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Quarkonium polarization in Pb-Pb and pp collisions with ALICE

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ICHEP 2022
BOLOGNA



Université Claude Bernard Lyon 1



ALICE

Quarkonium polarization in Pb—Pb and pp collisions with ALICE

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Institut de Physique des Deux Infinis de Lyon²

6th - 13th July, 2022





Introduction



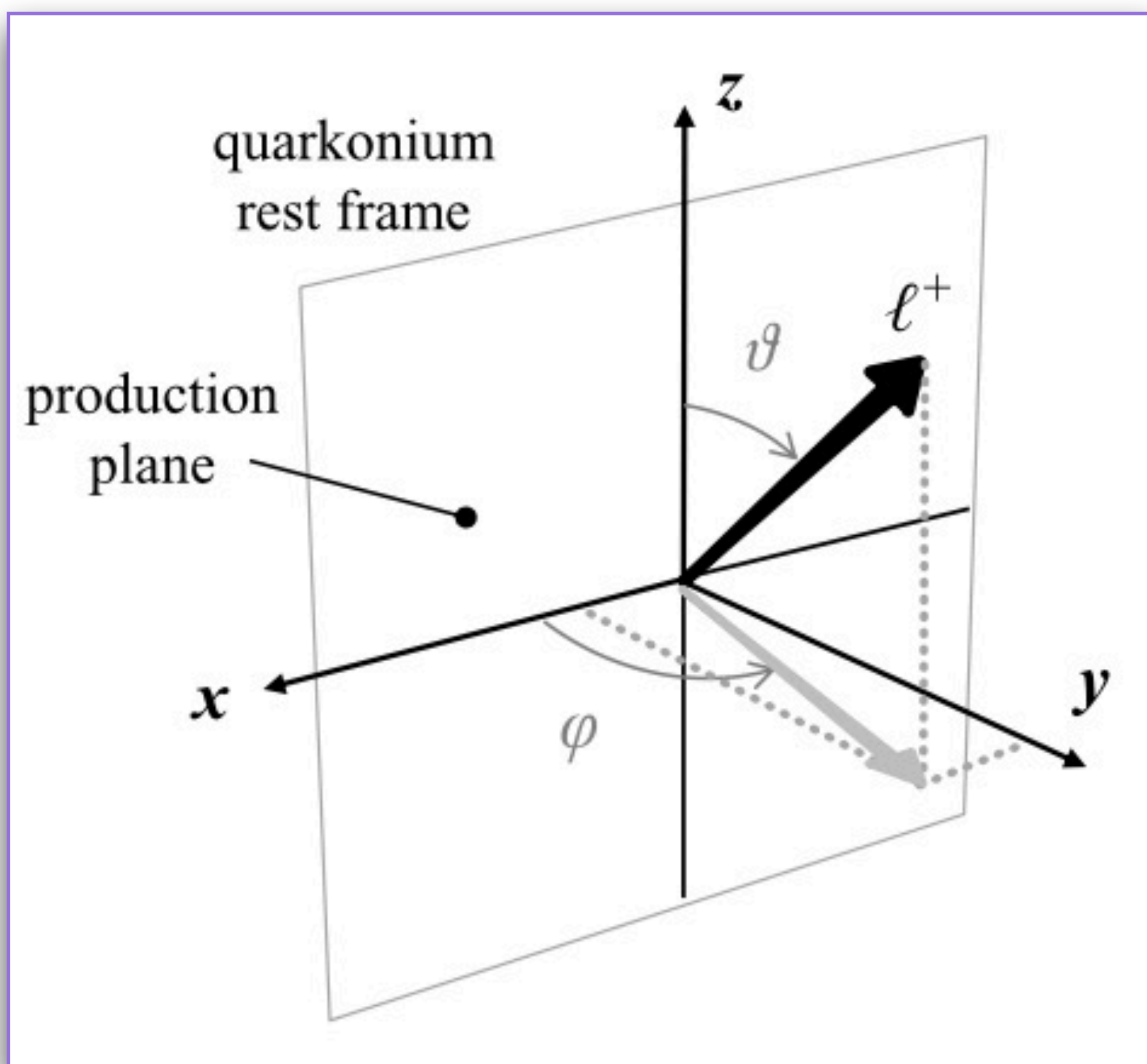
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Polarization:

- 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



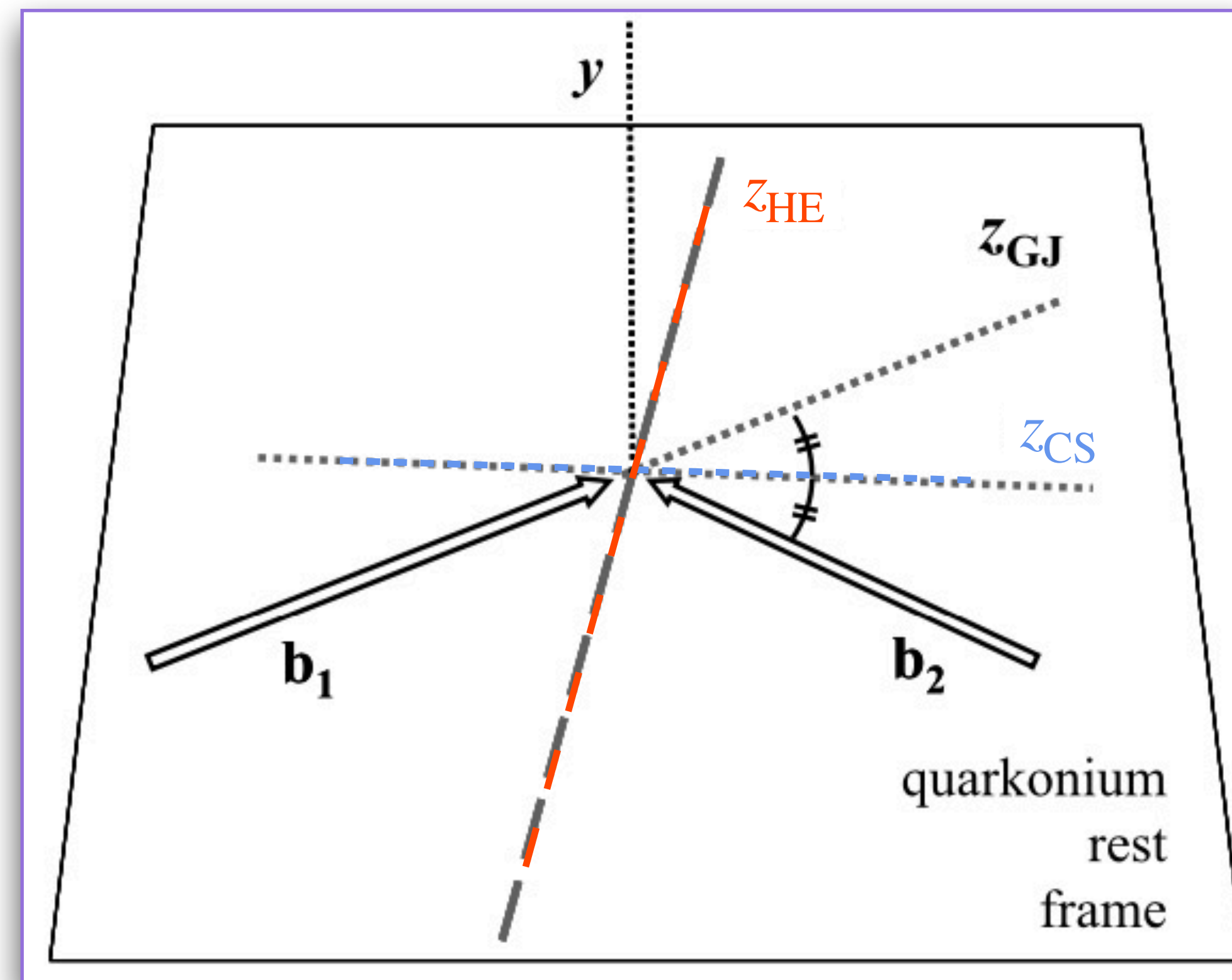
How to define polarization axis



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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





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 $\Upsilon(nS)$ 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



