Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

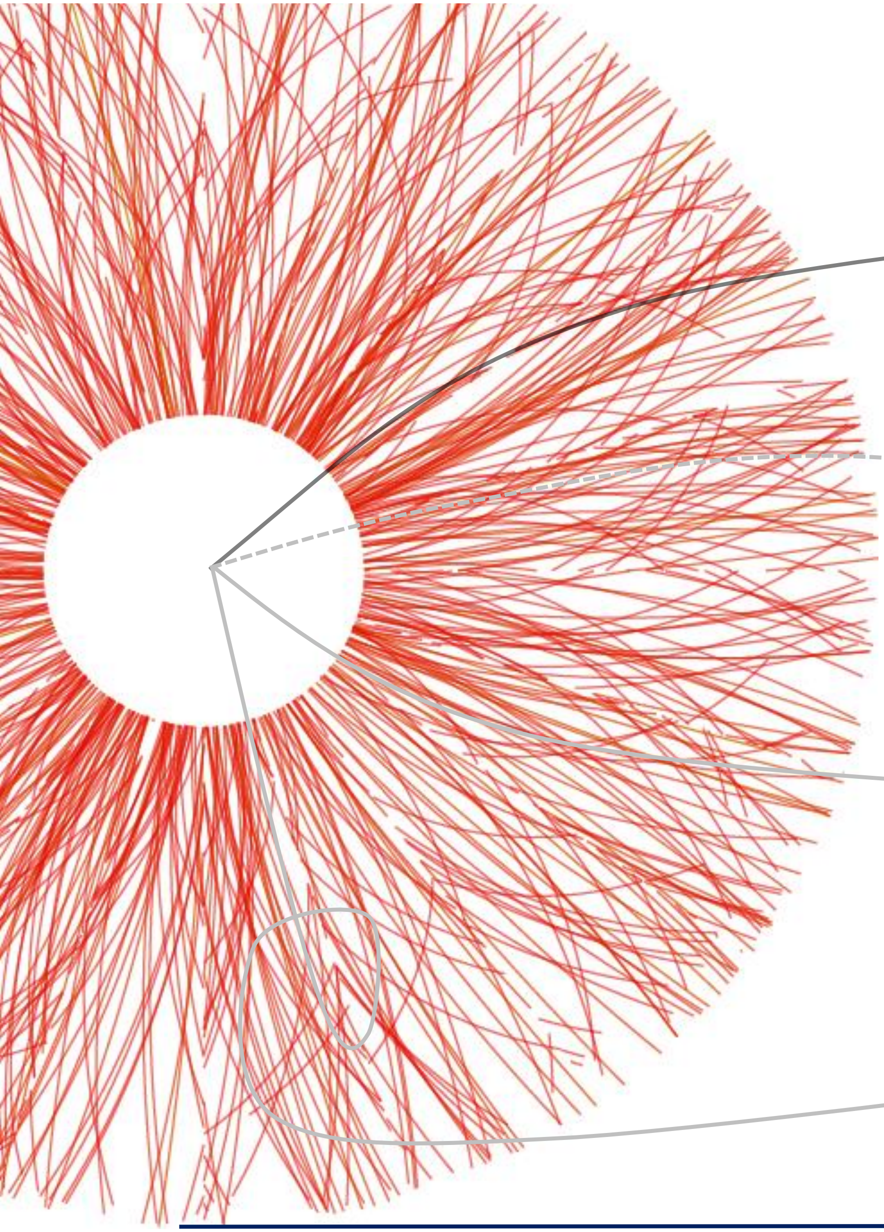
Terzo incontro di fisica con ioni pesanti
alle alte energie

Quarkonium polarization in heavy-ion collisions at the LHC

Luca Micheletti - INFN Torino

25/11/2021 - Padova

Outline



- Polarization: an introduction
- Polarization in Pb-Pb collisions
- Discussion on results and prospects
- Summary

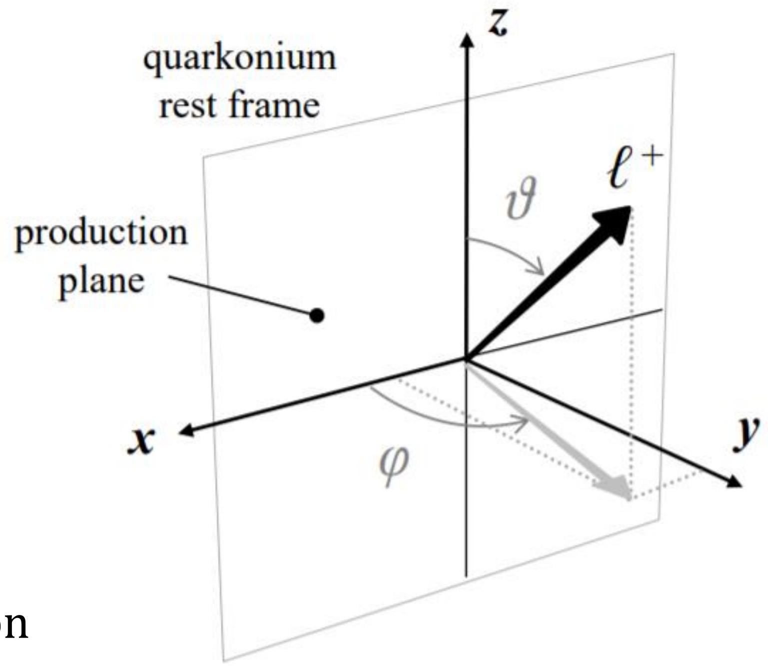
Quarkonium polarization: an introduction

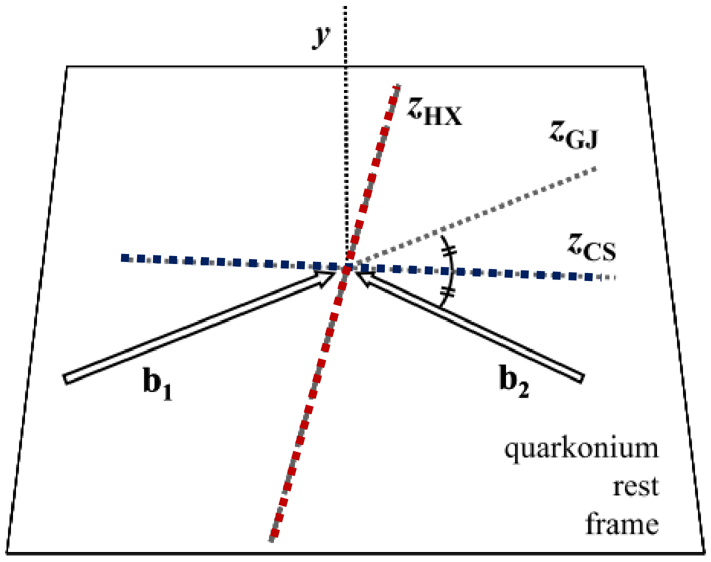
- **Polarization**: observable which measures the degree to which the spin of a particle is aligned w.r.t. a chosen axis

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

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

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (\pm 1,0,0) \Longrightarrow$ Pure **longitudinal**$(-)$/**transverse**$(+)$ polarization





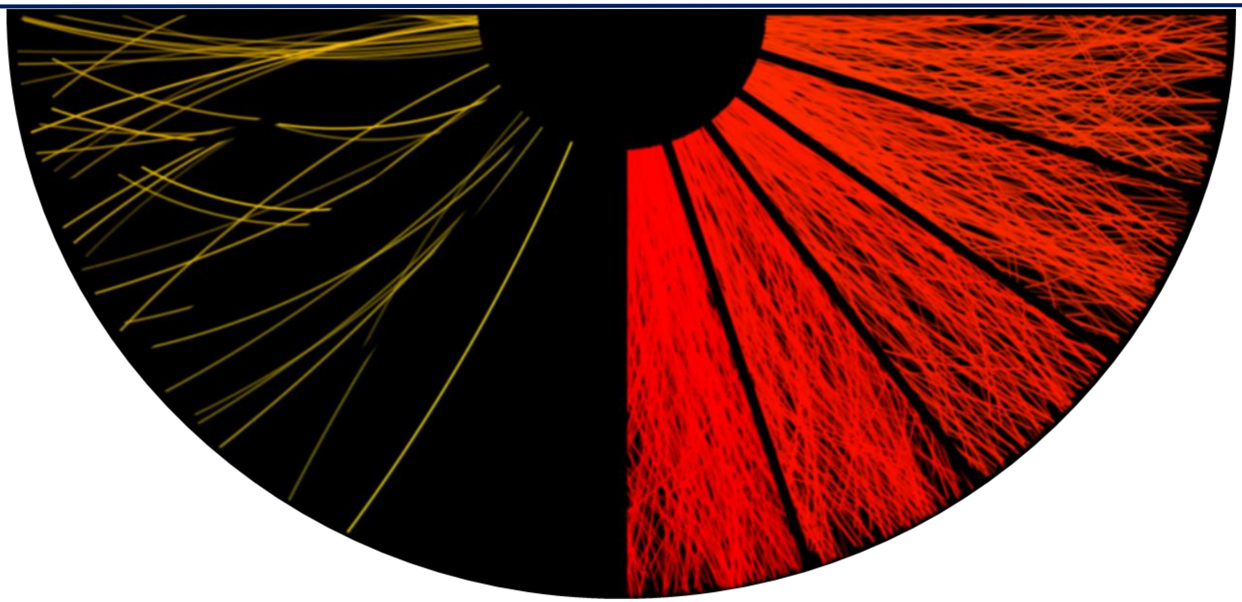
Figures from P.Faccioli et al. EPJ C69 (2010) 657-673

$\Longrightarrow$ 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

Quarkonium polarization: physics motivations

pp collisions



A–A collisions

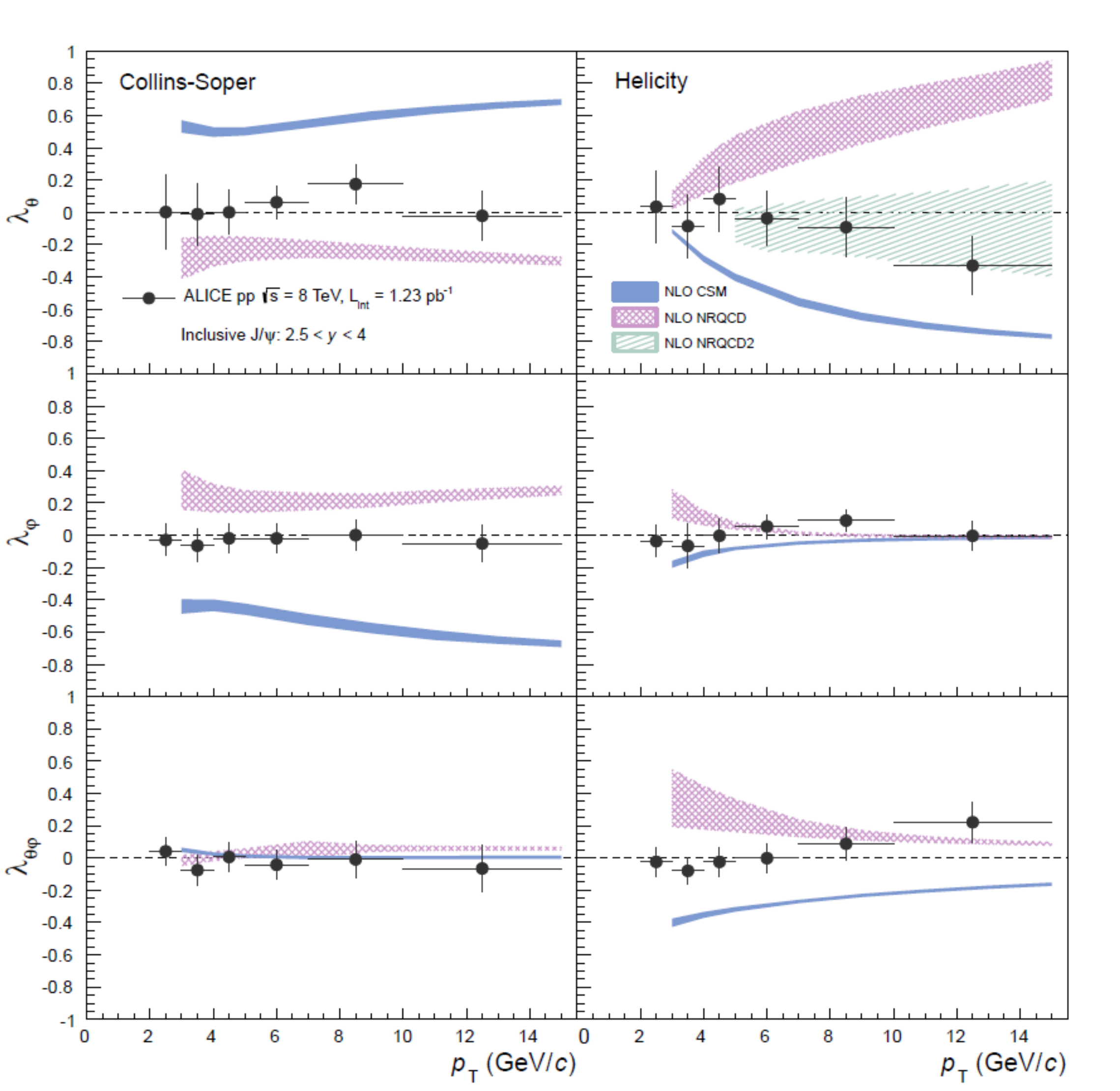
Quarkonium polarization: physics motivations

pp collisions

- Constrains quarkonium **production mechanism**

NRQCD
- **transverse polarization** for high-p_T J/ψ

Color Singlet Model (CSM)
- **longitudinal polarization**



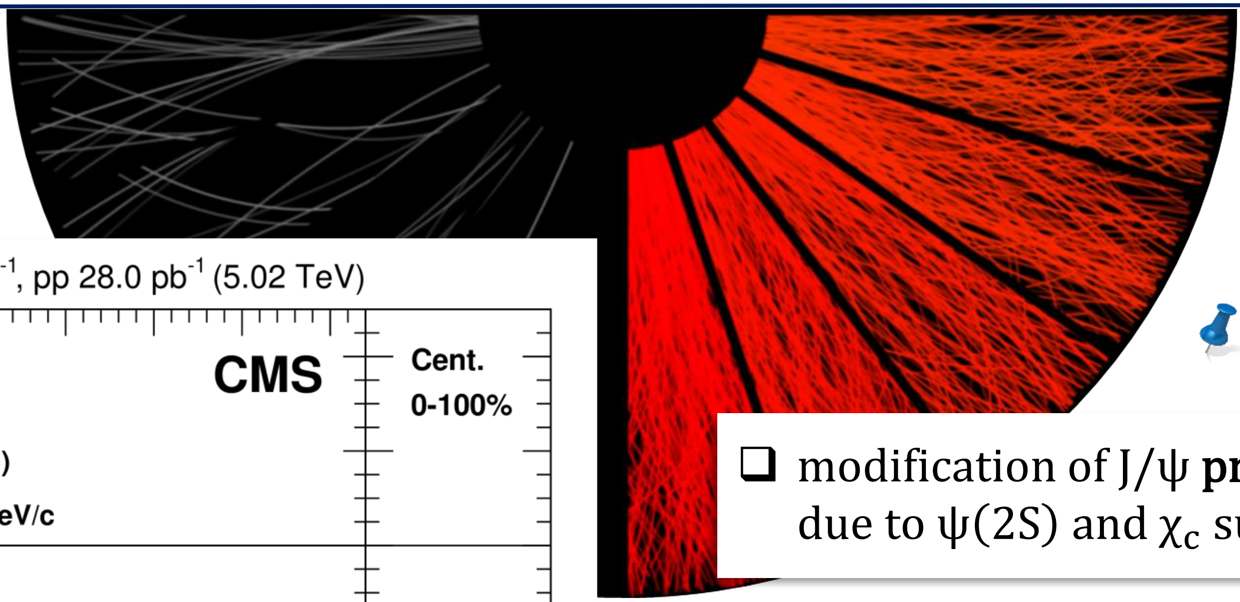
- No sizeable polarization observed at the LHC!

