ICHEP 2022 BOLOGNA

Quarkonium polarization in Pb—Pb and pp collisions with ALICE

Yanchun Ding[1,2] for the ALICE Collaboration

Central China Normal University[1]

Institut de Physique des Deux Infinis de Lyon[2]

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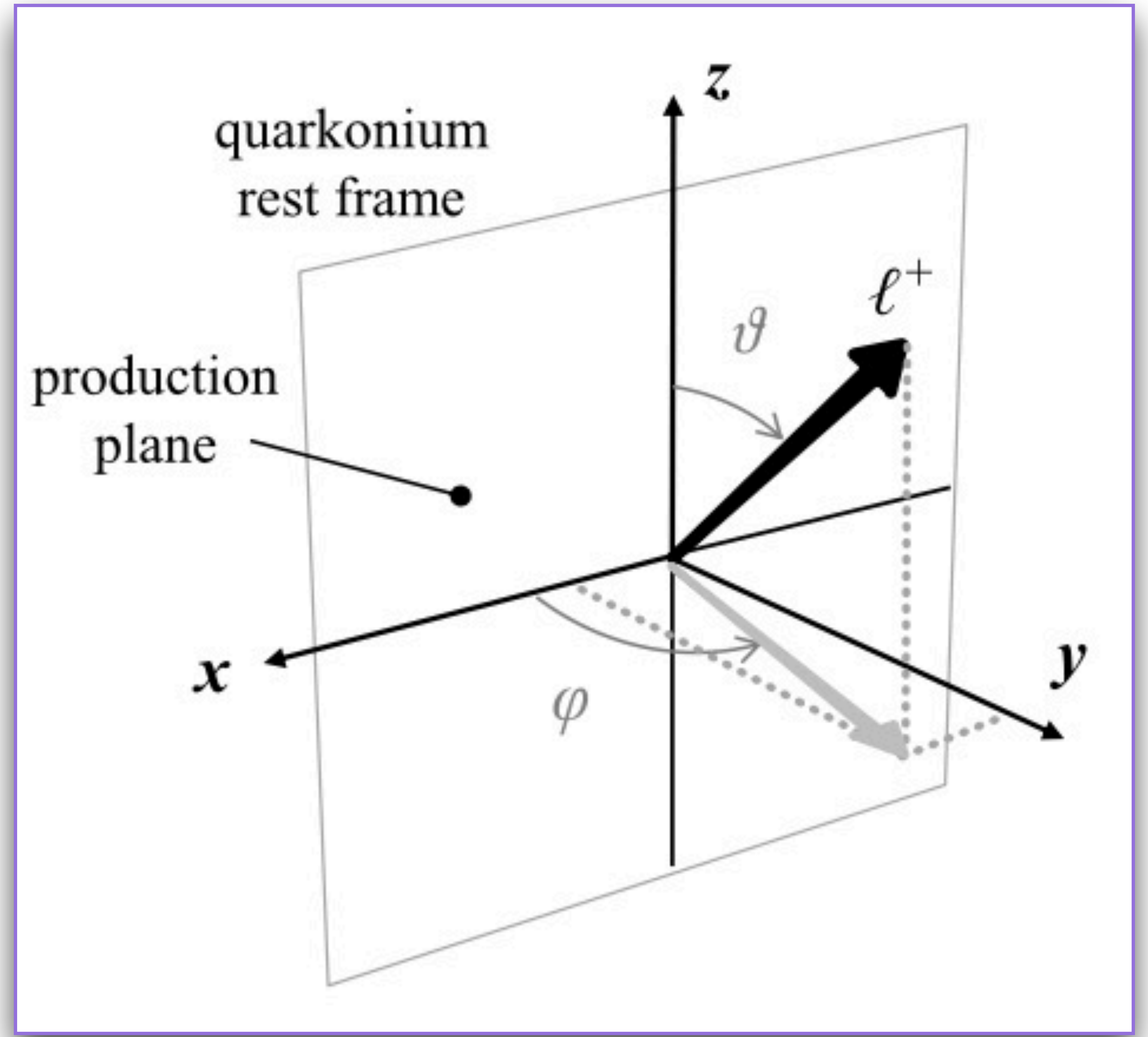
Introduction

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 $\lambda_{\theta\varphi}$

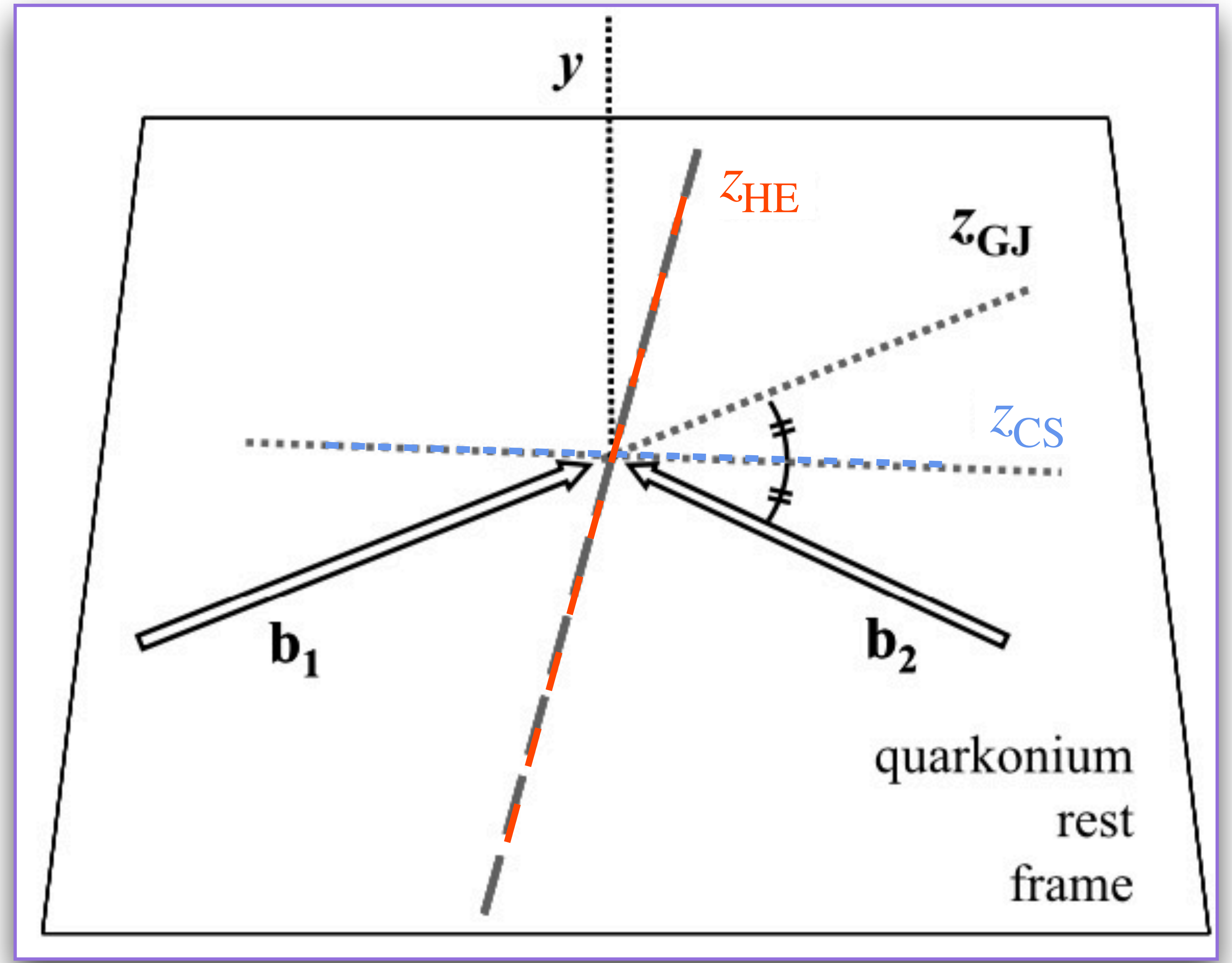
$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (0,\ 0,\ 0)$ No polarization

$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (+1,\ 0,\ 0)$ Pure transverse polarization

$(\lambda_\theta,\ \lambda_\varphi,\ \lambda_{\theta\varphi}) = (-1,\ 0,\ 0)$ Pure longitudinal polarization

How to define polarization axis

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



Physics motivation

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

Theoretically

- J/ψ:
  - **NLO NRQCD** ==> transverse polarization in Helicity frame
  - **NLO CSM** ==> longitudinal polarization in Helicity frame

M. Butenschoen *et al.*, *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}

    B. Gong *et al.*, *Phys. Rev. Lett.* 112 (2014) 3, 032001
  - **ICEM (k_{T}-factorization approach)** ==> transverse polarization and no significant differences in polarization among the $\Upsilon(\mathrm{nS})$ states

