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Quarkonium polarization in pp and Pb—Pb collisions with ALICE

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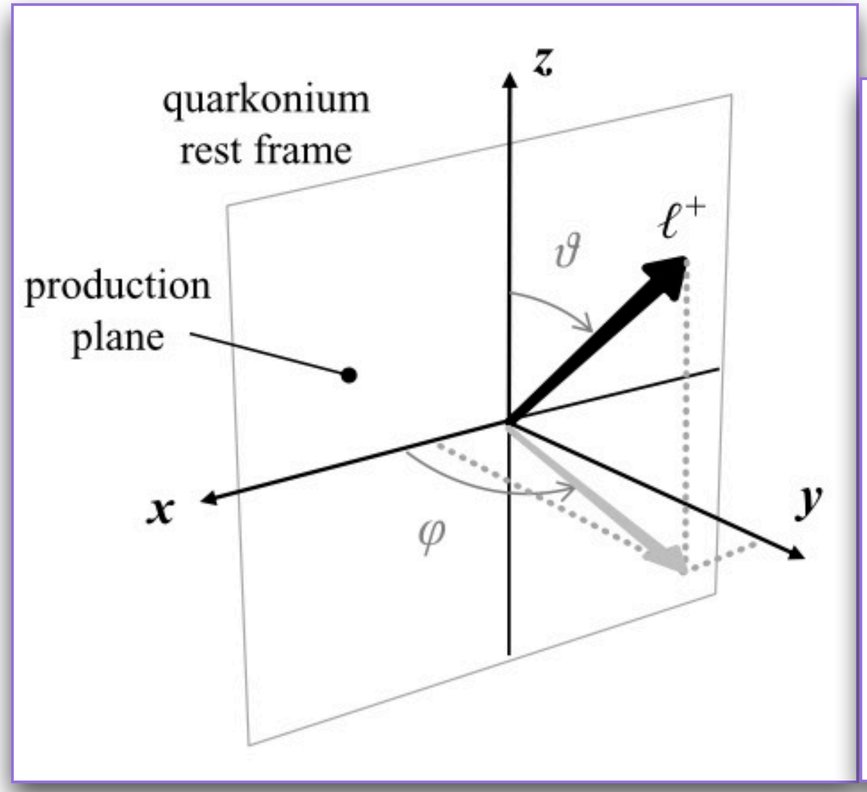
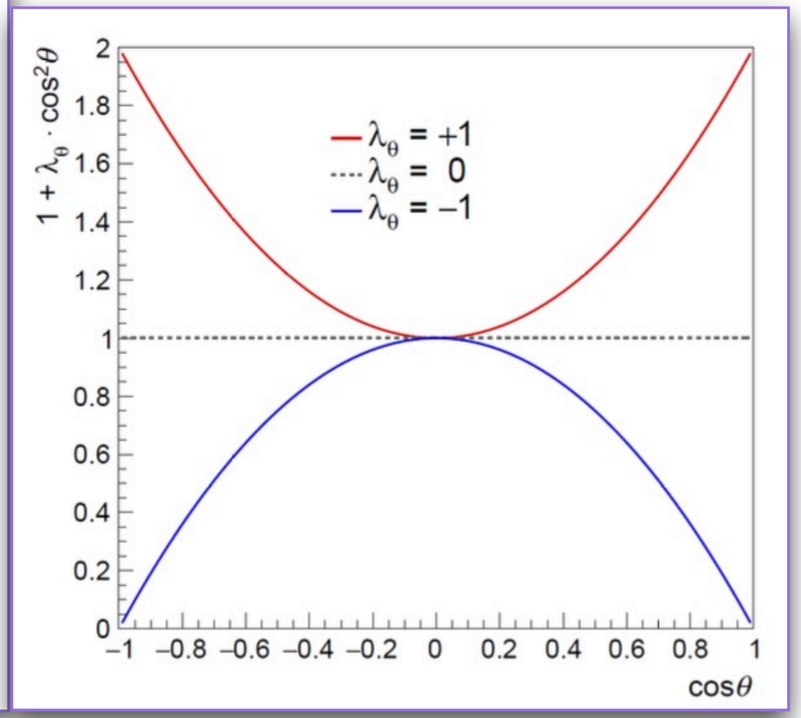
Introduction

Polarization:

- Defined as the particle spin-alignment with respect to a chosen direction
- Measured via anisotropies in the decay products angular distributions

$$W(\cos\theta,\ \varphi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\sin 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi)$$





GOAL: obtain λ_θ , λ_φ and $\lambda_{\theta\varphi}$

$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (0,\ 0,\ 0)$ No polarization

$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (+1,\ 0,\ 0)$ Transverse

$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (-1,\ 0,\ 0)$ Longitudinal

Physics motivation

Polarization in pp collisions: constrain **quarkonium production mechanisms**

Theoretically

- J/Ψ:
  - **NLO NRQCD** ==> transverse polarization
  - **NLO CSM** ==> longitudinal polarization

Phys. Rev. Lett. 108 (2012) 172002

- Υ:
  - **NLO NRQCD** ==> **no significant** polarization for $\Upsilon(1S)$ and $\Upsilon(2S)$ states, but a strong transverse polarization for $\Upsilon(3S)$ at high p_{T}

Phys. Rev. Lett. 112 (2014) 3, 032001

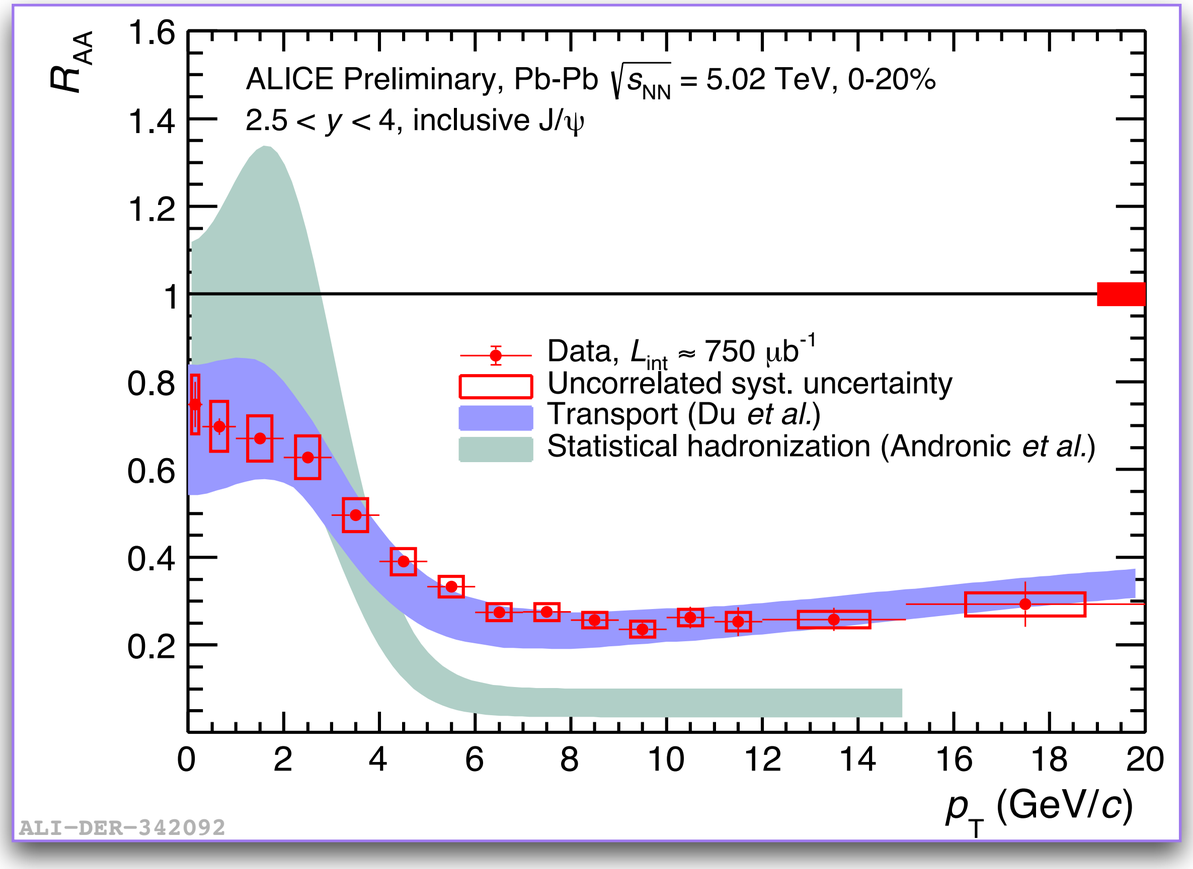
  - **ICEM** ==> transverse polarization and no significant differences in polarization among the $\Upsilon(nS)$ states

Phys. Rev. D 99 (2019) 3, 034007

No sizeable polarization is observed for the existing quarkonium polarization measurements

