ALICE

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

10th International conference on Hard and Electromagnetic probes of High-Energy Nuclear collisions

4th June 2020

Measurement of quarkonium polarization in Pb-Pb collisions with ALICE at the LHC

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on behalf of the ALICE collaboration

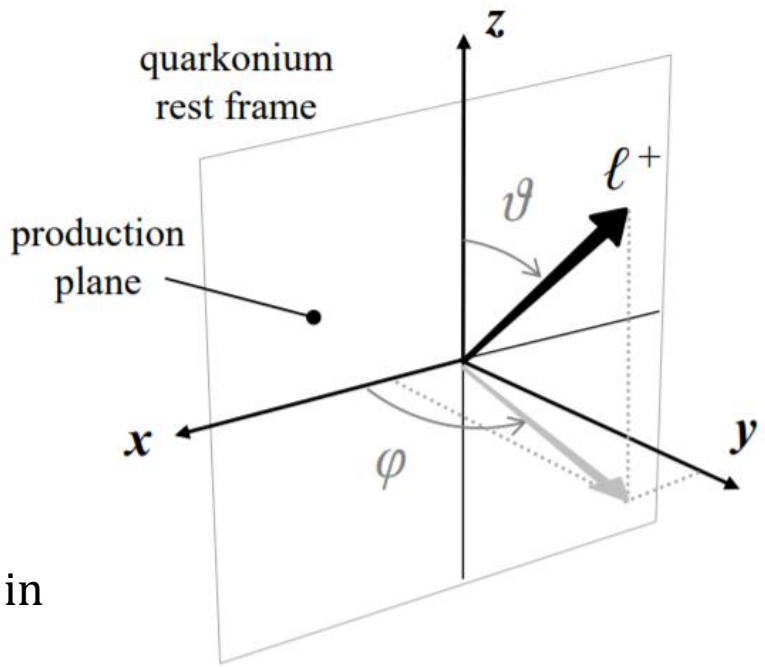
Vector meson polarization: basic concepts

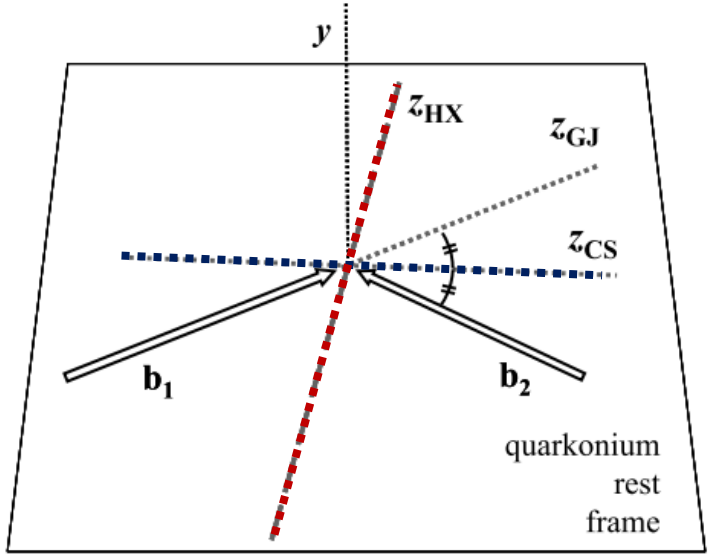
- **Polarization:**
  - Defined as the **spin-alignment** with respect to a chosen direction
  - Measured as **anisotropies** in the decay products angular distributions

$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos2\phi+\lambda_{\theta\phi}\sin2\theta\cos\phi)$$

$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (0,0,0)$ $\Longrightarrow$ **No polarization**

$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (\pm1,0,0)$ $\Longrightarrow$ Pure **longitudinal**$(-)$/**transverse**$(+)$ polarization





$\Longrightarrow$ Polarization axis:

- **Helicity (HX):** direction of vector meson in the collision center of mass frame
- **Collins-Soper (CS):** the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame

Figures from P.Faccioli et al. EPJ C69 (2010) 657-673

Quarkonium polarization in pp and AA collisions

Polarization in pp collisions

No sizeable polarization measured at LHC in pp collisions!

But…

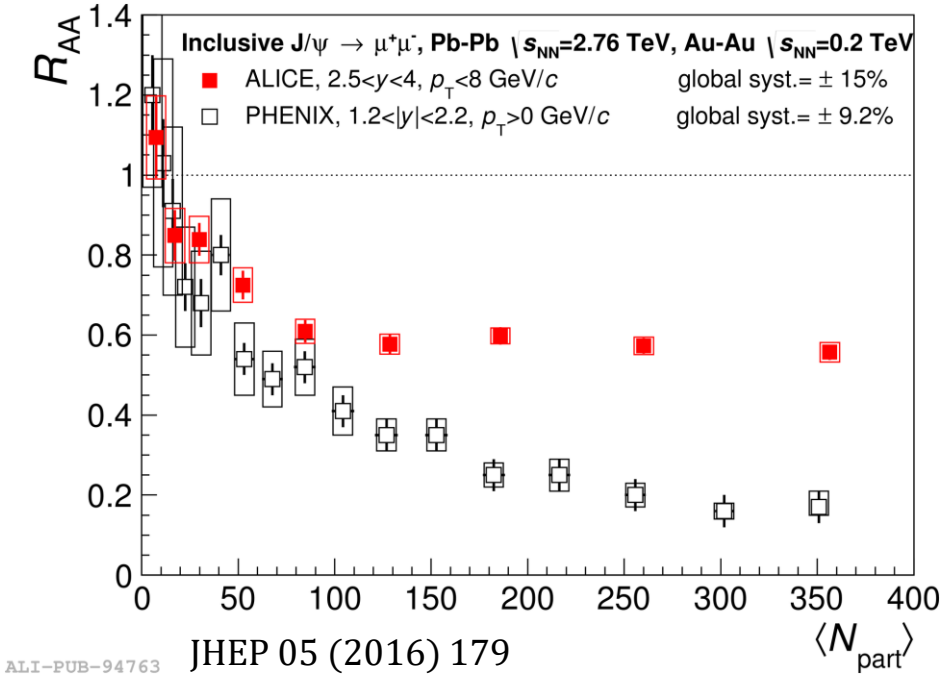
- Constrains **J/ψ production mechanism**

⟹ Originally:

- ❑ **LO NRQCD** ⟹ transverse polarization for high-p_T J/ψ
- ❑ **NLO color singlet model** ⟹ longitudinal polarization

⟹ ongoing theoretical developments…

Polarization in AA collisions



JHEP 05 (2016) 179

"Dense parton matter may then screen out of the existence a large part of quarkonia . . . but those of them that survive will carry the information about the mechanism of their formation throughout the collision"

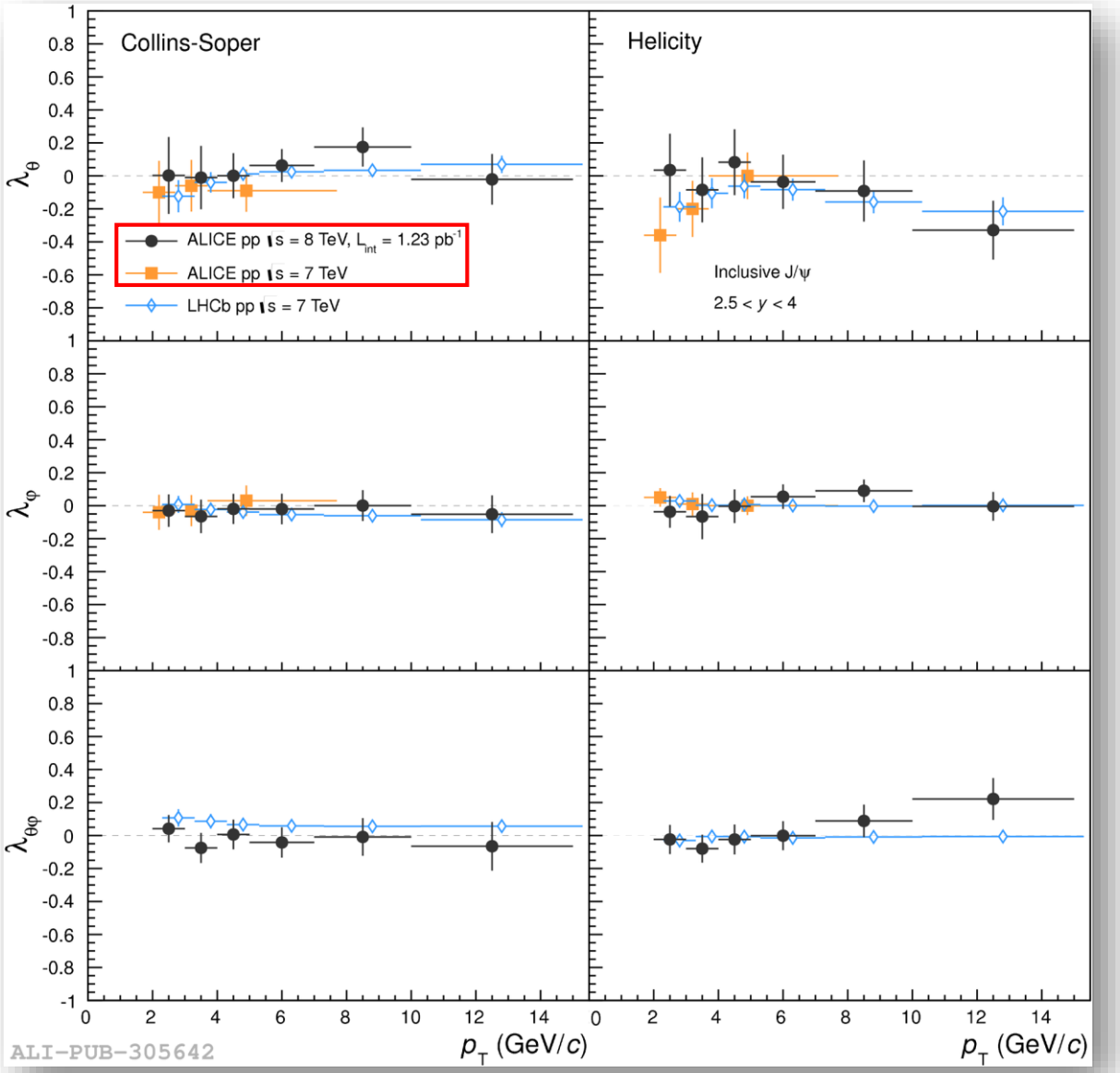
Ioffe & Kharzeev, Phys. Rev. C68 (2003) 061902

- The **suppression mechanism** in heavy ion collisions
  - ➡ affects differently the various quarkonium states
  - ➡ Possible modification of J/ψ polarization with respect to pp because the **prompt feed-down fractions** change

$$J/\psi^{\text{Prompt}} : (30\%)^{[J/\psi \leftarrow \chi_c]} \text{ and } (10-15\%)^{[J/\psi \leftarrow \psi(2S)]}$$

- At LHC energies **regeneration** plays an important role
  - ➡ possible modification of J/ψ polarization

