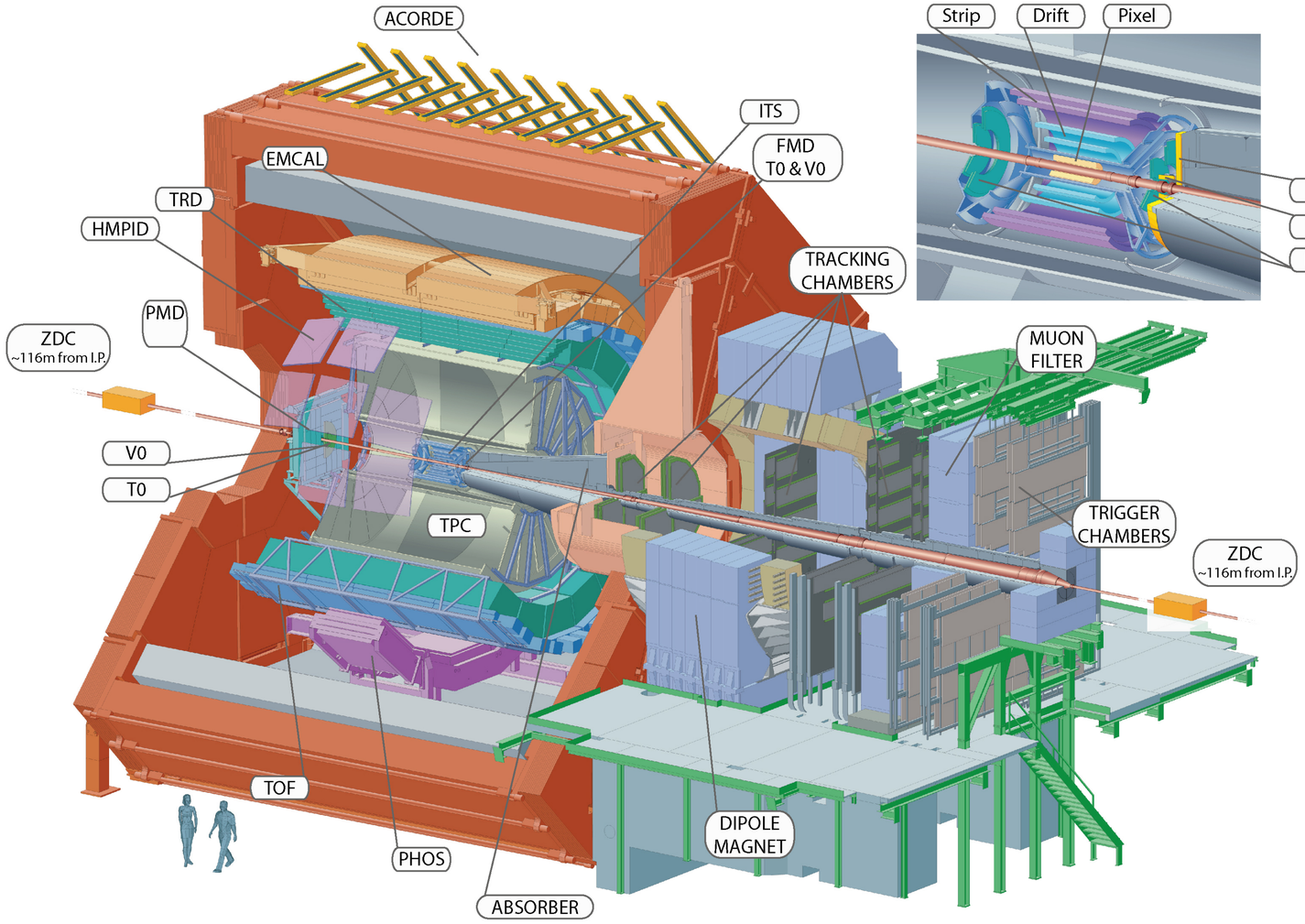
Recent highlights on polarization measurements with ALICE

Xiaoming Zhang (张晓明)

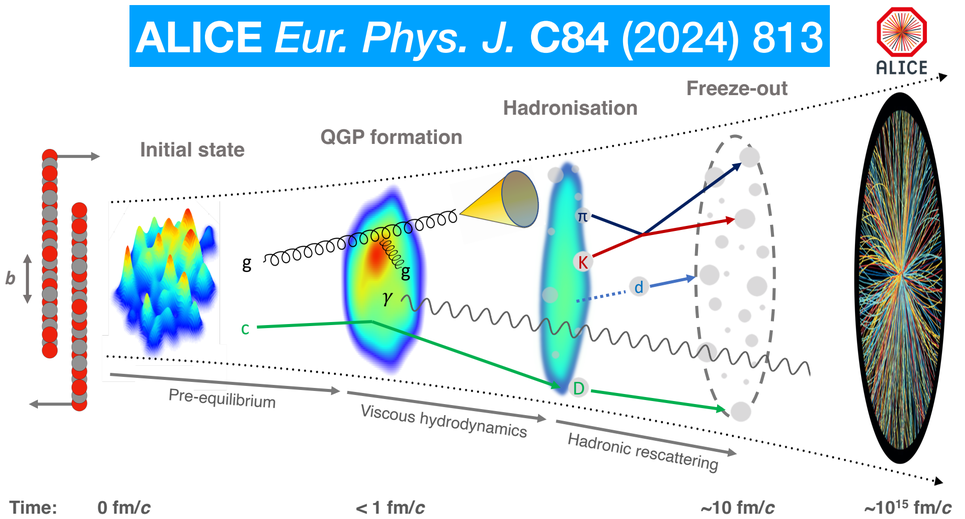
Central China Normal University

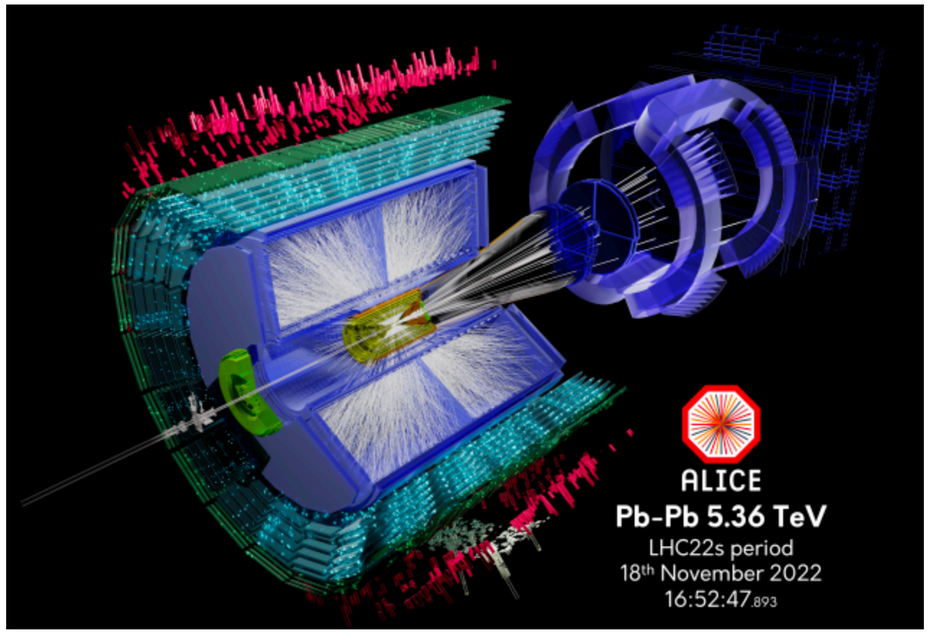
Chirality 2026, 15–21 Nov 2026, Zhuhai, China

ALICE experiment at the LHC

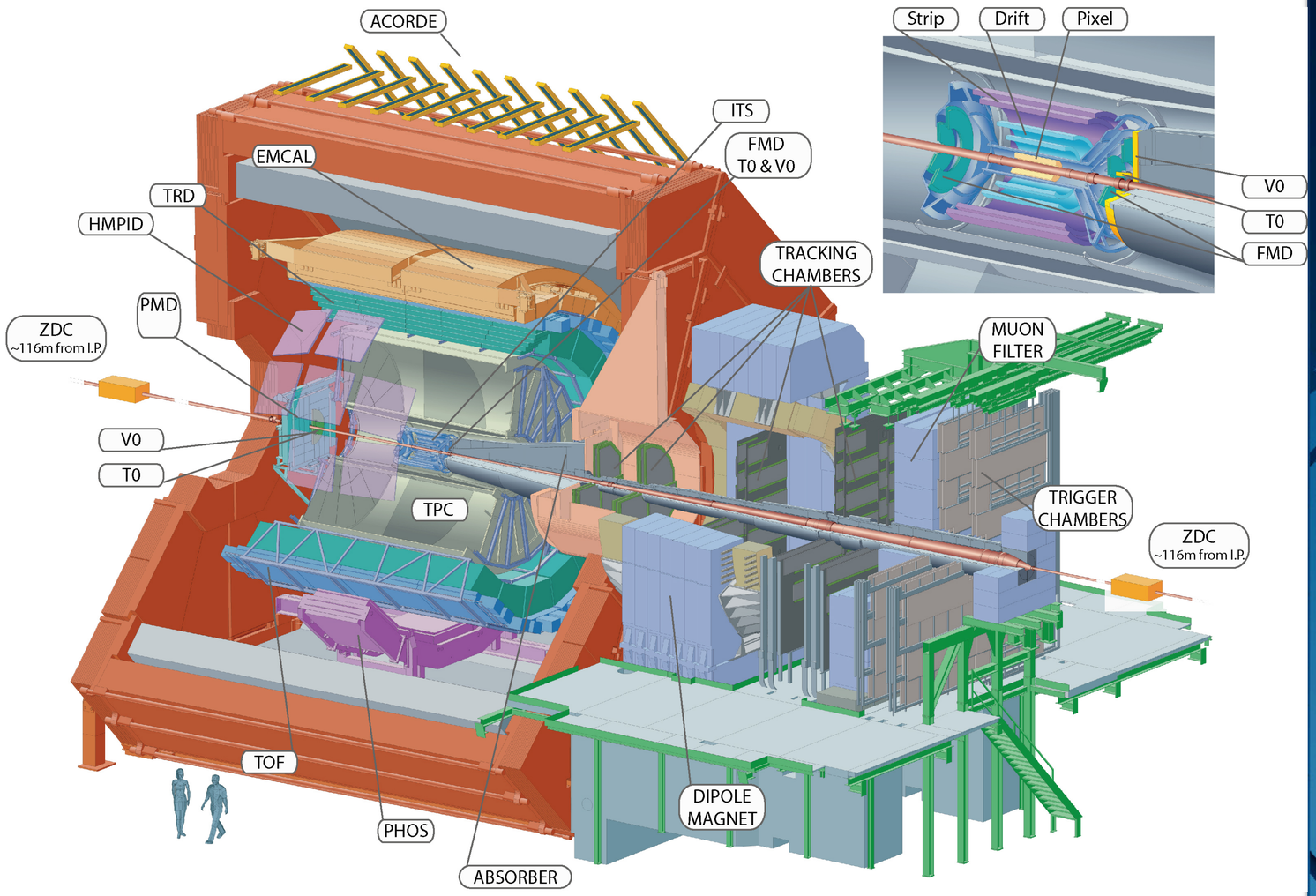


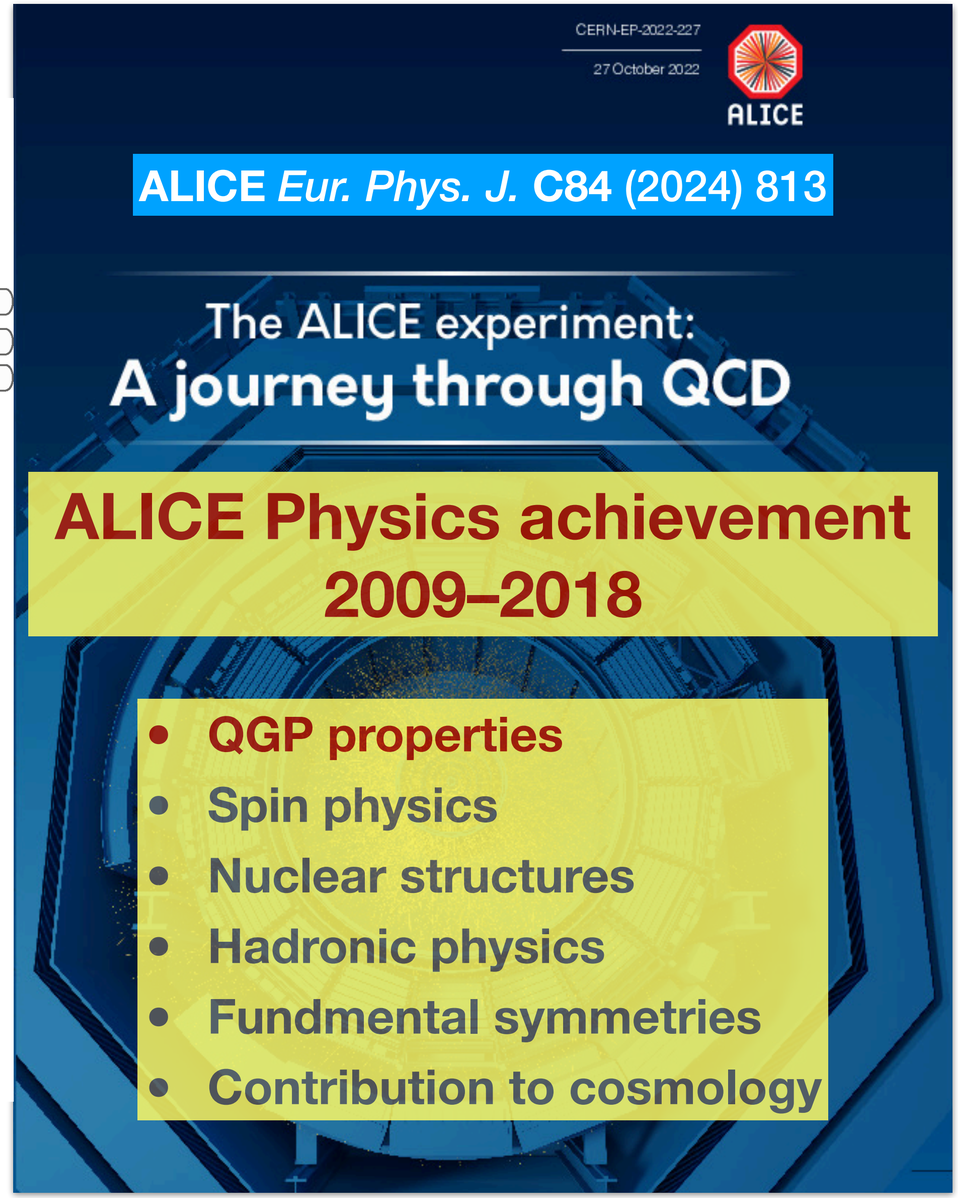
ALICE *Eur. Phys. J.* C84 (2024) 813



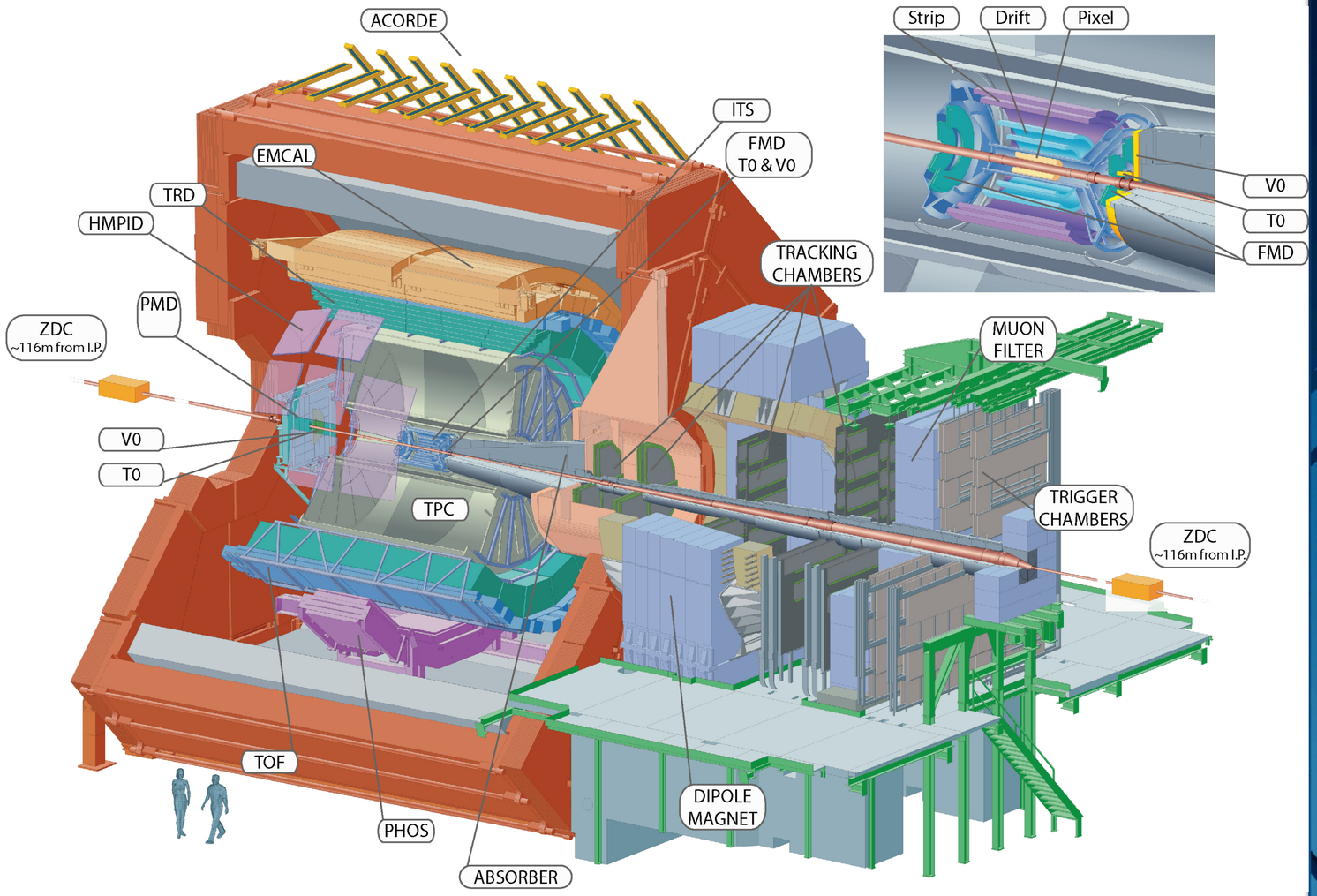


A journey through QCD





A journey through QCD



CERN-EP-2022-227

27 October 2022

ALICE

ALICE *Eur. Phys. J.* **C84** (2024) 813

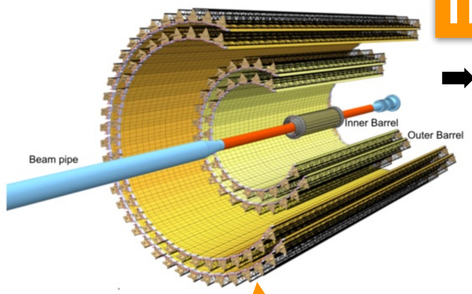
The ALICE experiment:

A journey through QCD

ALICE Physics achievement 2009–2018

- QGP properties
- ➡ Spin physics
- Nuclear structures
- Hadronic physics
- Fundmental symmetries
- Contribution to cosmology

ALICE at LHC Run 3 (2022–Jul 2026)

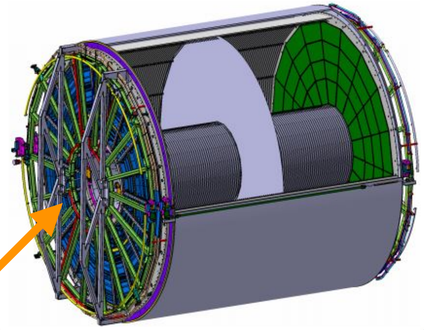


The 2nd generation inner tracking system (ITS2)

➡ 7 layers MAPS detector, the innermost layer closer to interaction point

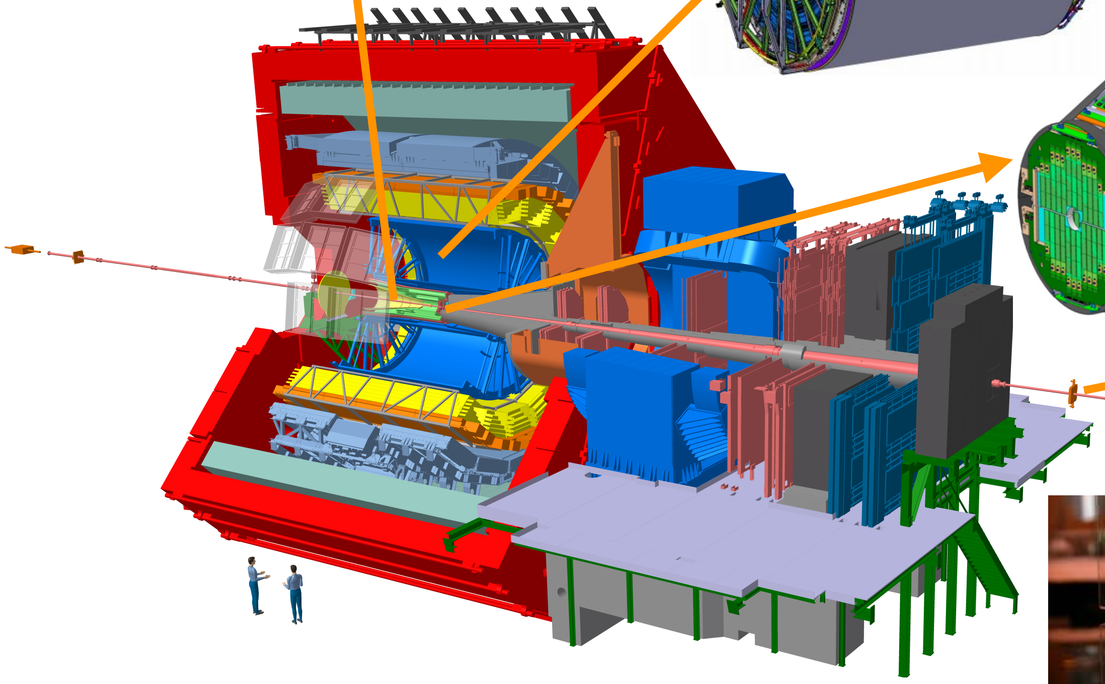
Readout of most detectors are upgraded to allow continuous readout

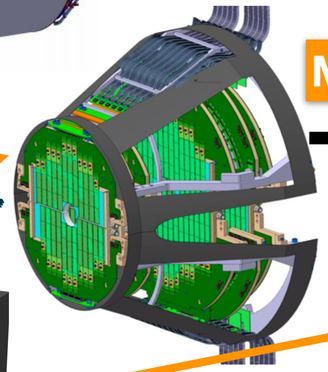
- **pp data taking at 500 kHz**
- **Pb–Pb data taking up to 50 kHz**
- **Improved vertexing**
- **Improved tracking at low p_T**



Time projection chamber (TPC)

➡ New readout: MWPC → GEM



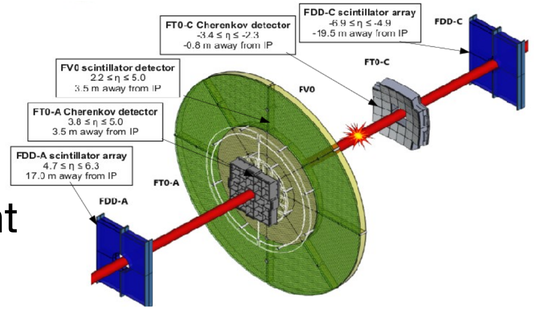


Muon forward tracker (MFT)

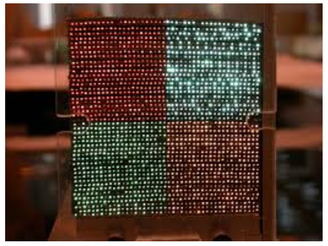
➡ 5 planes of MAPS, vertexing for forward rapidity muons

Fast integration trigger (FIT)

➡ Event trigger, luminometer, EP reconstruction

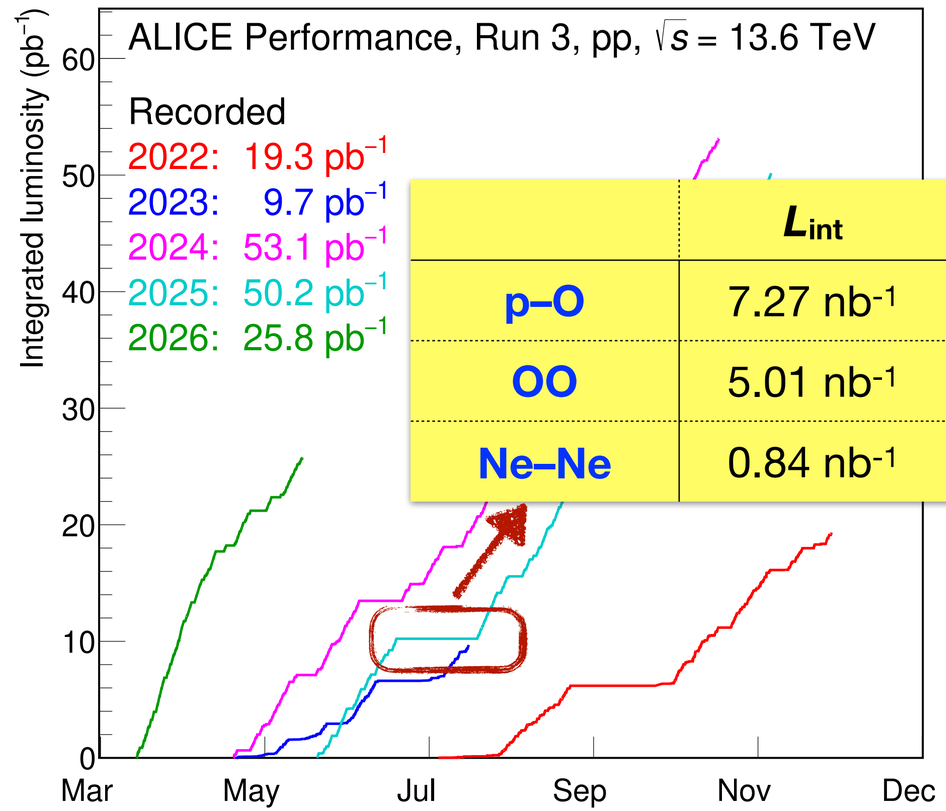


Zero-degree calorimeter (ZDC)