Physics motivation

Polarization in Pb—Pb collisions

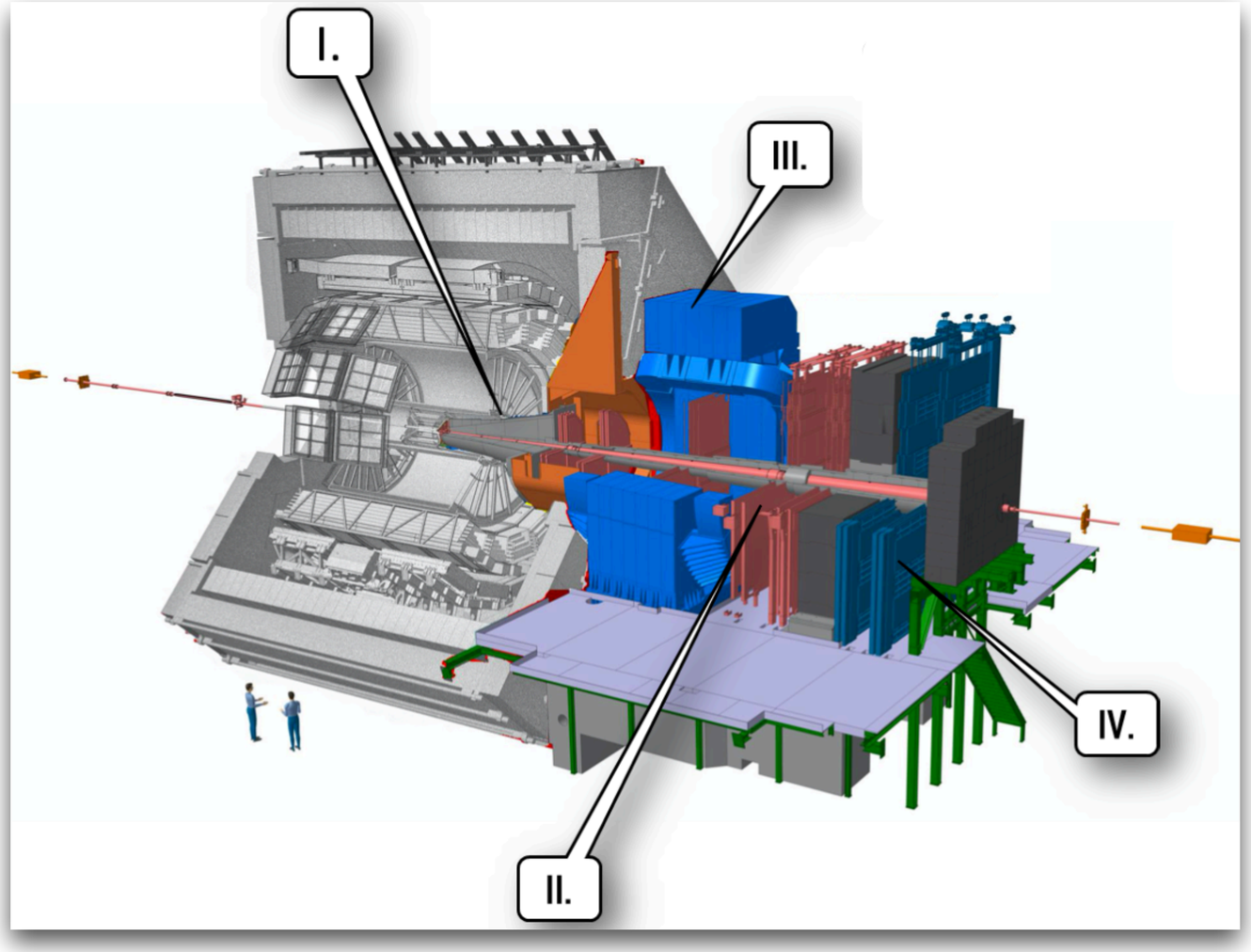


- Potential difference w.r.t pp collisions
  - In central collisions
    - Modification of **prompt** J/Ψ **feed-down fractions** due to $\Psi(2S)$ and χ_c suppression in the QGP

$$J/\Psi^{\text{Prompt}}: \ (60\%)^{\text{Direct}} + (30\%)^{\chi_c} + (10\%)^{\Psi(2S)}$$

    - Contribution from charmonium **(re)generation**
  - In non-central collisions
    - Large **angular momentum** due to the medium rotation is predicted — Phys. Rev. C **77**, 024906
    - Huge **magnetic field** is expected — Nucl. Phys. A 803 (2008) 227–253

A Large Ion Collider Experiment



A dedicated heavy-ion experiment at the LHC

Muon Spectrometer ($-4 < \eta < -2.5$)

I. Absorbers: muon from π and K background reduction

II. Tracking system + III. Dipole magnet: muon track reconstruction, muon momentum and its electric charge measurement

IV. Trigger system: muon PID and **unlike sign dimuon trigger** (for the quarkonium analyses)

Inclusive quarkonium detection down to $p_{\mathrm{T}} = 0$

A Large Ion Collider Experiment

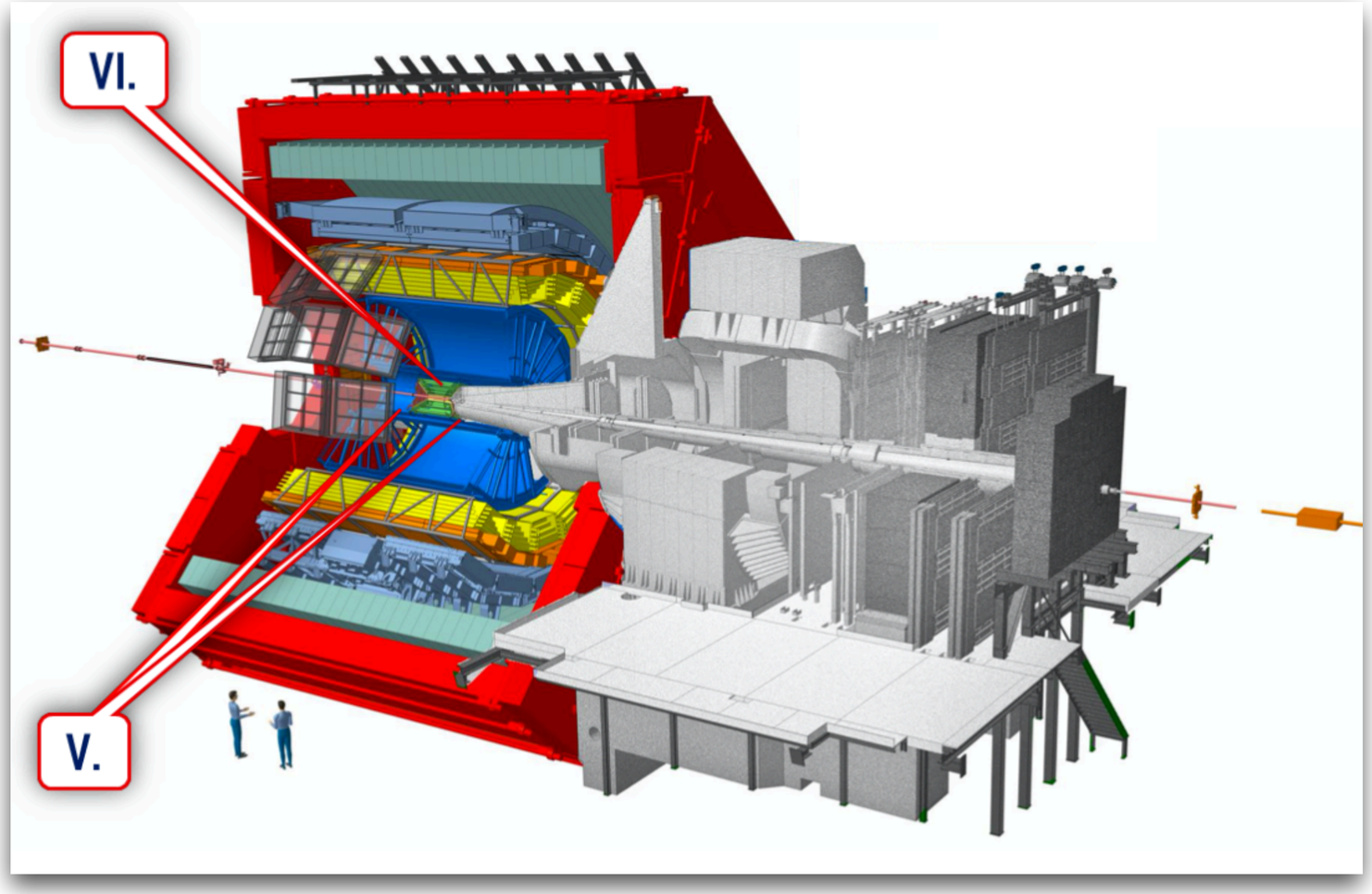
A dedicated heavy-ion experiment at the LHC

VI. Silicon Pixel Detector

- Vertex reconstruction
- Event Plane determination

V. V0 Detectors

- Event trigger
- Centrality determination
- Background rejection
- Event plane reconstruction

