Global and local polarization of Λ hyperons in heavy-ion collisions

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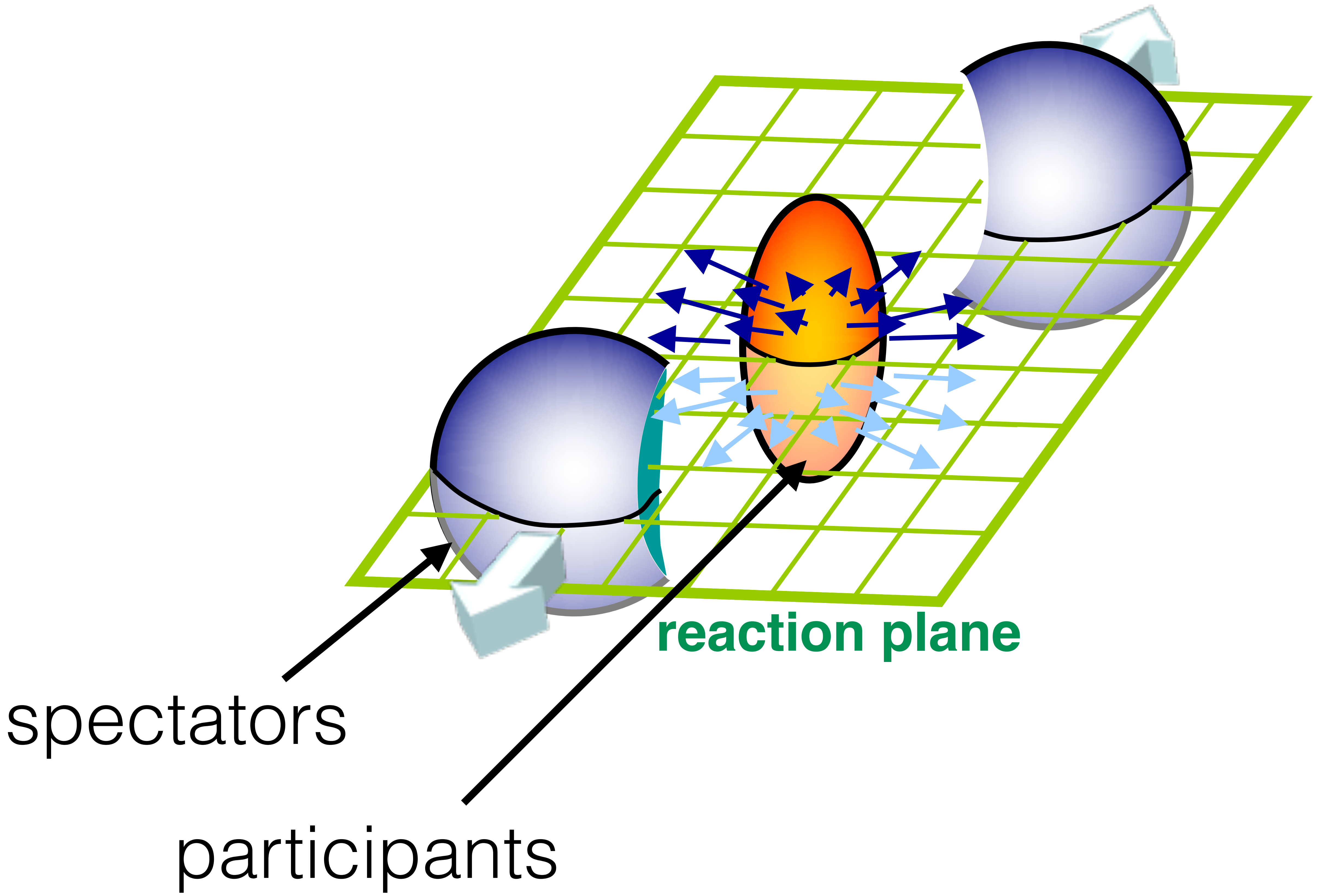
U.S. DEPARTMENT OF ENERGY | Office of Science

Nuclear Physics Seminar, BNL

Important features in non-central heavy-ion collisions



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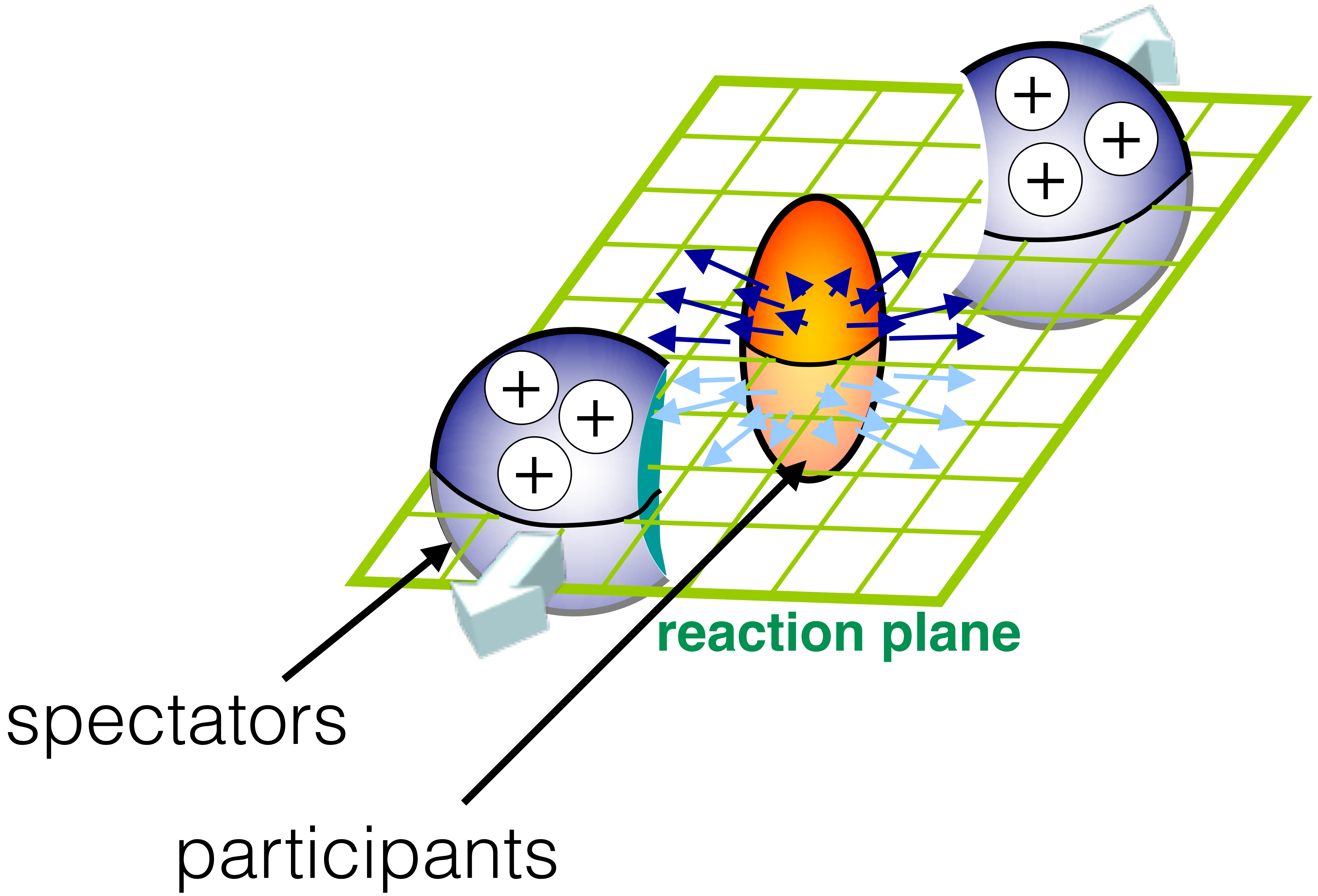

Important features in non-central heavy-ion collisions

Strong magnetic field

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

$$(eB \sim m_\pi^2\ (\tau \sim 0.2\ \mathrm{fm}))$$

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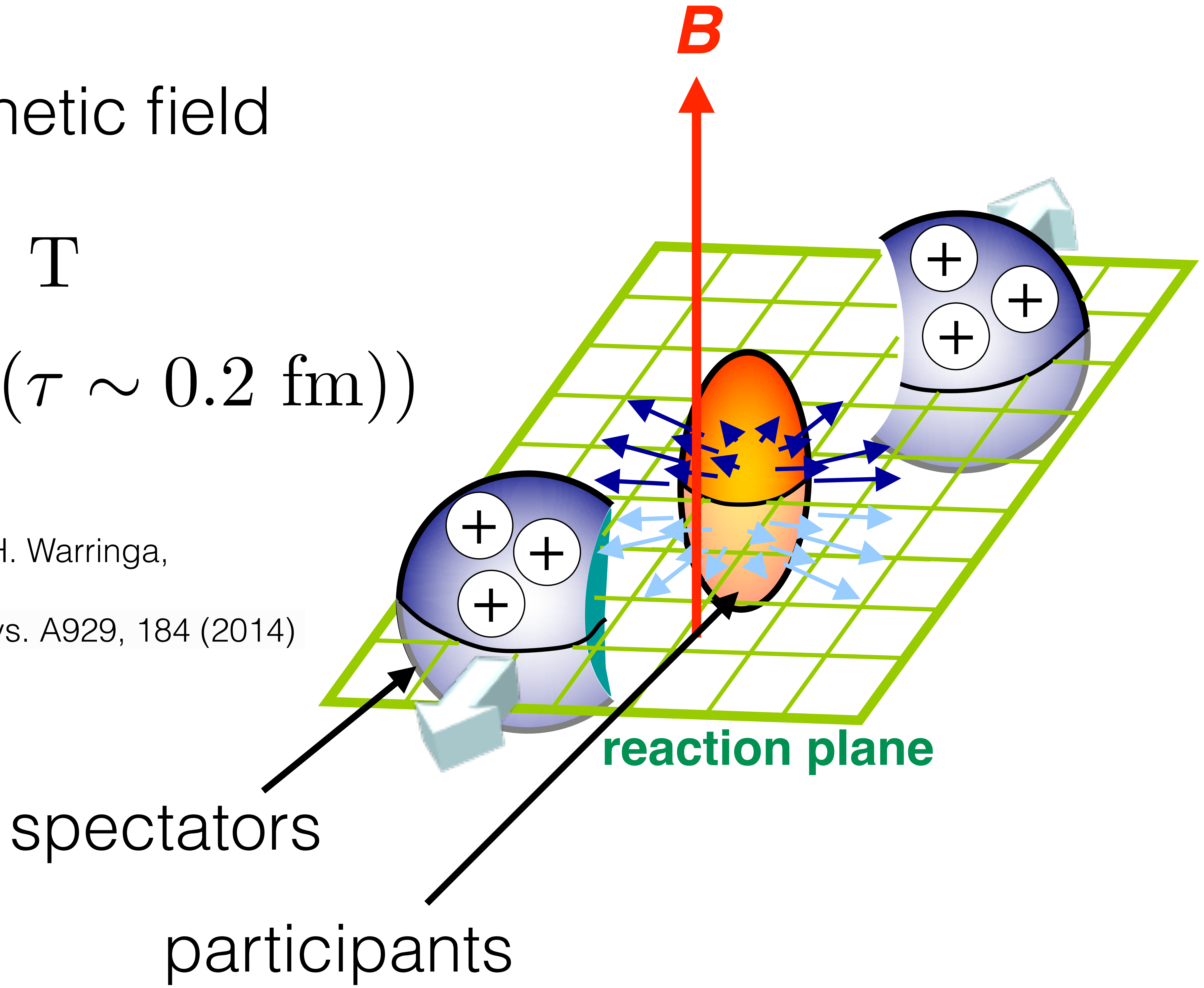

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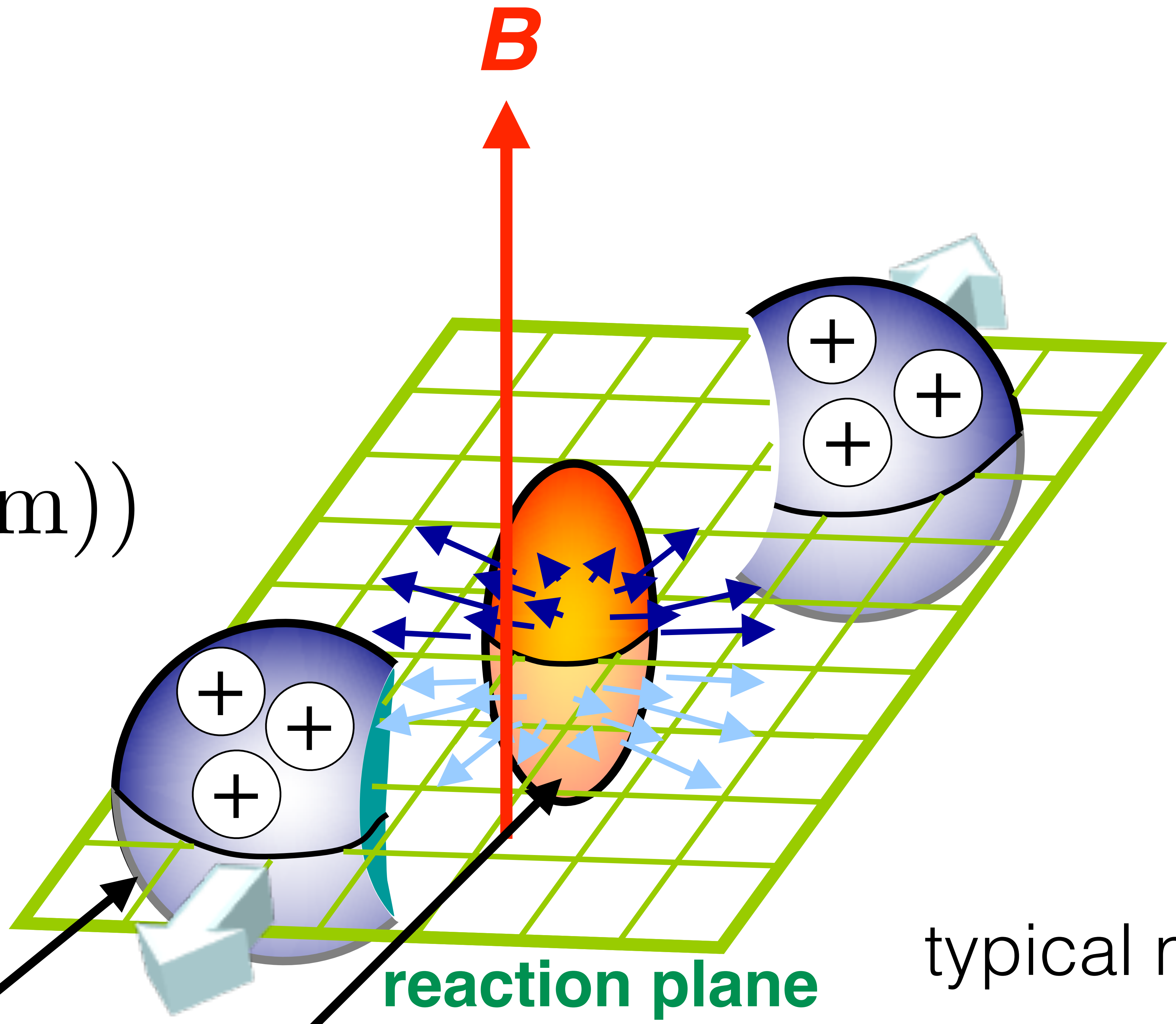

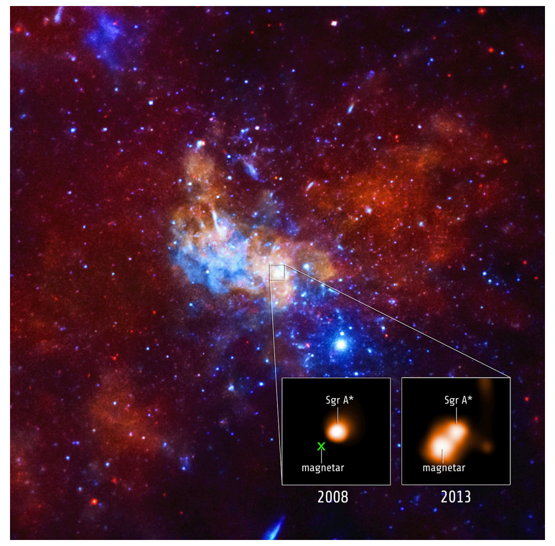

magnetar, wikipedia

typical magnet	$B \sim 0.1 - 0.5\ \mathrm{T}$
surface on magnetar	$B \sim 10^{11}\ \mathrm{T}$
HI (200 GeV)	$B \sim 10^{13}\ \mathrm{T}$

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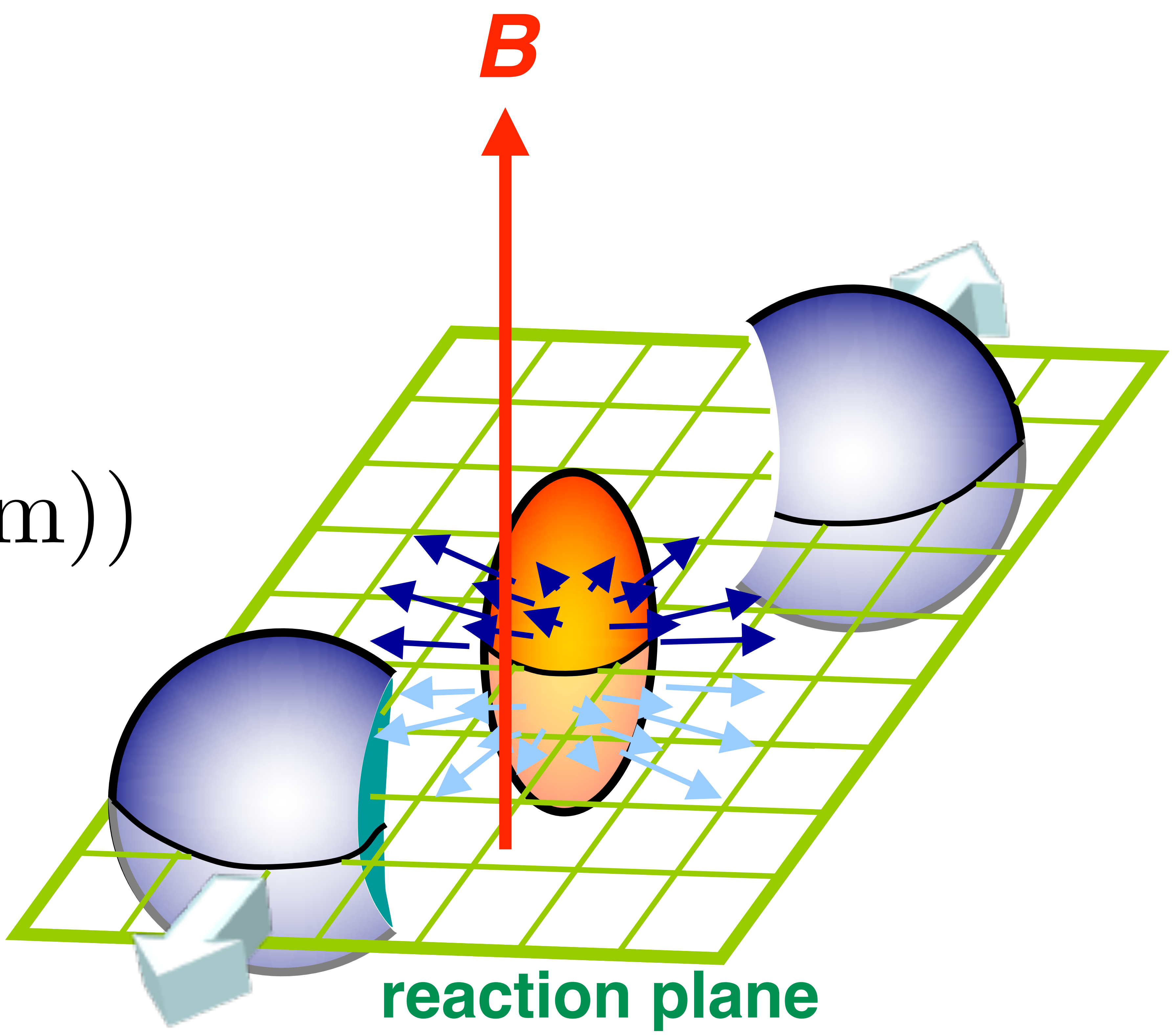

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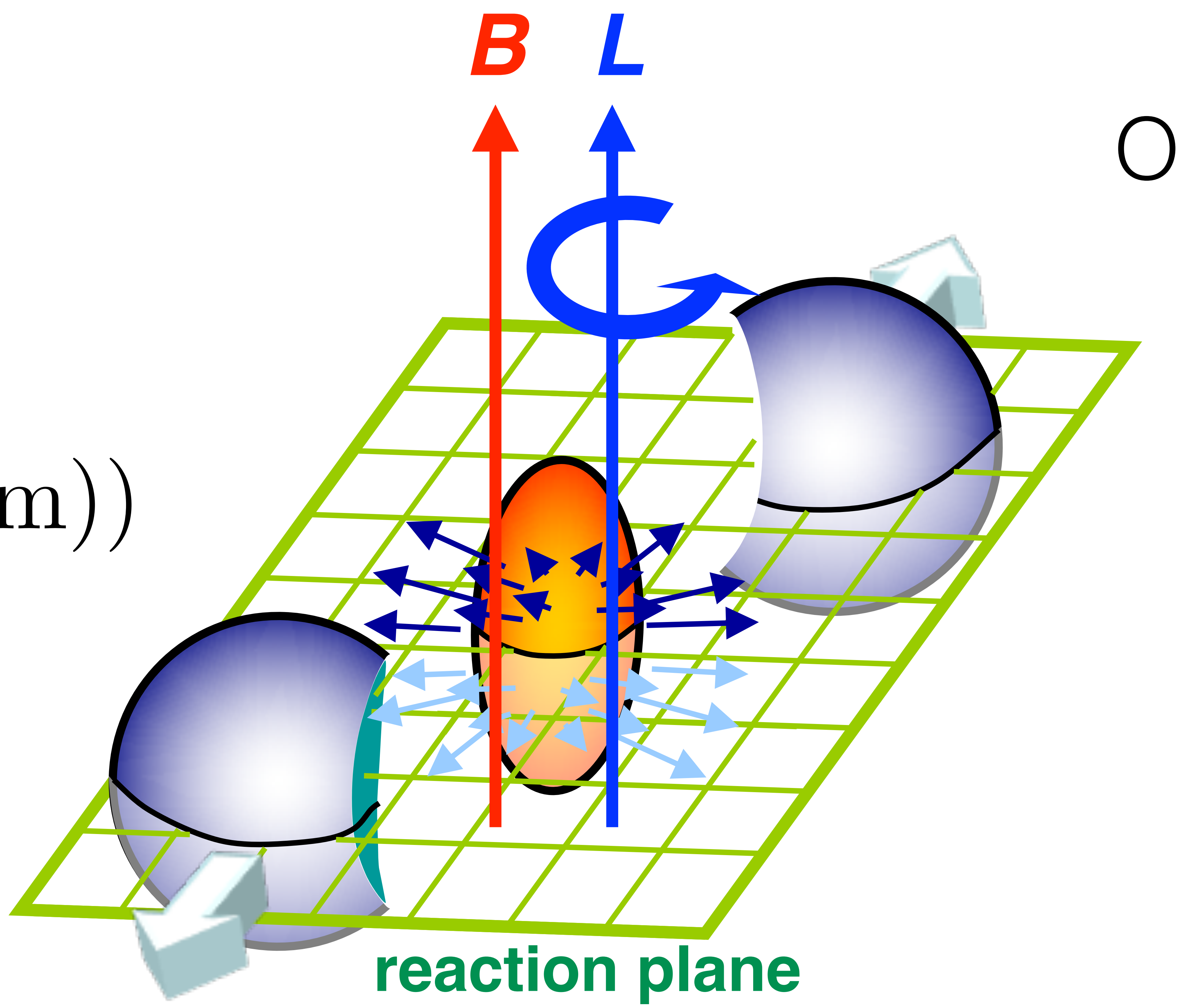

Orbital angular momentum

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

$$\sim bA\sqrt{s_{NN}} \sim 10^6\hbar$$

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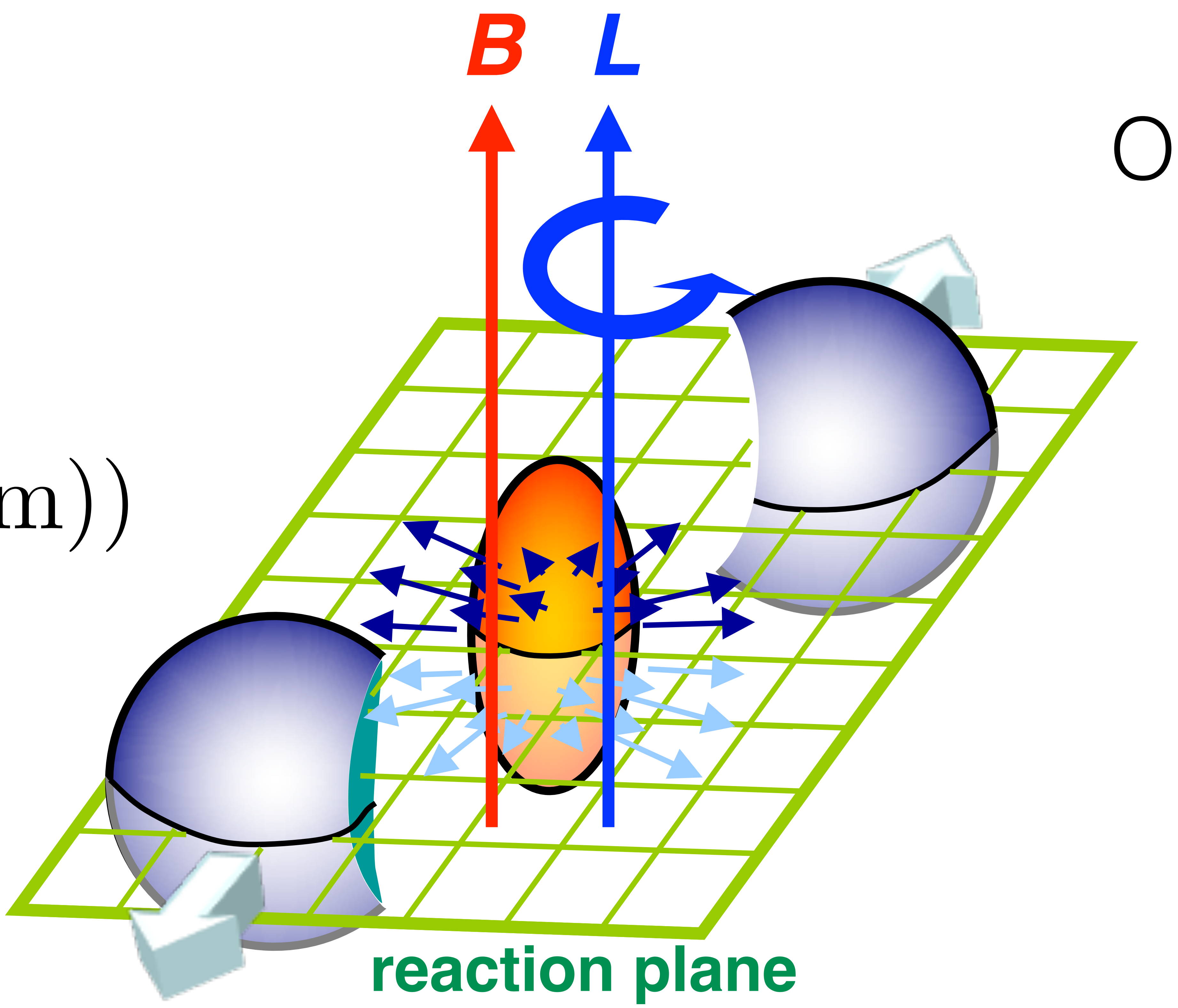

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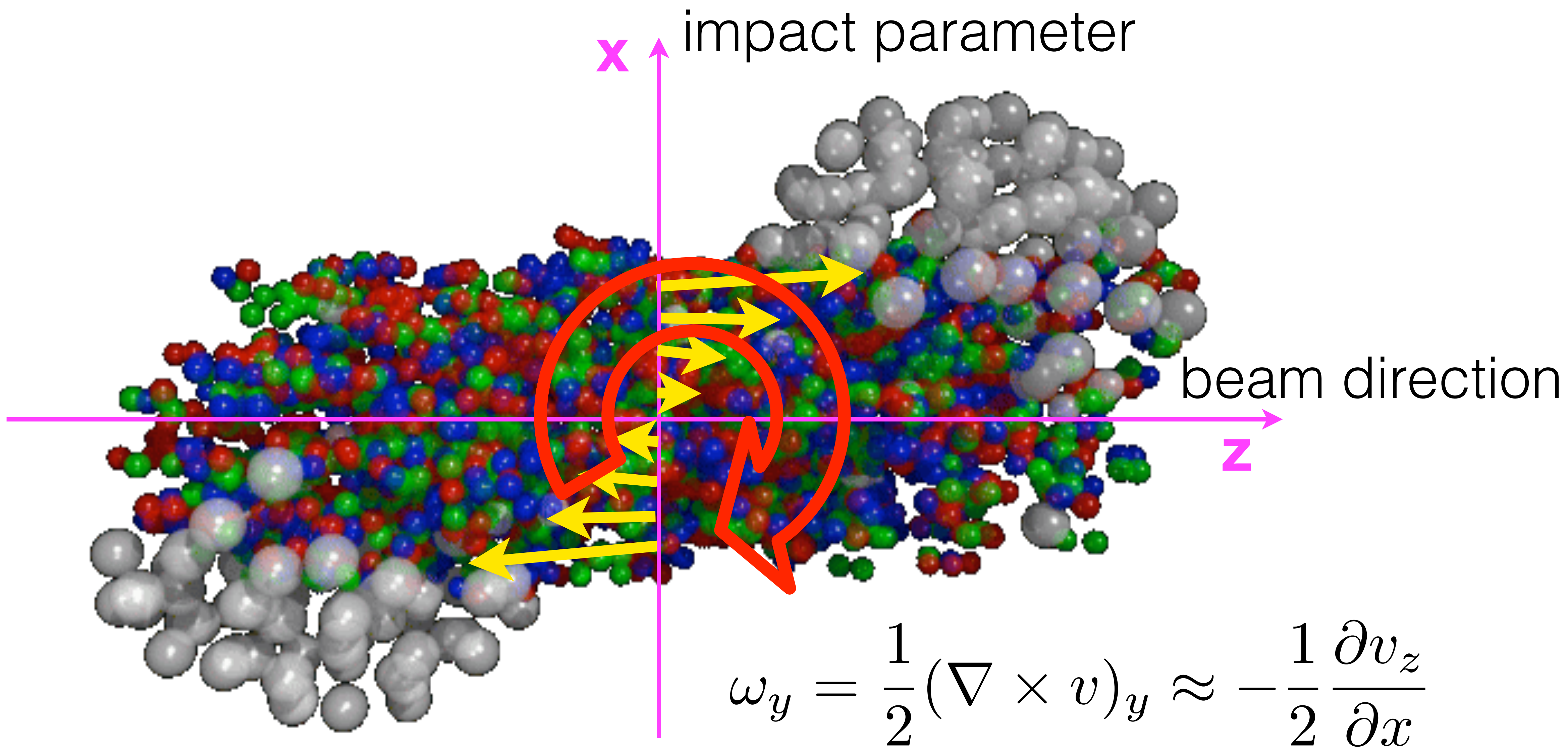
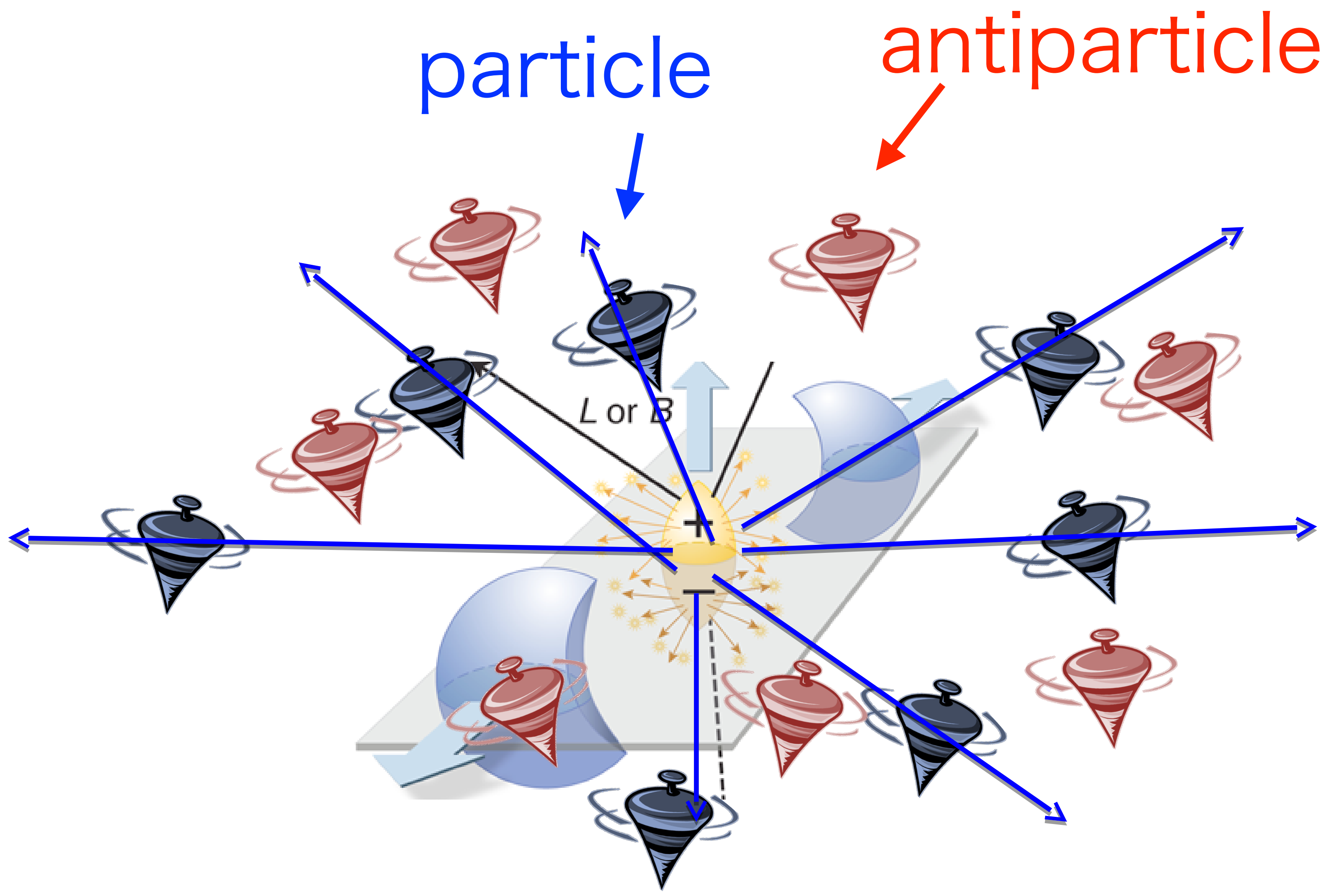
→Chiral magnetic effect
Chiral magnetic wave
Particle polarization

→Chiral vortical effect
Particle polarization

Global polarization



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



- 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
  - 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

How to measure the polarization?

Parity-violating weak decay of hyperons ("self-analyzing")

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

(BR: 63.9%, $c\tau$ ~7.9 cm)

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

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H \mathrm{P_H} \cos\theta^*$$

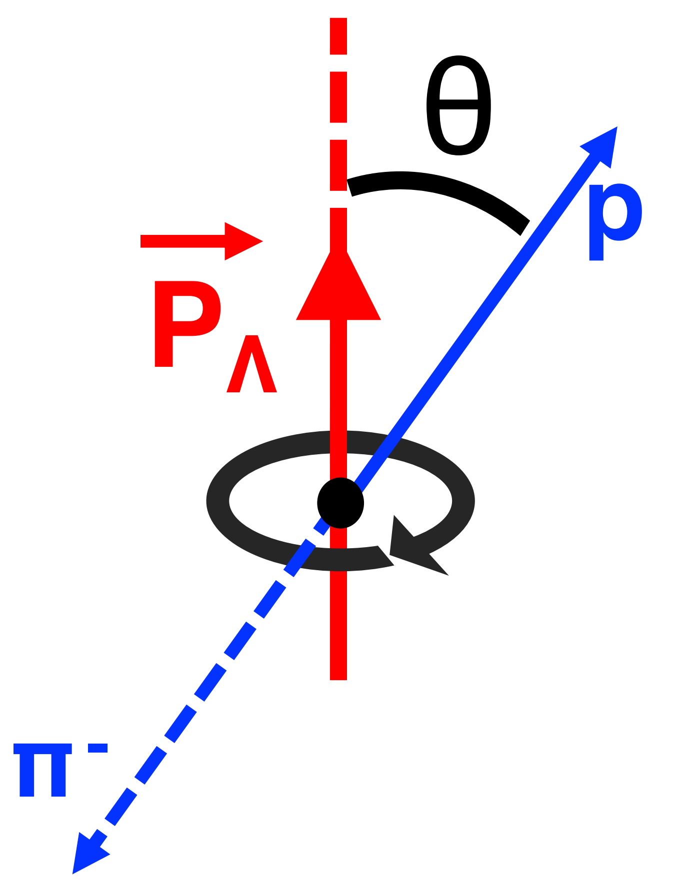
$\mathrm{P_H}$: Λ polarization

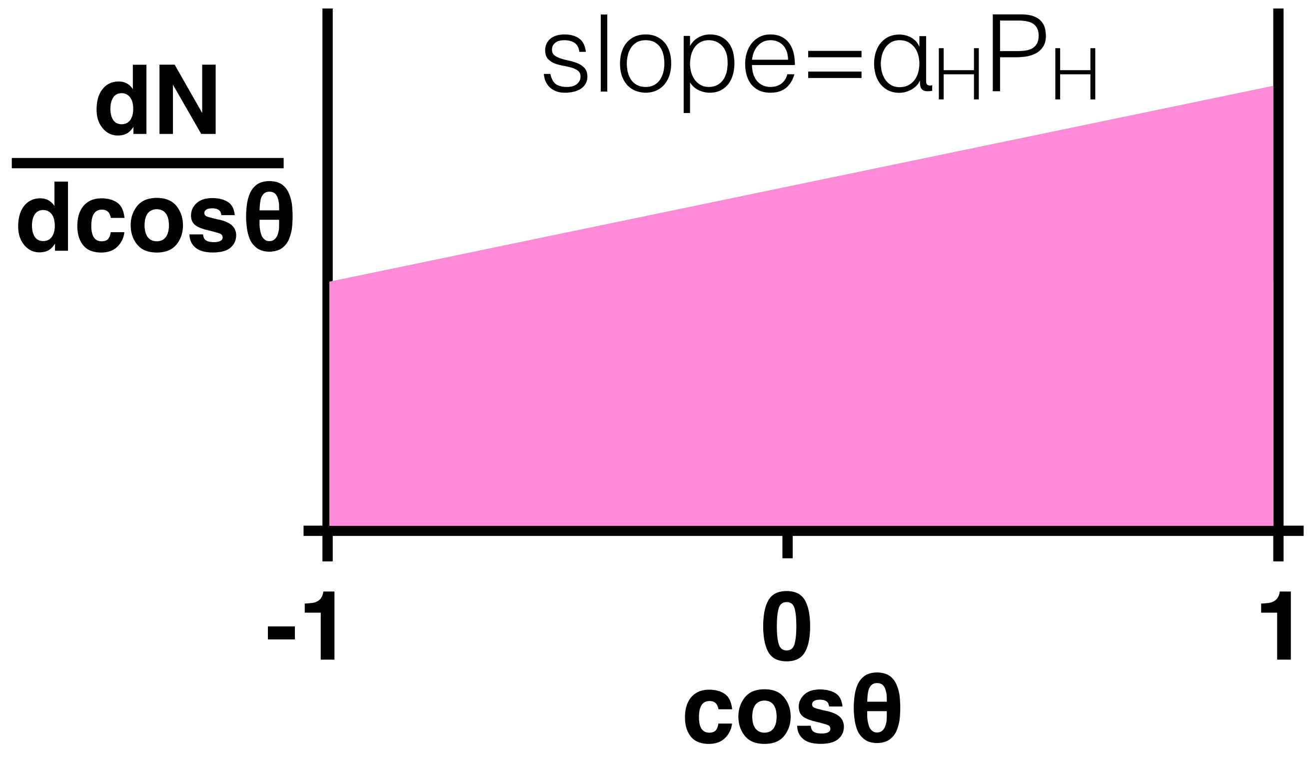
θ^*: polar angle of proton relative to the polarization direction in the Λ rest frame

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)





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Note: α_H recently updated by BESIII Collaboration

