Hyperon polarization in heavy-ion collisions

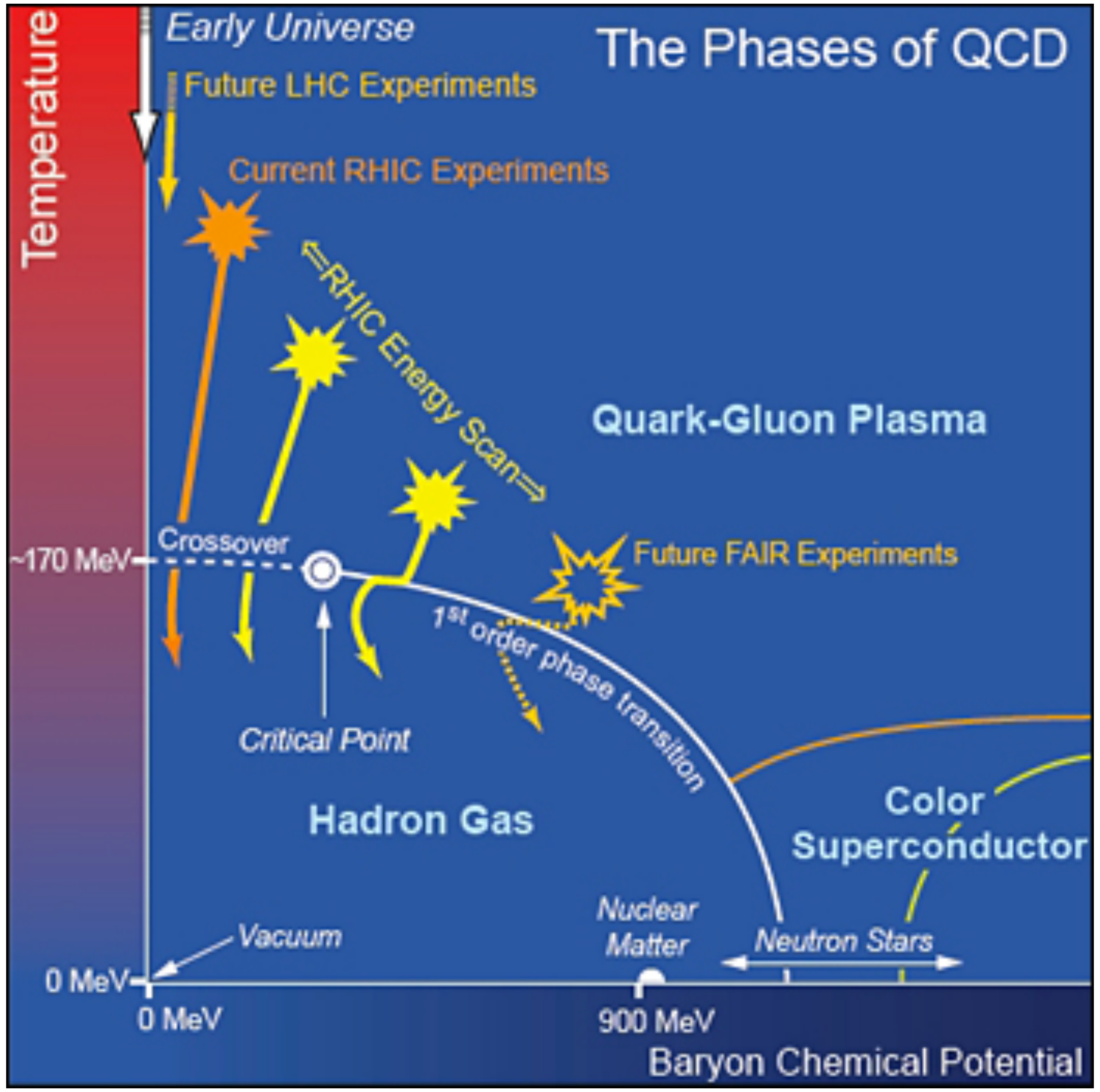
Takafumi Niida

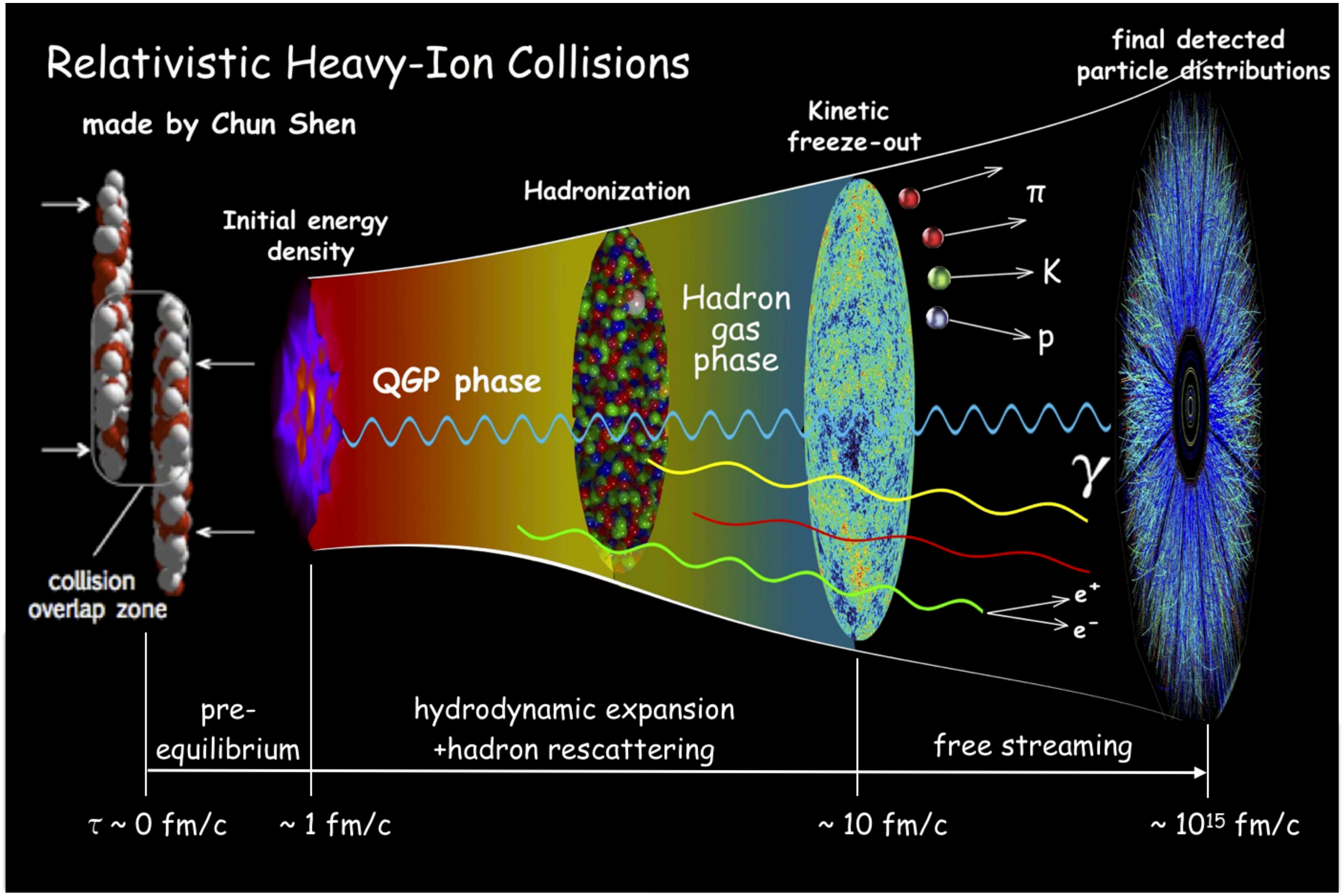
筑波大学
University of Tsukuba

筑波大学
宇宙史研究センター
Tomonaga Center for the History of the Universe

Reimei workshop, Yonsei University/Online
"*Polarization phenomena and Lorentz symmetry violation in dense matter*"

Heavy-ion collisions

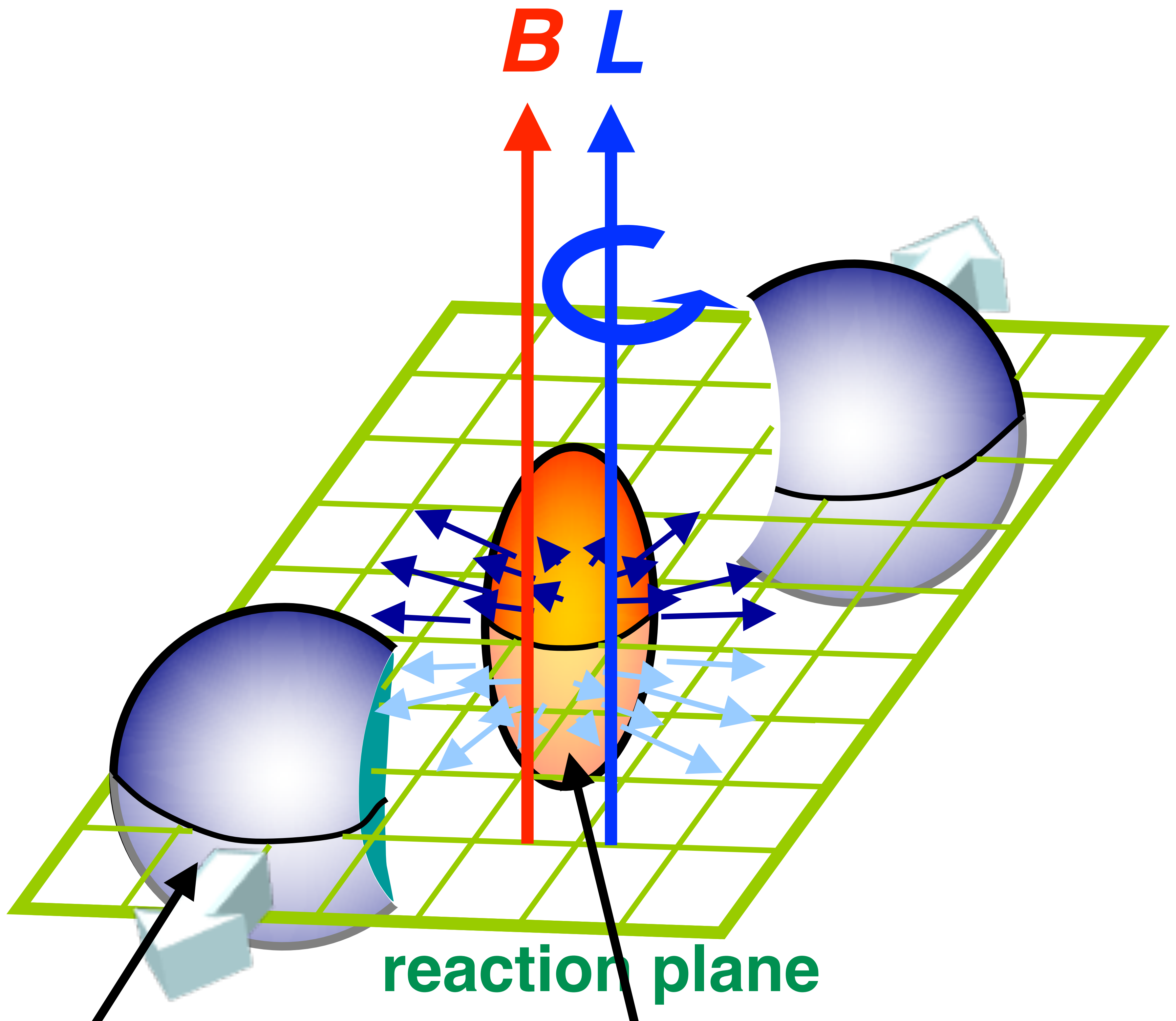




- Study the properties of quark-gluon plasm
- Explore the QCD phase structure, especially the location of a critical point/ signatures of 1st-order phase transition

→ Need better understanding of the initial condition and collision dynamics

Orbital angular momentum/magnetic field in HIC

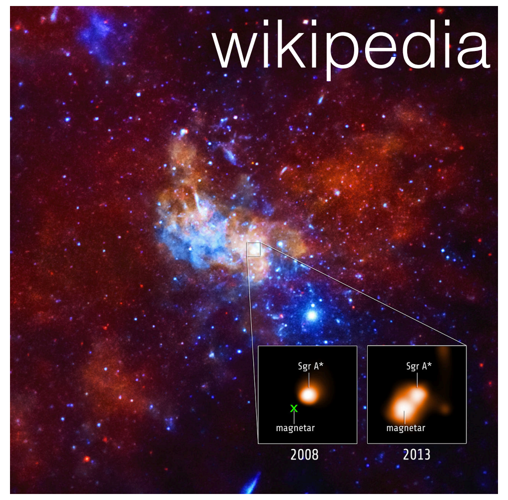


Strong magnetic field

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

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

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



magnetar

$B \sim 10^{11}\ \mathrm{T}$

Orbital angular momentum

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

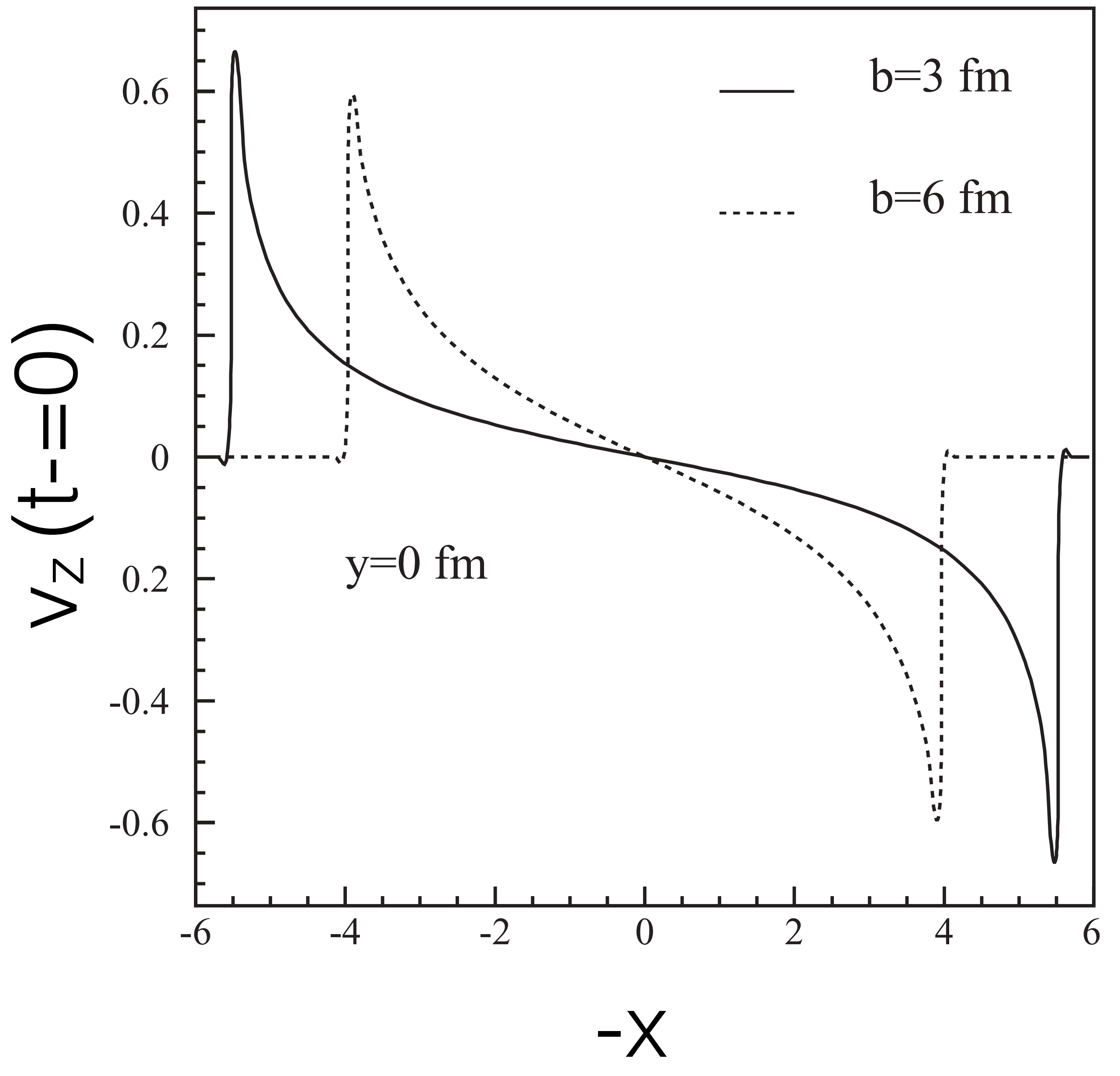
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

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

…leading to chiral magnetic effect/**global polarization**

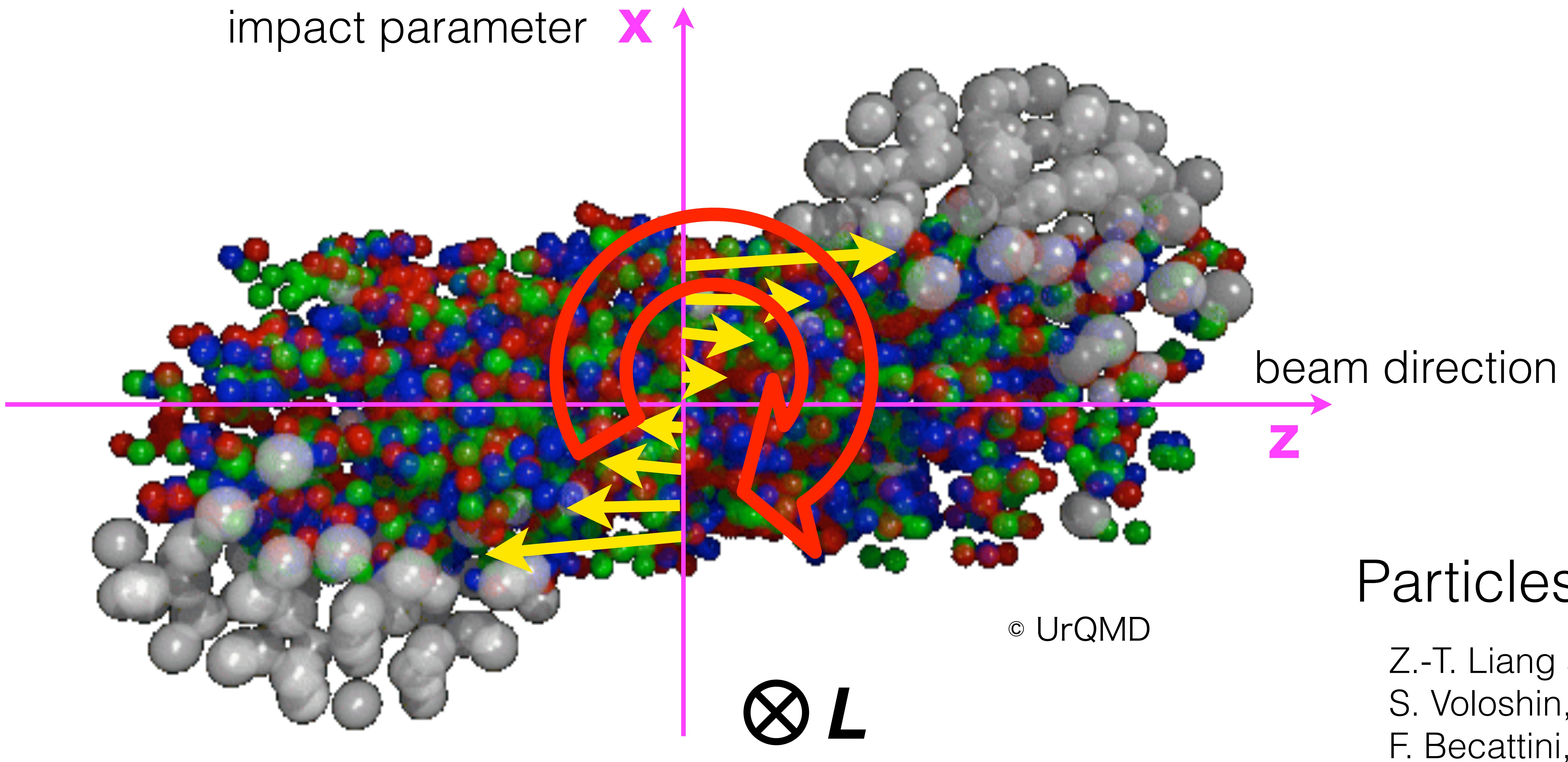
Vorticity and “global” polarization

F. Becattini et al., PRC77, 024906 (2008)



Longitudinal shear flow is produced, where flow velocity v_z depends on x.

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



Particles “globally" polarized along ***L***

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)
F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

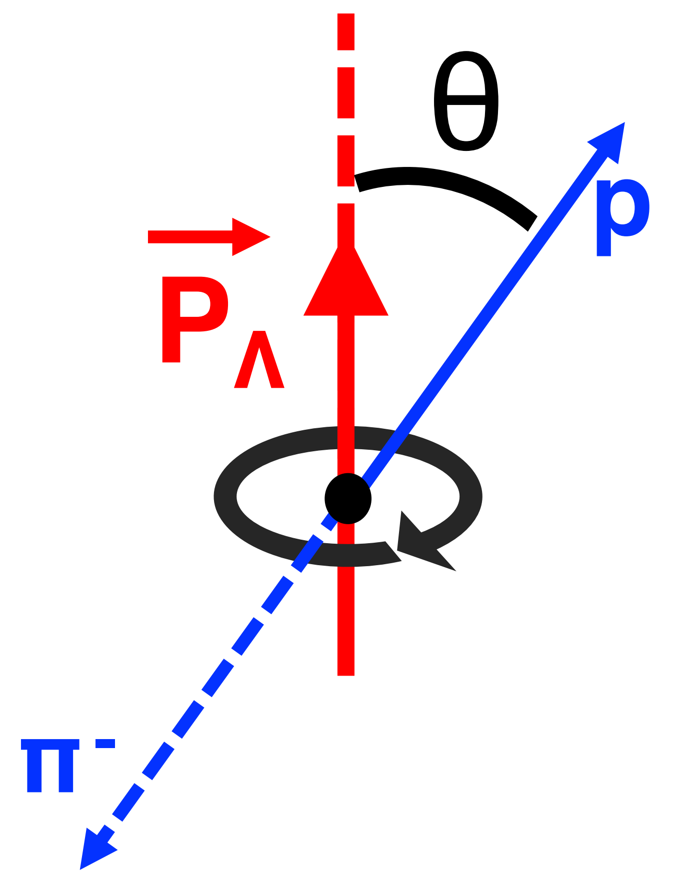
Global polarization measurement

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

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

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

$\mathbf{P}_H$: hyperon polarization
$\hat{\mathbf{p}}_B$: unit vector of daughter baryon momentum
α_H : hyperon decay parameter   * denotes in hyperon rest frame



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

(BR: 63.9%, cτ~7.9 cm)

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$
$$\alpha_{\Xi^-} = -0.401 \pm 0.010$$
$$\alpha_{\Omega^-} = -0.0157 \pm 0.0021$$

P.A. Zyla et al., PDG2021

Any hyperons can be used but the sensitivity is different, depending on α_H!

