EUROPEAN PHYSICAL SOCIETY
EPS HEP2025
MARSEILLE
07 11 JULY 2025

Longitudinal polarization of hyperons in Run 3 Pb-Pb collisions with ALICE

Chiara De Martin (CERN) on behalf of the ALICE Collaboration

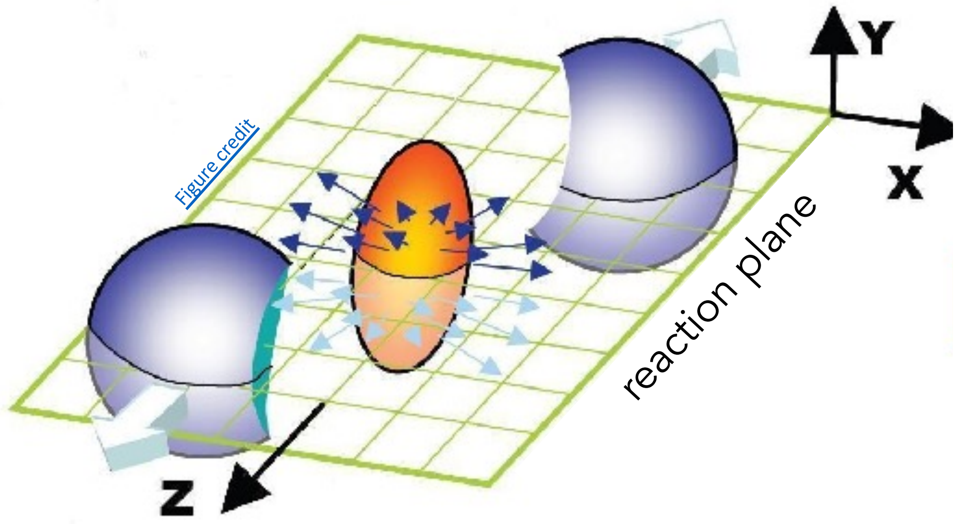
The origin of longitudinal polarization

- The longitudinal spin polarization is the **degree to which a particle's spin is aligned with the beam axis**

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

The origin of longitudinal polarization

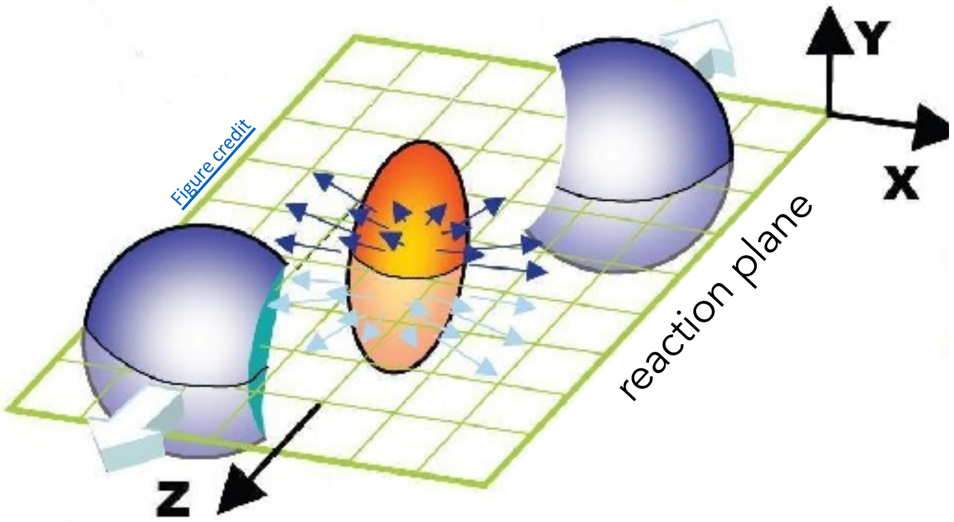
- The longitudinal spin polarization is the **degree to which a particle's spin is aligned with the beam axis**
- In non-central **heavy-ion collisions**, the **eccentricity** in the initial state is converted to momentum **anisotropy in the final state** distributions of particles → the second-order coefficient of the Fourier expansion is referred to as **elliptic flow**

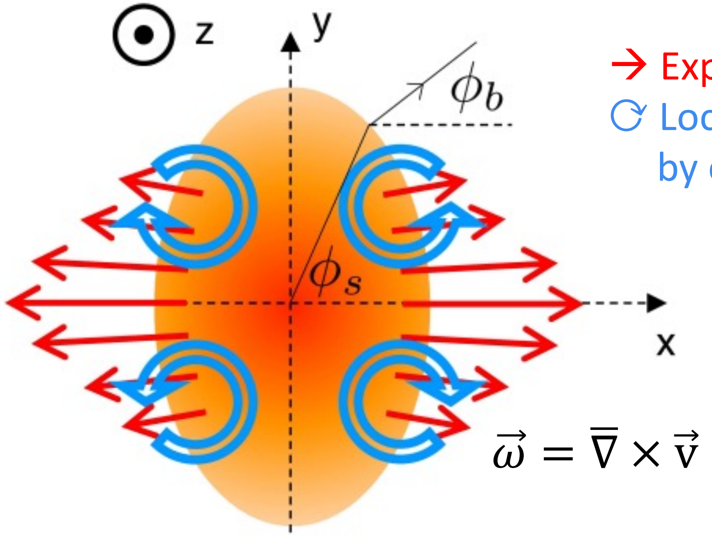


S. Voloshin and T. Niida, Phys. Rev. C 94 (2016) 021901(R)

The origin of longitudinal polarization

- The longitudinal spin polarization is the **degree to which a particle's spin is aligned with the beam axis**
- In non-central **heavy-ion collisions**, the **eccentricity** in the initial state is converted to momentum **anisotropy in the final state** distributions of particles → the second-order coefficient of the Fourier expansion is referred to as **elliptic flow**

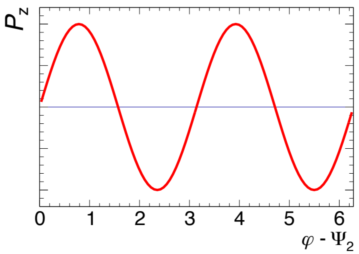




$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

→ Expansion velocity

⟳ Local vorticities induced by elliptic flow



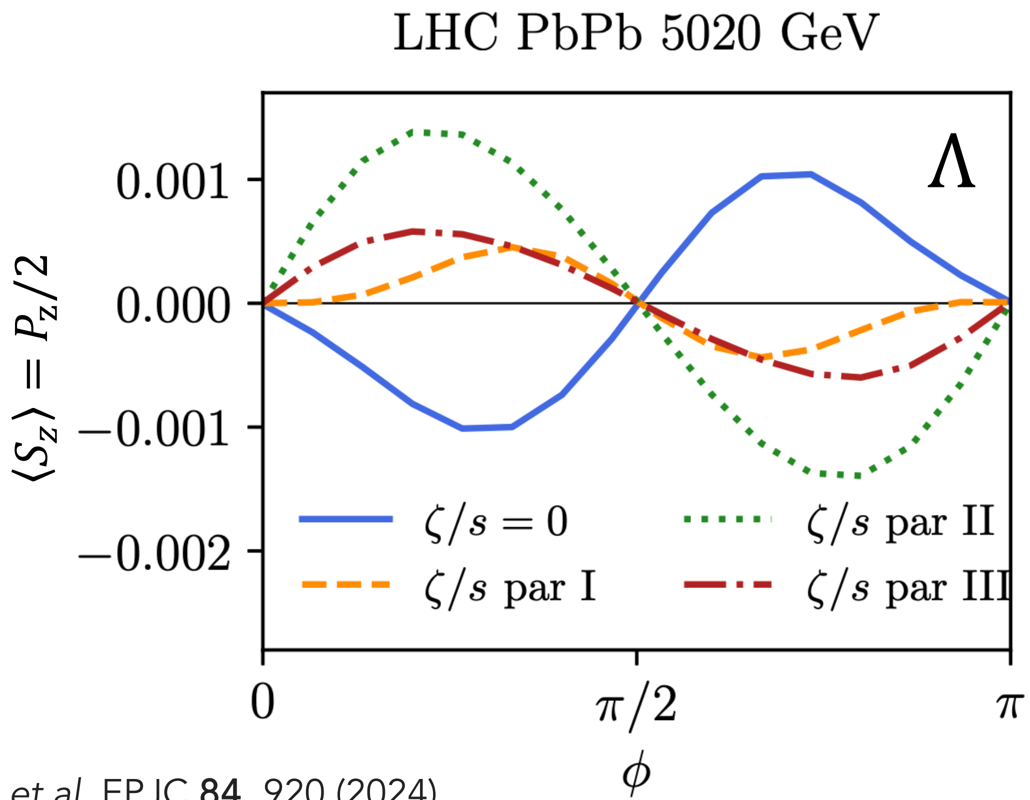
- The elliptic flow is expected to induce a vorticity **component along the** beam axis with a quadrupole structure in the transverse plane → due to the **spin-orbit coupling**, this is expected to lead to **a longitudinal component of particle spin polarization**

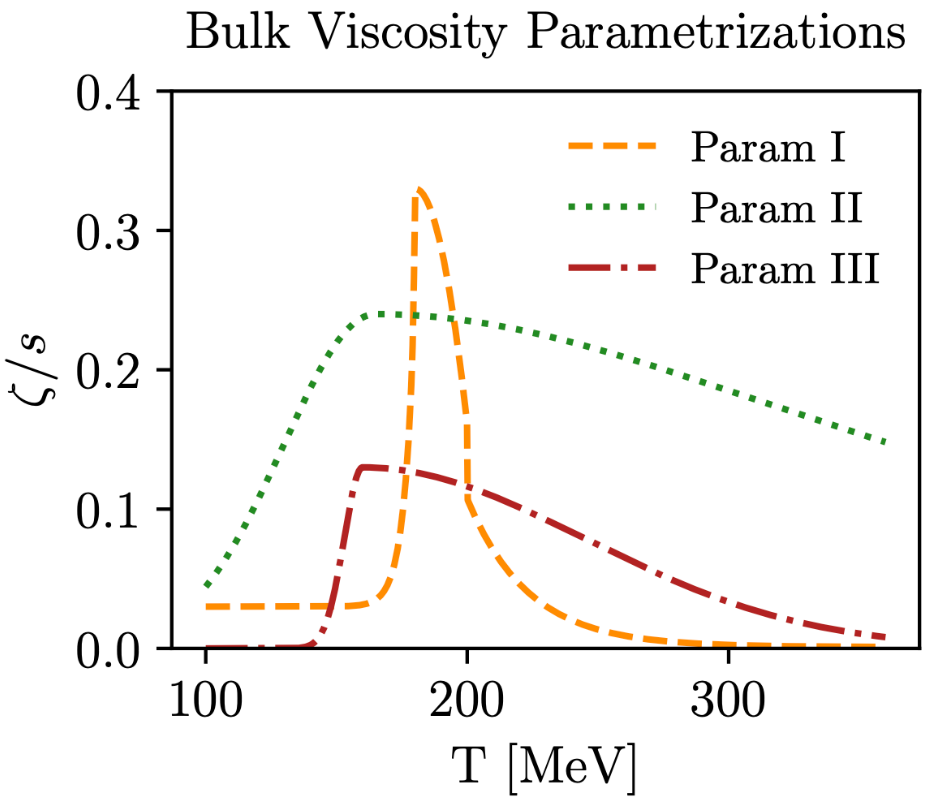
S. Voloshin and T. Niida, Phys. Rev. C 94 (2016) 021901(R)

Studying QGP with hyperon polarization

The polarization along the beam axis P_z is sensitive to:

- the **bulk viscosity** ζ/s of the QGP at the LHC energies → bulk viscosity can change the sign of the polarization
- the contribution from **shear-induced polarization (SIP),** whose origin is the **motion of particles in anisotropic fluid**, and which competes with the effect of thermal vorticity





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

Experimental technique for hyperon polarization measurements

The polarization can be experimentally measured via **parity violating weak decays** like $\Lambda \rightarrow p\pi$, in which the daughter baryon is preferentially emitted in the direction of the spin of the hyperon.

