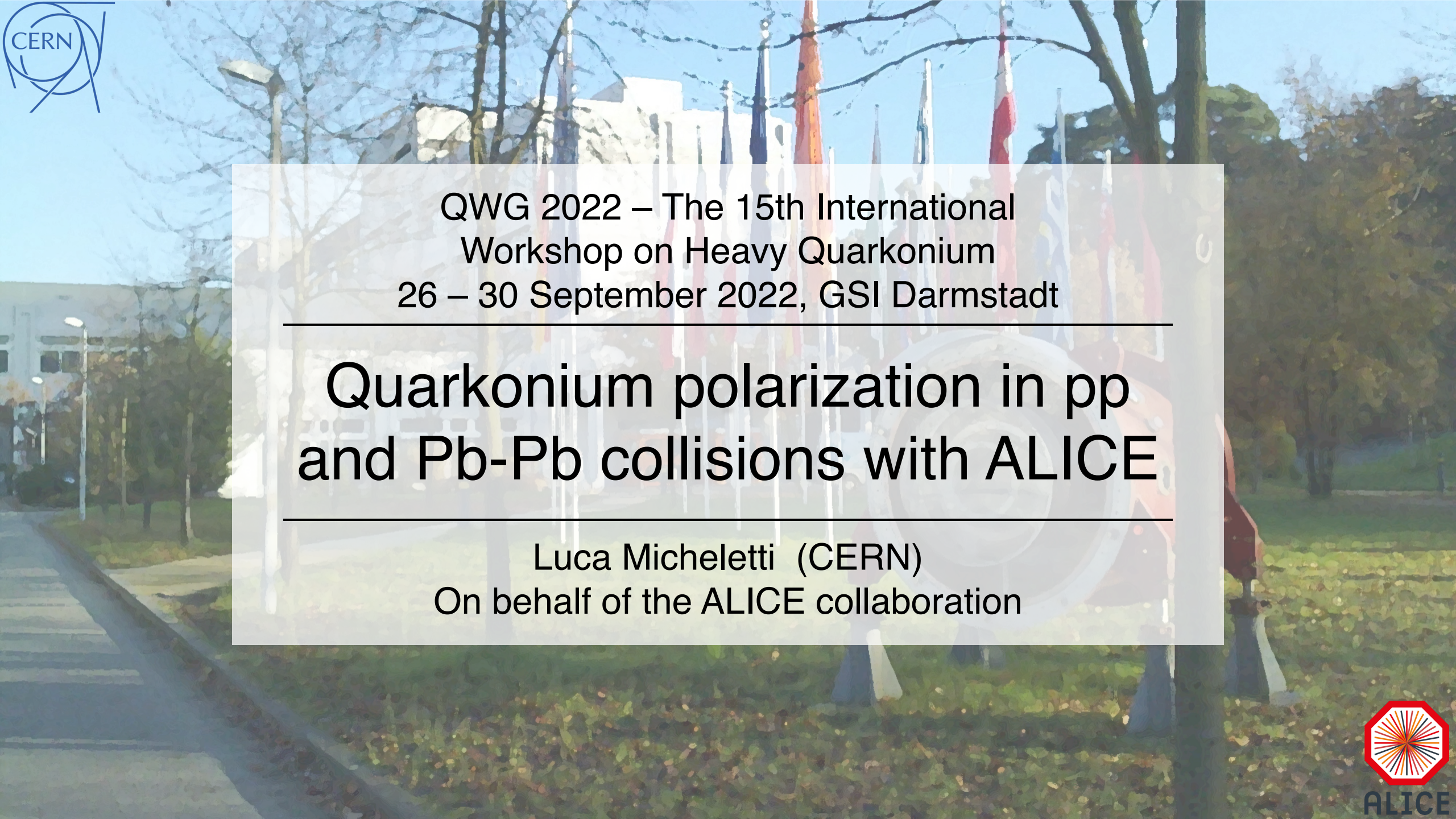


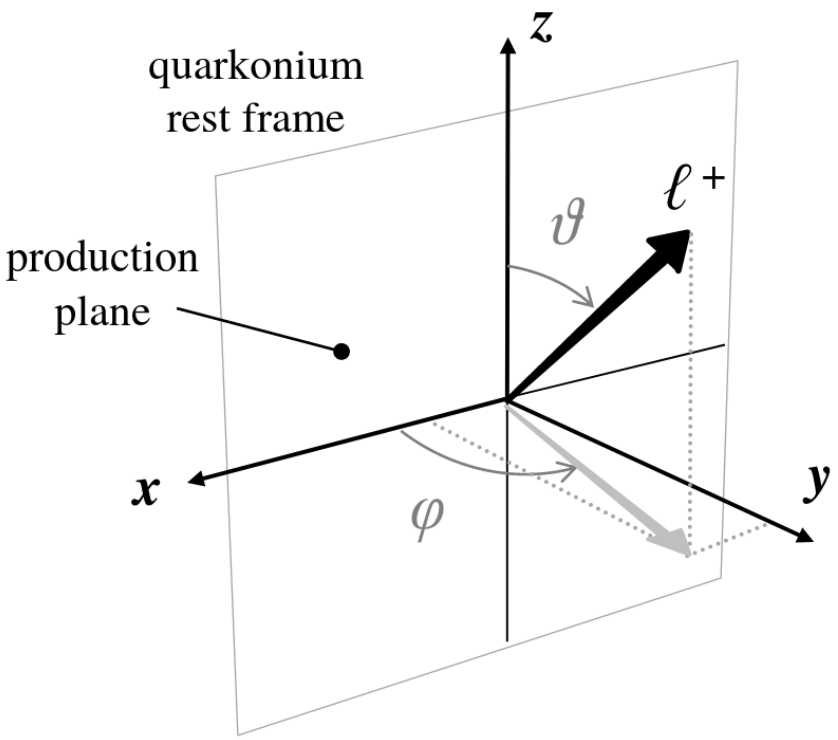
QWG 2022 – The 15th International
Workshop on Heavy Quarkonium
26 – 30 September 2022, GSI Darmstadt

