Global and local polarization of Λ hyperons in Au+Au collisions from STAR

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Important features in non-central heavy-ion collisions

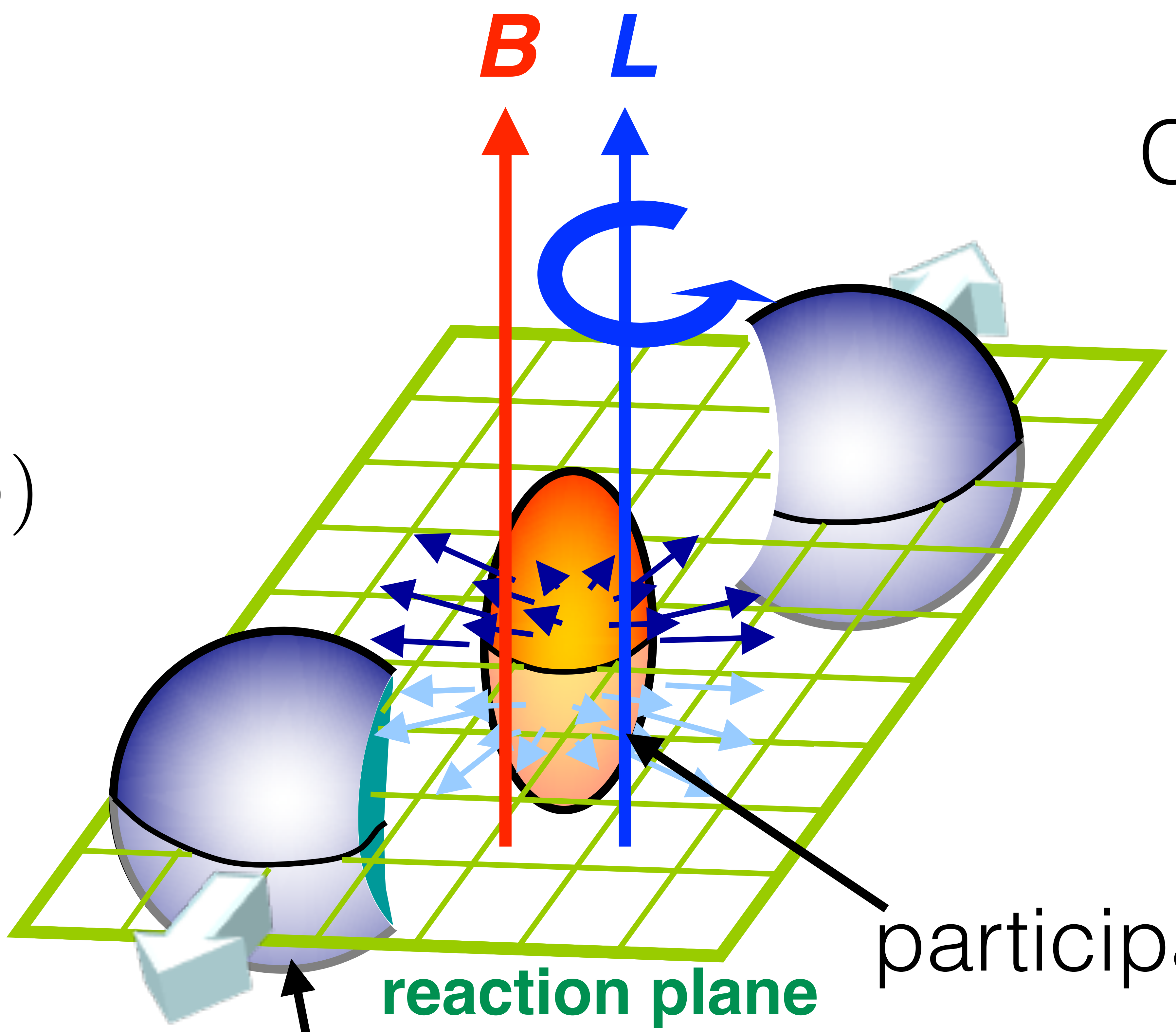
Strong magnetic field

$$B \sim 10^{13}\ \mathrm{T}$$

$$(eB \sim \mathrm{MeV}^2\ (\tau = 0.2\ \mathrm{fm}))$$

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)

→Chiral magnetic effect
Chiral magnetic wave



participants

spectators

Orbital angular momentum

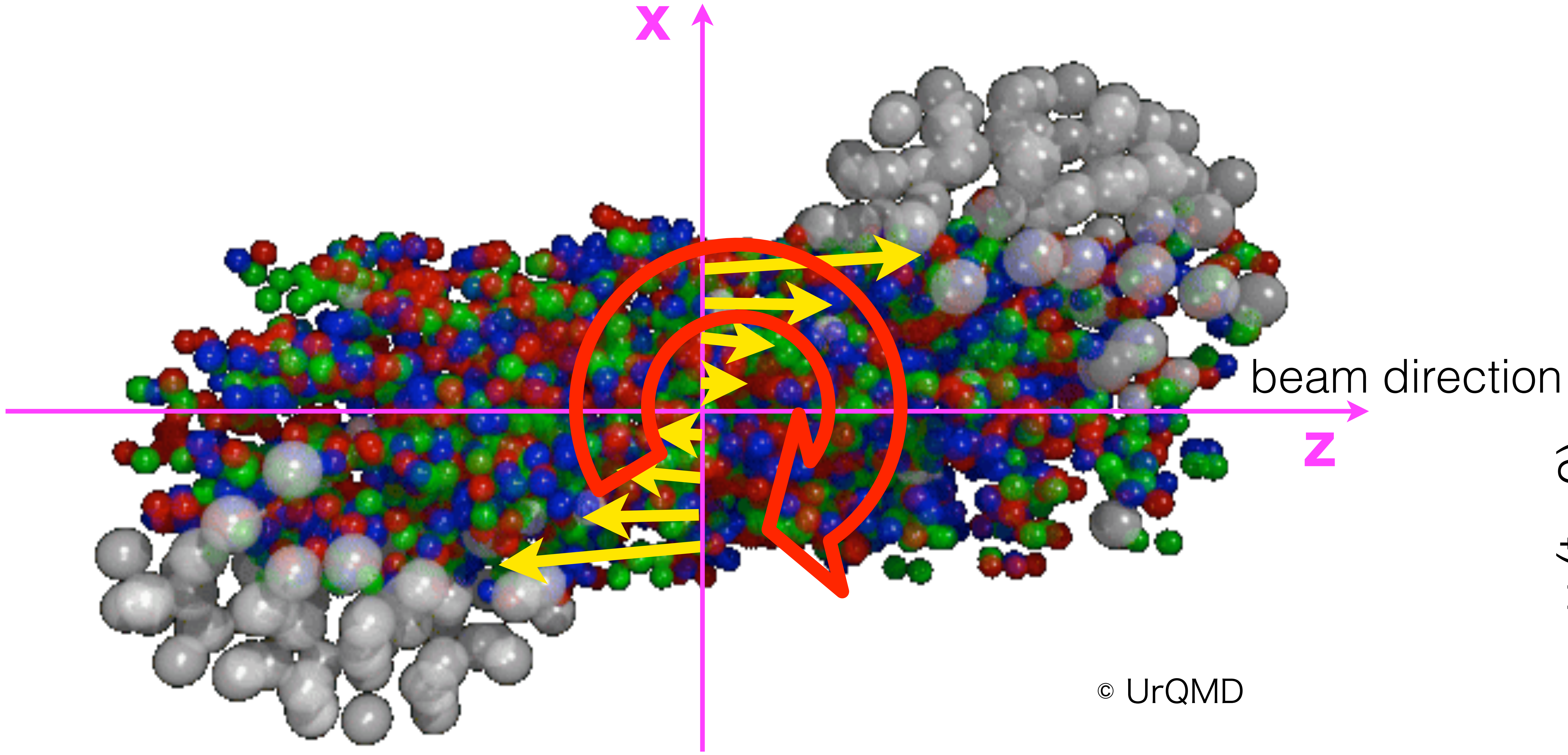
$$L \sim 10^5 \hbar$$

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

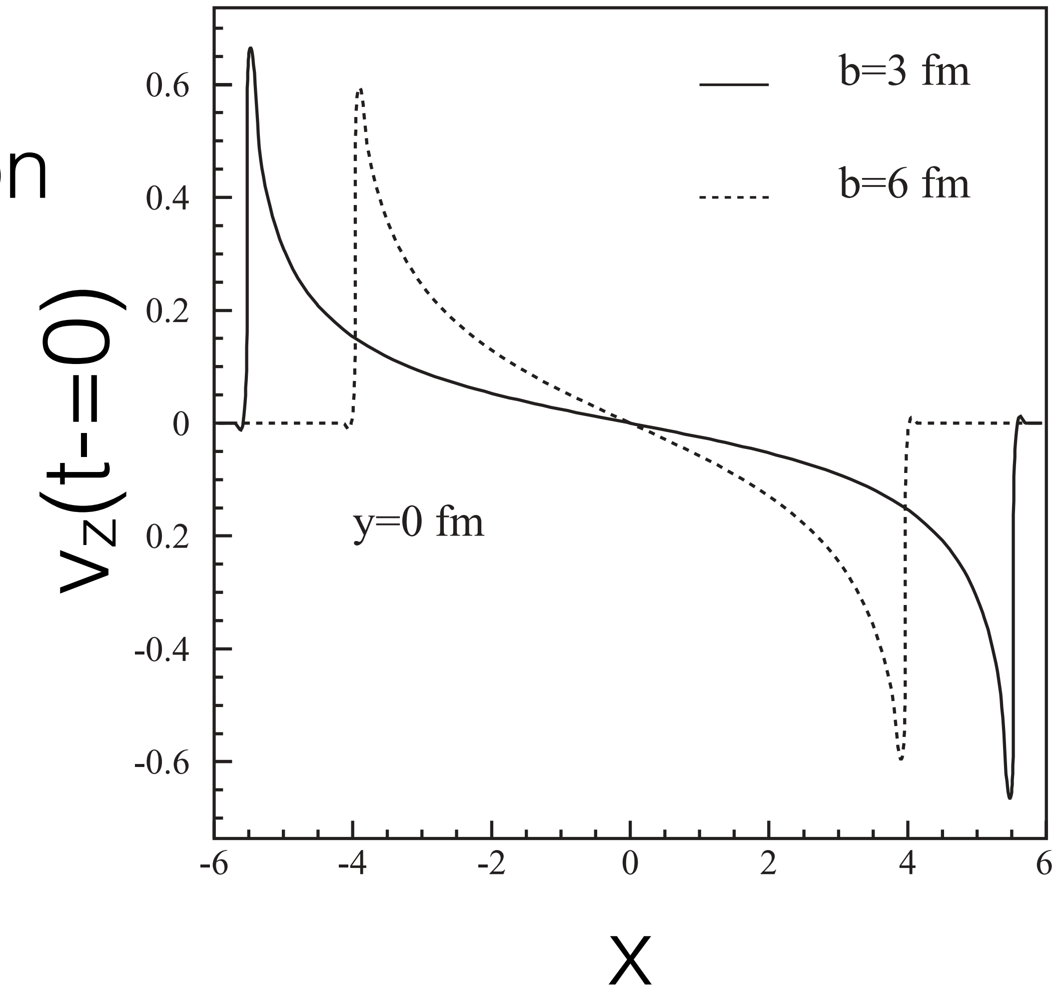
→Vorticity and particle polarization
Chiral vortical effect

Vorticity in HIC

impact parameter



Becattini et al.,
PRC77, 024906 (2008)

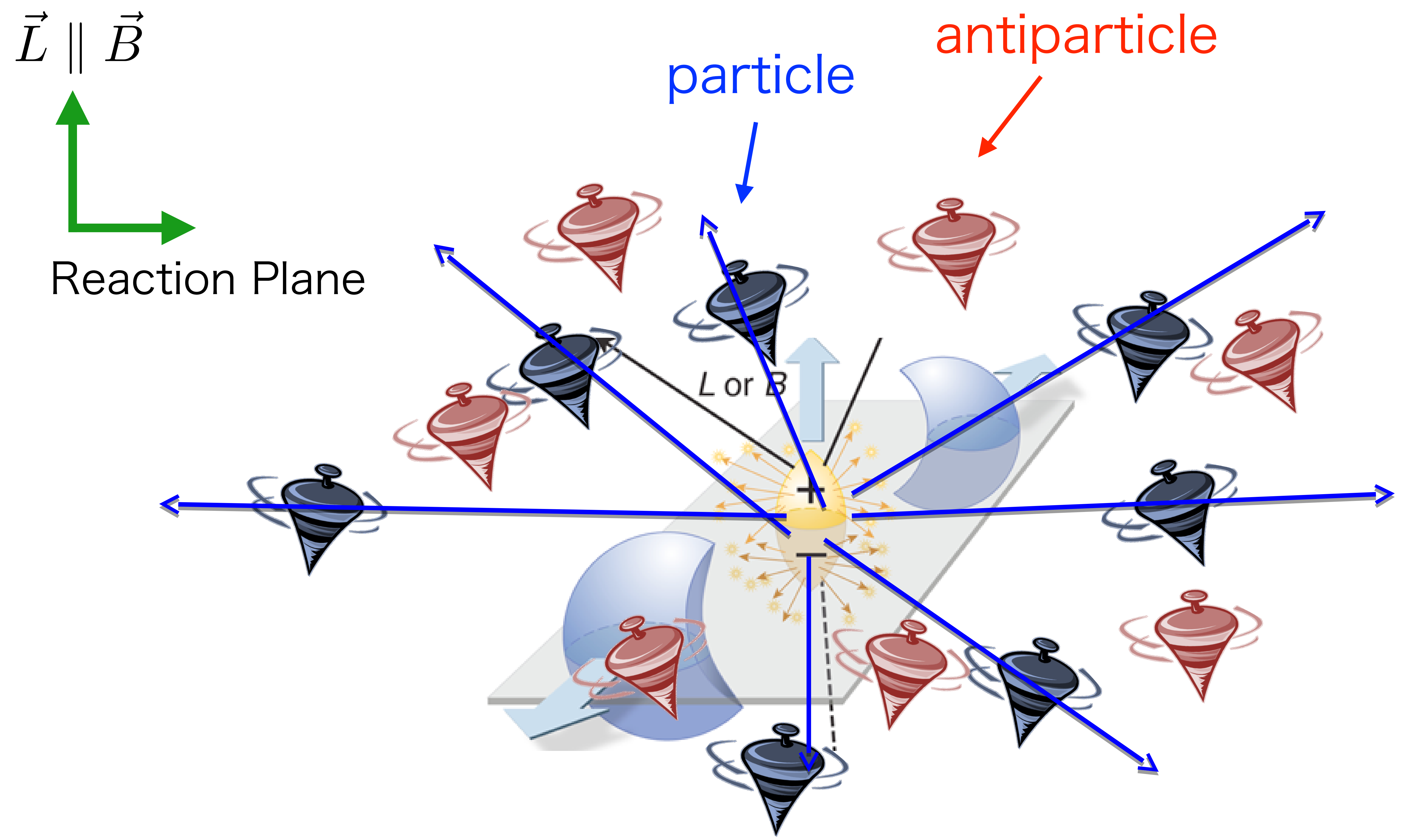


In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

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

Global polarization

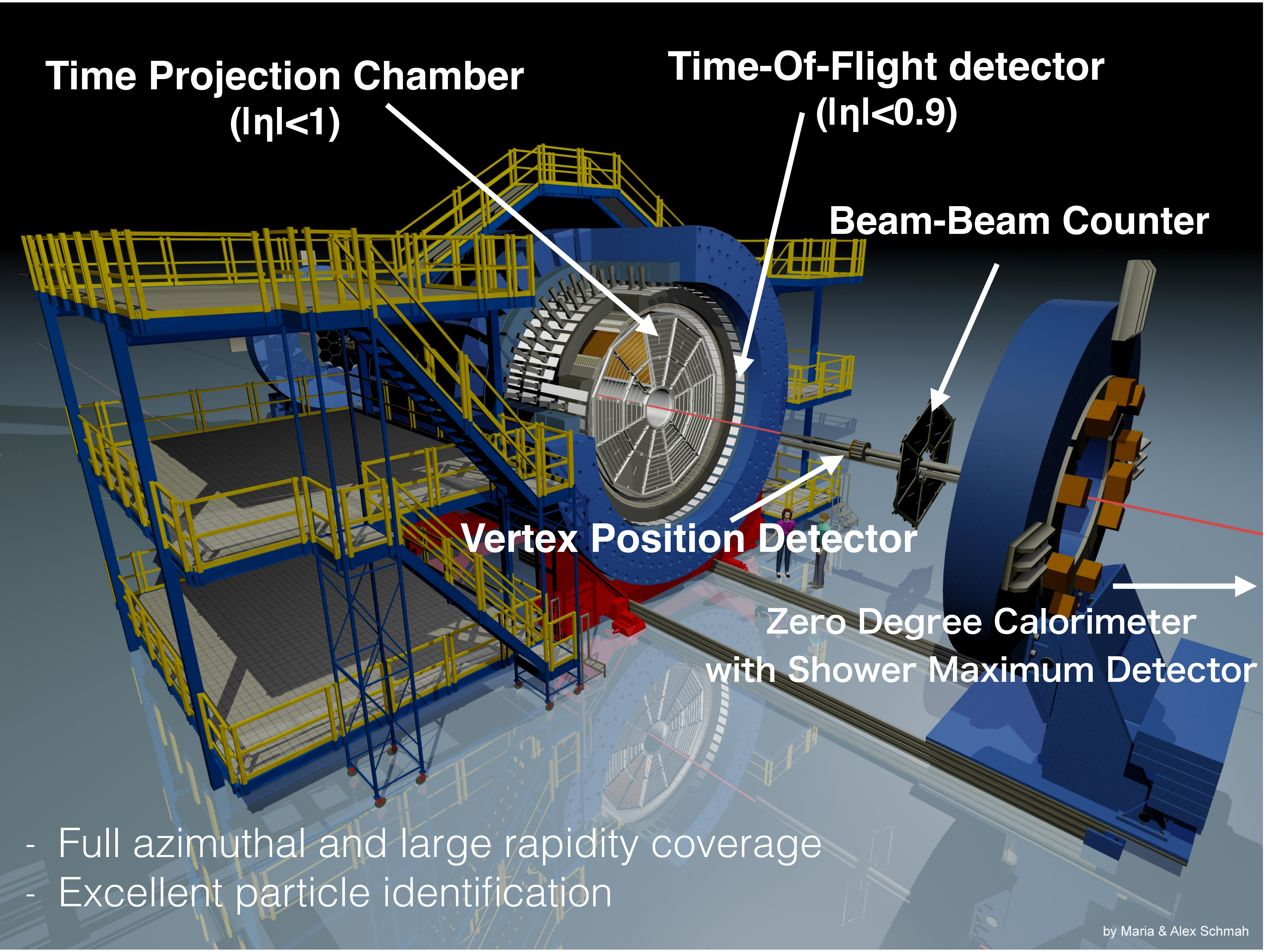
- Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
- S. Voloshin, nucl-th/0410089 (2004)



- Non-zero angular momentum transfers to the spin degrees of freedom (polarization)
    - Particles' and anti-particles' spins are aligned with angular momentum ***L***

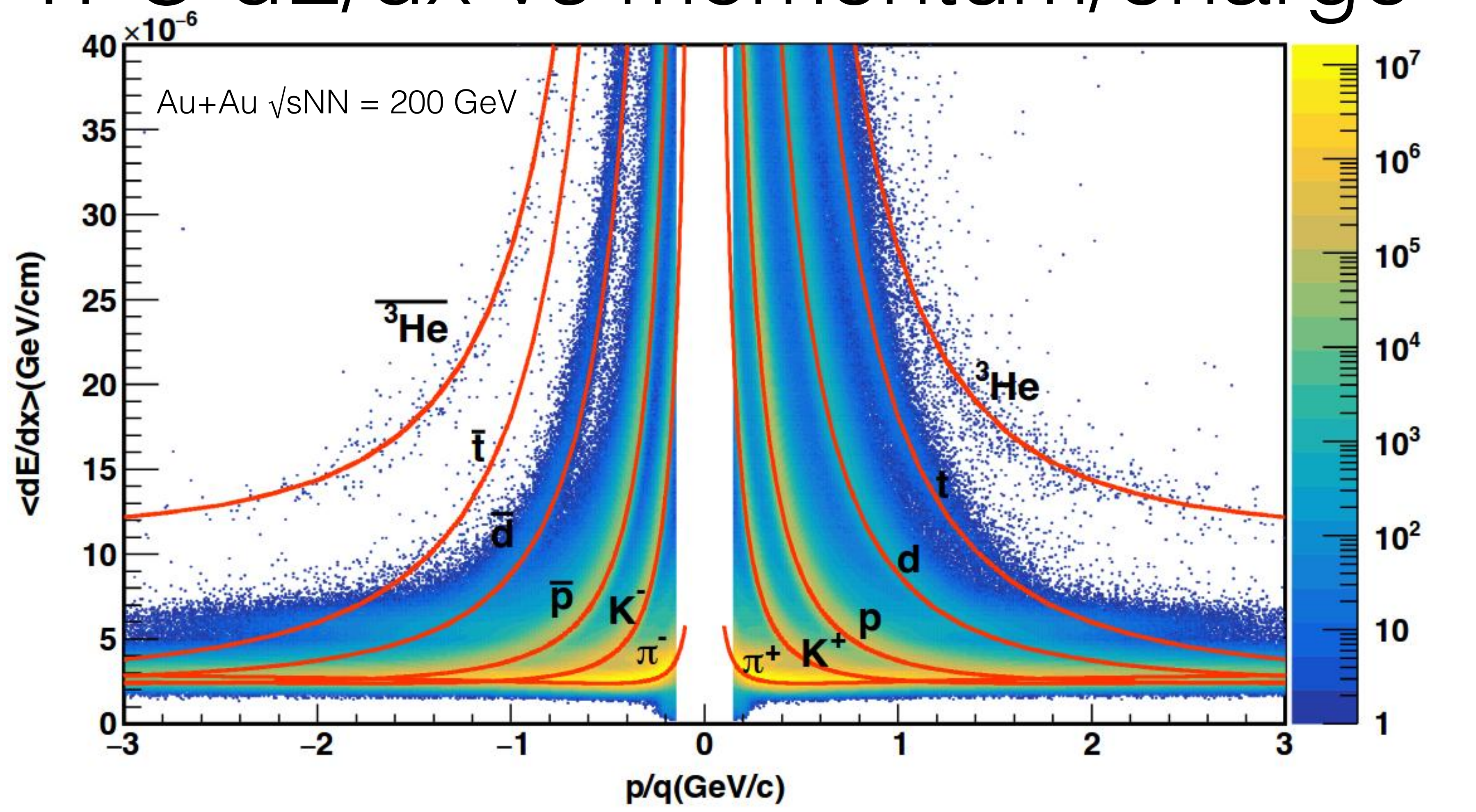
- Magnetic field align particle's spin
    - Particles' and antiparticles' spins are aligned oppositely along ***B*** due to the opposite sign of magnetic moment