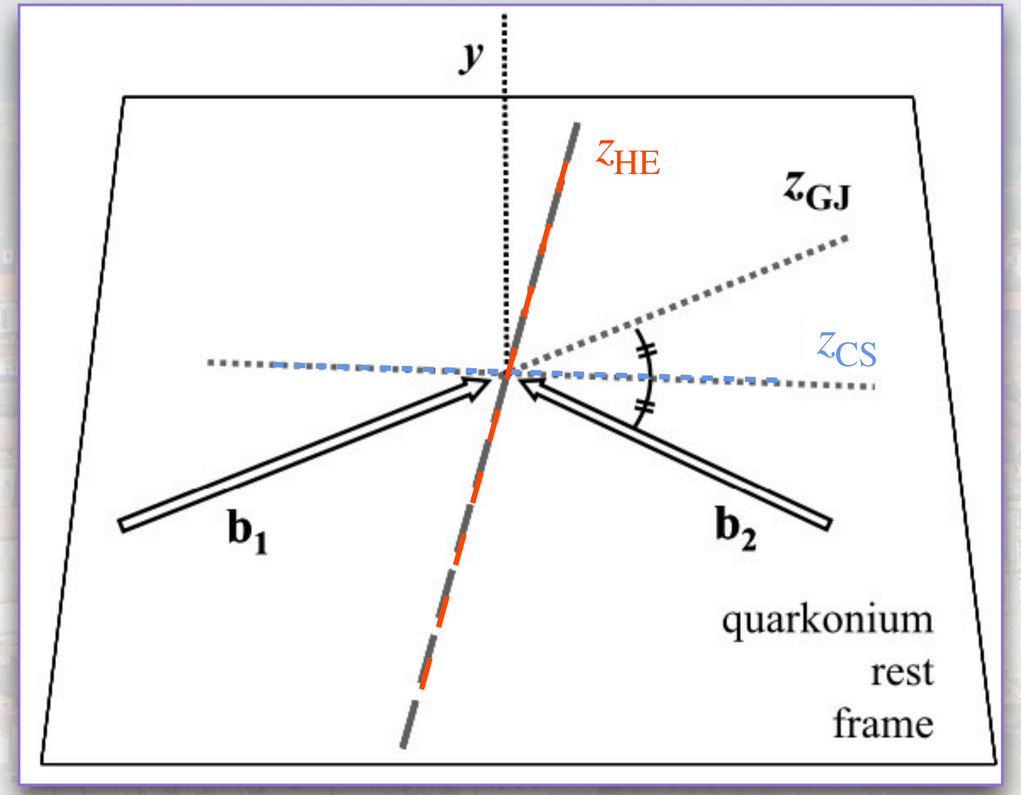


$\Upsilon(1S)$ polarization in pp collisions

$\Upsilon(1S)$ is measured based on the data from pp collisions at $\sqrt{s} = 13$ TeV

Reference frames:

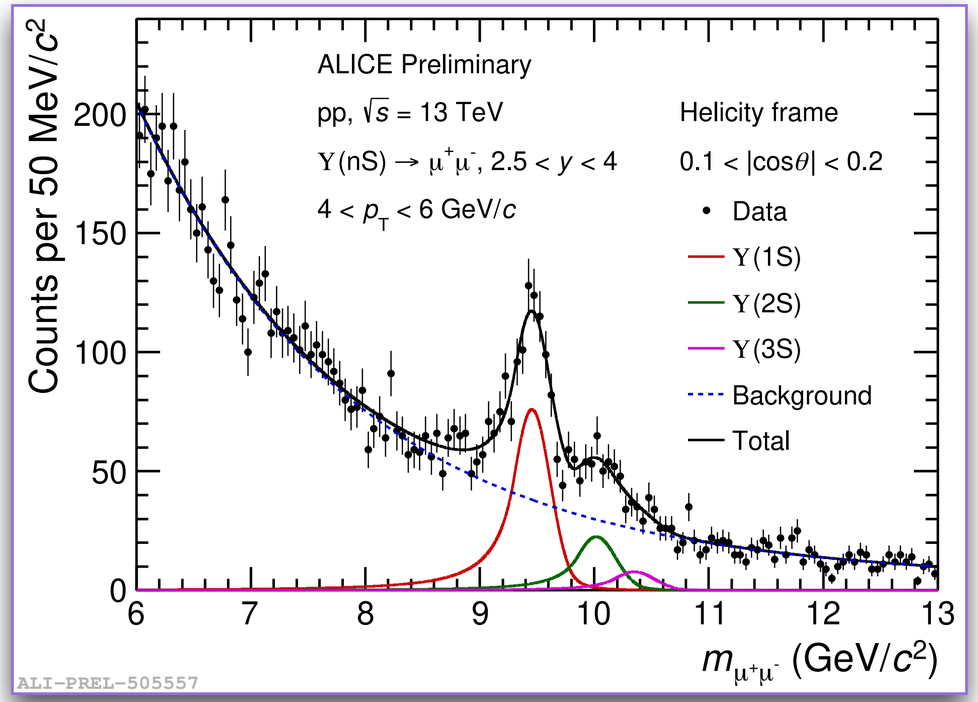
- Helicity (HE): the direction of quarkonium in the center-of-mass frame
- Collins-Soper (CS): the bisector of the angle between one beam and the opposite of the other beam in the quarkonium rest frame



$\Upsilon(1S)$ polarization in pp collisions: analysis strategy

Signal extraction

- **Raw** number of $\Upsilon(1S)$ obtained by fitting the dimuon invariant mass distribution

