Polarization in relativistic nuclear collisions: Experiment

Sergei A. Voloshin
WAYNE STATE UNIVERSITY

- Vorticity and polarization
- P_y energy dependence, centrality, p_T, η, ϕ_H dependence; average/global
- P_z higher harmonics, hydro, BW , SIP, Cooper-Frye
- P_x BW, SIP;
- P_ϕ track reconstruction efficiency
- Vector meson spin alignment:
  physics questions,
  acceptance effects

Recent review

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

DOI: 10.1142/S0218301324300108

World Scientific
www.worldscientific.com

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

Received 16 April 2024
Accepted 30 June 2024
Published 29 August 2024

arXiv:2404.11042v1 [nucl-ex] 17 Apr 2024

Contents

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

1987… +E 896, NA57

2003 first ideas/discussions
(STAR meeting in Prague)

2004 Idea goes "on-shell"
first publications

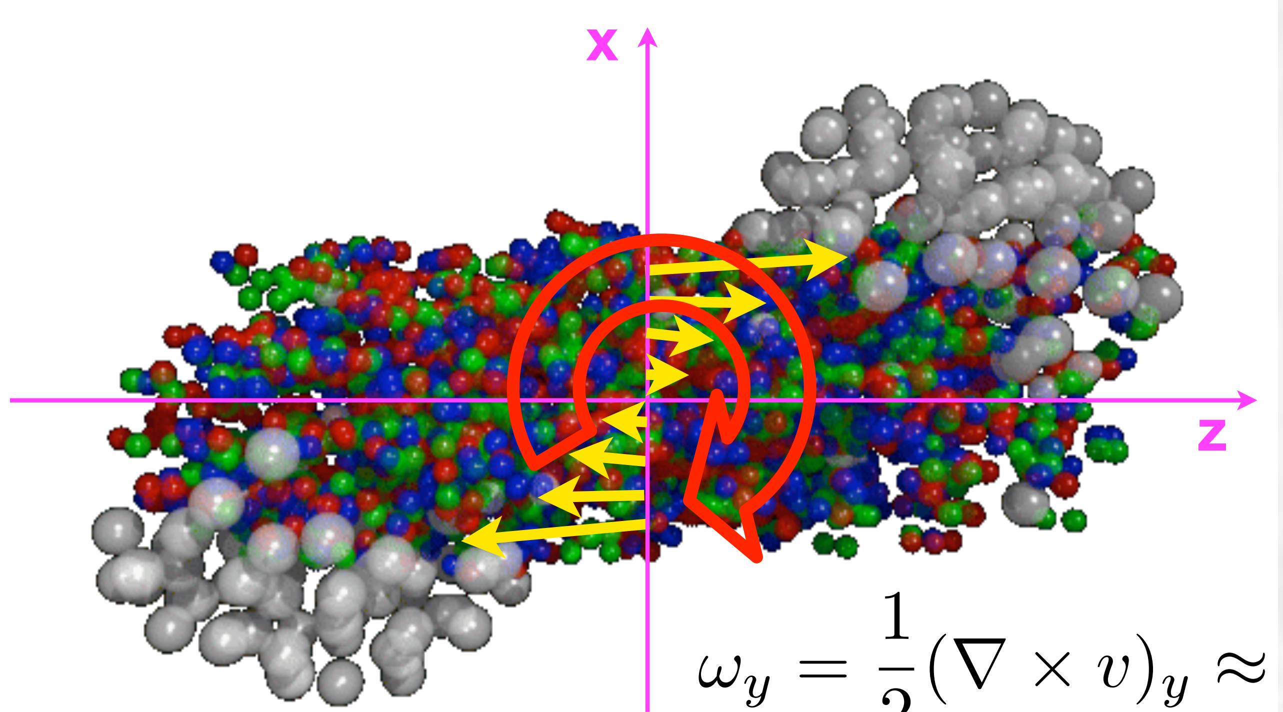
2007 Fist measurements

First ideas on local vorticity

2013 ALICE Physics Week in Padova
idea of thermodynamical equilibrium

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

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



$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

[nucl-th/0410079] Globally Polarized Quark-gluon Plasma in Non-c
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 ~ 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 → v_2
- Relation to single spin asymmetries?

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%

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.

I. Selyuzhenkov, et al.

~10M events

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

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).

M. Baznat, K. Gudima, A. Sorin and O. Teryaev, "Helicity separation in Heavy-Ion Collisions," Phys. Rev. C **88**, no. 6, 061901 (2013) [arXiv:1301.7003 [nucl-th]].

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.

Vorticity and polarization

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

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

S. A. Voloshin, "Vorticity and particle polarization in heavy ion collisions (experimental perspective)", *EPJ Web Conf.* **171** (2018) , arXiv:1710.08934 — SQM 2017

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]. — T. Niida, 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]. — M. Konyushikhin, 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]. — T. Niida, 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. — D. Sarkar, S.V

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

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

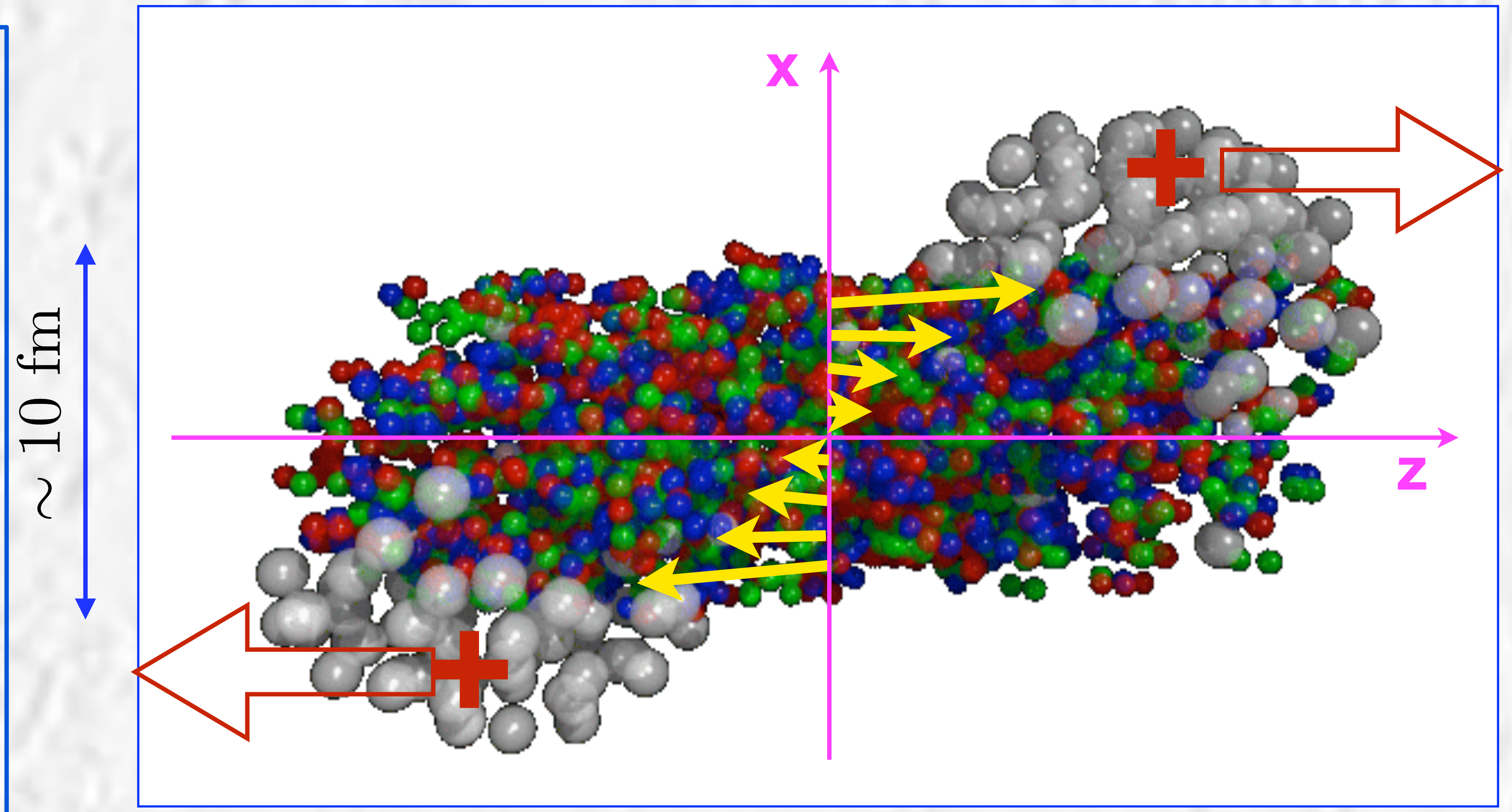
$$S^{\mu\nu} = \varepsilon^{\mu\nu\tau} S_\tau$$

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

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

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

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



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

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)

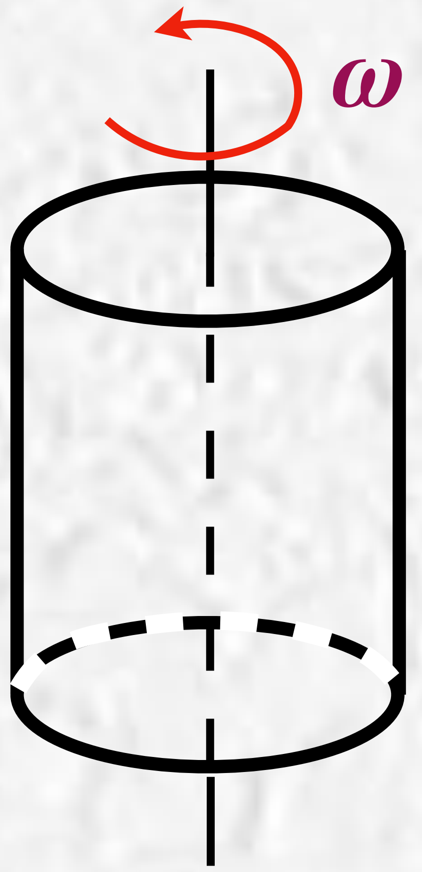
$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu}\cdot\mathbf{B} + \boldsymbol{\omega}\cdot\mathbf{S})/T]$$

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

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

[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



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

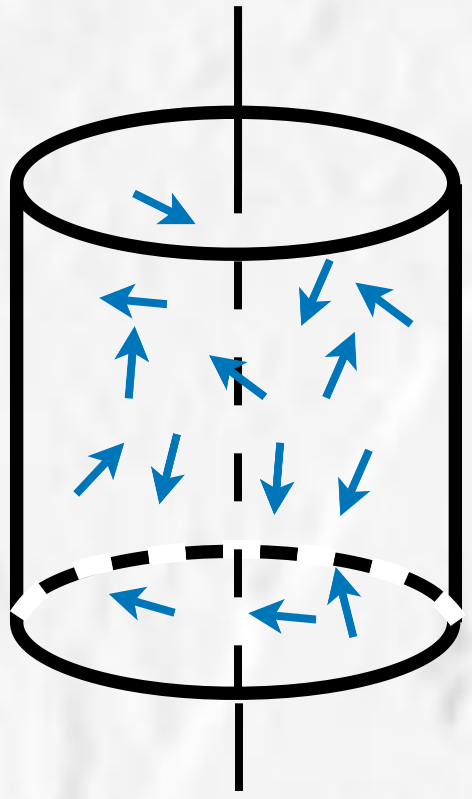
“Microcanonical” approach

N spin 1/2 particles in a cylinder,

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

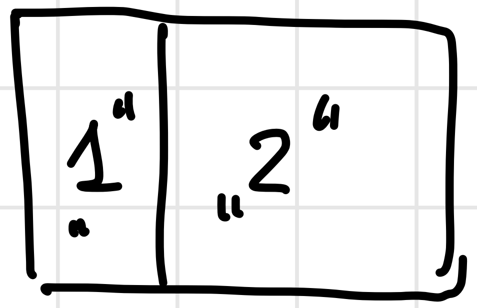
$E = \text{const}$

$S_z - ?$



$g(E)$ – # of microstates

$\sigma = \ln g$ – entropy



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

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

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

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

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

$\sigma = \sigma_S + \sigma_L$

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

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

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

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

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

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

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

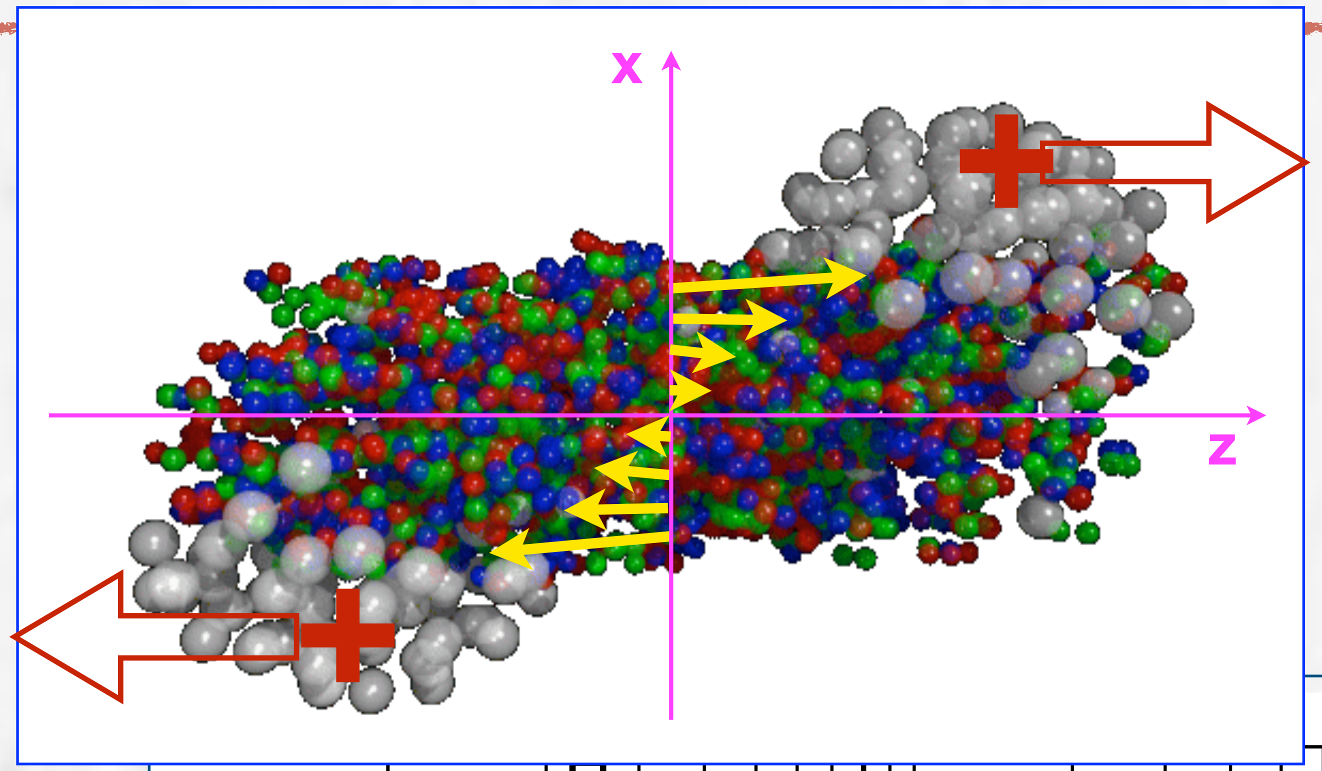
$$\frac{d\sigma}{dL} = 0 = \frac{d\sigma_0}{dL} - \frac{d\sigma}{dS_z} = 0$$

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

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

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

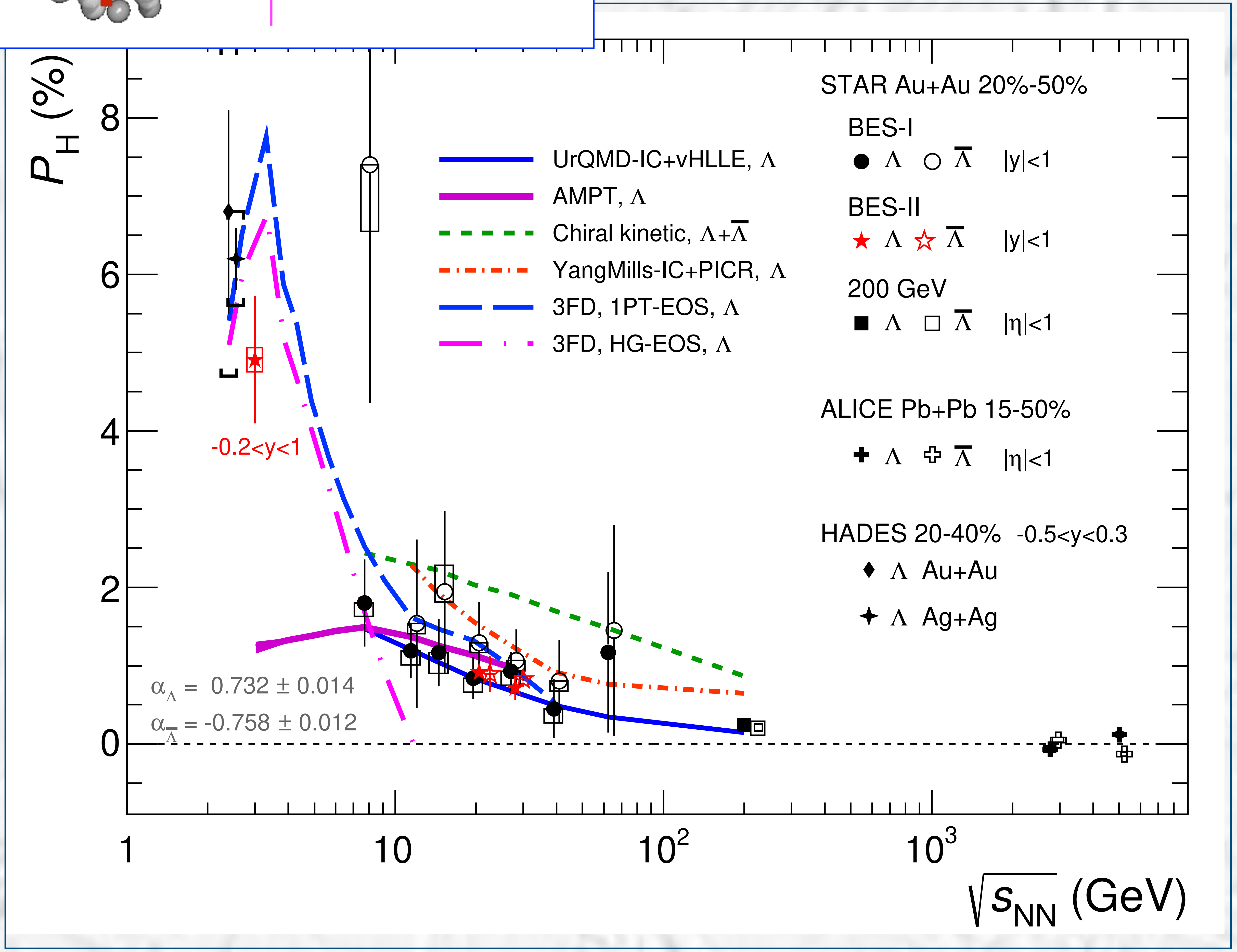
Collision energy dependence

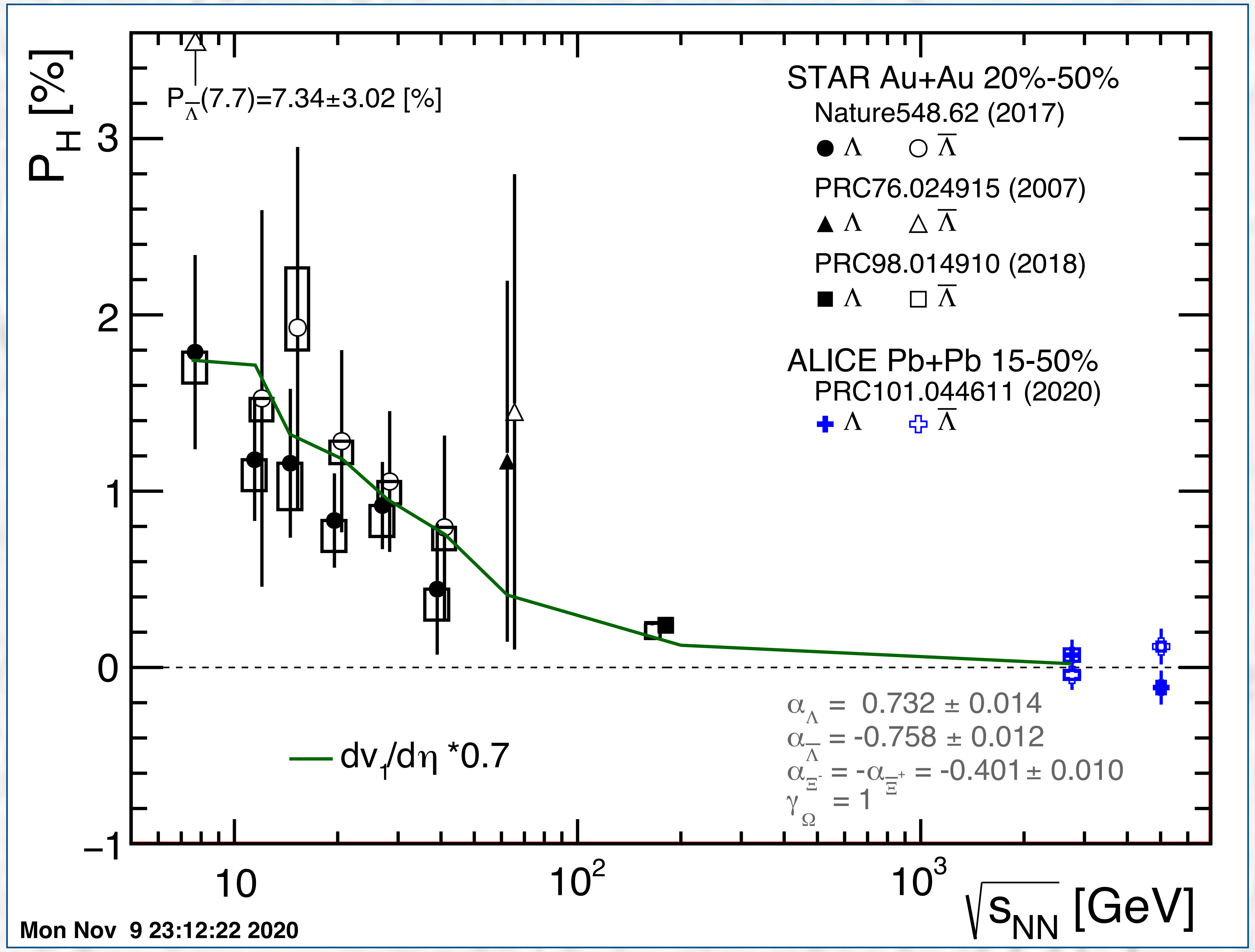


F. Becattini, G. Inghirami, V. Rolando, A. Beraudo, L. Del Zanna, A. De Pace, M. Nardi, G. Pagliara, and V. Chandra, Eur. Phys. J. **C75**, 406 (2015), arXiv:1501.04468 [nucl-th]

Good description of directed flow requires accounting for vorticity!

Slope, $dv_1/d\eta$ proportional to ω?

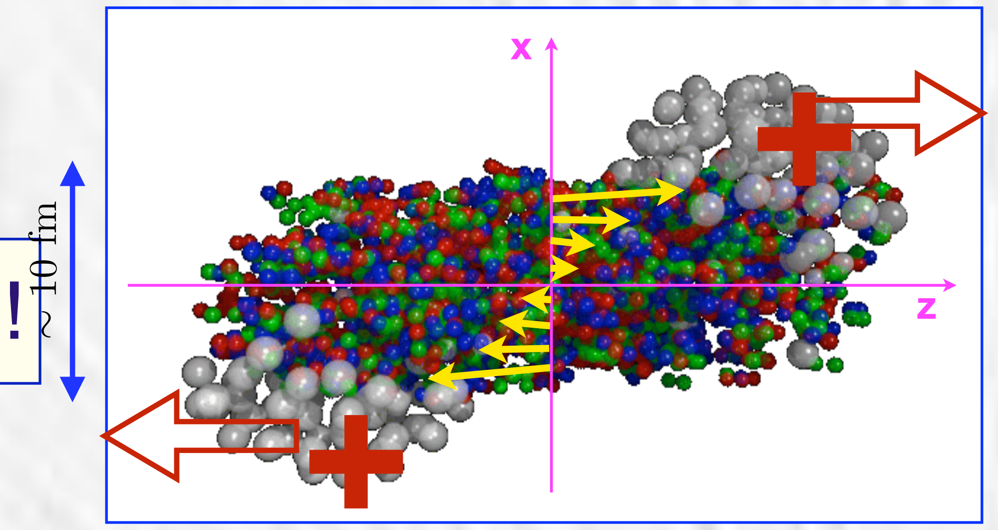




Directed flow: tilted source ⊕ dipole flow

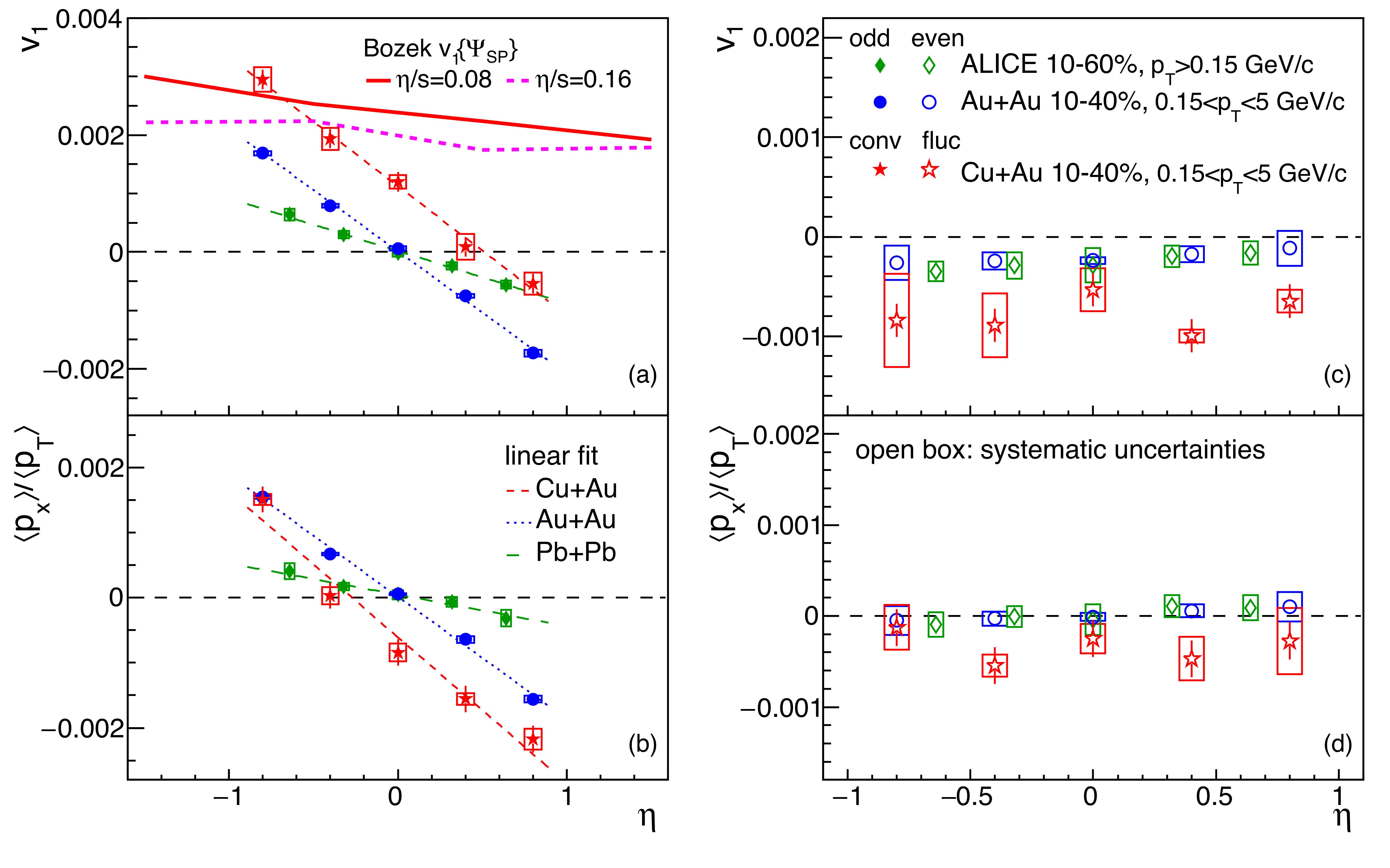
ALICE Collaboration, B. Abelev *et al.*, "Directed Flow of Charged Particles at Midrapidity Relative to the Spectator Plane in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV", *Phys. Rev. Lett.* **111** no. 23, (2013) 232302, arXiv:1306.4145 [nucl-ex].

← introduction and first measurements of v_1^{even} and $\langle p_x \rangle$!



STAR Collaboration, L. Adamczyk *et al.*, "Azimuthal anisotropy in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev.* **C98** no. 1, (2018) 014915, arXiv:1712.01332 [nucl-ex].

← idea of directed flow as a combination of "tilted source" and dipole flow



$$\frac{1}{\langle p_T \rangle}\frac{d\langle p_x \rangle}{d\eta} \approx 1.5\,\alpha_{ts}\frac{dv_1}{d\eta}$$

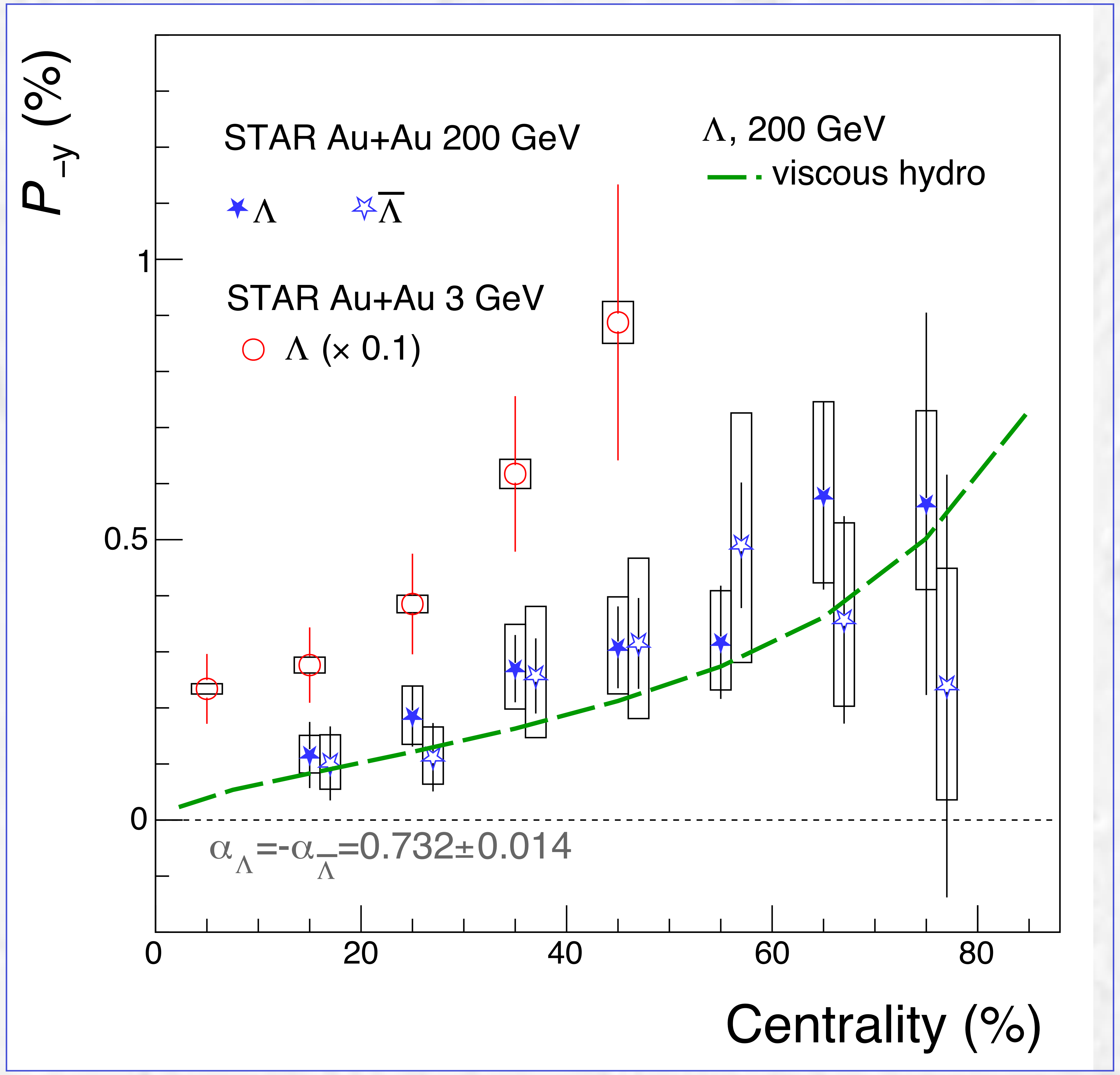
α_{ts} - fraction of "tilted source" contribution to v_1

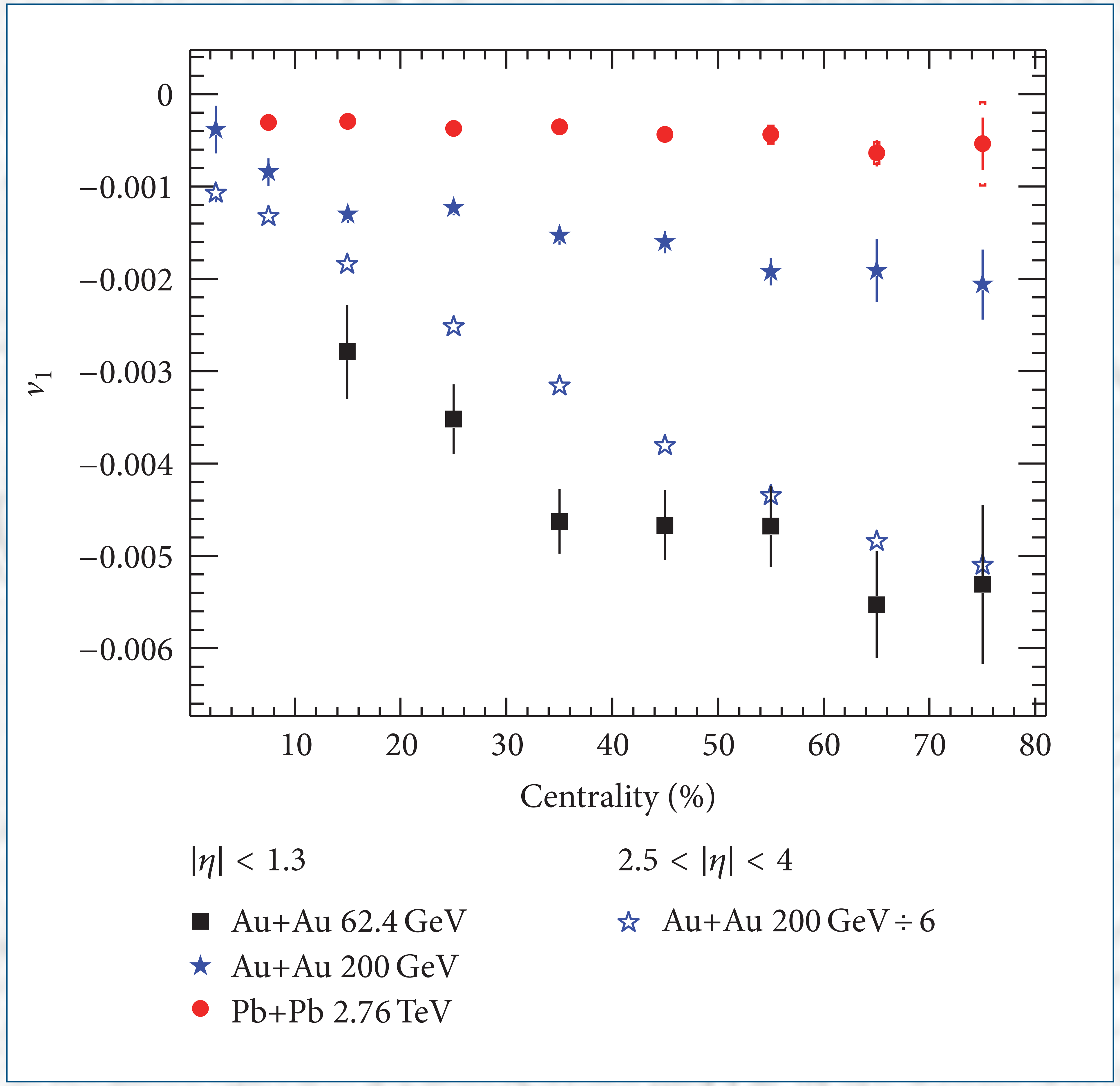
- For mid-central collisions (20% - 40%) tilted source contribution is about 2/3, its fraction increases in more peripheral collisions.
- At LHC energies "tilted sources" contribution is smaller, about 1/3

→ polarization at LHC ~ 1/6 of that at RHIC 200 GeV

FIG. 5. (Color online) Charged particle "conventional" (left) and "fluctuation" (right) components of directed flow v_1 and momentum shift $\langle p_x \rangle / \langle p_T \rangle$ as a function of η in 10%-40% centrality for Cu+Au, Au+Au, and Pb+Pb collisions. Thick solid and dashed lines show the hydrodynamic model calculations with η/s=0.08 and 0.16, respectively, for Cu+Au collisions [31]. Thin lines in the left panel show a linear fit to the data.

