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

Luca Micheletti (INFN Torino)
on behalf of the ALICE collaboration

106° congresso nazionale
Società italiana di fisica

14-18 September 2020

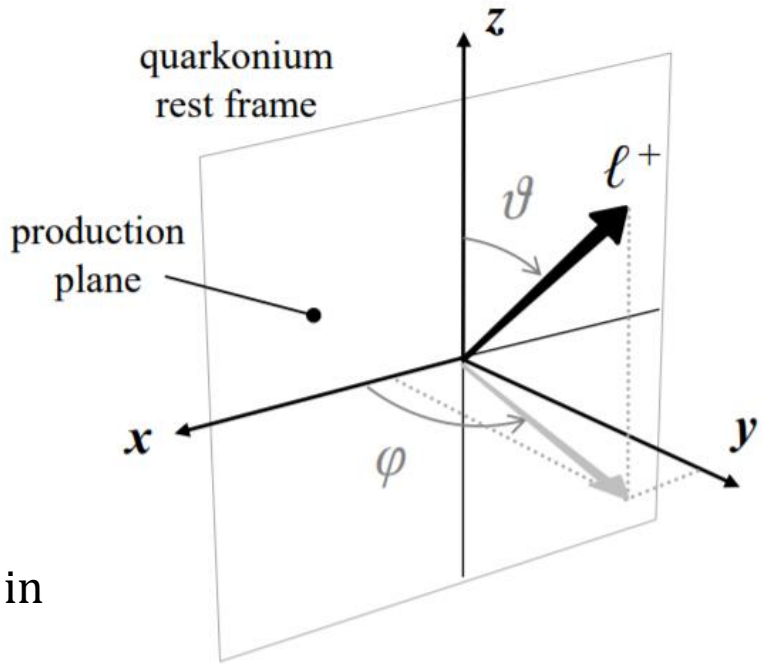
Quarkonium polarization: basic concepts

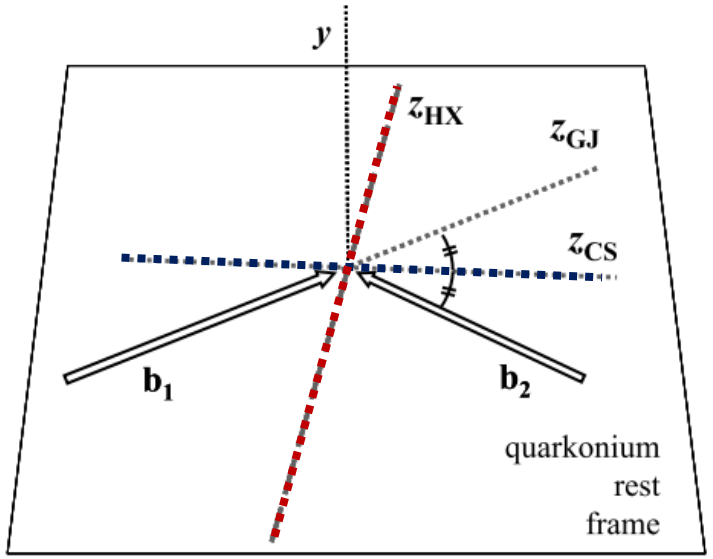
- **Polarization:**
  - Defined as the **spin-alignment** with respect to a chosen direction
  - Measured as **anisotropies** in the decay products angular distributions

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

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

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





$\implies$ 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

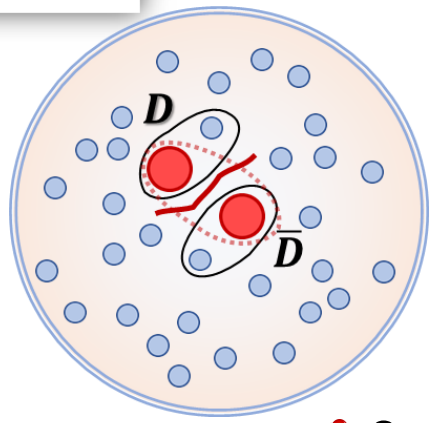
Quarkonium polarization in pp and AA collisions

Polarization in pp collisions

Polarization in AA collisions

- Constrains **J/ψ production mechanism**
  - ❑ No sizeable polarization measured at LHC
- At LHC energies a strongly-interacting medium (**QGP**) is produced in heavy-ion collisions
  - ❑ Presence of different mechanisms w.r.t. pp collisions

Light quark
Heavy quark



- **Quarkonium suppression**[1]

$c\bar{c}$ and $b\bar{b}$ bound states dissiociation in the **QGP** due to a **color screening** mechanism

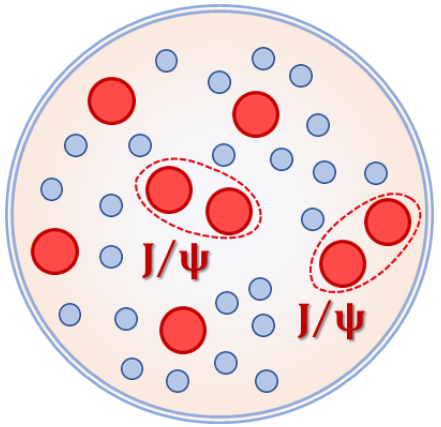
- ❑ **Color screening** affects differently the various states ($\psi(2S)$,χ_c,$\Upsilon(2S)$,...)
- ❑ Change of **prompt feed-down fractions** → **polarization** modification

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

- **Quarkonium regeneration**[2]

Statistical **recombination** of the $c\bar{c}$ pairs in the medium (**QGP**)

- ❑ **Regeneration** plays an important role at LHC energies
- ❑ Possible effect on the measured **polarization**



Outlook

Quarkonium polarization in Pb-Pb collisions is discissed in this presentation:

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

⟹ **Public result** (submitted to PLB)

