Spin and quantum features of QCD plasma

ECT*, (Trento, Italy)

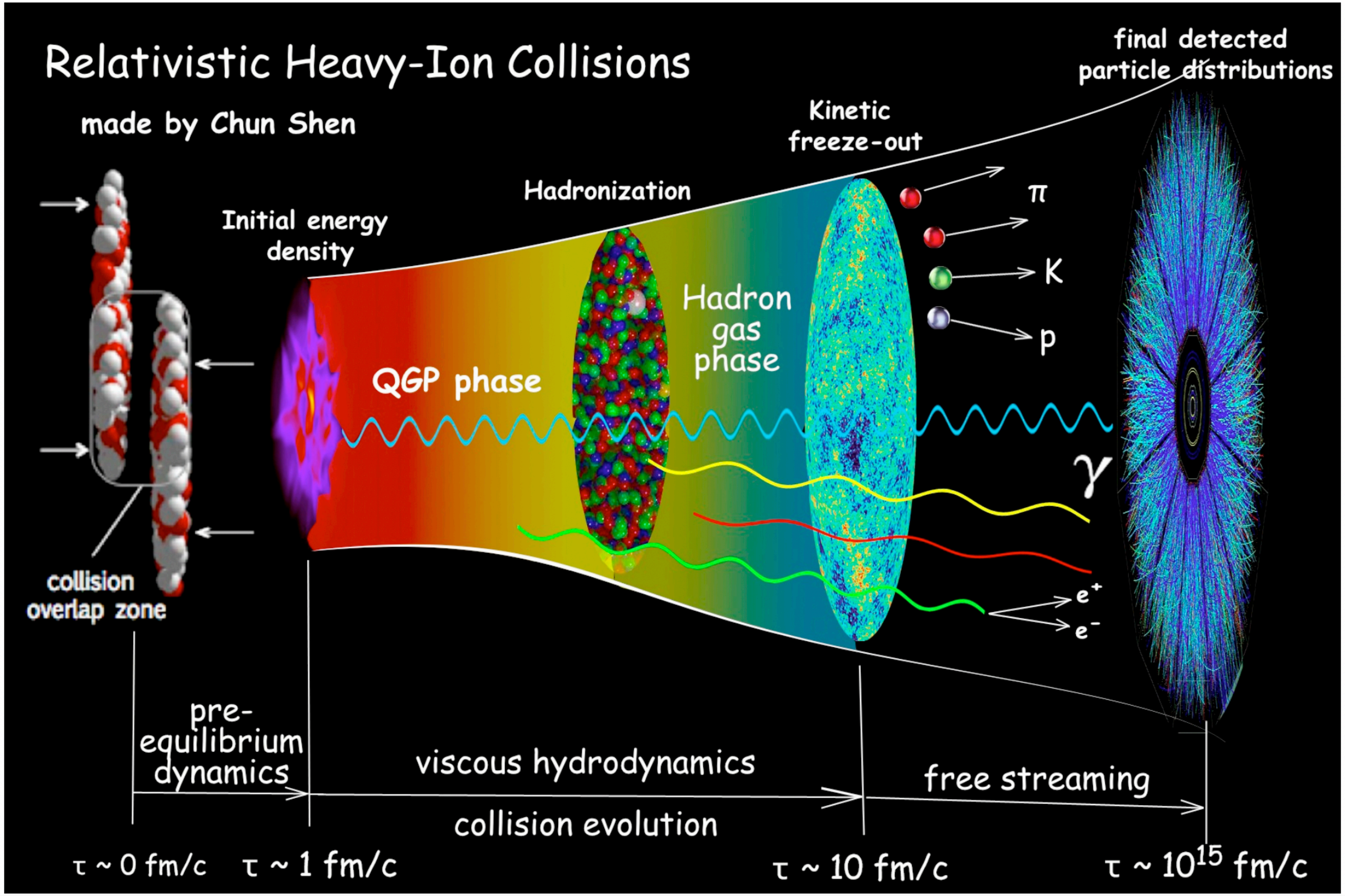
Spin polarization measurements in relativistic collisions

Debojit Sarkar

Niels Bohr Institute
University of Copenhagen
Denmark

THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Relativistic heavy-ion collisions

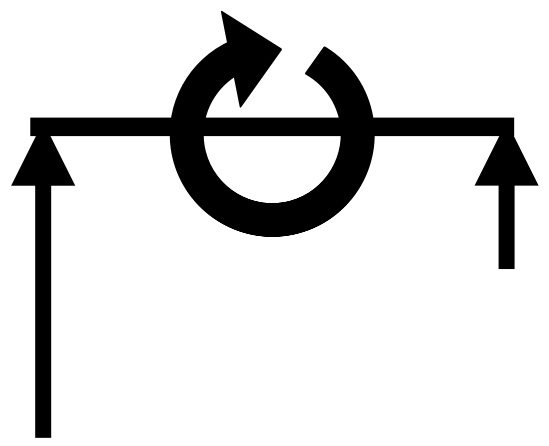


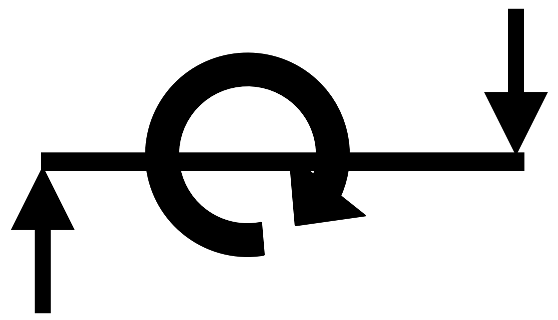
- Evolution of the medium is characterised by non-trivial velocity and vorticity fields.

Vorticity / Swirl / Rotation

vorticity ($\overrightarrow{\omega}$) – a measure of the “swirl” of the velocity flow field around any point

Non-relativistically: $\overrightarrow{\omega} = \frac{1}{2}\nabla \times \overrightarrow{v}$





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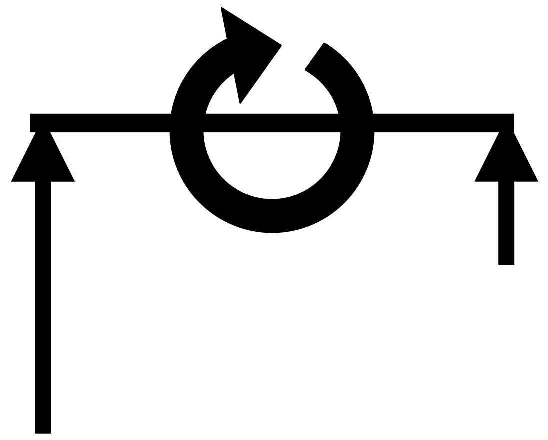
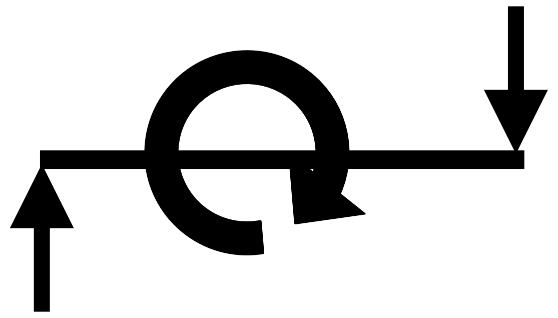
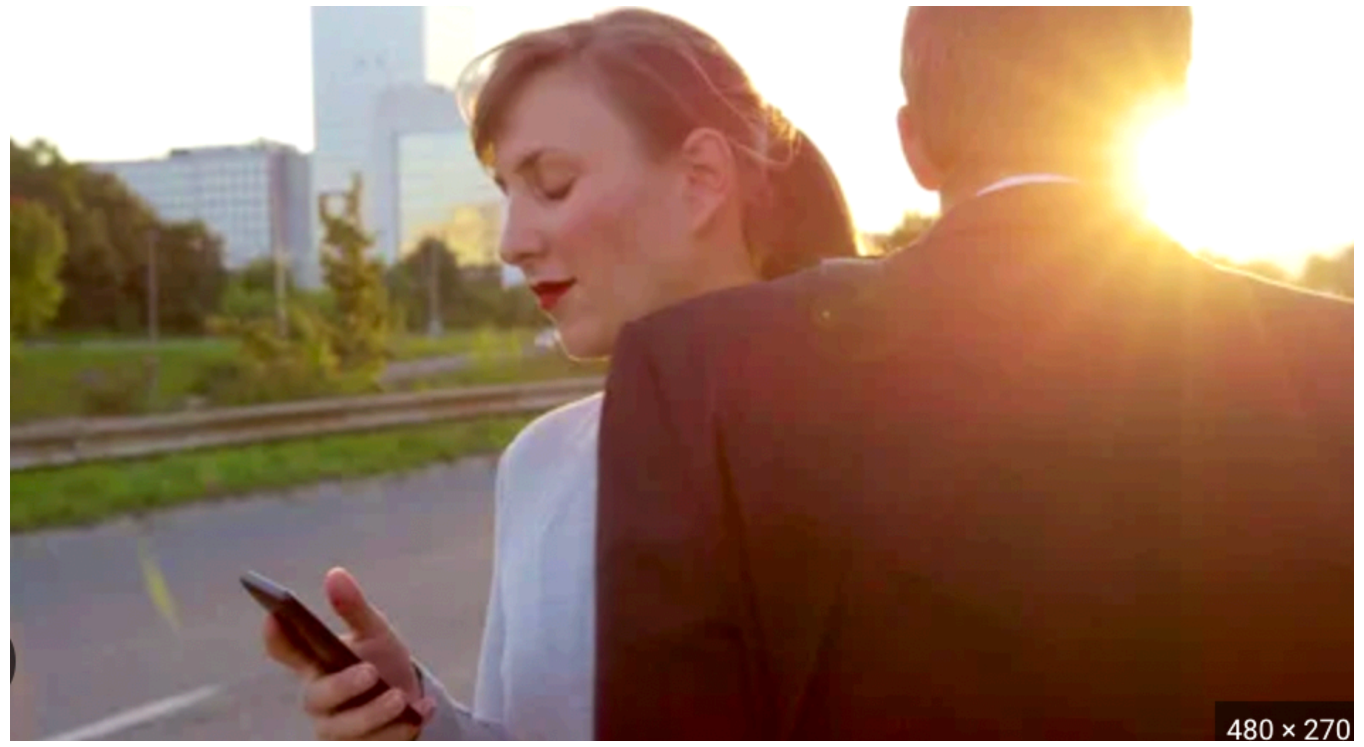
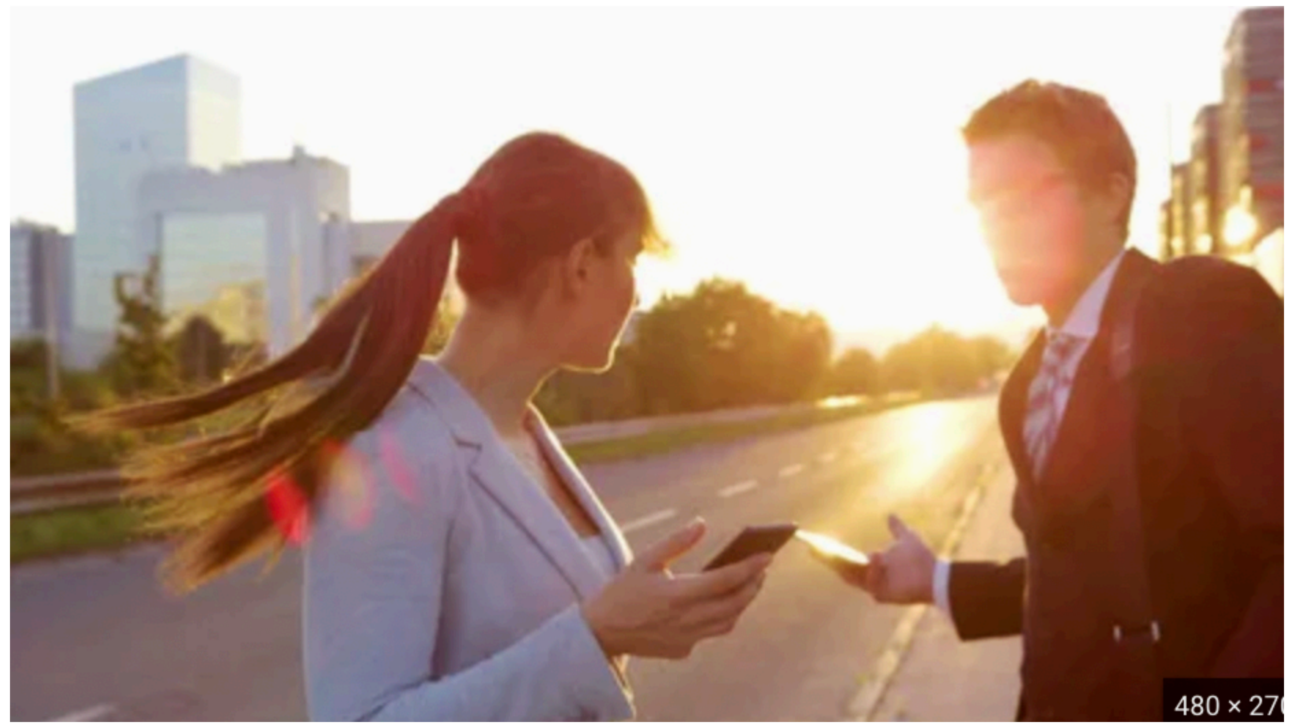




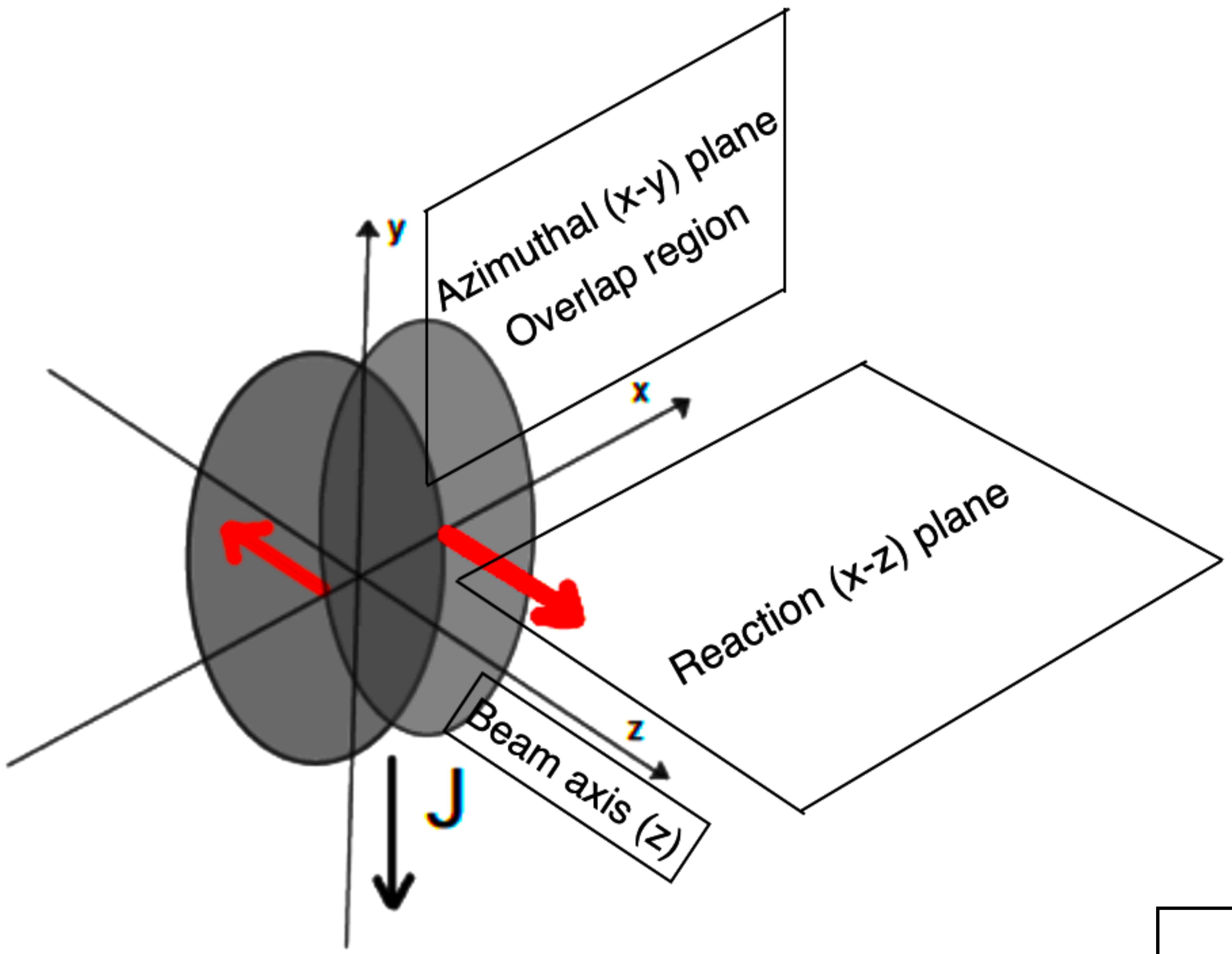
Want to experience vorticity? ⟶ Just bump into each other :)

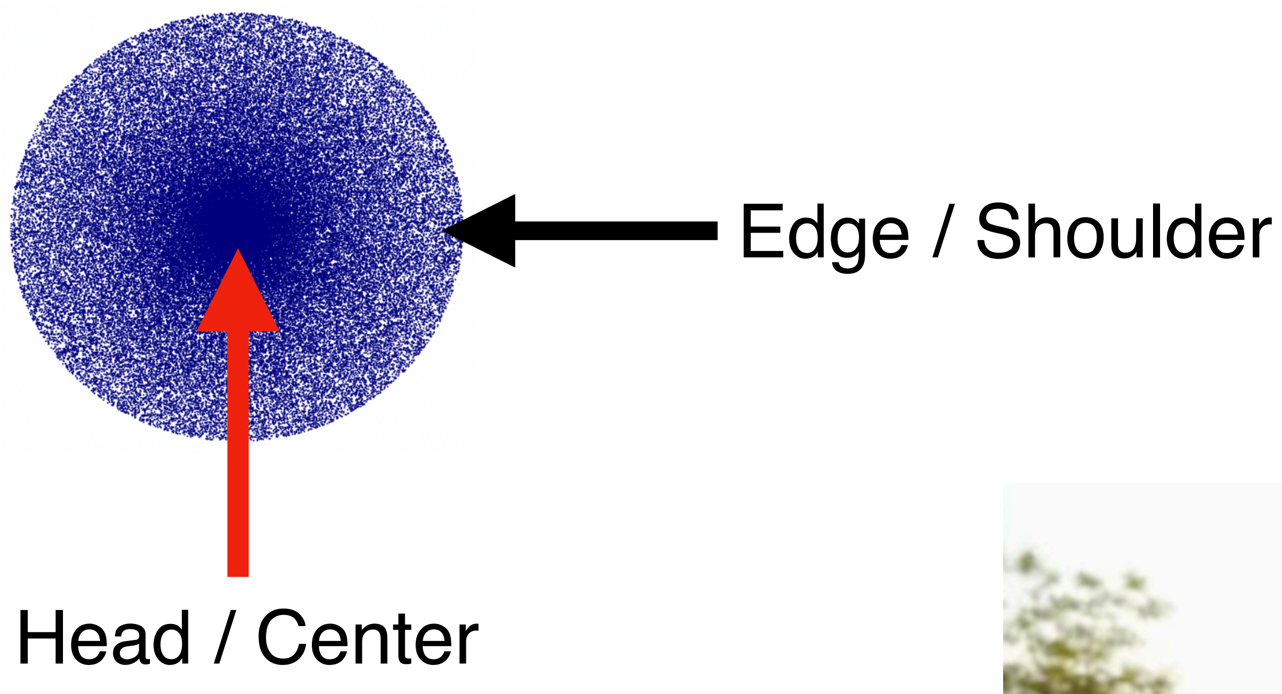


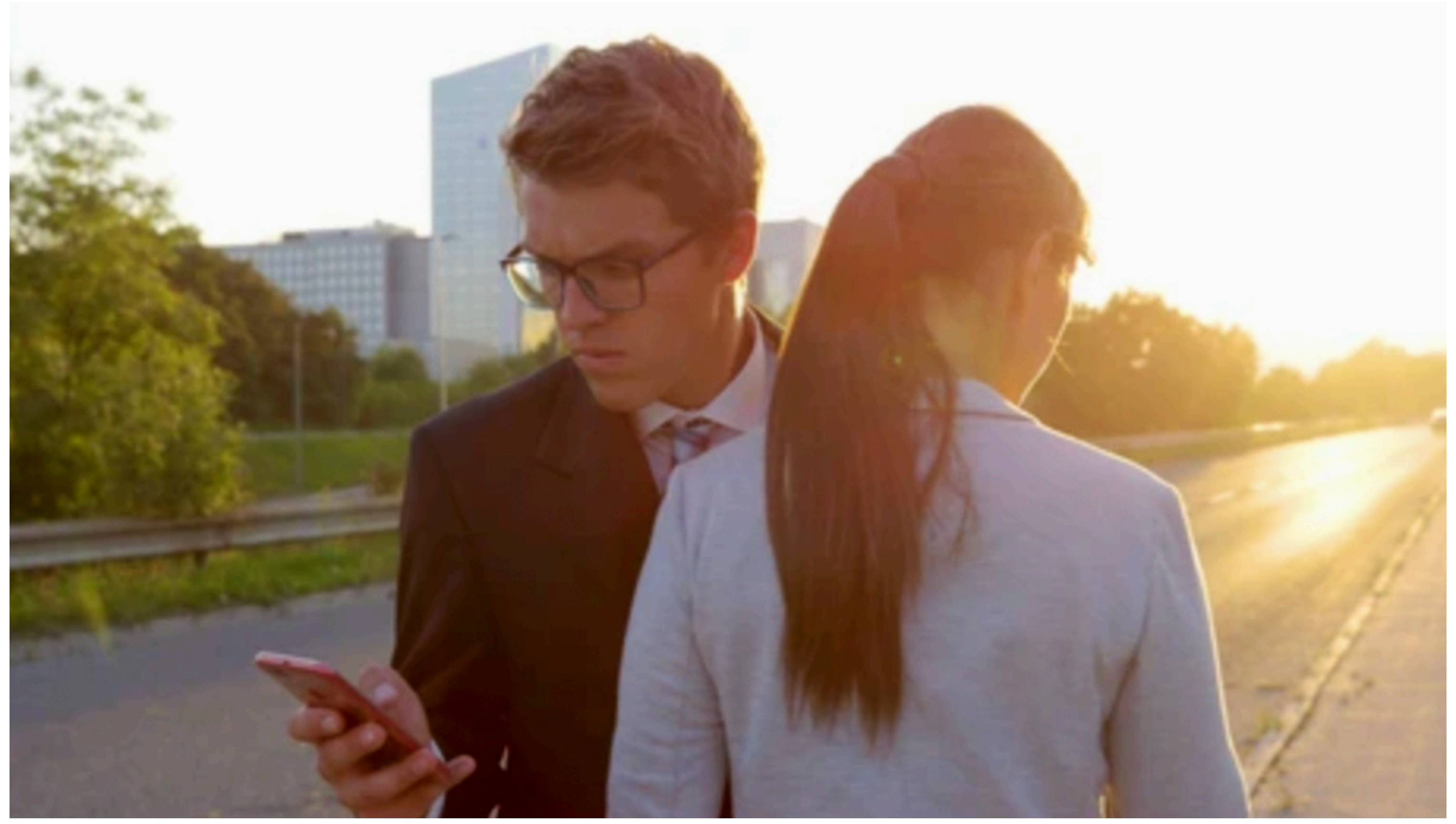


Global vorticity in heavy-ion collisions

- Relativistic Lorentz contracted nuclei bump into each other in the collider (LHC, RHIC):







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

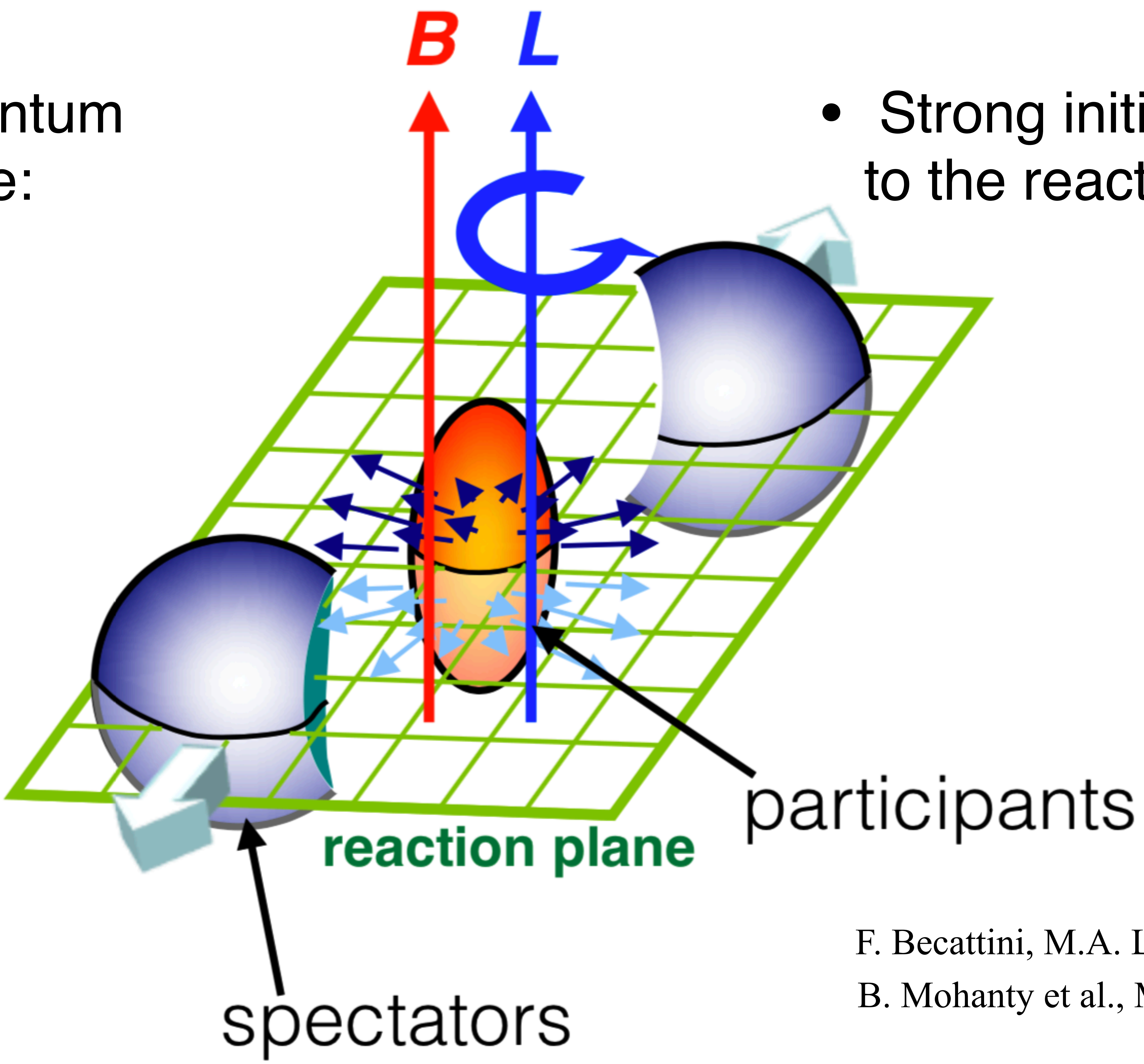
- Vorticity along the system orbital angular momentum due to initial longitudinal flow velocity gradients.