α_Λ=0.750±0.009, $\alpha_{\bar{\Lambda}}$=-0.758±0.010

M. Tanabashi et al., (PDG), Phys. Rev. D98, 030001 (2018) and 2019 update

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

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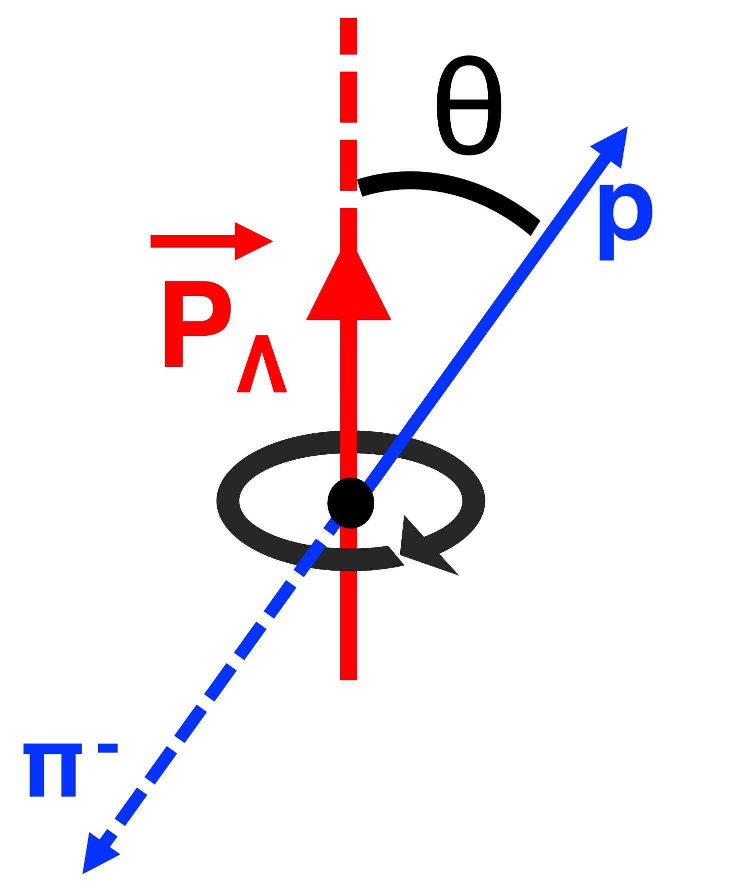
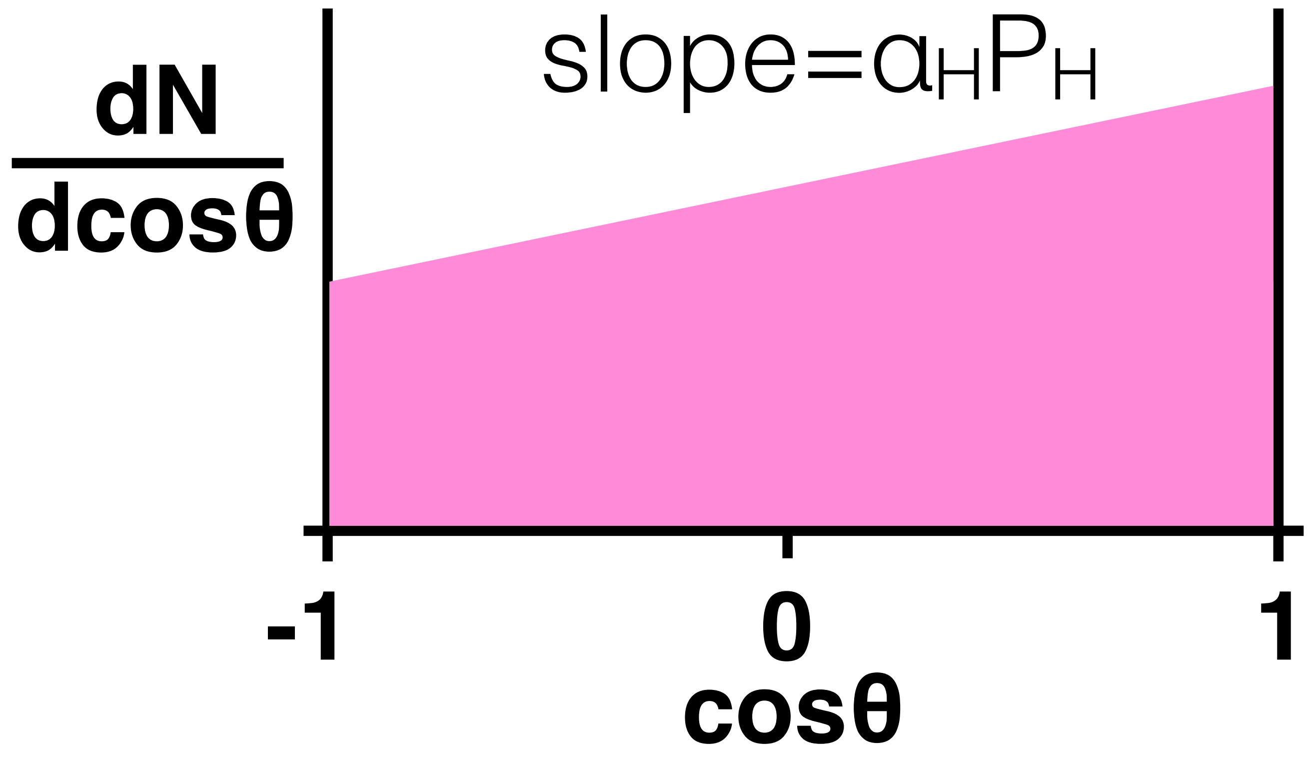
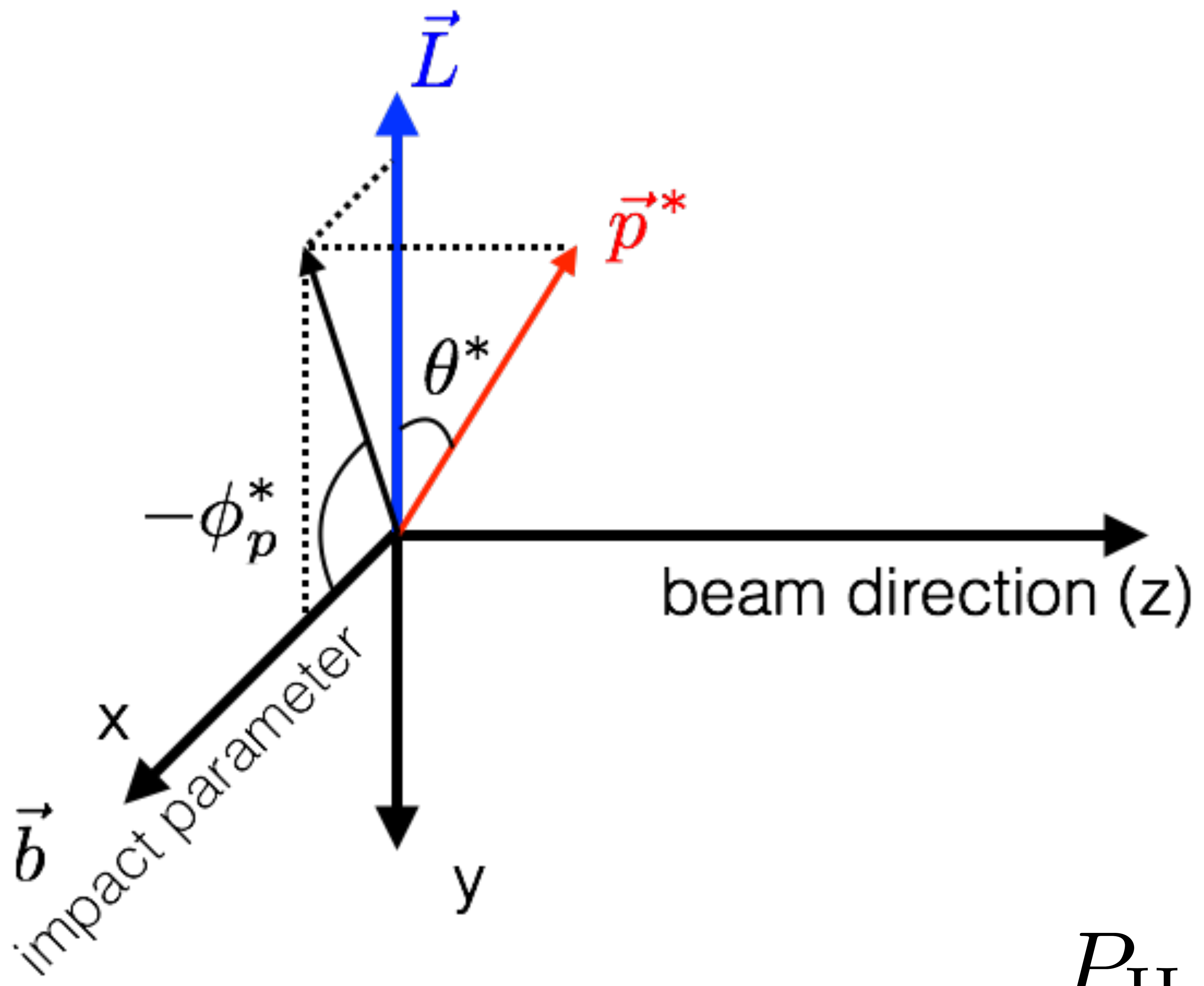


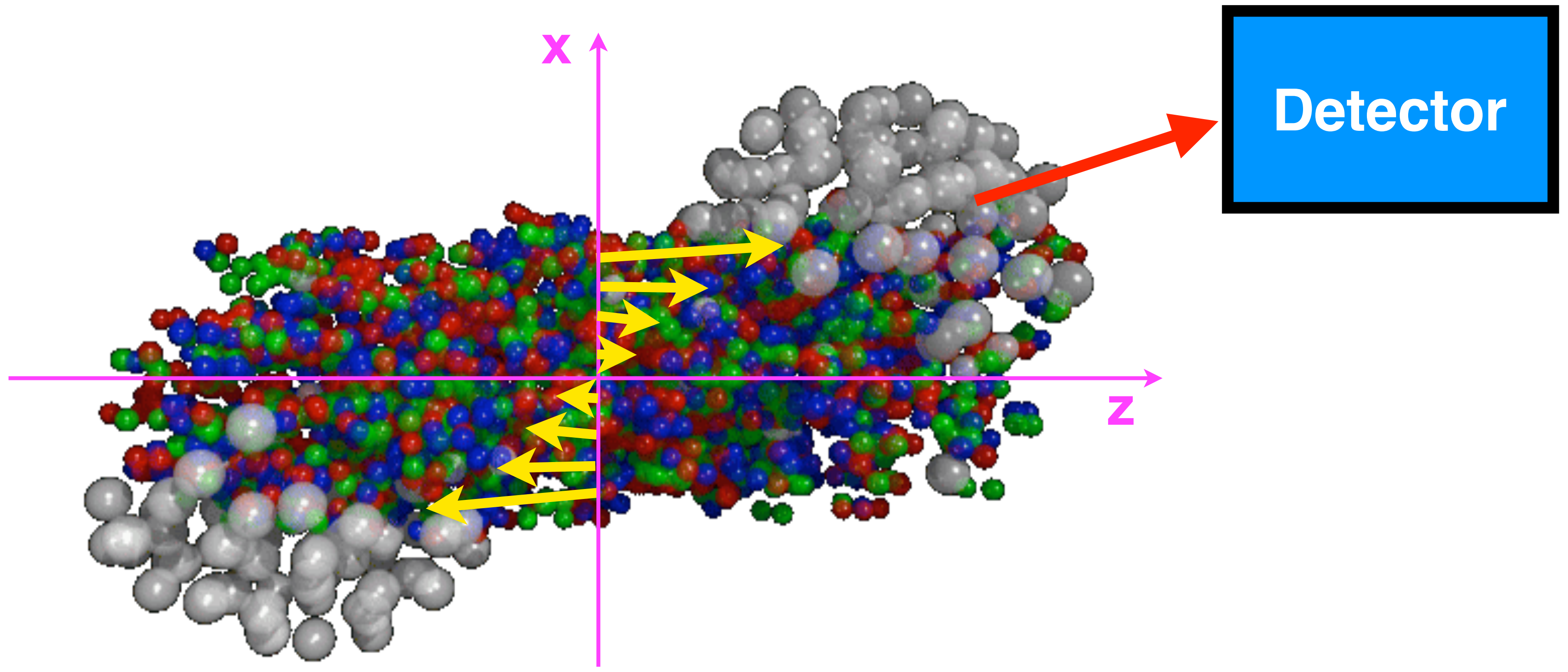


How to measure the "global" polarization?

"global" polarization : a net spin alignment along a specific direction

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)

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

Ψ_1: azimuthal angle of b

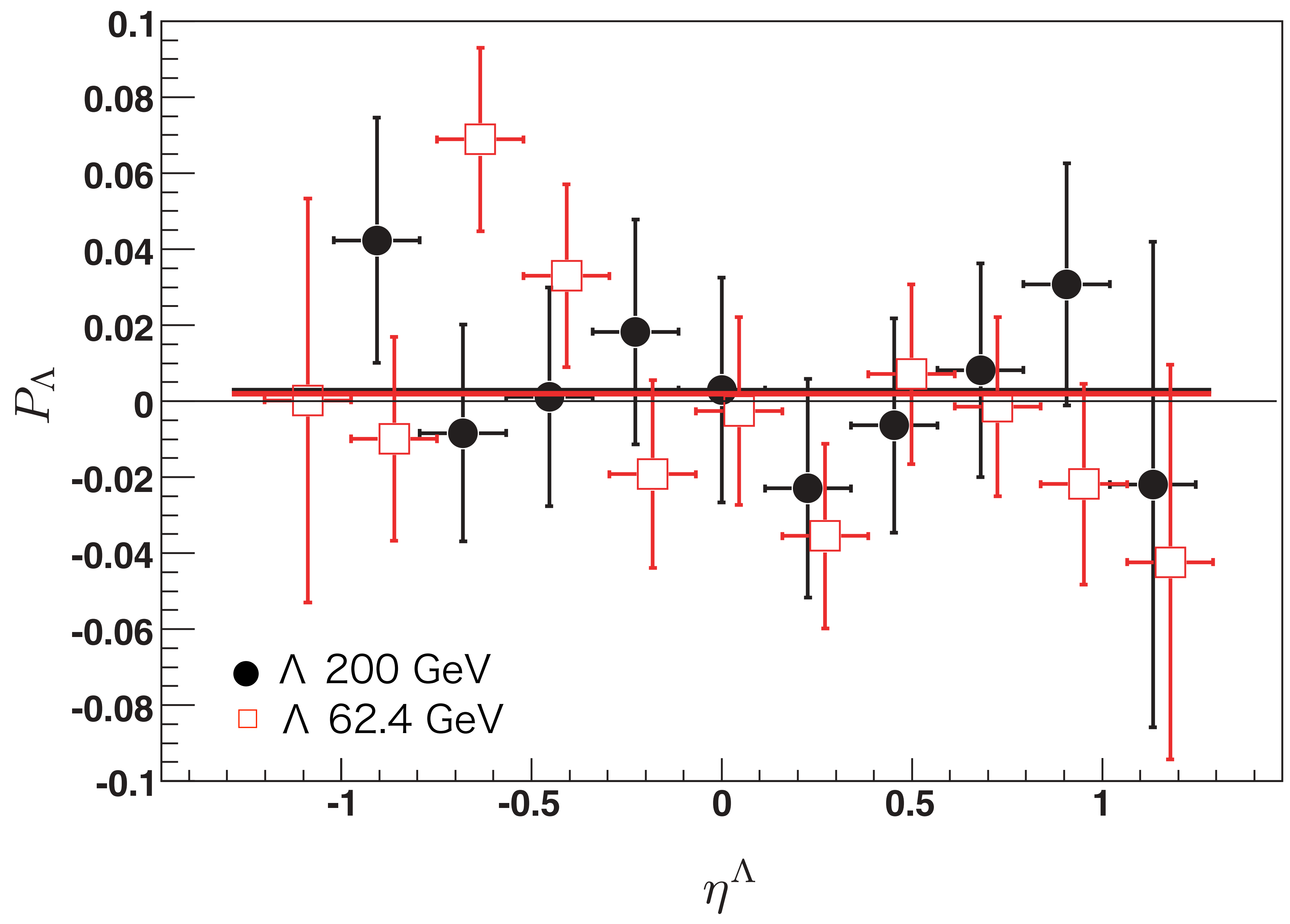
ϕ_p^*: ϕ of daughter proton in Λ rest frame

STAR, PRC76, 024915 (2007)

First paper from STAR in 2007

PHYSICAL REVIEW C **76**, 024915 (2007)

Global polarization measurement in Au+Au collisions



Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV in 2004 with very limited statistics (~9M events)

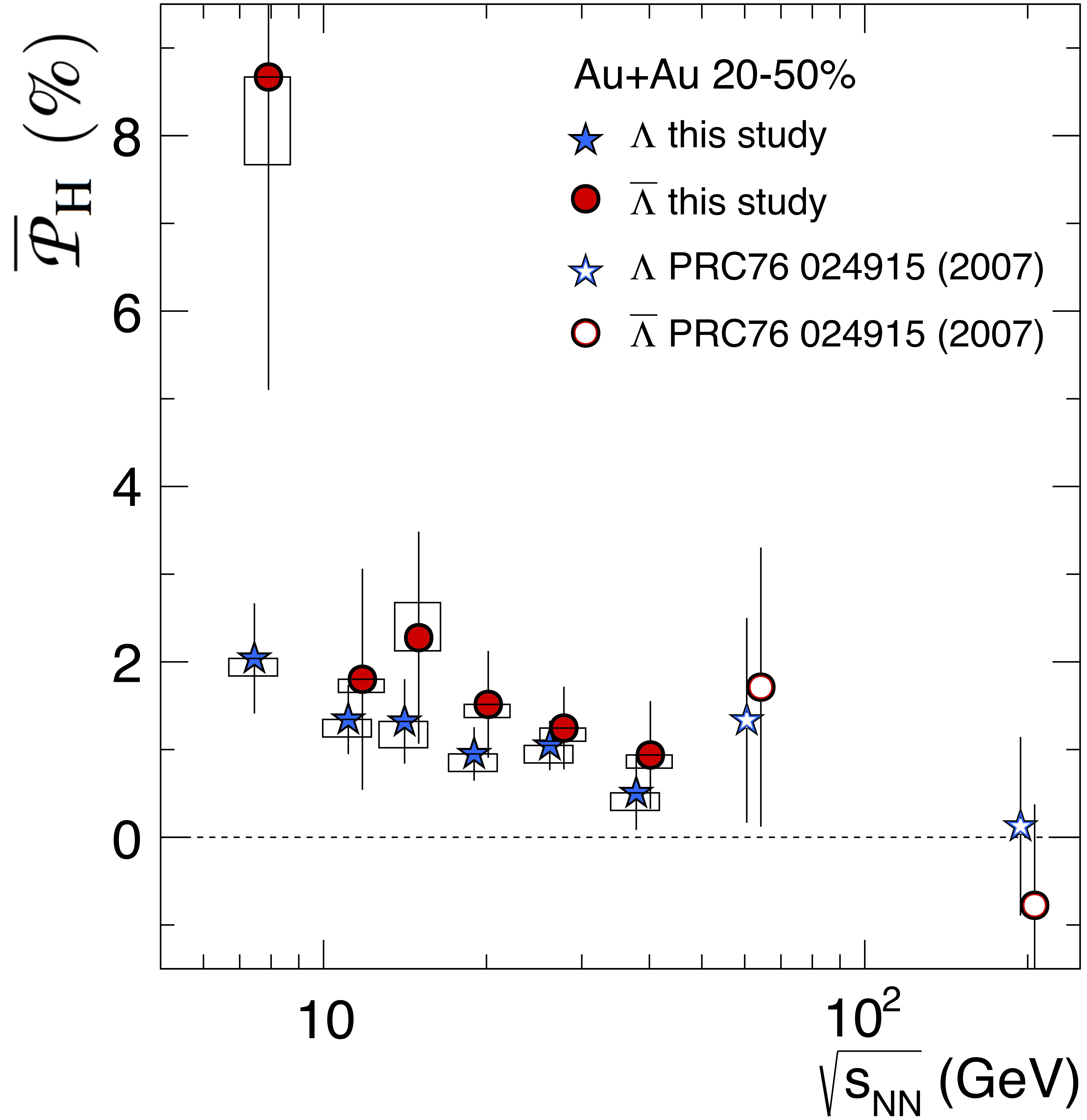
III. CONCLUSION

The Λ and $\bar{\Lambda}$ hyperon global polarization has been measured in Au+Au collisions at center-of-mass energies $\sqrt{s_{NN}} = 62.4$ and 200 GeV with the STAR detector at RHIC. An upper limit of $|P_{\Lambda,\bar{\Lambda}}| \leqslant 0.02$ for the global polarization of Λ and $\bar{\Lambda}$ hyperons within the STAR detector acceptance is

Results were consistent with zero…, giving an upper limit of P_H<2%

First observation in BES-I

STAR, Nature 548, 62 (2017)



Positive polarization signal at lower energies!

-- The most vortical fluid!

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

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

$$\sim 0.6\text{-}2.7 \times 10^{22} \mathrm{s}^{-1} \quad \text{(T=160 MeV)}$$

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- P_H looks to increase in lower energies

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

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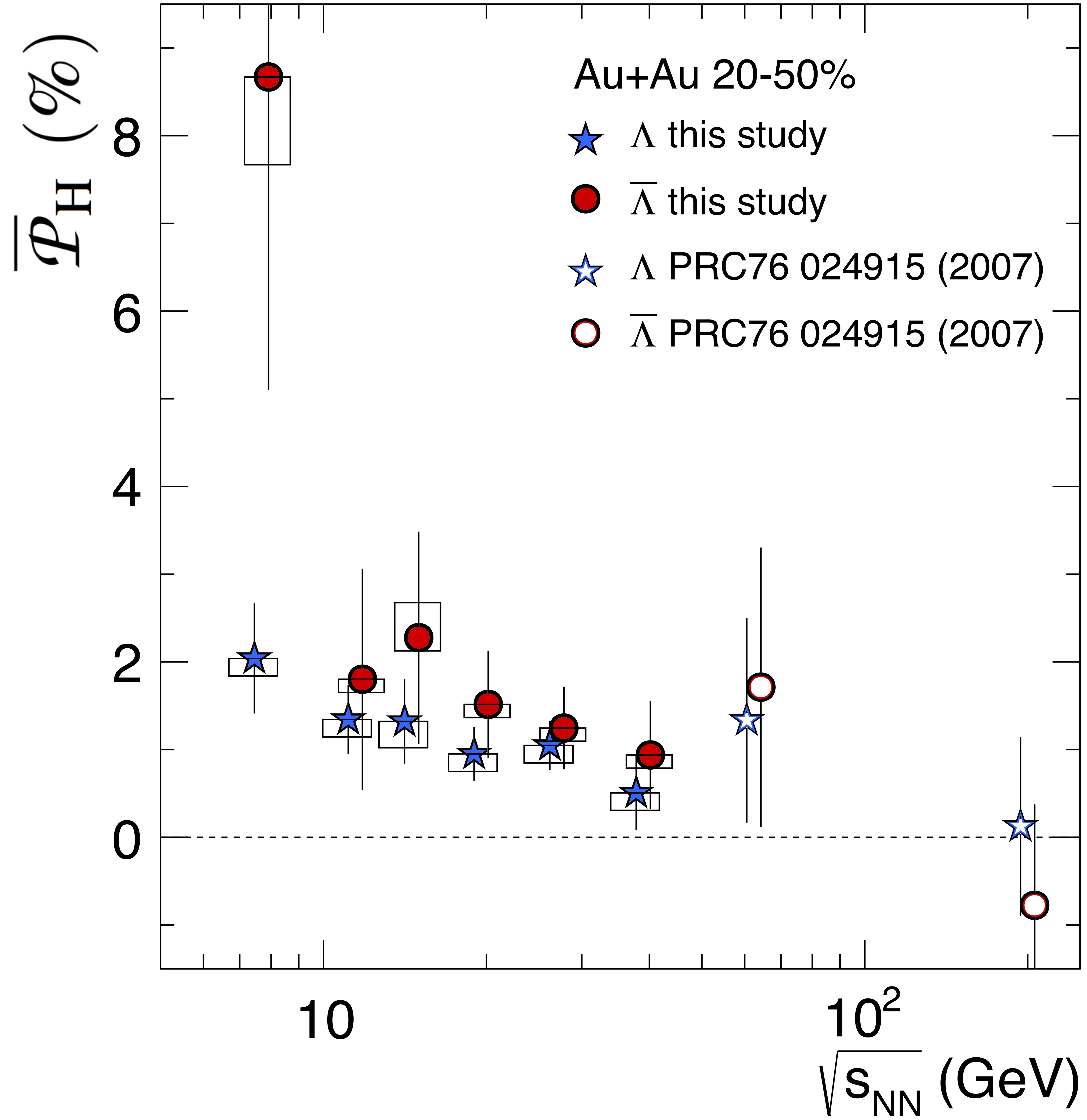

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- P_H looks to increase in lower energies

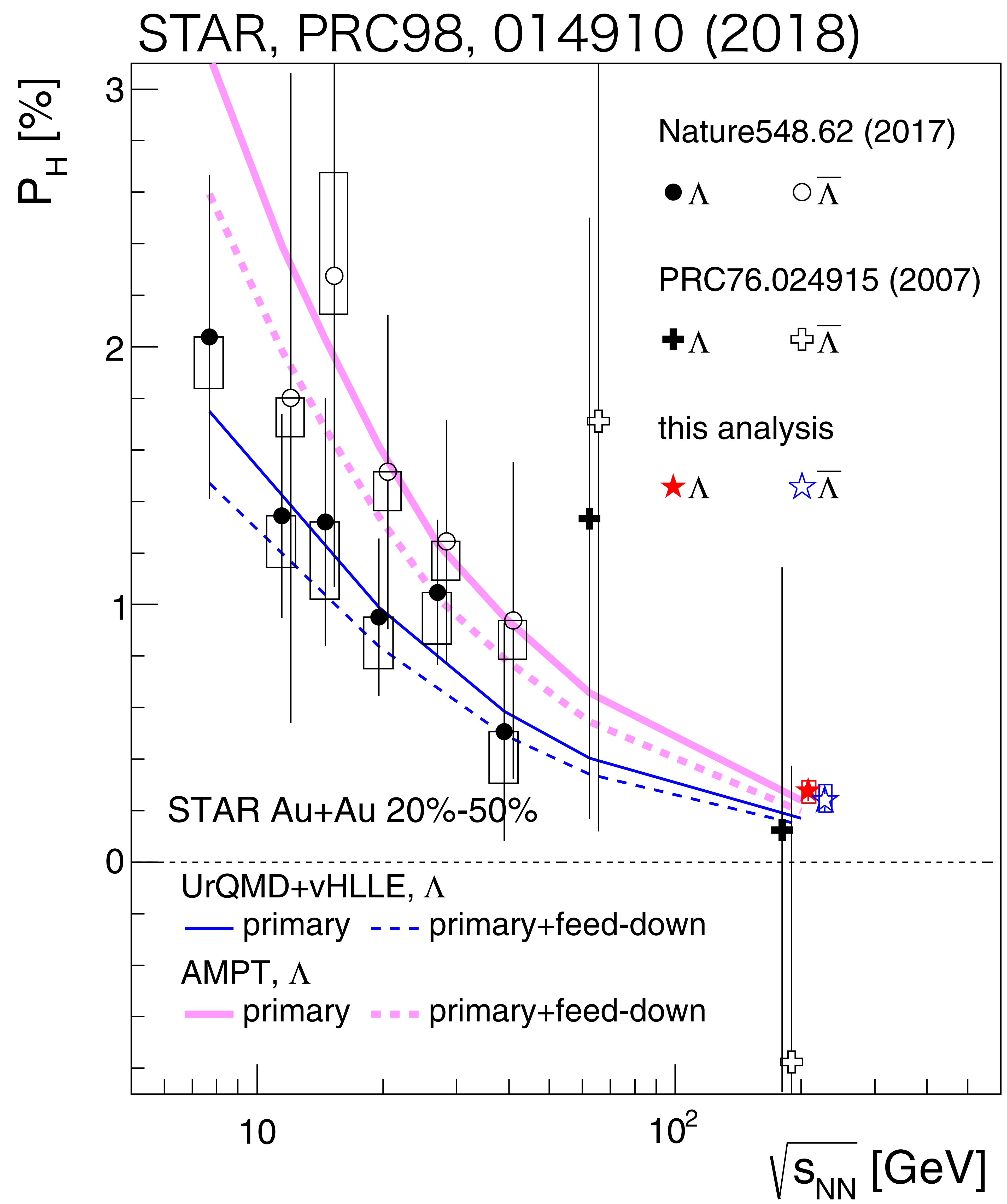
- Hint of the difference in P_H between Λ and anti-Λ
  -- Effect of the initial magnetic field? → BESII

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

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

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

Precise measurements at $\sqrt{s_{NN}}$ = 200 GeV



- Confirmed energy dependence of P_H with new results for 200 GeV
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  - partly due to stronger shear flow structure in lower $\sqrt{s_{NN}}$ because of baryon stopping

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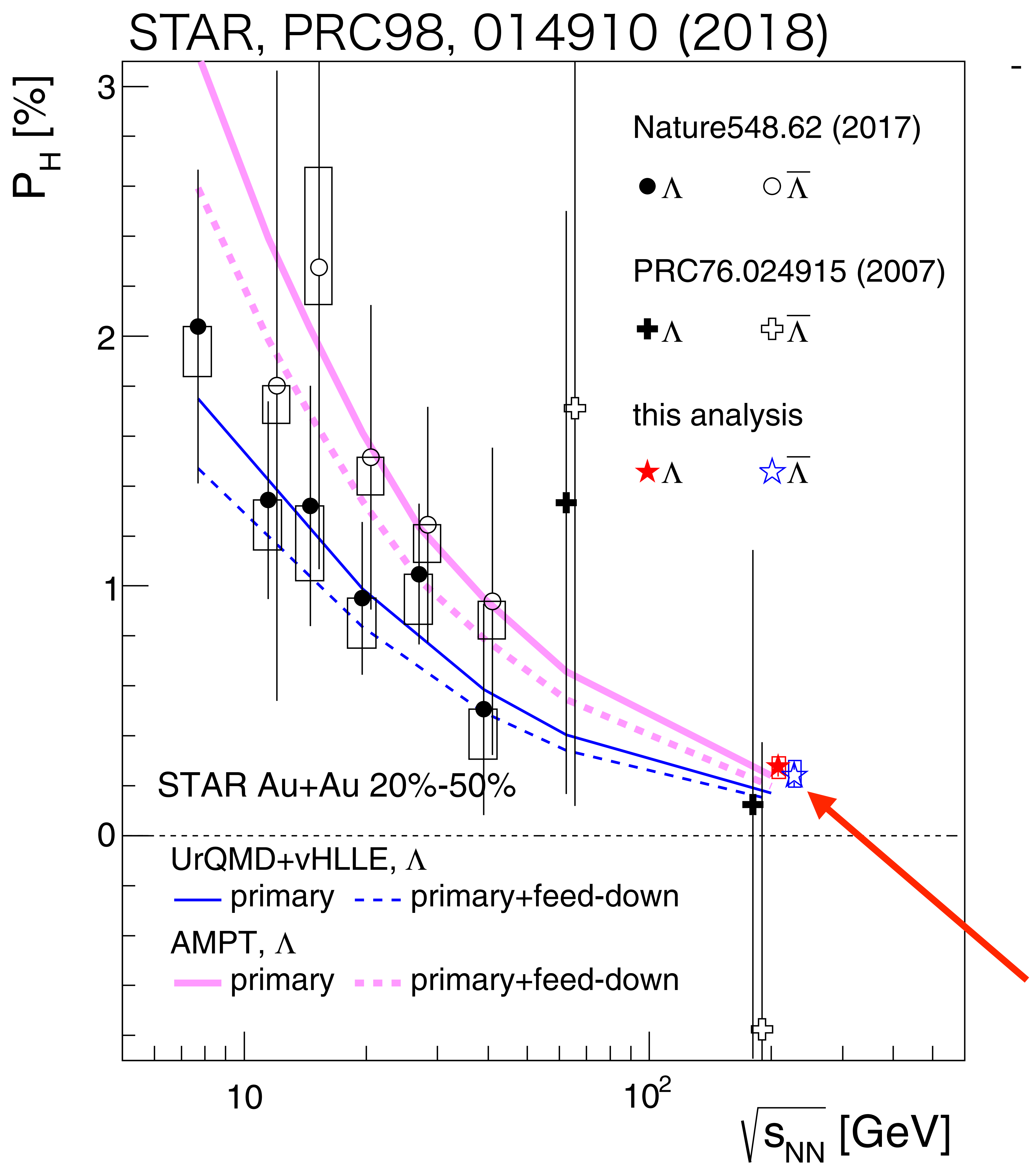

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$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}\ (\mathrm{sys})$$

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

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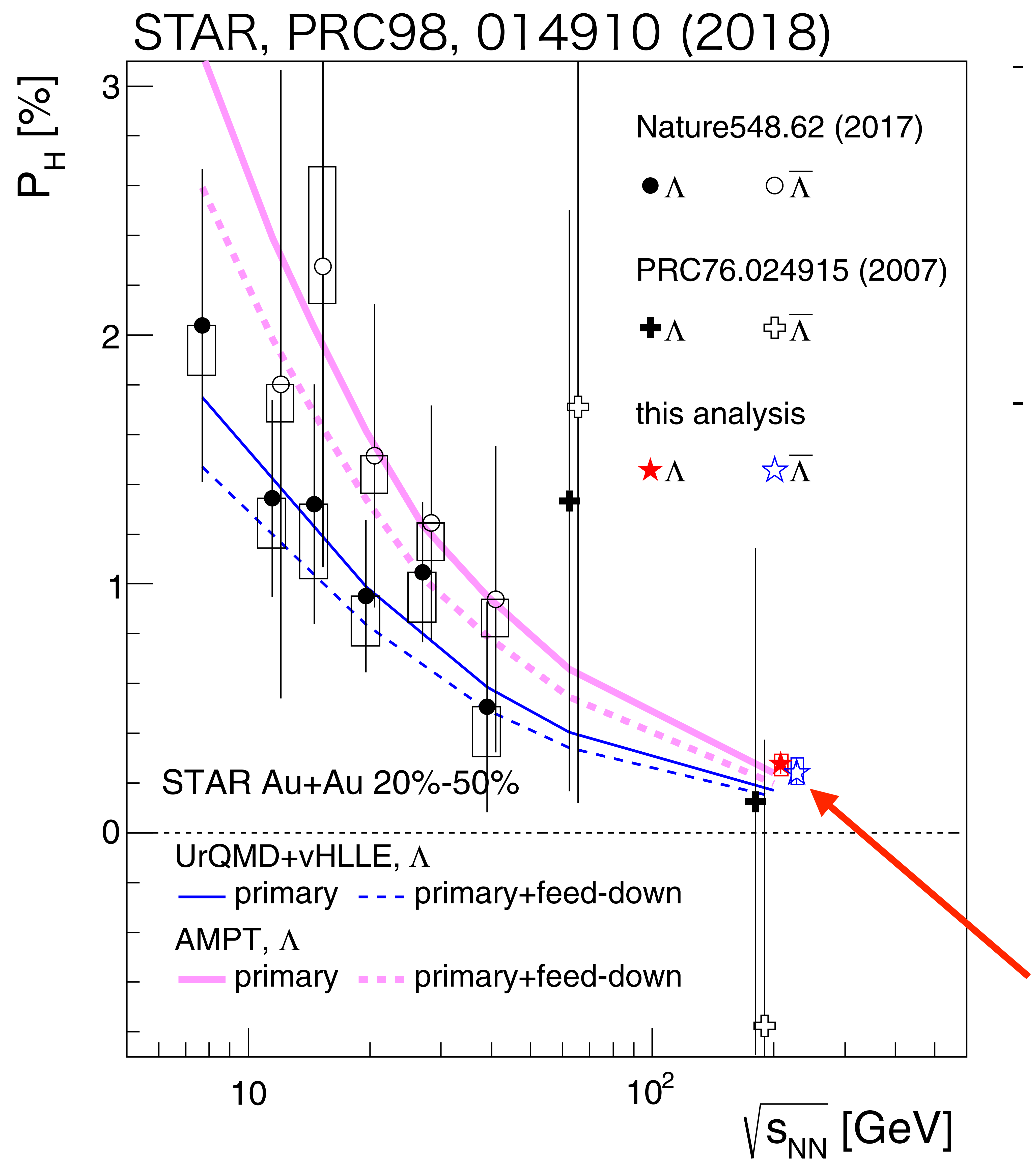

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- Theoretical models can describe the data well

  I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
  H. Li et al., PRC96, 054908 (2017), AMPT
  Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
  Y. Xie et al., PRC95, 031901(R) (2017), PICR
  D.-X. Wei et al., PRC99, 014905 (2019), AMPT

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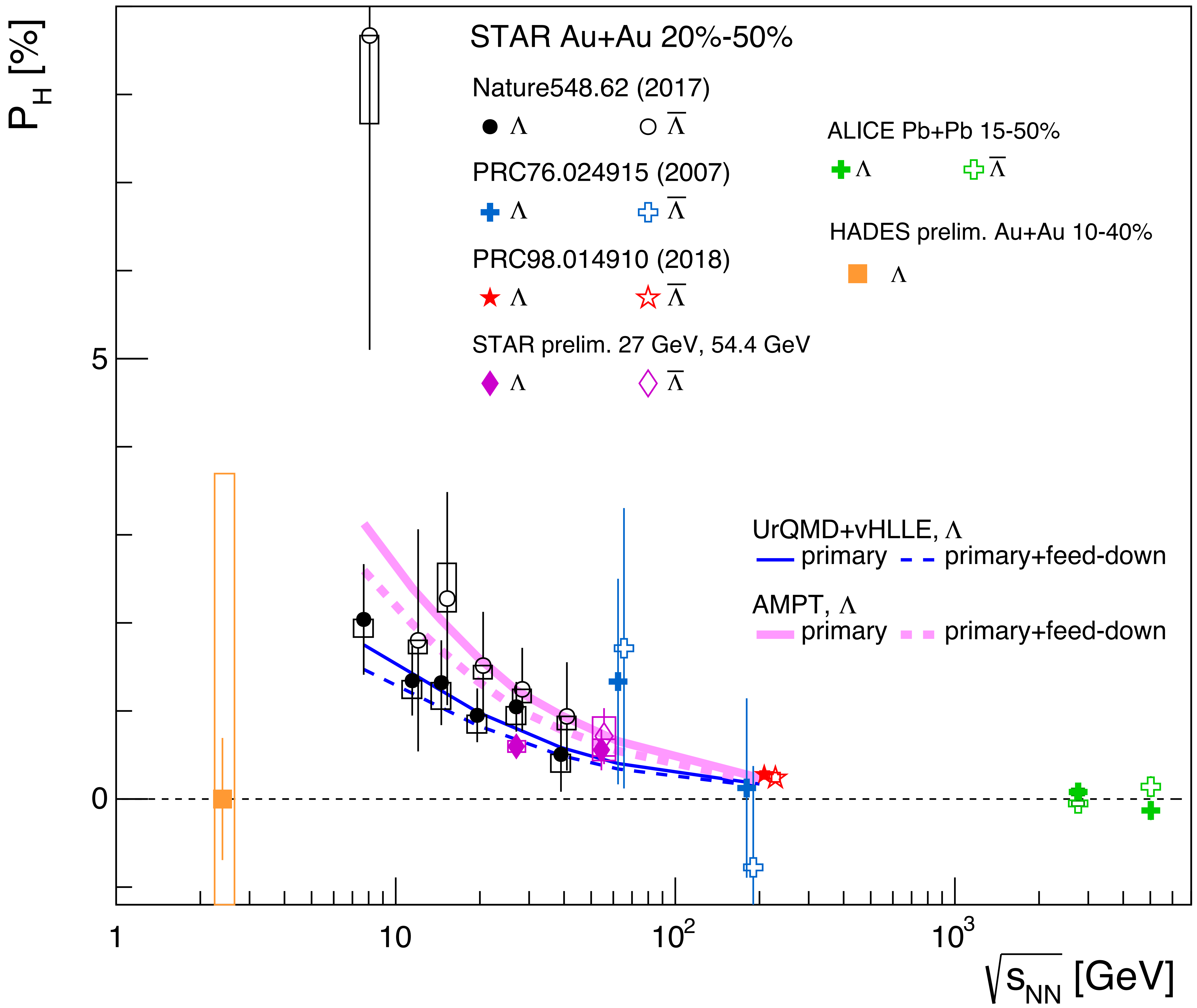
Collection of recent results

ALICE, arXiv1909.01281
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019



- **STAR** Au+Au at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV (preliminary)

- **ALICE** Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

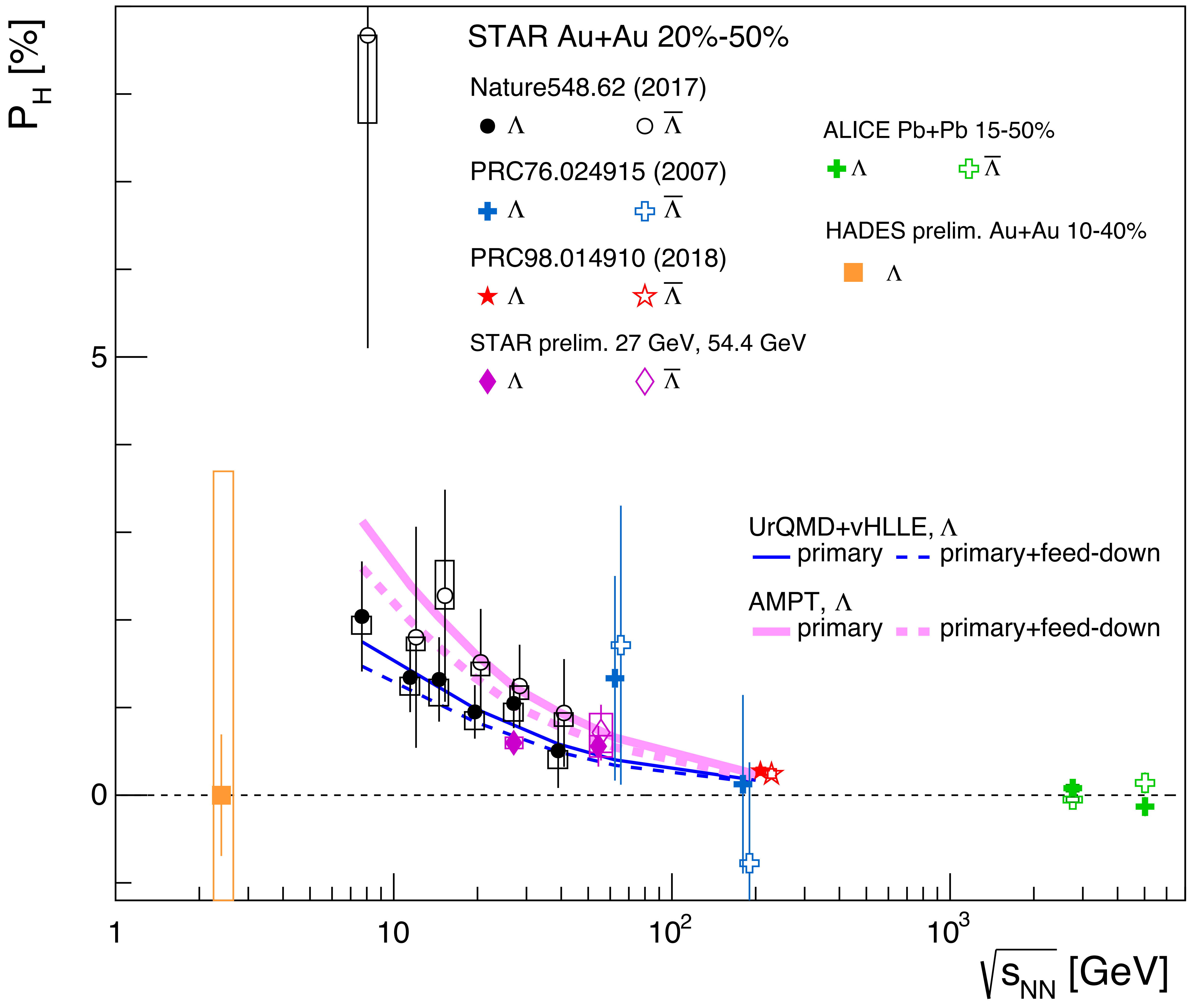
$$\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$$
$$P_H(\Lambda)\ [\%] = 0.08 \pm 0.10(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$$
$$P_H(\bar{\Lambda})\ [\%] = -0.05 \pm 0.10(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$$
$$\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$$
$$P_H(\Lambda)\ [\%] = -0.13 \pm 0.11(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.14 \pm 0.12(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$$