"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 $2.5 < y < 4$

⟹ **Preliminary result**

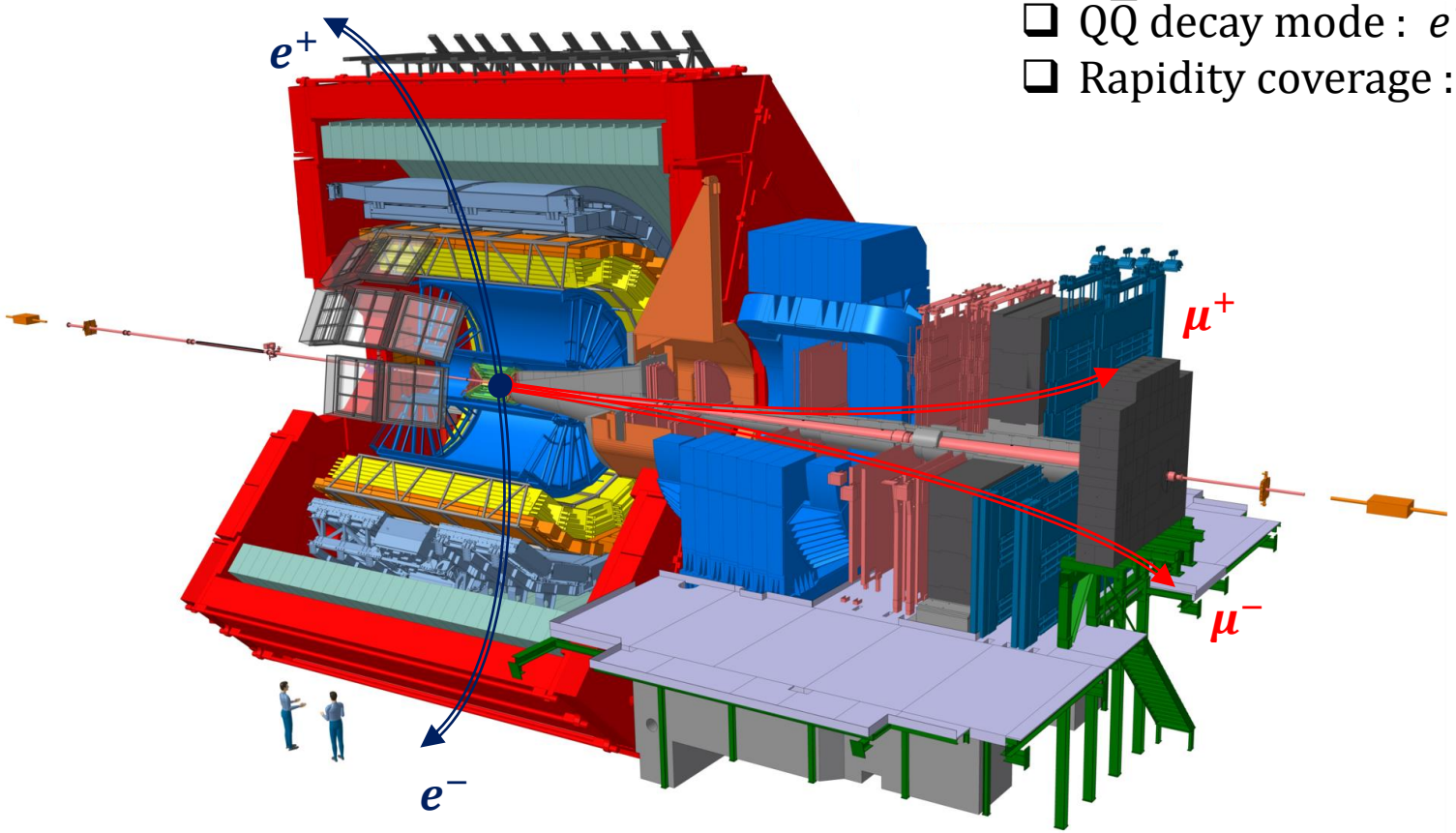
Data sample:

- 2015 and 2018 Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV ($L_{\mathrm{int}} \sim 0.75\ nb^{-1}$)
- J/ψ and Υ(1S) are studied in their dimon decay channel

	J^{PC}	m (GeV/c^2)	$B.R.$ ($\rightarrow \mu^+\mu^-$)
J/ψ	1^{--}	3.096	5.96%
Υ(1S)	1^{--}	9.460	2.48%

A Large Ion Collider Experiment

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



Central barrel :

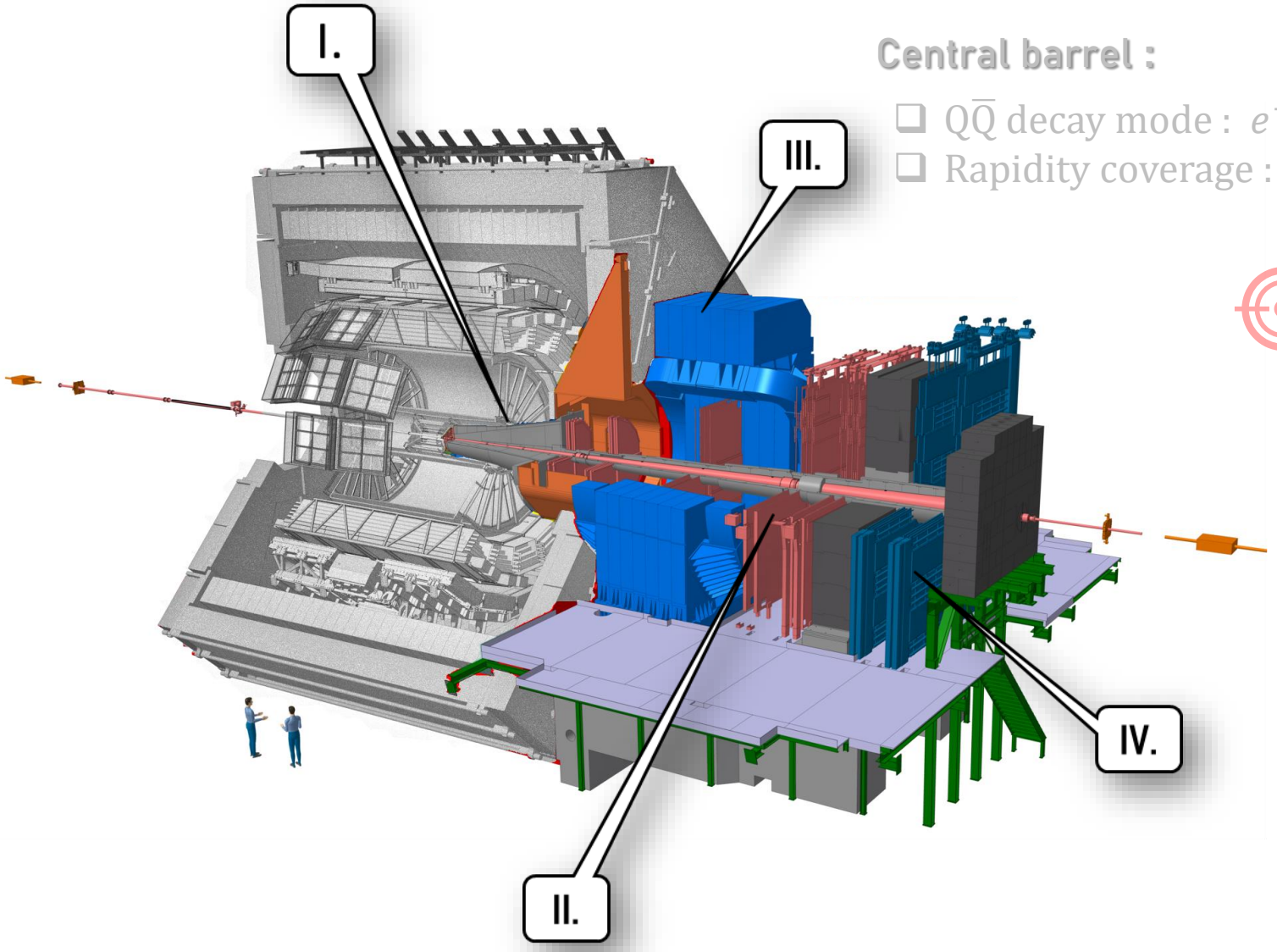
- ❑ $Q\bar{Q}$ decay mode : e^+e^-
- ❑ Rapidity coverage : $|y| < 0.9$

