Global polarization and spin alignment measurements

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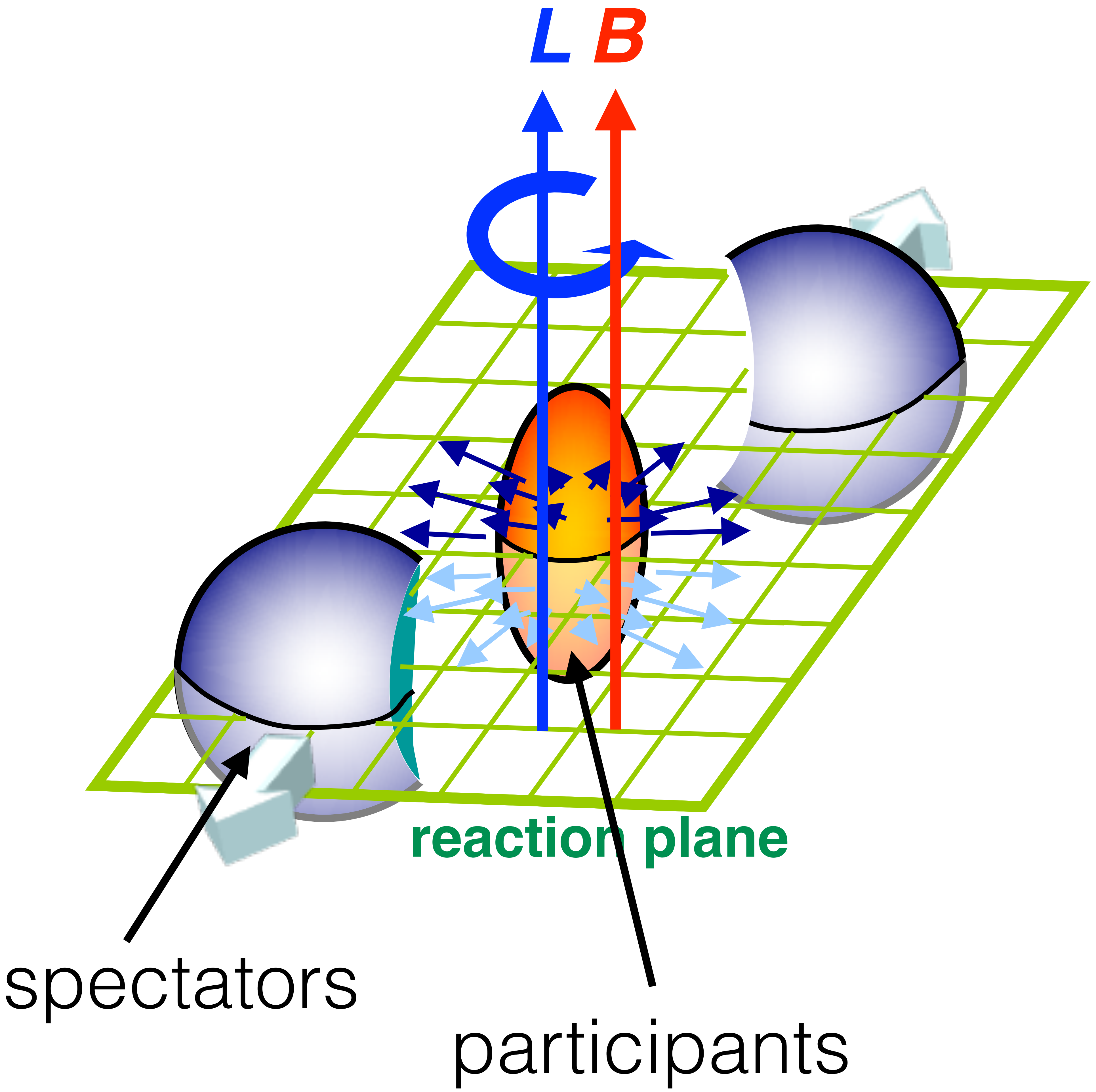
Outline

- Vorticity and magnetic field in heavy-ion collisions
- Recent experimental results
    - Global polarization
    - Local polarization
    - Global spin alignment
- Summary and Outlook

Orbital angular momentum/magnetic field in HIC



Orbital angular momentum

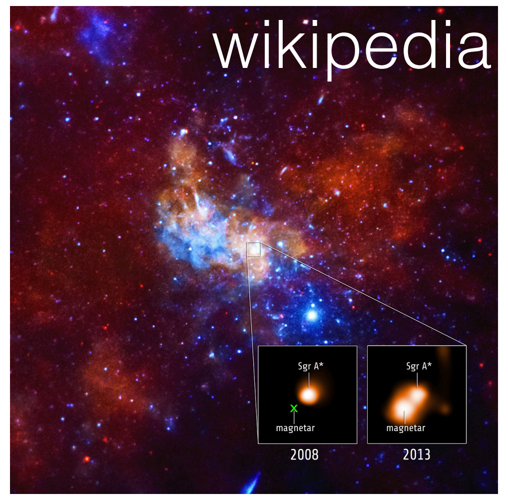
Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$
$$\sim bA\sqrt{s_{NN}} \sim 10^6\hbar$$

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)



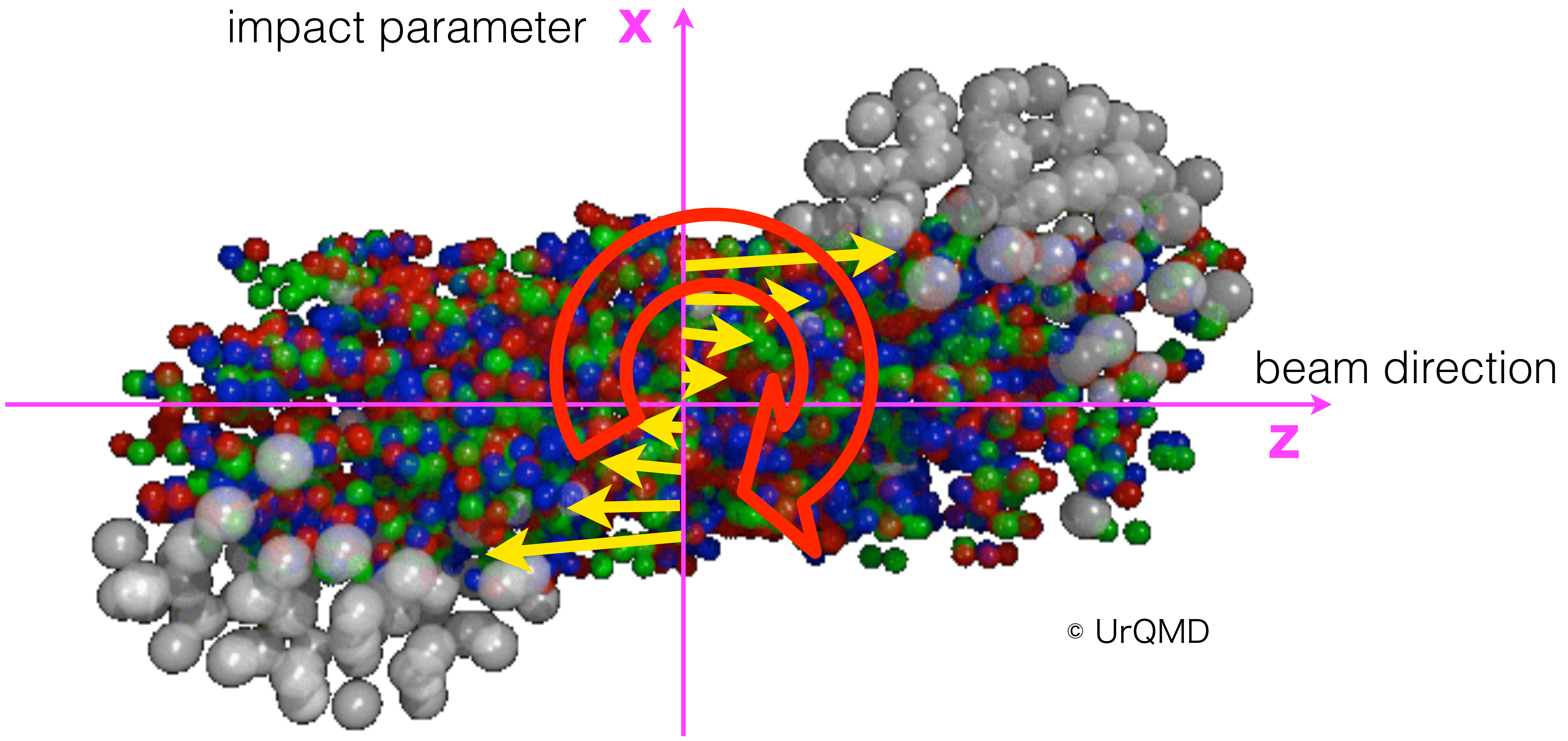
magnetar

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

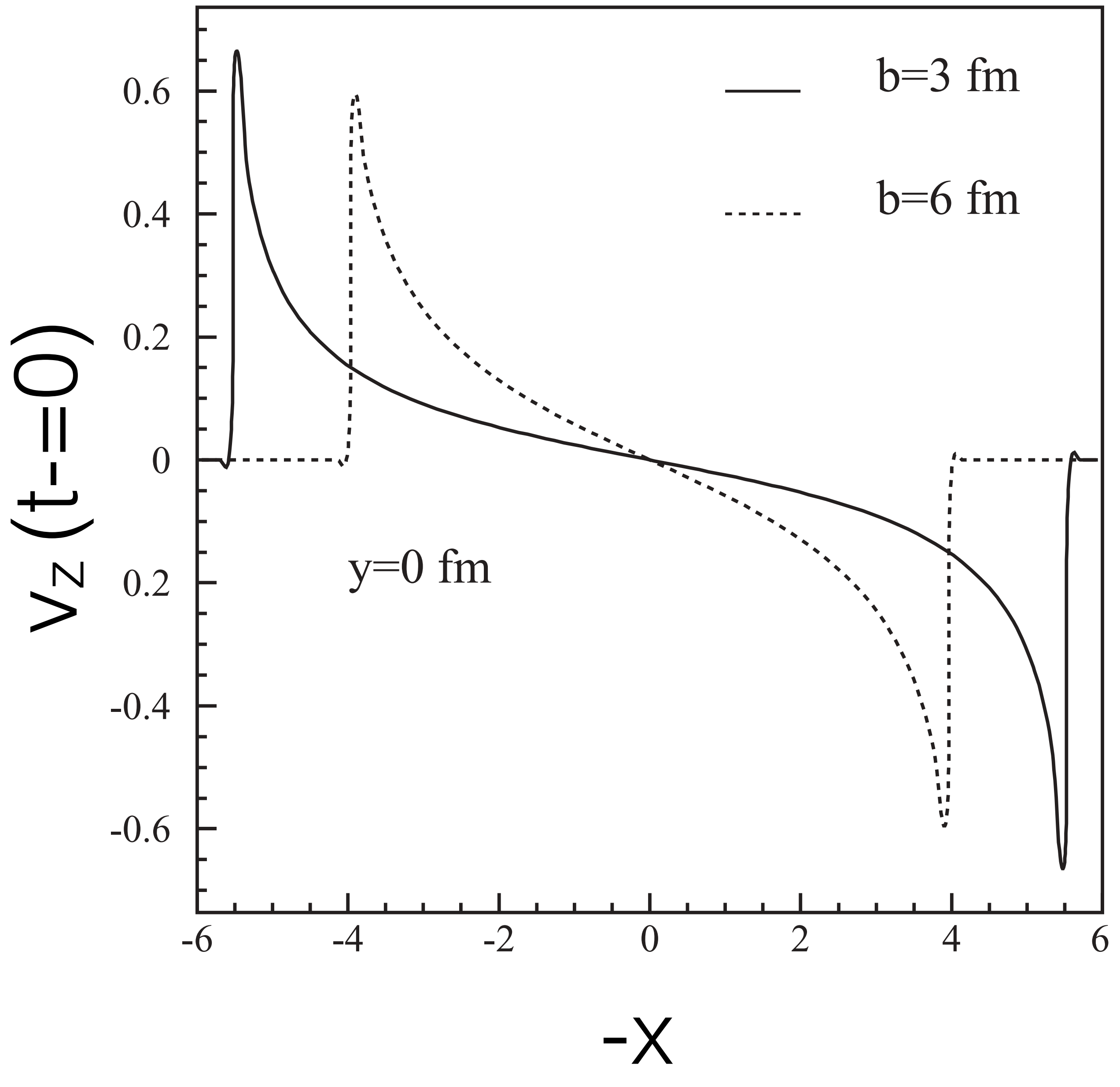
Vorticity in HIC

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

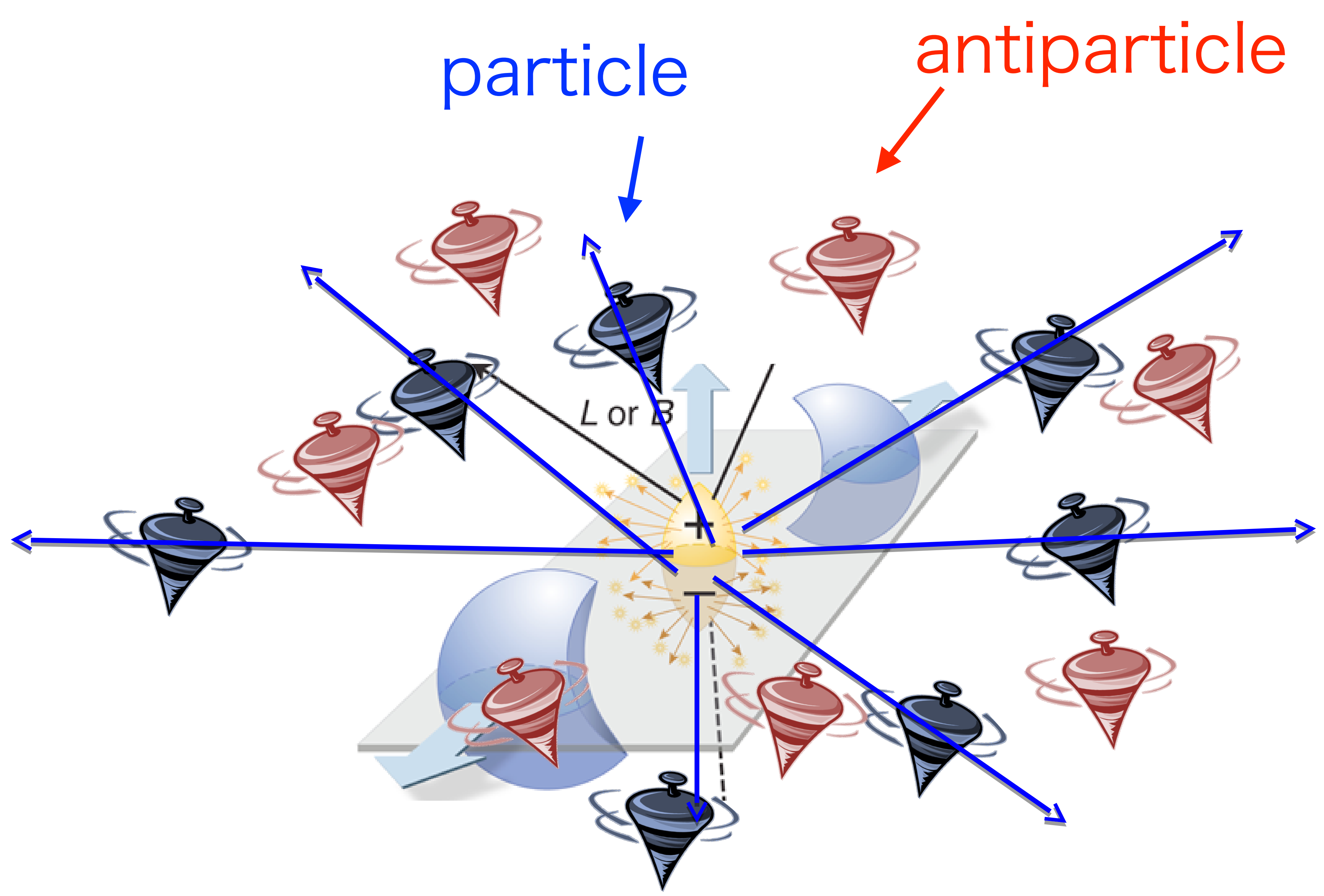
$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$



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



Global polarization/spin alignment



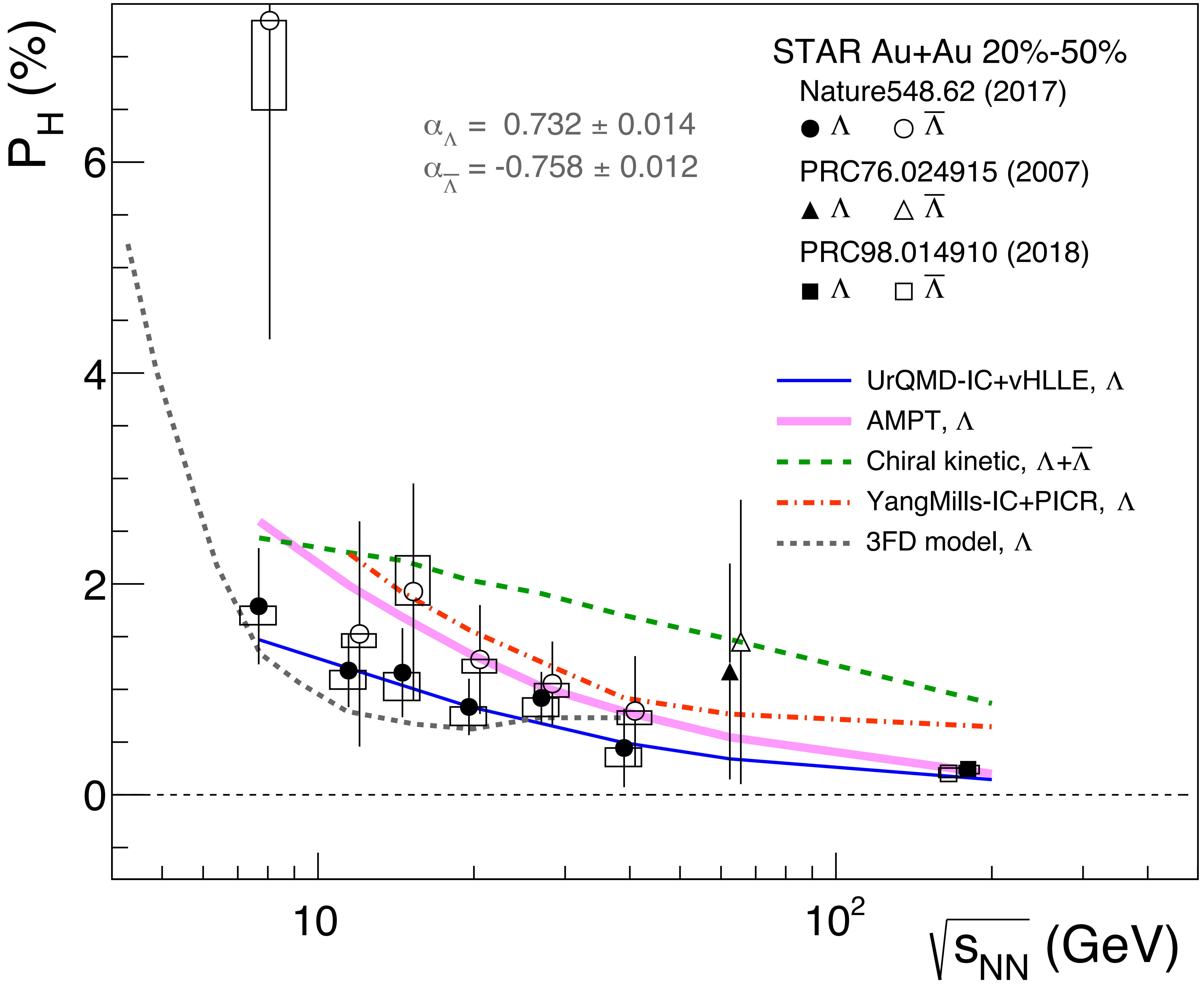
- Spin-orbit coupling
- Global polarization by the magnetic field
  - Spins of particles and antiparticles are oppositely aligned along ***B*** due to the opposite sign of magnetic moment

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)

Produced particles will be "globally" polarized along ***L*** or ***B***.
B might be studied by particle-antiparticle difference.

