# Global polarization of $\Lambda$ hyperons in Au+Au collision at STAR

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Heavy Ion Cafe
June 22-23
@Sophia University

# Important features in non-central heavy-ion collision

Orbital angular momentum

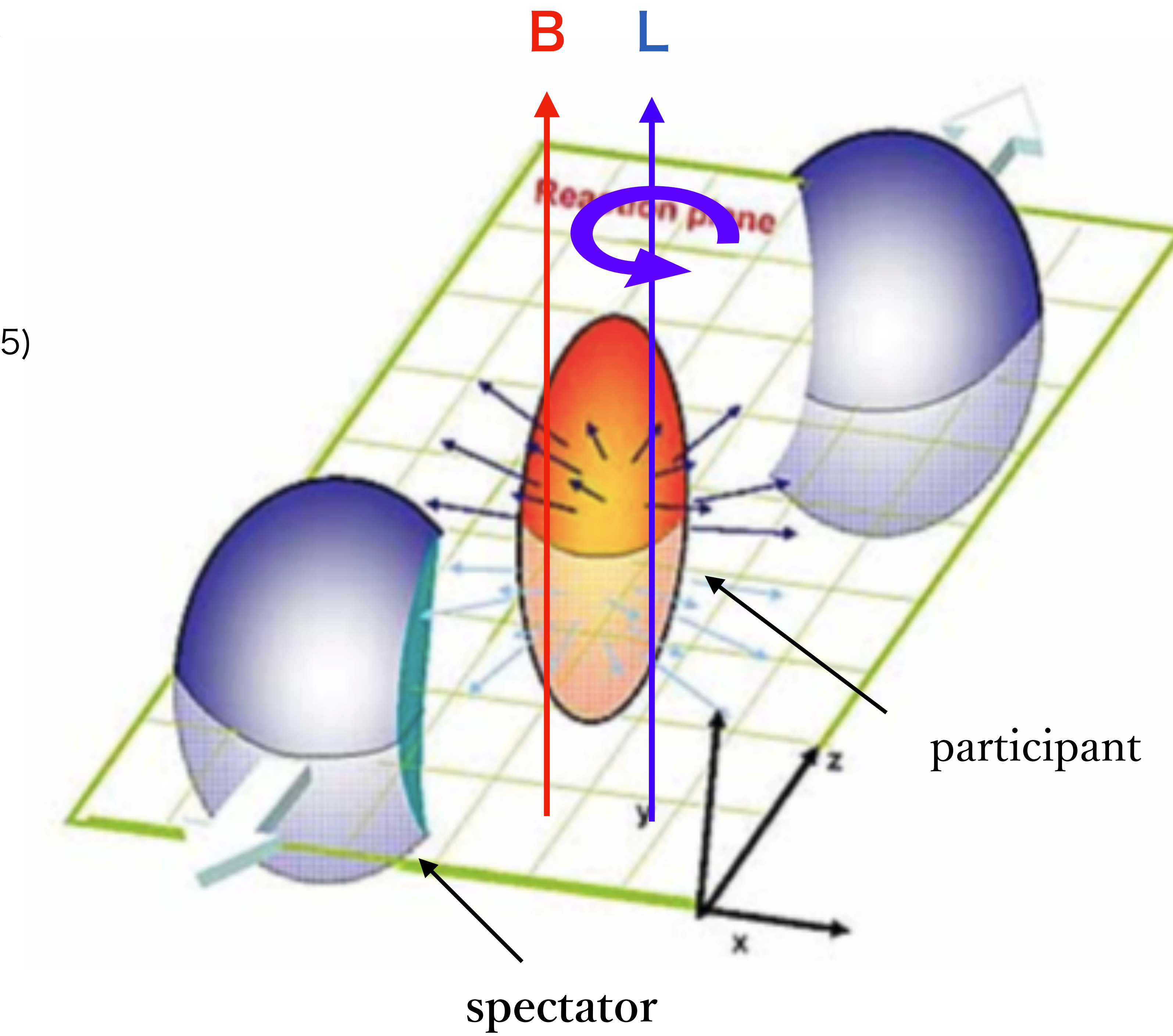
$$L \sim 10^5 \hbar$$

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

Strong magnetic field

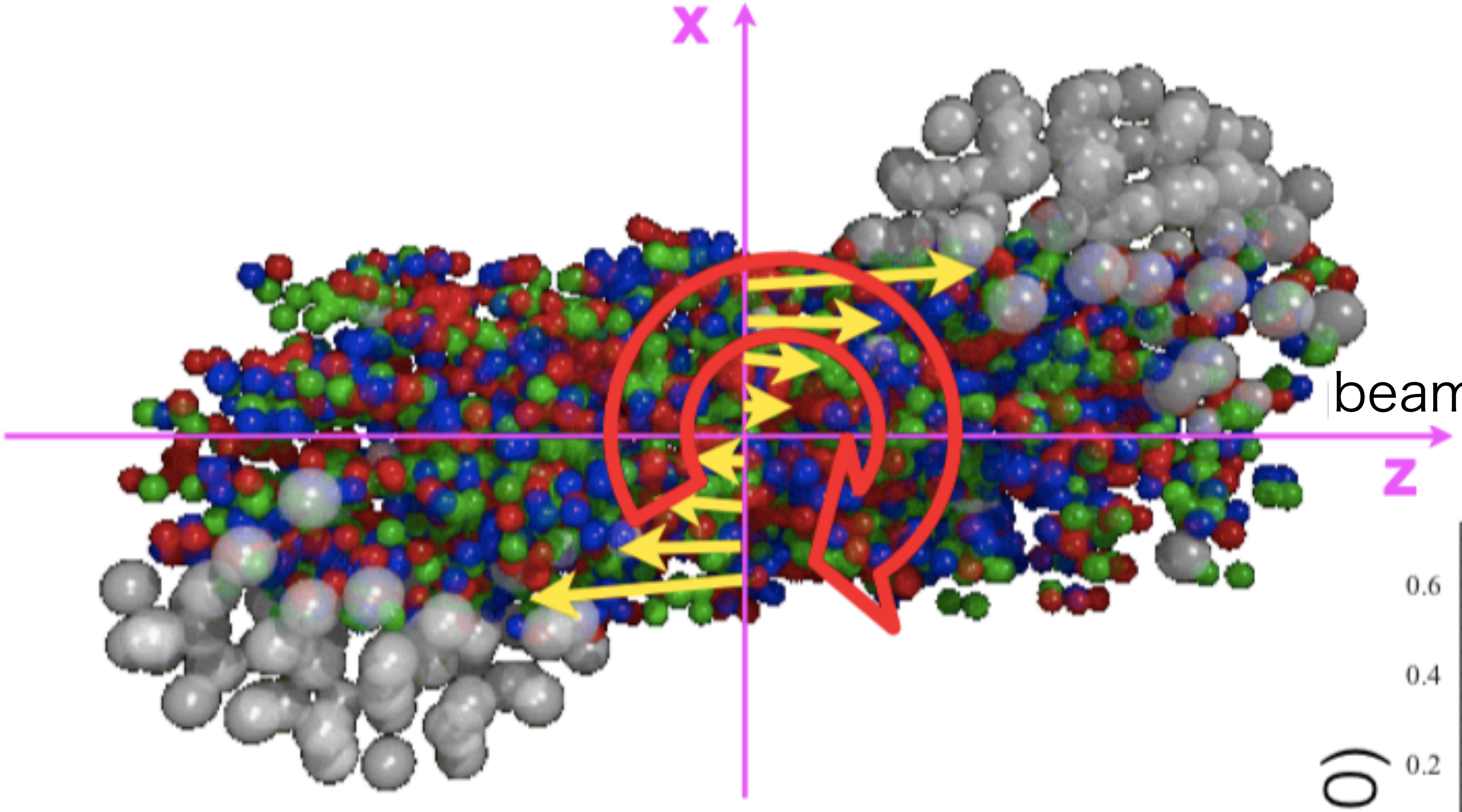
$$\mathrm{B} \sim 10^{13}\ \mathrm{T}$$

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



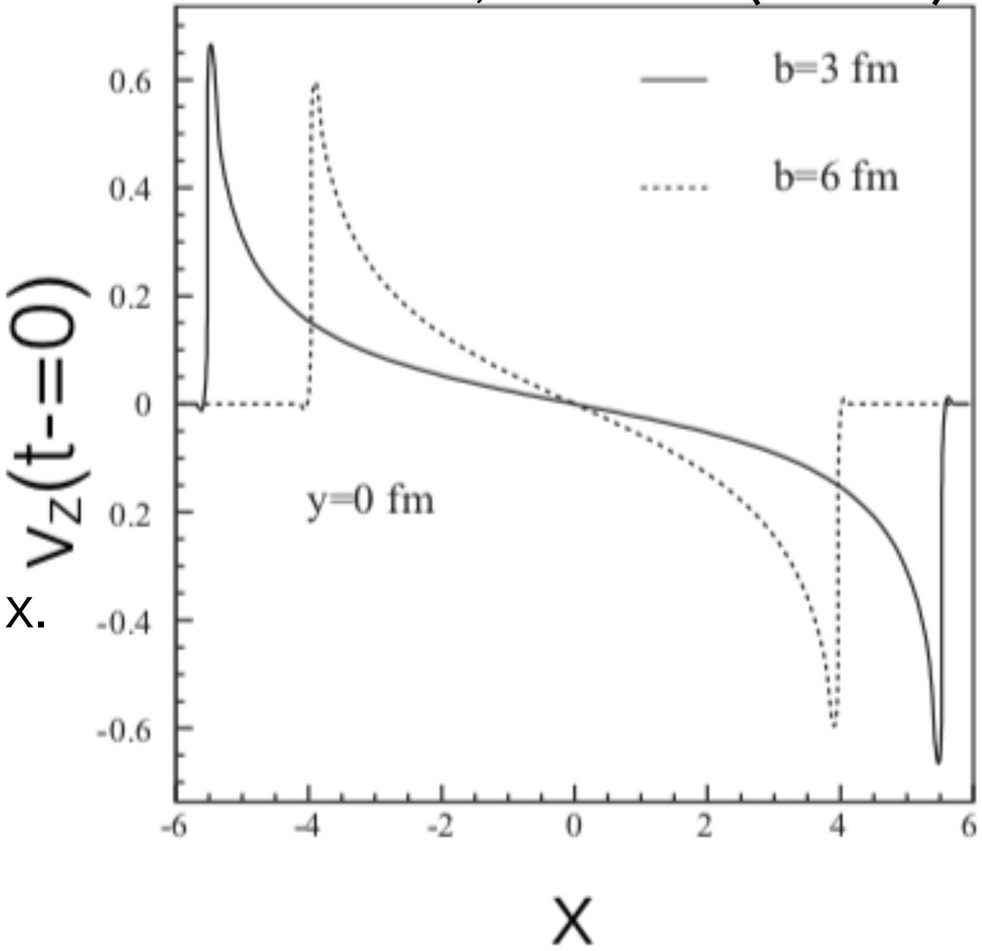
# Vorticity in heavy-ion collision

impact parameter



beam direction

PRC77,024906(2008)



In non-central collision,
The initial collective longitudinal flow velocity dependent on x.

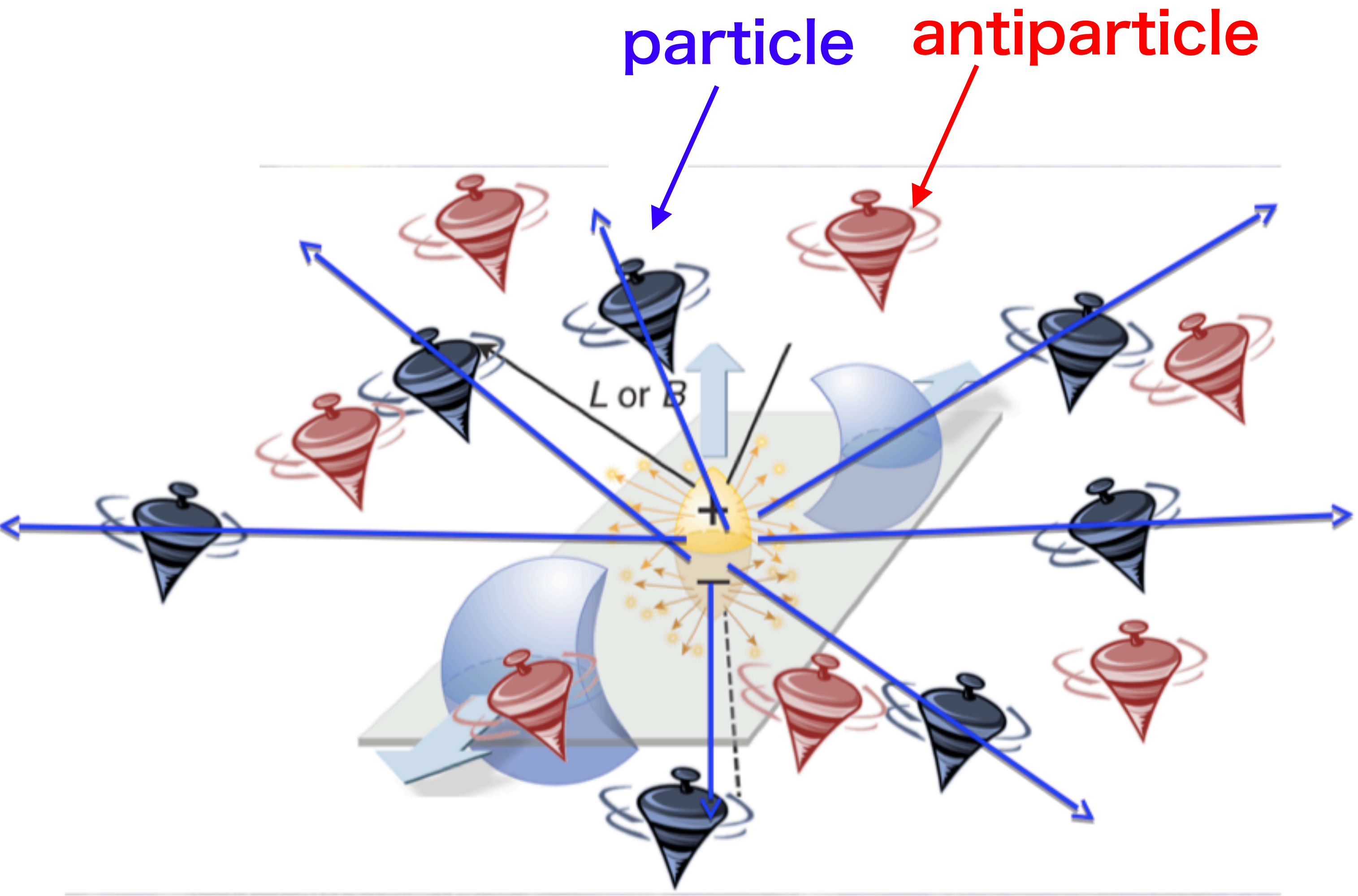
$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

