Global polarization of Λ hyperons in Au+Au collisions at 200 GeV from STAR

arXiv:1805.04400

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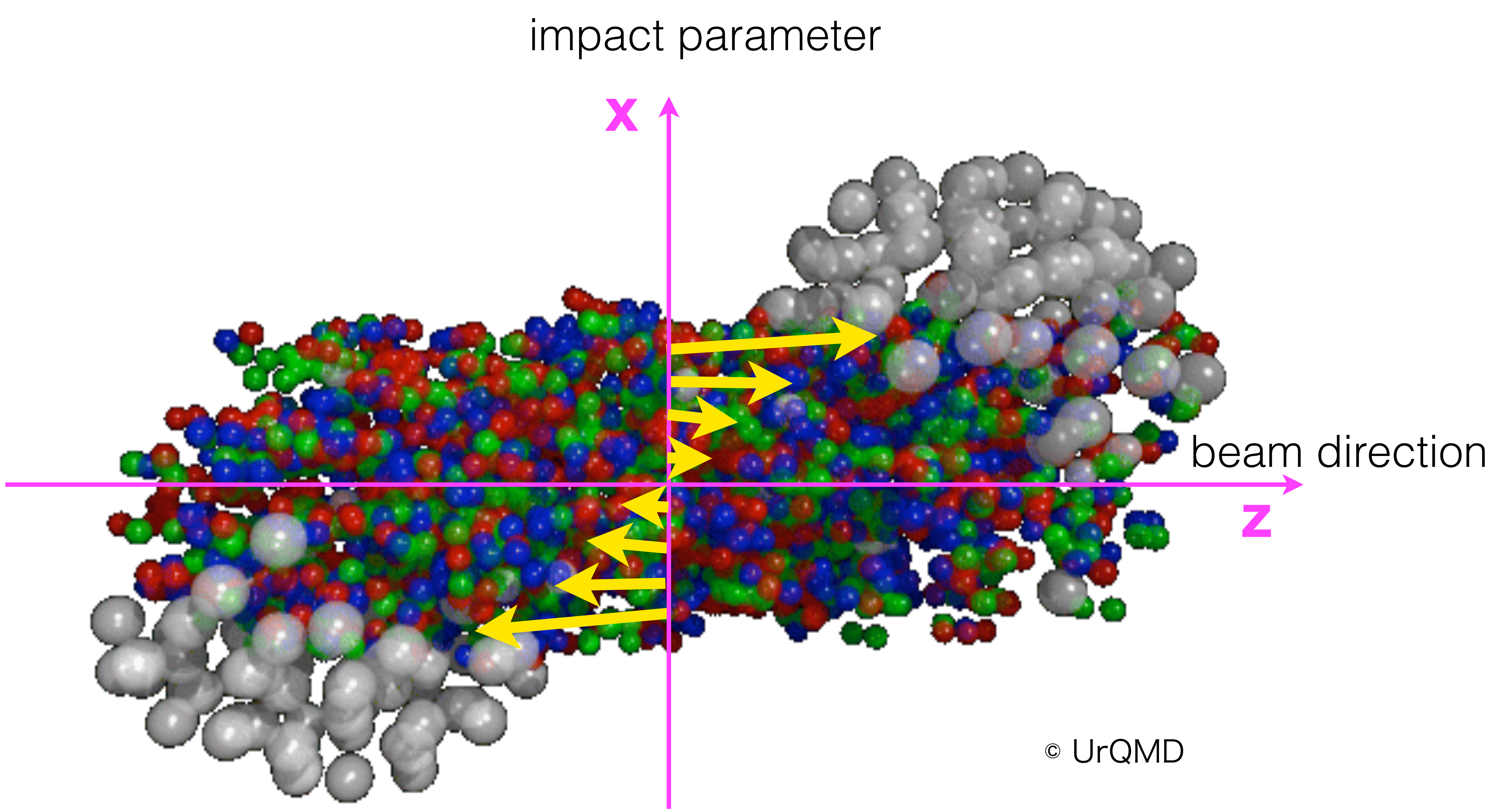
for the STAR Collaboration

WAYNE STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

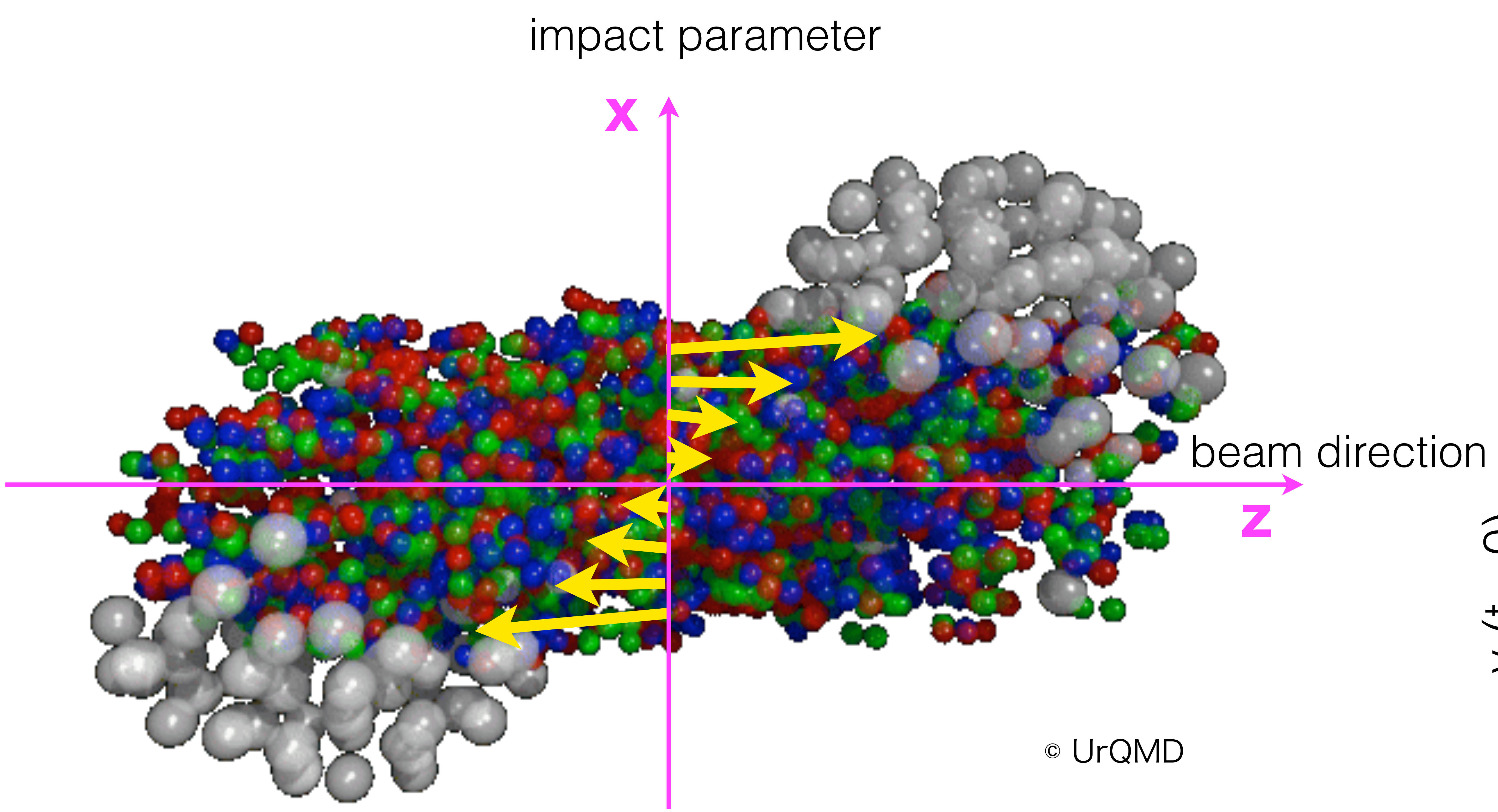
Venezia 2018 Quark Matter

Vorticity in HIC

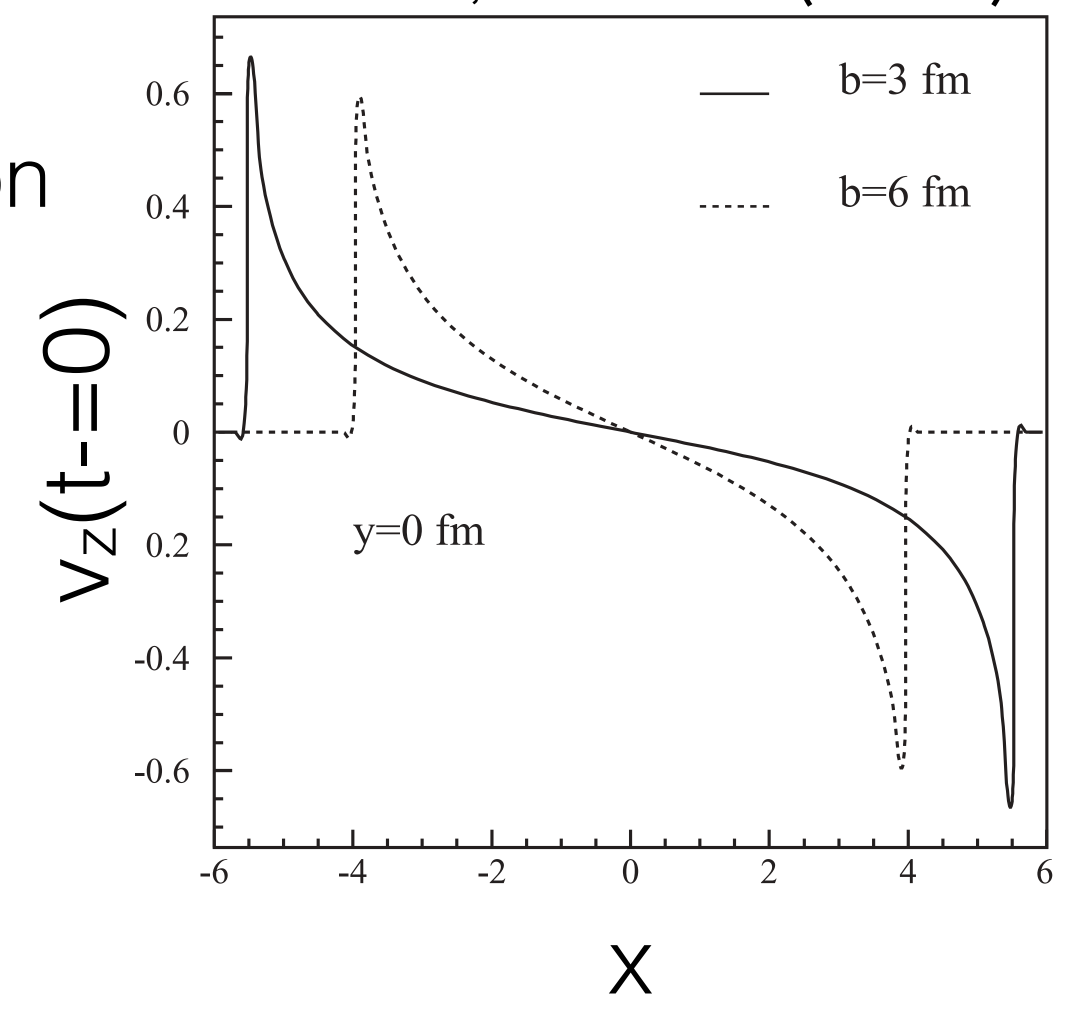


In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

Vorticity in HIC



Becattini et al.,
PRC77, 024906 (2008)



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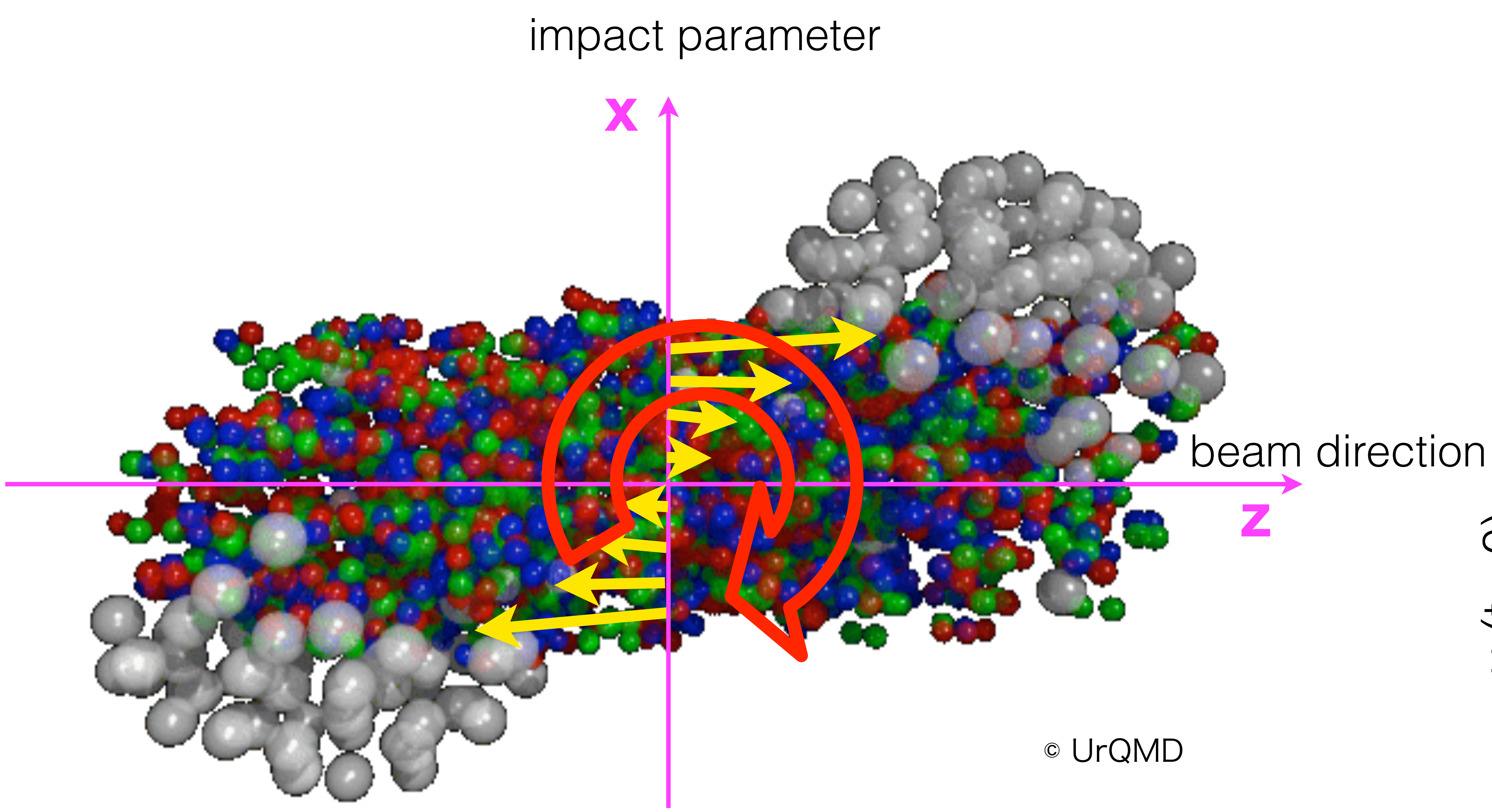

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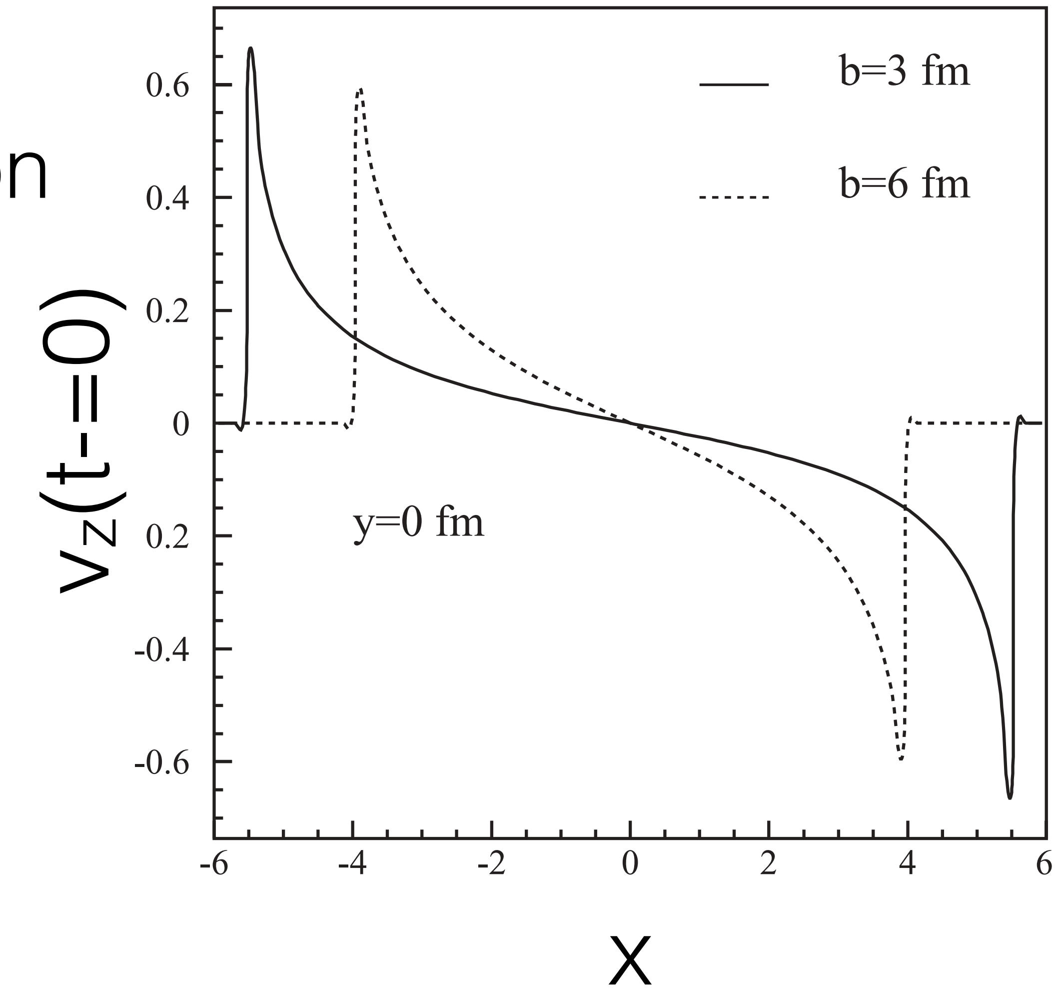


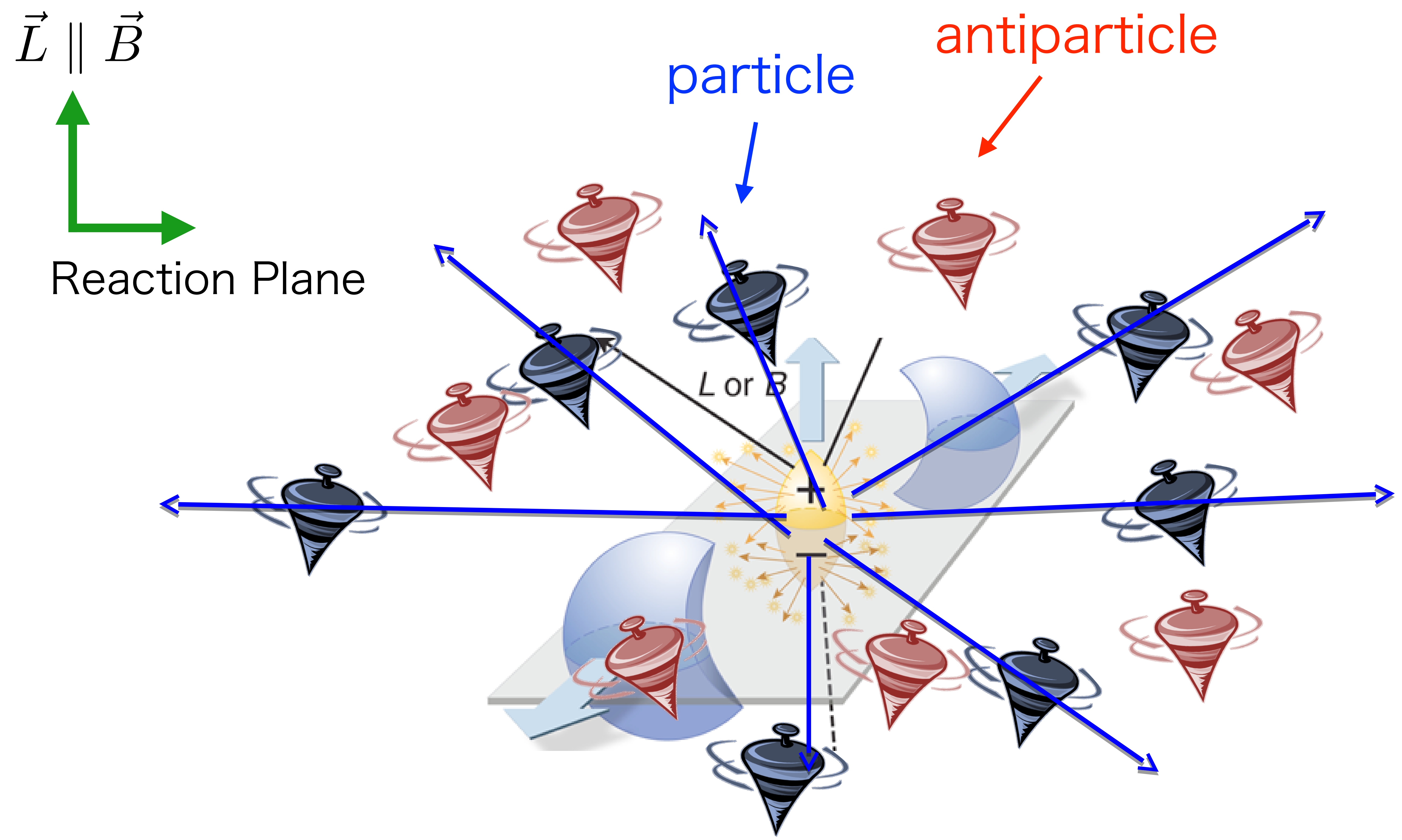
In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

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

Global polarization

★ Non-zero angular momentum transfers to the spin degrees of freedom

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



∗direction of ***B*** is the same as ***L***

- Polarization due to spin-orbit coupling
  - Particle' and anti-particle's spins 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

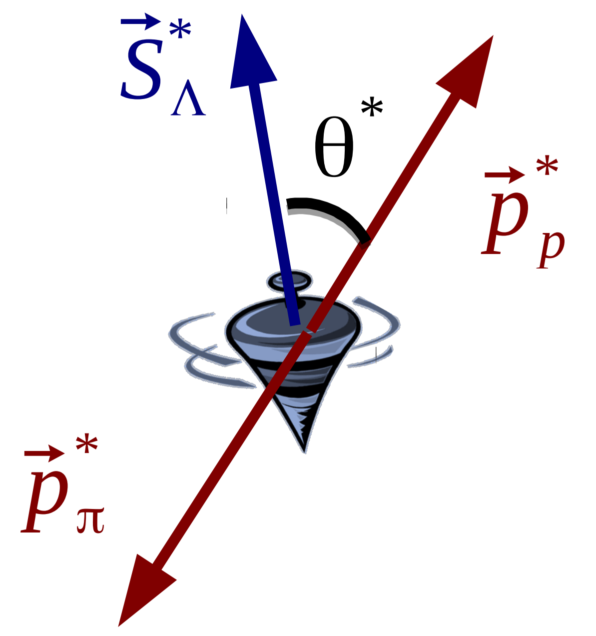
How to measure?