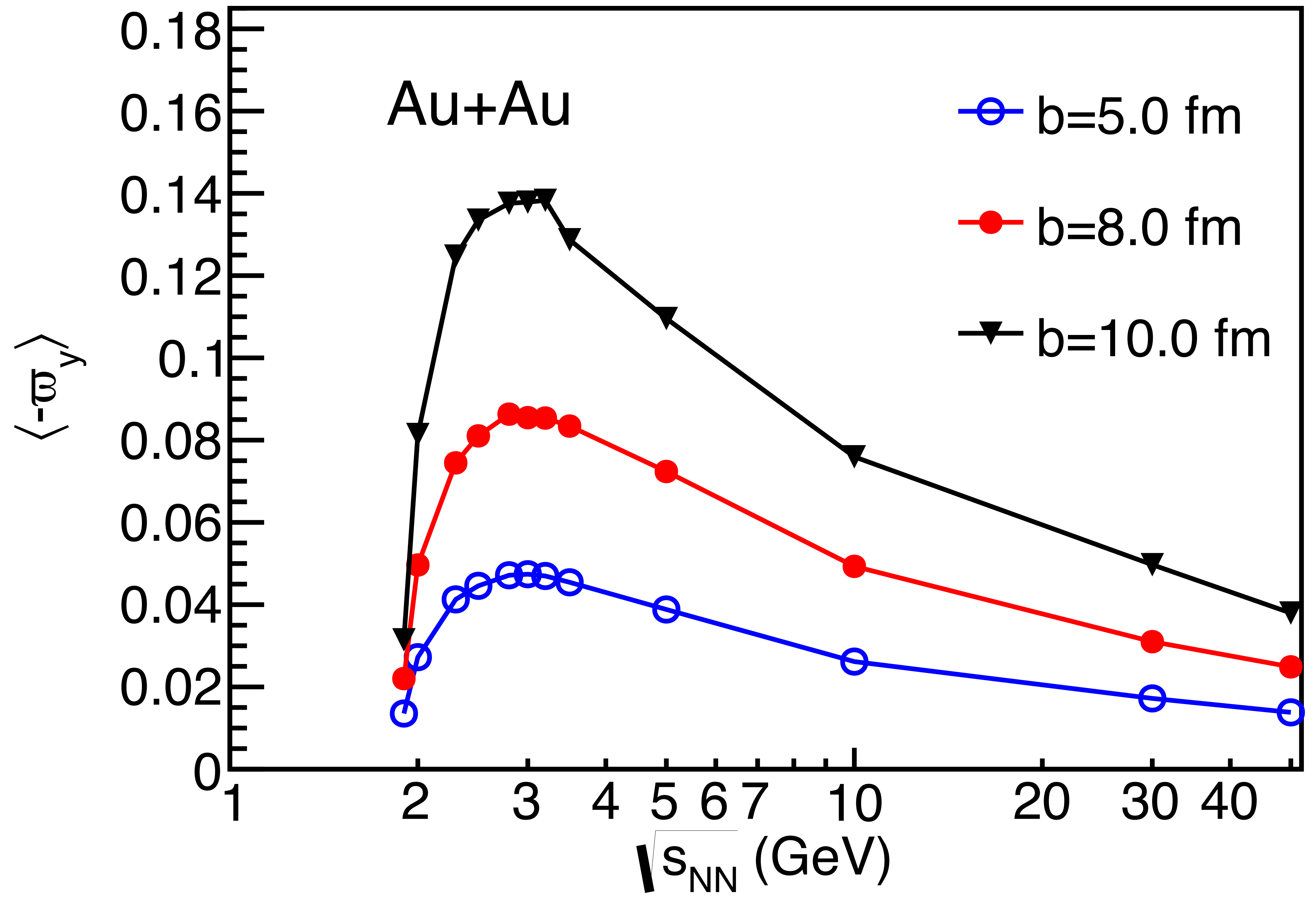
- **HADES** Au+Au at $\sqrt{s_{NN}}$ = 2.4 GeV (preliminary)

$$P_H(\Lambda)[\%] = 3.672 \pm 0.699\ (\mathrm{stat.})$$
$$P_H^{\mathrm{BG}}[\%] = 3.689 \pm 1.133\ (\mathrm{stat.})$$

Collection of recent results

ALICE, arXiv1909.01281
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019





Interesting energy dependence of thermal vorticity (UrQMD)
X.-G. Deng et al., arXiv:2001.01371

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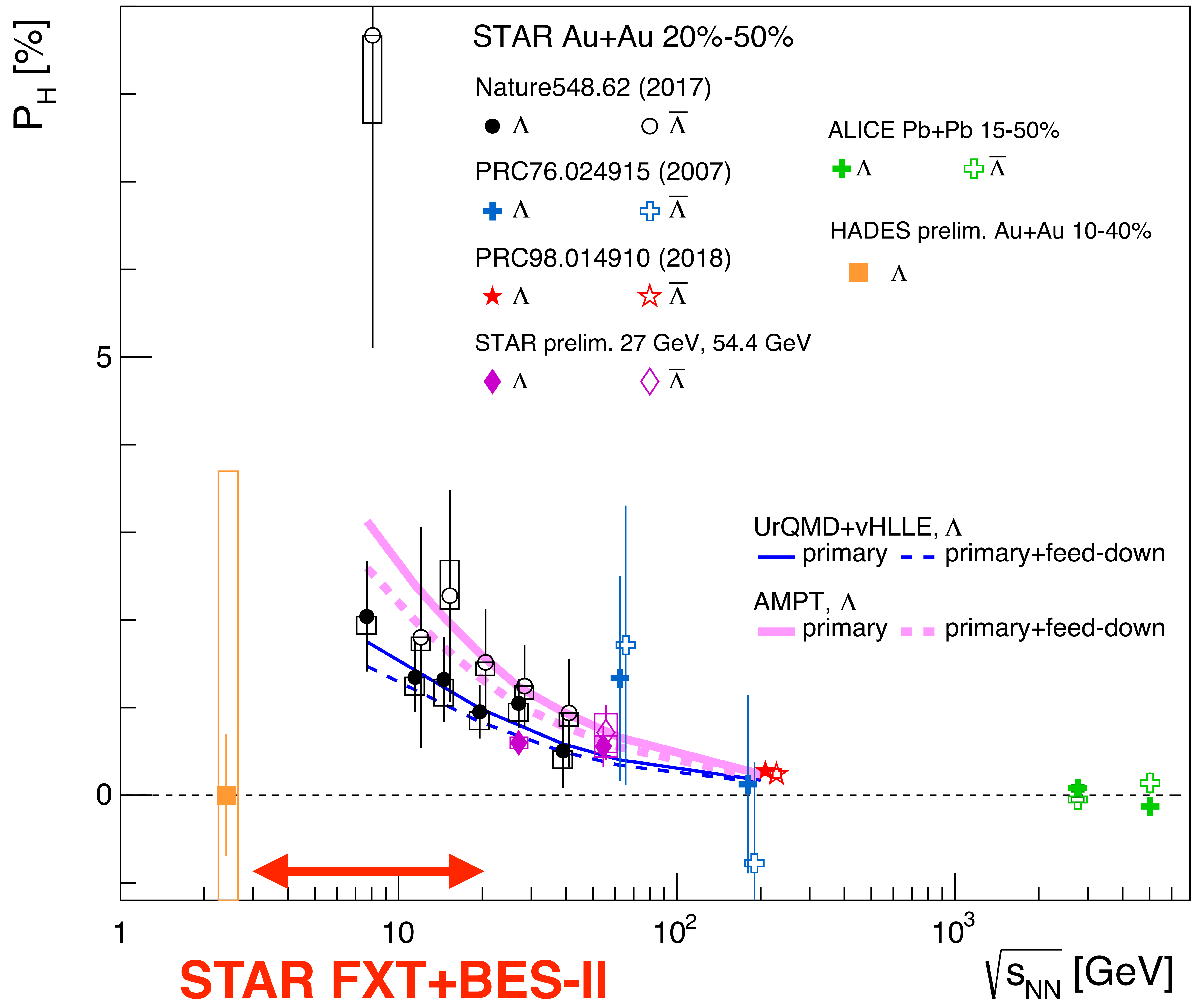
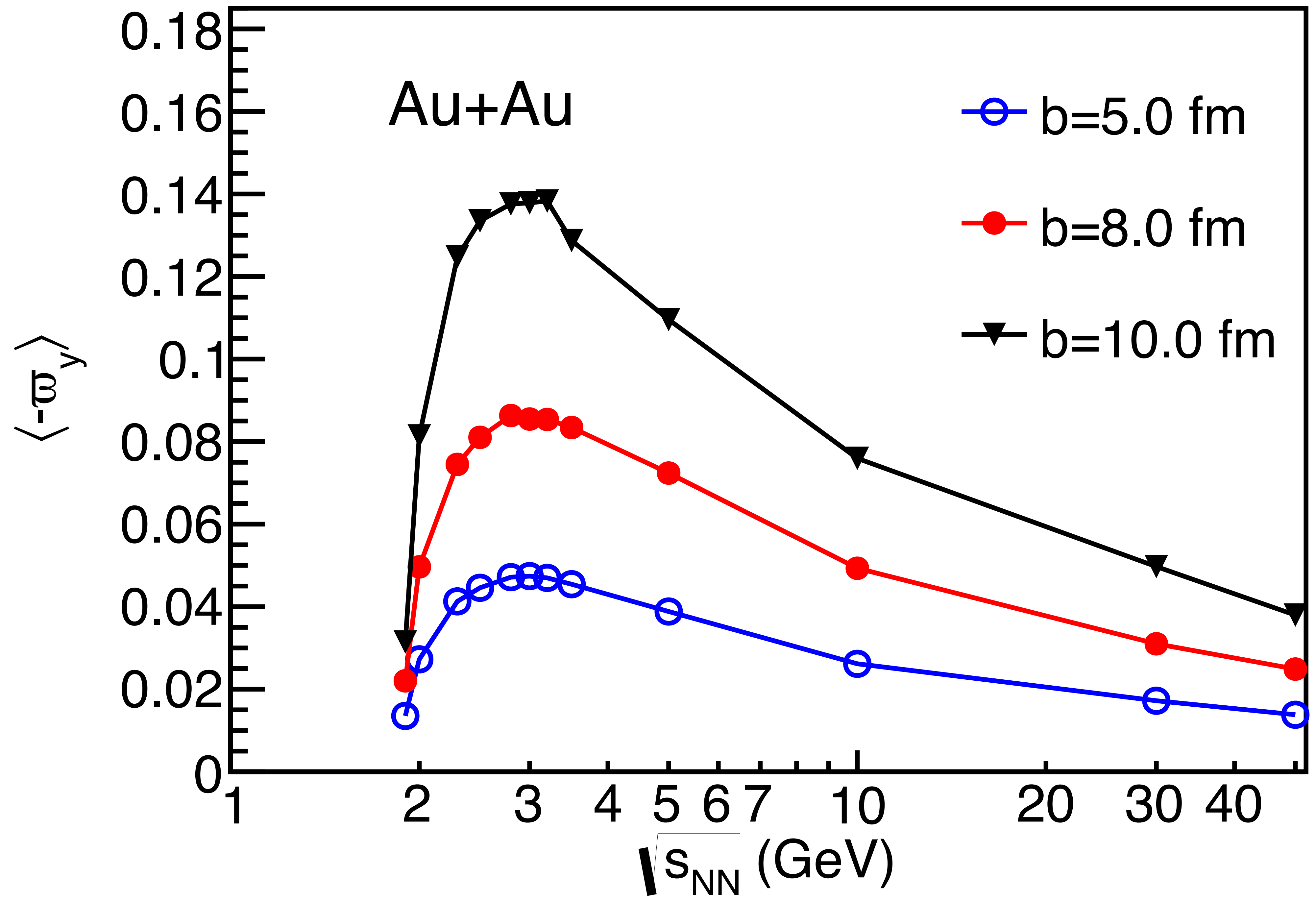


STAR FXT+BES-II
(ongoing now)



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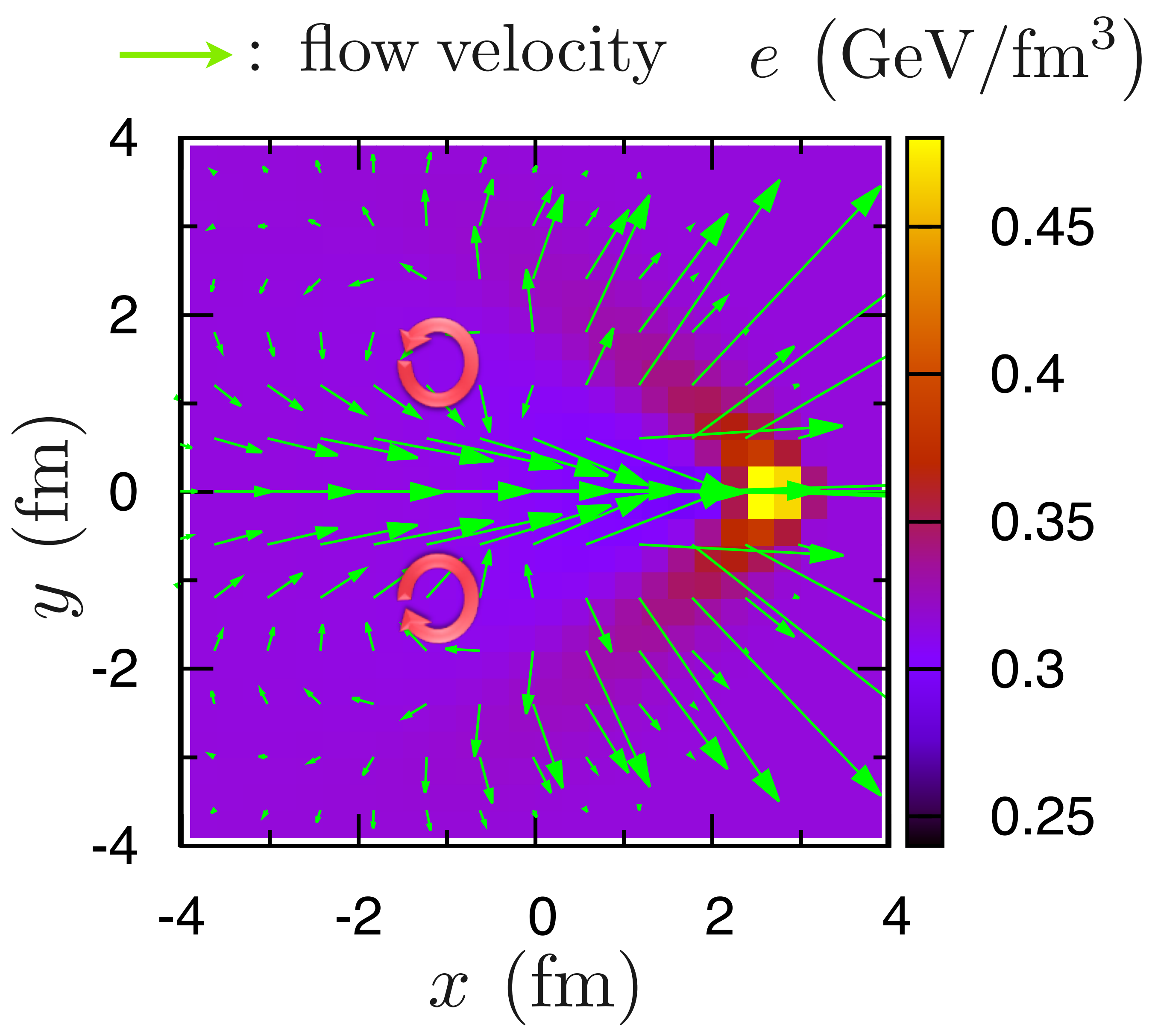
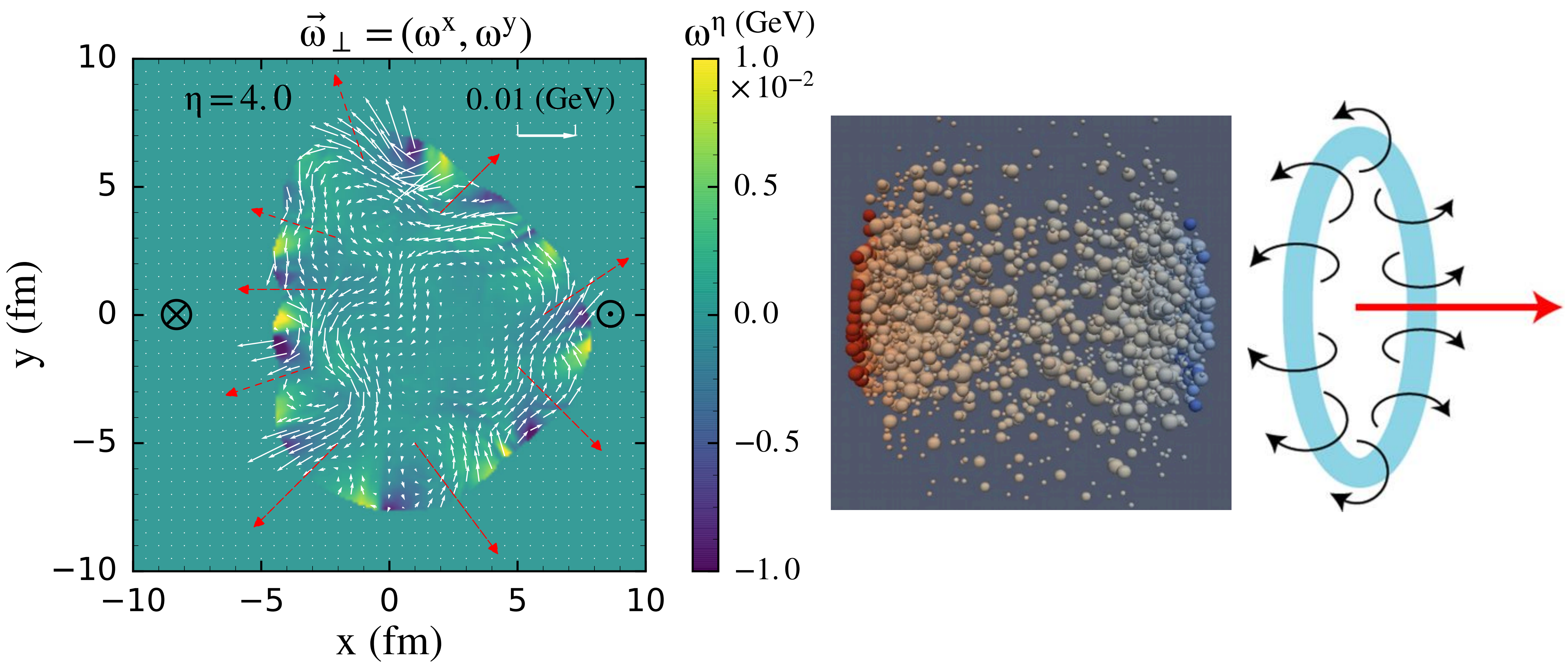
More interesting results will come!

Local vorticity

Vortex induced by jet

Local vorticity induced by collective flow





Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023
B. Betz, M. Gyulassy, and G. Torrieri, PRC76.044901 (2007)

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X.-L. Xia et al., PRC98.024905 (2018)

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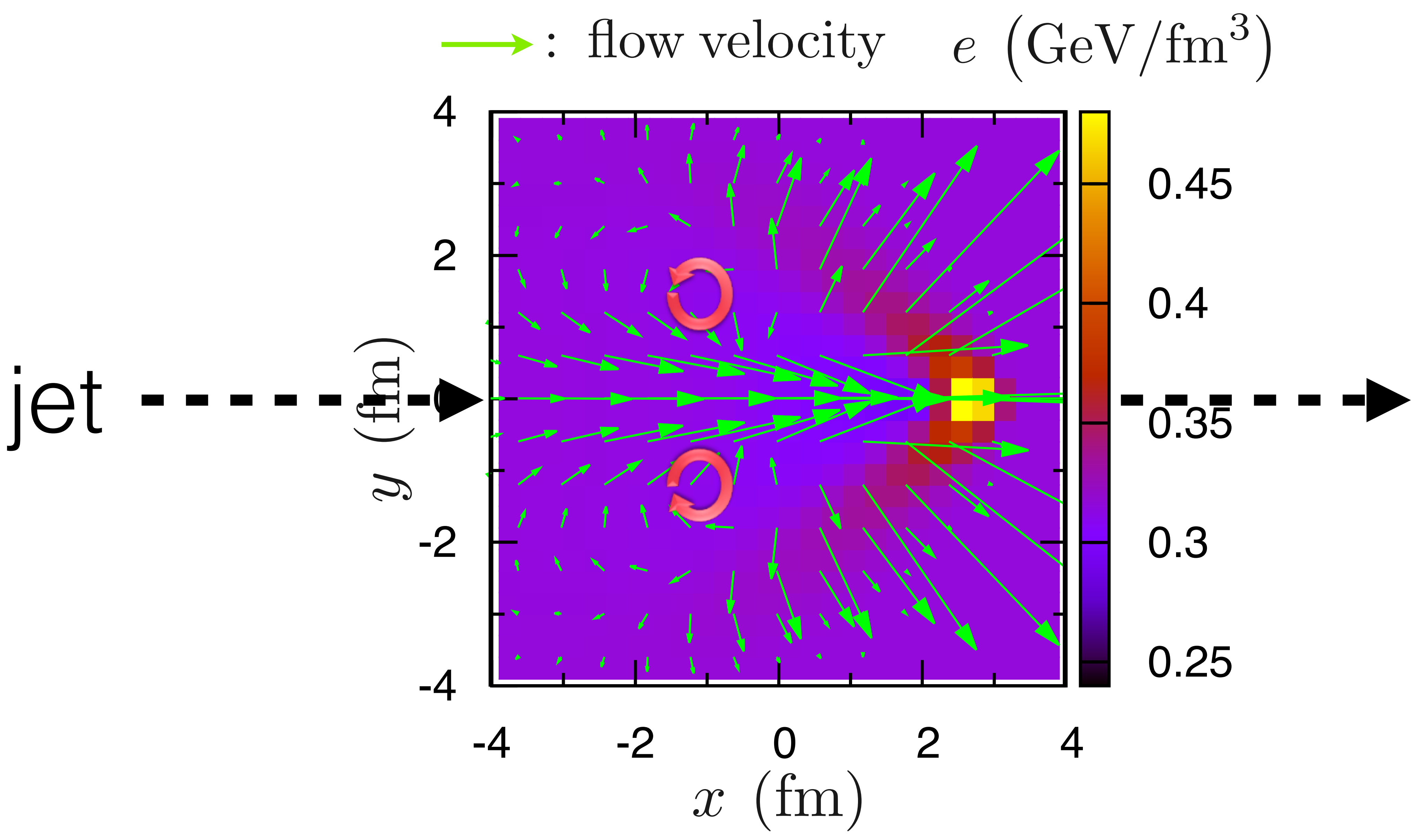

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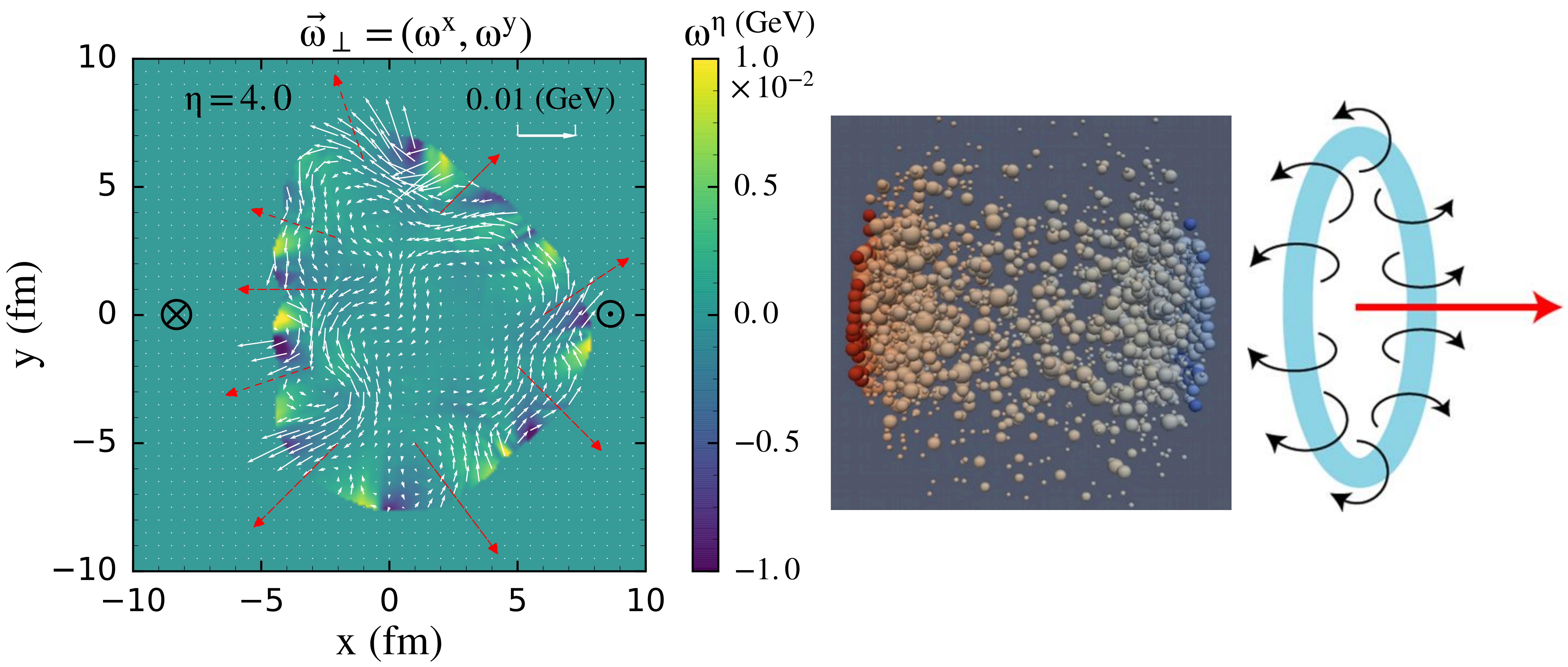

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Local vorticity due to the elliptic flow?

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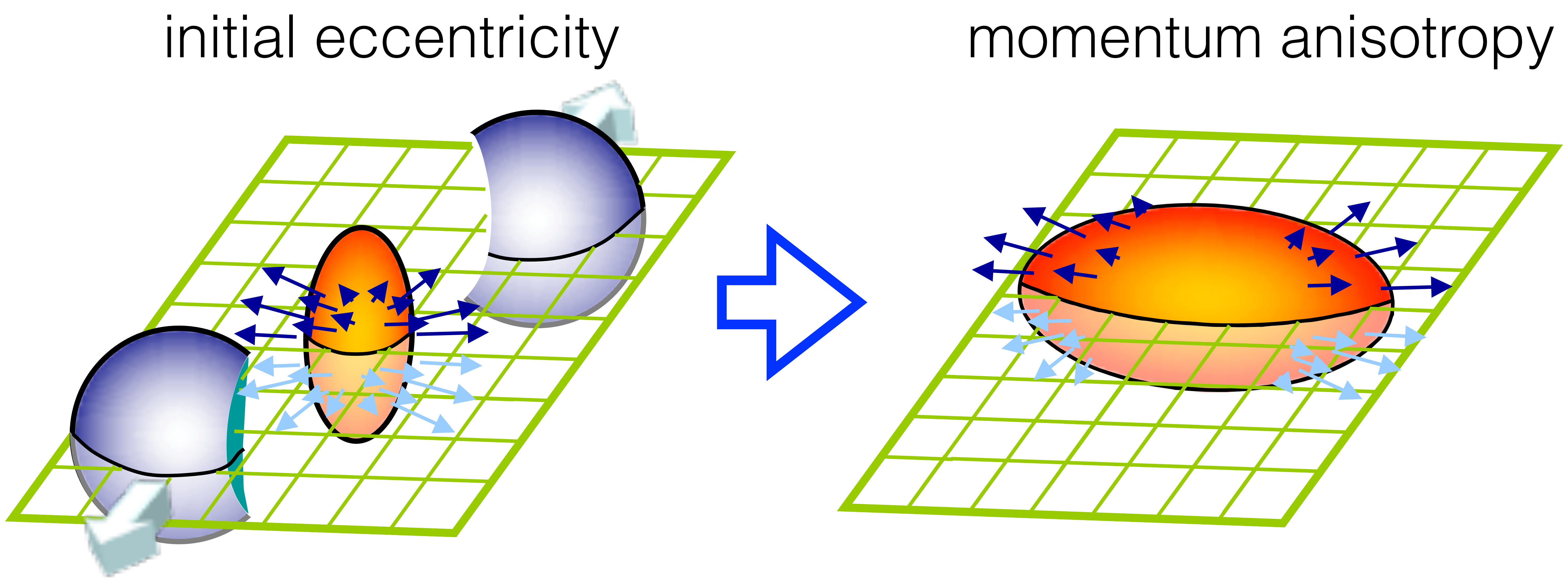

Stronger flow in in-plane (short-axis) than in out-of-plane (long axis) due to different pressure gradient, called the elliptic flow

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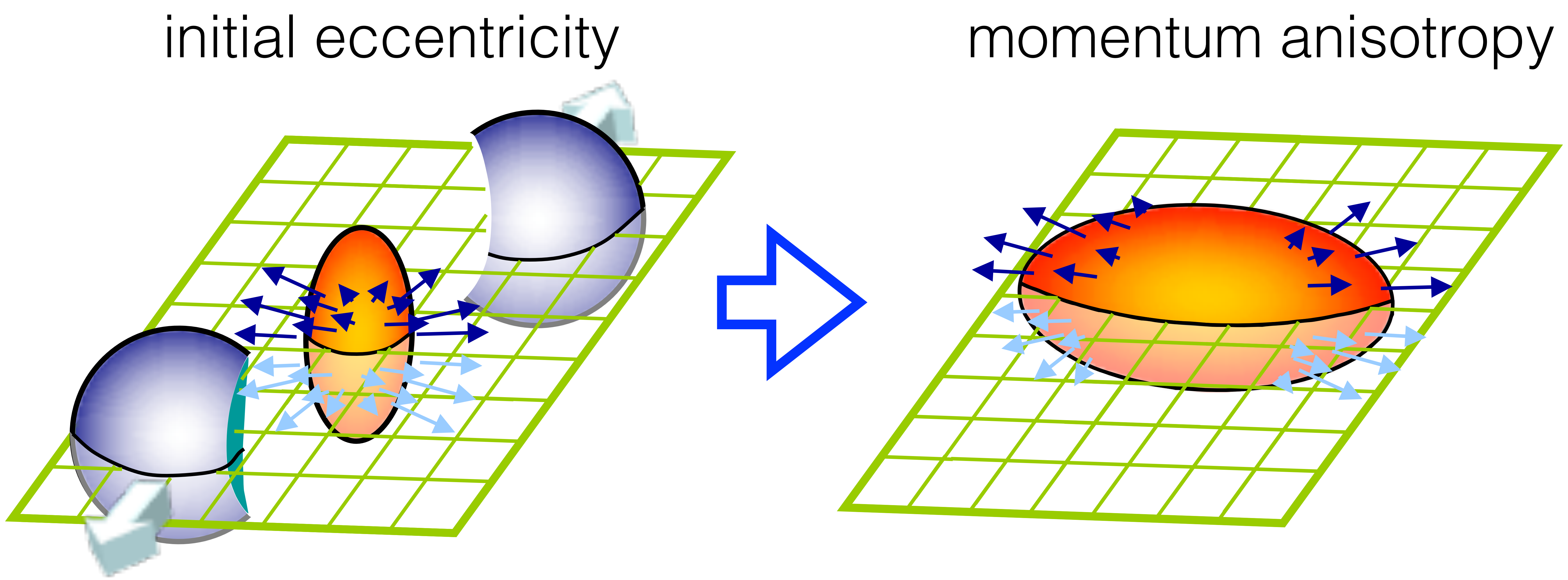

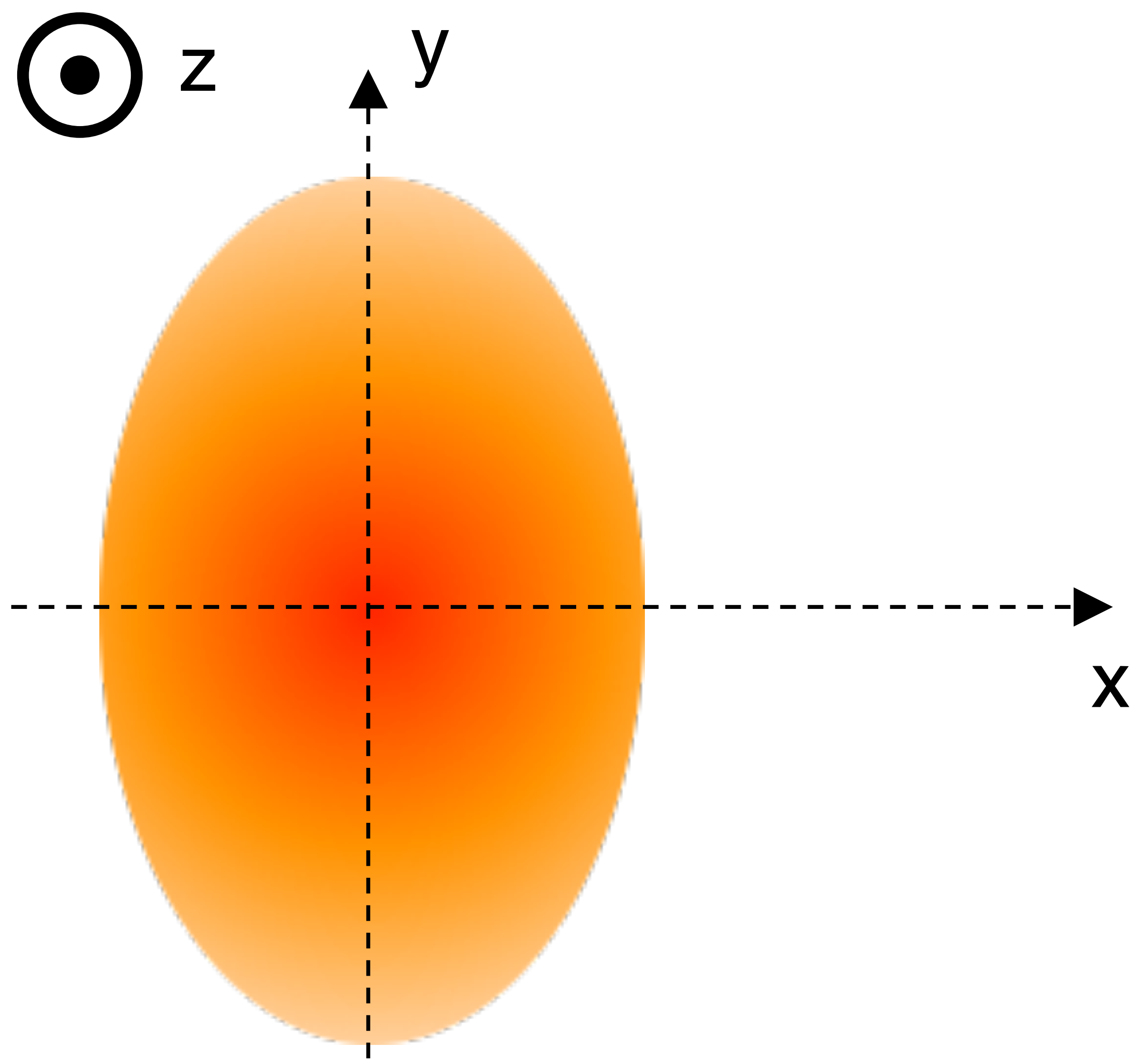

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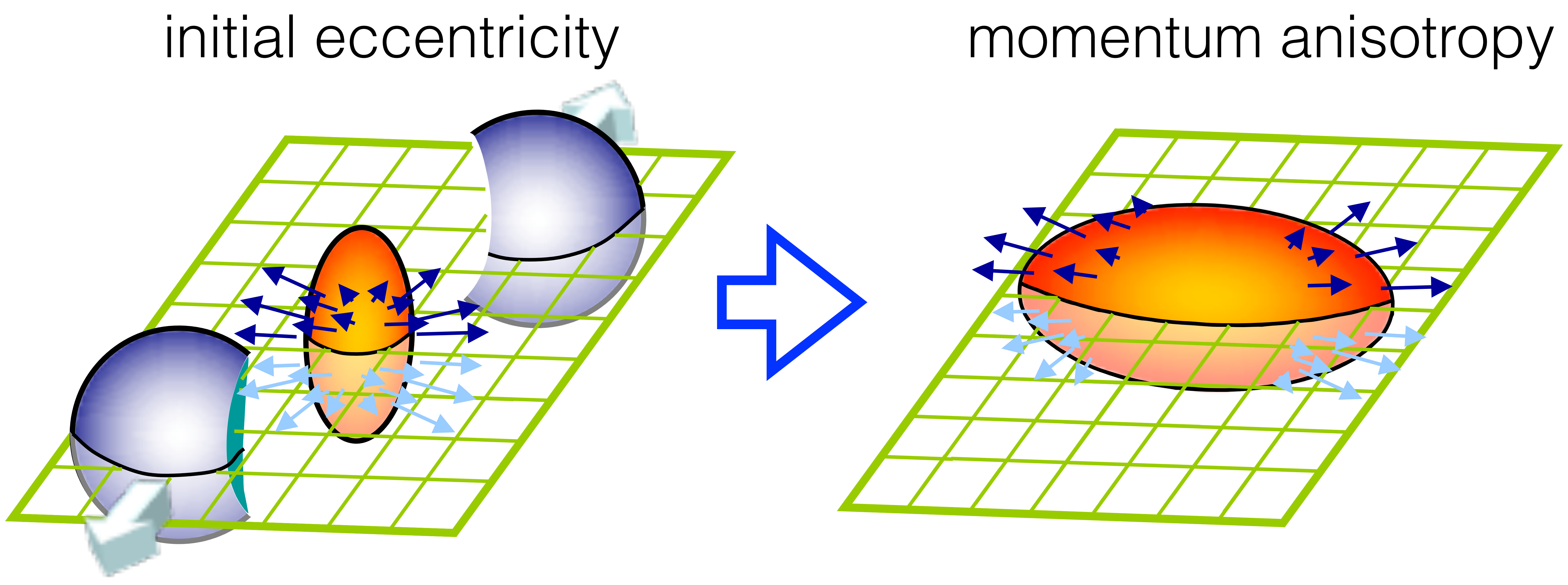