The angular distribution of protons in the Λ rest frame is:

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_\Lambda\, P_\Lambda \cos\theta^*$$

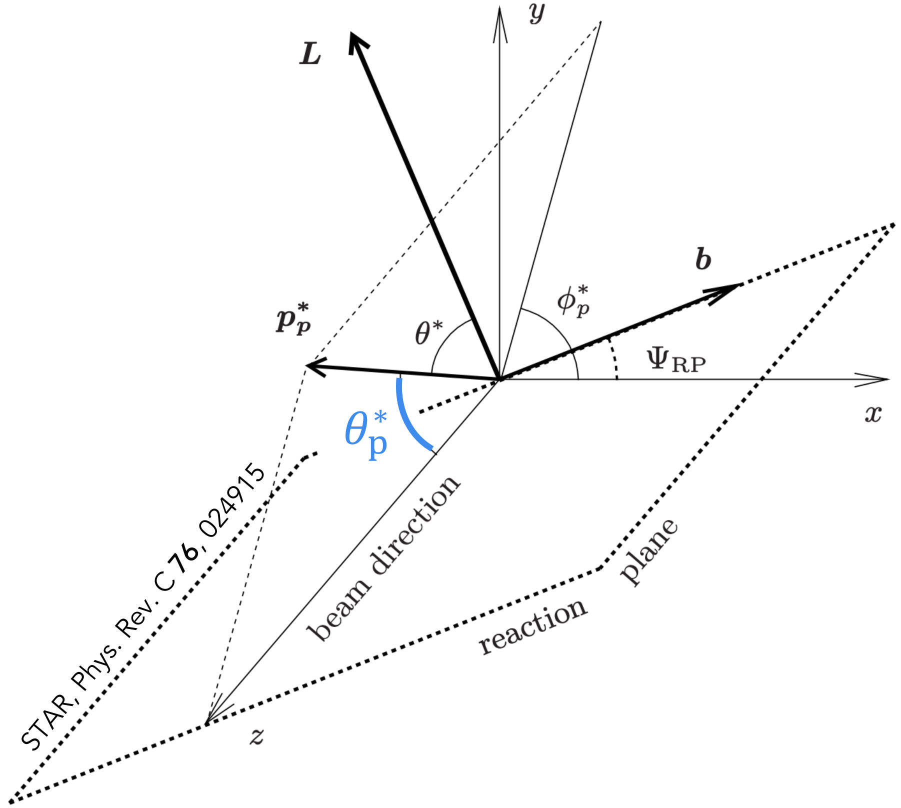
α_Λ = Λ decay parameter
P_Λ = Λ polarization

Λ Longitudinal Polarization:

$$P_z = \frac{\boxed{\langle \cos\theta_p^* \rangle}}{\alpha_\Lambda \boxed{\langle \cos^2\theta_p^* \rangle}}$$

θ_p^* : polar angle of the daughter proton in the Λ rest-frame

detector acceptance term



STAR, Phys. Rev. C **76**, 024915

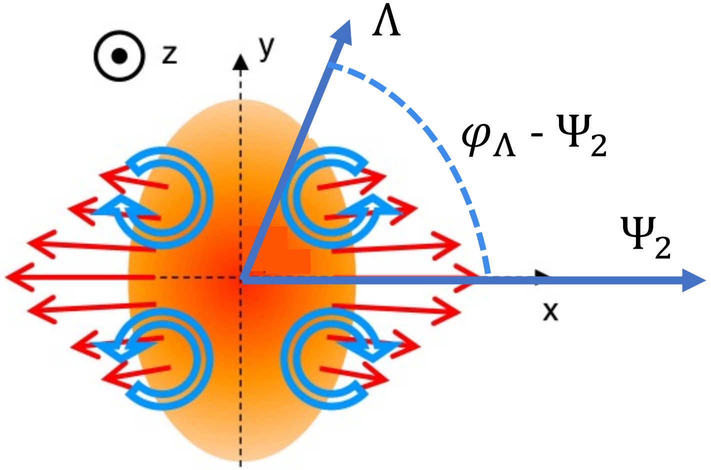
Experimental technique for hyperon polarization measurements

The polarization can be experimentally measured via **parity violating weak decays** like $\Lambda \rightarrow p\pi$, in which the daughter baryon is preferentially emitted in the direction of the spin of the hyperon.

The angular distribution of protons in the Λ rest frame is:

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_\Lambda \, P_\Lambda \cos\theta^*$$

α_Λ = Λ decay parameter
P_Λ = Λ polarization



Λ LONGITUDINAL POLARIZATION:

$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle \cos^2\theta_p^* \rangle}$$

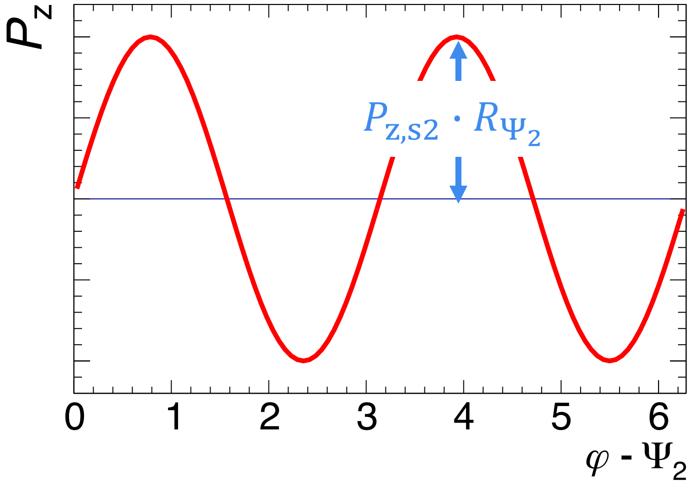
θ_p^* : polar angle of the daughter proton in the Λ rest-frame

detector acceptance term

$$P_{z,s2} = \frac{\langle P_z \sin 2(\varphi_\Lambda - \Psi_2) \rangle}{R_{\Psi_2}}$$

second-order Fourier sine coefficient

second-order event plane resolution



Experimental technique for hyperon polarization measurements

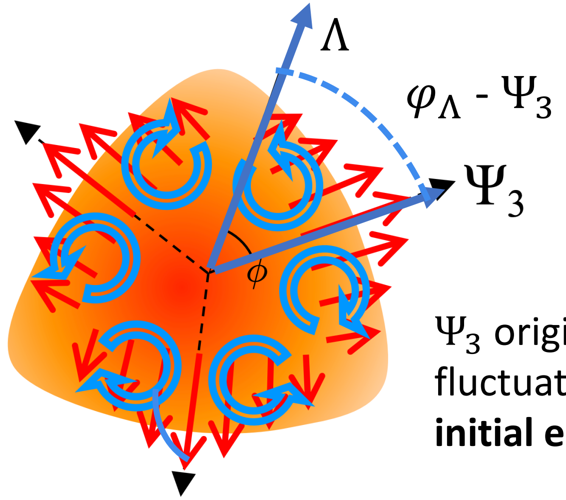
The polarization can be experimentally measured via **parity violating weak decays** like $\Lambda \rightarrow p\pi$, in which the daughter baryon is preferentially emitted in the direction of the spin of the hyperon.

The angular distribution of protons in the Λ rest frame is:

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_\Lambda \, P_\Lambda \cos\theta^*$$

α_Λ = Λ decay parameter

P_Λ = Λ polarization



Ψ_3 originates from fluctuations in the **initial energy density**

Λ LONGITUDINAL POLARIZATION:

$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle \cos^2\theta_p^* \rangle}$$

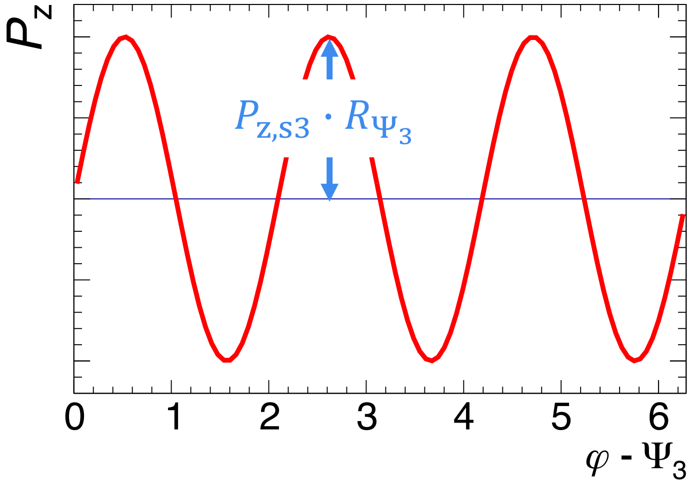
θ_p^* : polar angle of the daughter proton in the Λ rest-frame

detector acceptance term

$$P_{z,s3} = \frac{\langle P_z \sin 3(\varphi_\Lambda - \Psi_3) \rangle}{R_{\Psi_3}}$$

third-order Fourier sine coefficient

third-order event plane resolution



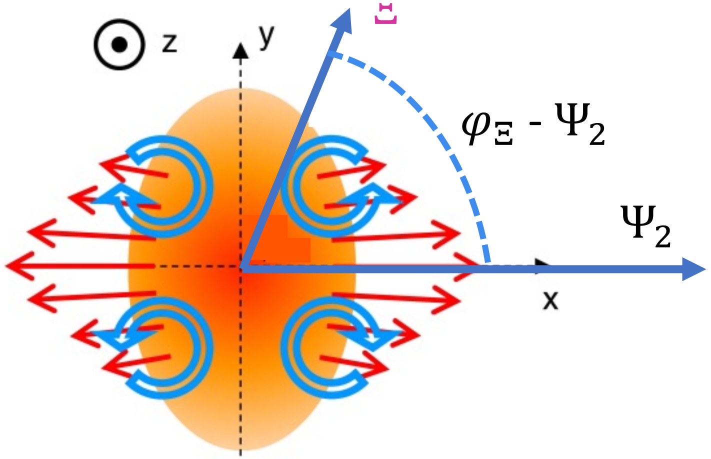
Experimental technique for hyperon polarization measurements

The polarization can be experimentally measured via **parity violating weak decays** like Λ → pπ, in which the daughter baryon is preferentially emitted in the direction of the spin of the hyperon.

The angular distribution of protons in the Λ rest frame is:

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_\Lambda\, P_\Lambda \cos\theta^*$$

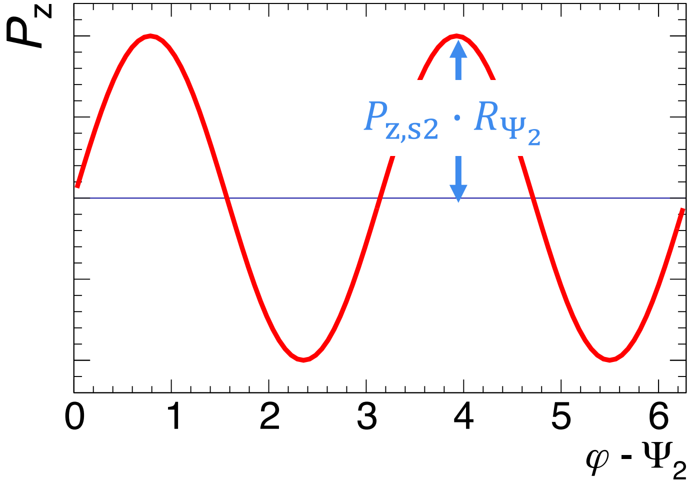
α_Λ = Λ decay parameter
P_Λ = Λ polarization



Ξ LONGITUDINAL POLARIZATION:

Ξ longitudinal polarization $P^{\Xi}_{z,s2}$ is obtained by measuring the polarization of the **daughter Λ** produced in the decay $\Xi^- \rightarrow \Lambda\pi^-$+ *c.c.*, where the Λ inherits $C_{\Xi\Lambda}$ = 92.5% [1] of Ξ polarization

$$P^{\Xi}_{z} = \frac{\langle \cos\theta^*_{\mathrm{p}} \rangle}{C_{\Xi\Lambda}\, \alpha_\Lambda \langle \cos^2\theta^*_{\mathrm{p}} \rangle} \qquad P^{\Xi}_{z,s2} = \frac{\langle P^{\Xi}_{z} \sin 2(\varphi_\Xi - \Psi_2) \rangle}{R_{\Psi_2}}$$



[1] PDG, Phys. Rev. D 110, 030001 (2024)

ALICE at the LHC in Run 3

Upgraded TPC JINST 16, P03022 (2021)