    C. Vincent *et al.*, *Phys. Rev. D* 99 (2019) 3, 034007

No sizeable polarization is observed for the existing quarkonium polarization measurements in pp collisions

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

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

J.-P. Lansberg, *Phys. Rept.* 889 (2020)

    - ↳ Contribution from charmonium **(re)generation**

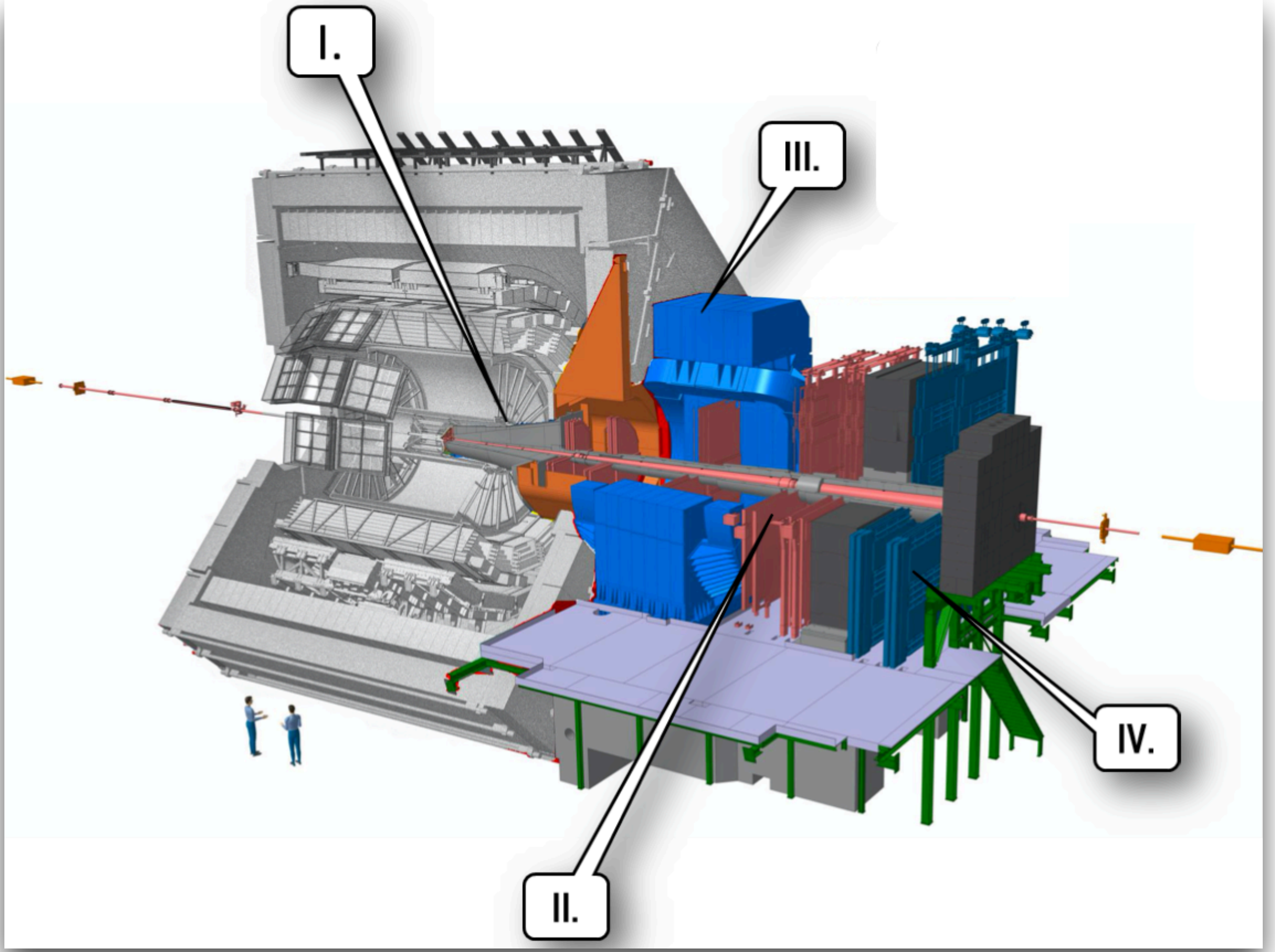
  - **In non-central collisions**
    - ↳ Large **angular momentum** due to the medium rotation is predicted

F. Becattini *et al.*, *Phys. Rev. C* **77**, 024906

    - ↳ Huge **magnetic field** is expected

D. E. Kharzeev *et al.*, *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: efficiently dump π, K and low-momentum muons
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 $p_{\mathrm{T}} = 0$

The other quarkonium talks from ALICE:

Raphaelle Marie Bailhache 7th July, 2022	Maurice Louis Coquet 9th July, 2022	Biswarup Paul 9th July, 2022
Theraa M A Tork 8th July, 2022	Himanshu Sharma 9th July, 2022	

A Large Ion Collider Experiment

ALICE

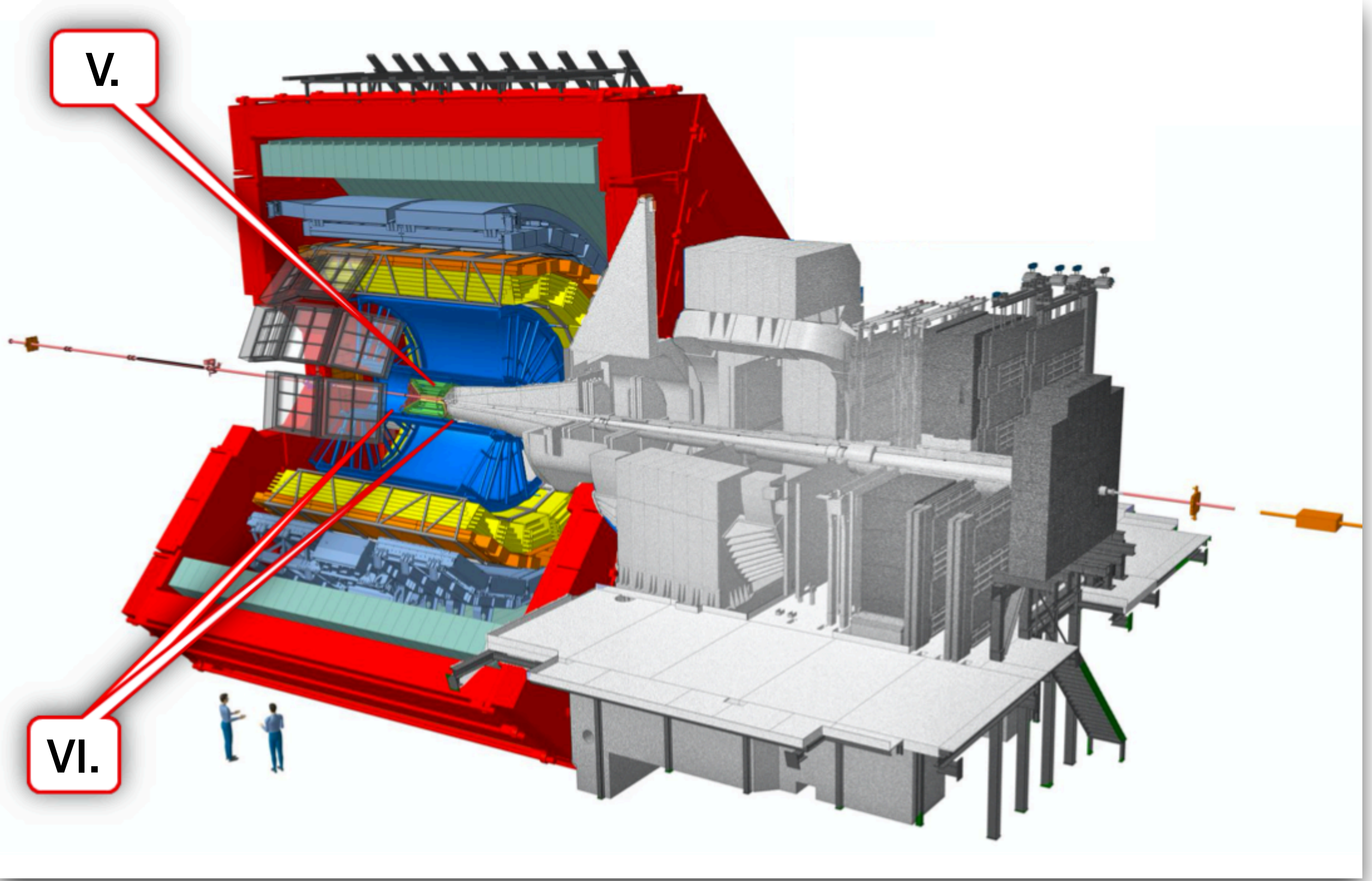
A dedicated heavy-ion experiment at the LHC

