T}\epsilon_{ikj}\frac{1}{2}(\partial_k u_j - \partial_j u_k)$$

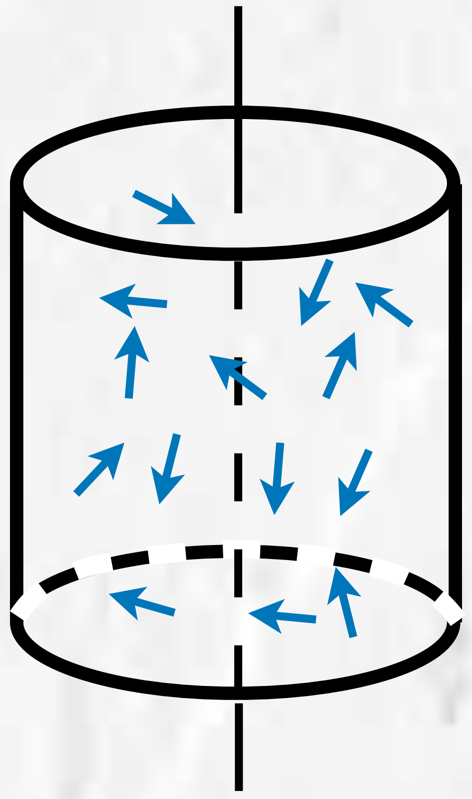
Vorticity

Will be difficult to separate the two contributions

$$\propto \sin[2(\phi_h - \Psi_2)]$$



"Microcanonical" approach



N spin 1/2 particles in a cylinder,

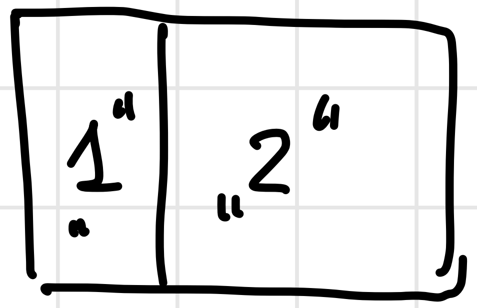
$S_z + L_z = J_z = \text{const}$

$E = \text{const}$

$S_z - ?$

$g(E)$ – # of microstates

$\sigma = \ln g$ – entropy



$E_1 + E_2 = E = \text{const}$

$g_{12} = g_1(E_1) \cdot g_2(E_2)$

$$\frac{d\sigma_{12}}{dE_1} = 0 = \frac{d\sigma_1}{dE_1} - \frac{d\sigma_2}{dE_2}$$

$$\Rightarrow \frac{d\sigma_1}{dE_1} = \frac{d\sigma_2}{dE_2}; \quad \frac{d\sigma}{dE} \equiv \frac{1}{T}$$

$$J_z = S_z + L_z = \text{const}$$

$$\sigma = \sigma_S + \sigma_L$$

$$N = U + D; \quad \frac{1}{2}(U - D) = S_z$$

$$\sigma = \ln \frac{N!}{U!\,D!} = N \ln N - U \ln U - D \ln D$$

$$U = \frac{N}{2} + S_z; \quad D = \frac{N}{2} - S_z$$

$$\frac{d\sigma}{dS_z} = -\ln U - 1 + \ln D + 1 =$$

$$= -\ln\left(1 + \frac{2S_z}{N}\right) + \ln\left(1 - \frac{2S_z}{N}\right)$$

$$= -\frac{4S_z}{N}$$

$$\sigma_L = \sigma_0\left(E - \frac{L^2}{2I}\right)$$

$$\frac{d\sigma}{dL} = 0 = \frac{d\sigma_0}{dL} - \frac{d\sigma}{dS_z} = 0$$

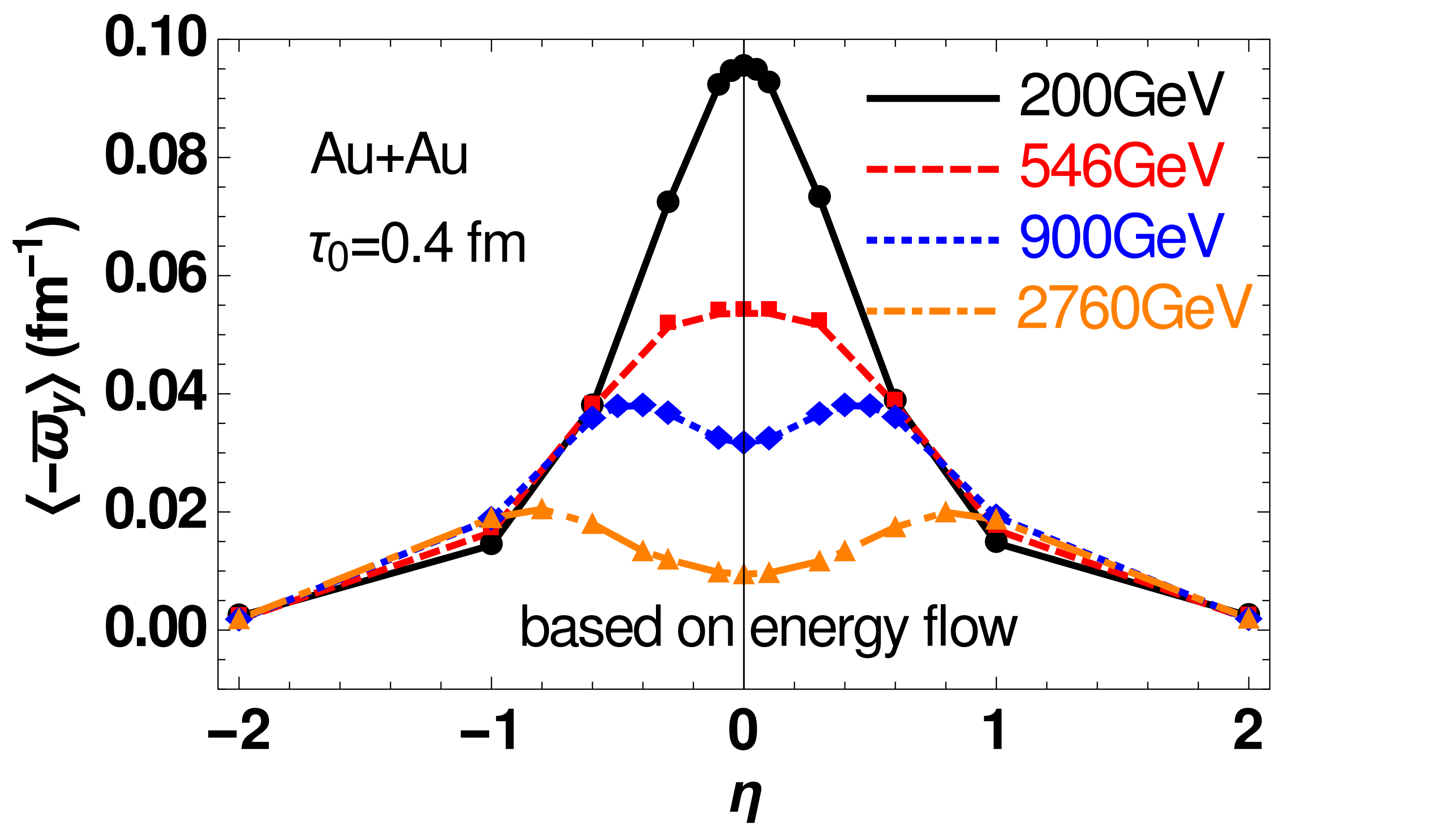
$$\frac{\partial\sigma_0}{\partial E}\left(-\frac{2L}{2I}\right) + \frac{4S_z}{N} = 0$$

