Global and local polarization of Λ and $\bar{\Lambda}$ hyperons in Pb-Pb collisions at ALICE

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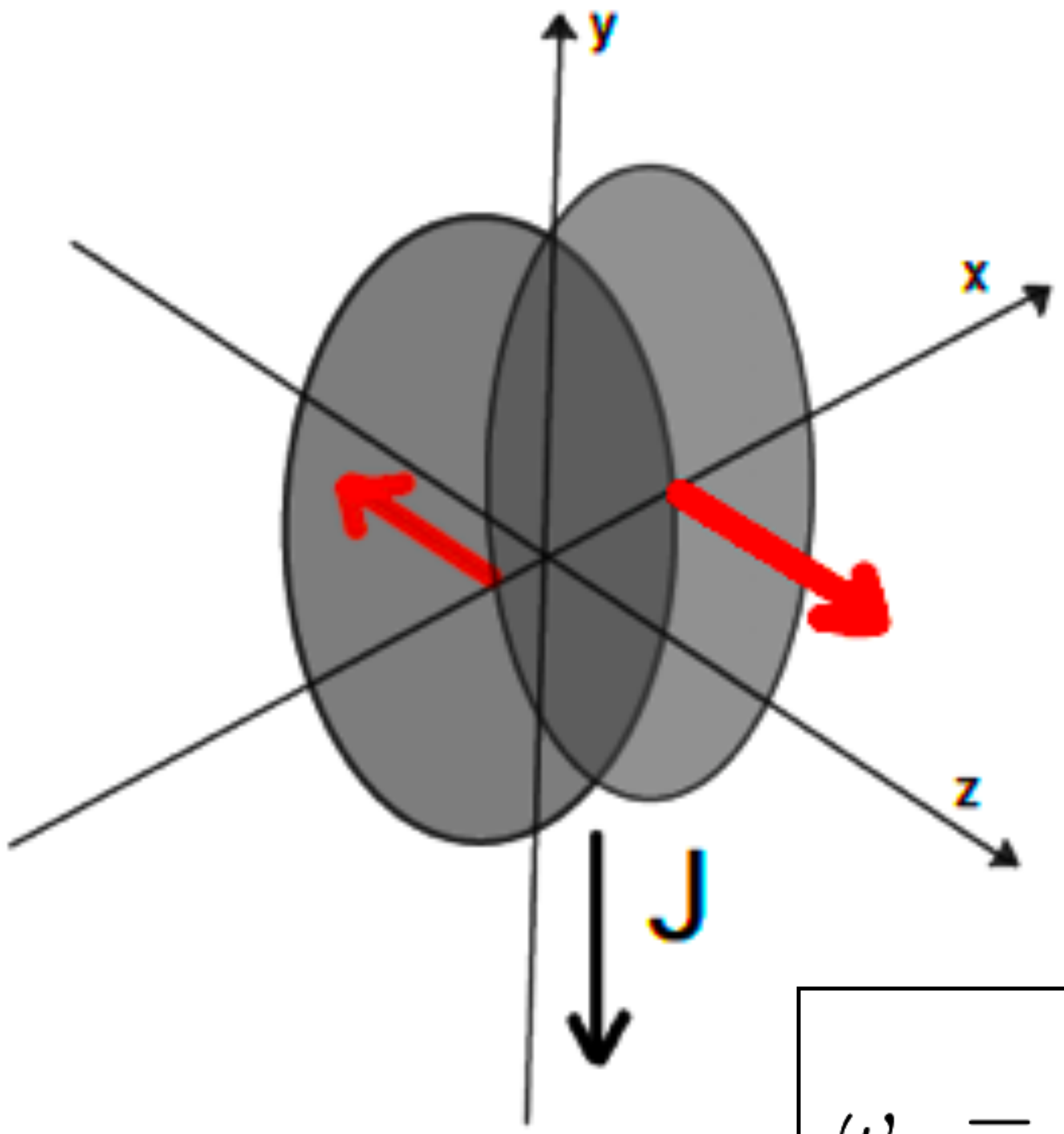
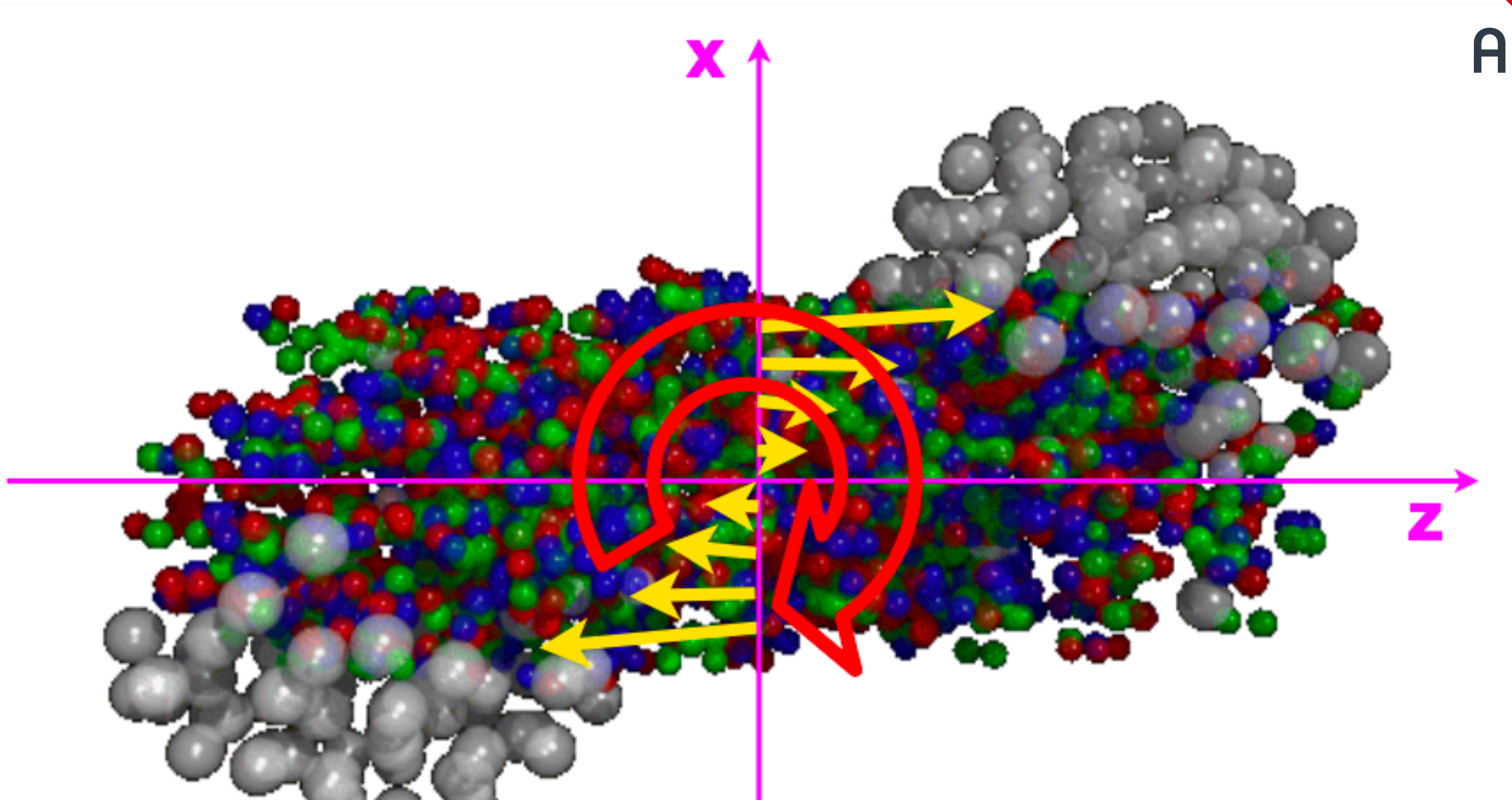
SQM2021

Global hyperon polarization (P_H)



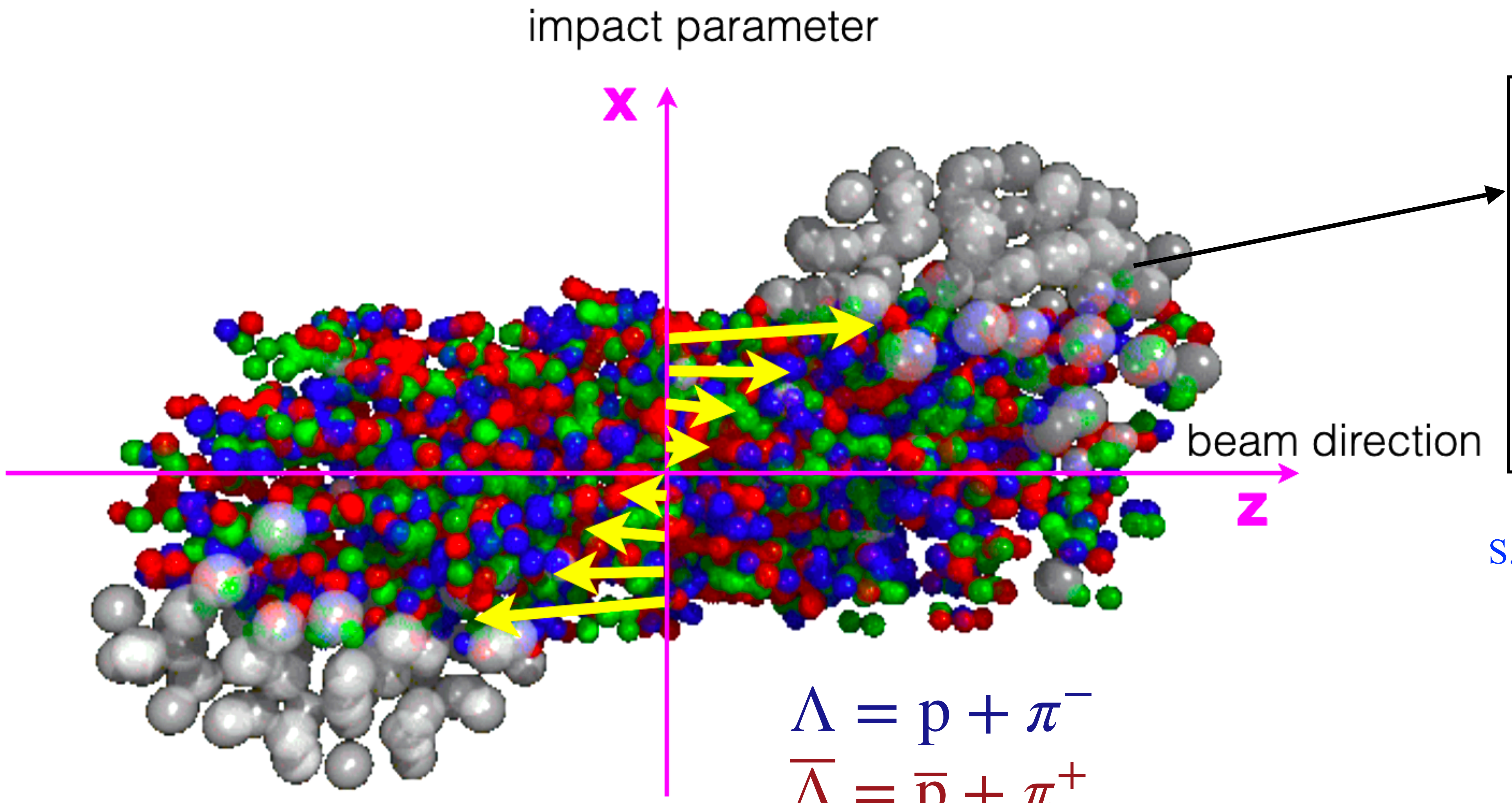


Modified from UrQMD

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

- Vorticity along the system orbital angular momentum due to initial shear in longitudinal flow velocity.
- **"Global polarization" → particle/antiparticle polarization along system's orbital angular momentum.**
- Strong magnetic field due to charged spectators → splitting in particle/antiparticle polarization.
- **Mostly sensitive to the initial stages of the collisions.**

P_H measurement in heavy-ion collisions



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

- Deflection of the spectators determines the direction of $\vec{L}(=\vec{b} \times \vec{P})$.
- On average spectators deflect outwards.

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

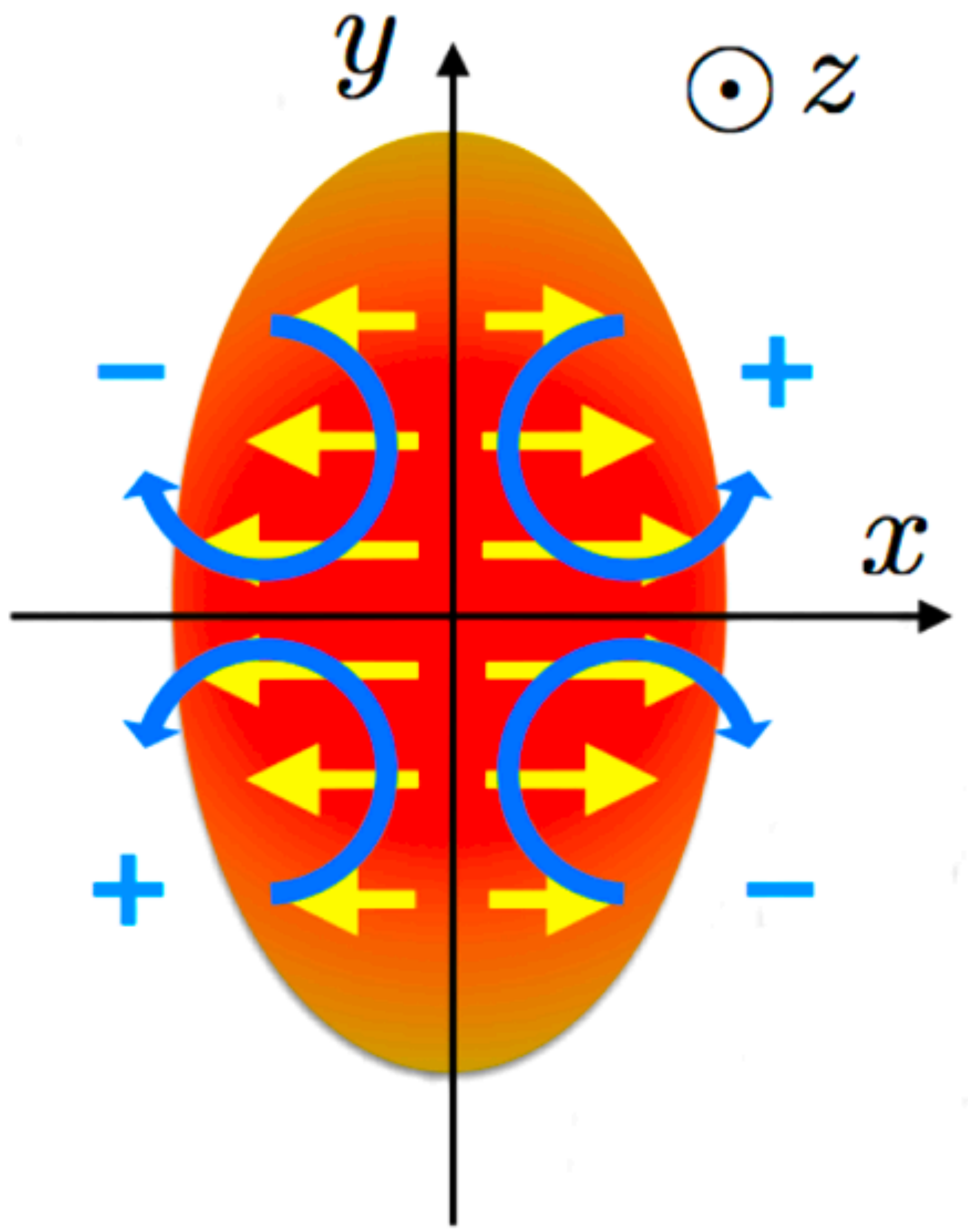
- Λ ($\bar{\Lambda}$) hyperons → Parity violating weak decay → used for polarization measurement.