# Global polarization

✔Non-zero angular momentum transfers to the spin of freedom

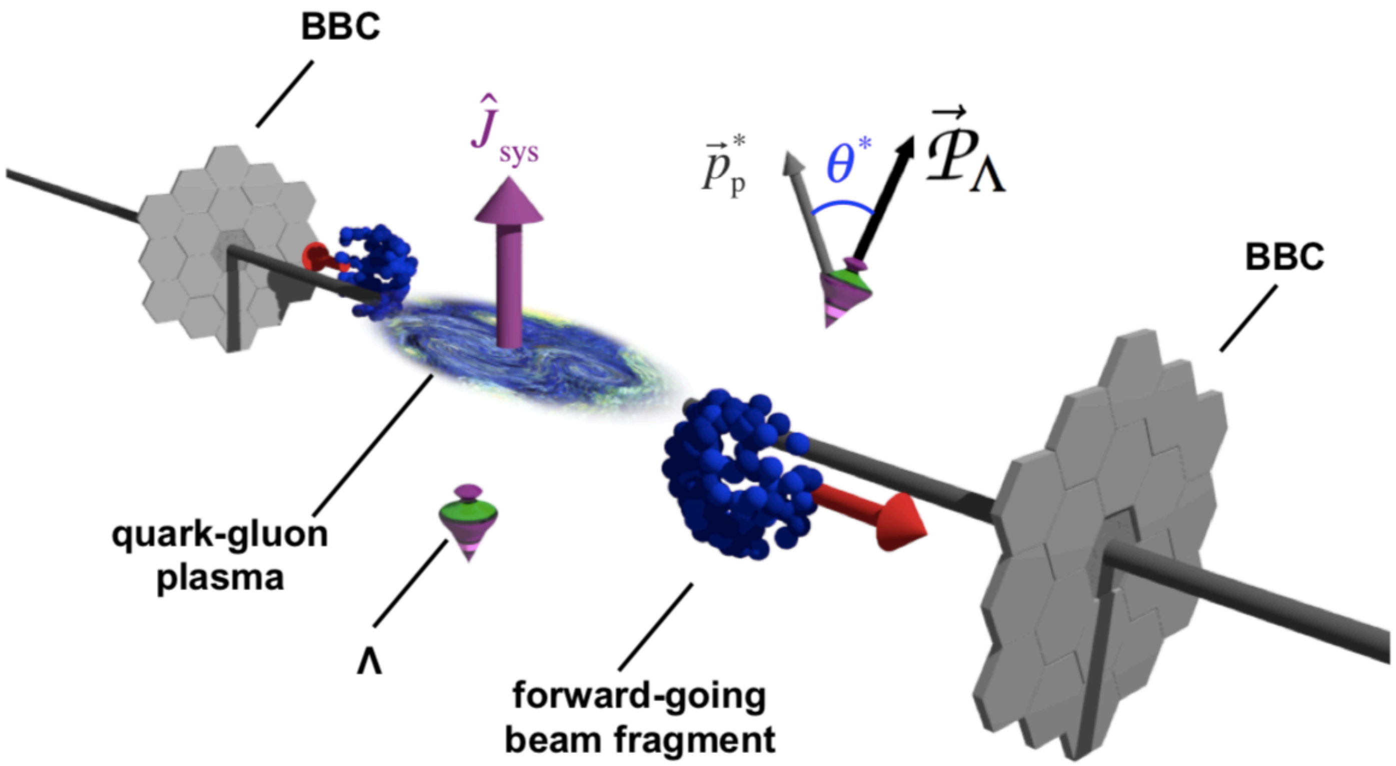
-Z-T.Liang and X.-N. Wang, PRL94, 102301 (2005)

-S.Voloshin, nucl-th/0410089(2004)



- **Polarization due to spin-orbit coupling**
  - Particle and anti-particle's spin are aligned with angular momentum L
- **Spin alignment by B-field**
  - Particle and antiparticle's spins are aligned oppositely along B due to the opposite sign of magnetic moment

# How to measure the polarization?



**parity-violating decay**

daughter proton preferentially decays into the direction of Λ's spin (opposite for anti-Λ)

$$\Lambda \rightarrow p + \pi^-$$
$$\overline{\Lambda} \rightarrow \overline{p} + \pi^+$$

(63.9%)

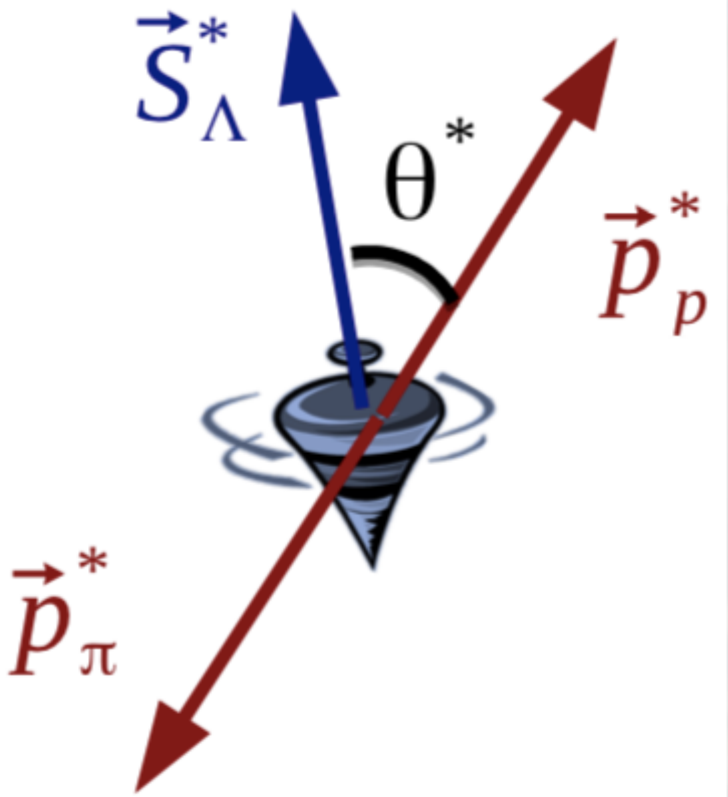
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1 - \phi_p^*)\rangle}{\text{Res}(\Psi_1)}$$

STAR,PRC76,024915

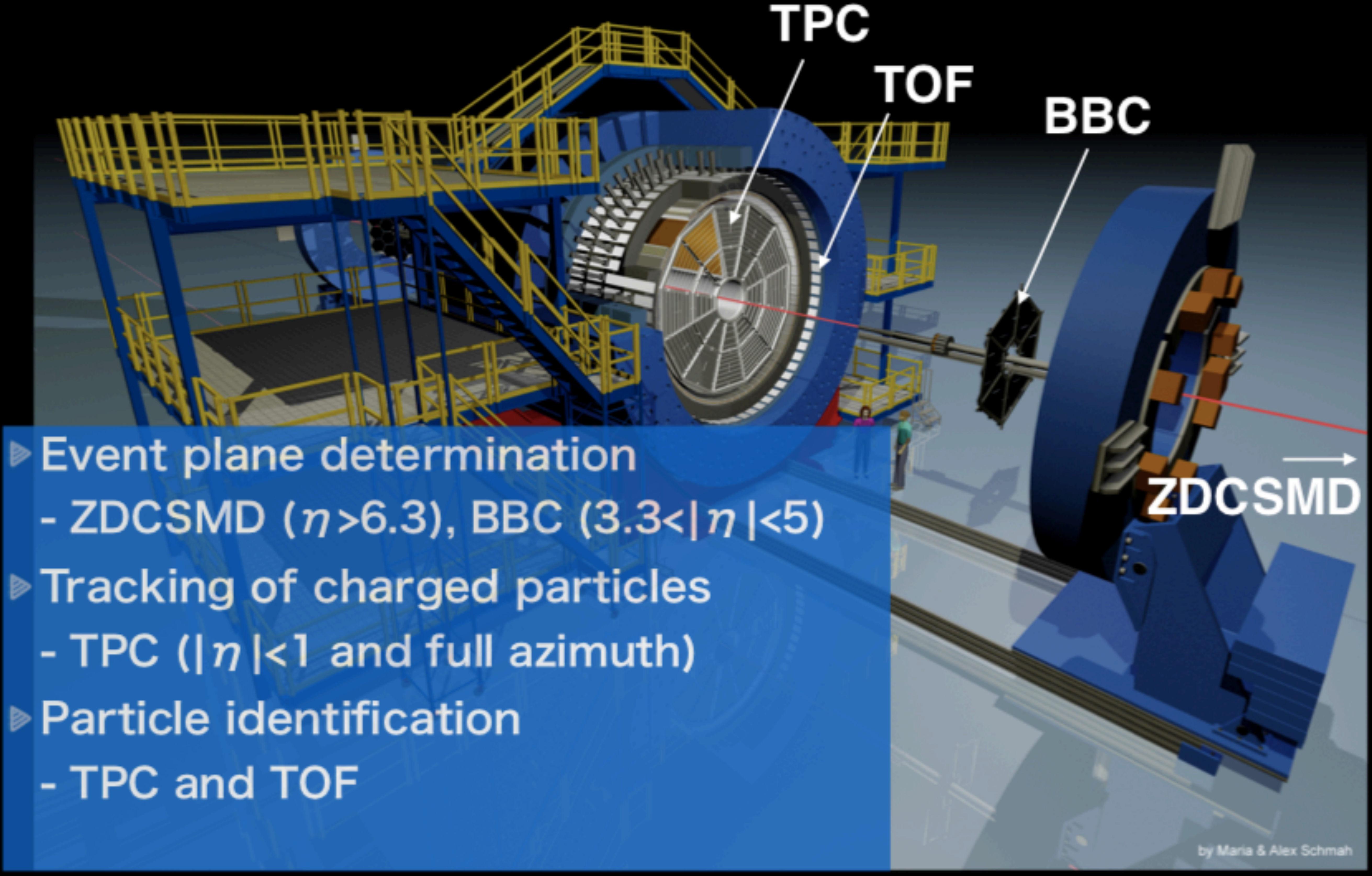
$\phi_{\text{p}}^*$:$\phi$ of daughter proton in Λ rest frame

$\Psi_1$:first order event plane

$\alpha_H$:decay parameter



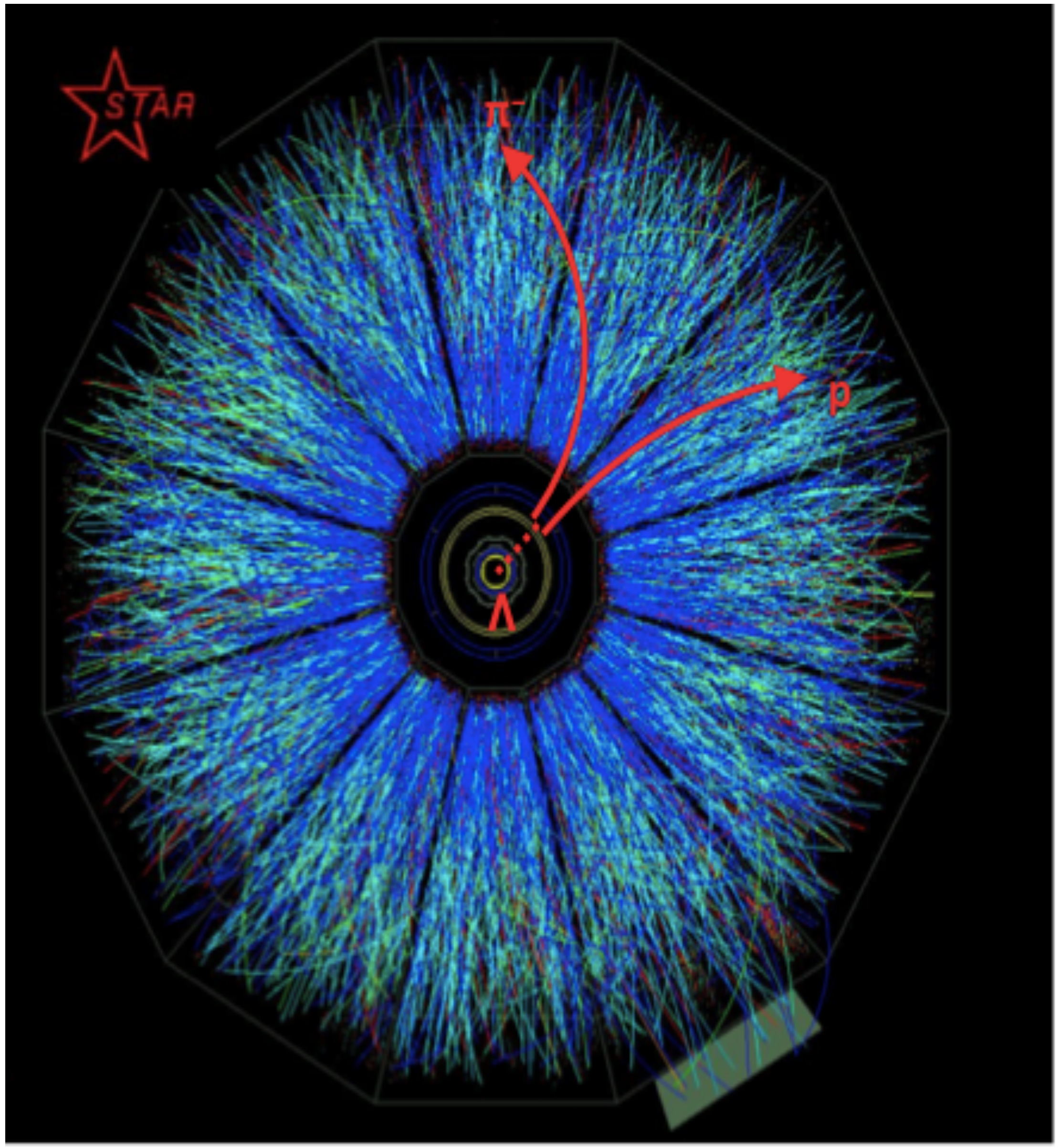
# Solenoidal Tracker At RHIC (STAR)



