Polarization: questions and next steps

Sergei A. Voloshin Wayne State University

- Ω global polarization, γ_Ω
- P_y ϕ_H dependence, physics, acceptance effects, average/global vs $P_{y,0}$
- P_z higher harmonics, hydro, BW , SIP, Cooper-Frye
- P_x BW, SIP
- P_ϕ track reconstruction efficiency
- spin alignment: physics questions, SA + elliptic flow + acceptance effects

In a spirit of a “retreat” - emphasis not on the “final” results but on current open questions/analyses details

sorry for jumping from one subject to another too often…

U.S. DEPARTMENT OF ENERGY
Office of Science

Discussions with T. Niida and many others are gratefully acknowledged

Ξ and Ω global polarization

PHYSICAL REVIEW LETTERS **126,** 162301 (2021)

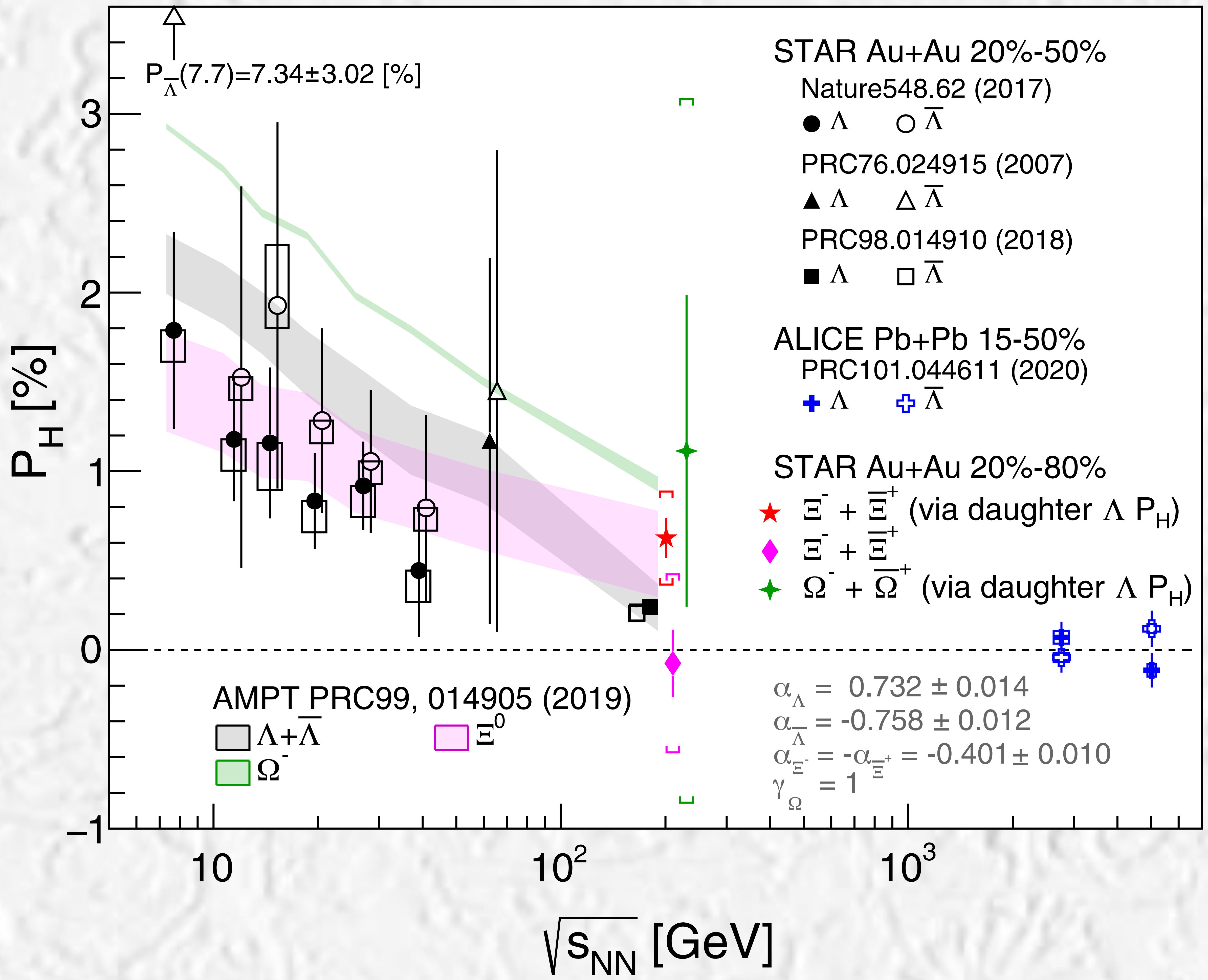
Global Polarization of Ξ and Ω Hyperons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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

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

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

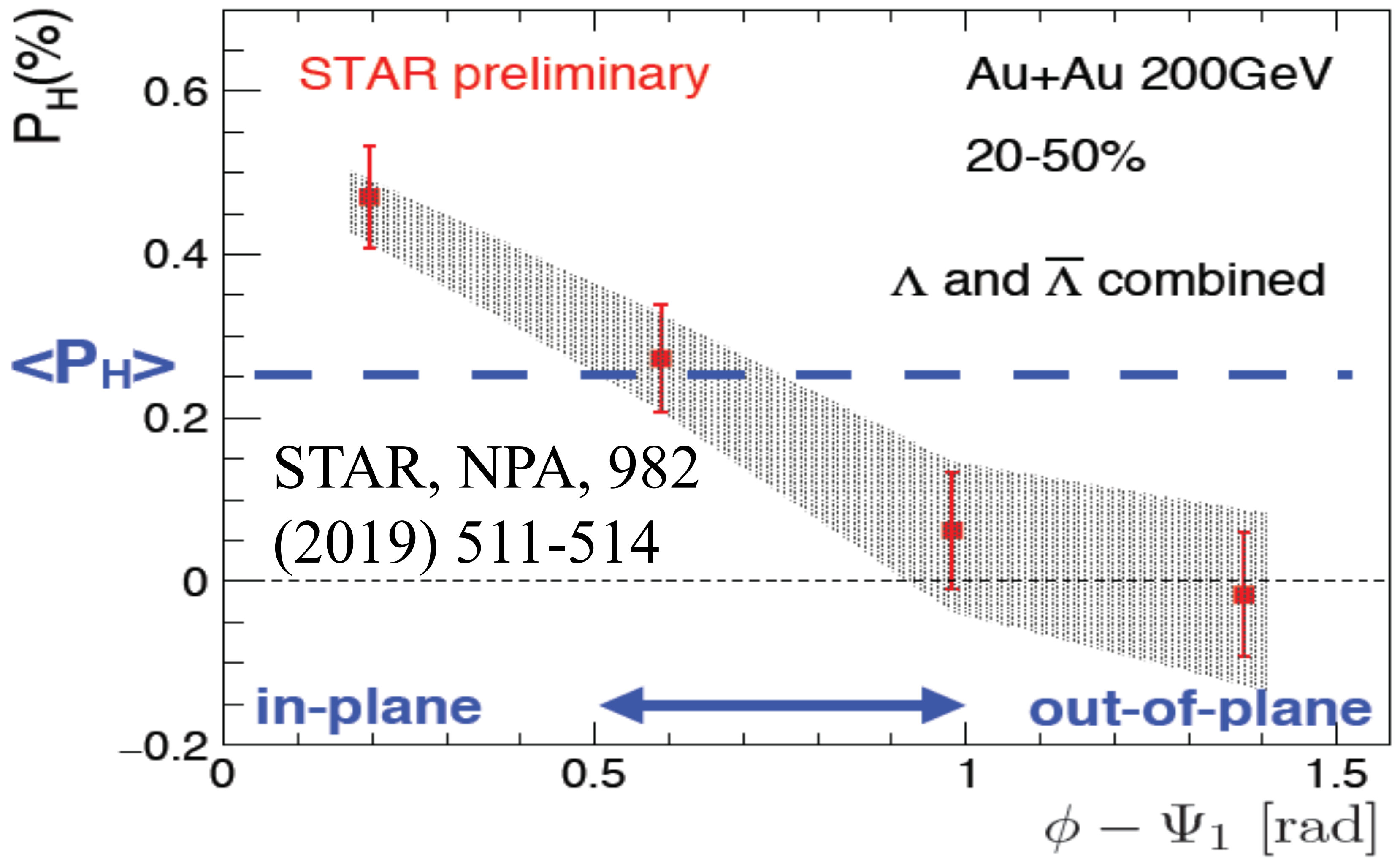
A way to measure the decay parameter γ_Ω !

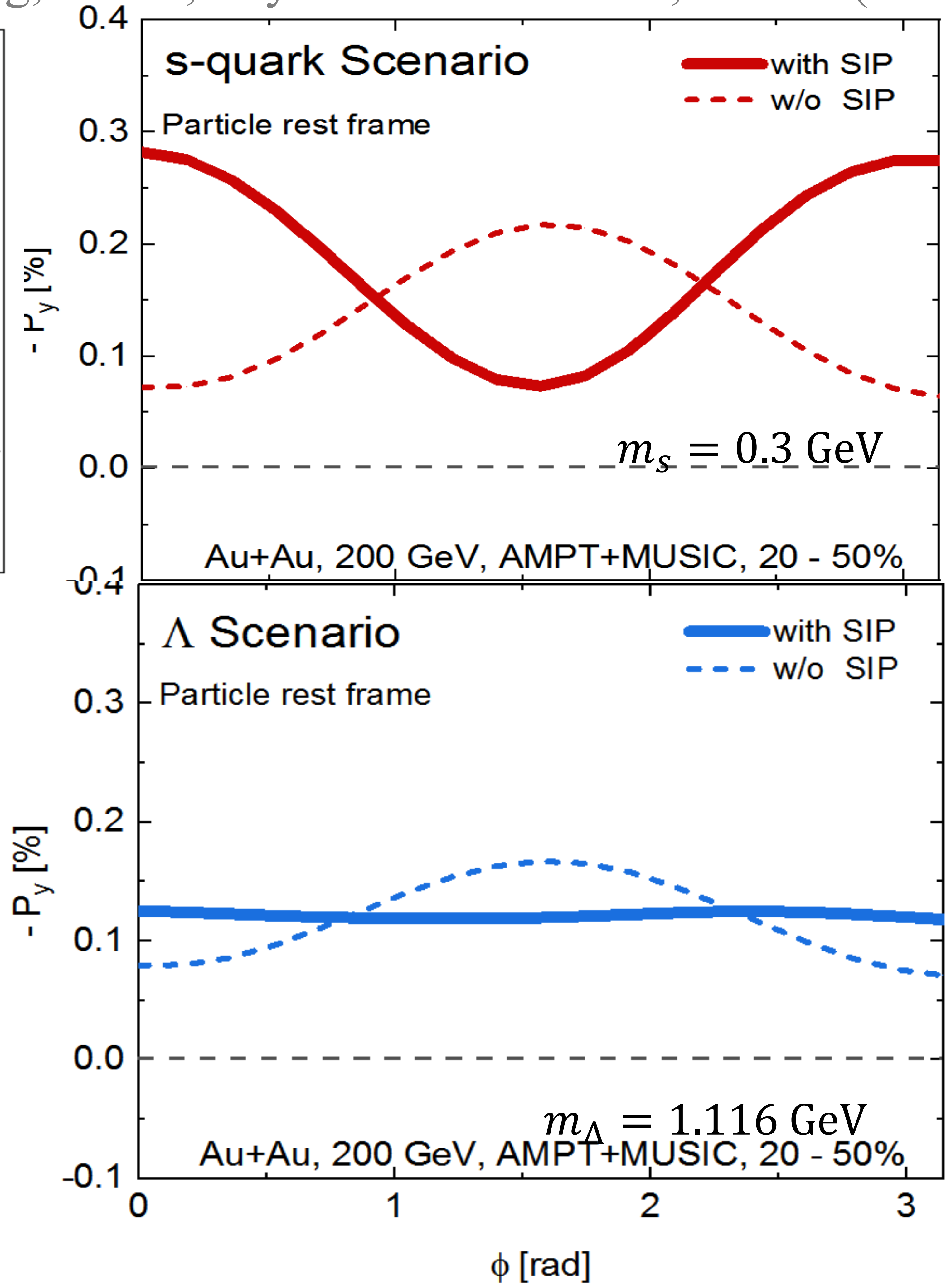


$P_y(\phi)$ physics

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

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

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

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

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

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

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

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

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

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

A better way?

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

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

$$\langle \sin(\Psi_{\rm RP} - \phi^*)\sin\theta^* \rangle = \frac{\alpha_H}{3}\left[\tilde{A}_0\,(P_0 + 2P_2 v_2) - \tilde{A}_2(P_2 + P_0 v_2)\right],$$

$$\langle \sin(\Psi_{\rm RP} - \phi^*)\sin\theta^* \cos[2(\phi_H - \phi^*)] \rangle = \frac{\alpha_H}{3}\left[\tilde{A}_0\,(P_2 + P_0 v_2) - \frac{1}{2}\tilde{A}_2(P_0 + 3P_2 v_2)\right],$$

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

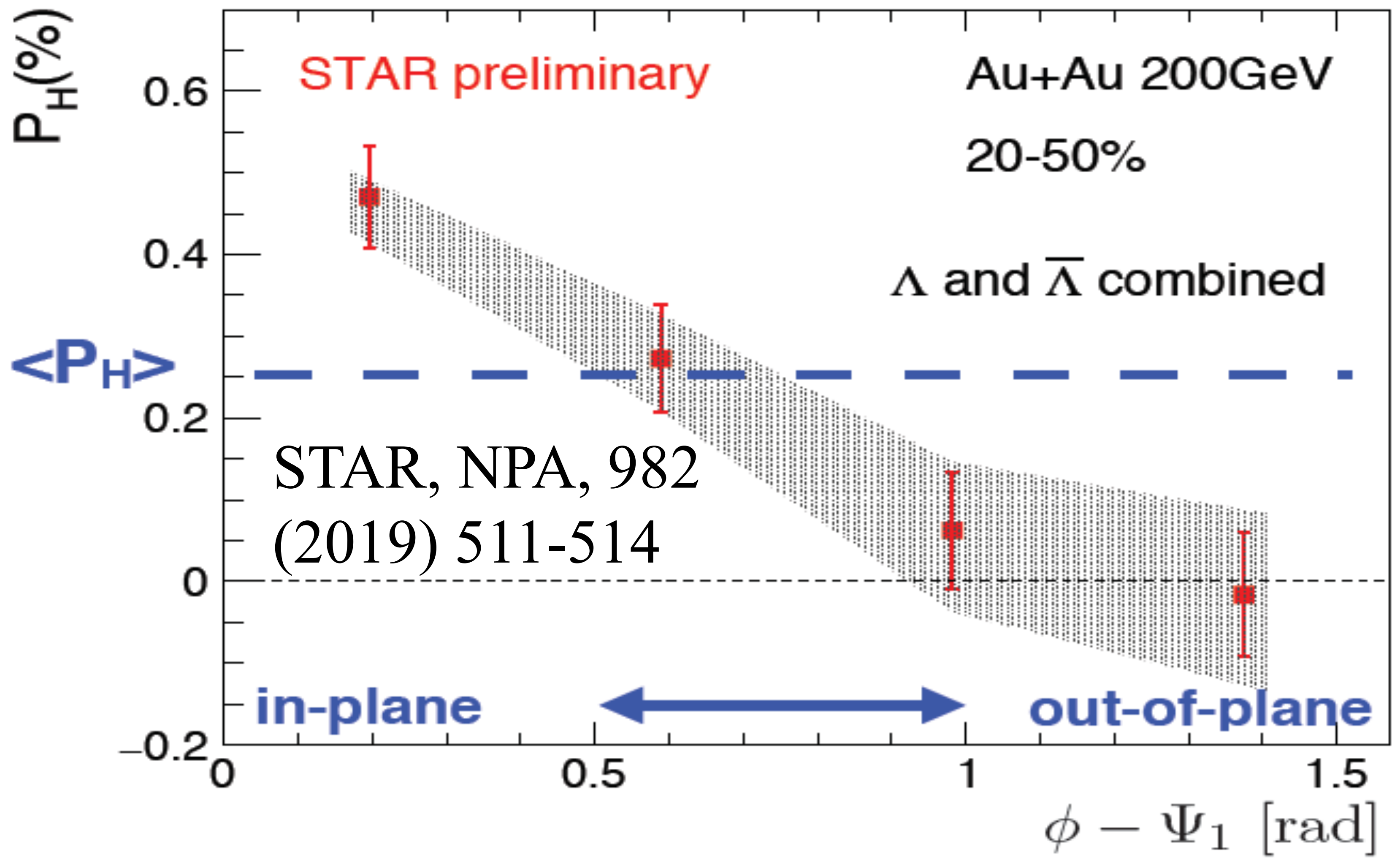
$$\tilde{A}_2(p_t^H, \eta^H) = \frac{3}{2}\int \frac{d\Omega^*}{4\pi}\frac{d\phi_H}{2\pi} A\left(\mathbf{p}_H, \mathbf{p}^*\right)\sin^2\theta^* \cos\left[2(\phi_H - \phi^*)\right].$$

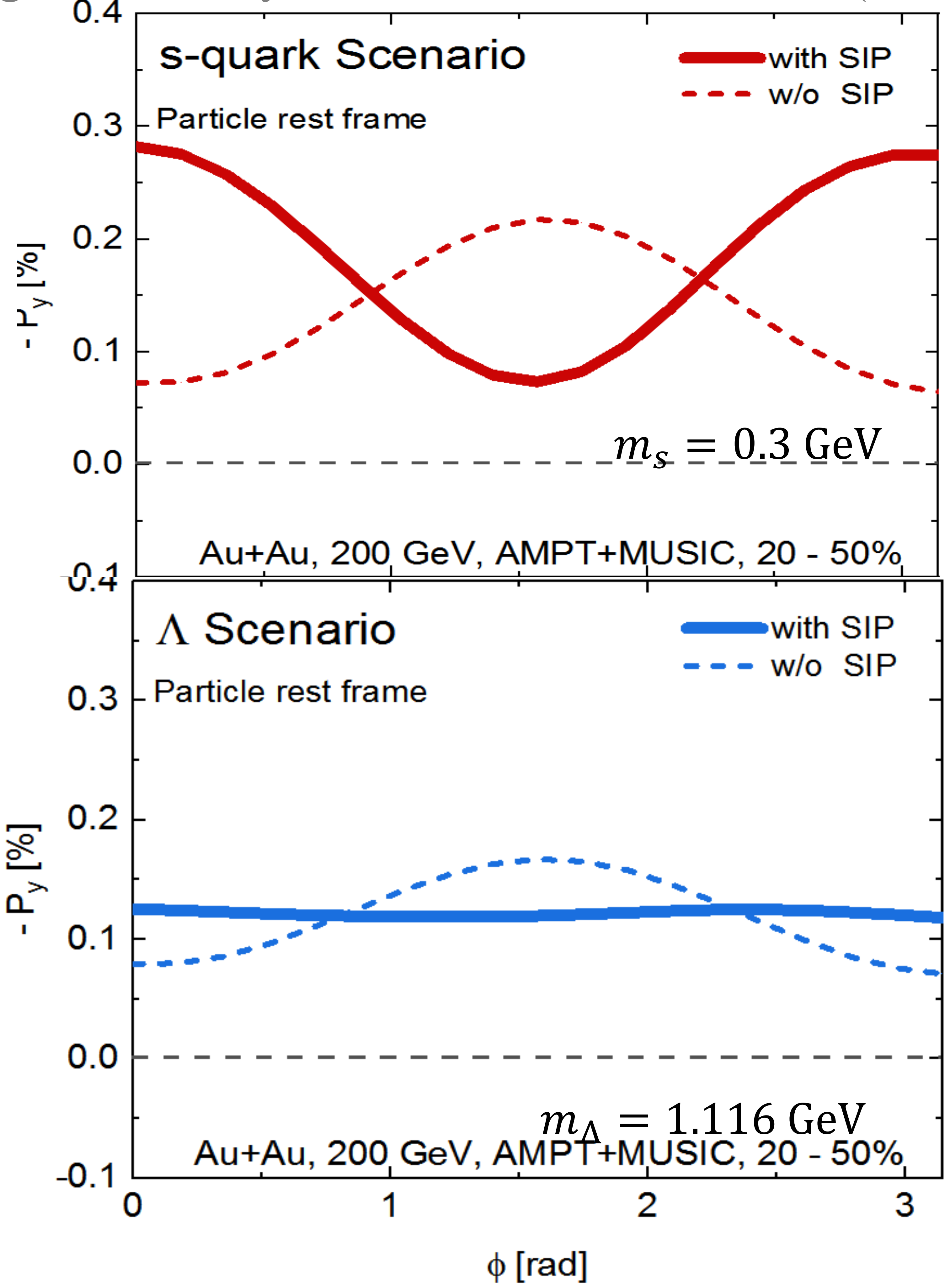
Decrease the statistical errors for about 10%

$P_y(\phi)$ 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)