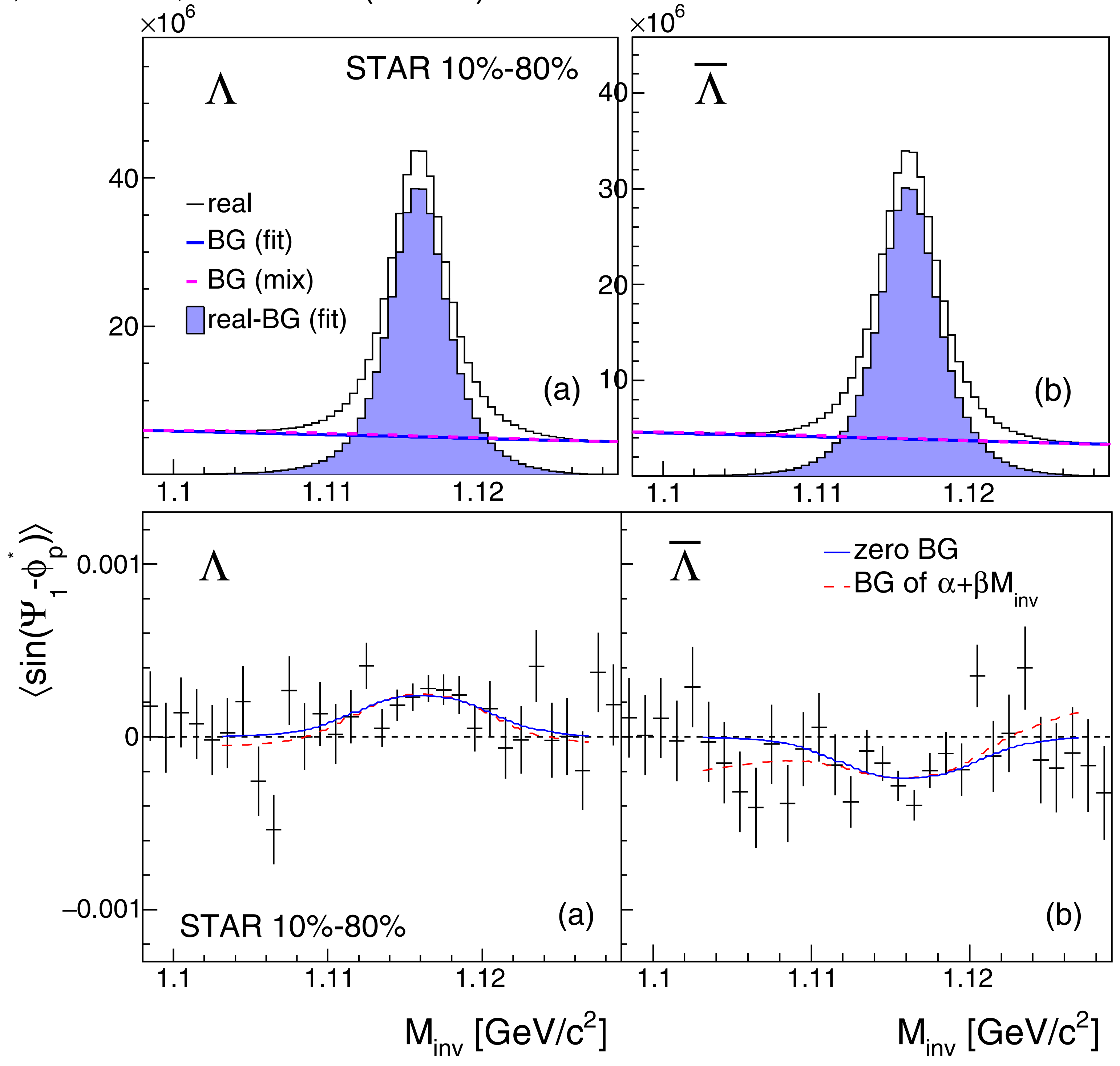
Global polarization measurement

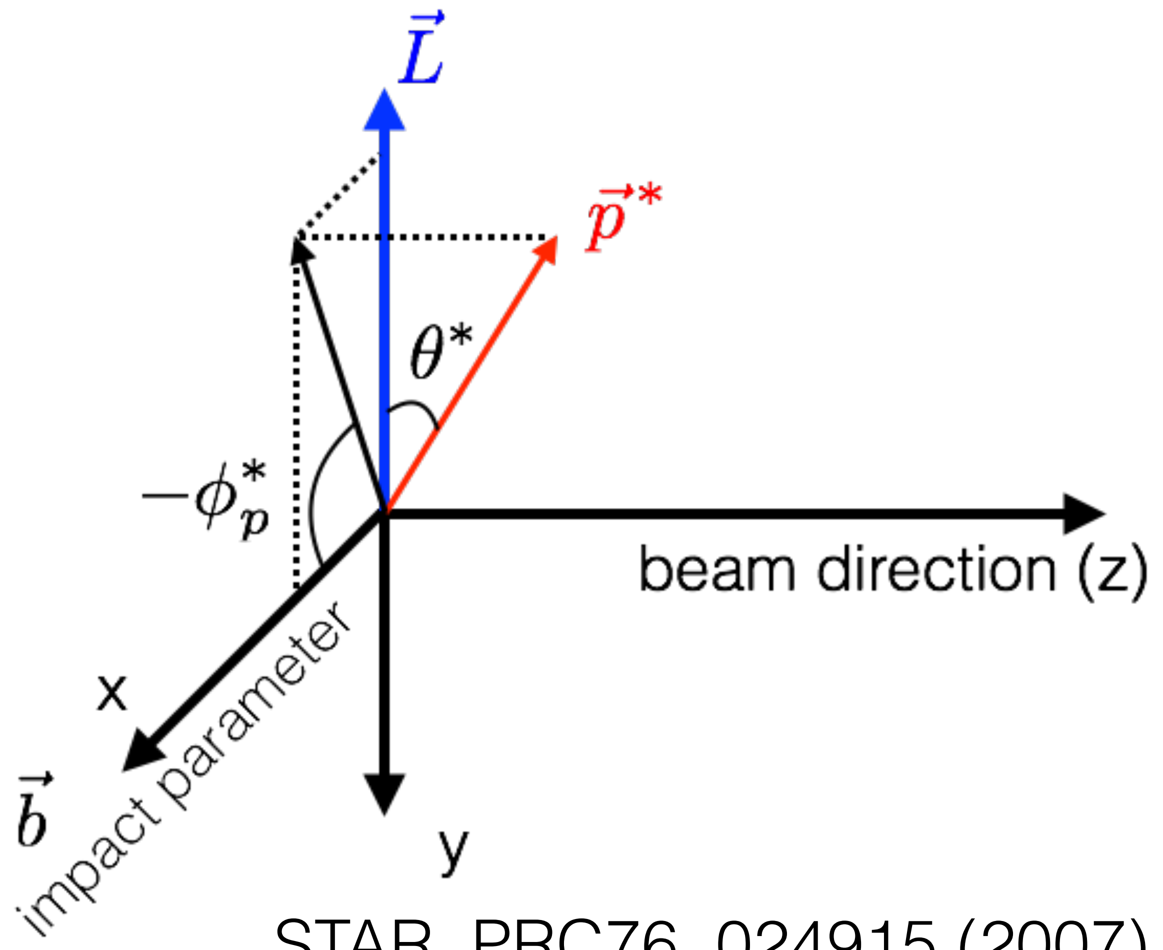
Projection onto the transverse plane

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

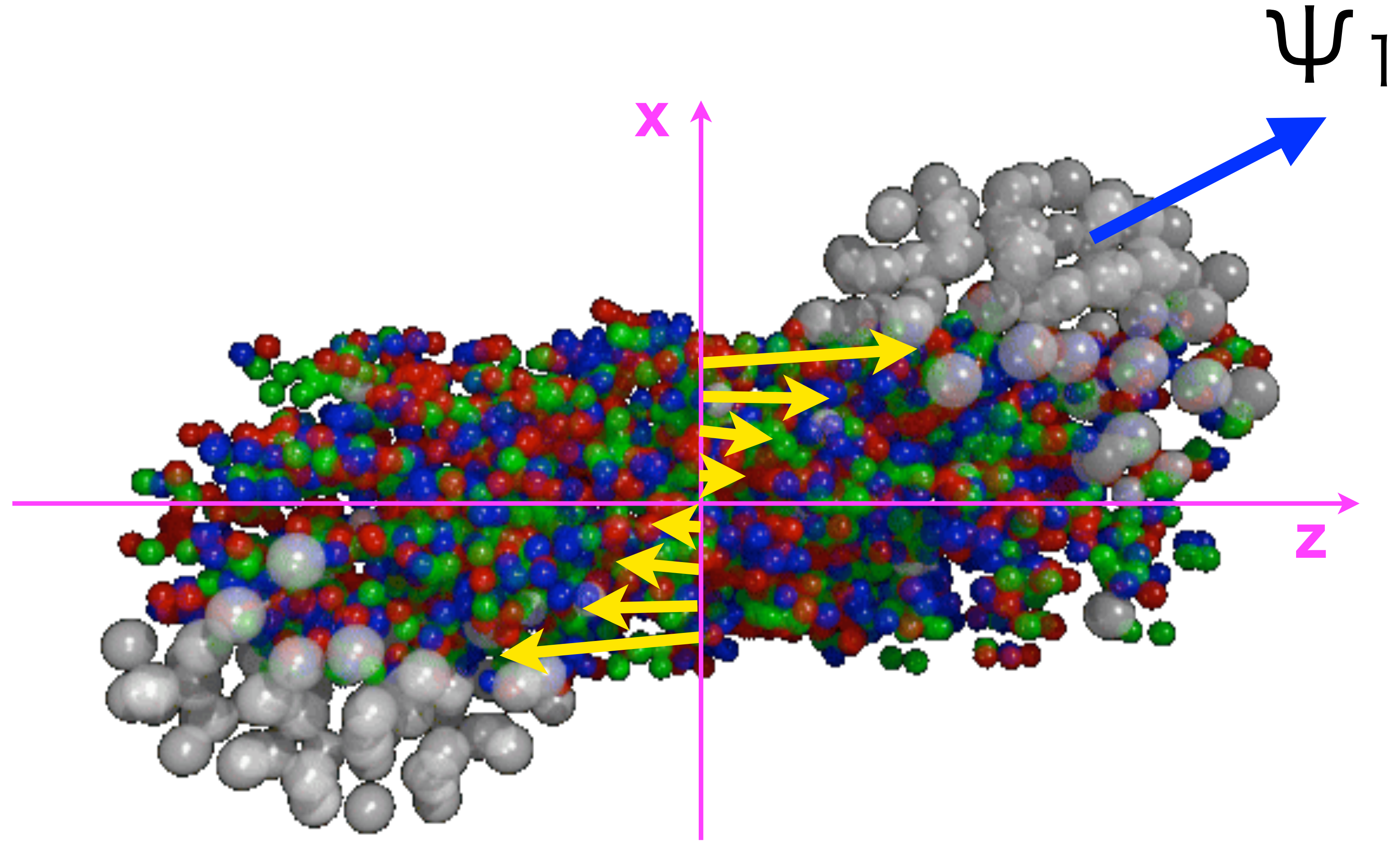
Ψ_1: azimuthal angle of impact parameter

STAR, PRC90, 014910 (2018)





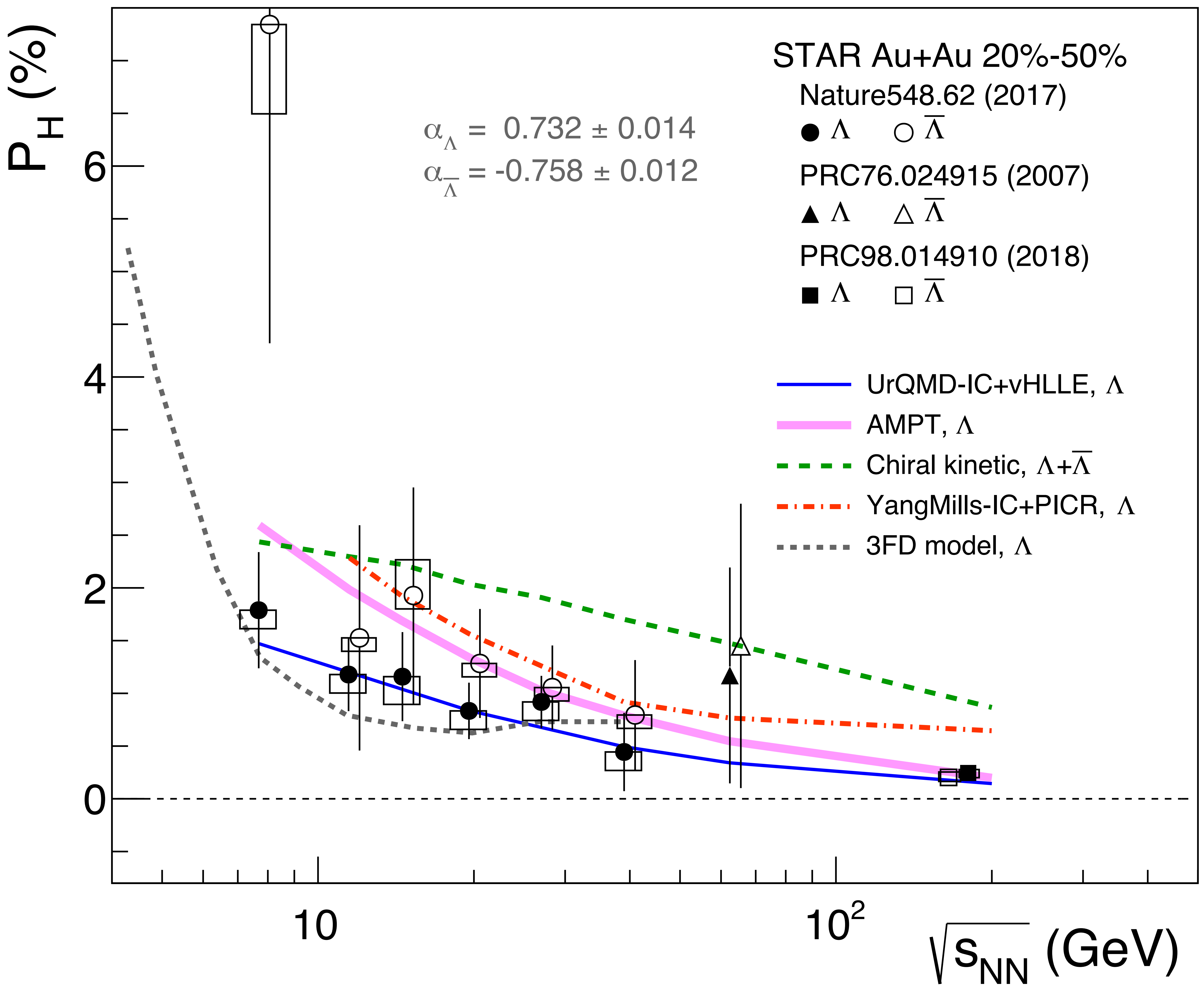
STAR, PRC76, 024915 (2007)



- Impact parameter direction determined by spectator deflection
  S. Voloshin and TN, PRC94.021901(R)(2016)
- COM vs. rest frames, ~3%(10%) reduction at low(higher) p_T
  W. Florkowski and R. Ryblewski, PRC106, 024905 (2022)

Observation of global polarization

STAR, Nature 548, 62 (2017)
STAR, PRC90, 014910 (2018)



- Increasing trend toward lower energies, described well by various theoretical models

  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
  Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model

- Indication of thermal vorticity

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T}$$

F. Becattini et al., PRC95, 054902 (2017)

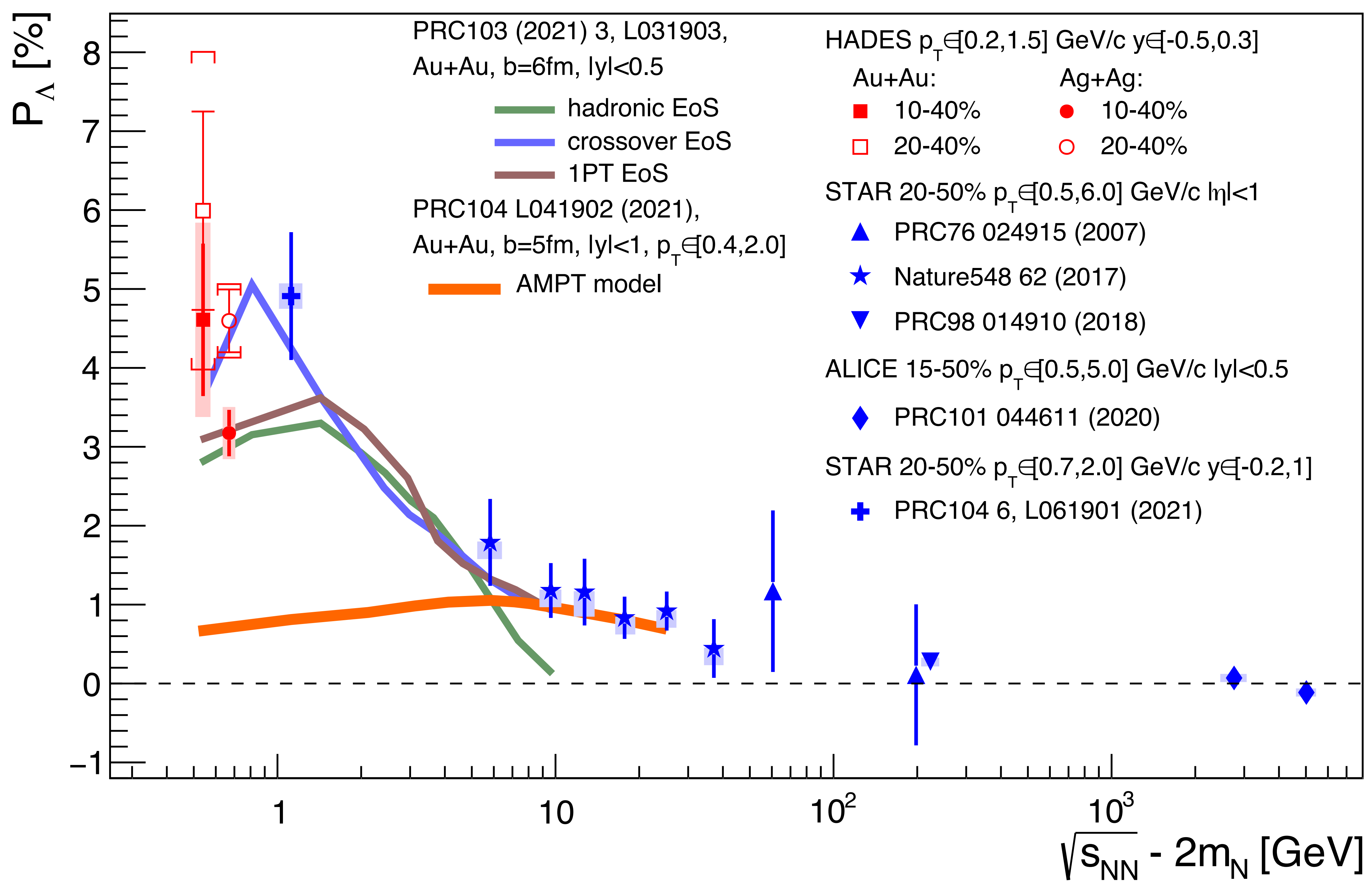
$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\,\mathrm{s}^{-1}$$

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- Possible difference between Λ and anti-Λ

Recent update on Λ global polarization

STAR, PRC104, L061901 (2021)
HADES, arXiv:2207.05160 (2022)



- New data from STAR/HADES at $\sqrt{s_{NN}}$ = 3/2.4-2.55 GeV
  - Also some new preliminaries from STAR BES-II (not shown here, see STAR talk in QM2022)
- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV

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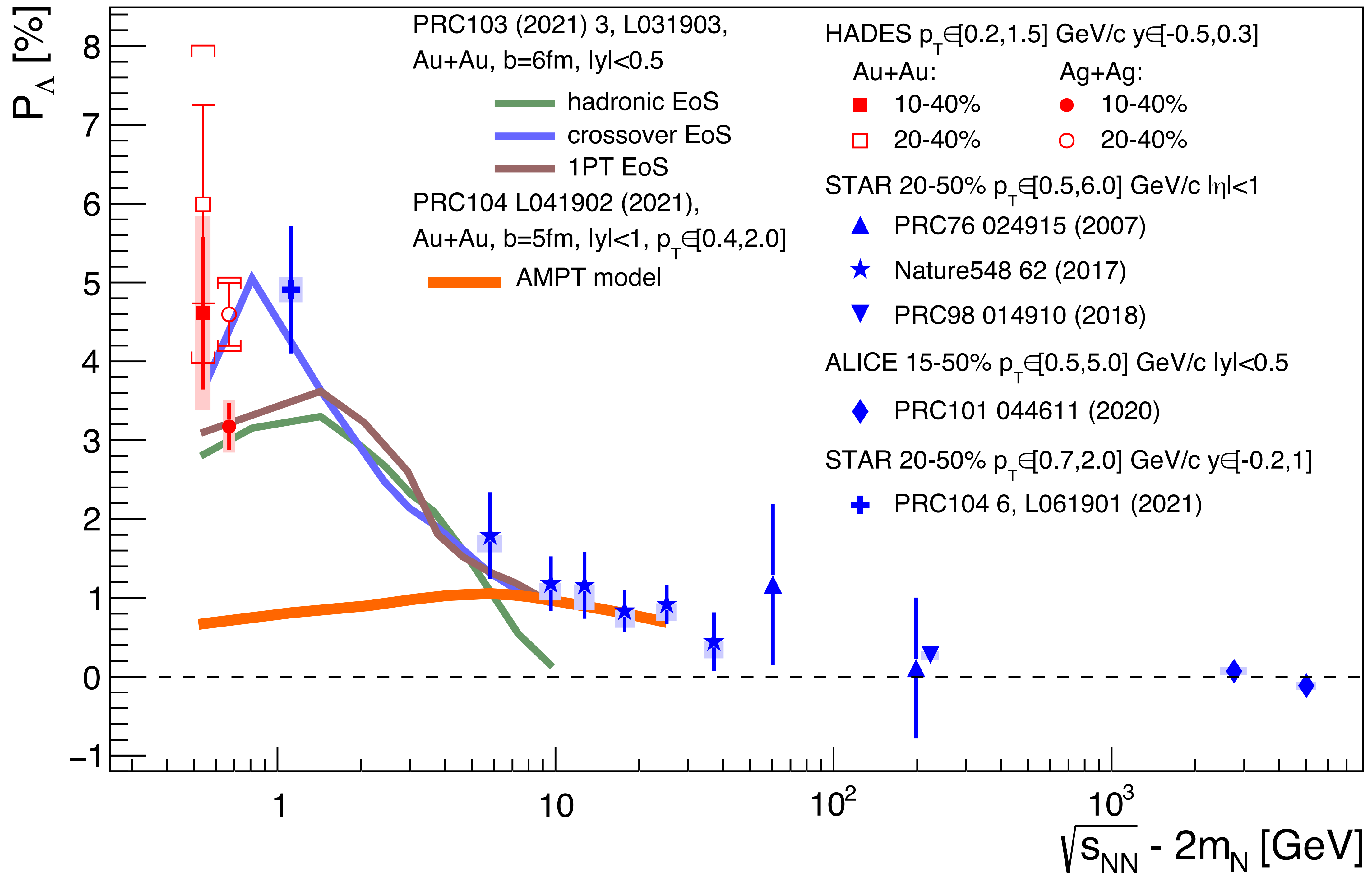