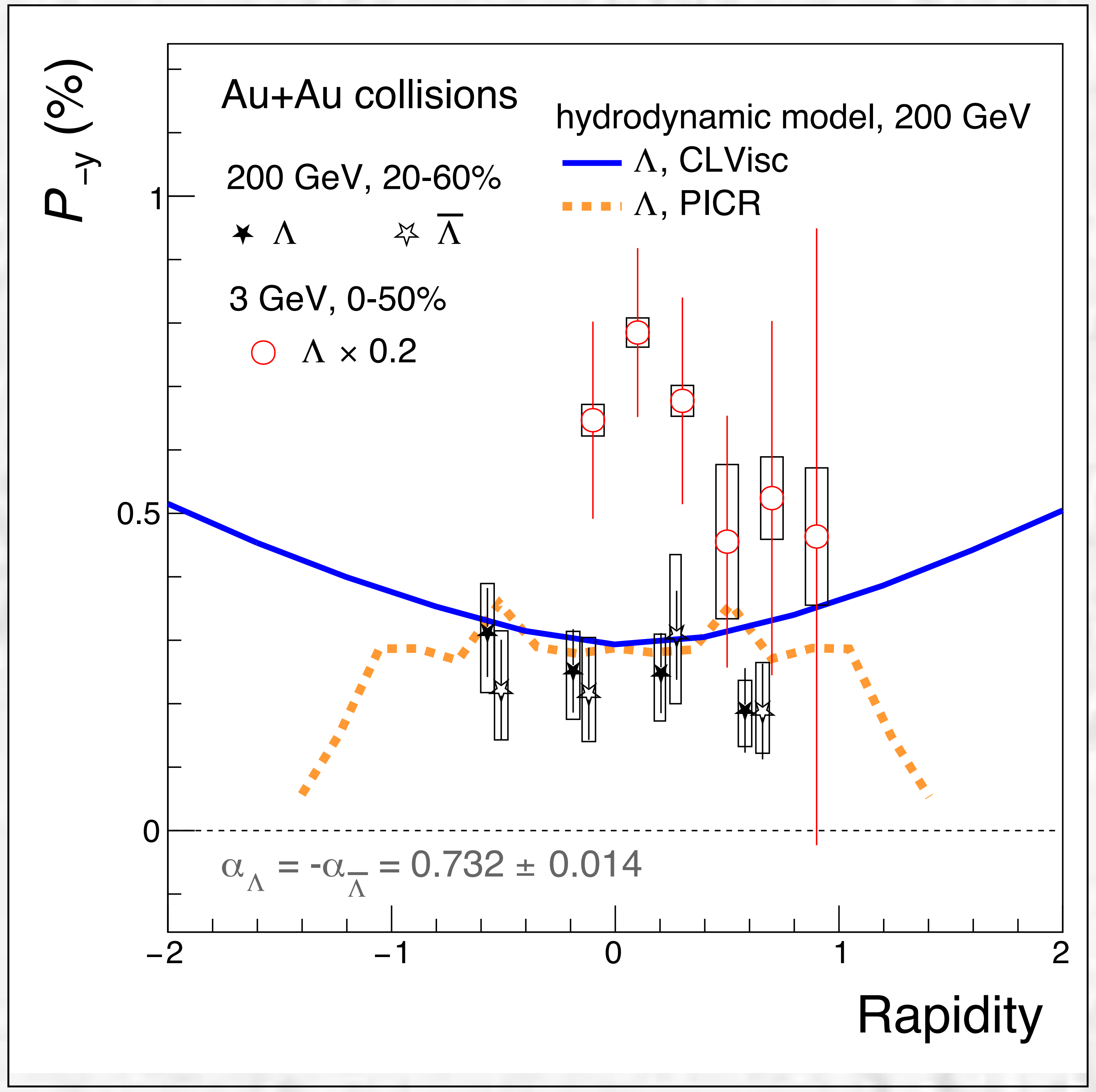
$$-\frac{\omega}{T} + \frac{4S_z}{N} = 0$$

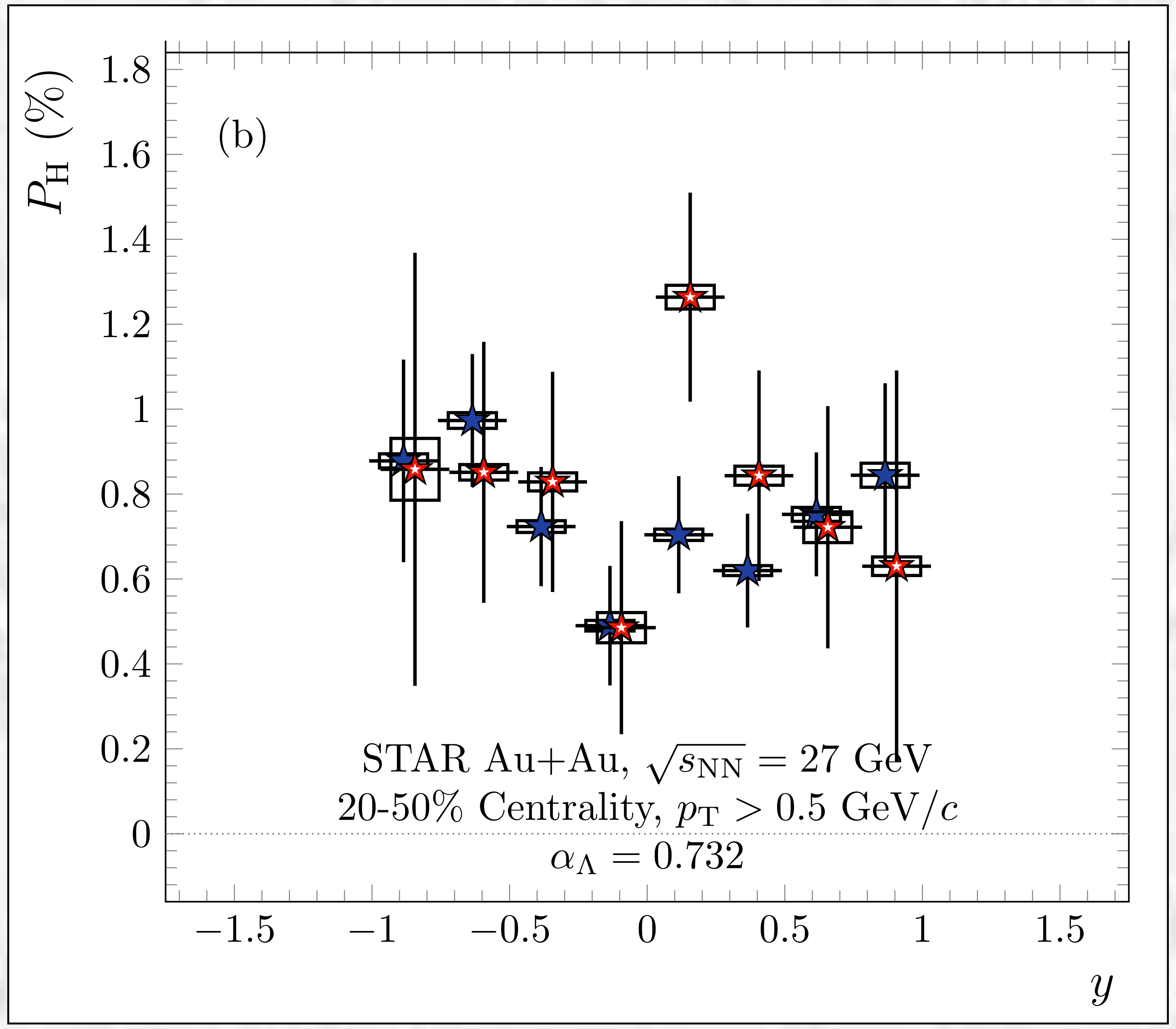
$$\boxed{\frac{S_z}{N} = \frac{\omega}{4T}}$$