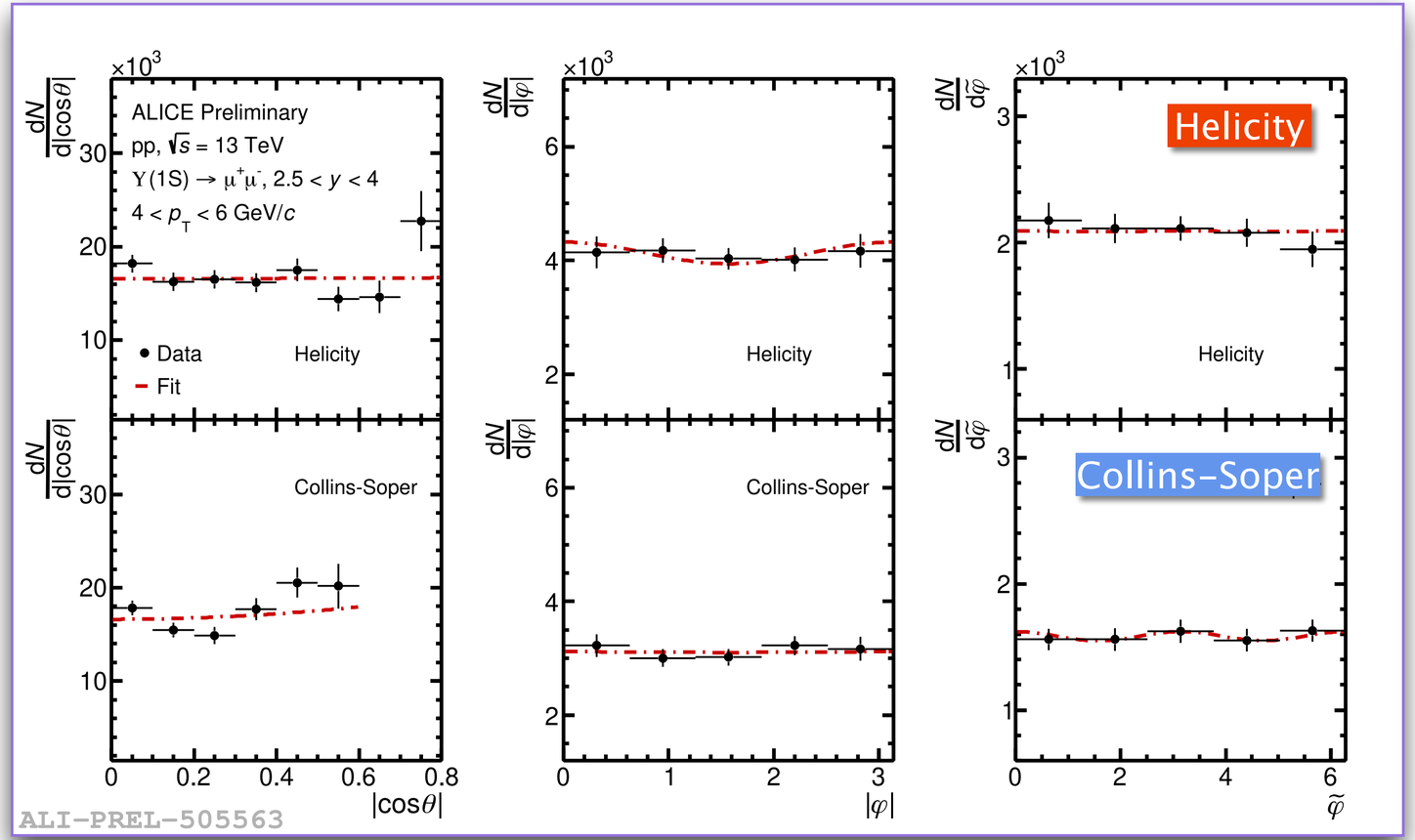


Acceptance x efficiency correction

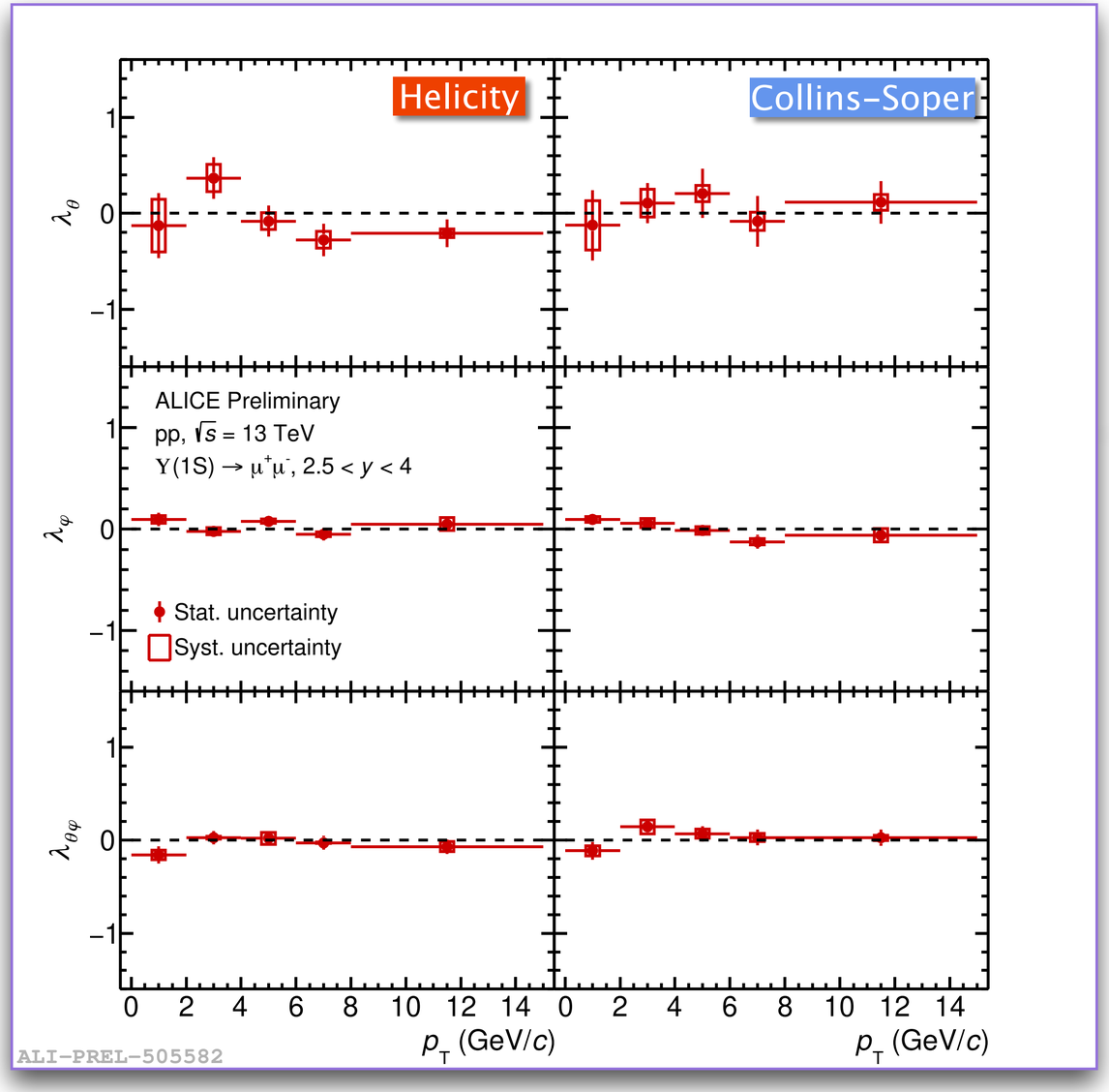
- **Corrected** number of $\Upsilon(1S)$ evaluation based on a MC simulation

Polarization parameters determination

- λ_θ , λ_φ and $\lambda_{\theta\varphi}$ extracted by fitting to the $A \times \varepsilon$-corrected $\Upsilon(1S)$ angular distributions in both frames simultaneously

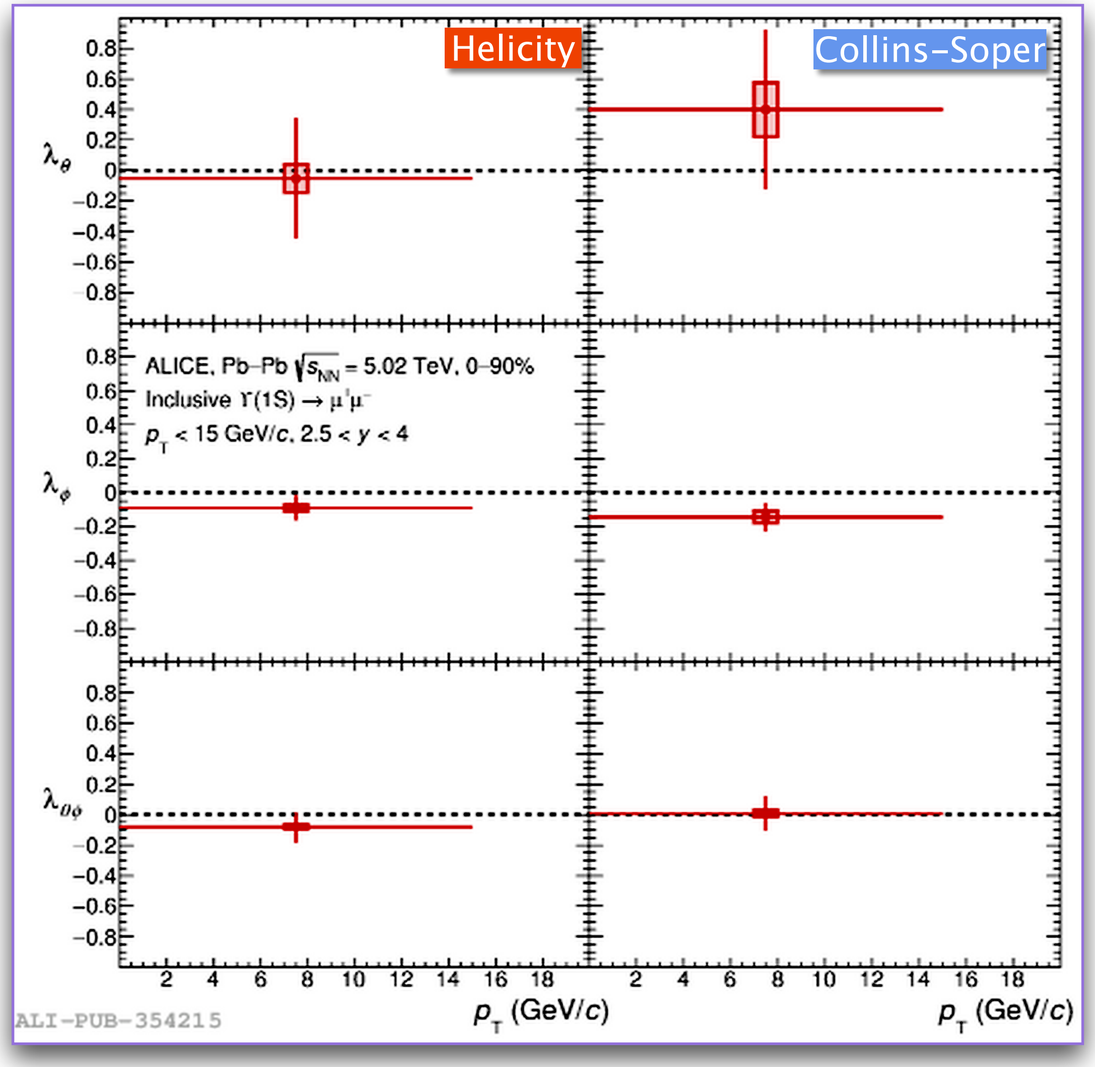


$\Upsilon(1S)$ polarization in pp collisions



- First ALICE $\Upsilon(1S)$ polarization measurement in pp collisions
  - λ_θ , λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both **HE** and **CS** frames