Global polarization, centrality dependence

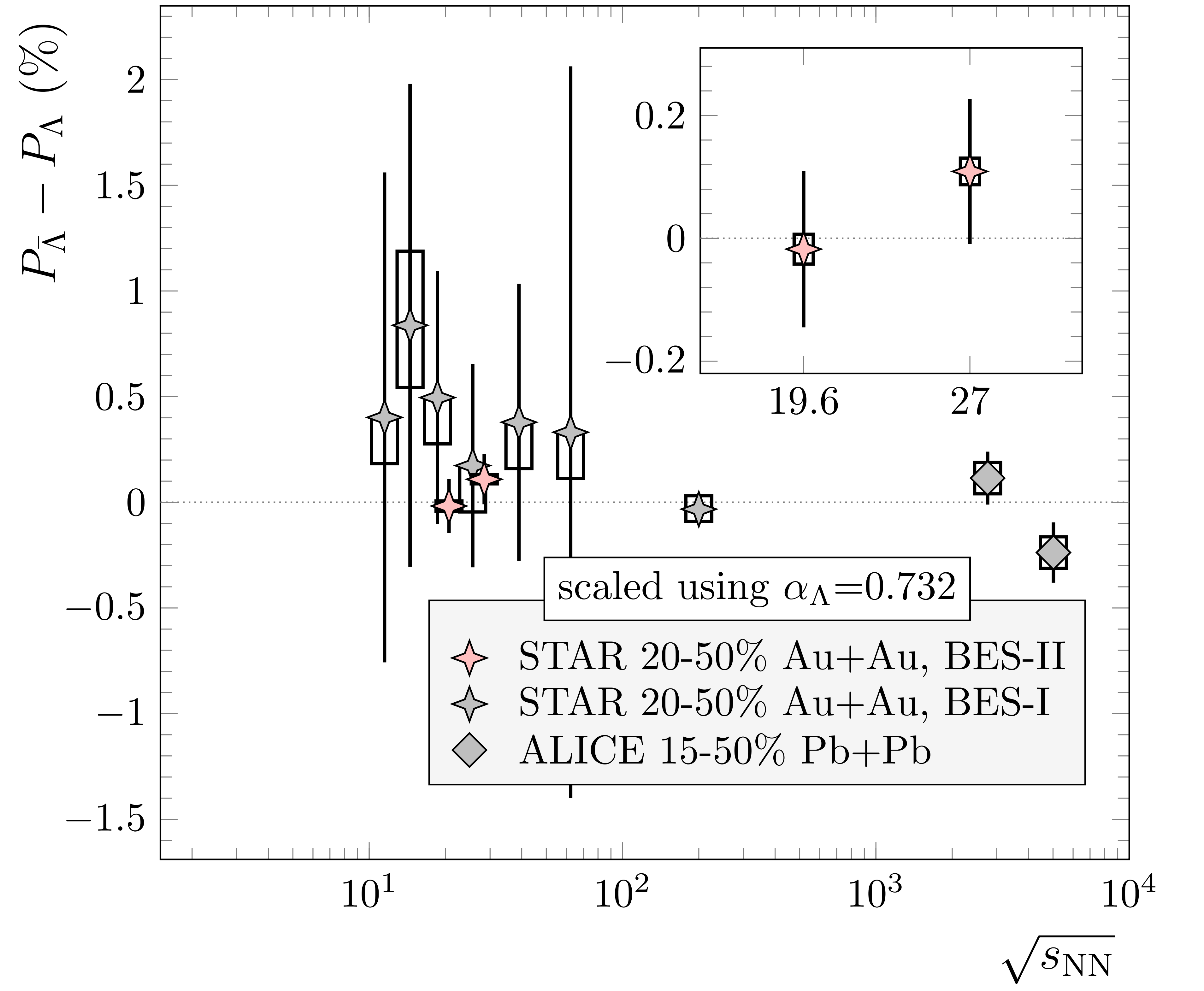




S. Singha, P. Shanmuganathan, and D. Keane, "The first moment of azimuthal anisotropy in nuclear collisions from AGS to LHC energies", *Adv. High Energy Phys.* **2016**, 2836989 (2016). arXiv:1610.00646.

Magnetic field at freeze-out

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



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

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

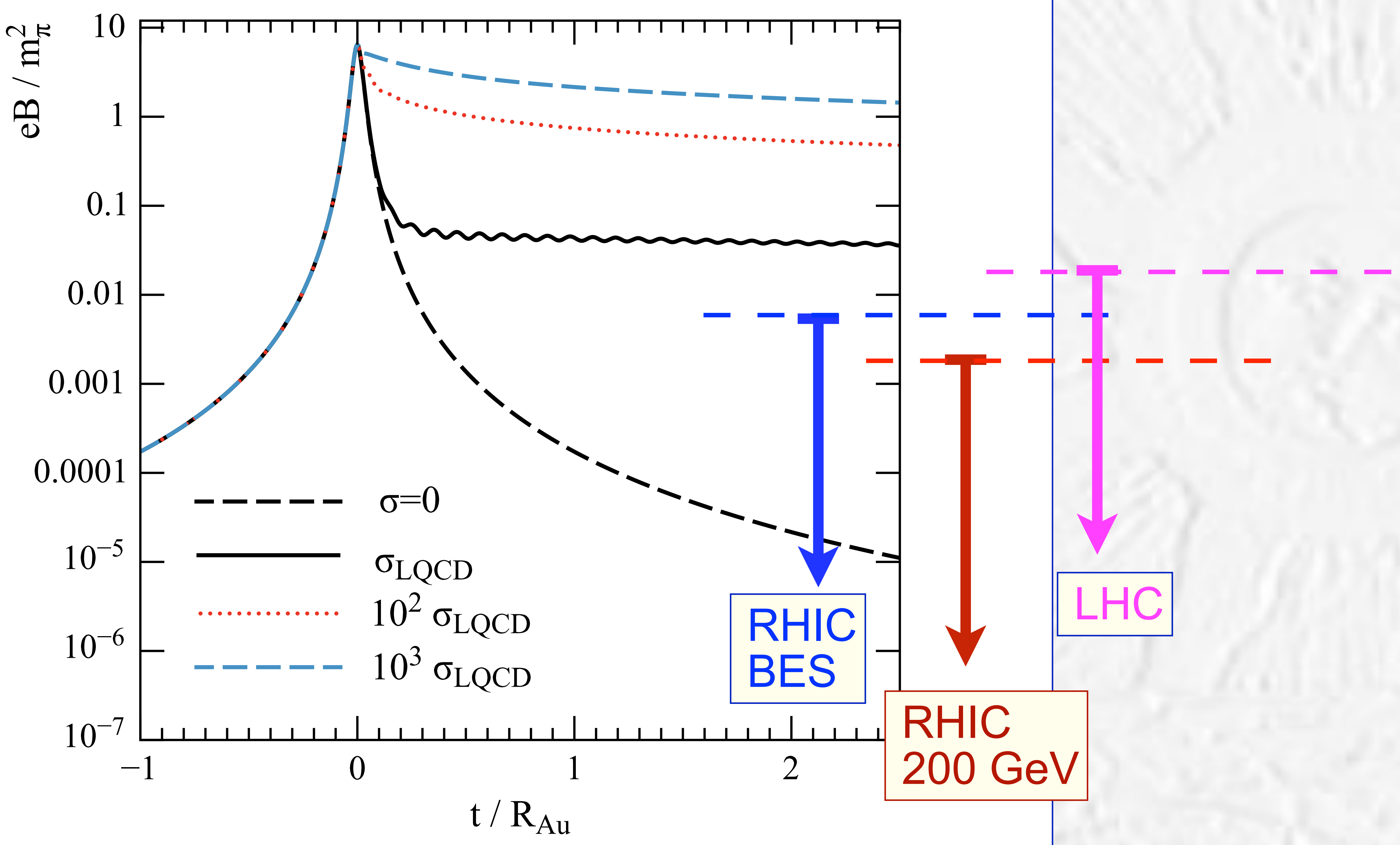


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

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

Feed-down and polarization transfer

~60% of measured Λ are feed-down from $\Sigma^* \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$, $\Xi \to \Lambda\pi$
Polarization of parent particle R is transferred to its daughter Λ
(Polarization transfer could be negative!)

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].

Decay	C
parity-conserving: $1/2^+ \to 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+ \; 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-1/3

TABLE I. Polarization transfer factors C (see eq. (36)) for important decays $X \to \Lambda(\Sigma)\pi$

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R$$

$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ
S_R : parent particle's spin

Primary Λ polarization is diluted by 15%-20% (model-dependent)

Spin transfer suggests that *the polarization of daughter particles can be used to measure the polarization of its parent!* e.g. Ξ, Ω

Ξ^-, (dss), spin 1/2
Ω, (sss), spin 3/2

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

- 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

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

Smaller α, more difficult to measure P

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

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

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

Ξ, spin 1/2

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

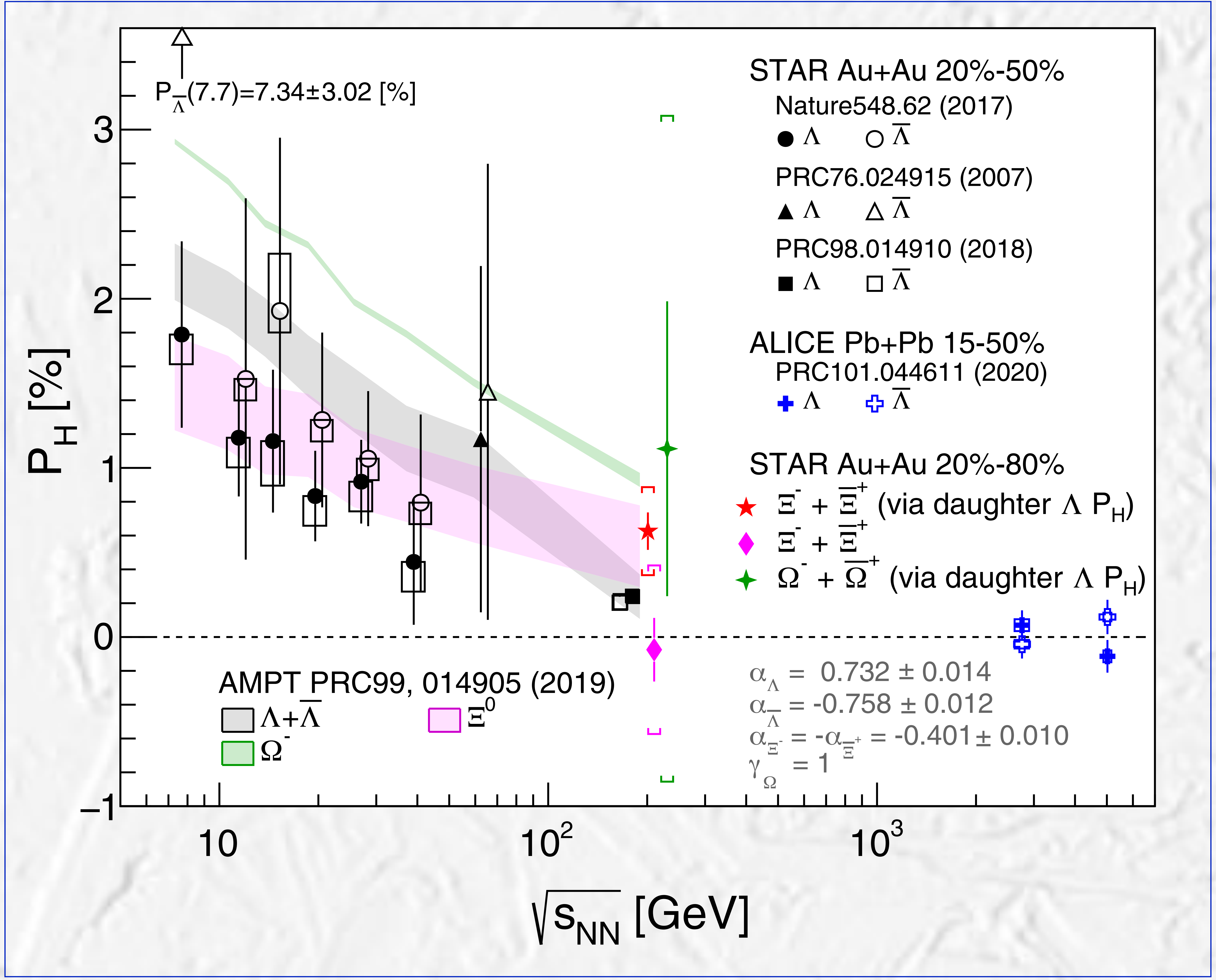
$$C_{\Omega^-\Lambda} \approx 1 \text{ or } C_{\Omega^-\Lambda} \approx -0.6$$

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



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].

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

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

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

A way to measure the decay parameter γ_Ω !

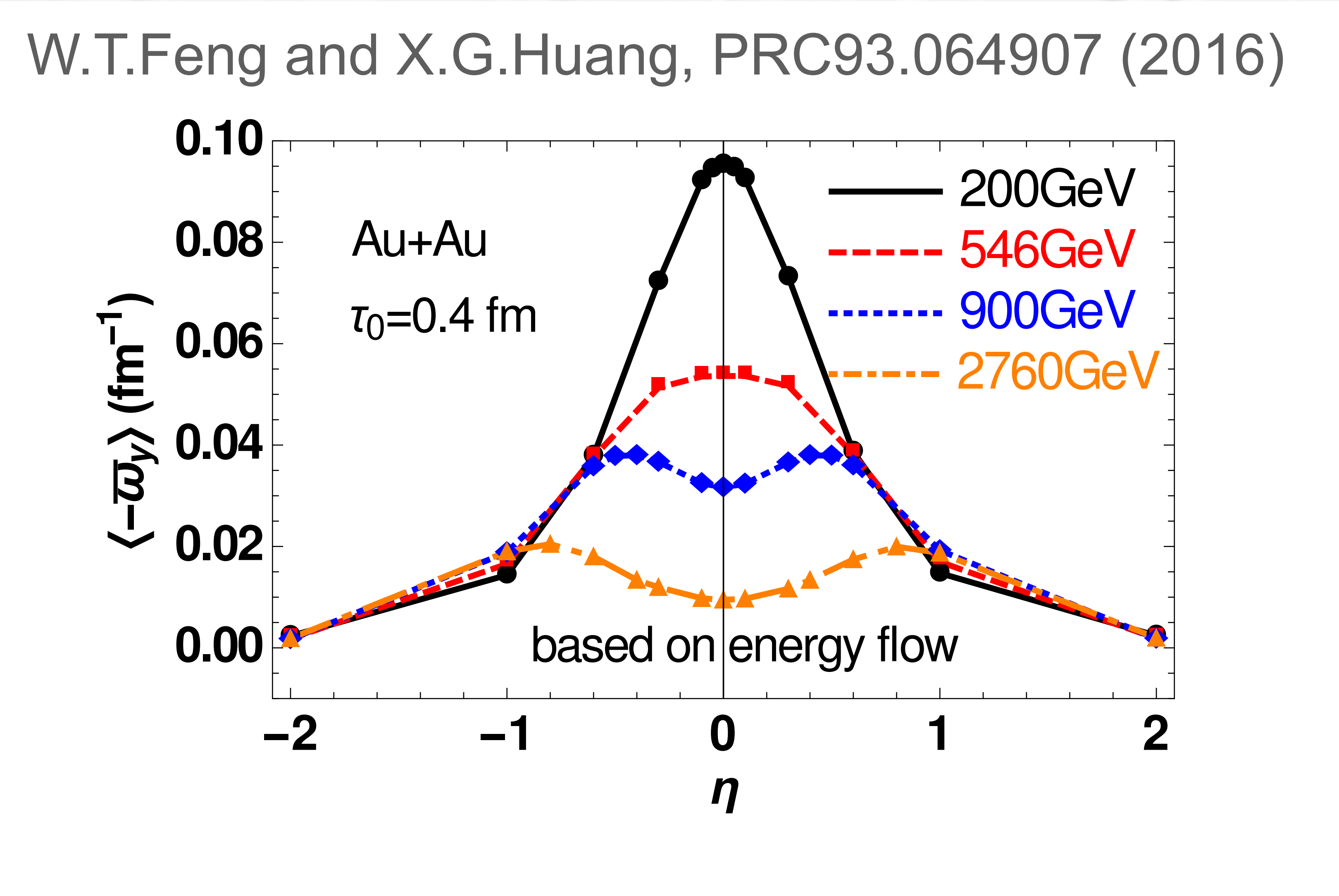
Ξ, spin 1/2

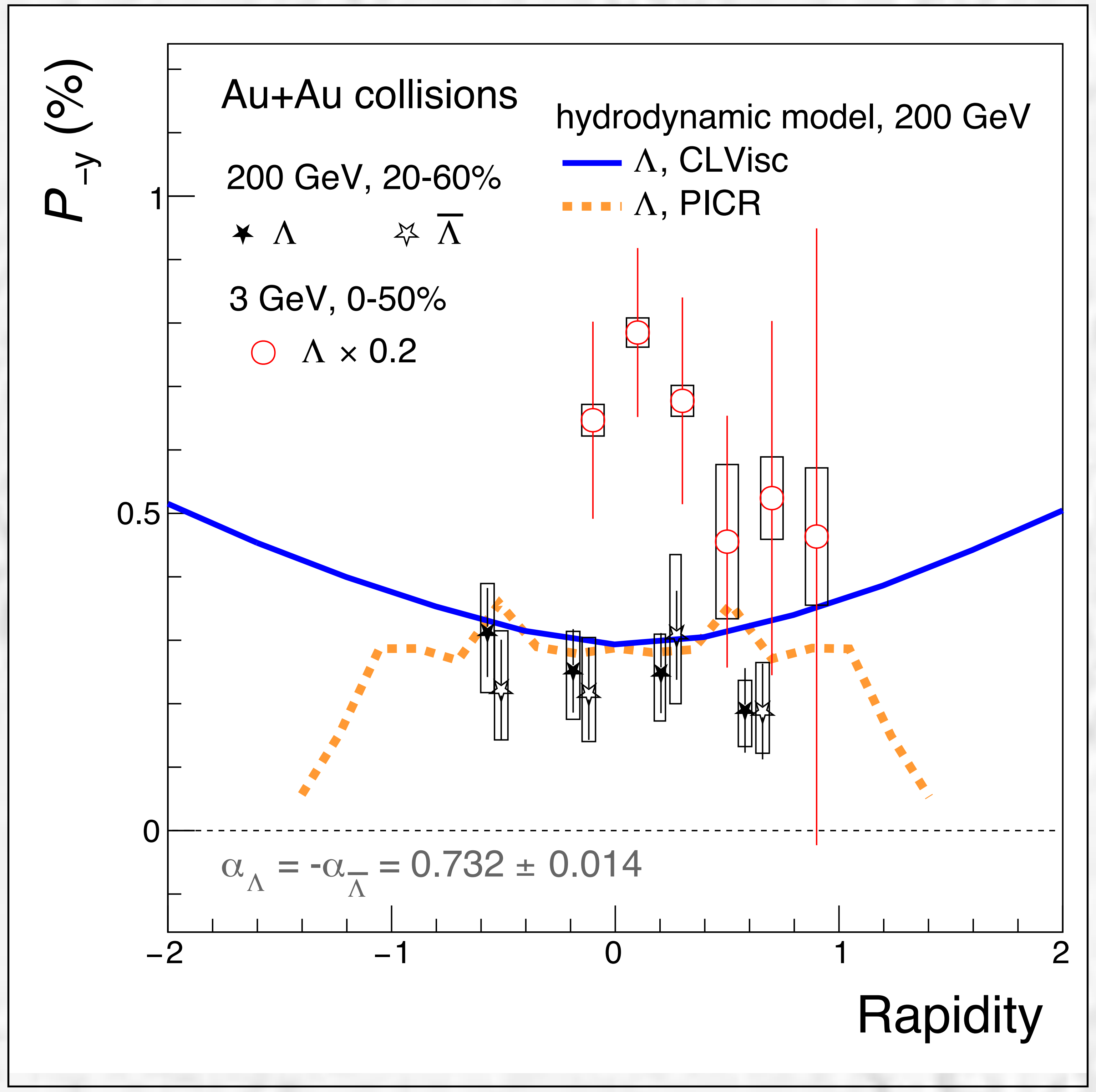
Ω, spin 3/2, γ not known $\gamma_\Omega \approx \pm 1$

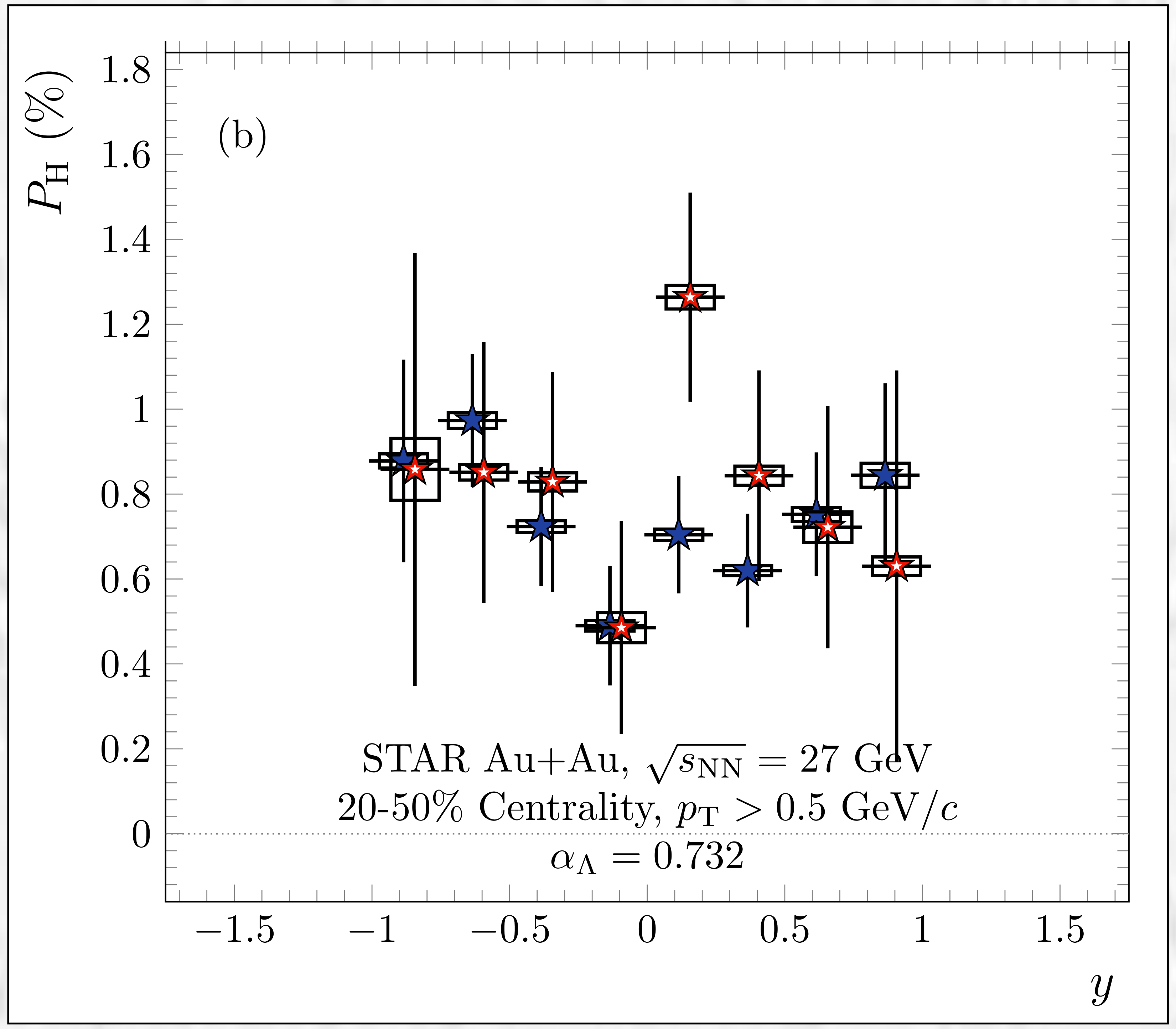
Ξ polarization might be slightly larger than that of Λ

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

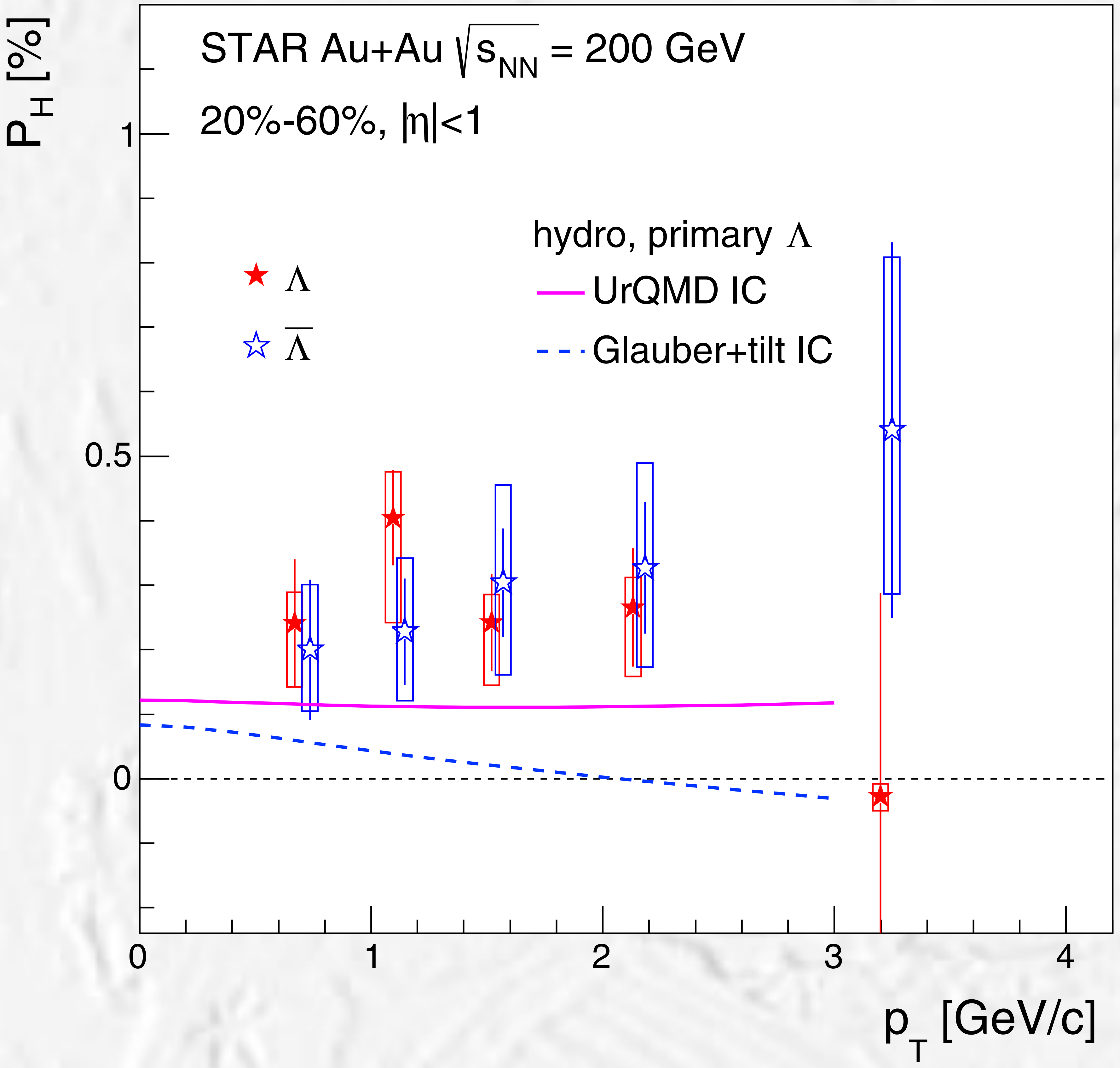
Global polarization, rapidity dependence

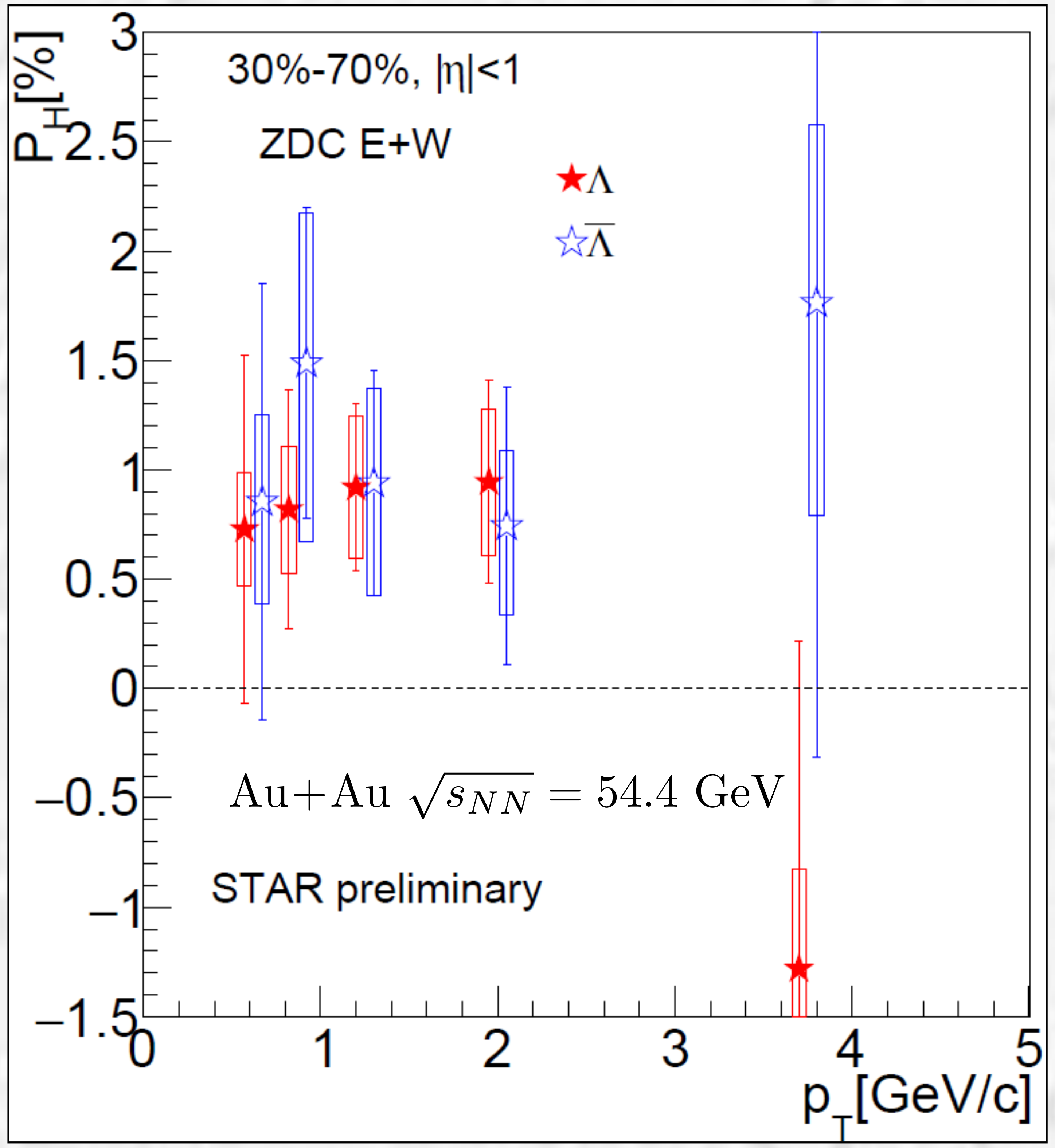


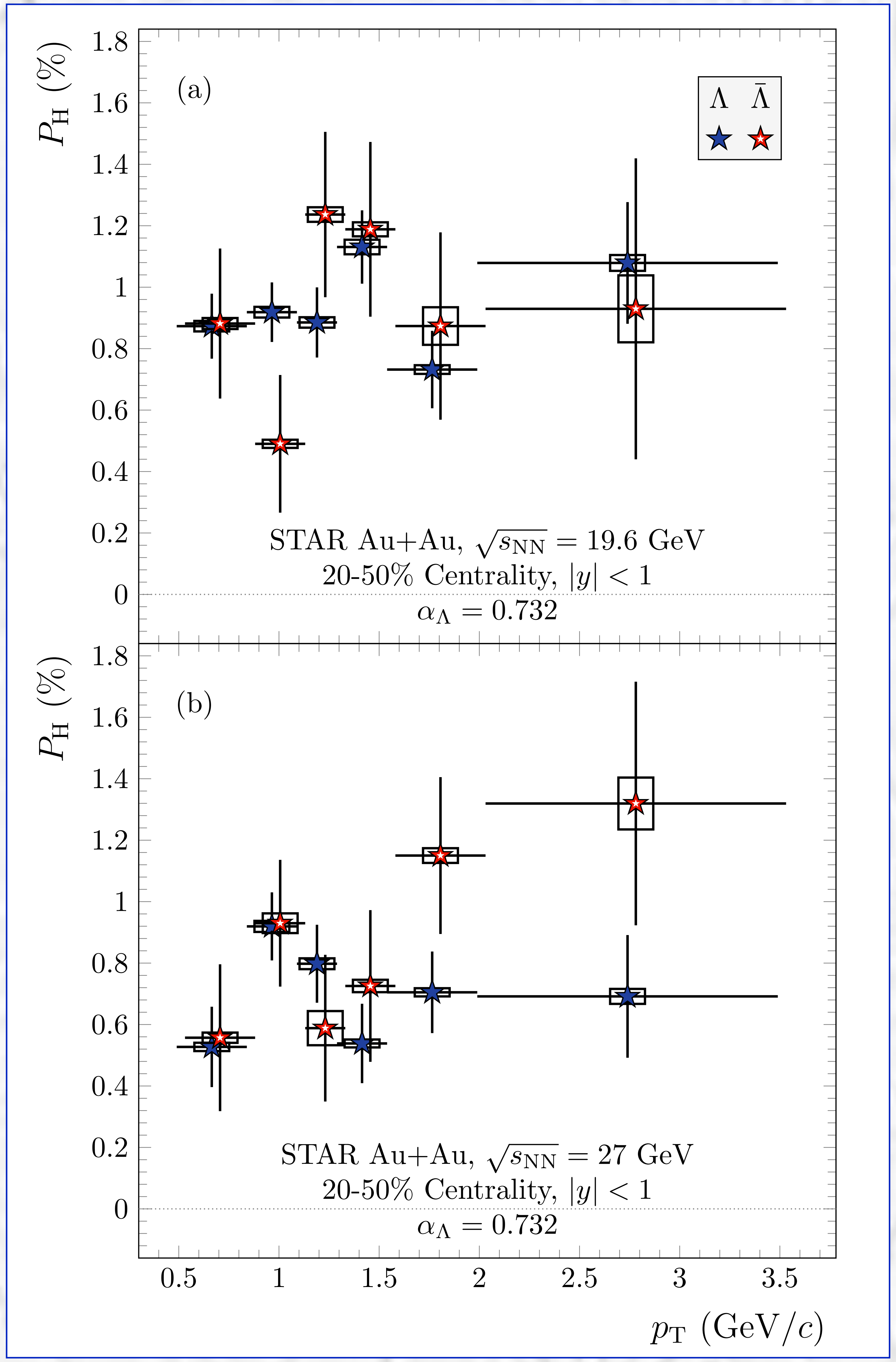




Global polarization, p_T dependence







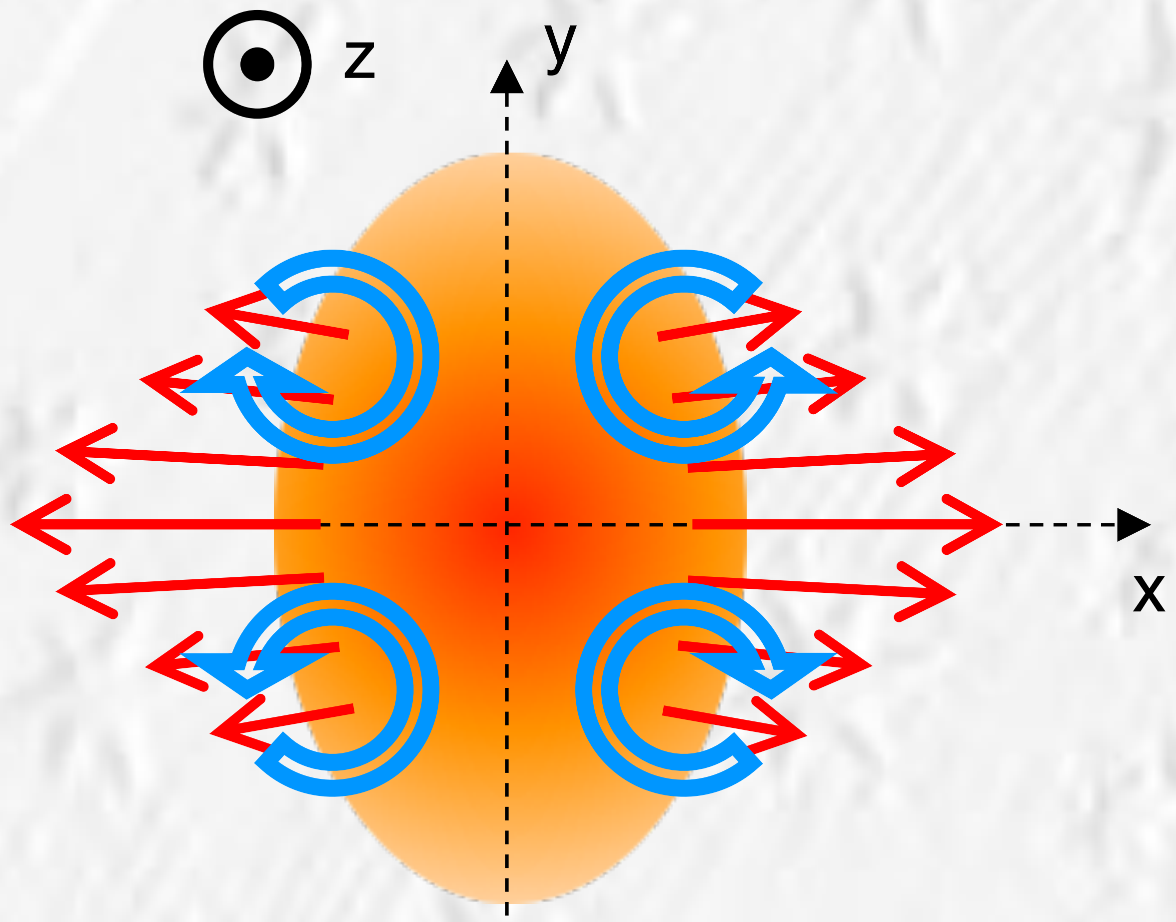
Weak p_T dependence (as expected?)