Global vorticity and polarization in heavy-ion collisions

- In relativistic non-central nuclear collisions:

- Large initial orbital angular momentum perpendicular to the reaction plane:

$$L \approx 10^5 - 10^7 \hbar$$



- Strong initial magnetic field perpendicular to the reaction plane:

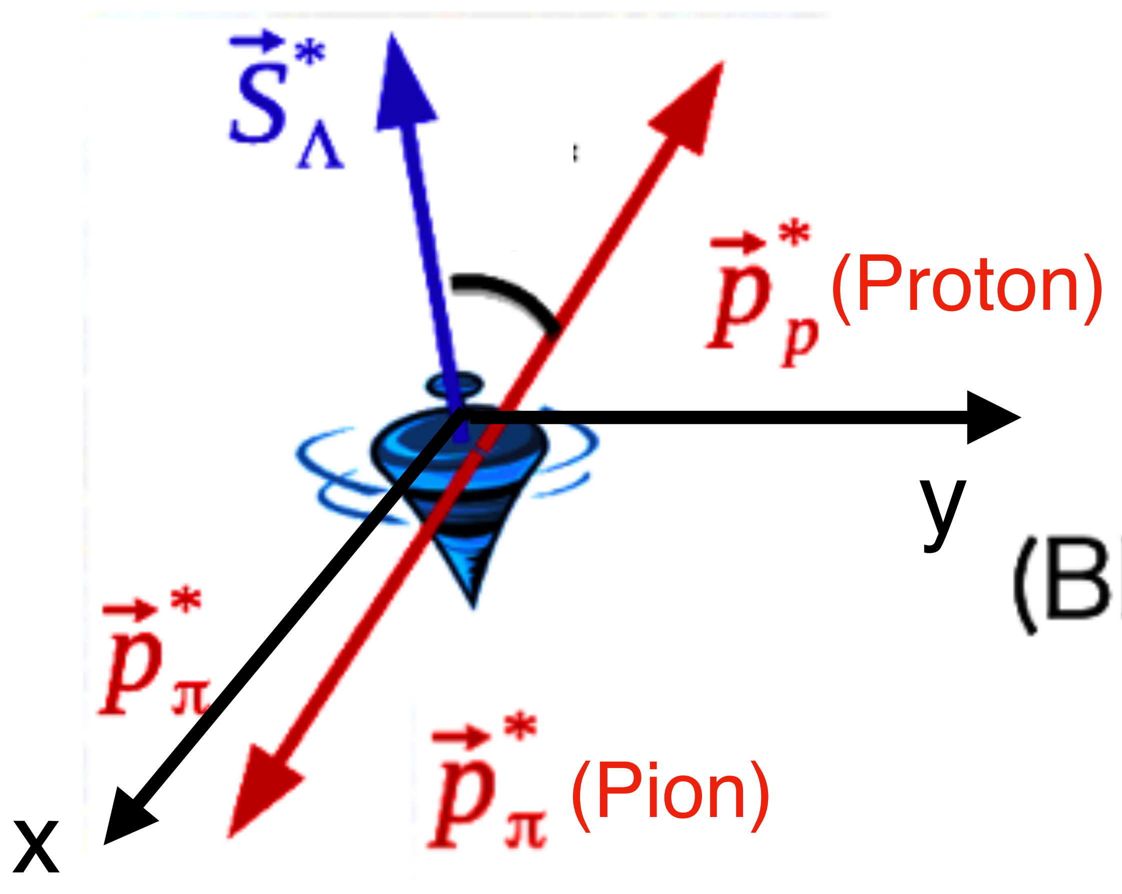
$$B \approx 10^{13} - 10^{14}\ \text{T}$$

F. Becattini, M.A. Lisa, Annu. Rev. Nucl. Part. Sci. 70, 395 (2020).
B. Mohanty et al., Mod. Phys. Lett. A 36, 2130026 (2021).

- Polarization due to vorticity ($\vec{L}$) ⟶ $\vec{L}.\vec{S}$ (same for particle and anti-particle)
- Polarization due to Magnetic field ($\vec{B}$) ⟶ $\vec{\mu}\,.\,\vec{B}$ (opposite for particle and anti-particle)

Hyperon polarization estimation

Λ ($\bar{\Lambda}$) hyperons ⟶ Parity violating weak decay (self analyzing)



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

(BR: 63.9%, cτ~7.9 cm)

- Daughter baryon is preferentially emitted in the direction of hyperon spin in hyperon rest frame.

Hyperon polarization estimation

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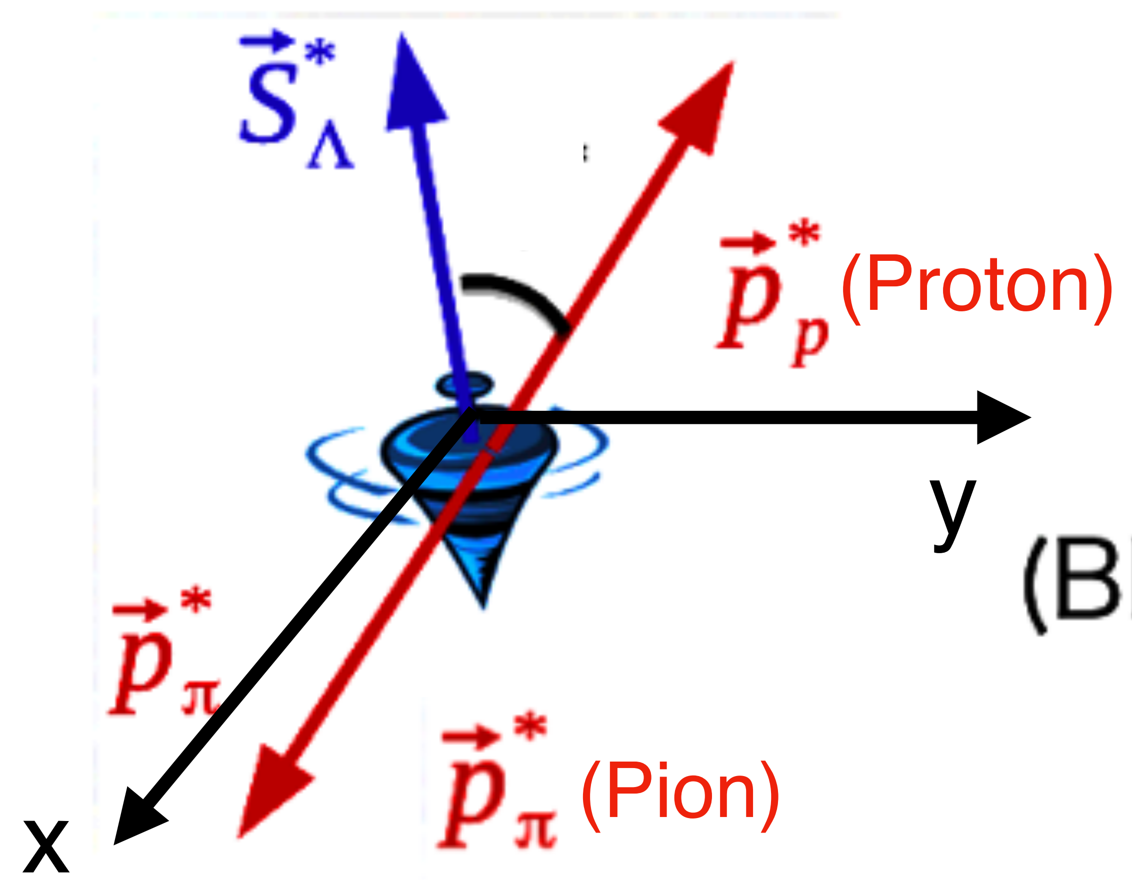


$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ~7.9 cm)

- Daughter baryon is preferentially emitted in the direction of hyperon spin in hyperon rest frame.

- Polarization estimation procedure:

a) Project the daughter proton's momentum direction on the vorticity axis.

b) Average over all hyperons.

$\hat{\mathbf{p}}^*_\mathrm{p}$ = unit vector along daughter momentum

Hyperon polarization along $\hat{L}$:

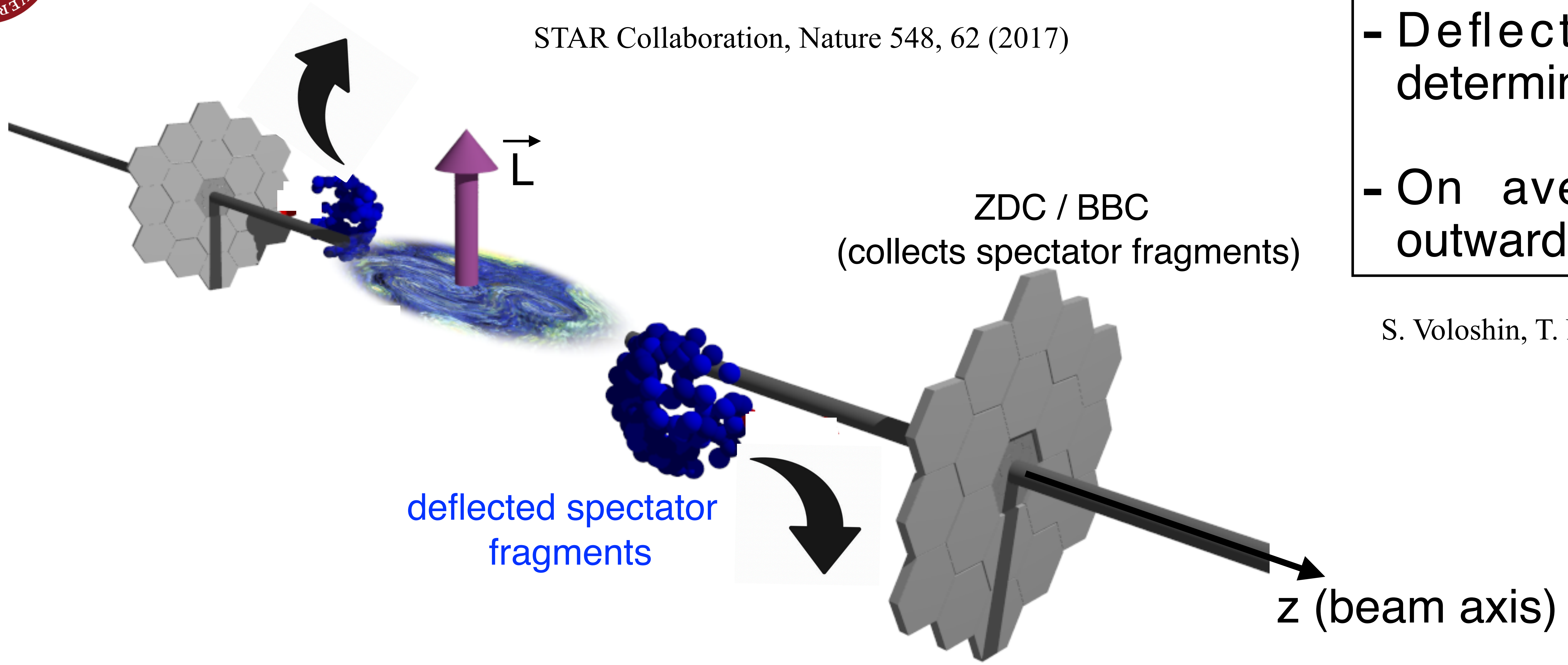
$$P_H = \frac{3}{\alpha_H}\langle(\hat{L}\cdot\hat{p}^*_p)\rangle \approx \langle \hat{L}\,.\,\hat{S}\rangle$$

α_H = hyperon decay parameter

Global polarization ⟶ one polarization direction (along $\hat{L}$) for the entire system.

Global hyperon polarization measurement in heavy-ion collisions

STAR Collaboration, Nature 548, 62 (2017)

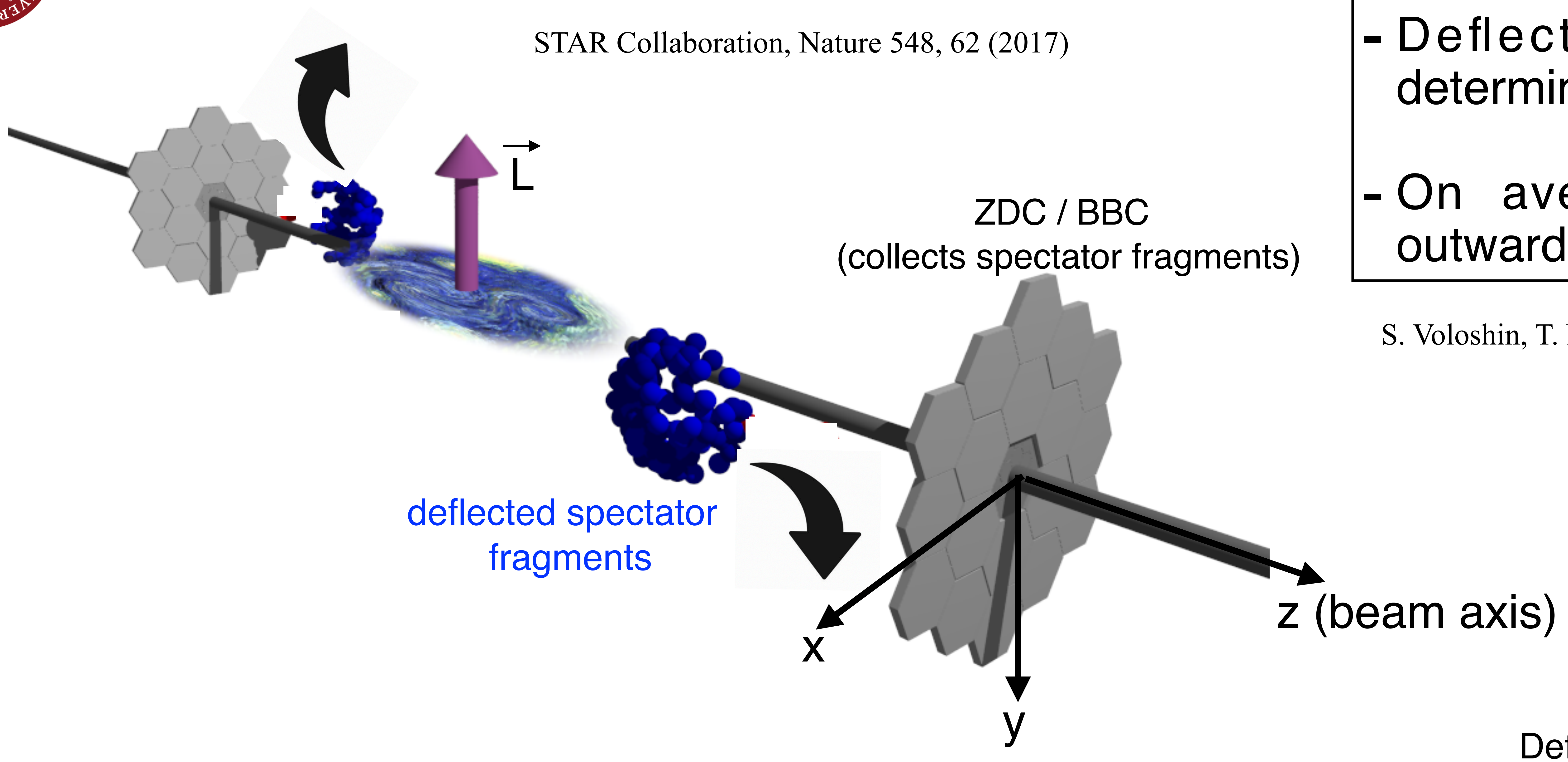


- Deflection of the spectators determines the direction of $\vec{L}$
- On average spectators deflect outwards.

S. Voloshin, T. Niida; Phys. Rev. C 94, 021901(R) (2016)

Global hyperon polarization measurement in heavy-ion collisions

STAR Collaboration, Nature 548, 62 (2017)



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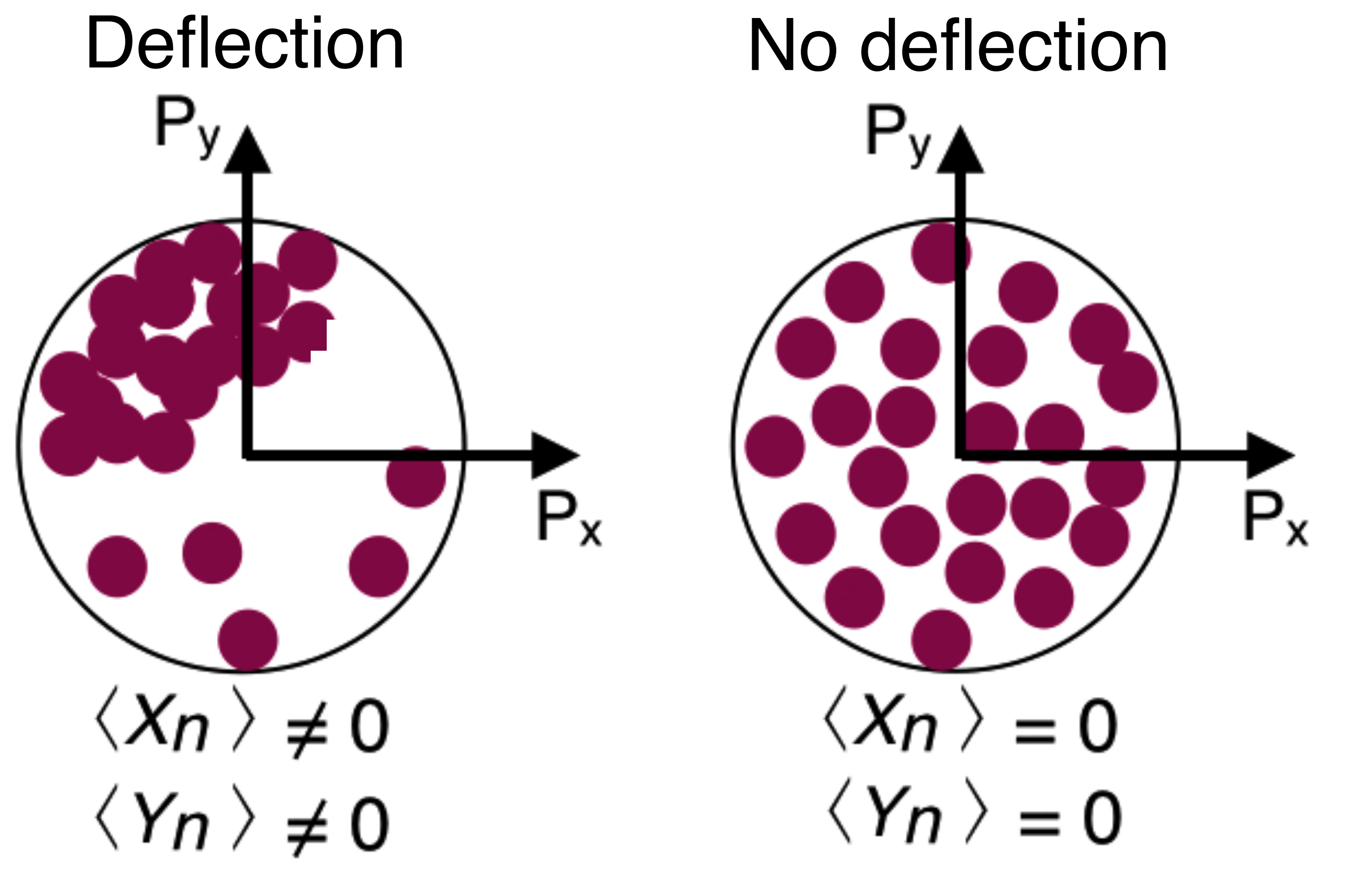
S. Voloshin, T. Niida; Phys. Rev. C 94, 021901(R) (2016)



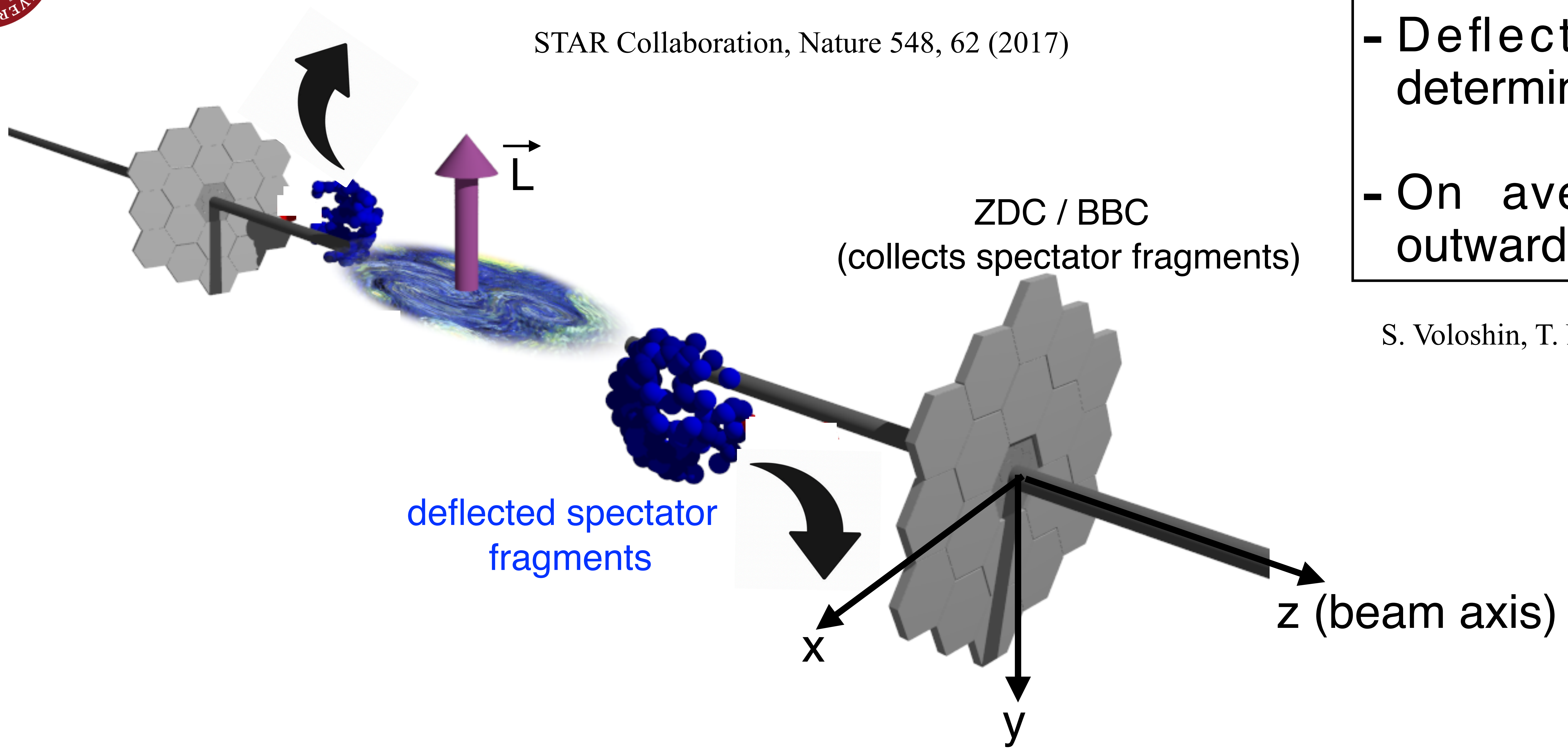
- Azimuthal distribution of the spectator fragments in the ZDC:

(Estimates spectator plane angle (Ψ_{SP}) ⟶ information about $\vec{L}$)

$$\Psi_{SP} = \tan^{-1}\left(\frac{Y_1}{X_1}\right)$$

Global hyperon polarization measurement in heavy-ion collisions

STAR Collaboration, Nature 548, 62 (2017)



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- Global hyperon polarization: $P_H = \frac{3}{\alpha_H}\langle(\hat{L}\cdot p_p^*)\rangle \approx \langle \hat{L}\,.\,\hat{S}\rangle$

$$P_{\rm H} = -\frac{8}{\pi\alpha_{\rm H}}\frac{\langle \sin(\varphi_{\rm p}^* - \Psi_{\rm SP})\rangle}{R_{SP}^1}$$

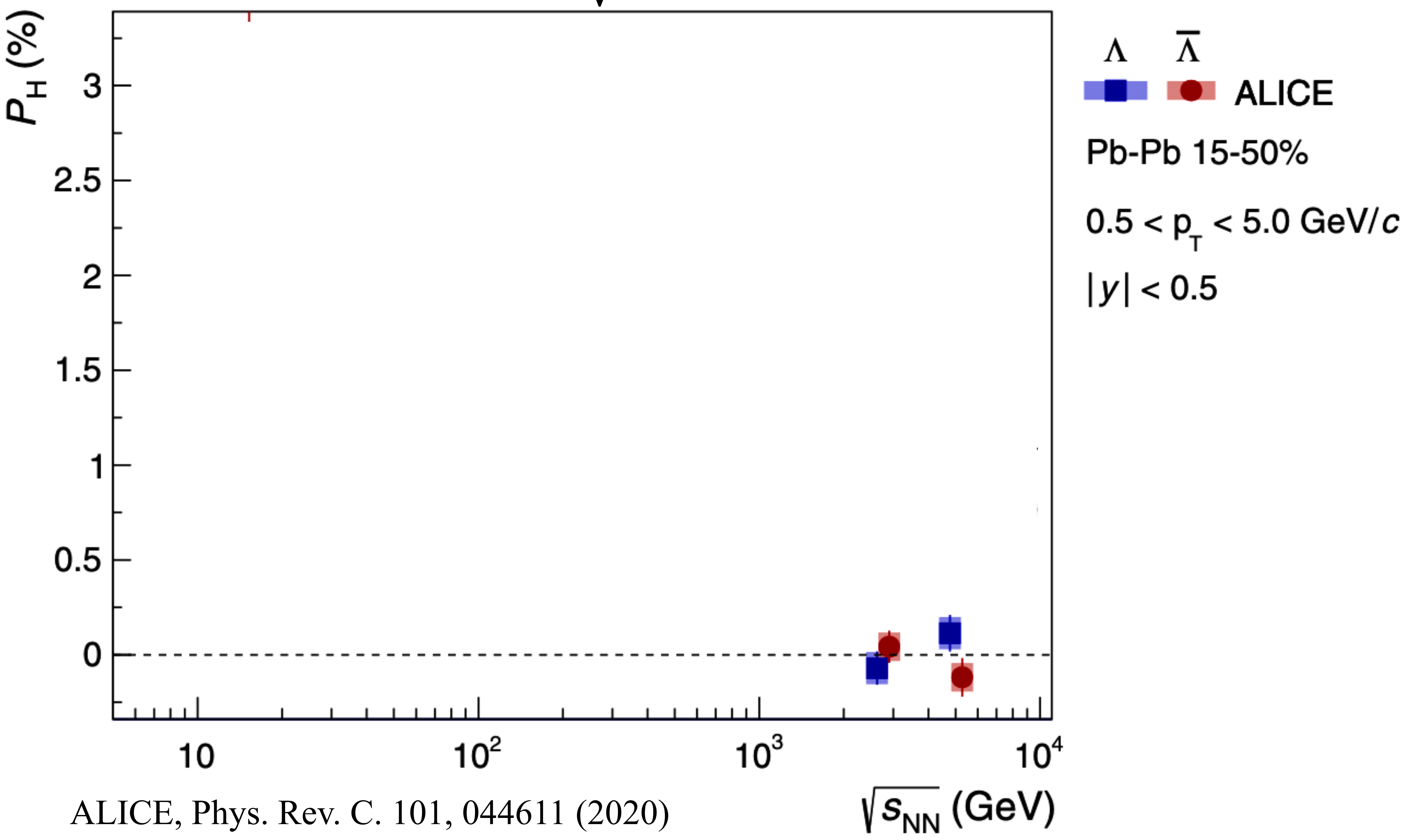
ALICE, Phys. Rev. C 101, 044611 (2020)[erratum]

α_H = hyperon decay parameter

- $\varphi_{\rm p}^*$ = azimuthal angle of daughter proton in $\Lambda(\bar{\Lambda})$ rest frame
- $R_{\rm SP}^1$ = Resolution of $\Psi_{\rm SP}$

$\Lambda(\bar{\Lambda})$ polarization in heavy-ion collisions: $\sqrt{s_{NN}}$ dependence

$L \approx bA\sqrt{s_{NN}}$ →



ALICE, Phys. Rev. C. 101, 044611 (2020)

PHYSICAL REVIEW C **101**, 044611 (2020)

Global polarization of Λ and $\bar{\Lambda}$ hyperons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

S. Acharya *et al.**
(ALICE Collaboration)

(Received 13 September 2019; accepted 24 February 2020; published 20 April 2020)

The global polarization of the Λ and $\bar{\Lambda}$ hyperons is measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV recorded with the ALICE at the Large Hadron Collider (LHC). The results are reported differentially as a function of collision centrality and hyperon's transverse momentum (p_T) for the range of centrality 5–50%, $0.5 < p_T < 5$ GeV/c, and rapidity $|y| < 0.5$. The hyperon global polarization averaged for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV is found to be consistent with zero, $\langle P_H \rangle (\%) \approx 0.01 \pm 0.06$ (stat.) ± 0.03 (syst.) in the collision centrality range 15–50%, where the largest signal is expected. The results are compatible with expectations based on an extrapolation from measurements at lower collision energies at the Relativistic Heavy Ion Collider, hydrodynamical model calculations, and empirical estimates based on collision energy dependence of directed flow, all of which predict the global polarization values at LHC energies of the order of 0.01%.