EPJC 73 (2013) 11 PLB 727 (2013) 381

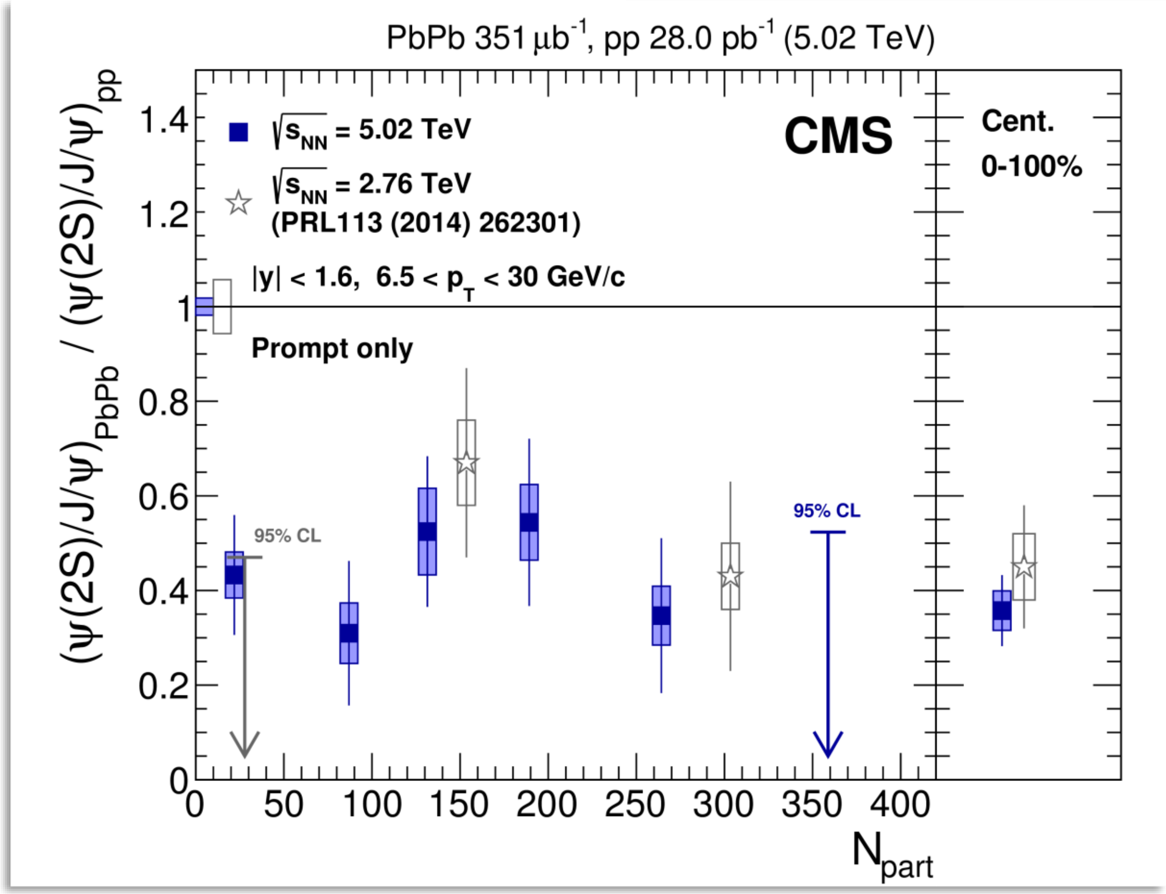
EPJC 78 (2018) 562

Quarkonium polarization: physics motivations

pp collisions



A–A collisions



Possible differencies w.r.t. pp:

- modification of J/ψ **prompt feed-down fractions** due to ψ(2S) and χ_c suppression in the QGP

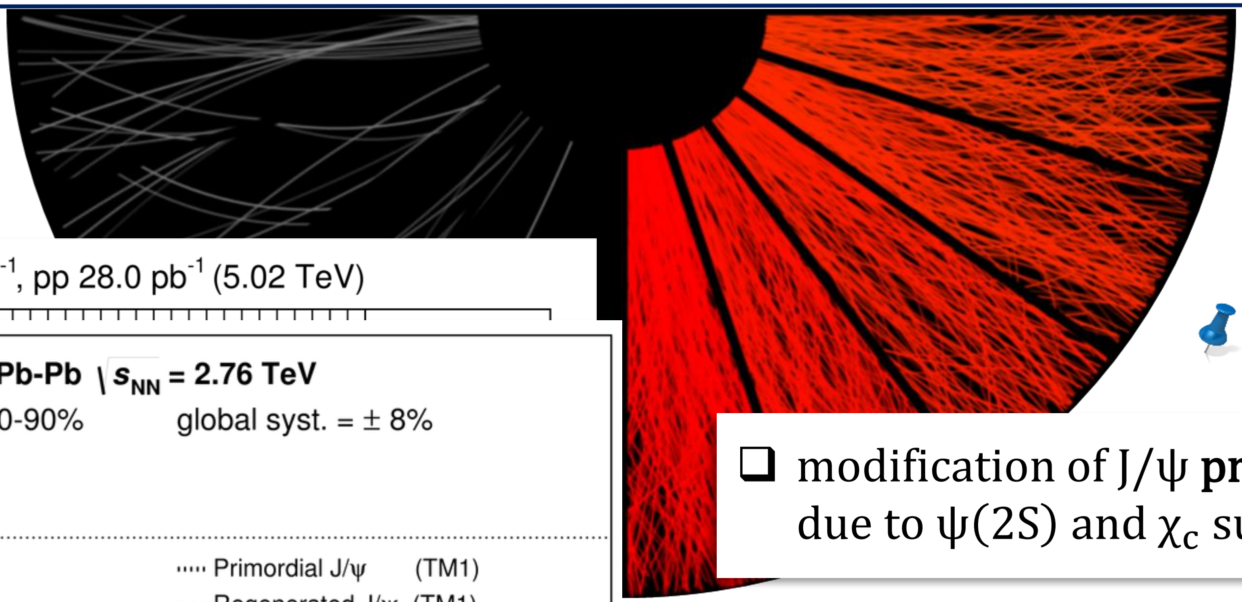
➢ $J/\psi^{\mathrm{Prompt}}:(60\%)^{\mathbf{Direct}}+(30\%)^{\chi_c}+(10\%)^{\psi(2S)}$

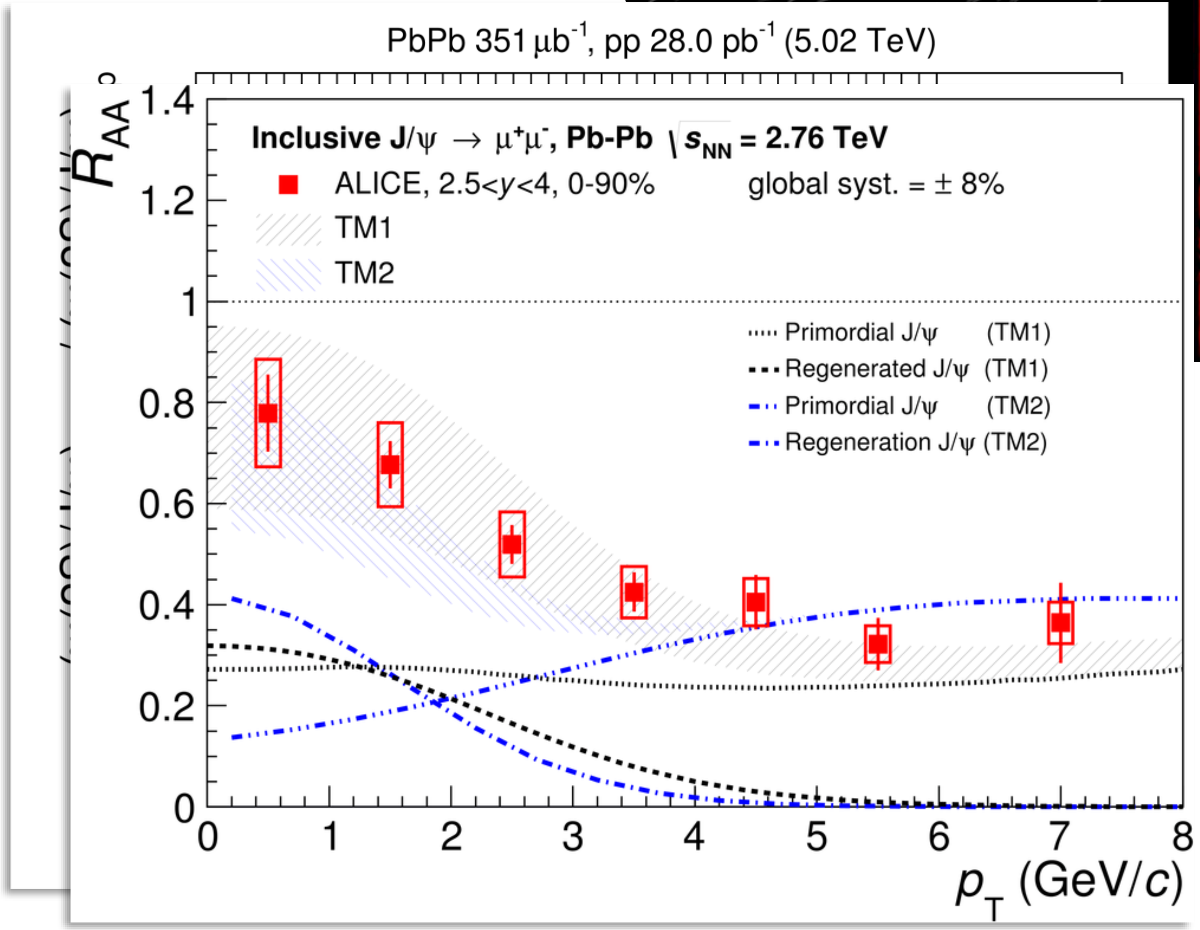
PRL 118 (2017) 162301

Quarkonium polarization: physics motivations

pp collisions

A–A collisions





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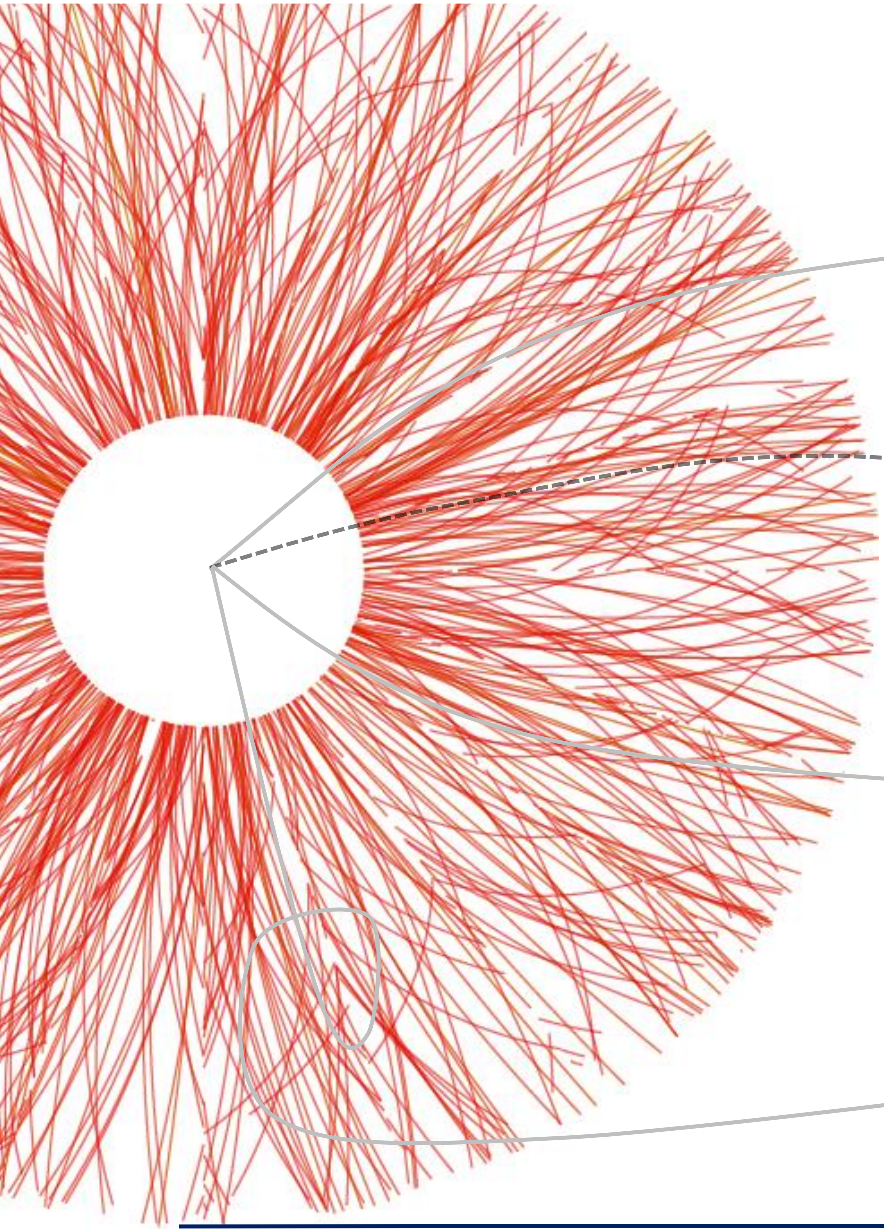
PRL 118 (2017) 162301

- ❑ contribution of **(re)generation** plays an important role at the LHC energies
  - ➢ J/ψ from recombination unpolarized(?)

PLB 734 (2014) 314-327

Outline



- Polarization: an introduction
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Data sample and analysis procedure

GOAL of the analysis: extract J/ψ and ϒ(1S) polarization parameters in Pb-Pb collisions

Data sample: collected by tha **ALICE experiment** in 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) studied in the **dimuon decay channel**

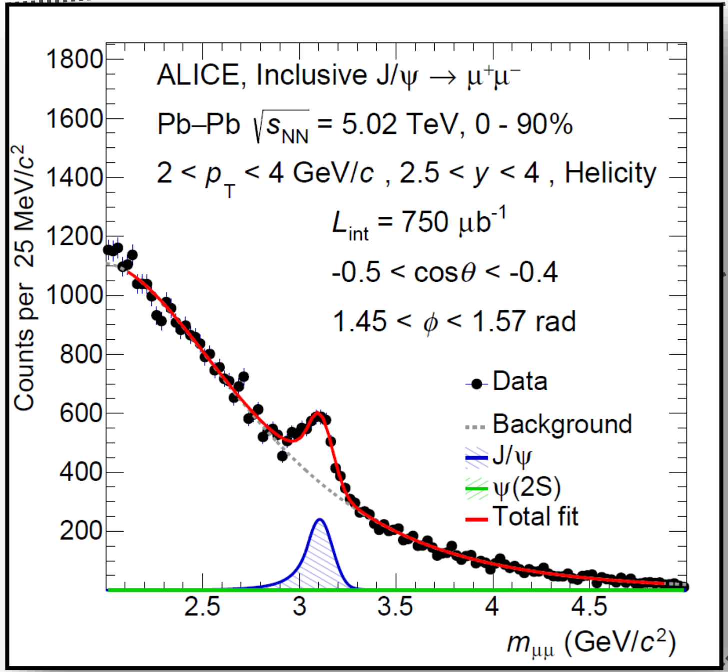
$$\begin{cases} \mathrm{B.R.}_{J/\psi \rightarrow \mu\mu} \sim 5.96\% \\ \mathrm{B.R.}_{\Upsilon(1S) \rightarrow \mu\mu} \sim 2.48\% \end{cases}$$

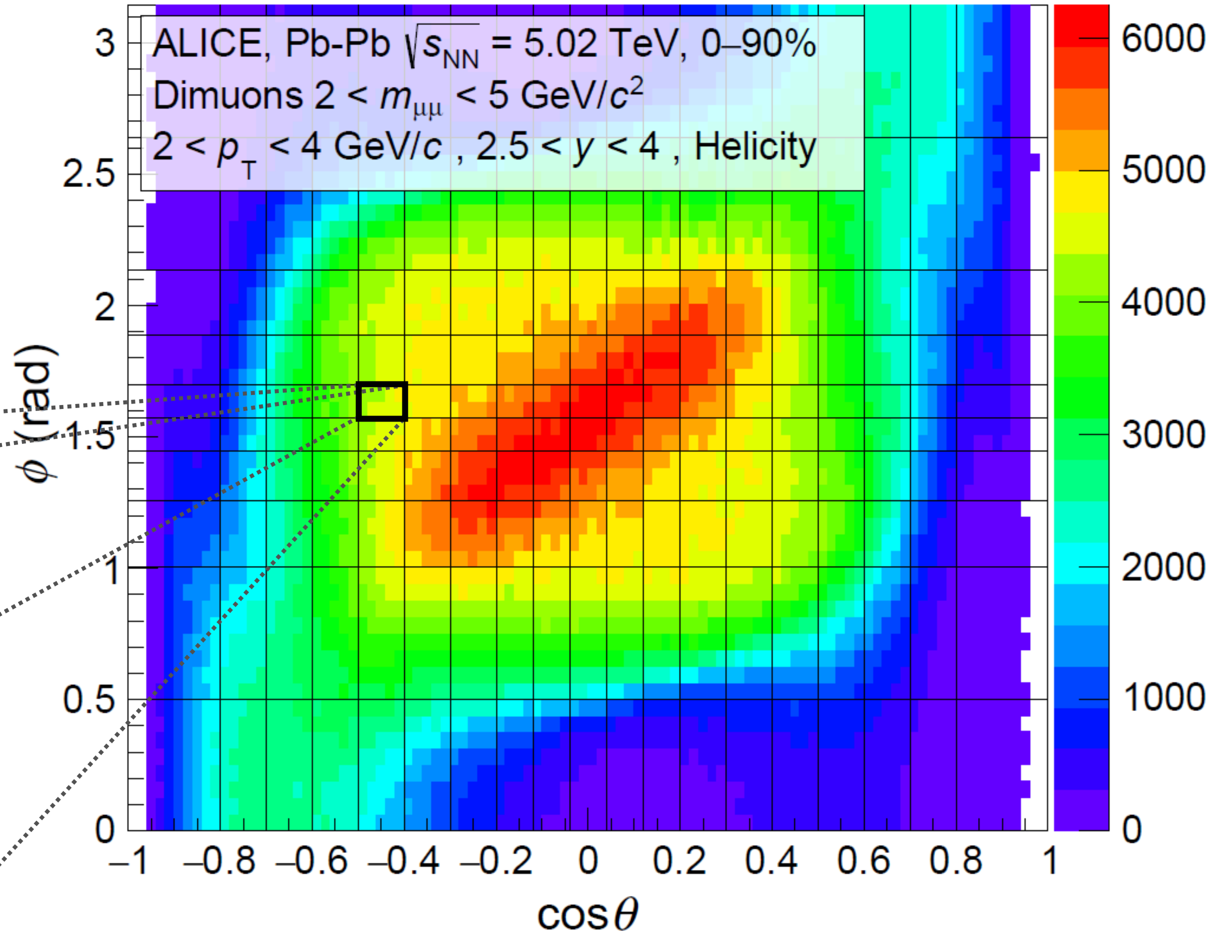
The ALICE experiment has a dedicated **spectrometer** for muon detection

Signal extraction

J/ψ polarization vs p_T

- **2D-approach**
- Creation of a **2D grid** for signal extraction
  - Angular binning tuned according to the statistical significance of the signal