Quarkonium polarization in pp and Pb-Pb collisions with ALICE

Luca Micheletti (CERN)
On behalf of the ALICE collaboration

Polarization: an introduction

- Polarization refers to the particle spin alignment with respect to a chosen direction
- For a vector meson ($\mathbf{v}$) the total angular momentum ($\mathbf{J}, \mathbf{J_z}$) state can be expressed as:



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

Spin-alignment ⇔ decay products angular distribution

EPJC 69 (657-673), 2010, Faccioli et al.

Dilepton decay angular distribution

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

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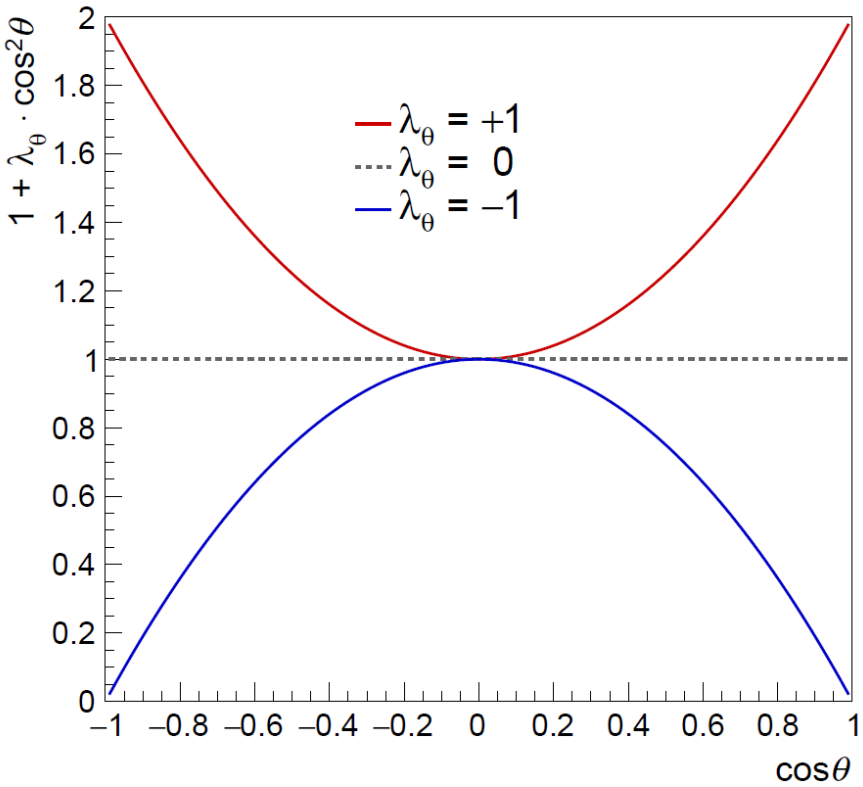

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❑ Polarization parameters

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

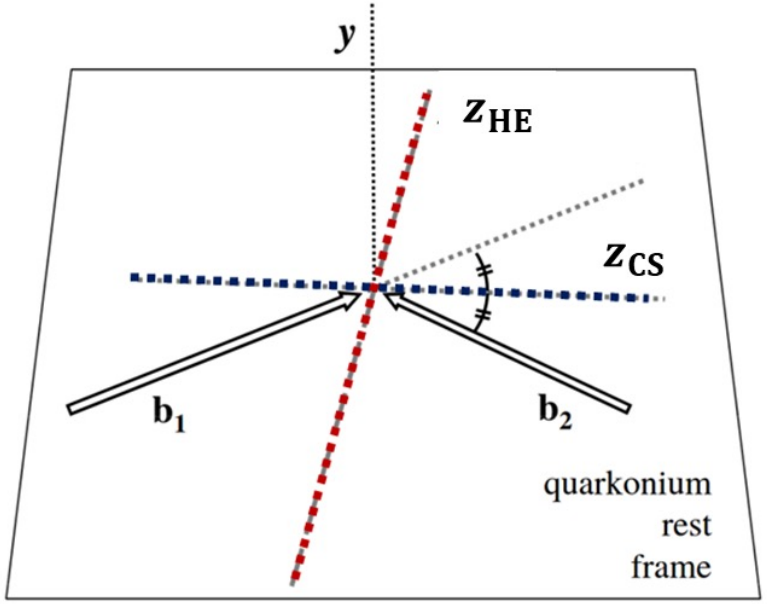
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1,0,0)$ ⟹ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0)$ ⟹ Longitudinal polarization

Polarization in pp collisions

Polarization in pp: definitions & motivations

- Important to constrain quarkonium production mechanisms in hadronic collisions



Reference frames

- Helicity (HE): 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

EPJC 69 (657-673), 2010, Faccioli et al.