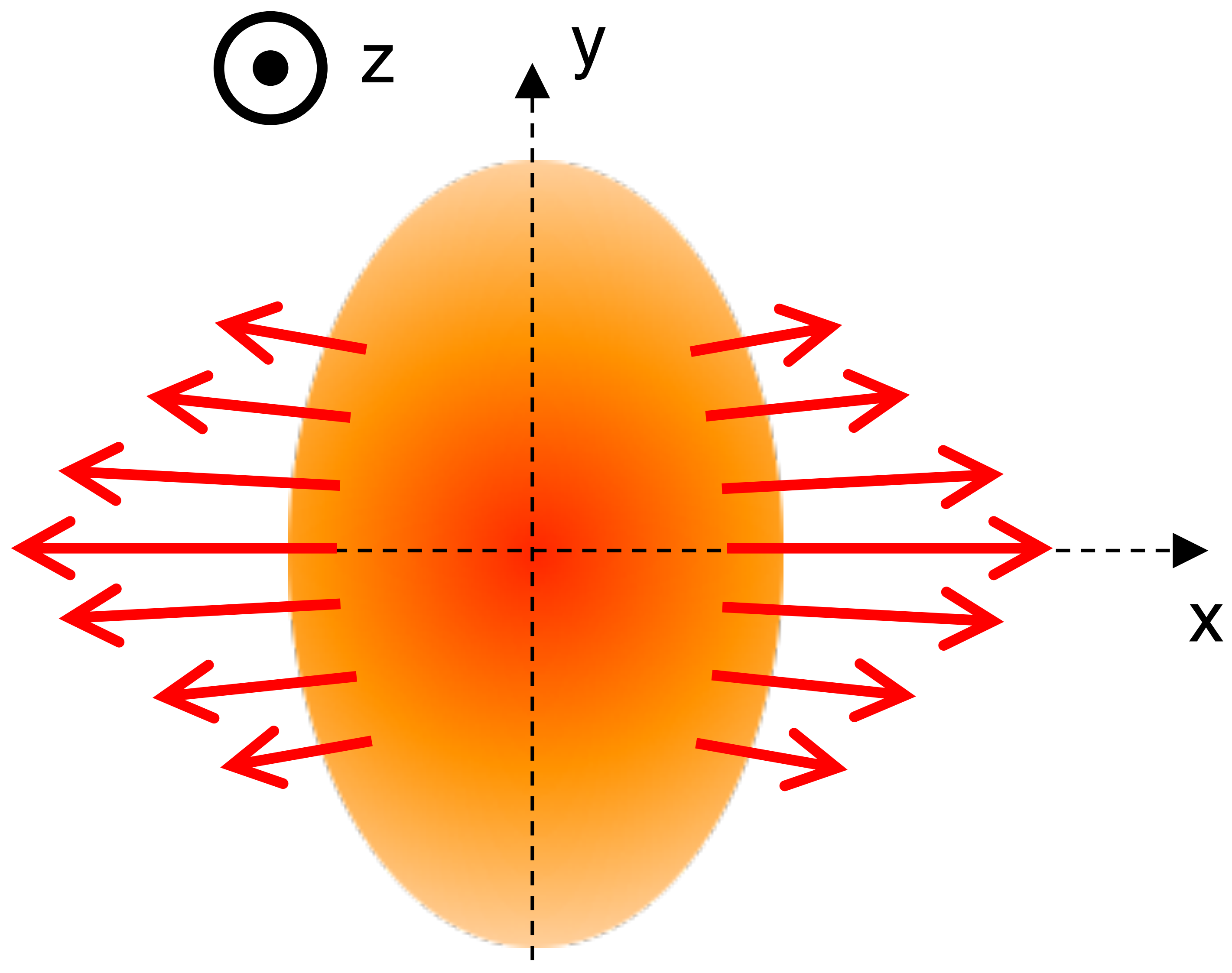

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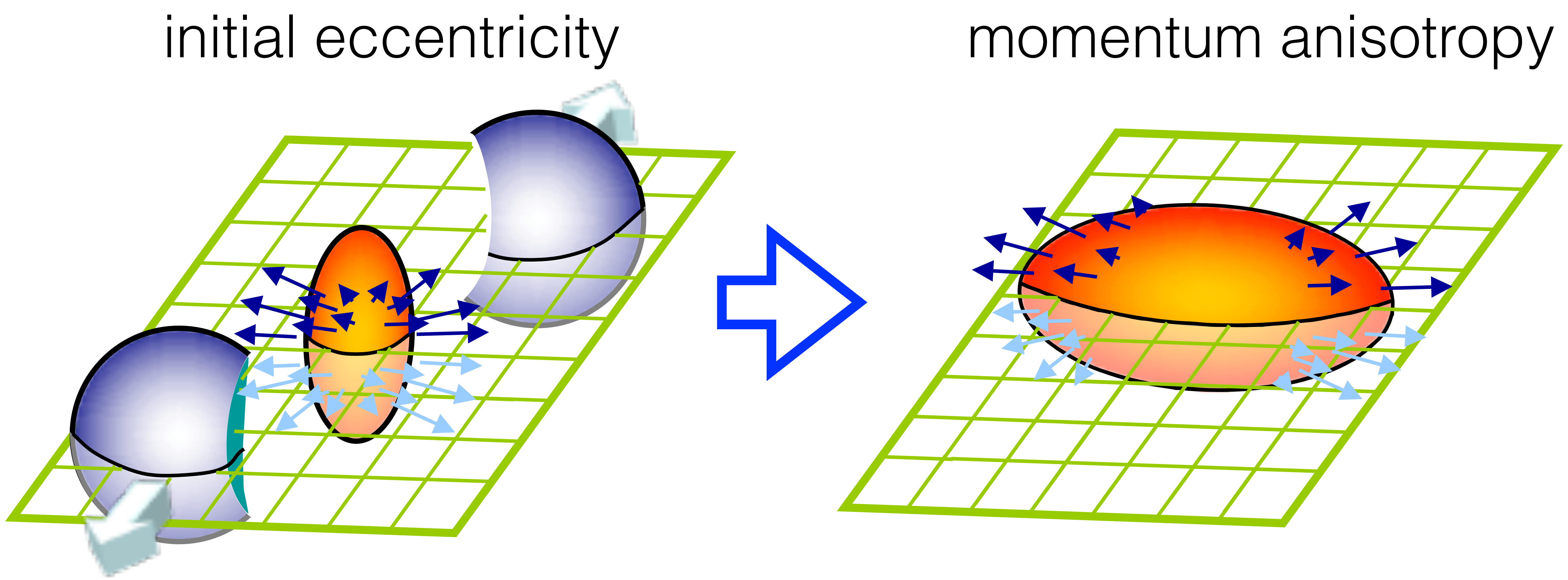
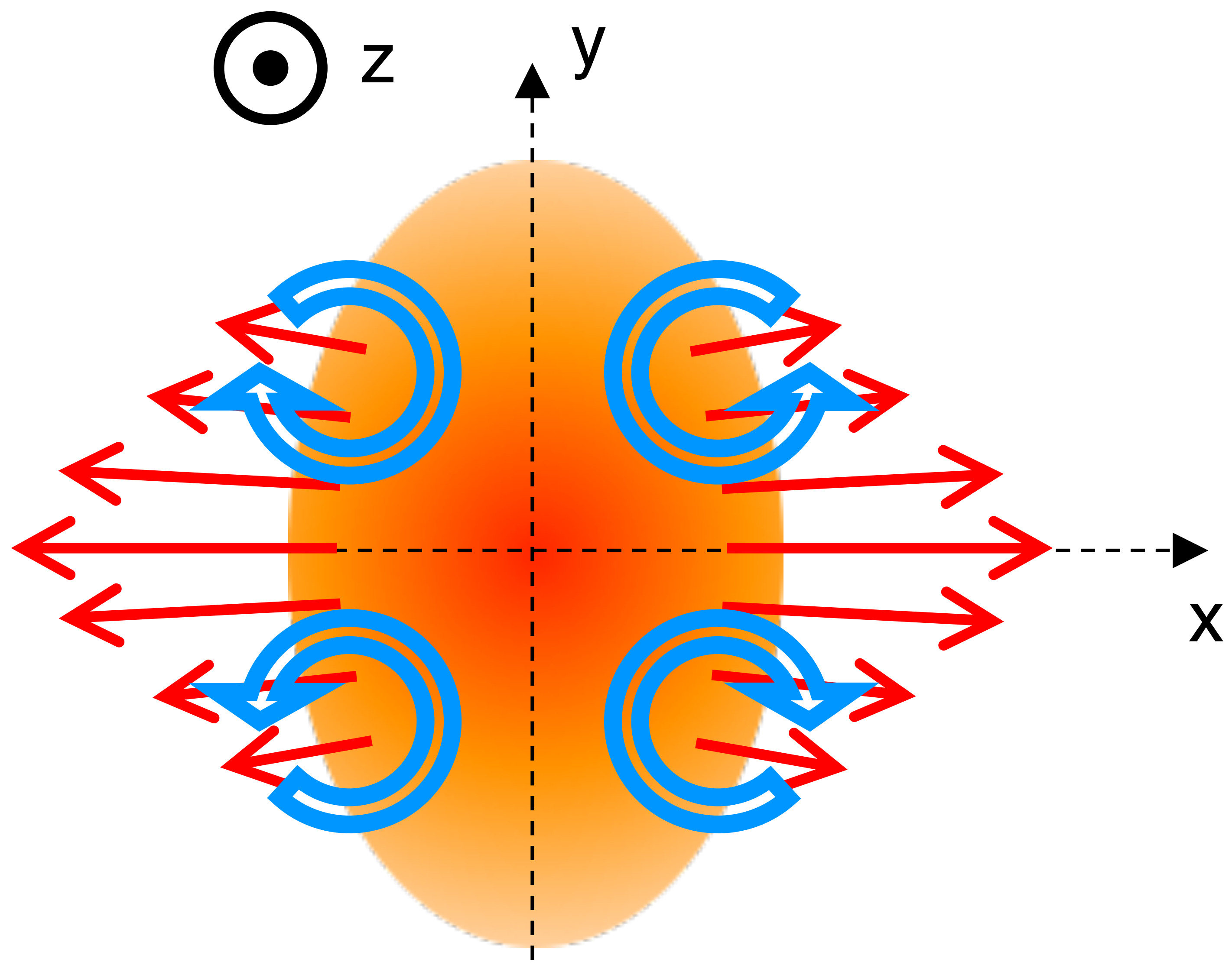


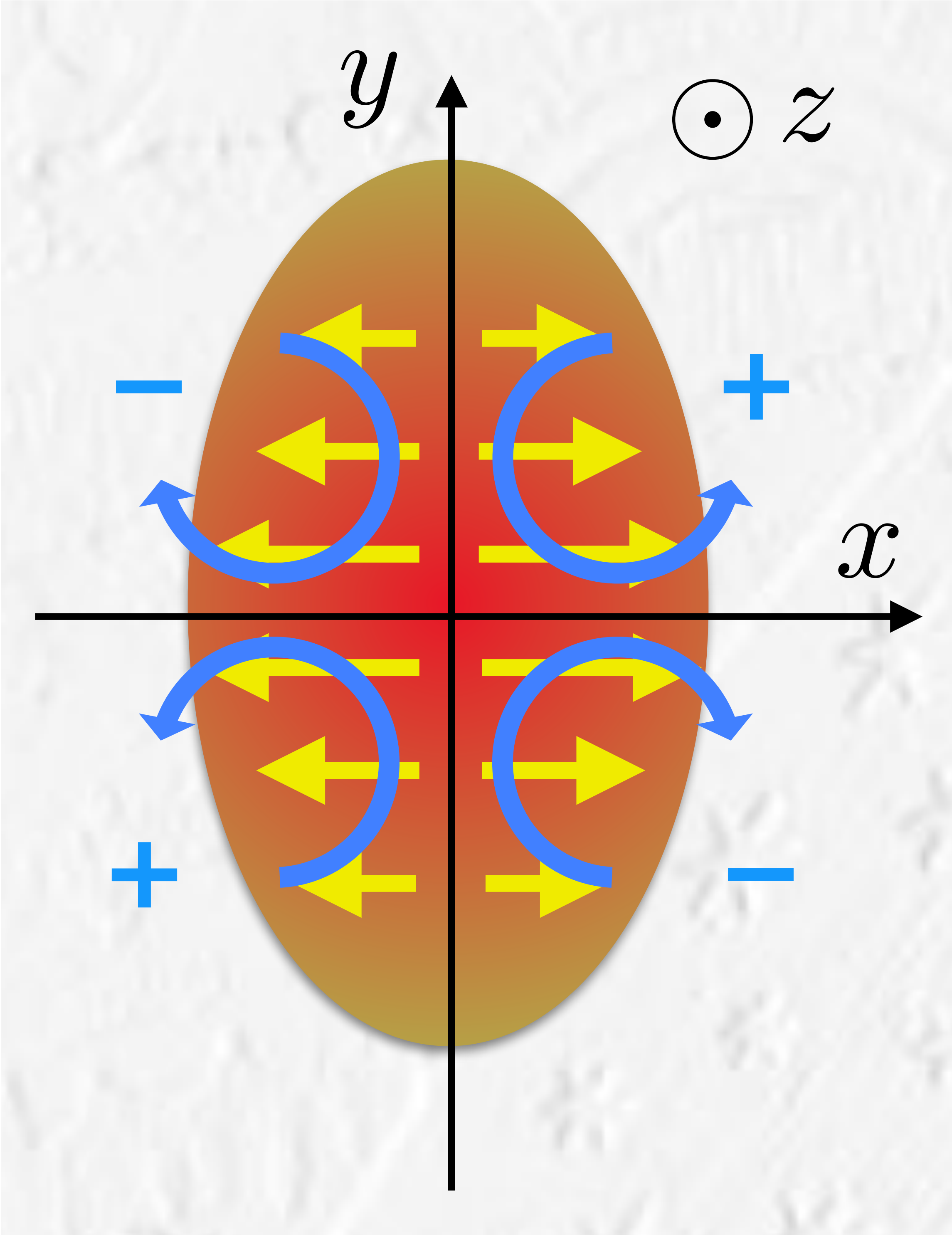


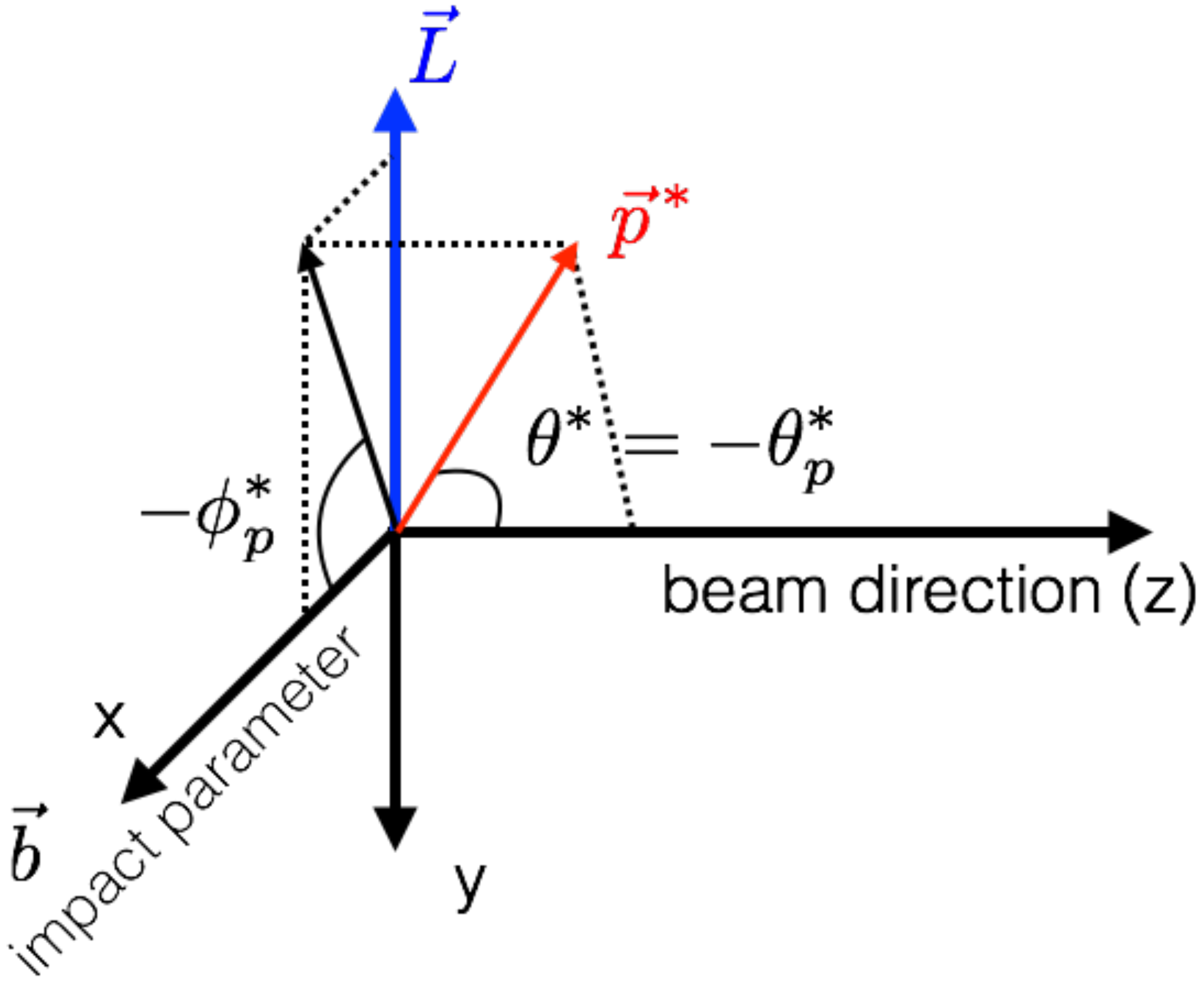
Stronger flow in in-plane (short-axis) than in out-of-plane (long axis) due to different pressure gradient, called the elliptic flow

Vorticity along the beam axis!?
The rotational axis would depend on azimuthal angle

Polarization along the beam direction

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





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

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

$$= \alpha_H P_z \langle (\cos\theta_p^*)^2 \rangle$$

$$\therefore \; P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle}$$

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

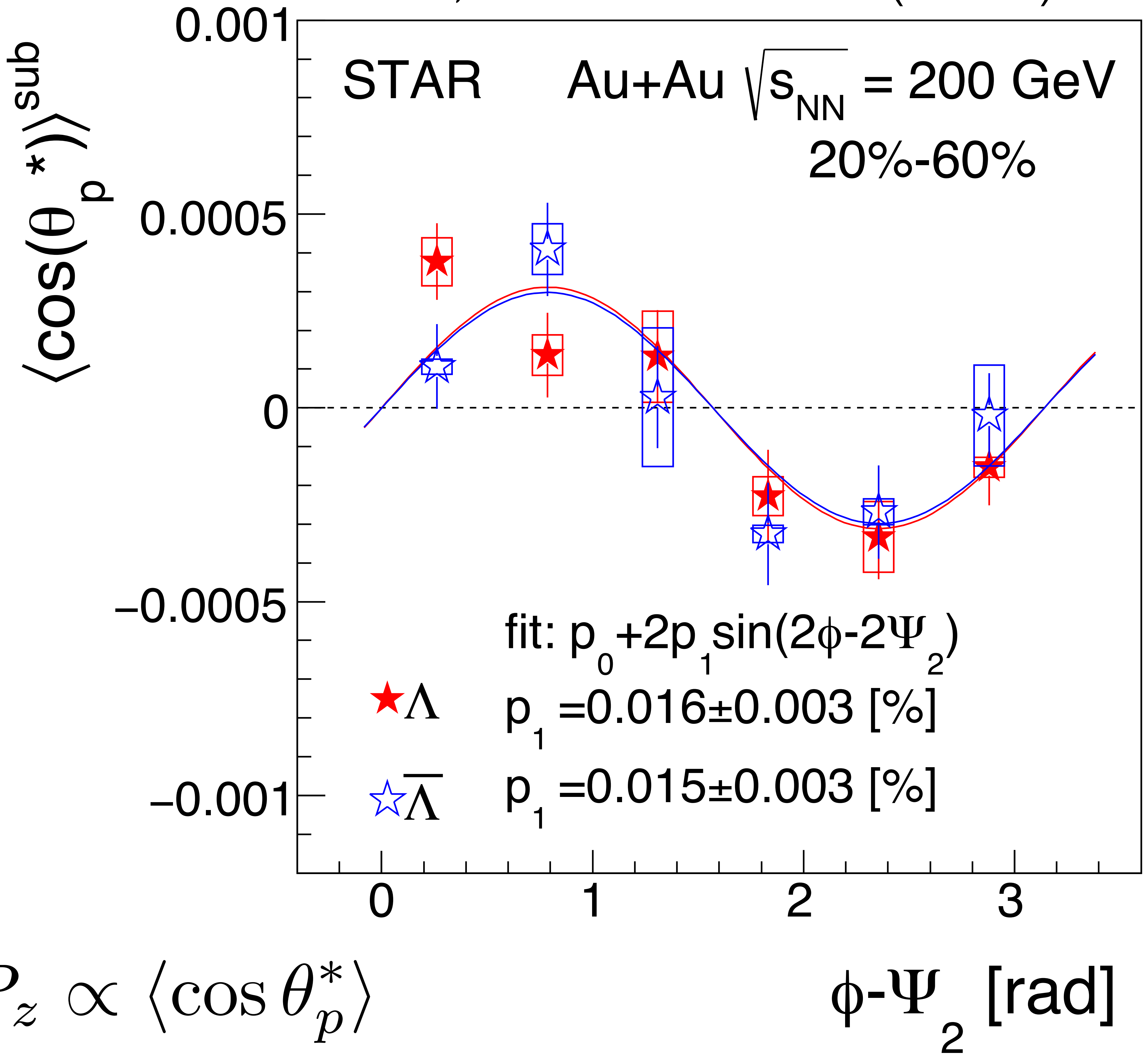
α_H: hyperon decay parameter
θ_p^*: θ of daughter proton in Λ rest frame

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

Polarization along the beam direction

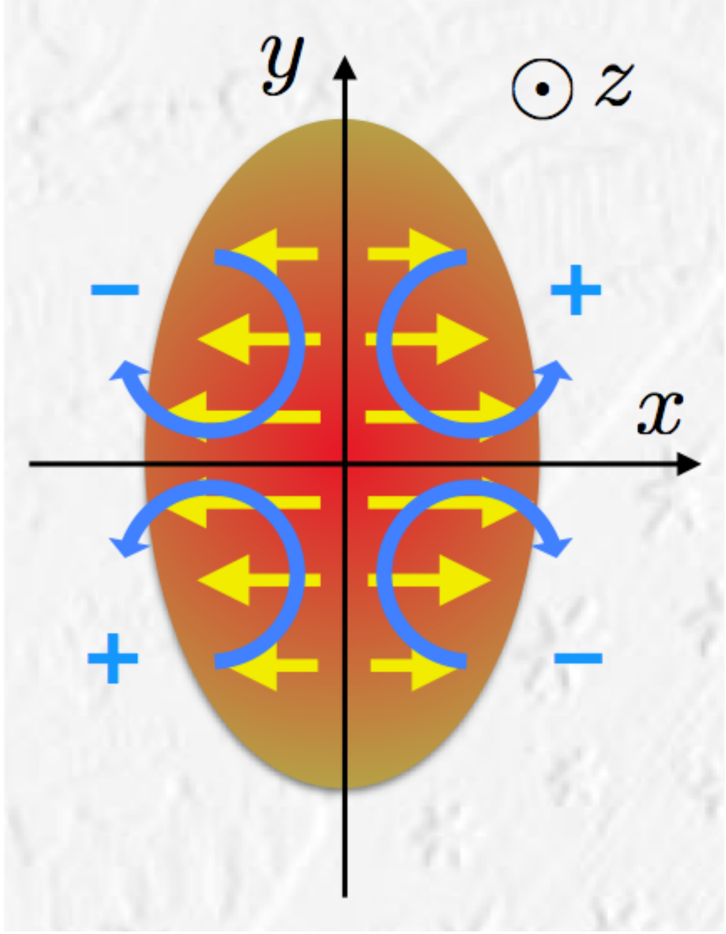
STAR, PRL123.13201 (2019)



$P_z \propto \langle \cos \theta_p^* \rangle$

- Effect of Ψ_2 resolution is not corrected here

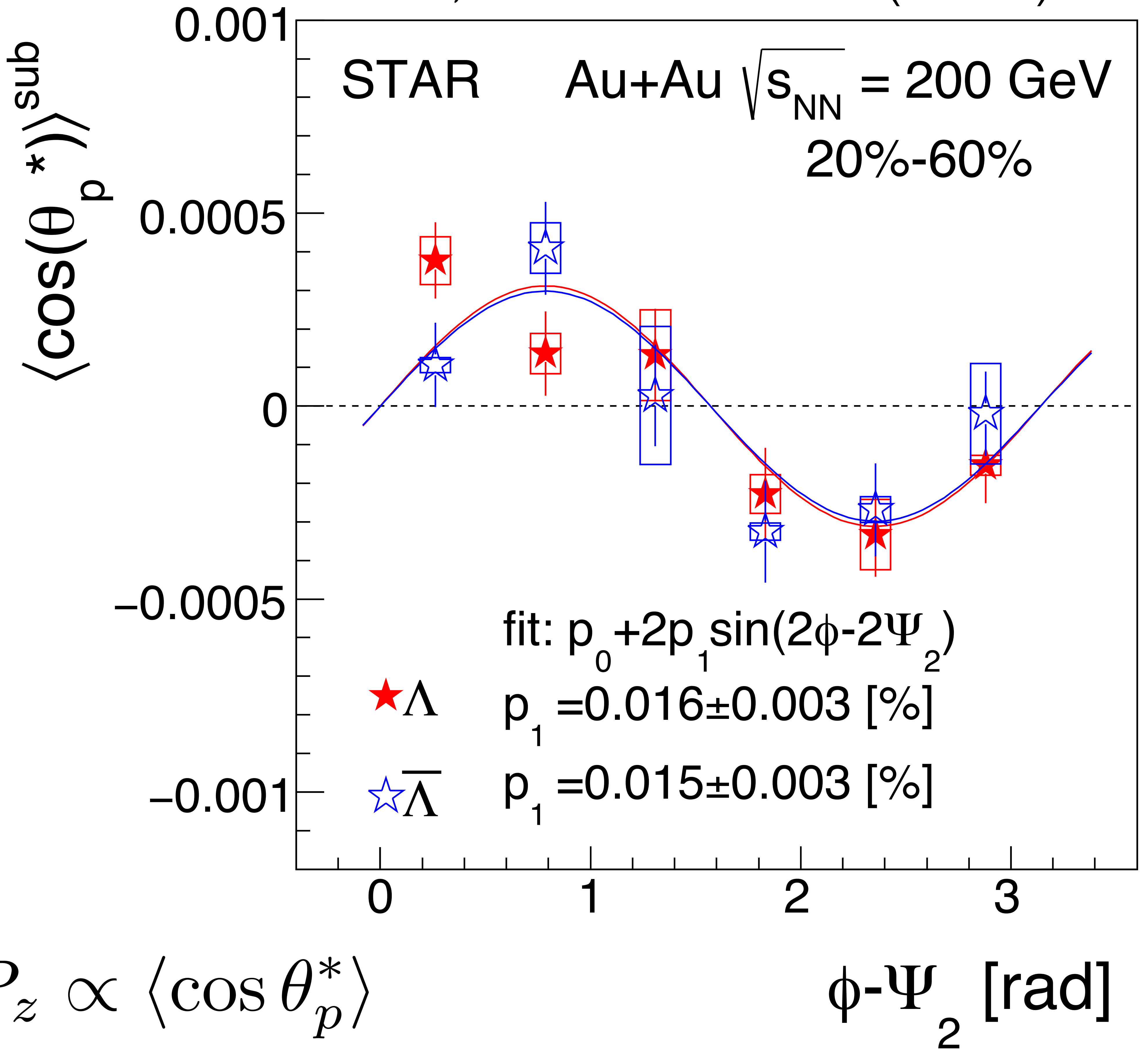
S. Voloshin, SQM2017



- Sine structure as expected from the elliptic flow!

Polarization along the beam direction

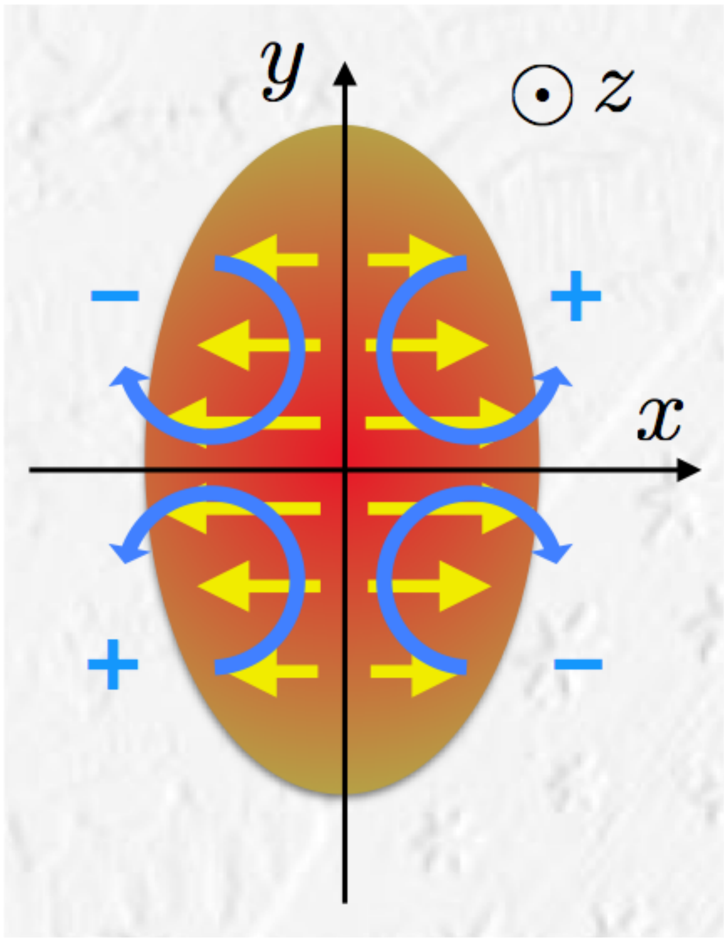
STAR, PRL123.13201 (2019)



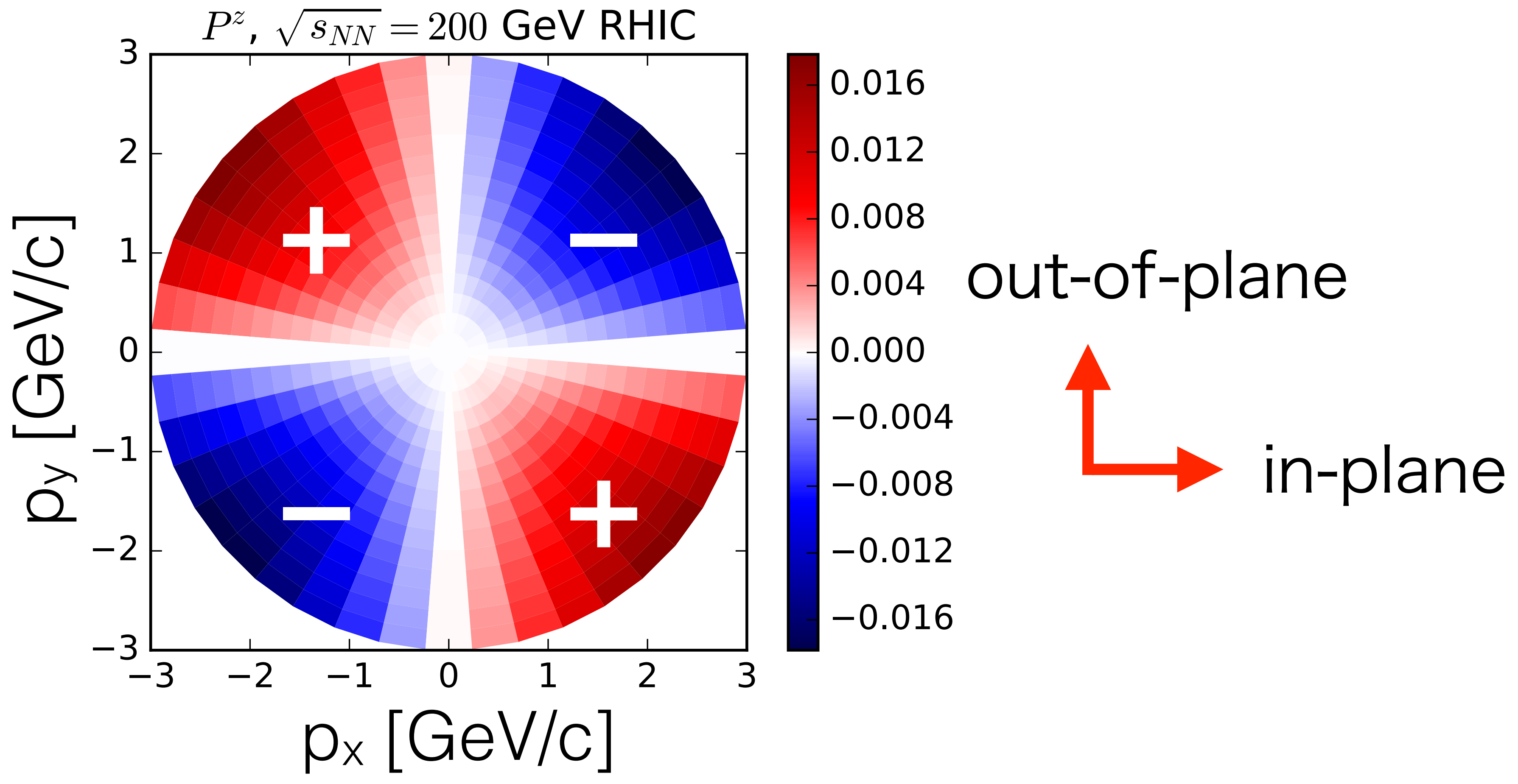
$P_z \propto \langle\cos\theta_p^*\rangle$

- Effect of Ψ_2 resolution is not corrected here

S. Voloshin, SQM2017



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

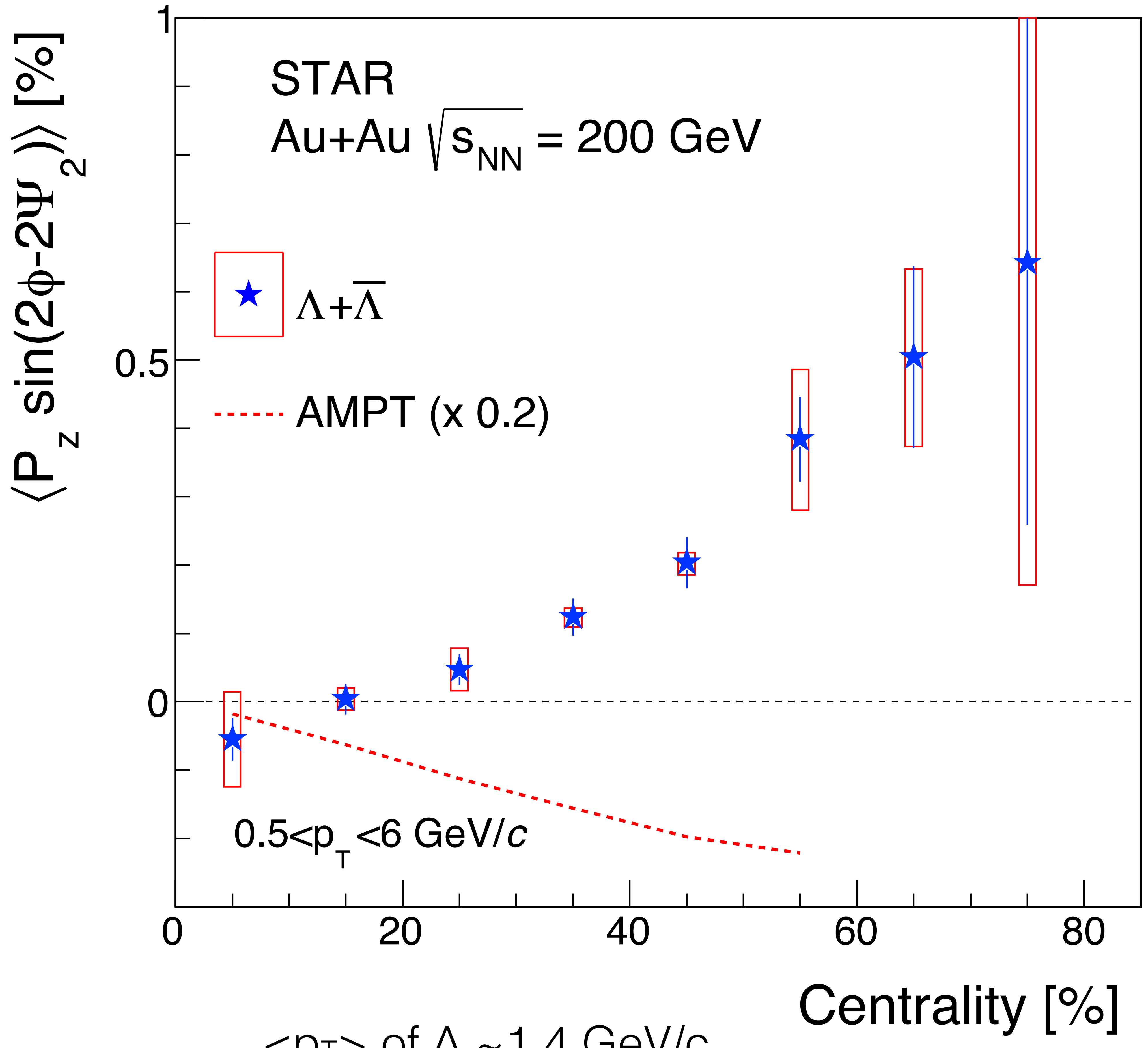


- Sine structure as expected from the elliptic flow!
- Some models (viscous hydro, AMPT) cannot describe the sign but some of them (chiral kinetic, PICR) can do.

- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)
- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Y. Xie, D. Wang, and L. P. Csernai, arXiv:1907.00773

Centrality dependence of P_z modulation

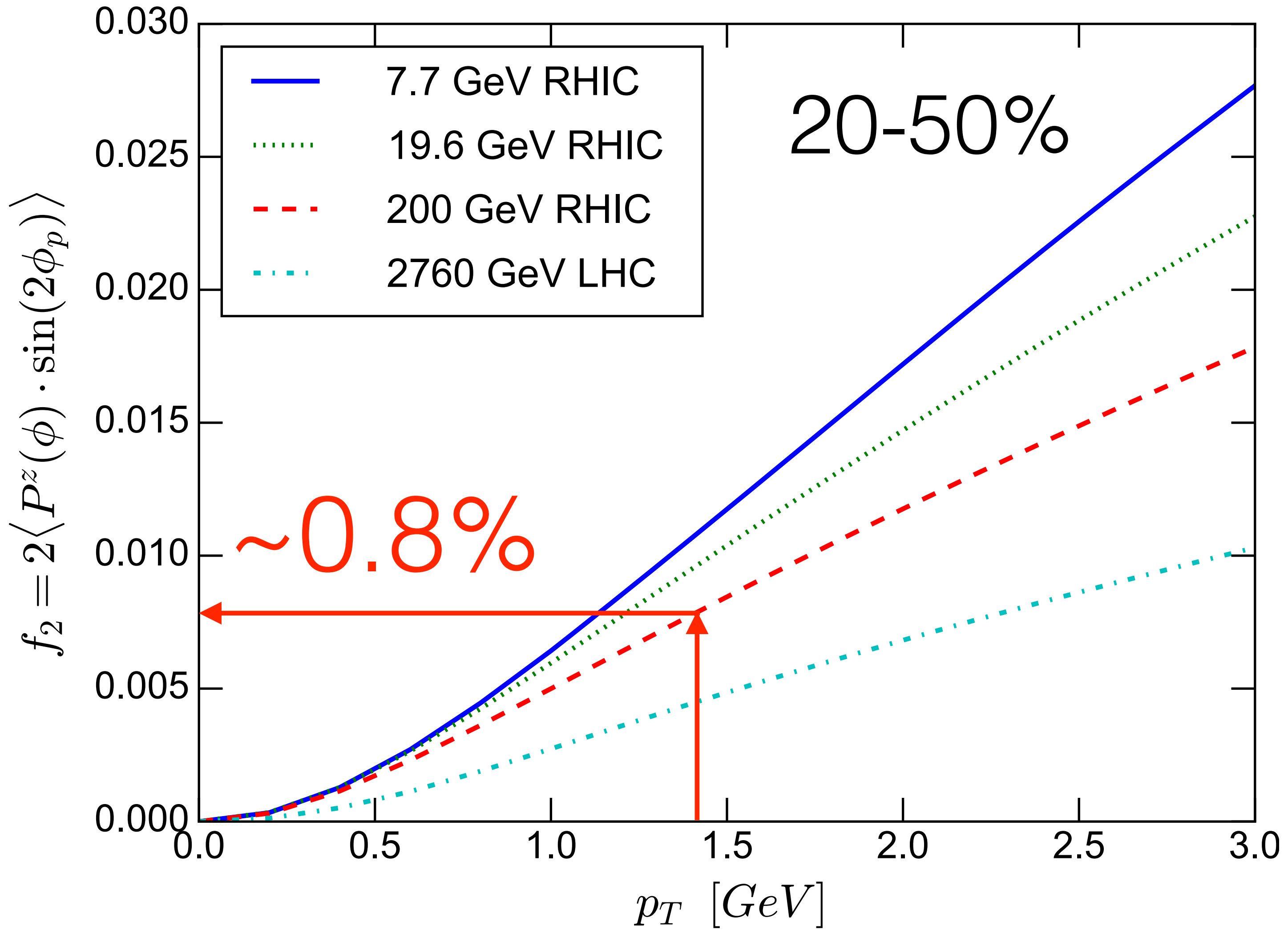
STAR, PRL123.13201 (2019)



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

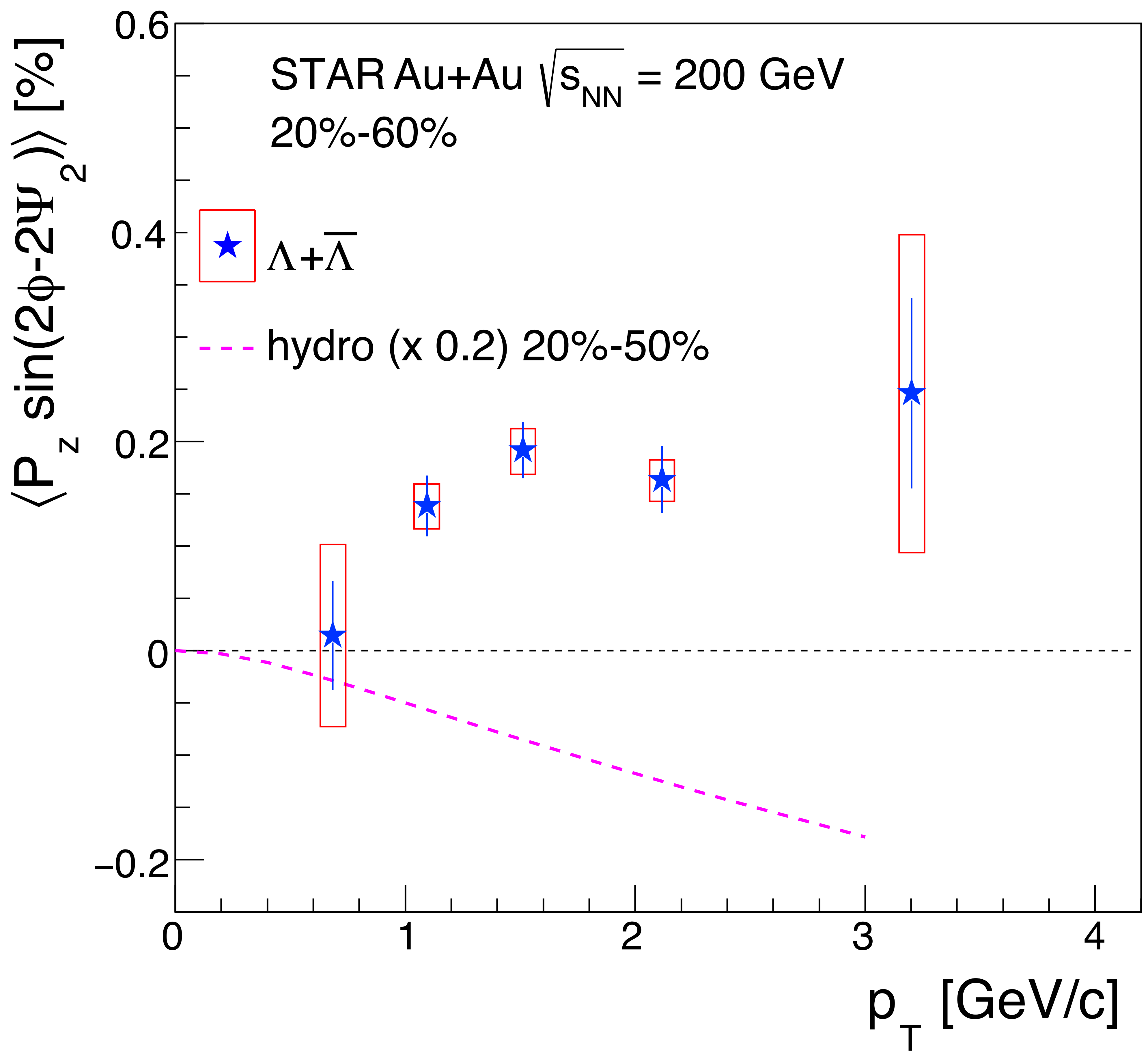
- Strong centrality dependence as in v_2
- Similar magnitude to the global polarization
- ~5 times smaller magnitude than the hydro and AMPT with the opposite sign!

