Quark-Gluon Plasma Characterization with Heavy Flavour Probes

Quarkonium polarization in heavy-ion collisions at the LHC

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17/11/2021 - Trento

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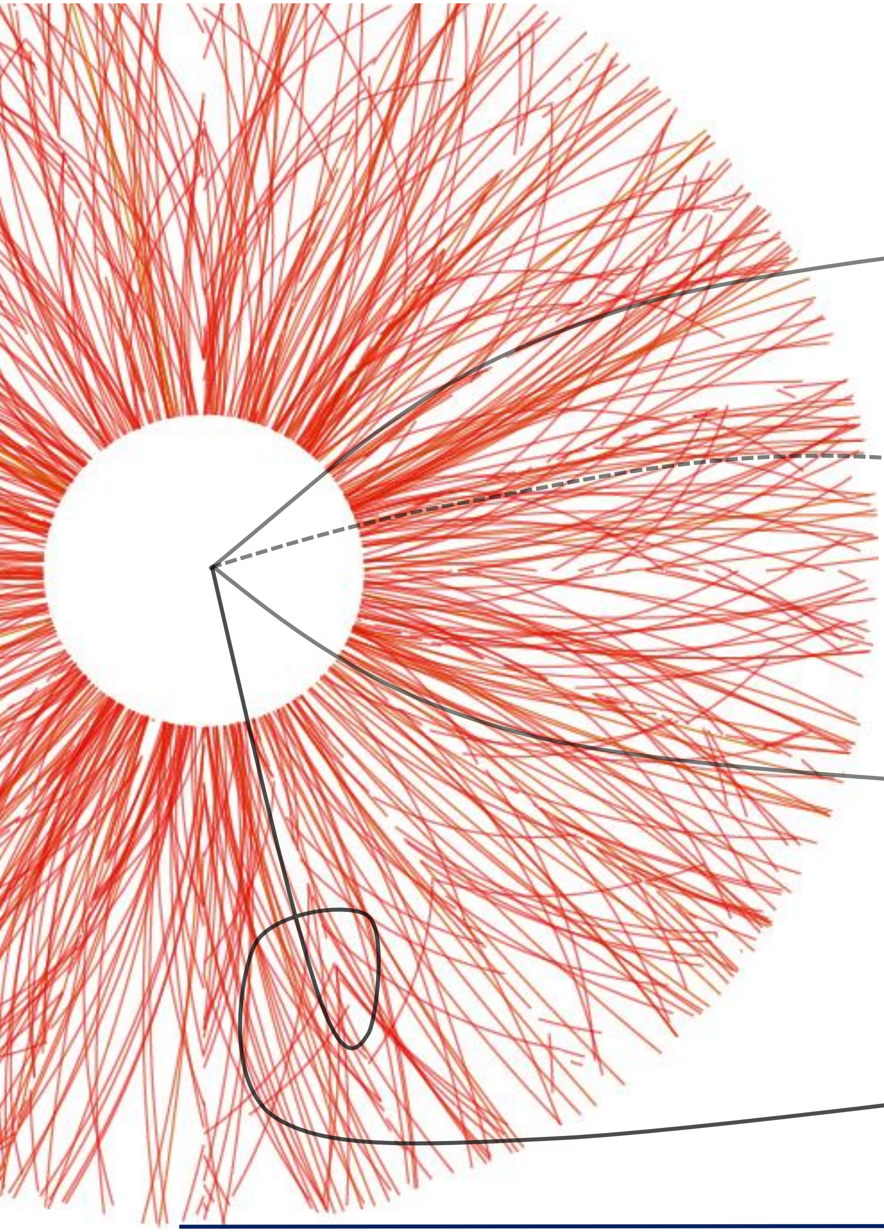
SEZIONE DI TORINO

Outline



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

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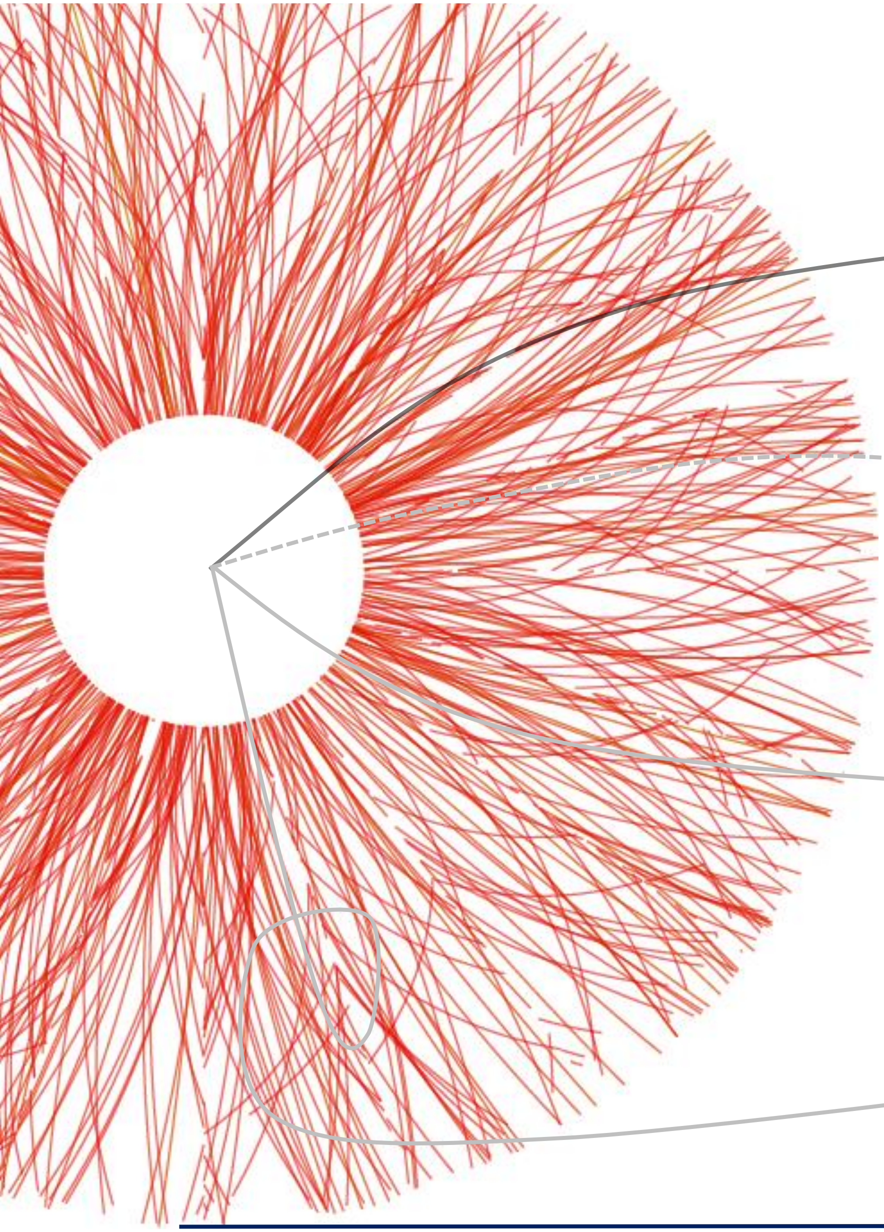

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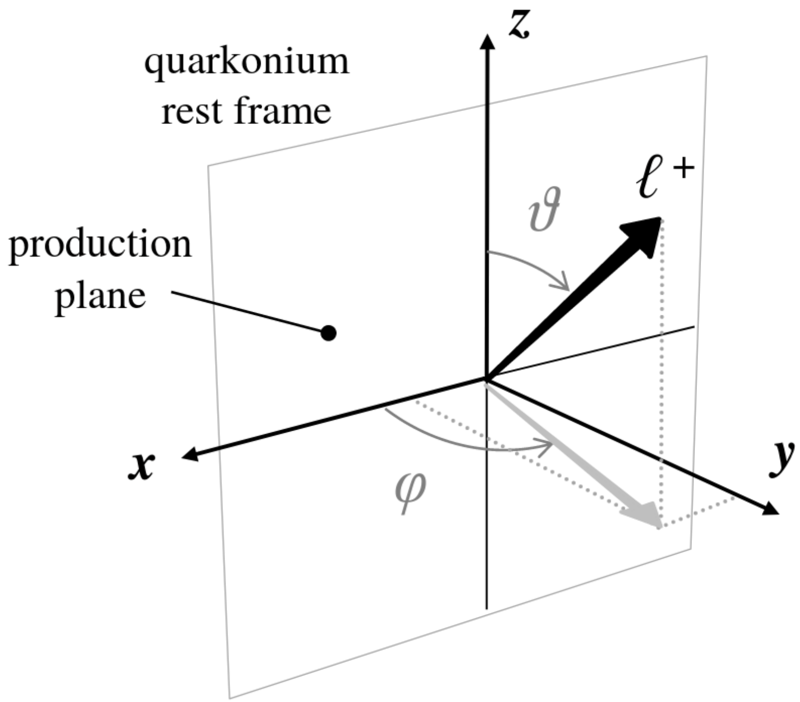
Quarkonium polarization: an introduction

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

e.g. J/ψ, Υ(1S) $[J^{PC} = 1^{--}]$

- For a **vector meson** ($\boldsymbol{v}$) the total angular momentum ($\boldsymbol{J}, \boldsymbol{J_z}$) state can be expressed as:



$$|\boldsymbol{v}: \boldsymbol{J}, \boldsymbol{J_z}\rangle = \boldsymbol{b_{+1}}|1,+1\rangle + \boldsymbol{b_0}|1,0\rangle + \boldsymbol{b_{-1}}|1,-1\rangle$$

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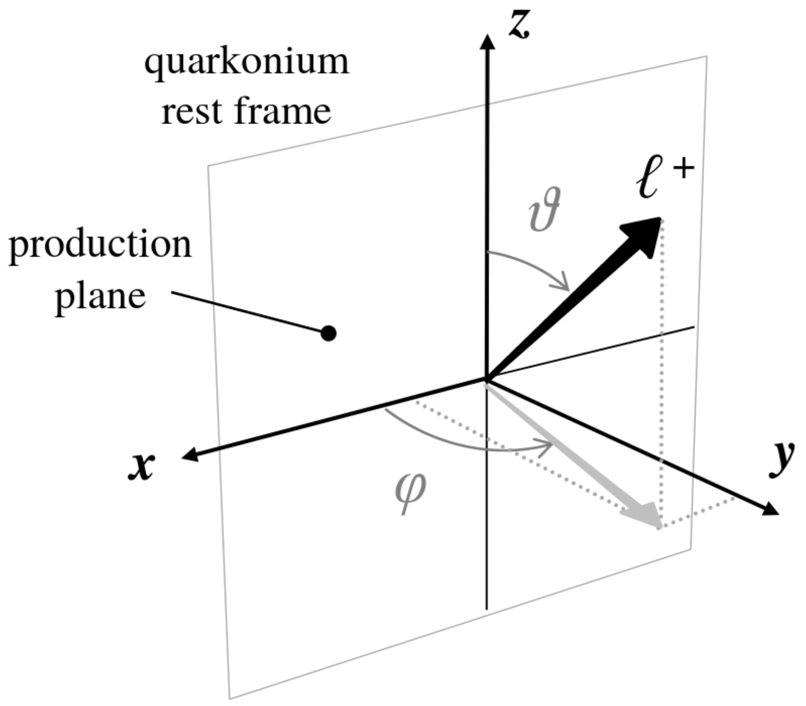

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Spin-alignment ⇔ decay products angular distribution

EPJC 69 (657-673), 2010

Dilepton decay angular distribution

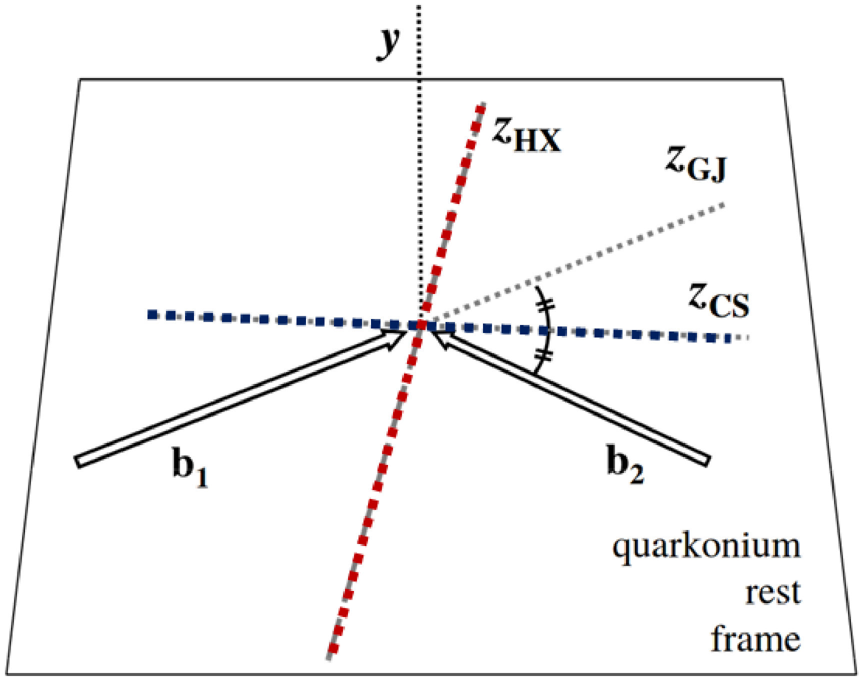
$$W(\cos\theta, \phi) \propto \frac{1}{3 + \boldsymbol{\lambda_\theta}} \cdot (1 + \boldsymbol{\lambda_\theta} \cos^2\theta + \boldsymbol{\lambda_\phi} \sin^2\theta \cos 2\phi + \boldsymbol{\lambda_{\theta\phi}} \sin 2\theta \cos\phi)$$

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

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

Quarkonium polarization: reference frames

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



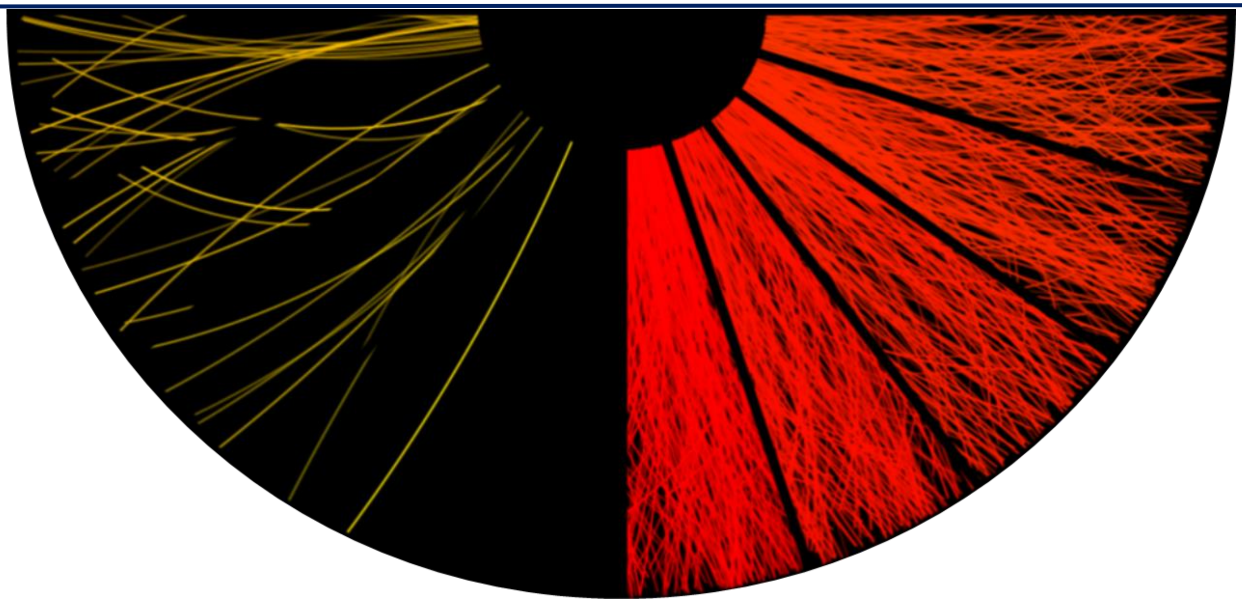
The quantization axis can be defined in different reference frames:

- **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

In principle everyone could define his own reference frame!

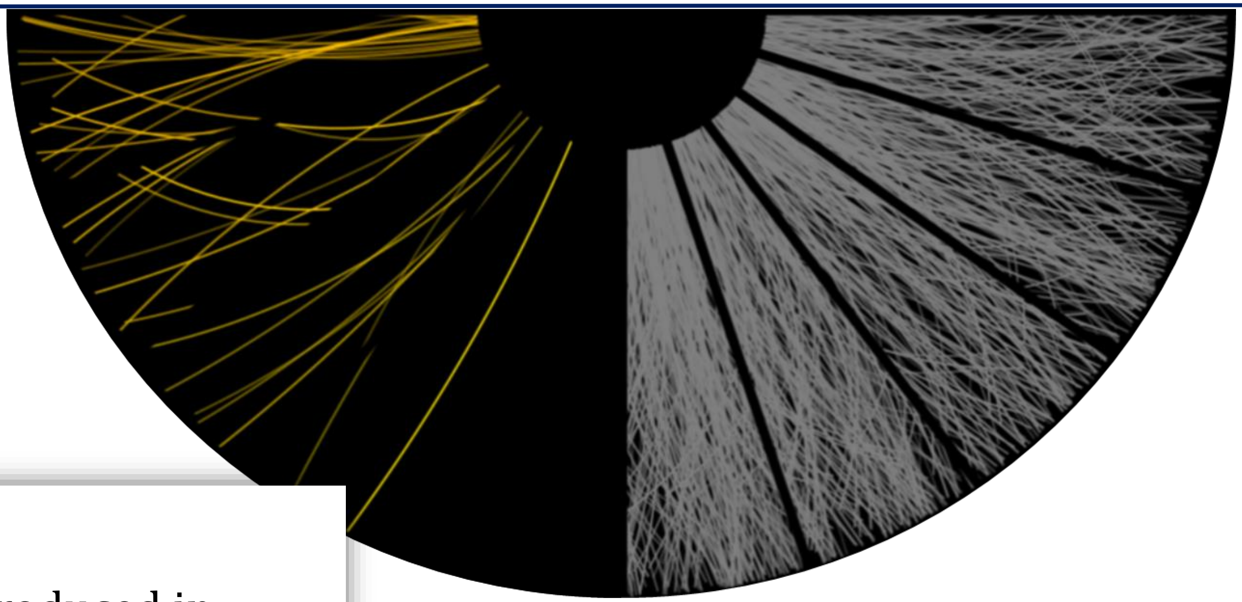
Quarkonium polarization: physics motivations

pp collisions



A–A collisions

Quarkonium polarization: physics motivations



pp collisions

A–A collisions

Constrains quarkonium **production mechanism**

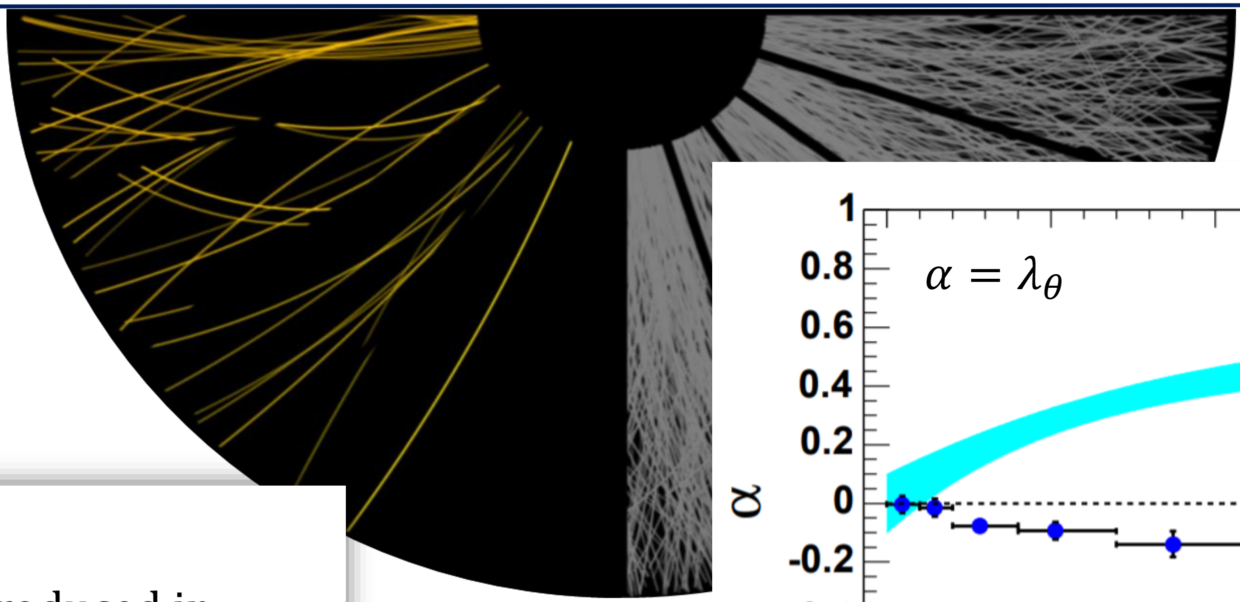
NRQCD

- The pre-resonant state produced in **color-singlet** and **color-octet** states
  - **<u>transverse polarization</u>** <u>for high-p_T J/ψ</u>