Observation of global polarization at STAR

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



- Indication of thermal vorticity

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \quad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar$$
$$\sim 10^{22}\mathrm{s}^{-1}$$

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

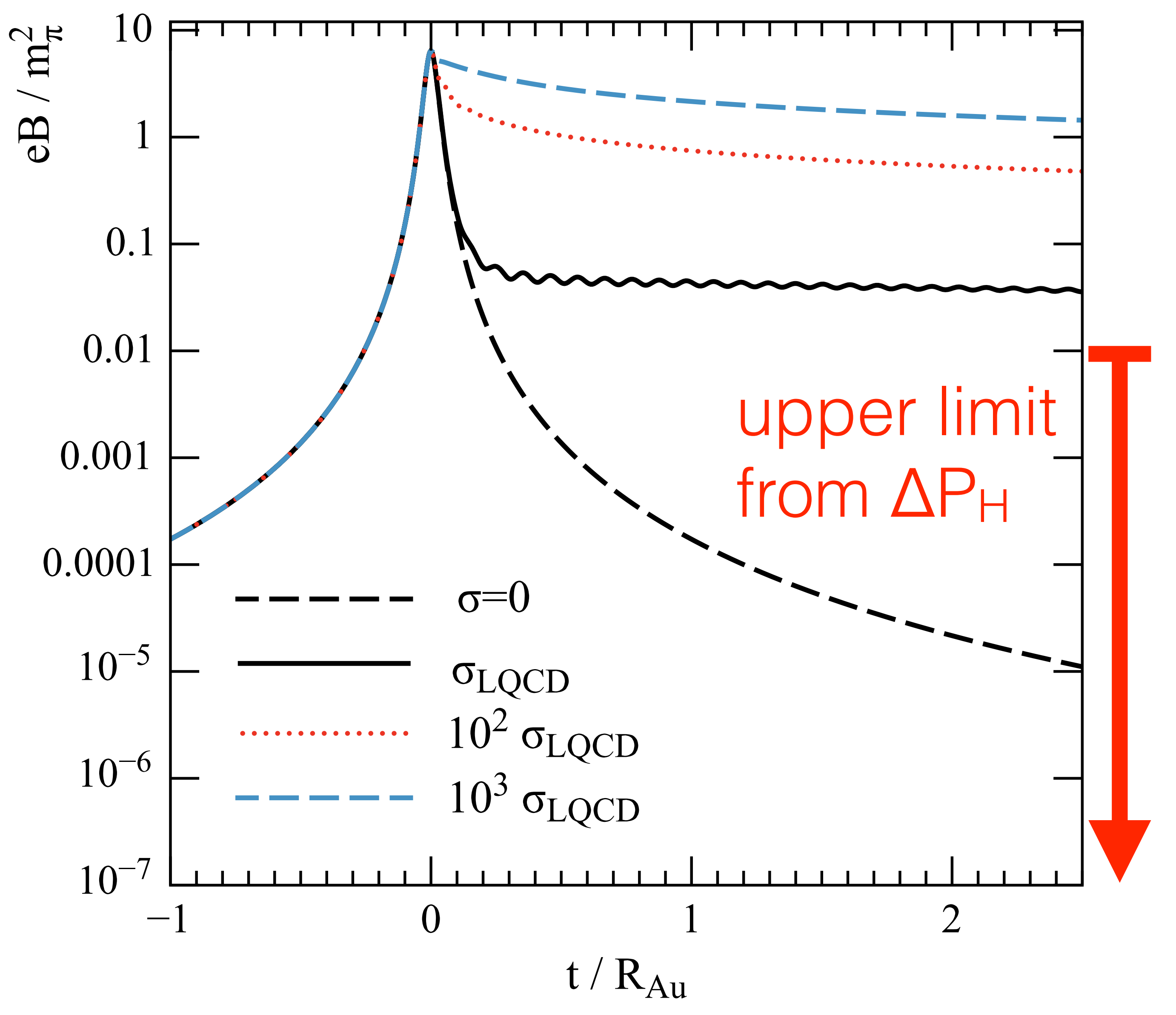
μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- 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

- Possible difference between Λ and anti-Λ

Open new direction

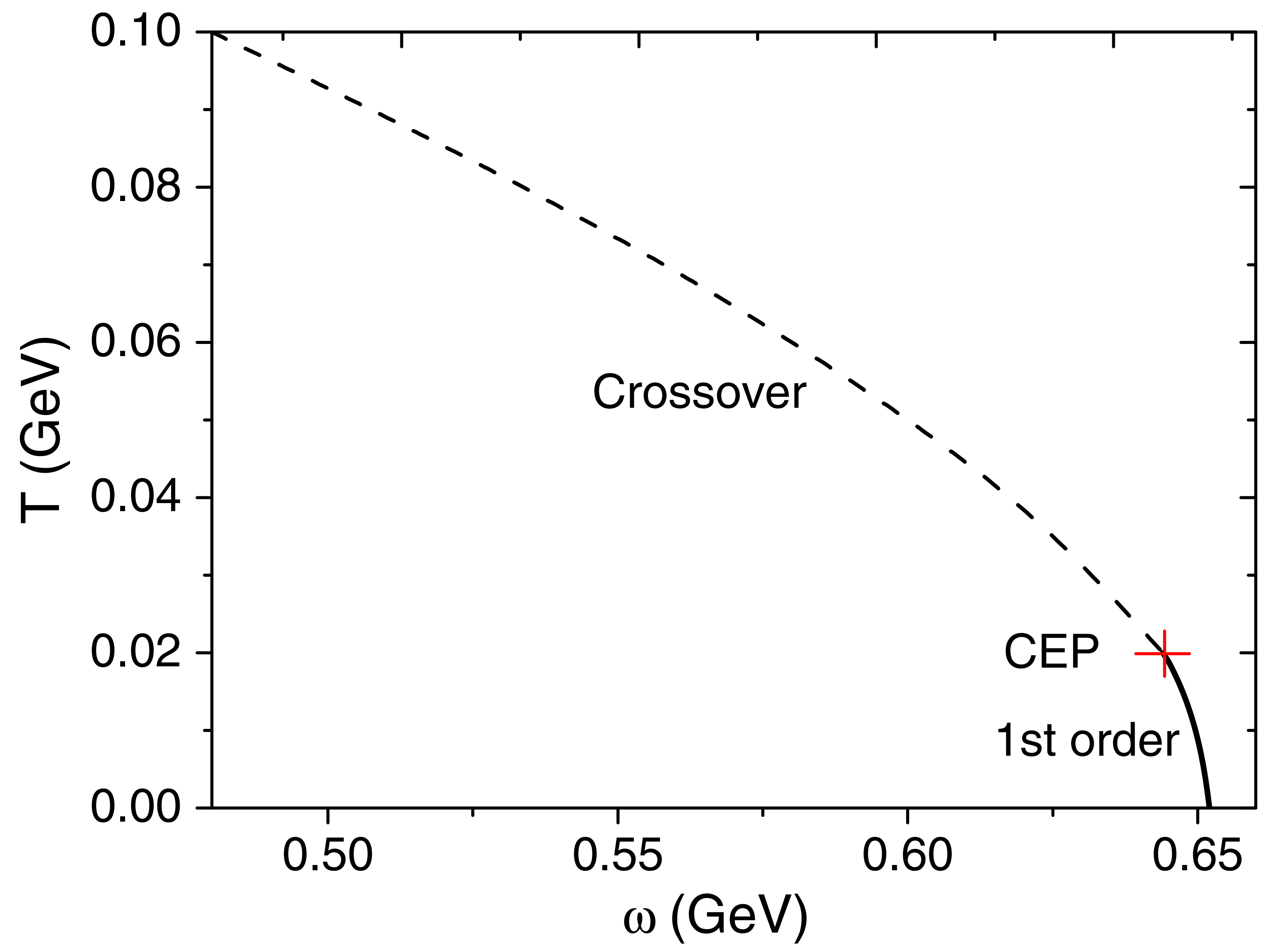
L. McLerran and V. Skokov, Nucl. Phys. A929, 184 (2014)



- Possible constraint on B-field lifetime
- Closely related to chiral phenomena

  M. Baznat et al., Phys. Rev. C 97, 041902 (2018)
  - chiral vortical effect, chiral separation effect
- New insight on initial conditions
  - velocity profile, initial tilt related to directed flow
- QCD phase diagram of rotating matter
  - lower deconfinement transition temperature for large ω

  Y. Jiang and J. Liao, PRL117.192302(2016)
  Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184



Global polarization measurement

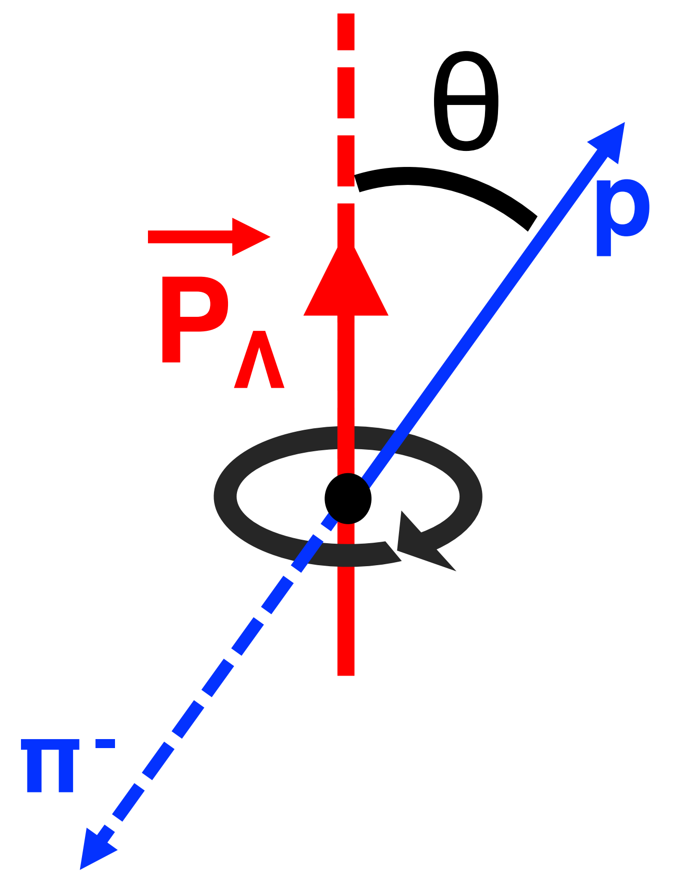
Parity-violating weak decay of hyperons ("self-analyzing")

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

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

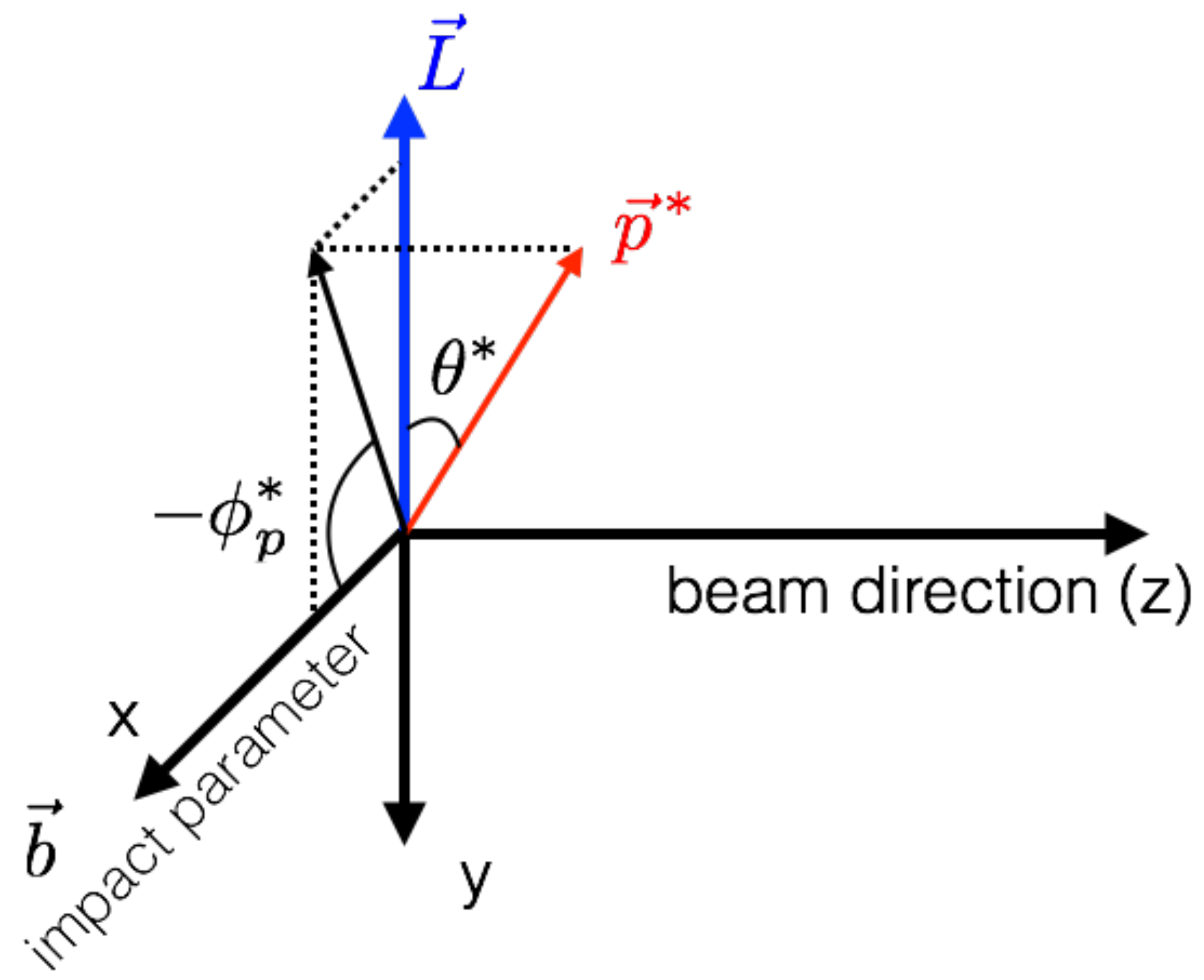
$\mathbf{P}_H$: hyperon polarization, α_H: hyperon decay parameter

$\hat{\mathbf{p}}_B$: unit vector of daughter baryon momentum, * denotes in hyperon rest frame



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

(BR: 63.9%, cτ~7.9 cm)



Projection onto the transverse plane

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

Ψ_1: azimuthal angle of b

STAR, PRC76, 024915 (2007)

Angular momentum direction determined by spectator deflection (spectators deflect outwards)

S. Voloshin and TN, PRC94.021901(R)(2016)

Quick note on the effect of new α_Λ

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

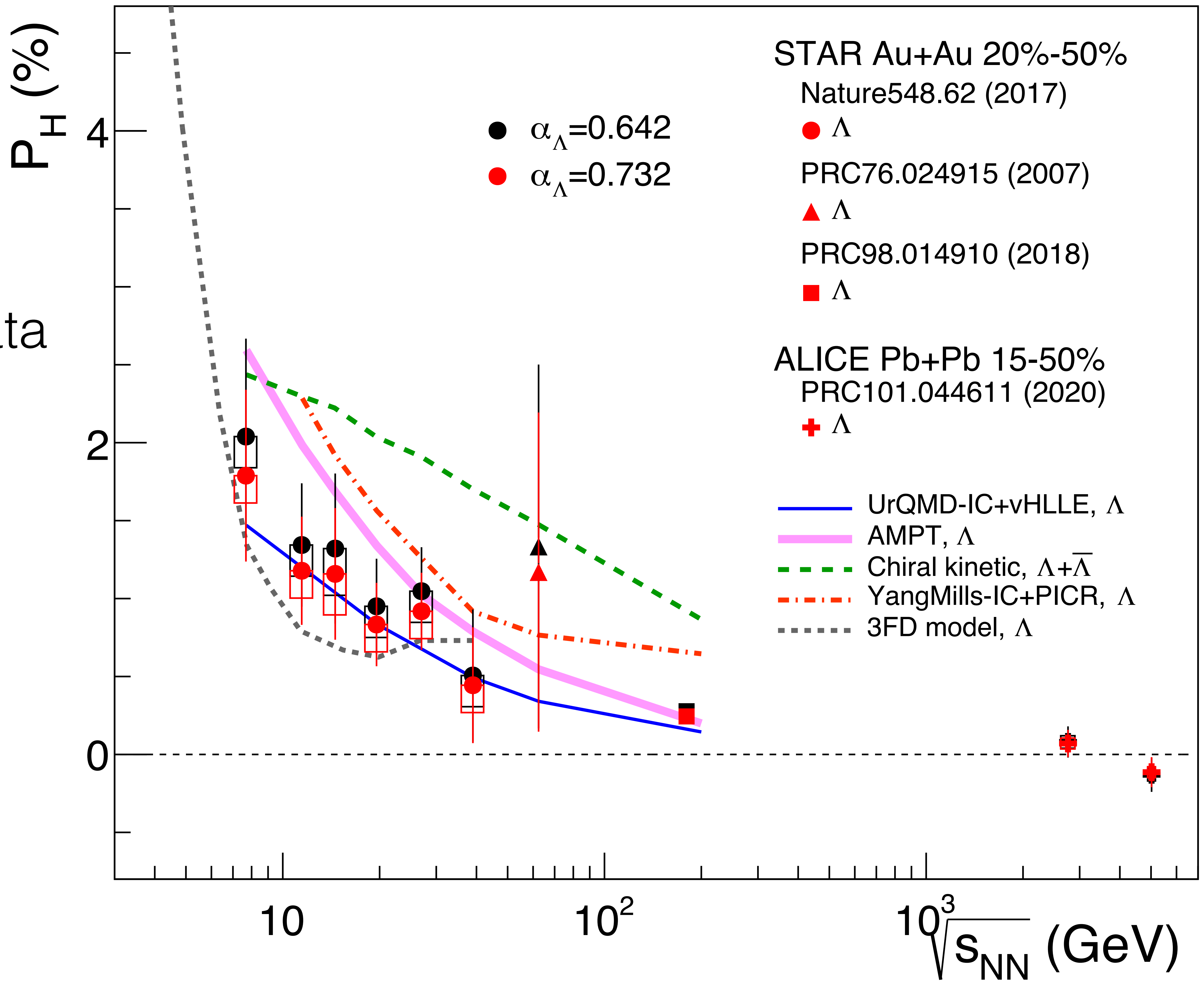
- Λ α_H in PDG has been recently updated based on BESIII and analysis of K-photoproduction data

