Image from BNL newsroom @Aug. 2, 2017

Spin in Heavy-Ion Collisions: Experimental Overview

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筑波大学

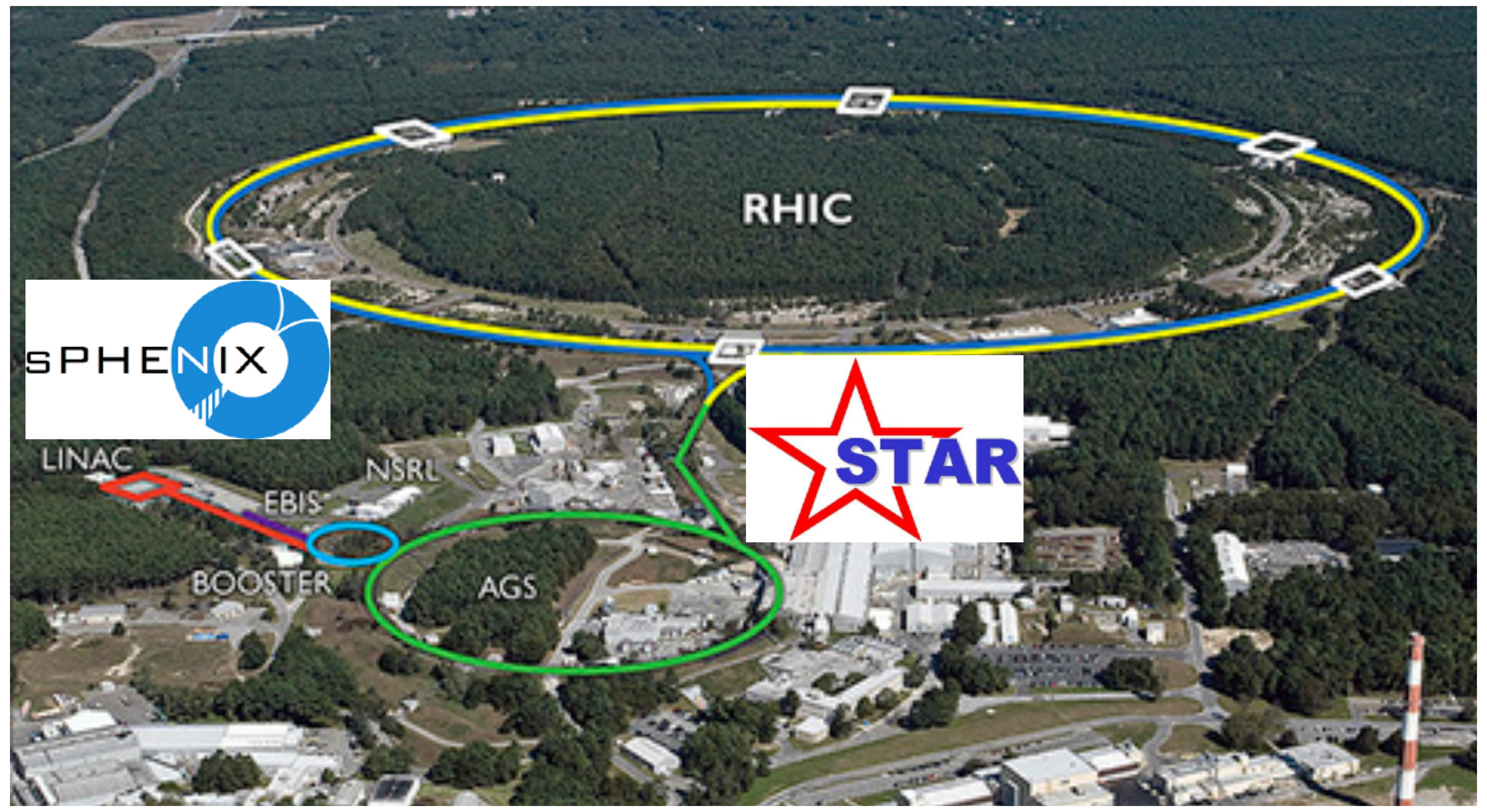
University of Tsukuba

The 26th International Symposium on Spin Physics

September 22-26, 2025 @Qingdao, Shandong

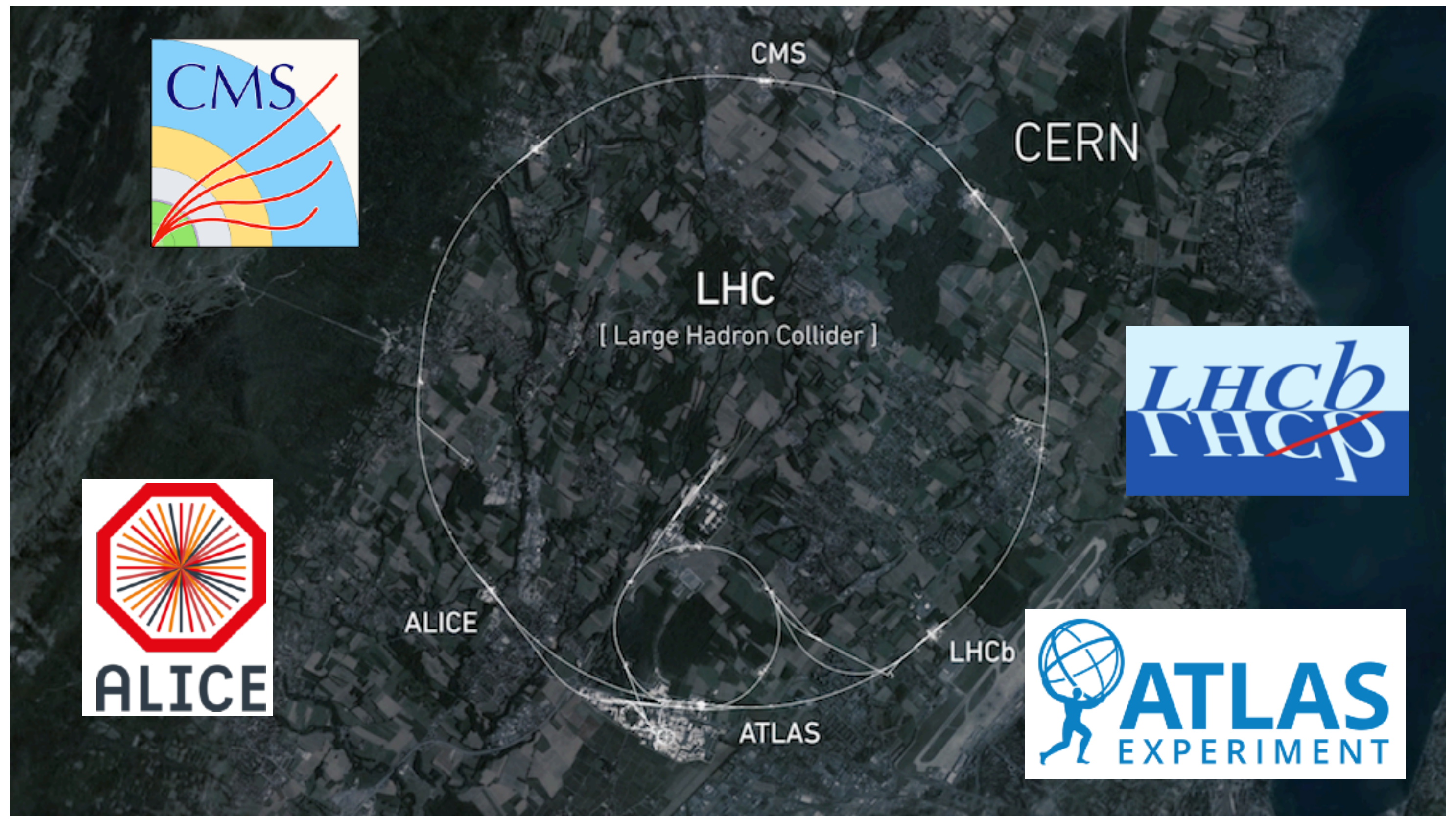
Relativistic Heavy Ion Collisions

Relativistic Heavy Ion Collider at BNL



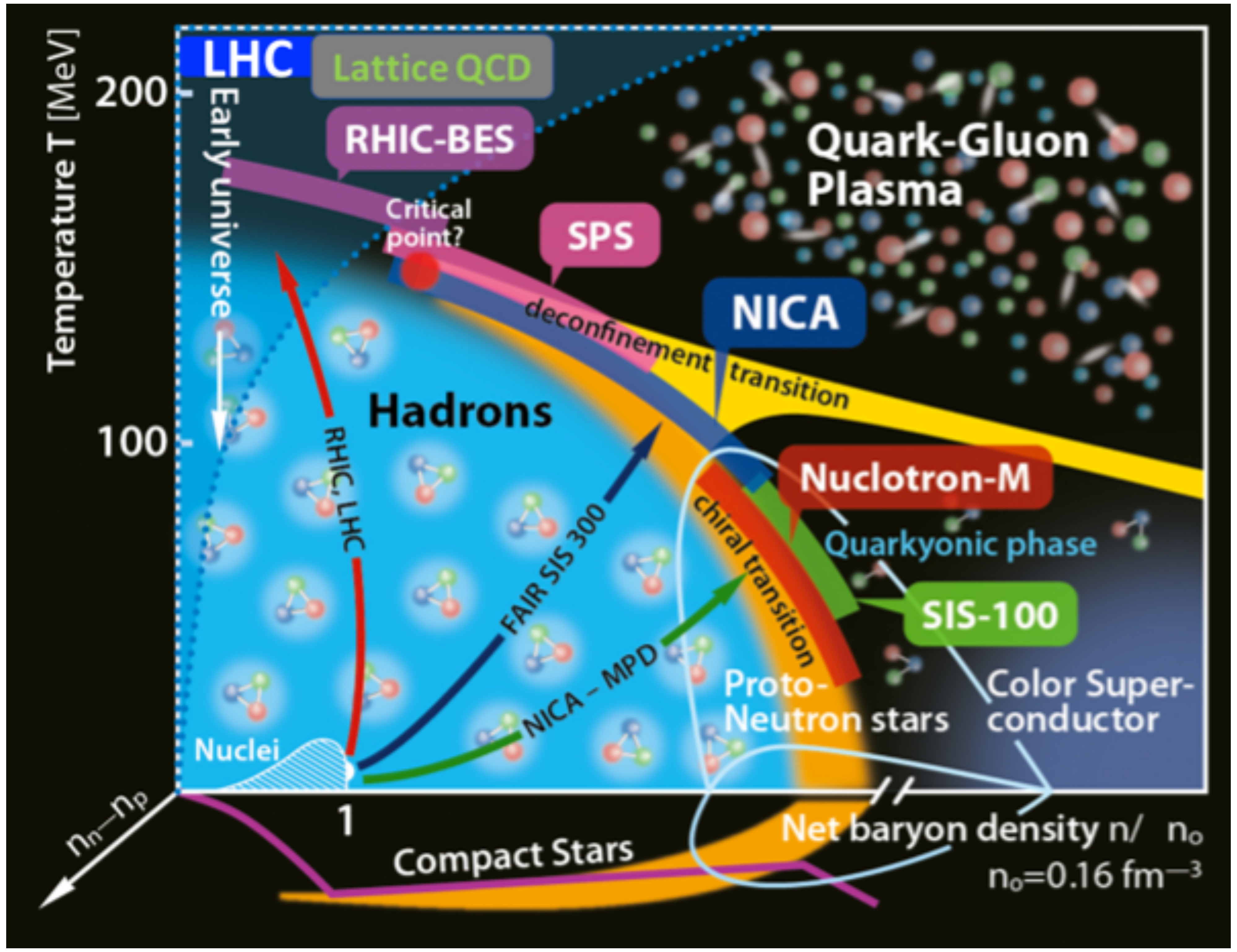
(2000-)

Large Hadron Collider at CERN



(First Pb-Pb collisions in 2010)

"conjectured" QCD phase diagram



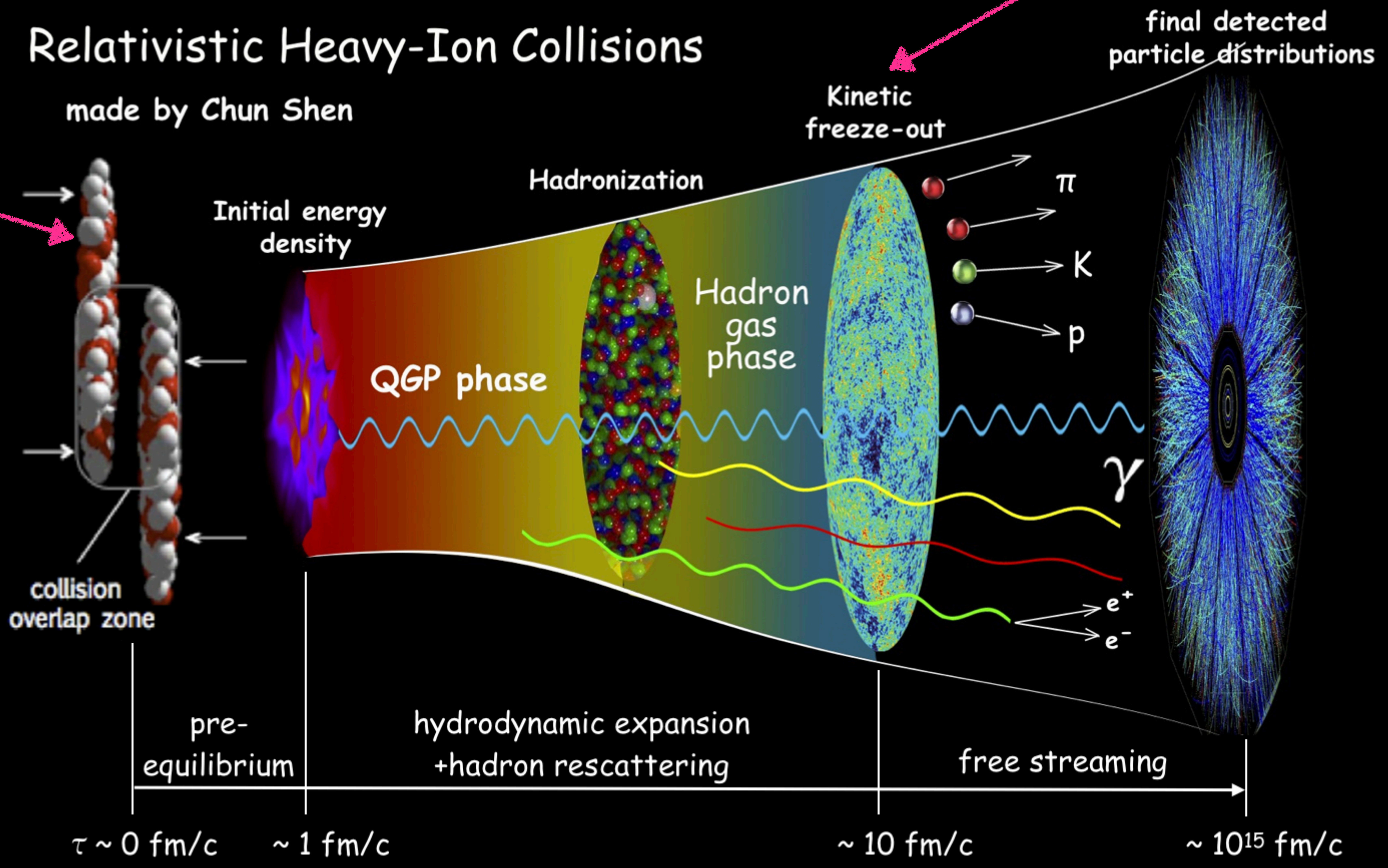
- Study properties of a deconfined state of matter, Quark-Gluon Plasma
- Search for QCD critical point and 1st-order phase transition
- Connection to the interior of neutron star at high baryon density

Time evolution of “Little Bang”

Most of hadrons are emitted here

Lorentz contracted
γ~100 (RHIC)
γ~2500 (LHC)

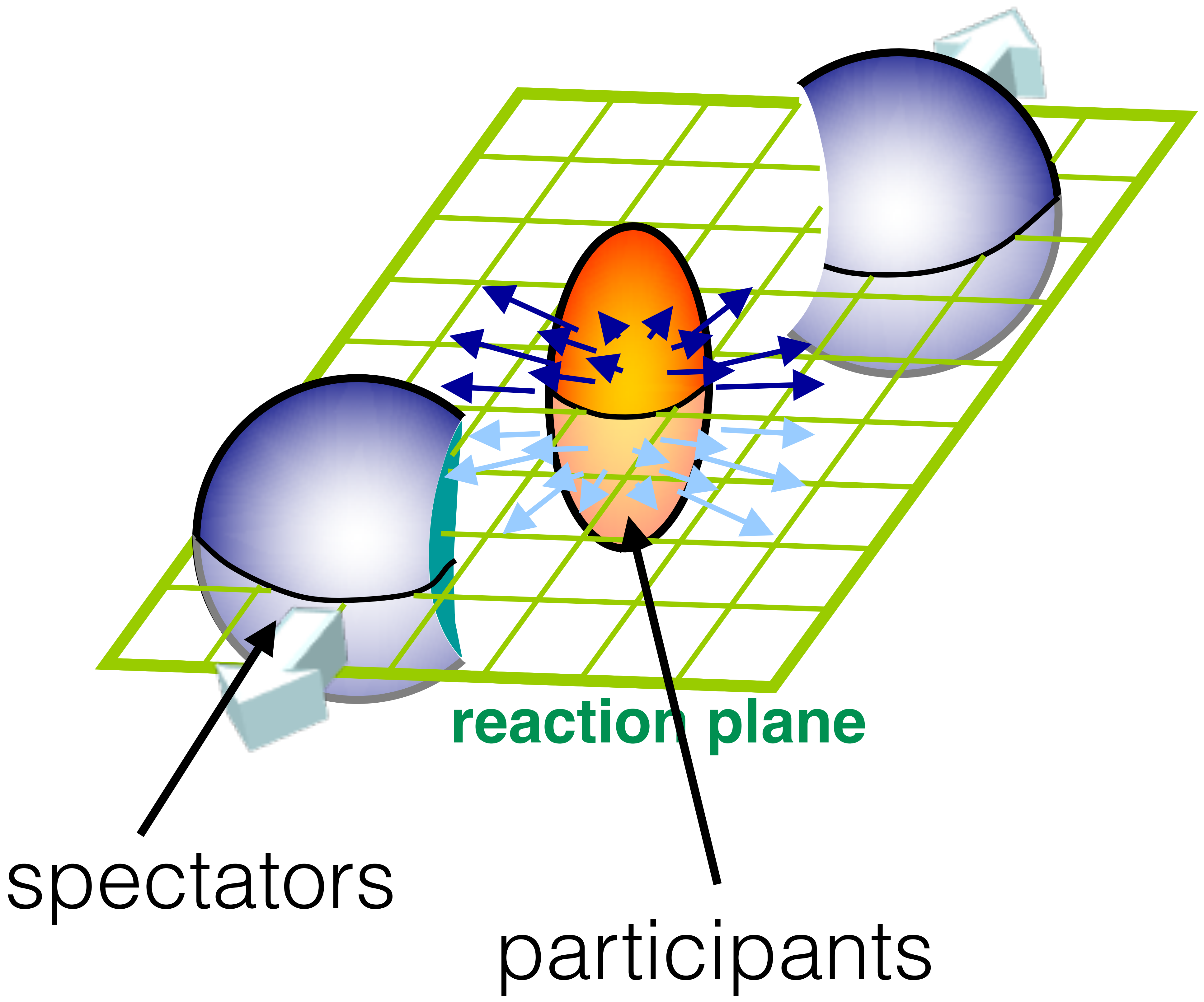
(99.995% the speed of light at RHIC)



Very short lifetime ~10 fm/c ~10^{-23} s

Orbital angular momentum / Strong magnetic field

For non-central heavy-ion collisions,



Large orbital angular momentum of the system:

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

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

PRL **94,** 102301 (2005) PHYSICAL REVIEW LETTERS 18

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]

Also, strong magnetic field created:

$$B \sim m_\pi^2 / e$$
$$\sim 10^{14}\ \mathrm{T}$$

D. Kharzeev et al., Nucl.Phys.A803, 227 (2008)
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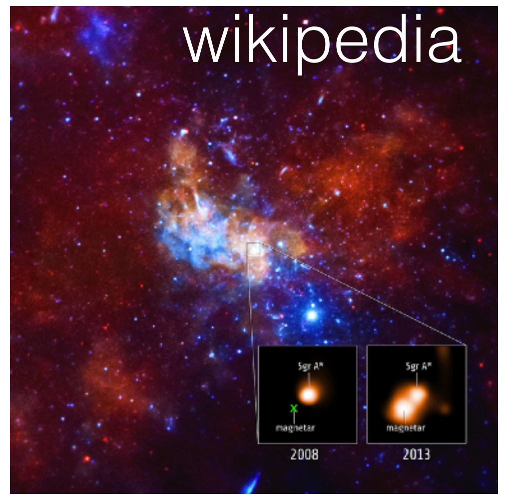
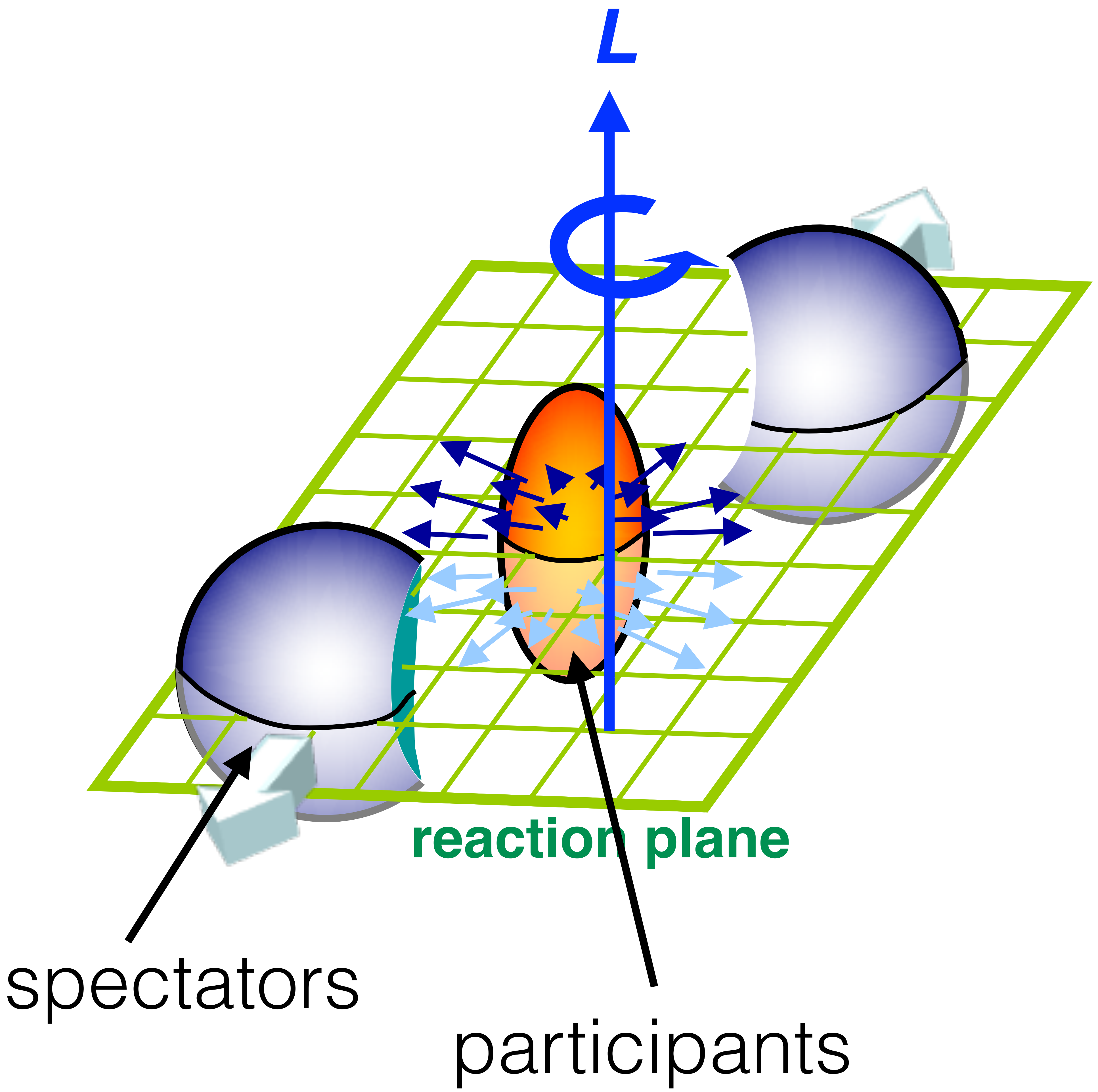


c.f. magnetar B~10^{11} T

Orbital angular momentum / Strong magnetic field



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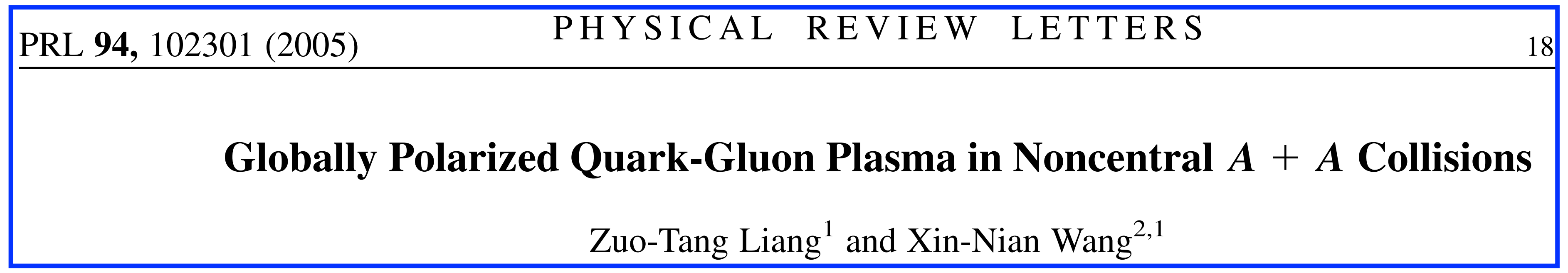

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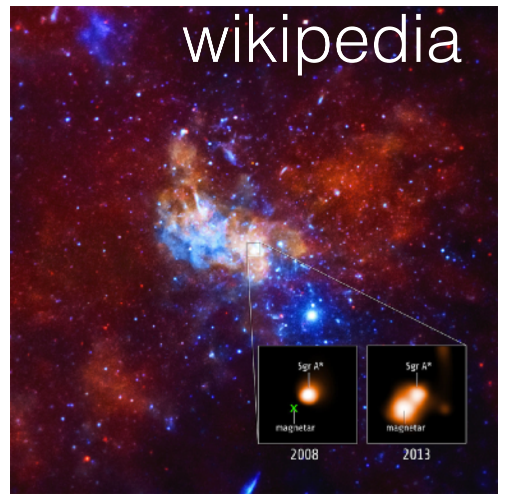

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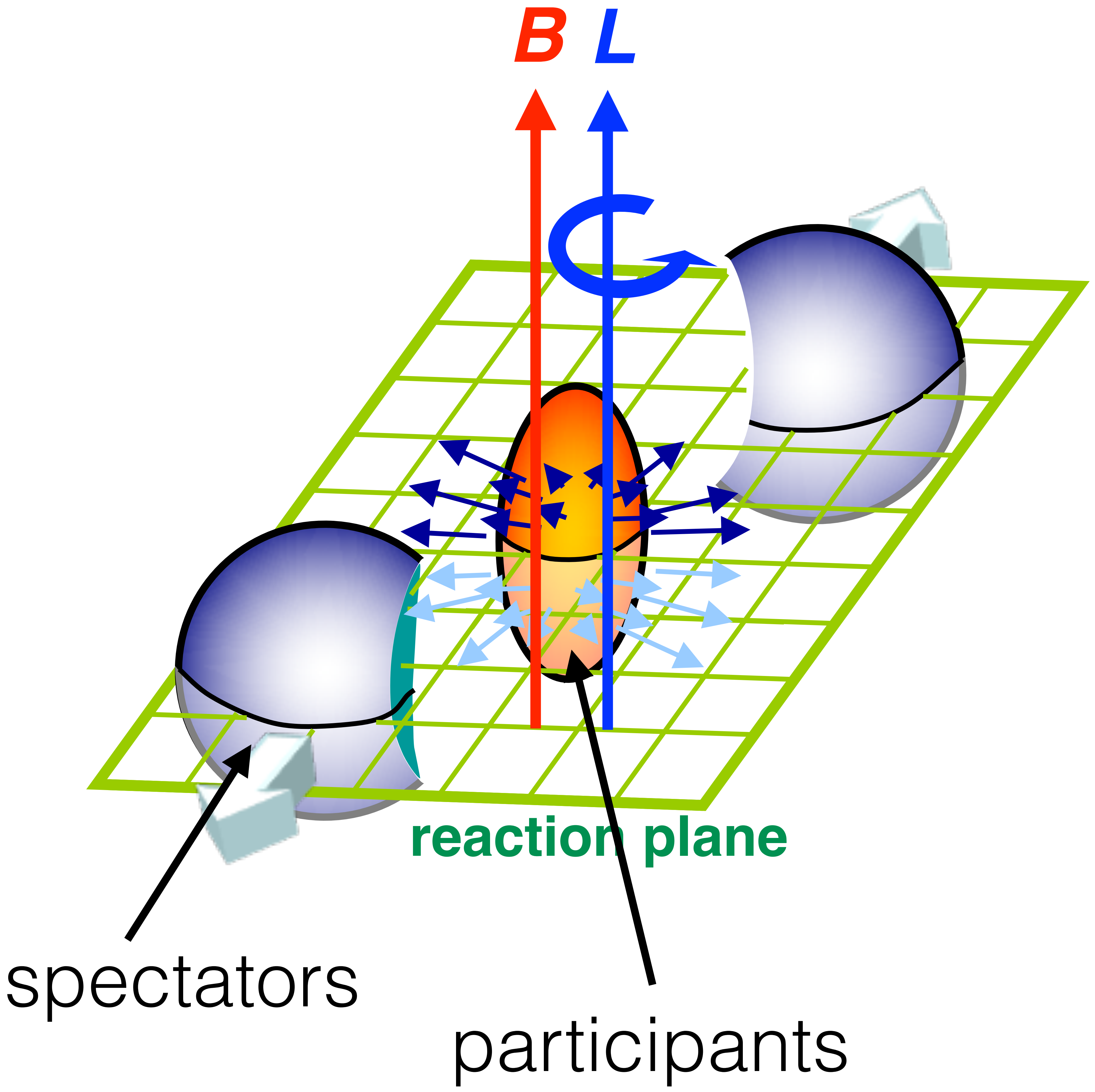

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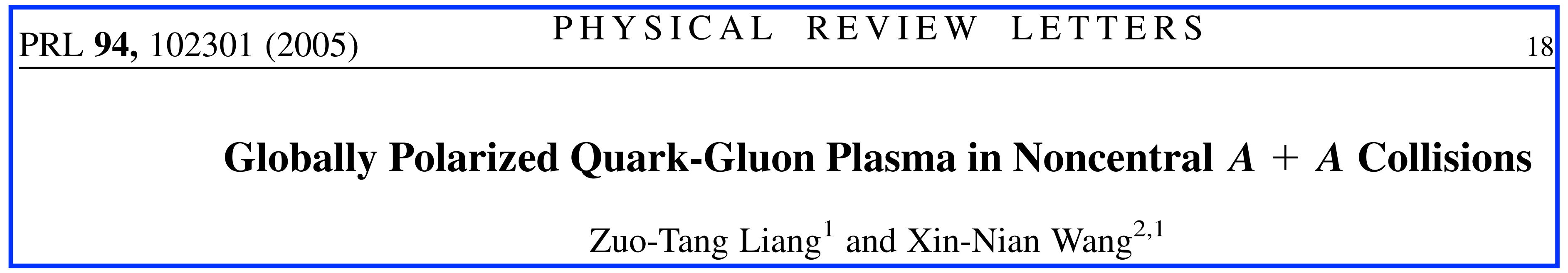
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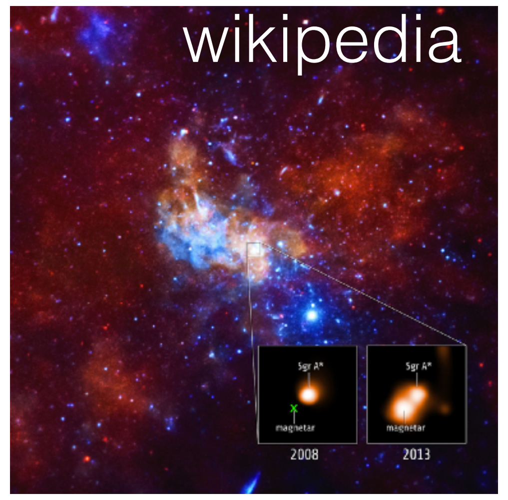

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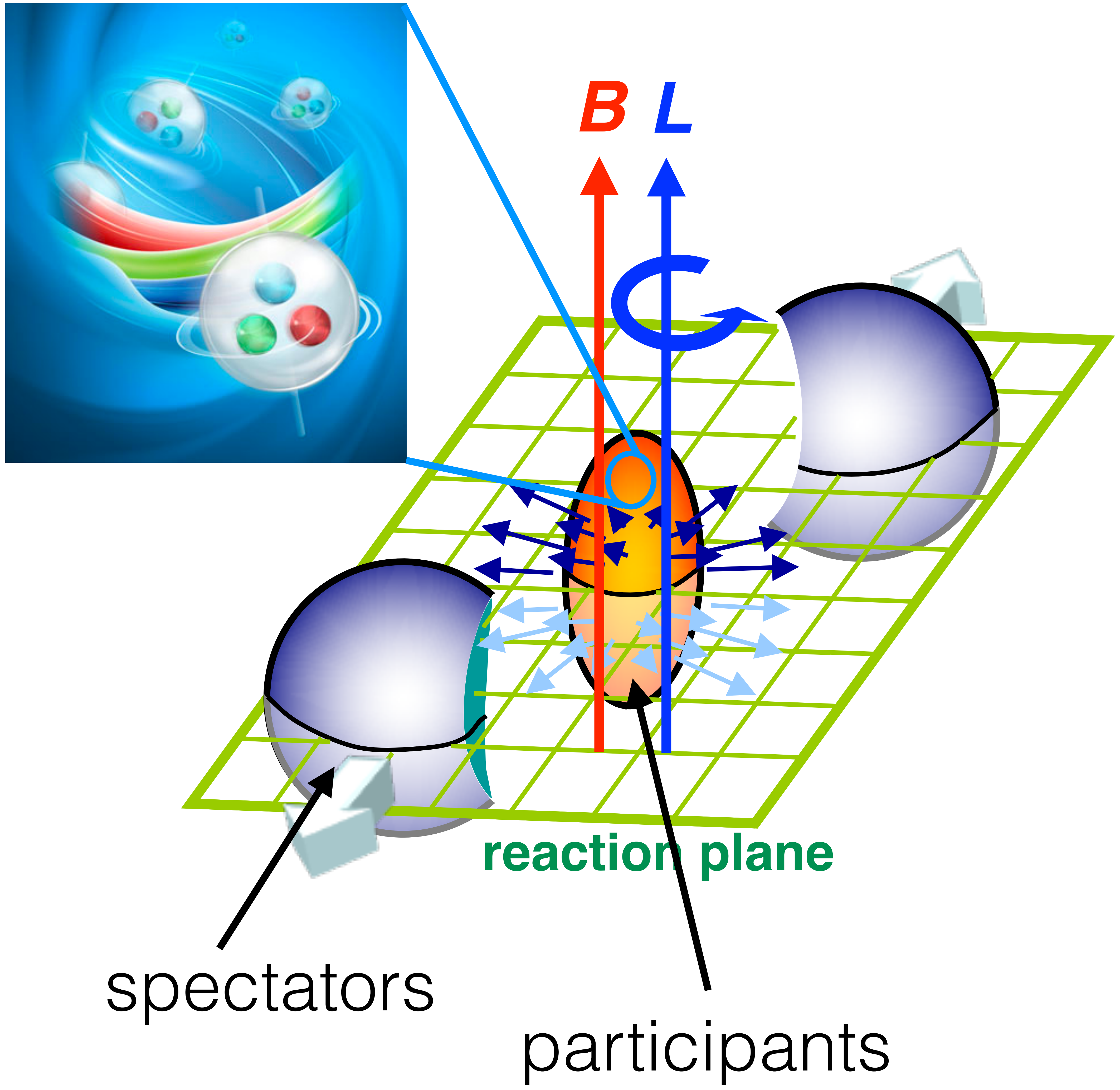
“Global” polarization



Rotating system under strong B-field:

- Particles “globally" polarized along ***L*** or ***B*** via spin-orbit/spin-magnetic couplings
- Particles and antiparticles are oppositely aligned along ***B***

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005), PLB629(2005)20
S. Voloshin, nucl-th/0410089
B. Betz, M. Gyulassy, and G. Torrieri, PRC76, 044901 (2007)

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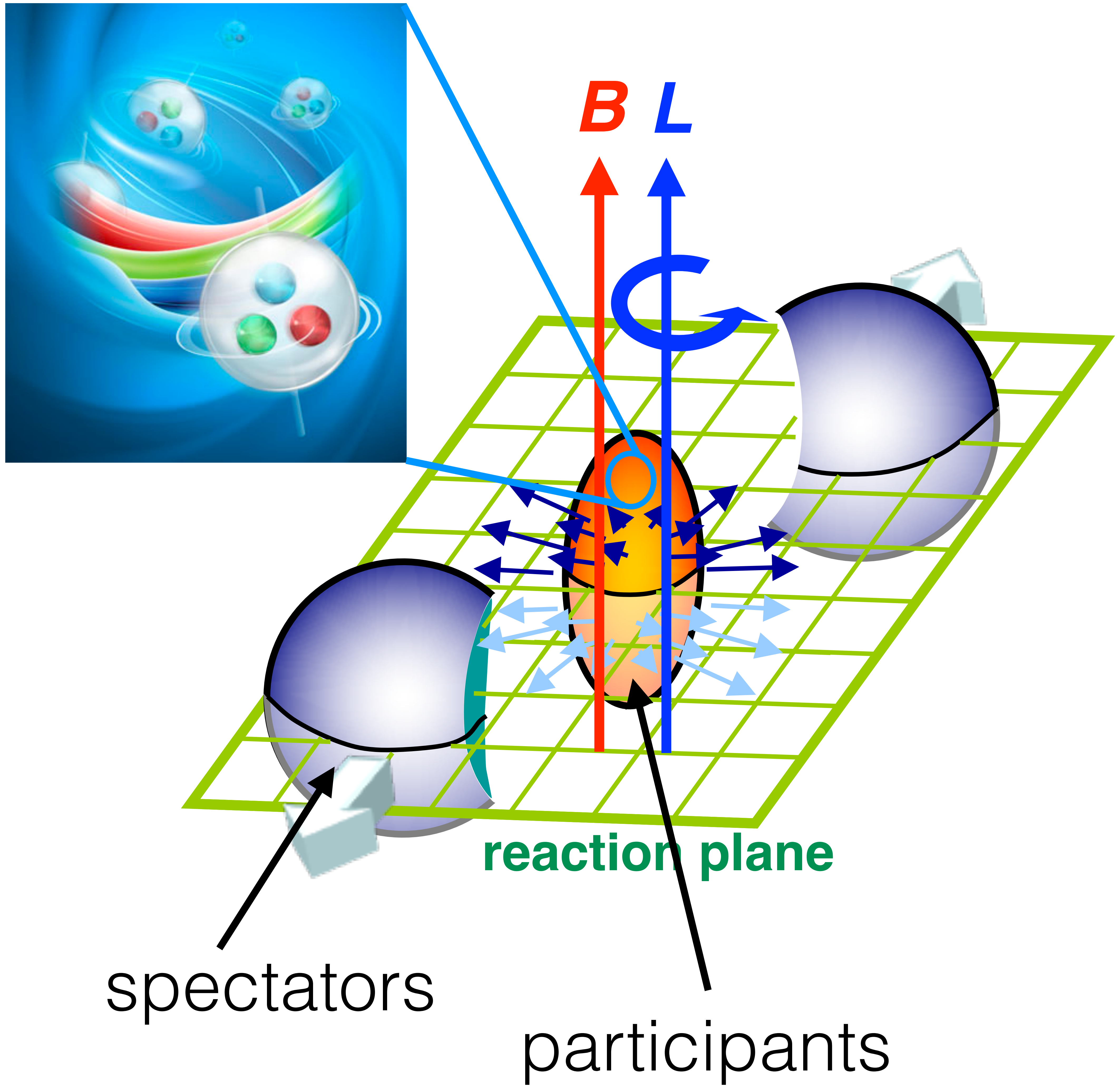

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- Polarization ***P*** in non-relativistic limit assuming local thermodynamic equilibrium

$$\boldsymbol{P} = \frac{(S+1)(\boldsymbol{\omega} + \mu_B \boldsymbol{B}/S)}{3T}$$

S: spin
ω: vorticity

F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

How we measure the polarization?