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



p_T dependence of P_z modulation

STAR, PRL123.13201 (2019)



- No strong p_T dependence for p_T>1 GeV/c
  - A hint of drop-off at pT<1 GeV/c
  - Hydrodynamic model also predicts a mild pT dependence but with the opposite sign and larger magnitude

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

Disagreement in P_z sign

Opposite sign

- UrQMD IC + hydrodynamic model
  -- Assuming a local thermal equilibrium
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)

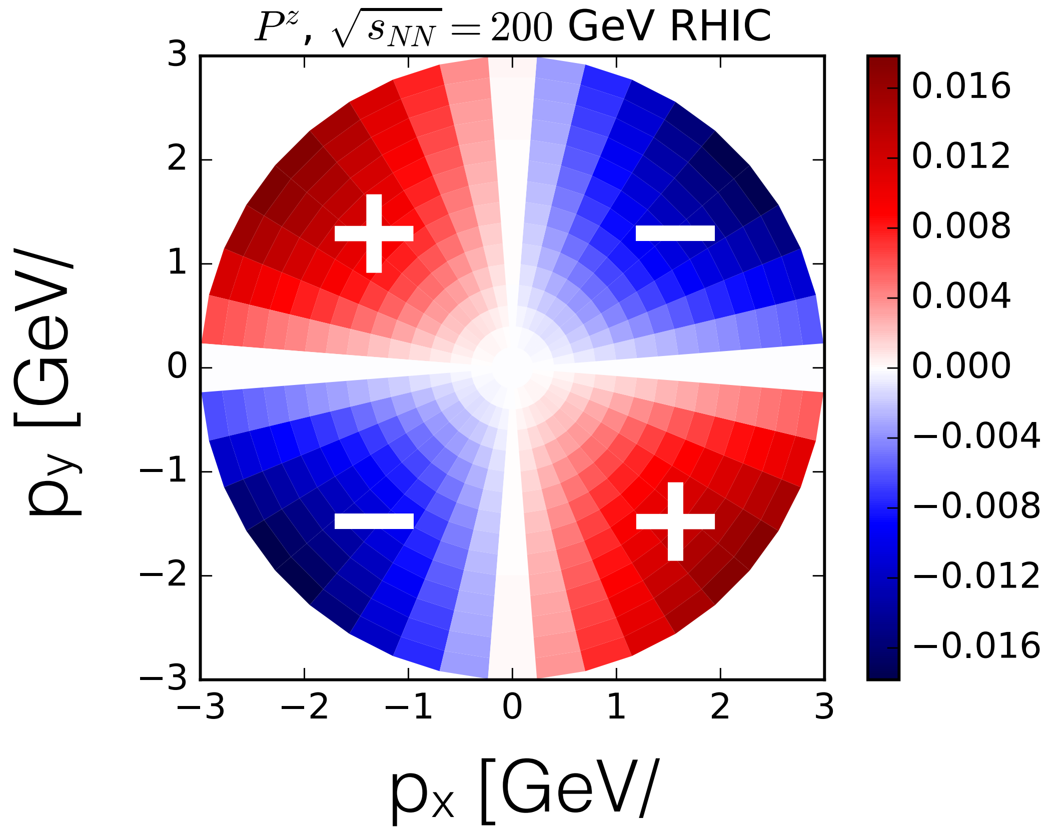
- AMPT
  X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

Same sign

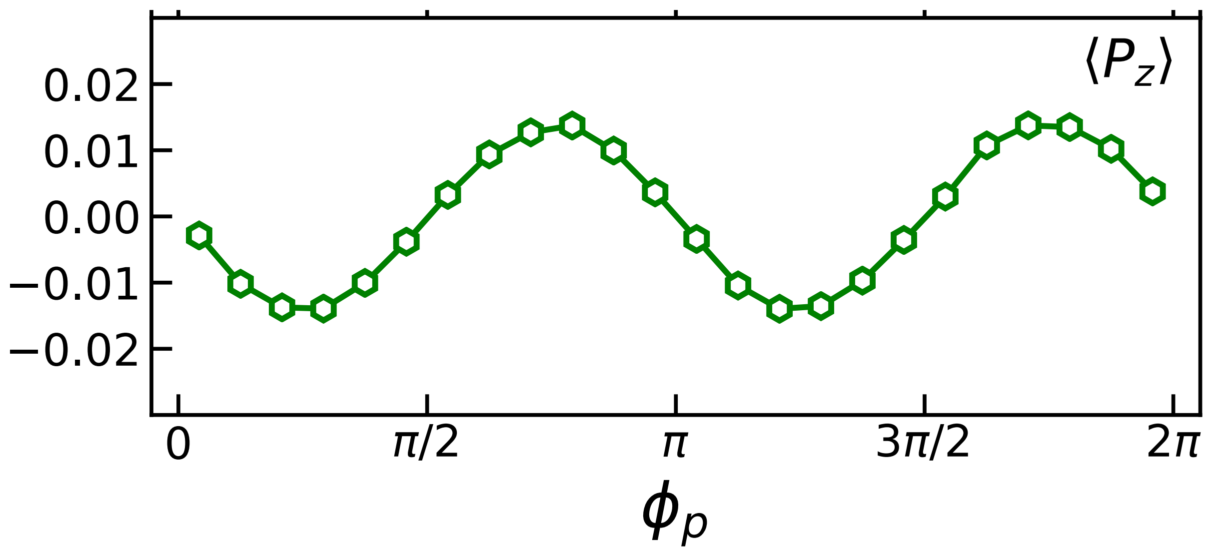
- Chiral kinetic approach
  -- Assuming non-equilibrium of spin degree of freedom
  Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)

- High resolution (3+1)D PICR hydrodynamic model
  -- Yang-Mills flux tube IC
  Y. Xie, D. Wang, and L. P. Csernai, arXiv:1907.00773

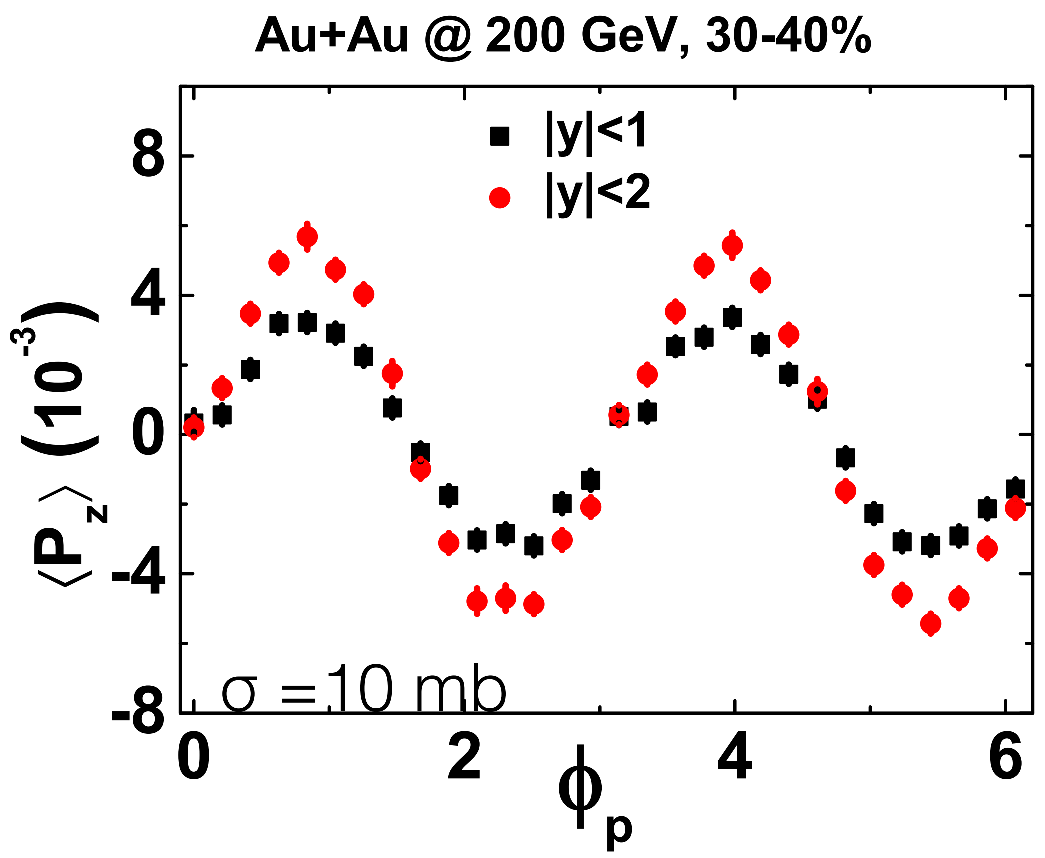
Hydrodynamic model



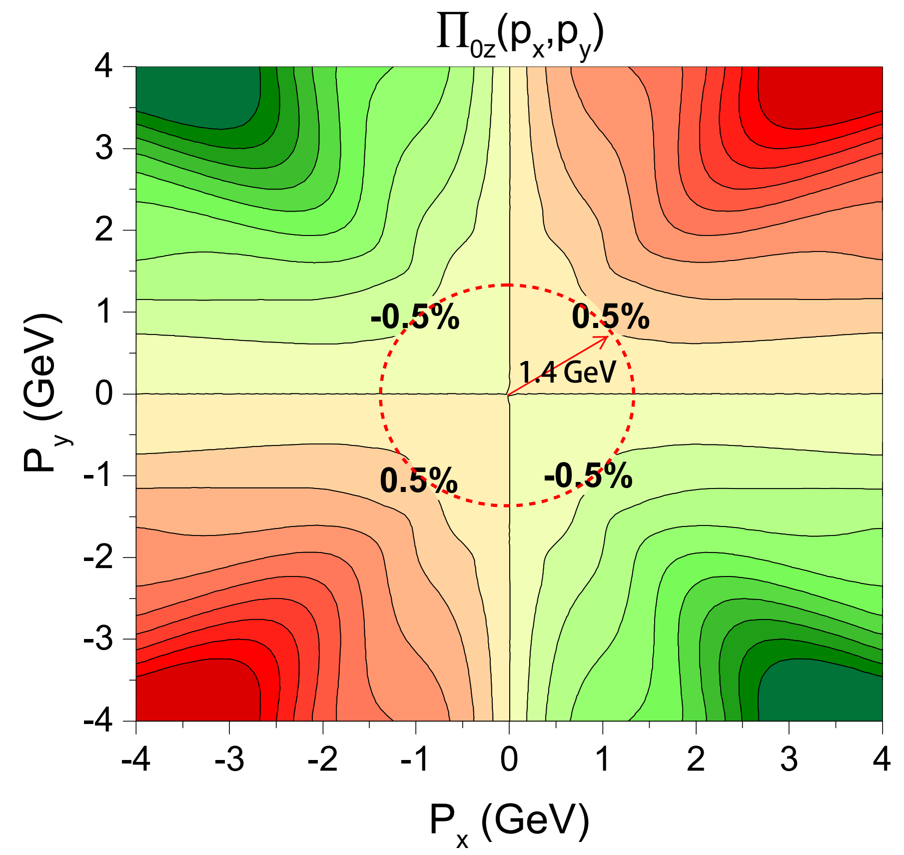
AMPT, Au+Au 200 GeV 20-50%



Chiral kinetic approach



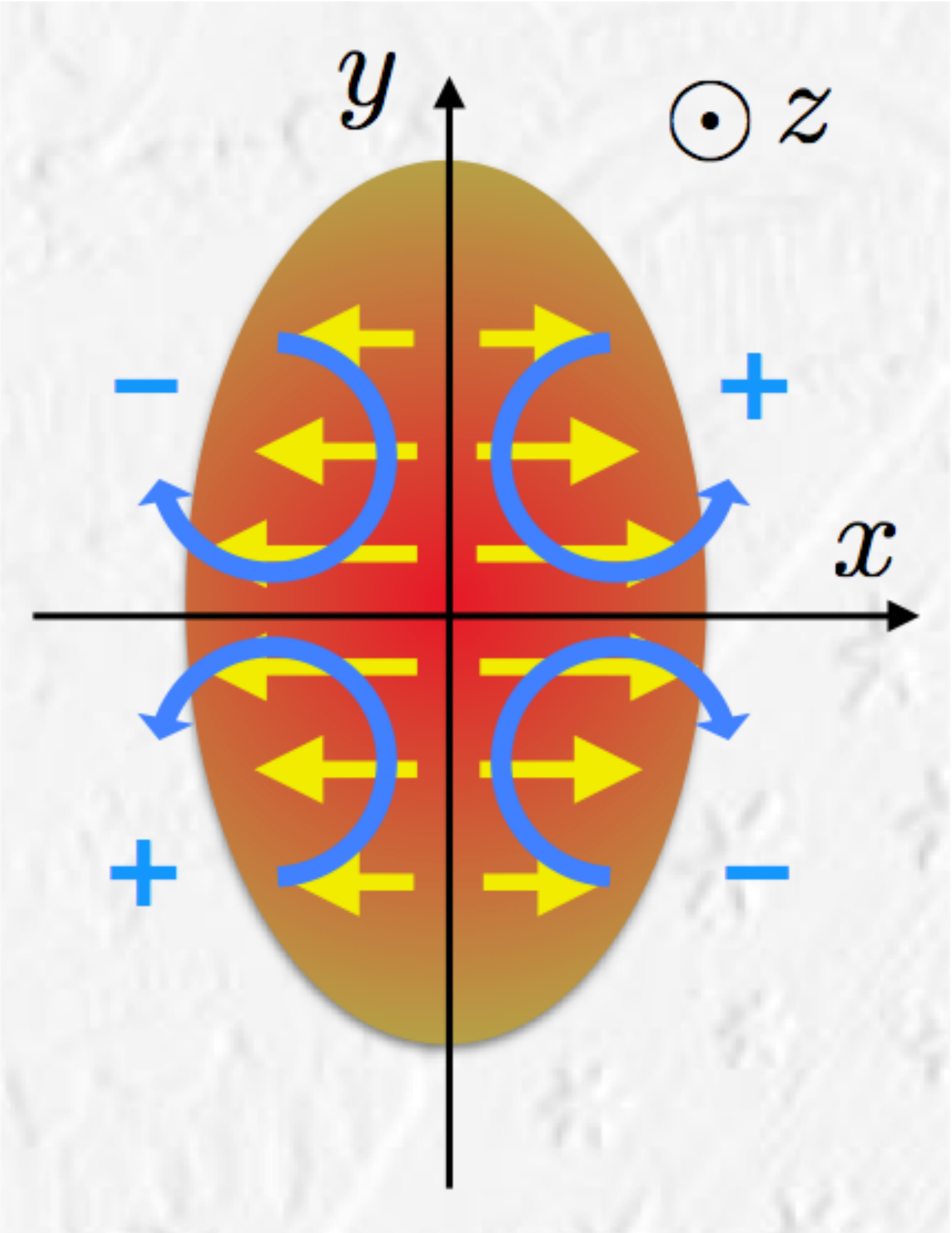
PICR model

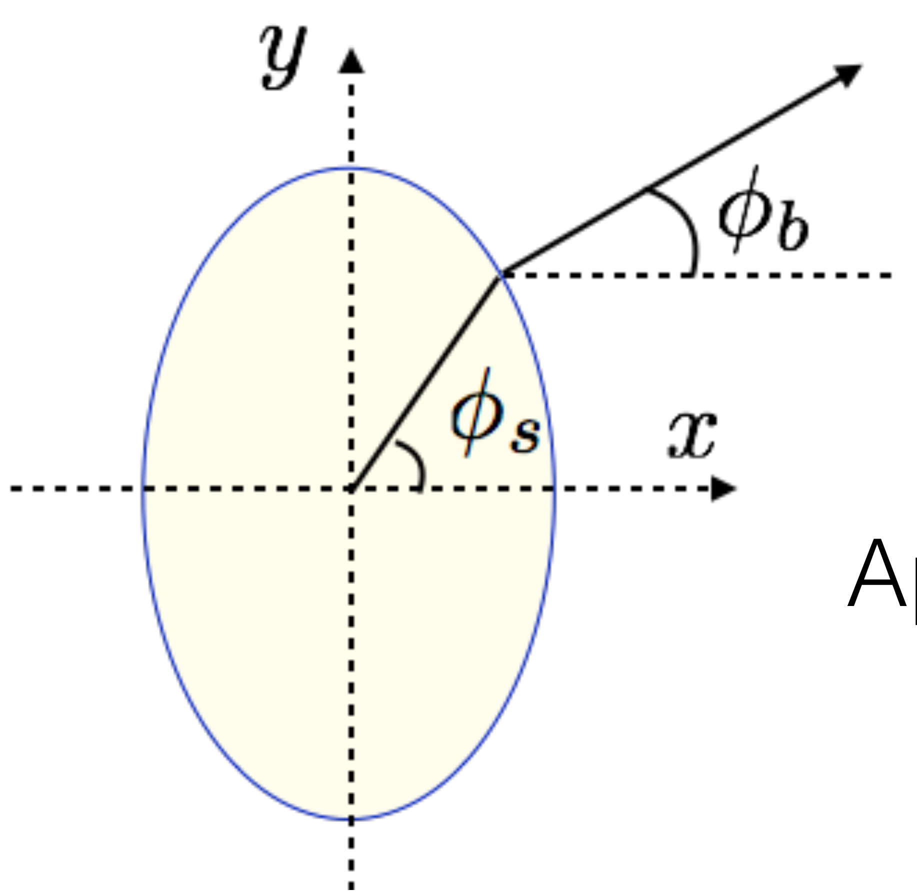


Incomplete thermal equilibrium of spin degree of freedom?
Importance of relativistic contribution as well as kinematic vorticity in hydro.

Estimate kinematic vorticity with the blast-wave model

S. Voloshin, SQM2017
EPJ Web Conf.171, 07002 (2018)





R: reference source radius

ρ_t: transverse flow velocity

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

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

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

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

flow anisotropy (a_n)

spatial anisotropy (b_n)

Sine modulation 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

$$\rho(r, \phi_s) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi_b)]$$
$$\tilde{r}(r, \phi_s) = \sqrt{(r\cos\phi_s)^2/R_x^2 + (r\sin\phi_s)^2/R_y^2}$$

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

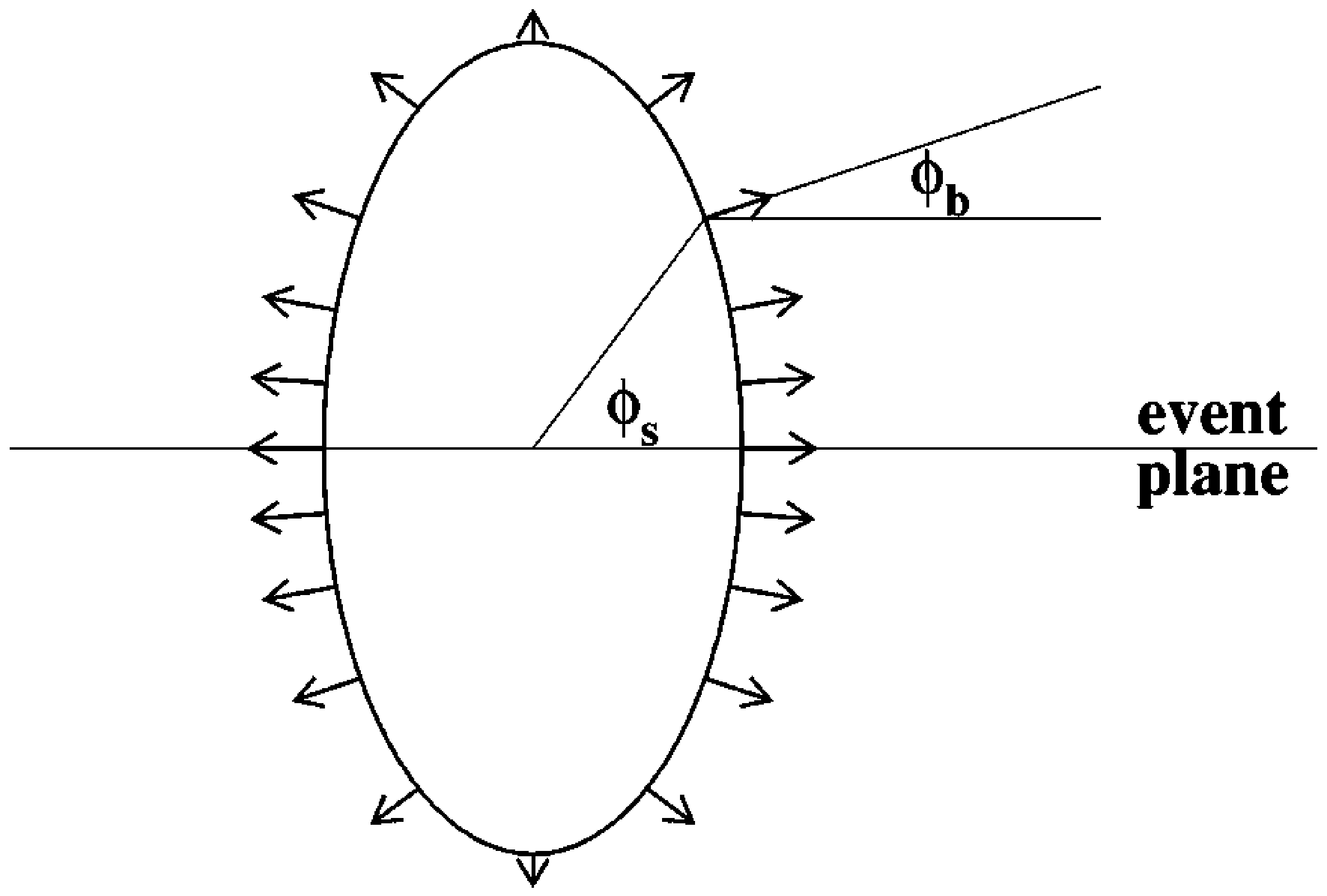


FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

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

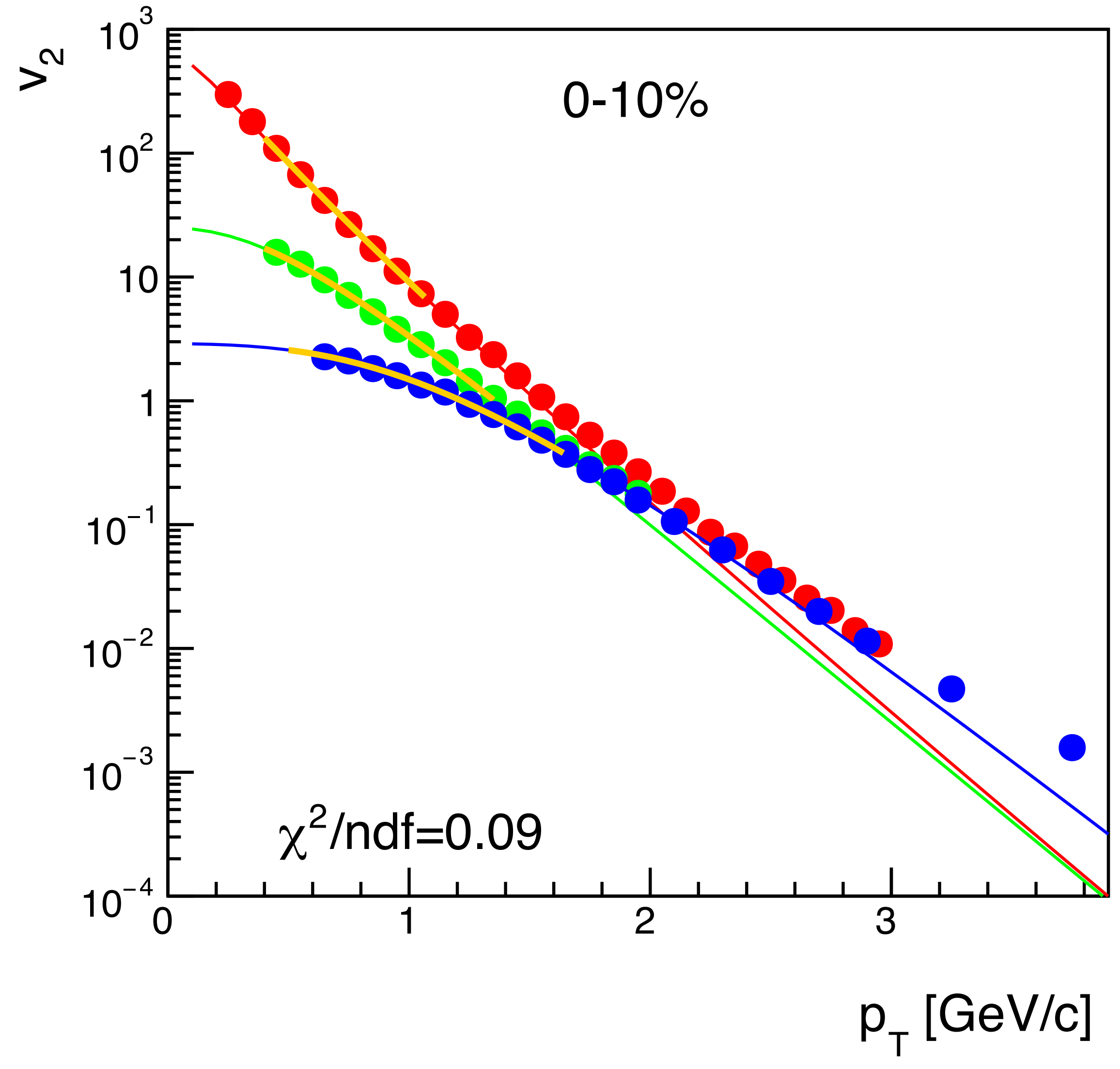
$$\langle \omega_z \sin(2\phi) \rangle = \frac{\int d\phi_s \int r dr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr\, I_0(\alpha_t) K_1(\beta_t)}$$
$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

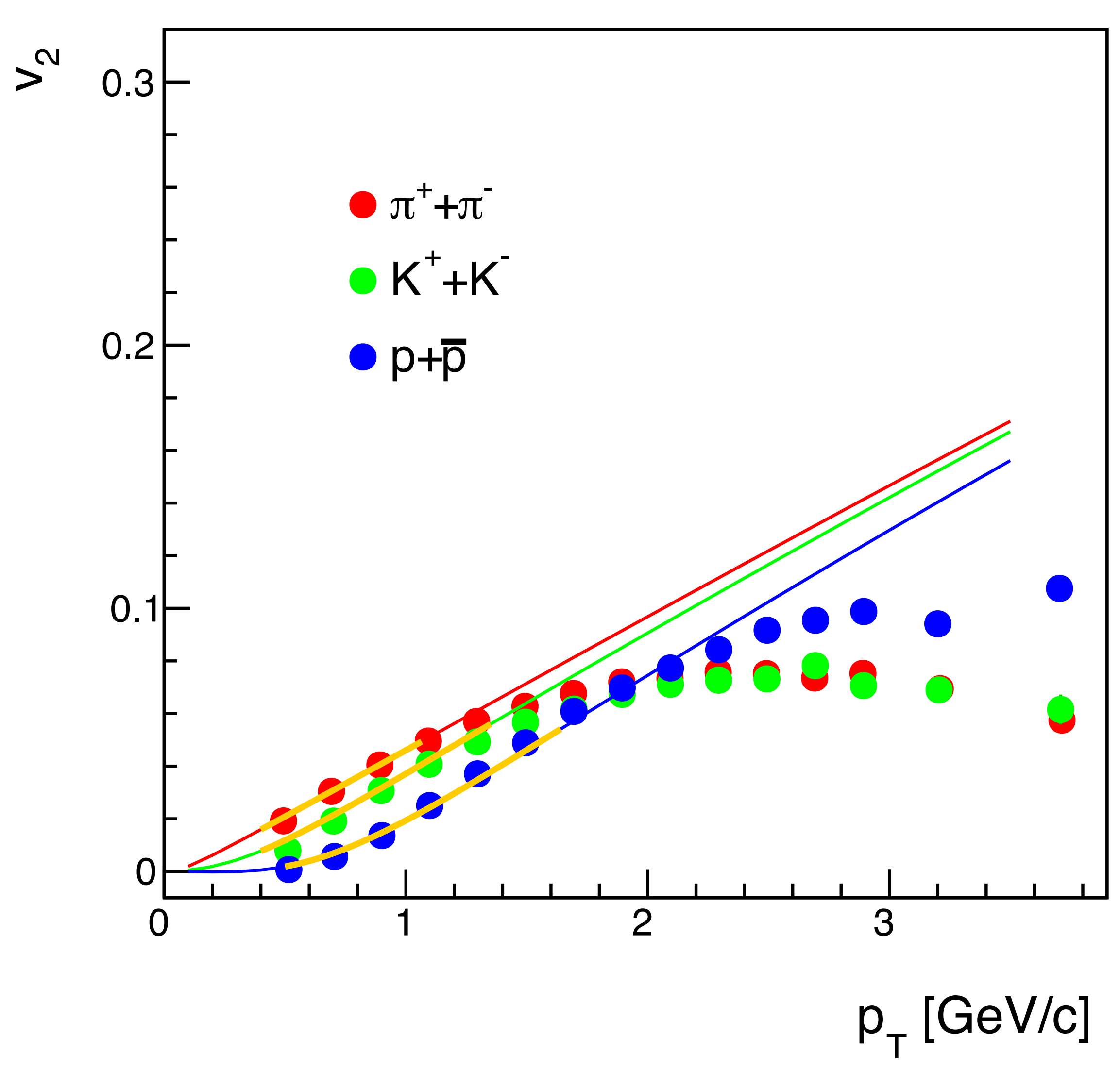
ϕ_s: azimuthal angle of the source element
ϕ_b: boost angle perpendicular to the elliptical subshell

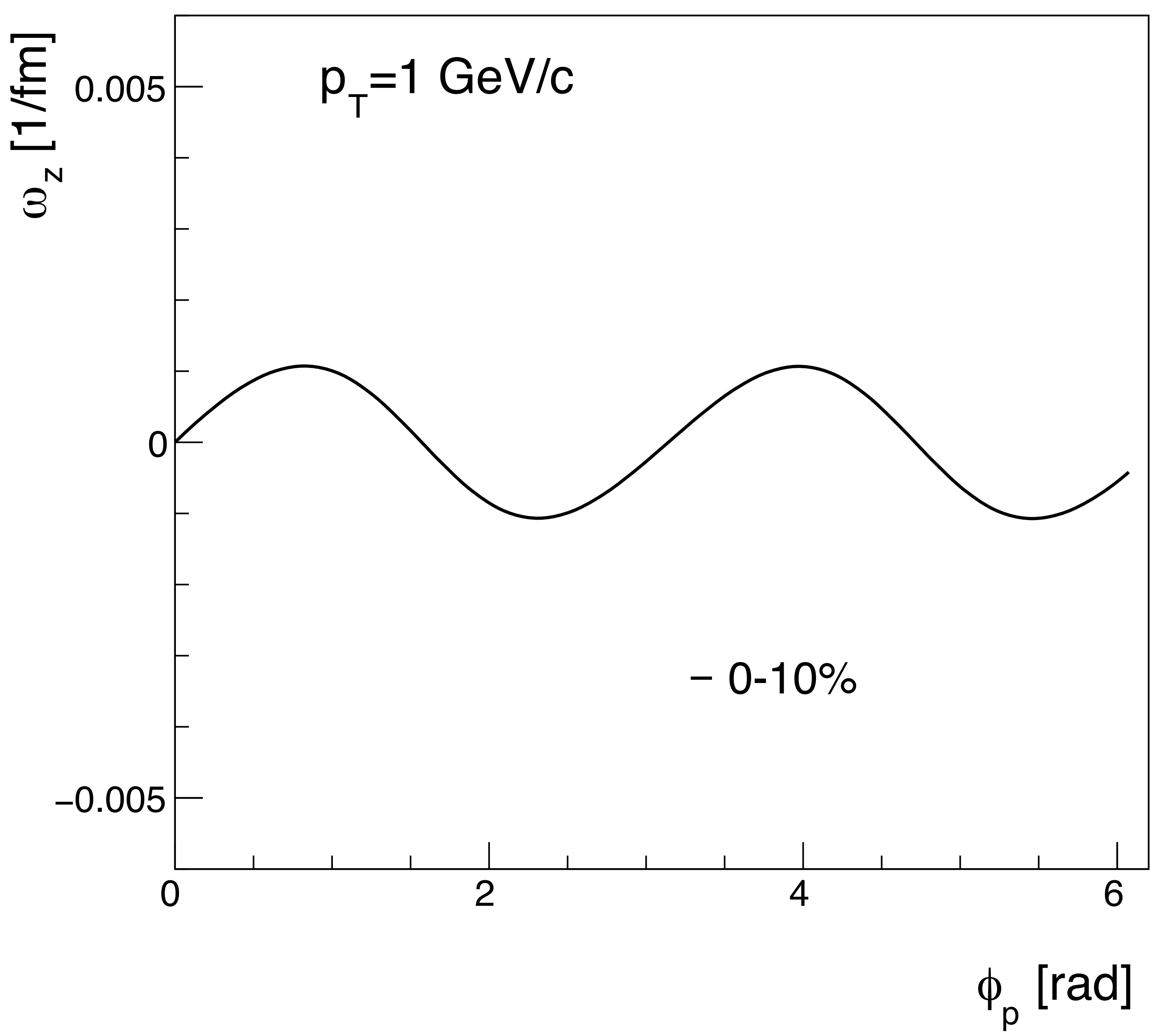
u: local flow velocity, I_n, K_n: modified Bessel functions

ω_z and P_z from the BW model

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







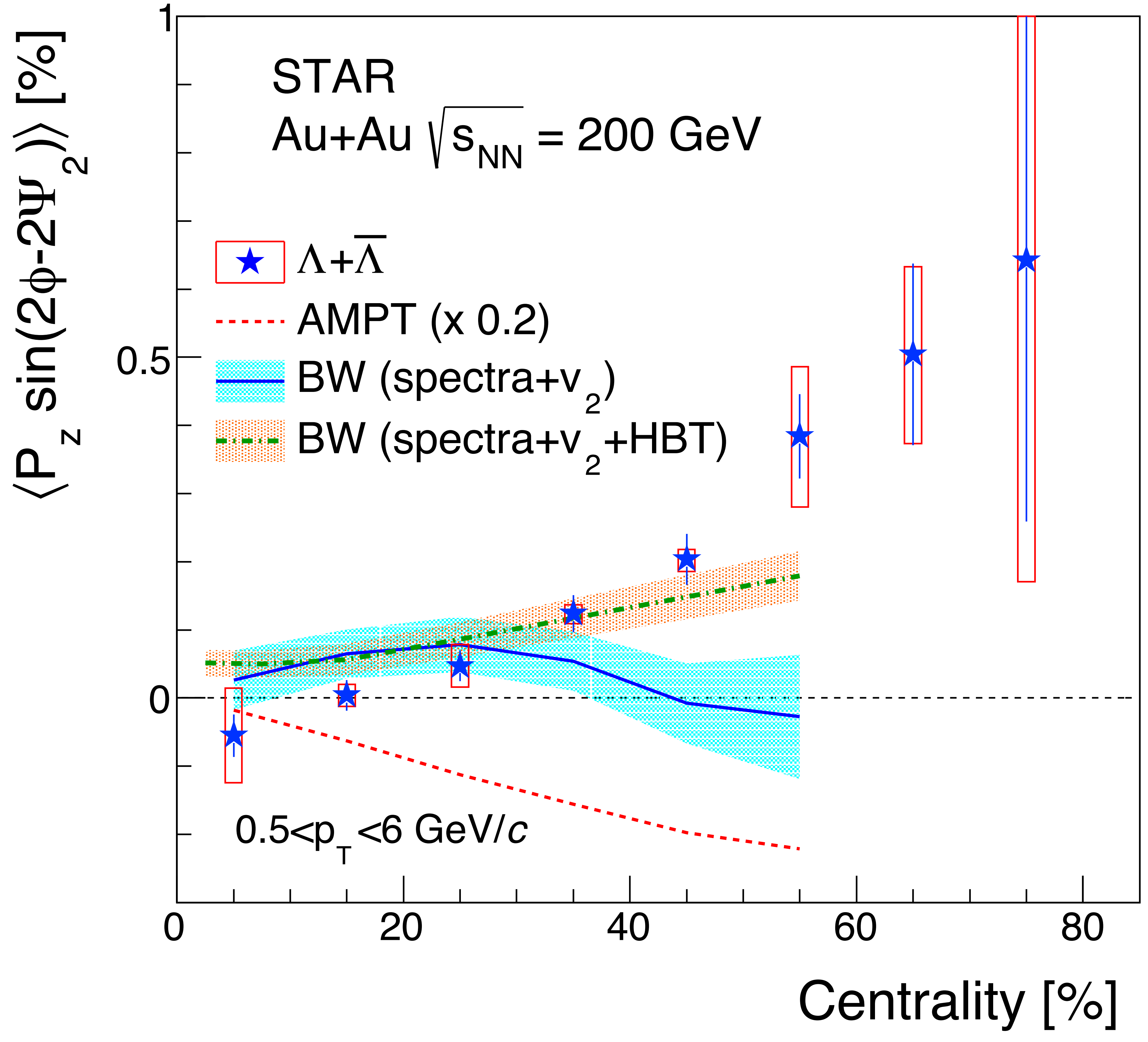
Data from:
PHENIX, PRC69.034909 (2004)
PHENIX, PRC93.051902(R) (2016)

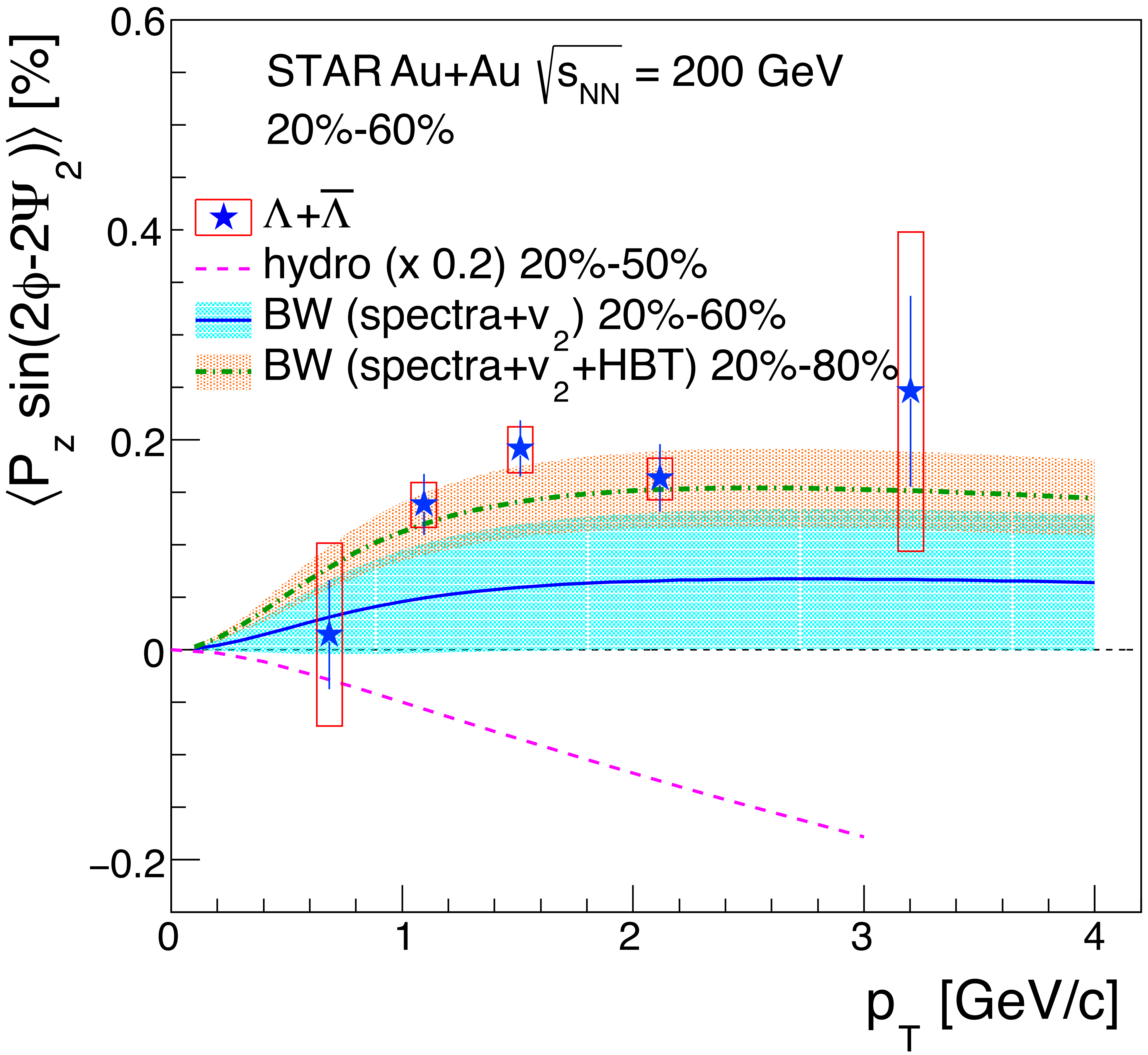
Calculated vorticity ω_z shows the sine modulation. Assuming a local thermal equilibrium, z-component of polarization is estimated as follows: $P_z \approx \omega_z/(2T)$