  BESIII, Nature Phys.15(2019)631-634
  D. G. Ireland et al., PRL123, 182301 (2019)

  - **α_Λ=0.642±0.013 → α_Λ=0.732±0.014**

    P.A. Zyla et al. (PDG), PTEP2020.083C01

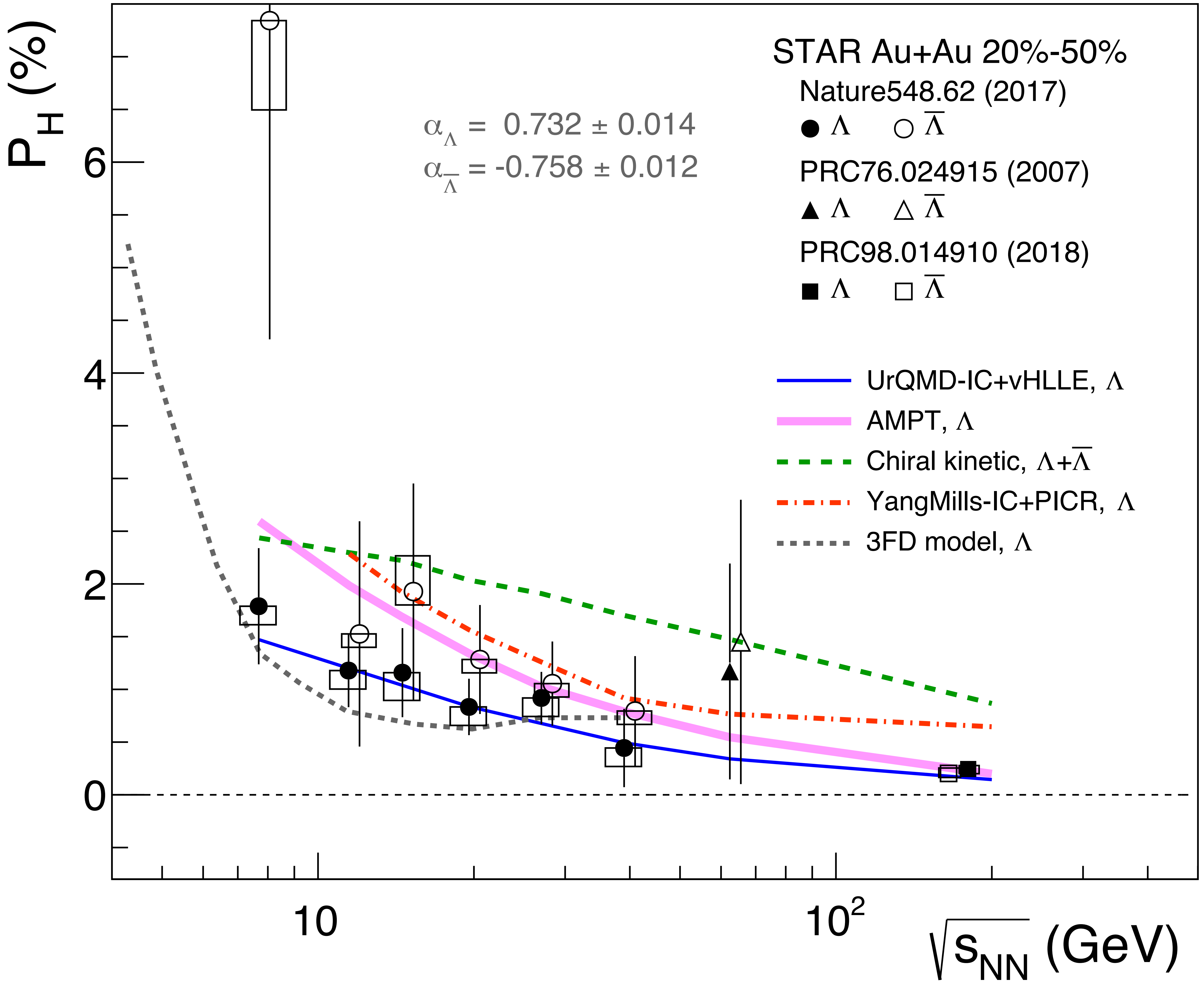
Polarization becomes smaller by ~12%.



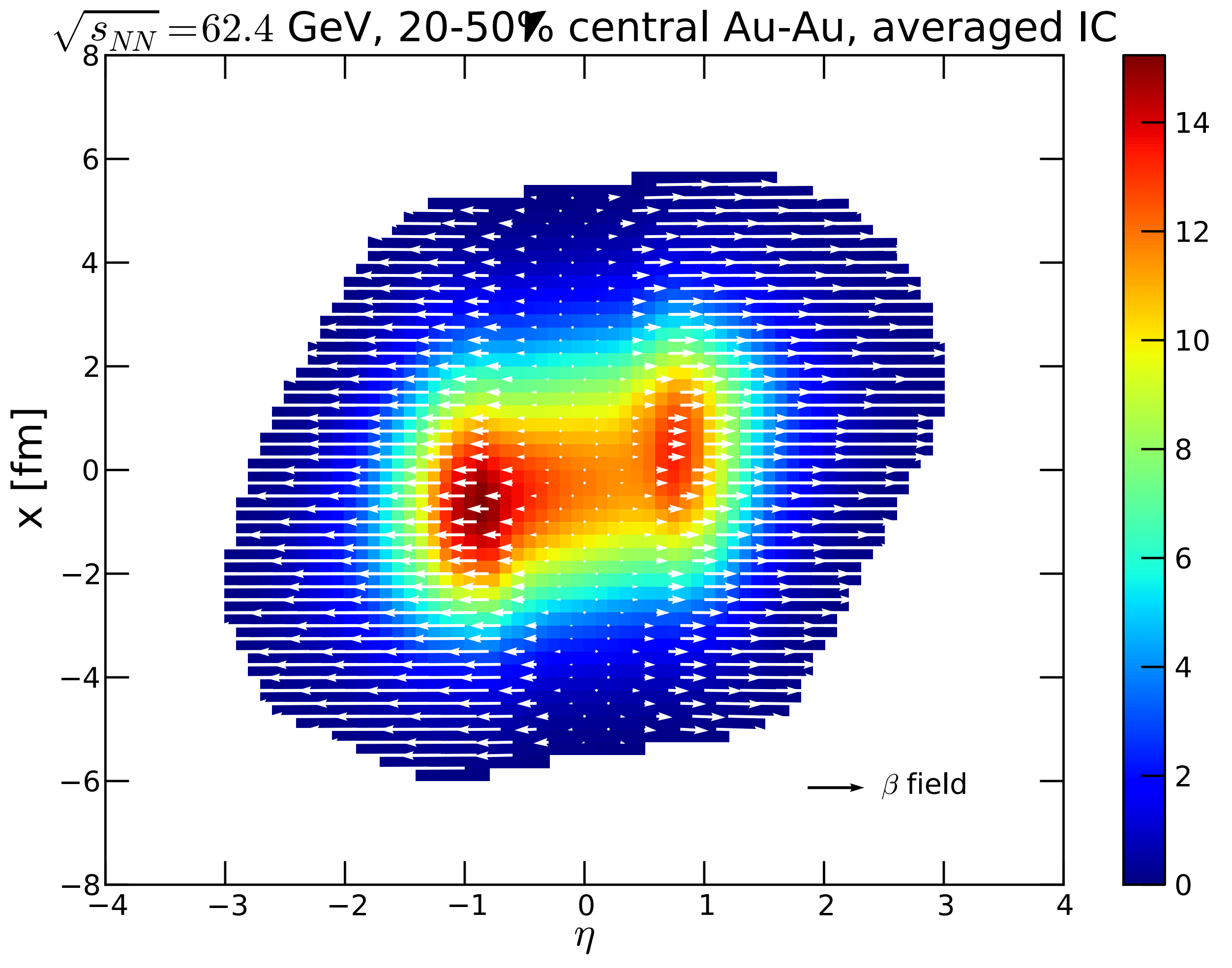
Rescaled data and figures of STAR papers are available here:
https://drupal.star.bnl.gov/STAR/publications/global-lambda-hyperon-polarization-nuclear-collisions-evidence-most-vortical-fluid
https://drupal.star.bnl.gov/STAR/publications/global-polarization-lambda-hyperons-auau-collisions-sqrtsnn200-gev

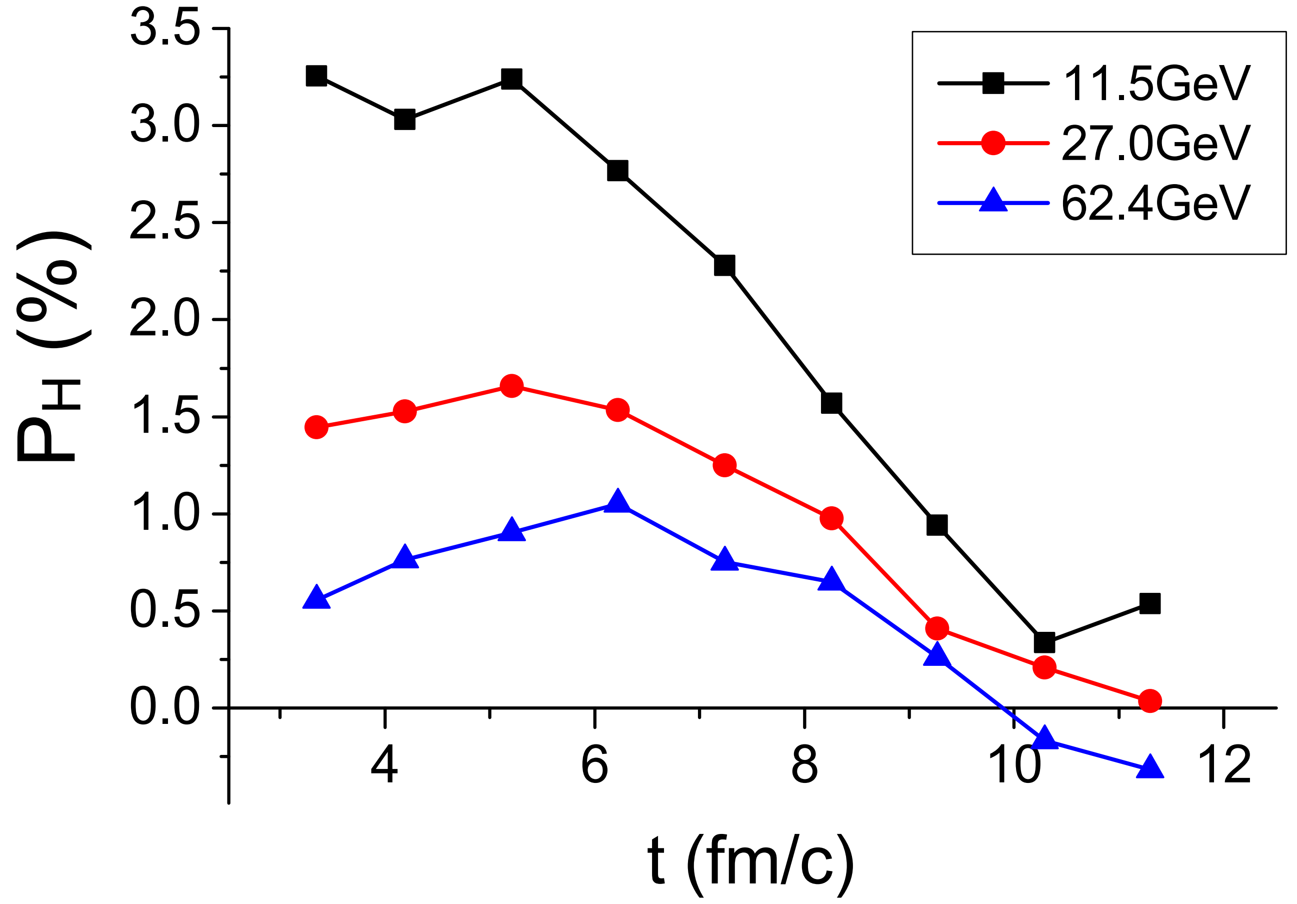
Energy dependence of P_H

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



I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)

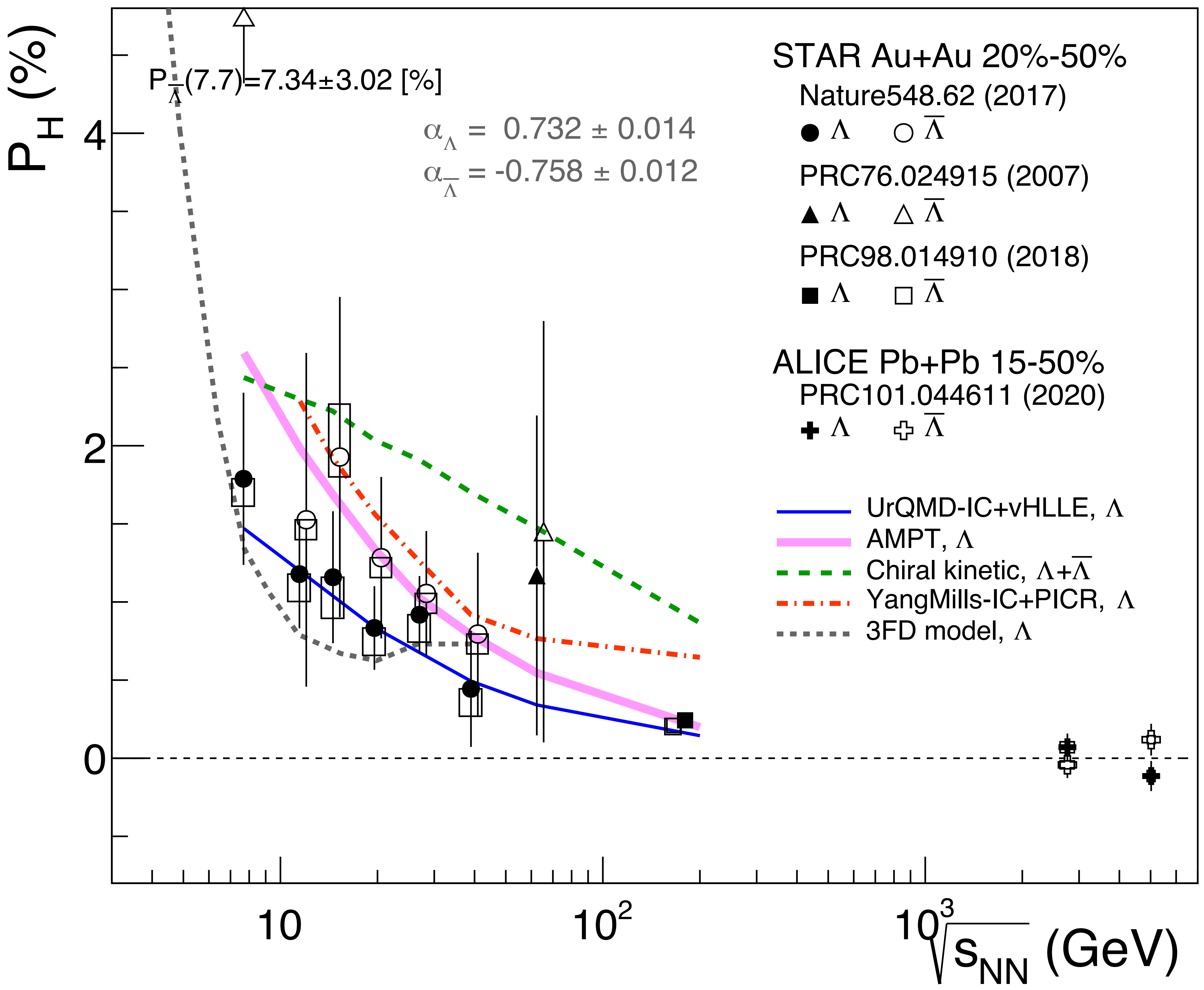




- Stronger shear flow in forward/backward regions + baryon stopping with limited acceptance (also related to unknown rapidity dependence)
- Longer lifetime of system may dilute the polarization

What about at LHC energy?
Still increasing at lower energies?

P_H at LHC energy



* data points rescaled by new α_Λ

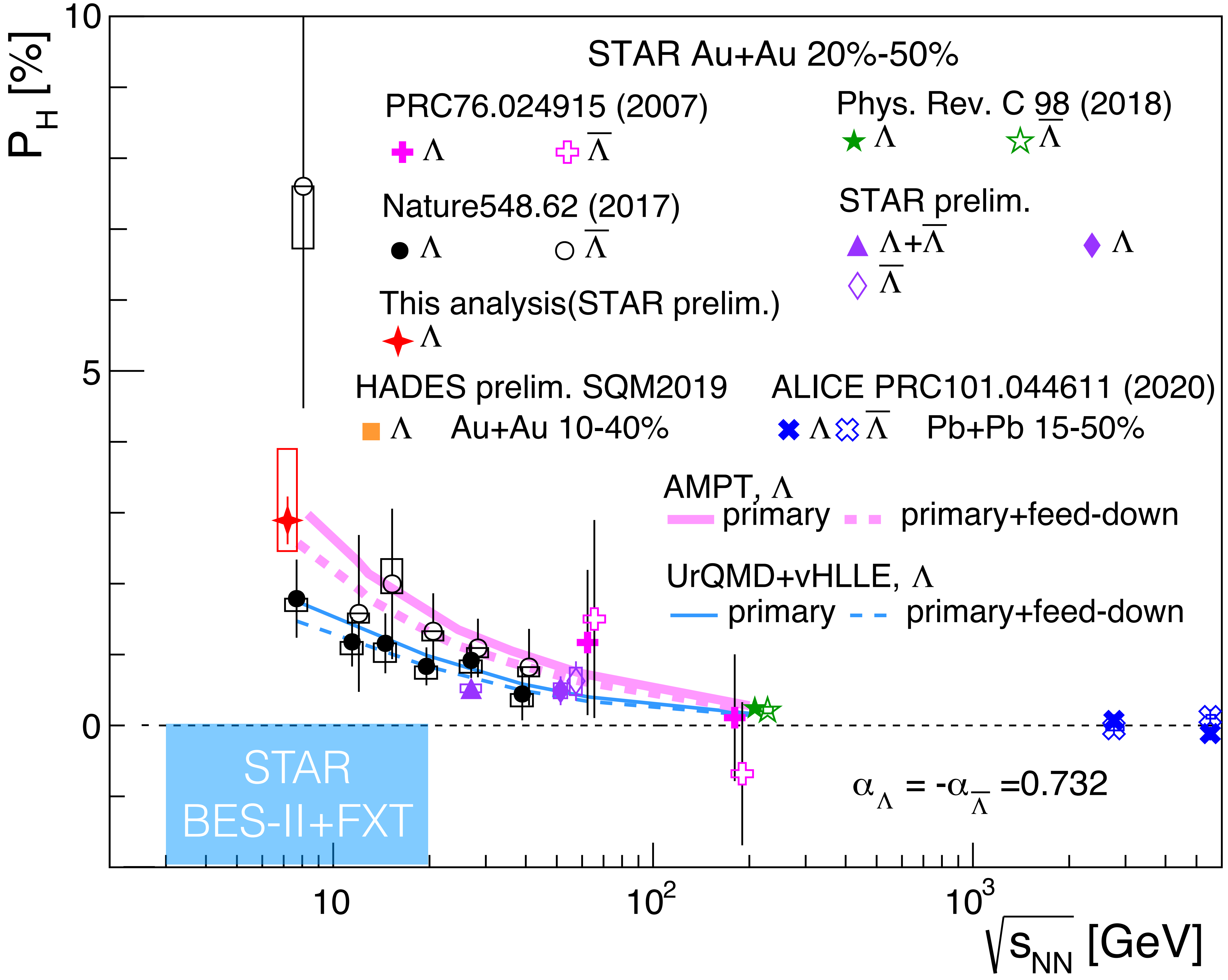
- ALICE results at 2.76 and 5.02 TeV Pb+Pb

  ALICE, PRC101, 044611 (2020)

  - Consistent with zero within uncertainties
  - Expected to be small, of the order of ~0.1%.
  - To be explored with high statistics in LHC-Run3.