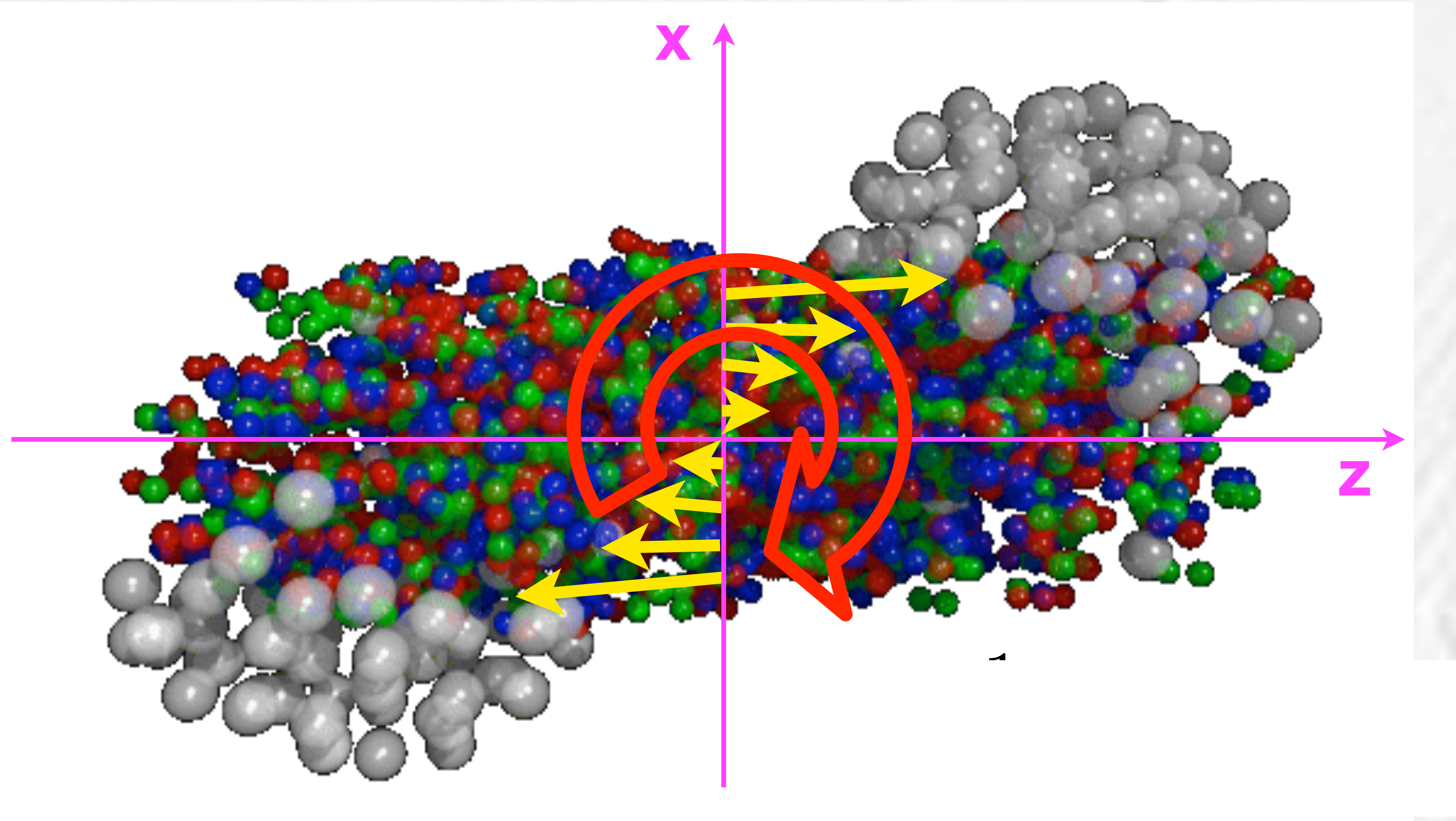
Total P^μ
=Thermal vorticity + Shear effects

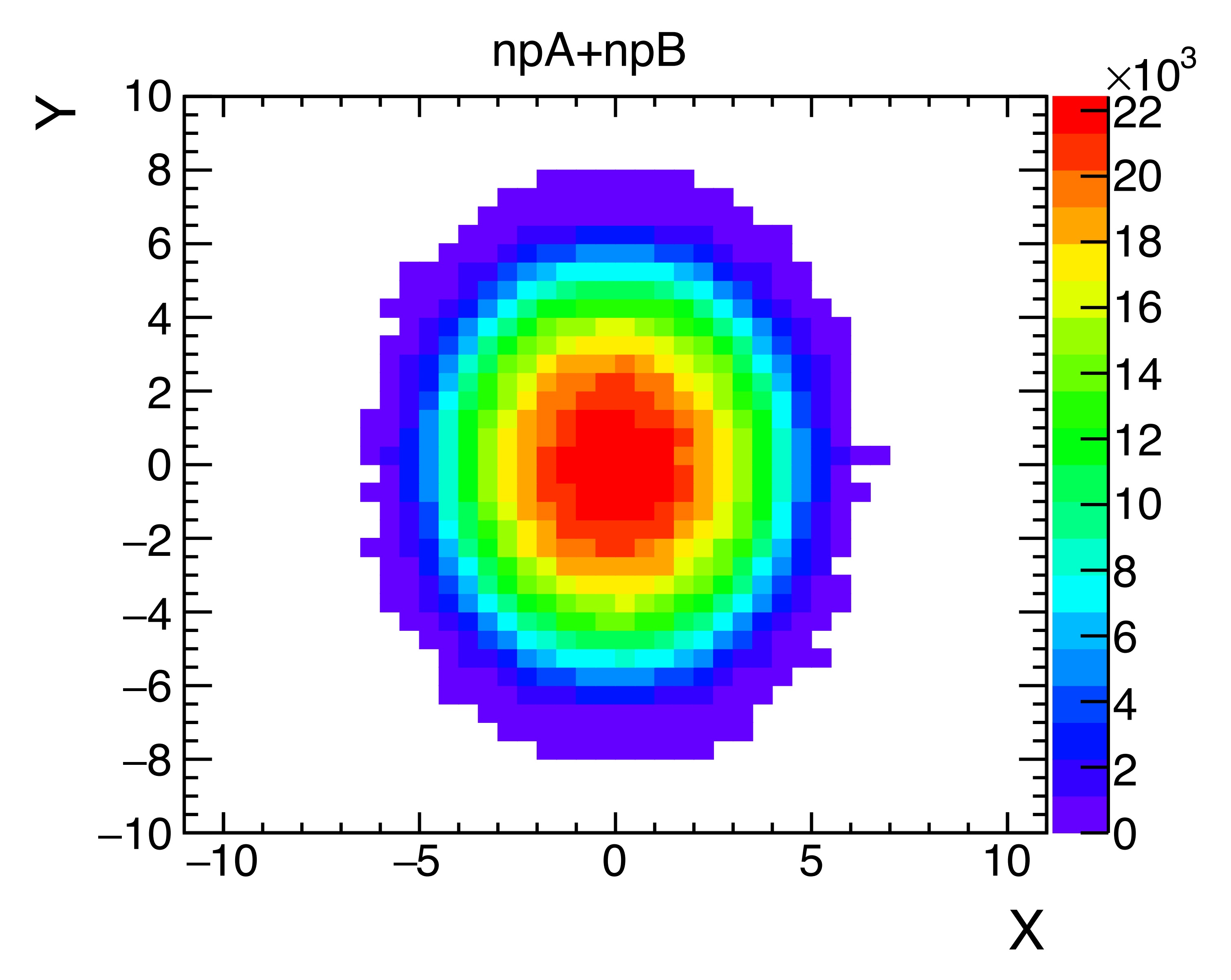
-In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