STAR Detectors

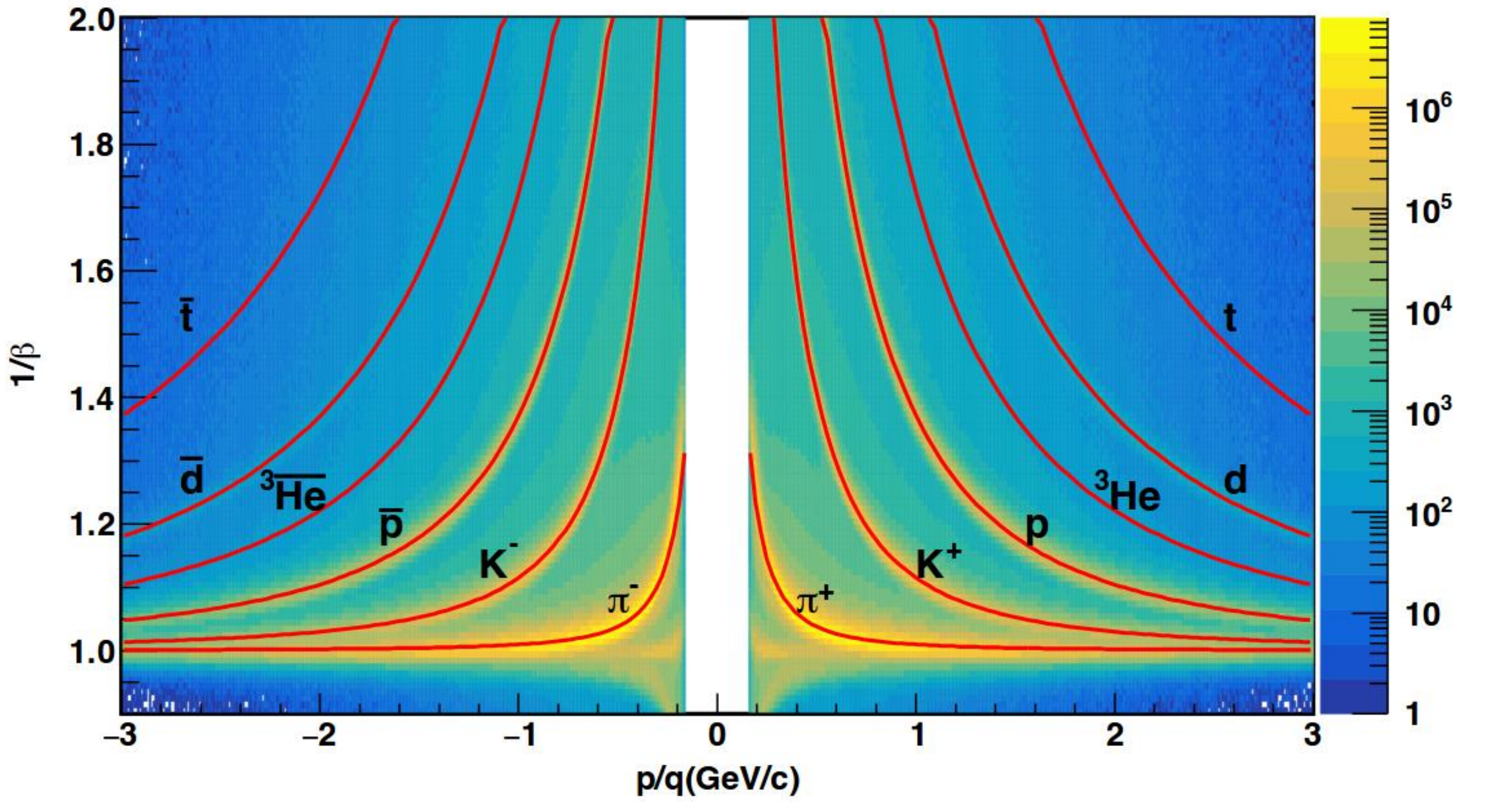


- Full azimuthal and large rapidity coverage
- Excellent particle identification

TPC dE/dx vs momentum/charge



TOF 1/β vs momentum/charge



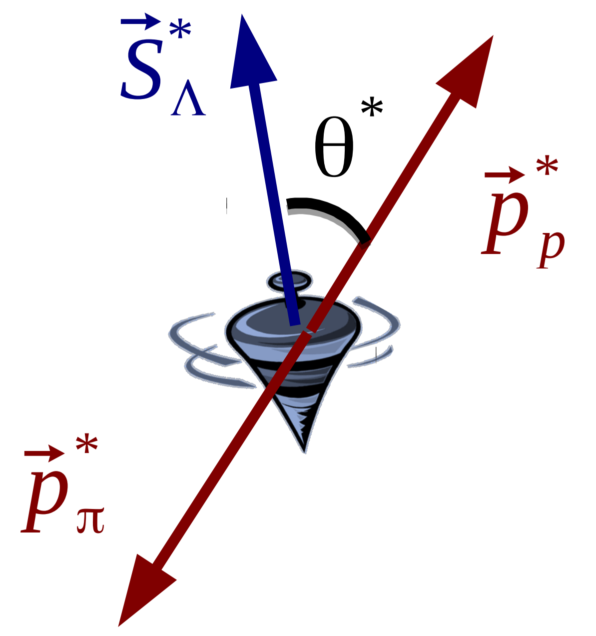
How to measure the polarization?

Parity-violating decay of hyperons

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P}_{\rm H} \cdot \mathbf{p}_{\mathbf{p}}^*)$$

P_H: Λ polarization
p_p^*: proton momentum in the Λ rest frame
α_H: Λ decay parameter
($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$)



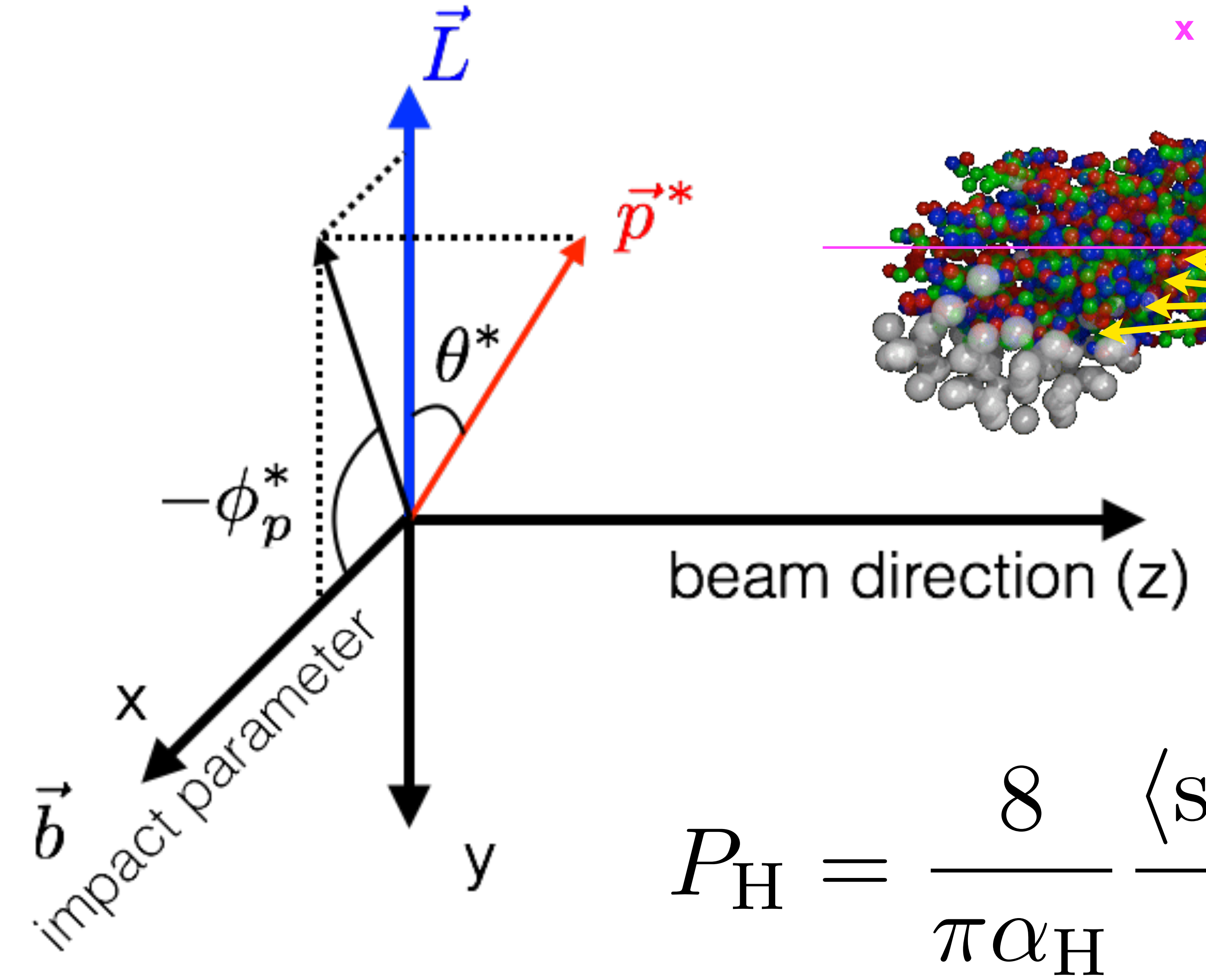
$$\Lambda \rightarrow p + \pi^-$$

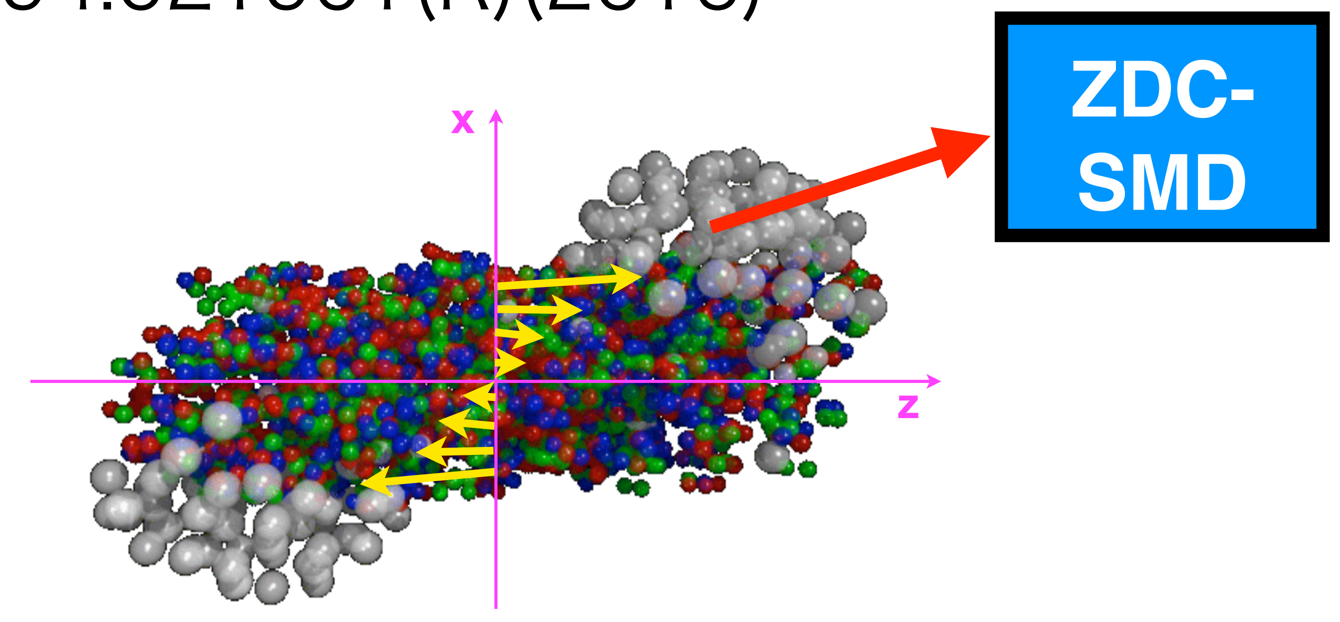
(BR: 63.9%, cτ ~7.9 cm)

C. Patrignani et al. (PDG), Chin. Phys. C 40, 100001 (2016)

Projection onto the transverse plane

Angular momentum direction can be determined by spectator deflection (spectators deflect outwards)
- S. Voloshin and TN, PRC94.021901(R)(2016)

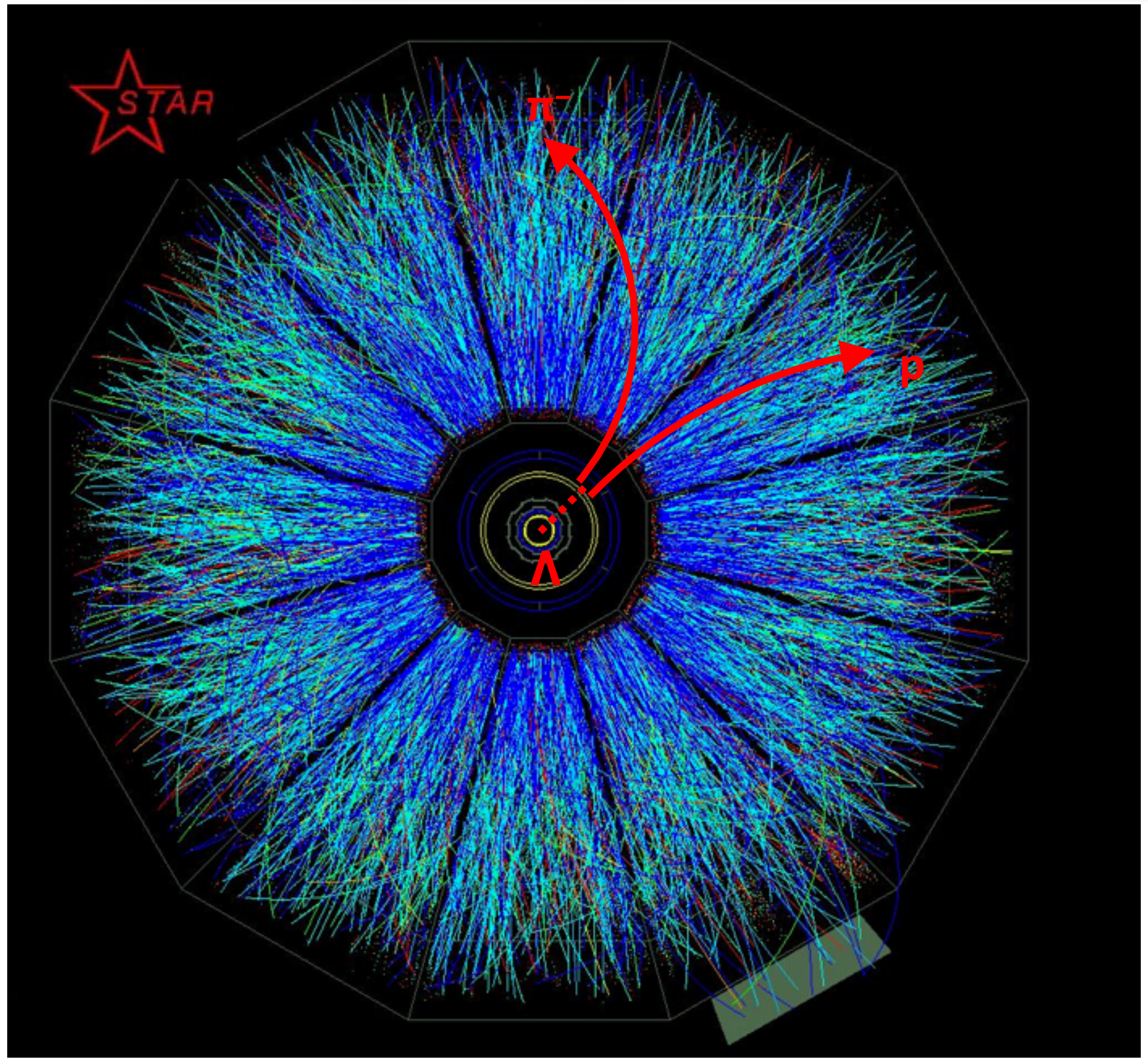


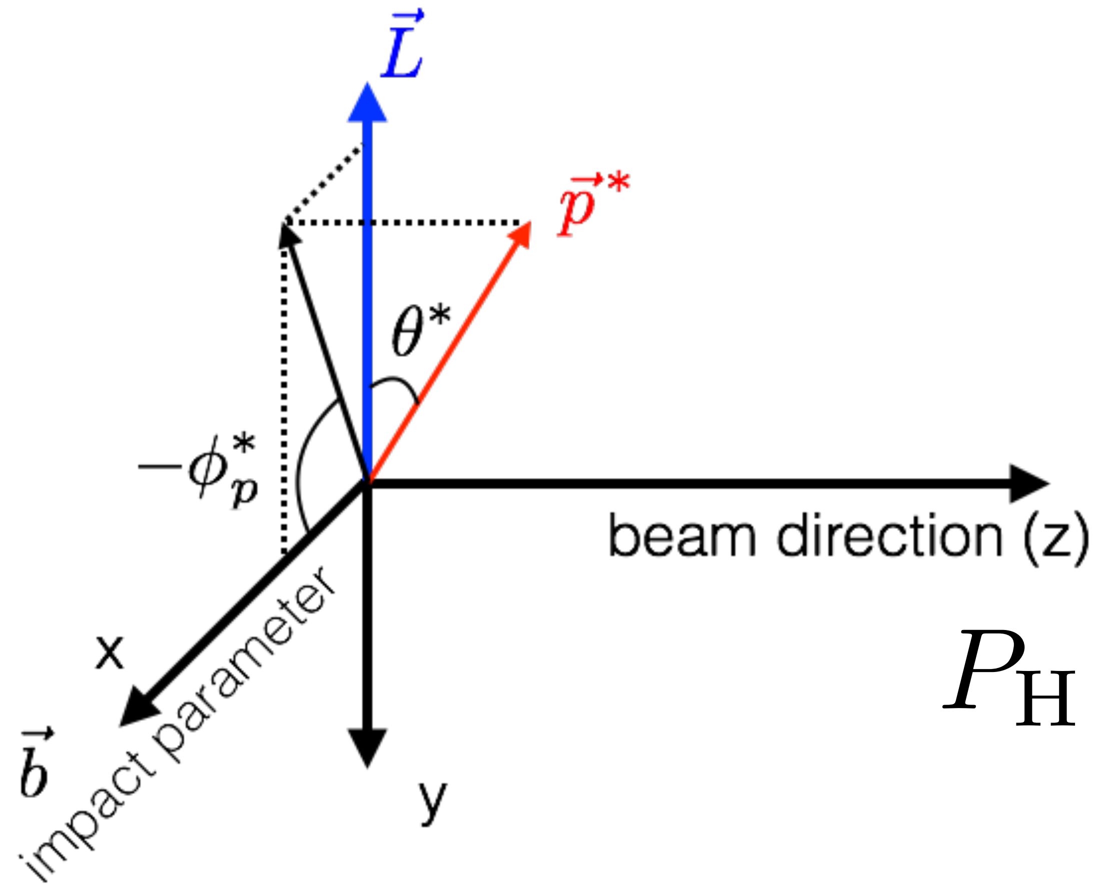


$$P_{\rm H} = \frac{8}{\pi\alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi^*_p)\rangle}{{\rm Res}(\Psi_1)}$$

Ψ_1: azimuthal angle of b
ϕ_p^*: ϕ of daughter proton in Λ rest frame
STAR, PRC76, 024915 (2007)

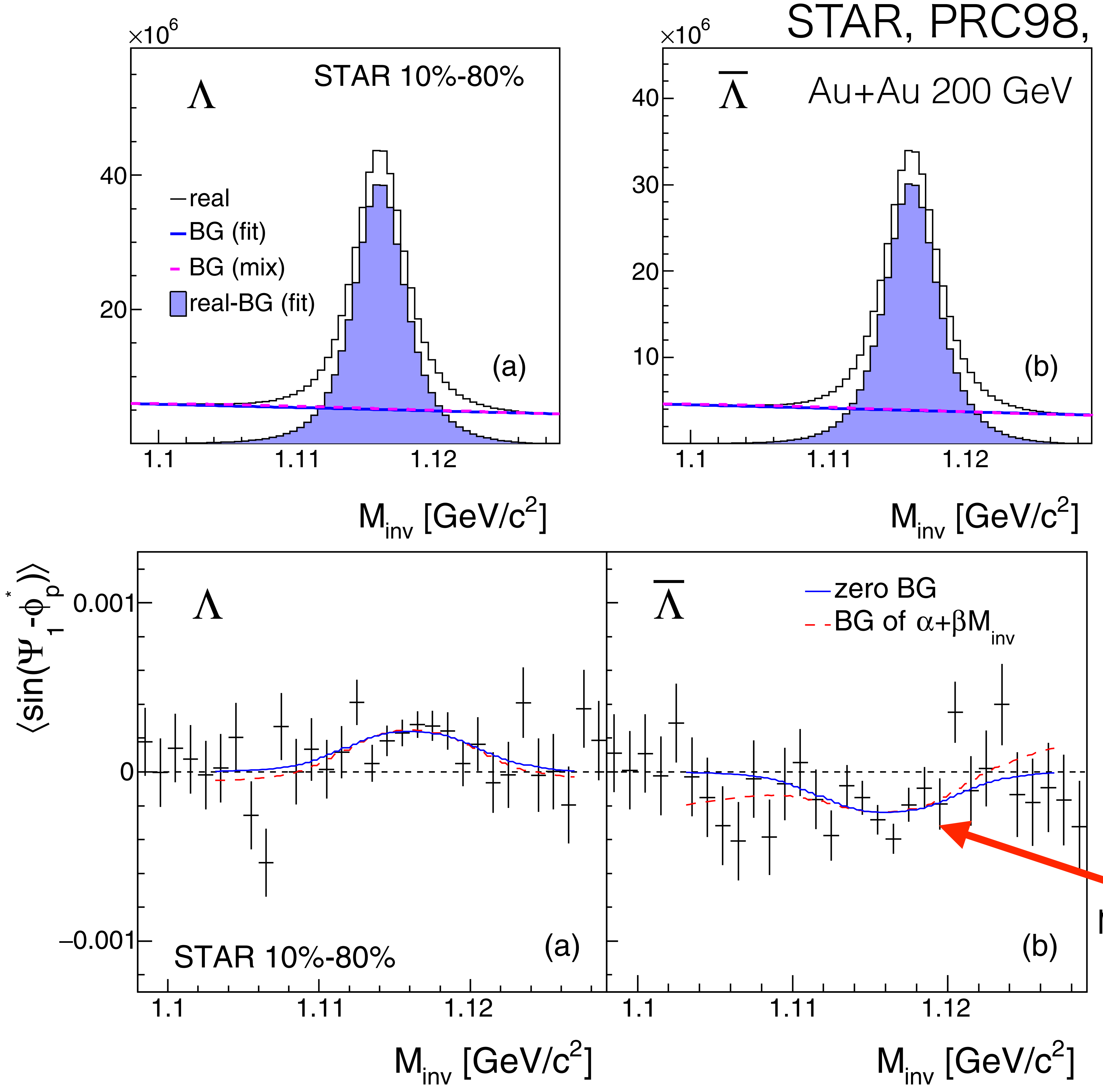
Signal extraction with Λ hyperons





$$P_{\mathrm{H}} = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

STAR, PRC98, 014910 (2018)