V. Silicon Pixel Detector

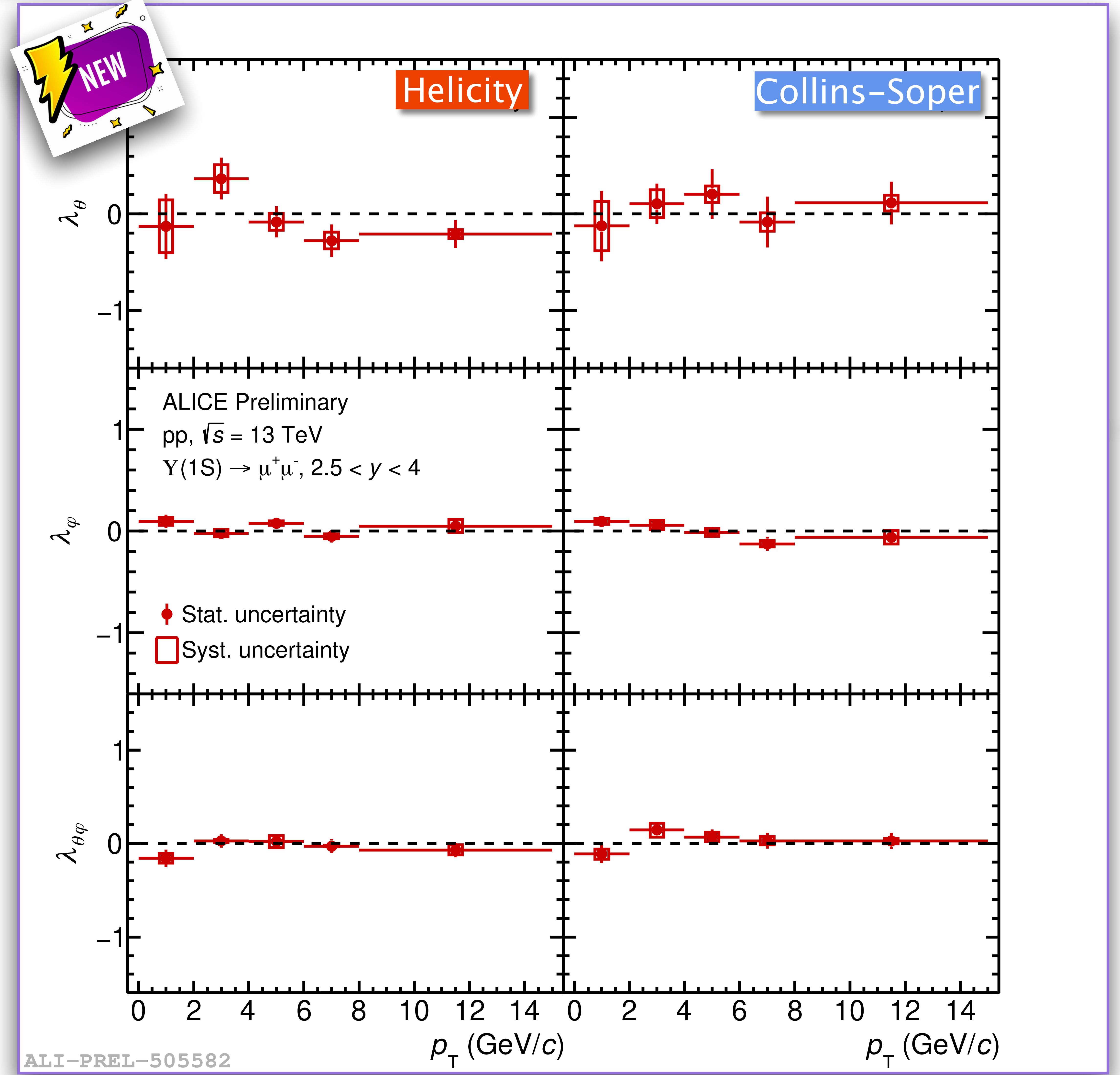
- ↳ Vertex reconstruction
- ↳ Event Plane determination

VI. V0 Detectors

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



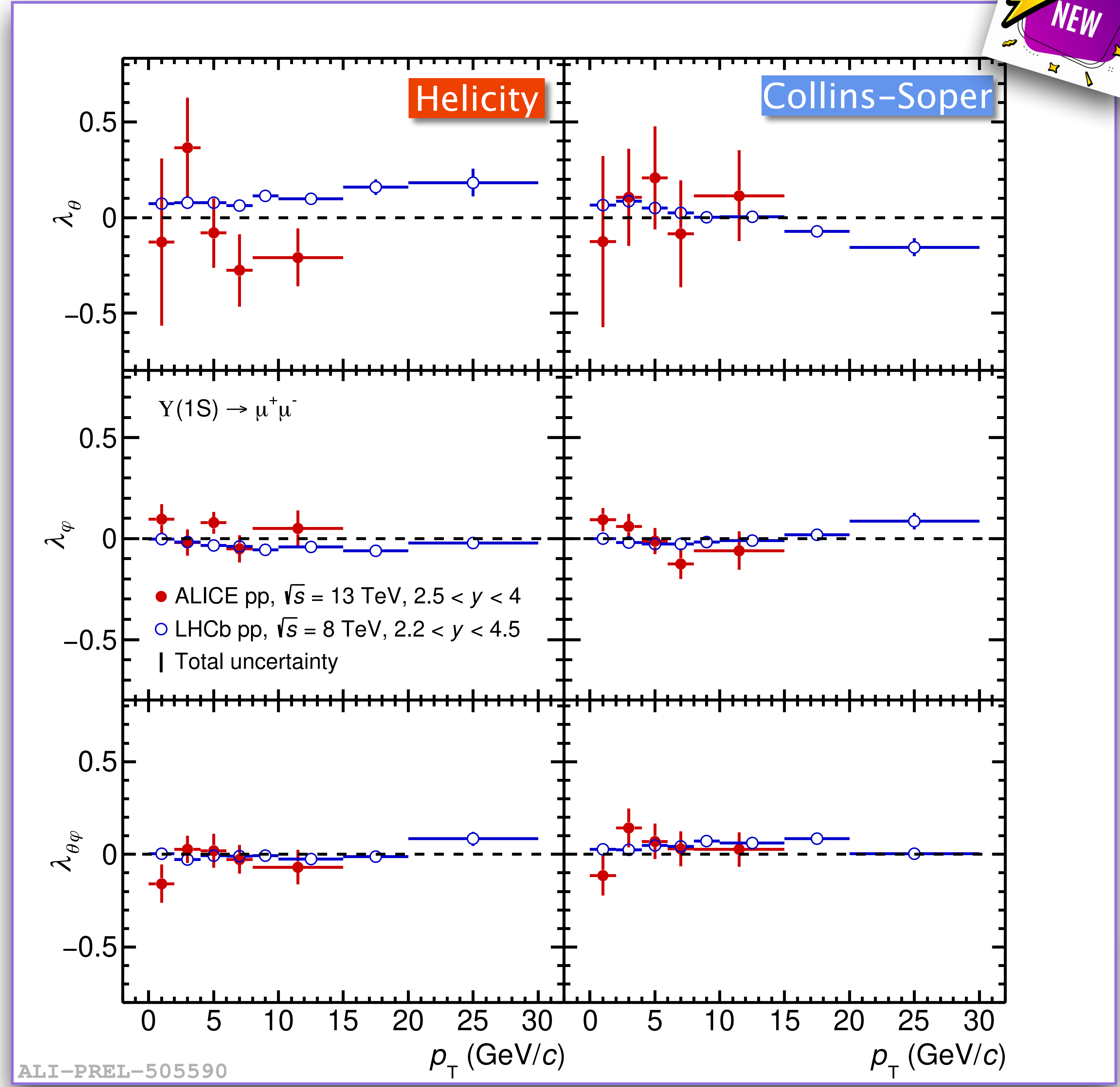
Υ(1S) polarization in pp collisions at $\sqrt{s}$ = 13 TeV