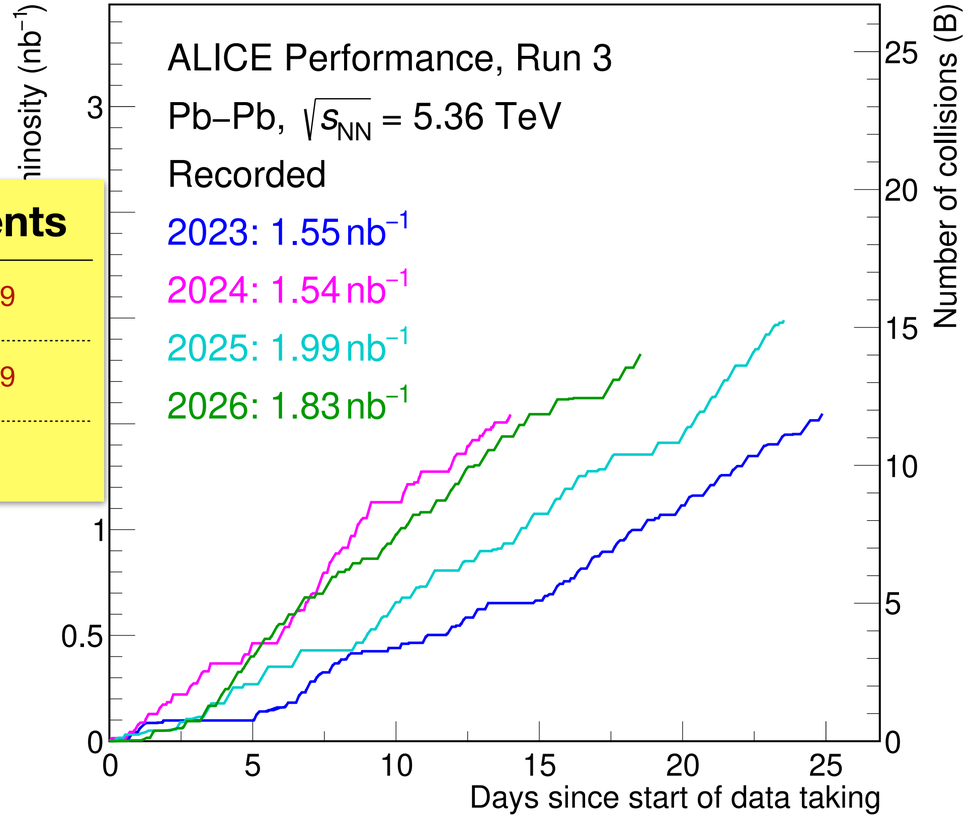
➡ First order event plane (EP) determination via measurement of spectator fragments

ALICE date taking in Run 3



	L_{int}	MB events
p–O	7.27 nb^{-1}	3×10^9
OO	5.01 nb^{-1}	6×10^9
Ne–Ne	0.84 nb^{-1}	10^9

ALI-PERF-632114



ALI-PERF-634120

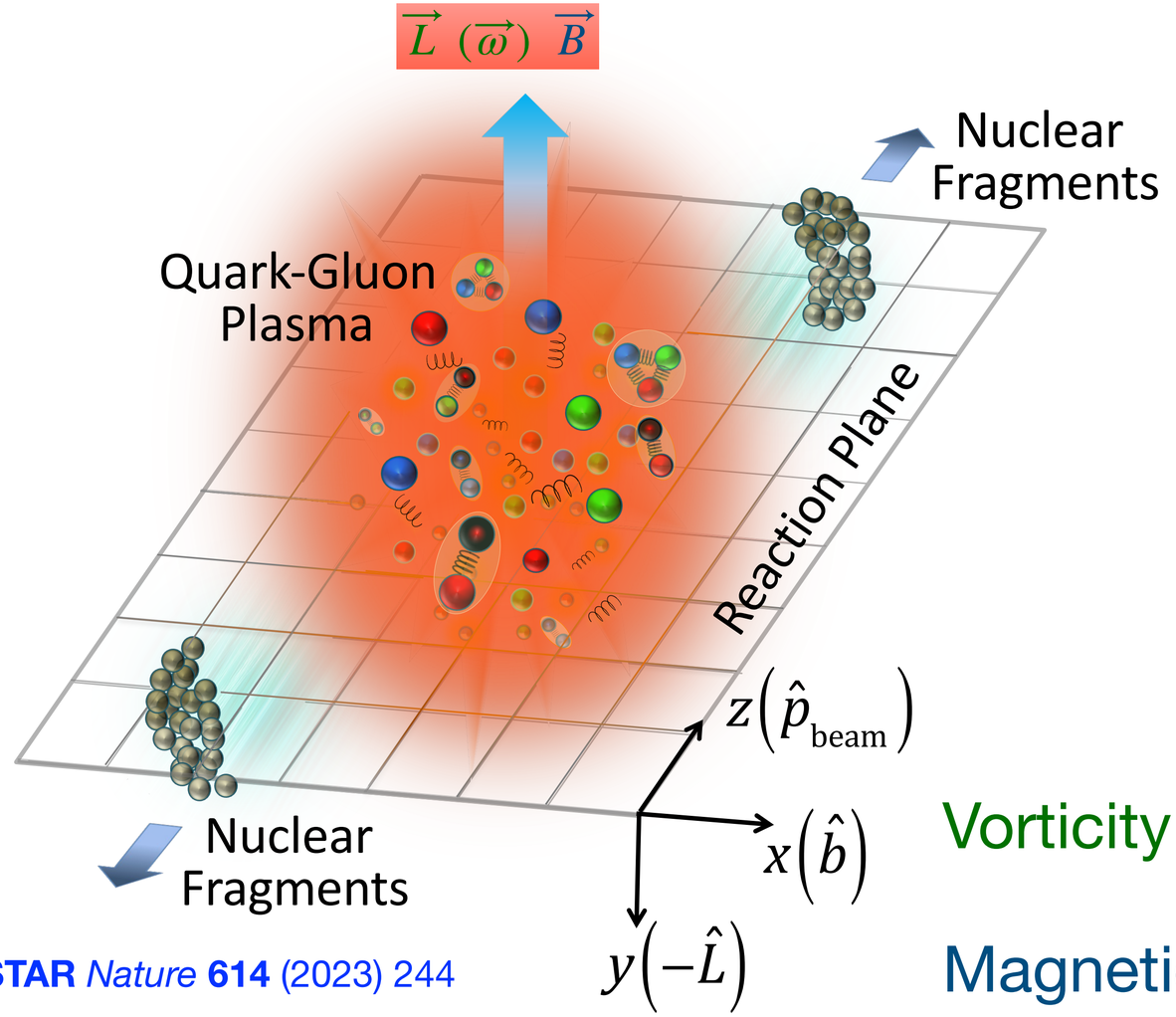
pp: 8 trillion MB events

×2000 more than Run 1+2

Pb–Pb: 52 billion MB events

×160 more than Run 1+2

QGP in extreme fields



STAR *Nature* **614** (2023) 244

High temperature (T) limit

[F. Becattini *et al.*, *Phys. Rev.* **C95** (2017) 054902]

$$\vec{P} = \frac{\langle \vec{s} \rangle}{s} \approx \frac{s+1}{3}\frac{\vec{\omega}}{T} + \frac{\mu/s}{T}\vec{B}$$

Spin-orbit coupling [S. J. Barnett, *Phys. Rev.* **6** (1915) 239]

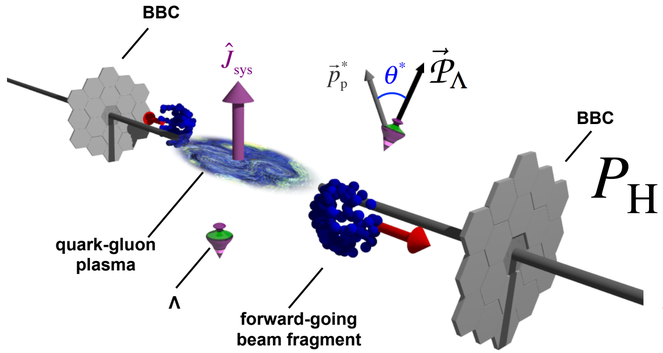
Z.-T. Liang and X.-N. Wang, *Phys. Rev. Lett.* **94** (2005) 102301

Z.-T. Liang and X.-N. Wang, *Phys. Lett.* **B629** (2005) 20

Vorticity ($\vec{\omega}$) ➡ polarization independent on charges

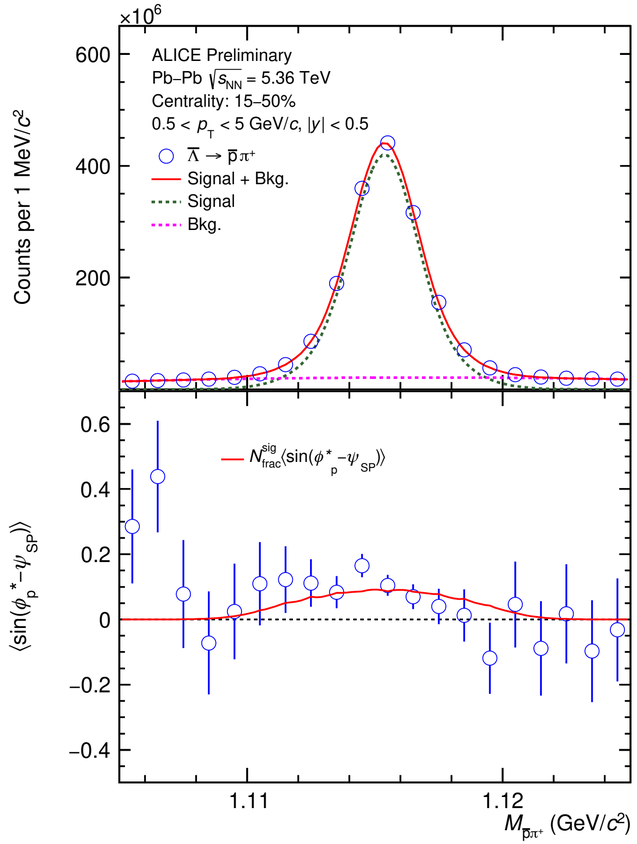
Magnetic Field ($\vec{B}$) ➡ charge-dependent polarization

Global polarization measurements



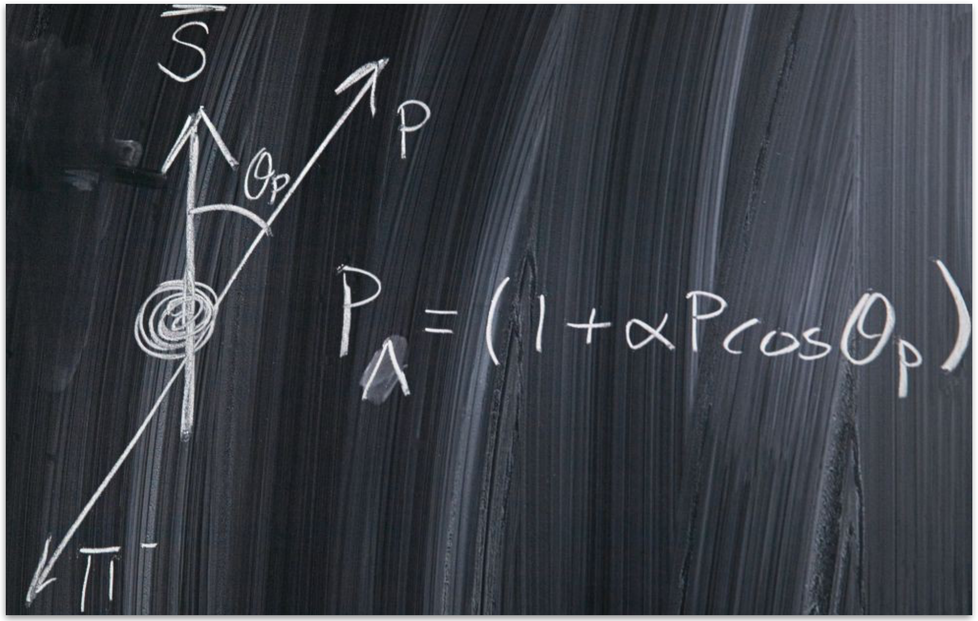
$$P_{\rm H} = -\frac{8}{\pi\alpha_{\rm H}}\frac{\langle \sin(\varphi^*_{\rm p} - \Psi^{(1)}_{\rm SP})\rangle}{R^{(1)}_{\rm SP}}$$

STAR *Nature* **548** (2017) 62



- Signal is extracted from simultaneous fit to $M_{\rm inv}$ and polarization variable distributions
- By default, polarization contribution of bkg is taken to be zero

The Feynman lectures on physics, Volume III, Chapter 17–5



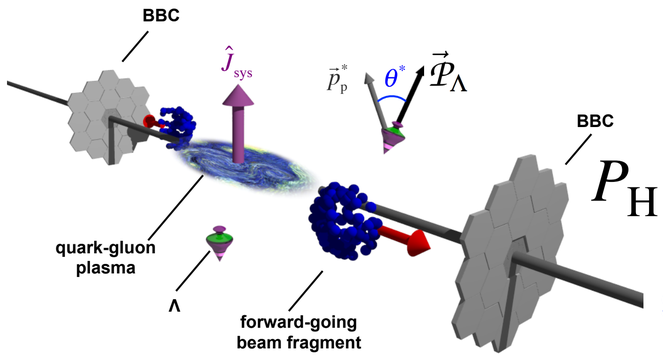
$$\frac{{\rm d}w}{{\rm d}\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\vec{P}_{\rm H}\cdot\hat{e}^*_P)$$

$$\alpha_\Lambda = 0.732 \pm 0.014 \quad \alpha_{\bar{\Lambda}} = -0.758 \pm 0.012$$

[**PDG** *Phys. Rev.* **D110** (2024) 030001]

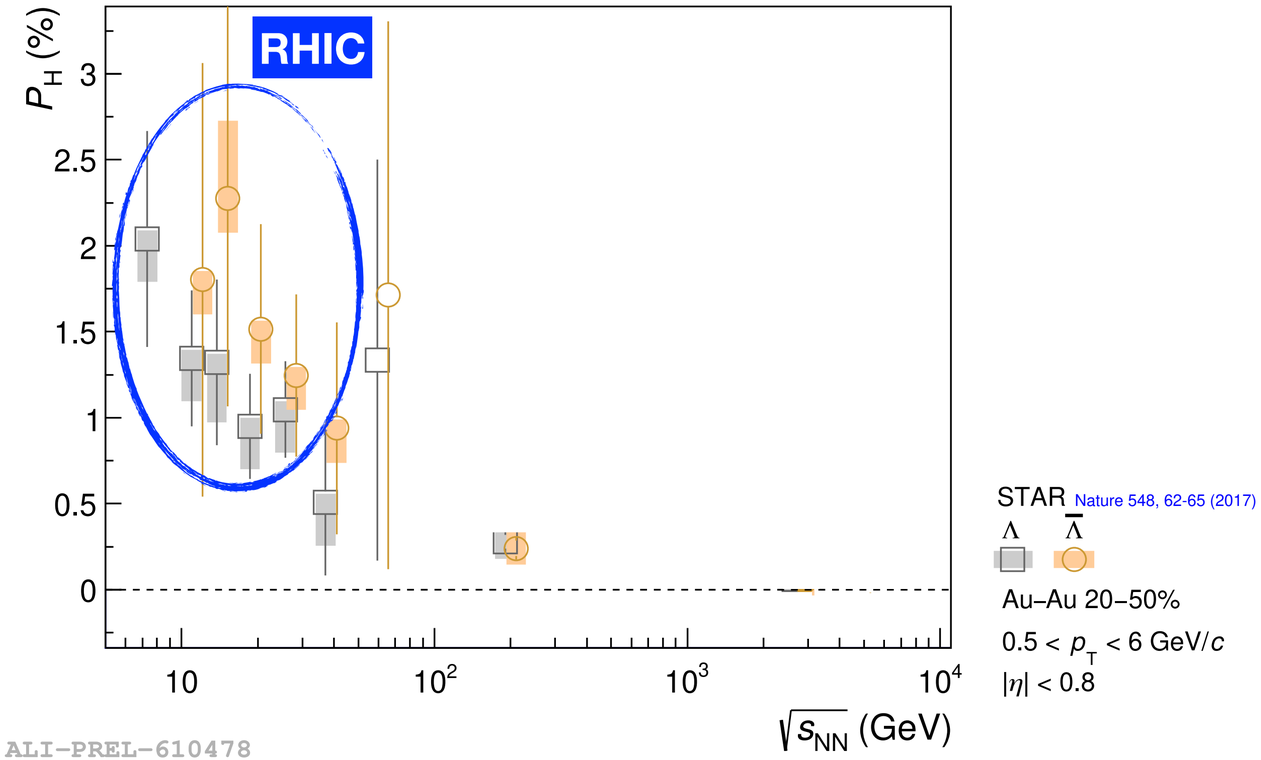
ALI-PREL-610461

Global polarization of Λ — RHIC



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

STAR *Nature* **548** (2017) 62

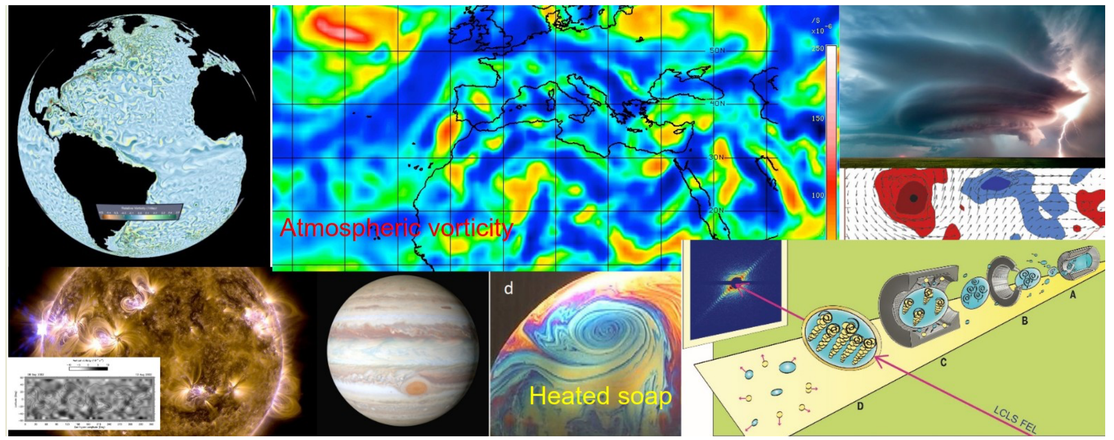


ALI-PREL-610478

Significant non-zero $P_{\rm H}$ at RHIC

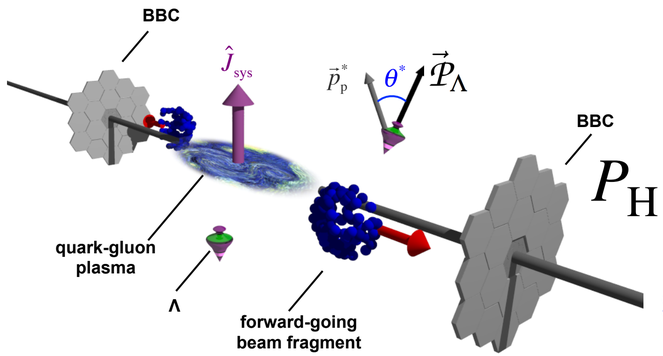
- Indicate QGP rotation ω ~ 10^{21} s^{-1}
  - ➡ Solar flow: ω ~ 10^{-6} s^{-1}
  - ➡ Jupiter's zonal winds: ω ~ 10^{-4} s^{-1}
  - ➡ Core of supercell tornado: ω ~ 10^{-1} s^{-1}
  - ➡ Superfluid He-II: ω ~ 10^{6} s^{-1}

➡ Most vortical fluid in nature



Science On a Sphere: Ocean Surface Vorticity

Global polarization of Λ — RHIC & LHC



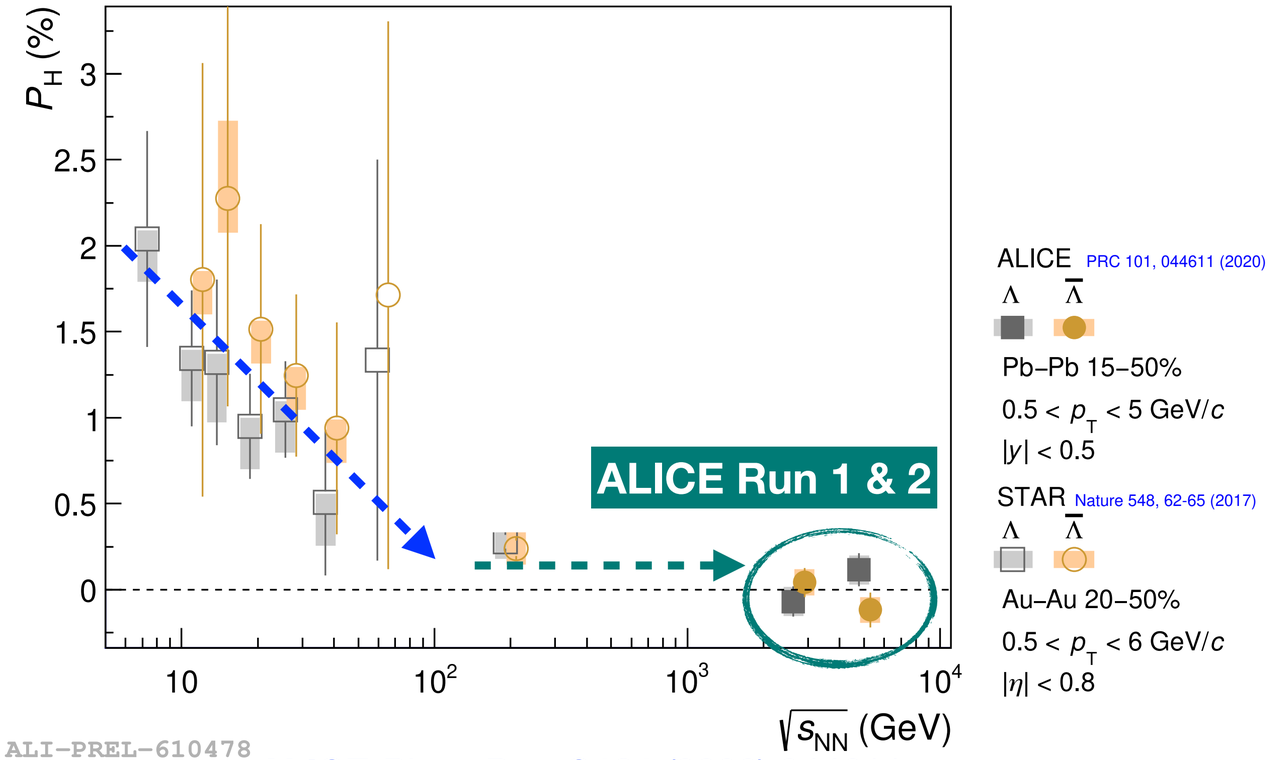
$$P_H = -\frac{8}{\pi\alpha_H}\frac{\langle \sin(\varphi^*_p - \Psi^{(1)}_{SP})\rangle}{R^{(1)}_{SP}}$$

STAR *Nature* **548** (2017) 62

ALICE Run 1 & 2

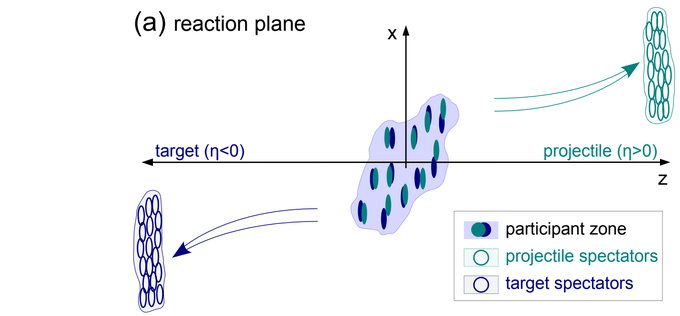
- P_H ~ 0 within large uncertainties
- Correlation of P_H and dv_1/dy

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

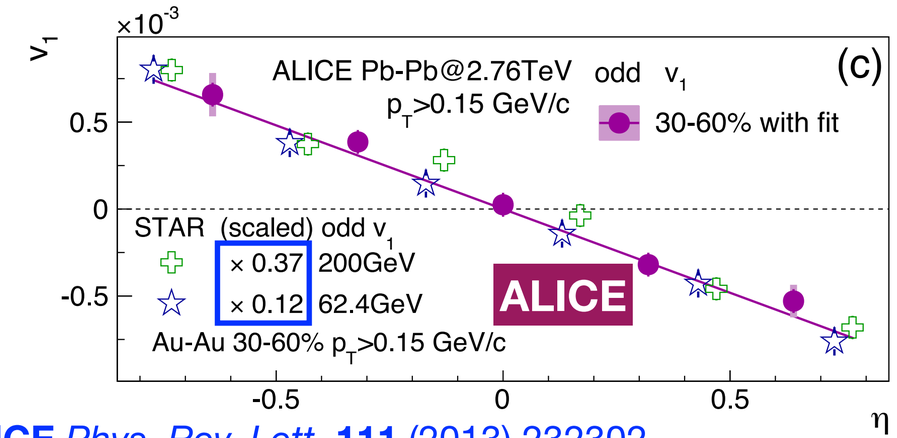


ALI-PREL-610478

ALICE *Phys. Rev.* **C101** (2020) 044611

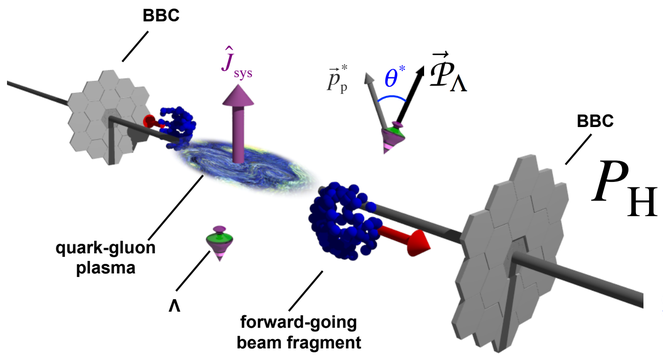


$$\omega_y = -\frac{1}{2}\frac{\partial v_z}{\partial x}$$



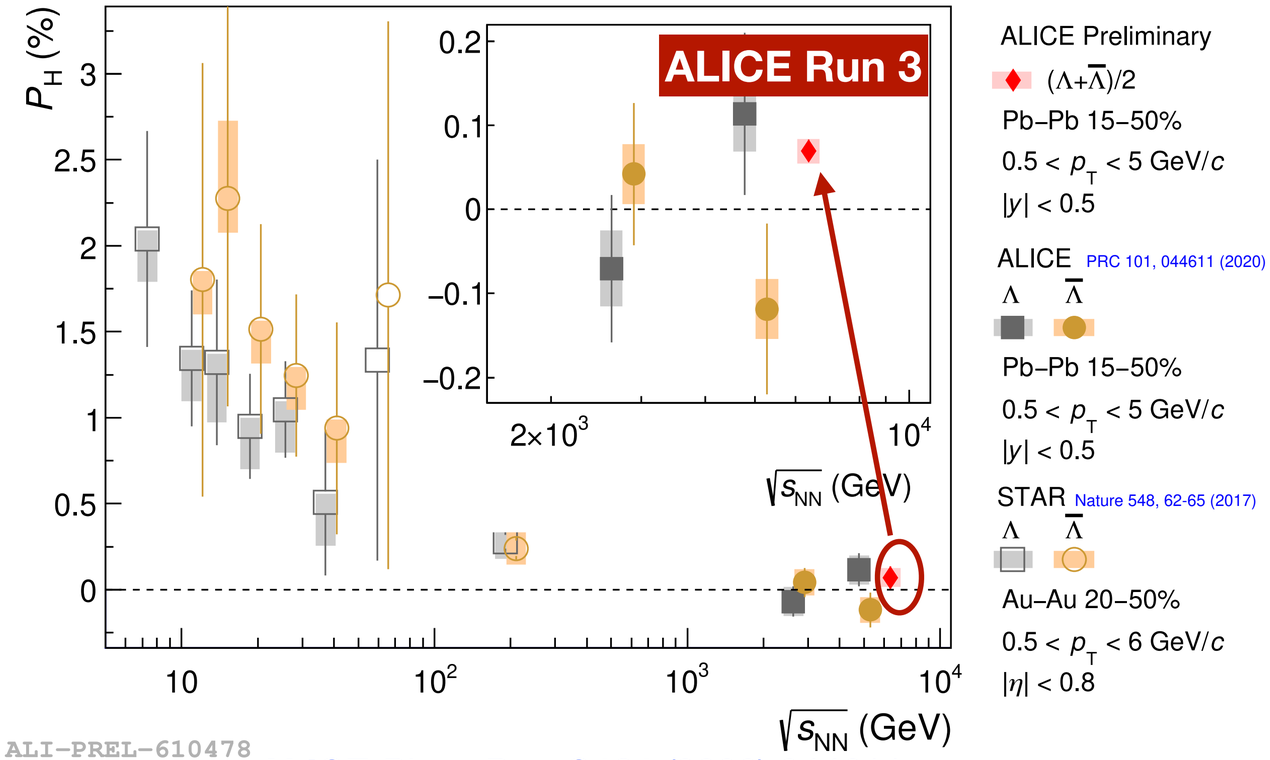
ALICE *Phys. Rev. Lett.* **111** (2013) 232302