Muon spectrometer:

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

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 : $2.5 < y < 4$

Focus on the **muon spectrometer**:

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

I. Front absorber

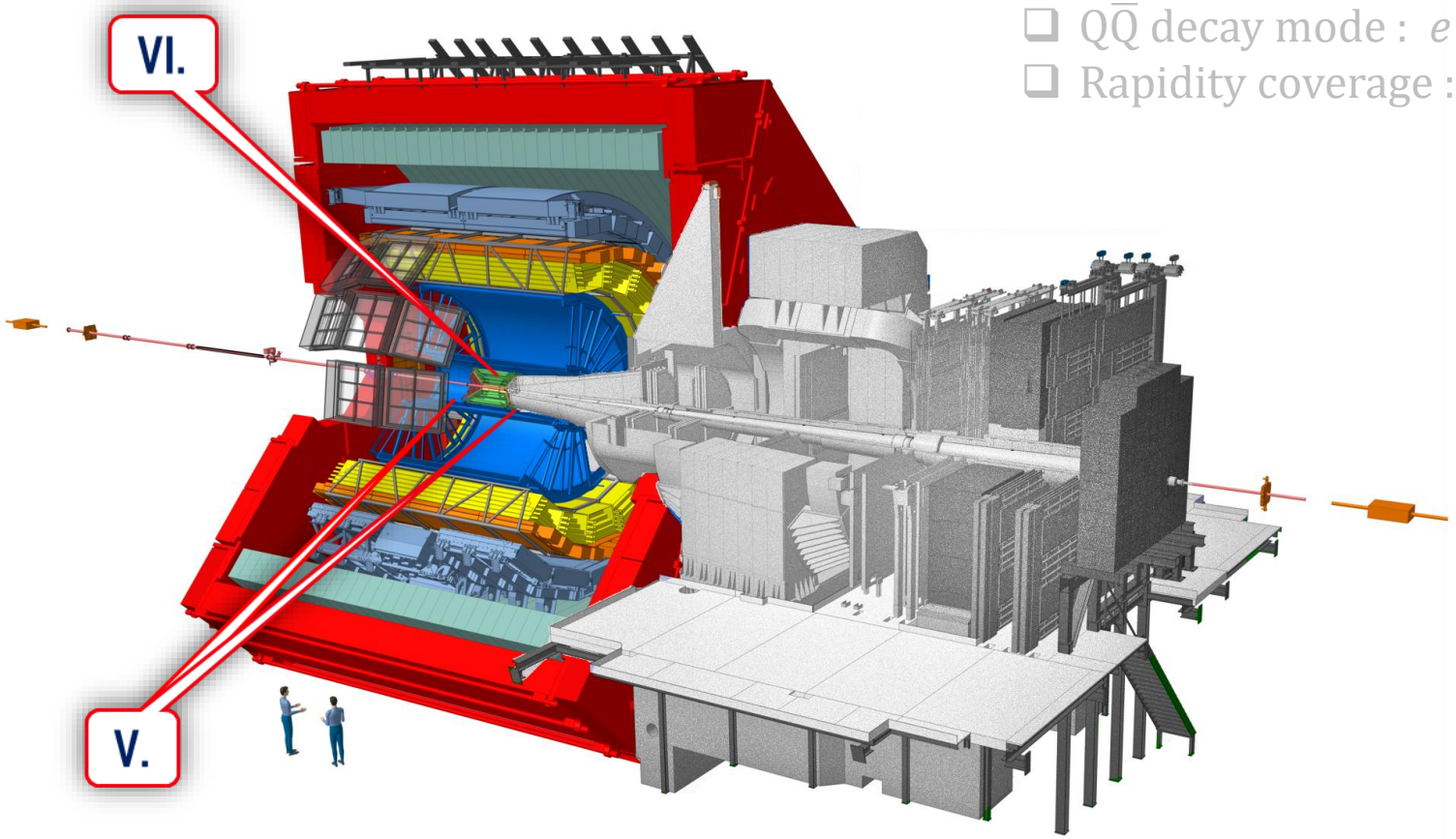
II. Tracking system

III. Dipole magnet

IV. Trigger system

A Large Ion Collider Experiment

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 : $2.5 < y < 4$

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

V. **V0** detectors
- Trigger
- Centrality estimation
- Background rejection

VI. **Silicon Pixel Detector**
- Vertex determination

Analysis procedure

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 steps

1. **Signal extraction**

   Number of J/ψ & ϒ(1S) obtained fitting the $\mu^+\mu^-$ invariant mass distribution as a function of $\cos\theta$ and ϕ