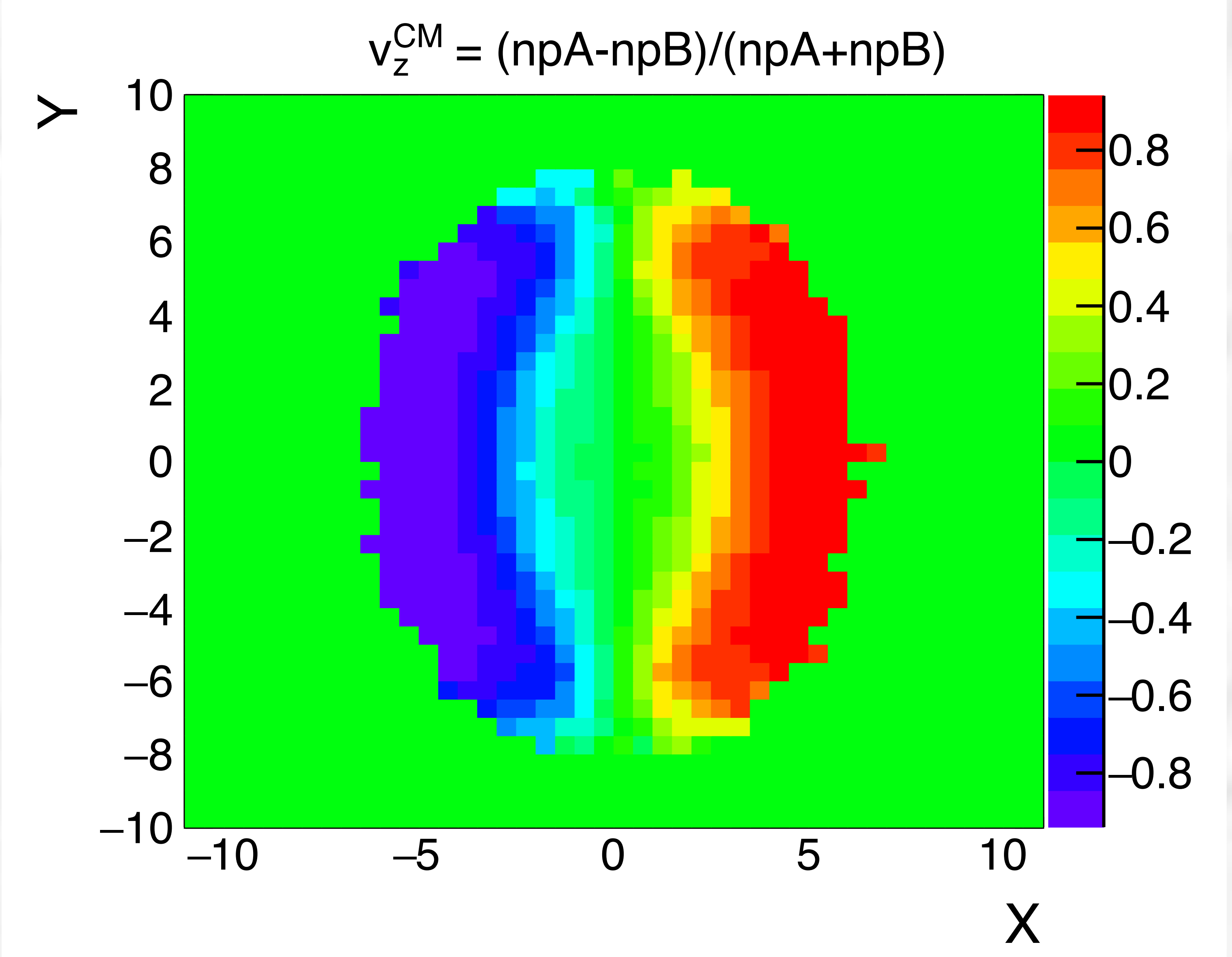
Global polarization - P_y

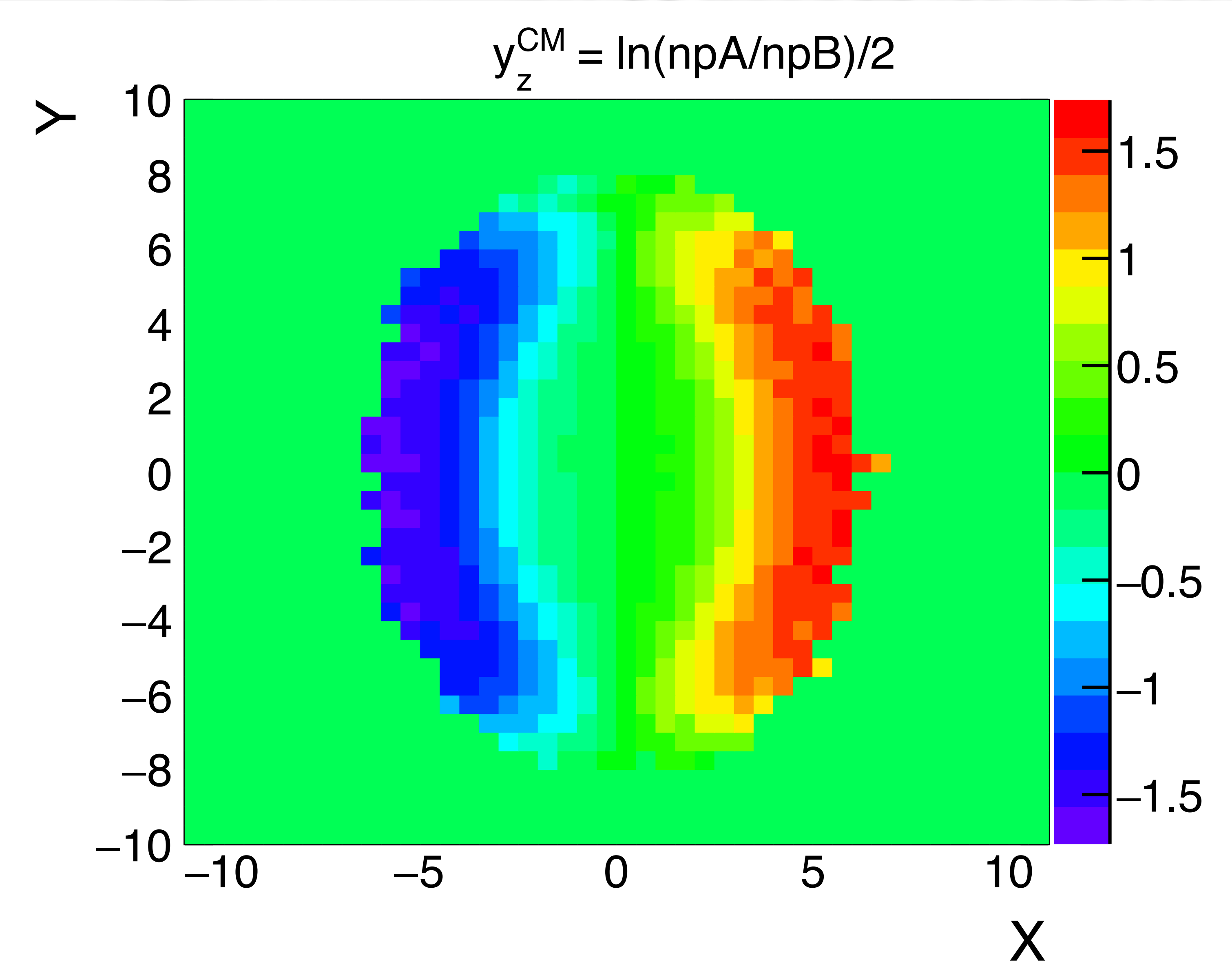
Au+Au, b=7 fm

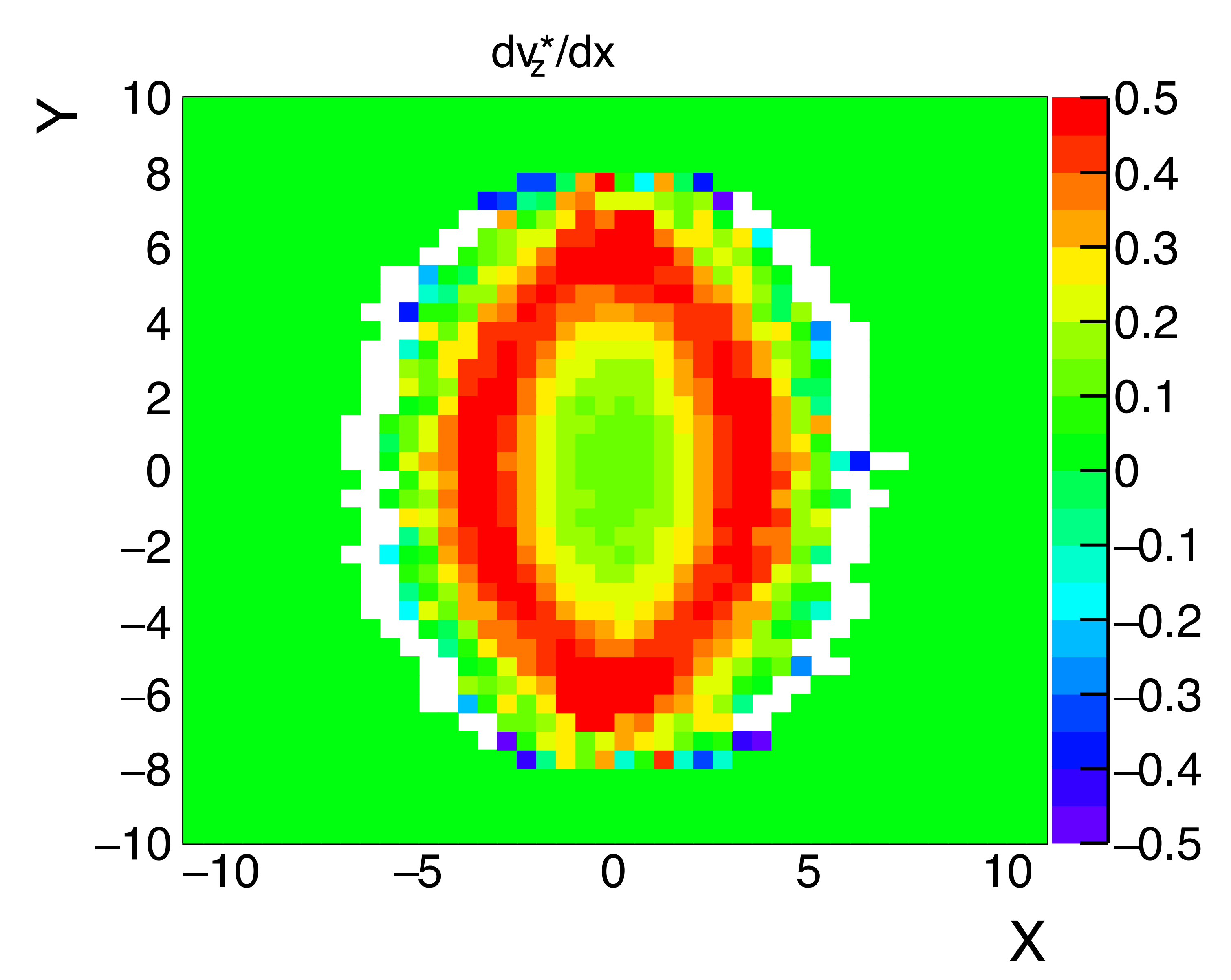
"np" - # of nucleon participants

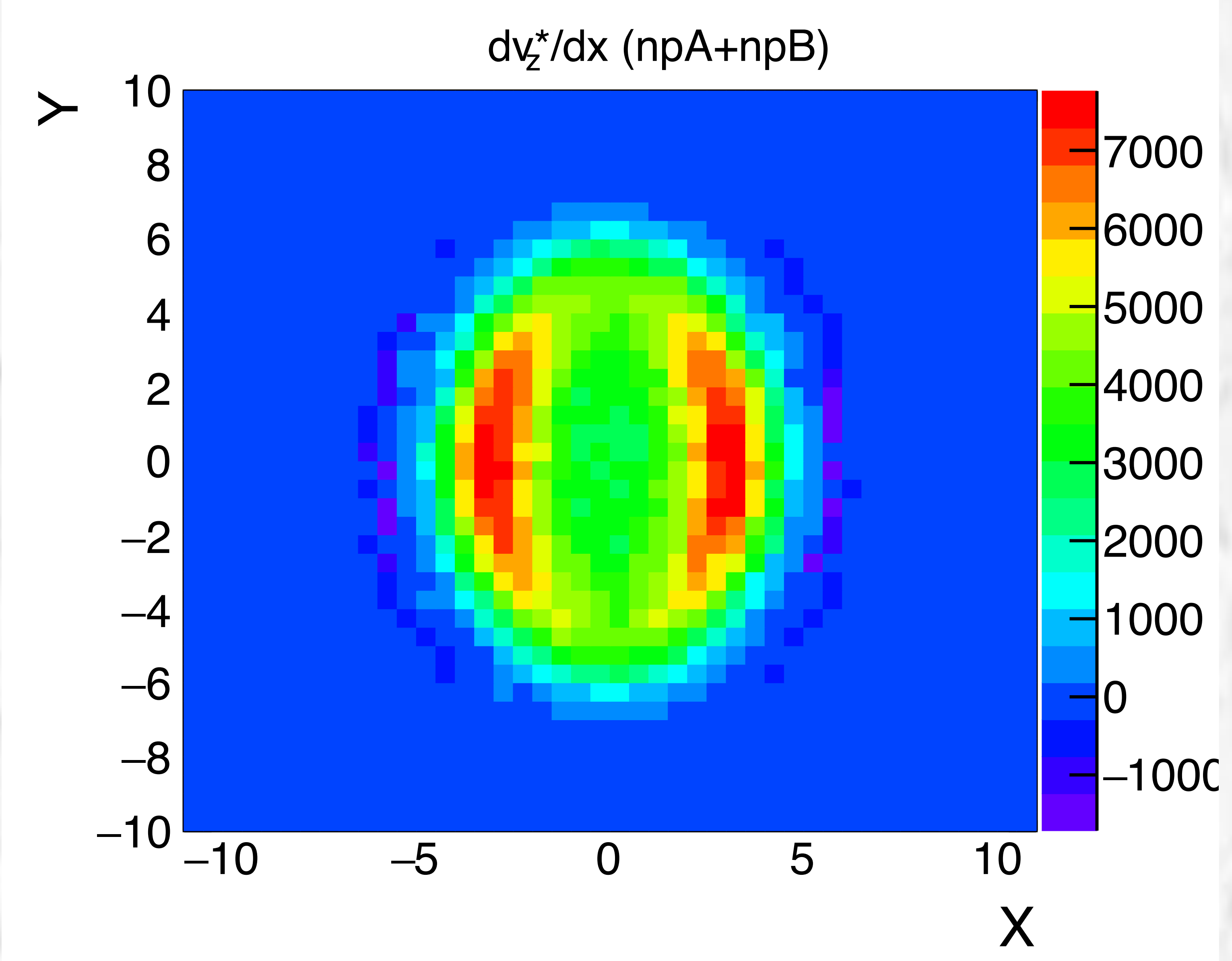












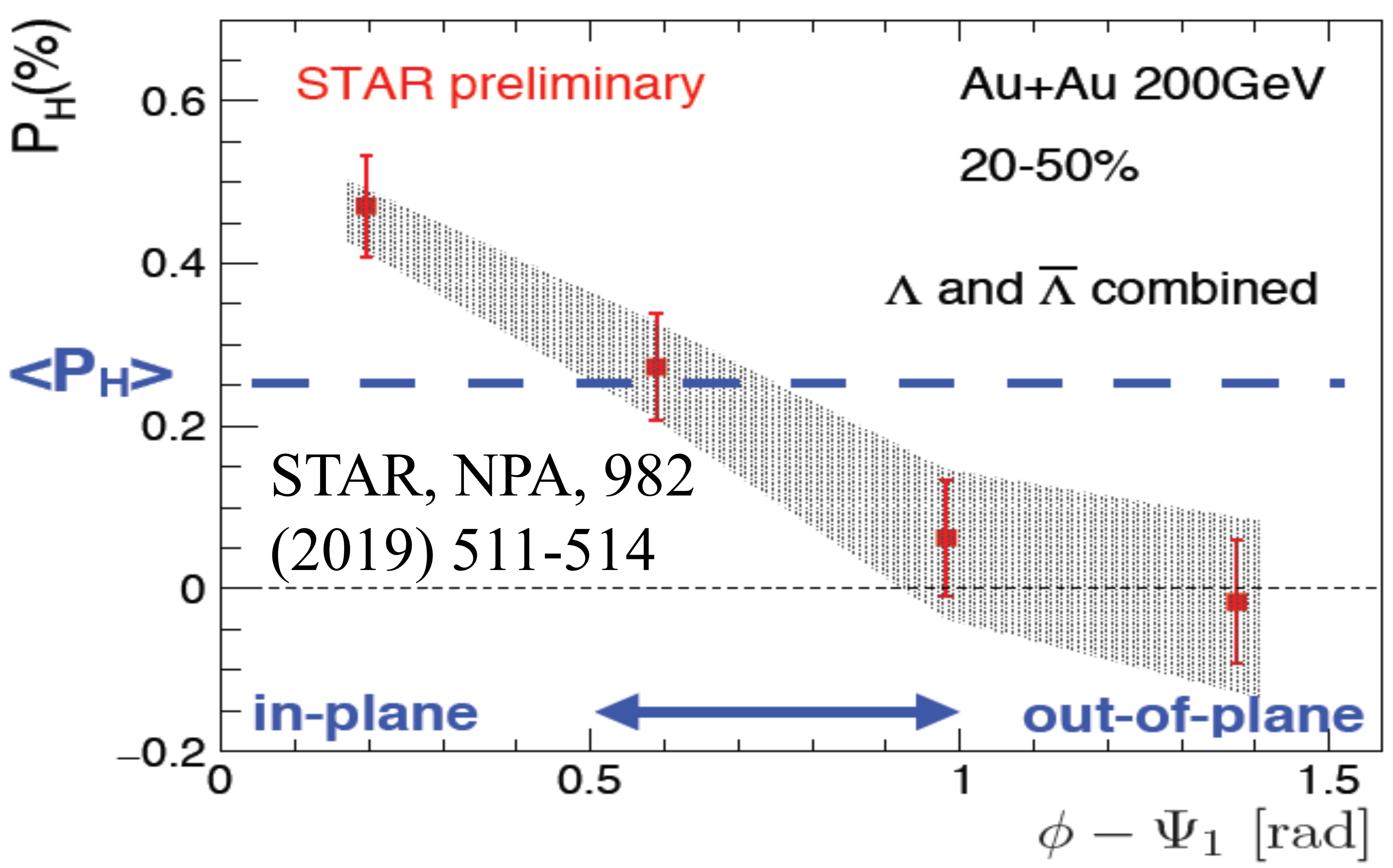
v_z is calculated as velocity of the center of mass

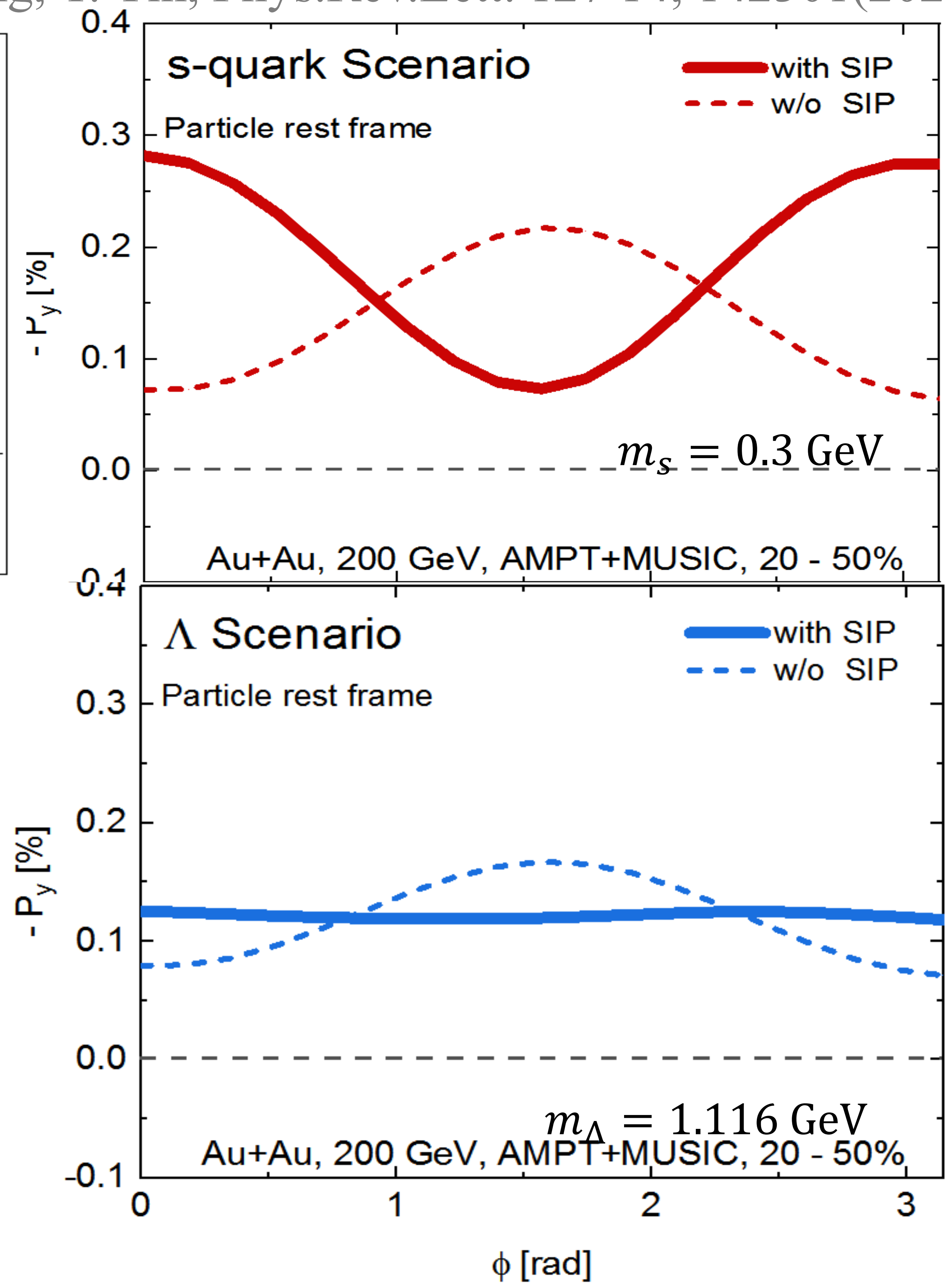
gradients are calculated with rapidity (e.g. in the "fluid" rest frame)

$P_y(\phi)$ physics

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

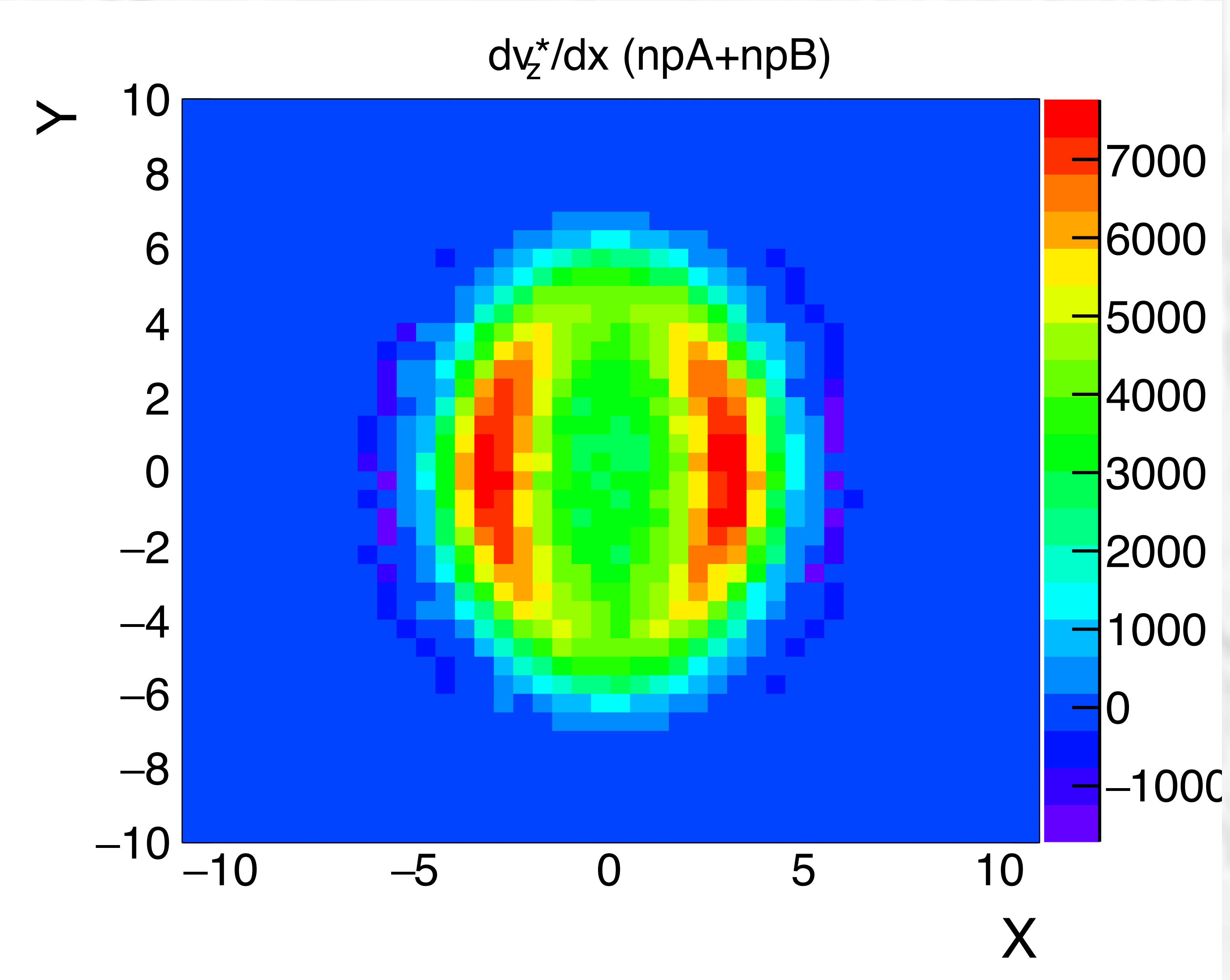
B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021)





Total P^μ
=**Thermal vorticity** + **Shear effects**

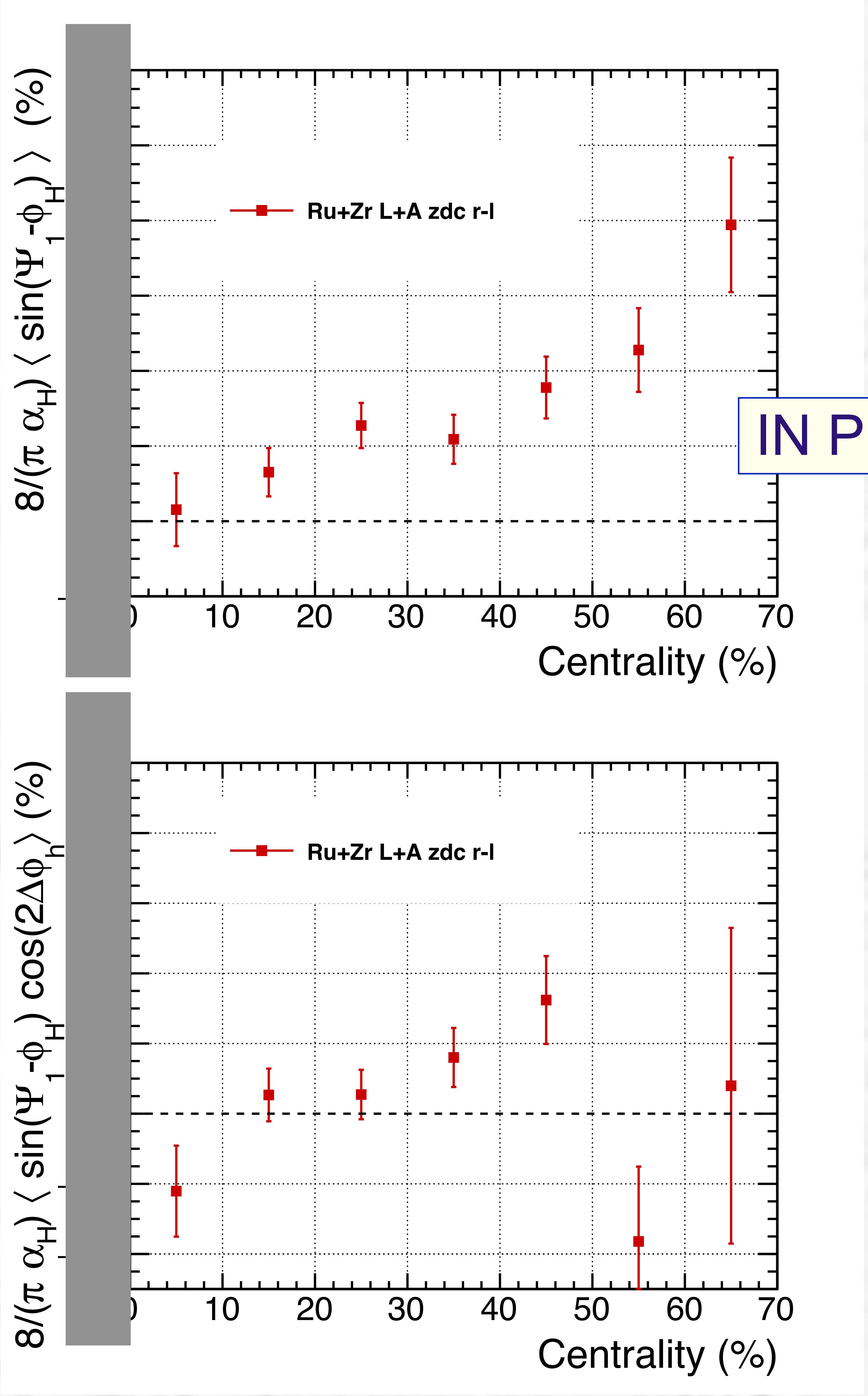
-In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data



$P_y(\phi)$ important for:
- check old preliminary
- SIP
- "Blast wave" - see dist. above

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

$P_{y,0}$ and $P_{y,c2}$

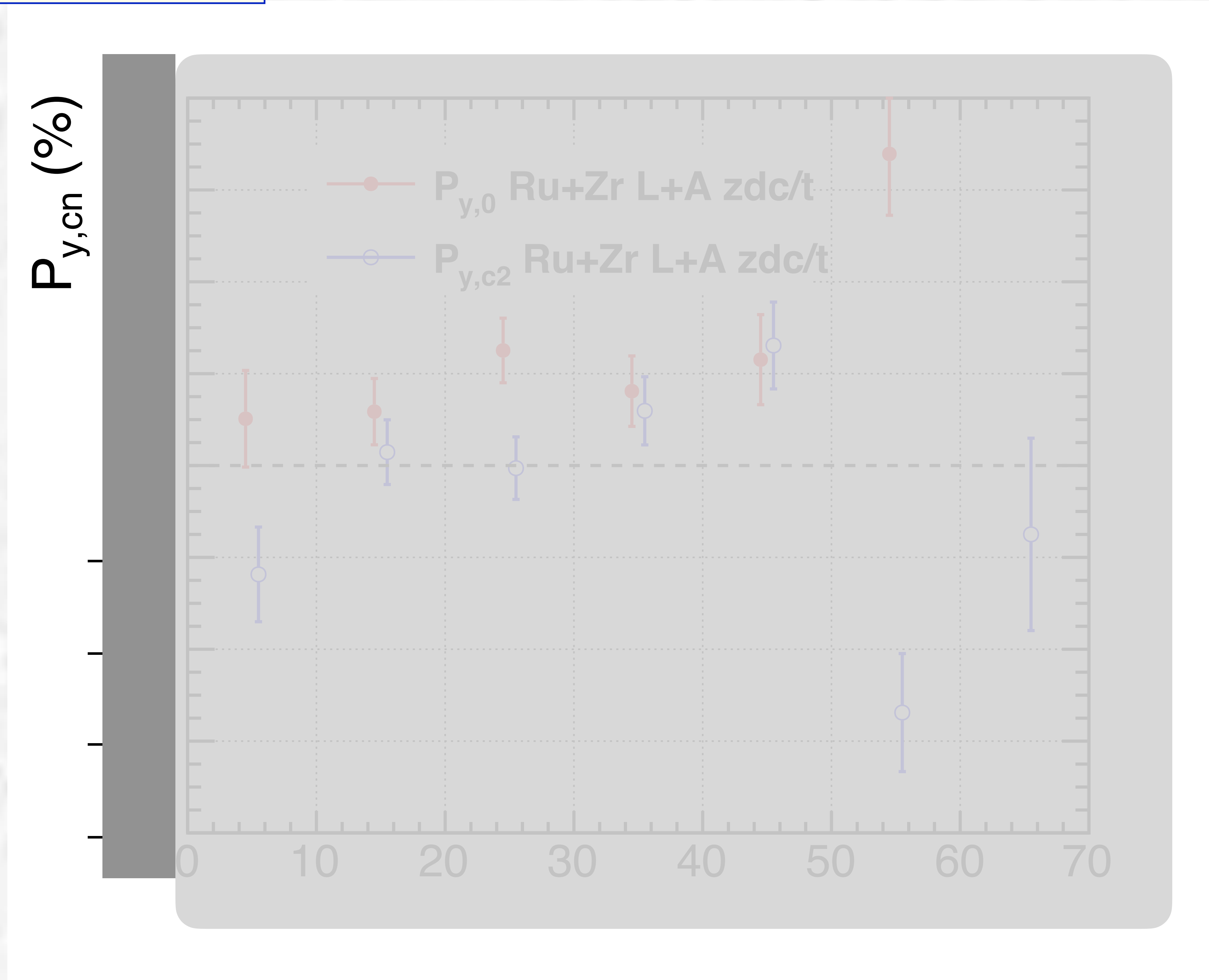


$$\boxed{P_H\left(\phi_H-\Psi_{\rm RP},p_t^H,\eta^H\right)=P_0\left(p_t^H,\eta^H\right)+2P_2\left(p_t^H,\eta^H\right)\cos\{2[\phi_H-\Psi_{\rm RP}]\}}$$

$$\langle\sin(\Psi_{\rm RP}-\phi^*)\rangle=\frac{\alpha_H\pi}{8}\left[A_0\,\left(P_0+2P_2v_2\right)-A_2(P_2+P_0v_2)\right],$$

$$\langle\sin(\Psi_{\rm RP}-\phi^*)\cos[2(\phi_H-\phi^*)]\rangle=\frac{\alpha_H\pi}{8}\left[A_0\,\left(P_2+P_0v_2\right)-\frac{1}{2}A_2(P_0+3P_2v_2)\right]$$