P_z modulation from the BW model

STAR, PRL123.13201 (2019)

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





- Simple estimate for kinematic vorticity contribution with BW model
  - Similar magnitude to the data
  - Inclusion of HBT in the fit affects the sign in peripheral collisions

T. Niida and S. Voloshin in preparation

Summary

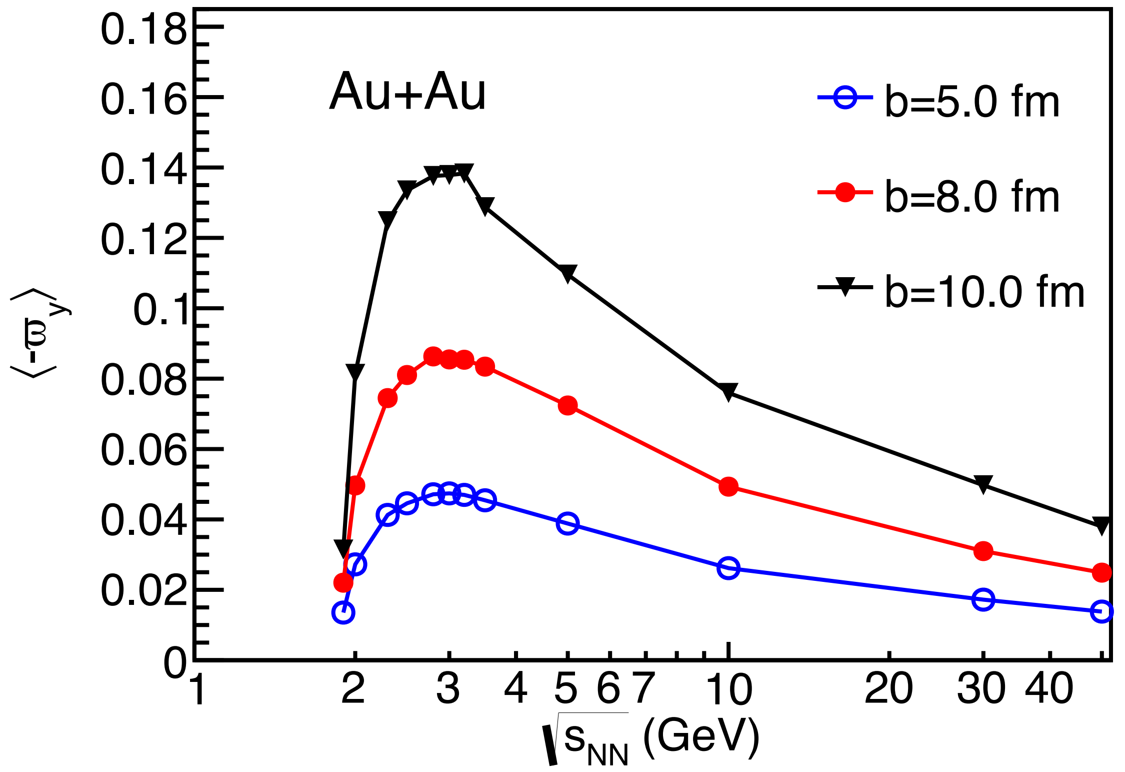
- Λ global polarization at $\sqrt{s_{NN}}$ = 7.7-200 GeV from STAR
  - Polarization increases in lower energies
    → **Quantitatively consistent with theoretical models**
- Λ global polarization at $\sqrt{s_{NN}}$ = 2.4 GeV from HADES and 2.7 TeV from ALICE
  - Preliminary results are consistent with zero but the HADES result indicates the polarization decreases around $\sqrt{s_{NN}}$ = 2.4 - 7.7 GeV
    → STAR-FXT $\sqrt{s_{NN}}$ = 3-7.7 GeV
- First study of Λ polarization along the beam direction at $\sqrt{s_{NN}}$ = 200 GeV
  - Quadrupole structure of the polarization relative to the 2^{nd}-order event plane
    → **Qualitatively consistent with a picture of the elliptic flow but agree/disagree among the data and theoretical calculations in the sign**
  - Blast-wave model predicts the same sign and similar magnitude to the data

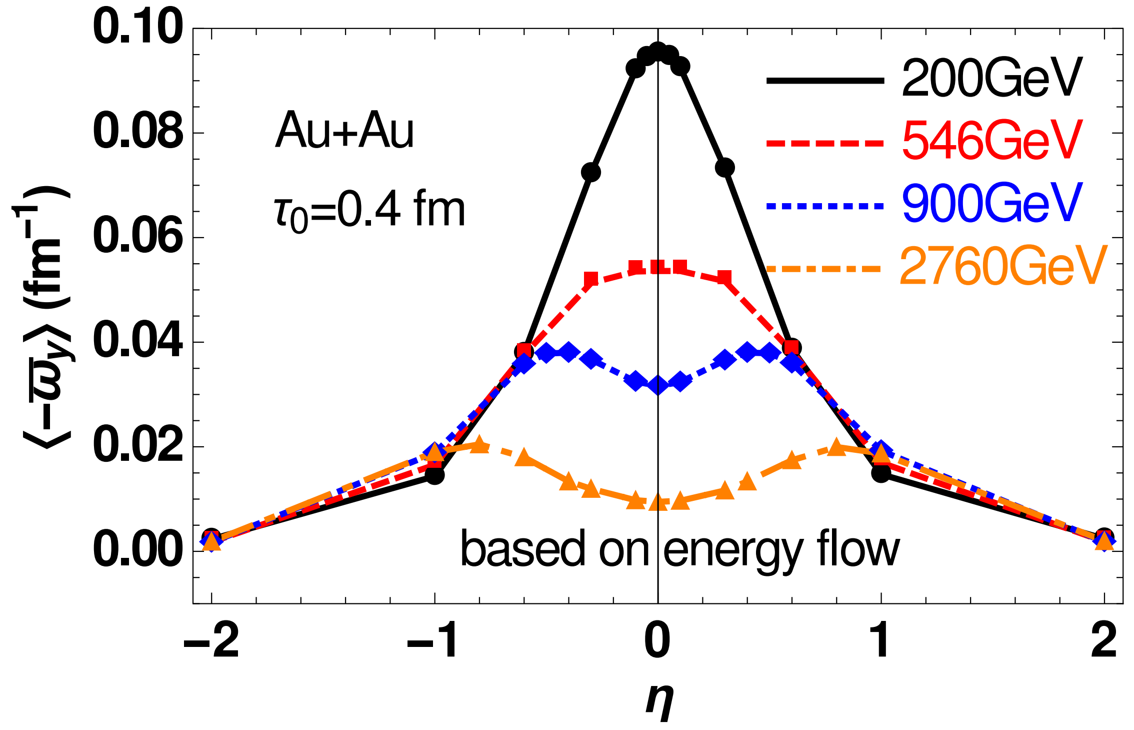
and Outlook…

Outlook

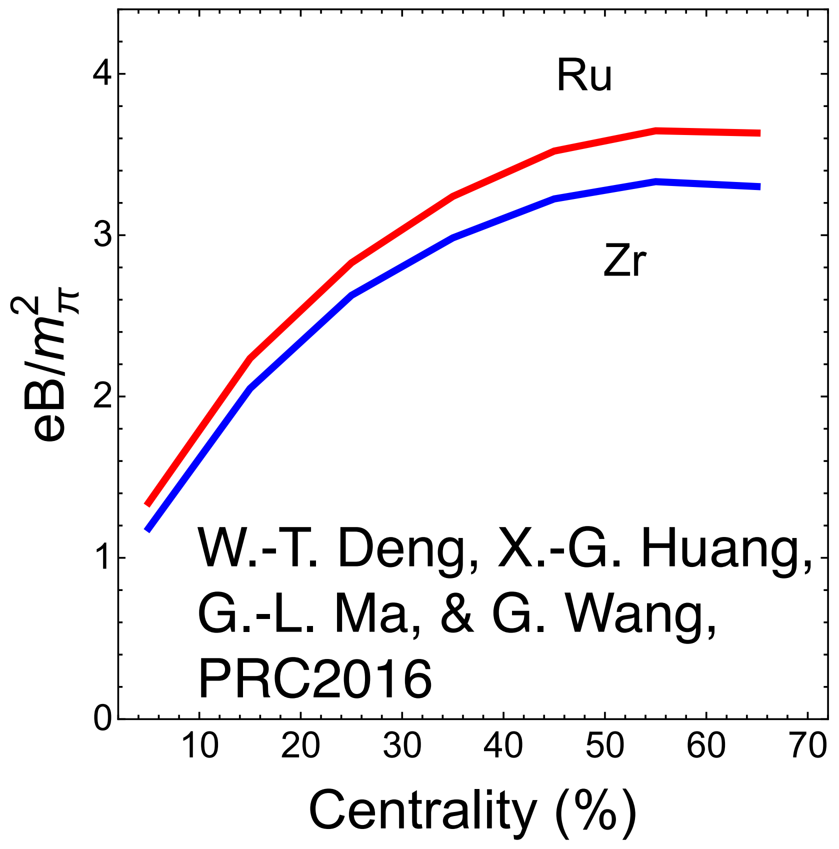
W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)
D.-X. Wei *et al.*, PRC99.014905 (2019)
X.-G. Deng et al., arXiv:2001.01371

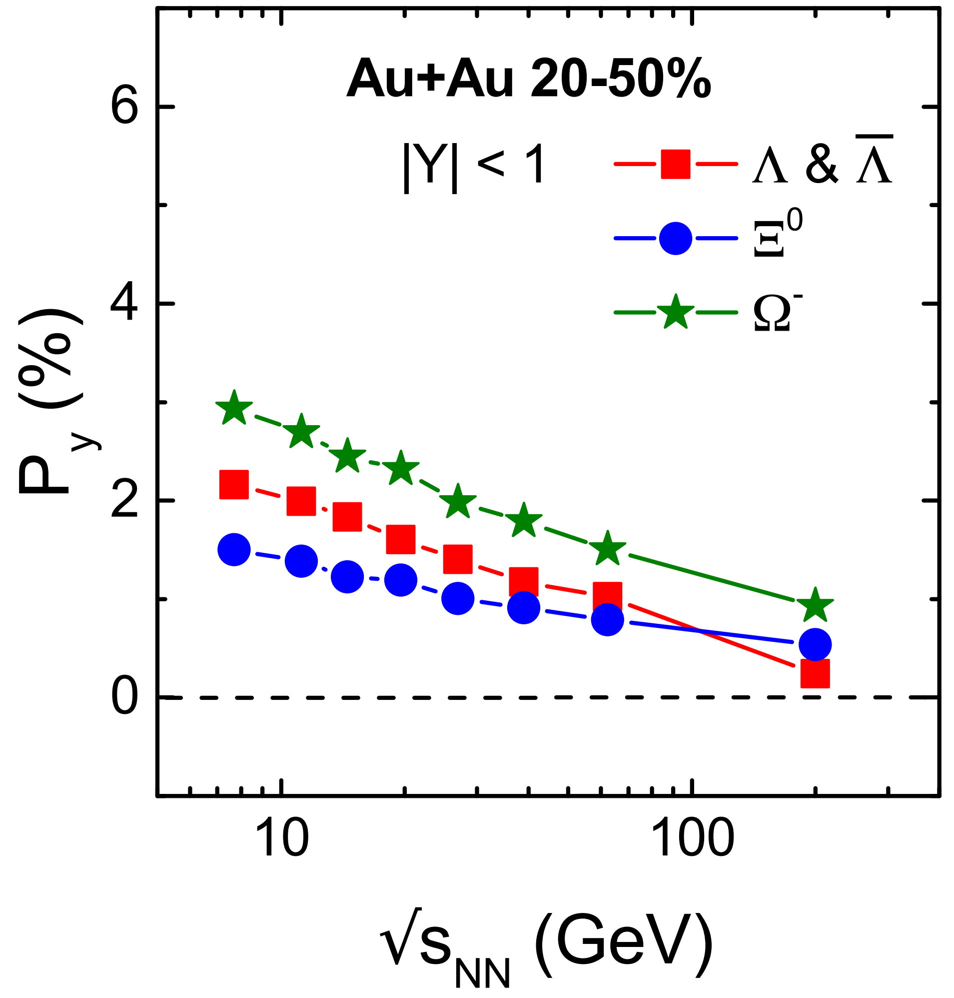
- STAR
  - High statistics data of 27 GeV and BES-II 7.7-19.6 GeV and Fixed-target 3-7.7 GeV with iTPC and EPD (x10 events, better EP, |η|<1.5)
  - Isobaric collision data (Ru+Ru, Zr+Zr), ~10% difference in B-field
  - Global polarization of multi-strangeness (Ξ and Ω)
  - Forward upgrade





- ALICE/CMS/ATLAS(?)
  - Global/local polarizations with more data at 5.02 TeV
- HADES
  - Systematic study with possible improvement is ongoing





Back up

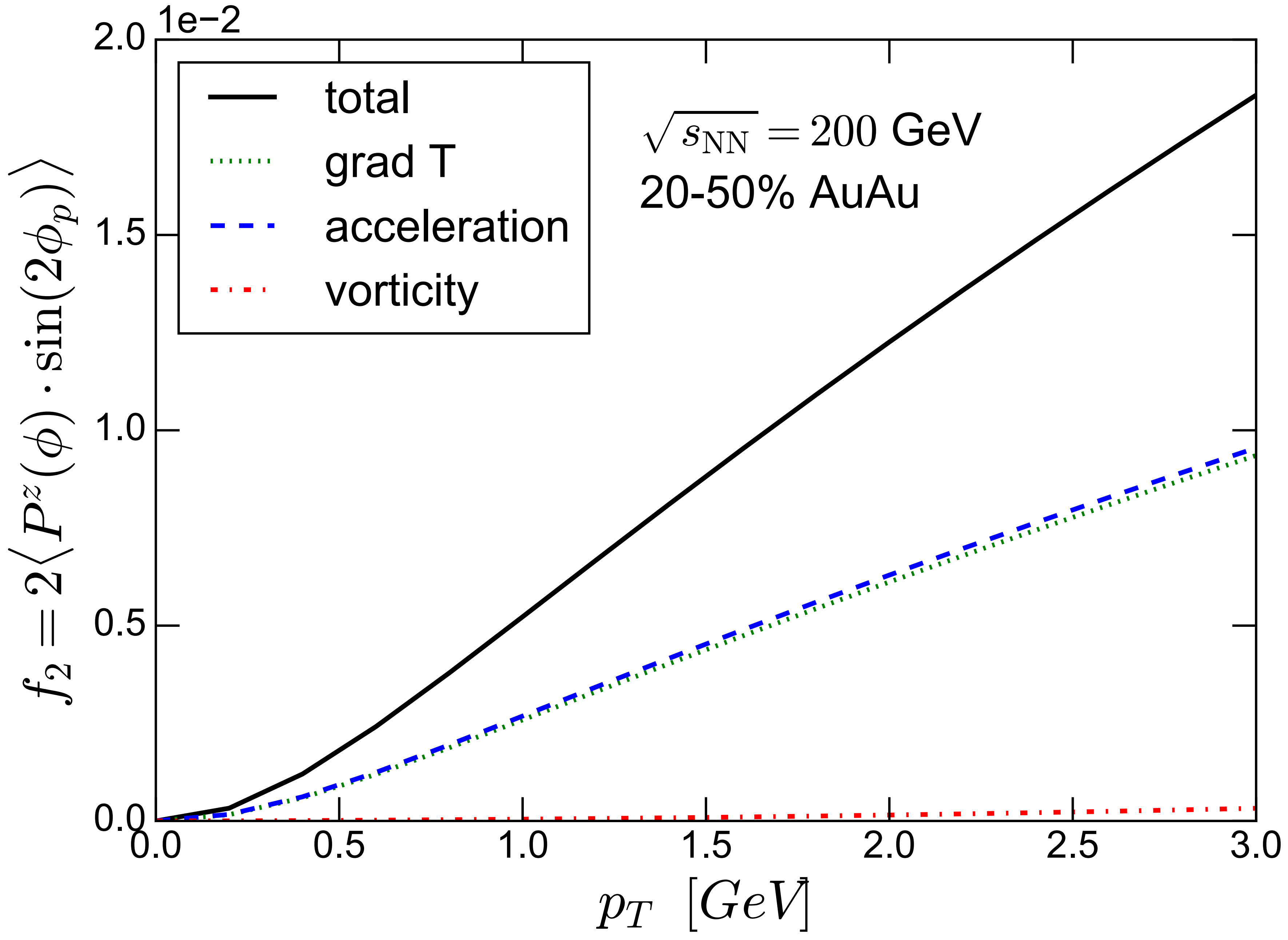
Contributions to P_z in hydro

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.

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

Variations of model parameters for P_H

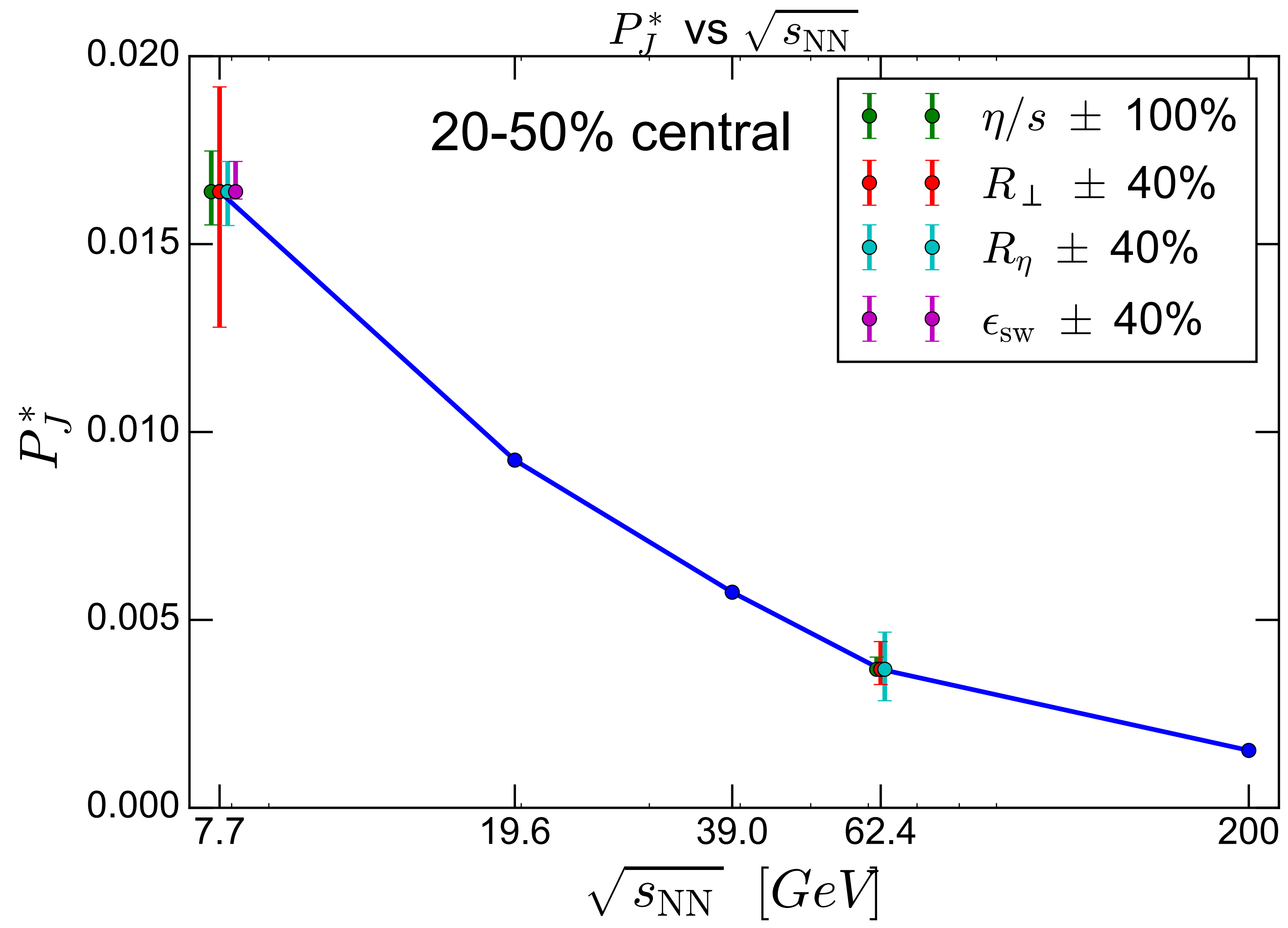
I. Karpenko, QM2017

Initial state:
$R_\perp$: transverse granularity
R_η: longitudinal granularity

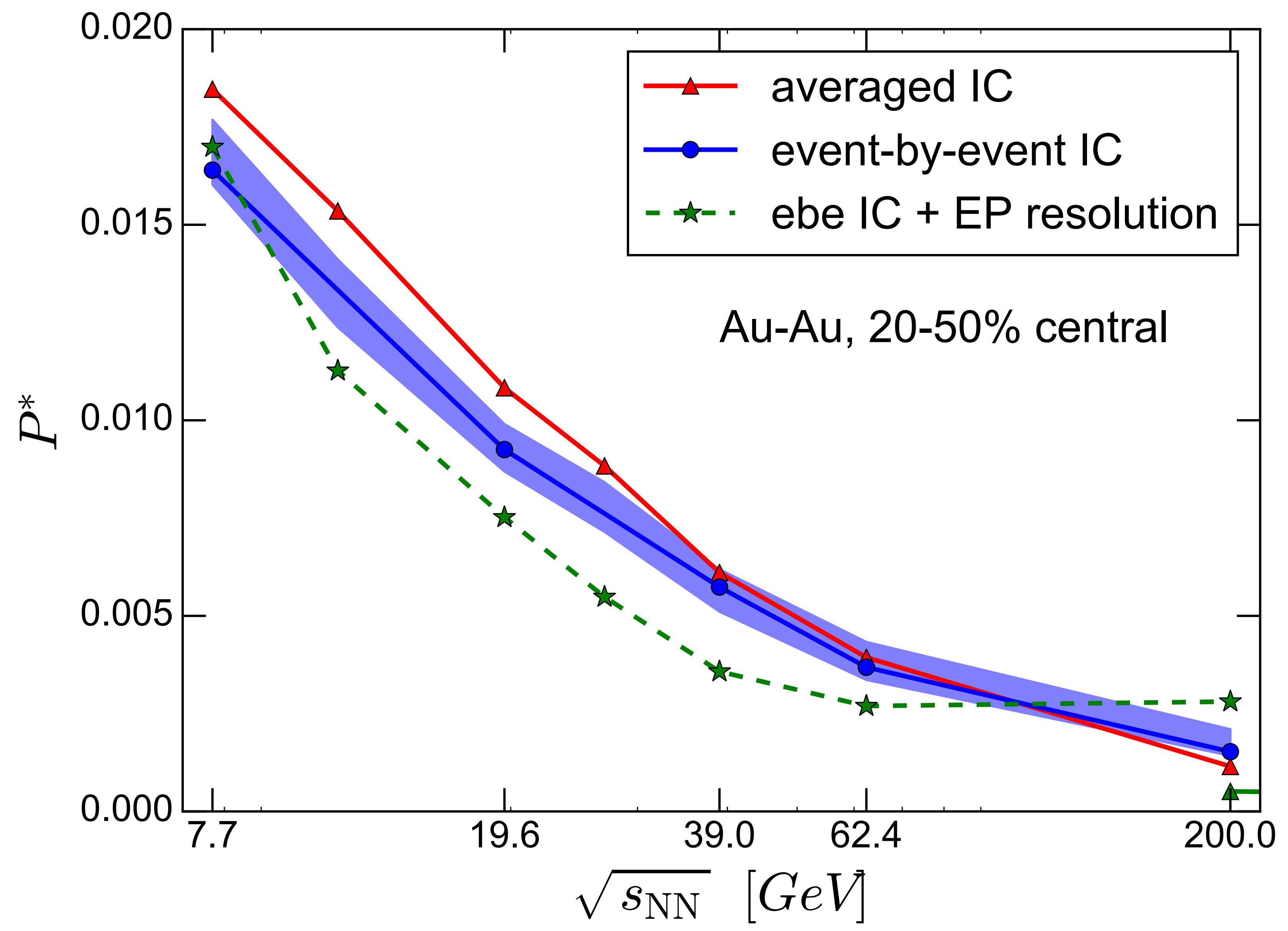
Fluid phase:
η/s: shear viscosity of fluid

Particlization criterion:
$\varepsilon_{sw} = 0.5$ GeV/fm^3

variation of model parameters



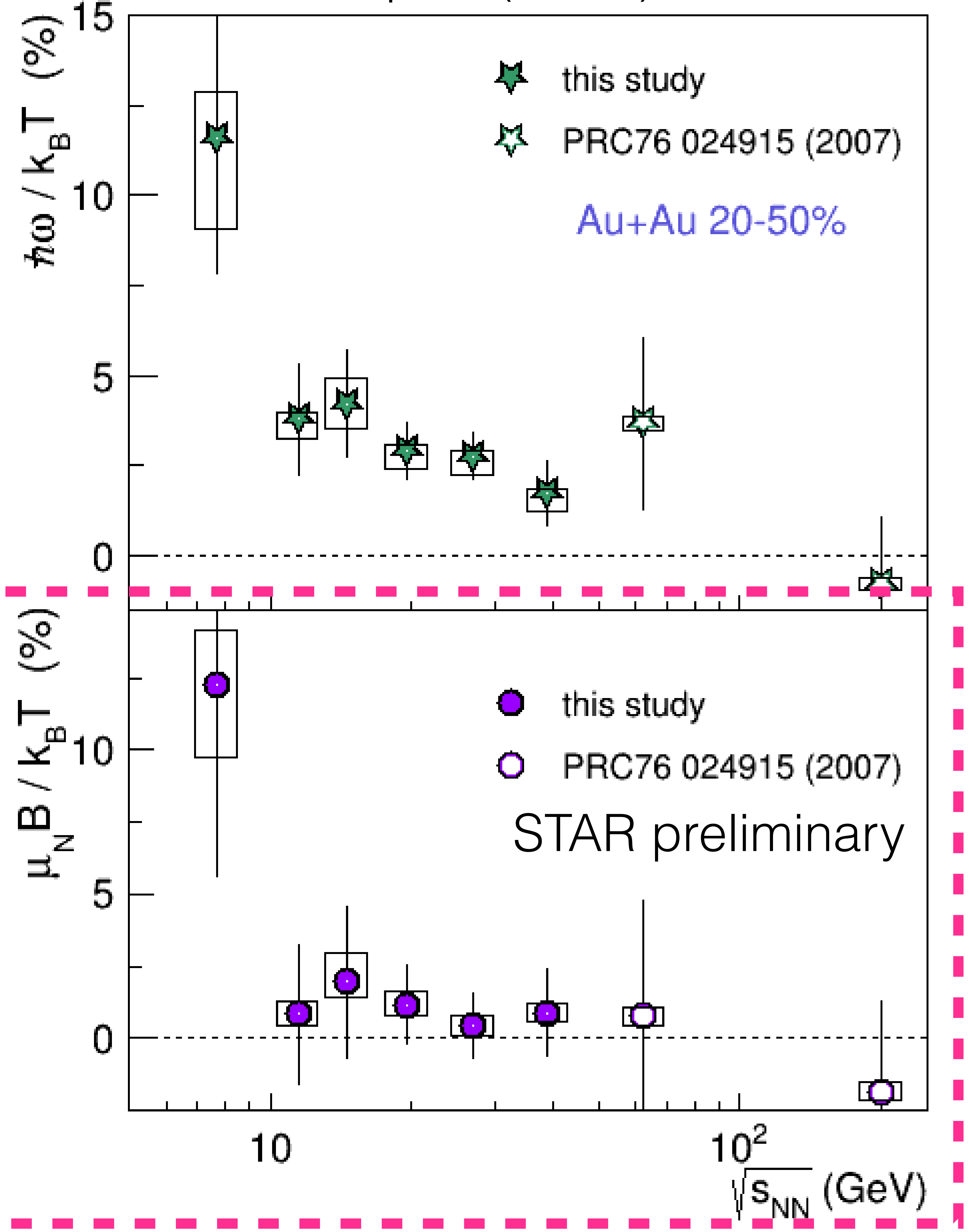
event-by-event vs. averaged



- Collision energy dependence is robust with respect to variation of the parameters of the model.
- There is no big difference between event-by-event and single shot hydrodynamic description.

Possible probe of magnetic field

QM17, I. Upsal (STAR)



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

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

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

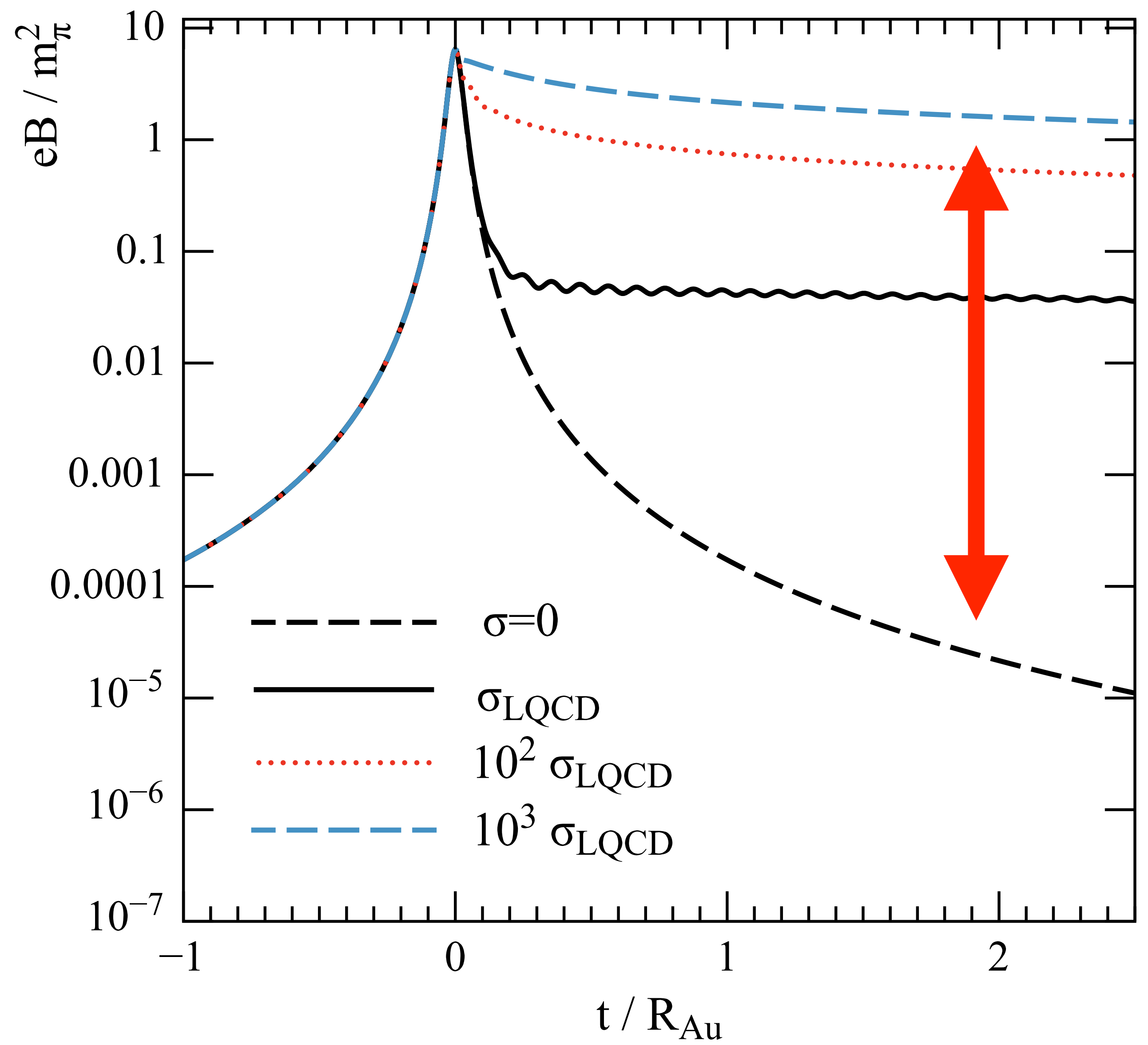
μ_Λ: Λ magnetic moment

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

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

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

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



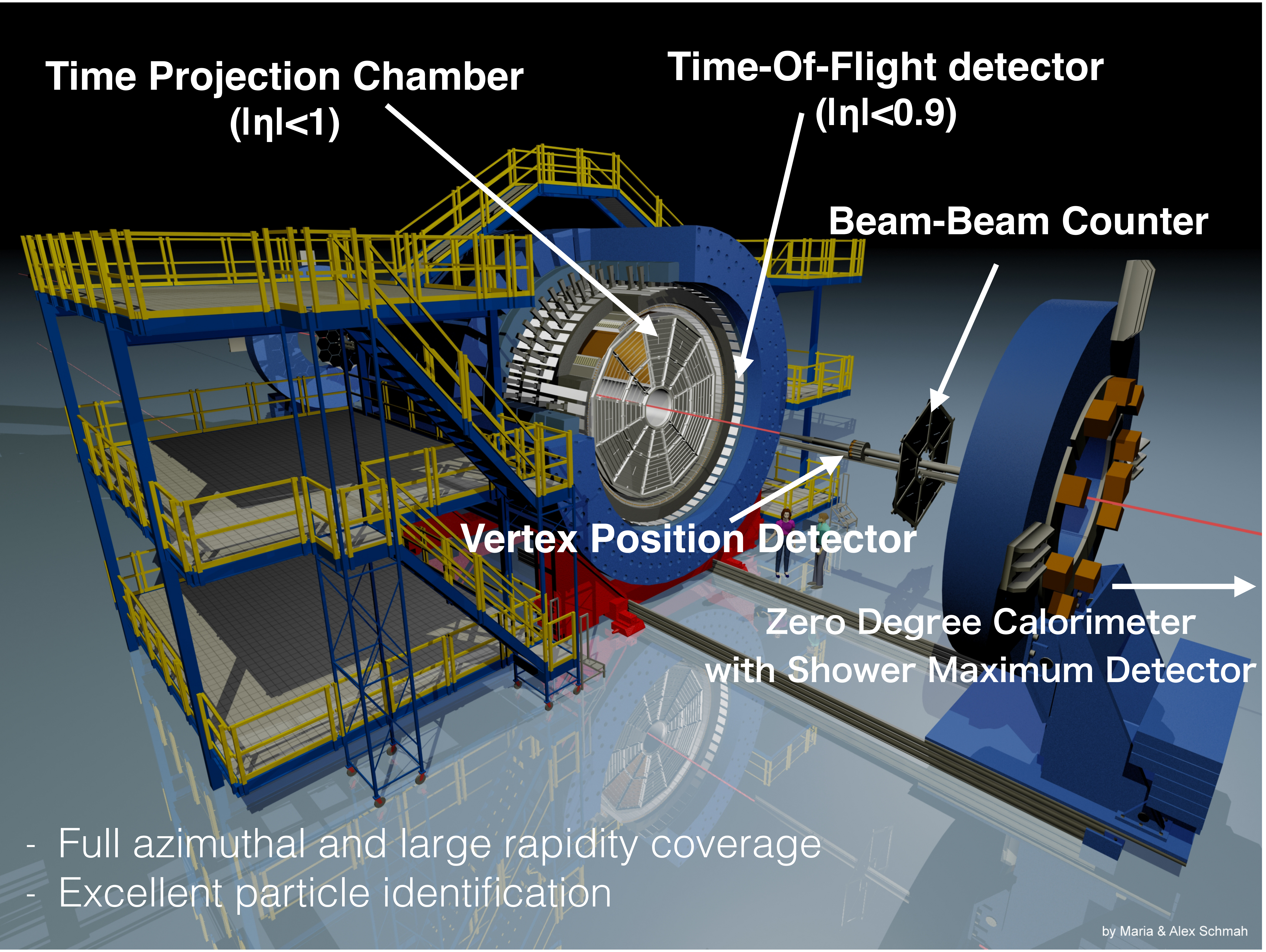
conductivity increases lifetime (not magnitude)

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

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

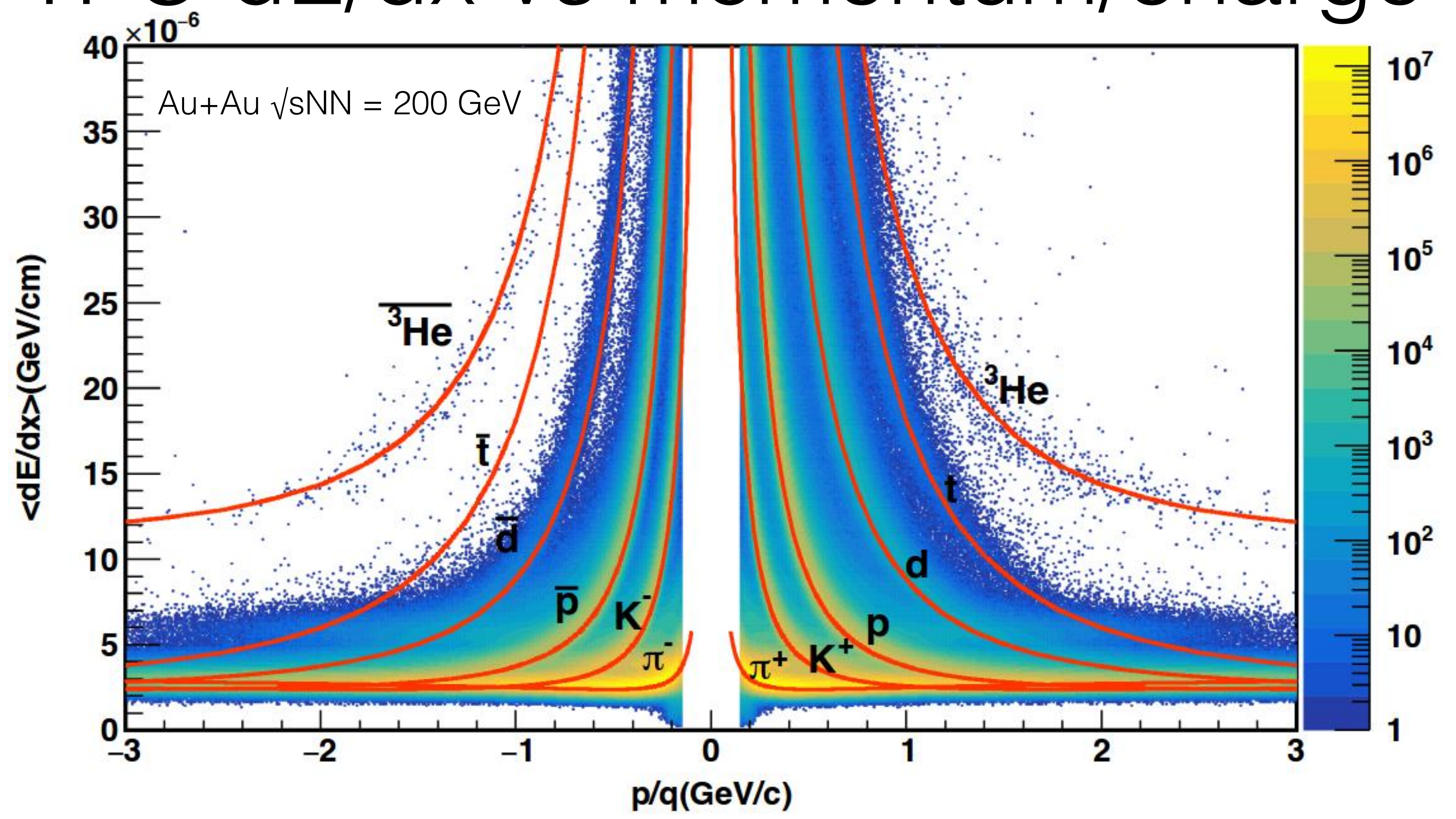
Extracted B-field is close to our expectation.
Need more data with better precision
→BES-II and Isobaric collisions