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 $W(\cos\theta, \phi)$

GOAL

$\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$ evaluation

Signal extraction

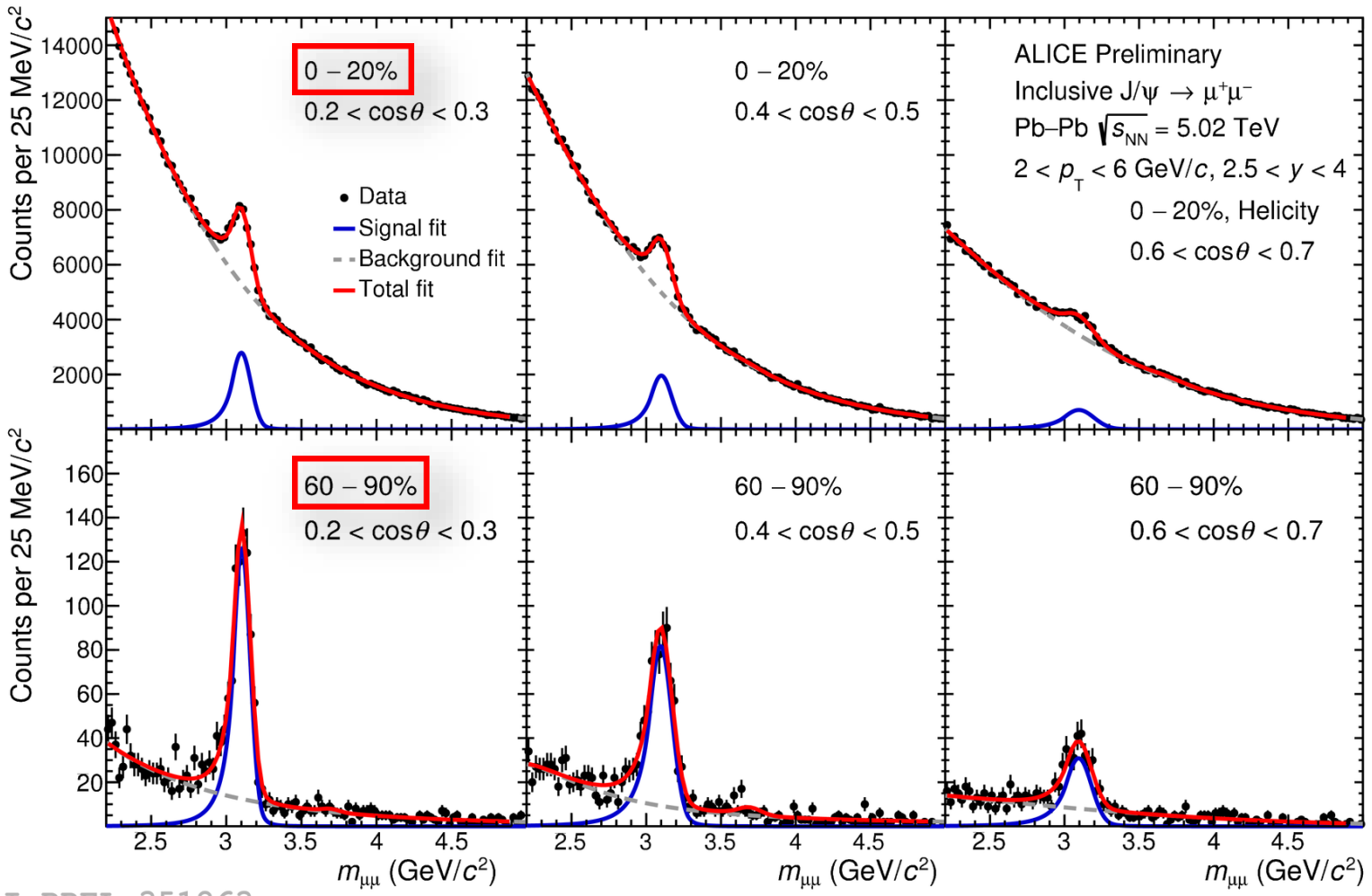
- J/ψ and ϒ(1S) yields extracted fitting the $\mu^+\mu^-$ invariant mass spectrum with a combination of **signal** and **background** functions

J/ψ polarization vs p_T

- $p_T^{J/\psi}$ =2–4 , 4–6, 6–10 GeV/c
- 0–90% centrality

J/ψ polarization vs centrality

- 0–20% , 20–40%, 40–60% and 60–90% centralities
- $2 < p_T^{J/\psi} < 6$ GeV/c



ALI-PREL-351263

Signal extraction

- J/ψ and ϒ(1S) yields extracted fitting the $\mu^+\mu^-$ invariant mass spectrum with a combination of **signal** and **background** functions

J/ψ polarization vs p_T

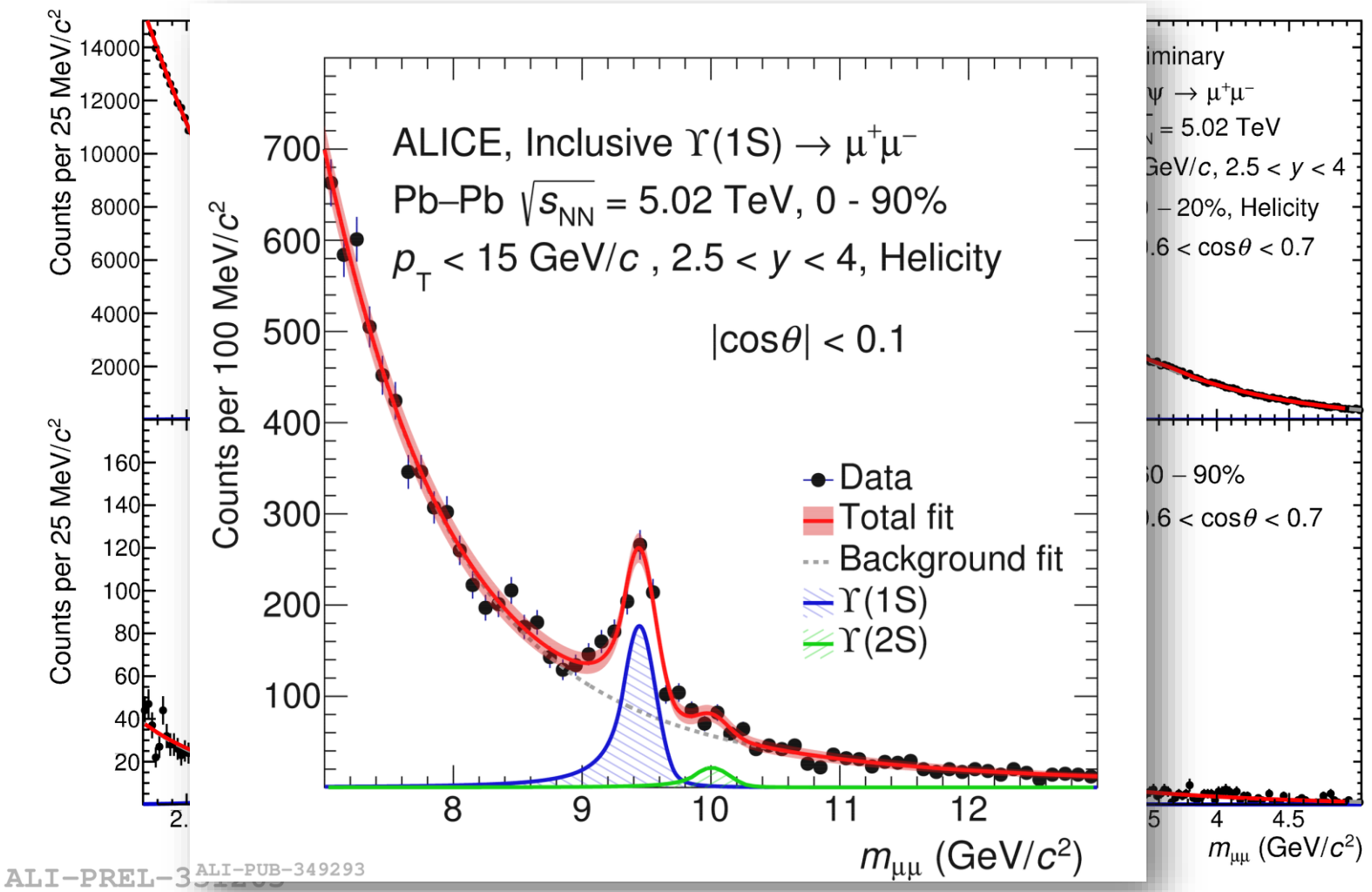
- $p_T^{J/\psi}$ =2–4 , 4–6, 6–10 GeV/c
- 0–90% centrality