Color Singlet Model (CSM)

- Only **color-singlet** channels are retained
  - **<u>longitudinal polarization</u>**

Quarkonium polarization: physics motivations



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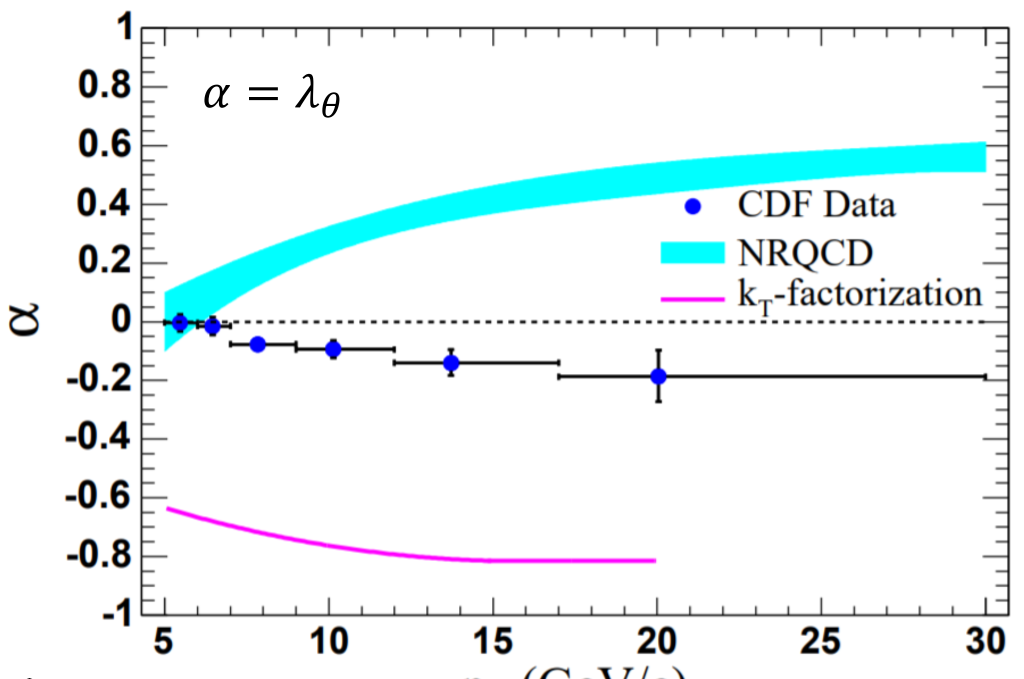
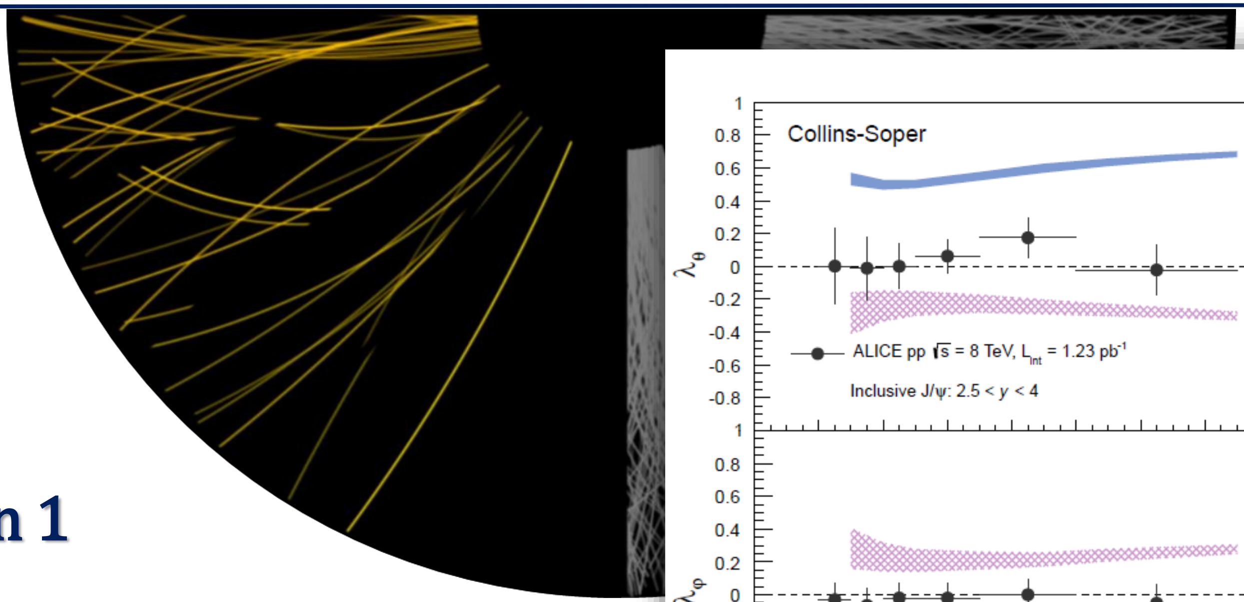


PRL 99 (2007)

Before LHC…

Quarkonium polarization: physics motivations

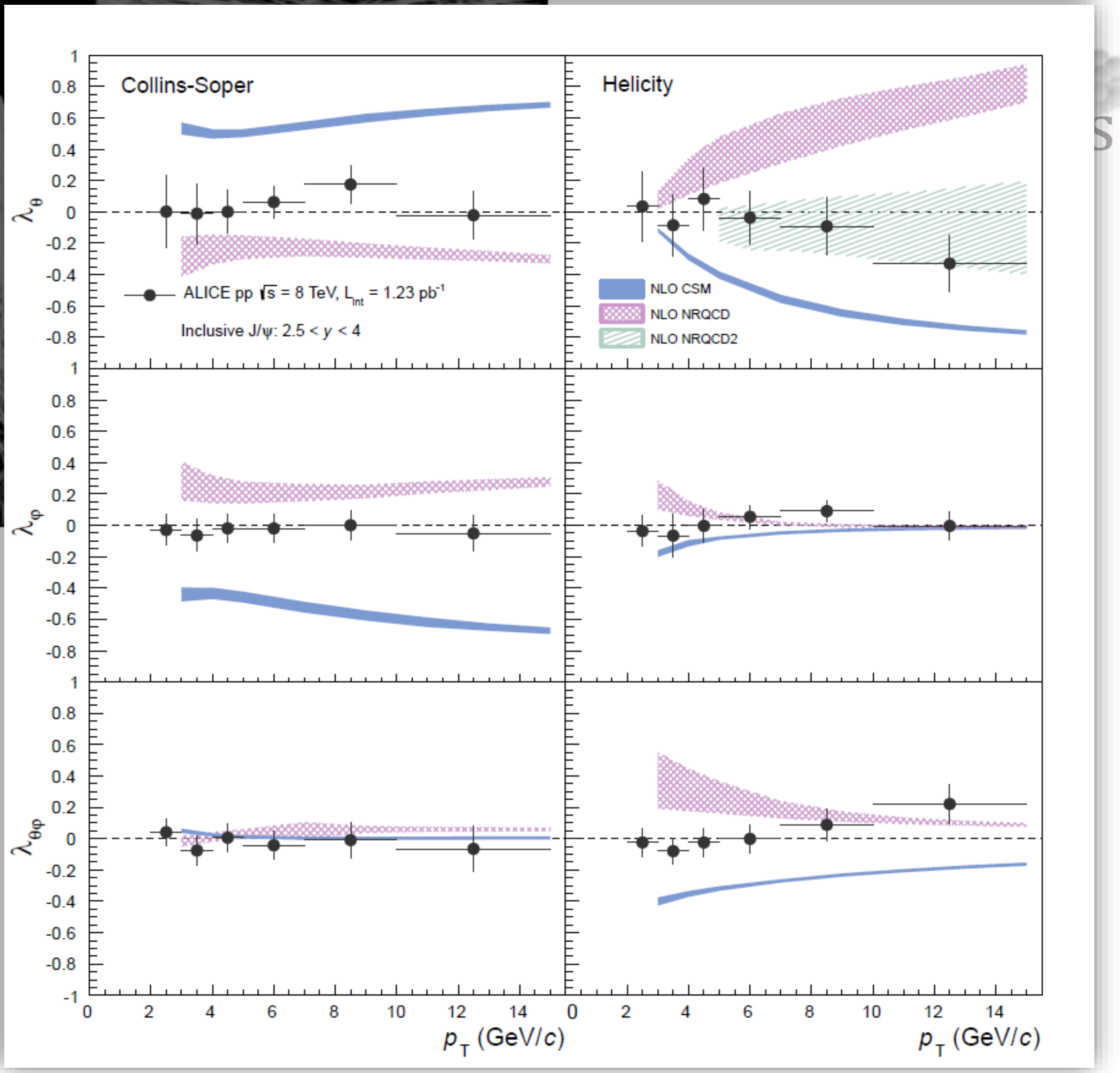


pp collisions

- Constrains quarkonium **production mechanism**

... But after LHC Run 1

- No strong polarization was observed by ALICE and LHCb at **forward rapidity** in the **low-p_T** region

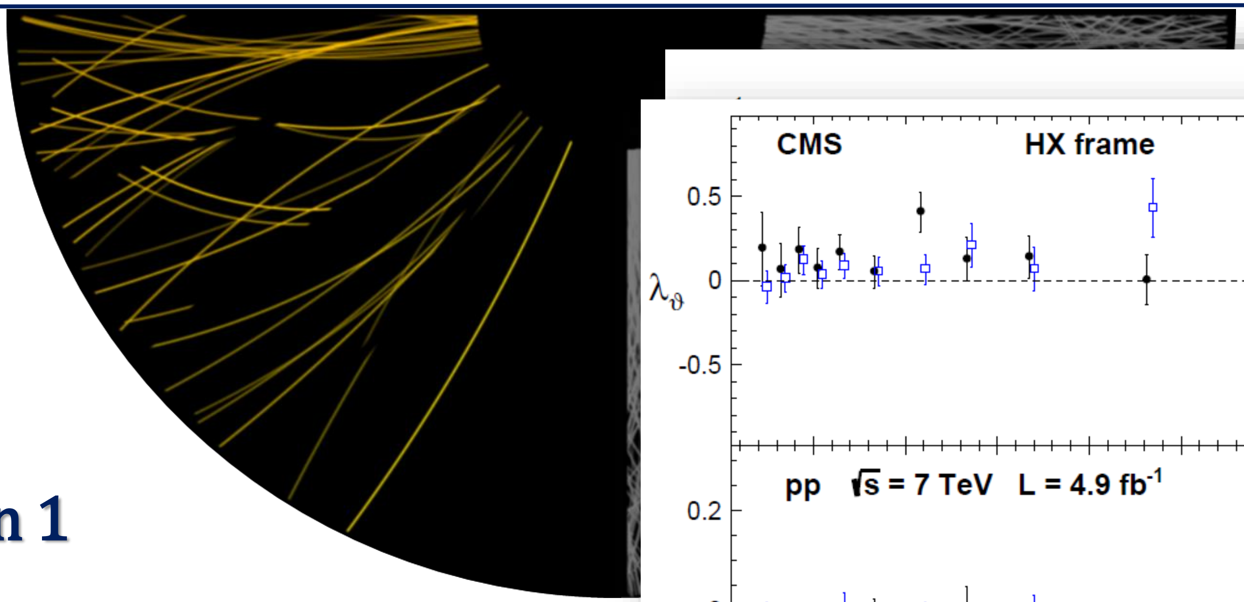


EPJC 78 (2018) 562

EPJC 73 (2013) 11

Quarkonium polarization: physics motivations

pp collisions



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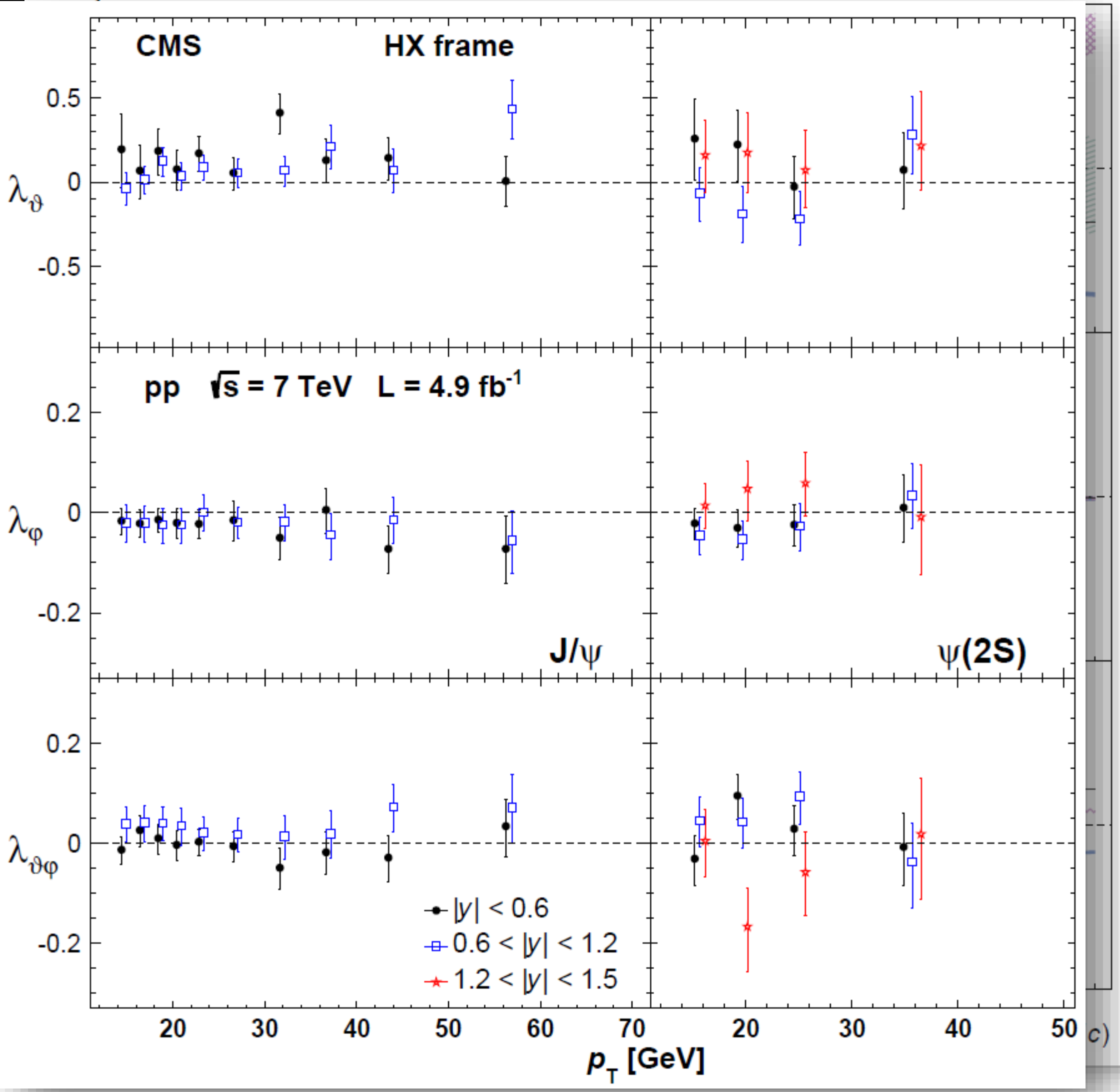


... But after LHC Run 1

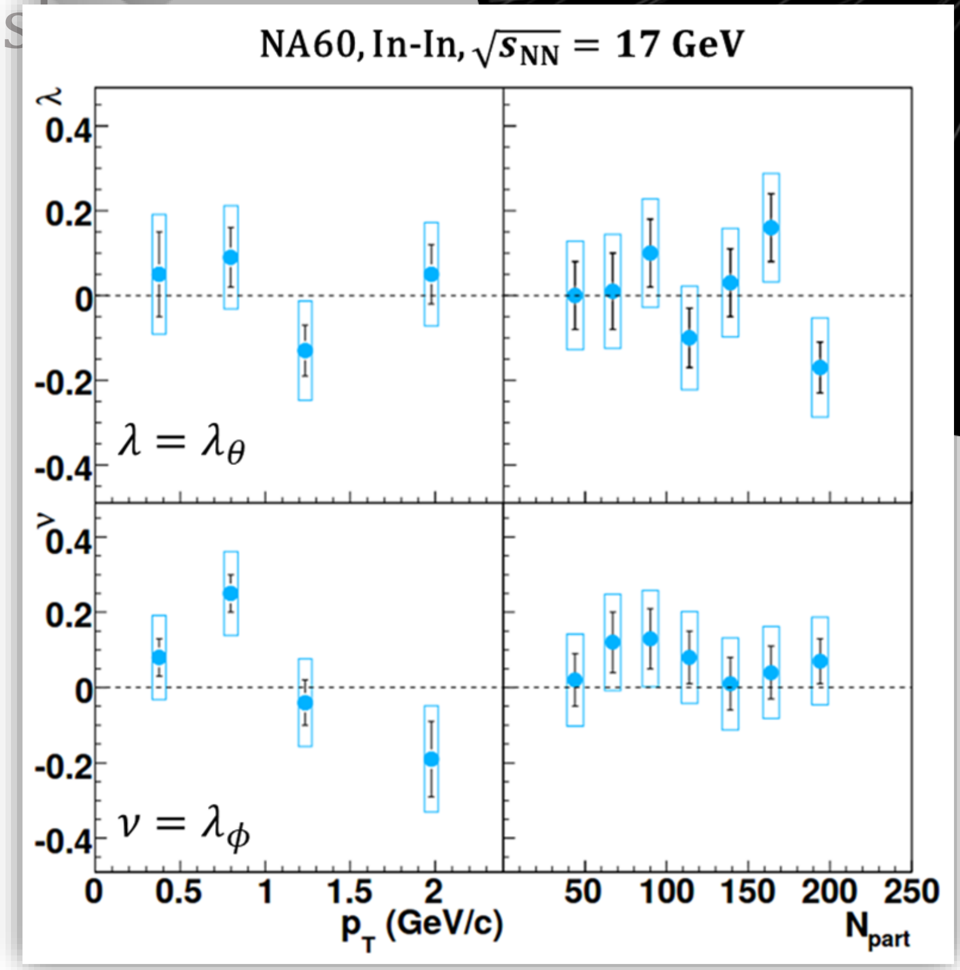
- ❑ No strong polarization was observed by ALICE and LHCb at **forward rapidity** in the **low-p_T** region
  - ❑ At **high-p_T** CMS did not observe any significant polarization