Parity-violating decay of hyperons

In case of Λ's decay, daughter proton is preferentially emitted in the direction of Λ's spin (opposite for anti-Λ)

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

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



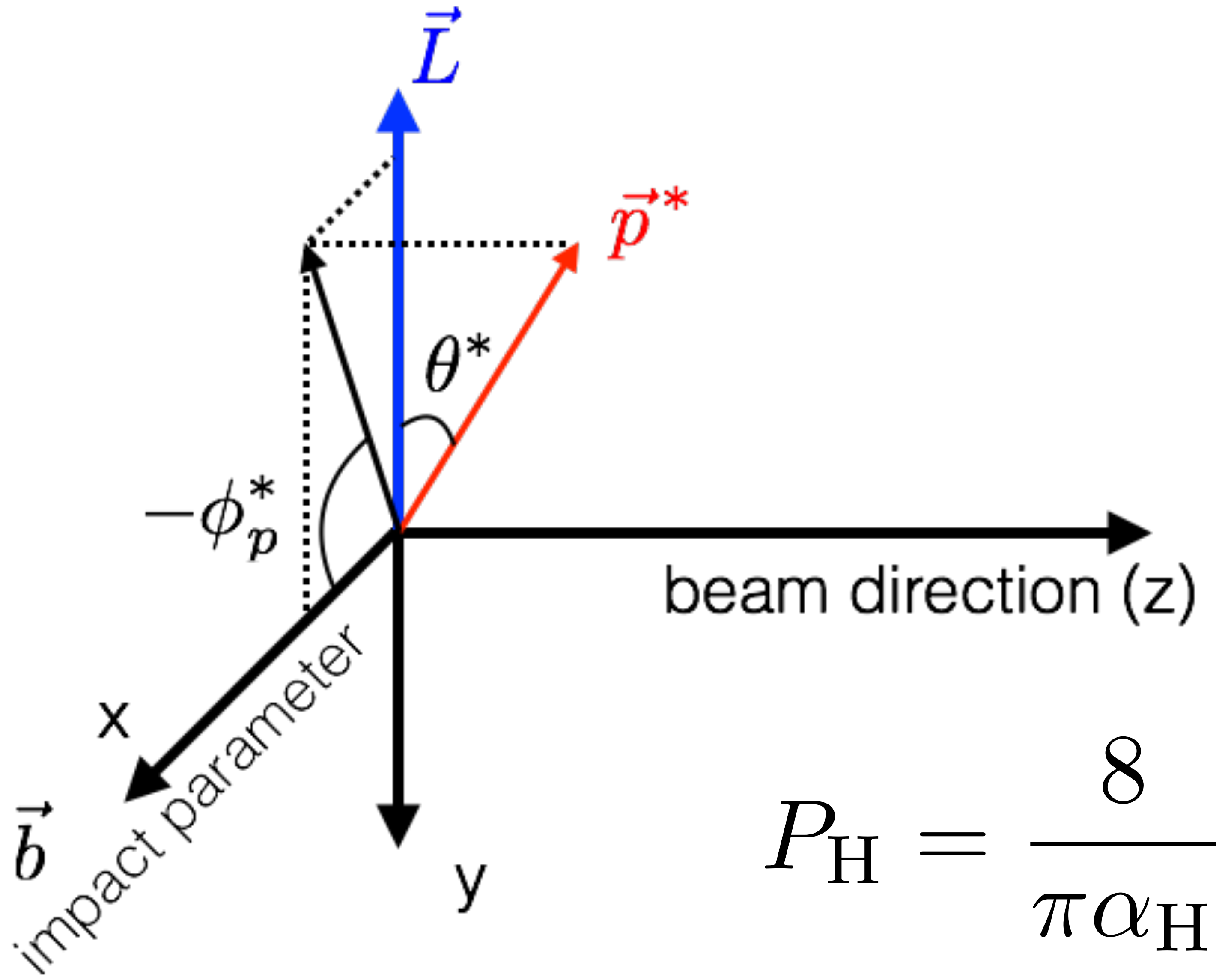
$$\Lambda \to p + \pi^-$$

(BR: 63.9%, cτ ~7.9 cm)

Projection onto the transverse plane

★ Direction of the angular momentum is determined by the angle of spectator plane (spectators deflect outwards)
- S. Voloshin and TN, PRC94.021901(R)(2016)

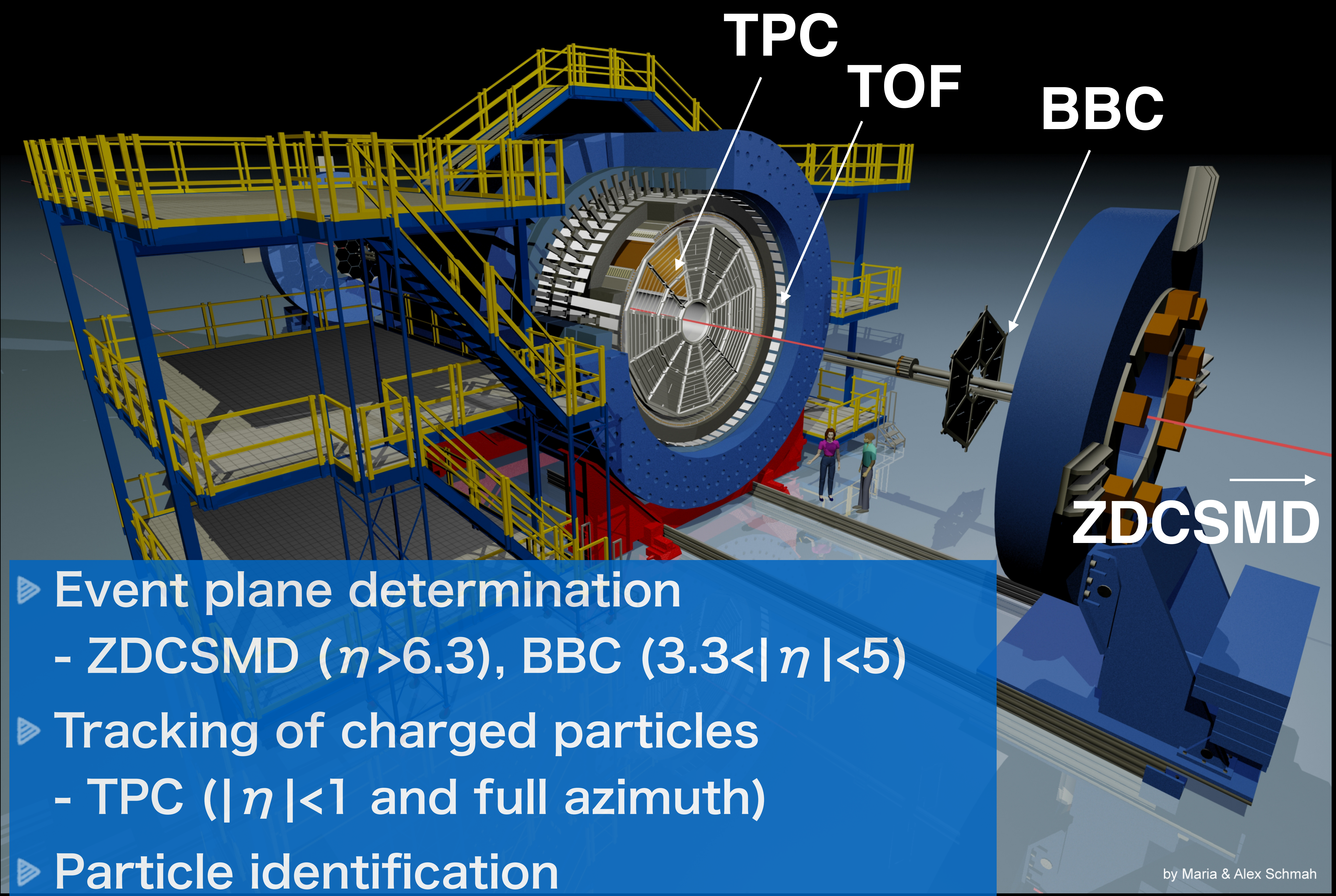
★ Flow analysis technique can be used for signal extraction
- STAR, PRC76, 024915 (2007)



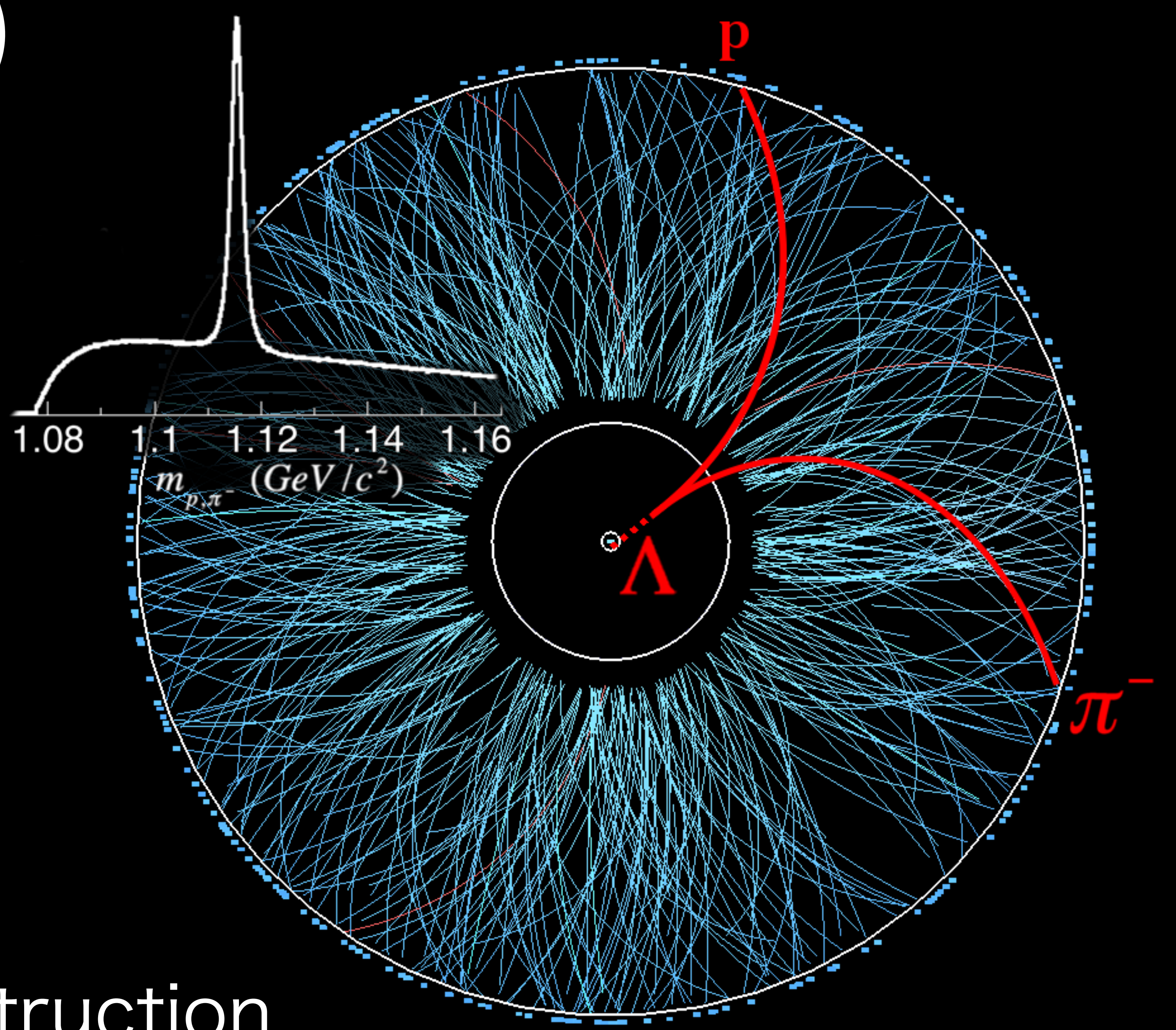
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

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

Solenoidal Tracker At RHIC (STAR)

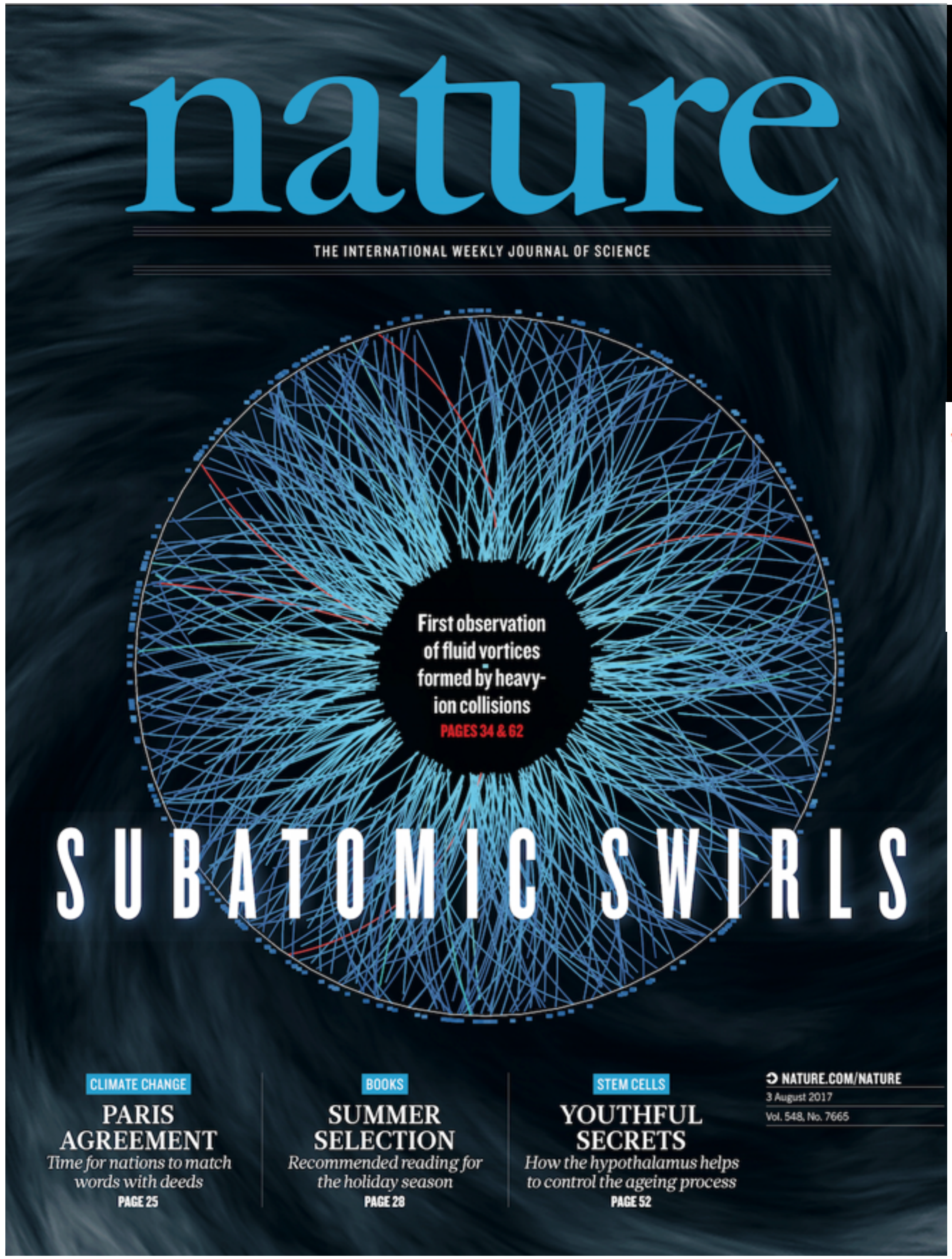


- Event plane determination
  - ZDCSMD (η>6.3), BBC (3.3<|η|<5)
- Tracking of charged particles
  - TPC (|η|<1 and full azimuth)
- Particle identification
  - TPC and TOF



- Λ reconstruction
  - ★Calculate the invariant mass of (π, p)
  - ★Cuts on decay topology helps to reduce the combinatorial background, B/(S+B)<30%
- The number of Λ hyperons per event
  - ★~1.0 for 10-20% centrality at 200 GeV (raw counts, depends on centrality, efficiency, and track selection criteria)

First observation of fluid vortices in HIC



#38

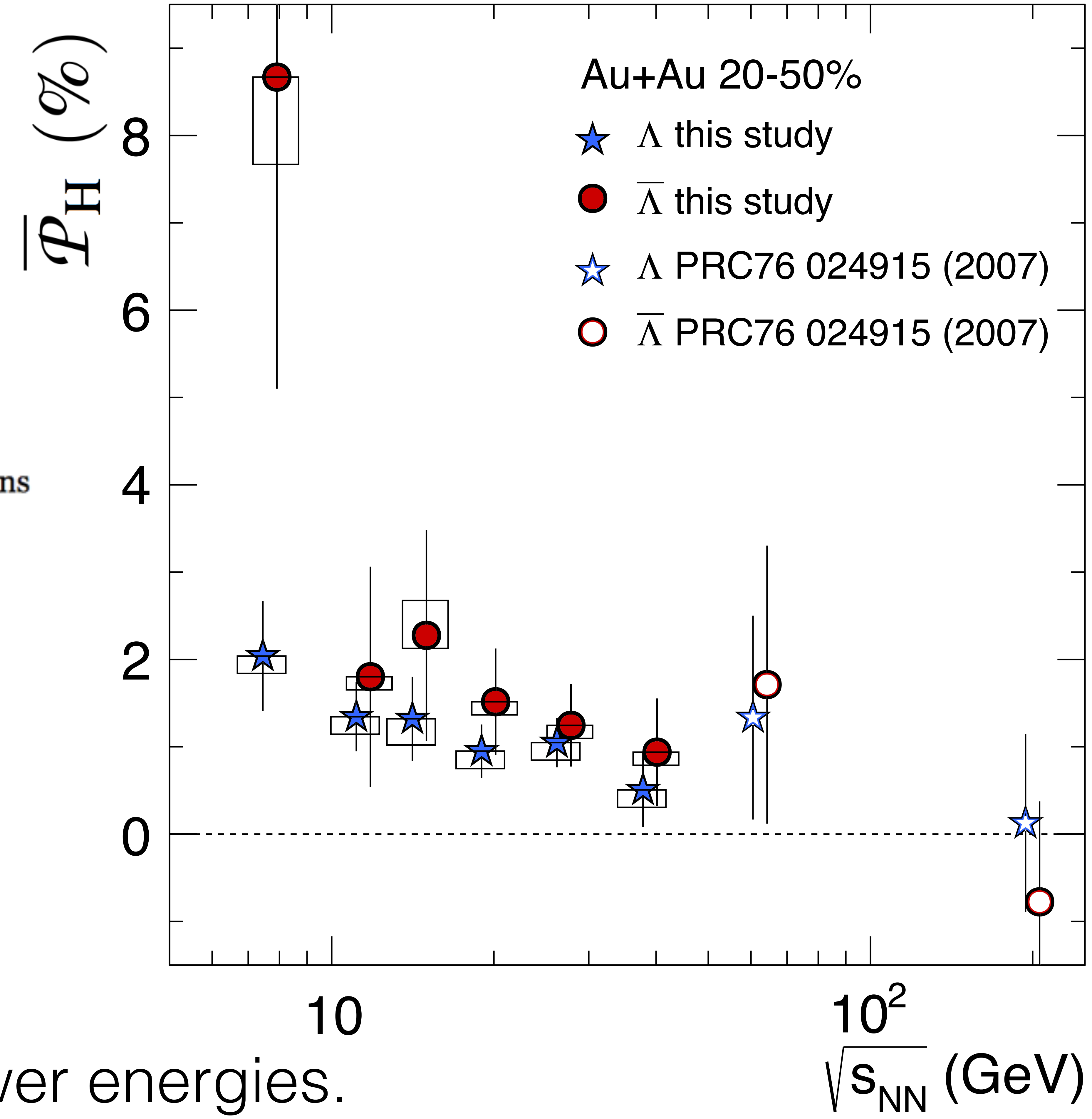
The Fastest Fluid

by Sylvia Morrow

Superhot material spins at an incredible rate.