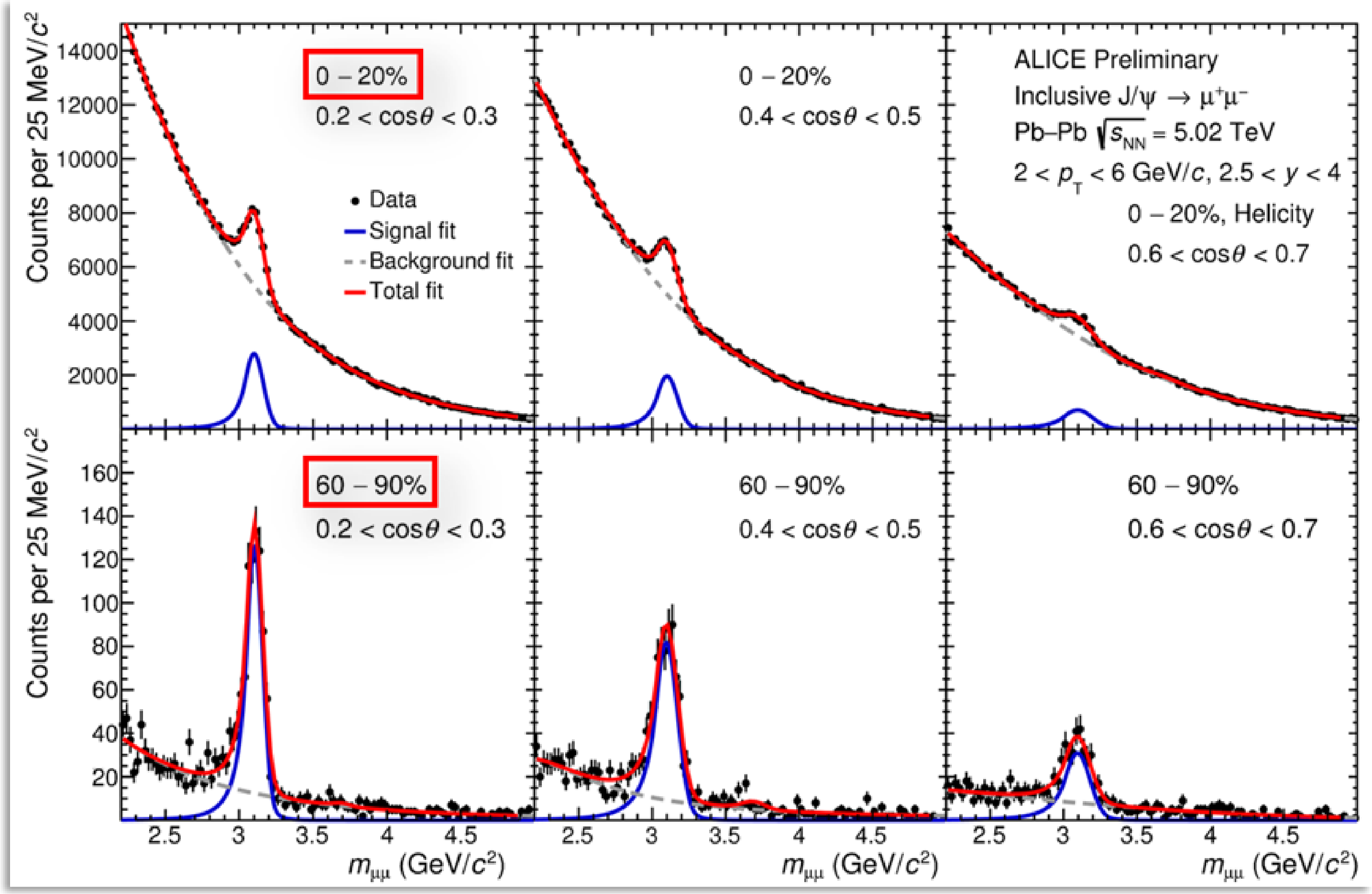


- J/ψ studied in:
  - Centrality: 0–90%
  - p_T : 2–4, 4–6 and 6–10 GeV/c

Signal extraction

J/ψ polarization vs centrality

- Statistics rapidly decreases with centrality
  - yield extracted vs $\cos\theta$ and ϕ separately
    - J/ψ studied in:
      - 0–20% , 20–40%, 40–60% and 60–90% centralities
      - $2 < p_{\mathrm{T}} < 6$ GeV$/c$



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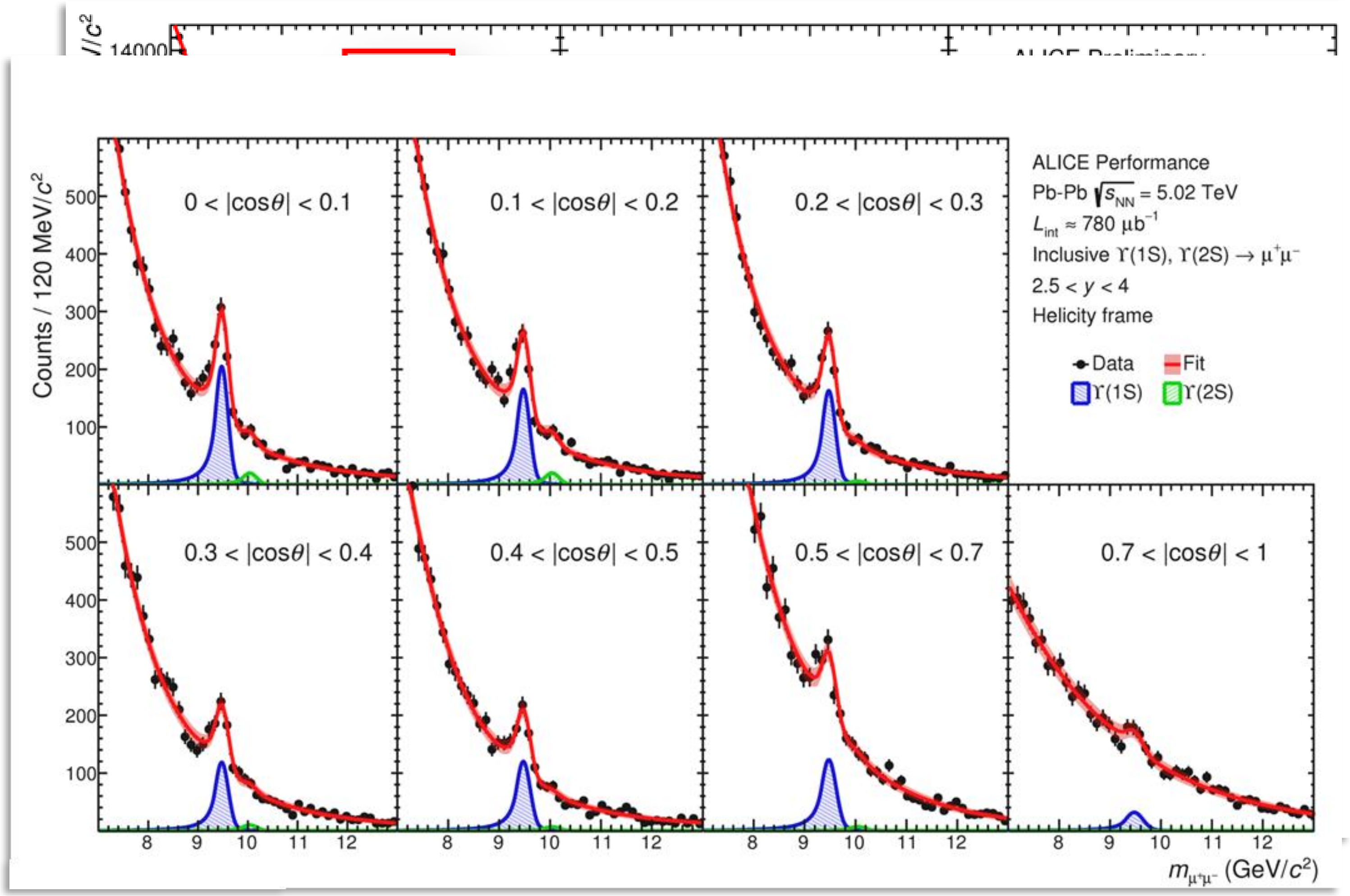
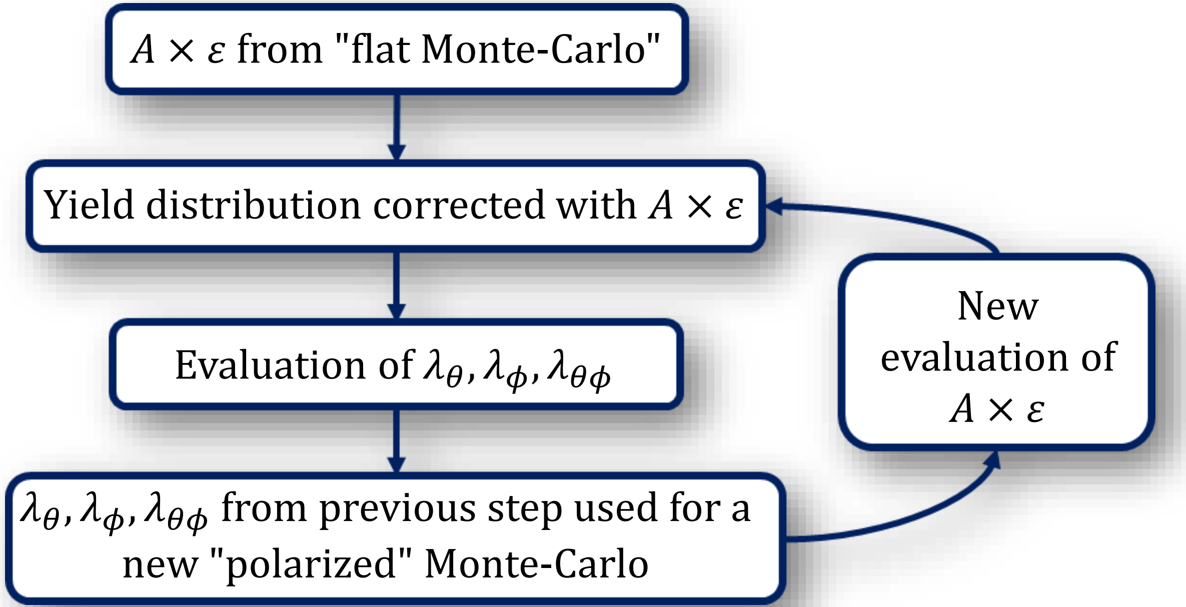
ϒ(1S) polarization

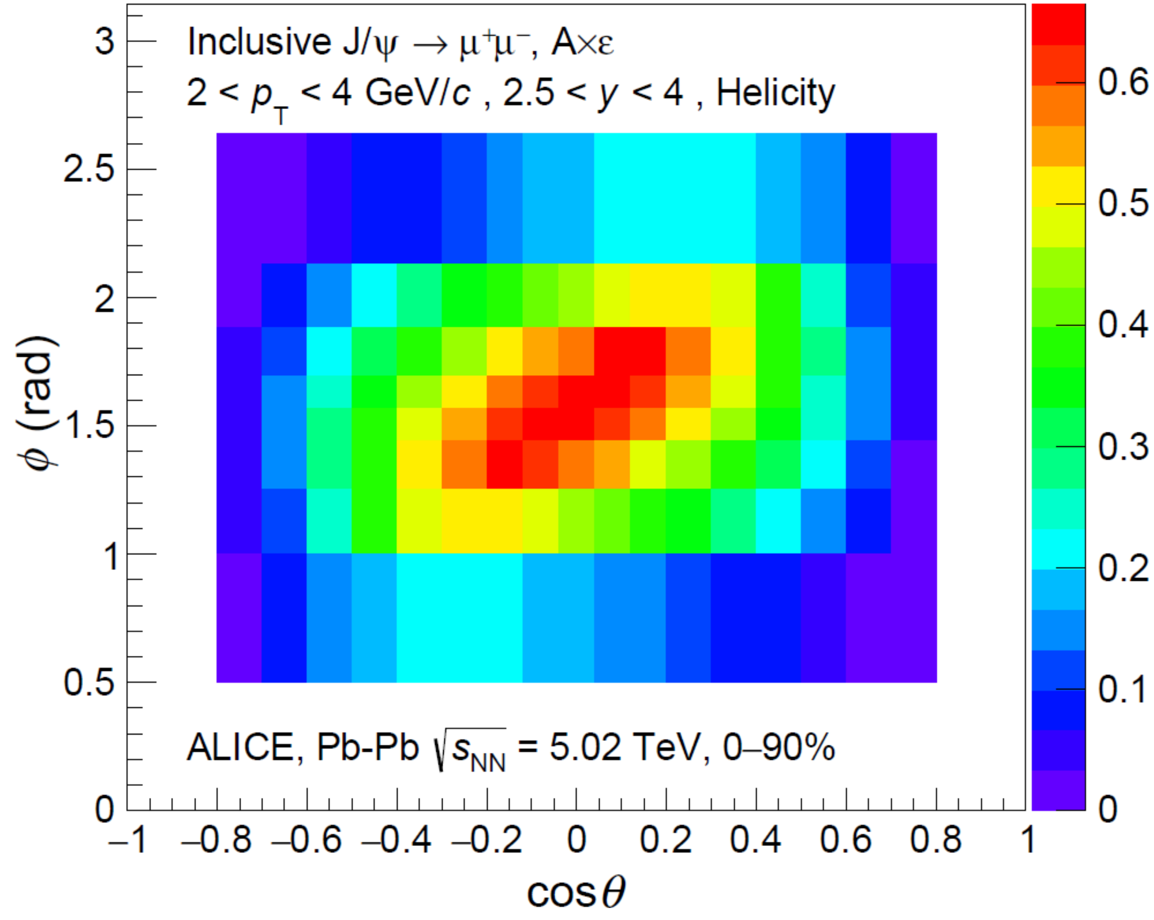
- Limited statistics for ϒ(1S) in Run2
  - yield extracted vs cosθ and ϕ separately
    - ϒ(1S) studied in:
      - Centrality: 0–90%
      - $p_{\mathrm{T}} < 15$ GeV/c



Acceptance × Efficiency

- J/ψ and $\Upsilon(1S)$ generated **unpolarized** in the Monte-Carlo
  - ❑ Impact of non-zero polarization from data?
- **Iterative procedure:** tuning of generated distribution according to the polarization observed in the data





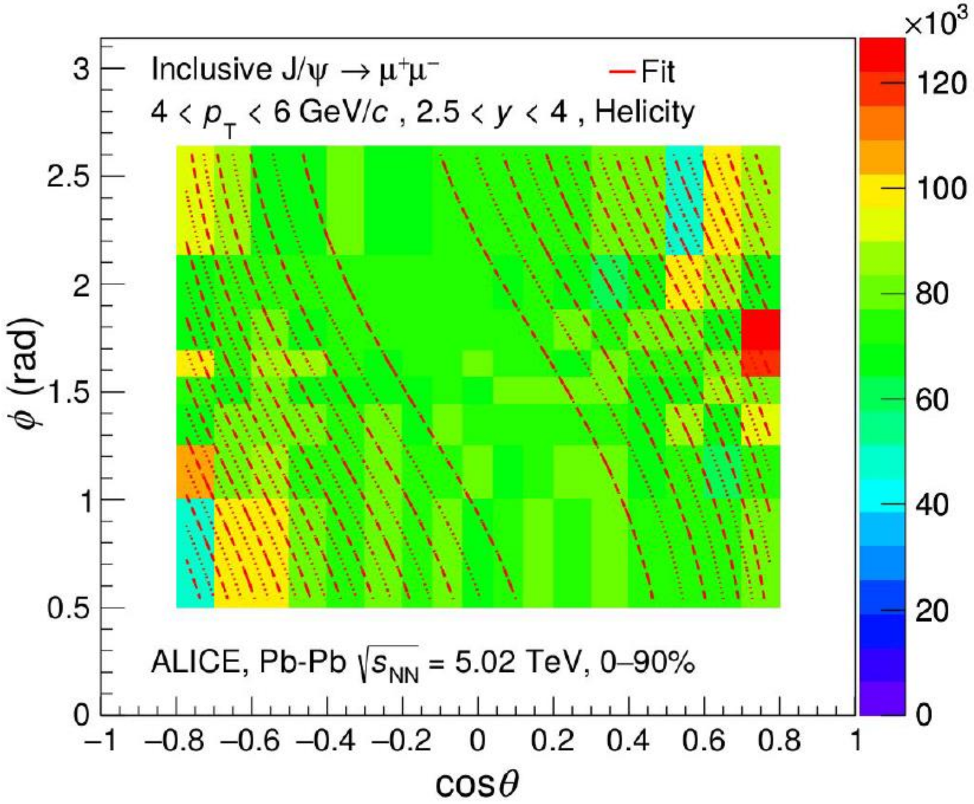
Polarization parameters extraction

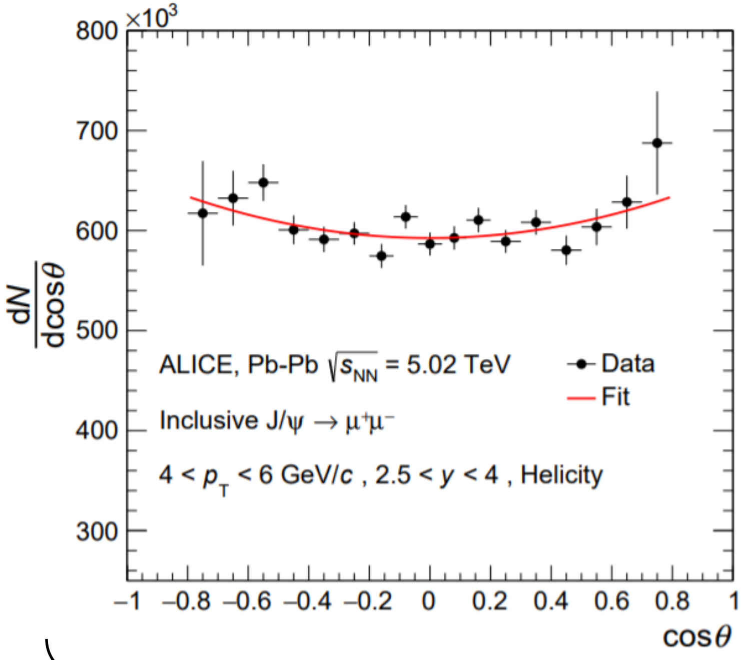
J/ψ polarization vs p_T

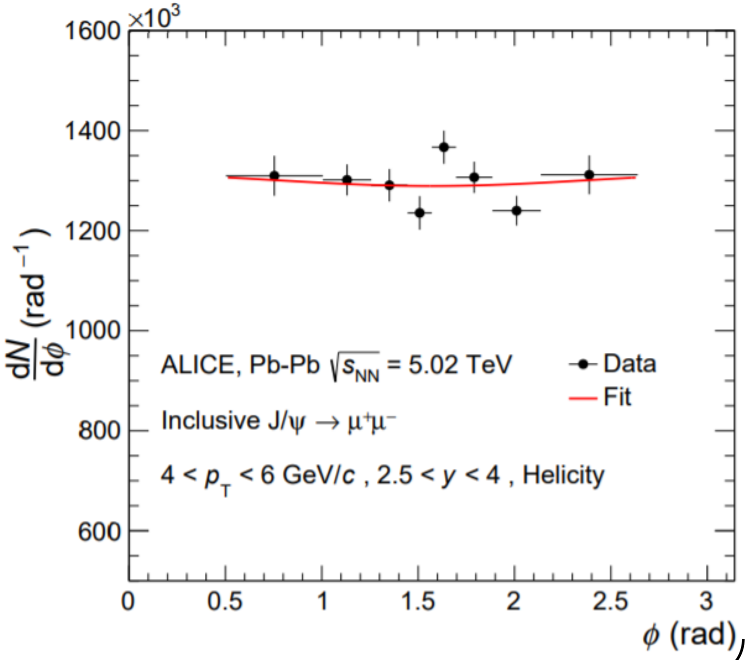
Fit to the $(\cos\theta, \phi)$ J/ψ angular distribution corrected for $A \times \varepsilon$ (**2D approach**) with $W(\cos\theta, \phi)$