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

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

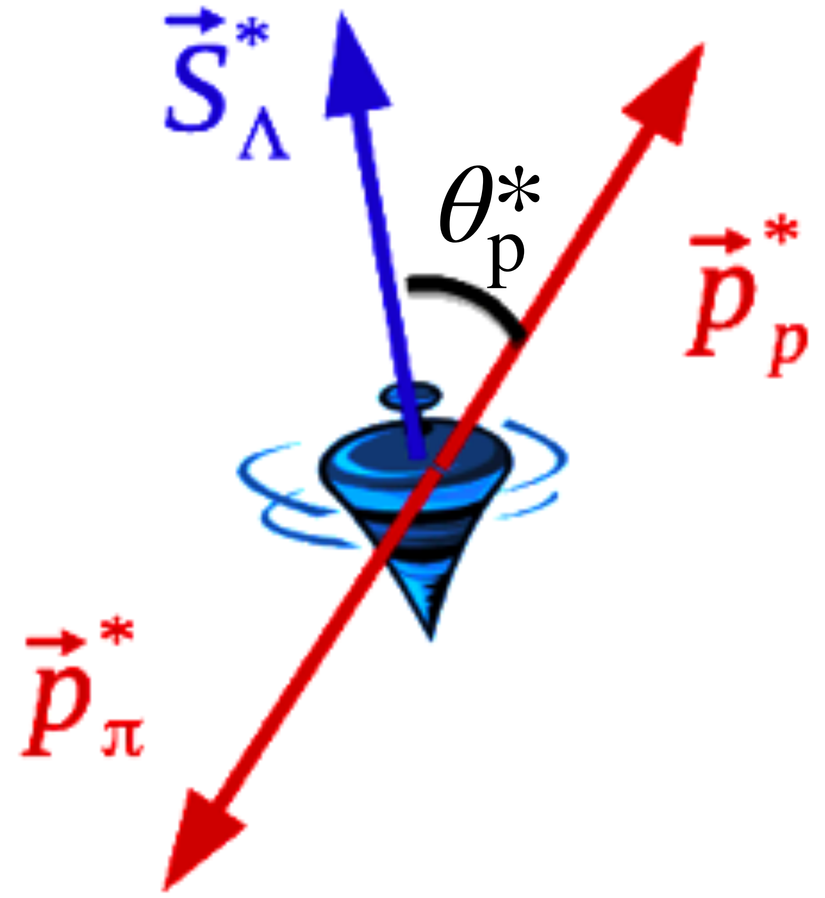
- $\Psi_{\rm SP}$ = Spectator plane angle (azimuthal angle of $\vec{b}$)
- $\varphi^{*}_{\rm p}$ = azimuthal angle of daughter proton in Λ($\bar{\Lambda}$) rest frame
- $R^{1}_{\rm SP}$ = Resolution of $\Psi_{\rm SP}$
- $\alpha_{\rm H}$ = Hyperon decay parameter

Polarization along the beam direction (P_z)



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

$$P_z \sim \sin(2\phi_H)$$



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

(BR: 63.9%, cτ~7.9 cm)

$$P_\mathrm{z} = \frac{<\cos\theta^*_\mathrm{p}>}{\alpha_H <(\cos\theta^*_\mathrm{p})^2>}$$

$$= \frac{3<\cos\theta^*_\mathrm{p}>}{\alpha_H} \text{ (if perfect detector)}$$

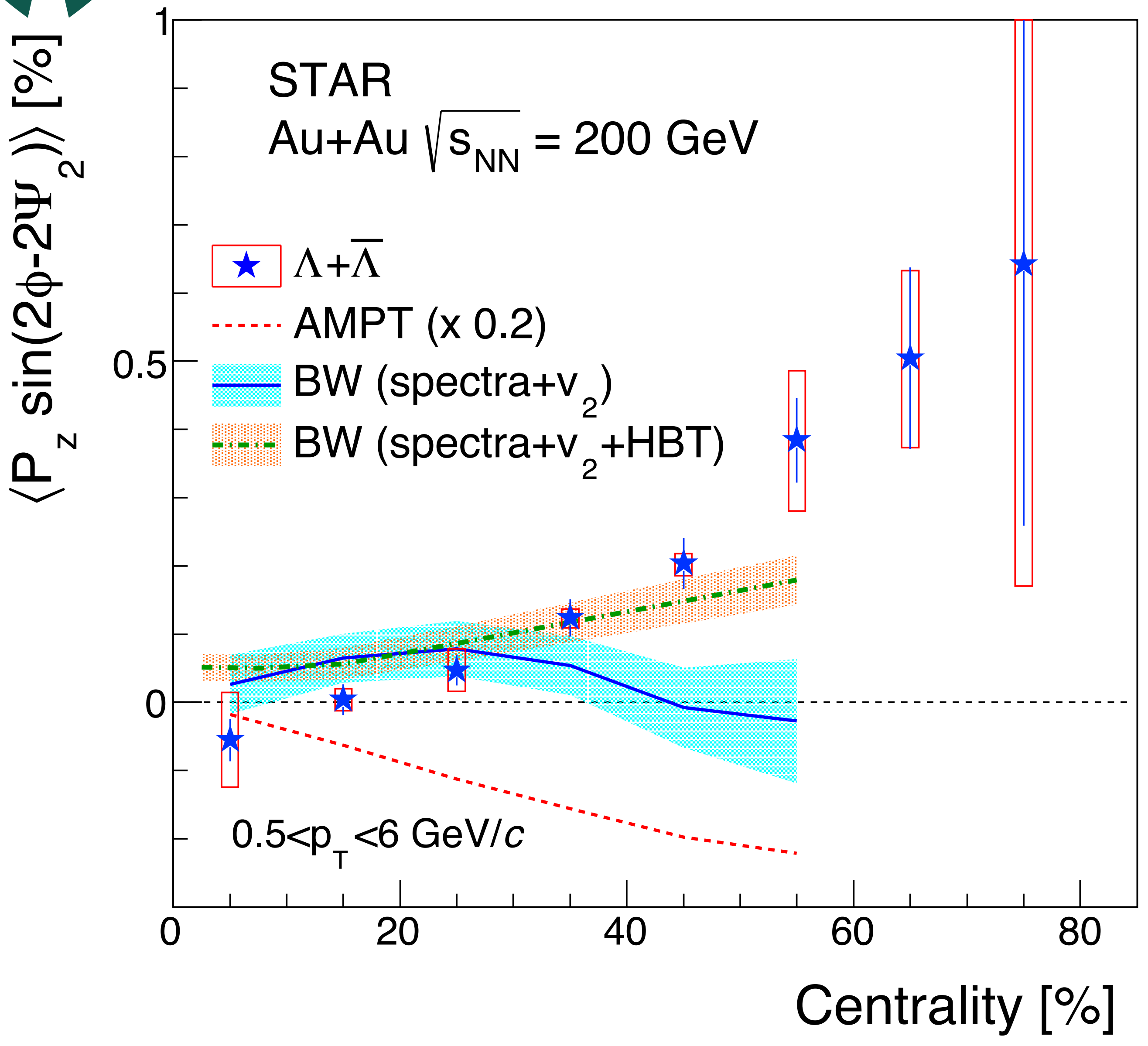
$<(\cos\theta^*_\mathrm{p})^2>$ = correction for finite acceptance along z

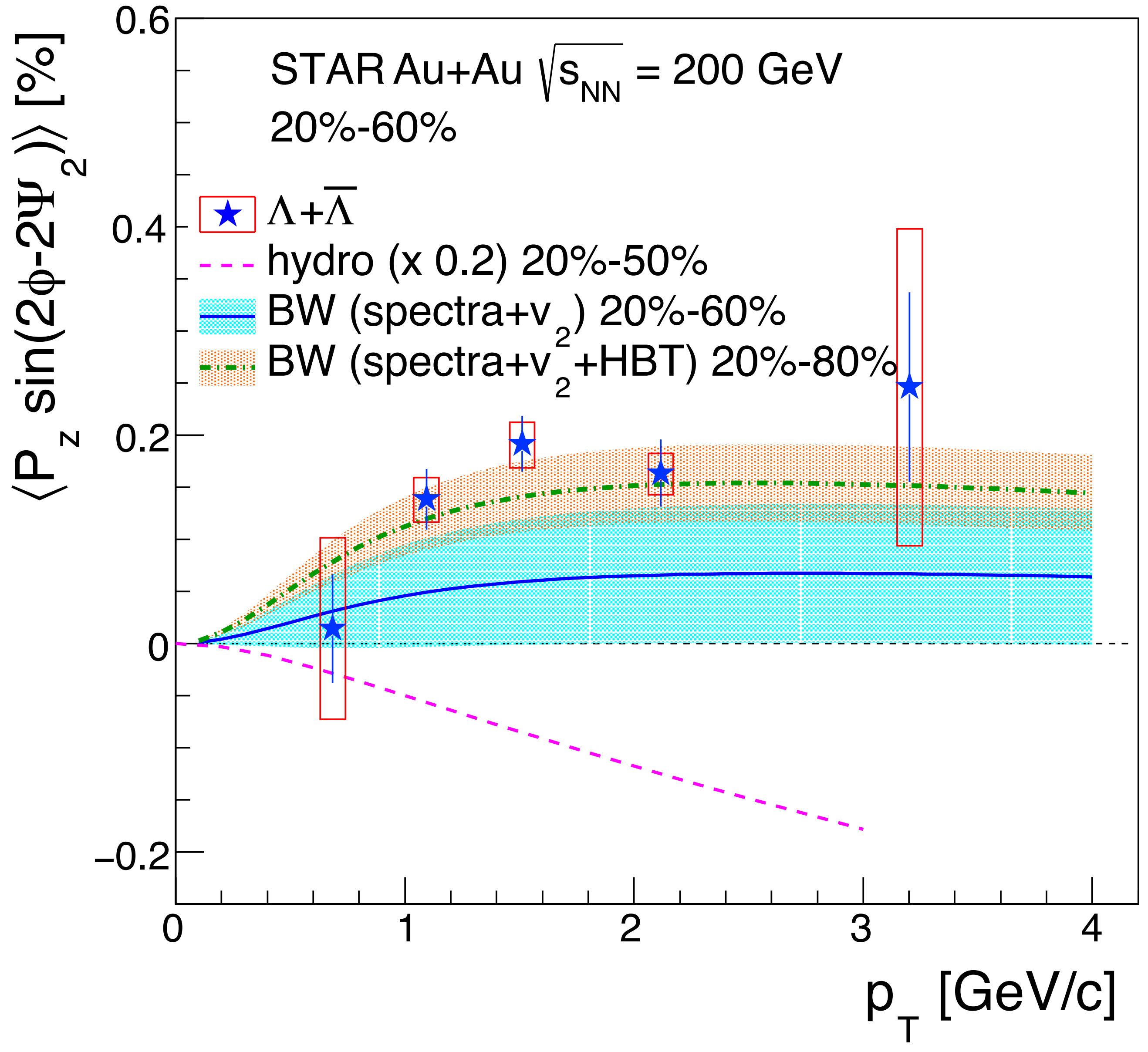
$$P_{\mathrm{z,s2}} = <P_\mathrm{z}\sin(2\varphi - 2\Psi_2)>$$ → estimates magnitude and phase of P_z.