Global polarization, rapidity dependence

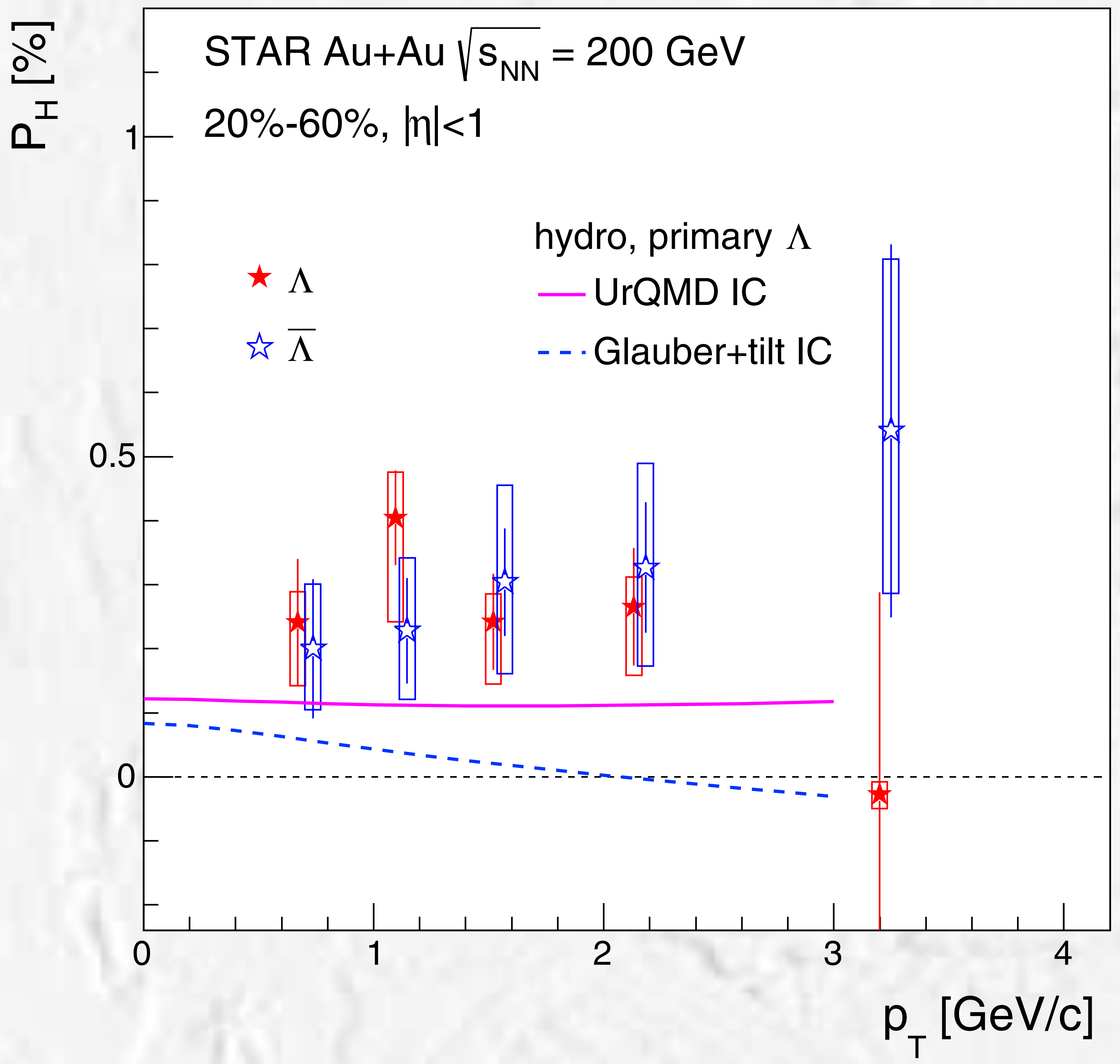
W.T.Feng and X.G.Huang, PRC93.064907 (2016)