Quarkonium polarization in pp collisions at LHC



- The **ALICE** experiment measured **inclusive J/ψ polarization** in pp collisions at $\sqrt{s} = 7$ [1] and **8 TeV** [2]

  ⟹ all polarization parameters compatible with zero

- **LHCb** measured **prompt J/ψ polarization** in pp collisions at $\sqrt{s} = 7$ **TeV** [3]

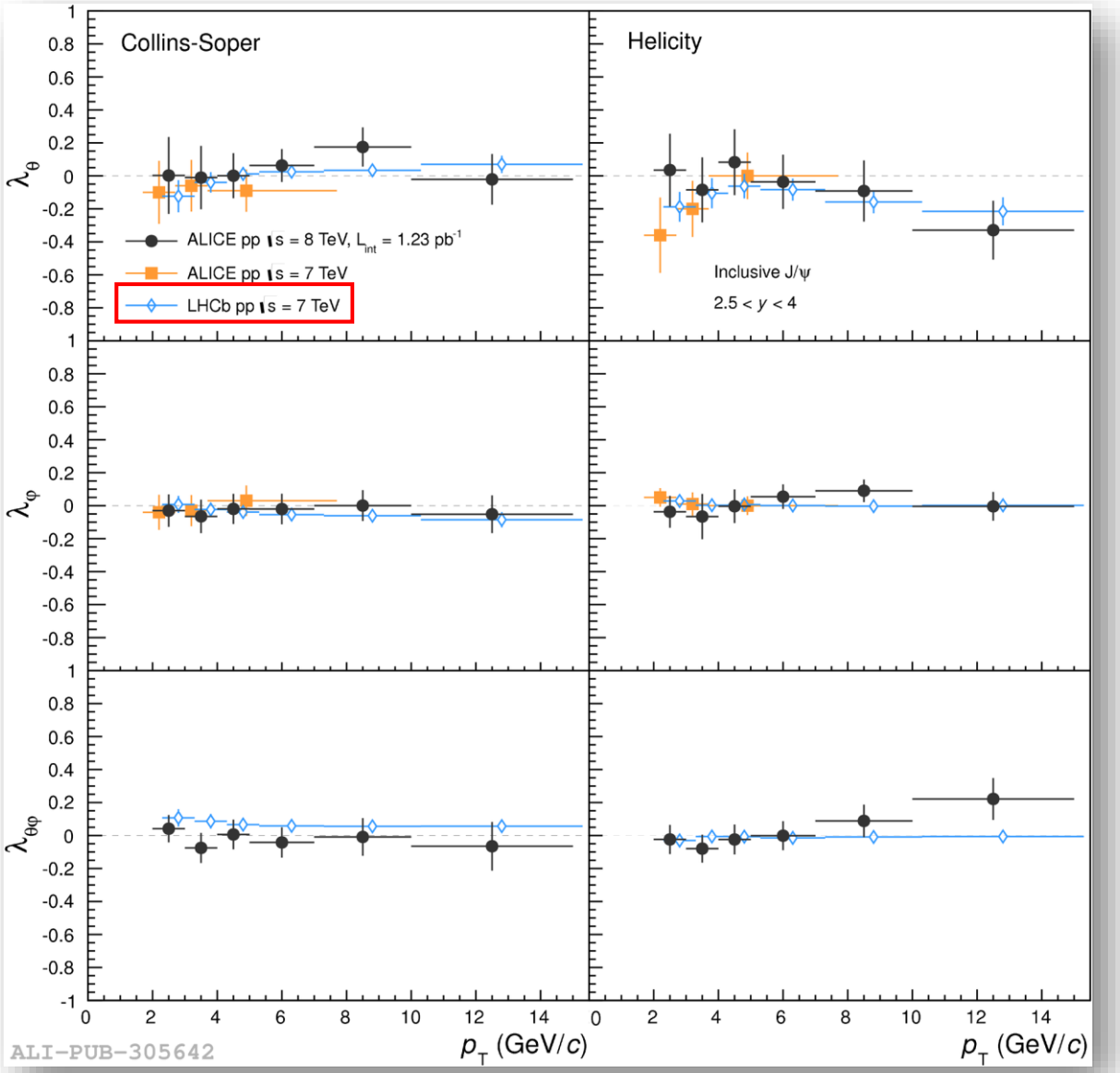
  ⟹ the weighted average over all the (p_T, y) bins shows a small longitudinal polarization ($\lambda_\theta = -0.145 \pm 0.027$)

- **CMS** measured **prompt J/ψ and ψ(2S) polarization** in pp collisions up to 70 GeV/c at $\sqrt{s} = 7$ **TeV** [4]

  ⟹ $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero even at high p_T

(1) PRL 108 (2012) 082001
(2) EPJ C 78 (2018) 562
(3) EPJ C 73 (2013) 2631
(4) PLB 727 (2013) 381-402

Quarkonium polarization in pp collisions at LHC



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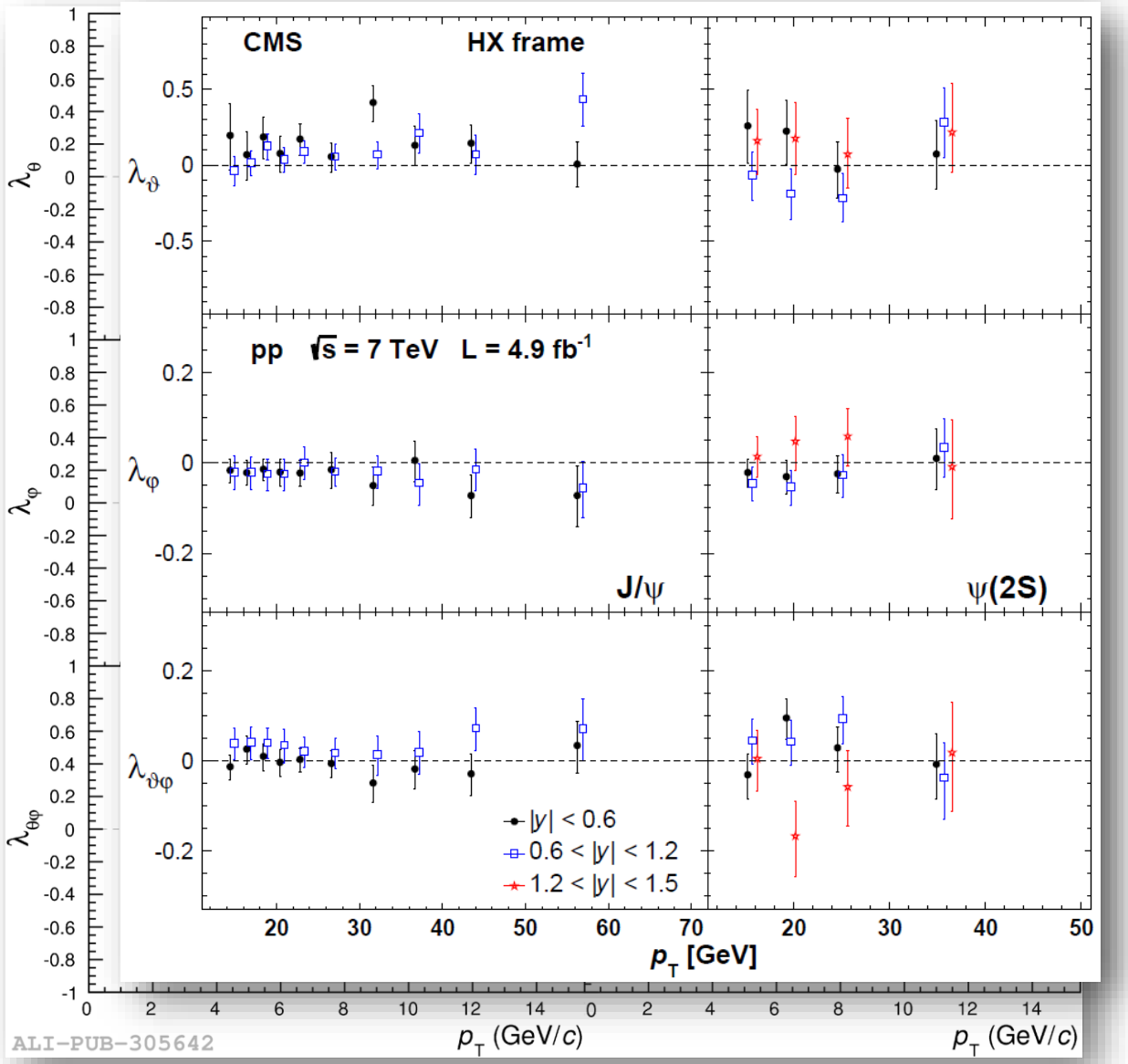

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A Large Ion Collider Experiment

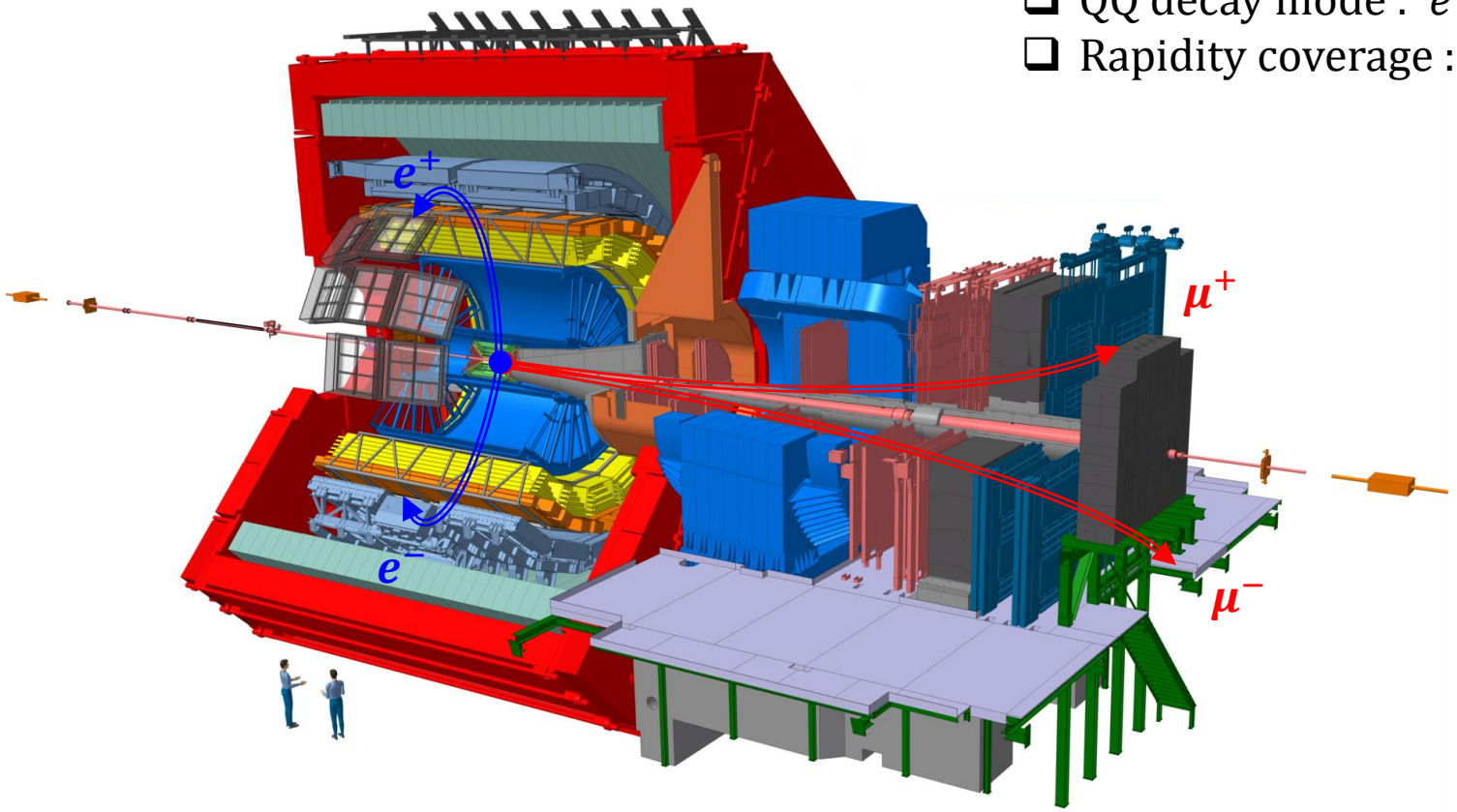
The **ALICE experiment** at LHC is designed for the study of heavy-ion collisions