- Vorticity along the beam direction due to strong elliptic flow.
- **"Local polarization": exhibits a quadrupole pattern, i.e. $\sin(2\varphi - 2\Psi_2)$ dependence.**
- **Sensitive to the later stages of the evolution of the system.**

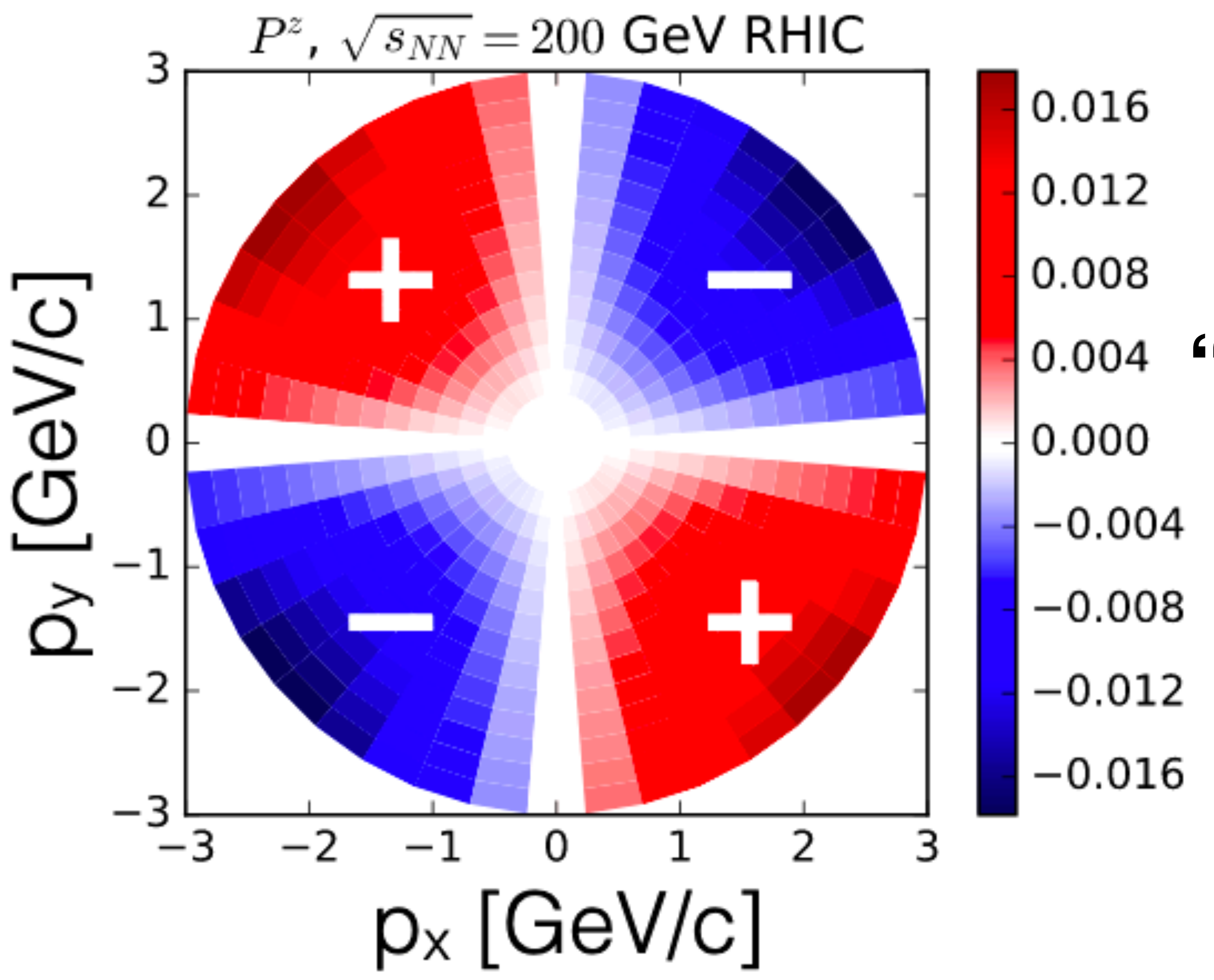
P_z in heavy-ion collisions (story so far…)

STAR, Physical Review Letters 123, 132301 (2019)
X. Xia, H. Li, Z. Tang, Q. Wang, arXiv:1803.00867 (AMPT)





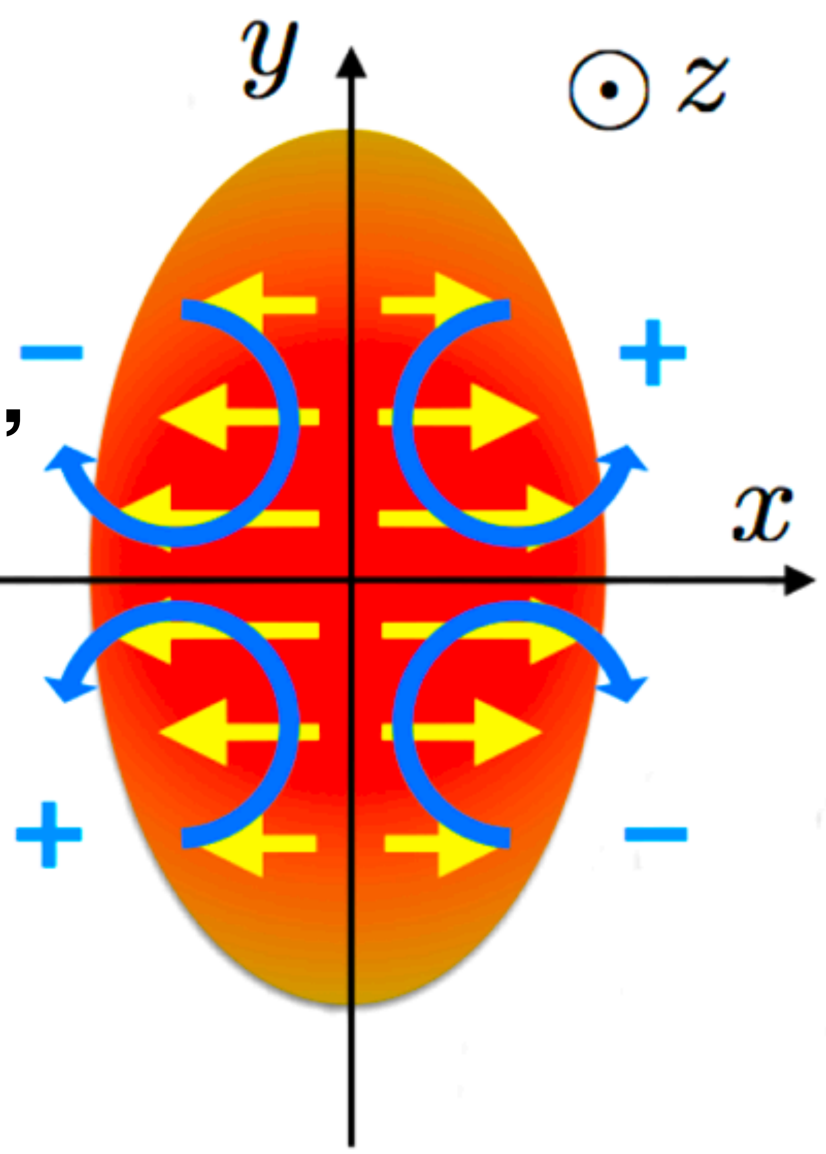
Model prediction



Becattini, Karpenko, PRL.120.012302 (2018) (Hydro)

Experimental observation

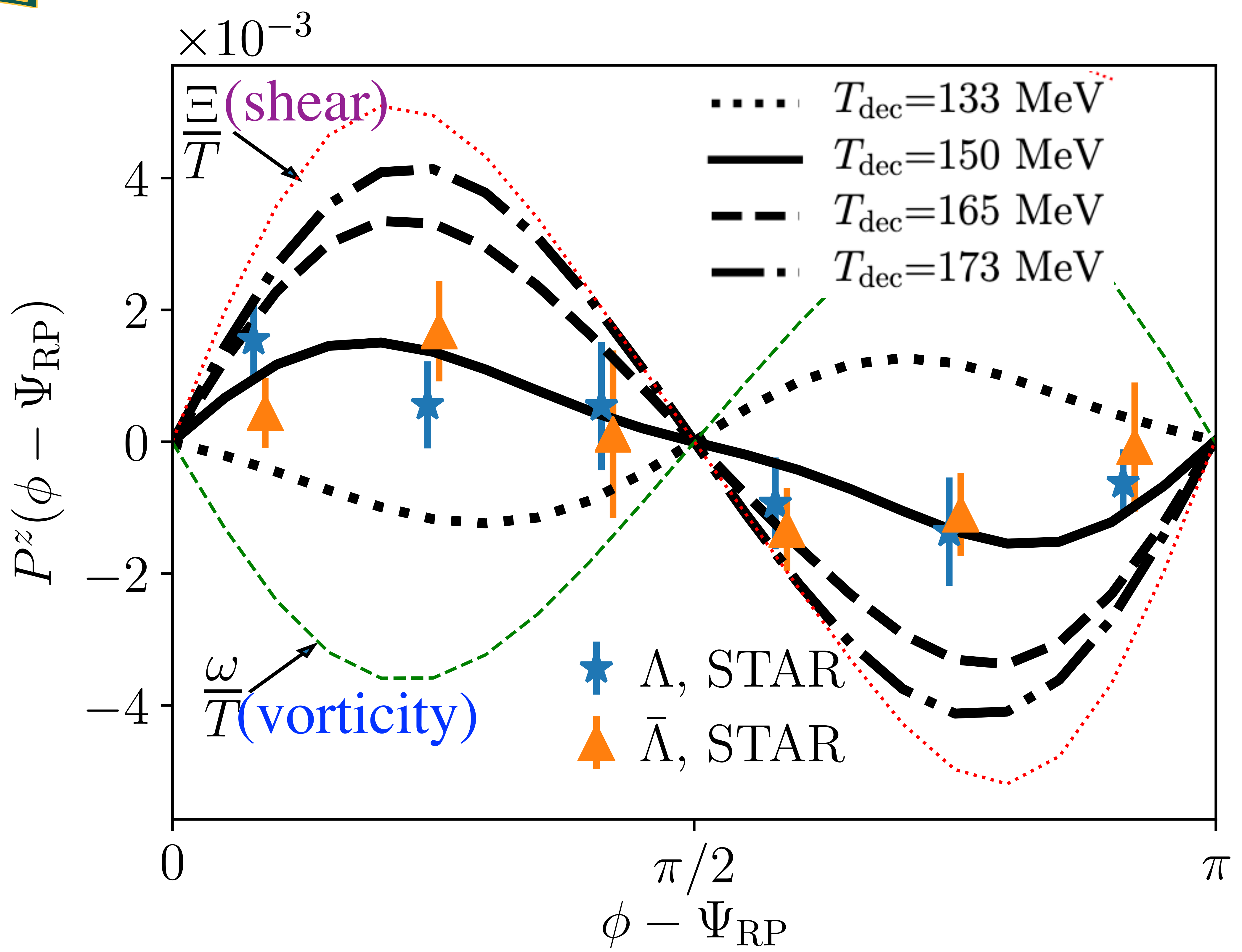
"Spin sign puzzle"



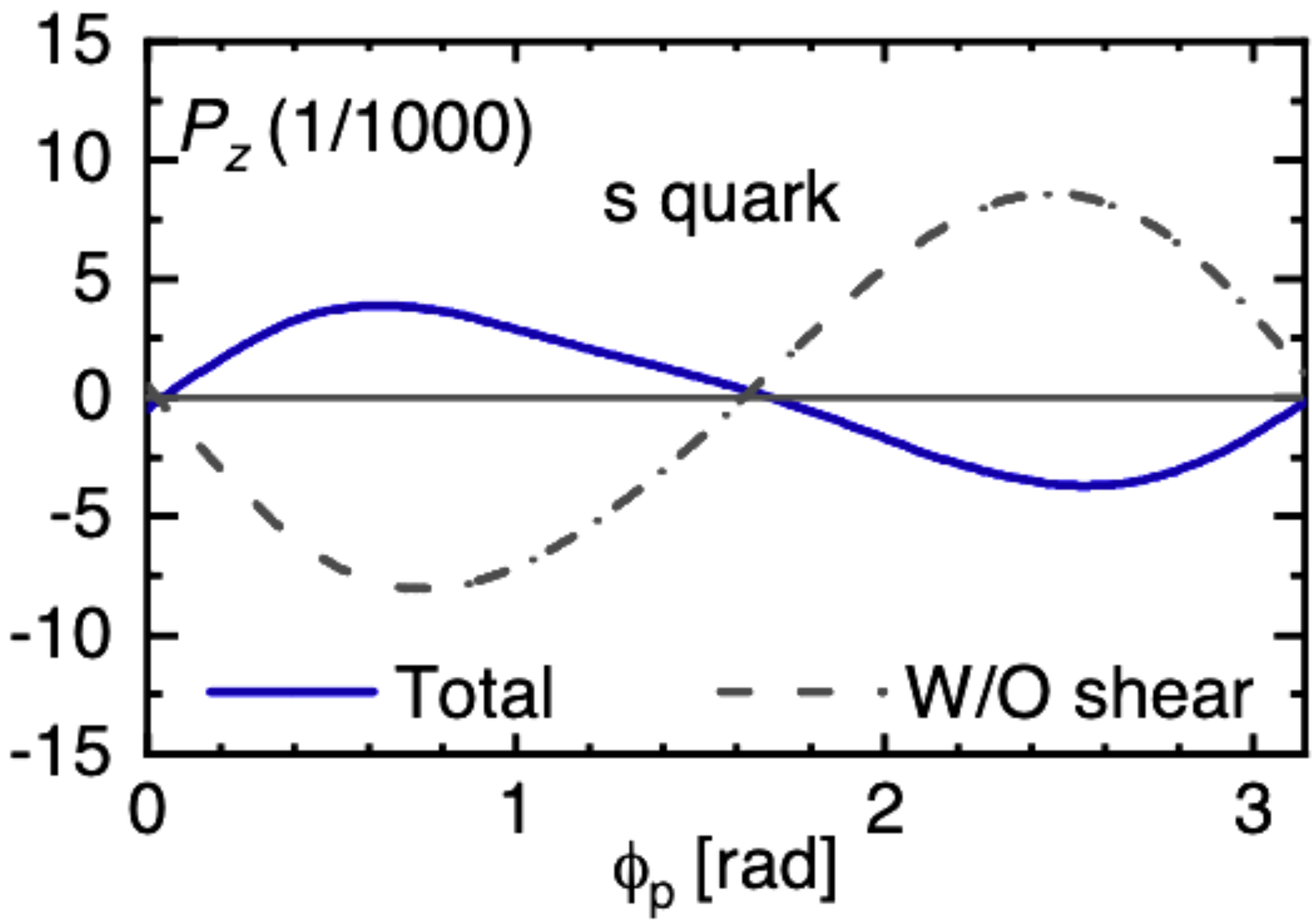
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

- Hydro models and AMPT estimate P_z from thermal vorticity at the kinetic freeze-out.
- Both generate negative $P_{z,s2}$ (opposite to experimental observation → "spin sign puzzle").
- Blast-Wave model (kinematic vorticity) describes the $P_{z,s2}$ measured in STAR!