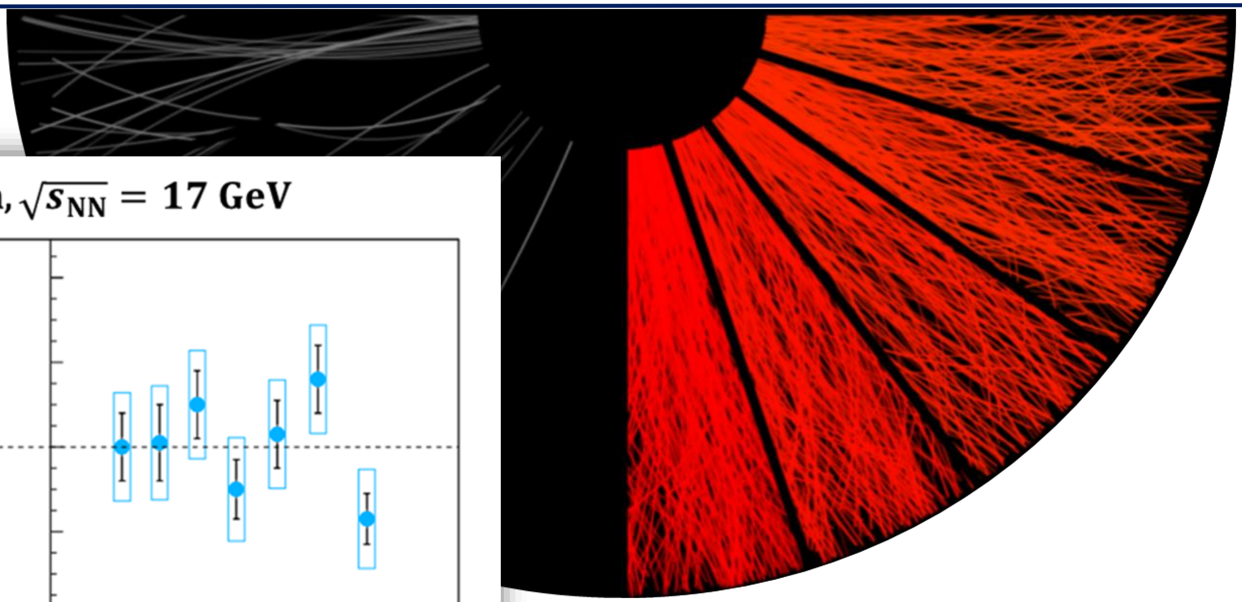
- All measurements are copatible with **zero**

PLB 727 (2013) 381

Quarkonium polarization: physics motivations

pp collisions

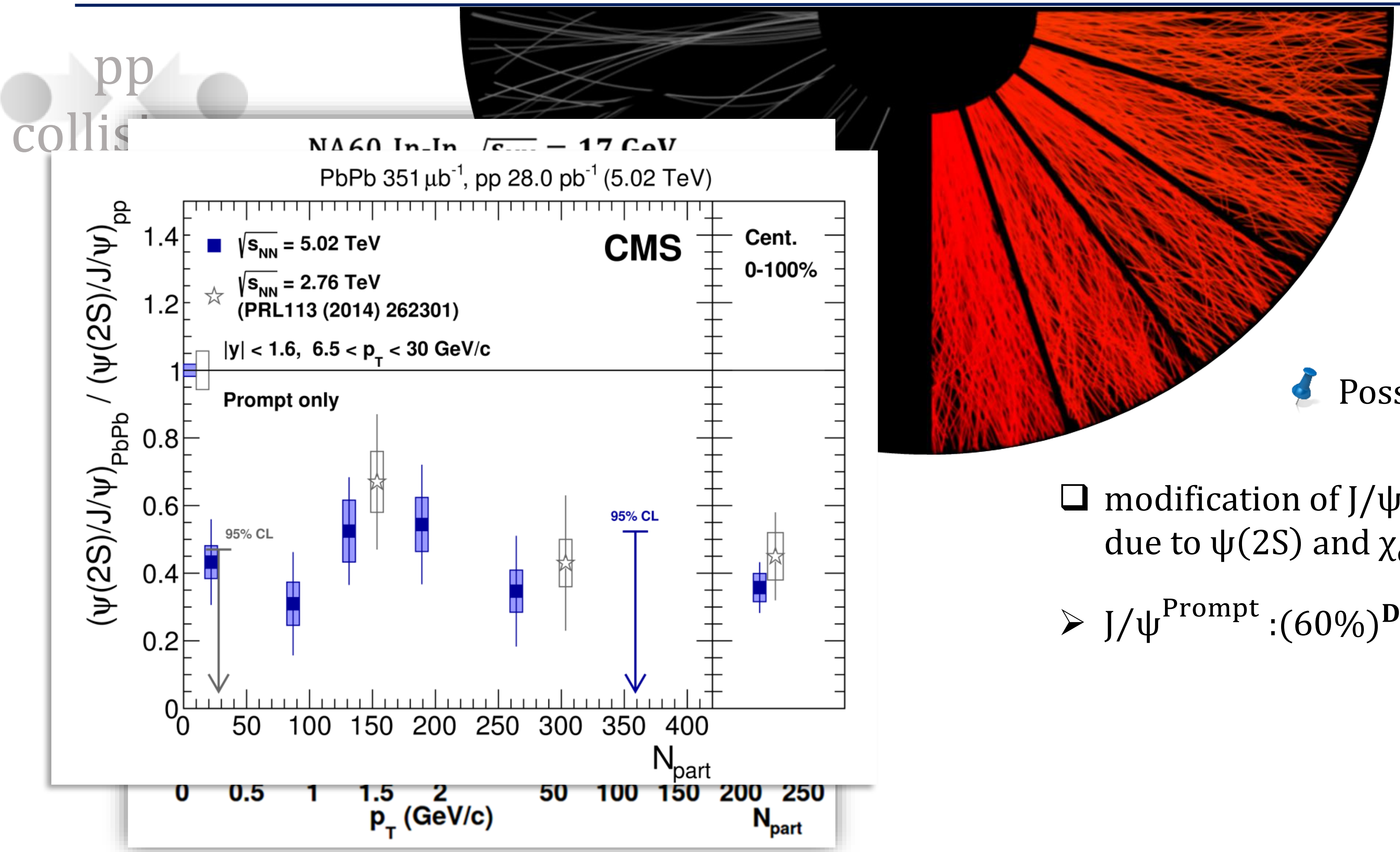




A–A collisions

- Never measured at LHC energies…

Quarkonium polarization: physics motivations



- Never measured at LHC energies…
- Possible differencies w.r.t. pp:

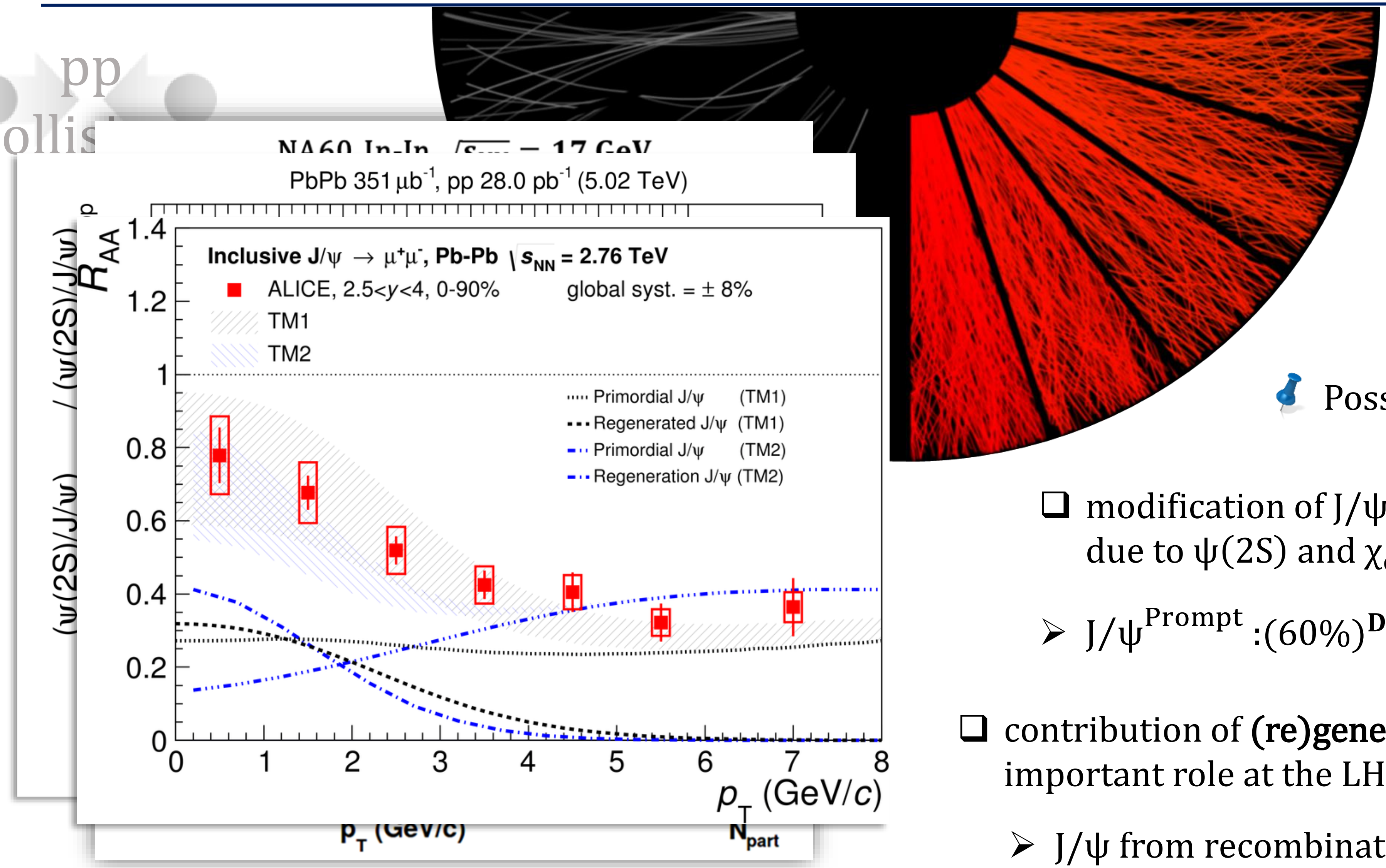
❑ modification of J/ψ **prompt feed-down fractions** due to ψ(2S) and χ_c suppression in the QGP

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

PRL 118 (2017) 162301

Quarkonium polarization: physics motivations

pp collis



A–A collisions

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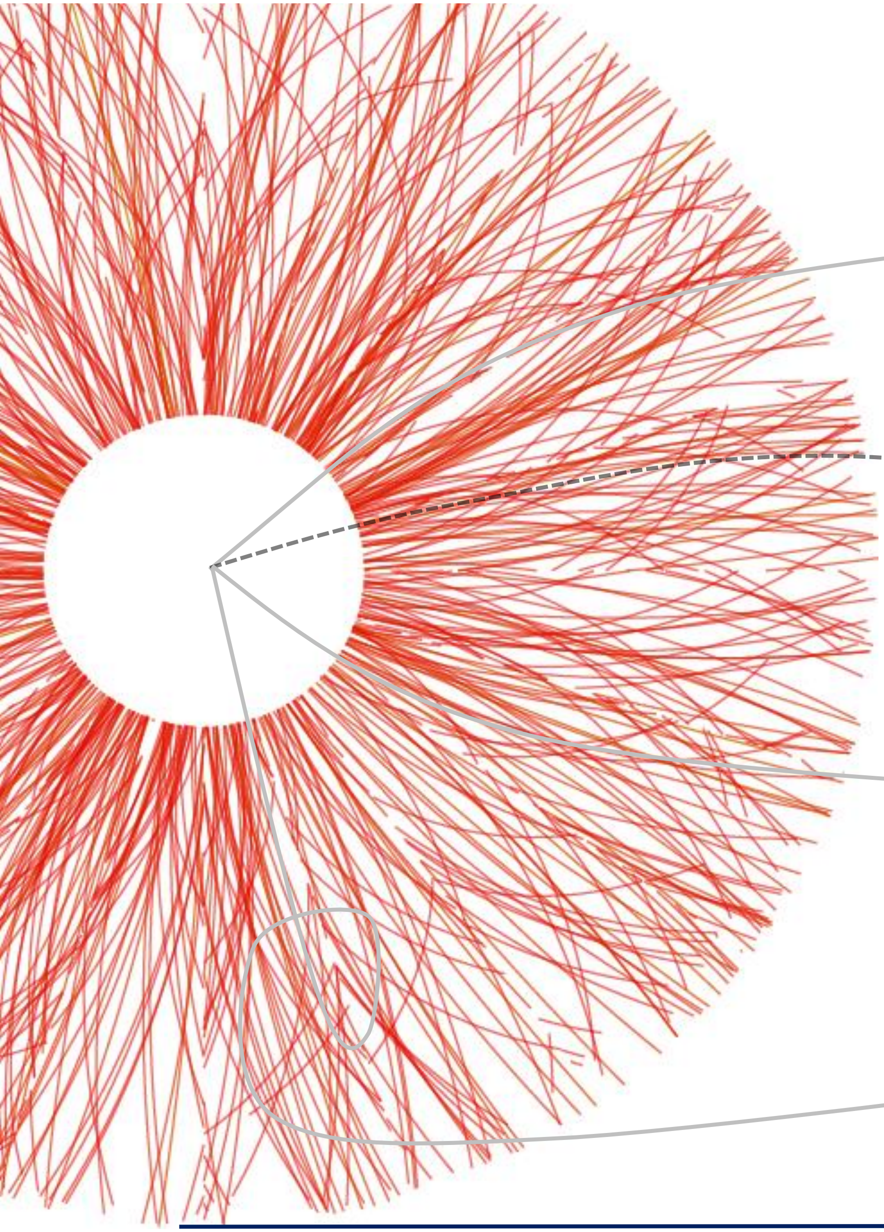
- Possible differencies w.r.t. pp:

  - ❑ modification of J/ψ **prompt feed-down fractions** due to ψ(2S) and χ_c suppression in the QGP
    - ➢ $J/\psi^{\text{Prompt}} : (60\%)^{\textbf{Direct}} + (30\%)^{\chi_c} + (10\%)^{\psi(2S)}$

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

PLB 734 (2014) 314-327

Outline



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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

Data sample and analysis procedure

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

Analysis procedure

1. **Signal extraction**

   ➢ J/ψ & ϒ(1S) raw yield obtained fitting the $\mu^{+}\mu^{-}$ invariant mass distribution vs $(\cos\theta, \phi)$

2. **Acceptance × efficiency correction**

   ➢ J/ψ & ϒ(1S) raw yield corrected with the $A \times \varepsilon$ obtained with a Monte-Carlo simulation

3. **Polarization parameters extraction**

   ➢ fit to the J/ψ & ϒ(1S) $A \times \varepsilon$-corrected distribution with $W(\cos\theta, \phi)$

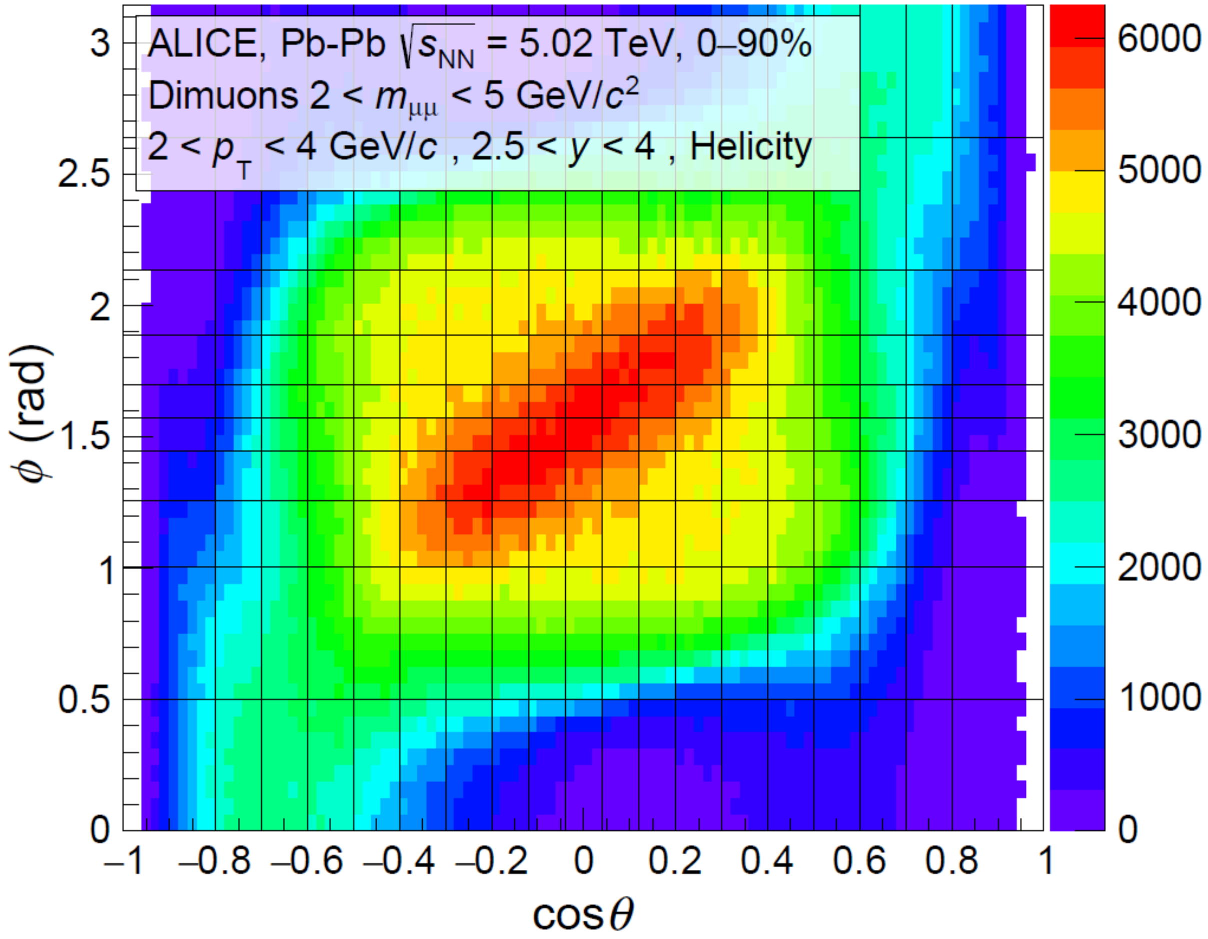
Signal extraction

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%
  - $p_T^{J/\psi}$: 2–4, 4–6 and 6–10 GeV/c