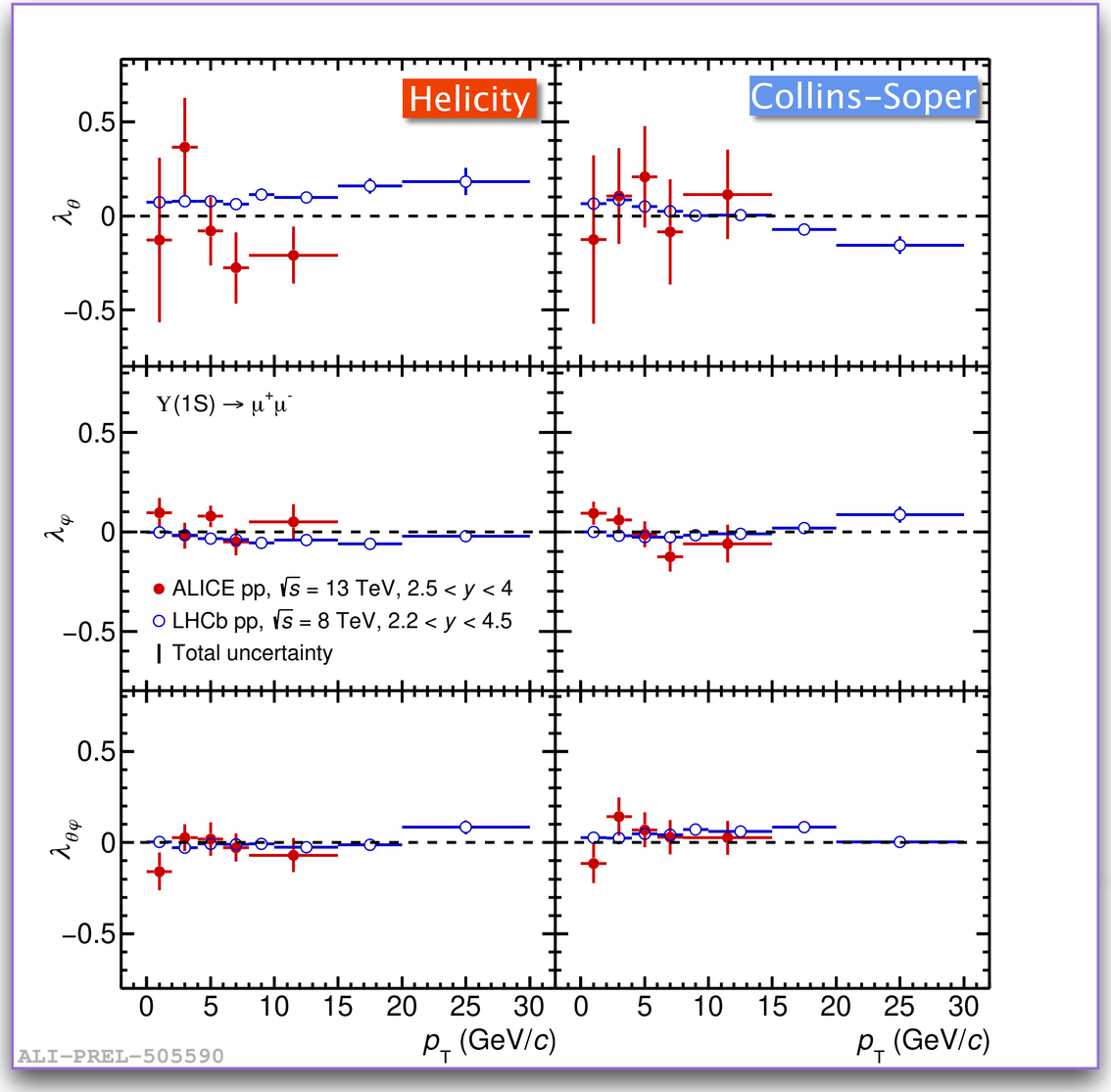
Υ(1S) polarization in Pb—Pb collisions



- First ALICE Υ(1S) polarization measurement in pp collisions
  - λ_θ , λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both **HE** and **CS** frames
  - Compatible with **Pb—Pb** results

Phys. Lett. B 815 (2021) 136146

Υ(1S) polarization in pp collisions



- First ALICE Υ(1S) polarization measurement in pp collisions
  - λ_θ , λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both **HE** and **CS** frames
  - Compatible with **Pb—Pb** results

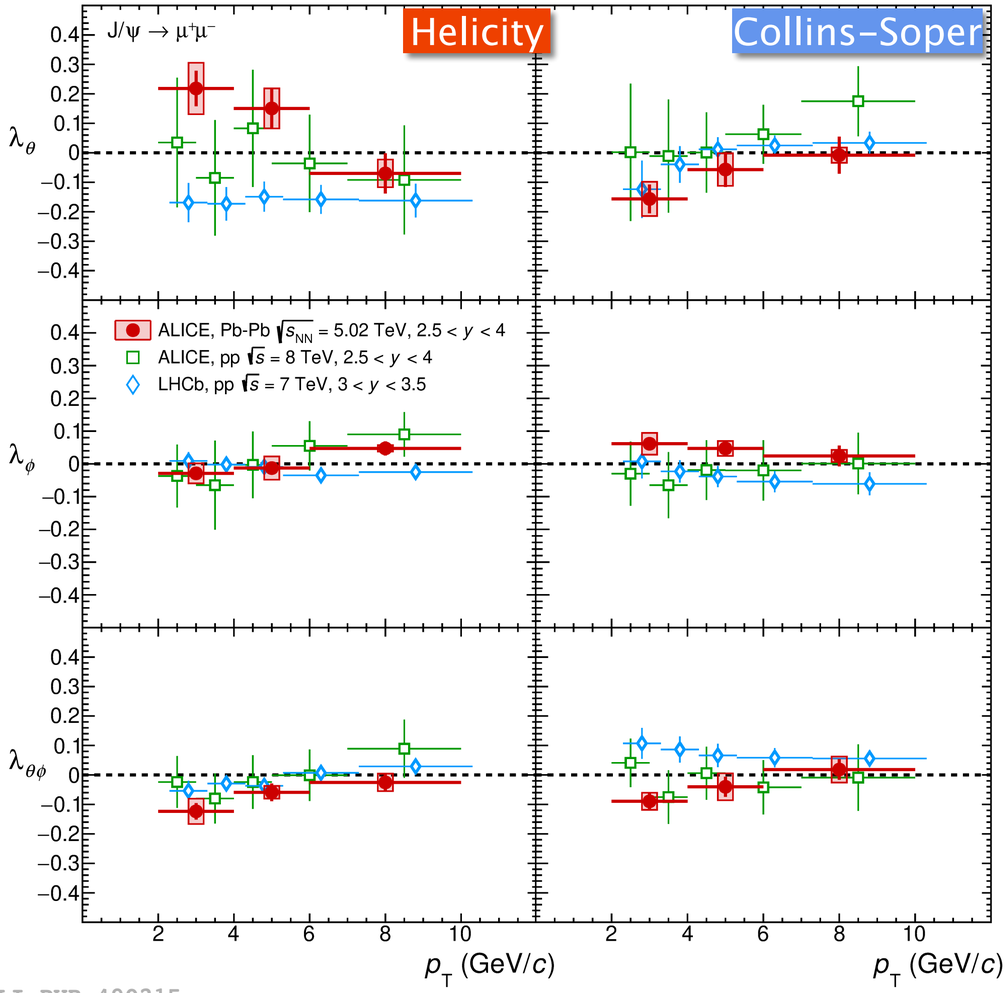
    Phys. Lett. B 815 (2021) 136146
  - Good agreement with **LHCb** in a similar rapidity range within the large experimental uncertainties

    JHEP 12 (2017) 110
  - **LHCb** data qualitatively described by **NLO NRQCD** calculations

    Phys. Rev. Lett. 112 (2014) 3, 032001

J/Ψ polarization in pp and Pb—Pb collisions

- **ALICE** measured J/Ψ polarization in Pb—Pb collisions
  - All polarization parameters are close to zero within uncertainties
    - λ_θ shows a maximum 2σ deviation w.r.t zero in both **HE** and **CS** frames for $2 < p_{\mathrm{T}} < 4$ GeV/c
  - Compatible with **ALICE** results in **pp** collisions within uncertainties — EPJC 78 (2018) 562
  - 3σ difference w.r.t **LHCb** in **pp** collisions in **HE** frame — EPJC 73 (2013) 11