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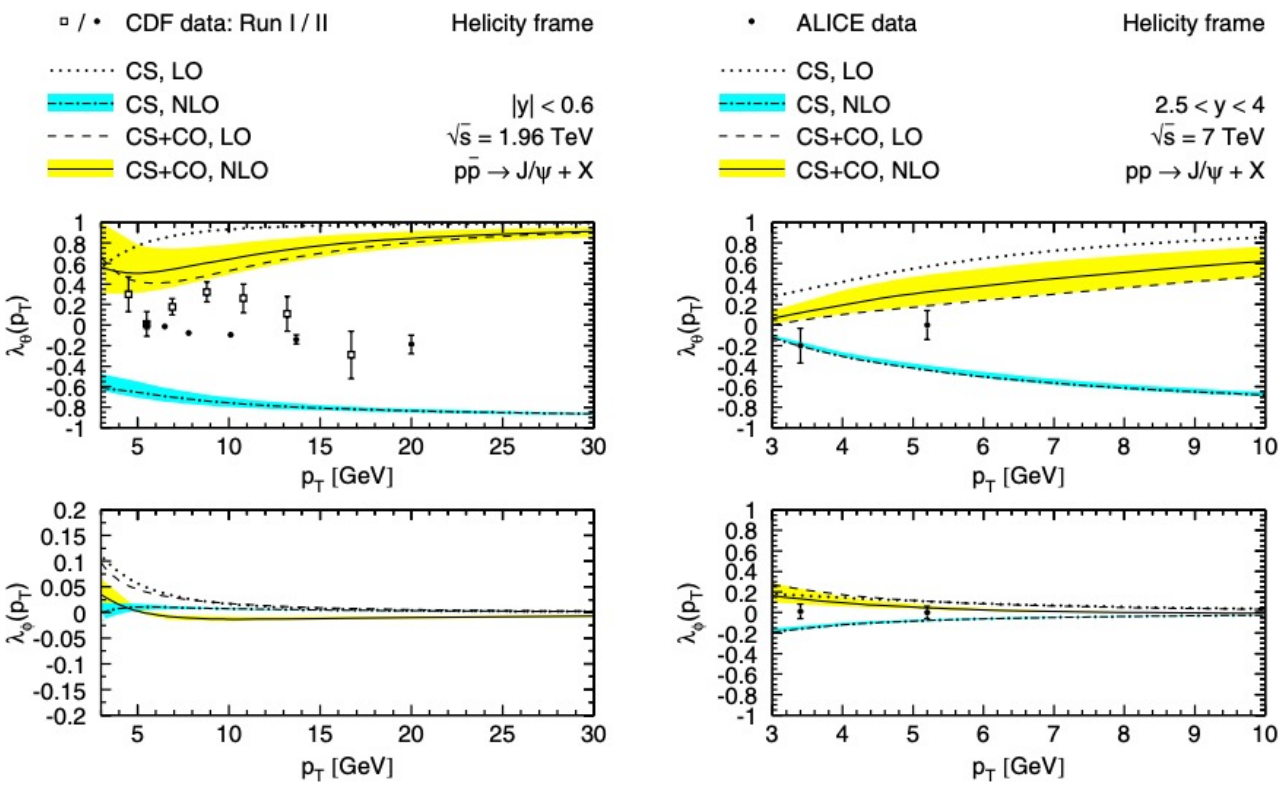

Phys. Rev. Lett. 108, 172002, Butenschoen et al.

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❑ …models provide different predictions for quarkonium polarization according to their **production mechanism**