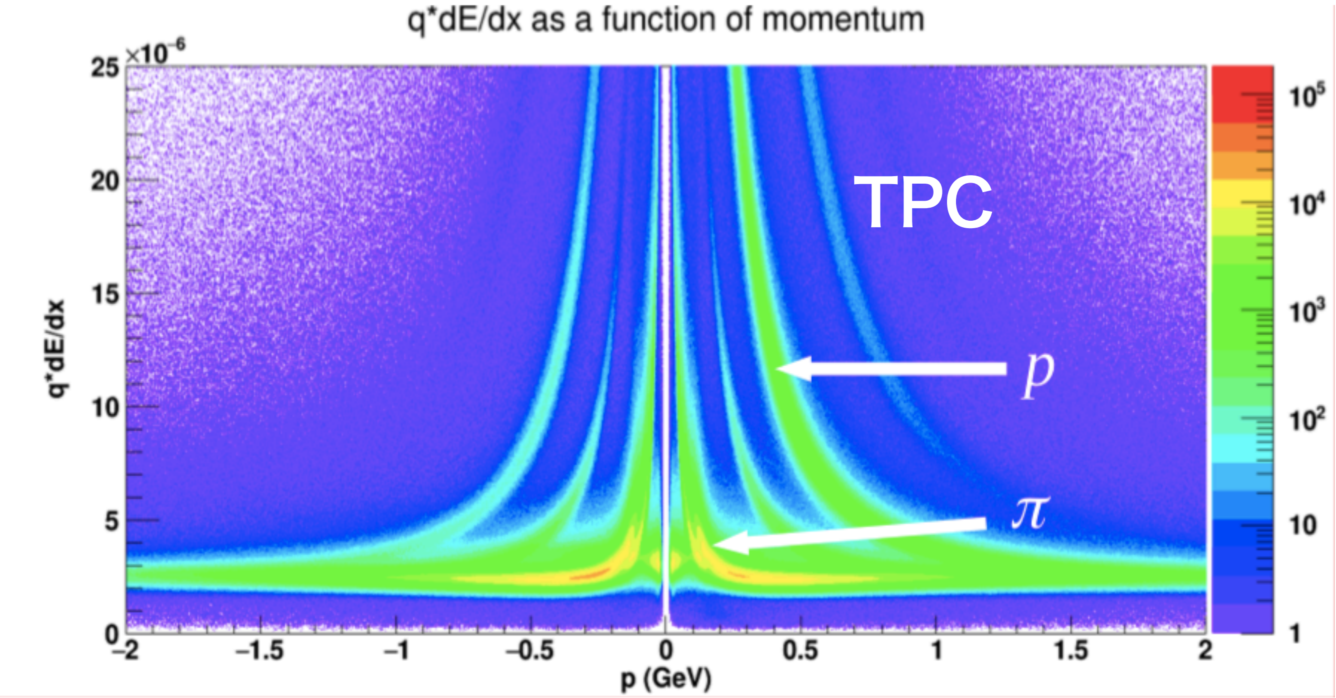
by Maria & Alex Schmah

- Event plane determination
  - ZDCSMD ($\eta>6.3$), BBC ($3.3<|\eta|<5$)
- Tracking of charged particles
  - TPC ($|\eta|<1$ and full azimuth)
- Particle identification
  - TPC and TOF

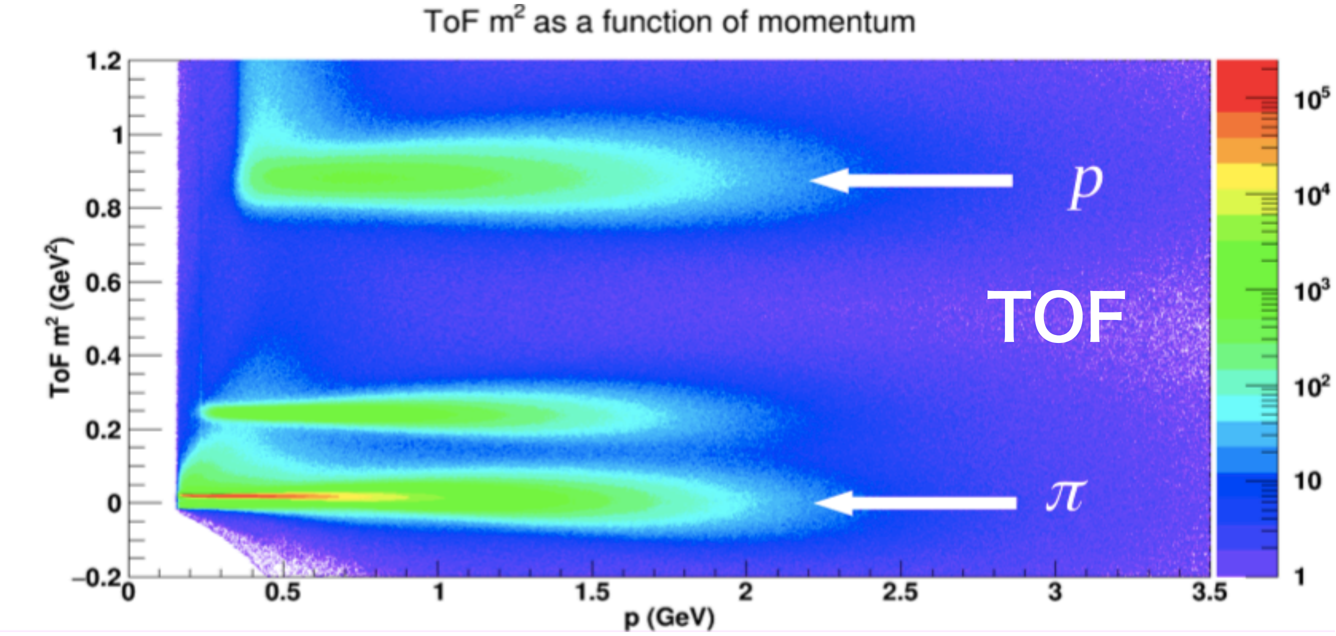
# Lambda reconstruction



q*dE/dx as a function of momentum



ToF m$^2$ as a function of momentum



- use the information on decay topology to reduce the contribution background

- identify daughter (p, $\pi$) with TPC and TOF

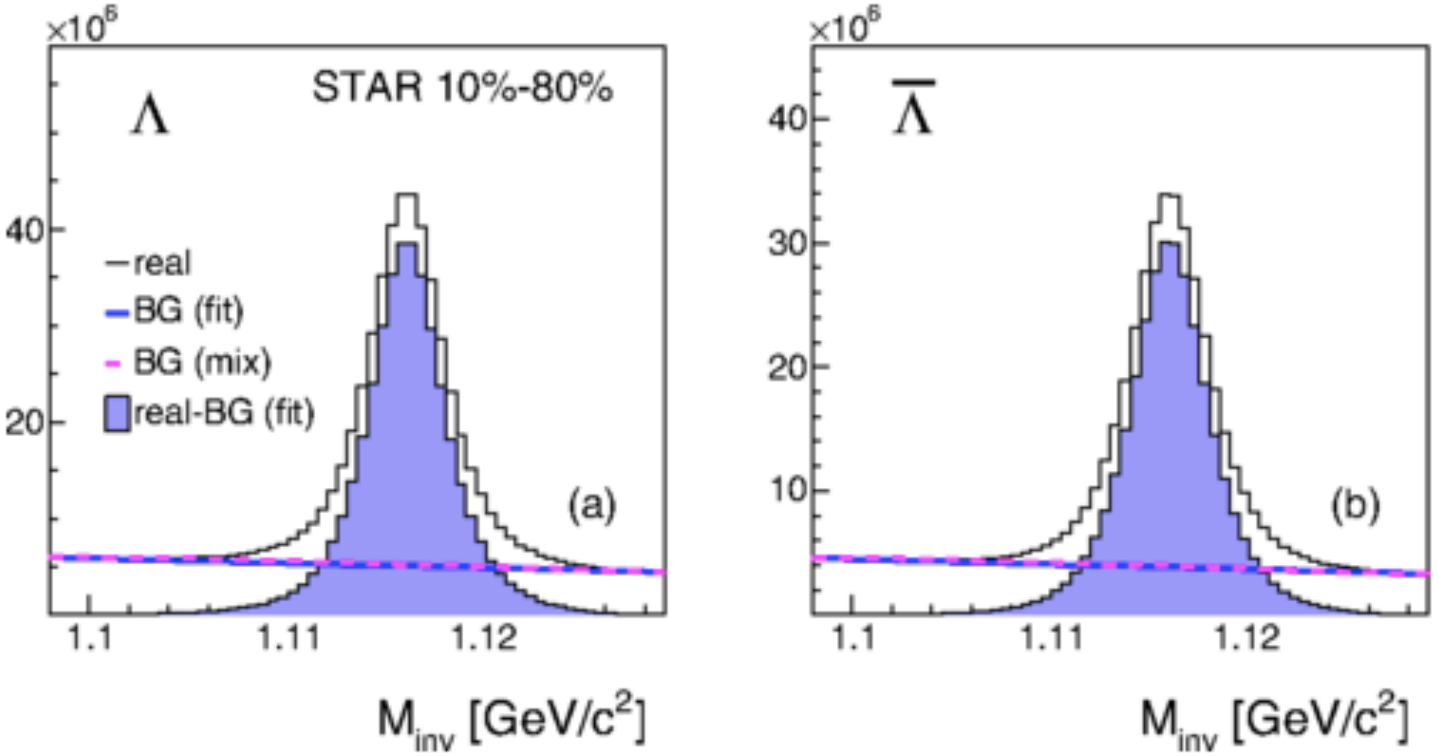
# Signal extraction with Λ hyperons

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

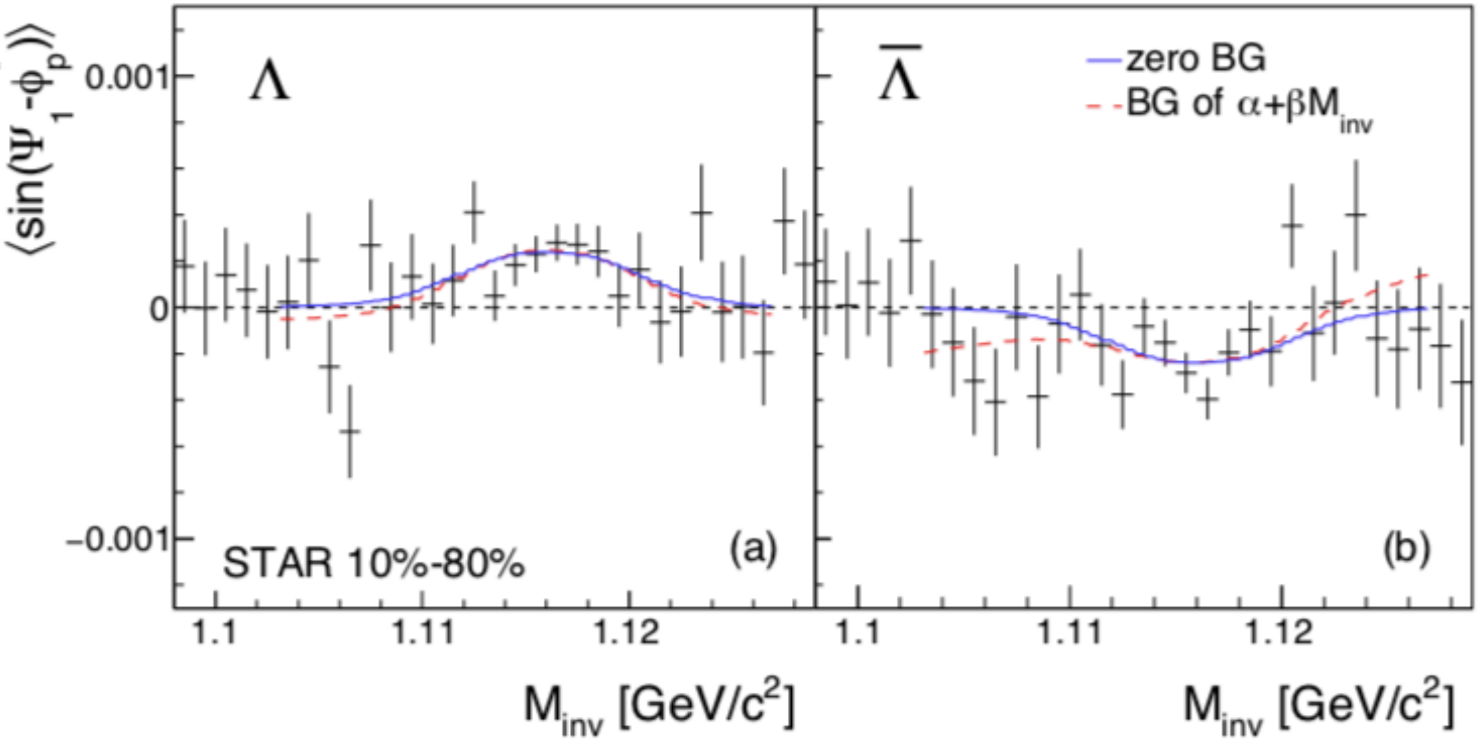
$$\langle\sin(\Psi_1-\phi_\mathrm{p}^*)\rangle^{\mathrm{obs}} = (1-f^{Bg}(M_{inv})\langle\sin(\Psi_1-\phi_p^*)\rangle^{Sg}$$

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

STAR, PRC98, 014910 (2018)



STAR, PRC98, 014910 (2018)

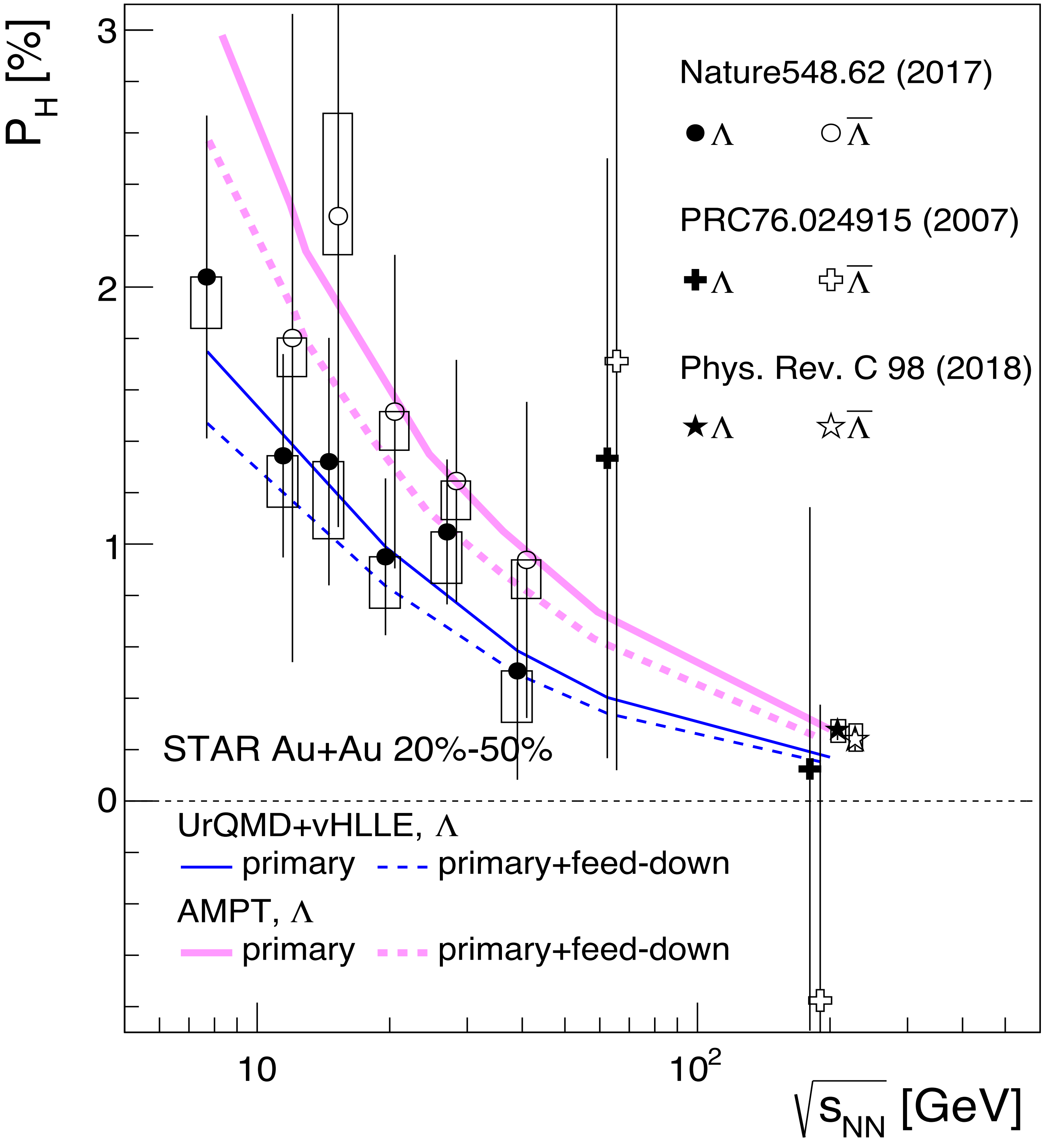


Λ's signal is opposite to anti-Λ's

→ Λ and anti-Λ are polarized in the same direction

(parity-violating decay)

# Energy dependence of polarization



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

AMPT:H.Li et al.,Phys,Rev.C96,054908(2017)

✔Positive polarization Signal !