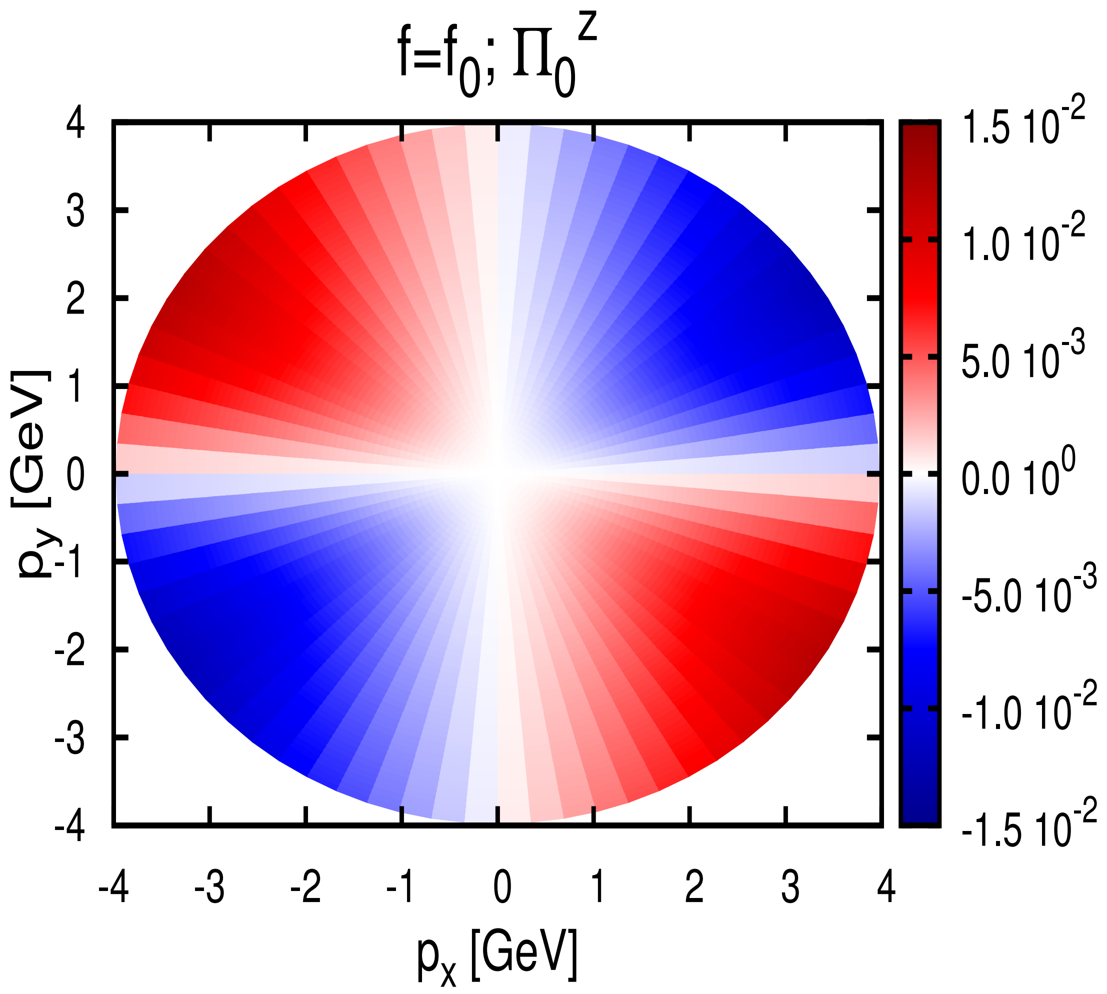
zPolarization

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 $\Rightarrow$ ω_z

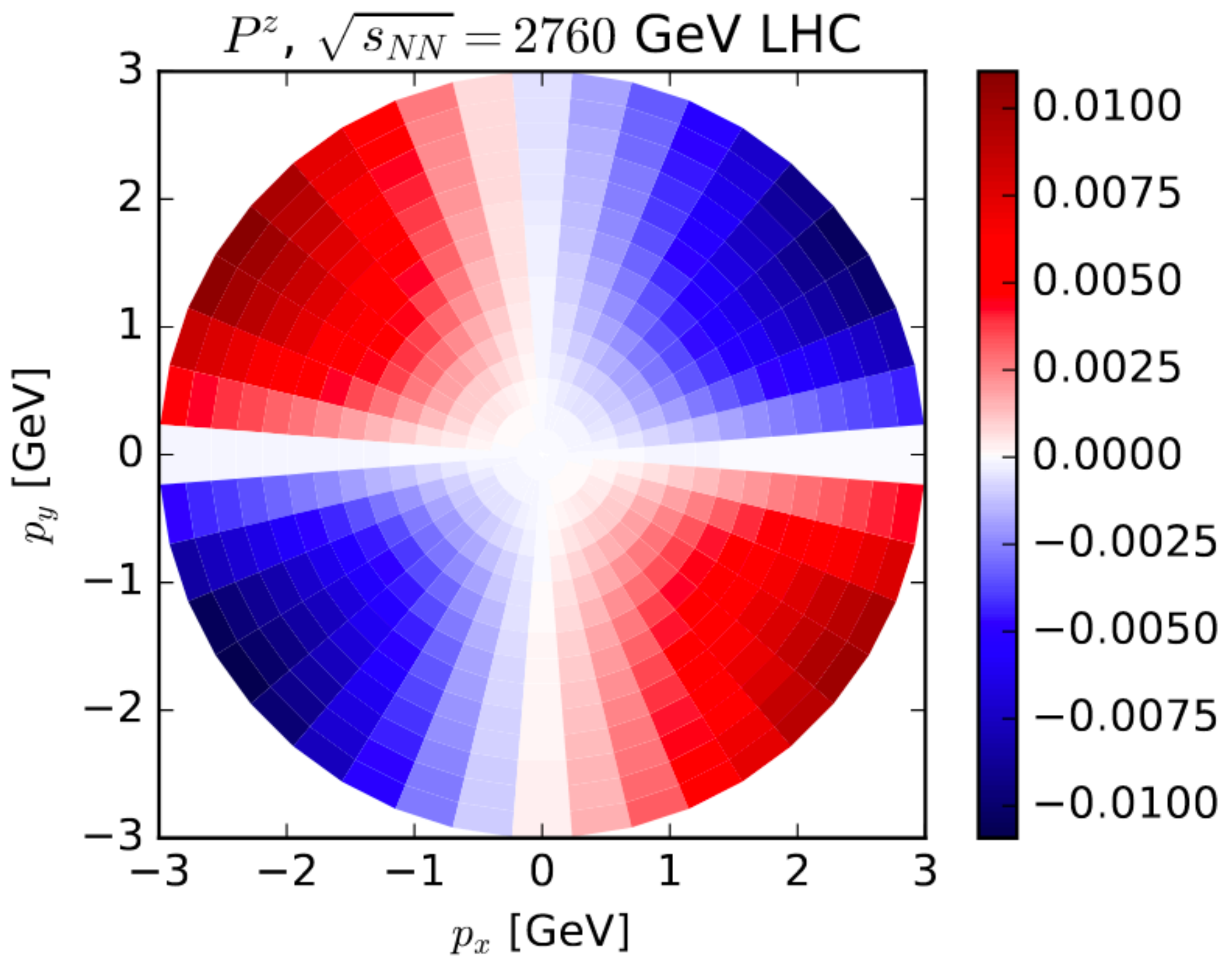




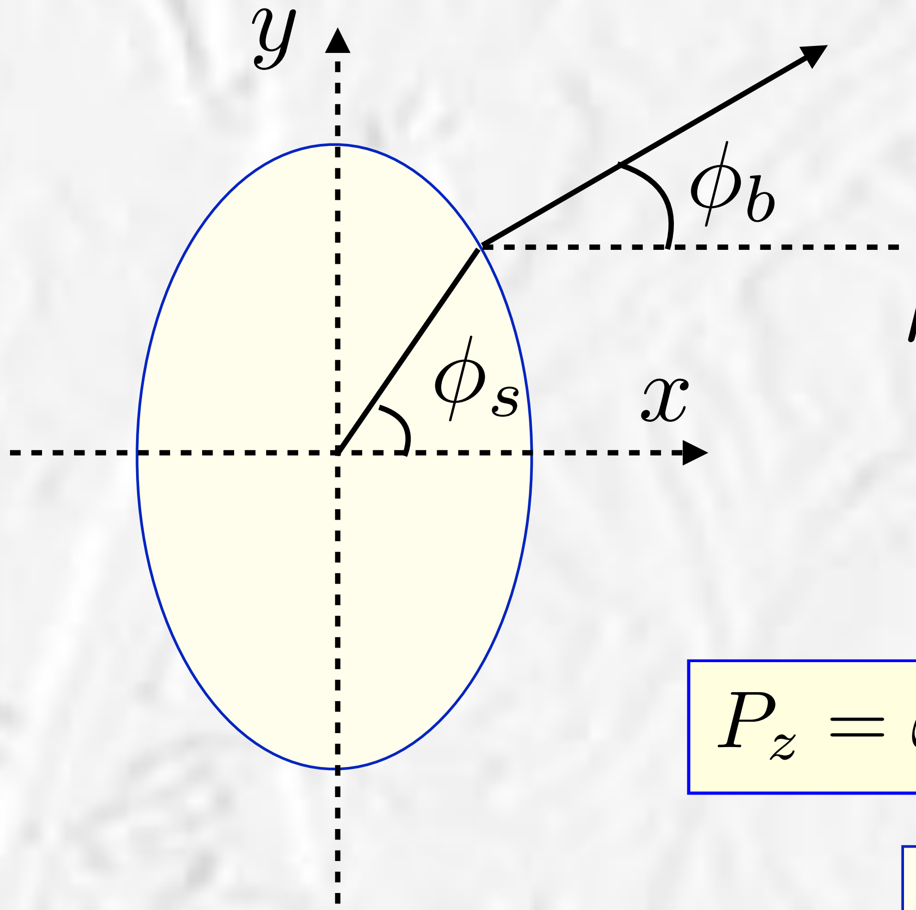
Plot not included in the orig. paper.

F. Becattini, G. Inghirami, V. Rolando, A. Beraudo, L. Del Zanna, A. De Pace, M. Nardi, G. Pagliara, and V. Chandra, "A study of vorticity formation in high energy nuclear collisions", *Eur. Phys. J. C* **75**, no. 9, 406 (2015), `arXiv:1501.04468`. [Erratum: Eur.Phys.J.C 78, 354 (2018)].

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:



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

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

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

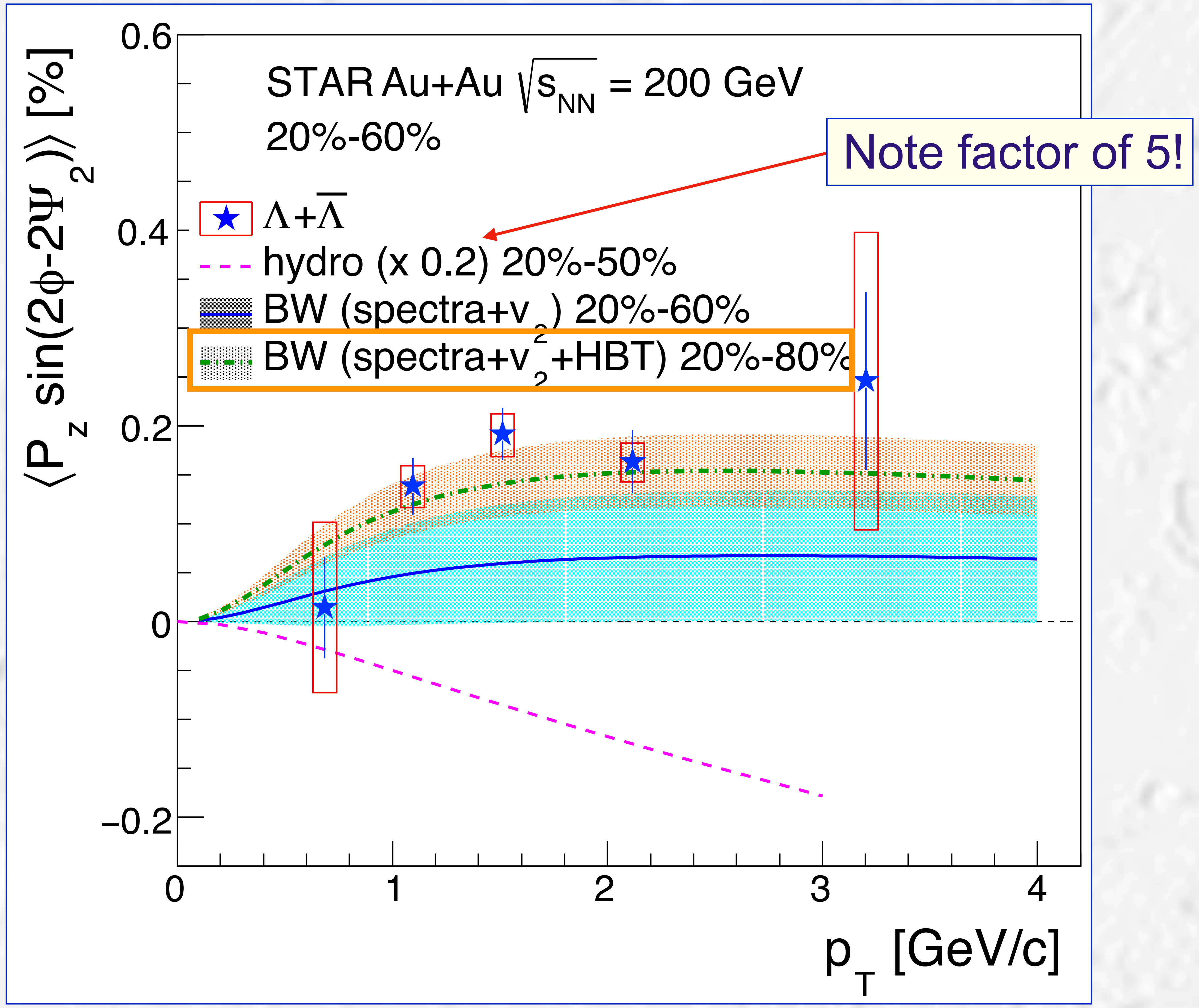
$$P_z = \omega_z/(2T) \approx 0.1\sin(n\phi_s)[b_n - a_n]$$

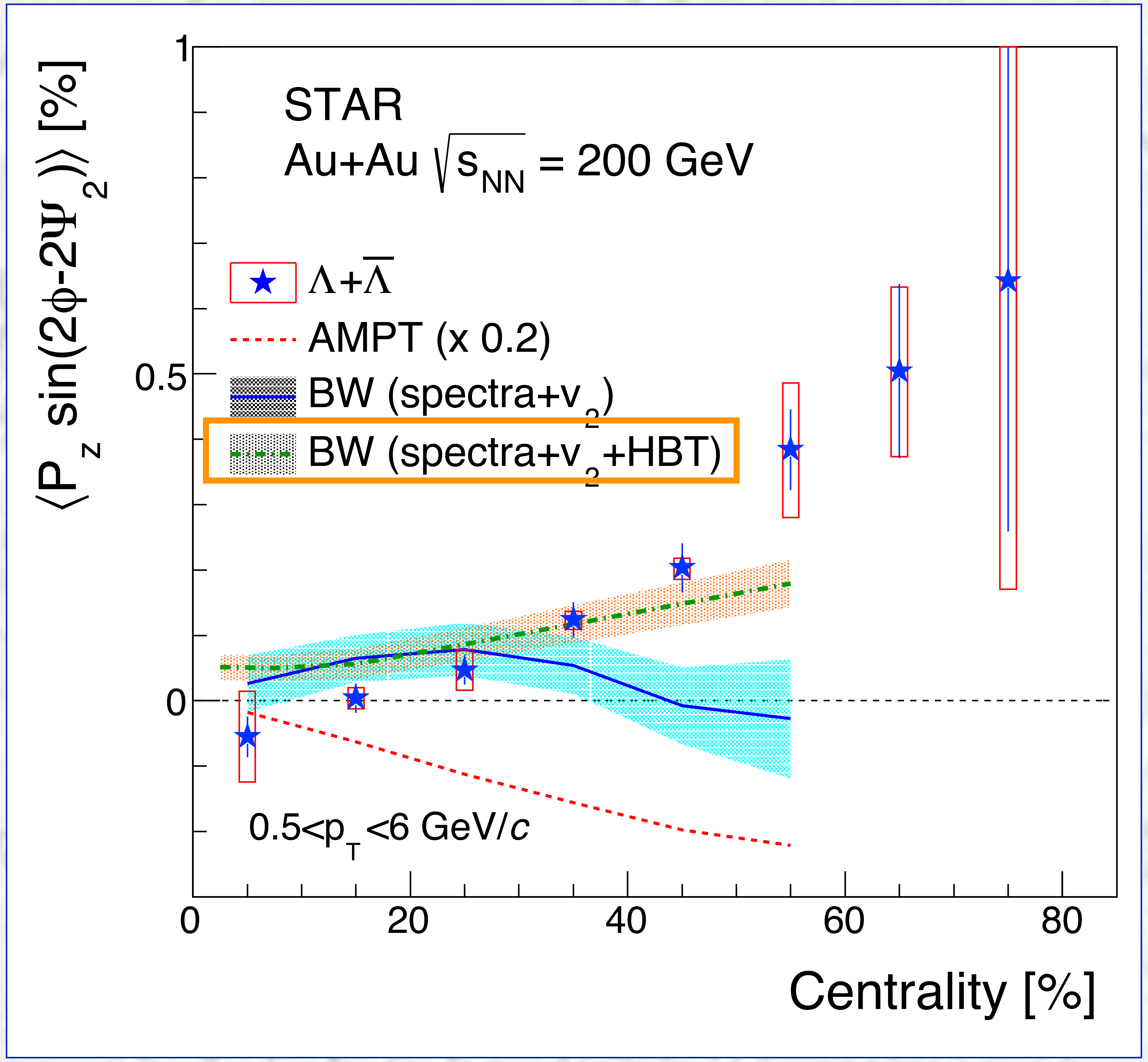
R≈10 fm, T≈100 MeV

$a_n,\ b_n$ 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 (Λ̄) 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].





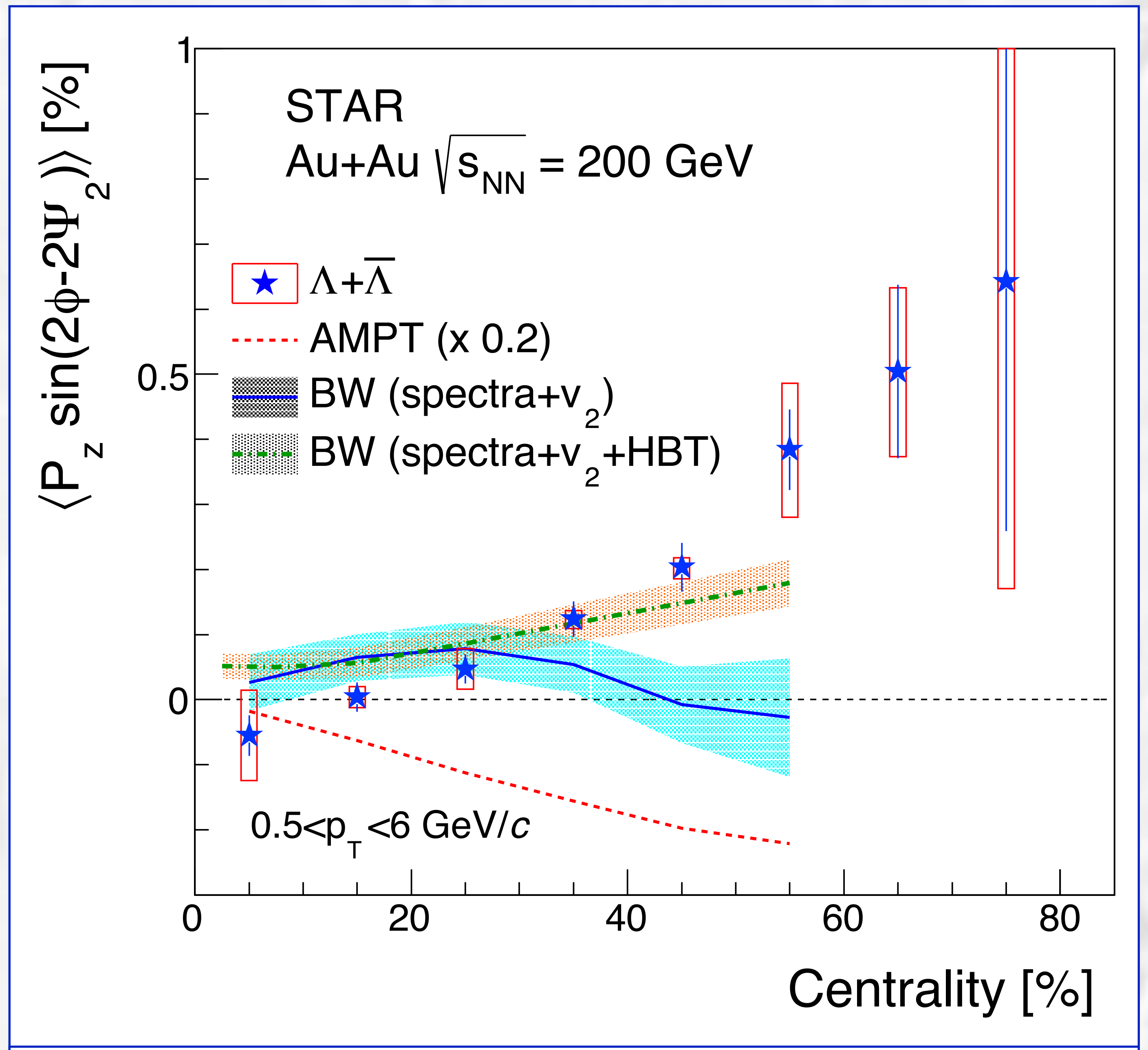
$$\langle \omega_z \sin(2\phi)\rangle = \frac{\int d\phi_s \int r dr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr\, I_0(\alpha_t) K_1(\beta_t)}$$

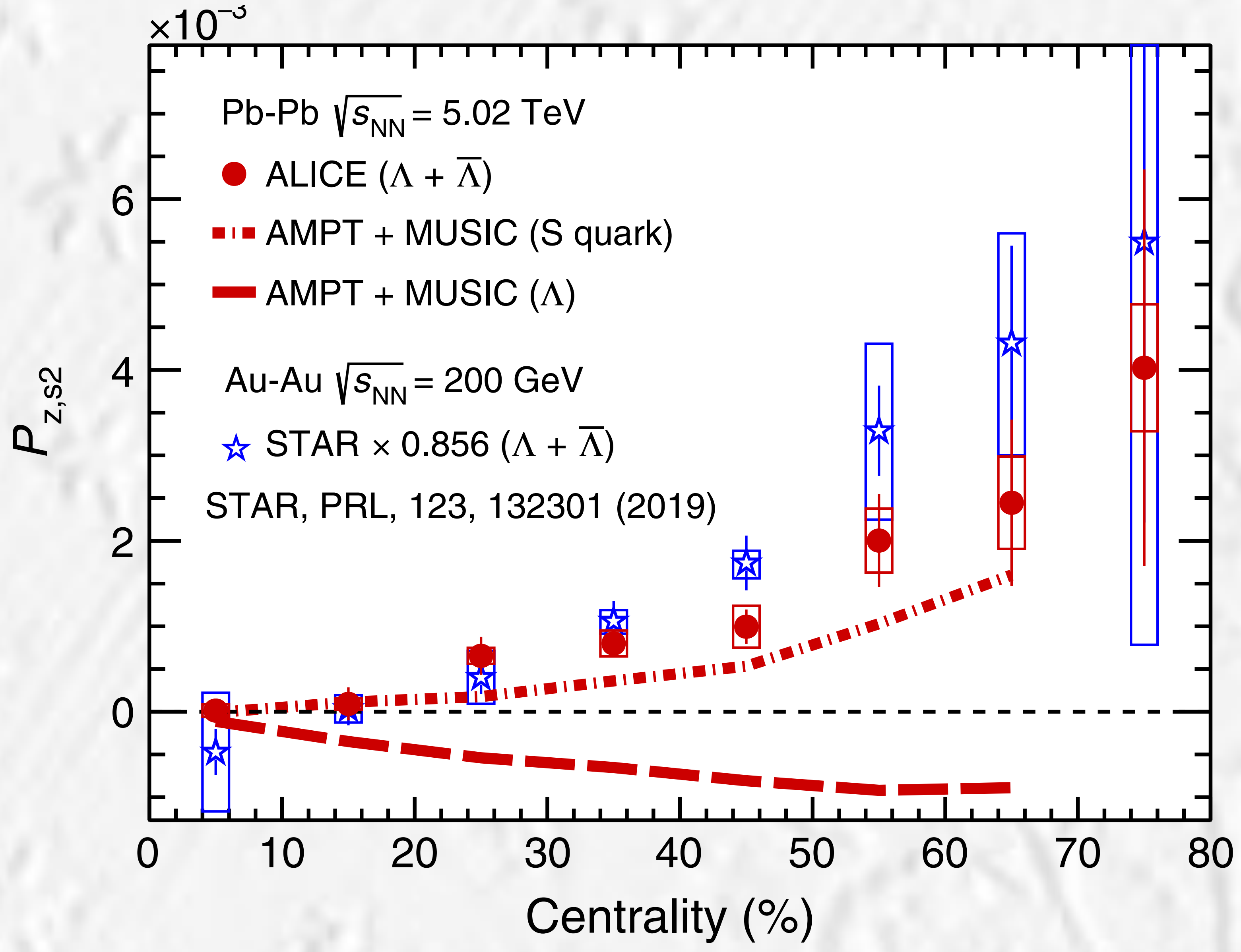
$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

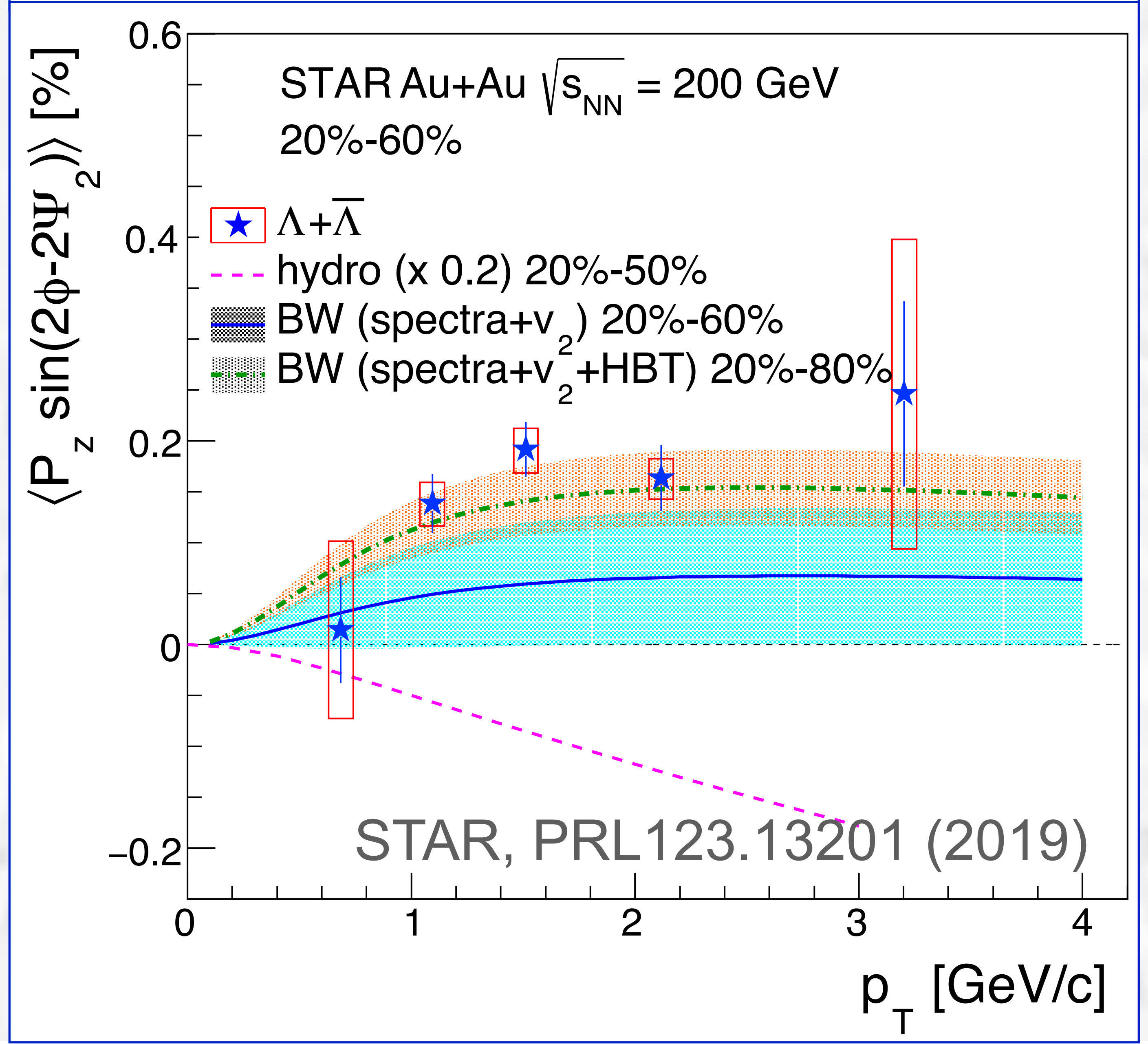
BW parameters obtained with fits to spectra and HBT: STAR, PRC71.044906 (2005) !!!