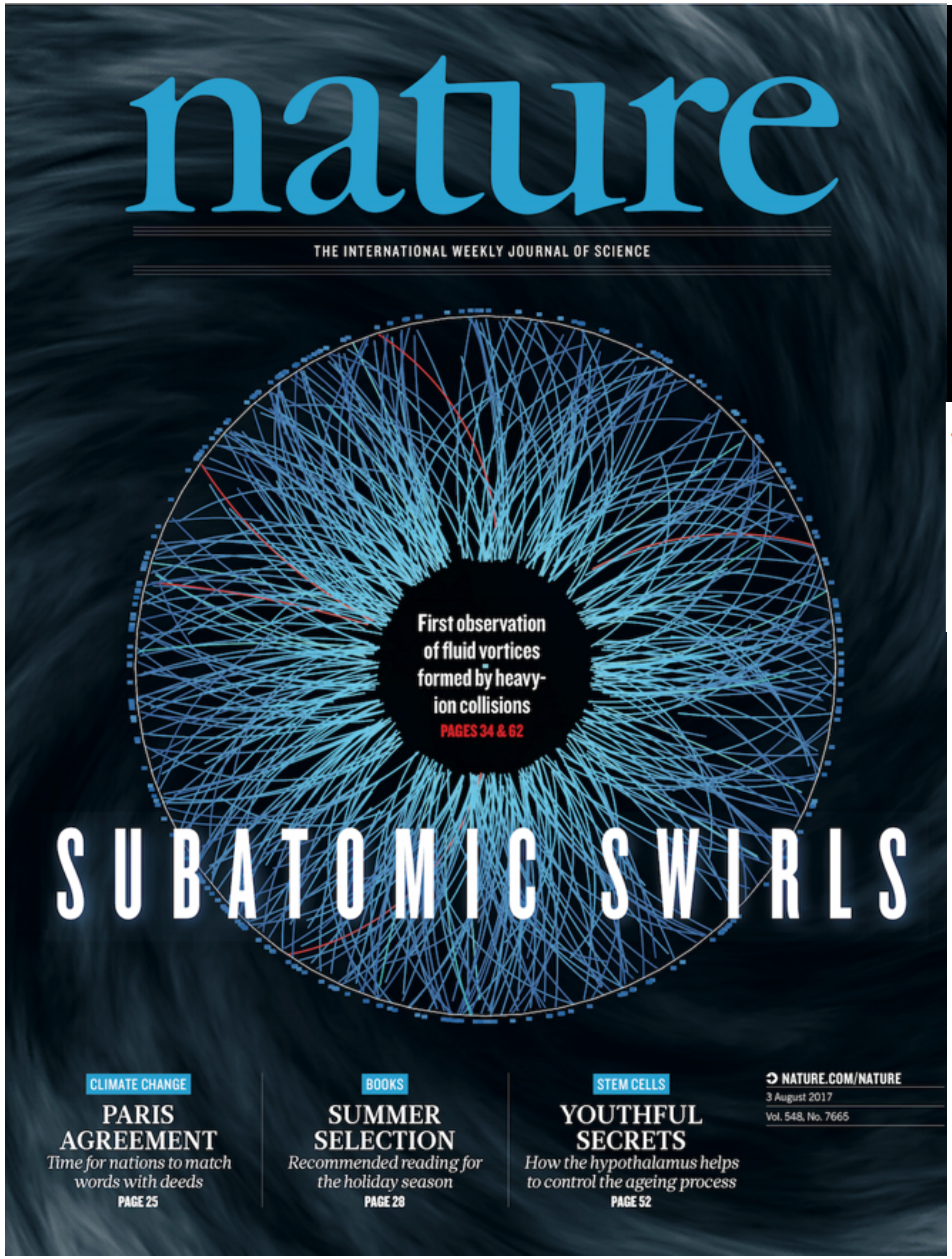
$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T / \hbar$$
$$\sim 10^{22}\ s^{-1}$$ (T=160 MeV)

STAR, Nature 548, 62 (2017)



Positive signal at lower energies.
The most vortical fluid ever observed!

First observation of fluid vortices in HIC



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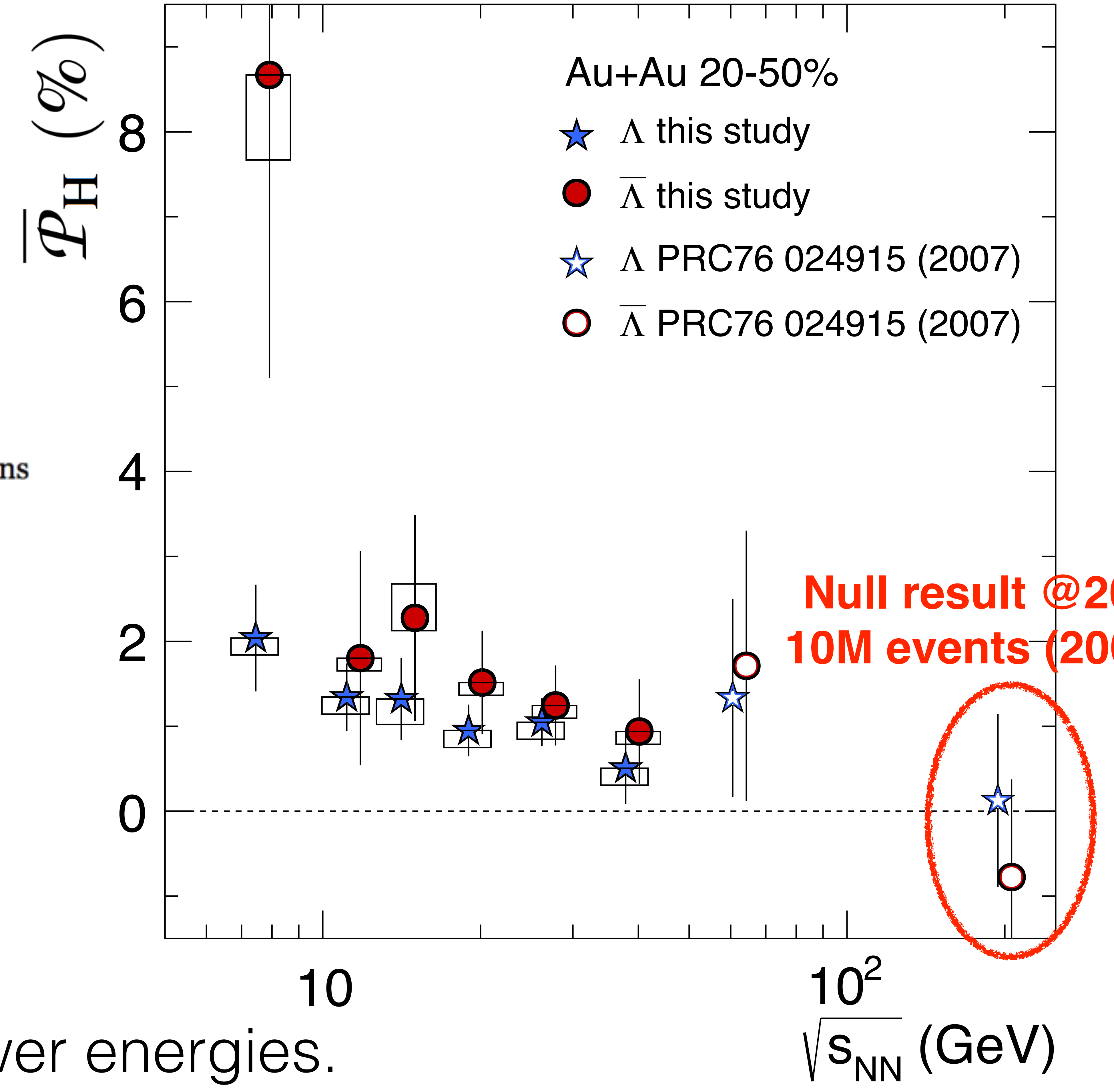

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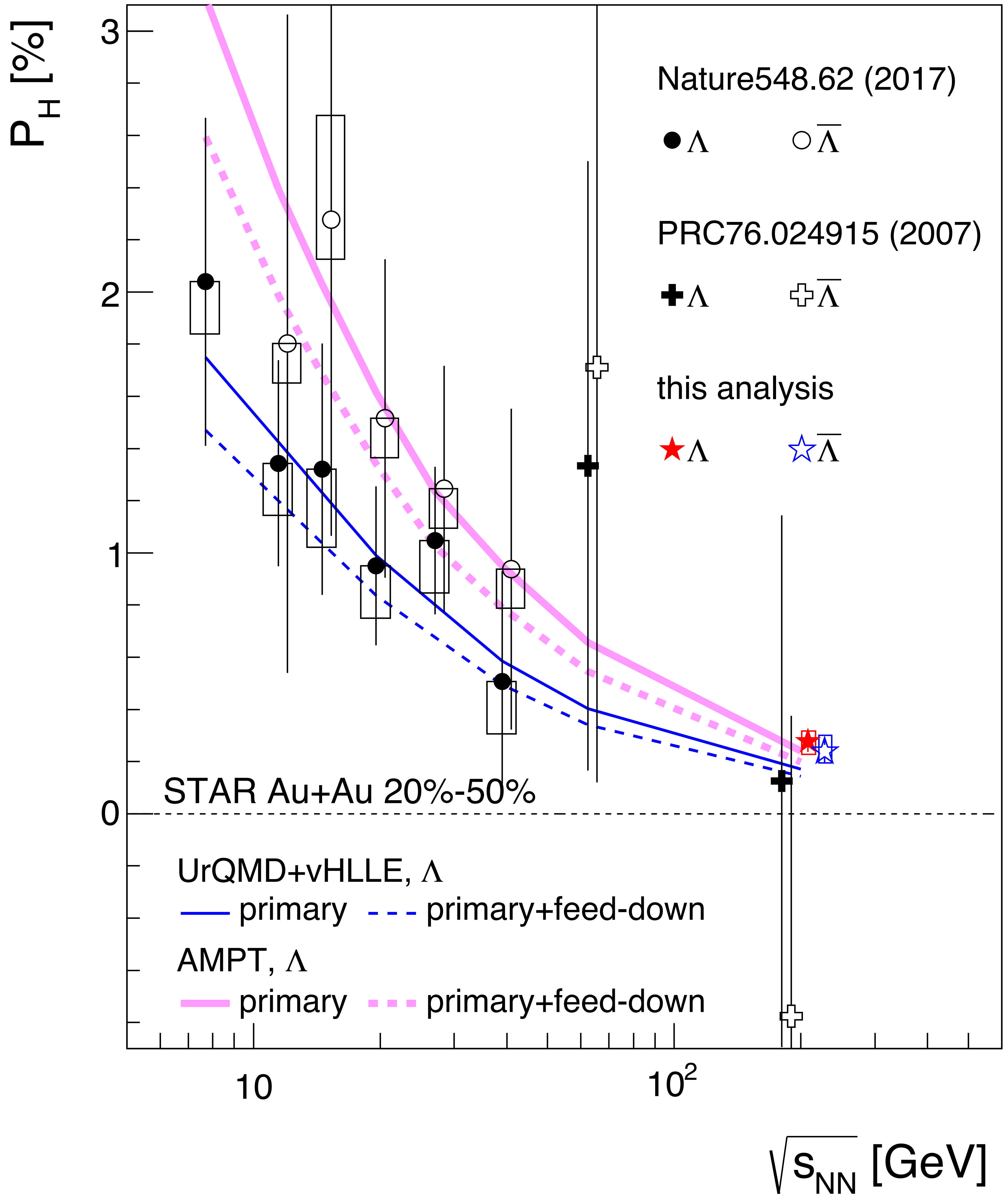
The most vortical fluid ever observed!

Let's revisit 200 GeV with ~150 times more events!
using recent data (2010, 2011, and 2014)

Revisiting 200 GeV

STAR, arXiv:1805.04400



- Finite signal at $\sqrt{s_{NN}}$ = 200 GeV !!

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

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

- ~15% dilution of the signal due to feed-down for all √s (model-dependent estimation)

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

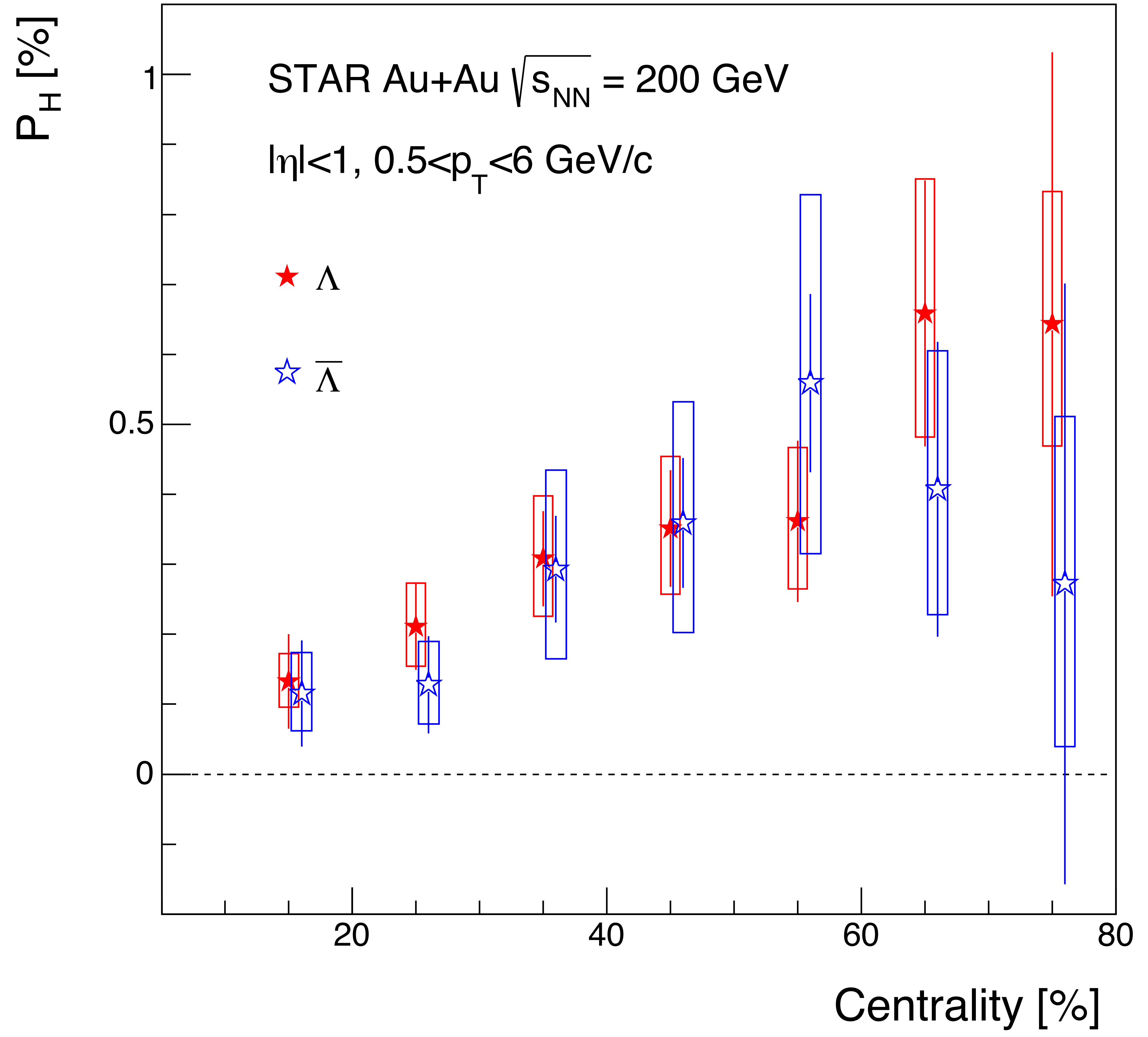
- Following the trend of BES data and close to UrQMD-IC +viscous-hydro and AMPT predictions in all energies

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

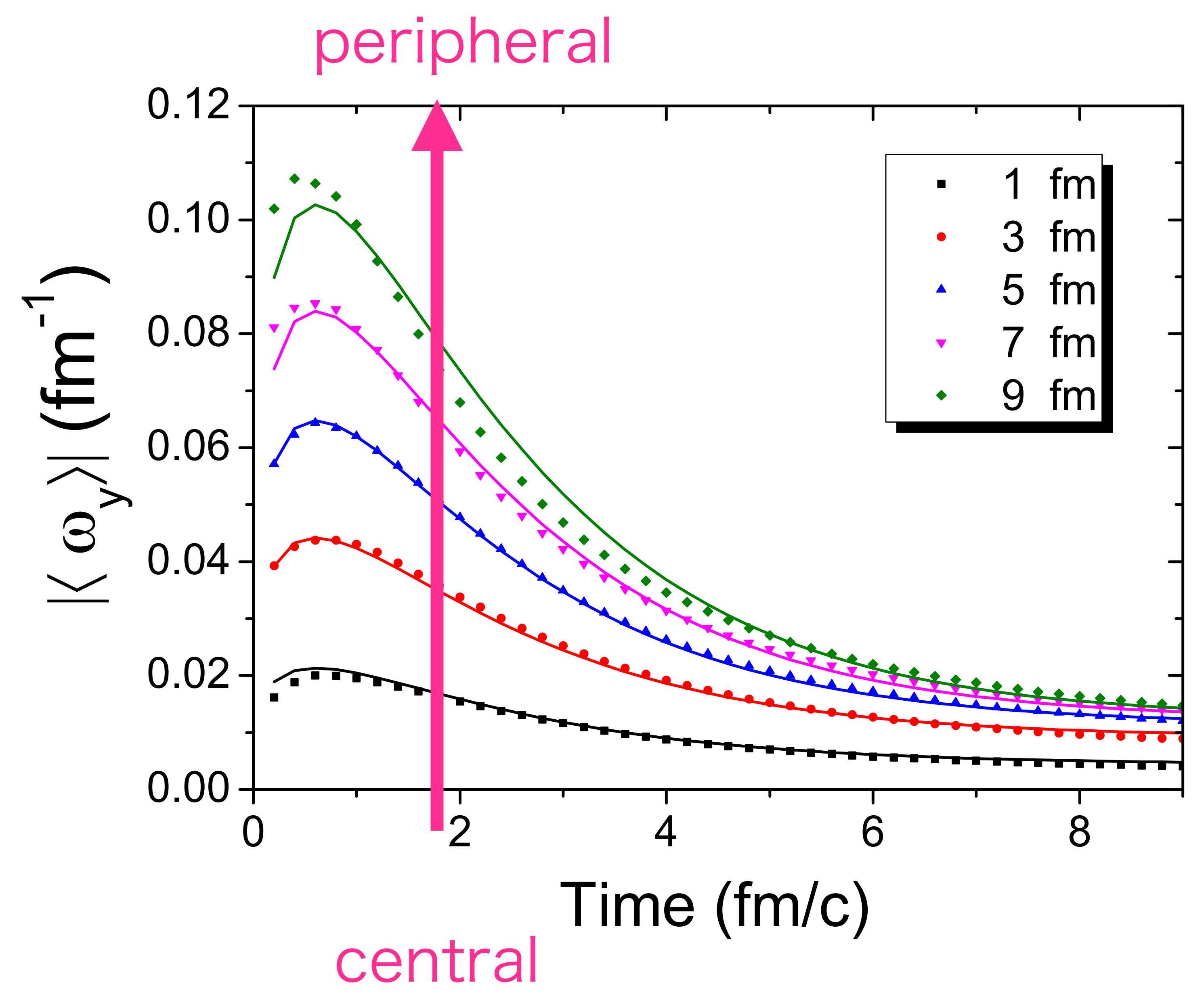
- No significant difference between Λ and anti-Λ at 200 GeV