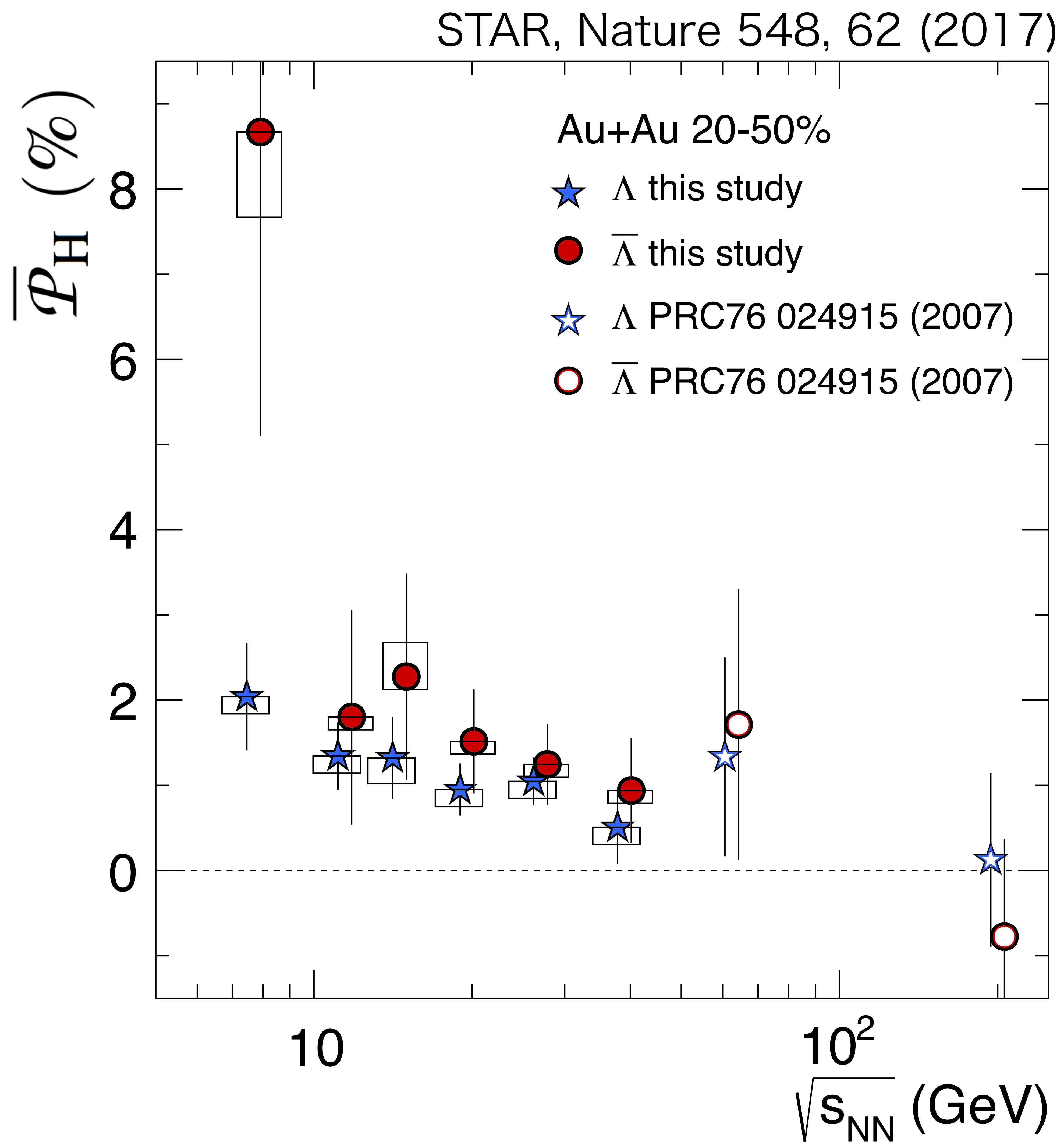


negative for anti-Λ

$$\alpha_H = -\alpha_{\bar{H}}$$

$$\langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{obs}} = (1 - f^{\mathrm{Bg}}(M_{\mathrm{inv}})) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{Sg}} + f^{\mathrm{Bg}}(M_{\mathrm{inv}}) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{Bg}},$$

First observation of fluid vortices in HIC



#38

The Fastest Fluid

by Sylvia Morrow

Superhot material spins at an incredible rate.

Positive polarization signal at lower energies!

- polarization looks to increase in lower energies
- anti-Λ is systematically larger than Λ

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

μΛ: Λ magnetic moment

T: temperature at thermal equilibrium

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

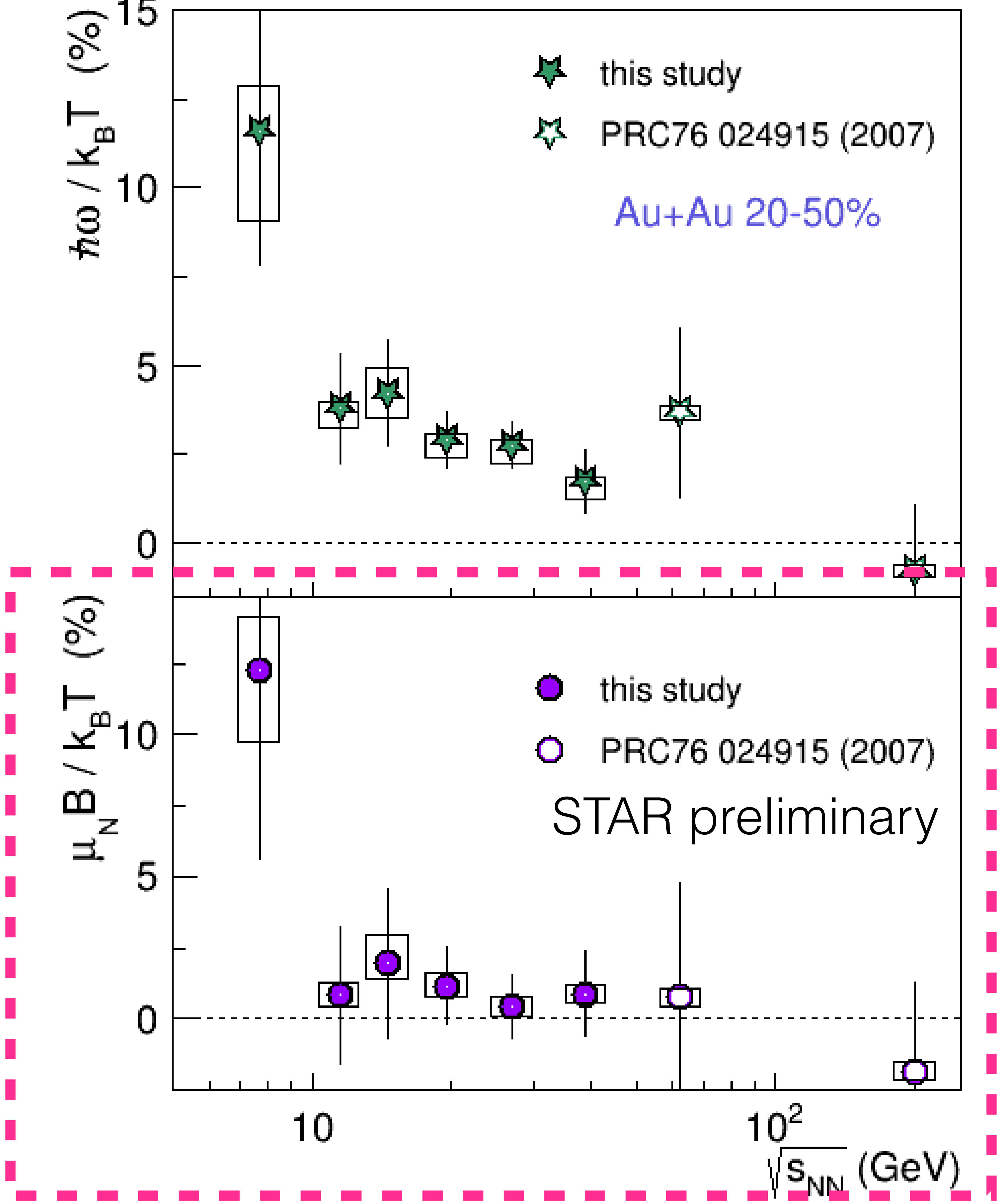
$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar$$
$$\sim 0.02\text{-}0.09 \text{ fm}^{-1}$$
$$\sim 0.6\text{-}2.7 \times 10^{22} \text{s}^{-1}$$

(T=160 MeV)

The most vortical fluid ever observed!

Possible probe of magnetic field

QM17, I. Upsal (STAR)



Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

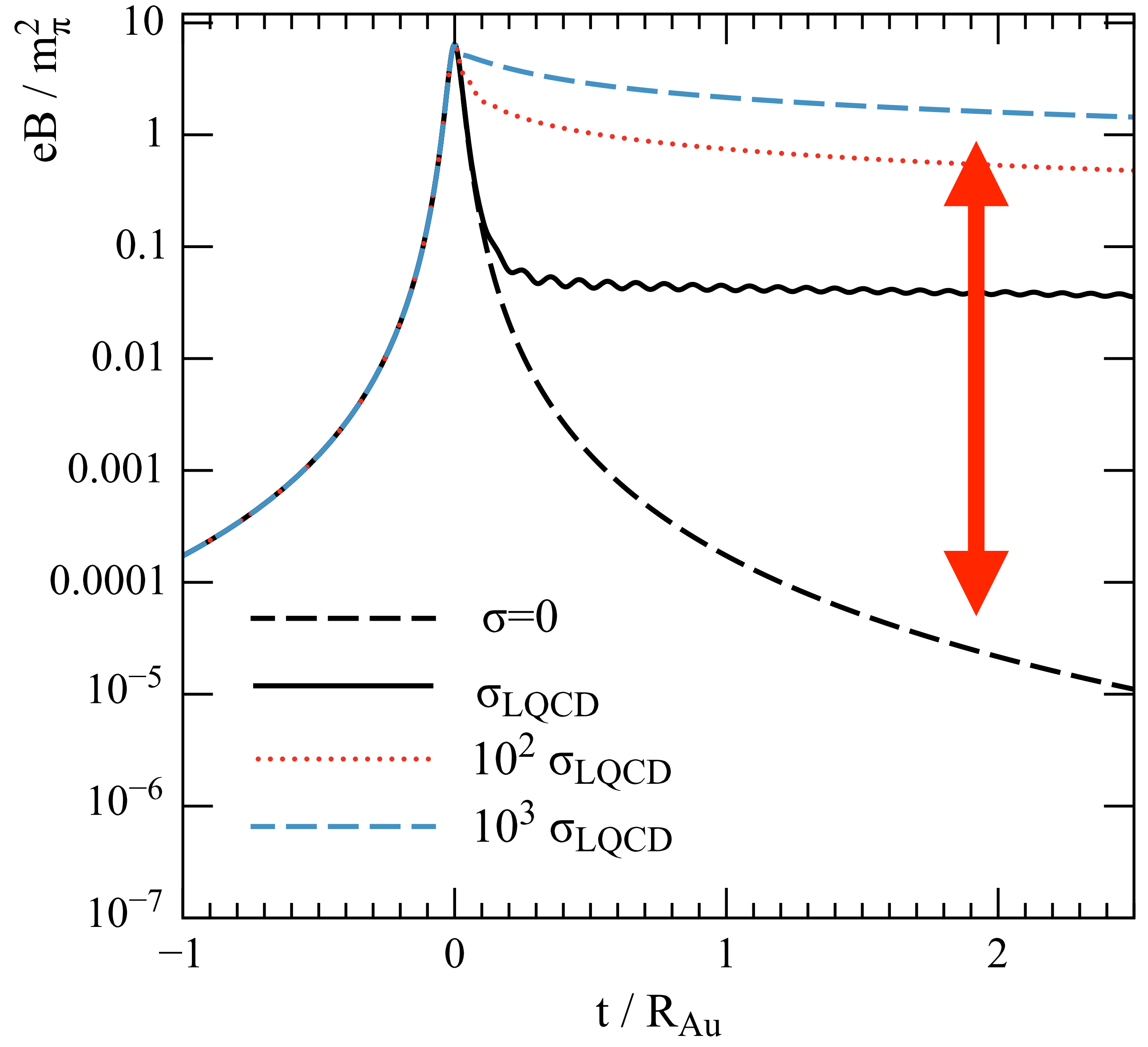
μ_Λ: Λ magnetic moment

$$B = (P_\Lambda - P_{\bar{\Lambda}}) k_B T / \mu_N$$

$$\sim 5.0 \times 10^{13} \ [\text{Tesla}]$$

nuclear magneton $\mu_N = -0.613\mu_\Lambda$

McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



conductivity increases lifetime (not magnitude)

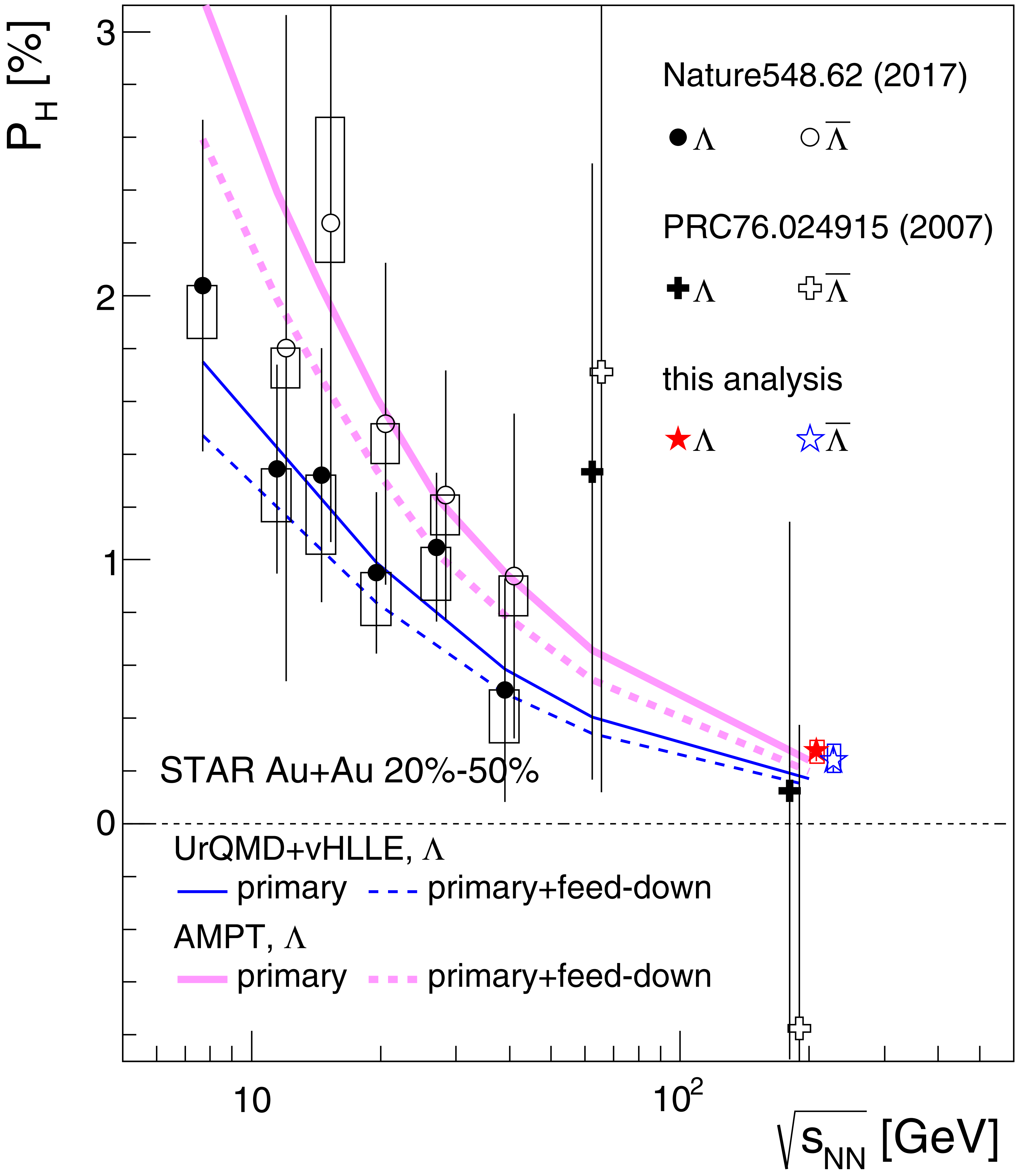
$$B \sim 10^{13}\ \text{T}$$

$$(eB \sim \text{MeV}^2\ (\tau = 0.2\ \text{fm}))$$

Extracted B-field is close to our expectation.
Need more data with better precision
→BES-II and Isobaric collisions

Positive signal at $\sqrt{s_{NN}}$ = 200 GeV

STAR, PRC98, 014910 (2018)



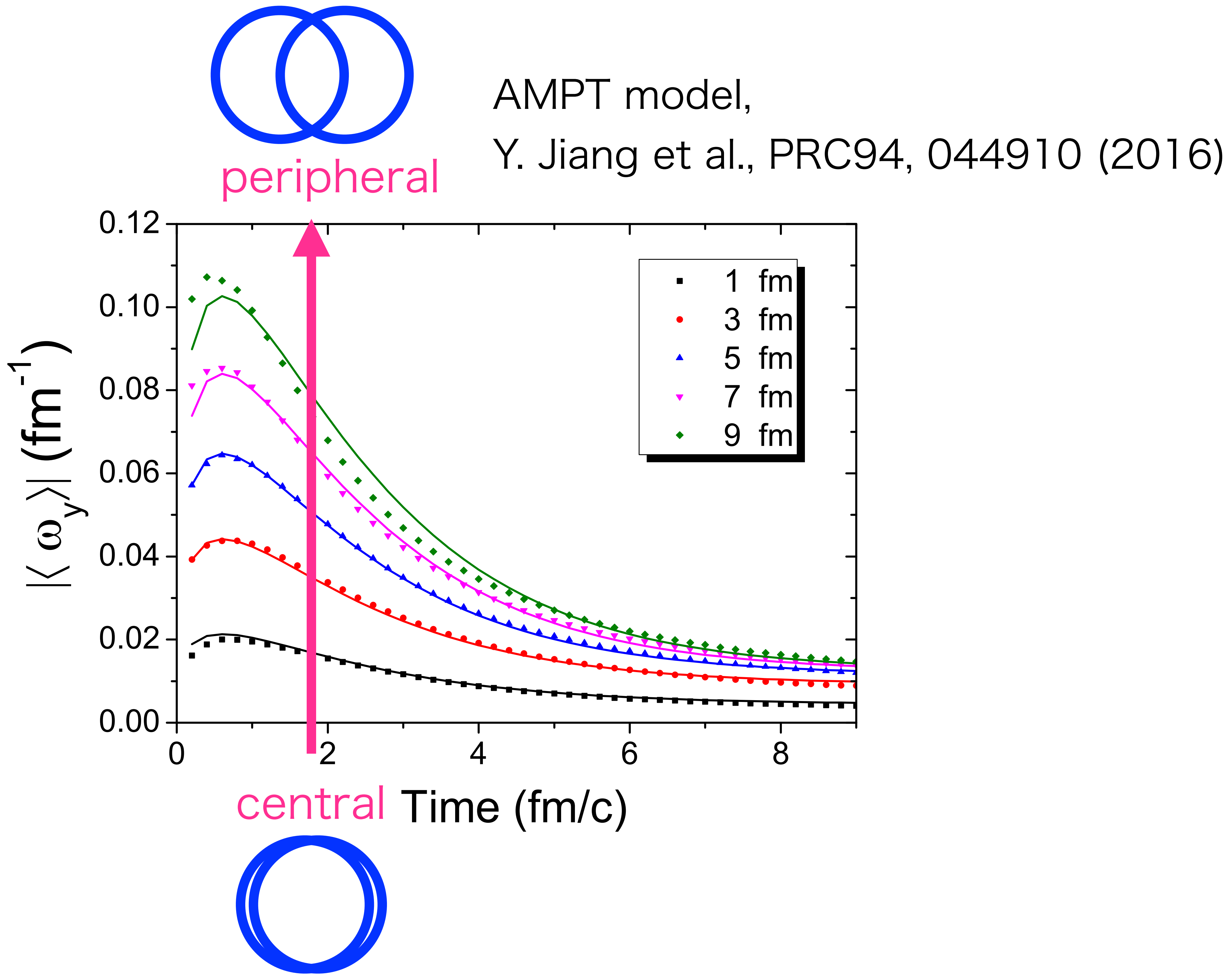
$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}\ (\mathrm{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}\ (\mathrm{sys})$$