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

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

📎 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

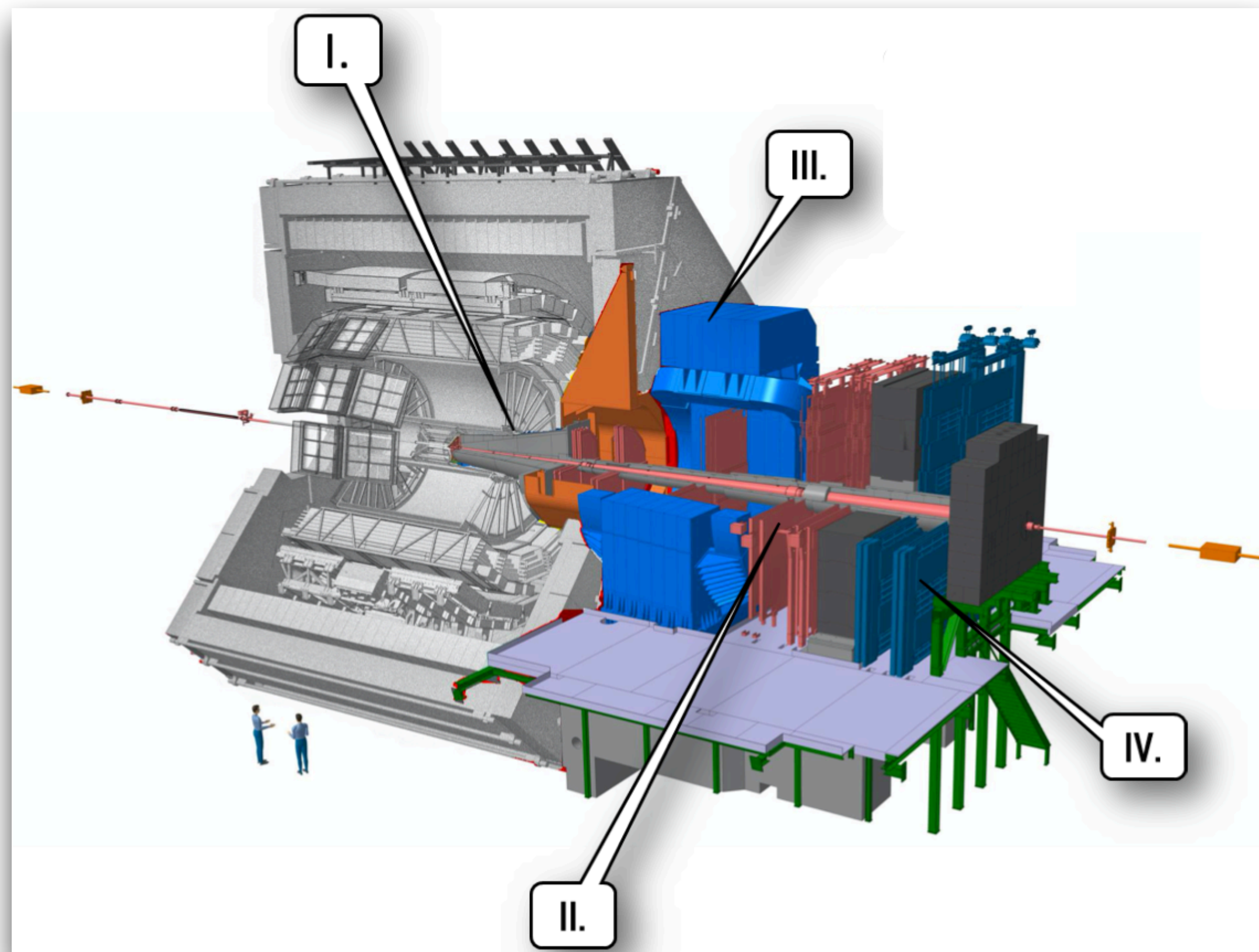
📎 D. E. Kharzeev *et al.*, *Nucl. Phys. A* 803 (2008) 227-253



A Large Ion Collider Experiment



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 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 $p_T = 0$

The other quarkonium talks from ALICE:

 Raphaëlle 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



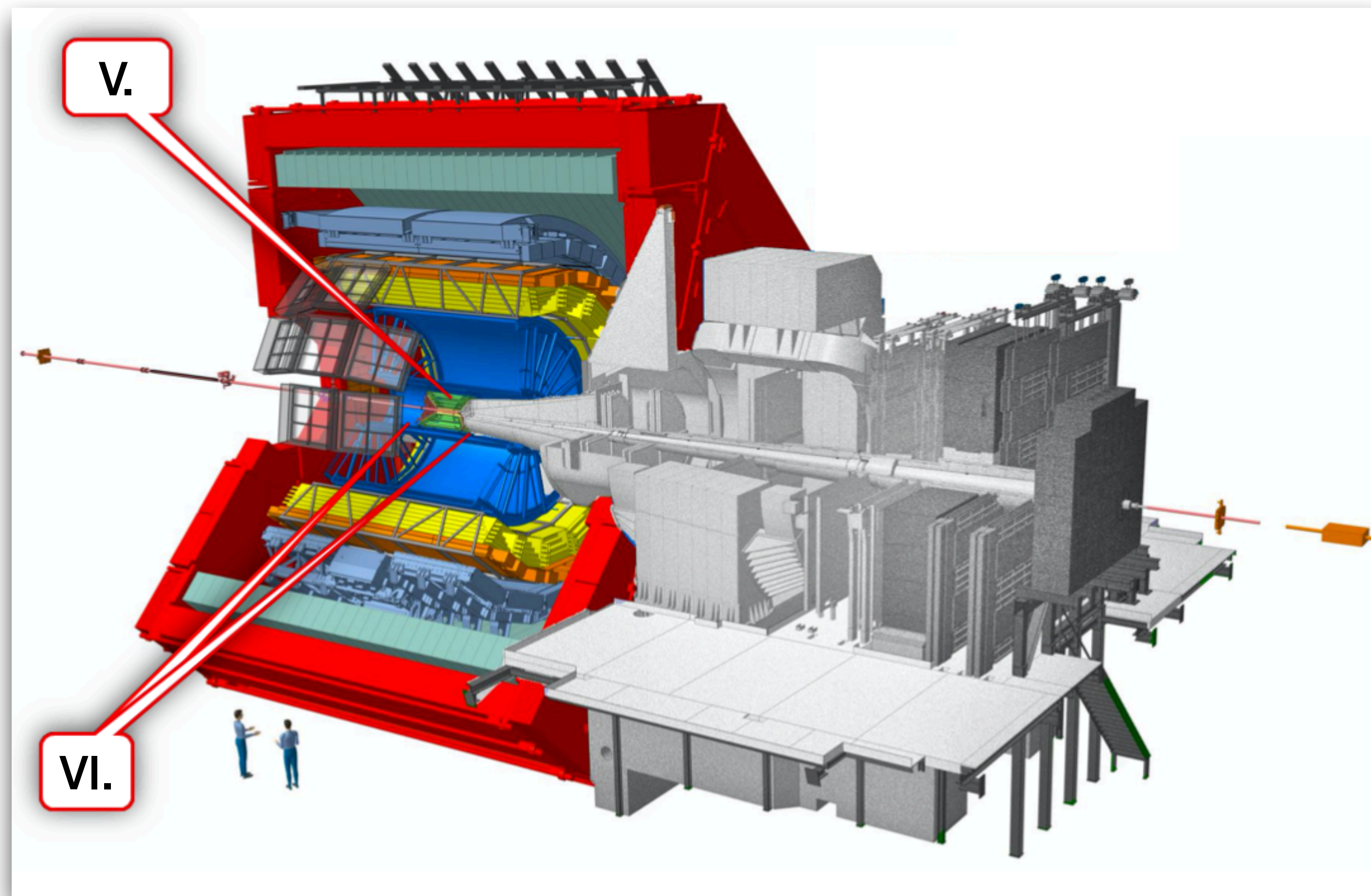
 A dedicated heavy-ion experiment at the LHC