P_z in heavy-ion collisions (Recent developments)



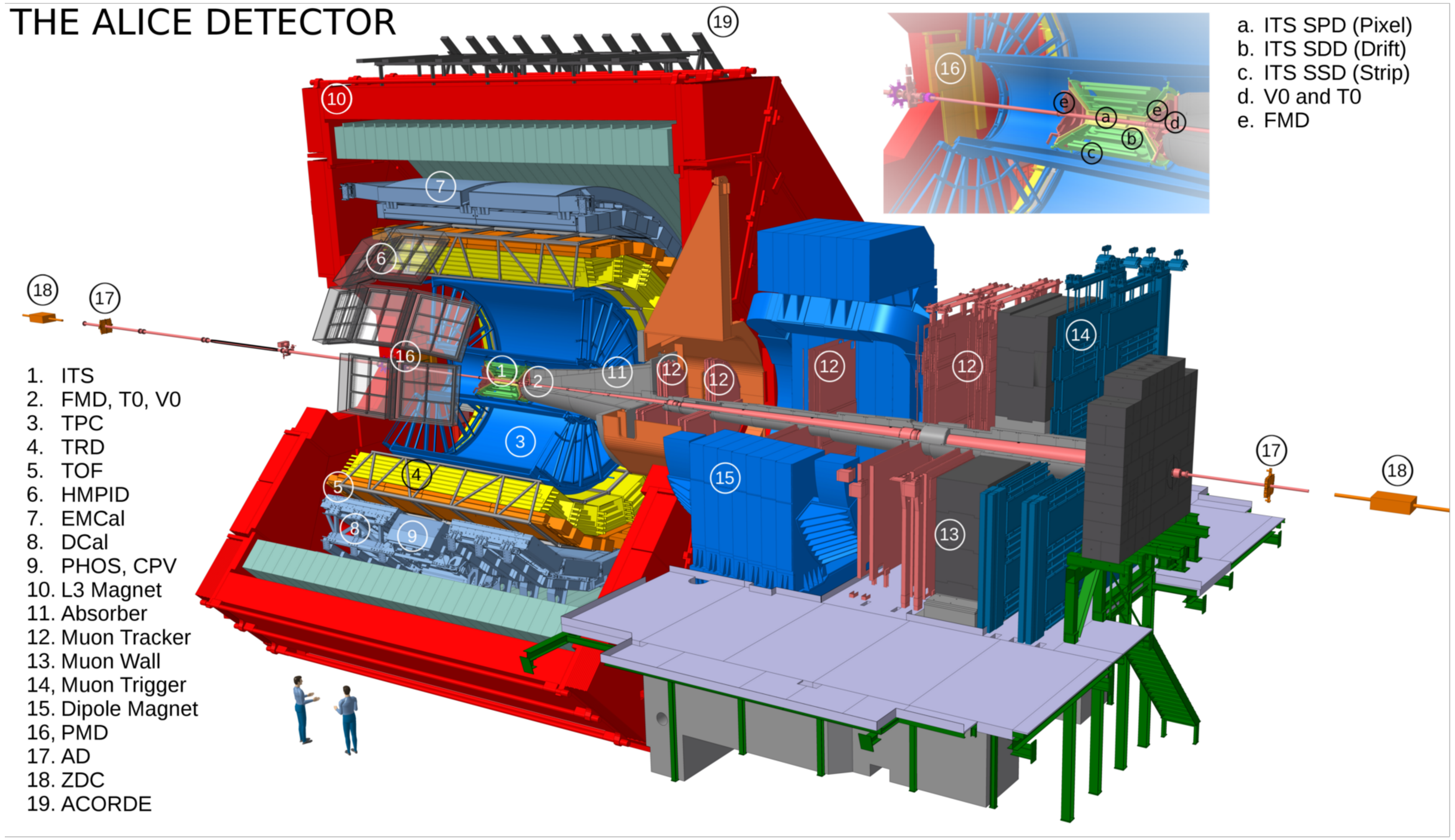
Ref. 1: F. Becattini et al.; arXiv:2103.14621 [nucl-th]



Ref. 2: B. Fu et al.; arXiv:2103.10403 [hep-ph]

- Refs.1,2: Polarization estimated from thermal shear + thermal vorticity.
- Ref.1: Explains $P_z(\varphi - \Psi_2)$ in Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with T_{dec} = 150–160 MeV. Assumption: Isothermal local equilibrium.
- Ref.2: $\Lambda(\bar{\Lambda})$ inherits the spin polarization of the strange quark → qualitatively explains $P_z(\varphi - \Psi_2)$ measured in STAR.

Measuring hyperon polarization in ALICE

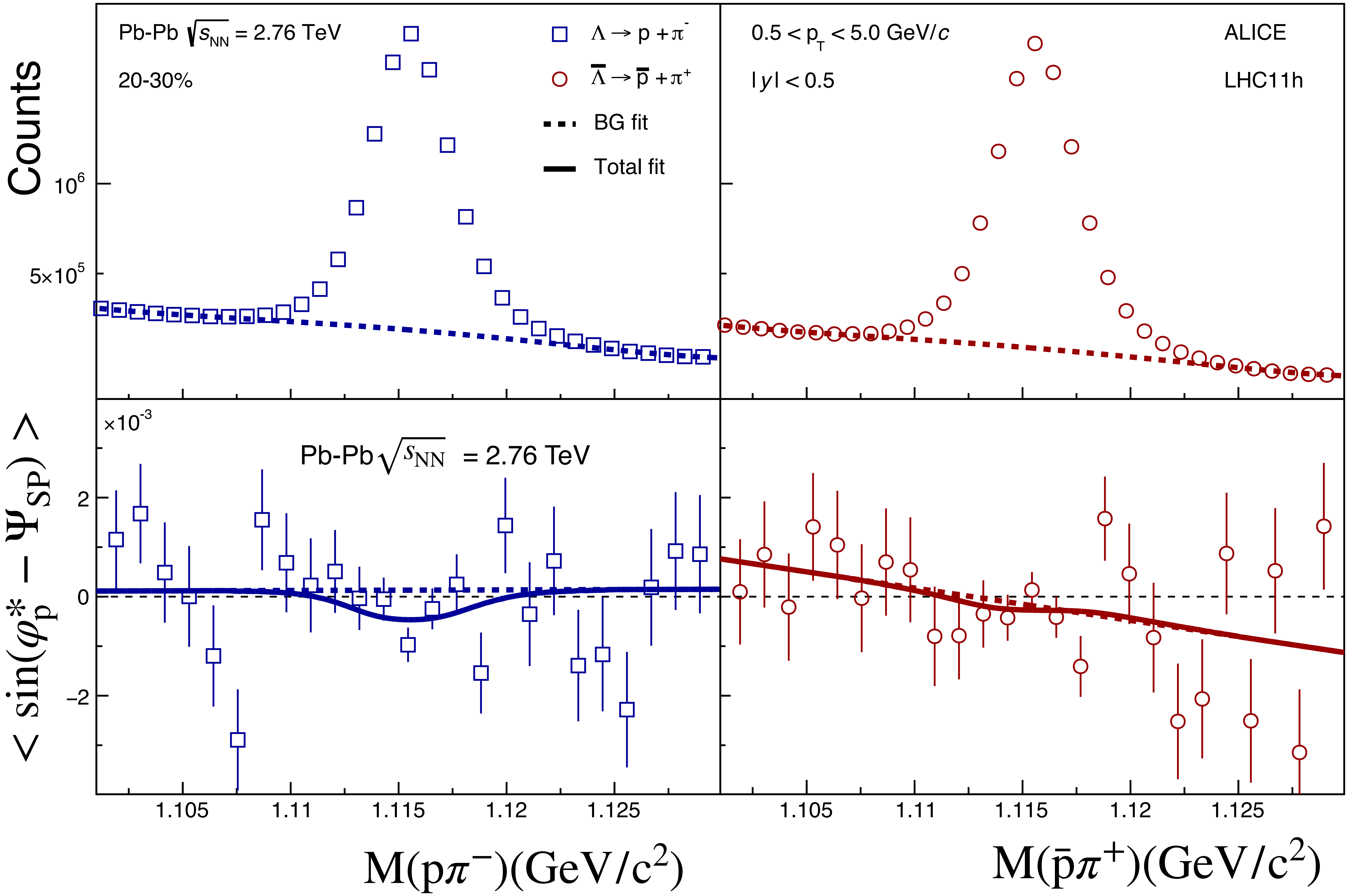


- Dataset - Pb-Pb (P_H measurement: $\sqrt{s_{NN}}$ = 2.76 TeV (~ 49 M events), 5.02 TeV (~ 75 M events)),
  (P_z measurement: $\sqrt{s_{NN}}$ = 5.02 TeV, ~ 270 M events).
- V0 scintillators (V0A, V0C) - centrality estimation, second harmonic flow plane (Ψ_2) reconstruction.
- Time Projection Chamber (TPC) - $\Lambda(\bar{\Lambda})$ reconstruction ($p_T > 0.5$ GeV/c, $|y| < 0.5$), Ψ_2 reconstruction.
- Neutron Zero Degree Calorimeter (ZNA and ZNC) - spectator plane (Ψ_{SP}) reconstruction.

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

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

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



$$P_H = -\frac{8}{\pi\alpha_H}\frac{< \sin(\varphi_p^* - \Psi_{SP}) >}{R_{SP}^1}$$

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

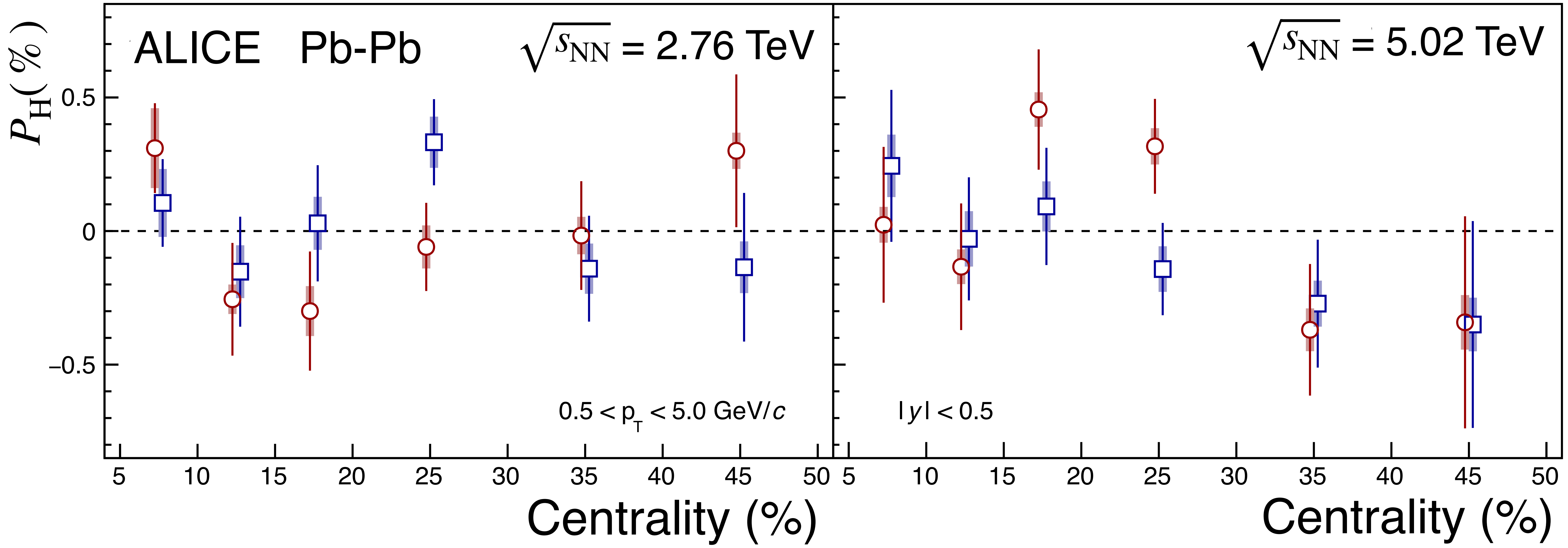
$$Q(M_{inv}) = f^S(M_{inv})Q^S + f^{BG}(M_{inv})Q^{BG}(M_{inv})$$

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

Q^S → polarization signal,

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

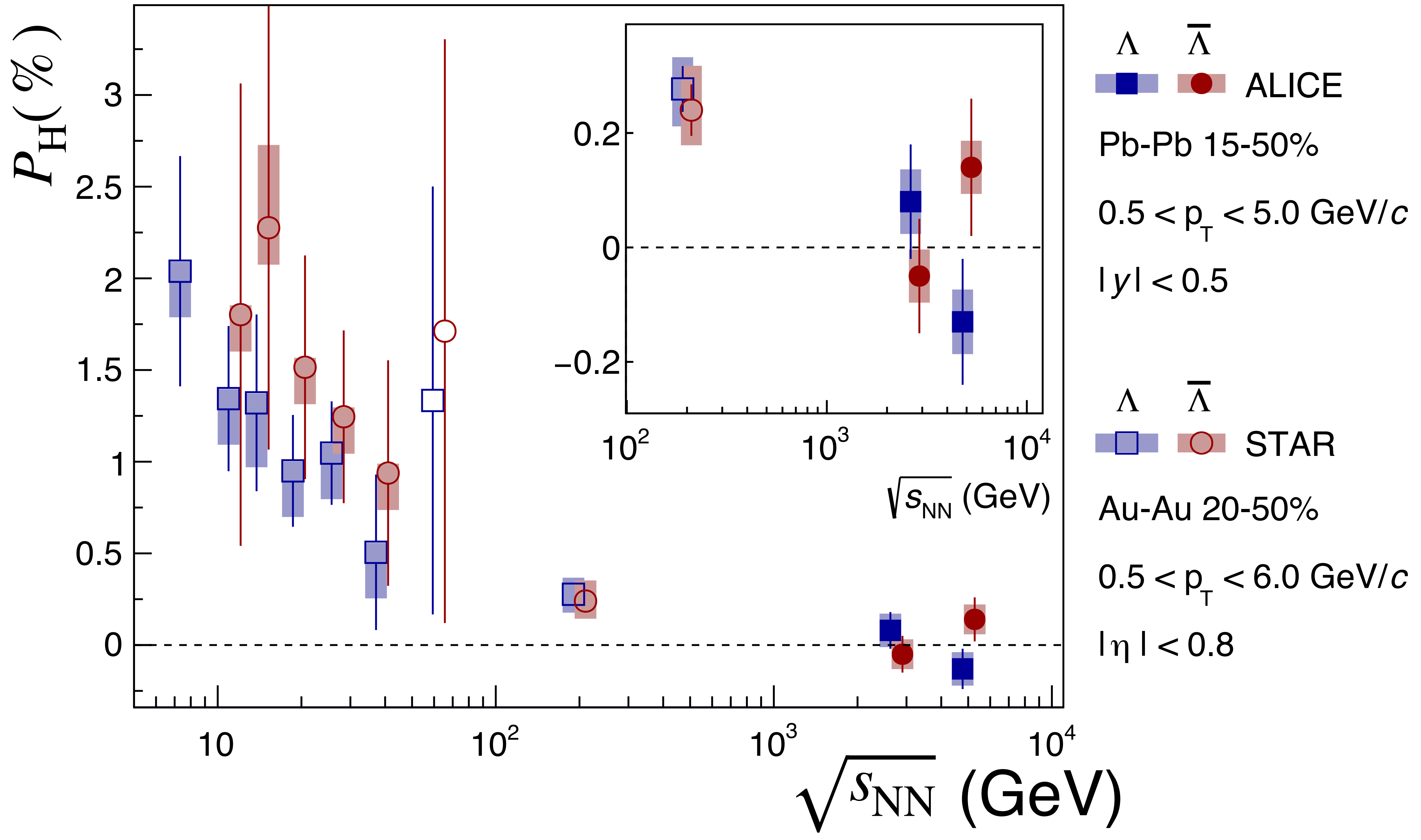
Global polarization (P_H) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV in ALICE