Centrality dependence of P_H

STAR, arXiv:1805.04400



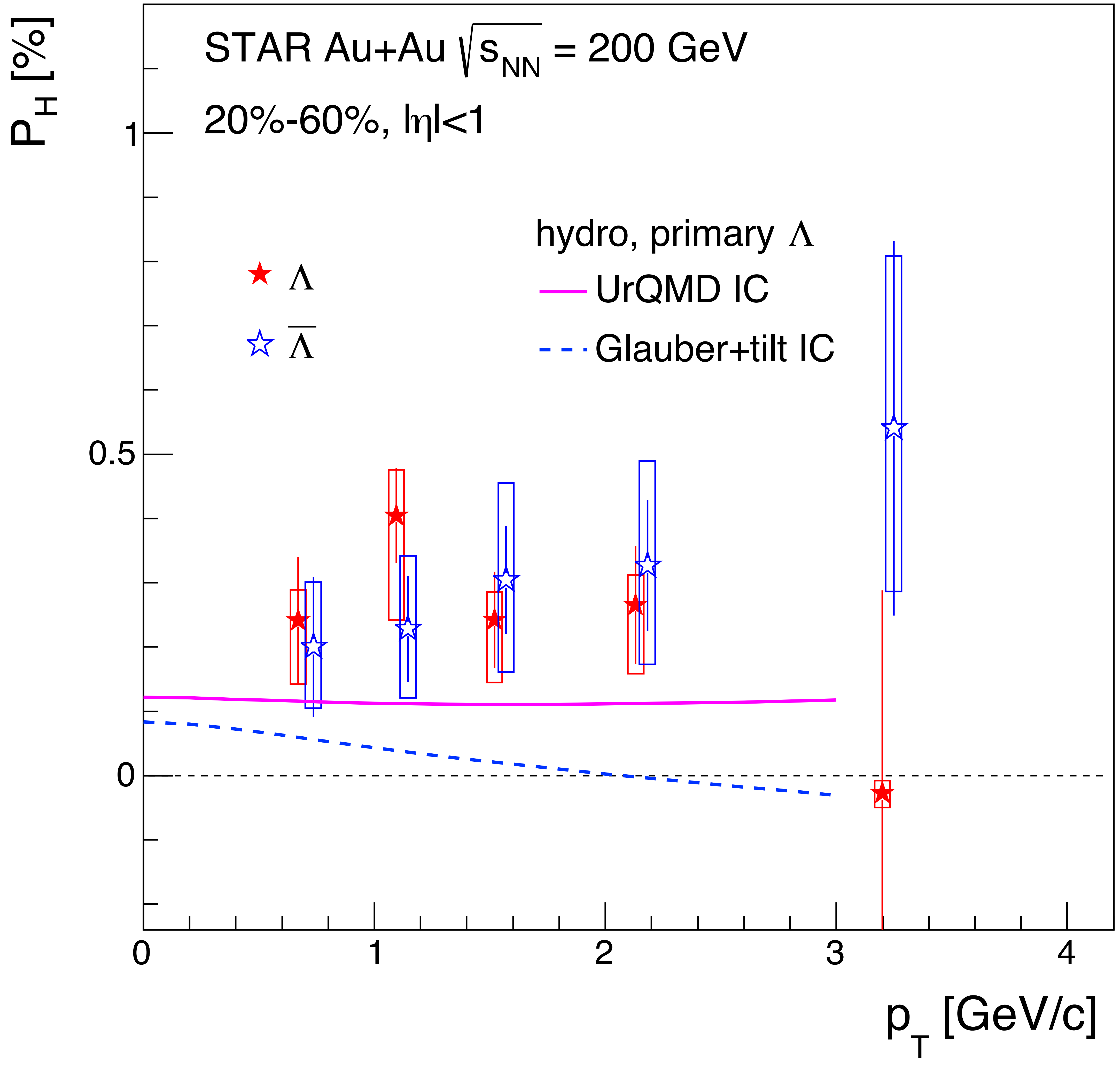
AMPT model,
Y. Jiang et al., PRC94, 044910 (2016)



- Polarization increases in more peripheral collisions
  - qualitatively consistent with AMPT calculations
- Not clear if there is a saturation or decrease in most peripheral collisions

p_T dependence of P_H

STAR, arXiv:1805.04400

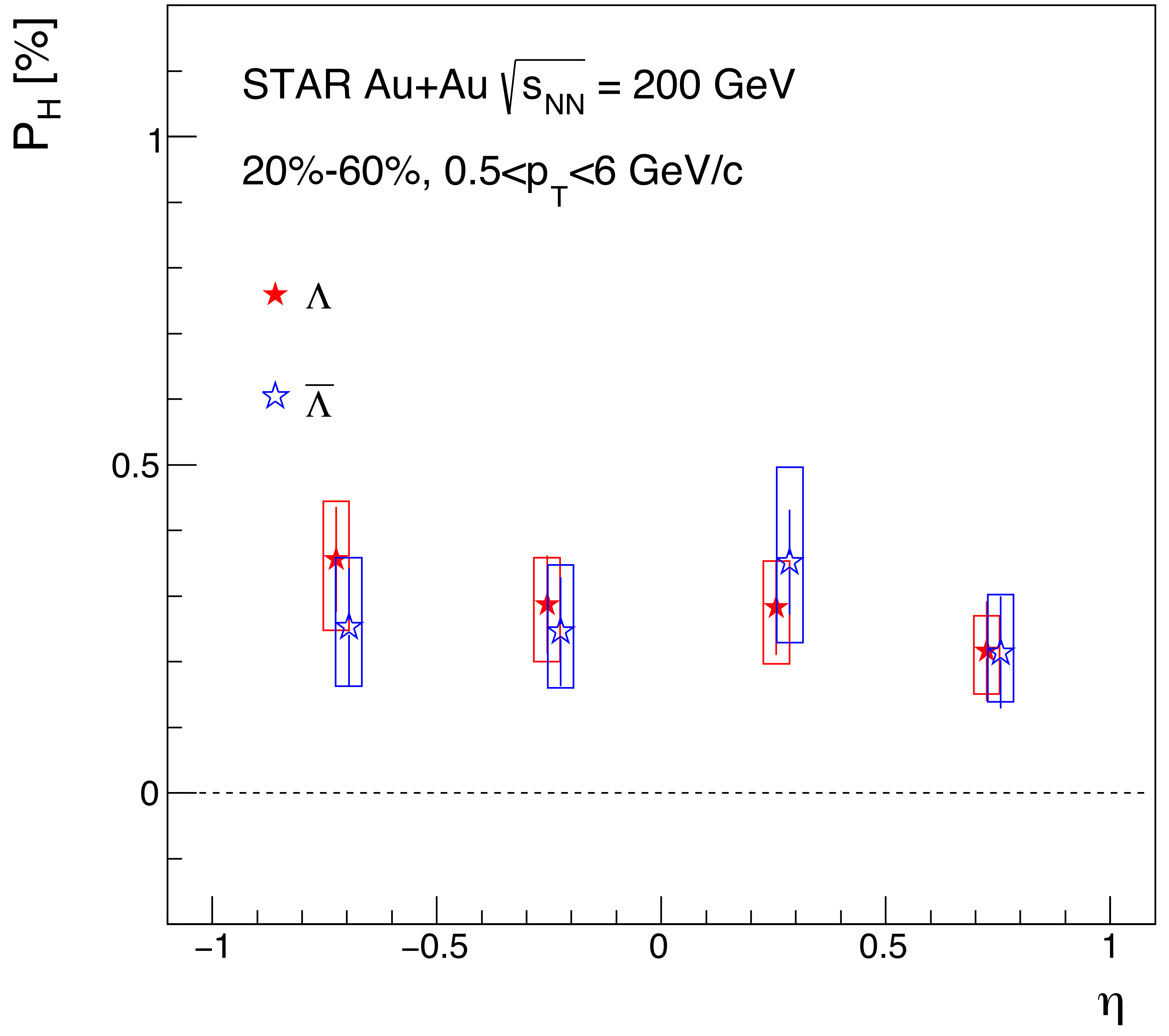


- No significant p_T dependence, as expected from the initial angular momentum of the system
- Hydrodynamic model underestimates the data. Initial conditions affect the magnitude and dependence on p_T

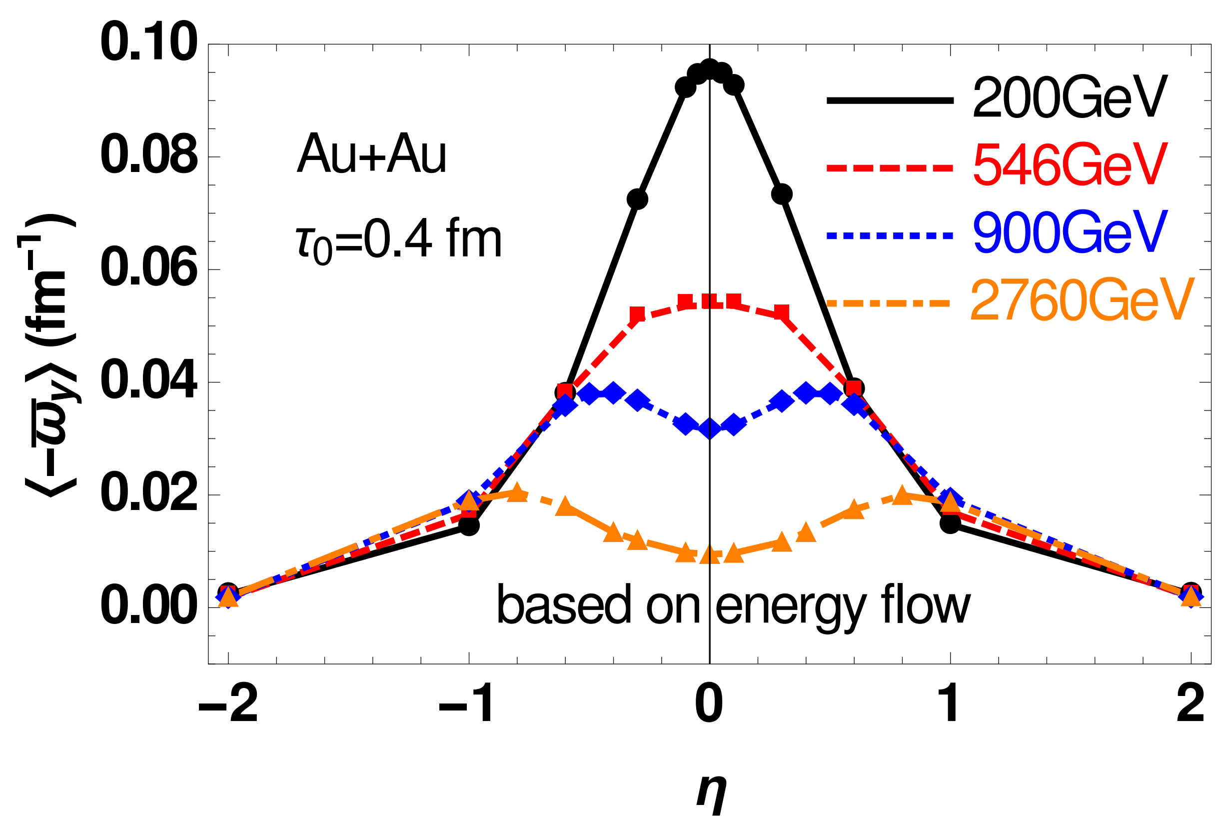
3D viscous hydro-model with two initial conditions (ICs)
(F. Becattini and I. Karpenko, PRL120.012302, 2018)
- UrQMD IC
- Glauber with source tilt IC

η dependence of P_H

STAR, arXiv:1805.04400

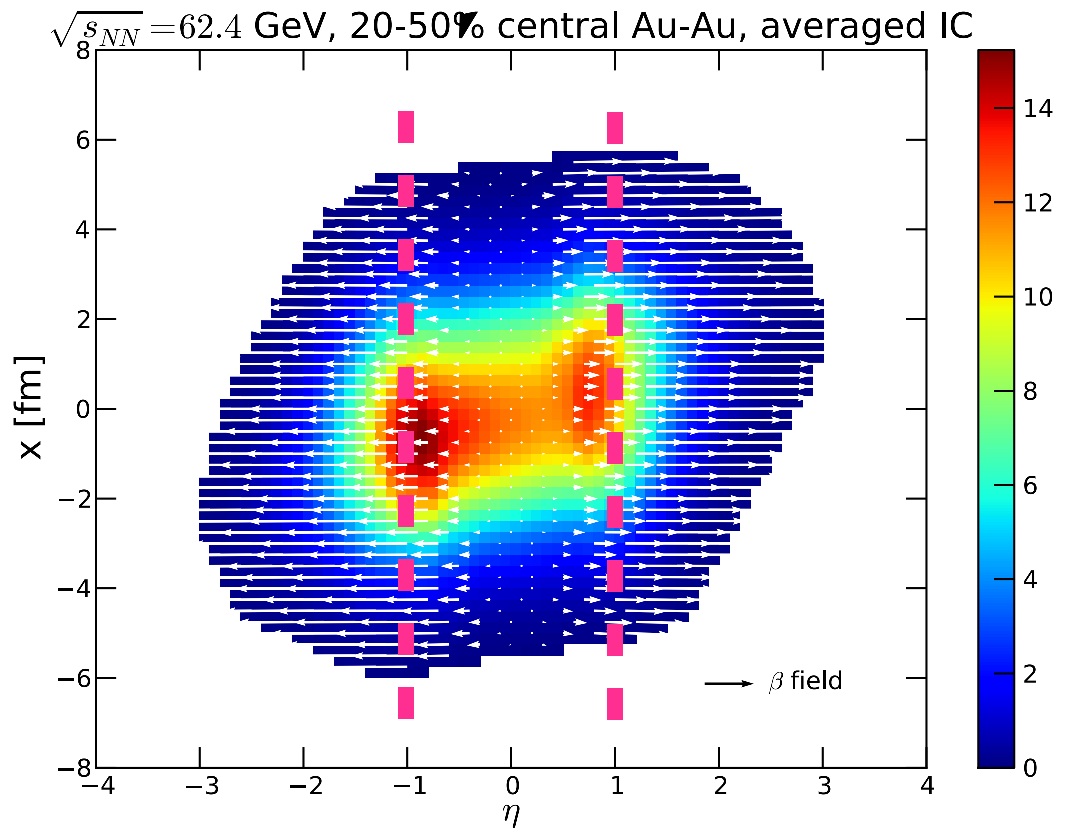


W.-T. Deng and X.-G. Huang, arXiv:1609.01801



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

Au+Au 62.4 GeV

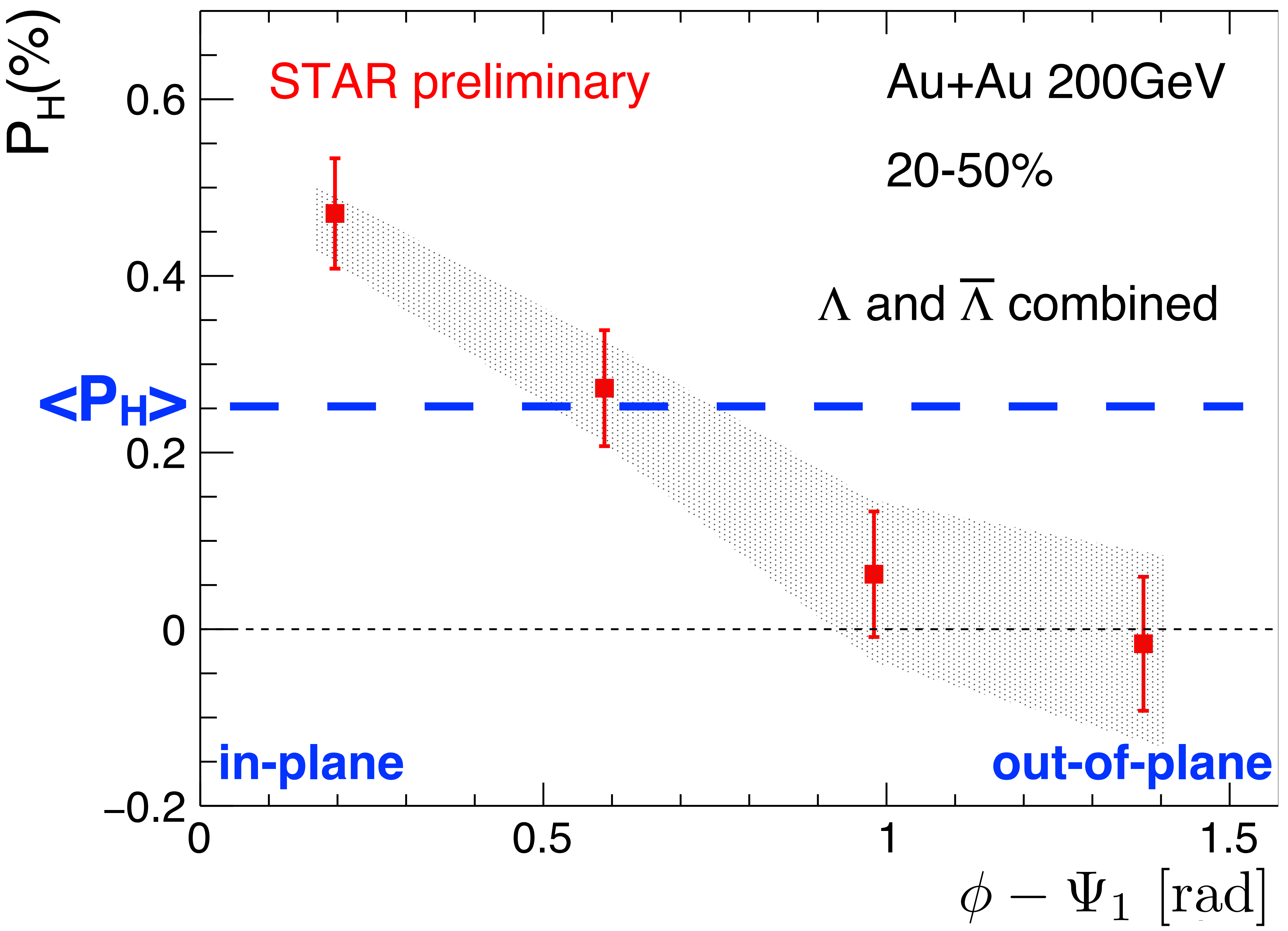


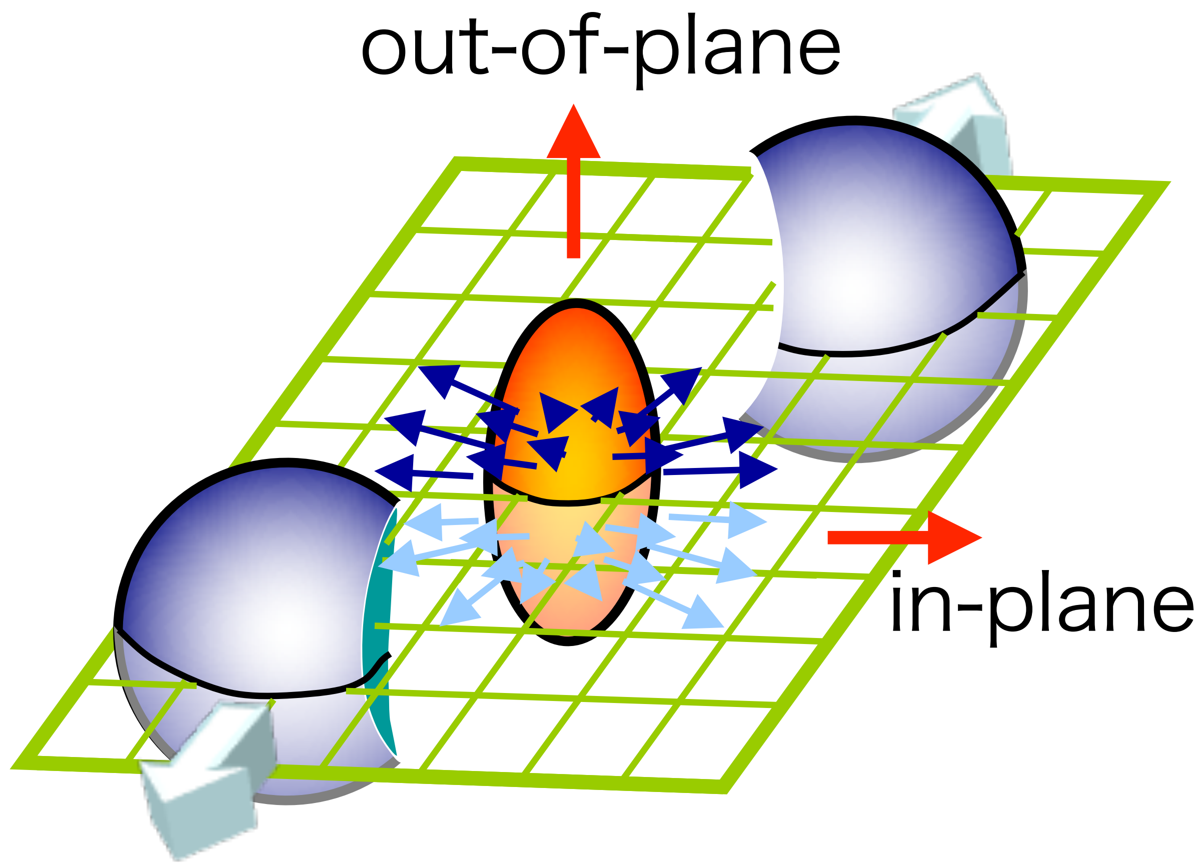
- No significant η dependence
  - Smaller shear flow structure at mid-rapidity due to baryon transparency at higher energy
  - Maybe due to event-by-event C.M. fluctuations
- May be measured at lower energies in BES- II with STAR upgrade or with larger acceptance in ATLAS and CMS?