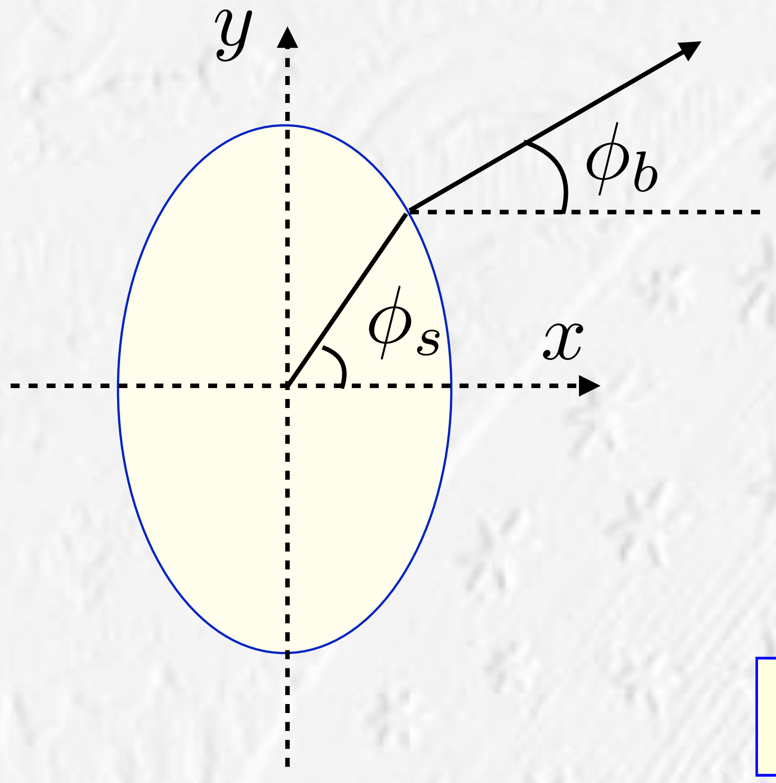
IN PROGRESS



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

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

Blast wave parameterization



Number of emitting "sources":

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

Transverse rapidity (boost):

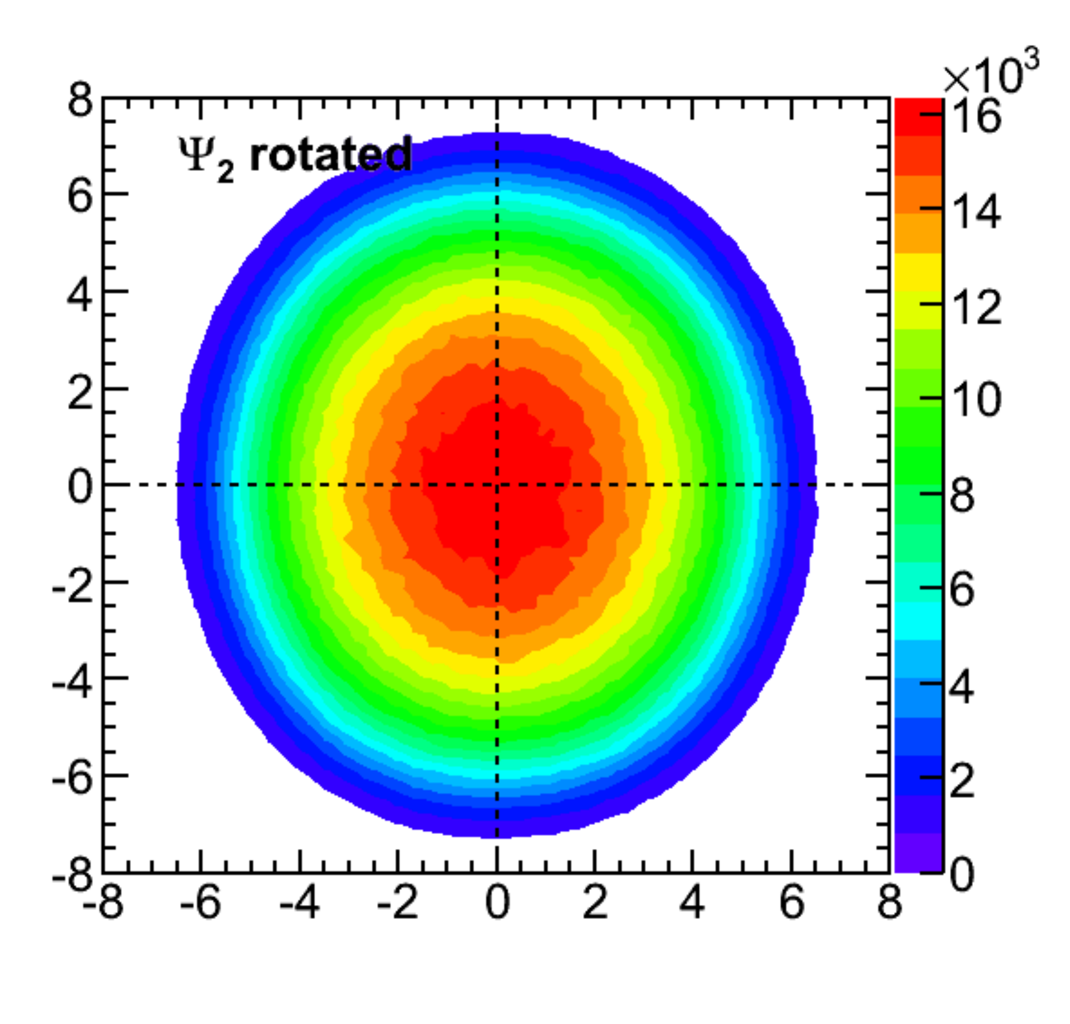
$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + a_2 \cos(2\phi_s)]$$

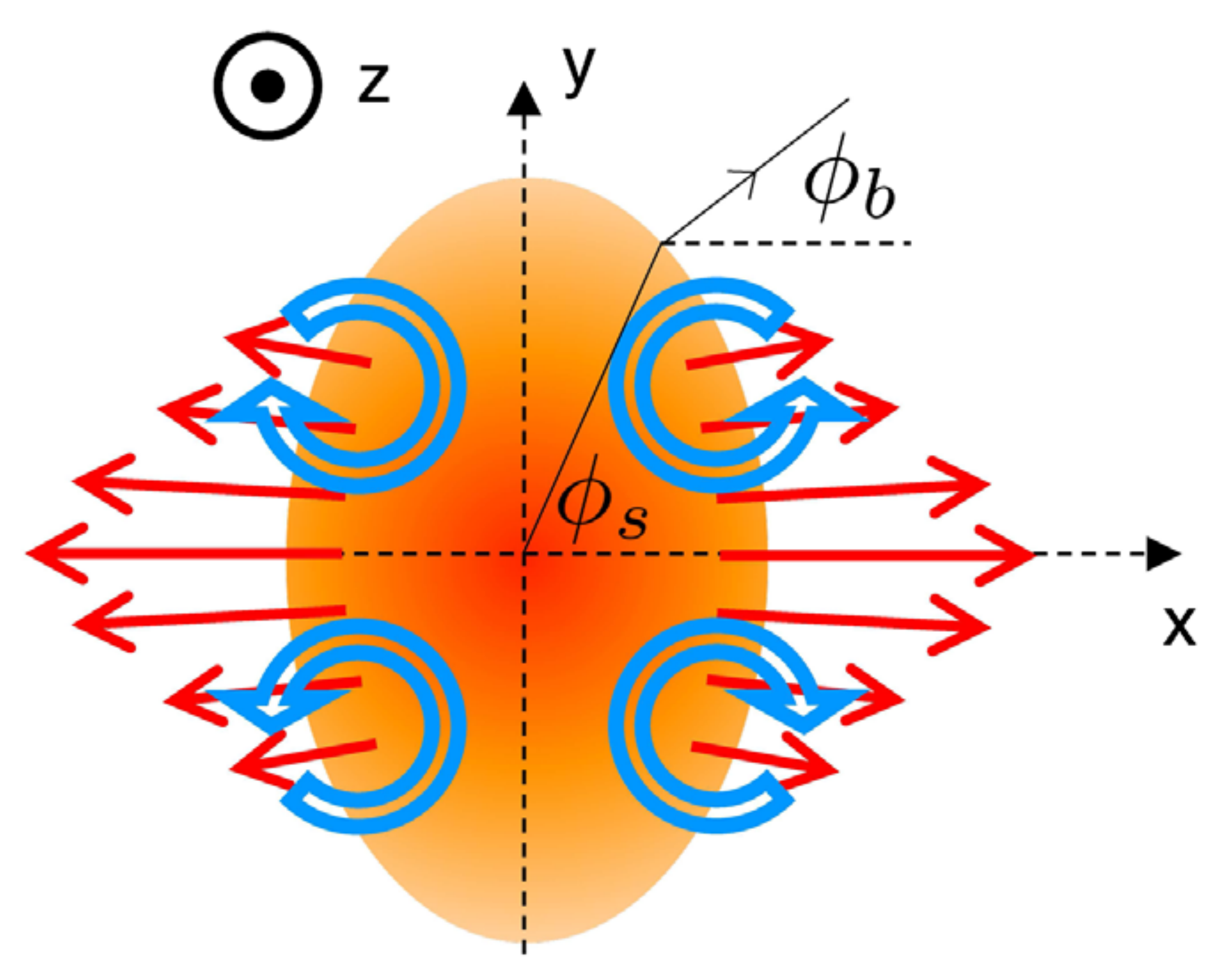
$$\omega_z \approx \rho_{t,max} \sin(n\phi_s)[a_n - 2s_n]$$

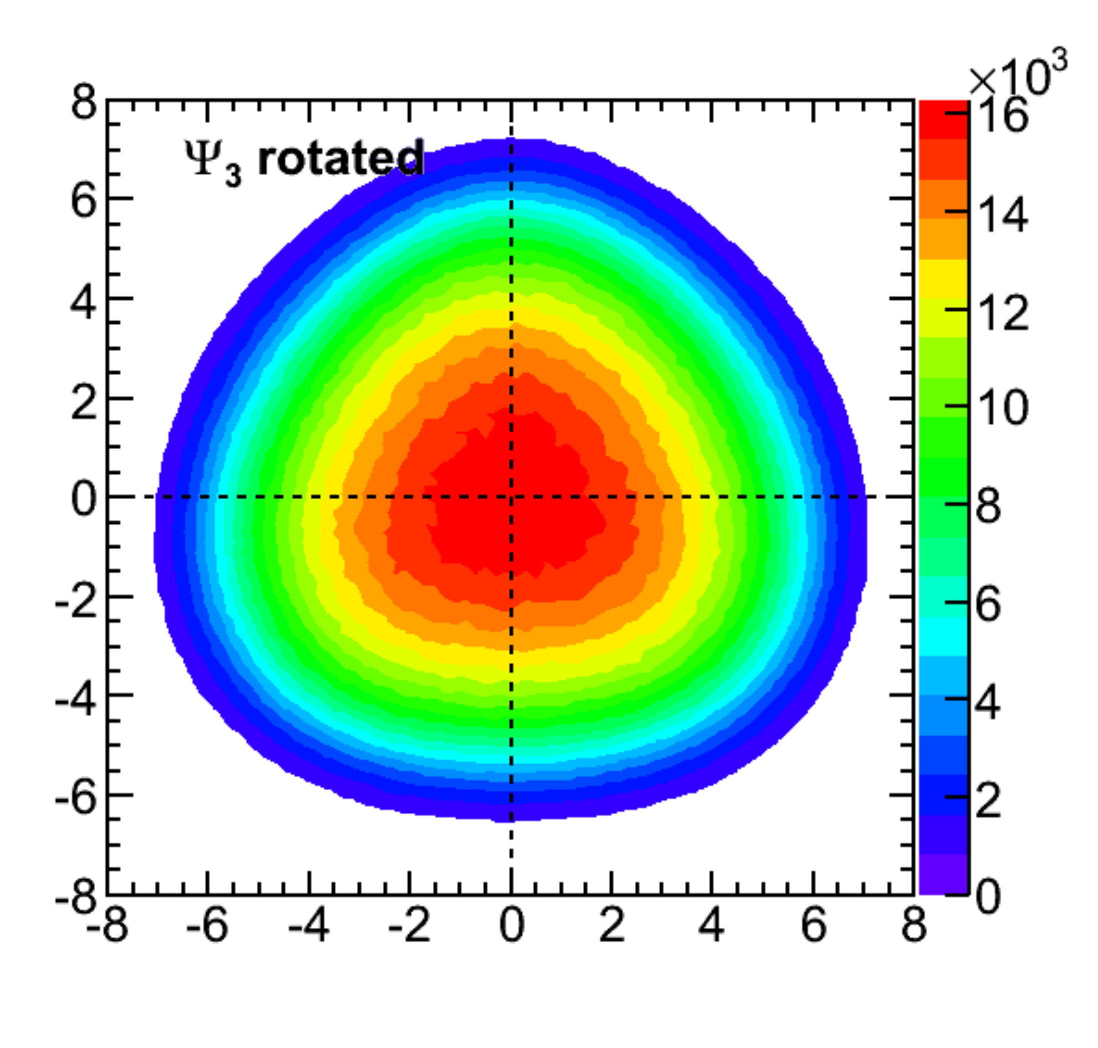
The effects should be present also at higher harmonics, e.g. for triangular flow.

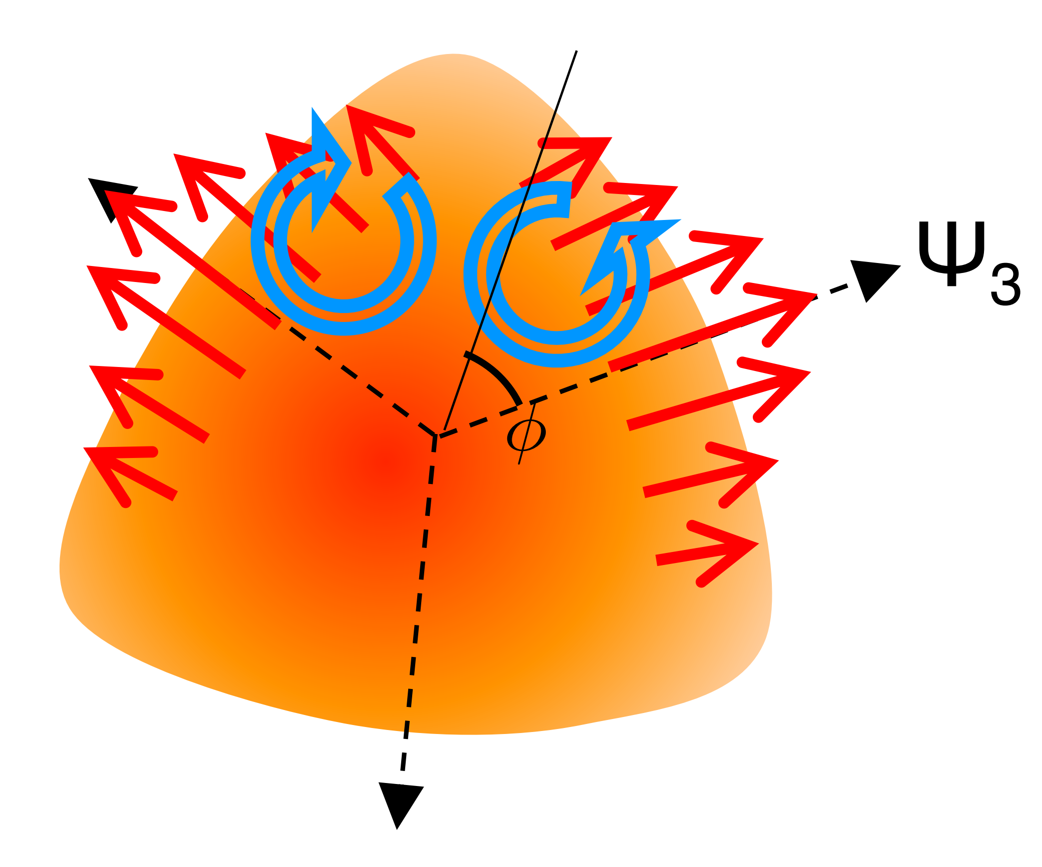
Provides connection to $v_n(p_t)$ and azFemto measurements

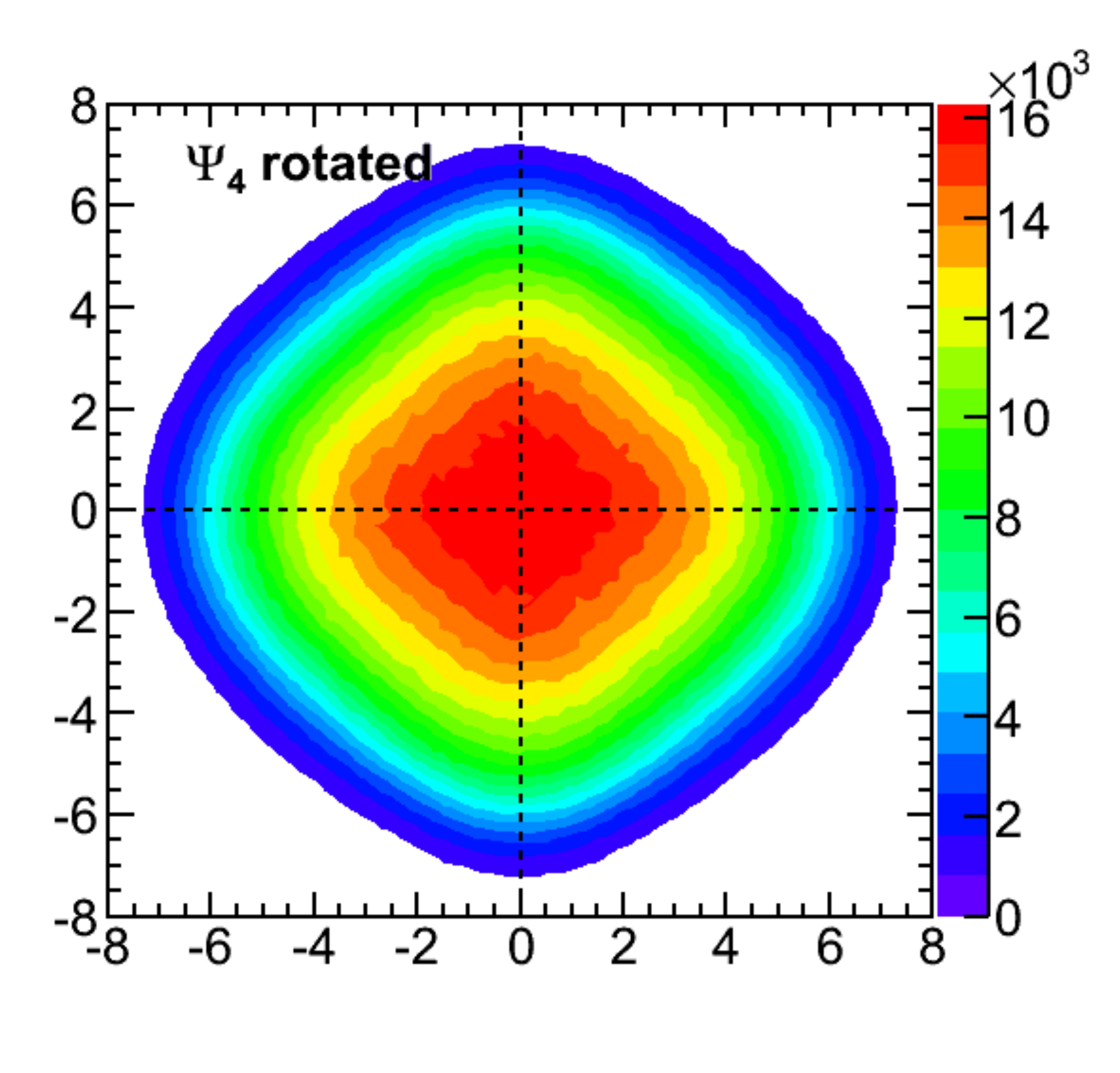
page 19 Strangeness in Quark Matter, Utrecht University, July 10-15,2017 S.A. Voloshin