✔polarization looks to increase in lower energies

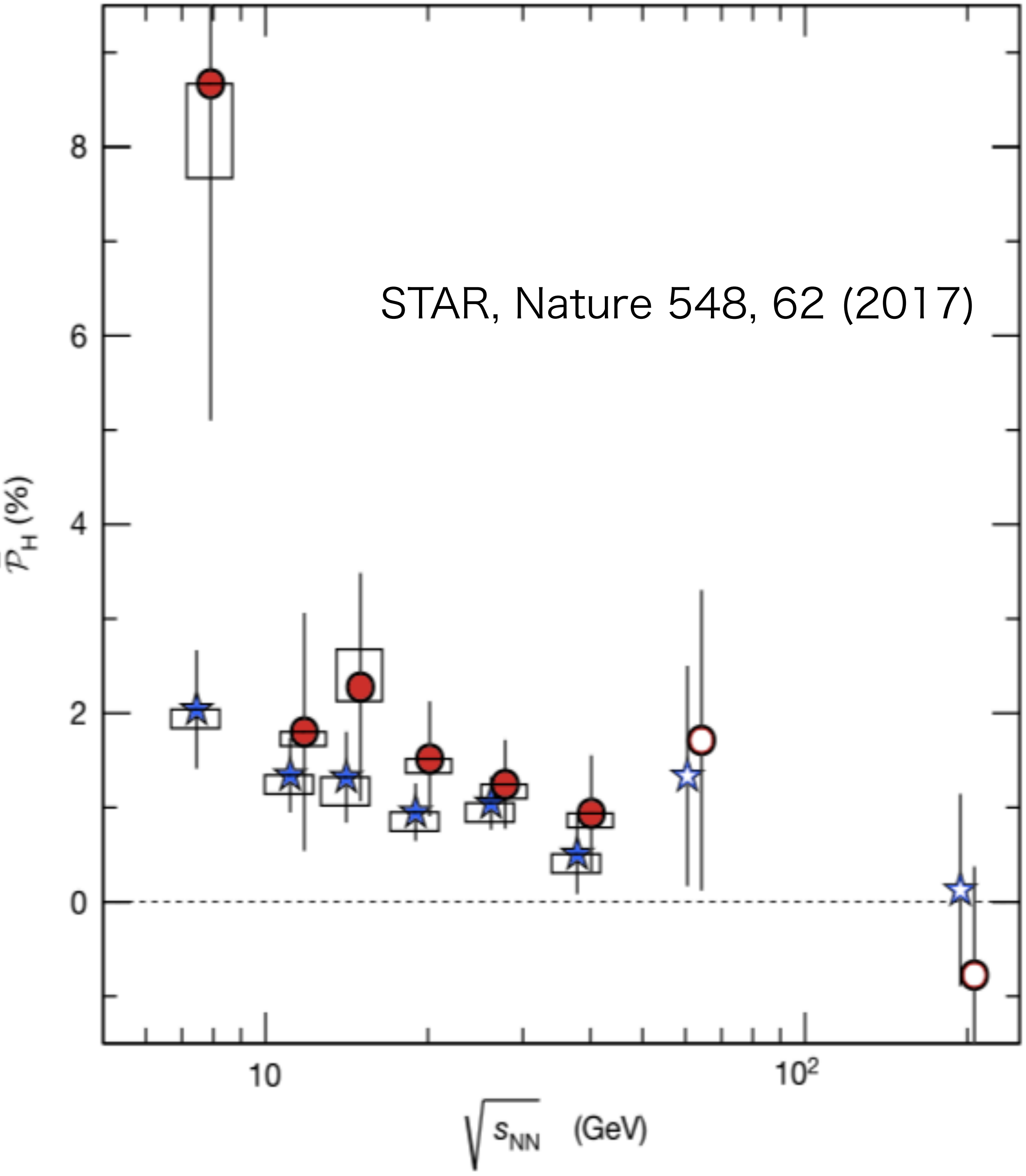
✔anti-Λ is systematically larger than Λ

→ imply magnetic coupling

need more events

→ **BES-II**

# Observation of fluid vortices in HIC



STAR, Nature 548, 62 (2017)

T:temperature at Thermal equilibrium

$\mu_\Lambda$:Λ magnetic moment

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

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \quad , \quad P_{\overline{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

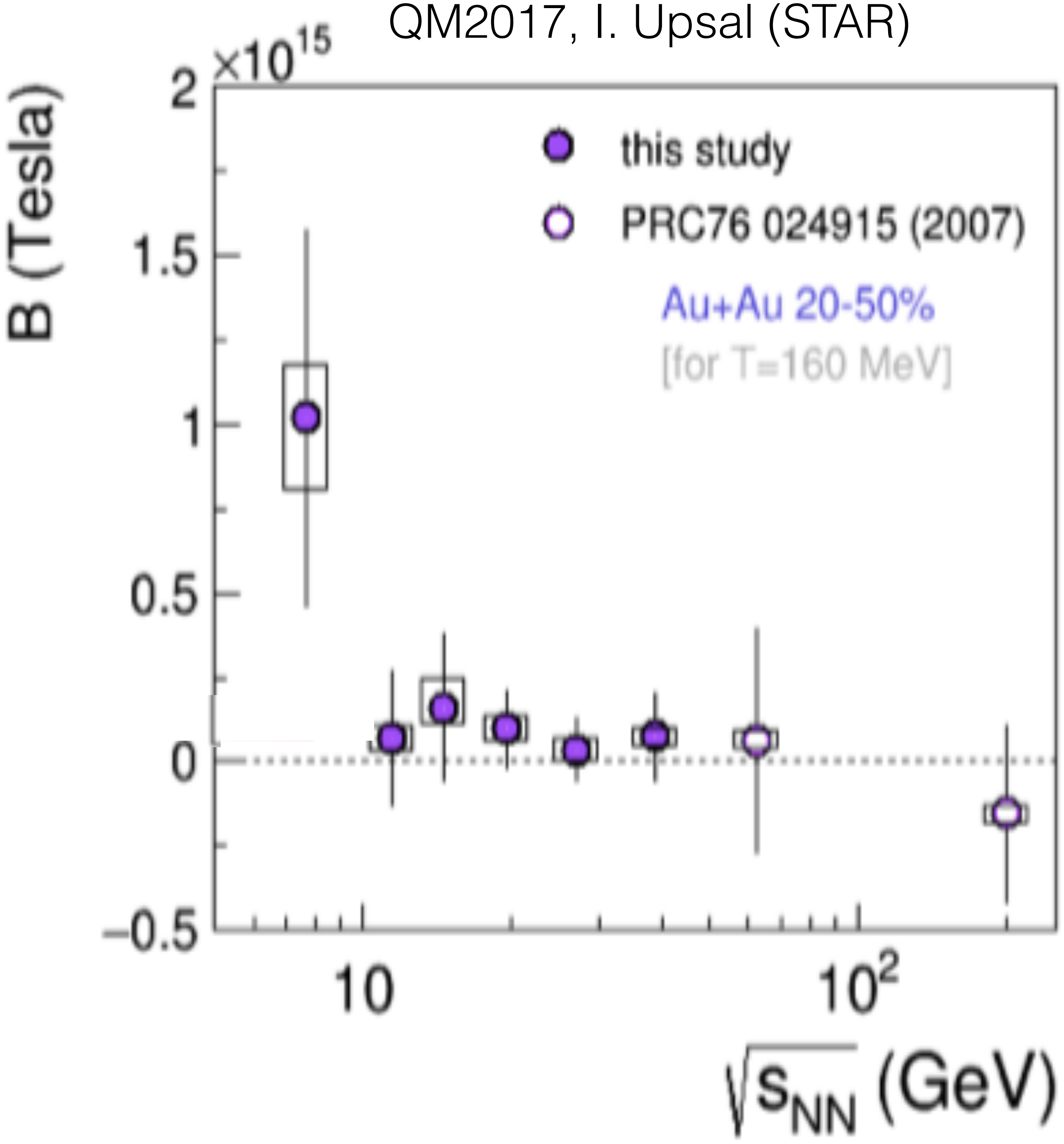
$$\omega = (P_\Lambda + P_{\overline{\Lambda}}) k_B T/\hbar$$

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

The most vortical fluid ever observed

# Possible probe of magnetic field

QM2017, I. Upsal (STAR)



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

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

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

$$B = (P_\Lambda + P_{\overline{\Lambda}})k_B T/\mu_N$$

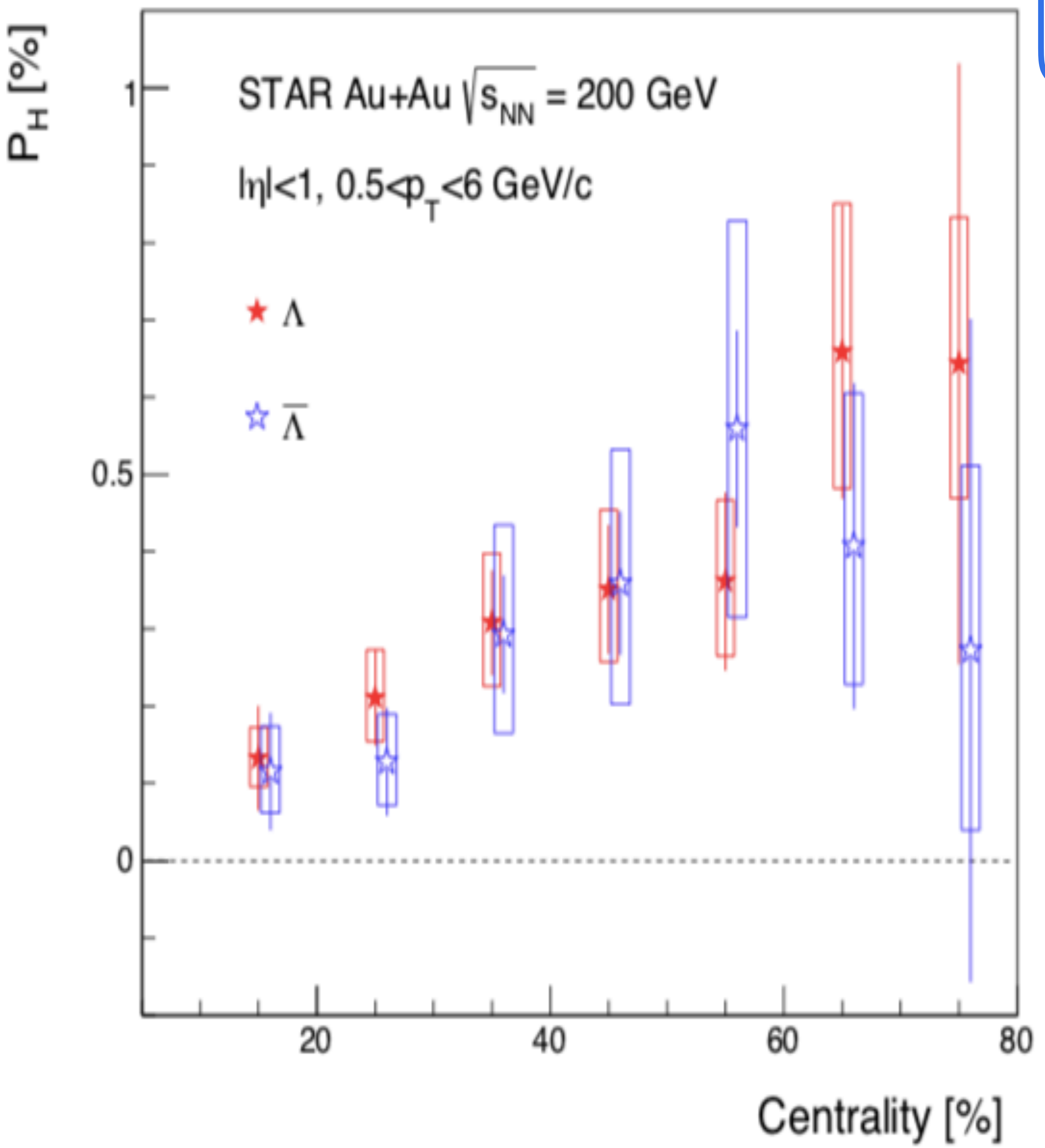
$$\sim 5.0 \times 10^{13}\ [\mathrm{Tesla}]$$

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

✔Extracted B-field is close to our expectation.