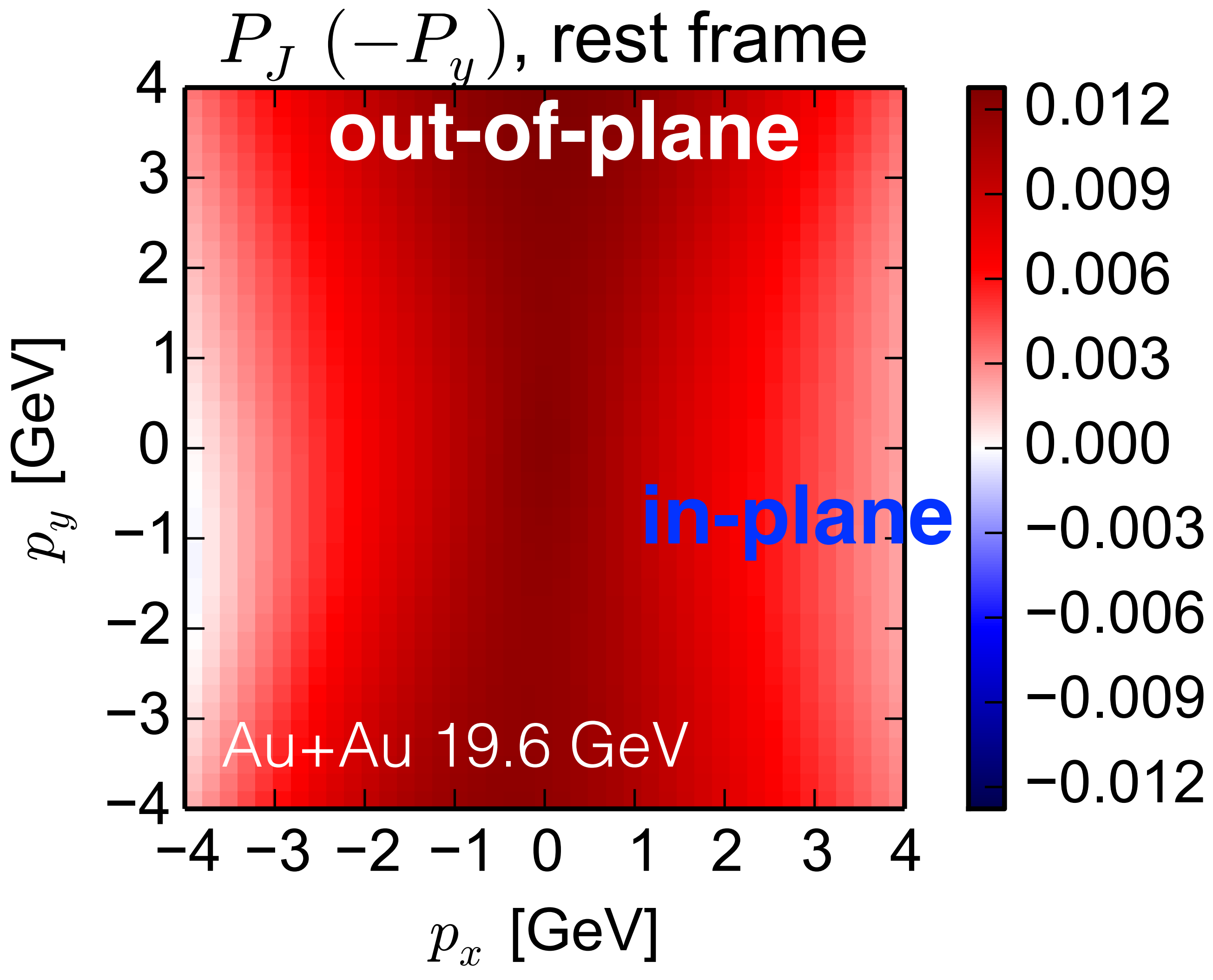
Azimuthal angle dependence of P_H

F. Becattini et al., PRC93, 069901(E)(2016) PRC88, 034905 (2013)

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







- More polarized in in-plane than in out-of-plane
- Opposite trend to the hydrodynamic model

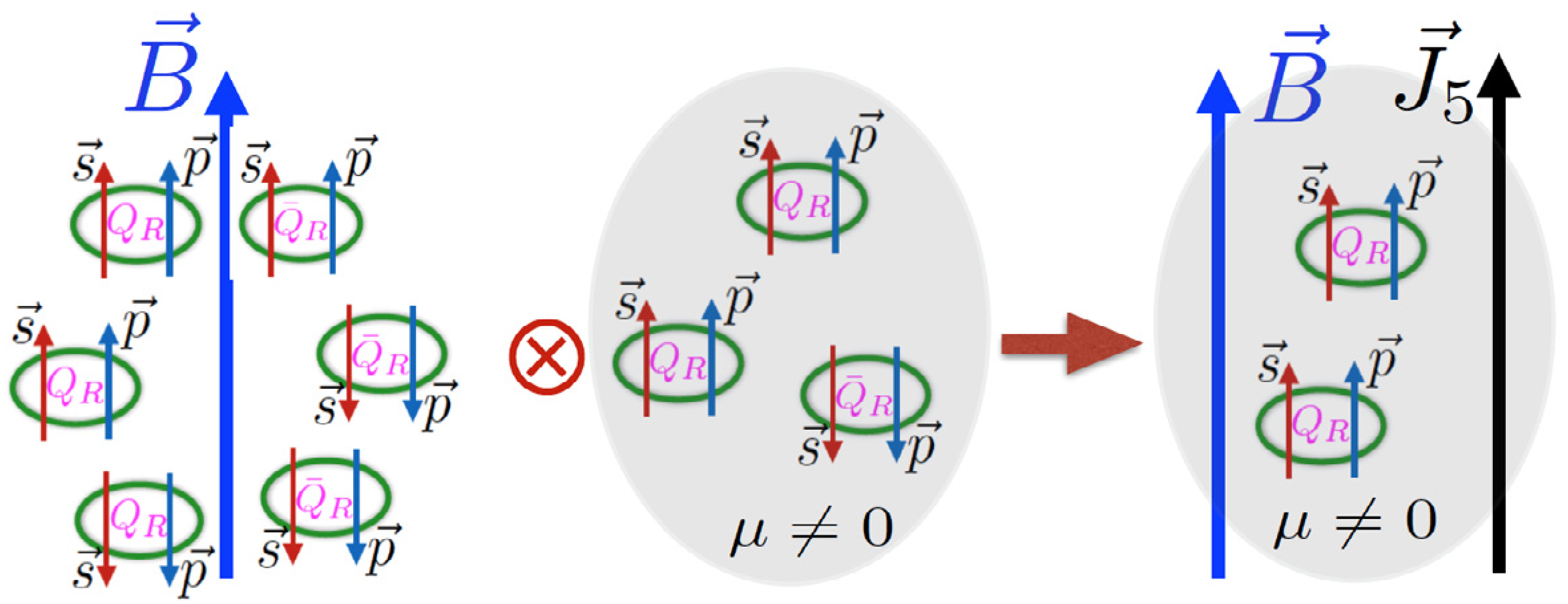
Correction on EP resolution (for x-axis) is applied.

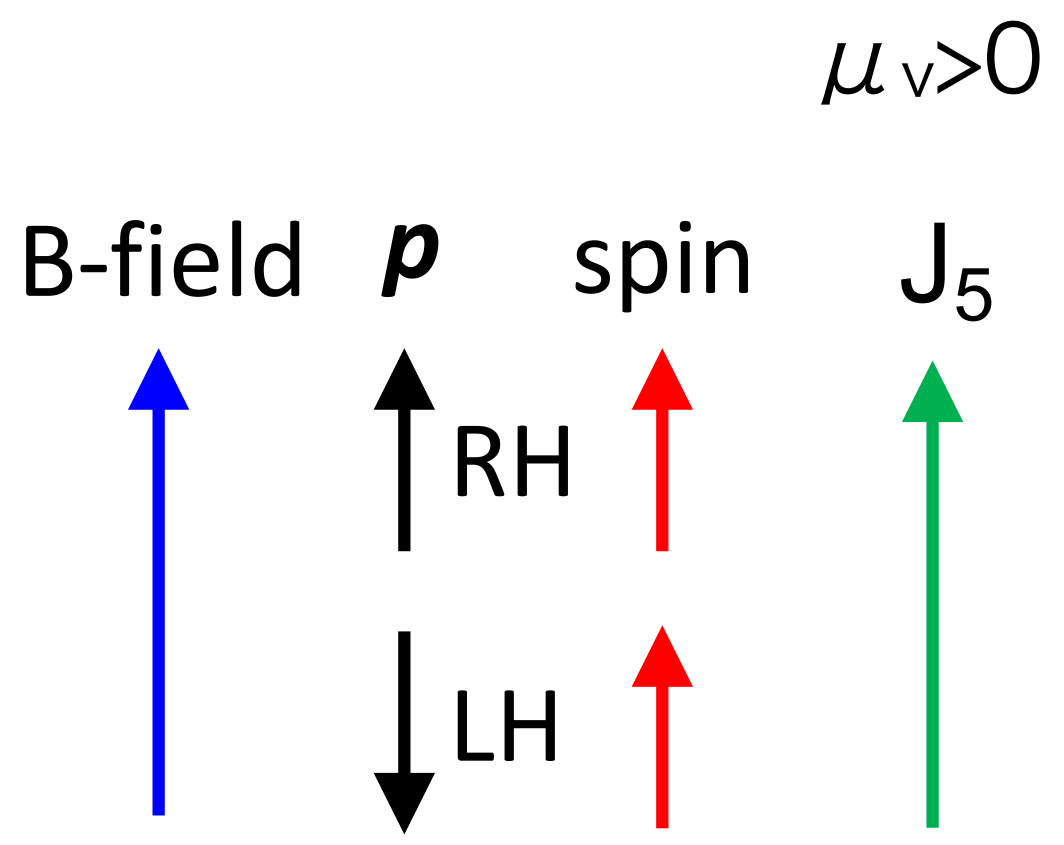
A. H. Tang, B. Tu, and C. S. Zhou, arXiv:1803.05777

See Biao Tu's poster #452 for more detail

Λ polarization vs charge asymmetry?

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

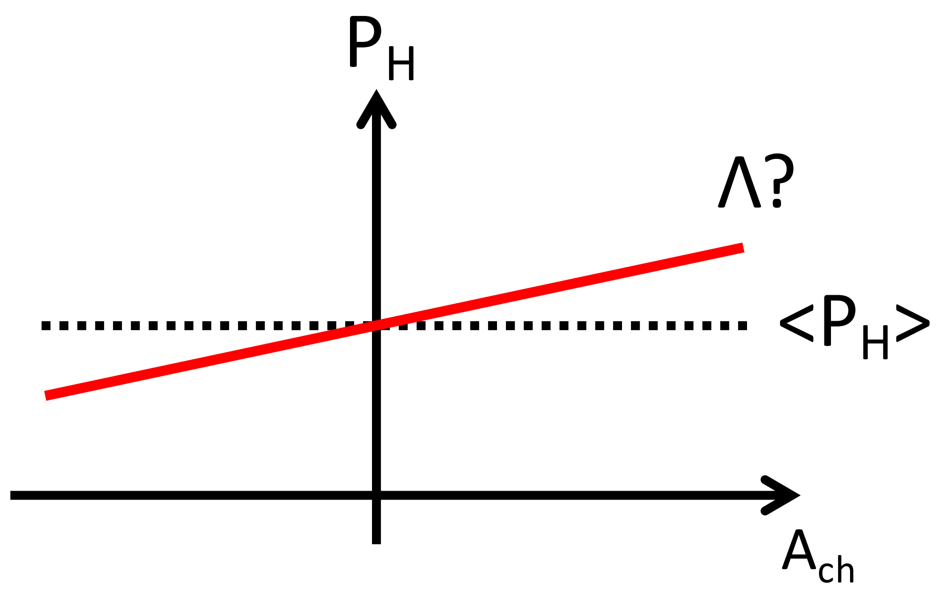




- Λ polarization may have a contribution from the axial current J_5 induced by B-field (Chiral Separation Effect), S. Shlichting and S. Voloshin, in preparation
- Use charge asymmetry A_{ch} instead of μ_v

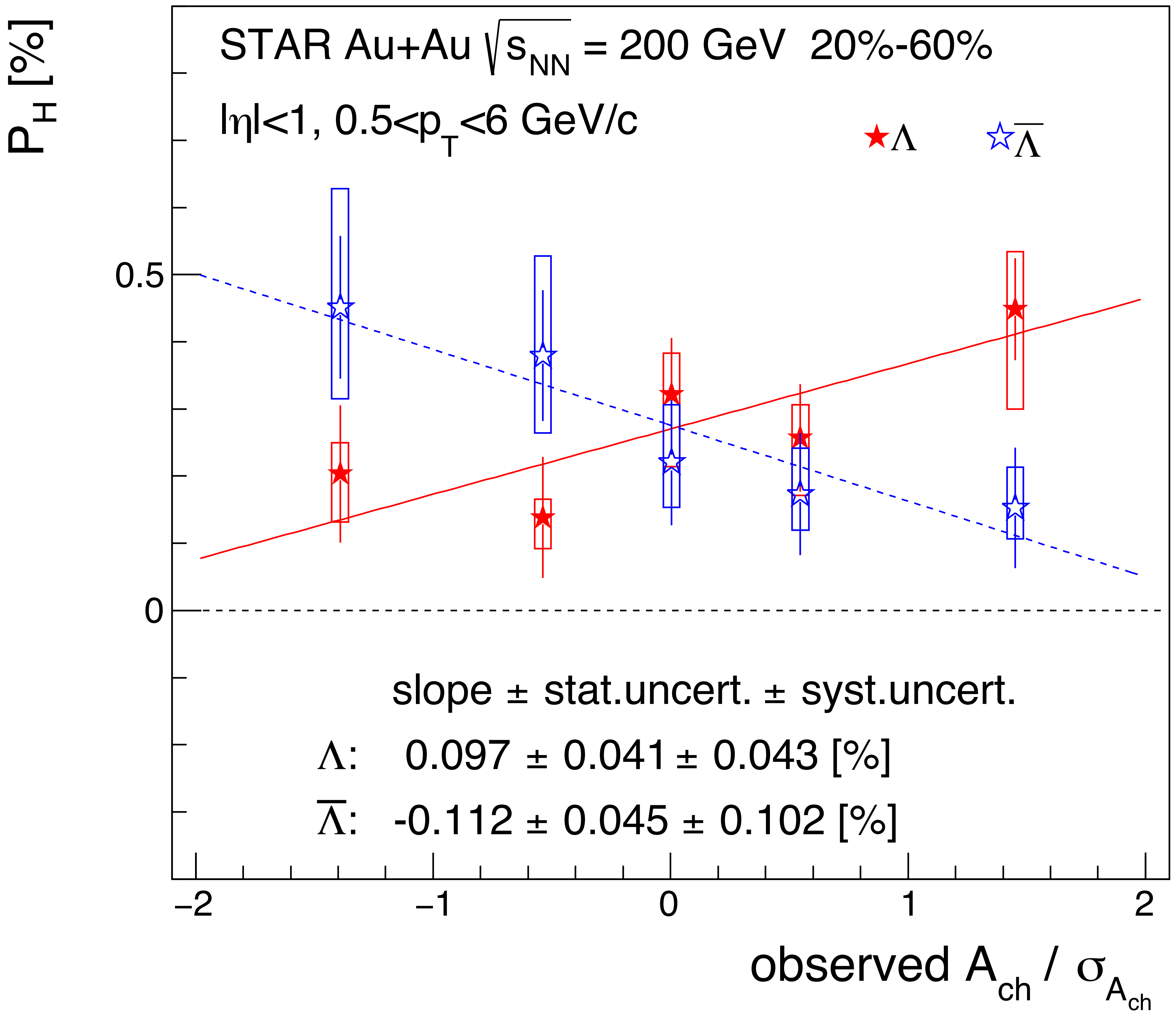
$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{ch}$$

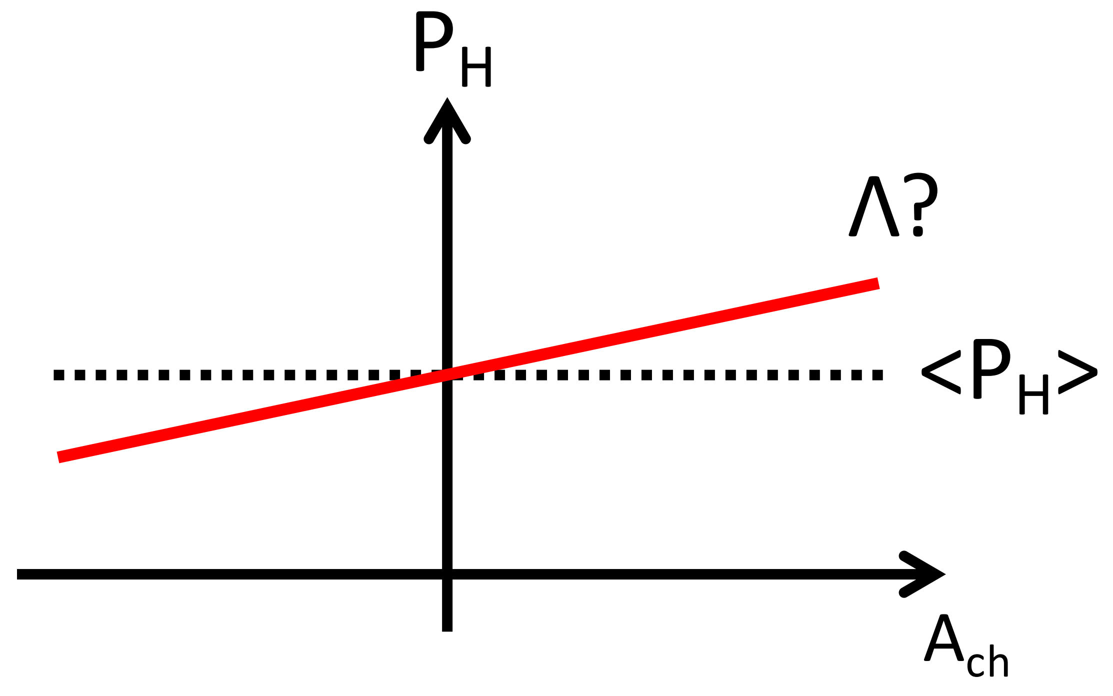
what's the expectation?
true for u-quark but also for Λ?



Λ polarization vs charge asymmetry?

STAR, arXiv:1805.04400



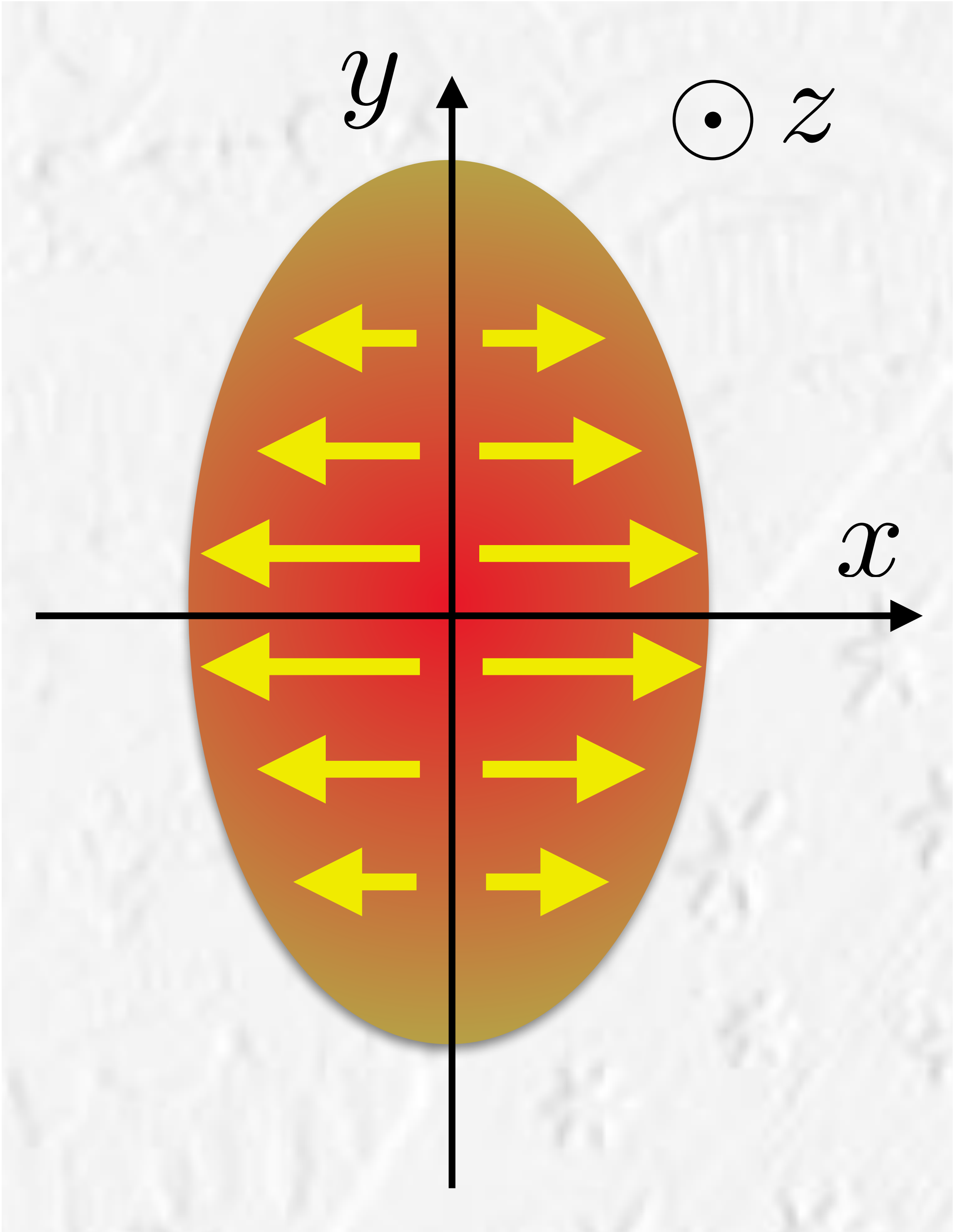


Slopes of Λ and anti-Λ seem to be different.
Possibly a contribution from the axial current?