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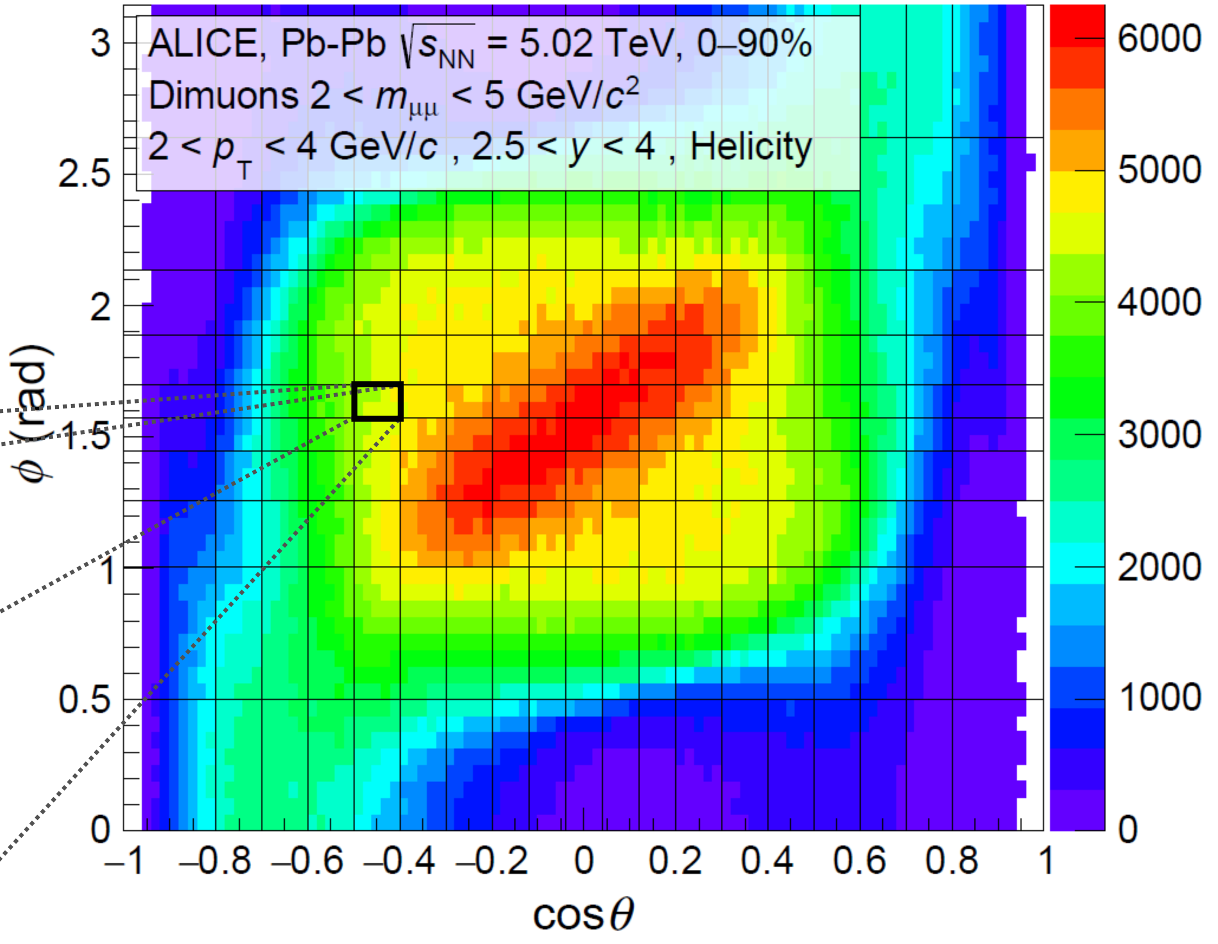
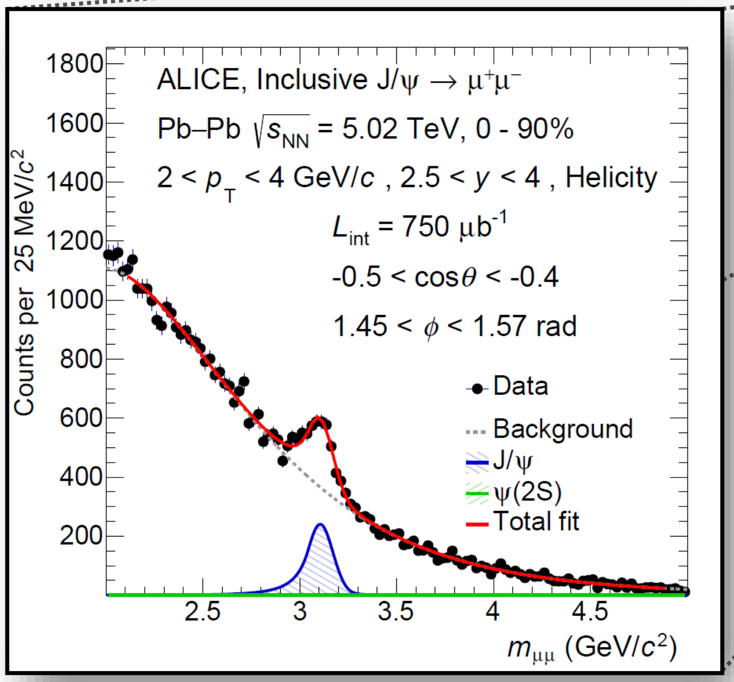




- **Signal**: pseudo-gaussian functions (**CB2, NA60**)
- **Background**: phenomenological functions

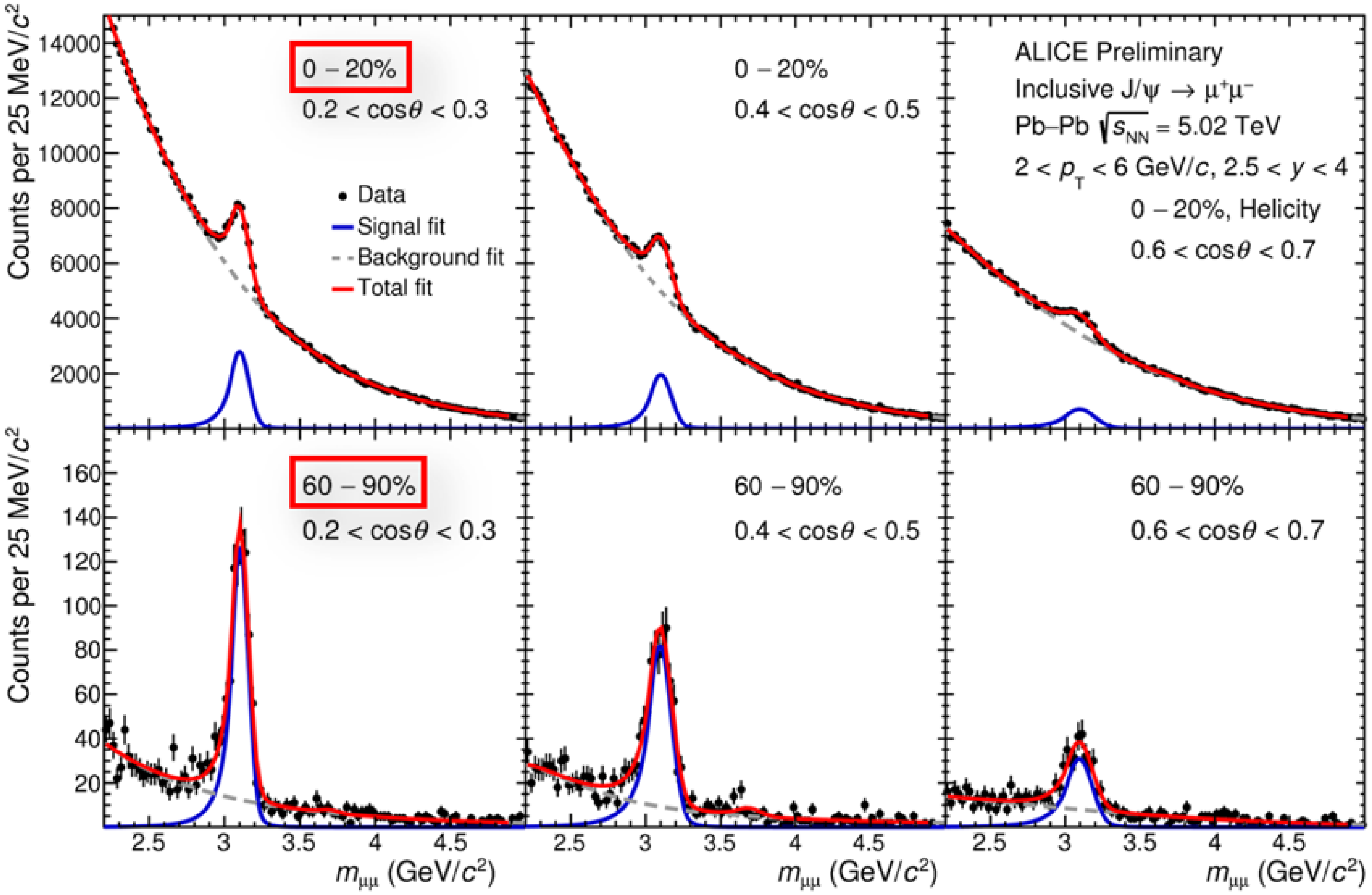
Signal extraction

J/ψ polarization vs centrality

1D-approach

- Statistics rapidly decreases with centrality
  - yield extracted vs cosθ and ϕ separately

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



Low p_{T} ragion chosen for:

- good compromise between **statistics** and **S/B ratio**
- interesting to study **(re)generation**

Signal extraction

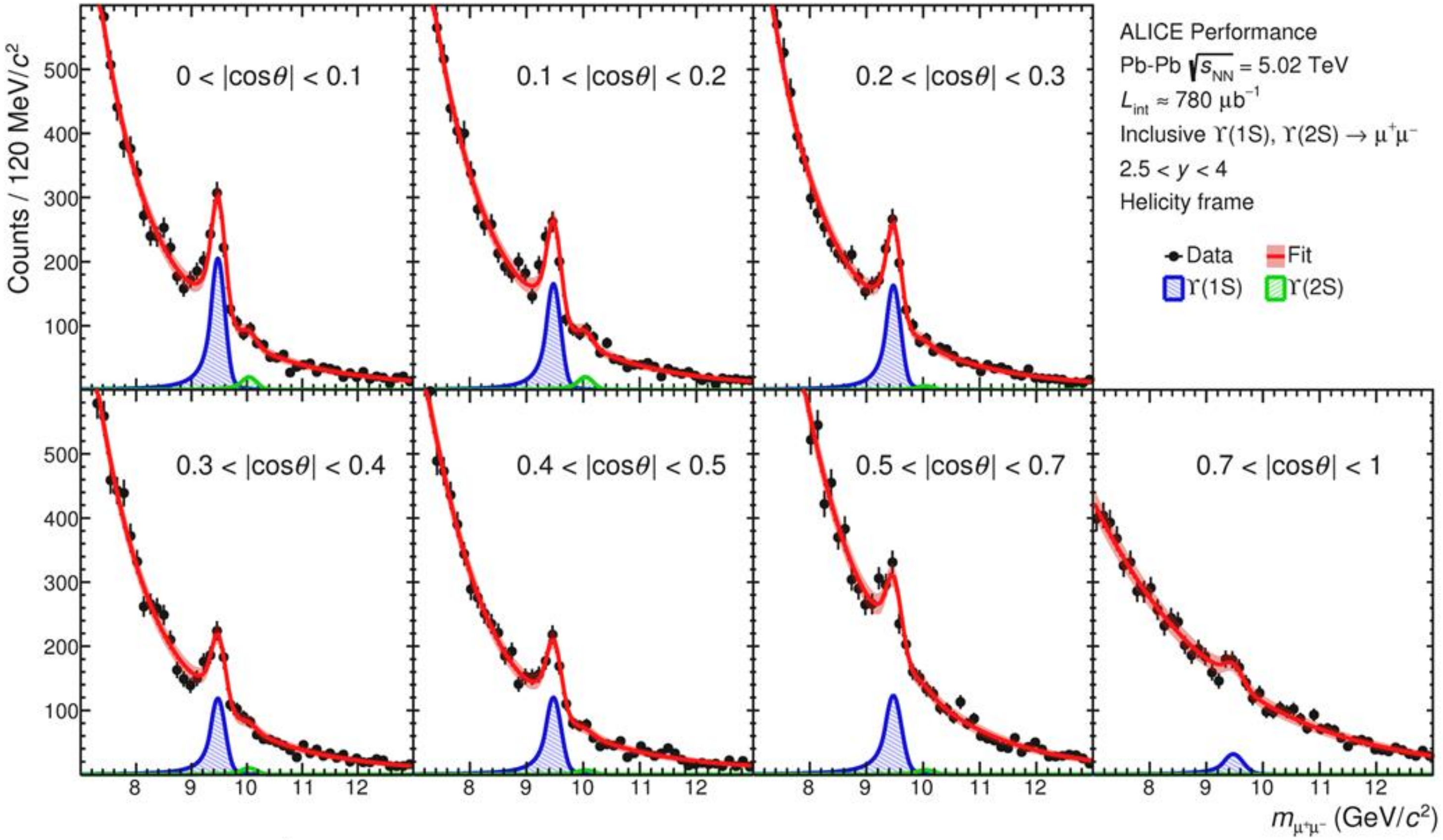
$\Upsilon(1S)$ polarization

1D-approach

- Limited statistics for $\Upsilon(1S)$ in Run2
  - yield extracted vs $\cos\theta$ and ϕ separately

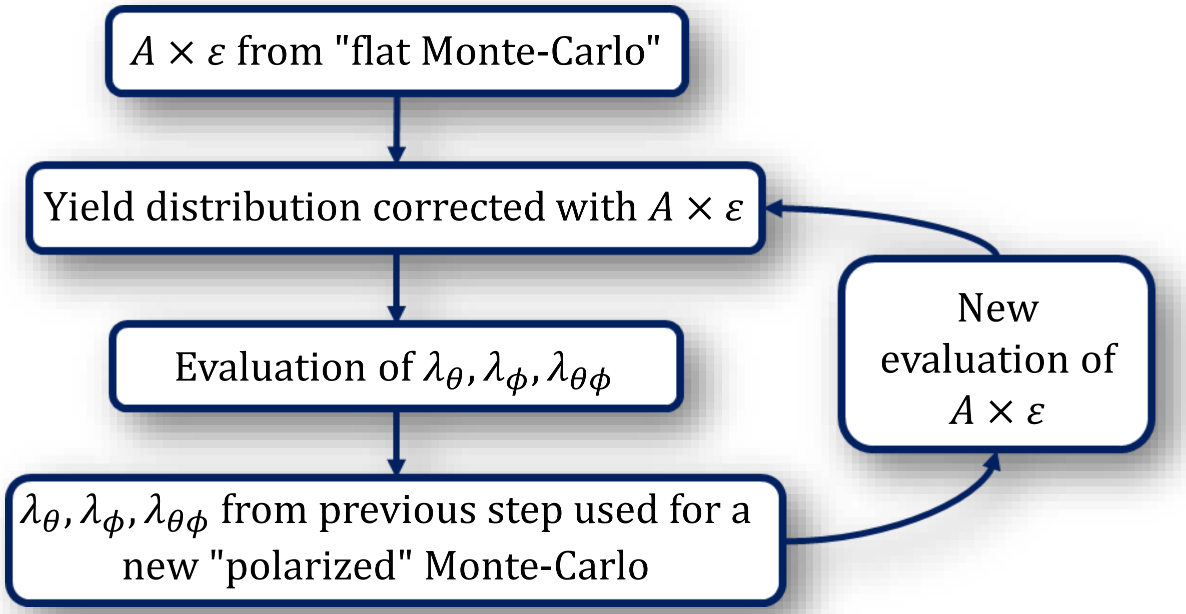
- $\Upsilon(1S)$ studied in:
  - Centrality: 0–90%
  - $p_T^{\Upsilon(1S)} < 15$ GeV/c

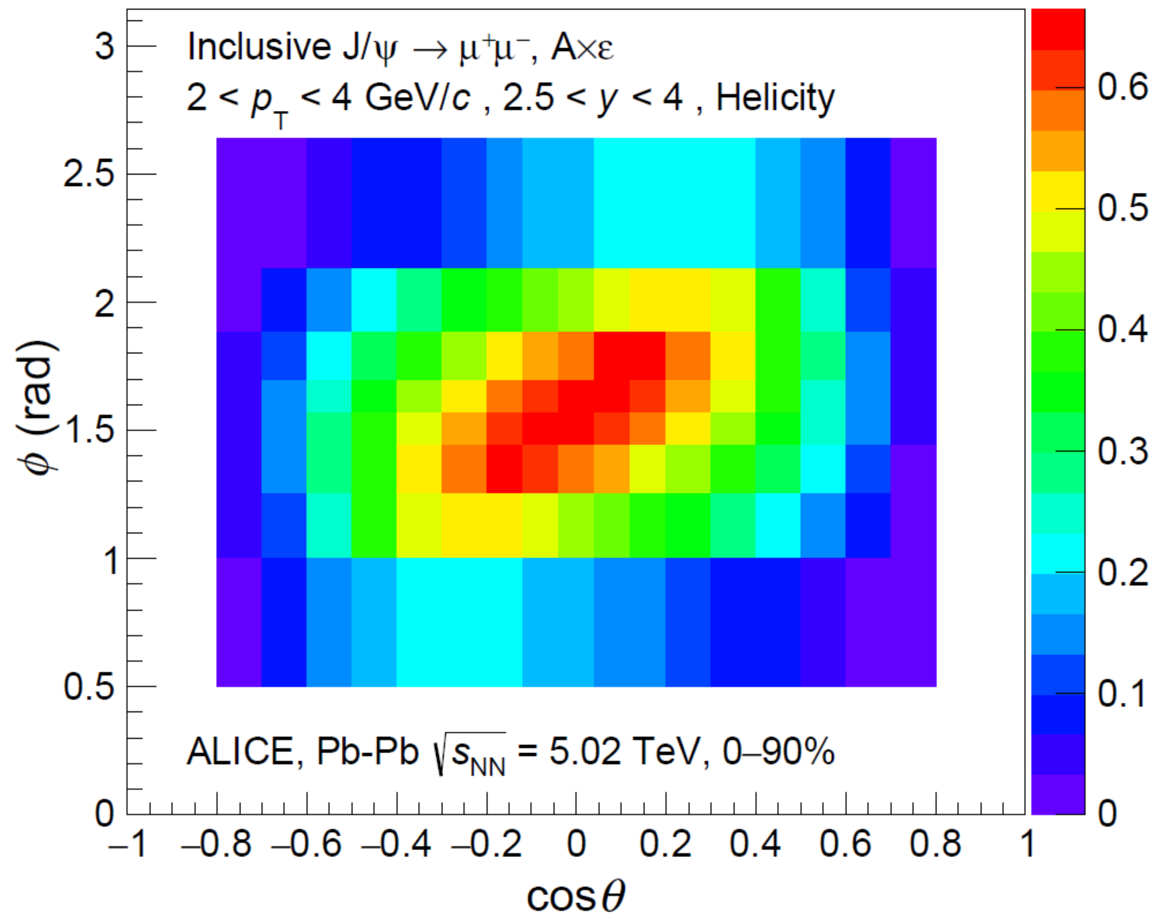
$p_T < 15$ GeV/$c \Rightarrow \sim 3000\ \Upsilon(1S)$