Central barrel :

- ❑ $Q\bar{Q}$ decay mode : e^+e^-
- ❑ Rapidity coverage : $|y| < 0.9$

Muon spectrometer:

- ❑ $Q\bar{Q}$ decay mode : $\mu^+\mu^-$
- ❑ Rapidity coverage : $2.5 < y < 4$



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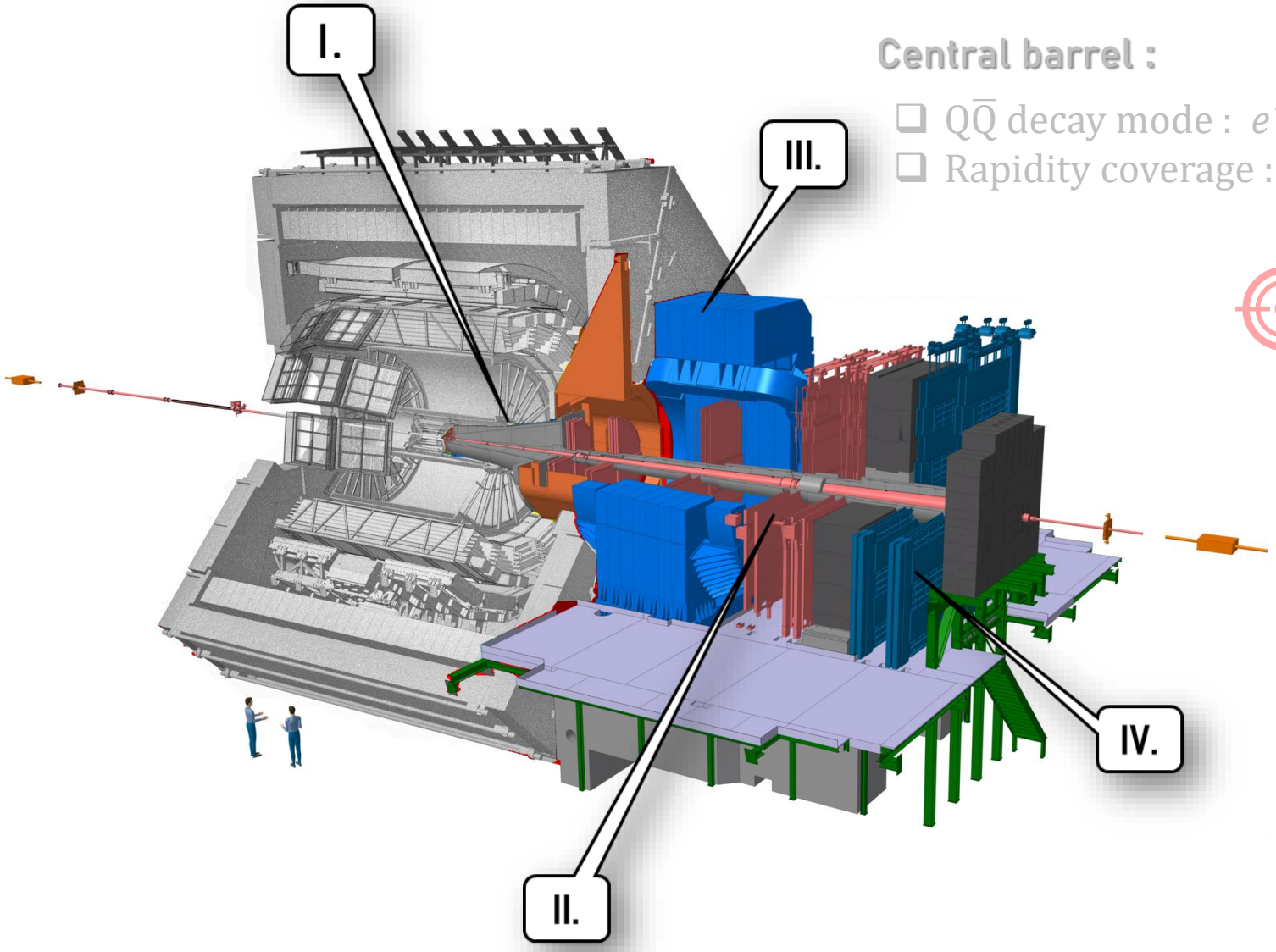

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Focus on the **muon spectrometer**:

- In this analysis quarkonium is studied via its decay to a muon pair

I. Front absorber

II. Tracking system

III. Dipole magnet

IV. Trigger system

A Large Ion Collider Experiment

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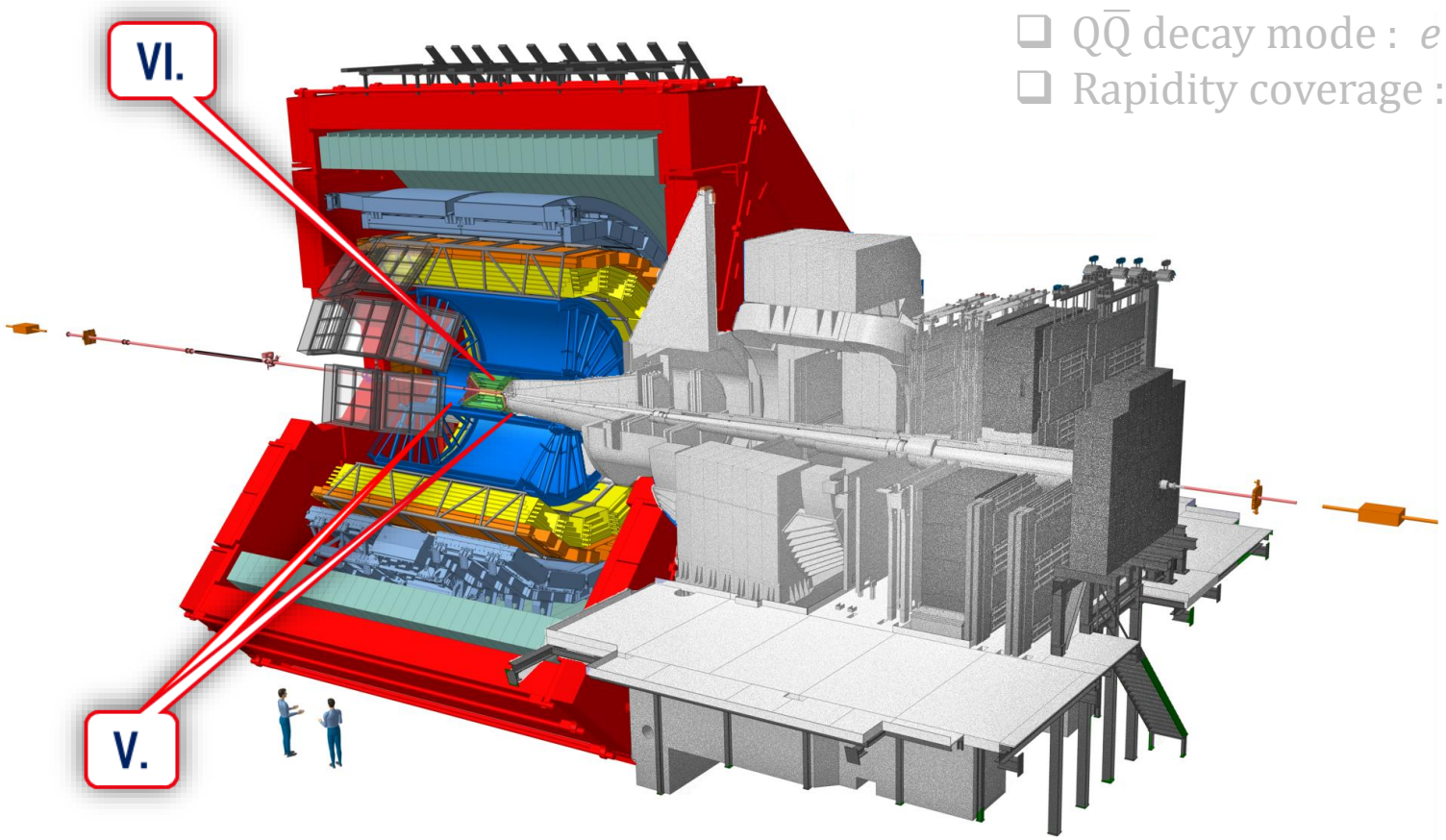

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- **Central barrel** detectors crucial for this analysis:

V. **V0** detectors

- Trigger
- Centrality estimation
- Background rejection

VI. **Silicon Pixel Detector**

- Vertex determination

Data sample and analysis procedure

Data sample: 2015 and 2018 Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV ($L_{\mathrm{int}} \sim 0.75\ nb^{-1}$)

Candidate selection

J/ψ and ϒ(1S) candidates are built combining muon pairs reconstructed in the muon spectrometer

- Application of all the standard cuts for quarkonium analysis

Analysis procedure

1. **Signal extraction**: number of J/ψ & ϒ(1S) obtained fitting the $\mu^+\mu^-$ invariant mass distribution vs $(\cos\theta, \phi)$
2. **Acceptance × efficiency correction**: number of J/ψ corrected with the $A \times \varepsilon$ obtained with a MC simulation
3. **Polarization parameters extraction**: fit to the J/ψ $A \times \varepsilon$-corrected distribution with $W(\cos\theta, \phi)$

Data sample and analysis procedure

Data sample: 2015 and 2018 Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV ($L_{\mathrm{int}} \sim 0.75\ nb^{-1}$)

Candidate selection

In this presentation:

- J/ψ polarization as a function of p_{T} from 2 to 10 GeV/c in $2.5 < y < 4$
- $\Upsilon(1S)$ polarization for $p_{\mathrm{T}} < 15$ GeV/c in $2.5 < y < 4$

