Local and global polarization of hyperons in Run 3 Pb-Pb collisions with ALICE

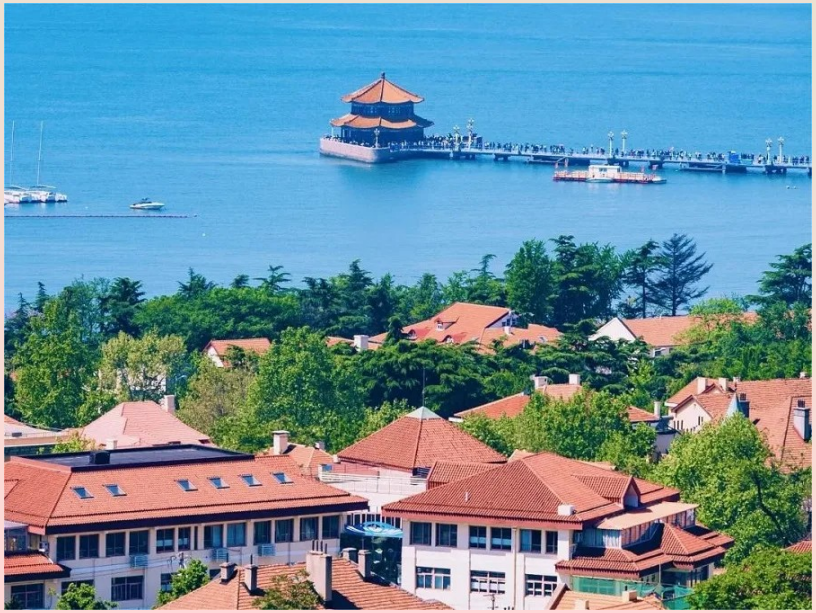
Prottay Das (for the ALICE Collaboration)

CERN

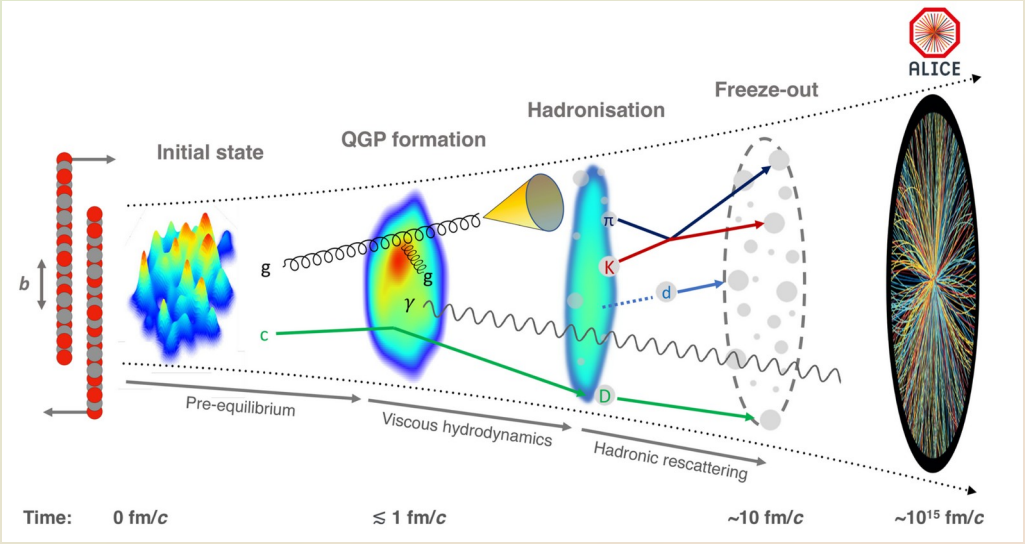
Geneva, Switzerland

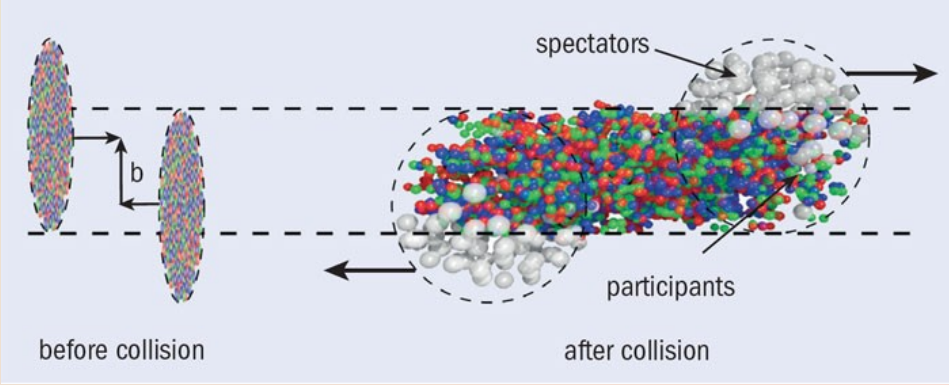
26th International Symposium on Spin Physics

A Century of Spin



Evolution of heavy-ion collisions



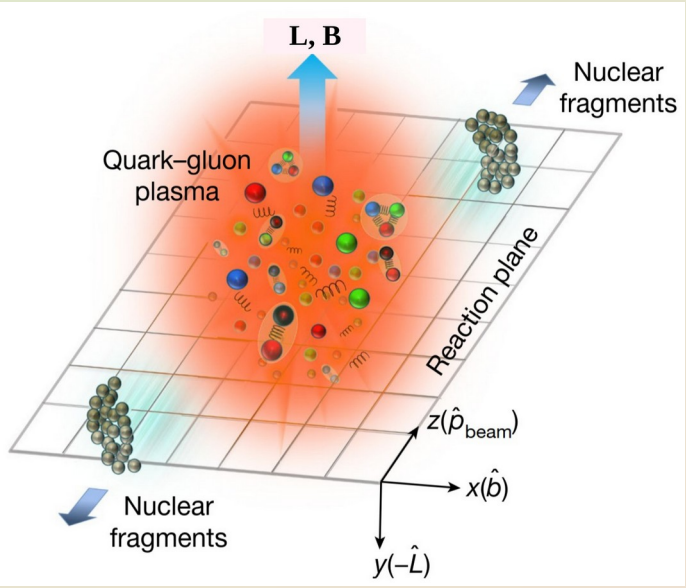


Two interesting large initial state effects

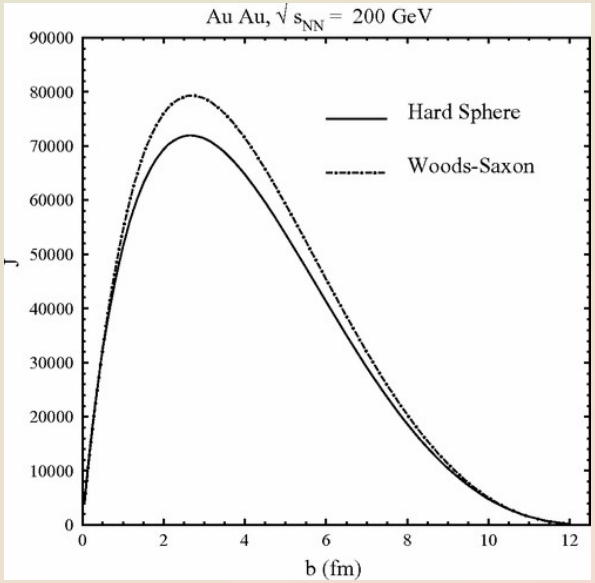
- ✓ (1) Angular momentum
- ✓ (2) Magnetic field

ALICE Collaboration,
Eur. Phys. J. C 84 (2024) 813

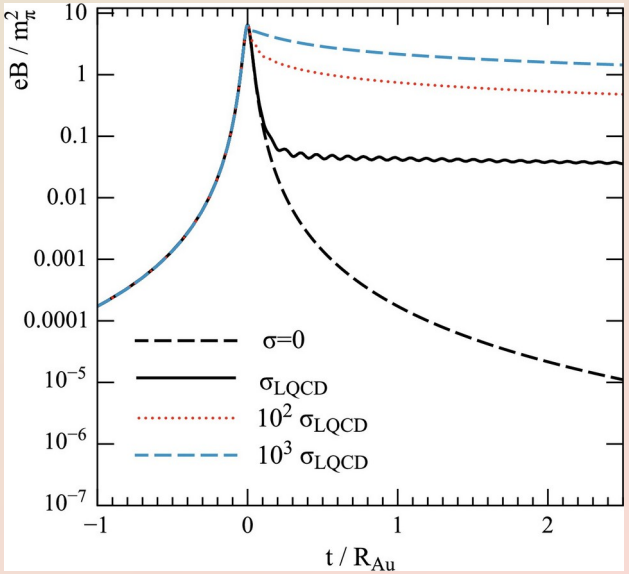
Theoretical model predictions



STAR Collaboration,
Nature volume 614, pages 244–248 (2023)



