



Λ polarization along the beam direction in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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**U.S. DEPARTMENT OF
ENERGY**

Office of
Science

***The 5th Workshop on Chirality, Vorticity, and
Magnetic Field in Heavy Ion Collisions
@Tsinghua University, Beijing***

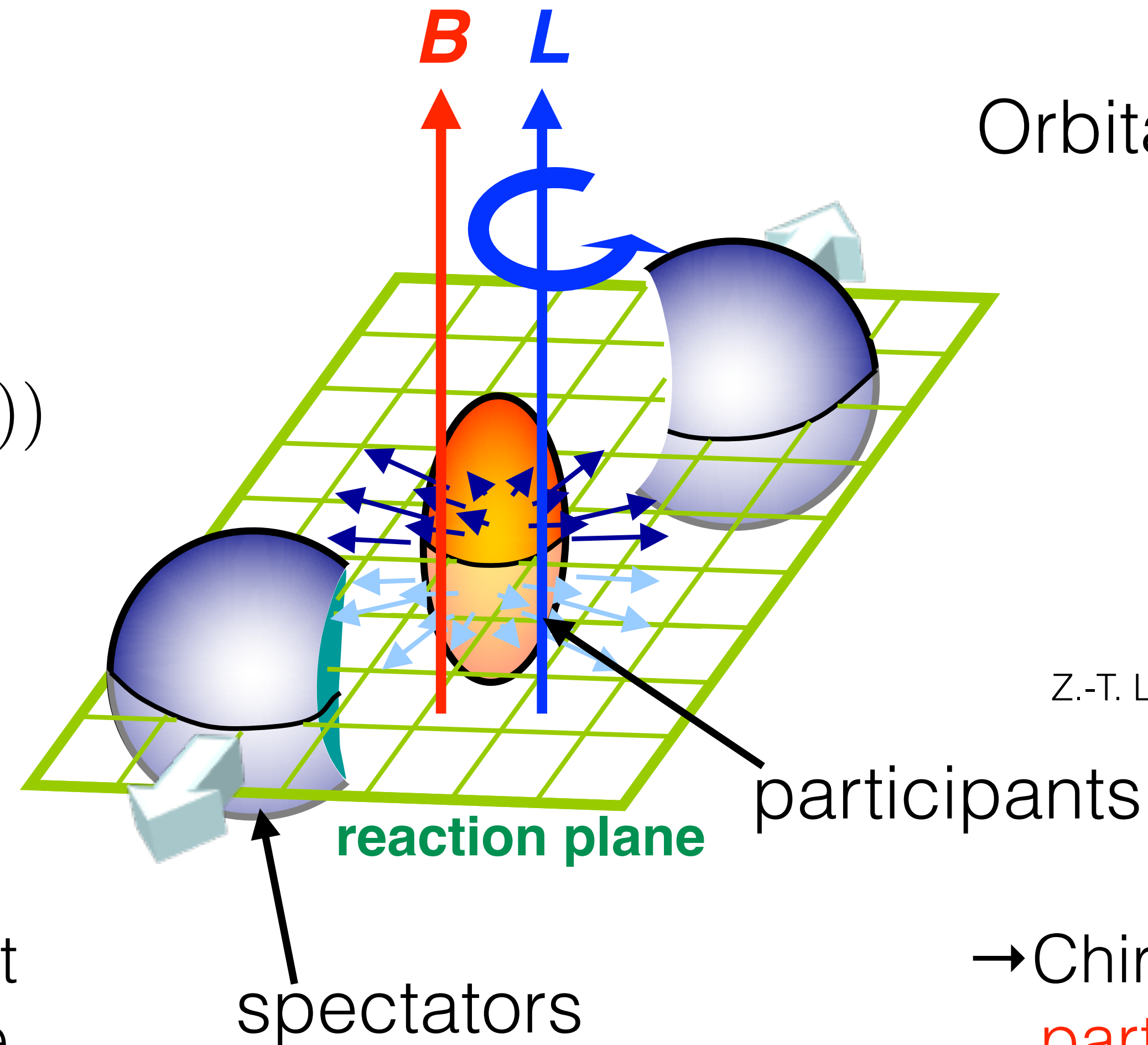
Important features in non-central heavy-ion collisions

Strong magnetic field

$$B \sim 10^{13} \text{ T}$$
$$(eB \sim \text{MeV}^2 \text{ } (\tau = 0.2 \text{ fm}))$$

Orbital angular momentum

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



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

→ Chiral magnetic effect
Chiral magnetic wave
particle polarization

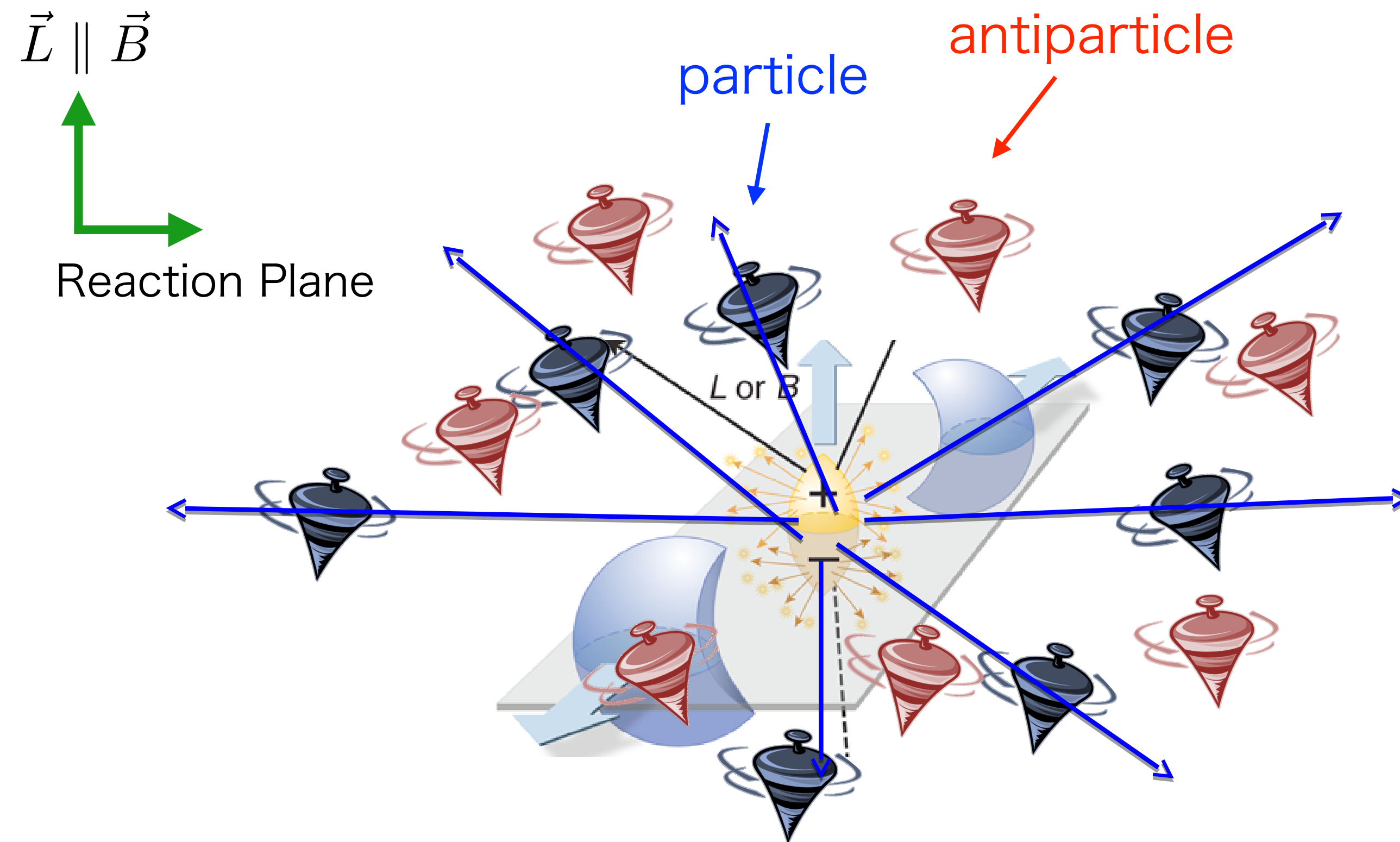
→ Chiral vortical effect
particle polarization

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



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, $\mathbf{L}$
- Magnetic field align particle's spin
 - Particles' and antiparticles' spins are aligned oppositely along $\mathbf{B}$ due to the opposite sign of magnetic moment



How to measure the global polarization?

Parity-violating decay of hyperons

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

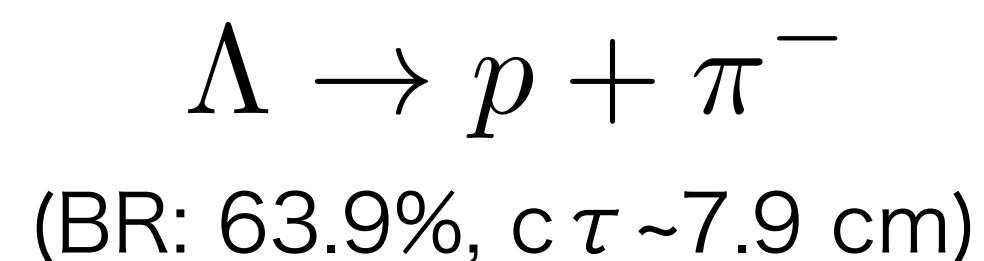
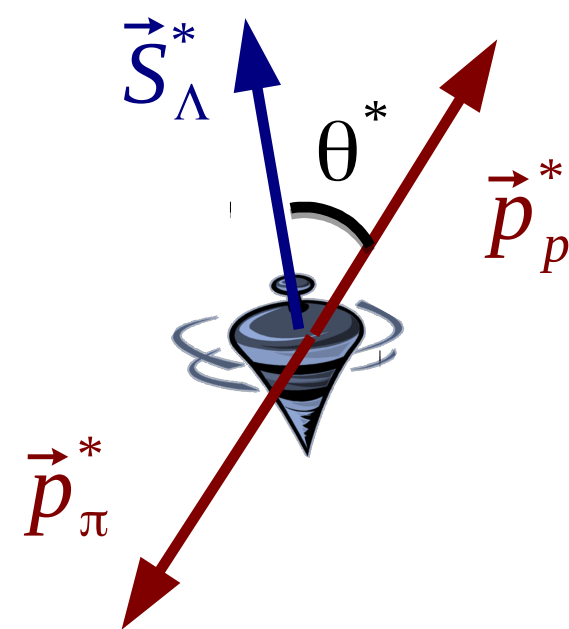
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)$$

P_H : Λ polarization

p_p^* : proton momentum in the Λ rest frame

α_H : Λ decay parameter

$$(\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013)$$

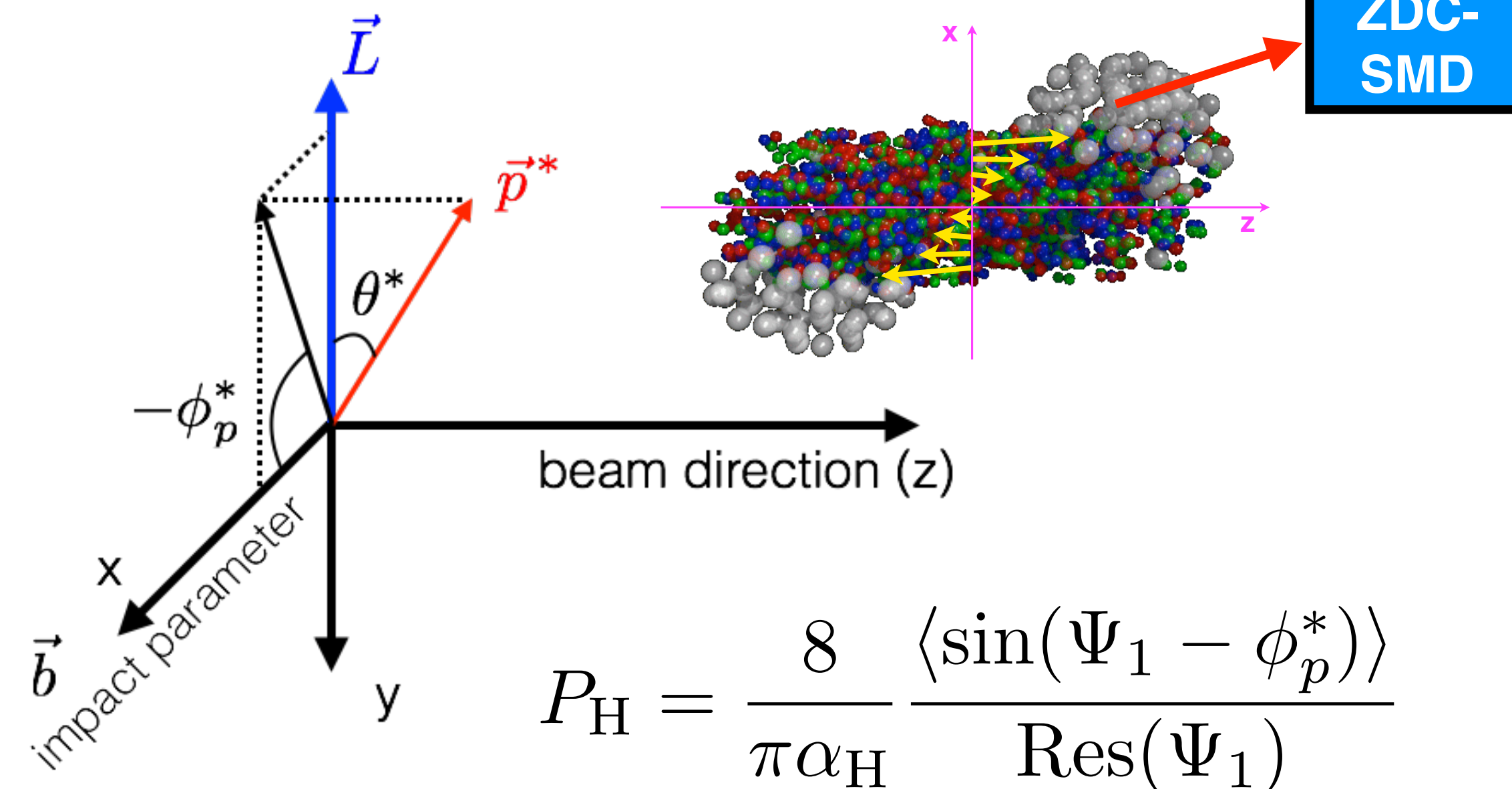


C. Patrignani et al. (PDG), Chin. Phys. C 40, 100001 (2016)

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)



Ψ_1 : azimuthal angle of b

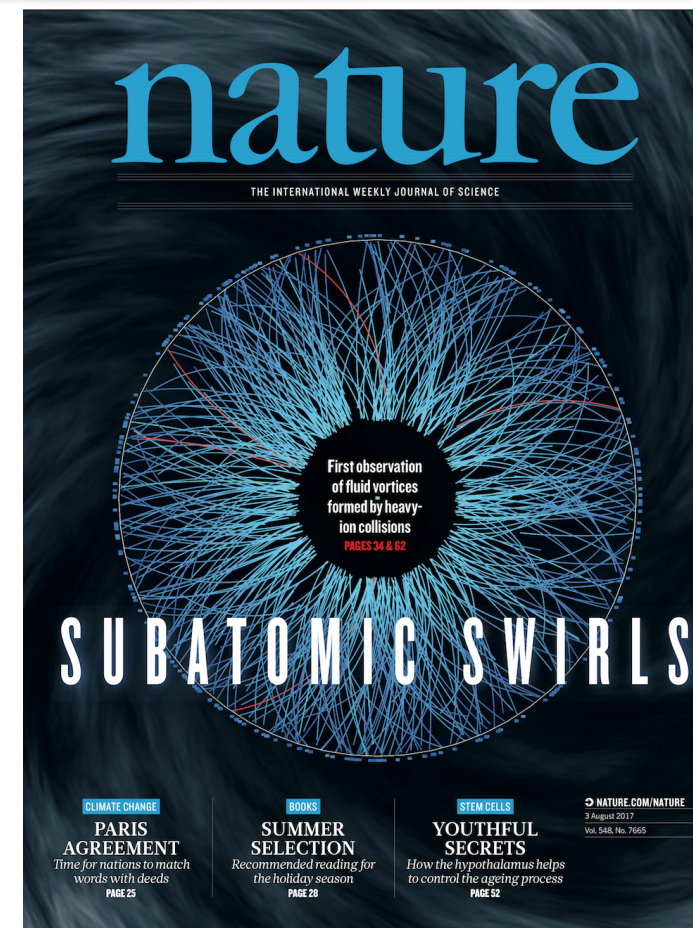
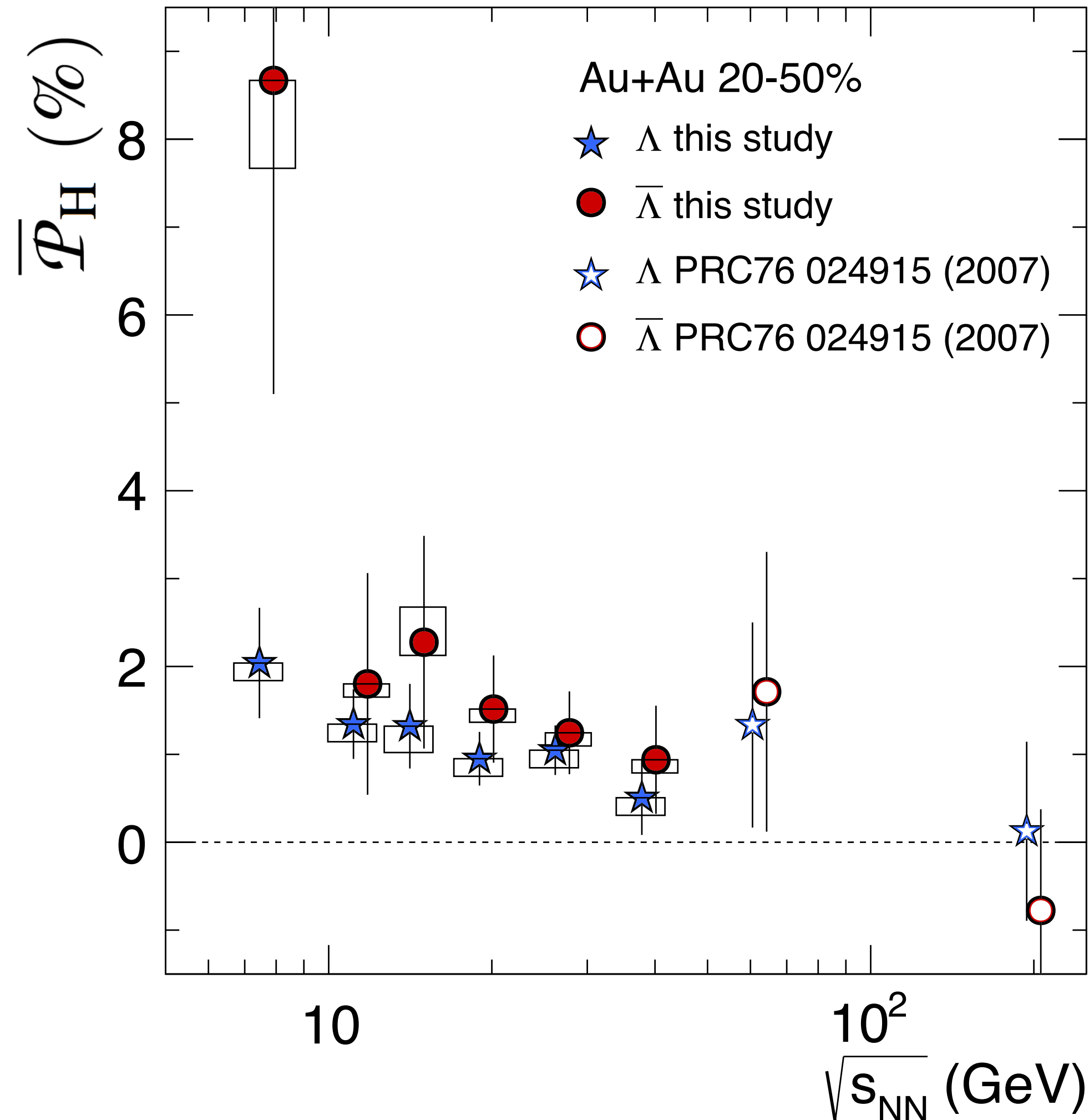
ϕ_p^* : ϕ of daughter proton in Λ rest frame

STAR, PRC76, 024915 (2007)



First observation of fluid vortices in HIC

STAR, Nature 548, 62 (2017)



#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 looks larger than Λ , possible effect of B-field?

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

μ_Λ : Λ magnetic moment
T: temperature at thermal equilibrium

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

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

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T / \hbar$$

$$\sim 0.02-0.09 \text{ fm}^{-1}$$

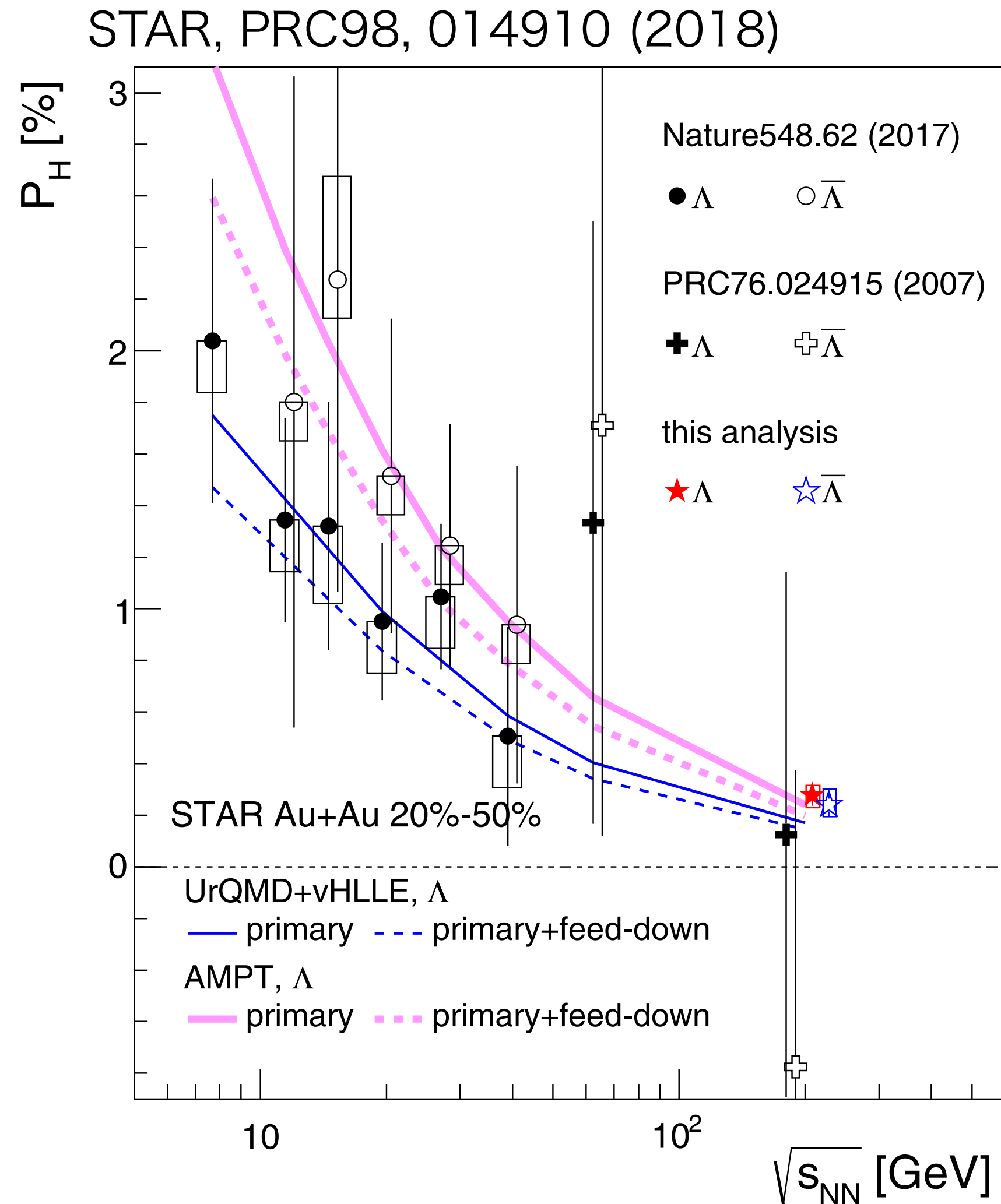
$$\sim 0.6-2.7 \times 10^{22} \text{ s}^{-1}$$

(T=160 MeV)

The most vortical fluid ever observed!