J/ψ polarization vs centrality

- 0–20% , 20–40%, 40–60% and 60–90% centralities
- $2 < p_T^{J/\psi} < 6$ GeV/c

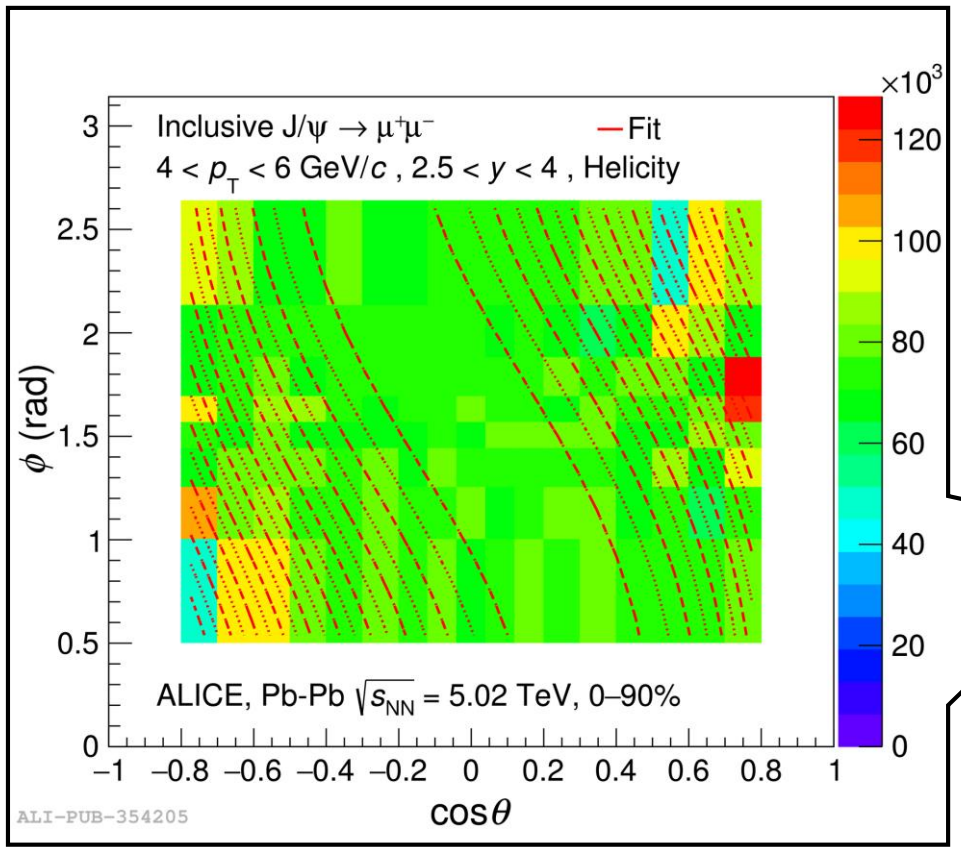
ϒ(1S) polarization vs p_T

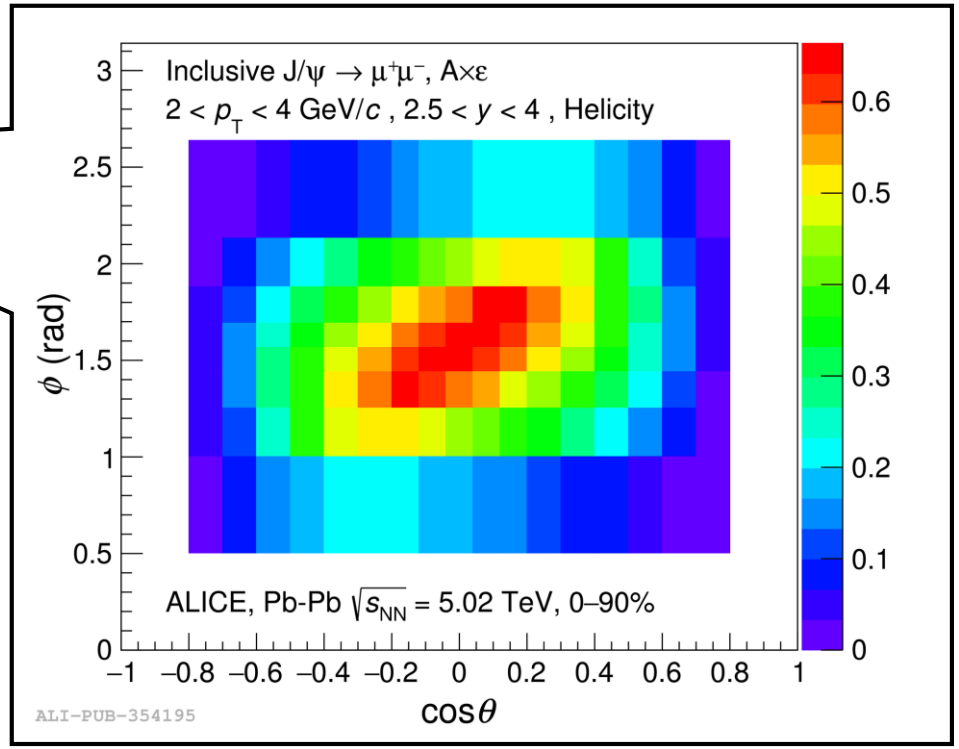
- $p_T^{\Upsilon(1S)} < 15$ GeV/c
- 0–90% centrality



Extraction of the polarization parameters

- **Acceptance × efficency ($A \times \varepsilon$)**
  - ❑ $A \times \varepsilon$ obtained with a MC simulation
  - ❑ J/ψ and ϒ(1S) angular distributions generated according to the measured polarization