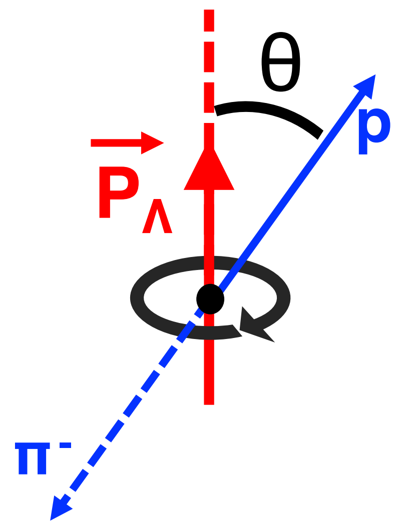
Parity-violating weak decay of hyperons

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

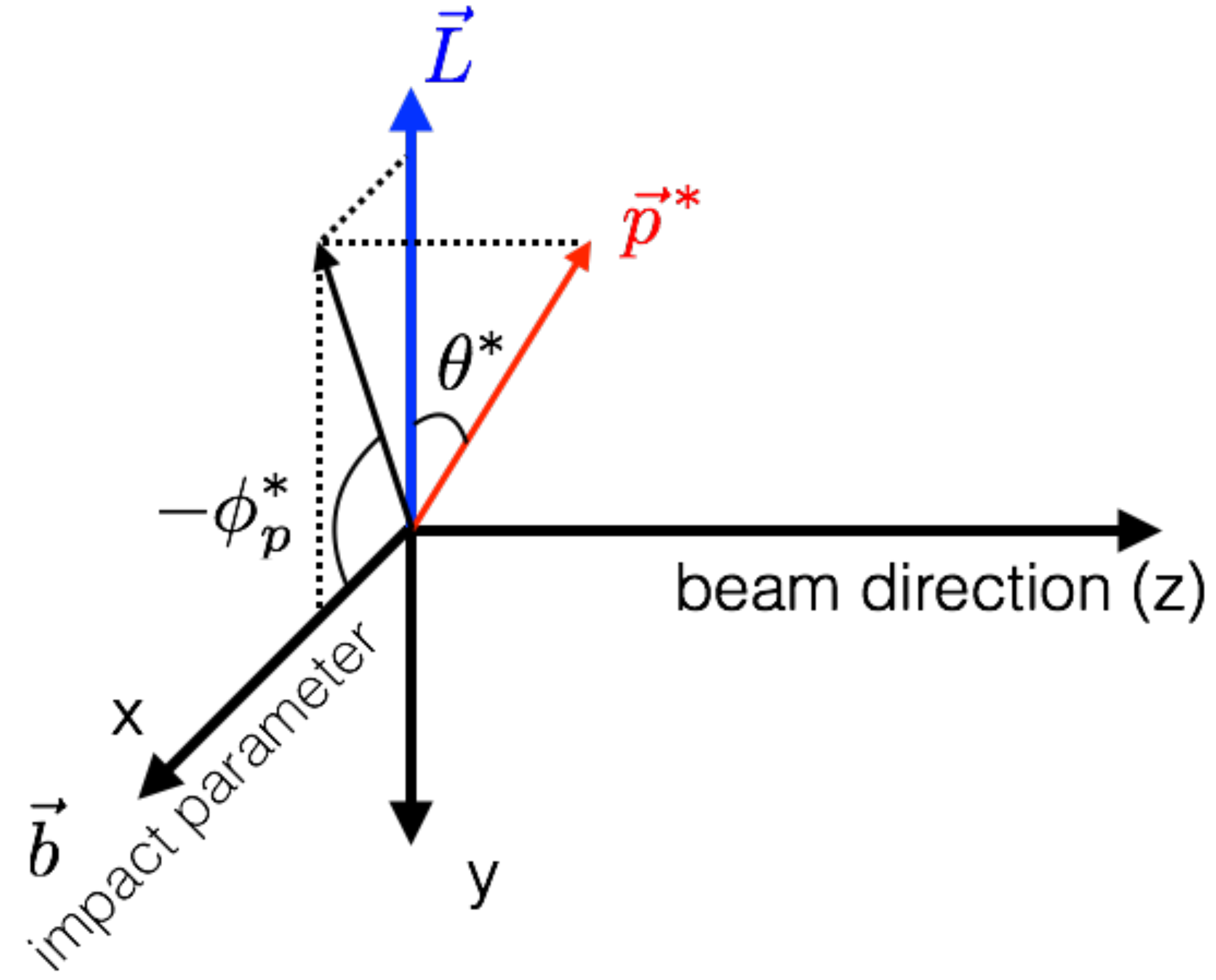
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*)$$

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

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



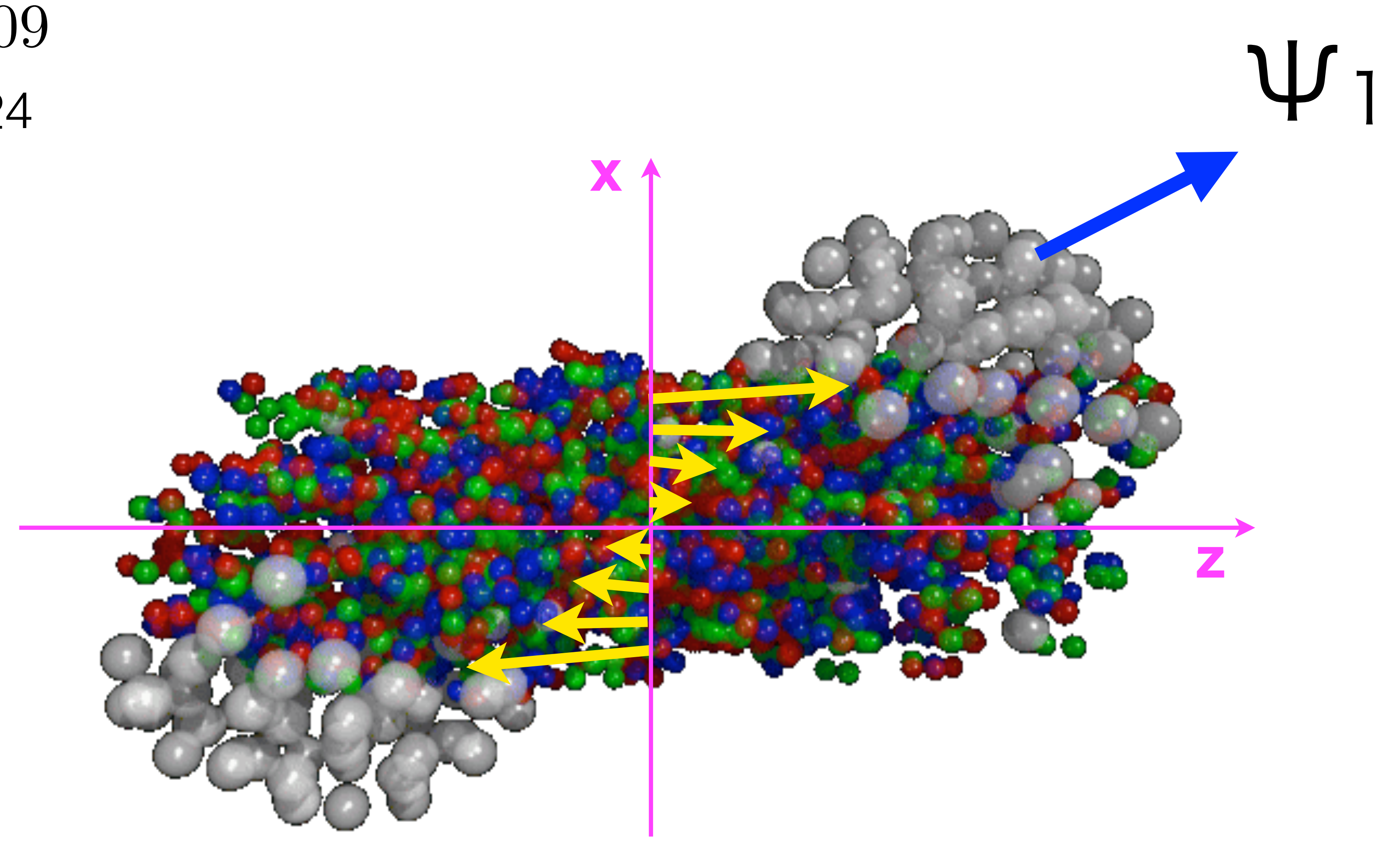
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.747 \pm 0.009$
PDG2024



Polarization along the initial L direction

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

Ψ_1: azimuthal angle of spectator fragment
STAR, PRC76, 024915 (2007)

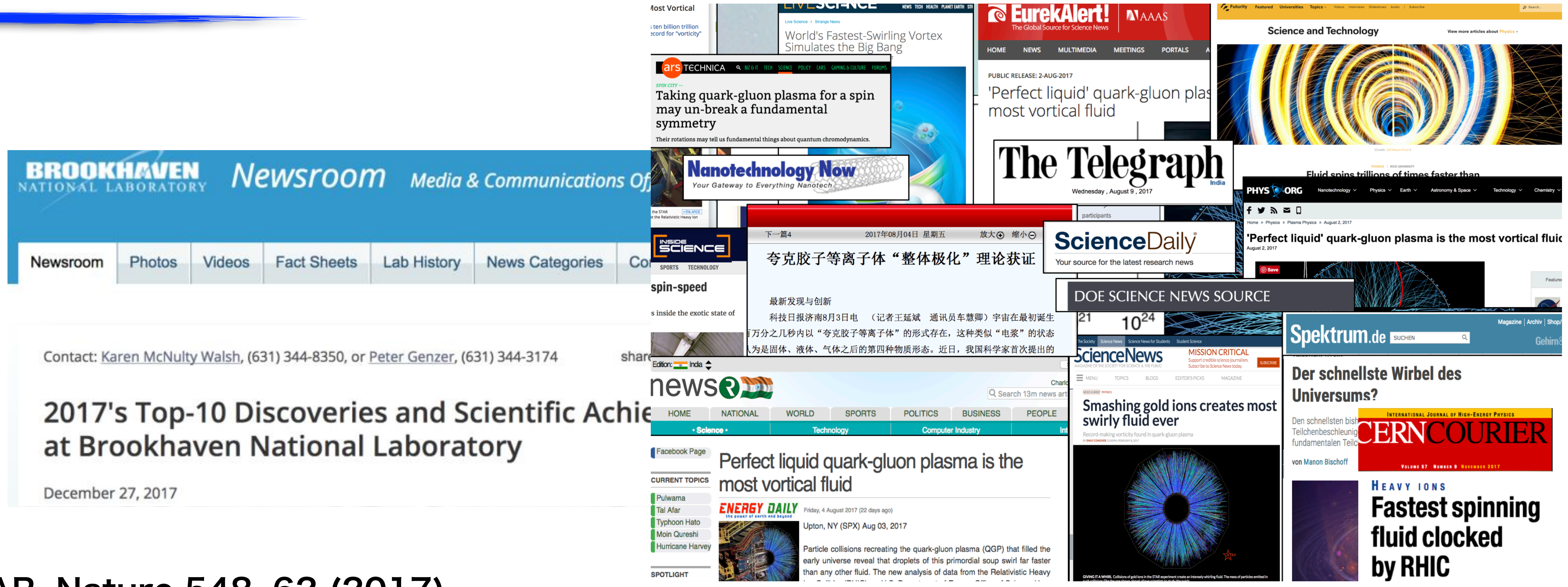


Spectators fly away from the beam axis (at high energy)

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

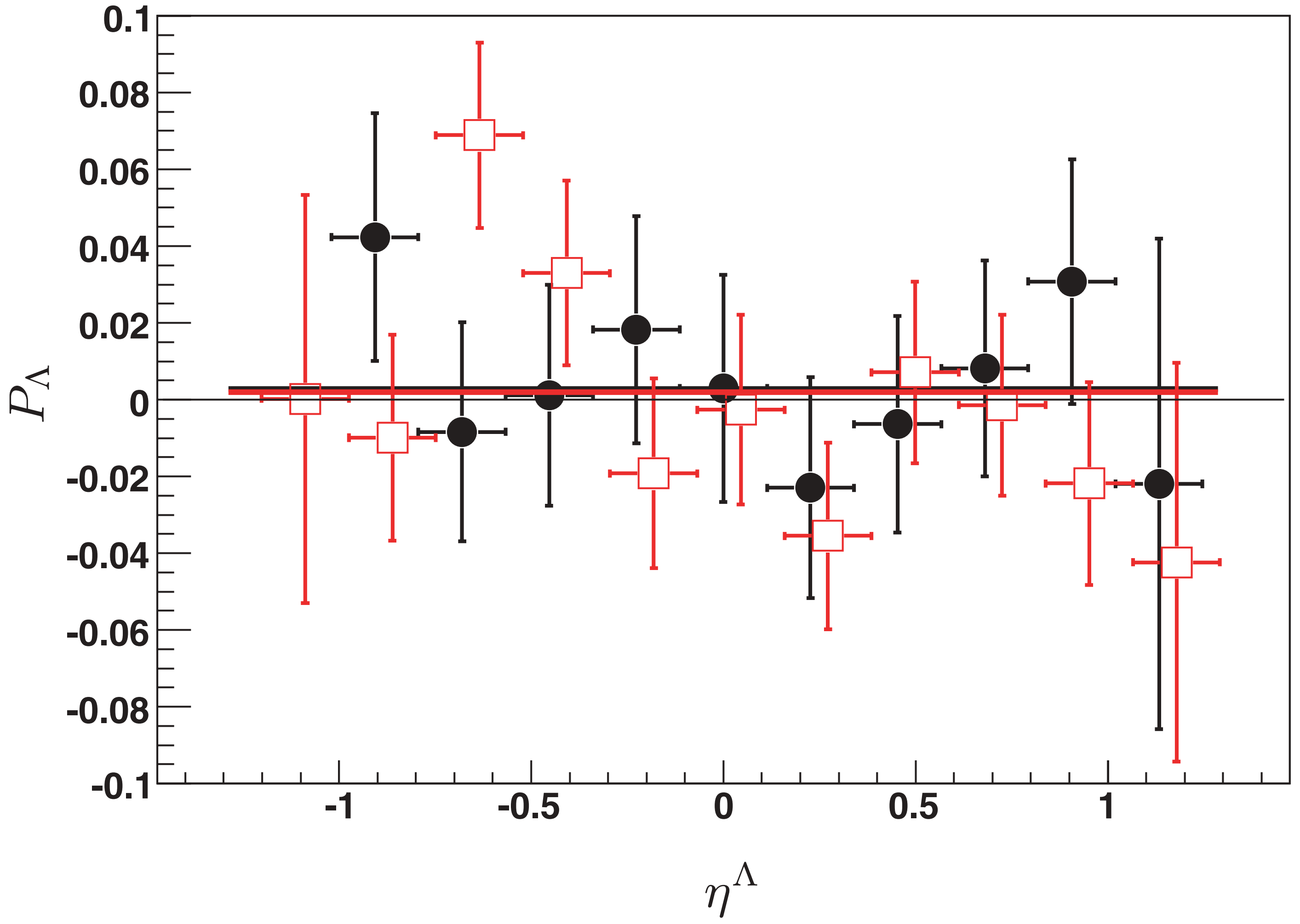
First observation of Λ global polarization

2005: Theoretical prediction
2007: First attempt of the measurement (null result)
…
2017: First observation by STAR experiment!



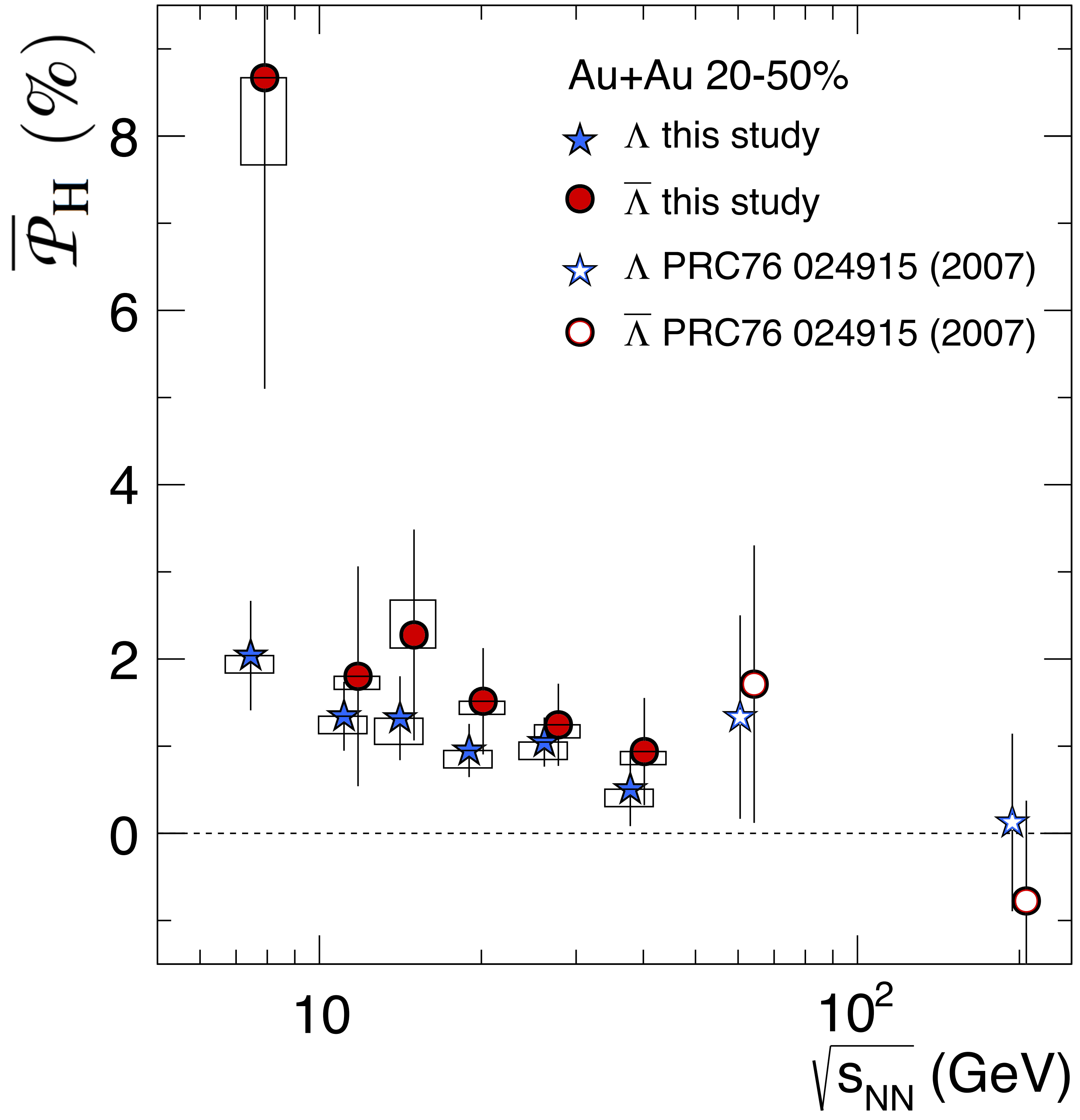
STAR PHYSICAL REVIEW C **76**, 024915 (2007)

Global polarization measurement in Au+Au collisions



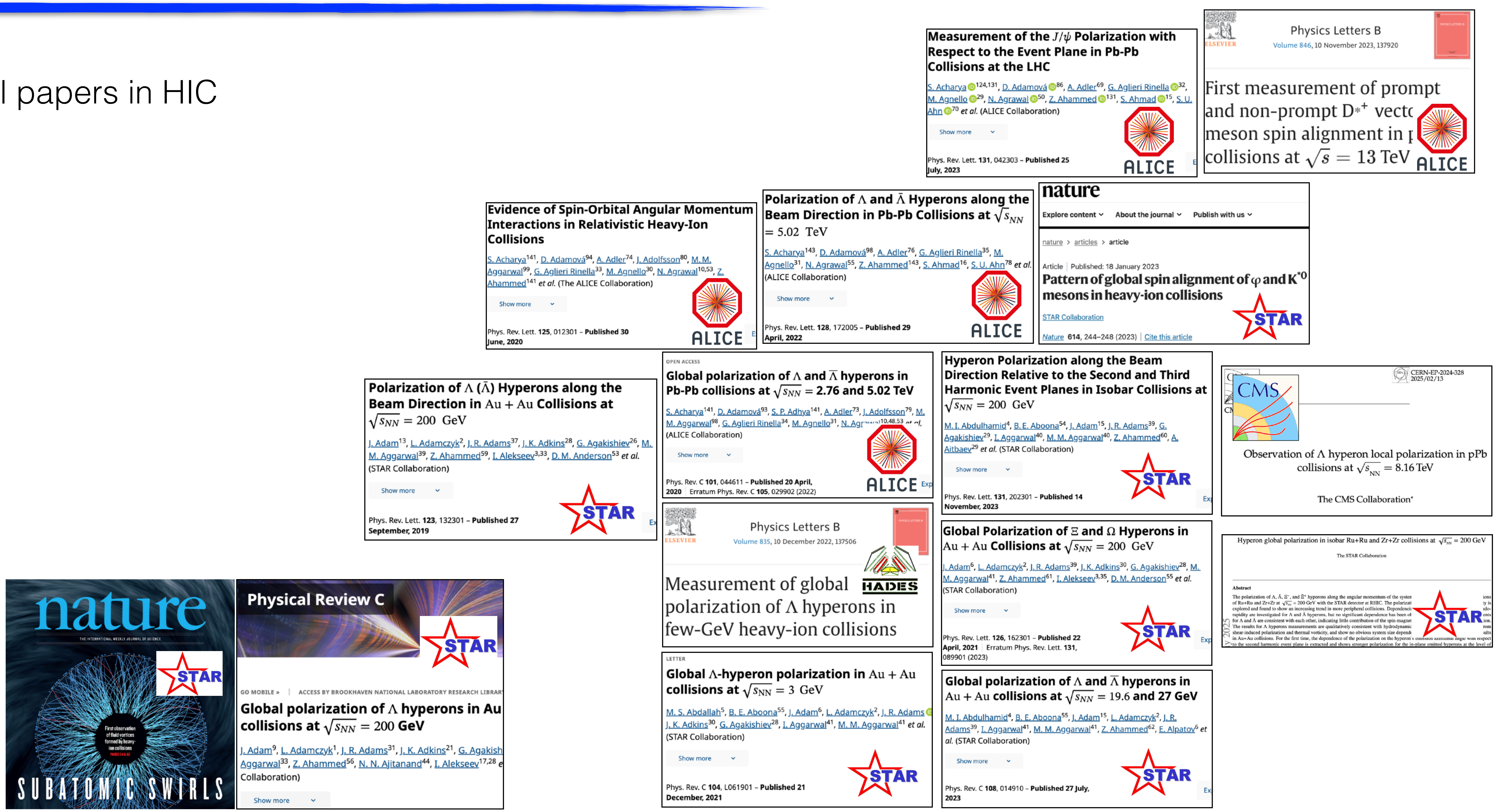
Upper limit of P_H <2%

STAR, Nature 548, 62 (2017)



Rapidly growing topic with new measurements

*Only experimental papers in HIC



2005 Prediction

2007 First attempt

2017 First observation

2018

2019

2020

P_z (along the beam direction)

φ and K^{*0} (LHC)

Ξ and Ω

φ and K^{*0} (RHIC)

J/ψ

D^{*0}

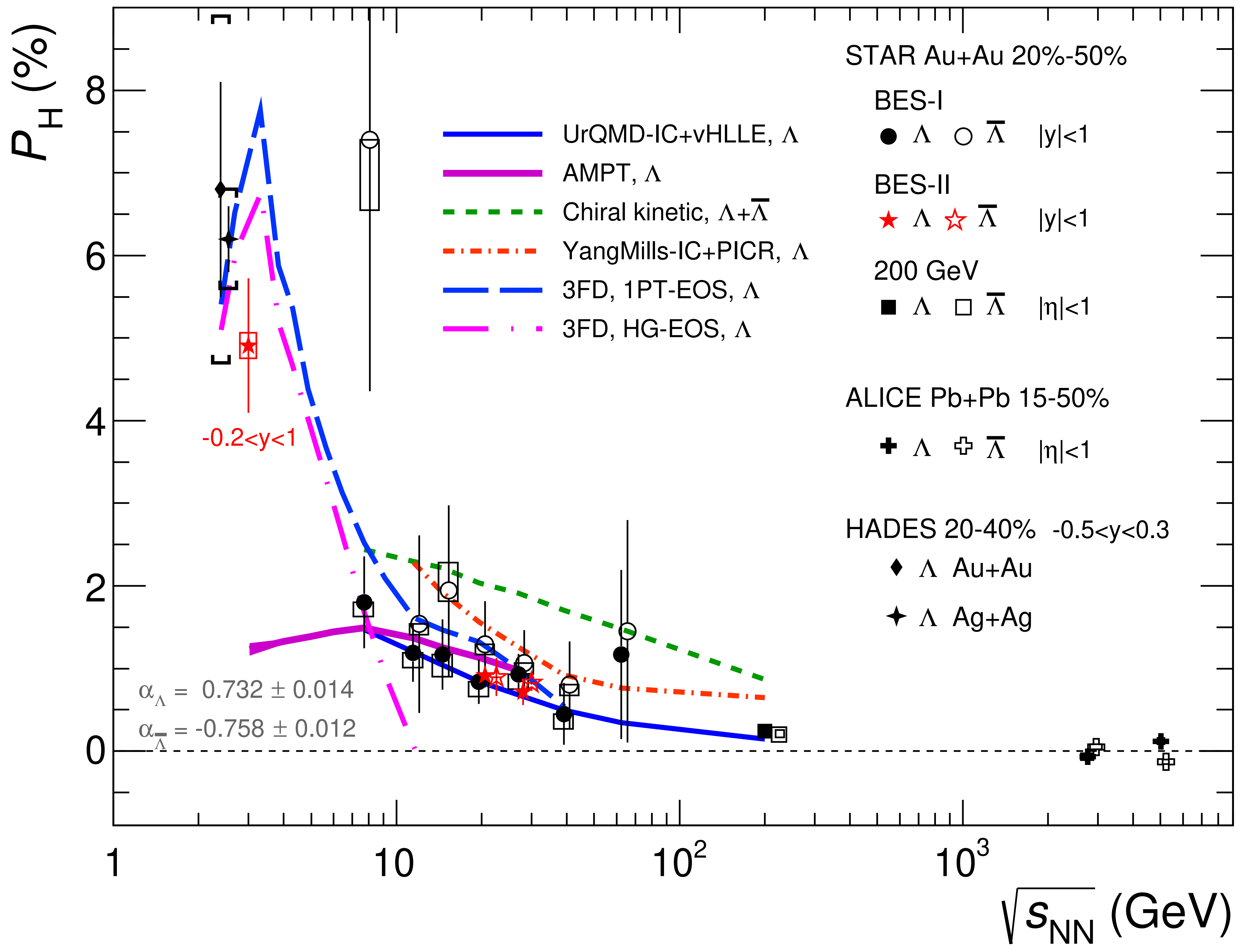
Isobar $P_{z,3}$

pPb $P_{z,2}$

2025

Λ global polarization vs. $\sqrt{s_{NN}}$

Recent reviews
TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010
F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006



- 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
  - …and more

- Based on thermal vorticity field, relating it to spin

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

F. Becattini et al., Ann.Phys. 338 (2013), 32-49
F. Becattini et al., PRC95, 054902 (2017)

- ***The most vortical fluid ever observed***

STAR, Nature 548.62(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

Λ global polarization vs. $\sqrt{s_{NN}}$

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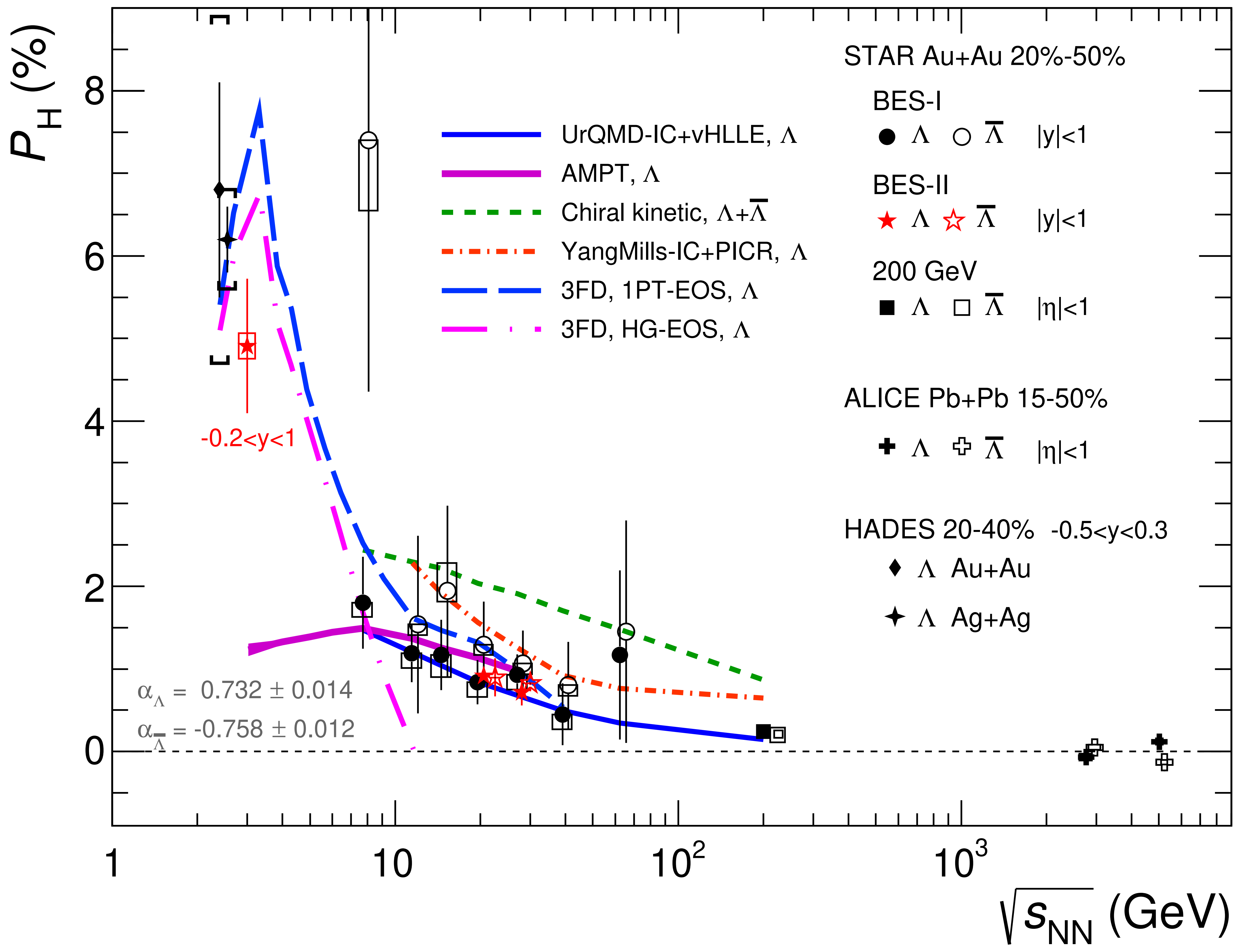
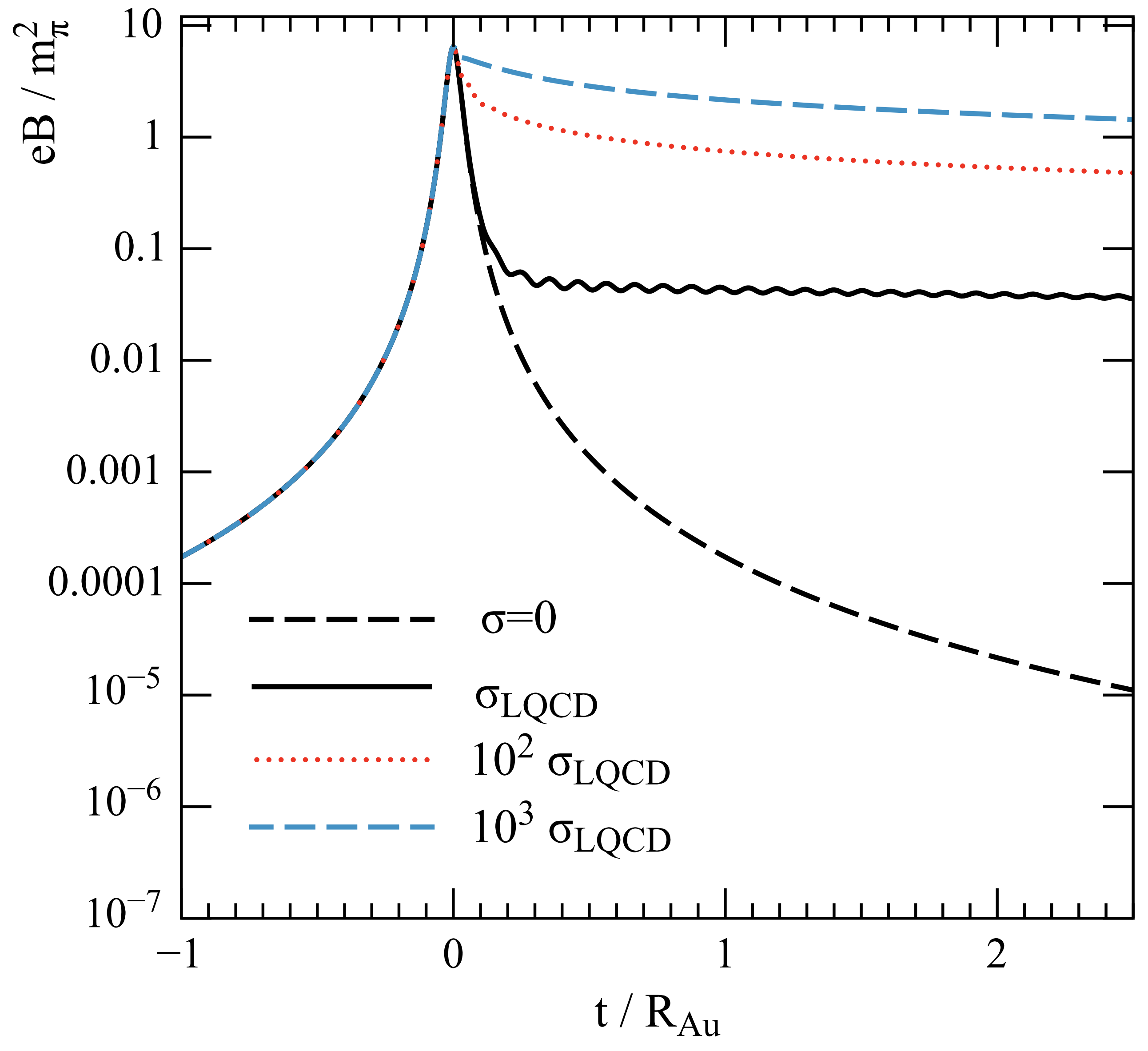


- Any difference between Λ and $\overline{\Lambda}$ from B-field effect?
- Does P_H smoothly increase towards lower energy? Any changes from partonic (>a few 10 GeV) to hadronic matter (a few GeV)?
- Can we see spin-dependence? e.g. in Ξ, Ω
- System size dependence?
- "Puzzles" remain in differential measurements? e.g. $P_y(\phi)$ and $P_y(y)$

Any effect of magnetic field?