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



Average P_H for 20-50%:

$$P_H(\Lambda) [\%] = 0.277 \pm 0.040(\text{stat}) \pm_{0.049}^{0.039} (\text{sys})$$

$$P_H(\bar{\Lambda}) [\%] = 0.240 \pm 0.045(\text{stat}) \pm_{0.045}^{0.061} (\text{sys})$$

- Having new results for 200 GeV, P_H decreases in higher energy
 - partly due to stronger shear flow structure in lower $\sqrt{s_{NN}}$ because of baryon transparency
- Both hydrodynamic and AMPT models describe the data
 - 15%-20% smearing effect in the data due to feed-down

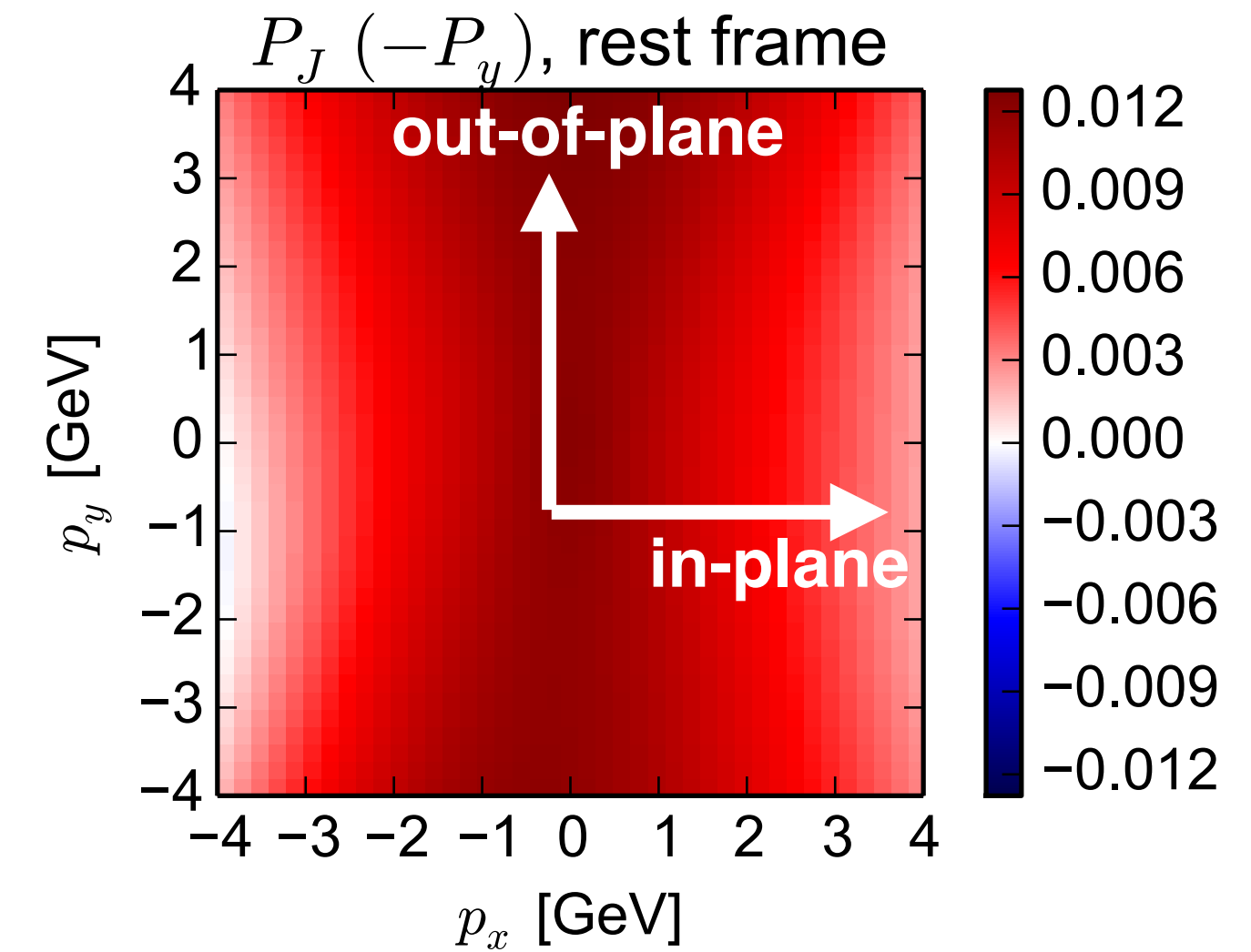
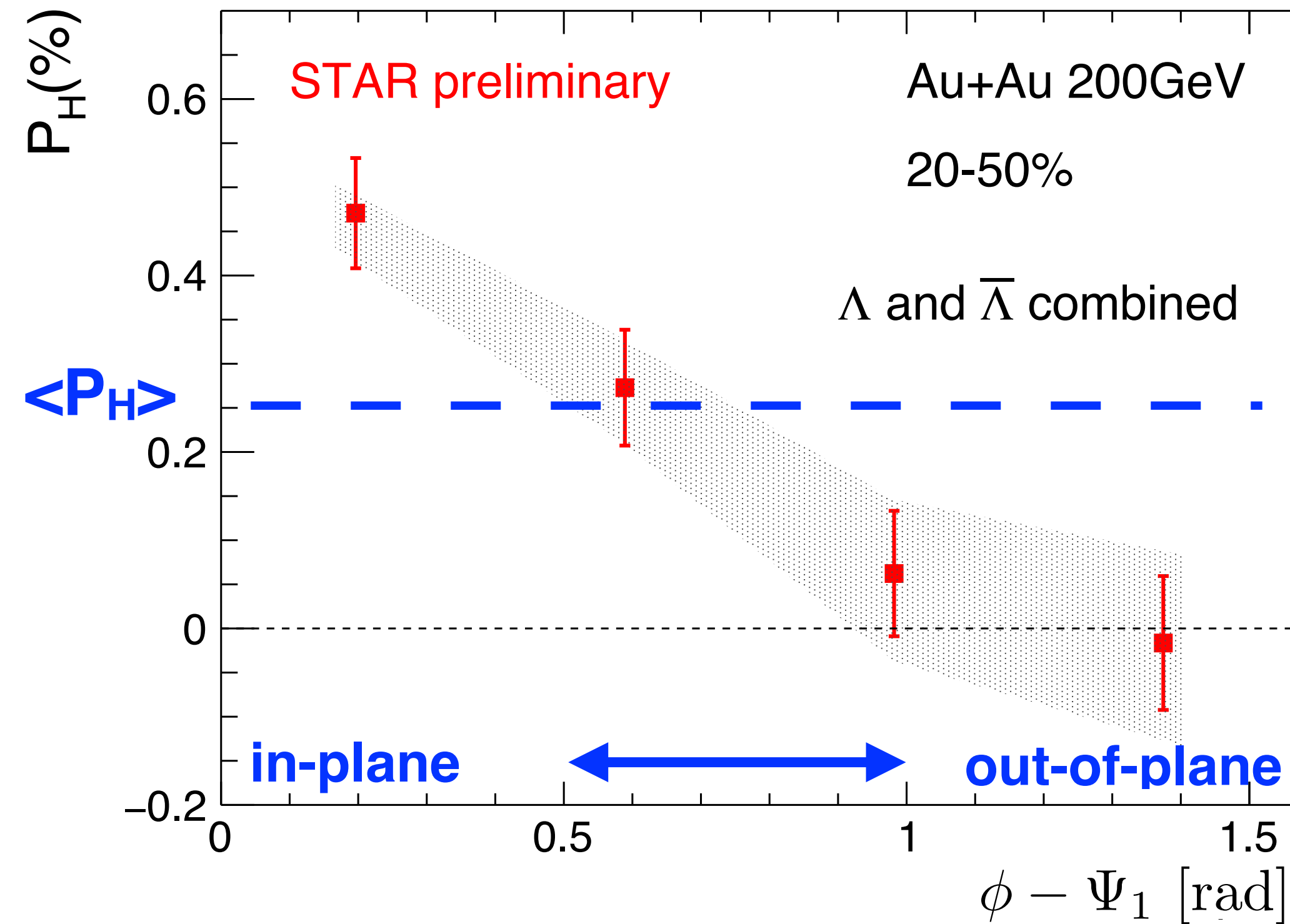
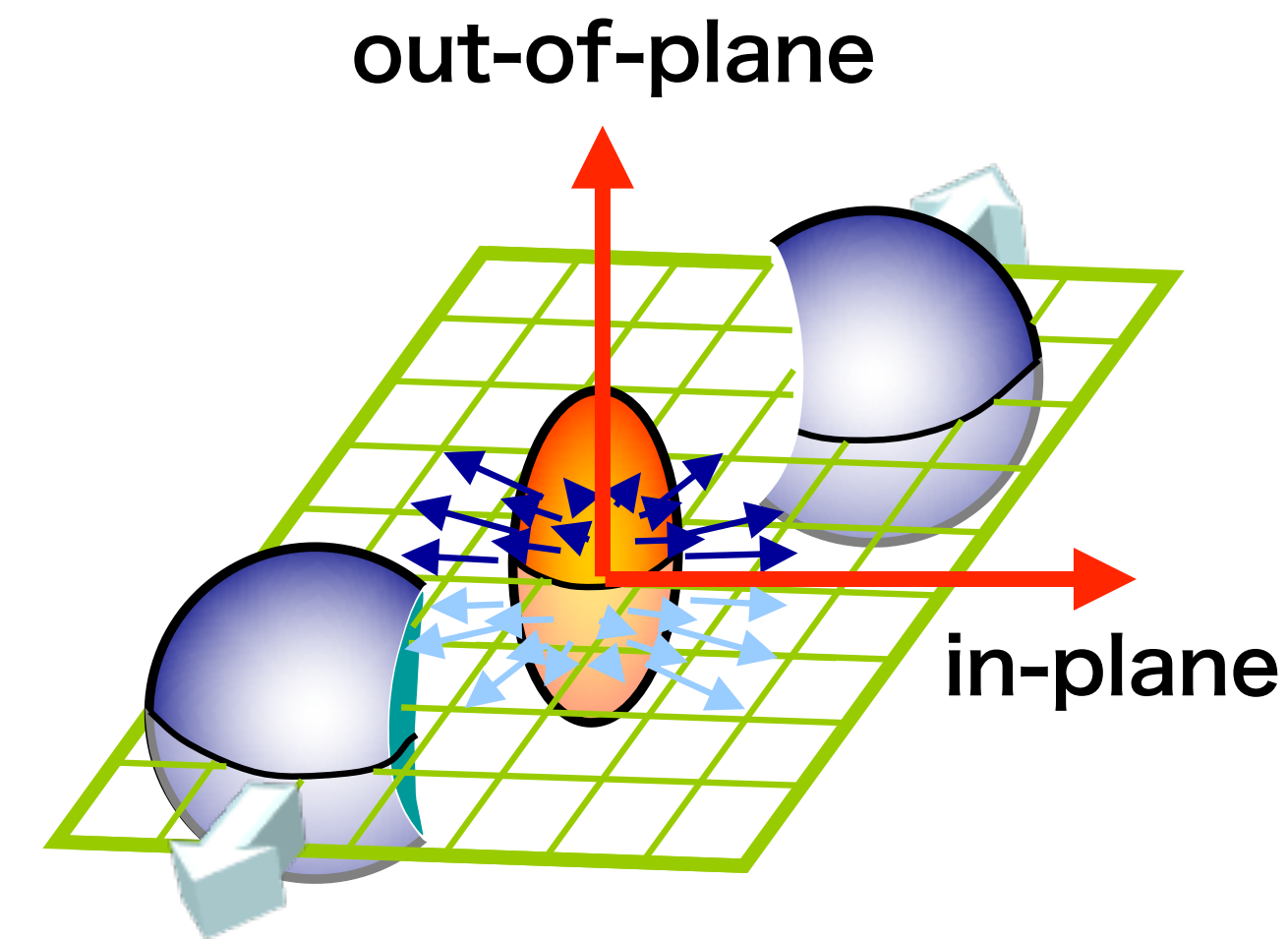
F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin,
PRC95.054902 (2017)

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

AMPT: H. Li et al., Phys. Rev. C 96, 054908 (2017)



Azimuthal angle dependence of P_H



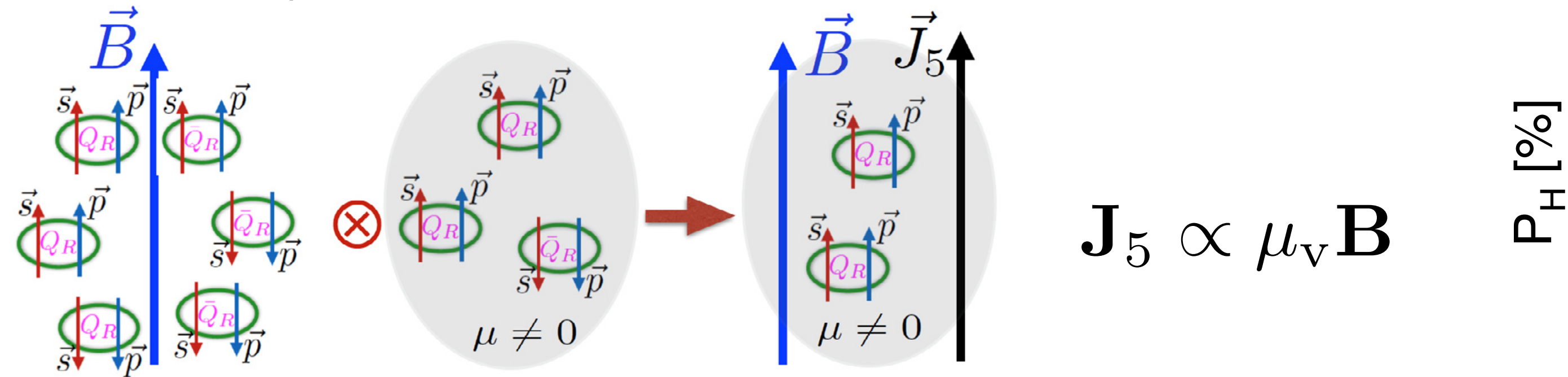
I. Karpenko and F. Becattini, EPJC(2017)77:213

- ◆ Larger polarization in in-plane than in out-of-plane
- ◆ Opposite to the hydrodynamic expectation (larger in out-of-plane)



Λ polarization vs. charge asymmetry

Chiral Separation Effect



B-field + massless quarks + non-zero $\mu_v \rightarrow$ axial current J_5

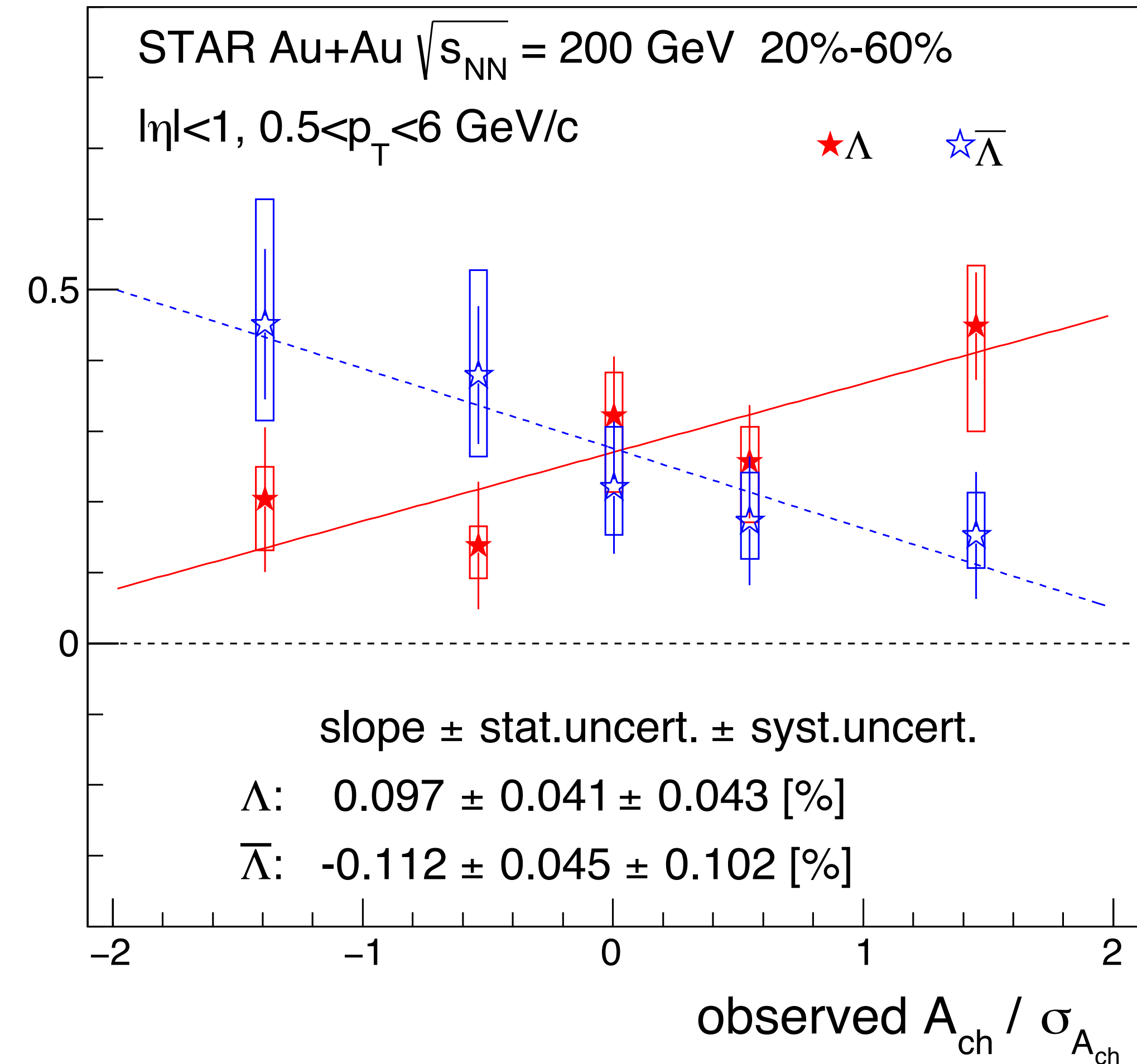
$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{\text{ch}}$$

$\mu_v > 0$
B-field $\uparrow$
 $\mathbf{p}$ $\uparrow_{\text{RH}}$ $\downarrow_{\text{LH}}$
spin $\uparrow$
 J_5 $\uparrow$

- Slopes of Λ and anti- Λ seem to be different ($\sim 2\sigma$ level)
- Possible contribution to the polarization from the axial current J_5 induced by B-field (Chiral Separation Effect)

S. Shlichting and S. Voloshin

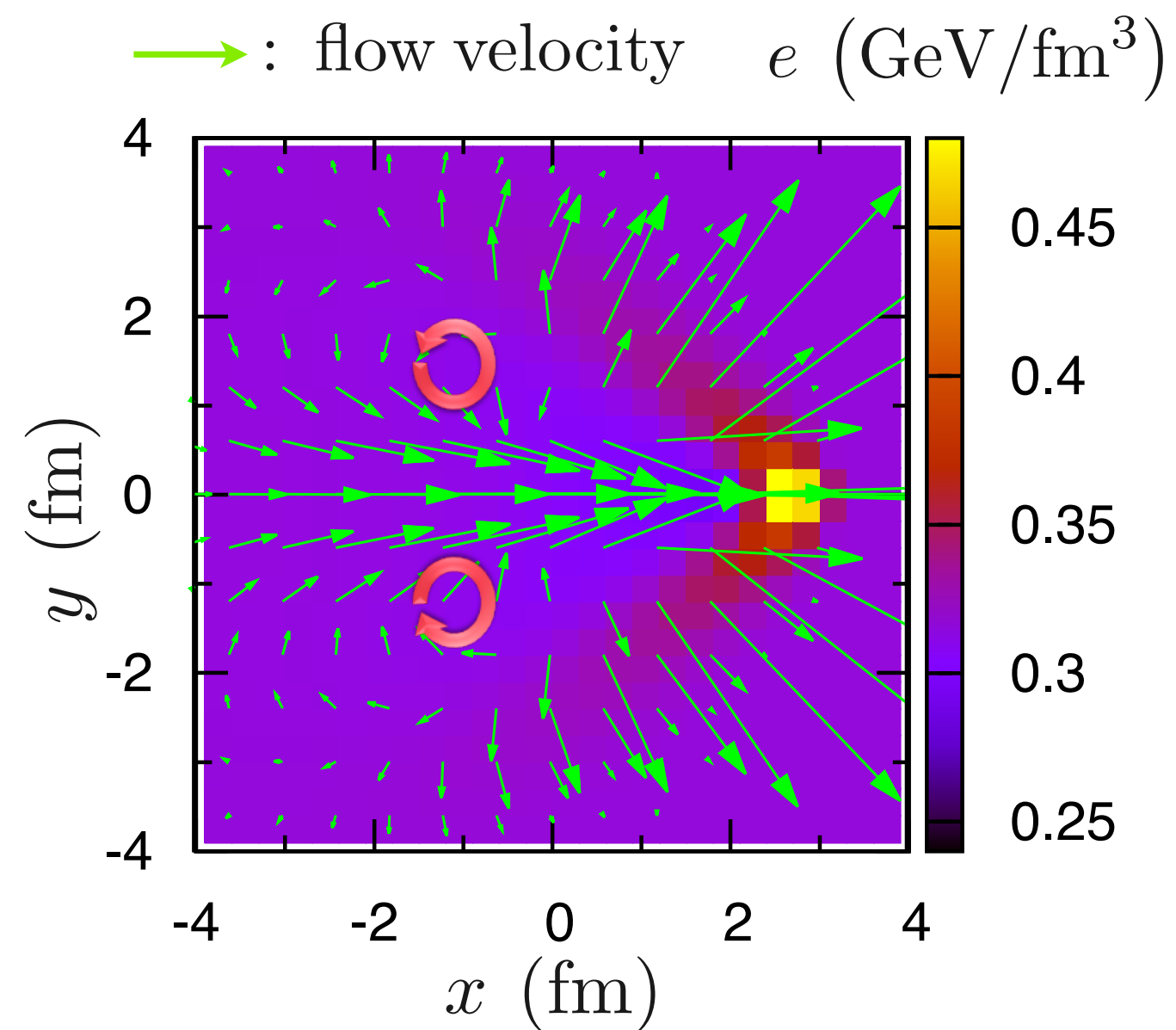
STAR, PRC98, 014910 (2018)