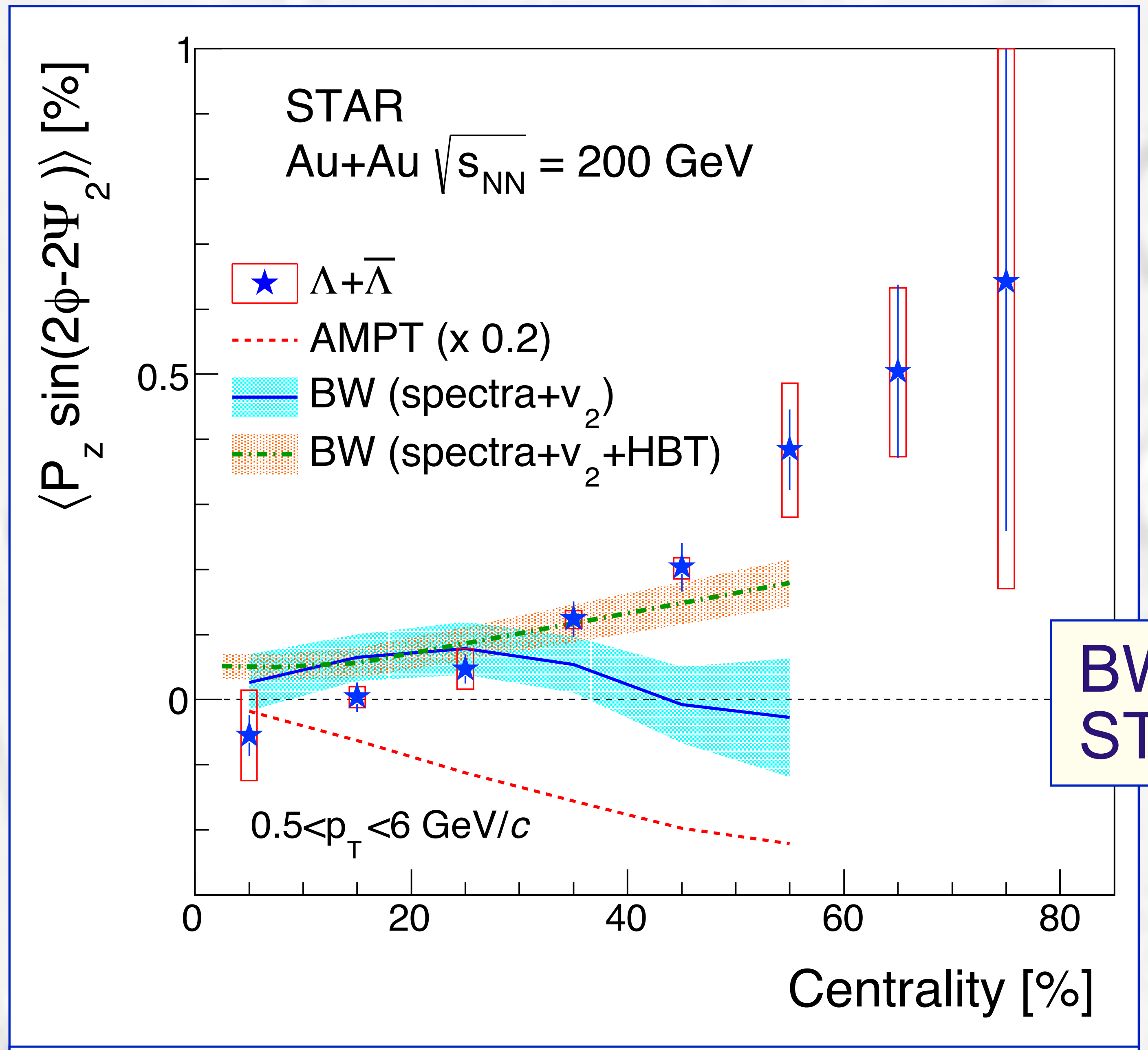


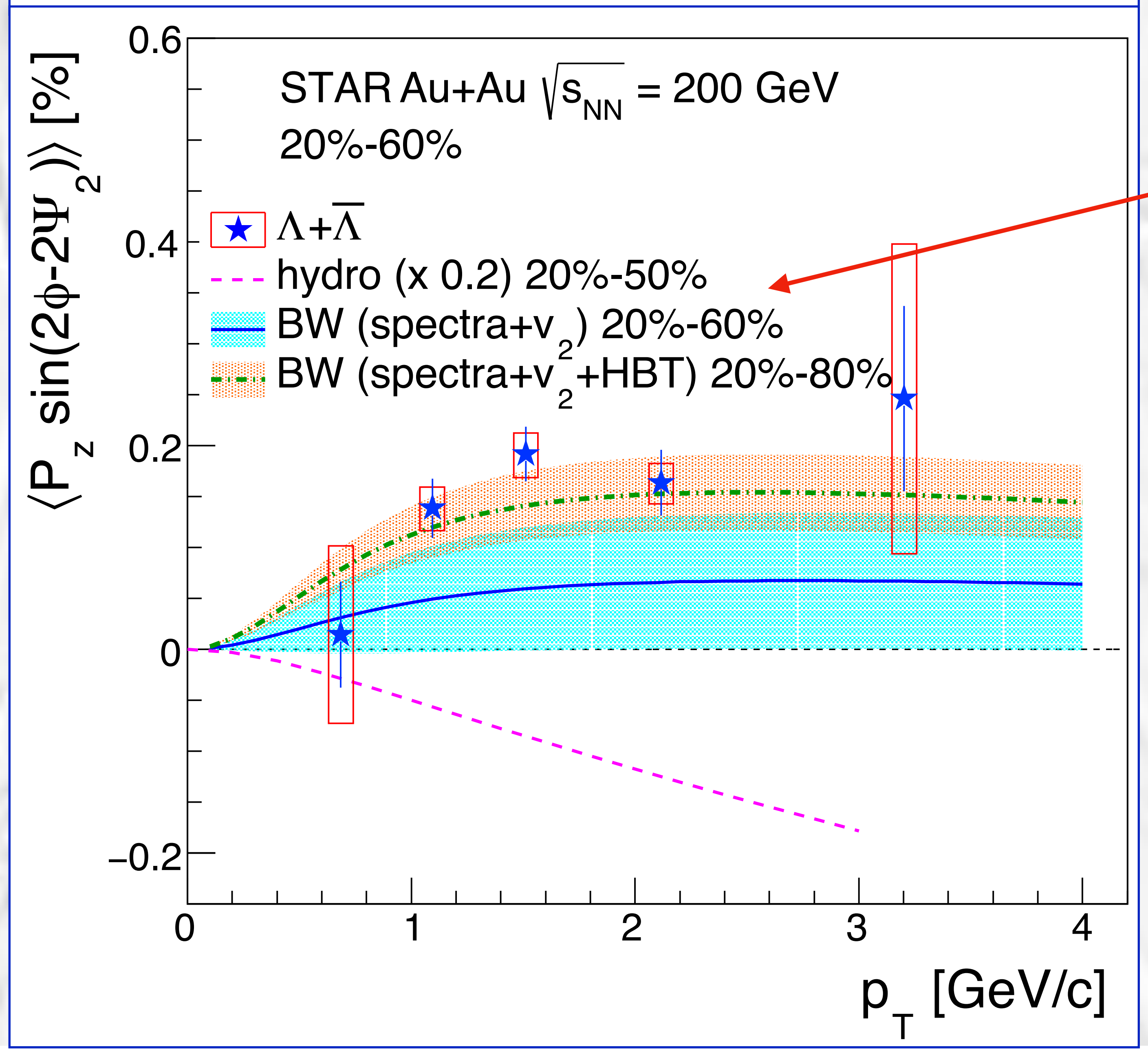




Measurements and models

STAR, PRL123.13201 (2019)





BW parameters obtained with HBT:
STAR, PRC71.044906 (2005) !!!

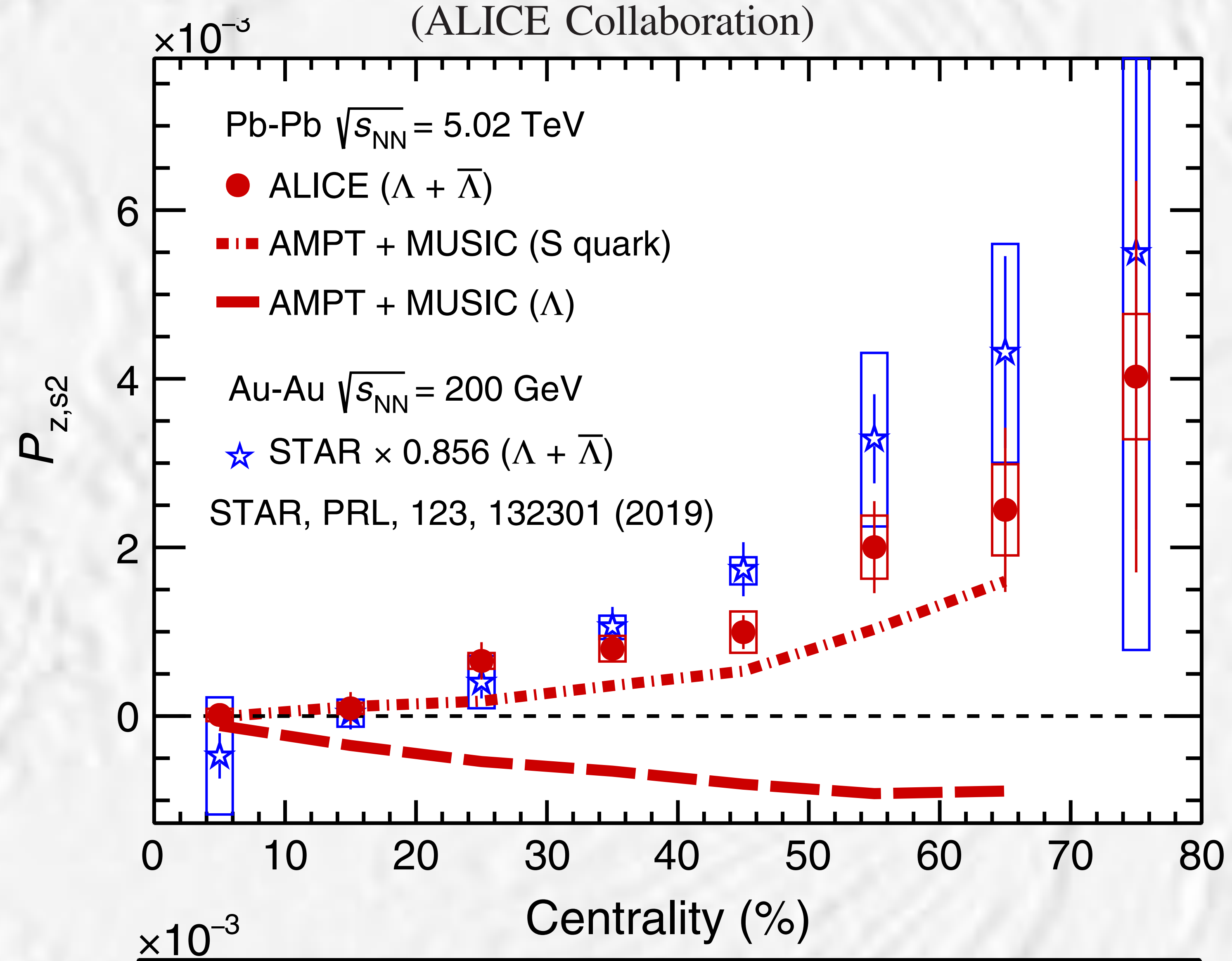
Note factor of 5!

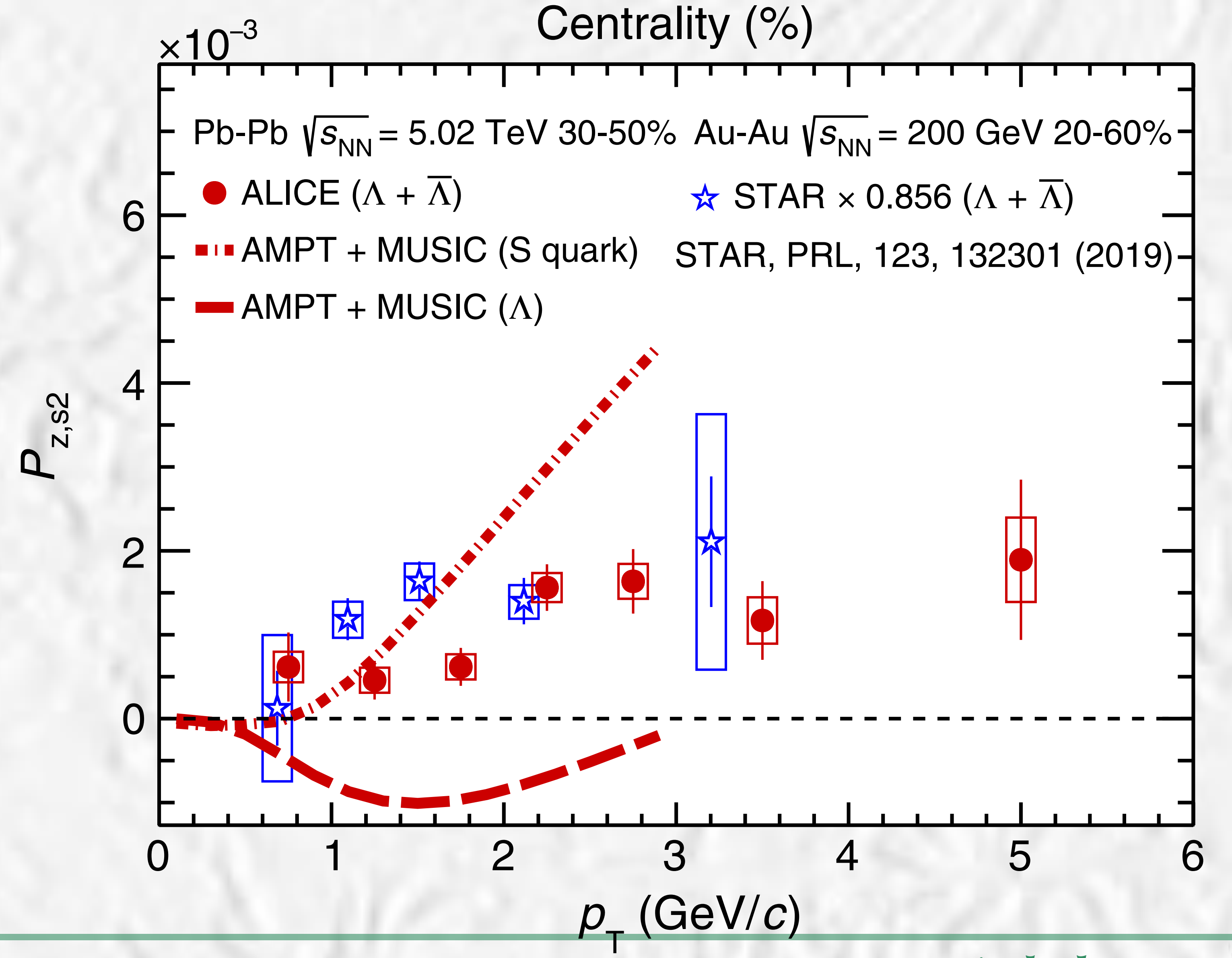
Would higher harmonics measurements help to observe the SIP contribution?

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

Polarization of Λ and Λ̄ Hyperons along the Beam Direction in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

S. Acharya *et al.**
(ALICE Collaboration)





Relative contributions to polarization

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

$\omega^\mu = (0, \boldsymbol{\omega})$:

$$S^0(x,p) = \frac{1}{8m}(1-n_F)\,\frac{\boldsymbol{\omega}\cdot\mathbf{p}}{T},$$
$$\mathbf{S}(x,p) = \frac{1}{8m}(1-n_F)\left(-\frac{\mathbf{p}\times\boldsymbol{\nabla}T}{T^2} + 2\,\frac{E\,\boldsymbol{\omega}}{T} + \frac{\mathbf{p}\times\mathbf{A}}{T}\right)$$

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

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

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

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

Similarly for SIP

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.

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?

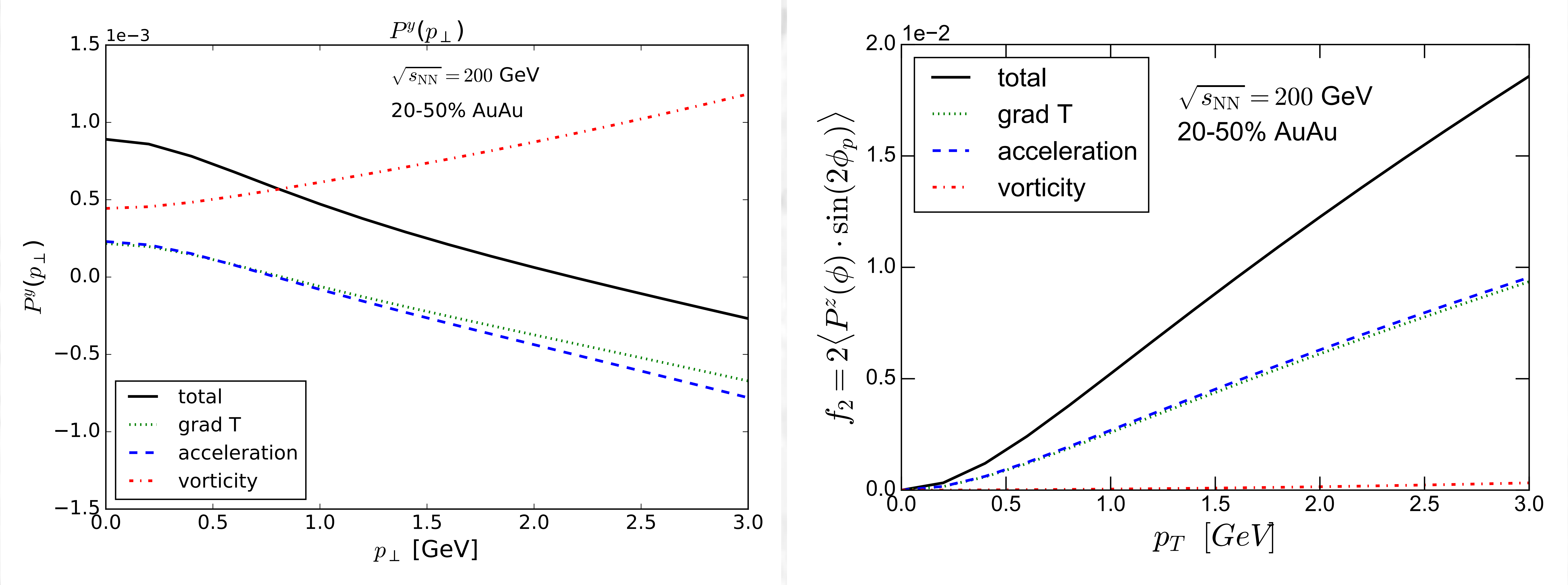
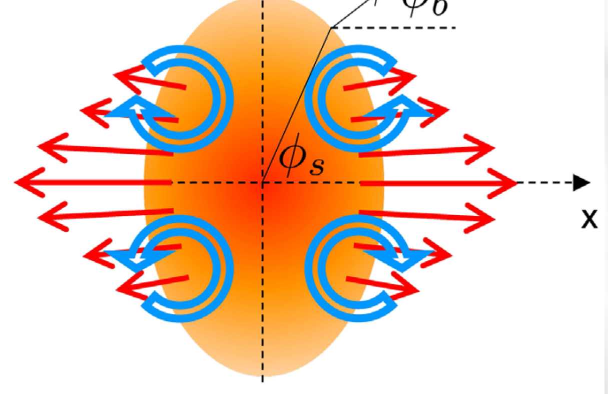
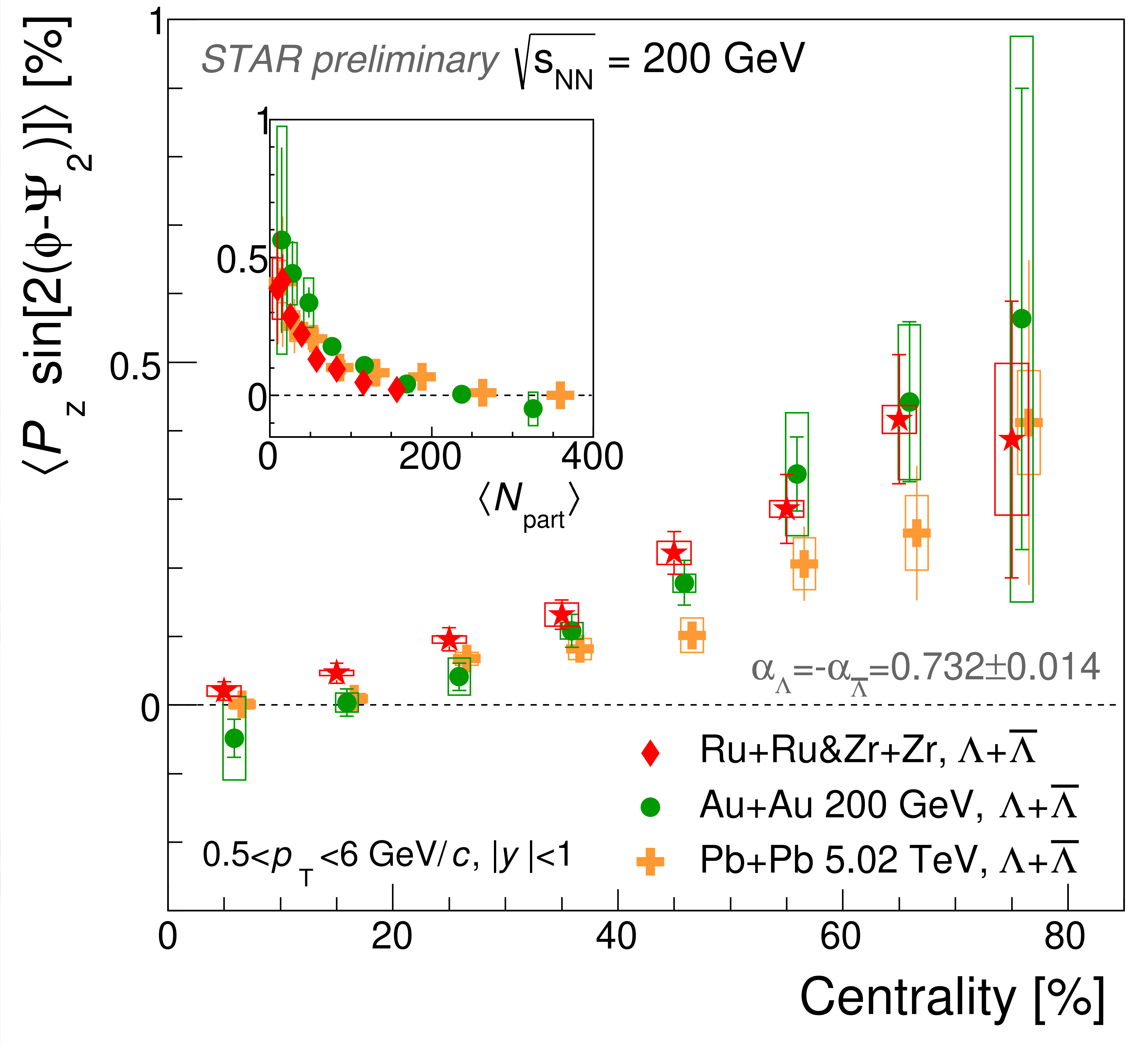


Fig. 26 Contributions to the global (left panel) and quadrupole longitudinal (right panel) components of Λ polarization stemming from gradients of temperature (dotted lines), acceleration (dashed lines) and vorticity (dash-dotted lines). Solid lines show the sums of all 3 contributions. The hydrodynamic 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.