Acceptance × Efficiency

- J/ψ and ϒ(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





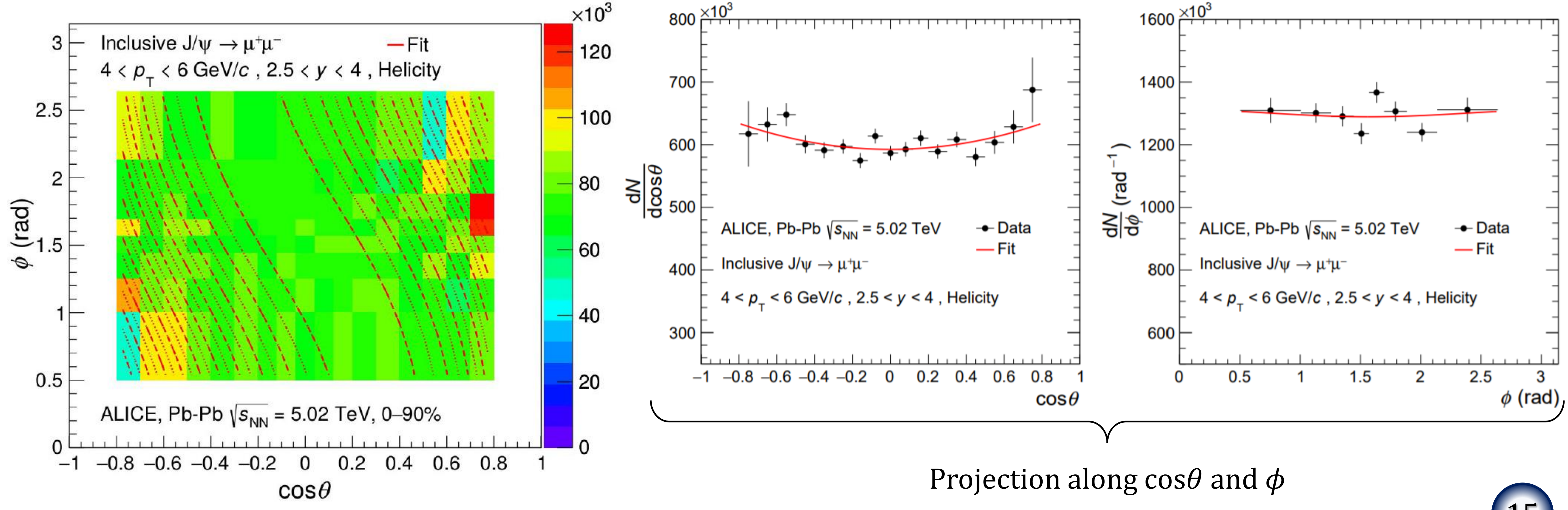
Polarization parameters extraction

J/ψ polarization vs p_T

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

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

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

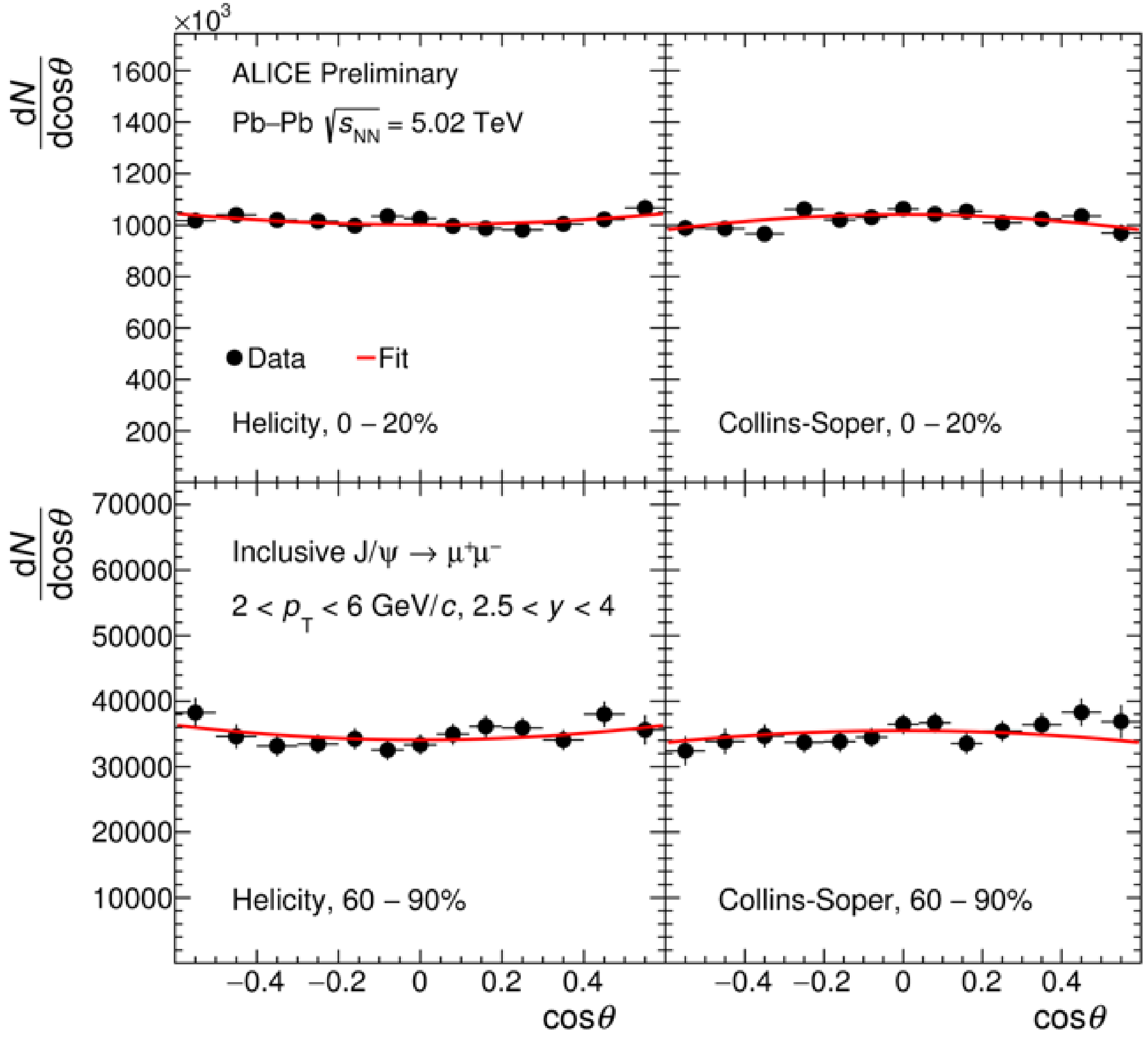
$$\int W(\cos\theta, \phi) d\phi \propto \frac{1}{3 + \boldsymbol{\lambda_\theta}} \cdot (1 + \boldsymbol{\lambda_\theta} \cos^2\theta)$$

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

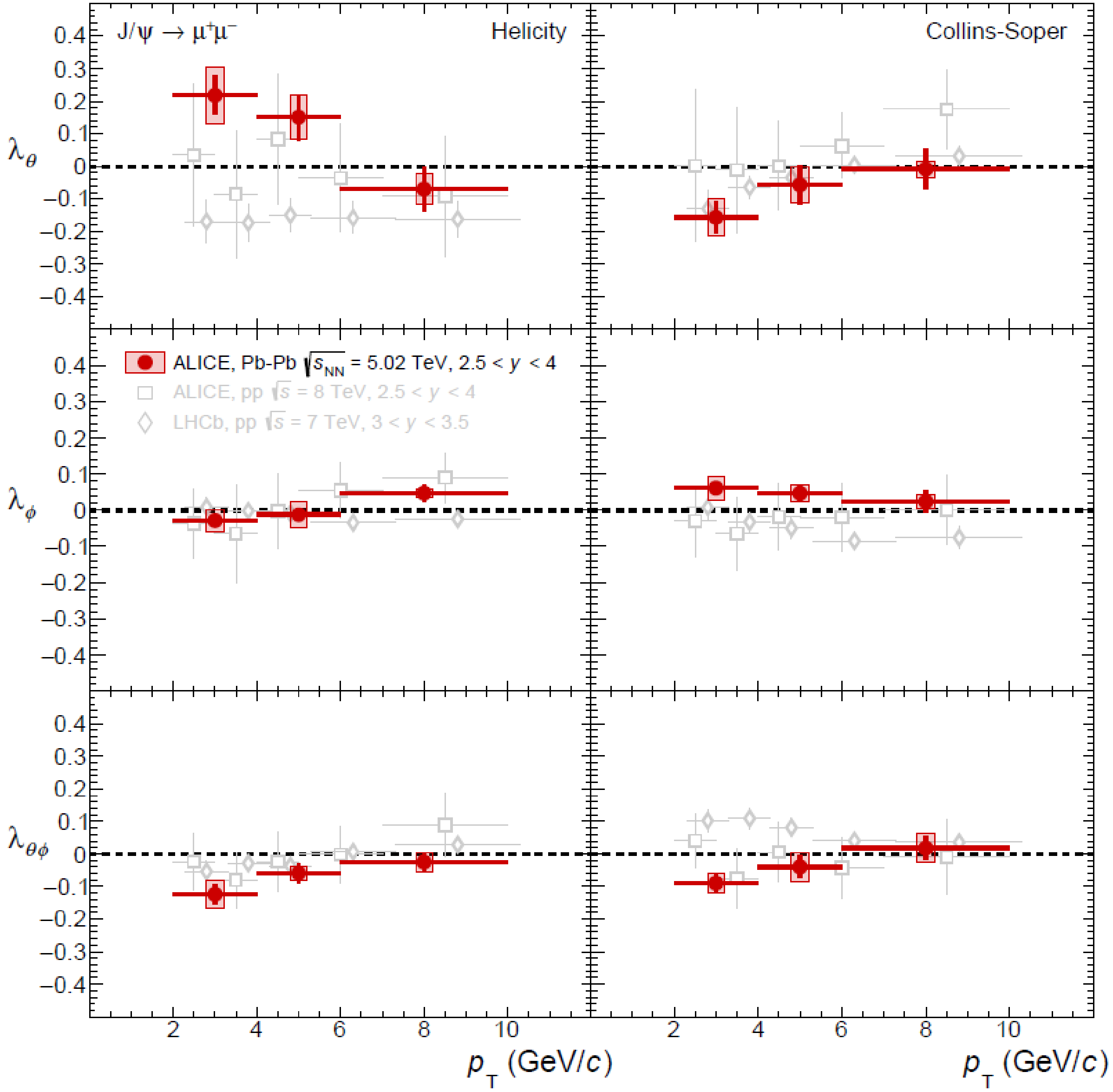
- $\lambda_{\theta\phi}$ can be extracted defining the variable $\tilde{\phi}$

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

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



Results

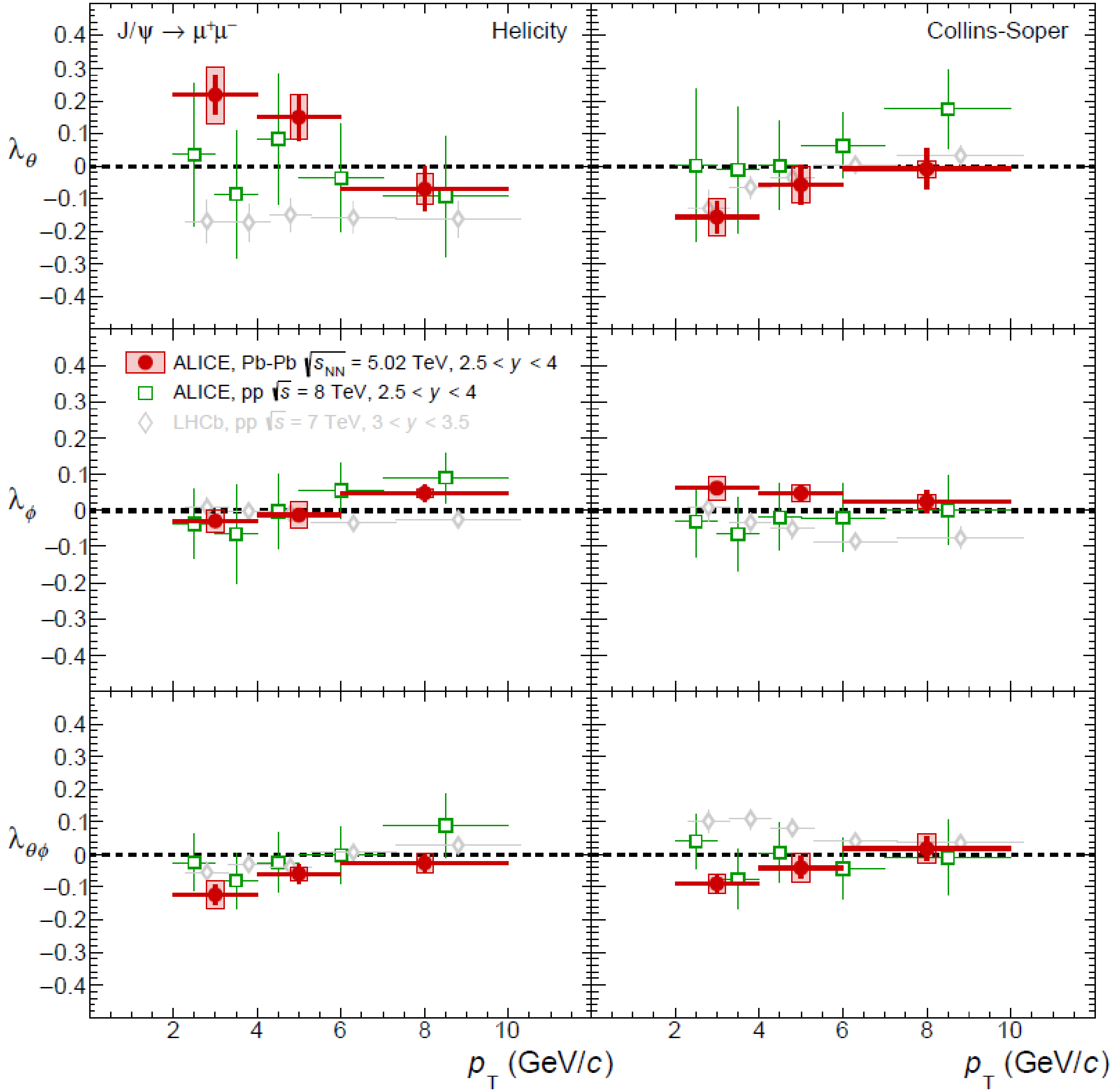


J/ψ polarization vs p_T

- 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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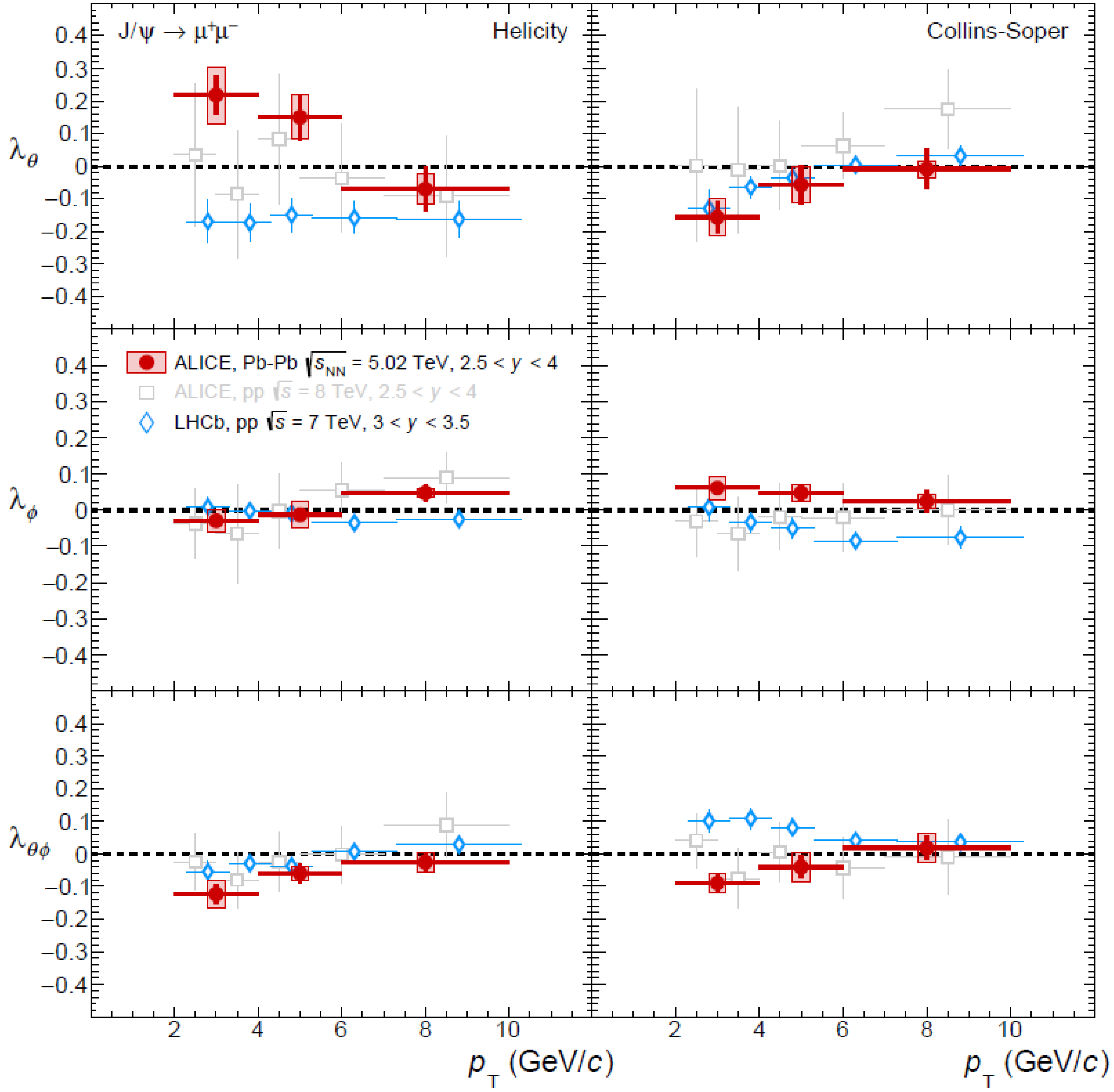
PLB 815 (2021)

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

EPJC 78 (2018) 562

Results



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PLB 815 (2021)

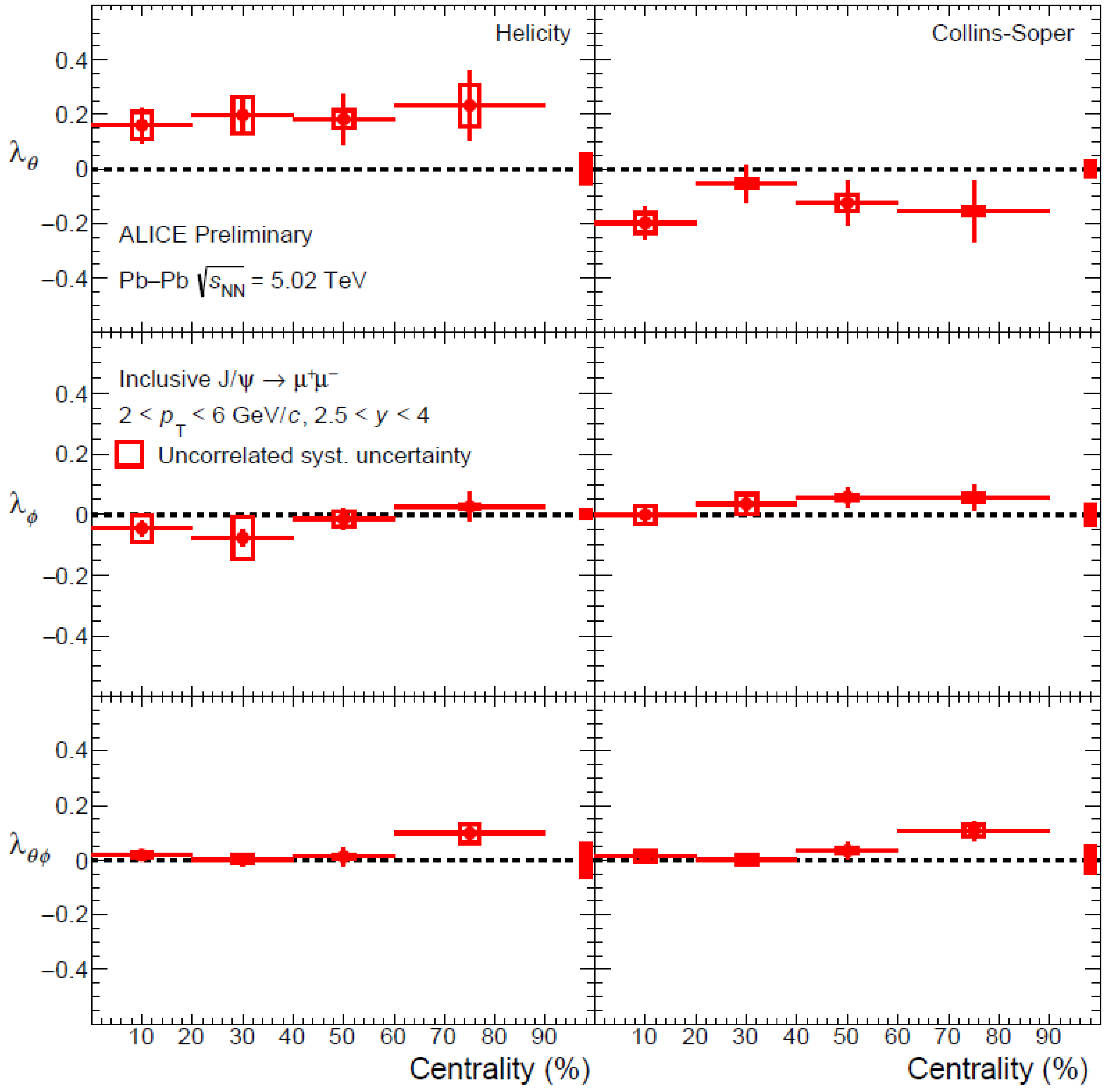
- ❑ Comparison with **ALICE pp** results at $\sqrt{s}$ = 8 TeV
  - ➢ compatible within the uncertainties