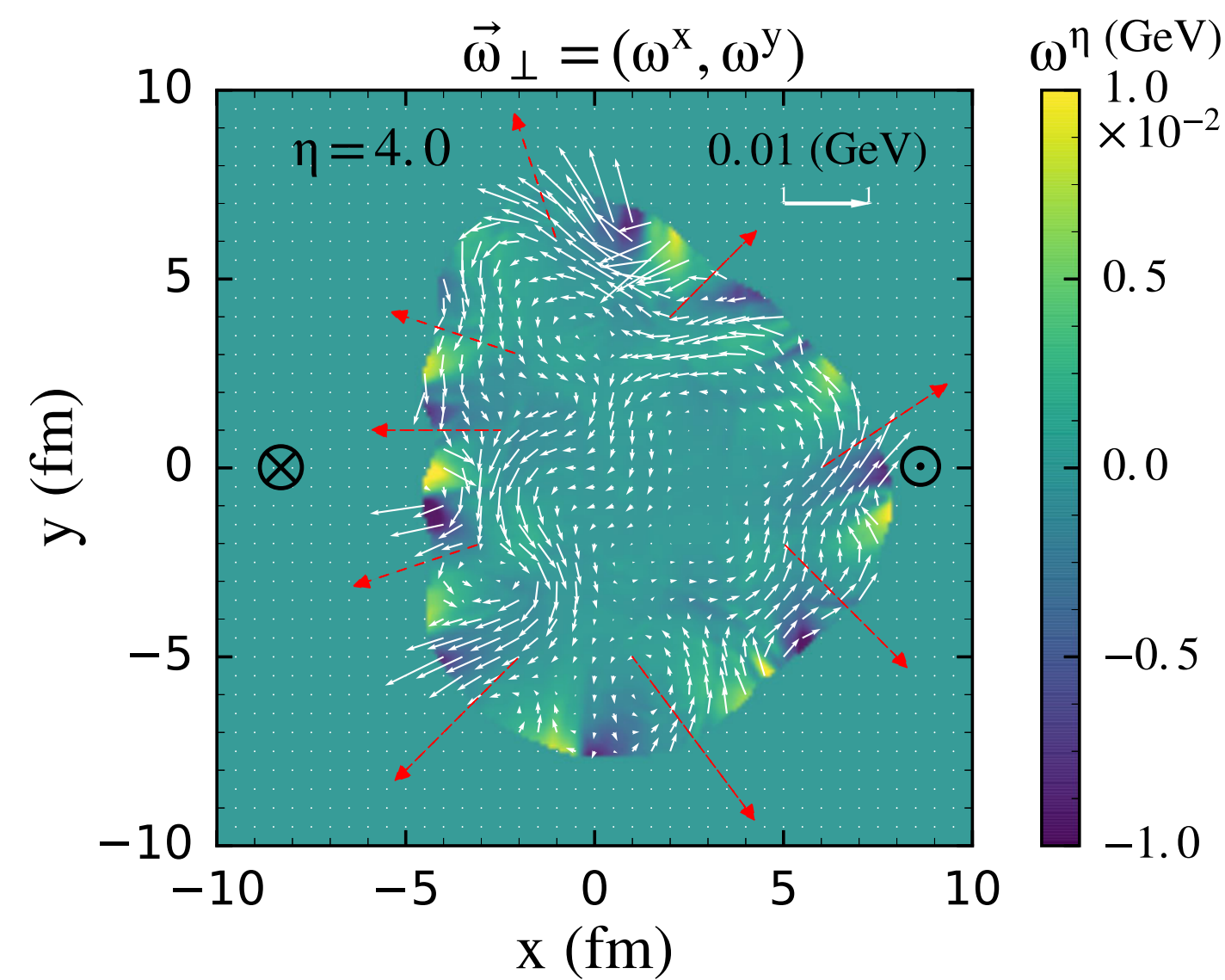
Local vorticity

vortex induced by jet

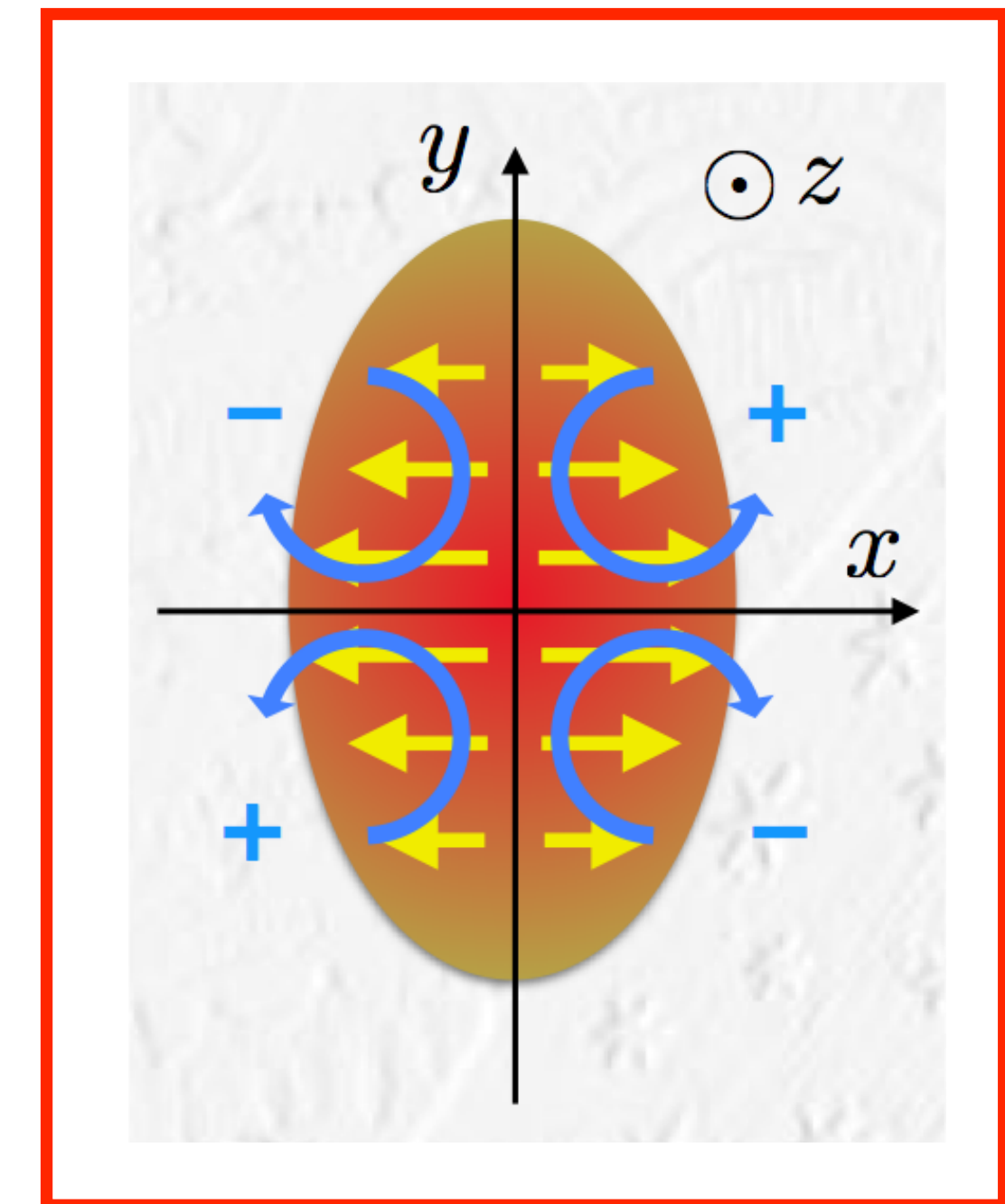


Y. Tachibana and T. Hirano,
NPA904-905 (2013) 1023

local vorticity induced by collective flow



L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang
PRL117, 192301 (2016)



F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

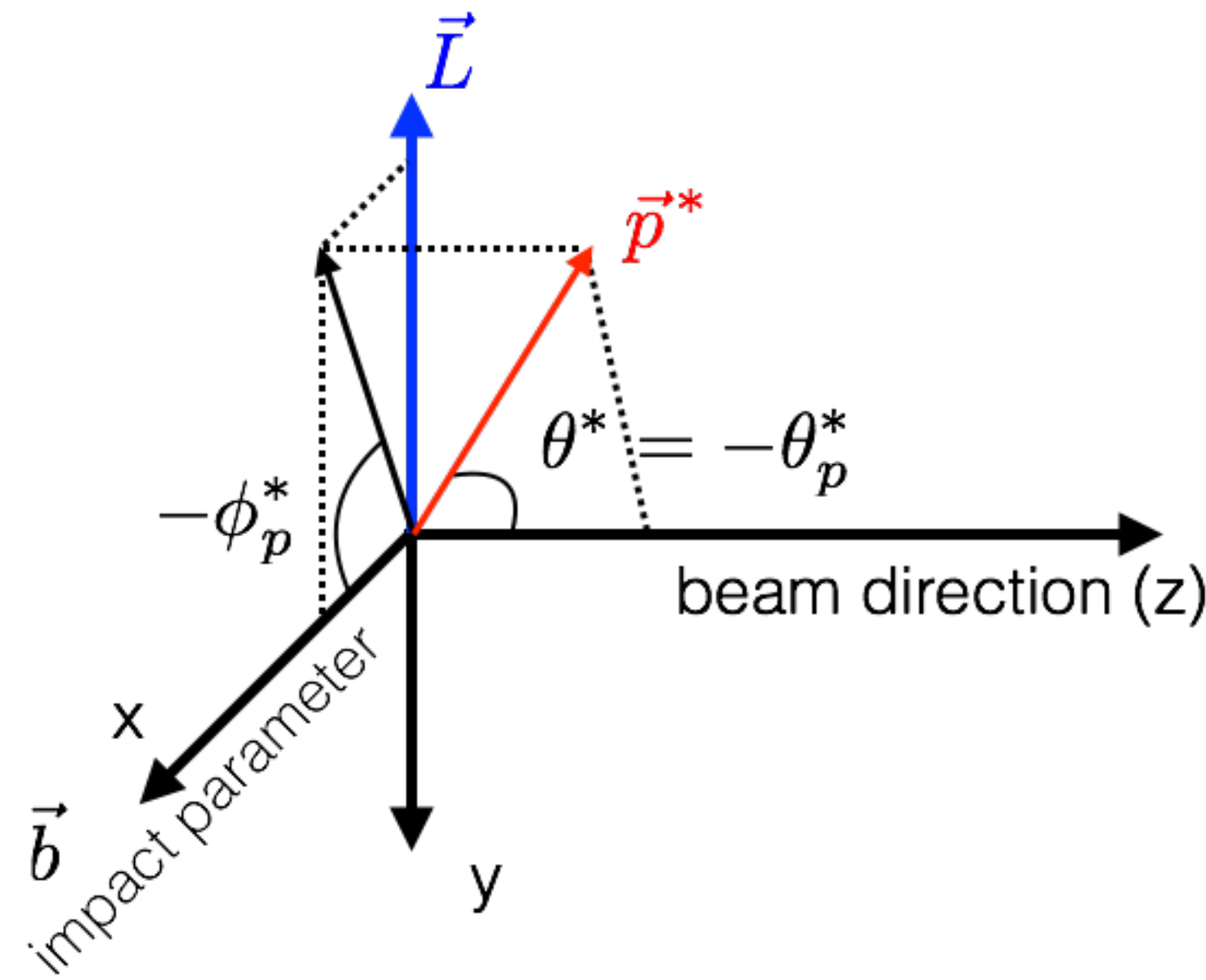
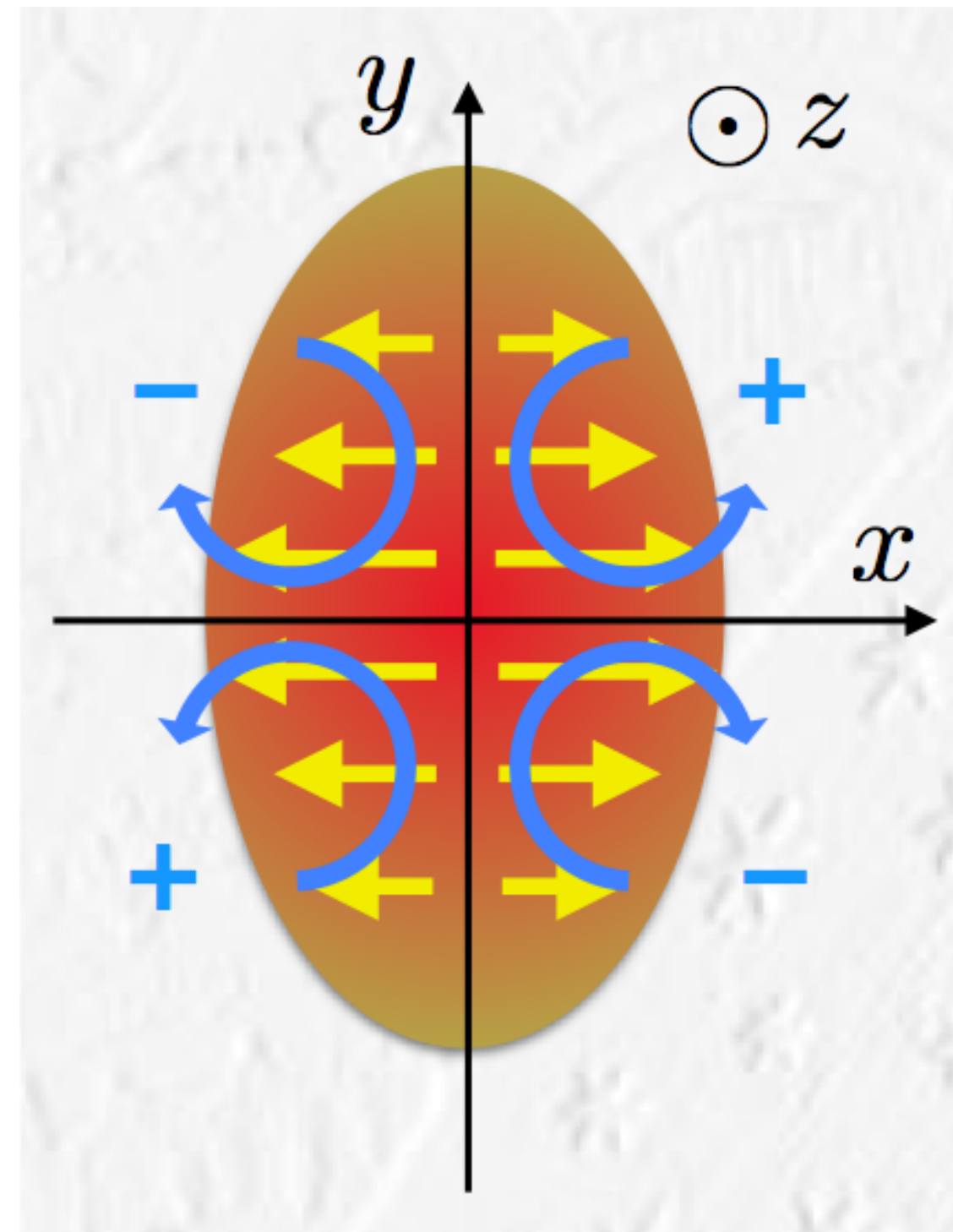
Vorticity (polarization) along the beam direction due to the elliptic flow



Polarization along the beam direction

S. Voloshin, SQM2017

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



$$\begin{aligned}\frac{dN}{d\Omega^*} &= \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*) \\ \langle \cos \theta_p^* \rangle &= \int \frac{dN}{d\Omega^*} \cos \theta_p^* d\Omega^* \\ &= \alpha_H P_z \langle (\cos \theta_p^*)^2 \rangle \\ \therefore P_z &= \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle (\cos \theta_p^*)^2 \rangle} \\ &= \frac{3 \langle \cos \theta_p^* \rangle}{\alpha_H} \quad (\text{if perfect detector})\end{aligned}$$

α_H : hyperon decay parameter

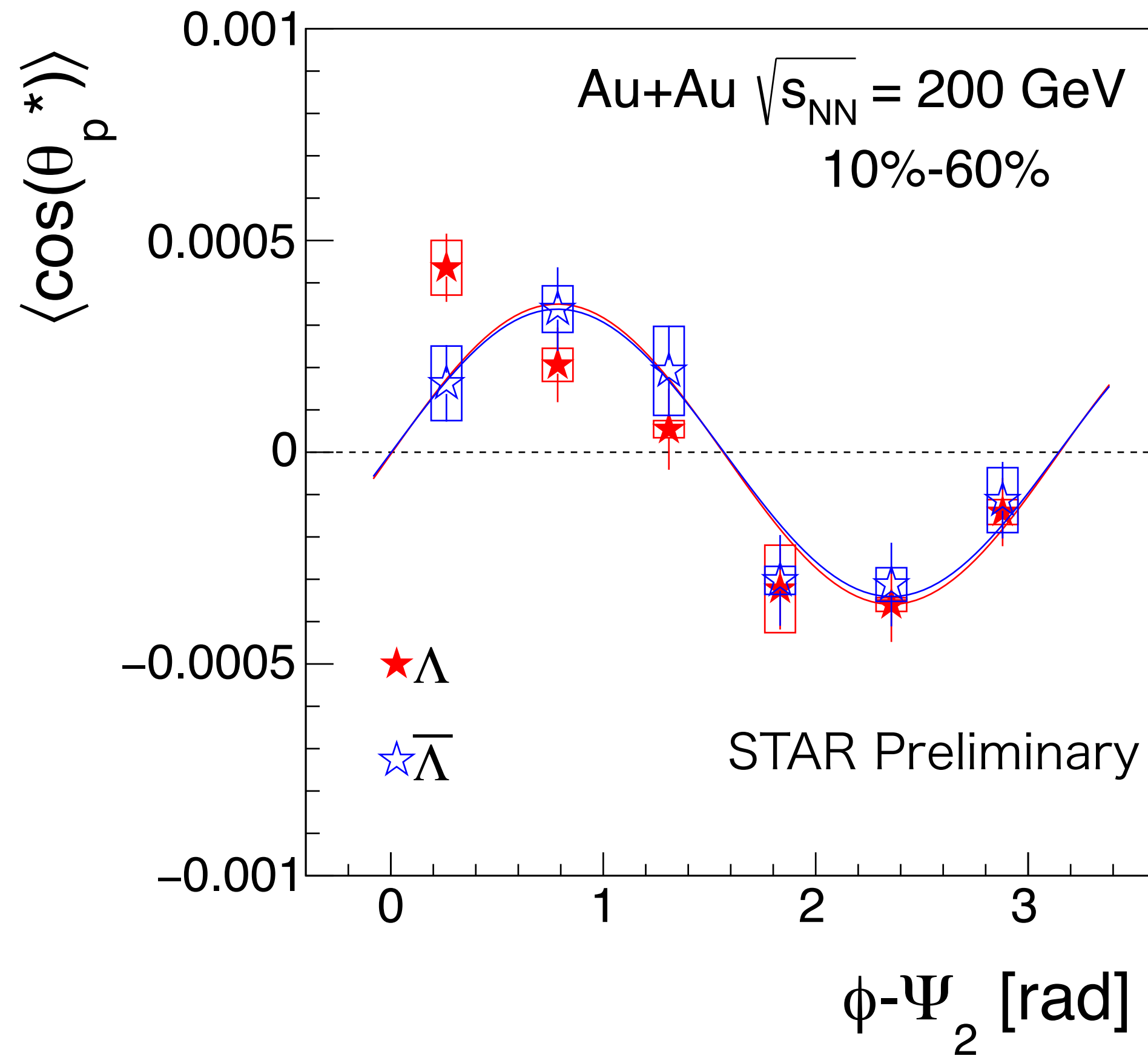
θ_p^* : θ of daughter proton in Λ rest frame

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 $\langle \cos \theta_p^* \rangle$. $\langle (\cos \theta_p^*)^2 \rangle$ accounts for an acceptance effect