F. Becattini et al.,
Phys.Rev.C 77 (2008) 024906

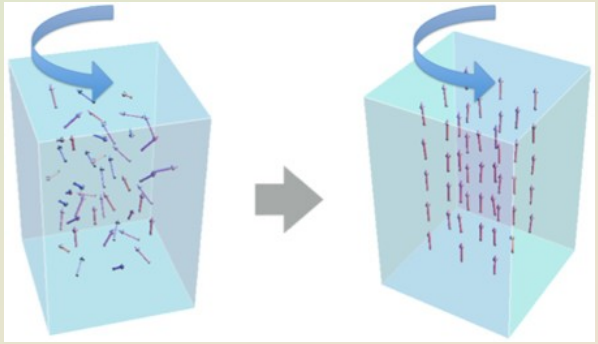


McLerran and Skokov,
Nucl.Phys.A 929 (2014) 184-190

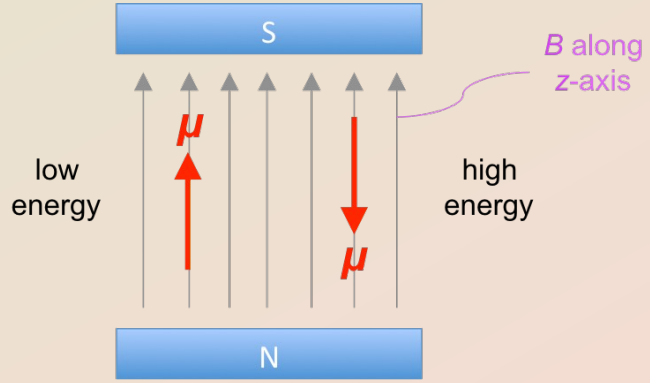
- ✓ Huge orbital angular momentum (vorticity) perpendicular to reaction plane (y axis), of the order of $10^4\ \hbar$
- ✓ Intense initial magnetic field (**B**) along the system orbital angular momentum direction is theorized (O~ 10^{19} Gauss)
- ✓ Retention of **B** depends on **medium conductivity**

Liang and Wang, PRL94 102301 (2005)
Voloshin, nucl-th/0410089
Liang et al., Phys.Rev.Lett 94 (2008) 102301
Jiang et al., Phys. Rev. C 94 (2016) 044910

Rotation, spin and fields



https://www.researchgate.net/figure/



https://monomole.com/nuclear-magnetic-dipole-moment-nmr/

Barnett effect
(Rotation to polarization)

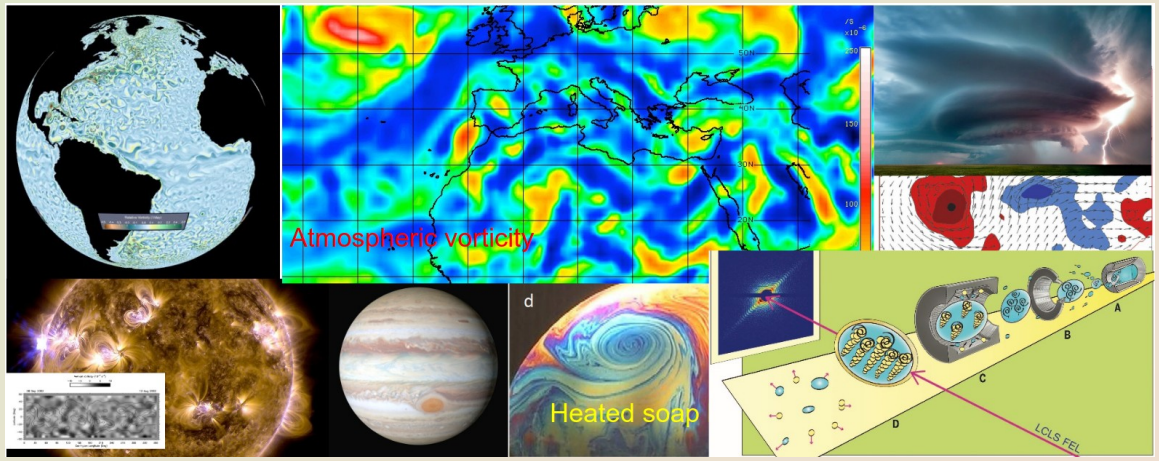
- ✓ Spontaneous magnetization
- ✓ Polarization (spin-orbital coupling)

Barnett, Phys. Rev. 6 (4) (1915) 239
Barnett, Rev. Mod. Phys. 7 (1935) 129

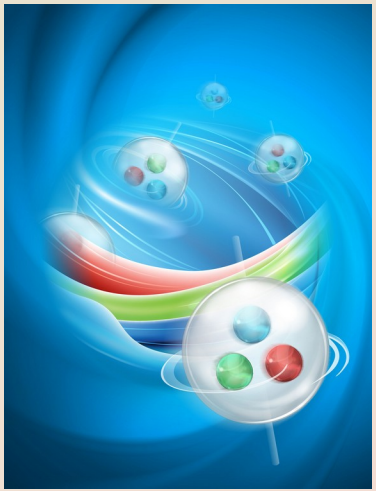
- ✓ Magnetic field polarizes particles based on their magnetic moment

Take home message: Large Angular Momentum (vorticity) -> Polarization of quarks (independent of their charge)
Large Magnetic Field -> Polarization of quarks (charge dependent)

World data on vorticity



https://sos.noaa.gov/catalog/datasets/ocean-surface-vorticity/



https://www.bnl.gov/newsroom/news.php?a=112068

STAR Collaboration, Nature volume 548, pages 62–65 (2017)

- ✓ Ocean flows: $\omega \sim 10^{-5}\,s^{-1}$
- ✓ Terrestrial atmosphere: $\omega \sim 10^{-4}\,s^{-1}$
- ✓ Core of supercell tornado: $\omega \sim 10^{-1}\,s^{-1}$
- ✓ Solar flow: $\omega \sim 10^{-6}\,s^{-1}$
- ✓ Jupiter's zonal winds: $\omega \sim 10^{-4}\,s^{-1}$
- ✓ Nanodroplets of superfluid He-II: $\omega \sim 10^{6}\,s^{-1}$

Science, 345(6199)

Most vortical fluid in nature

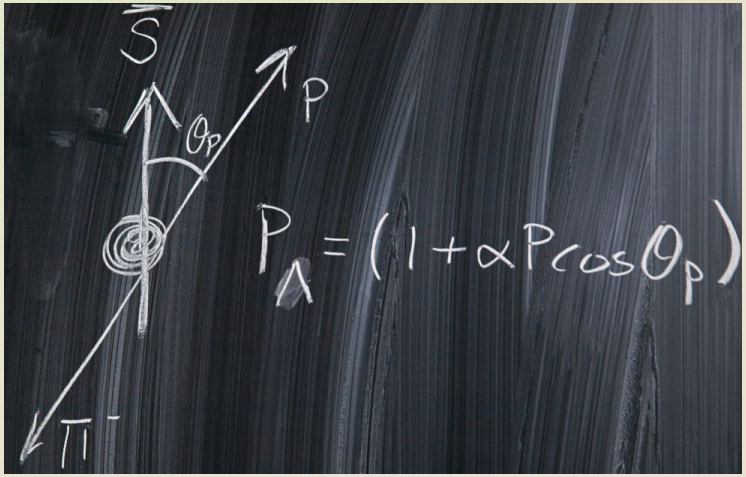
- ✓ Heavy-ion collisions: $\omega_y \sim 10^{21}\,s^{-1}$

(First quantitative experimental estimate at RHIC energies)

NOTE: No quantitative estimate at LHC energies exist !!

Polarization estimation

✓ Polarization measurement of hyperons -> Parity violating weak decay E. Cummins, Weak Interactions (McGraw-Hill, 1973)



The Feynman Lectures on Physics, Volume3, Chapter17

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

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

(* denotes hyperon rest frame)

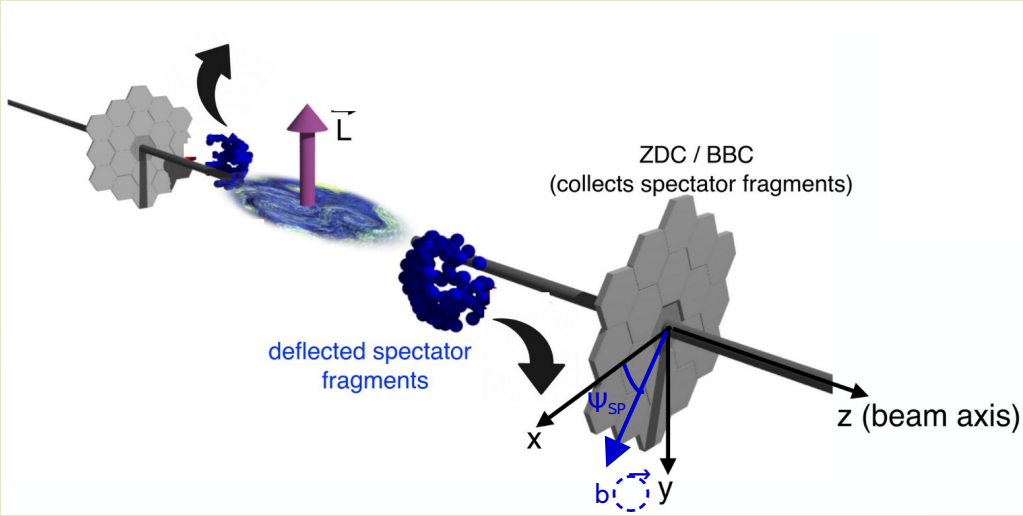
$\boldsymbol{P}_H$ = hyperon polarization vector
α_H = hyperon decay parameter
$\boldsymbol{p}_P$ = unit vector along daughter baryon momentum