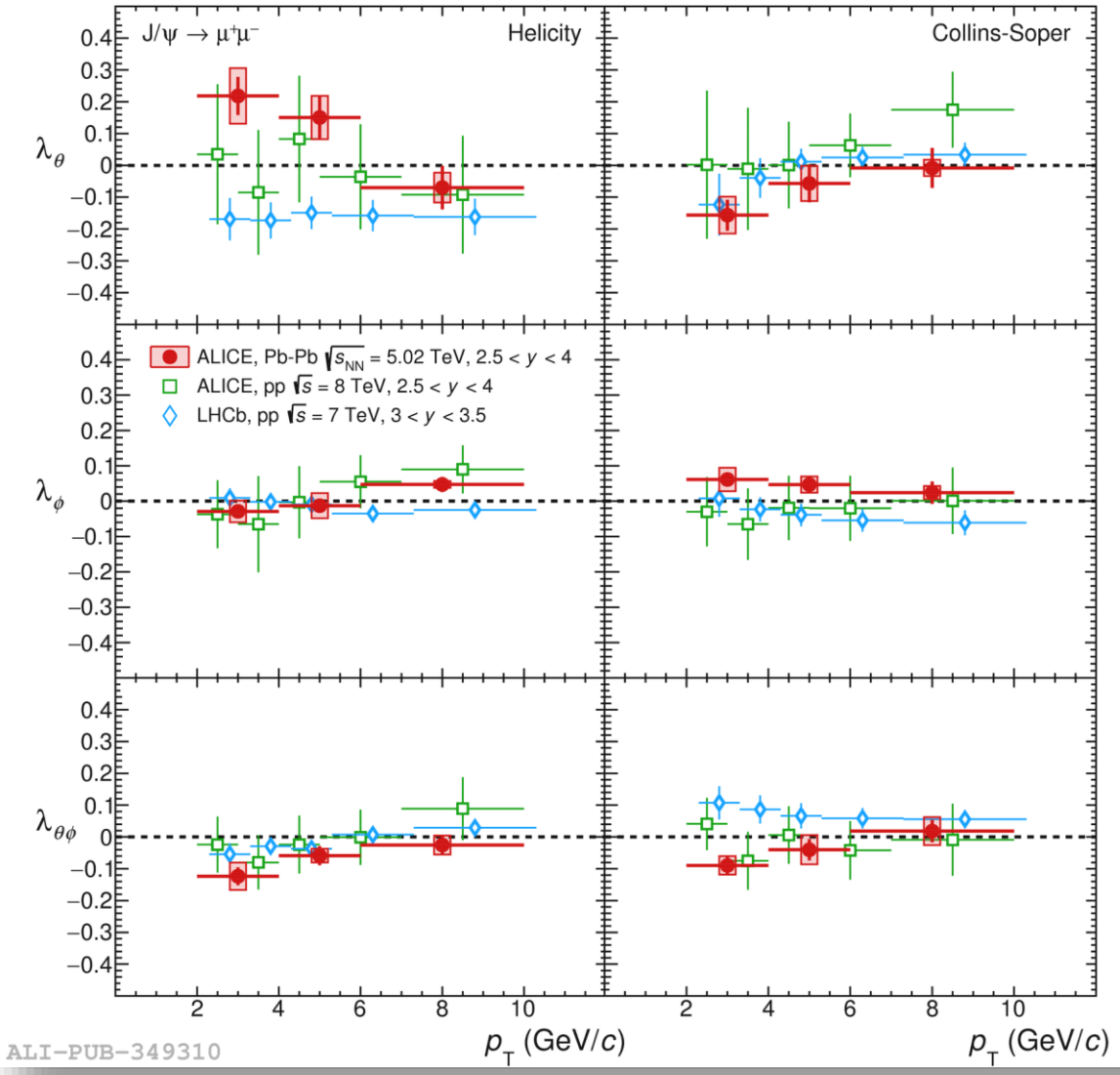
- **Fit to the corrected distribution**
  - ❑ Fit to the $(\cos\theta, \phi)$ J/ψ and ϒ(1S) angular distributions corrected for $A \times \varepsilon$ with $W(cos\theta, \phi)$

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

Quarkonium polarization results

New paper!