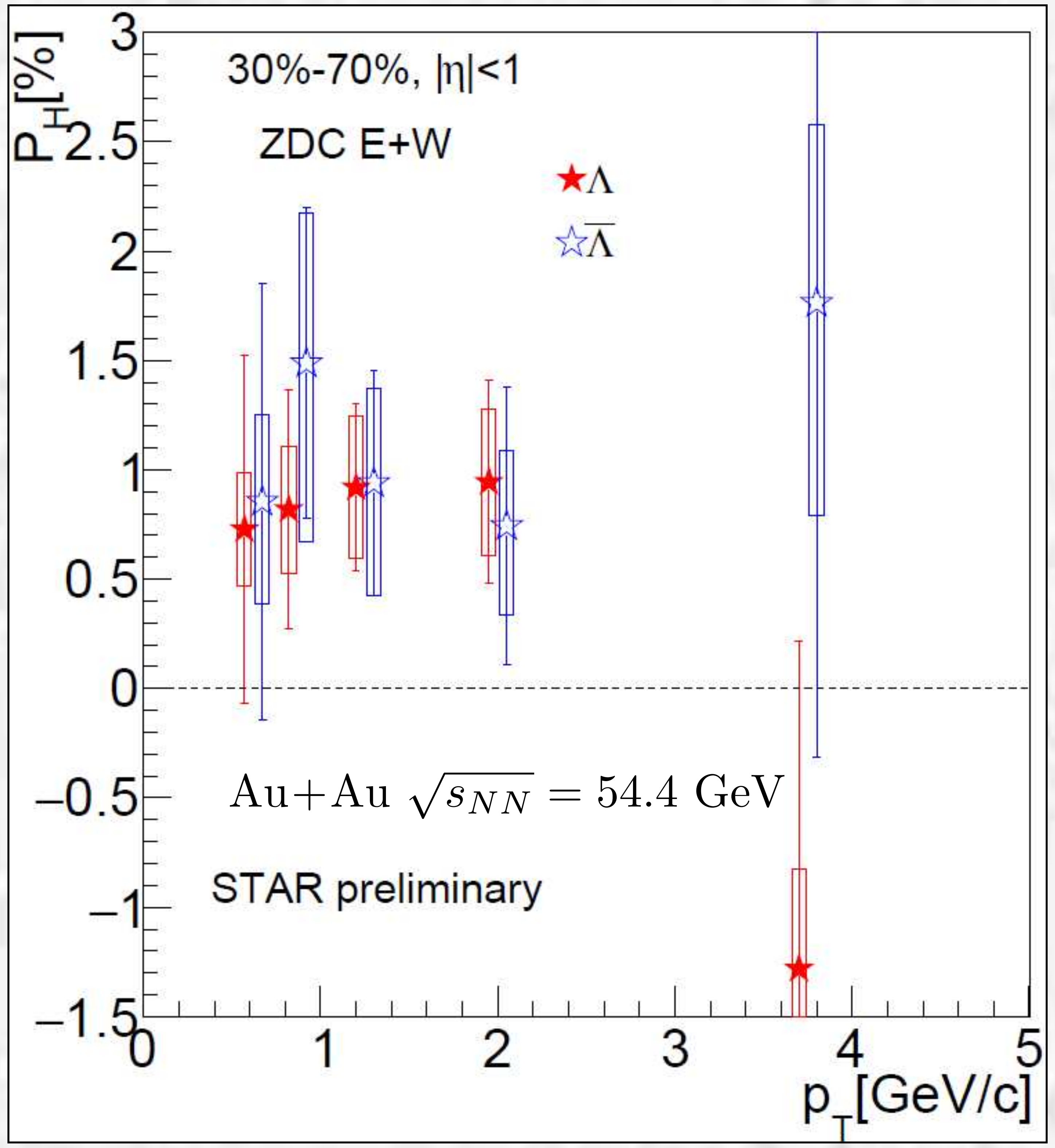


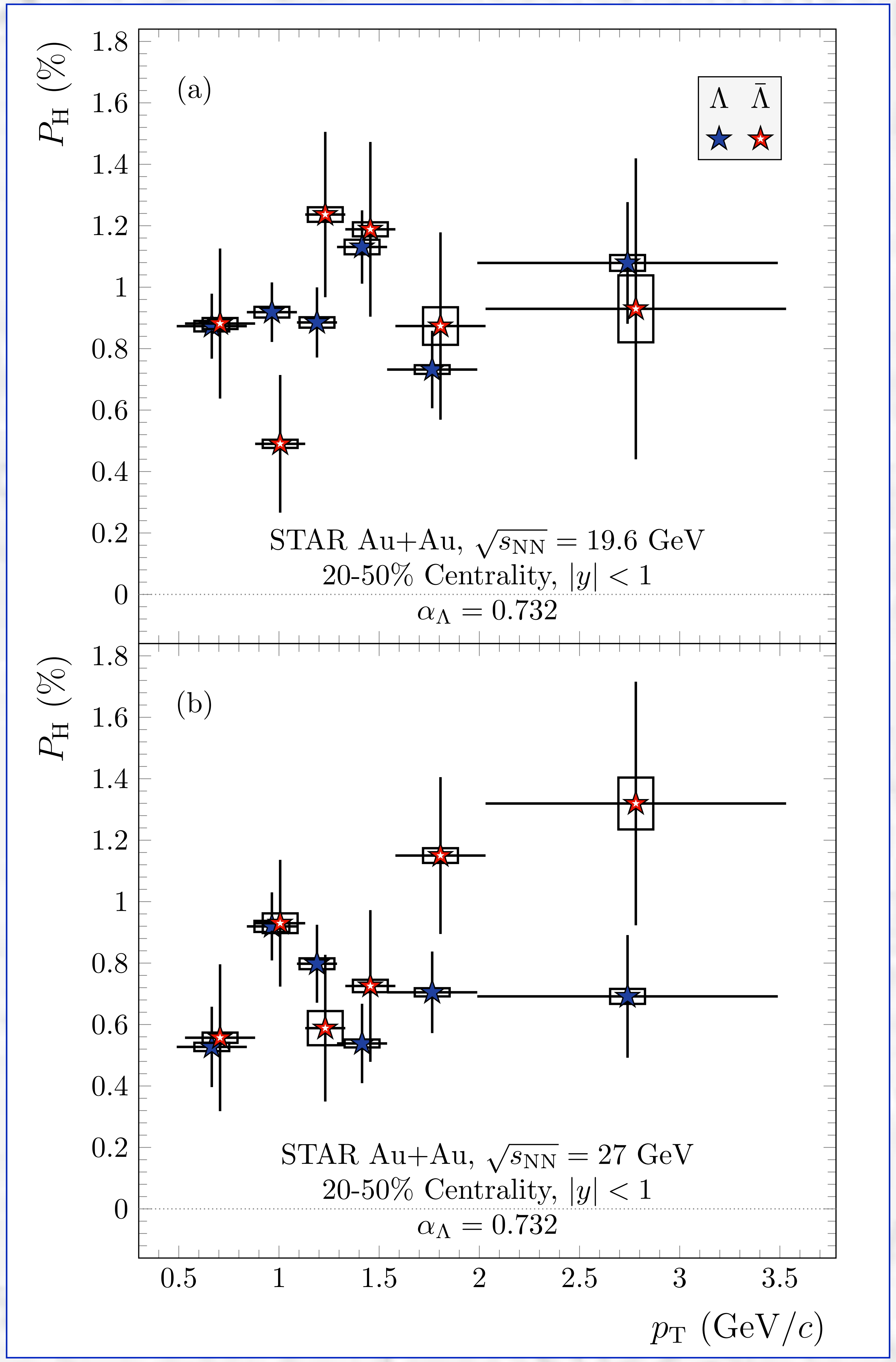




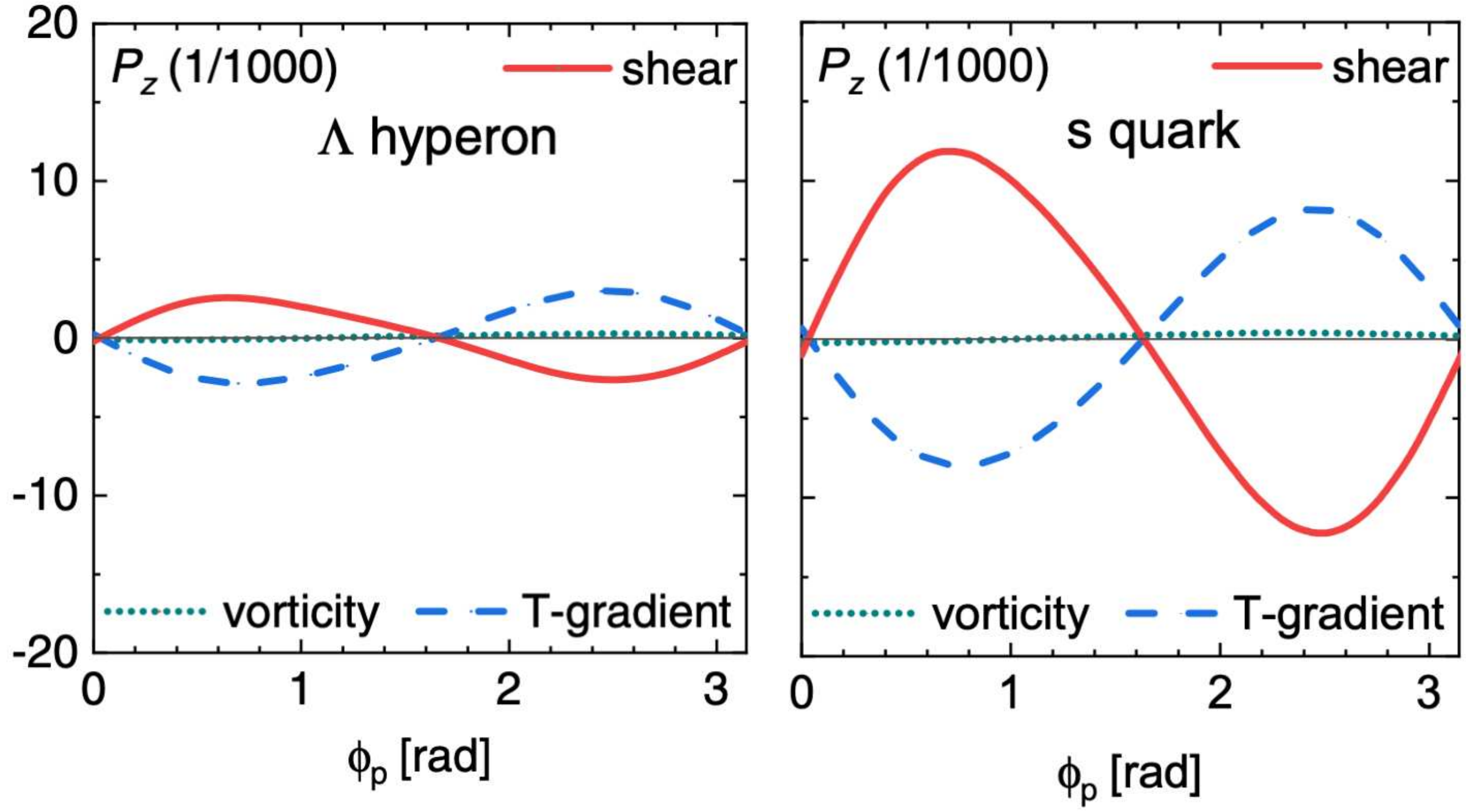
Global polarization, p_T dependence







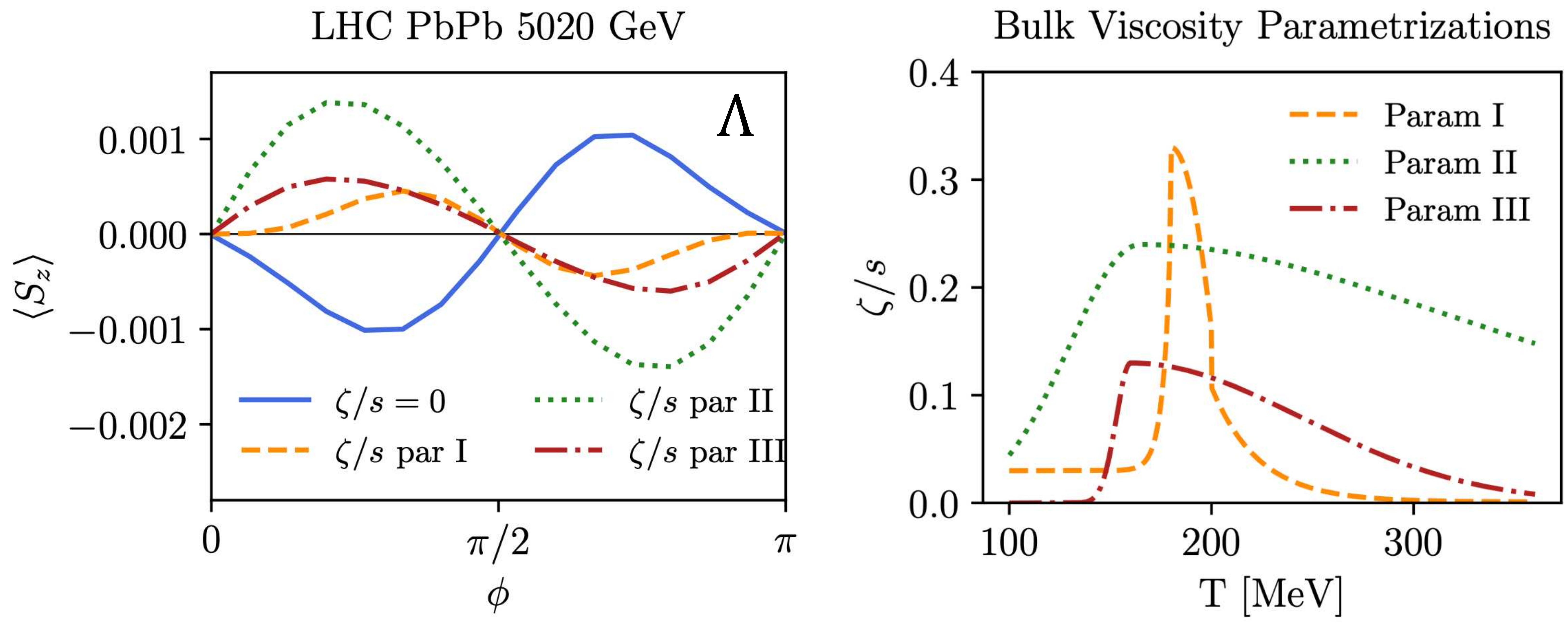
Weak p_T dependence (as expected?)



- The SIP contribution competes with thermal vorticity effects
- SIP contribution prevails in the scenario that **Λ inherits the strange quark spin polarisation** at the hadronisation stage → qualitative **agreement with data** (correct polarization sign)

B. Fu *et al.* PRL 127, 142301 (2021)

$$S_i^{(\text{shear})} \approx \frac{1}{4mTE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j v_m + \partial_m v_j)$$