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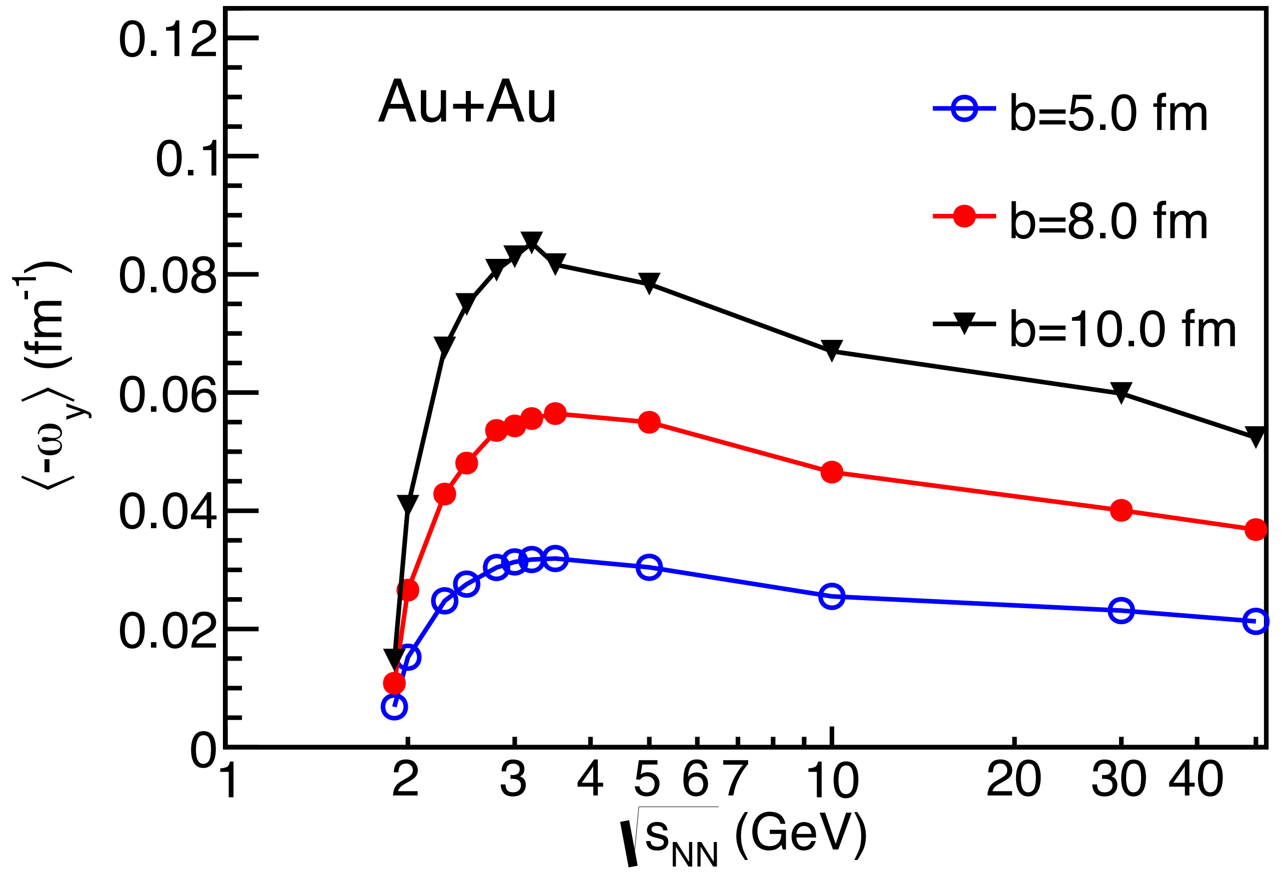
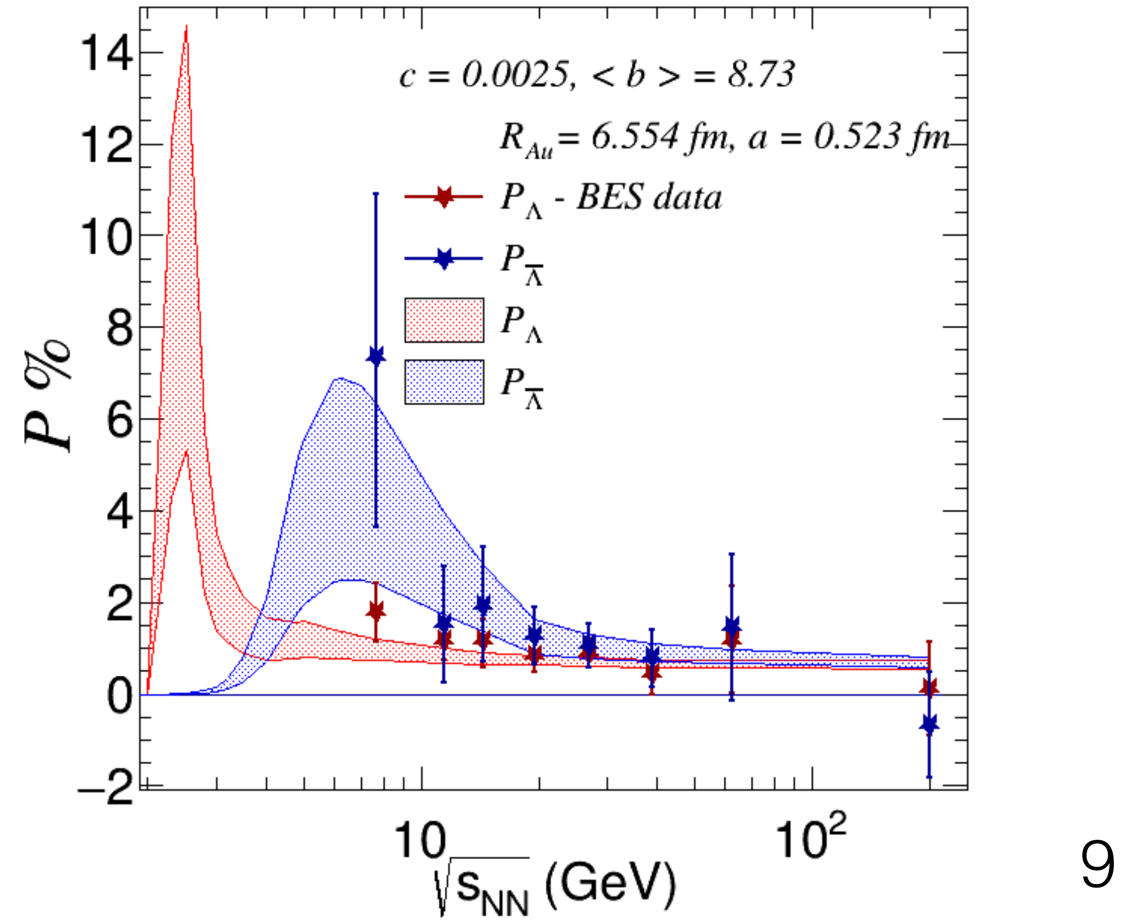
- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV
  - Predicted to have the maximum around $\sqrt{s_{NN}}$ = 3 GeV
    - initial L & "stopping" to "transparency" at midrapidity

X.-G. Deng et al., PRC101.064908 (2020)



A. Ayala et al., PRC105.034907 (2022)



Recent update on Λ global polarization

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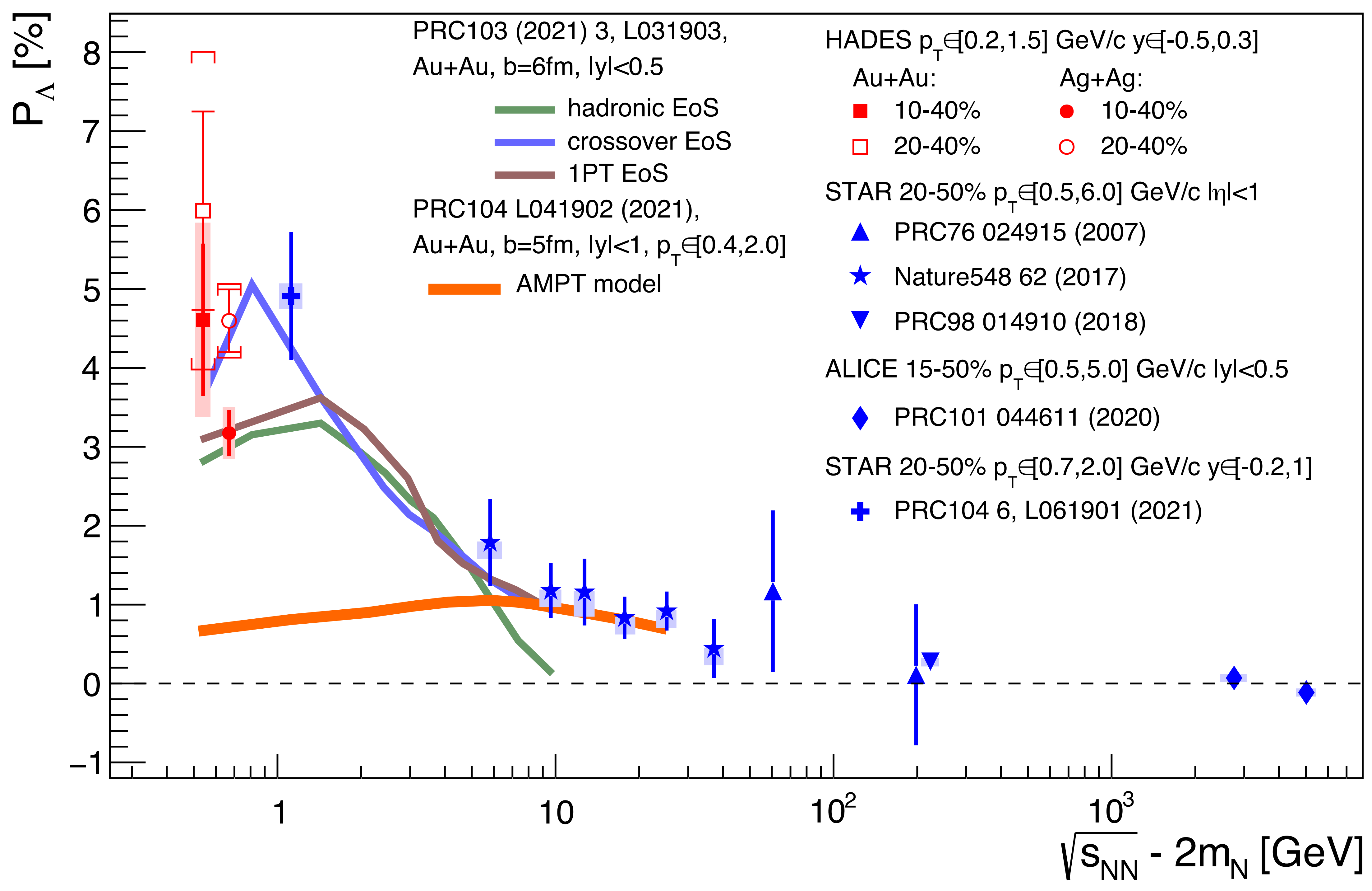
HADES, arXiv:2207.05160 (2022)



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  - Slope seems to change around $\sqrt{s_{NN}}$ = 7-10 GeV, relying on model calculations (need data)
  - Should we expect such a change when going from hadronic matter to partonic matter?

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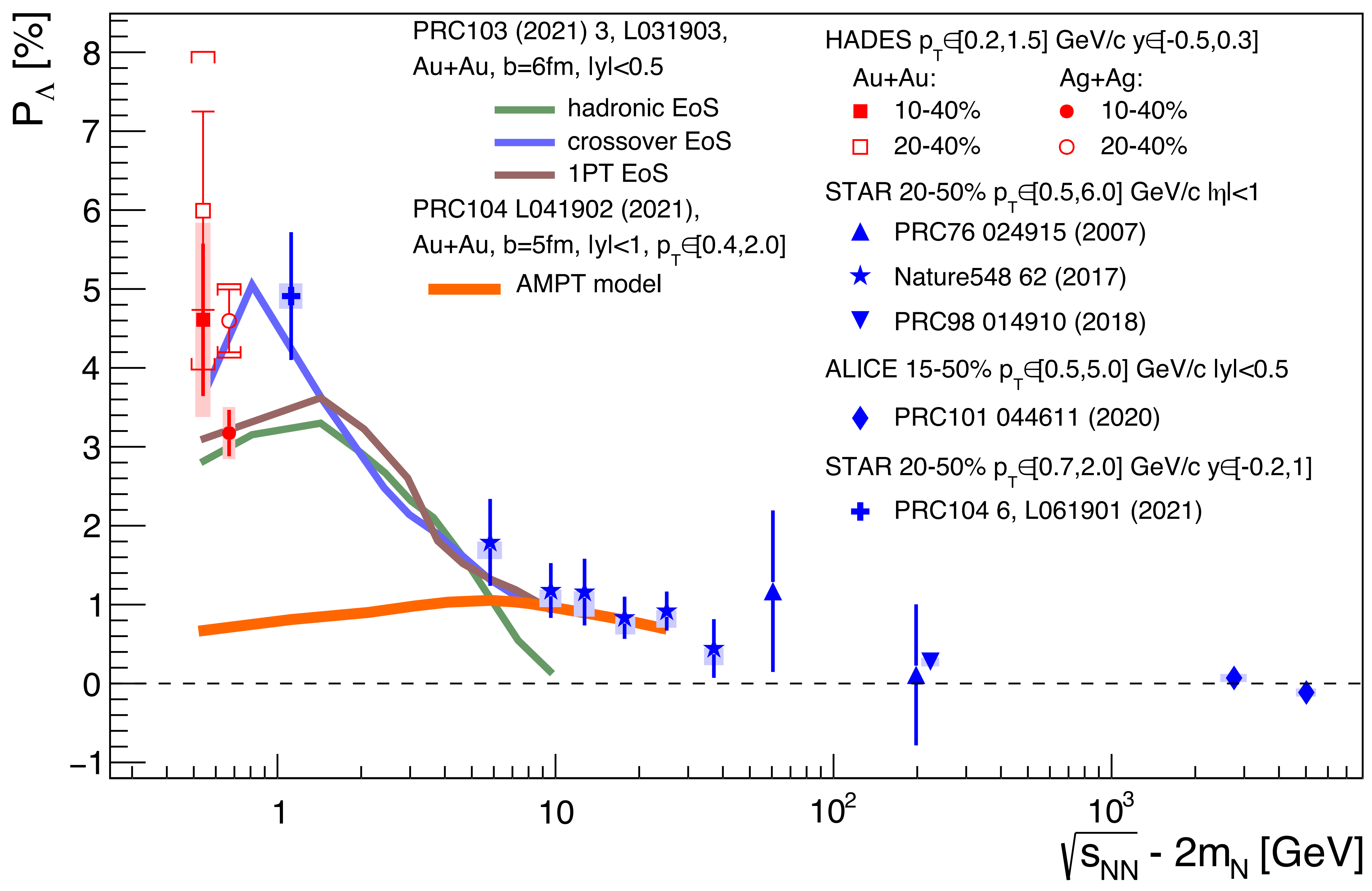
STAR, PRC104, L061901 (2021)
HADES, arXiv:2207.05160 (2022)



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  - Should we expect such a change when going from hadronic matter to partonic matter?
- New data will come from STAR BES-II (3-27 GeV)

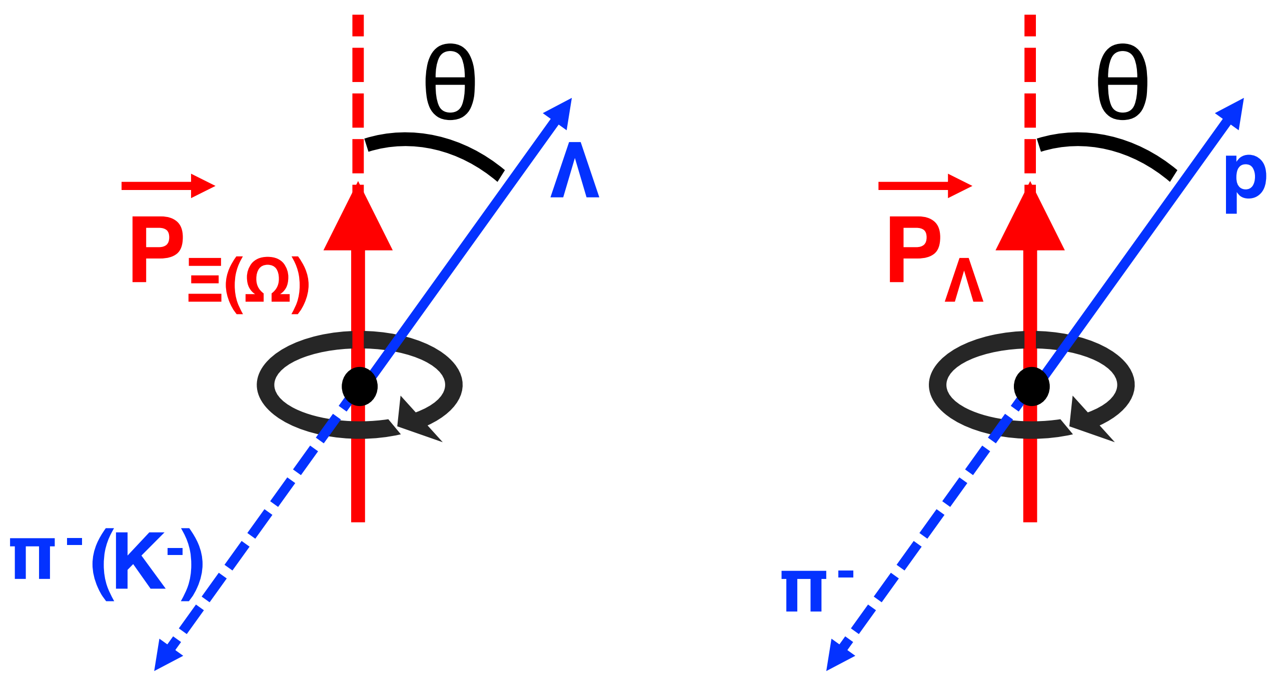
Caveat: be careful for different centrality/rapidity acceptance for a fair comparison

Multistrange hyperons: Ξ and Ω

- Extend measurement to Ξ and Ω hyperons
  - ✓ different spin, decay parameter
  - ✓ less feed-down
  - ✓ different freeze-out
  - ✓ # of s-quarks
- Challenge: small α_H (low sensitivity), low production rate

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \to p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \to \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \to \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2



Daughter Λ polarization can be used to know parent particle polarization!

- Polarization of daughter Λ in Ξ and Ω decays

T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda}\mathbf{P}_\Xi^* = \tfrac{1}{3}\left(1 + 2\gamma_\Xi\right)\mathbf{P}_\Xi^*.$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$C_{\Xi^-\Lambda} = +0.944$$

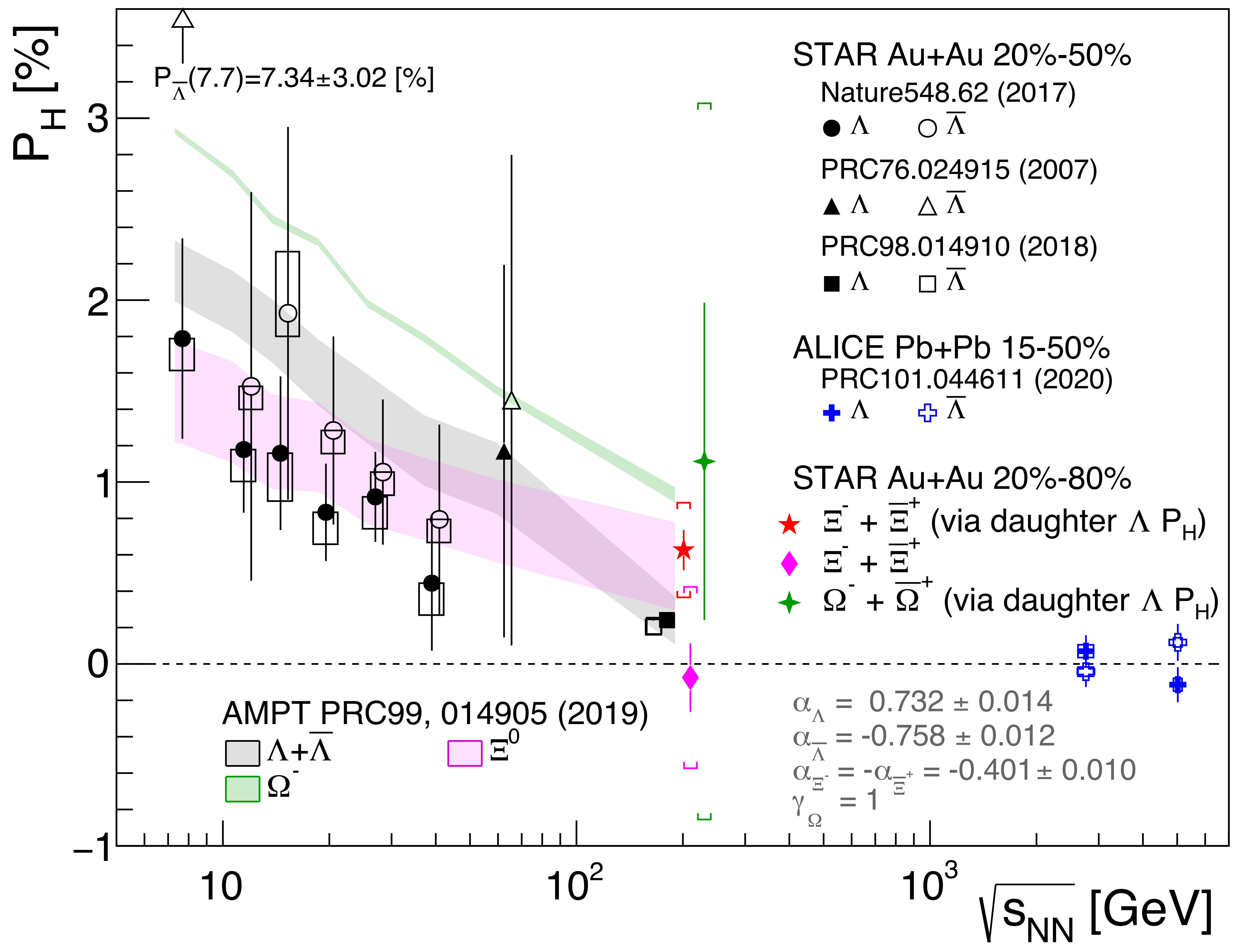
$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda}\mathbf{P}_\Omega^* = \tfrac{1}{5}\left(1 + 4\gamma_\Omega\right)\mathbf{P}_\Omega^*.$$

γ_Ω is unknown $\alpha_\Omega, \beta_\Omega \ll 1 \to \gamma_\Omega \sim \pm 1$

Polarization transfer factor $C_{\Omega\Lambda}$ $C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$

Ξ and Ω global polarizations at $\sqrt{s_{NN}}$ = 200 GeV

STAR, PRL126, 162301 (2021)