Becattini F, Lisa M. 2020; Annu. Rev. Nucl. Part. Sci, Vol. 70:395-423

✓ **Polarization estimation procedure**

- Identify the reference axis (e.g along x, y or z) -> vorticity sources are different along different directions
- Take a projection of the daughter's proton momentum direction on the reference axis
- Average the projection over all hyperons in all events under consideration

Global hyperon polarization measurement procedure



STAR Collaboration, Nature volume 548, pages 62–65 (2017)

- ✓ Deflection of the spectators determines the direction of angular momentum
- ✓ On average spectators deflect outwards

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

Experimental observable

- ✓ Global hyperon polarization (along y axis)

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

STAR Collaboration, Nature volume 548, pages 62–65 (2017)

- ✓ Thermal limit

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

- Vorticity : $\frac{\omega}{T} = P_\Lambda + P_{\bar{\Lambda}}$

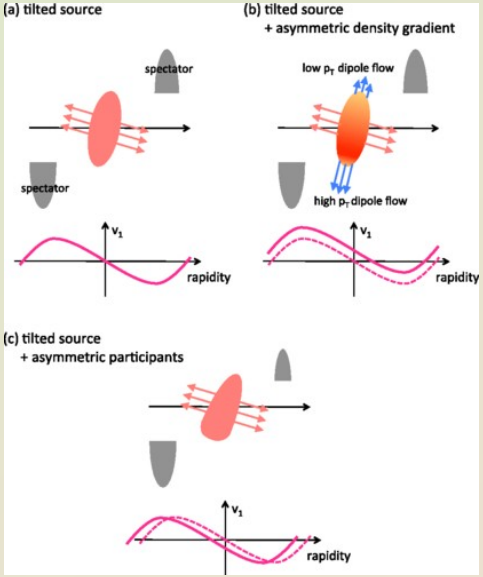
Becattini et al., Phys. Rev. C 95 (2017) 054902

φ^*_p = azimuthal angle of daughter proton in hyperon rest frame

Ψ_{SP} = spectator plane angle

R^1_{SP} = resolution correction factor of spectator plane

Vorticity and directed flow



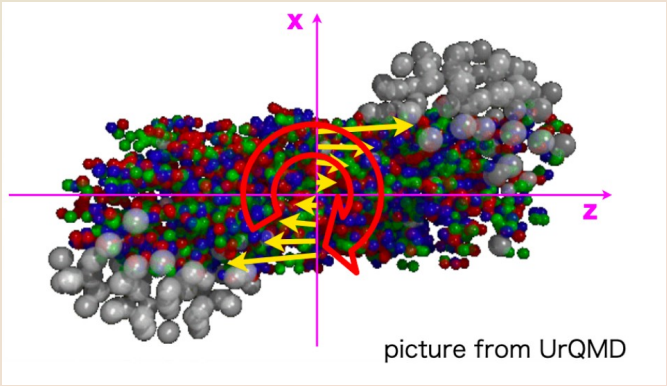
STAR Collaboration, Phys. Rev. C 98, 014915

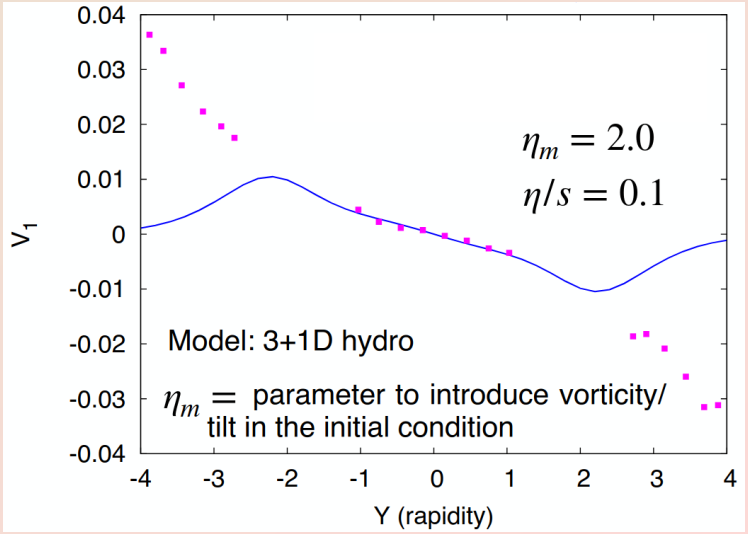
- ✓ Asymmetries in the initial velocity field generate vorticity (tilt) in the system -> generates directed flow

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

- ✓ To describe directed flow (v_1) in heavy-ion collisions -> vorticity (tilt) has to be taken into account

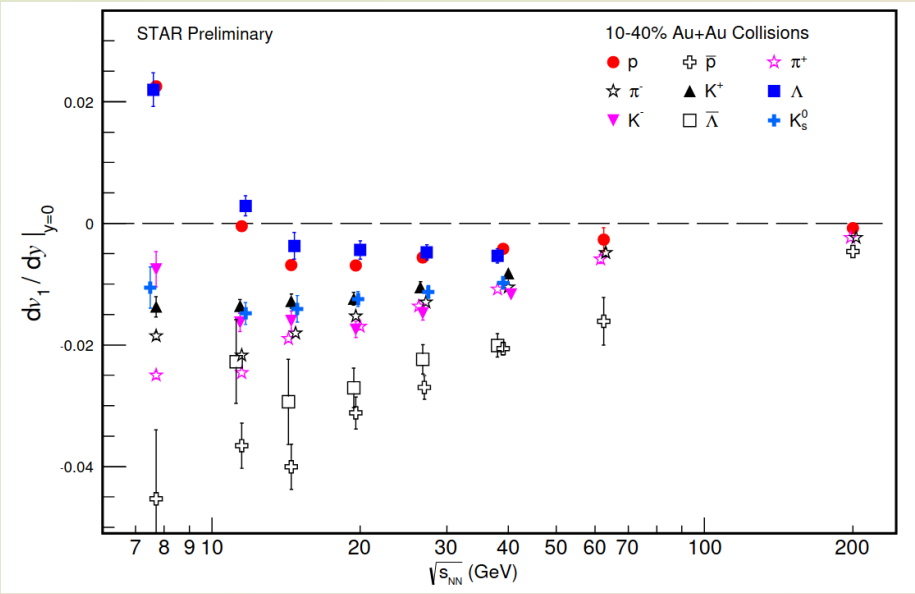
$$\omega_y = \frac{-1}{2}\frac{\partial v_z}{\partial x}$$



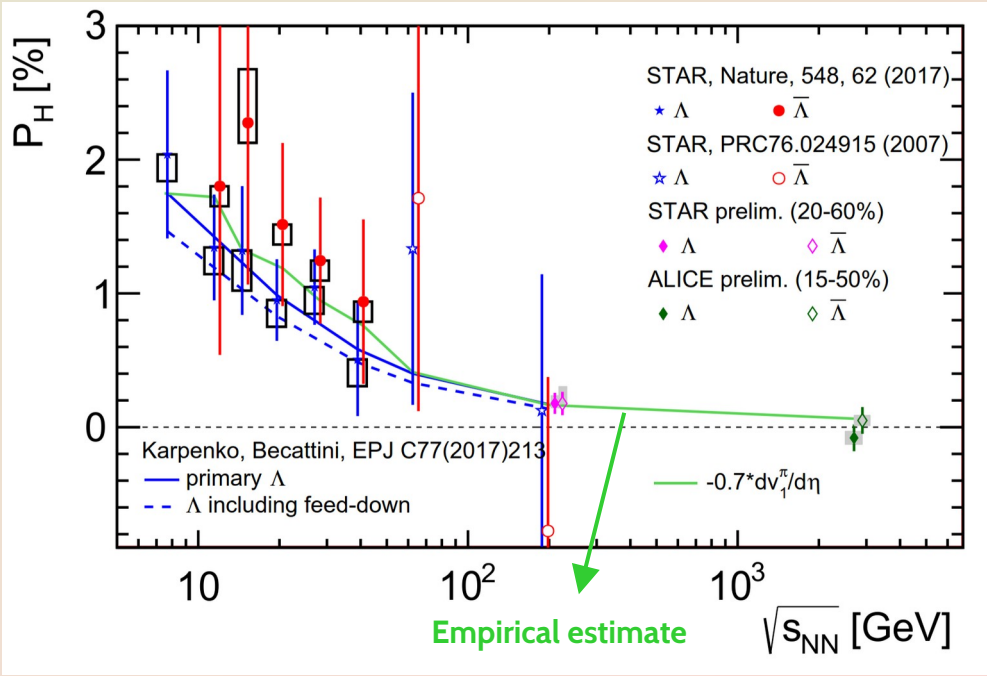


Becattini et al, Eur. Phys. J. C 78, 354 (2018)