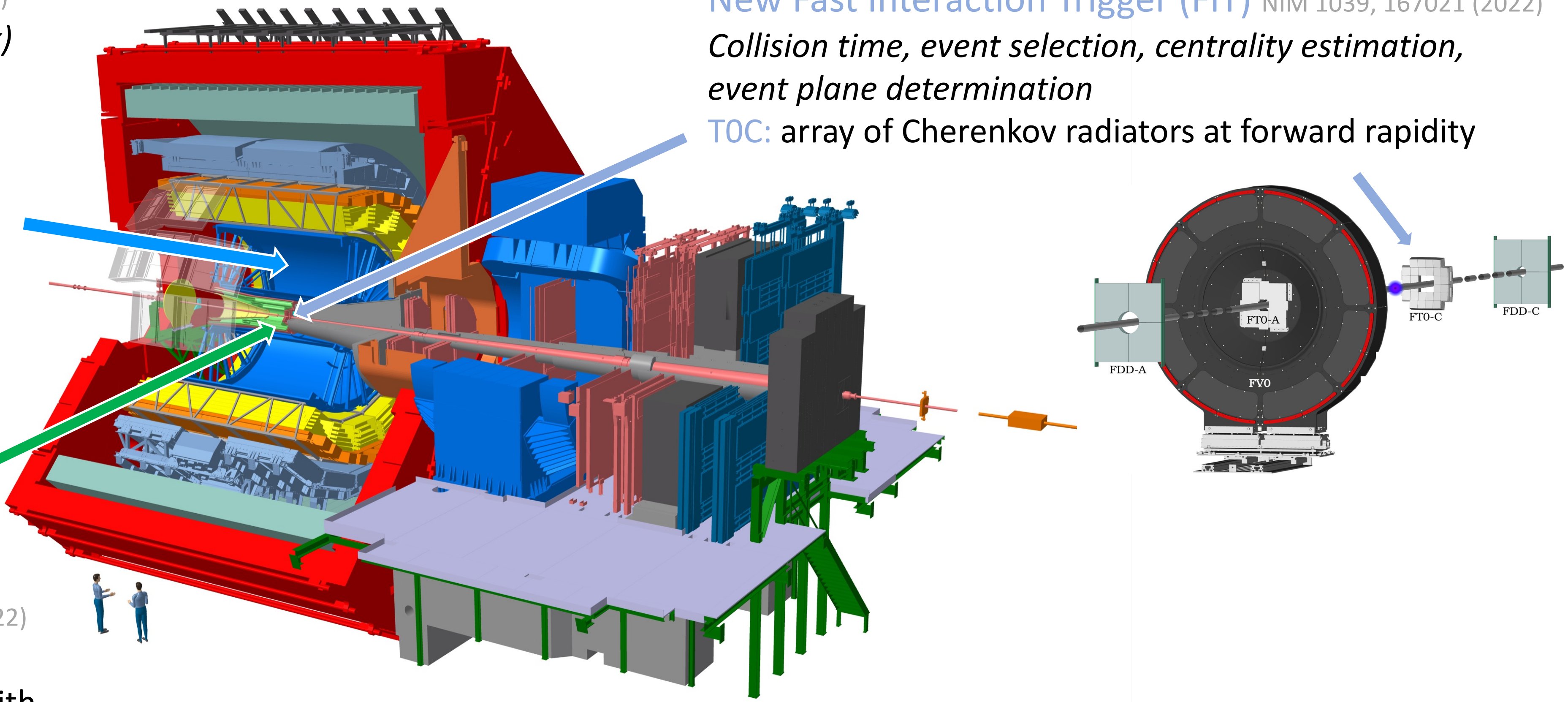
Main tracking detector, PID (dE/dx)

- MWPCs replaced with GEMs
- Continuous readout up to interaction rate of 50 kHz in Pb-Pb collisions

New Fast Interaction Trigger (FIT) NIM 1039, 167021 (2022)

Collision time, event selection, centrality estimation, event plane determination

T0C: array of Cherenkov radiators at forward rapidity



Upgraded ITS NIM 1032, 166632 (2022)

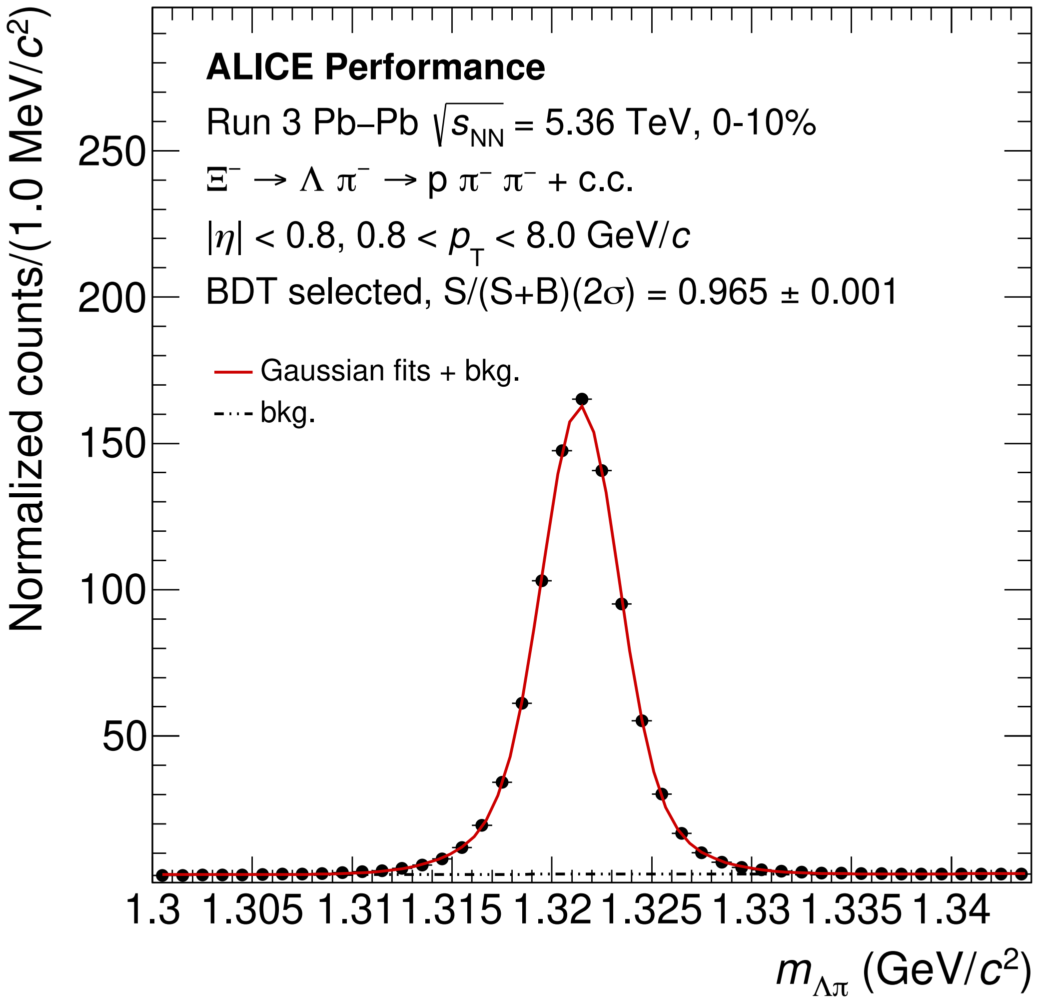
Tracking, vertexing

- 7 layers of silicon detectors with reduced material budget
- First layer closer to the beam pipe (L0 at 22 mm)

New O^2 framework CERN-LHCC-2015-006, ALICE-TDR-019

- Common **O**nline-**O**ffline computing system
- Process data throughput x 100 wrt Run 2

Identification of Λ and Ξ



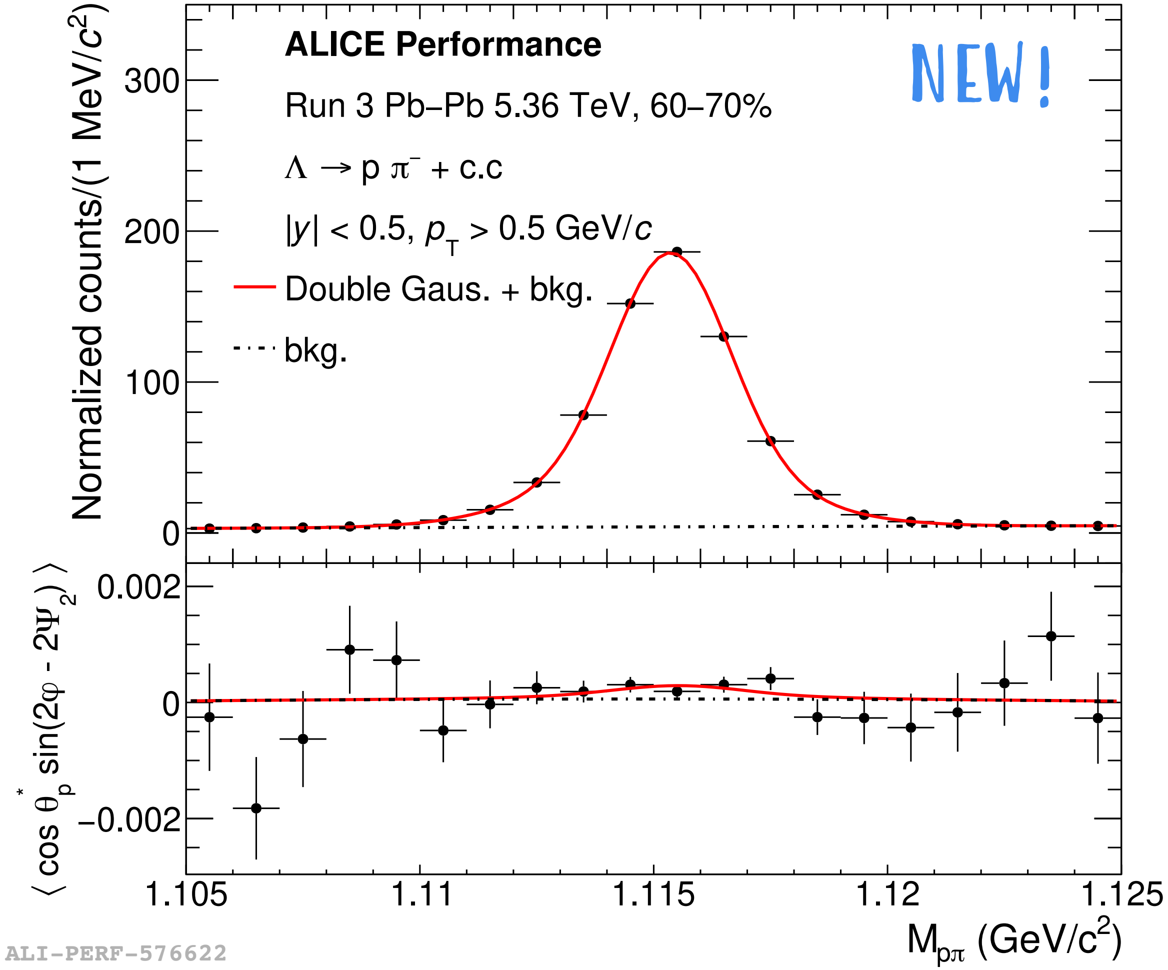
ALI-PERF-597758

- Λ and Ξ candidates are identified via **invariant mass analysis** after applying **topological and kinematic selections** to the variables describing their weak decays:

$$\Lambda \rightarrow p\pi^- \text{ (and } c.c.\text{)}$$
$$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^- \text{ (and } c.c.\text{)}$$

- The application of a **boosted decision tree** algorithm guarantees a Ξ sample purity S/(S+B) > 0.95 across all centrality classes

Longitudinal polarization of Λ in Run 3



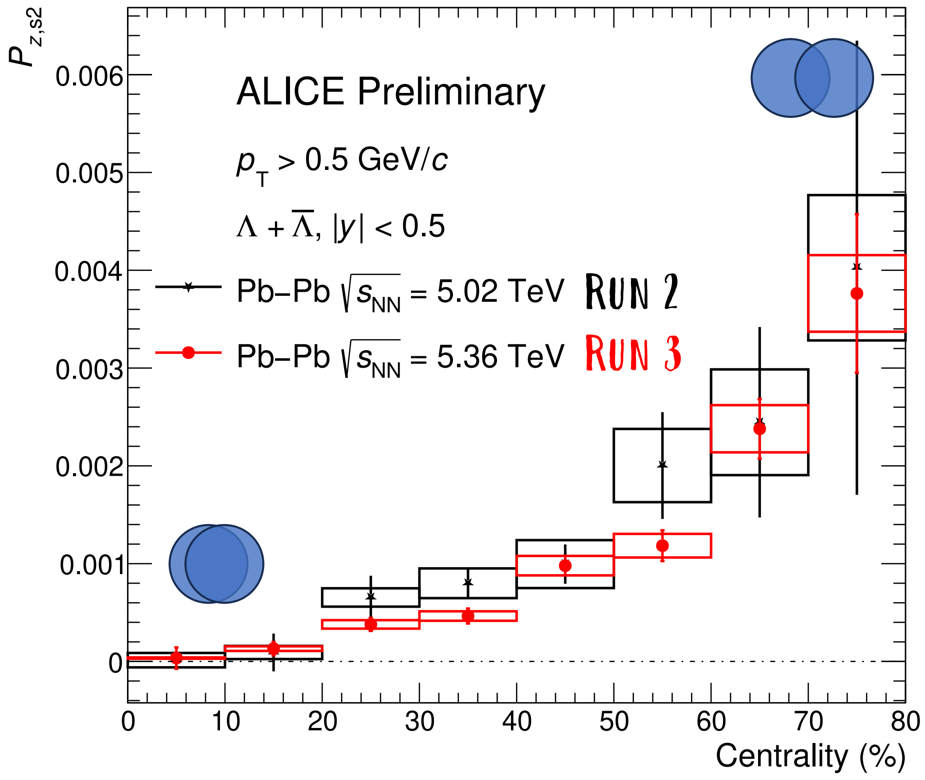
The Λ invariant mass distributions are fit with:

- a Gaussian to describe the signal
- a second degree polynomial to describe the background (dotted black line)

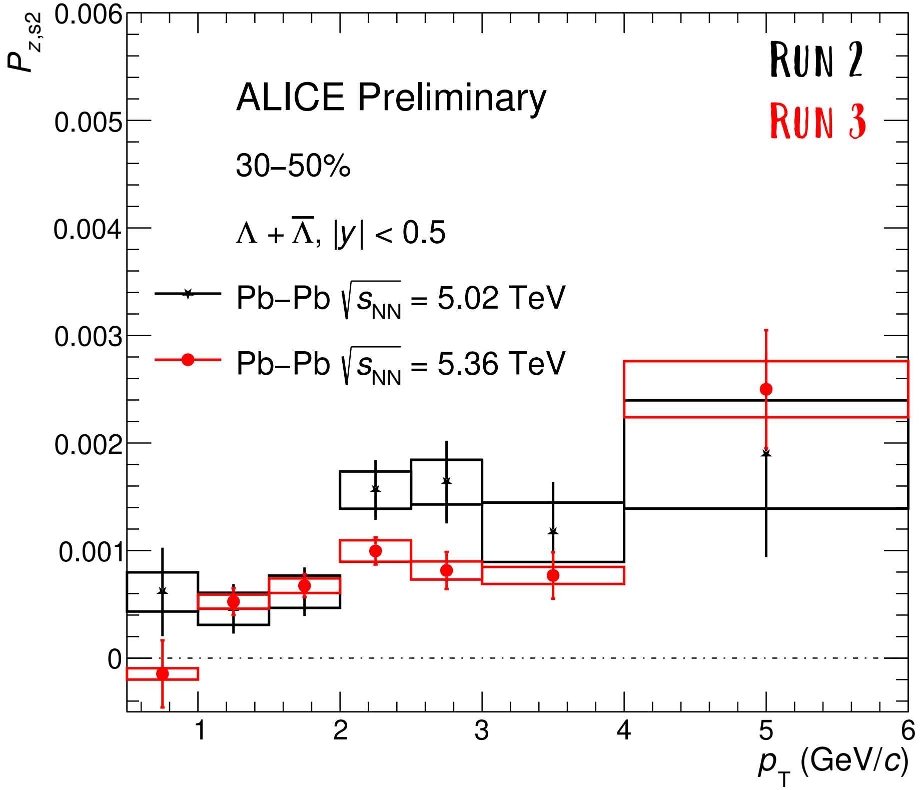
$P_{z,s2}$ is estimated as **a function of the invariant mass** of the Λ, in order to account for combinatorial background contamination

Longitudinal polarization of Λ in Run 3

NEW!



ALI-PREL-597366

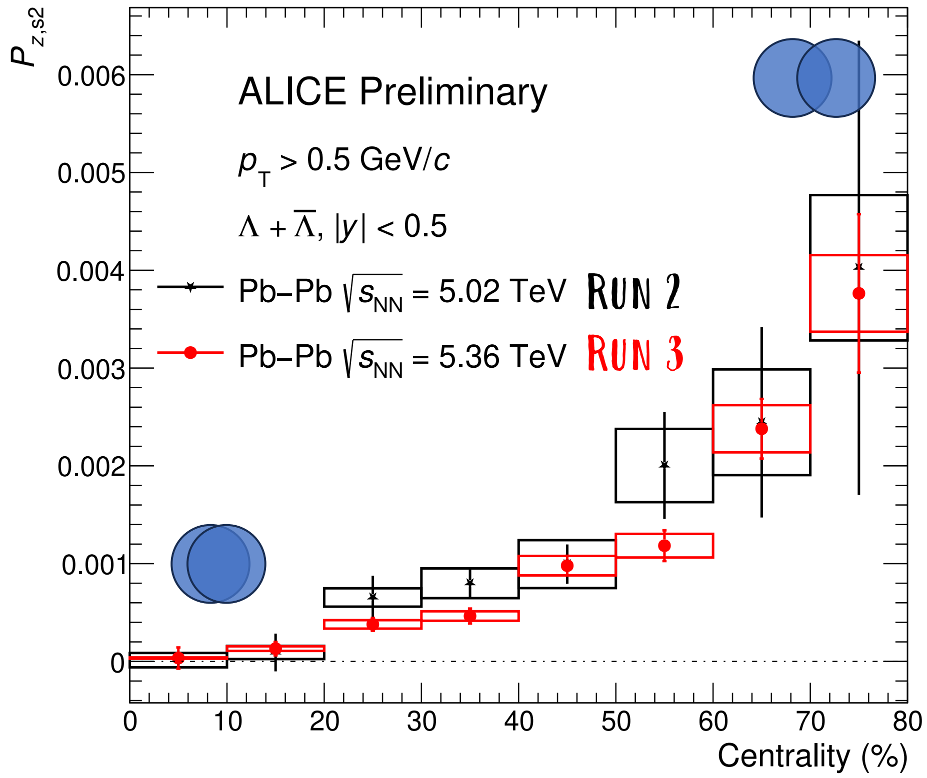


ALI-PREL-597371

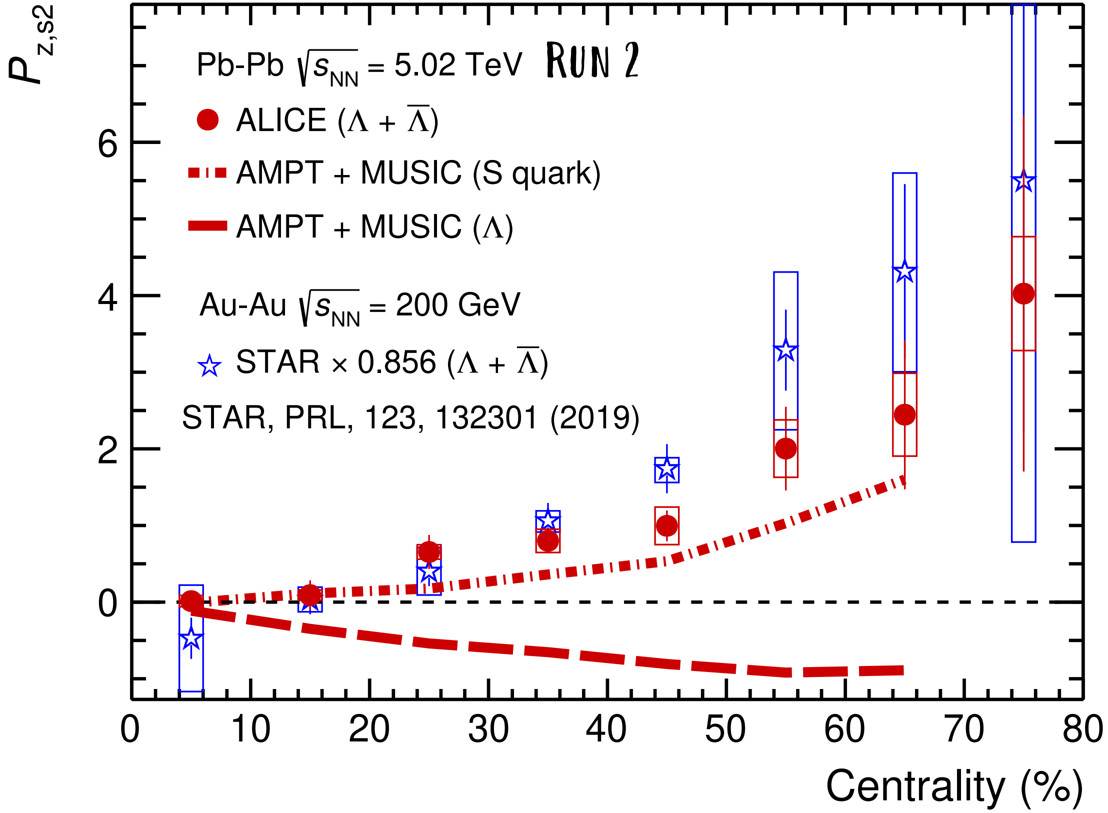
- $P_{\mathrm{z,s2}}$ **increases from central to peripheral collisions** due to increasing system anisotropy, and mildly increases with p_{T}
- **Run 3 results** are compatible with Run 2 ones and have **smaller statistical and systematic** uncertainties, thanks to the x20 data sample ($\sim 6 \times 10^9$ collisions)

Comparison to model predictions

NEW!