STAR Detectors

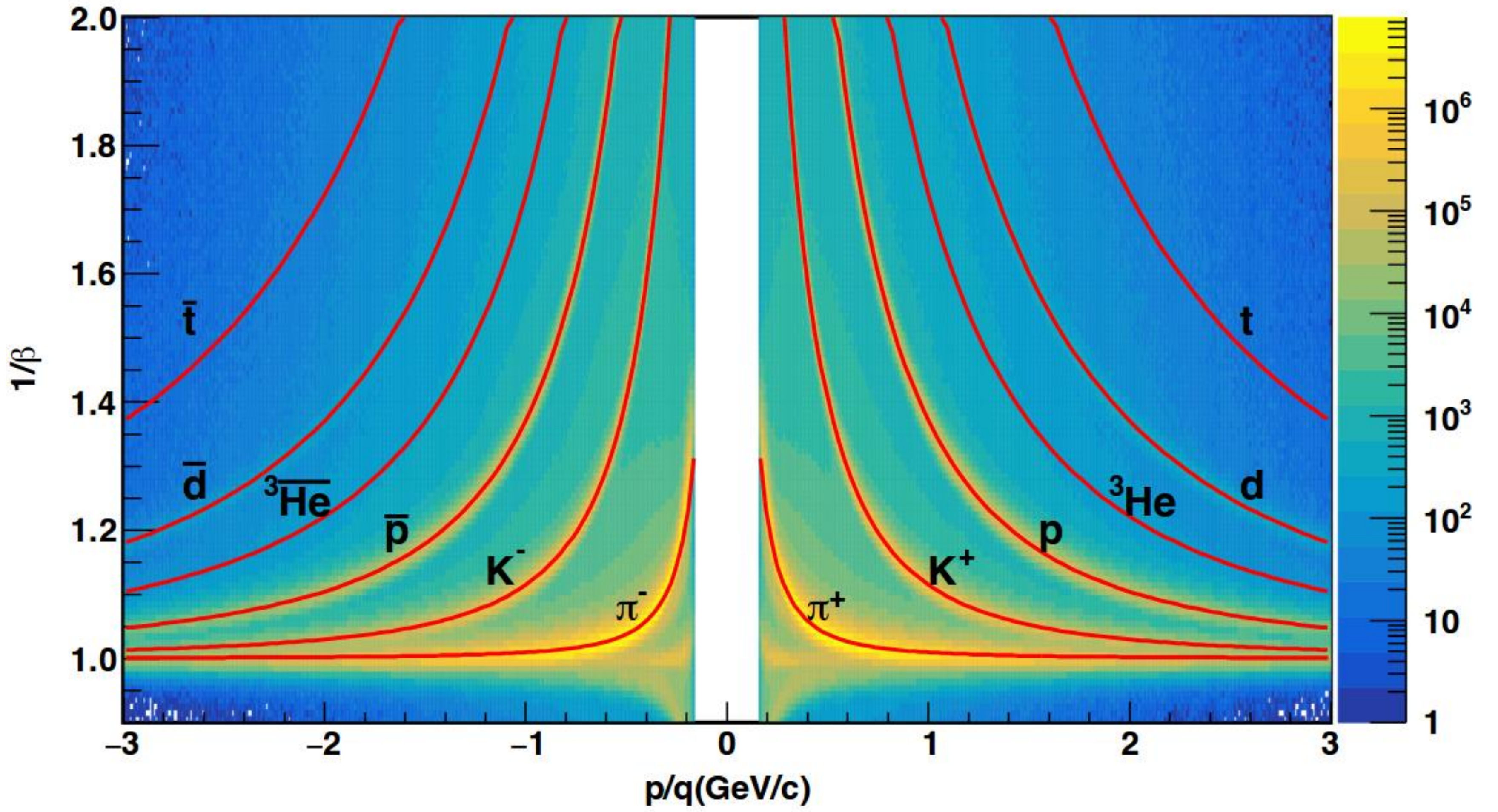


- Full azimuthal and large rapidity coverage
- Excellent particle identification

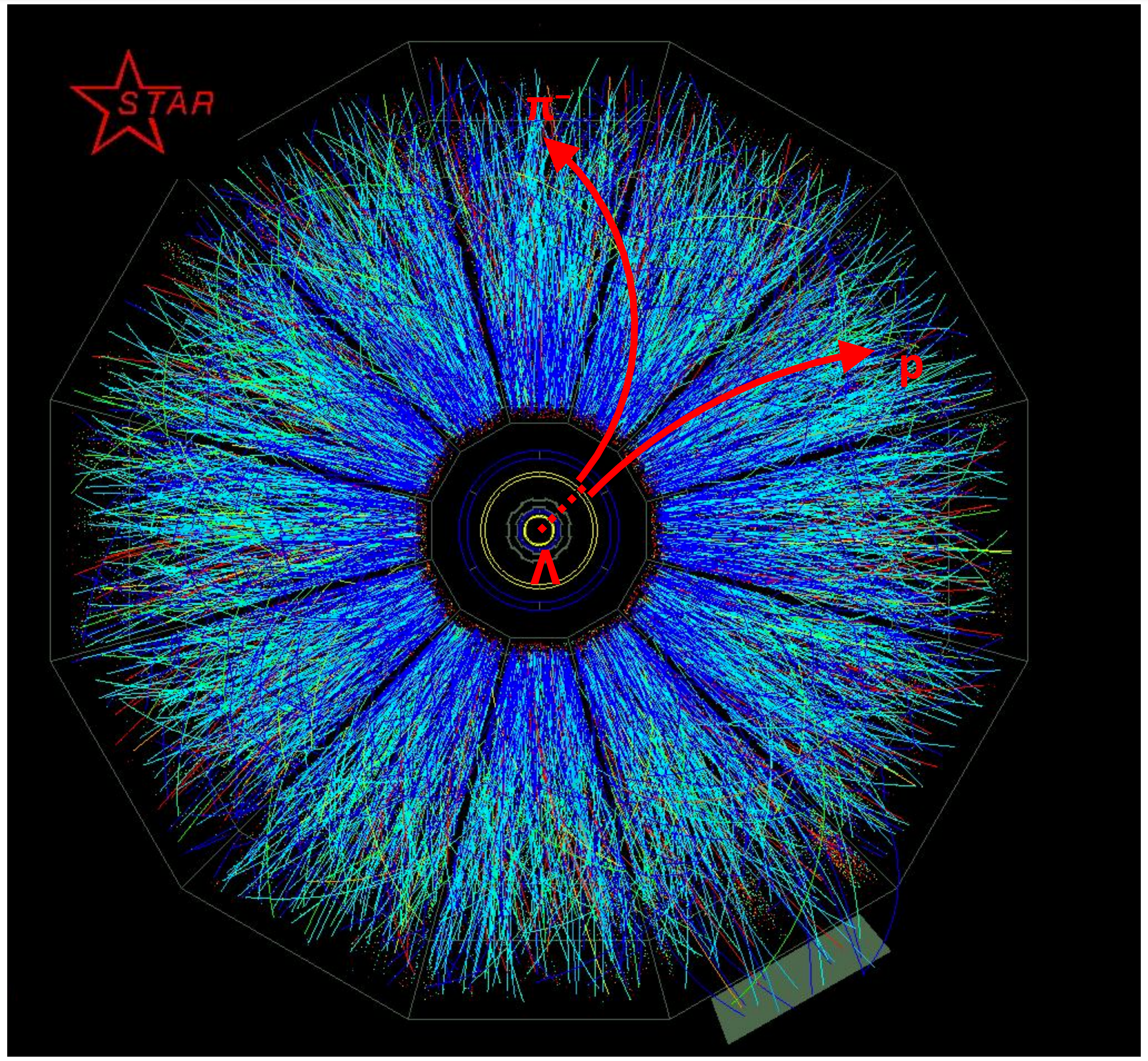
TPC dE/dx vs momentum/charge

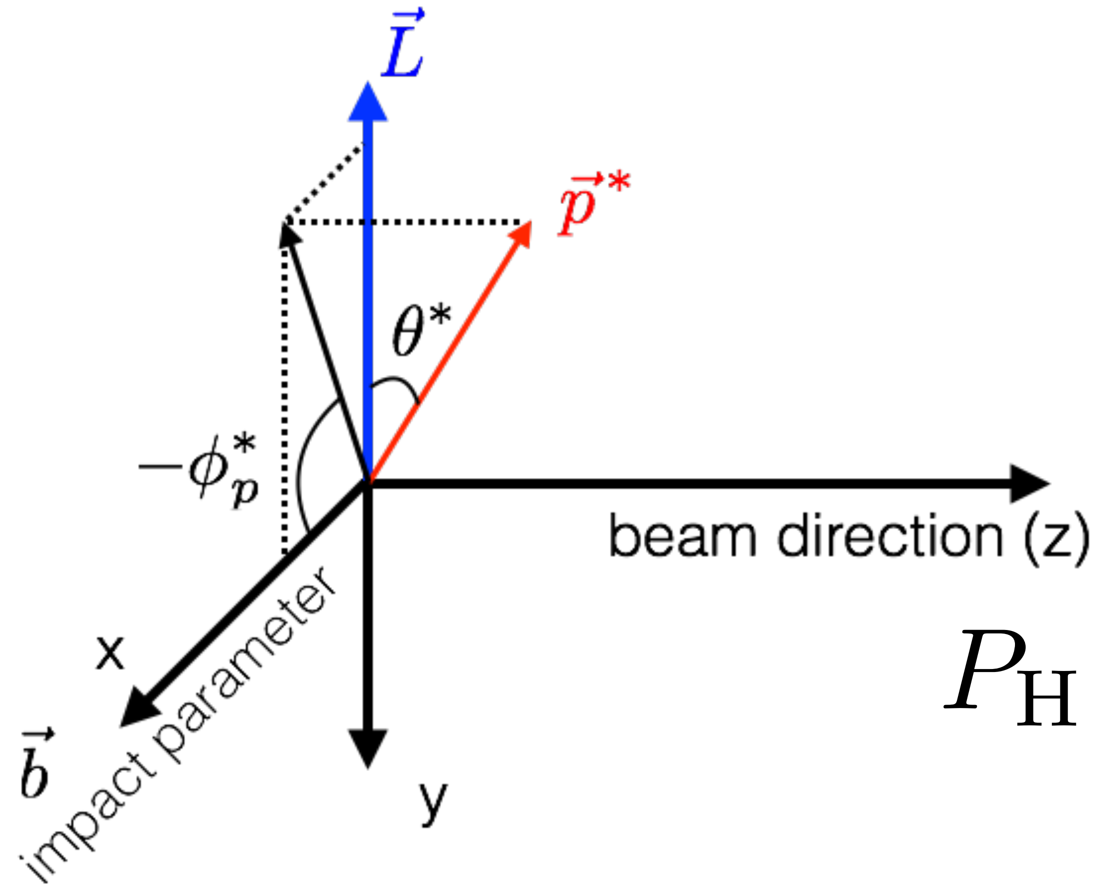


TOF 1/β vs momentum/charge



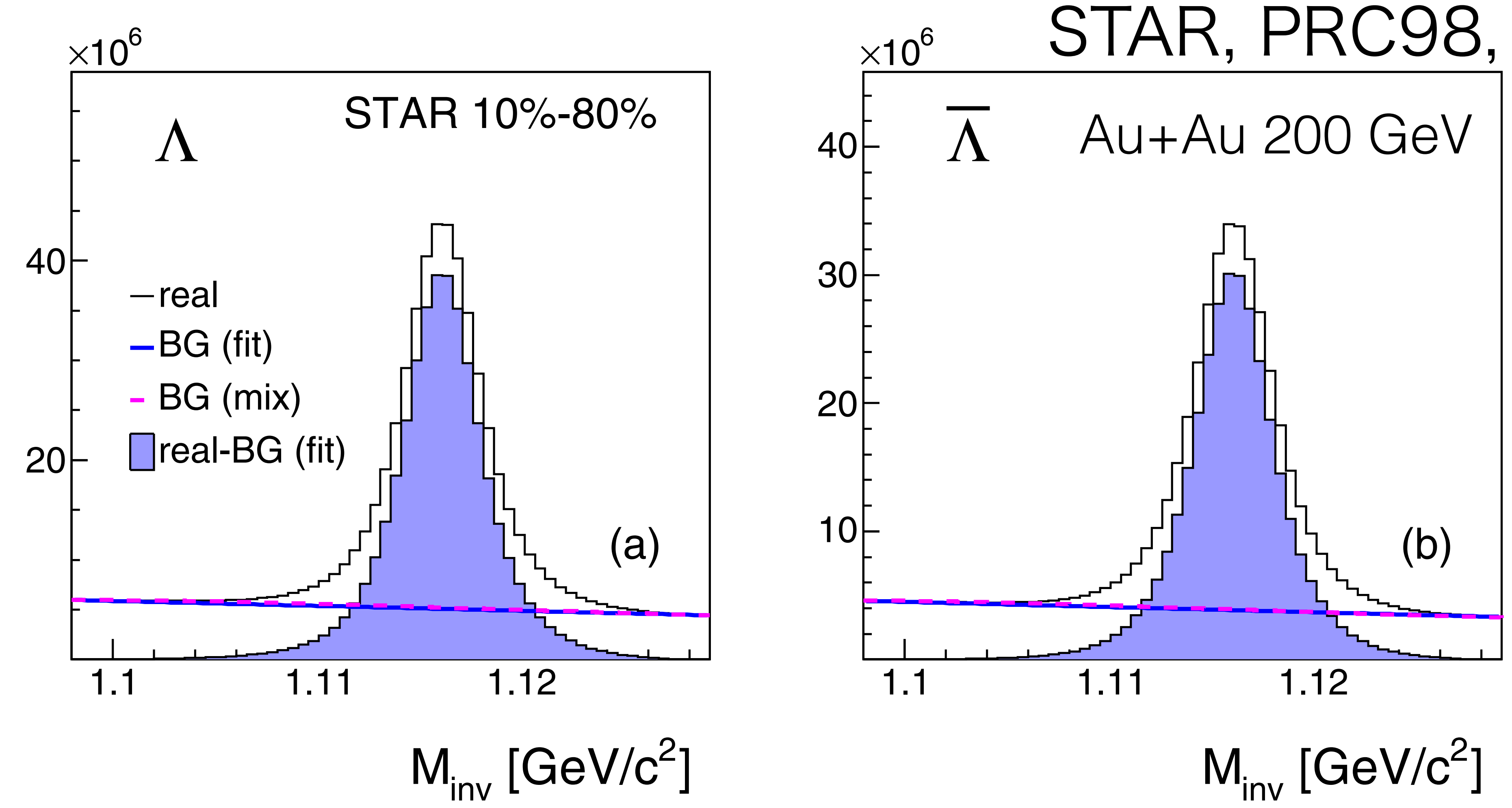
Signal extraction with Λ hyperons

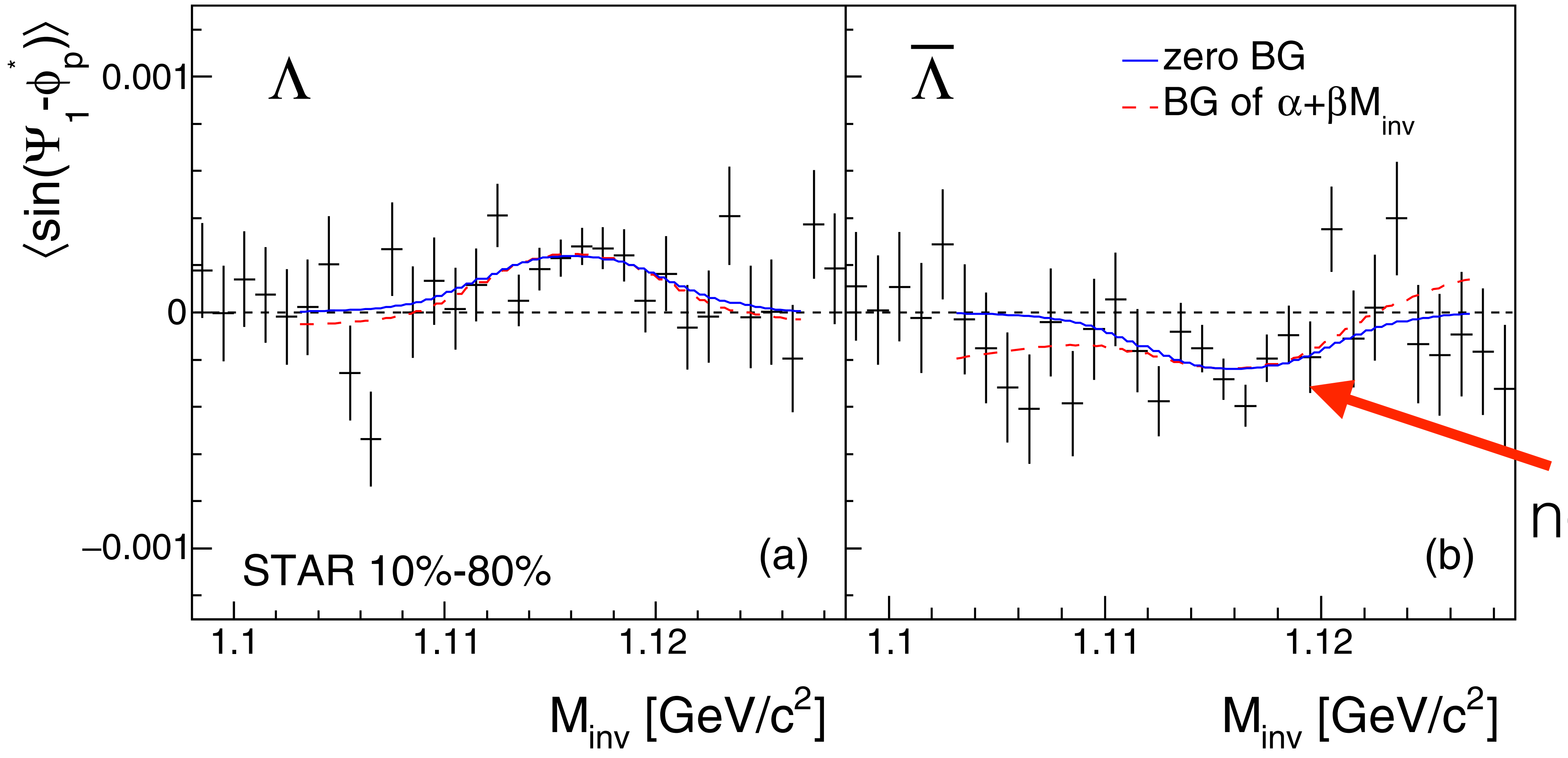




$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

STAR, PRC98, 014910 (2018)



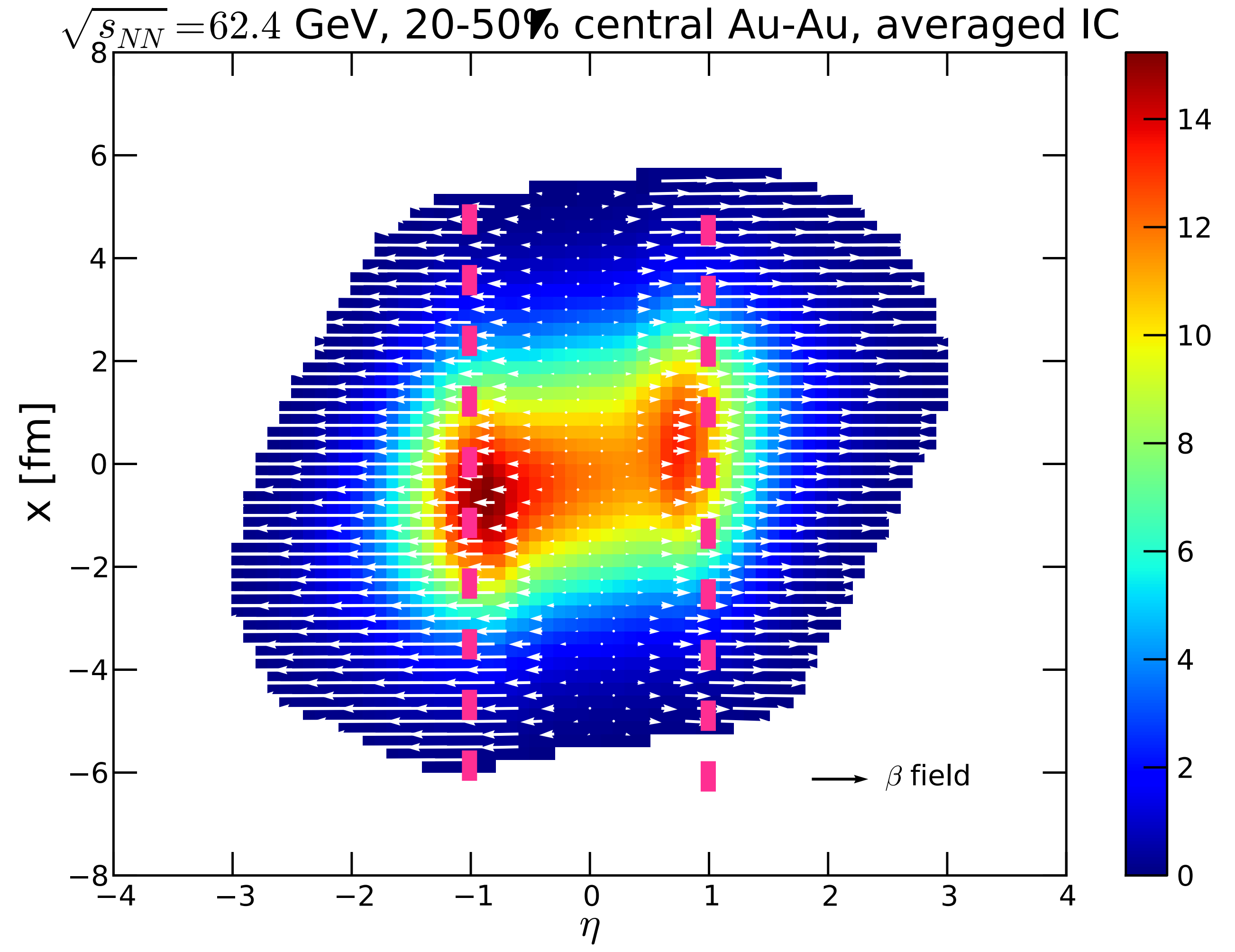


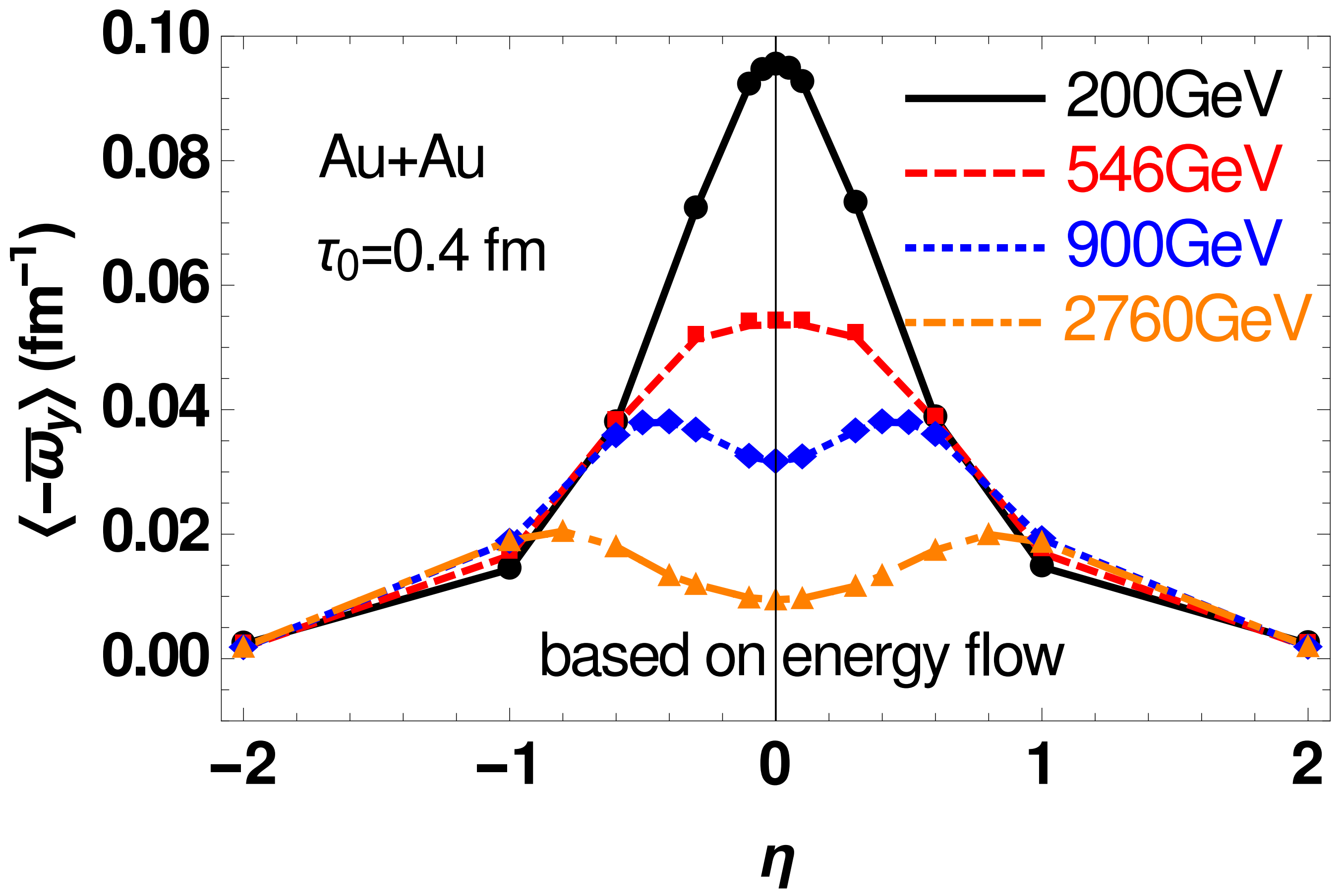
negative for anti-Λ

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

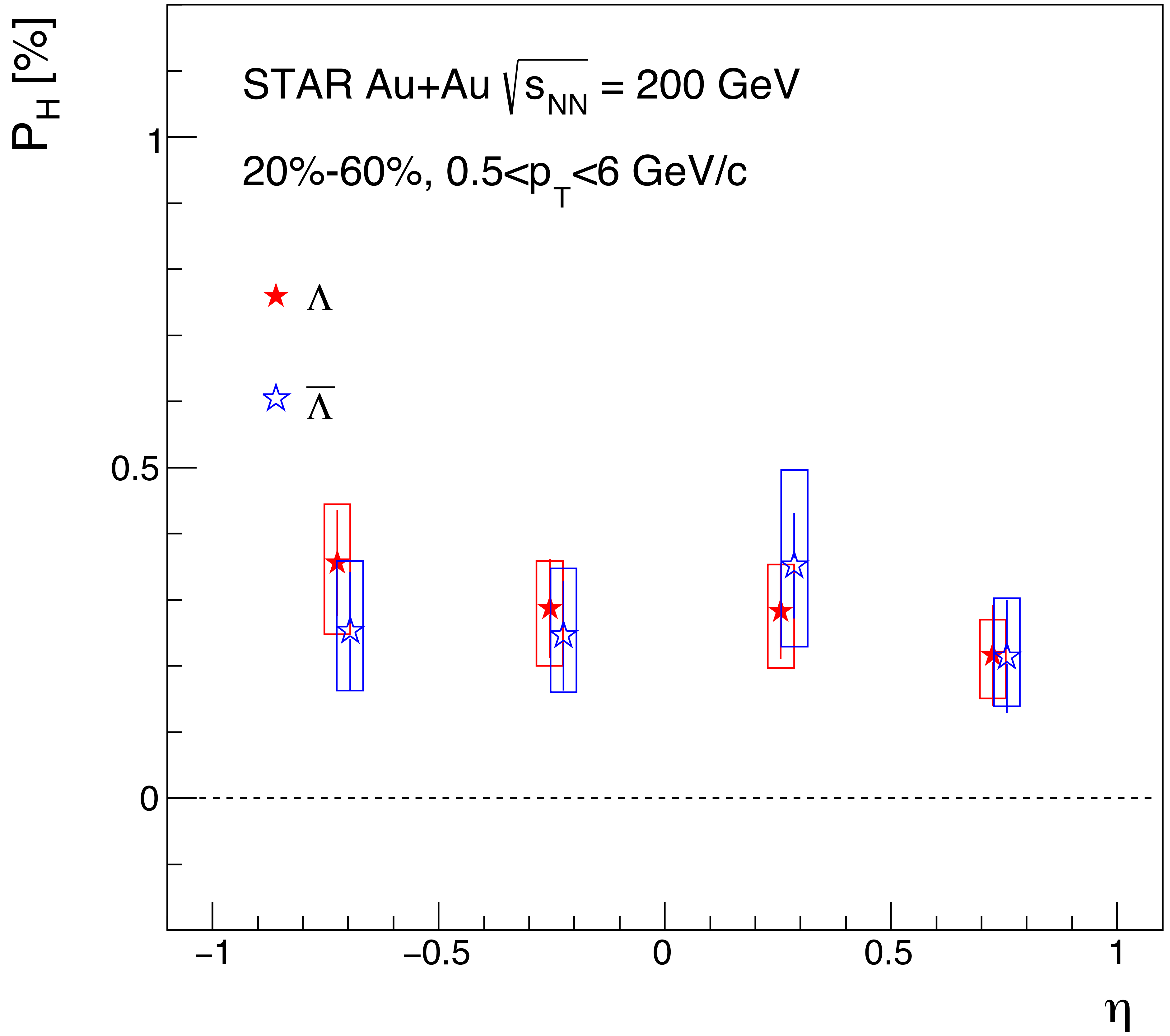
$$\langle \sin(\Psi_1 - \phi_p^*) \rangle^{\rm obs} = (1 - f^{\rm Bg}(M_{\rm inv})) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\rm Sg} + f^{\rm Bg}(M_{\rm inv}) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\rm Bg},$$

η dependence of P_H





STAR, PRC98, 014910 (2018)



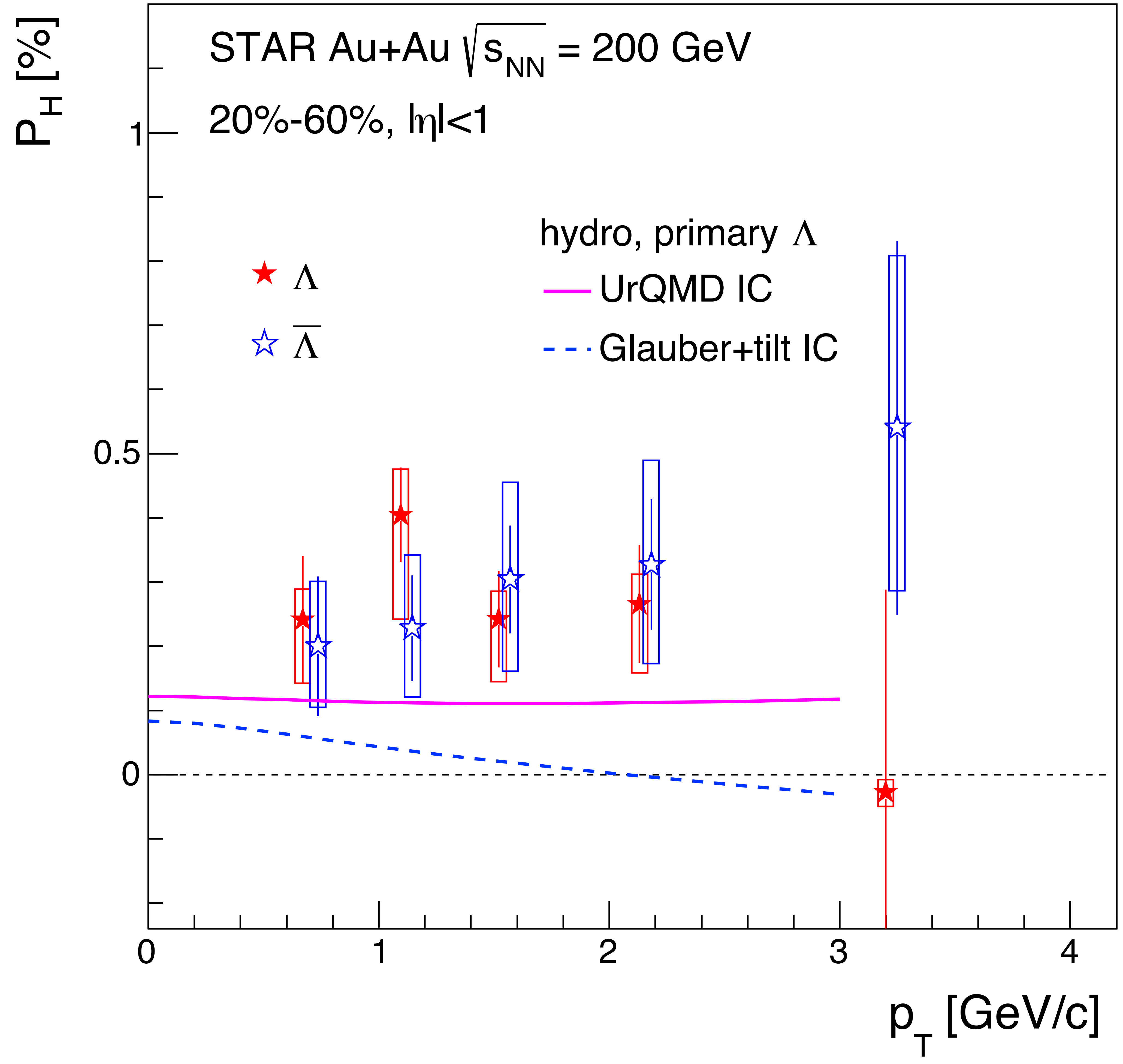
- Shear flow structure/initial flow velocity would be stronger in forward/backward region
- Expect rapidity dependence of the polarization

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)



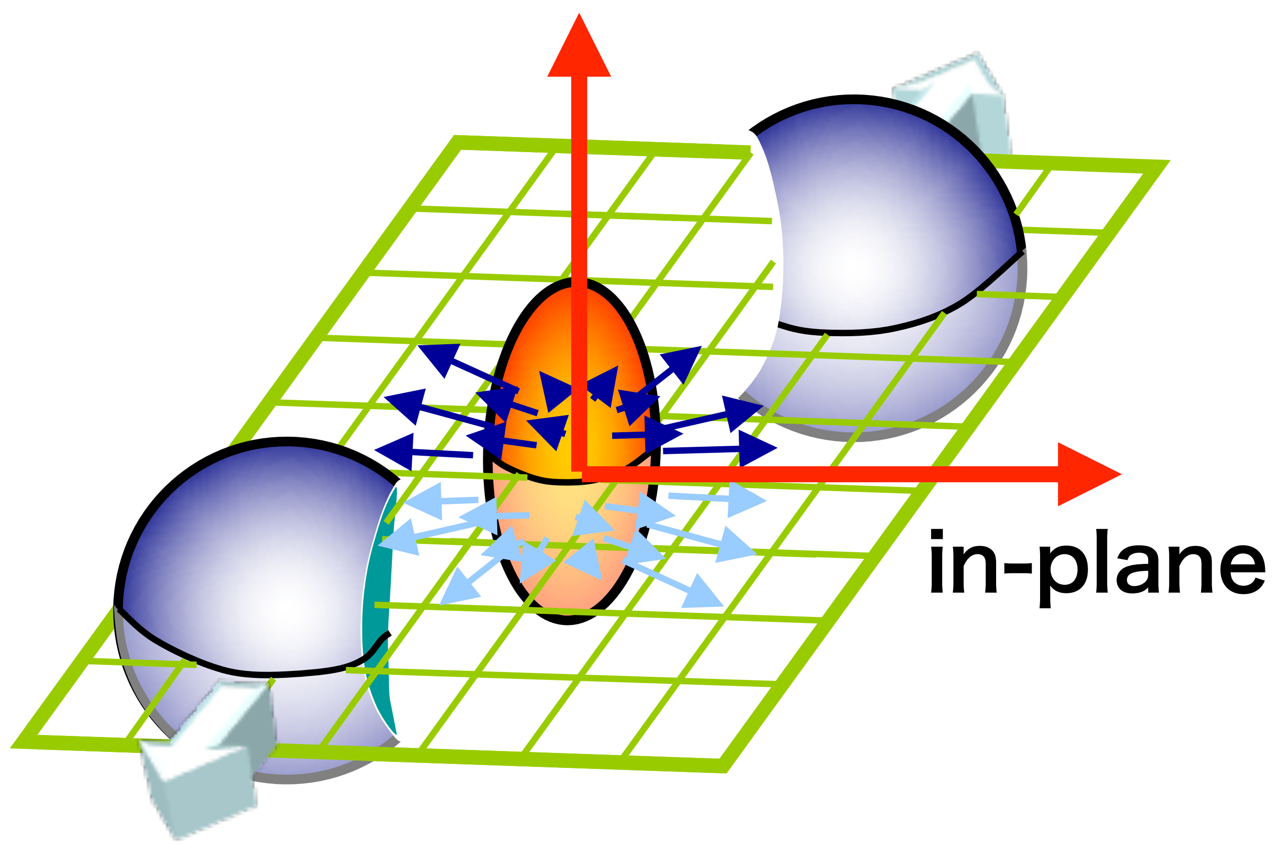
- No significant p_T dependence, as expected from the initial angular momentum of the system
- Hydrodynamic model underestimates the data. Initial conditions affect the magnitude and dependence on p_T

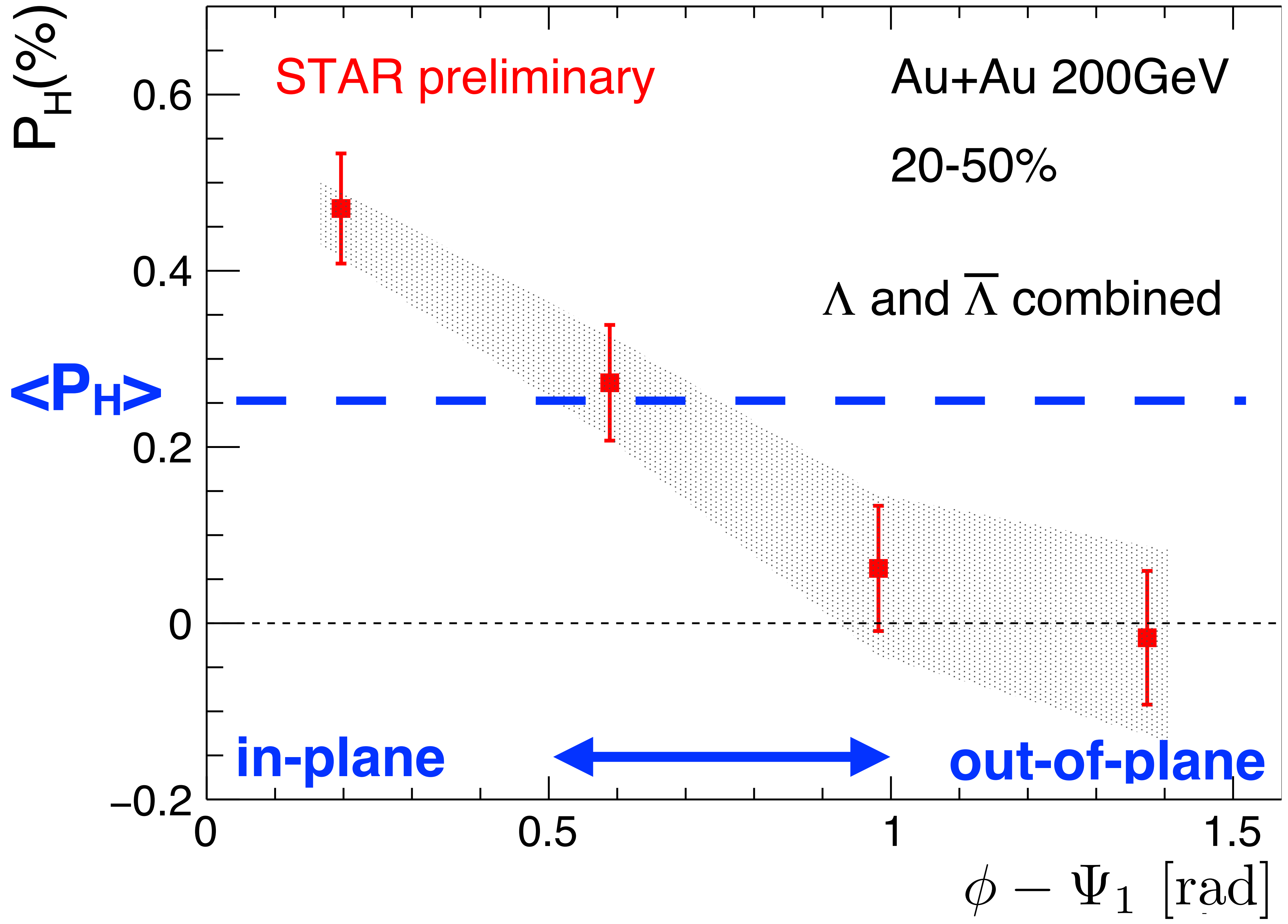
3D viscous hydrodynamic model with two initial conditions (ICs)