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

- Likely hierarchy in P_H, though not significant yet

$$\langle P_\Lambda \rangle = 0.24 \pm 0.03\ (\text{stat}) \pm 0.03\ (\text{syst})\ \%$$
$$\langle P_\Xi \rangle = 0.47 \pm 0.10\ (\text{stat}) \pm 0.23\ (\text{syst})\ \%$$
$$\langle P_\Omega \rangle = 1.11 \pm 0.87\ (\text{stat}) \pm 1.97\ (\text{syst})\ \%$$

(20-80% centrality)

* combined Ξ P_H from the two methods

- Thermal model: $P_\Lambda = P_\Xi = 3/5 * P_\Omega$

$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3} \frac{\boldsymbol{\omega}}{T}$$

F. Becattini et al., PRC95.054902 (2017)

- Earlier freeze-out leads to larger P_H

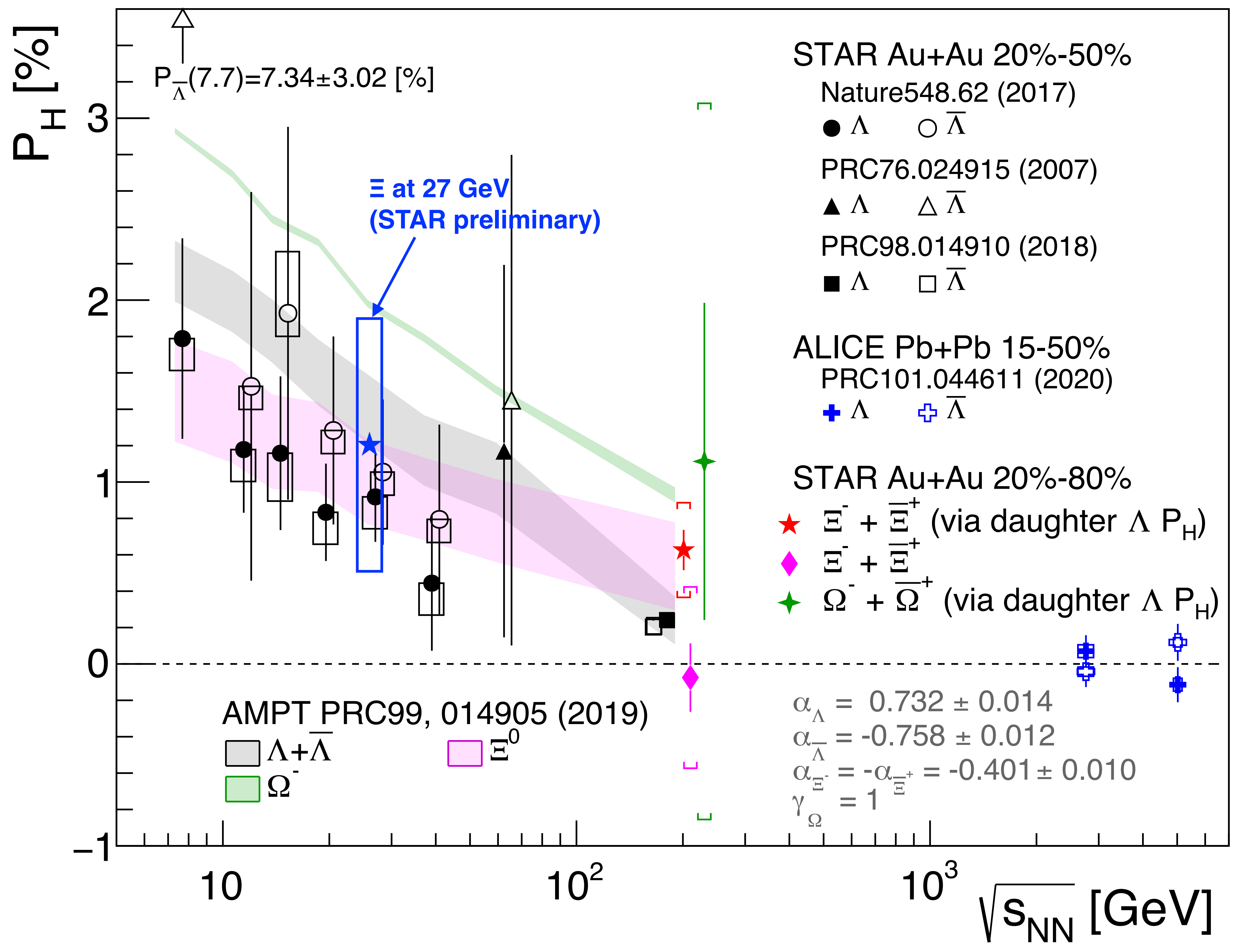
O.Vitiuk, L.V.Bravina, and E.E.Zabrodin, PLB803(2020)135298

- Different feed-down contribution
- AMPT and hydro calculations capture the trend

D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)
B. Fu et al., PRC103.024903 (2021)

Ξ and Ω global polarizations at $\sqrt{s_{NN}}$ = 200 GeV

STAR, PRL126, 162301 (2021)



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

- STAR preliminary at 27 GeV: P_Ξ~1.2%±0.7(stat+sys)

  E. Alpatov (STAR), ICPPA2020

- Large uncertainty of $P_{\Xi/\Omega}$ to be improved in future, especially in 2023+2025 RHIC runs
- Unmeasured γ_Ω (γ_Ω=+1 or -1) can be constrained based on the vorticity picture

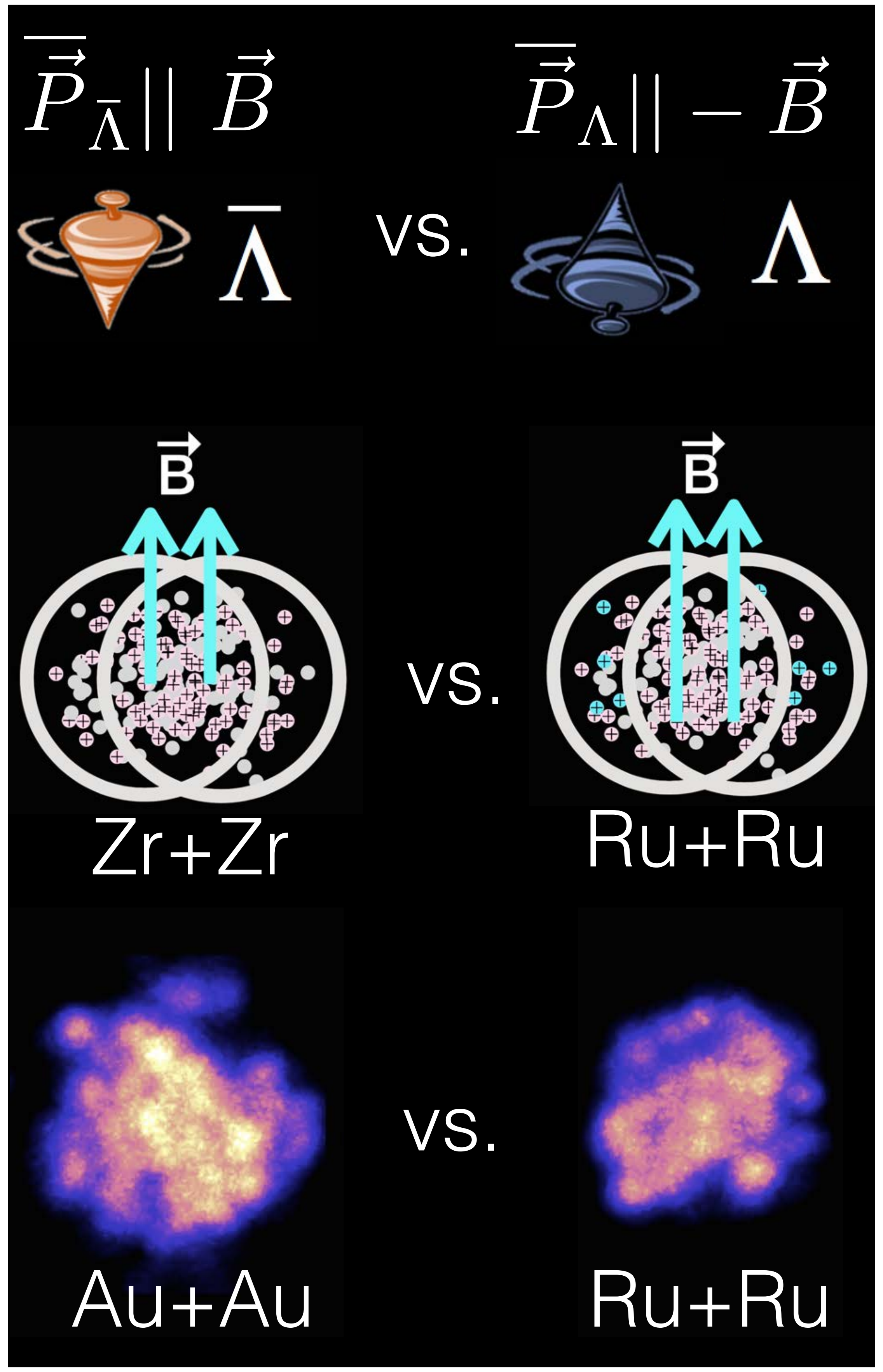
$$\mathbf{P}^*_\Lambda = C_{\Omega^-\Lambda}\mathbf{P}^*_\Omega = \frac{1}{5}\left(1+4\gamma_\Omega\right)\mathbf{P}^*_\Omega.$$

- Larger splitting of P_Ω and $P_{anti\text{-}\Omega}$ due to B-field?

$$\mu_\Omega = -2.02,\ \mu_\Lambda = -0.613$$

P_H in isobar collisions

picture from P. Tribedy (QM2022)

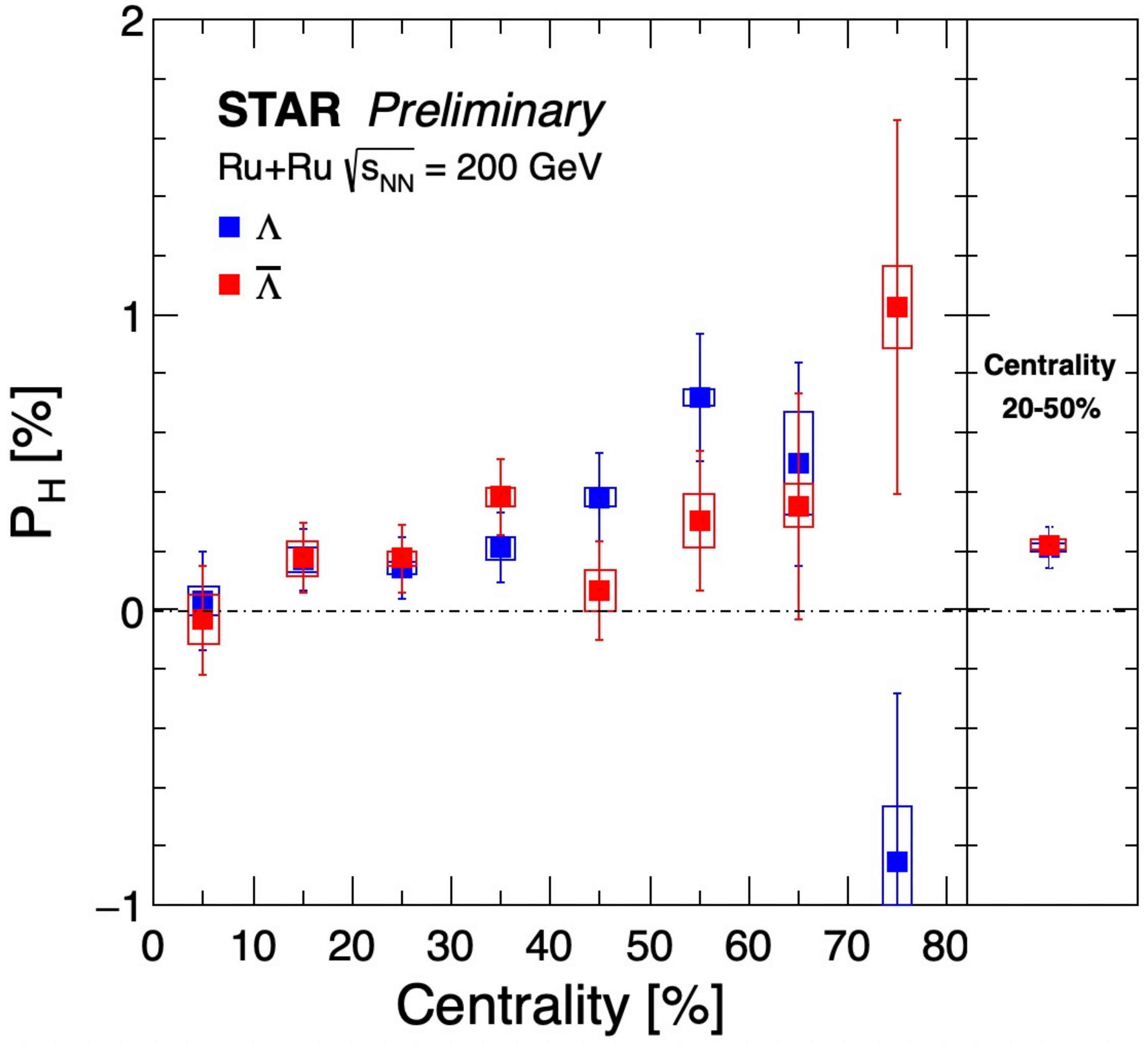


$$P_\Lambda^{\mathrm{Au}} < P_\Lambda^{\mathrm{Ru}} \approx P_\Lambda^{\mathrm{Zr}} < P_\Lambda^{\mathrm{Cu}} < P_\Lambda^{\mathrm{O}} \ ?$$

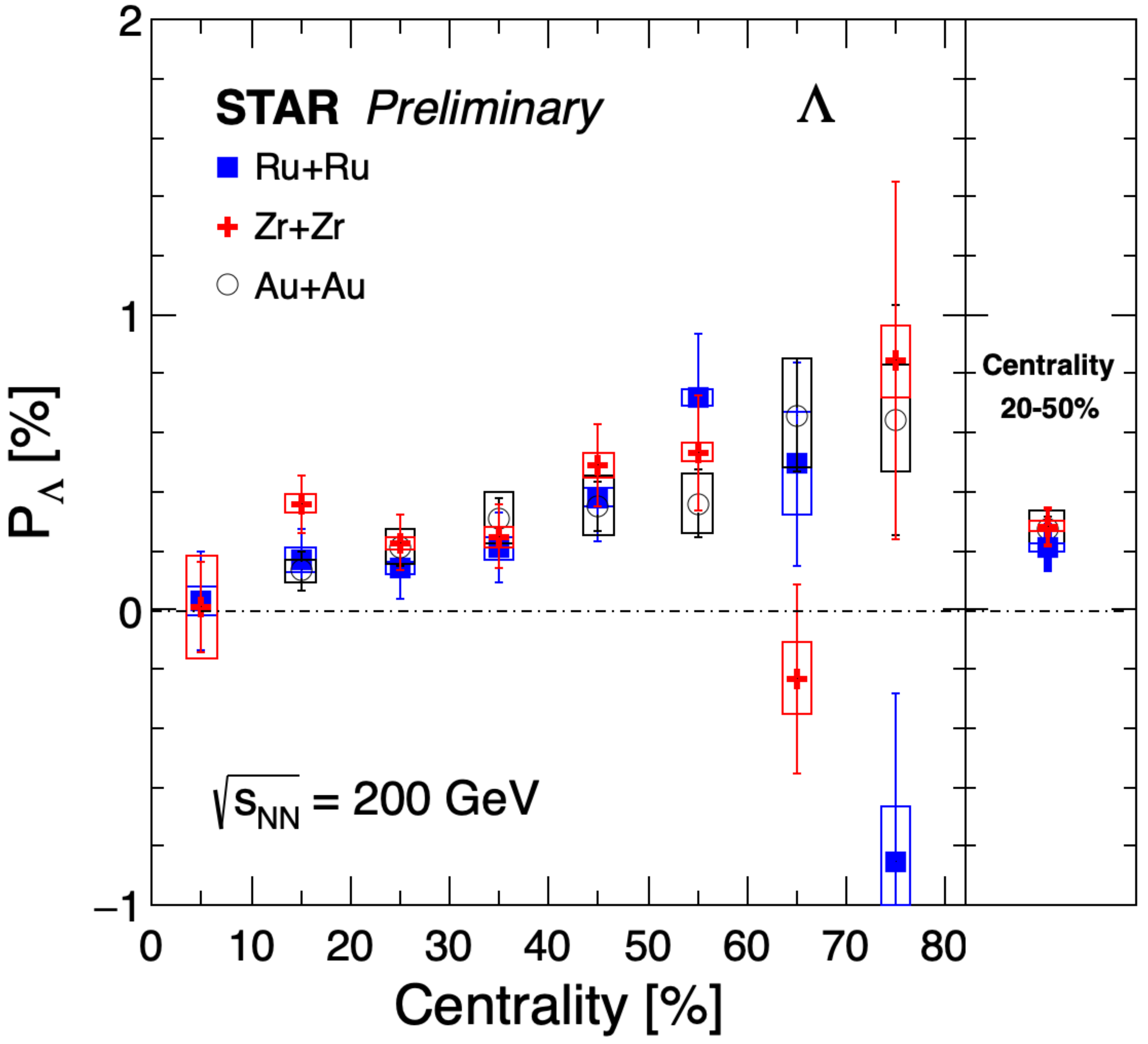
- Initial B-field ($|B|^2$) difference is 10-15% between Ru+Ru and Zr+Zr
- System size dependence predicted: longer lifetime dilutes the vorticity

S. She et al., PLB788(2019)409

Λ vs. anti-Λ in Ru+Ru



Isobar vs. Au+Au for Λ

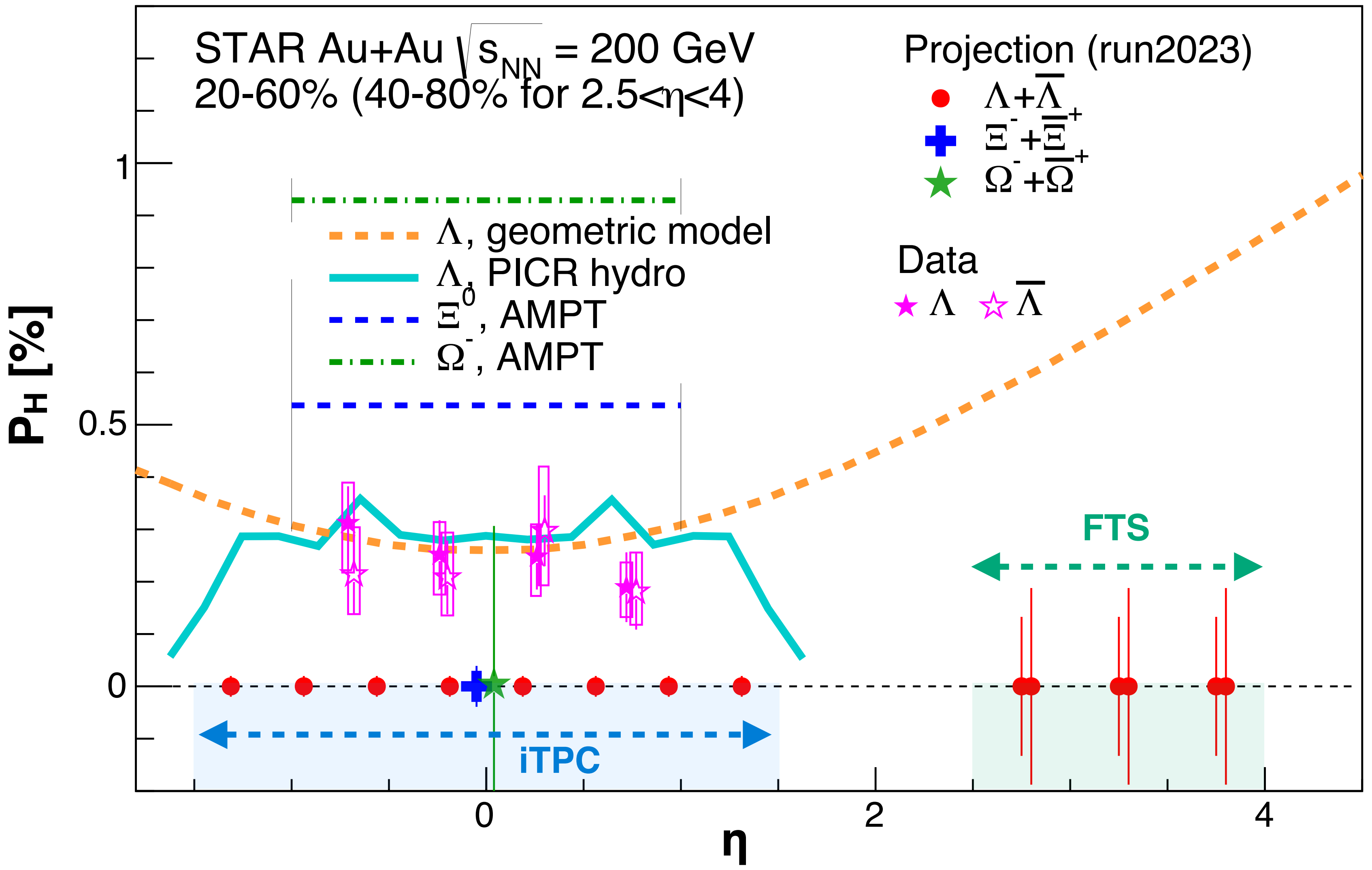


X. Gou (STAR), QM2022

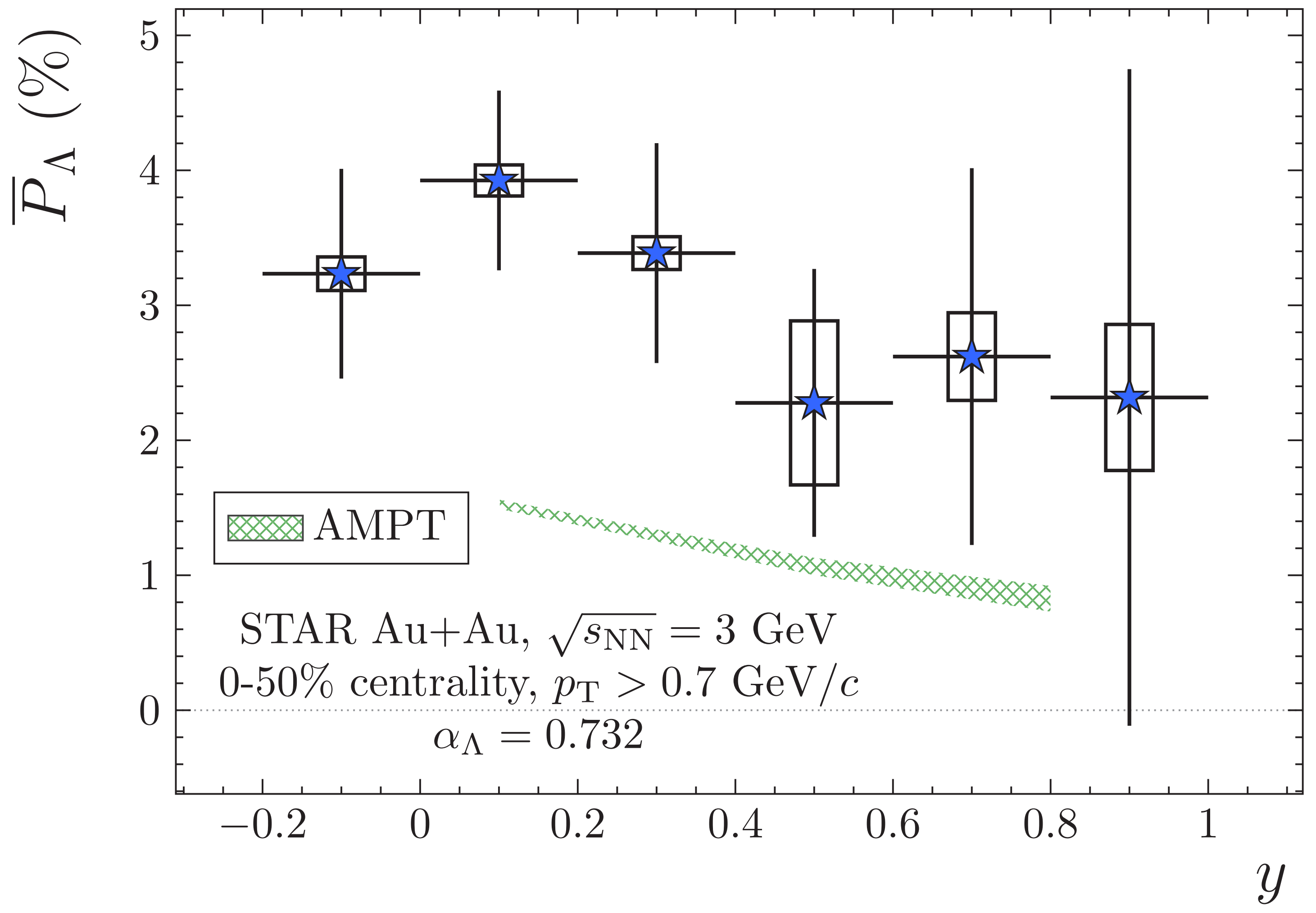
No significant difference between Λ-antiΛ, isobar vs. Au+Au