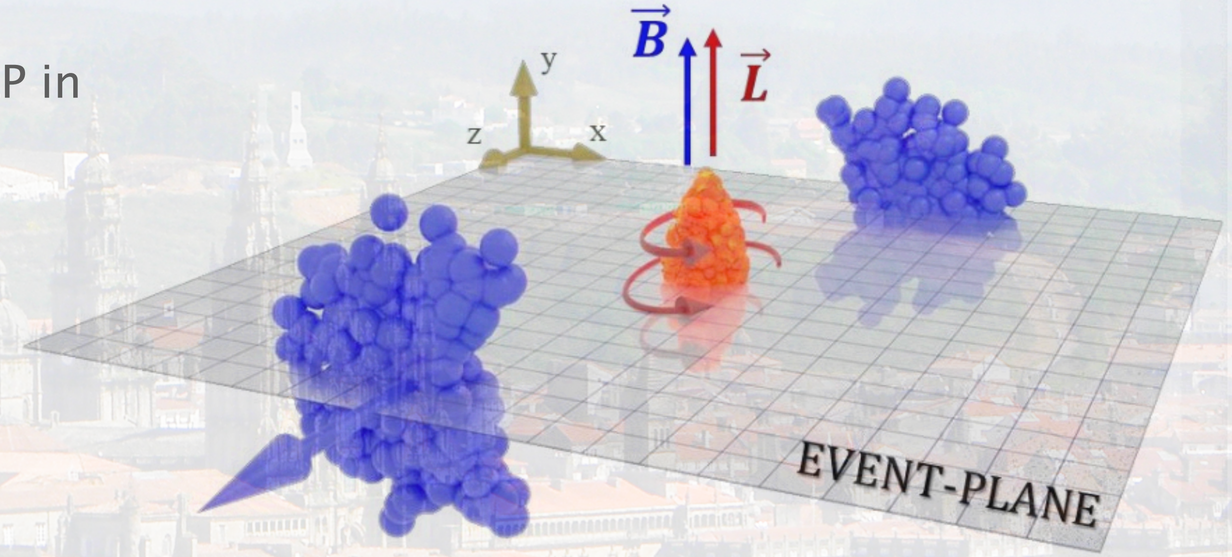
- Difference due to **suppression/regeneration** effects in Pb—Pb w.r.t pp collisions?
- What is the role of the angular momentum ($\vec{L}$) and the magnetic fields ($\vec{B}$)?

J/Ψ polarization as a function of Event Plane

J/Ψ is measured based on the data from Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Reference frame:

- Event Plane based frame (EP): axis orthogonal to the EP in the collision center-of-mass frame
- EP normal to $\vec{B}$ and $\vec{L}$
- Significant spin alignment observed for light vector mesons (K^{*0}, Φ) Phys. Rev. Lett 125 (2020) 012301
- Heavy quark pair production
  - Occurs early in the collision ($t \sim 0.1$ fm/c)
  - Experiences both the short living $\vec{B}$ and the $\vec{L}$ of the rotating medium

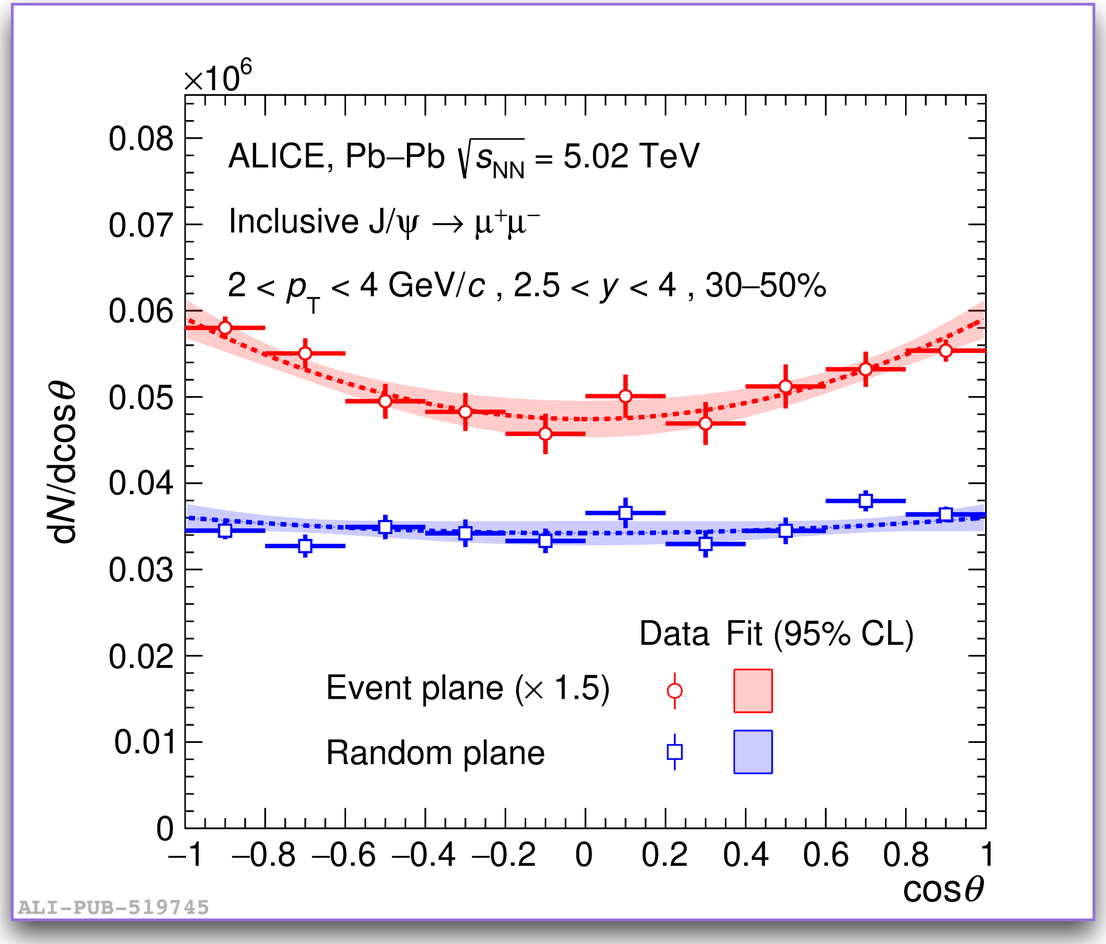


J/Ψ polarization vs EP in Pb—Pb collisions: analysis strategy

- Signal extraction
  - **Reweighting** applied at the dimuon candidate level with a 2-dimensions $(p_{\mathrm{T}}, \cos\theta)$ $A \times \varepsilon$ **map**
  - Fitting the corrected dimuon invariant mass distribution for the extraction of the raw yield
- Polarization parameters determination
  - Fitting the corrected angular distributions and extracting the polarization parameters

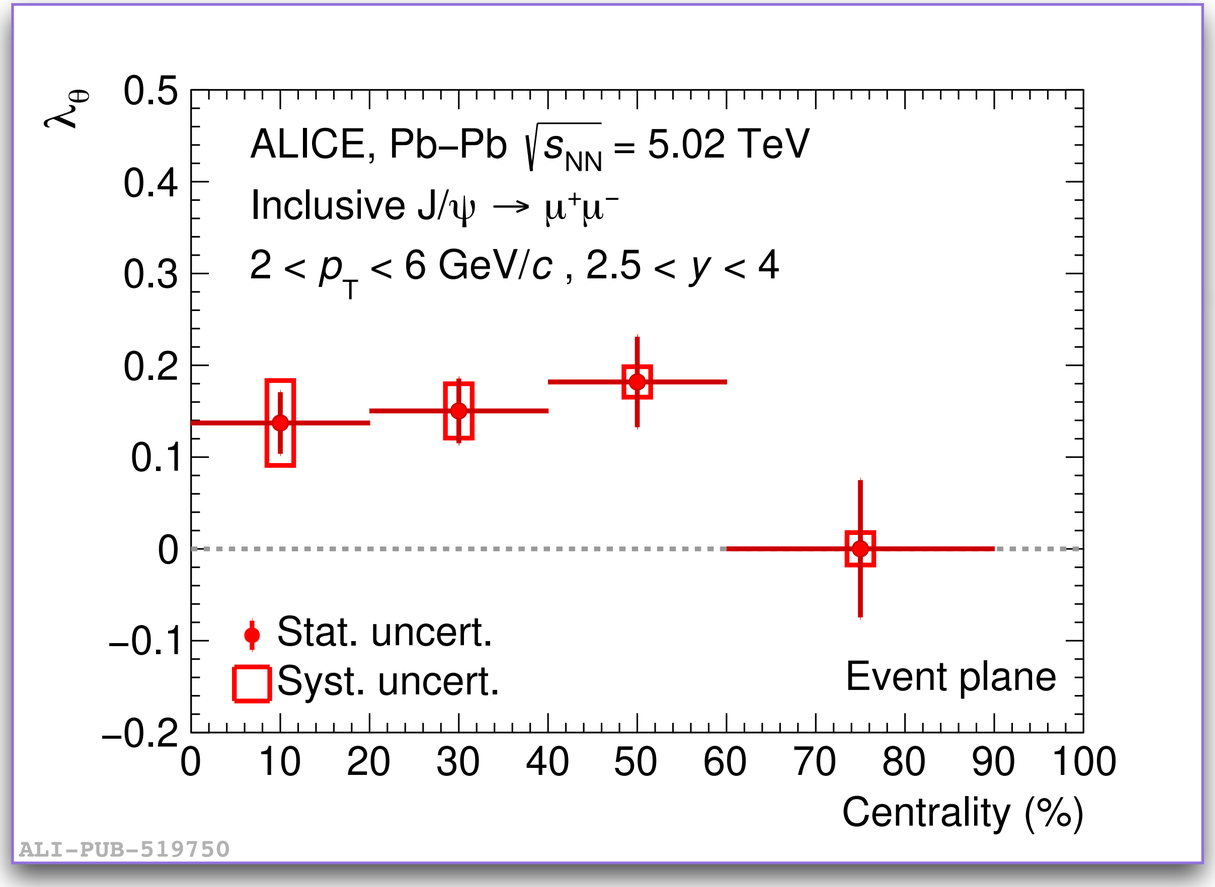
Cross check: λ_θ compatible with zero when evaluated w.r.t a **random EP**