 **V. Silicon Pixel Detector**

- ↳ Vertex reconstruction
- ↳ Event Plane determination

 **VI. V0 Detectors**

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

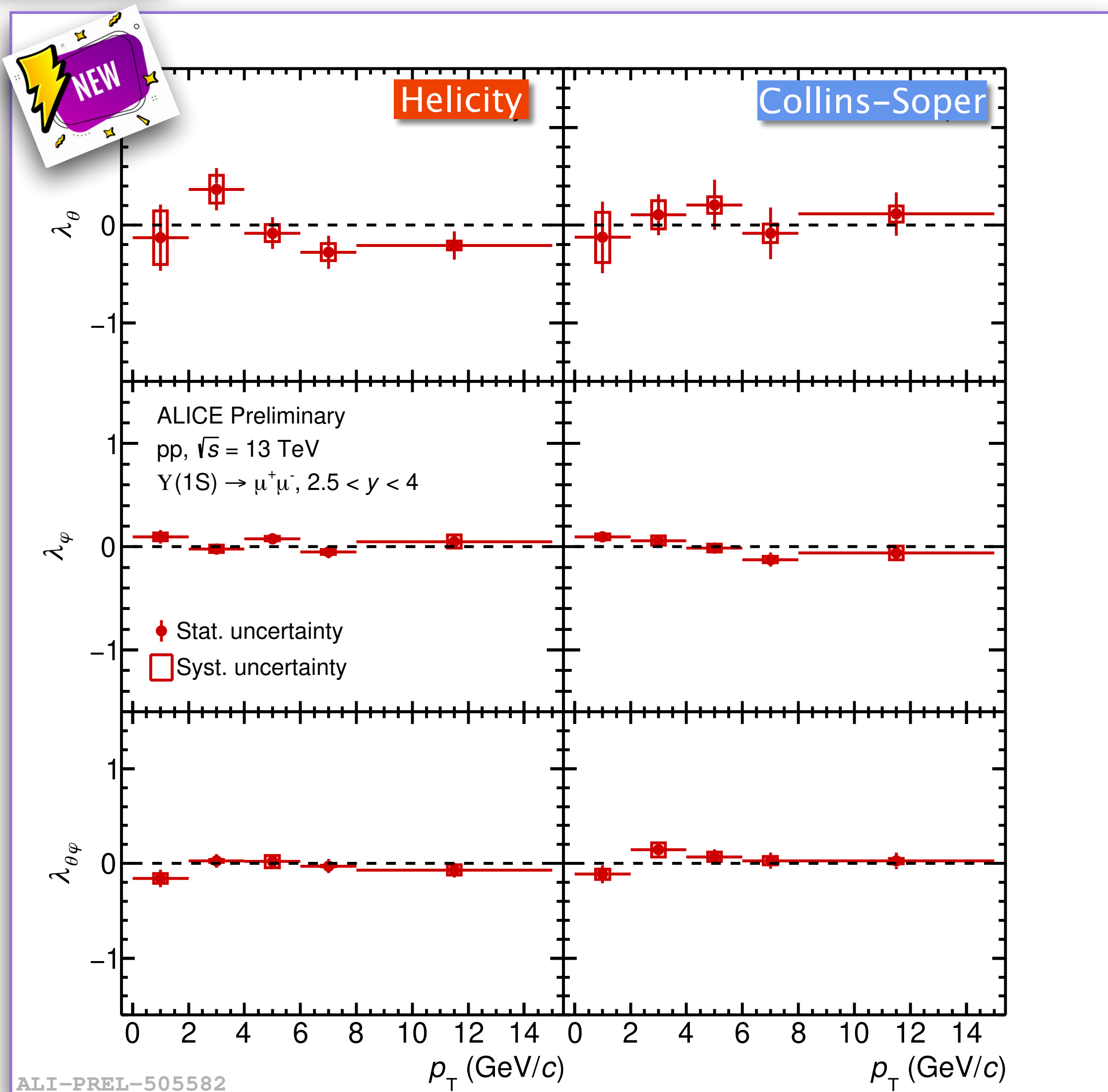




$\Upsilon(1S)$ polarization in pp collisions at $\sqrt{s} = 13$ TeV



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

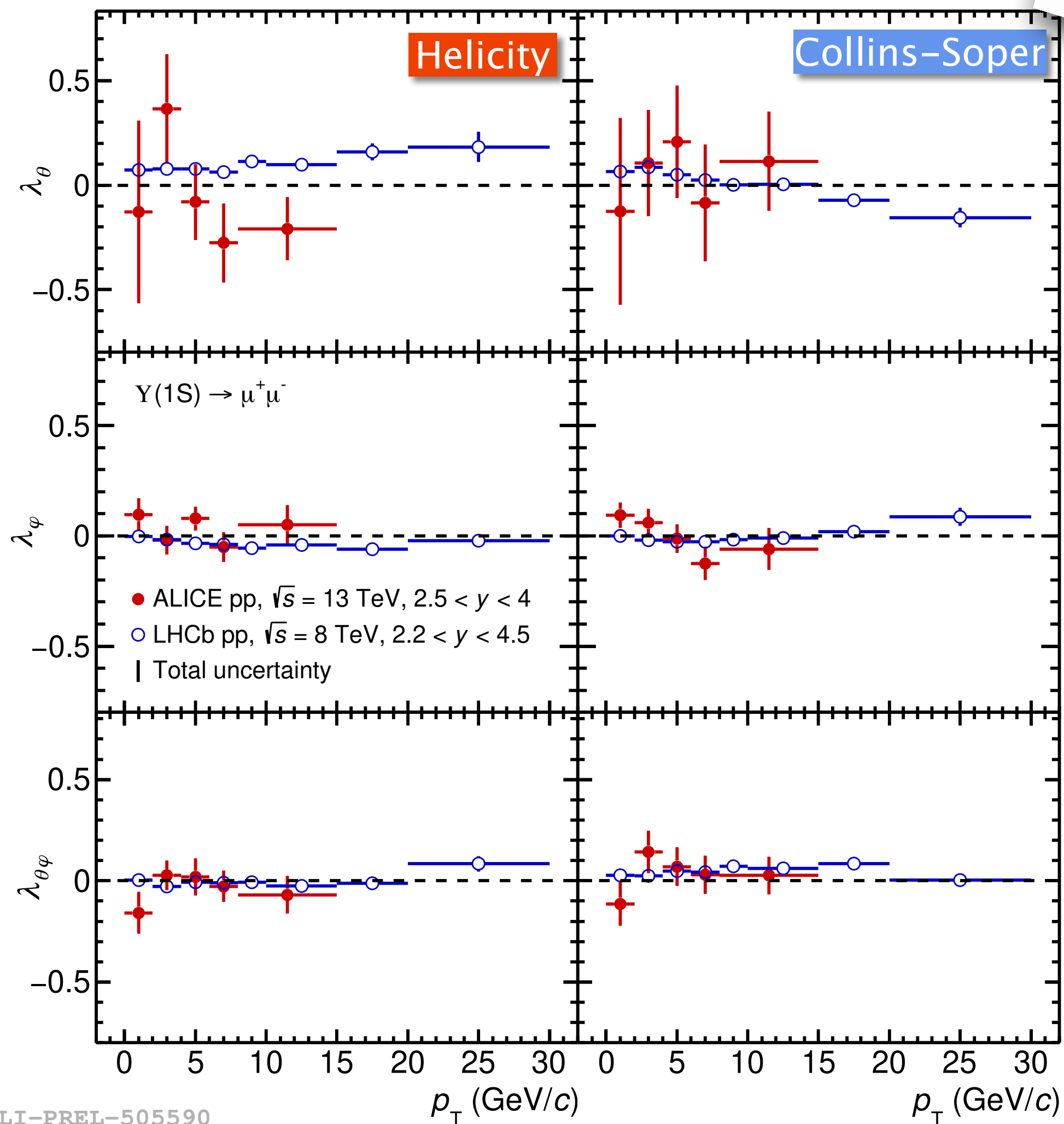
👉 λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ consistent with zero within uncertainties in both HE and CS frames



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



ALICE



ALI-PREL-505590

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

👉 λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ 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



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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 $2 < p_T < 4$ GeV/c

Compatible with **ALICE** results in **pp** collisions within uncertainties

EPJC 78 (2018) 562

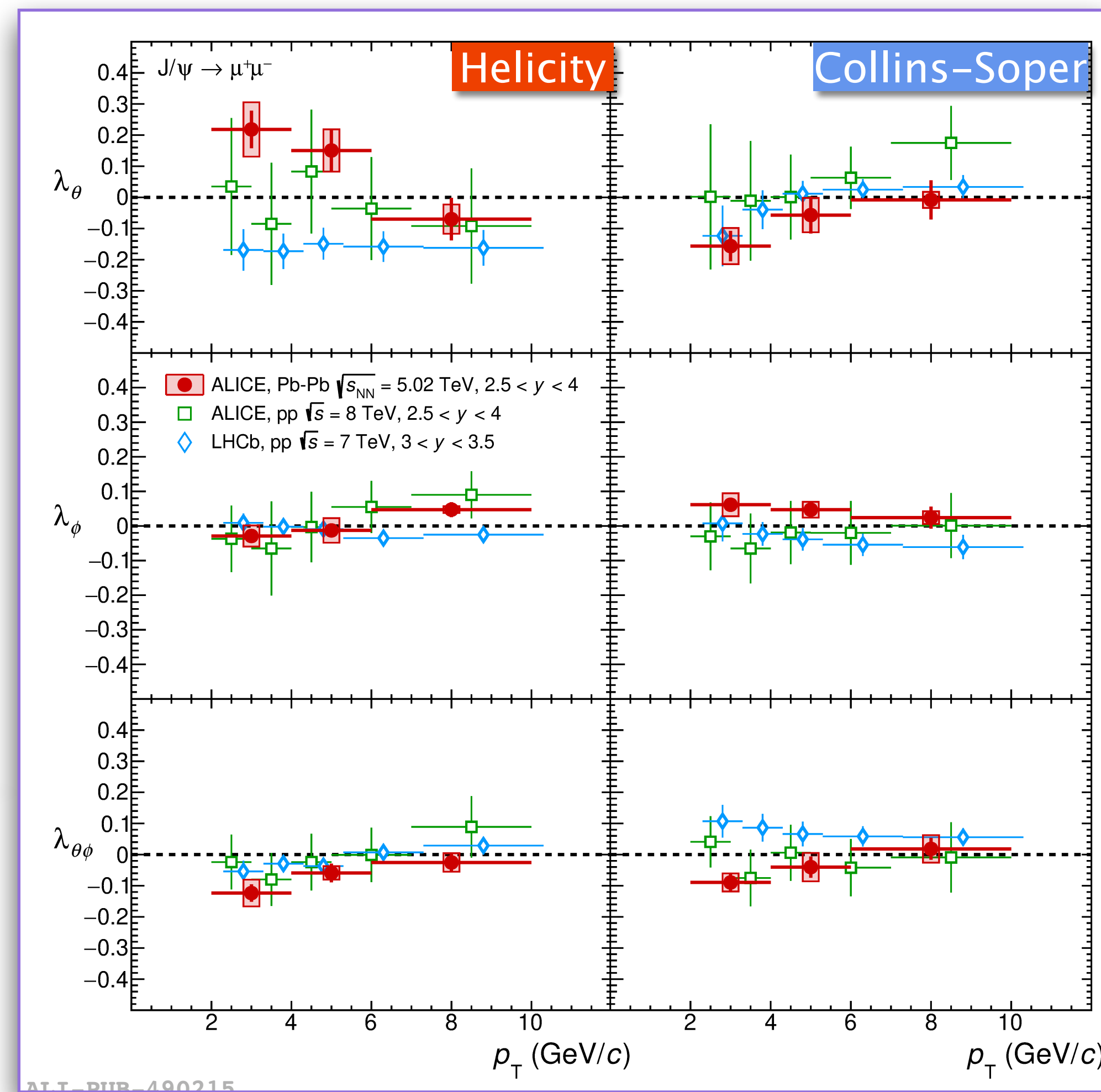
3σ difference w.r.t **LHCb** in **pp** collisions in **HE** frame