Rapidity dependence

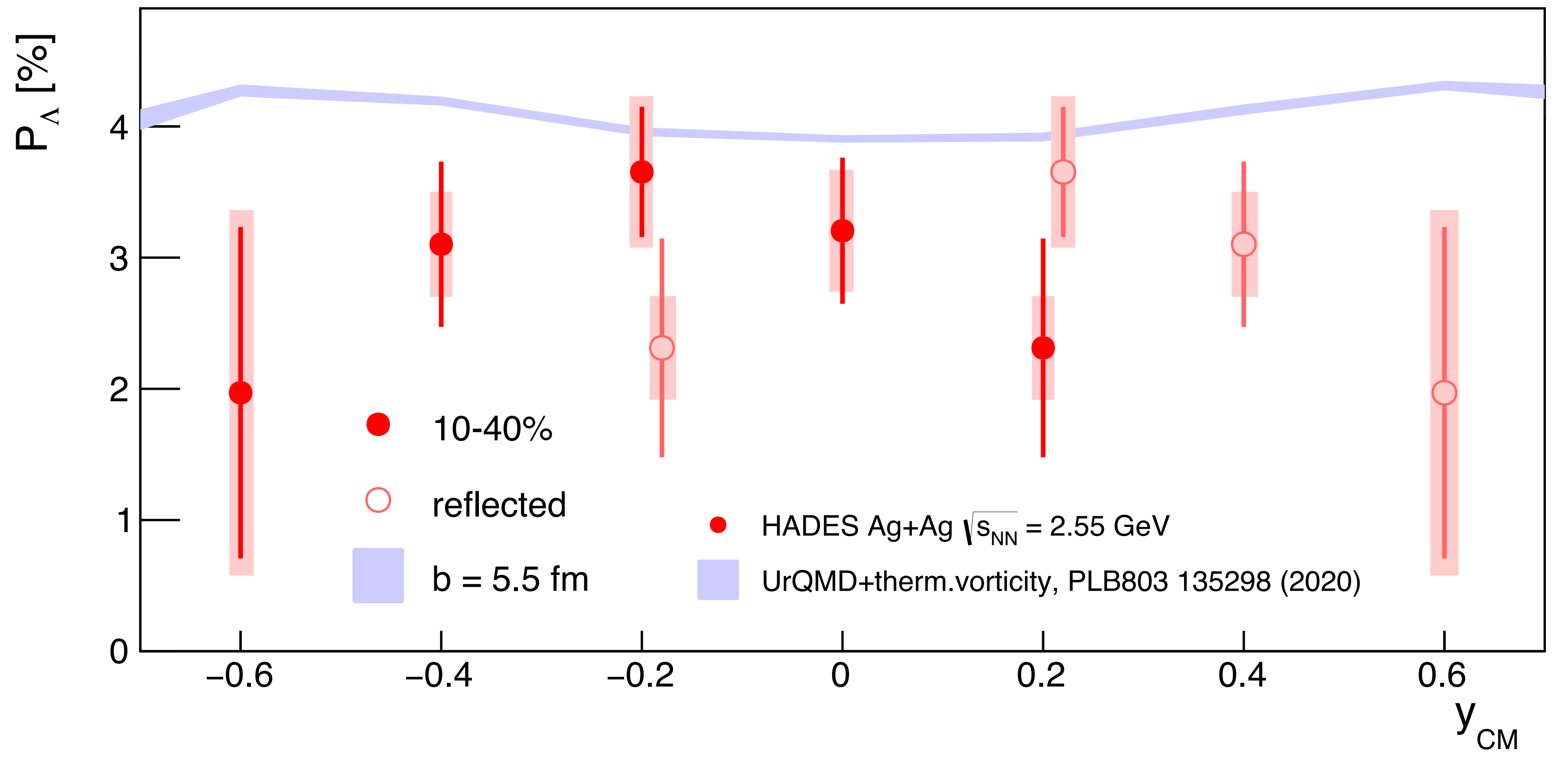
BUR2020, STAR Note SN0755



W.T.Feng and X.G.Huang, PRC93.064907 (2016)
D.X.Wei, W.T.Deng and X.G.Huang, PRC99.014905 (2019)
H.Z.Wu et al, PRResearch1.033058 (2019)
Y.Xie, D.Wang, and L.P.Csernai, RPJ (2020) 80:39
Z.T.Liang et al., Chin.Phys.C45, 014102 (2021)



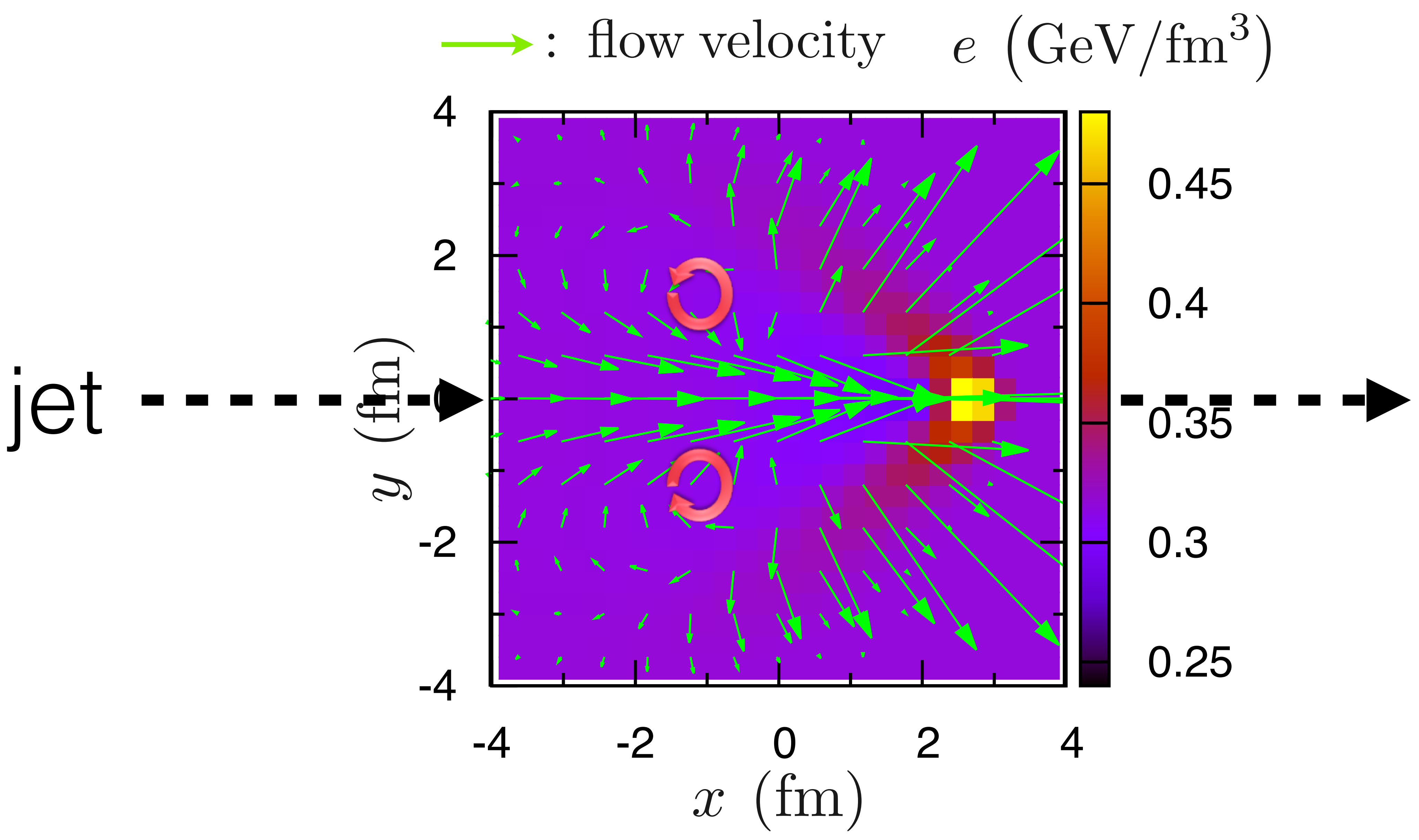
STAR, PRC104, L061901 (2021)
HADES, arXiv:2207.05160 (2022)



- Models predict the rapidity dependence differently
- So far no strong dependence within acceptance. In lower energies, the measurement close to the beam rapidity was done (y_{beam} ~1 at $\sqrt{s_{NN}}$ = 3 GeV)