Global polarization of Λ — New Run 3



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

STAR *Nature* **548** (2017) 62



ALICE Preliminary
$(\Lambda+\bar{\Lambda})/2$
Pb–Pb 15–50%
$0.5 < p_T < 5$ GeV/c
$|y| < 0.5$

ALICE PRC 101, 044611 (2020)
Λ $\bar{\Lambda}$
Pb–Pb 15–50%
$0.5 < p_T < 5$ GeV/c
$|y| < 0.5$

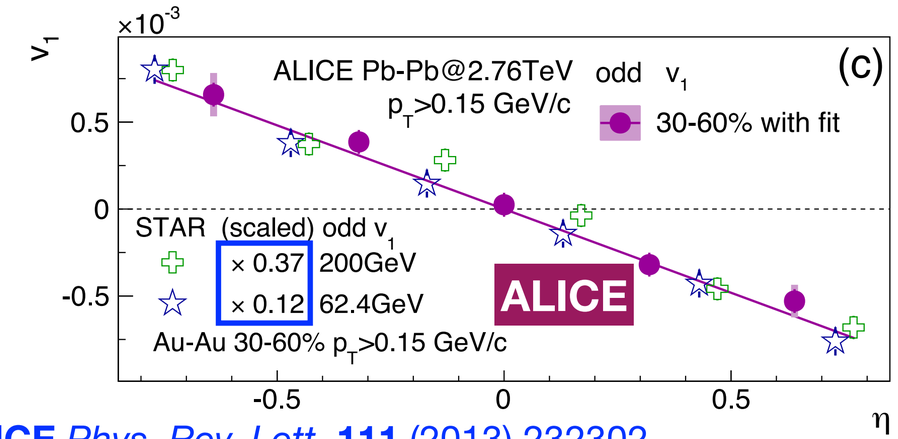
STAR Nature 548, 62-65 (2017)
Λ $\bar{\Lambda}$
Au–Au 20–50%
$0.5 < p_T < 6$ GeV/c
$|\eta| < 0.8$

ALI-PREL-610478

ALICE *Phys. Rev.* **C101** (2020) 044611

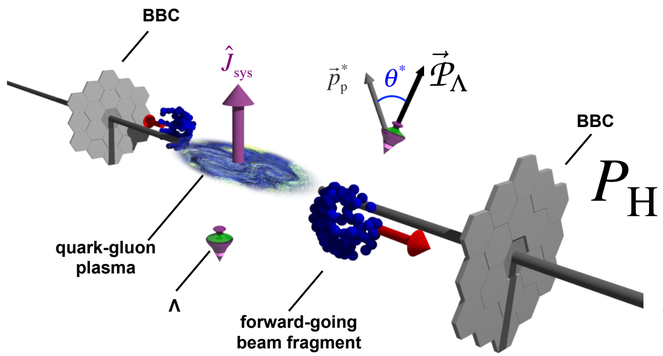
New ALICE Run 3

- First observation of polarized Λ at LHC energies with 5σ
- $\omega \sim 10^{20}$ s^{-1} at the LHC
  - ➡ $\omega \sim 10^{21}$ s^{-1} at RHIC
  - ➡ Consistent with the empirical prediction based on dv_1/dy



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

Global polarization of Λ — New Run 3



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

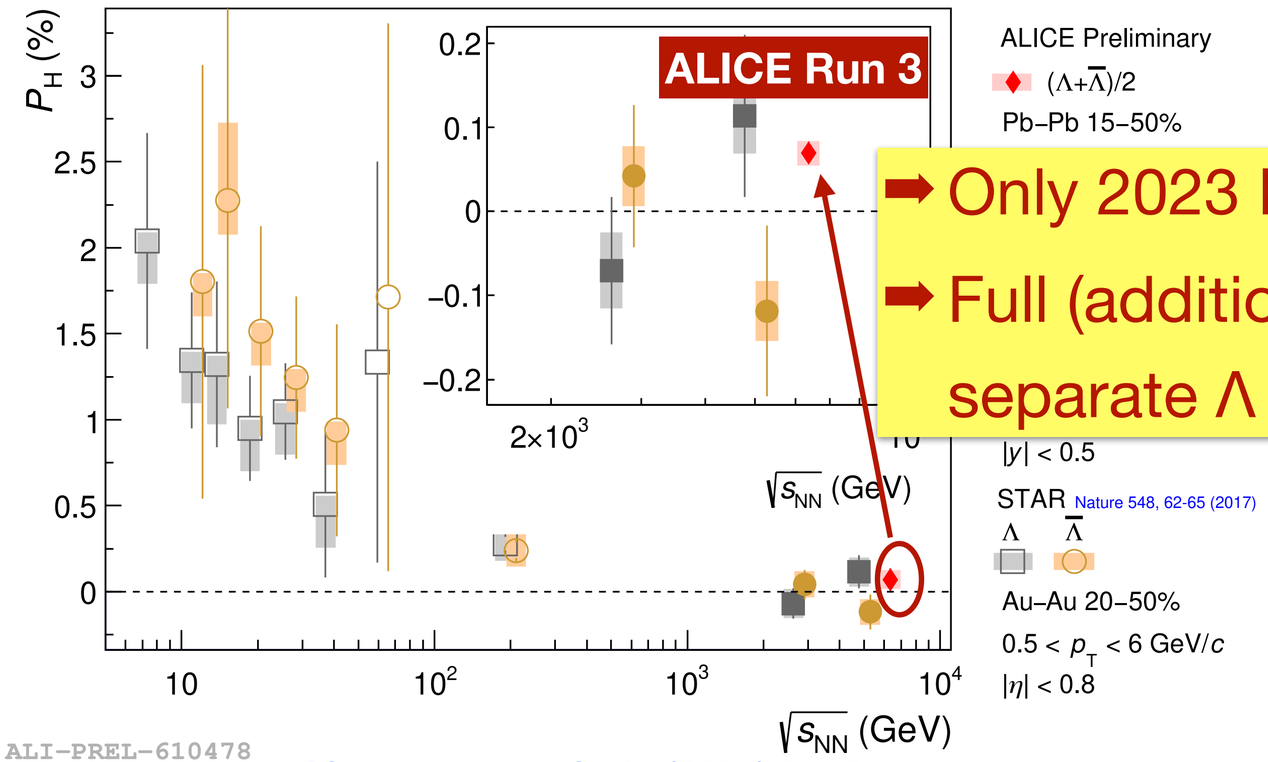
STAR *Nature* **548** (2017) 62

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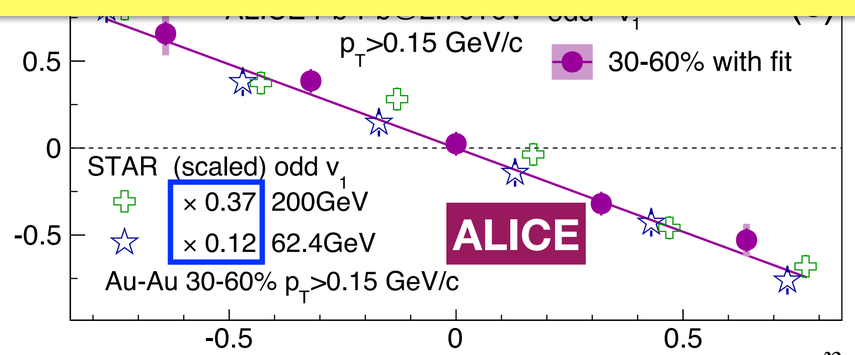
➡ Only 2023 Pb–Pb sample is used (~6×10^9 collisions)

➡ Full (addition 2024–2026) data will allow us to separate Λ and $\overline{\Lambda}$



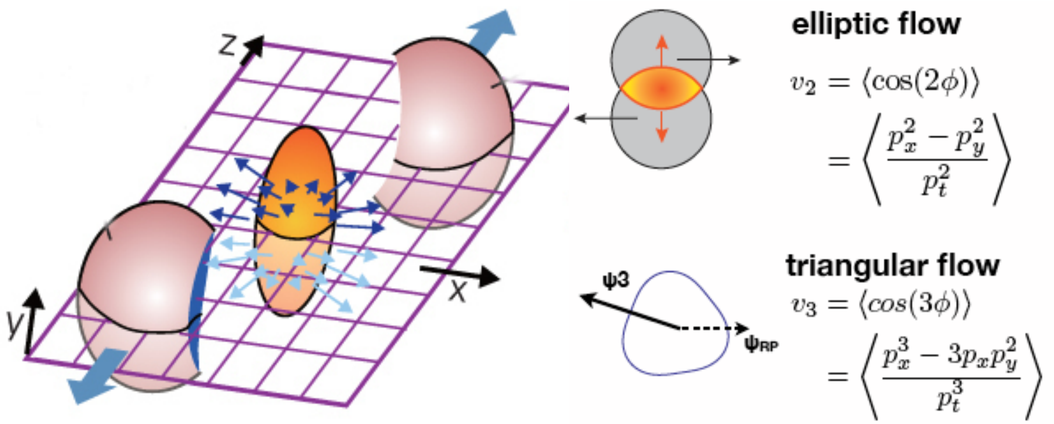
ALI-PREL-610478

ALICE *Phys. Rev.* **C101** (2020) 044611



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

Polarization along the beam direction

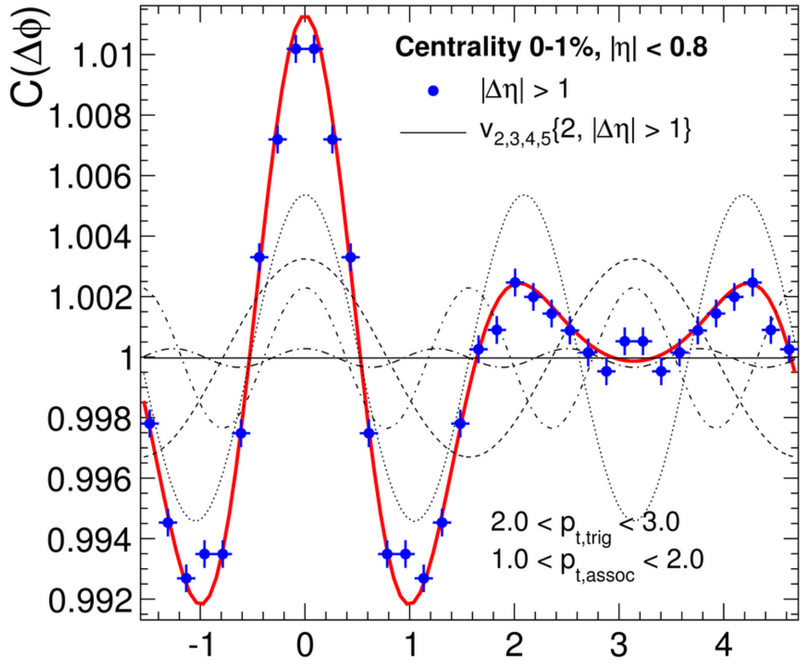


elliptic flow

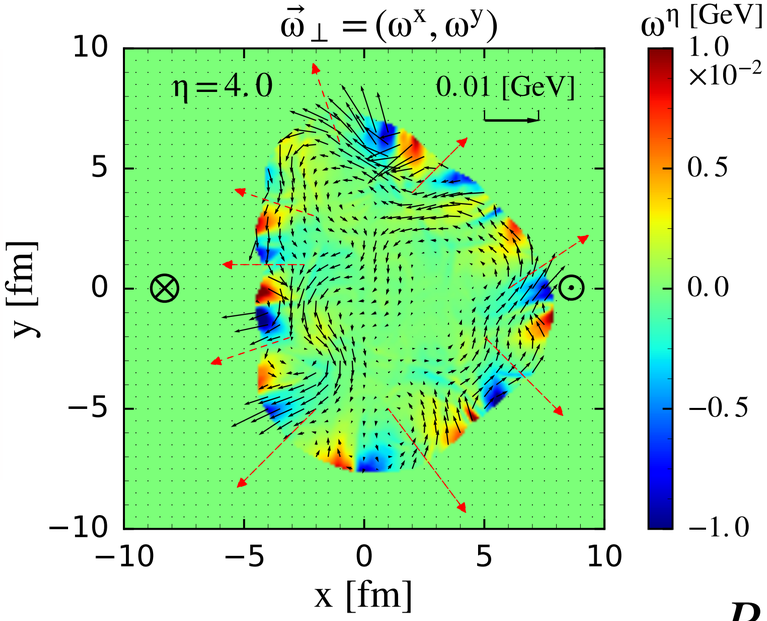
$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

triangular flow

$$v_3 = \langle \cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle$$



ALICE *Phys. Rev. Lett.* **107** (2011) 032301

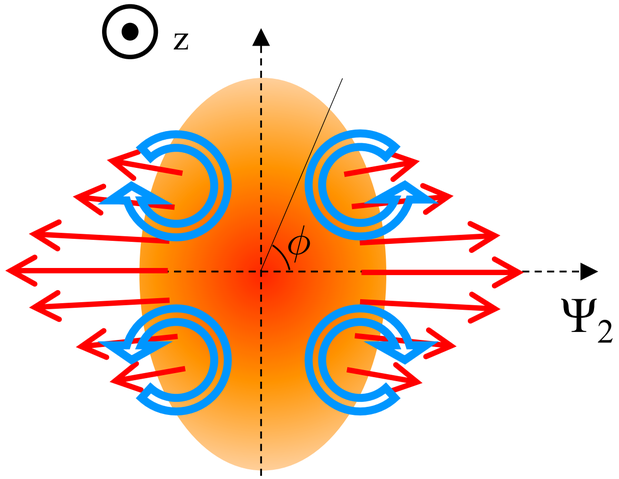


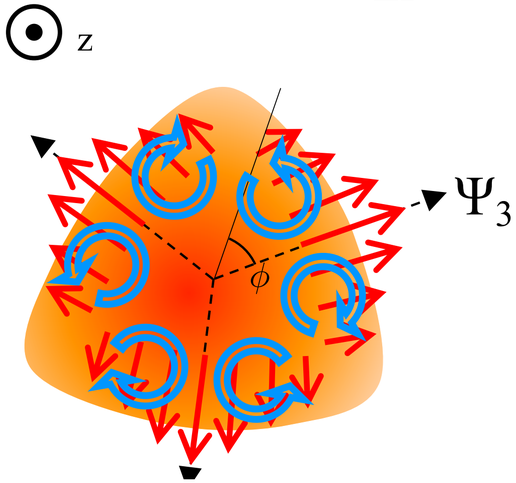
L.-G. Pang, Q. Wang, X.-N. Wang *et al.* *Phys. Rev. Lett.* **117** (2016) 192301

S. A. Voloshin, T. Niida *Phys. Rev.* **C94** (2016) 021901

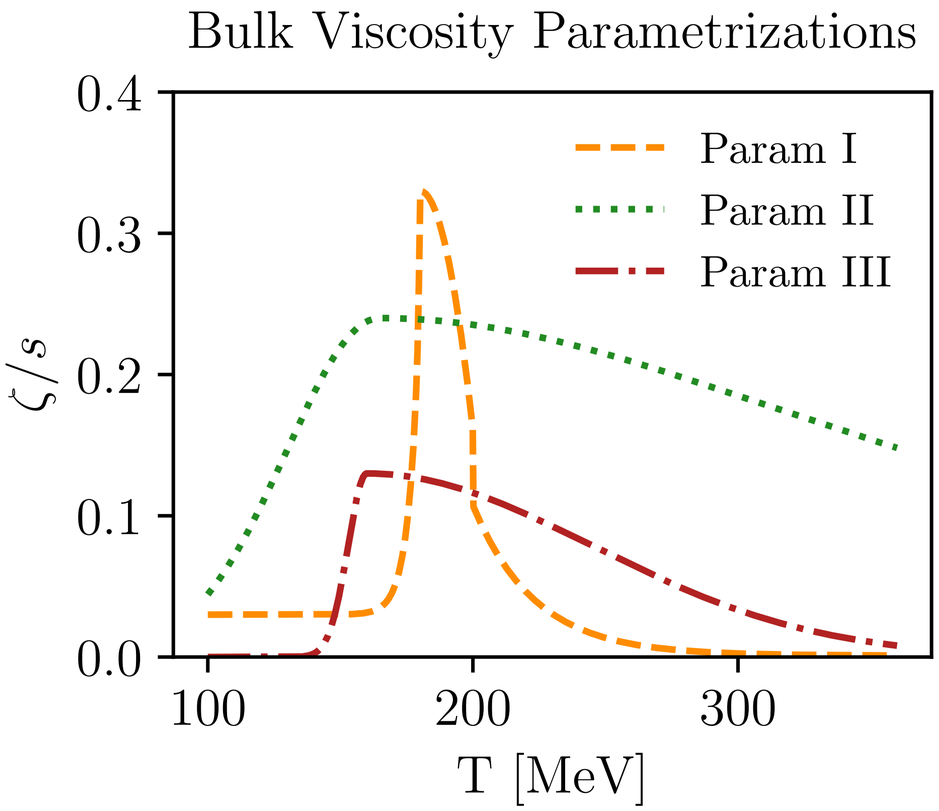
$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$

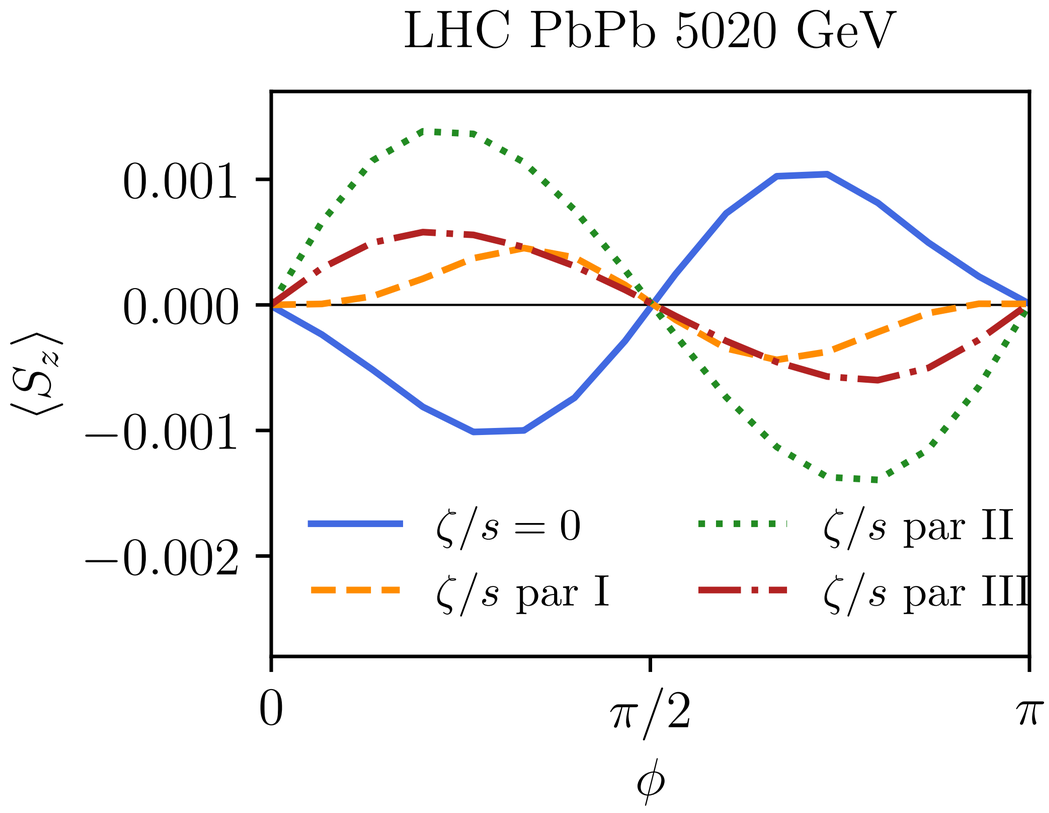
$$P_{z,sn} = \frac{\langle P_z \sin n(\varphi_H - \Psi_n) \rangle}{R_{EP}^{(n)}}$$





QGP property with local polarization



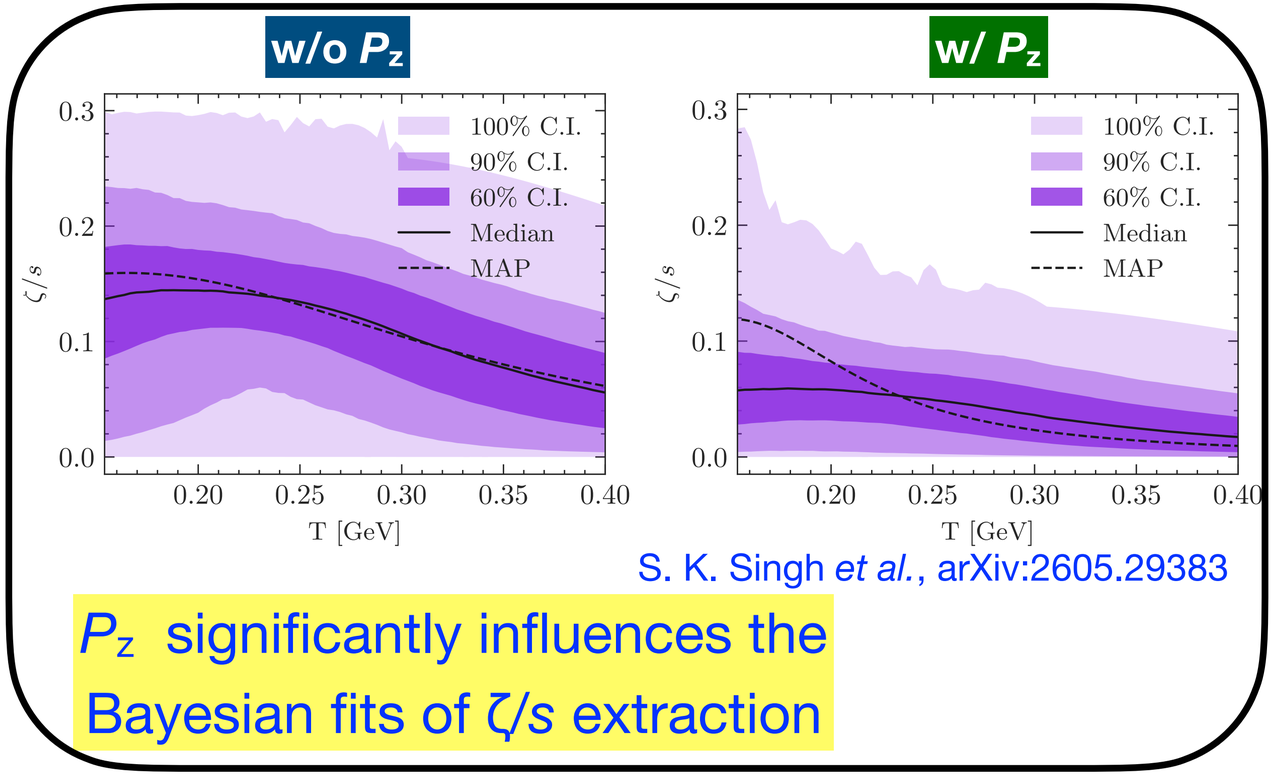


At LHC P_z is sensitive to

A. Palermo *et al.*, *Eur. Phys. J.* **C84** (2024) 920
B. Fu *et al.*, *Phys. Rev. Lett.* **127** (2021) 142301

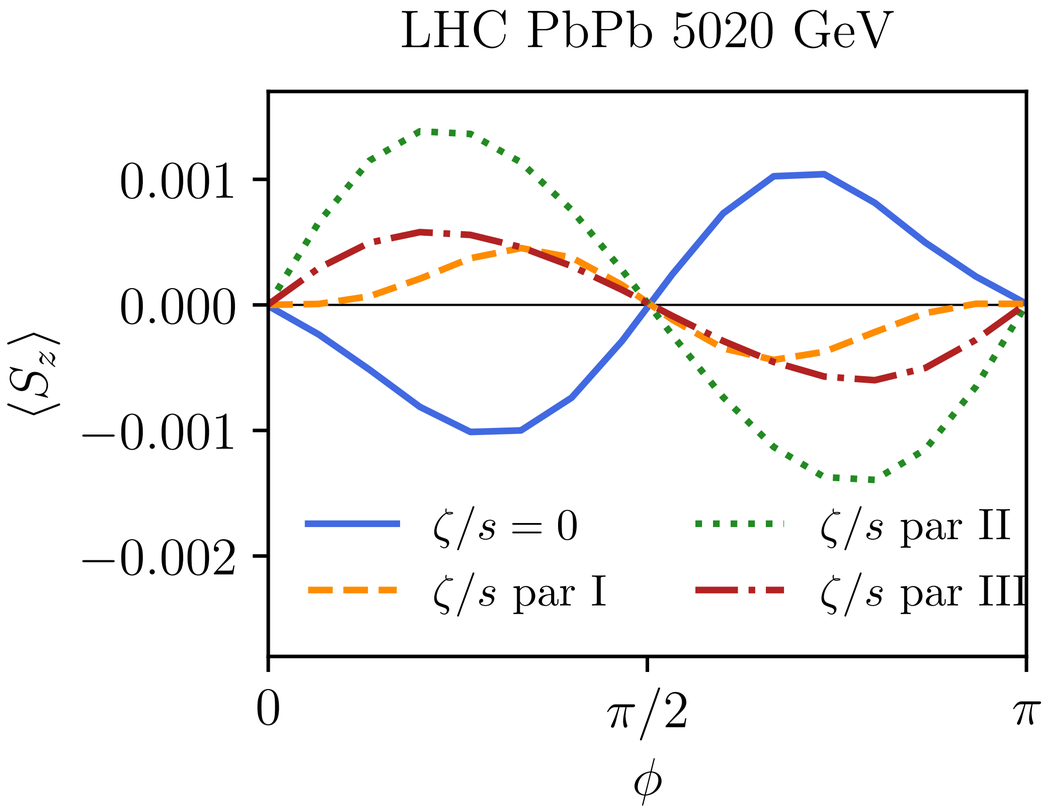
- Bulk viscosity ζ/*s* of the QGP at LHC energies ➡ change the sign of P_z
- Shear-induced polarization ➡ competes with the thermal vorticity