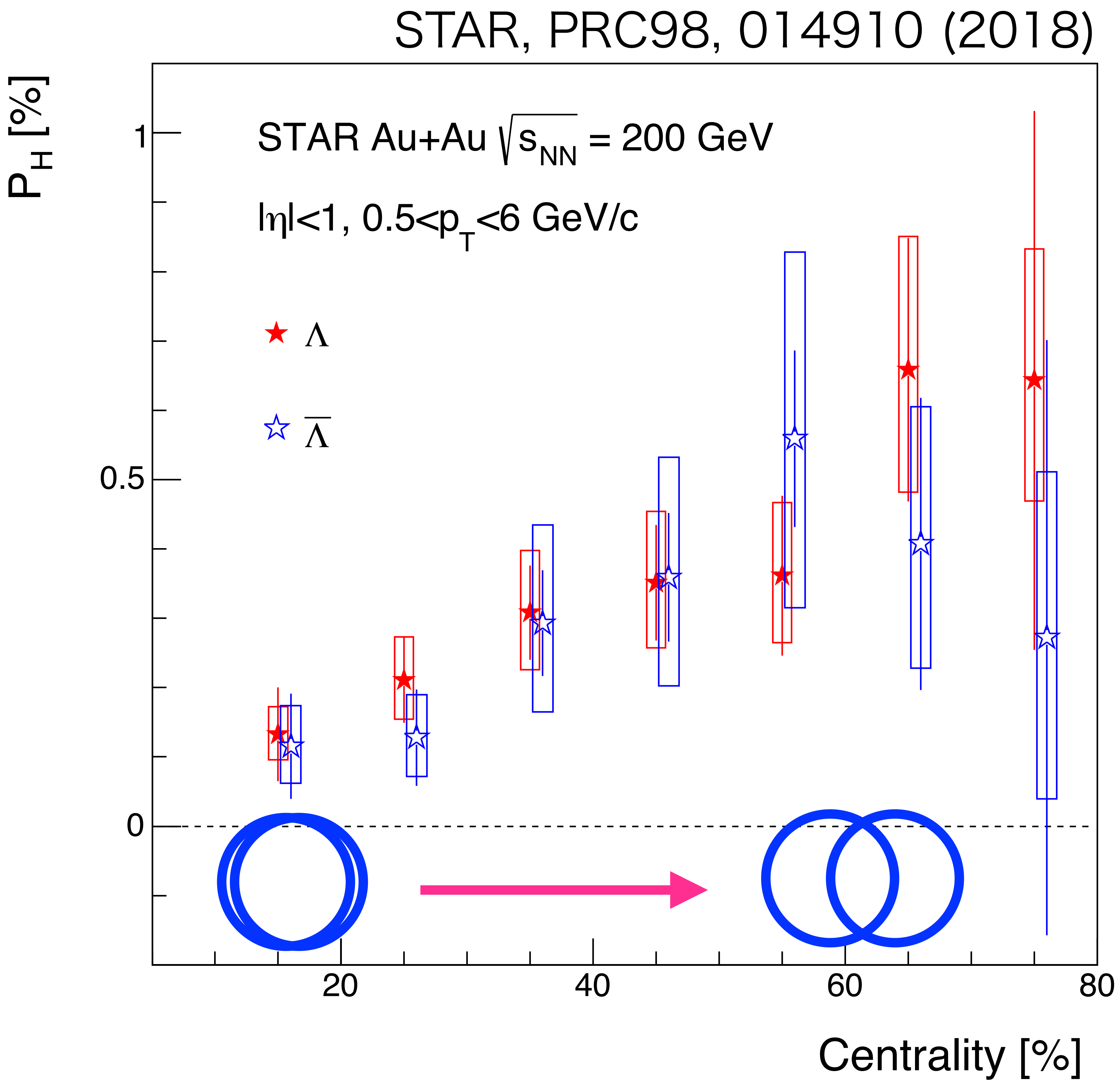
- 5-7σ significance, comparable to the combined result of 7.7-39 GeV

- Feed-down ~15%-20% reduction of P_H (model-dependent)
  Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

UrQMD+vHLLE: I. Karpenko and F. Becattini, EPJC(2017)77:213
AMPT: H. Li et al., Phys. Rev. C 96, 054908 (2017)

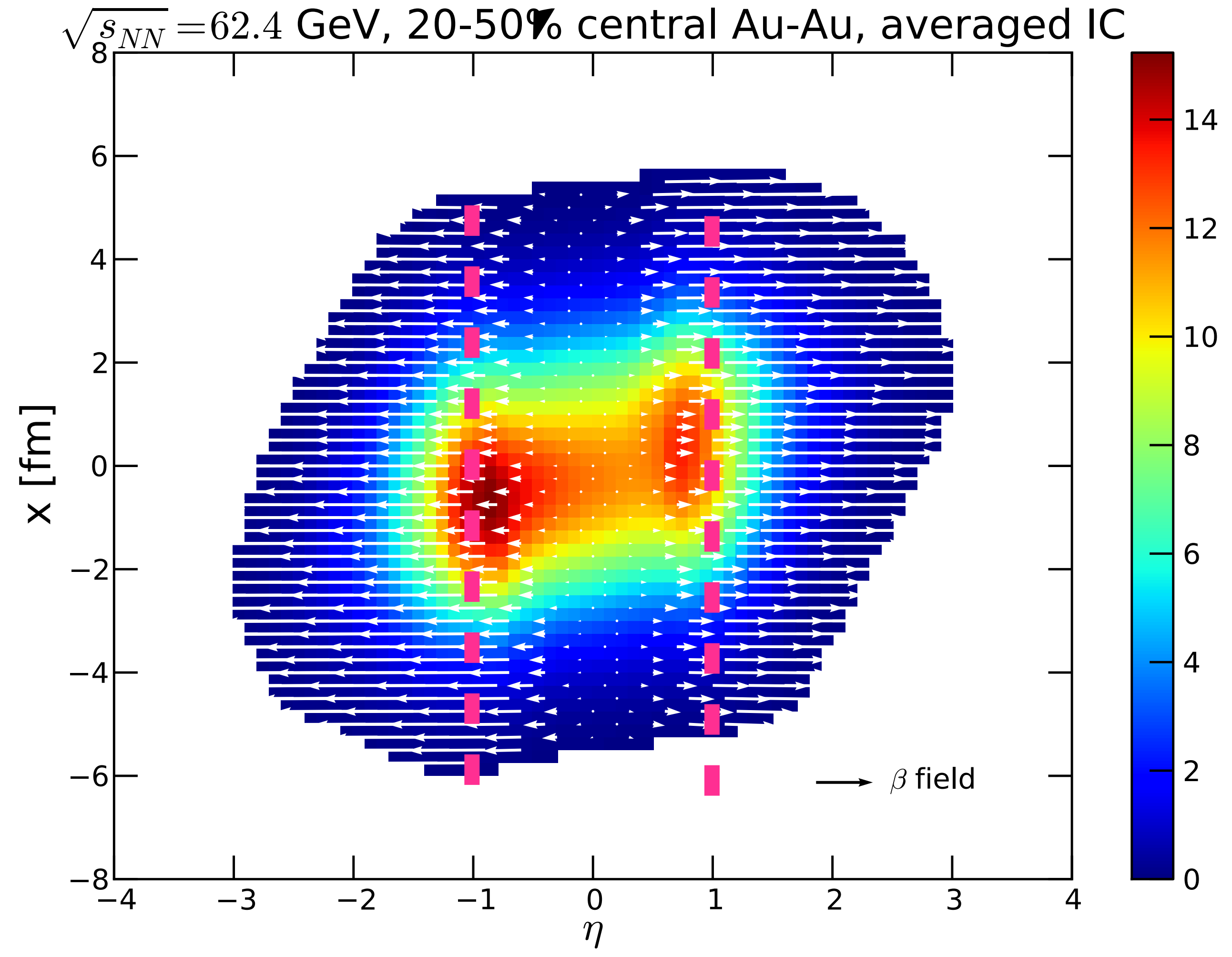
Centrality dependence of P_H

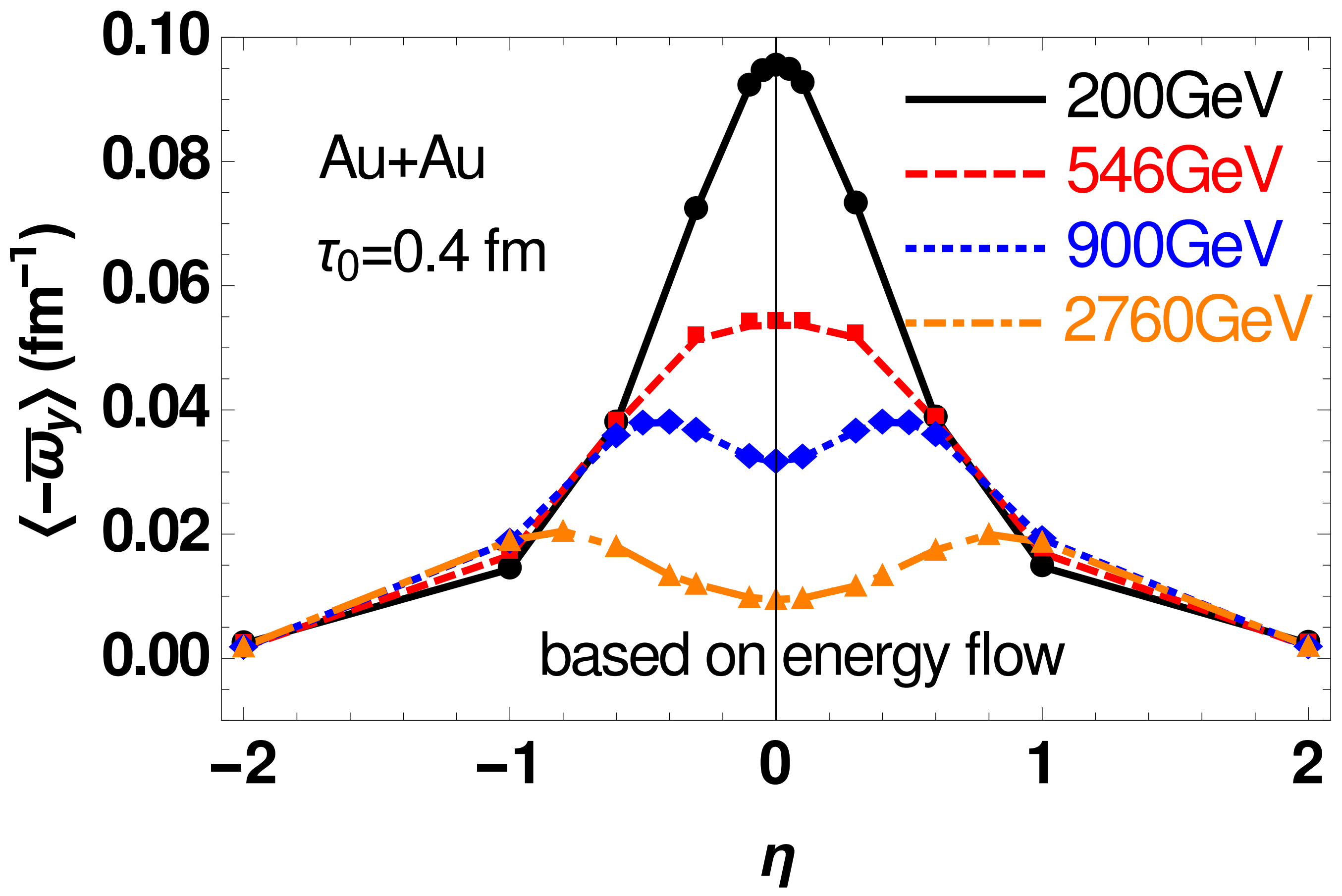




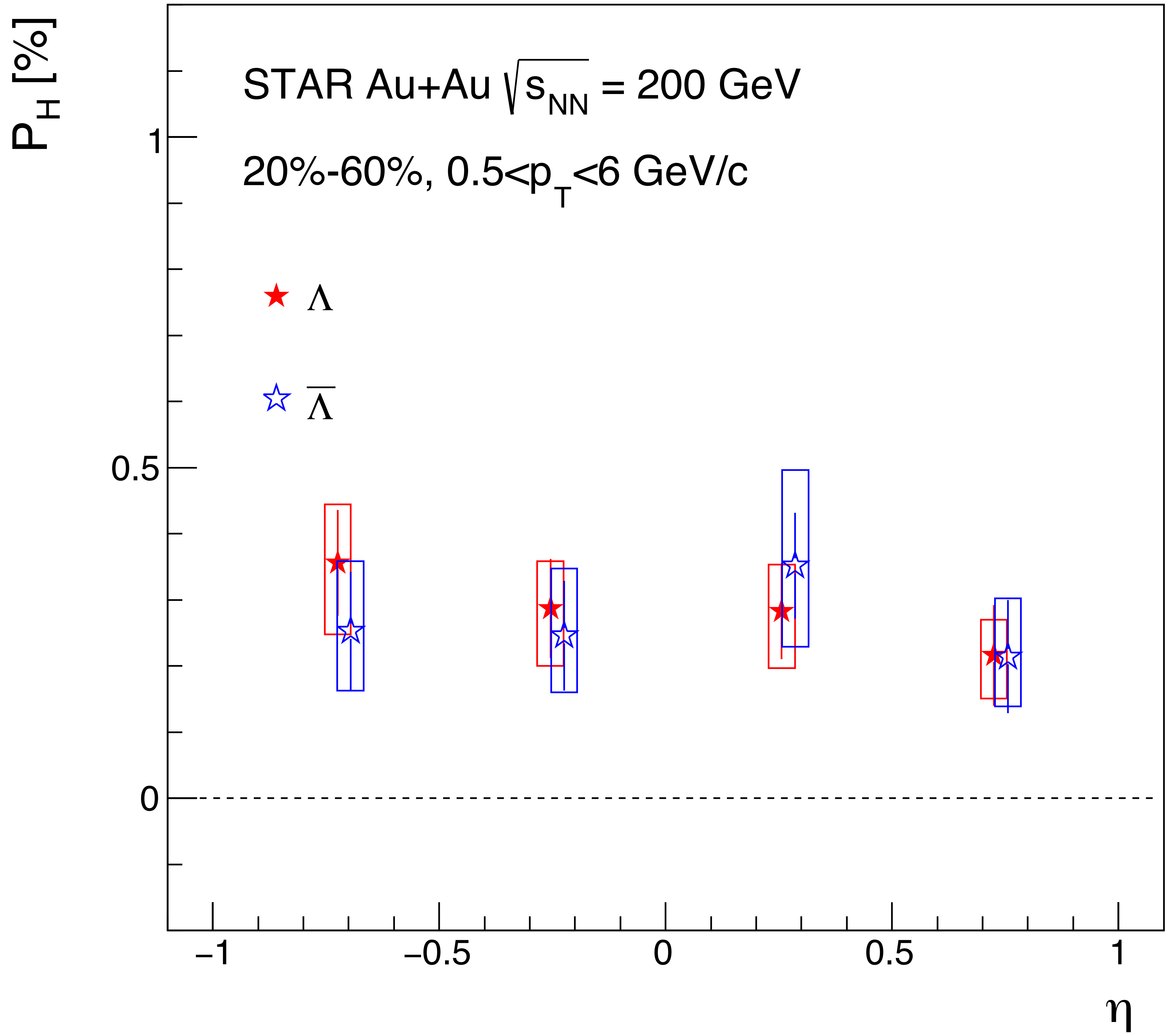
In most central collision → no initial angular momentum
As expected, the polarization decreases in more central collisions

η dependence of P_H





STAR, PRC98, 014910 (2018)



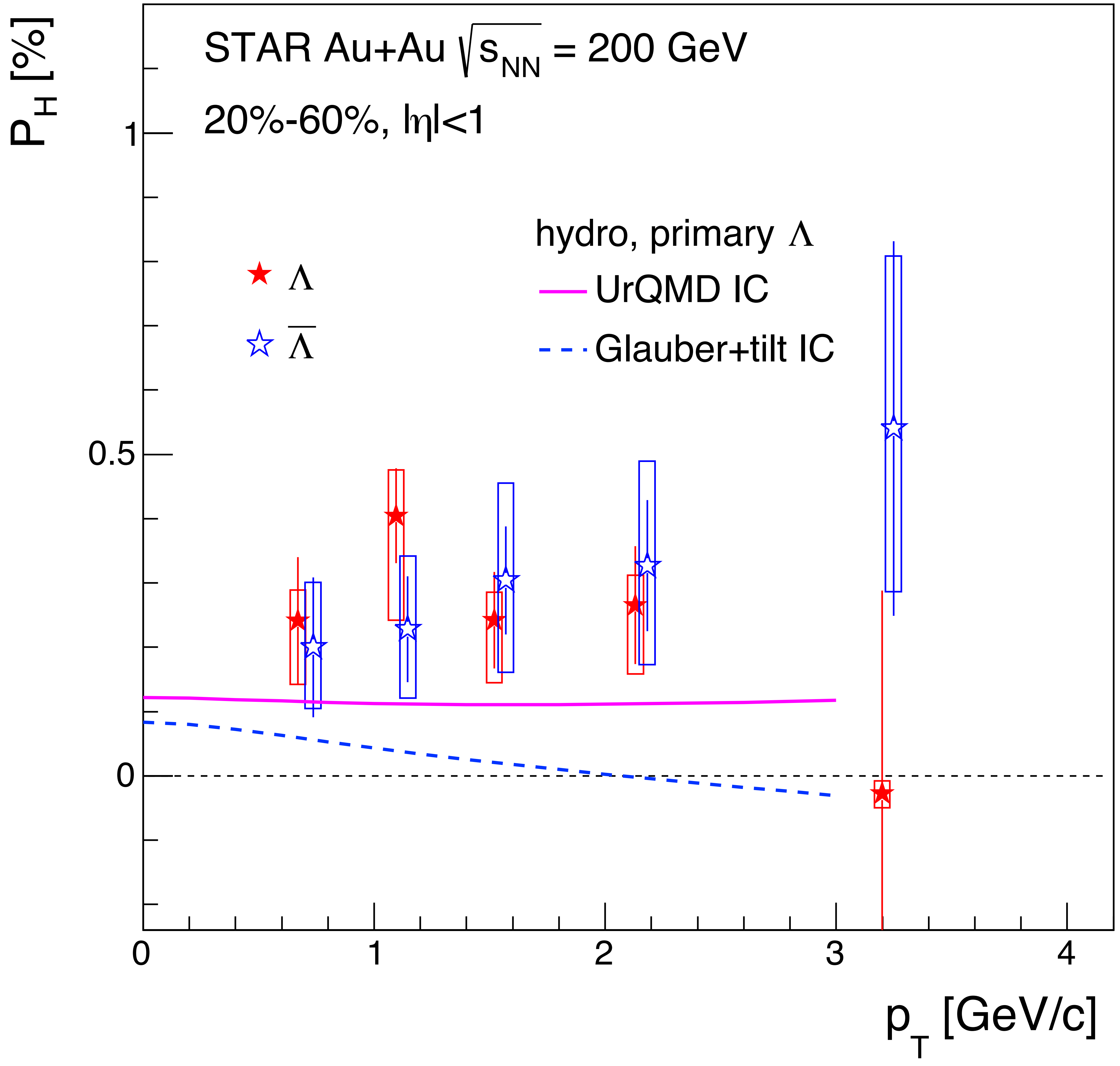
- Shear flow structure/initial flow velocity would be stronger in forward/backward region
- Expect rapidity dependence of the polarization

I. Karpenko and F. Becattini, EPJC(2017)77:213
W.-T. Deng and X.-G. Huang, arXiv:1609.01801

- The data do not show significant η dependence
  - Maybe due to baryon transparency at higher energy
  - Also due to event-by-event C.M. fluctuations

p_T dependence of P_H

STAR, PRC98, 014910 (2018)



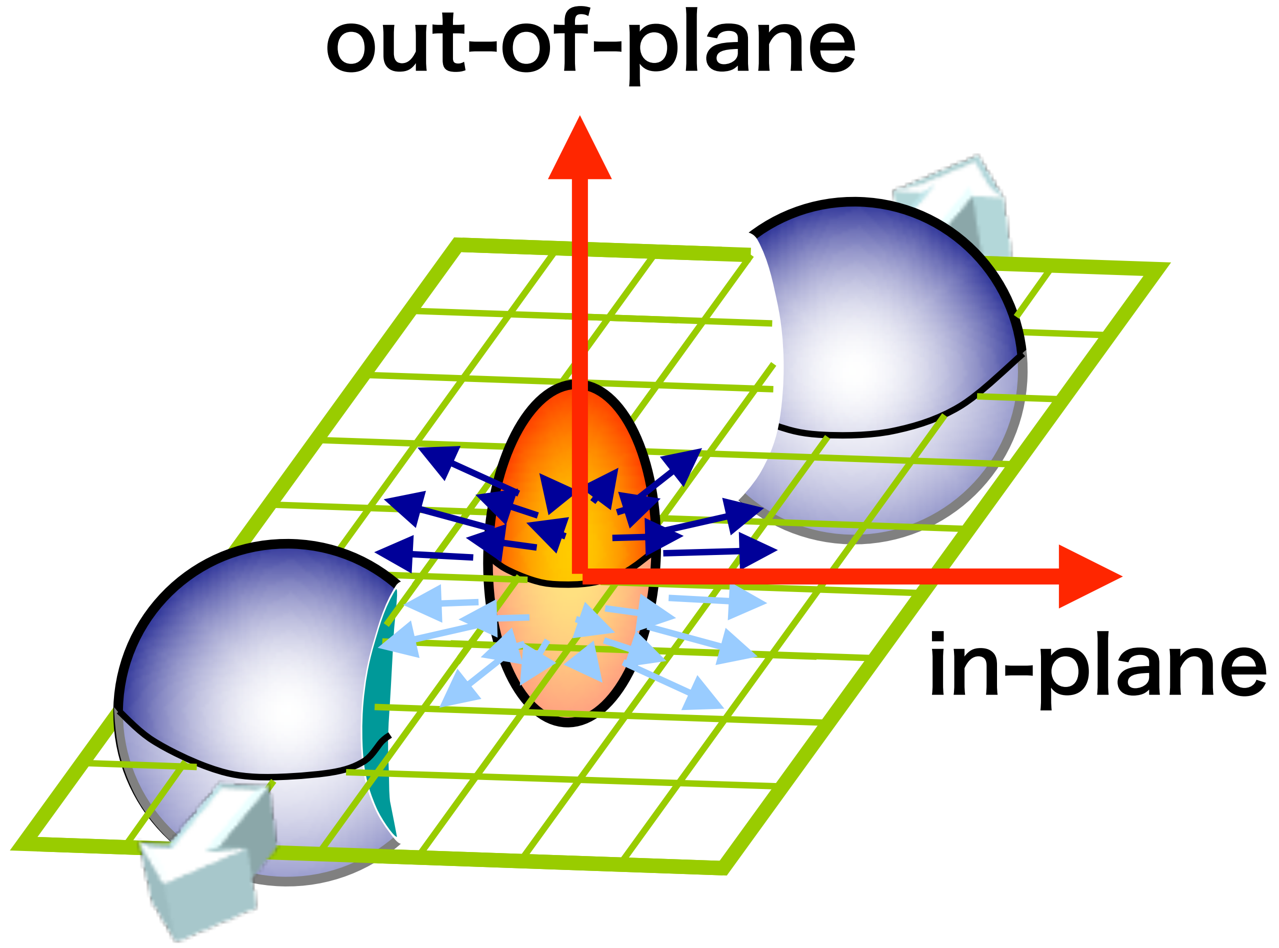
- No significant p_T dependence, as expected from the initial angular momentum of the system
- Hydrodynamic model underestimates the data. Initial conditions affect the magnitude and dependence on p_T