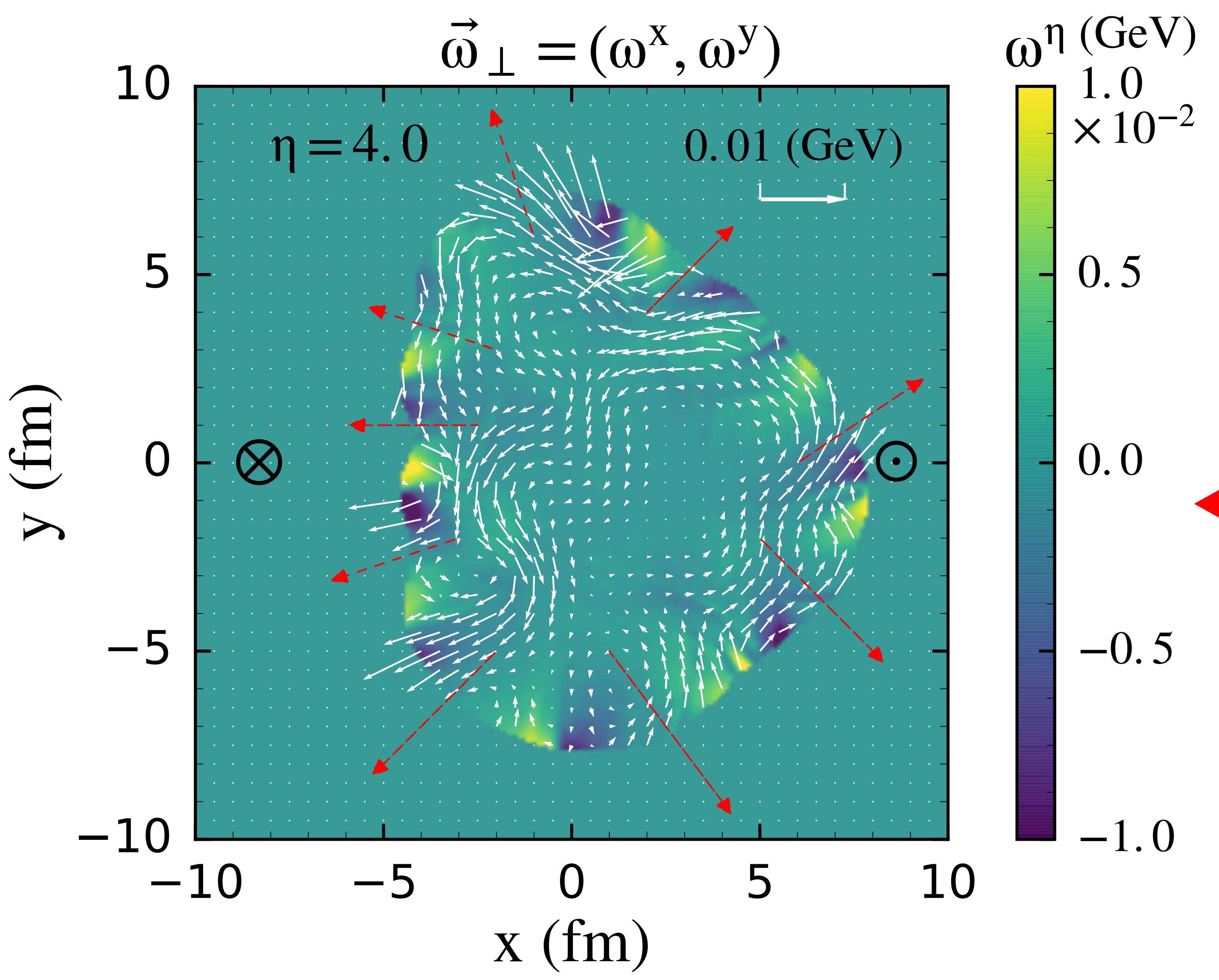
Local vorticity

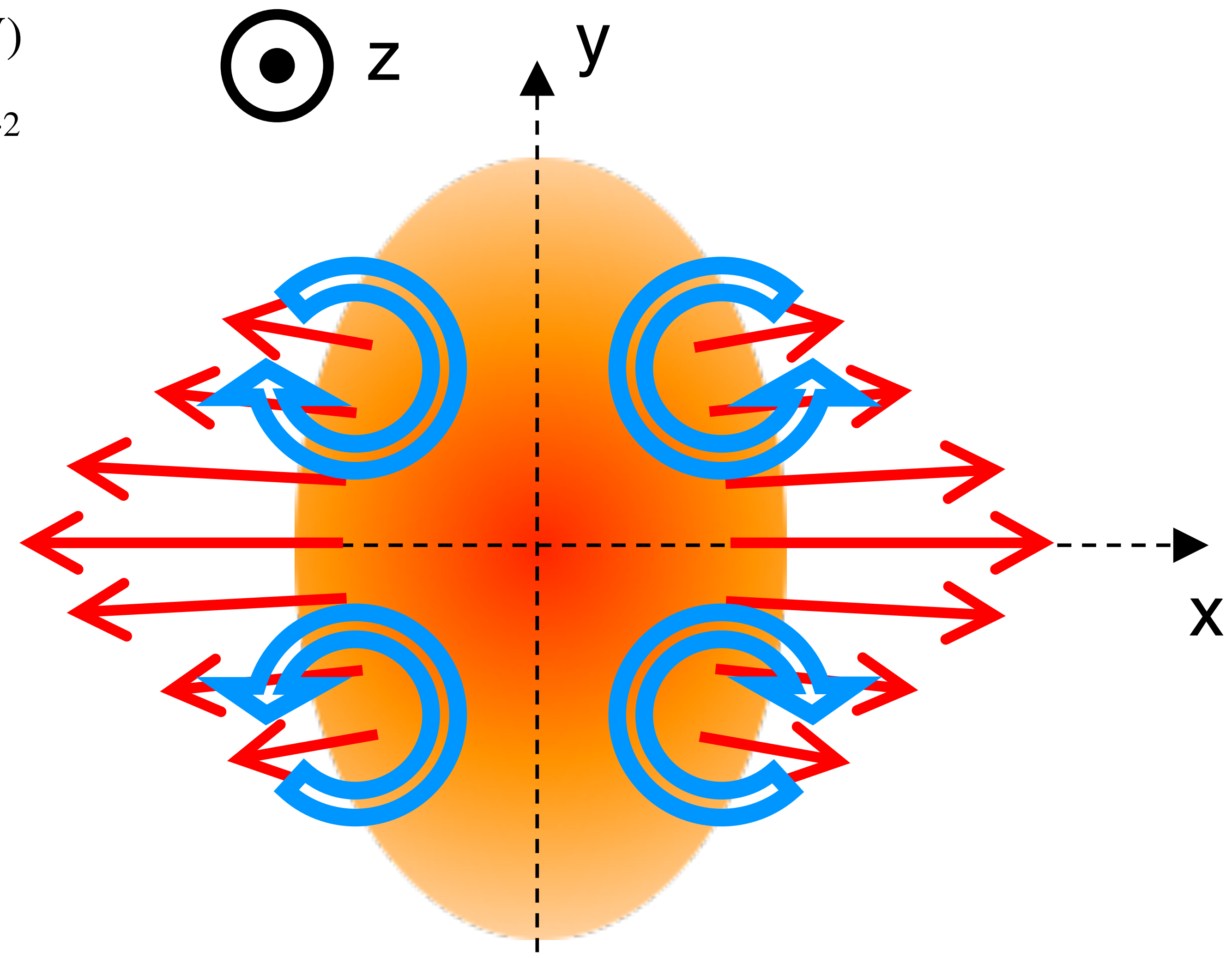
Vortex induced by jet



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

Local vorticity induced by collective flow

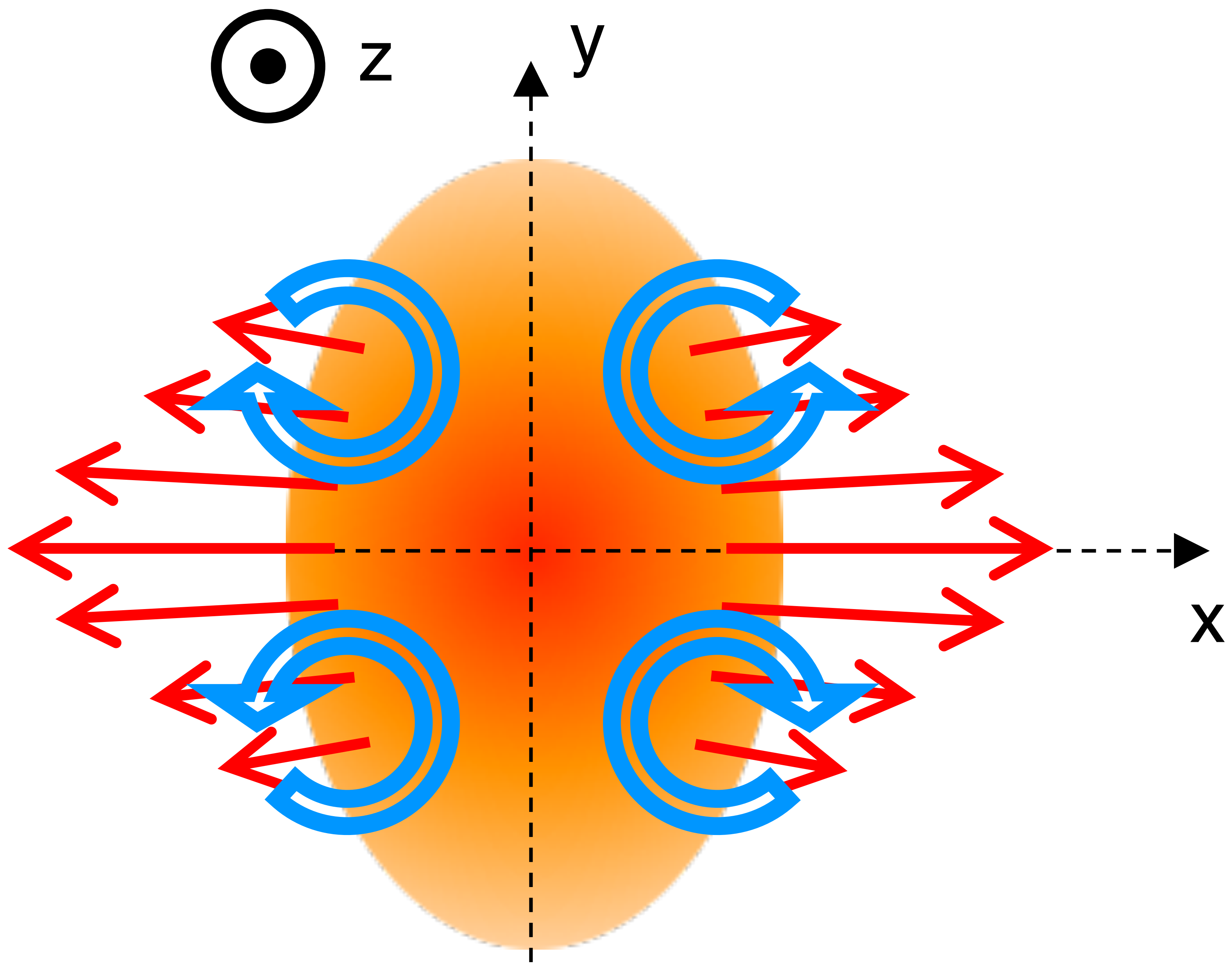


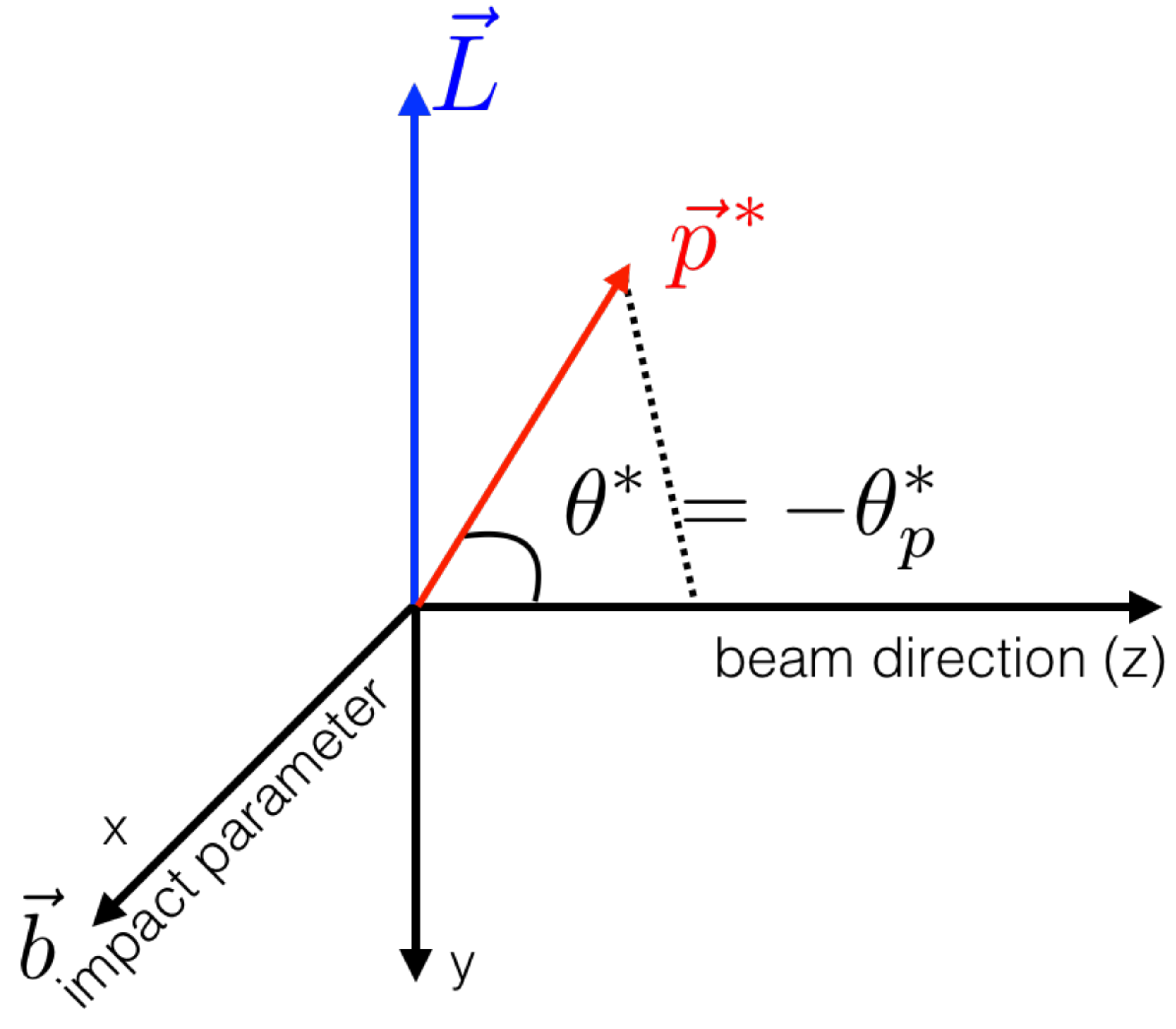


L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

Polarization along the beam direction

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





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

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

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

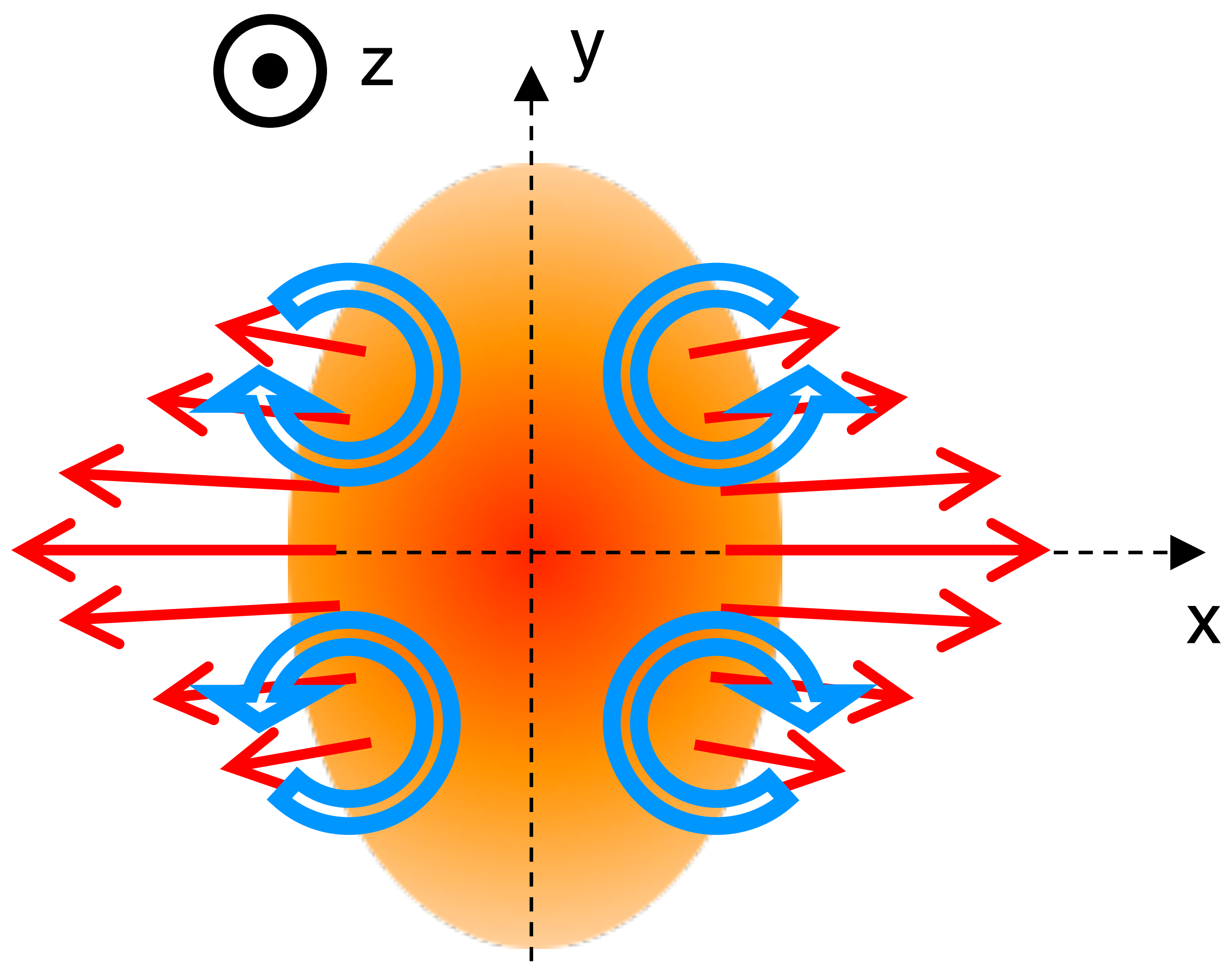
$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

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

$\alpha_{\rm H}$: hyperon decay parameter
θ_p^*: θ of daughter proton in Λ rest frame

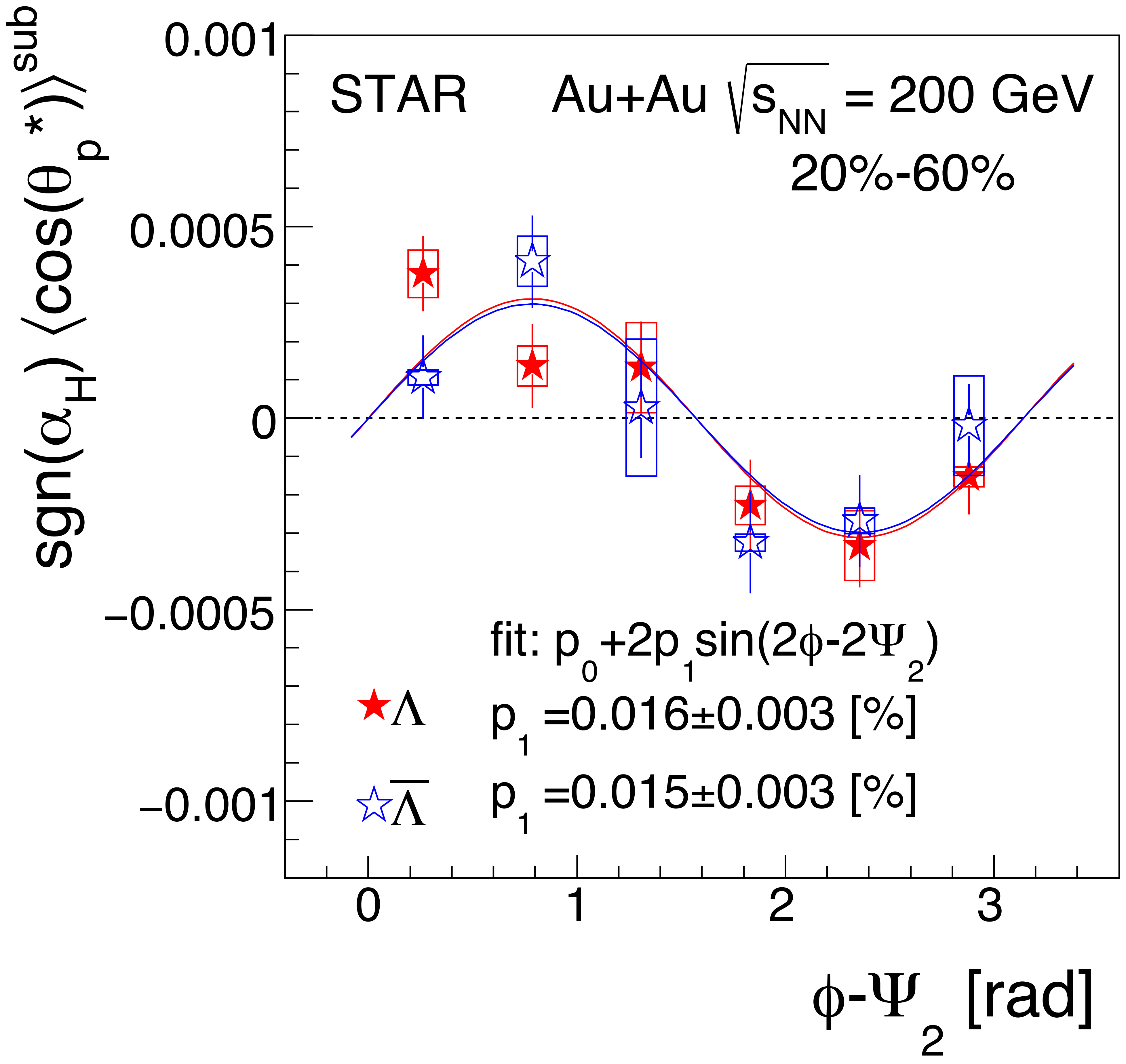
Stronger flow in in-plane than in out-of-plane, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.

"z-component" of polarization: P_z



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

STAR, PRL123.13201 (2019)



- Polarization <u>along the beam direction</u> expected from the "elliptic flow"
- STAR data indeed show such a longitudinal polarization depending on azimuthal angle (sine function)

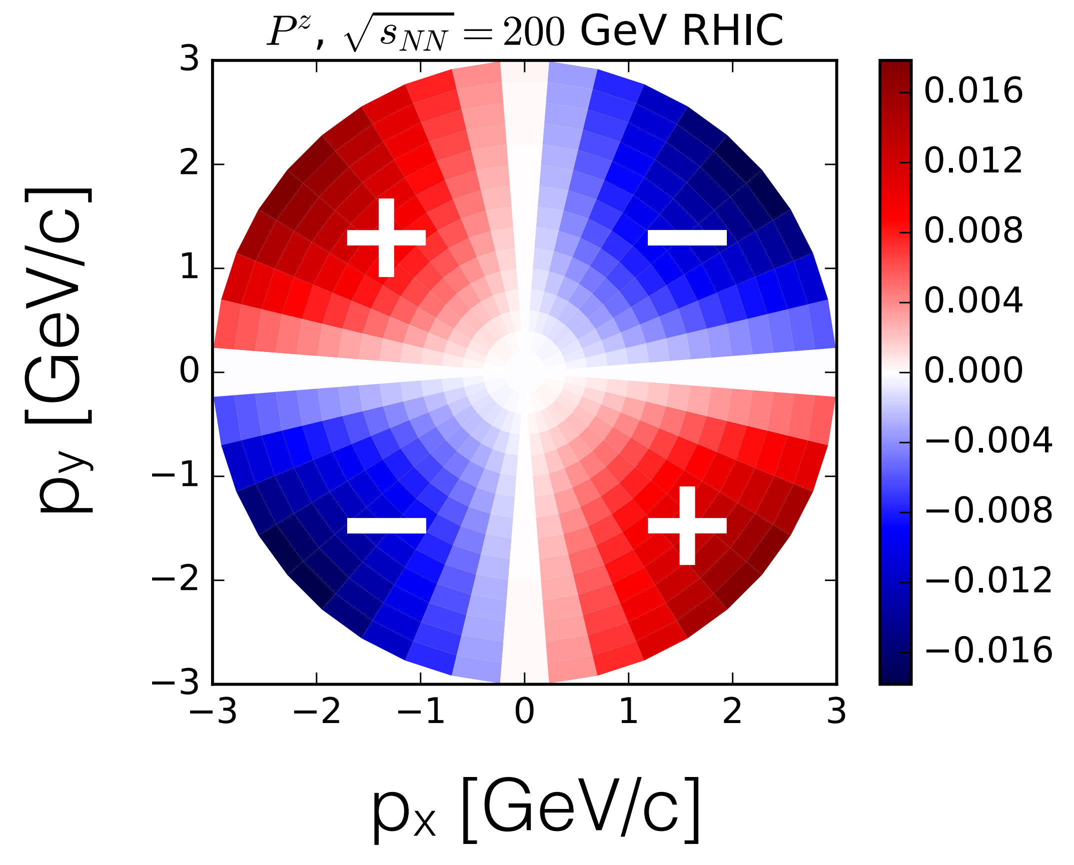
Flow-driven polarization!

"Sign puzzle" in $P_z(\phi)$

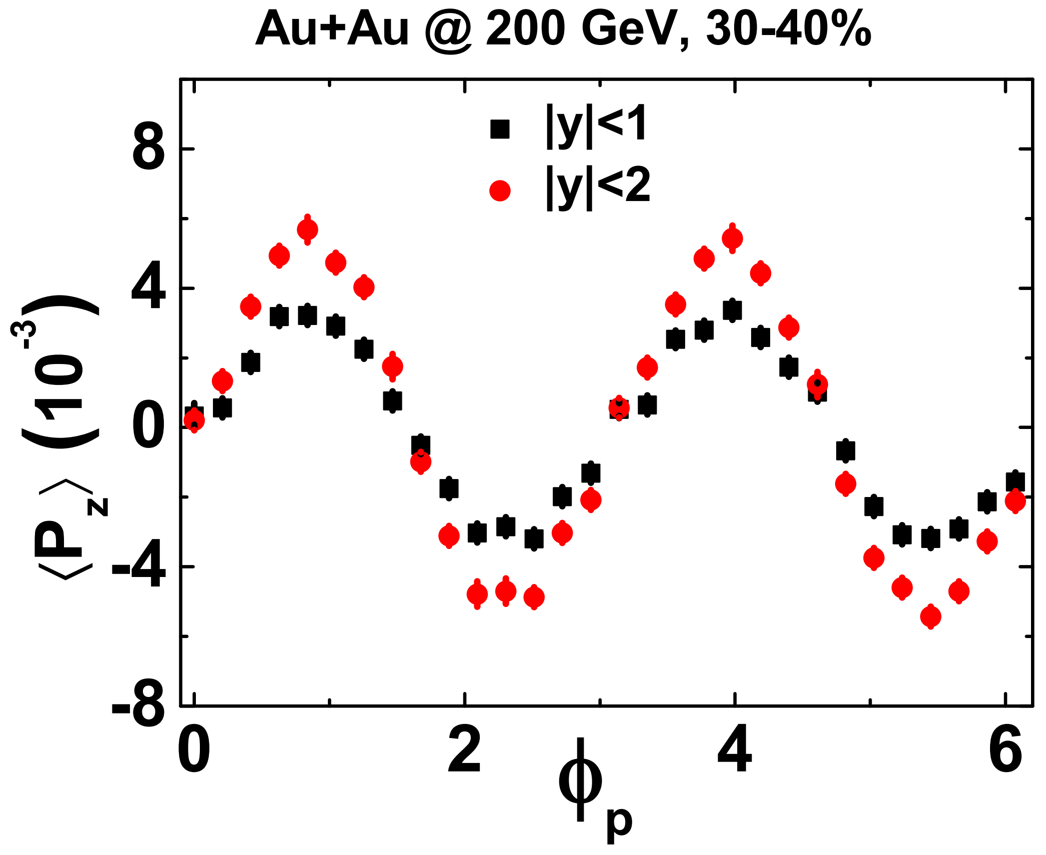
Theoretical models predict $P_z(\phi)$ differently

- UrQMD-IC + hydrodynamic model
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- AMPT X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)
- Chiral kinetic approach Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- AMPT-IC + MUSIC B. Fu et al., PRC103, 024903 (2021)
- High resolution (3+1)D PICR hydrodynamic model
  Y. Xie, D. Wang, and L. P. Csernai, EPJC80.39 (2020)
- Blast-wave model
  S. Voloshin, EPJ Web Conf.171, 07002 (2018), STAR, PRL123.13201
- Thermal model W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)
- (3+1)D hydro CLVisc, "T-vorticity"
  H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)
- New term: "shear tensor"
  S. Liu, Y. Yin, JHEP07(2021)188
  B. Fu et al., PRL127, 142301 (2021)
  F. Becattini et al., PLB820(2021)136519
  F. Becattini et al., PRL127, 272302 (2021)