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

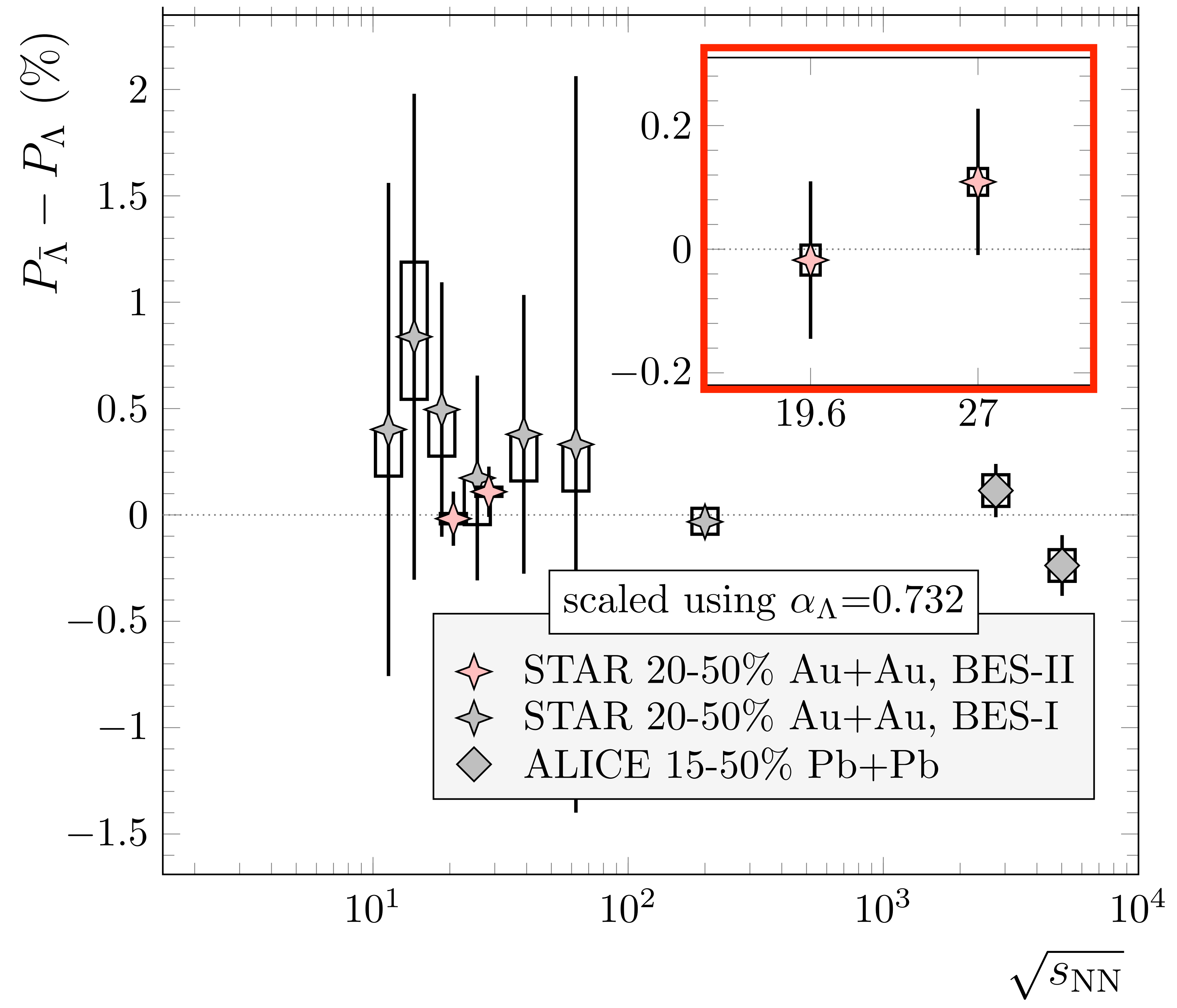


$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

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

μ_Λ: Λ magnetic moment

STAR, PRC108, 014910 (2023)



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- Could be sustained by (unknown) QGP electric conductivity

Tong Fu, Sep. 23 (Tue)

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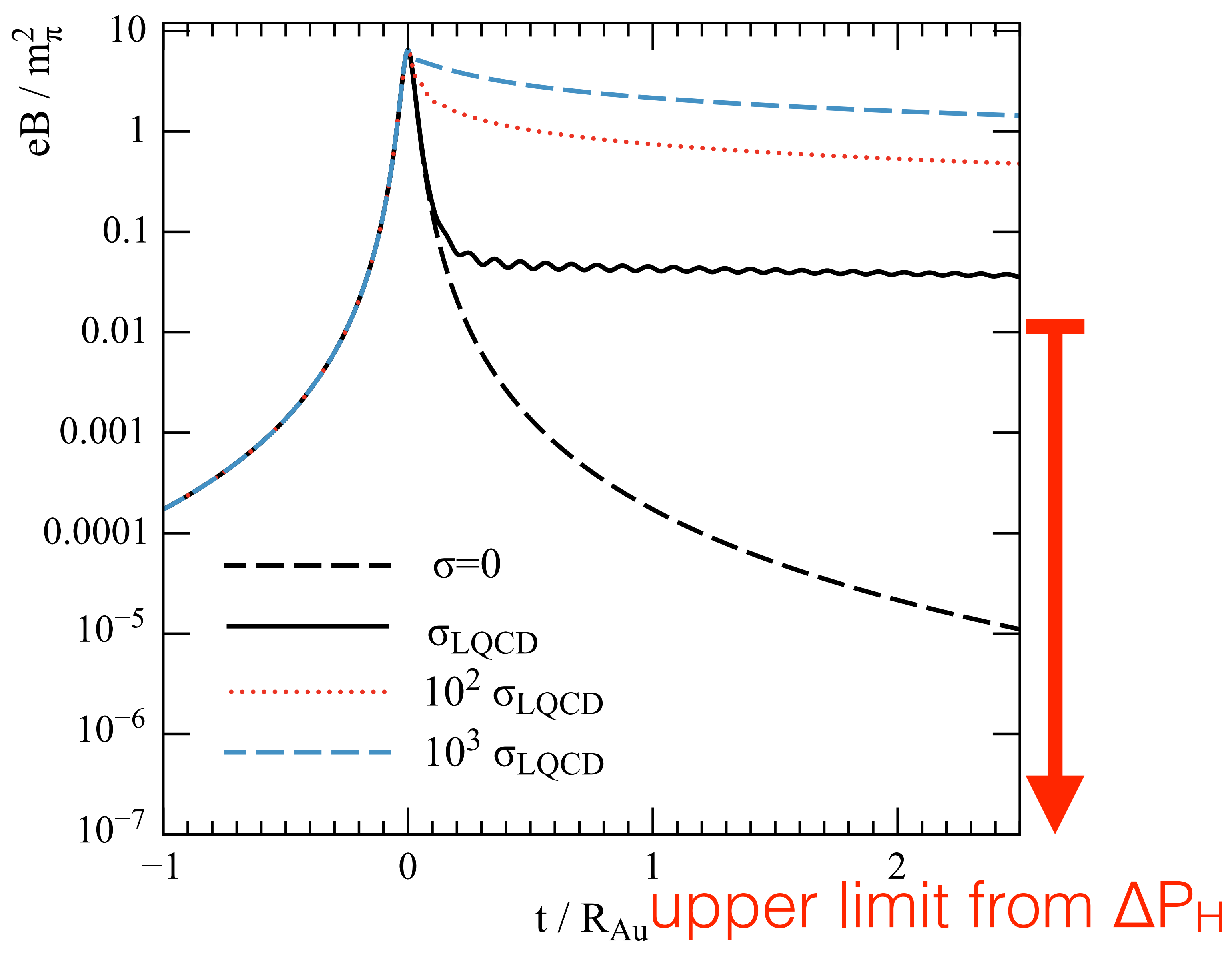

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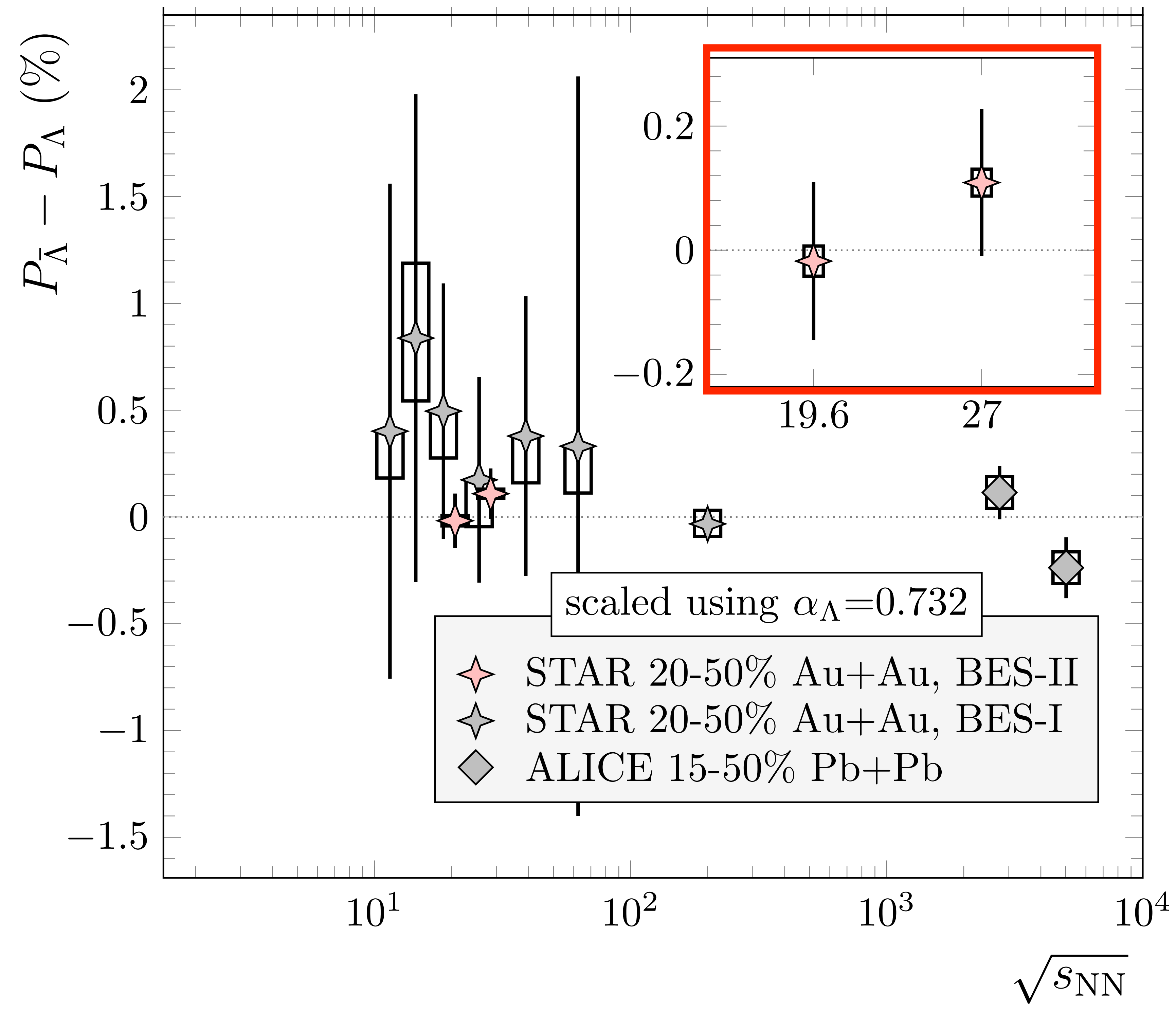
$$B = (P_{\bar{\Lambda}} - P_\Lambda)T/(-2\mu_\Lambda)$$

$$\approx 30\Delta P_\Lambda \times 10^{14}\ [T]$$

$$eB/m_\pi^2 \sim 10\Delta P_\Lambda$$ (T=120 MeV)

STAR, PRC108, 014910 (2023)



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- An upper limit of the late-stage B-field is <10^{13} T

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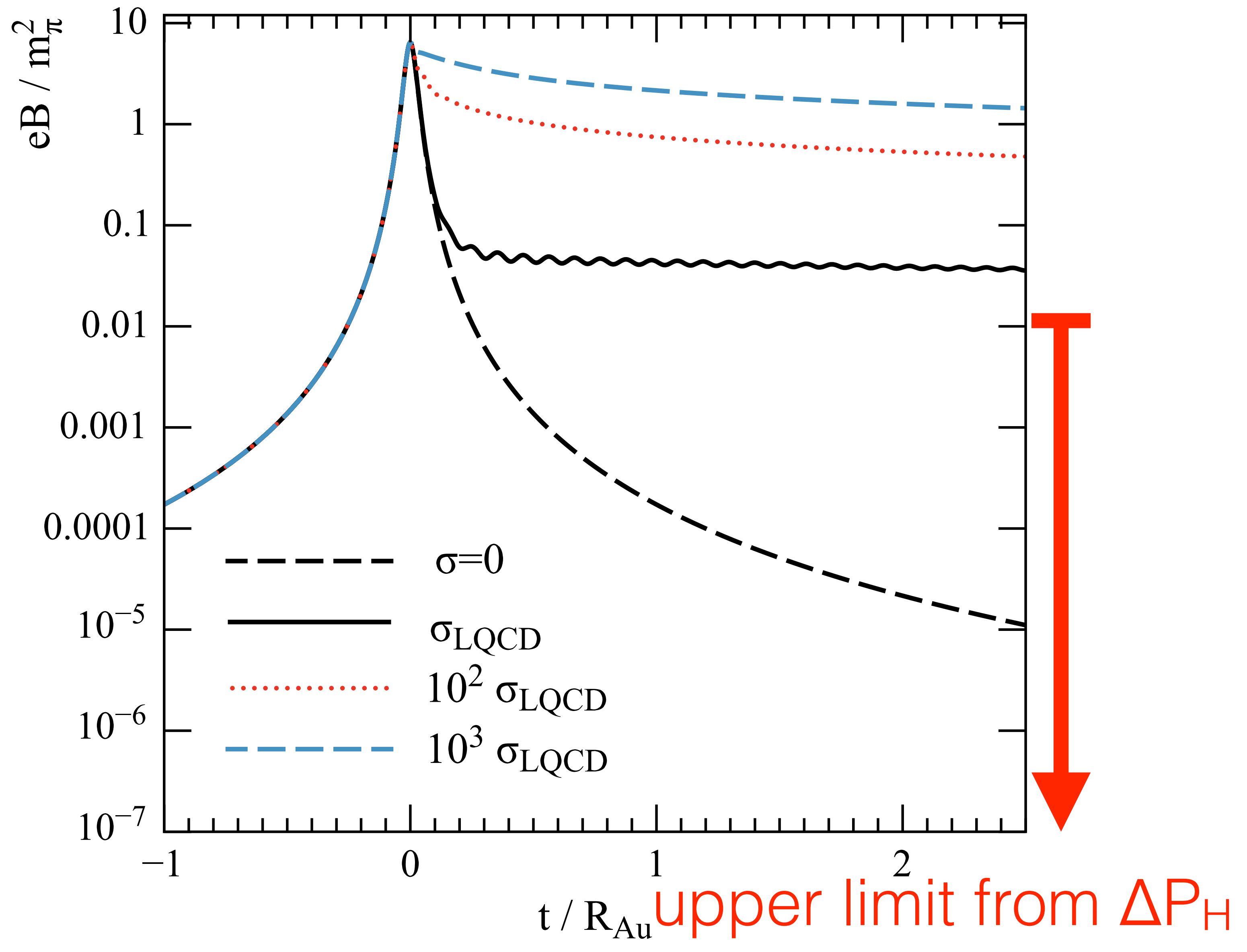

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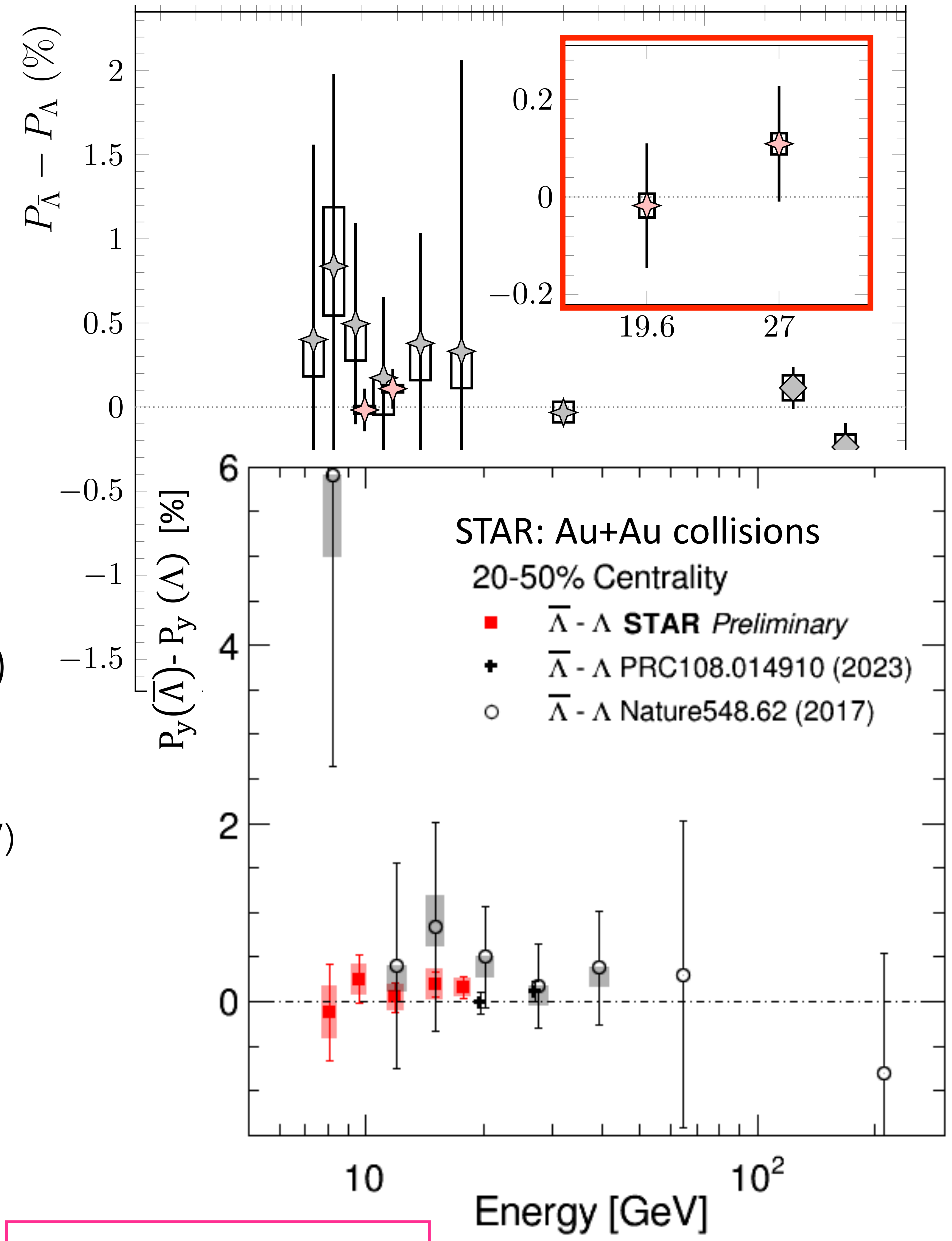

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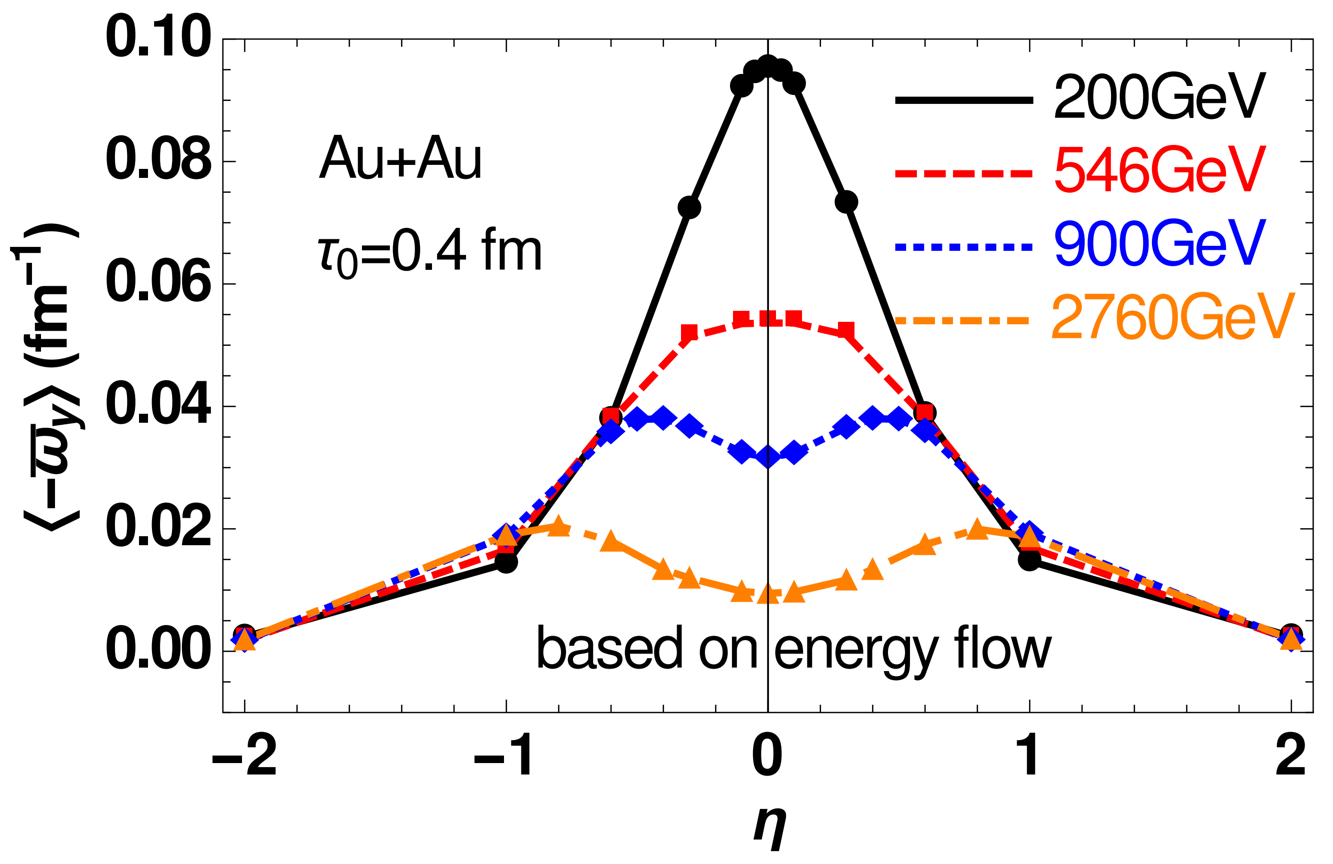
Tong Fu, Sep. 23 (Tue)

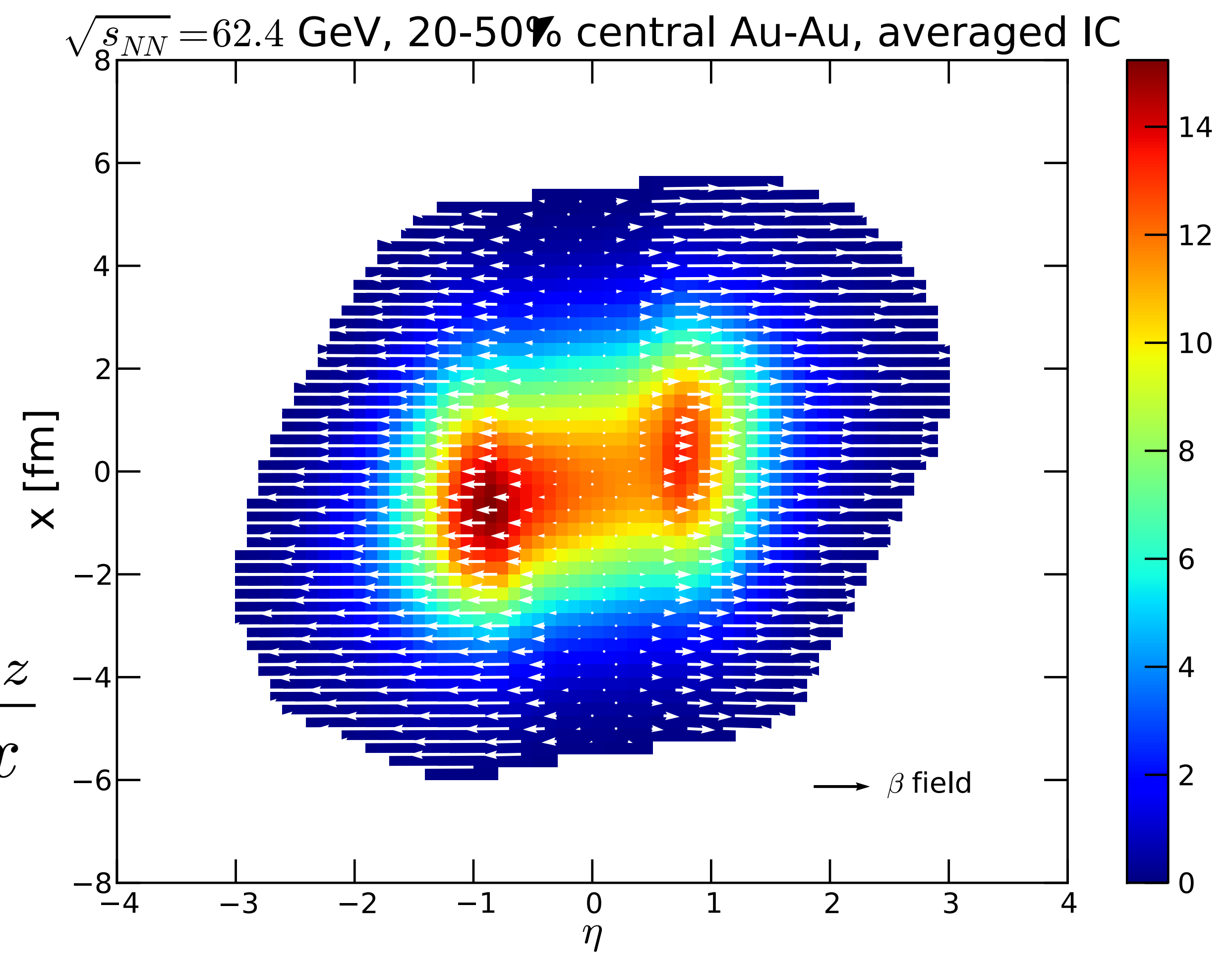
Finite polarization at the LHC

Prottay Das, Sep. 23 (Tue)

W.T.Feng and X.G.Huang, PRC93.064907 (2016)

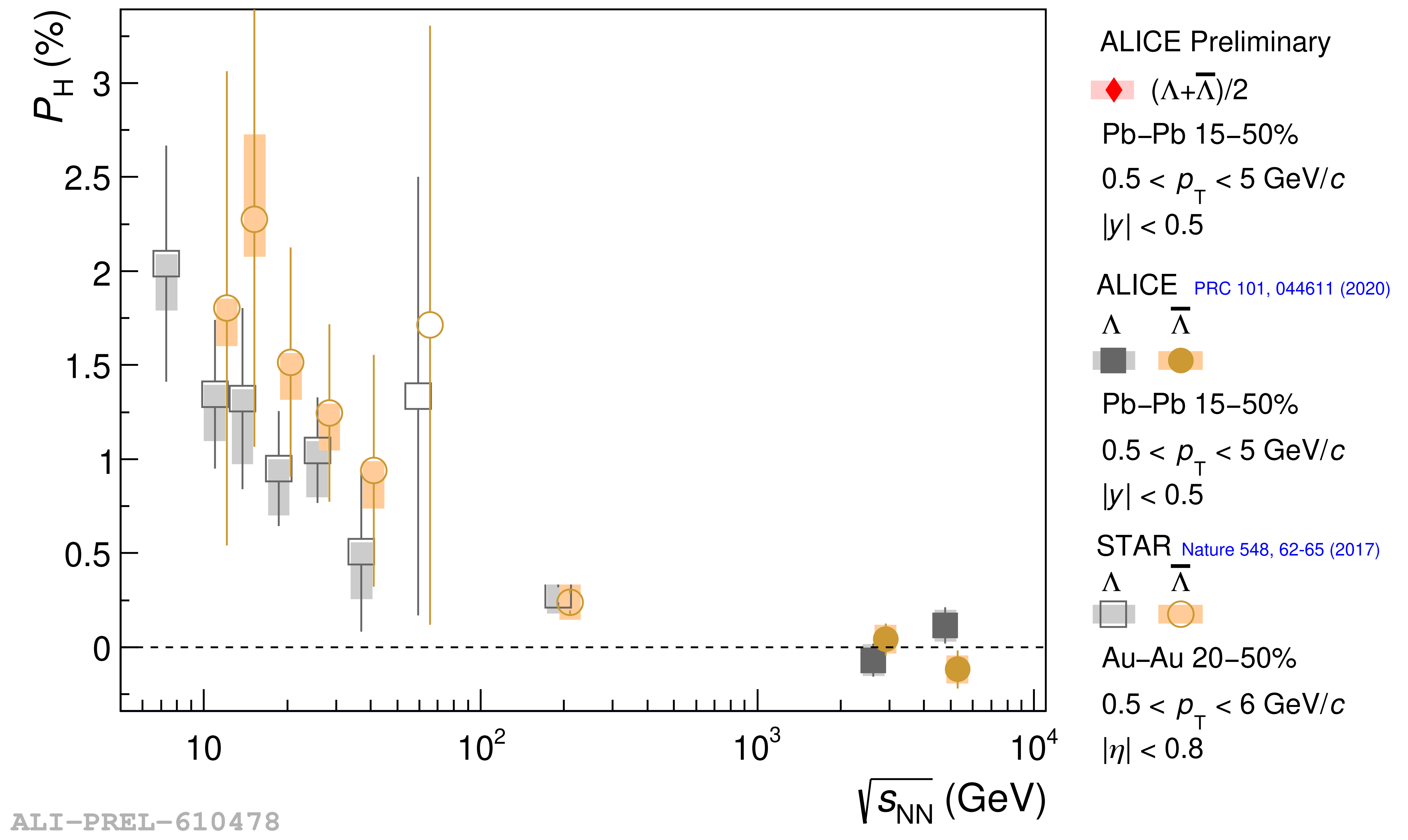


I.Karpenko and F.Becattini, EPJ(2017)77.213



$$\omega_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

ALICE, IS2025



- Shear flow gets smaller at mid-rapidity at higher energy, due to baryon transparency →Partly explain the energy dependence of P_H
- Empirical estimate with directed flow: P_H^{LHC} ~0.05-0.1%

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

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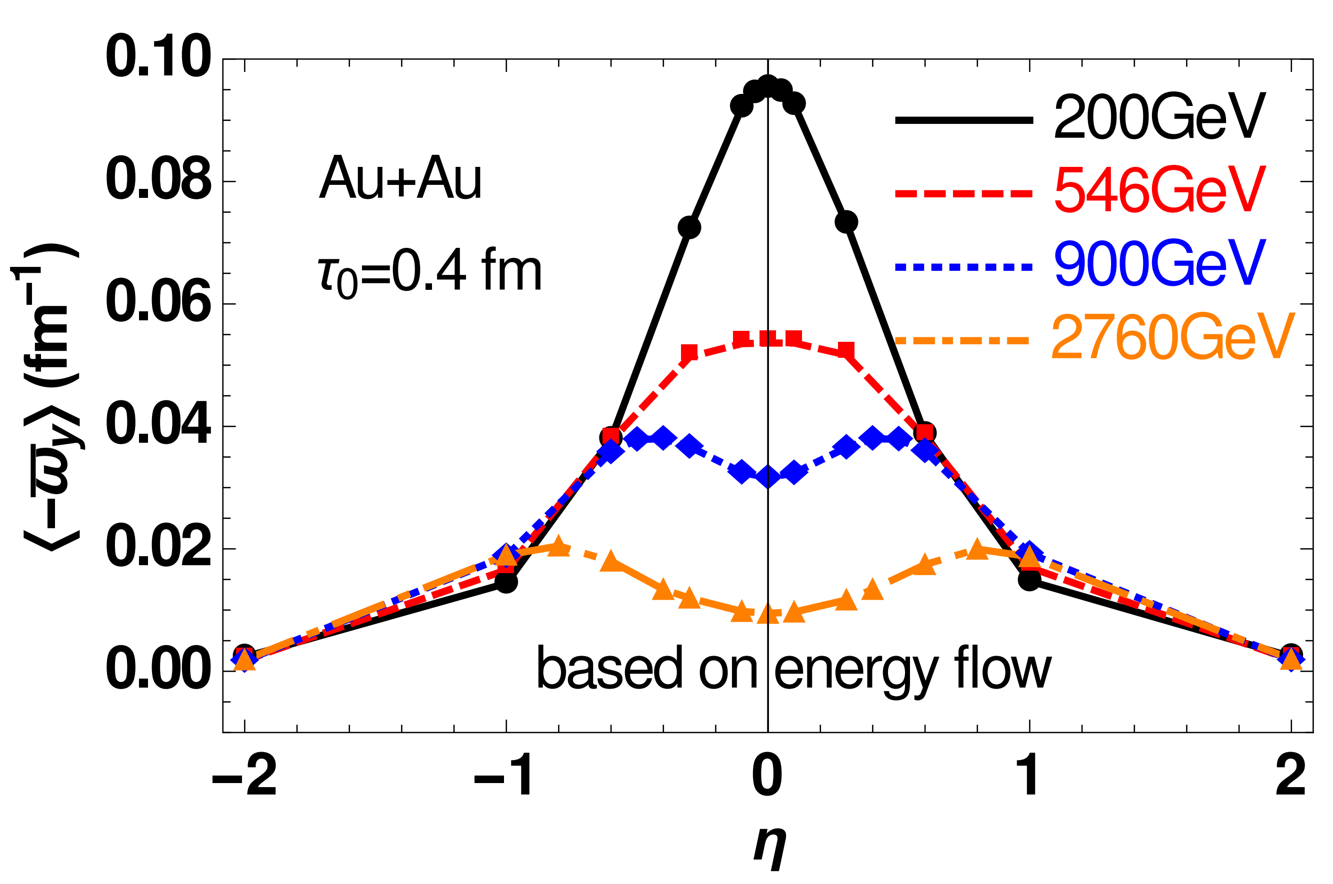

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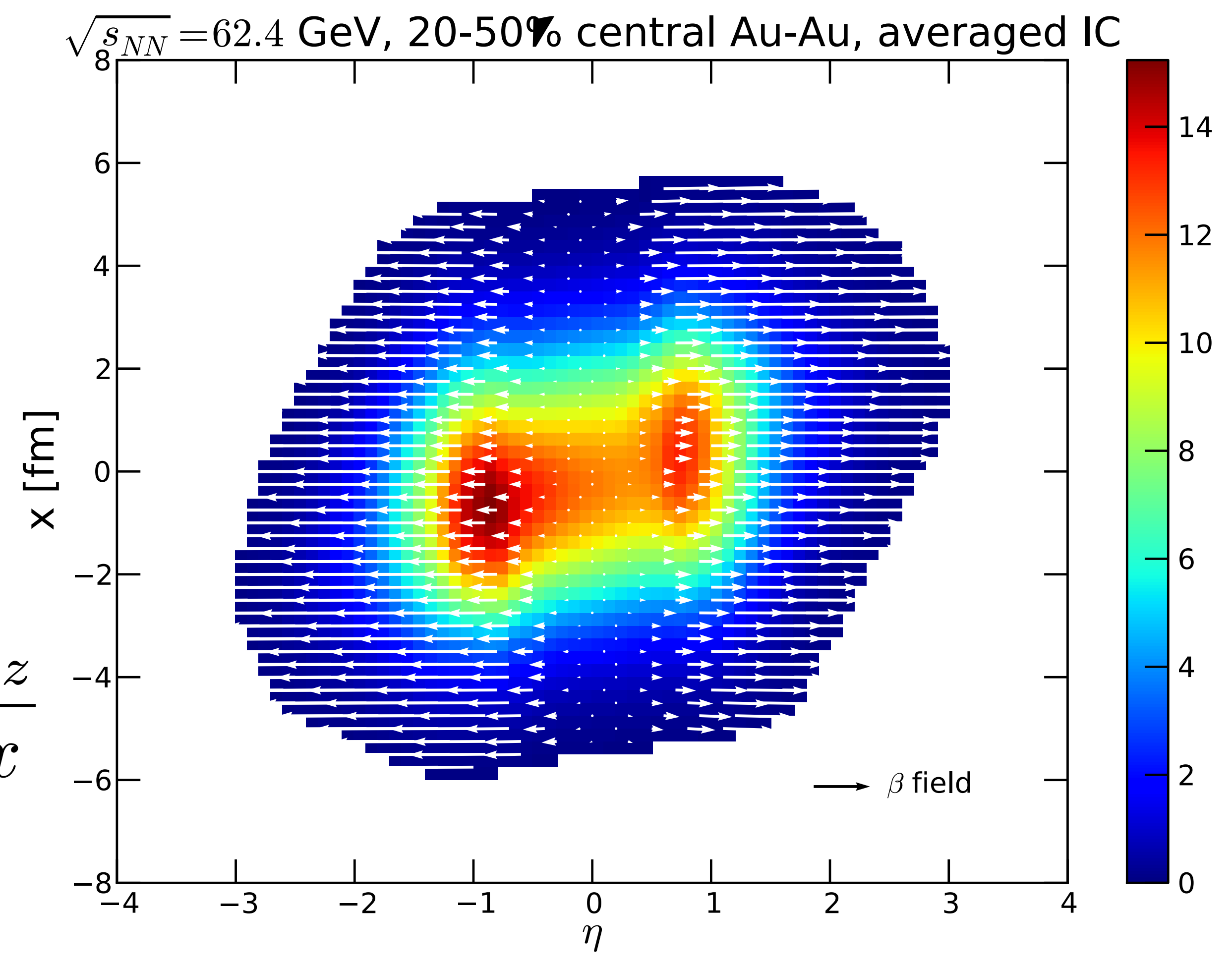

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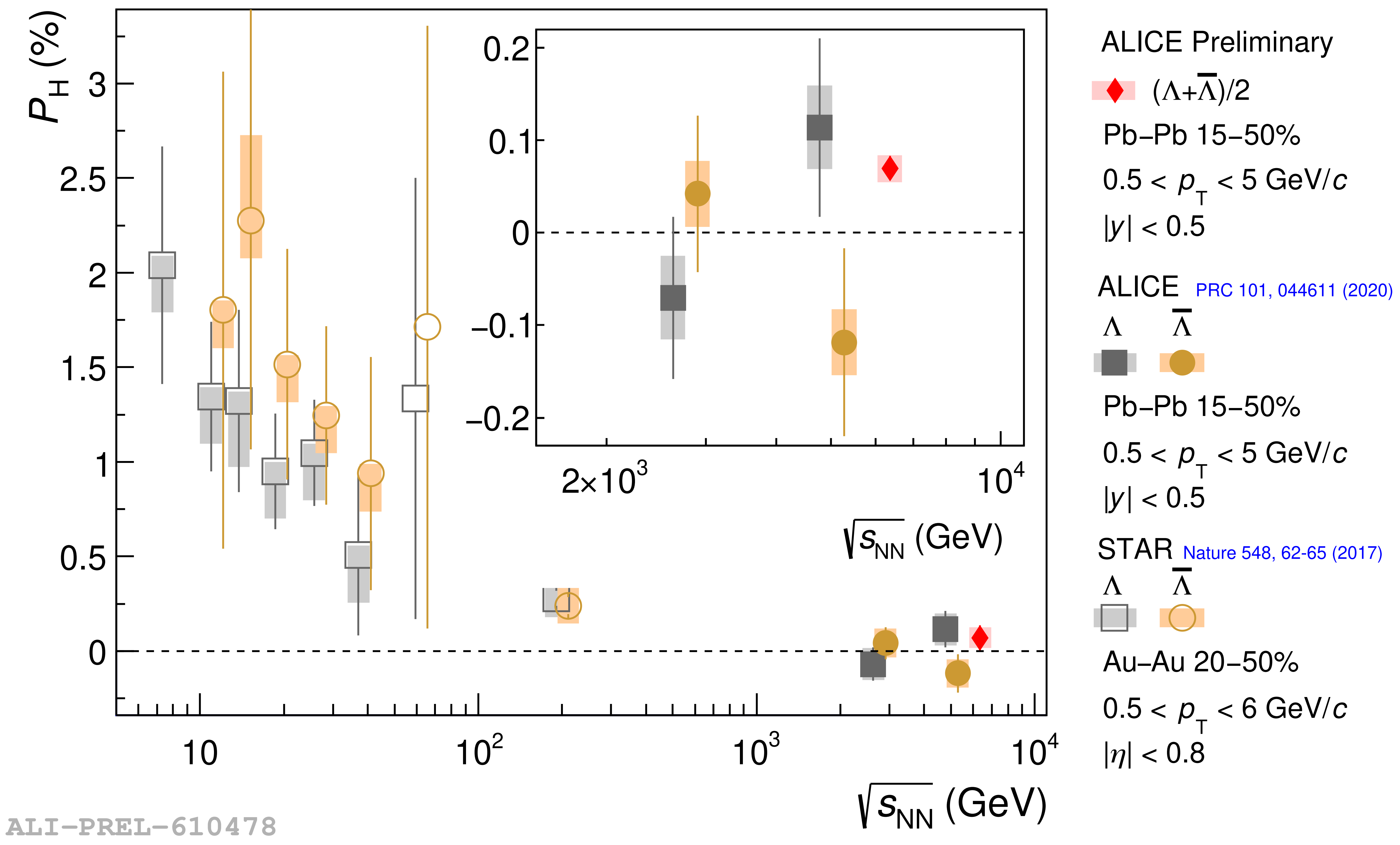

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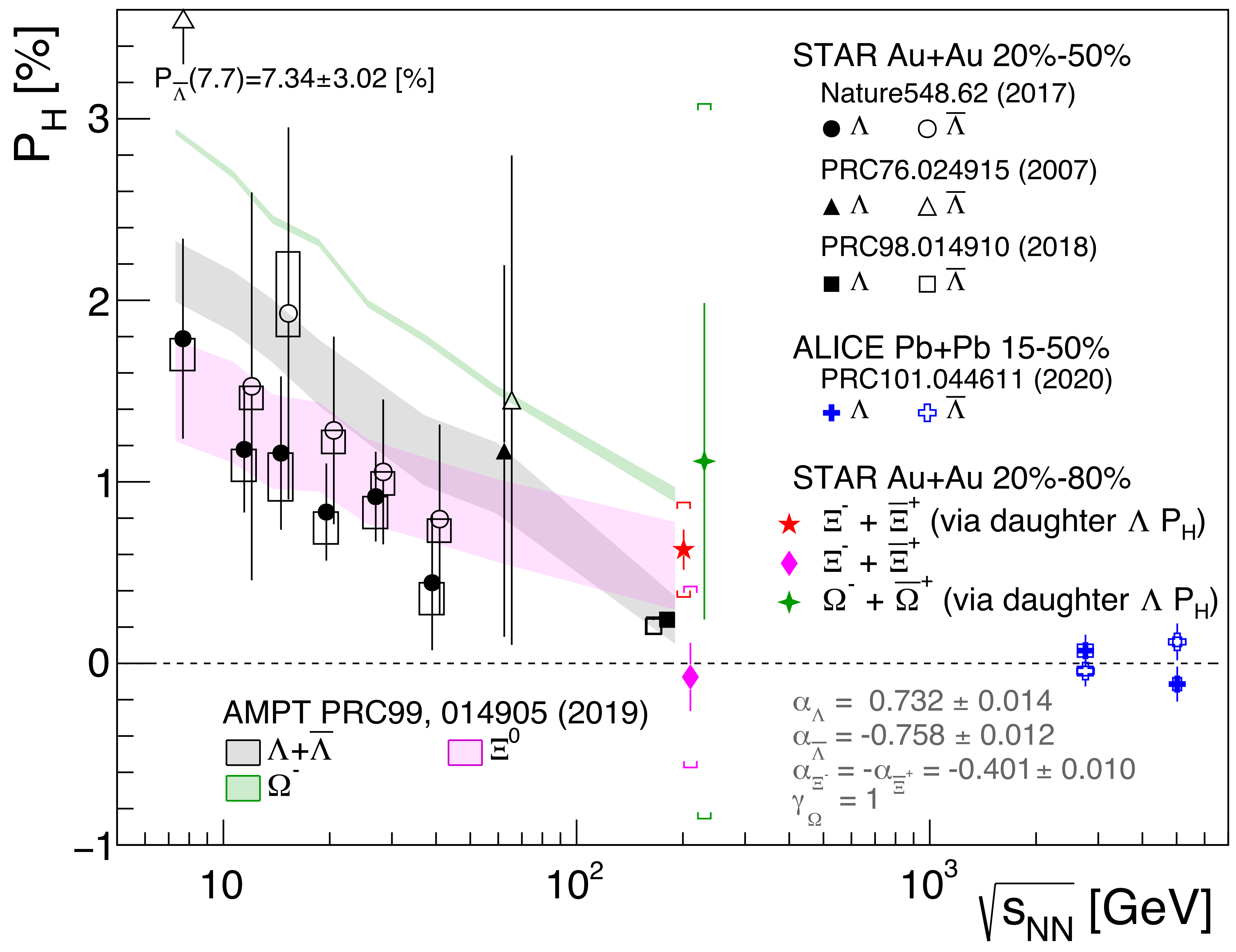
New ALICE measurement shows P_Λ ~ 0.07% with 5σ significance