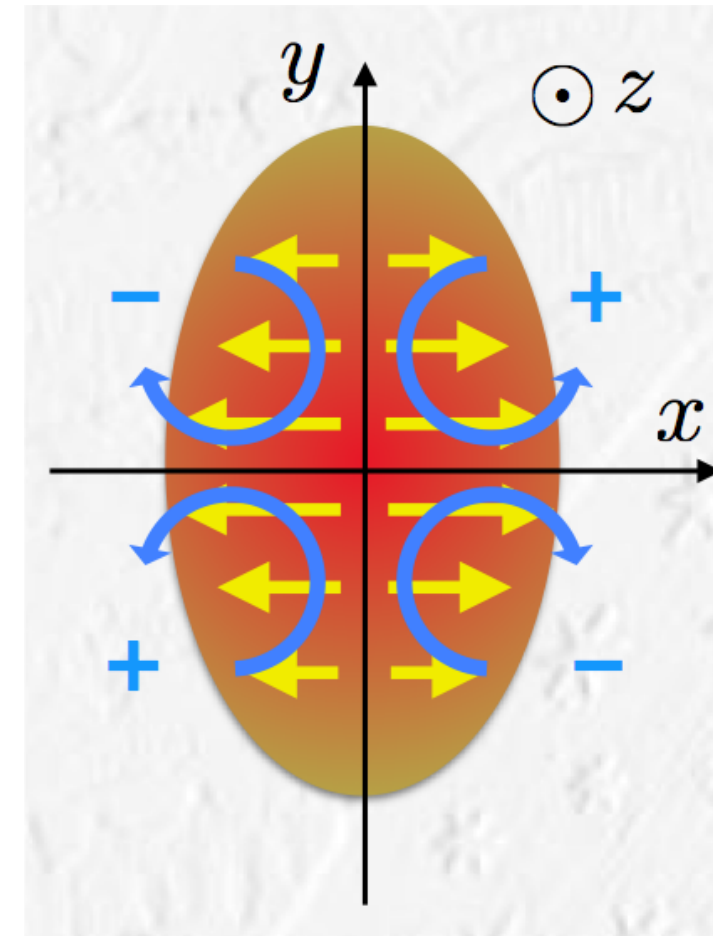


Polarization along the beam direction

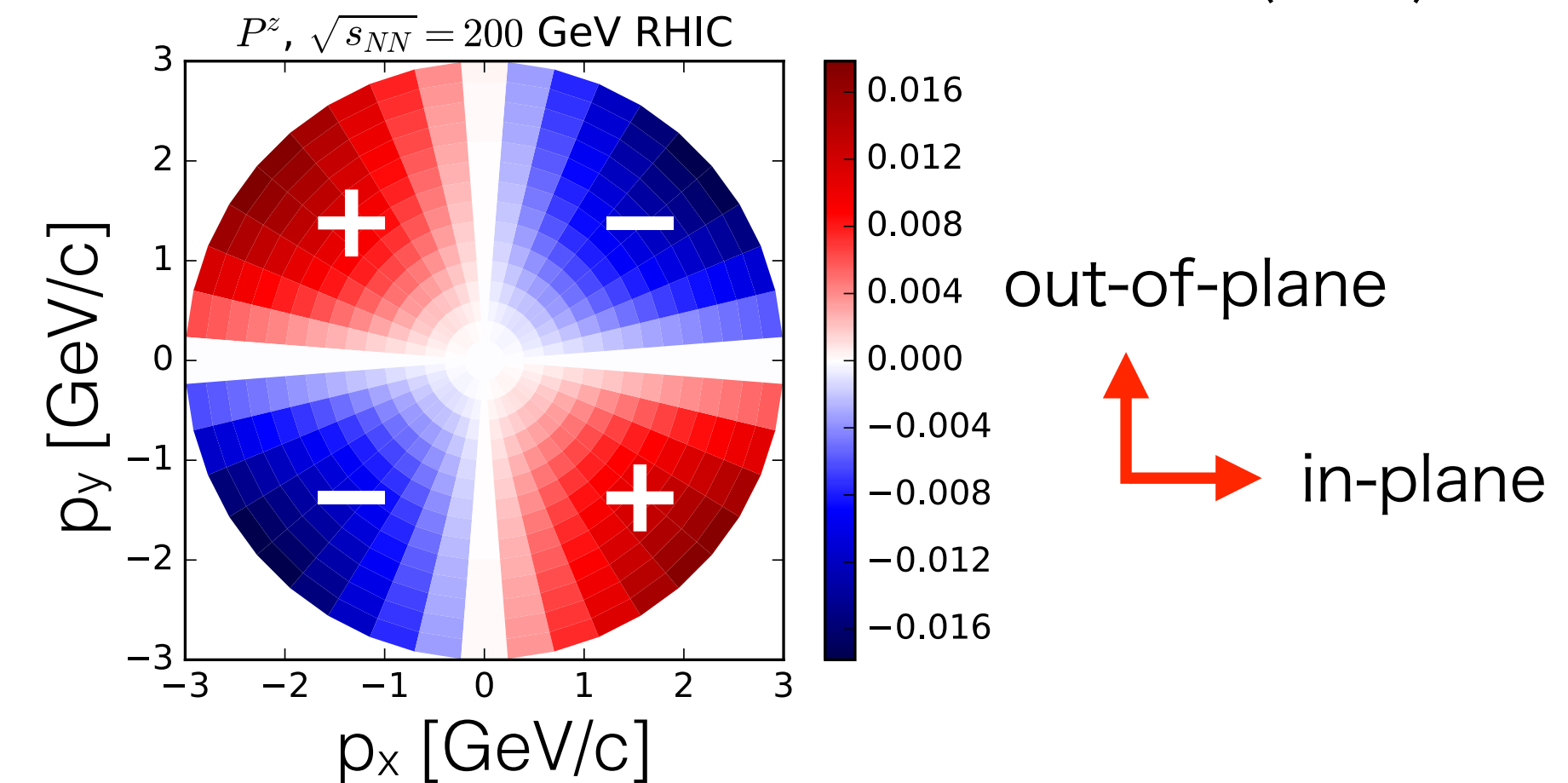


- Effect of Ψ_2 resolution is not corrected here

S. Voloshin, SQM2017



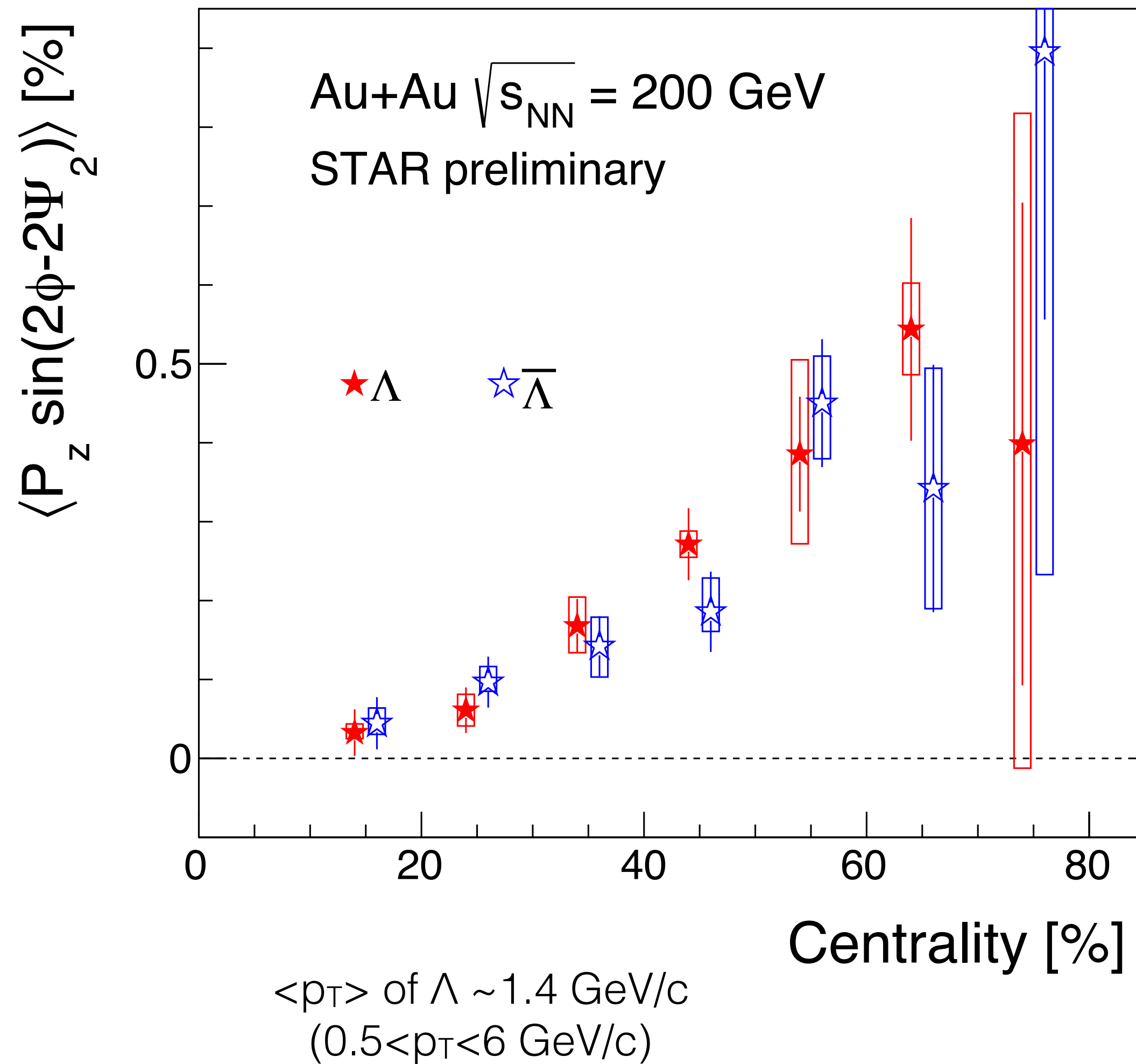
Hydro calculation of P_z
F. Becattini and I. Karpenko,
PRL.120.012302 (2018)



- Sine structure as expected from the elliptic flow!
- Opposite sign to the hydrodynamic model and 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

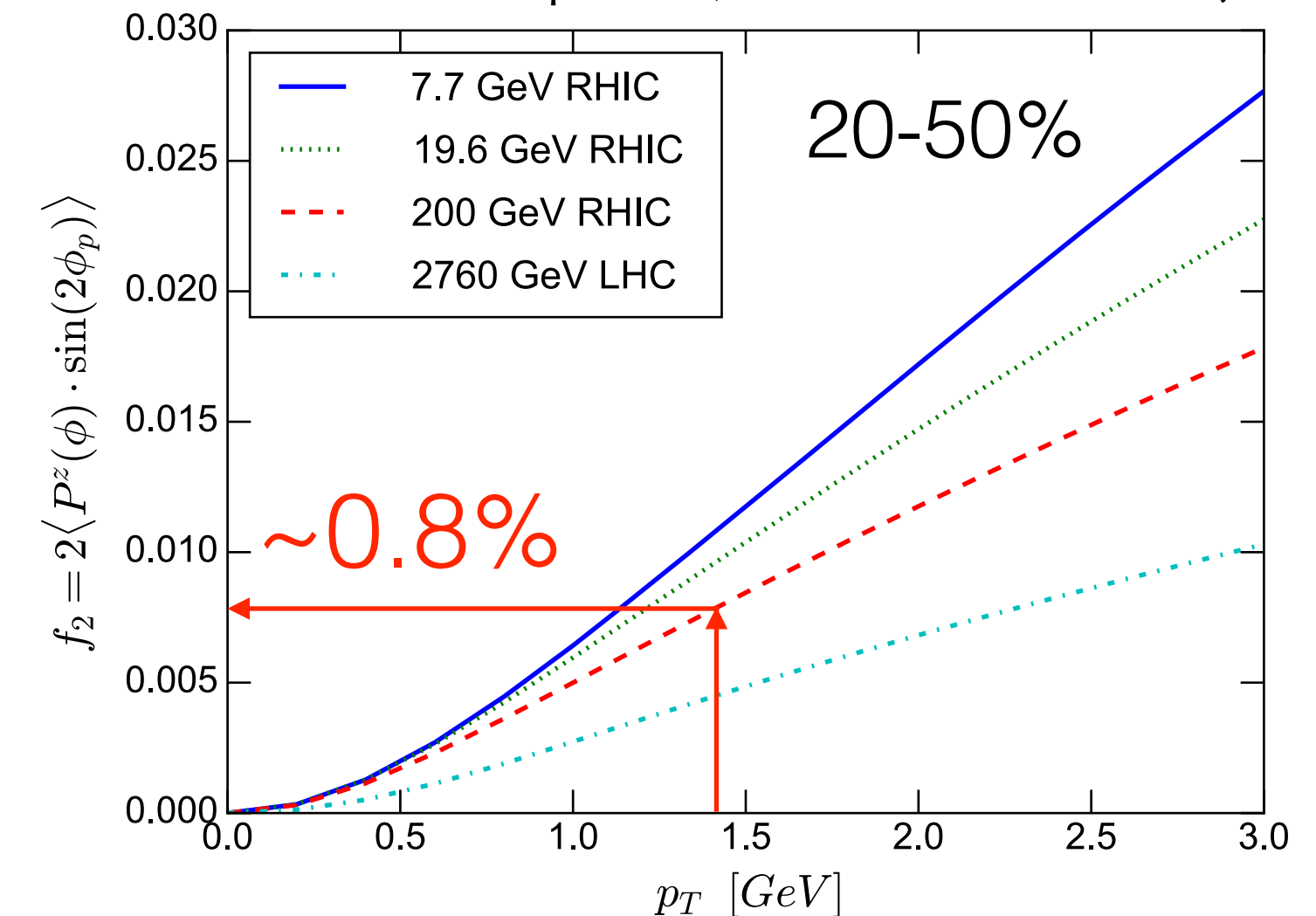


Centrality dependence of P_z modulation



- 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

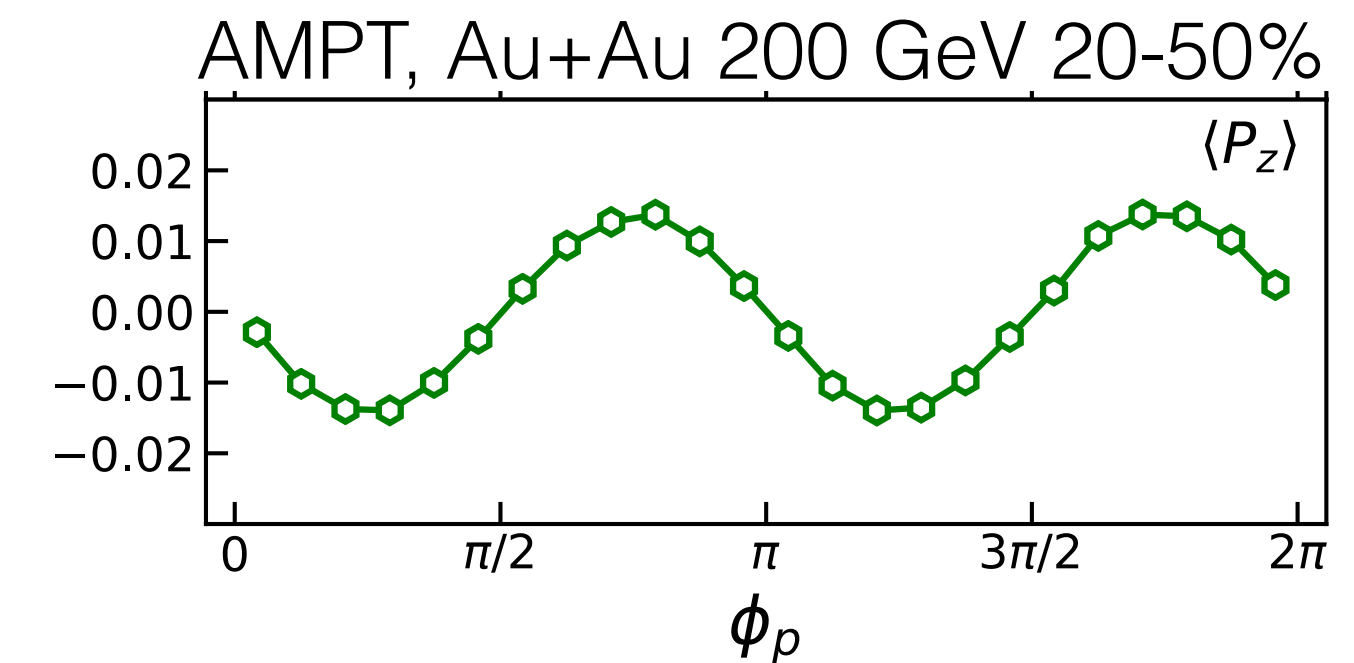
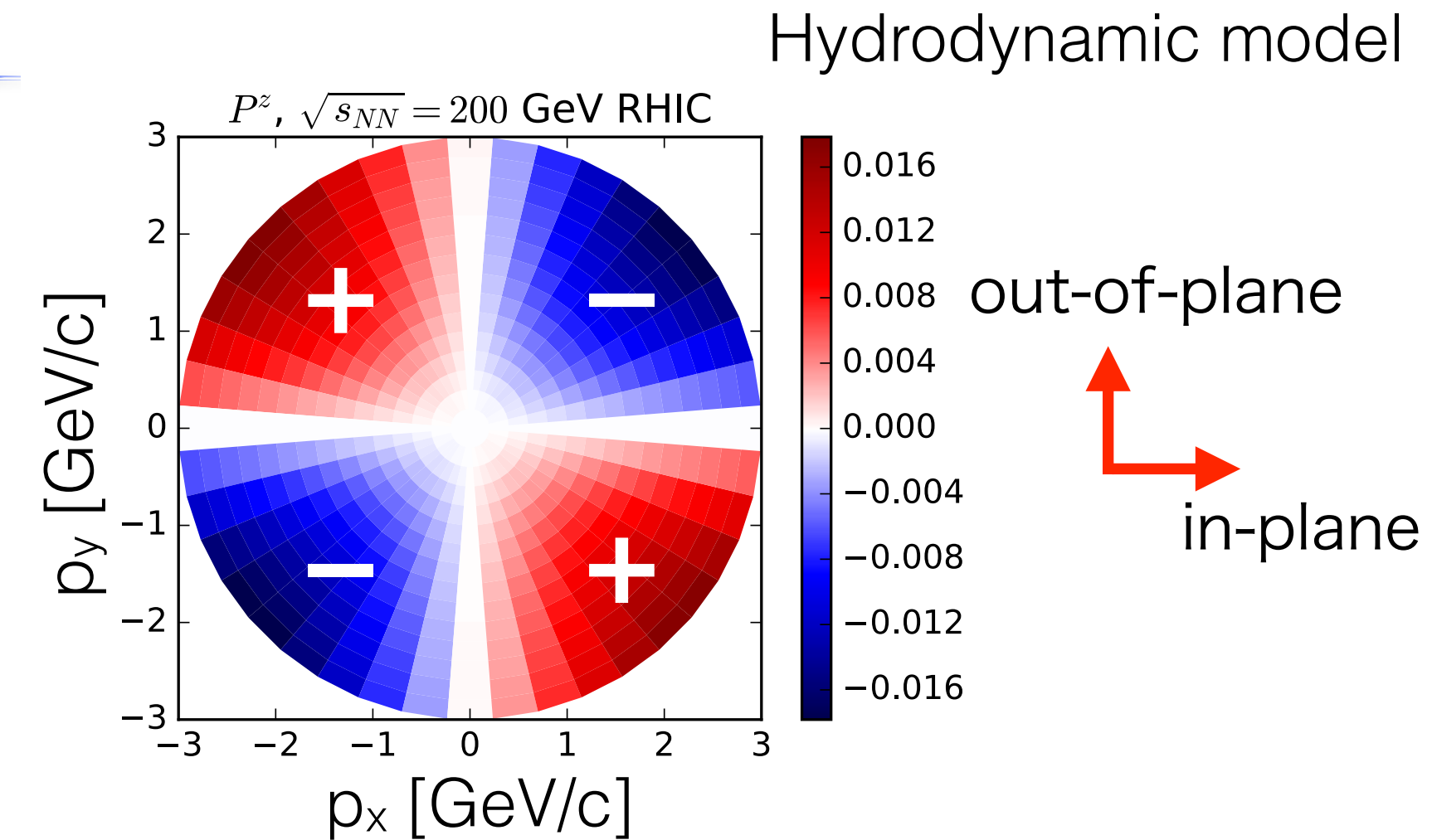
Opposite sign to hydrodynamic model and AMPT model

- 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)

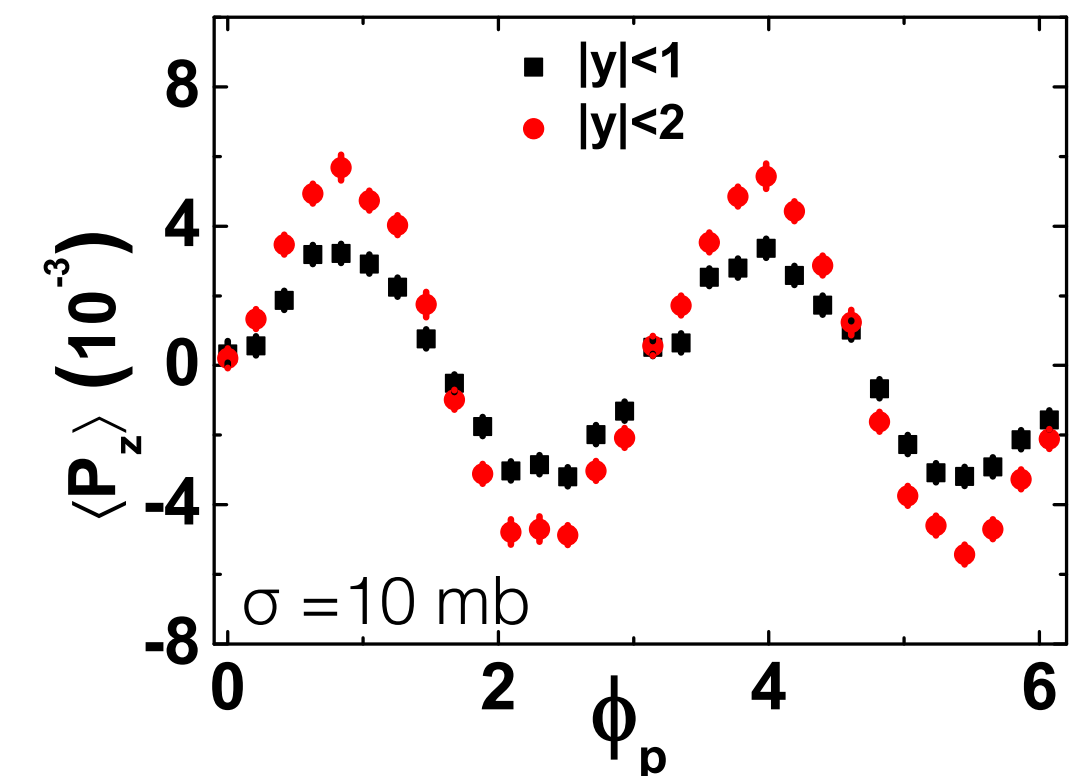
Same sign as chiral kinetic approach

- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- 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 may develop later in time unlike the global polarization?*



chiral kinetic approach 200 GeV, 30-40%



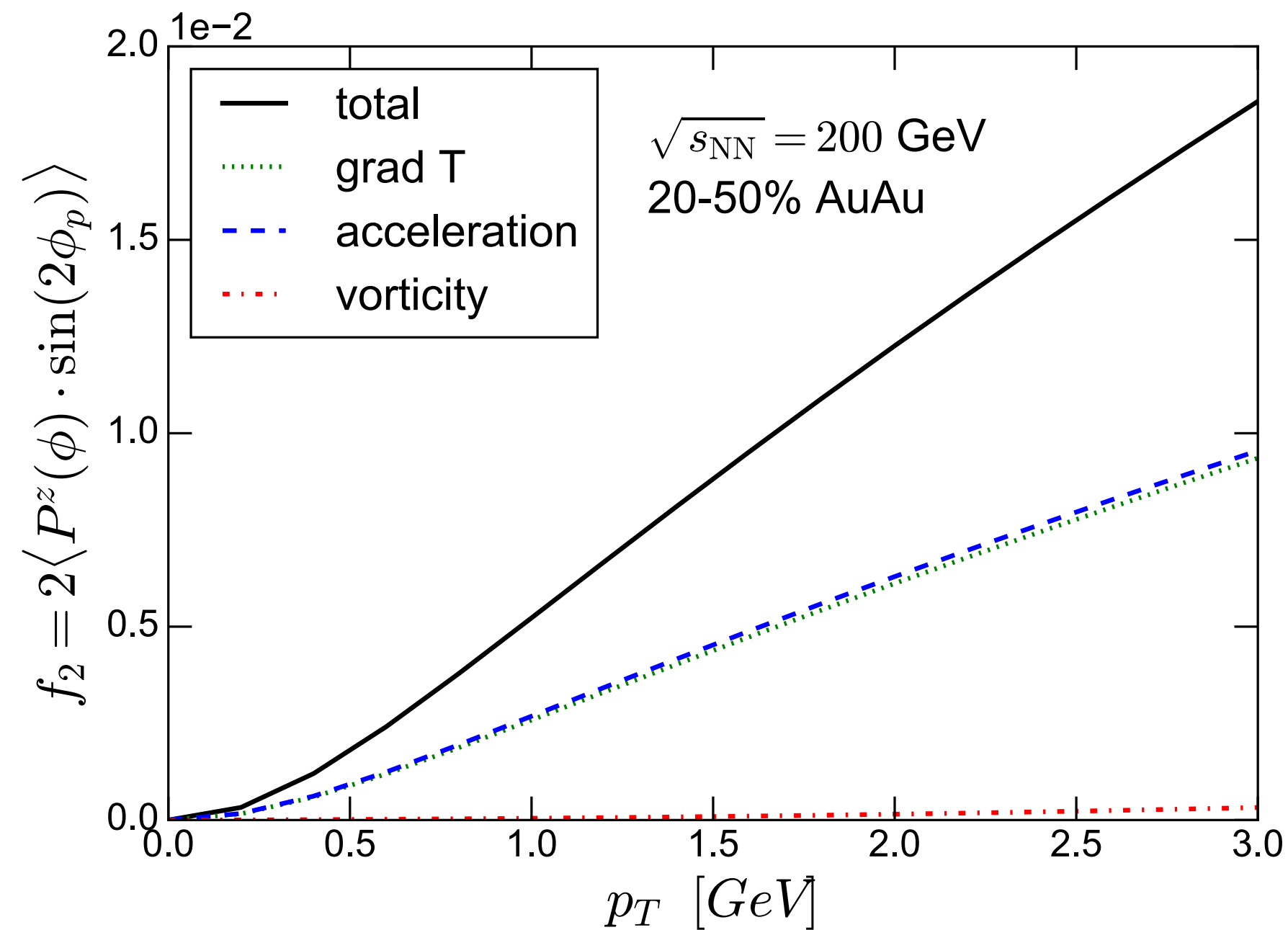


Contributions to P_z in hydro

I. Karpenko, QM2018

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

Longitudinal quadrupole f_2 :



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

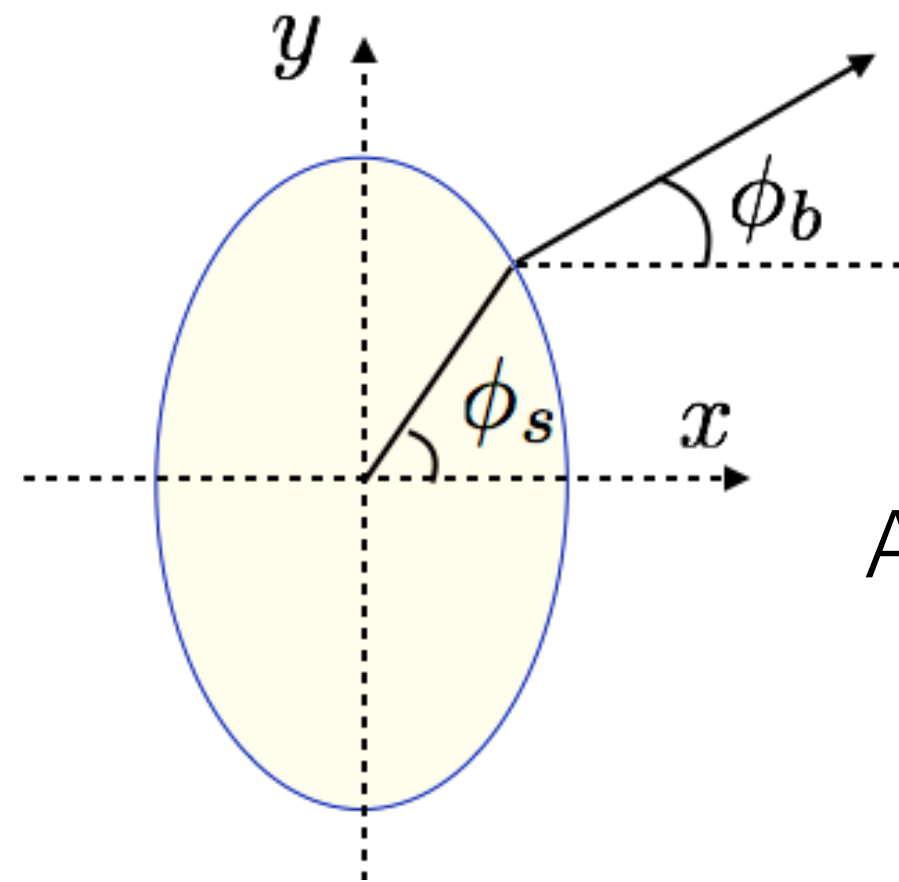
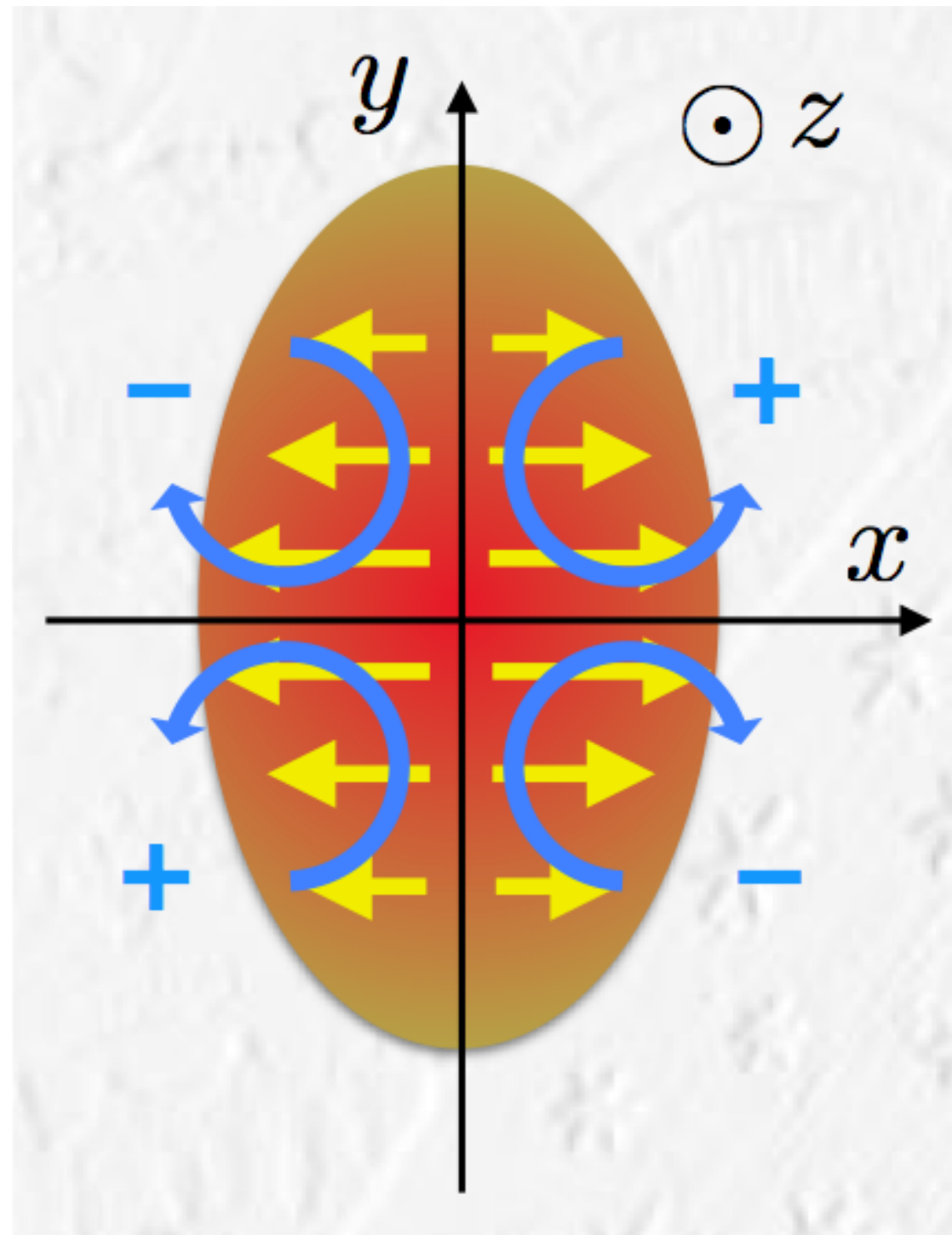
Can we get such a small kinetic vorticity in the blast-wave model?