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



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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

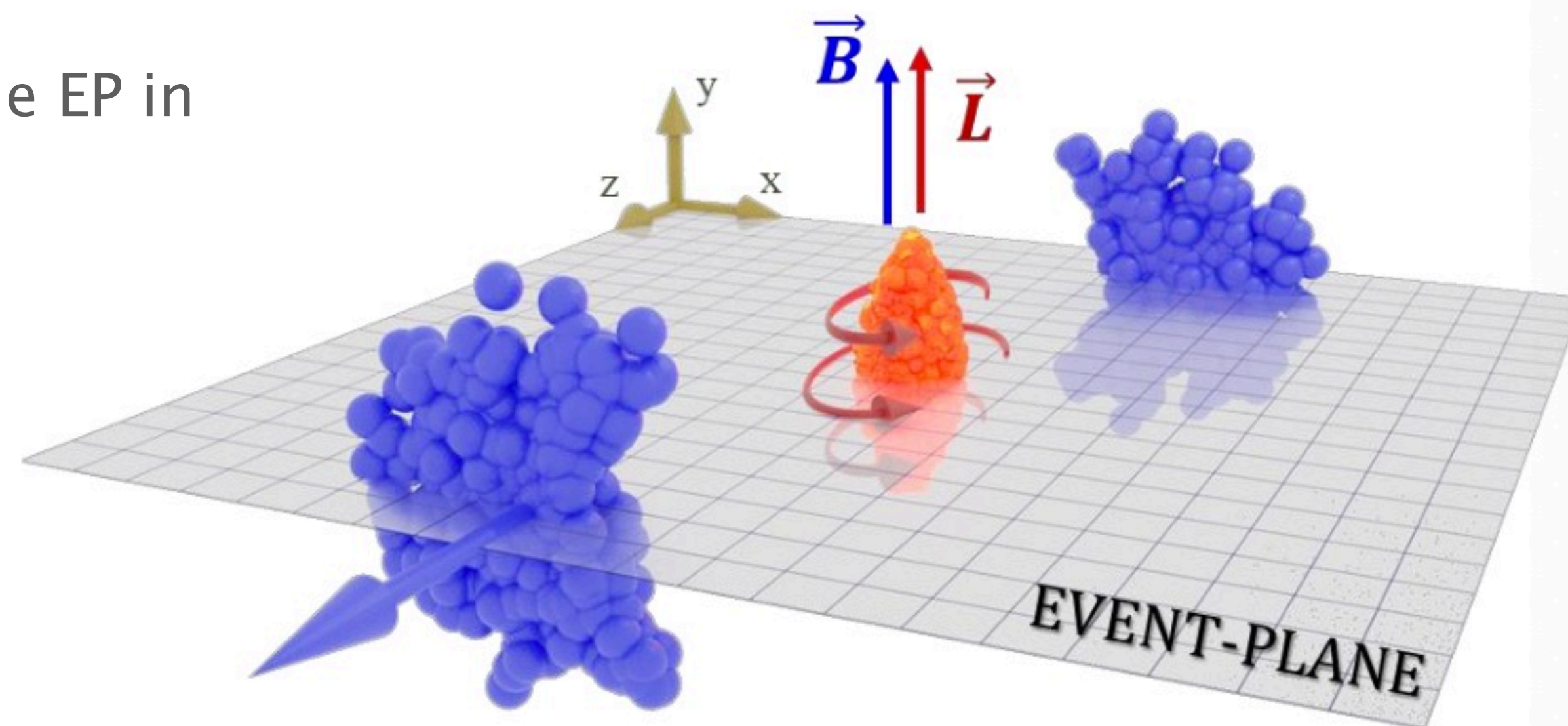
👉 EP normal to \vec{B} and \vec{L}

🔔 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



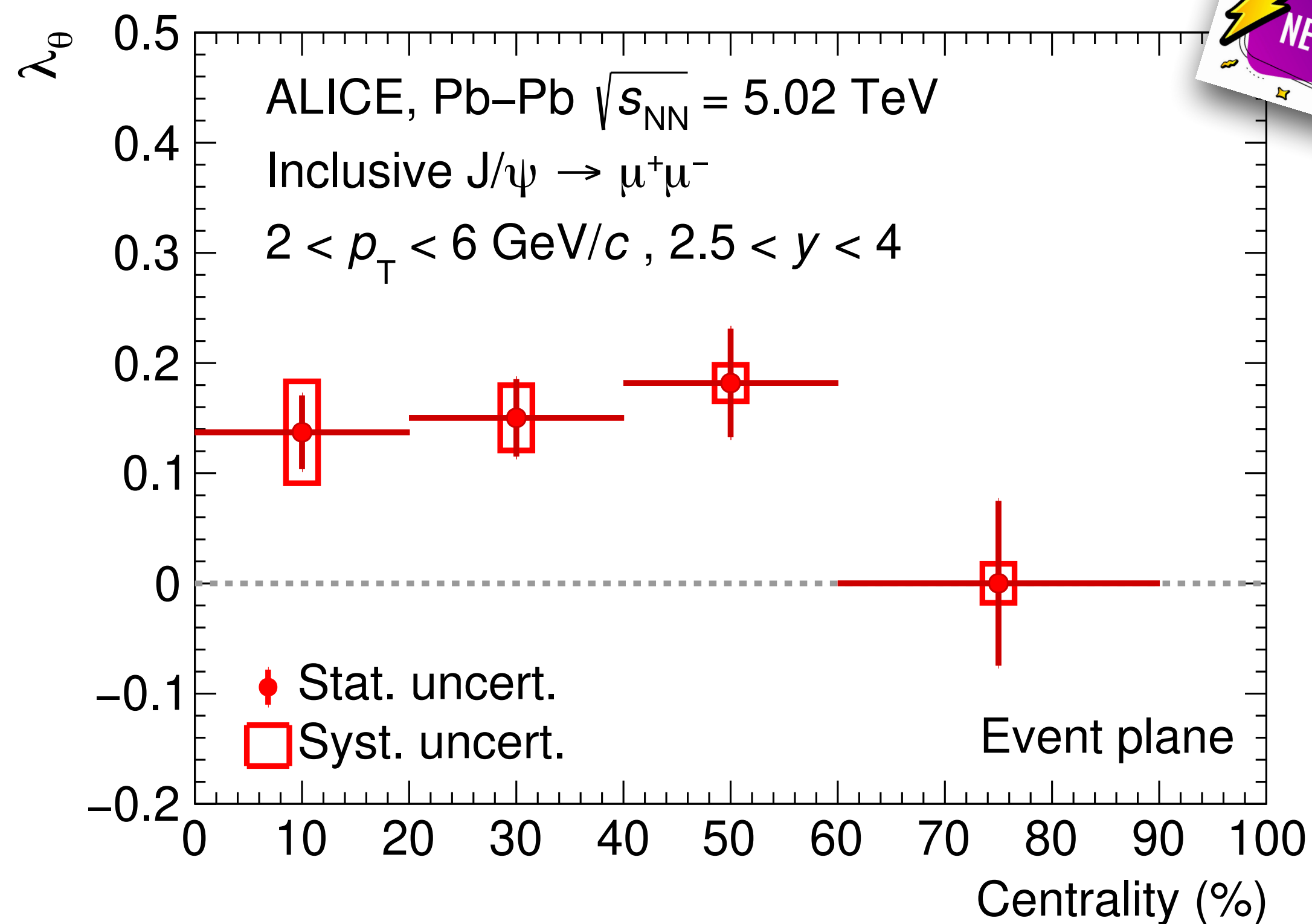


J/ψ polarization as a function of EP in Pb—Pb collisions



ALICE

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