Global polarization of multi-strangeness

- Thermal model predicts: $P_{\Xi} = P_{\Lambda},\ P_{\Omega} = \dfrac{5}{3} P_{\Lambda}$

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

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



STAR, PRL126, 162301 (2021)

- Hint of hierarchy in P_H but not significant yet

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

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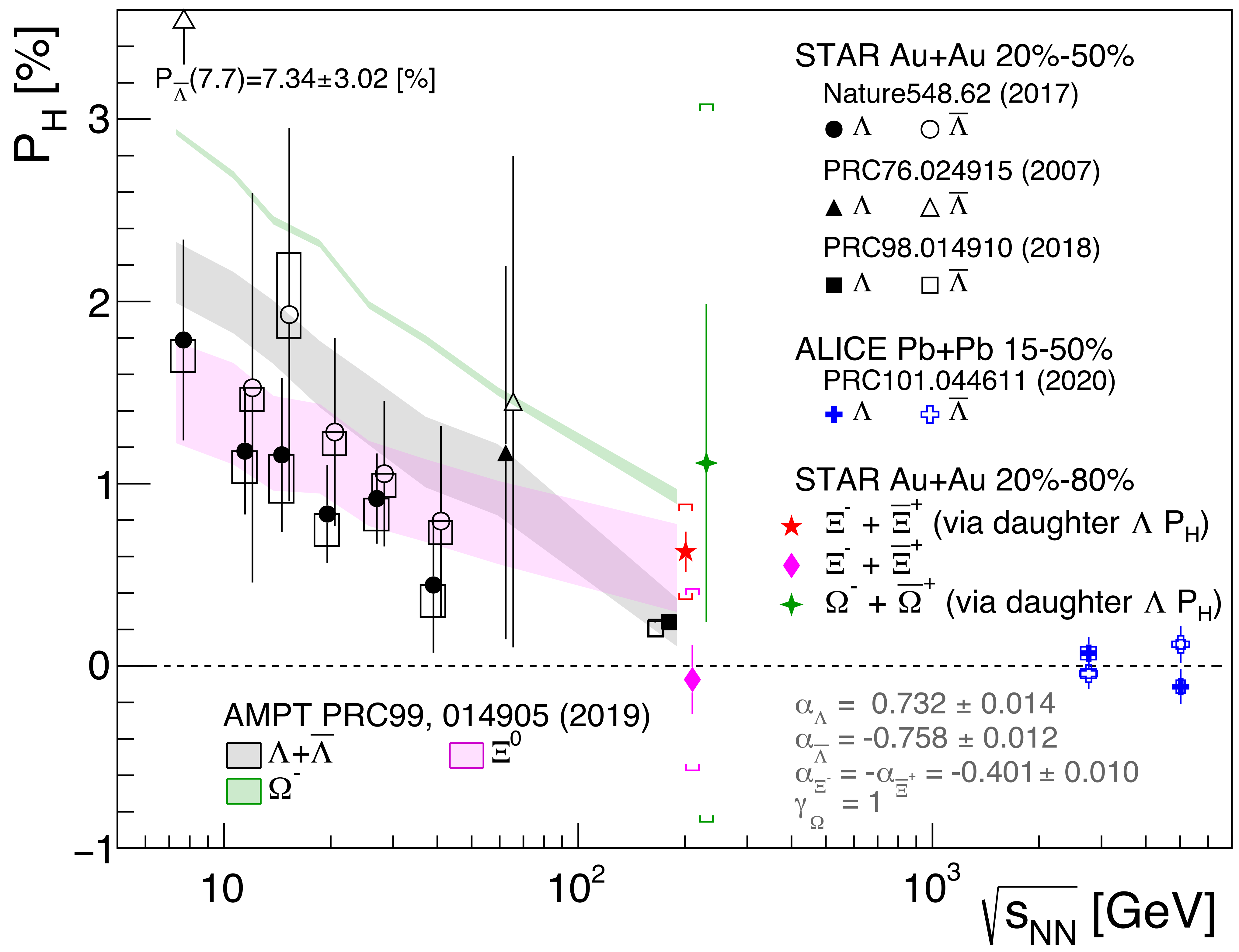

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$$\langle P_\Xi \rangle = 0.47 \pm 0.10\ (\mathrm{stat}) \pm 0.23\ (\mathrm{syst})\ \%$$
$$\langle P_\Omega \rangle = 1.11 \pm 0.87\ (\mathrm{stat}) \pm 1.97\ (\mathrm{syst})\ \%$$

- Feed-down effect can explain the hierarchy
  - 10-15% reduction of primary P_Λ
  - ~25% increase of primary P_Ξ

F. Becattini et al., PRC95.054902(2017)
H. Li et al., PLB827(2022)136971

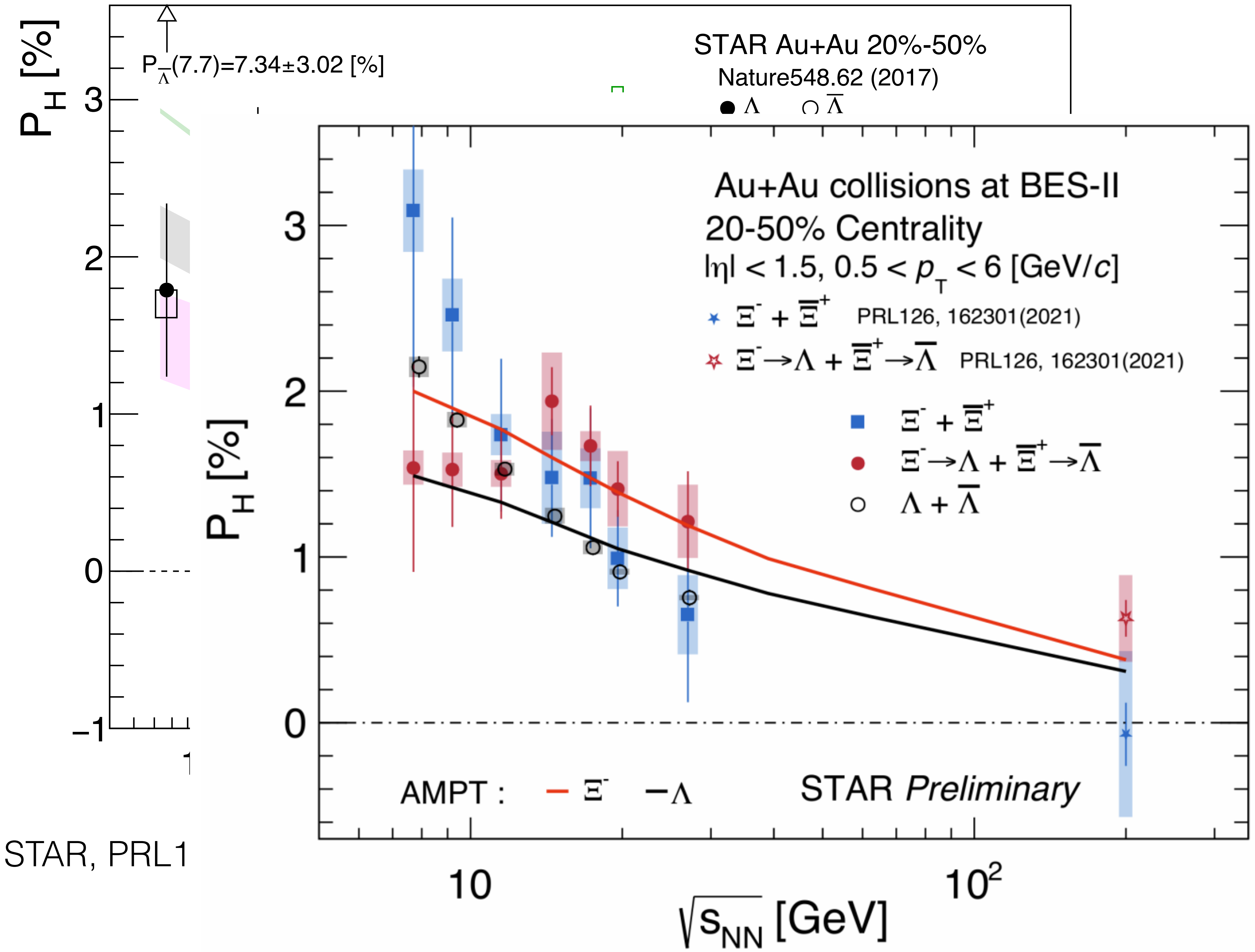
Confirmation of global vorticity picture!

New results from STAR BES-II program

- Thermal model predicts: $P_\Xi = P_\Lambda,\ P_\Omega = \frac{5}{3}P_\Lambda$

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

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



- Hint of hierarchy in P_H but not significant yet

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

- Feed-down effect can explain $P_\Xi > P_\Lambda$
  - 10-15% reduction of primary P_Λ
  - ~25% increase of primary P_Ξ

F. Becattini et al., PRC95.054902(2017)
H. Li et al., PLB827(2022)136971

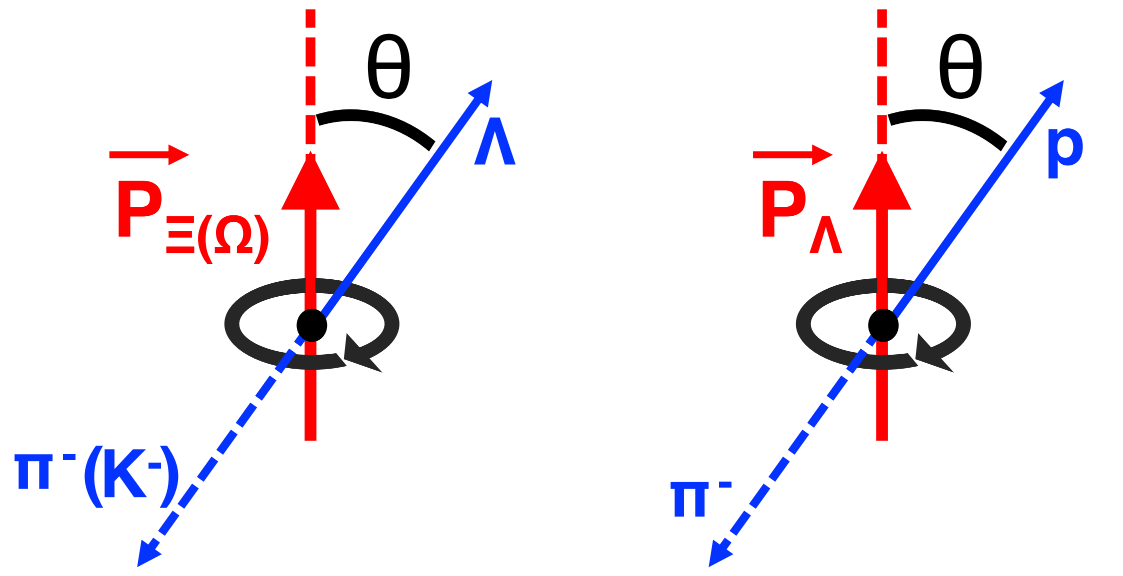
Better significance of P_Ξ (~5σ) from STAR BES-II

$$P_\Xi(\%) = 1.94 \pm 0.21 \pm 0.29\ (14.6\ \mathrm{GeV})$$

Tong Fu, Sep. 23 (Tue)

Ω global polarization / unknown γ_Ω

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



T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)
* Values below based on PDG2020

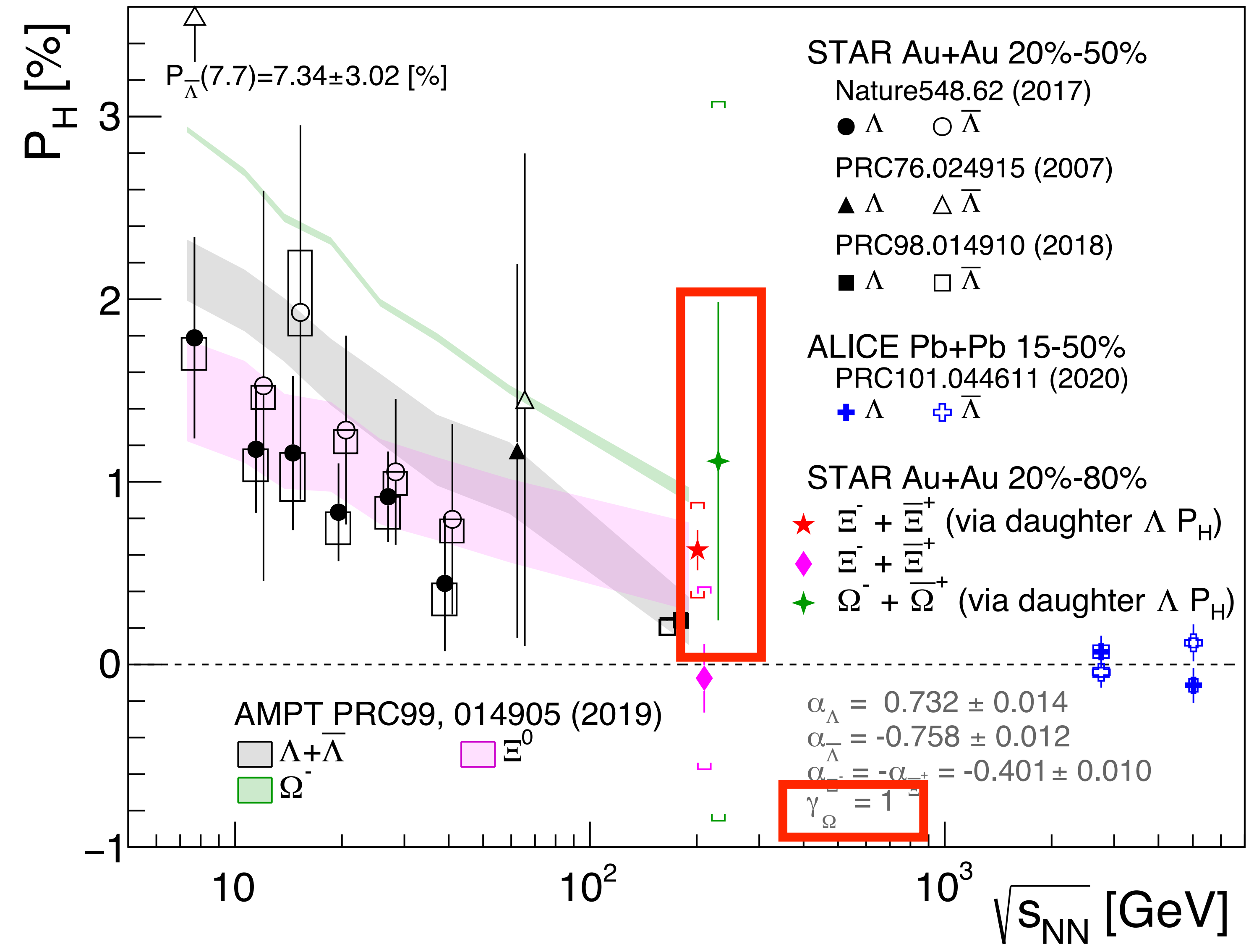
Ω^- (spin 3/2)

$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda}\mathbf{P}_\Omega^* = \tfrac{1}{5}\left(1 + 4\gamma_\Omega\right)\mathbf{P}_\Omega^*. \qquad \alpha^2 + \beta^2 + \gamma^2 = 1$$

＊γ_Ω is unknown, but α_Ω, $\beta_\Omega \ll 1$ → $\gamma_\Omega \sim \pm 1$

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

STAR, PRL126, 162301 (2021)



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

Based on global vorticity picture (P_Ω>0), positive γ_Ω is favored

Ω global polarization / unknown γ_Ω

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

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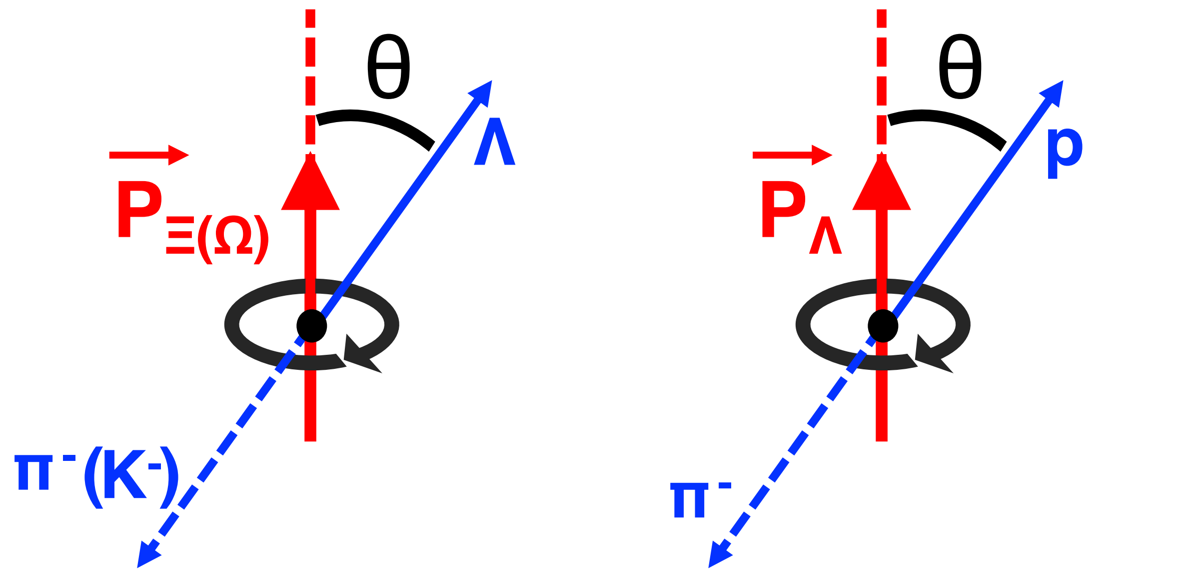

Ω^- (spin 3/2)

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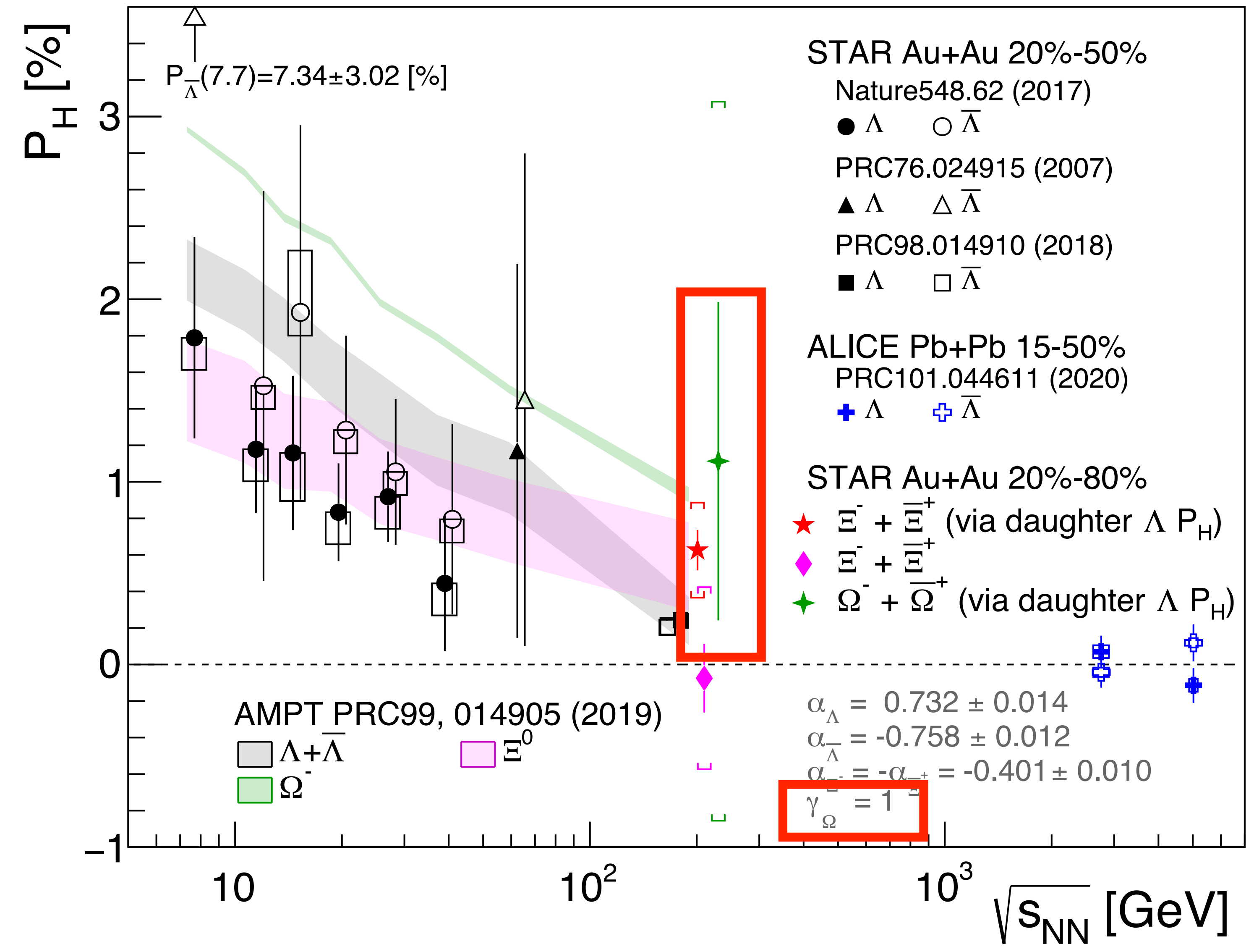
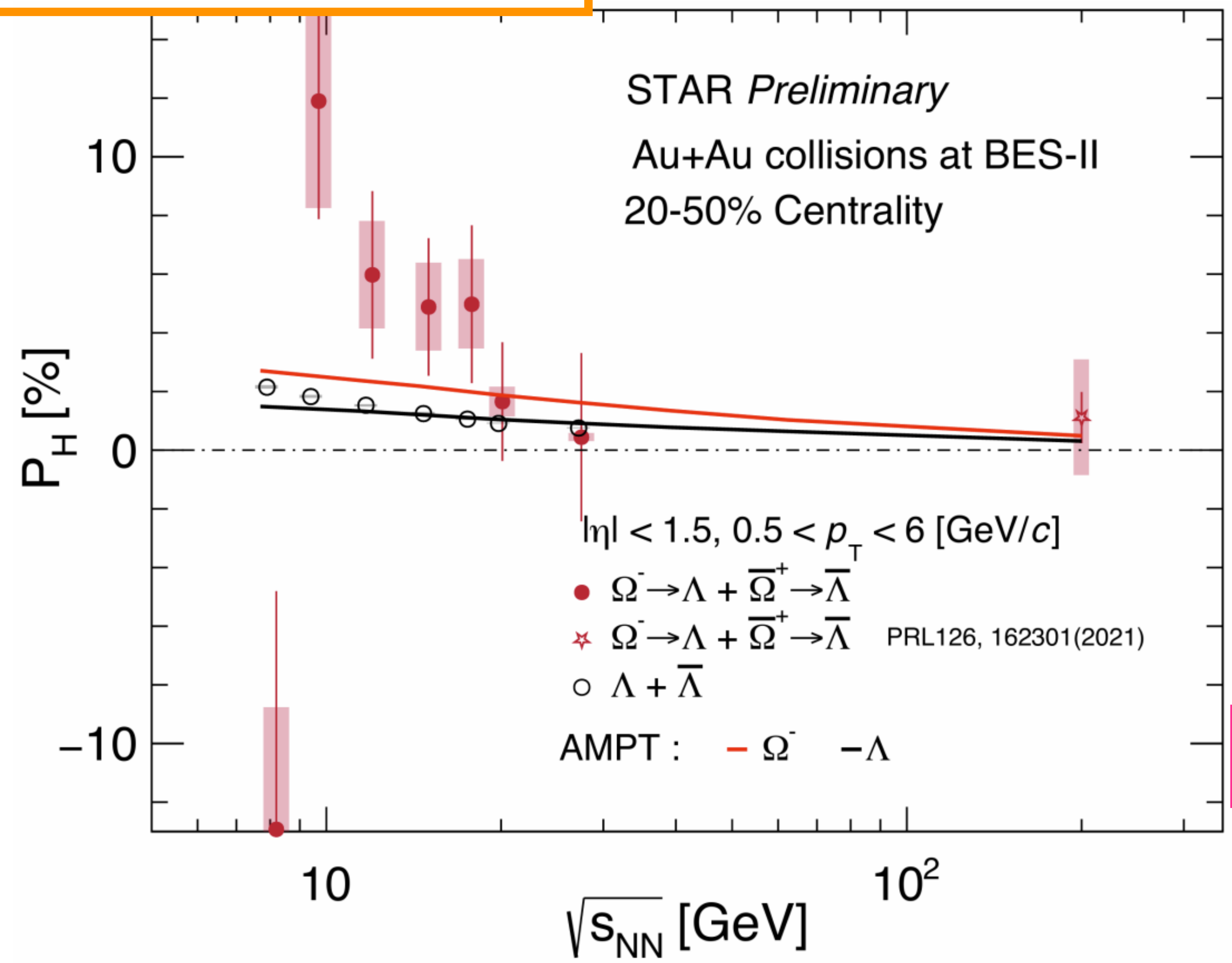
STAR, PRL126, 162301 (2021)



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

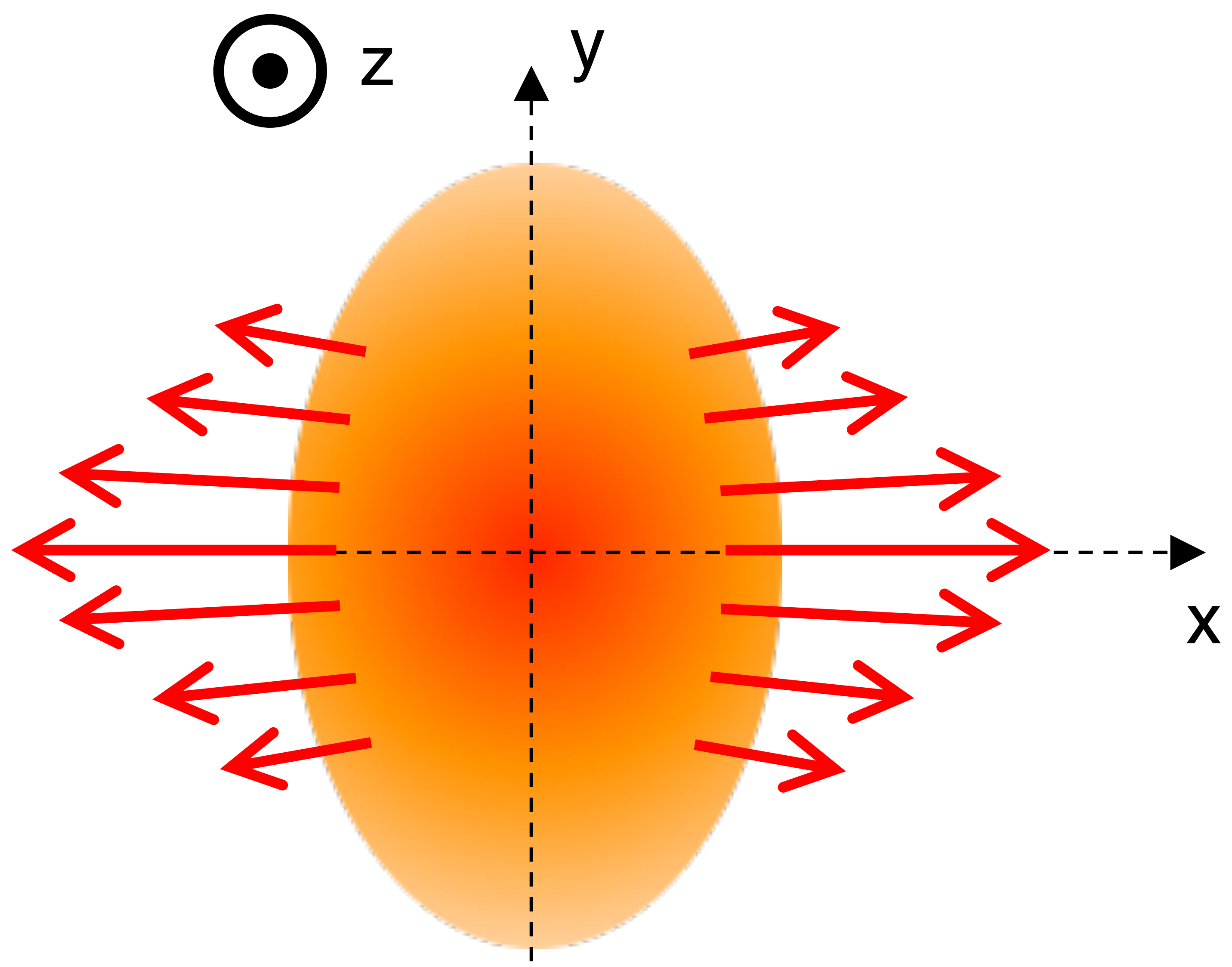
Update from STAR BES-II



Tong Fu, Sep. 23 (Tue)

Based on global vorticity picture (P_Ω>0), positive γ_Ω is favored

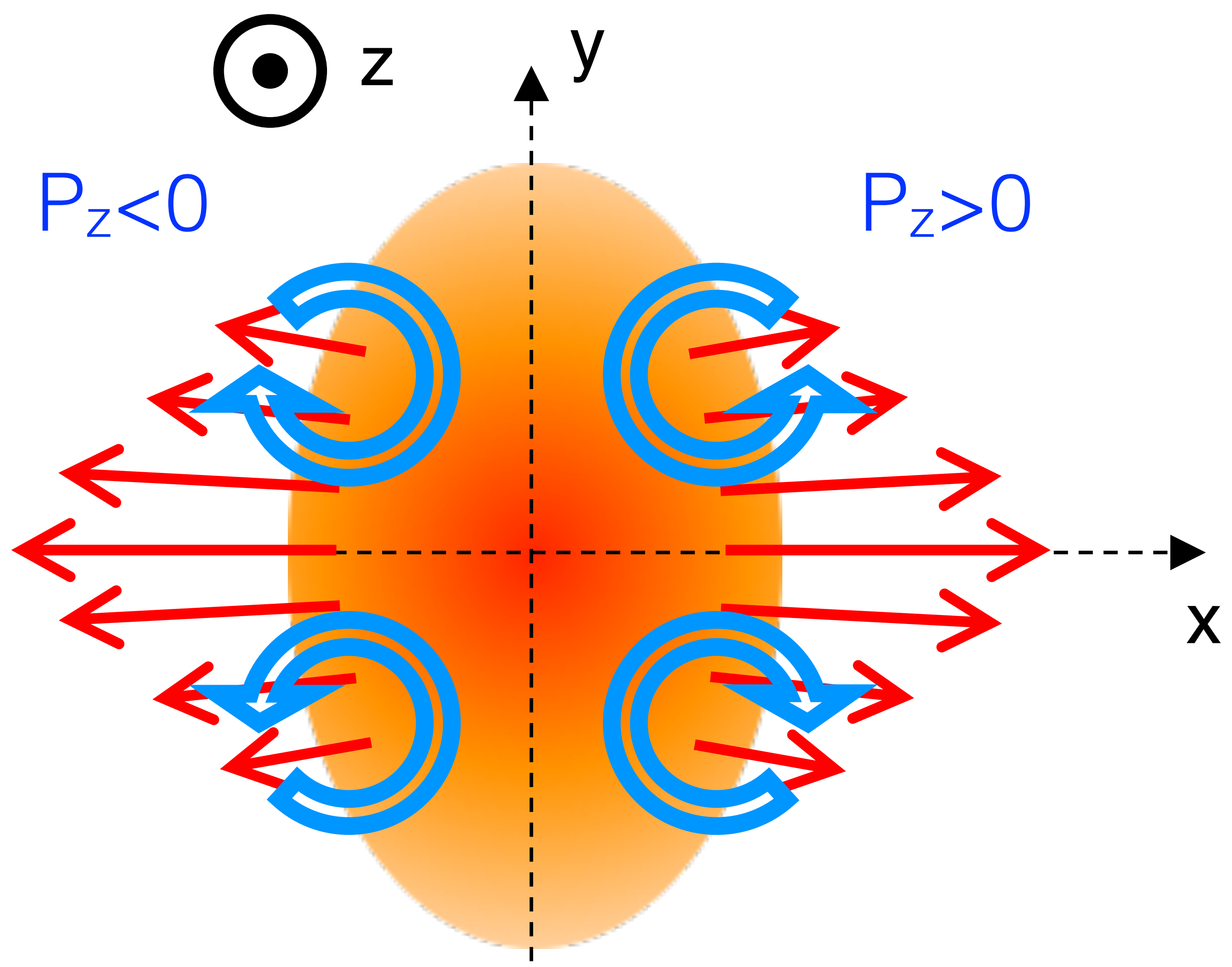
Polarization along the beam direction: P_z



- Polarization <u>along the beam direction</u> expected from the "elliptic flow"

F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

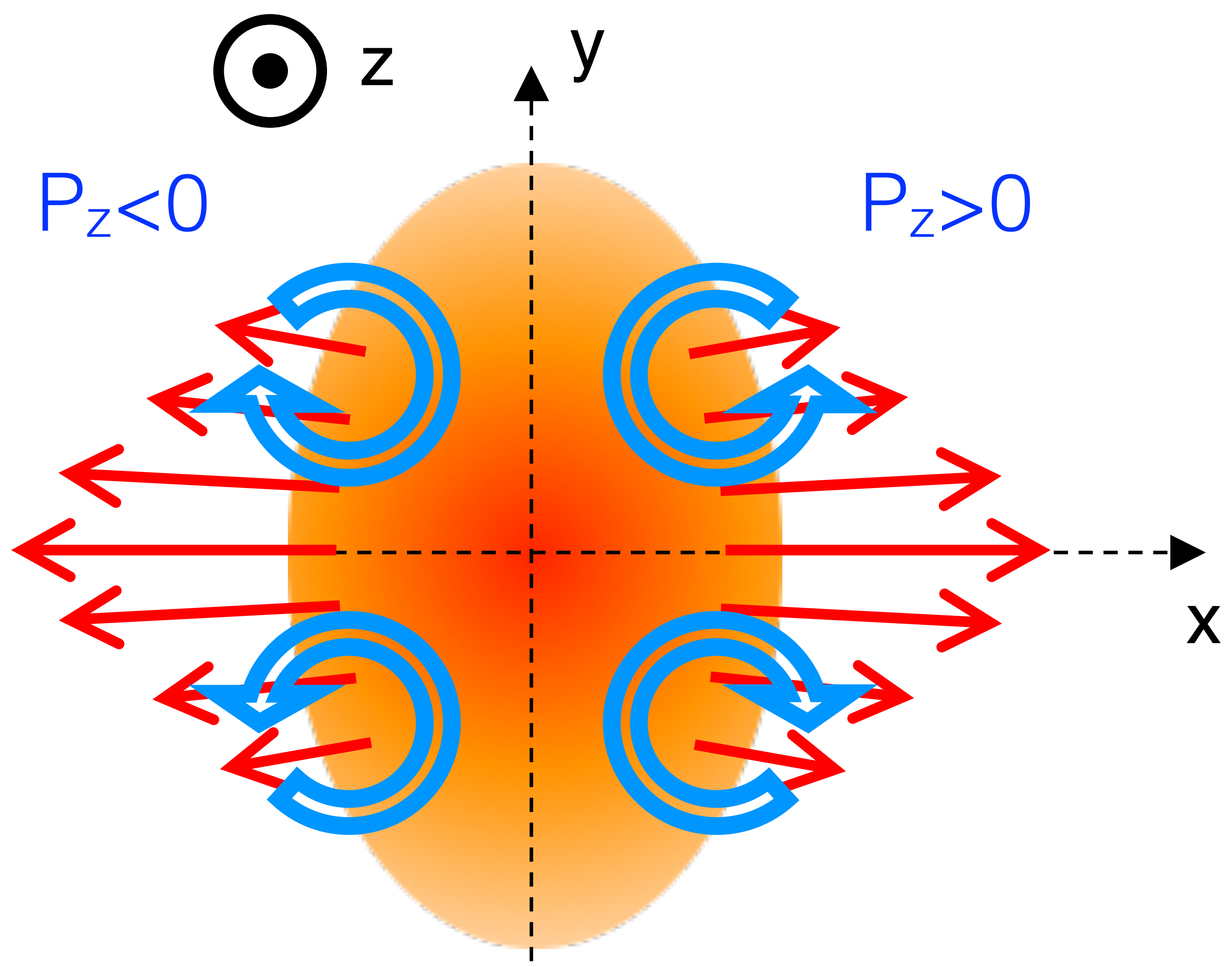
Polarization along the beam direction: P_z



- Polarization along the beam direction expected from the "elliptic flow"