ALI-PREL-597366



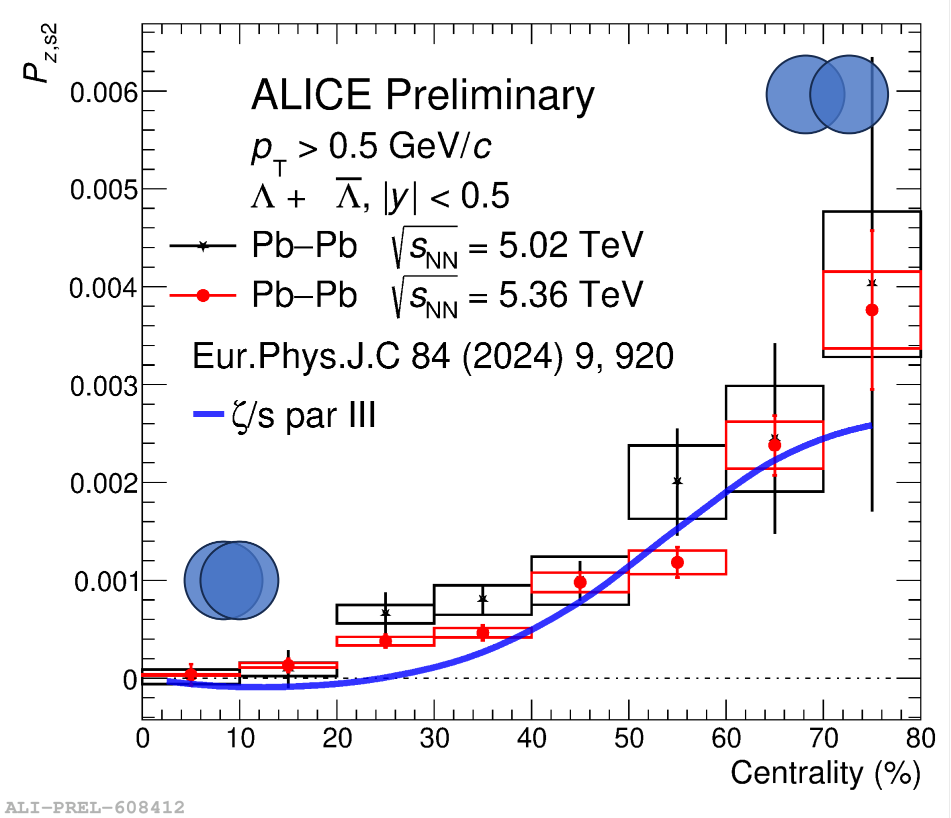
ALICE, PRL 128 (2022) 172005

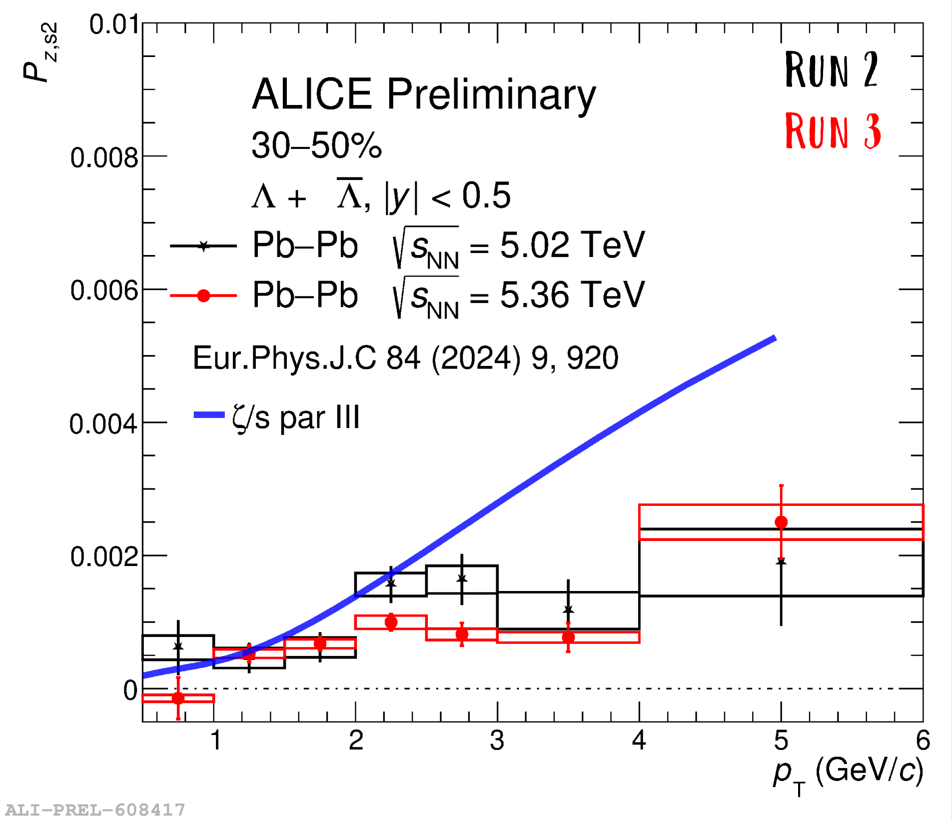
- The comparison with STAR measurement shows a **weak collision energy dependence**
- **3+1 D hydro model MUSIC + AMPT initial conditions** predicts correct sign polarisation if shear-induced polarisation is included and the **Λ inherits quark s polarisation at the hadronisation stage** [1]

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

Comparison to model predictions

NEW!



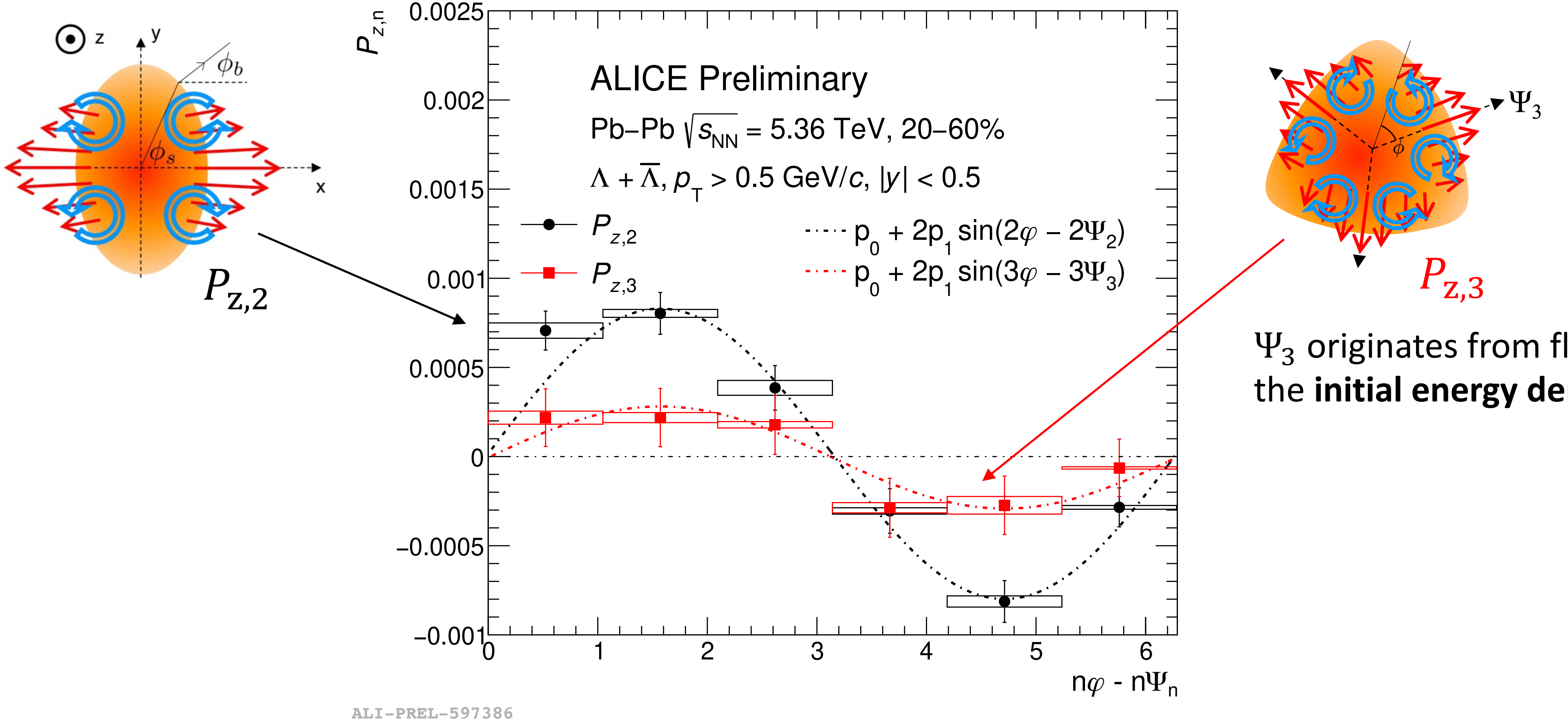


- **Good agreement** between data and model [1] including **SIP** and assuming a **temperature dependent bulk viscosity ζ/s** (parametrization III) and an **isothermal hadronisation hypersurface**

[1] A. Palermo *et al.* EPJC **84**, 920 (2024)

Λ polarization induced by triangular flow

NEW!



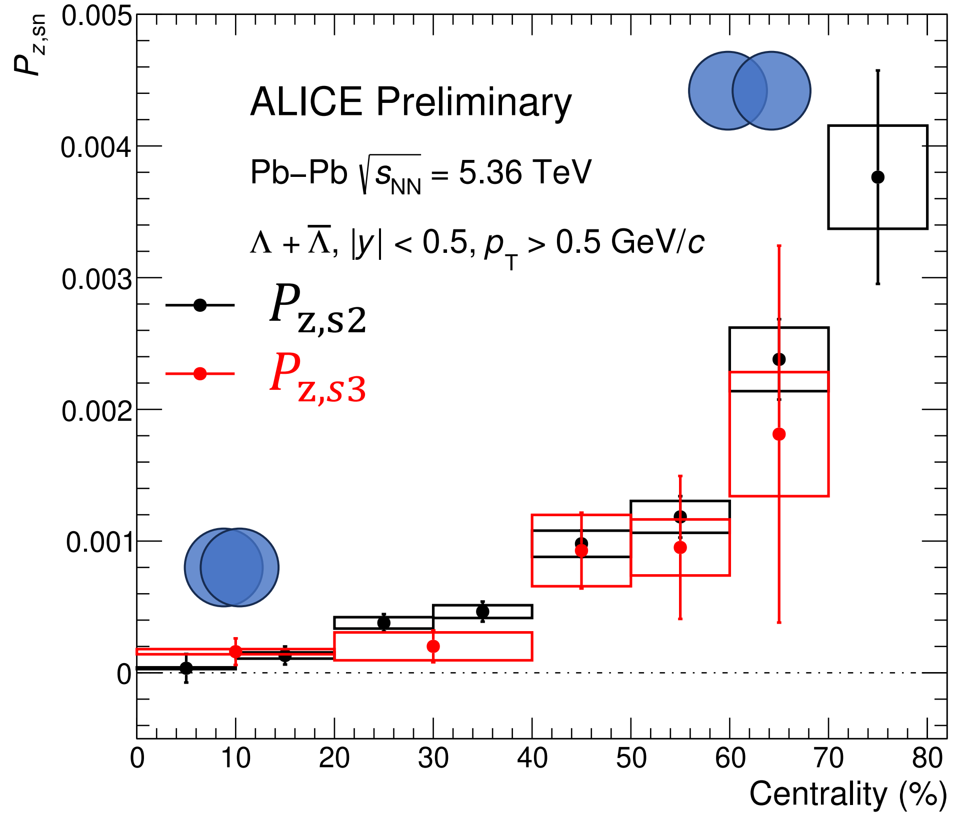
Ψ_3 originates from fluctuations in the **initial energy density**

- The polarization induced by the **triangular flow** is measured for the first time at the LHC energies

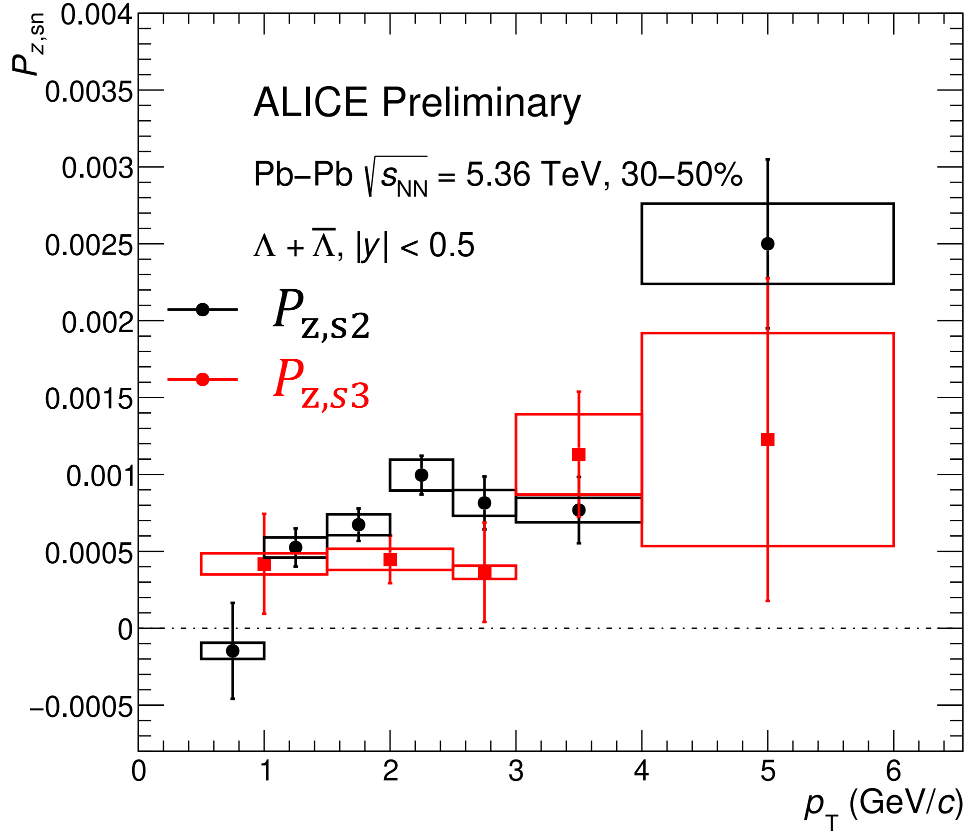
→ it helps **identify the contribution from SIP**, which is expected to be different for different harmonics

Λ polarization induced by triangular flow

NEW!