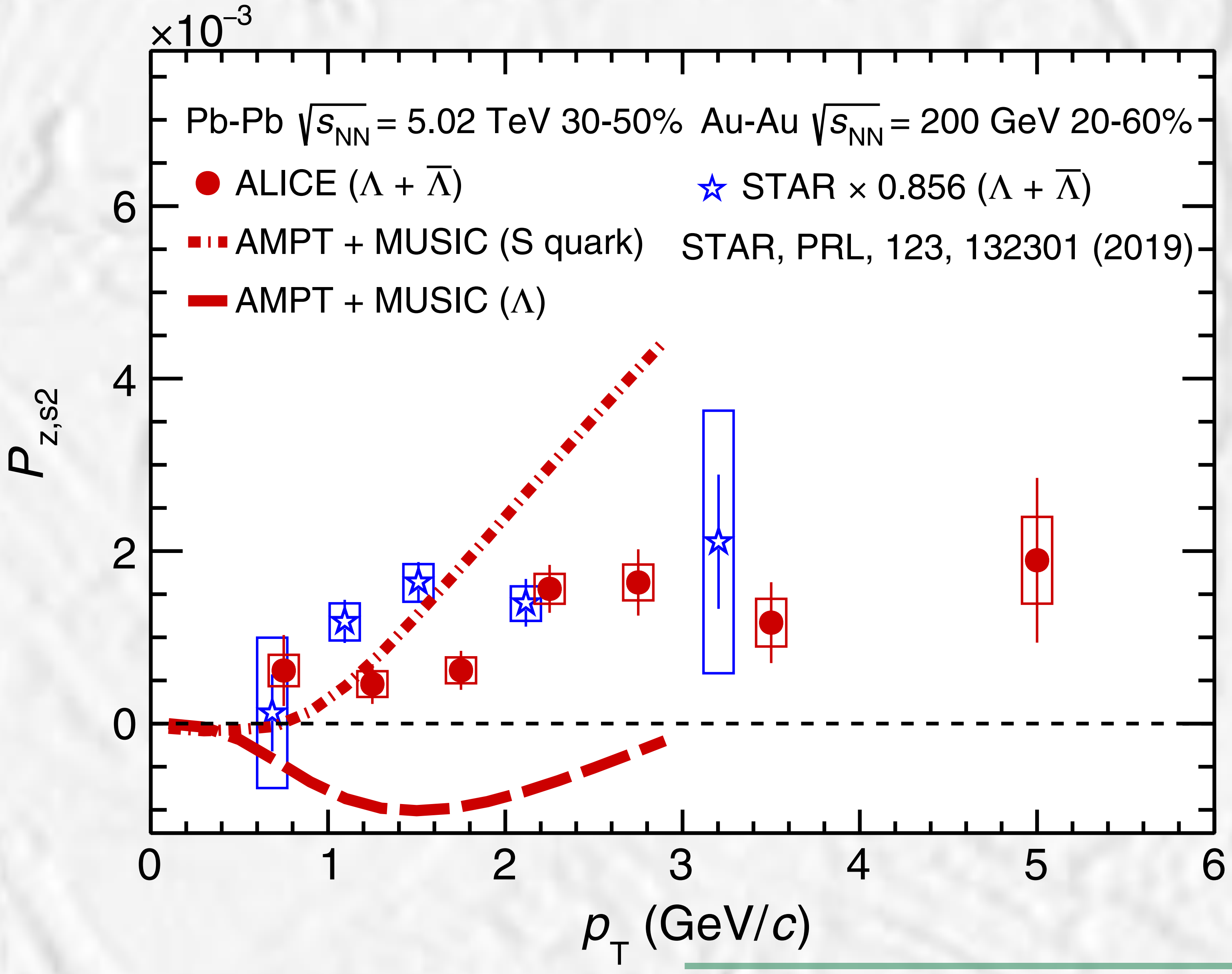
+ LHC measurements

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", arXiv:2107.11183









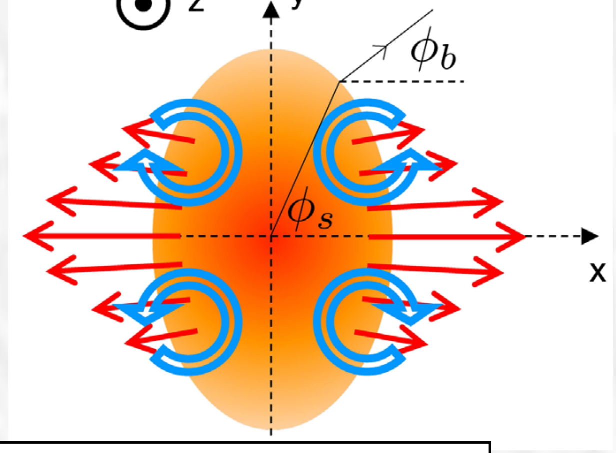
Neither sign nor magnitude of P_z could be reproduced by models based on thermal vorticity - "spin sign puzzle"

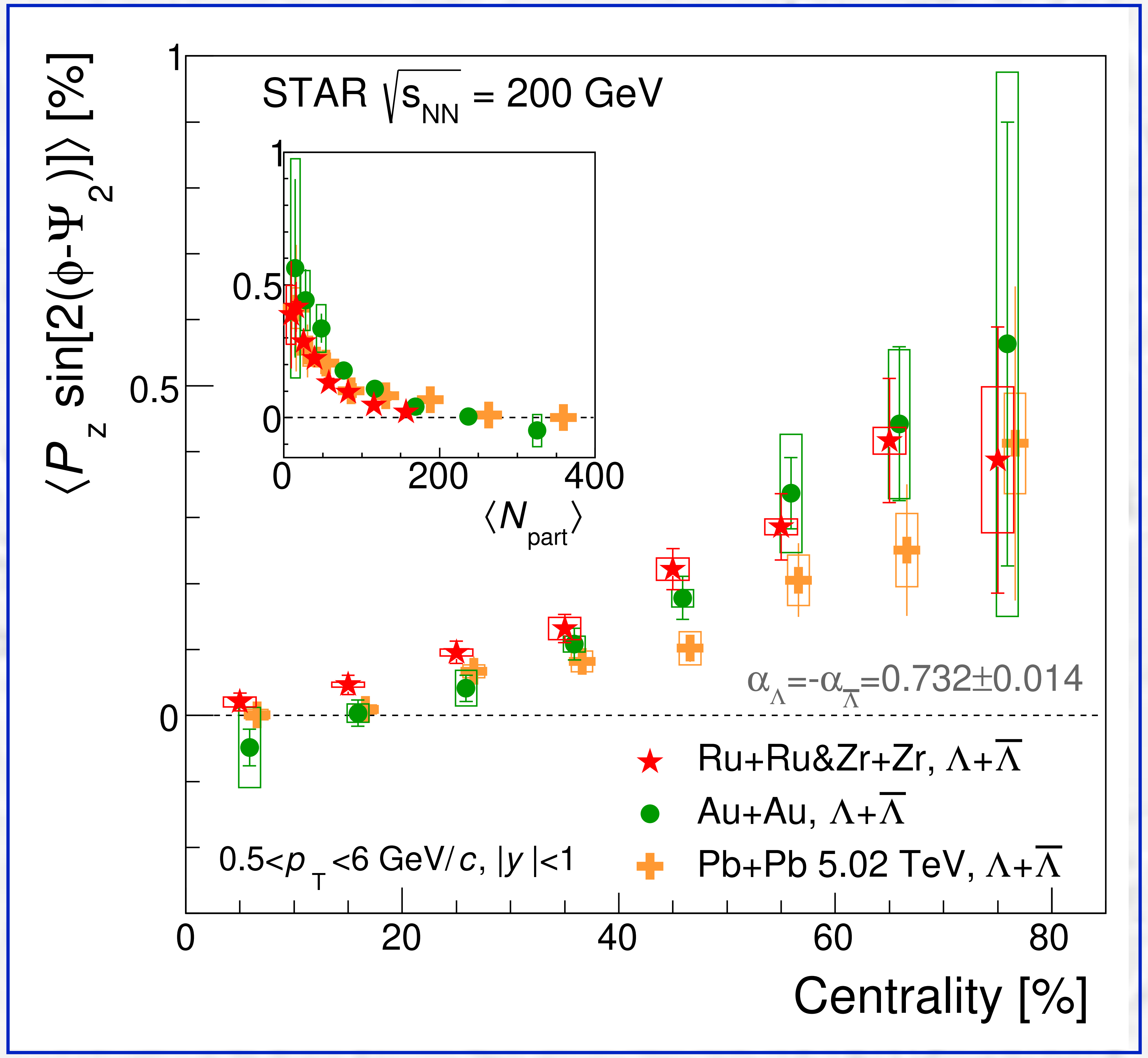
- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- X. Xia et al., PRC98.024905 (2018)
- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Y. Xie, D. Wang, and L. P. Csernai, Eur. Phys. J. C (2020) 80:39
- W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)
- H.-Z. Wu et al., Phys. Rev. Research 1,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

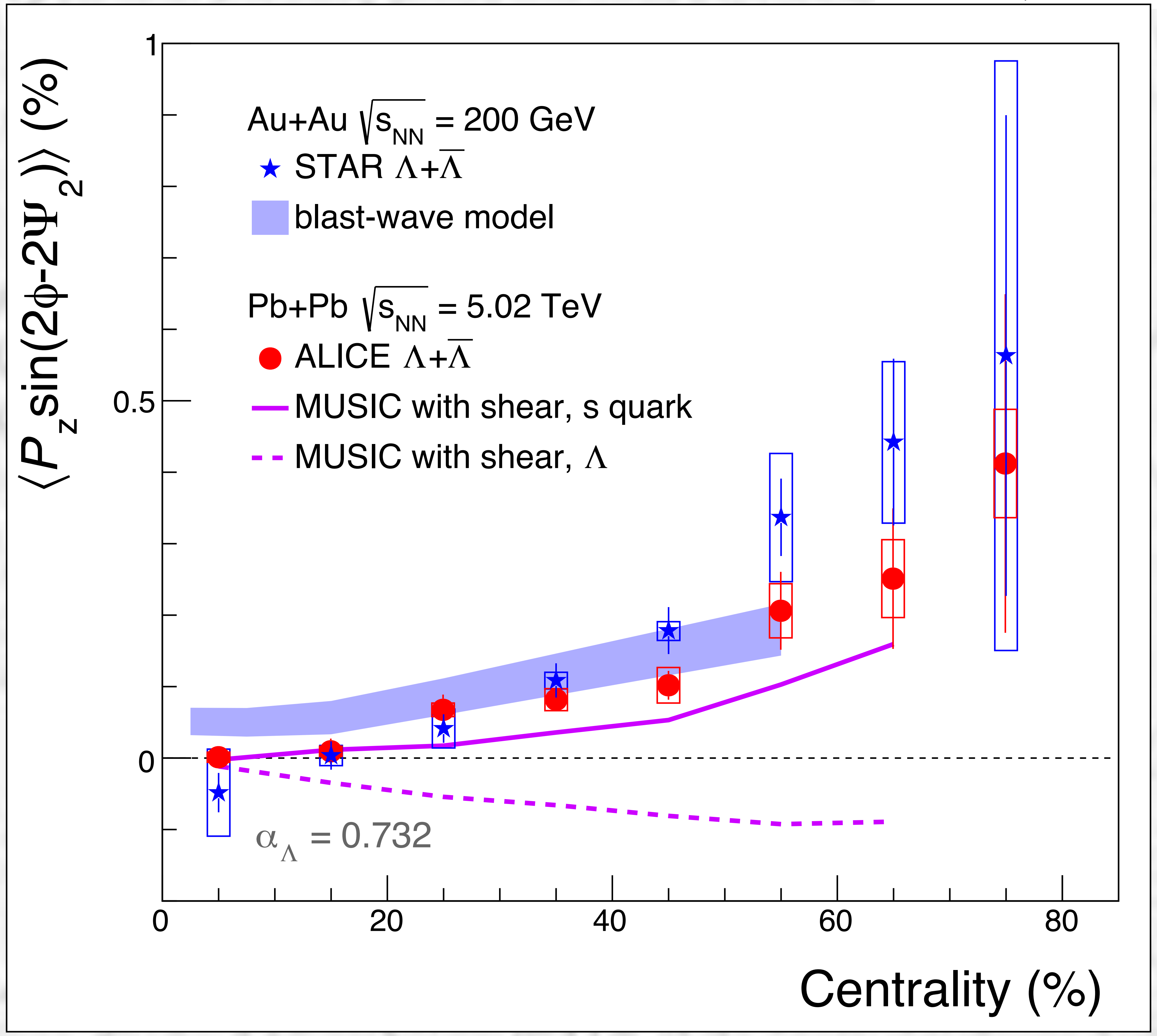
HYDRO, AMPT: It was noticed that the "kinematic non-relativistic vorticity" fits data well, but is (much) smaller than that including contributions from acceleration and temperature gradients

More recently: shear induced polarization (SIP)

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







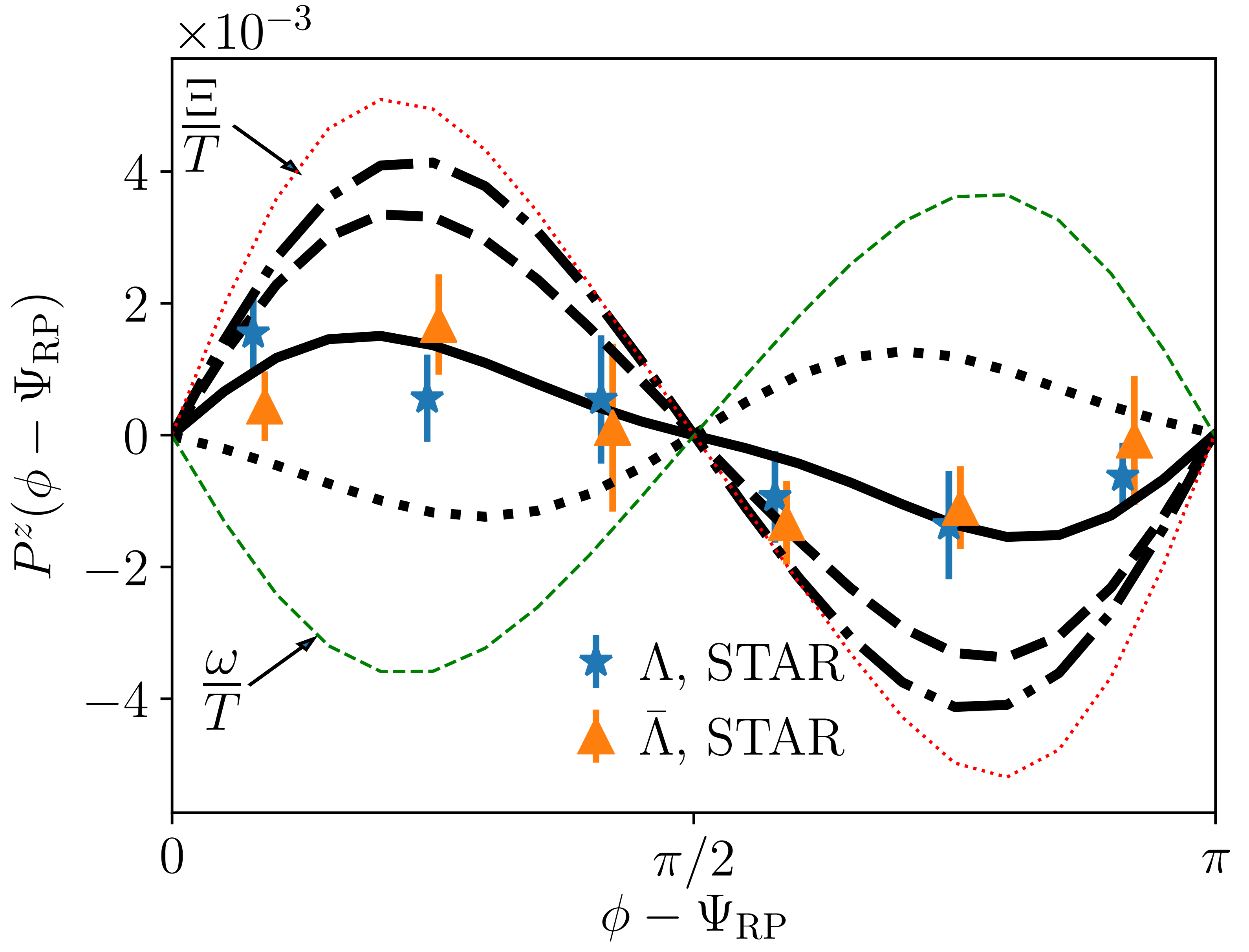
$$r_{max} = R(1 - a\cos(2\phi_s))$$

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

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

Centrality dependence - follows eccentricity ? (not v_2)

Shear induced polarization (SIP)

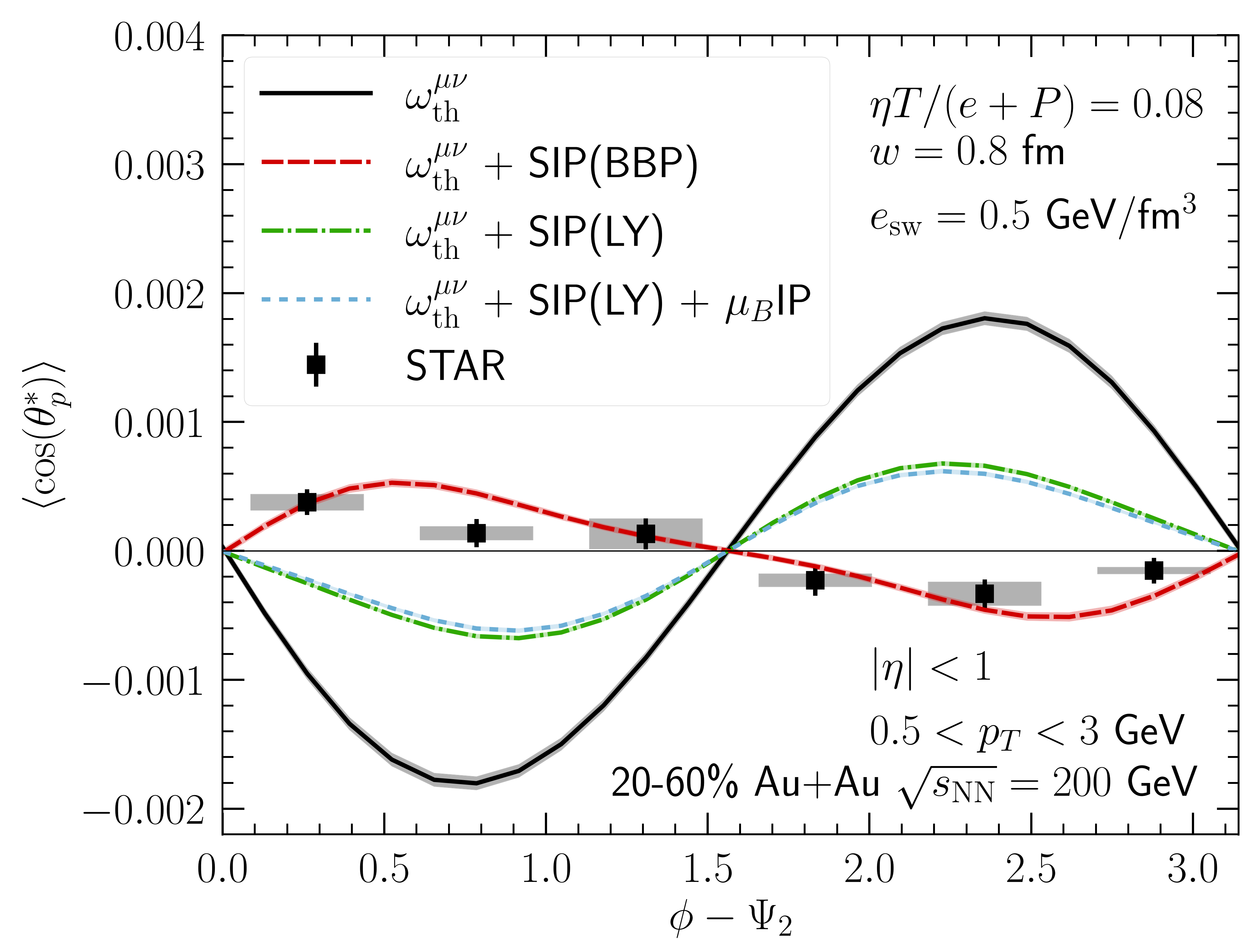


vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

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)

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

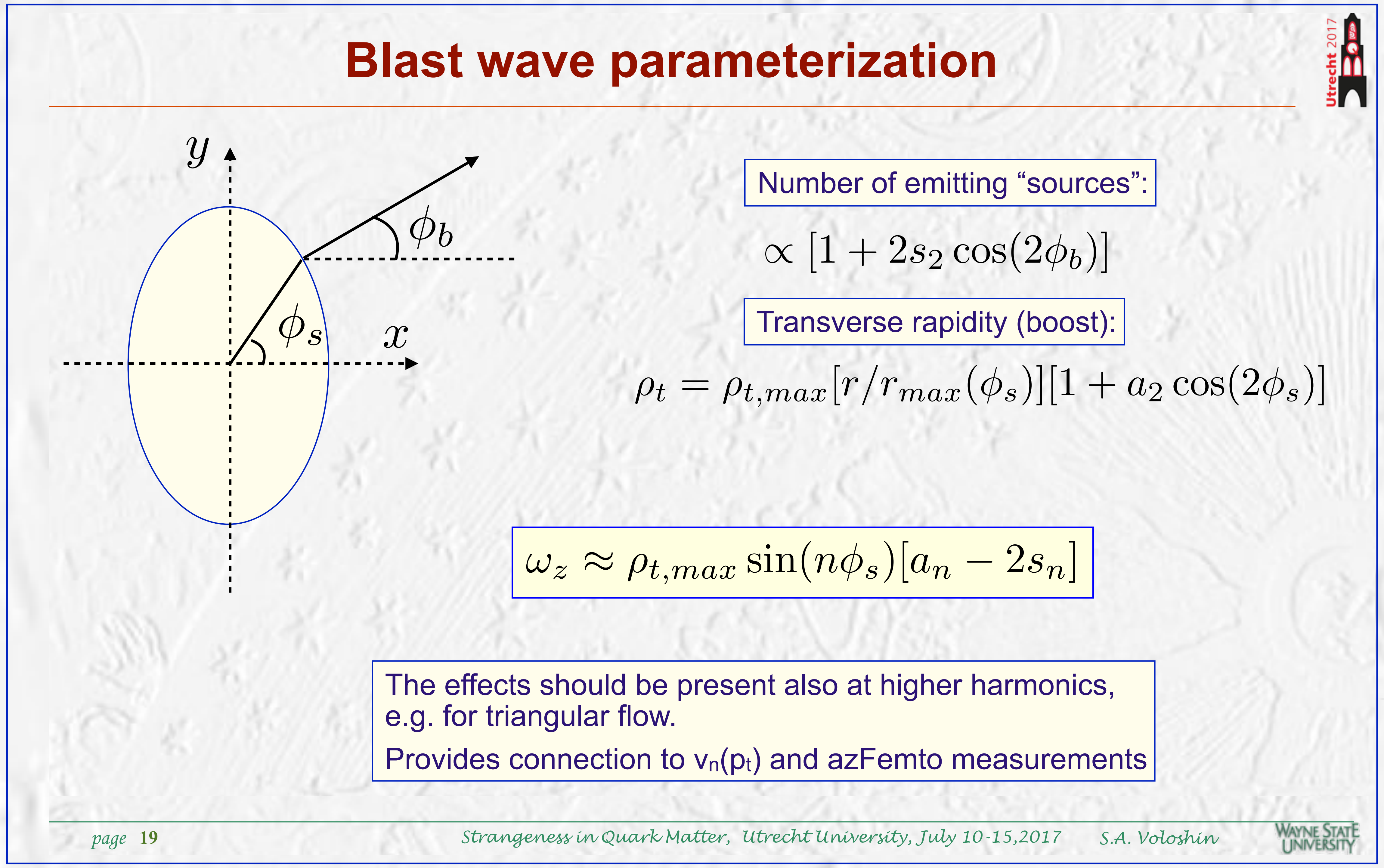


Would higher harmonics measurements help to observe the SIP contribution?

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":

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

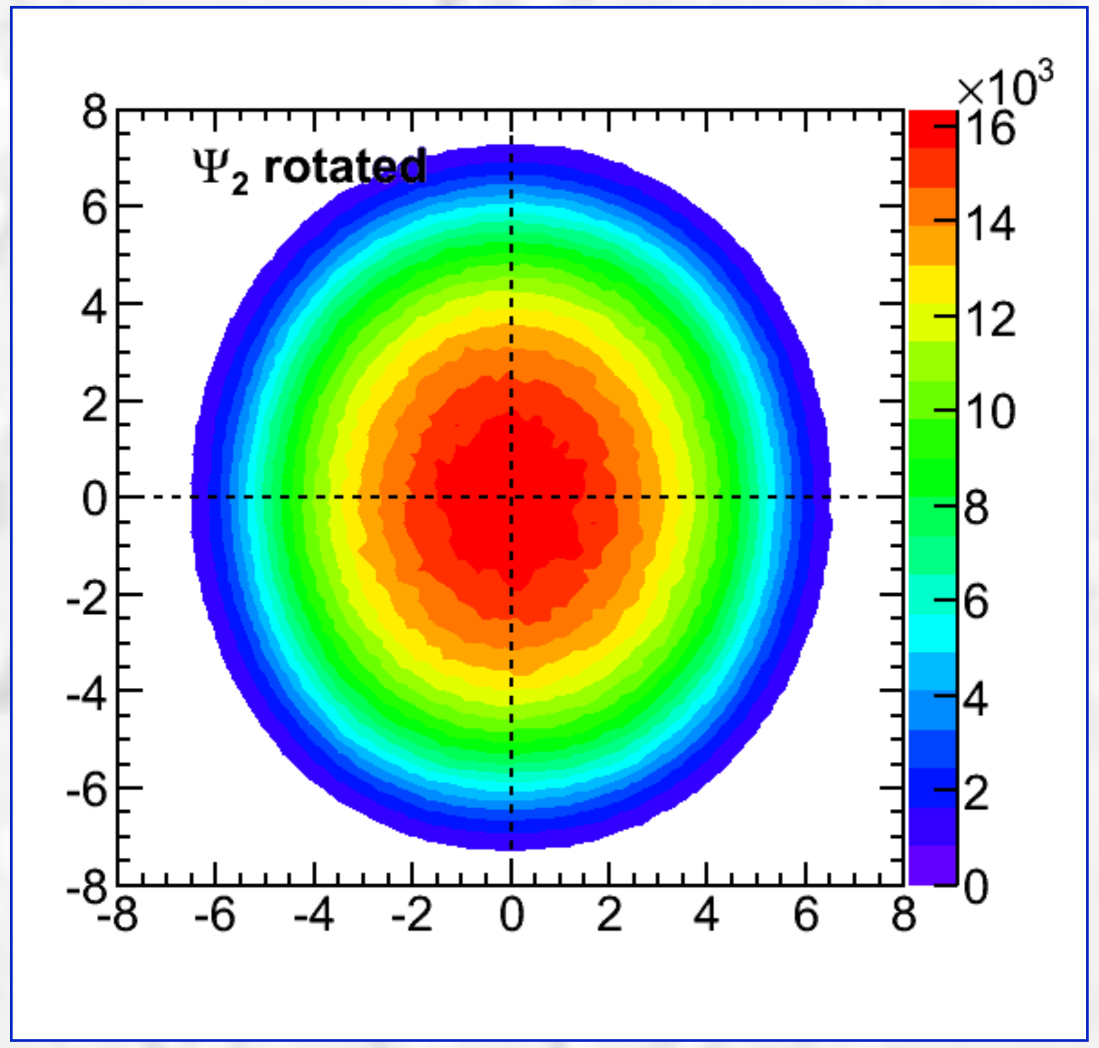
Transverse rapidity (boost):

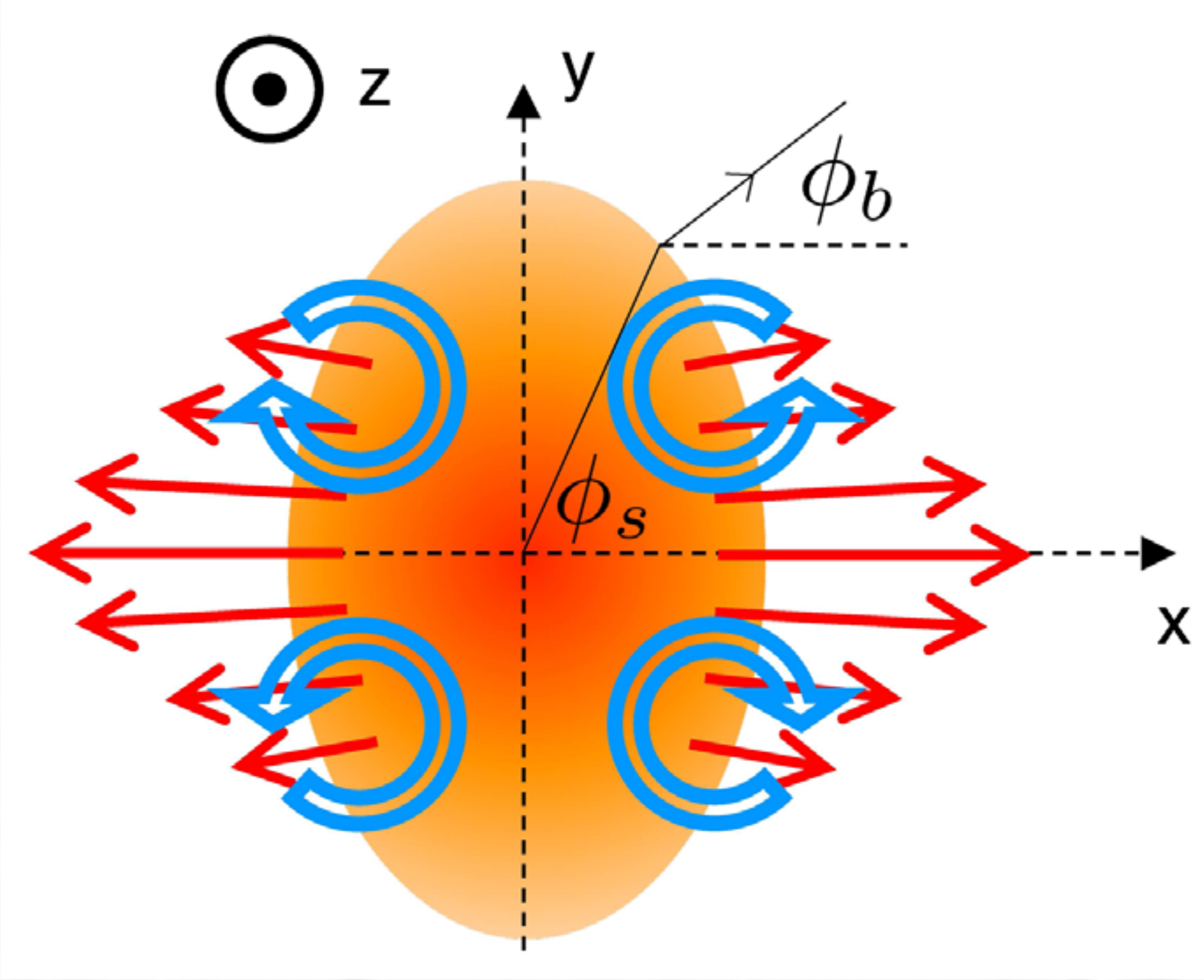
$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + a_2\cos(2\phi_s)]$$

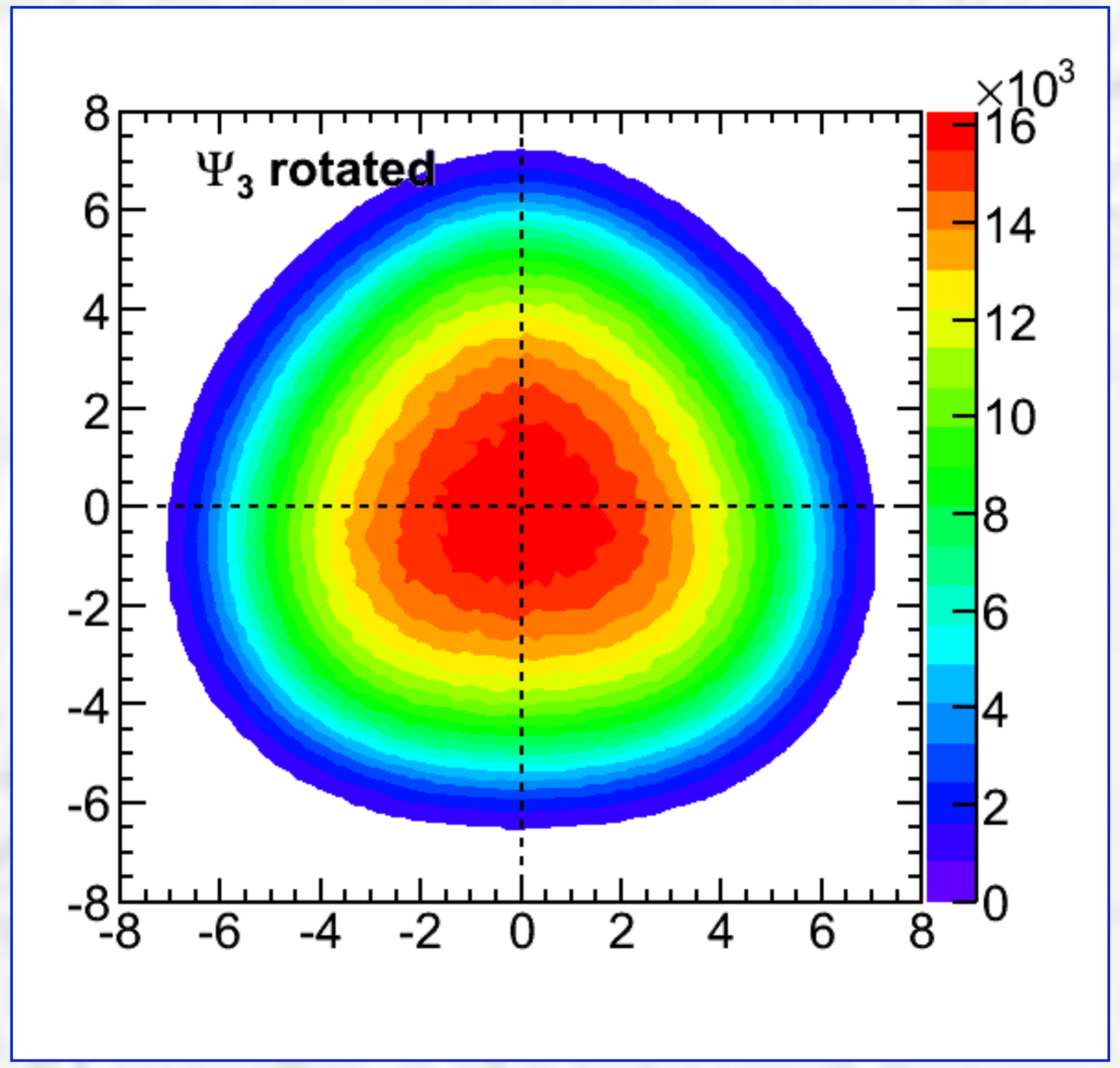
$$\omega_z \approx \rho_{t,max}\sin(n\phi_s)[a_n - 2s_n]$$

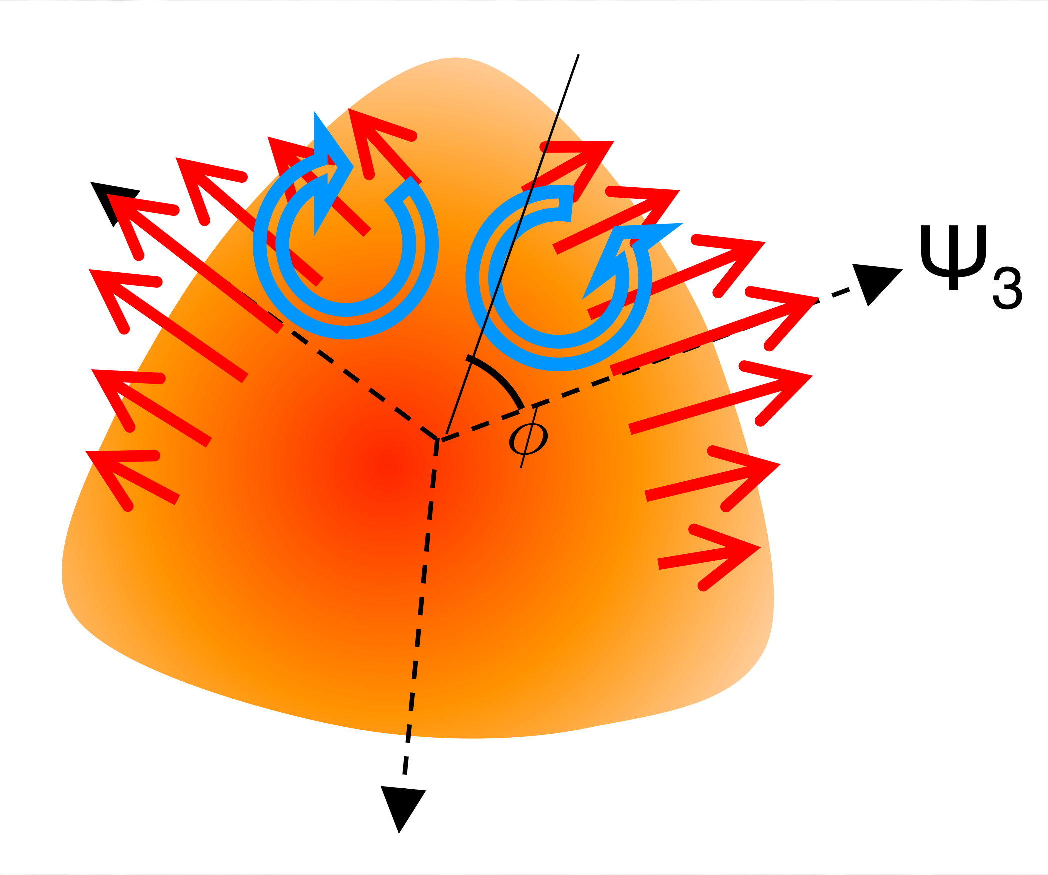
The effects should be present also at higher harmonics, e.g. for triangular flow.