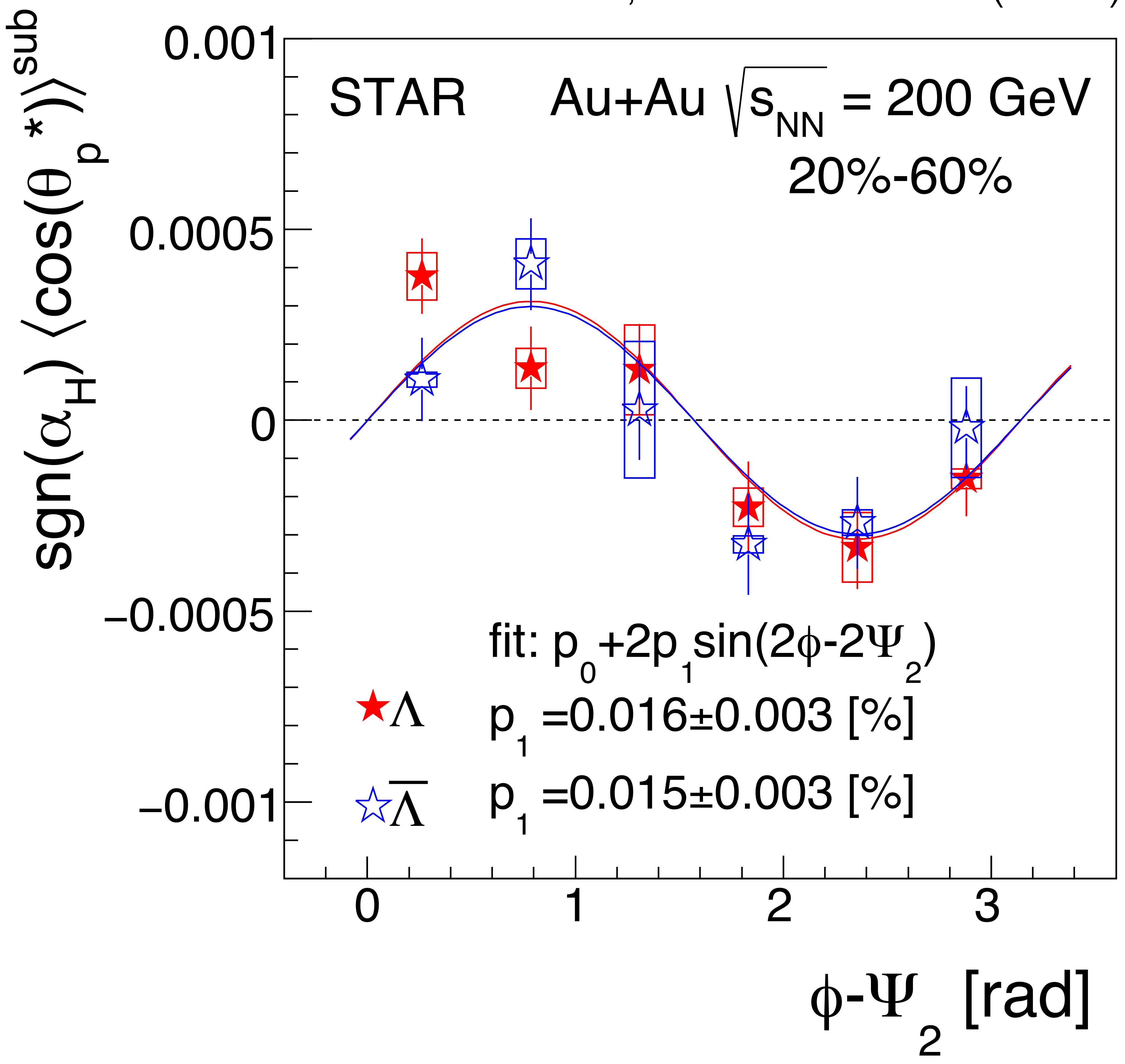
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

Polarization along the beam direction: P_z



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

STAR, PRL123.132301 (2019)



- Polarization along the beam direction expected from the "elliptic flow"

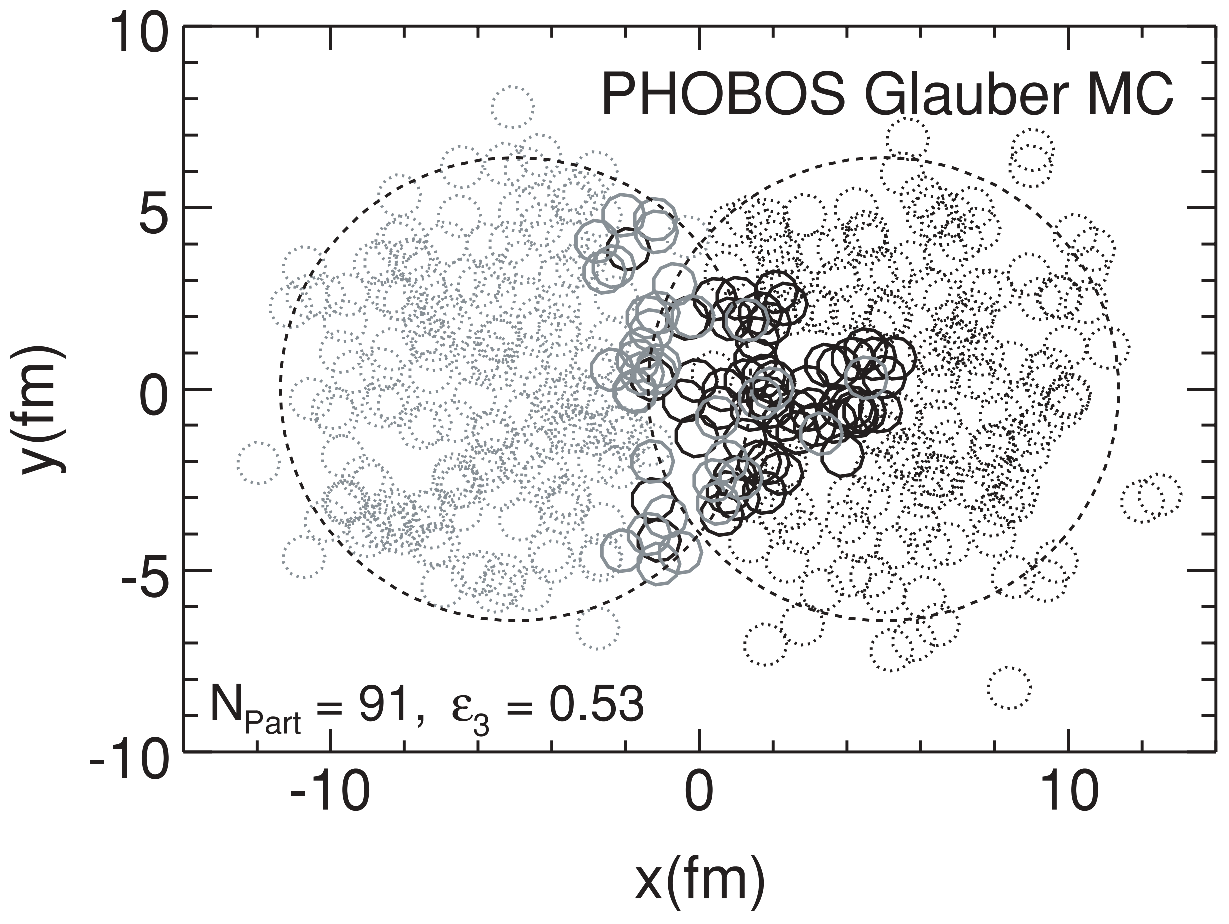
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

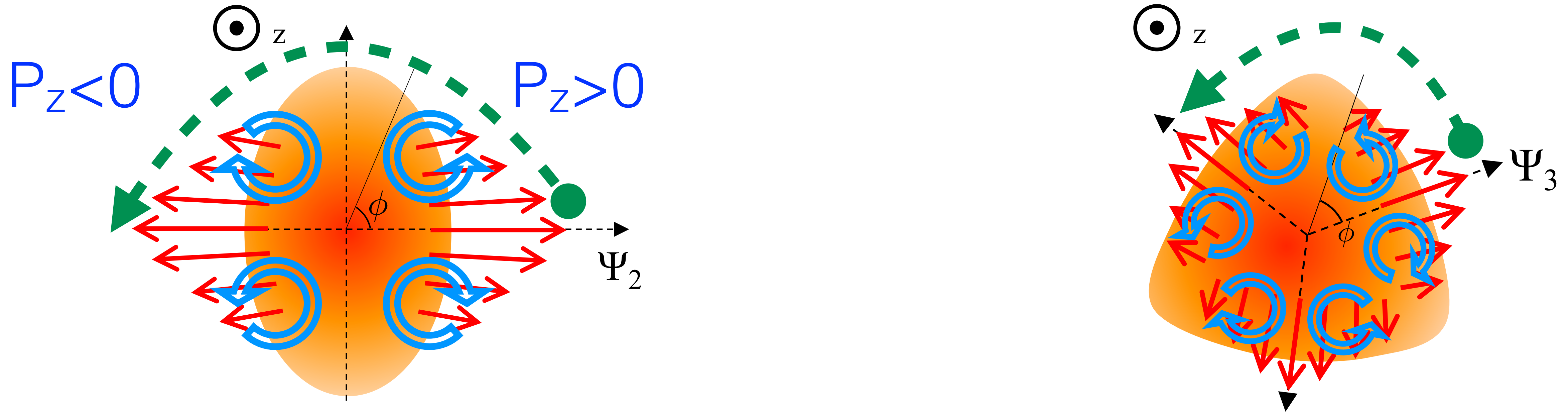
- Data indeed show a quadrupole (sine) pattern; the sign of P_z depends on azimuthal angle

Anisotropic-flow-driven polarization!

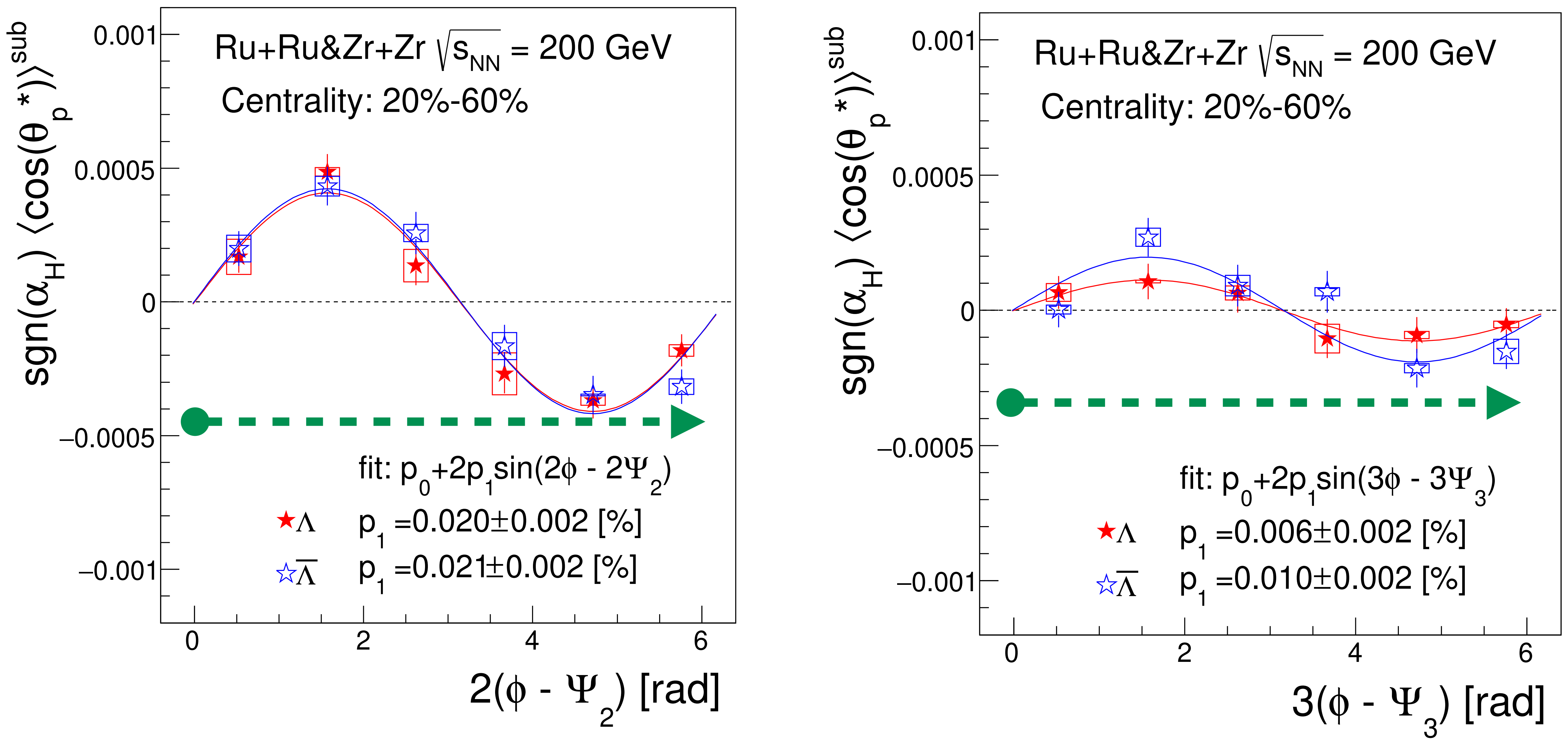
Flow-driven polarization, and vorticities

Alver and Roland, PRC81.054905(2010)





STAR, PRL131, 202301 (2023)



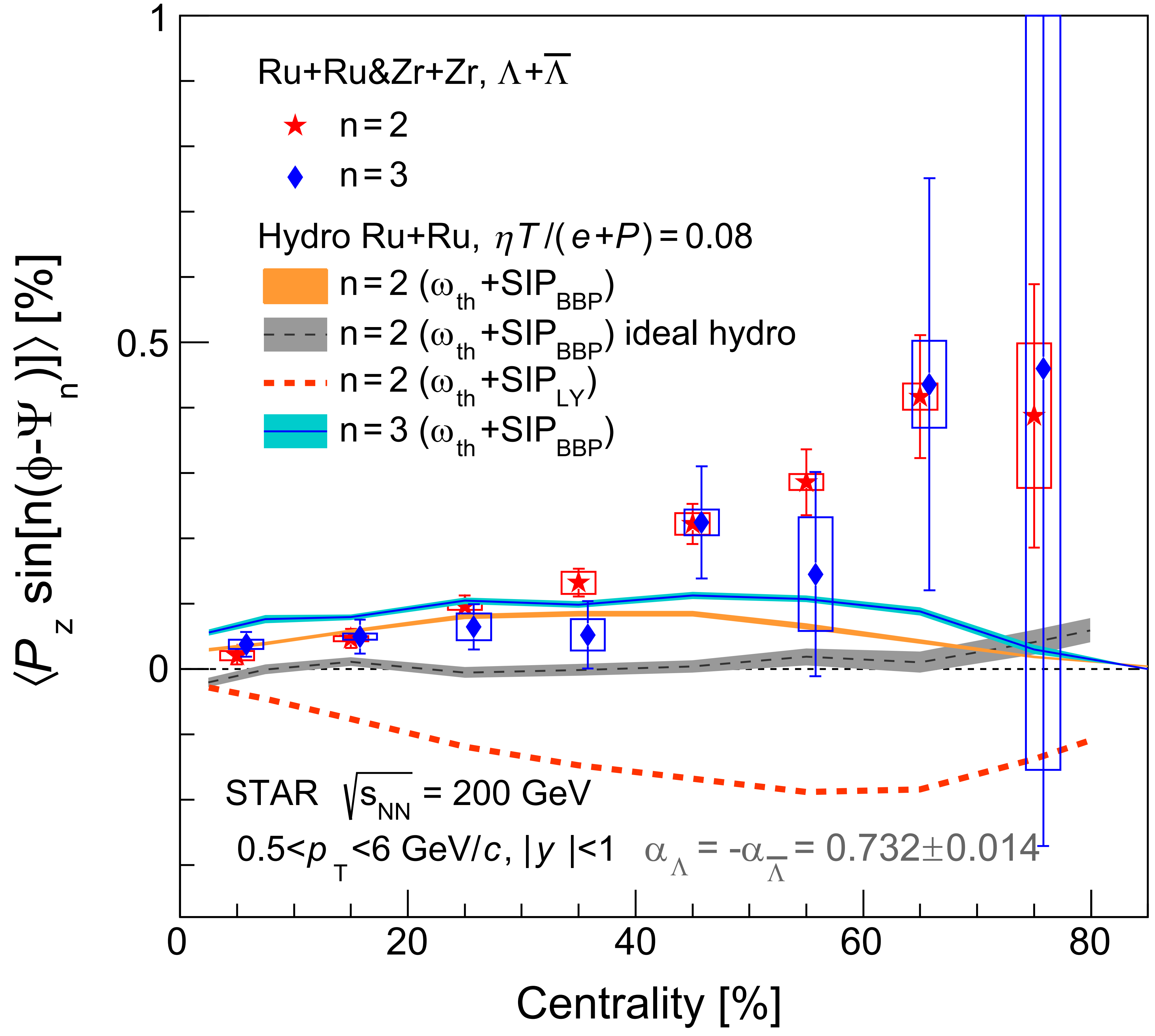
- Initial geometry → anisotropy in momentum space
- Even-by event fluctuations create a triangular shape at the initial state, leading to triangular flow (v_3)

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

- Triangular-flow-driven polarization observed!
  → A complex vortex pattern created in heavy-ion collisions

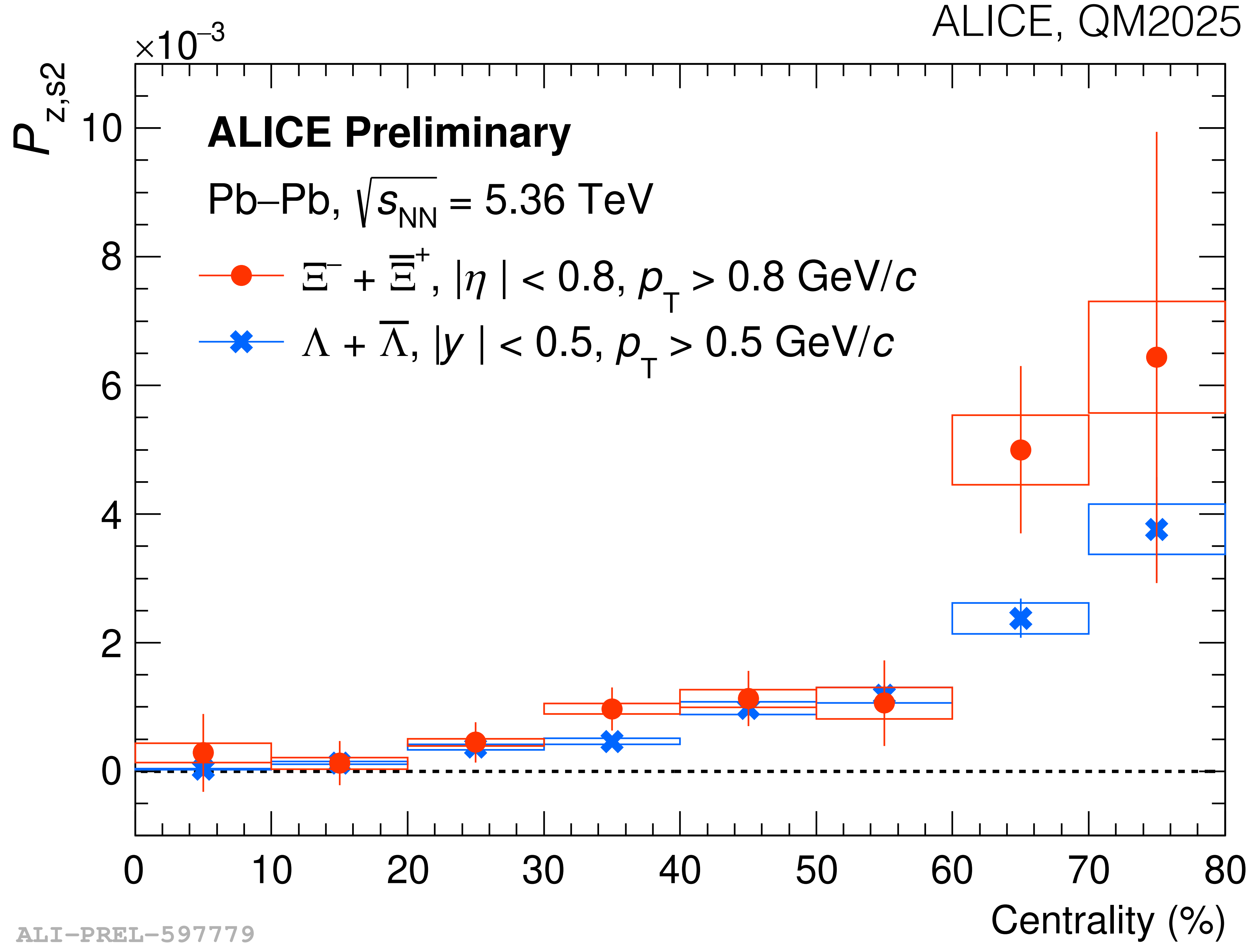
P_z sine modulation

STAR, PRL131, 202301 (2023)



Prottay Das, Sep. 23 (Tue)

ALICE, QM2025

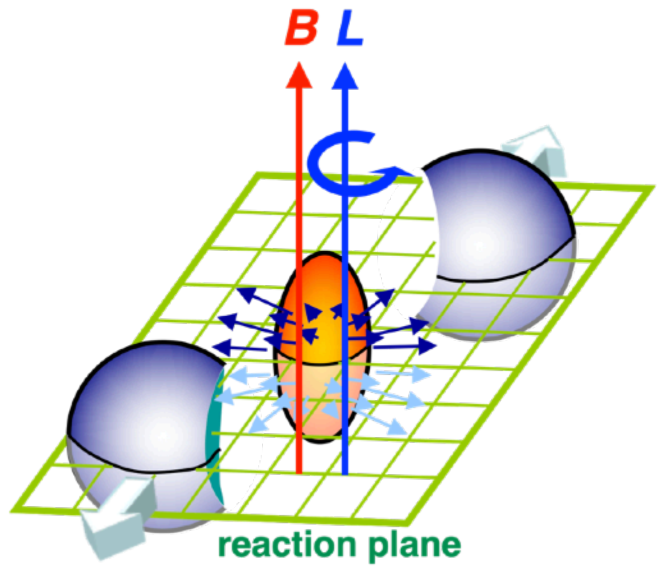


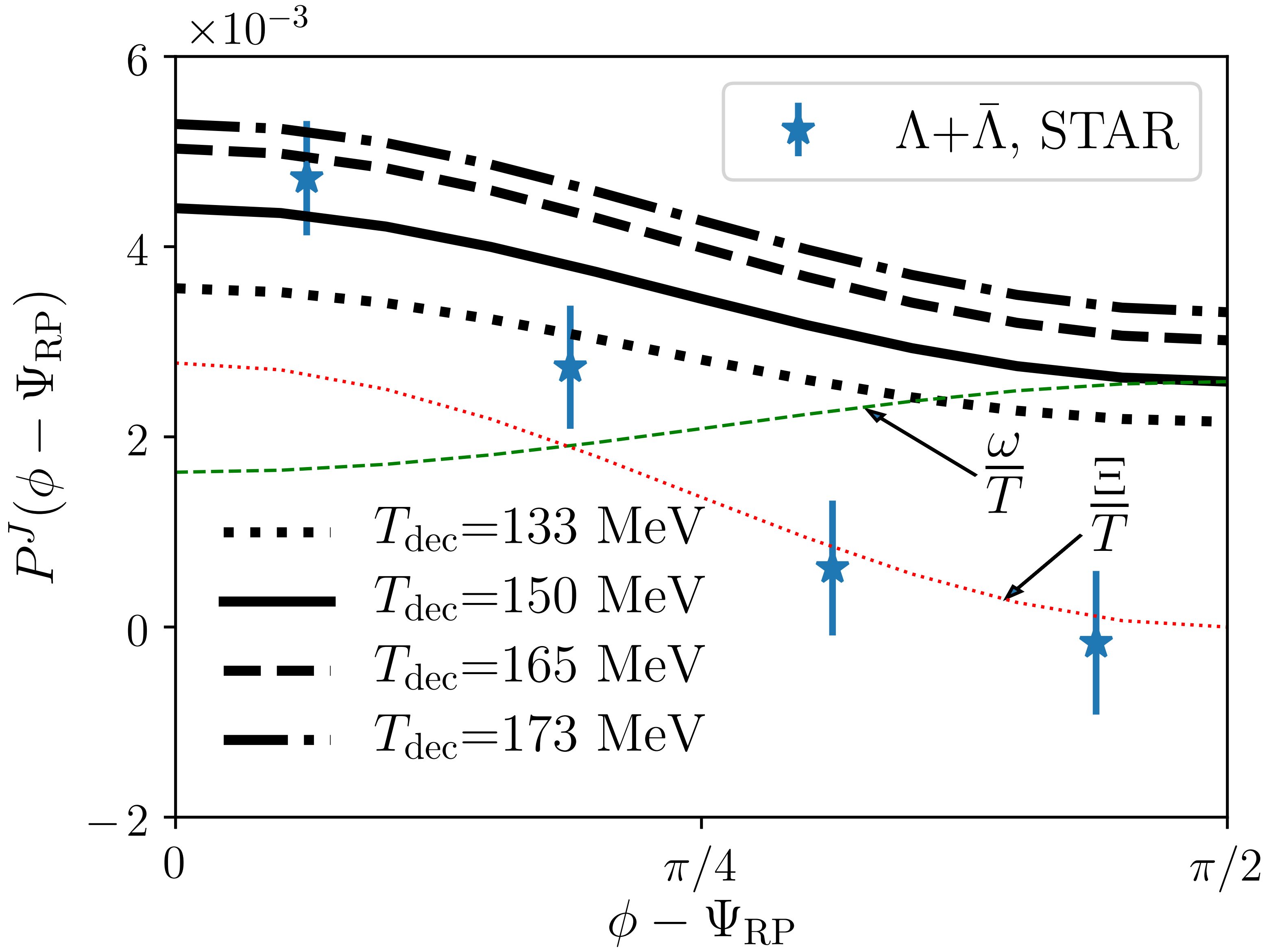
- Sensitive to specific shear and bulk viscosities of the medium, and the initial conditions in HIC
- First measurement of P_z for Ξ from ALICE

Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
S. Alzharani et al., PRC106.014905 (2022)
A. Palermo et al., EPJC84.920 (2024)

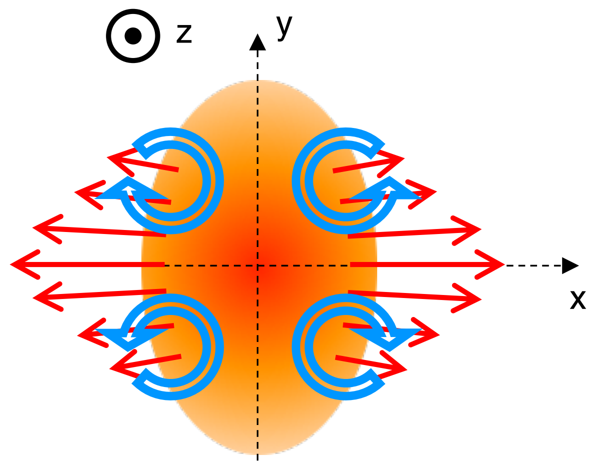
Spin sign puzzle

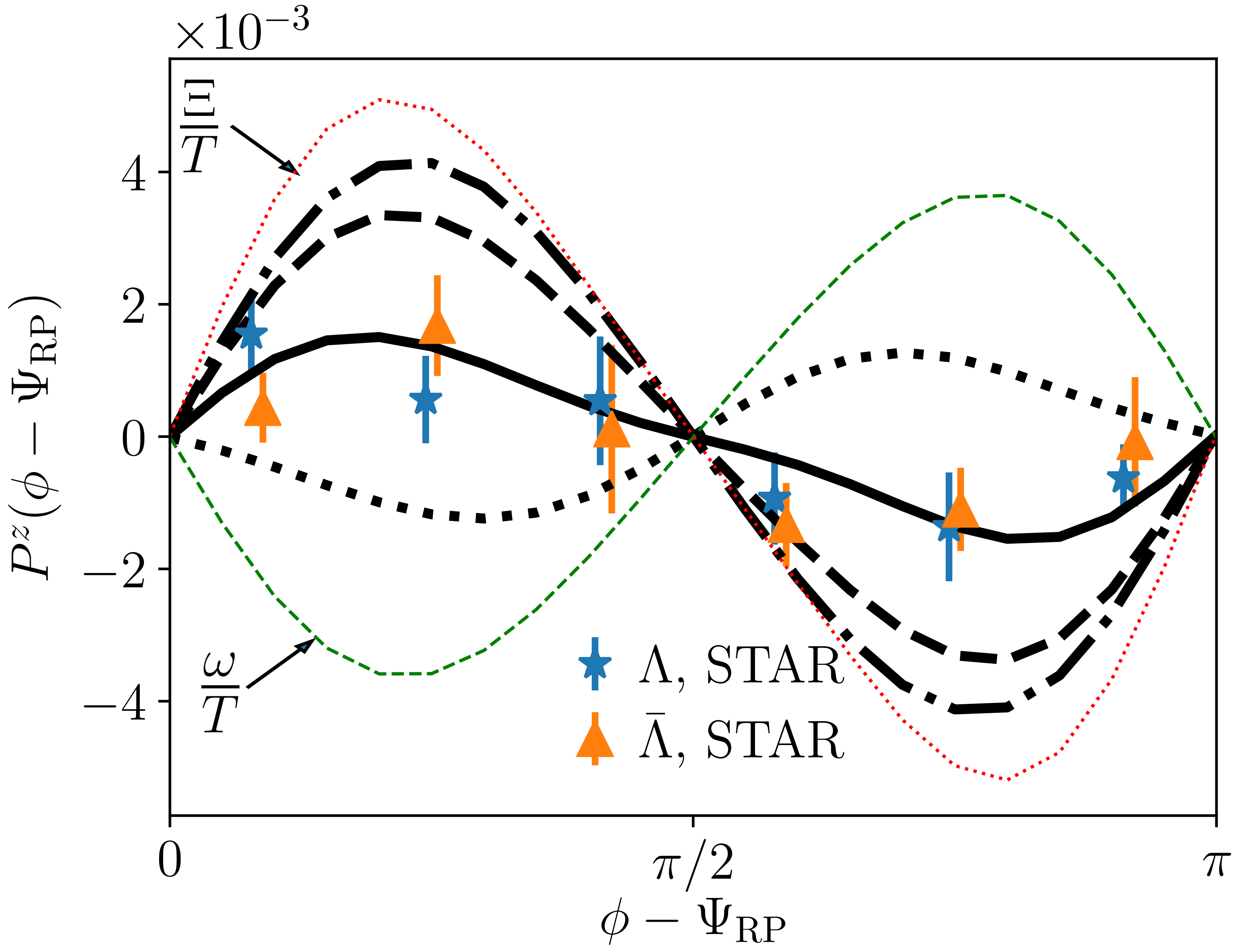
P_{J}=$P_{\text{-y}}$





P_z





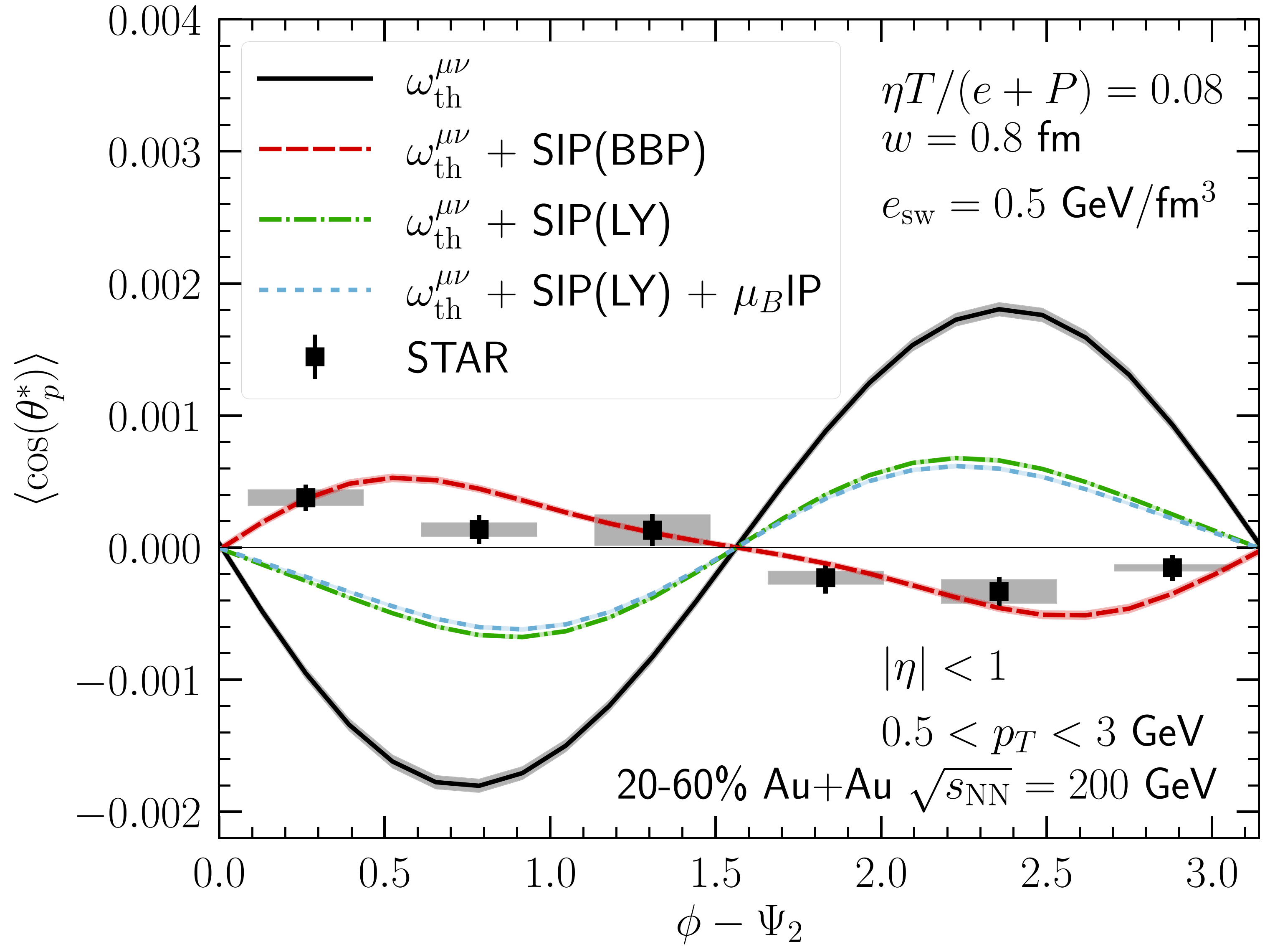
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

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

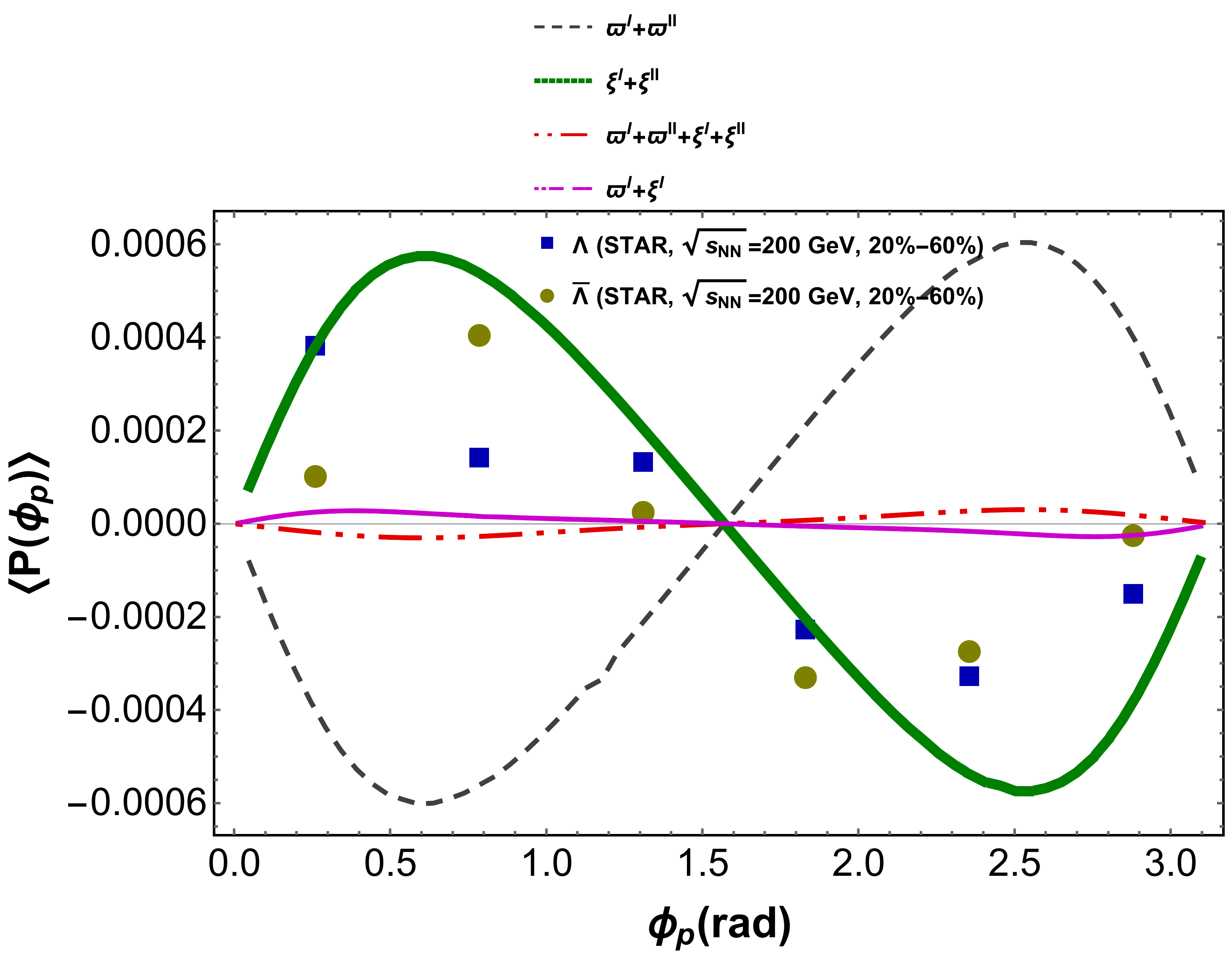
S. Liu, Y. Yin, JHEP07(2021)188
B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PLB820(2021)136519
F. Becattini et al., PRL127, 272302 (2021)

- Thermal vorticity can explain the "global" (average) polarization but not the sign of P_z or $P_{\text{-y}}$ modulation, referred to as "spin sign puzzle" in HIC
  - Non-equilibrium effect? Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Shear-induced polarization is needed to explain the data but…

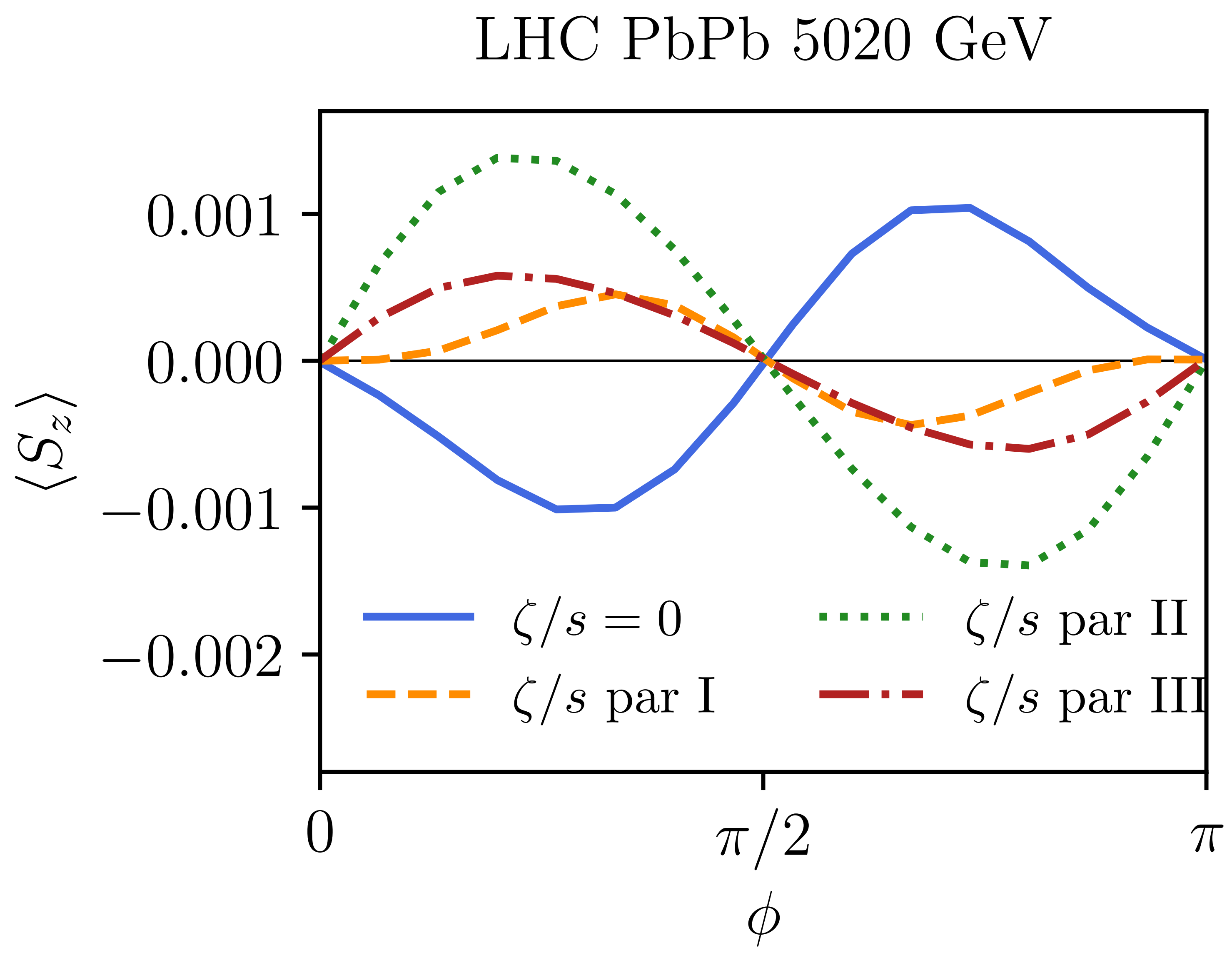
Spin sign puzzle still remains?