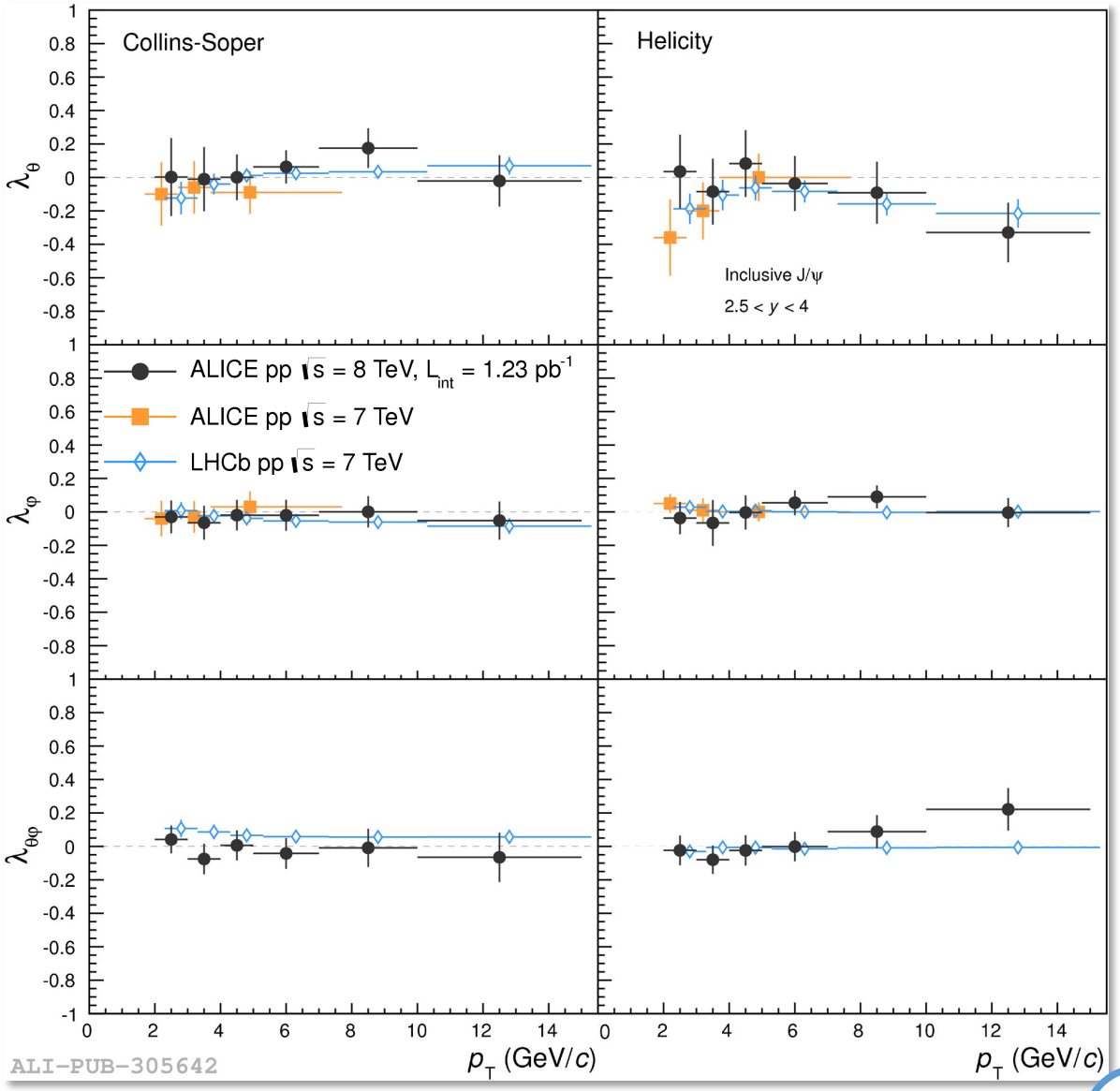
- **Color Singlet**: Longitudinal polarization
- **NRQCD**: Transverse polarization

Polarization in pp: charmonia

- No strong J/ψ polarization observed by **ALICE** and **LHCb** at forward rapidity and up to p_T = 15 GeV/c

PRL 108 (2012) 082001 EPJC 78 (2018) 562

EPJC 73 (2013) 11



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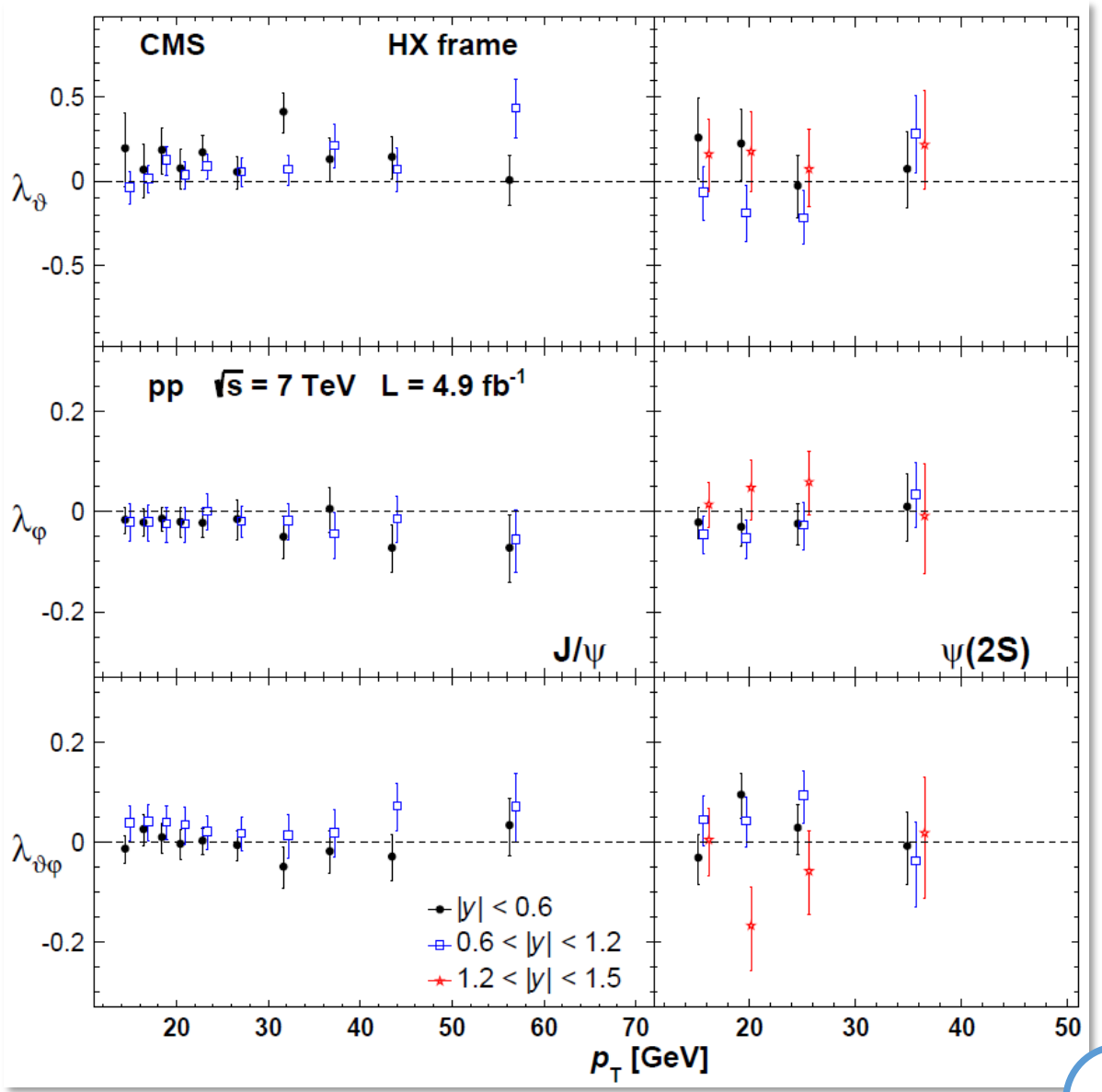
  PLB 727 (2013) 381 PLB 761 (2016) 31