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

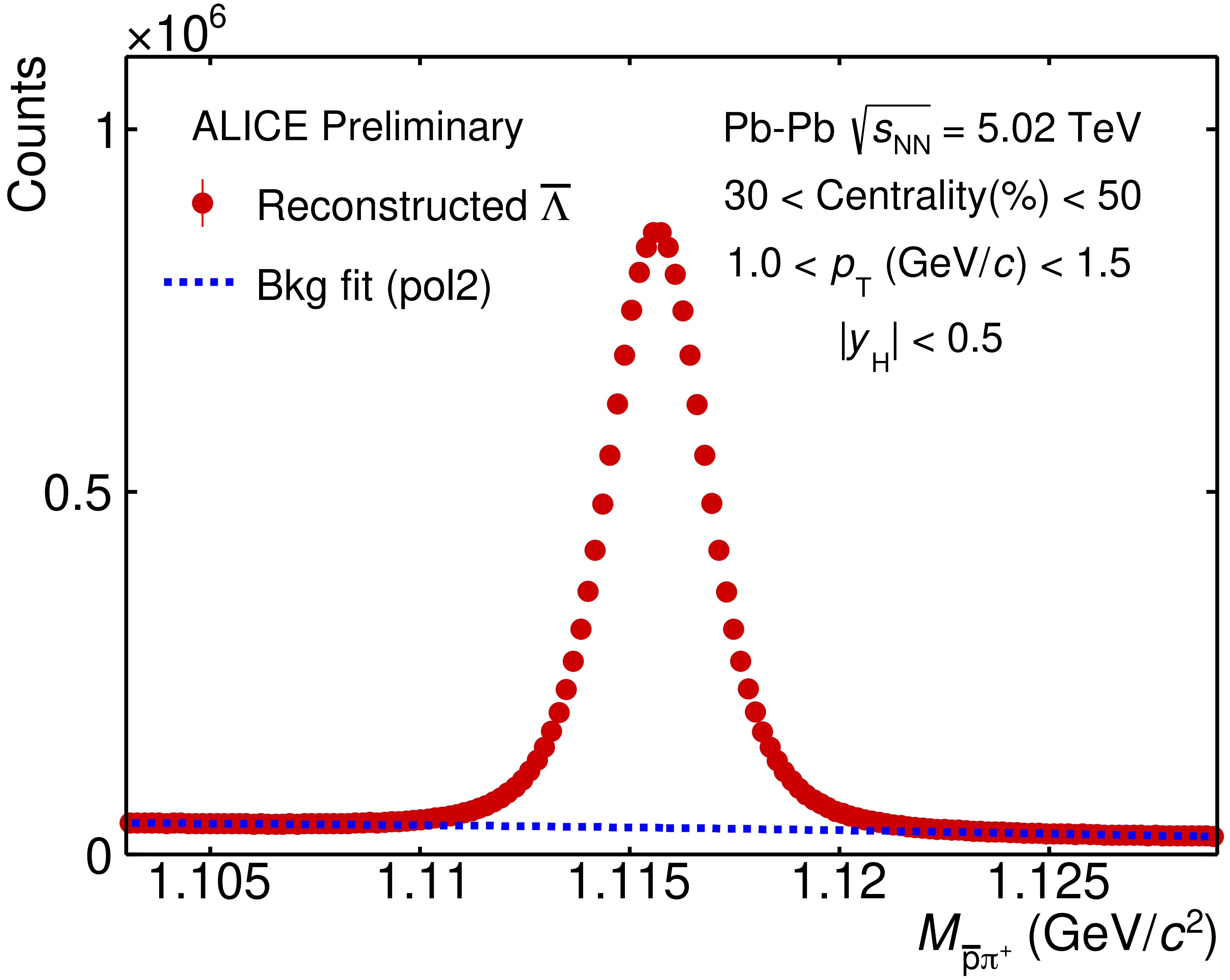
$$\Lambda = p + \pi^-$$

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

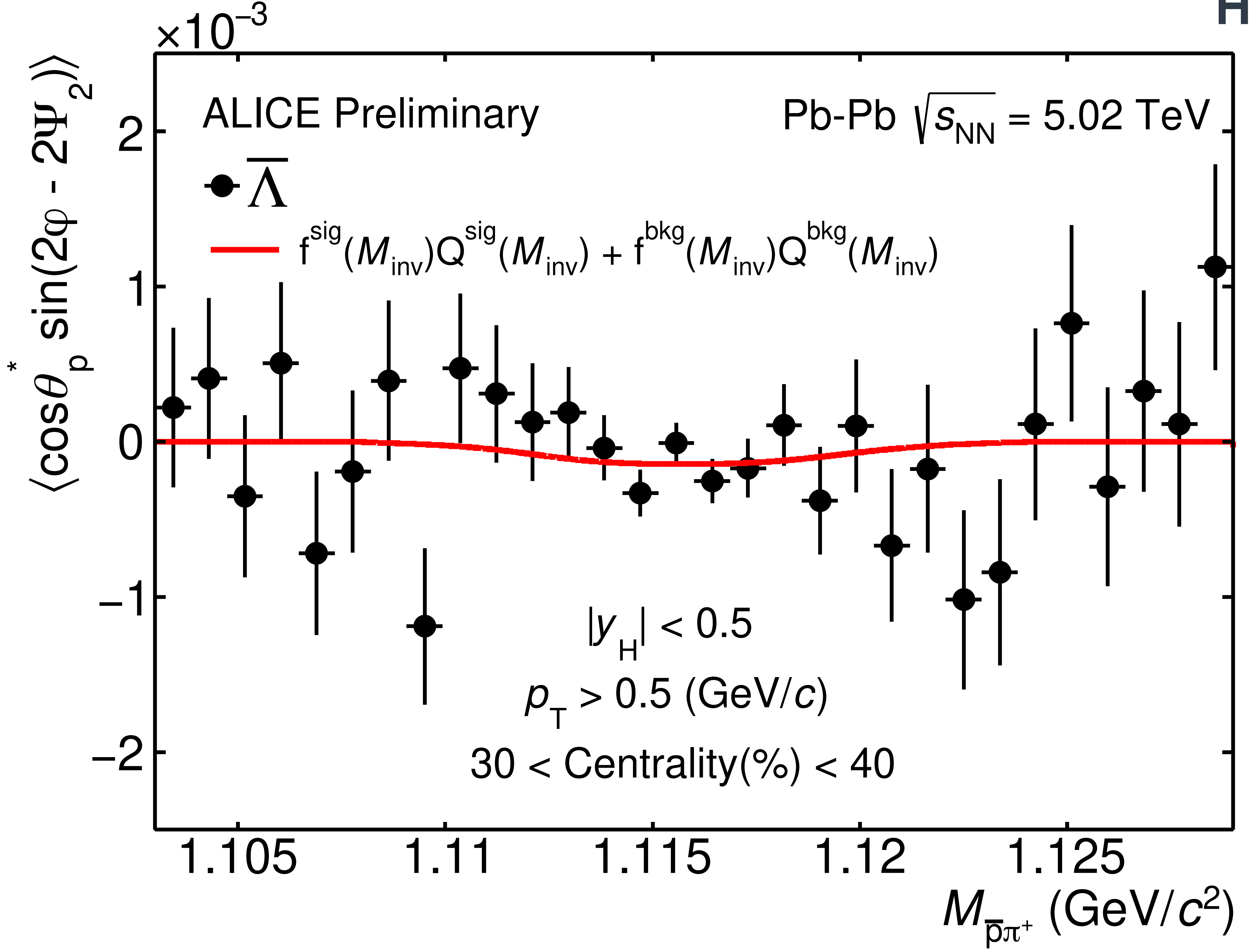


- P_H consistent with zero within experimental uncertainties.
- No difference between Λ and $\bar{\Lambda}$ polarization observed.
- P_H decreases with collision energy as expected due to higher baryon transparency at higher collision energies.

Measuring local polarization (P_z) in ALICE using invariant mass method



ALI-PREL-367067

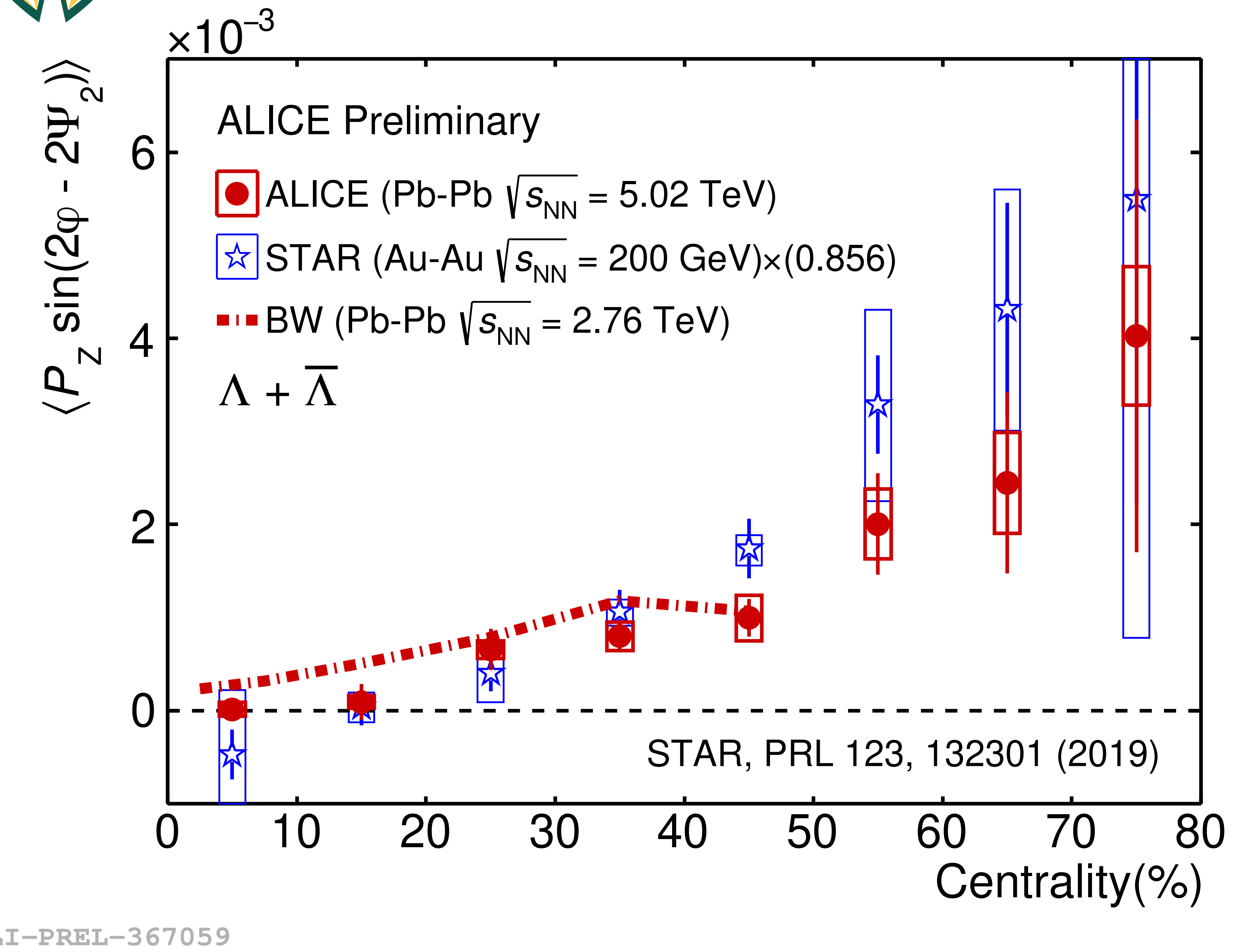


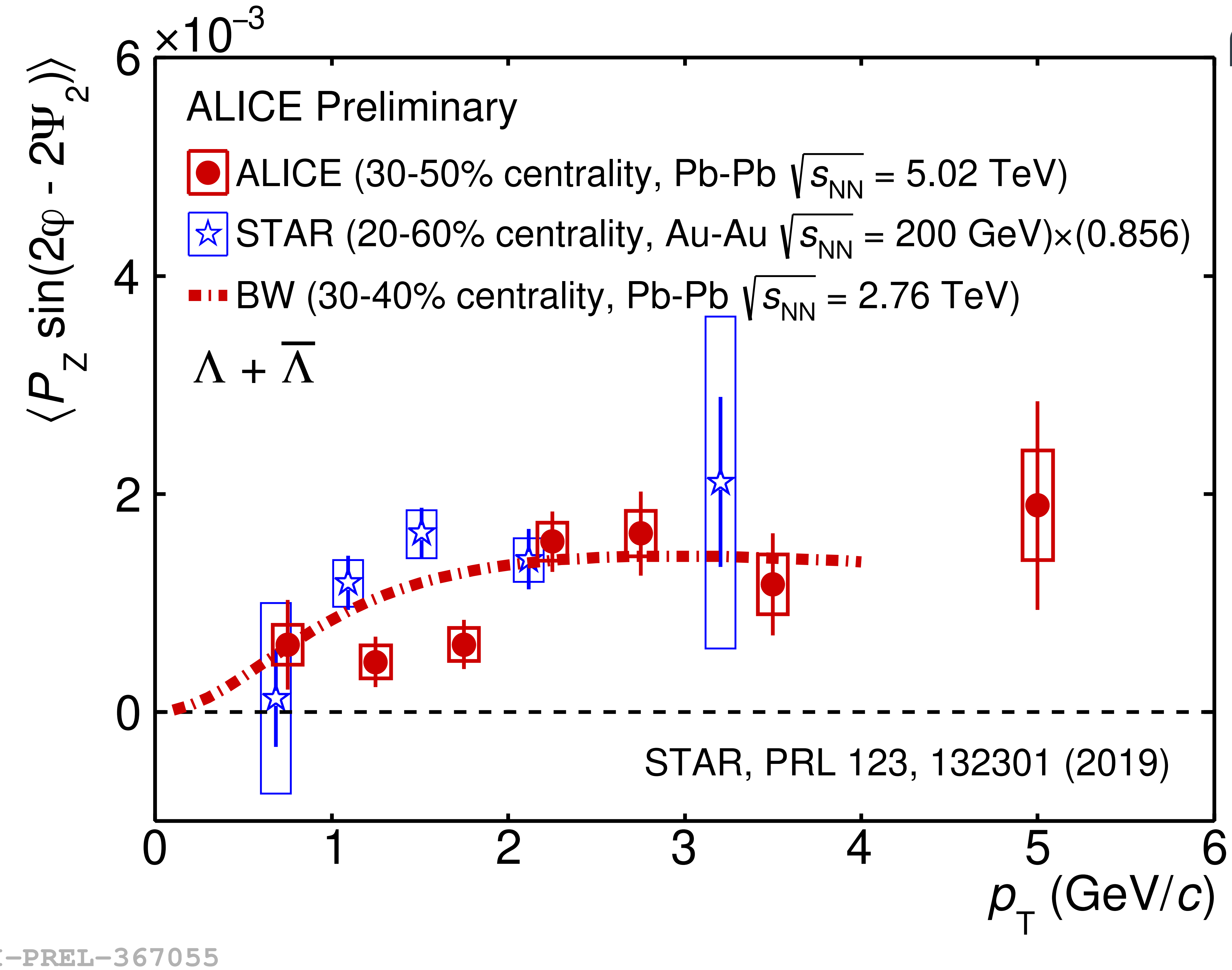
ALI-PREL-367063

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

- Ψ_2 reconstructed using TPC, V0A, and V0C detectors.
- $P_{z,s2}$ measured with Ψ_2 in TPC and V0 detectors are combined for final result.
- $P_{z,s2}$ for Λ and $\bar{\Lambda}$ hyperons are consistent ⟶ combined to calculate the average $P_{z,s2}$.