Vorticity and directed flow



S. Singha, P. Shanmuganathan and D. Keane, Adv. High Energy Phys. 2016, 2836989 (2016)



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

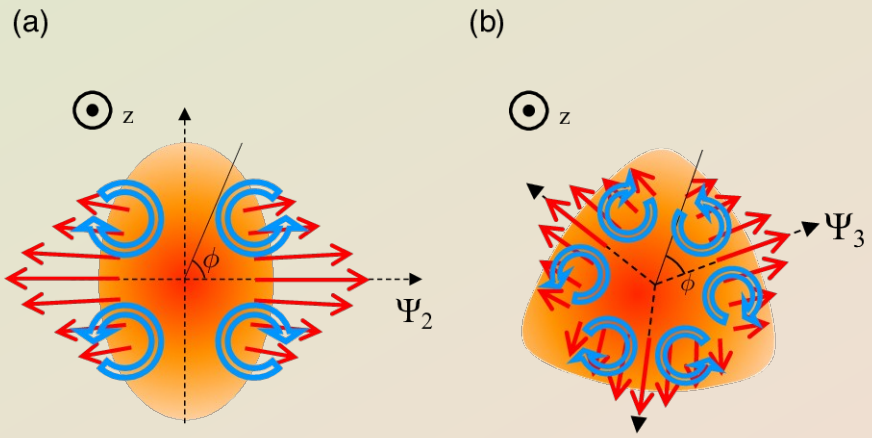
- ✓ Polarization and dv_1/dy are strongly correlated -> decreases with increase in collision energy
- ✓ v_1 at the LHC three times smaller than v_1 at top RHIC energy

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

- ✓ Expect P_H at LHC atleast three times smaller than at RHIC

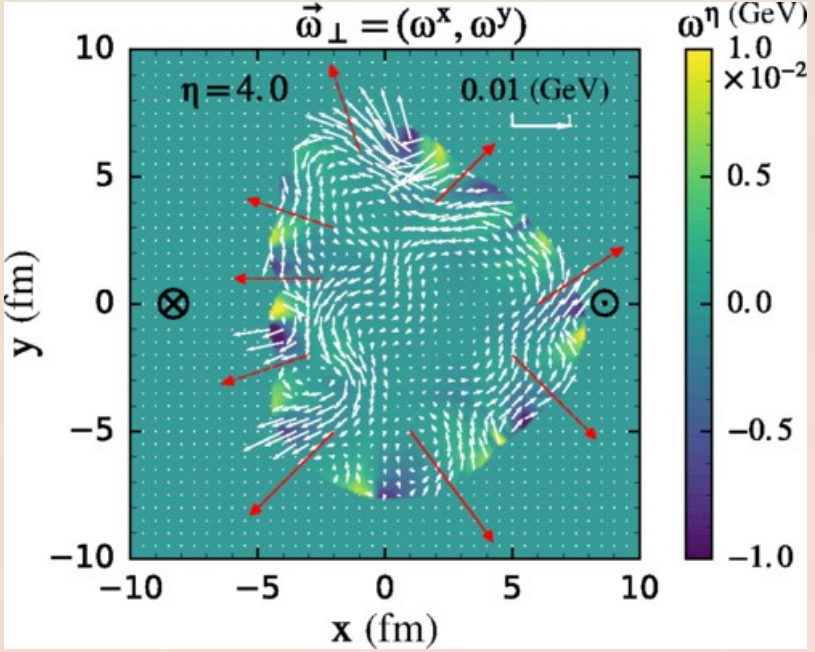
Source of vorticity along beam direction

Elliptical (a) and triangular (b) flow



Voloshin, EPJ Web Conf., 171 07002 (2018)
Becattini and Karpenko, Phys. Rev. Lett.120, 012302 (2018)
Becattini et al., Phys. Rev. Lett. 127, 272302 (2021)
B.Fu et al., Phys. Rev. Lett. 127, 142301 (2021)
STAR Collaboration, Phys. Rev. Lett., 123, 132301 (2019)

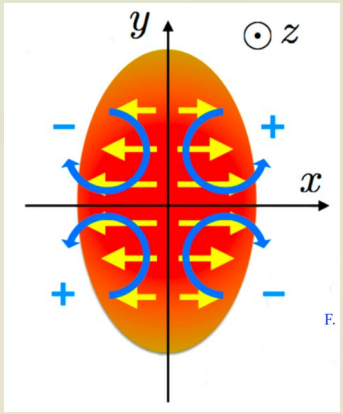
Non-uniform expansion of the fireball



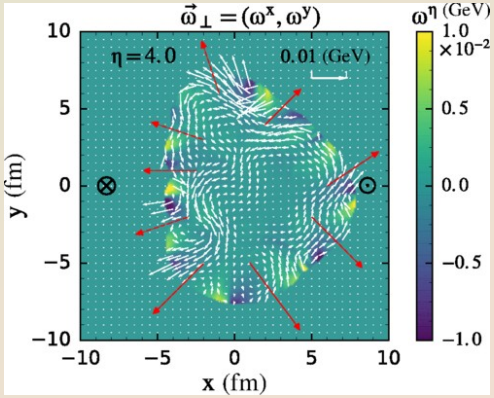
Wang et al., Phys. Rev. Lett. 117, 192301 (2016)

✓ Particle spin polarization has azimuthal dependence -> local polarization

Polarization along beam direction (P_z)



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



Wang et al., Phys. Rev. Lett. 117, 192301 (2016)

Experimental observable

✓ Local hyperon polarization (along z axis)

$$P_z \approx \langle \hat{p}^*_p . \hat{z} \rangle$$

$$P_z = \frac{\langle \cos\theta^*_p \rangle}{\alpha_H \langle (\cos\theta^*_p)^2 \rangle}$$

$$P_{z,sn} = \frac{\langle P_z \sin(n\varphi - n\psi_n) \rangle}{R_{\psi_n}}$$

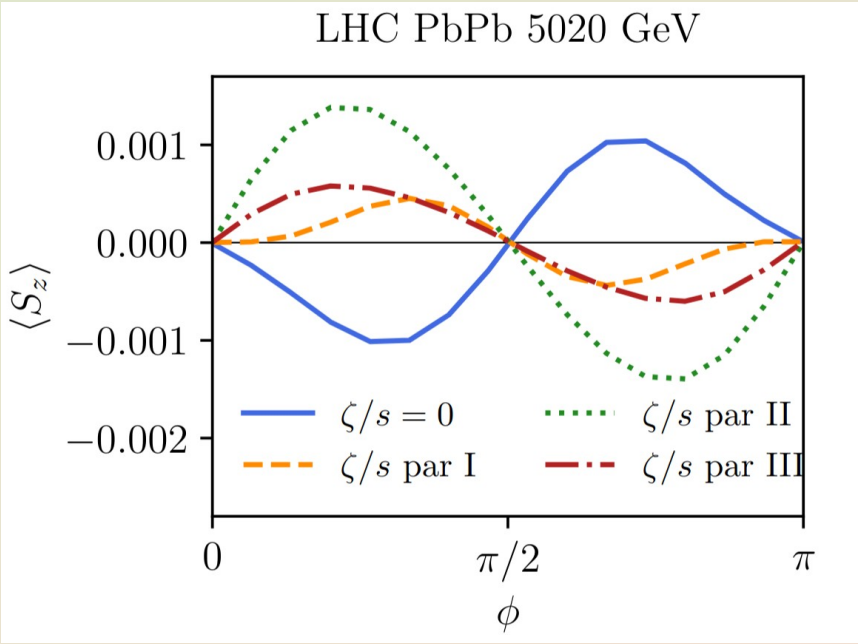
STAR Collaboration, Phys. Rev. Lett., 123, 132301 (2019)
ALICE Collaboration, Phys. Rev. Lett. 128, 172005 (2022)

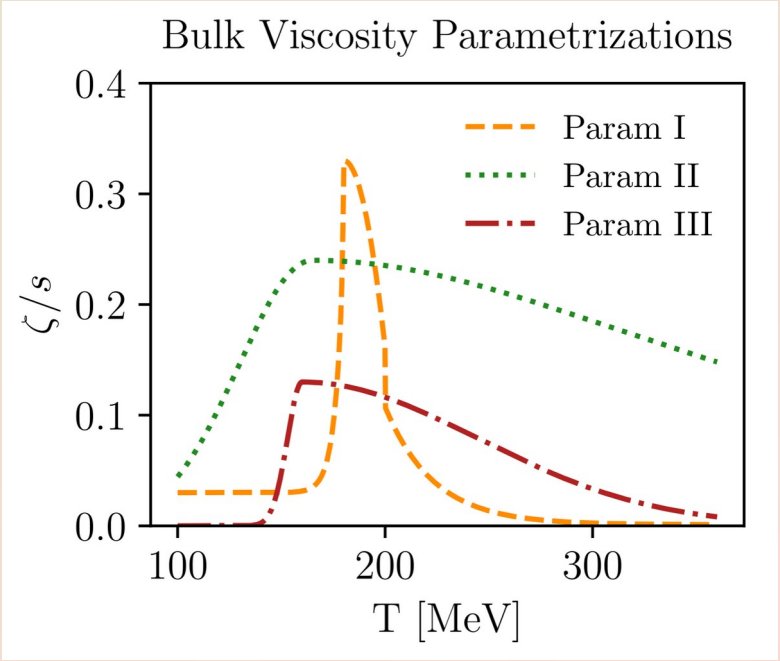
θ^*_p = polar angle of daughter proton in hyperon rest frame