QGP property with local polarization



S. K. Singh *et al.*, arXiv:2605.29383

P_z significantly influences the Bayesian fits of ζ/*s* extraction

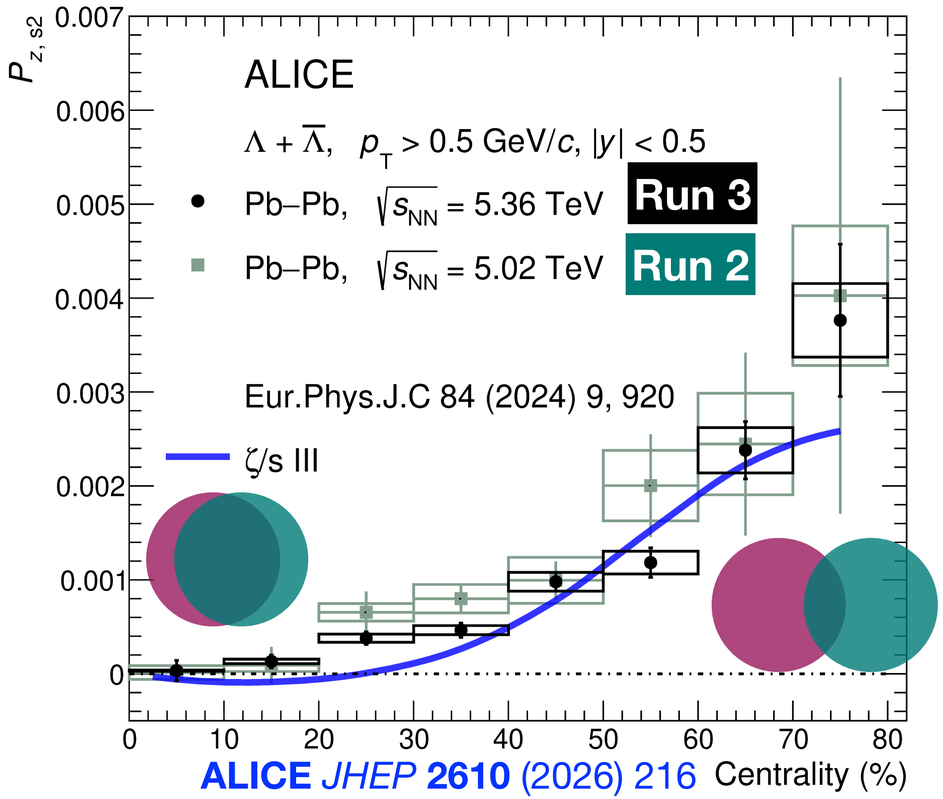


A. Palermo *et al.*, *Eur. Phys. J.* **C84** (2024) 920
B. Fu *et al.*, *Phys. Rev. Lett.* **127** (2021) 142301

At LHC P_z is sensitive to

- Bulk viscosity ζ/*s* of the QGP at LHC energies ➡ change the sign of P_z
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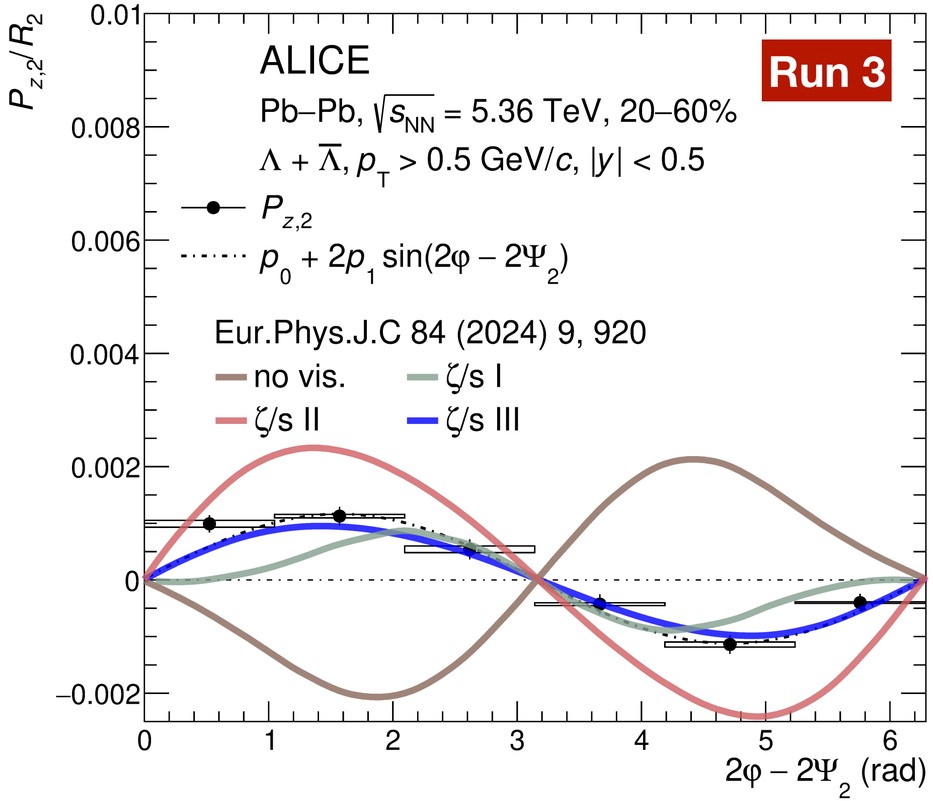
New Run 3 results compare to model



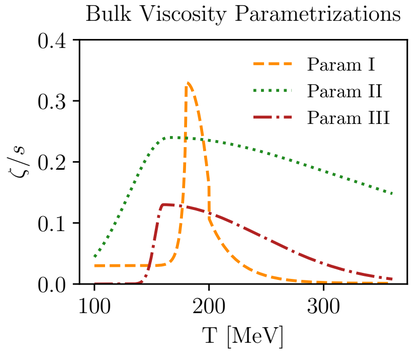
ALICE *JHEP* **2610** (2026) 216

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

ALI-PUB-635108



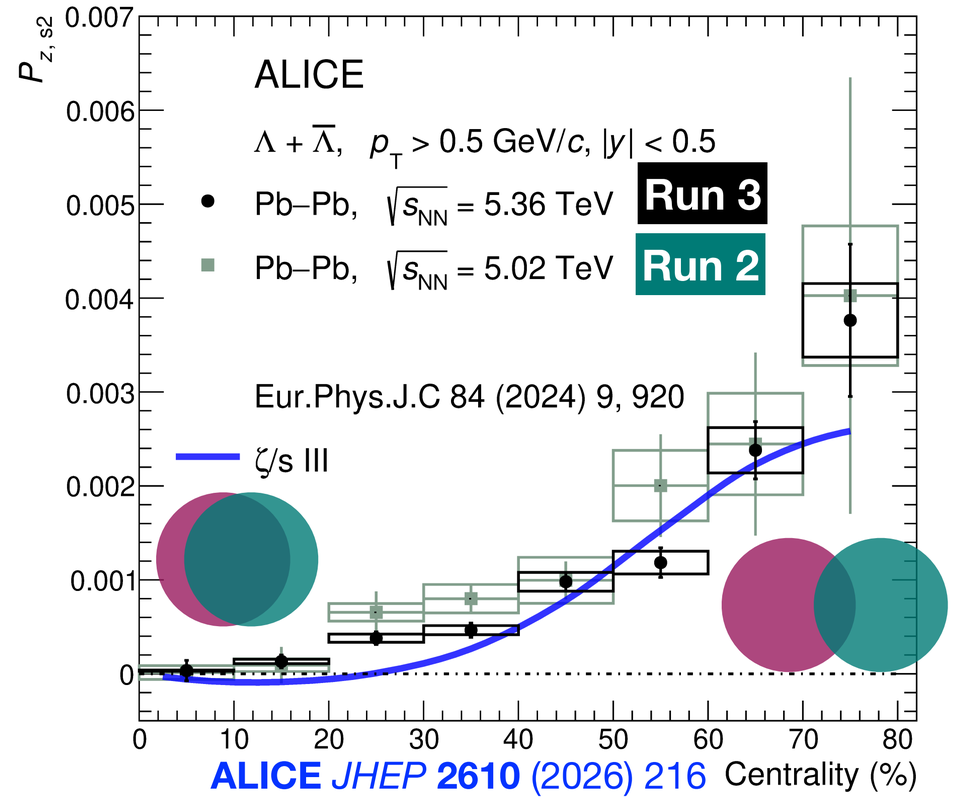
ALI-PUB-635098



Good agreement between data and model including

- ➡ Shear-induced polarization
- ➡ Assuming a temperature dependent bulk viscosity ζ/*s* (**par III**)
- ➡ An isothermal hadronization hypersurface

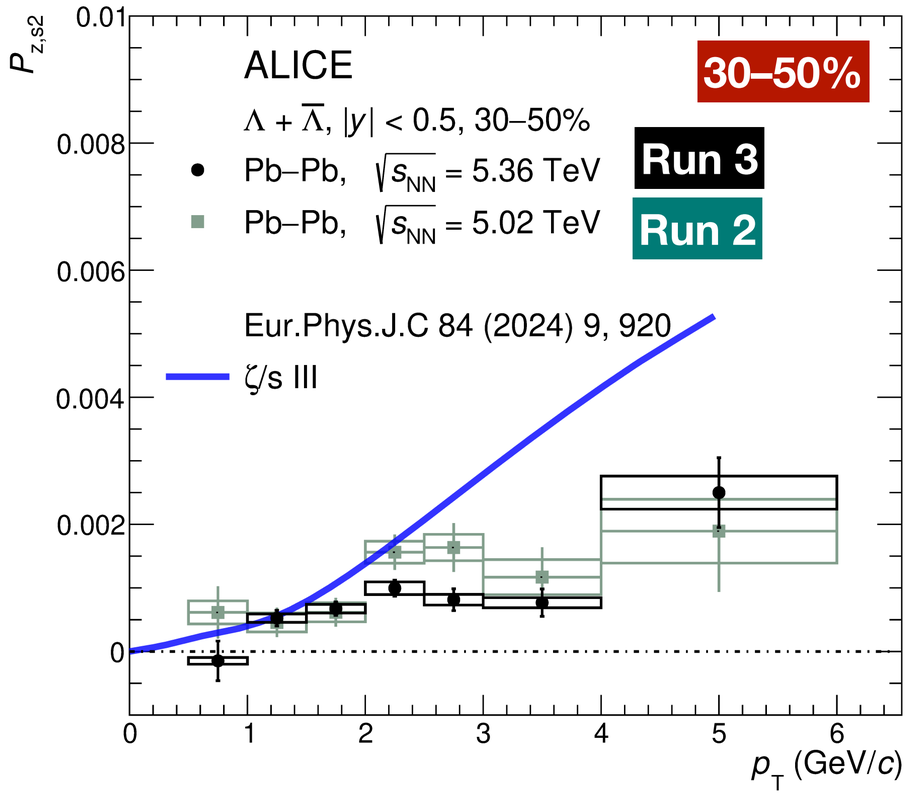
New Run 3 results p_T-dependence



ALICE *JHEP* **2610** (2026) 216

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

ALI-PUB-635108

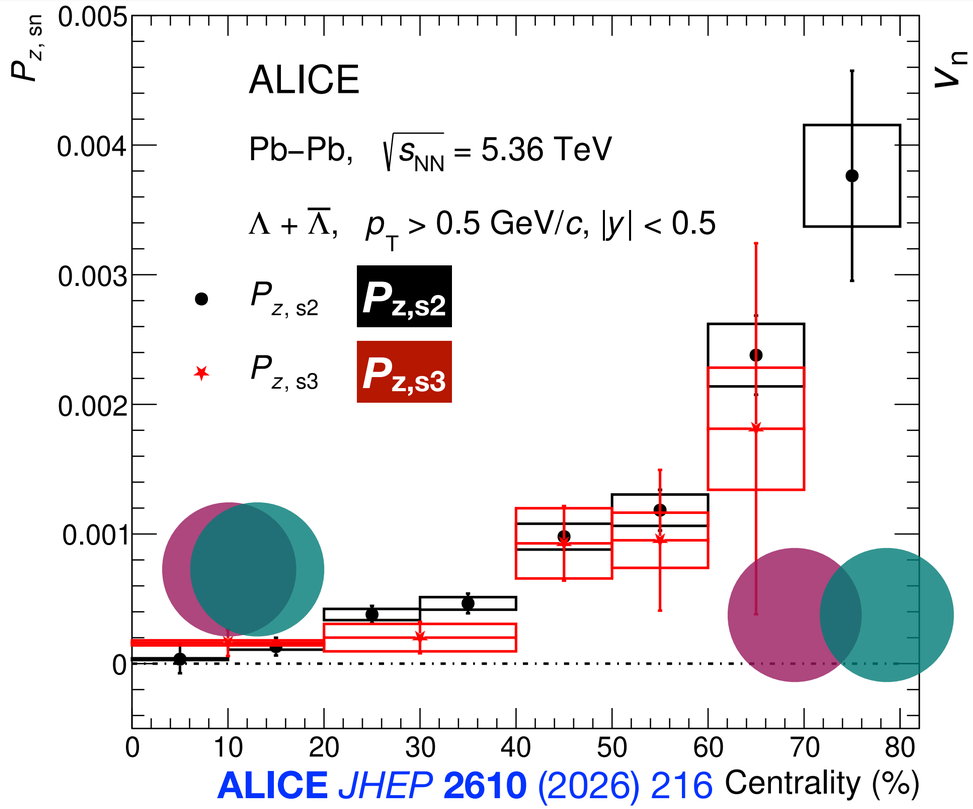


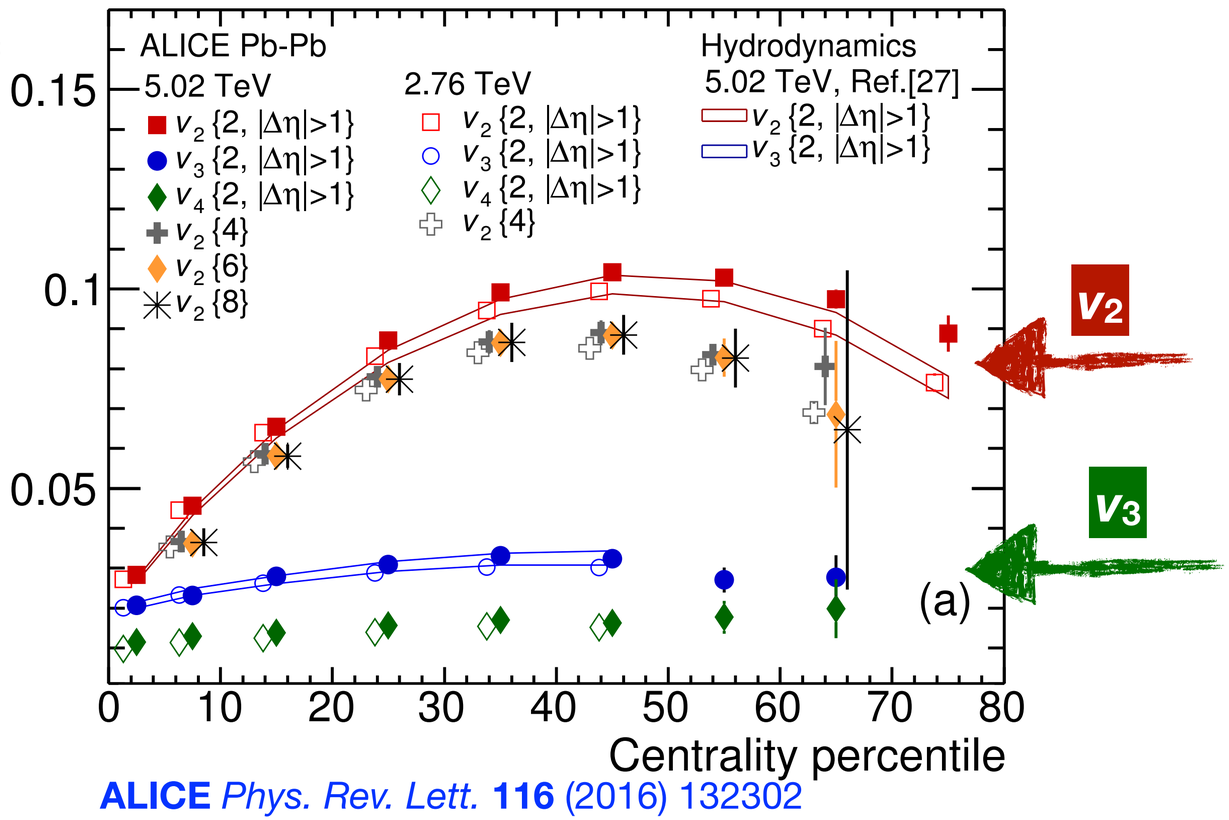
ALI-PUB-635113

The measured p_T dependence is not fully described by the model, which predicts a steeper increase with p_T, indicating the need for further model development

➡ Only 2023 Pb–Pb data is used, to be improved with full Pb–Pb sample

Polarization induced by triangle flow

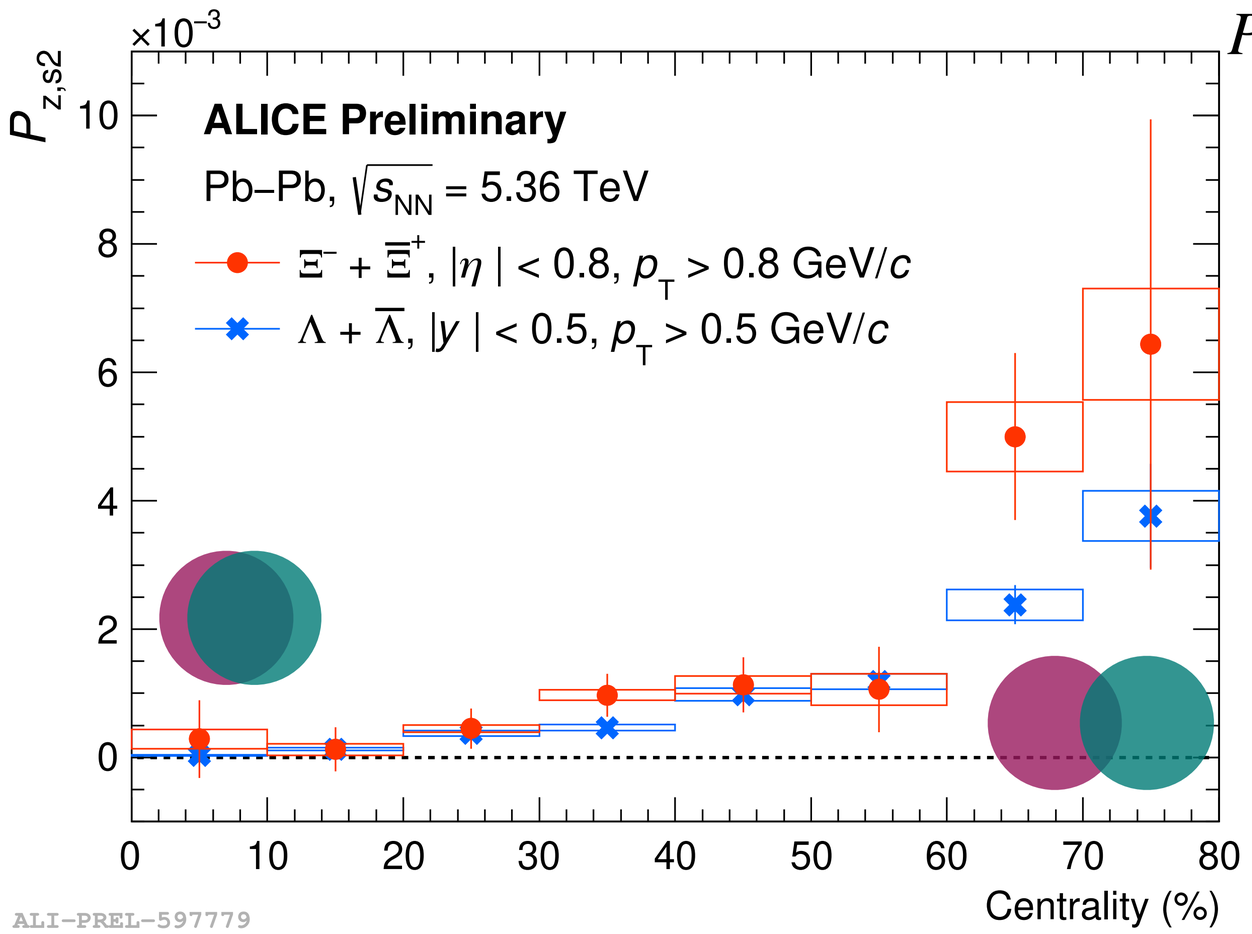




ALI-PUB-635118

- $P_{z,s3}$ is compatible with $P_{z,s2}$, despite the v_3 is smaller v_2
  - ➡ Similar relations is observed by STAR [**STAR** *Phys. Rev. Lett.* **131** (2023) 202301]
  - ➡ Model predictions are needed to interpret these results

Longitudinal polarization of Ξ

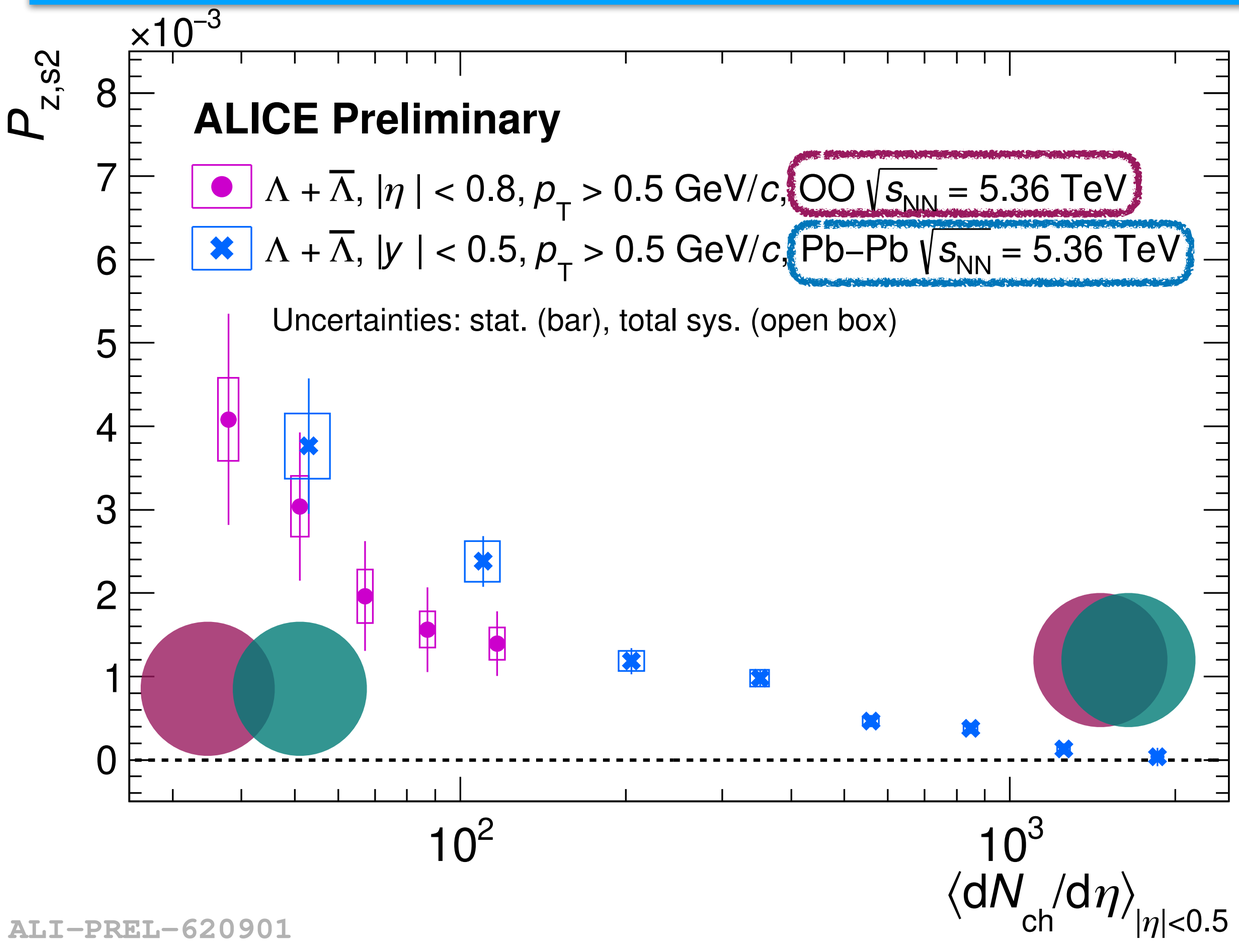


$$P_z^{\Xi} = \frac{\langle \cos\theta_p^* \rangle}{c_{\Xi\Lambda}\alpha_H \langle \cos^2\theta_p^* \rangle} \qquad P_{z,sn}^{\Xi} = \frac{\langle P_z^{\Xi} \sin n(\varphi_{\Xi} - \Psi_n) \rangle}{R_{EP}^{(n)}}$$

- The first measurement of Ξ longitudinal polarization in Pb–Pb collisions
  - ➡ Only 2023 Pb–Pb data is used
- The Ξ longitudinal polarization shows a hint of increase from central to peripheral collisions
  - ➡ It is compatible with Λ, confirming the spin hierarchy ($s_\Lambda = s_\Xi = 1/2$)

2024–2026 data allows us to reduce uncertainty and to test spin hierarchy by measuring Ω ($s_\Omega = 3/2$)