DOI: 10.1103/PhysRevC.101.044611

- Global hyperon polarization at the LHC (ALICE) is consistent with zero.

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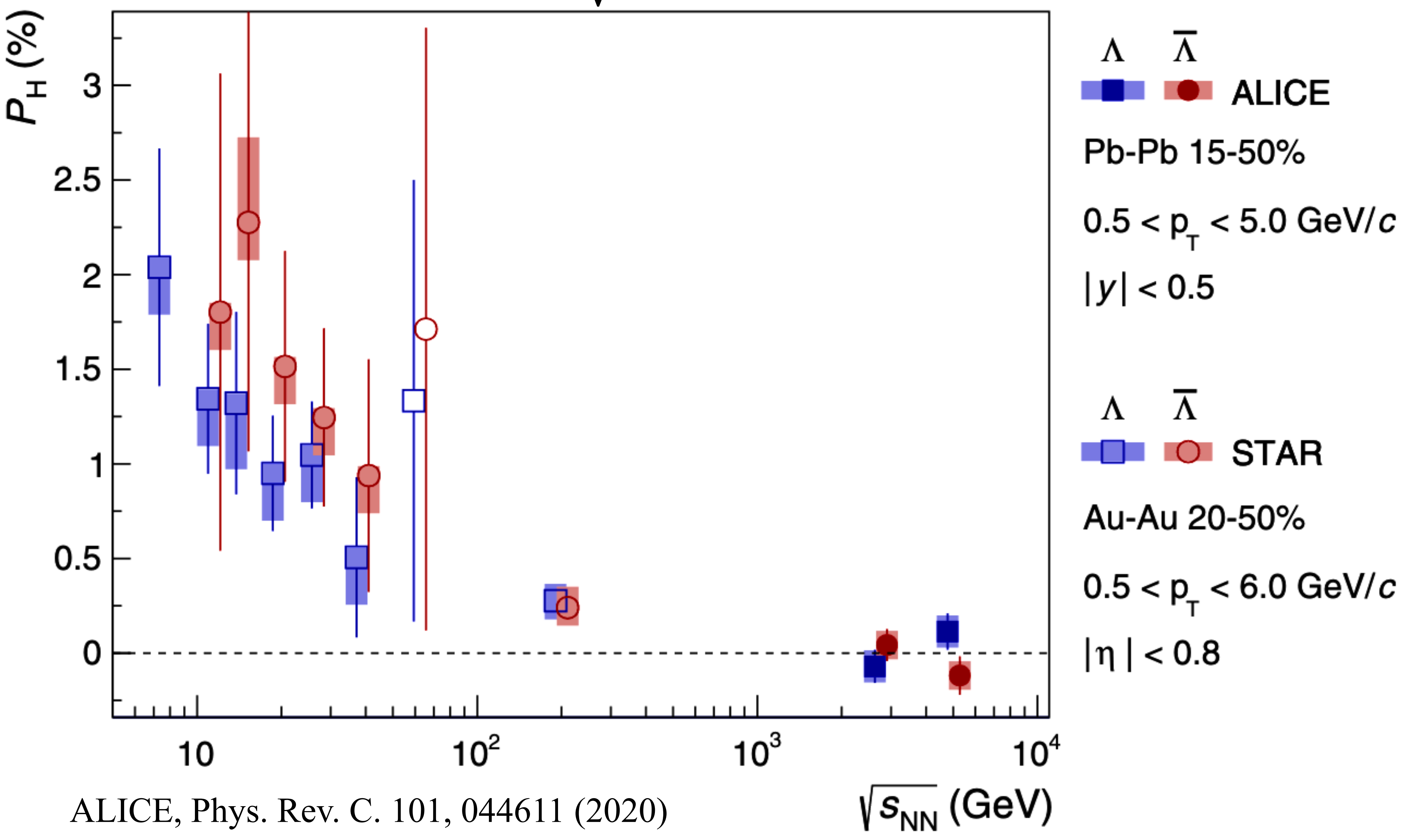
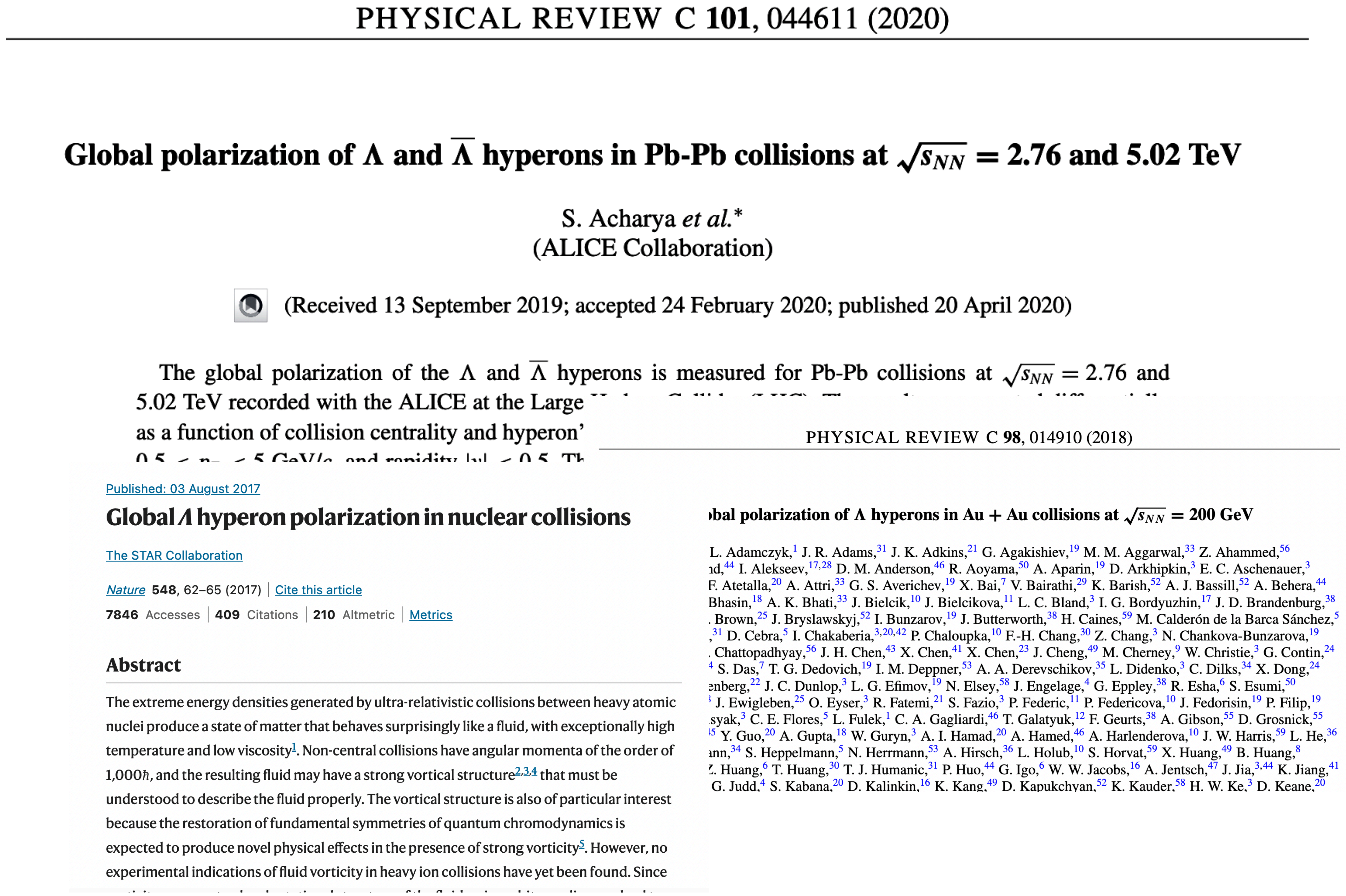


ALICE, Phys. Rev. C. 101, 044611 (2020)

STAR, Phys. Rev. C 98, 014910 (2018)



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Published: 03 August 2017

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration

Nature 548, 62–65 (2017) | Cite this article

7846 Accesses | 409 Citations | 210 Altmetric | Metrics

Abstract

The extreme energy densities generated by ultra-relativistic collisions between heavy atomic nuclei produce a state of matter that behaves surprisingly like a fluid, with exceptionally high temperature and low viscosity[1]. Non-central collisions have angular momenta of the order of 1,000ħ, and the resulting fluid may have a strong vortical structure[2,3,4] that must be understood to describe the fluid properly. The vortical structure is also of particular interest because the restoration of fundamental symmetries of quantum chromodynamics is expected to produce novel physical effects in the presence of strong vorticity[5]. However, no experimental indications of fluid vorticity in heavy ion collisions have yet been found. Since

PHYSICAL REVIEW C **98**, 014910 (2018)

obal polarization of Λ hyperons in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

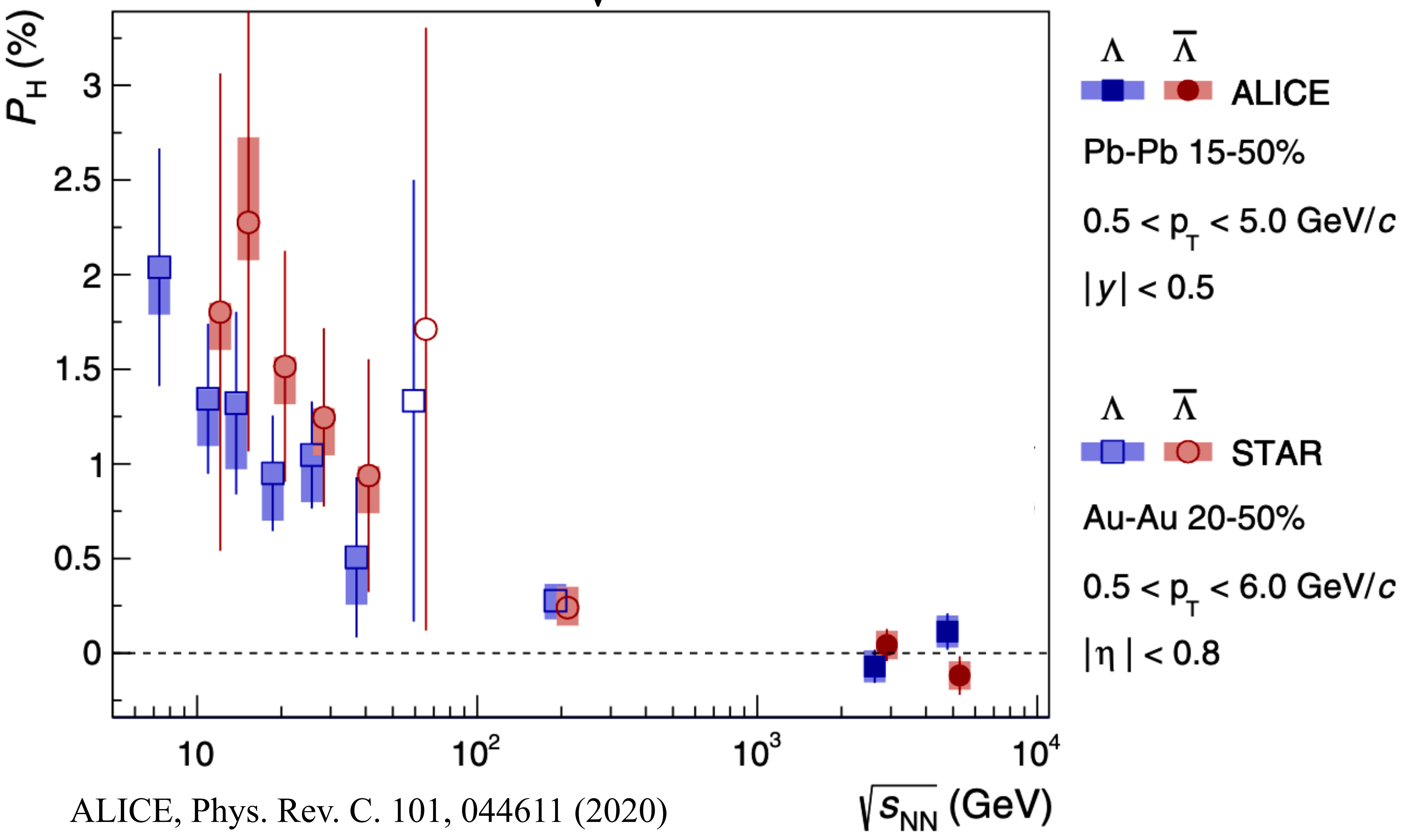
L. Adamczyk,[1] J. R. Adams,[31] J. K. Adkins,[21] G. Agakishiev,[19] M. M. Aggarwal,[33] Z. Ahammed,[56] ıd,[44] I. Alekseev,[17,28] D. M. Anderson,[46] R. Aoyama,[50] A. Aparin,[19] D. Arkhipkin,[3] E. C. Aschenauer,[3] F. Atetalla,[20] A. Attri,[33] G. S. Averichev,[19] X. Bai,[7] V. Bairathi,[29] K. Barish,[52] A. J. Bassill,[52] A. Behera,[44] Bhasin,[18] A. K. Bhati,[33] J. Bielcik,[10] J. Bielcikova,[11] L. C. Bland,[3] I. G. Bordyuzhin,[17] J. D. Brandenburg,[38] Brown,[25] J. Bryslawskyj,[52] I. Bunzarov,[19] J. Butterworth,[38] H. Caines,[59] M. Calderón de la Barca Sánchez,[5] D. Cebra,[5] I. Chakaberia,[3,20,42] P. Chaloupka,[10] F.-H. Chang,[30] Z. Chang,[3] N. Chankova-Bunzarova,[19] Chattopadhyay,[56] J. H. Chen,[43] X. Chen,[41] X. Chen,[23] J. Cheng,[49] M. Cherney,[9] W. Christie,[3] G. Contin,[24] S. Das,[7] T. G. Dedovich,[19] I. M. Deppner,[53] A. A. Derevschikov,[35] L. Didenko,[3] C. Dilks,[34] X. Dong,[24] enberg,[22] J. C. Dunlop,[3] L. G. Efimov,[19] N. Elsey,[58] J. Engelage,[4] G. Eppley,[38] R. Esha,[6] S. Esumi,[50] J. Ewigleben,[25] O. Eyser,[3] R. Fatemi,[21] S. Fazio,[3] P. Federic,[11] P. Federicova,[10] J. Fedorisin,[19] P. Filip,[19] syak,[3] C. E. Flores,[5] L. Fulek,[1] C. A. Gagliardi,[46] T. Galatyuk,[12] F. Geurts,[38] A. Gibson,[55] D. Grosnick,[55] Y. Guo,[20] A. Gupta,[18] W. Guryn,[3] A. I. Hamad,[20] A. Hamed,[46] A. Harlenderova,[10] J. W. Harris,[59] L. He,[36] ınn,[34] S. Heppelmann,[5] N. Herrmann,[53] A. Hirsch,[36] L. Holub,[10] S. Horvat,[59] X. Huang,[49] B. Huang,[8] Z. Huang,[6] T. Huang,[30] T. J. Humanic,[31] P. Huo,[44] G. Igo,[6] W. W. Jacobs,[16] A. Jentsch,[47] J. Jia,[3,44] K. Jiang,[41] G. Judd,[4] S. Kabana,[20] D. Kalinkin,[16] K. Kang,[49] D. Kapukchyan,[52] K. Kauder,[58] H. W. Ke,[3] D. Keane,[20]

ALICE, Phys. Rev. C. 101, 044611 (2020)
STAR, Phys. Rev. C 98, 014910 (2018)
STAR, Nature, volume 548, pages 62–65 (2017)

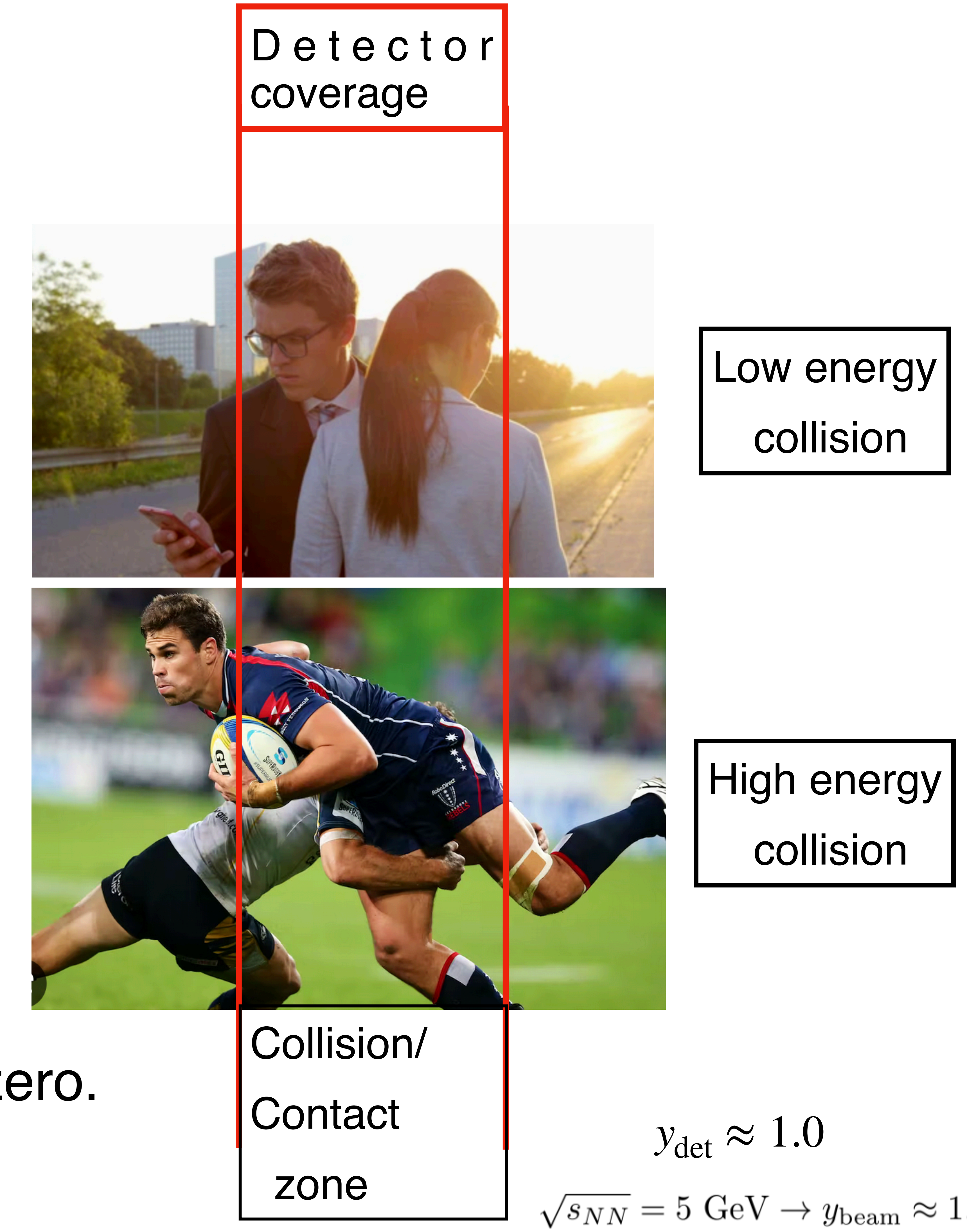
- Global hyperon polarization at the LHC (ALICE) is consistent with zero.
- Polarization at mid-rapidity decreases with collision energy.

$\Lambda(\bar{\Lambda})$ polarization in heavy-ion collisions: $\sqrt{s_{NN}}$ dependence

$L \approx bA\sqrt{s_{NN}}$ →



ALICE, Phys. Rev. C. 101, 044611 (2020)
STAR, Phys. Rev. C 98, 014910 (2018)



$y_{det} \approx 1.0$

$\sqrt{s_{NN}} = 5$ GeV $\rightarrow y_{beam} \approx 1.5$

$\sqrt{s_{NN}} = 39$ GeV $\rightarrow y_{beam} \approx 3.7$

$\sqrt{s_{NN}} = 200$ GeV $\rightarrow y_{beam} \approx 5.4$

$\sqrt{s_{NN}} = 2700$ GeV $\rightarrow y_{beam} \approx 8$

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- Polarization at mid-rapidity decreases with collision energy.
- Longitudinal boost invariance at mid-rapidity? Vorticity migrates to forward rapidity?
- For higher $\sqrt{s_{NN}}$, P_H measurement at forward rapidity needs detector upgrade.

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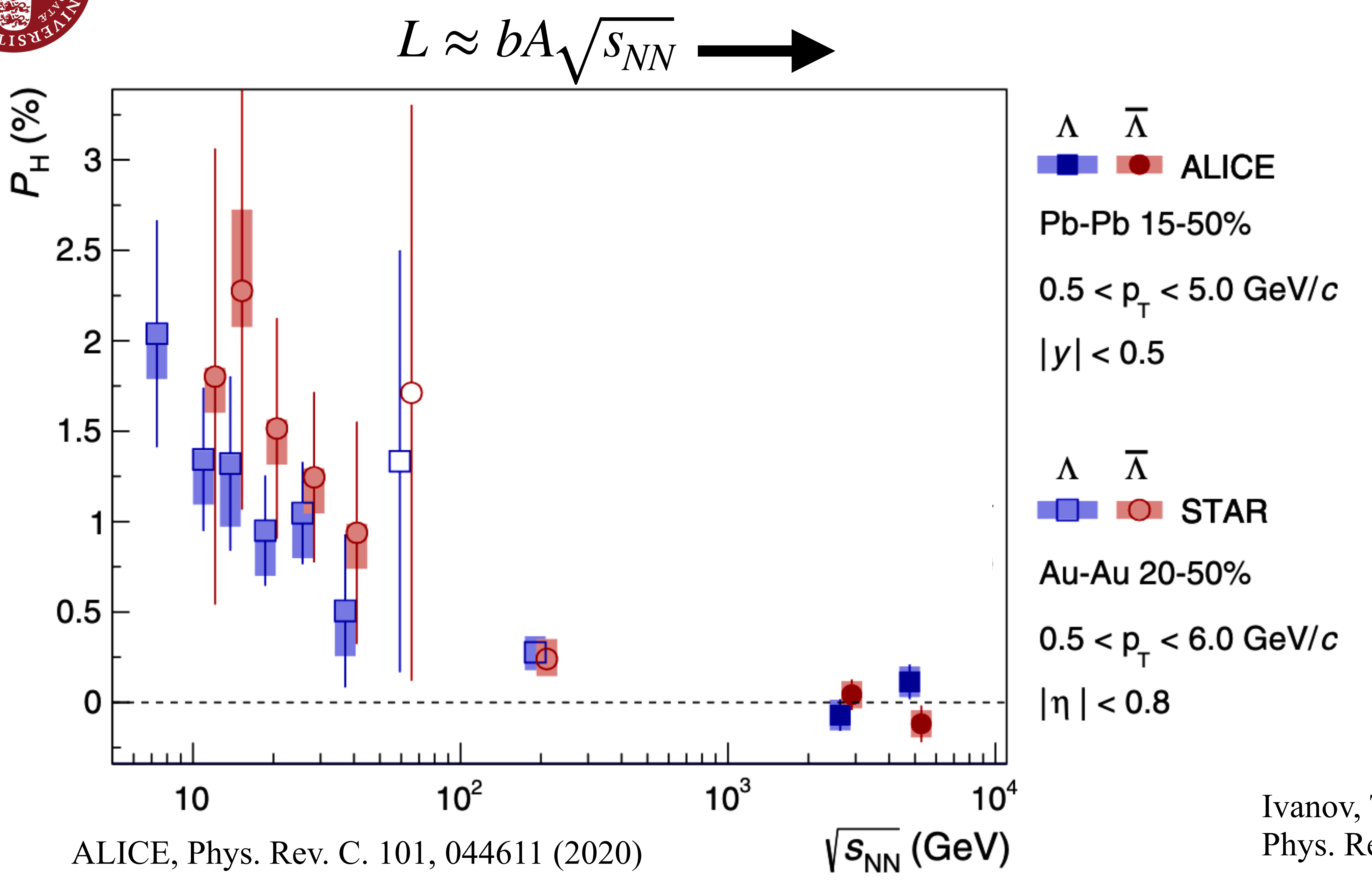
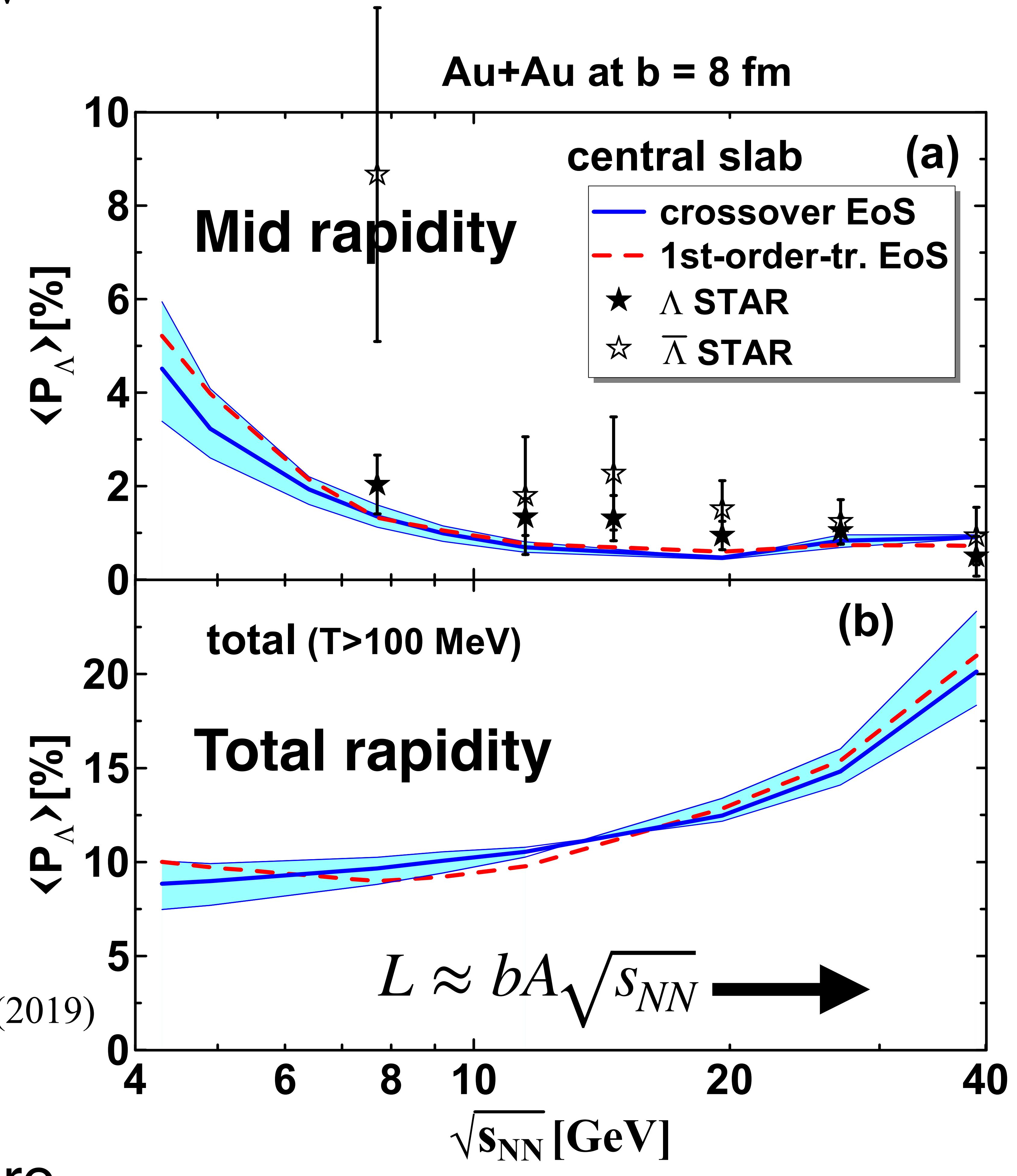