# Centrality dependence of polarization

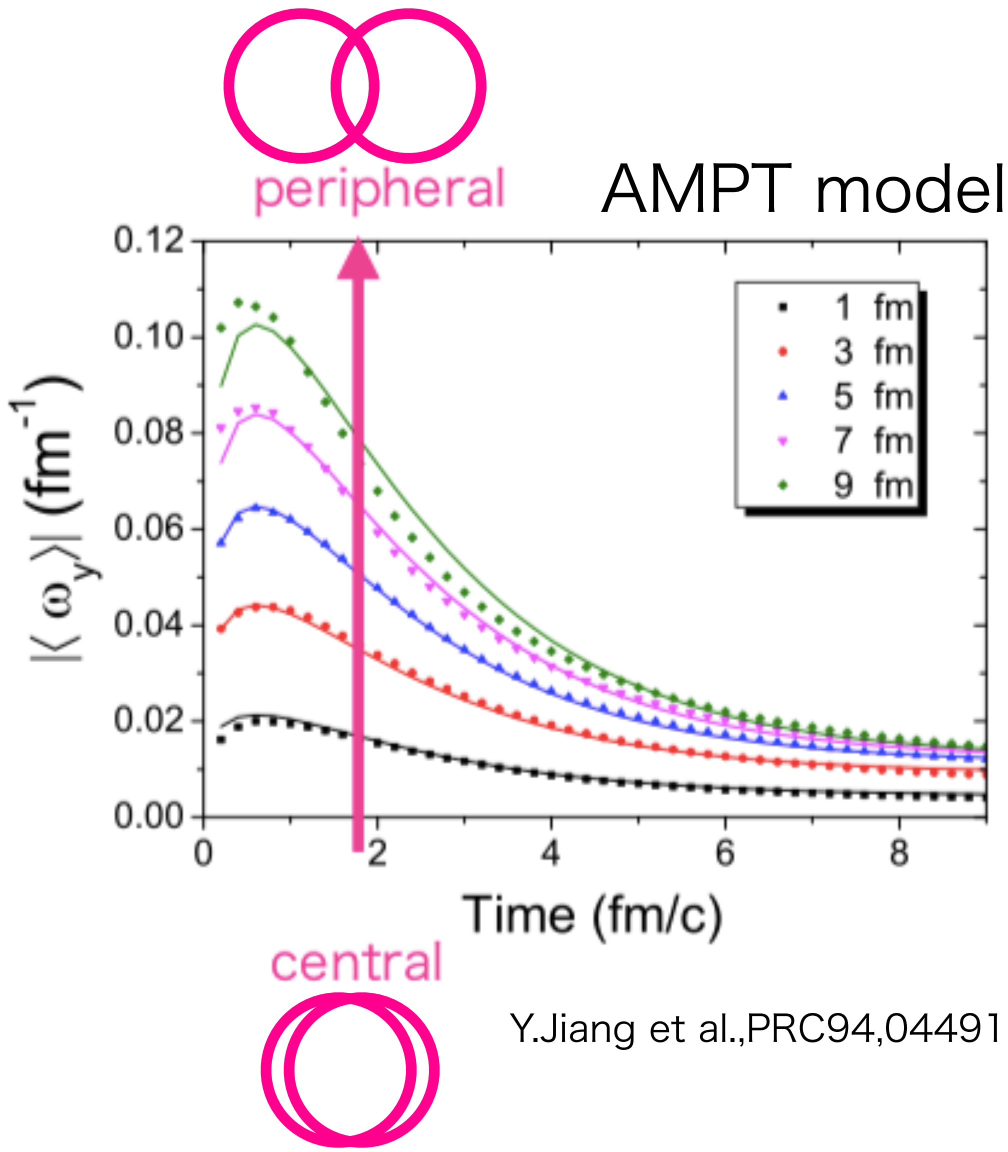
STAR PRC 98, 014910 (2018)



In most central collision

→ no initial angular momentum

the polarization decrease
in more central collision

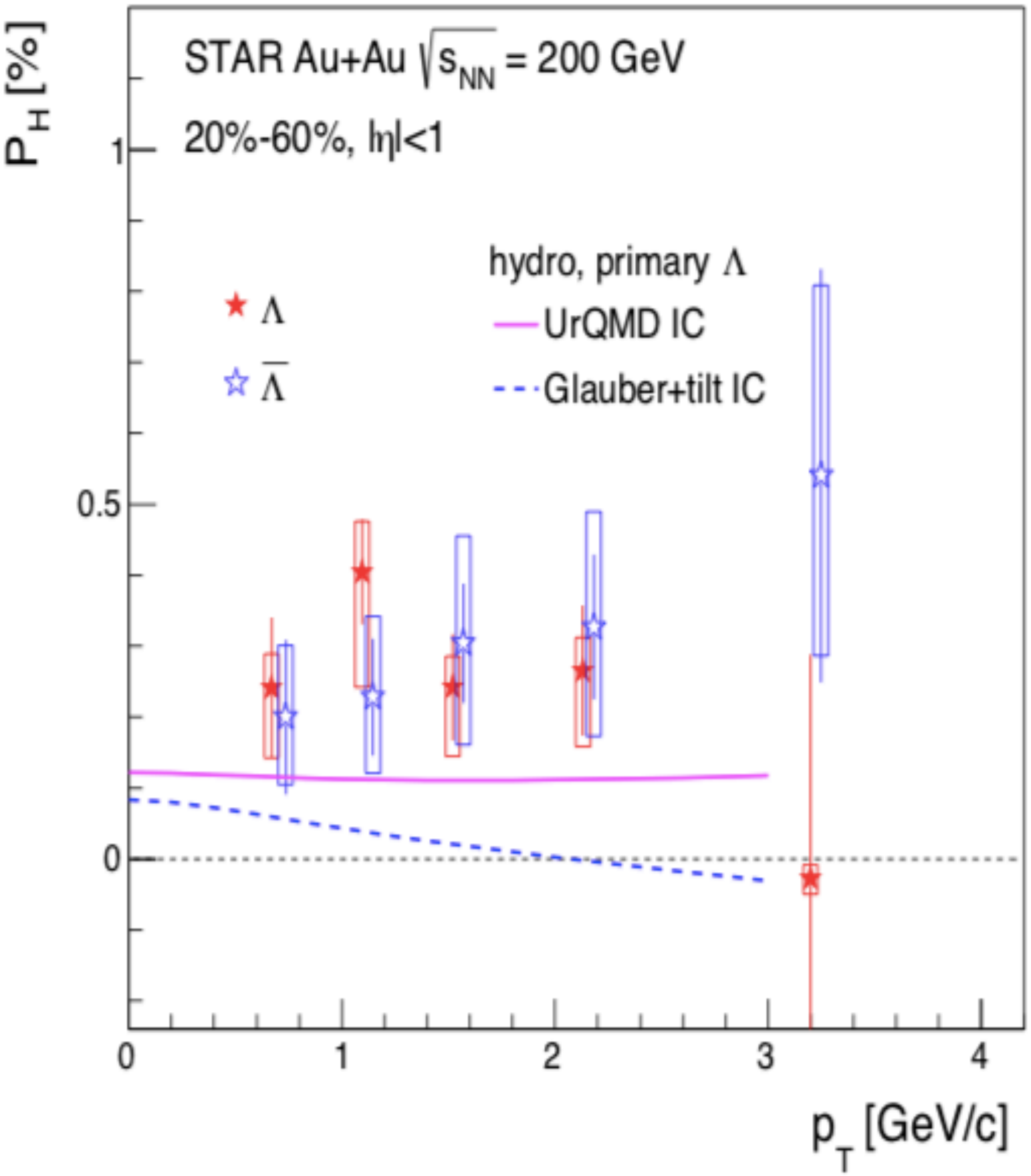


AMPT model

Y.Jiang et al.,PRC94,044910(2016)

# $p_T$ dependence of polarization

STAR PRC 98, 014910 (2018)



✔No significant $p_T$ dependence

✔One might expect....

1.The polarization decrease in low $p_T$

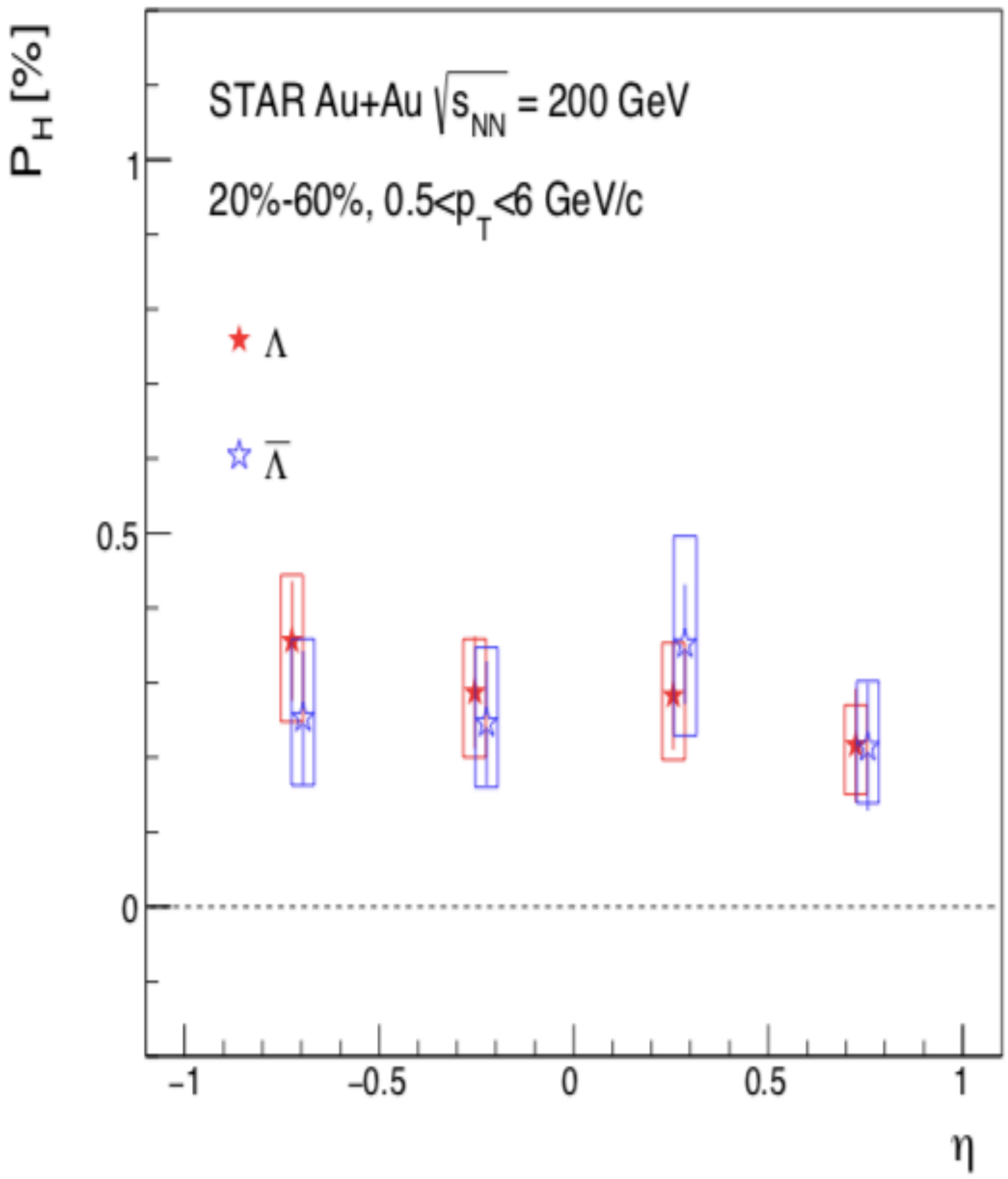
— smearing effect

2.The polarization decrease in high $p_T$

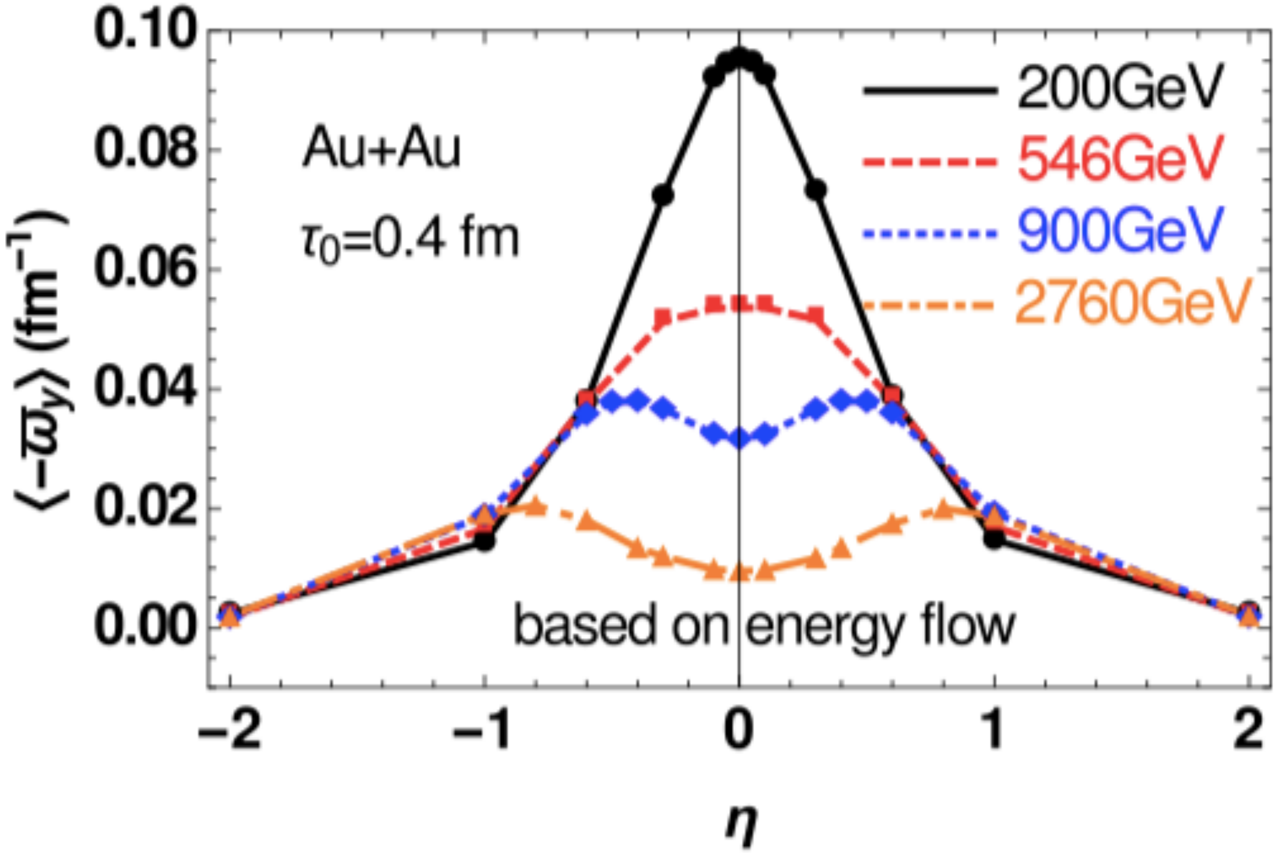
—jet fragmentation

# $\eta$ dependence of polarization

STAR PRC 98, 014910 (2018)