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

➢ All polarization parameters are extracted in one single fit







Projection along $\cos\theta$ and ϕ

Polarization parameters extraction

J/ψ polarization vs centrality & ϒ(1S) polarization

Fit to the $\cos\theta$ and ϕ distributions corrected for $A \times \varepsilon$ with the integrated expression of $W(\cos\theta, \phi)$

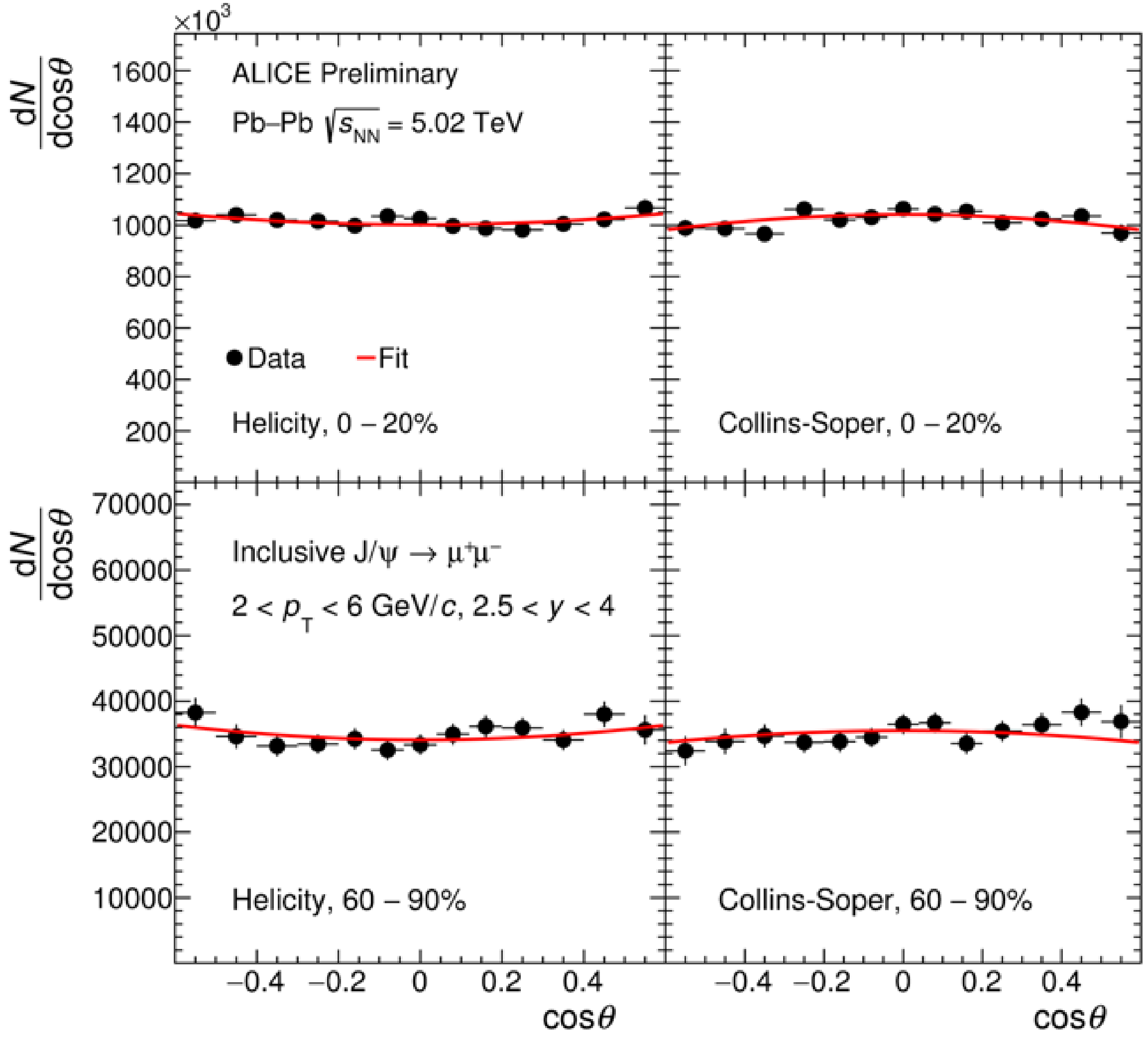
$$\int W(\cos\theta,\phi)d\phi \propto \frac{1}{3+\boldsymbol{\lambda_\theta}} \cdot (1 + \boldsymbol{\lambda_\theta} \cos^2\theta)$$

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

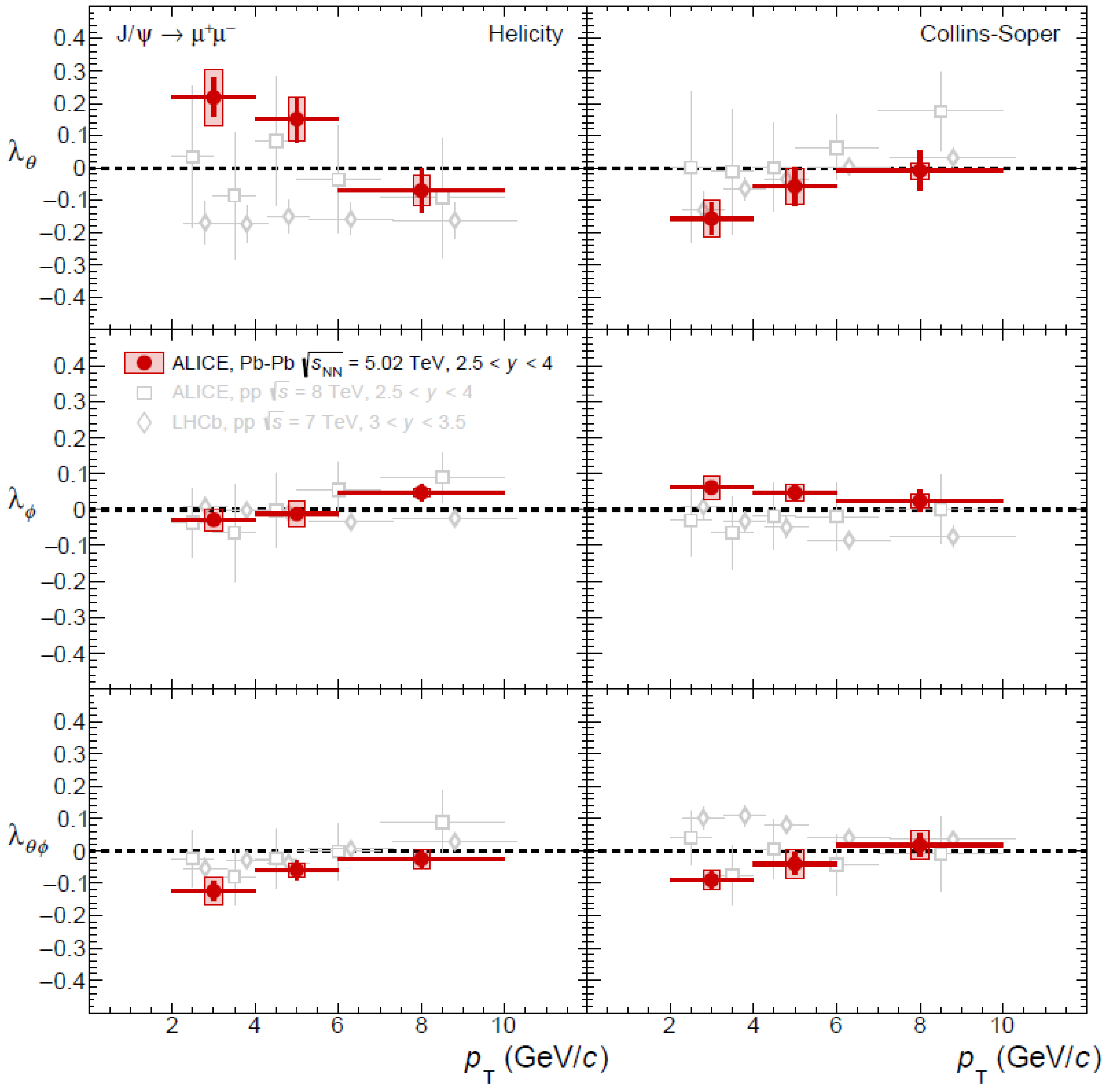
- $\lambda_{\theta\phi}$ can be extracted defining the variable $\tilde{\phi}$

$$\begin{cases} \tilde{\phi} = \phi - 3/4\,\pi, \cos\theta < 0 \\ \tilde{\phi} = \phi - 1/4\,\pi, \cos\theta > 0 \end{cases}$$

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



Results

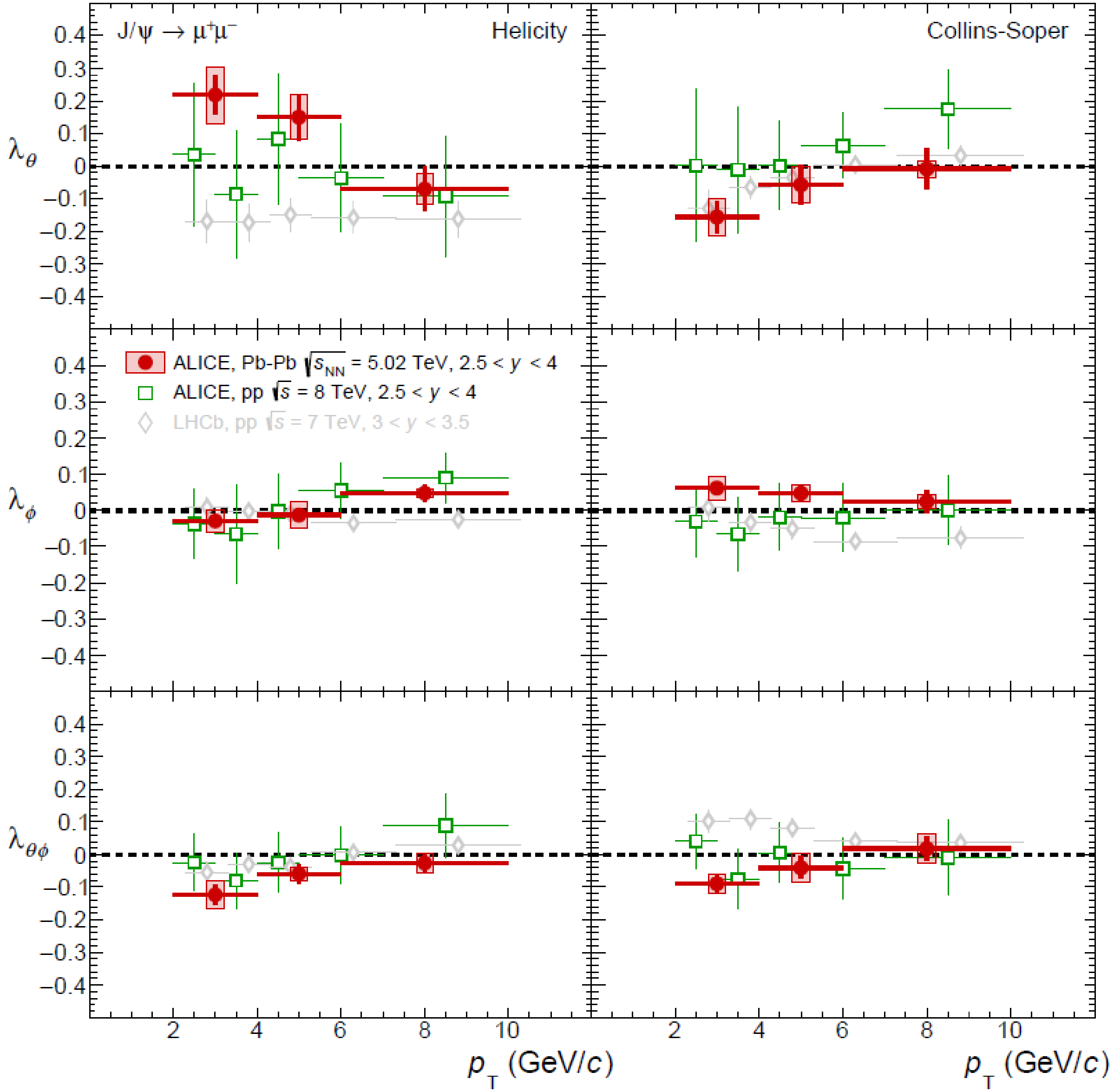


J/ψ polarization vs p_T

- Indication of small **transverse/longitudinal** polarization at low p_T for **HE/CS**
  - ➢ Maximum deviation of ~ $\mathbf{2\sigma}$ in the low p_T bin

PLB 815 (2021)

Results



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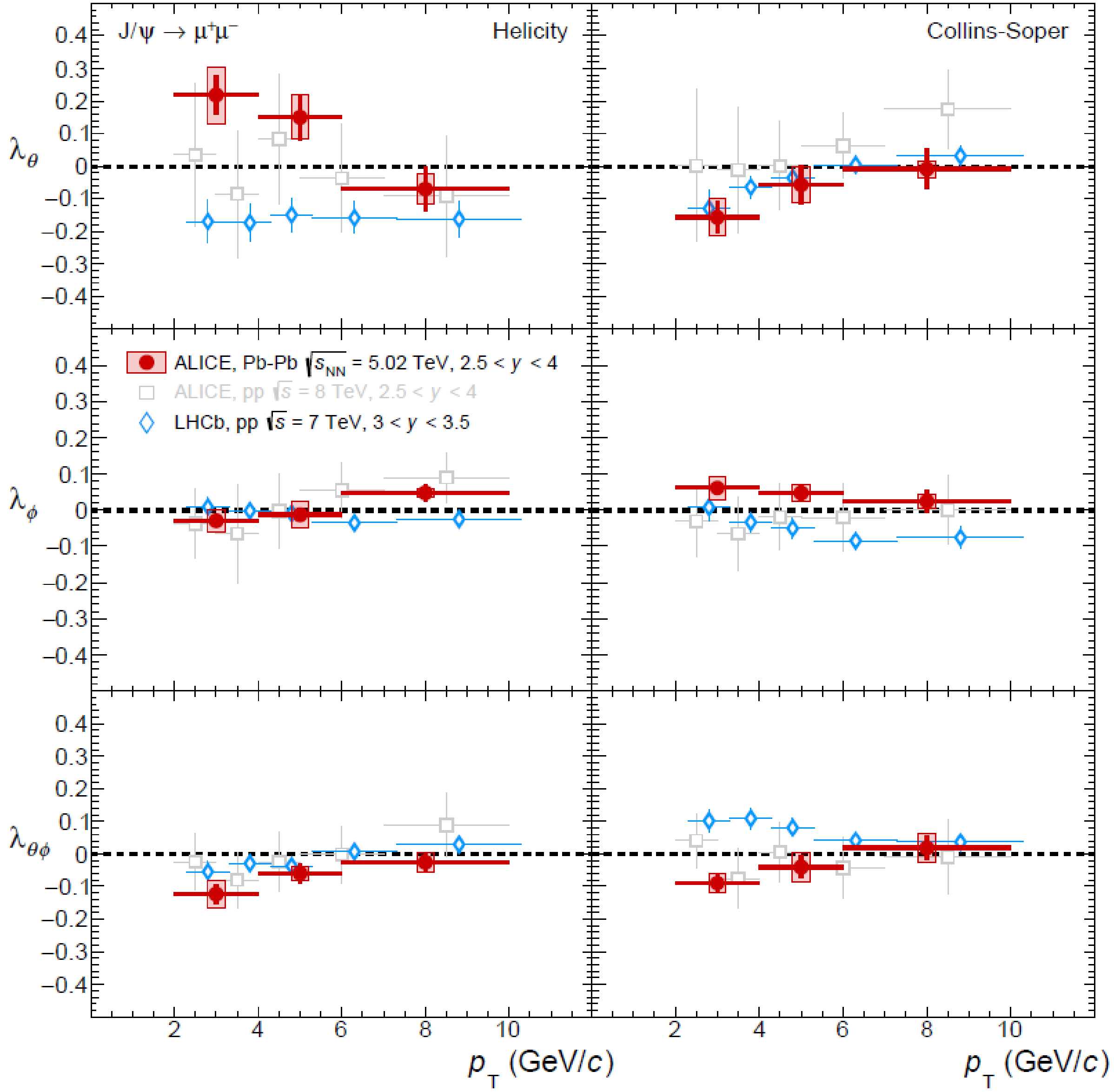
- Comparison with **ALICE pp** results at $\sqrt{s} = 8$ TeV
  - compatible within the uncertainties