Hydrodynamic model

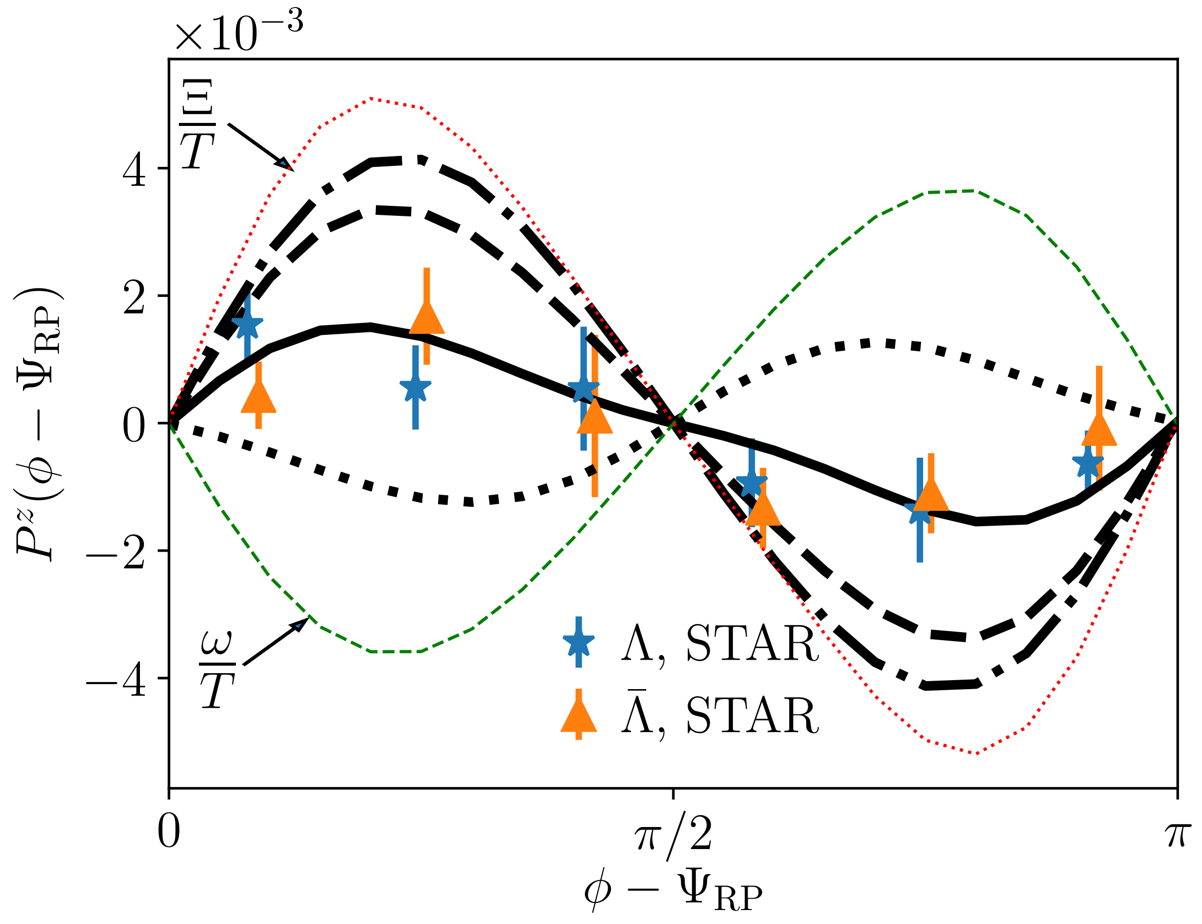


Chiral kinetic approach



vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

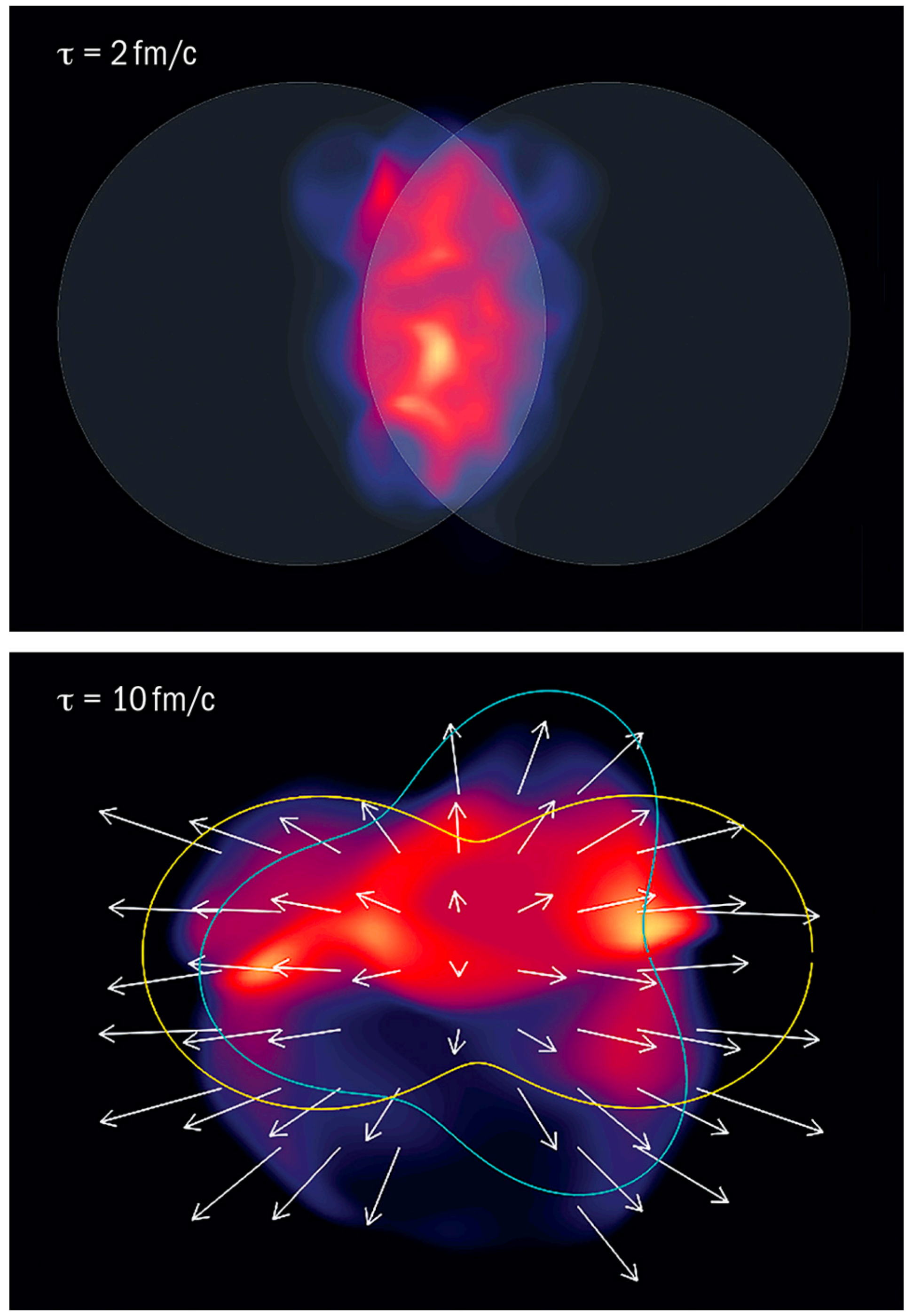


Disagreement among models and data

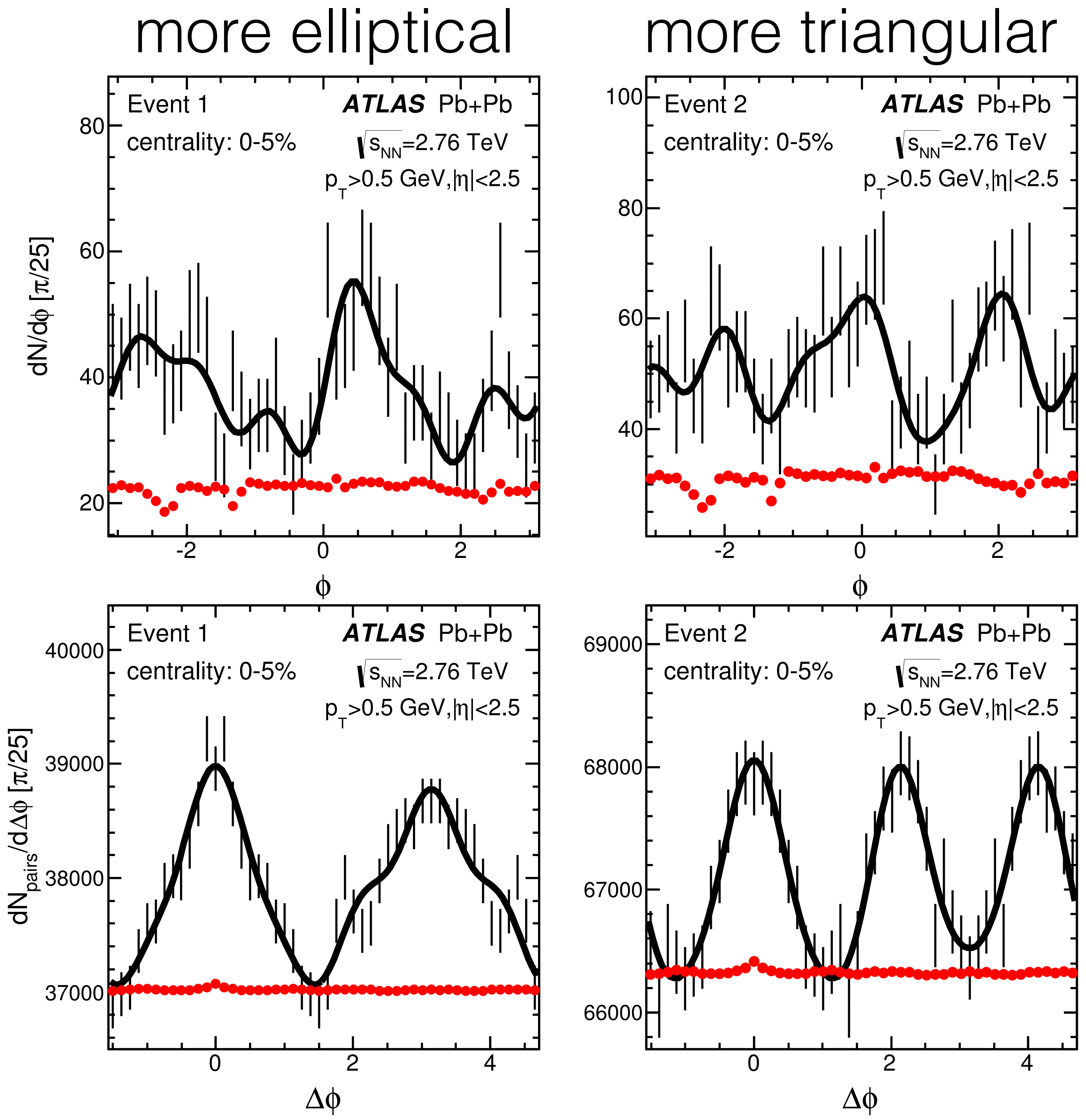
Incomplete thermal equilibrium of spin degree of freedom as the flow develops later in time? "shear tensor" explains everything?

Higher harmonic flow

B. Alver and G. Roland, PRC81, 054905 (2010)
ATLAS, JHEP11(2013)183



picture from CERN COURIER (MUSIC)



Single particle distribution

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_n)$$

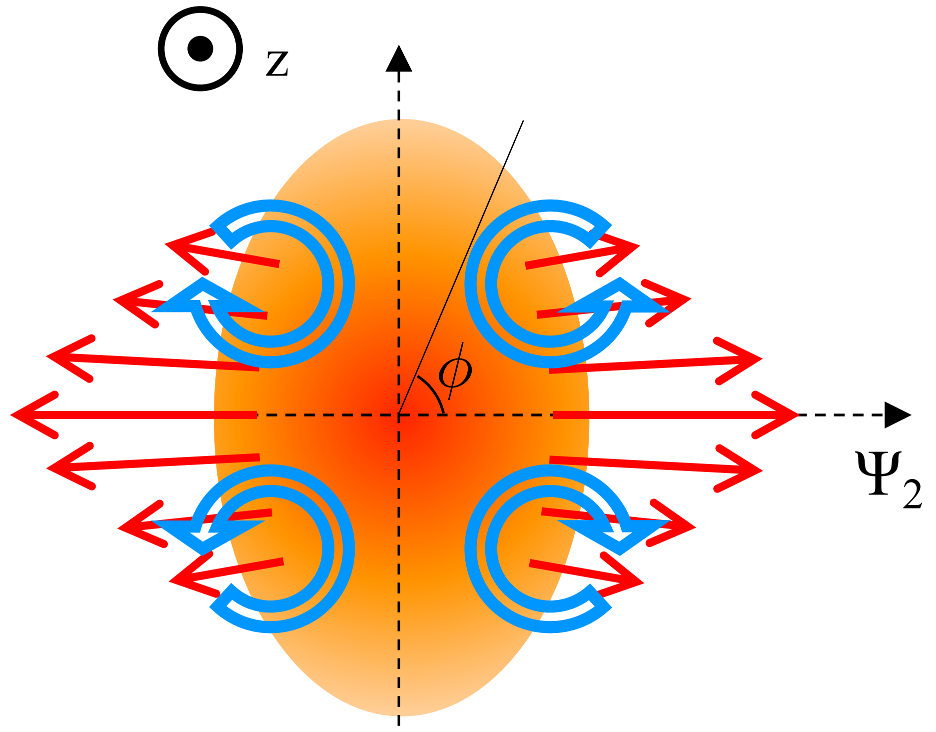
Two particle correlations

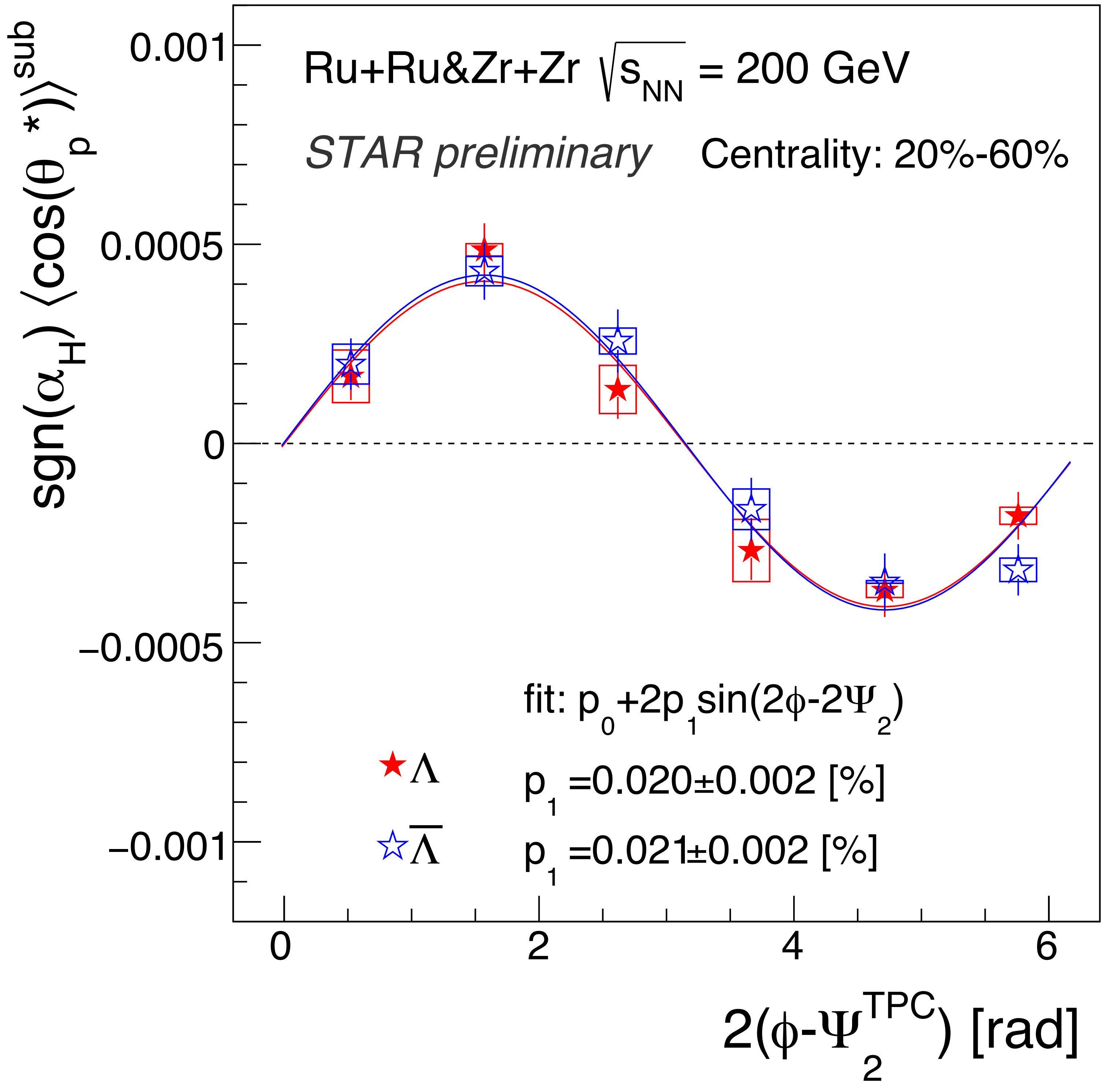
$$\frac{dN_{\mathrm{pair}}}{d\Delta\phi} \propto 1 + \sum_n 2v_n^2 \cos(n\Delta\phi)$$

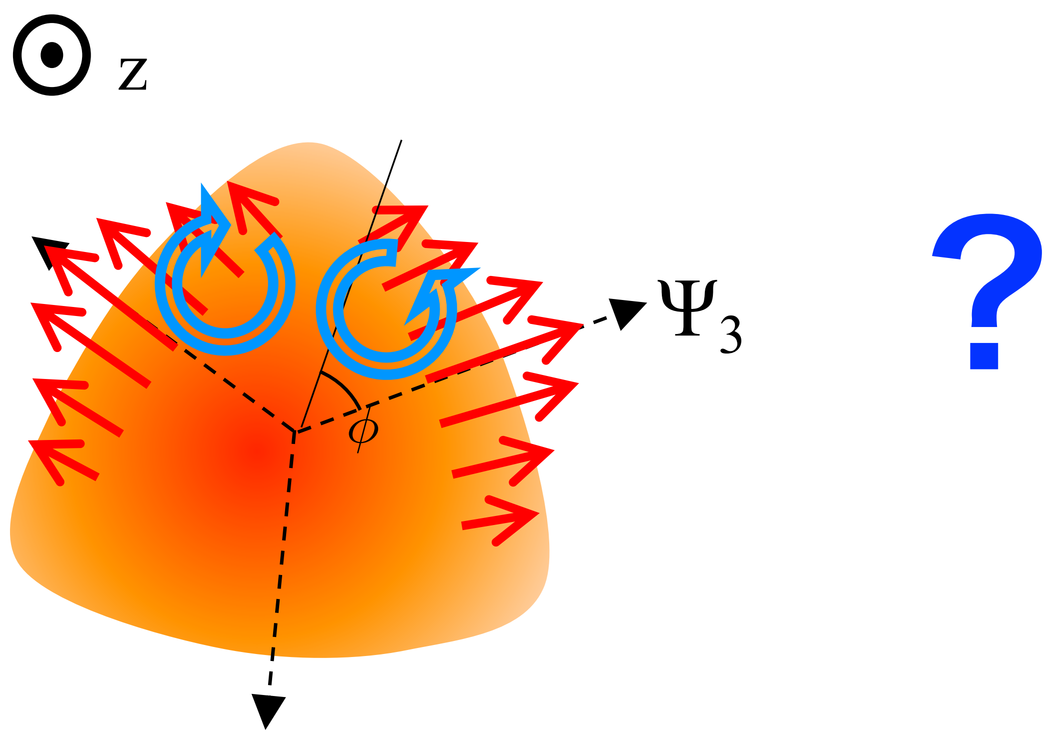
- Initial density fluctuations lead to higher harmonic flow
- Can higher harmonic flow also create vorticity, thus polarization?

P_z in isobar collisions

TN (STAR), QM2022





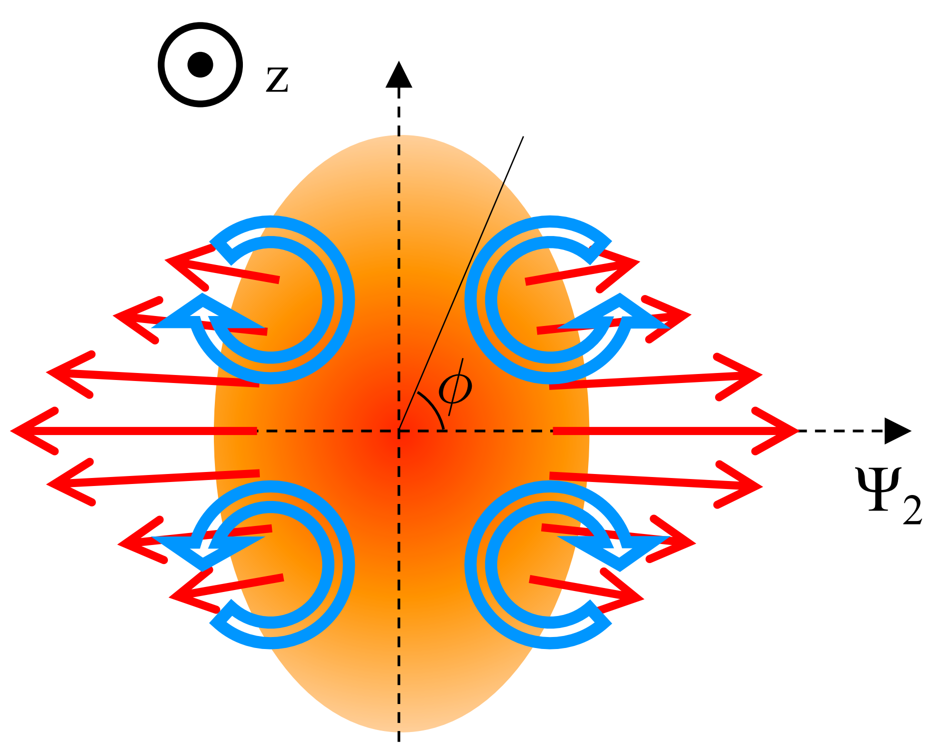


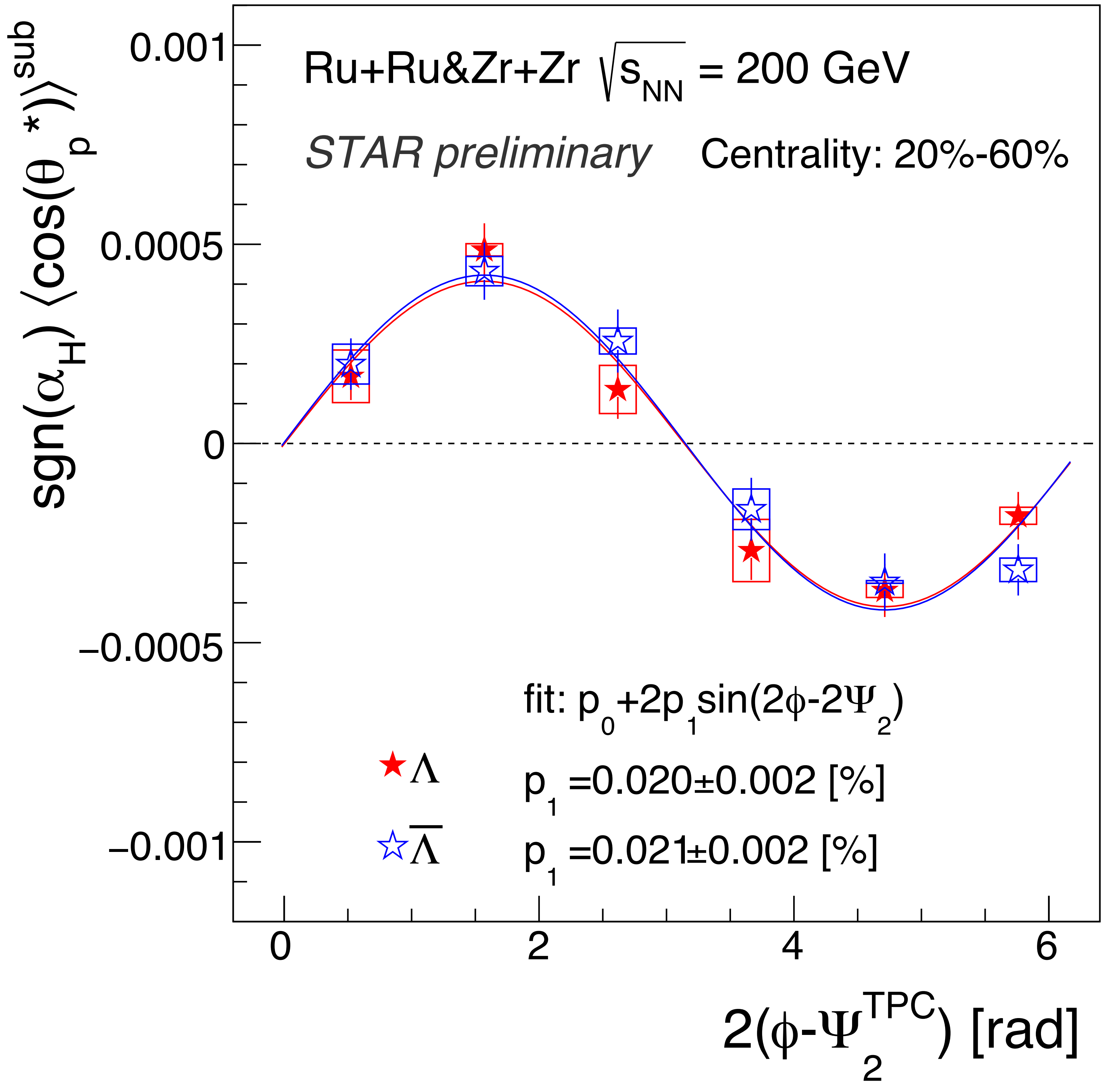
- Clear Ψ_2 dependence as seen in Au+Au at 200 GeV