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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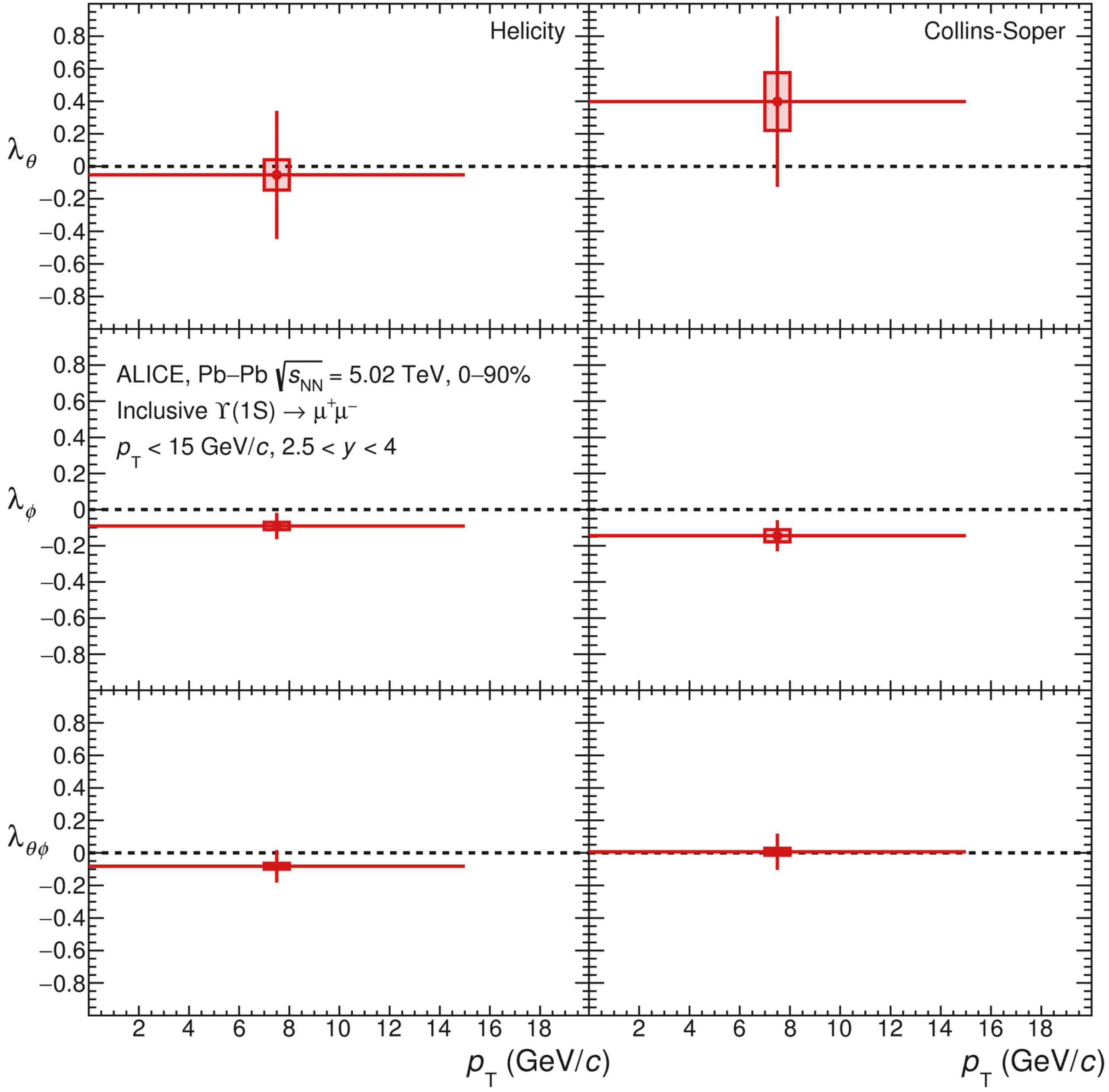
J/ψ polarization vs centrality

- 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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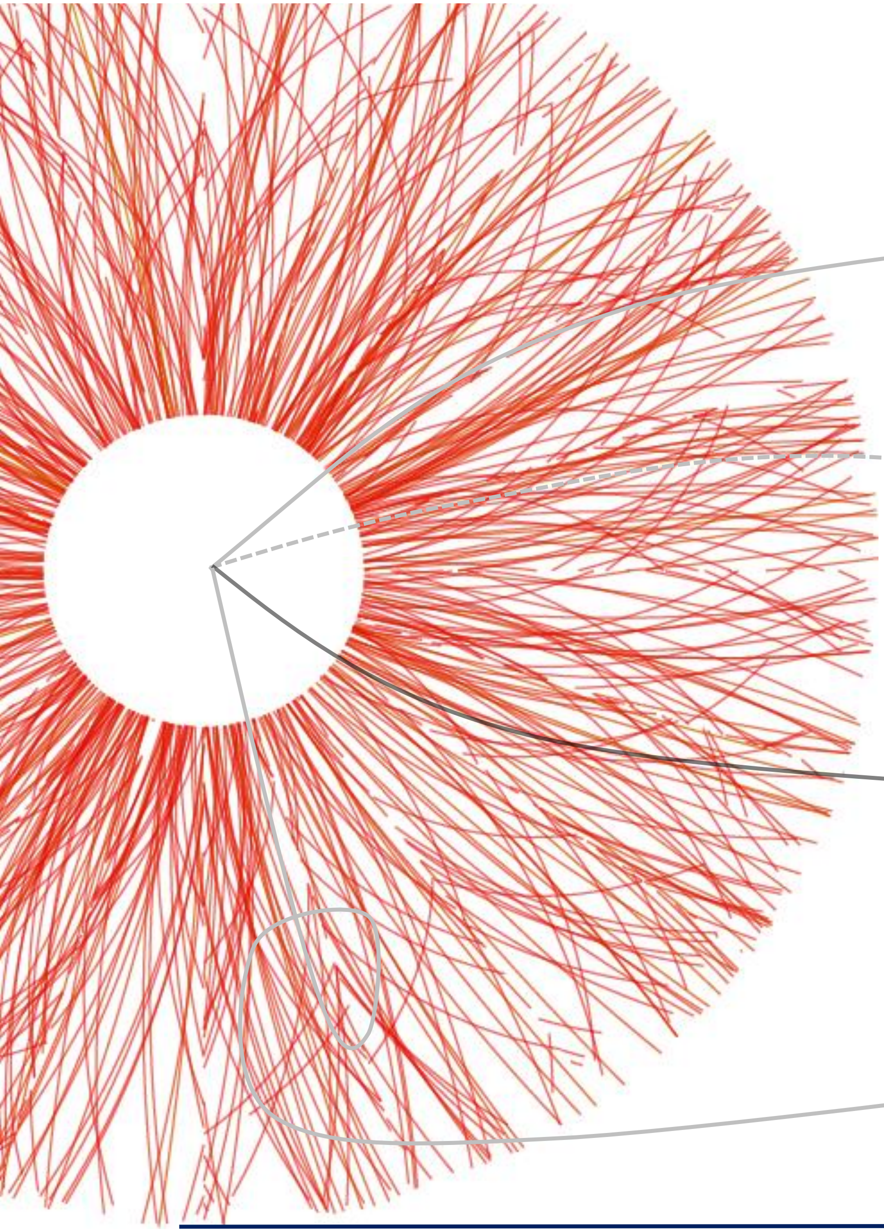
Υ(1S) polarization

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

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

arxiv:1711.02404

Outline



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Discussion on results

- **$\Upsilon(1S)$ polarization vs p_{T}**
  - $\lambda_{\theta}, \lambda_{\phi}, \lambda_{\theta\phi}$ compatible to **zero** in Pb-Pb collisions and with measurements in **pp** collisions
- The increase of a factor ~ 10 in the luminosity in Run 3 and 4 will increase the precision of the measurement

- **J/ψ polarization vs p_{T} and centrality**
  - $\sim \mathbf{2\sigma}$ deviation from zero for λ_{θ} in $2 < p_{\mathrm{T}} < 4$ GeV/c
  - $\sim \mathbf{3\sigma}$ difference with **LHCb** (pp collisions) at low p_{T}

! Full theoretical theoretical description of polarization in HICs is missing **!**

Discussion on results

$\Upsilon(1S)$ polarization vs p_T

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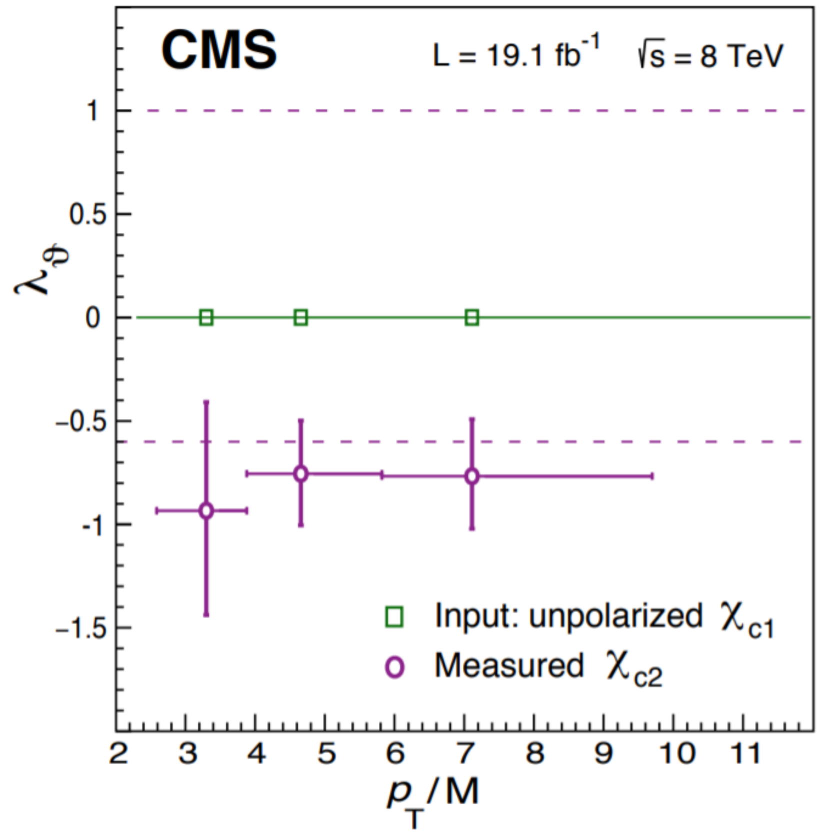
J/ψ polarization vs p_T and centrality

- $\sim$ **2σ** deviation from zero for λ_θ in $2 < p_T < 4$ GeV/c
- $\sim$ **3σ** difference with **LHCb** (pp collisions) at low p_T

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 ?



EPJC 74 (2014) 5, 2872

PRL 124, 162002 (2020)

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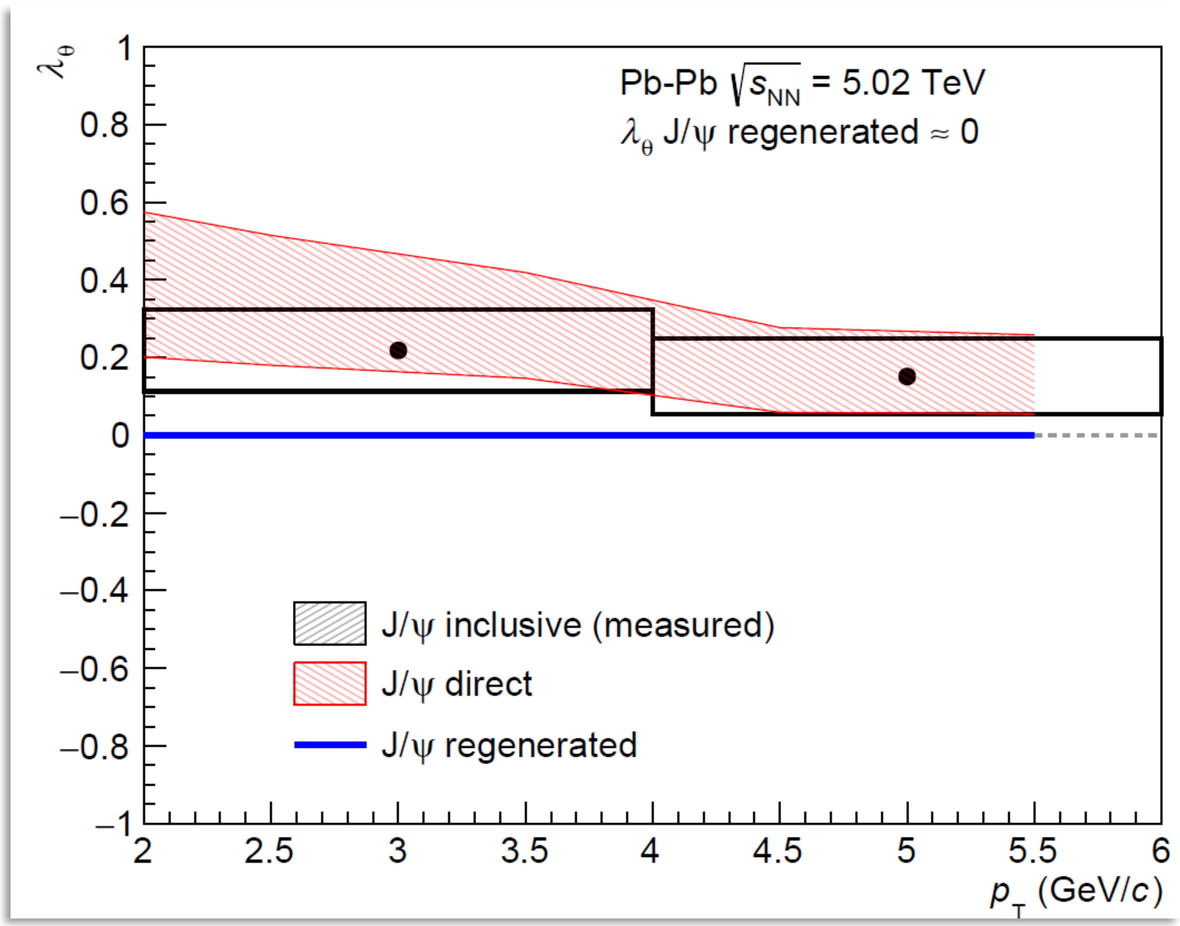
Significant J/ψ **(re)generation** at low-p_T

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

Exercise

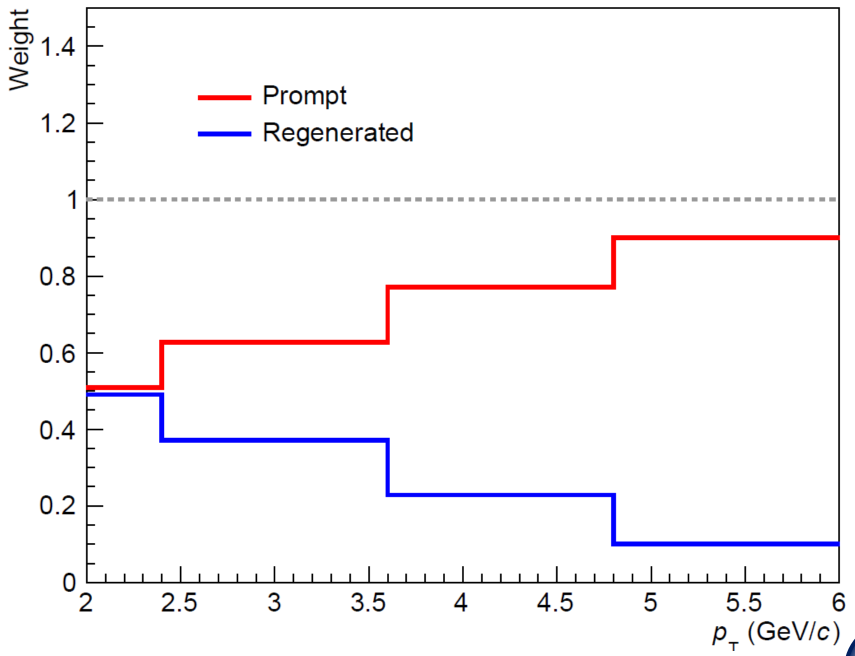
📌 Exercise: constrain χ_{c1} **and** χ_{c2} **average polarization** using the existing measurements



λ_θ in Pb-Pb collisions

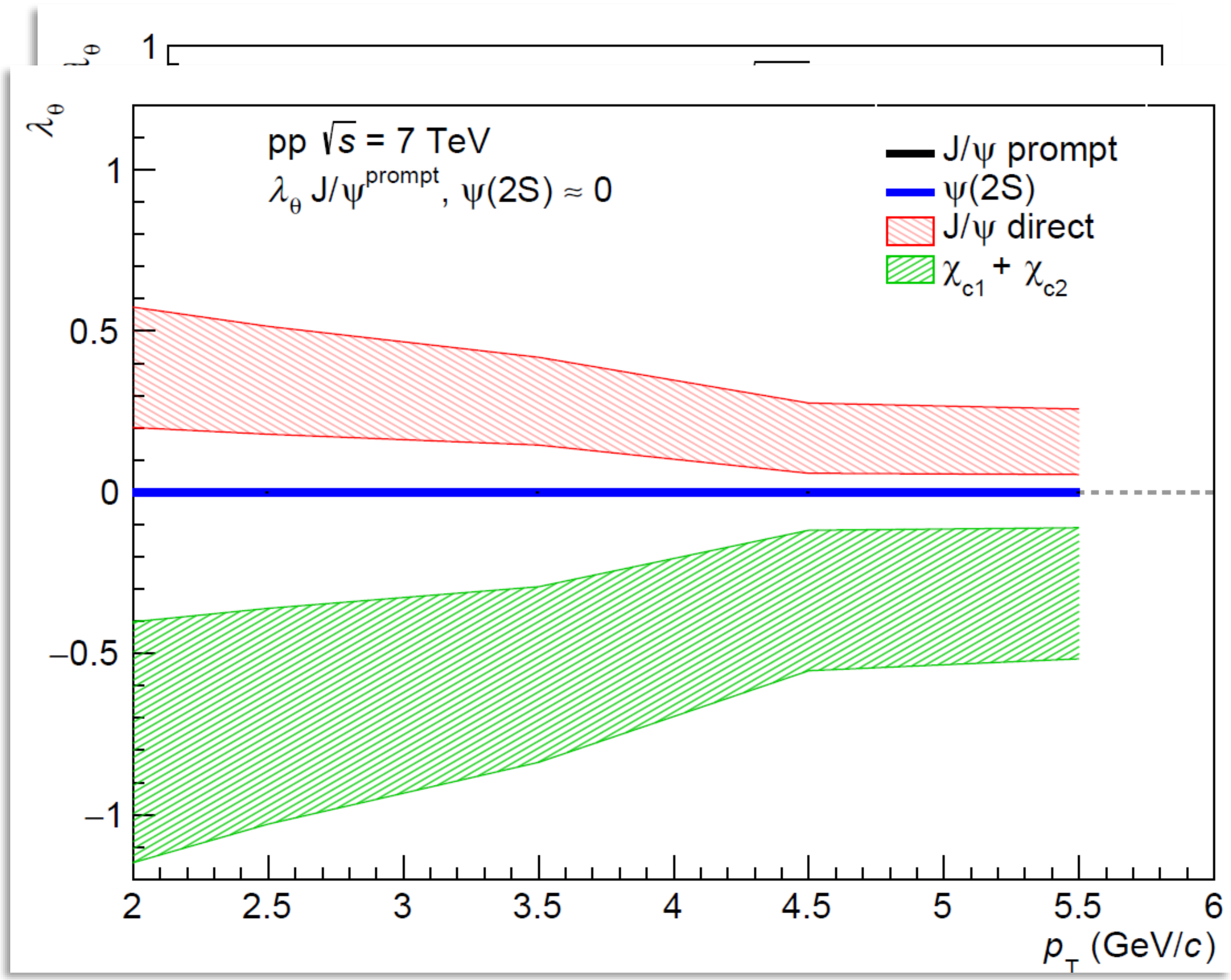
- Inclusive J/ψ ⇒ measured
- Regenerated J/ψ ⇒ unpolarized (?)
- $J/\psi \leftarrow \chi_c, \psi(2S)$ ⇒ suppressed

⇒ Direct J/ψ polarization



Exercise

Exercise: constrain χ_{c1} **and** χ_{c2} **average polarization** using the existing measurements



λ_θ in Pb-Pb collisions

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

⇒ Direct J/ψ polarization

λ_θ in pp collisions

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

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

Discussion on results

- **Υ(1S) polarization vs p_T**
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible to **zero** in Pb-Pb collisions and with measurements in **pp** collisions

- The increase of a factor ~ 10 in the luminosity in Run 3 and 4 will increase the precision of the measurement

- **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

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)?