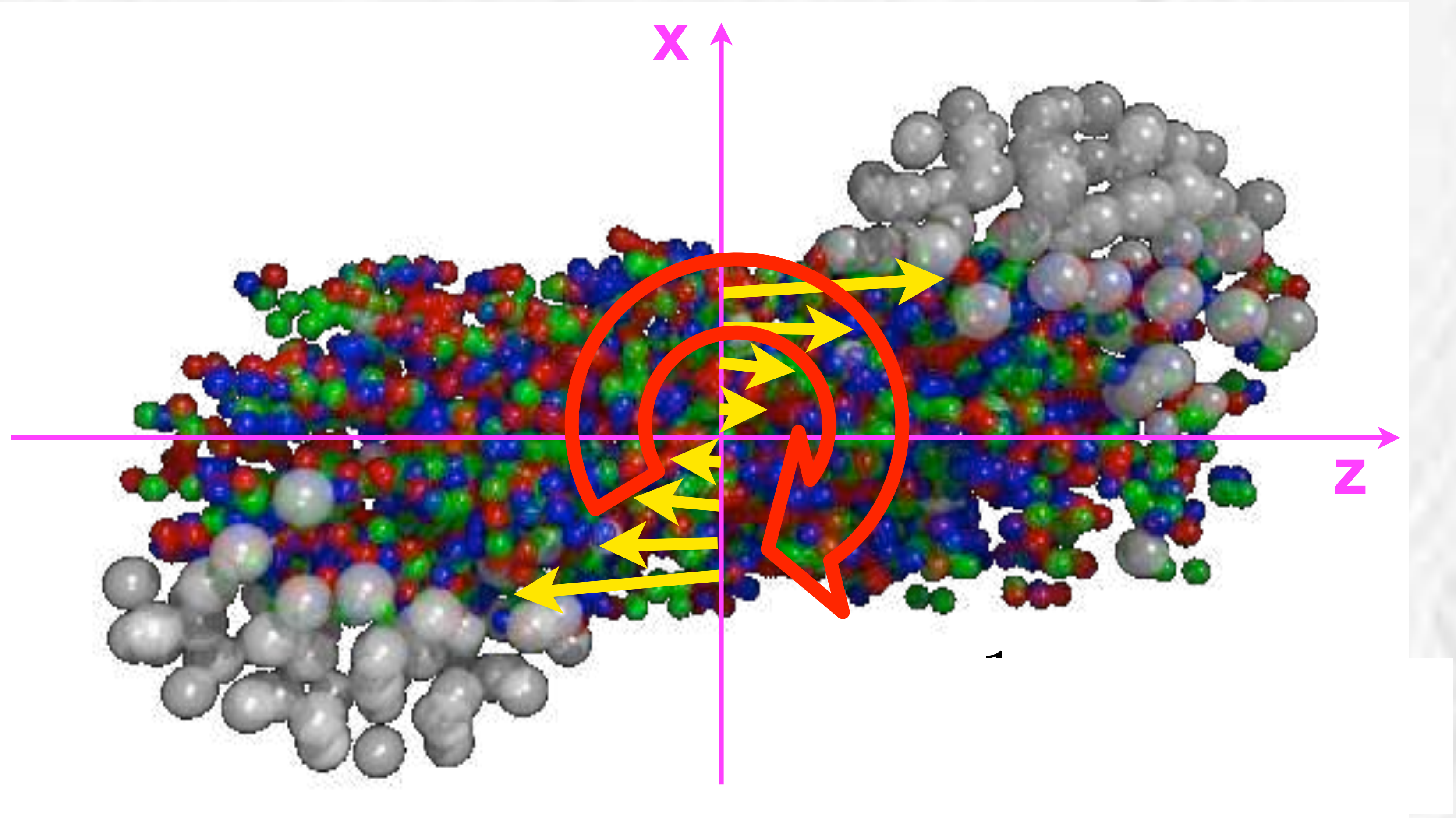


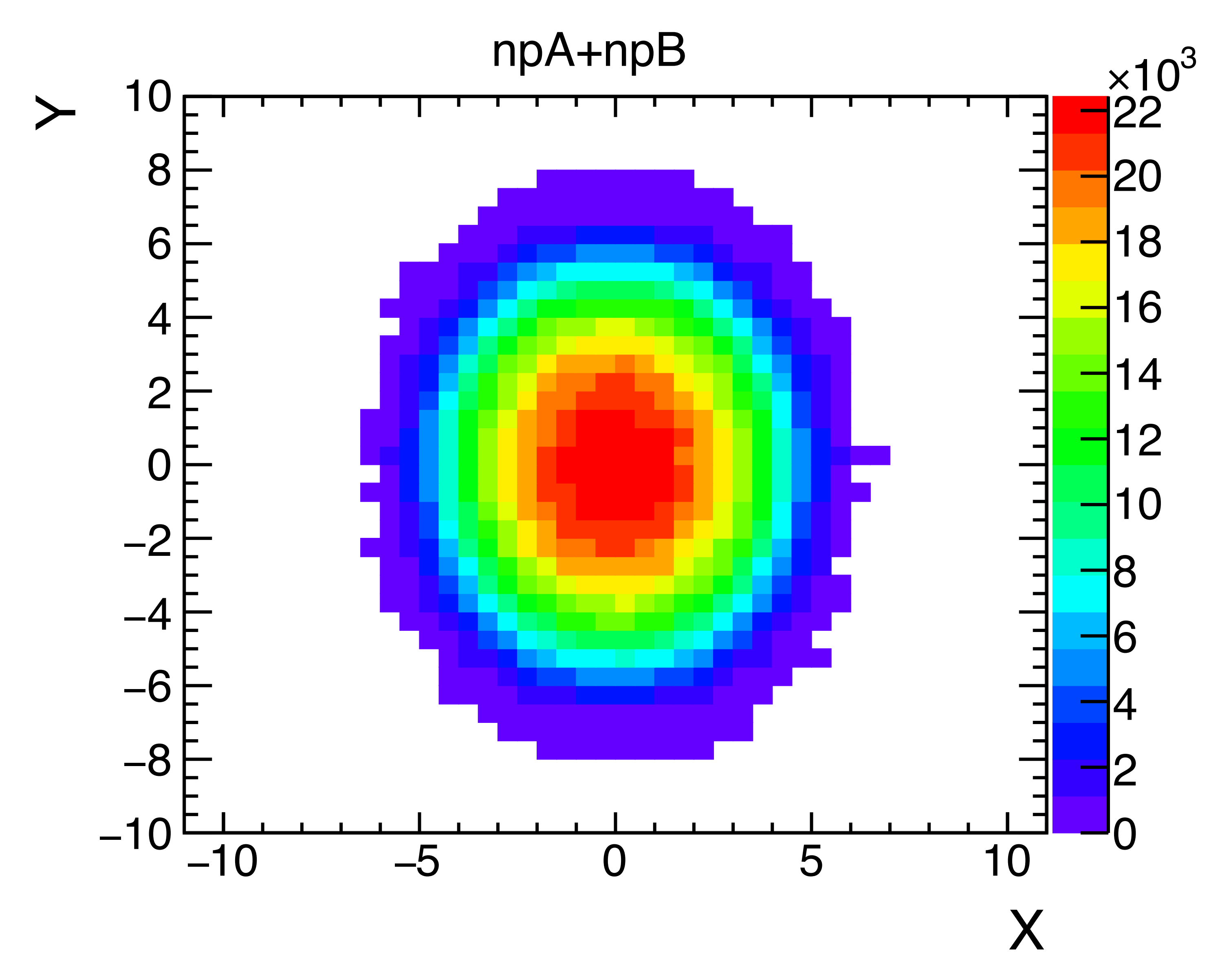
A. Palermo *et al.* EPJC **84**, 920 (2024)