ALI-PREL-597381

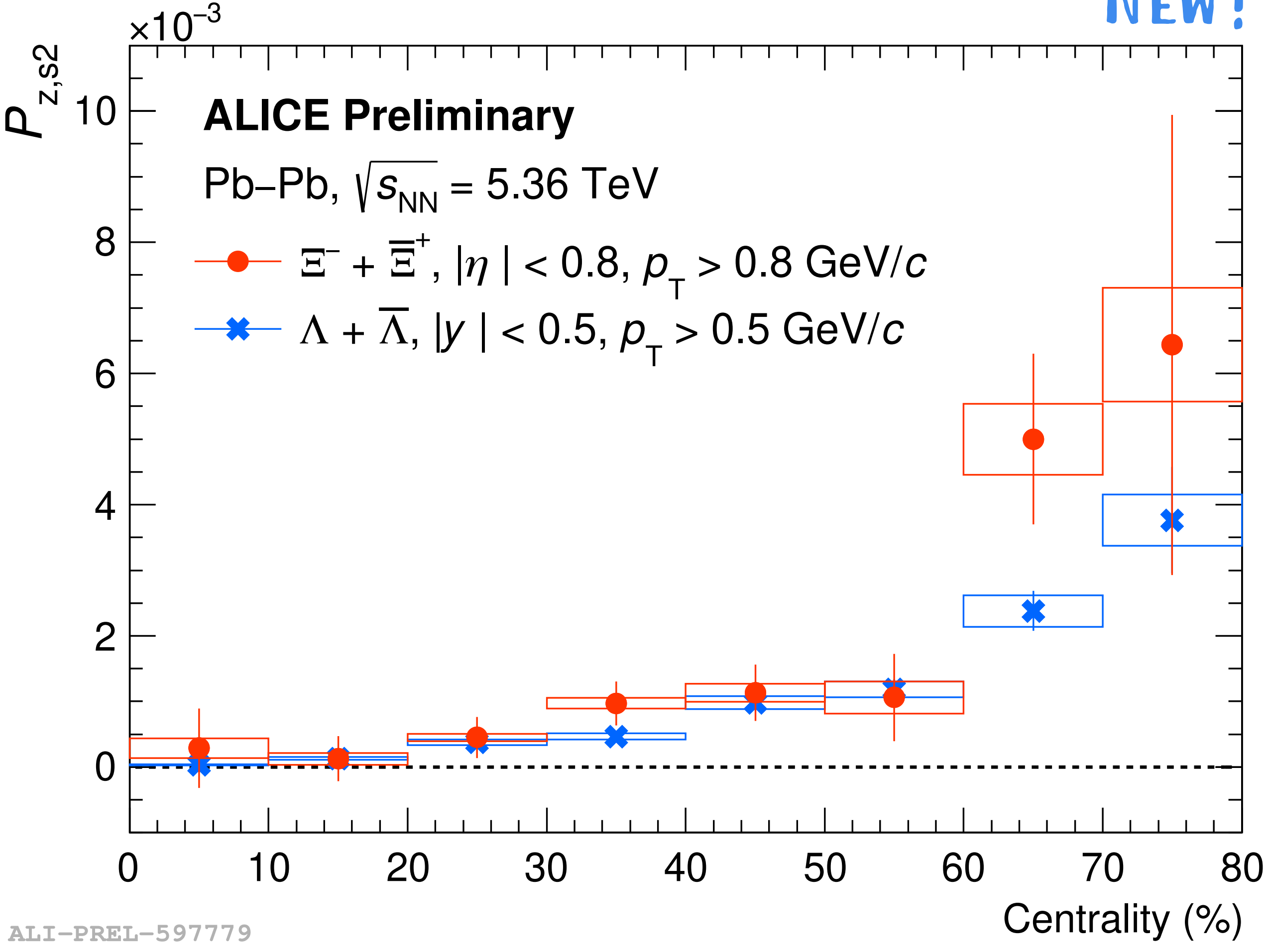


ALI-PREL-597376

- The third-order polarization $P_{z,s3}$ is **compatible** with the second-order polarization, despite the **triangular flow being smaller than the elliptic flow** → comparison to model predictions needed to interpret these results
- With 2024 and 2025 data, the measurement of polarization induced by **higher harmonic flow** will be possible

Longitudinal polarization of Ξ in Run 3

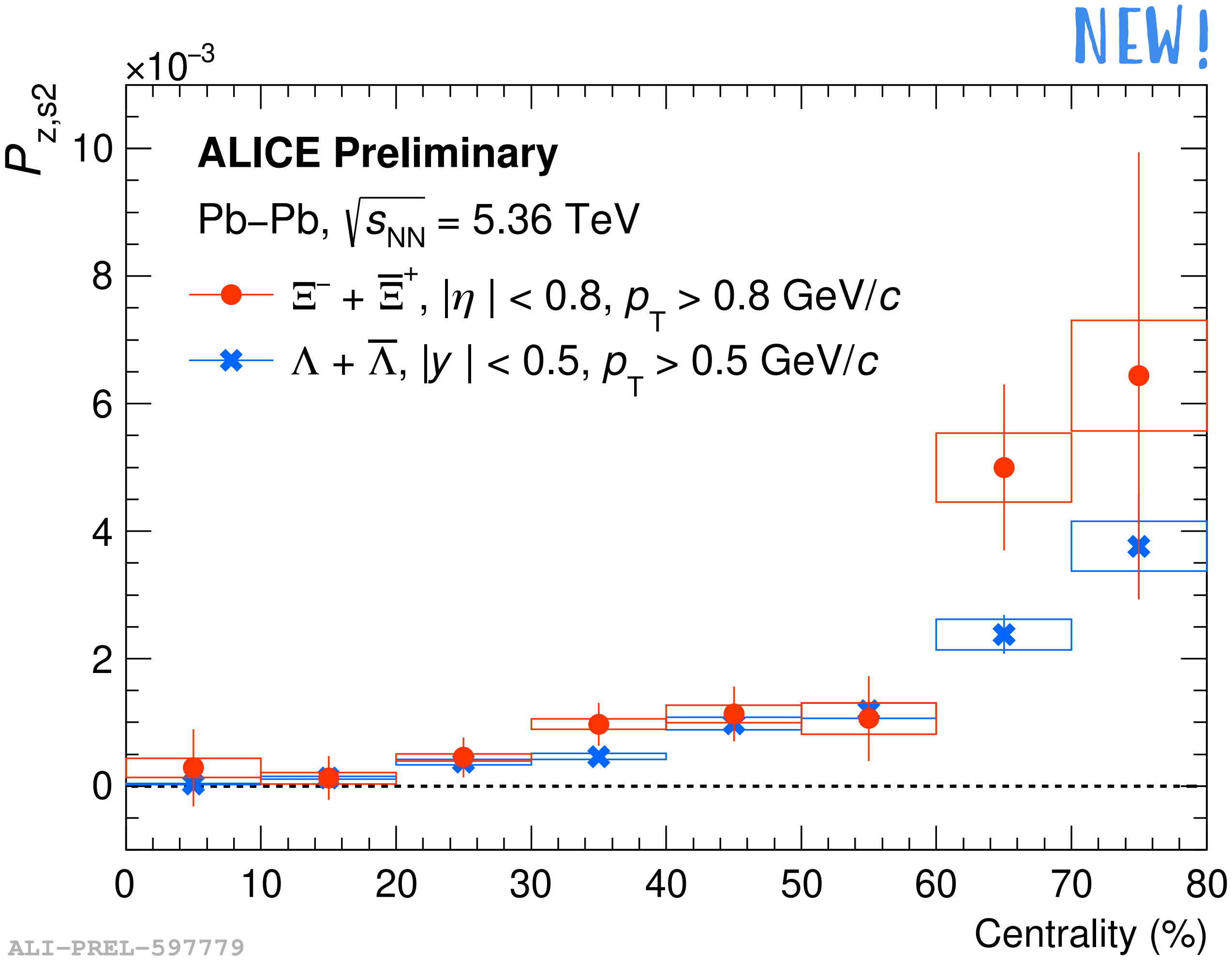
NEW!



The **first measurement of Ξ longitudinal polarization** in Pb–Pb collisions was performed using a sample of $\sim 6 \times 10^9$ Pb–Pb collisions collected during the LHC Run 3 in 2023

The **Ξ longitudinal polarization** shows a **hint of increase from central to peripheral collisions** and is compatible with **Λ** one, confirming the **spin hierarchy** $(s_\Lambda = s_\Xi = 1/2)$

Longitudinal polarization of Ξ in Run 3



The **first measurement of Ξ longitudinal polarization** in Pb–Pb collisions was performed using a sample of $\sim 6 \times 10^9$ Pb–Pb collisions collected during the LHC Run 3 in 2023

The **Ξ longitudinal polarization** shows a **hint of increase from central to peripheral collisions** and is compatible with **Λ** one, confirming the **spin hierarchy** ($s_\Lambda = s_\Xi = 1/2$)

The analysis of 2024 data will allow us:

- to **reduce the statistical uncertainty**
- to test the spin hierarchy by measuring **Ω polarization** ($s_\Omega = 3/2$)

Summary and outlook

- **The longitudinal polarization of Λ** induced by elliptic flow was measured with **improved precision** using Run 3 data, confirming the increasing trend towards more peripheral events

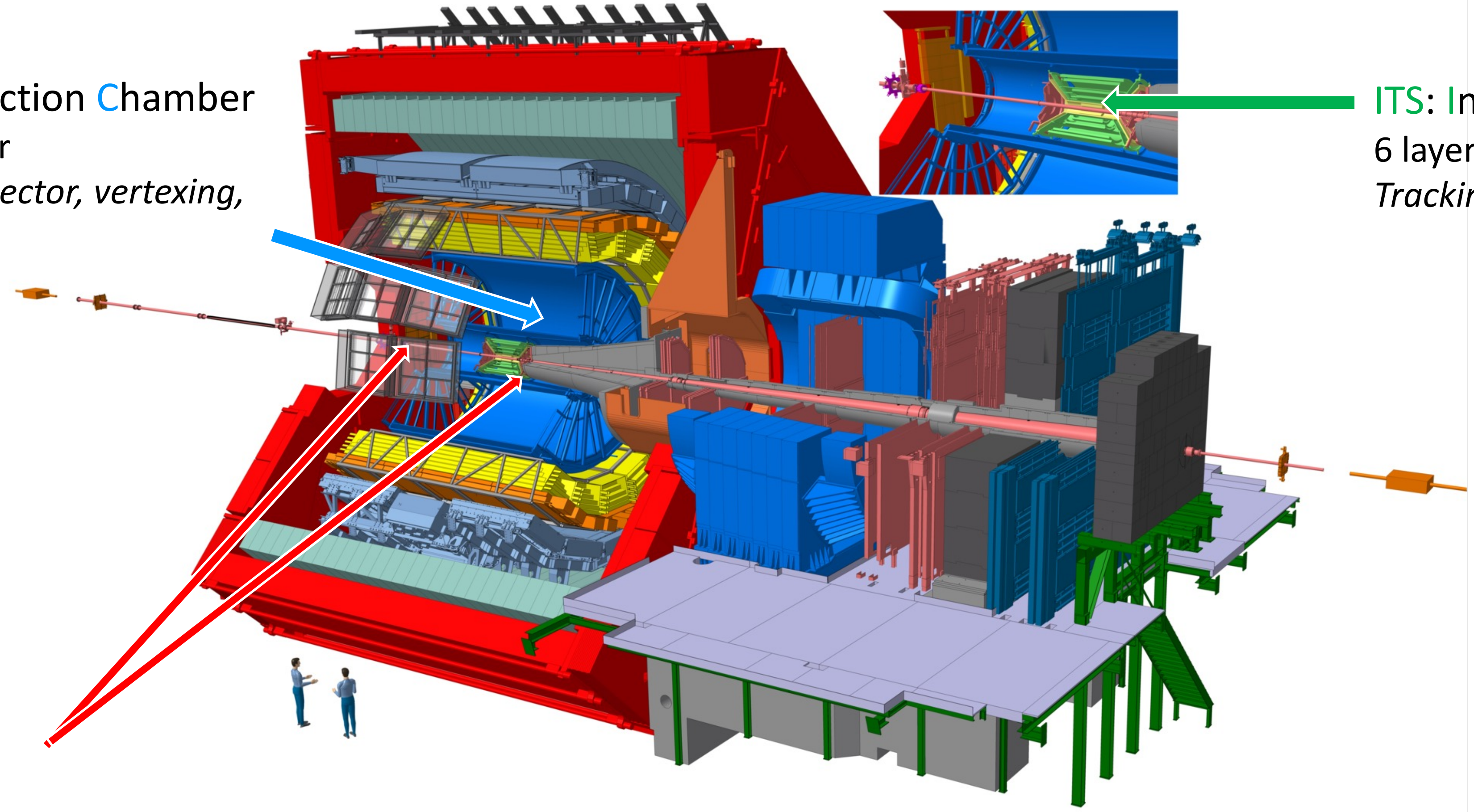
- The **first measurement** at the LHC of **Λ longitudinal polarization** induced by **triangular flow** is compatible with second-order one

- The first measurement of **Ξ longitudinal polarization** is compatible with Λ one, confirming the **spin hierarchy**

Further measurements with 2024 data:
- **azimuthal angle** and p_{T} dependence of **Ξ longitudinal polarization**
- centrality dependence of **Ω longitudinal polarization** to test the **effect of different spin**, mass and strangeness content, and to probe the **dynamics of the spin** degrees of freedom

Backup

ALICE at the LHC in Run 2



TPC: Time Projection Chamber
Gas-filled detector
Main tracking detector, vertexing, PID (dE/dx)

ITS: Inner Tracking System
6 layers of silicon detectors
Tracking, triggering, vertexing