Local polarization (P_z) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in ALICE





Blast-Wave calculations: Takafumi Niida and Sergei Voloshin (private communication)

- $P_{z,s2}$ at the LHC is similar in magnitude to top RHIC energy (tends to be smaller in semi-central collisions).
- At $p_T < 2.0$ GeV/c, $P_{z,s2}$ at the LHC is smaller than the STAR results in semi-central collisions.
- Blast-Wave model explains $P_{z,s2}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV!
- Comparison with the newly introduced (shear + vorticity) based polarization estimation would provide valuable constraints to the models.

Summary and Outlook

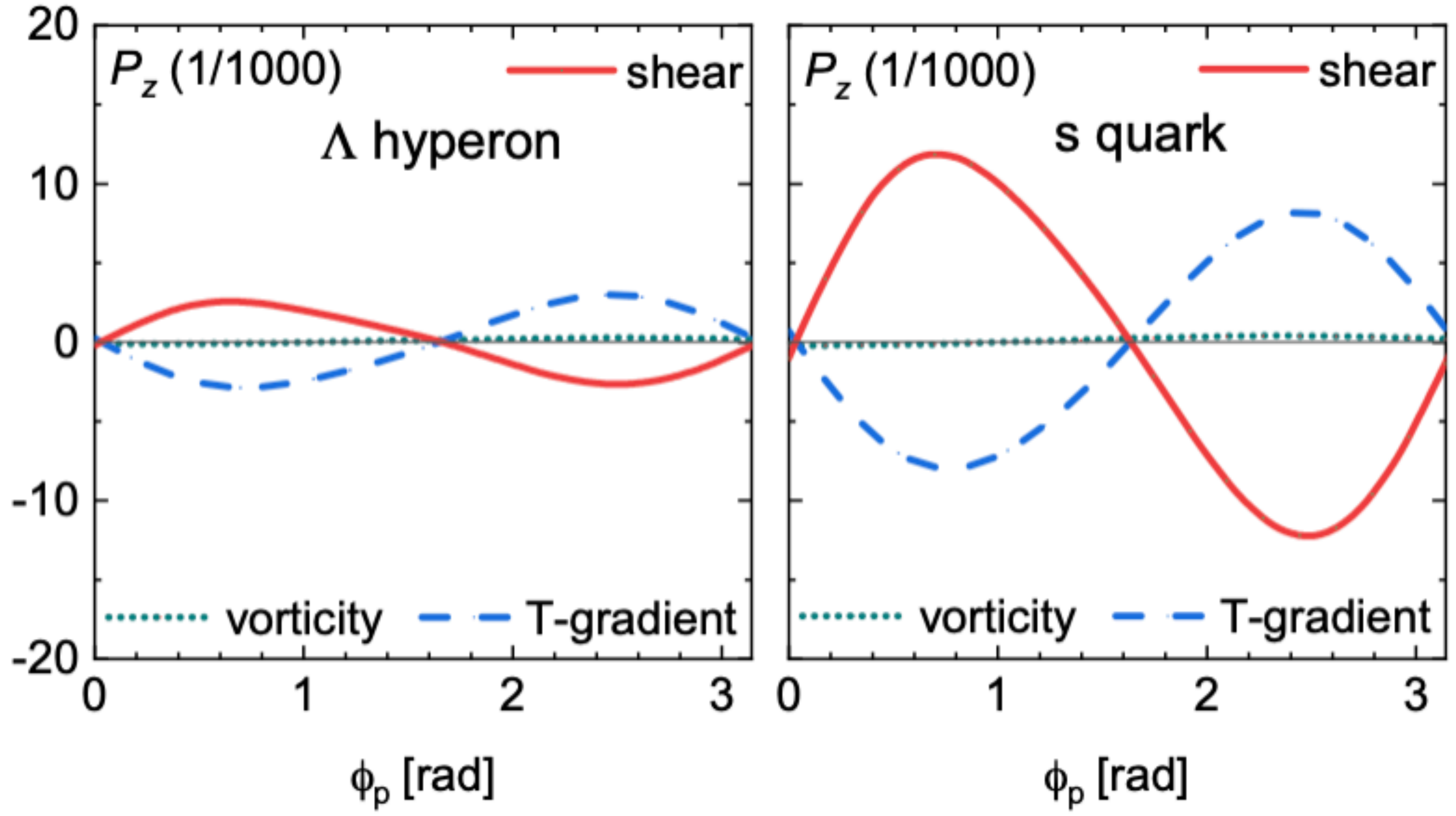
- Global hyperon polarization (P_H) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV is consistent with zero within experimental uncertainties ($\sim 10^{-3}$).

- Polarization along the beam direction ($< P_z \sin(2\varphi - 2\Psi_2) >$) is positive at RHIC and the LHC → opposite to thermal vorticity based model predictions.

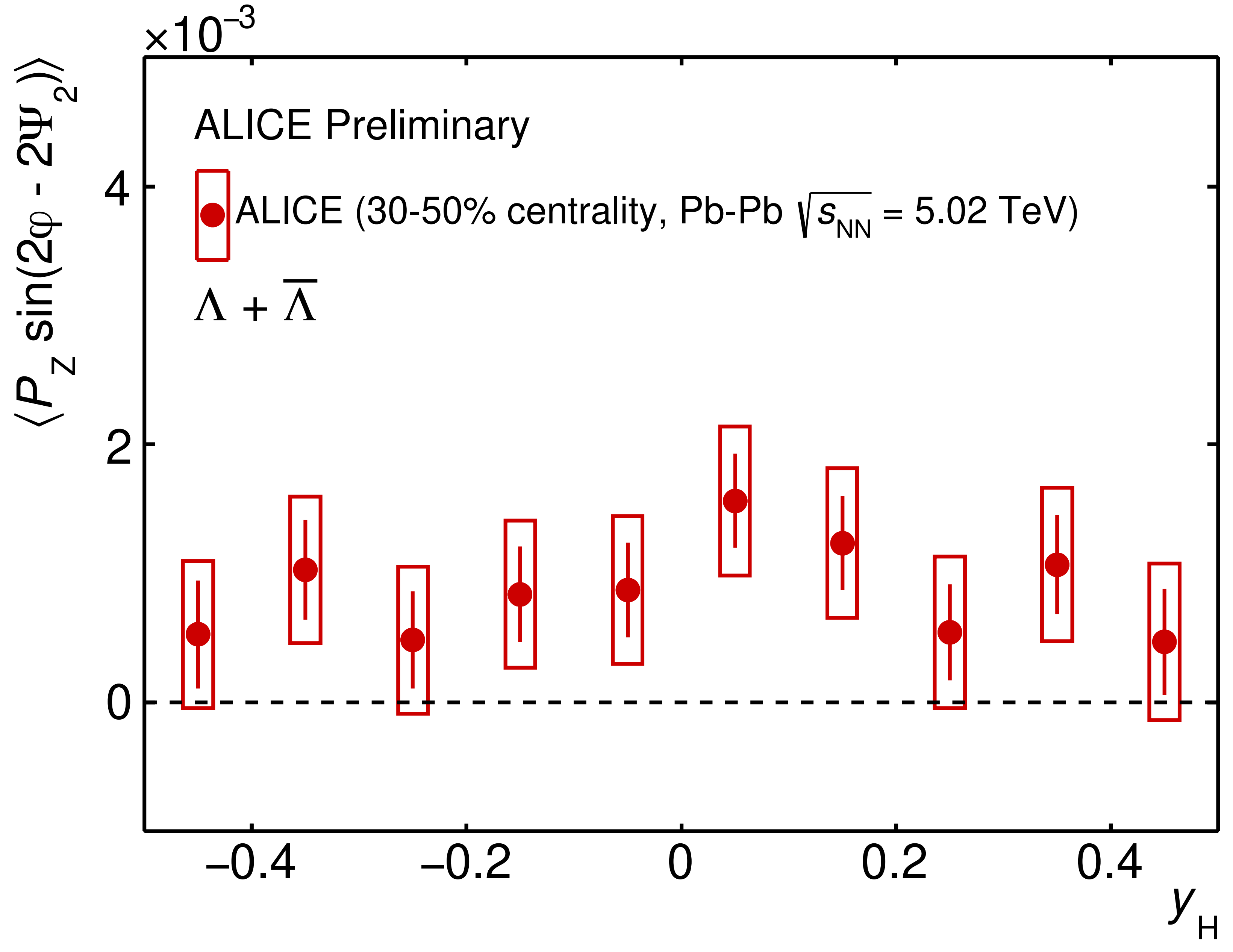
- Comparison between the $P_{z,s2}$ measured by ALICE and (shear + vorticity) based model calculations would provide valuable constraints to the models.

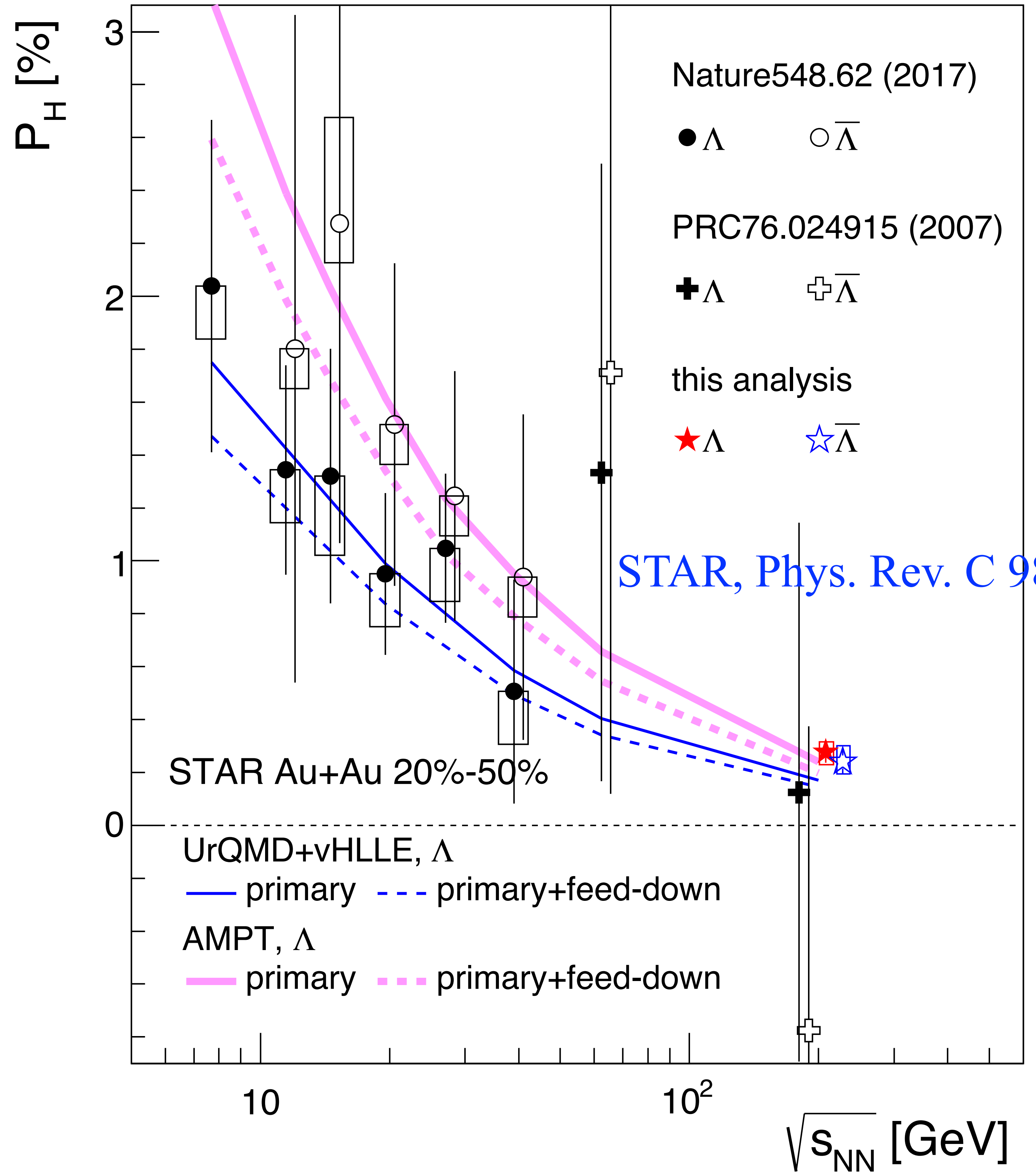
- Upcoming Run 3 at the LHC will allow more differential and precision measurements of P_H and P_z to further investigate the vorticity dynamics and particle polarization in heavy-ion collisions.