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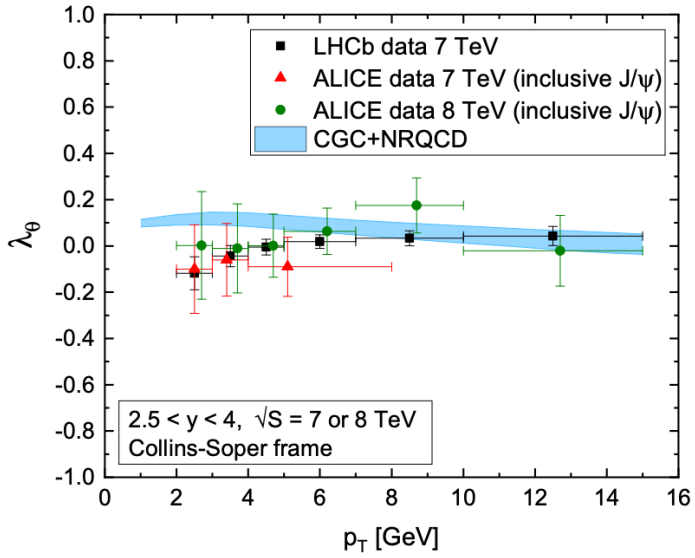
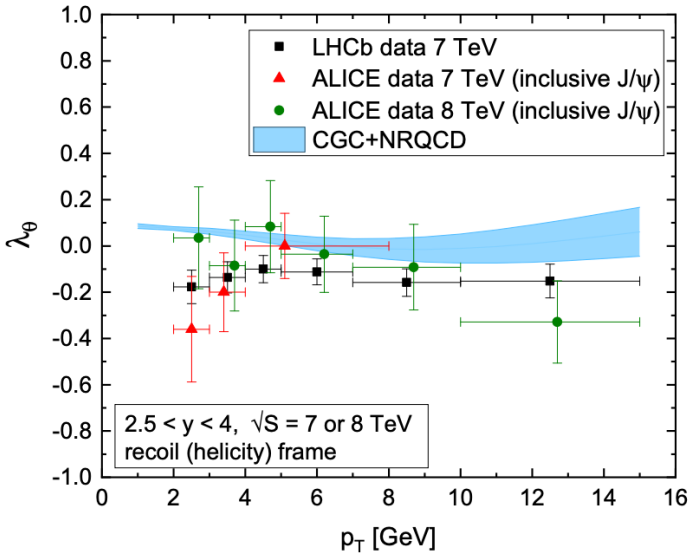
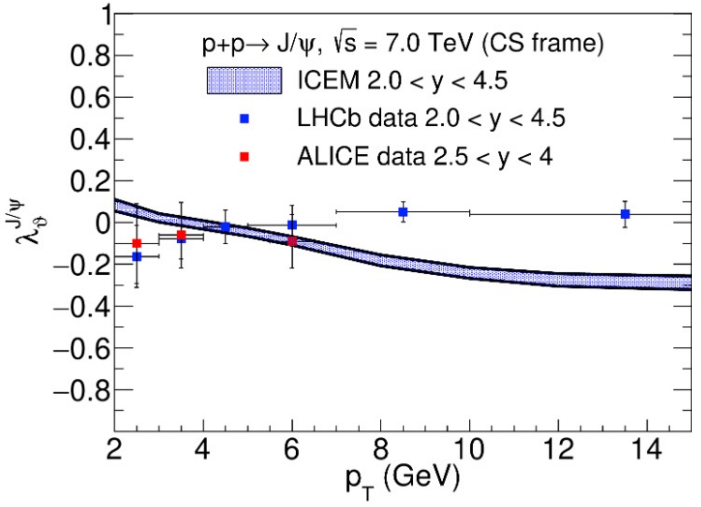
- Recent improvements in the theoretical description of J/ψ production with **ICEM** and **CGC + NRQCD**