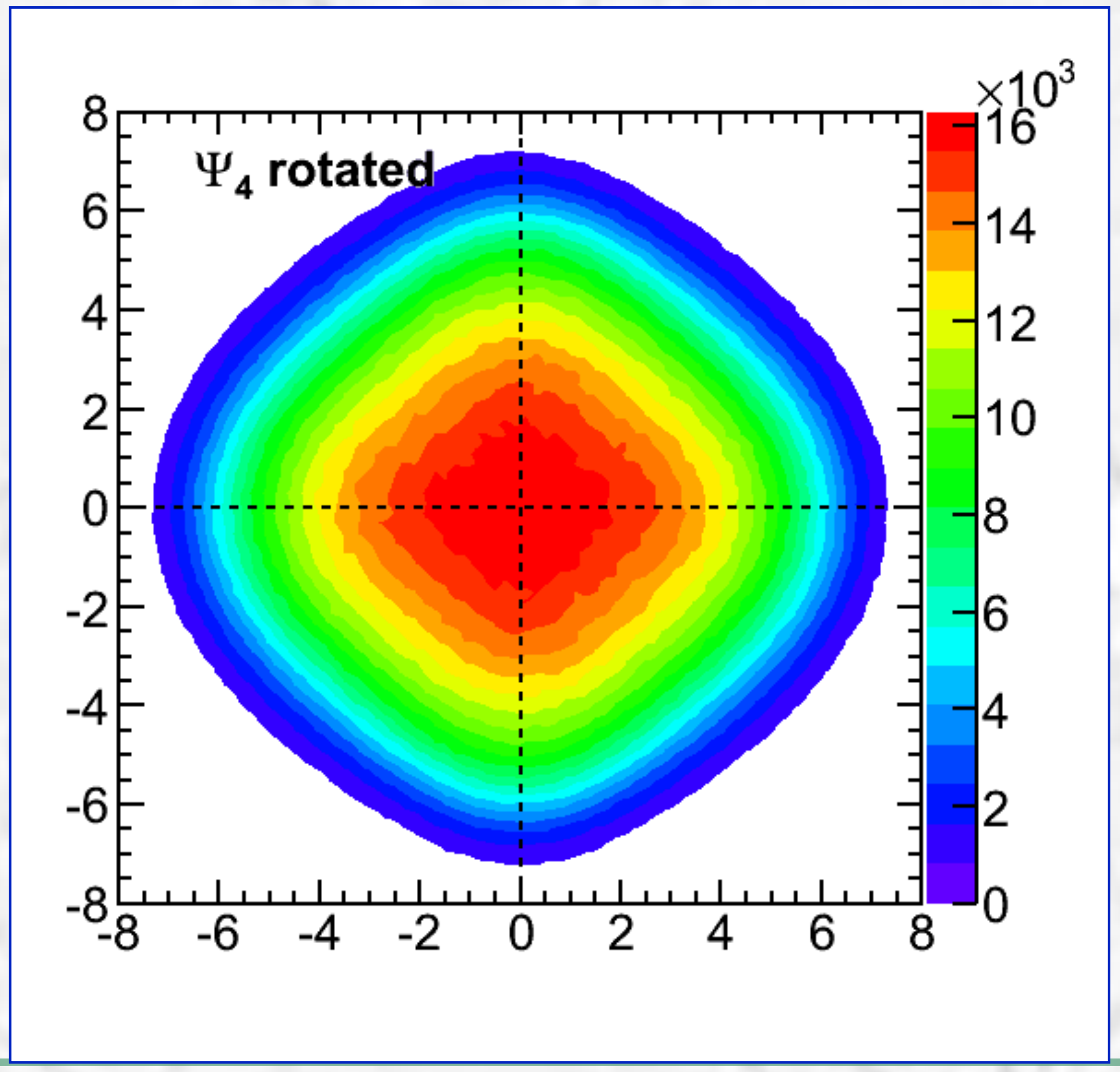
Provides connection to $v_n(p_t)$ and azFemto measurements







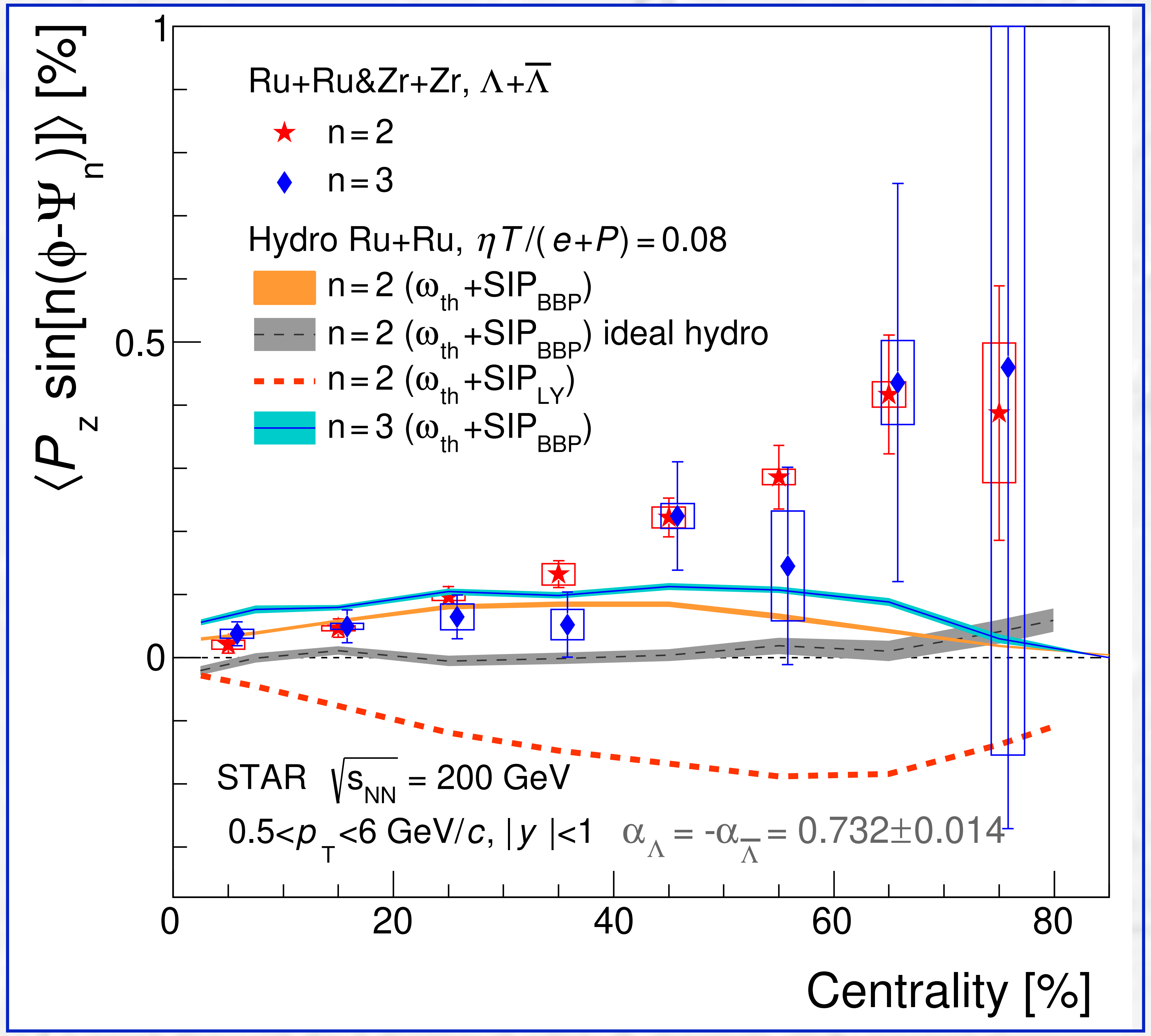


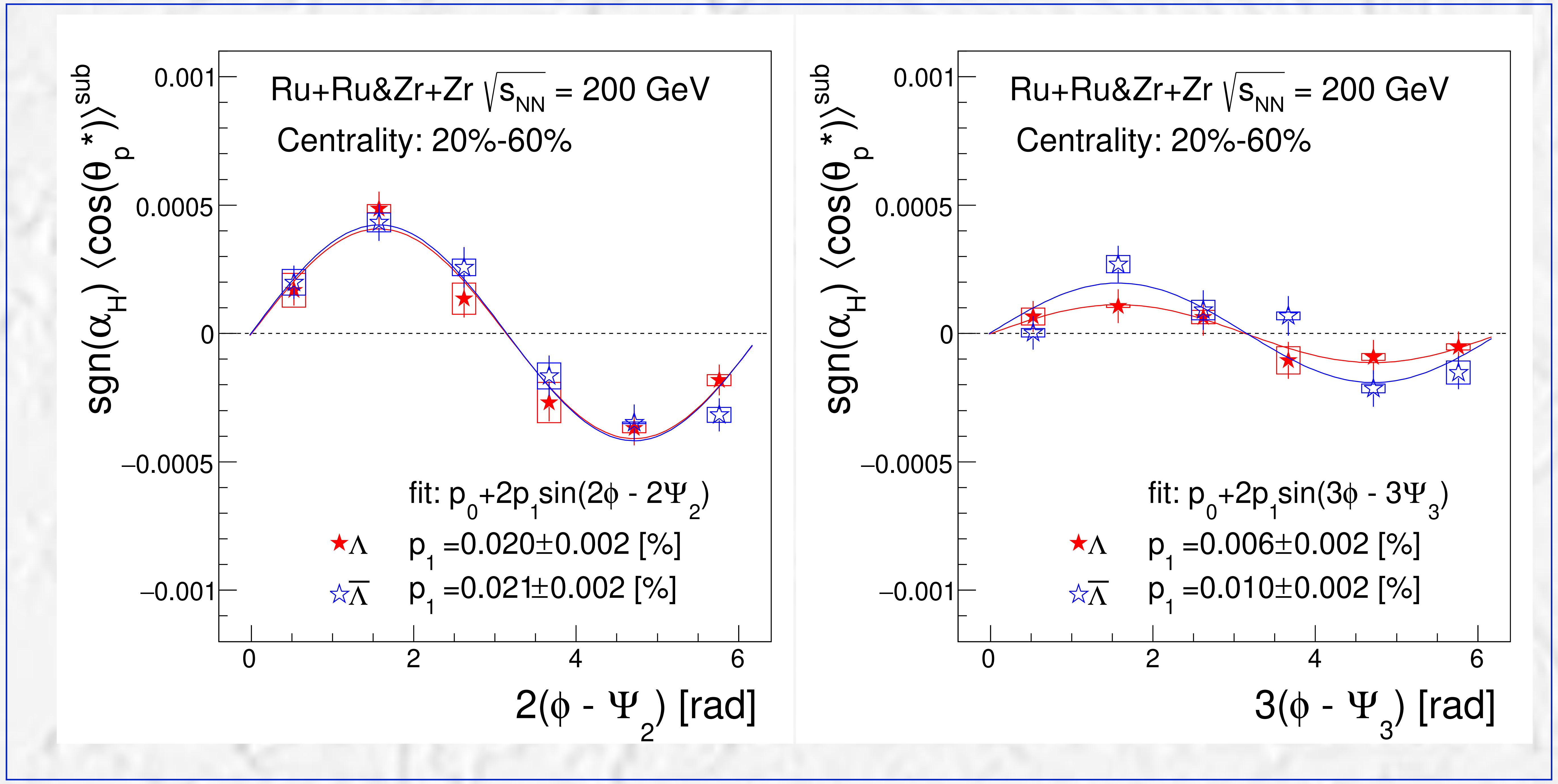


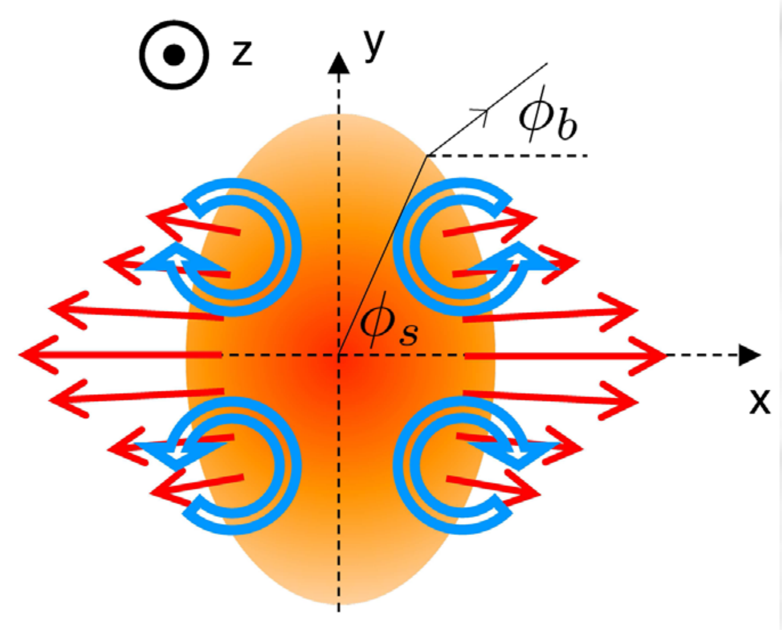
P_z in isobar collisions, + third harmonic

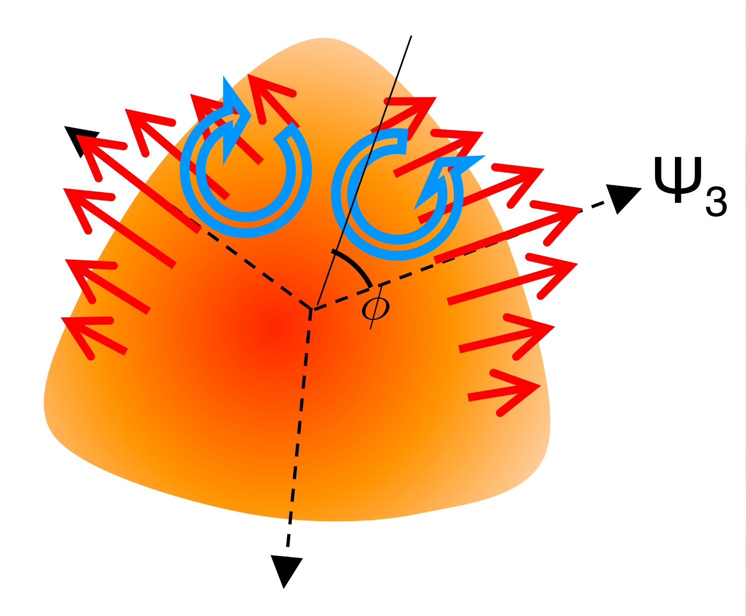
STAR Collaboration, "Hyperon polarization along the beam direction relative to the second and third harmonic event planes in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV", `arXiv:2303.09074 [nucl-ex]`.

~4B events





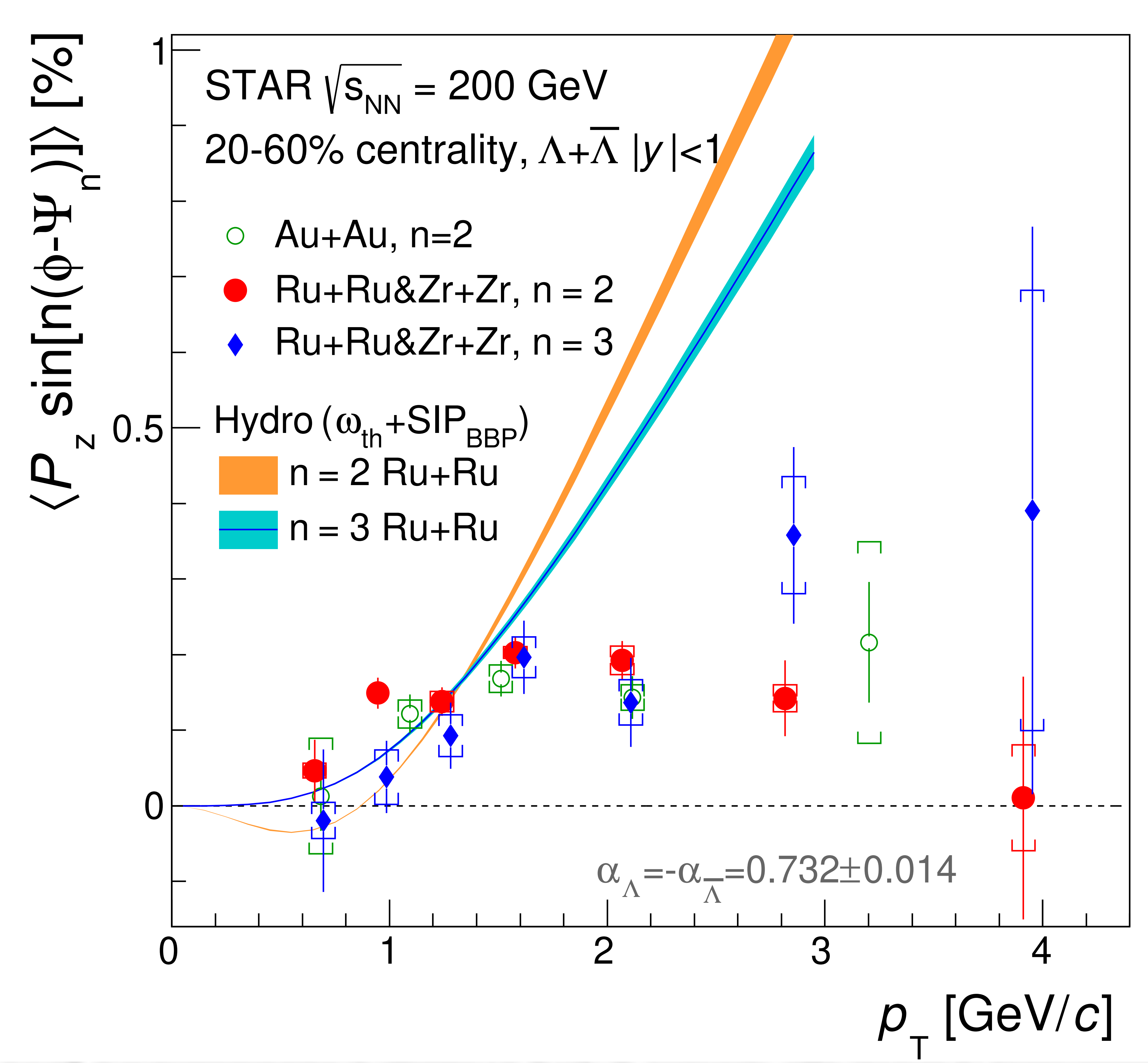


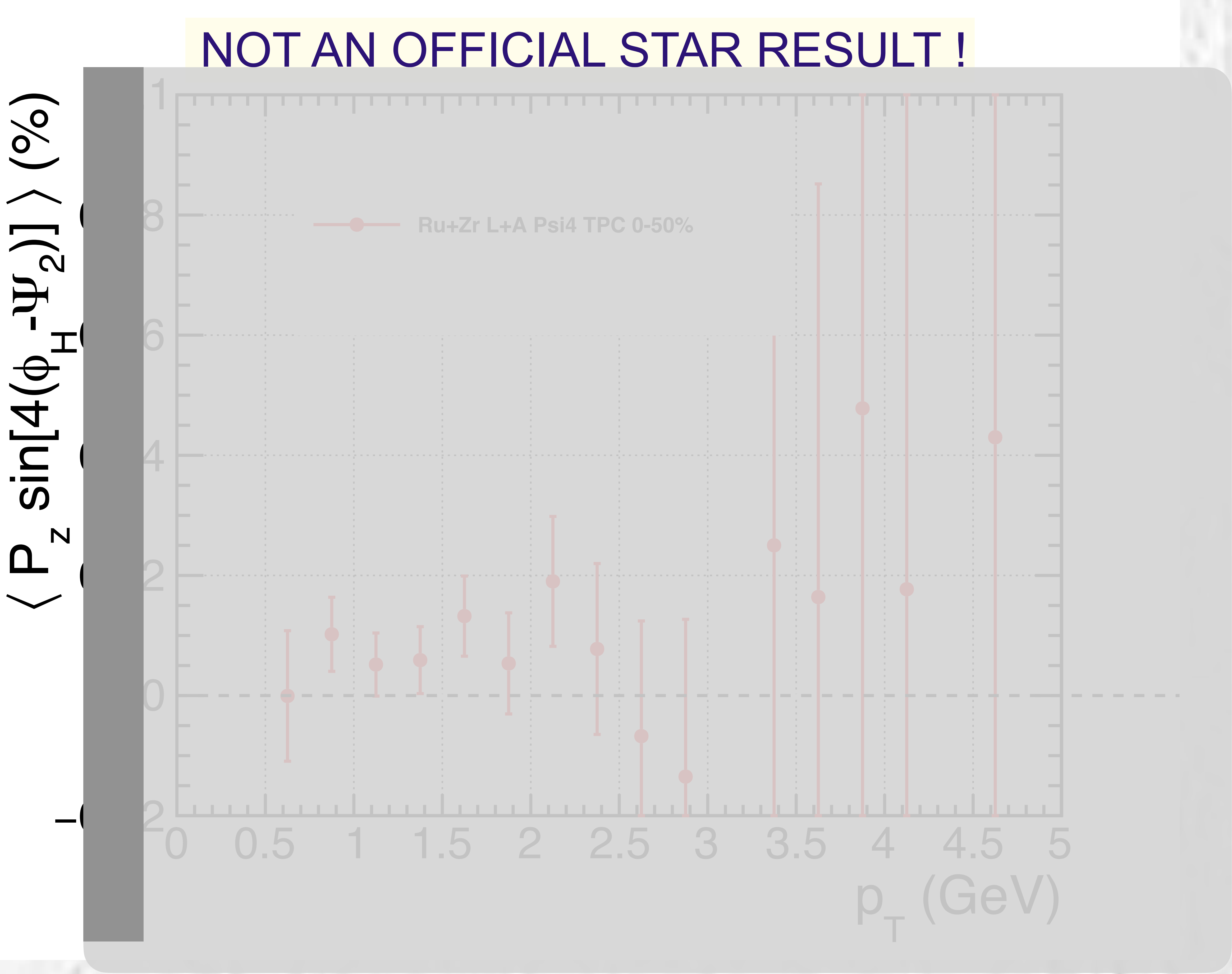


Model calc's:

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





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:

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

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

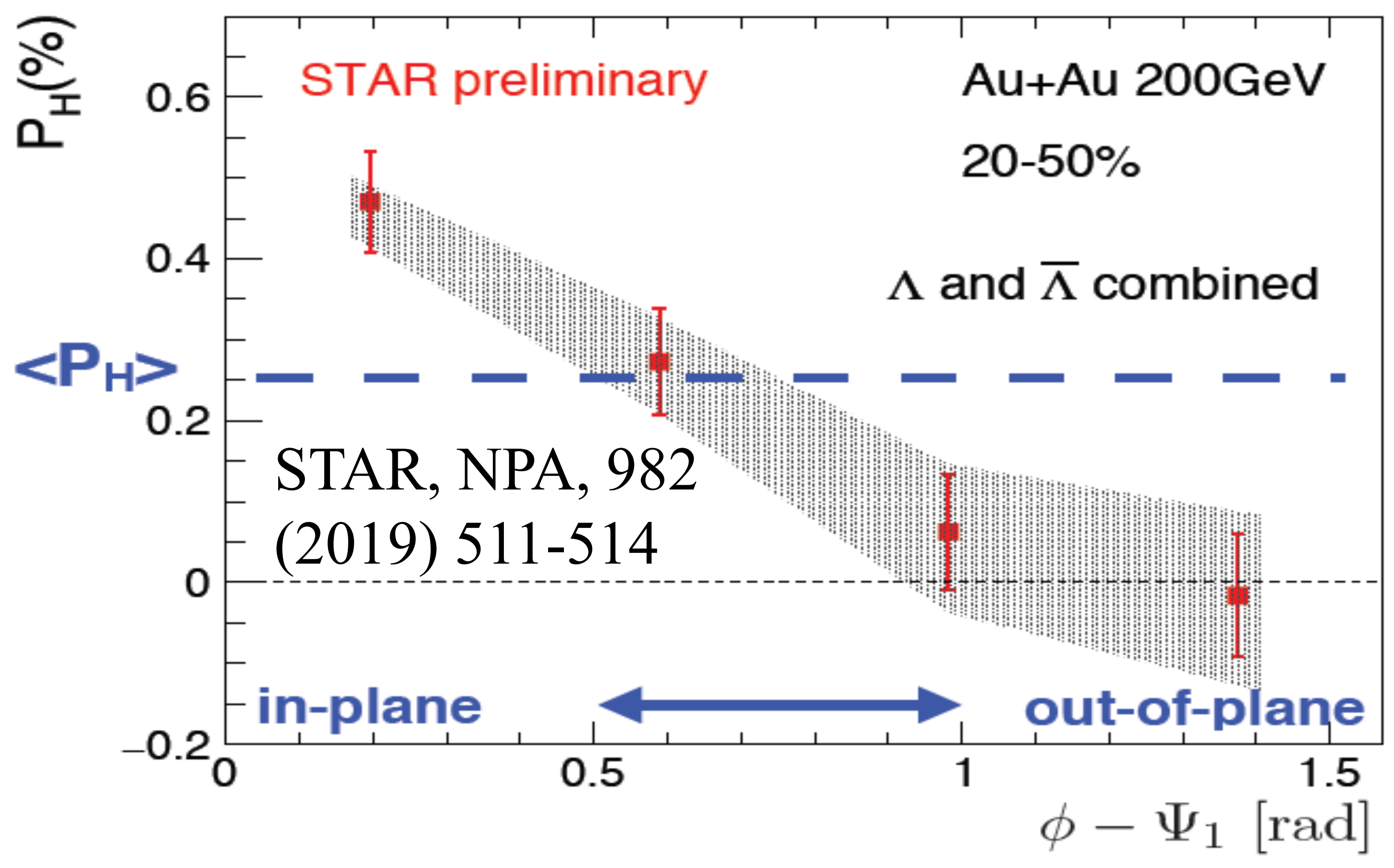
$$S_z \propto p_y p_z \propto \sin(2\theta)\,\sin(\phi)$$

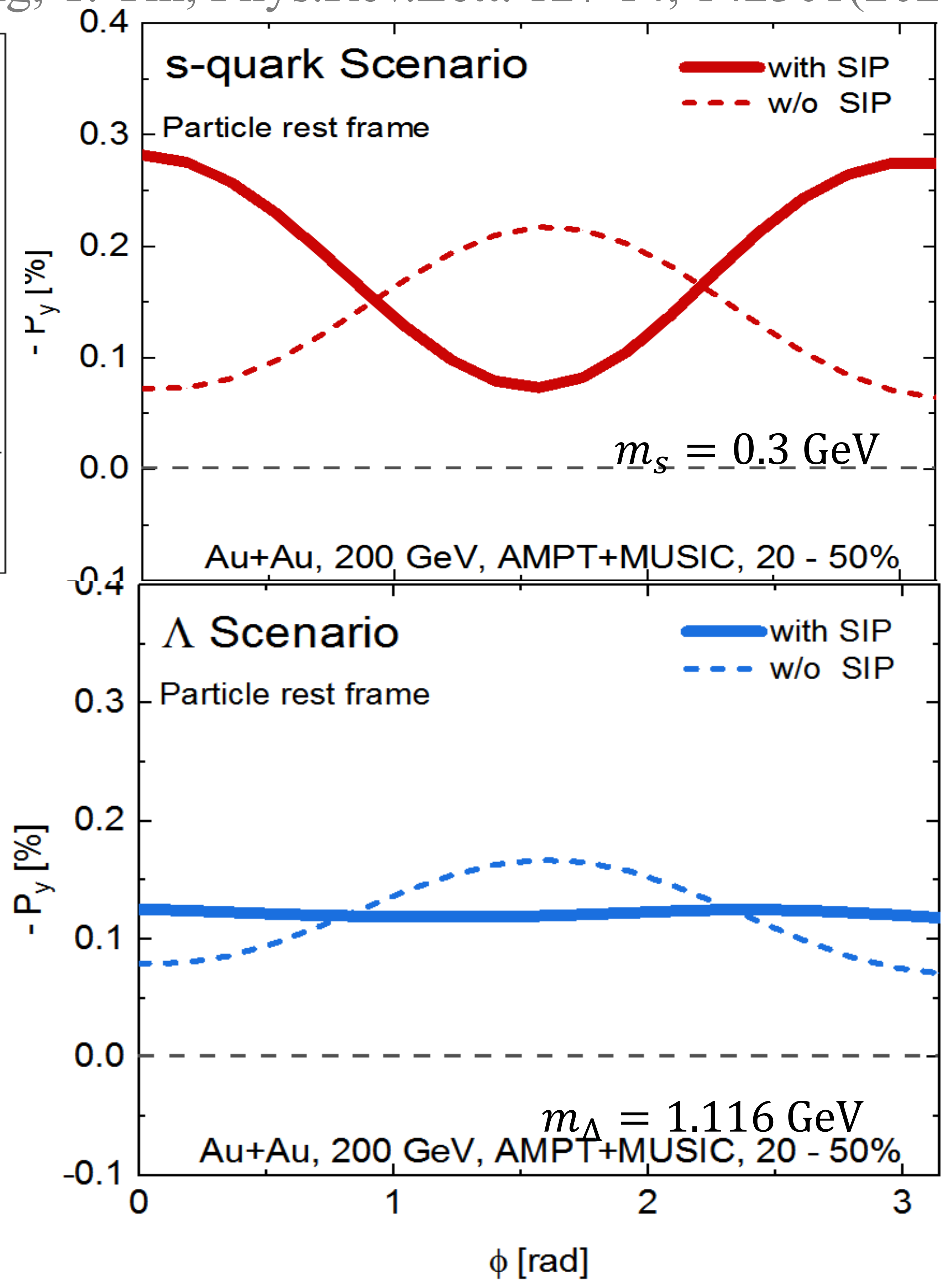
Momentum in the rest frame of the fluid - averaging over the production volume should further suppress such contributions.