- UrQMD IC
- Glauber with source tilt IC

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

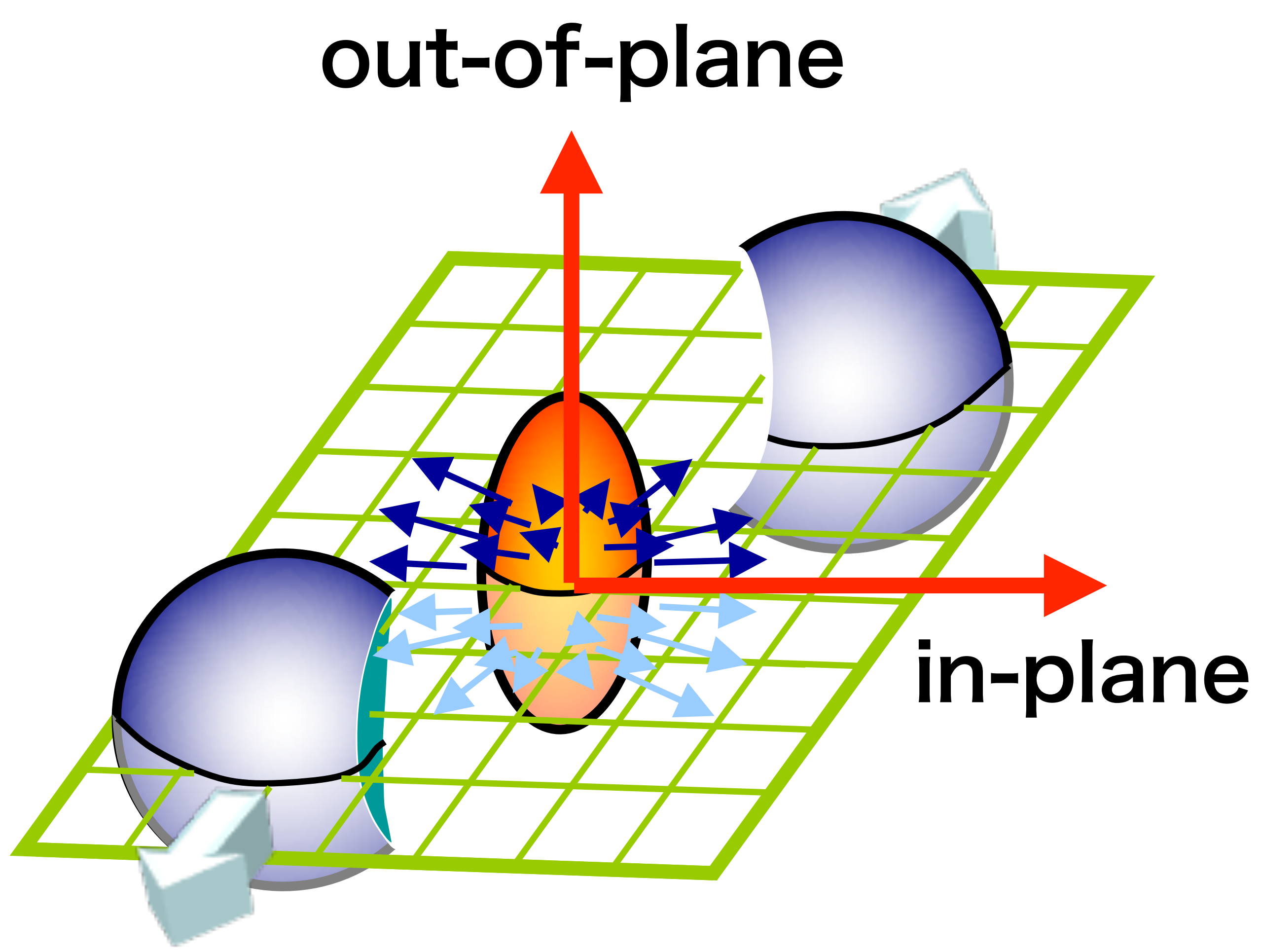
Azimuthal angle dependence of P_H

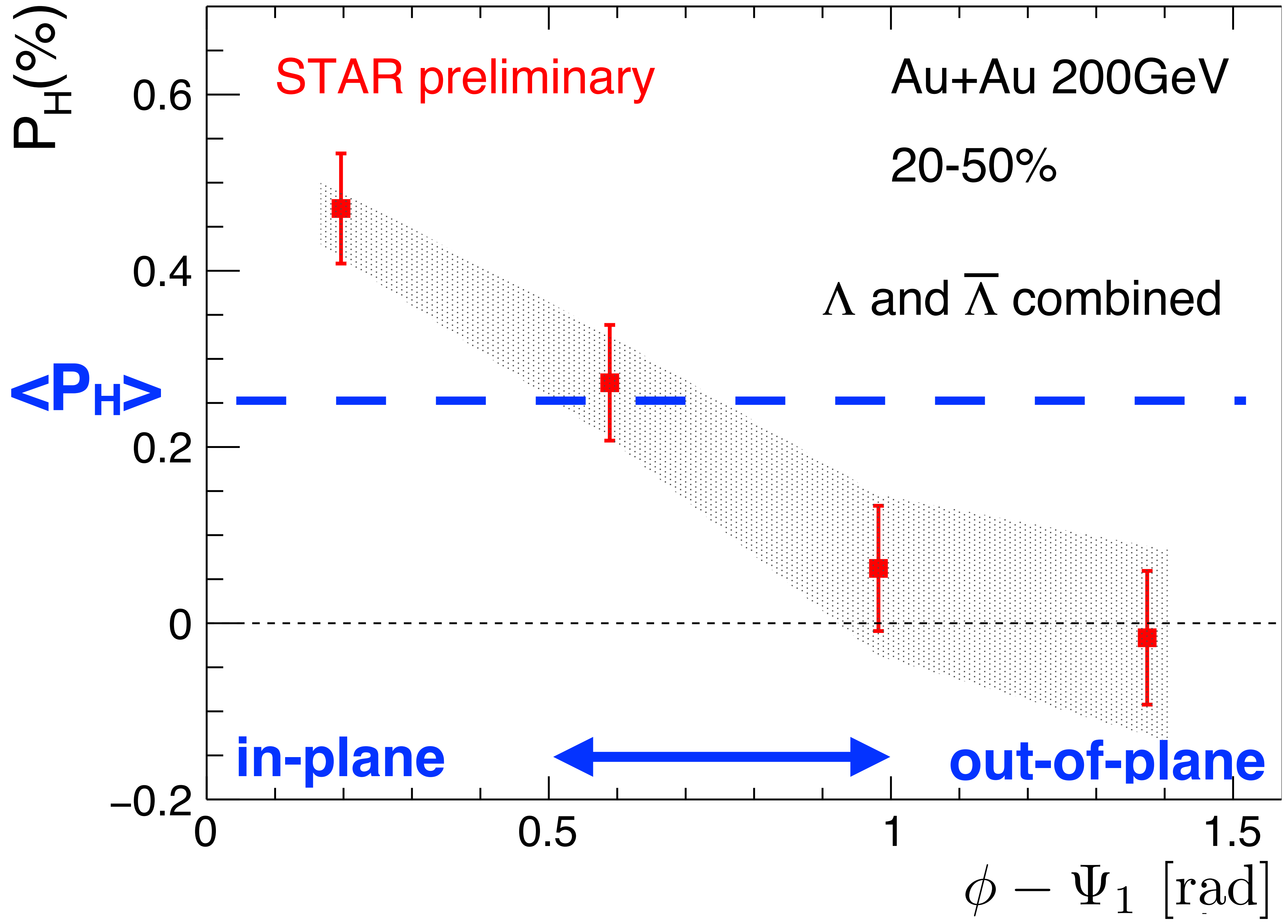


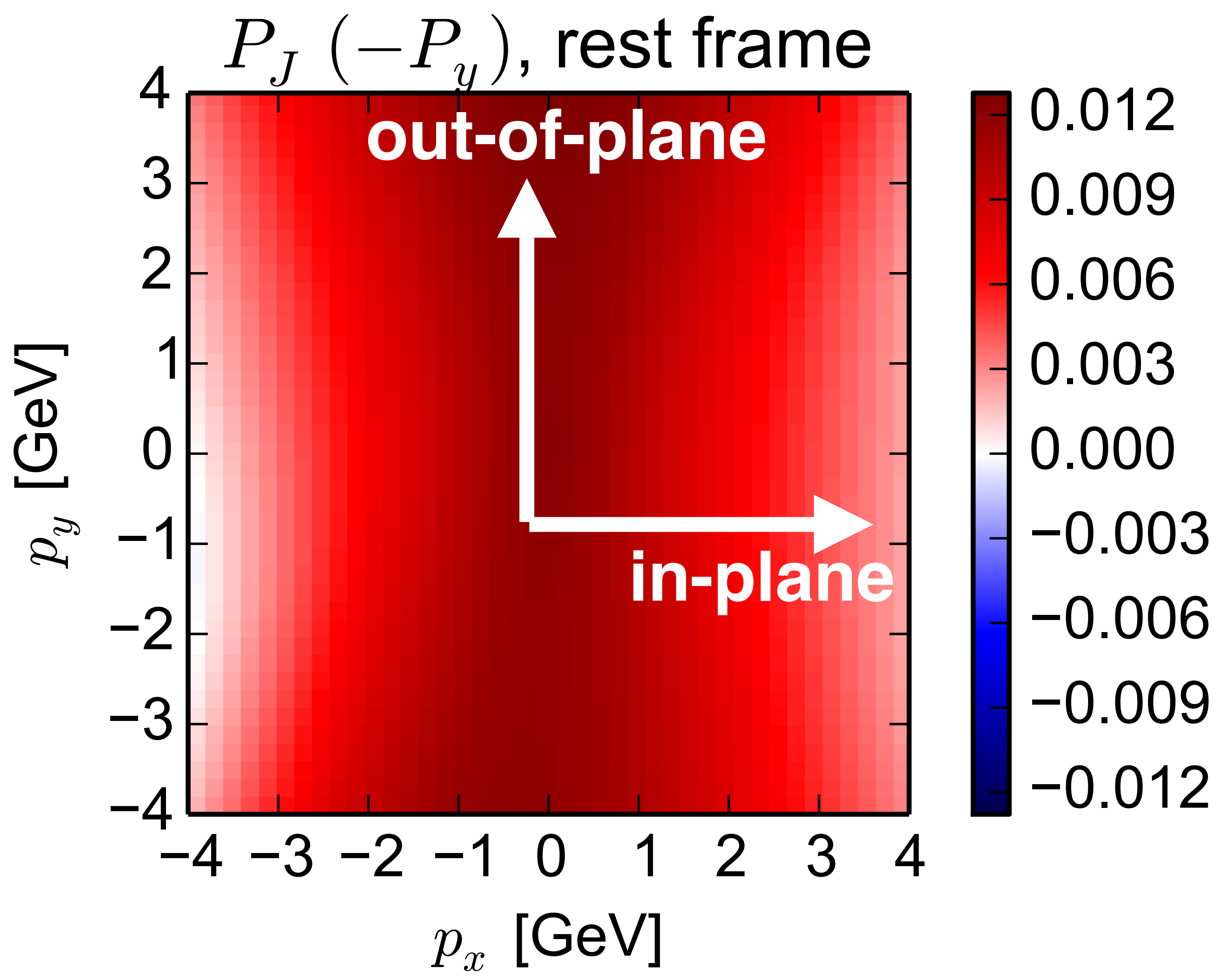


✦ Larger polarization in in-plane than in out-of-plane

Azimuthal angle dependence of P_H





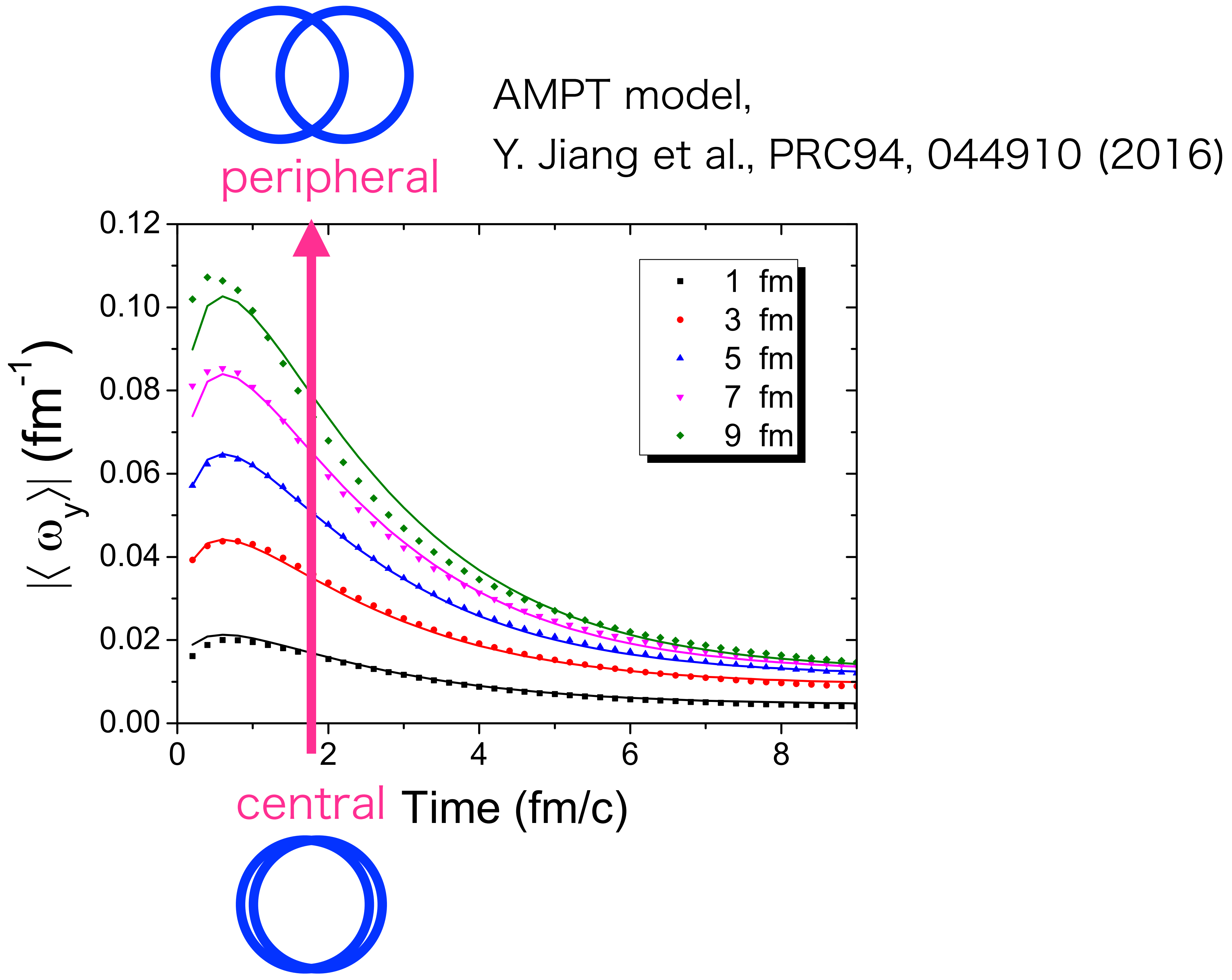


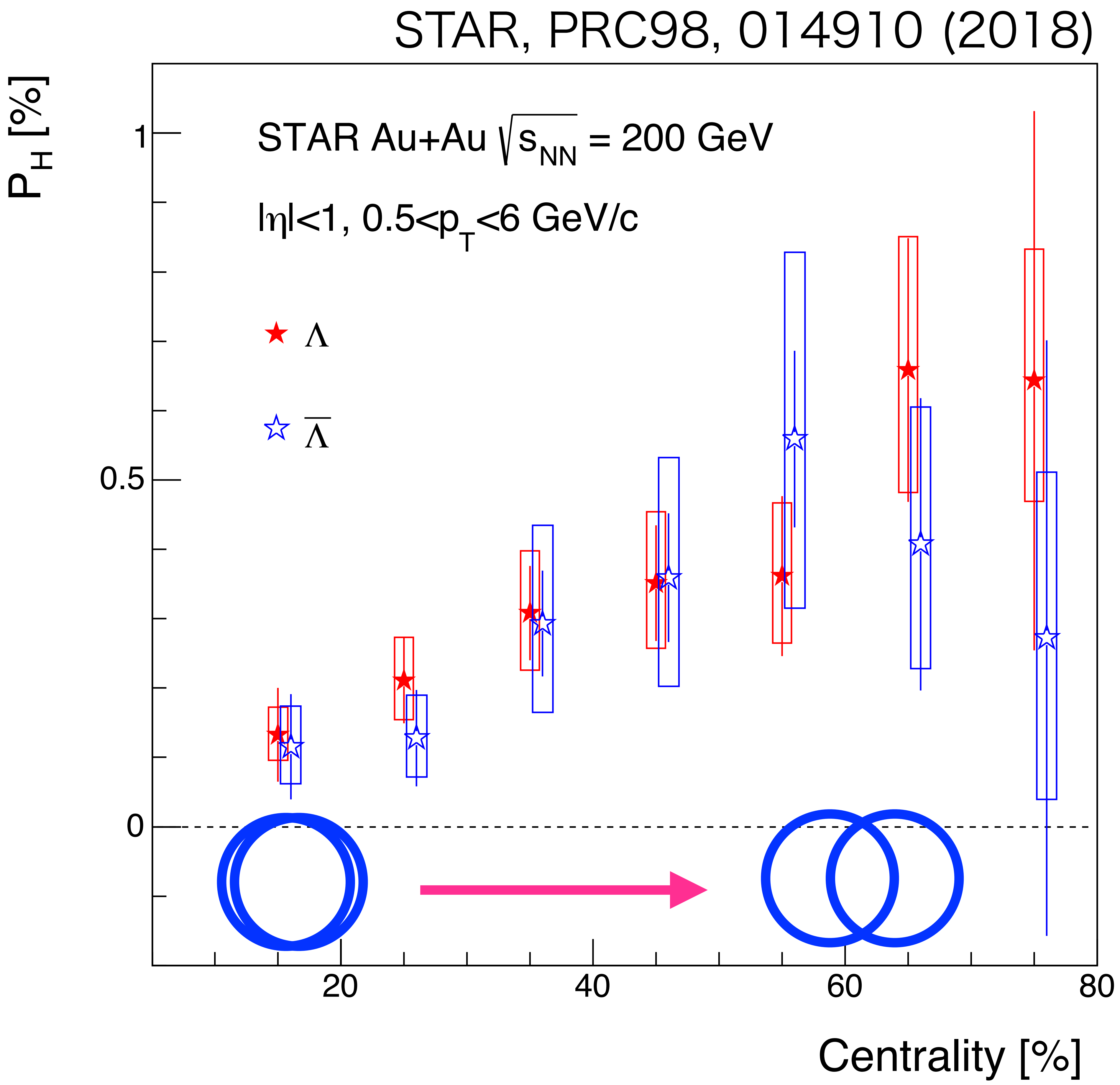
I. Karpenko and F. Becattini, EPJC(2017)77:213

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

✦ Opposite to the hydrodynamic expectation (larger in out-of-plane)

Centrality dependence of P_H

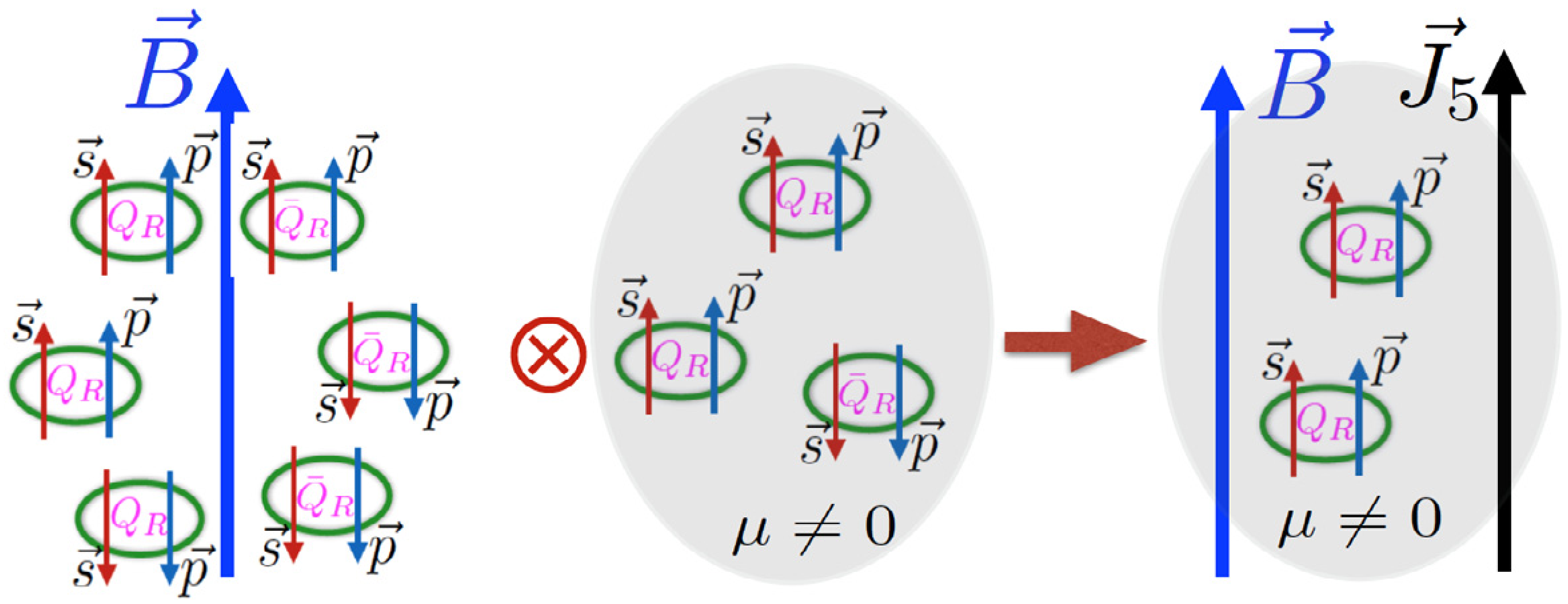




In most central collision → no initial angular momentum
As expected, the polarization decreases in more central collisions

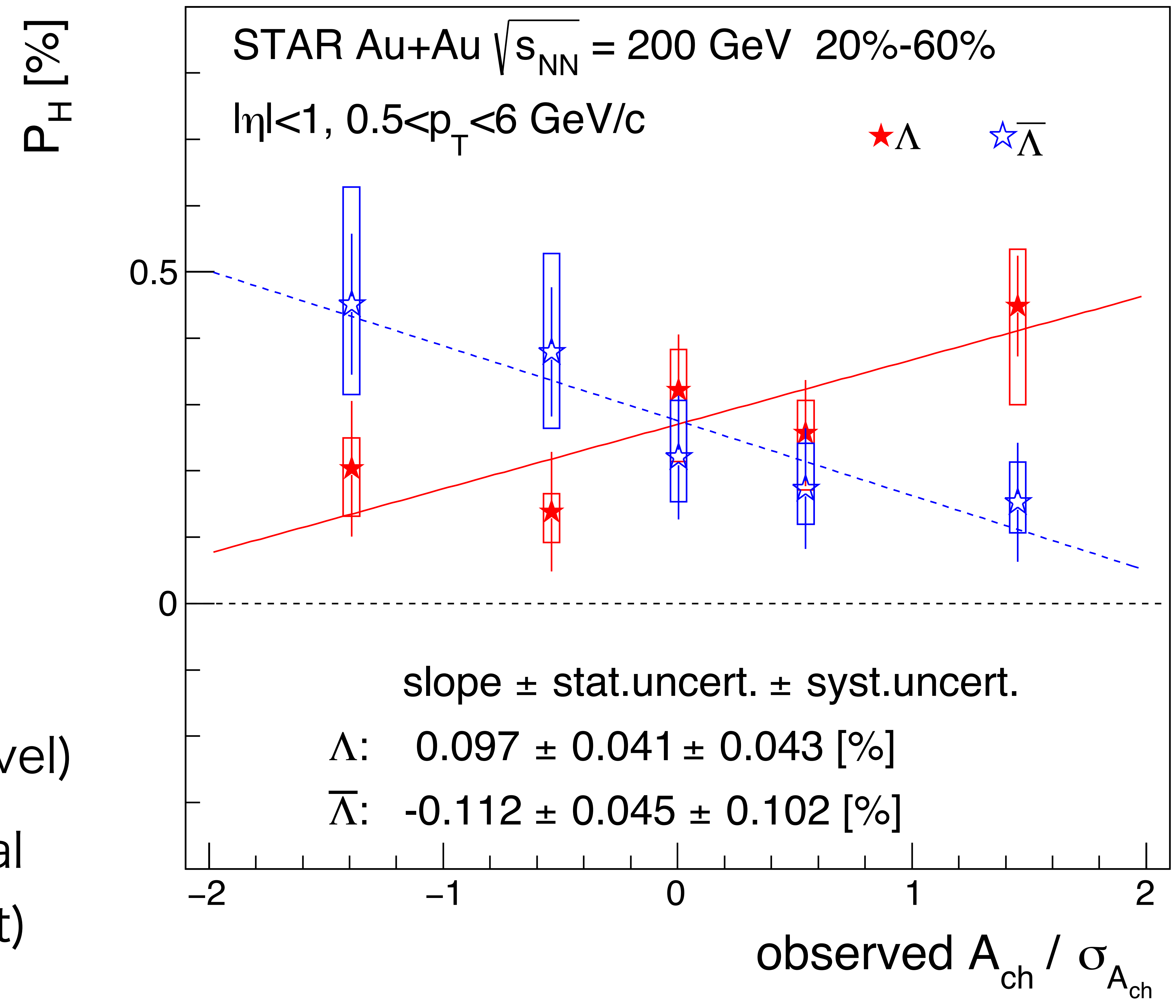
Λ polarization vs. charge asymmetry

Chiral Separation Effect



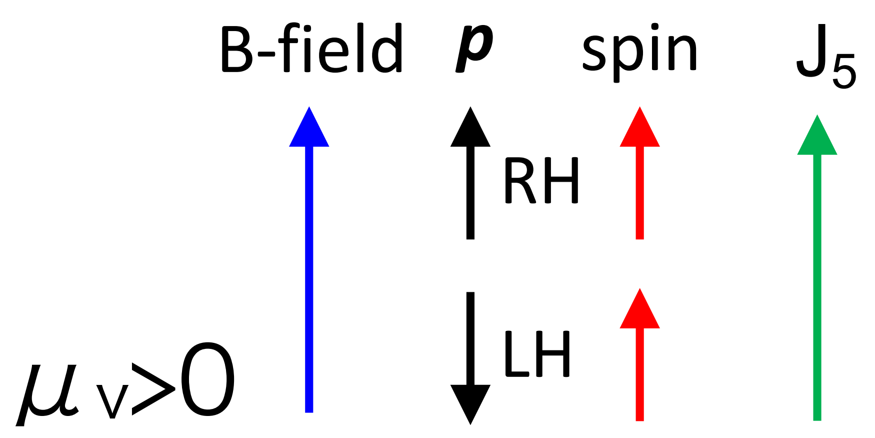
$$\mathbf{J}_5 \propto e\mu_{\mathrm{v}}\mathbf{B}$$

STAR, PRC98, 014910 (2018)



B-field + massless quarks + non-zero μ_V → axial current J_5

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



- Slopes of Λ and anti-Λ seem to be different (~2σ level)
- Possible contribution to the polarization from the axial current J_5 induced by B-field (Chiral Separation Effect)
  S. Shlichting and S. Voloshin

Rotation vs. Polarization

<u>Barnett effect:</u>

rotation→polarization

Magnetization of an uncharged body when spun on its axis

S. Barnett, Phys. Rev. 6, 239 (1915)

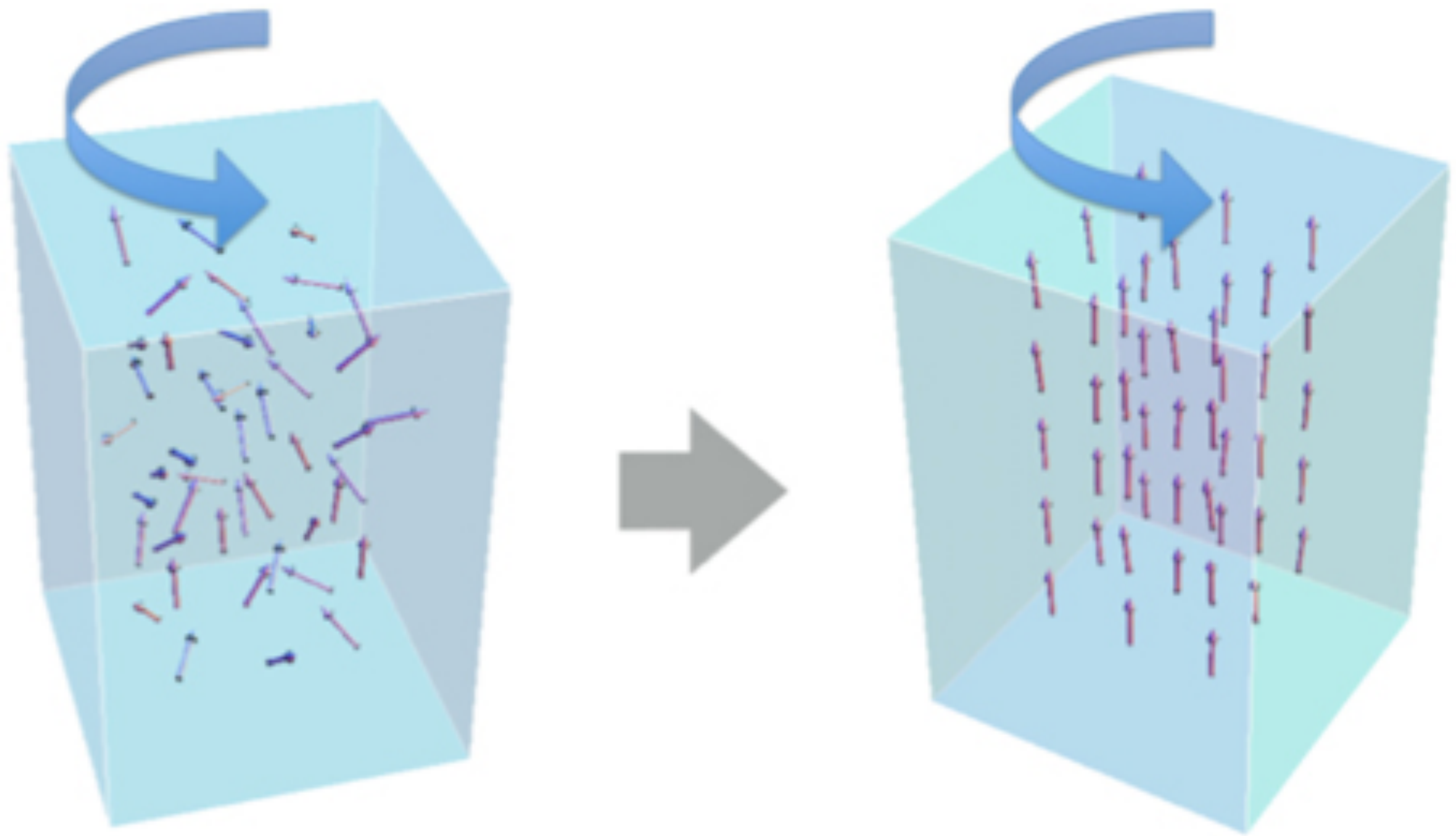


figure: M. Matsuo et al., Front. Phys., 30 (2015)

$$M = \frac{\chi\omega}{\gamma}$$

χ: magnetic susceptibility

γ: gyromagnetic ratio

<u>Einstein-de-Haas effect:</u>

polarization→rotation

"the only experiment by Einstein"

Rotation of a ferromagnet under change in the direction/strength of magnetic-field to conserve the total angular momentum.

$$\vec{J} = \vec{L} + \vec{S}$$

A.Einstein, W. J. de Haas,
B.Koninklijke Akademie van Wetenschappen te Amsterdam,
C.Proceedings, 18 I, 696-711 (1915)

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)

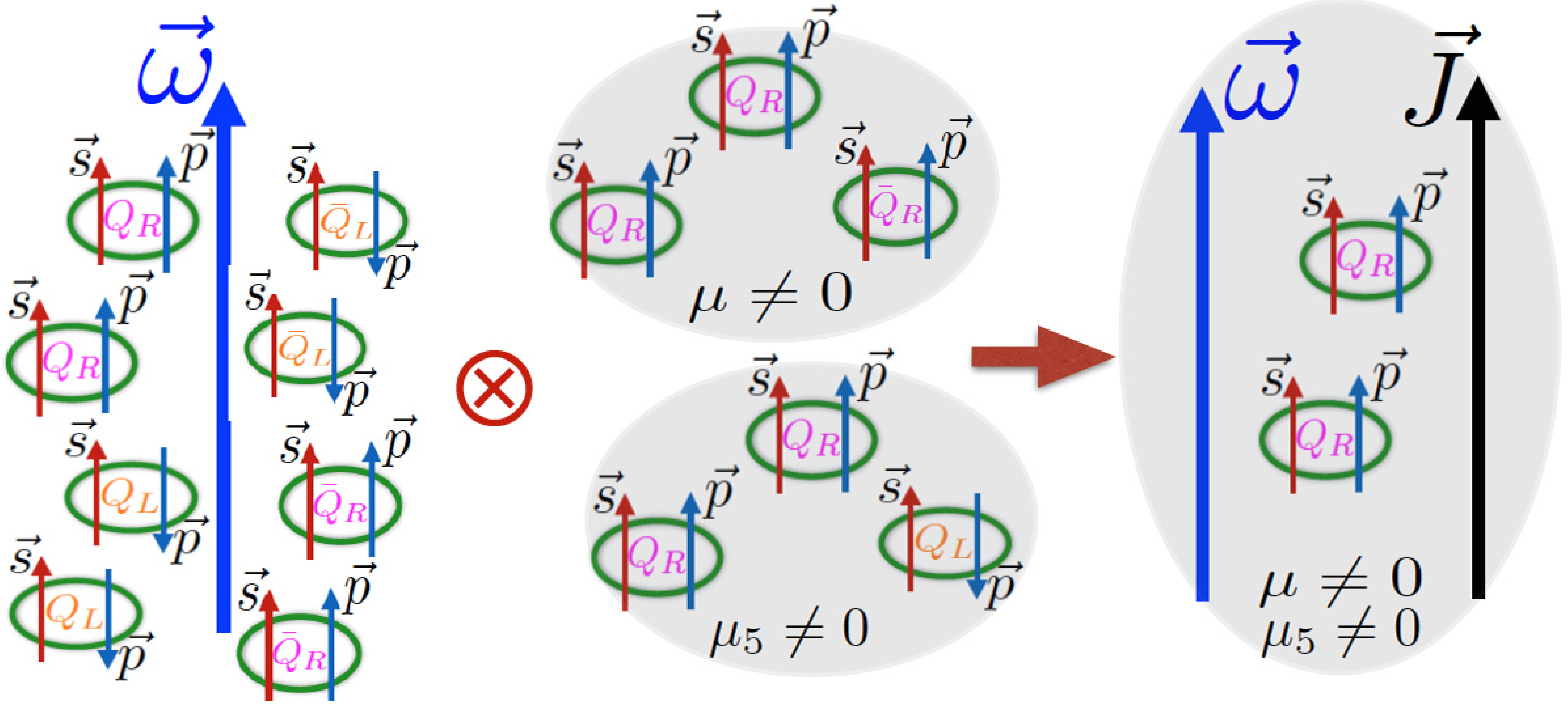
$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ
S_R : parent particle's spin
$f_{\Lambda R}$: fraction of Λ originating from parent R
μ_R : magnetic moment of particle R

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

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)

Chiral Vortical Effect



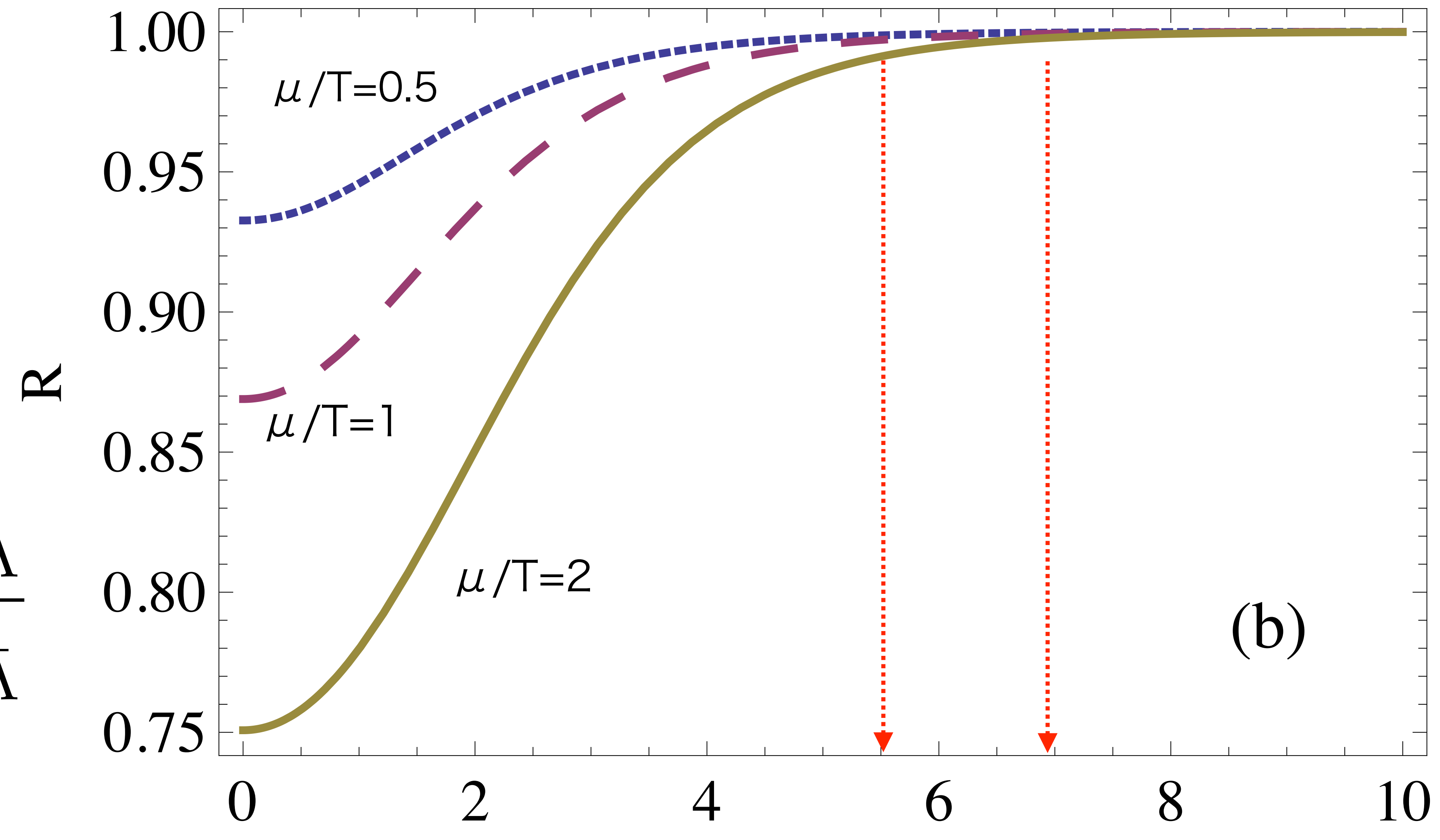
$$\vec{J}_{\mathrm{v}} = \frac{1}{\pi^2}\mu\mu_5\vec{\omega} \qquad \vec{J}_5 = \left[\frac{1}{2\pi^2}(\mu^2+\mu_5^2) + \frac{1}{6}T^2\right]\vec{\omega}$$

Observed polarization may get an offset from CVE

Effect of non-zero chemical potential

R. Fang, L. Pang, Q. Wang, and X. Wang,
PRC94, 024904 (2016)

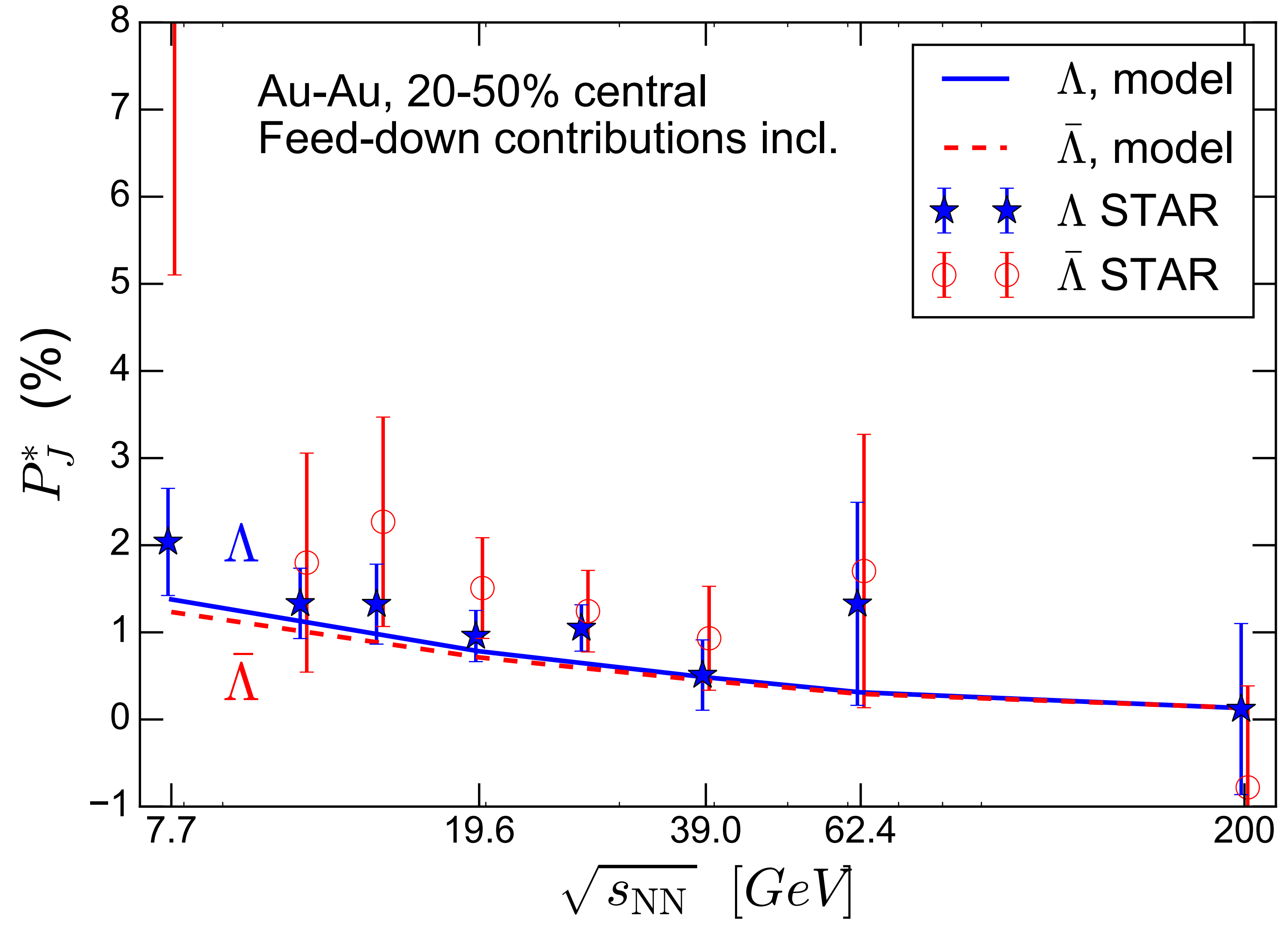
$$R = \frac{P_\Lambda}{P_{\bar{\Lambda}}}$$



βm = m/T
~ 1.1GeV/(160-200)MeV
~ 5.5-6.8

Y. Karpenko, sQM2017

Λ and $\bar{\Lambda}$: UrQMD+vHLLE vs experiment



only μ_B effect in model

Non-zero chemical potential makes polarization splitting between Λ and anti-Λ, but the effect seems to be small.