- 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

yanchun.ding@cern.ch

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



NEW

First **ALICE** $\Upsilon(1S)$ polarization measurement in pp collisions

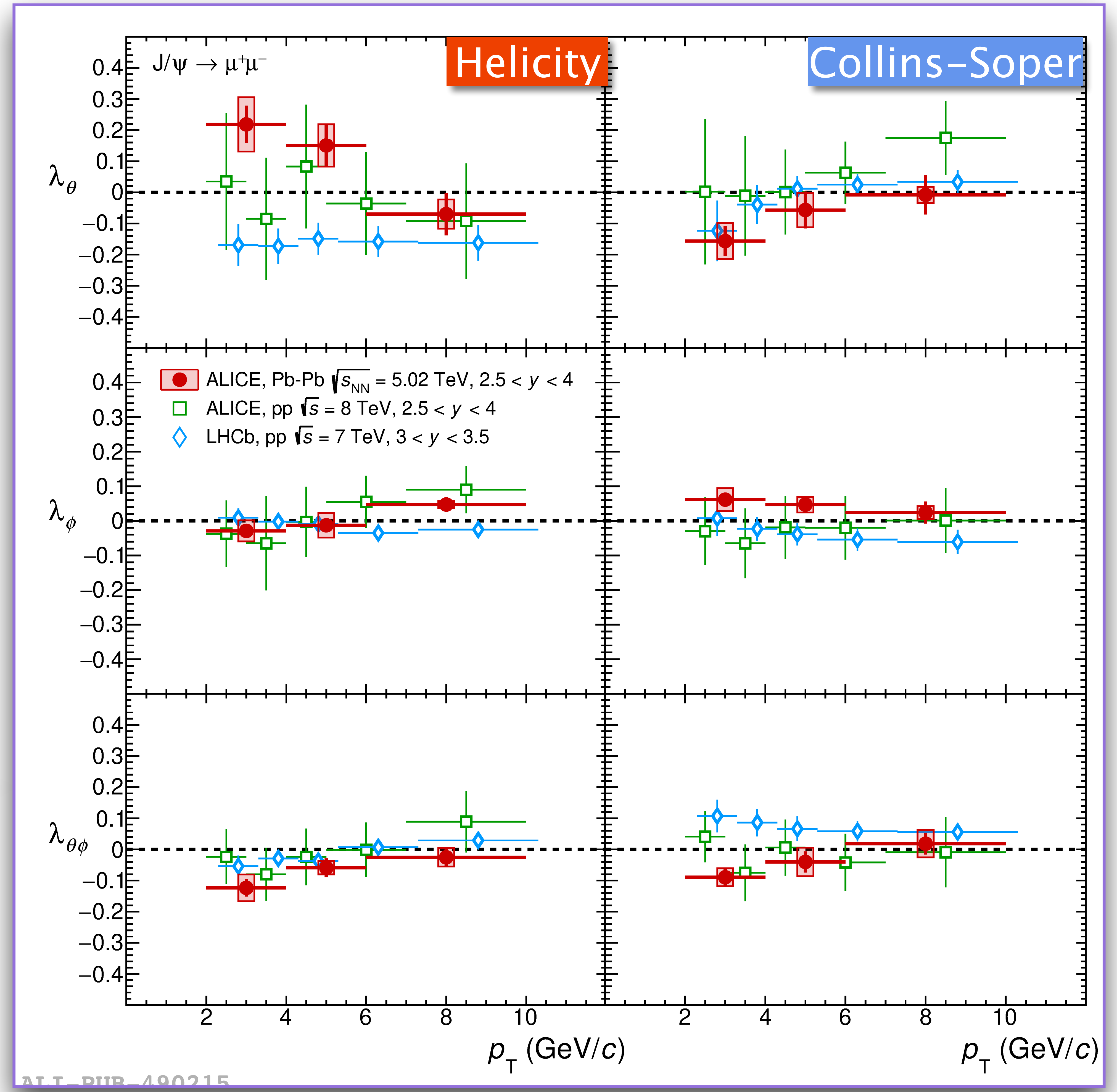
- λ_θ , λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both **HE** and **CS** frames
- Compatible with **Pb—Pb** results
  Phys. Lett. B 815 (2021) 136146
- Good agreement with **LHCb** pp data at $\sqrt{s}$ = 8 TeV, in a similar rapidity range, within the large experimental uncertainties
  LHCb Collaboration, *JHEP* 12 (2017) 110
- Qualitatively described by **NLO NRQCD** calculations
  M. Butenschoen *et al.*, *Phys. Rev. Lett.* 108 (2012) 172002

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
    LHCb Collaboration, *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 ($\vec{B}$)?