W.-T.Deng and X.-G Huang:C93,064907

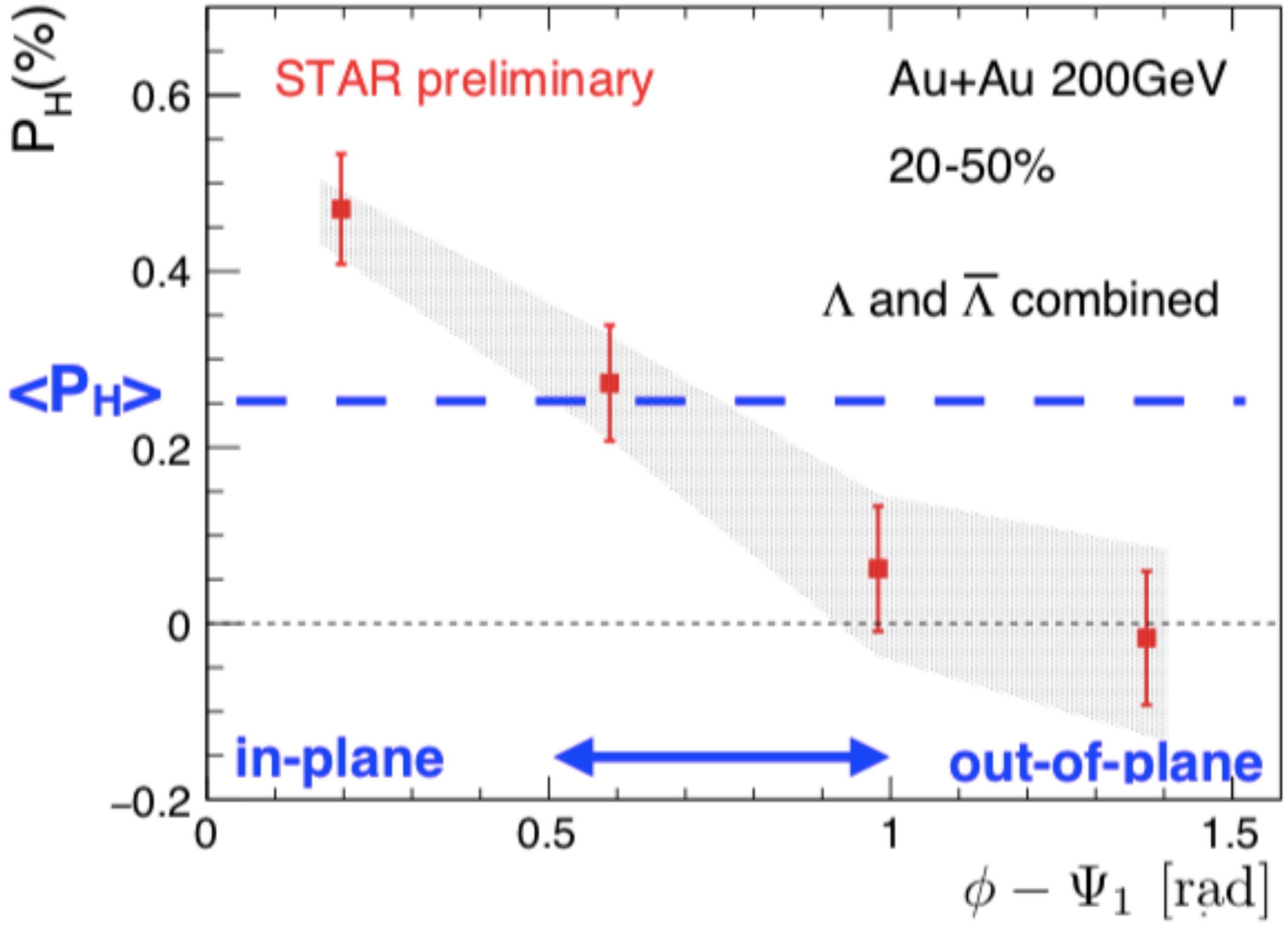


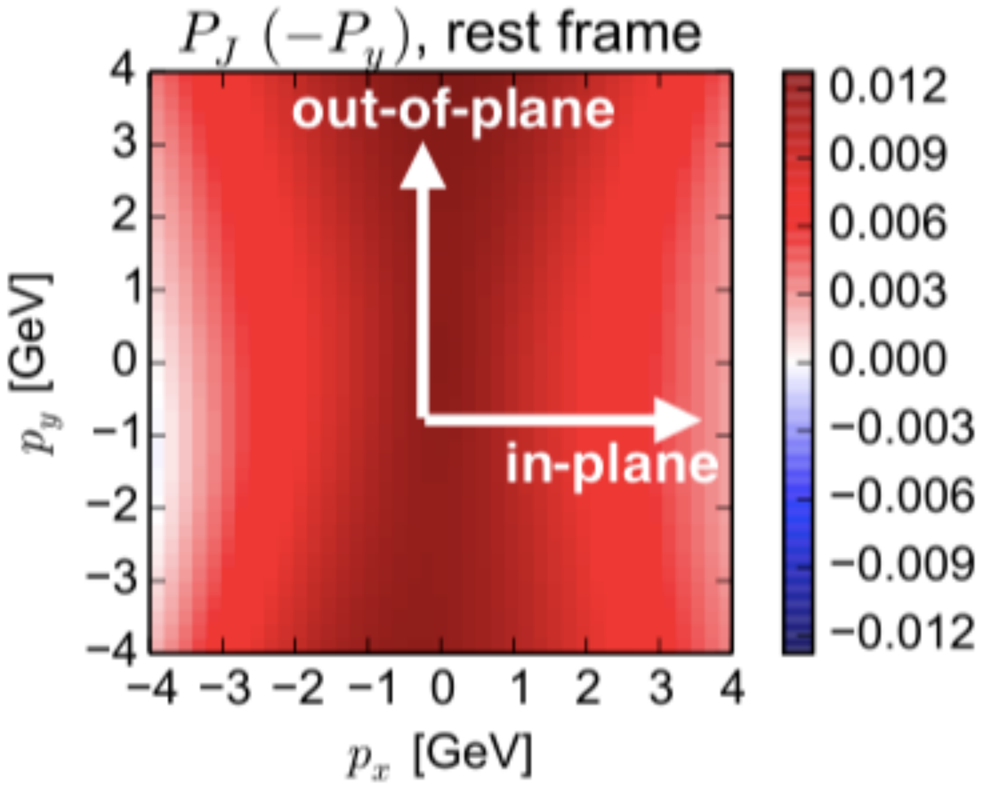
✔The vorticity is expected decrease at large rapidities

✔The data do not show significant $\eta$ dependence

# Azimuthal angle dependence of polarization

IMSD 2018 Biao

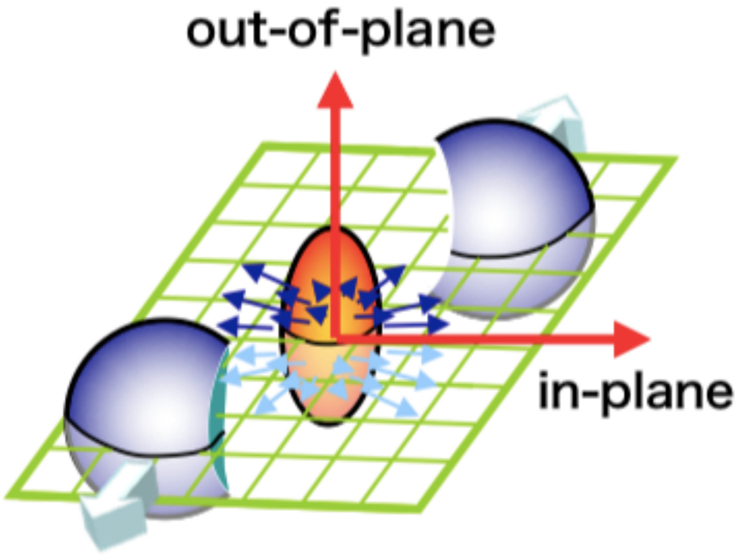




I.Karpenko and F.Becattini, EPJC(2017)77:213

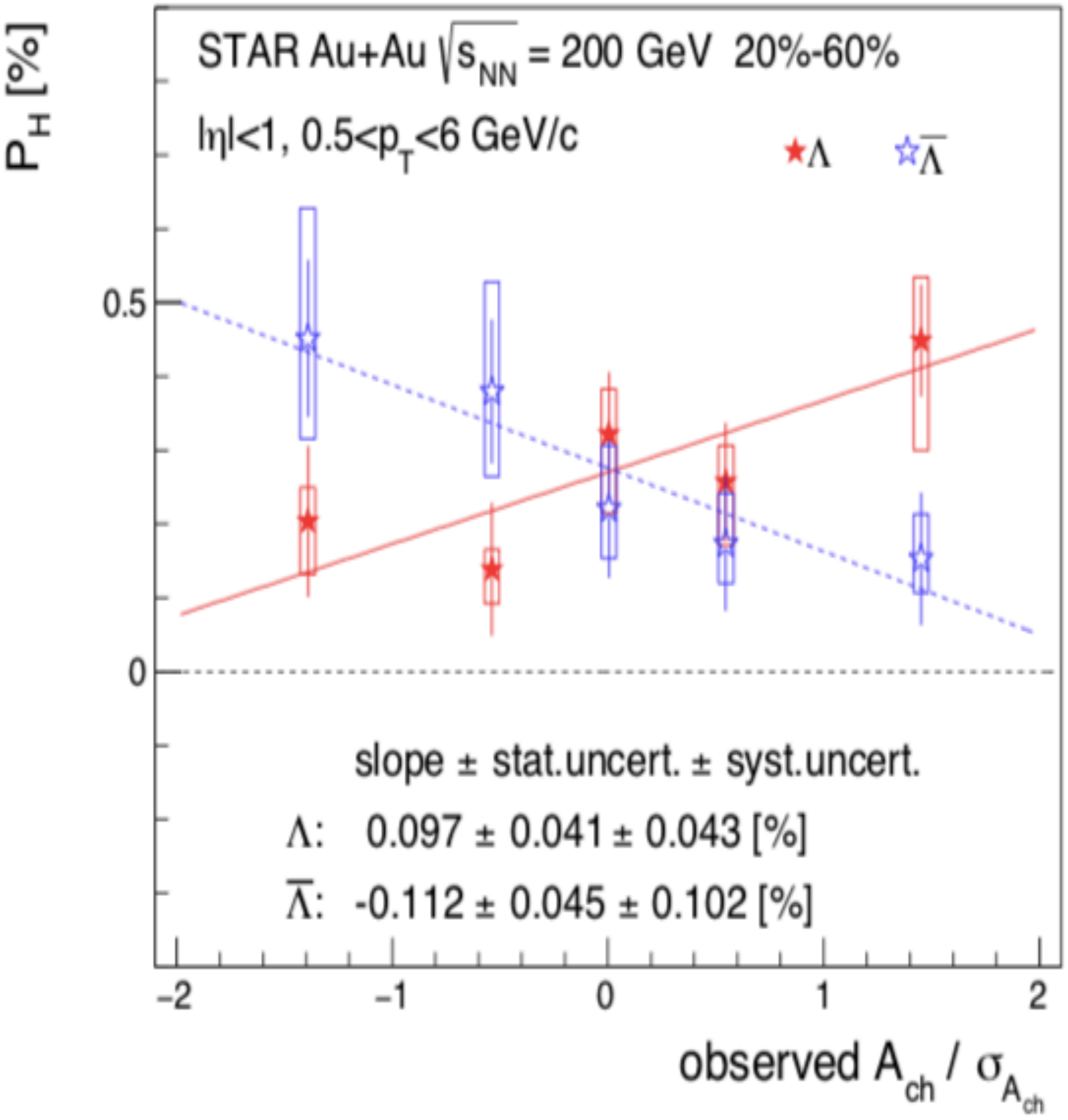
- Larger polarization in in-plane than out-of-plane

- Opposite to hydrodynamic model

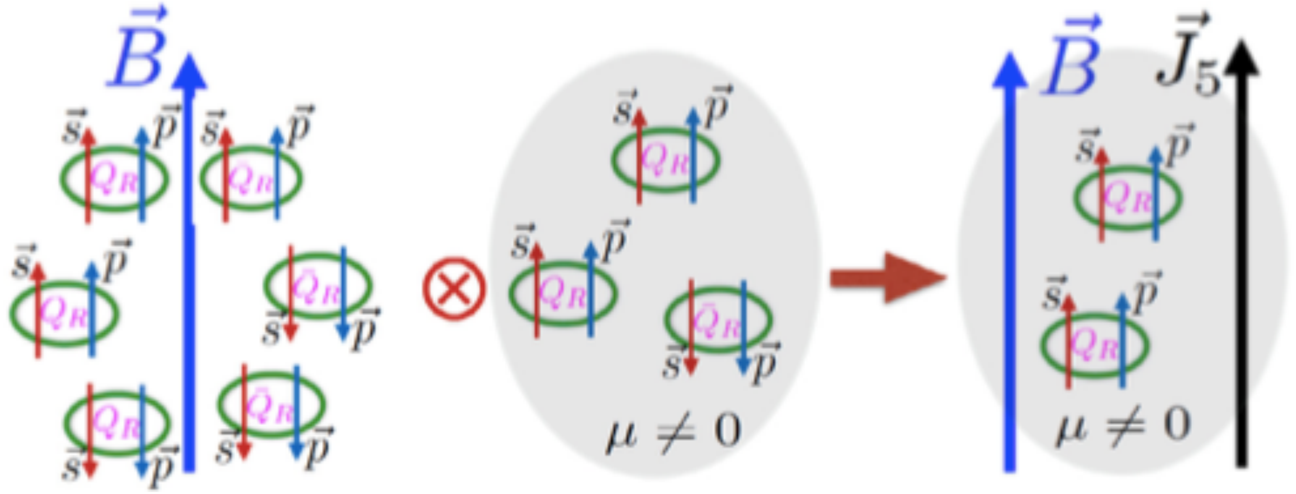


# Λ polarization vs charged asymmetry

STAR PRC 98, 014910 (2018)