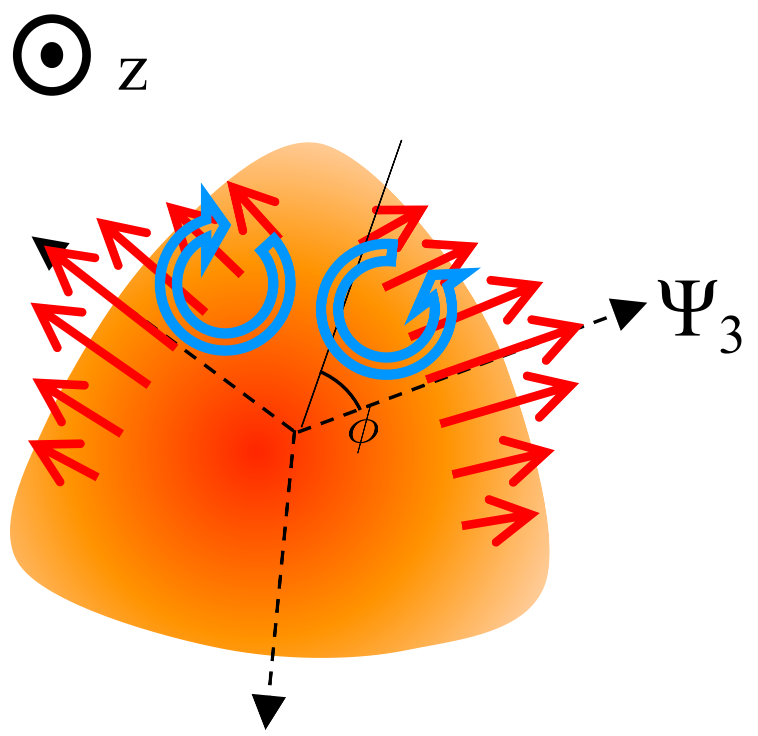
P_z in isobar collisions

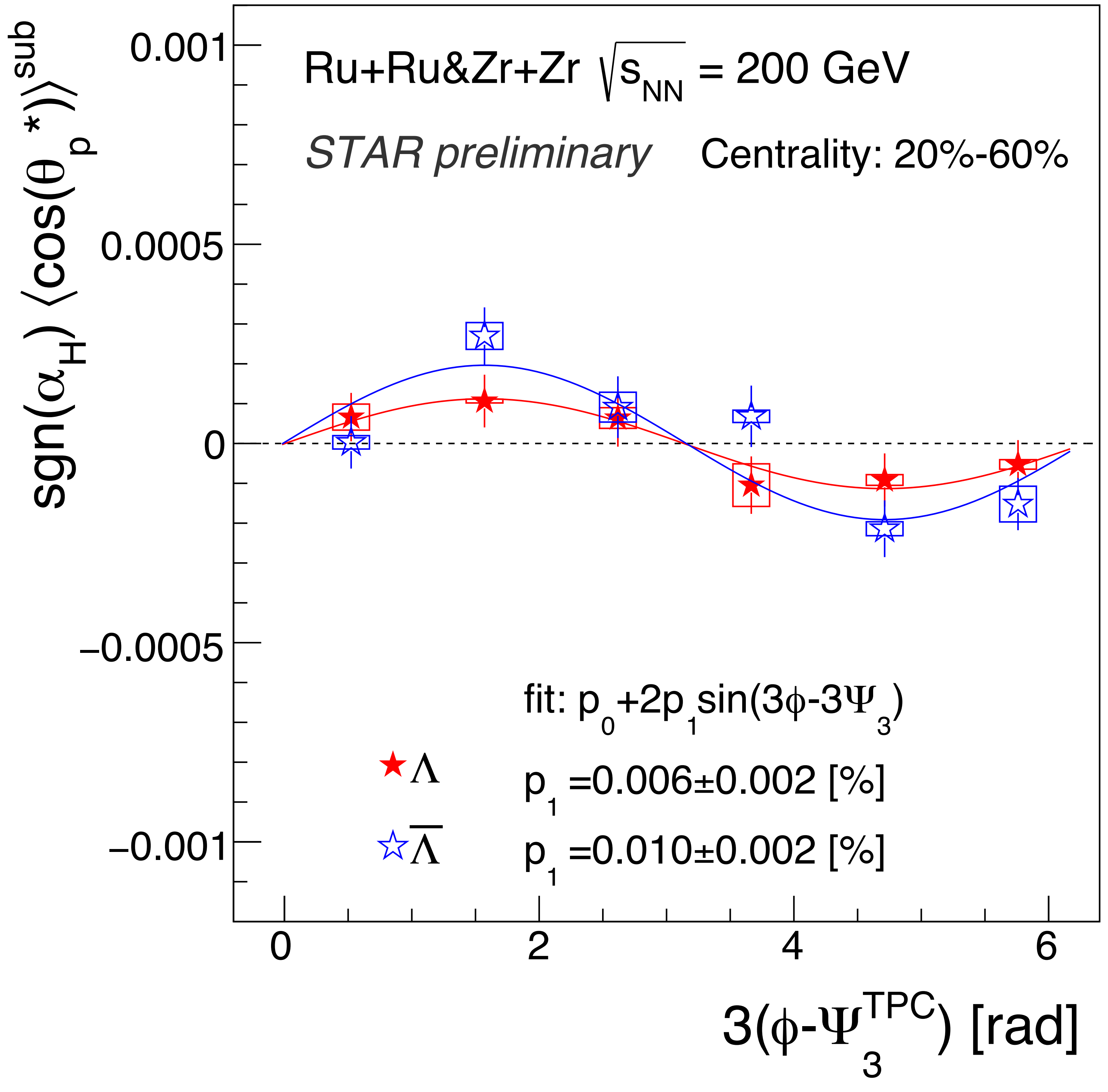
TN (STAR), QM2022

*Not accounted for EP resolution and decay parameter





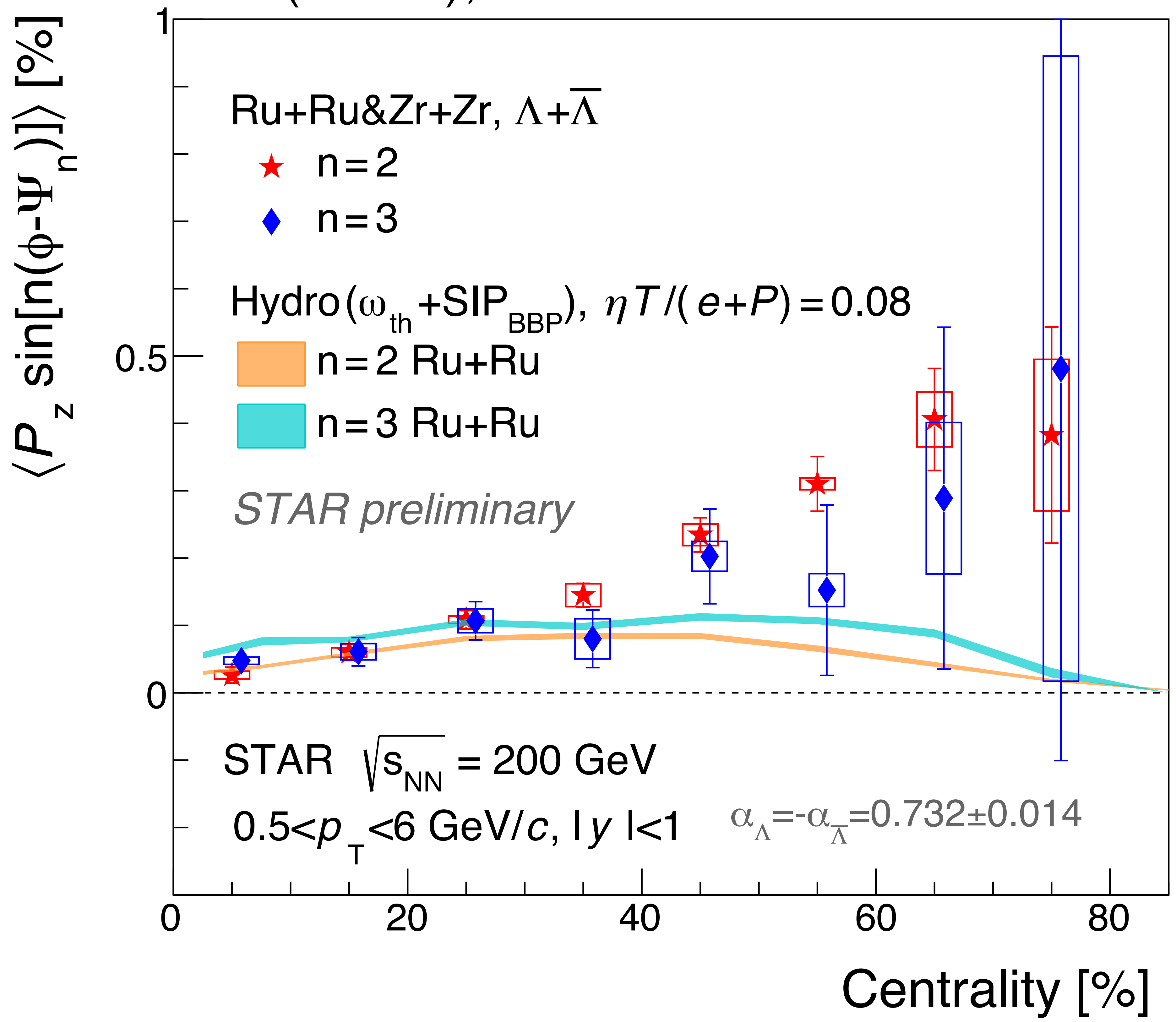




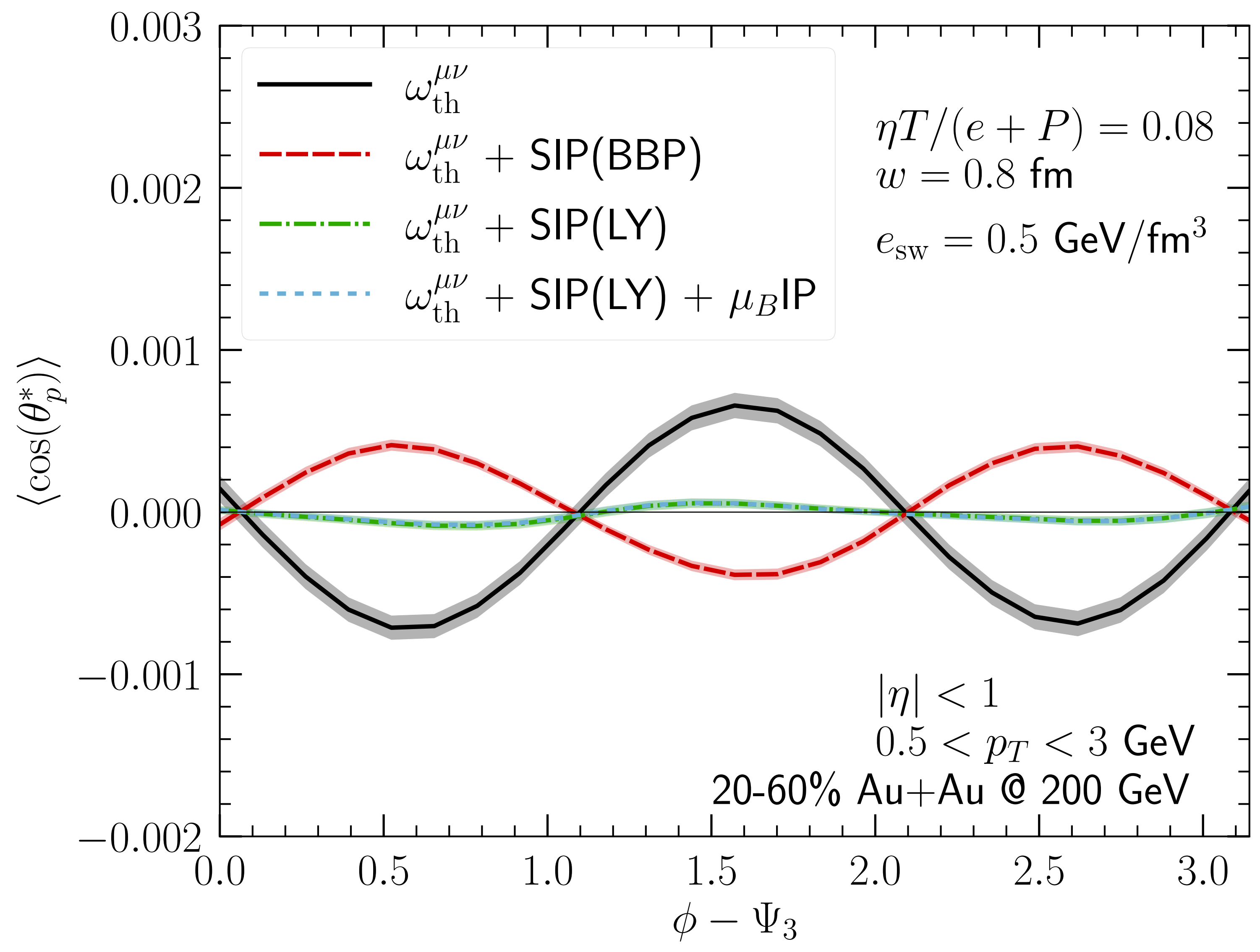
- Clear Ψ_2 dependence as seen in Au+Au at 200 GeV
- First measurement relative to the 3rd-order event plane Ψ_3!
    - Similar pattern to the 2nd-order, indicating v_3-driven polarization
    - Can models describe the data with correct sign?

Centrality dependence of $P_{z,n}$

TN (STAR), QM2022



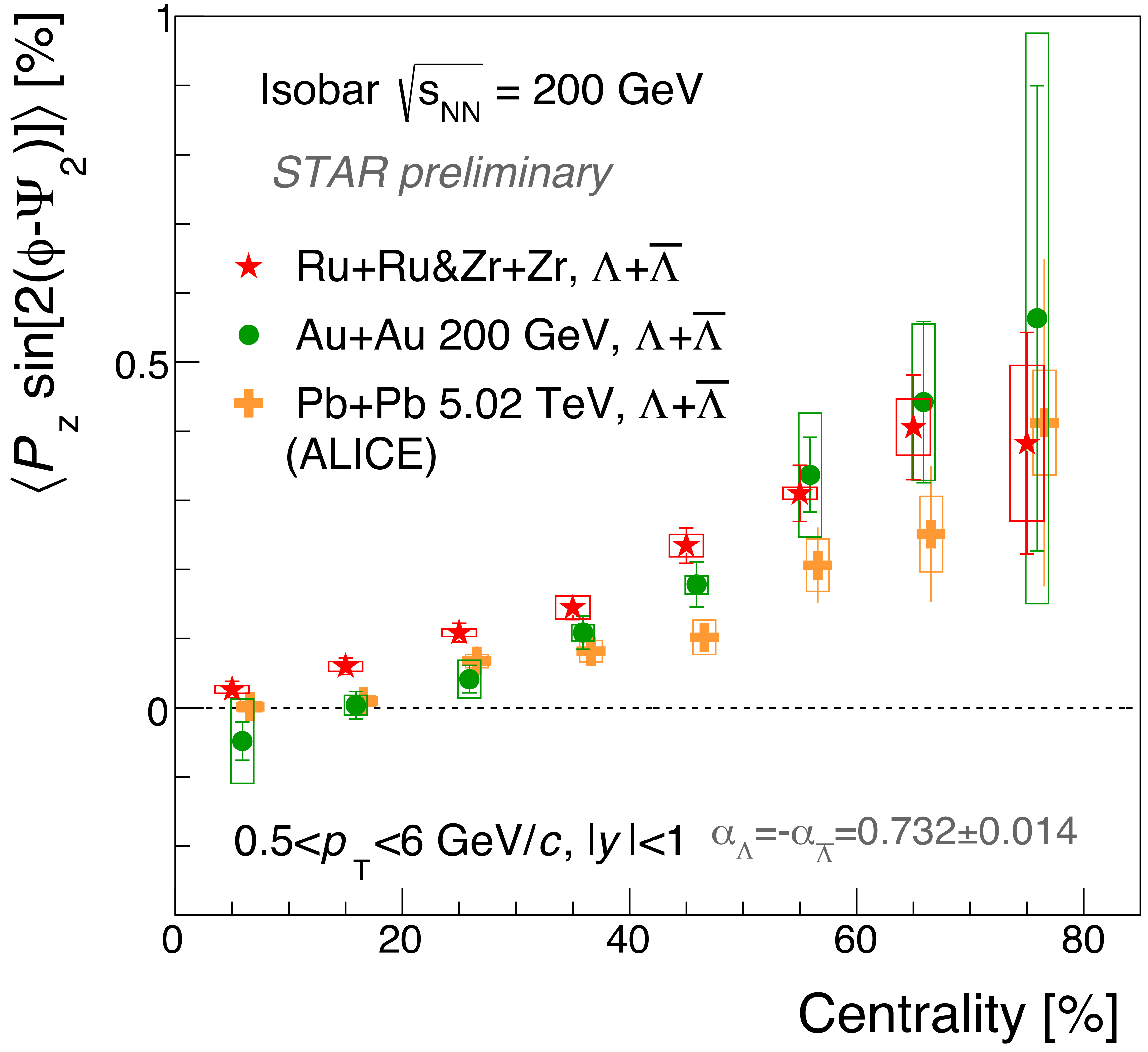
S. Alzharani, S. Ryu, and C. Shen, PRC106, 014905 (2022)



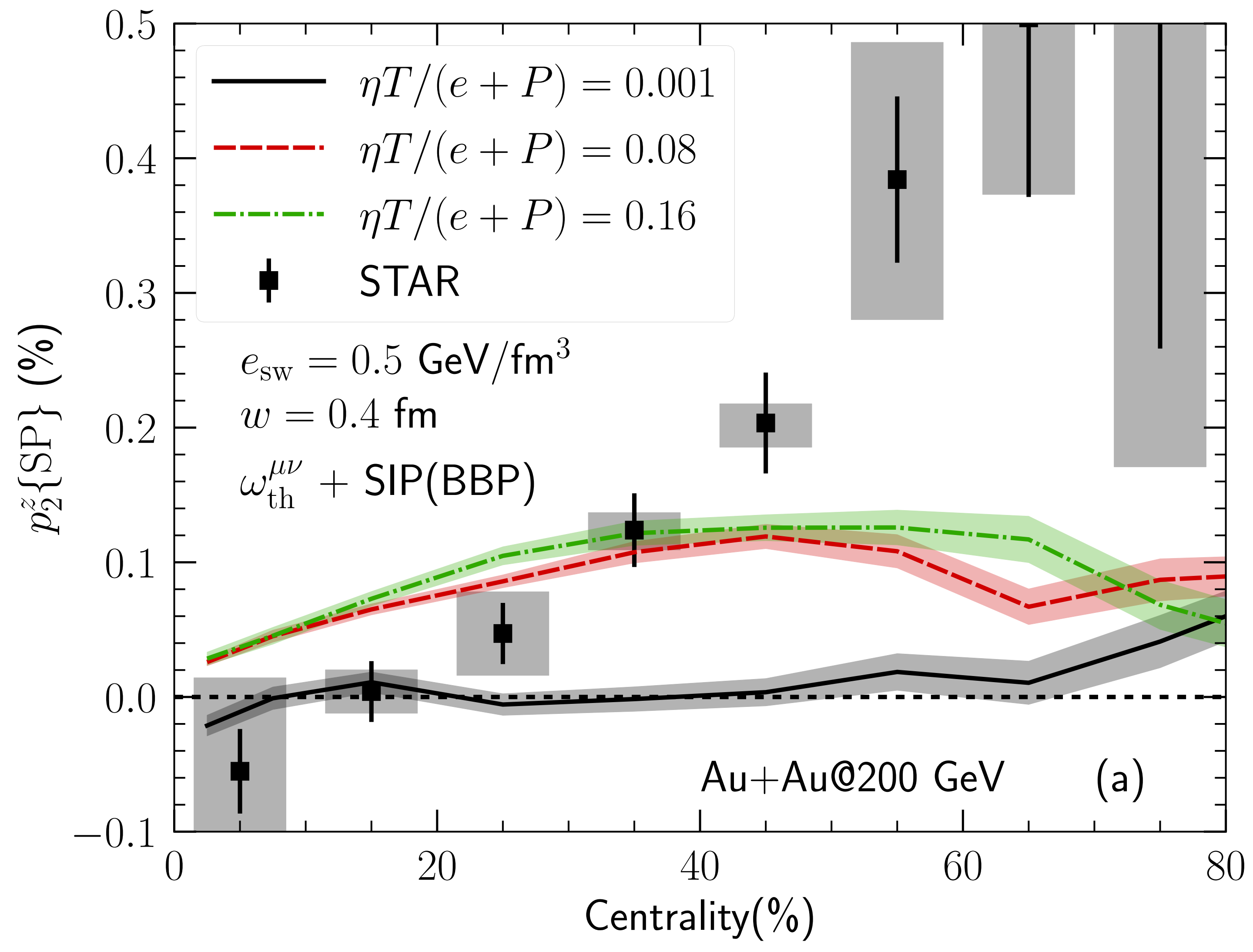
- Comparable 2nd and 3rd order sine coefficients of P_z, especially in most central events
- Hydrodynamic models with shear term reasonably describes the data for central but not for peripheral collisions. Still need more investigation on how to implement the shear

Collision system size dependence of $P_{z,2}$

TN (STAR), QM2022



S. Alzharani, S. Ryu, and C. Shen, PRC106, 014905 (2022)



- $P_{z,2}$ from Isobar data comparable to Au+Au and Pb+Pb
  - There may be a small system size dependence, rather than energy dependence
- Additional constraint on the specific shear viscosity

Summary

- Observation of global polarization open new directions in the study of QCD matter and its dynamics in heavy-ion collisions

  "*the hottest, least viscous, and now most vortical, fluid*"

- A lot of progress in measurements since the first observation by STAR
  - Global polarization measurements in a wide range of energy: 2.4 GeV to 5.02 TeV
  - Differential measurements with some open questions: rapidity/azimuthal angle
  - Extended measurements to Ξ and Ω hyperons, to be improved in future
  - Flow-induced polarization along the beam direction, now extended to 3^{rd}-order. The shear term seems important to explain the data.

Outlook

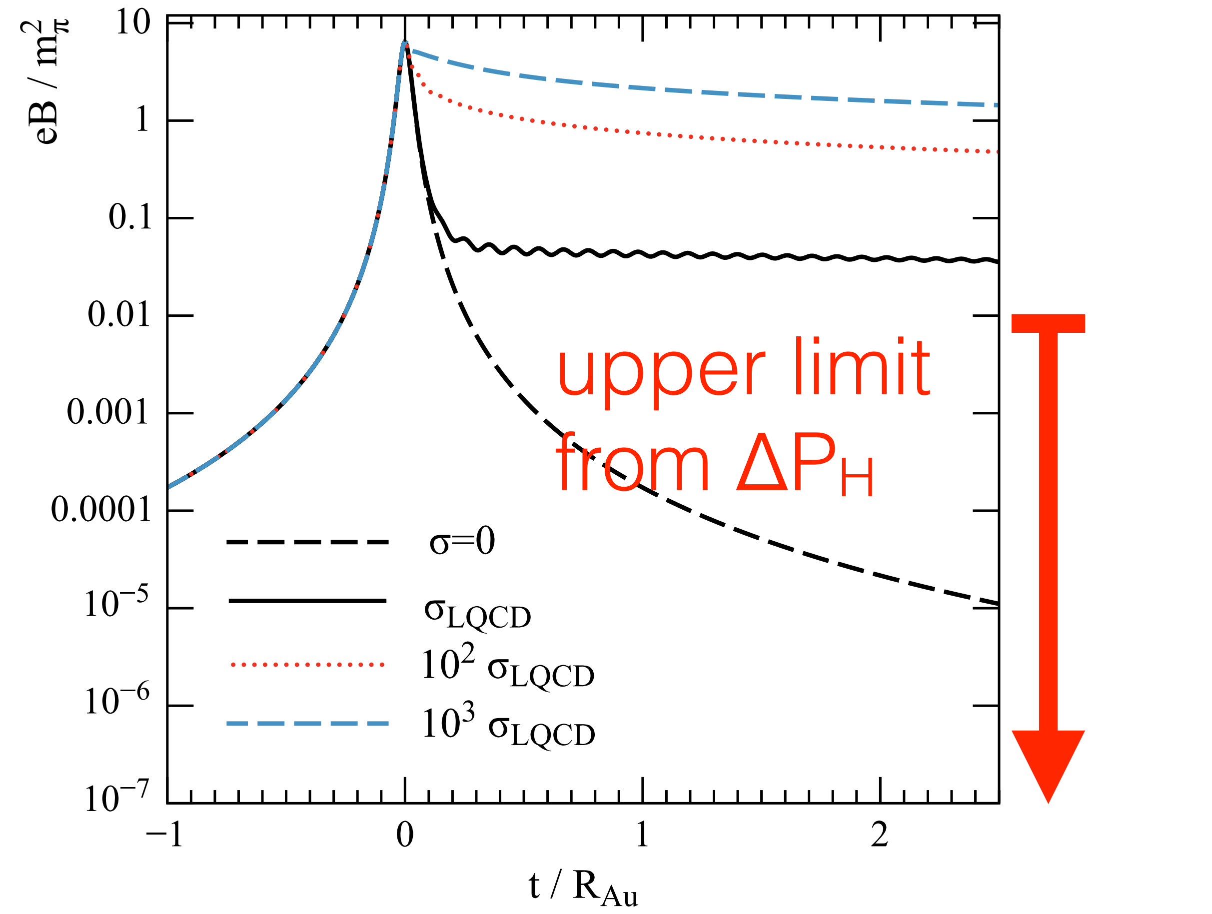
- Global polarization
  - Any Λ-Λbar P_H splitting? If so, is it due to B-field?
  - Need more precise measurements of Ξ and Ω
  - What's rapidity dependence? At more forward/backward rapidity
- Local polarizations
  - Higher-order P_z and one remaining component P_x, if any
  - ϕ-polarization (toroidal vortex)
  - Spin Hall Effect?
    S.Y.F. Liu and Y. Yin, PRD104, 054043 (2021)

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98, 024905 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)

- Connection to the phase diagram
  Y. Jiang and J. Liao, PRL117.192302(2016)
  Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184

More interesting results will come!
→STAR BES-II/Run2023+, LHC Run-3, HADES, NA61/SHINE, and future experiments

L. McLerran and V. Skokov, NPA929.184 (2014)



BUR2020, STAR Note SN0755