ALICE, Phys. Rev. C. 101, 044611 (2020)

STAR, Phys. Rev. C 98, 014910 (2018)



Ivanov, Toneev, Soldatov
Phys. Rev. C 100, 014908 (2019)

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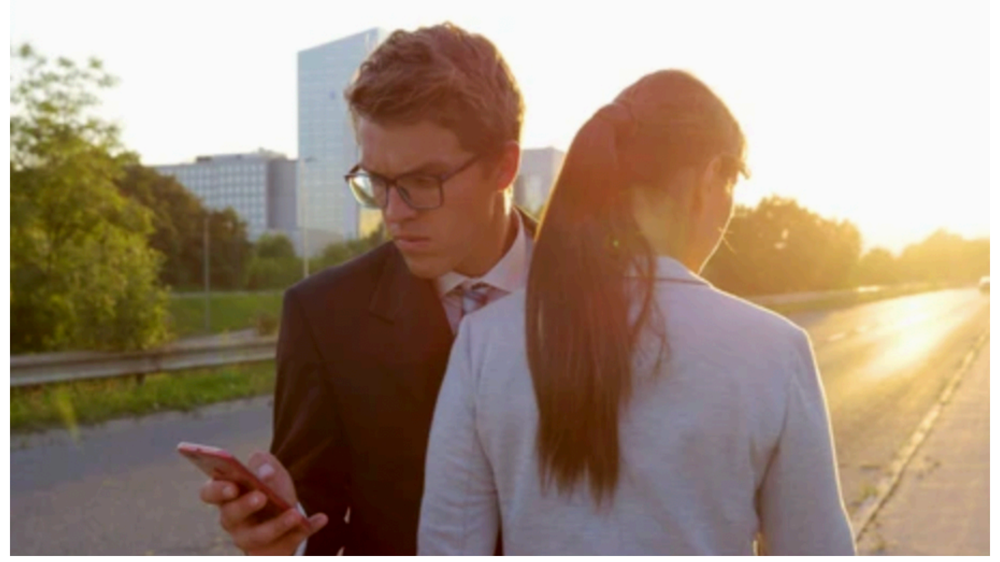
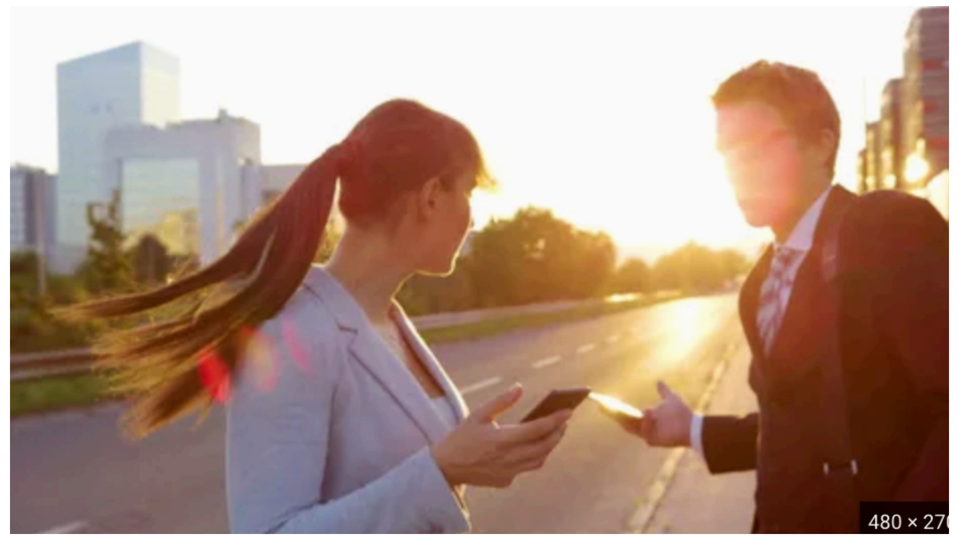
Global vorticity and directed flow from tilted source

Straight motion before collsion



Tilted motion after collsion



Directed flow:

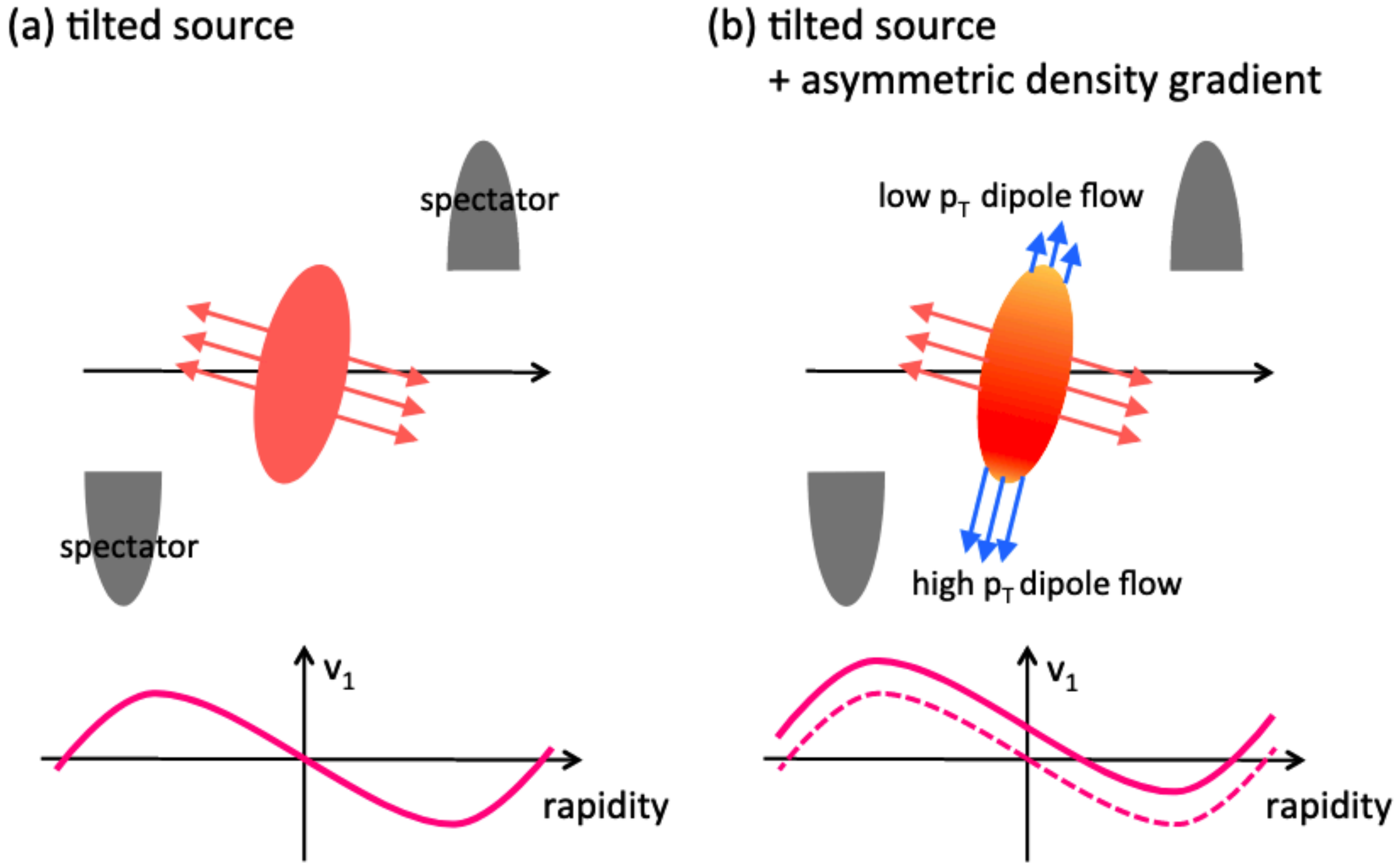
$$v_1 = \cos(\phi - \Psi_{RP})$$

- Finite vorticity (tilt) in the system → generates directed flow (V_1).

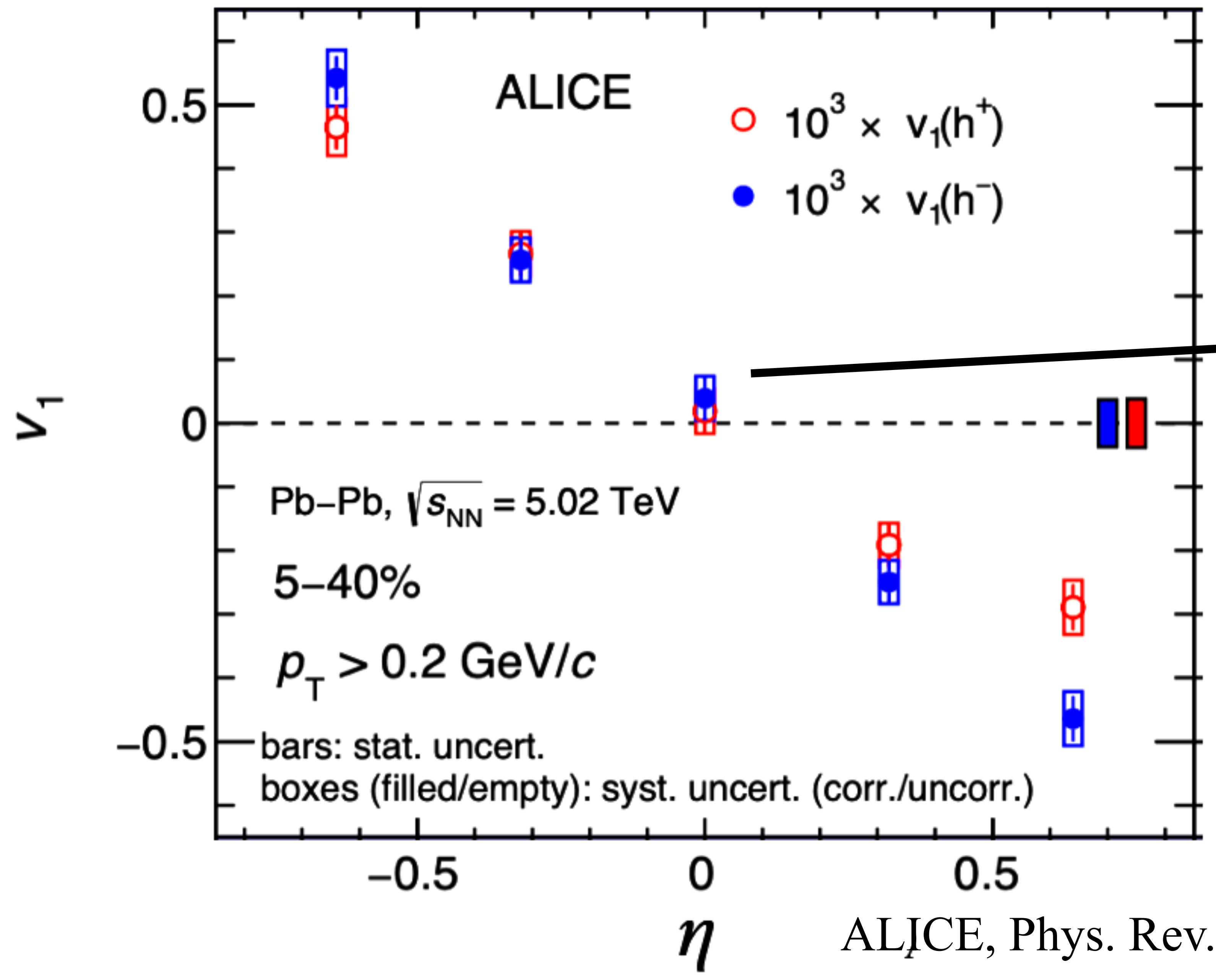
S. A. Voloshin, EPJ Web Conf., 171 (2018) 07002

- Finite v_1 in heavy-ion collisions → vorticity (tilt) must be present.

Becattini et al, Eur. Phys. J. C **78,** 354 (2018) (arXiv:1501.04468 [nucl-th] v3)



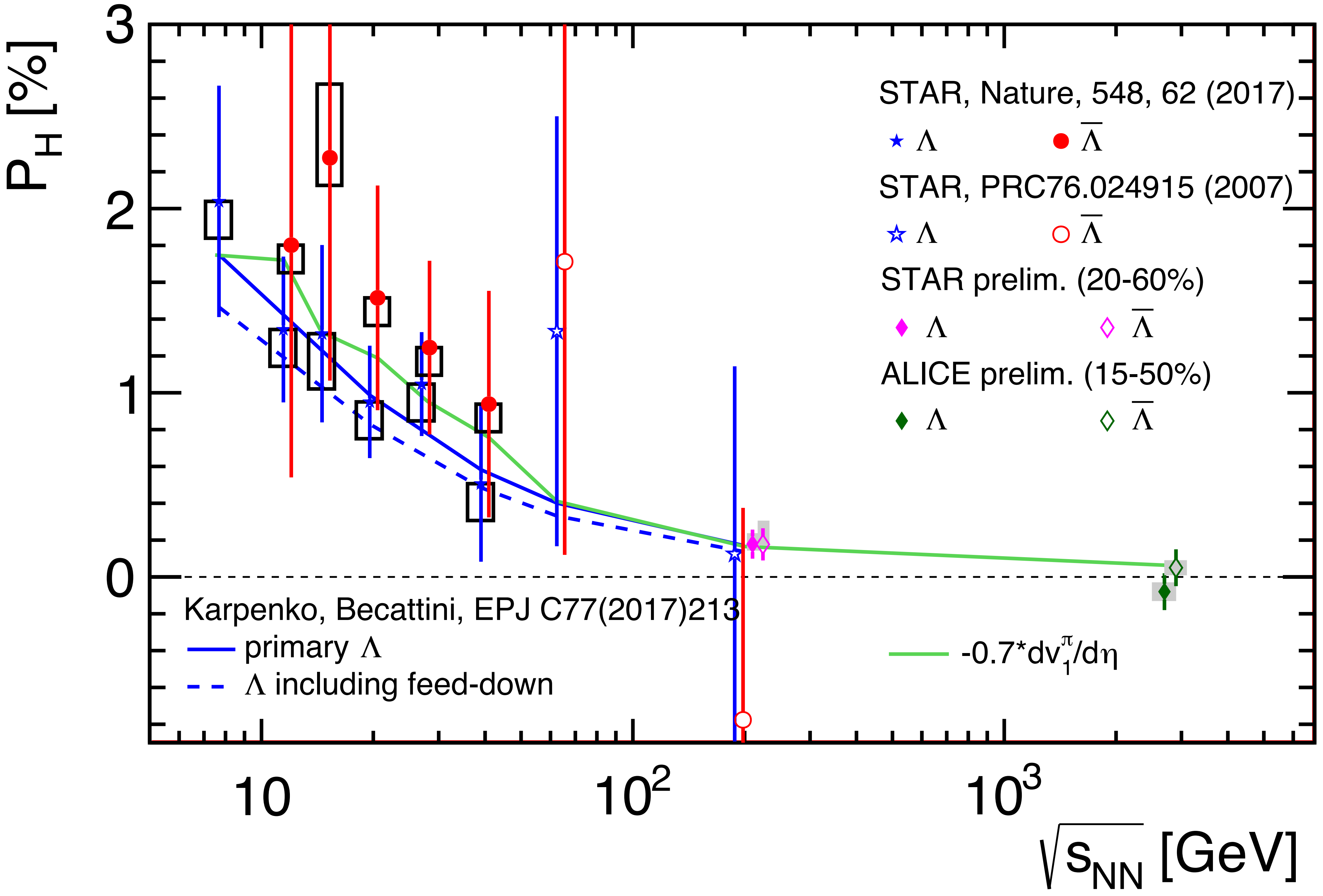
STAR Collaboration, Phys. Rev. C 98, 014915



$\frac{dv_1}{d\eta}$ is a measure of the tilt (vorticity)

ALICE, Phys. Rev. Lett. 125 (2020) 022301

Global vorticity and directed flow from tilted source



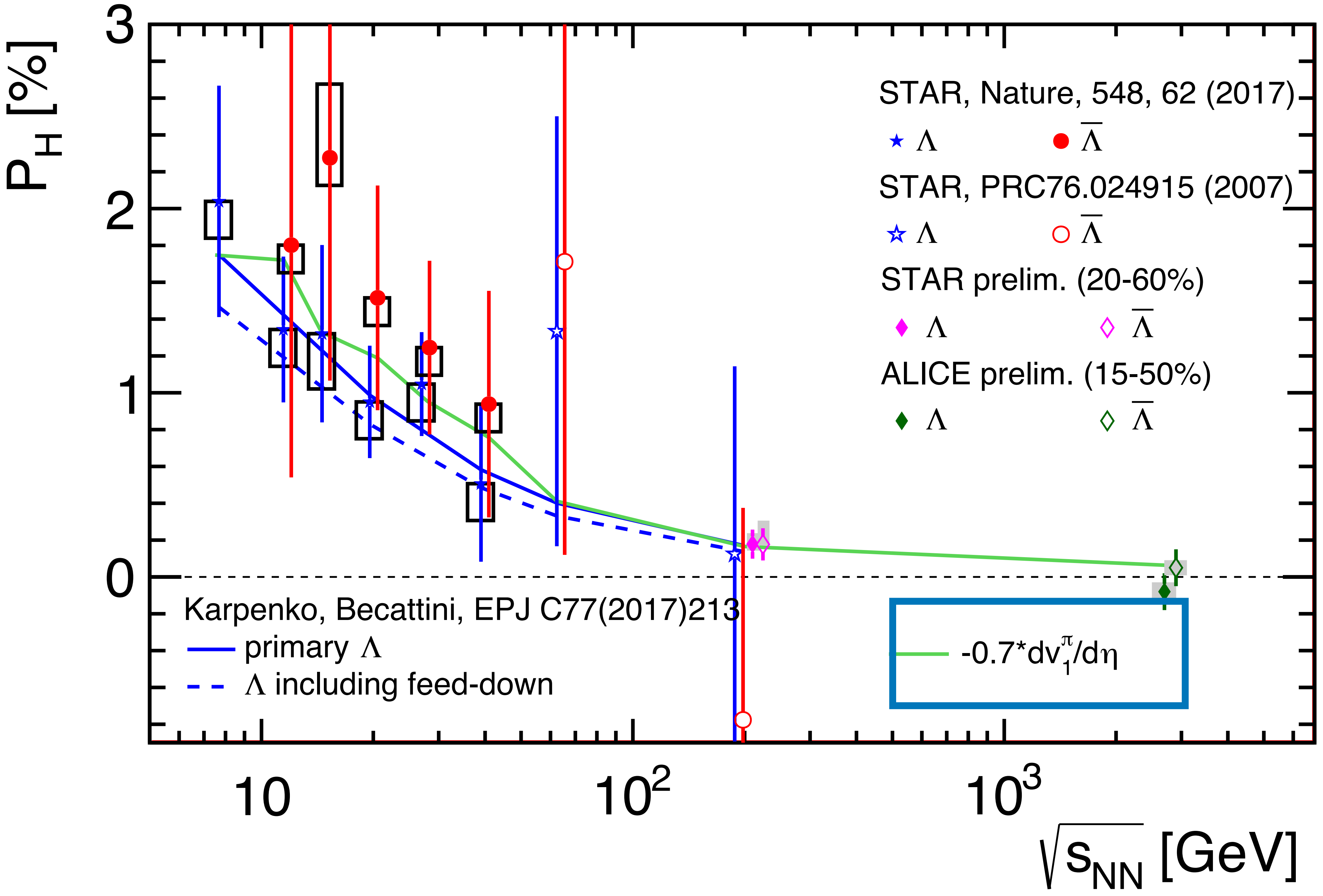
S. Voloshin, EPJ Web Conf., 171 (2018) 07002
(Talk in SQM 2017)

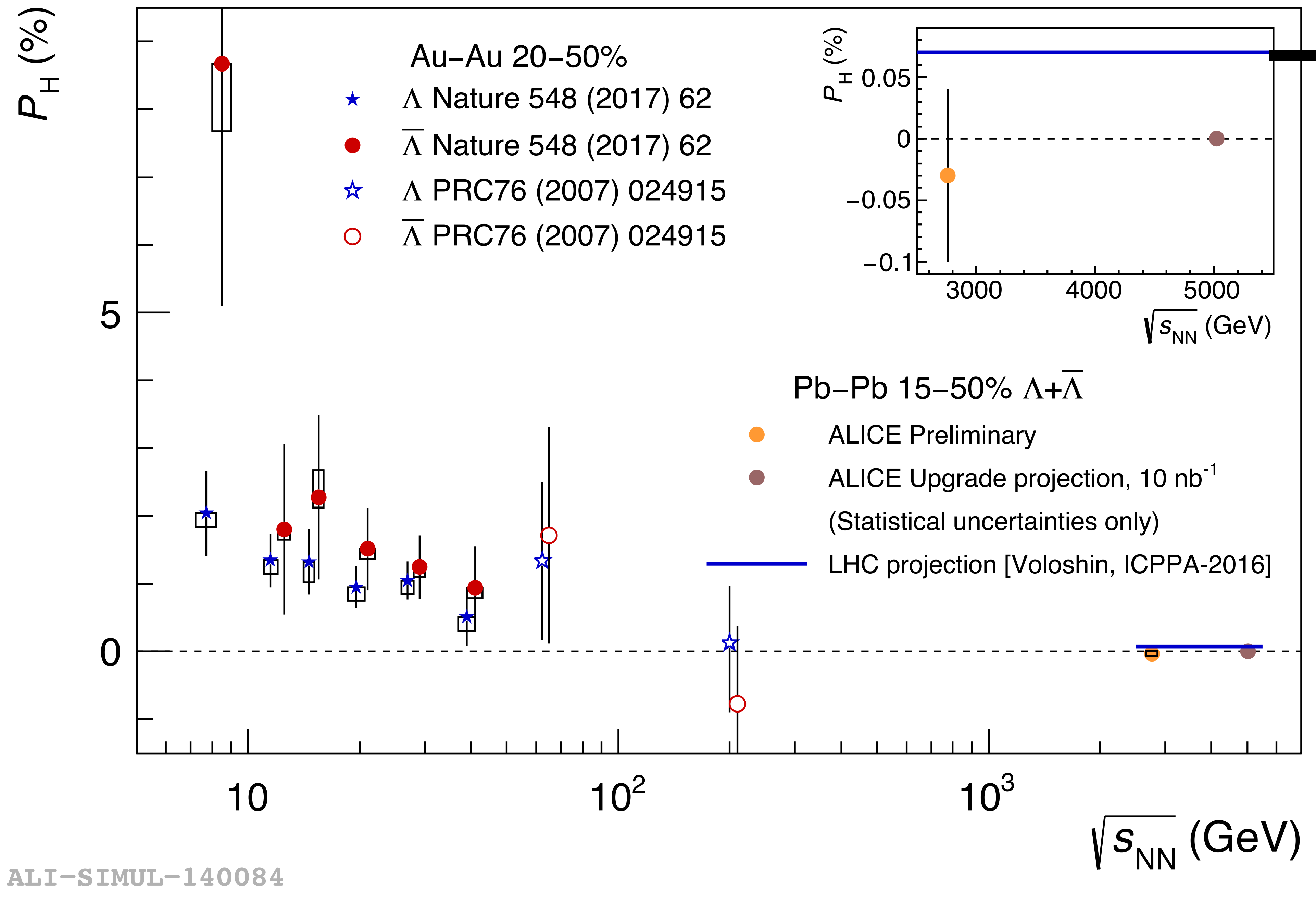
- Polarization and $\frac{dv_1}{d\eta}$ are strongly correlated ⟶ decreases with increase in $\sqrt{s_{NN}}$
- v_1 at the LHC ⟶ three times smaller than v_1 at top RHIC energy.

ALICE, Phys. Rev. Lett. 111 (2013) 232302

- P_H at the LHC energies ⟶ at least three times smaller than at RHIC (need high statistics for precision measurement).

Global polarization (P_H) in Pb-Pb collisions in Run-3 in ALICE





projected non-zero value at Run 3

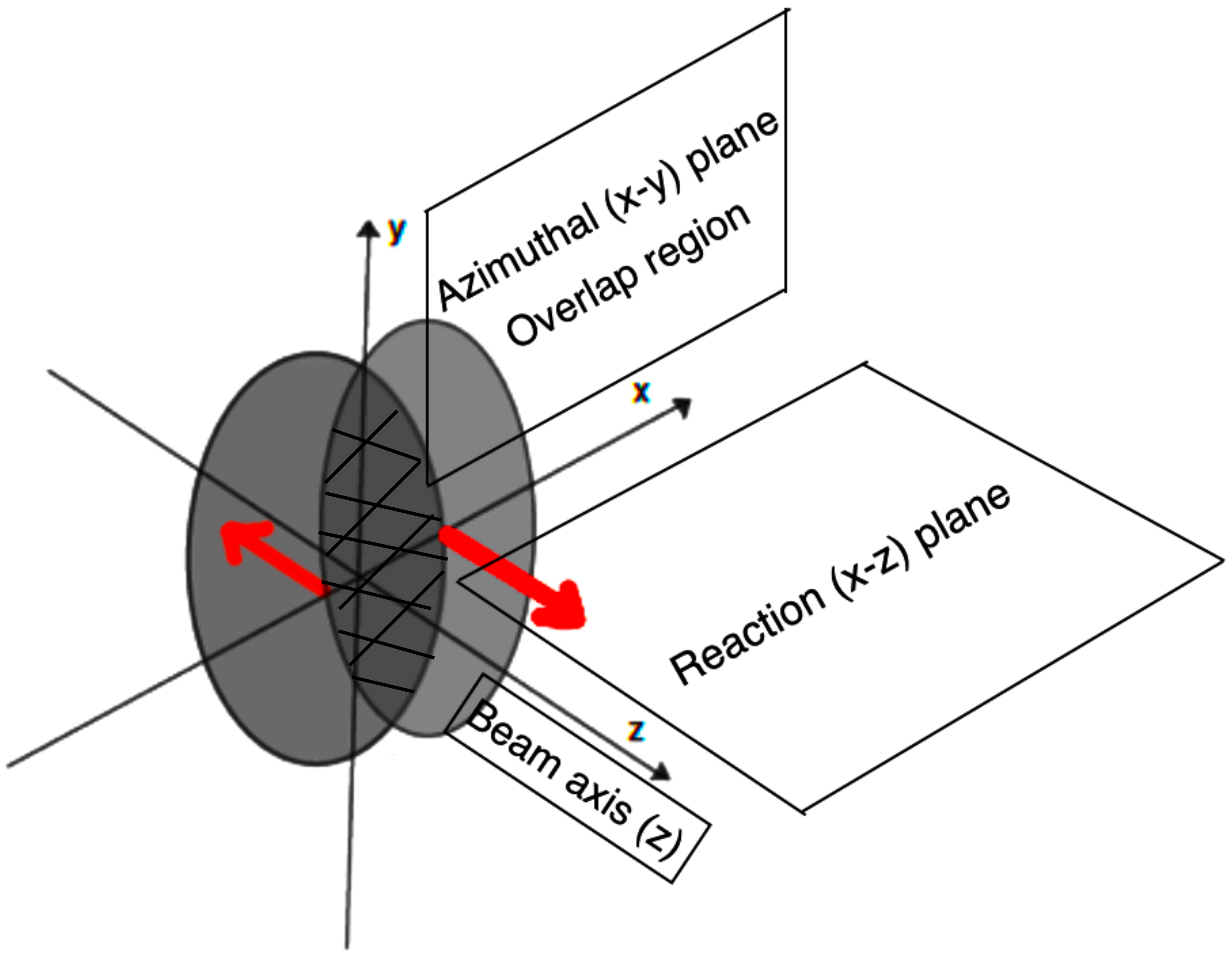
ALICE-PUBLIC-2019-001, https://cds.cern.ch/record/2661798
S. A. Voloshin, ICPPA - 2016

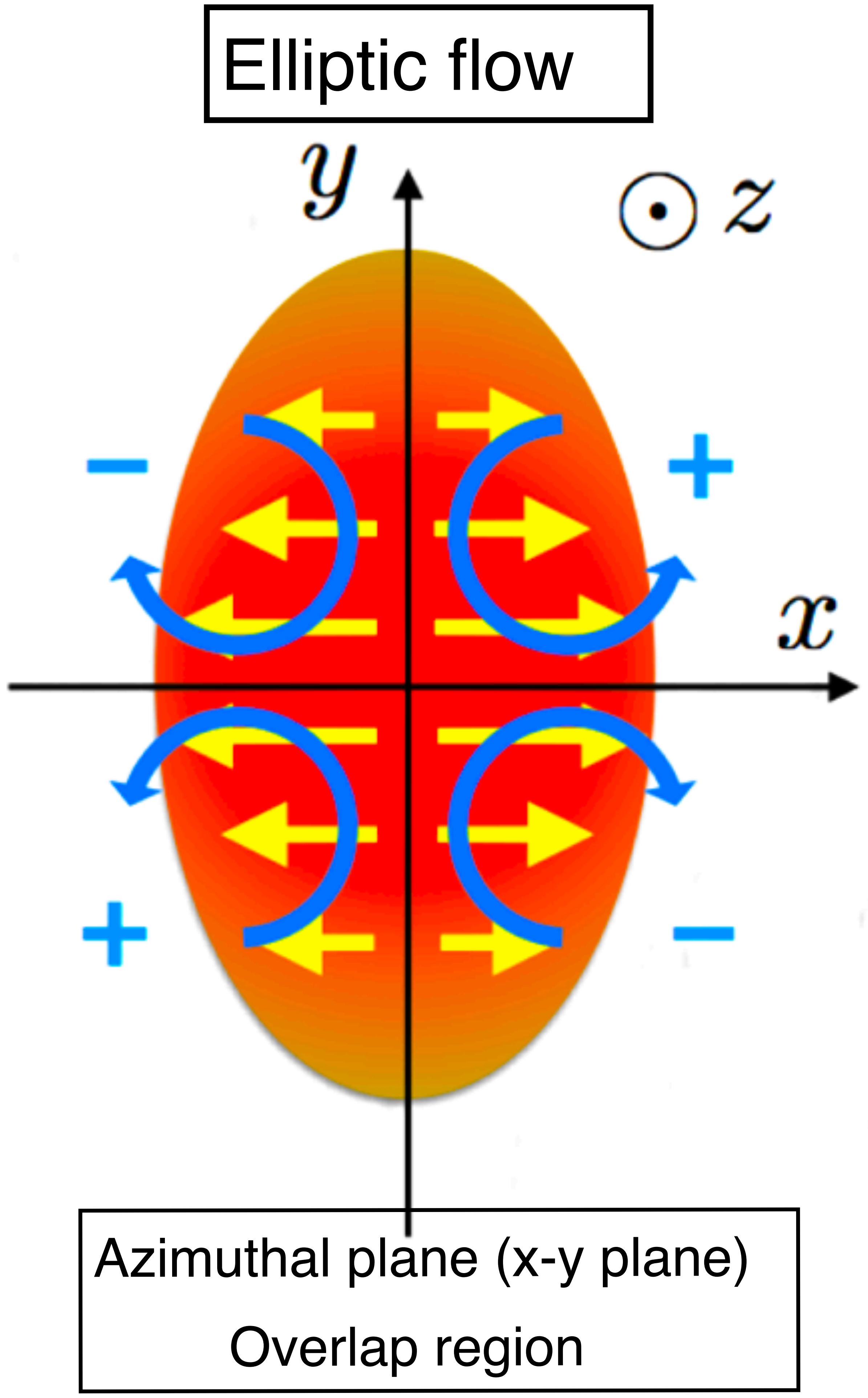
$\Lambda = p + \pi^-$ $\quad \overline{\Lambda} = \overline{p} + \pi^+$

- P_H decreases with collision energy (due to higher baryon transparency at higher collision energies).
- P_H can't be zero even at LHC (Projected value ~0.05 %).
- Global polarization at LHC awaits disovery (for Λ and multi-strange hyperons).