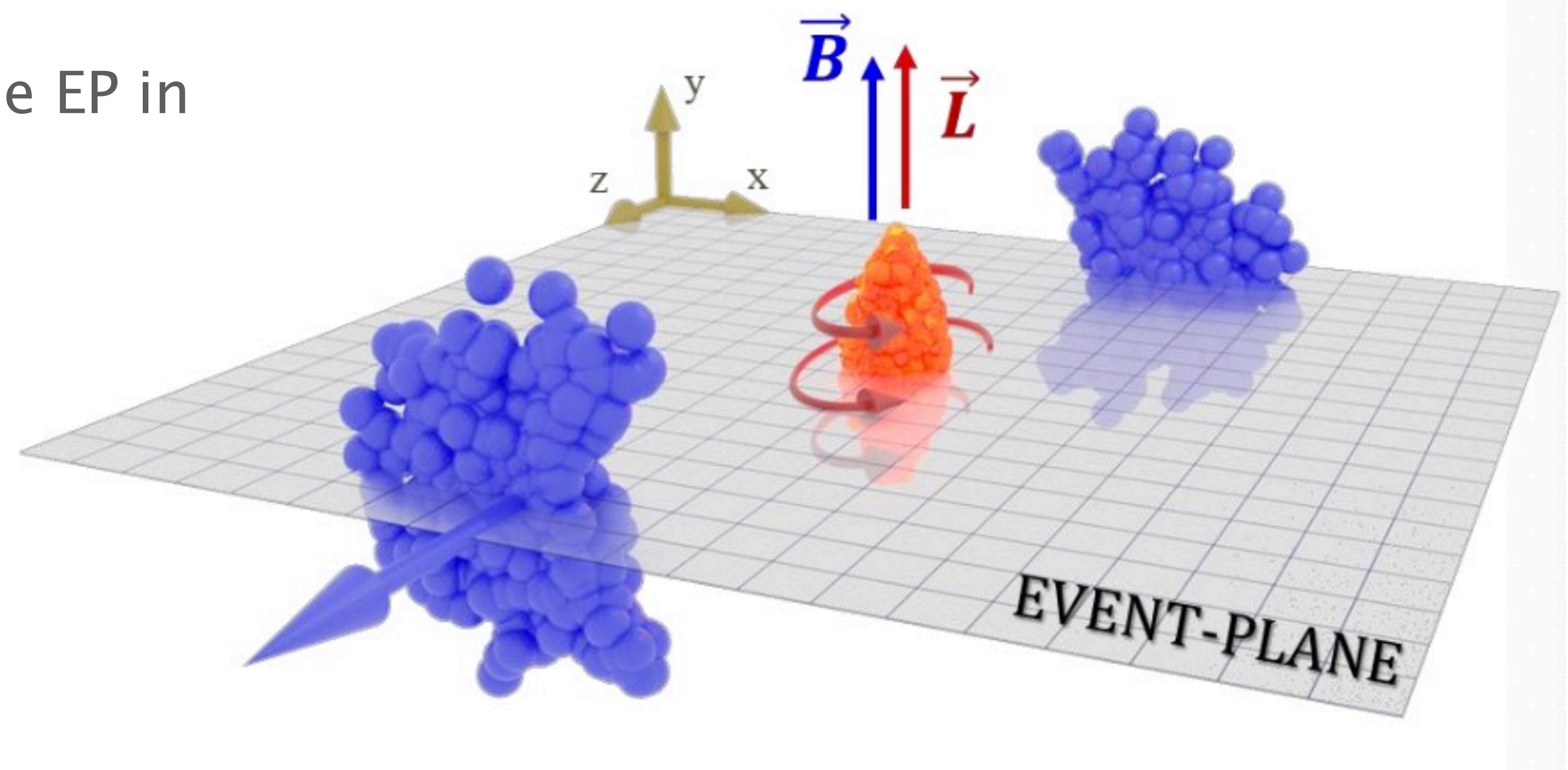
Phys. Lett. B 815 (2021) 136146



J/ψ polarization as a function of the event plane

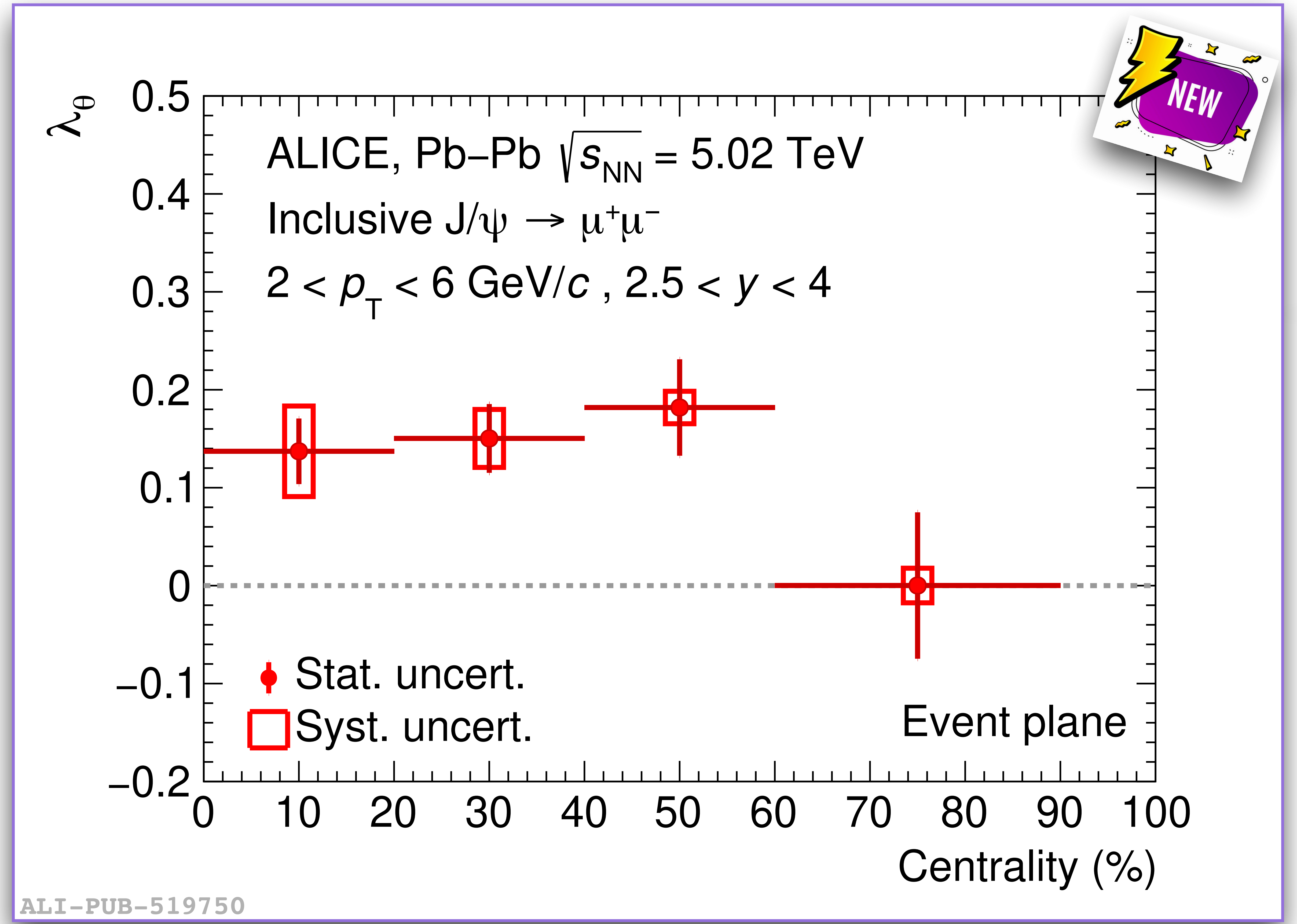
J/ψ polarization in Pb—Pb collisions measured using another reference frame

- 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 as a function of EP in Pb—Pb collisions

arXiv:2204.10171

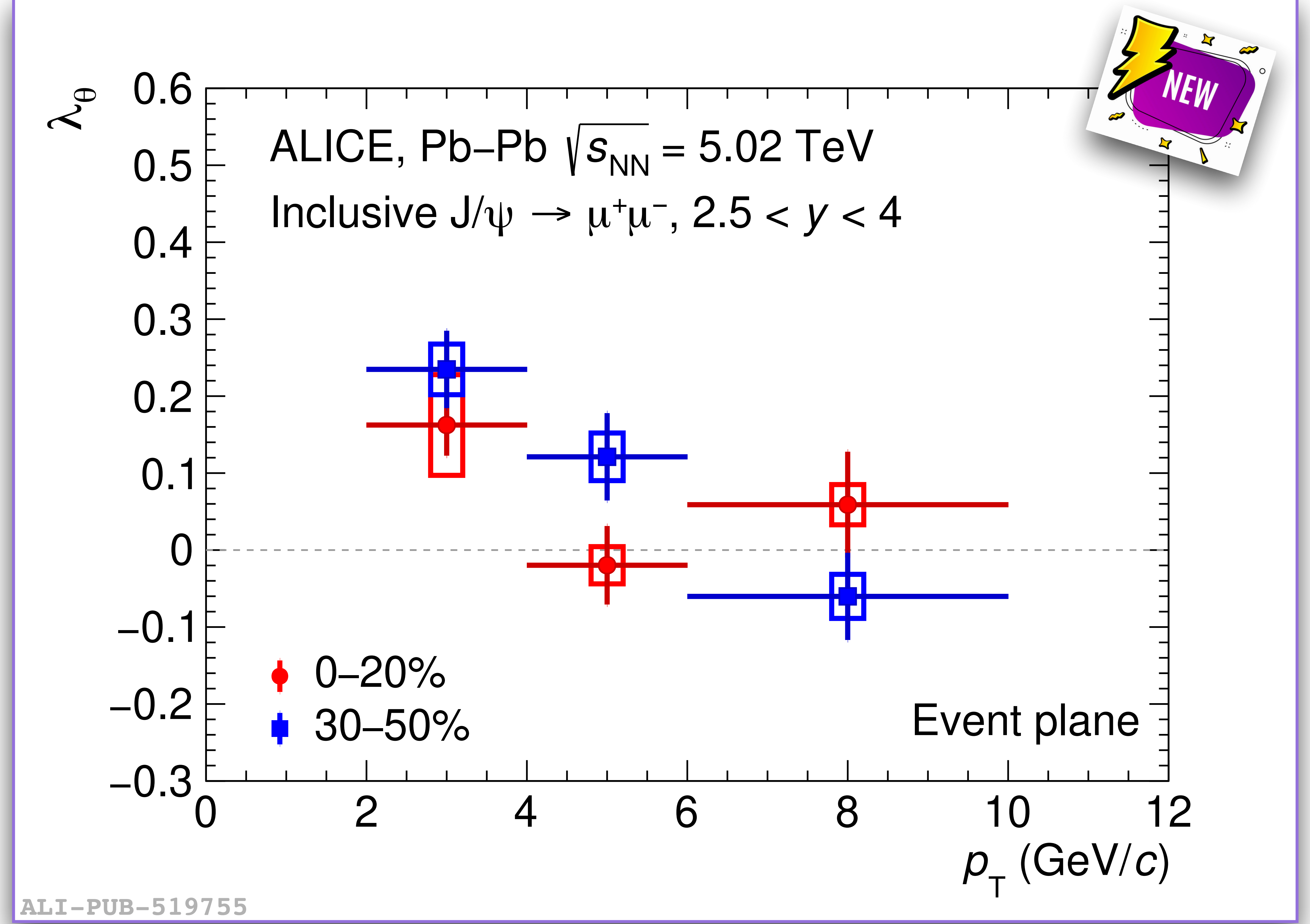


First measurement of J/ψ polarization w.r.t the EP

- Centrality dependence
  - Significant polarization (3.5σ) observed in 40–60% for $2 < p_T < 6$ 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 semicentral collisions, but:
    - Smaller absolute polarization

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

    - Different sign of the deviation

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

Phys. Rev. Lett 125 (2020) 012301

- **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
- **First J/ψ polarization measurement as a function of the event plane in Pb—Pb collisions**
  - Significant deviation w.r.t zero is observed for λ_θ in semicentral collisions at low p_T