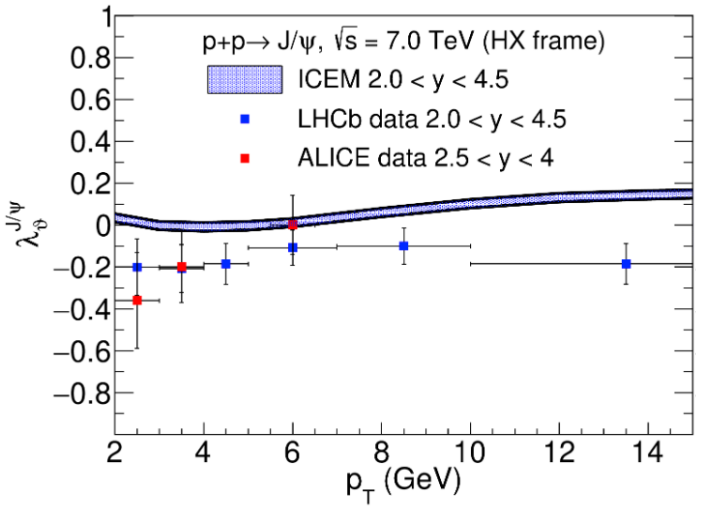
  JHEP 12 (2018) 057, Yan-Qing Ma et al.