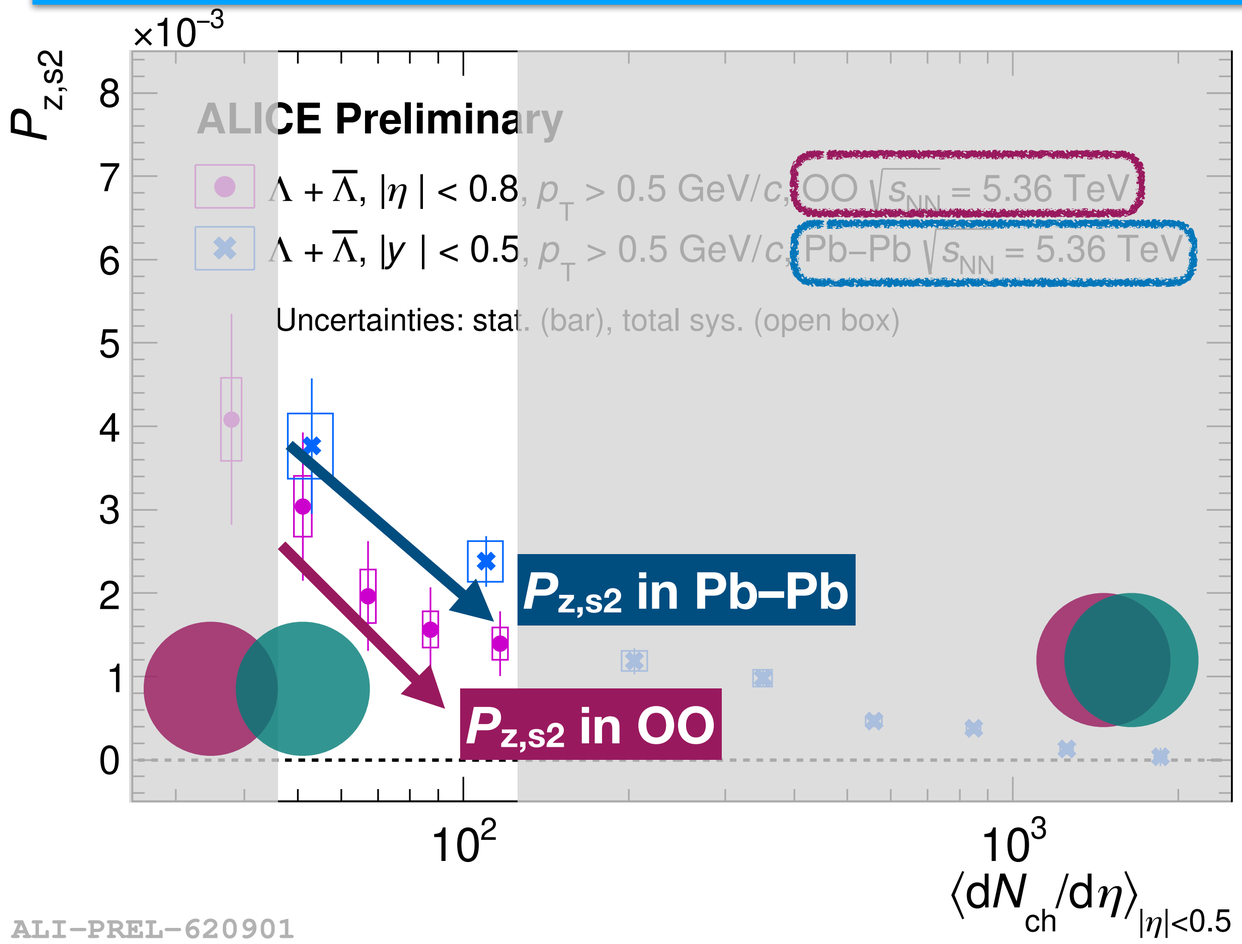
Longitudinal polarization of Λ in OO



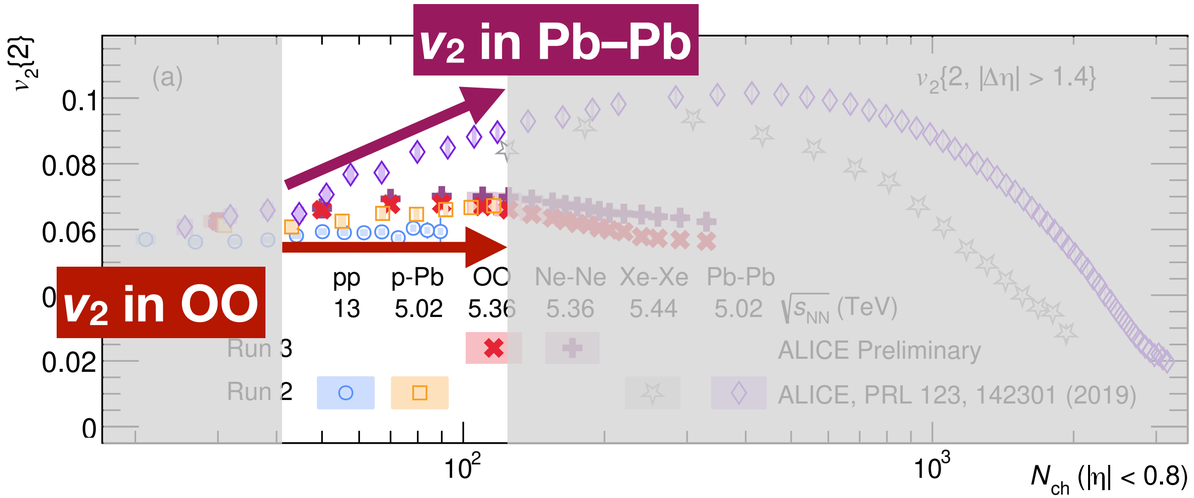
ALI-PREL-620901

- Very first measurement of Λ longitudinal polarization in OO collisions
  - ➡ ~5×10⁹ collisions collected in 2025
- Significantly non-zero values for 0–50% centrality class with 6σ
- $P_{z,s2}$ approximately scales with event multiplicity
  - ➡ Used as a proxy for the produced system size

Longitudinal polarization of Λ in OO



ALI-PREL-620901



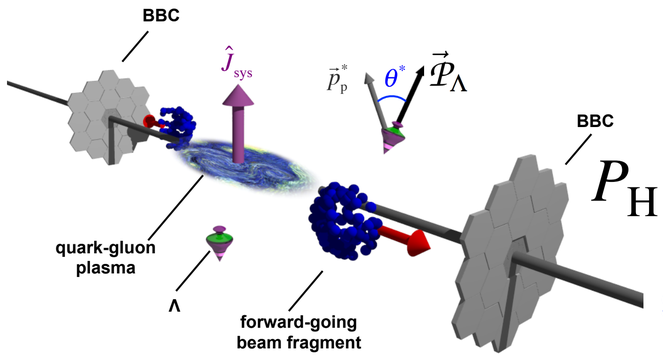
ALI-PREL-623658

- Compatible with the one observed in **Pb–Pb** collisions at similar multiplicity

- $P_{z,s2}$ does not scale with v_2: **OO** and **Pb–Pb** collisions show different polarization at comparable v_2

Comparison with model predictions would constrain for the first time the bulk viscosity of the medium in OO collisions

Polarization puzzle



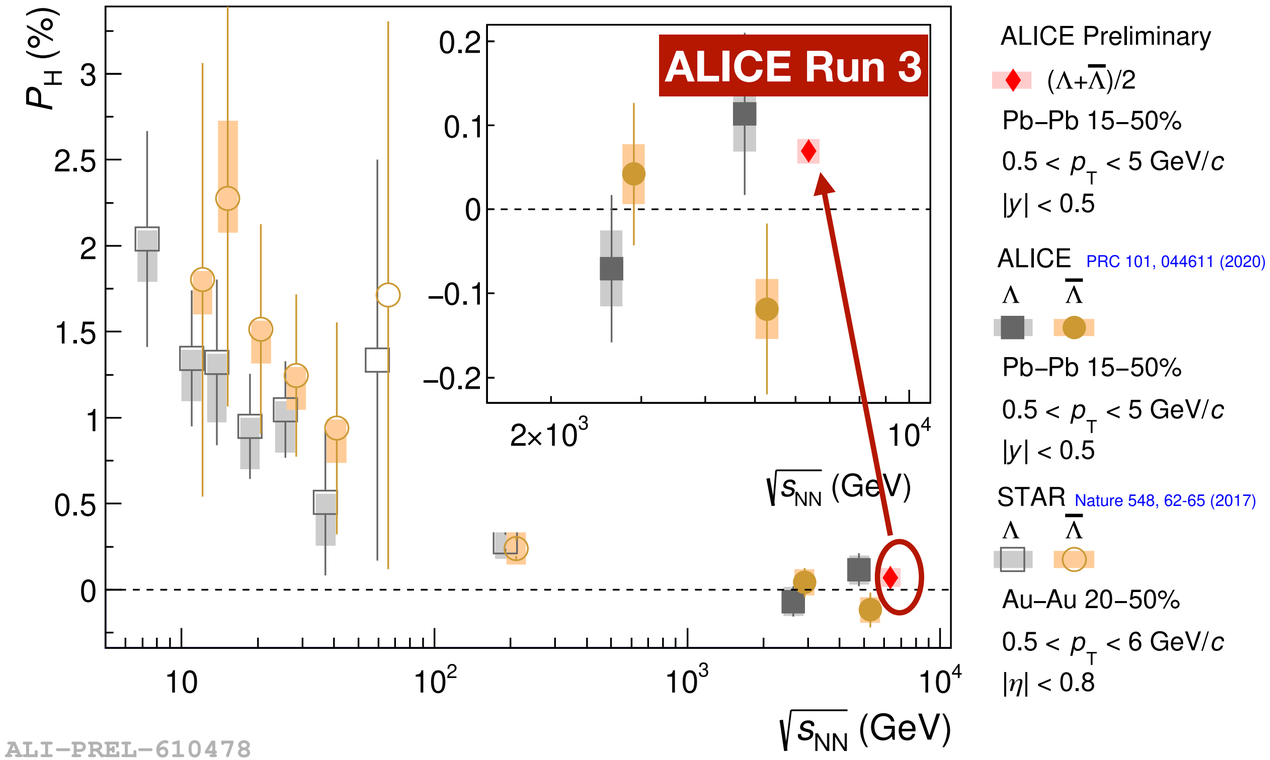
$$P_{\mathrm{H}} = -\frac{8}{\pi\alpha_{\mathrm{H}}}\frac{\langle \sin(\varphi_{\mathrm{p}}^{*} - \Psi_{\mathrm{SP}}^{(1)})\rangle}{R_{\mathrm{SP}}^{(1)}}$$

STAR *Nature* **548** (2017) 62

Thermal estimation

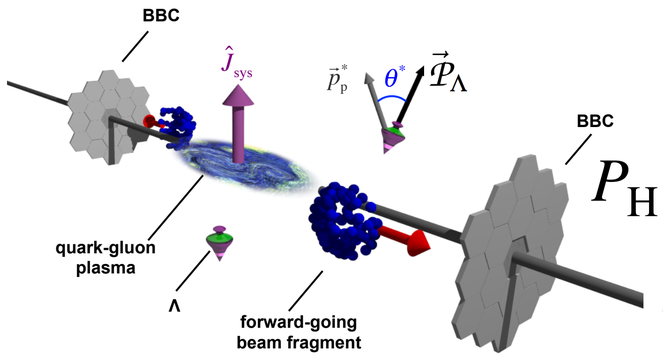
$$\rho_{00} - 1/3 \sim \mathcal{O}(P_{\mathrm{H}}^2)$$

$$P_{\mathrm{H}} < 0.1\,\% \Rightarrow \rho_{00} - 1/3 \sim 0$$



ALI-PREL-610478

Polarization puzzle



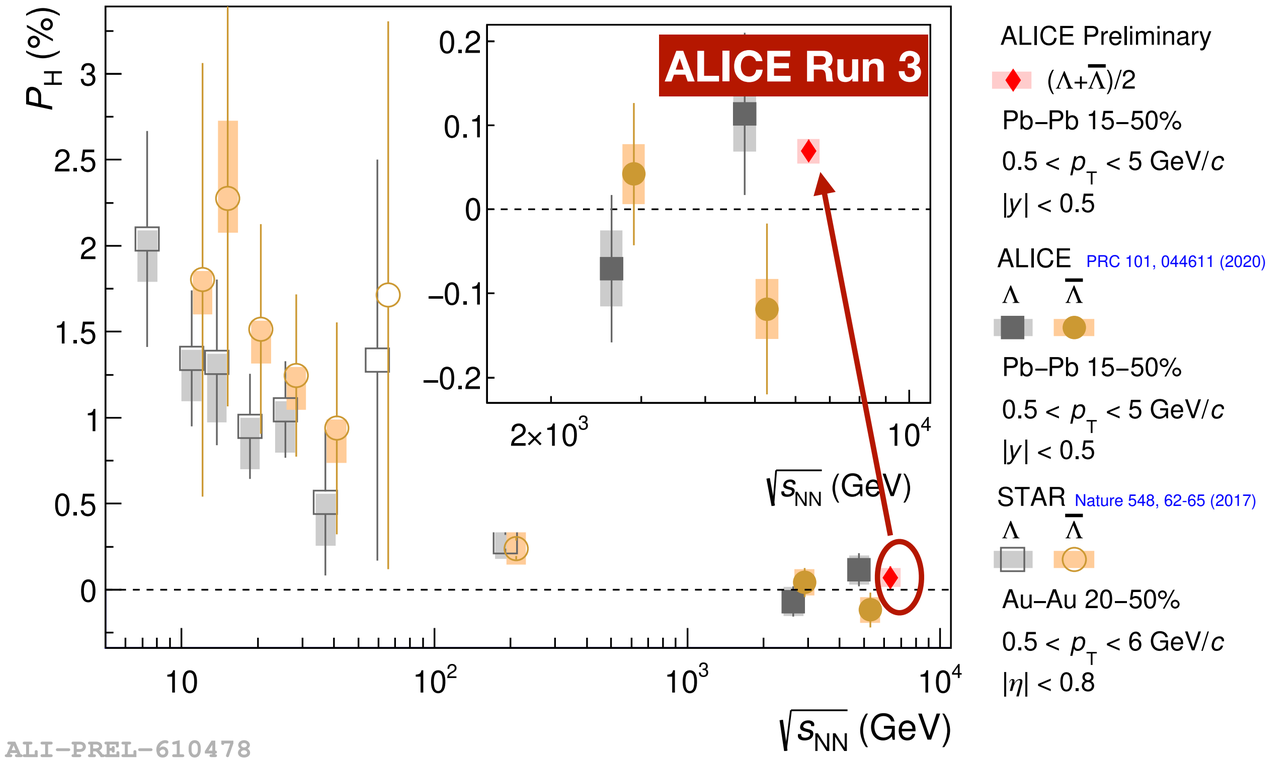
$$P_{\mathrm{H}} = -\frac{8}{\pi\alpha_{\mathrm{H}}}\frac{\langle \sin(\varphi_{\mathrm{p}}^{*} - \Psi_{\mathrm{SP}}^{(1)})\rangle}{R_{\mathrm{SP}}^{(1)}}$$

STAR *Nature* **548** (2017) 62

Thermal estimation

$$\rho_{00} - 1/3 \sim \mathcal{O}(P_{\mathrm{H}}^2)$$

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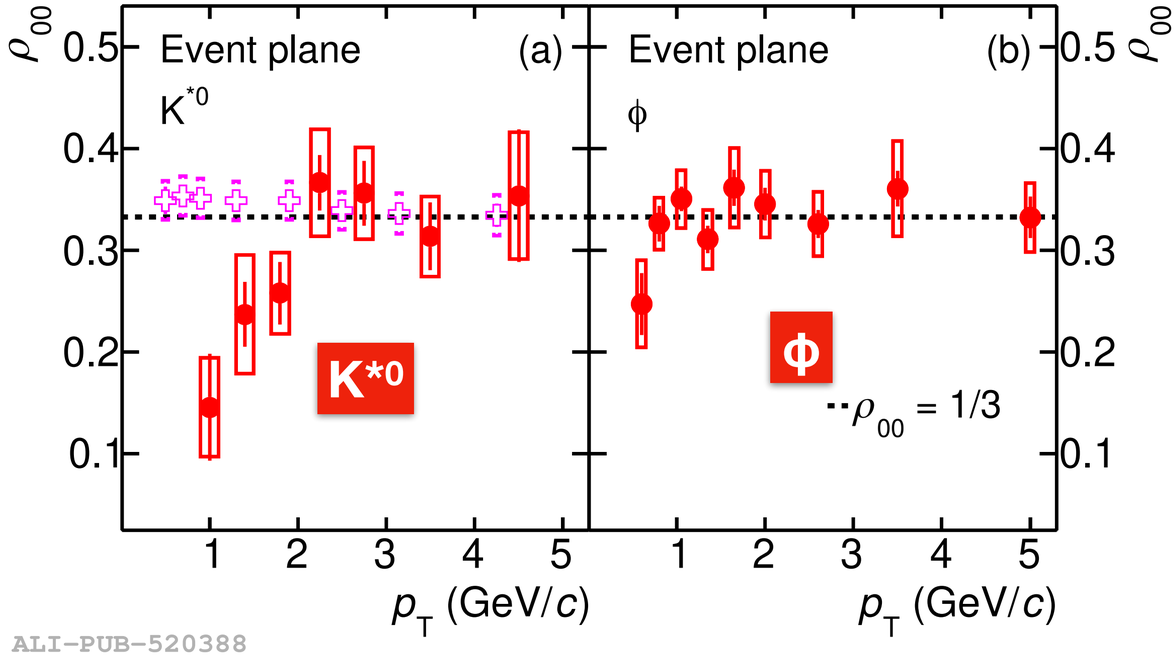


ALICE Preliminary
$(\Lambda+\bar{\Lambda})/2$
Pb–Pb 15–50%
$0.5 < p_T < 5$ GeV/c
$|y| < 0.5$

ALICE PRC 101, 044611 (2020)
Λ $\bar{\Lambda}$
Pb–Pb 15–50%
$0.5 < p_T < 5$ GeV/c
$|y| < 0.5$

STAR Nature 548, 62-65 (2017)
Λ $\bar{\Lambda}$
Au–Au 20–50%
$0.5 < p_T < 6$ GeV/c
$|\eta| < 0.8$

ALI-PREL-610478

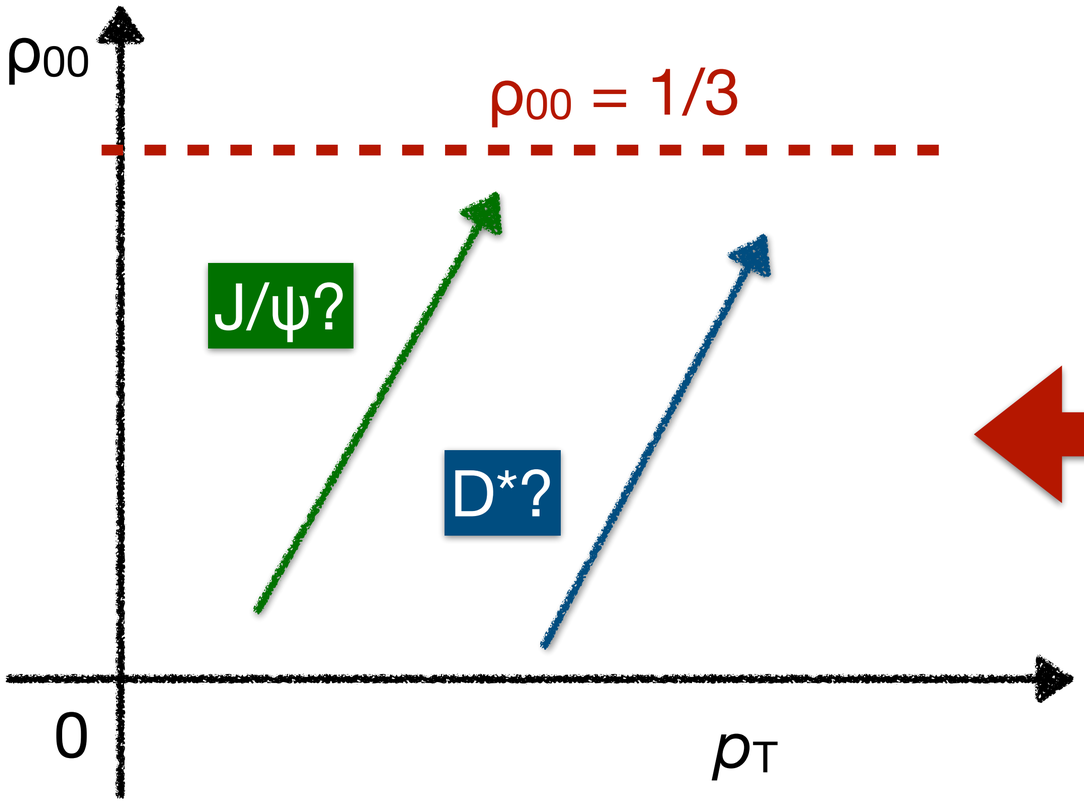


ALI-PUB-520388

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

Spin alignment of HF particles

Prediction at heavy-quark sector

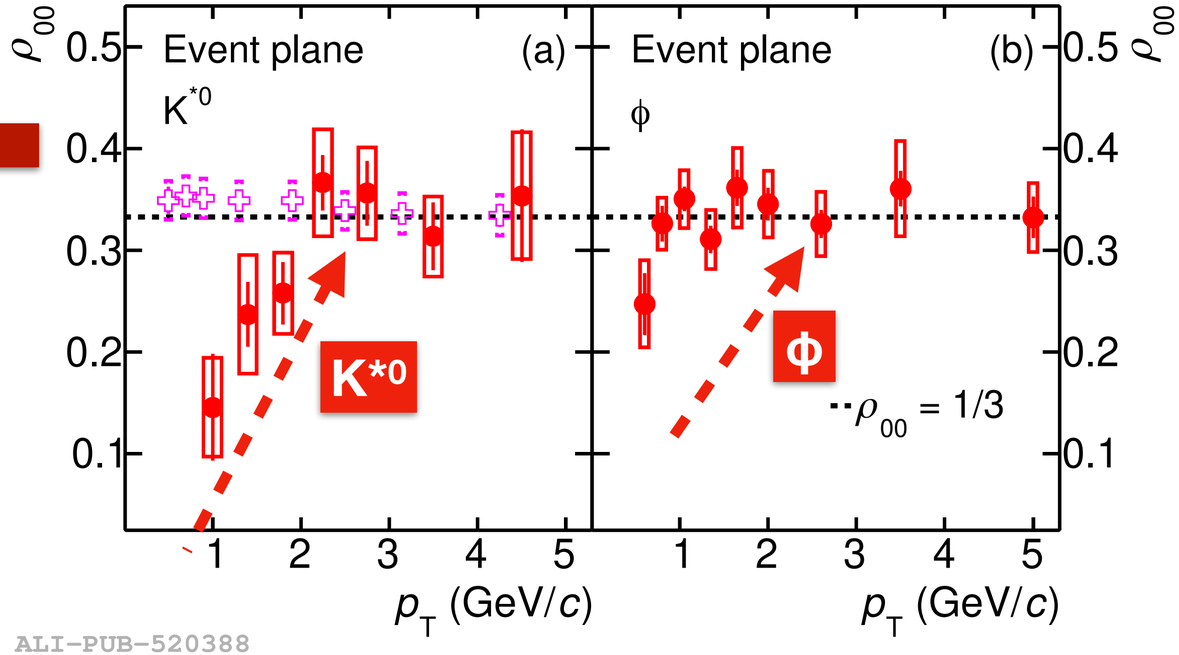


Would a similar trend show at heavy-quark sector?

Thermal estimation

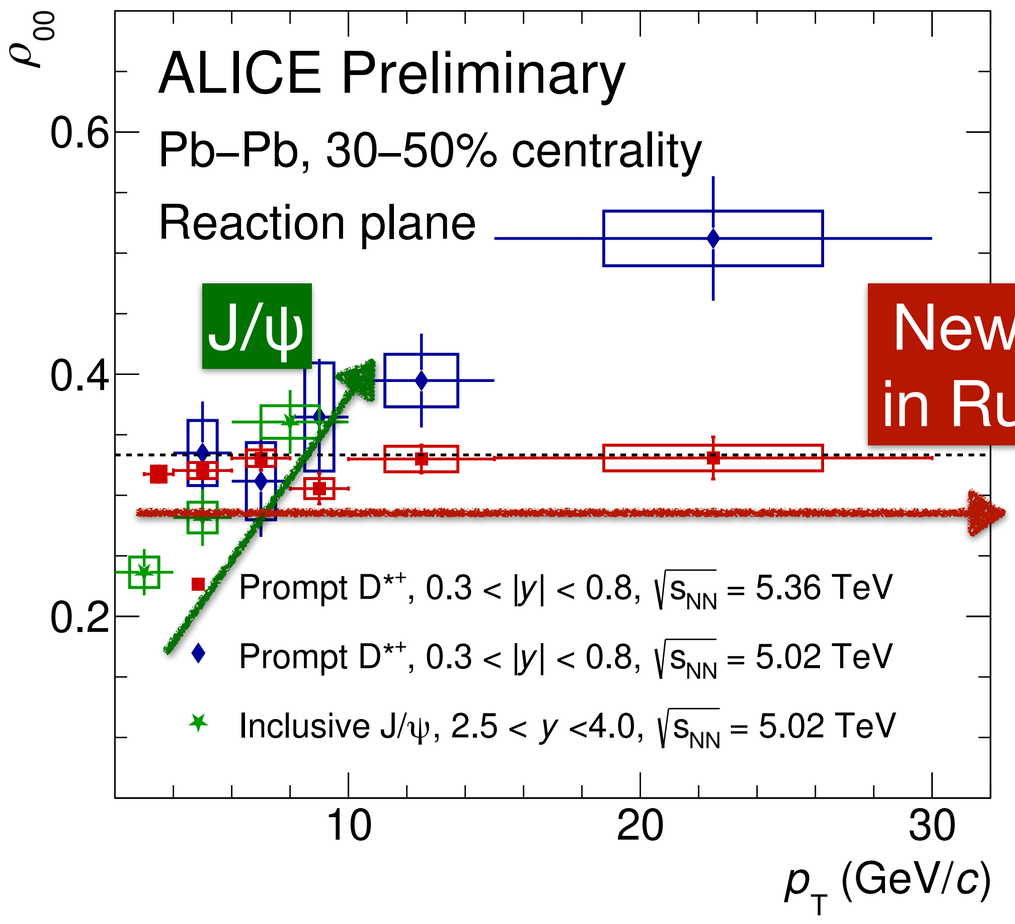
$$\rho_{00} - 1/3 \sim \mathcal{O}(P_{\mathrm{H}}^2)$$