Local polarization along beam direction

S. Voloshin, SQM2017

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



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

Local polarization along beam direction

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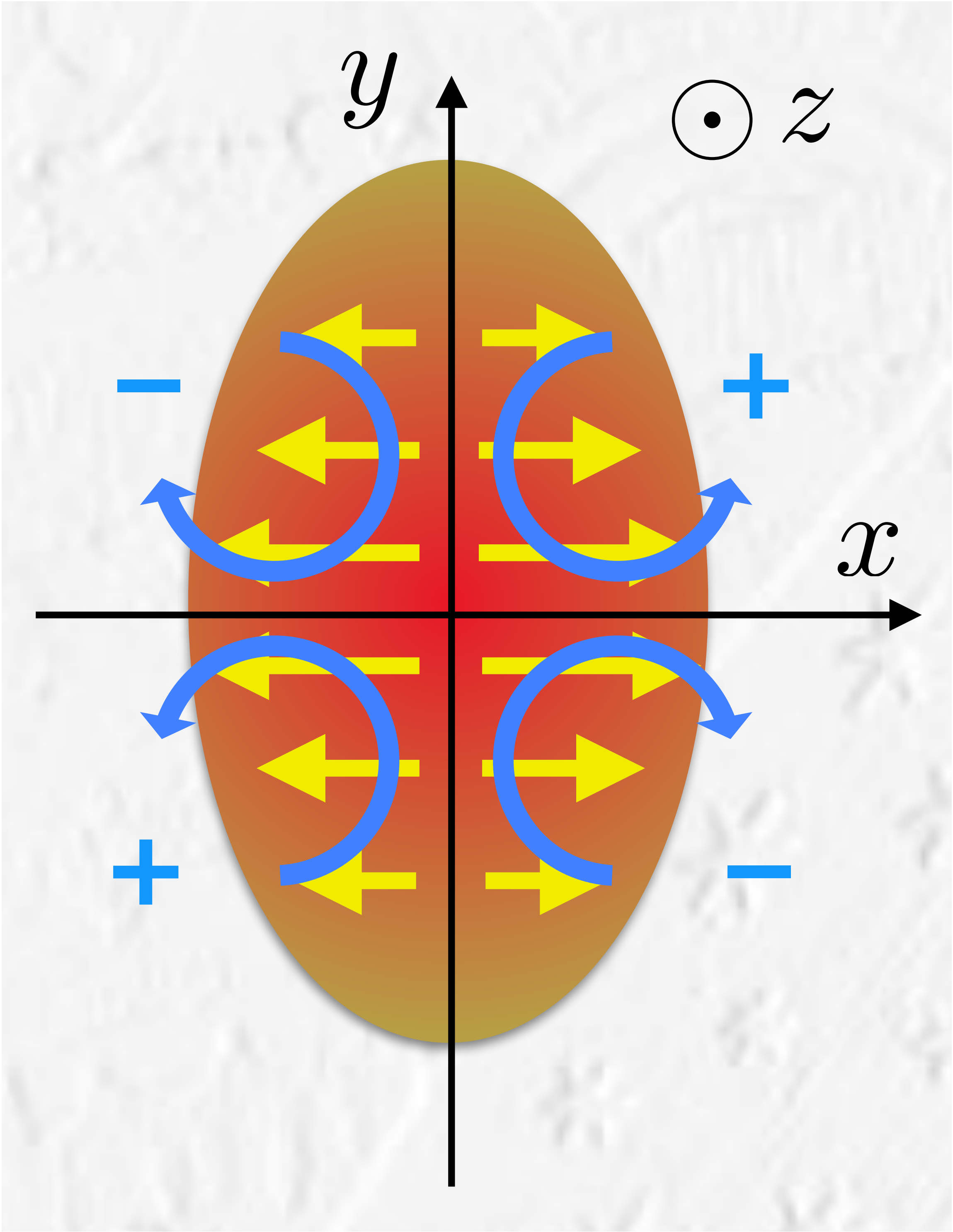

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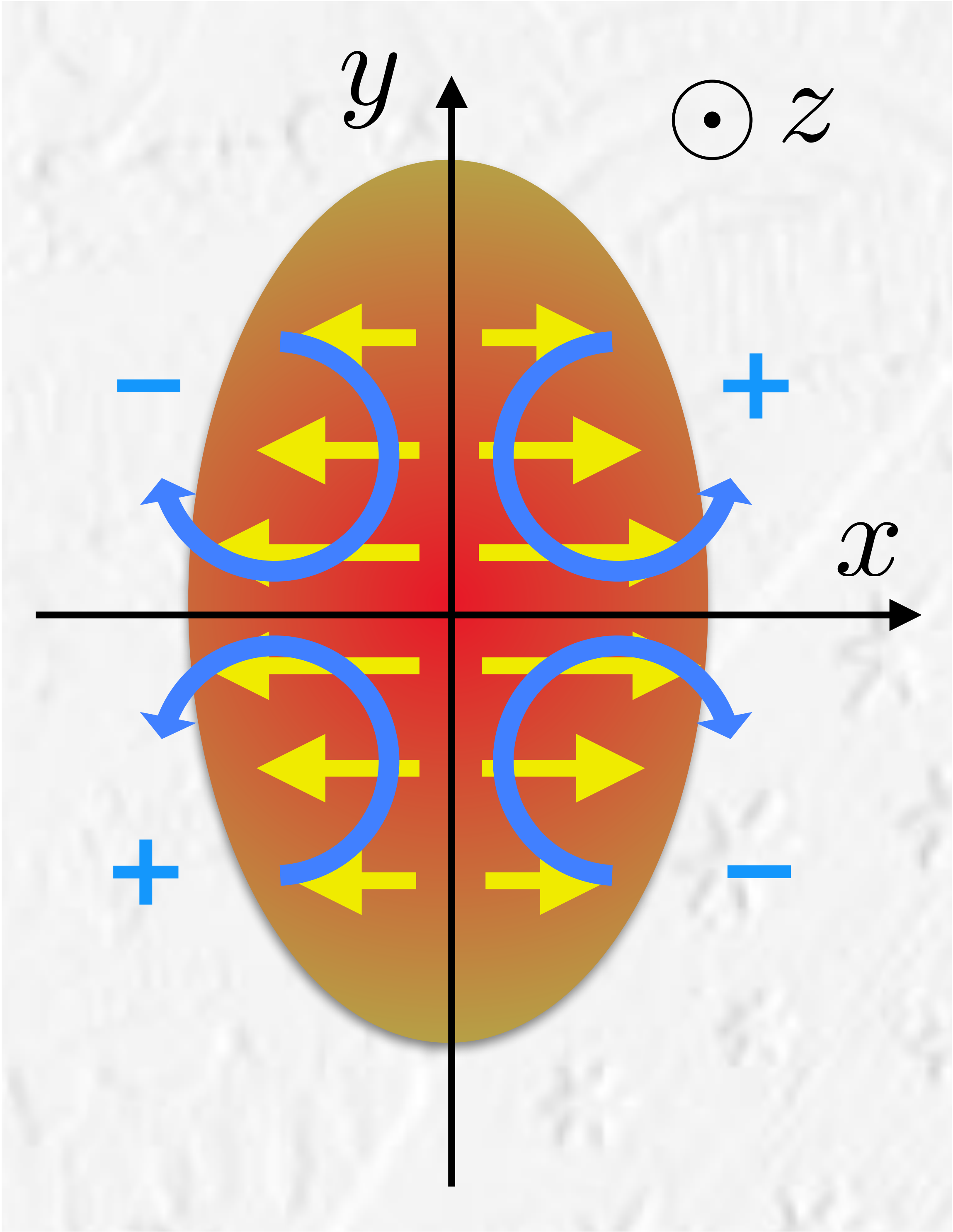
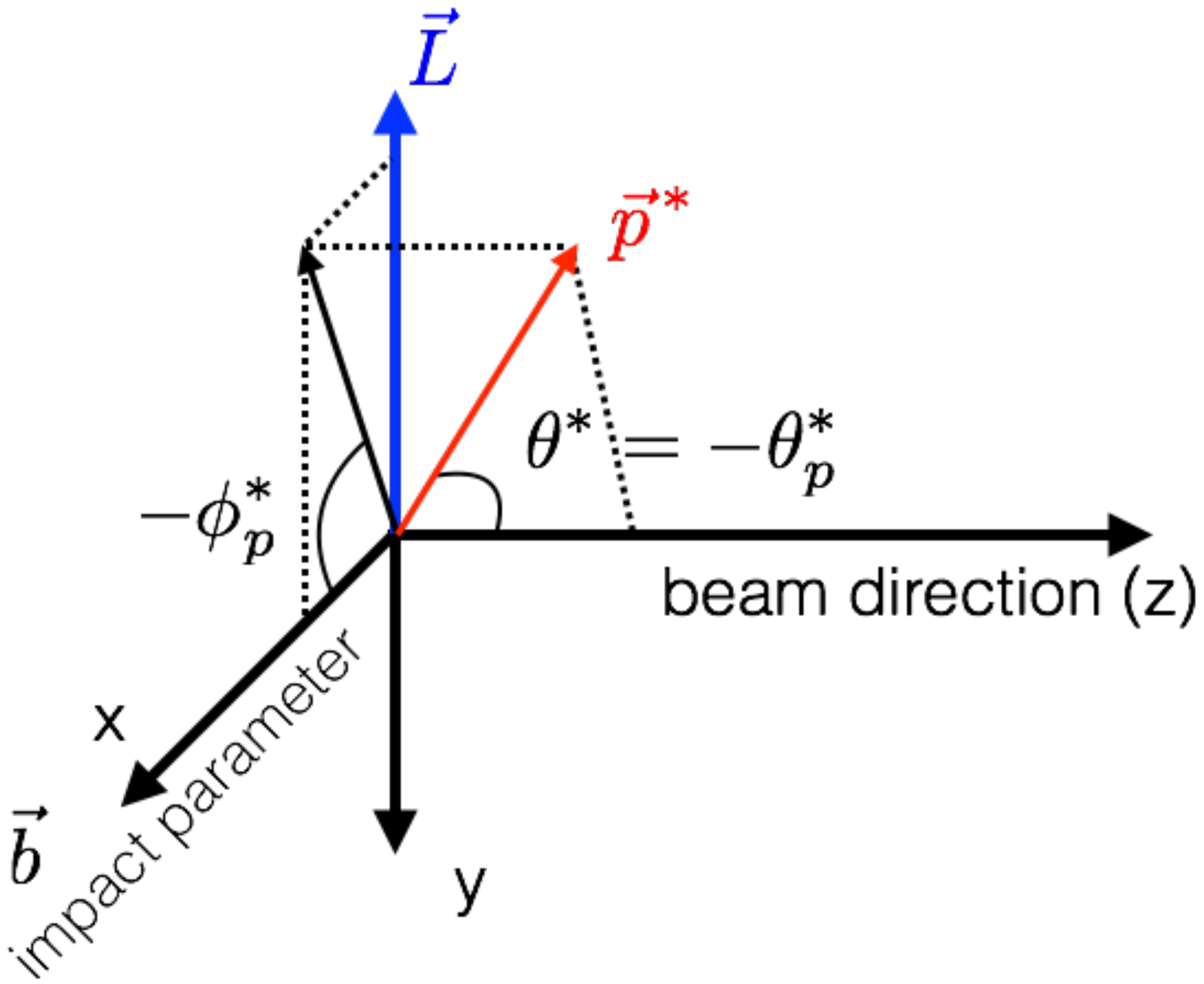




$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P_H}\cdot\mathbf{p}_p^*)$$

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

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

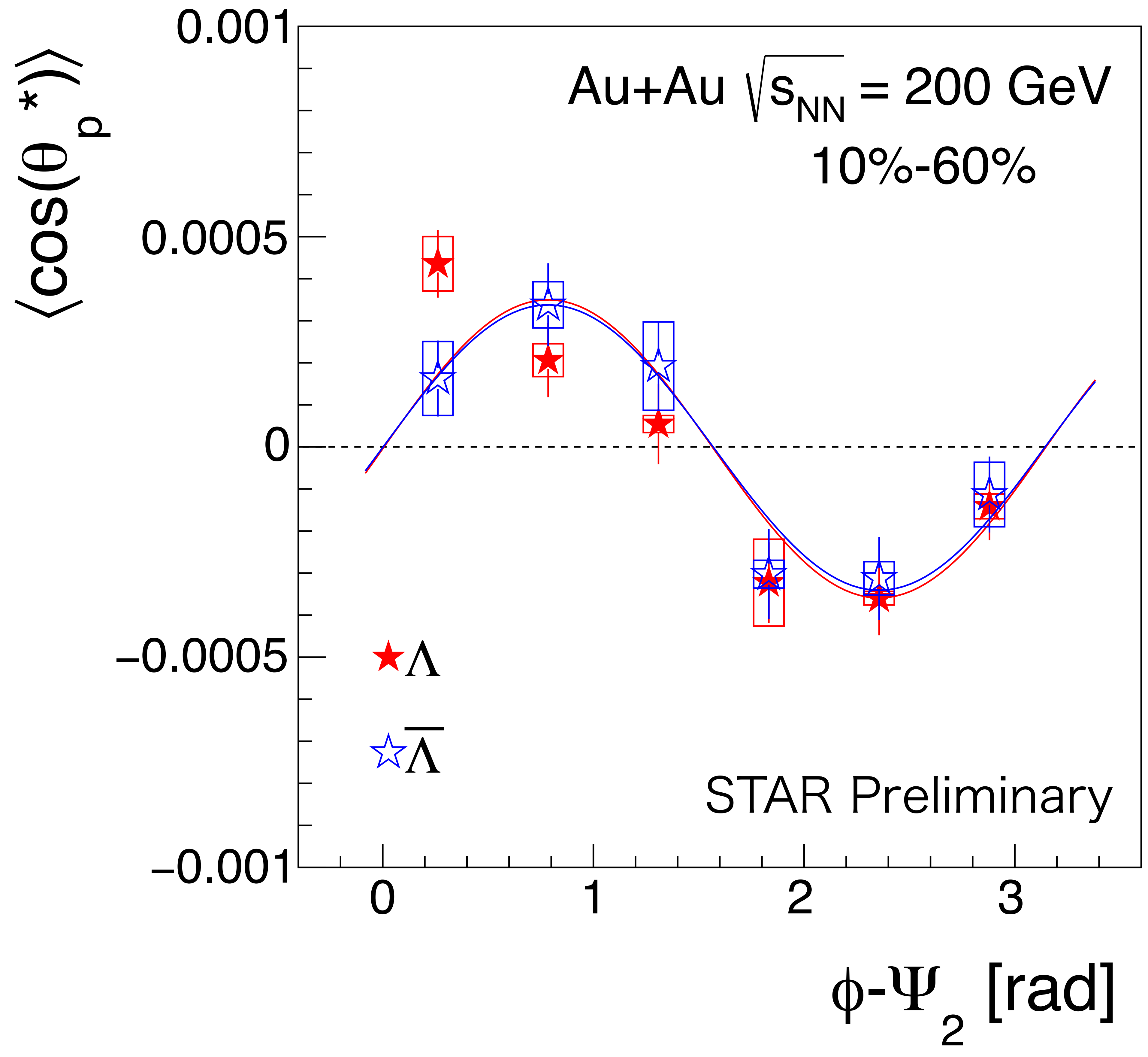
$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

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

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

Similar to the global polarization (y-component), longitudinal component P_z can be expressed with $\langle\cos\theta_p^*\rangle$. $\langle(\cos\theta_p^*)^2\rangle$ accounts for an acceptance effect, especially inefficiency at forward/backward rapidity

Local polarization along beam direction



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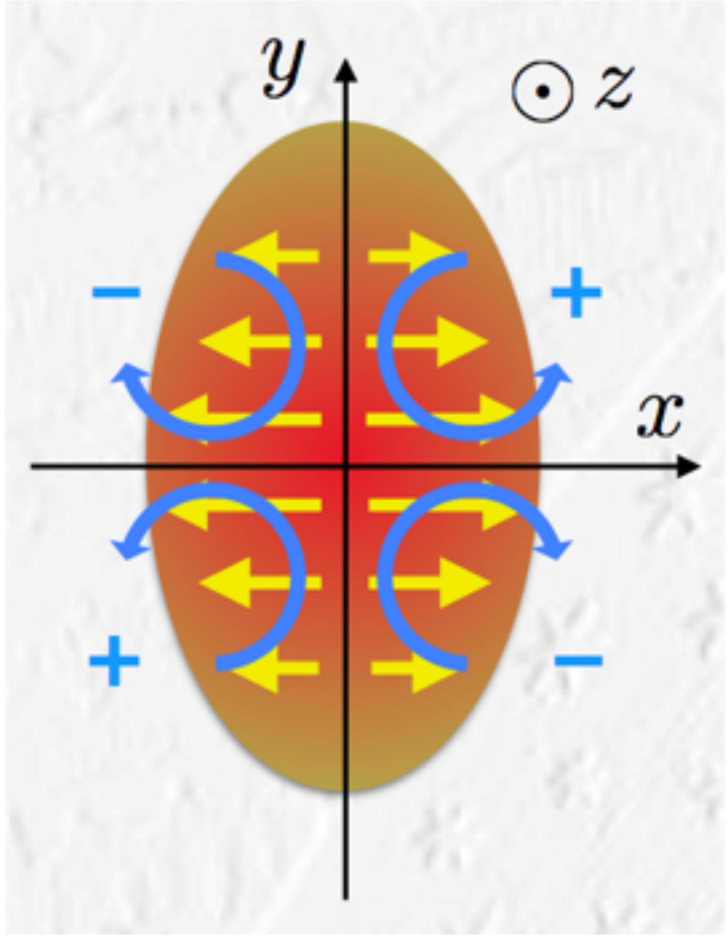
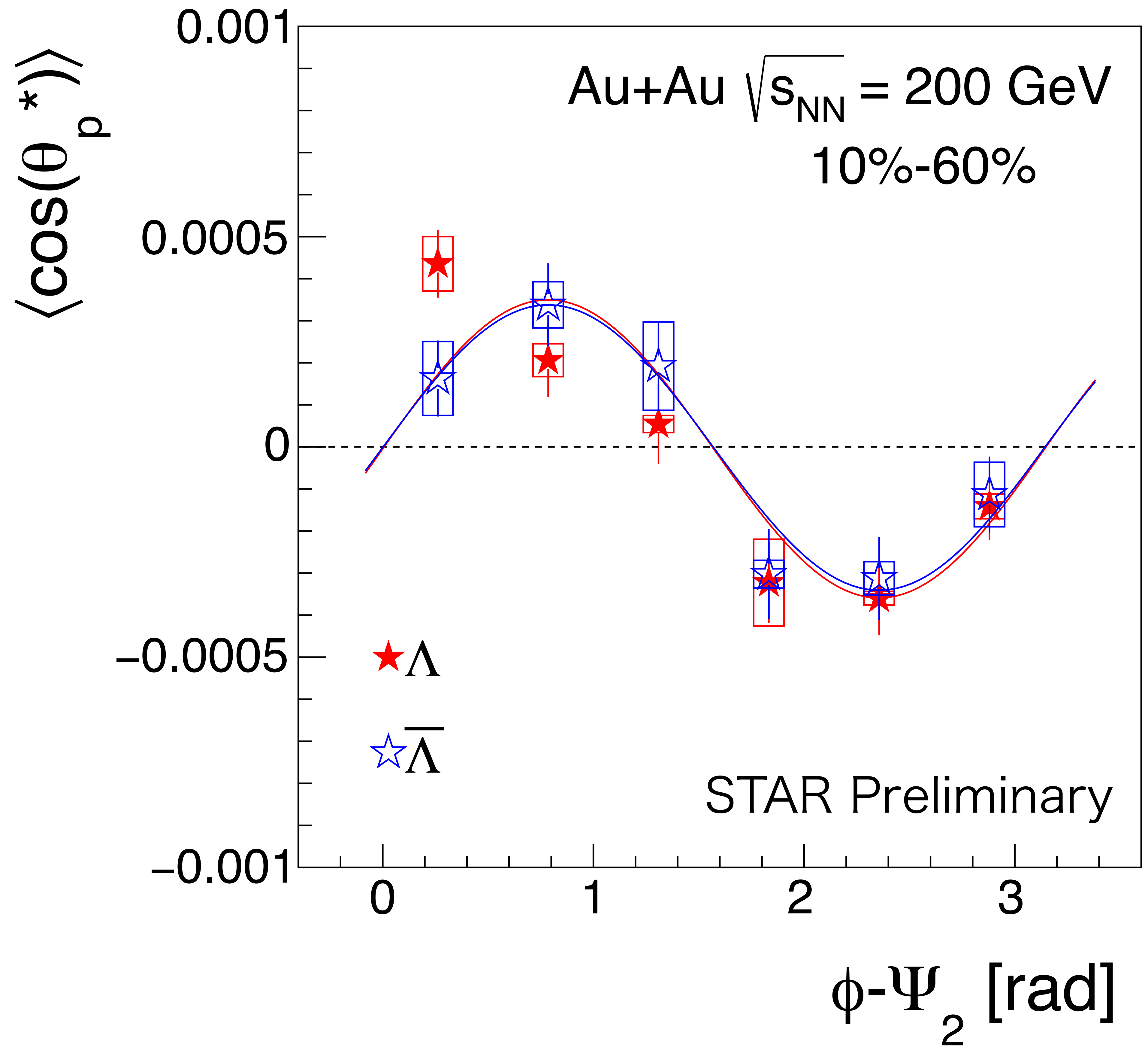


- Sine structure as expected from the elliptic flow!