See Debojit Sarkar's talk

P_H at lower enegies

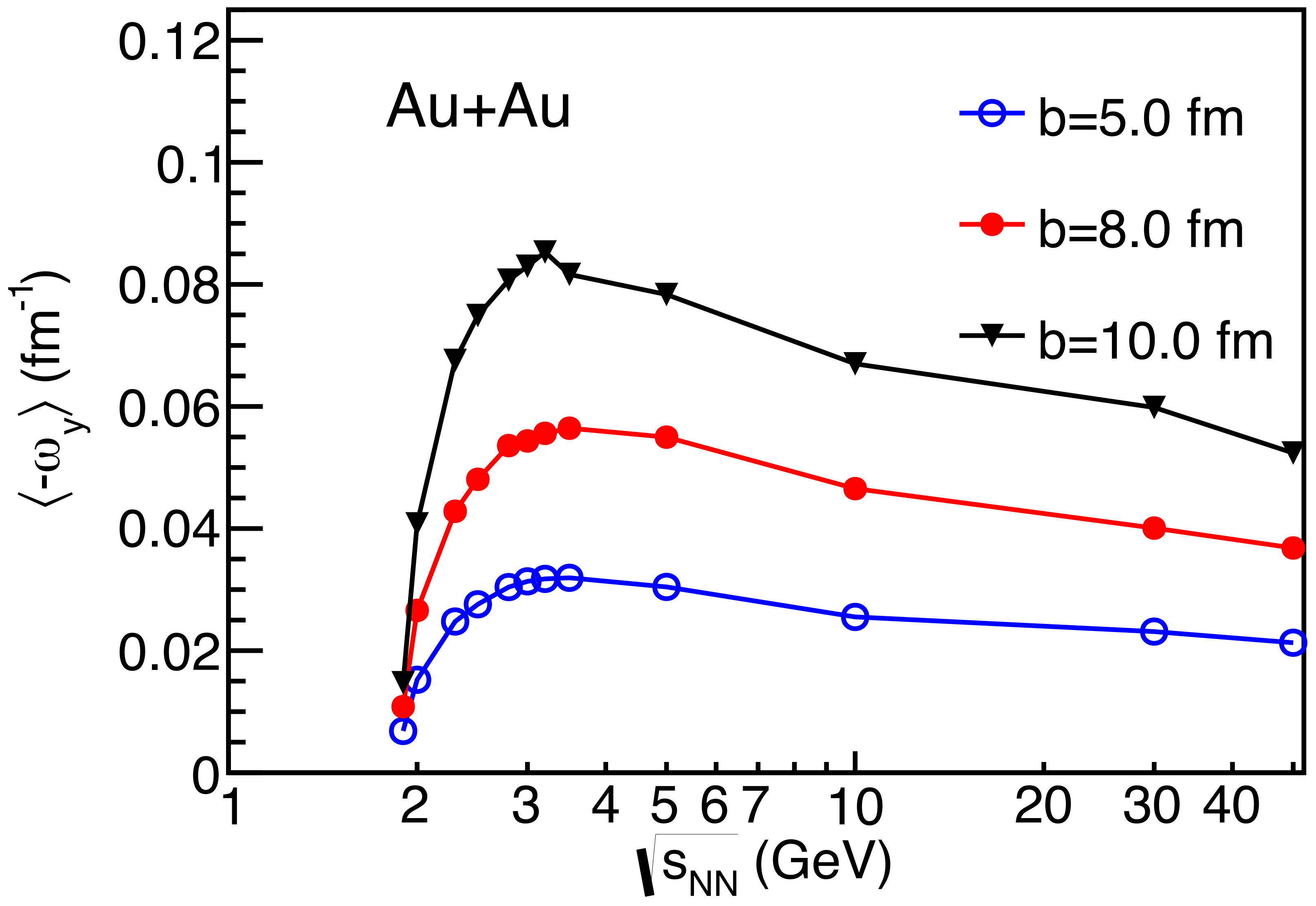


- STAR preliminary at 27 and 54.4 GeV fits into the energy dependence
- New STAR preliminary at 7.2 GeV from fixed-target (FXT) mode follows the global trend, showing the capability of STAR-FXT
  - More data will come from BES-II+FXT
    FXT (GeV): 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 5.2, 6.2, 7.7
    Collider (GeV): 7.7, 9.1, 11.5, 14.5, 17.3, 19.6

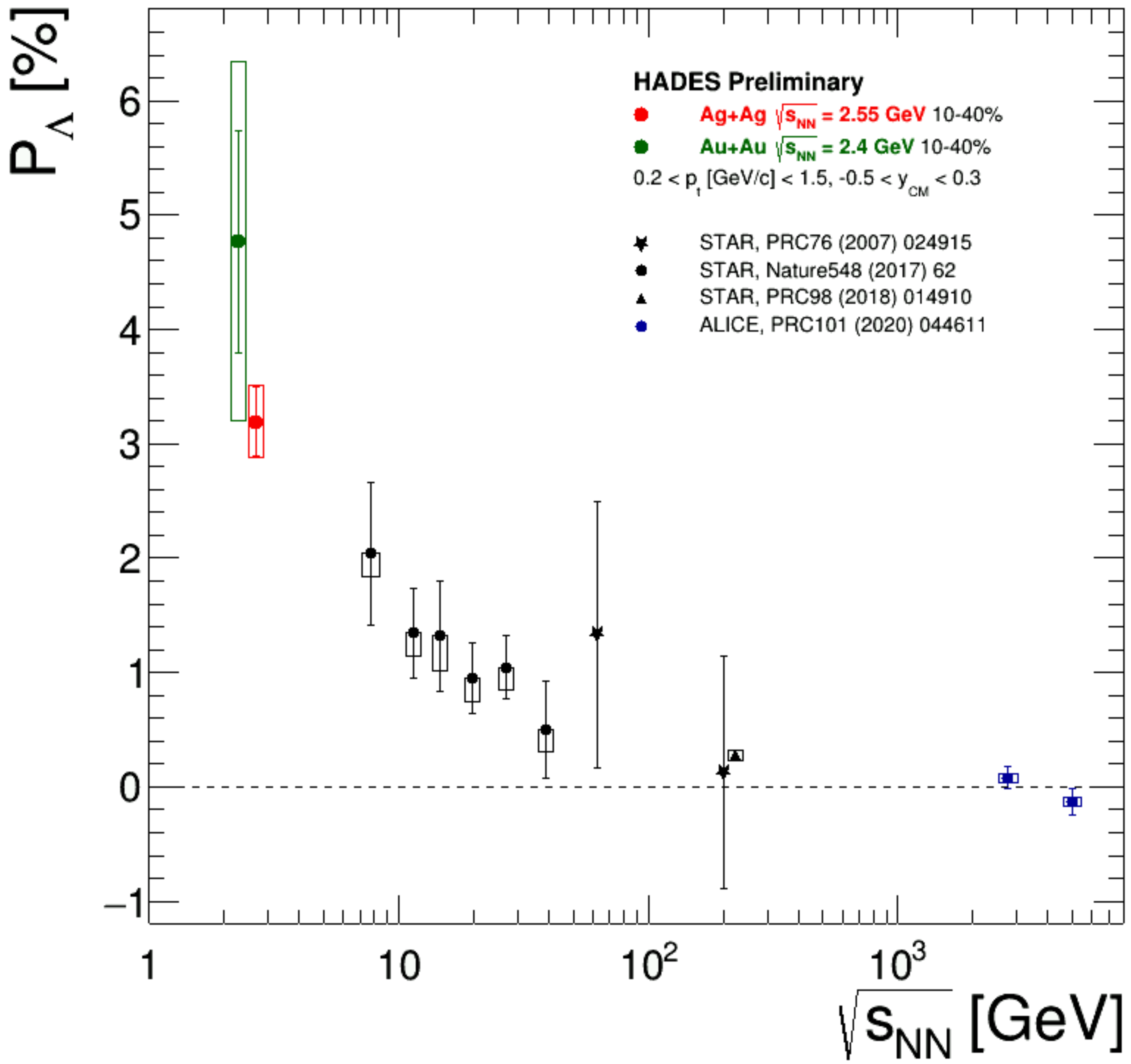
See Kosuke Okubo's talk

P_H at lower energies

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



- UrQMD model predicts a maximum kinetic/thermal vorticity around 3 GeV



See Frederic Kornan’s talk

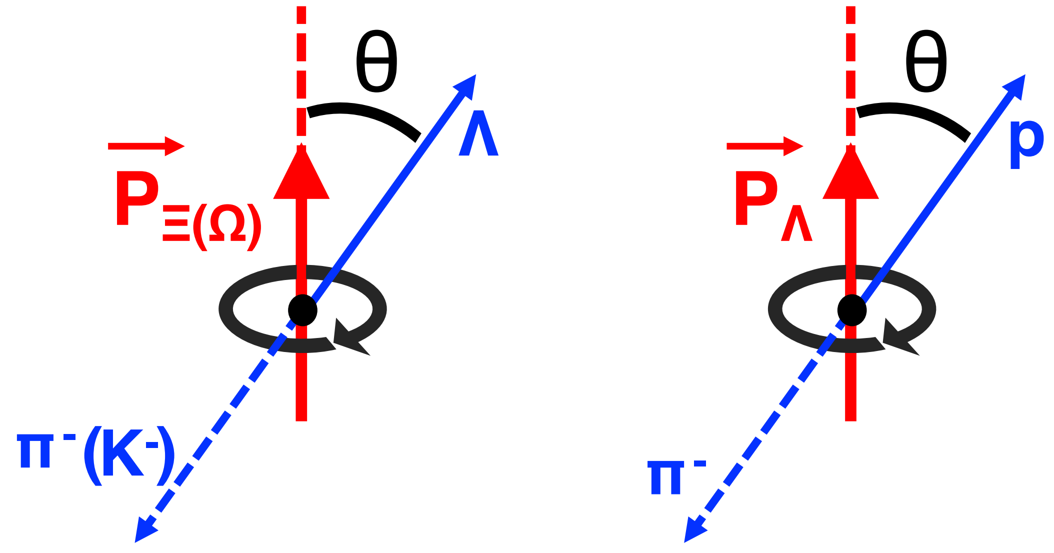
- New HADES results in Ag+Ag 2.55 GeV and Au+Au 2.4 GeV
- P_H still shows the increasing trend from 7.7 GeV down to 2.4 GeV

Extend to Ξ and Ω polarizations

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

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

- Naturally one can extend measurements to Ξ and Ω hyperons
- Challenging due to smaller decay parameter for Ξ and Ω and low production rate…



- Polarization of daughter Λ in a weak decay of Ξ (s=1/2)

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

$$\mathbf{P}_\Lambda^* = \frac{(\alpha_\Xi + \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*)\hat{\boldsymbol{p}}_\Lambda^* + \beta_\Xi \mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^* + \gamma_\Xi \hat{\boldsymbol{p}}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^*)}{1 + \alpha_\Xi \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*}$$

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

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda}\mathbf{P}_\Xi^* = \tfrac{1}{3}\left(1 + 2\gamma_\Xi\right)\mathbf{P}_\Xi^*. \qquad C_{\Xi^-\Lambda} = +0.944$$

- Similarly, daughter Λ polarization from Ω (s=3/2)

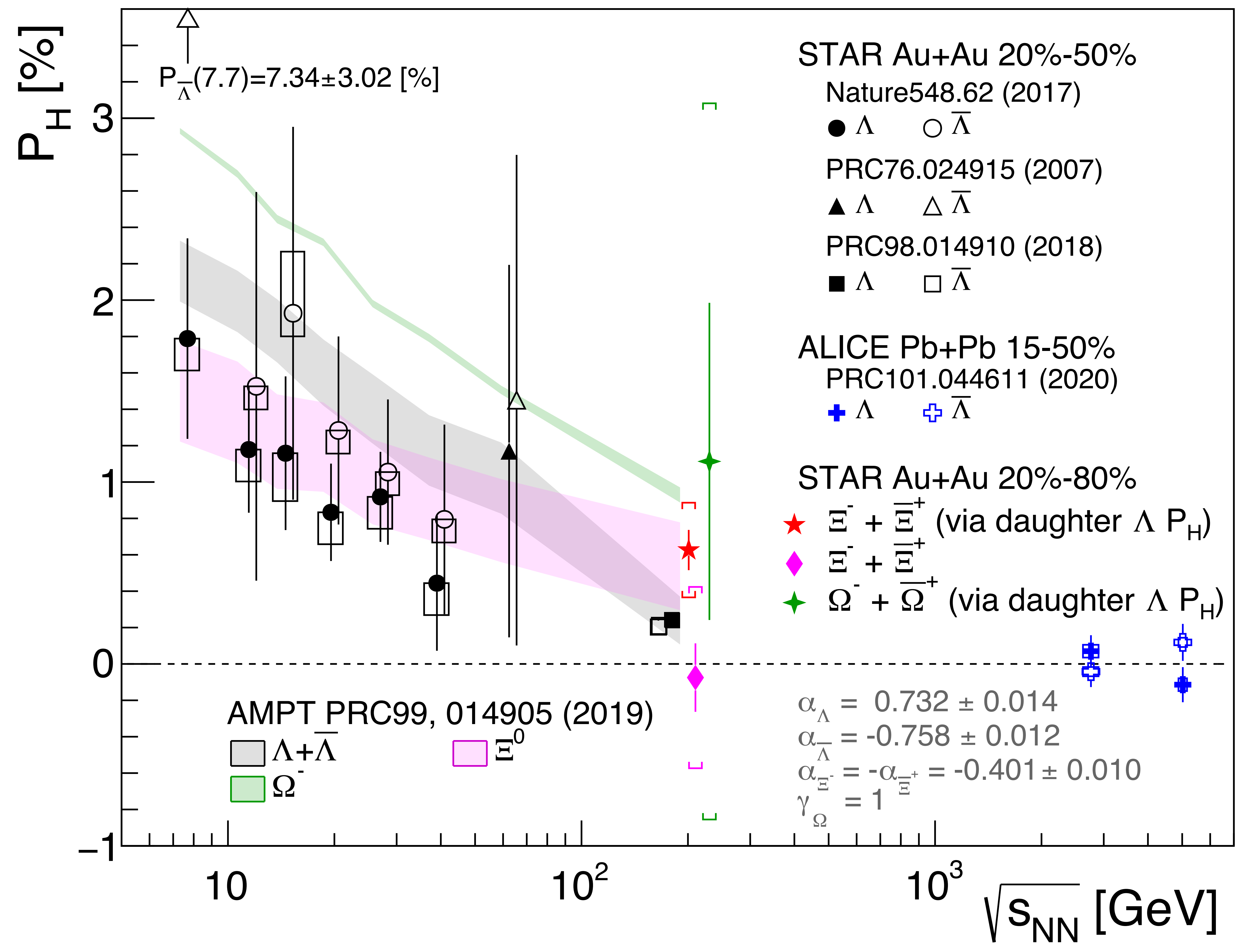
$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda}\mathbf{P}_\Omega^* = \tfrac{1}{5}\left(1 + 4\gamma_\Omega\right)\mathbf{P}_\Omega^*.$$

Here **γ_Ω is unknown**. Considering α_Ω, $\beta_\Omega \ll 1$, $\gamma_\Omega \sim \pm 1$. the polarization transfer $C_{\Omega\Lambda}$ leads to: $C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$

Parent particle polarization can be known by measuring daughter particle polarization!