arXiv:2204.10171



J/Ψ polarization as a function of EP in Pb—Pb collisions

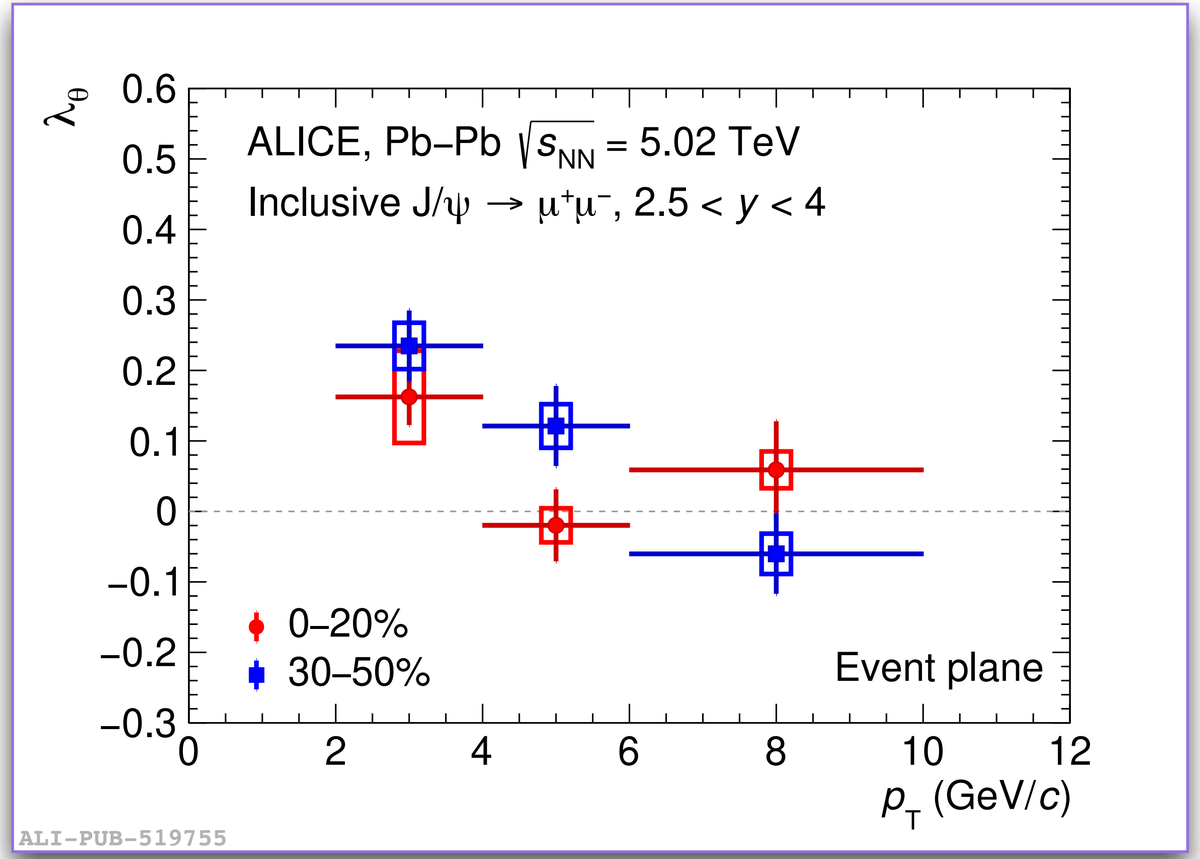
arXiv:2204.10171



- **First** measurement of J/Ψ polarization w.r.t the EP
  - Centrality dependence
    - Significant polarization (3.5σ) observed in 40–60% for $2 < p_{\mathrm{T}} < 6$ GeV/c

J/Ψ polarization as a function of EP in Pb—Pb collisions

arXiv:2204.10171



First measurement of J/Ψ polarization w.r.t the EP

- p_T dependence
  - Significant deviation (3.9σ) at **low** p_T ($2 < p_T < 4$ GeV/c) for **30–50%**
  - Similar to light flavor hadrons (K^{*0}, Φ): maximum polarization at low p_T for semi-central collisions
    - Smaller absolute polarization

$$|\lambda_\theta^{J/\Psi}| < |\lambda_\theta^{\Phi}| < |\lambda_\theta^{K^{*0}}|$$

    - Different sign of the deviation

$$\lambda_\theta^{J/\Psi} > 0,\ \lambda_\theta^{\Phi,\ K^{*0}} < 0$$

- **Different production mechanisms** for J/Ψ and light flavor hadrons in nuclear collisions
- **Different rapidity** range for the two measurements

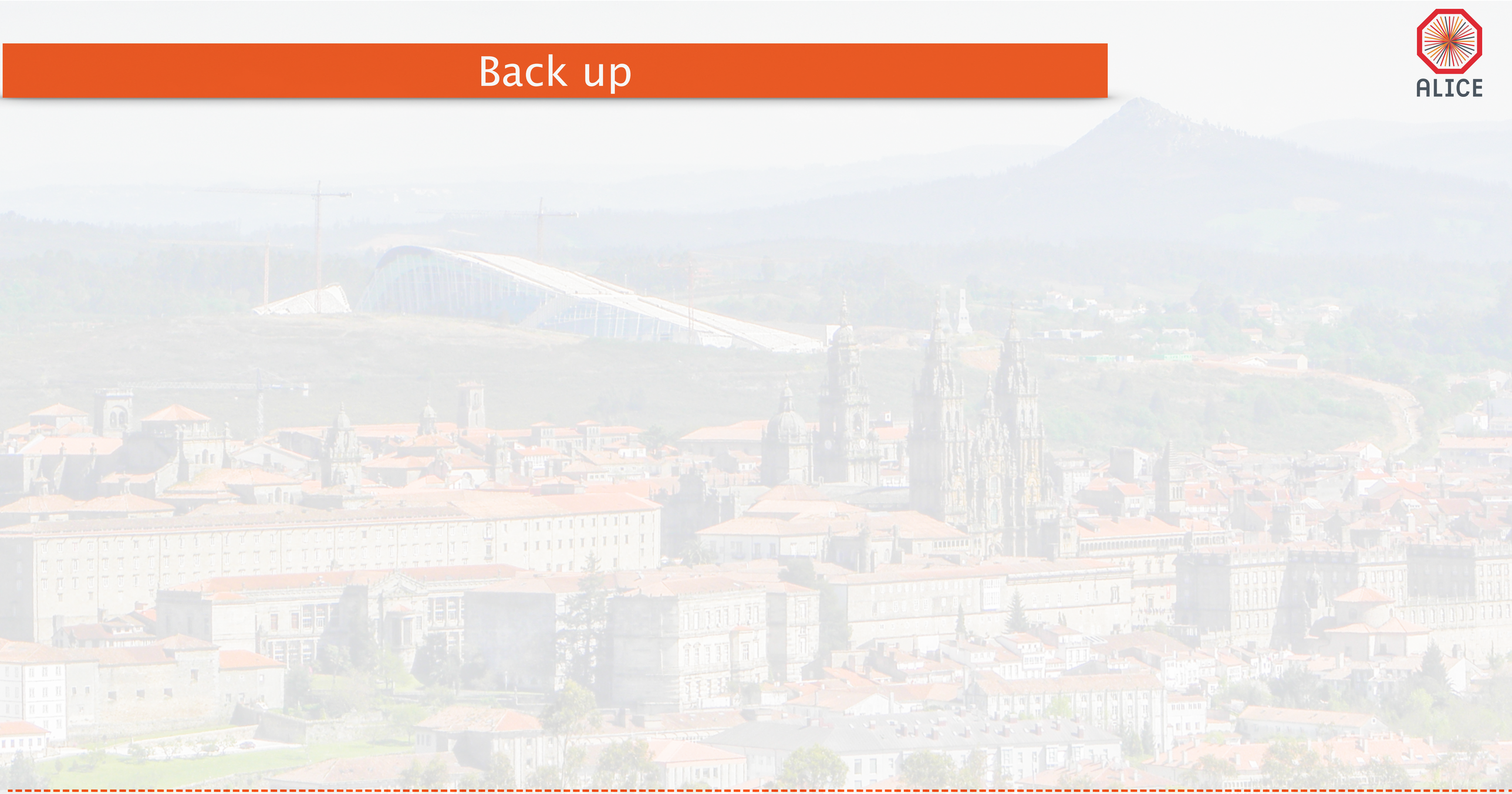
Summary

- **First ALICE $\Upsilon(1S)$ polarization measurement in pp collisions**
  - All polarization parameters are compatible with zero in both **HE** and **CS** frames
    - Good agreement with **LHCb** measurement in pp collisions at a different energy
    - Qualitatively described by **NLO NRQCD** predictions