- Effect of Ψ_2 resolution is not corrected here
- Applied acceptance correction so that average of ω_y over $\Delta\phi$ should be zero due to symmetry

Local polarization along beam direction



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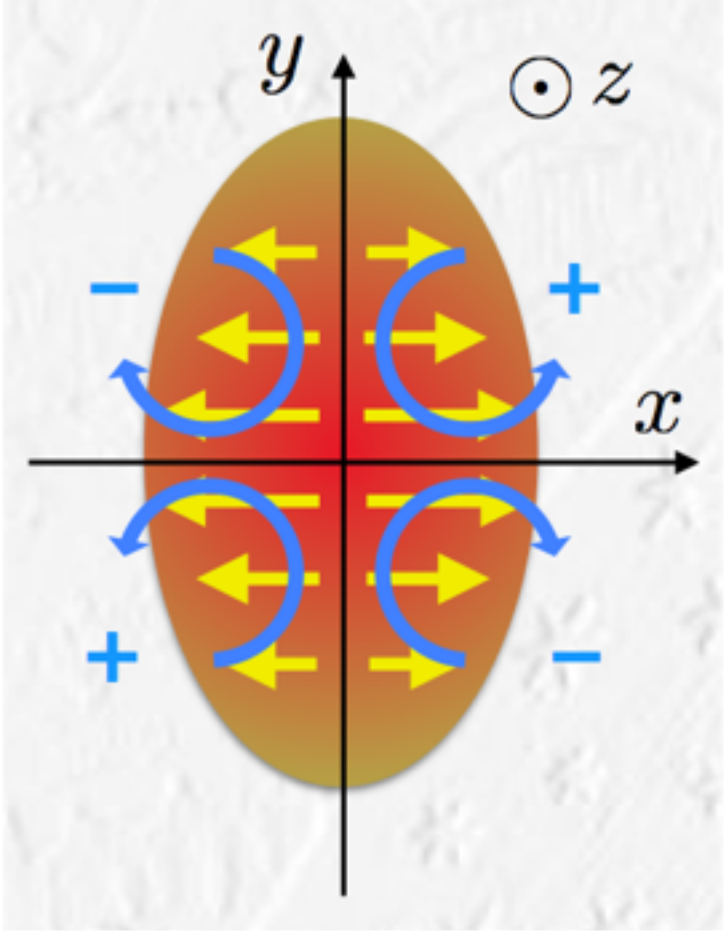
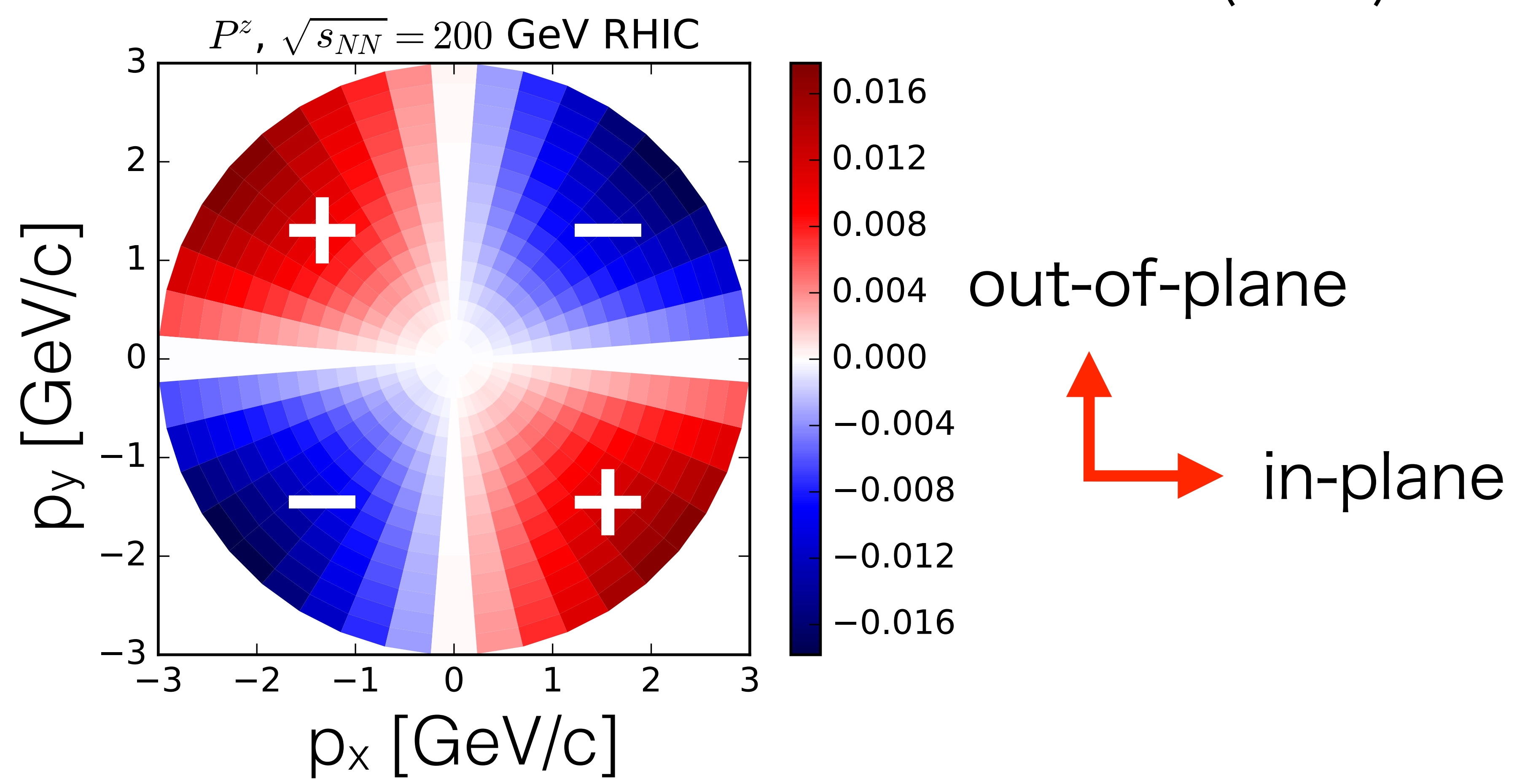


Hydro calculation of P_z
F. Becattini and I. Karpenko, PRL.120.012302 (2018)



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

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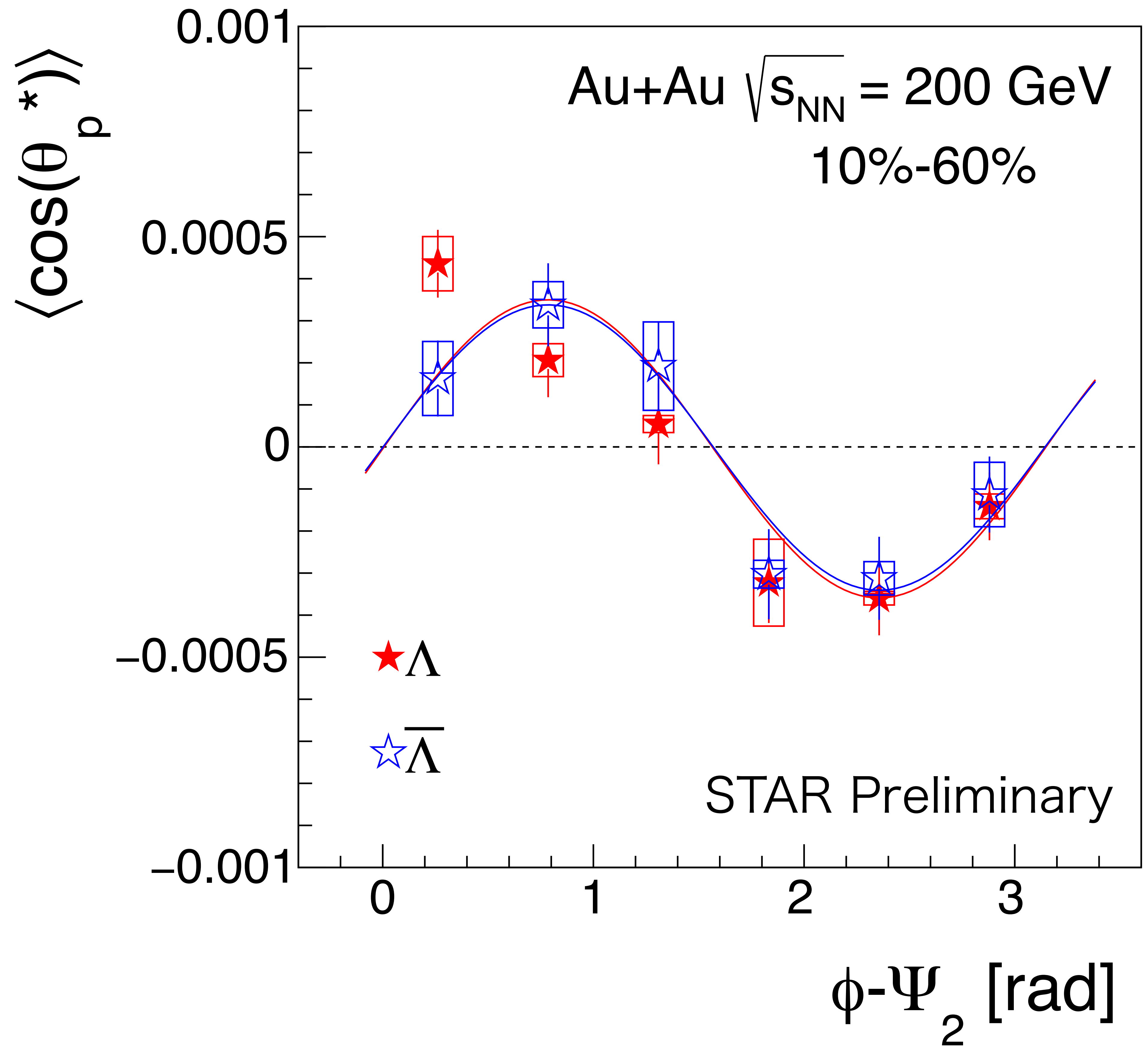

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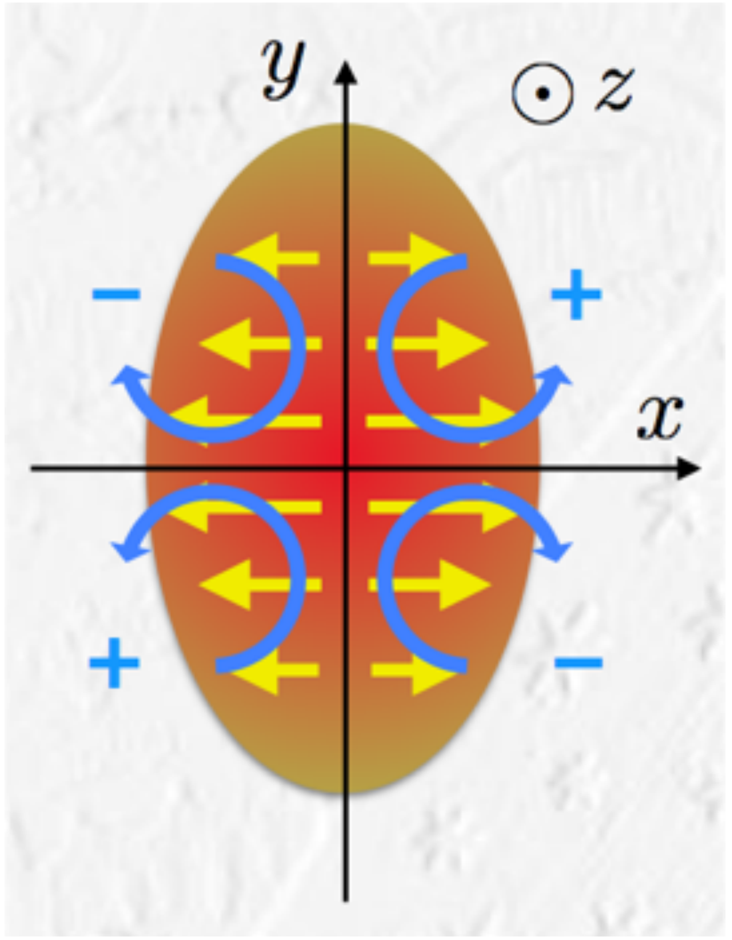

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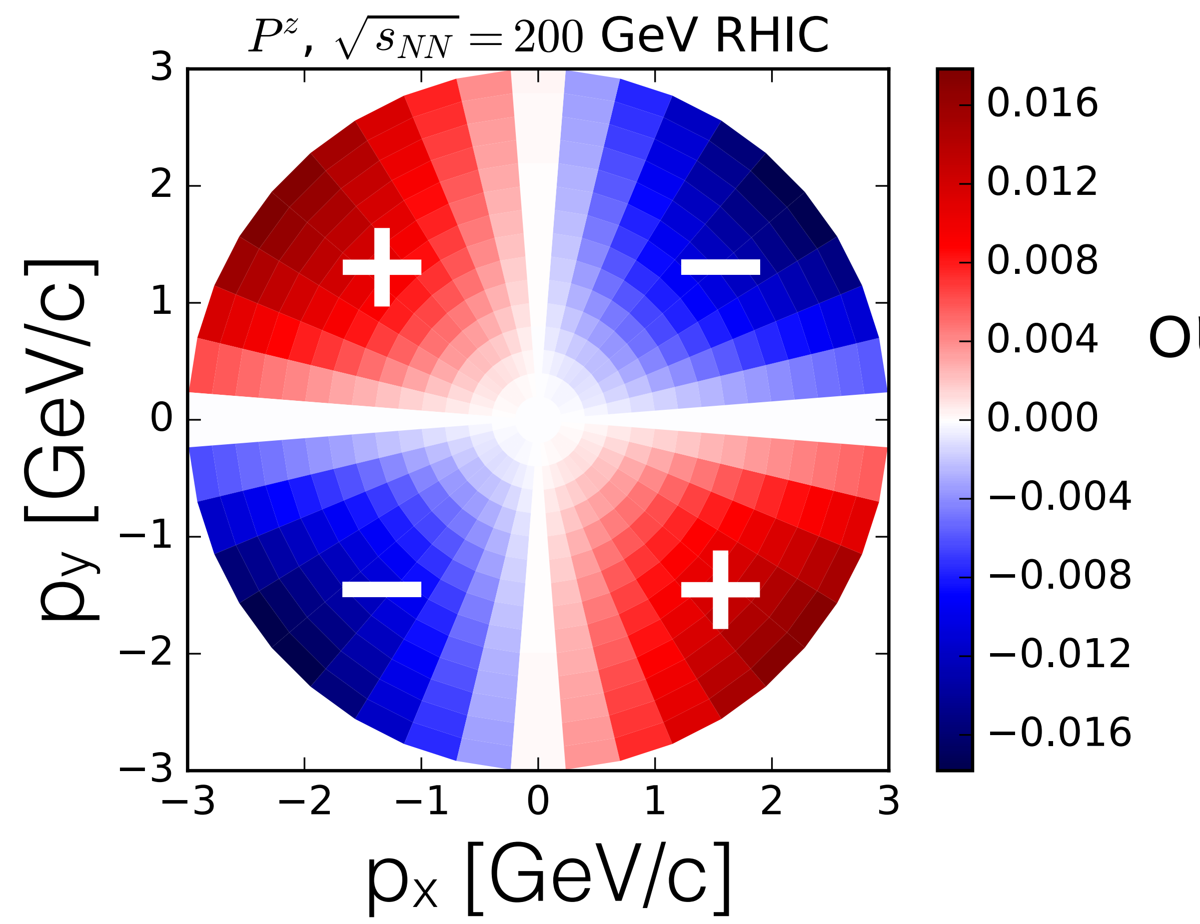

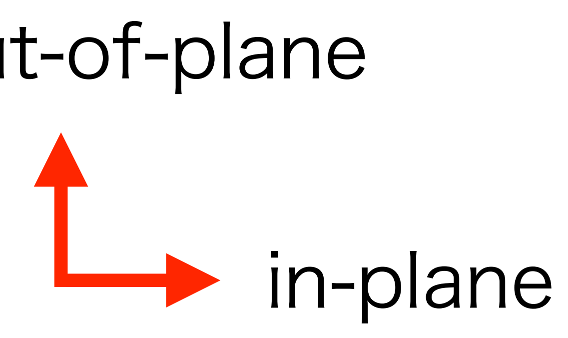

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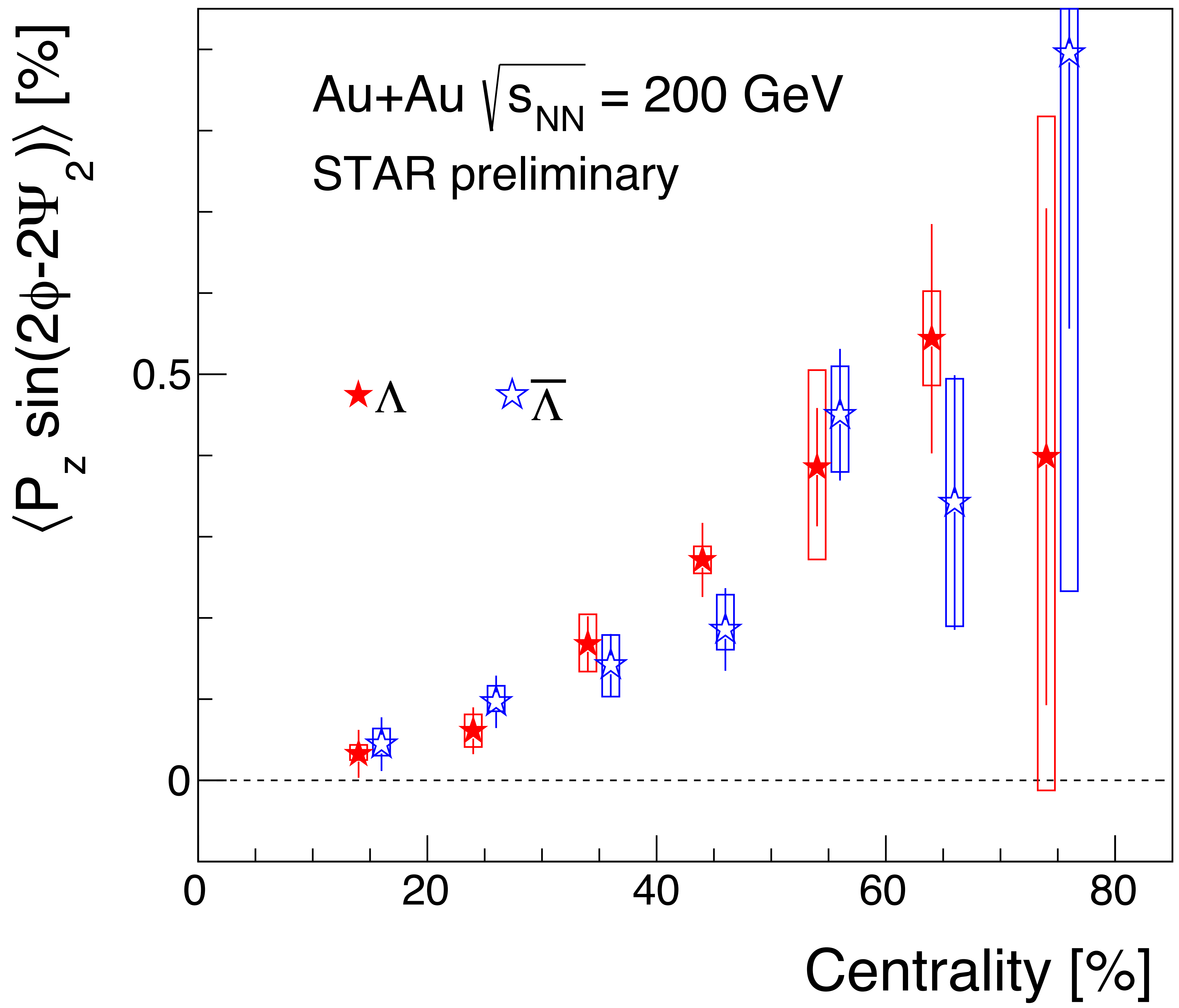
  - Hydro model: F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  - AMPT model: X. Xia, H. Li, Z. Tang, Q. Wang, arXiv:1803.0086
- The sign of <cos θ_p^*> may depend on the relation between the magnitudes of spatial and flow anisotropy based on BW model