ALI-PUB-519750

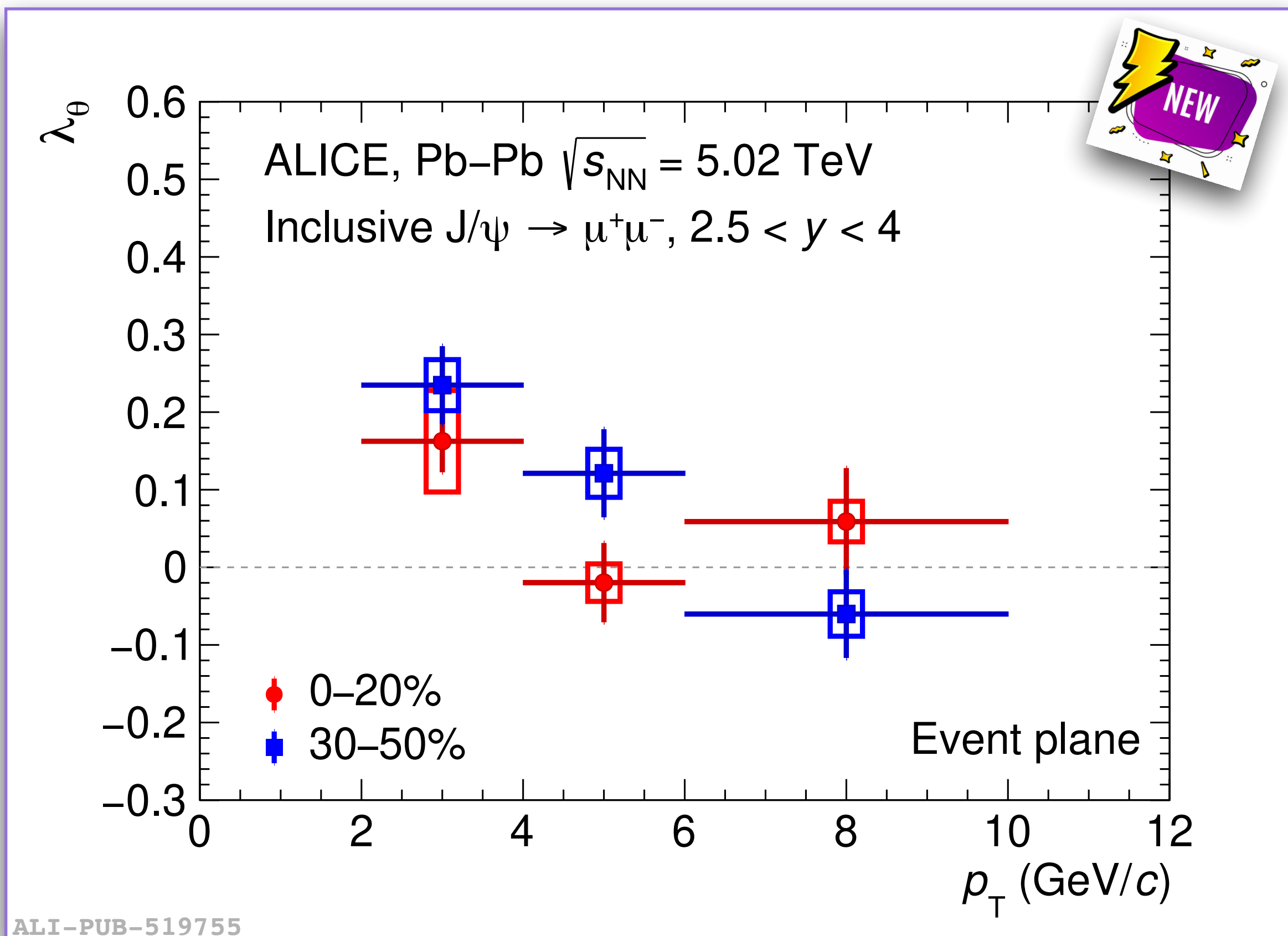


J/ψ polarization as a function of EP in Pb—Pb collisions



ALICE

arXiv:2204.10171



ALI-PUB-519755

🔔 **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



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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**

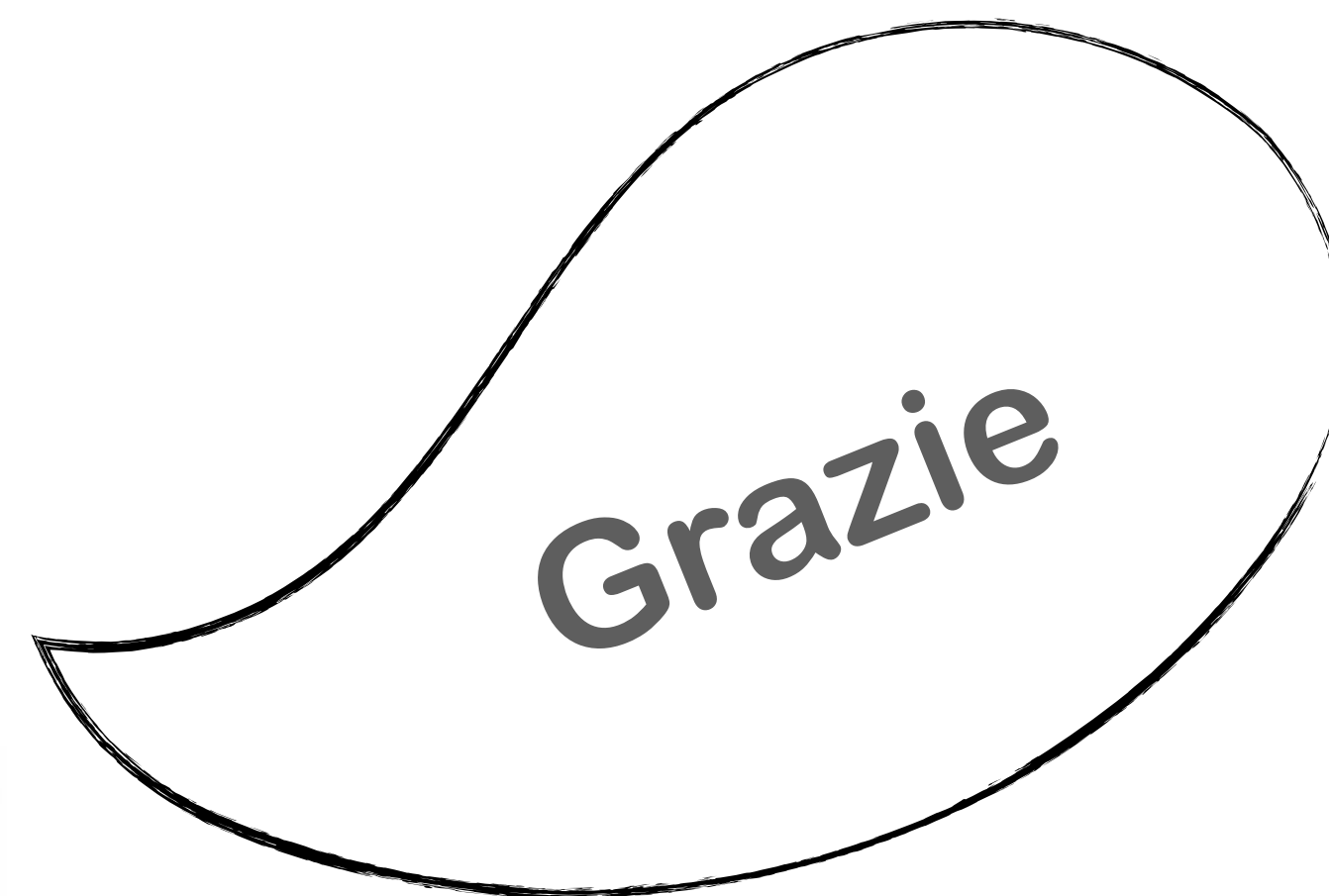
 **More precise measurements can be expected from large data sample with LHC Run 3**