Kinematic vorticity in the blast-wave model

S. Voloshin, SQM2017

EPJ Web Conf.171, 07002 (2018)



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

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

Approximation of the kinetic vorticity in the blast-wave model:

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

a_n : spatial anisotropy R : reference source radius

b_n : flow anisotropy ρ_t : transverse flow velocity

Quadrupole or sine structure of ω_z is expected with the factor $[b_n - a_n]$.

The sign could be negative depending on the relation of flow and spatial anisotropy.



Blast-wave model parameterization

- 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)

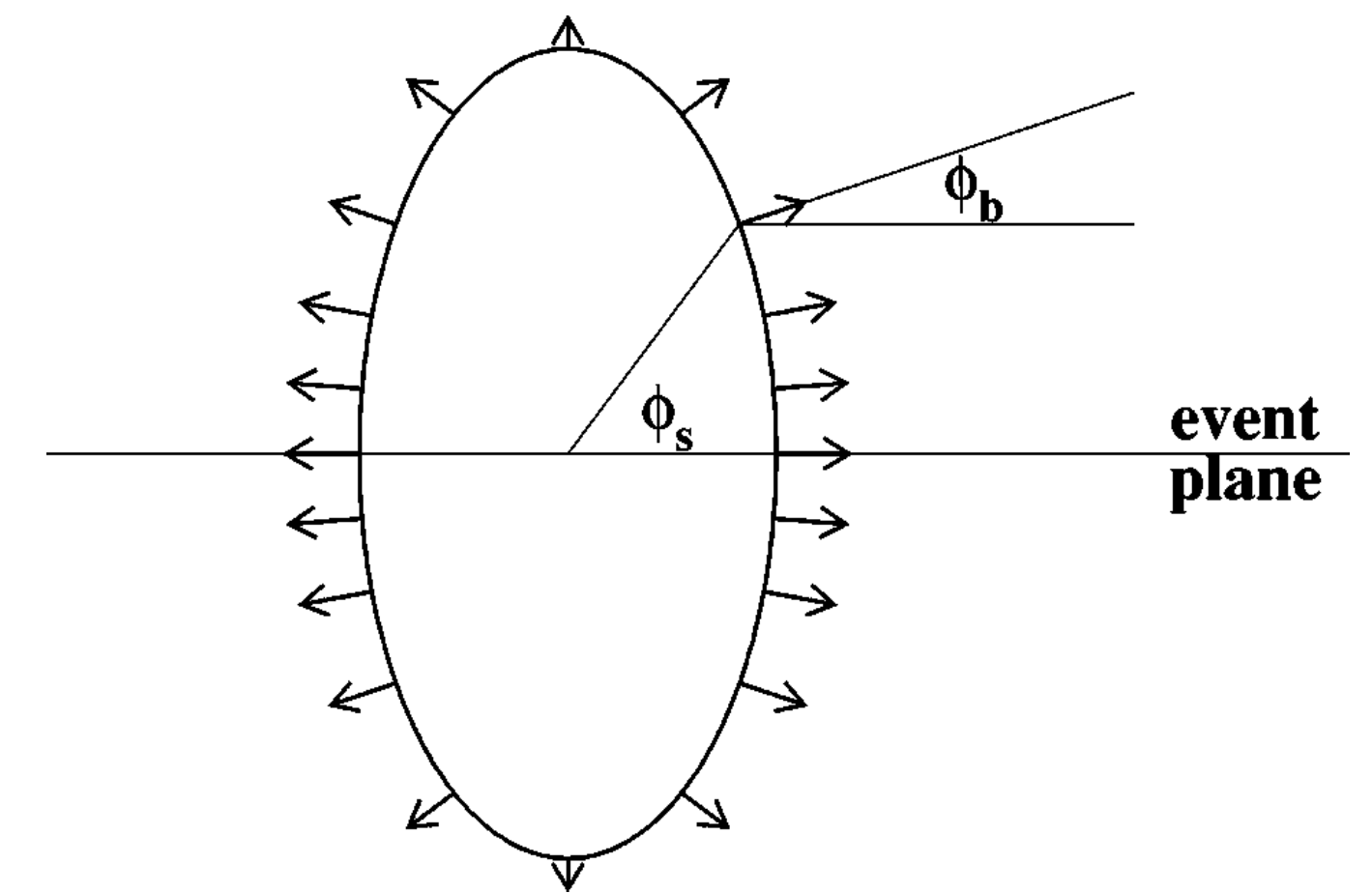


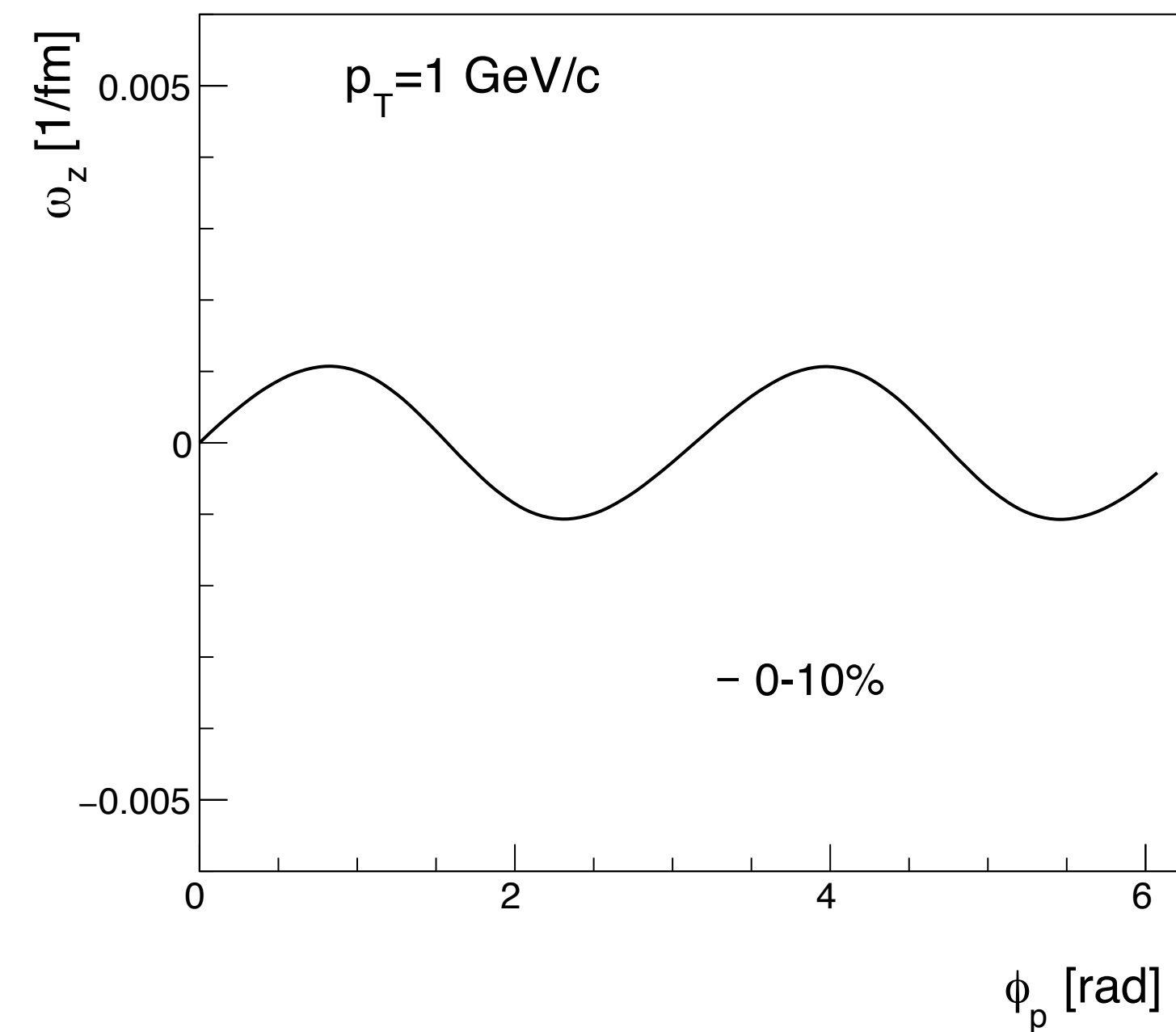
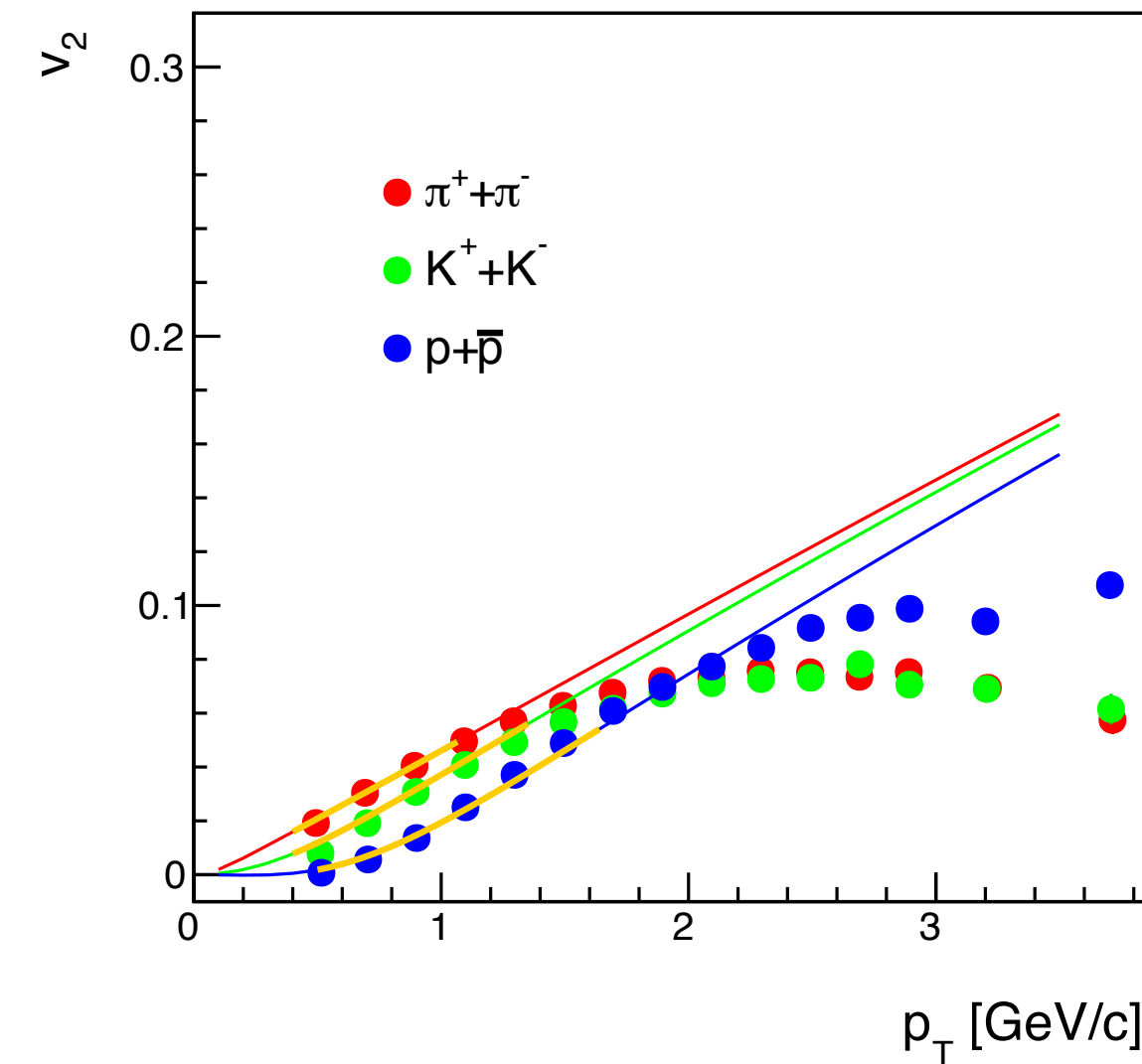
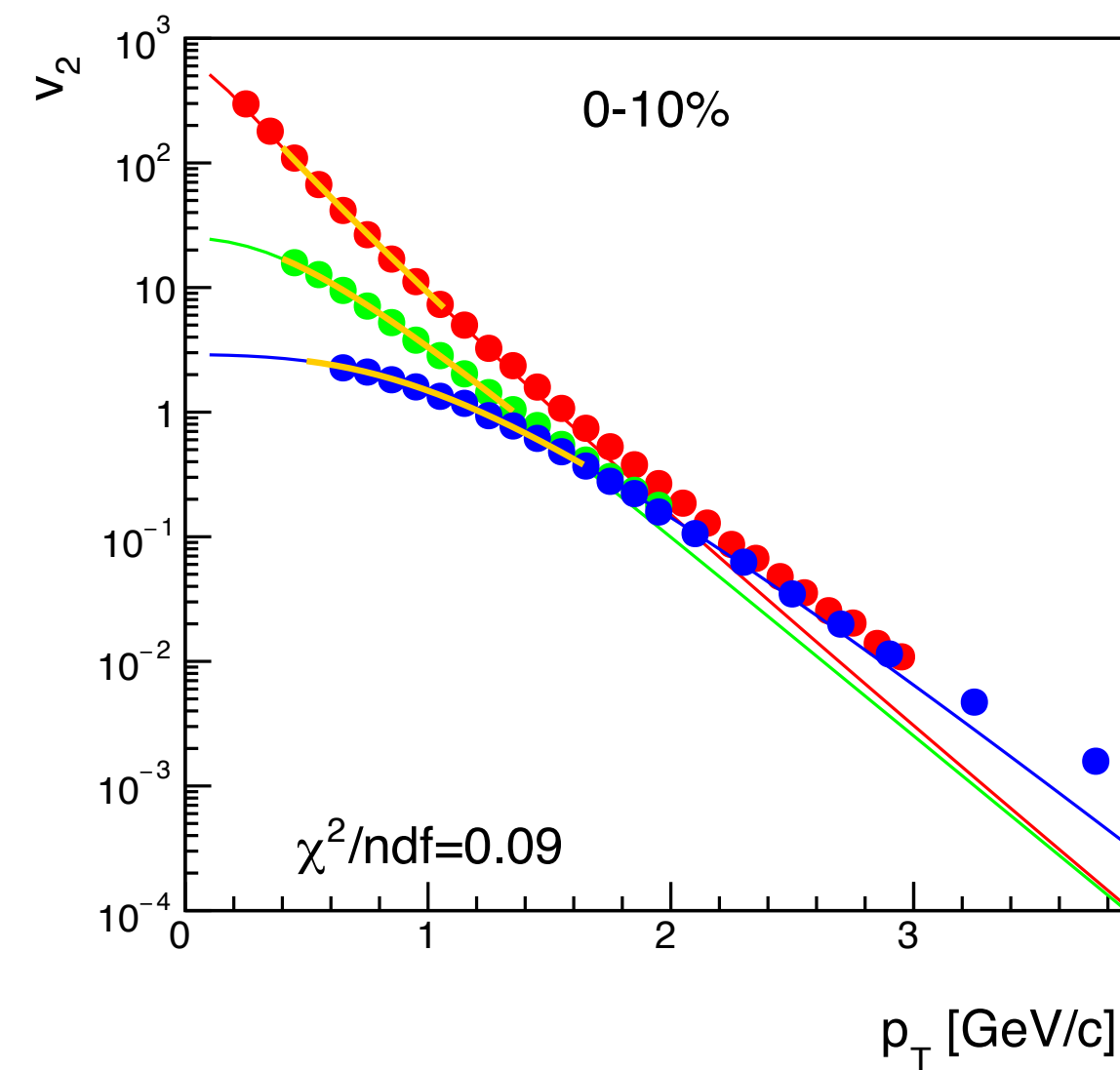
FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

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



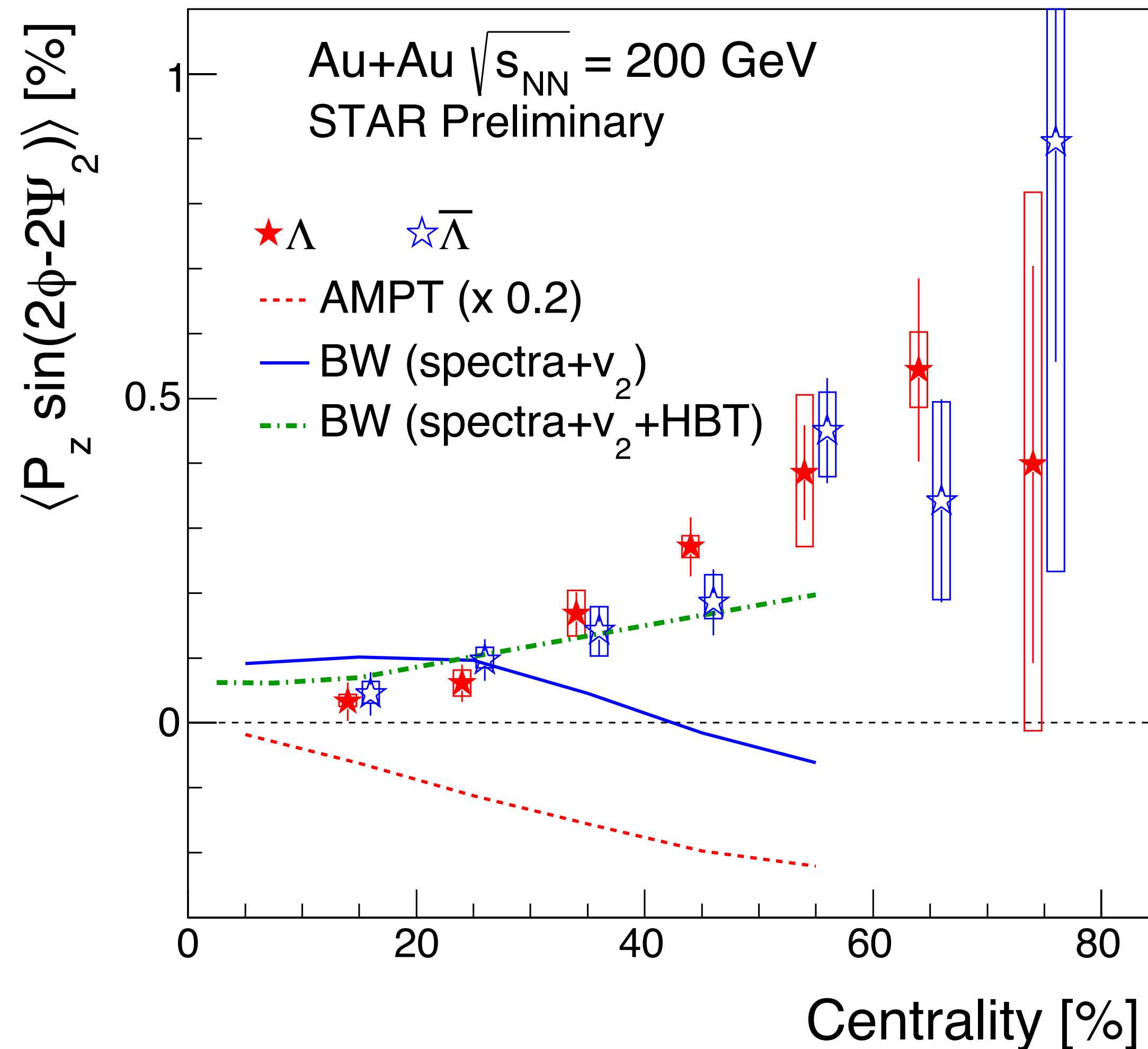
Data:
PHENIX, PRC69.034909 (2004)
PHENIX, PRC93.051902(R) (2016)