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

For 20-80% Au+Au at 200 GeV,

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

* 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

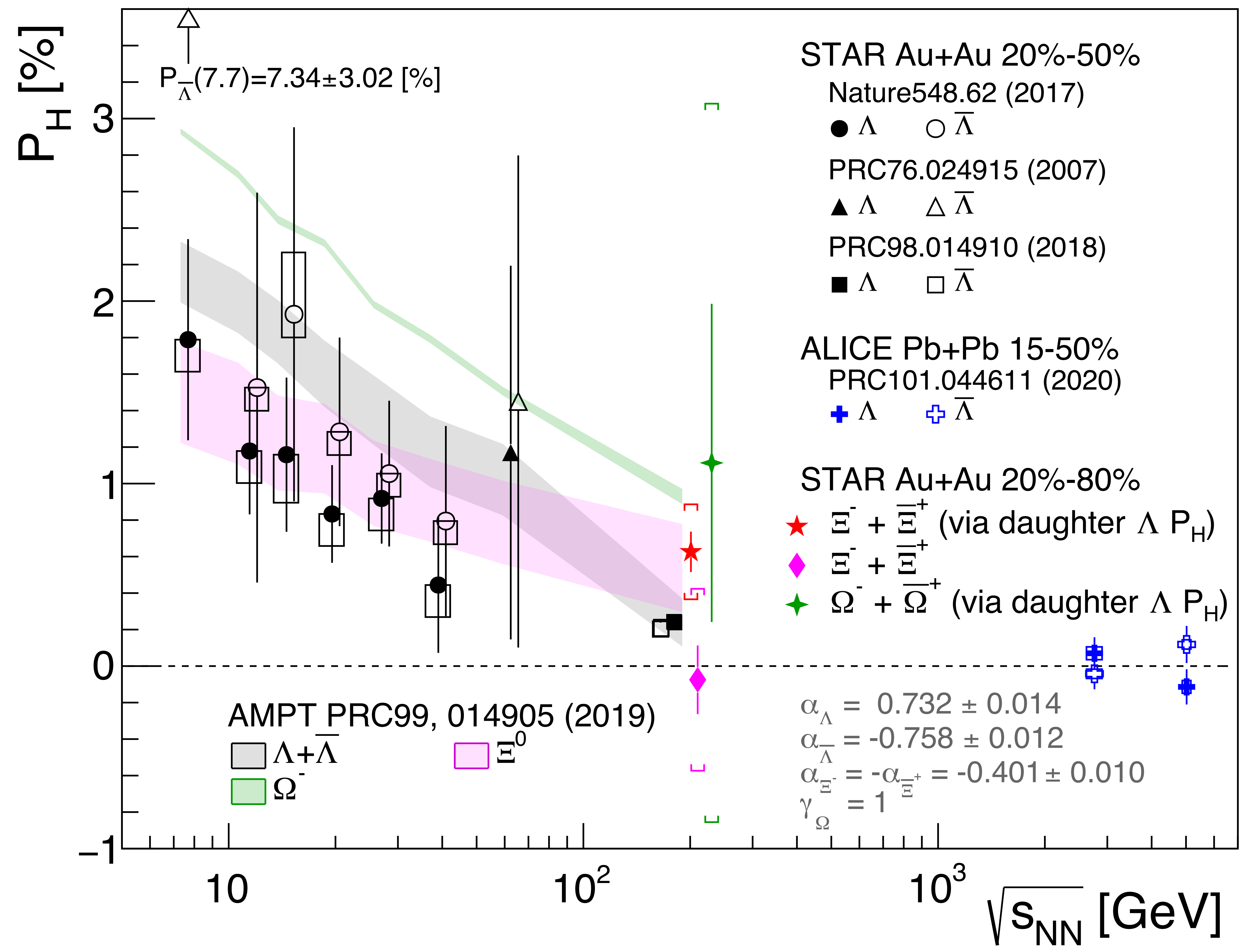
- Different feed-down contribution See Hui Li's talk
- AMPT and hydro calculations capture the trend

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)



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$$\langle P_\Omega \rangle = 1.11 \pm 0.87\ (\mathrm{stat}) \pm 1.97\ (\mathrm{syst})\ \%$$

* combined Ξ P_H from the two methods

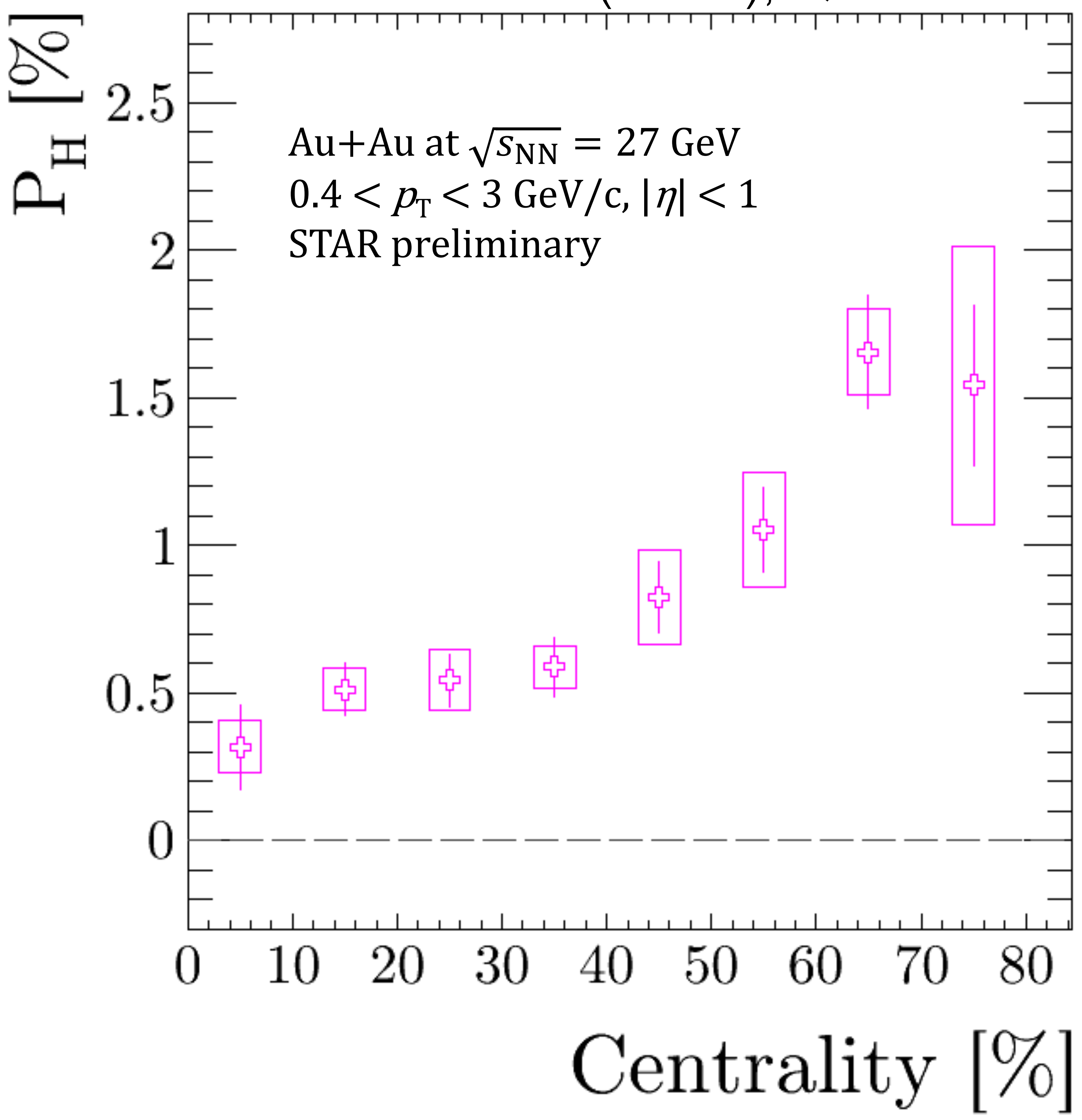
- STAR preliminary at 27 GeV: P_Ξ~1.2%±0.7(stat+sys)

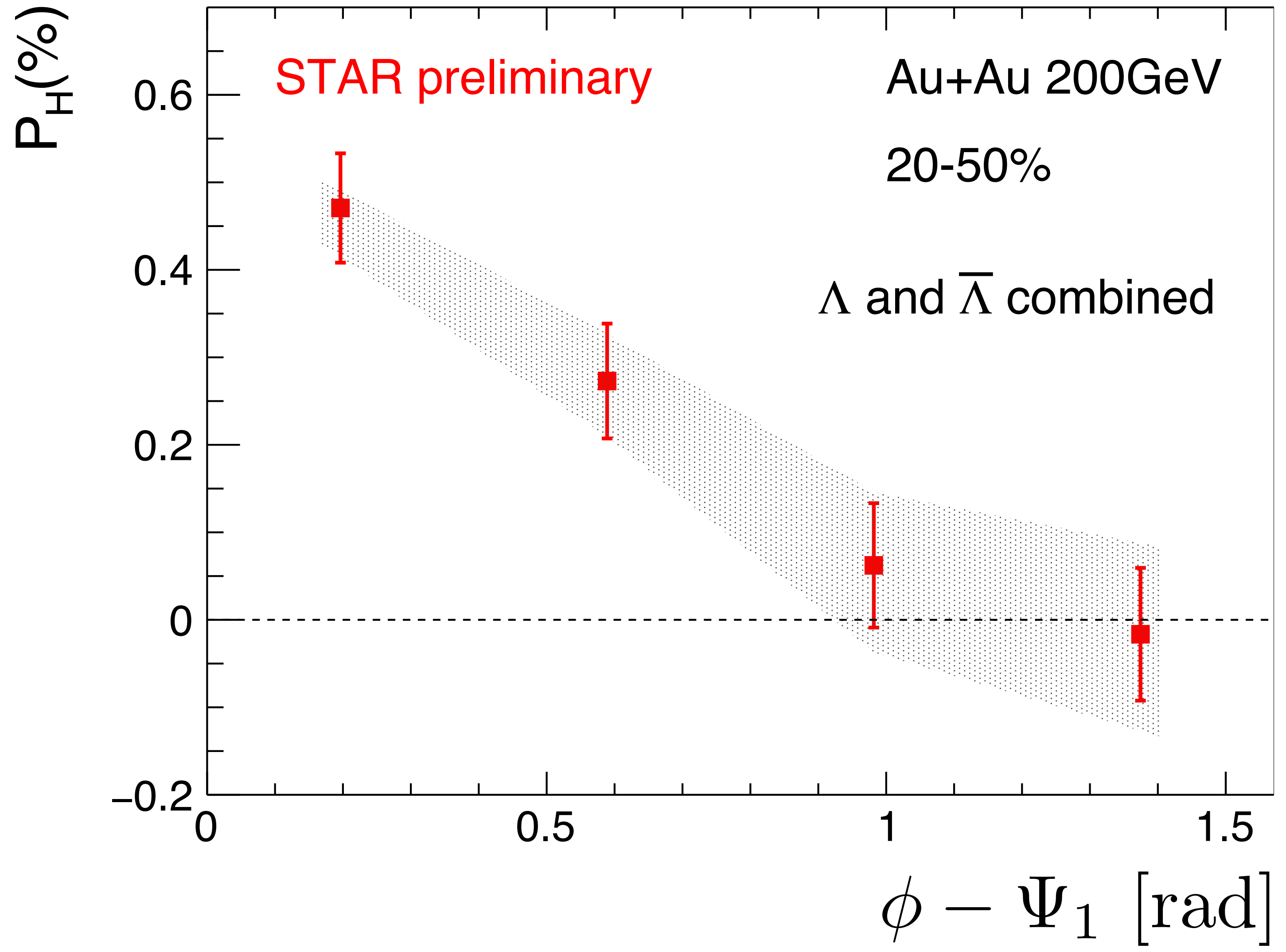
  E. Alpatov (STAR), ICPPA2020

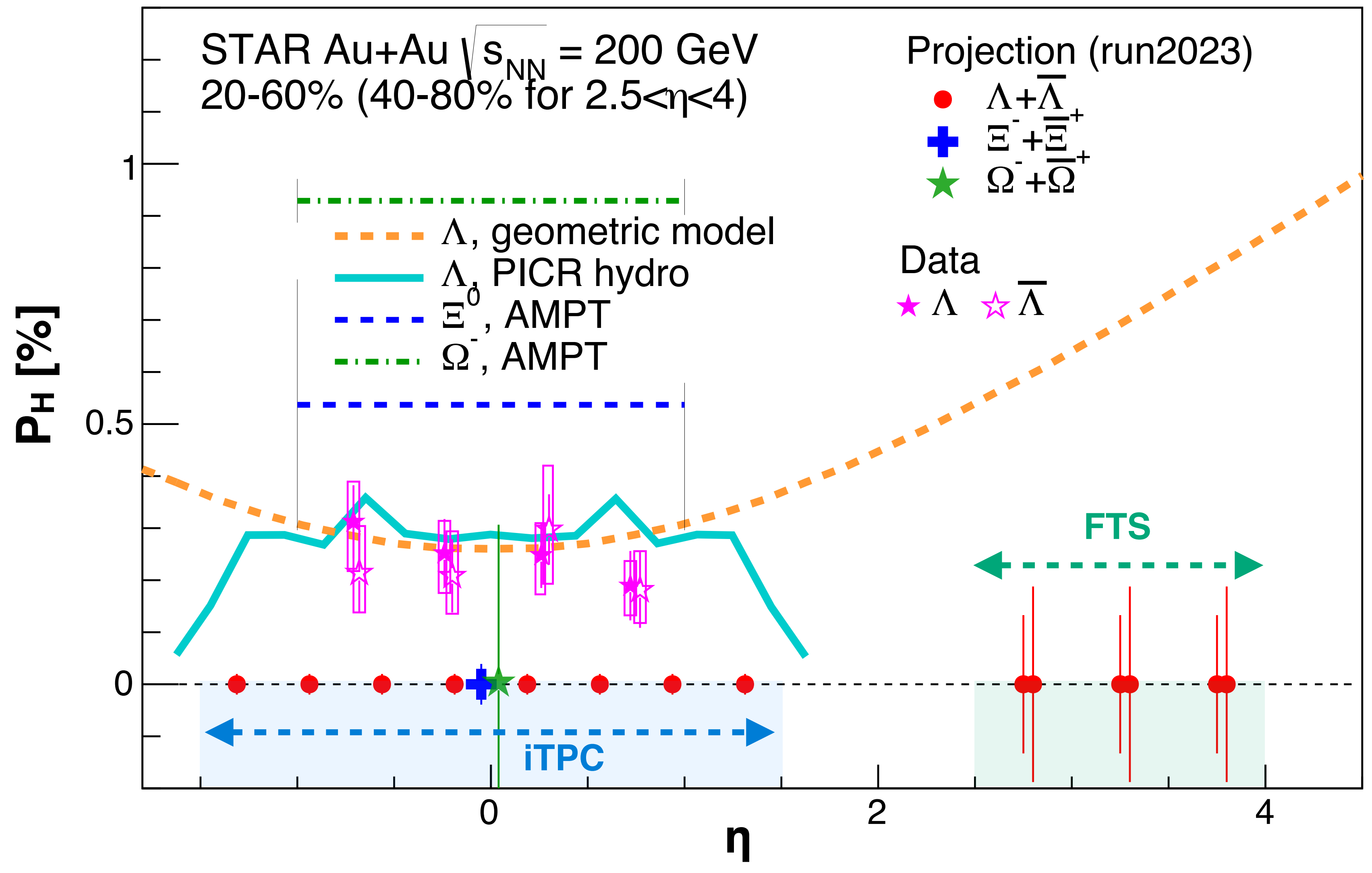
- Large uncertainty of P_Ω to be improved in future
- The value of γ_Ω (γ_Ω=+1 or -1) can be constrained based on the vorticity picture
- Larger splitting of P_Ω and P_Ω due to B-field? (larger magnetic moment $|\mu_\Omega|$ than $|\mu_\Lambda|$)

T. Niida, SQM2021

Differential measurements of P_H





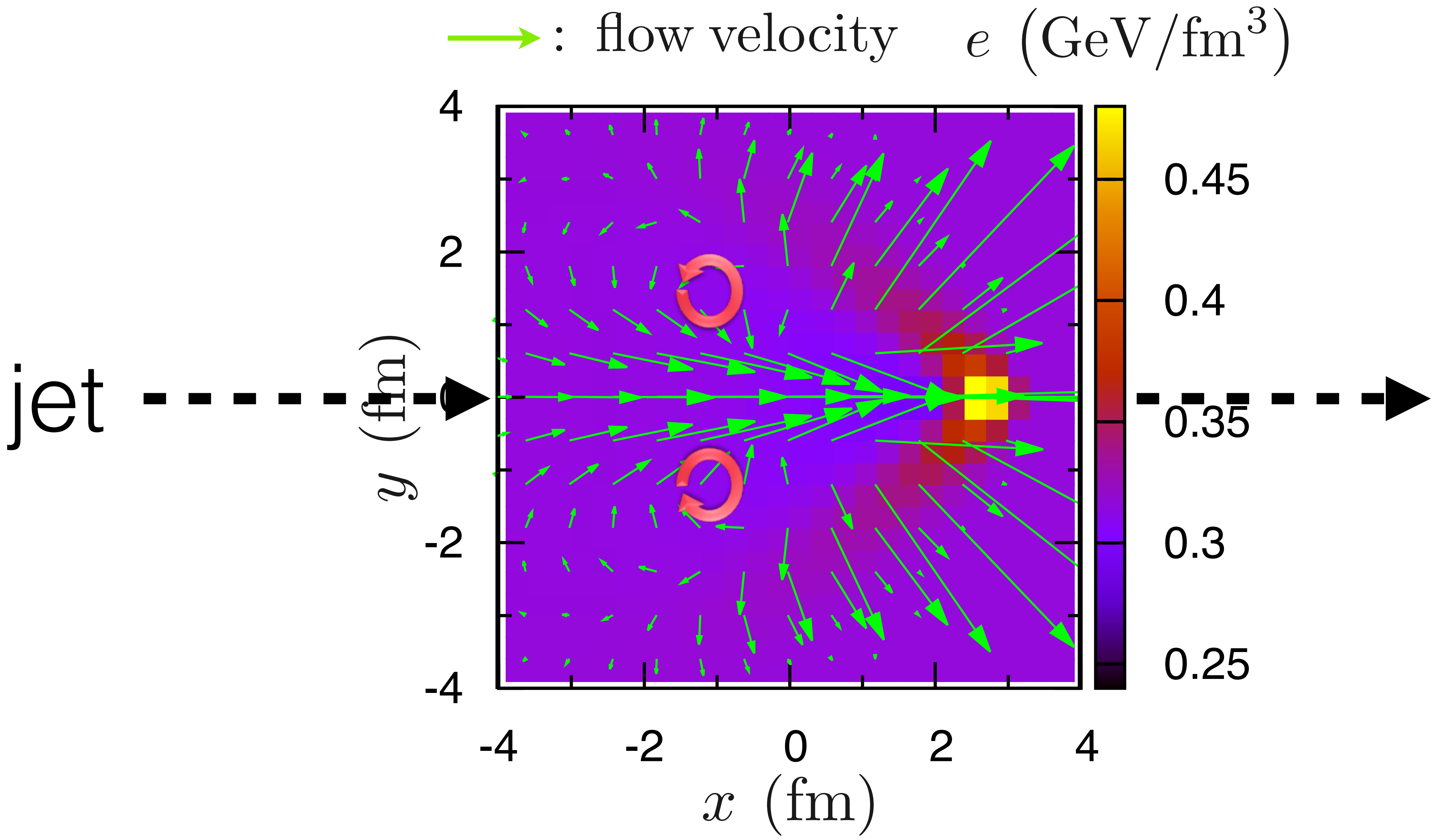


- Larger polarization in peripheral collisions as expected
- Azimuthal dependence: discrepancy between data and models
- Unknown rapidity dependence to be explored
- p_T, A_{ch} dependence…
  STAR, PRC90, 014910 (2018)