  ⟹ New paper!
  "First measurement of quarkonium polarization in nuclear collisions at the LHC" arXiv:2005.11128

- J/ψ polarization as a function of centrality for $2 < p_{\mathrm{T}} < 6$ GeV/c in $2.5 < y < 4$

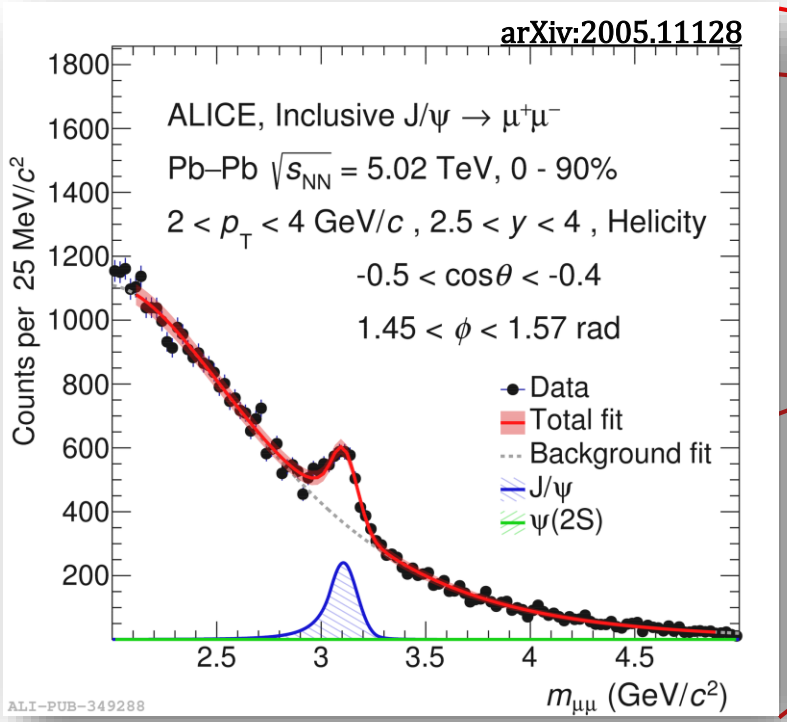
  ⟹ New preliminary result!

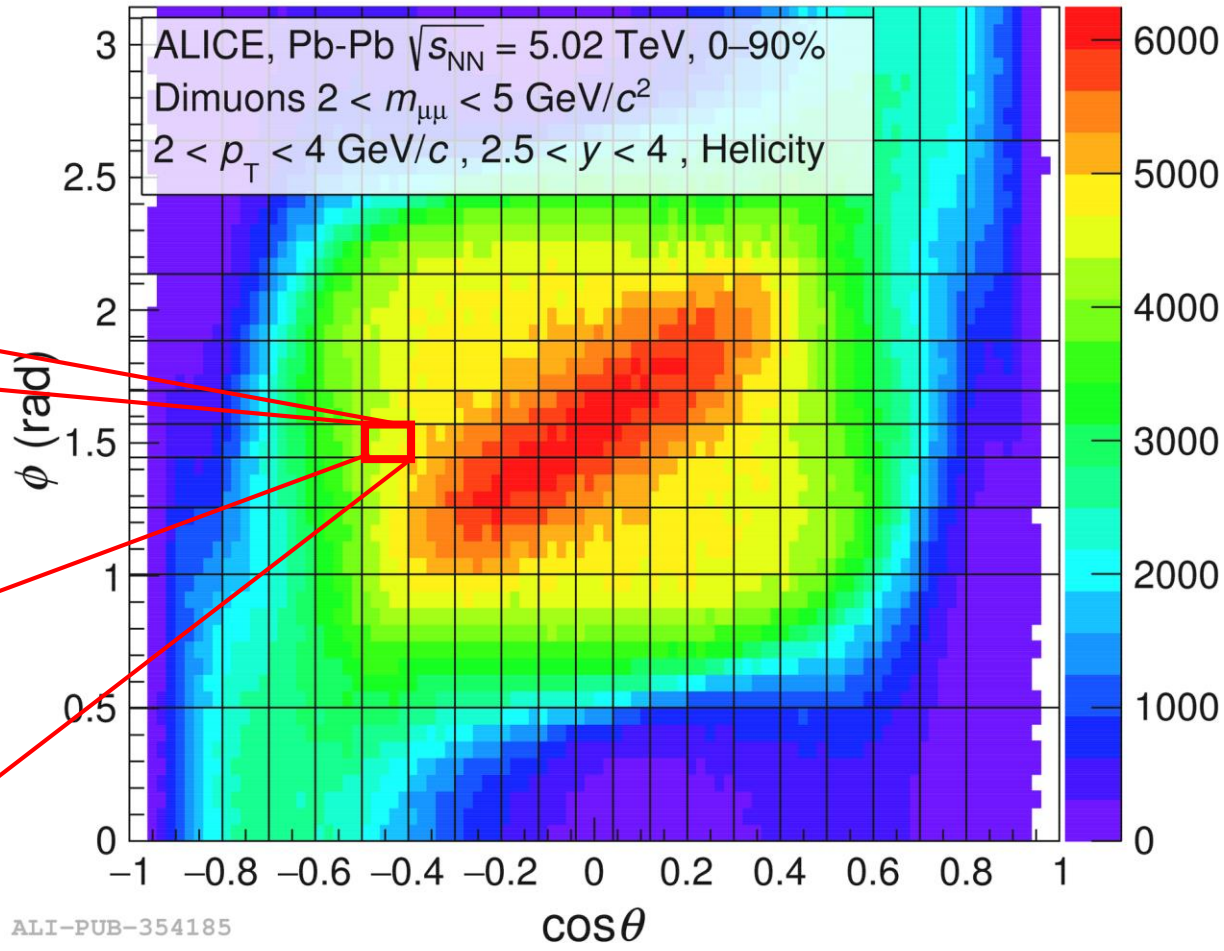
3. **Polarization parameters extraction**: fit to the J/ψ $A \times \varepsilon$-corrected distribution with $W(\cos\theta, \phi)$

Signal extraction

J/ψ polarization vs p_T

- The sizeable data sample collected allows to extract the J/ψ yield in ($\cos\theta$, ϕ) cells (**2D approach**)
  - ❑ Creation of a 2D grid for signal extraction
  - ❑ Angular binning tuned according to the statistical significance of the signal



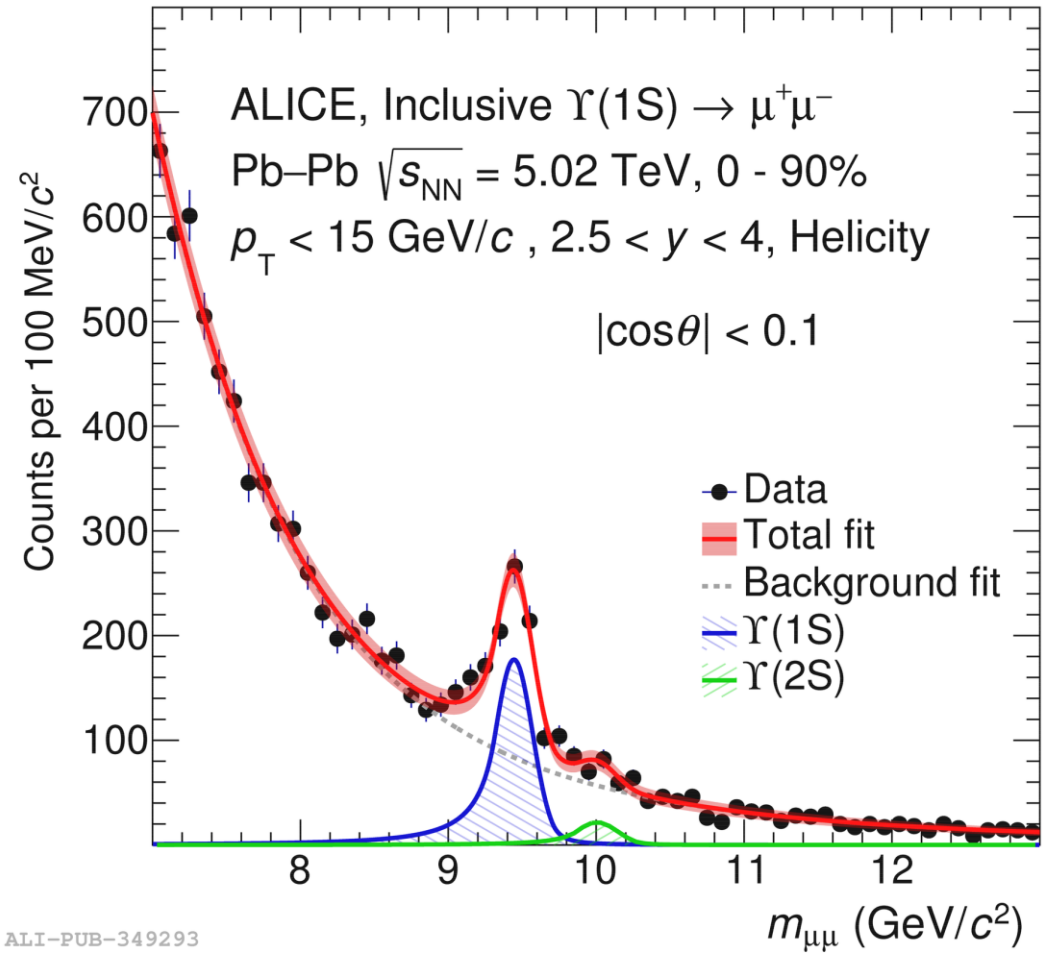


Signal extraction

$\Upsilon(1S)$ polarization vs p_T

- $\Upsilon(1S)$ studied in:
  - $p_T^{\Upsilon(1S)} < 15\ \mathrm{GeV}/c$
  - $2.5 < y^{\Upsilon(1S)} < 4$