EPJC 78 (2018) 562

Results



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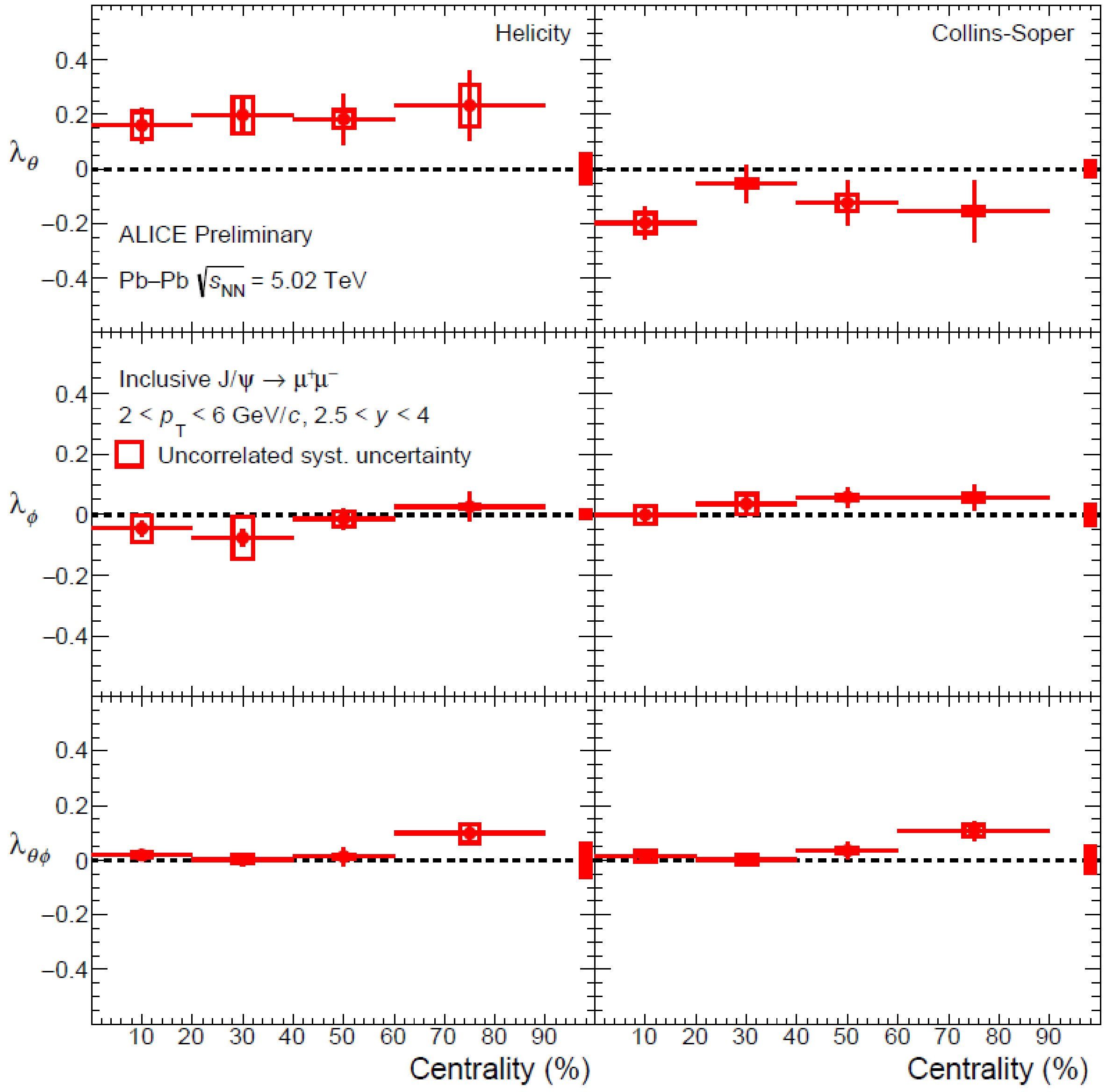
EPJC 78 (2018) 562

- Comparison with **LHCb pp** results at $\sqrt{s}$ = 7 TeV
  - Smaller uncertainties on $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$
  - Significant (~ $\mathbf{3\sigma}$) difference in λ_θ^{HE} at low p_T

! LHCb result obtained for prompt J/ψ

EPJC 73 (2013) 11

Results



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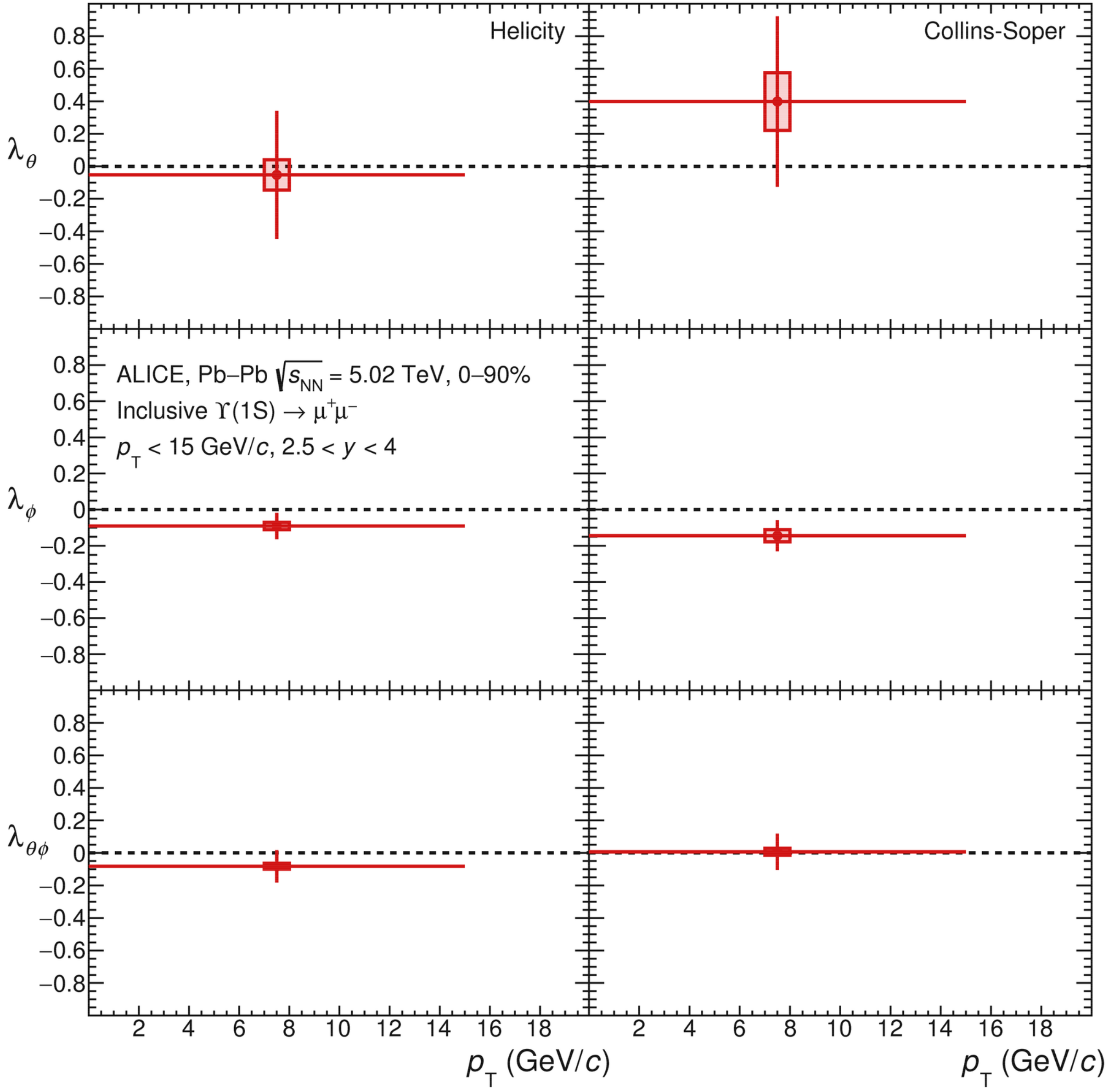
J/ψ polarization vs centrality

- Non-zero polarization (λ_θ) observed
  - Useful to disentangle different effects (suppression, (re)generation, …)
  - No visible dependence of $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ moving from central to peripheral collisions

Results



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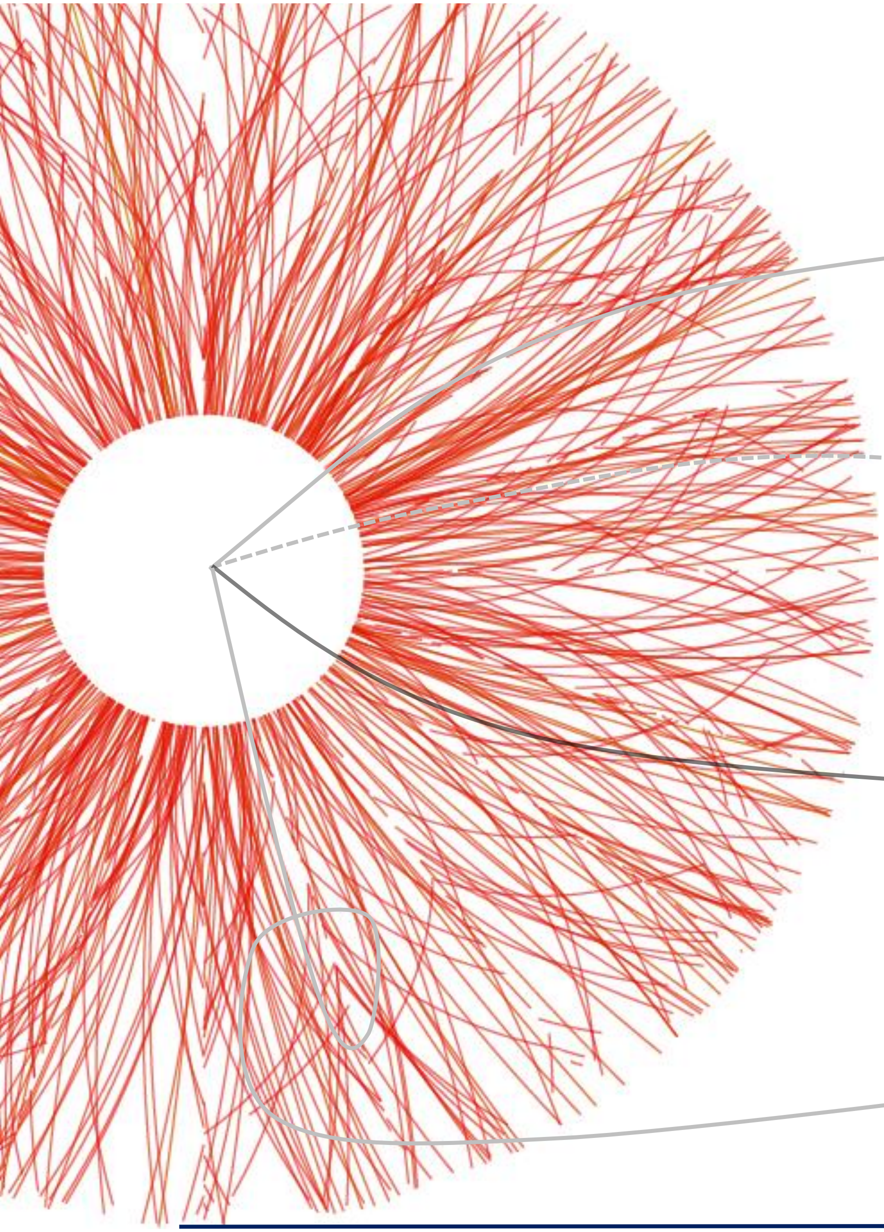
ϒ(1S) polarization

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in HE and CS

➢ Compatible with **LHCb pp** results at $\sqrt{s} = 7$ TeV

arxiv:1711.02404

Outline



- Polarization: an introduction
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Discussion on results

J/ψ polarization vs p_T and centrality

- ~ $\mathbf{2\sigma}$ deviation from zero for λ_θ in $2 < p_T < 4$ GeV/c
- ~ $\mathbf{3\sigma}$ difference with **LHCb** (pp collisions) at low p_T

! Full theoretical theoretical description of polarization in HICs is missing

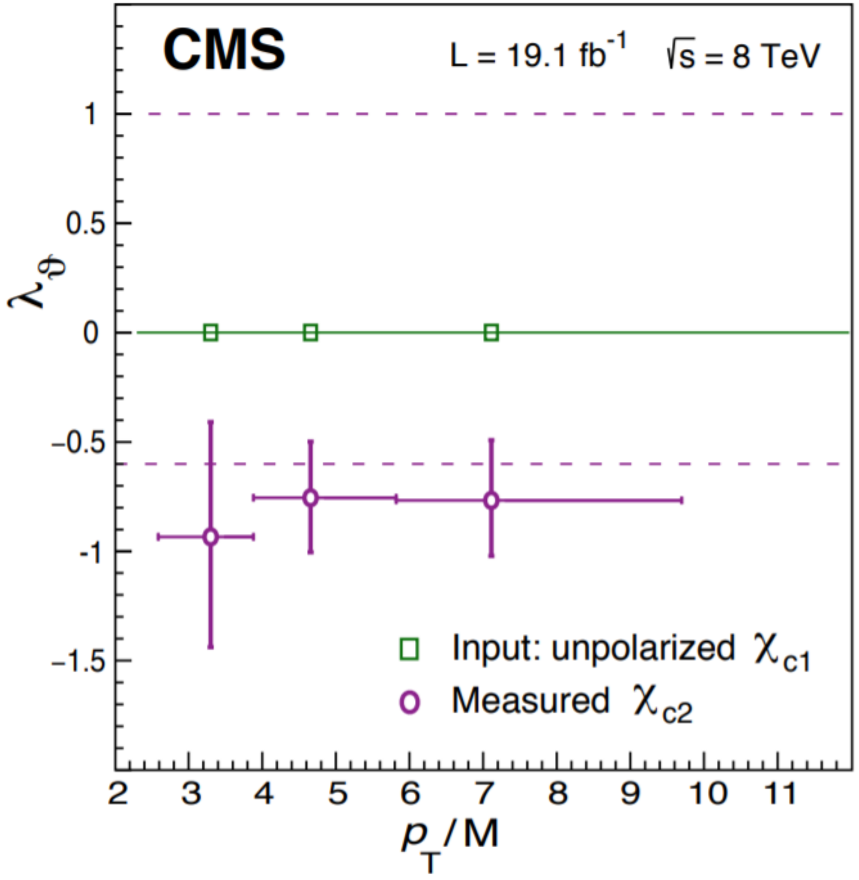
Feed-down fractions modification w.r.t. pp collisions

- ψ(2S) unpolarized (pp)
- χ_c strong "relative" polarization (pp)

- Increase in λ_θ related to χ_c suppression in Pb-Pb ?

Significant J/ψ **(re)generation** at low-p_T

- Polarization modified by J/ψ from recombination (unpolarized)?



EPJC 74 (2014) 5, 2872

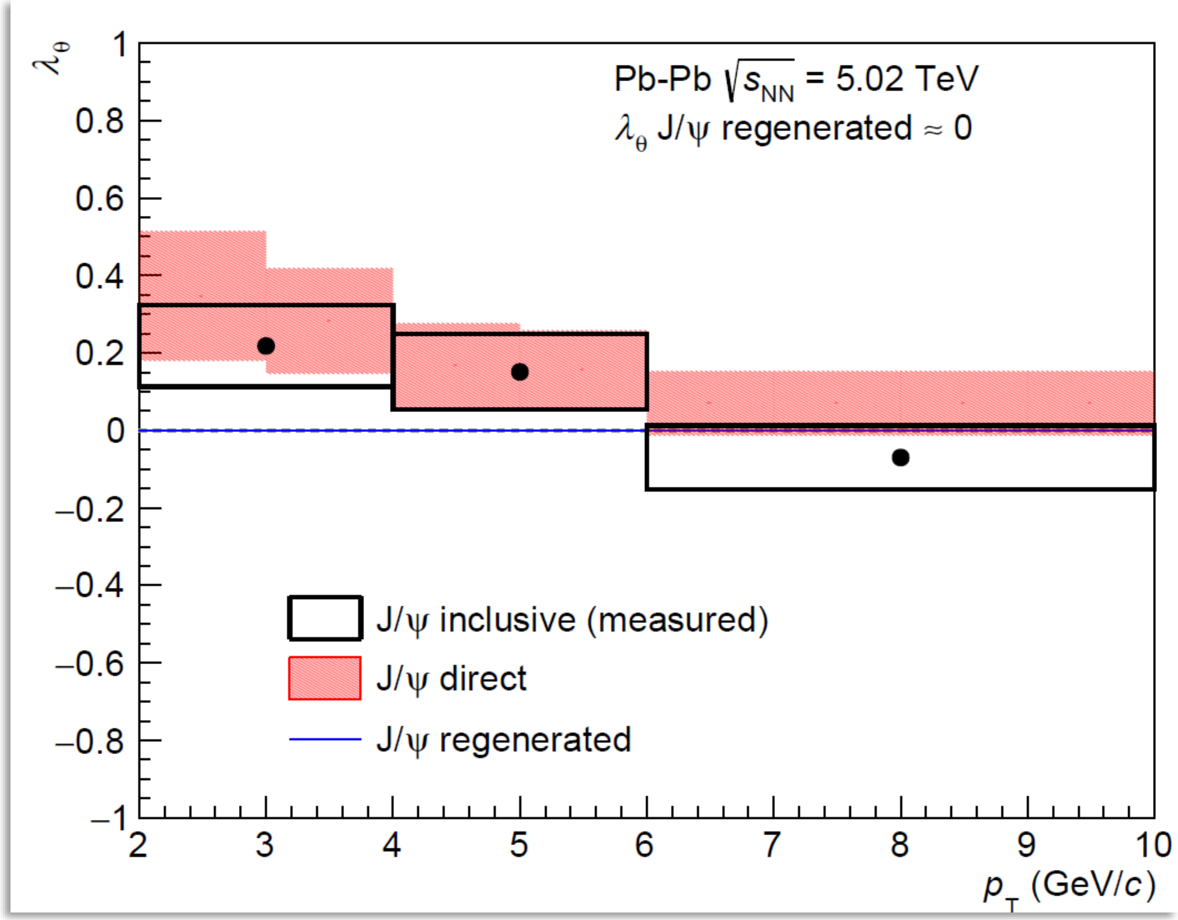
PRL 124, 162002 (2020)

Exercise

Is it possible to constrain χ_{c1} **and** χ_{c2} **average polarization** using the existing measurements?