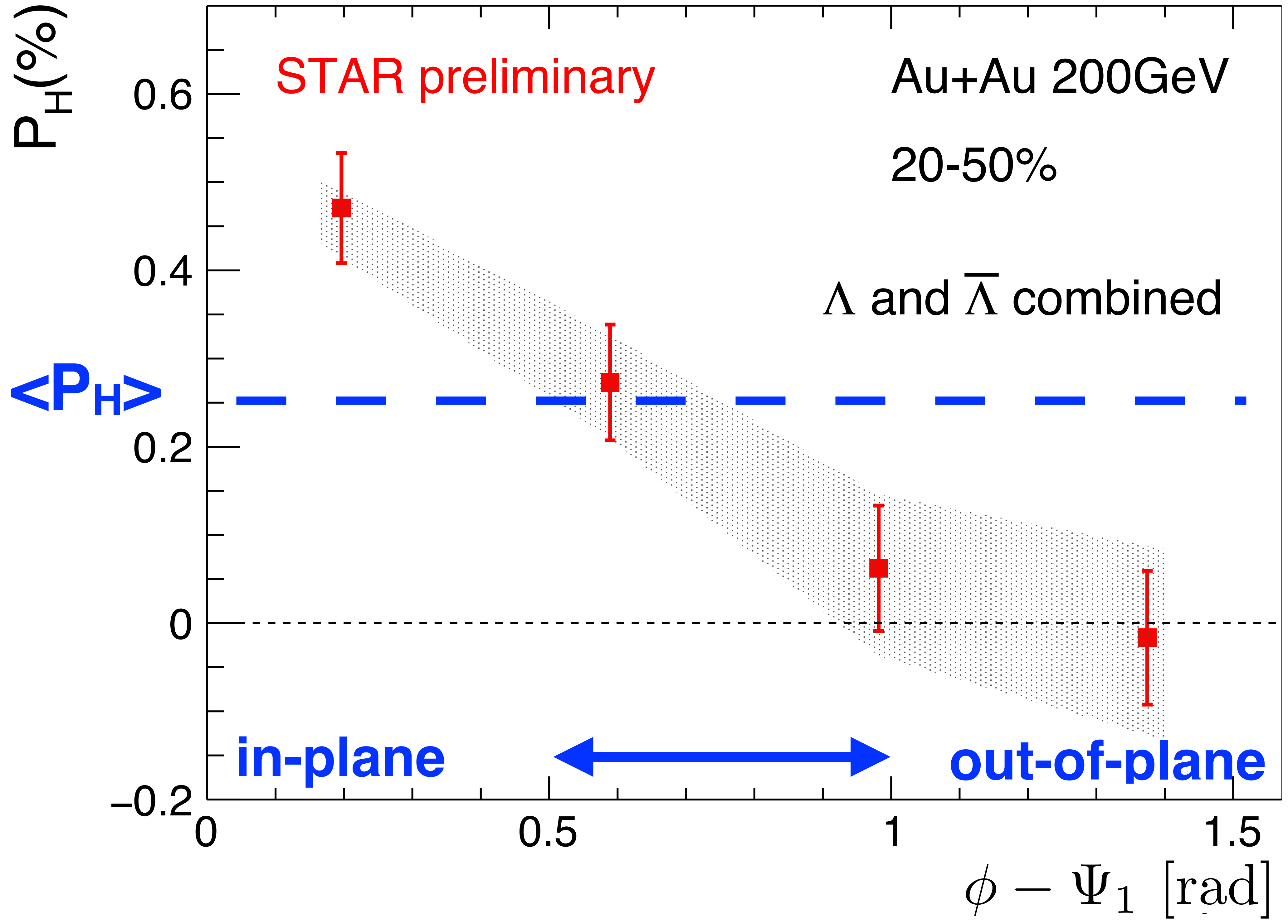
3D viscous hydrodynamic model with two initial conditions (ICs)

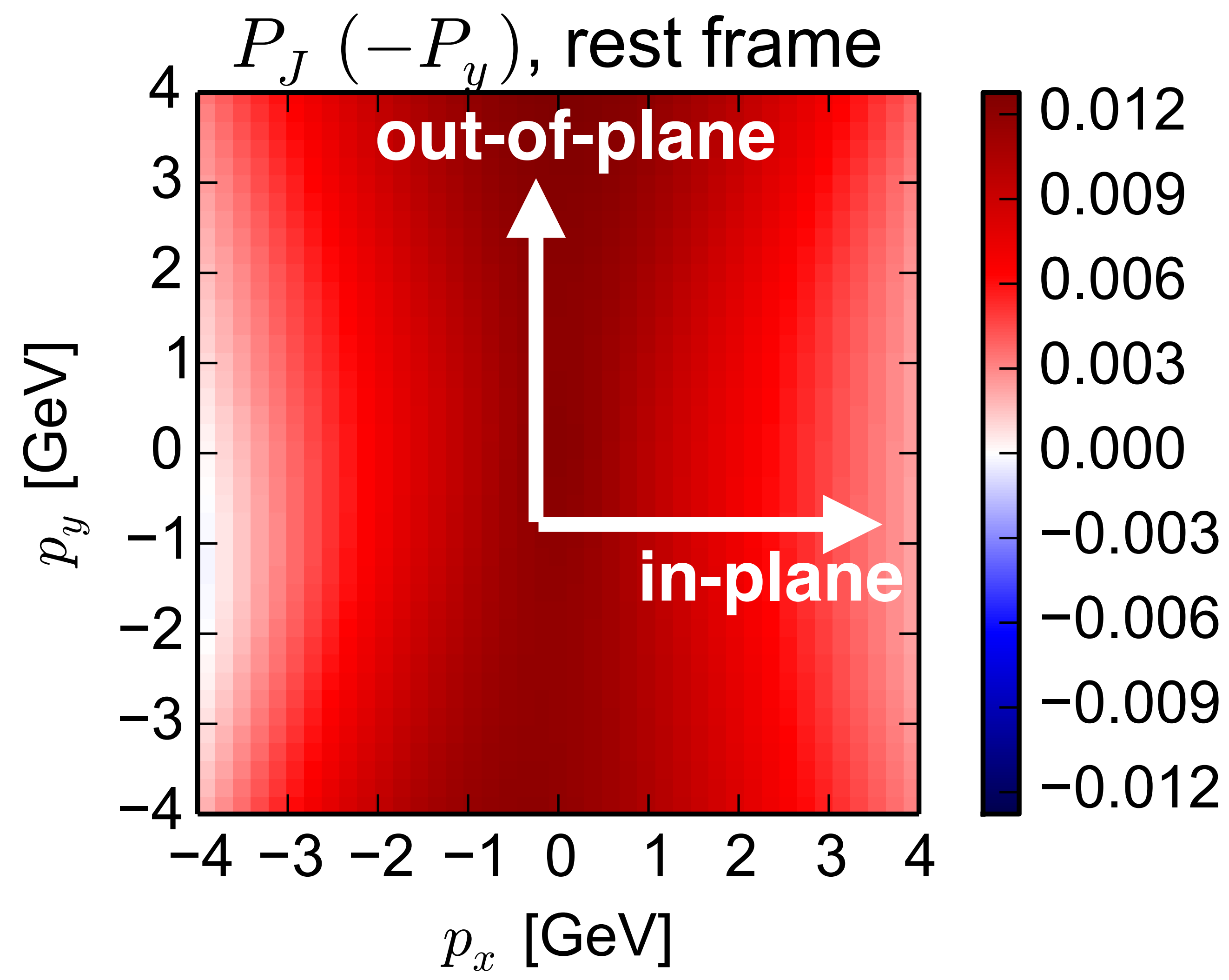
- UrQMD IC
- Glauber with source tilt IC

F. Becattini and I. Karpenko, PRL120.012302, 2018

Azimuthal angle dependence of P_H







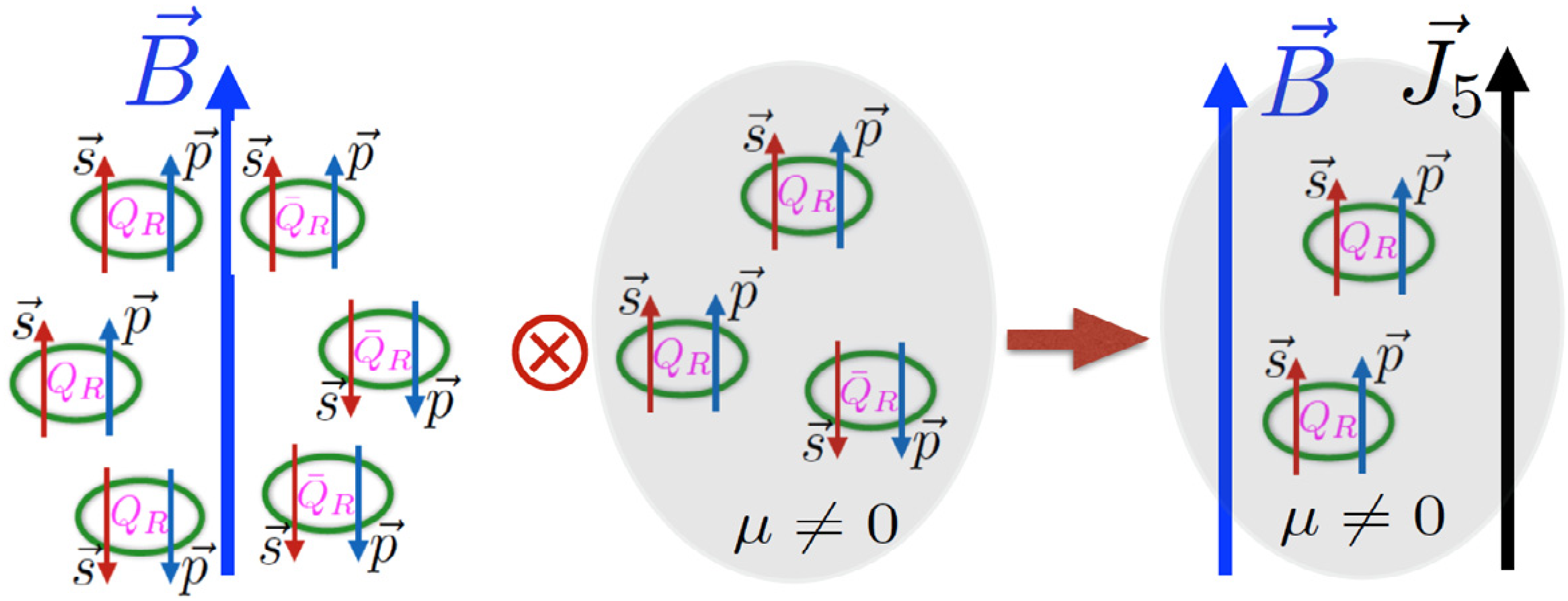
I. Karpenko and F. Becattini, EPJC(2017)77:213

✦ Larger polarization in in-plane than in out-of-plane

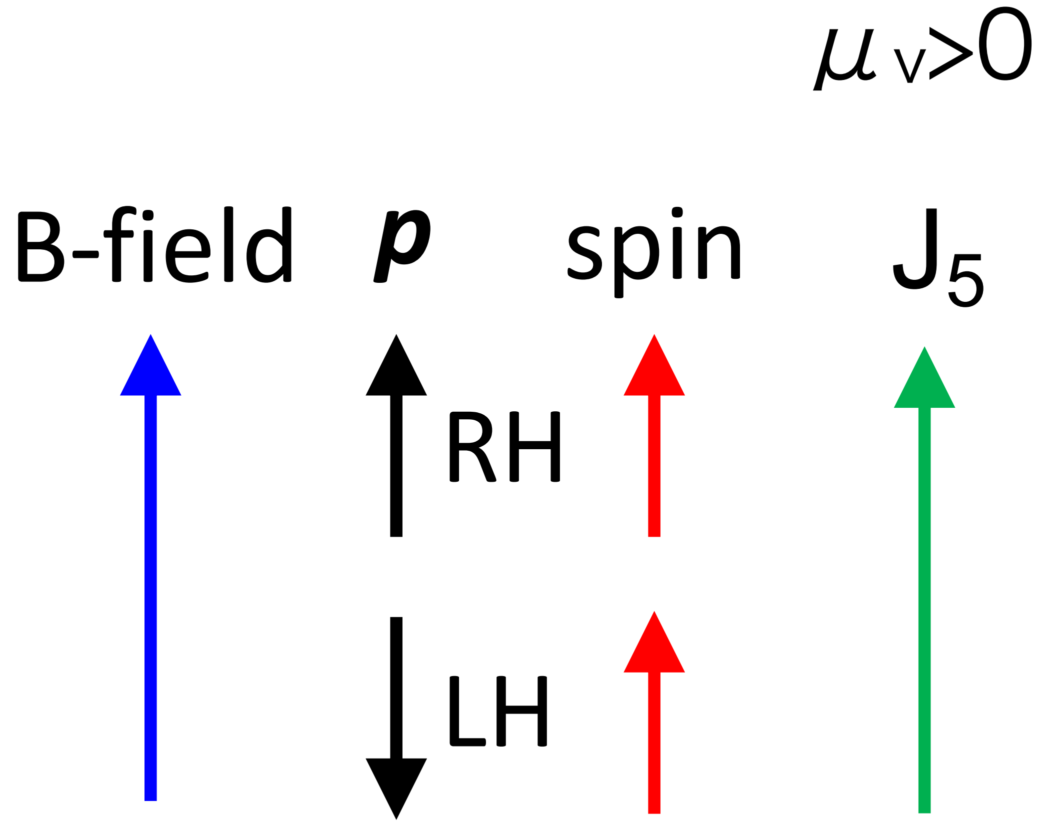
✦ Opposite to hydrodynamic model! (larger in out-of-plane)

Λ polarization vs. charge asymmetry?

Chiral Separation Effect



$$\mathbf{J}_5 \propto \mu_\mathrm{v}\mathbf{B}$$

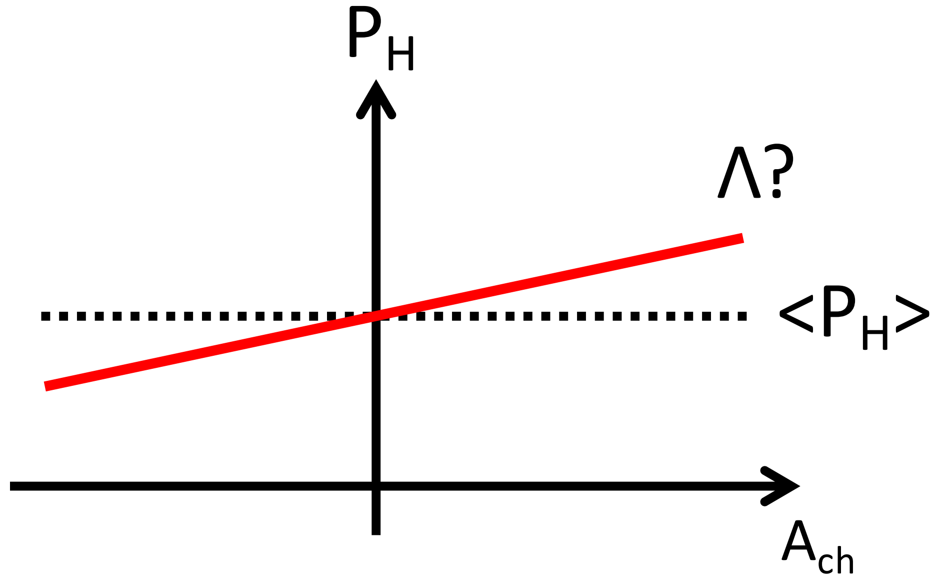


B-field + massless quarks + non-zero μ_v → axial current J_5
(spin alignment + spin and momentum in (anti)parallel for RH(LH) quarks)

- Λ polarization may have a contribution from the axial current J_5 induced by B-field (Chiral Separation Effect), S. Shlichting and S. Voloshin
- Use charge asymmetry A_{ch} instead of μ_v

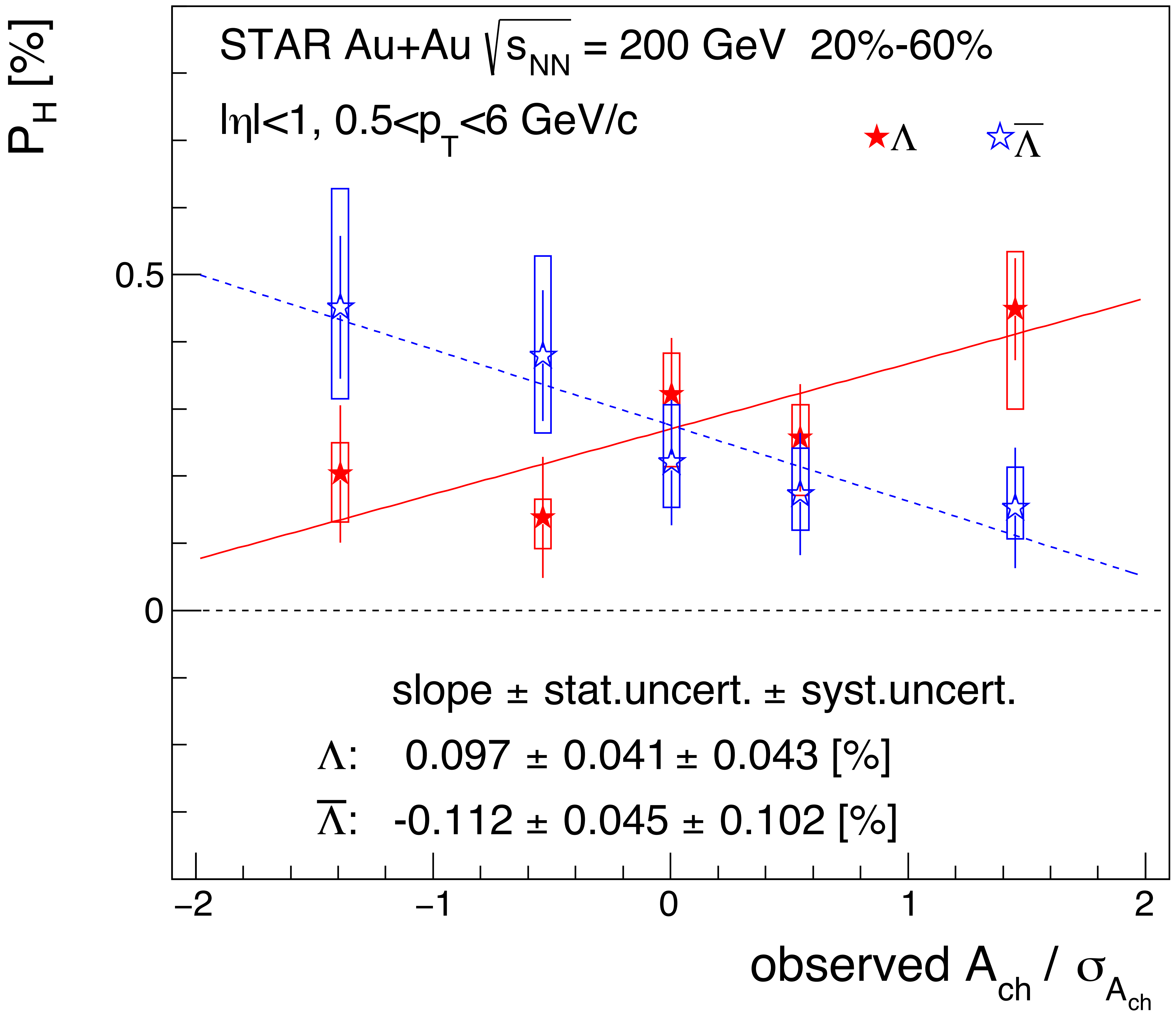
what's the expectation?
true for u-quark but also for Λ?

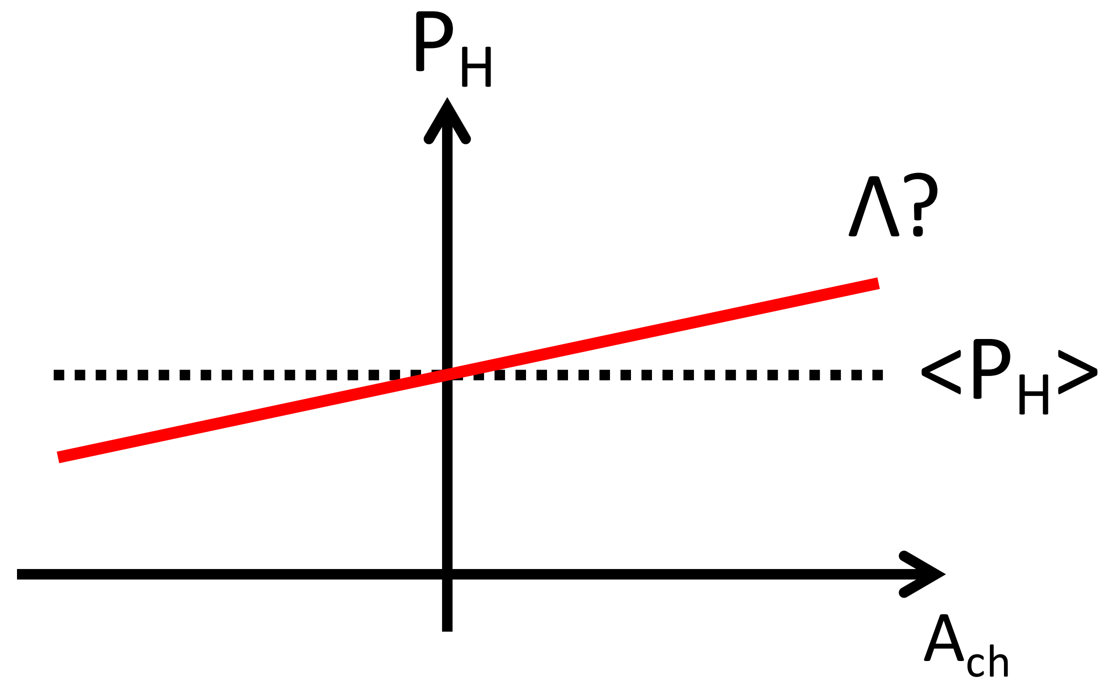
$$\mu_\mathrm{v}/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_\mathrm{ch}$$



Λ polarization vs charge asymmetry?