arXiv:2005.11128



Signal extraction

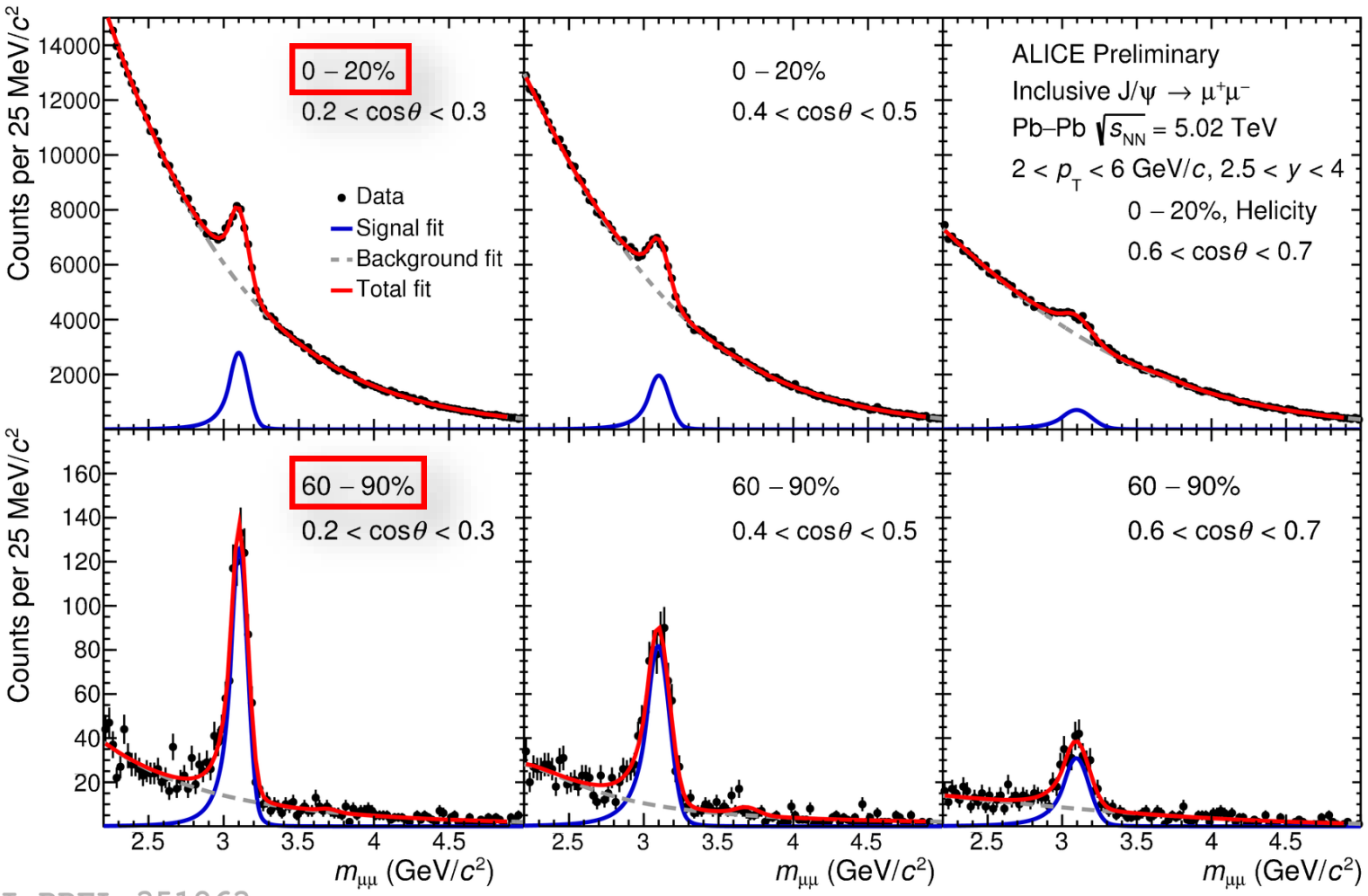
$\Upsilon(1S)$ polarization vs p_T

- $\Upsilon(1S)$ studied in:
  - $p_T^{\Upsilon(1S)} < 15$ GeV/c
  - $2.5 < y^{\Upsilon(1S)} < 4$

J/ψ polarization vs centrality

- J/ψ studied in:
  - 0–20% , 20–40%, 40–60% and 60–90% centralities
  - $2 < p_T^{J/\psi} < 6$ GeV/c
  - $2.5 < y^{J/\psi} < 4$

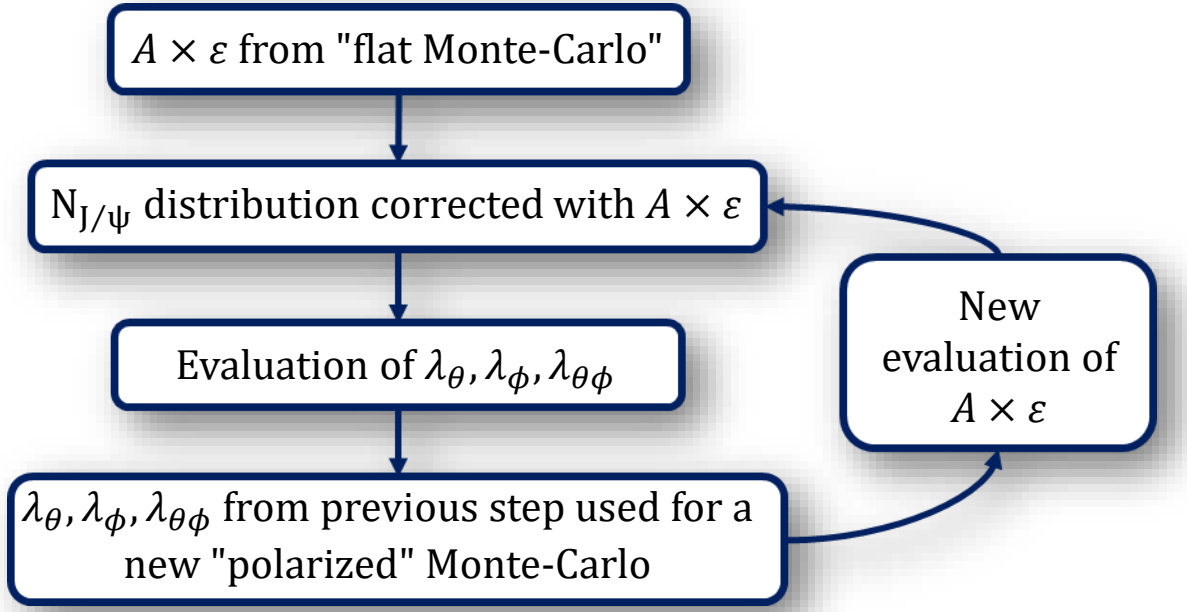
- J/ψ & $\Upsilon(1S)$ yields extracted as a function of cosθ and ϕ separately (**1D approach**)



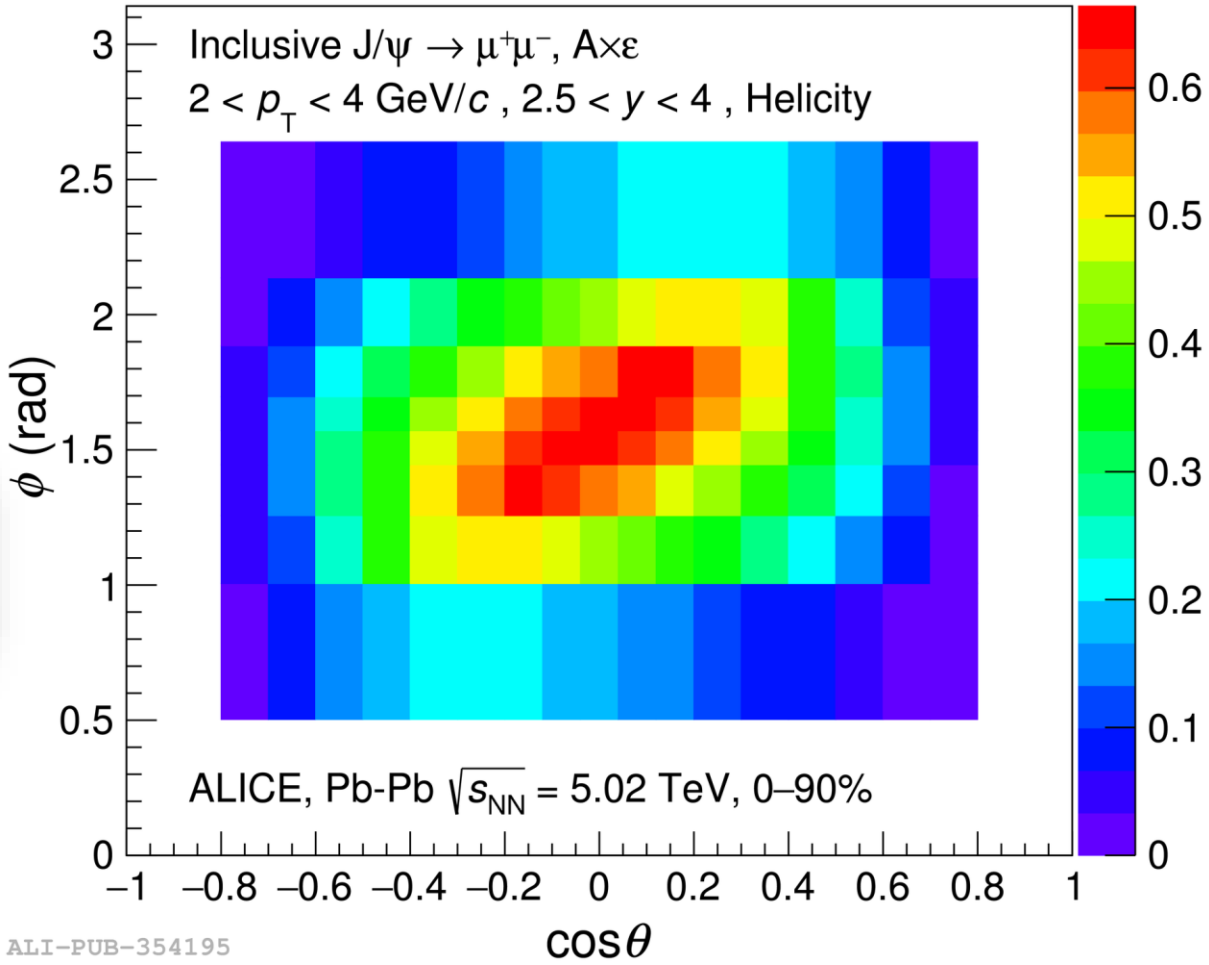
Acceptance × Efficiency

J/ψ polarization vs p_T and centrality

- Tuning of the cosθ and ϕ input MC shapes
  - **iterative procedure**: tuning of J/ψ generated distribution according to data



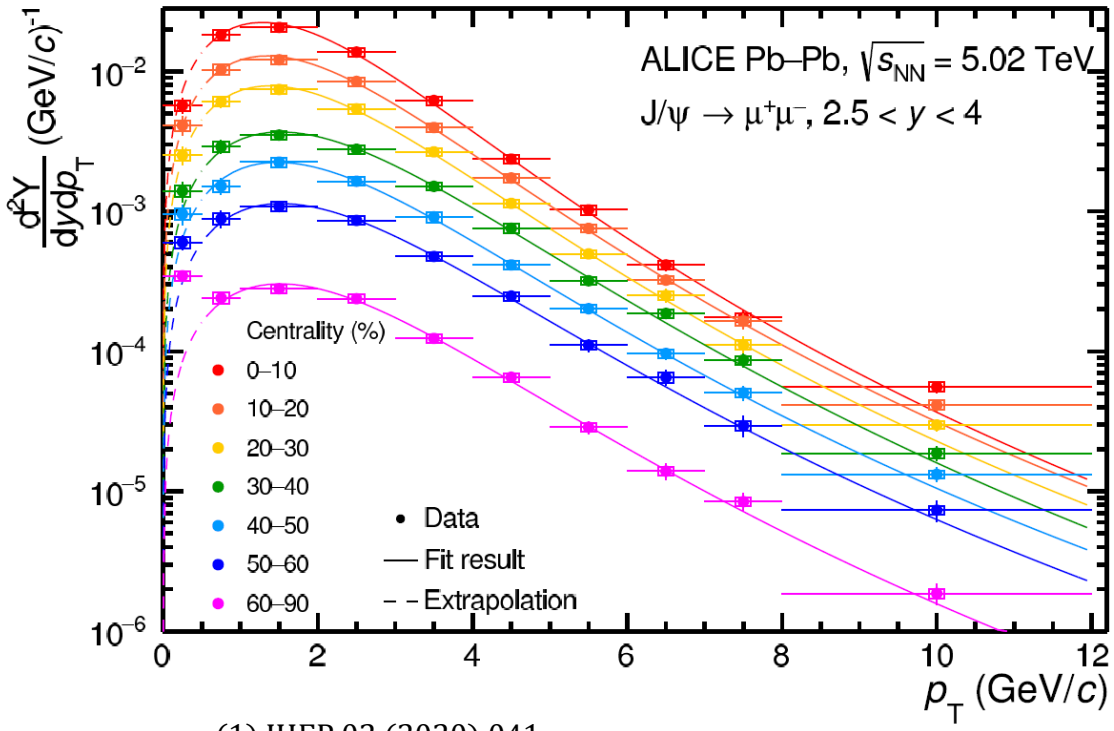
STOP: no significant variation from one iteration to the other (3 iterations done)