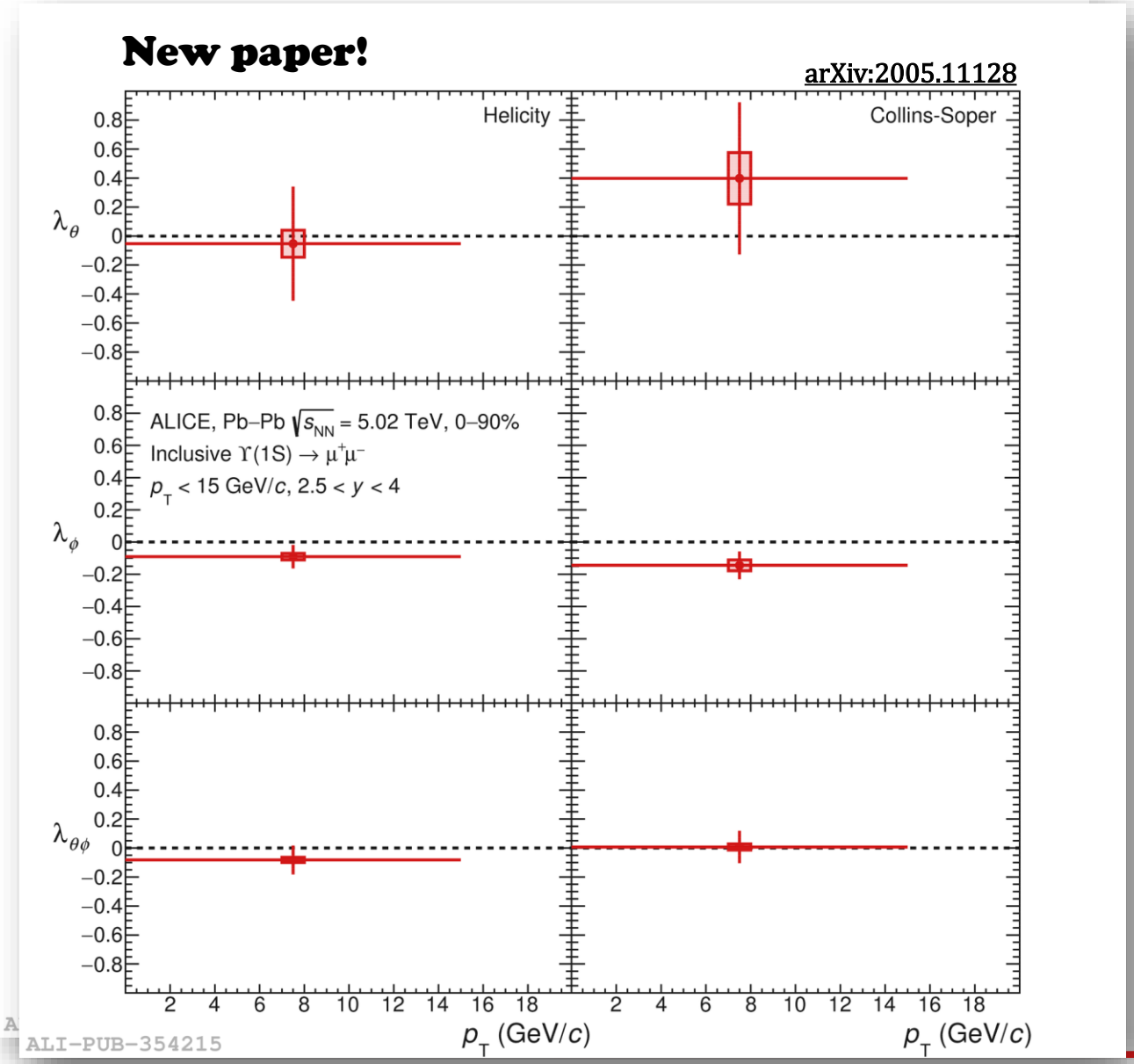
arXiv:2005.11128



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



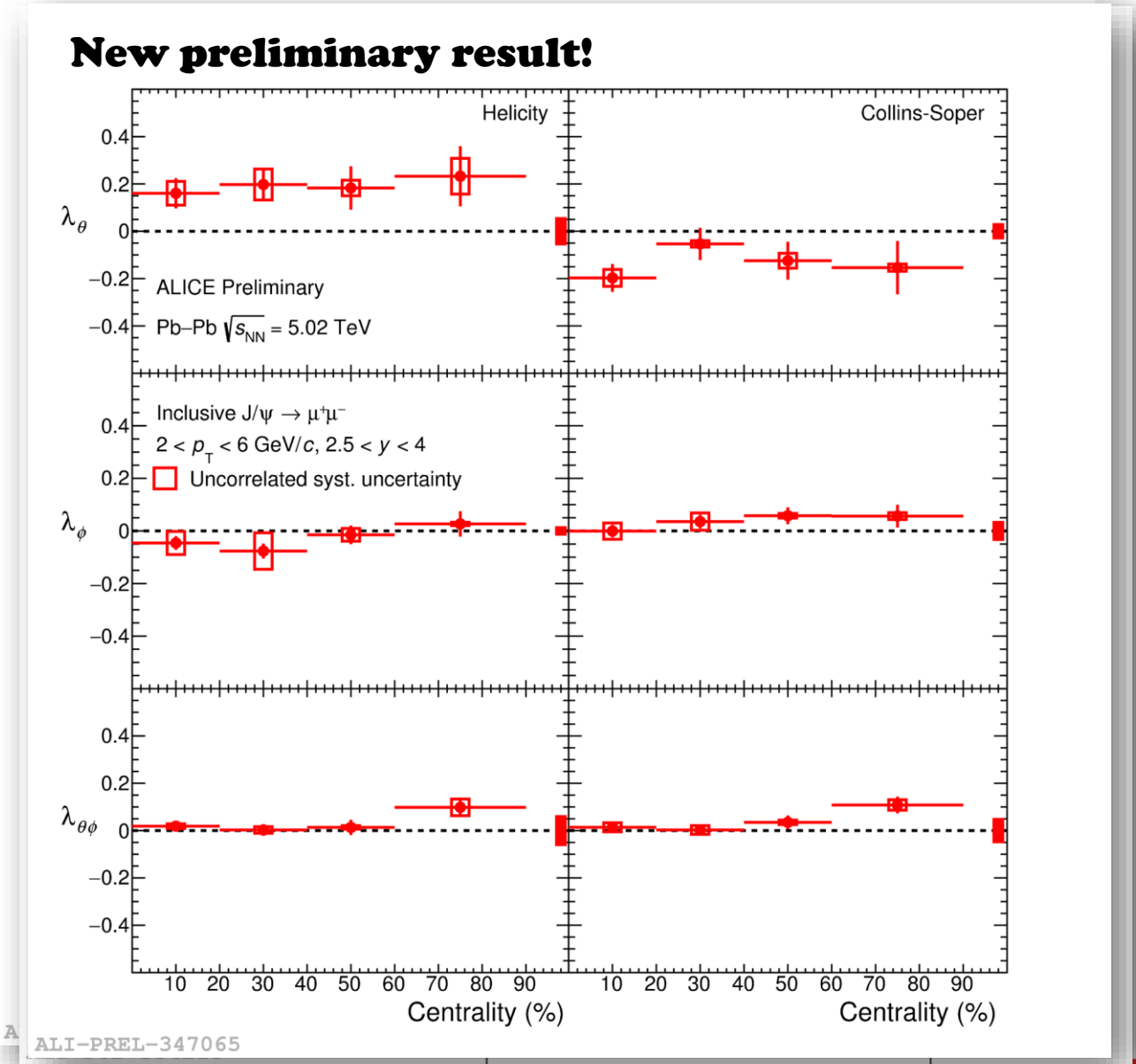
J/ψ polarization vs p_T

- 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**

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



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**

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}

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero
- Indication of small transverse/longitudinal polarization in $2 < p_{\mathrm{T}} < 4$ 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}

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

J/ψ polarization vs centrality

- 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!