Pb-Pb

$$\lambda_\theta^{J/\psi\ Prompt} \sim \lambda_\theta^{J/\psi\leftarrow\chi_c} + \lambda_\theta^{J/\psi\leftarrow\psi(2S)} + \lambda_\theta^{J/\psi\ Direct} + \lambda_\theta^{J/\psi\ (Re)generated}$$



- J/ψ from *b* assumed negligible
- **prompt J/ψ** ⇒ measured
- **Regenerated J/ψ** ⇒ unpolarized (?)
- **J/ψ ← χ_c, ψ(2S)** ⇒ suppressed

⇒ Direct J/ψ polarization

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Is it possible to constrain χ_{c1} **and** χ_{c2} **average polarization** using the existing measurements?

pp

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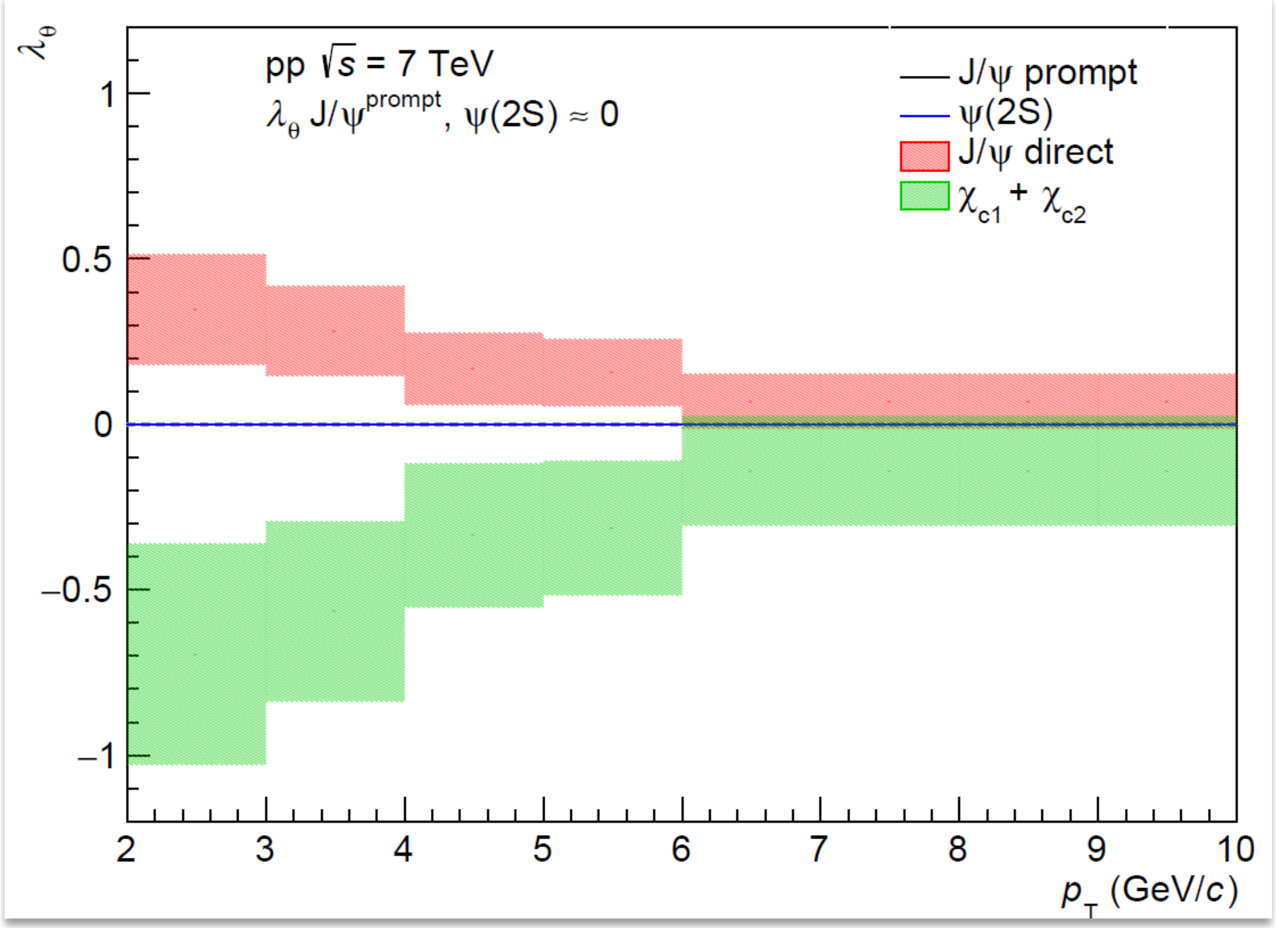

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- **Regenerated J/ψ** ⇒ unpolarized (?)
- **J/ψ ← χ_c, ψ(2S)** ⇒ suppressed

⇒ Direct J/ψ polarization

- **ψ(2S)** ⇒ unpolarized
- **Direct J/ψ** ⇒ extracted
- **Prompt J/ψ** ⇒ measured

⇒ χ_{c1} and χ_{c2} average polarization

Discussion on results

- **J/ψ polarization vs p_T and centrality**
  - ~ **2σ** deviation from zero for λ_θ in $2 < p_T < 4$ GeV/c
  - ~ **3σ** difference with **LHCb** (pp collisions) at low p_T

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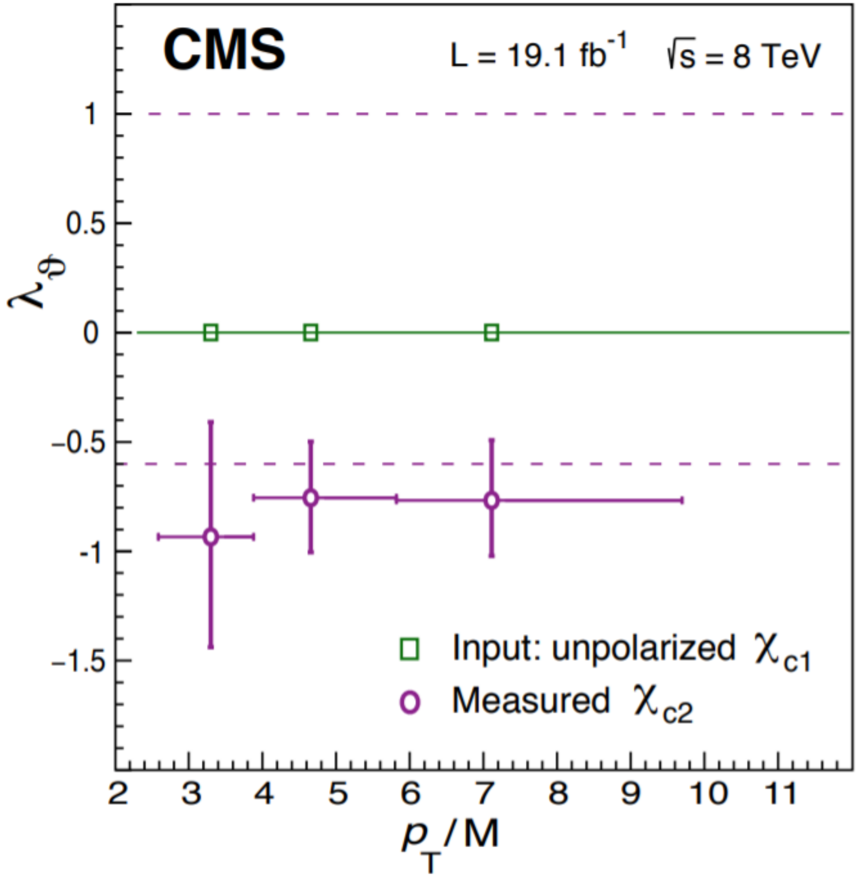
Significant J/ψ **(re)generation** at low-p_T

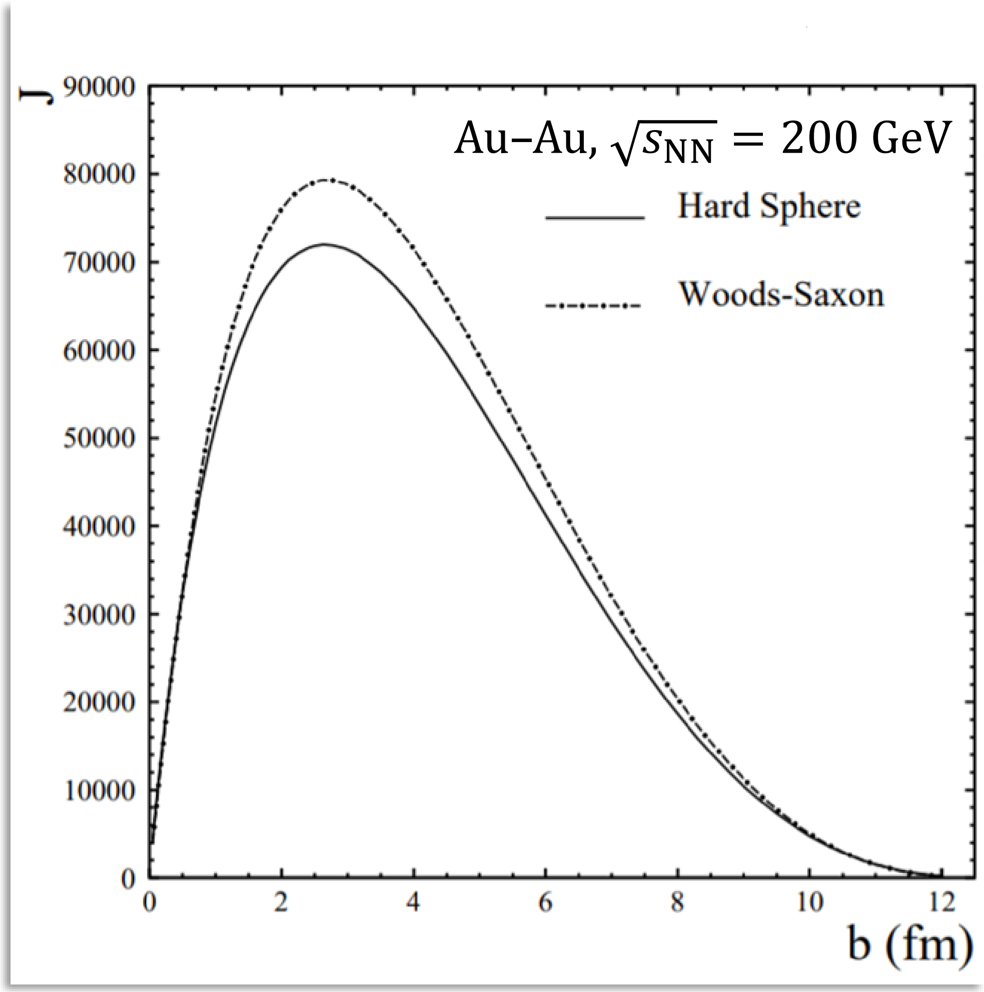
- Polarization modified by J/ψ from recombination (unpolarized)?

Magnetic field and **angular momentum** in non-central HICs modify polarization?



Polarization: other effects

- Spin alignment (polarization) sensitive to other mechanisms beyond **hadronization**



- Large **angular momentum** due to the medium rotation is predicted in non-central HICs

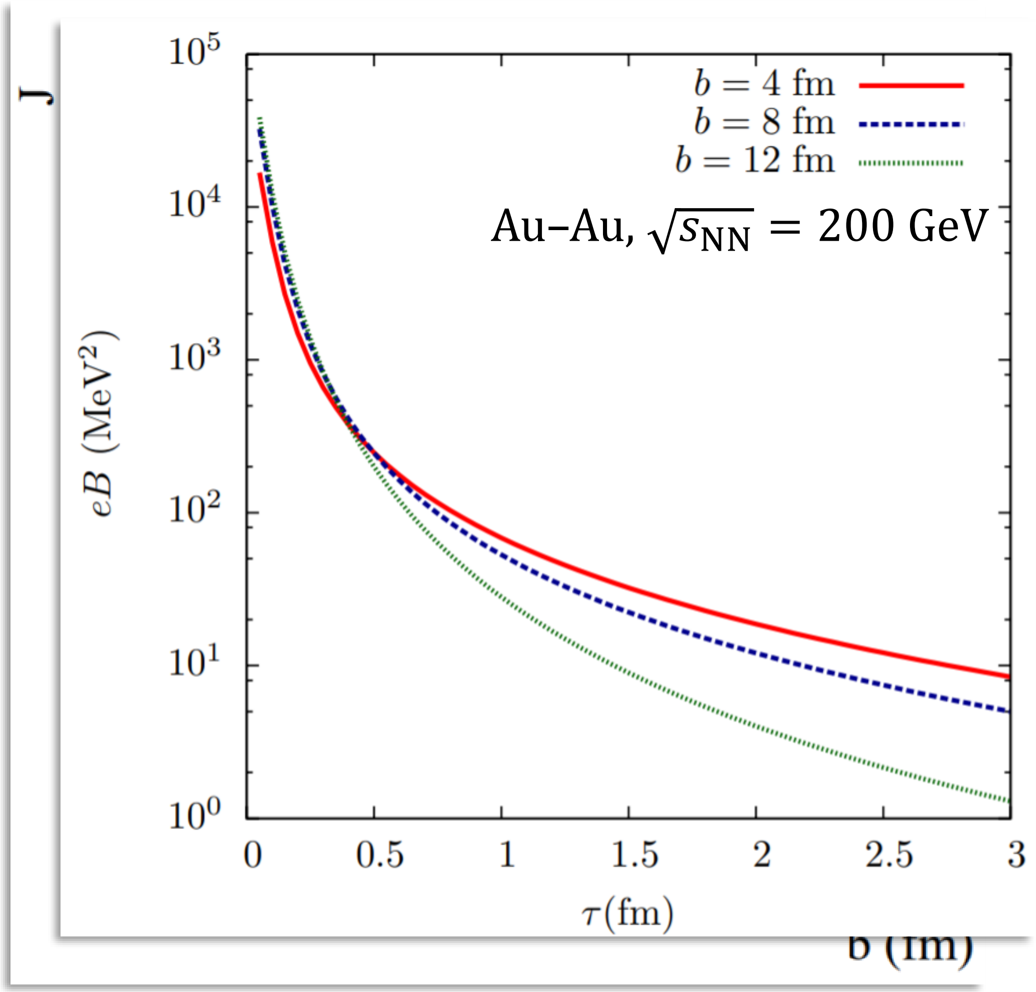
PRC 77 (2008) 024906, Beccattini et al.

- Spin alignment of the vector meson can be related to the **spin-orbit coupling**
- Sensitivity to the **vortical structure** of the QGP

? Possible effect on **(re)generated J/ψ**

Polarization: other effects

- Spin alignment (polarization) sensitive to other mechanisms beyond **hadronization**



- Large **angular momentum** due to the medium rotation is predicted in non-central HICs

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- Huge **magnetic field** ($|\vec{B}| \sim 10^{14}$ T) is expected to be formed and to be short-living

  NPA 803 (2008), Kharzeev et al.