  PRD 104 (2021) 9, Cheung, Vogt









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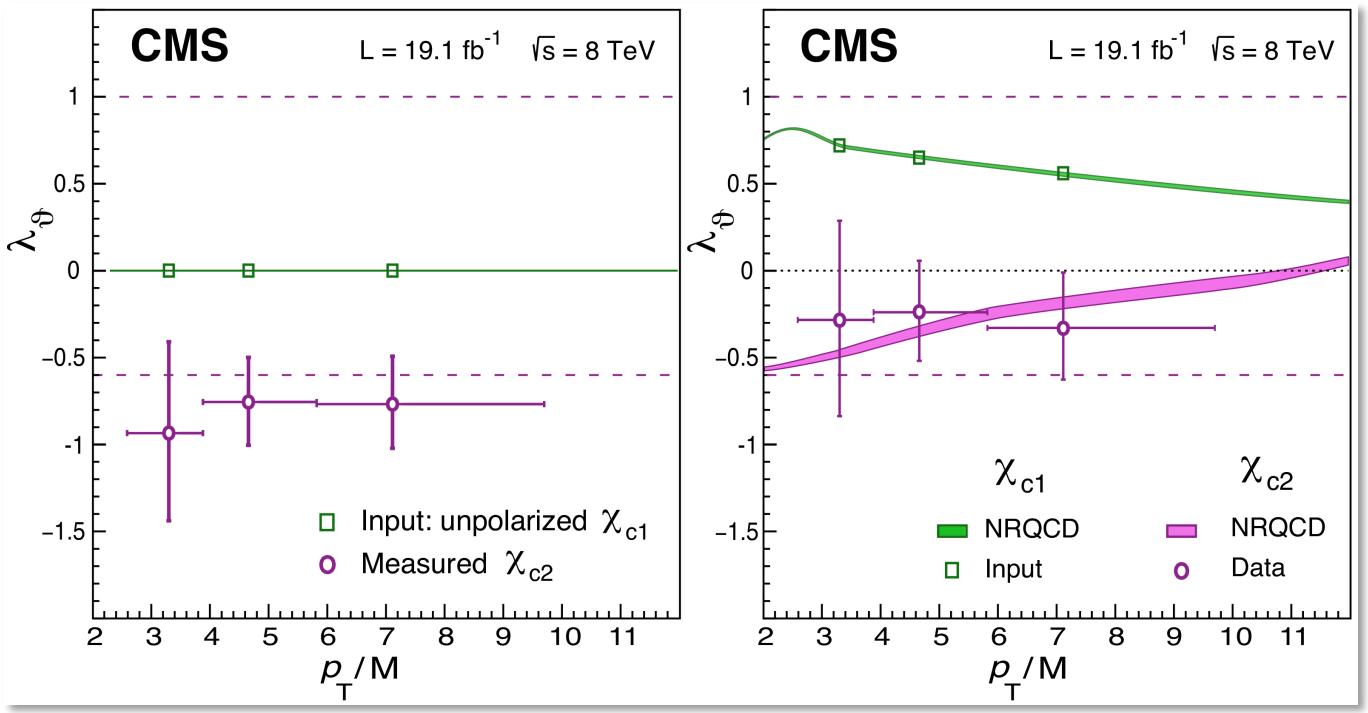
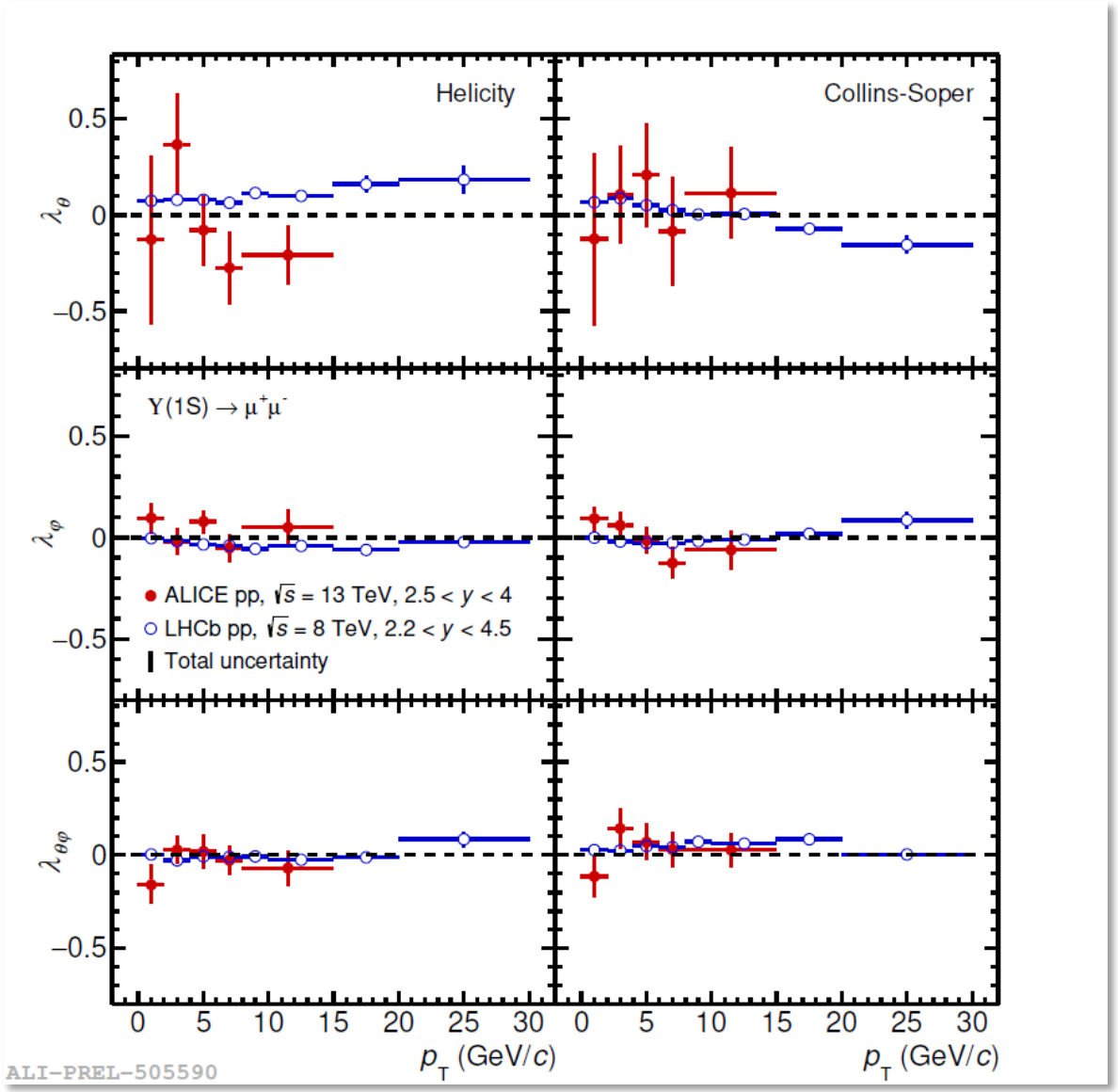
- Interestingly **CMS** observed a sizeable relative polarization between χ_{c1} and χ_{c2}, reproduced by NRQCD

  PRL 124, 162002 (2020), CMS collaboration



- Expected λ_θ for χ_{c2} from the χ_{c1}/χ_{c2} ratio measurement, assuming either no polarization for χ_{c1} or expectations from **NRQCD**

Polarization in pp: bottomonia



- Recent preliminary measurement of $\Upsilon(1S)$ polarization at $\sqrt{s}$ = 13 TeV from ALICE
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ evaluated down to zero p_T
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ are all compatible with zero within uncertainties in HE and CS reference frames
  - No evidence for p_T dependence

- Results compatible within uncertainties with LHCb mesurements at $\sqrt{s}$ = 8 TeV

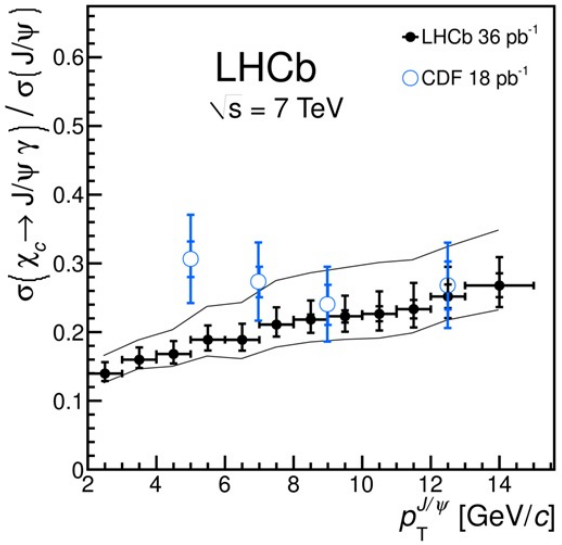
  JHEP 12 (2017) 110, Artamonov et al.