Elliptic flow induced polarization along the beam direction (P_z)

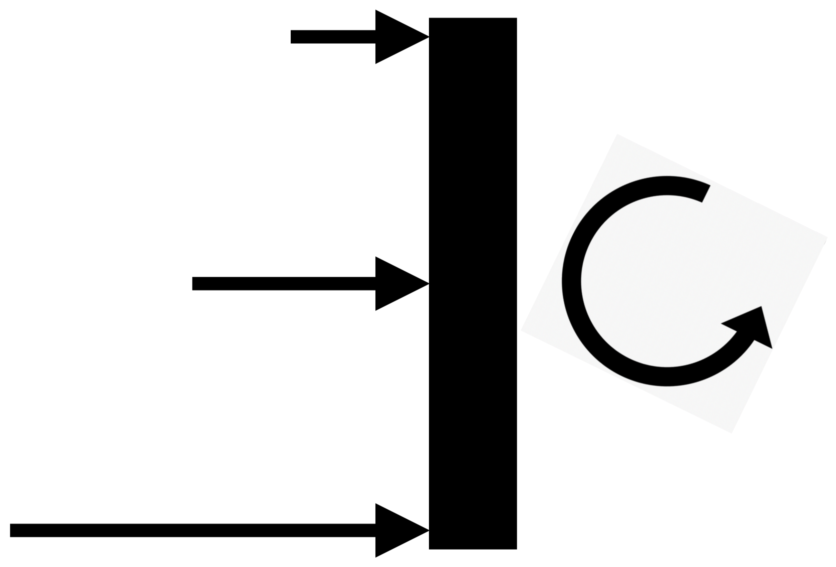
- Source of vorticity along the beam direction (z axis):





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

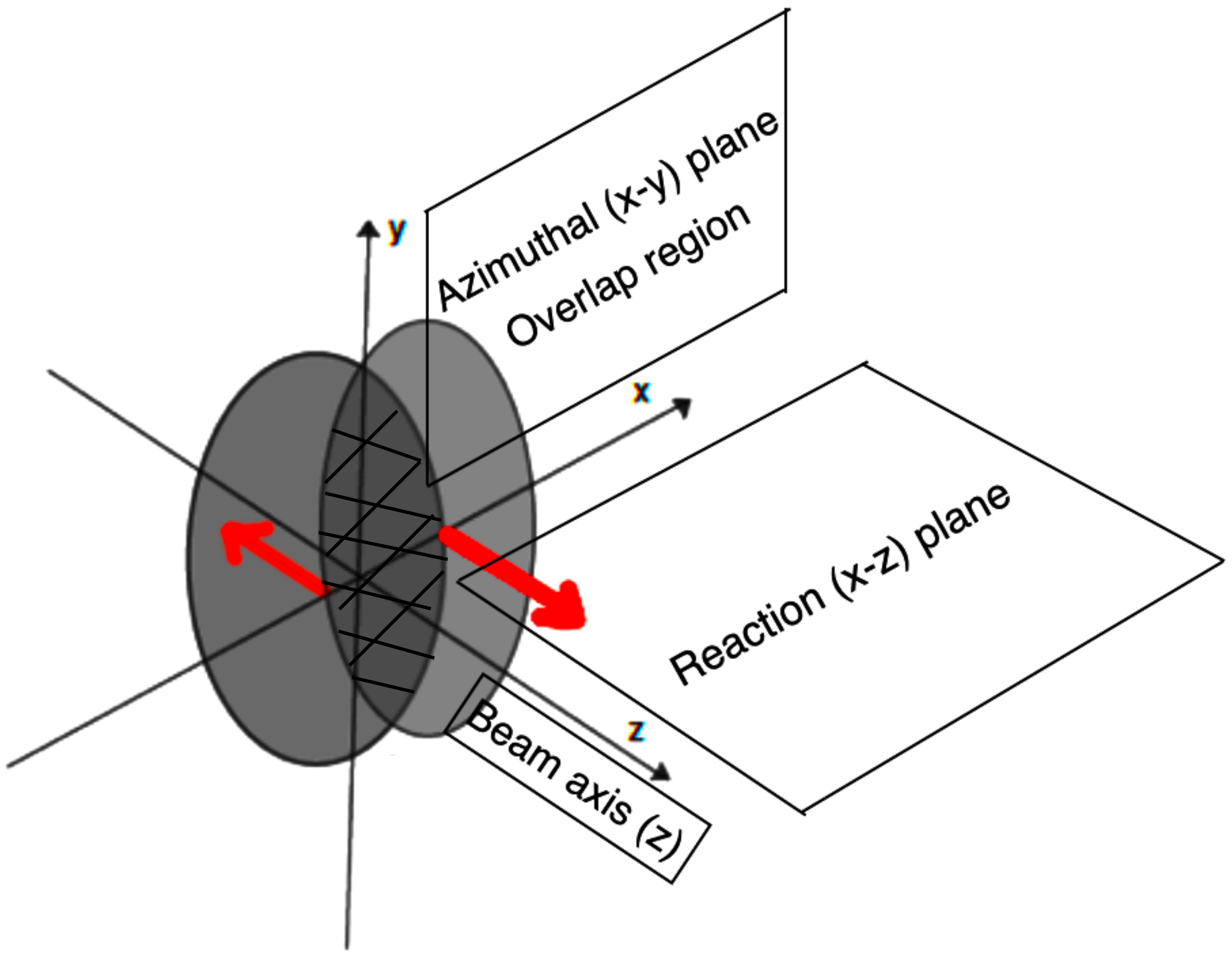
$$\vec{\omega} = \frac{1}{2}\nabla \times \vec{v}$$

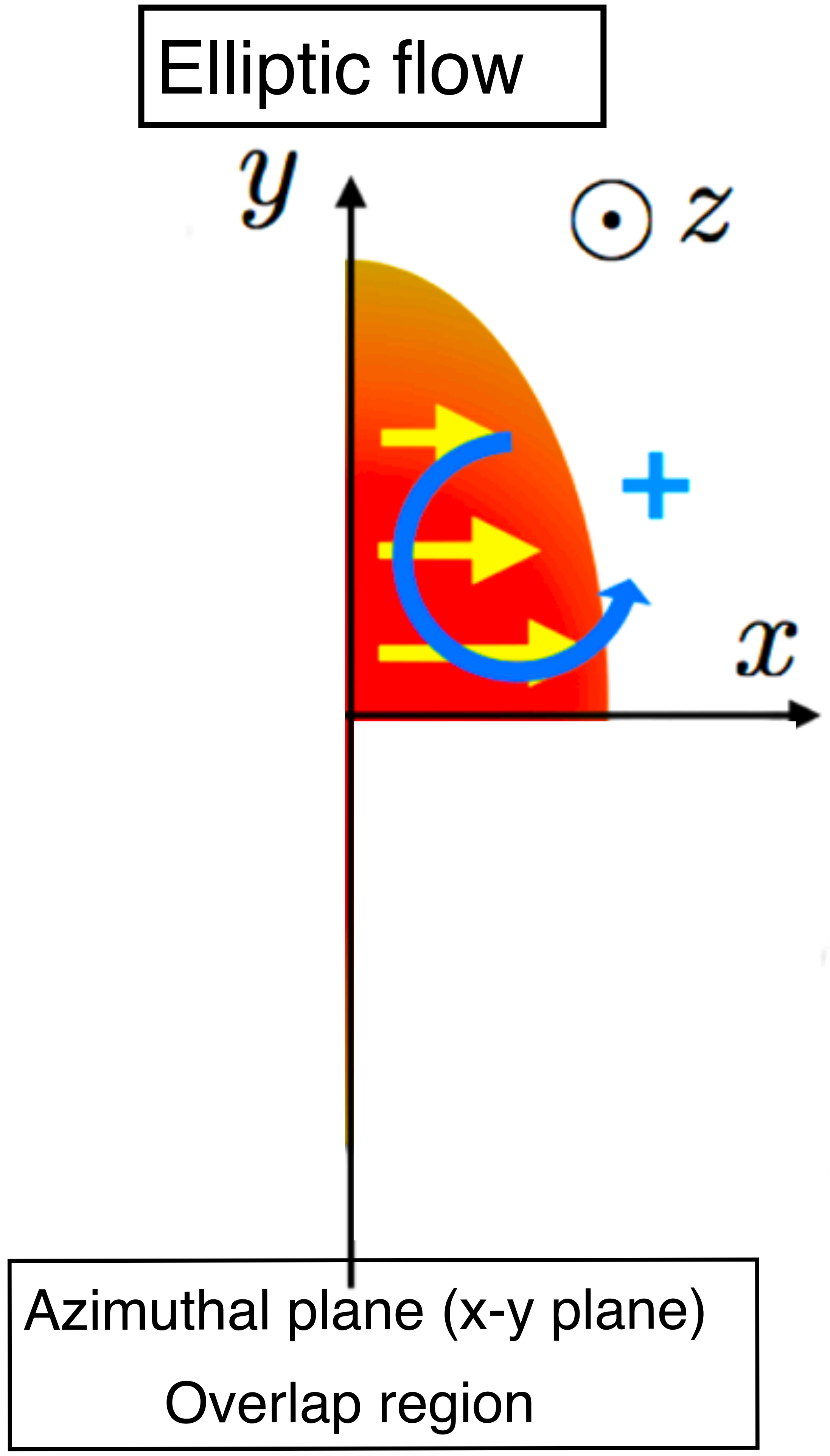


- Particle spin polarization along beam (z) axis has azimuthal angle dependence - local polarization.

Elliptic flow induced polarization along the beam direction (P_z)

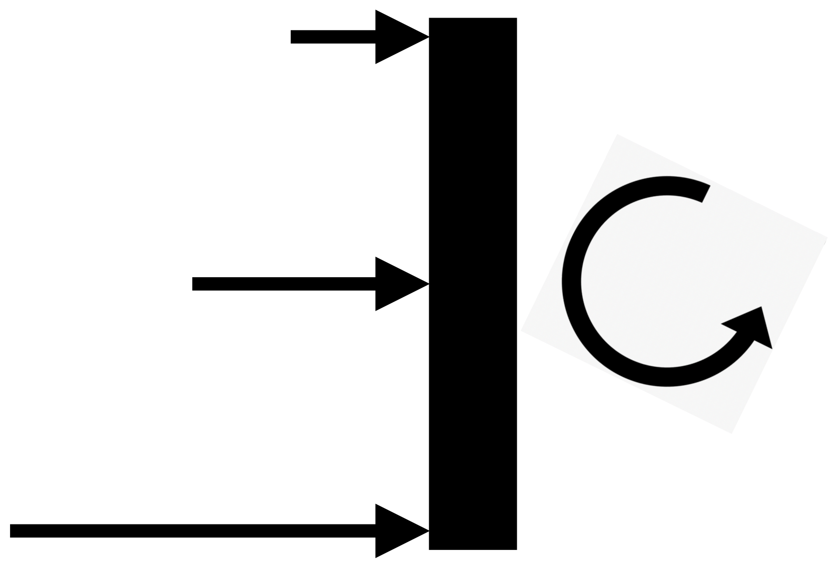
- Source of vorticity along the beam direction (z axis):





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

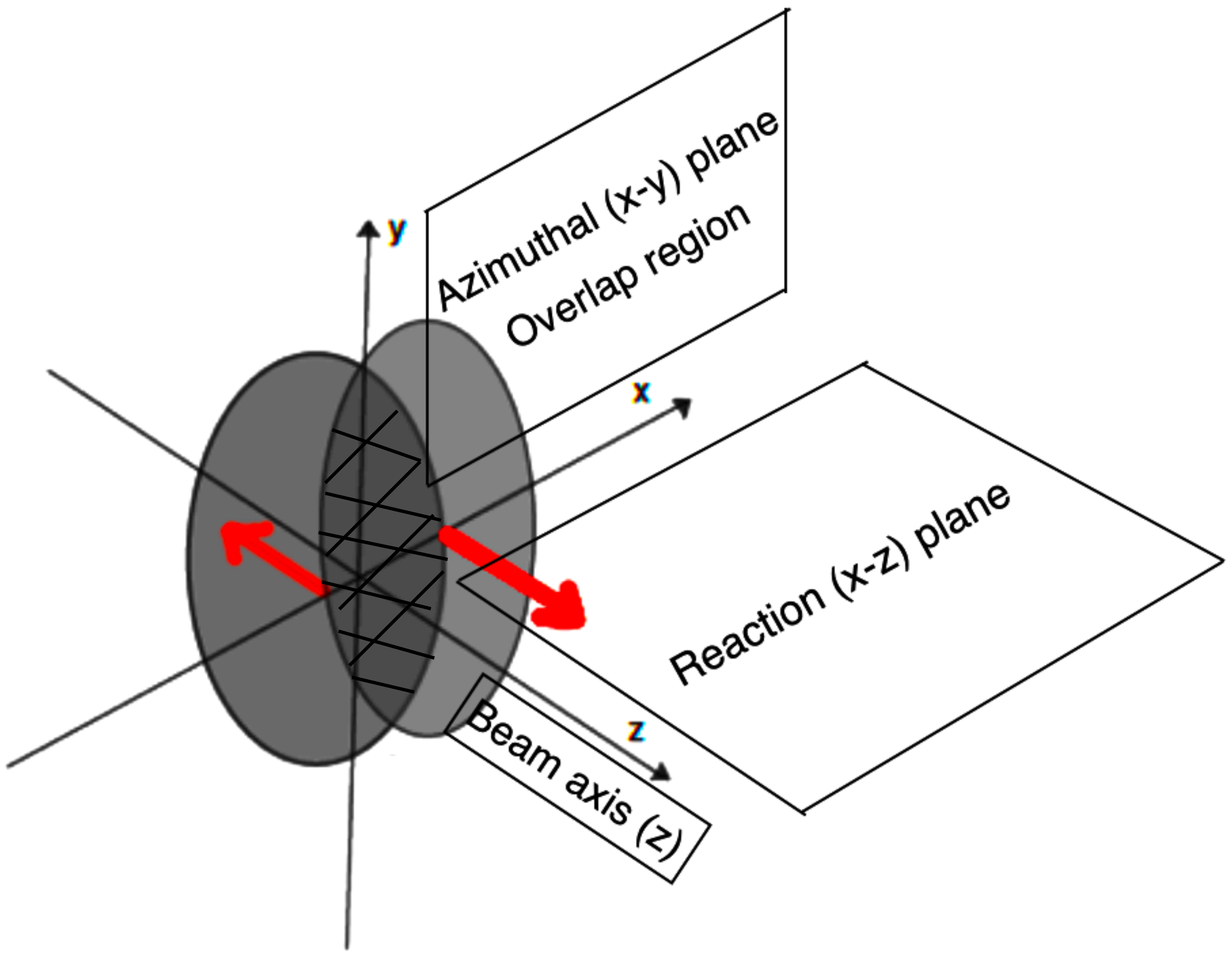
$$\vec{\omega} = \frac{1}{2}\nabla \times \vec{v}$$

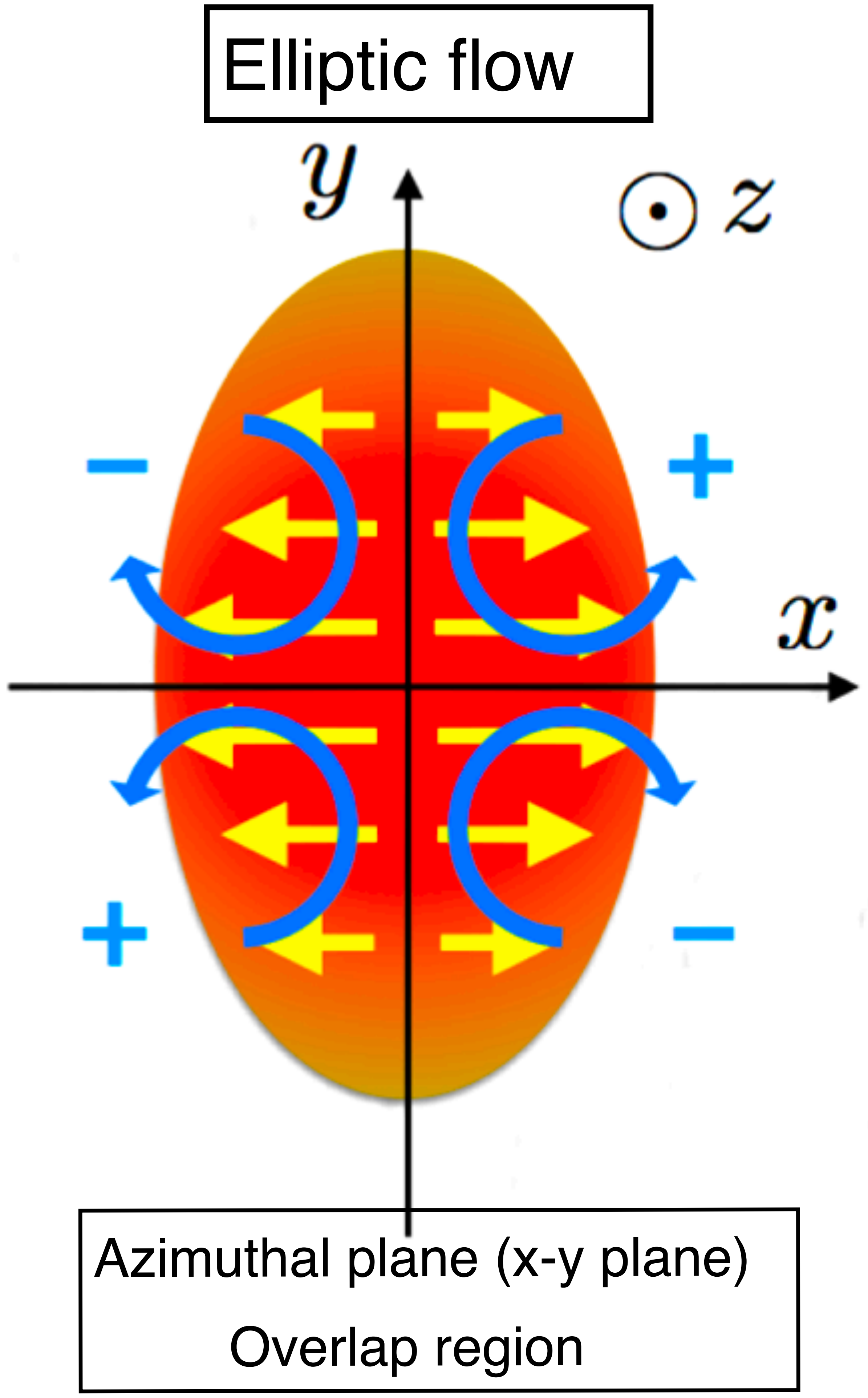


- Particle spin polarization along beam (z) axis has azimuthal angle dependence - local polarization.

Elliptic flow induced polarization along the beam direction (P_z)

- Source of vorticity along the beam direction (z axis):





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

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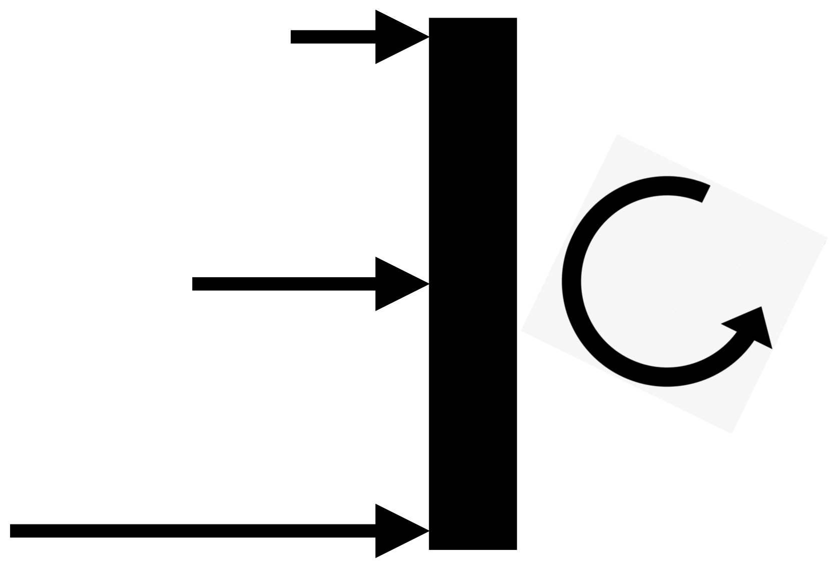
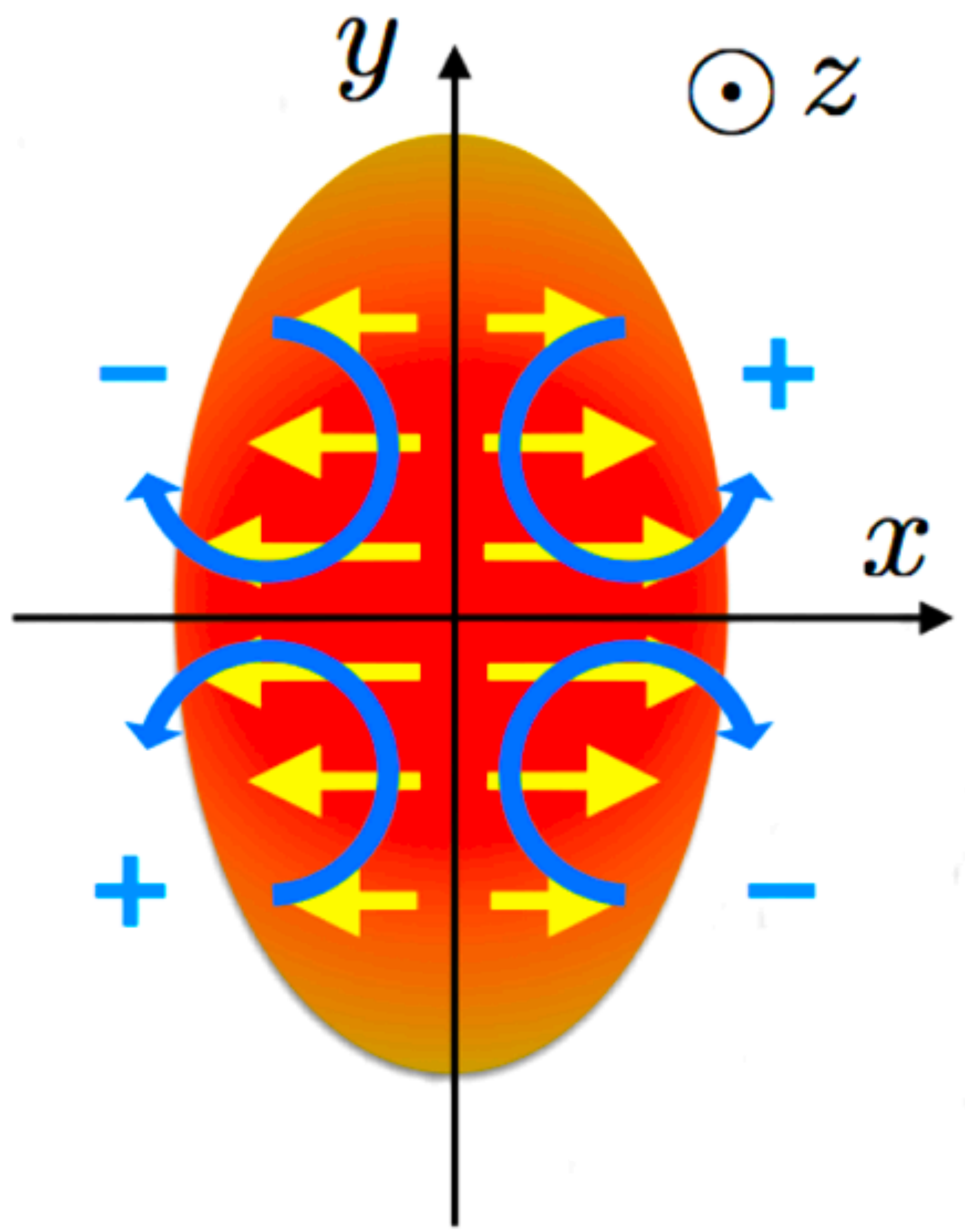


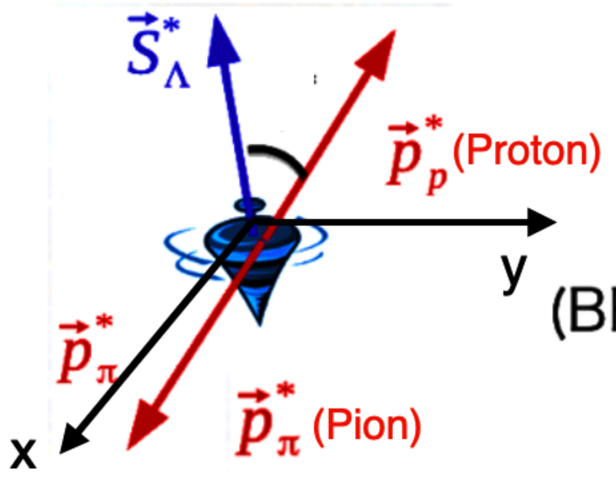
- Particle spin polarization along beam (z) axis has azimuthal angle dependence - local polarization.