STAR, PRC98, 014910 (2018)





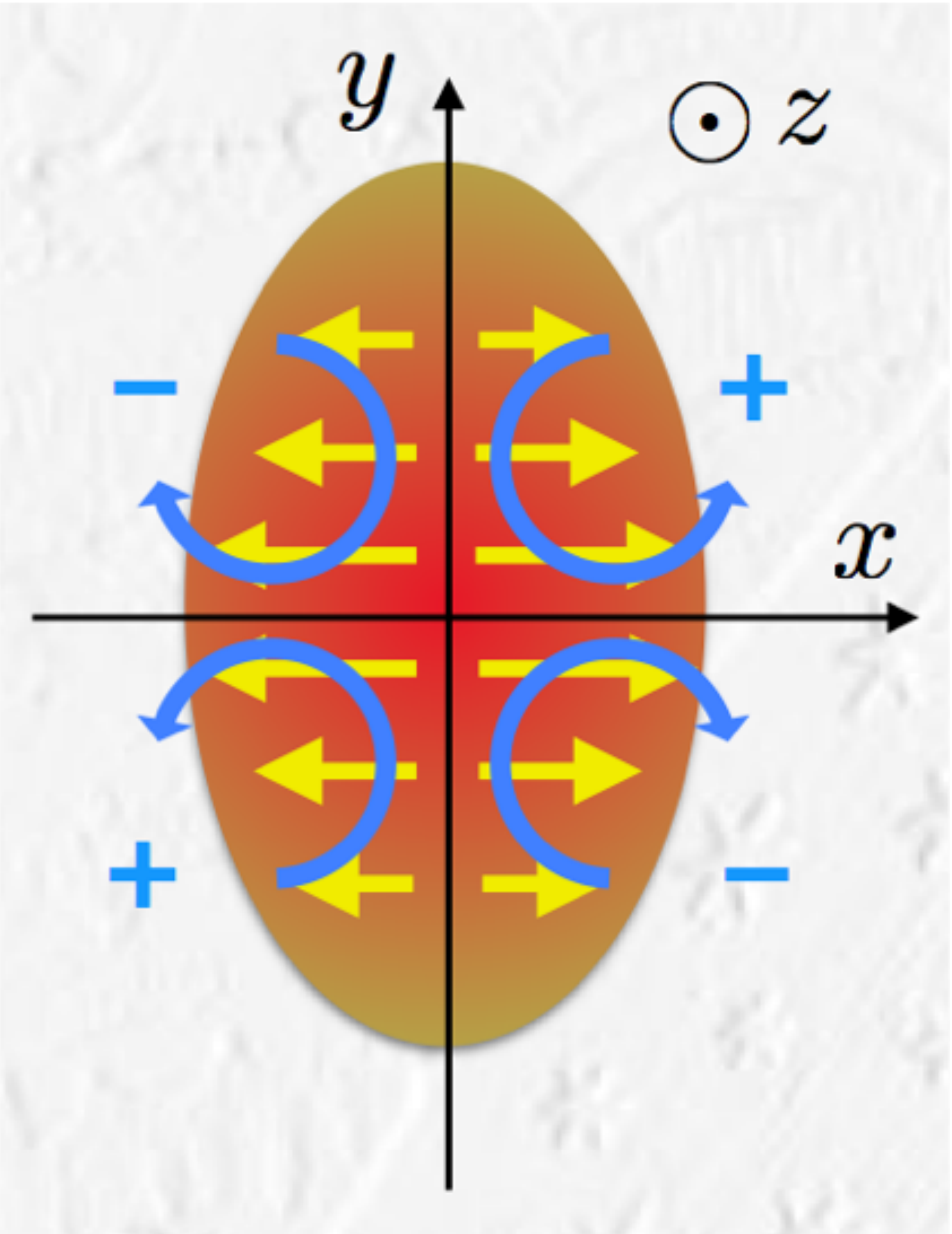
Slopes of Λ and anti-Λ seem to be different.
(statistical significance is ~2σ level)

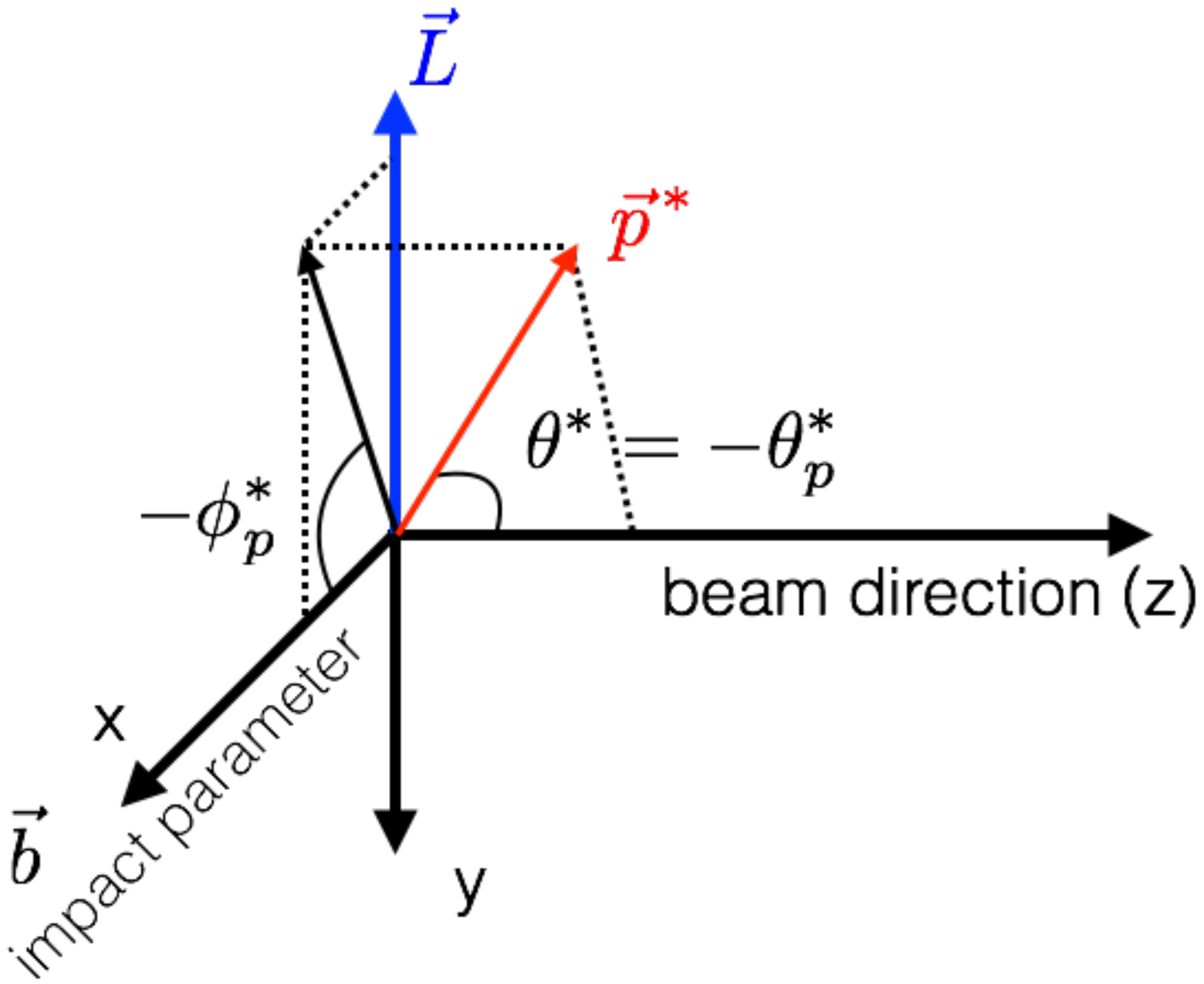
Possibly a contribution from the axial current?

Polarization along the beam direction

S. Voloshin, SQM2017

F. Becattini and I. Karpenko, PRL120.012302 (2018)





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\mathrm{H}} \mathbf{P_H} \cdot \mathbf{p}_p^*)$$

$$\langle \cos\theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos\theta_p^* d\Omega^*$$

$$= \alpha_{\mathrm{H}} P_z \langle (\cos\theta_p^*)^2 \rangle$$

$$\therefore \ P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}} \langle (\cos\theta_p^*)^2 \rangle}$$

$$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}}} \quad \text{(if perfect detector)}$$

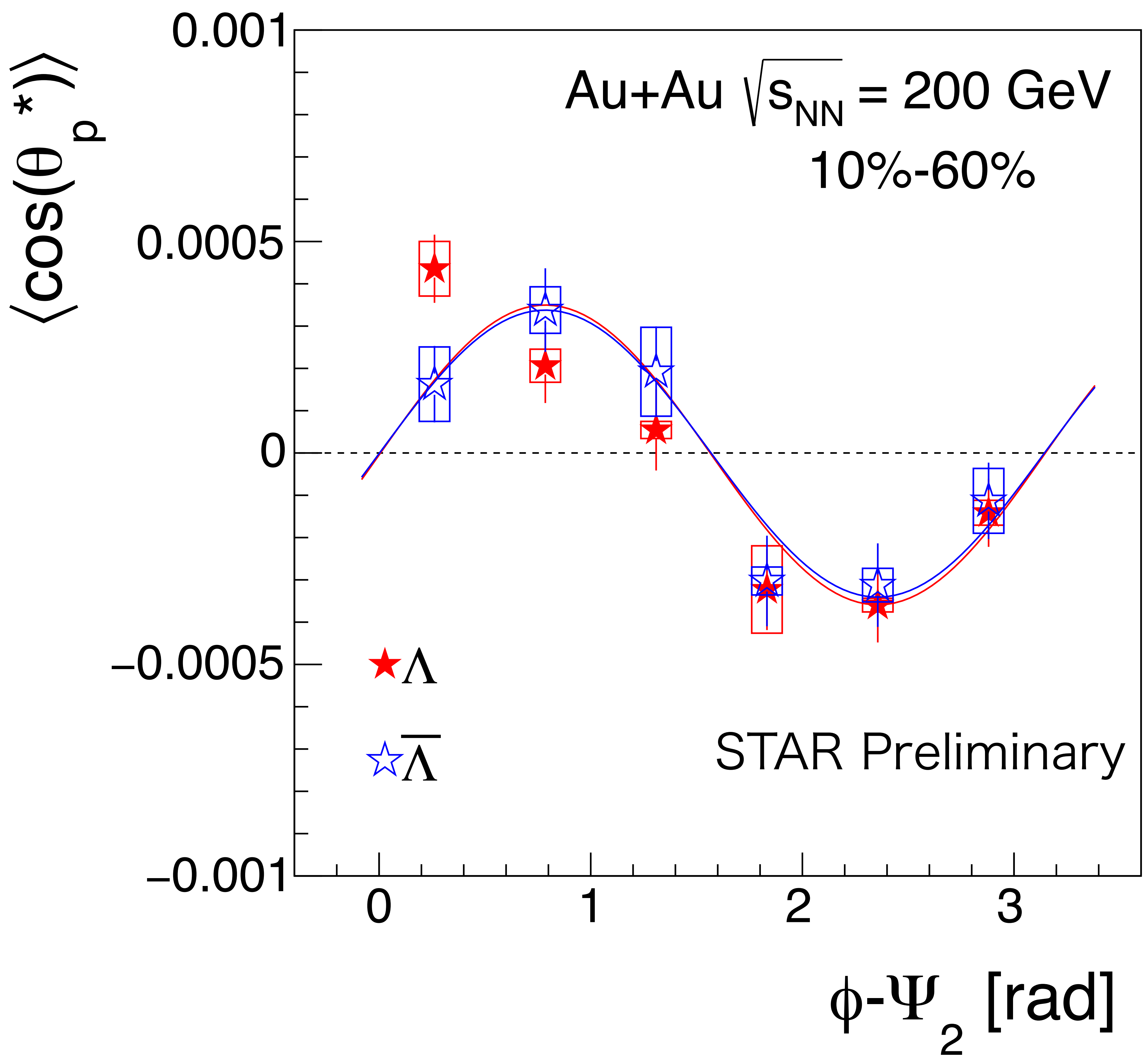
α_{H}: hyperon decay parameter

θ_p^*: θ of daughter proton in Λ rest frame

Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

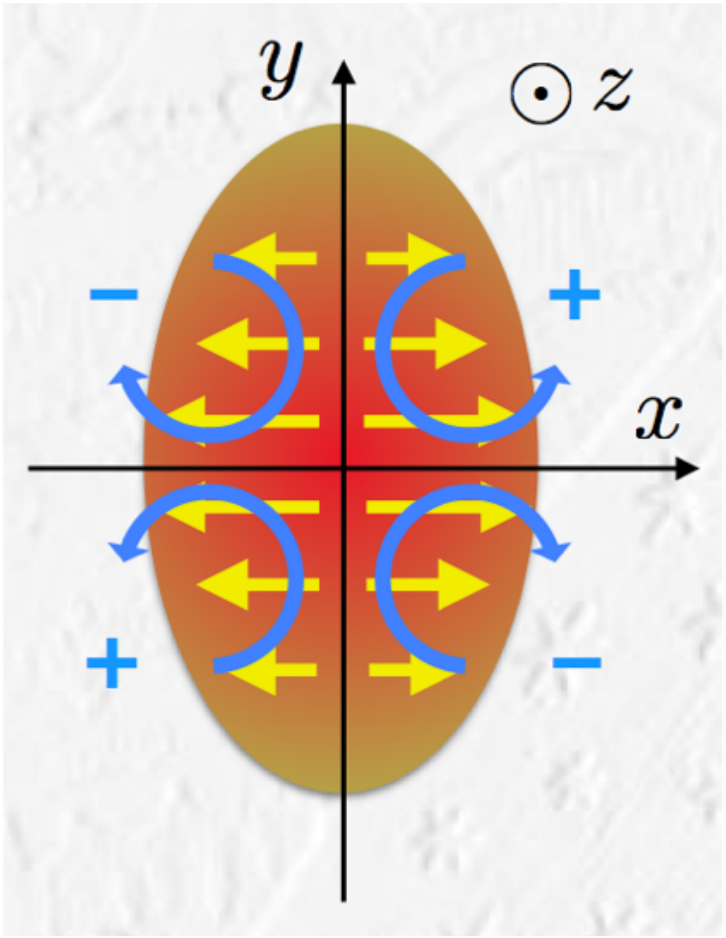
Longitudinal component, P_z, can be expressed with $<\cos\theta_p^*>$.
$<(\cos\theta_p^*)^2>$ accounts for an acceptance effect

Polarization along the beam direction

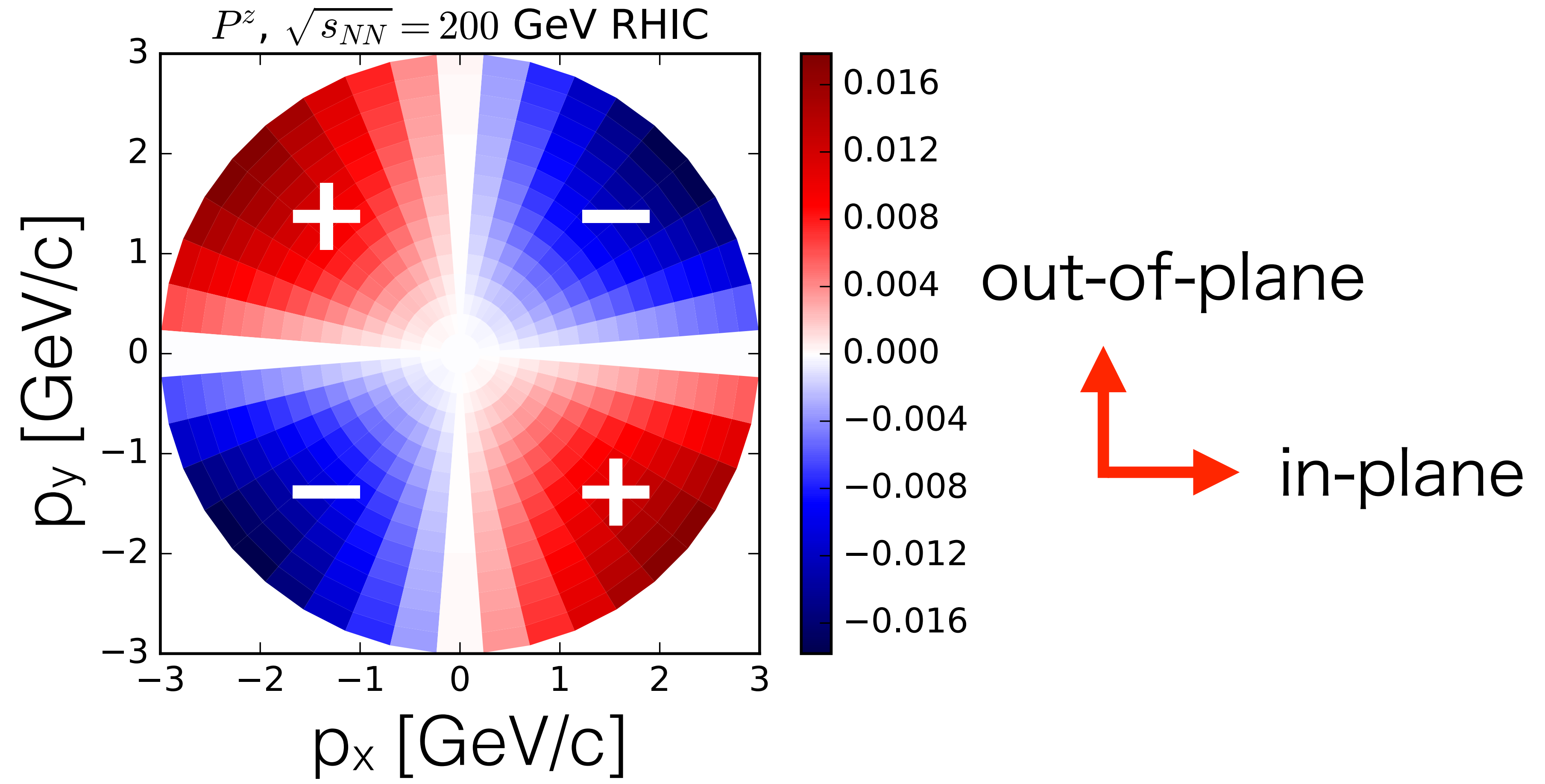


- Effect of Ψ_2 resolution is not corrected here

S. Voloshin, SQM2017

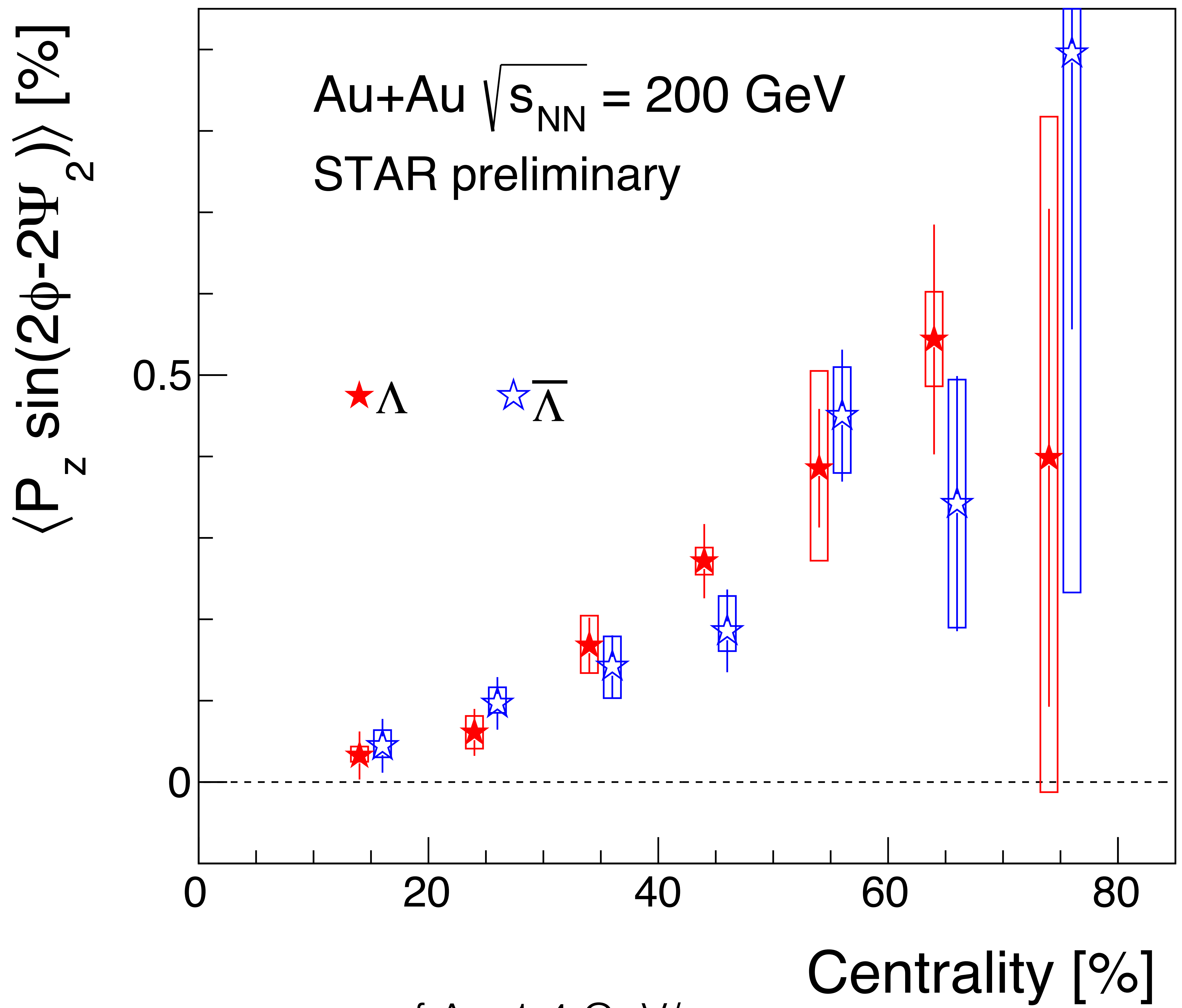


Hydro calculation of P_z
F. Becattini and I. Karpenko, PRL.120.012302 (2018)