V0A and V0C
Arrays of scintillators at forward rapidity
Triggering, event selection, centrality estimation, event plane determination

Measurement of the event plane

The second-order event plane $\vec{Q}\ (T0C)$ is determined using the T0C forward detector:

$$Q_x(T0C) = \sum_{T0C\ channels} A_{ch} \cos 2\varphi_{ch} \,/ \sum_{T0C\ channels} A_{ch}$$

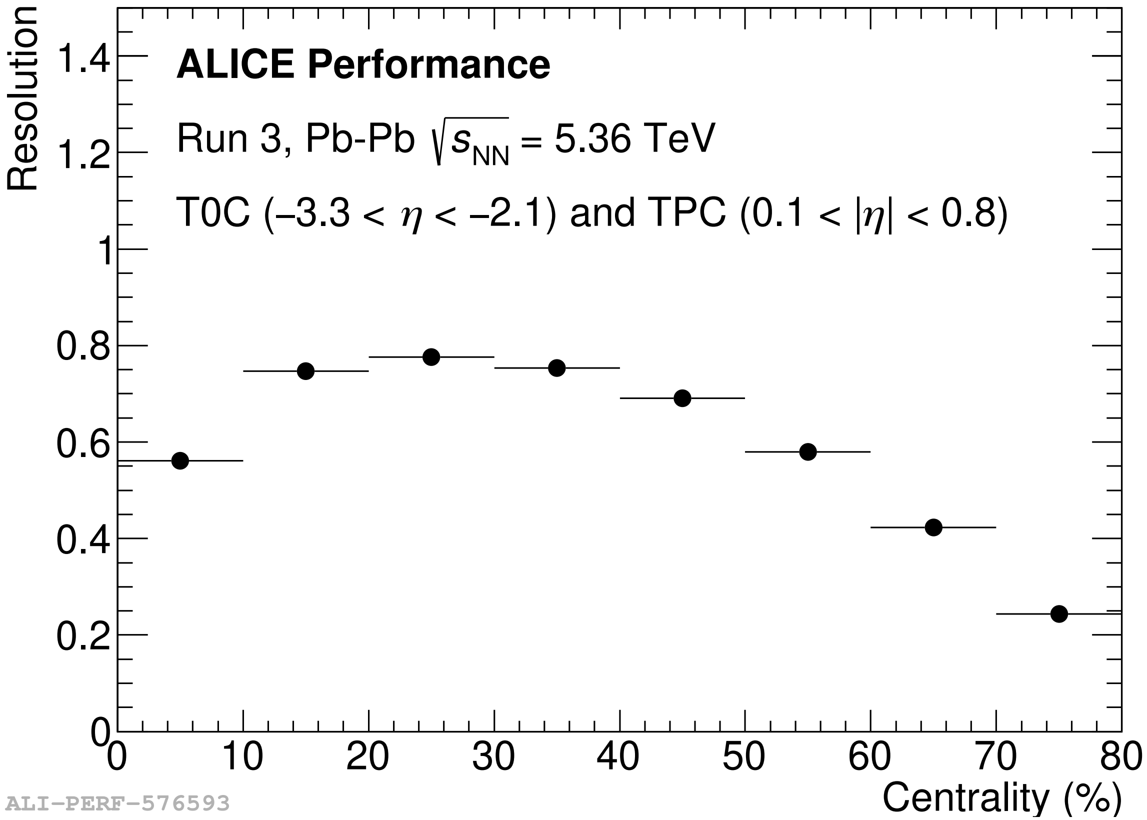
$$Q_y(T0C) = \sum_{T0C\ channels} A_{ch} \sin 2\varphi_{ch} \,/ \sum_{T0C\ channels} A_{ch}$$

where A_{ch} is the signal amplitude measured in a given T0C channel

The **event plane resolution** R_{Ψ_2} is measured using the event planes determined with forward and backward tracks in the TPC:

$$Q_x(TPC) = \sum_{Ntracks} p_{\mathrm{T},tr} \cos 2\varphi_{tr} \ /N_{tracks}$$

$$Q_y(TPC) = \sum_{Ntracks} p_{\mathrm{T},tr} \sin 2\varphi_{tr} \ /N_{tracks}$$



$$R_{\Psi_2} = \sqrt{\frac{\langle \overrightarrow{Q_{T0C}} \cdot \overrightarrow{Q_{TPCa}} \rangle \langle \overrightarrow{Q_{T0C}} \cdot \overrightarrow{Q_{TPCc}} \rangle}{\langle \overrightarrow{Q_{TPCa}} \cdot \overrightarrow{Q_{TPCc}} \rangle}}$$

Experimental technique for Ξ polarization measurements

Λ decay parameter describing the parity-violating weak decay $\Lambda \rightarrow p\pi^-$

Polar angle of the proton in the Λ rest frame

Azimuthal modulation of polarization with respect to the second-order event plane

$$P^{\Xi}_{z,s2} = \frac{1}{R_{\Psi_2}\, f_{\Xi}\, C_{\Xi\Lambda}} \left\langle \frac{1/\alpha_{\Lambda} \cos\theta^{*}_{\mathrm{p}} \cdot \sin\left(2(\varphi_{\Xi} - \Psi_2)\right)}{\langle \cos^2 \theta^{*}_{\mathrm{p}} \rangle} \right\rangle$$

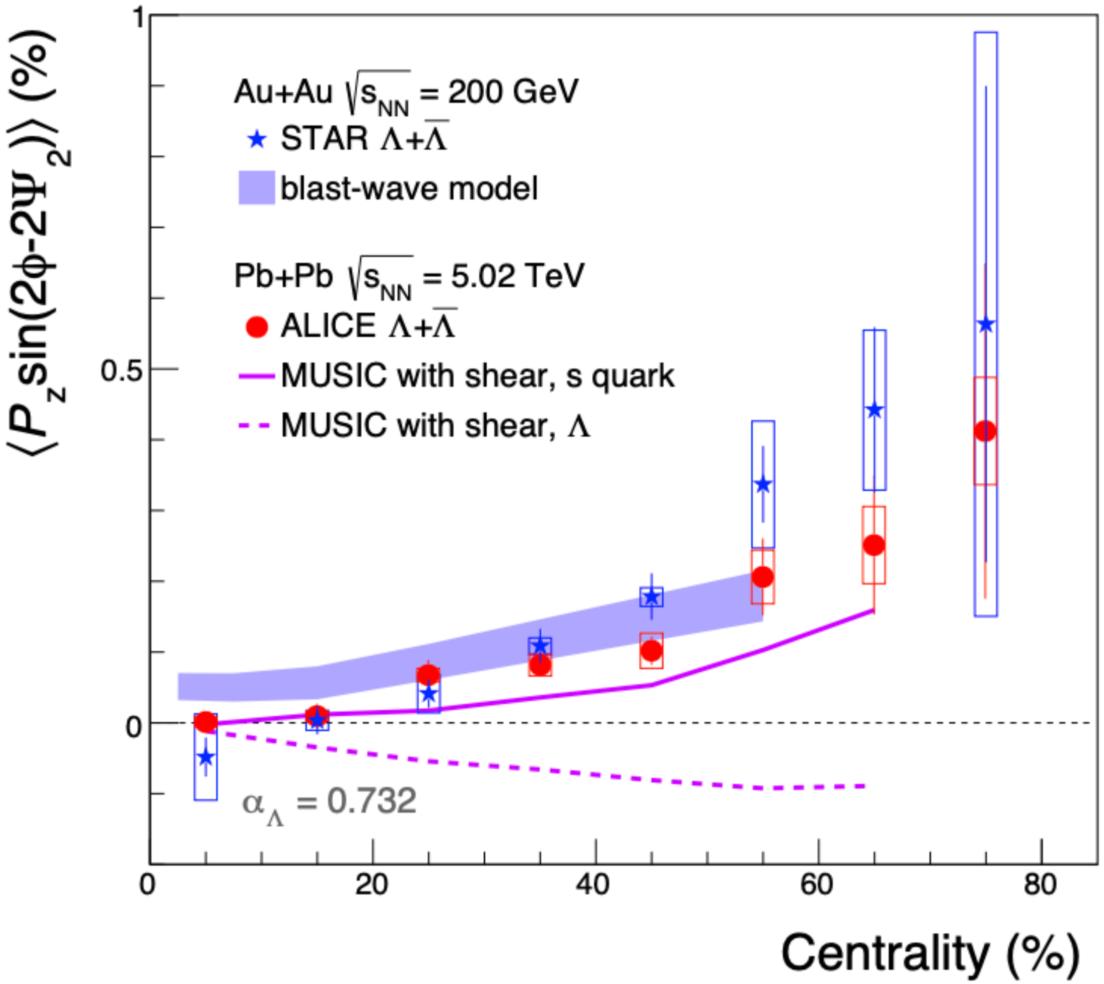
Detector acceptance

Second-order event plane resolution

Polarization transfer coefficient from Ξ to Λ ($C_{\Xi\Lambda} = 0.925$)

Ξ purity (~0.95)

Longitudinal polarization of Λ in Run 2

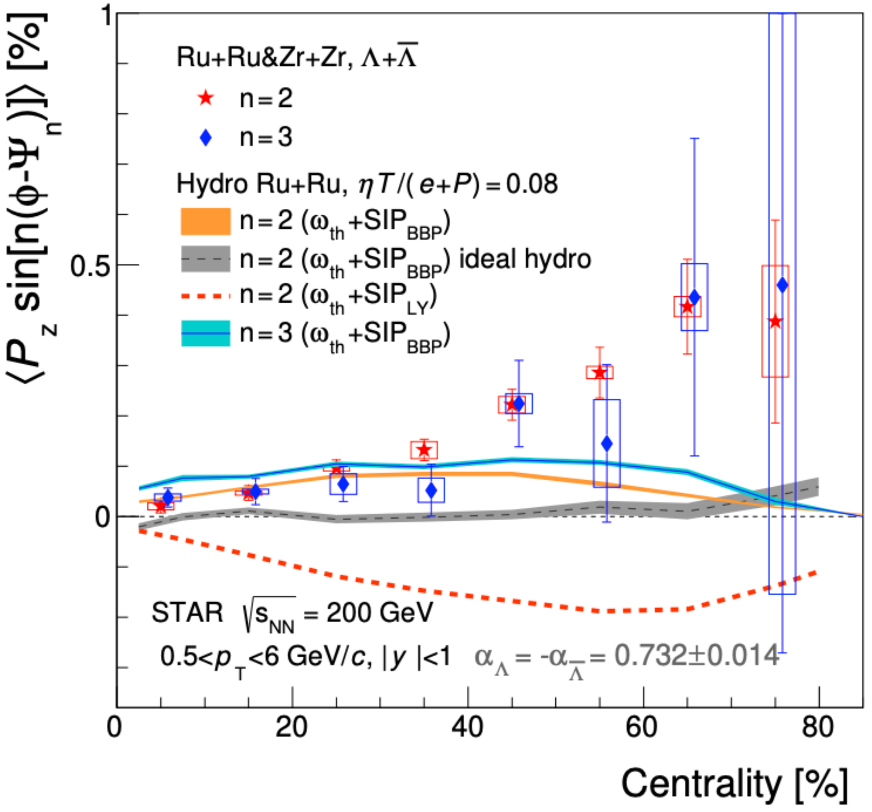


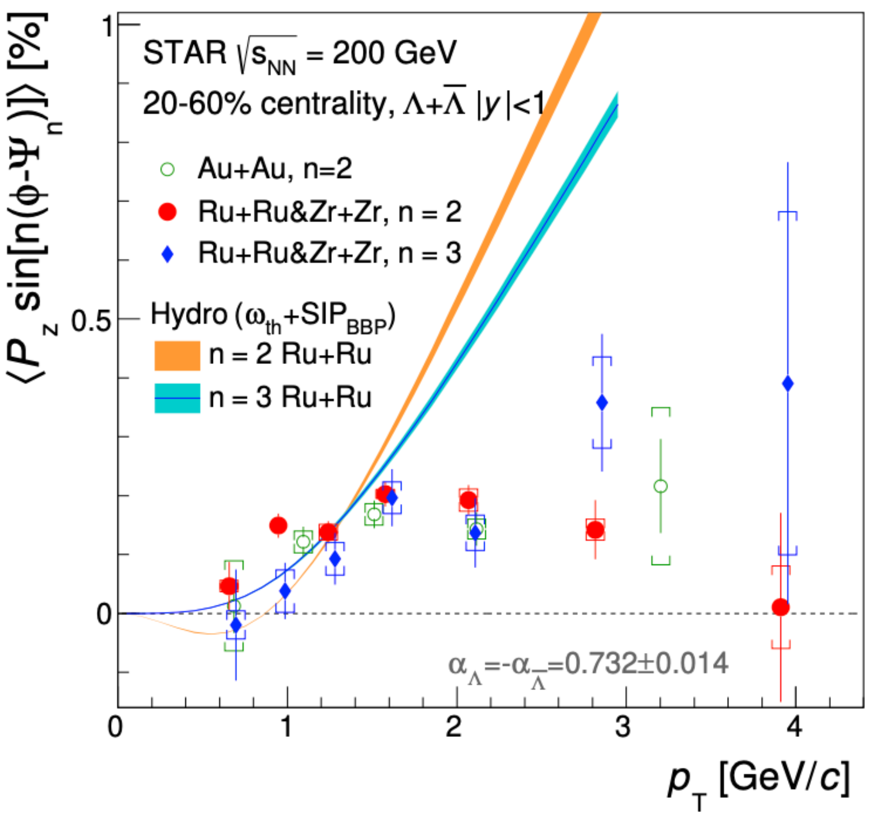
- $P_{z,s2}$ **increases with from central to peripheral collisions,** likely due to increasing system anisotropy
- The comparison with STAR measurement in Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV shows a **weak collision energy dependence**
- **3+1 D hydro model MUSIC + AMPT initial conditions** predicts correct sign polarisation if shear-induced polarisation is included and the hyperon inherits quark s polarisation at the hadronisation stage