Elliptic flow induced polarization along the beam direction (P_z)



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

$$P_z(\phi) \approx sin(2\phi - 2\Psi_2)$$



$\Lambda \rightarrow p + \pi^-$
(BR: 63.9%, c τ ~7.9 cm)

- Local polarization (along z axis)-

$$P_z \approx \langle(\hat{p}_p^* \cdot \hat{z})\rangle$$

$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle} = \frac{3\langle \cos\theta_p^* \rangle}{\alpha_H} \text{ (if perfect detector)}$$

ALICE, Phys. Rev. Lett. 128, 172005. (2022)

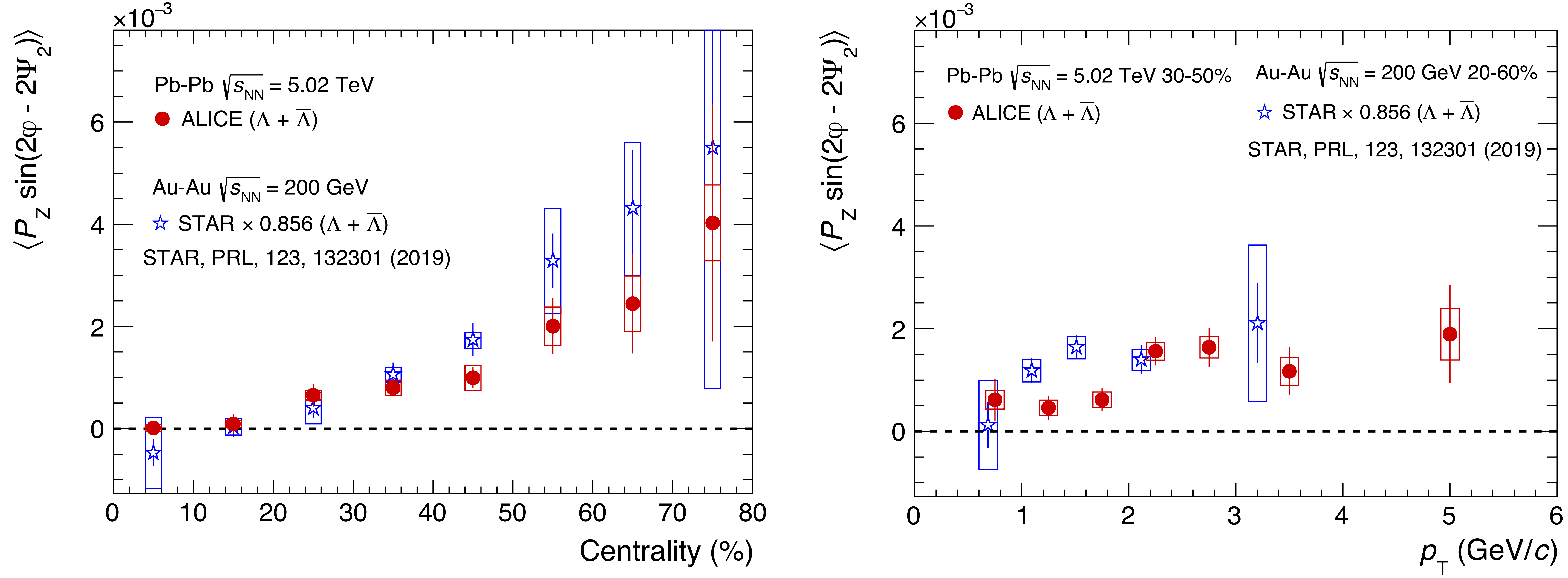
$\langle (\cos\theta_p^*)^2 \rangle$ = correction for finite acceptance along z

$$P_{z,s2} = \frac{\langle P_z \sin(2\varphi - 2\Psi_2) \rangle}{Res(\Psi_2)}$$

$P_{z,s2}$ estimates magnitude and phase of P_z.

Elliptic flow induced polarization along the beam direction (P_z)

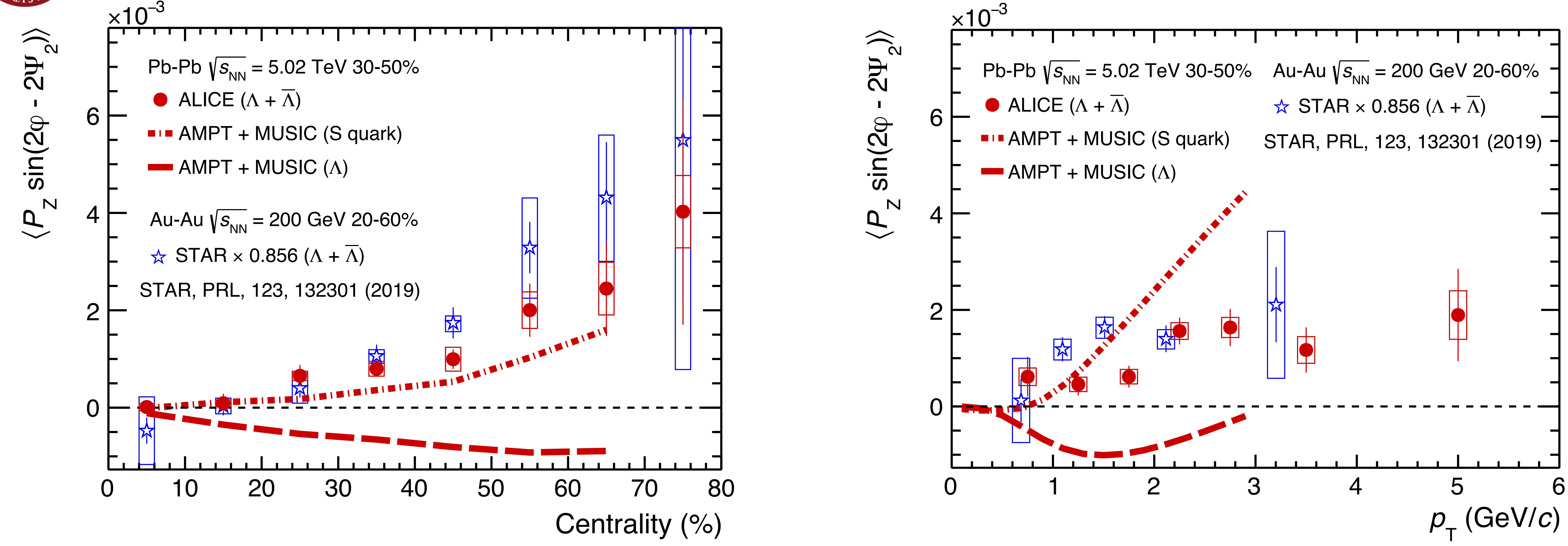
ALICE, Phys. Rev. Lett. 128, 172005. (2022)



- $P_{z,s2}$ at the LHC is similar in magnitude to top RHIC energy.

Elliptic flow induced polarization along the beam direction (P_z)

ALICE, Phys. Rev. Lett. 128, 172005. (2022)



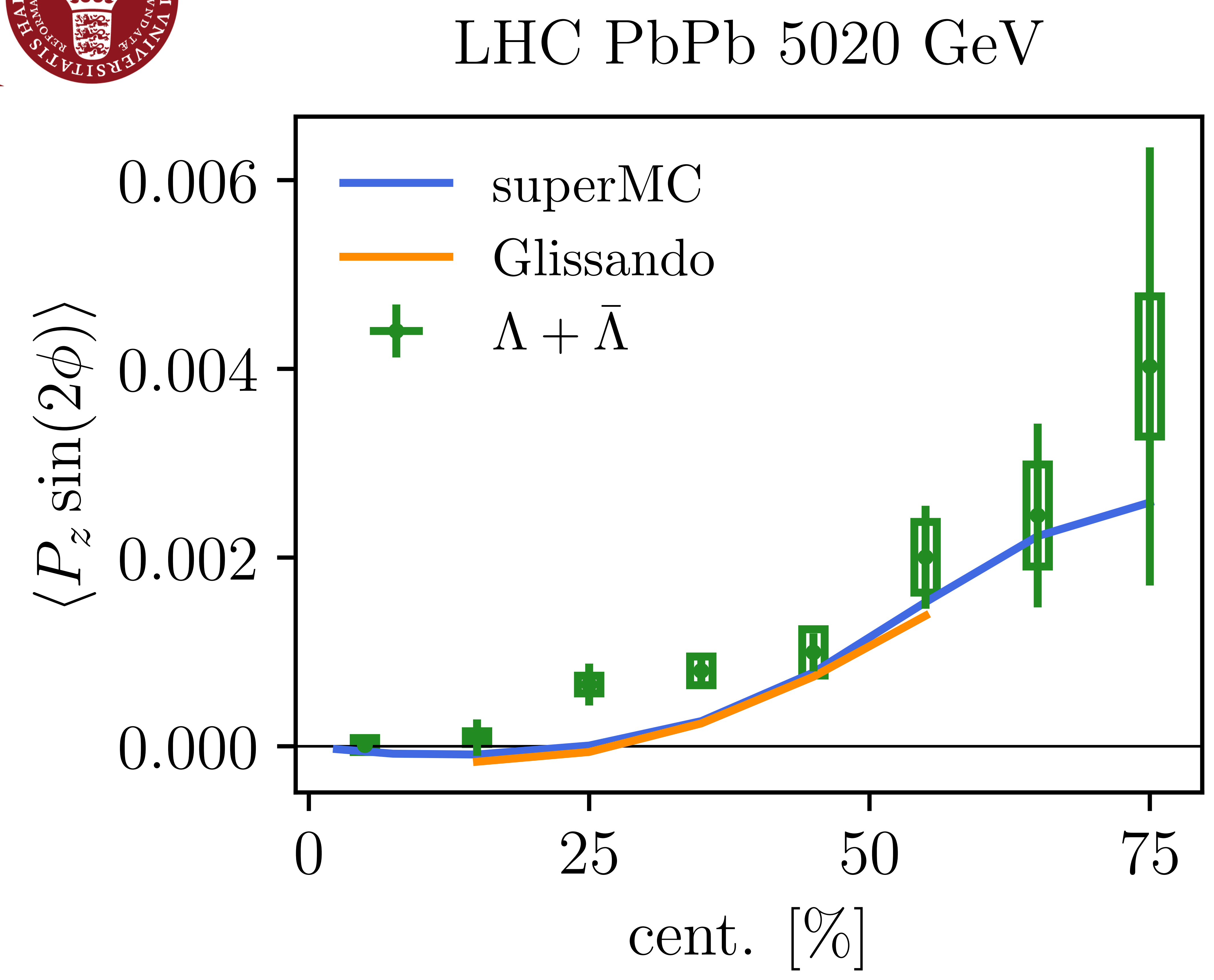
Model description: B. Fu et al.; PRL 127, 142301 (2021)

- Also look at:

F. Becattini et al., Phys. Rev. Lett. 127, 272302 (2021)

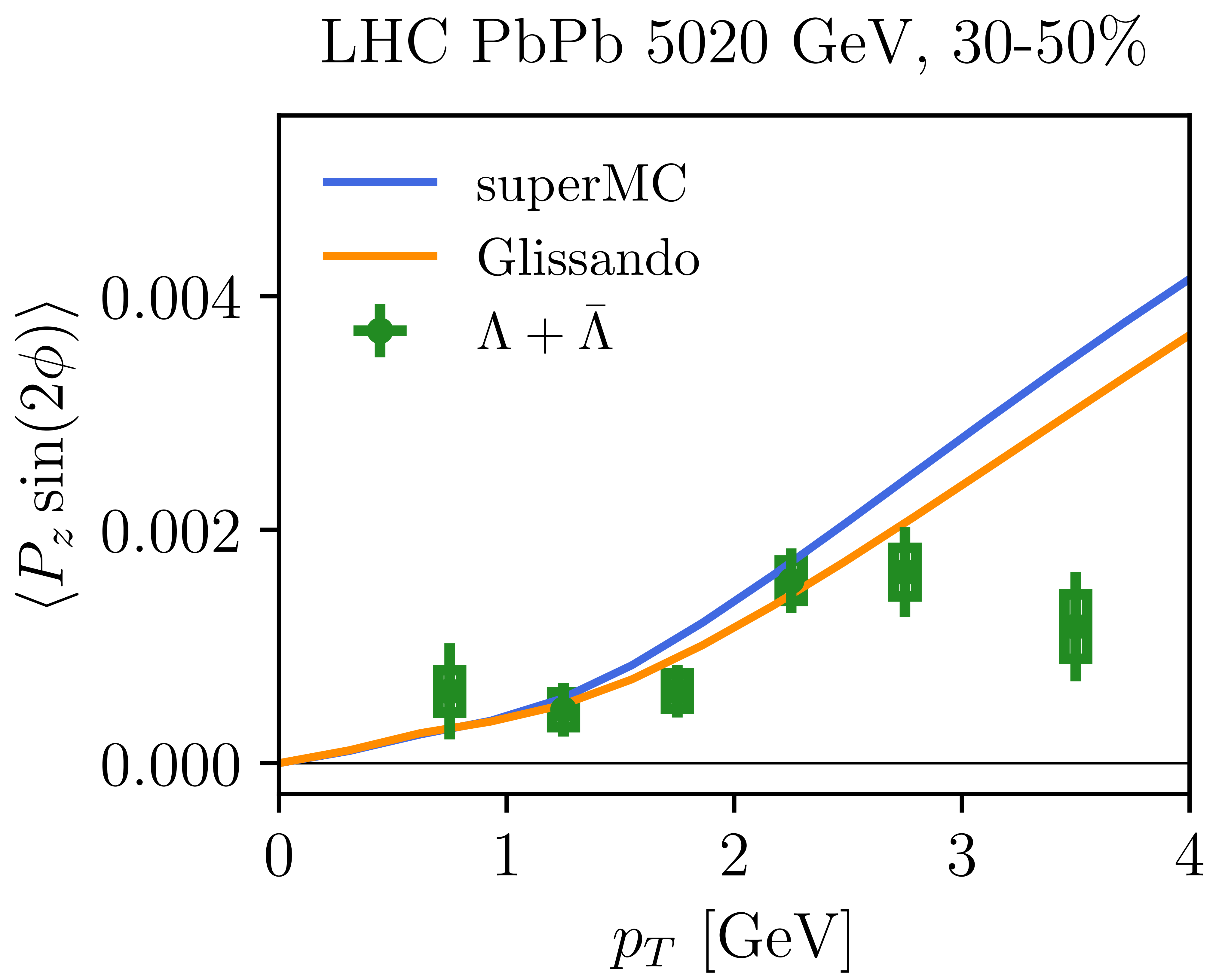
S. Banerjee et al., Phys. Rev. C 105, 064901 (2022)

- $P_{z,s2}$ at the LHC is similar in magnitude to top RHIC energy.
- The data results are compared with the (fluid shear + thermal vorticity) based AMPT + MUSIC model.
- The model qualitatively explains the data with constituent strange quark mass as spin carrier mass! Spin-orbit coupling happens only at the partonic level?



ALICE, Phys. Rev. Lett. 128, 172005. (2022)

A Palermo et al., arXiv:2404.14295 [nucl-th]



- Also look at:

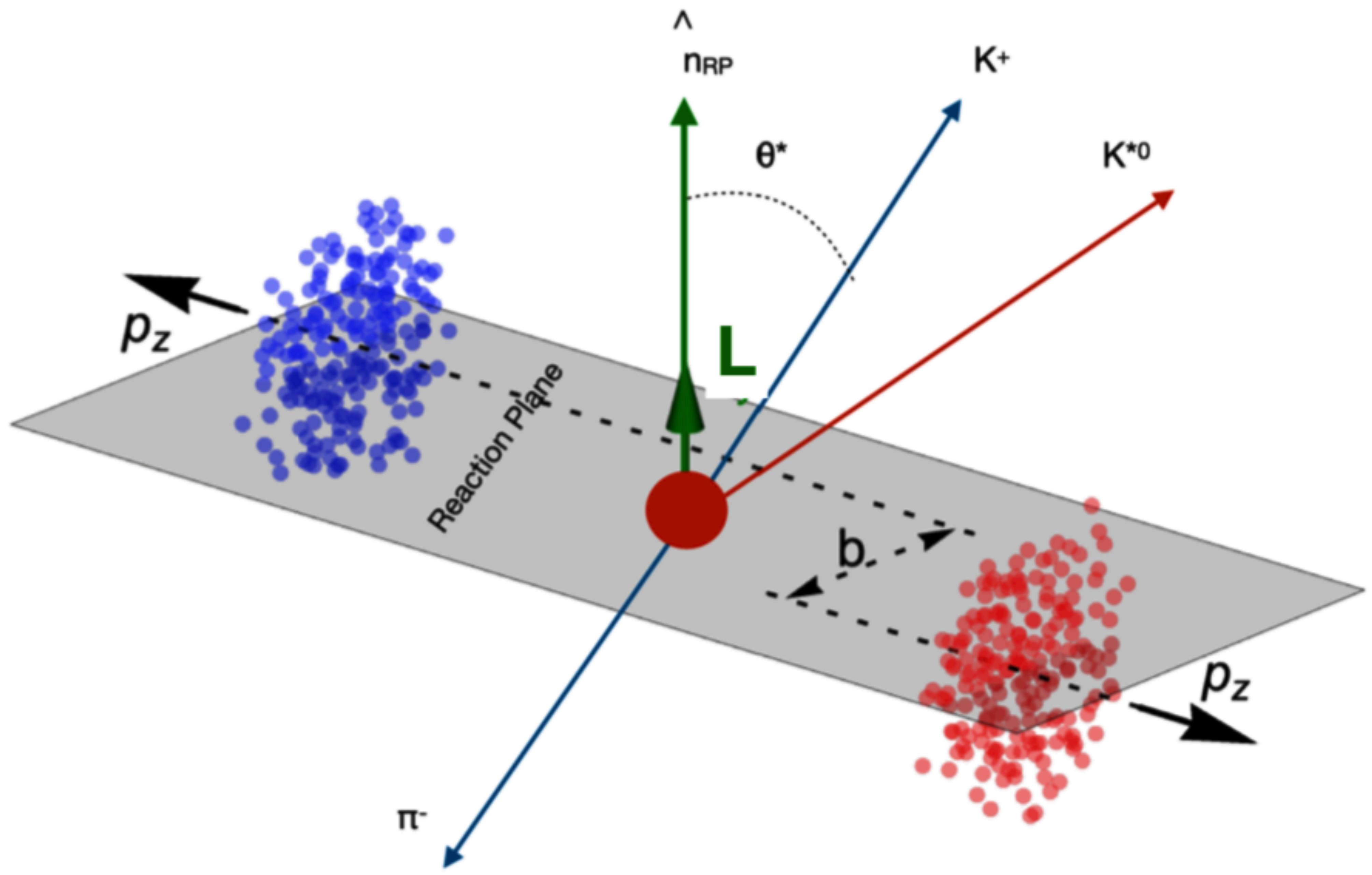
F. Becattini et al., arXiv:2402.04540 [nucl-th] (2024)

S. Banerjee et al., Phys. Rev. C 105, 064901 (2022)

- The data results are compared with the (fluid shear + thermal vorticity) based 3+1D hydro model.
- The model reasonably explains the data with isothermal hadronization hypersurface (also sensitive to bulk viscosity).

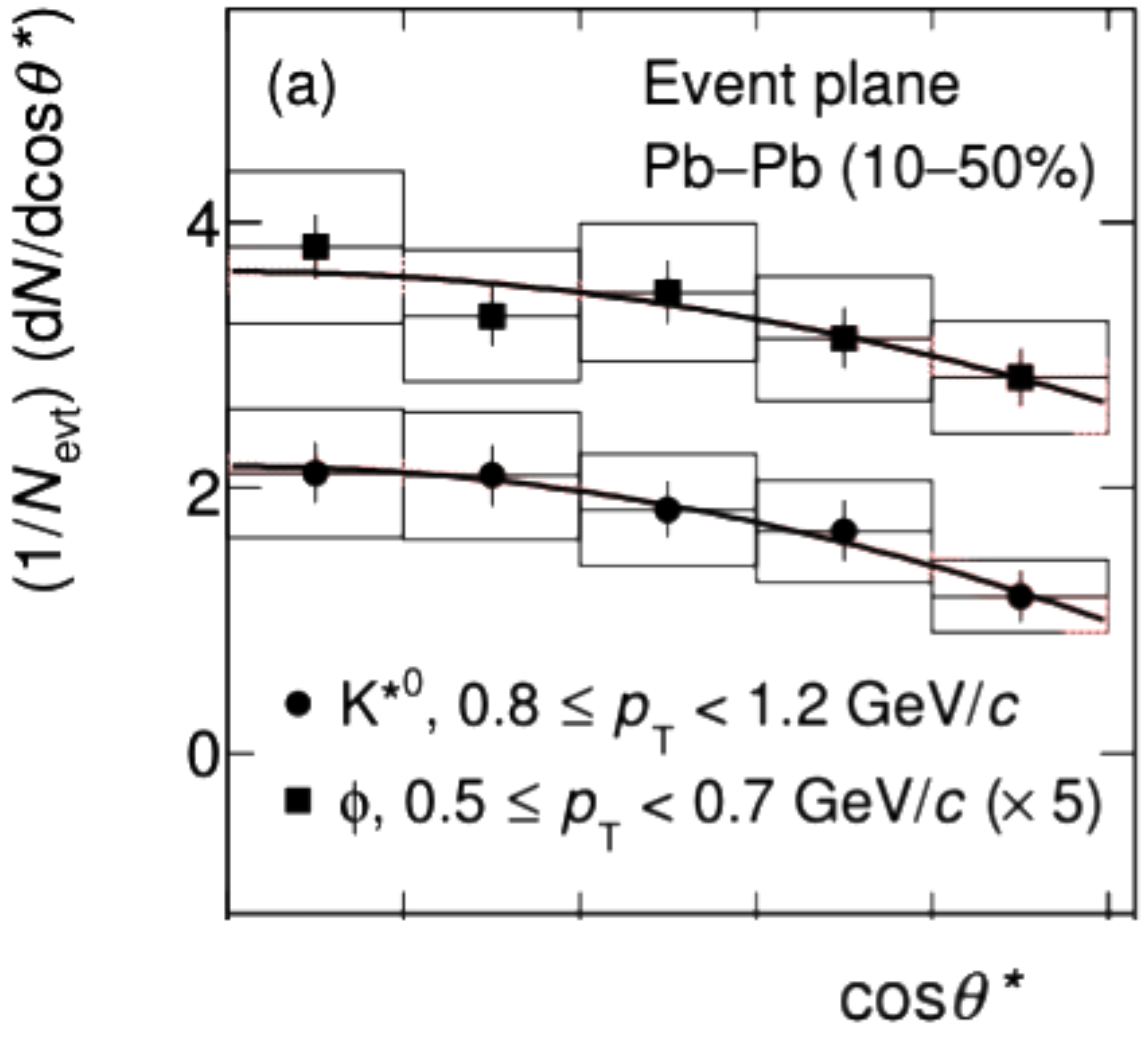
Spin alignment of Vector mesons (ρ_{00})

- Measured from the angular distribution of the daughter particle in parent's rest frame:



K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta^*} = N_0[1 - \rho_{0,0} + \cos^2\theta^*(3\rho_{0,0} - 1)]$$

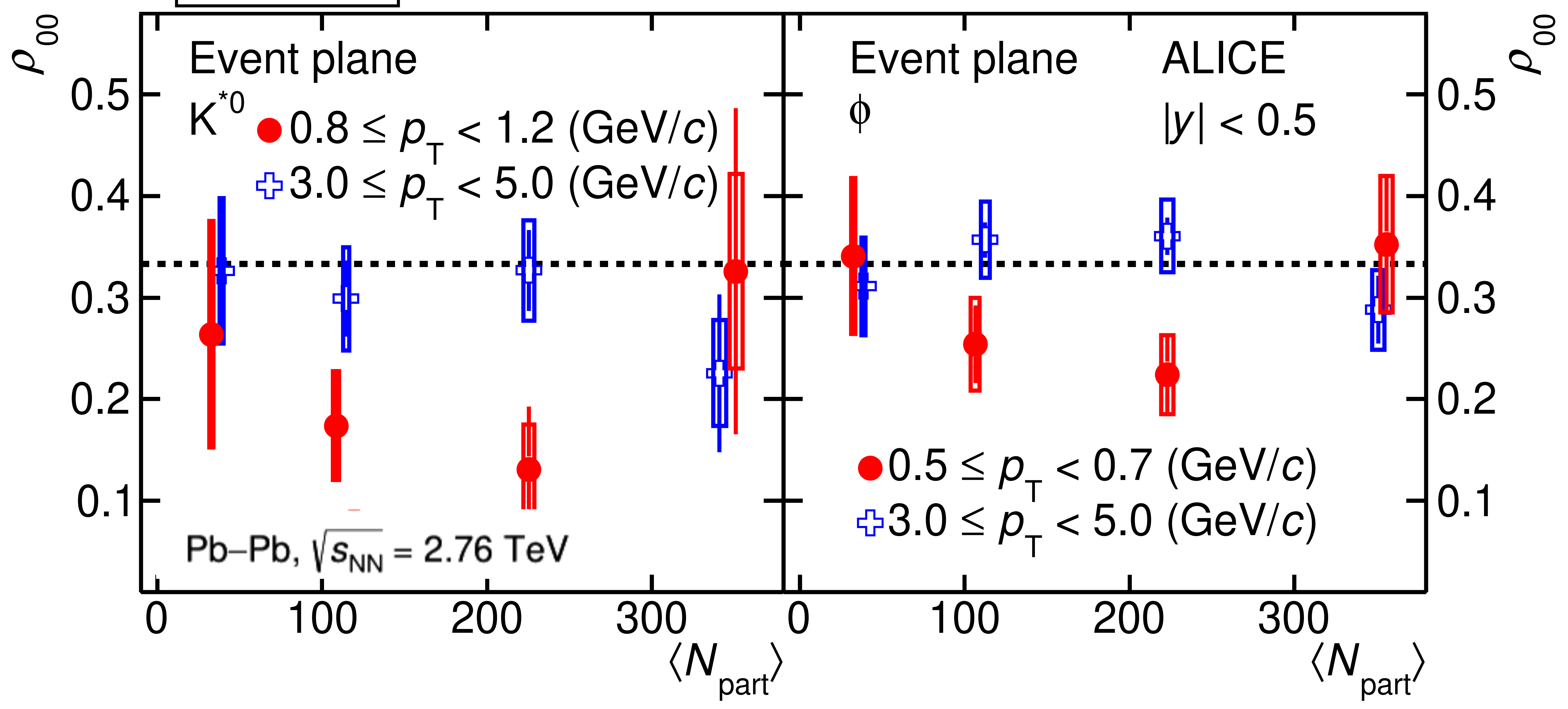


ALICE, Phys. Rev. Lett. 125, 012301 (2020)

- θ^*: Angle between momentum of daughter and polarization axis in parent's rest frame.
- $\rho_{0,0}$: Spin density matrix element, Probability that vector meson is in spin state = 0.