- Sine structure as expected from the elliptic flow!
- Opposite sign to hydrodynamic model and a transport model (AMPT)
  - Hydro model: F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  - AMPT model: X. Xia, H. Li, Z. Tang, Q. Wang, arXiv:1803.0086

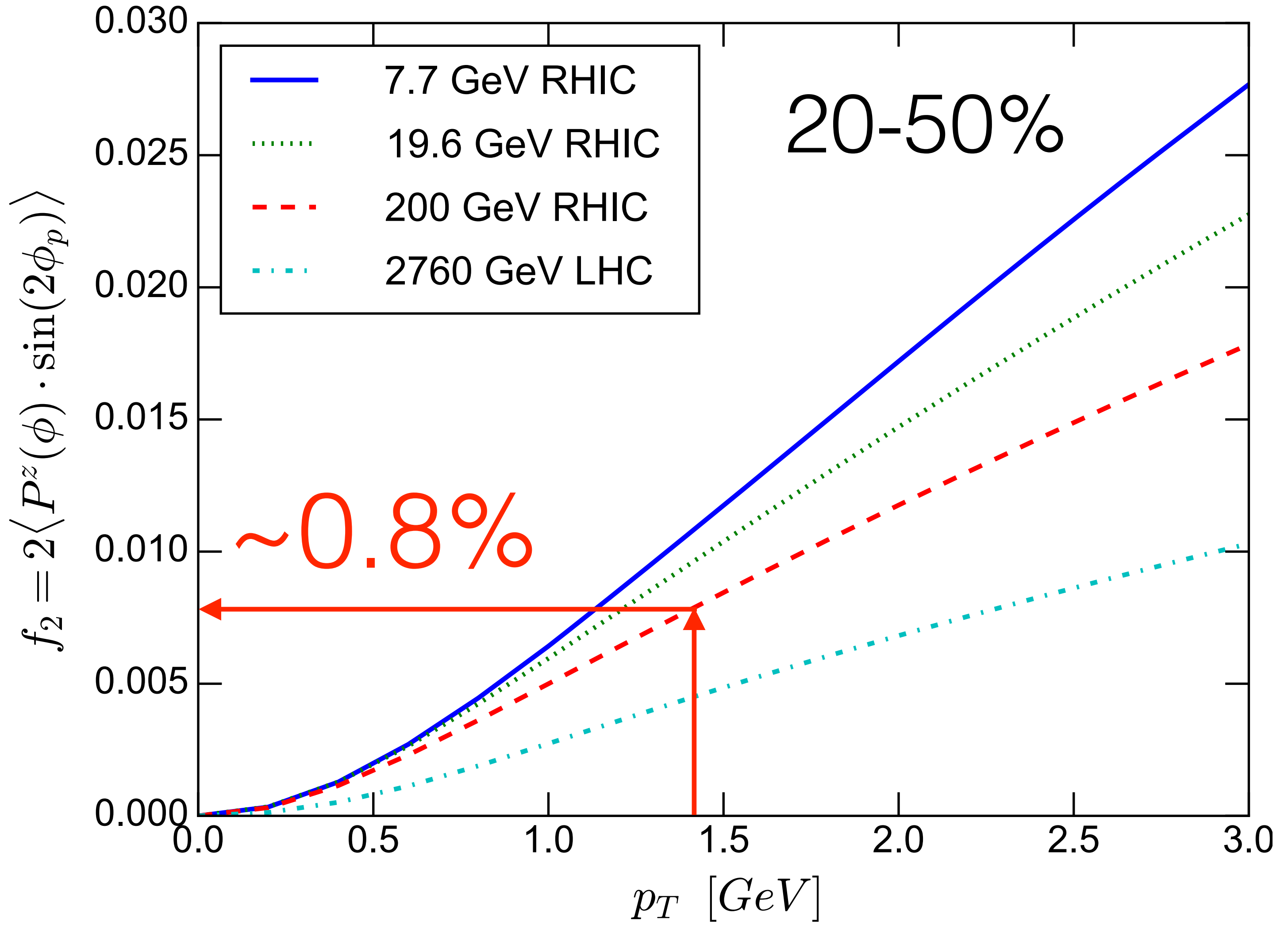
Centrality dependence of P_z modulation



<p_T> of Λ ~1.4 GeV/c
(0.5<p_T<6 GeV/c)

- Strong centrality dependence as in v_2
- Similar magnitude to the global polarization
- ~5 times smaller magnitude than the hydro and AMPT with the opposite sign!

F. Becattini and I. Karpenko, PRL.120.012302 (2018)



Sign problem in P_z

Opposite sign to hydrodynamic model and AMPT model

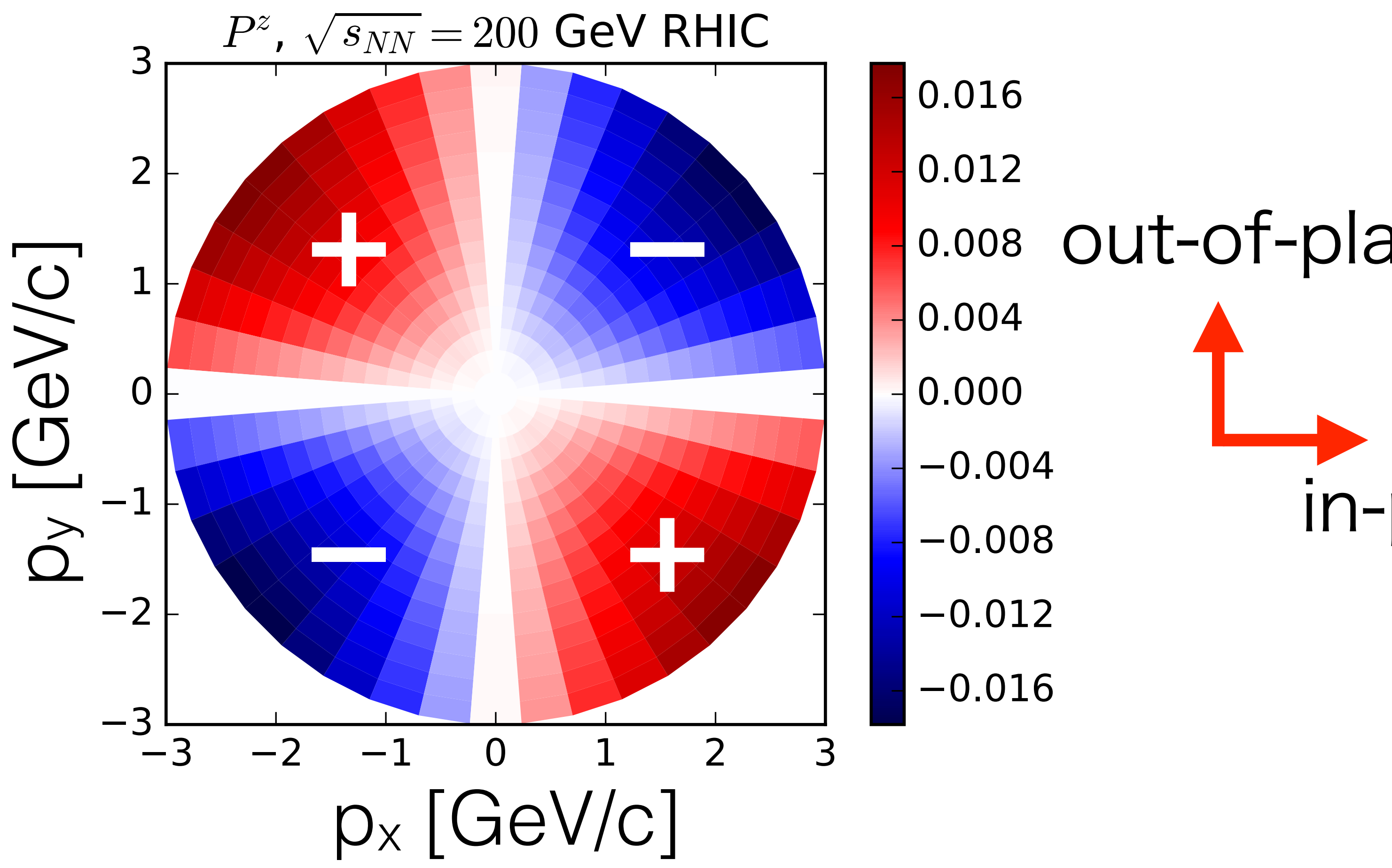
- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  3D viscous hydrodynamic model with UrQMD initial condition assuming a local thermal equilibrium
- AMPT: X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

Same sign as chiral kinetic approach

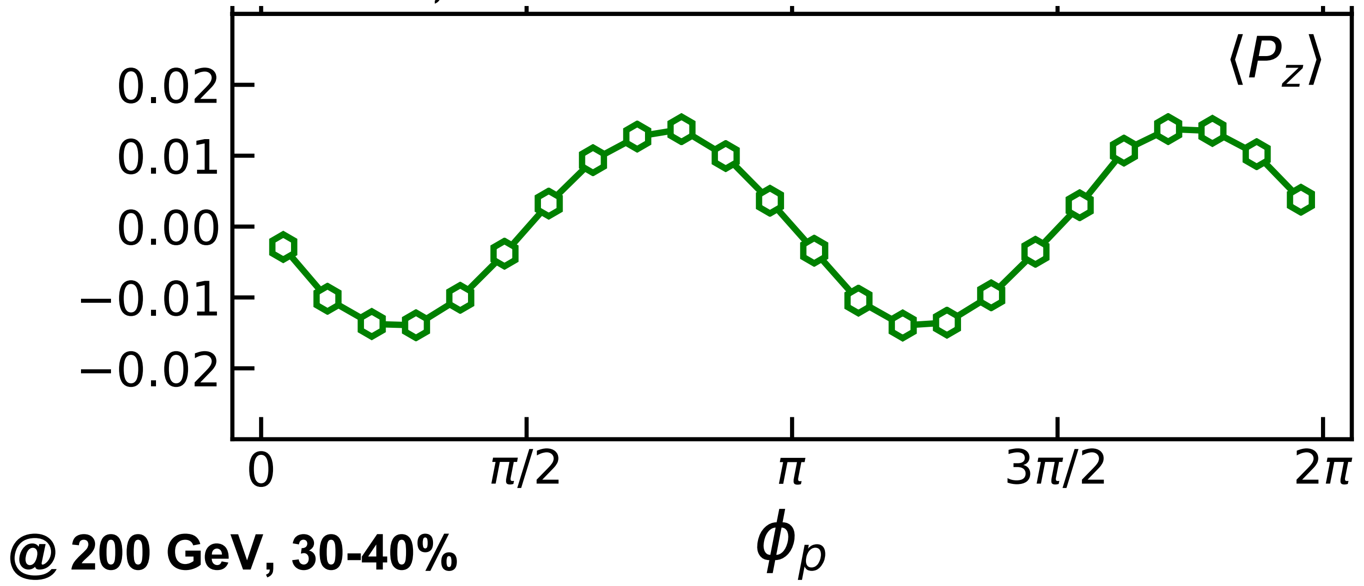
- Y. Sun and C.-M. Ko, arXiv:1810.10359
- Assuming non-equilibrium of spin degree of freedom
- Smaller quark scattering cross section changes the sign

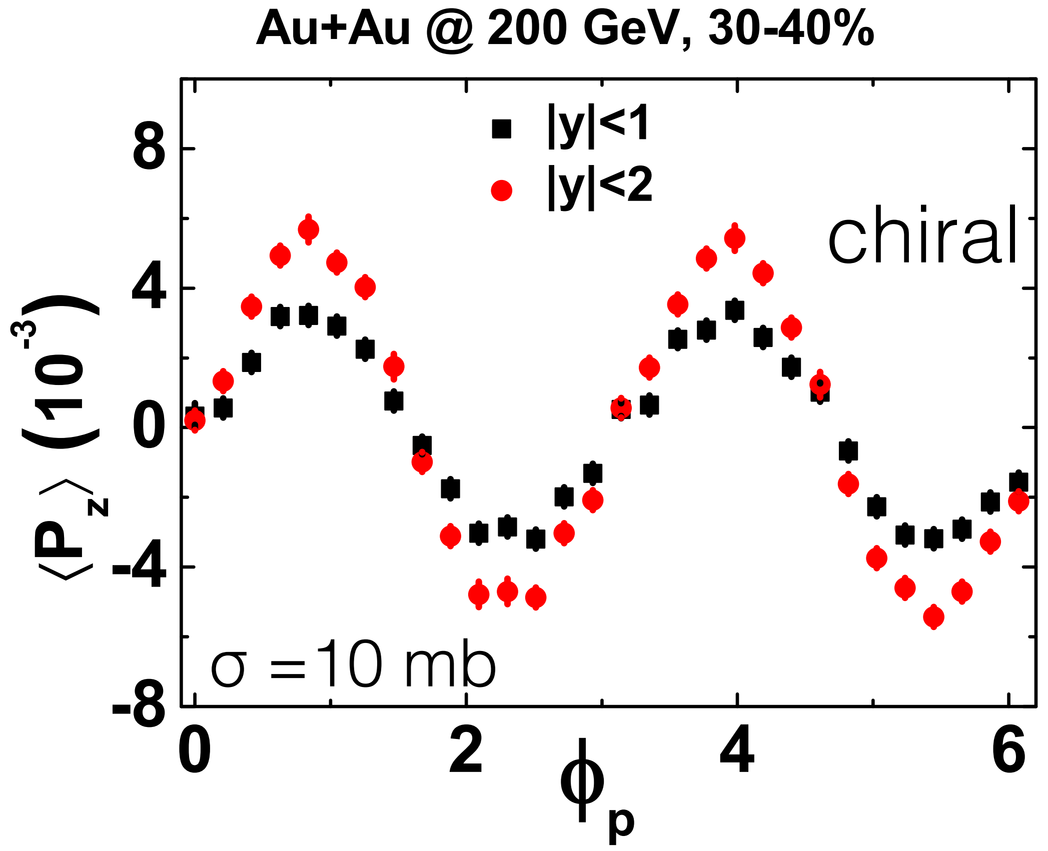
Suggest incomplete thermal equilibrium of spin degree of freedom as it develops later in time unlike the global polarization?

Hydrodynamic model



AMPT, Au+Au 200 GeV 20-50%





chiral kinetic approach

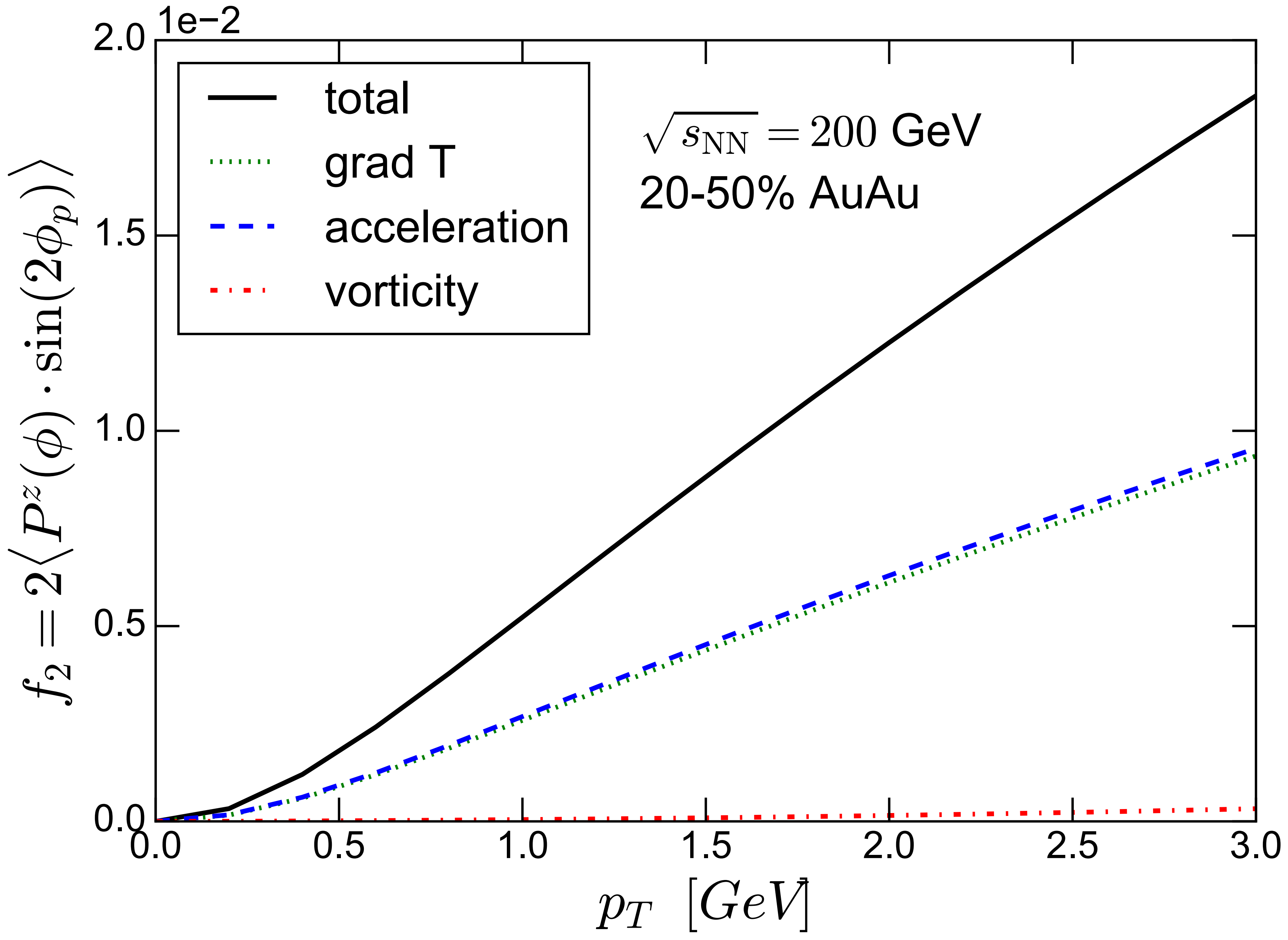
Contributions to P_z in hydro

I. Karpenko, QM2018

$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau}\varpi_{\rho\sigma}p_\tau = \varepsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau = \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau\partial_\rho\left(\frac{1}{T}\right)u_\sigma}_{\text{grad}T} + \underbrace{\frac{1}{T}2\left[\omega^\mu(u\cdot p) - u^\mu(\omega\cdot p)\right]}_{\text{“NR vorticity”}} + \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau A_\sigma u_\rho}_{\text{acceleration}}$$

temperature gradient **kinematic vorticity** **relativistic term**

Longitudinal quadrupole f_2:



P_z dominated by temperature gradient and relativistic term, but not by kinematic vorticity based on the hydro model.

How small is the kinematic vorticity?
Can we estimate it with the blast-wave model?