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

ALICE, PRL 128 (2022) 172005 – STAR, PRL 123 (2019)132301 – S. Voloshin and T. Niida, Phys. Rev. C 94 (2016) 021901(R)

Second- and third-order Λ polarization at RHIC





- The third-order polarization seems to **increase towards peripheral collisions** as the second-order one
- The **p_T trend is similar to the elliptic and triangular flow** → supports the picture of anisotropic-flow-driven polarization
- The calculations from [1] describe the data fairly well except for peripheral collisions and at high p_T

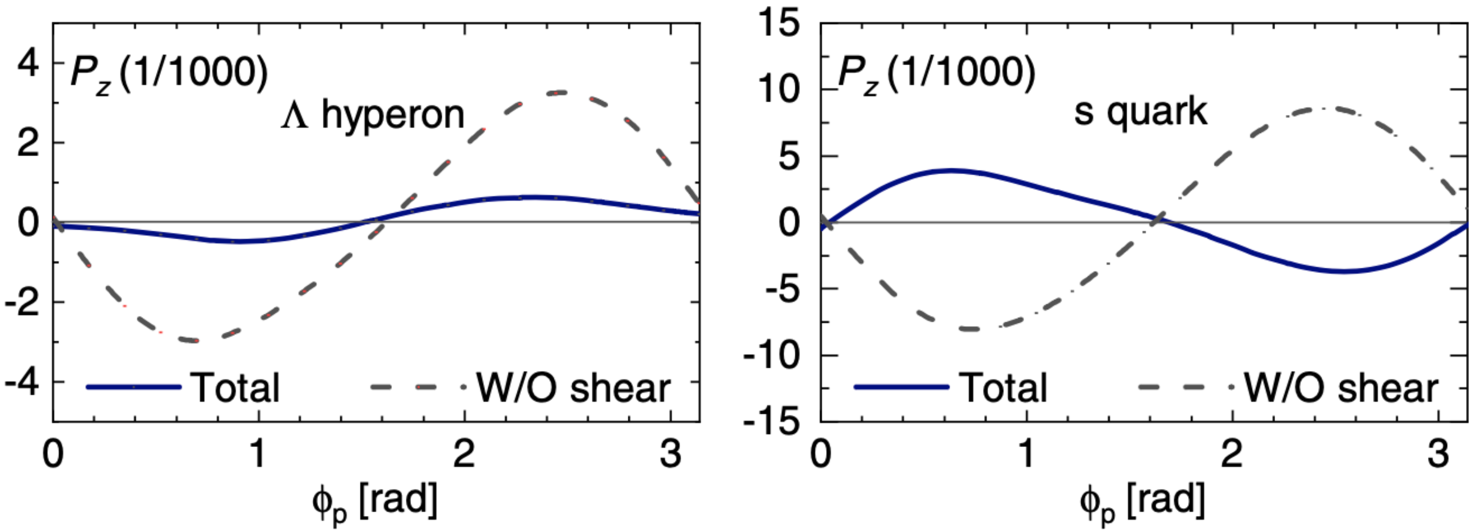
[1] Phys. Lett. B 820, 136519 (2021)

STAR, PRL 131 (2023) 202301

Studying QGP with hyperon polarization

The polarization along the beam axis is sensitive to:

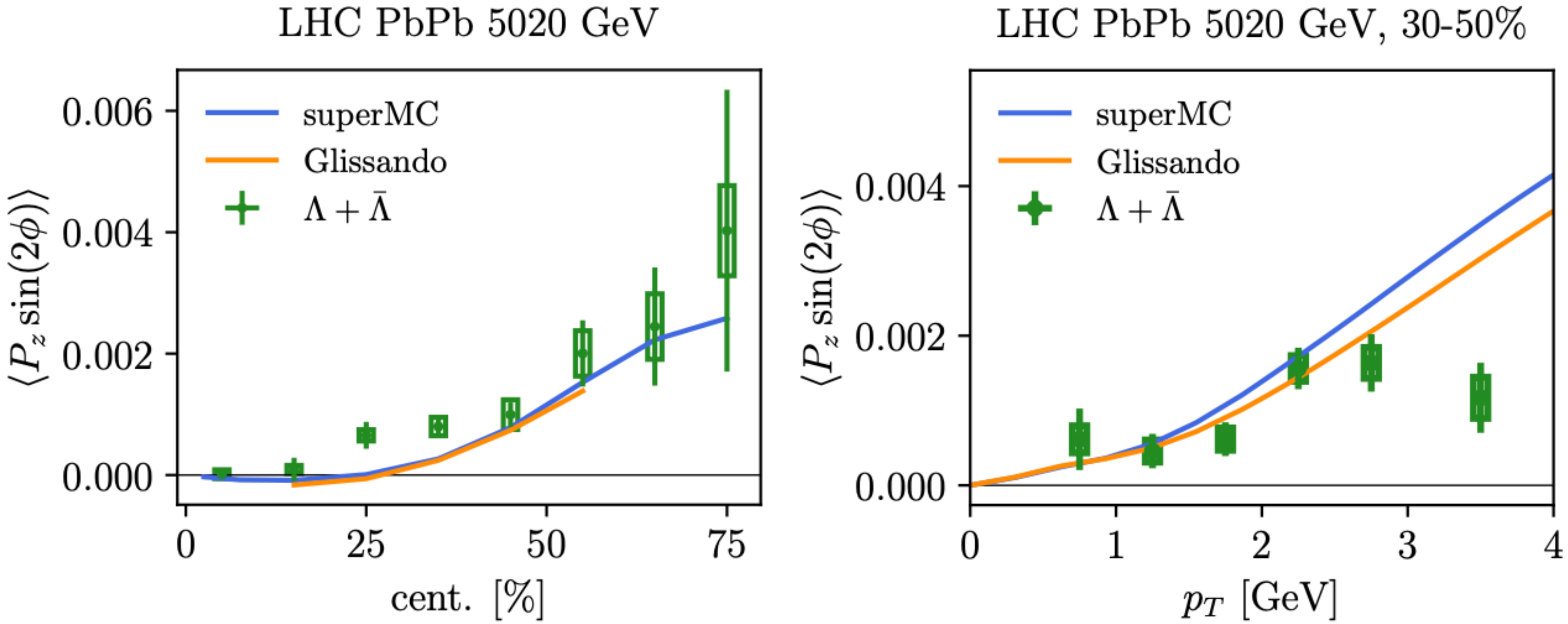
- the contribution from **shear-induced polarization (SIP),** whose origin is the **motion of particles in anisotropic fluid**, and which competes with the effect of thermal vorticity
- the **dynamics of the spin** degrees of freedom



- ○ The SIP contribution competes with thermal vorticity effects
- ○ SIP contribution prevails in the scenario that **Λ inherits the strange quark spin polarisation** at the hadronisation stage → qualitative **agreement with data** (correct polarization sign)

B. Fu *et al*. PRL 127, 142301 (2021)

Comparison to model predictions

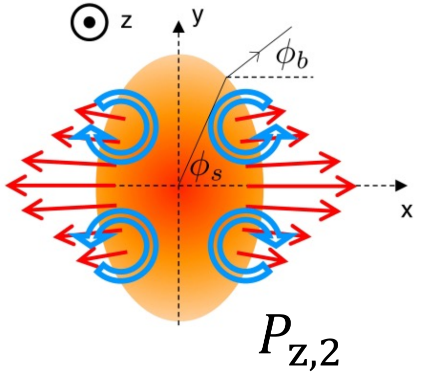


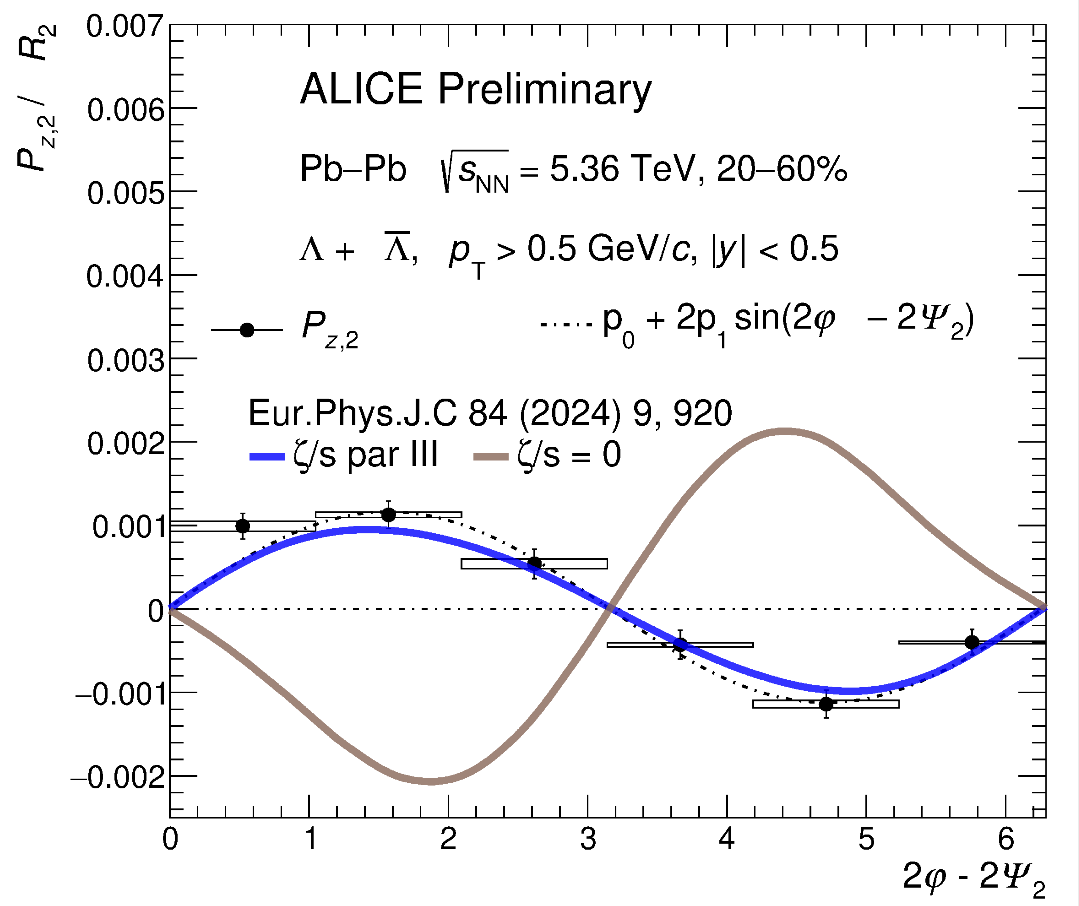
- **Good agreement** between data and models [1] if **SIP is included** and the **hadronisation hypersurface is isothermal**
- The two predictions agree with each other → longitudinal polarization is **not sensitive to the initial longitudinal velocity** at LHC energies (initialised to zero in GLISSANDO, different from zero in superMC)

[1] A. Palermo *et al.* EPJC **84**, 920 (2024)

Comparison to models

NEW!





ALI-PREL-608475

- **Good agreement** between data and model [1] including **SIP** and assuming a **temperature dependent bulk viscosity ζ/s** and an **isothermal hadronisation hypersurface**

[1] A. Palermo *et al.* EPJC **84**, 920 (2024)