$\langle P_z \sin[2(\phi_H - \Psi_n)]\rangle$



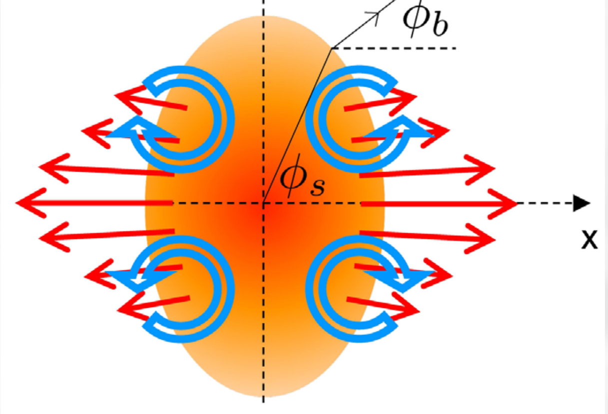


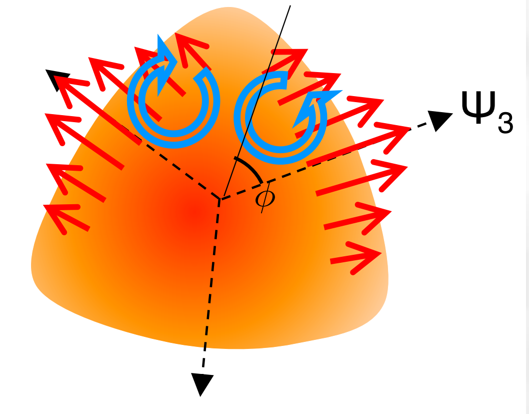
Size dependence?

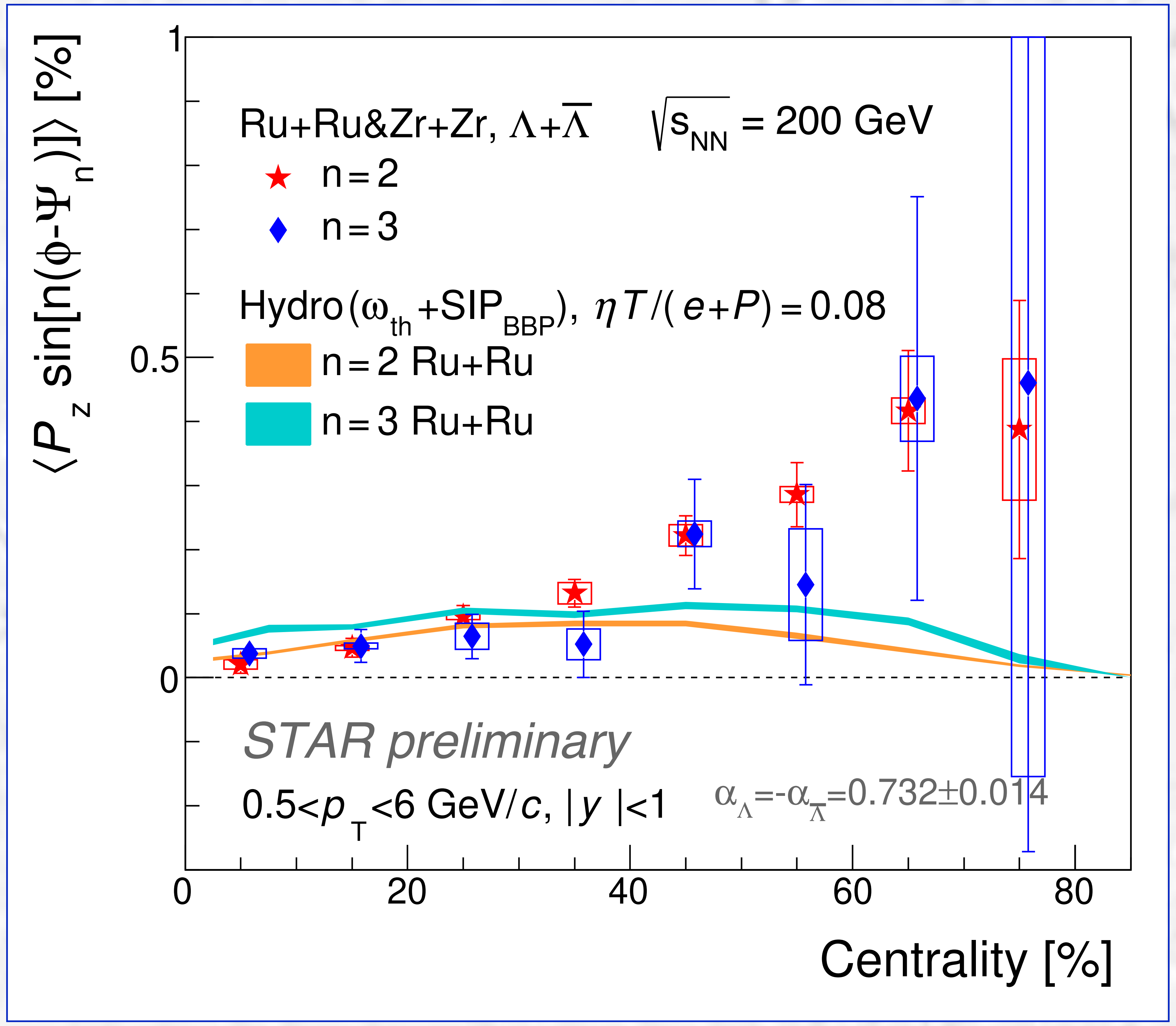
Using average over Ru+Ru and Zr+Zr

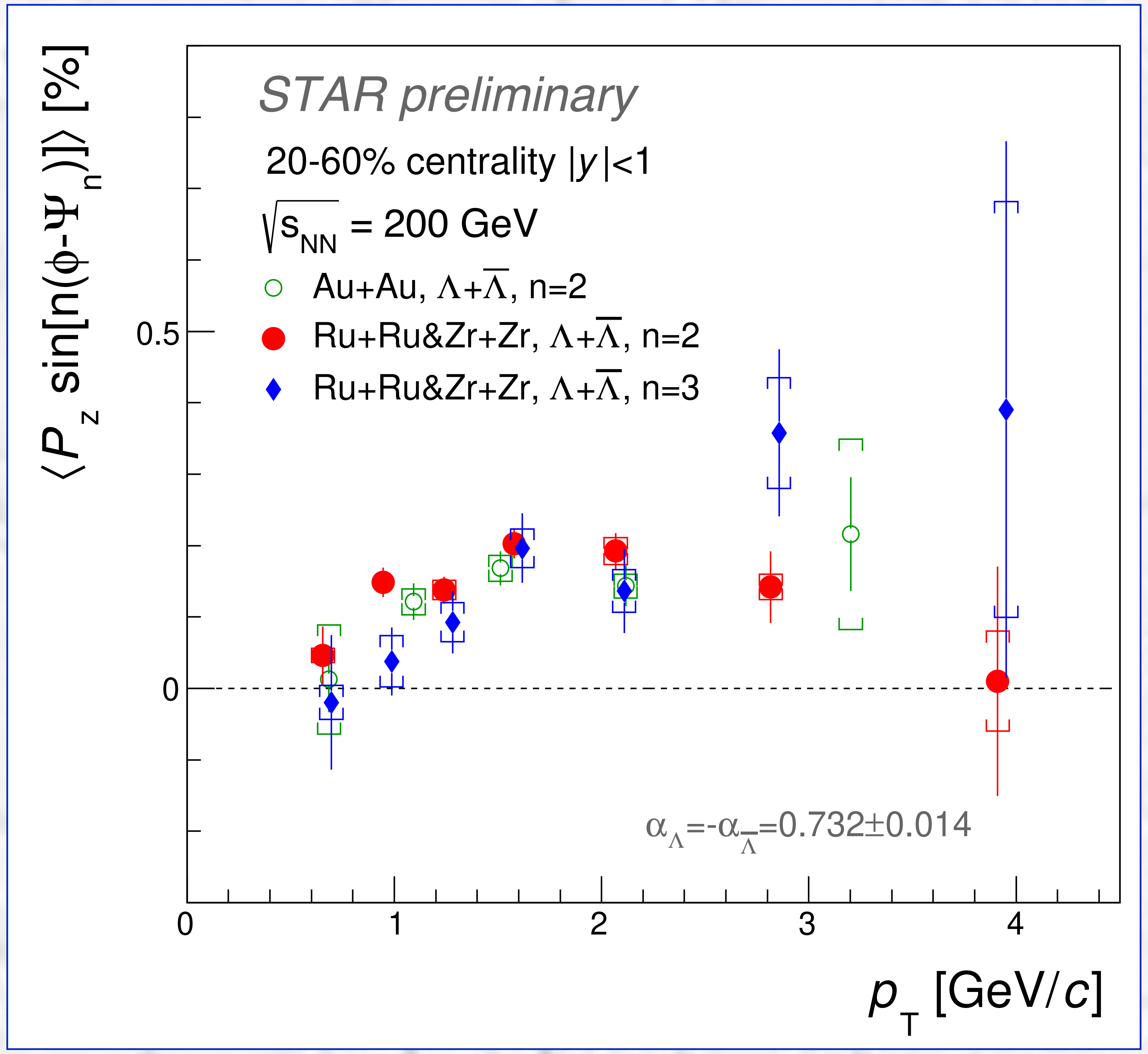
Assuming the same polarization for Λ and $\bar{\Lambda}$

$\langle P_z \sin[n(\phi_H - \Psi_n)] \rangle$



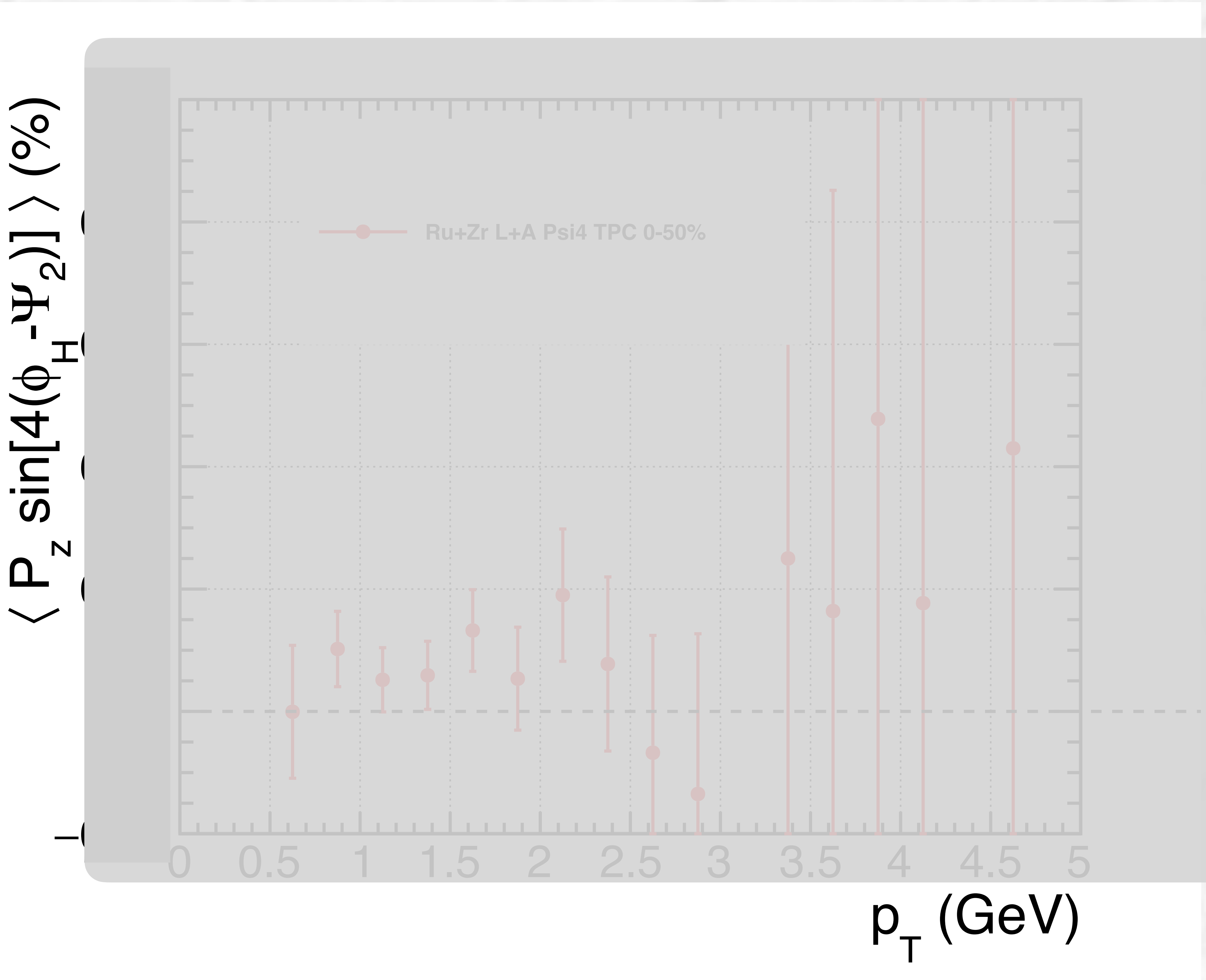


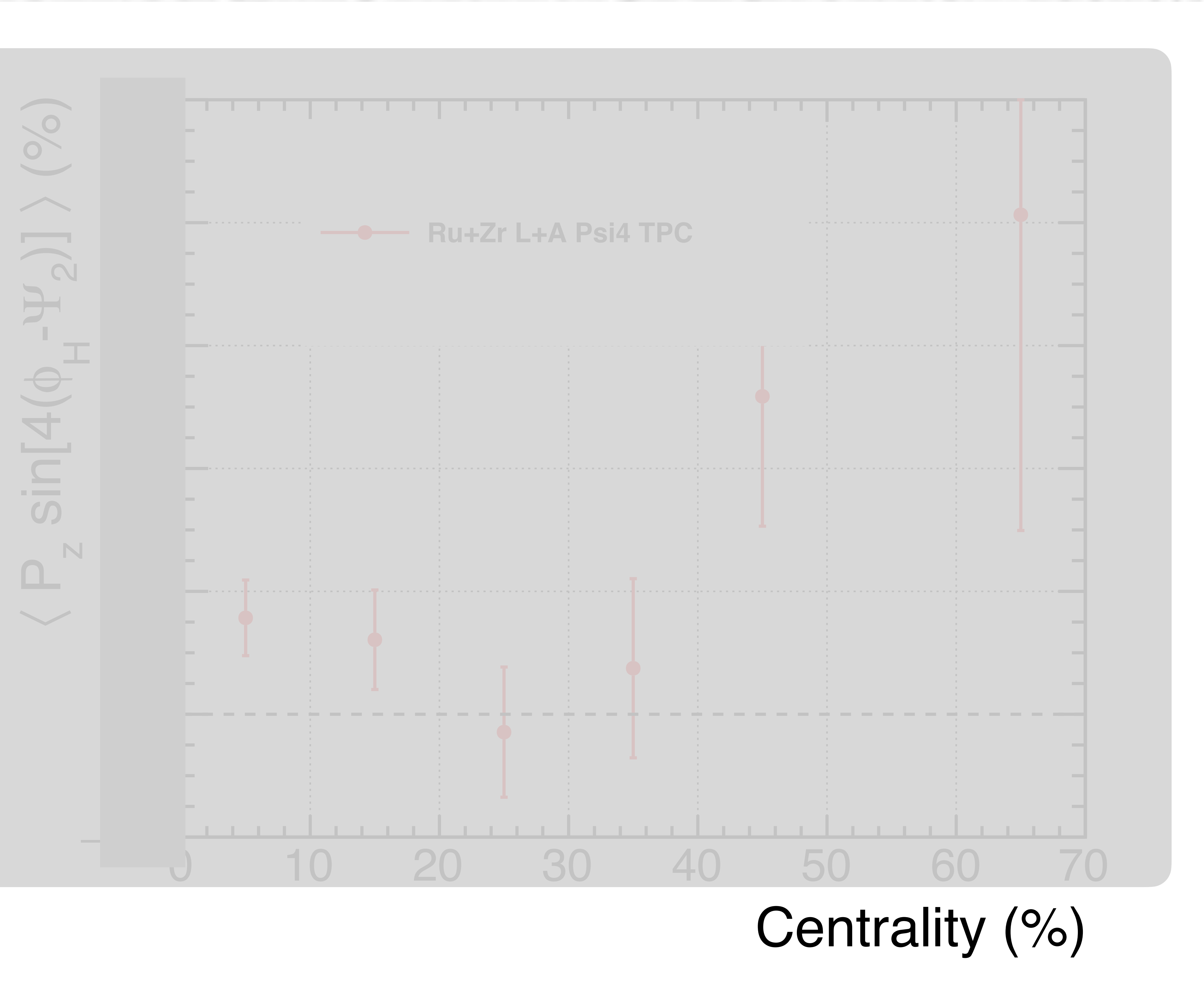




Using average over Ru+Ru and Zr+Zr
Assuming the same polarization for Λ and $\bar{\Lambda}$

$\langle P_z \sin[4(\phi_H - \Psi_n)] \rangle$





P_x : SIP vs vorticity

SIP:

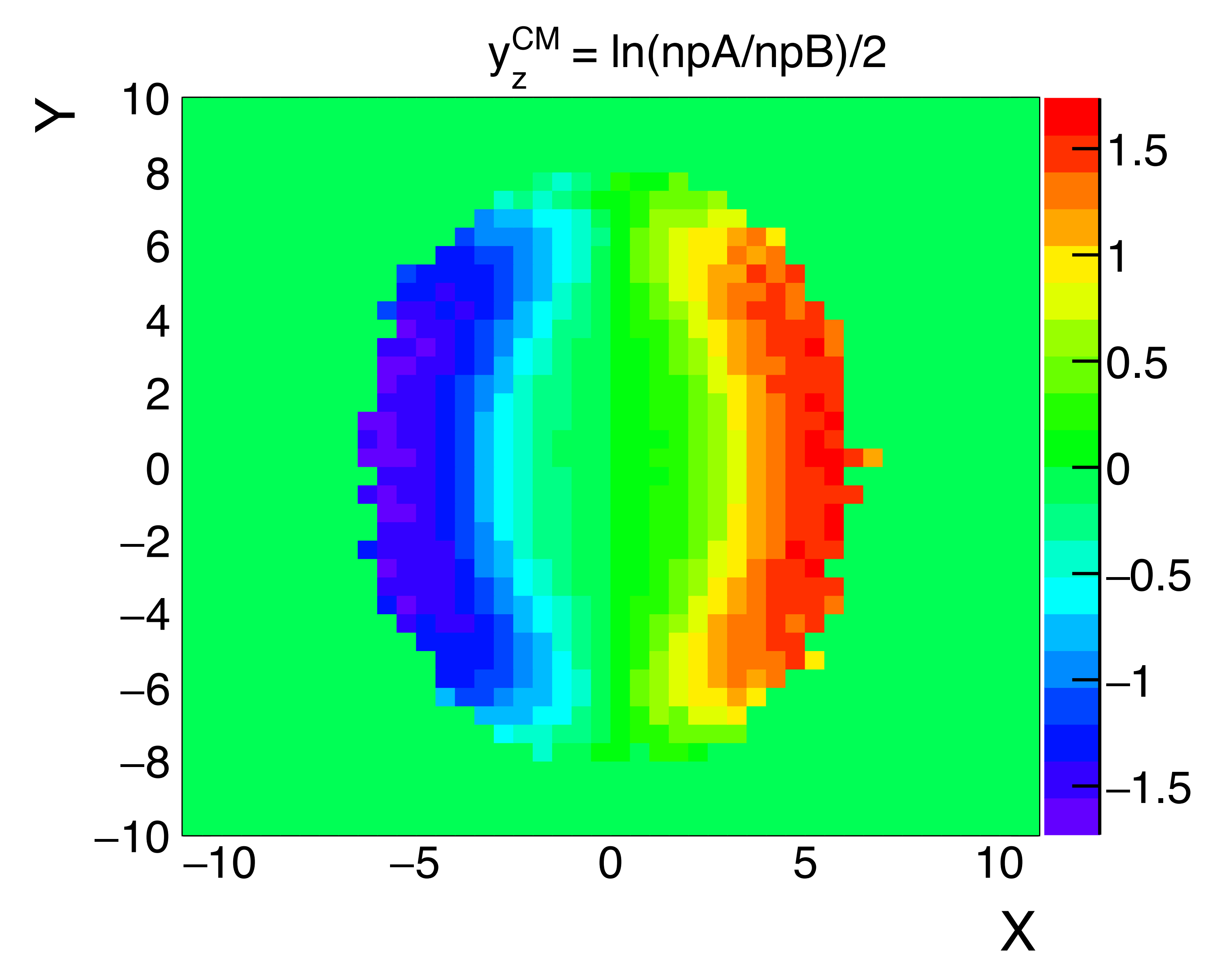
$$S_i^{(\xi)} \approx \frac{1}{4T}\frac{1}{mE}\epsilon_{ikj}p_k p_m \frac{1}{2}(\partial_j u_m + \partial_m u_j)$$