See Frederic Kornan's talk and Kosuke Okubo's talk

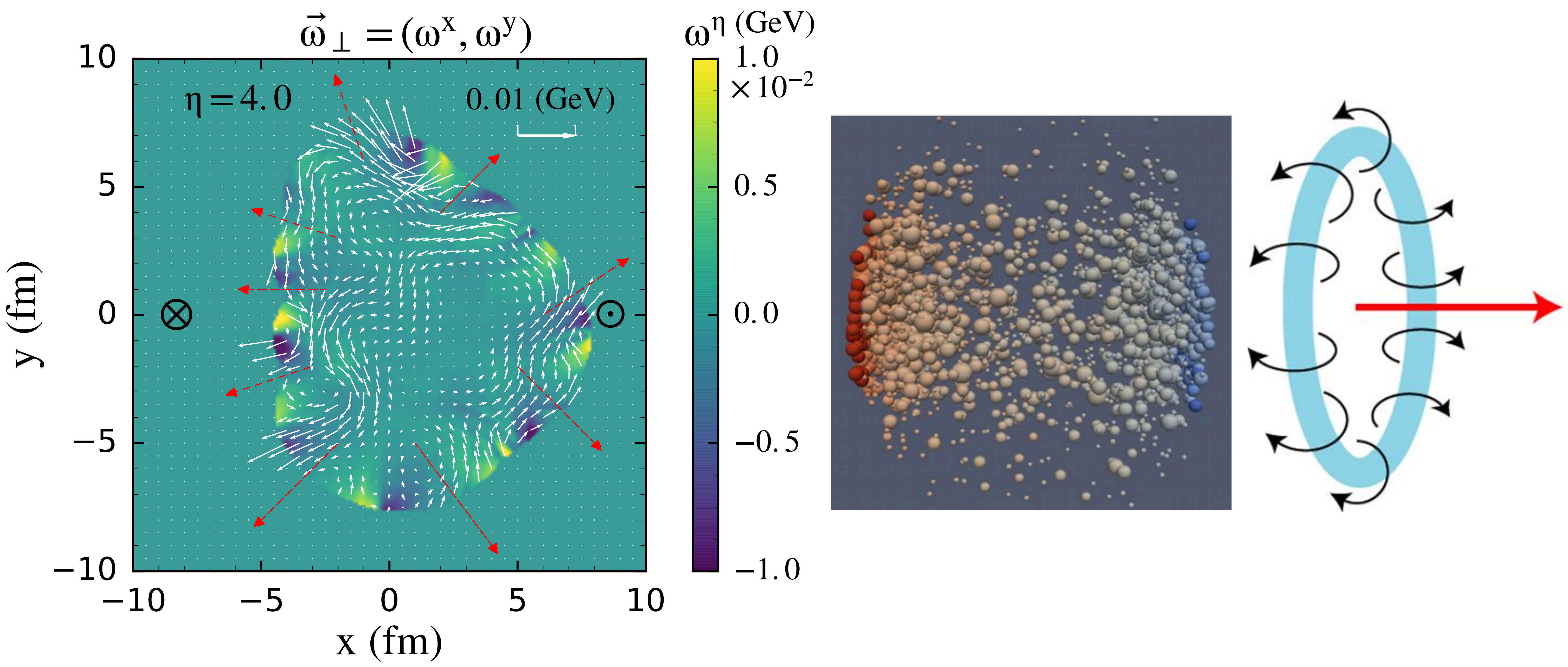
Local vorticity

Vortex induced by jet



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

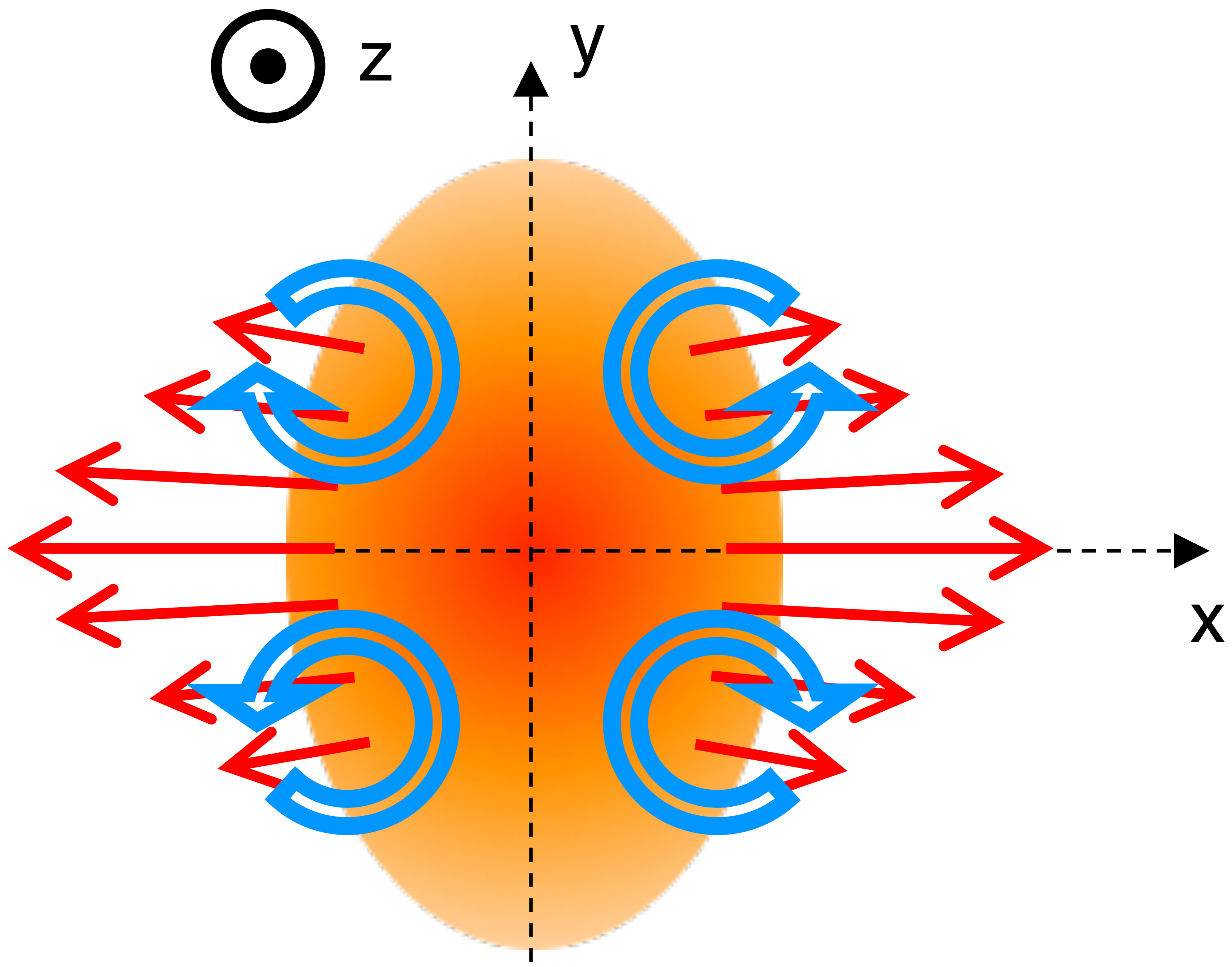
Local vorticity induced by collective flow

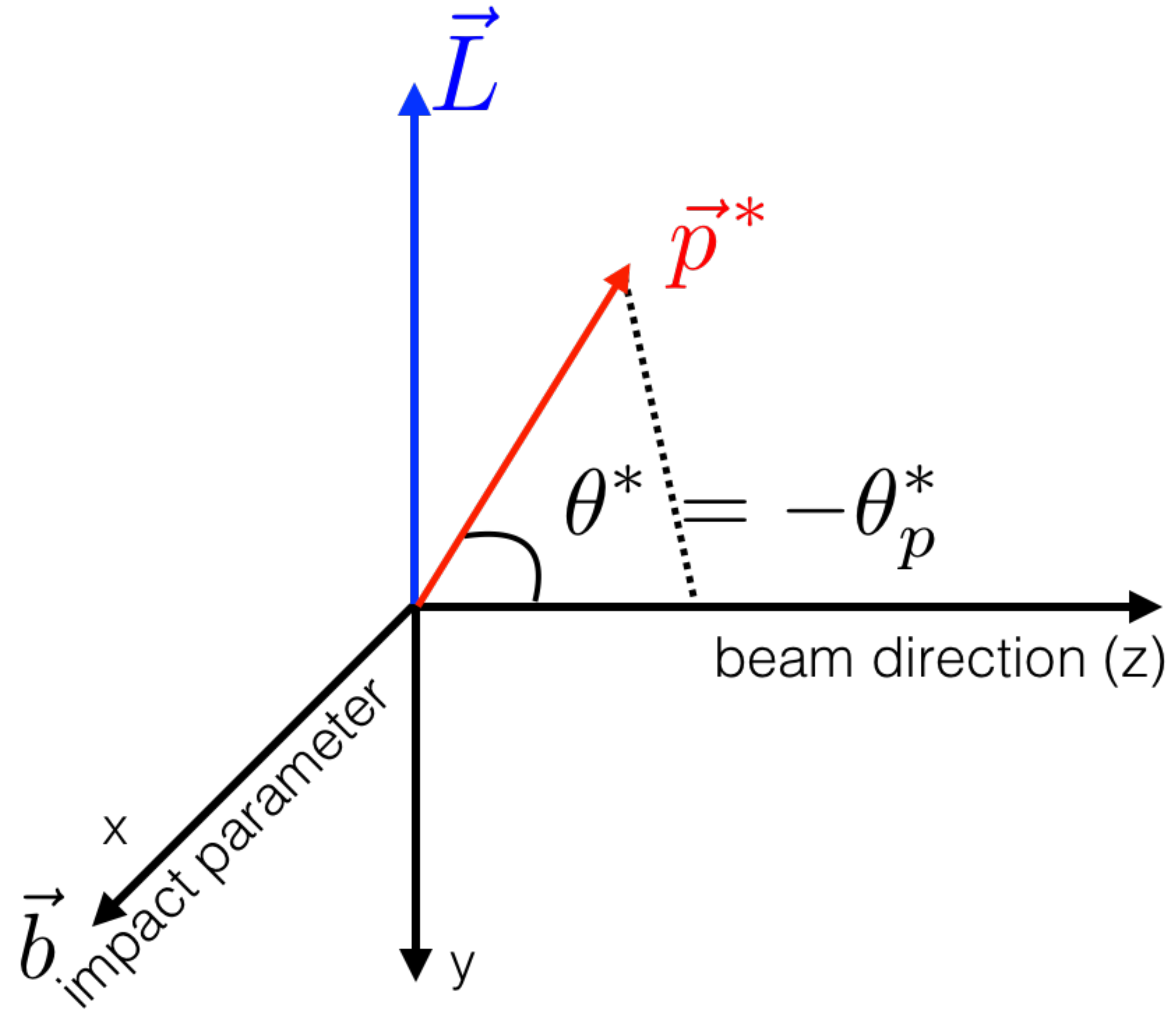


L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

Polarization along the beam direction

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





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

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

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

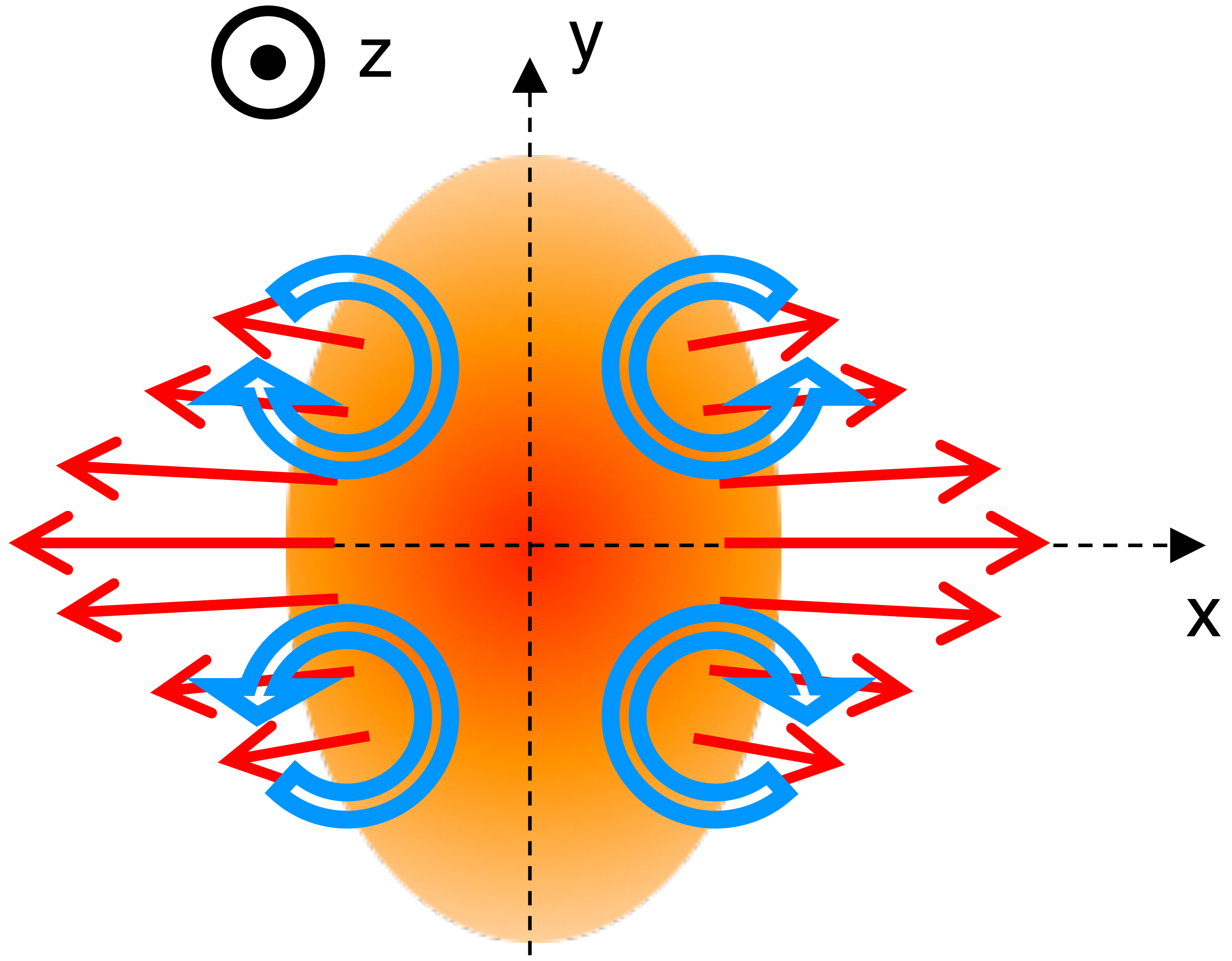
$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

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

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

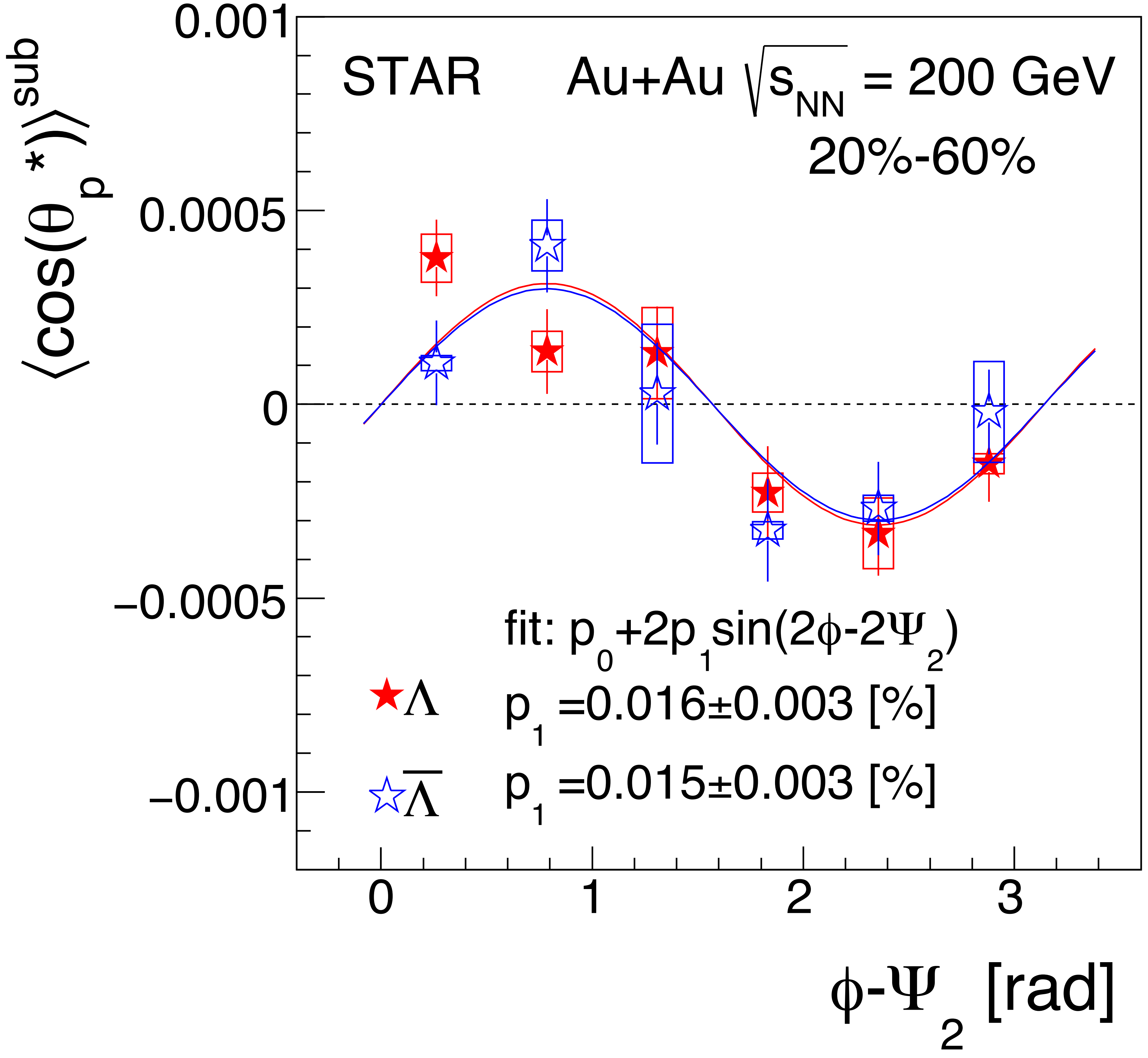
Stronger flow in in-plane than in out-of-plane, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.