Happy ending



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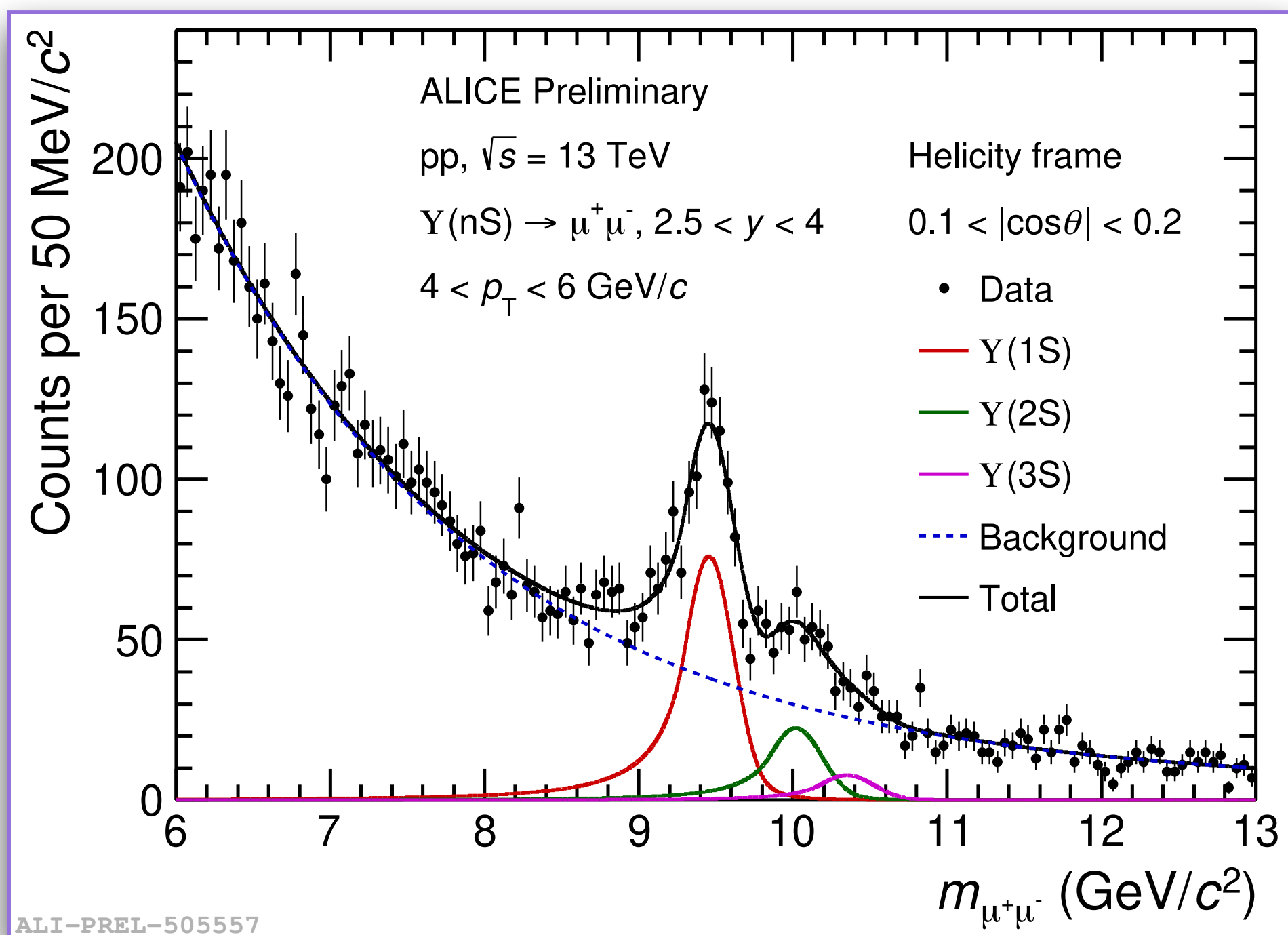
$\Upsilon(1S)$ polarization in pp collisions: analysis strategy



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Signal extraction

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

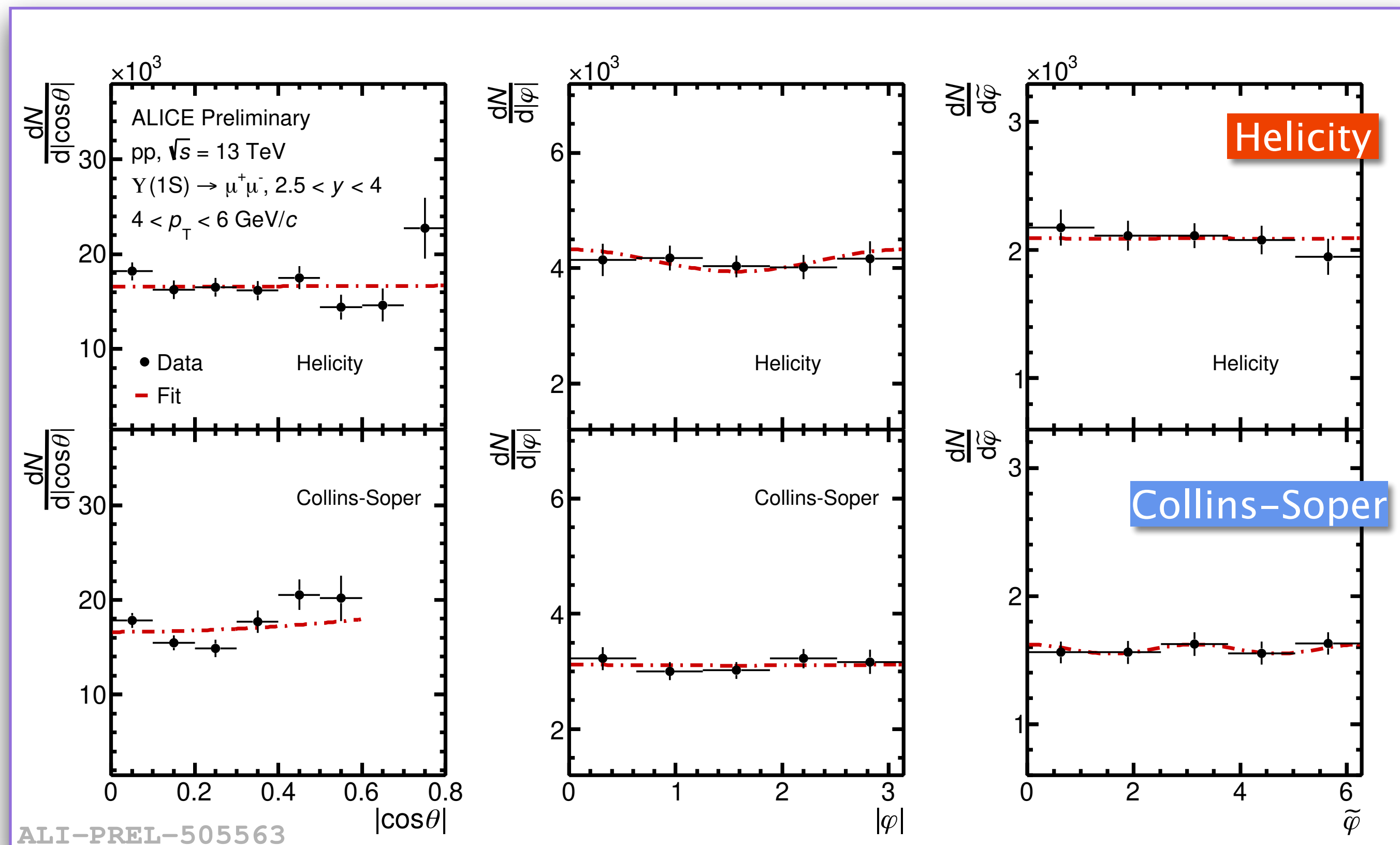


Acceptance x efficiency correction

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





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



ALICE

arXiv:2204.10171

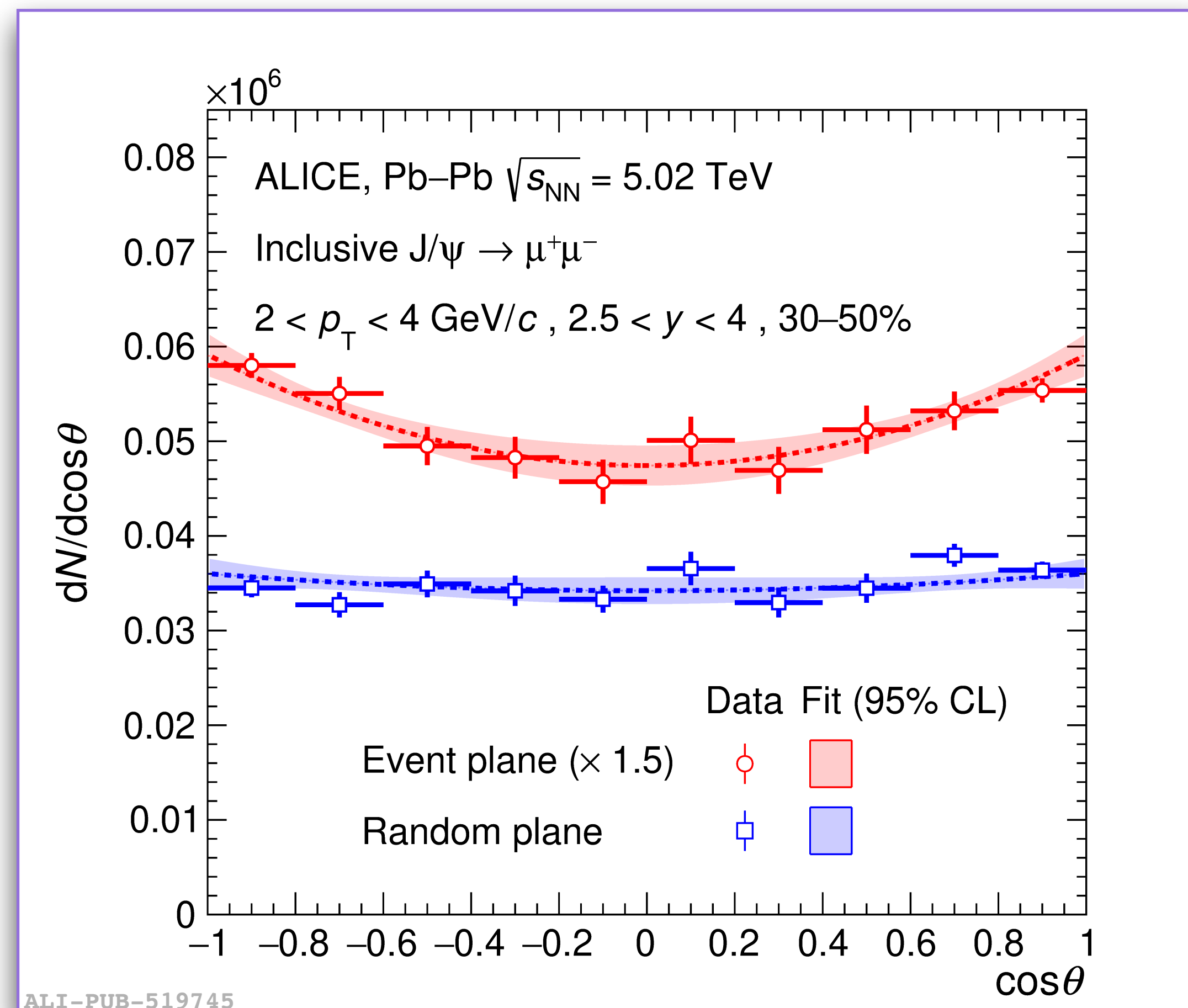
Signal extraction

- ↳ **Reweighting** applied at the dimuon candidate level with a 2-dimensions $(p_T, \cos\theta)$ $A \times \varepsilon$ **map**
- ↳ Fitting the corrected dimuon invariant mass distribution for the extraction of the raw yield