Chiral Separation Effect



$$\mathbf{J}_5 \propto \mu_v \mathbf{B}$$

- Use charge asymmetry Ach instead of μv

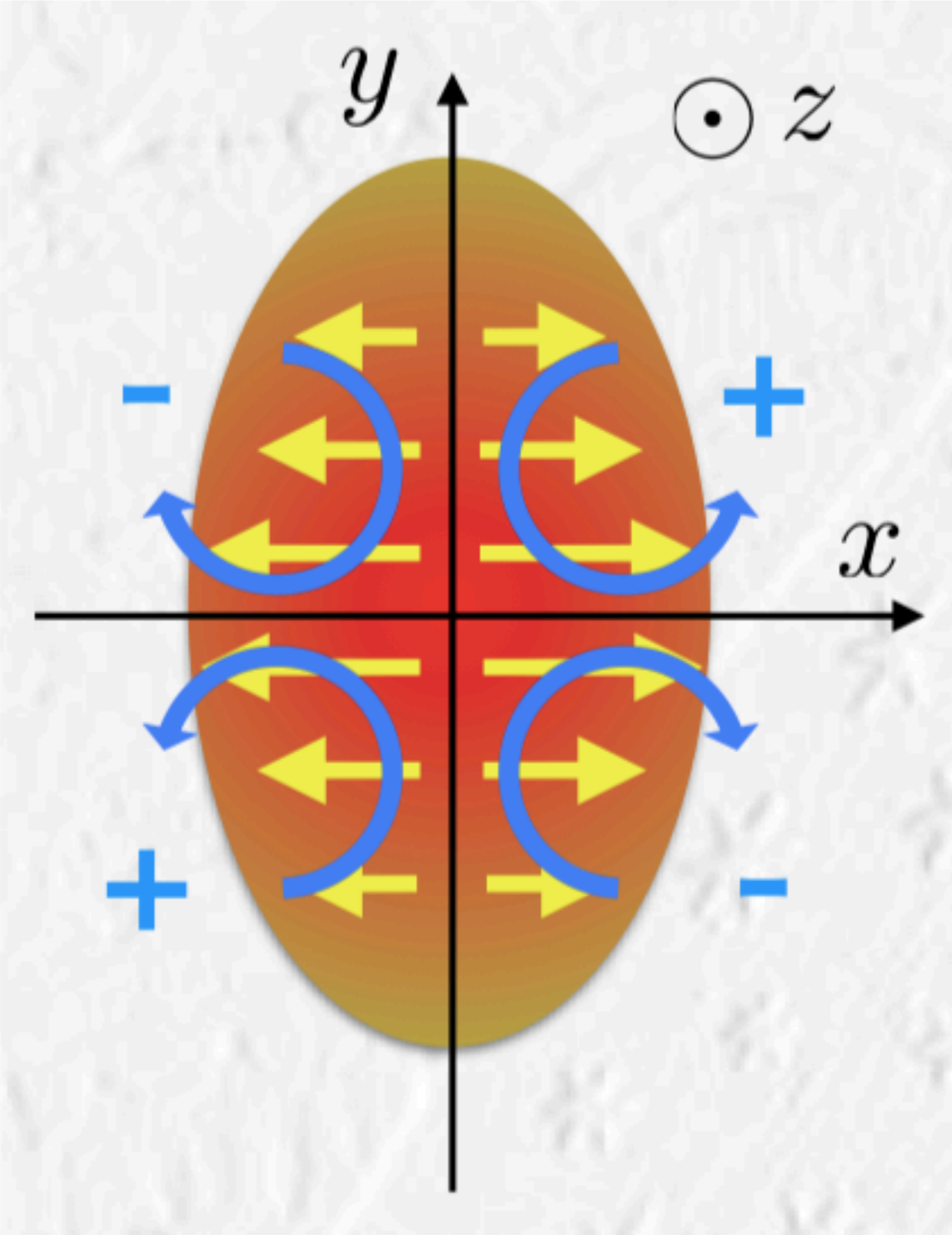
$$\mu_v / T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{ch}$$

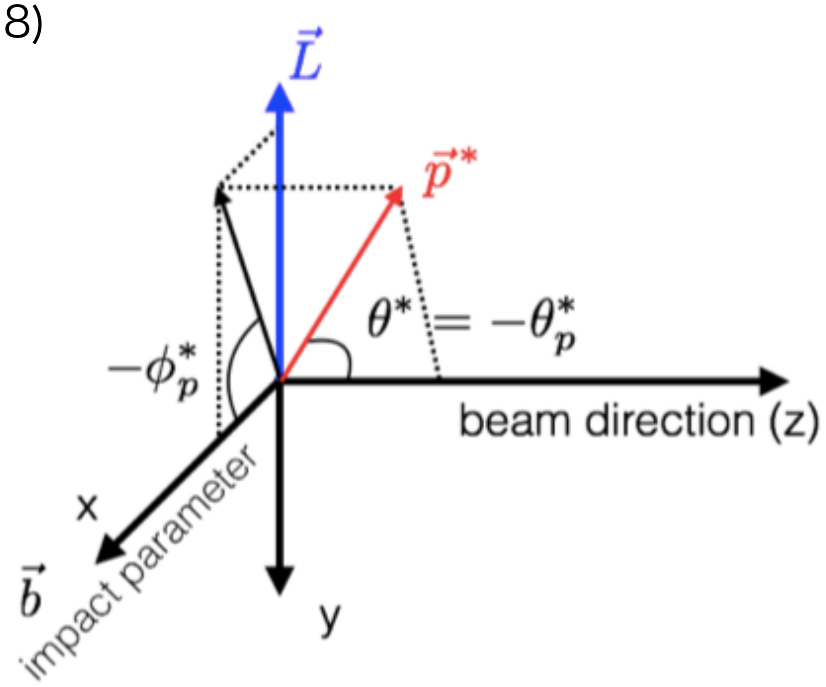
✔Slopes of Λ and anti-Λ seem to be different

✔Possibly a contribution from axial current?

# Polarization along the beam direction

S.Volshin,SQM2017
F.Becattini and I. Karpenko, PRL120.012302(2018)





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

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

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

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

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

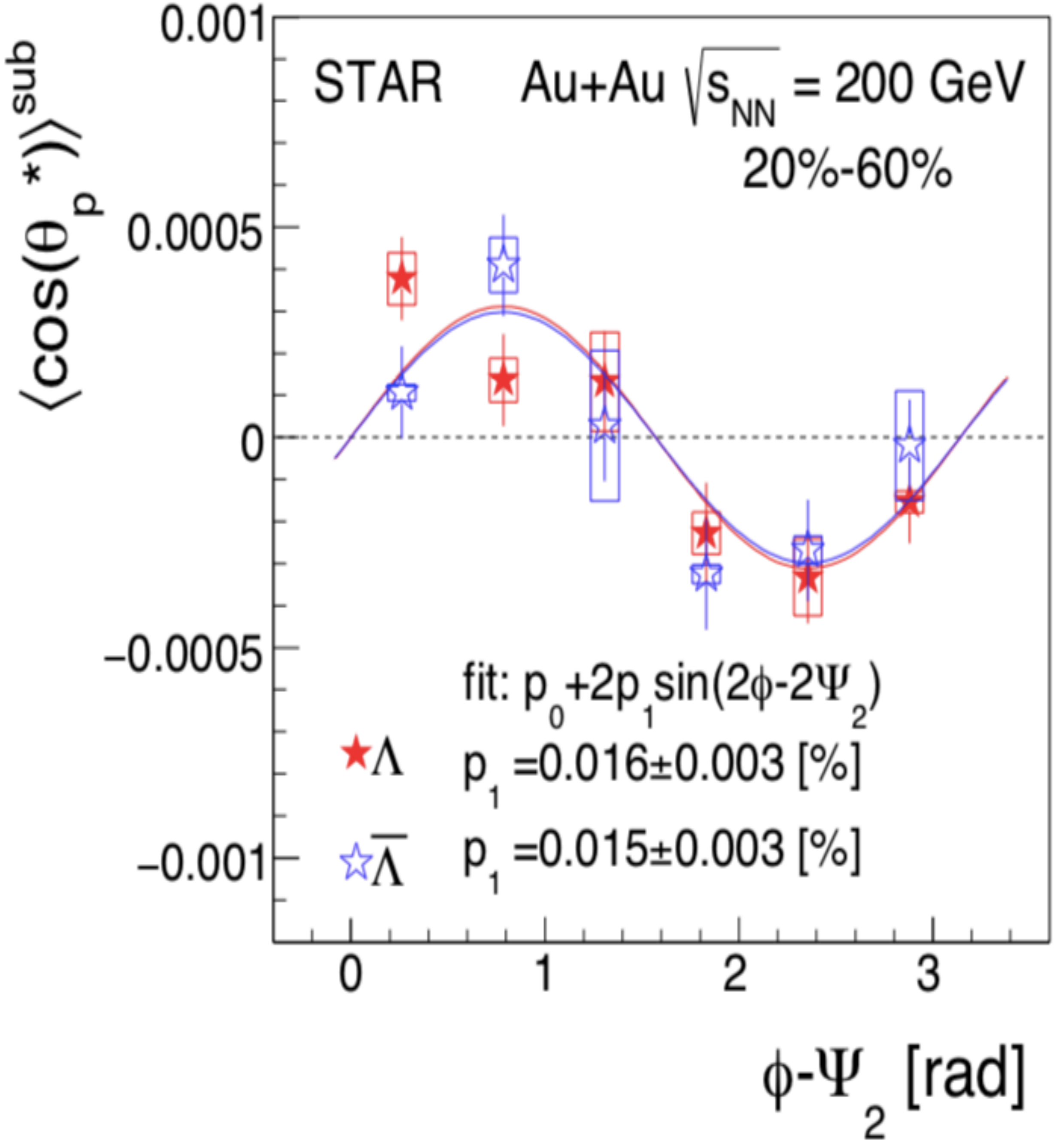
$\alpha_H$ :decay parameter

$\theta_p^*$: $\theta$ of daughter proton in $\Lambda$ rest frame

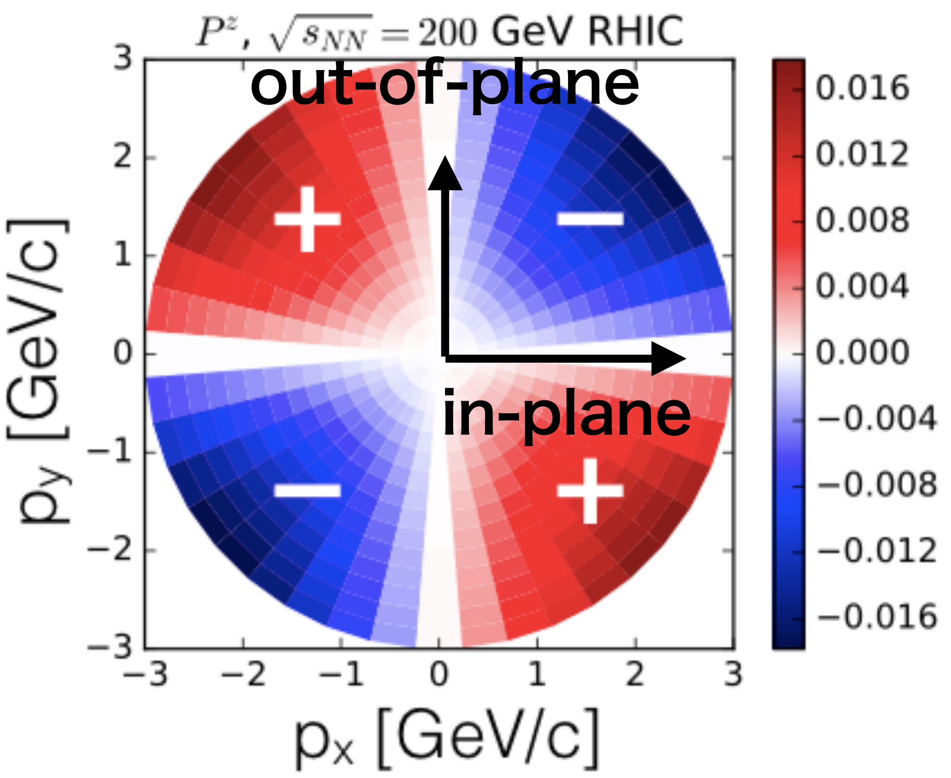
✔Stronger flow in in-plane than in out-of-plane cloud make local polarization along beam axis

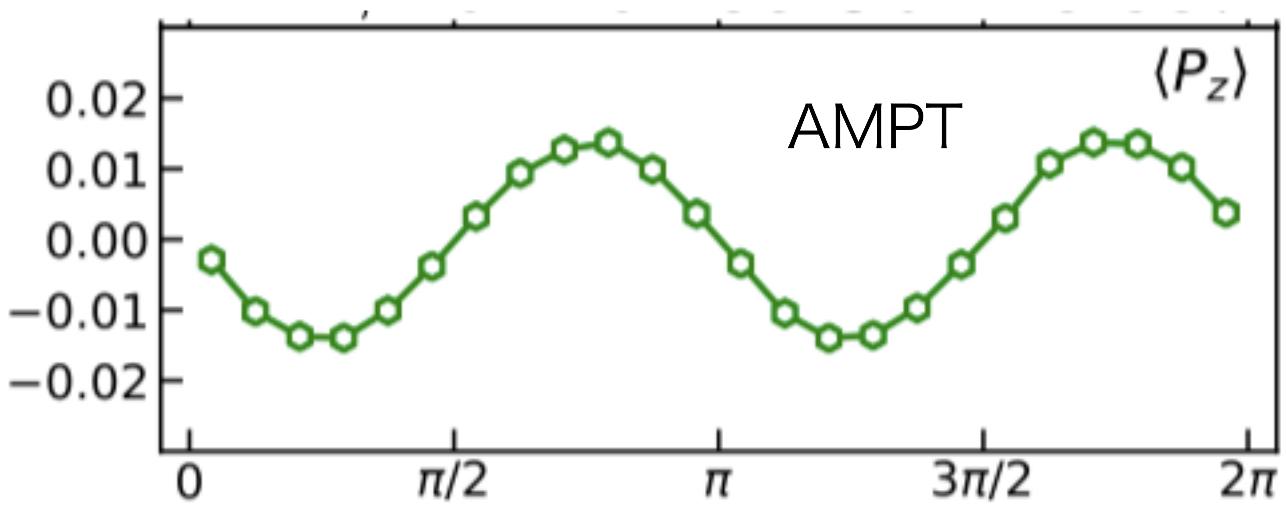
✔Longitudinal component, Pz, can be expressed with $\langle \cos\theta_p^* \rangle$

# Polarization along the beam direction



Hydrodynamic model



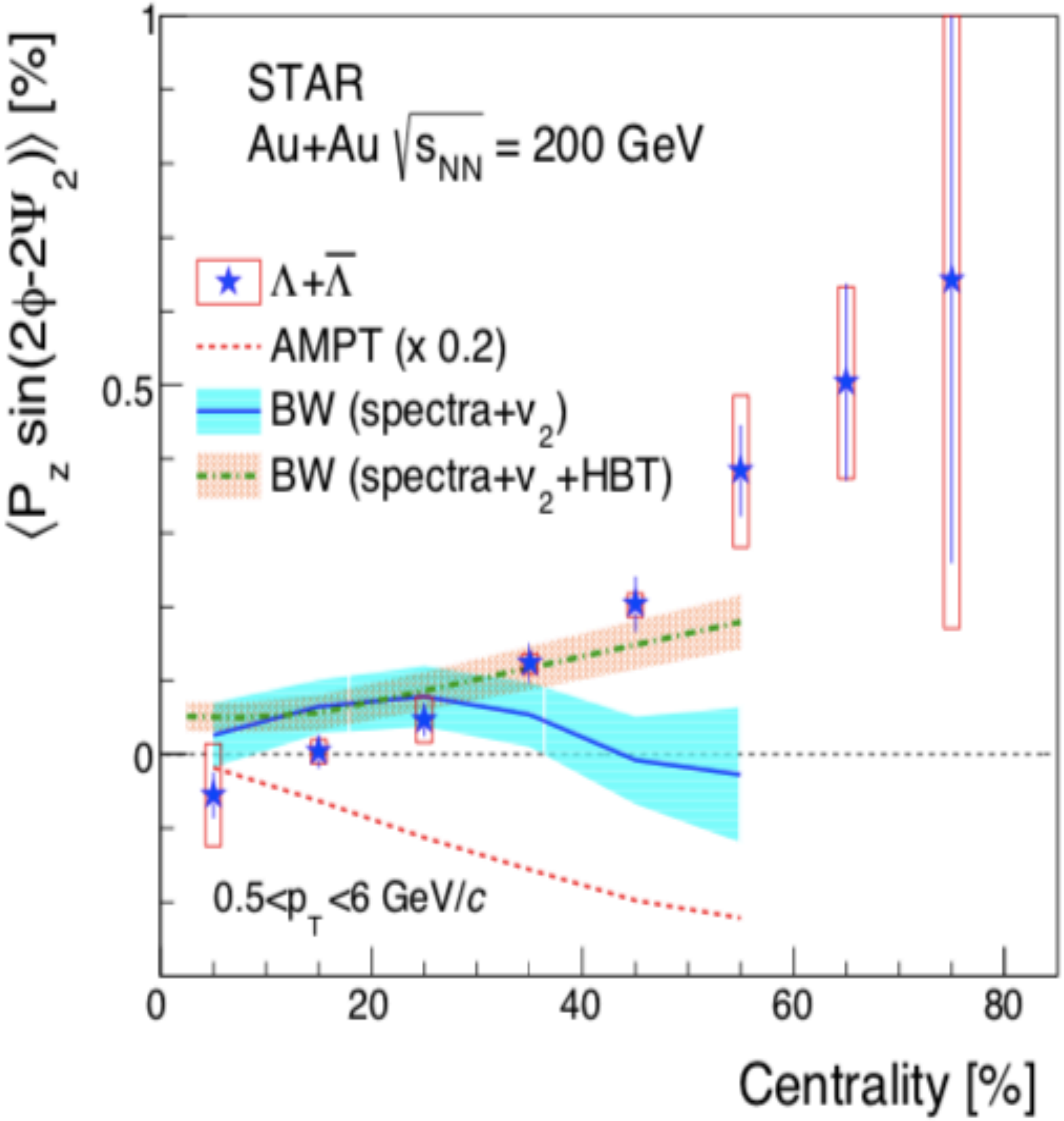


✔Sin structure as expected from the elliptic flow

✔Opposite sign to hydrodynamics 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 $P_Z$