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



□ 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

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



Summary

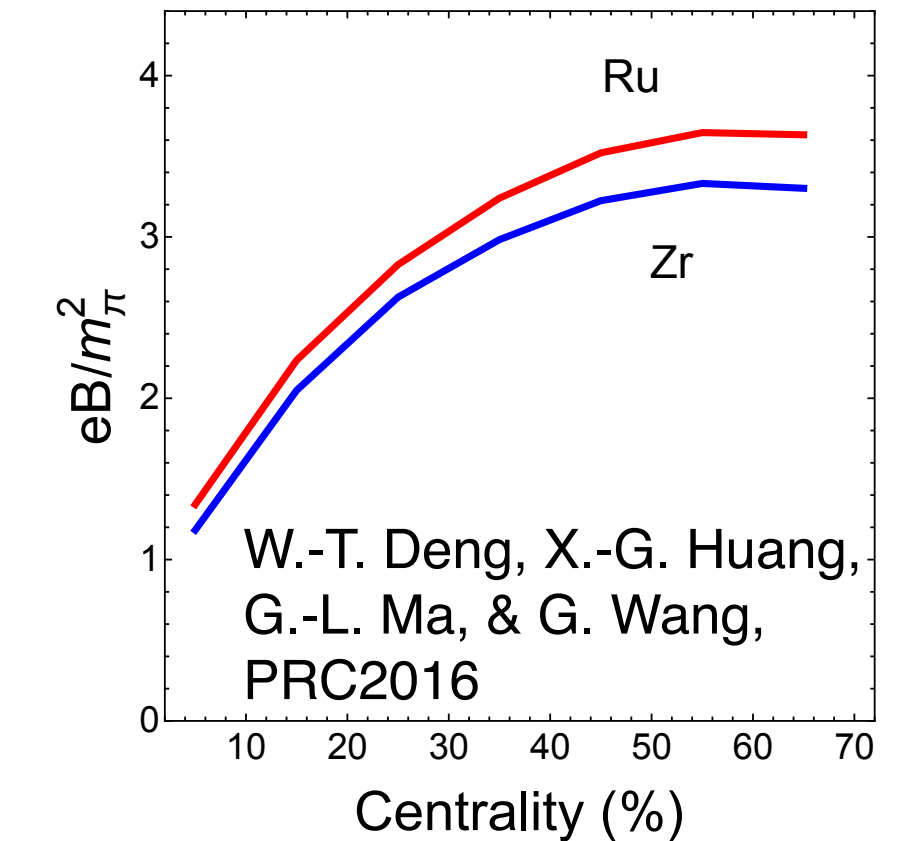
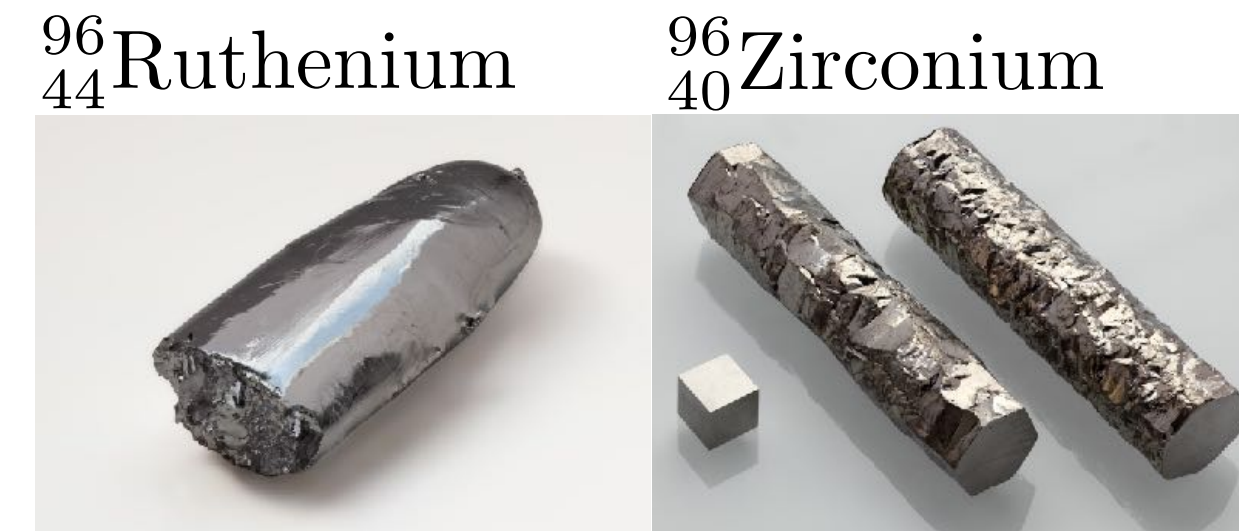
- Observation of Λ global polarization at $\sqrt{s_{NN}} = 7.7-200$ GeV
 - Polarization decreases at higher energies, qualitatively consistent with the models
→ **Quantitatively consistent with hydrodynamic and AMPT models**
 - Larger signal in in-plane than in out-of-plane, opposite to the hydrodynamic model
→ **Disagree with hydrodynamic model**
 - Charge-asymmetry dependence with different slopes between Λ and anti- Λ ($\sim 2\sigma$ level)
→ **A possible relation to the axial current induced by B-field?**

- First study of Λ polarization along the beam direction at $\sqrt{s_{NN}} = 200$ GeV
 - Quadrupole structure of the polarization relative to the 2nd-order event plane
→ **Qualitatively consistent with a picture of the elliptic flow but agree/disagree among the data and theoretical calculations in the sign**
 - 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

Outlook

□ Isobar collision data (Ru+Ru, Zr+Zr) already taken in 2018!

- Same mass number but different number of protons
 - 10% difference in the magnetic field
 - More P_H splitting between Λ and anti- Λ in Ru?



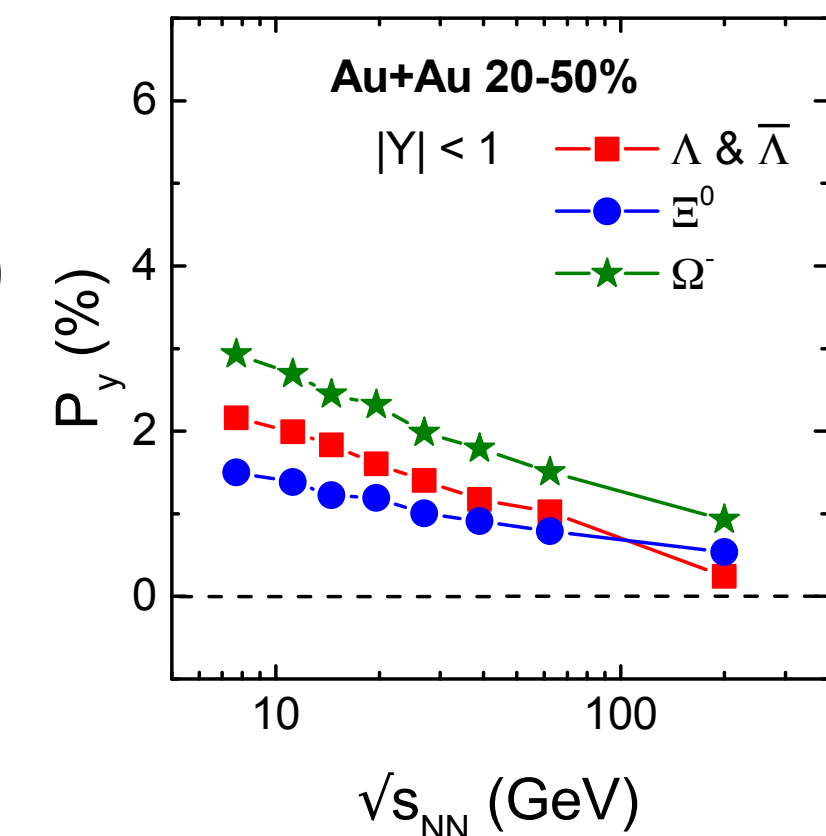
□ New 27 GeV data taken in 2018! (x10 events with ~ 1.5 better EP resolution)

- Possible probe of the magnetic field from Λ vs anti- Λ global polarization

D.-X. Wei *et al.*, arXiv:1810.00151

□ Beam Energy Scan II (2019+) with STAR detector upgrade

- x10 events for $\sqrt{s_{NN}} = 7.7-19.6$ GeV (collider mode) + $\sqrt{s_{NN}} = 3-7.7$ GeV (Fixed target)
- How about at forward/backward rapidity? How about for multi-strangeness?

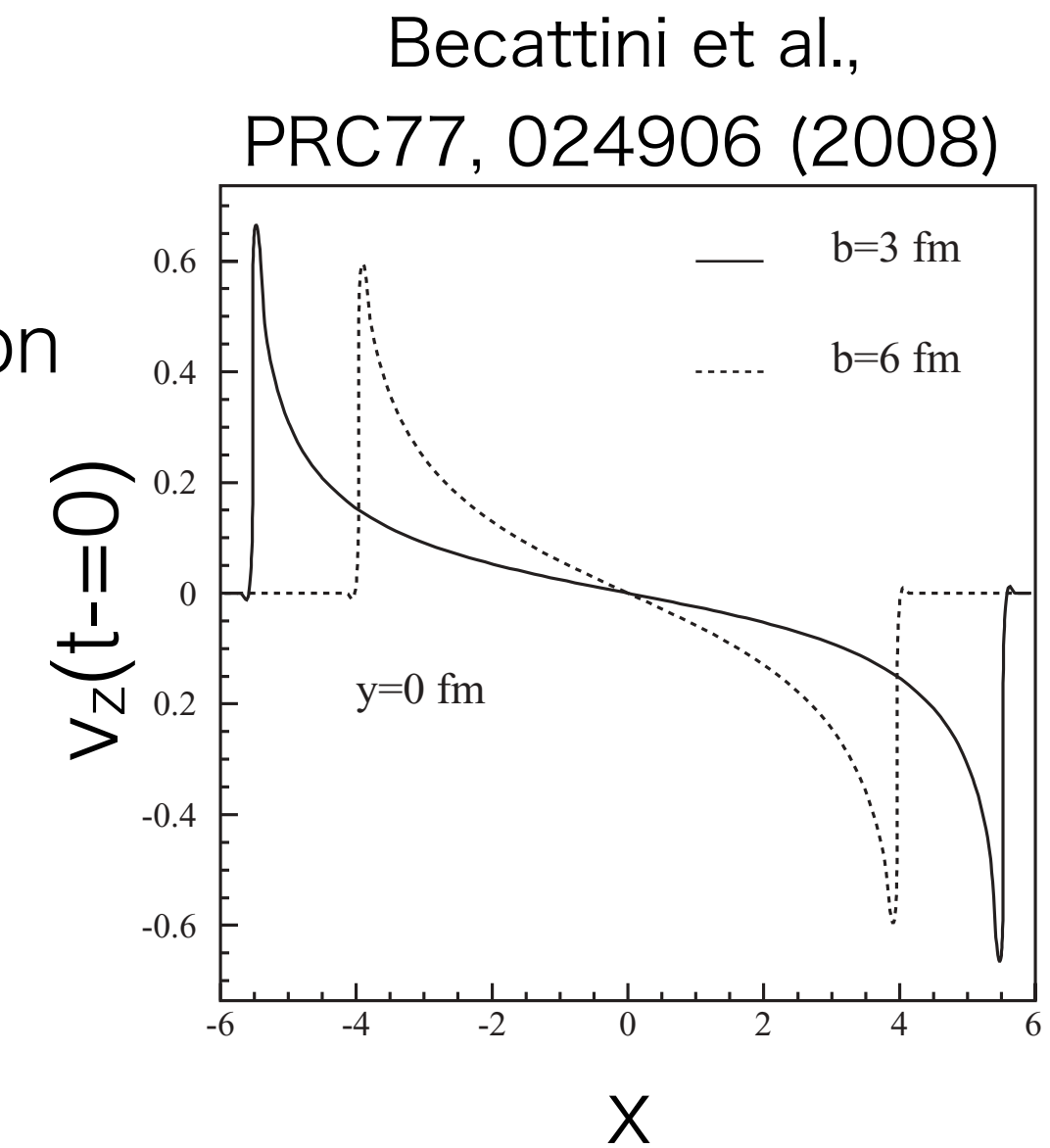
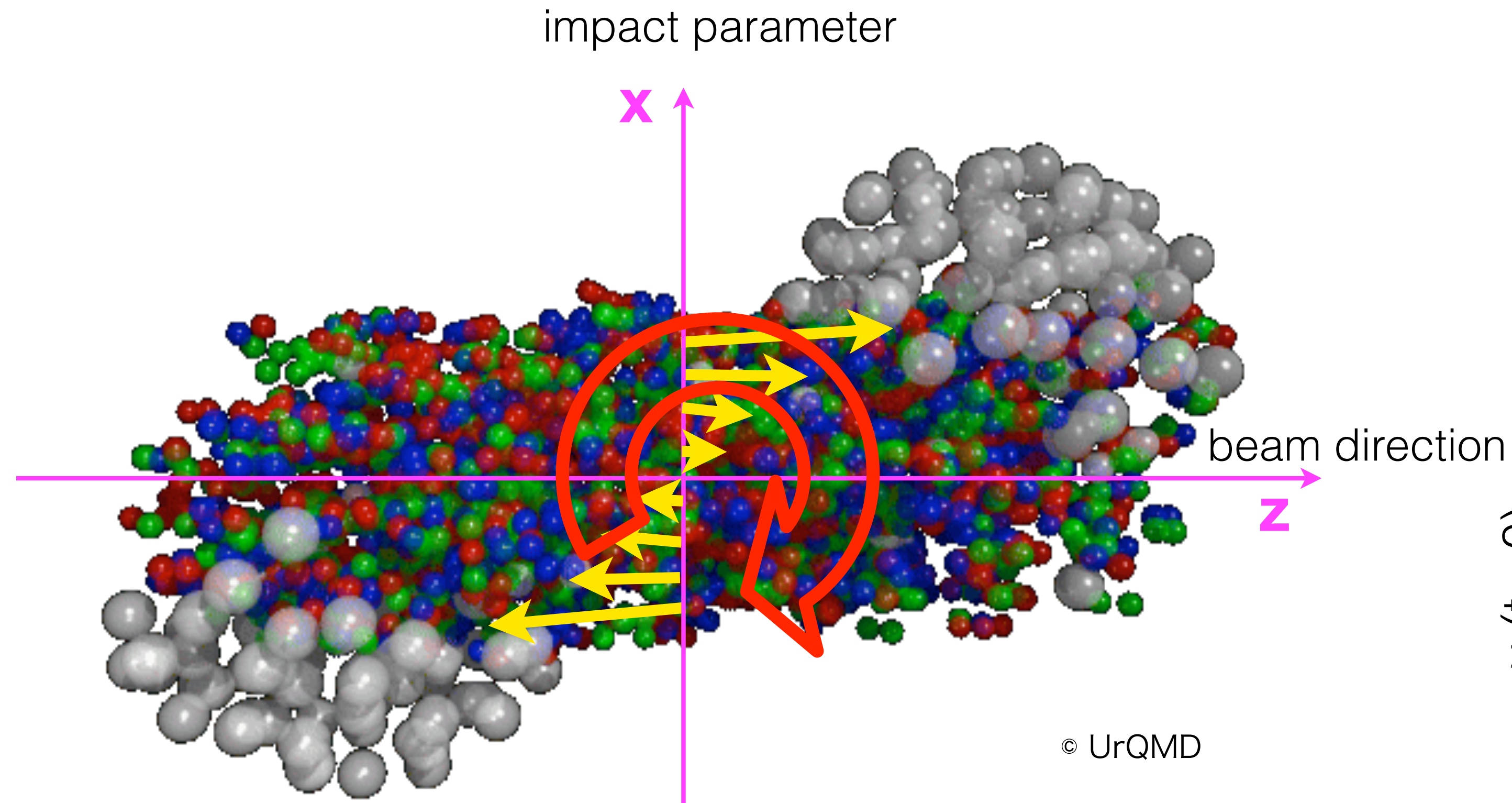




Back up



Vorticity in HIC



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

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



STAR Detectors

Time Projection Chamber
($|η| < 1$)

Time-Of-Flight detector
($|η| < 0.9$)

Beam-Beam Counter

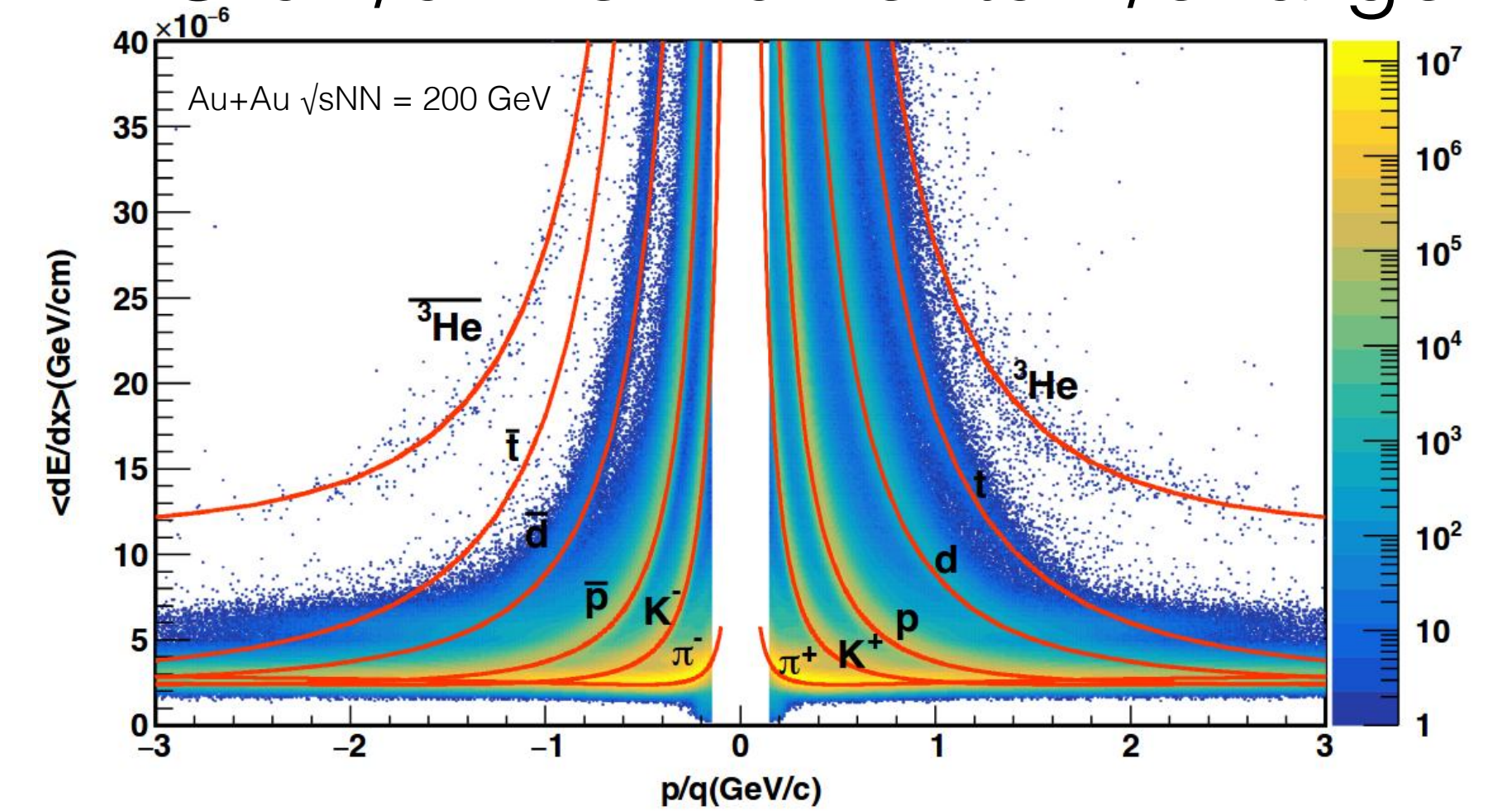
Vertex Position Detector

Zero Degree Calorimeter
with Shower Maximum Detector

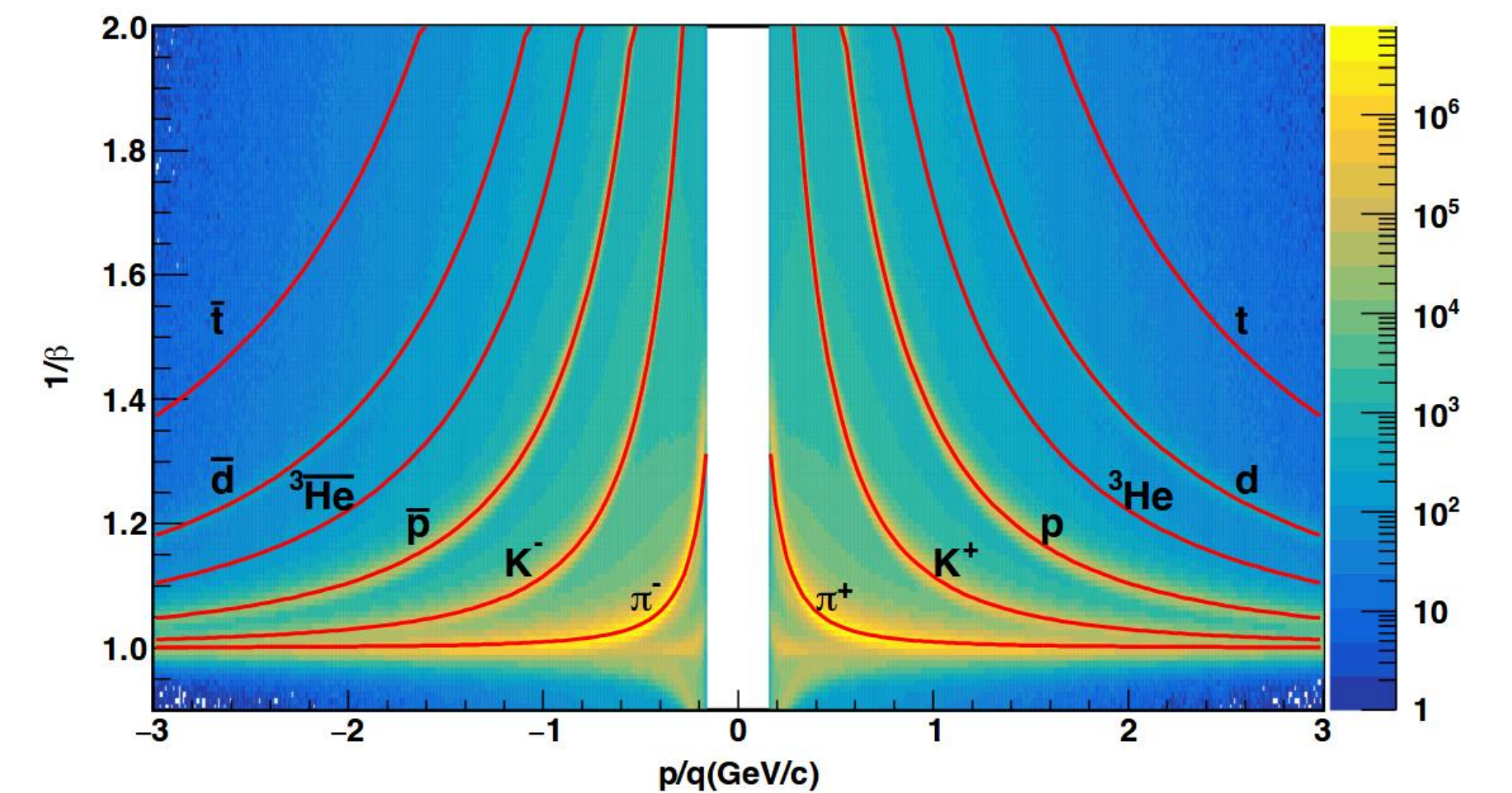
- Full azimuthal and large rapidity coverage
- Excellent particle identification