Analogies with **light vector mesons** ($\boldsymbol{\phi}/\boldsymbol{K^{*0}}$) results?

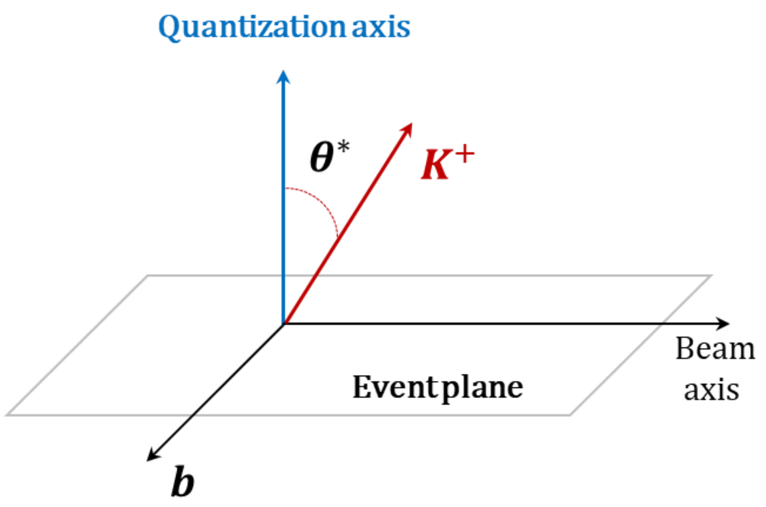
Spin alignment: observables

- Angular distribution of the decay products

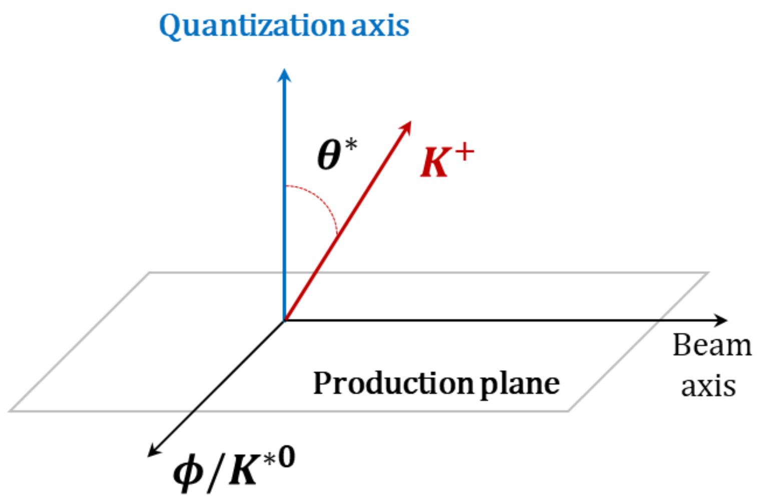
$$\frac{dN}{d\cos\theta^*} \propto (1-\boldsymbol{\rho_{00}}) + (3\boldsymbol{\rho_{00}}-1)\cos^2\theta^*$$

- $\boldsymbol{\rho_{00}}$ = 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

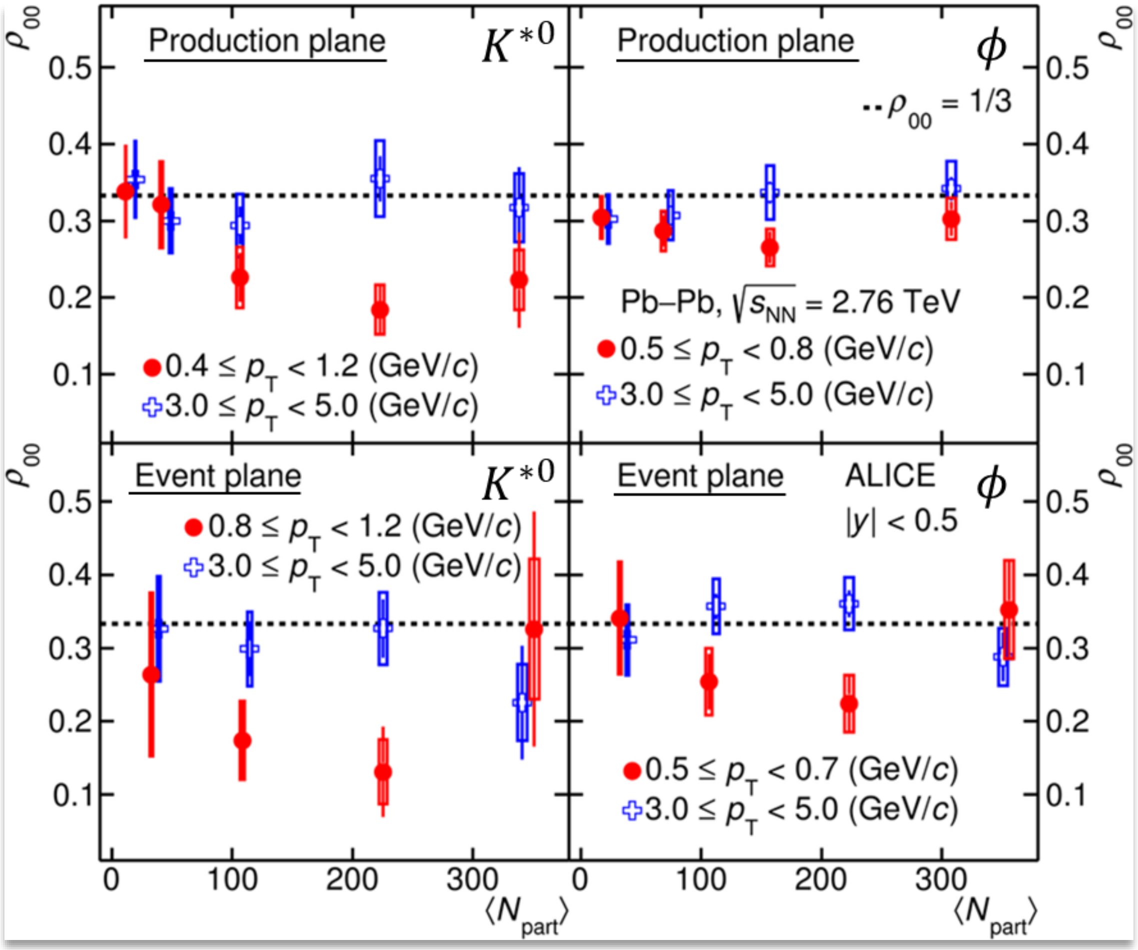


Event plane (EP): **normal** to the plane identified by the impact parameter ($\boldsymbol{b}$) and the **beam axis**



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

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

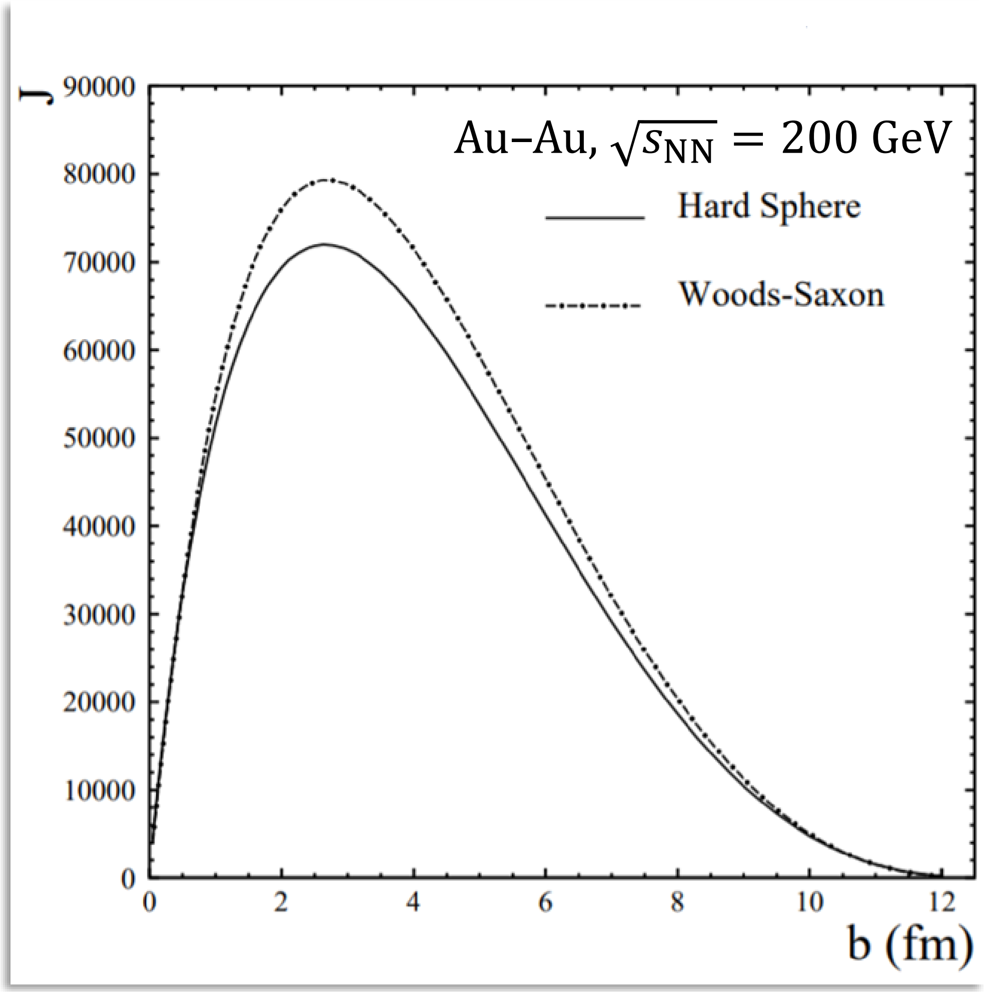
  - ✓ $\rho_{00} < 1/3$ at low p_T & $\rho_{00} \sim 1/3$ at high p_T
  - ✓ Quark mass dependence
  - ✓ Maximum effect in non-central collisions

? Surprisingly large effect if compared with Λ polarization

PRC 101, 044611 (2020)

Spin alignment: other effects

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



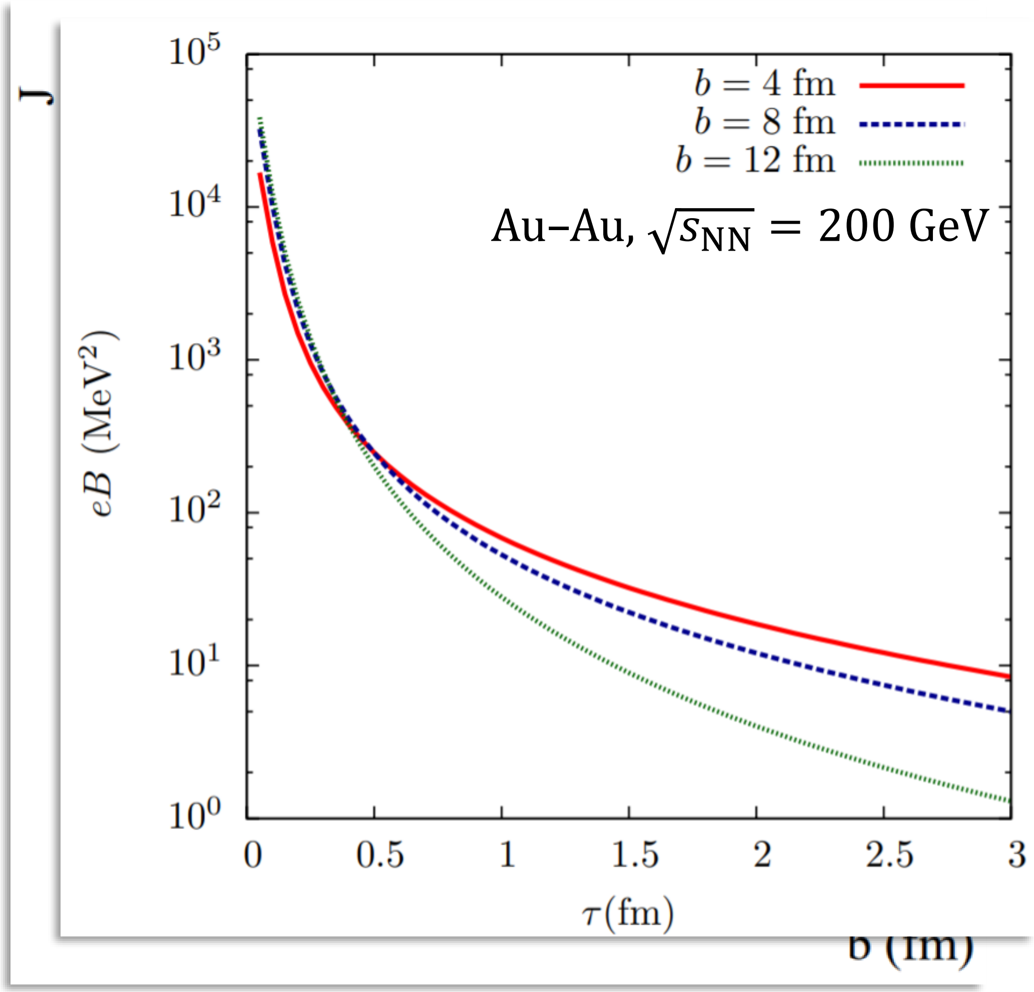
- Large **angular momentum** due to the medium rotation is predicted in non-central HICs

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**

Spin alignment: 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.

- 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

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

$\vec{B}$

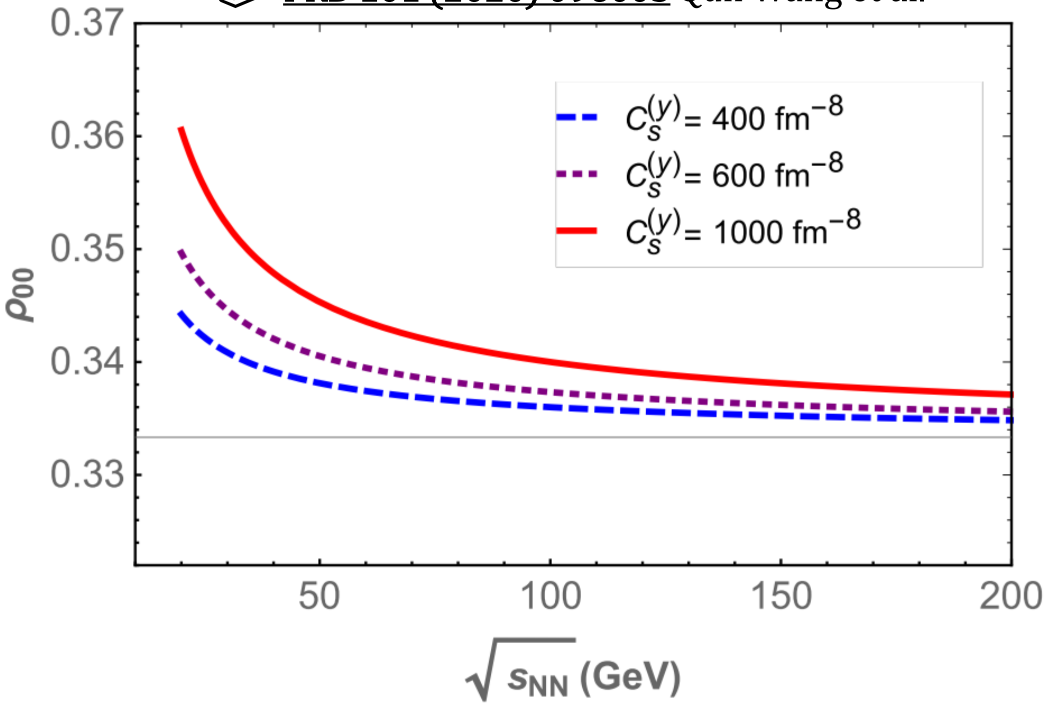
  - ❑ c-quarks production compatible with $\vec{B}$

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

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.



$$\rho_{00}^{\phi} \sim \frac{1}{3} + c_V + c_M + c_E + c_\phi$$

Vorticity term

Electro-magnetic term

Mean ϕ field term

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

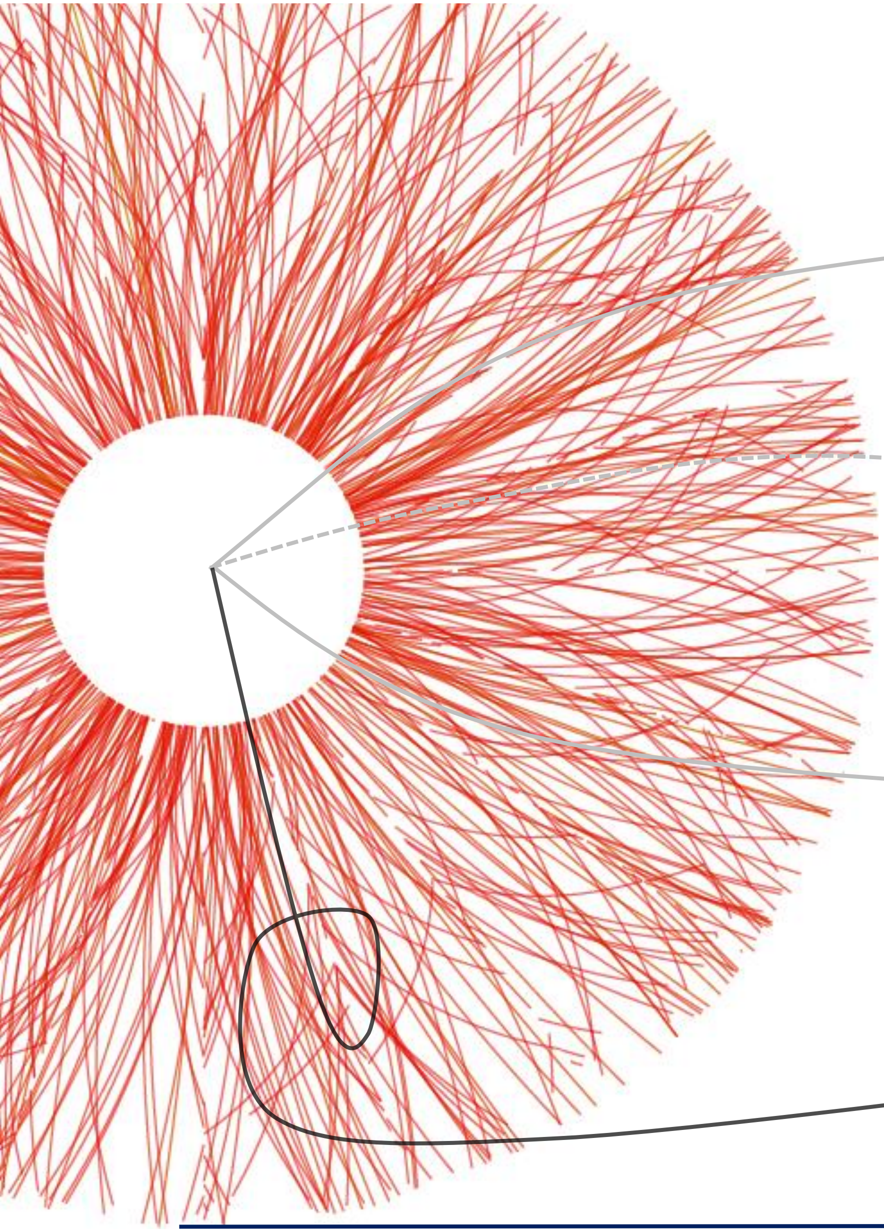
? Is it possible to extend this approach for J/ψ?