$$P_{\mathrm{H}} < 0.1\,\% \Rightarrow \rho_{00} - 1/3 \sim 0$$



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

Spin alignment of HF particles

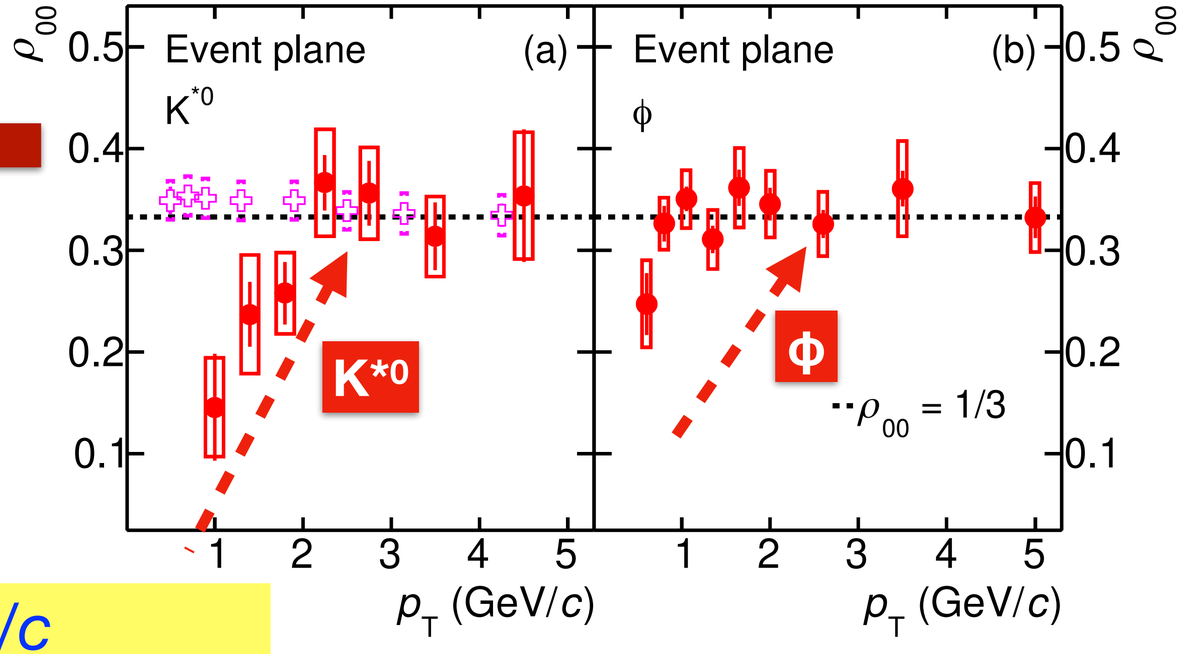


ALI-PREL-633298

Thermal estimation

$$\rho_{00} - 1/3 \sim \mathcal{O}(P_{\mathrm{H}}^2)$$

$$P_{\mathrm{H}} < 0.1\,\% \Rightarrow \rho_{00} - 1/3 \sim 0$$



No significant signal observed in $p_{\mathrm{T}} > 1$ GeV/c

➡ Todo: push the measurements down to lower p_{T}

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

Possible mechanisms

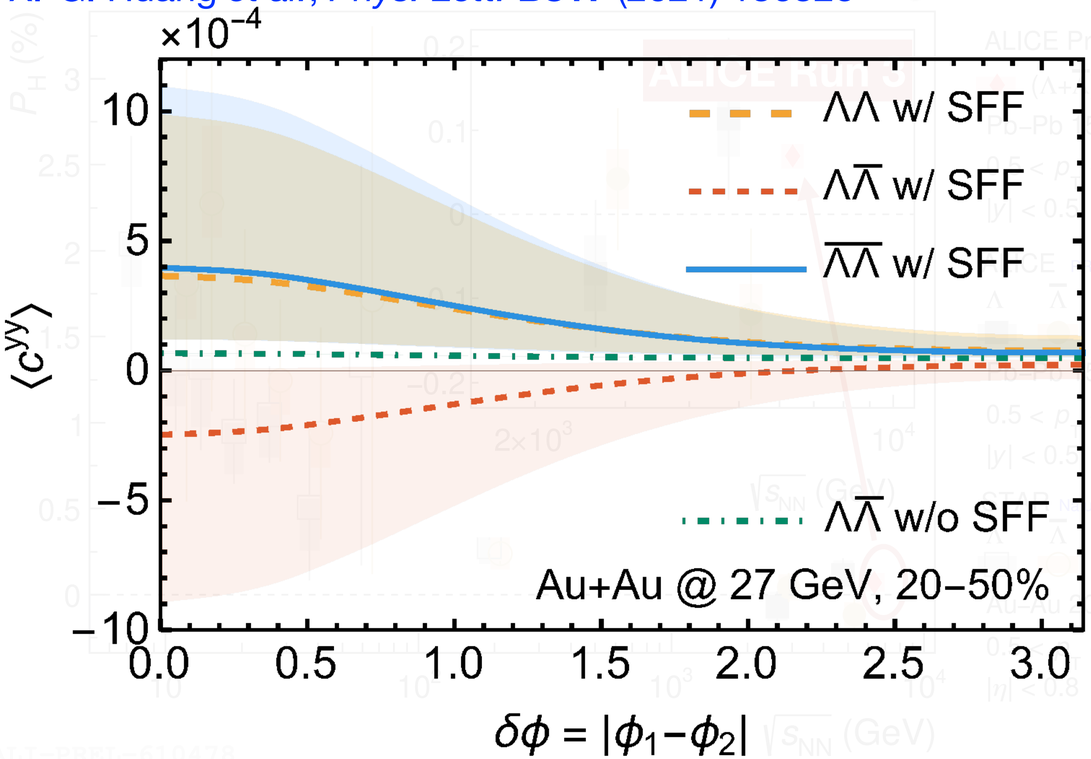
D. Hou *et al.*, *Phys. Rev.* **D110** (2024) 056047
A. Kumar *et al.*, *Phys. Rev.* **D109** (2024) 054038
Z.-T. Liang, Q. Wang, and X.-N. Wang *et al.*, *Phys. Rev.* **D109** (2024) 114003
S. Pu *et al.*, *Phys. Rev.* **D109** (2024) 034034
A. Kumar *et al.*, *Phys. Rev.* **D108** (2023) 016020
B. Muller *et al.*, *Phys. Rev.* **D105** (2022) L011901
Q. Wang *et al.*, *Phys. Rev.* **D105** (2022) 099903
X.-G. Huang *et al.*, *Phys. Lett.* **B817** (2021) 136325

Uncompleted list

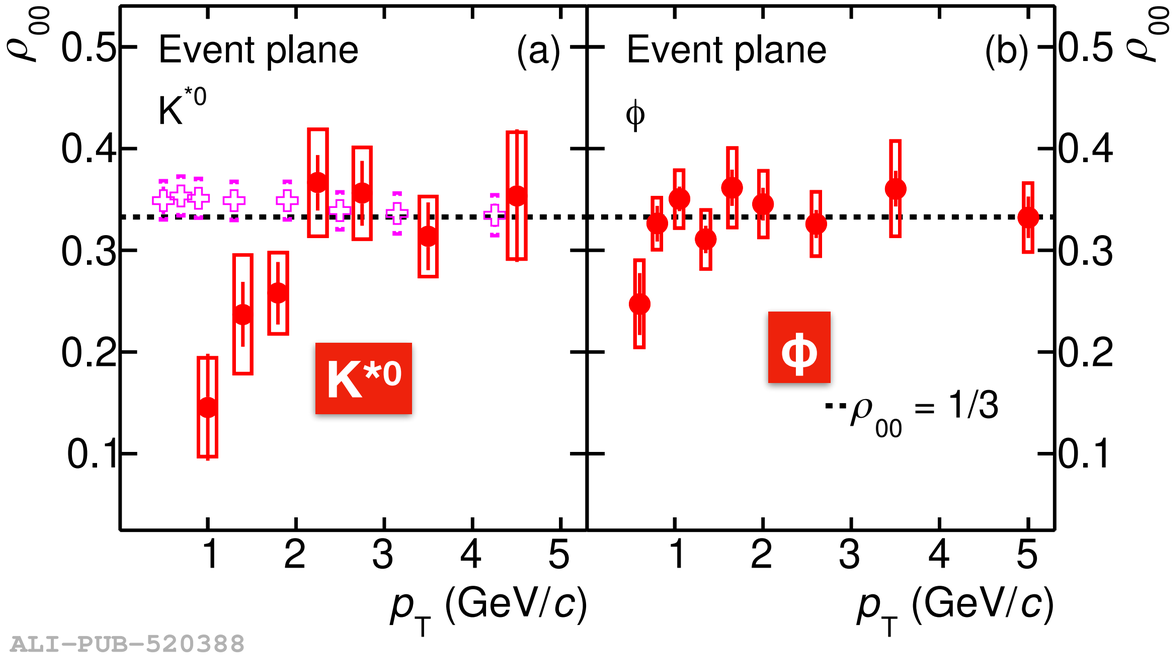
Thermal estimation

$$\rho_{00} - 1/3 \sim \mathcal{O}(P_{\mathrm{H}}^2)$$

$$P_{\mathrm{H}} < 0.1\,\% \Rightarrow \rho_{00} - 1/3 \sim 0$$

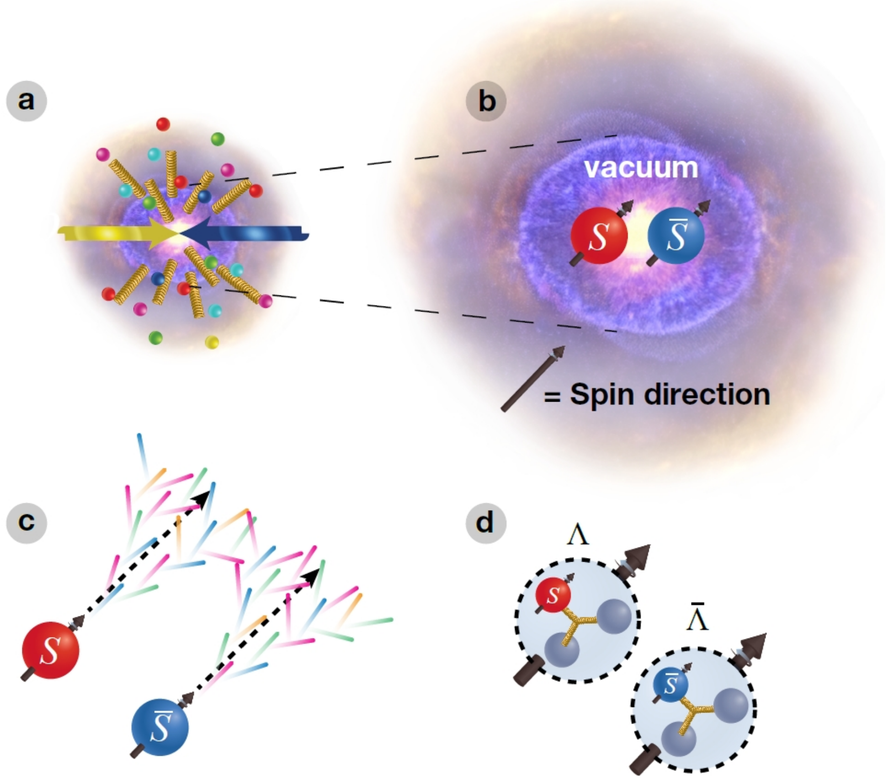


X.-N. Wang *el al.*, *Phys. Rev. Lett.* **136** (2026) 082301

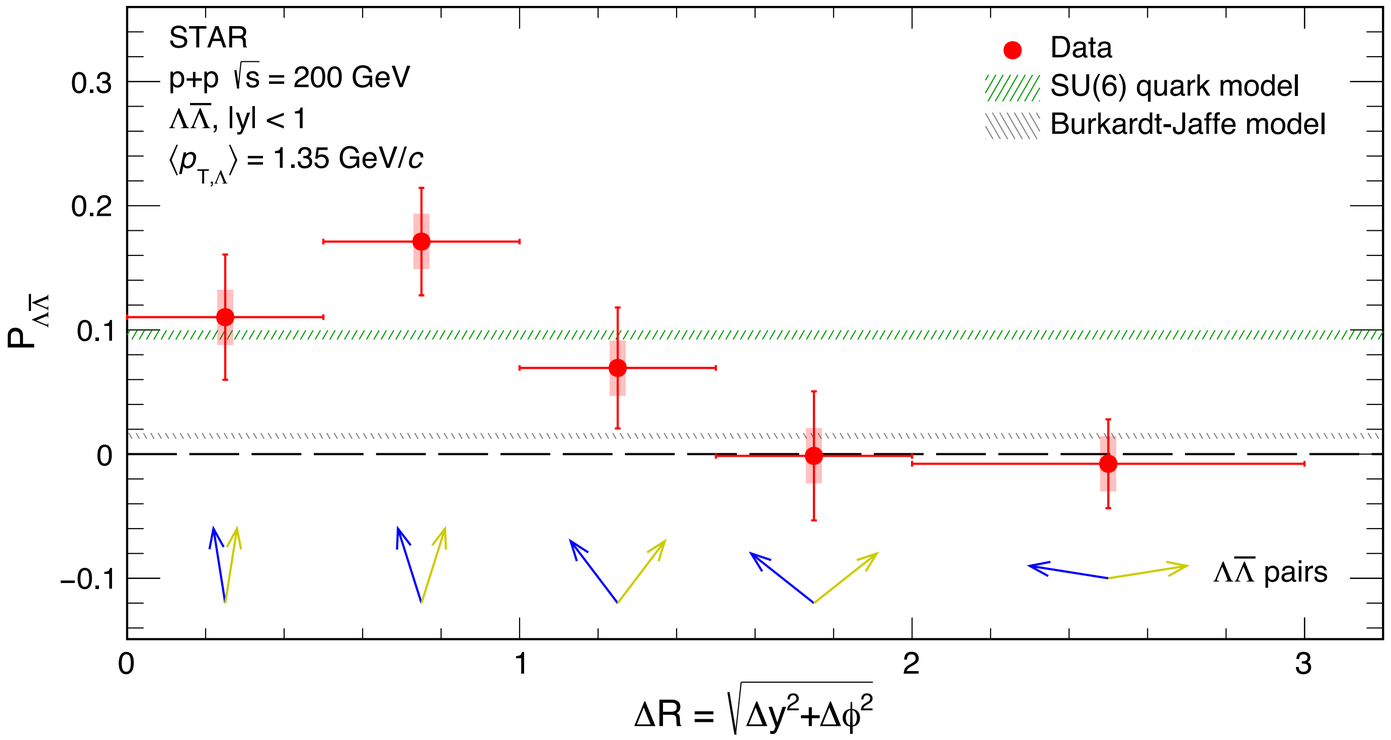


ALICE *Phys. Rev. Lett.* **125** (2020) 012301

Spin correlation of $\Lambda\bar{\Lambda}$ in pp at RHIC

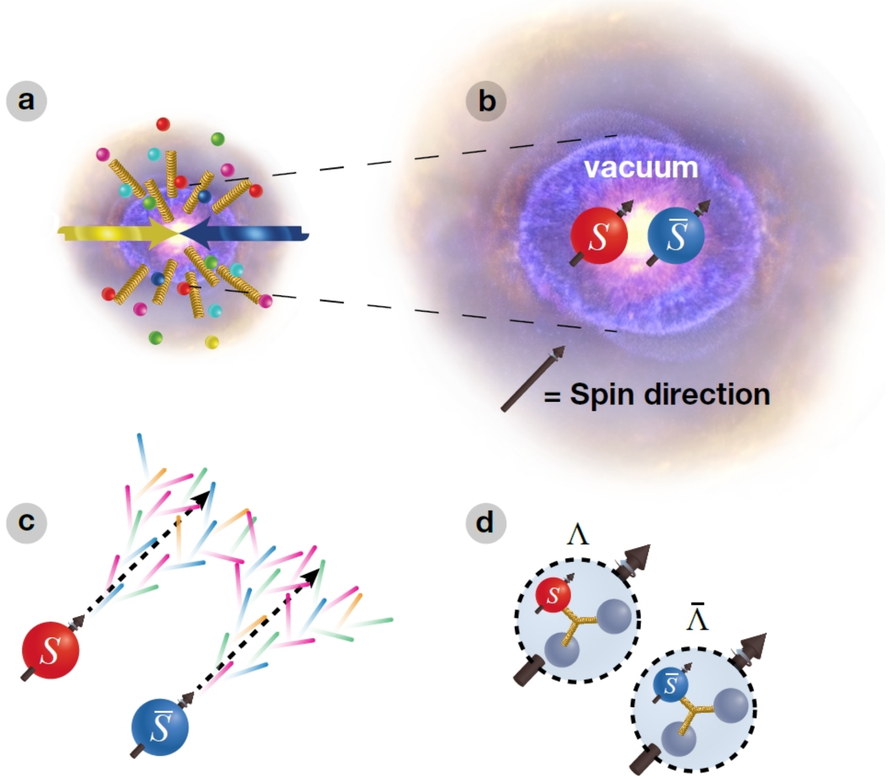


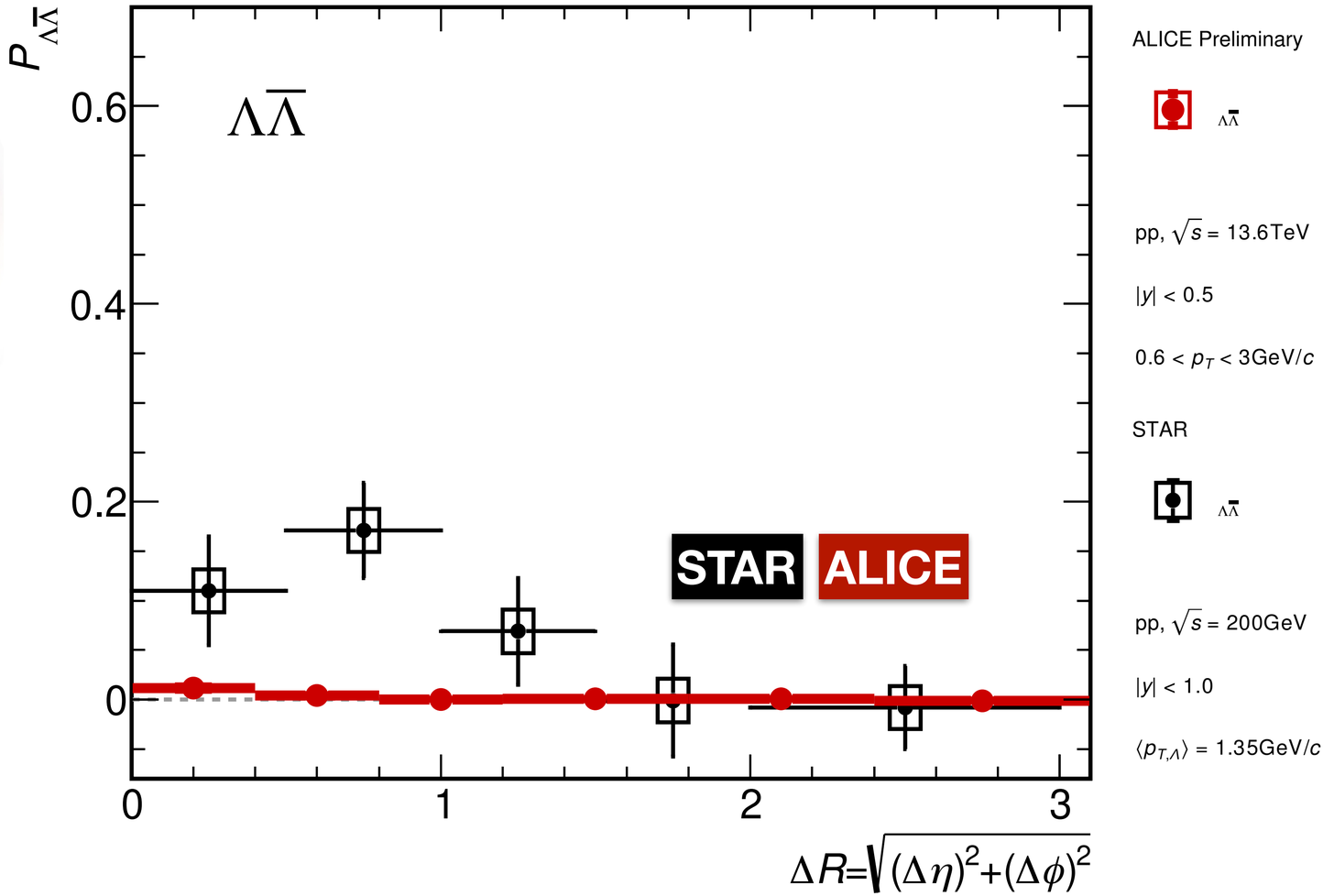
STAR *Nature* **650** (2026) 65



- Will parton spin correlation and entanglement manifest in Λ polarization?
- Does polarization of Λ depend on spin of the target/projectile?
- Are there contributions of the initial-/final-state effects?

Spin correlation of $\Lambda\overline{\Lambda}$ in pp at the LHC



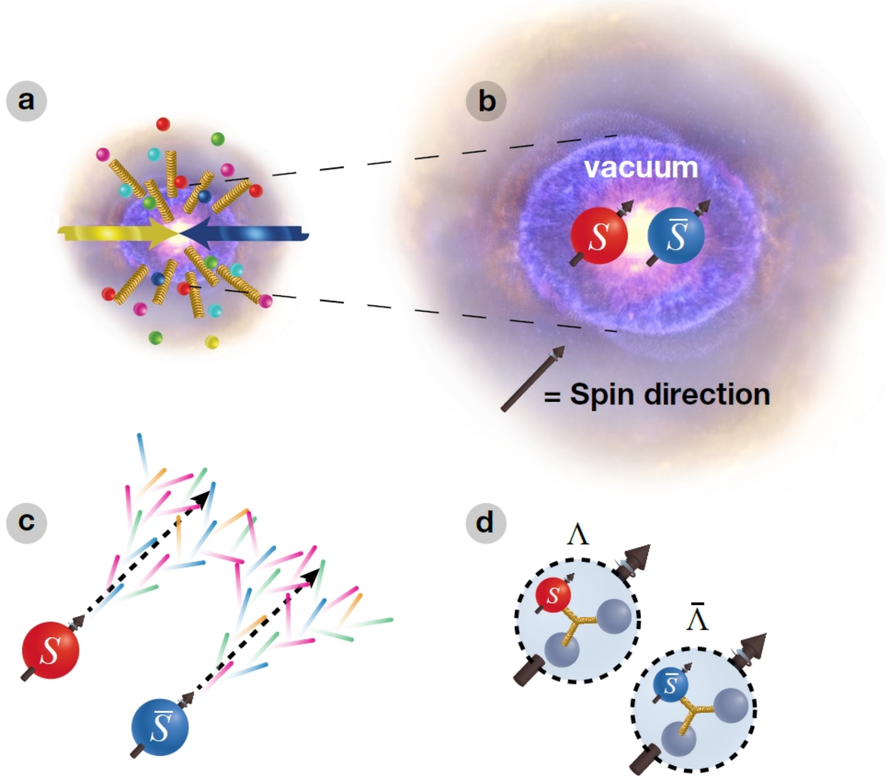


Weaker signal at the LHC that at RHIC

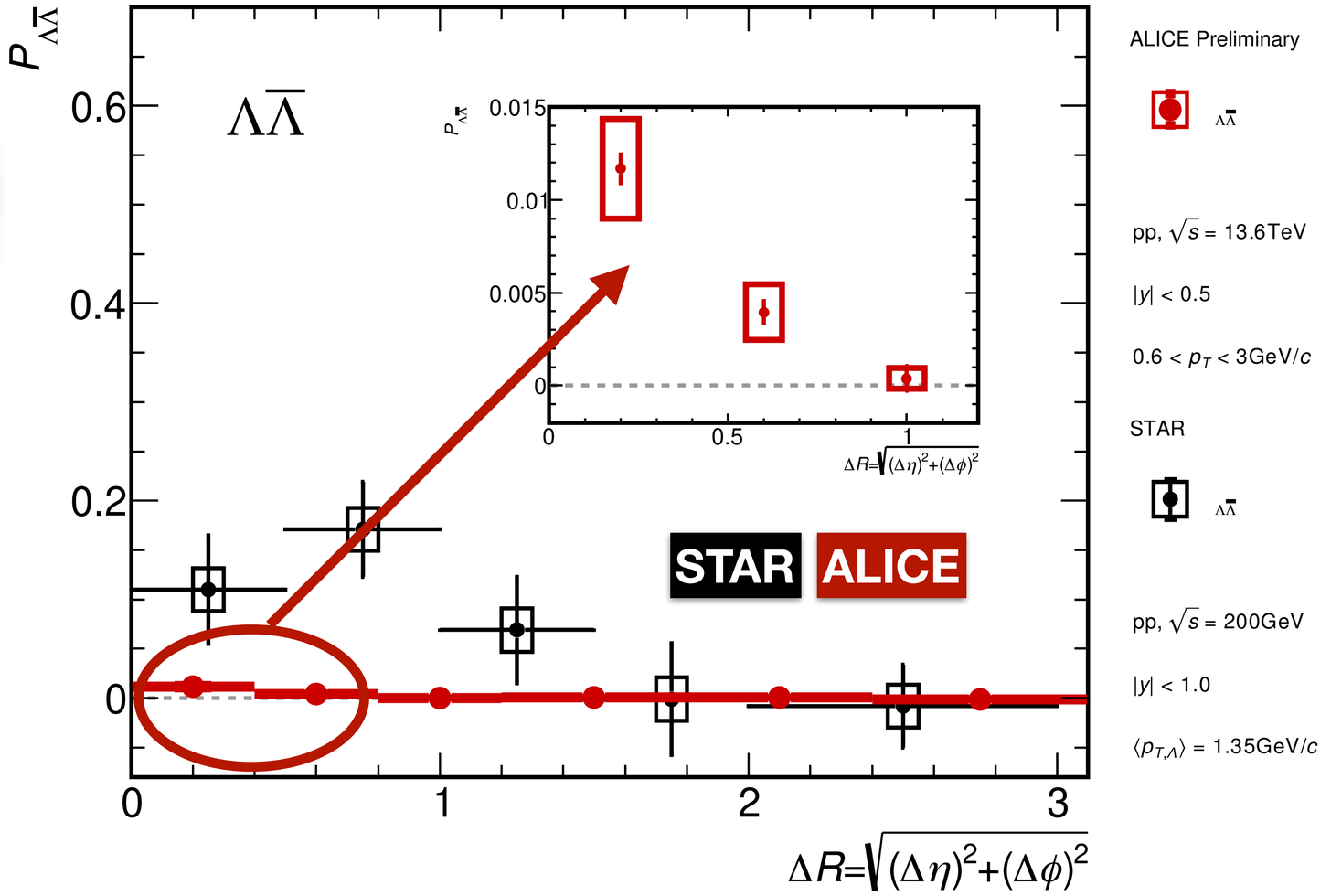
ALI-PREL-642489

ALICE measurement: part of 2026 pp data, 3.4 billion events

Spin correlation of $\Lambda\overline{\Lambda}$ in pp at the LHC



Evidence for non-zero correlations with a significant of 4.2σ observed with ALICE