Acceptance × Efficiency

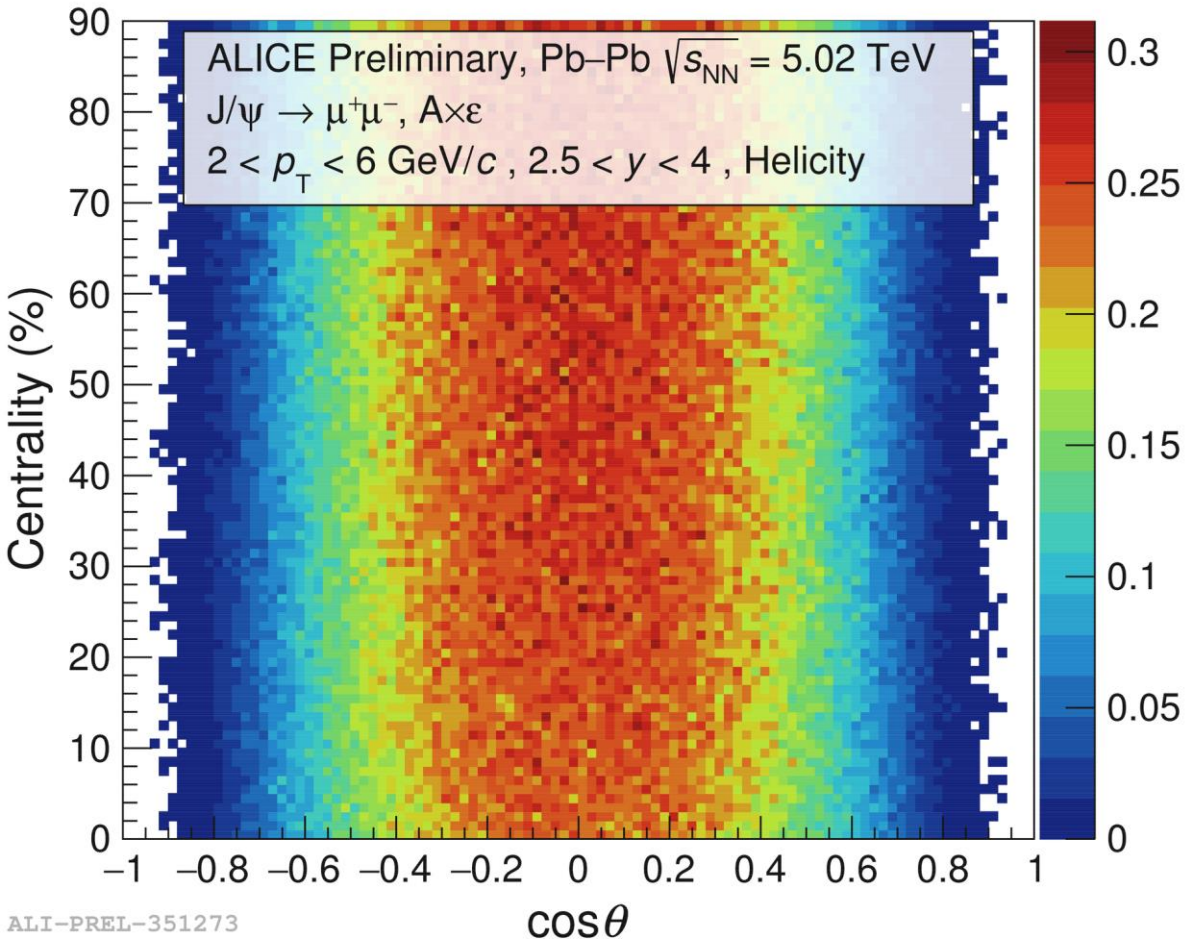
J/ψ polarization vs centrality

- J/ψ p_T and y distributions have shown a clear evolution with centrality in Pb-Pb collisions[(1)]
  - ❑ Taken into account in the Monte-Carlo



ALI-PUB-341555

(1) JHEP 02 (2020) 041



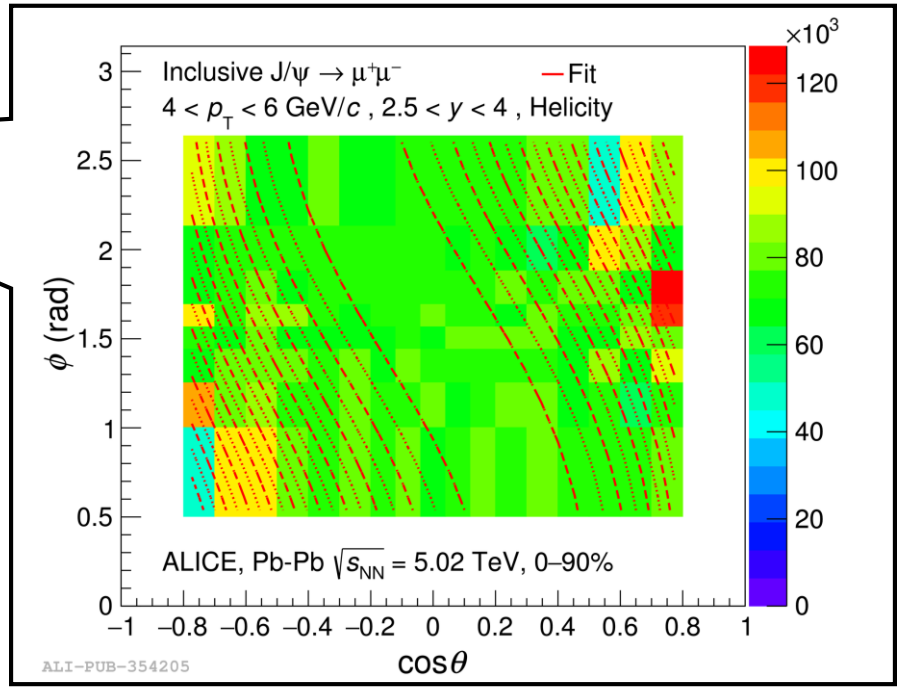
ALI-PREL-351273

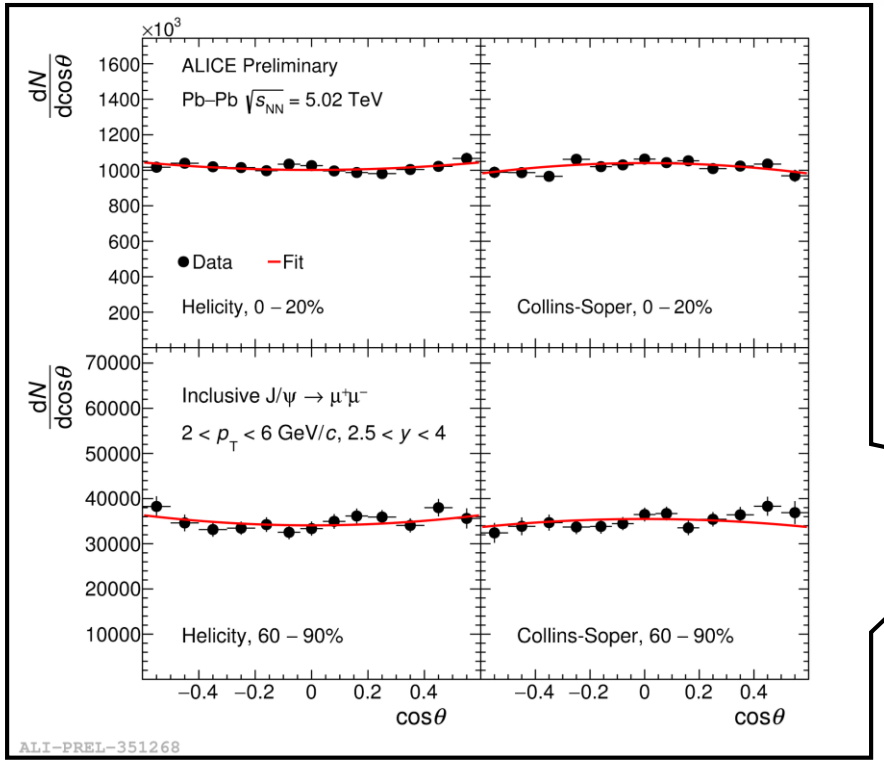
Extraction of the polarization parameters

J/ψ polarization vs p_T

- Fit to the $(\cos\theta, \phi)$ J/ψ angular distribution corrected for $A \times \varepsilon$ (**2D approach**) with $W(\cos\theta, \phi)$