Blast-wave model

- Hydro inspired model parameterized with freeze-out condition assuming the longitudinal boost invariance
  - Freeze-out temperature T_f
  - Radial flow rapidity ρ_0 and its modulation ρ_2
  - Source size R_x and R_y

$$\rho(r, \phi_s) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi_b)]$$

$$\tilde{r}(r, \phi_s) = \sqrt{(r\cos\phi_s)^2/R_x^2 + (r\sin\phi_s)^2/R_y^2}$$

- Calculate vorticity at the freeze-out using the parameters extracted from spectra, v_2, and HBT fit

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

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

u: local flow velocity, I_n, K_n: modified Bessel functions

F. Retiere and M. Lisa, PRC70.044907 (2004)

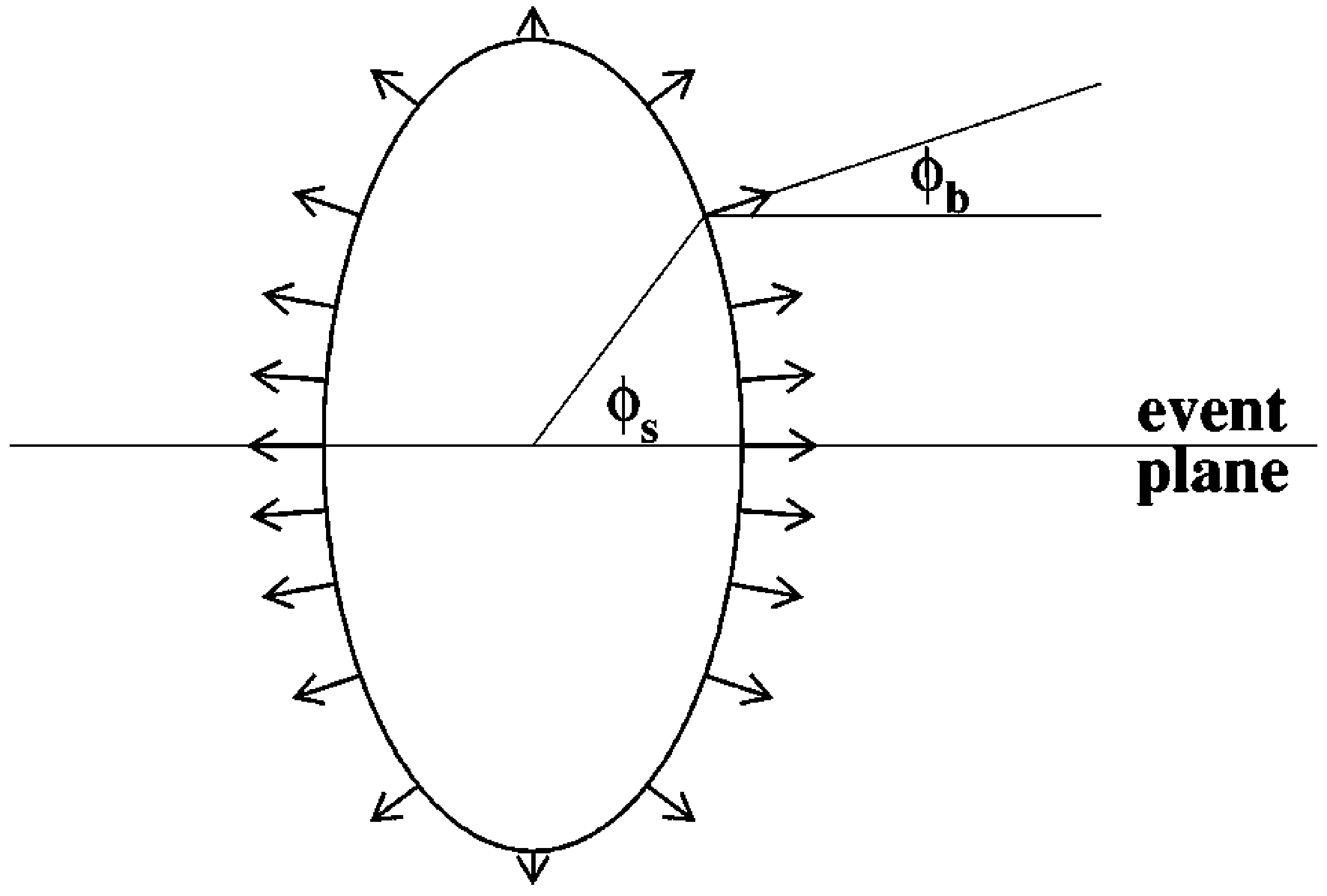


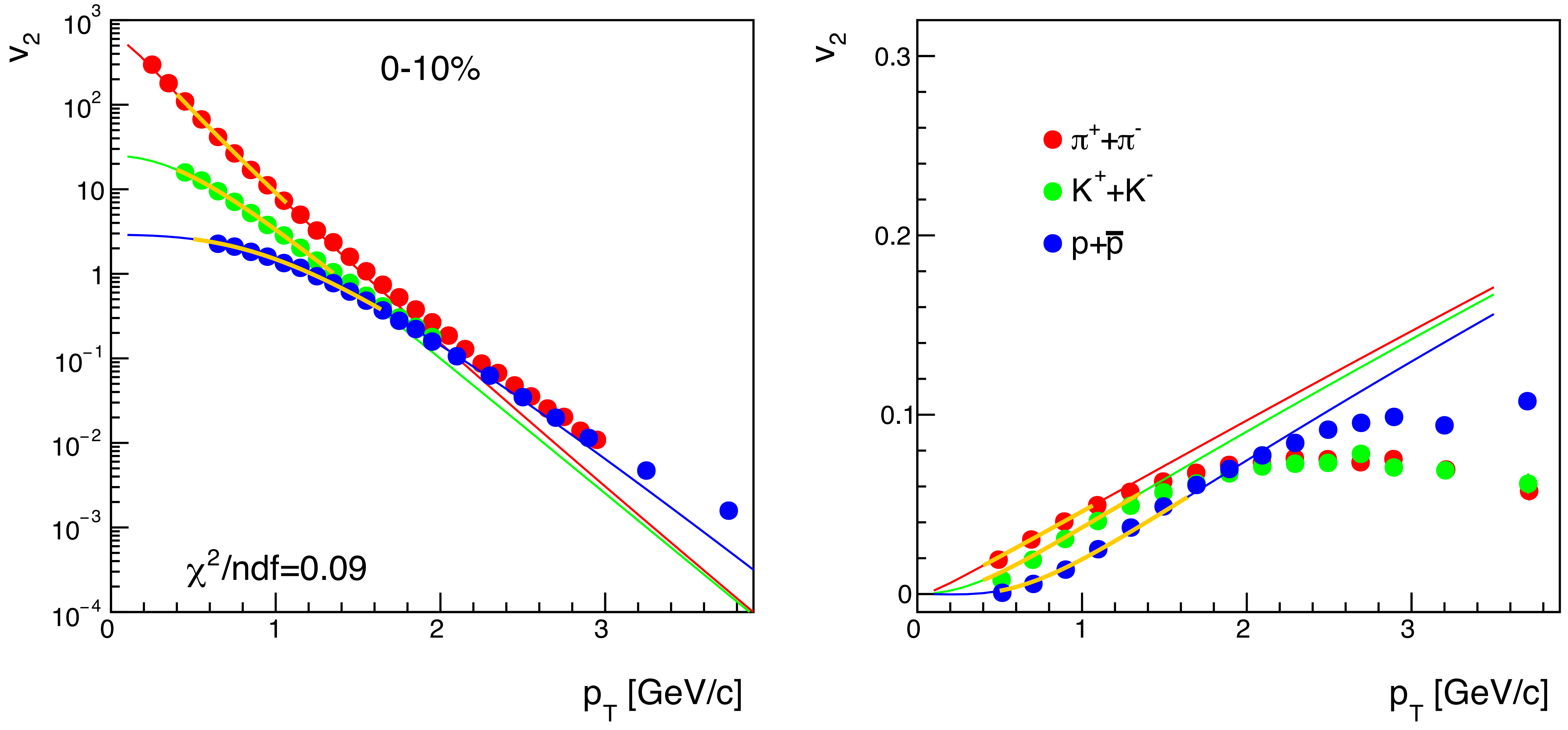
FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

ϕ_s: azimuthal angle of the source element

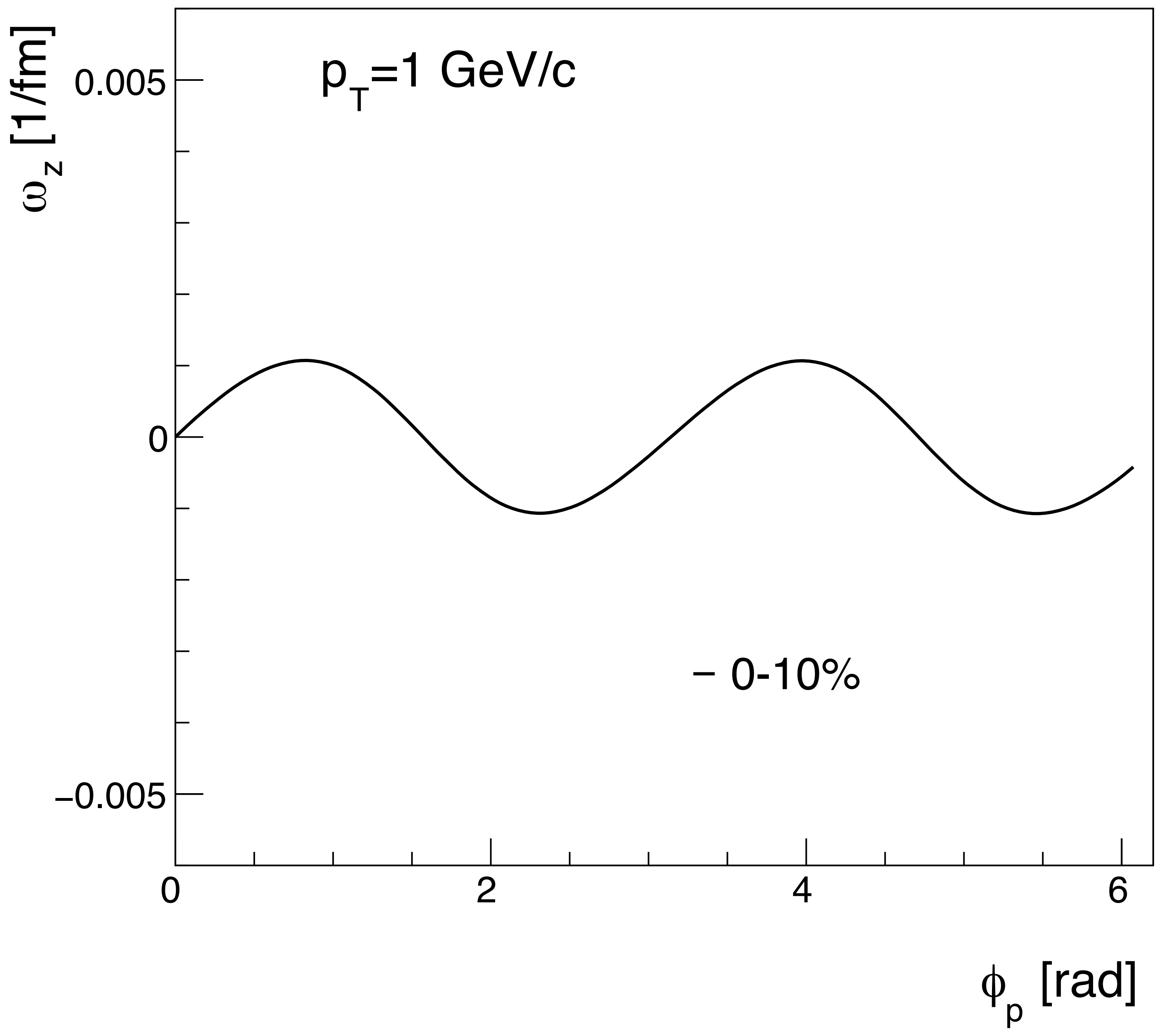
ϕ_b: boost angle perpendicular to the elliptical subshell

ω_z and P_z from the BW model

e.g. Blast-wave fit to spectra and v_2

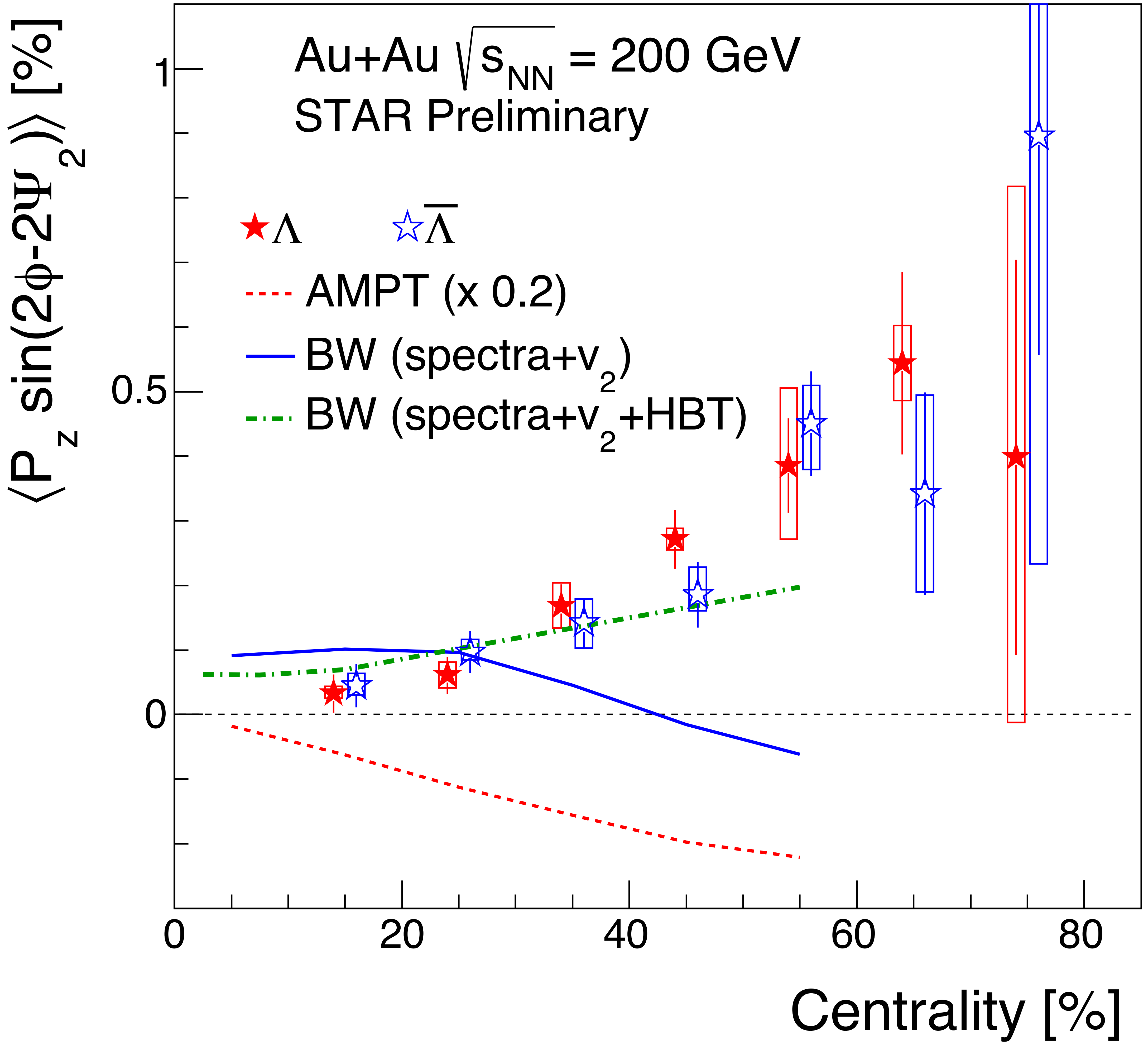


Data:
PHENIX, PRC69.034909 (2004)
PHENIX, PRC93.051902(R) (2016)



Calculated vorticity ω_z shows the sine modulation. Assuming a local thermal equilibrium, z-component of polarization is estimated as follows: $P_z \approx \omega_z/(2T)$

P_z modulation from the BW model



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

- AMPT model
  - opposite sign and 5 times larger in magnitude

    X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

- Blast-wave model
  - simple estimate for kinematic vorticity
  - similar magnitude to the data
  - inclusion of HBT in the fit affects the sign in peripheral collisions

  T. Niida, S. Voloshin, A. Dobrin, and R. Bertens, in preparation

Summary

- Observation of non-zero Λ global polarization at $\sqrt{s_{NN}}$ = 7.7-62.4 GeV, and later at 200 GeV
  - Polarization decreases at higher energies, qualitatively consistent with the models
  - Larger signal in more peripheral collisions
  - Larger signal in in-plane than in out-of-plane, opposite to the hydrodynamic model
  - No significant dependence on p_T and η
  - Charge-asymmetry dependence (~2σ level) with a possible relation to the axial current induced by B-field
- Λ polarization along the beam direction at $\sqrt{s_{NN}}$ = 200 GeV
  - Quadrupole structure of the polarization relative to the 2nd-order event plane, as expected from the elliptic flow
  - Strong centrality dependence as in the elliptic flow
  - Sign problem among different models and data, but the blast-wave model predicts the same sign and similar magnitude to the data

Back up

Feed-down effect

- Only ~25% of measured Λ and anti-Λ are primary, while ~60% 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

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R \qquad \langle S_y \rangle \propto \frac{S(S+1)}{3}(\omega + \frac{\mu}{S}B)$$

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

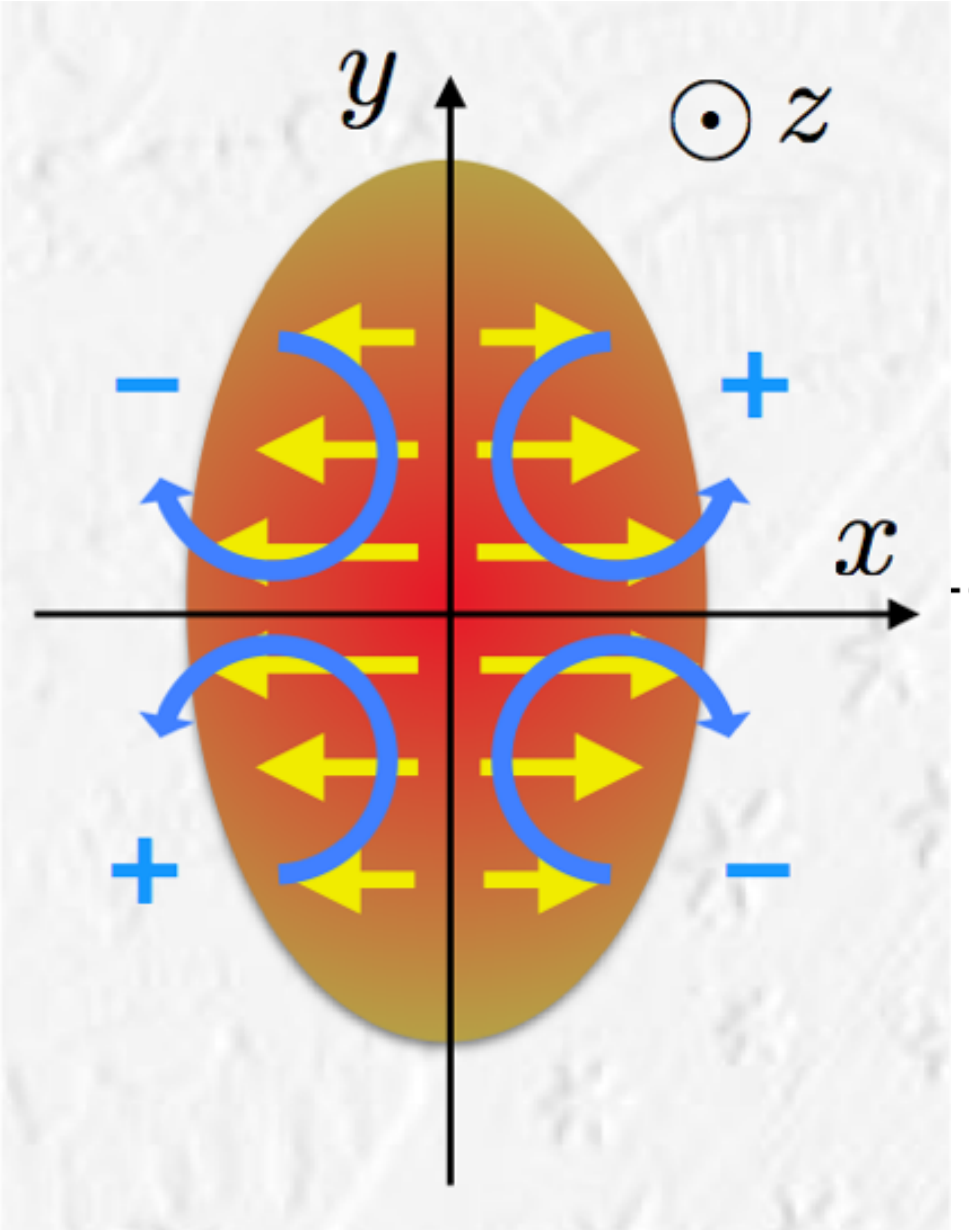
$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ
S_R : parent particle's spin
$f_{\Lambda R}$: fraction of Λ originating from parent R
μ_R : magnetic moment of particle R

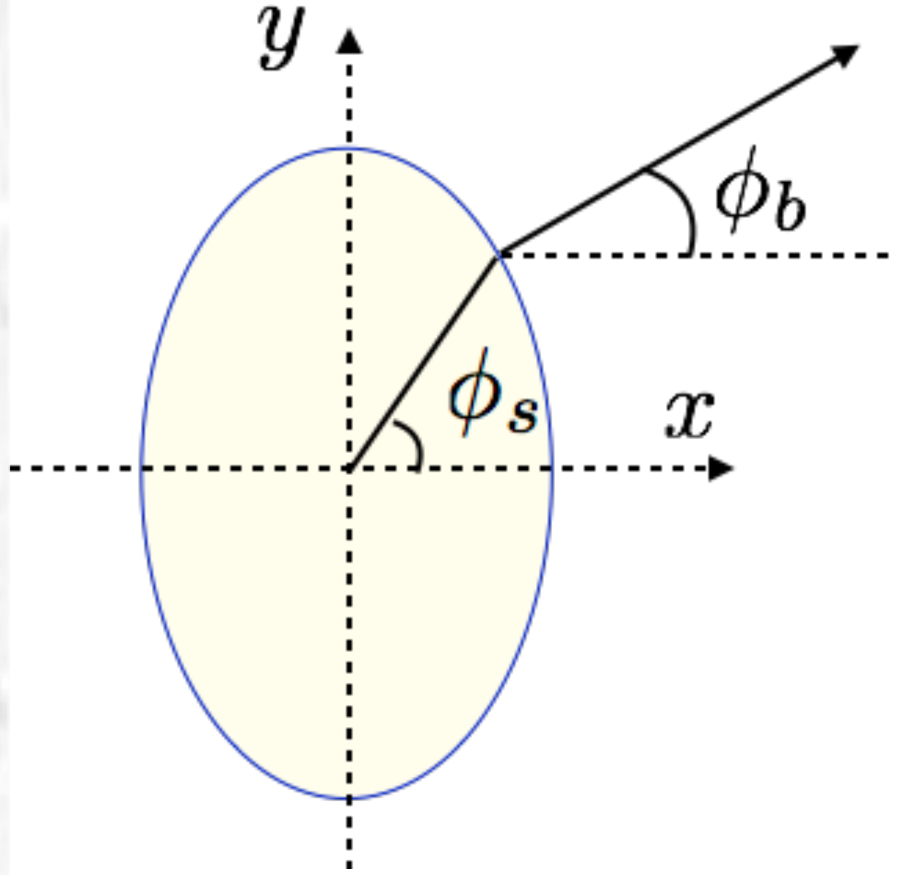
$$\begin{pmatrix} \varpi_c \\ \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\, S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\, (S_R+1)\,\mu_R \\ \\ \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right)\, S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right)\, (S_{\overline{R}}+1)\,\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P^{\rm meas}_\Lambda \\ \\ P^{\rm meas}_{\overline{\Lambda}} \end{pmatrix}$$

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
$\Sigma^0 \to \Lambda + \gamma$	$-1/3$

15%-20% dilution of primary Λ polarization (model-dependent)

Blast-wave parameterization





S. Voloshin, arXiv:1710.08934

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

$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s)] \approx \rho_{t,max}(r/R)[1 + (a + b)\cos(2\phi_s)].$$

$$\omega_z = 1/2(\nabla \times \mathbf{v})_z \approx (\rho_{t,nmax}/R)\sin(n\phi_s)[b_n - a_n].$$

a_n: spatial anisotropy
b_n: flow anisotropy
R: reference source radius
ρ_t: transverse flow velocity

Quadrupole or sine structure of ω_z is expected.

Systematic uncertainties

Case of 200 GeV as an example

- Event plane determination: ~22%
- Methods to extract the polarization signal: ~21%
- Possible contribution from the background: ~13%
- Topological cuts: <3%
- Uncertainties of the decay parameter: ~2% for Λ, ~9.6% for anti-Λ
- Extraction of Λ yield (BG estimate): <1%

Also, the following studies were done to check if there is no experimental effect:

- Two different polarities of the magnetic field for TPC
- Acceptance effect
- Different time period during the data taking
- Efficiency effect