S. Alzharani et al., PRC106.014905 (2022)



W. Florkowski et al., PRC105, 064901 (2022)



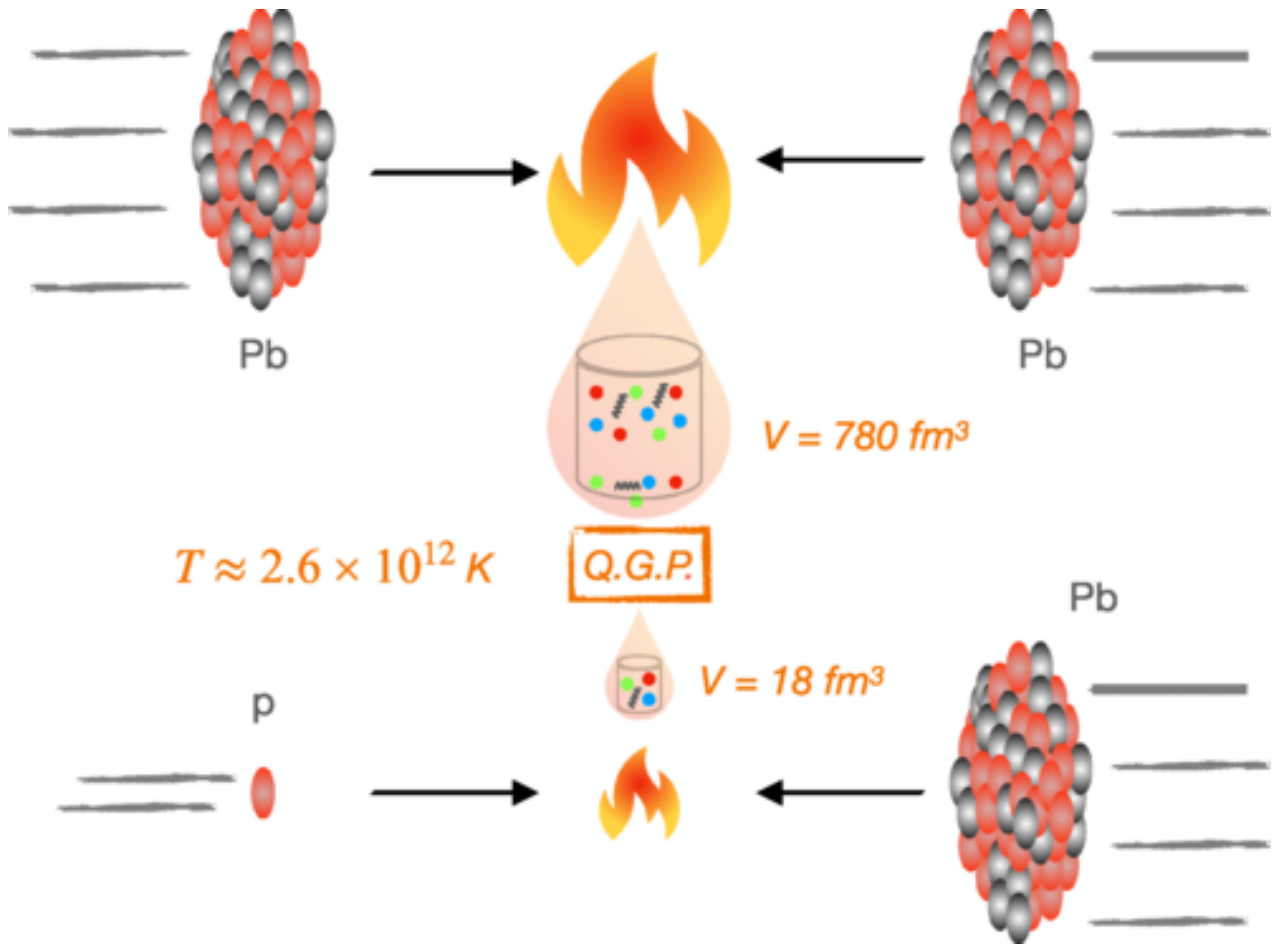
Palermo et al., EPJC84(2024)920

- The sign depends on the implementation detail of the shear induced polarization (SIP)
  - Large cancellation of thermal vorticity and SIP!
- Bulk viscosity could change the P_z sign. Large effect of longitudinal flow on $P_y(\phi)$

See similar studies, e.g.
C. Yi et al., PRC104, 064901 (2021)
Y. Sun et al., PRC105, 034911 (2022)

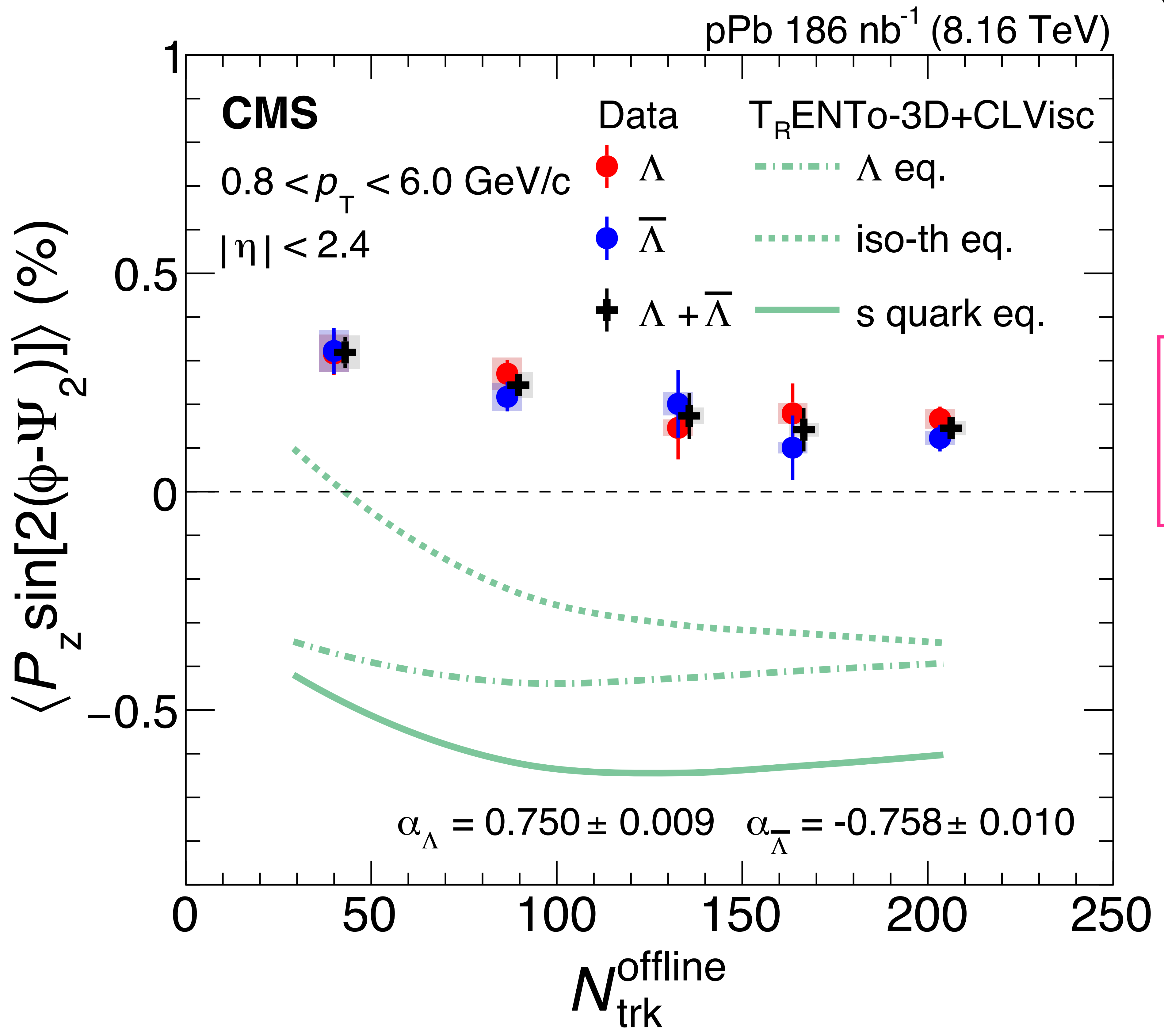
P_z in small system

F. Gardim et al., PRC109.014904(2024)



QGP droplet is likely created in pPb collisions

CMS, arXiv:2502.07898



Sep. 23 (Tue)
Chenyan Li (EXP)
Cong Yi (TH)

- Recently, P_z has been observed in pPb collisions by CMS, with multiplicity and p_T dependence
  - But the models cannot explain the sign of the data…
- Another way to search for collectivity in small systems? Other mechanism of the polarization?

Spin alignment of vector mesons

- Vector mesons (spin-1) can be used to study the polarization
  - Since they decay via strong interaction, the sign of polarization cannot be determined
- Angular distribution of the decay products can be written with spin density matrix ρ_{nn}.

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

$$\propto (1-\rho_{0,0}) + (3\rho_{0,0} - 1)\cos^2\theta^*$$

$$|s, s_z\rangle = |1, s_z\rangle$$

$$(s_z = -1,\ 0,\ +1)$$

- The diagonal element ρ_{00}: probability to have spin projection to be 0
  - ρ_{00} = 1/3: spin randomly oriented
  - $\rho_{00} \neq$ 1/3: spin aligned along quantization axis chosen

$$\rho_{00} = \frac{1}{3} + \frac{5}{2}(\langle\cos^2\theta^*\rangle - \frac{1}{3})$$

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

Theoretical expectation for ρ_{00}

$$\rho_{00}^{(\rm reco)}(\omega) \approx \frac{1}{3} - \frac{1}{9}(\beta\omega)^2 < \frac{1}{3}$$

$$\rho_{00}^{(\rm reco)}(B) \approx \frac{1}{3} - \frac{1}{9}\beta^2\frac{Q_1Q_2}{m_1m_2}B^2$$

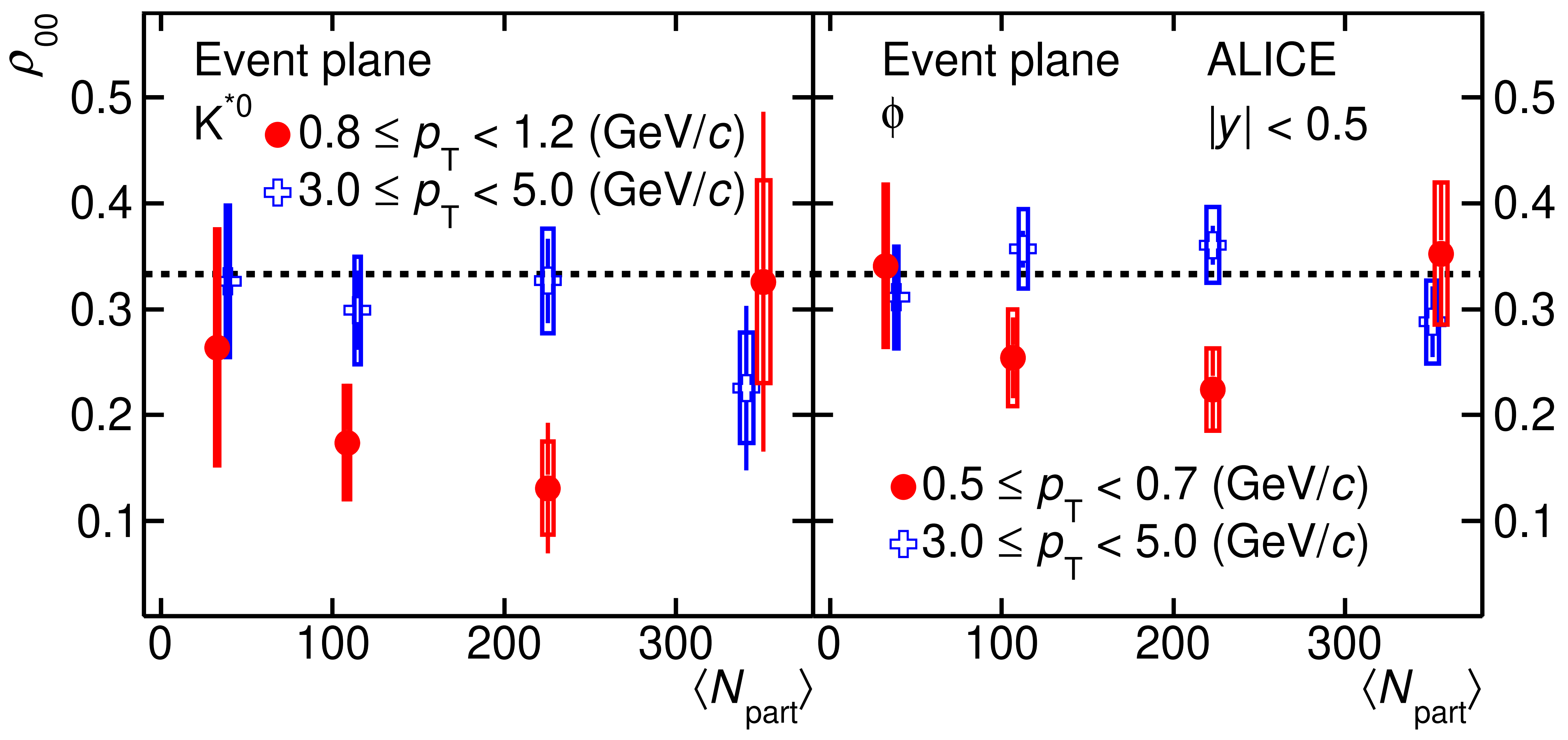
$$\rho_{00}^{(\rm frag)} \approx \frac{1+\beta P_q^2}{3-\beta P_q^2} > \frac{1}{3}$$

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

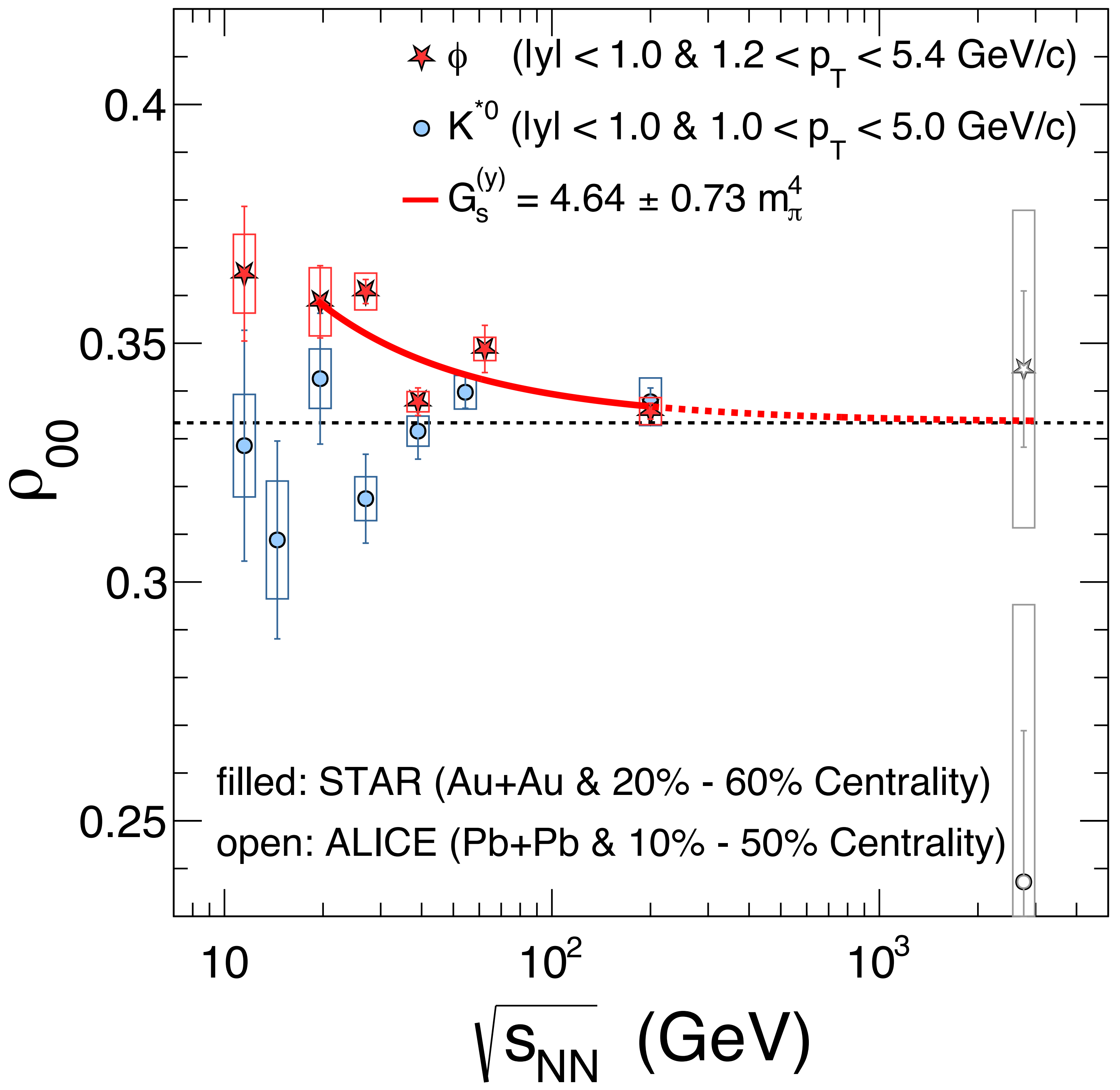
The sign of (ρ_{00} - 1/3) depends on hadronization process (recombination or fragmentation) and the polarization mechanism

Global spin alignment: ϕ and K^{*0}

ALICE, PRL125, 012301 (2020)



STAR, Nature 614, 244 (2023)



$$\rho_{00}^{(\mathrm{reco})} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} < 1/3$$

$$\rho_{00}^{(\mathrm{frag})} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2} > 1/3$$

Z.-T. Liang and X.-N. Wang, PLB629(2005)20

- Surprisingly, large deviation of ρ_{00} from 1/3
  - But energy, centrality, p_T, and y dependence is not fully understood
- The vorticity picture cannot explain the magnitude, e.g. P_Λ ~a few%
  Importance of spin-spin correlation?

$$P_\Lambda \sim \langle P_s \rangle$$

$$(\rho_{00}^{\phi} - \frac{1}{3}) \sim \langle P_s P_{\bar{s}} \rangle$$

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

Global spin alignment: J/ψ and D*+

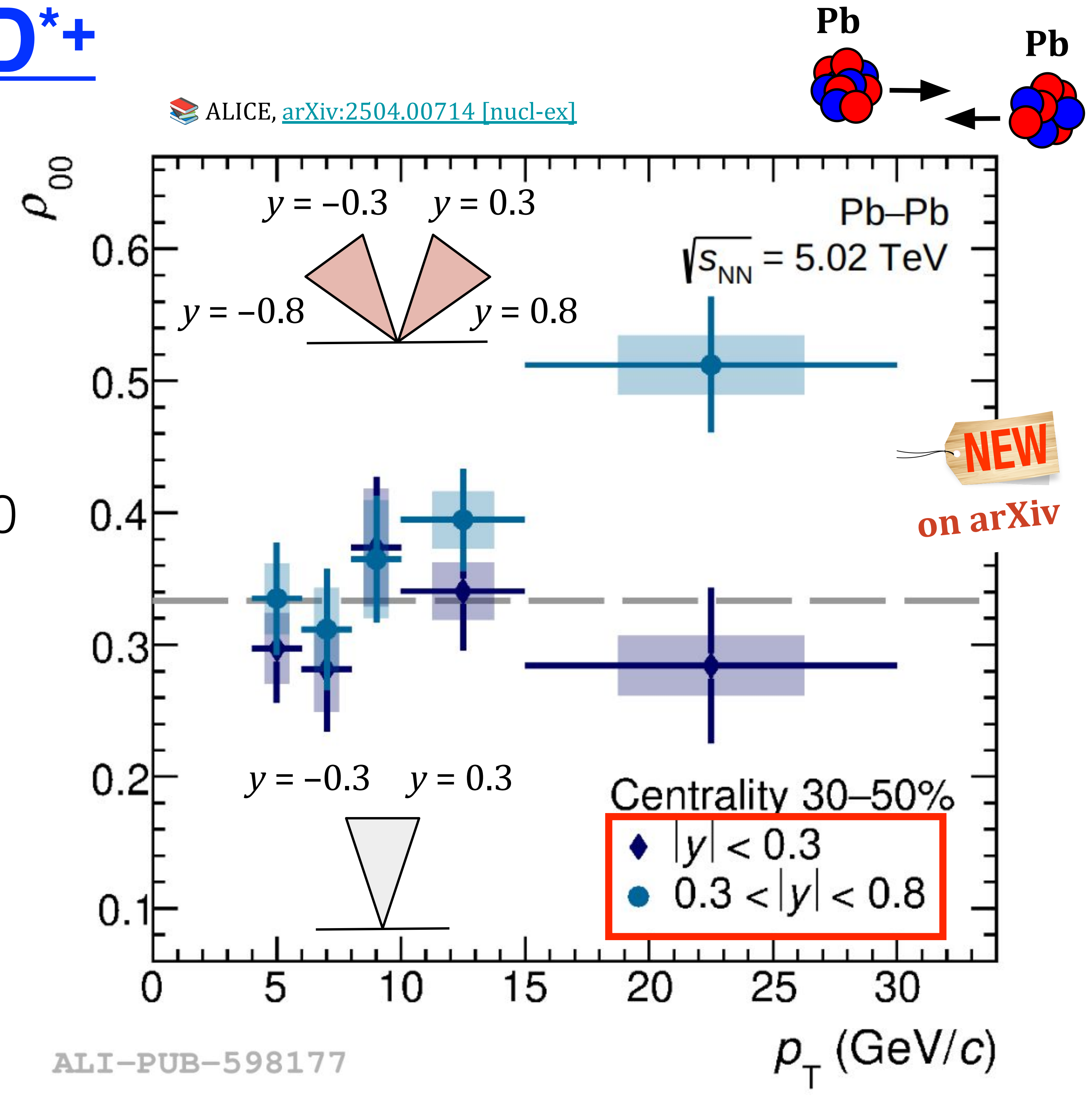
ALICE, PRL131.042303 (2023)
ALICE, arXiv:2504.00714

D*+

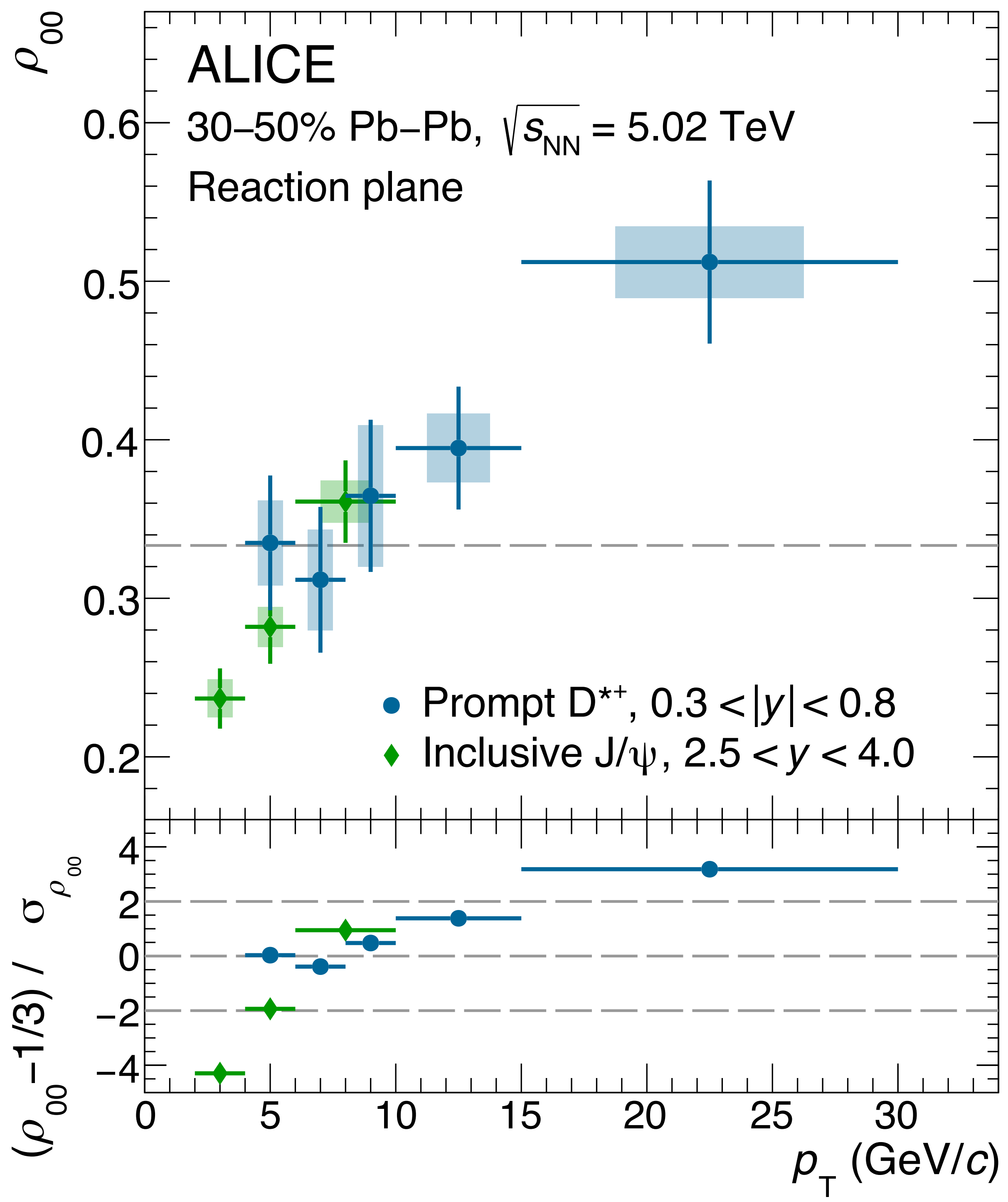
$$D^{*+} \to D^0 \pi^+$$

J=1 J=0 J=0

BESIII, PLB846(2023)138245



D*+ vs. J/ψ



$$\rho_{00}^{(\text{reco})}(\omega) \approx \frac{1}{3} - \frac{1}{9}(\beta\omega)^2 < \frac{1}{3}$$

$$\rho_{00}^{(\text{reco})}(B) \approx \frac{1}{3} - \frac{1}{9}\beta^2 \frac{Q_1 Q_2}{m_1 m_2} B^2$$

$$\rho_{00}^{(\text{frag})} \approx \frac{1+\beta P_q^2}{3-\beta P_q^2} > \frac{1}{3}$$

$$J/\psi(c\bar{c}) : Q_c Q_{\bar{c}} < 0$$

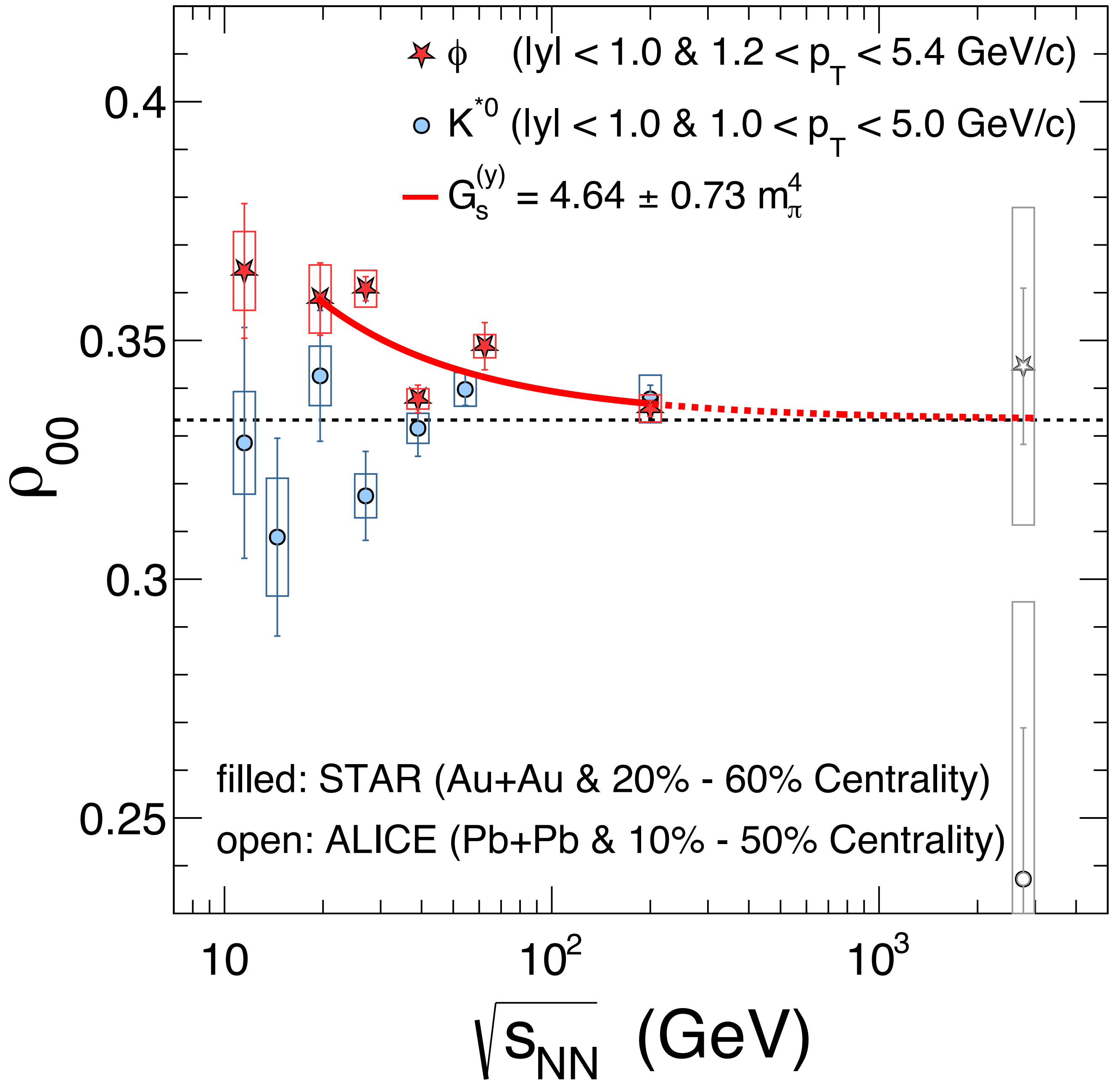
$$D^{*+}(c\bar{d}) : Q_c Q_{\bar{d}} > 0$$

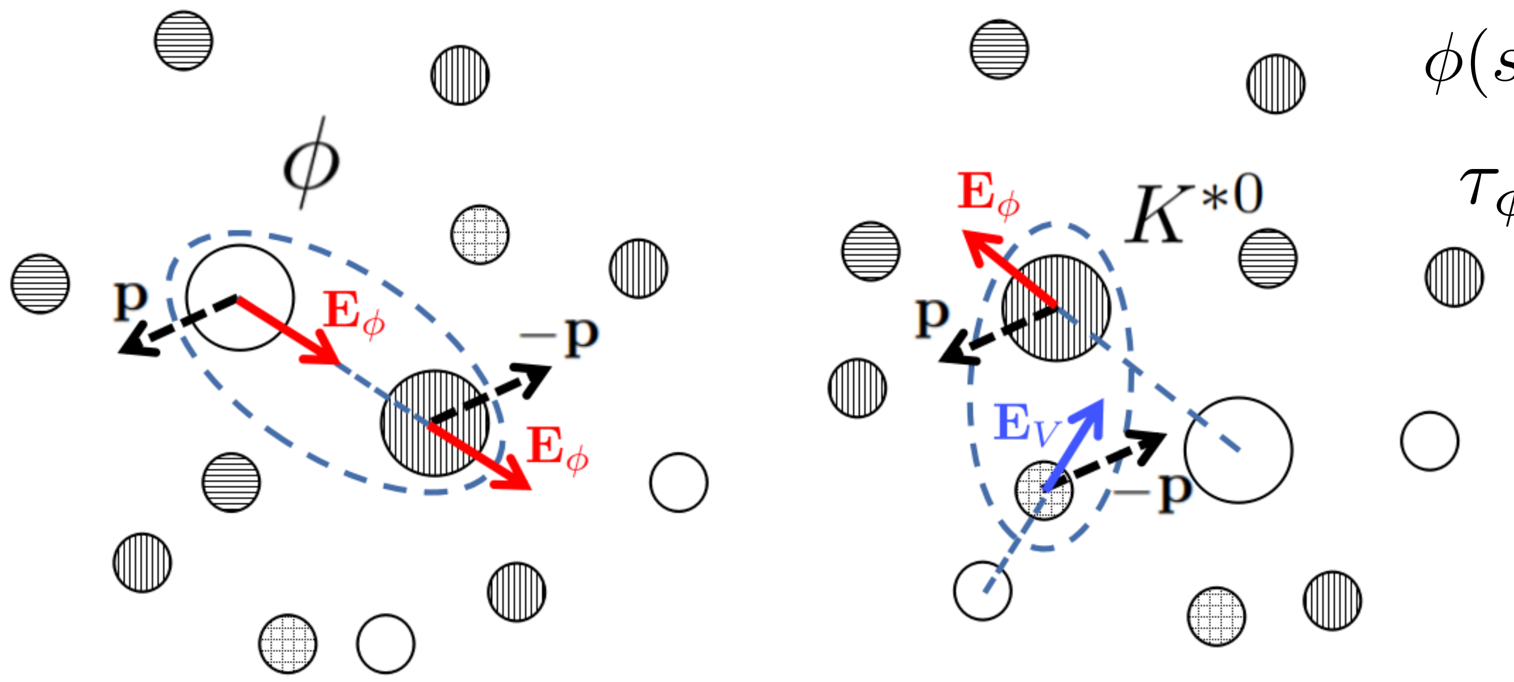
Sep. 23 (Tue)
Mingze Li
Xiaozhi Bai

- D*+ ρ_{00}: Positive deviation from 1/3 at high p_T at forward-y, and consistent with1/3 at mid-y
- Inclusive J/ψ ρ_{00}: Negative deviation at low p_T at forward-y
  - Effect of B-field (charm τ_{prod} ~0.1 fm/c, τ_B<0.5 fm/c)?
  - Do we have consistent picture to explain both light and heavy vector mesons?

Possible explanations?

STAR, Nature 614, 244 (2023)





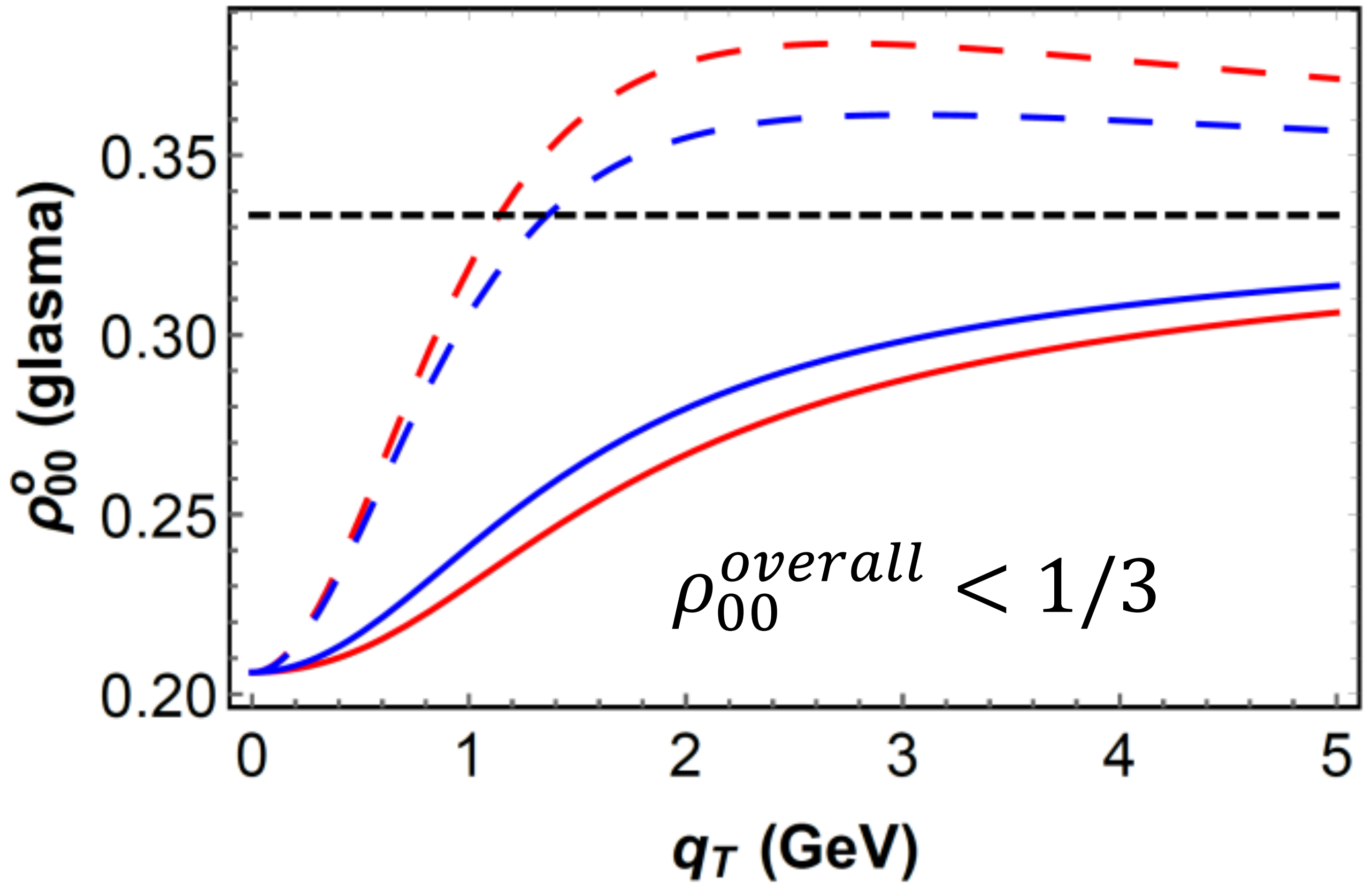
$\phi(s\bar{s}), \quad K^{*0}(d\bar{s})$

$\tau_\phi \approx 10\tau_{K^{*0}}$

effective coupling constant — ϕ-field strength

$$G_s^{(y)} \equiv g_\phi^2 \left[3\langle B_{\phi,y}^2 \rangle + \frac{\langle \mathbf{p}^2 \rangle_\phi}{m_s^2} \langle E_{\phi,y}^2 \rangle - \frac{3}{2} \langle B_{\phi,x}^2 + B_{\phi,z}^2 \rangle - \frac{\langle \mathbf{p}^2 \rangle_\phi}{2m_s^2} \langle E_{\phi,x}^2 + E_{\phi,z}^2 \rangle \right],$$

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



D.L. Yang, PRD111, 056005 (2025)
A. Kumar, B. Muller, D.L. Yang, PRD108, 016020 (2023)

Sep. 23 (Tue)
Di-Lun Yang

- Positive deviation of ϕ ρ_{00} at lower energy is possibly explained by strong force field
- At high energy, the initial state (gluon field) may play a role for the spin alignment

But can we understand all the data (ϕ, K^{*0}, J/ψ, D^{*+} from RHIC and the LHC)?