Polarization parameters determination

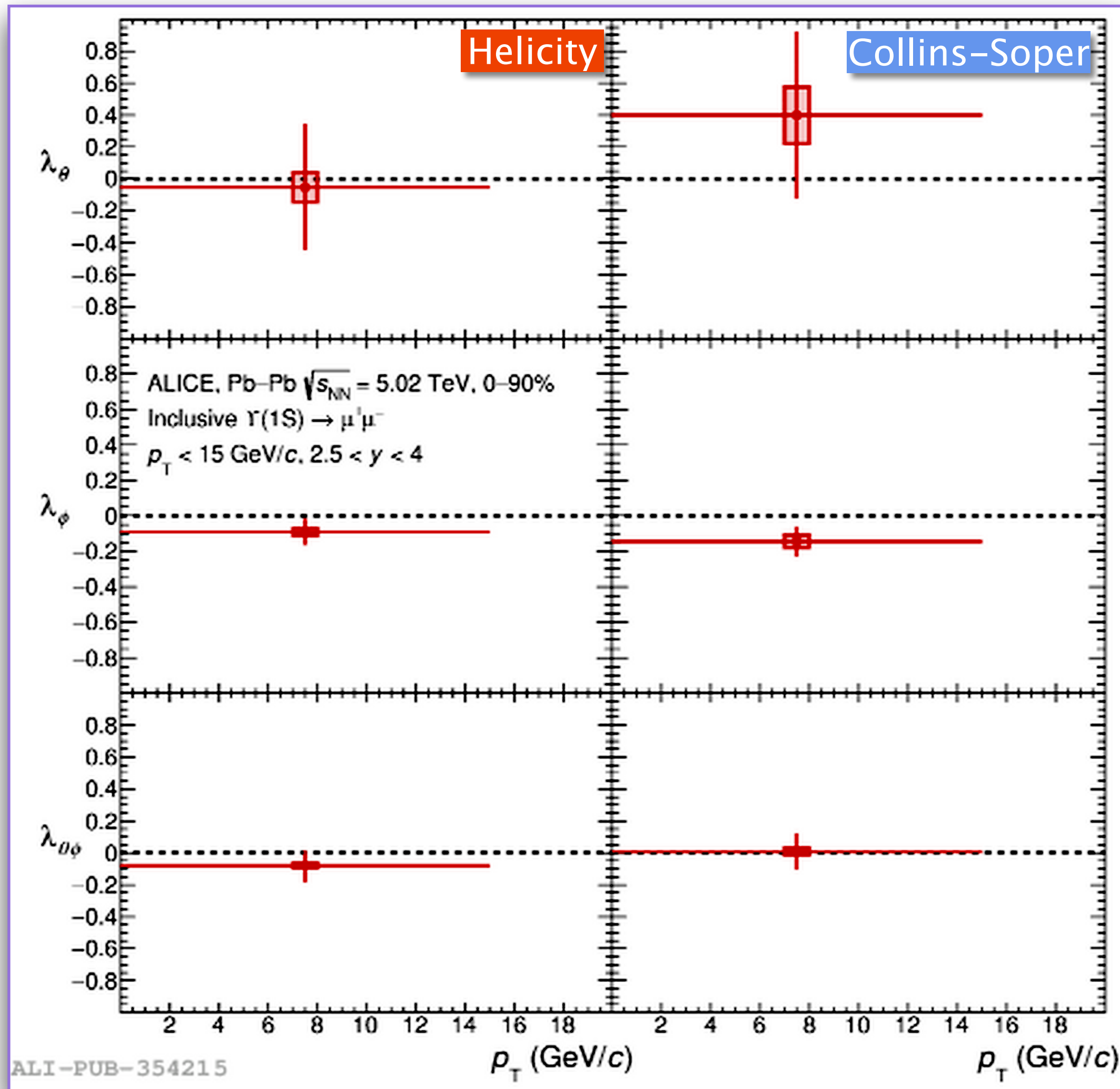
- ↳ Fitting the corrected angular distributions and extracting the polarization parameters

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





$\Upsilon(1S)$ polarization in Pb—Pb collisions



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

👉 λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ 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