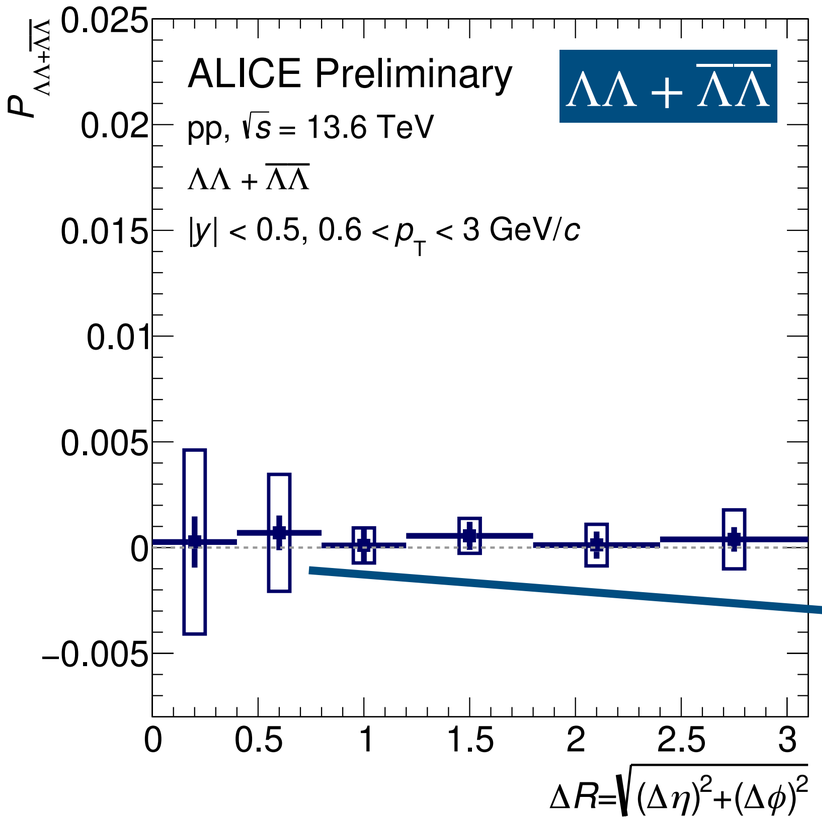


ALI-PREL-642489

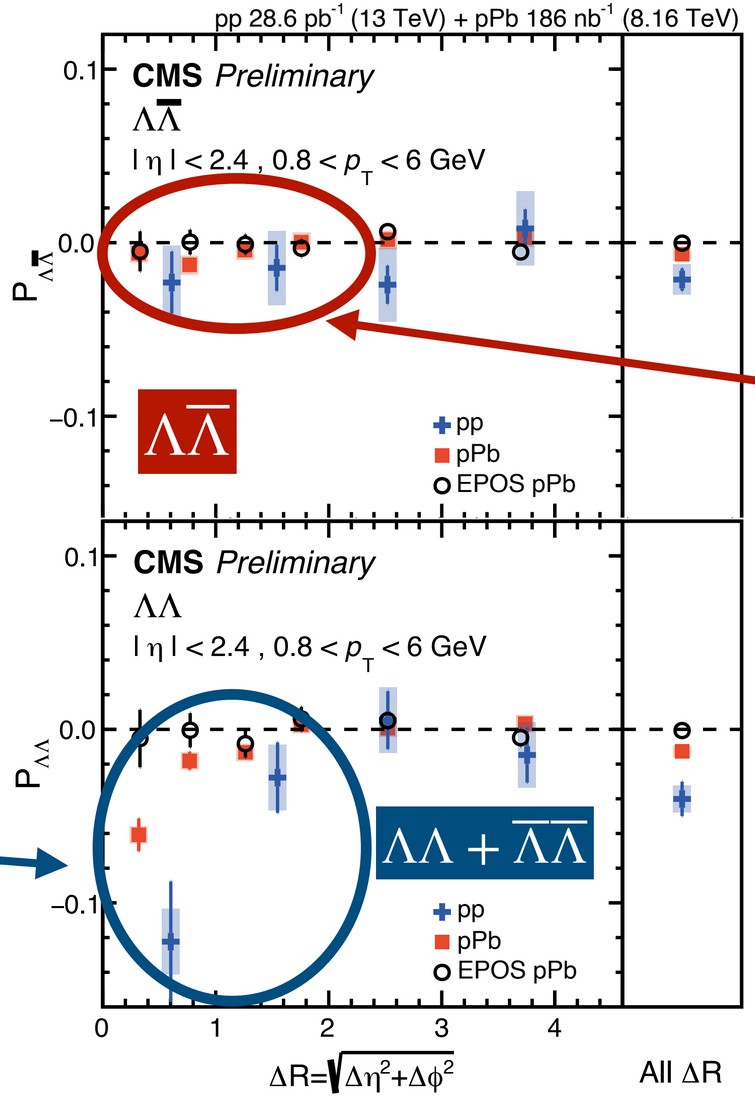
ALICE measurement: part of 2026 pp data, 3.4 billion events

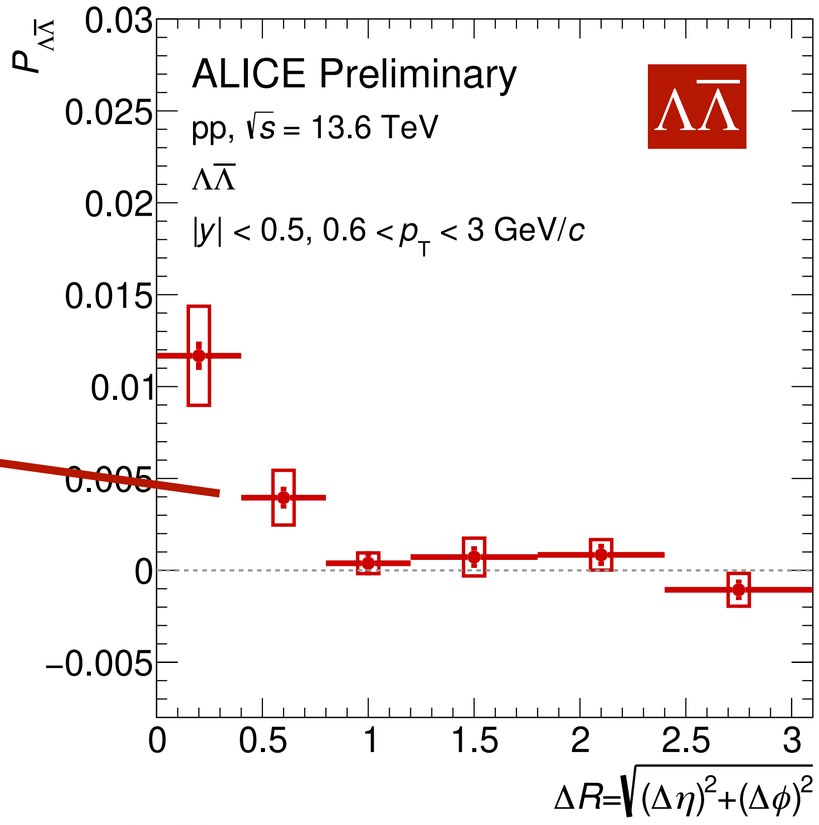
Comparison with CMS

- $\Lambda\overline{\Lambda}$: different trend at least
- $\Lambda\Lambda + \overline{\Lambda\Lambda}$: different trend and magnitude



CMS PAS-HIN-26-002



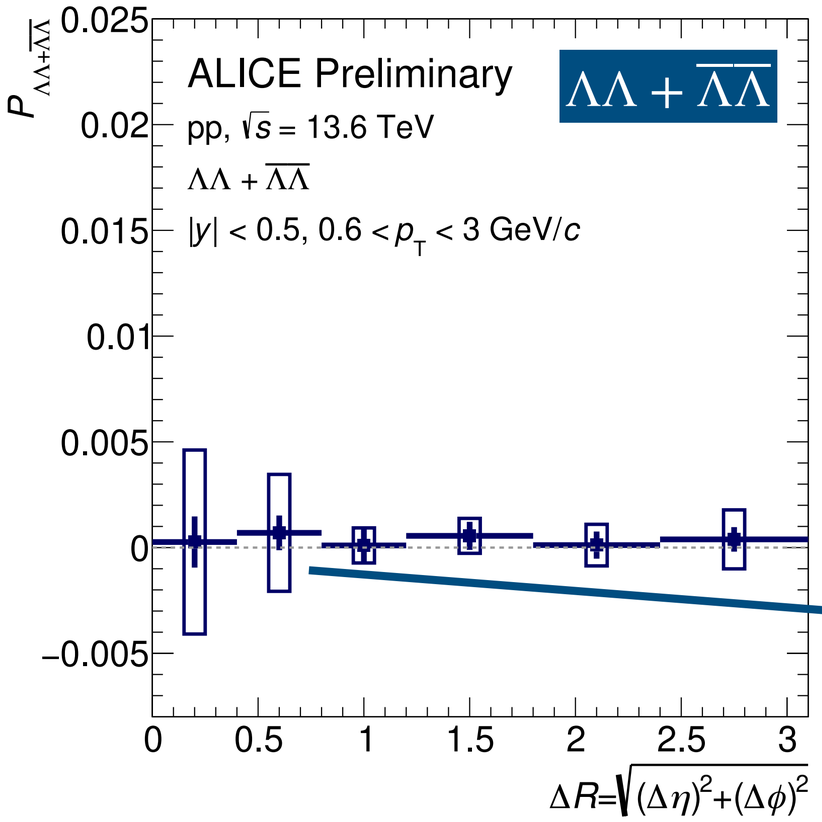


Tensions?

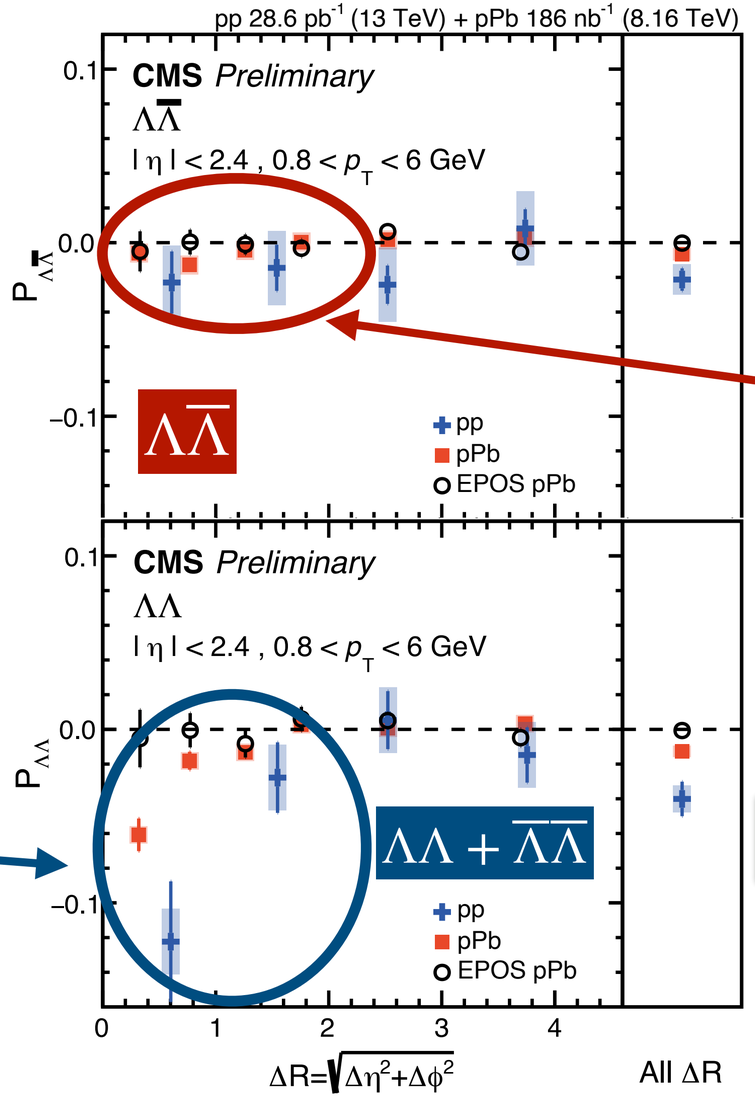


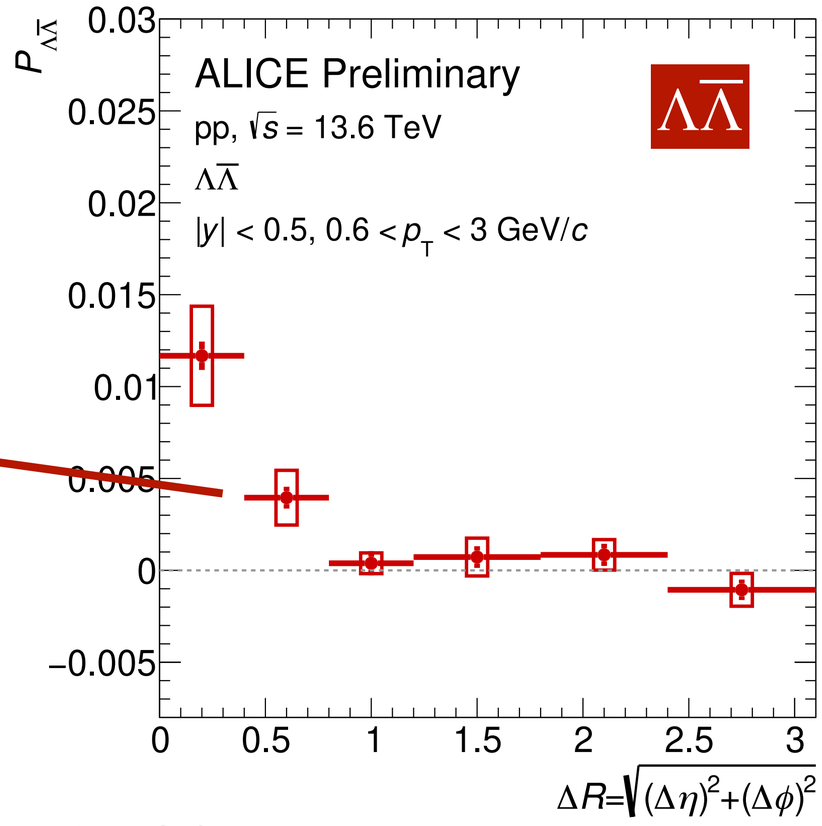
Comparison with CMS

- $\Lambda\overline{\Lambda}$: different trend at least
- $\Lambda\Lambda + \overline{\Lambda}\overline{\Lambda}$: different trend and magnitude



CMS PAS-HIN-26-002





ALICE $|y| < 0.5$ **CMS** $|\eta| < 2.4$

Acceptance driven effect?

➡ Guidance is needed

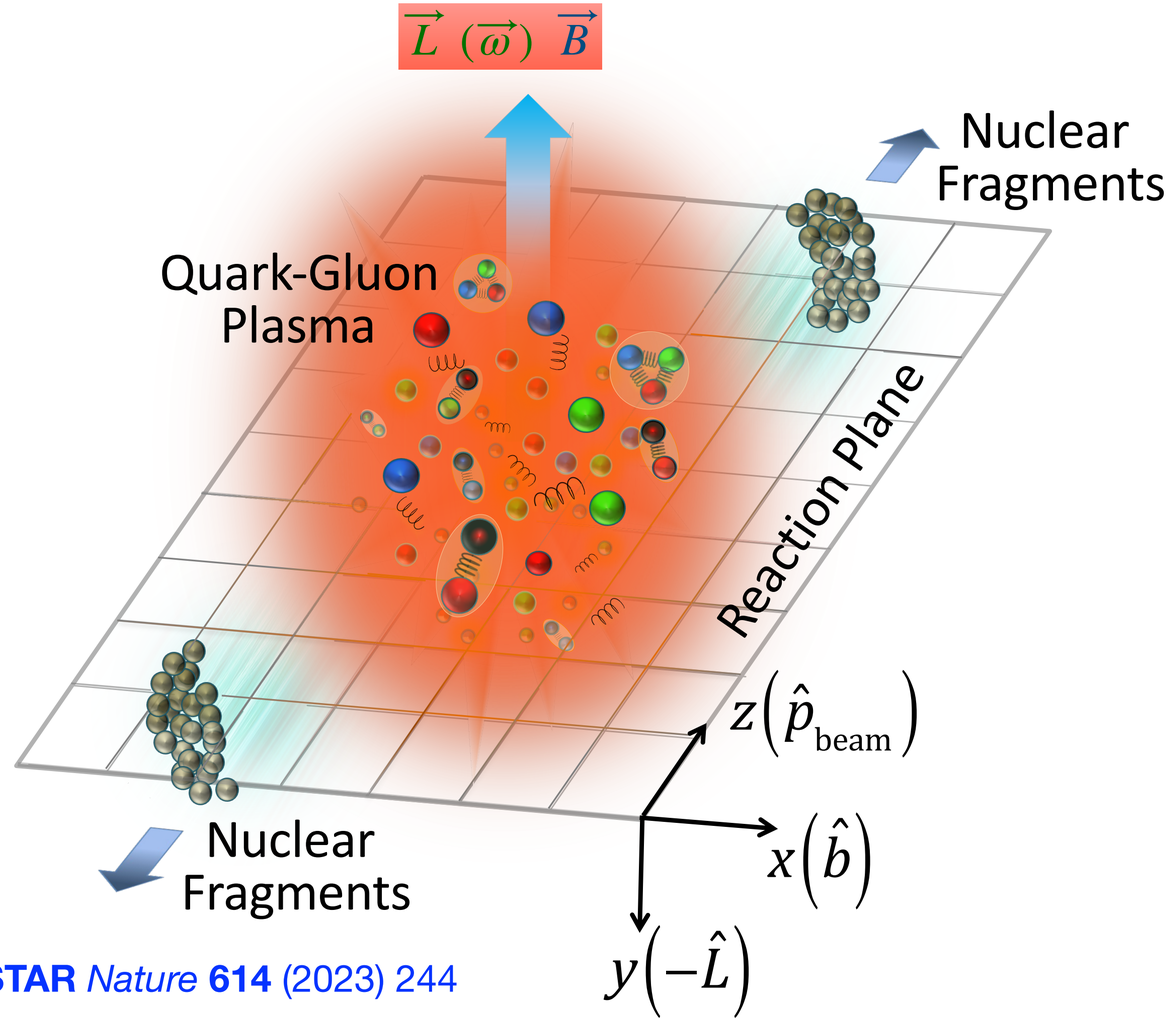
Conclusion

With Run 3 data, ALICE has performed new and more precise measurements of hyperon polarization in Pb-Pb and OO collisions

- First observation of non-zero Λ polarization at LHC energies with 5σ
- The first measurement at the LHC of Λ longitudinal polarization induced by triangular flow is compatible with second-order one
- First measurement of Ξ longitudinal polarization in Pb-Pb, compatible with Λ and supporting the expected spin hierarchy
- First measurement of Λ longitudinal polarization in OO collisions, positive and consistent with Pb-Pb at similar multiplicities
- Λ spin correlations are measured pp — first step toward understanding quark–hadron spin transfer

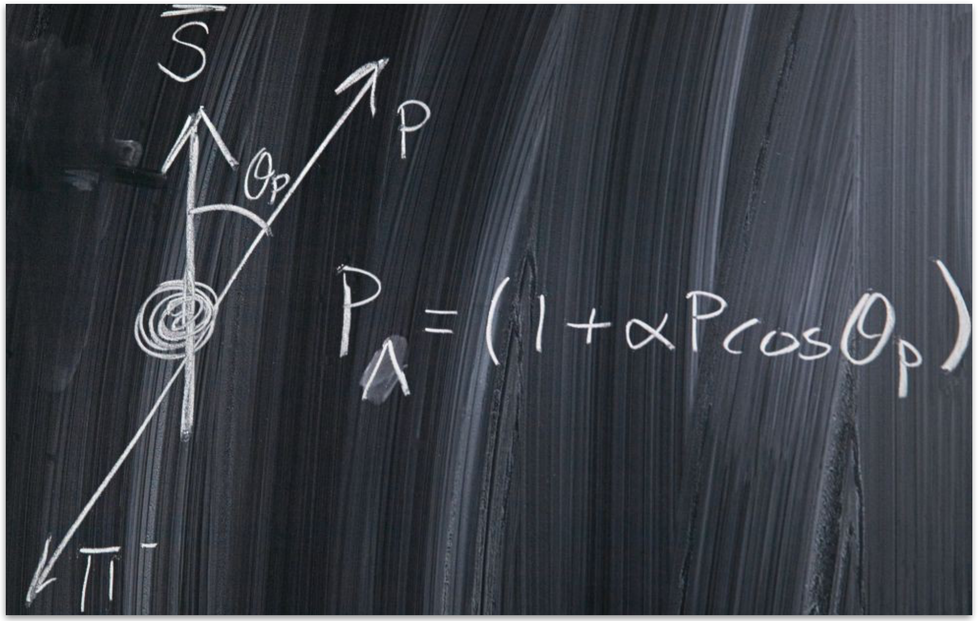
Backup

Polarization estimation



STAR *Nature* **614** (2023) 244

The Feynman lectures on physics, Volume III, Chapter 17–5

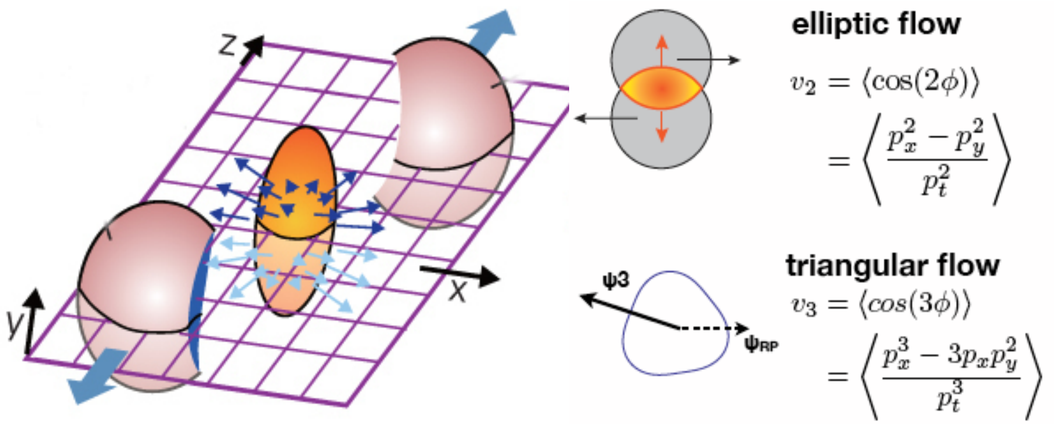


$$\frac{\mathrm{d}w}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\mathrm{H}} \vec{P}_{\mathrm{H}} \cdot \hat{e}_P^*)$$

$$\alpha_\Lambda = 0.732 \pm 0.014 \quad \alpha_{\bar{\Lambda}} = -0.758 \pm 0.012$$

[**PDG** *Phys. Rev.* **D110** (2024) 030001]

Polarization along the beam direction

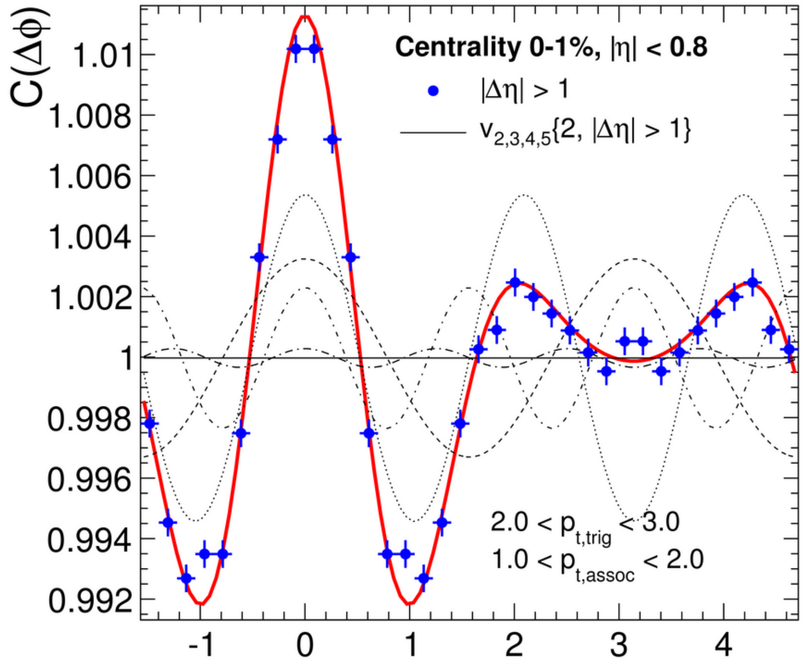


elliptic flow

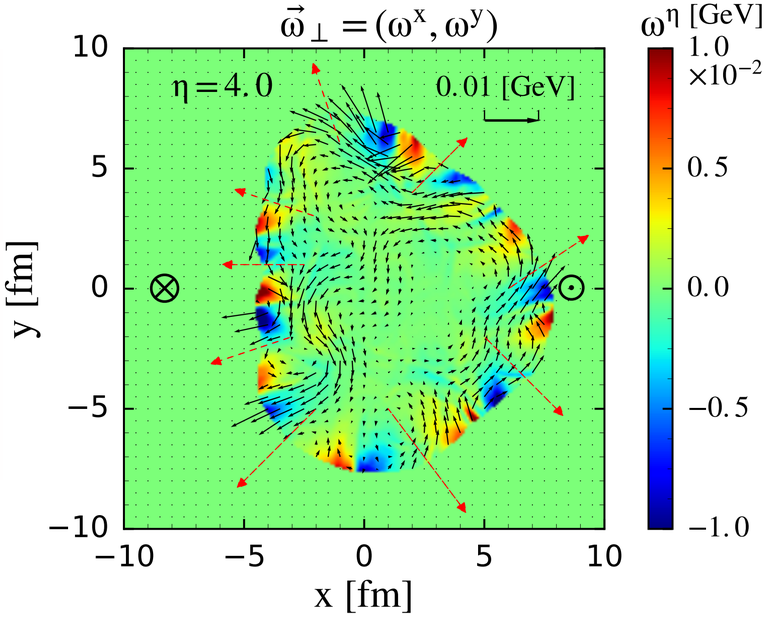
$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

triangular flow

$$v_3 = \langle cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle$$



ALICE *Phys. Rev. Lett.* **107** (2011) 032301

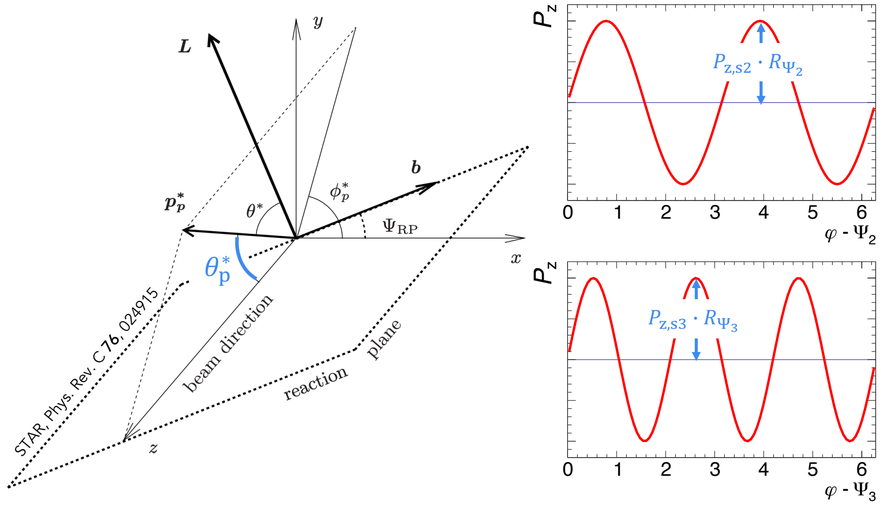


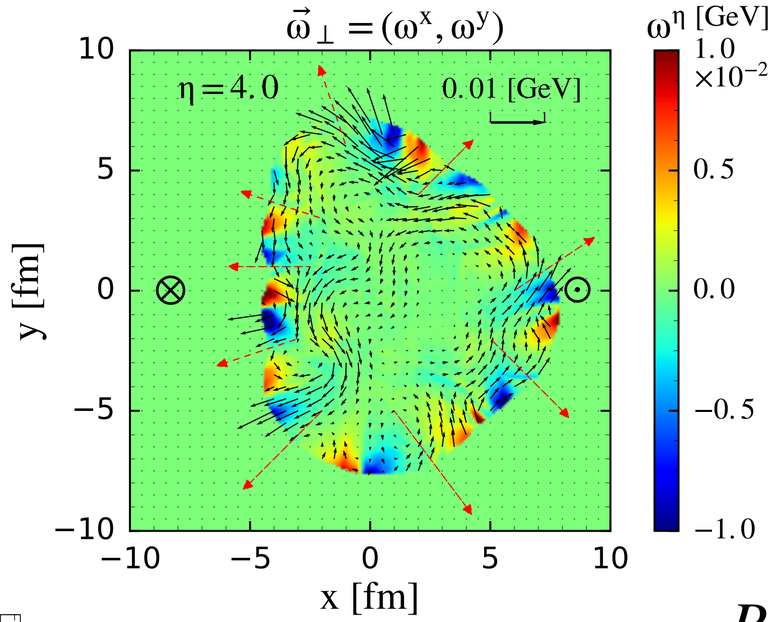
L.-G. Pang, Q. Wang, X.-N. Wang *el al.* *Phys. Rev. Lett.* **117** (2016) 192301