“z-component” of polarization: P_z



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

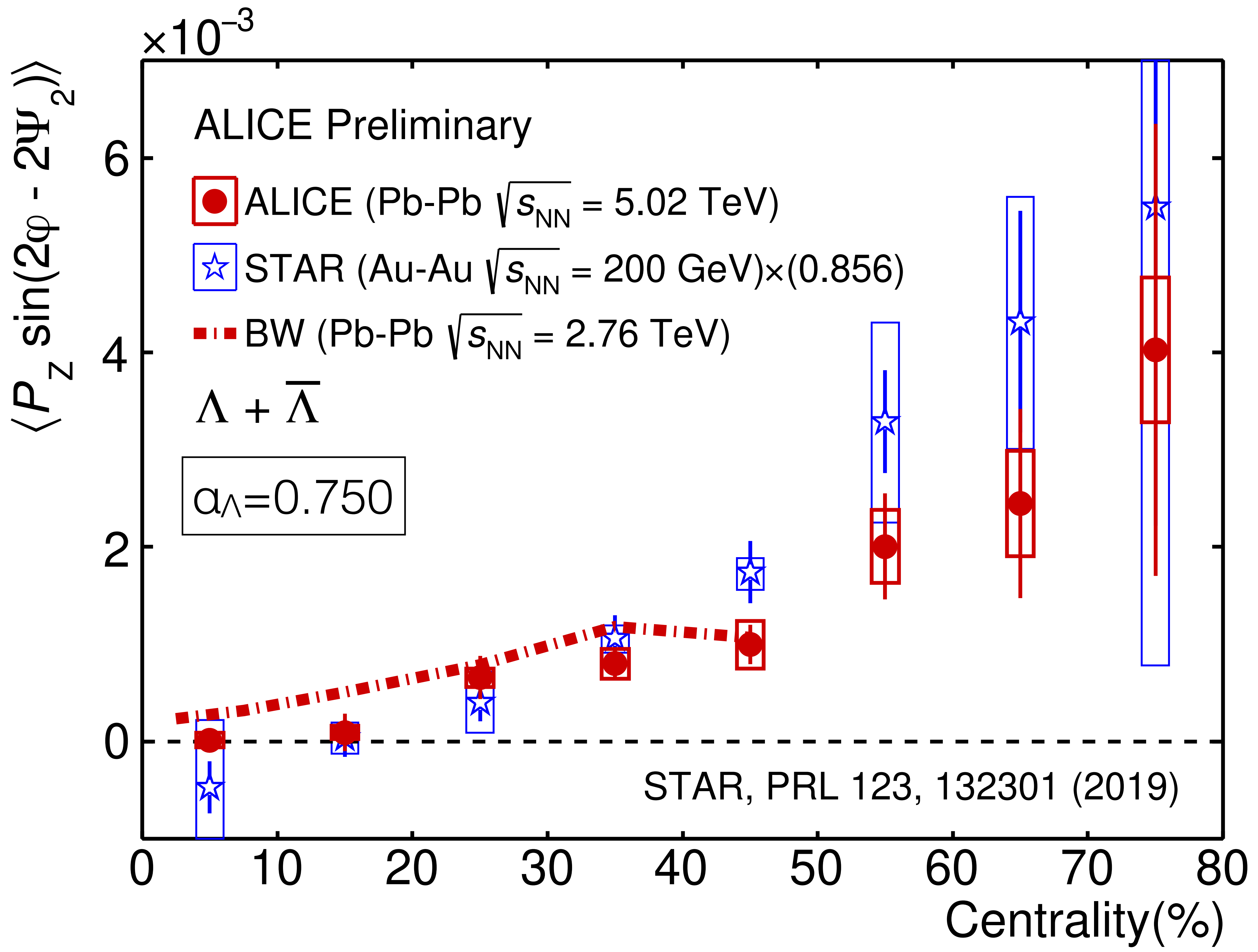
STAR, PRL123.13201 (2019)

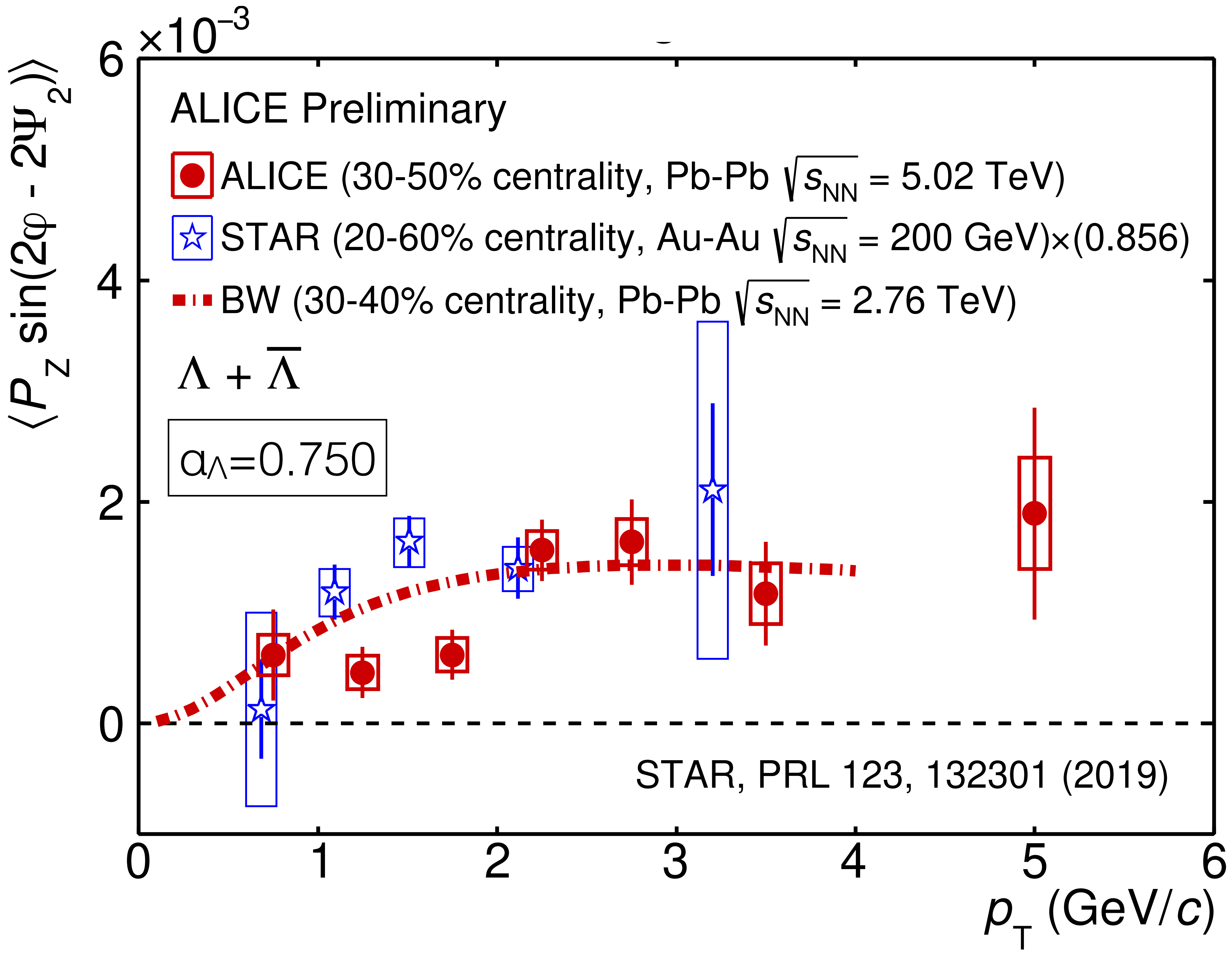


- Polarization along the beam direction expected from the “elliptic flow”
- STAR data indeed show such a longitudinal polarization depending on azimuthal angle (sine function)

P_z at RHIC and the LHC

See Debojit Sarkar's talk





- Same sign and magnitude of P_z sine modulation at RHIC and the LHC
- BW model captures the trend with correct sign, while many models fail to explain the data

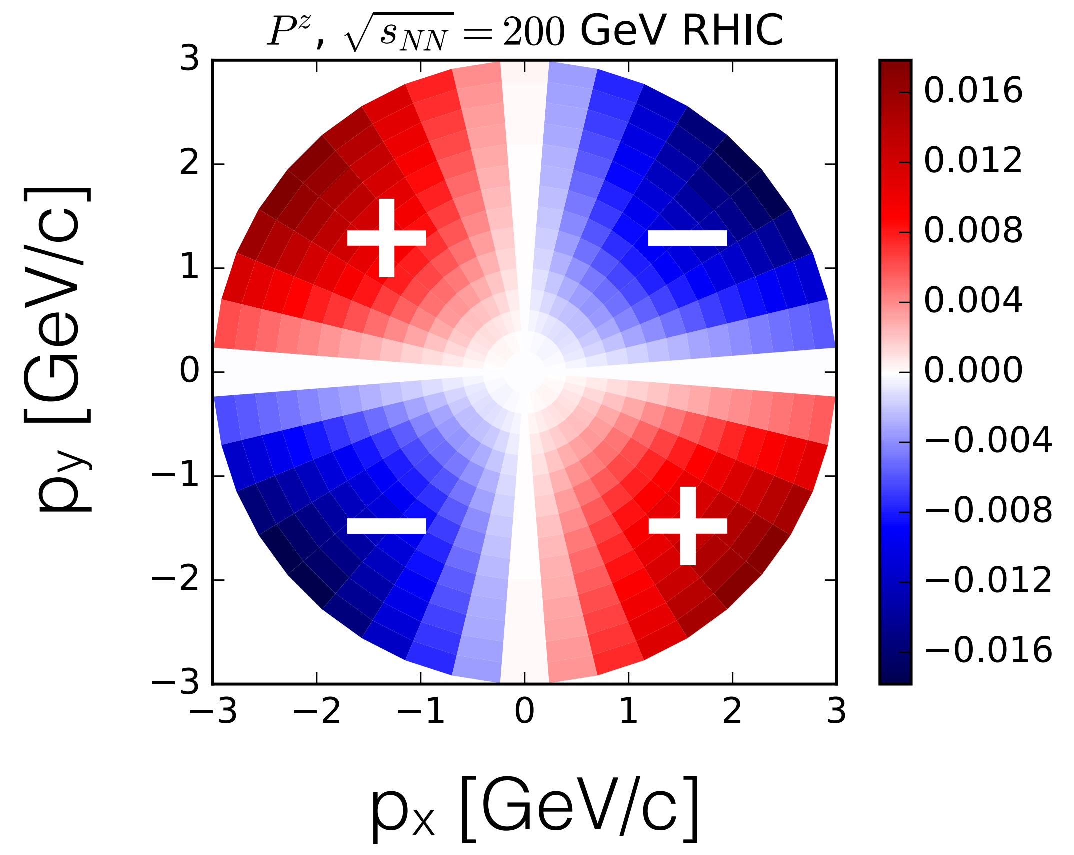
Sign puzzle in $P_z(\phi)$

Under discussion and many models calculations

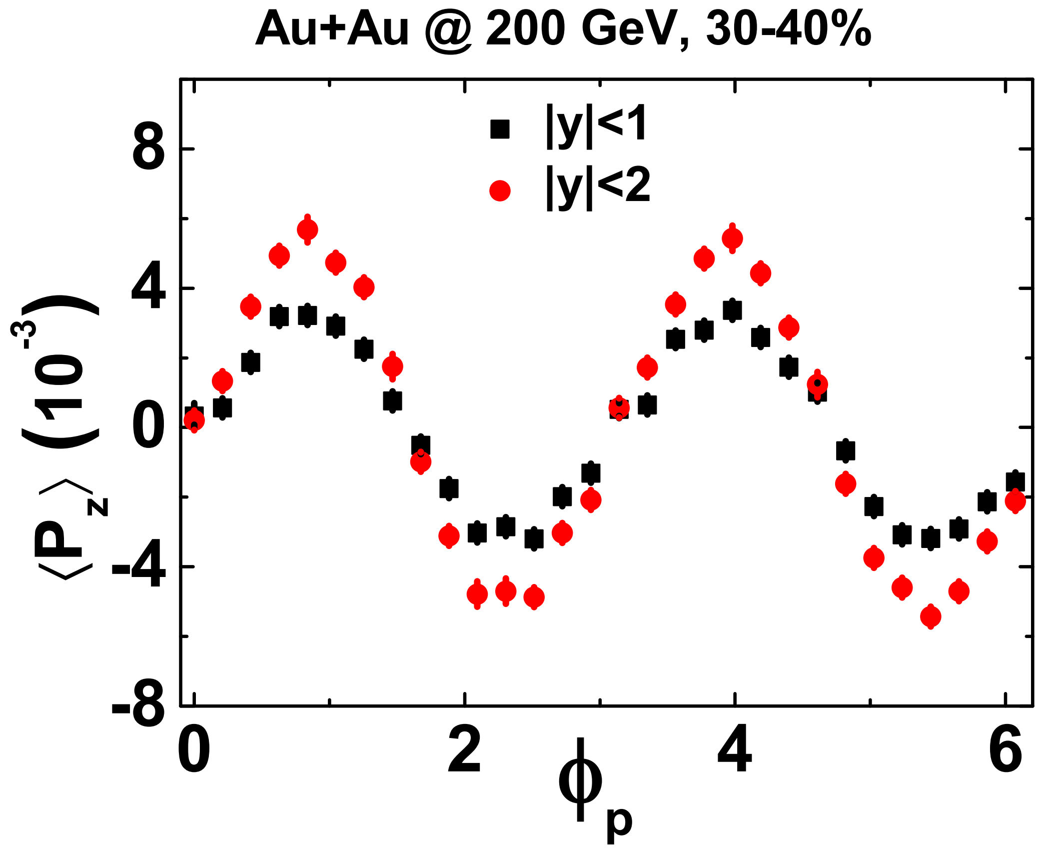
- UrQMD-IC + hydrodynamic model
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- AMPT
  X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)
- Chiral kinetic approach
  Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- AMPT-IC + MUSIC
  B. Fu et al., PRC103, 024903 (2021)
- High resolution (3+1)D 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)
- Contribution from shear tensor
  B. Fu et al., arXiv:2103.10403
  F. Becattini et al., arXiv:2103.14621

See Shuai Liu’s talk

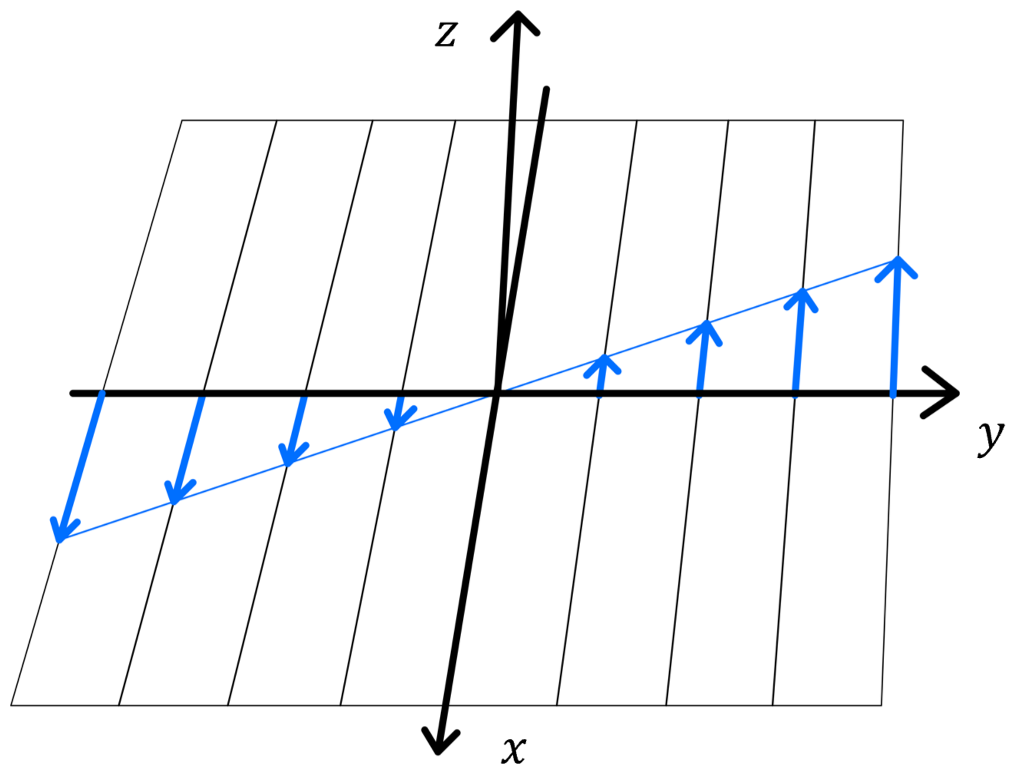
Hydrodynamic model



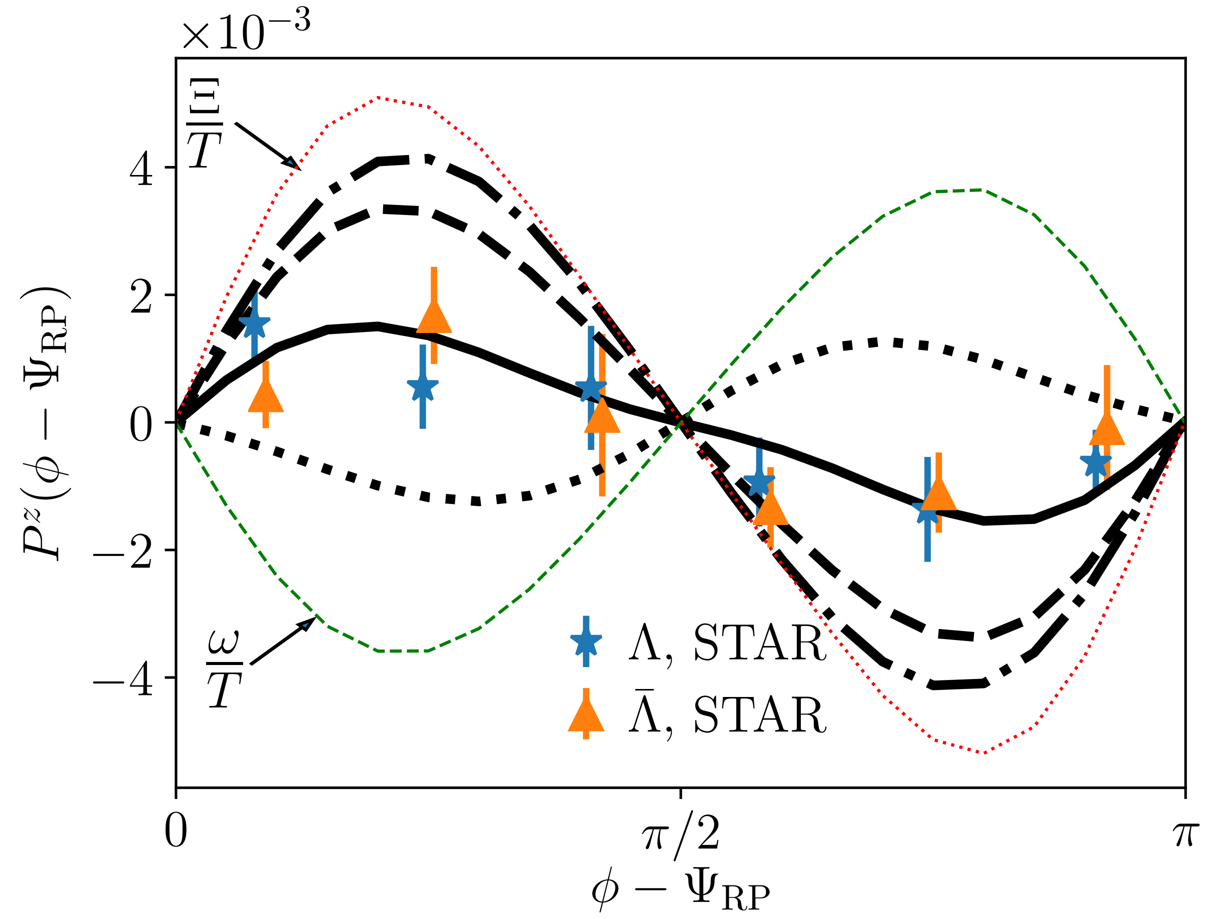
Chiral kinetic approach



S. Liu and Y. Yin, arXiv:2103.09200



F. Becattini et al., arXiv:2103.14621



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

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

Global spin alignment of vector mesons

- Angular distribution of the decay products can be written with spin density matrix ρ_{nn}.