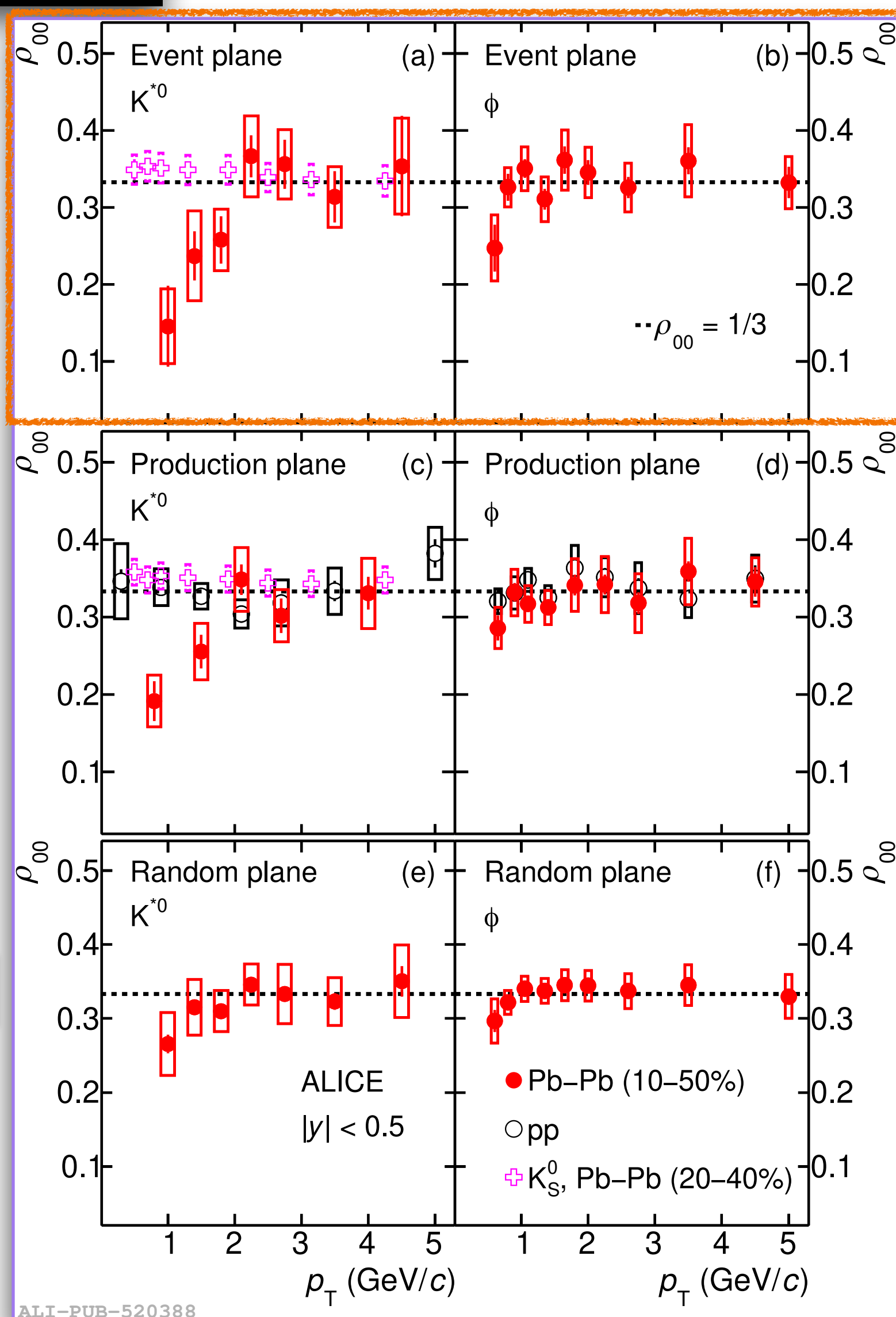


ALICE

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


ALI-PUB-520388




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




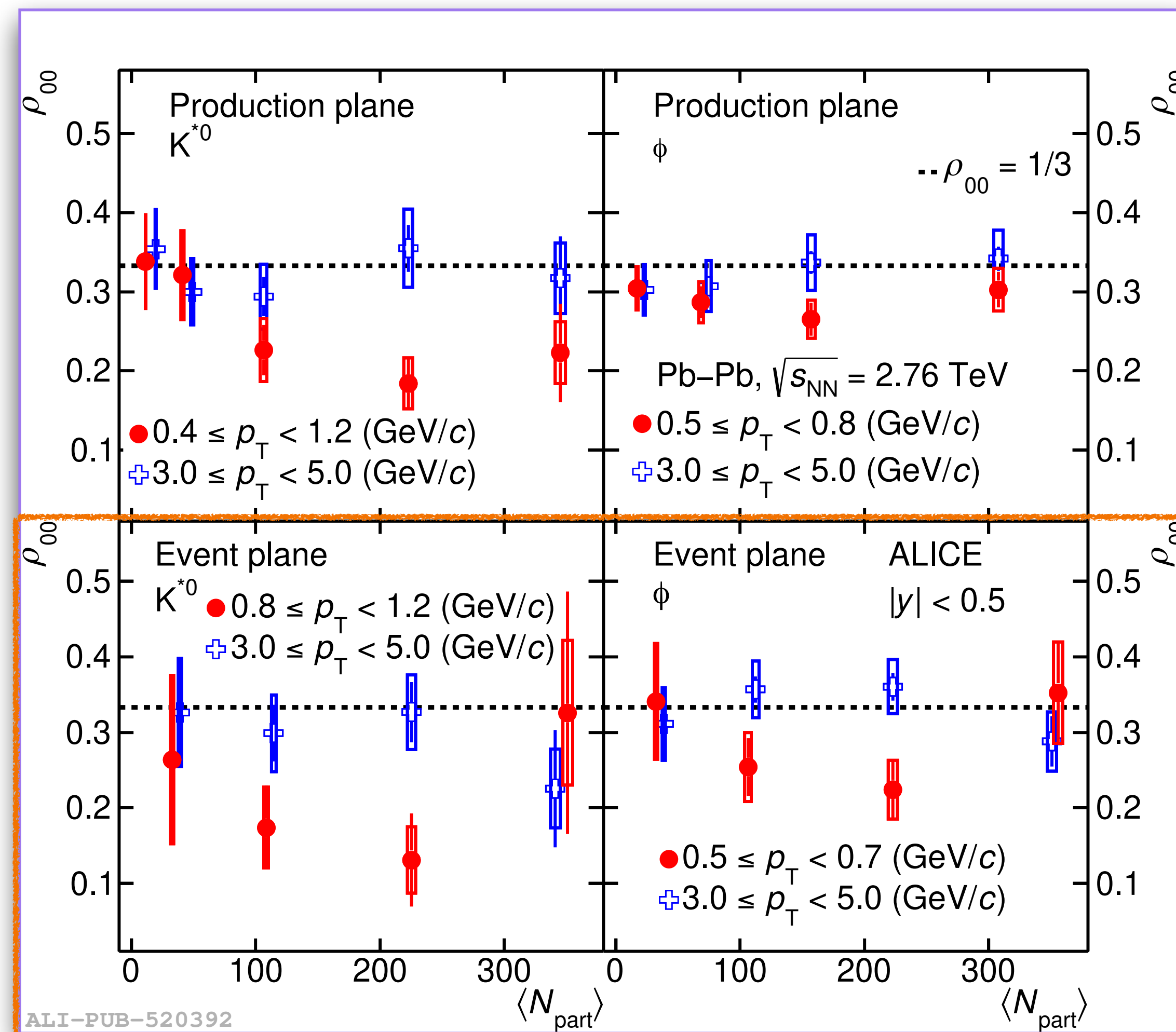
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 ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 13$ TeV

 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



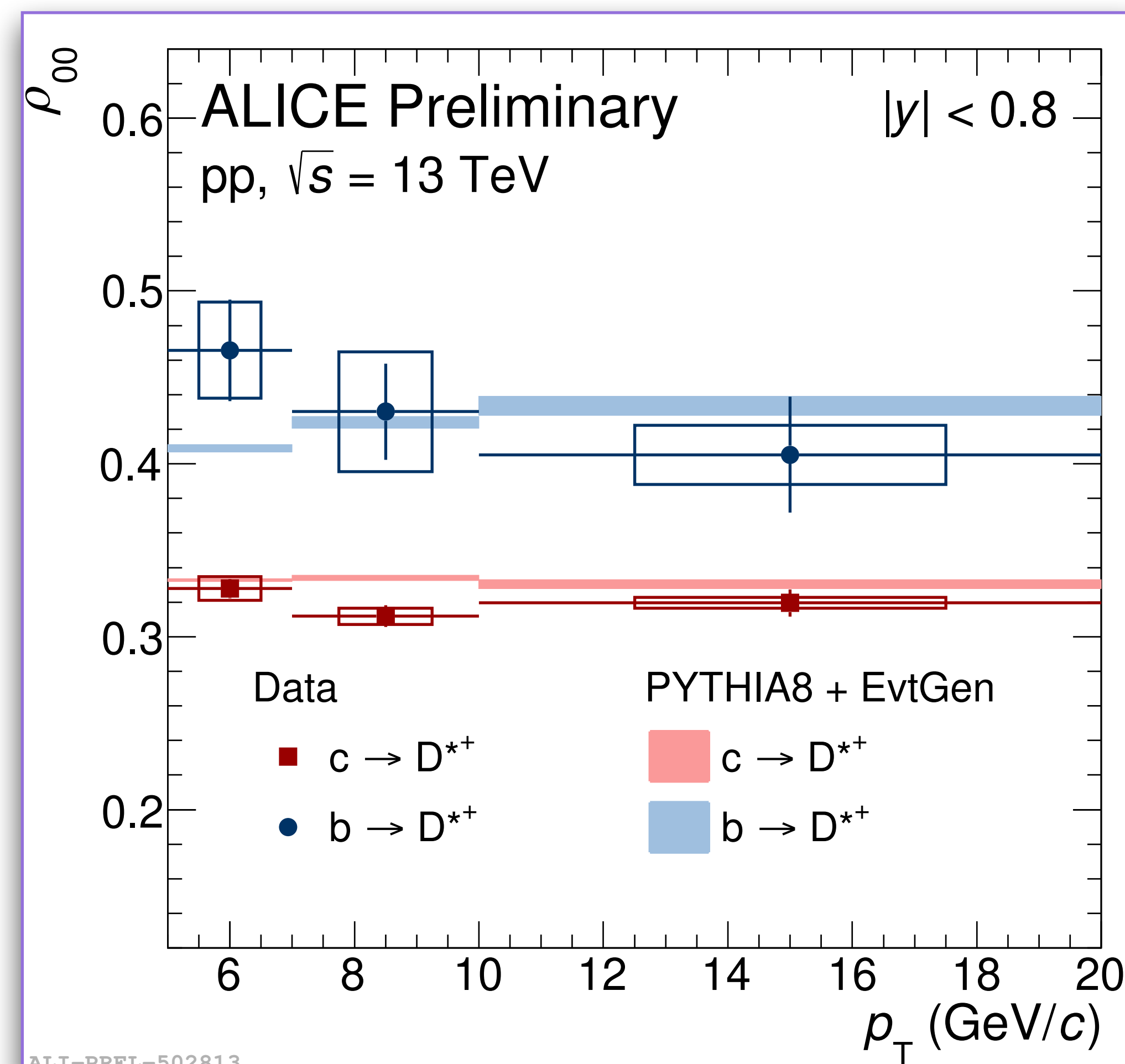


Charmed mesons polarization



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- 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^{*+} ($c \rightarrow D^{*+}$) unpolarized
 - Non-zero polarization for non-prompt D^{*+} ($b \rightarrow D^{*+}$)
 - Both well predicted by PYTHIA 8 + EVTGEN





Angular distribution



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

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

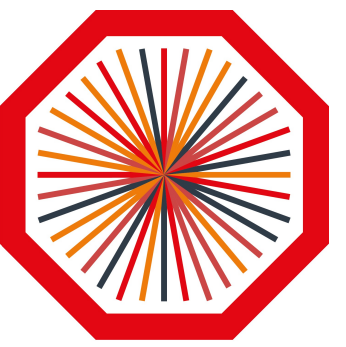
$$W(\tilde{\varphi}) \propto 1 + \frac{\sqrt{2}\lambda_{\theta\varphi}}{3 + \lambda_\theta} \cos 2\tilde{\varphi}$$

$$\tilde{\varphi} = \varphi - 3\pi/4, \quad \cos \theta < 0$$

$$\tilde{\varphi} = \varphi - \pi/4, \quad \cos \theta > 0$$



J/ ψ polarization in theory



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Phys. Rev. Lett. 108 (2012) 172002