Outlook

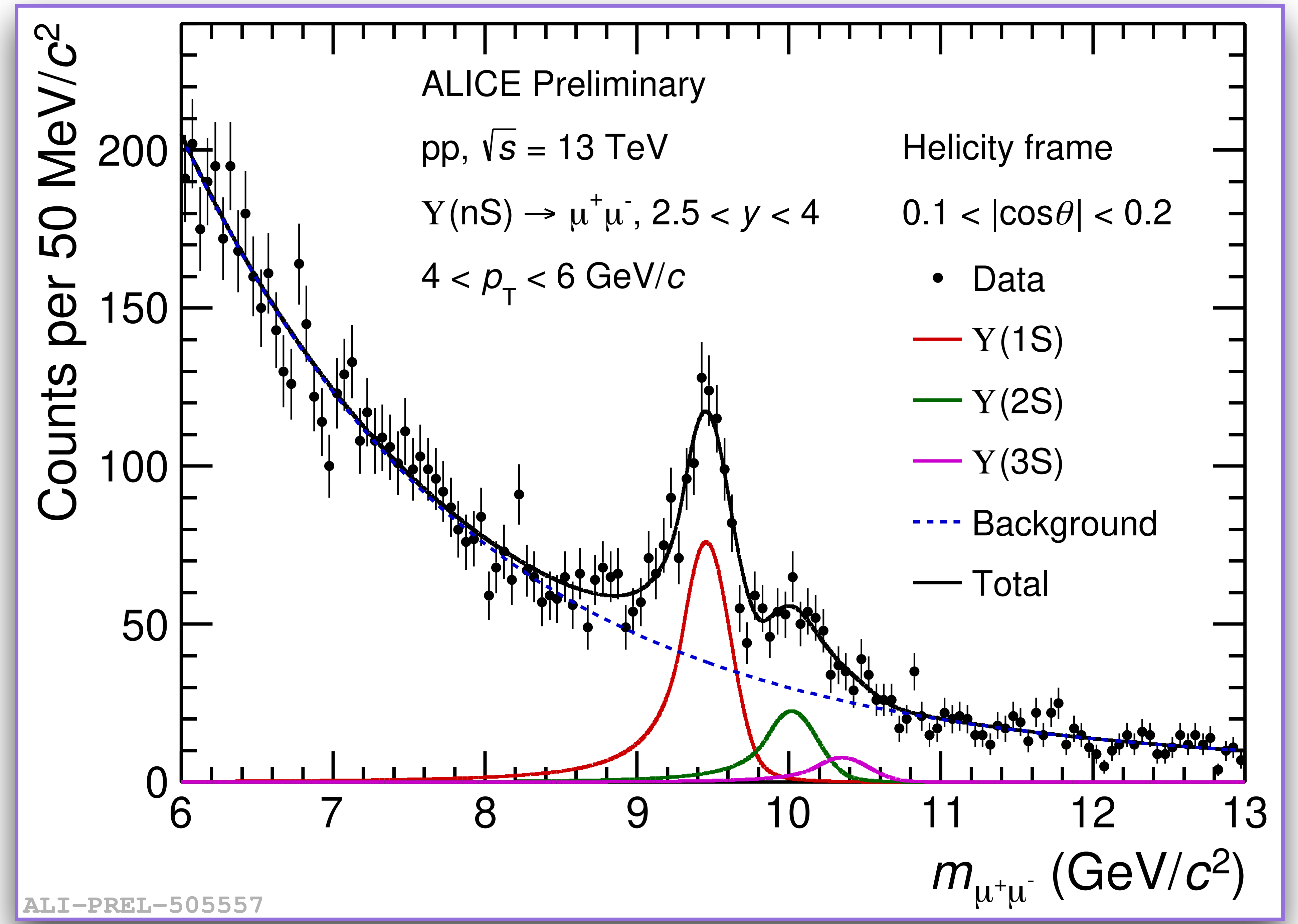
- **Theoretical description of vector meson polarization in heavy-ion collisions is needed**
- **More precise measurements can be expected from large data sample with LHC Run 3**

Happy ending

Υ(1S) polarization in pp collisions: analysis strategy

Signal extraction

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

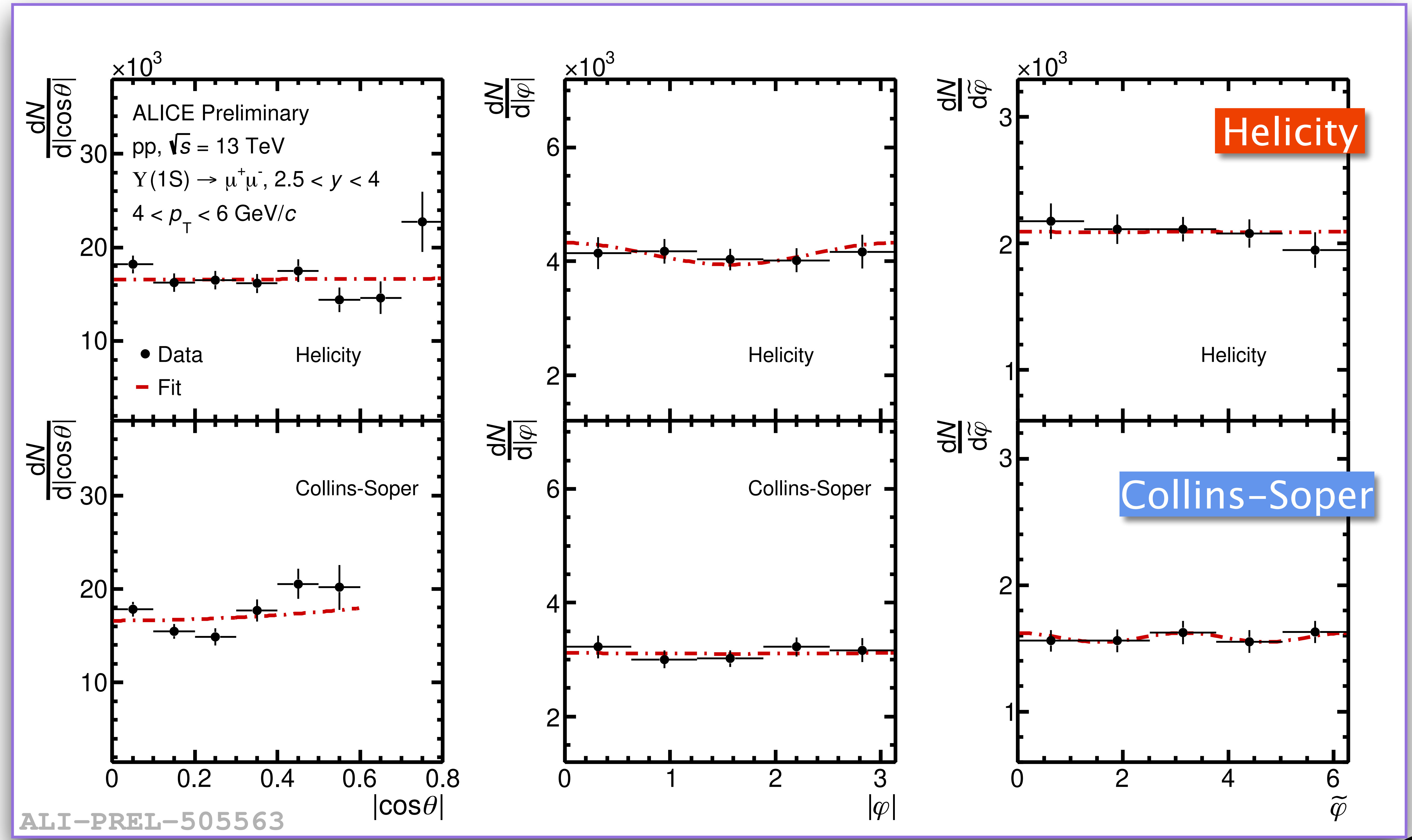


Acceptance x efficiency correction

- **Corrected** number of Υ(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 Υ(1S) angular distributions in both frames simultaneously