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





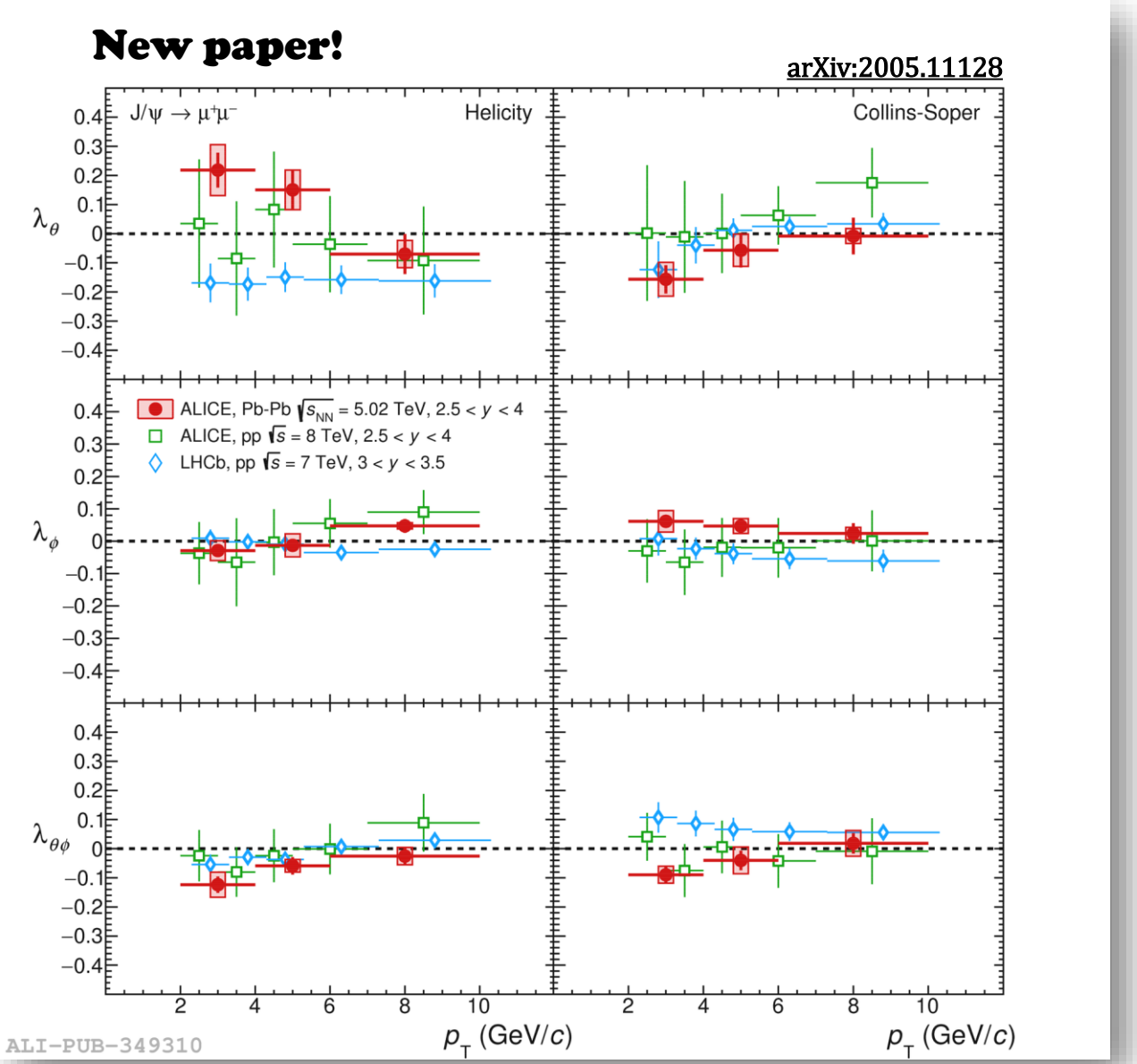
J/ψ polarization vs centrality

- Fit to the $\cos\theta$ and ϕ J/ψ distributions corrected for $A \times \varepsilon$ (**1D approach**) with the integrated expression of $W(\cos\theta, \phi)$

$$\int W(\cos\theta, \phi) d\phi \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta)$$

$$\int W(\cos\theta, \phi) d\cos\theta \propto \frac{2\lambda_\phi}{3+\lambda_\theta} \cdot \cos 2\phi$$

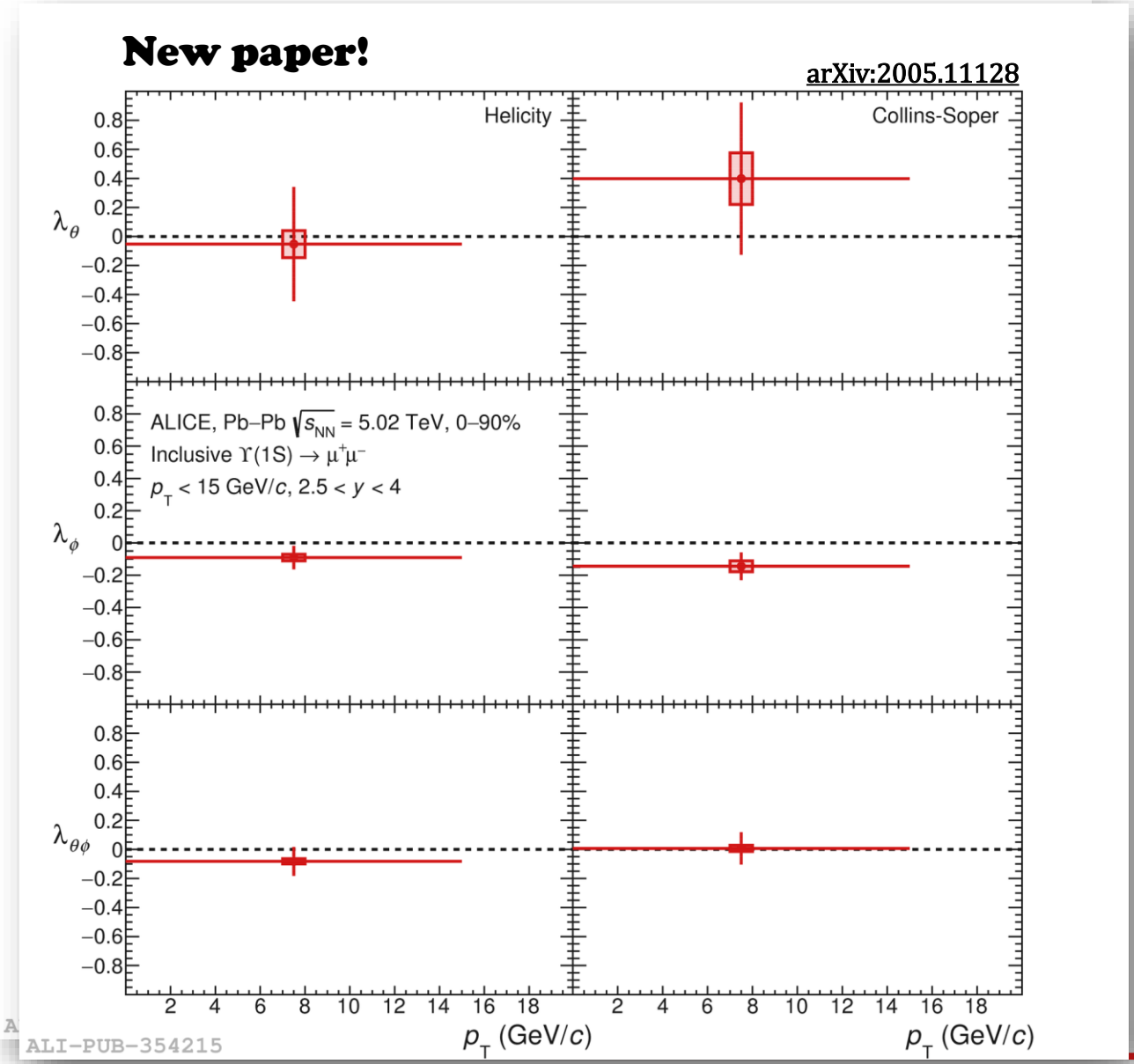
Quarkonium polarization results



J/ψ polarization vs p_T

- Polarization parameters as a function of p_T in the **Helicity** and **Collins-Soper** reference frames
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero in HE and CS
  - Maximum deviation of $\sim 2\sigma$ in the low p_T bin
  - Indication of small **transverse**/**longitudinal** polarization in $2 < p_T < 4$ GeV/c for **HE**/**CS**
- Comparison with **ALICE** results at $\sqrt{s} = 8$ TeV
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible within the uncertainties
- Comparison with **LHCb** results at $\sqrt{s} = 7$ TeV
  - Significant difference in $\lambda_\theta^{\mathrm{HE}}$ at low p_T

Quarkonium polarization results



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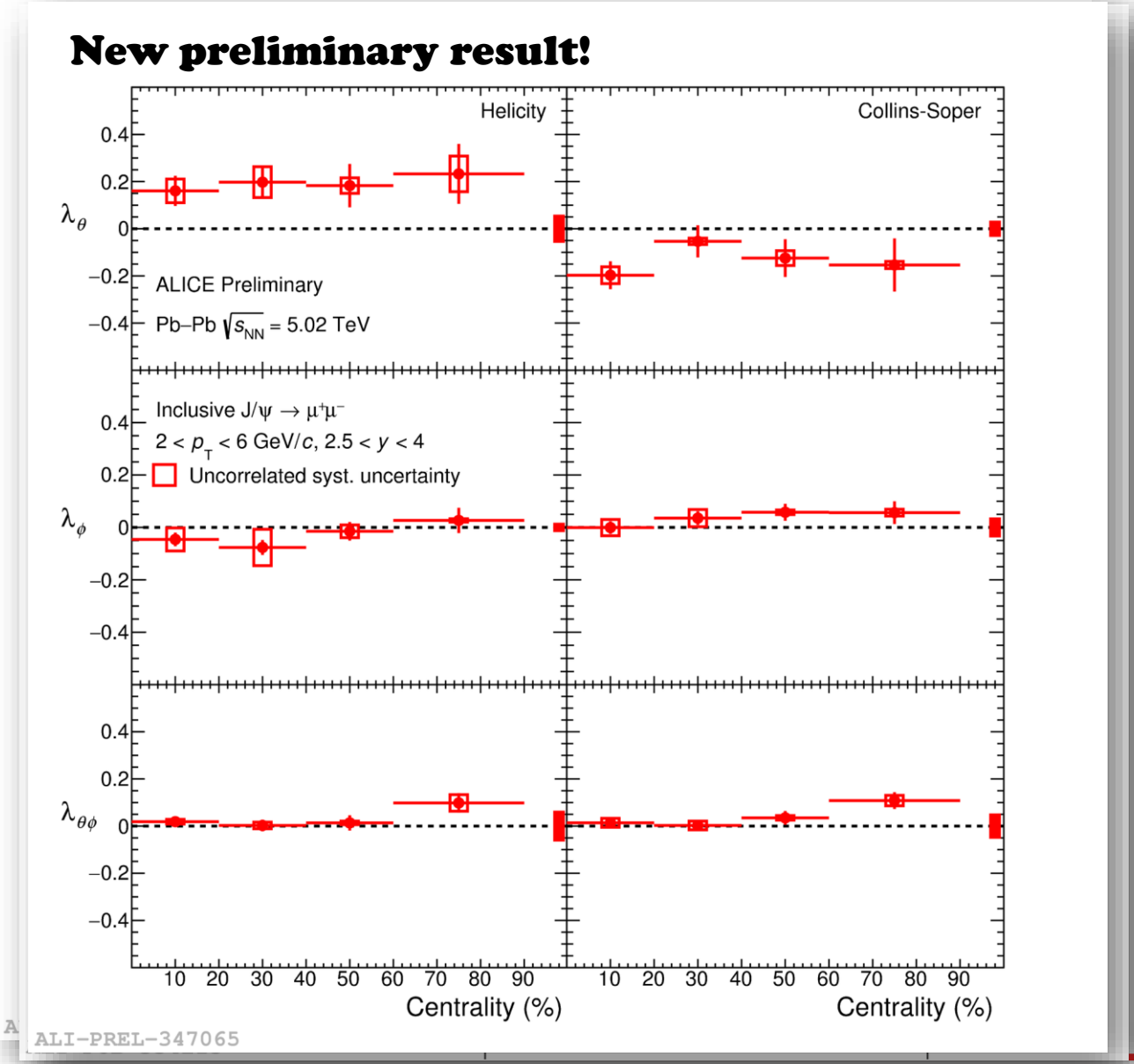
Υ(1S) polarization vs p_T

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in HE and CS
  - Significance limited by the available statistics

Quarkonium polarization results



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Υ(1S) polarization vs p_T

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in HE and CS
  - Significance limited by the available statistics

J/ψ polarization vs centrality

- Flat trend for all the polarization parameters as a function of centrality
  - No visible dependence of $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ moving from central to peripheral events

Conclusions & future steps

! "First measurement of quarkonium polarization in nuclear collisions at the LHC" arXiv:2005.11128

J/ψ polarization vs p_T **New paper!**

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero
- Indication of small transverse/longitudinal polarization in $2 < p_T < 4$ GeV/c for the Helicity/Collins-Soper reference frames ($\sim 2\sigma$ deviation from zero)
- Pb–Pb results compatible with **ALICE** pp measurement at $\sqrt{s} = 8$ TeV
- Comparison with pp results (**LHCb**) may indicate a significant difference at low p_T

Υ(1S) polarization vs p_T **New paper!**

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in Helicity and Collins-Soper reference frames

J/ψ polarization vs centrality **New preliminary result!**

- No centrality dependence observed within uncertainties

FUTURE STEPS

- **Event-Plane dependence:** effects related to the intense magnetic field produced in heavy ion collisions

Thank you for the attention!