ψ_n = n^{th} order event plane angle

R_{ψ_n} = Resolution correction factor for n^{th} order event plane

QGP property with local polarization

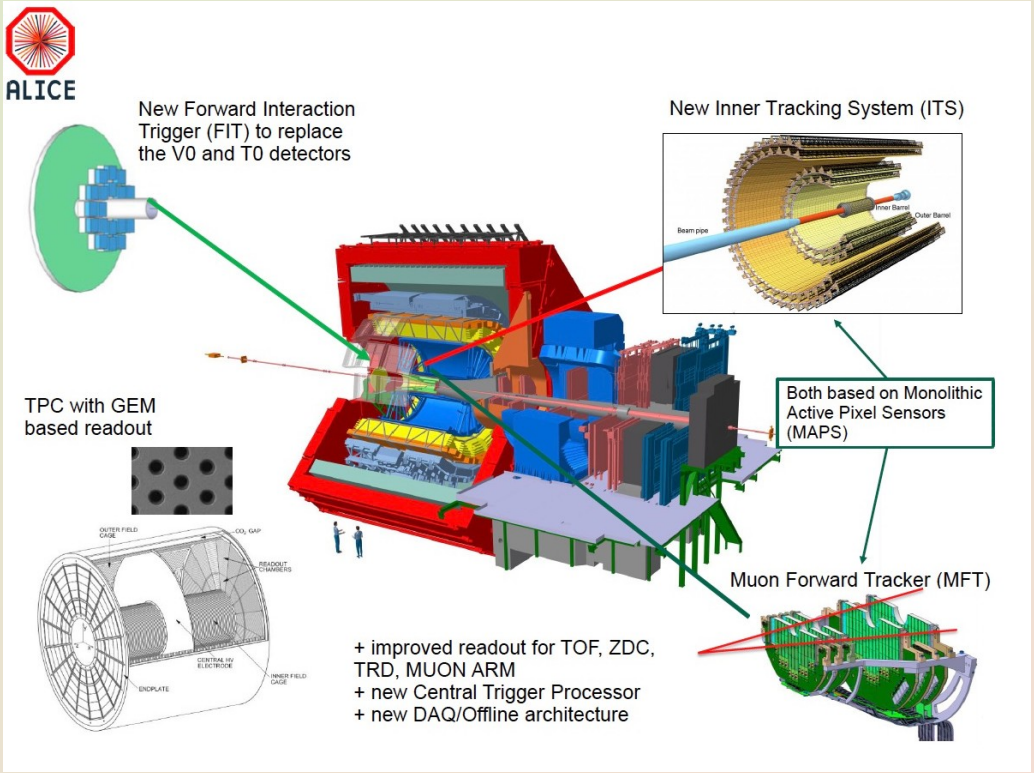




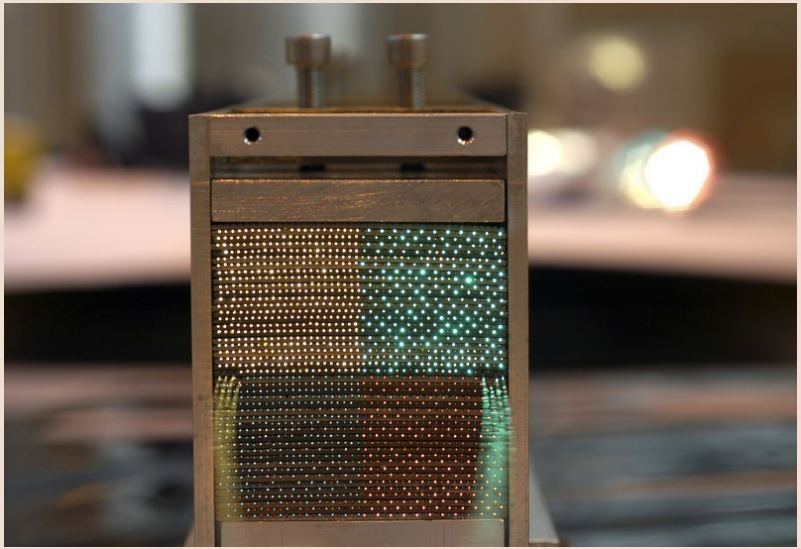
- ✓ Polarization along the beam axis is sensitive to:
- the bulk viscosity of the QGP at LHC energies
- the contribution from shear-induced polarization

A. Palermo, F. Becattini et al. EPJC 84, 920 (2024)
B.Fu et al., Phys. Rev. Lett. 127, 142301 (2021)

ALICE detector



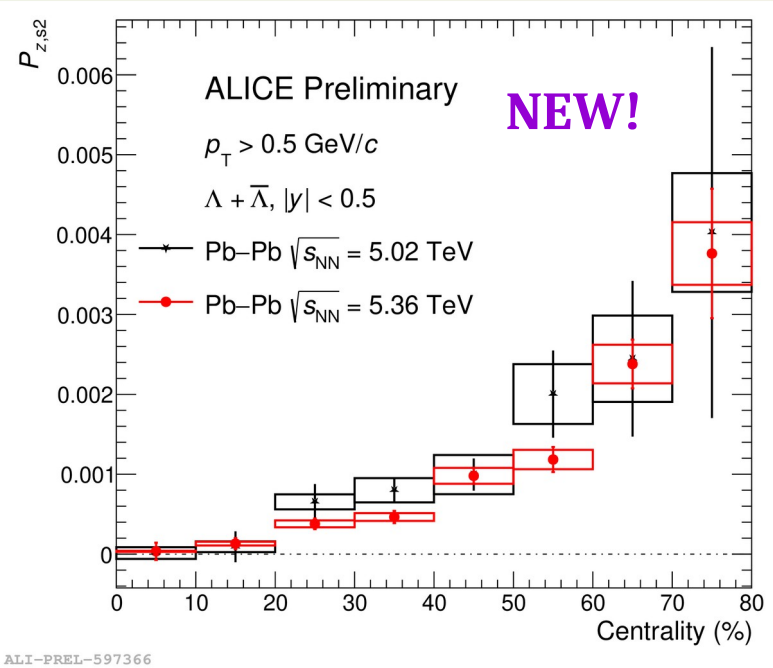
ZDC ($|\eta| > 8.78$)

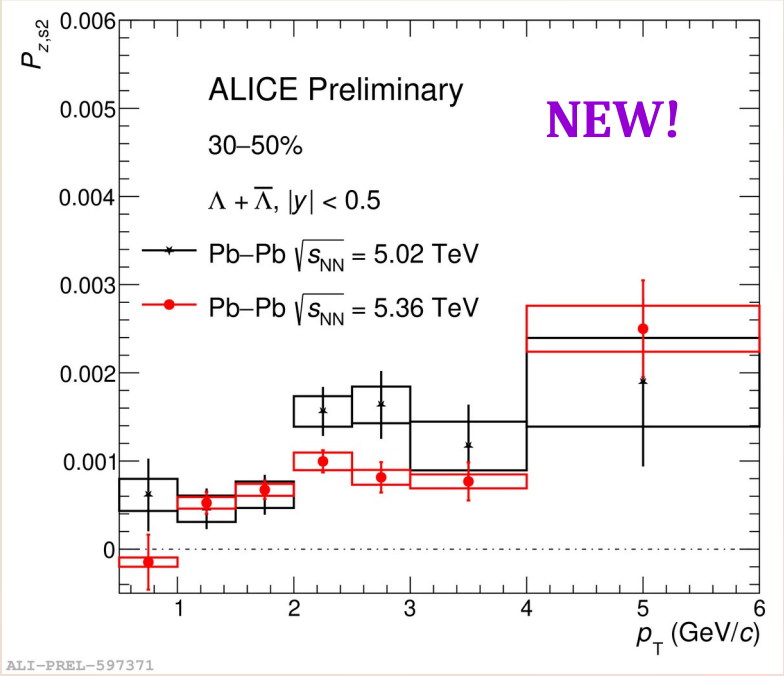


- ✓ Dataset: Pb-Pb $\sqrt{s_{NN}}$ = 5.36 TeV (~6 billion events)
- ✓ FIT: Collision time, event selection, centrality estimation, event plane determination
- ✓ TPC: Hyperon reconstruction ($p_T > 0.5$ GeV/c, $|y| < 0.5$)
- ✓ ZDC: Spectator plane Ψ_{SP} reconstruction