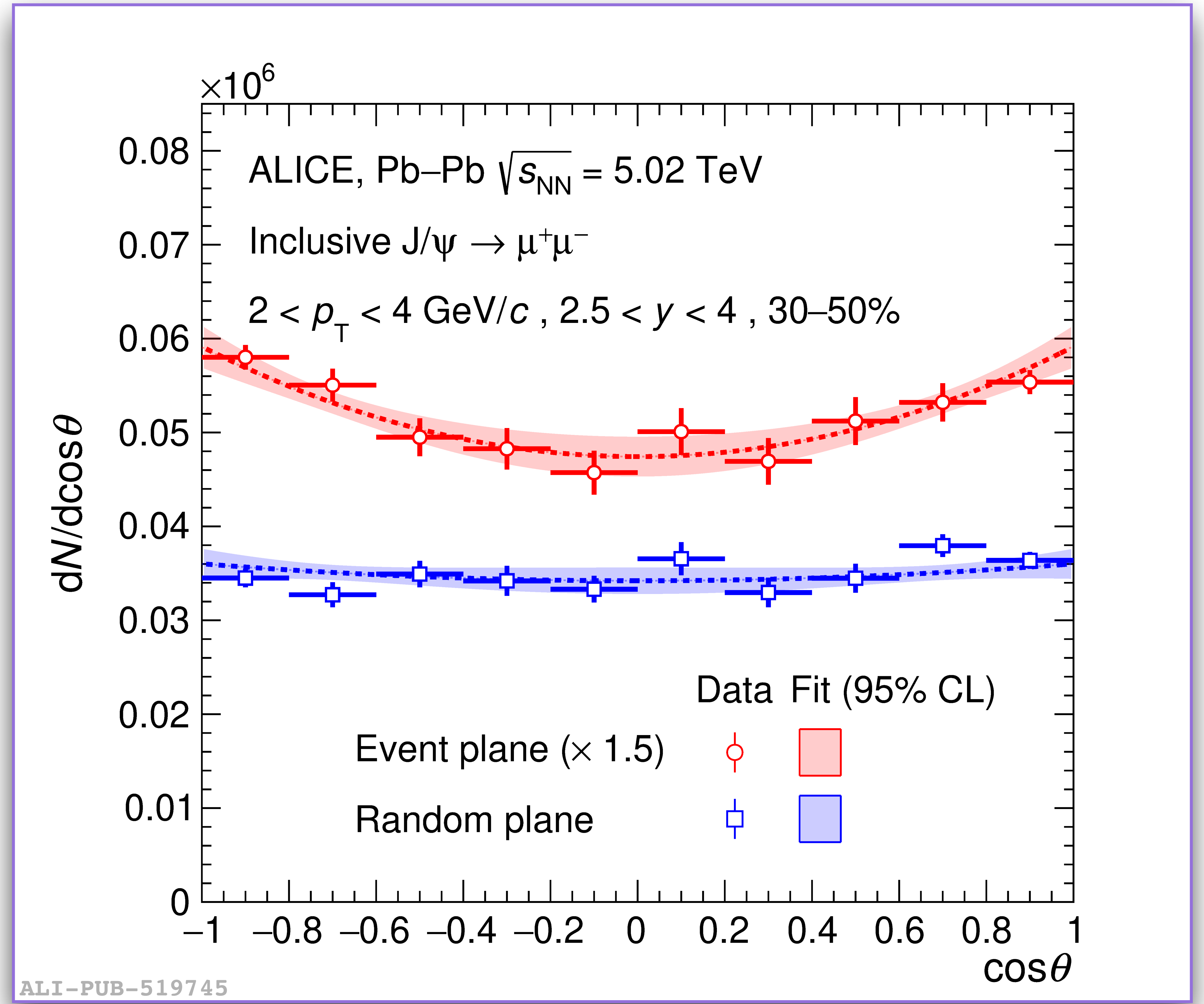


J/ψ polarization vs EP in Pb—Pb collisions: analysis strategy

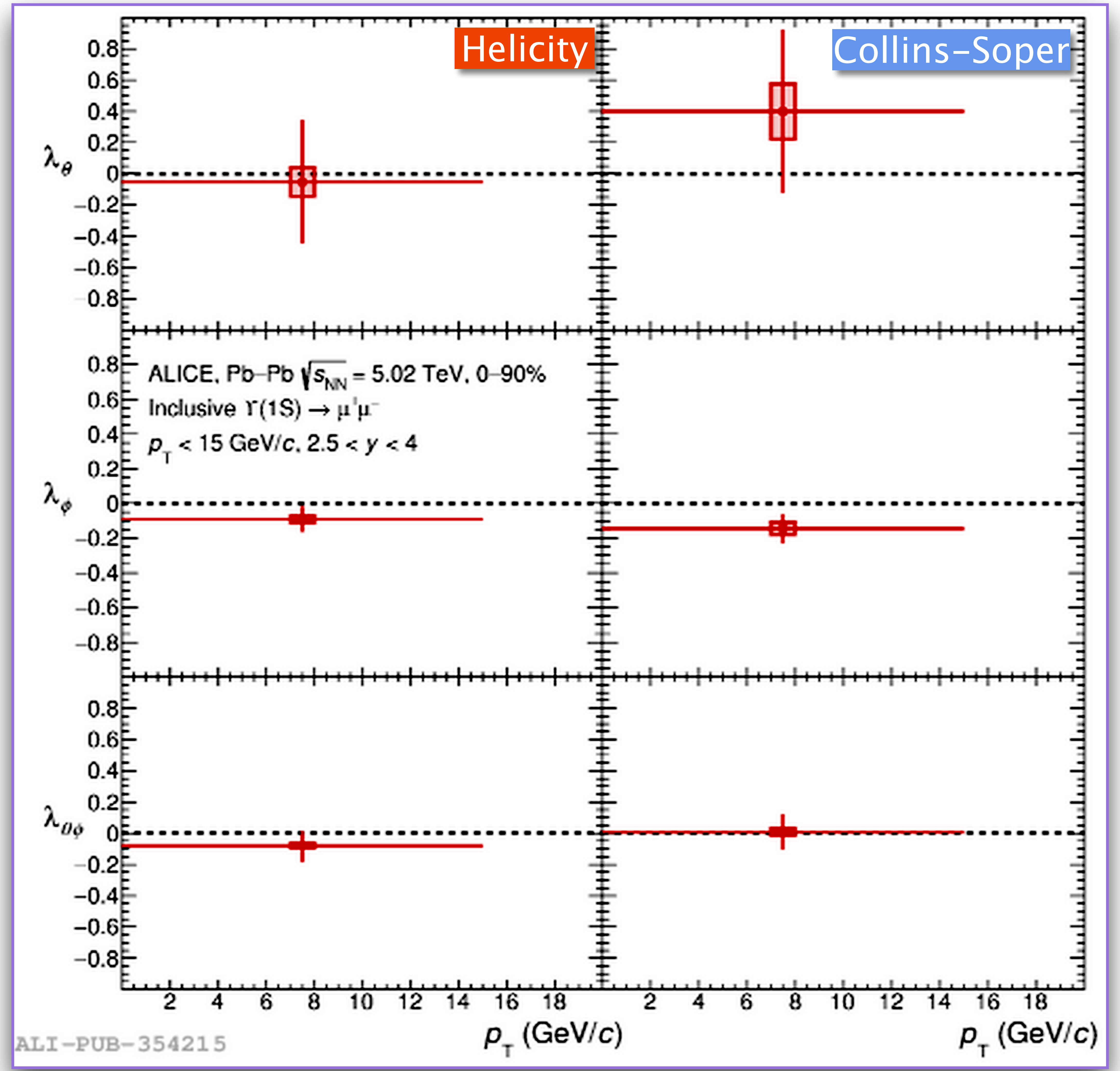
arXiv:2204.10171

- 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**



Υ(1S) polarization in Pb—Pb 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
  - Compatible with **Pb—Pb** results