$P_y(\phi)$ physics

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)

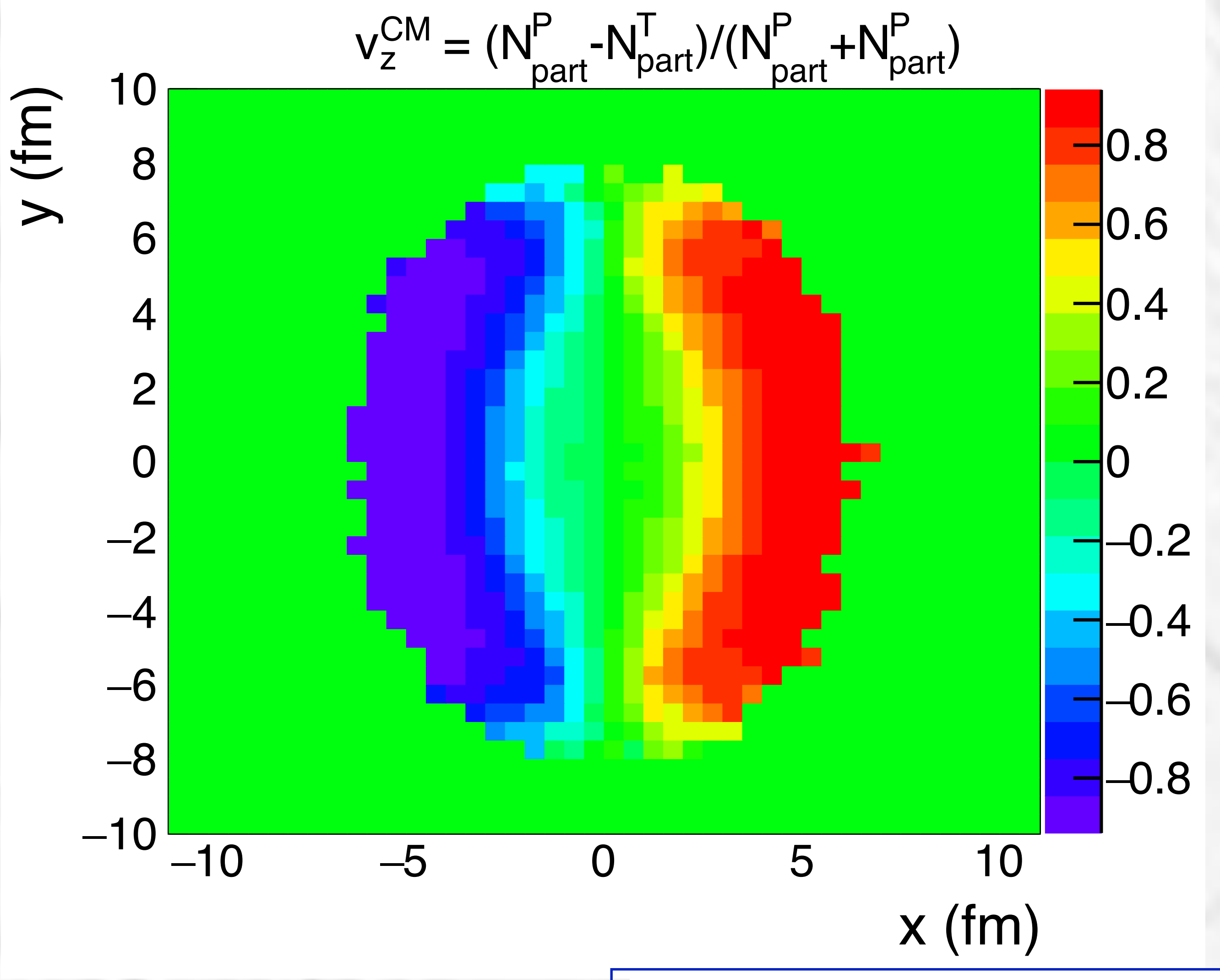


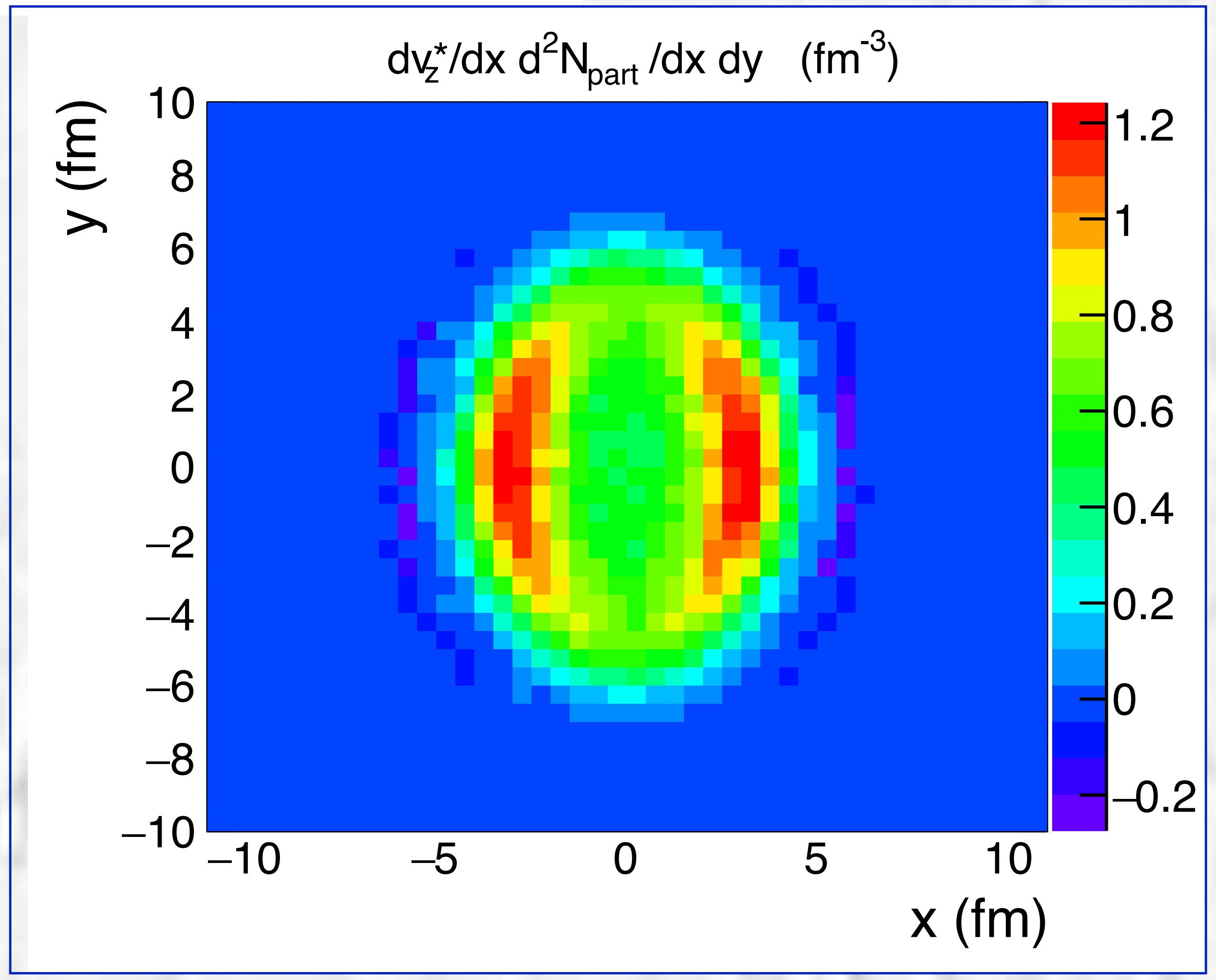


Total P^μ
=Thermal vorticity + Shear effects

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

Vorticity



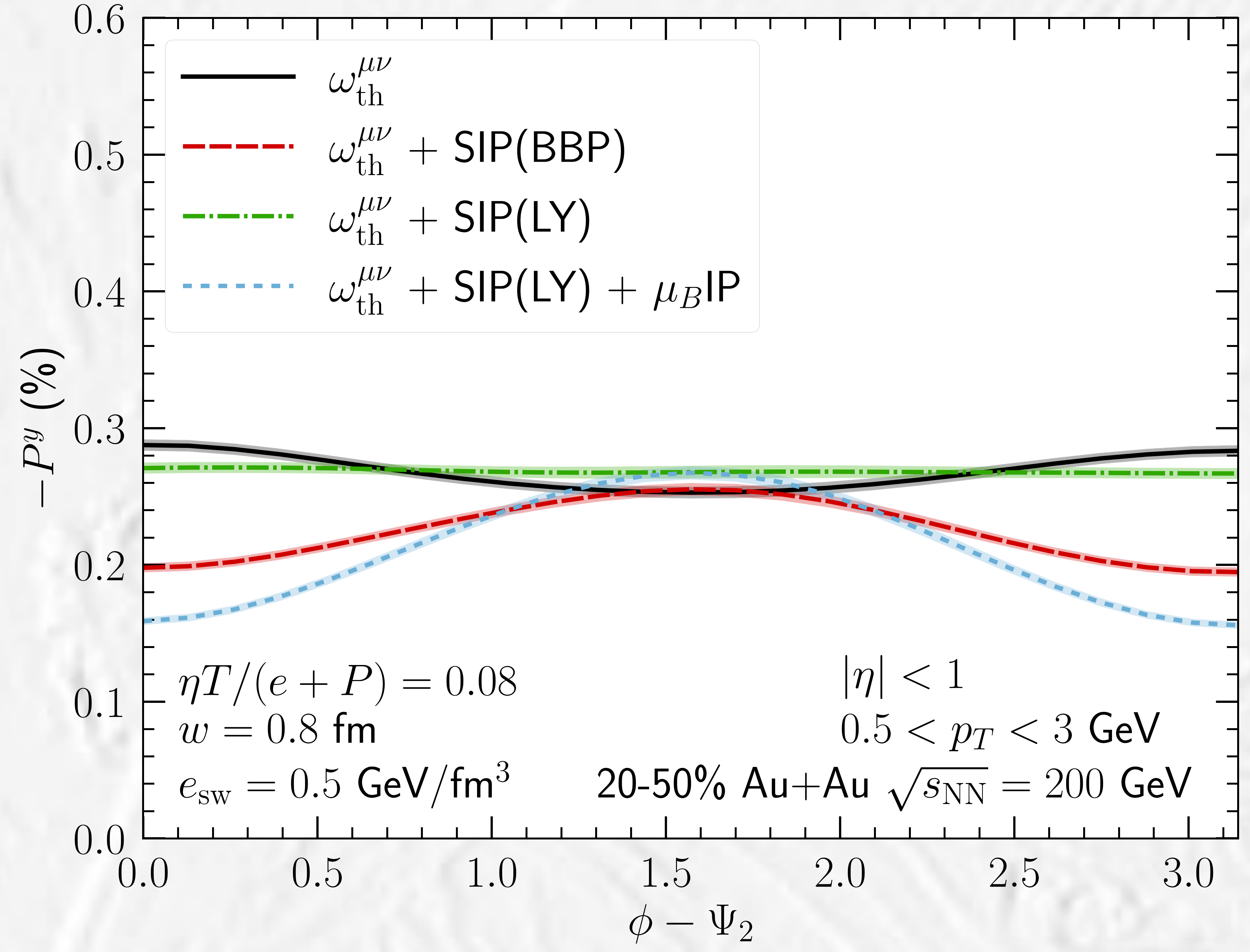


It is not clear why hydro without SIP predicts larger polarization "out-of-plane" — which is at odds with expectation from the right plot

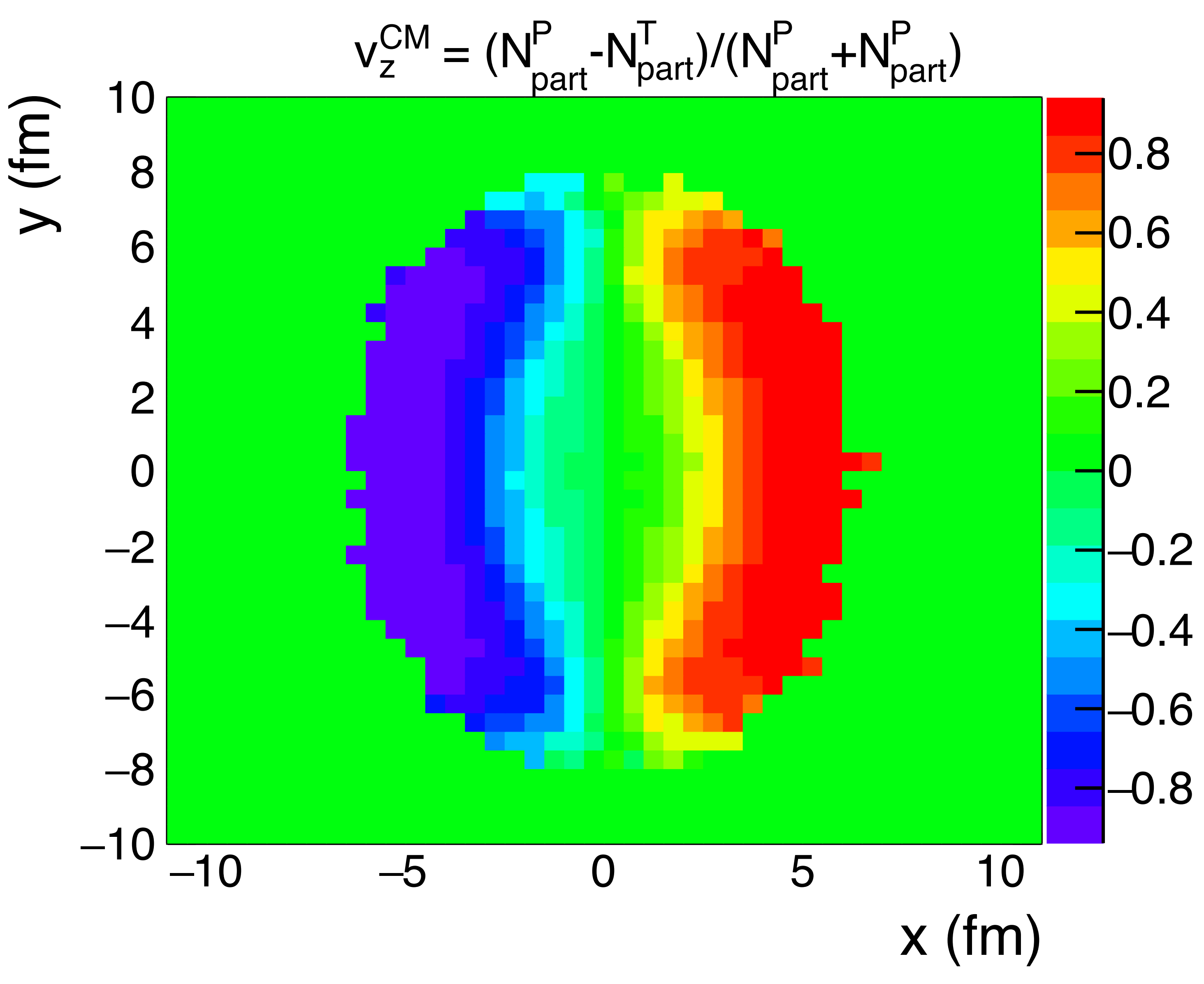
P_y : SIP vs vorticity

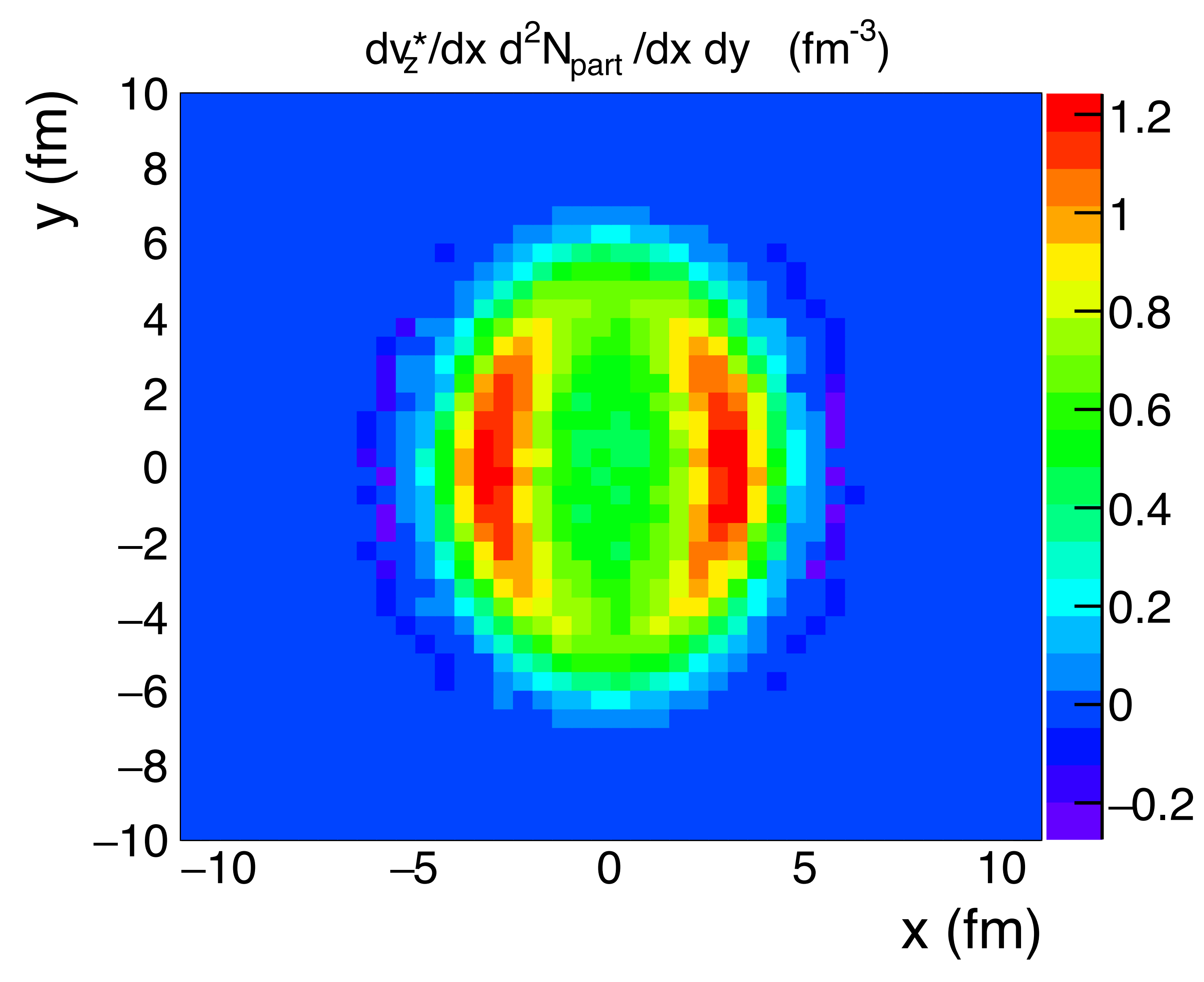
SIP:

SAHR ALZHRANI, SANGWOOK RYU, AND CHUN SHEN



Vorticity





Results from different calculations under the same conditions differ!

Will be difficult to separate the two contributions

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.

P_x : SIP vs vorticity

SIP:

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

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

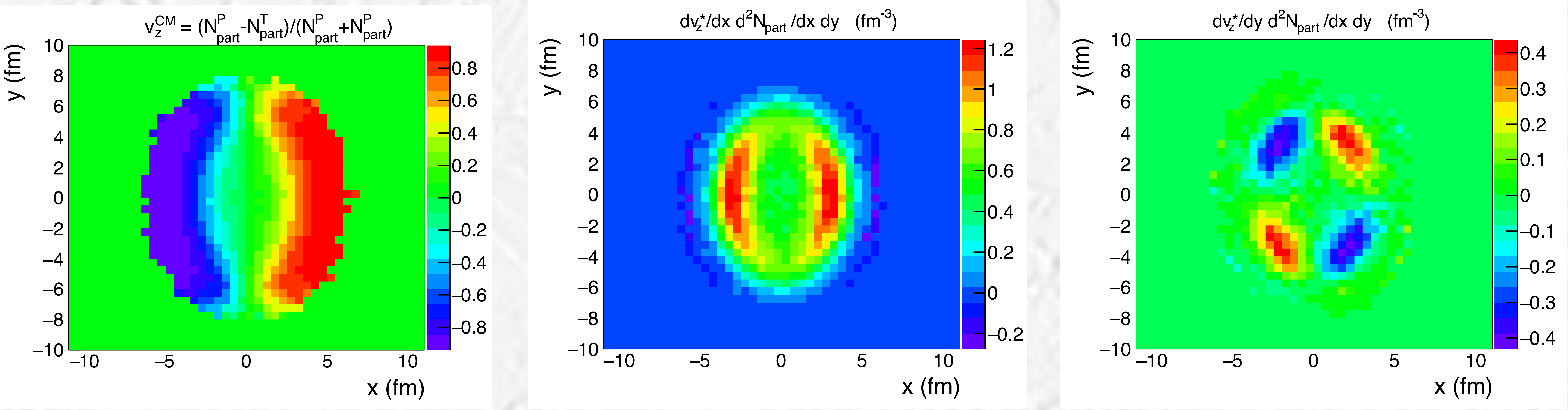
u_i - fluid velocity
Star denotes the value in the rest frame of fluid element

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

Vorticity

Will be difficult to separate the two contributions

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



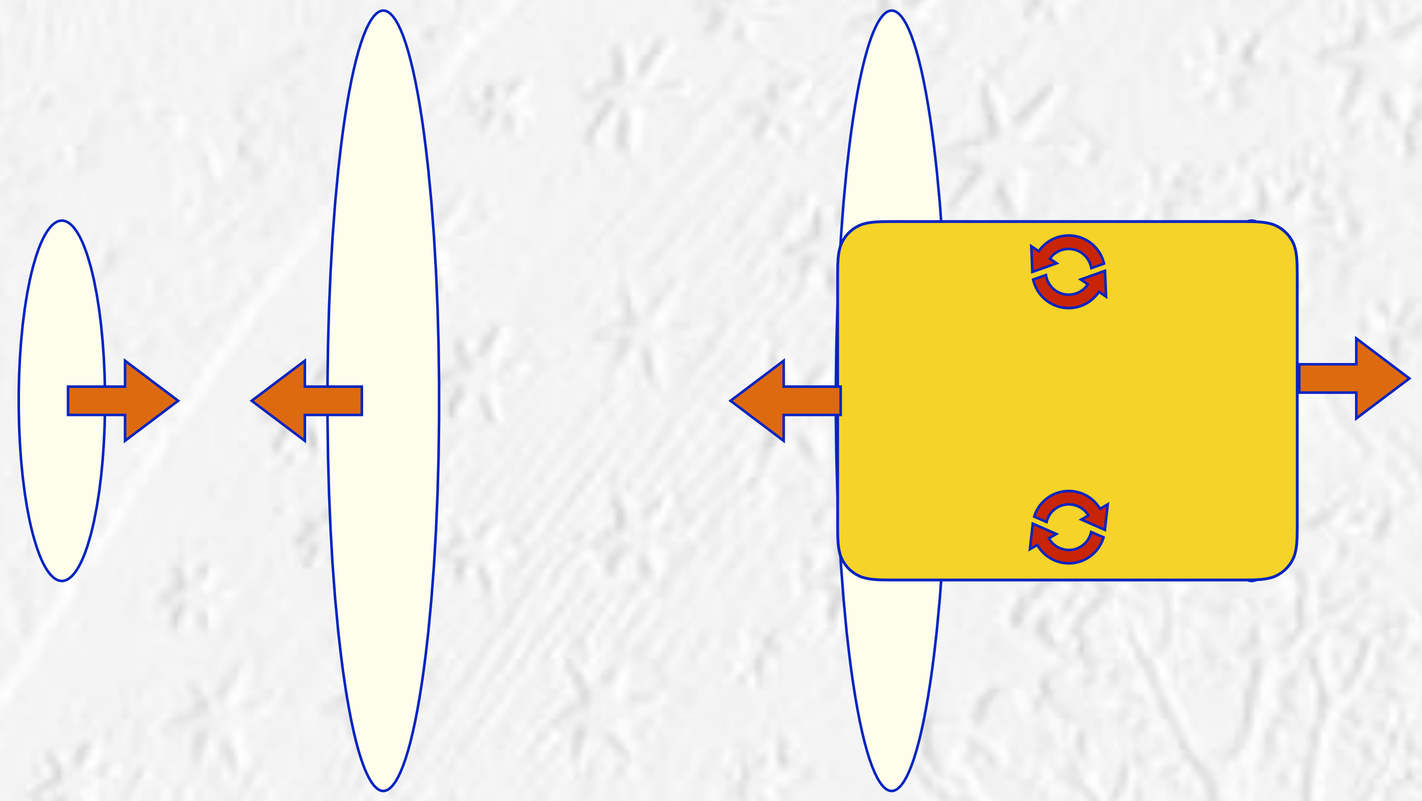
P_ϕ in asymmetric collisions

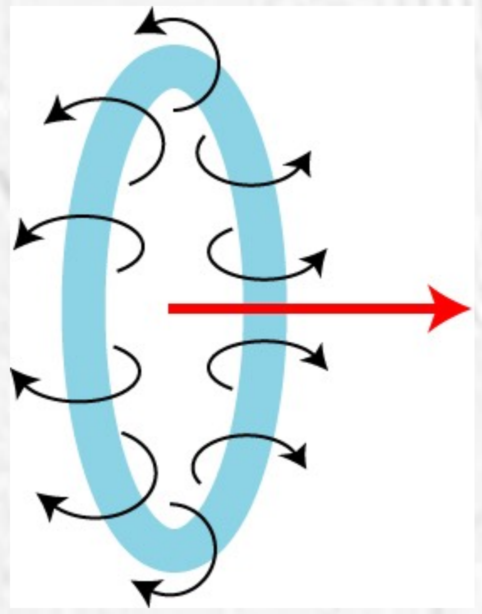
Global/local polarization and…

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

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

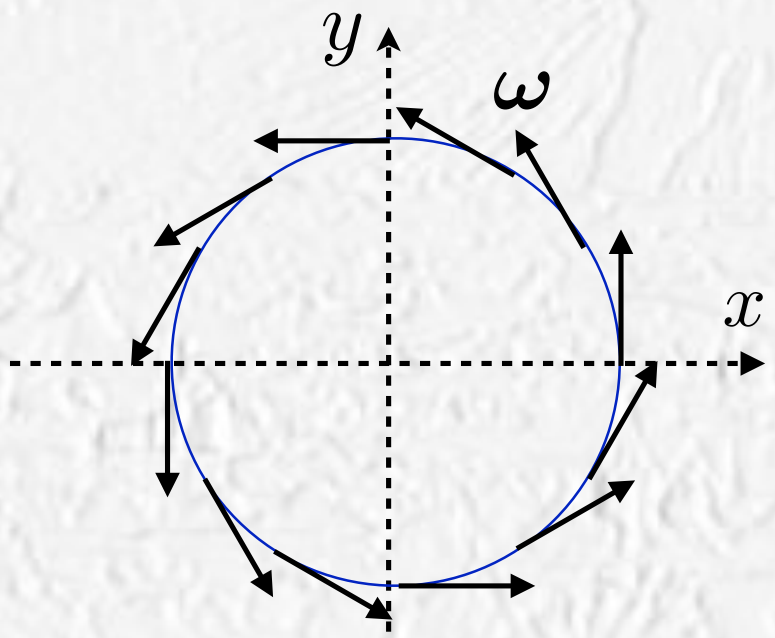
+ anisotropic flow => $\omega_\phi(\phi)$





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)

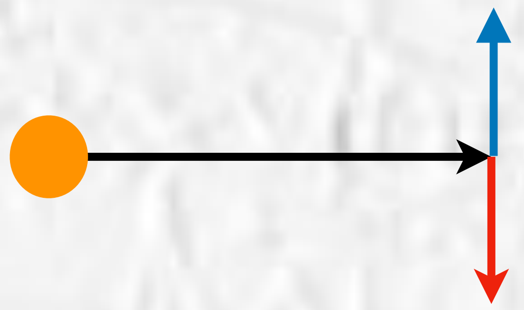
Sergei A. Voloshin[1,*]

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



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.

Similar to:

Y. B. Ivanov and A. A. Soldatov, “Vortex rings in fragmentation regions in heavy-ion collisions at $\sqrt{s_{NN}}$ = 39 GeV,” Phys. Rev. C **97**, no.4, 044915 (2018)

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

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

Dilepton decay of vector mesons $V \to l^+l^-$

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

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

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

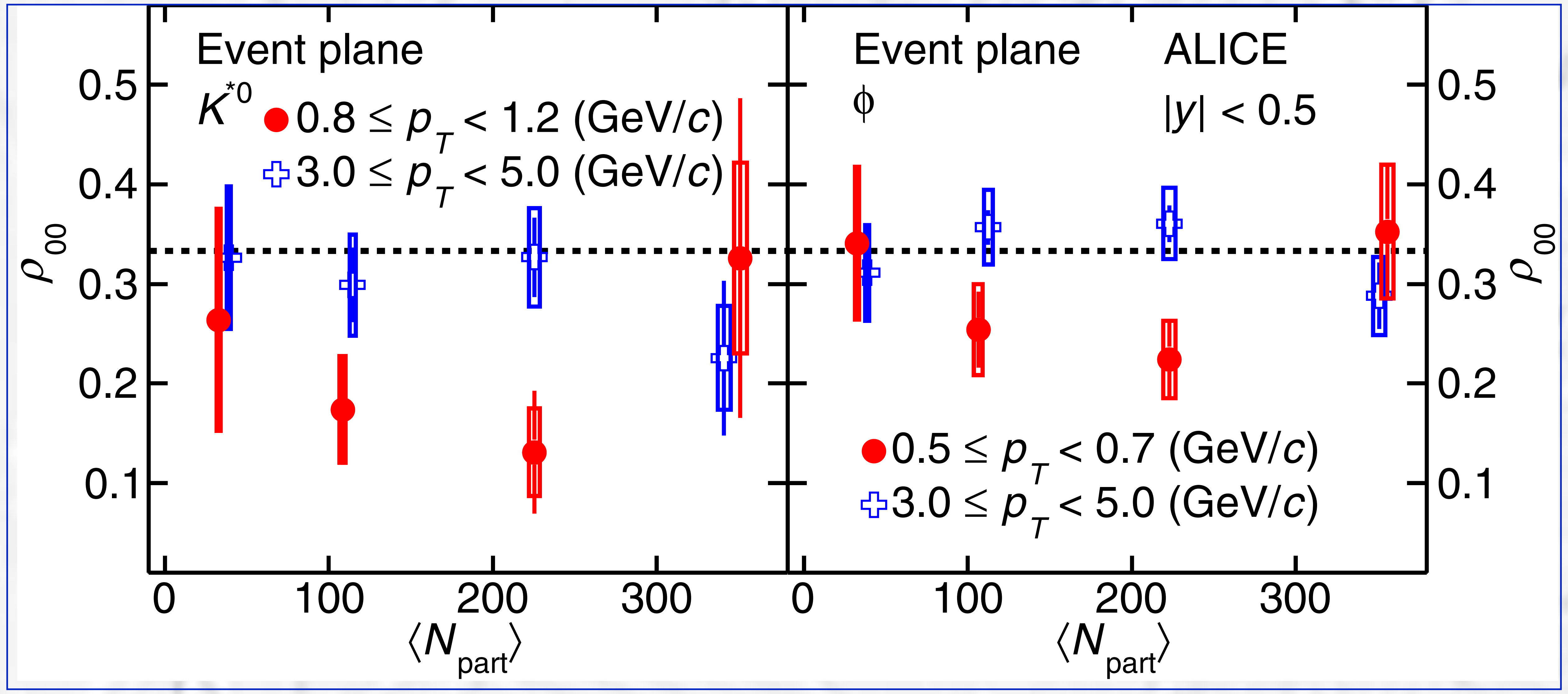
Spin-alignment: ALICE

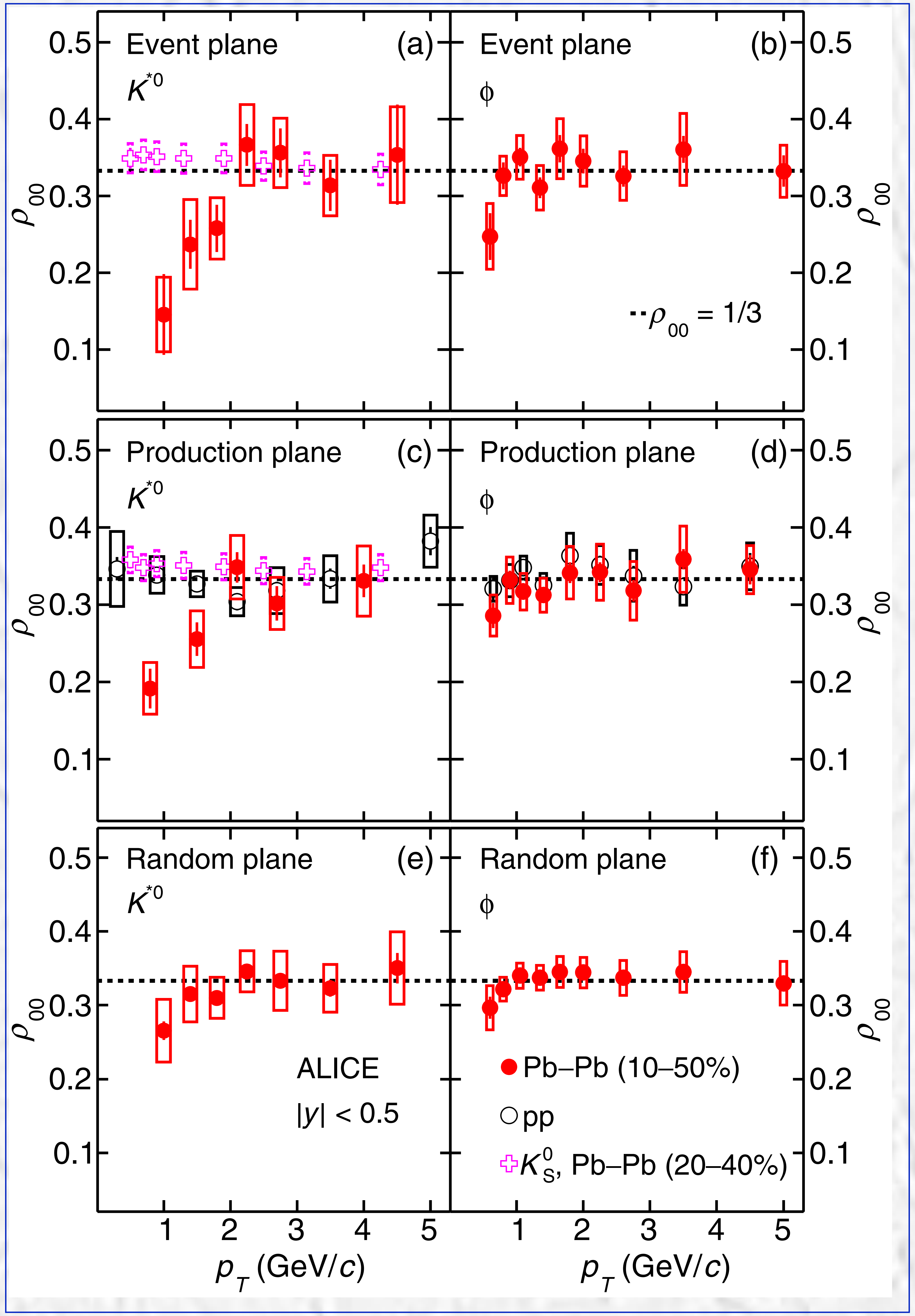
PHYSICAL REVIEW LETTERS **125,** 012301 (2020)

Editors' Suggestion

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

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



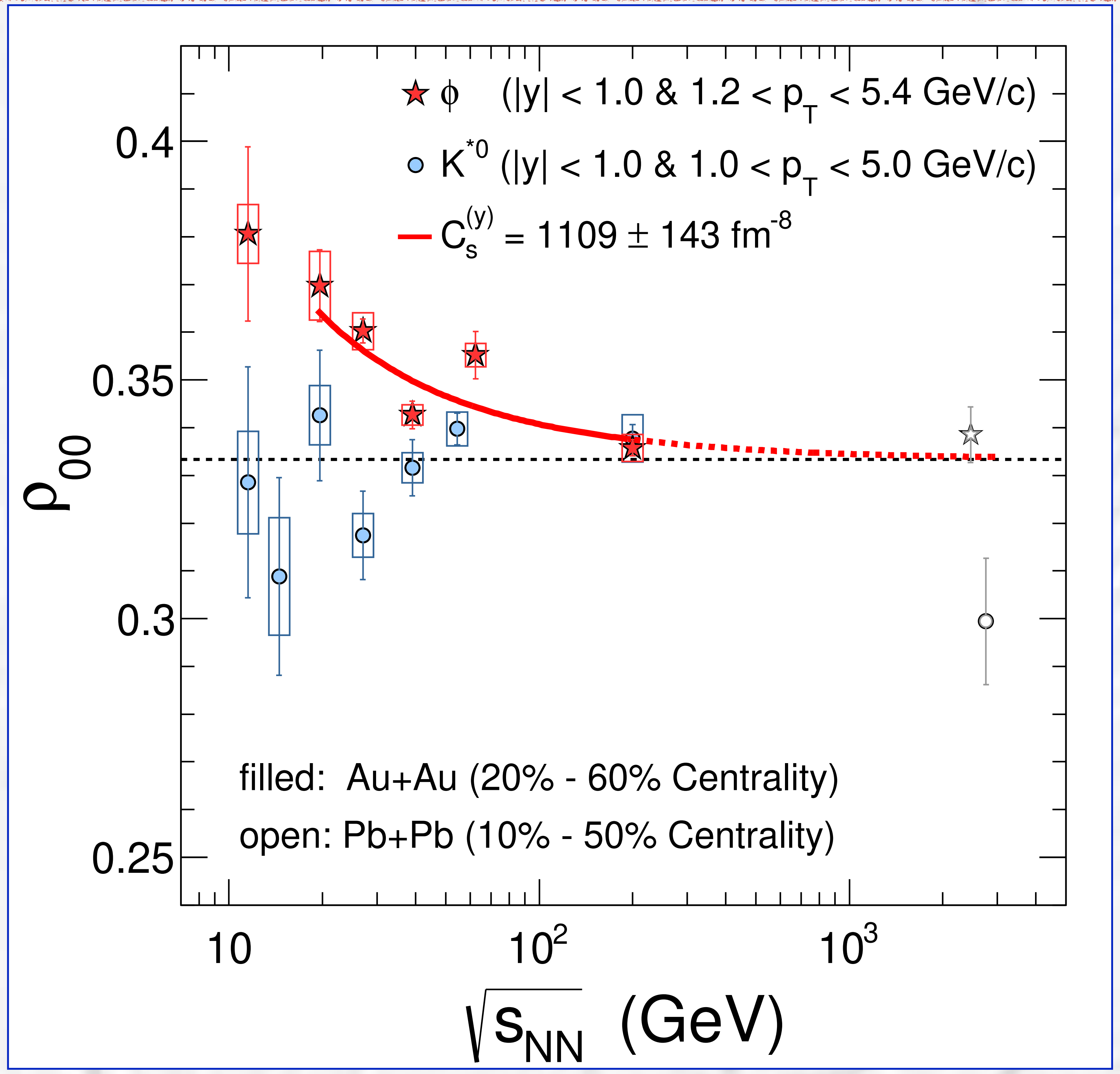


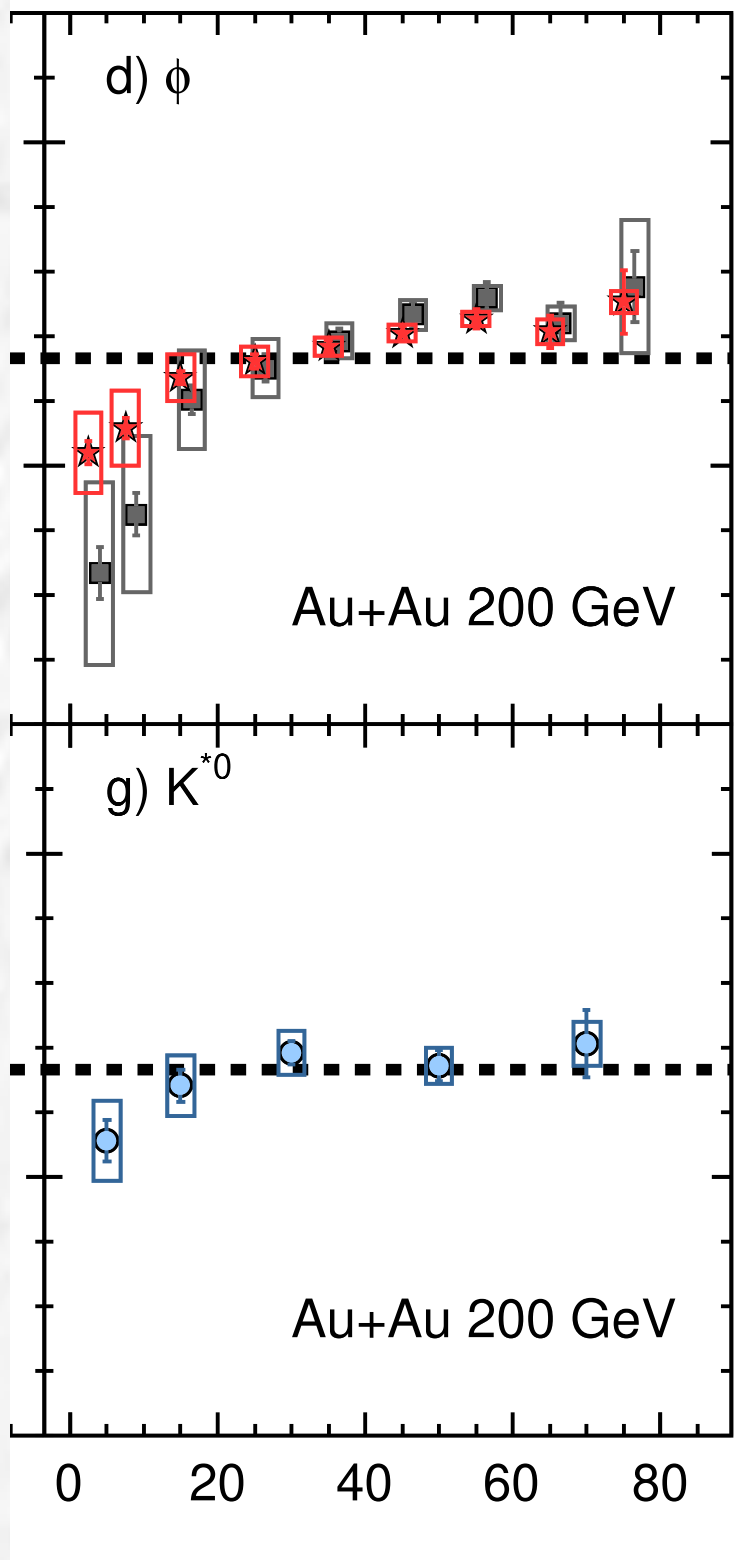
Thermal model:

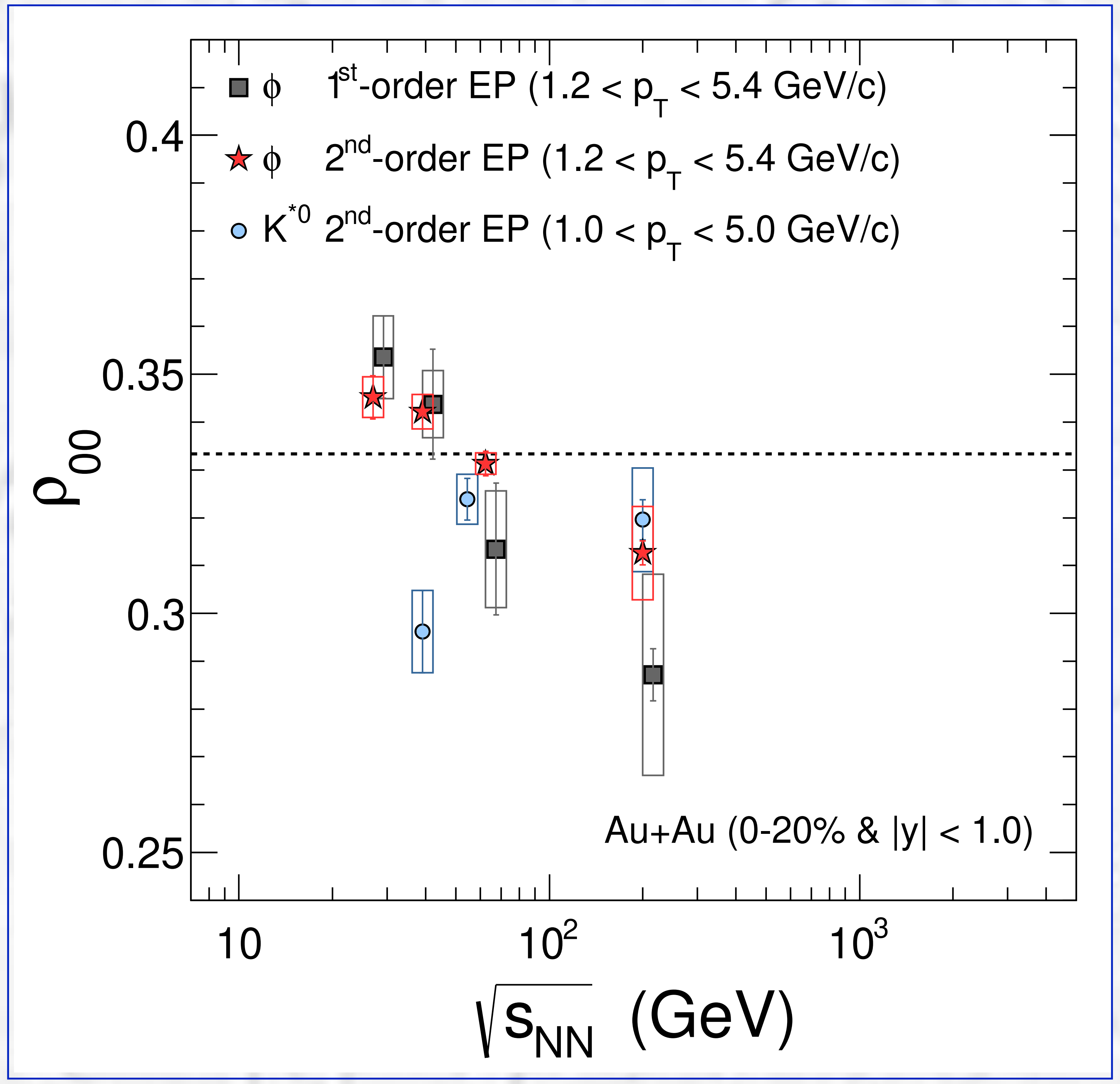
$$\rho_{00} = 0.15 \Rightarrow w(s_z = +1) = 0.82,$$
$$w(0) = 0.15, w(-1) = 0.03$$

Spin-alignment: 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?

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 $\rho_{-1,-1}$?

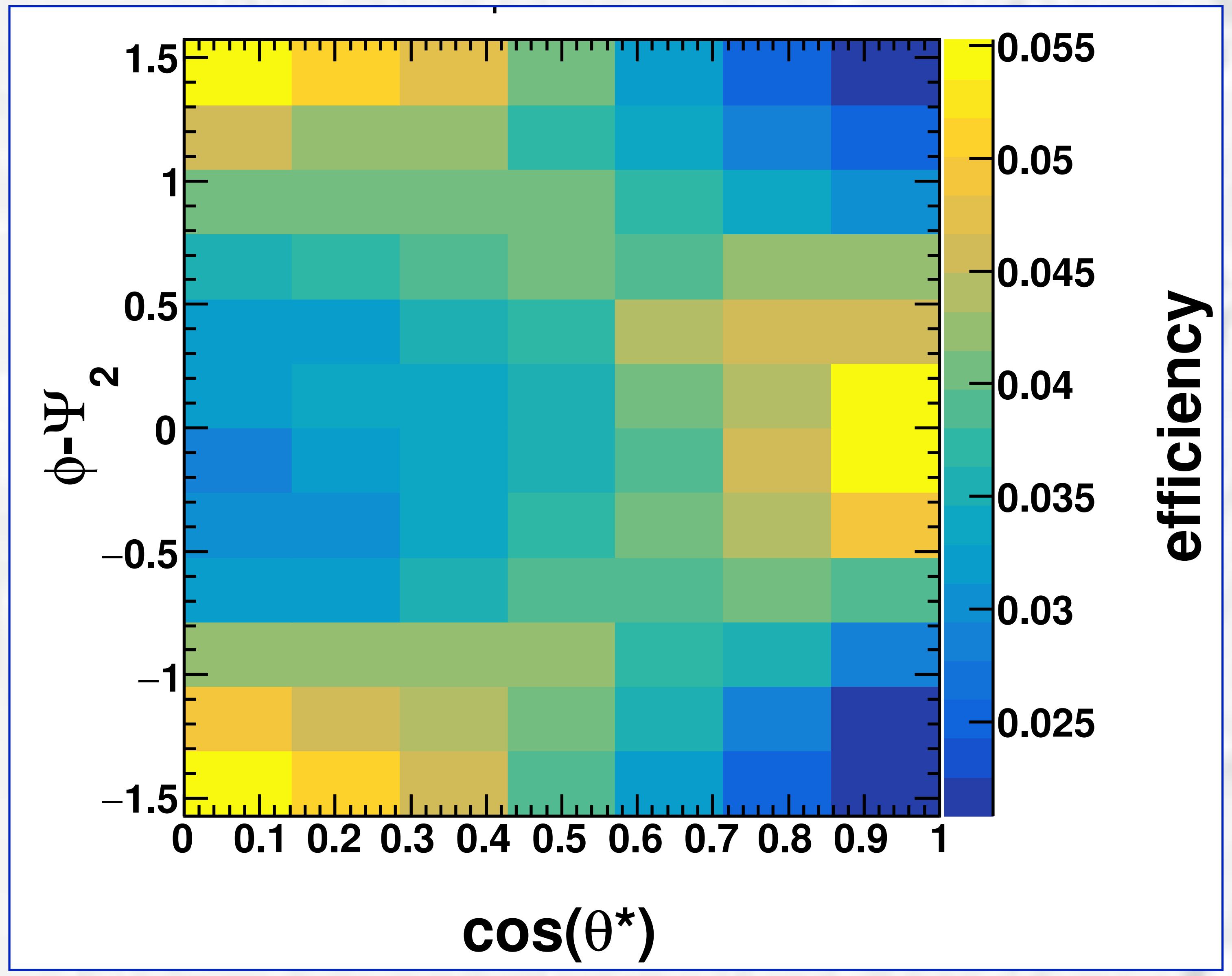
One possibility for noticeable spin alignment might be strong, fluctuating in direction, polarization, e.g vorticity, (the mechanism discussed by B. Mueller & D.L. Yang).

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

Helicity conservation and heavy resonance decays into vector mesons?

Spin alignment, elliptic flow, and efficiency

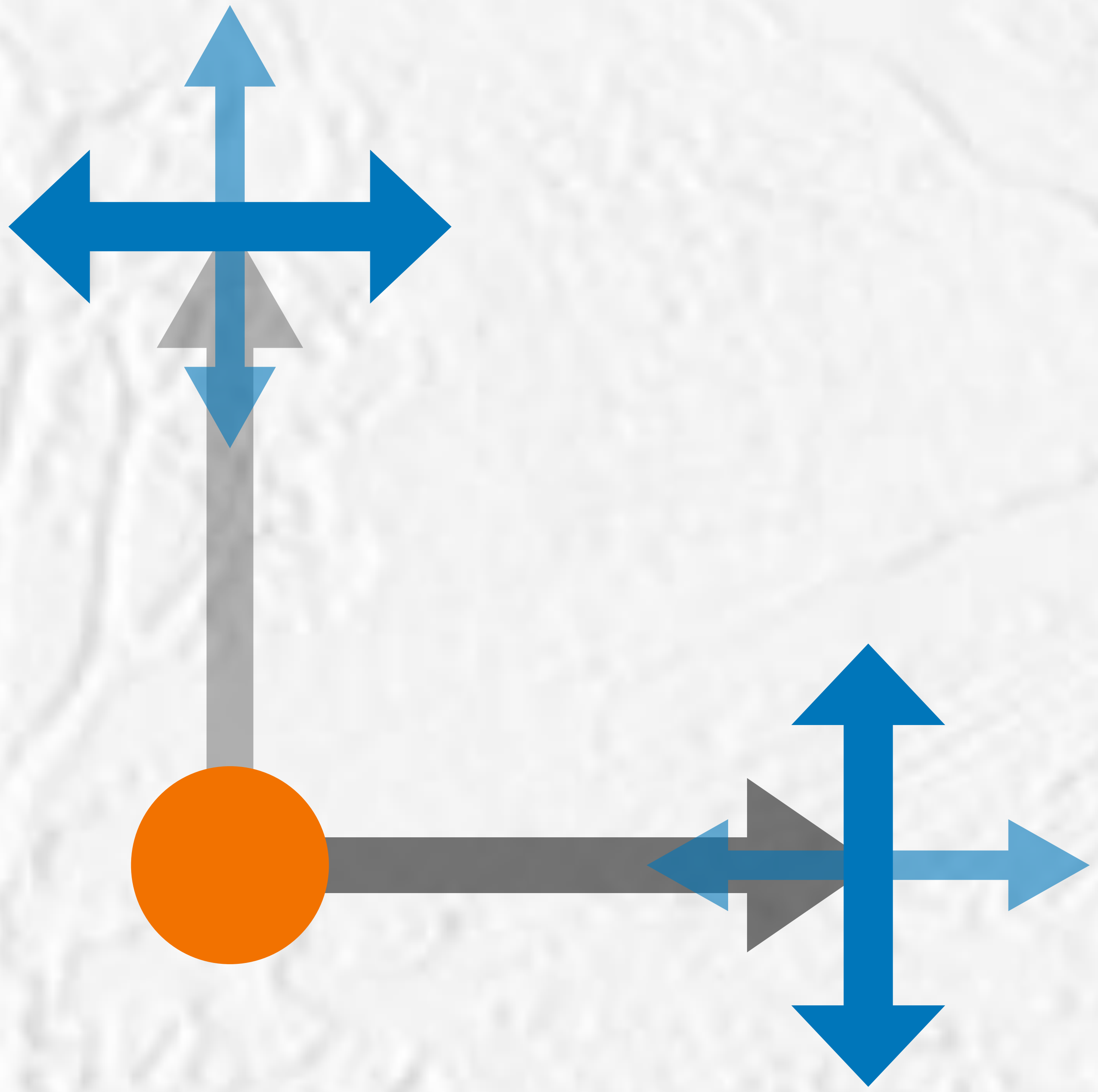
$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$



STAR

It might be better to present efficiency (1d) plot vs $\hat{n}_p^* \cdot \hat{n}_\Lambda$

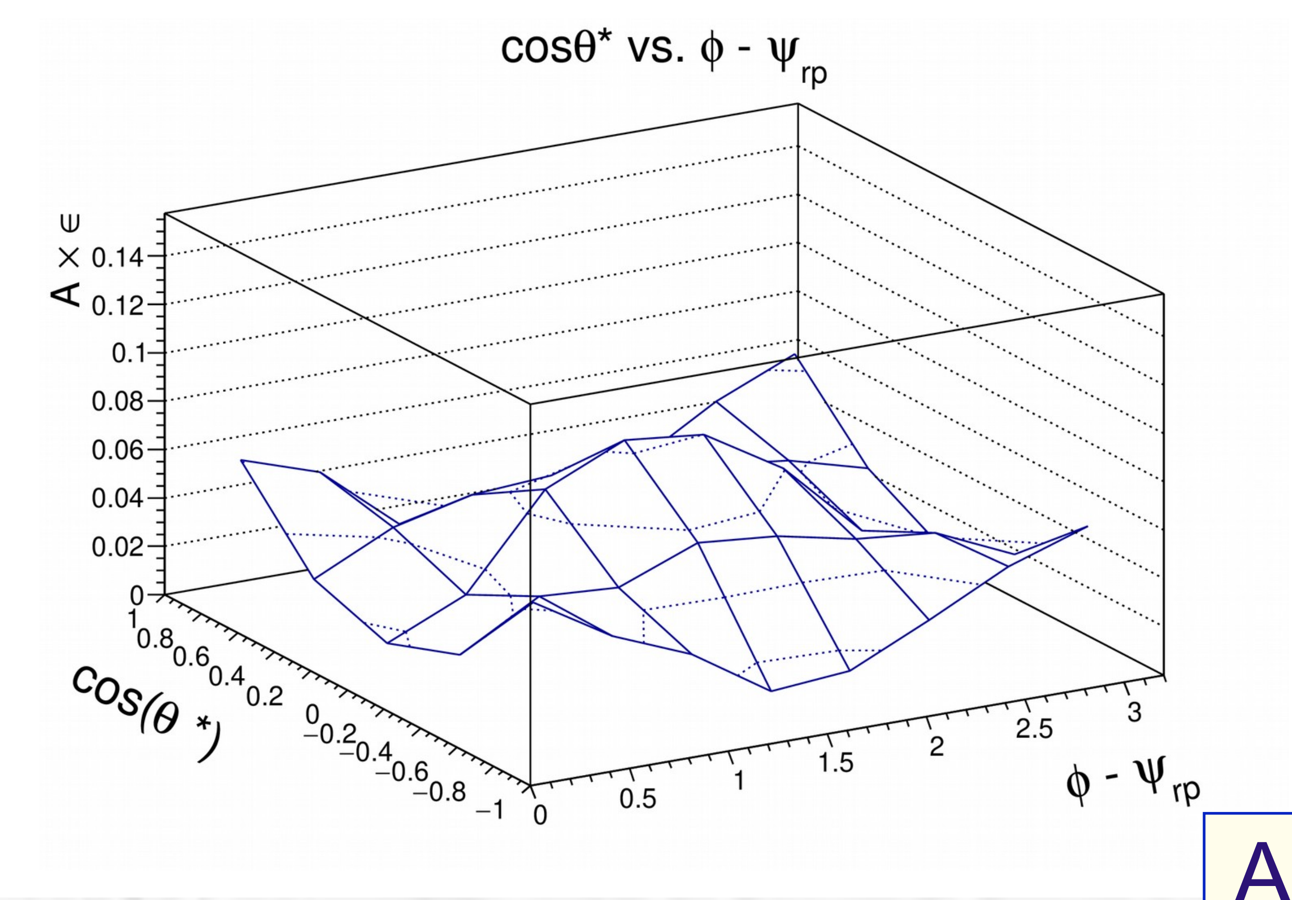
Reconstruction efficiency changes ~$\mathcal{O}(1)$ with the emission angle relative to the reaction plane

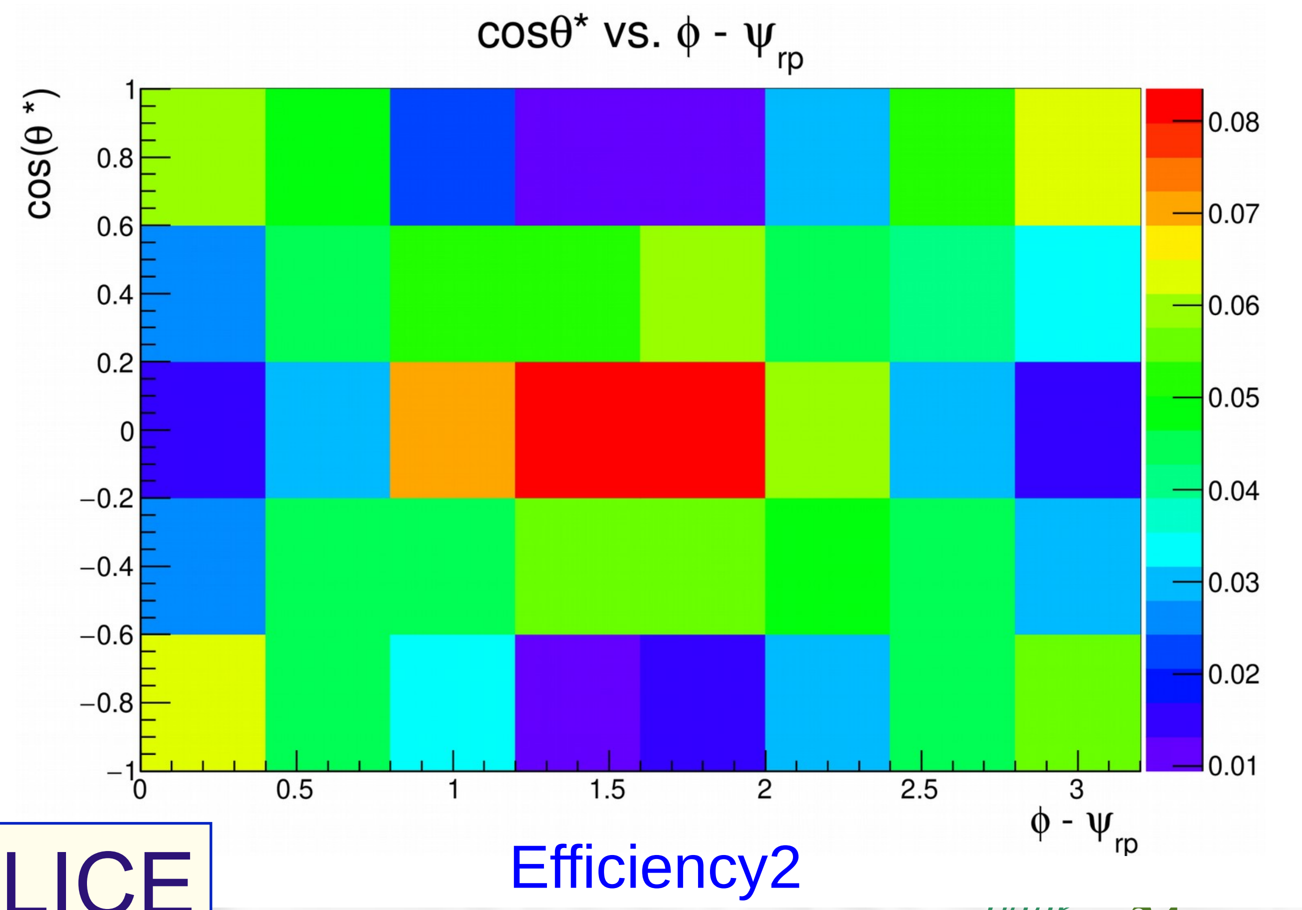


Opacity/width reflects efficiency and/or multiplicity

The efficiency entangles elliptic flow and polarization, neither of them can be measured independently

2D Efficiency : cosθ* vs. φ-Ψ_{rp} for K_S^0 $0.6 < p_T < 0.8$ GeV/c (AMPT)





ALICE

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

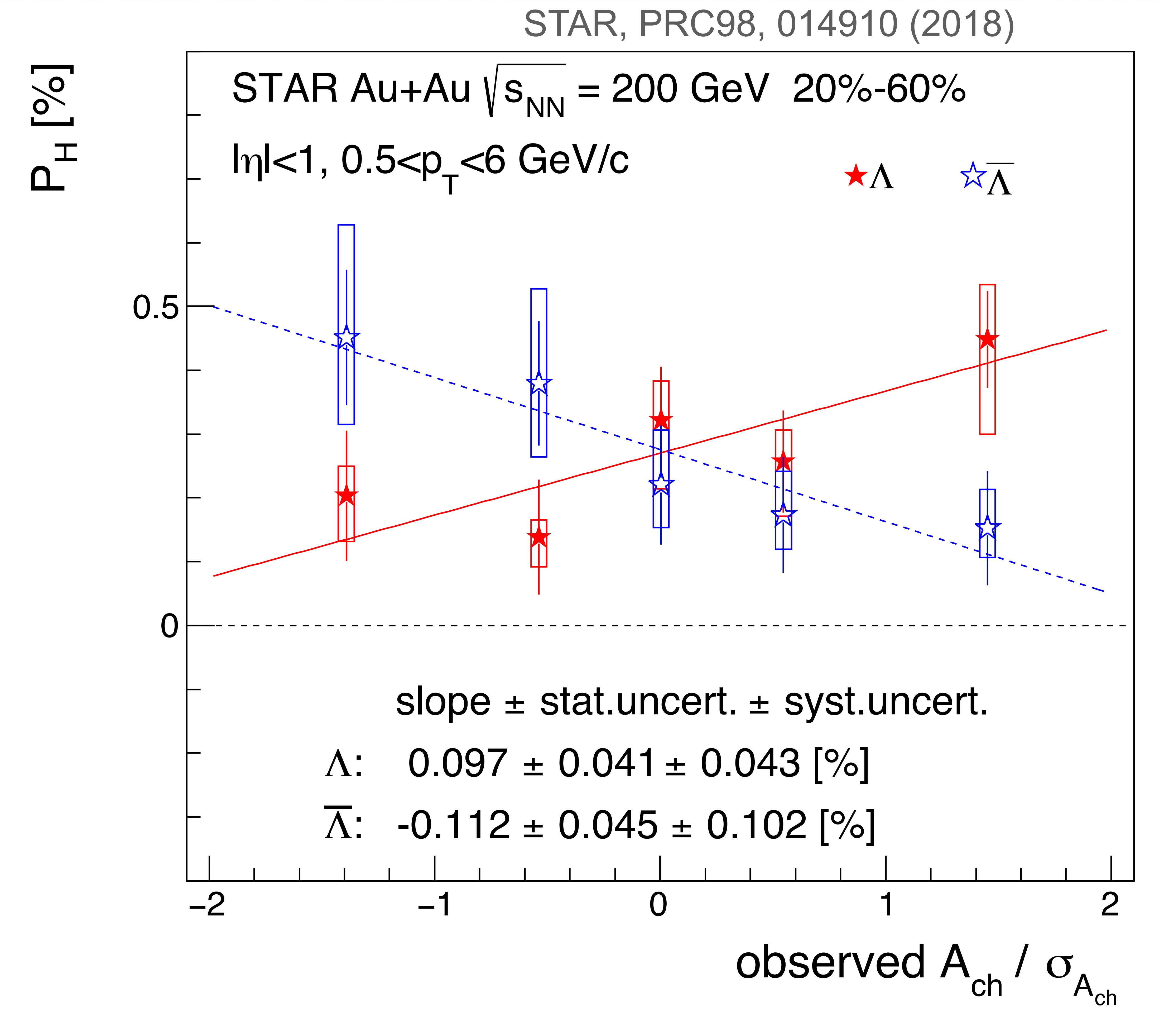
Spin alignment and efficiency, momentum resolution

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

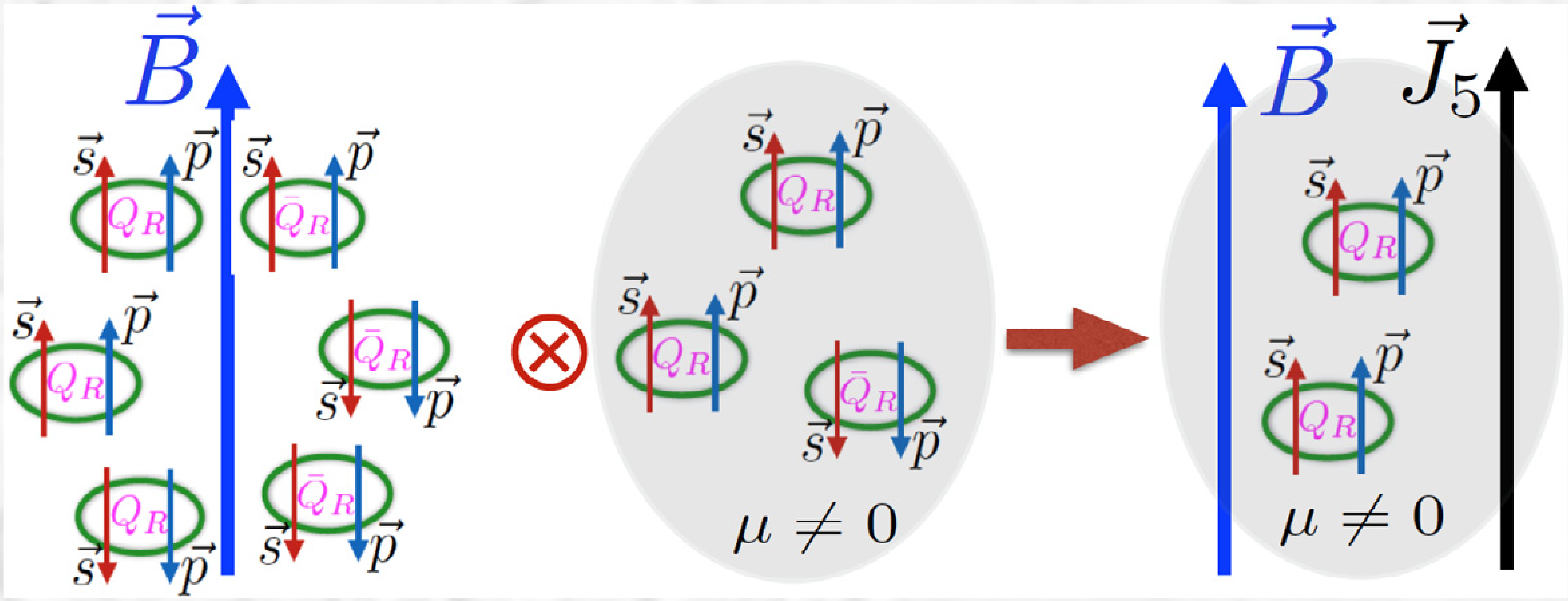
Different approaches and methods and different correction procedures should lead to the same result.

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

Dependence on the event charge



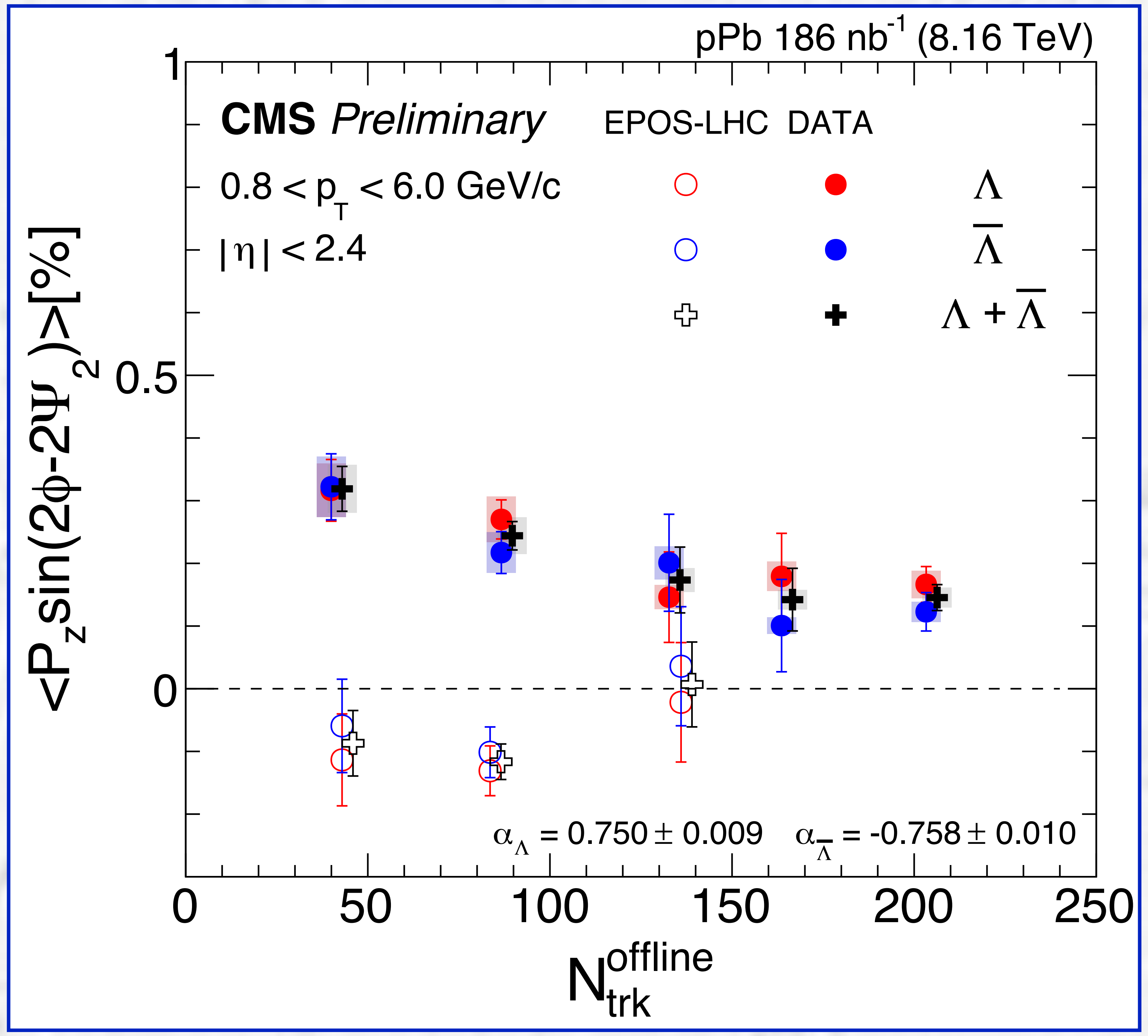
Chiral Separation Effect $\mathbf{J}_5 \propto e\mu_{\rm v}\mathbf{B}$