Results

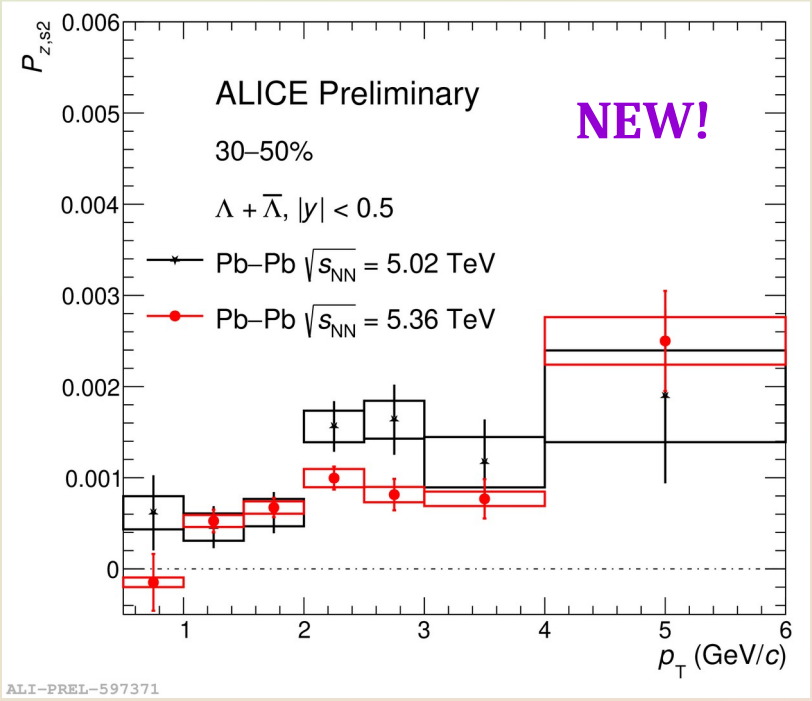
Longitudinal second order polarization of Λ

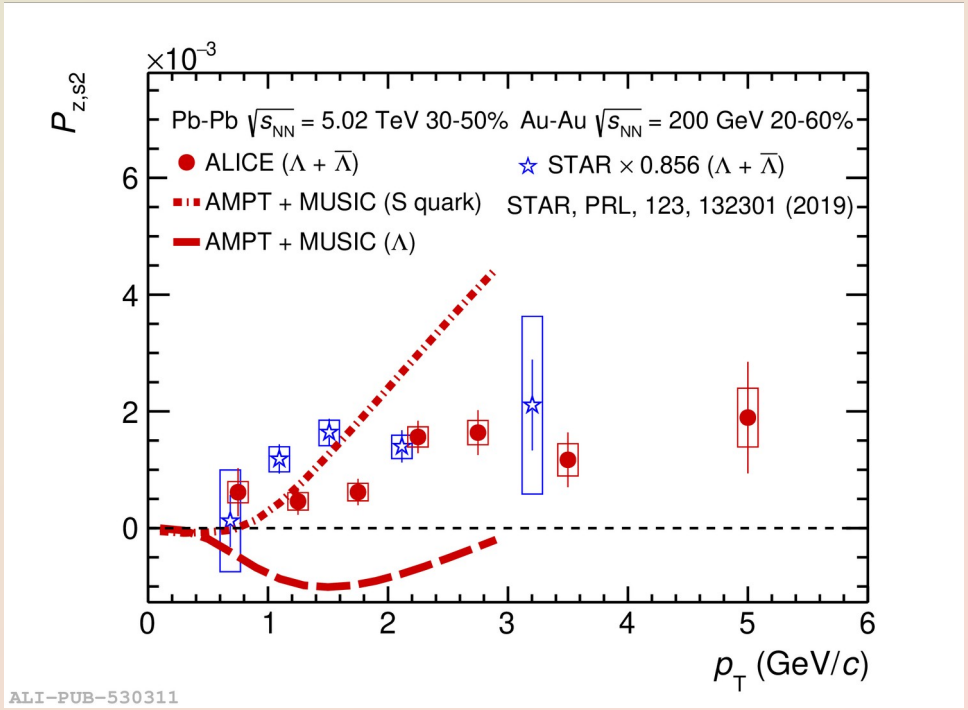




- ✓ $P_{z,s2}$ increases from central to peripheral collisions due to increasing anisotropy
- ✓ $P_{z,s2}$ increases mildly with p_T
- ✓ Run 3 results are compatible with Run 2 with much smaller statistical uncertainties due to x20 data sample

Comparison with STAR energy and model predictions



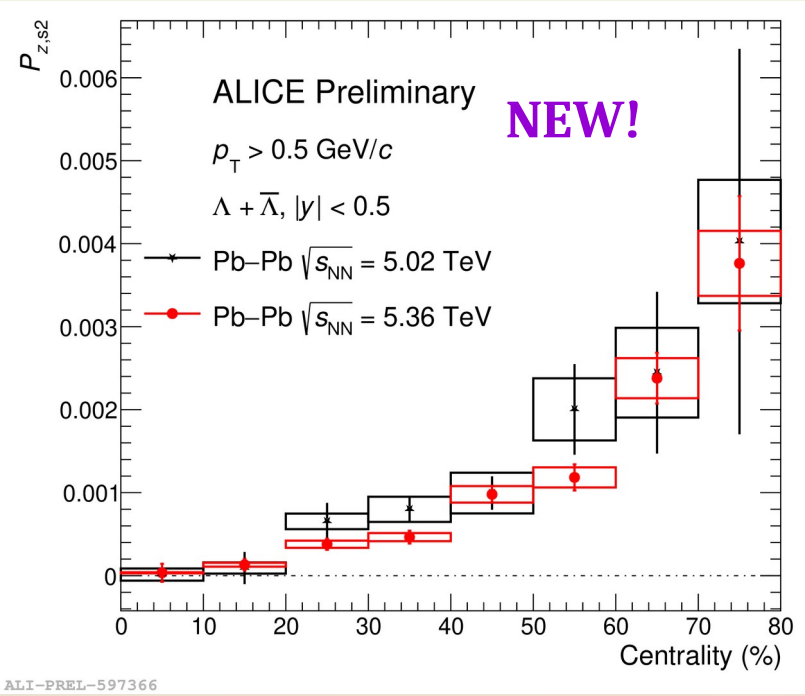


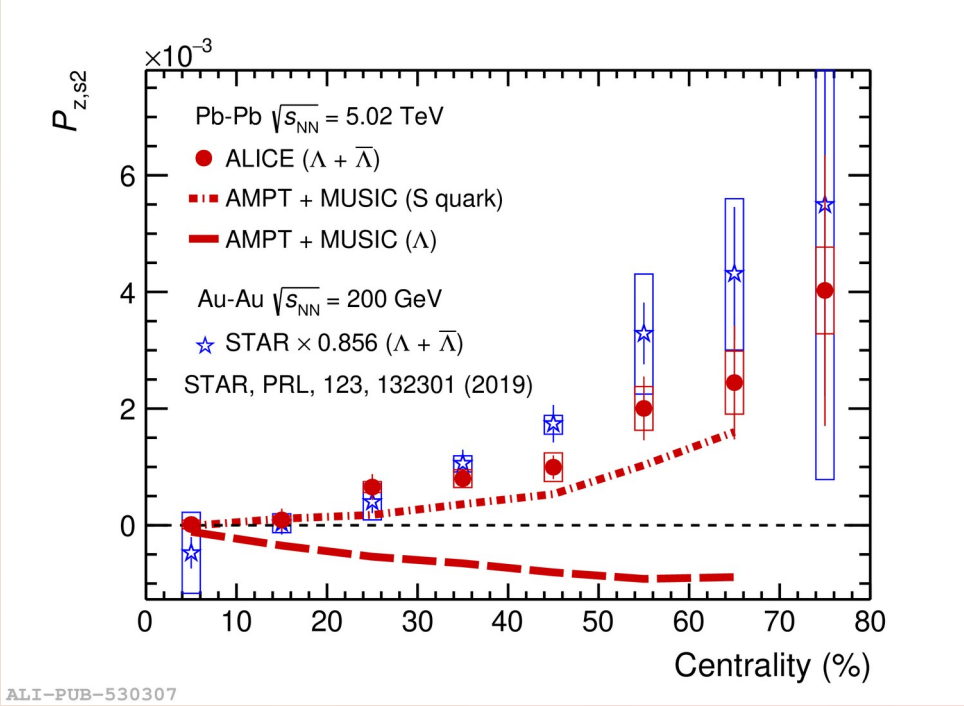
ALICE Collaboration, Phys. Rev. Lett. 128, 172005 (2022)

- ✓ $P_{z,s2}$ at the LHC is smaller in magnitude to top RHIC energy at low p_T
- ✓ 3+1 D hydro model MUSIC + AMPT initial conditions predicts correct sign polarization if shear-induced polarisation is included and the inherits quark s polarisation at the hadronisation stage

B.Fu et al., Phys. Rev. Lett. 127, 142301 (2021)