by Maria & Alex Schmah

TPC dE/dx vs momentum/charge

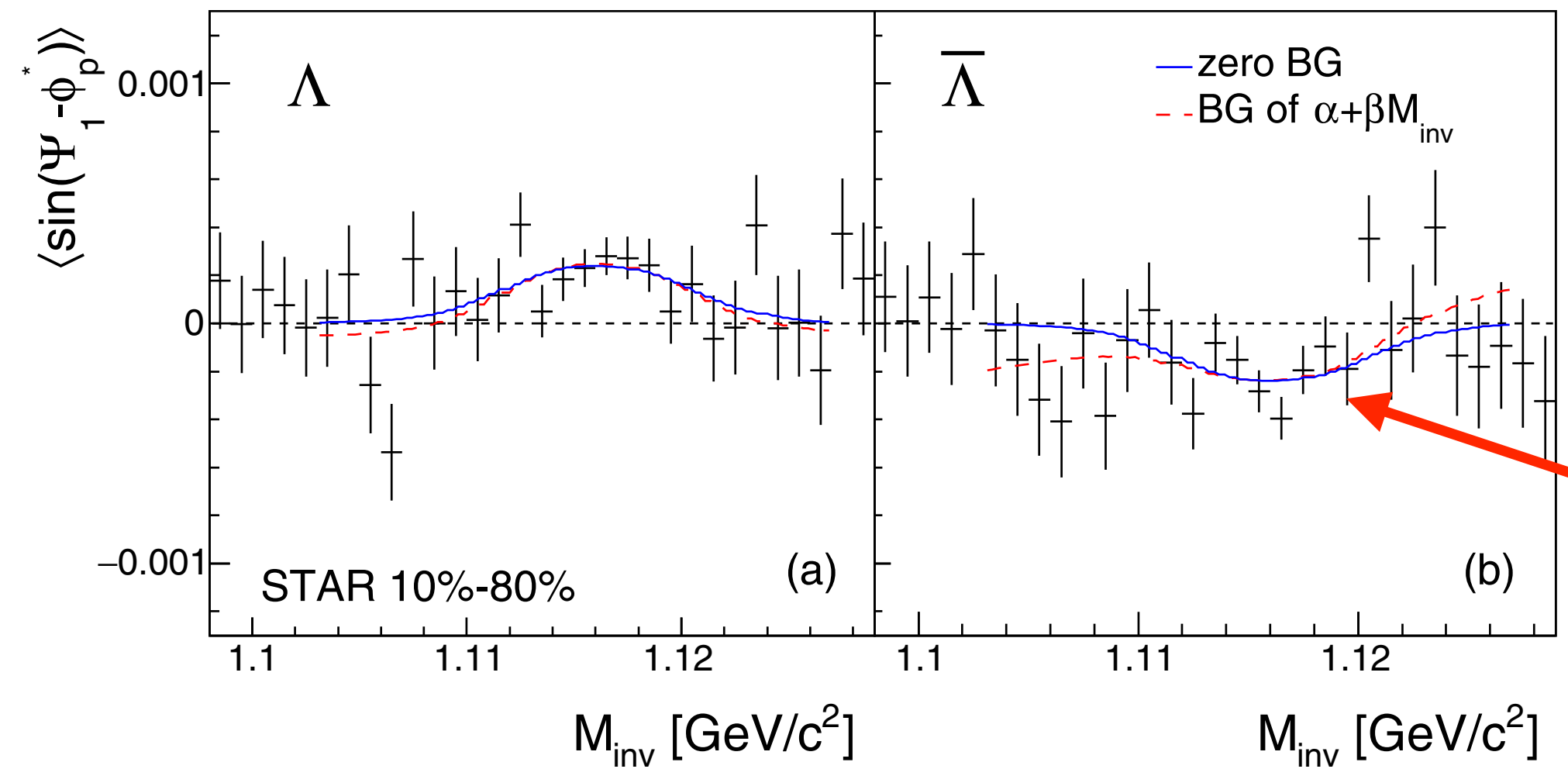
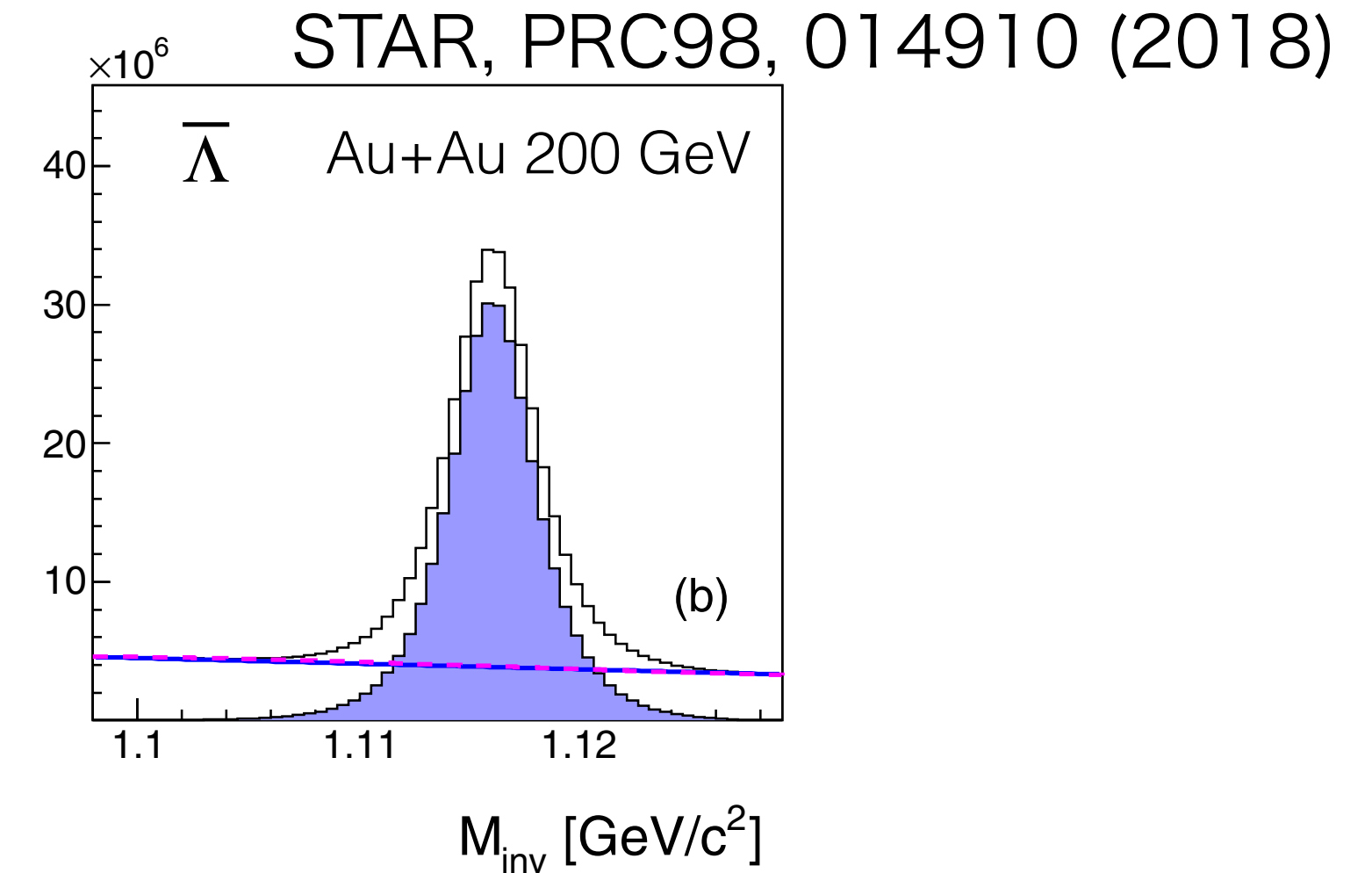
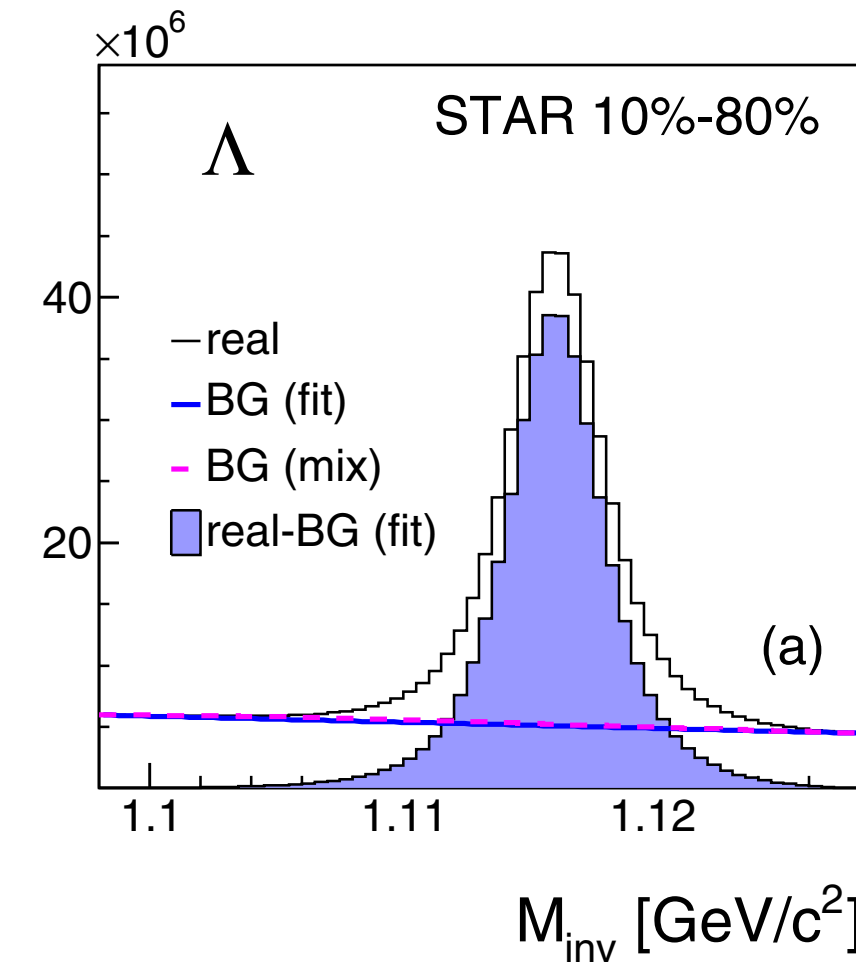
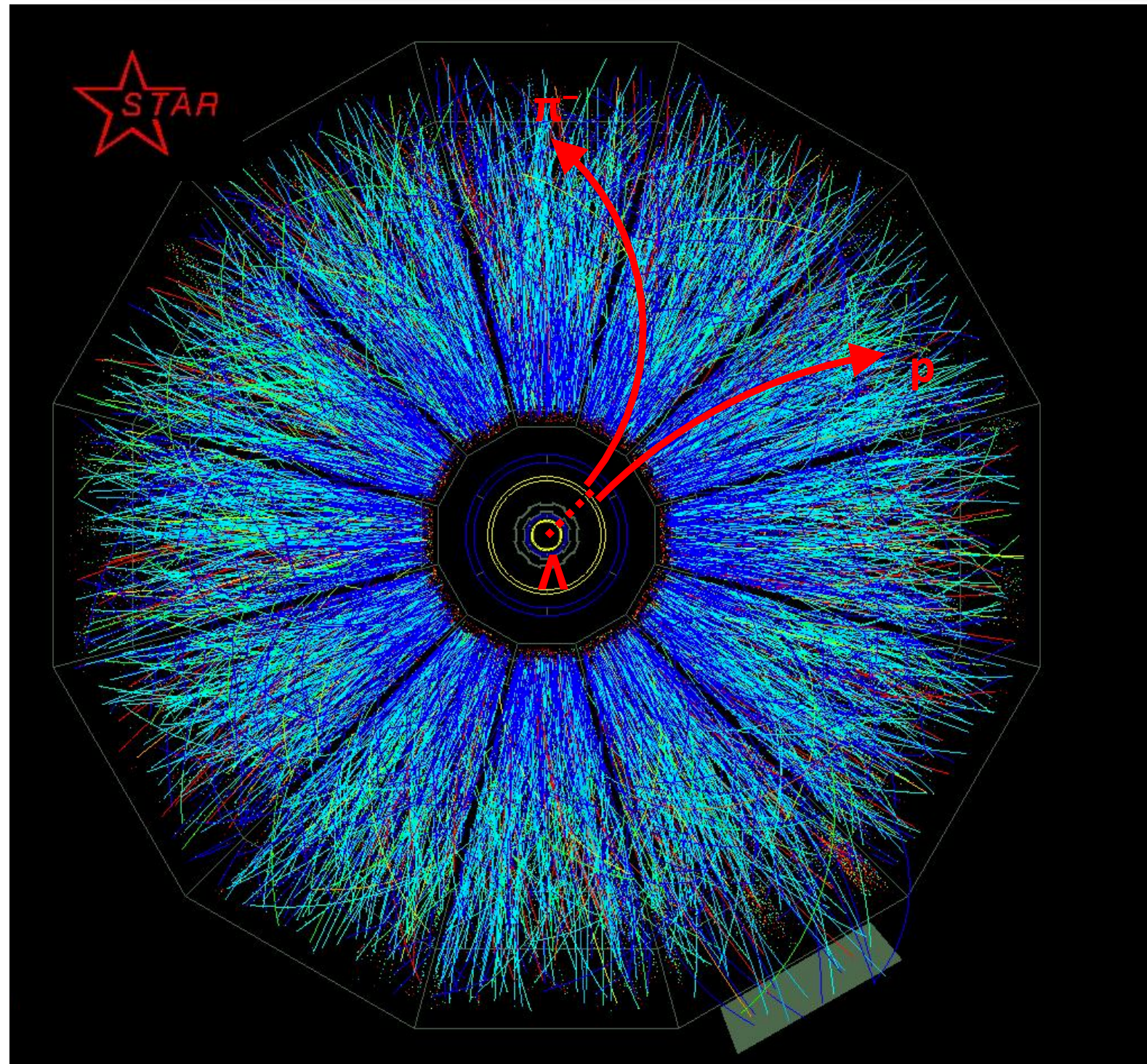


TOF $1/\beta$ vs momentum/charge

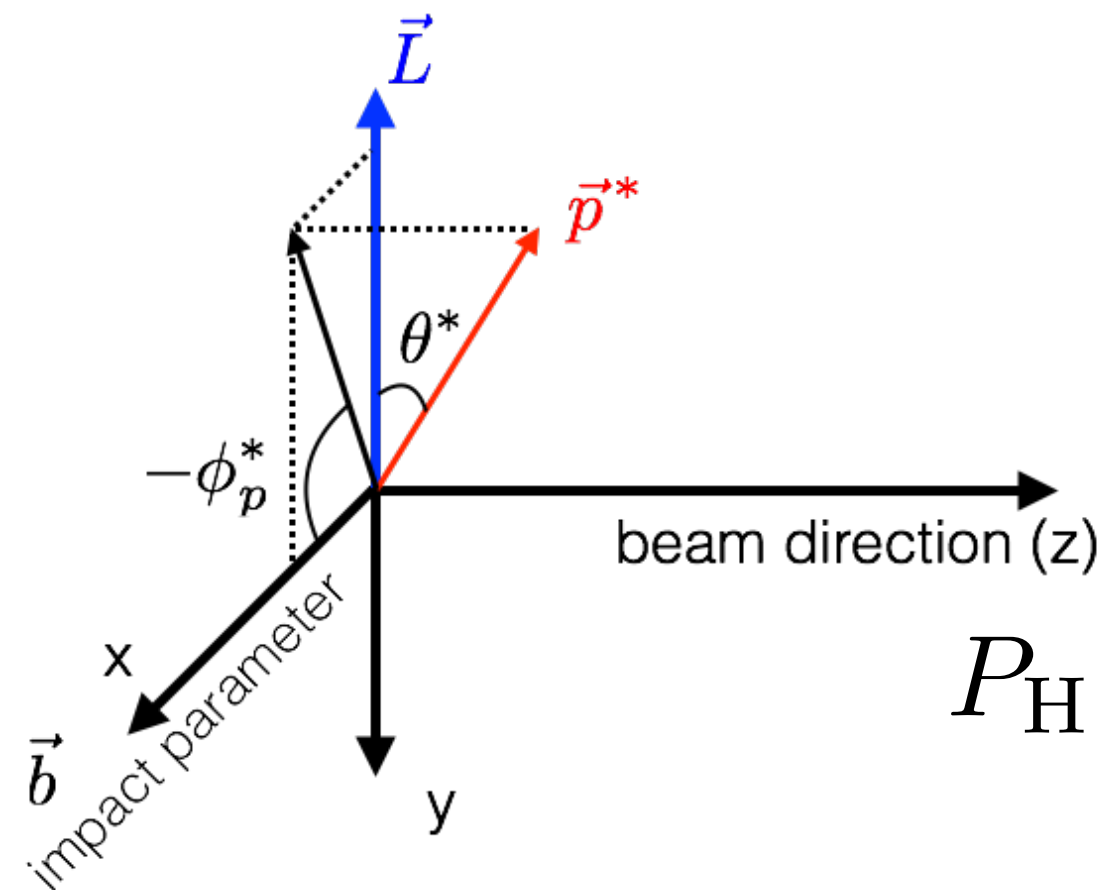




Signal extraction with Λ hyperons



negative for anti- Λ
 $\alpha_H = -\alpha_{\bar{H}}$



$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)}$$

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



Feed-down effect

- Only ~25% of measured Λ and anti- Λ are primary, while ~60% are feed-down from $\Sigma^* \rightarrow \Lambda \pi$, $\Sigma^0 \rightarrow \Lambda \gamma$, $\Xi \rightarrow \Lambda \pi$
- Polarization of parent particle R is transferred to its daughter Λ

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

$$\langle S_y \rangle \propto \frac{S(S+1)}{3} (\omega + \frac{\mu}{S} B)$$

$C_{\Lambda R}$: 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

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

$$\begin{pmatrix} \varpi_c \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3} \sum_R (f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}) S_R(S_R + 1) & \frac{2}{3} \sum_R (f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}) (S_R + 1) \mu_R \\ \frac{2}{3} \sum_{\bar{R}} (f_{\Lambda \bar{R}} C_{\Lambda \bar{R}} - \frac{1}{3} f_{\bar{\Sigma}^0 \bar{R}} C_{\bar{\Sigma}^0 \bar{R}}) S_{\bar{R}}(S_{\bar{R}} + 1) & \frac{2}{3} \sum_{\bar{R}} (f_{\Lambda \bar{R}} C_{\Lambda \bar{R}} - \frac{1}{3} f_{\bar{\Sigma}^0 \bar{R}} C_{\bar{\Sigma}^0 \bar{R}}) (S_{\bar{R}} + 1) \mu_{\bar{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\ P_{\bar{\Lambda}}^{\text{meas}} \end{pmatrix}$$

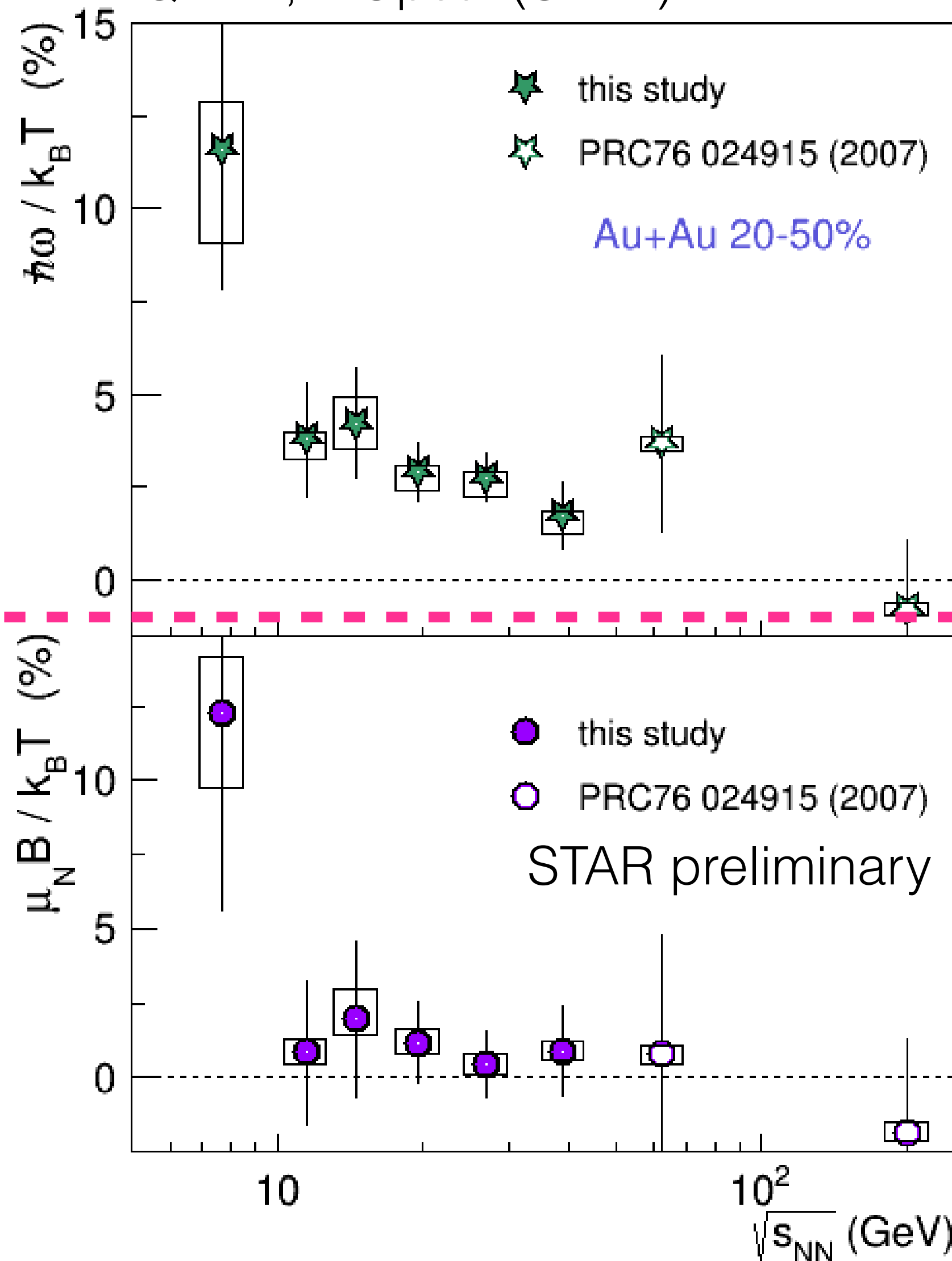
Decay	C
Parity conserving: $1/2^+ \rightarrow 1/2^+ 0^-$	-1/3
Parity conserving: $1/2^- \rightarrow 1/2^+ 0^-$	1
Parity conserving: $3/2^+ \rightarrow 1/2^+ 0^-$	1/3
Parity-conserving: $3/2^- \rightarrow 1/2^+ 0^-$	-1/5
$\Xi^0 \rightarrow \Lambda + \pi^0$	+0.900
$\Xi^- \rightarrow \Lambda + \pi^-$	+0.927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

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



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

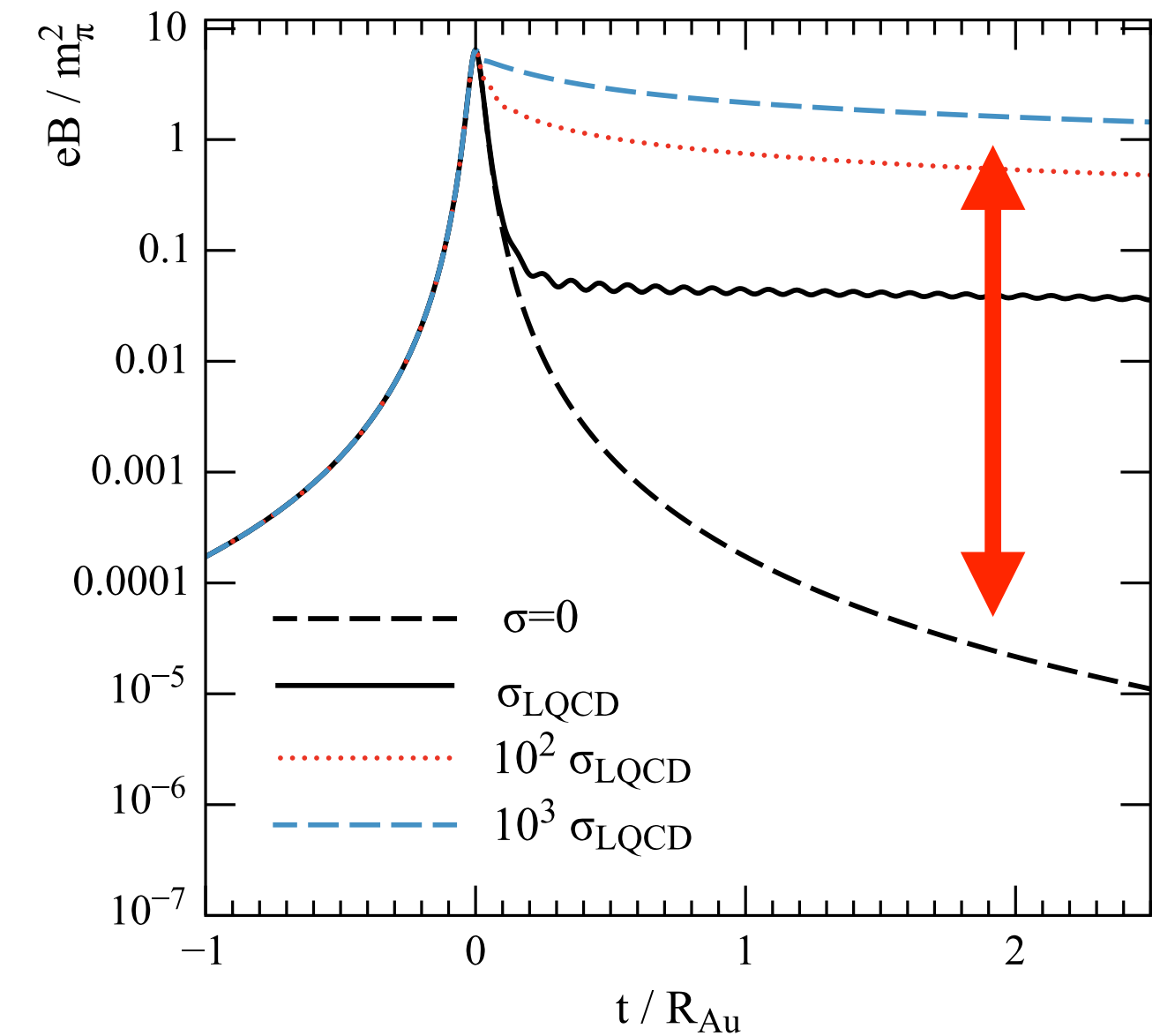
$$B = (P_{\Lambda} - P_{\bar{\Lambda}}) k_B T / \mu_N$$