S. A. Voloshin, T. Niida *Phys. Rev.* **C94** (2016) 021901

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

Longitudinal polarization harmonics



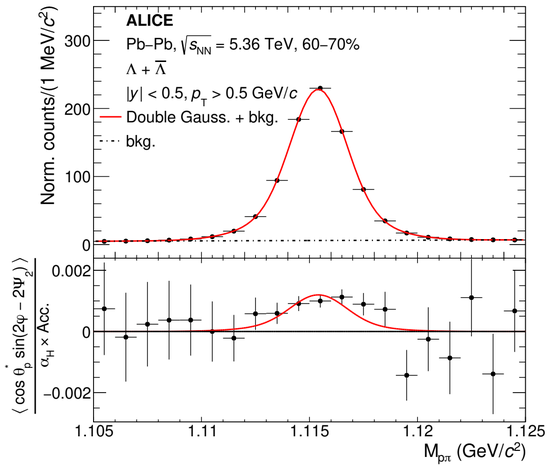


L.-G. Pang, Q. Wang, X.-N. Wang *el al.*
Phys. Rev. Lett. **117** (2016) 192301

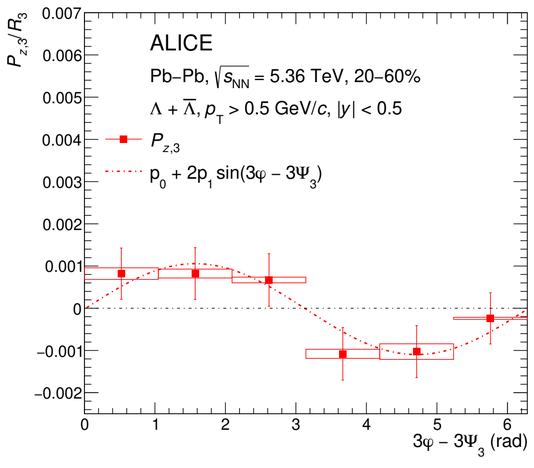
S. A. Voloshin, T. Niida
Phys. Rev. **C94** (2016) 021901

$$P_z = \frac{\langle \cos\theta^*_{\rm p} \rangle}{\alpha_{\rm H} \langle \cos^2\theta^*_{\rm p} \rangle}$$

$$P_{z,sn} = \frac{\langle P_z \sin n(\varphi_{\rm H} - \Psi_n) \rangle}{R^{(n)}_{\rm EP}}$$

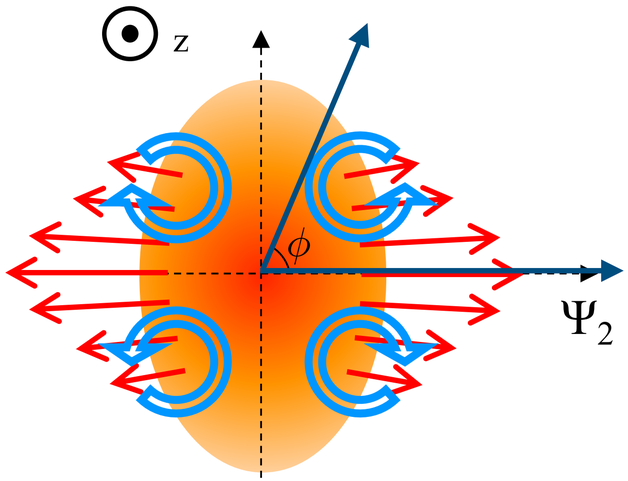


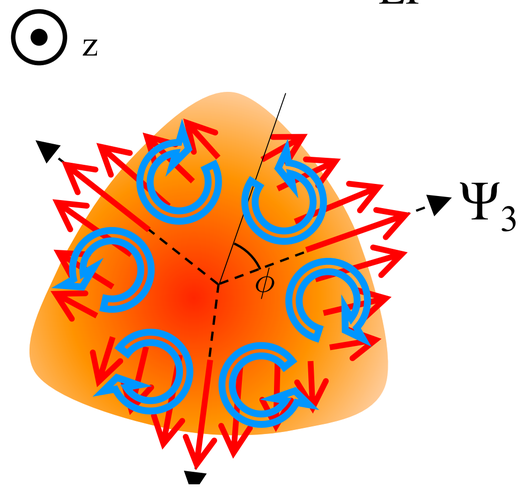
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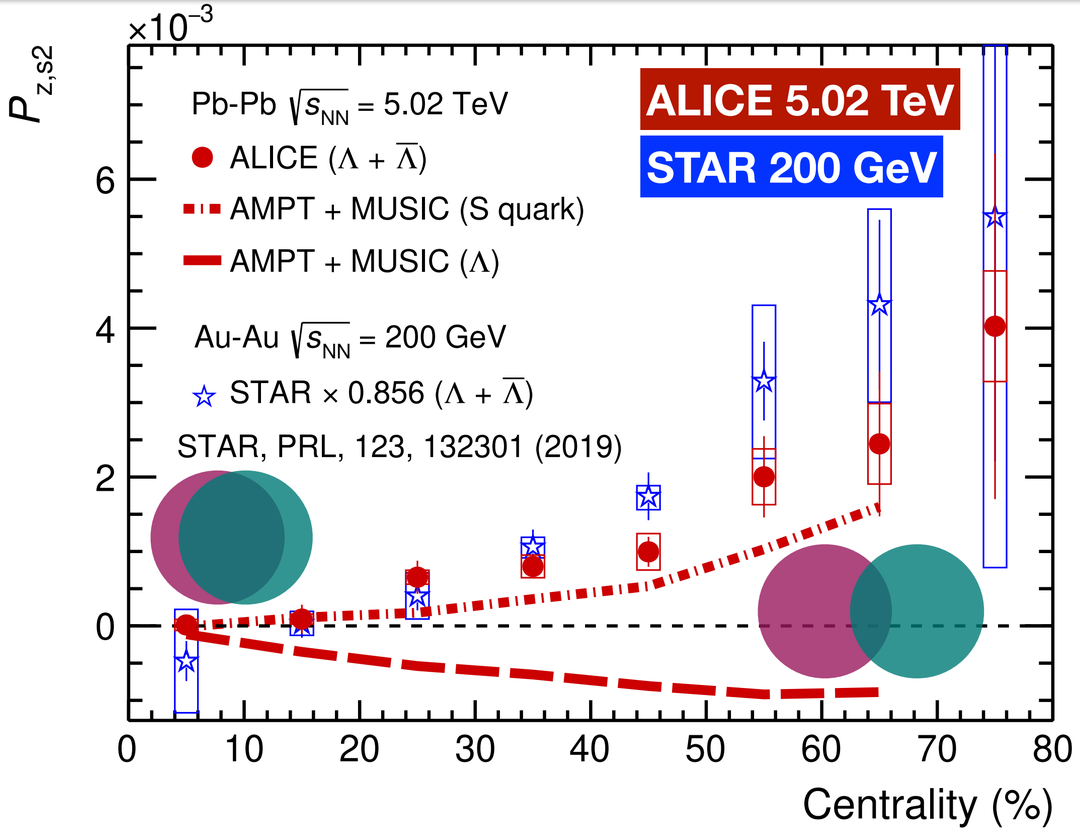
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ALICE *JHEP* **2610** (2026) 216

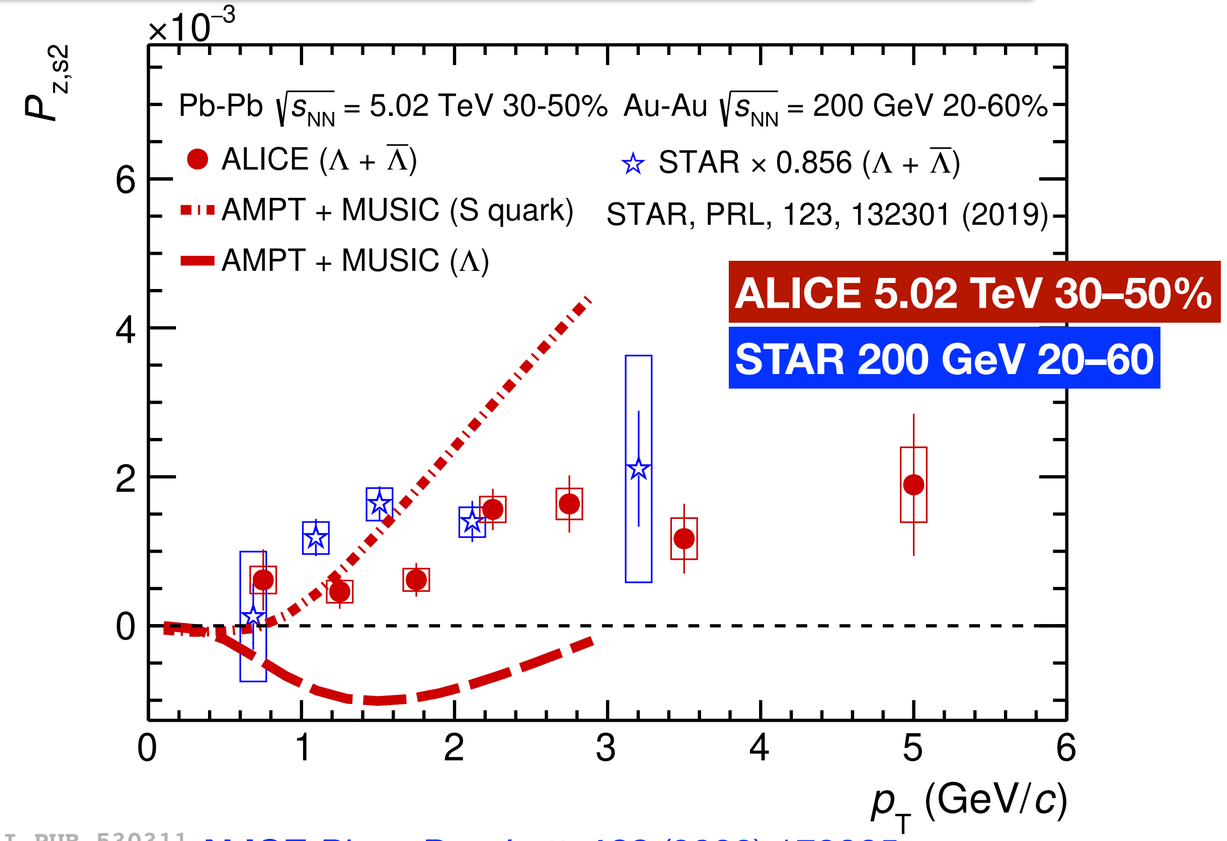




Comparison with STAR and predictions



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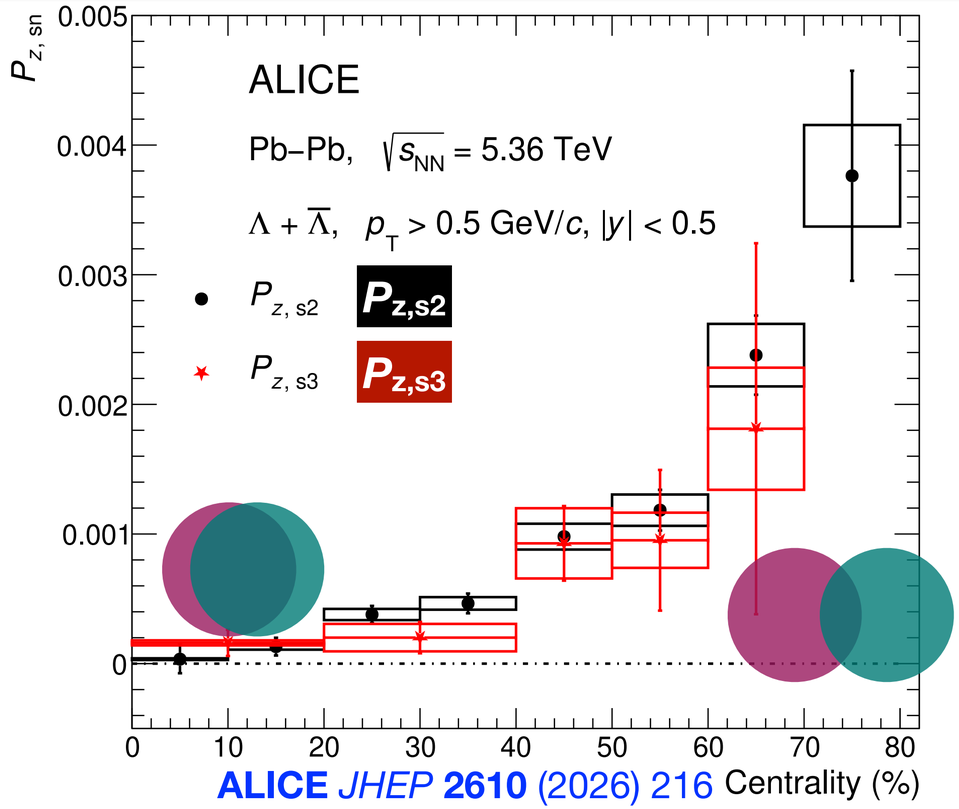
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ALICE *Phys. Rev. Lett.* **128** (2022) 172005

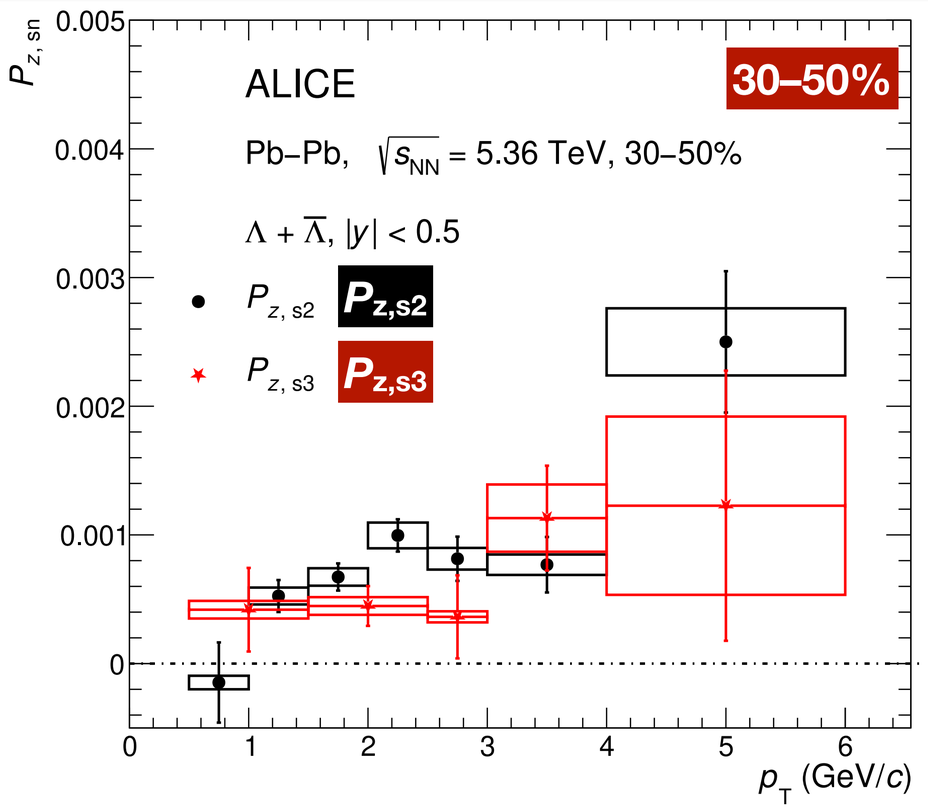
B. Fu *et al.*, *Phys. Rev. Lett.* **127** (2021) 142301

- $P_{z,s2}$ at the LHC is similar in magnitude to top RHIC energy
- Model predicts correct sign if shear-induced polarization is included and Λ inherits *s*-quark polarization

Polarization induced by triangle flow

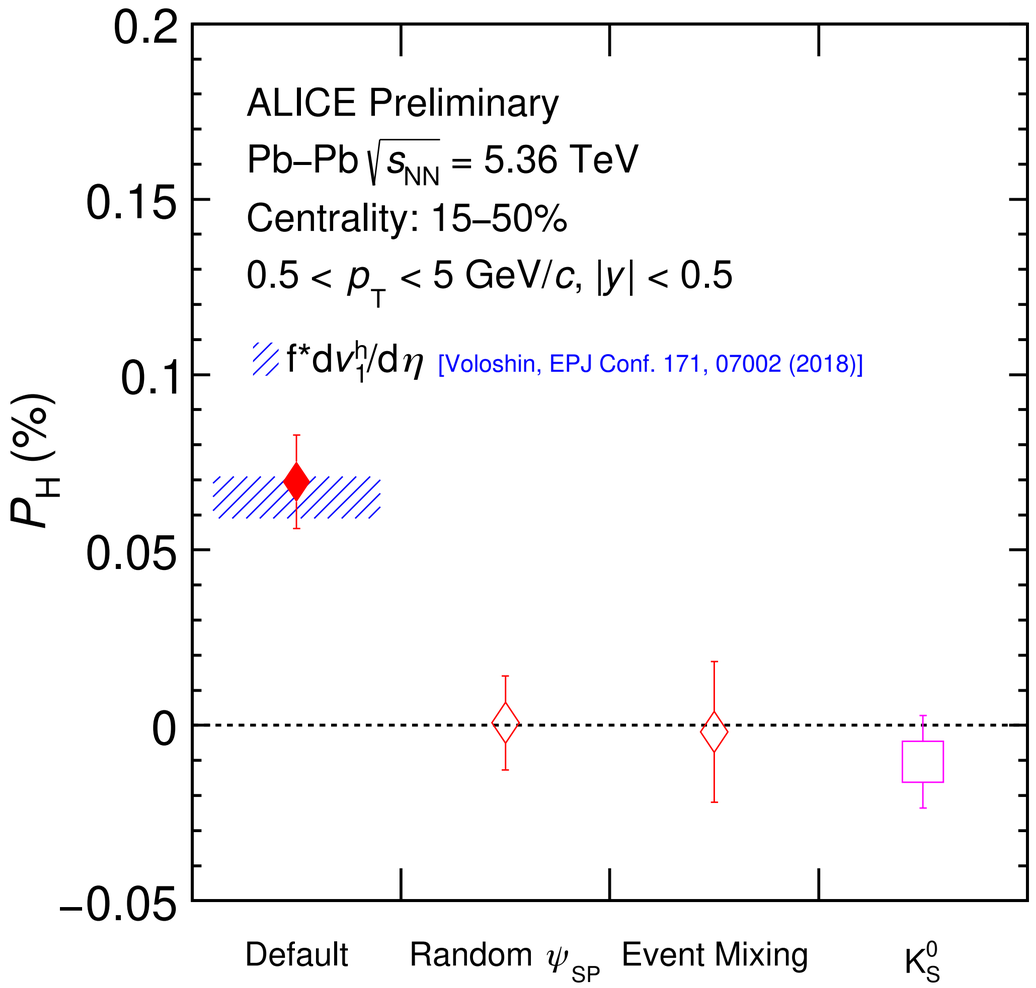


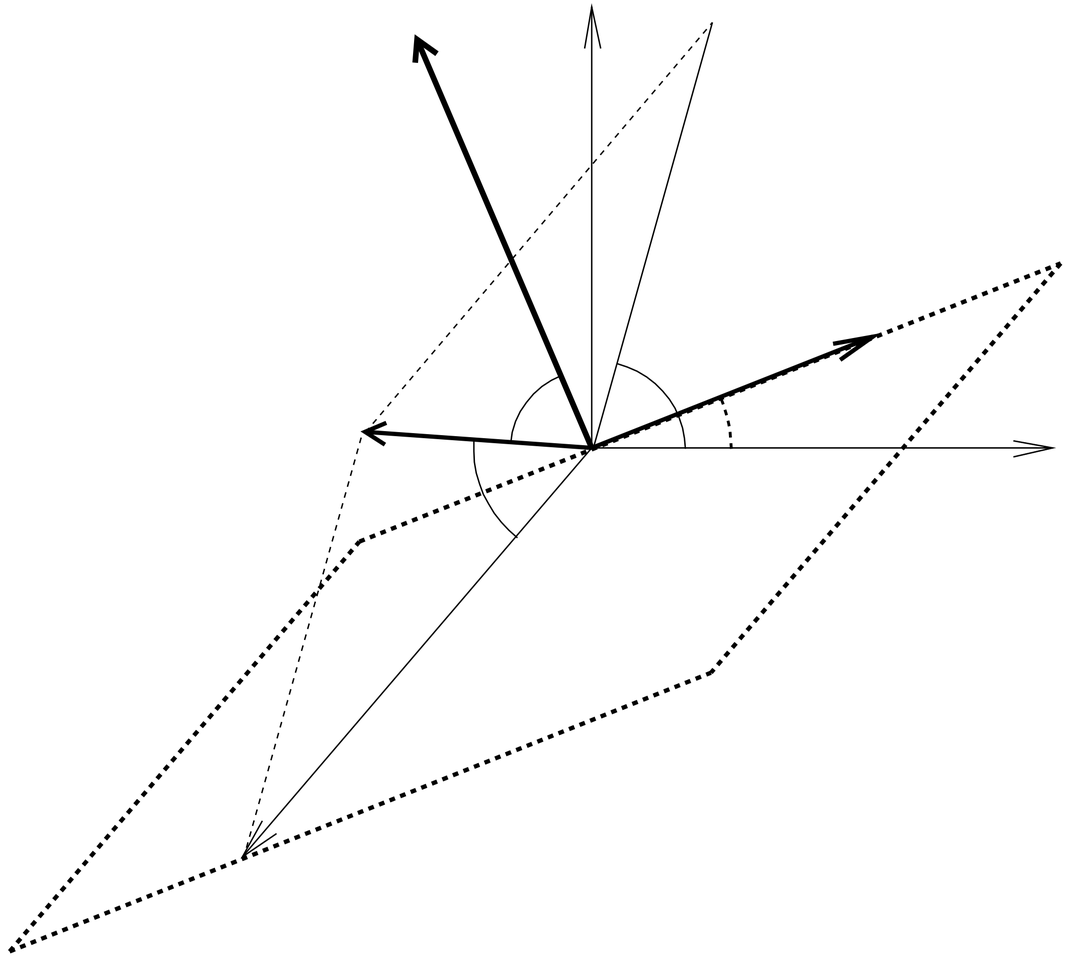
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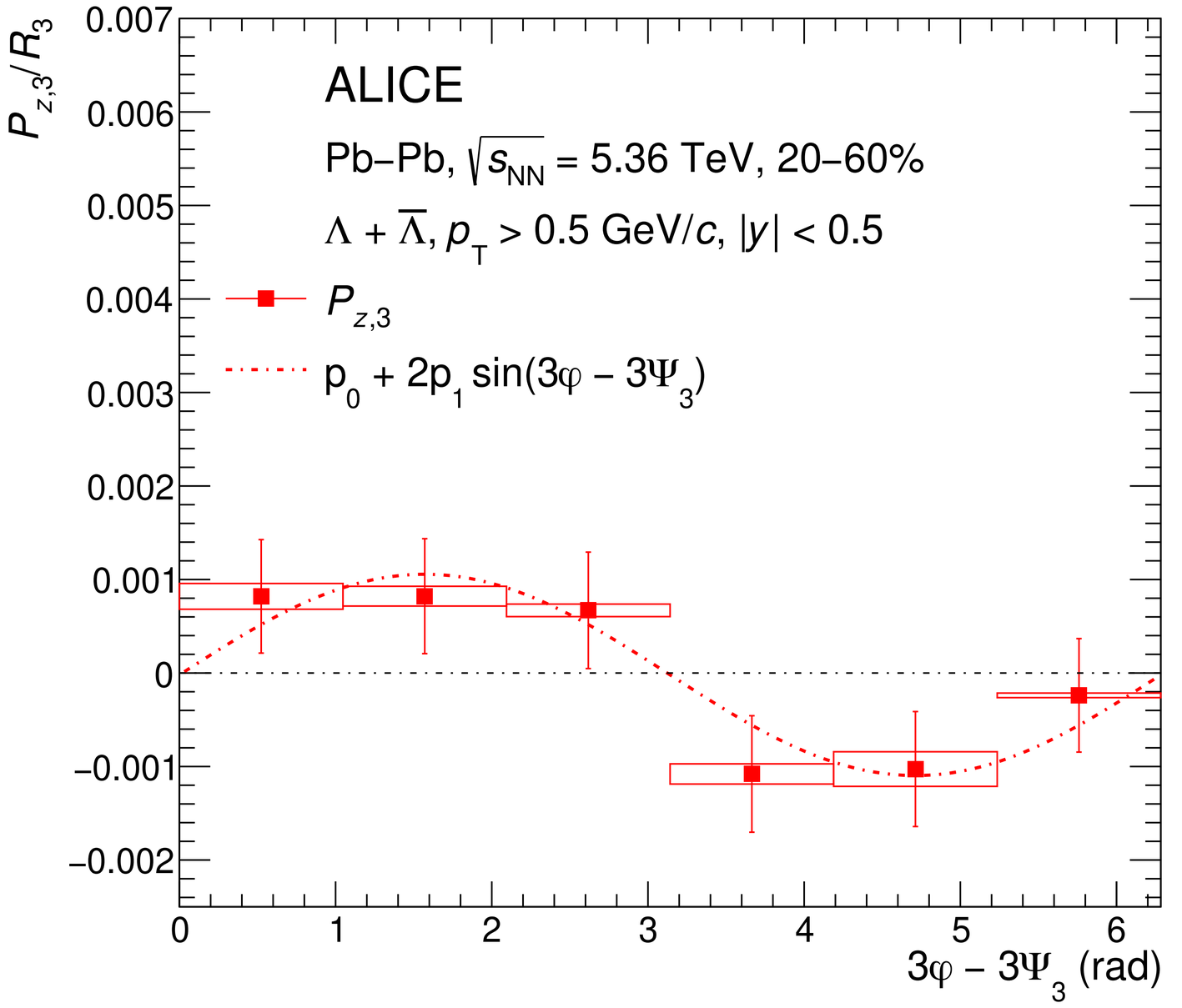
ALI-PUB-635123

- $P_{z,s3}$ is compatible with $P_{z,s2}$, despite the v_3 is smaller v_2
- Measurements of polarization induced by higher harmonics flow will be possible with 2024, 2025 and 2026 data





ALI-PREL-610485



ALI-PUB-635103

ALICE arXiv:2606.18070