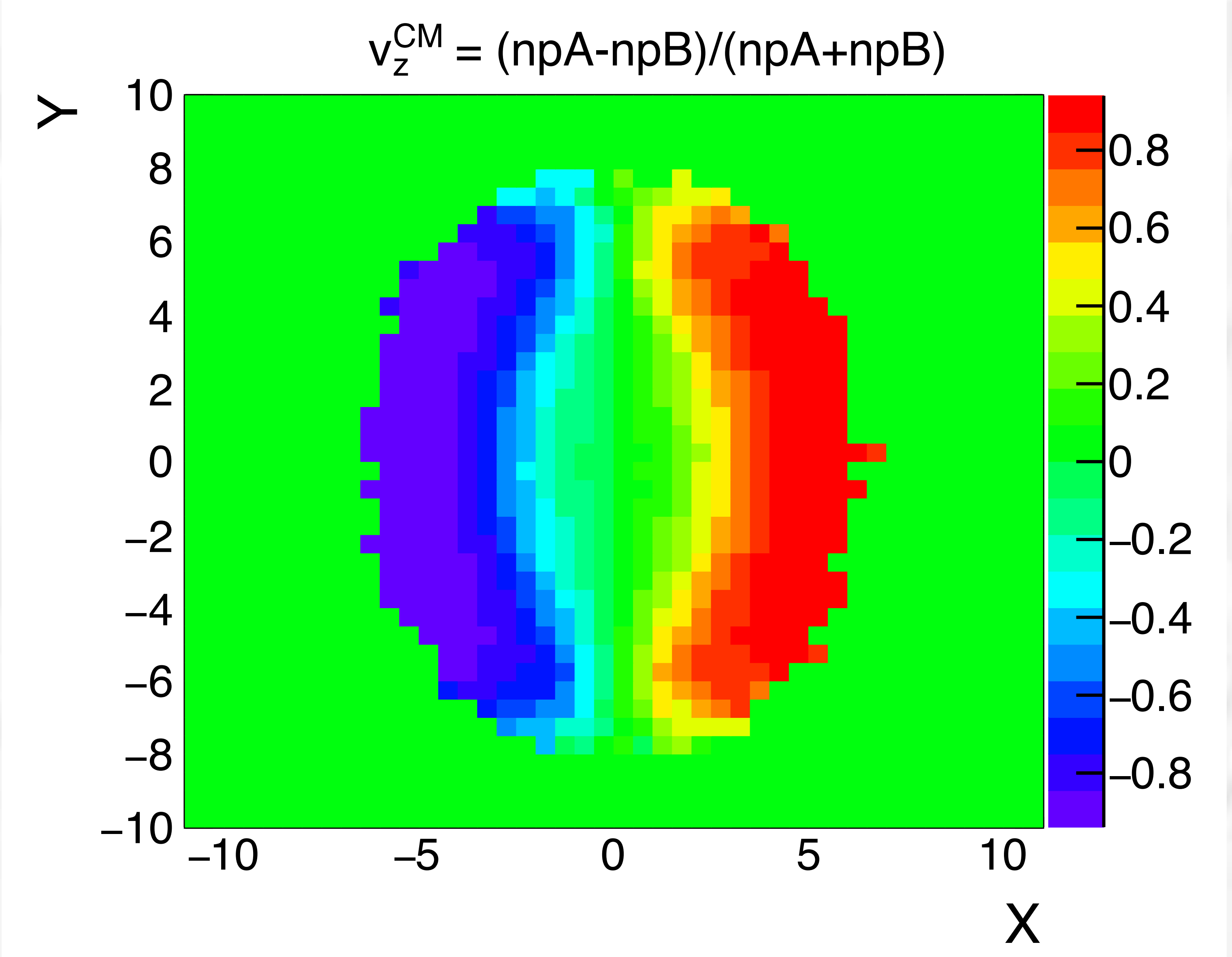
Global polarization, P_y

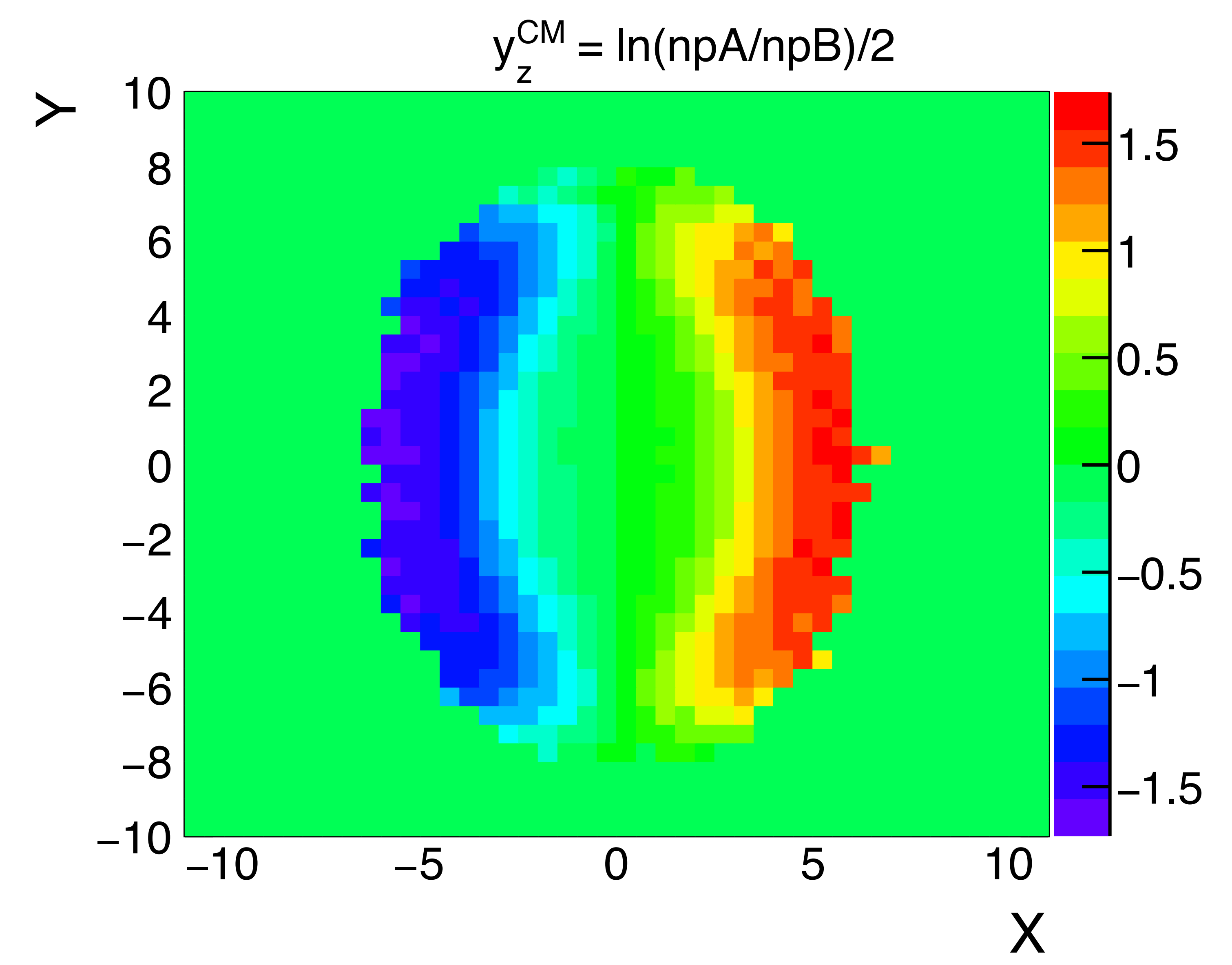
Au+Au, b=7 fm

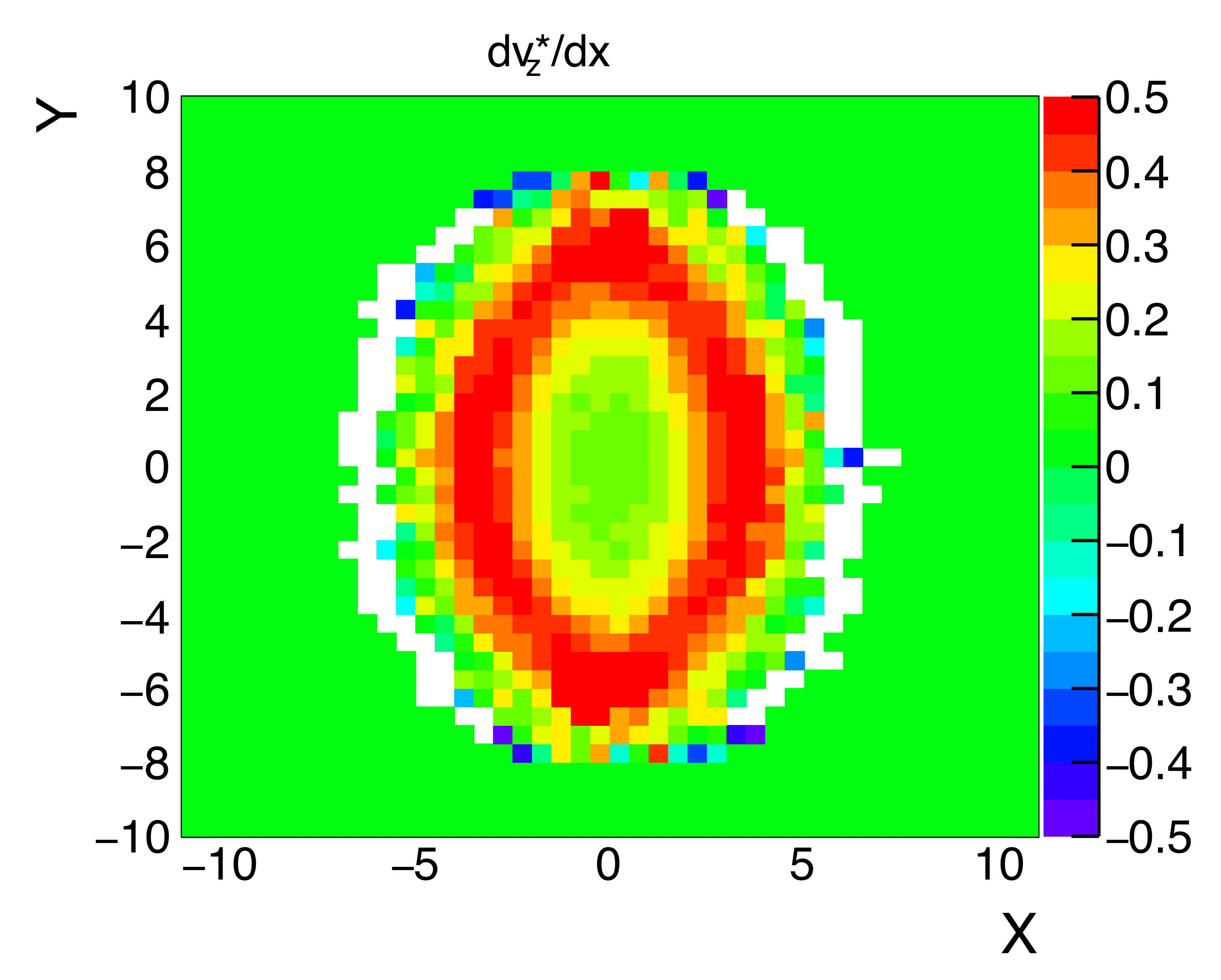
"np" - # of nucleon participants