Spin-spin correlation

Average of quark polarization by hyperons

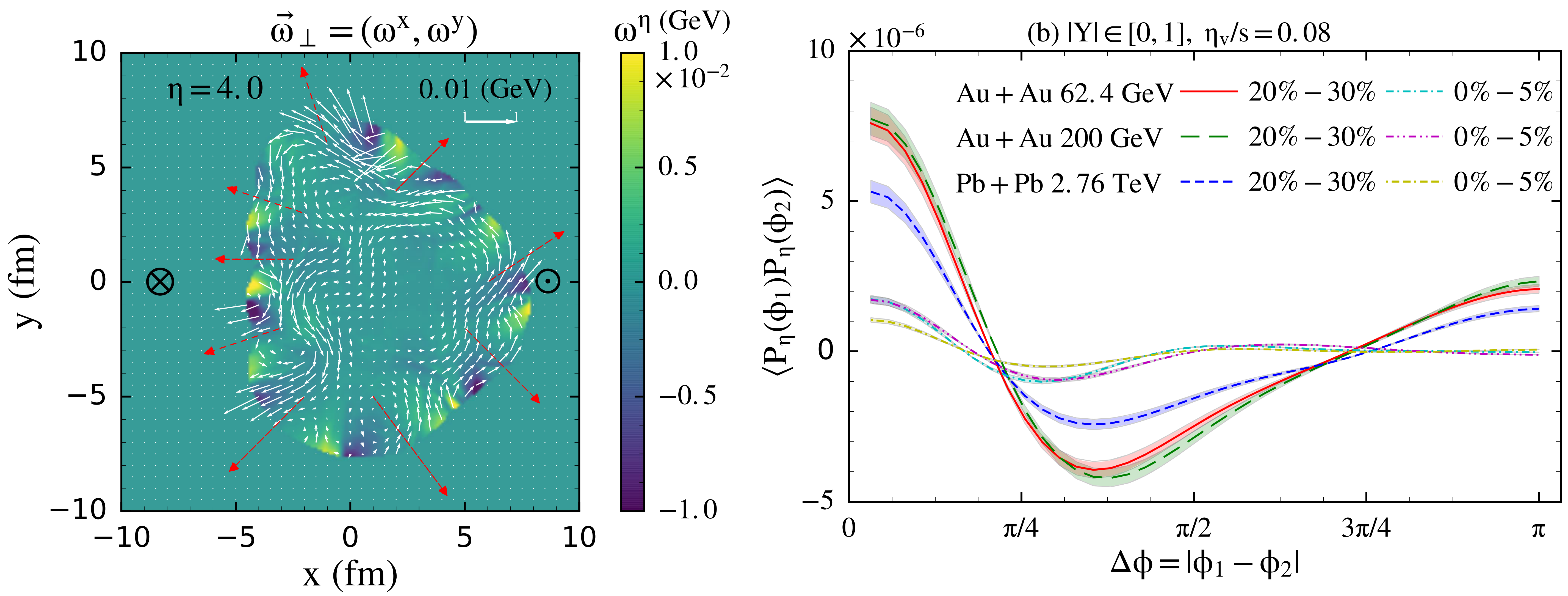
$$P_\Lambda = \langle P_s \rangle$$

while spin-spin **correlation** by vector mesons

$$\rho_{00}^V = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle} \neq \frac{1 - \langle P_q \rangle \langle P_{\bar{q}} \rangle}{3 + \langle P_q \rangle \langle P_{\bar{q}} \rangle}$$

- Spin-spin correlation proposed to search for complex vortical structures

L.-G. Pang et al., PRL117, 192301 (2016)

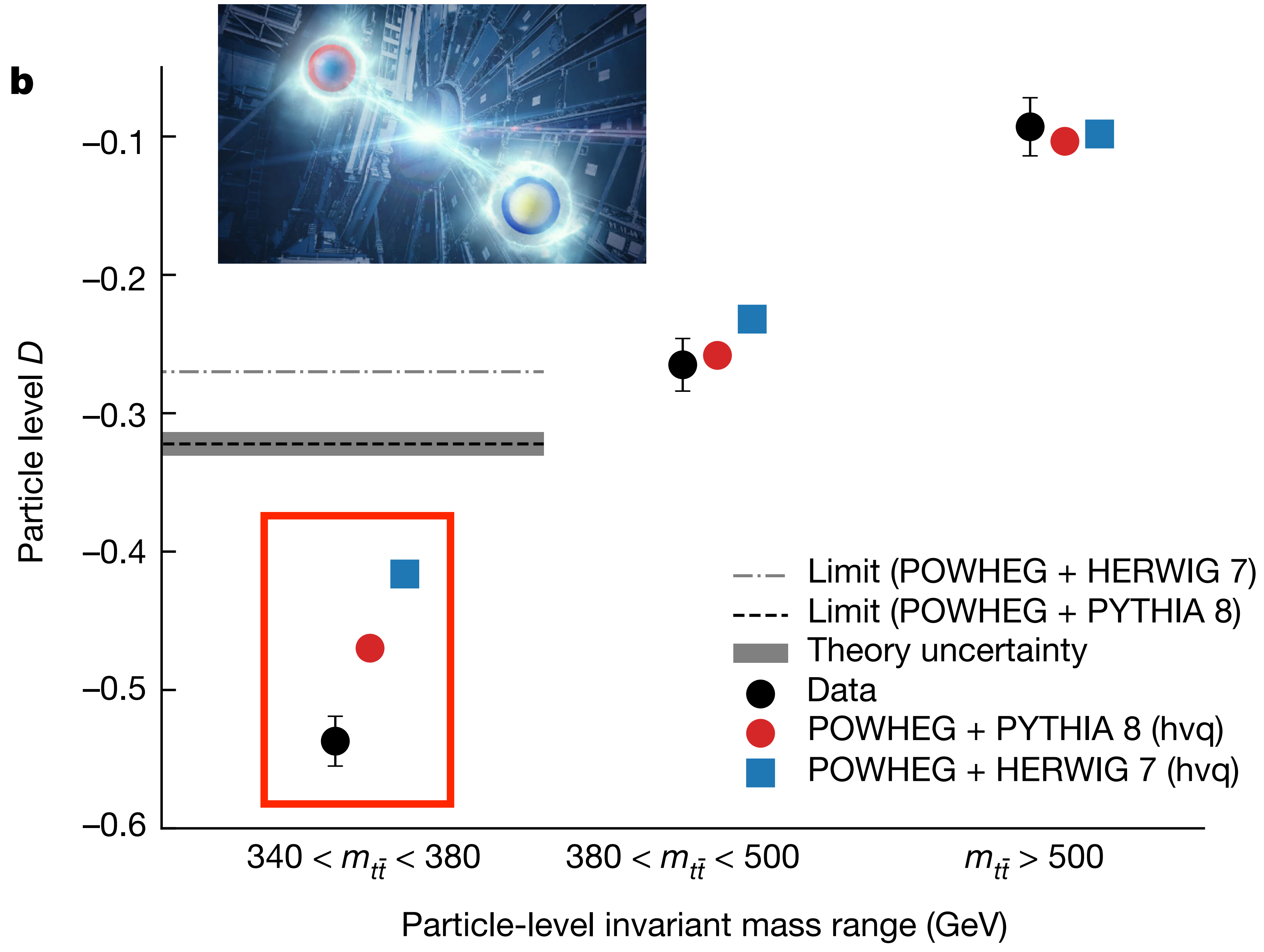


Large signal of ρ_{00} could arise if vorticity fluctuations or spin correlation are larger than its average

Spin-spin correlation

- Quantum entanglement of $t\bar{t}$ in 13 TeV pp collisions

ATLAS, Nature 633, 542 (2024)
CMS, PRD110, 112016 (2024)



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

entangled if D<-1/3

Top quark pairs from gluon-gluon fusion
- expected to be maximally entangled

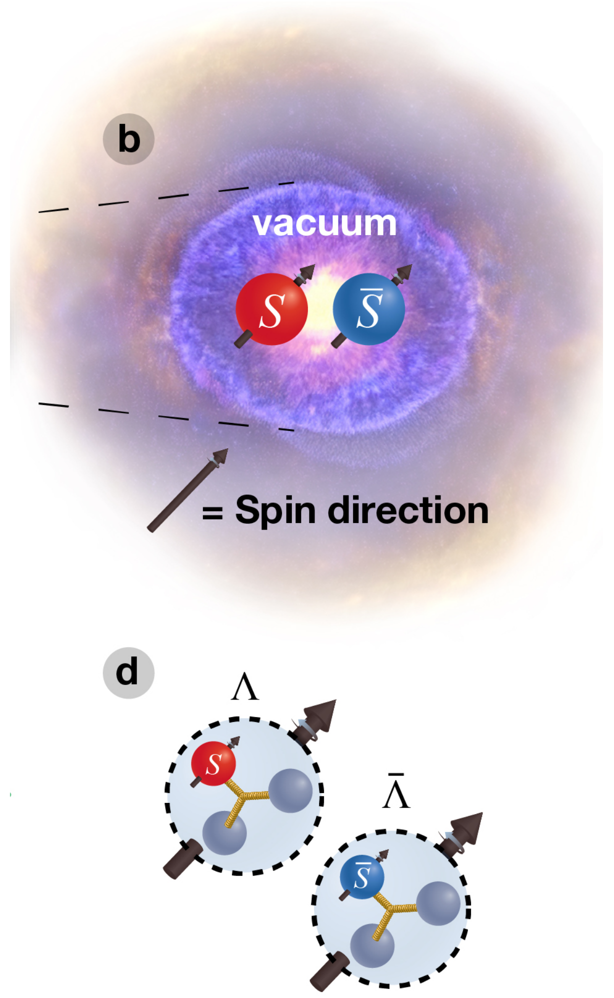
- CP test utilizing spin-entangled hyperons in $e^+e^- \to J/\psi \to Y\overline{Y}$

BESIII, Nature 606, 64 (2022)

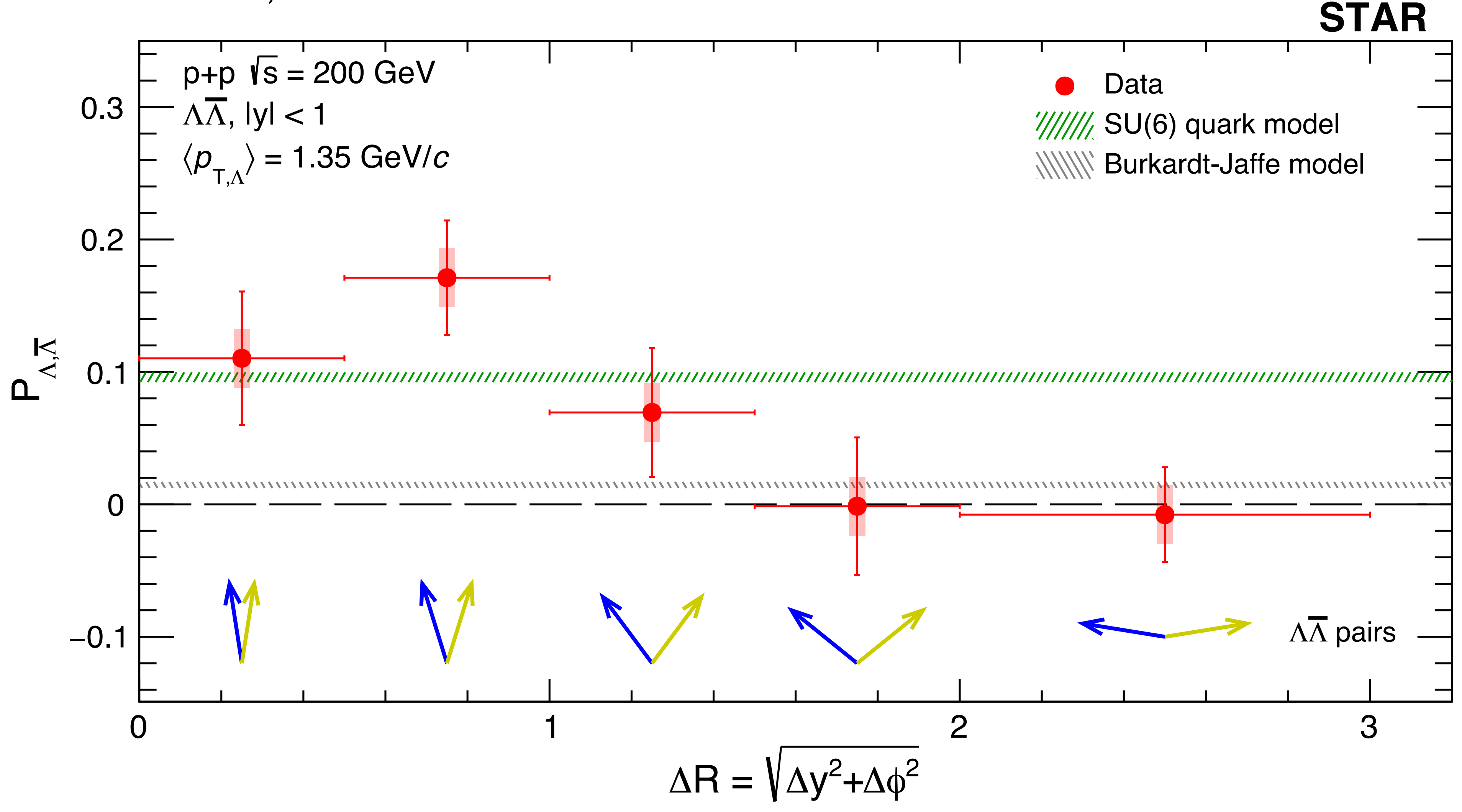
Sep. 22 (Mon)
Hai-Bo Li

Spin-spin correlation

- $\Lambda\bar{\Lambda}$ spin-spin correlation in 200 GeV pp collisions



STAR, arXiv:2506.05499

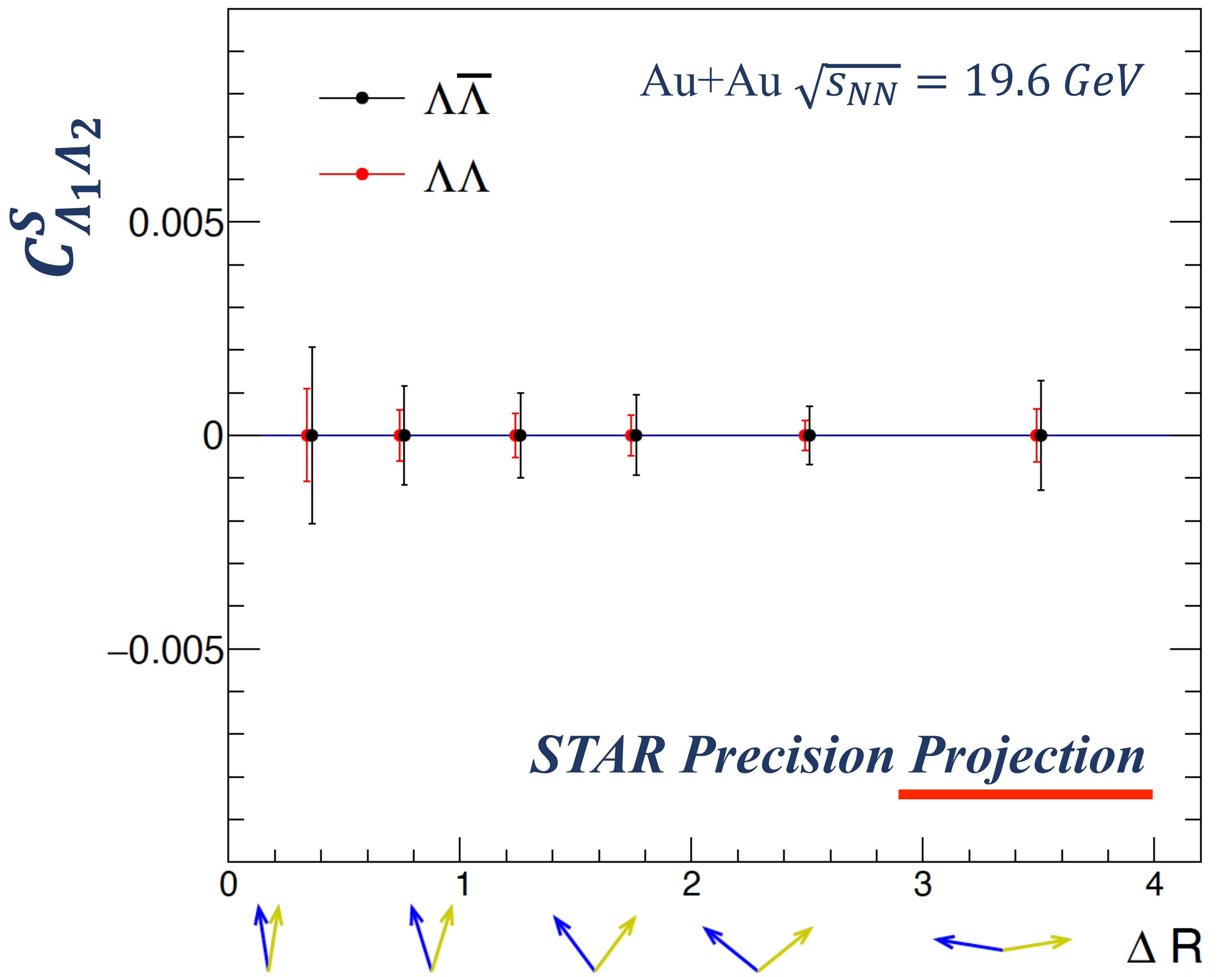


$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^\star} = \frac{1}{2}[1+\alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos\theta^\star],$$

Sep. 24 (Wed)
Qinghua Xu, Jan Vanek

- Entangled $s\bar{s}$ from chiral condensate in QCD vacuum
- Correlation vanishes at large separation. Quantum decoherence?

- in 19.6 GeV Au+Au collisions



$$\frac{dN}{d\cos\theta^*} \propto 1+\alpha_1\alpha_2 C^S_{\Lambda_1\Lambda_2}\cos\theta^*$$

Sep. 23 (Tue)
Xingrui Gou

- Analysis is ongoing for Au+Au BES

Summary and Outlook

- Observations of hyperon global and local polarization and vector meson spin alignment open new directions in the study of QCD matter and spin dynamics in heavy-ion collisions
- A lot of progress have been made in both experimental and theoretical studies but still many open questions remain

Summary and Outlook

- Observations of hyperon global and local polarization and vector meson spin alignment open new directions in the study of QCD matter and spin dynamics in heavy-ion collisions
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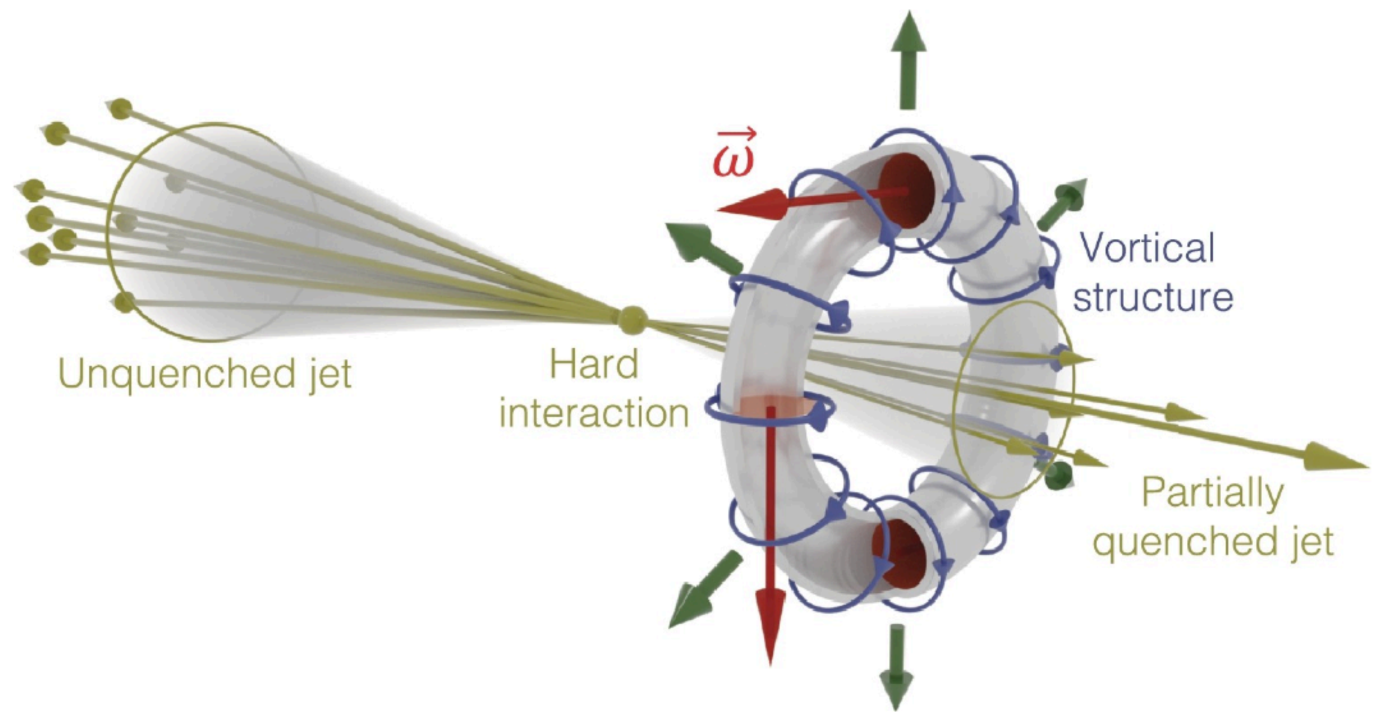
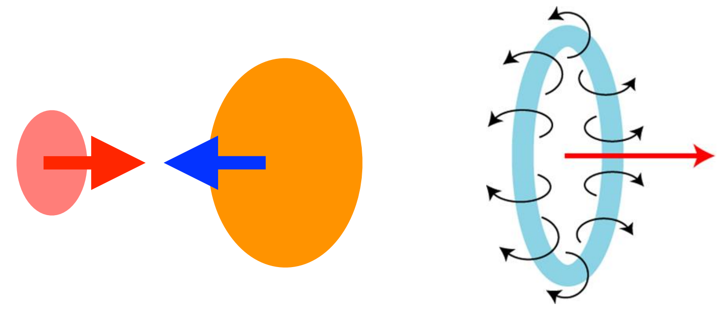
TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010

- Polarization splitting between particles and antiparticles, including particles with larger magnitude of the magnetic moment such as Ω. It will further constrain the magnetic field time evolution and its strength at freeze-out, and the electric conductivity of QGP.
- Precise measurements of multistrange hyperon polarization to study particle species dependence and confirm the vorticity-based picture of polarization. Measurement with Ω will also constrain unknown decay parameter γ_Ω. P_Ω and γ_Ω
- Precise differential measurements of the azimuthal angle and rapidity dependence of $P_J(P_{-y})$. $P_H(\phi)$ and $P_H(y)$
- Detailed measurement of P_z induced by elliptic and higher harmonic flow. In particular this study could help to identify the contribution from SIP, which is expected to be different for different harmonics.
- Application of the event-shape-engineering technique[126] testing the relationship between anisotropic flow and polarization.
- Measuring P_x to complete all the components of polarization and compare the data to the Glauber estimates and full hydrodynamical calculations.
- Circular polarization P_ϕ to search for toroidal vortex structures
- The particle–antiparticle difference in the polarization dependence on azimuthal angle at lower collision energies testing the SHE. Spin Hall Effect
- Understanding of the vector meson spin alignment measurements including new results with corrections of different detector effects.
- Measurement of the hyperon polarization correlations to access the scale of vorticity fluctuations. spin-spin correlation

▸ Toroidal vortex due to jet or in asymmetric collisions?





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

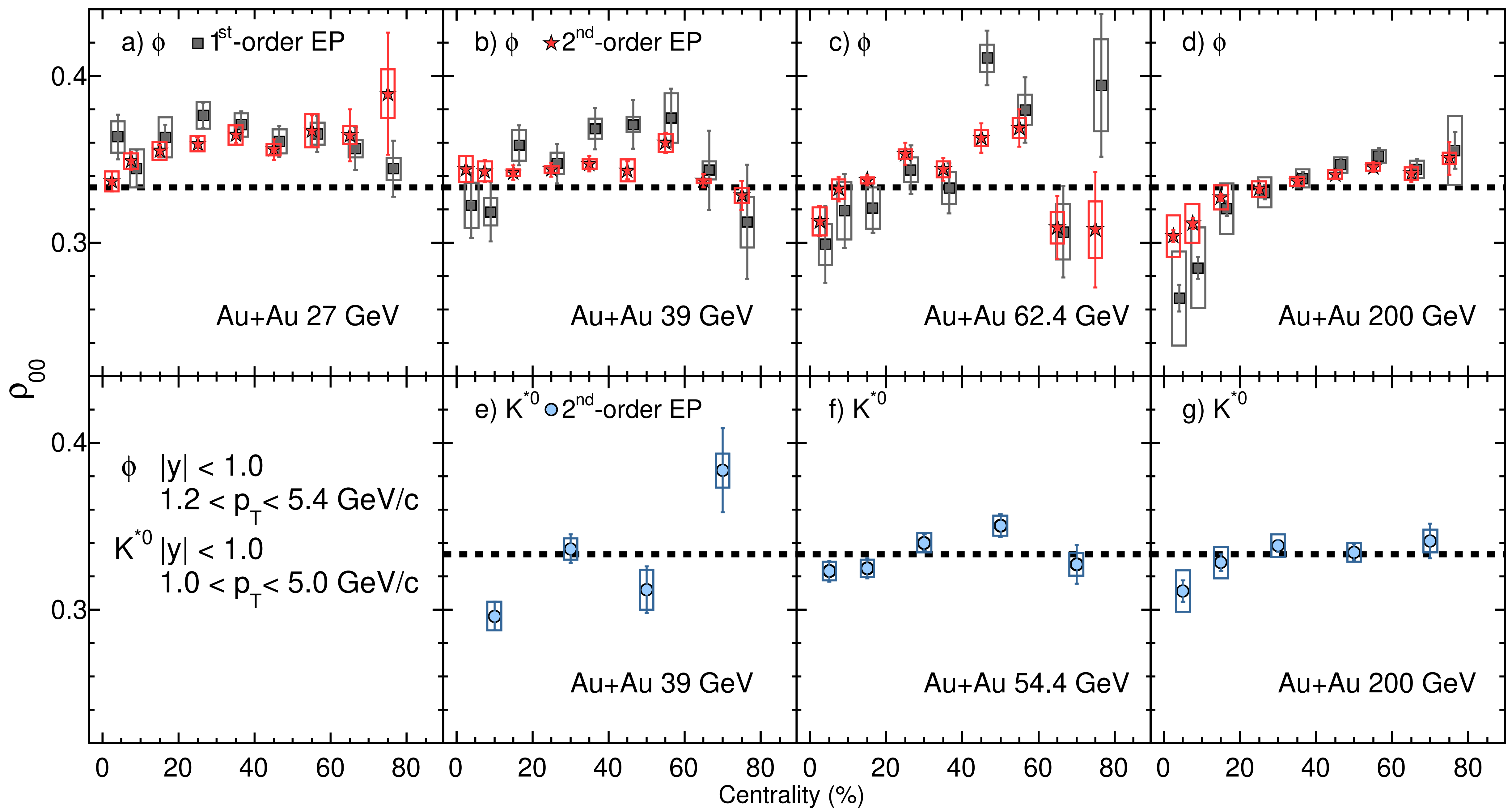
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)
Chinellato et al., arXiv:2407.02212

▸ Global (P_{-y}) and longitudinal (P_z) polarization were measured. What about the remaining component P_x?

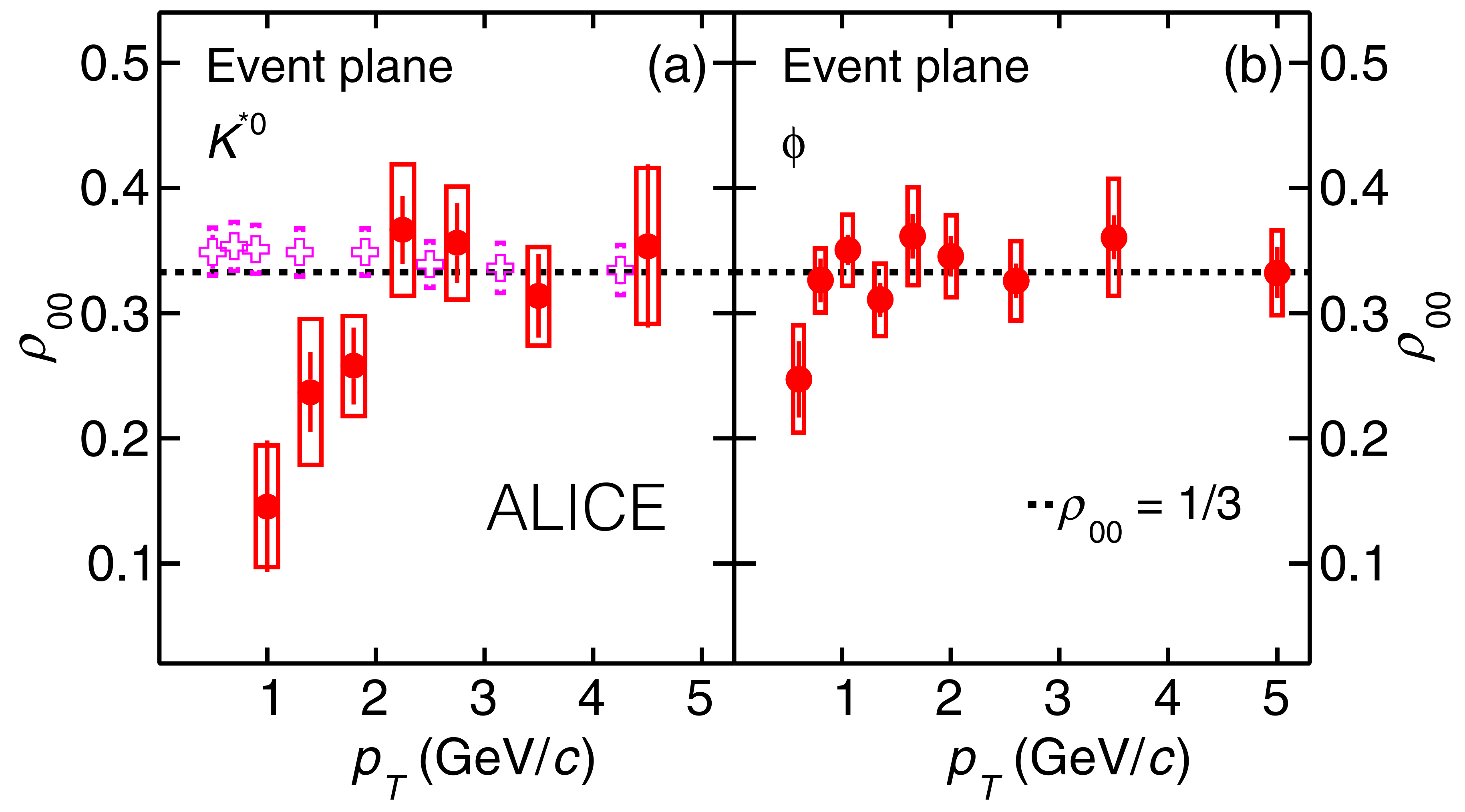
Sep. 23 (Tue)
Qun Wang

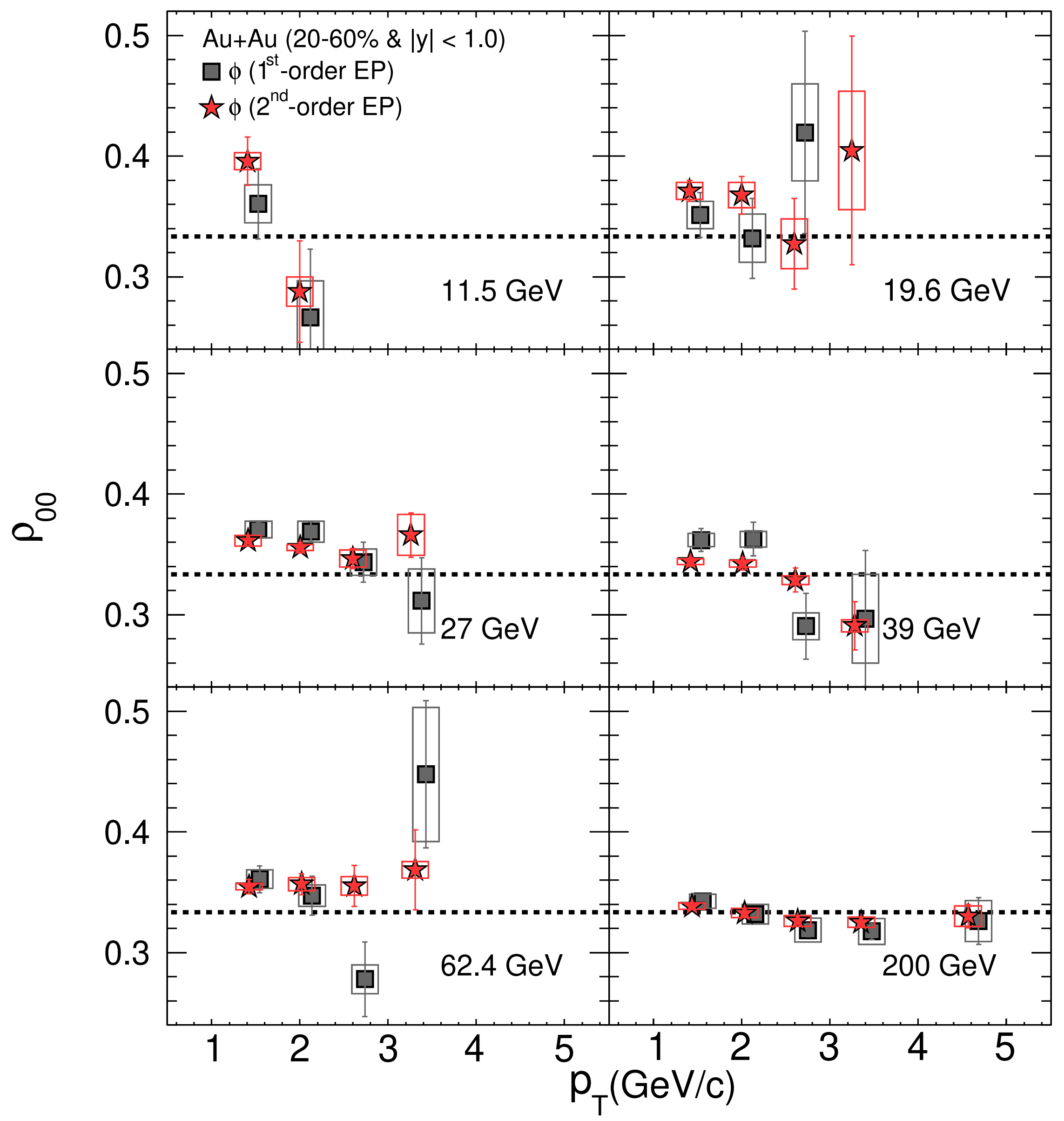
More on ϕ/K^{*0} spin alignment…

STAR, Nature 614, 244 (2023)



ALICE, PRL125, 012301 (2020)

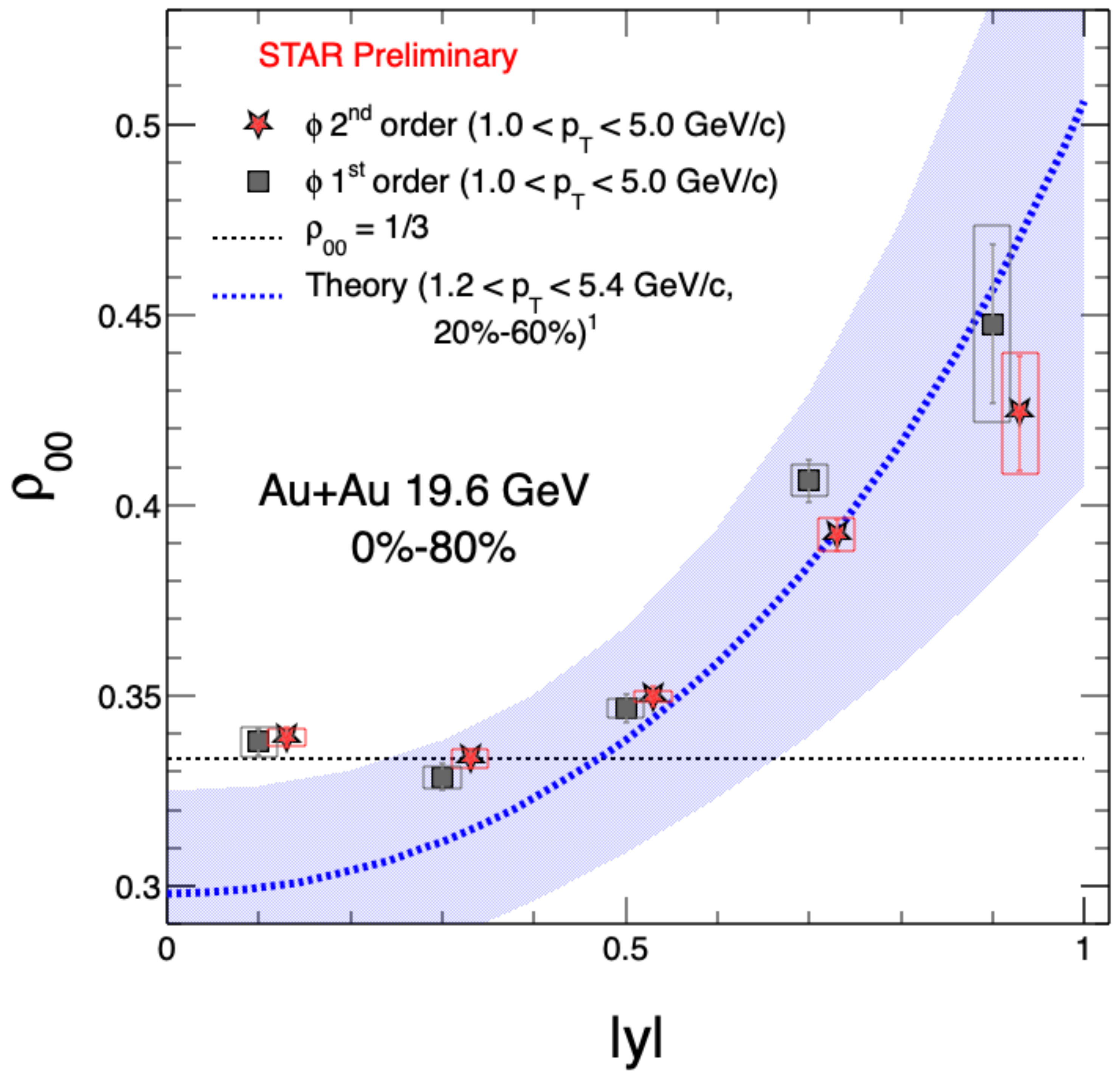




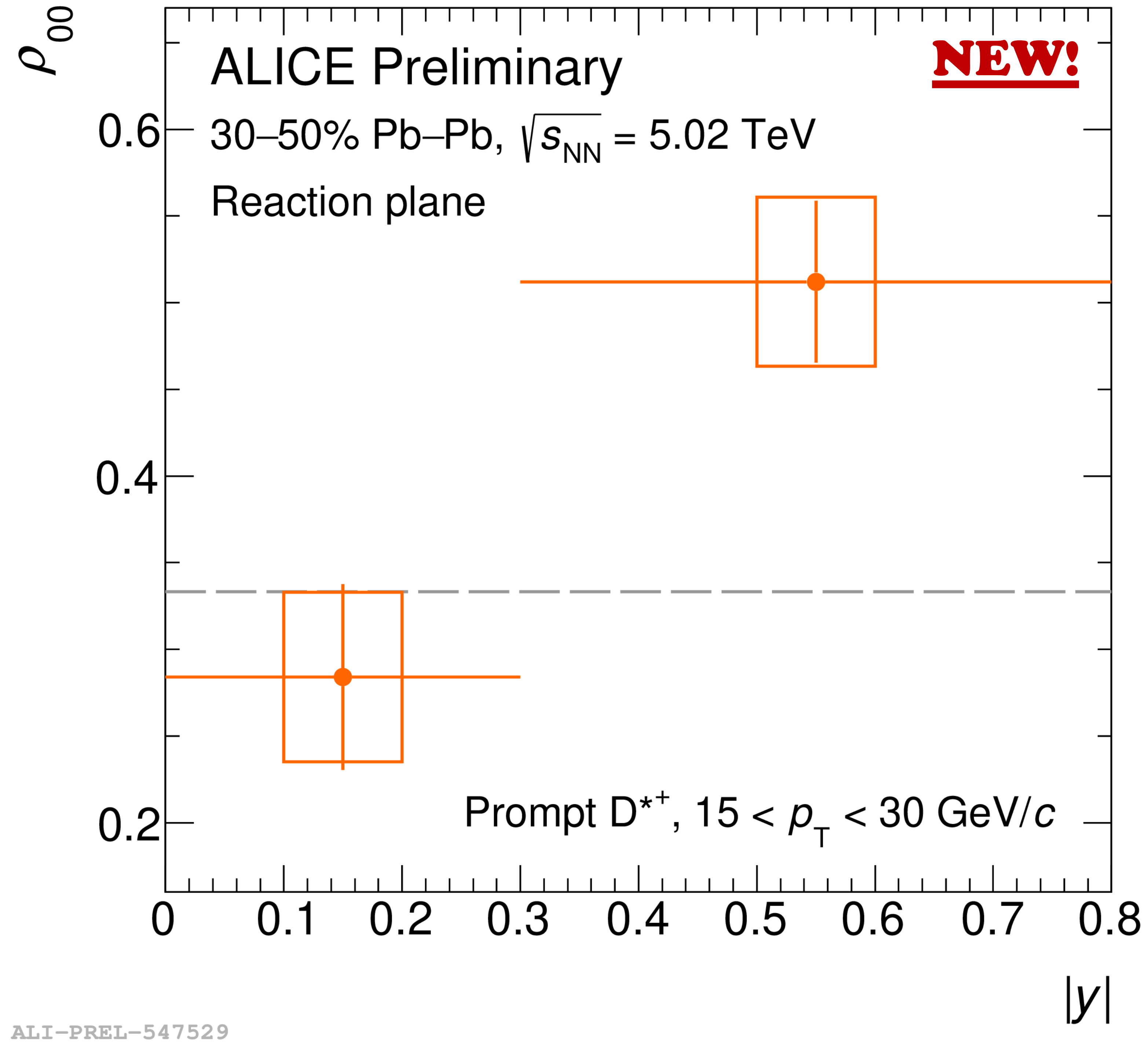
- Can we understand centrality and p_T dependence across all the energies?