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

arxiv:2110.15630, Muller and Yang

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

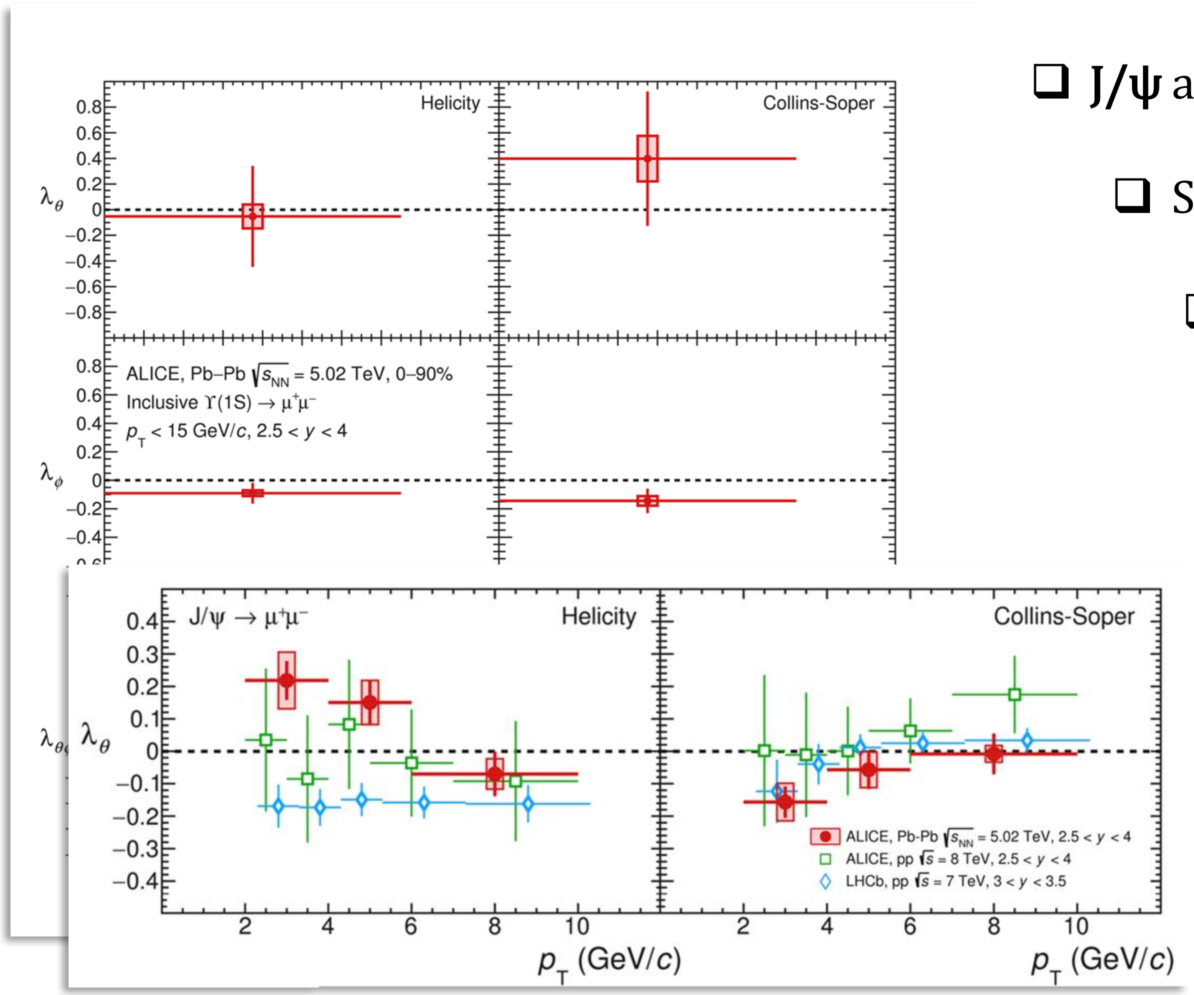
Outline



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

Summary

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



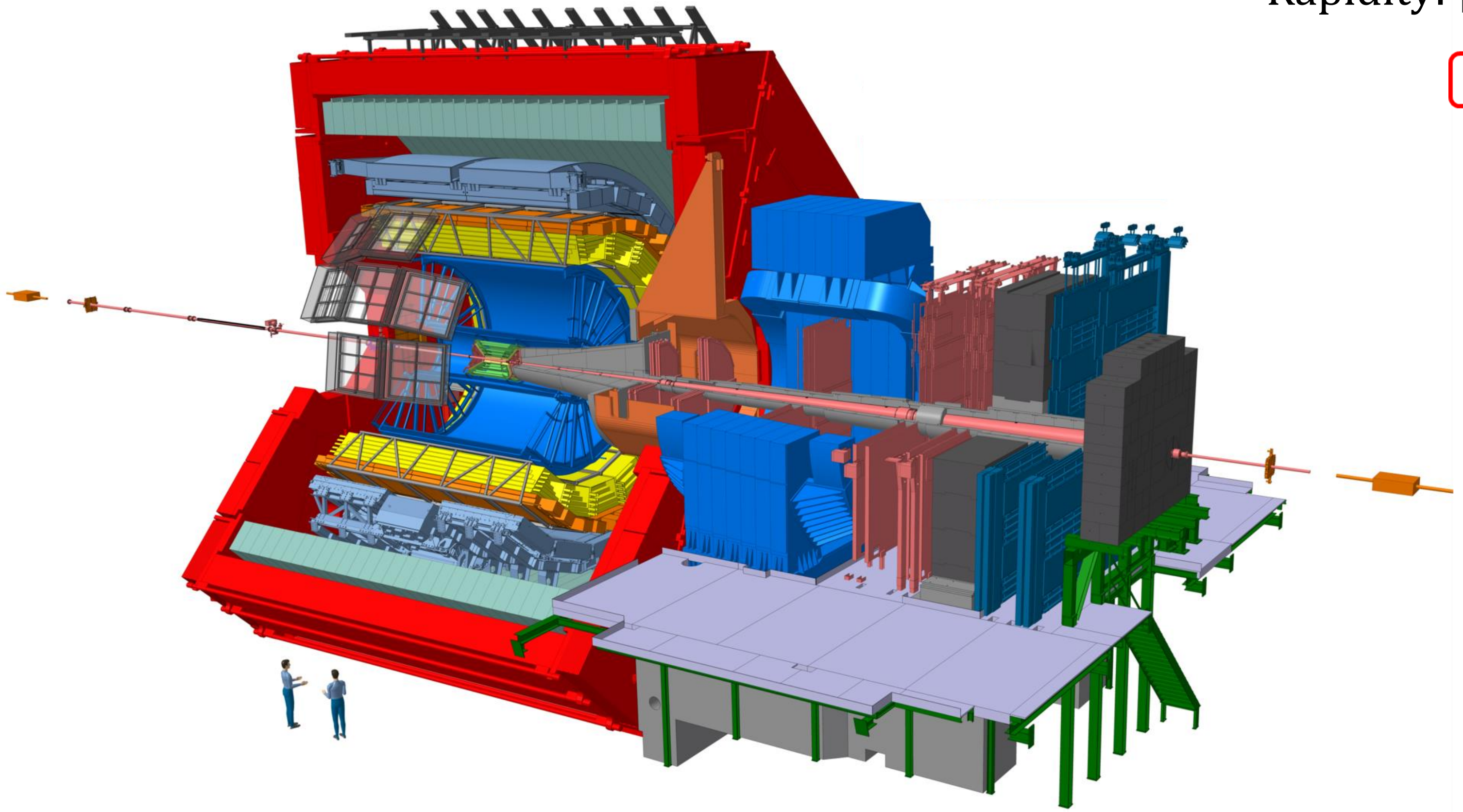
- J/ψ and **ϒ(1S)** do not exhibit a strong polarization in HICs
  - Significant difference for **J/ψ** w.r.t. **LHCb** at low p_T
    - New measurements of **J/ψ polarization w.r.t. the event-plane** and paper is in preparation
      - Many effects needs to be considered in the theoretical desctription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

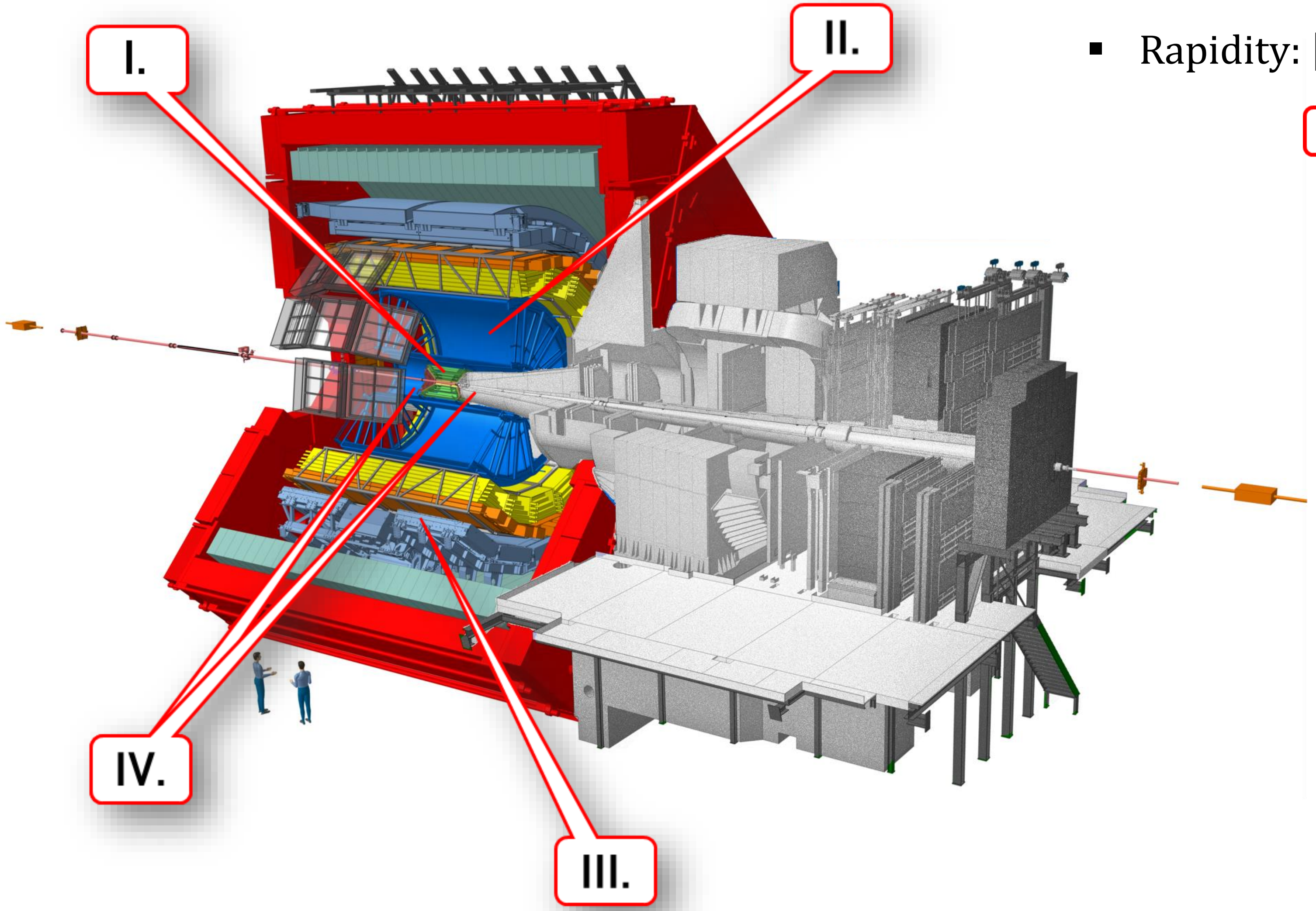
II. Tracking system

III. Dipole magnet

IV. Trigger system

A Large Ion Collider Experiment

ALICE is designed for the study of heavy-ion collisions



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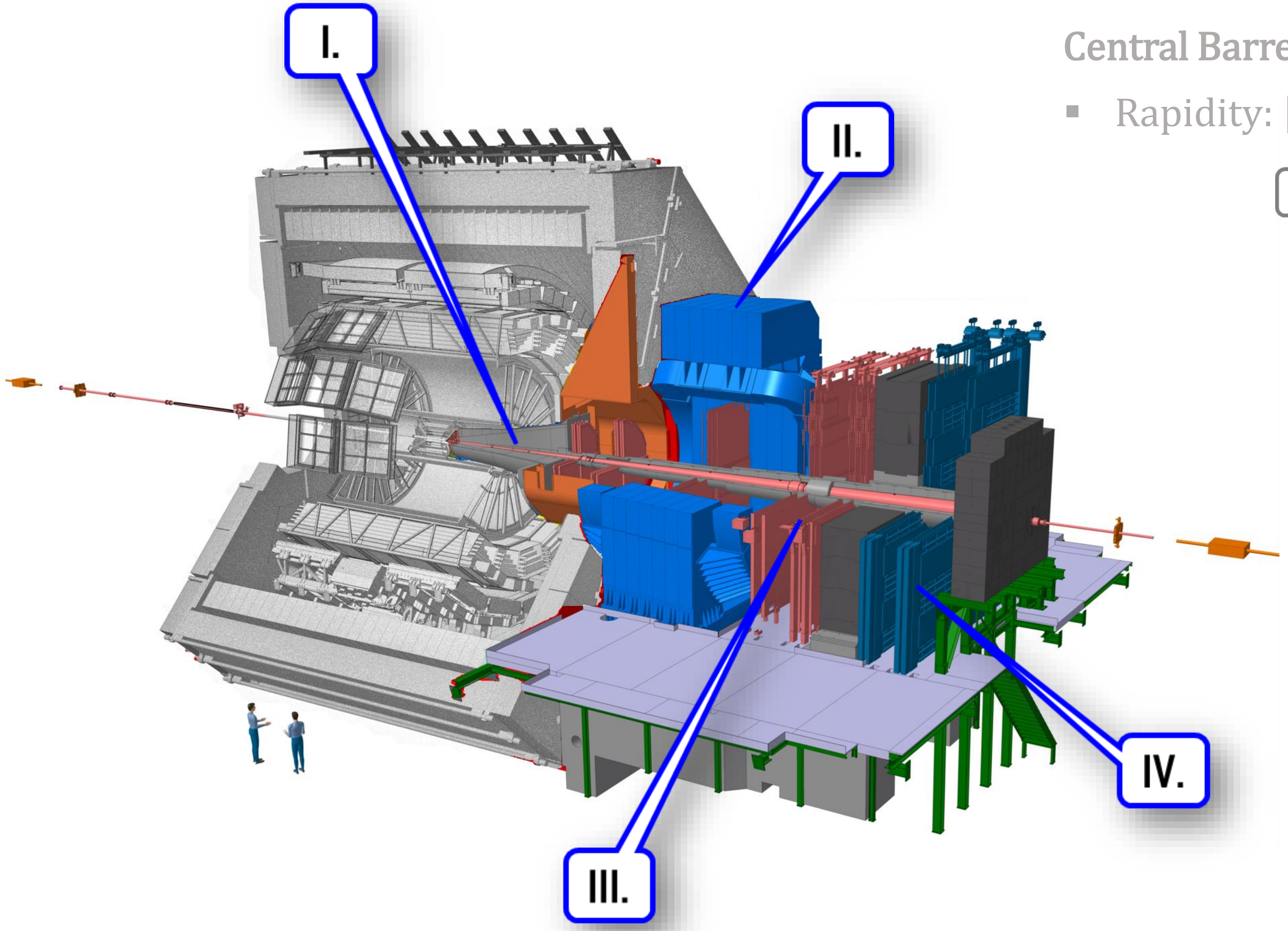


Central Barrel

- Rapidity: $|y| < 0.9$

I. Inner Tracking System

II. Time Projection Chamber

III. Time of Flight

IV. V0 detectors

Muon Spectrometer

- Rapidity: $2.5 < y < 4$

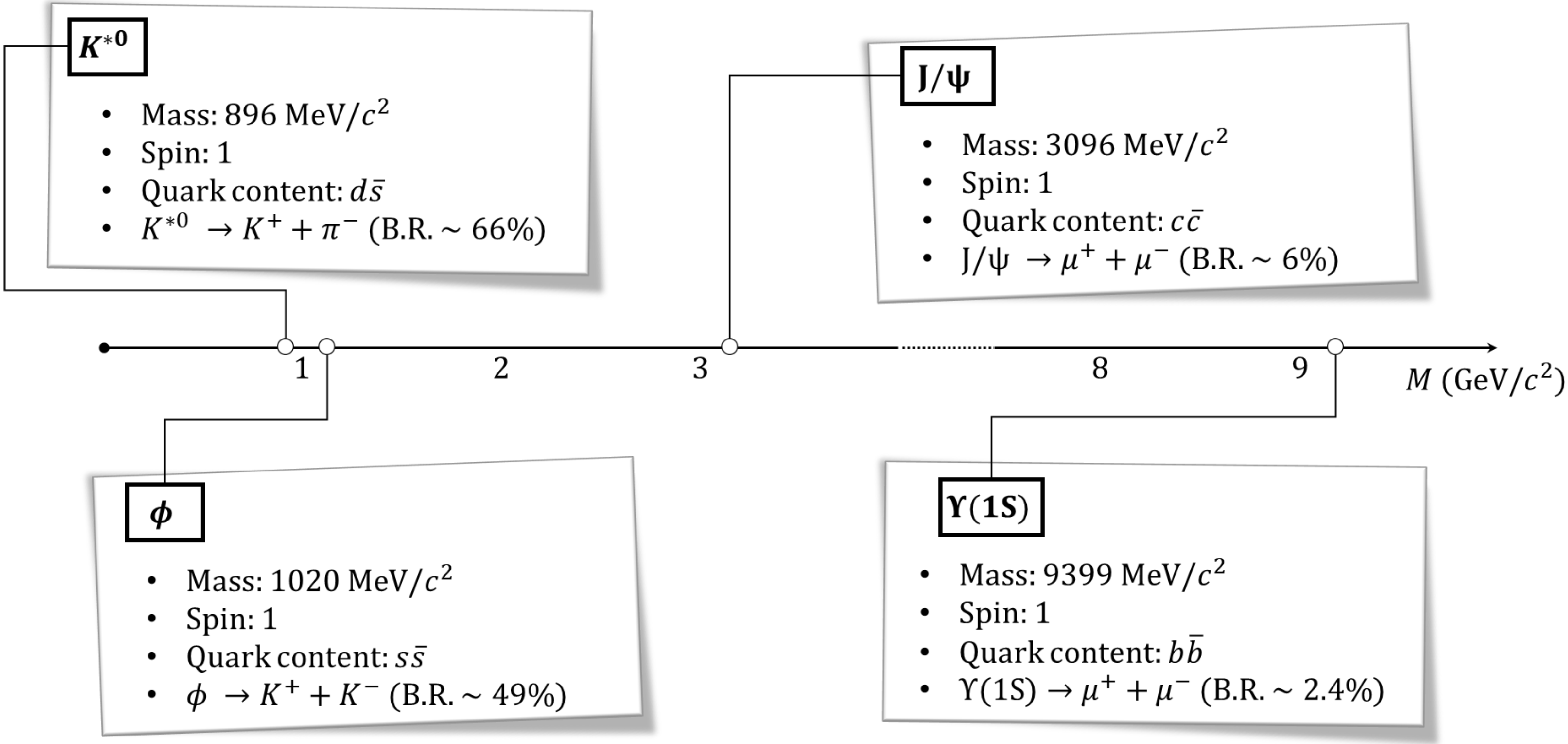
I. Front absorber

II. Tracking system

III. Dipole magnet

IV. Trigger system

Vector mesons polarization



Light vector mesons polarization at RHIC