106° congresso nazionale
Società italiana di fisica

14-18 settembre 2020

Backup

Quarkonium analysis standard cuts

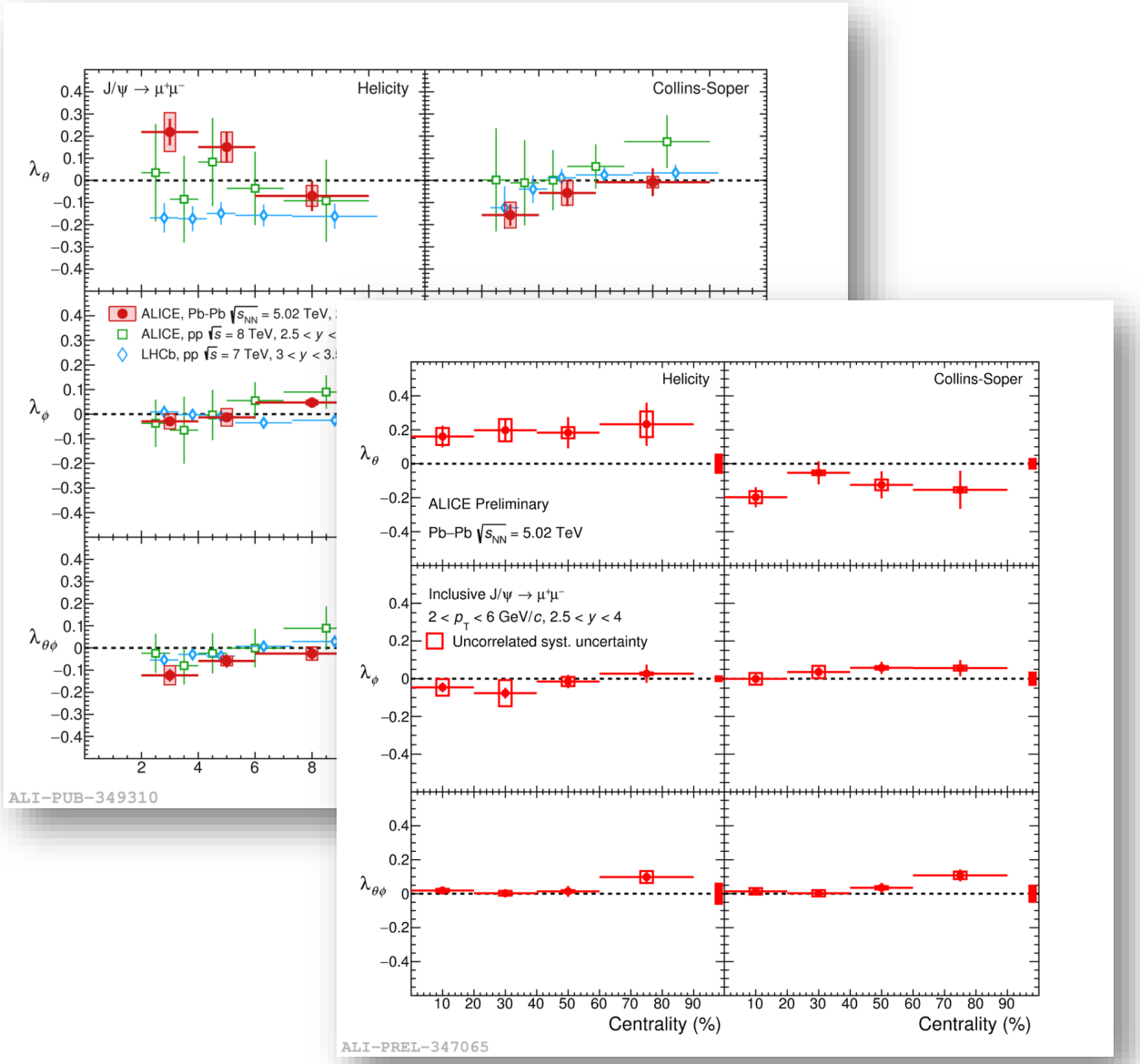
Single muon cuts:

- $-4 < \eta_{\mu} < -2.5$ 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 $p_{\mathrm{T}} > 1$ 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:

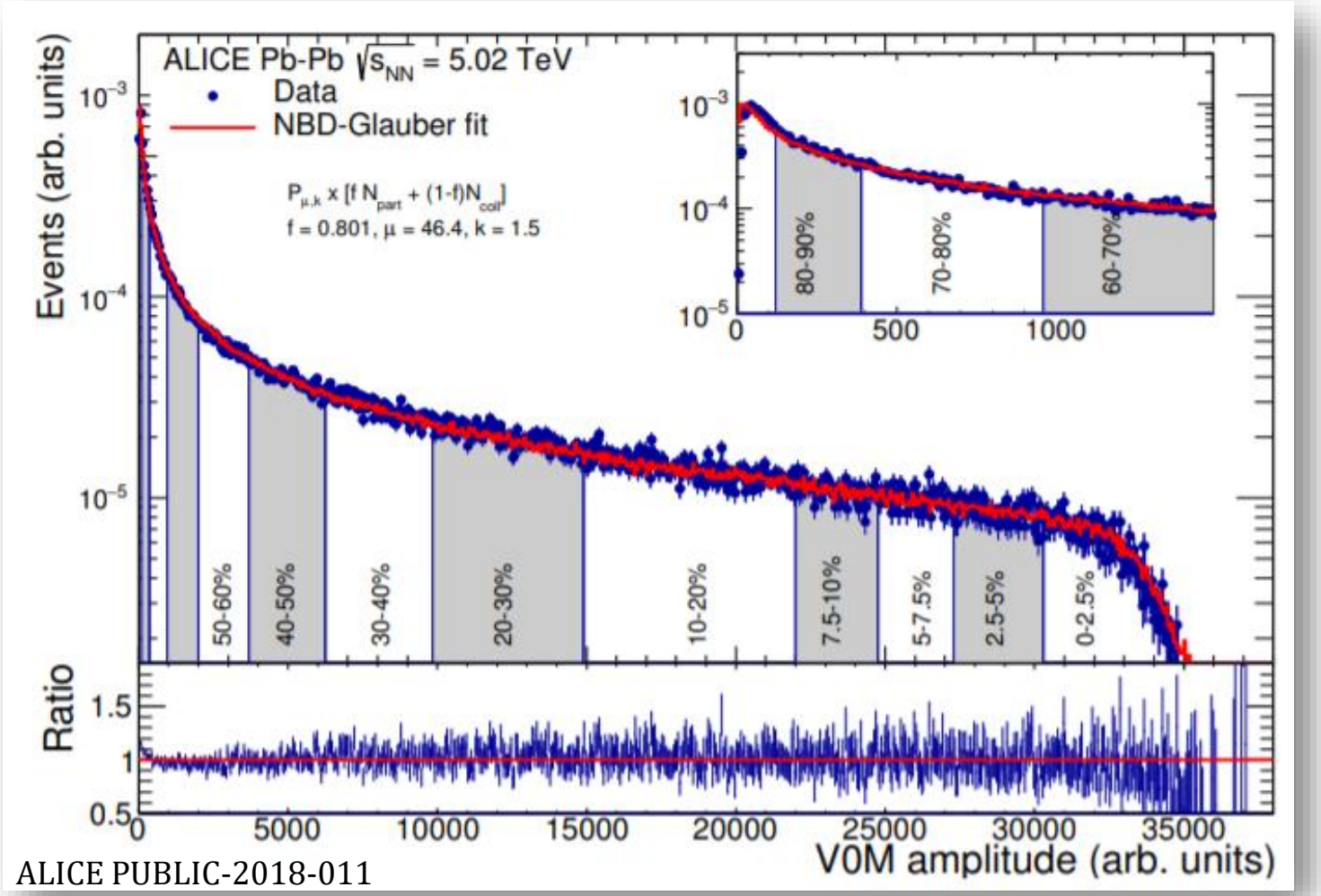
- Dimuon rapidity in the range $2.5 < y_{\mu\mu} < 4$

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