Rapidity dependence?

G. Wilks (STAR), SPIN2023



L. Micheletti (ALICE), QM2023

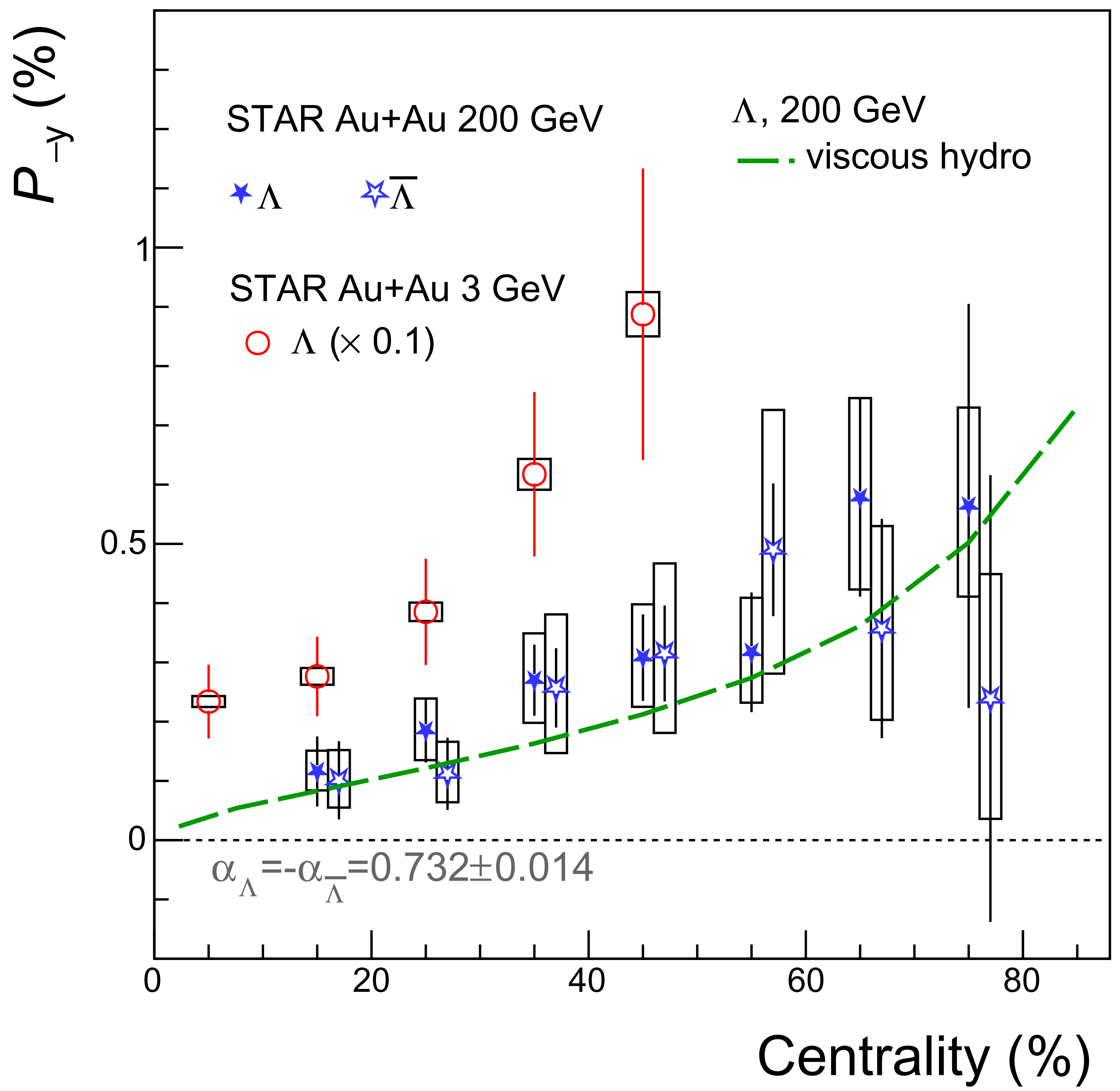


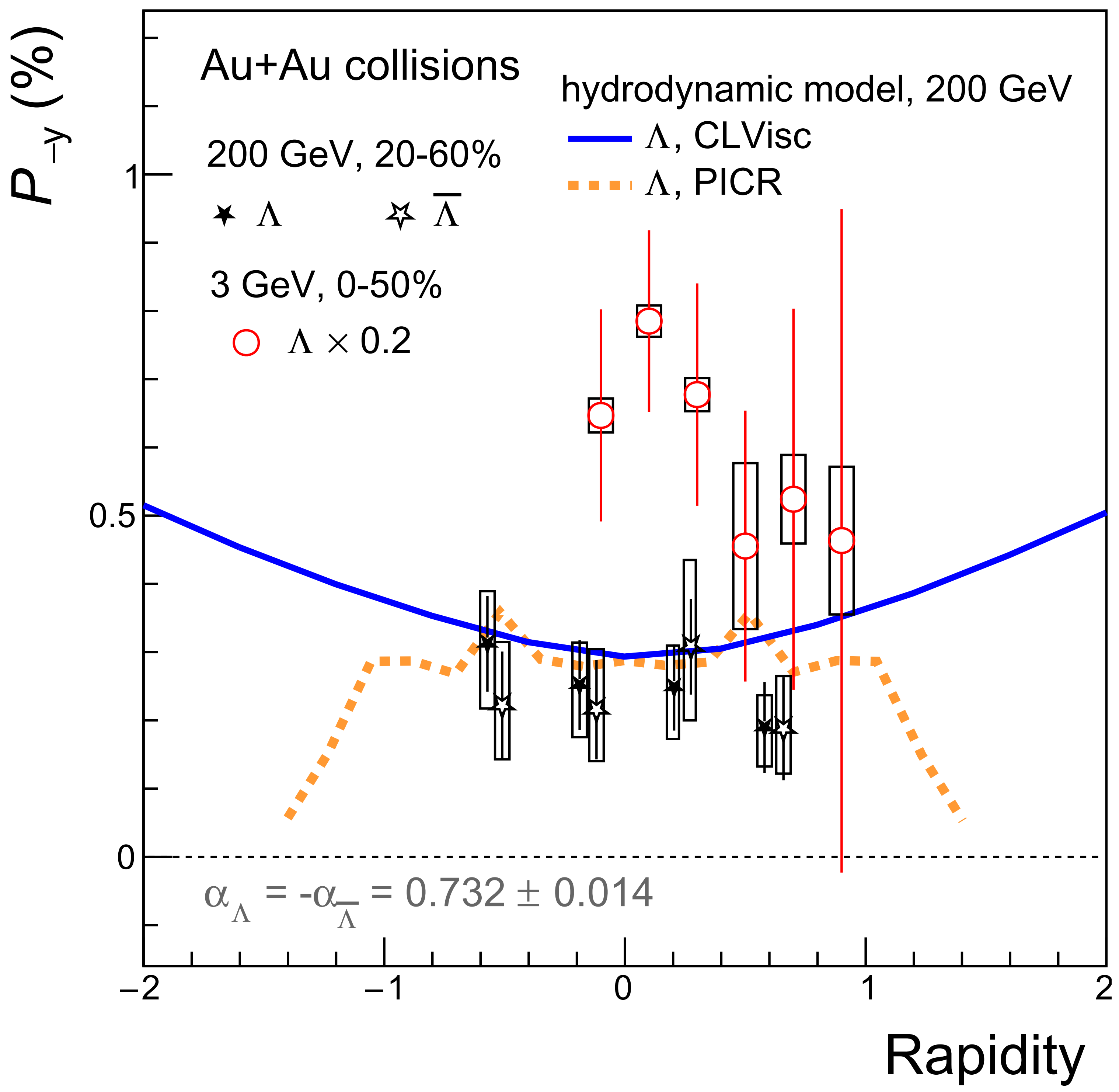
- Strong rapidity dependence in both $\phi(\mathrm{s\bar{s}})$ and $D^{*+}(\mathrm{c\bar{d}})$
- The model involving the strong force field may explain the trend for ϕ, except midrapidity
  - How about D^{*+} ?

Centrality and rapidity dependence

Data: STAR, PRC90.014910(2018), PRC104.L061901(2021)
Models: S.Ryu et al., PRC104.954908(2021), H.Wu et al., PRRes.1033058(2019)

Figures: TN and S. Voloshin, arXiv:2404.11042



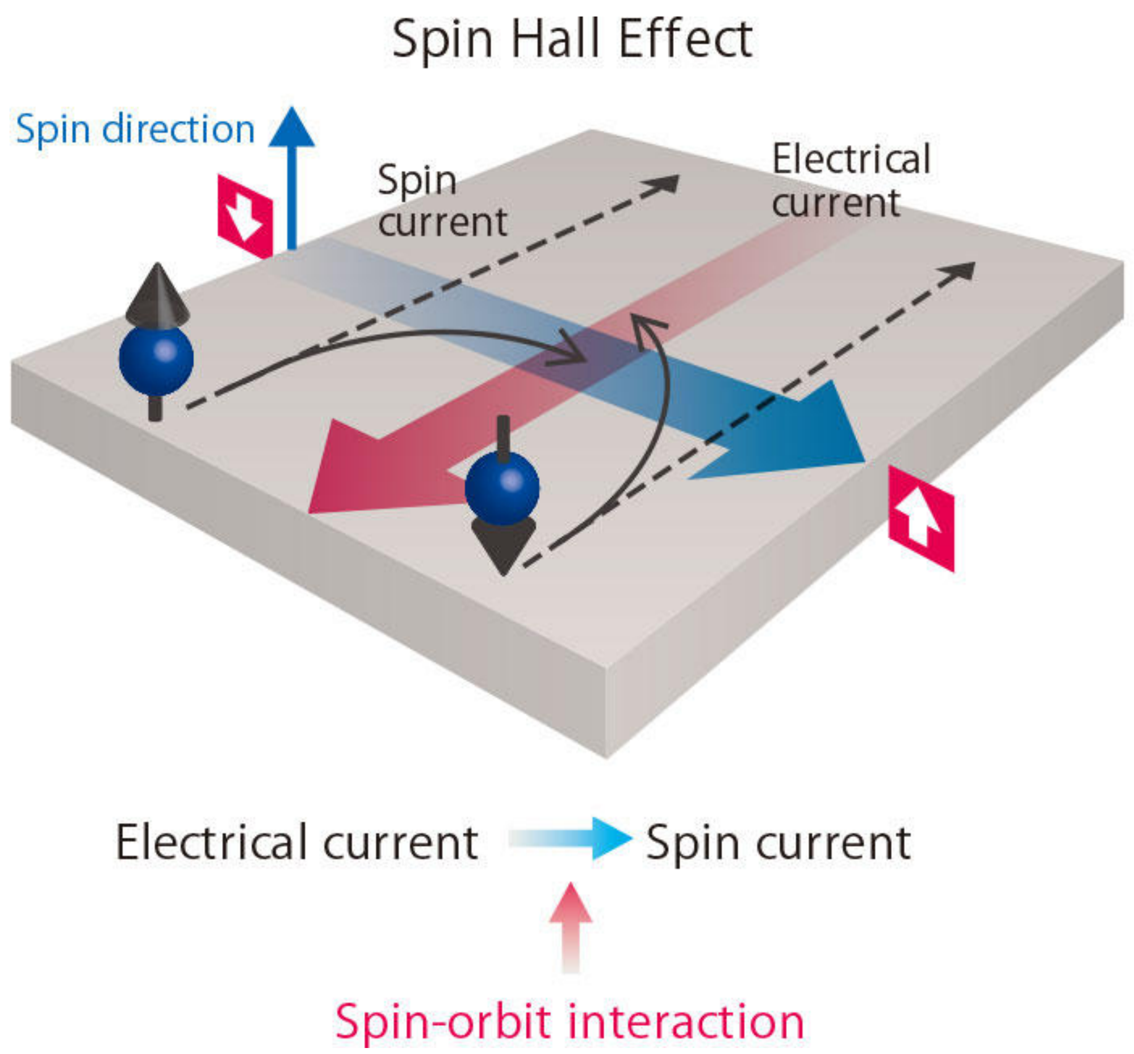


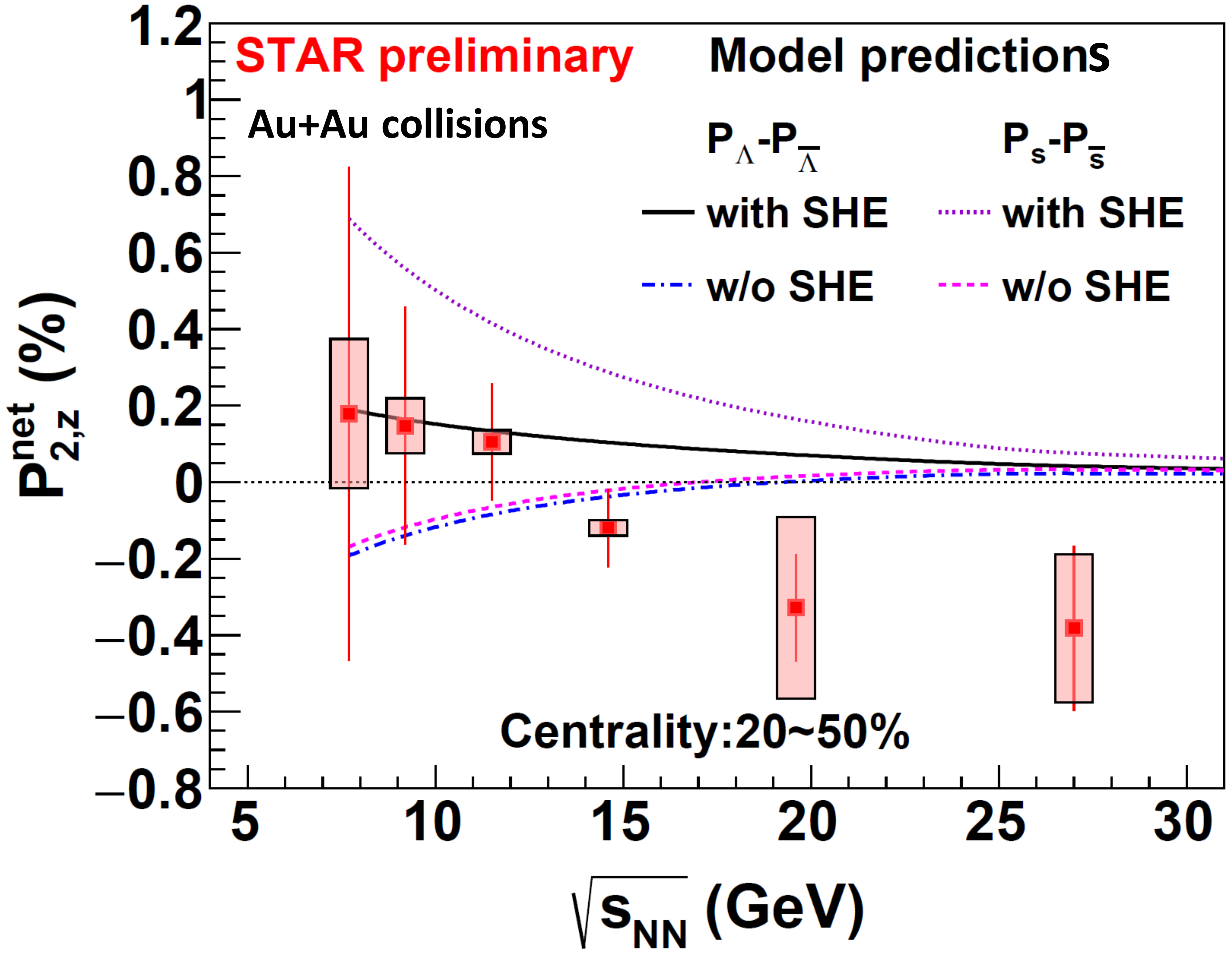
- Clear centrality dependence as expected from b-dependence of the initial *L*
- Rapidity dependence predicted differently. Still large uncertainty in the data

Spin Hall Effect

Q. Hu (STAR), SQM2024

S.Liu and Y.Yin, PRD104.054043(2021)
B.Fu et al., arXiv:2201.12970





- Spin current (polarization) due to gradient in the baryon chemical potential $\boldsymbol{P} \propto -\boldsymbol{p} \times (q_B \nabla \mu_B)$
- Expected to appear as the difference of P_z(P_y) modulation between Λ and anti-Λ at lower energies

Feed-down effect

- ~60% of measured Λ 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
  (Polarization transfer could be negative!)

$C_{\Lambda R}$: 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

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

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

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

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: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	$-1/3$

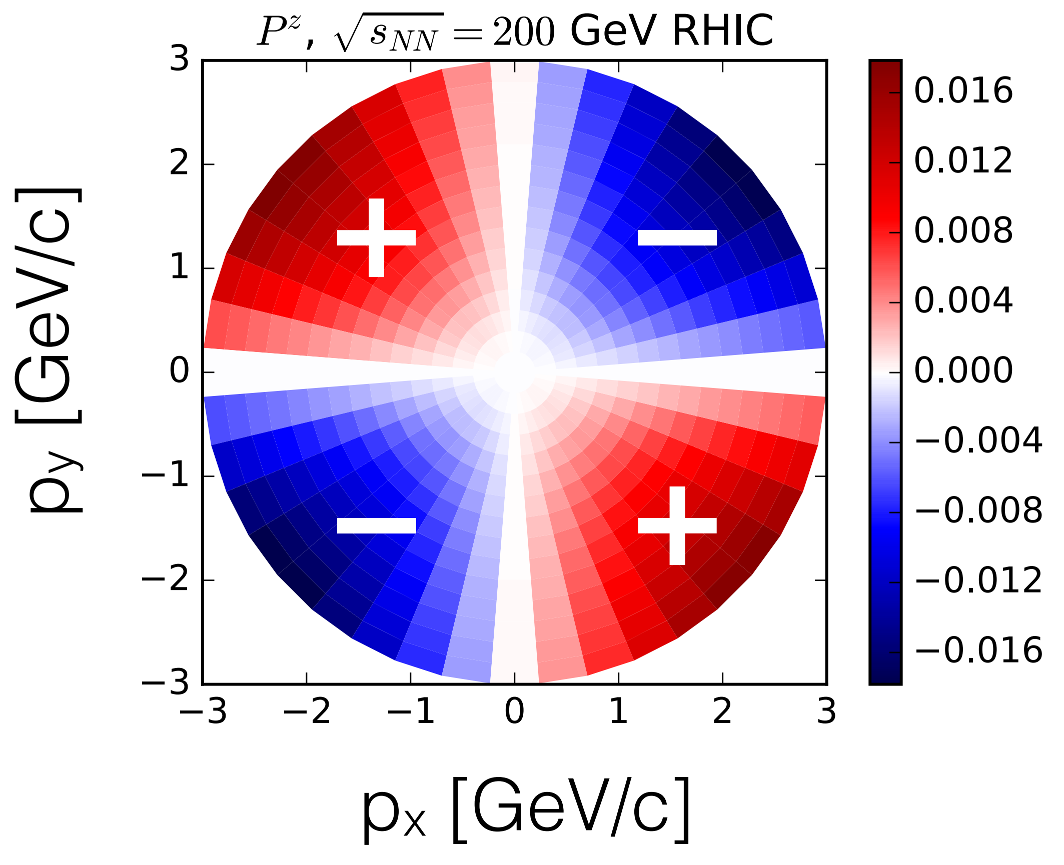
Primary Λ polarization will be diluted by 15%-20% (model-dependent)
This also suggests that **the polarization of daughter particles can be used to measure their parent polarization!** e.g. Ξ, Ω

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

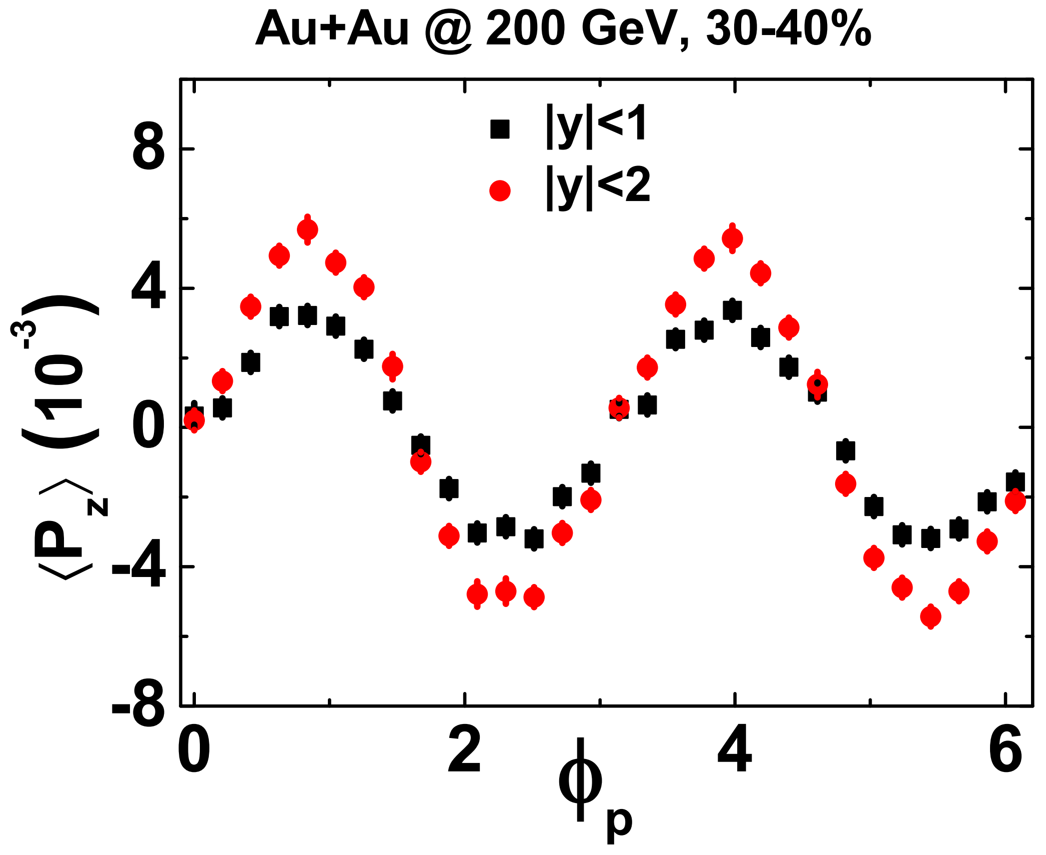
Theoretical models predict $P_z(\phi)$ differently

- 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

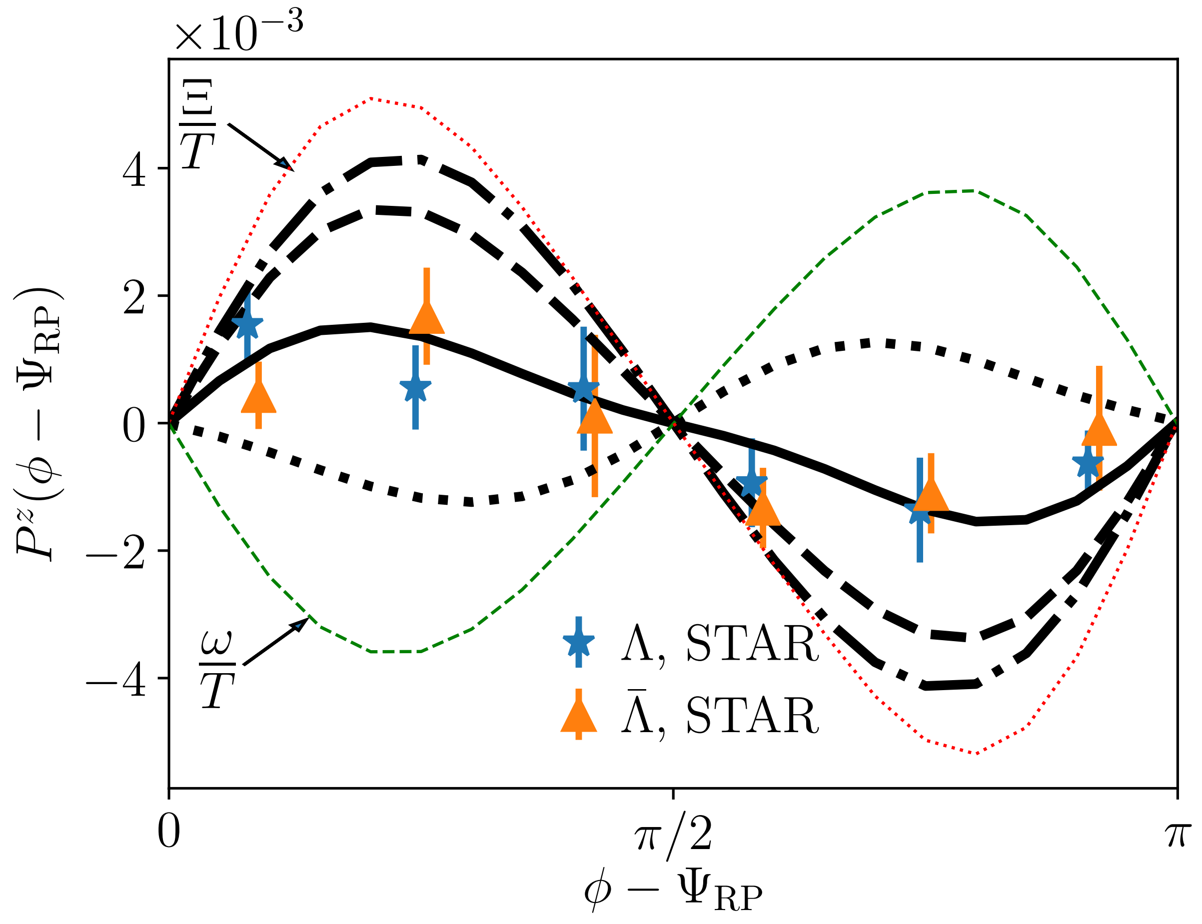


Chiral kinetic approach



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

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

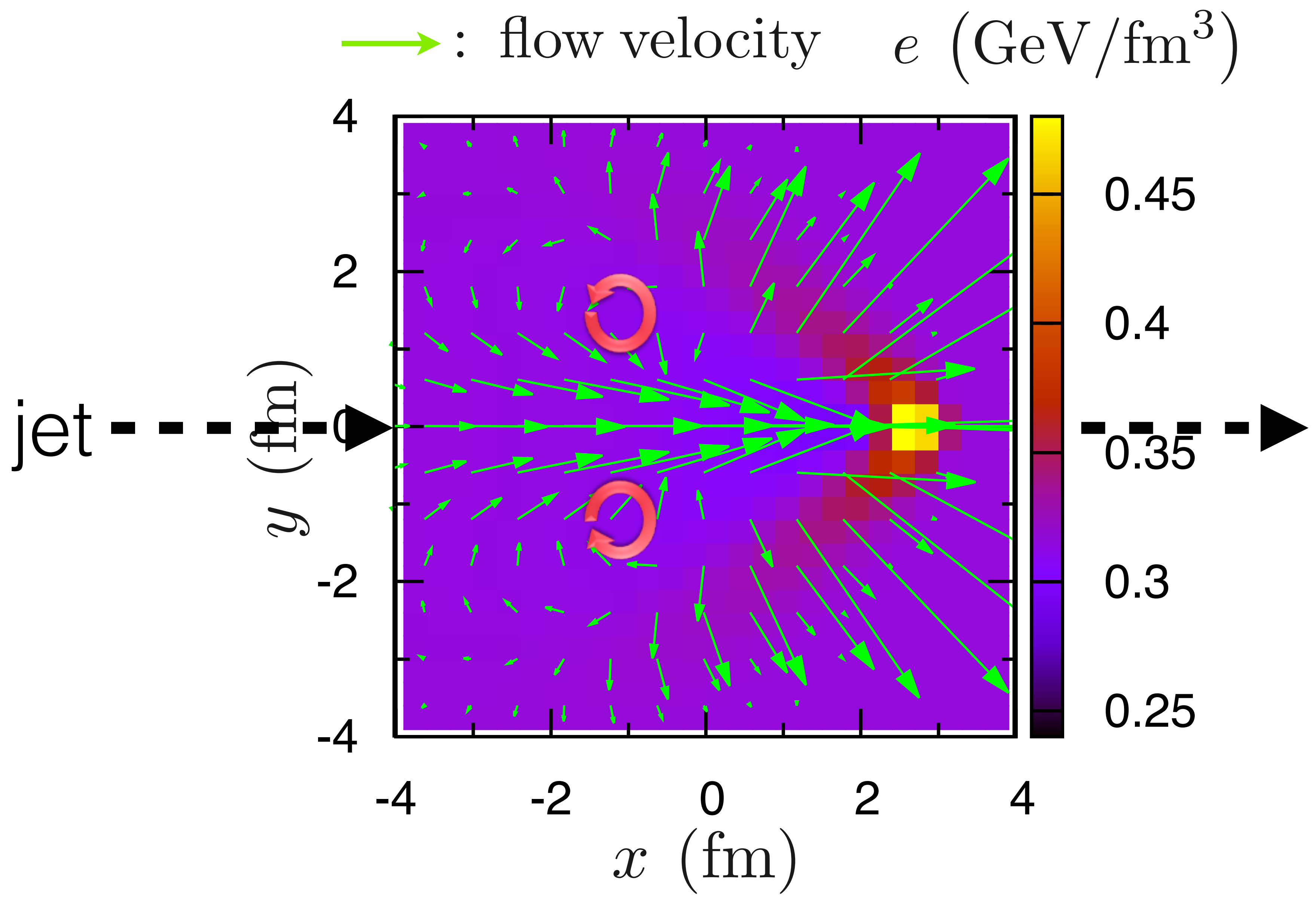


Disagreement among models and data

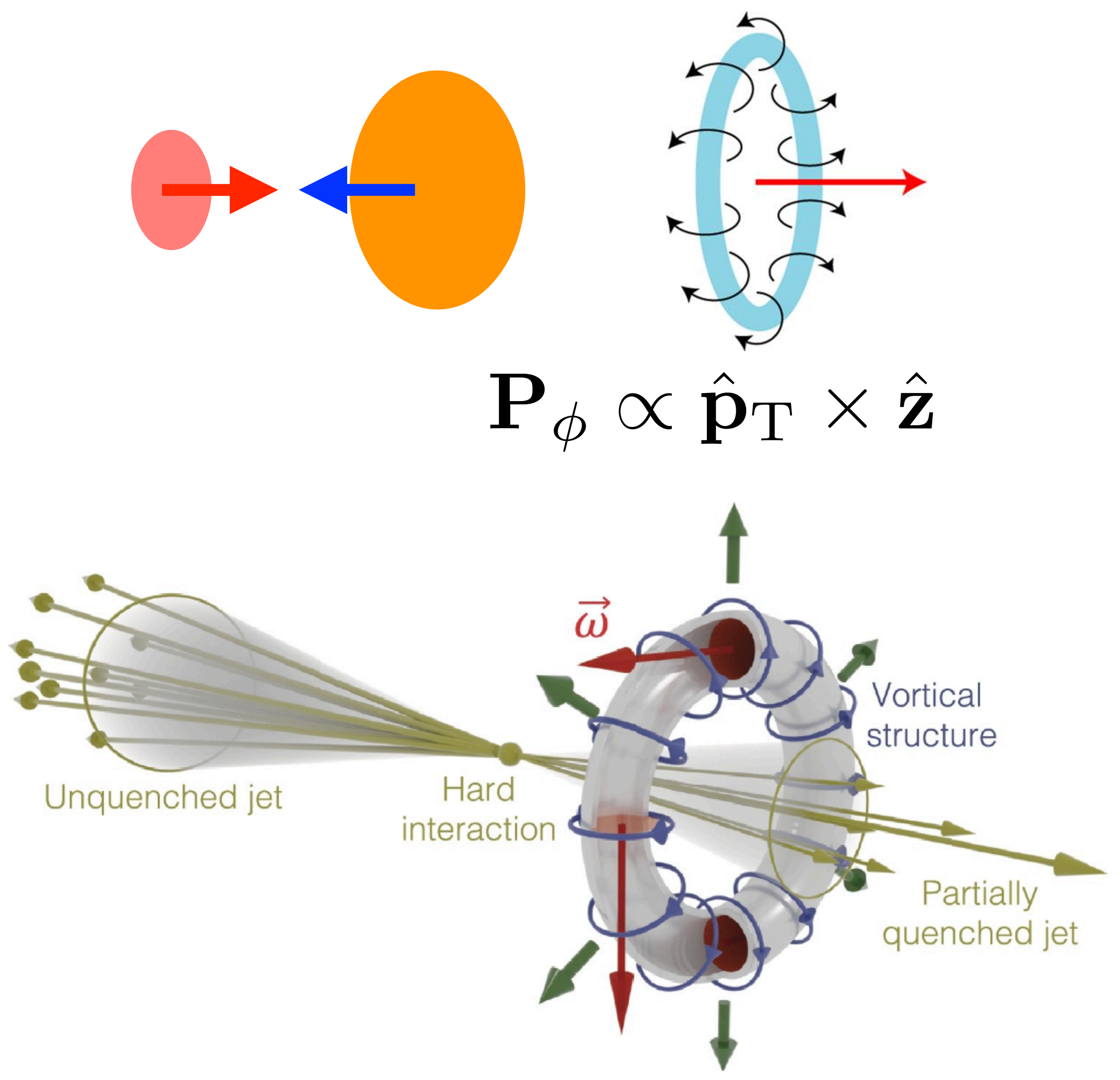
Incomplete thermal equilibrium of spin degree of freedom as the flow develops later in time? "shear tensor" explains everything?

Local vorticity

Vortex induced by jet or in asymmetric collisions

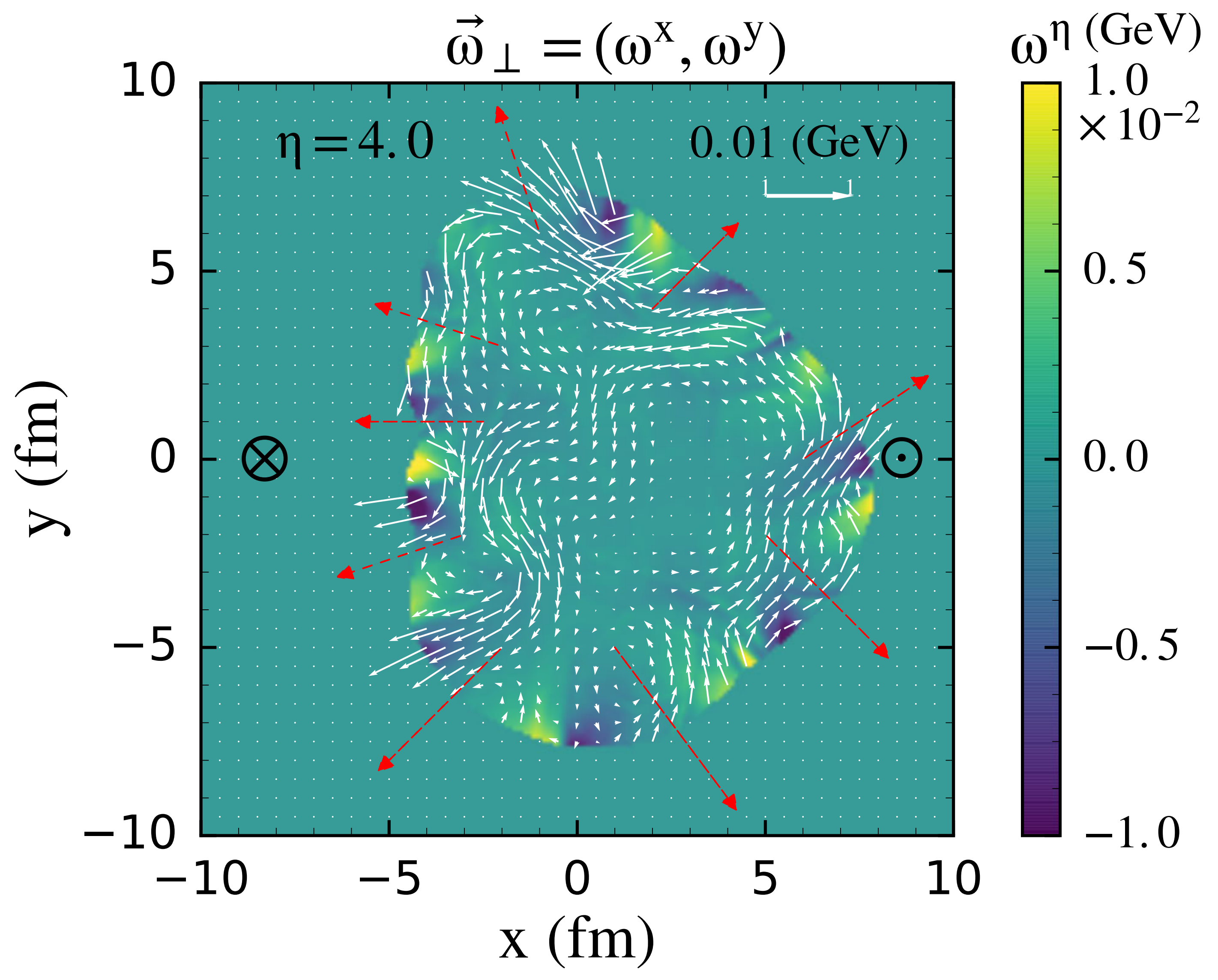


Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023
B. Betz et al., PRC76.044901 (2007)



S. Voloshin, EPJ Web Conf.171, 07002 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)

Local vorticity induced by collective expansion with density fluctuations



L.-G. Pang et al., PRL117, 192301 (2016)
X.-L. Xia et al., PRC98.024905 (2018)

Complex vortical structures are expected!