Thank you

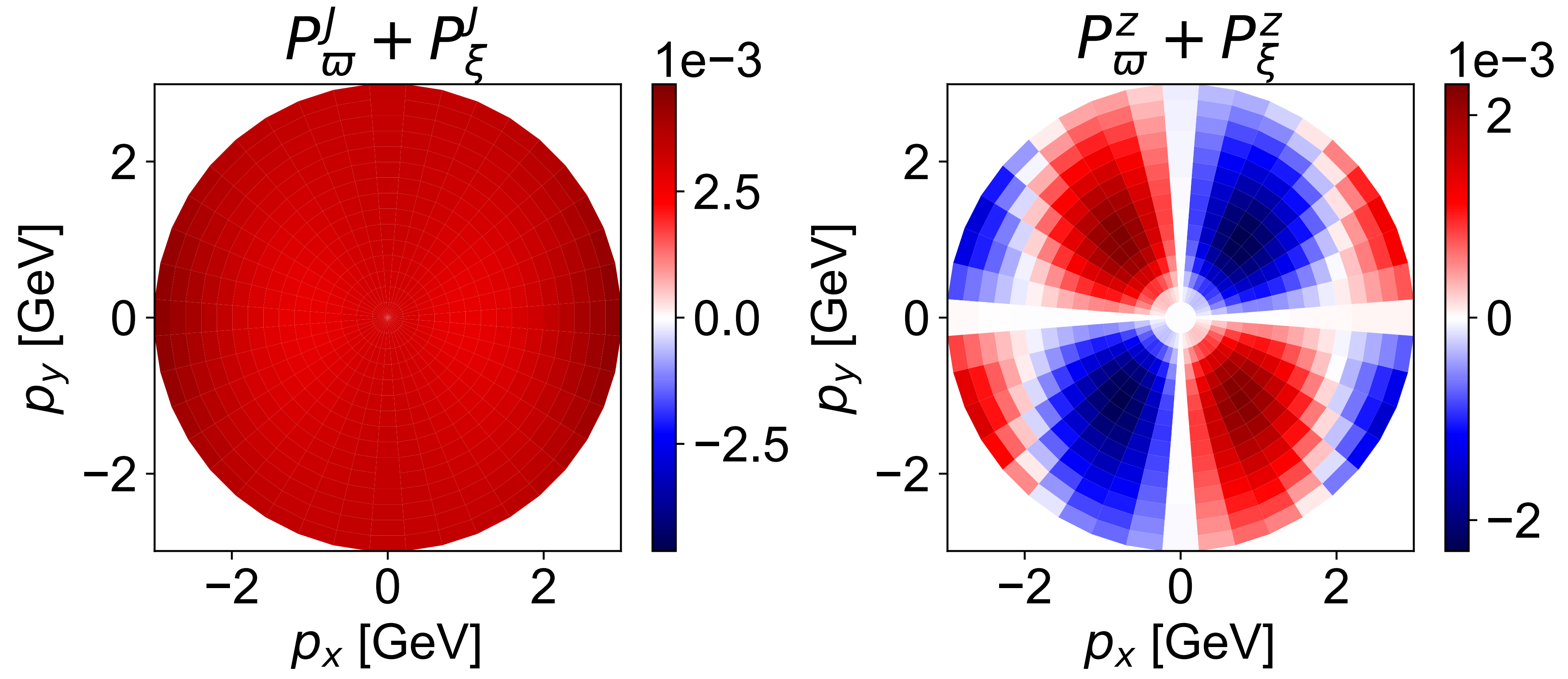


B. Fu et al; [arXiv:2103.10403](https://arxiv.org/abs/2103.10403) [hep-ph]



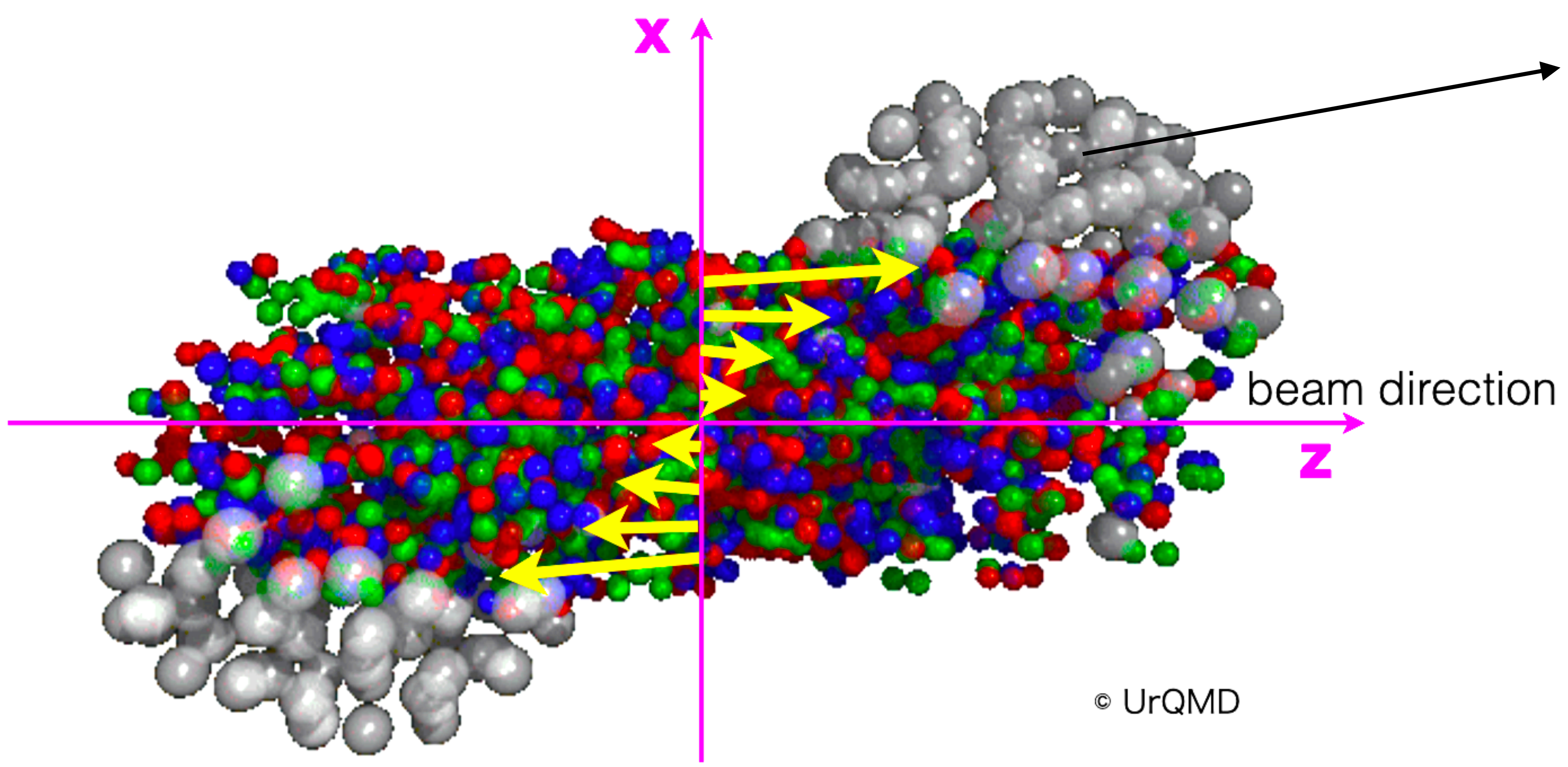


STAR, Phys. Rev. C 98, 014910 (2018)



F. Becattini et al; [arXiv:2103.14621](https://arxiv.org/abs/2103.14621) [nucl-th]

Measurement of P_H in ALICE



- Deflection of the spectators estimates the direction of $\vec{b}$ and in turn $\vec{L}$.
- On average: spectators deflect outwards.

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

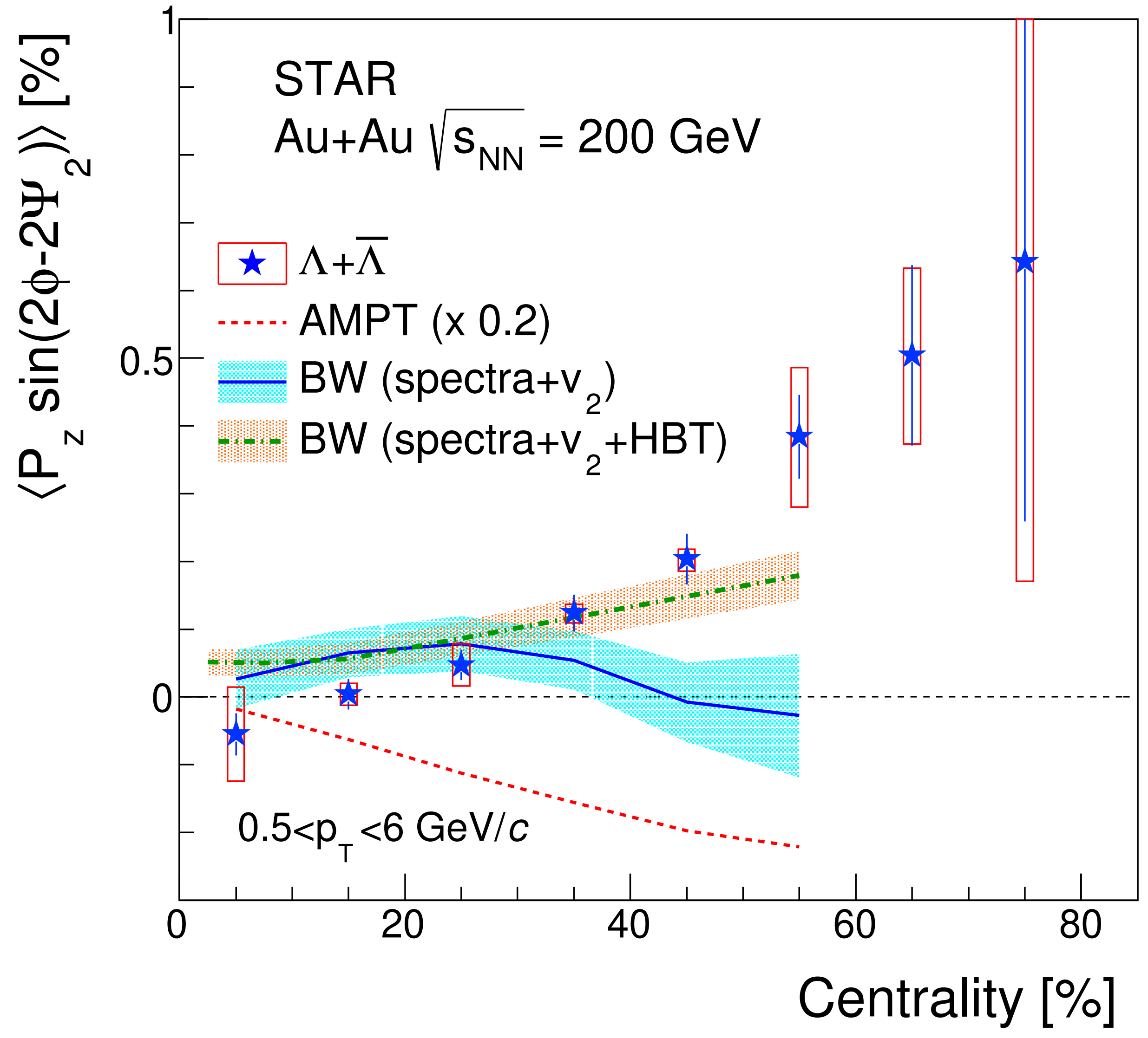
$$P_{\mathrm{H}} = \frac{-8}{\pi \alpha_{\mathrm{H}}} \frac{\langle \sin(\varphi_{\mathrm{p}}^{*} - \Psi_{\mathrm{SP}}) \rangle}{R_{\mathrm{SP}}^{(1)}}.$$

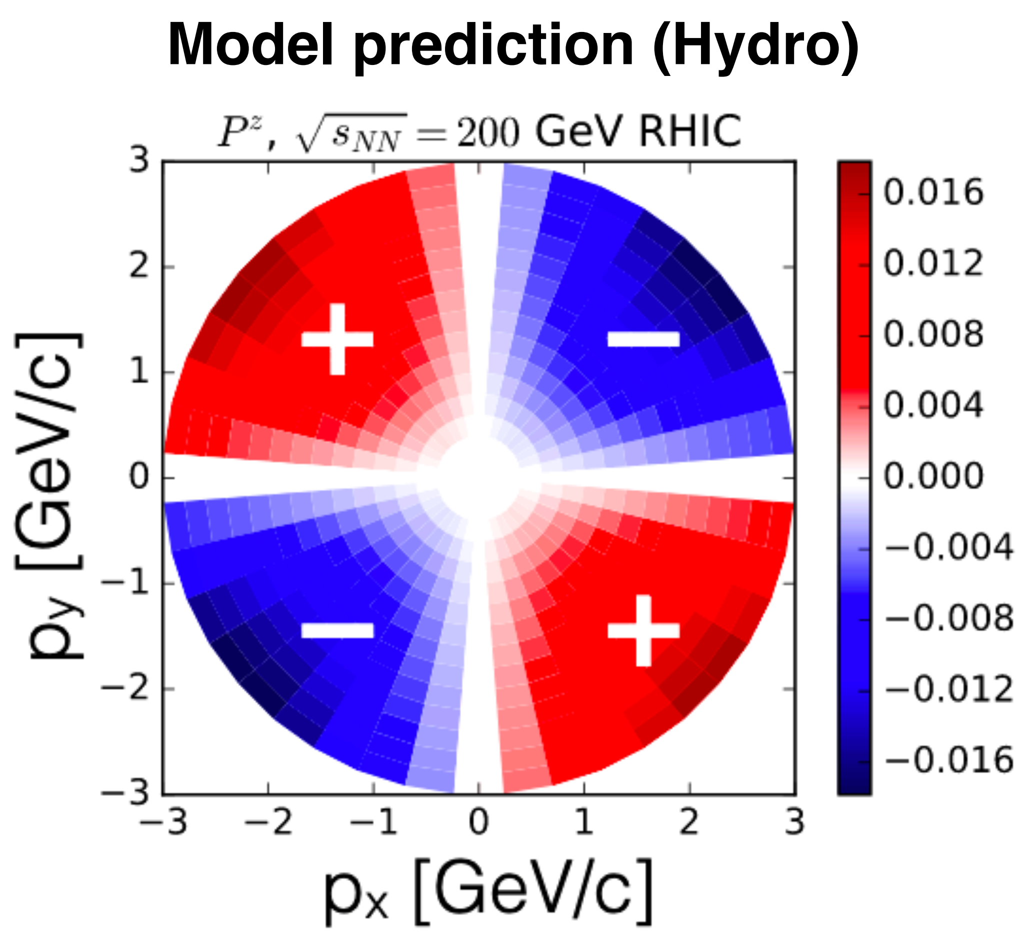
ALICE, Phys. Rev. C 101, 044611 (2020)

- To measure P_H, the direction of orbital angular momentum ($\vec{L} = \vec{b} \times \vec{P}$) need to be known.
- P is the momentum of the projectile (moving toward positive rapidity: known). Need to know the direction of impact parameter vector ($\vec{b}$).
- Direction of $\vec{b}$ can be estimated from the deflection of the projectile spectators.
- Spectator plane angle (Ψ_{SP}) characterizes the deflection direction of the spectator nucleons.
- P_H is measured with respect to Ψ_{SP} (azimuthal angle of $\vec{b}$).