Backup

Quarkonium analysis standard cuts

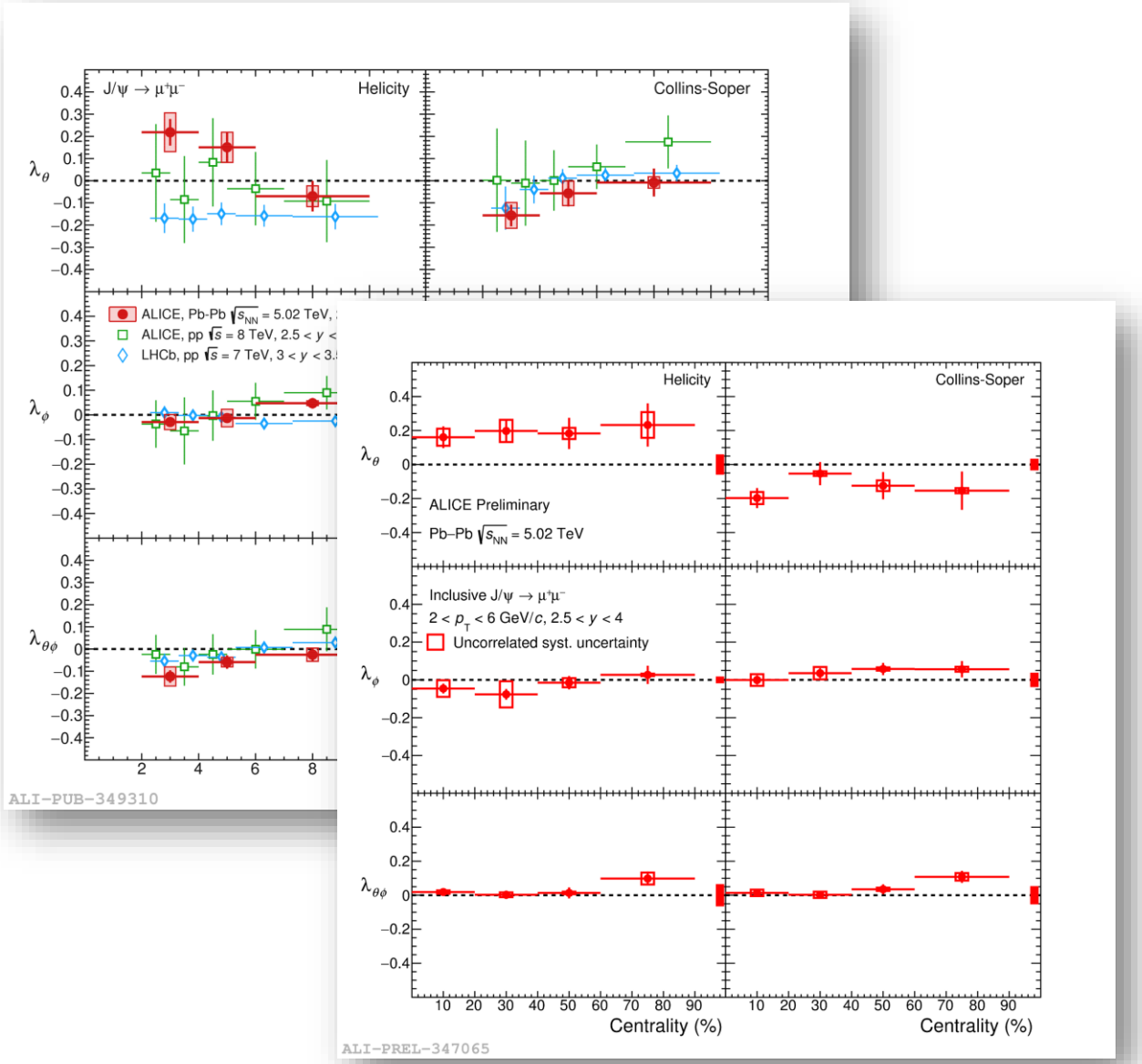
Single muon cuts:

- $-4 < \eta_{\mu} < -2.5$ to reject tracks at the edge of the spectrometer acceptance
- the matching of a track reconstructed in the tracking chambers with a track reconstructed in the trigger system with $p_{\mathrm{T}} > 1\ \mathrm{GeV}/c$
- Radial transverse position at the end of the absorber in the range $17.6 < R_{\mathrm{abs}} < 89.5$ cm to remove tracks passing through the inner and denser part of the absorber

Dimuon cuts:

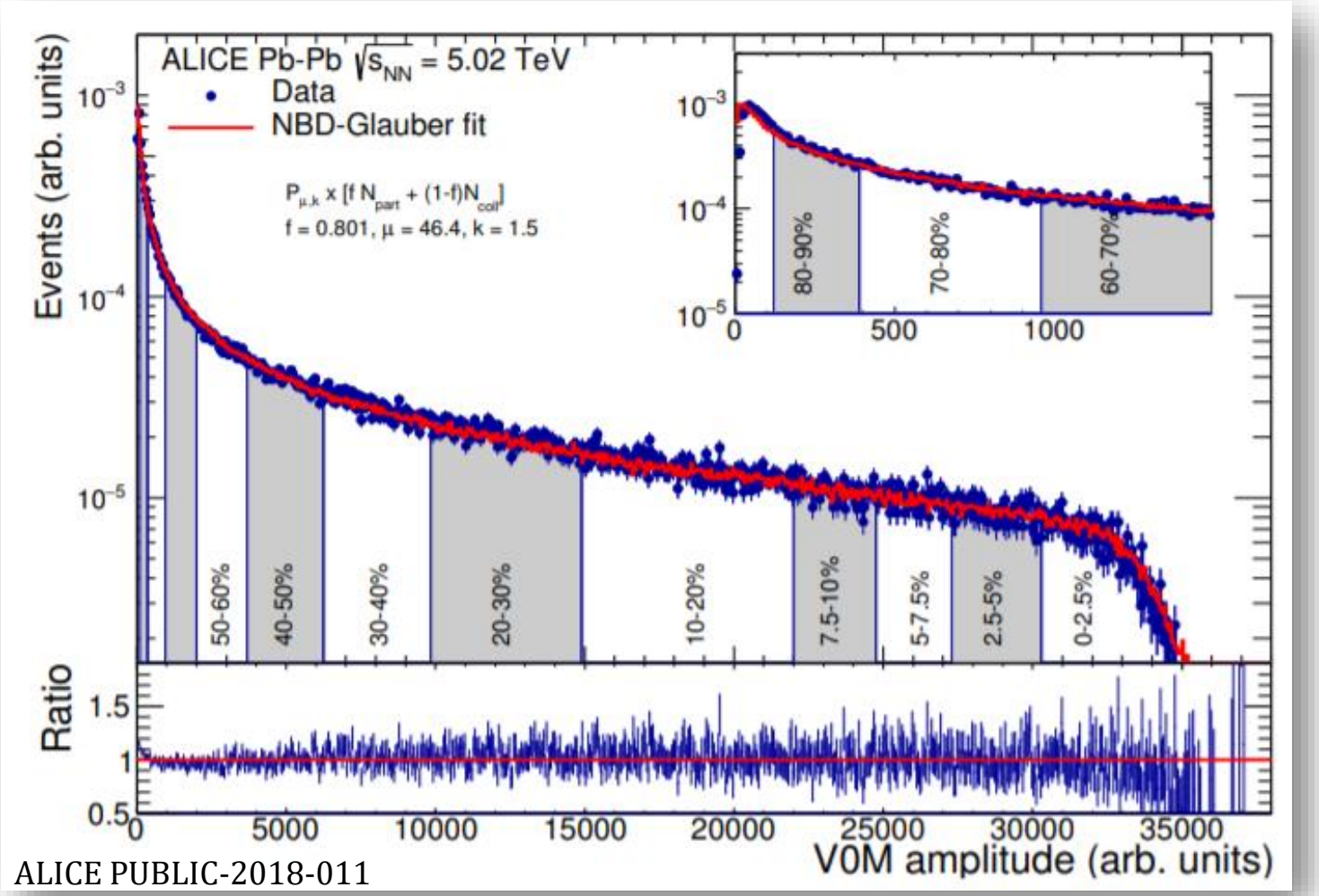
- Dimuon rapidity in the range $2.5 < y_{\mu\mu} < 4$

J/ψ polarization systematic uncertainties



- **Signal extraction**
  - Choice of various signal and background shapes for the fit to the invariant mass distributions
  - Fix to the MC or keep free the J/ψ width in the signal extraction procedure
- **Trigger efficiency**
  - Use single muon trigger response function extracted from data or MC
- **Input MC distributions**
  - Evaluation of the impact of different p_T, y MC input distributions on the polarization parameters

Centrality determination in ALICE



ALICE PUBLIC-2018-011

Prompt / non-Prompt J/ψ polarization

Evaluated in "J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV" (1)

1.) LHCb measured **J/ψ←B** in $2 < y < 4.5$(2)
   - $10 < f_B < 15\%$ in $2 < p_{\mathrm{T}} < 10$ GeV/c

2.) **Non-prompt J/ψ** polarization measured by CDF in $p\bar{p}$ collisions(3)
   - $\lambda_\theta(\mathrm{J/\psi} \leftarrow \mathrm{B}) \sim -0.1 \Longrightarrow$ calculated w.r.t. the J/ψ direction in the LAB

3.) Assuming $|\lambda_\theta(\mathrm{J/\psi} \leftarrow \mathrm{B})| \sim 0.2$ and f_B from LHCb

➡ $\Delta\lambda_\theta^{\mathrm{Max}} < 0.05$

➡ Smaller than the systematic uncertainties!

(1) PRL 108 (2012) 082001
(2) EUR. PHYS. J. C71 (2011) 1645
(3) PRL 99 (2007) 132001