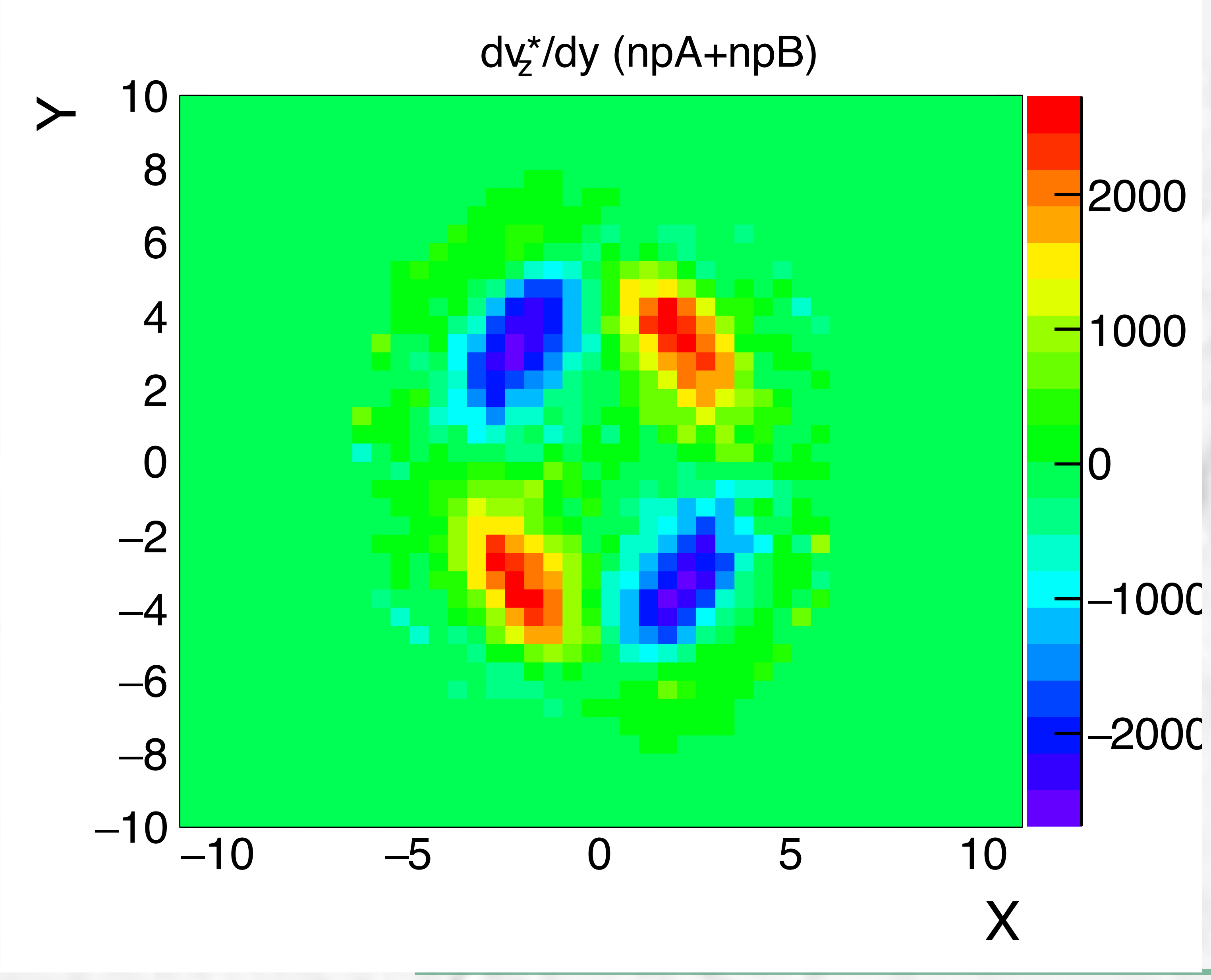
$$\propto \sin[2(\phi_h^* - \Psi_2)]$$

u_i - fluid velocity

Star denotes the value in the rest frame of fluid element

Vorticity





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

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

Wiil 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

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

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

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

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

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

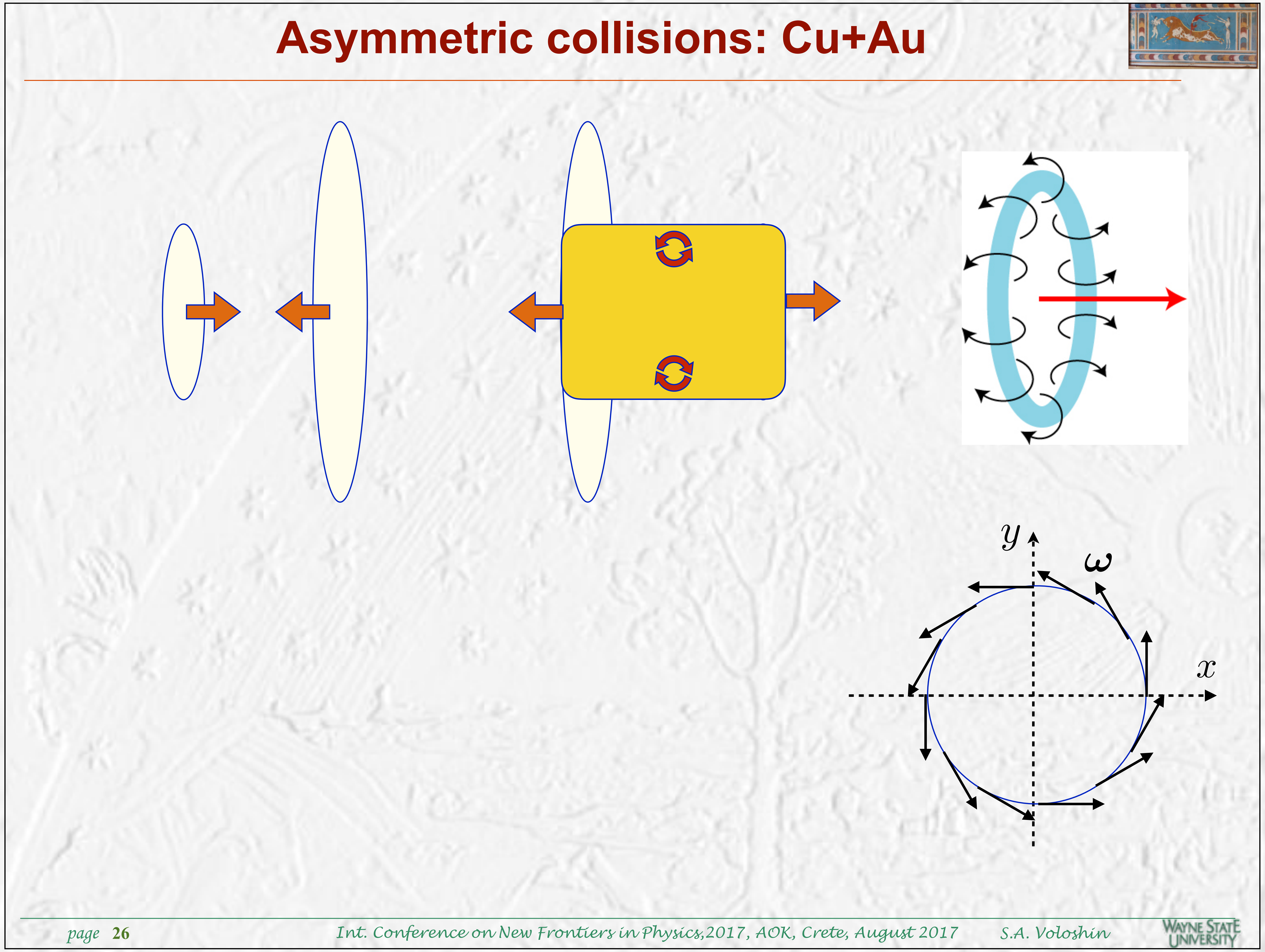
Equation (9) is to be compared with Eq. (5) under the assumption that the fluid is locally in thermodynamic equilibrium,

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

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 BW "closer" to Milekhin's prescription?

P_ϕ in asymmetric collisions



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)

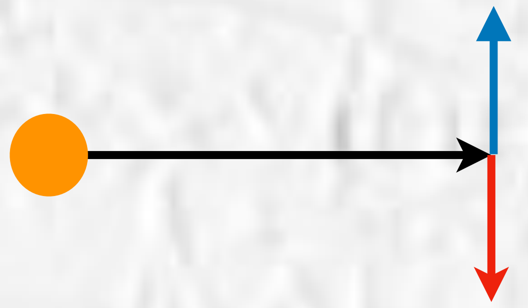
Sergei A. Voloshin[1,*]

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 3 years old Cu-Au analysis being still "in progress"

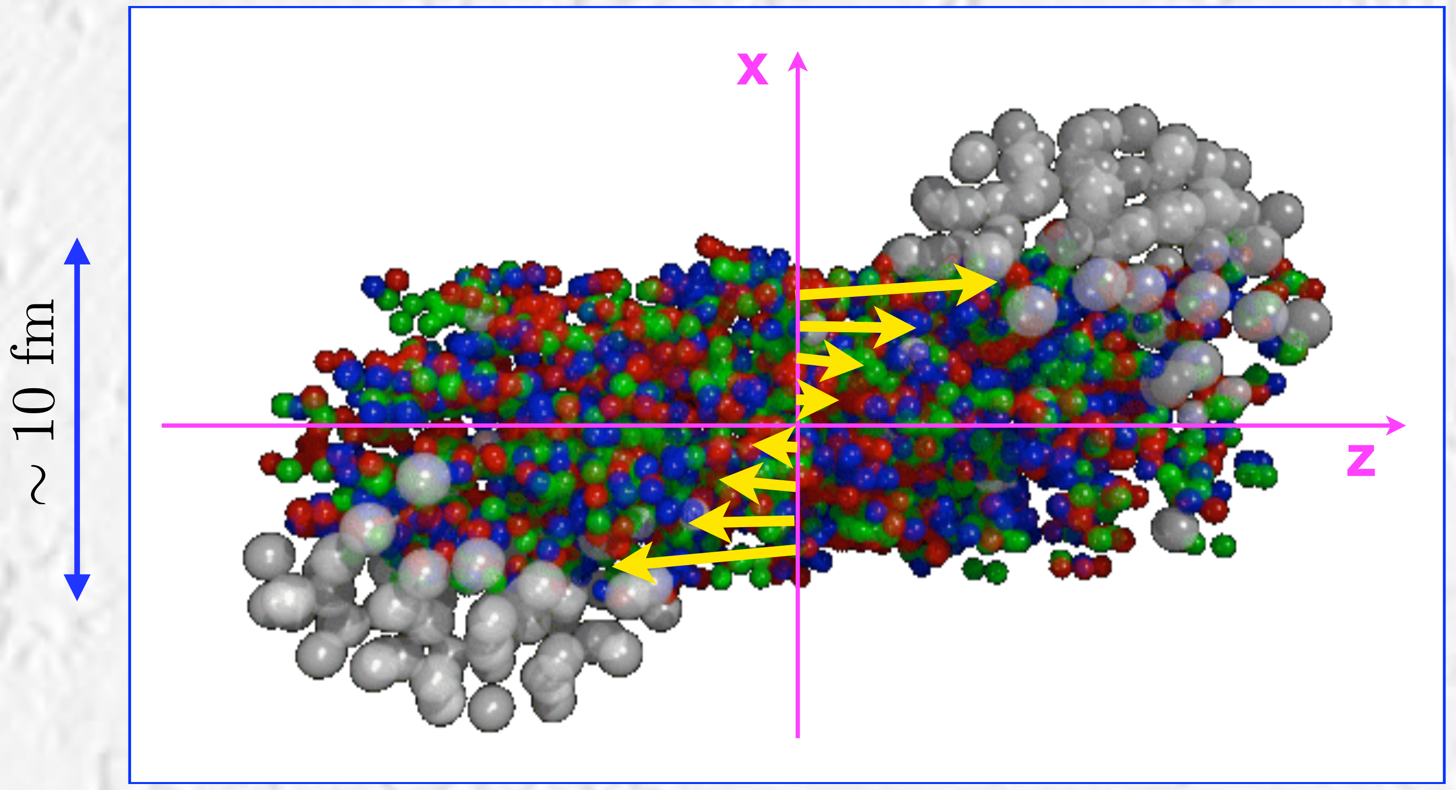
Spin alignment and elliptic flow

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

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

$\Updownarrow$

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



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

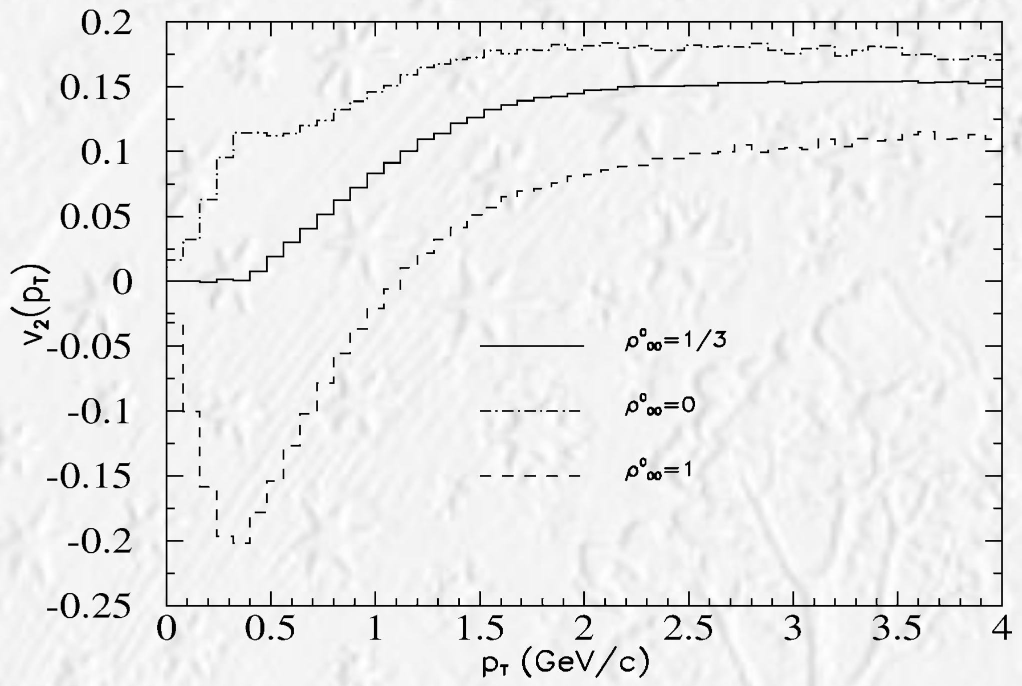


Fig. 1. Azimuthal anisotropy v_2 of pions from the decay of ρ vector mesons that have spin alignment according to Eq. (13) with $\rho^0_{00} = 1/3$ (solid line), 0 (dot-dashed line) and 1 (dashed line).

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

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

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

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

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

v2 of pions from 100% polarized rho decays is ~20%!

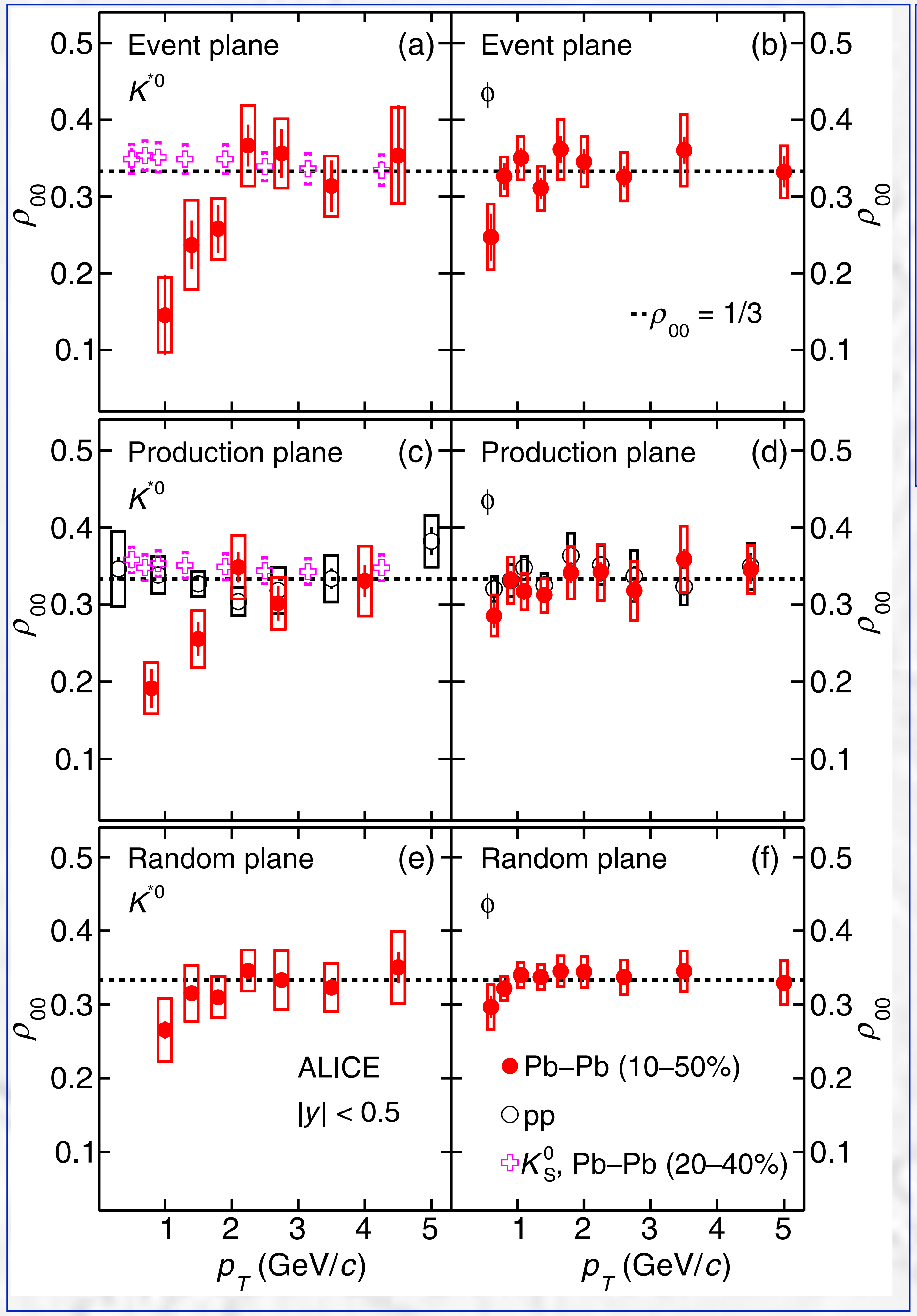
Spin-alignment: ALICE

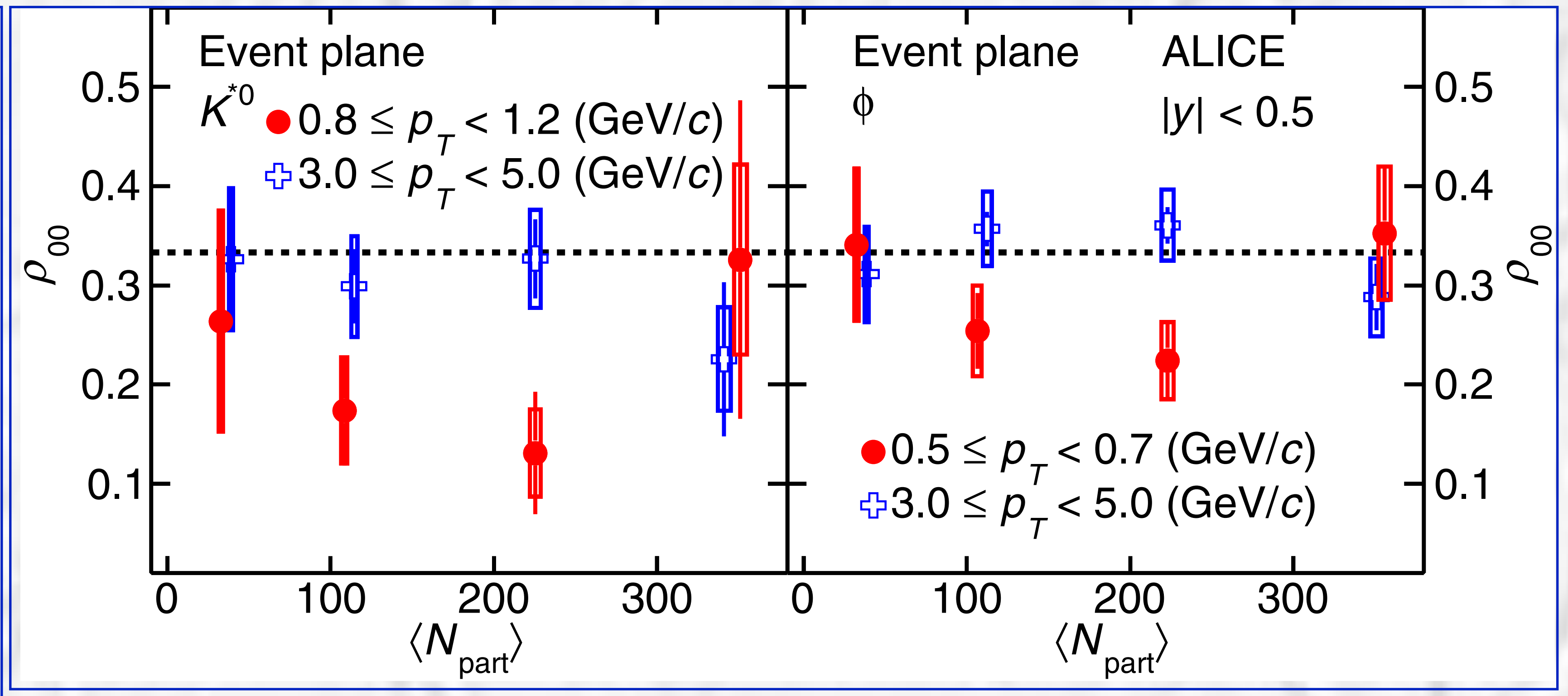
PHYSICAL REVIEW LETTERS **125,** 012301 (2020)