$$\frac{dN}{d\cos\theta^*} \propto \rho_{0,0}|Y_{1,0}|^2 + \rho_{1,1}|Y_{1,-1}|^2 + \rho_{-1,-1}|Y_{1,1}|^2 \propto \rho_{0,0}\cos^2\theta^* + \frac{1}{2}(\rho_{1,1} + \rho_{-1,-1})\sin^2\theta^*$$
$$\propto (1-\rho_{0,0}) + (3\rho_{0,0} - 1)\cos^2\theta^*$$

Species	K^{*0}	φ
Quark content	$\bar{d}s$	$s\bar{s}$
Mass (MeV/c^2)	896	1020
Lifetime (fm/c)	4	45
Spin (J^P)	1^-	1^-
Decays	Kπ	KK
Branching ratio	**~100%**	66%

- Probability to have spin projection to be 0, ρ_{00}:

$$\rho_{00} = \frac{1}{3} - \frac{8}{3}\langle\cos[2(\phi_p^* - \Psi_{RP})]\rangle$$

$$|s, s_z\rangle = |1, s_z\rangle$$
$$(s_z = -1,\ 0,\ +1)$$

- $\rho_{00} = 1/3$: spin randomly oriented
- $\rho_{00} \neq 1/3$: indication of spin aligned

∗ One cannot determine the sign of polarization, therefore this is called "spin alignment measurement"

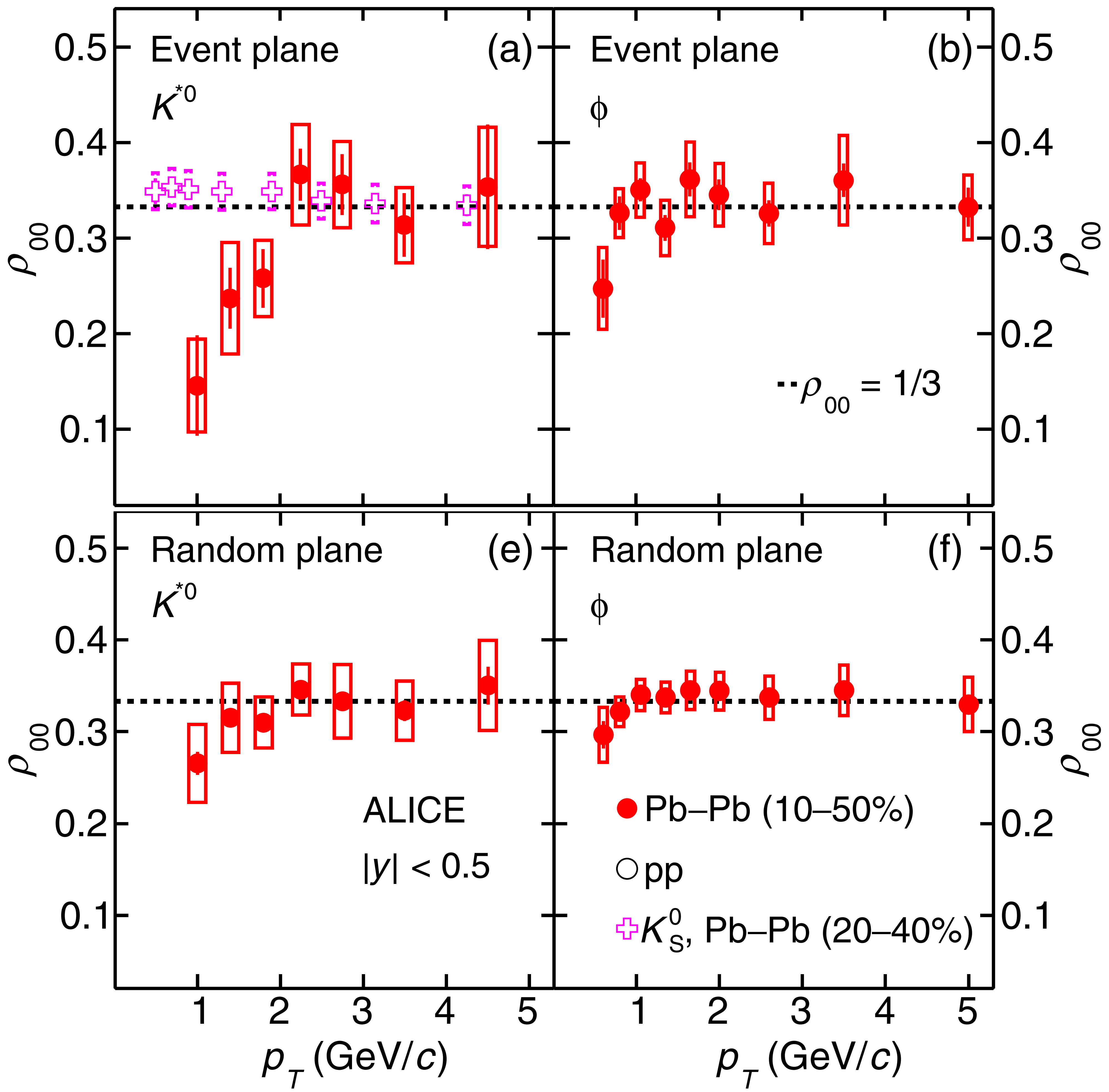
Theoretical expectation for ρ_{00}

Vorticity	
recombination	$\rho_{00} < 1/3$
fragmentation	$\rho_{00} > 1/3$
Magnetic field	$\rho_{00} > 1/3$ (for neutral vector mesons)

Z.-T. Liang and X.-N. Wang, PRL94.102301(2005)
Y. Yang et al., PRC97.034917(2018)

Global spin alignment at the LHC

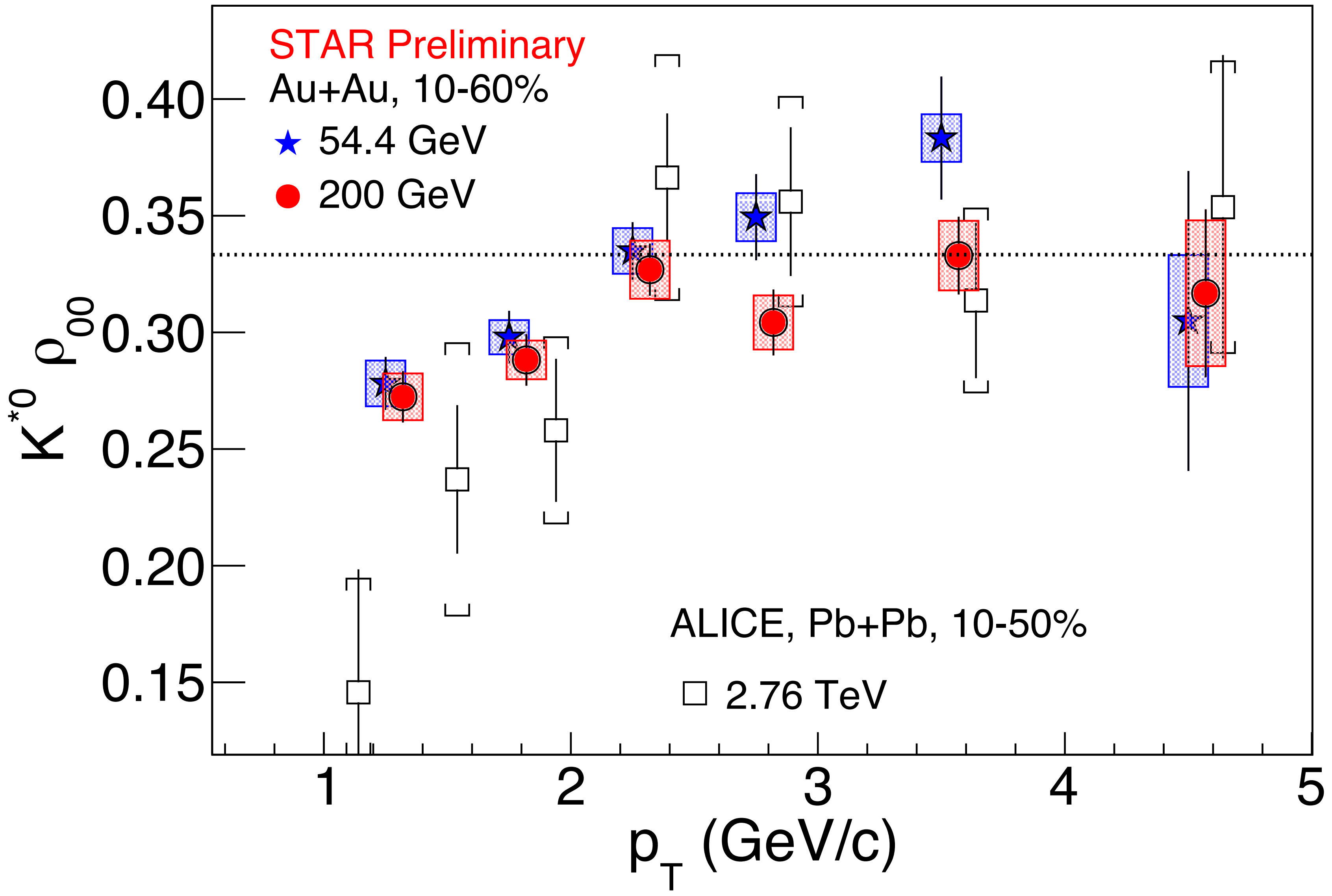
ALICE, PRL125, 012301 (2020)



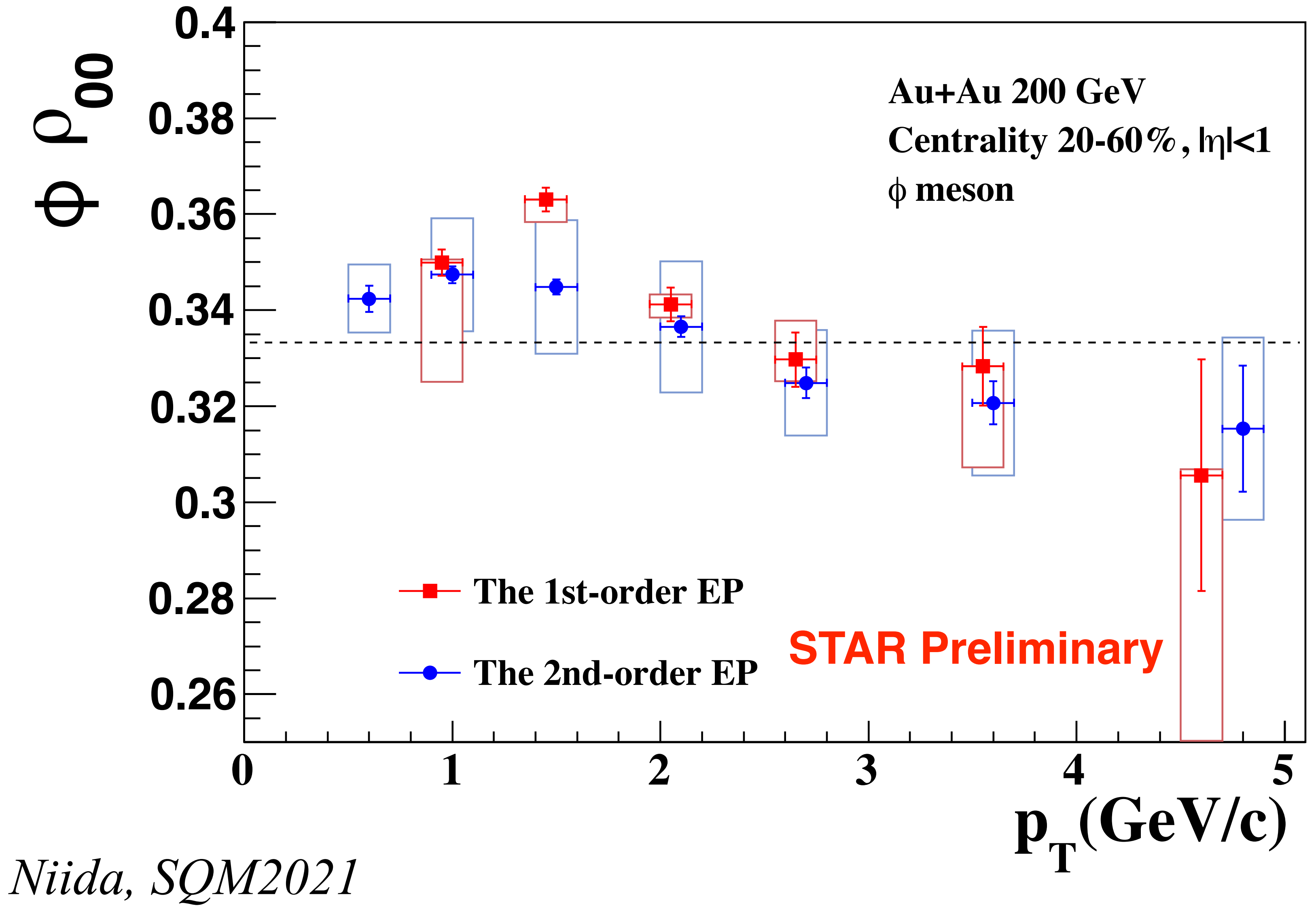
- ρ_{00}<1/3 observed for K^{*0} (spin-1) at p_T<2 GeV/c in Pb+Pb at 2.76 TeV by ALICE
  - ρ_{00} w.r.t. random EP shows similar trend but with smaller in magnitude
- ρ_{00} ~1/3 for K_s^0 (spin-0), indicating no spin alignment as expected, though slightly >1/3 systematically

Global spin alignment at RHIC

S. Singha (STAR), QM2019



C. Zhou (STAR), QM2018



- Similar trend at RHIC: $\rho_{00}<1/3$ for K^{*0} at low p_T
- $\rho_{00} > 1/3$ for ϕ at low p_T, different from LHC!
- Mean field of ϕ meson may play a role?
  - positive contribution to ϕ ρ_{00} (not for K^{*0})
  - Does it change from RHIC to LHC?

See Xin-Li Sheng's talk

X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

- Large deviation from 1/3 cannot be explained by vorticity
  - Also, no clear energy dependence unlike Λ P_H

$$\rho_{00} = 1/[3 + (\omega/T)^2].$$

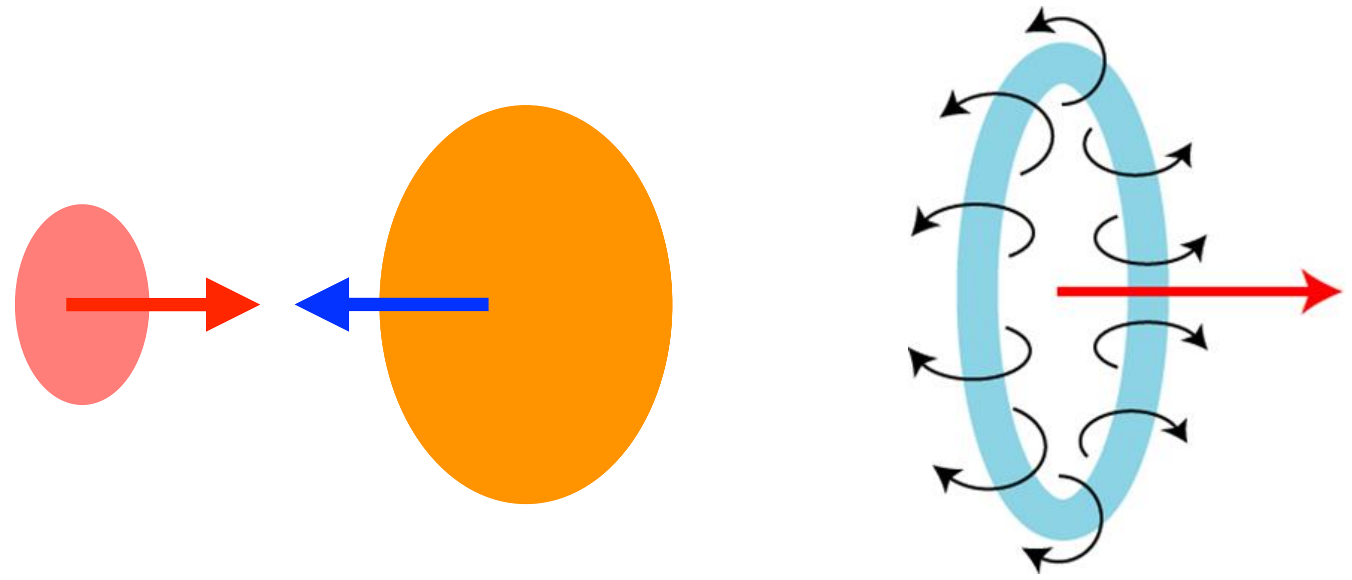
- Any residual acceptance effects? S. Lan, et al., PLB780(2018)319-324
- Significant deviation from 1/3 should contribute to the elliptic flow

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

Outlook

- Any difference in P_H between particles and antiparticles?
- P_H at more forward/backward rapidity look?
- More precise measurements of Ξ and Ω
- Global spin alignment of J/Ψ?
- Local polarizations: higher-order P_z, ϕ-polarization, spin-spin correlations

→ STAR BES-II+Run2023-2025, LHC Run-3 (ALICE/CMS/ATLAS/LHCb), HADES, NA61/SHINE and other future experiments



$$\mathbf{P}_\phi \propto \hat{\mathbf{p}}_\mathrm{T} \times \hat{\mathbf{z}}$$

- asymmetric collisions like Cu+Au, d+Au, p+Au
- A+A at forward region due to longitudinal expansion
- with respect to jet

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)
W. M. Serenone et al., arXiv:2102.11919

Summary

- Observation of global polarization, indicating vortical fluid, open new direction for study of QCD/hadronic matter in heavy-ion collisions
- A lot of progress in experimental measurements (all results are not covered in this talk)
  - Global polarization from 2.4 GeV to 5.02 TeV from HADES, STAR, ALICE
  - More differential measurements: some open questions there
  - Extending the measurement to Ξ and Ω hyperons, to be improved in future
  - Longitudinal polarization at RHIC and the LHC: sign problem with models, under discussion
  - Global spin alignment of ϕ and K^{*0}: deviation from 1/3, not well understood yet

There are still many open questions and more precise data are needed
for better understanding the nature of vorticity, polarization/spin alignment in HIC.
More interesting results will come!