Comparison with STAR energy and model predictions



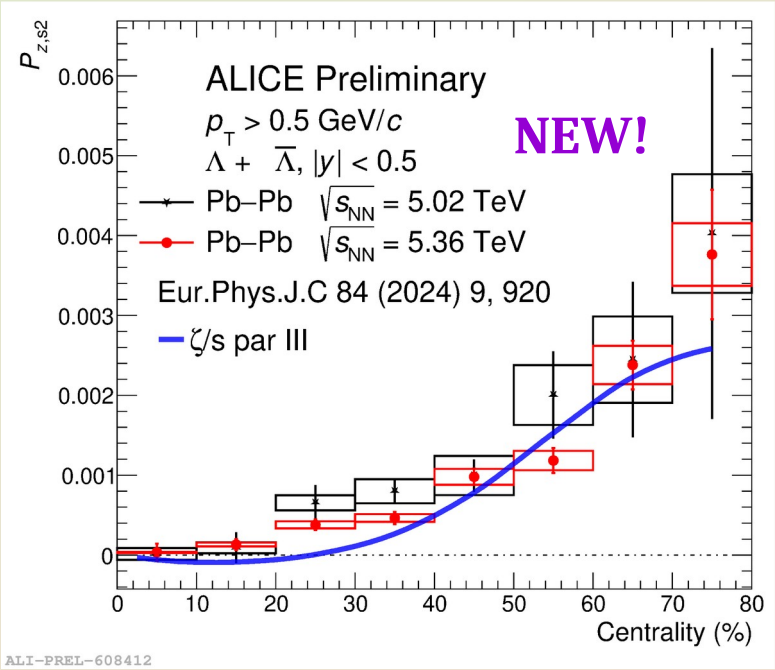


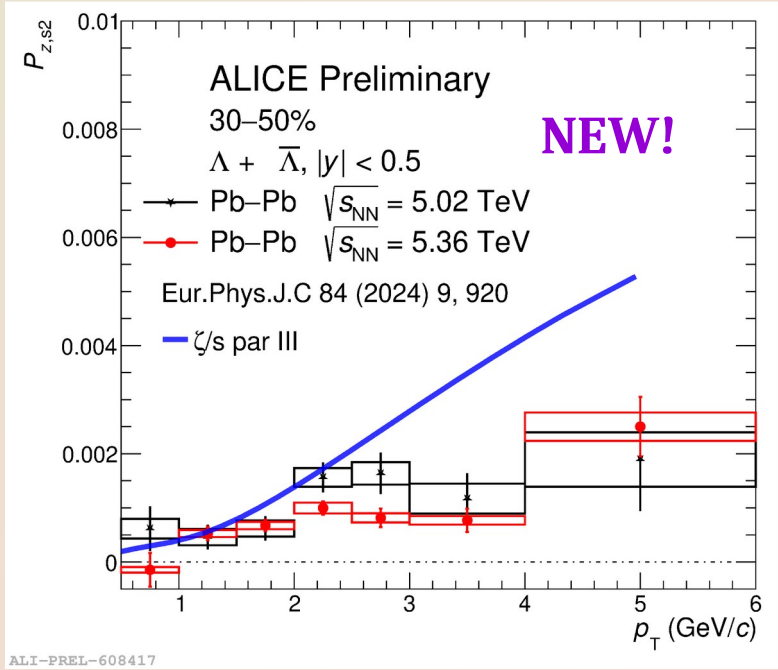
ALICE Collaboration, Phys. Rev. Lett. 128, 172005 (2022)

- ✓ $P_{z,s2}$ at the LHC is similar in magnitude to top RHIC energy (in central collisions)
- ✓ 3+1 D hydro model MUSIC + AMPT initial conditions predicts correct sign polarization if shear-induced polarisation is included and the inherits quark s polarisation at the hadronisation stage

B.Fu et al., Phys. Rev. Lett. 127, 142301 (2021)

Comparison with model predictions

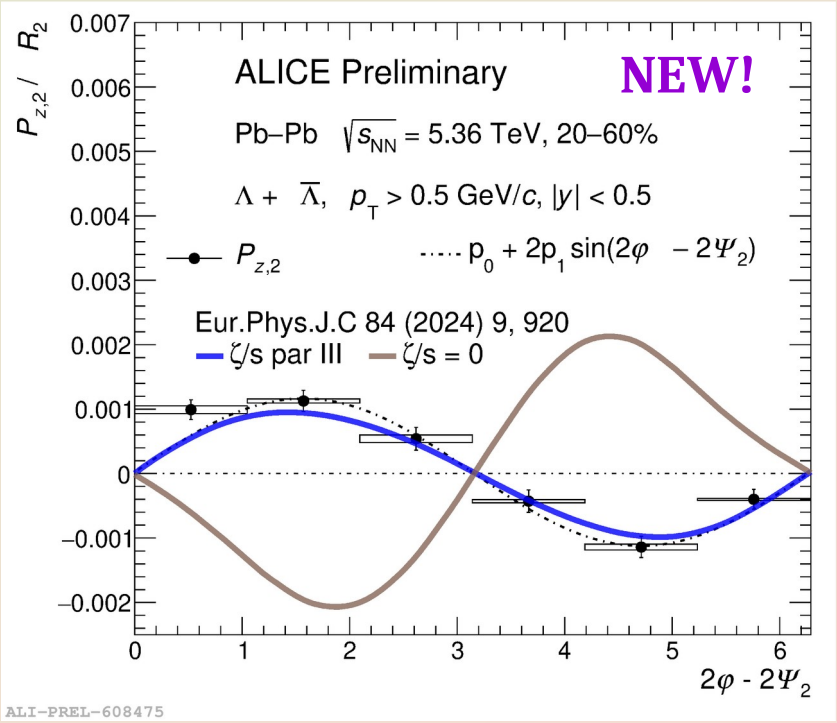




- ✓ Good agreement between data and model prediction which includes:
- Shear induced polarization
- Temperature dependent bulk viscosity
- Isothermal hadronization hypersurface

A. Palermo, F. Becattini et al. EPJC 84, 920 (2024)

Azimuthal dependence



- ✓ Good agreement between data and model prediction which includes:
- Shear induced polarization
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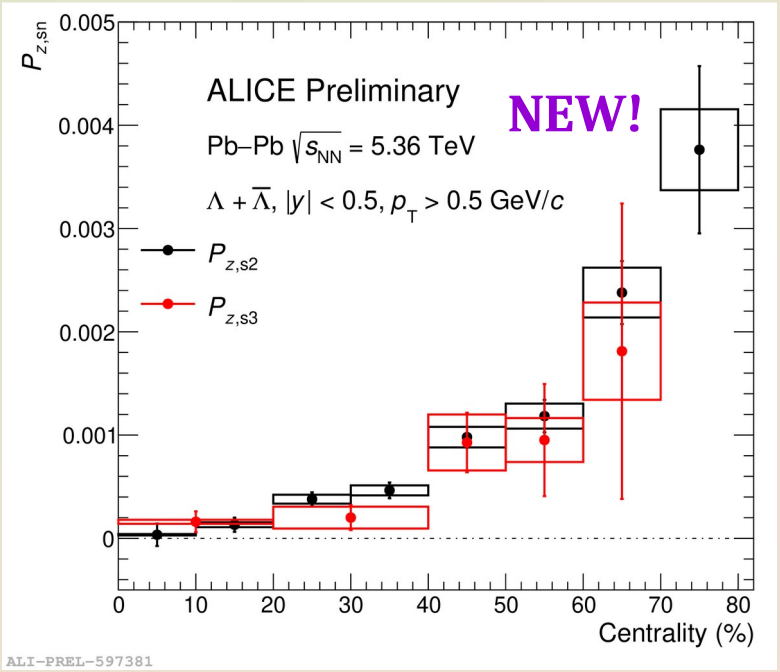
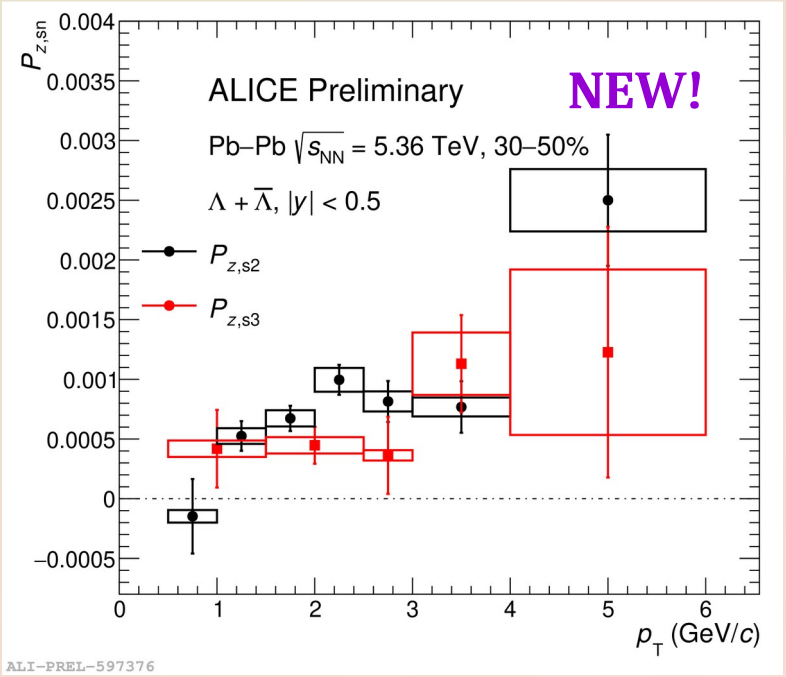
A. Palermo, F. Becattini et al. EPJC 84, 920 (2024)