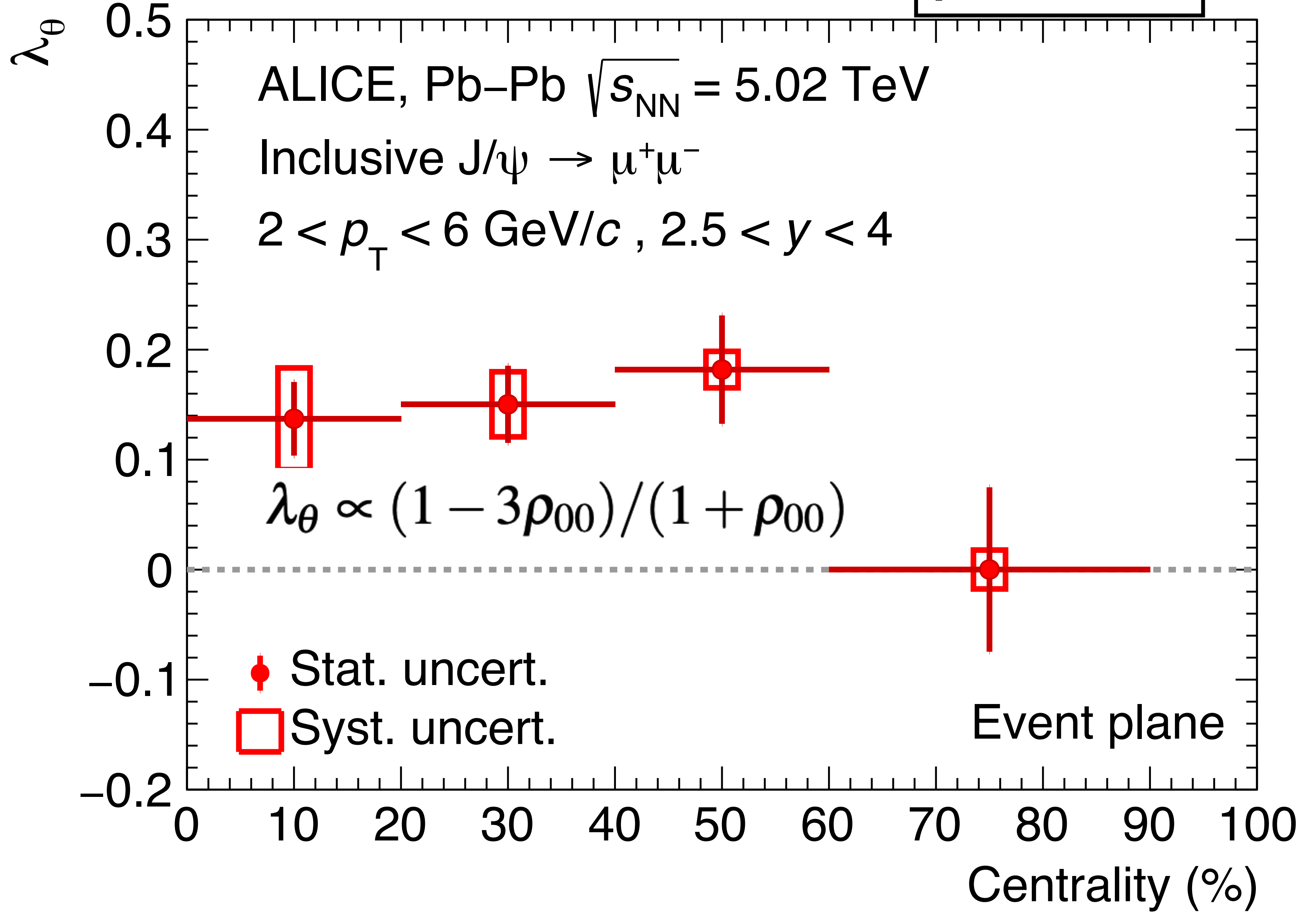
Spin alignment of Vector mesons (ρ_{00})

$\rho_{00} < 1/3$



ALICE, Phys. Rev. Lett. 125, 012301 (2020)

$\rho_{00} < 1/3$

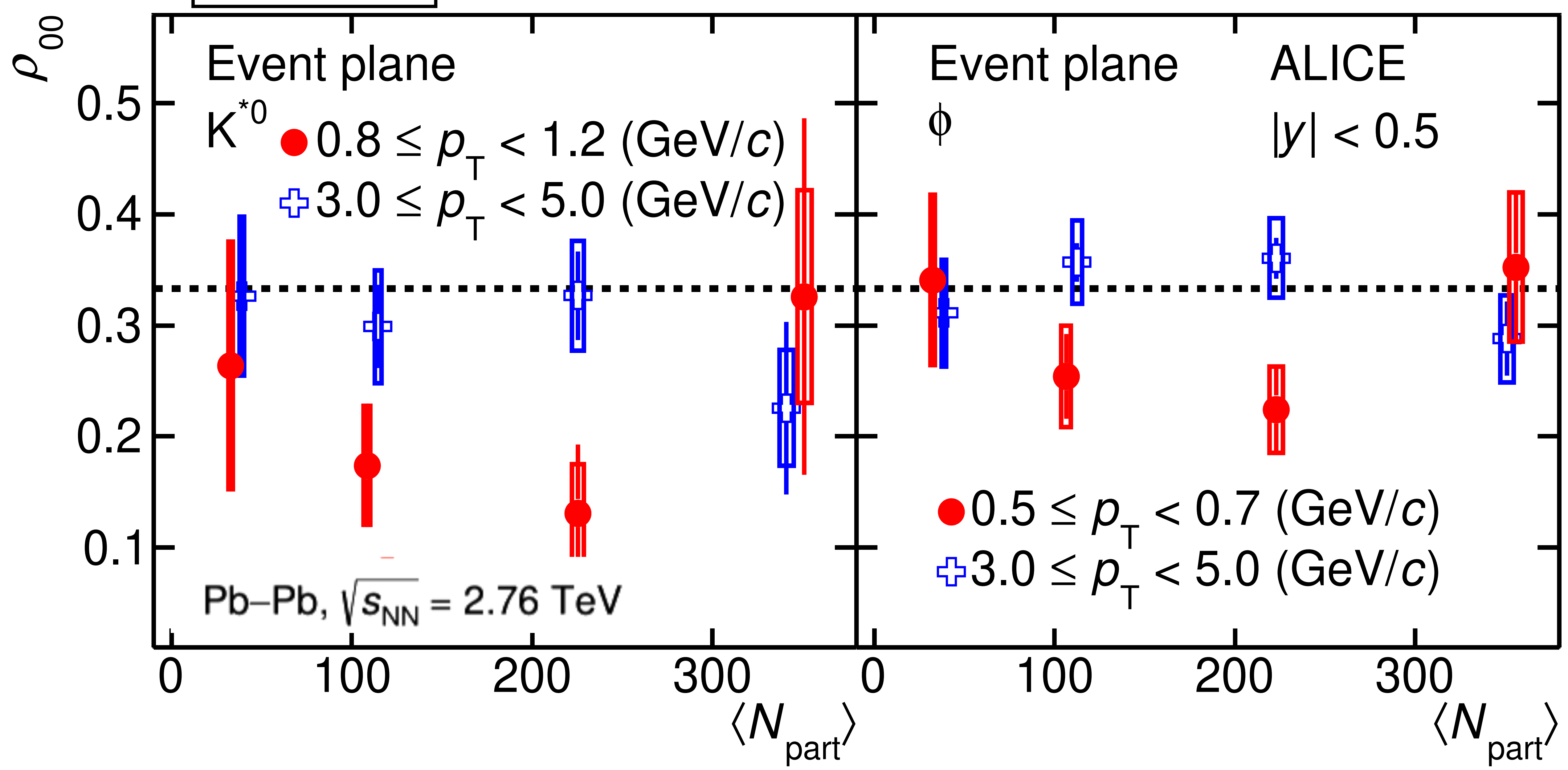


ALICE, Phys. Rev. Lett. 131, 042303 (2023)

- Spin Alignment ($\rho_{00} < 1/3$) observed for spin 1 particle at low p_T.
- Maximum spin alignment observed for mid-central collisions.
- No spin alignment ($\rho_{00} \sim 1/3$) observed for spin 0 particle and in pp collisions.

Spin alignment of Vector mesons (ρ_{00})

$\rho_{00} < 1/3$



ALICE, Phys. Rev. Lett. 125, 012301 (2020)

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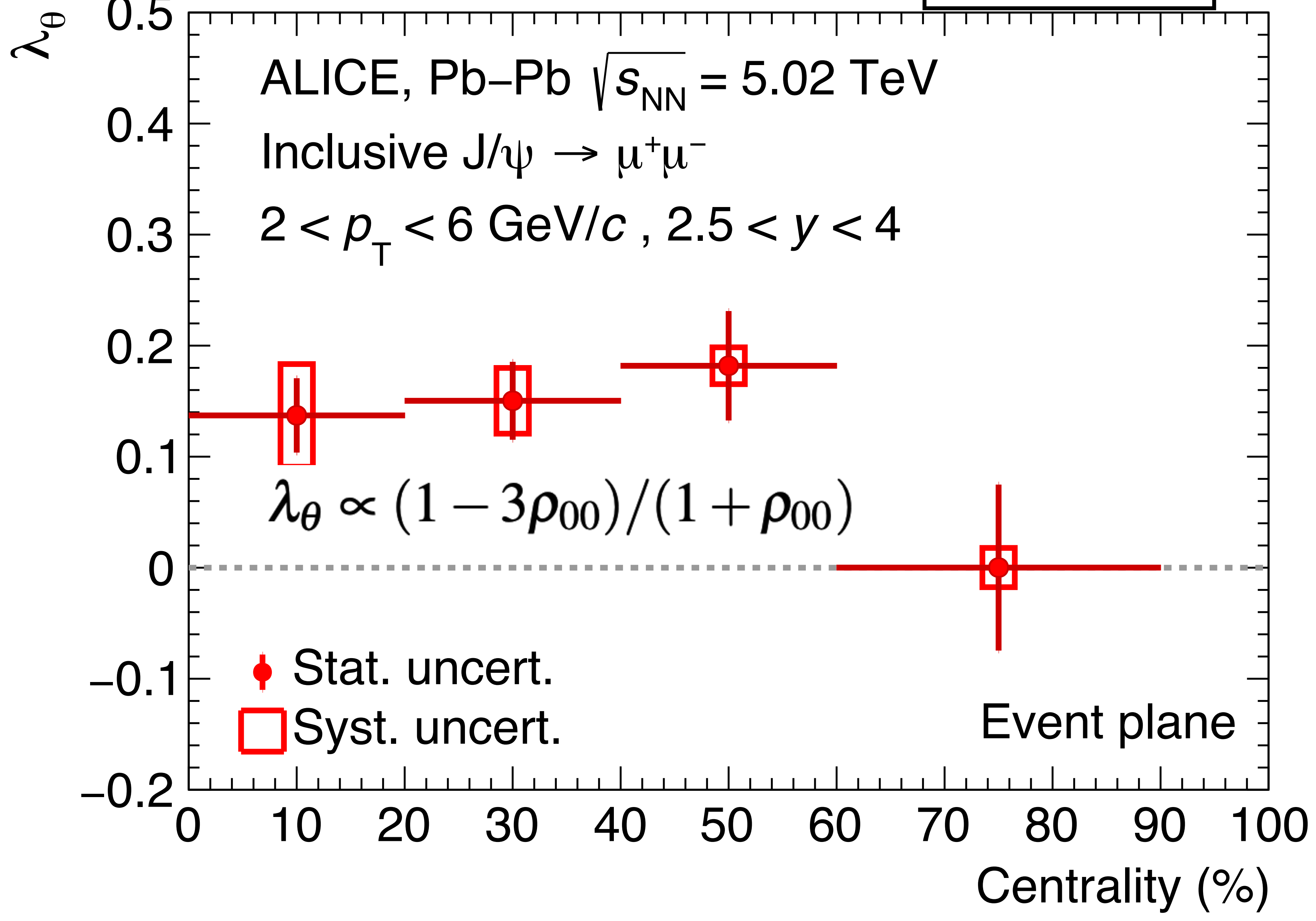


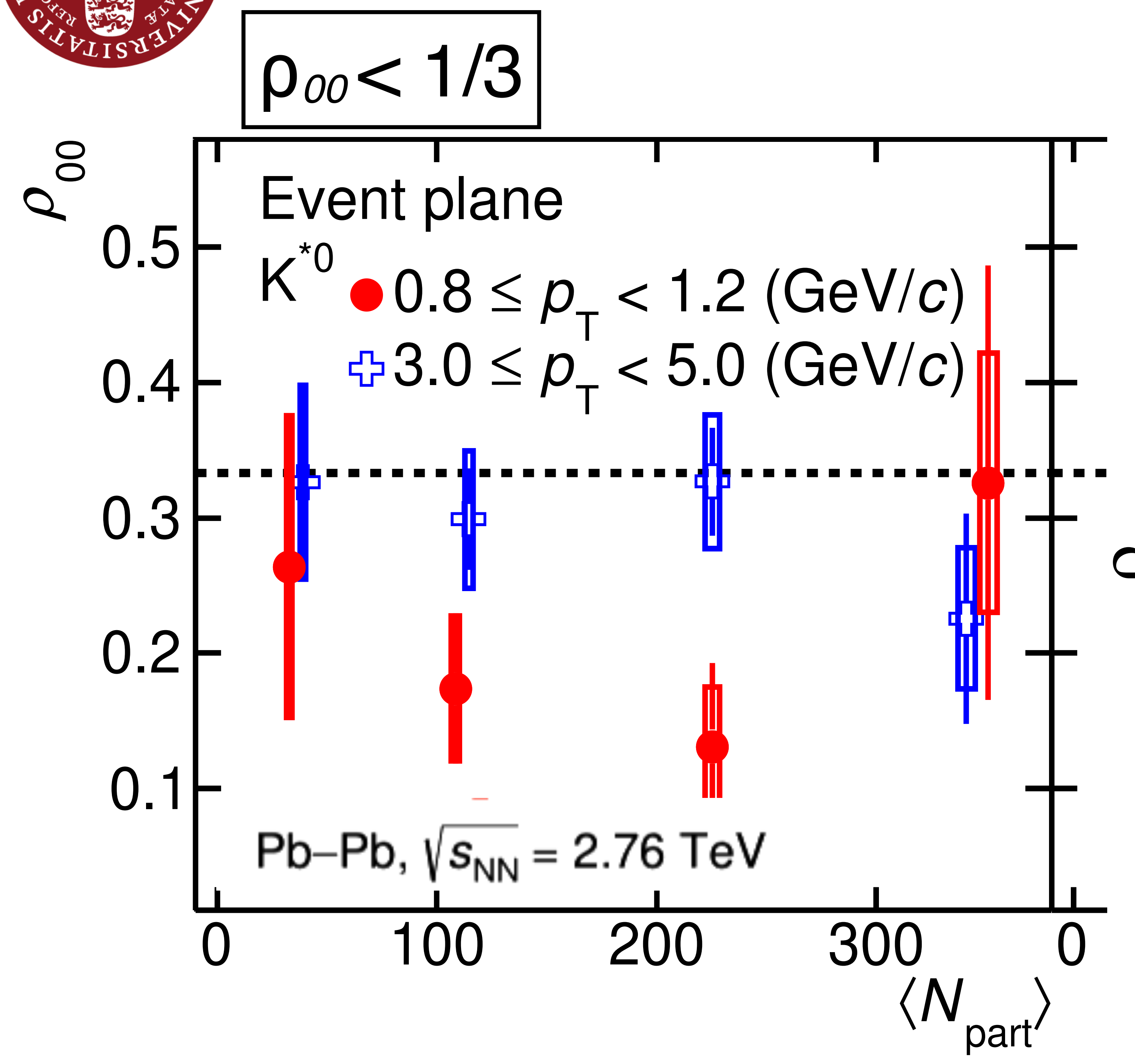
ALICE, Phys. Rev. Lett. 131, 042303 (2023)

Hydrodynamic-local equilibrium model : $P_\Lambda \simeq \frac{1}{4}\frac{\omega}{T}$; $\rho_{00} \simeq \frac{1}{3}\left(1 - \frac{(\omega/T)^2}{3}\right)$ → $\rho_{00} \sim 1/3$

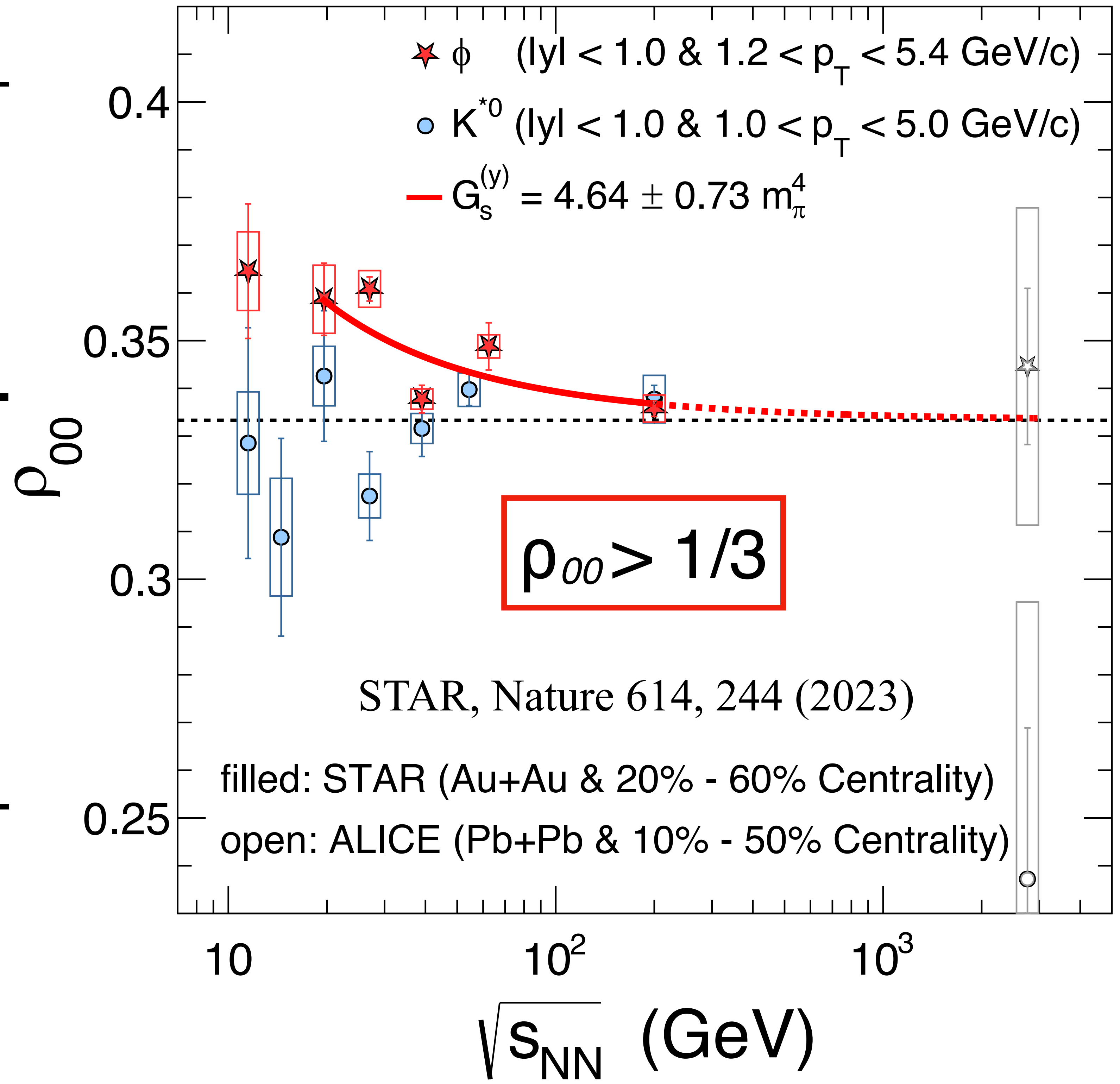
Quark combination model : $\rho_{00} - 1/3 \sim P_q P_{\bar{q}},$ → $\rho_{00} \sim 1/3$

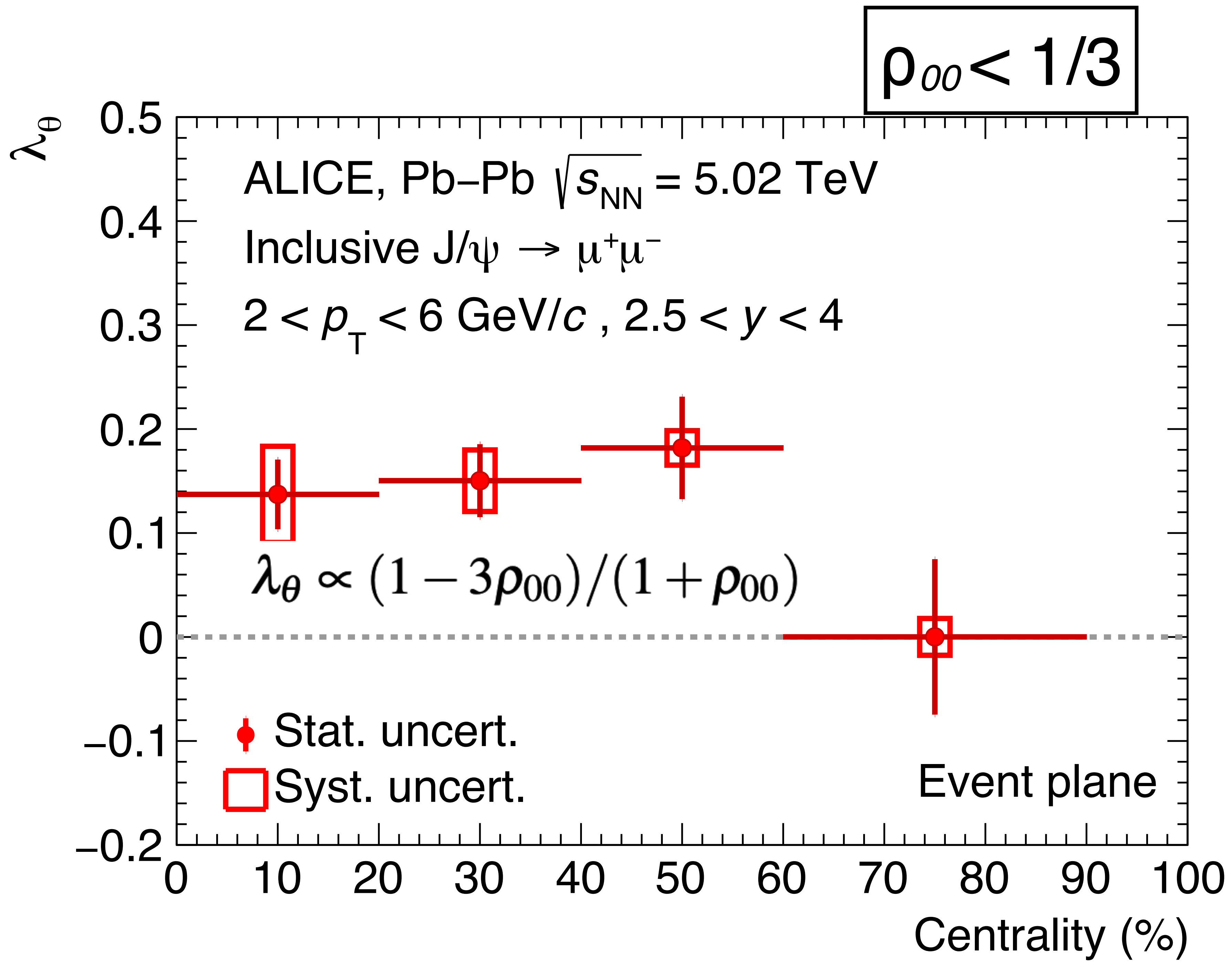
- Hyperon polarization and vector meson spin alignment results are inconsistent!

Spin alignment of Vector mesons (ρ_{00})



ALICE, Phys. Rev. Lett. 125, 012301 (2020)





ALICE, Phys. Rev. Lett. 131, 042303 (2023)

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Quark combination model (fluctuating ϕ field) : $\rho_{00} - 1/3 \sim \langle P_q P_{\bar{q}} \rangle$ → $\rho_{00} > 1/3$

X.-L. Sheng et al., Phys. Rev. Lett. 131, 042304 (2023)

- Hyperon polarization and vector meson spin alignment results are inconsistent!
- Vector meson spin alignment results are inconsistent between LHC and RHIC!

The puzzle remains…

Summary and Outlook

- Spin polarization is sensitive to the gradients of velocity and temperature fields → probes the “fine structure” of the QGP.

- Local and global spin polarization measurements can probe initial conditions and transpoprt co-efficients, magnetic field, local parity violation, jet-medium interactions, critical point etc—a new avenue to explore the properties of the QGP.

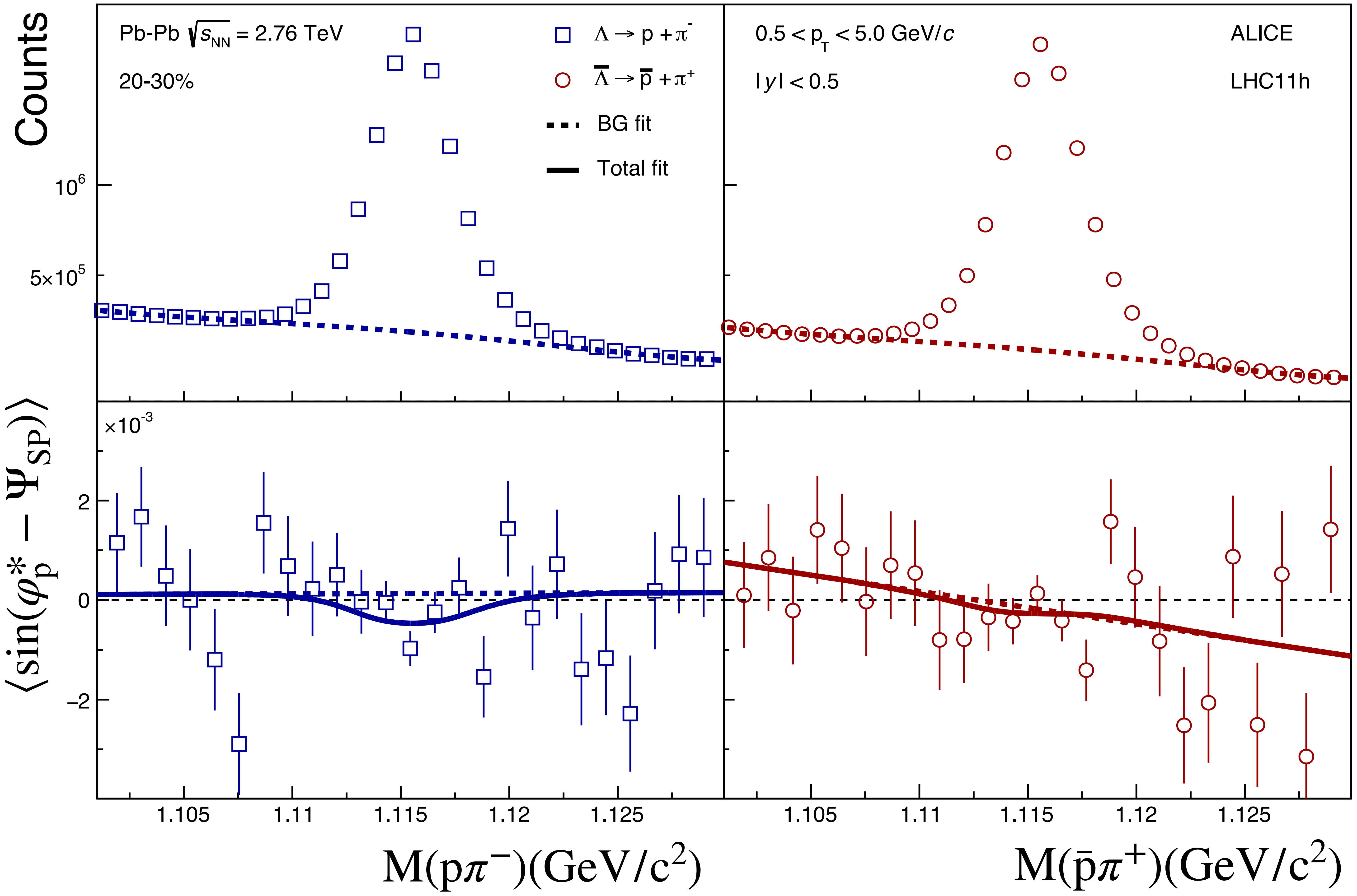
- Spin polarization/alignment results provide critical constraints for the development of theoretical framework involving spin degrees of freedom and E.M fields.