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

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

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

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



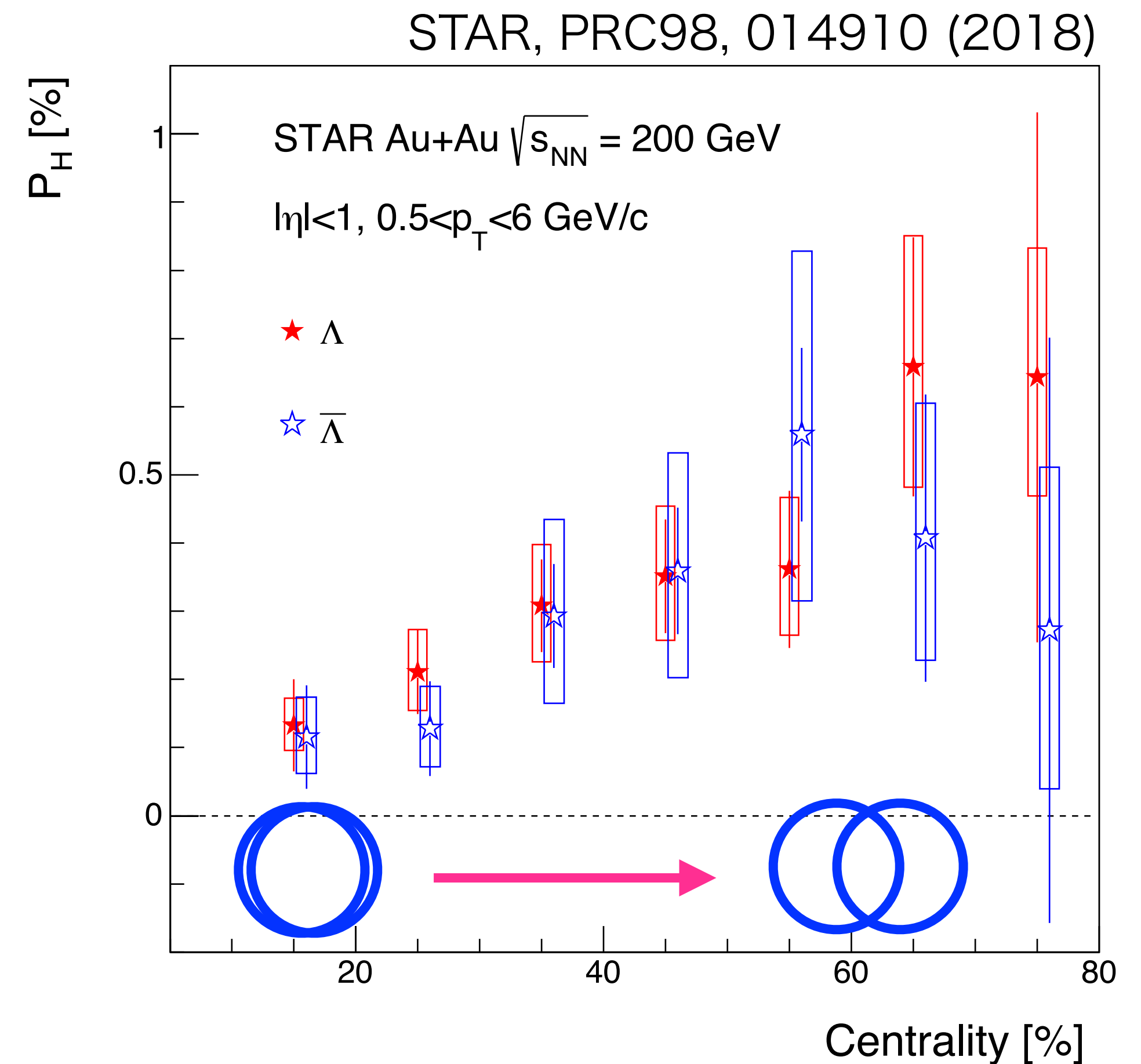
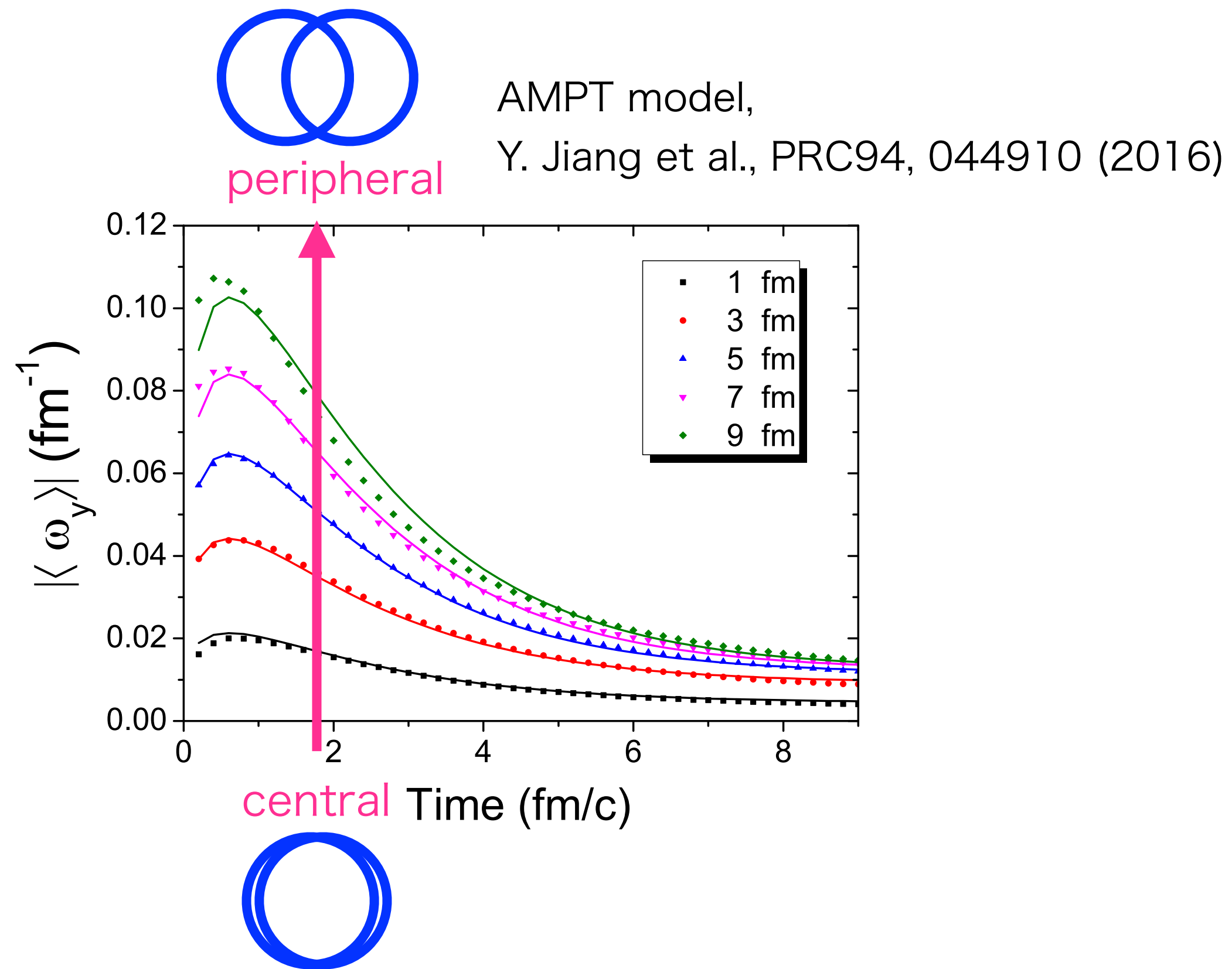
conductivity increases lifetime
(not magnitude)

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

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



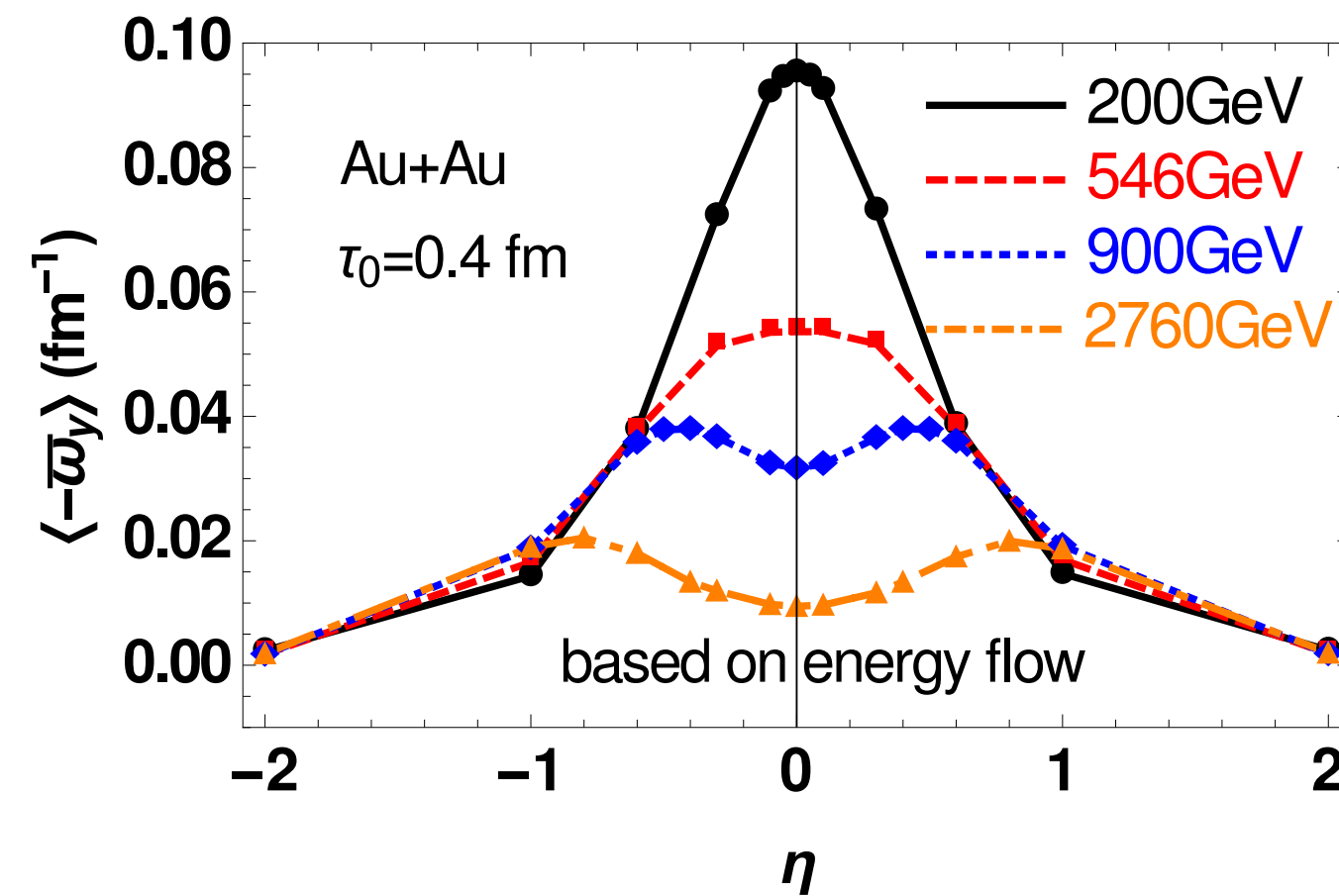
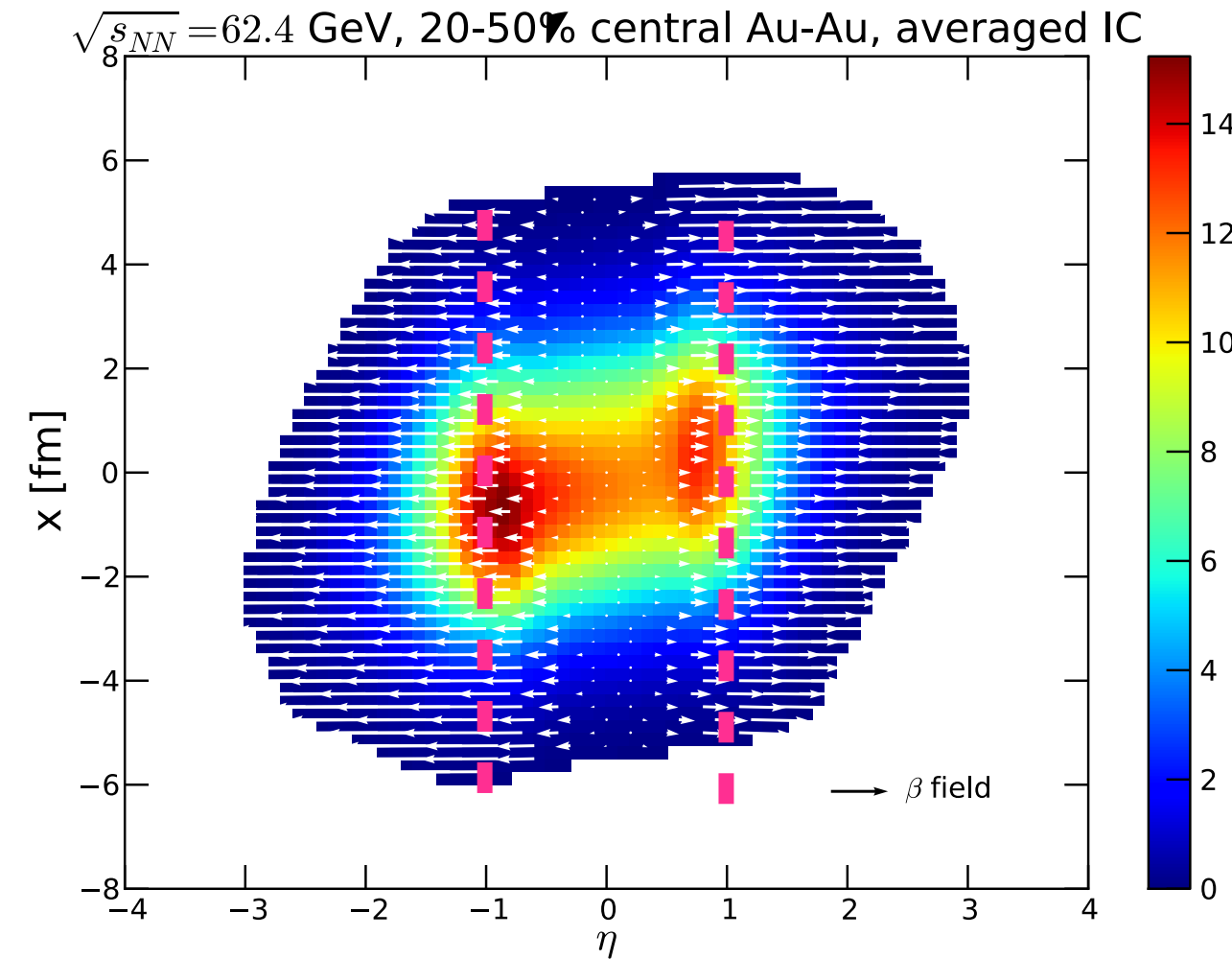
Centrality dependence of P_H



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



η dependence of P_H

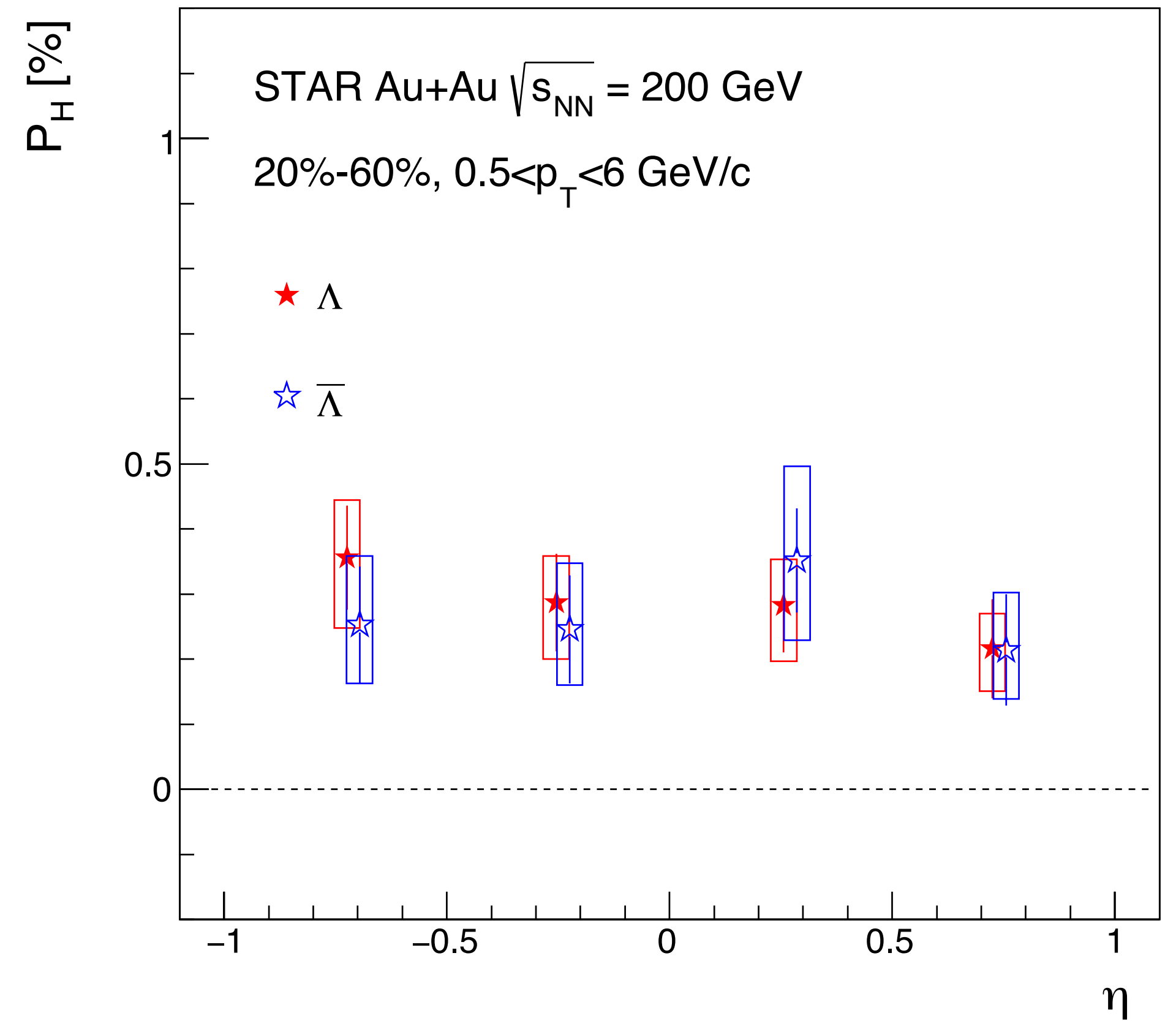


- Shear flow structure/initial flow velocity would be stronger in forward/backward region
- Expect rapidity dependence of the polarization

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

W.-T. Deng and X.-G. Huang, arXiv:1609.01801

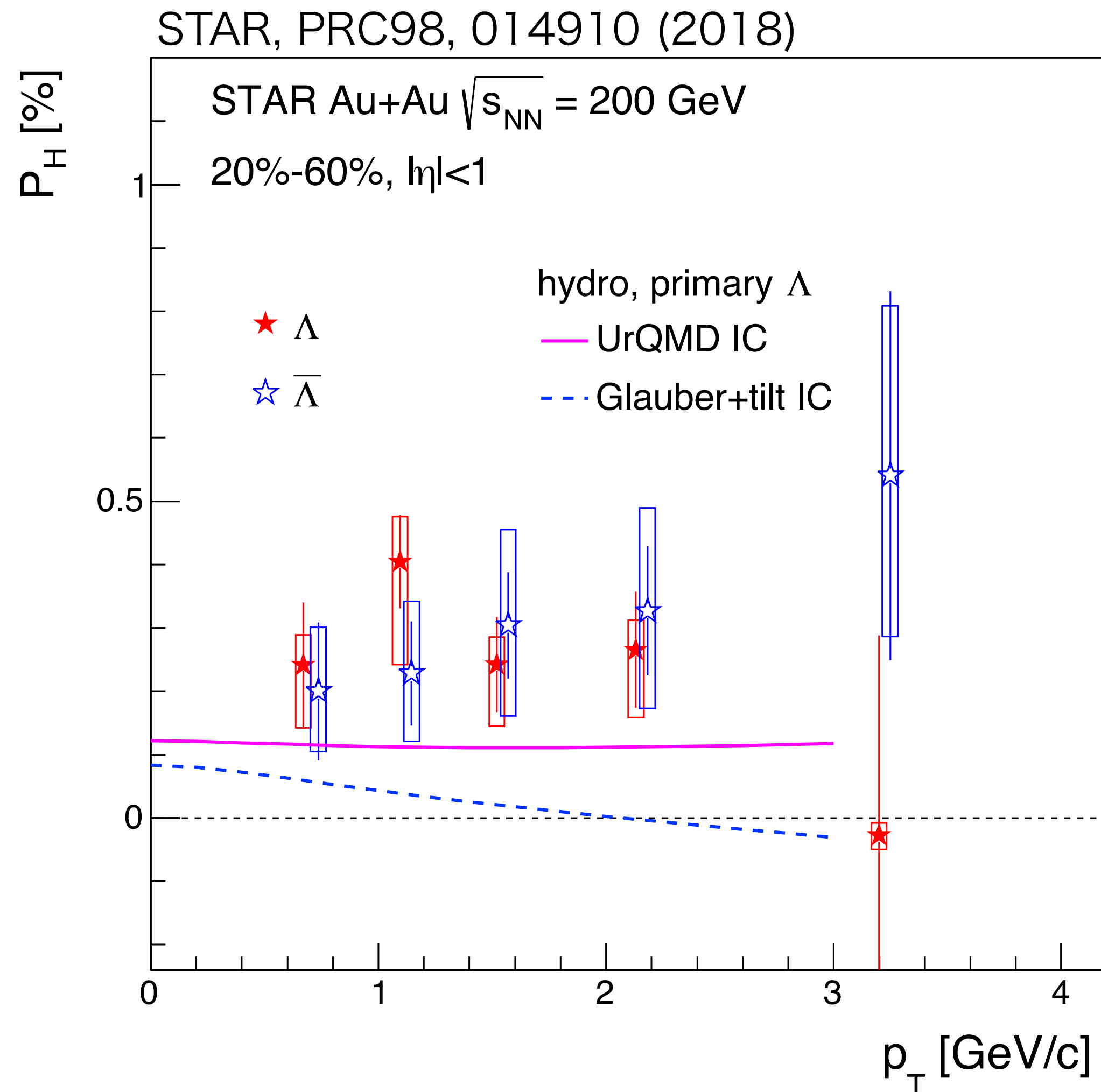
STAR, PRC98, 014910 (2018)



- 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



- 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



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