- **First J/Ψ polarization measurement as a function of Event Plane in Pb—Pb collisions**
  - Significant deviation w.r.t zero is observed for λ_θ in semi-central collisions at low p_{T}

Theoretical description of vector meson polarization in heavy-ion collisions is needed

Back up

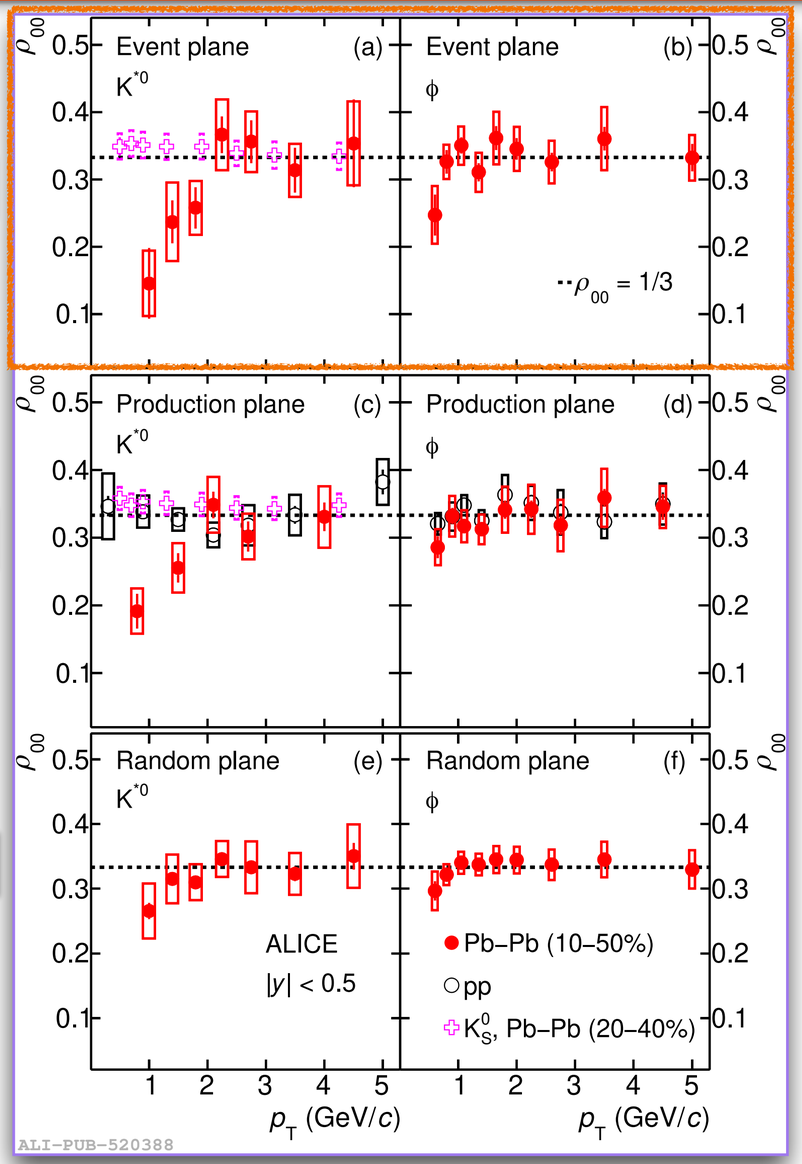


Light flavor hadrons (K^{*0}, Φ) polarization

EP

PP

RP

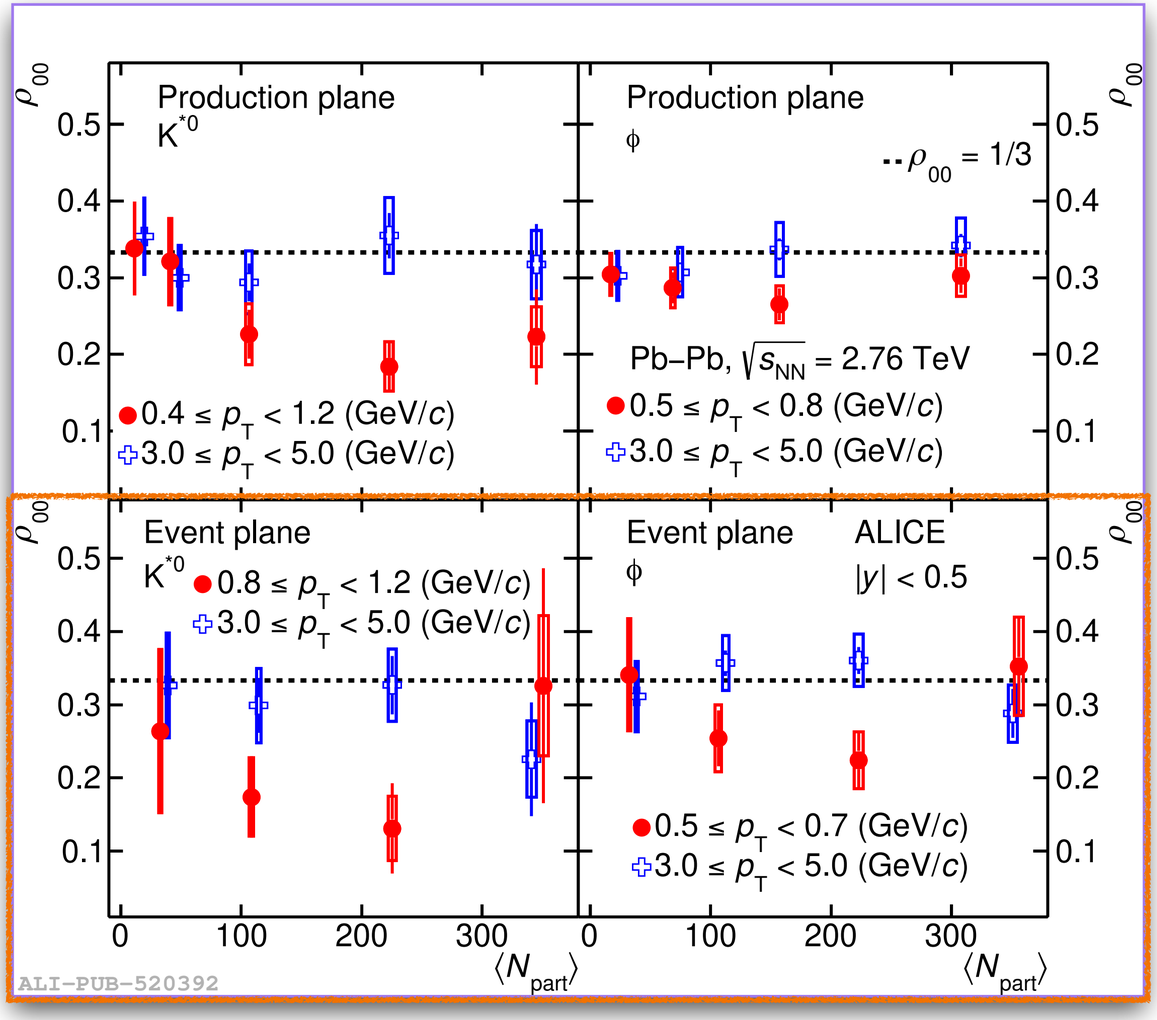


- ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 13$ TeV
  - p_{T} dependence
    - $\rho_{00} < 1/3$ for K^{*0} and Φ at low p_{T} (smaller central value for K^{*0}) in Pb—Pb collisions
    - $\rho_{00} \sim 1/3$ for:
      - $p_{\mathrm{T}}^{K^{*0}} > 2$ GeV/c and $p_{\mathrm{T}}^{\Phi} > 0.8$ GeV/c
      - A random event plane (**RP**)
      - K^{*0} and Φ in pp collisions

Zero spin hadron K^0_S: no spin alignment is observed

Light flavor hadrons (K^{*0}, Φ) polarization

- ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 13$ TeV
  - Centrality dependence
    - ρ_{00} deviates w.r.t 1/3 **at low p_{T} in semi-central collisions**
    - No centrality dependence of ρ_{00} at high p_{T}



Charmed mesons polarization

- Charmed vector meson (D^{*+}) polarization crucial to complete the picture in HICs
- D^{*+} polarization in pp collisions at $\sqrt{s}$ = 13 TeV
  - ρ_{00} spin matrix element (1/3 means no polarization)
    - Prompt D^{*+} ($c \to D^{*+}$) unpolarized
    - Non-zero polarization for non-prompt D^{*+} ($b \to D^{*+}$)
    - Both well predicted by PYTHIA 8 + EVTGEN