P_z in heavy-ion collisions (Story so far…)

STAR, Physical Review Letters 123, 132301 (2019)
F. Becattini and I. Karpenko, PRL.120.012302 (2018) (Hydro)
X. Xia, H. Li, Z. Tang, Q. Wang, arXiv:1803.00867 (AMPT)





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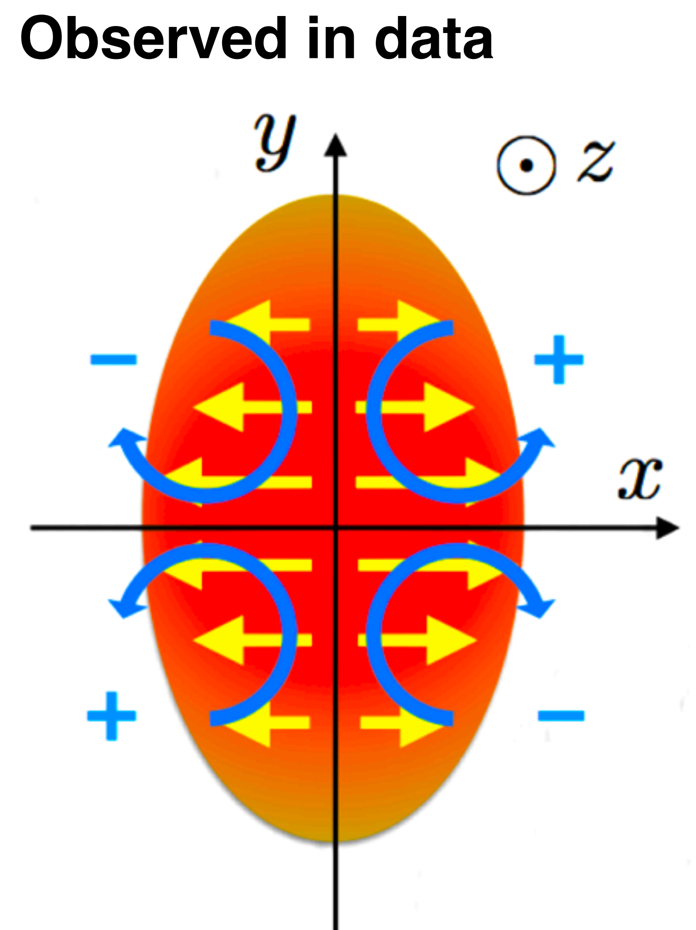
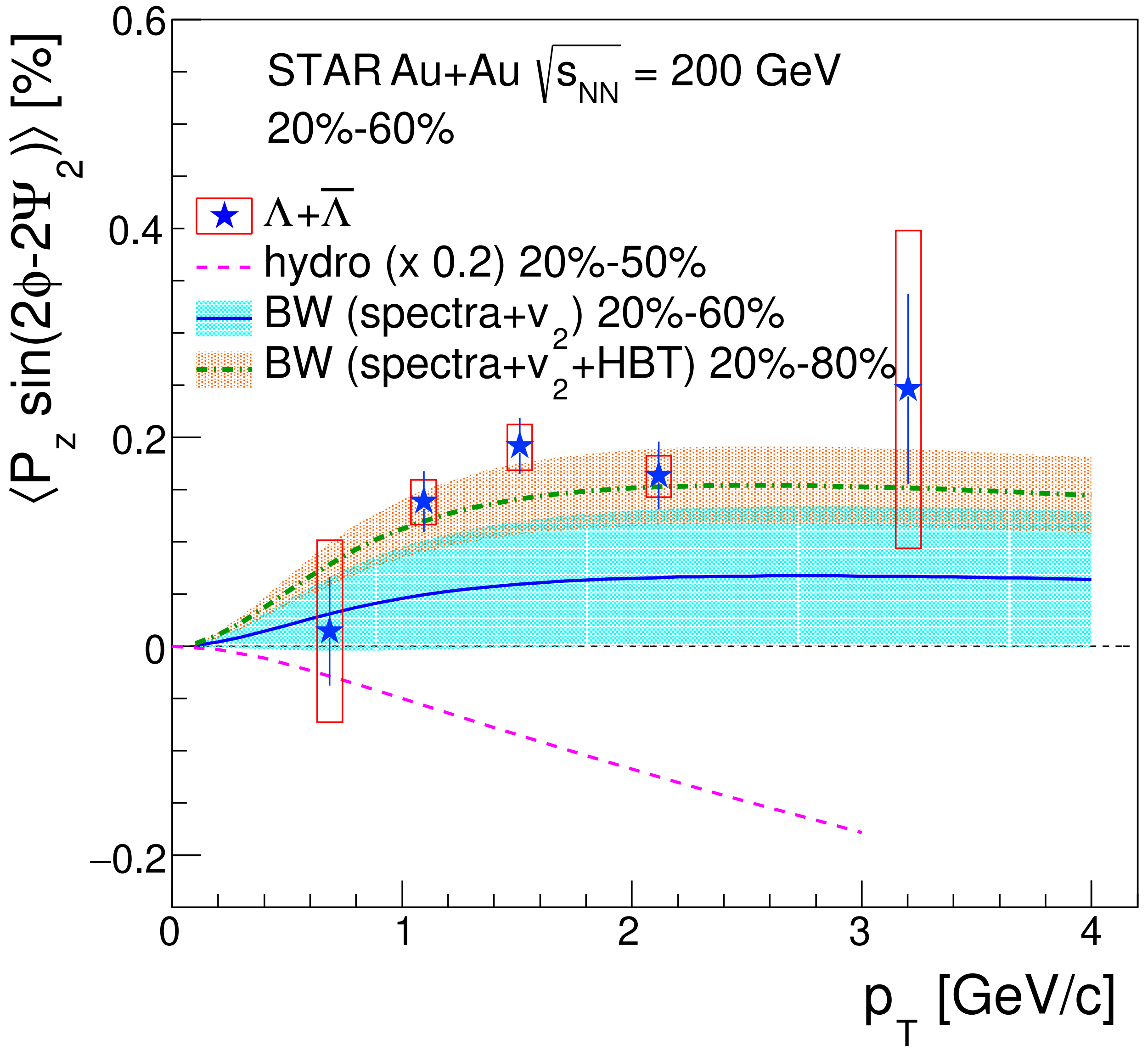


S. Voloshin, EPJ Web Conf.171, 07002 (2018)



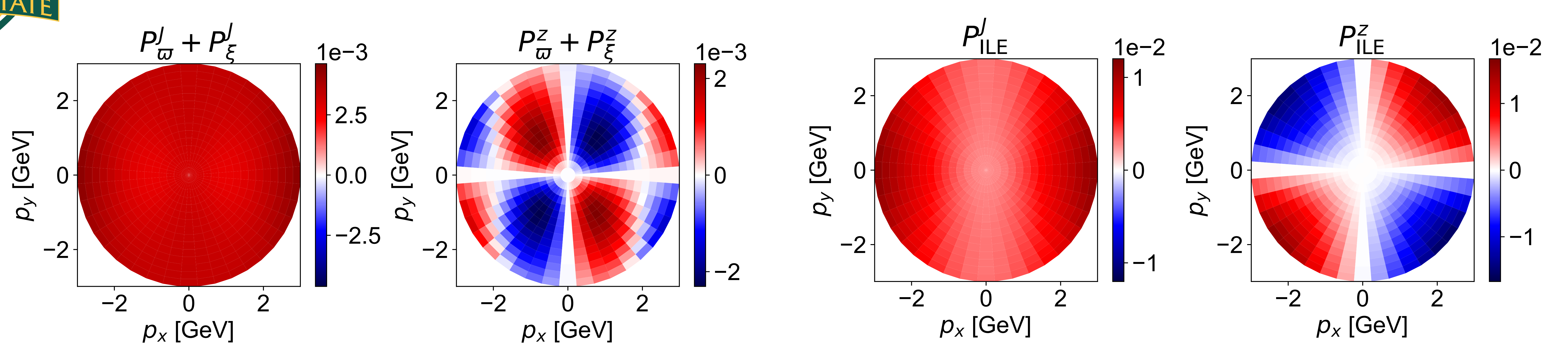
- The Blast-Wave (BW) model explains the P_z data in STAR. The sign of the phase modulation of P_z depends on the interplay between spatial and flow anisotropy at freeze-out in the BW model:

(S. Voloshin, arXiv:1710.08934)

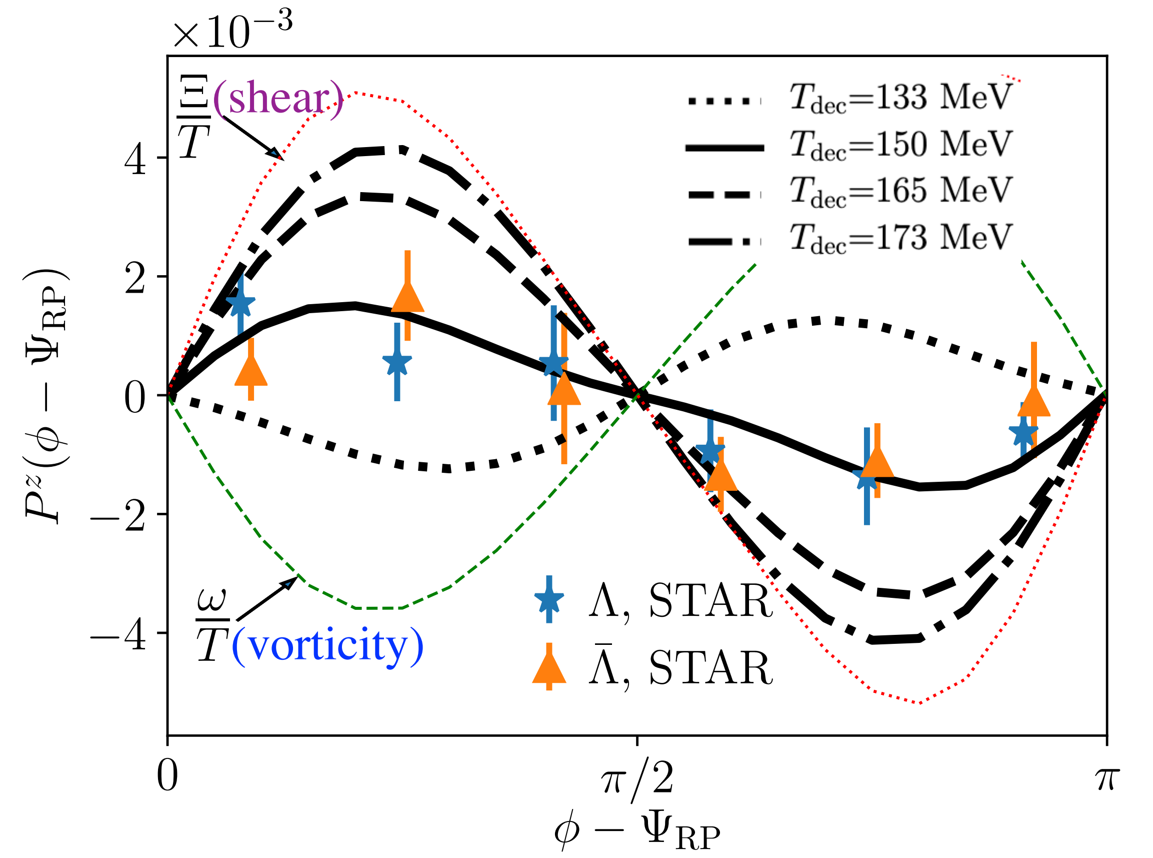
$$\omega_z \approx [\rho_{t,max}/R]\sin(2\phi_H)(a_2 - b_2)$$

$$P_z \approx \omega_z/(2T)$$ a2: spatial anisotropy, b2: flow anisotropy

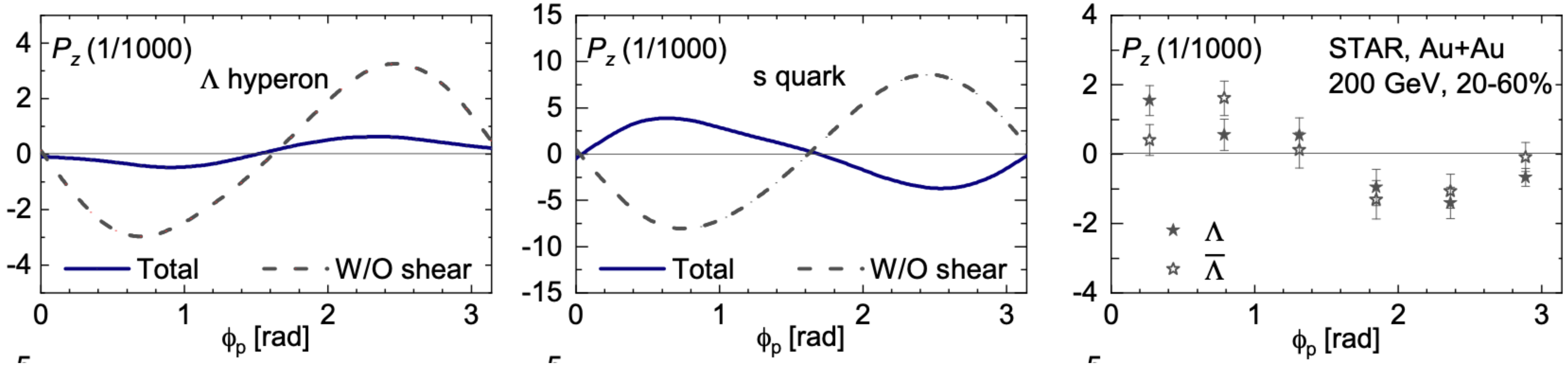
P_z in heavy-ion collisions (Recent developments)



Ref. 1: F. Becattini et al.; arXiv:2103.14621 [nucl-th]



- Ref.1: Assumption : Isothermal Local equilibrium (T_{dec}) ⟶ gets rid of the temperature gradient term in the vorticity.
- Ref.1: (Shear + Vorticity) explain the experimentally measured $P_z(\varphi - \Psi_2)$ in Au–Au collisions at 200 GeV with T_{dec} = 150–160 MeV. The sign flips for T_{dec} < 135 MeV.



Ref. 2: B. Fu et al.; arXiv:2103.10403 [hep-ph]

Thermal shear:

$$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu).$$

Thermal vorticity:

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

- Ref.2: $\Lambda(\bar{\Lambda})$ inherits and memorizes the spin polarization of the strange quark⟶effect of shear prevails over thermal vorticity and qualitatively explain $P_z(\varphi - \Psi_2)$ in Au–Au collisions at 200 GeV.