  - Time-evolution of $\vec{B}$ not fully understood

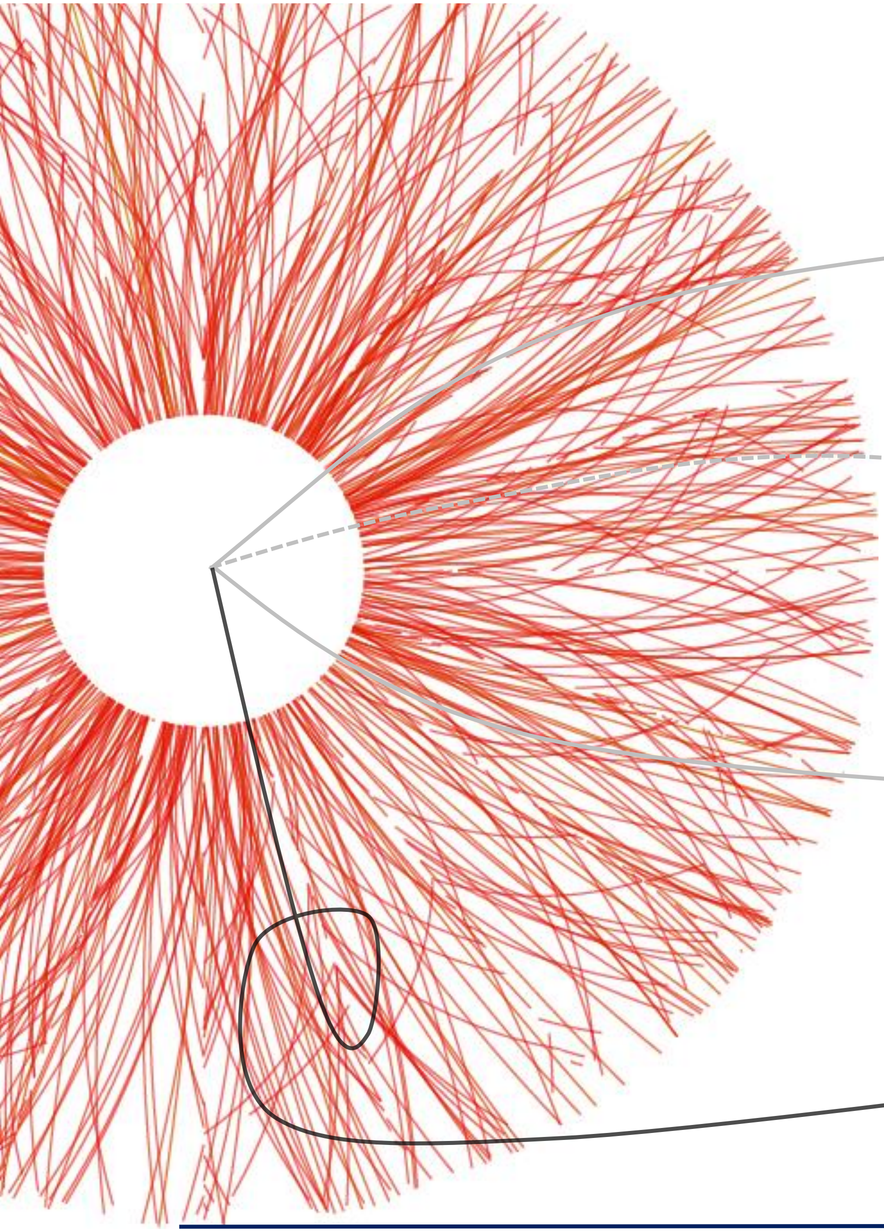
$$\tau_{\text{Form}}^{Q\bar{Q}} \leq \tau_{\text{Form}}^{\text{QGP}} < \tau_{\text{Form}}^{\text{Quarkonia}} \leq \tau_{\text{Life}}^{\text{QGP}}$$

$\vec{B}$

  - c-quarks production compatible with $\vec{B}$

$$\tau_{\text{c-Prod}} < \hbar/m_c \sim 0.1\ \text{fm}/c$$

Outline



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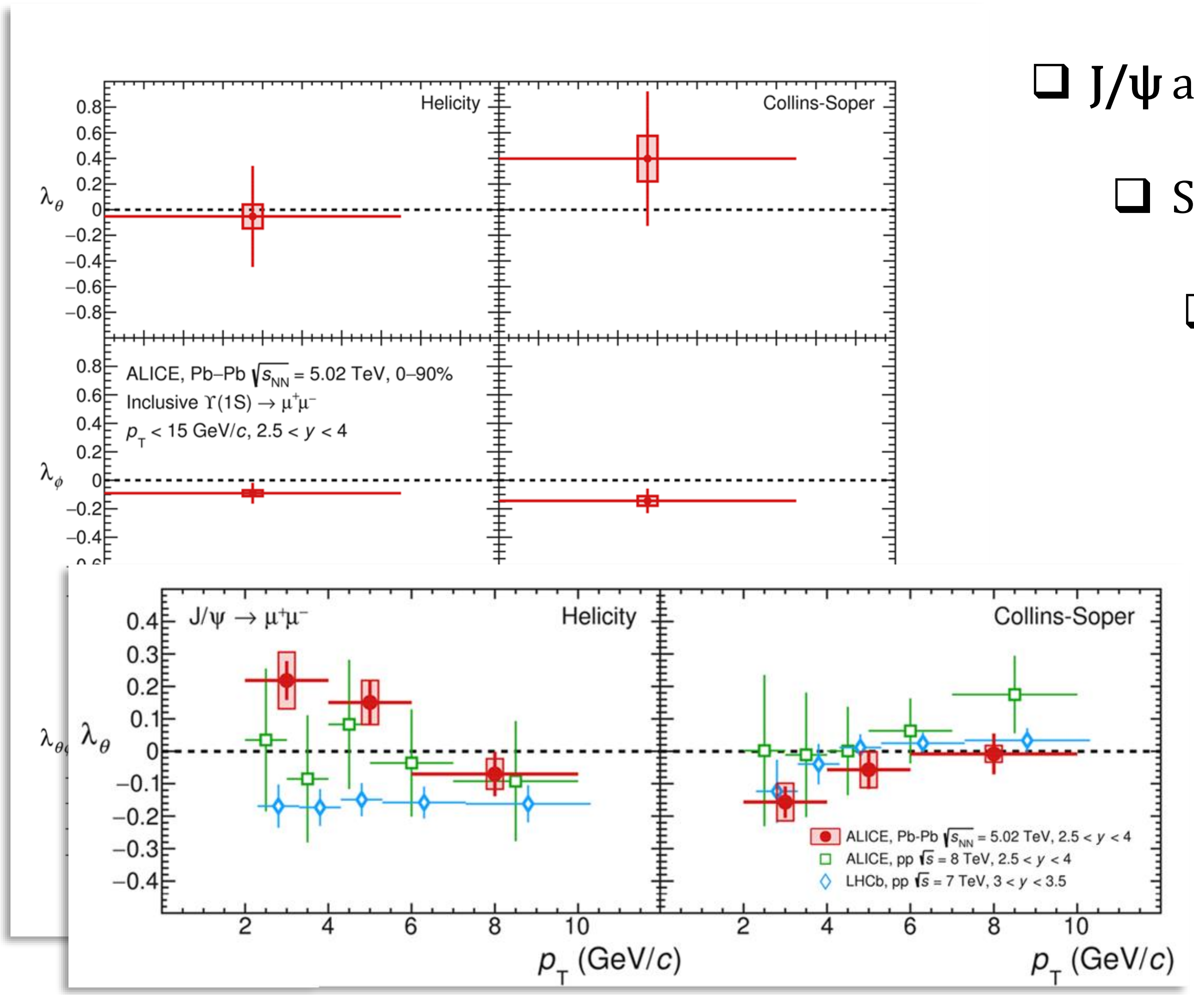
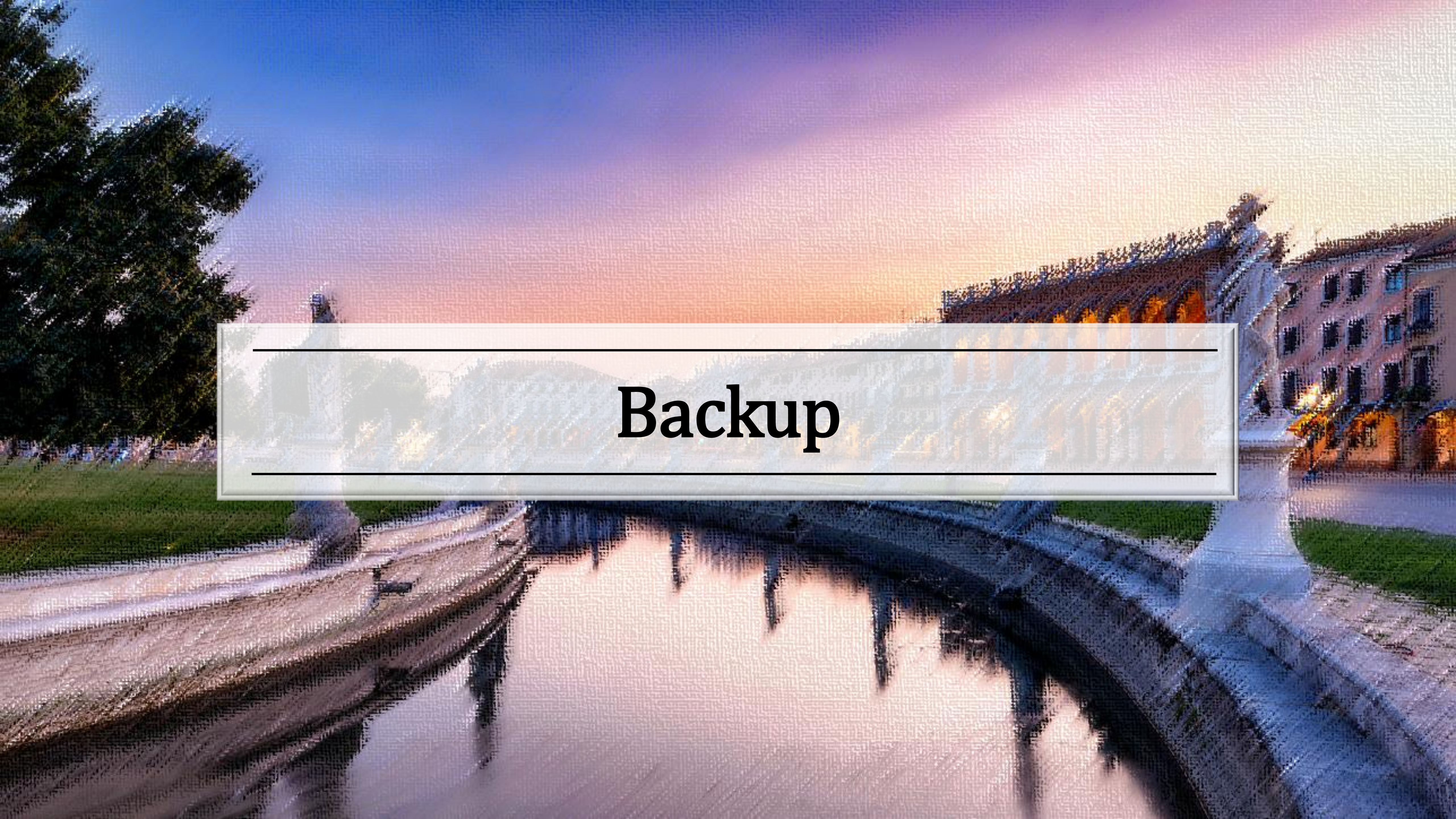
Summary

First measurement of **quarkonium polarization** in nuclear collisions at the LHC



- **J/ψ and Υ(1S)** do not exhibit a strong polarization in HICs
  - Significant difference for **J/ψ** w.r.t. **LHCb** at low p_T
    - New measurements of **J/ψ polarization w.r.t. the event-plane** and paper is in preparation
      - Many effects needs to be considered in the theoretical desctription of quarkonium polarization

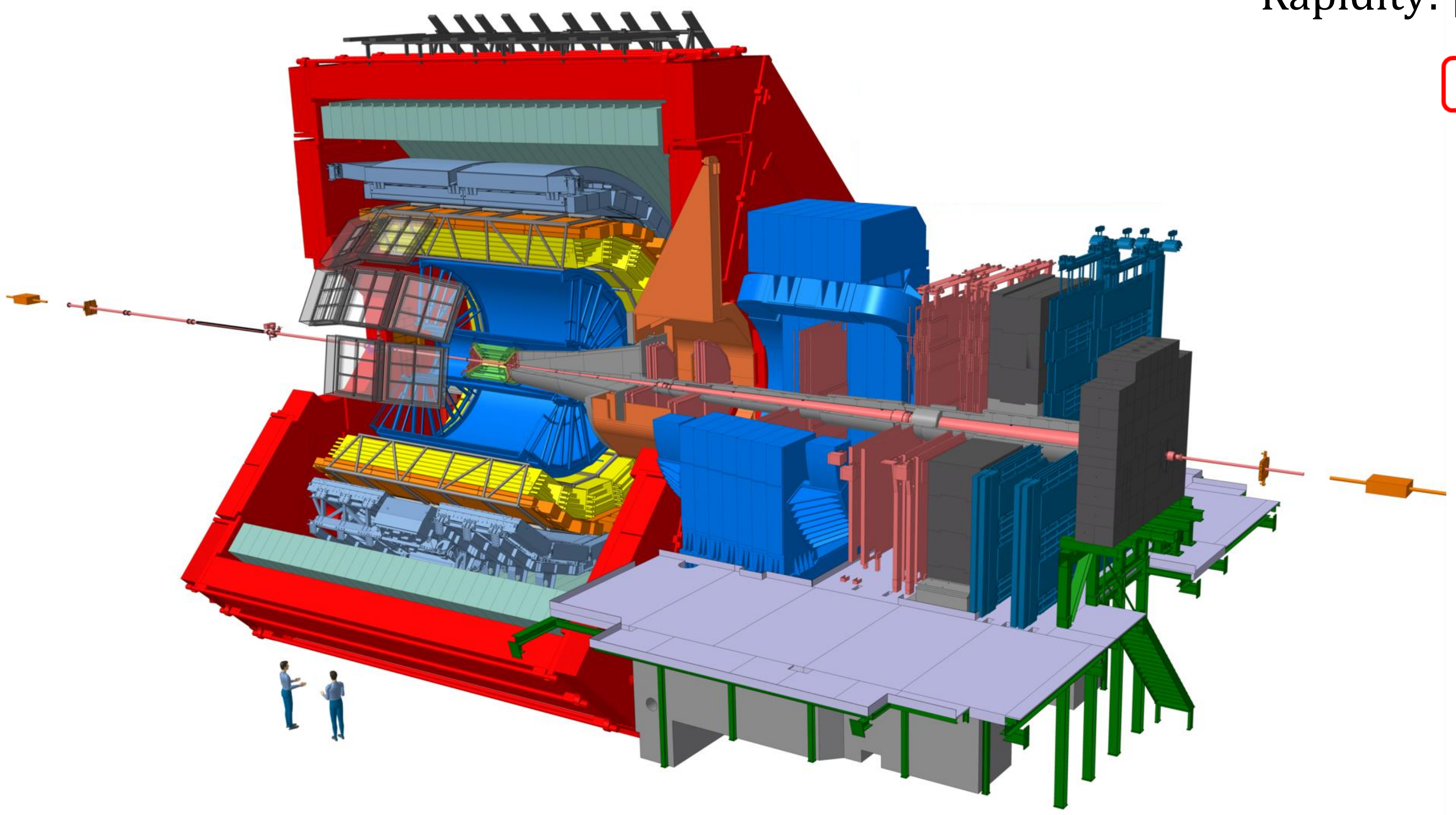
Thank you for the attention!



Backup

A Large Ion Collider Experiment

ALICE is designed for the study of heavy-ion collisions



Central Barrel

- Rapidity: $|y| < 0.9$

I. **I**nner **T**racking **S**ystem

II. **T**ime **P**rojection **C**hamber

III. **T**ime **o**f **F**light

IV. **V0** detectors

Muon Spectrometer

- Rapidity: $2.5 < y < 4$

I. Front absorber

II. Tracking system

III. Dipole magnet

IV. Trigger system

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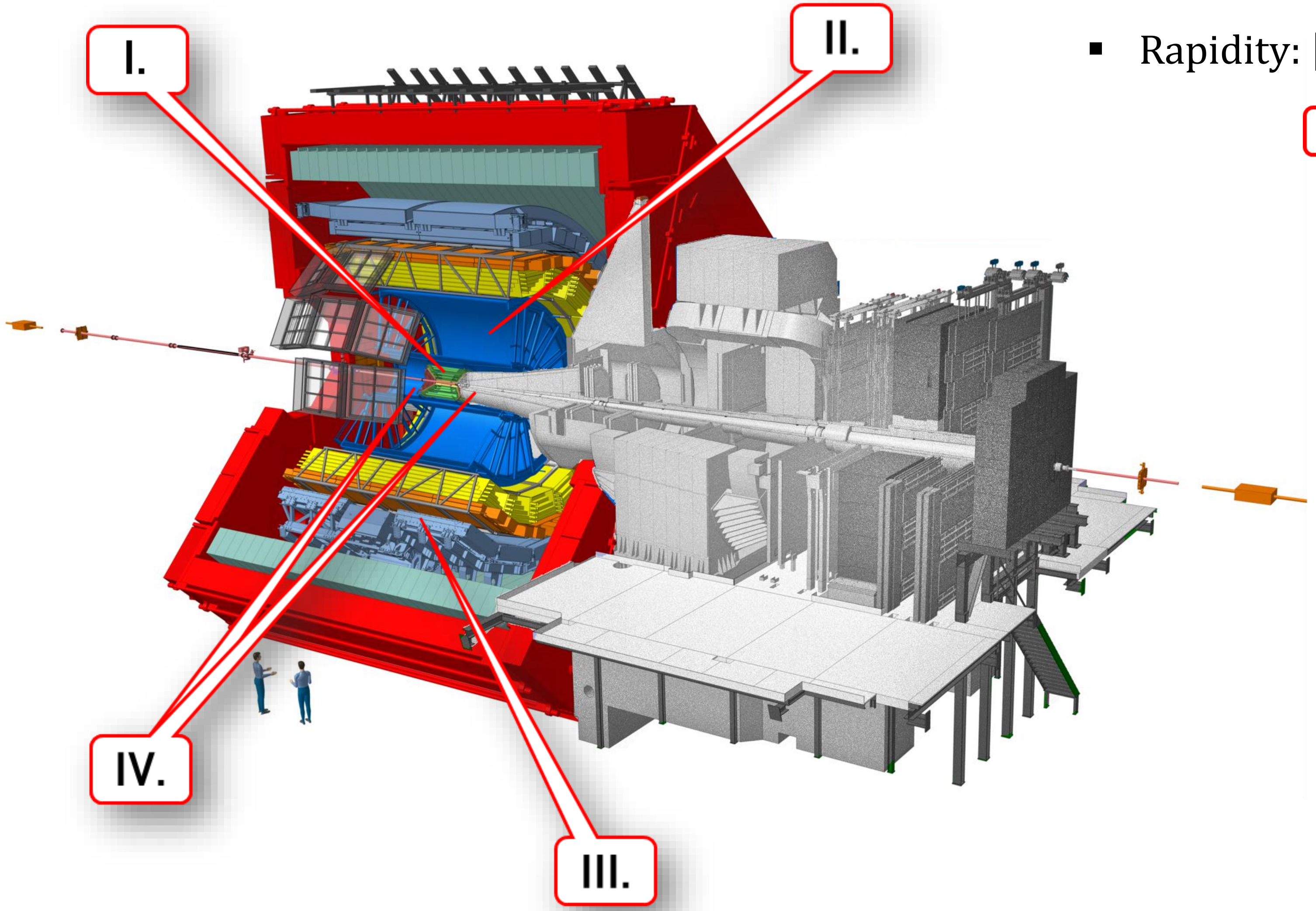