Thank you

Measuring global polarization (P_H) in ALICE using invariant mass method

ALICE, Phys. Rev. C 101, 044611 (2020)[erratum]

$\Lambda = p + \pi^-$ $\overline{\Lambda} = \bar{p} + \pi^+$



$$P_H = -\frac{8}{\pi\alpha_H}\frac{\langle \sin(\varphi_p^* - \Psi_{SP})\rangle}{R^1_{SP}}$$

- P_H measured from the fit to Q ($\langle \sin(\varphi_p^* - \Psi_{SP}) \rangle$) -

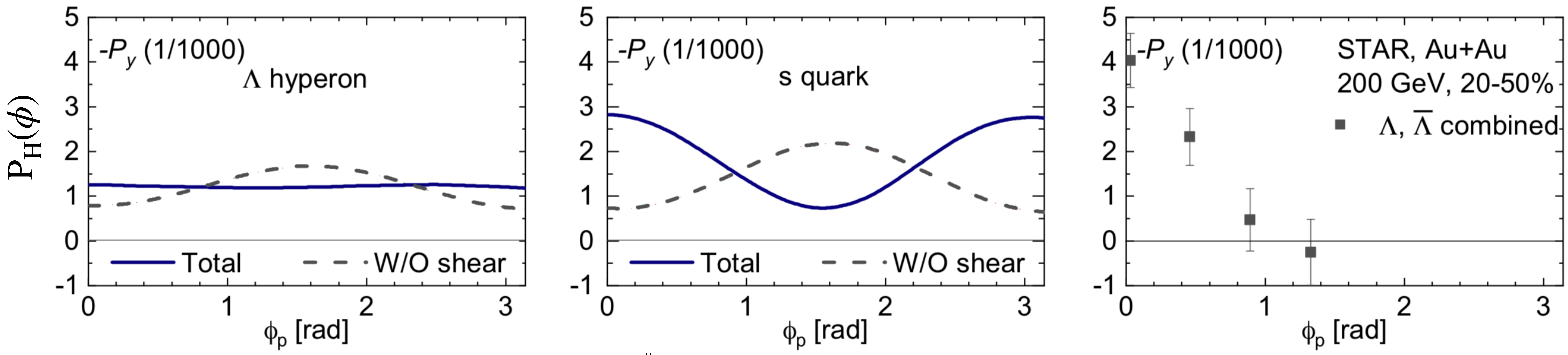
$$Q(M_{inv}) = f^S(M_{inv})Q^S + f^{BG}(M_{inv})Q^{BG}(M_{inv})$$

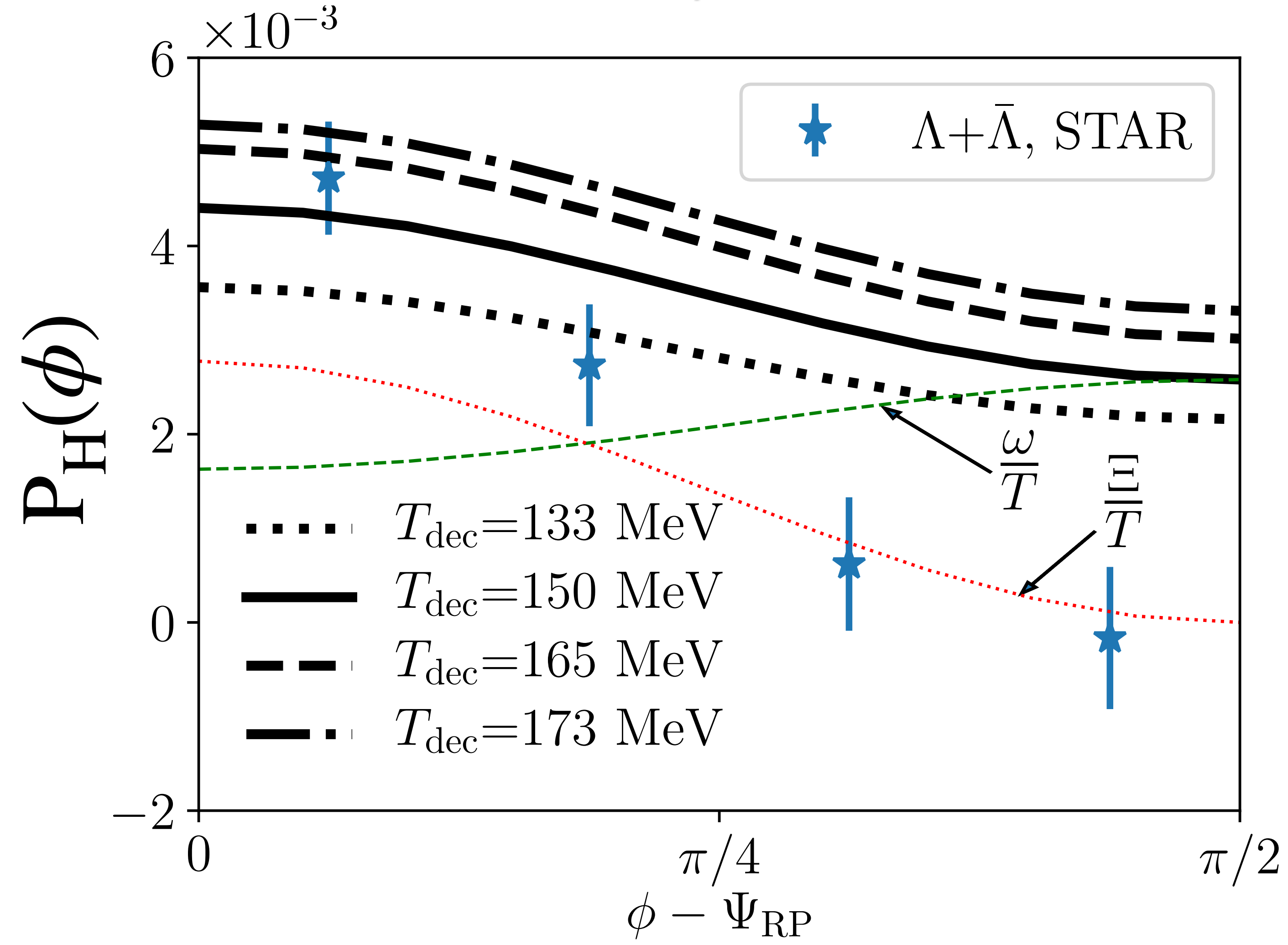
f^S , f^{BG} signal, background fraction of Λ ($\bar{\Lambda}$)

Q^S ⟶polarization signal,

$Q^{BG}(M_{inv})$⟶Λ ($\bar{\Lambda}$) background contribution.

Phase puzzle in P_H



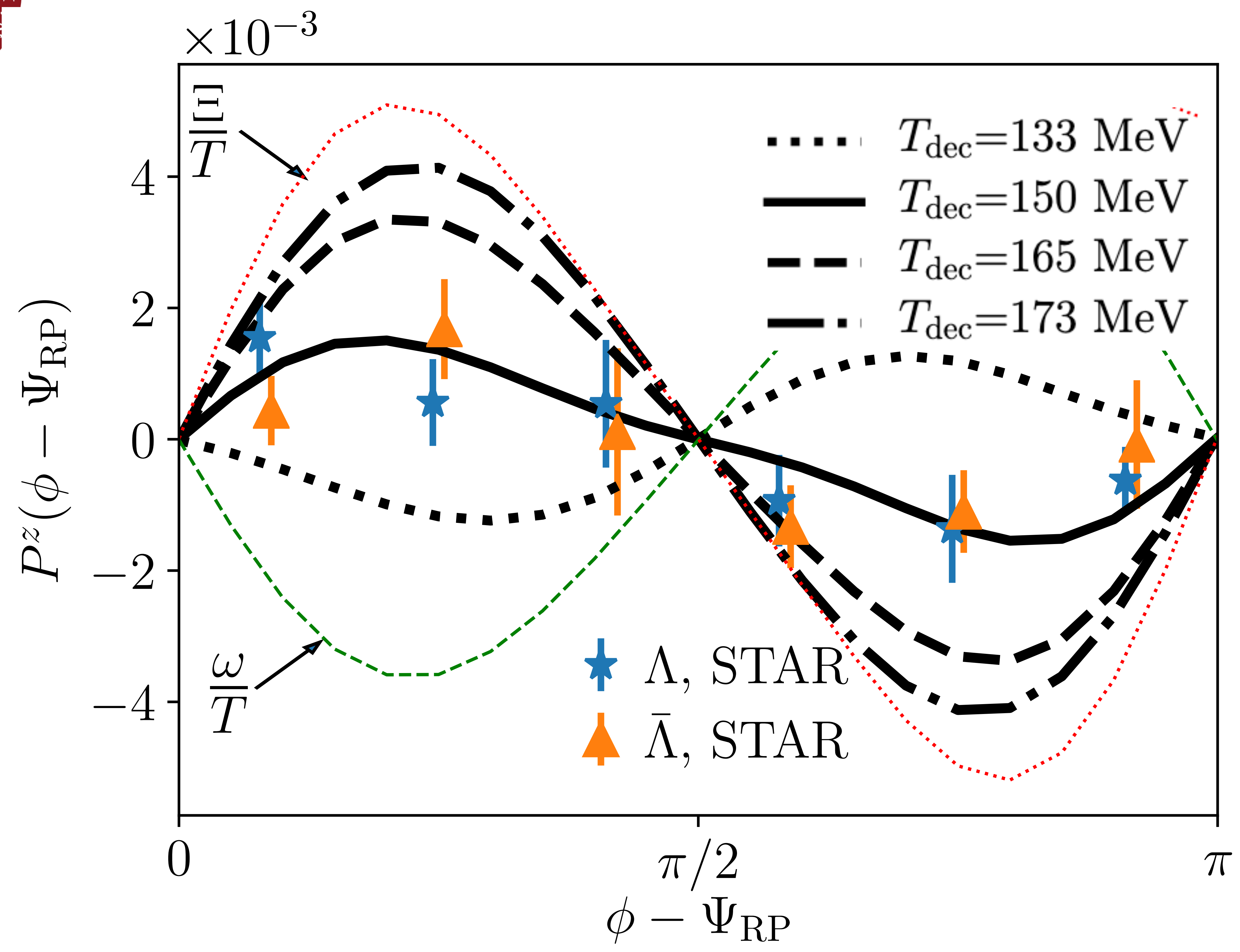


F. Becattini et al.; arXiv:2103.14621 [nucl-th]

B. Fu et al.; arXiv:2103.10403 [hep-ph]

- The global vorticity is along orbital angular momentum (along -y direction)
- P_H (P^J) has higher value in plane (along x) compared to out of plane (along y)!
- (Fluid shear +thermal vorticity) based P_H estimation can explain this (with the assumption of isothermal local equilibrium or using s quark as the spin carrier).

Pz in heavy ion collisions (Recent theoretical developments)



- Spin polarization from vorticity:

$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma d\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma d\Sigma \cdot p\, n_F},$$

Cooper-Frye

Vorticity: $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$.

Fermi-Dirac distribution: $n_F = \{\exp[\beta\cdot p - q\mu/T]+1\}^{-1}$.

F. Becattini et al., Phys. Rev. Lett. 127, 272302 (2021)

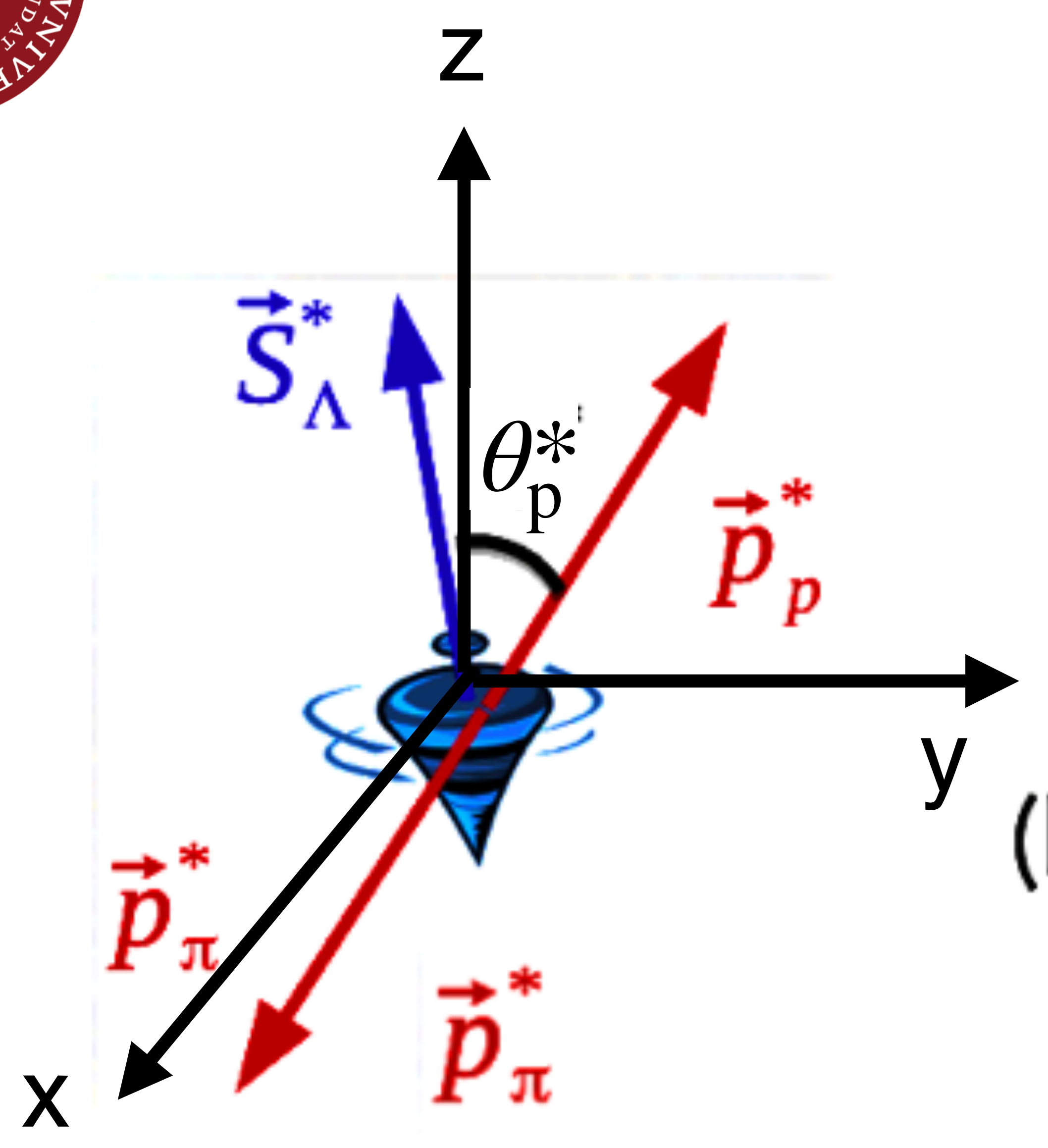
Total Vorticity = $\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu\beta_\mu - \partial_\mu\beta_\nu)$ + $\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu)$

(Thermal vorticity) (shear)

Model: 3+1D hydro

- Vorticity and shear contribute oppositely to the $P_z(\varphi - \Psi_2)$ and are highly sensitive to the T_{dec}.
- T_{dec} >= 150–160 MeV: (*Shear > Vorticity*) ⟶ explain the experimentally measured $P_z(\varphi - \Psi_2)$ at RHIC.
- T_{dec} < 135 MeV : (*Shear < Vorticity*) ⟶ The sign flips for $P_z(\varphi - \Psi_2)$

Hyperon polarization estimation



Λ ($\bar{\Lambda}$) hyperons ⟶ Parity violating weak decay

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

(BR: 63.9%, cτ~7.9 cm)

$$\alpha_\Lambda = 0.750 \pm 0.009$$

$$\alpha_{\overline{\Lambda}} = -0.758 \pm 0.01$$

BESIII Collaboration, Nature Phys. 15 (2019)

ALICE Collaboration, arXiv:2107.11183 **[nucl-ex]**

($\alpha_\Lambda = 0.732$)⟶Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

- Daughter baryon is preferentially emitted in the direction of hyperon spin (opposite for antiparticle)-

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}(1 + \alpha_\mathrm{H}\mathbf{P}_\mathrm{H} \cdot \hat{\mathbf{p}}^*_\mathrm{p}),$$

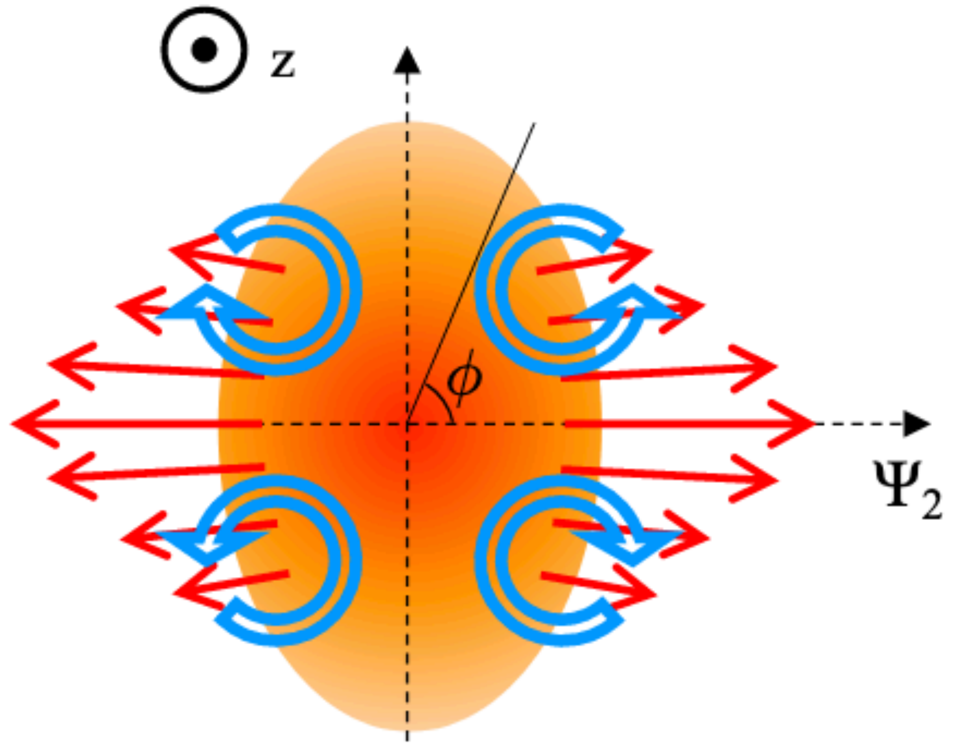
(* denotes hyperon rest frame)

$\mathbf{P}_\mathrm{H}$ = hyperon polarization vector

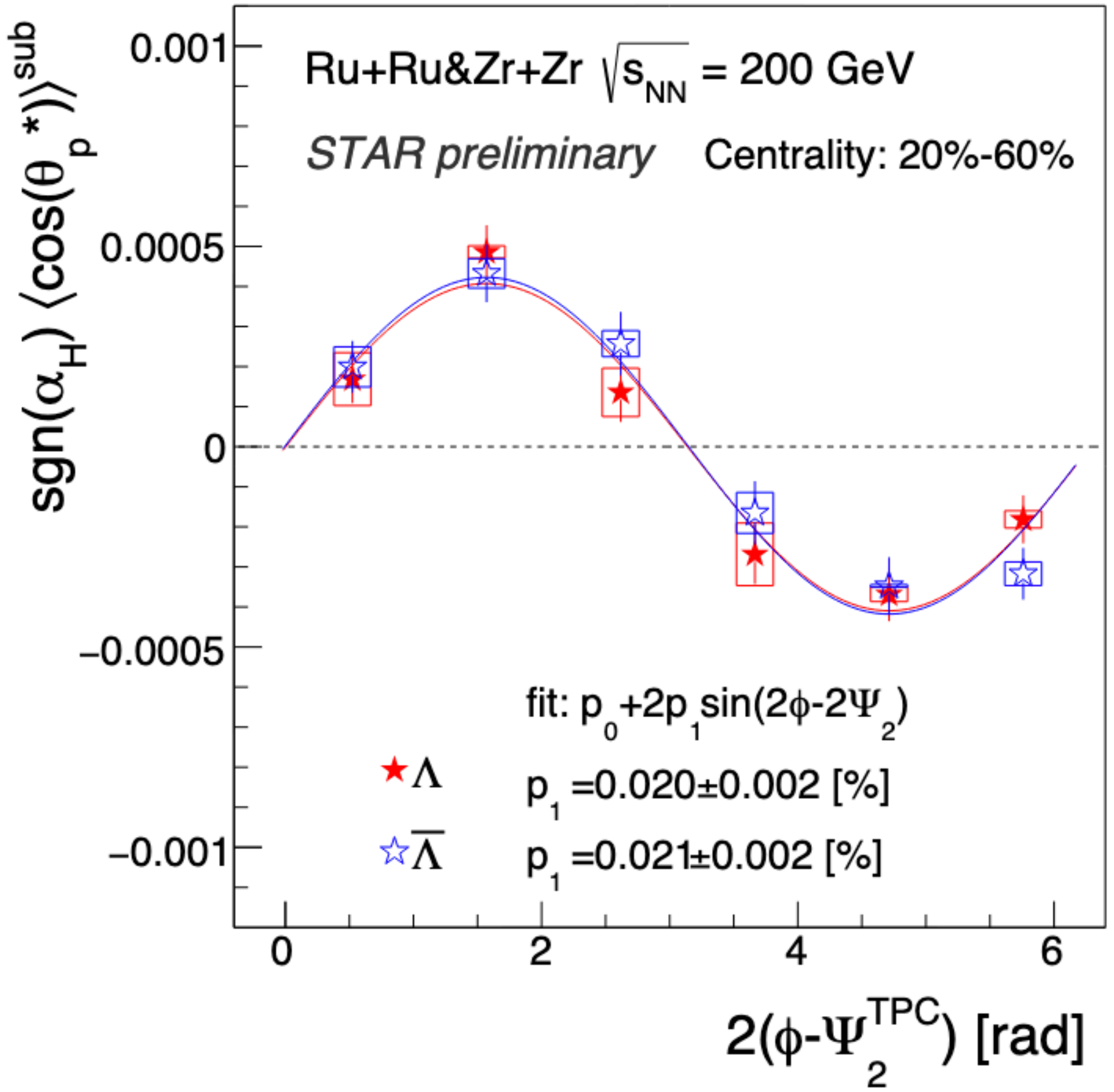
α_H = hyperon decay parameter

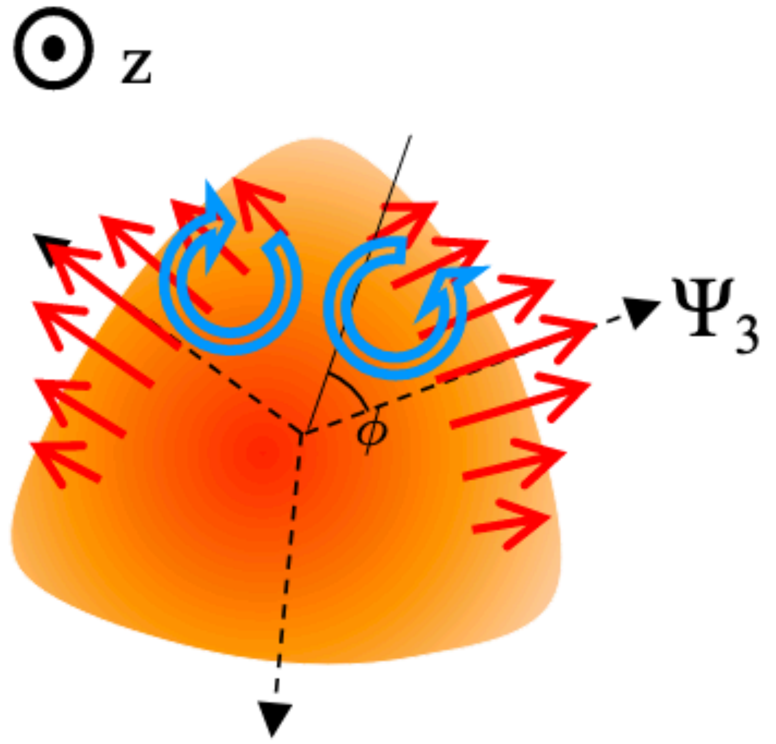
$\hat{\mathbf{p}}^*_\mathrm{p}$ = unit vector along daughter baryon momentum

Anisotropic flow induced polarization along the beam direction (P_z)



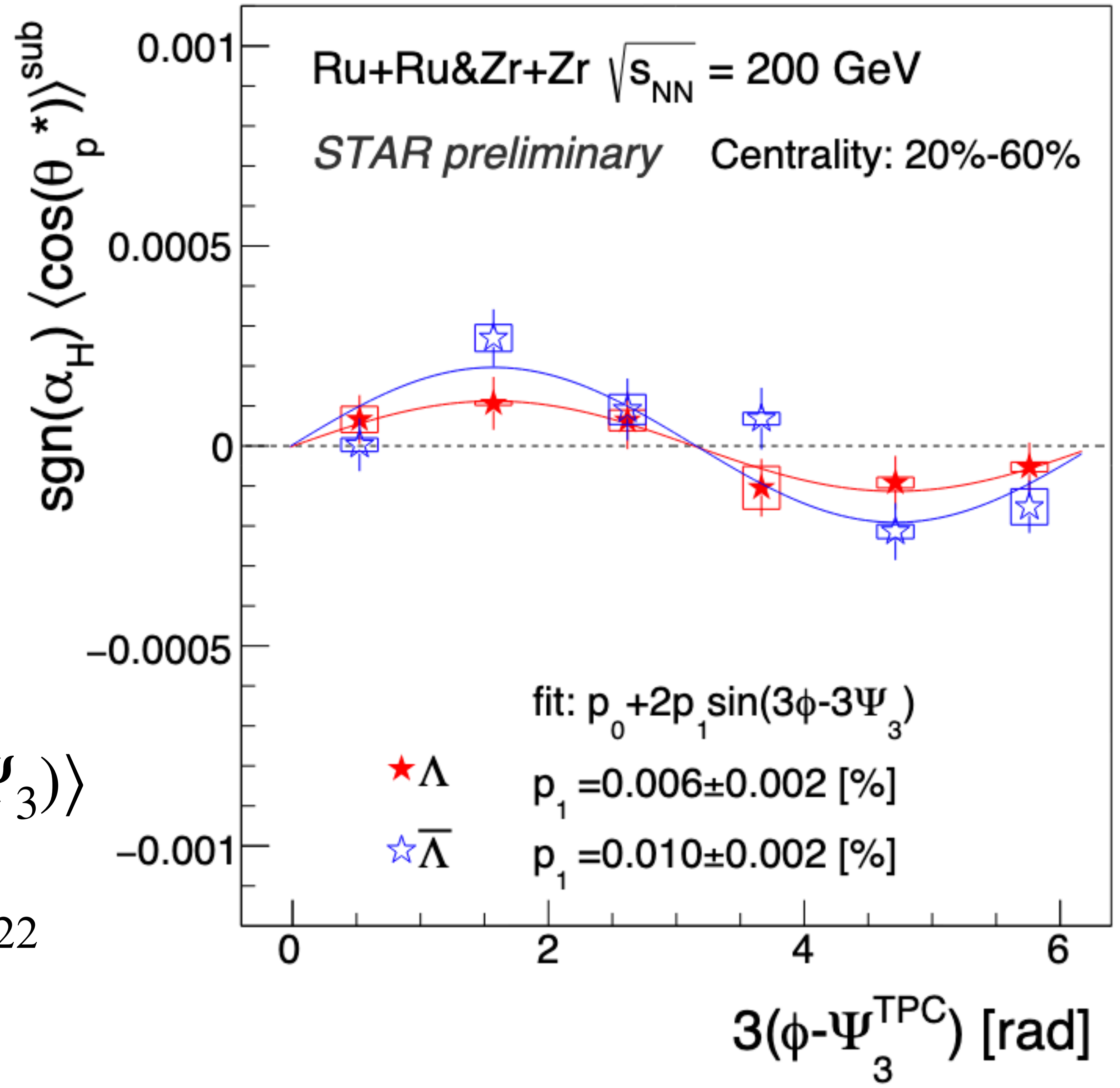
$P_{z,s2} = \langle P_z \sin(2\varphi - 2\Psi_2)\rangle$





$P_{z,s3} = \langle P_z \sin(3\varphi - 3\Psi_3)\rangle$

STAR preliminary, QM2022



- Local polarization (along z axis)- $P_z \approx \langle(\hat{p}_p^* \cdot \hat{z})\rangle$ $\quad P_z = \dfrac{\langle\cos\theta_p^*\rangle}{\alpha_H\langle(\cos\theta_p^*)^2\rangle}$

- Elliptic flow induced polarization along beam axis: $\sin(2\varphi - 2\Psi_2)$ dependence
- Triangular flow induced polarization along beam axis: $\sin(3\varphi - 3\Psi_3)$ dependence
- No difference between Λ and $\bar{\Lambda}$ polarization.