S. Voloshin, arXiv:1710.08934

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

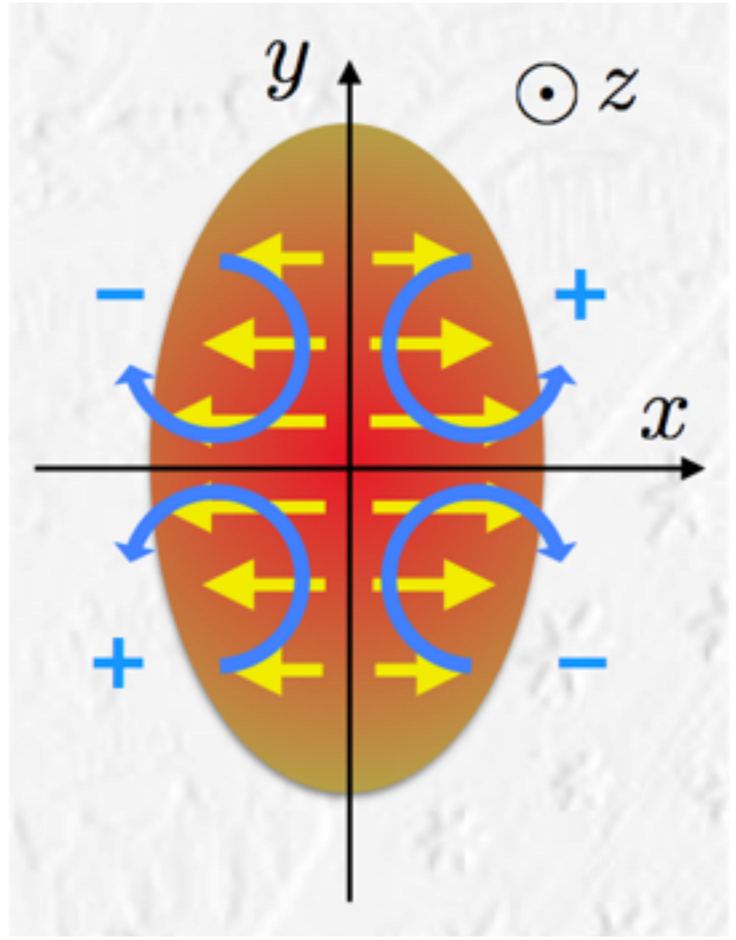
a_n: spatial anisotropy, b_n: flow anisotropy

Centrality dependence of P_z modulation



<p_T> of Λ ~1.4 GeV/c

S. Voloshin, SQM2017



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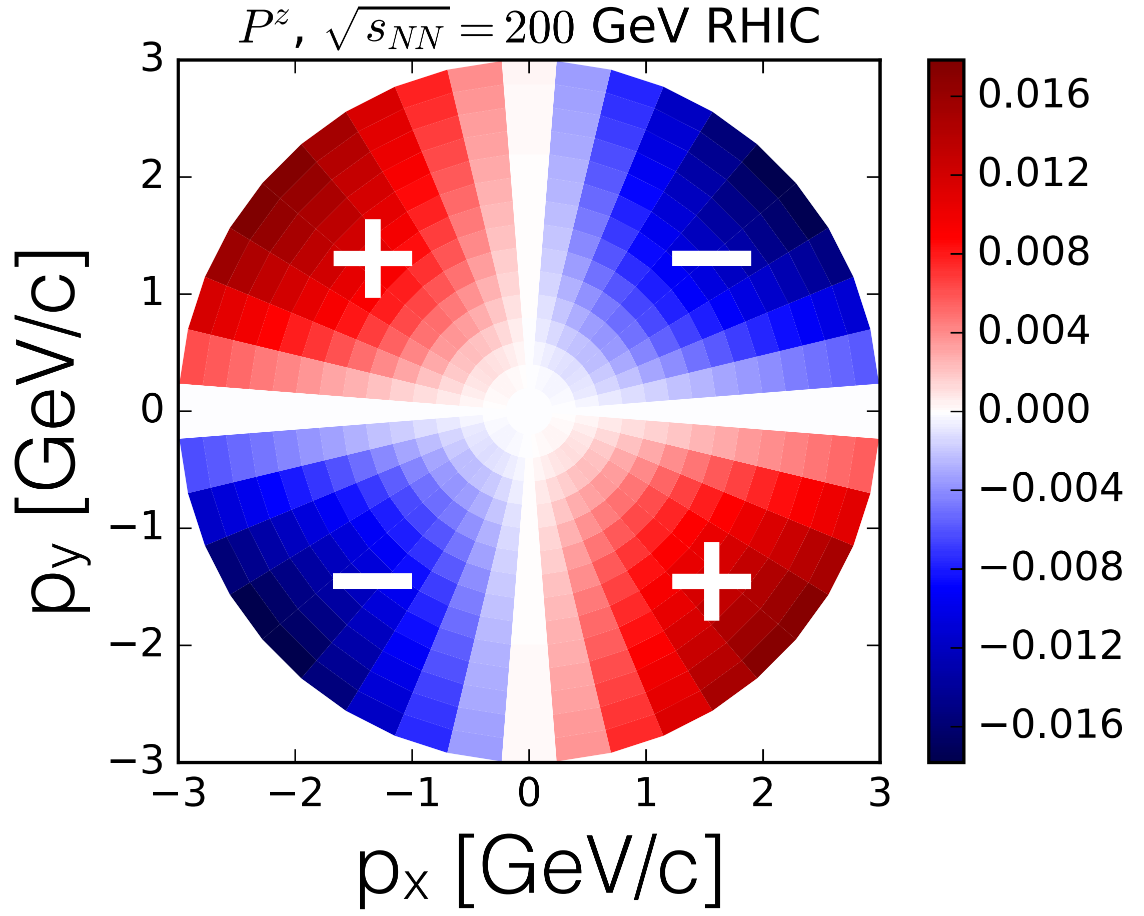


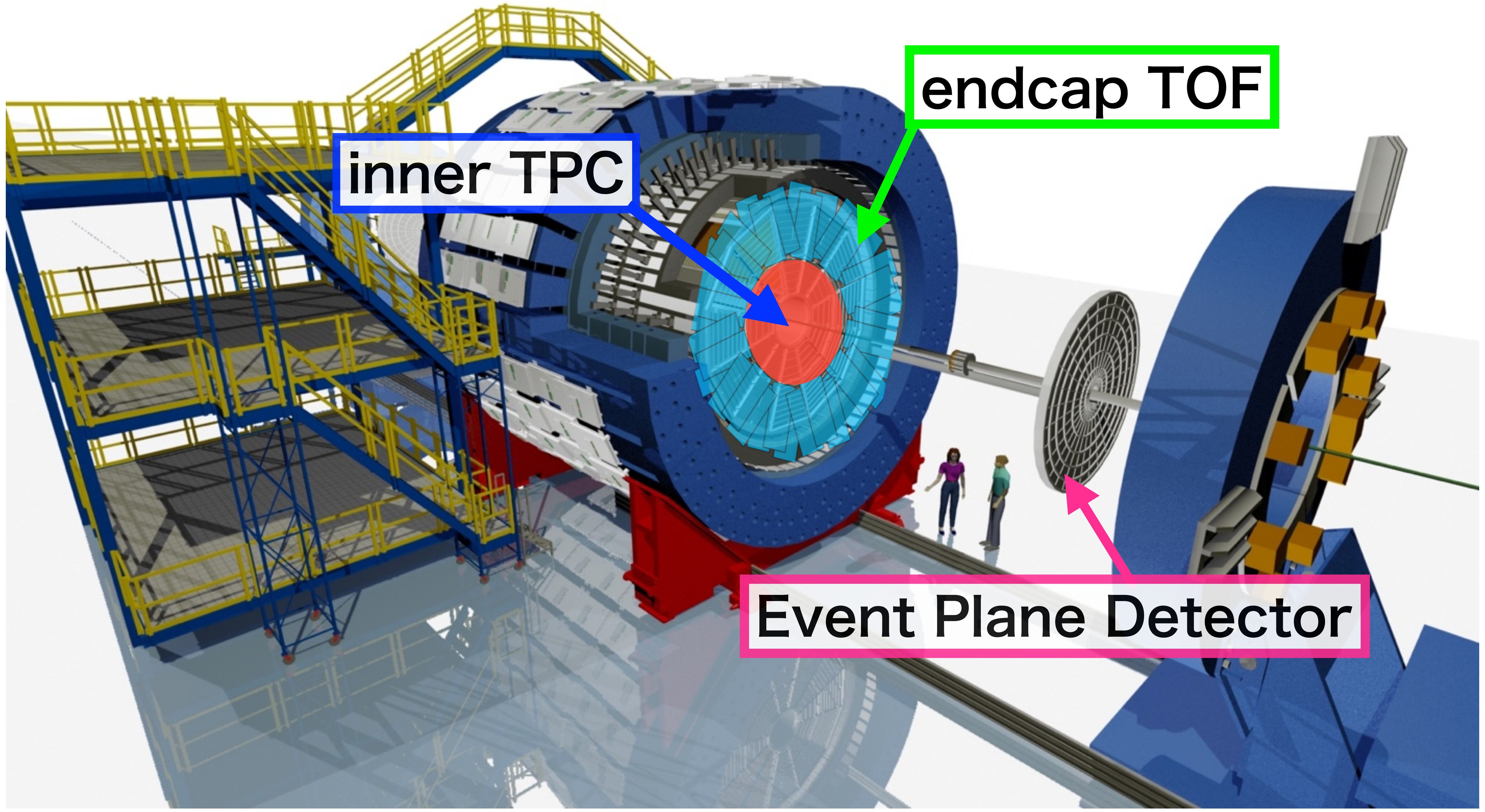
- Strong centrality dependence as in the elliptic flow
  - Similar magnitude to the global polarization

Summary

- First observation of non-zero Λ global polarization at $\sqrt{s_{NN}}$ = 200 GeV
  - Larger signal in more peripheral collisions
  - Larger signal in in-plane than in out-of-plane
  - 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
- Local vorticity along the beam direction
  - Quadrupole structure of the polarization along the beam direction, as expected from the elliptic flow
  - Strong centrality dependence similar to that of the elliptic flow

Back up

Outlook



EPD upgrade installed
- $2.1<|\eta|<5.1$
- Improves EP resolution
- Independent trigger

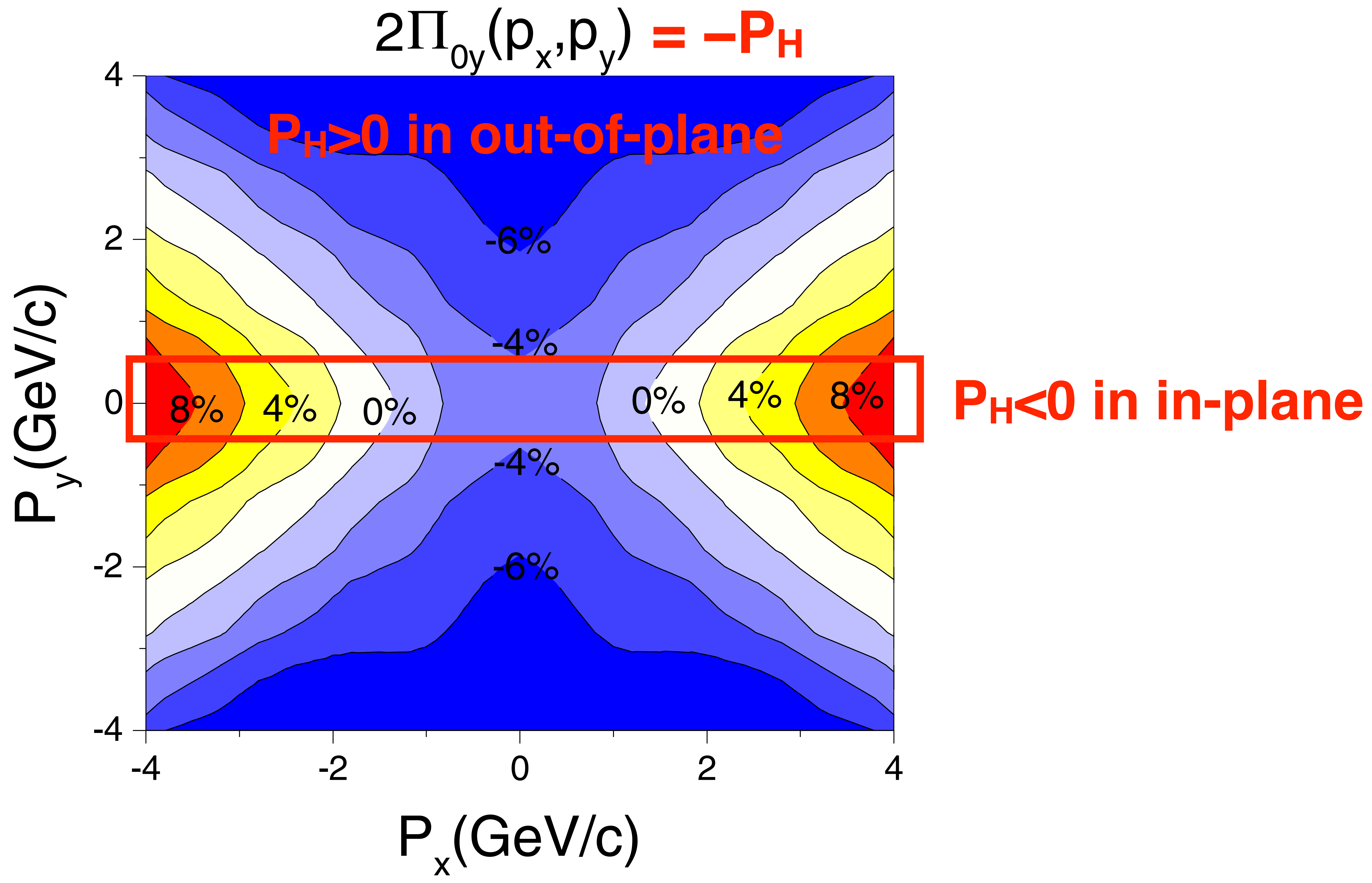
iTPC upgrade ready in 2019
- $p_T>60$ MeV/c
- Extension from $|\eta|<1$ to $|\eta|<1.5$
- Improvement of dE/dx resolution

eTOF upgrade ready in 2019
- $-1.6<\eta<-1.1$
- Extends forward PID capability

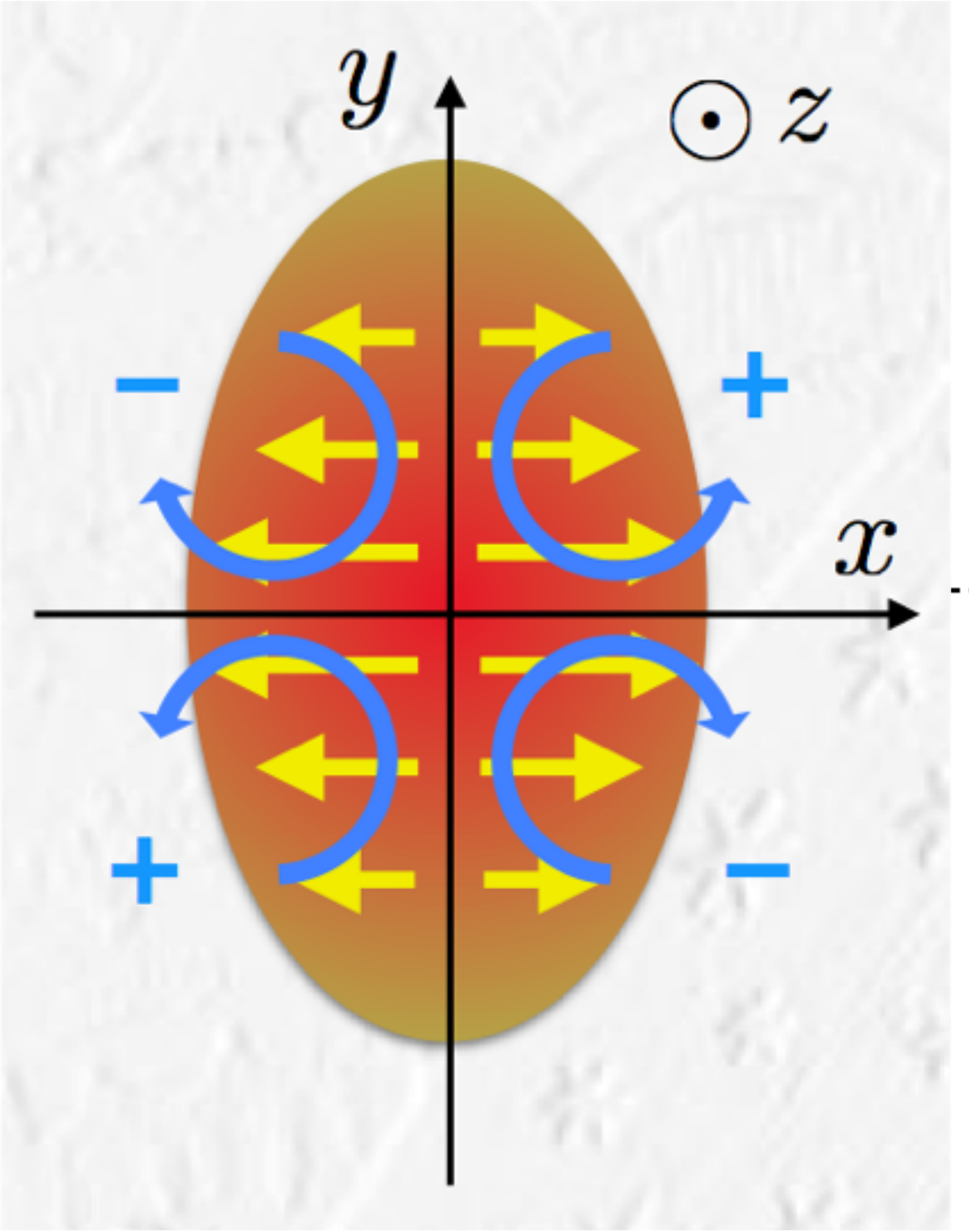
- Isobaric collisions and Au+Au 27 GeV in 2018 (taking data now!)
  - ~1B events for each collision with EPD (better EP resolution)
  - Any splitting of Λ and anti-Λ? Any difference btw Ru+Ru and Zr+Zr?
- Beam Energy Scan II (2019+)
  - 7.7-19.6 GeV (10 times more events than BES-I)
    + Fixed-target program with iTPC and eTOF (wider η coverage)

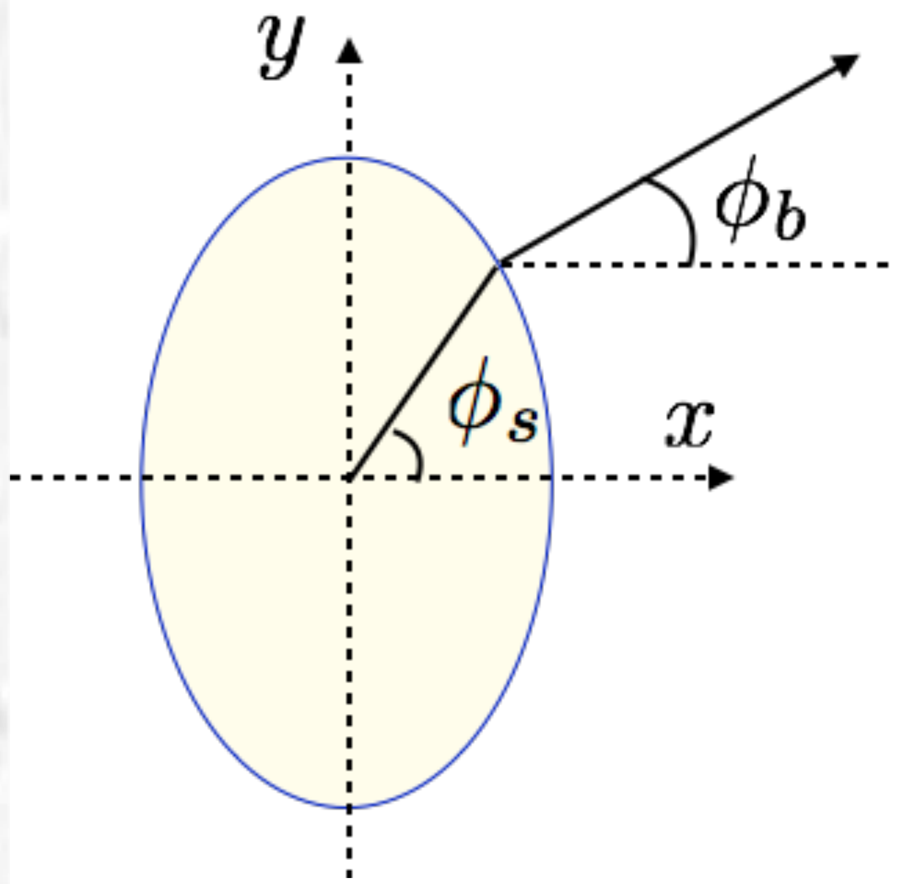
F. Becattini et al.,
PRC93, 069901(E)(2016)
PRC88, 034905 (2013)

Au+Au 200 GeV



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.

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

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

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

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

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

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

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