Longitudinal second and third order polarization of Λ

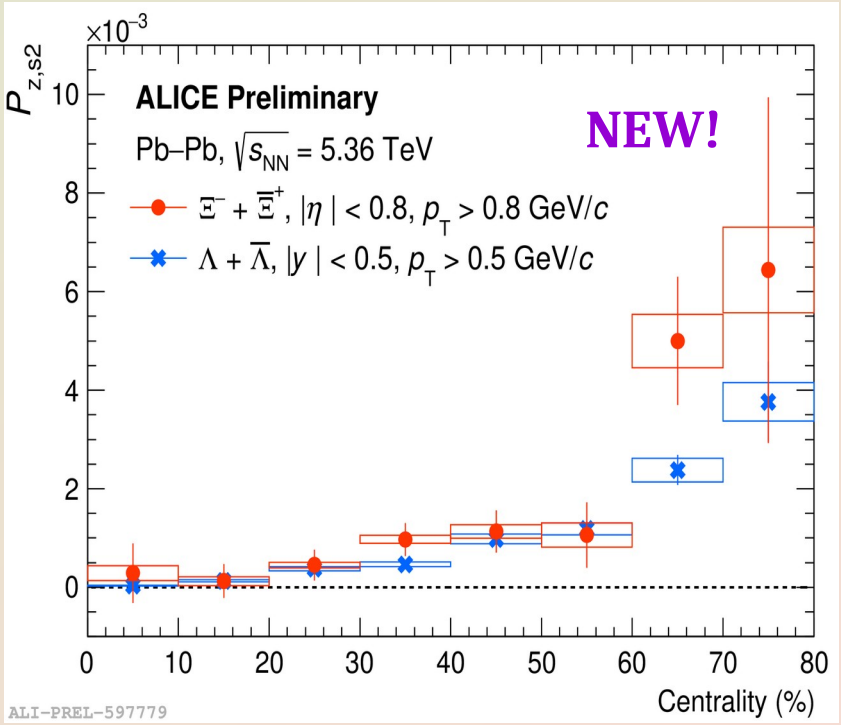




✓ $P_{z,s3}$ is compatible with $P_{z,s2}$ within large uncertainties despite the triangular flow being smaller than elliptic flow

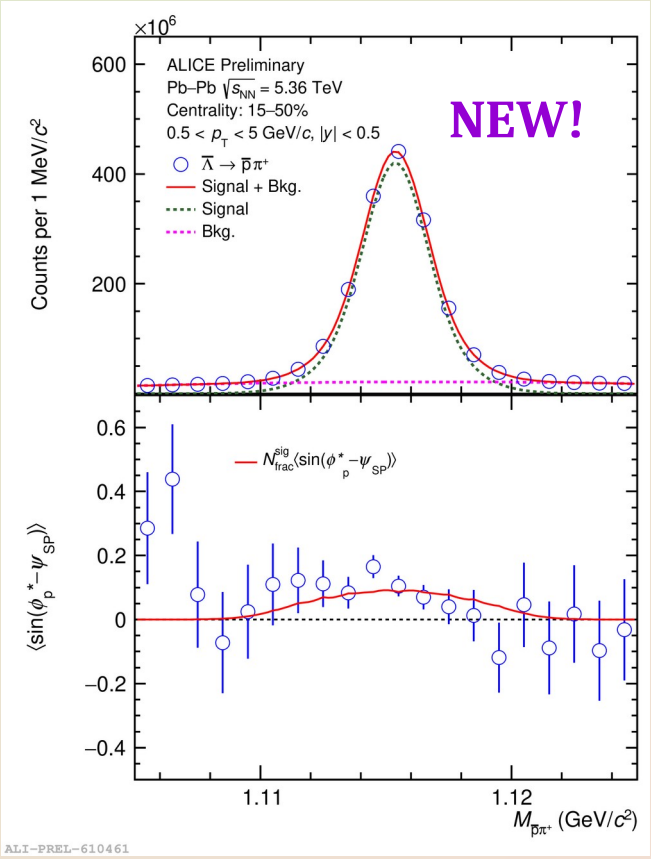
More statistics and model predictions are needed to interpret the results!

Longitudinal second order polarization of Ξ



- ✓ First measurement of Ξ longitudinal polarization in Pb-Pb collisions at LHC energy
- ✓ Results are compatible with the hyperon confirming the spin hierarchy

Global polarization measurement at LHC

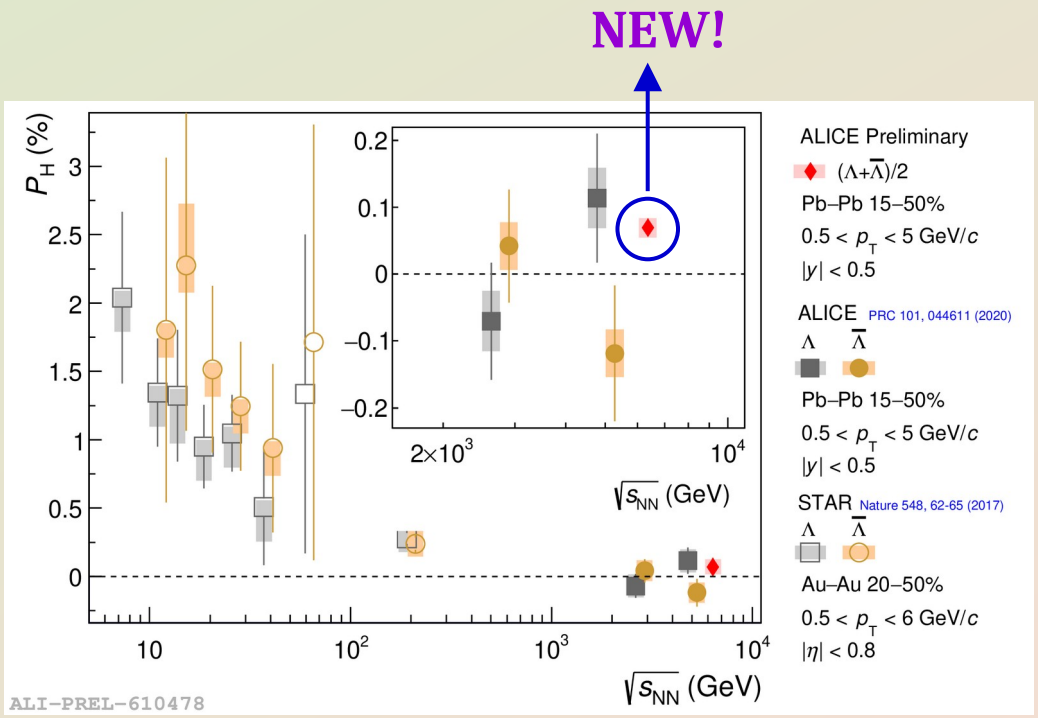


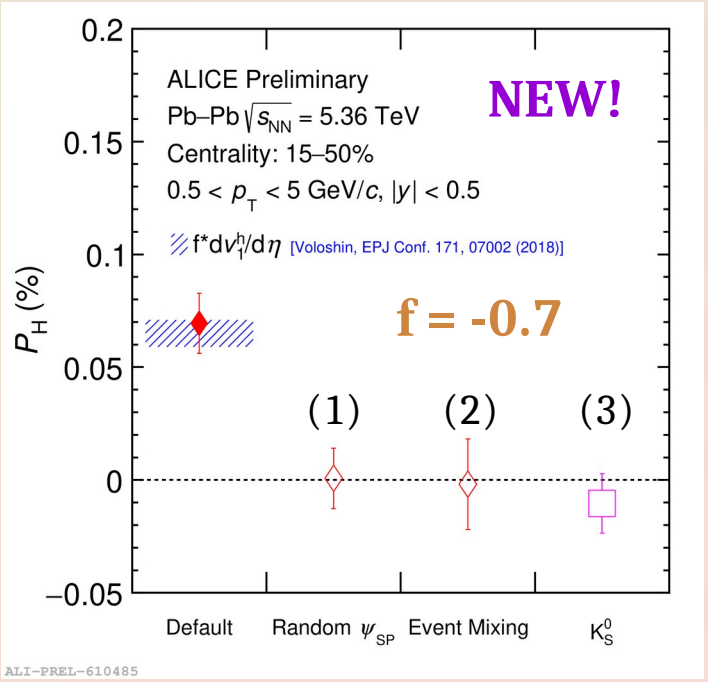
- ✓ Global hyperon polarization

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

- ✓ P_H measured from the simultaneous fit to invariant mass and polarization variable distribution
- ✓ In default case, polarization contribution of background is taken to be zero

Global polarization measurement at LHC





- ✓ **First observation of non-zero polarization of hyperons at LHC energies with 5σ significance**
- ✓ **Vorticity at LHC energy: (3.27± 0.66) 10^{20} s^{-1}**
- ✓ Average polarization consistent with the empirical prediction based on directed flow slope at mid-rapidity
- ✓ Several null hypothesis tests (1, 2, 3) performed succesfully

Summary and outlook

- ✓ The longitudinal polarization of induced by elliptic flow is measured with improved precision using Run3 data confirming its increasing trend towards more peripheral collisions
- ✓ The longitudinal polarization is well described by model including shear induced polarization, temperature dependent bulk viscosity and isothermal hadronisation hypersurface
- ✓ Comparible local polarization observed for different order of harmonics
- ✓ The first measurement of Ξ longitudinal polarization at LHC energy confirms spin hierarchy
- ✓ First observation of globally polarized hyperons at LHC energy with 5σ significance
- ✓ First quantitative extraction of vorticity of QGP at LHC energy is found to be of the order of $10^{20}\ s^{-1}$
- ✓ 2024+2025 data will allow further differential and precision polarization measurements.

Backup