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- Rapidity: $2.5 < y < 4$

I. Front absorber

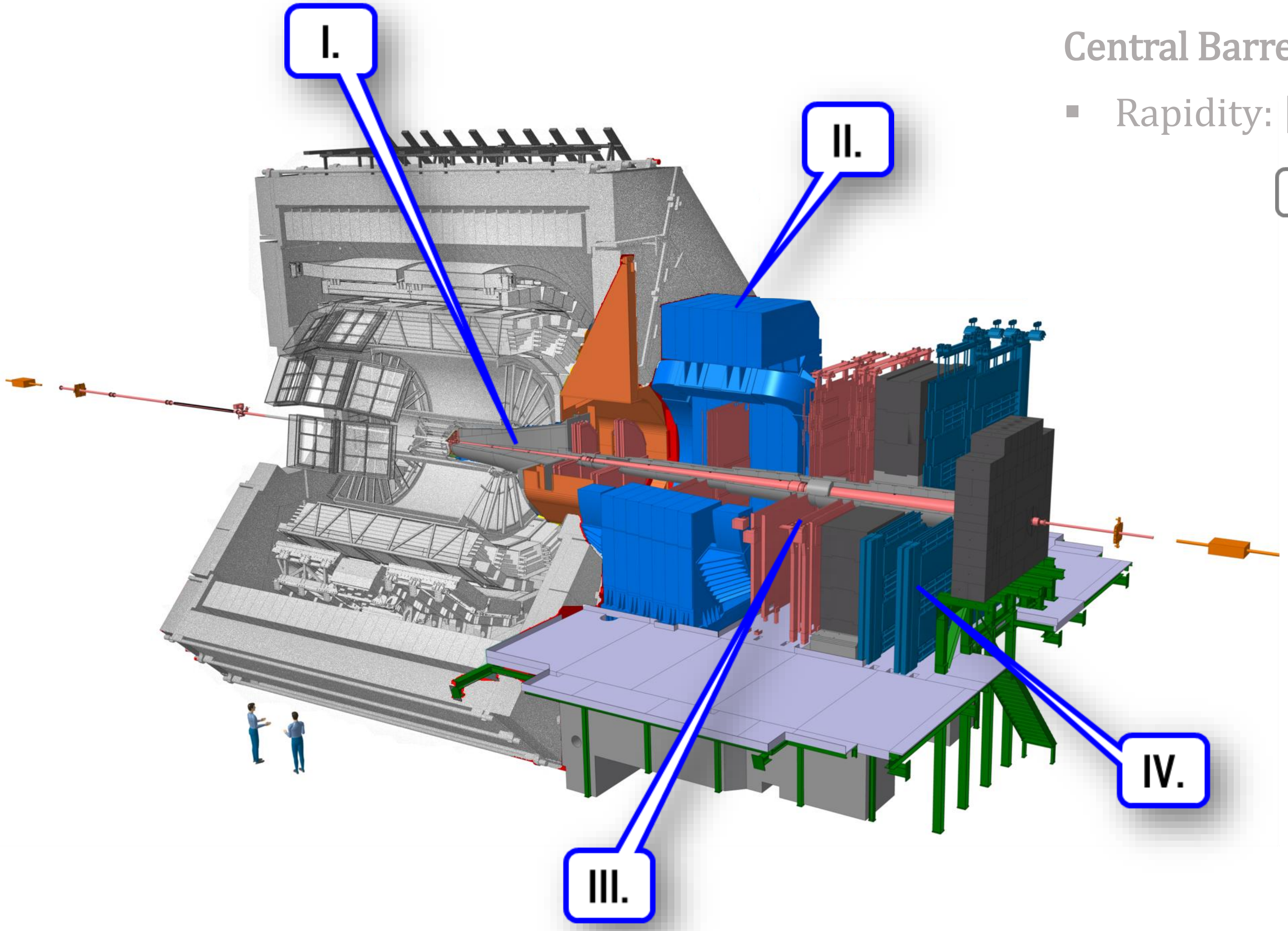
II. Tracking system

III. Dipole magnet

IV. Trigger system

A Large Ion Collider Experiment

ALICE is designed for the study of heavy-ion collisions



Central Barrel

- Rapidity: $|y| < 0.9$

I. Inner Tracking System

II. Time Projection Chamber

III. Time of Flight

IV. V0 detectors

Muon Spectrometer

- Rapidity: $2.5 < y < 4$

I. Front absorber

II. Tracking system

III. Dipole magnet

IV. Trigger system

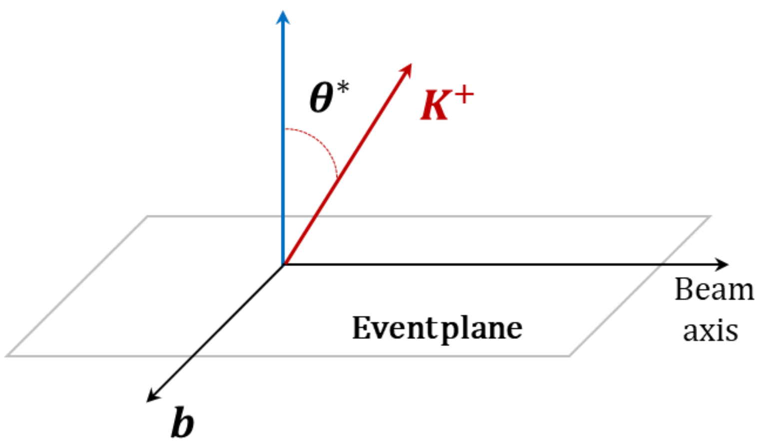
Spin alignment: observables

- Angular distribution of the decay products

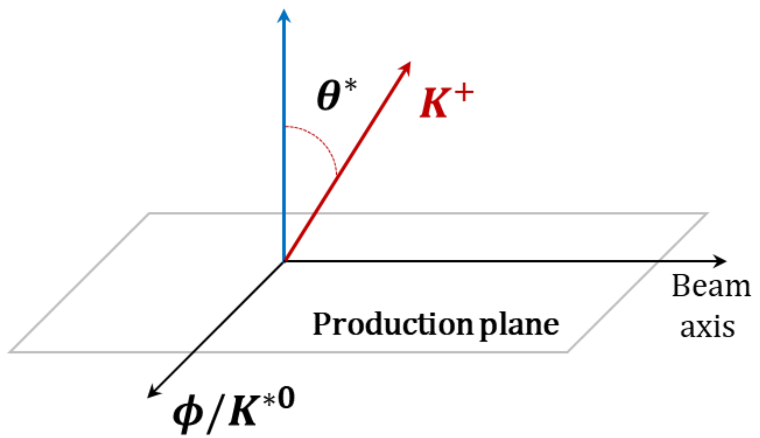
$$\frac{dN}{d\cos\theta^*} \propto (1-\boldsymbol{\rho_{00}}) + (3\boldsymbol{\rho_{00}}-1)\cos^2\theta^*$$

- $\boldsymbol{\rho_{00}}$ = spin density matrix element
- $\boldsymbol{\rho_{00}} = 1/3$ no spin alignment
- $\boldsymbol{\lambda_\theta} = (3\boldsymbol{\rho_{00}}-1)/(1-\boldsymbol{\rho_{00}})$

- Reference frames



Event plane (EP): **normal** to the plane identified by the impact parameter ($\boldsymbol{b}$) and the **beam axis**



Production plane (PP): **normal** to the plane identified by $\boldsymbol{\phi/K^{*0}}$ momentum and the **beam axis**

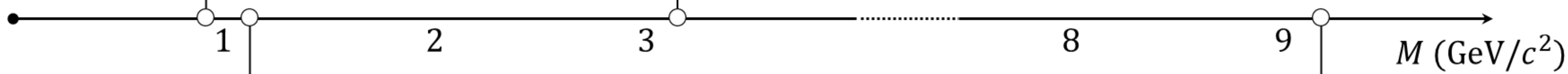
Vector mesons polarization

K^{*0}

- Mass: 896 MeV/c^2
- Spin: 1
- Quark content: $d\bar{s}$
- $K^{*0} \rightarrow K^+ + \pi^-$ (B.R. ~ 66%)

J/ψ

- Mass: 3096 MeV/c^2
- Spin: 1
- Quark content: $c\bar{c}$
- J/ψ $\rightarrow \mu^+ + \mu^-$ (B.R. ~ 6%)



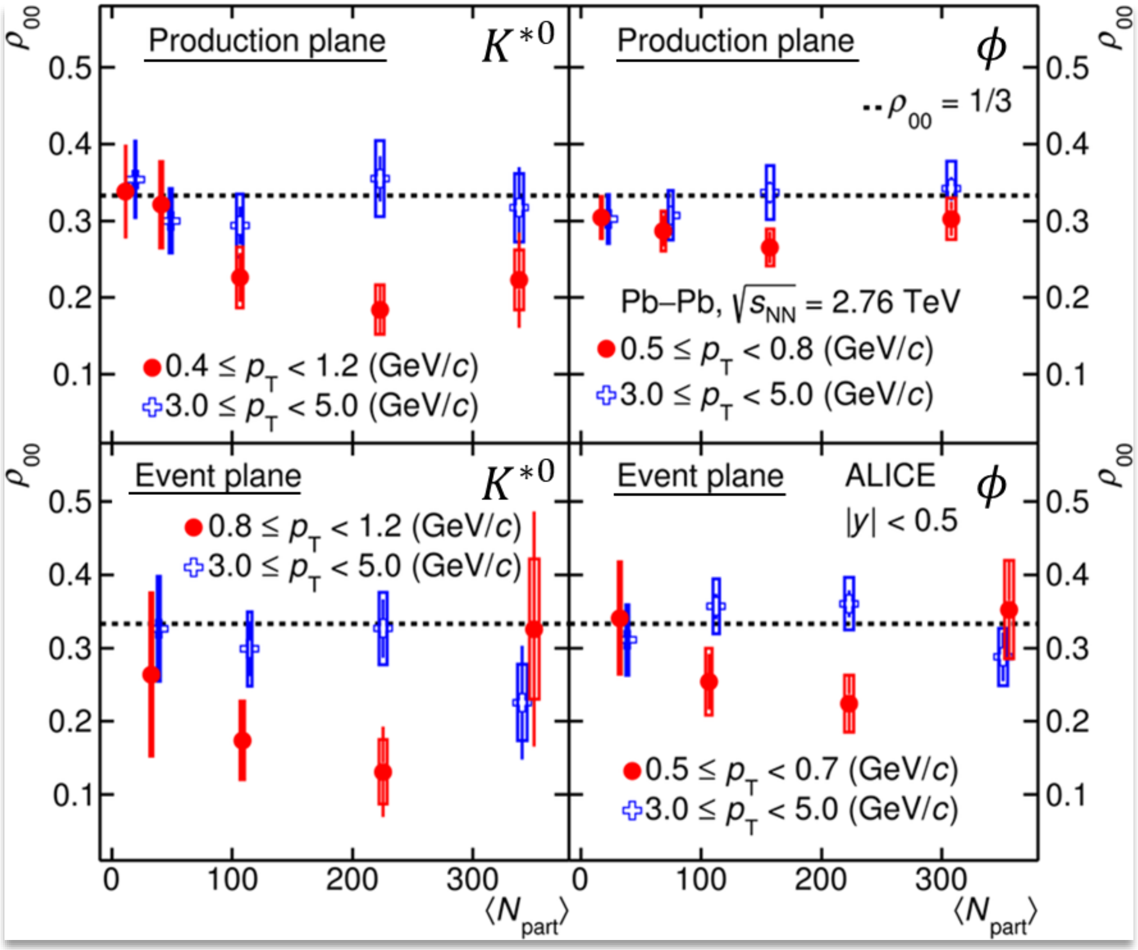
ϕ

- Mass: 1020 MeV/c^2
- Spin: 1
- Quark content: $s\bar{s}$
- $\phi \rightarrow K^+ + K^-$ (B.R. ~ 49%)

Υ(1S)

- Mass: 9399 MeV/c^2
- Spin: 1
- Quark content: $b\bar{b}$
- Υ(1S) $\rightarrow \mu^+ + \mu^-$ (B.R. ~ 2.4%)

Spin alignment: results



- K^{*0} and ϕ spin alignment — PRL 125 (2020)
  - $\rho_{00} < 1/3$ at low p_T in **semi-central collisions**
    - K^{*0}: 3.2σ (PP), 2.6σ (EP)
    - ϕ: 2.1σ (PP), 1.9σ (EP)

- Expectations from **quark recombination** scenario at the phase boundary

  PLB 629 (2005), Liang, Wang

  - ✓ $\rho_{00} < 1/3$ at low p_T & $\rho_{00} \sim 1/3$ at high p_T
  - ✓ Quark mass dependence
  - ✓ Maximum effect in non-central collisions

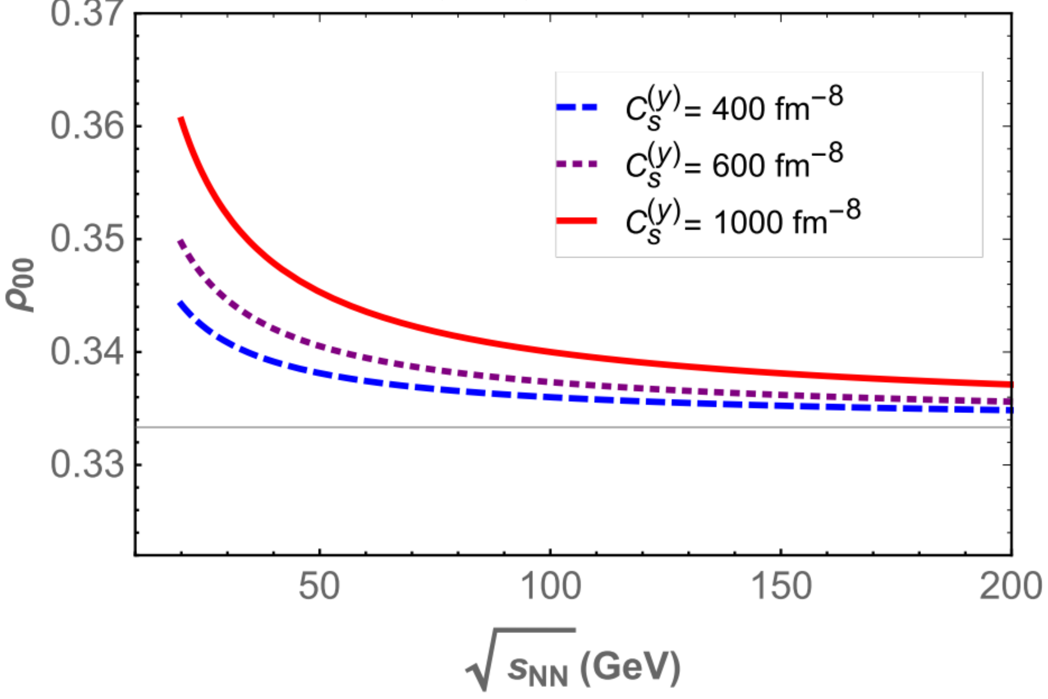
? Surprisingly large effect if compared with Λ polarization

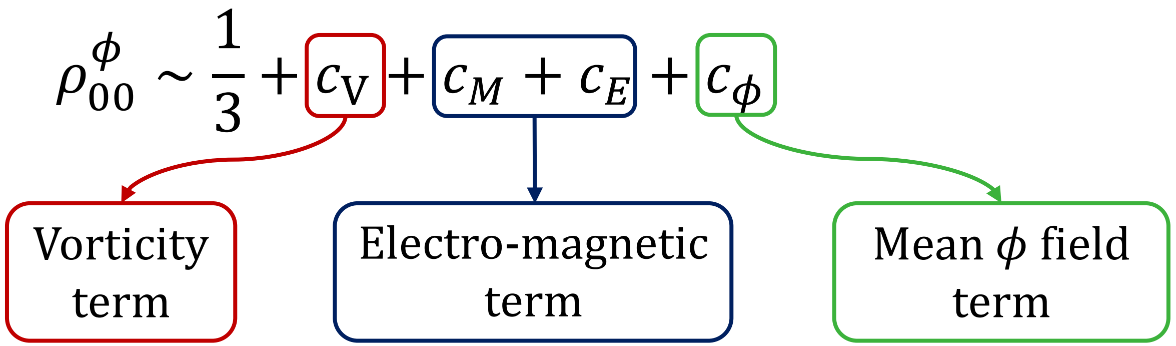
PRC 101, 044611 (2020)

ϕ meson spin alignment: theory

$\boldsymbol{\phi}(s\bar{s})$ spin alignment described at low energy considering different contributions

PRD 101 (2020) 096005 Qun Wang et al.





- Dependence of each term on the **quark mass** and on the **temperature** of the system
- The sign of each contribution impacts on ρ_{00}

! New measurements of **J/ψ polarization w.r.t. the event-plane** and paper in preparation

? Is it possible to extend this approach for J/ψ?

- c_V, c_M, c_E could be adapted
- c_ϕ sobstituted by another term(color fields ?)

arxiv:2110.15630, Muller and Yang

Light vector mesons polarization at RHIC