Editors' Suggestion

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

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





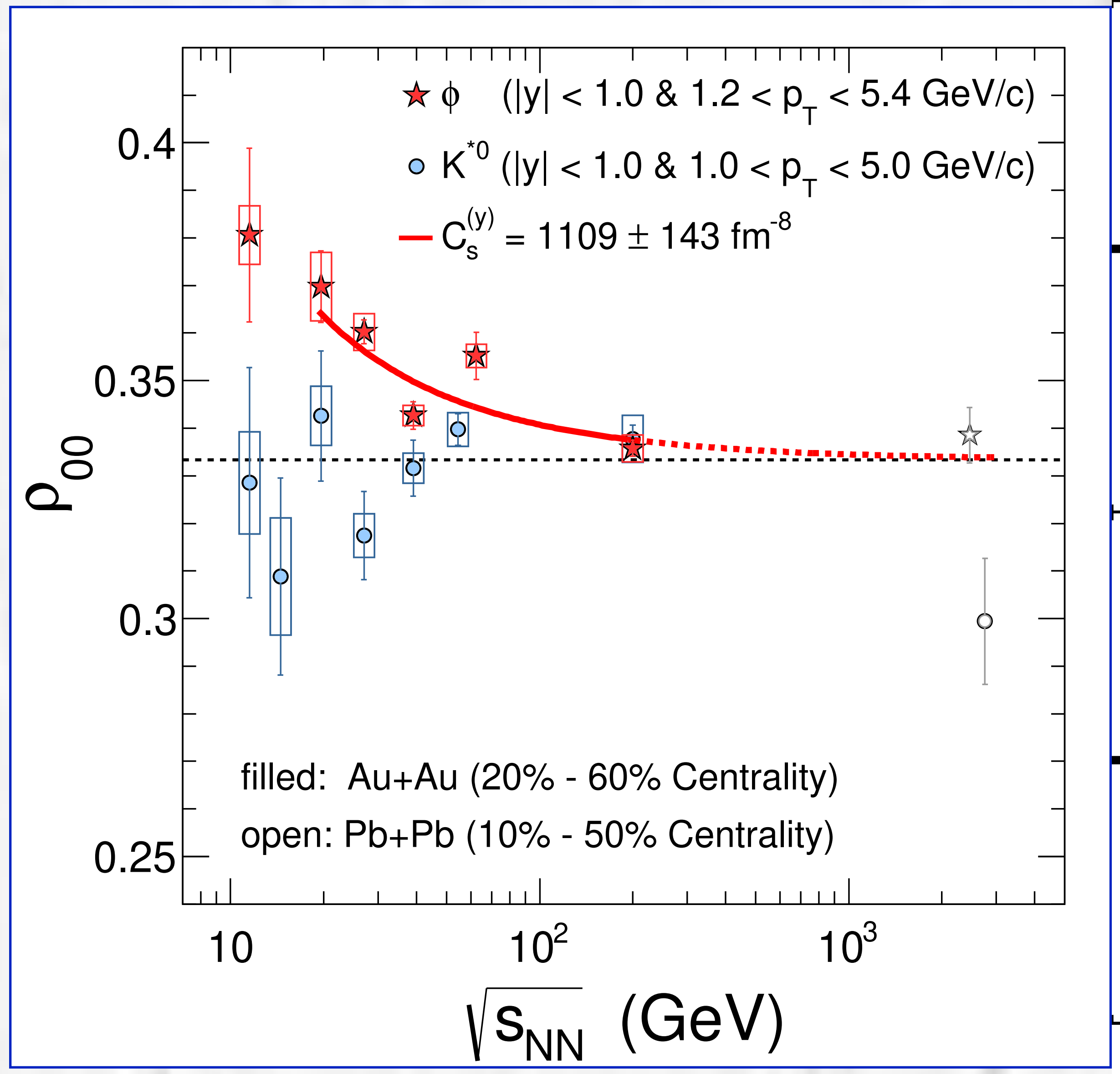
Thermal model:

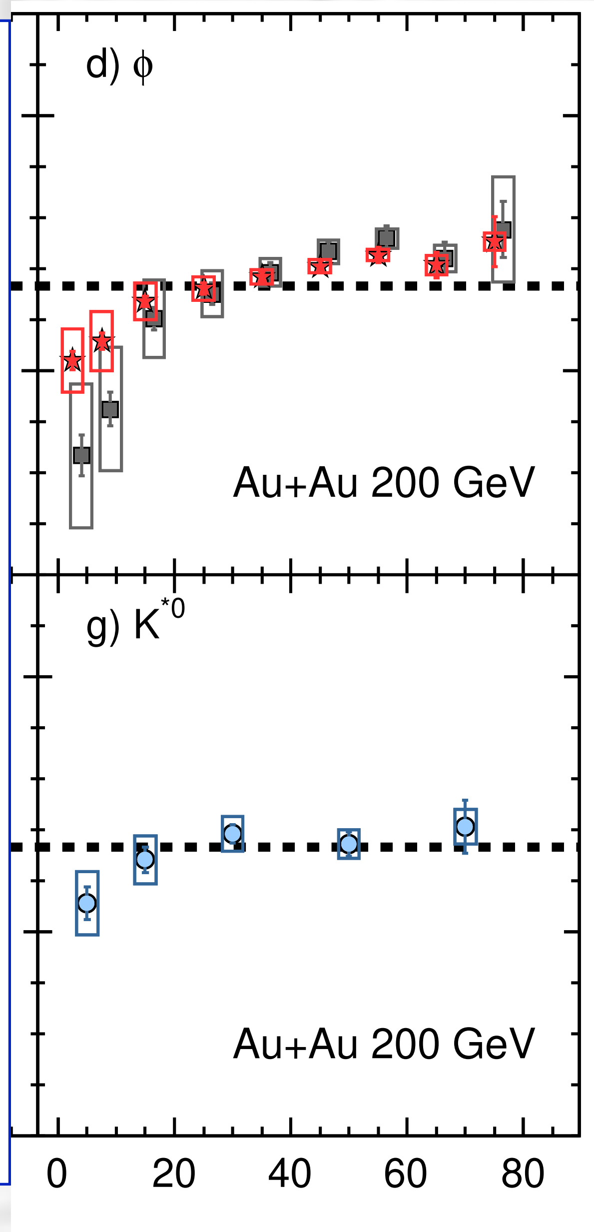
$$\rho_{00} = 0.15 \Rightarrow w(s_z = +1) = 0.82,$$
$$w(0) = 0.15, w(-1) = 0.03$$

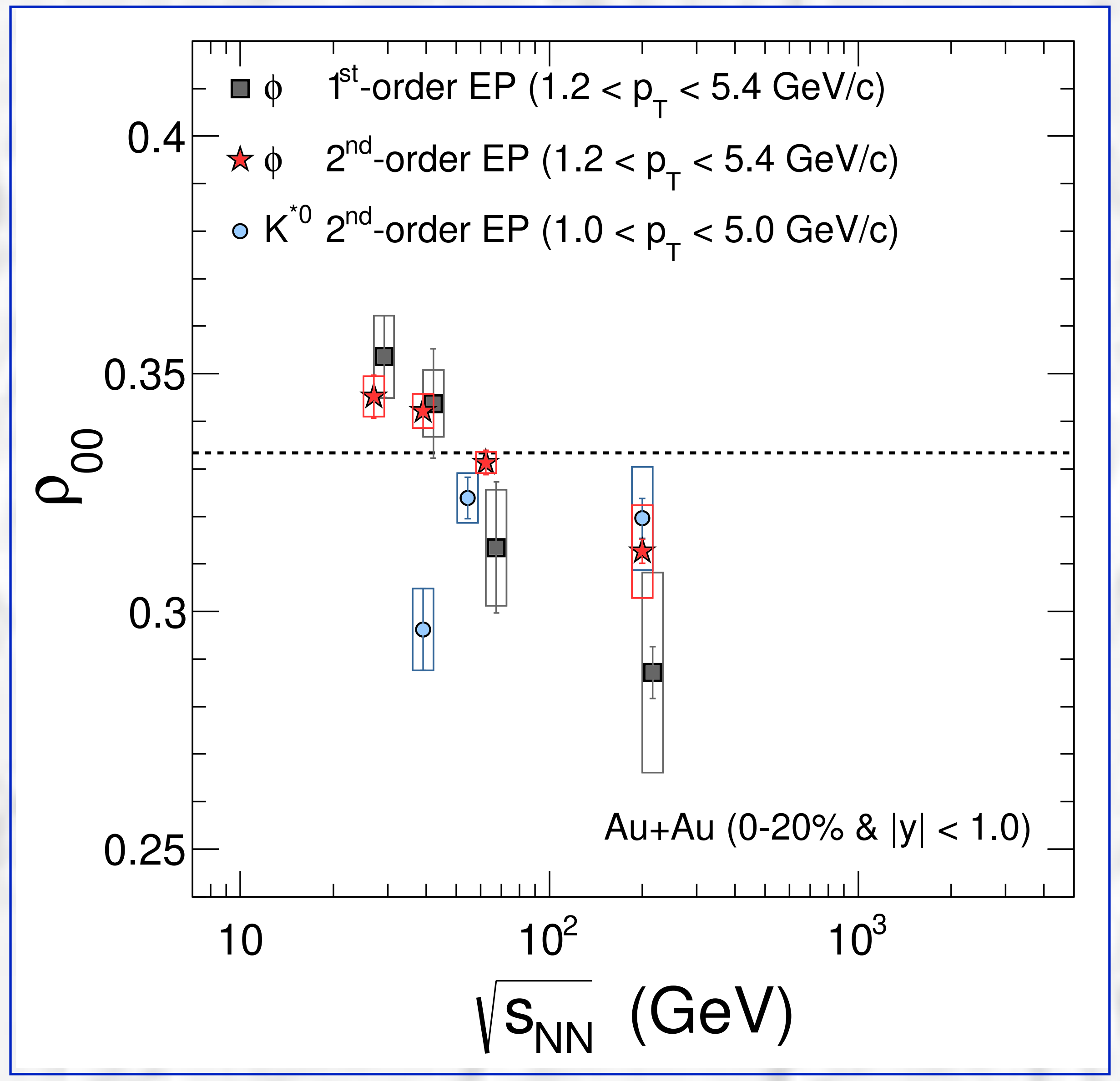
Spin-alignment: STAR

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

(STAR Collaboration)







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).

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

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)

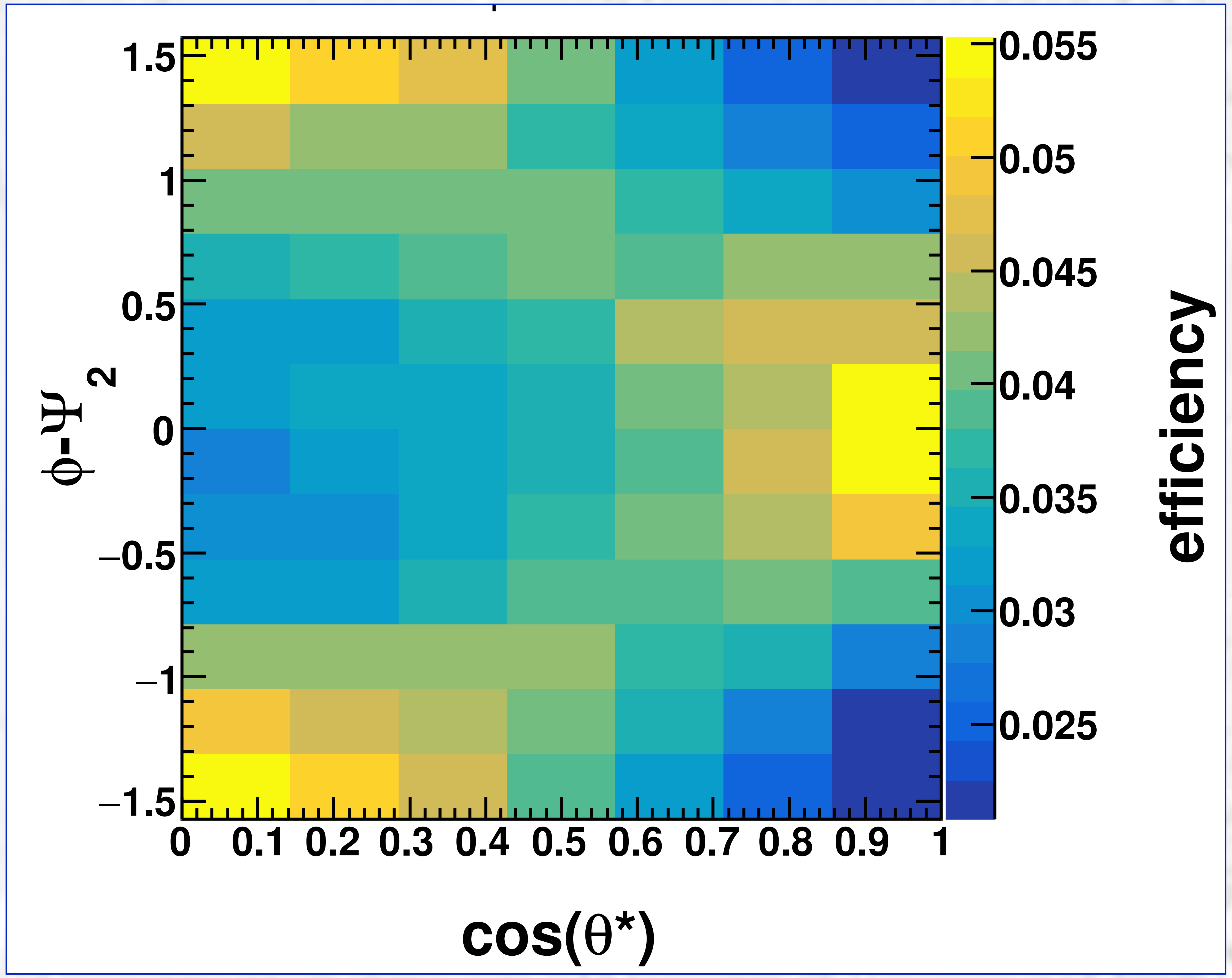
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

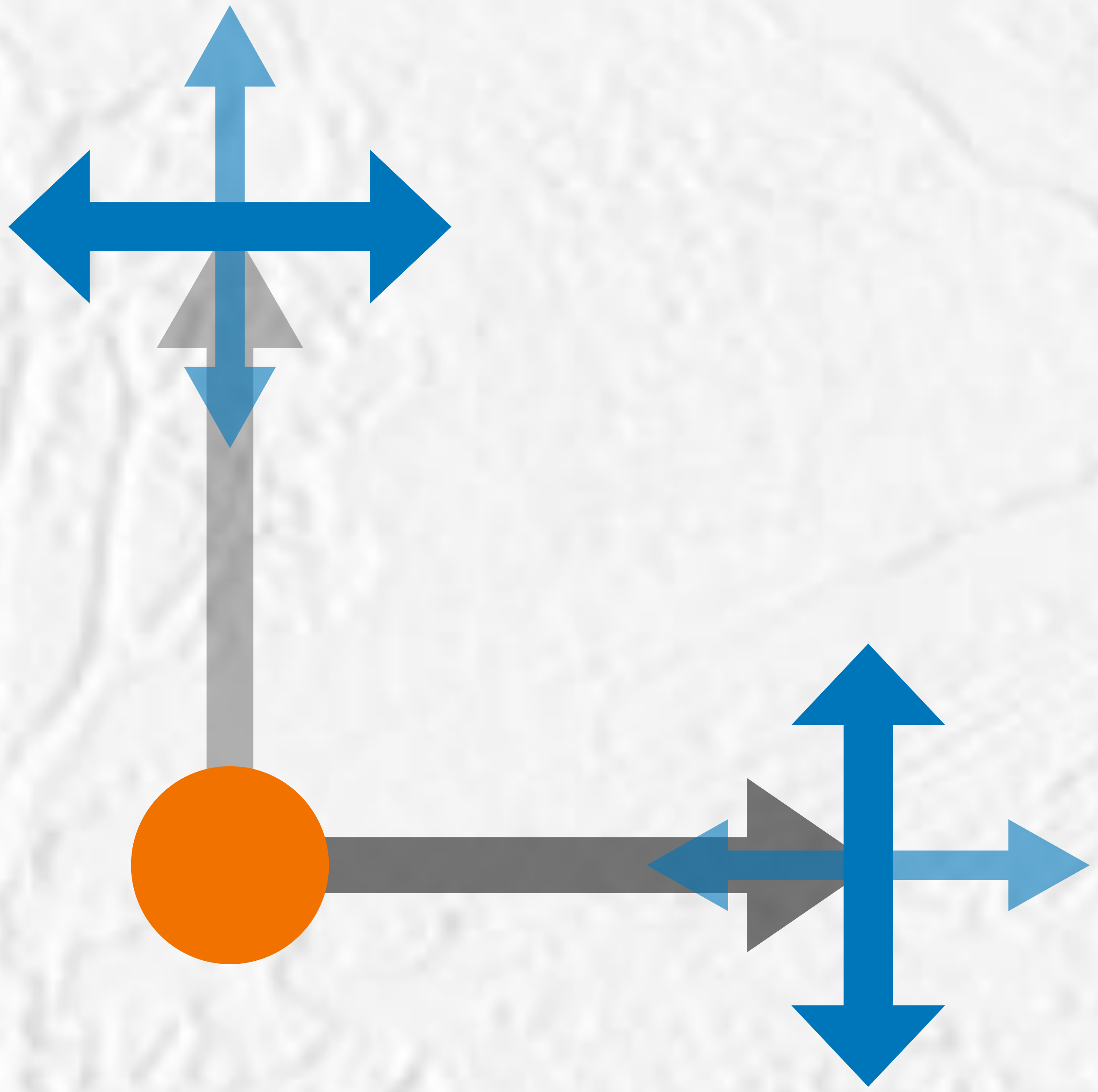
Helicity conservation and heavy resonance decays into vector mesons?

Spin alignment, elliptic flow, and efficiency

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

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

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

Summary

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, better unique, predictions for SIP, SHE, etc. are needed

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

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

New techniques are being developed,
Many new measurements appear and many will be available soon
including higher harmonics, P_x, differential P_y

EXTRA SLIDES

Spin alignment in vector meson decays

Strong decays of vector mesons in to 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 $s_z = 0$

$$\rho_{00} = \frac{1}{3} - \frac{4}{3}\langle\cos[2(\phi_p^* - \Psi_{\mathrm{RP}})]\rangle$$

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

$V \to l^+l^-$

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

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