B-field + massless quarks + non-zero μ_v → axial current J_5

$$\mu_{\rm v}/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{\rm ch}$$

pPb

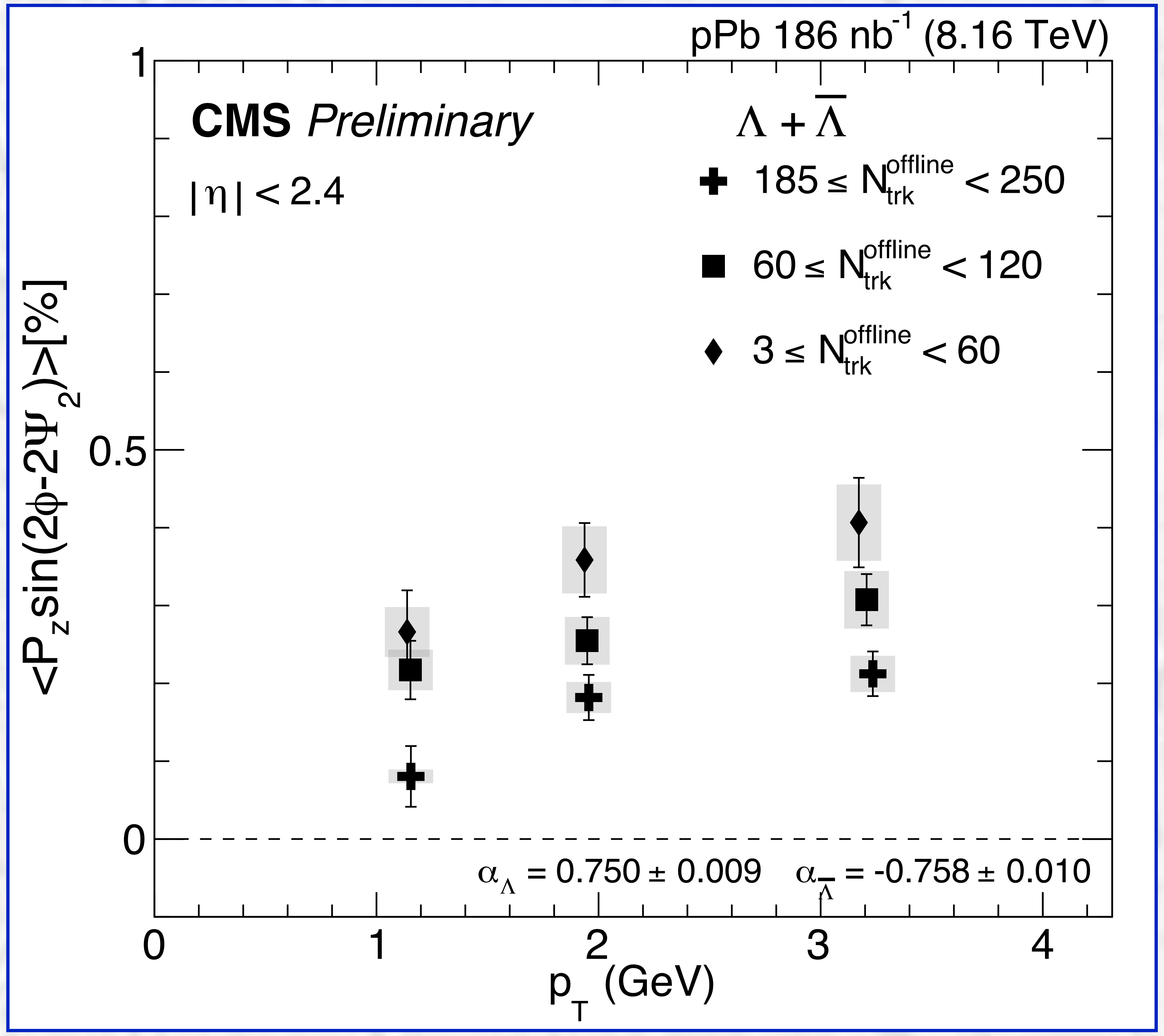


Available on the CERN CDS information server **CMS PAS HIN-24-002**

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

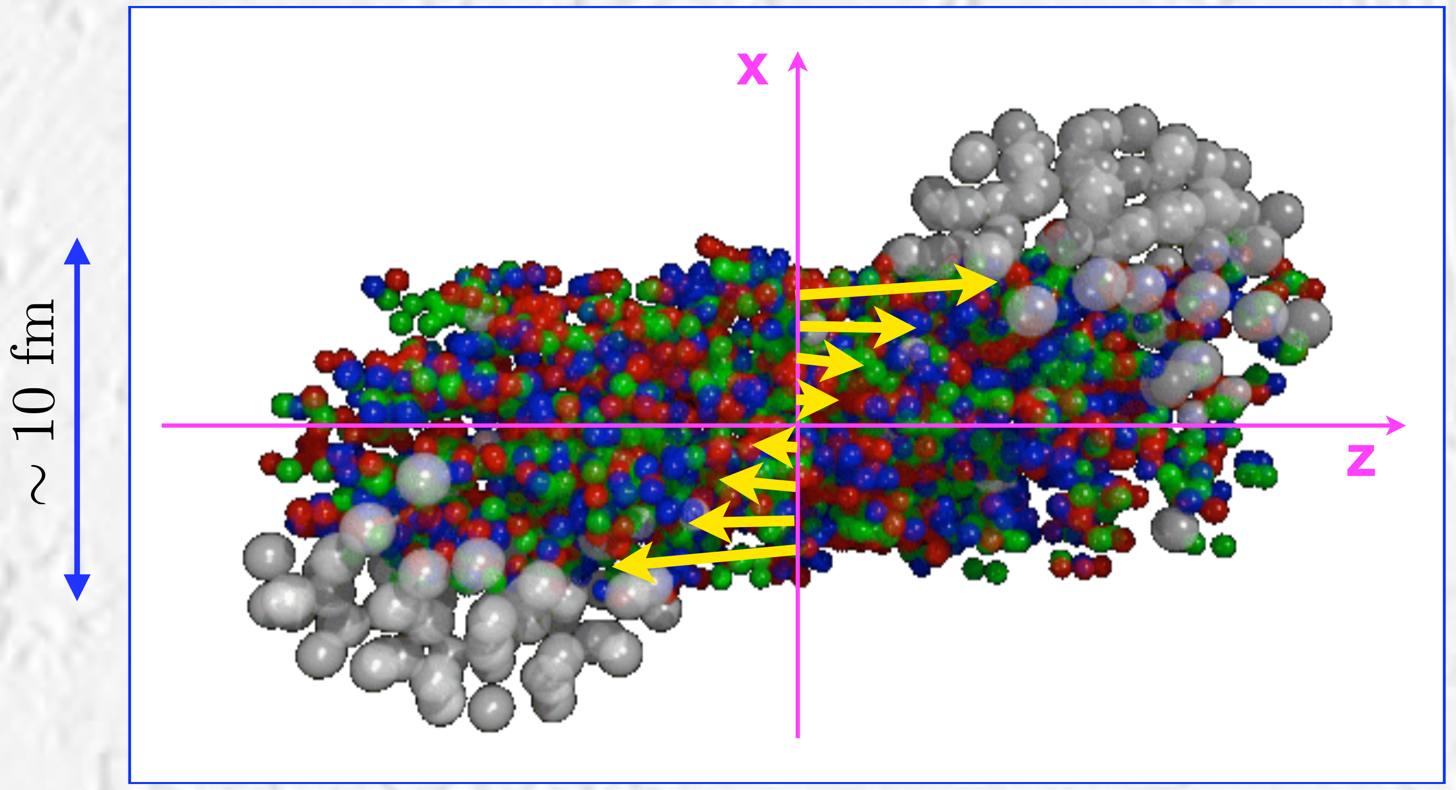


Spin alignment and elliptic flow

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

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

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



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

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

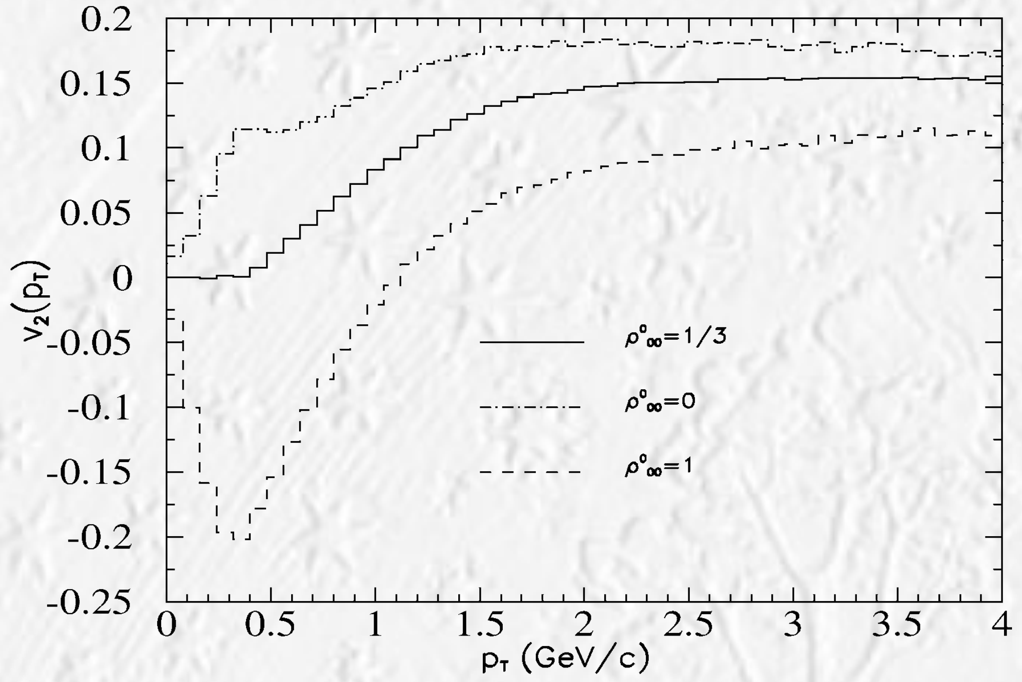


Fig. 1. Azimuthal anisotropy v_2 of pions from the decay of ρ vector mesons that have spin alignment according to Eq. (13) with $\rho^0_{00} = 1/3$ (solid line), 0 (dot-dashed line) and 1 (dashed line).

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

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

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

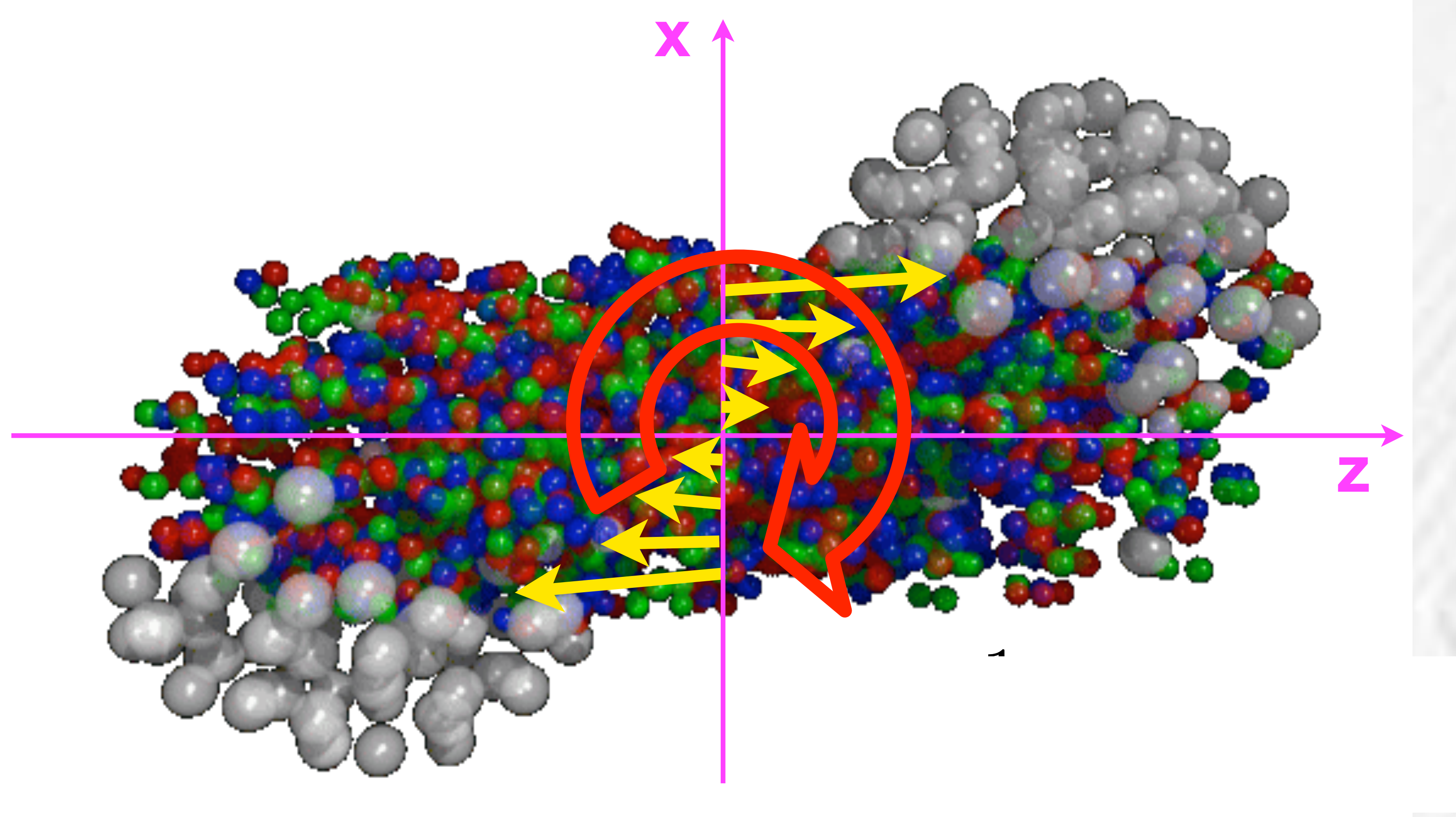
Z.-T. Liang, X.-N. Wang / Physics Letters B 629 (2005) 20–26

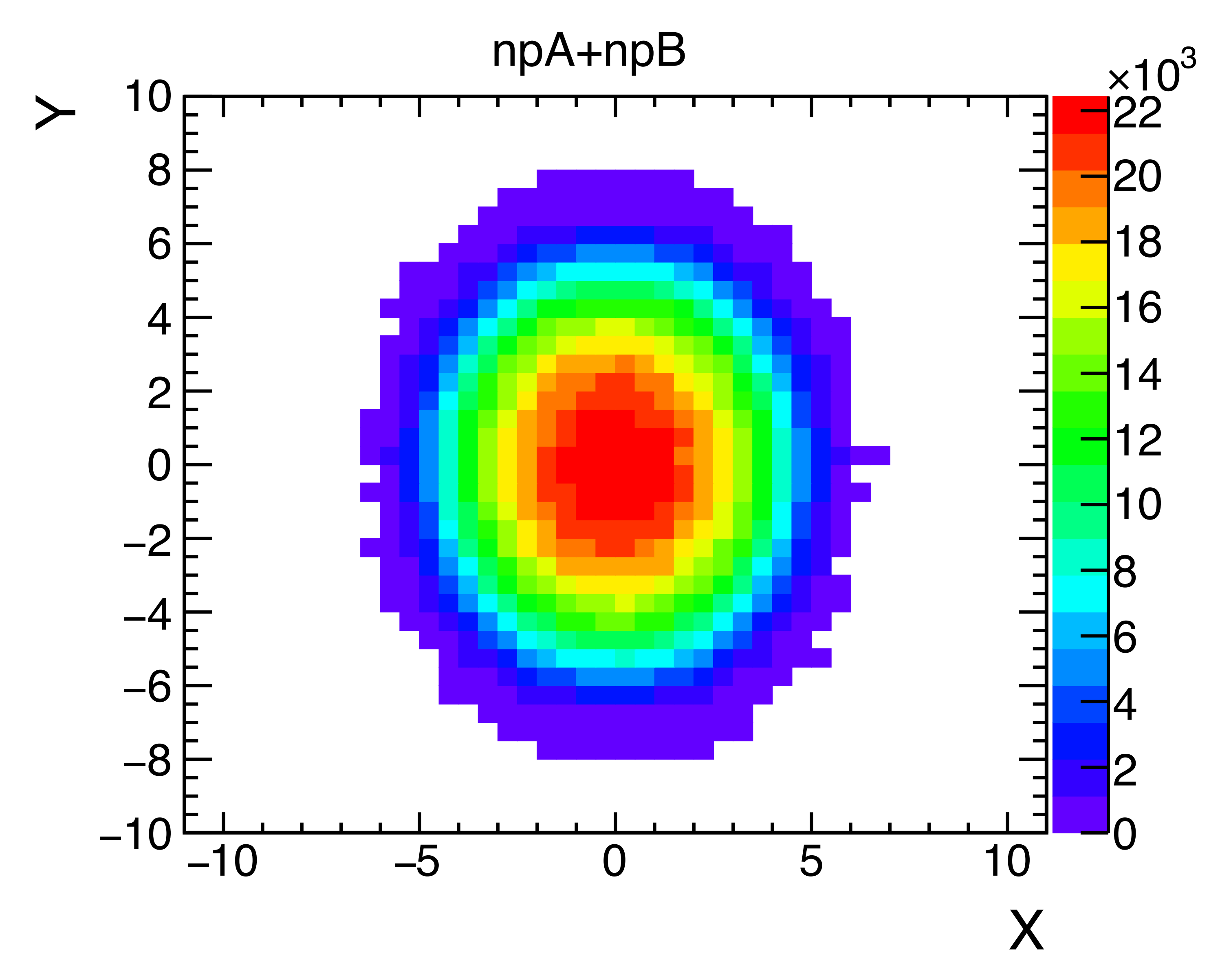
v_2 of pions from 100% polarized rho decays is ~20%!

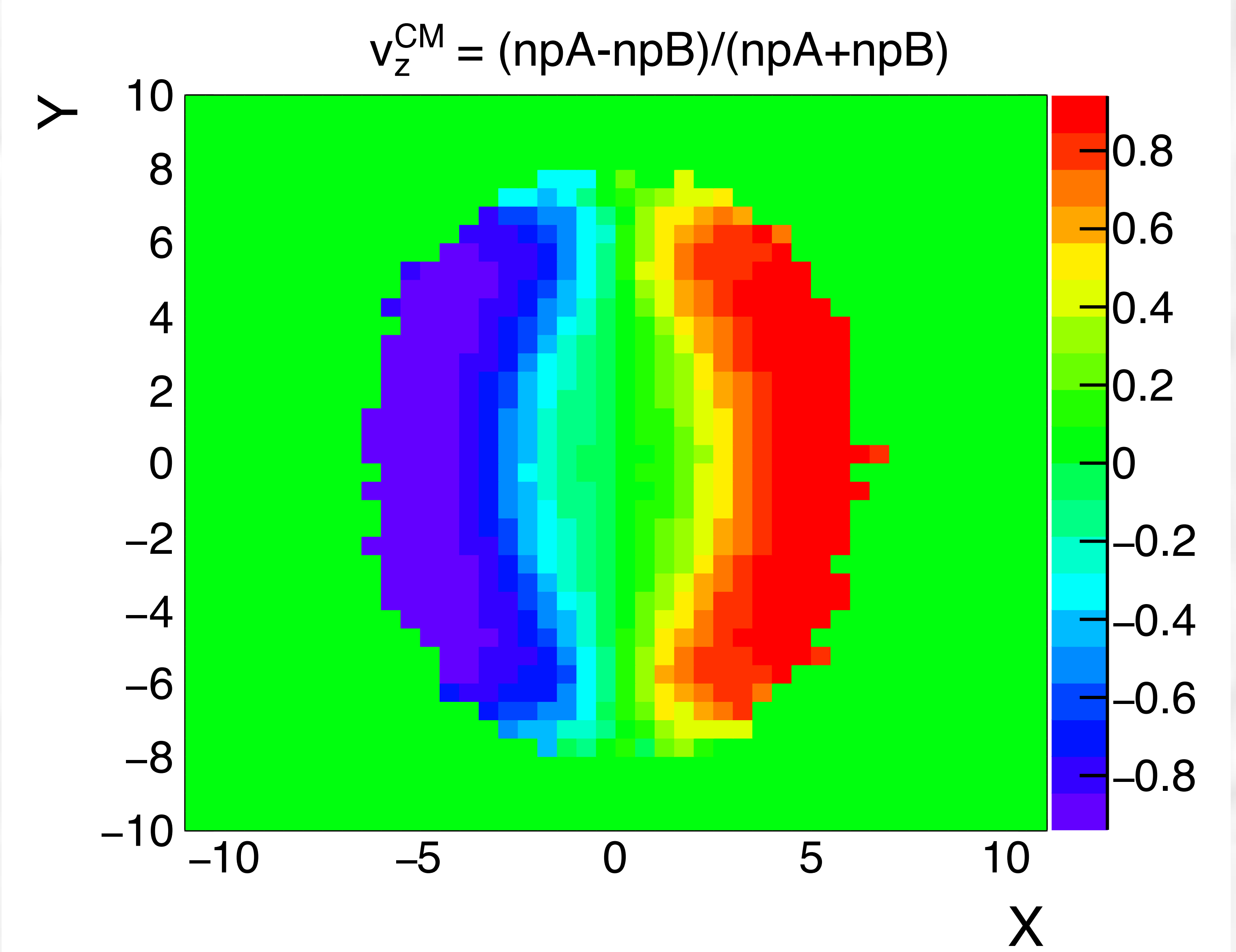
Global polarization, P_y

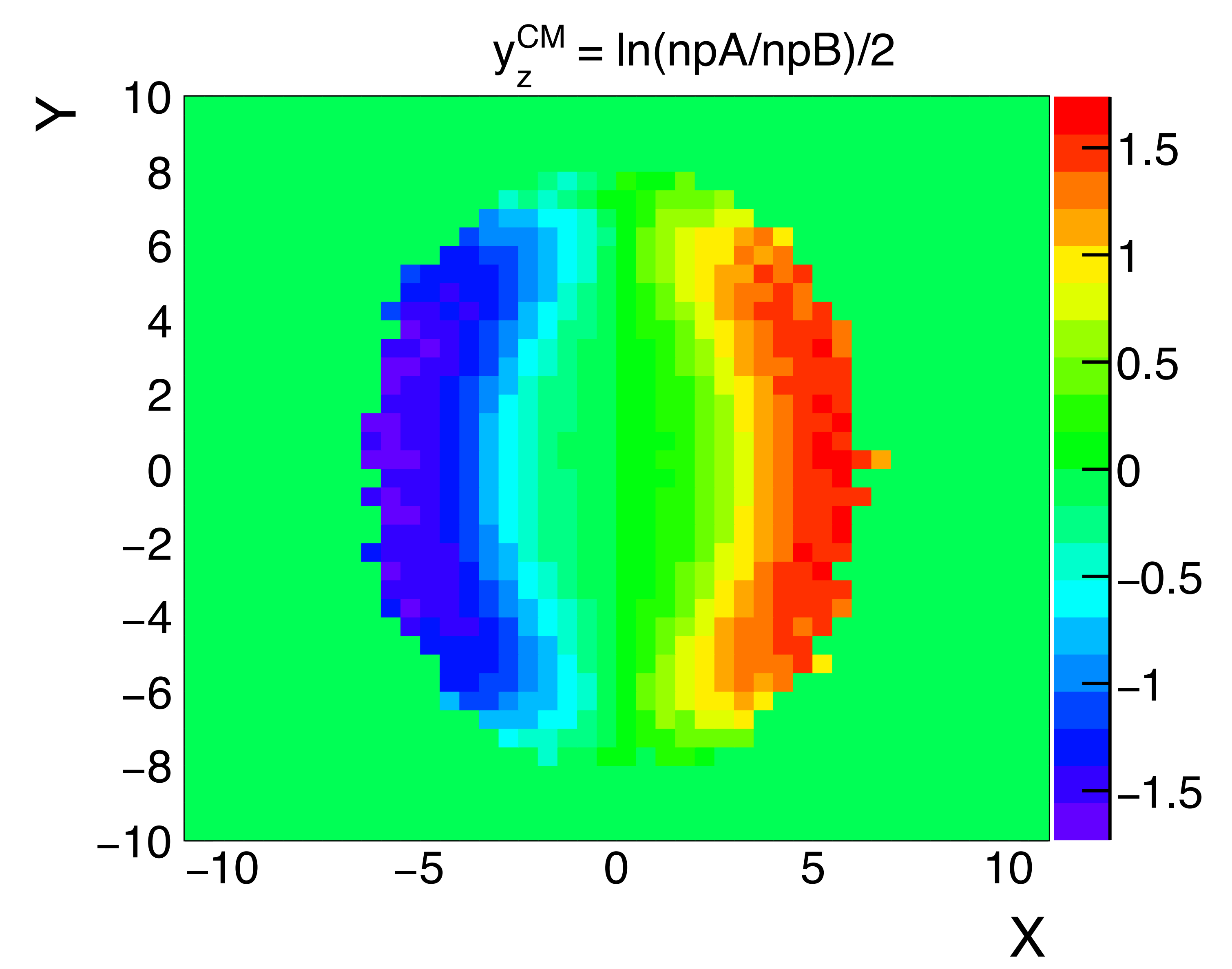
Au+Au, b=7 fm

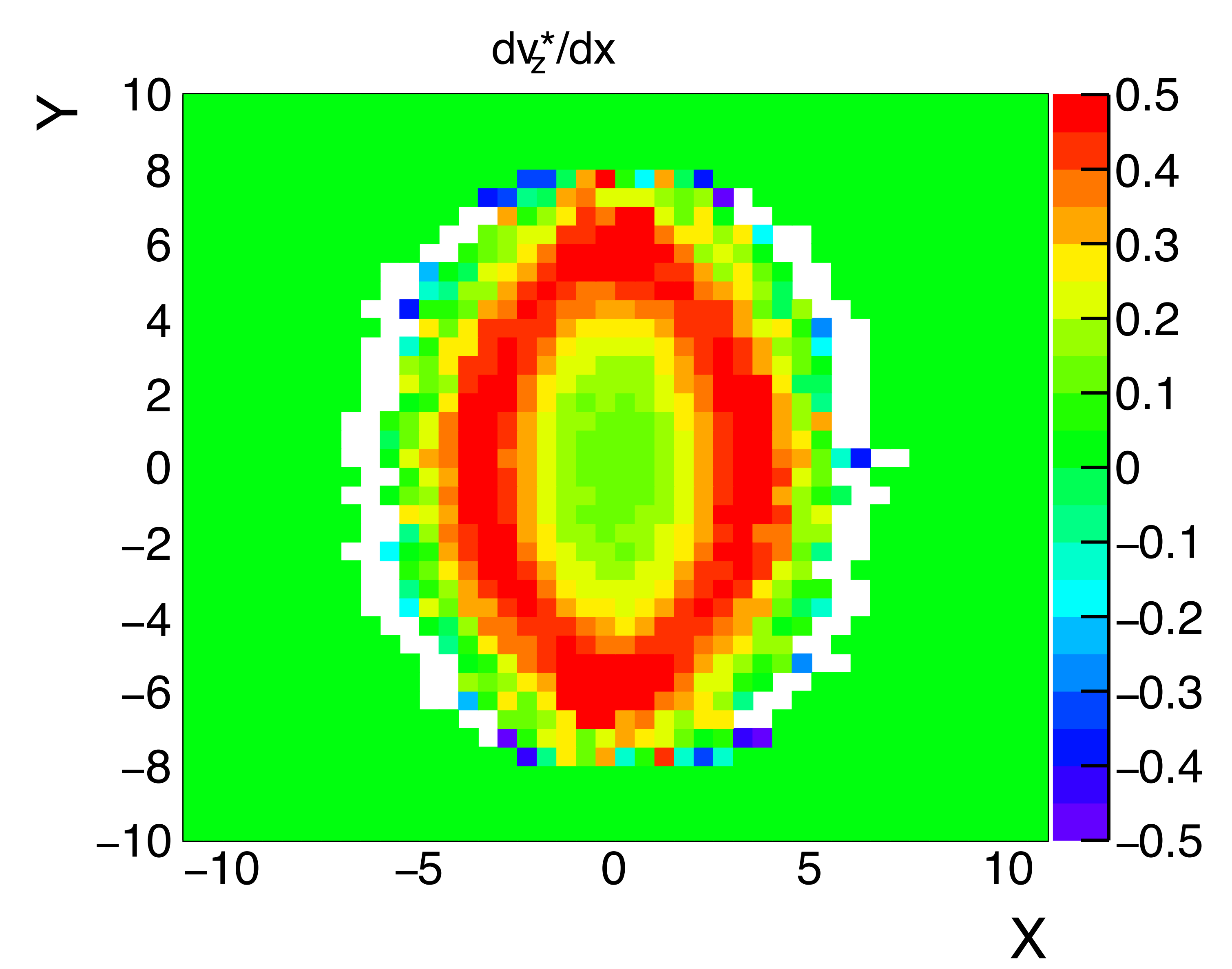
"np" - # of nucleon participants

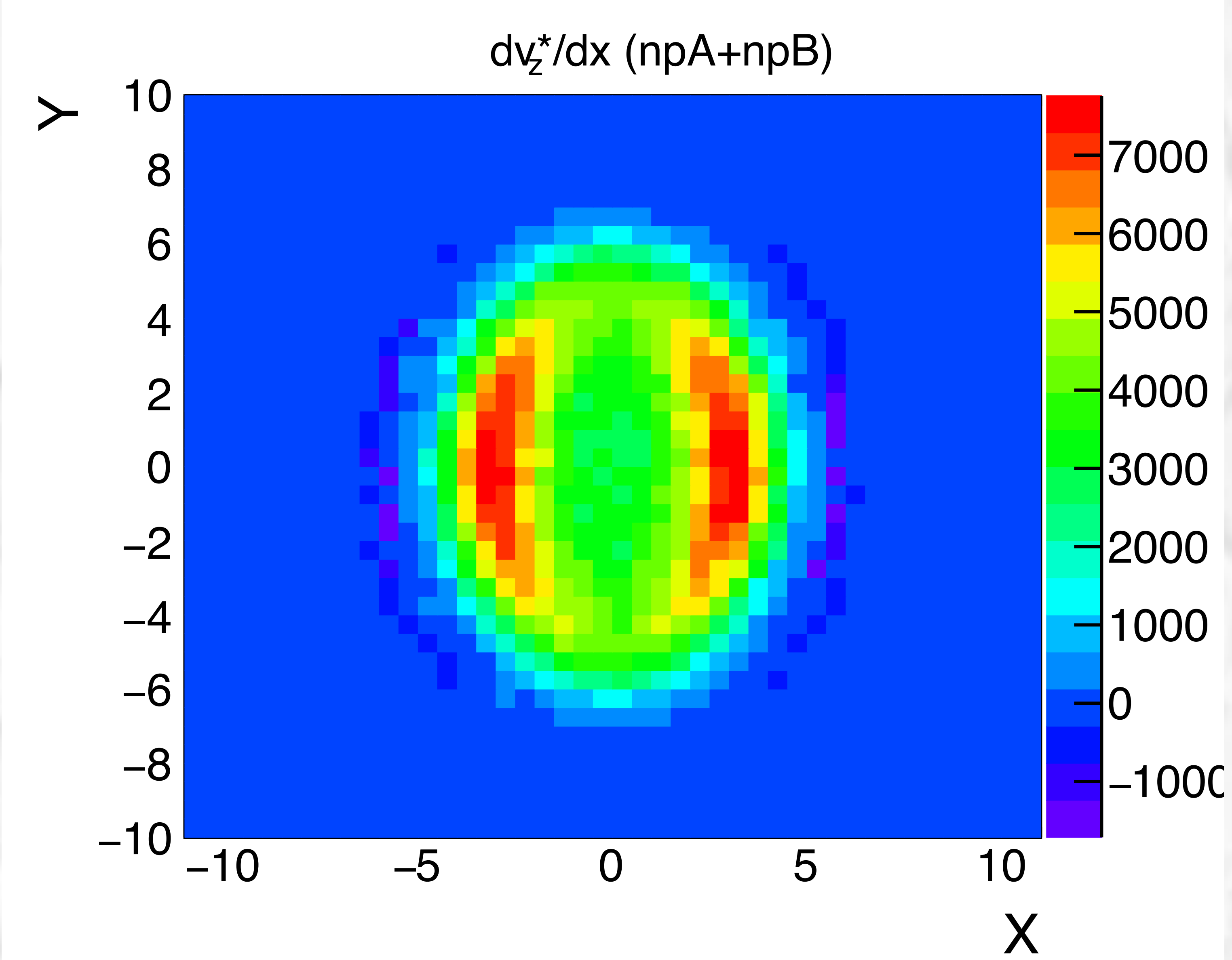












v_z is calculated as velocity of the center of mass

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

A better way?

Idea: calculate $\langle\cos(\Theta^*)\rangle$, where Θ^* is the angle relative to the quantization axis

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

$$\langle\sin(\Psi_{\rm RP}-\phi^*)\sin\theta^*\rangle=\frac{\alpha_H}{3}\left[\tilde{A}_0\,(P_0+2P_2v_2)-\tilde{A}_2(P_2+P_0v_2)\right],$$

$$\langle\sin(\Psi_{\rm RP}-\phi^*)\sin\theta^*\cos[2(\phi_H-\phi^*)]\rangle=\frac{\alpha_H}{3}\left[\tilde{A}_0\,(P_2+P_0v_2)-\frac{1}{2}\tilde{A}_2(P_0+3P_2v_2)\right],$$

$$\tilde{A}_0(p_t^H,\eta^H)=\frac{3}{2}\int\frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi}A\left(\mathbf{p}_H,\mathbf{p}^*\right)\sin^2\theta^*.$$

$$\tilde{A}_2(p_t^H,\eta^H)=\frac{3}{2}\int\frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi}A\left(\mathbf{p}_H,\mathbf{p}^*\right)\sin^2\theta^*\cos\left[2(\phi_H-\phi^*)\right].$$

Decrease the statistical errors for about 10%

$P_y(\phi)$, parametrization, acceptance effects

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

Note extra factors of "2" in the definitions, compared to 2007 paper.

$$\langle \sin(\Psi_{\rm RP} - \phi^*)\rangle = \int \frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi} A(\mathbf{p}_H, \mathbf{p}^*) \int_0^{2\pi} \frac{d\Psi_{\rm RP}}{2\pi}\{1 + 2v_{2,H}\cos[2(\phi_H - \Psi_{\rm RP})]\}$$
$$\sin(\Psi_{\rm RP} - \phi^*)\left[1 + \alpha_H\ P_H(\mathbf{p}_H; \Psi_{\rm RP})\ \sin\theta^* \cdot \sin(\phi^* - \Psi_{\rm RP})\right].$$

Note that $\langle P_y\rangle \neq P_{y,0}$

$$\langle \sin(\Psi_{\rm RP} - \phi^*)\rangle = \frac{\alpha_H \pi}{8}\left[A_0\ (P_0 + 2P_2 v_2) - A_2(P_2 + P_0 v_2)\right],$$

$$\langle \sin(\Psi_{\rm RP} - \phi^*)\cos[2(\phi_H - \phi^*)]\rangle = \frac{\alpha_H \pi}{8}\left[A_0\ (P_2 + P_0 v_2) - \frac{1}{2}A_2(P_0 + 3P_2 v_2)\right]$$

$$A_0(p_t^H, \eta^H) = \frac{4}{\pi}\int \frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi} A(\mathbf{p}_H, \mathbf{p}^*)\sin\theta^*.$$

$$A_2(p_t^H, \eta^H) = \frac{4}{\pi}\int \frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi} A(\mathbf{p}_H, \mathbf{p}^*)\sin\theta^*\cos[2(\phi_H - \phi^*)]$$

Hydro calculation

Vorticity and Polarization in Heavy Ion Collisions: Hydrodynamic Models

Iurii Karpenko arXiv:2101.04963v1 [nucl-th] 13 Jan 2021

How is it consistent with equation in the previous slide?

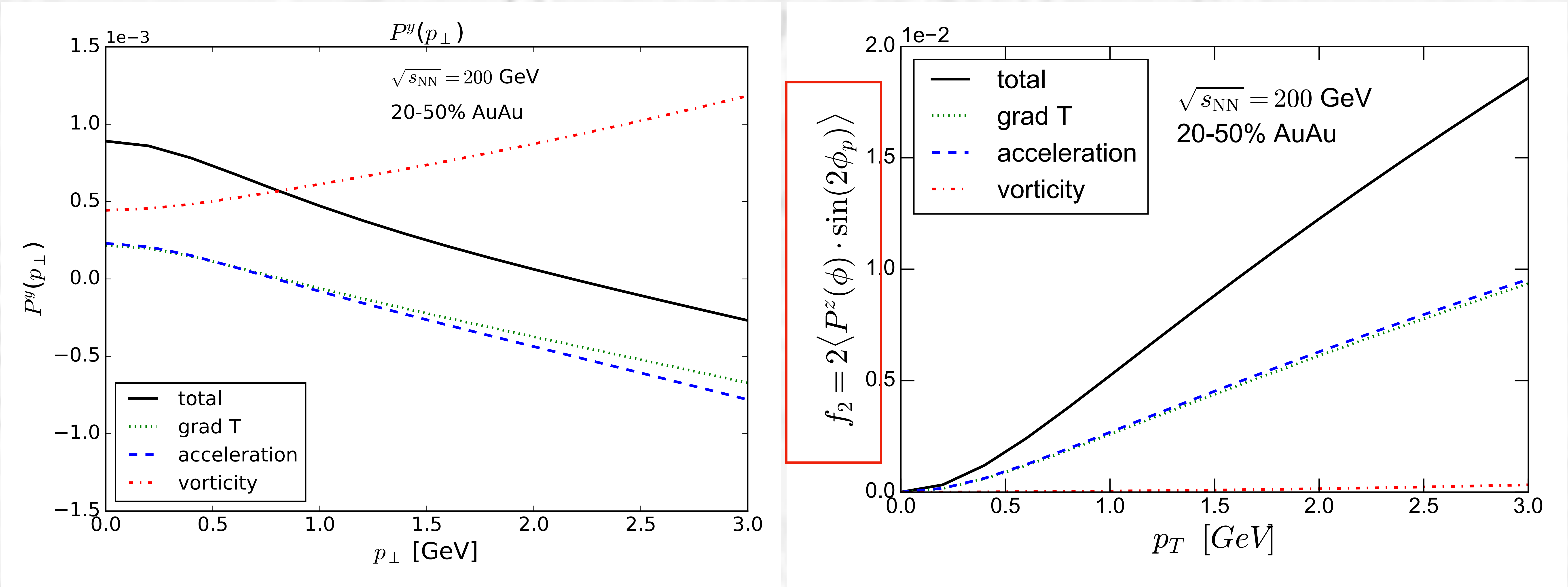


Fig. 26 Contributions to the global (left panel) and quadrupole longitudinal (right panel) components of Λ polarization stemming from gradients of temperature (dotted lines), acceleration (dashed lines) and vorticity (dash-dotted lines). Solid lines show the sums of all 3 contributions. The hydrodynamic calculation with vHLLE is performed with an averaged Monte Carlo Glauber IS corresponding to 20-50% central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV RHIC energy.