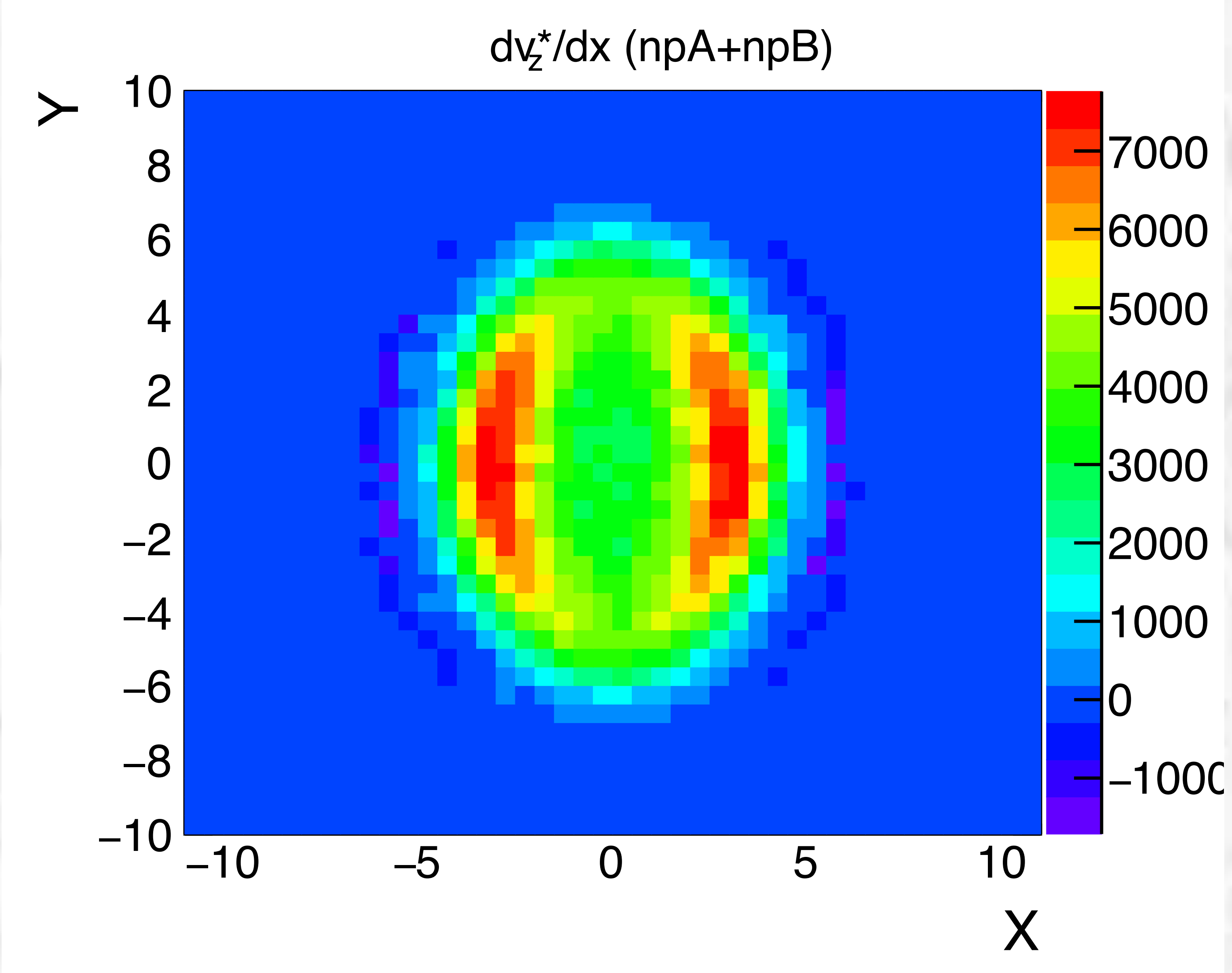












v_z is calculated as velocity of the center of mass

gradients are calculated with rapidity (e.g. in the "fluid" rest frame)