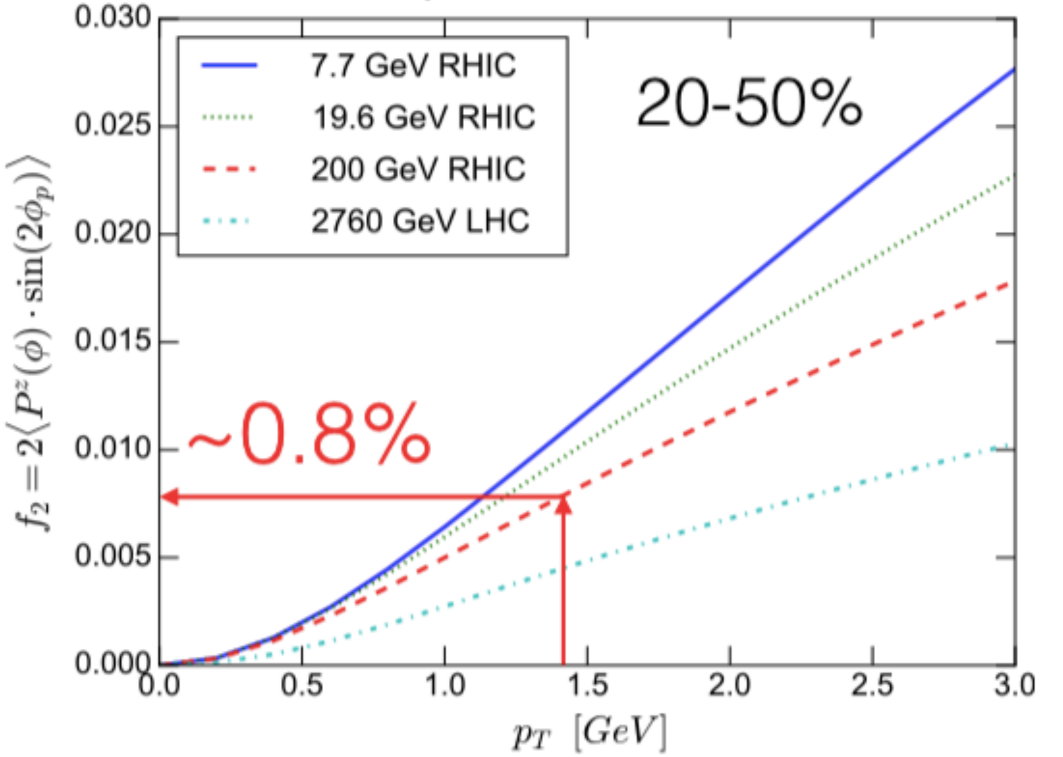
$\langle p_T \rangle$ of Λ ~1.4 GeV/c

(0.5<pT<6 GeV/c)

✔Strong centrality dependence

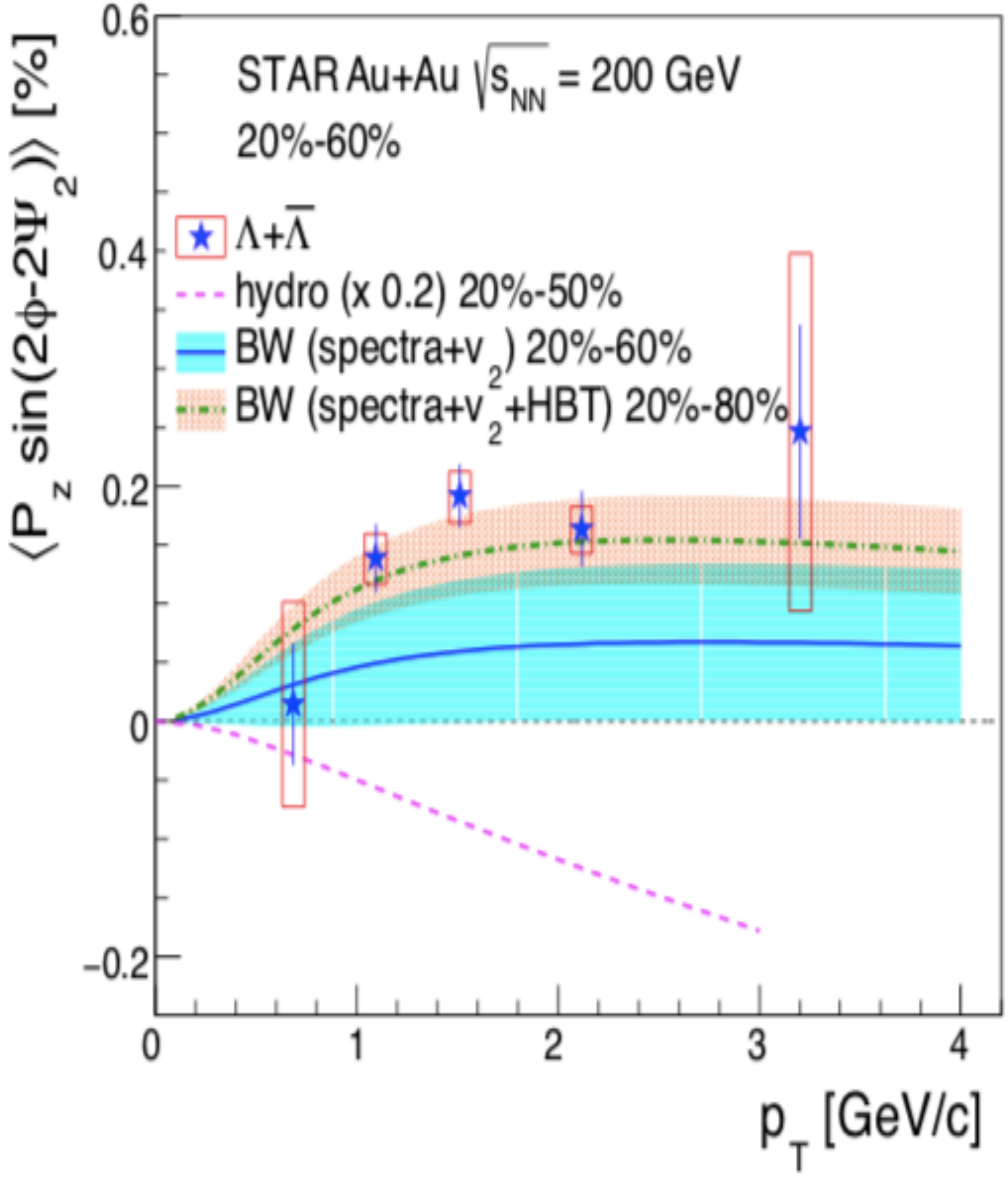
✔Similar magnitude to the global polarization

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



✔~5 times smaller magnitude than the Hydro and AMPT

# $p_T$ dependence of local polarization



✔No significant $p_T$ dependence for $p_T > 1.0$ GeV

✔can not conclusion about low $p_T$ dependence

✔Opposite sign to hydrodynamics model

# Summary

**✔Observation of positive Λ polarization at √sNN = 7.7-200GeV**

- Indicating the thermal vorticity of system in HIC $\omega \sim 10^{22} s^{-1}$.
- Polarization decrease at higher energies.
- Larger signal in more peripheral collision but no significant dependence on pt and $\eta$
- Larger signal in in-plane than in out-of-plane

→ **Disagree with hydrodynamic model**

- Charged asymmetry dependence (~2$\sigma$ level) in the polarization

→ **A possible relation to the axial current induced by B-filed**

**✔Λ polarization along the beam direction at $\sqrt{s_{NN}}$ = 200 GeV**

- Quadrupole structure relative to the 2nd-order event plane, as expected from the elliptic flow
- Strong centrality dependence as in the elliptic flow but no significant dependence on pt

# Back up

# Contribution to Pz in hydro

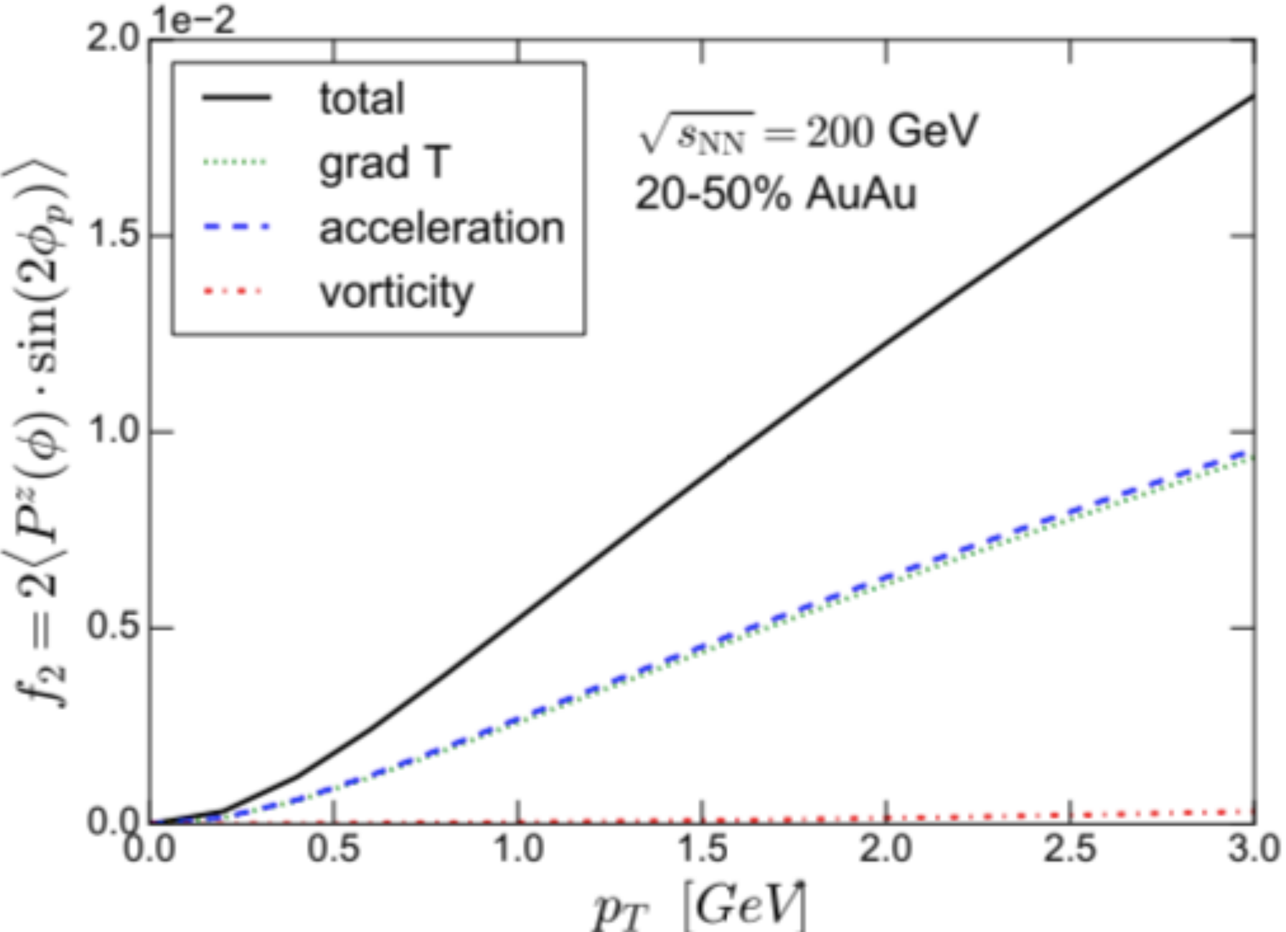
$$s^\mu \propto \epsilon^{\mu\rho\sigma\tau}\omega_{\rho\sigma}p_\tau = \epsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau$$

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

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

I.Karpenko,QM2018

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



# Blast-wave model parameterization

✔Hydro-inspired model parameterized with freeze-out condition assuming the longitudinal boost invariance

-Freeze-out temperature $T_f$

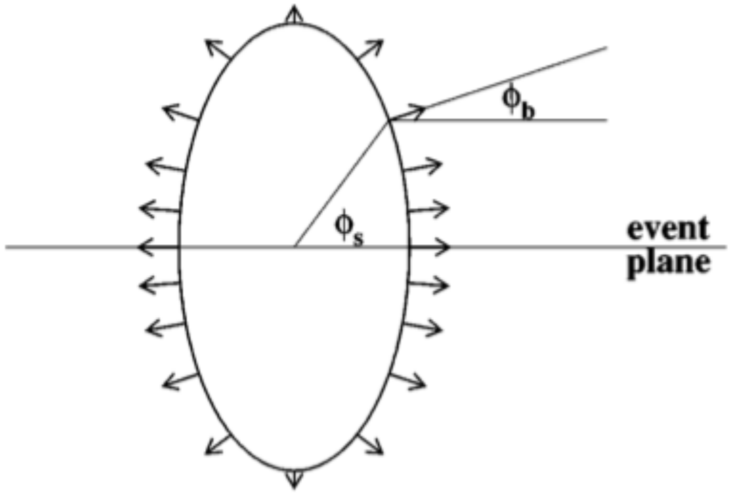
-Radial flow rapidity $\rho_0$ and its modulation $\rho_2$

-Source size $R_x$ and $R_y$

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

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

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



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

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

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

$\phi_s$: azimuthal angle of the source element

$\phi_b$: boost angle perpendicular to the elliptical subshell

u : local flow velocity,    Ln, Kn: modified Bessel function