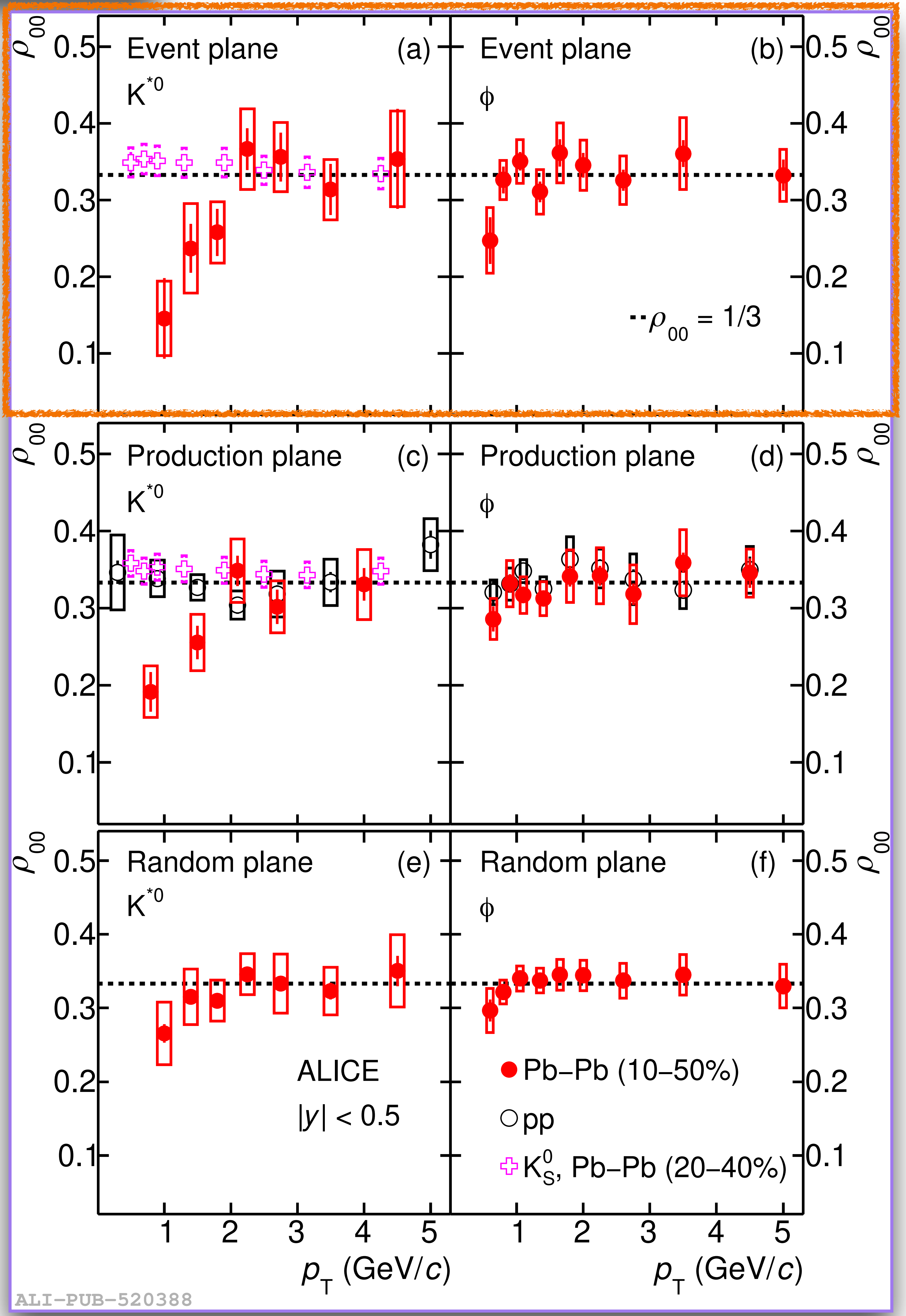
Phys. Lett. B 815 (2021) 136146

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

EP

PP

RP



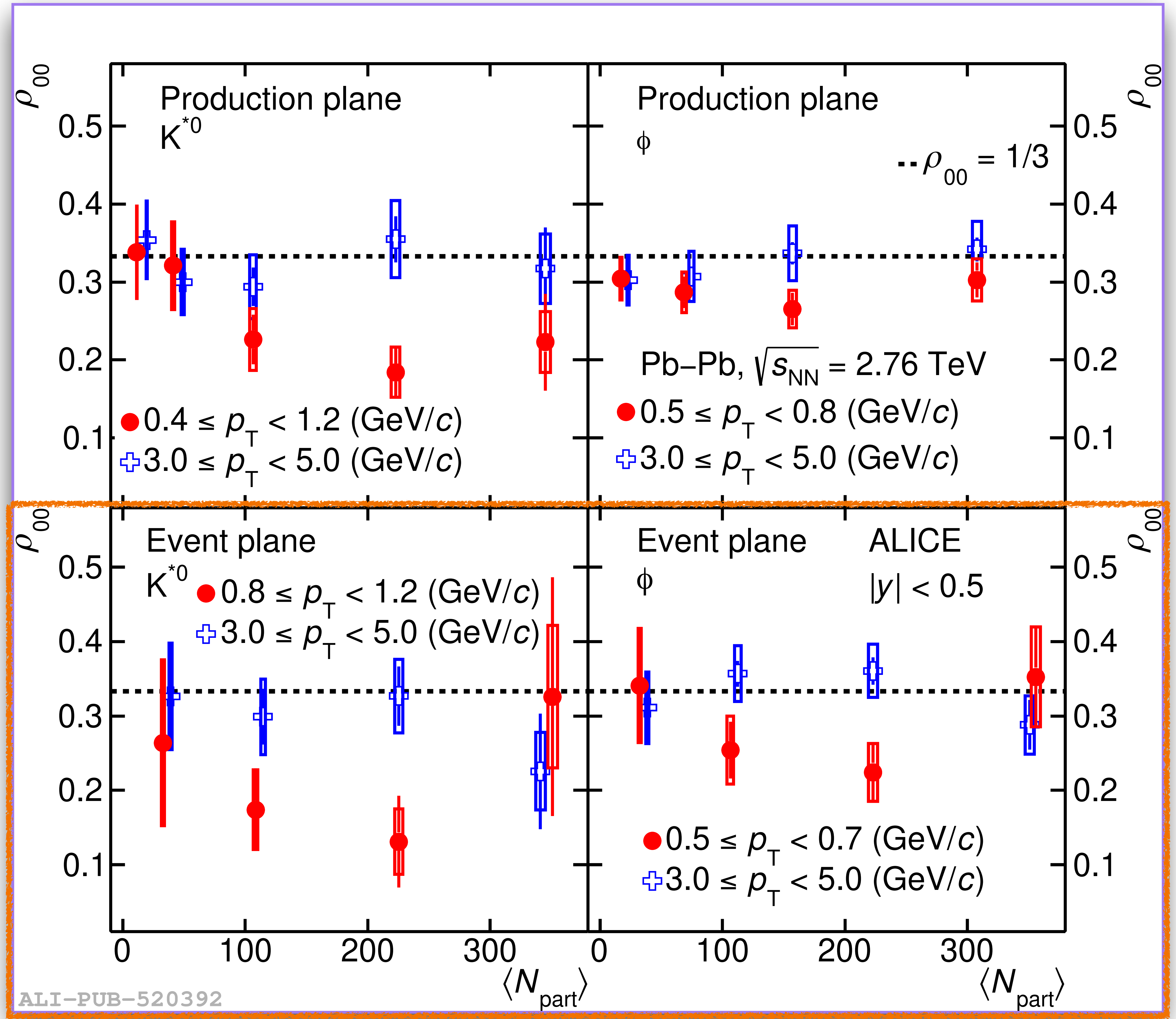
ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 13$ TeV

- 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:
    - $p_T^{K^{*0}} > 2$ GeV/c and $p_T^{\Phi} > 0.8$ GeV/c
    - A random event plane (**RP**)
    - K^{*0} and Φ in pp collisions

Zero spin hadron K_S^0: no spin alignment is observed

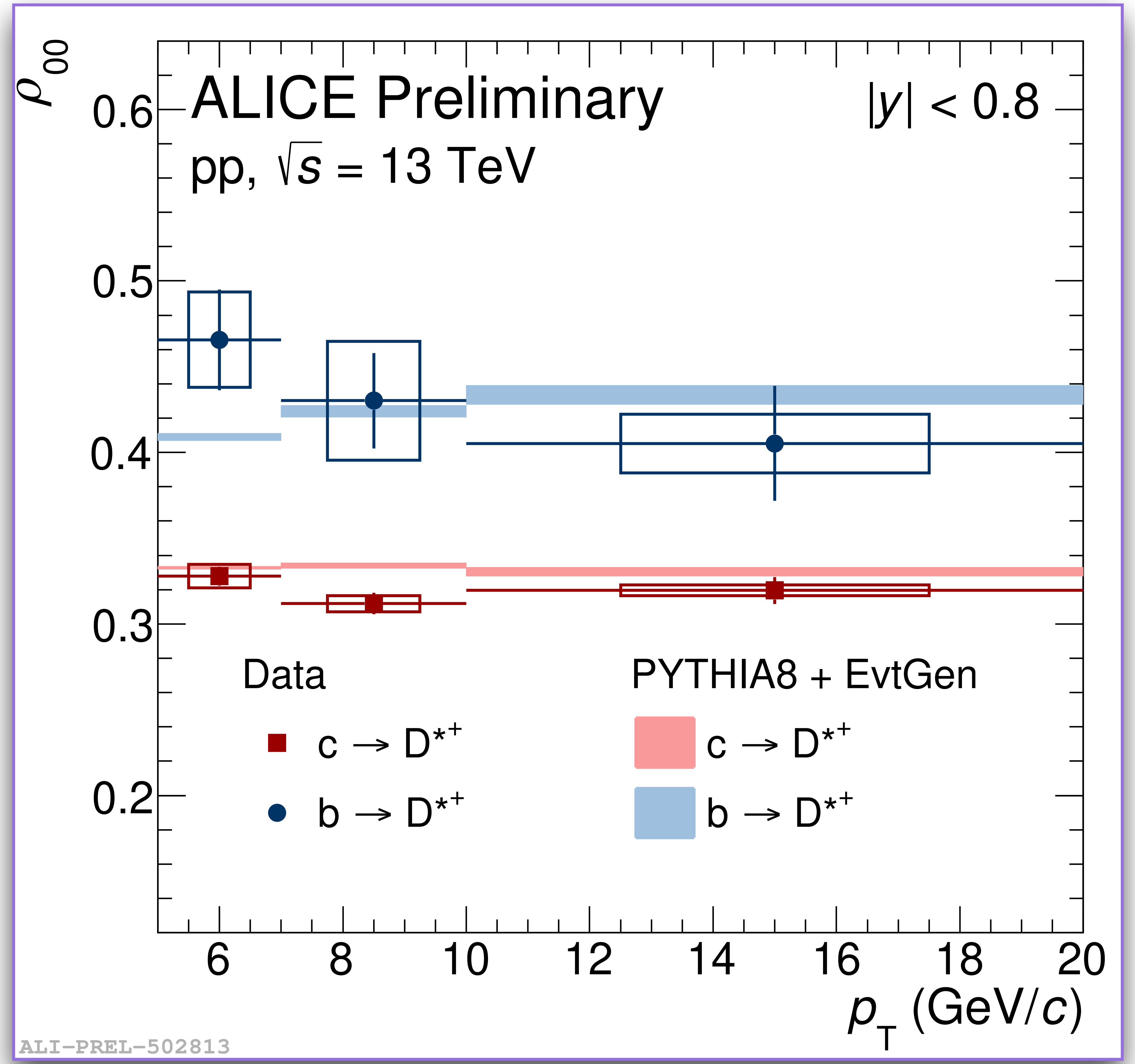
Light flavor hadrons (K^{*0}, Φ) polarization

- 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



Angular distribution

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

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

$$\boxed{W(\tilde{\varphi}) \propto 1 + \frac{\sqrt{2}\lambda_{\theta\varphi}}{3+\lambda_\theta}\cos 2\tilde{\varphi} \qquad \begin{array}{ll} \tilde{\varphi} = \varphi - 3\pi/4, & \cos\theta < 0 \\ \tilde{\varphi} = \varphi - \pi/4, & \cos\theta > 0 \end{array}}$$

J/ψ polarization in theory

Phys. Rev. Lett. 108 (2012) 172002