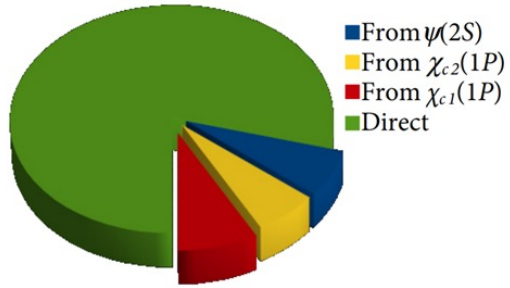
- Qualitatively in agreement with NLO NRQCD

  PRL 112, 032001 (2014), Gong et al.

Polarization in AA collisions

Polarization in AA: motivations





PLB 718 (2012) 431

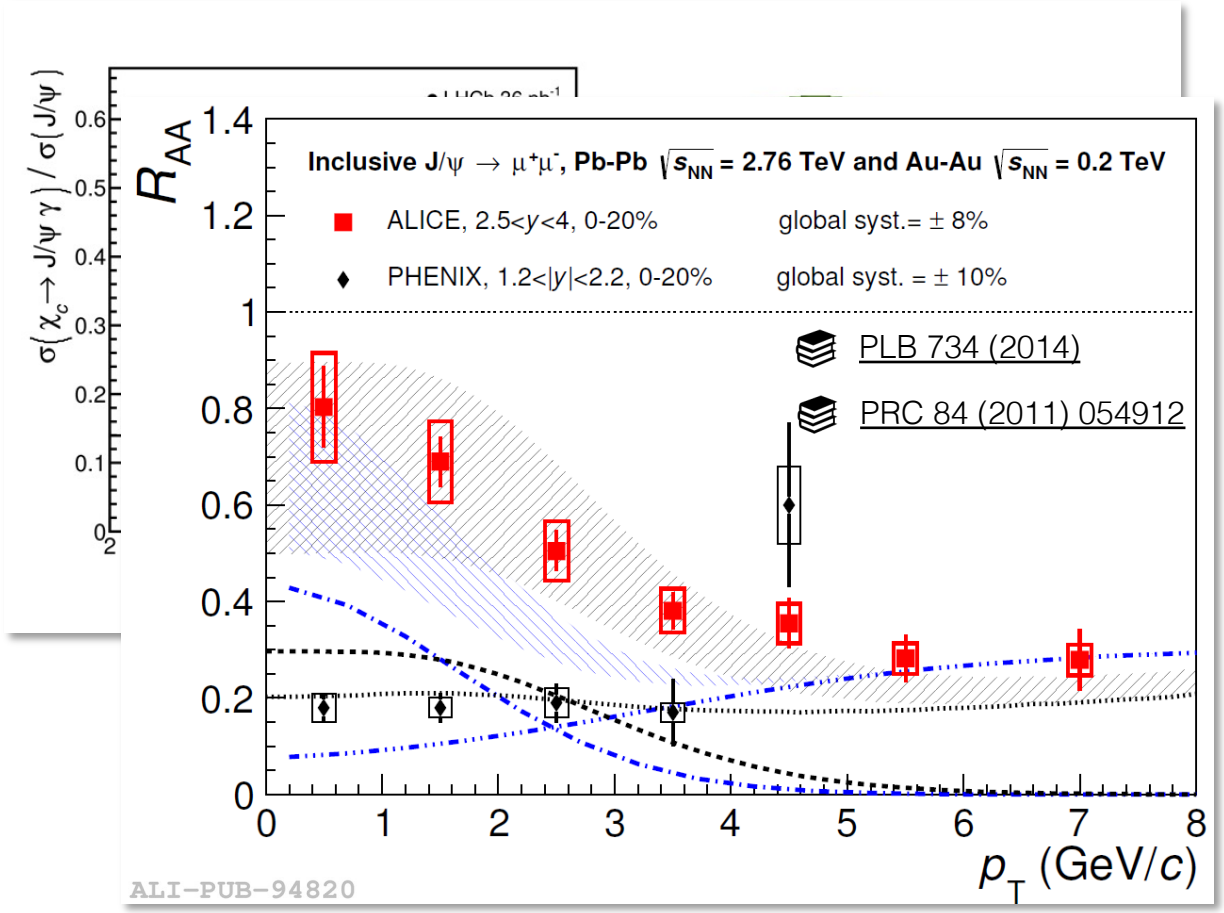
Phys.Rept. 889 (2020)

In central HICs…

- Modification of J/ψ prompt feed-down fractions due to $\psi(2S)$ and χ_c suppression in the QGP

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

Polarization in AA: motivations



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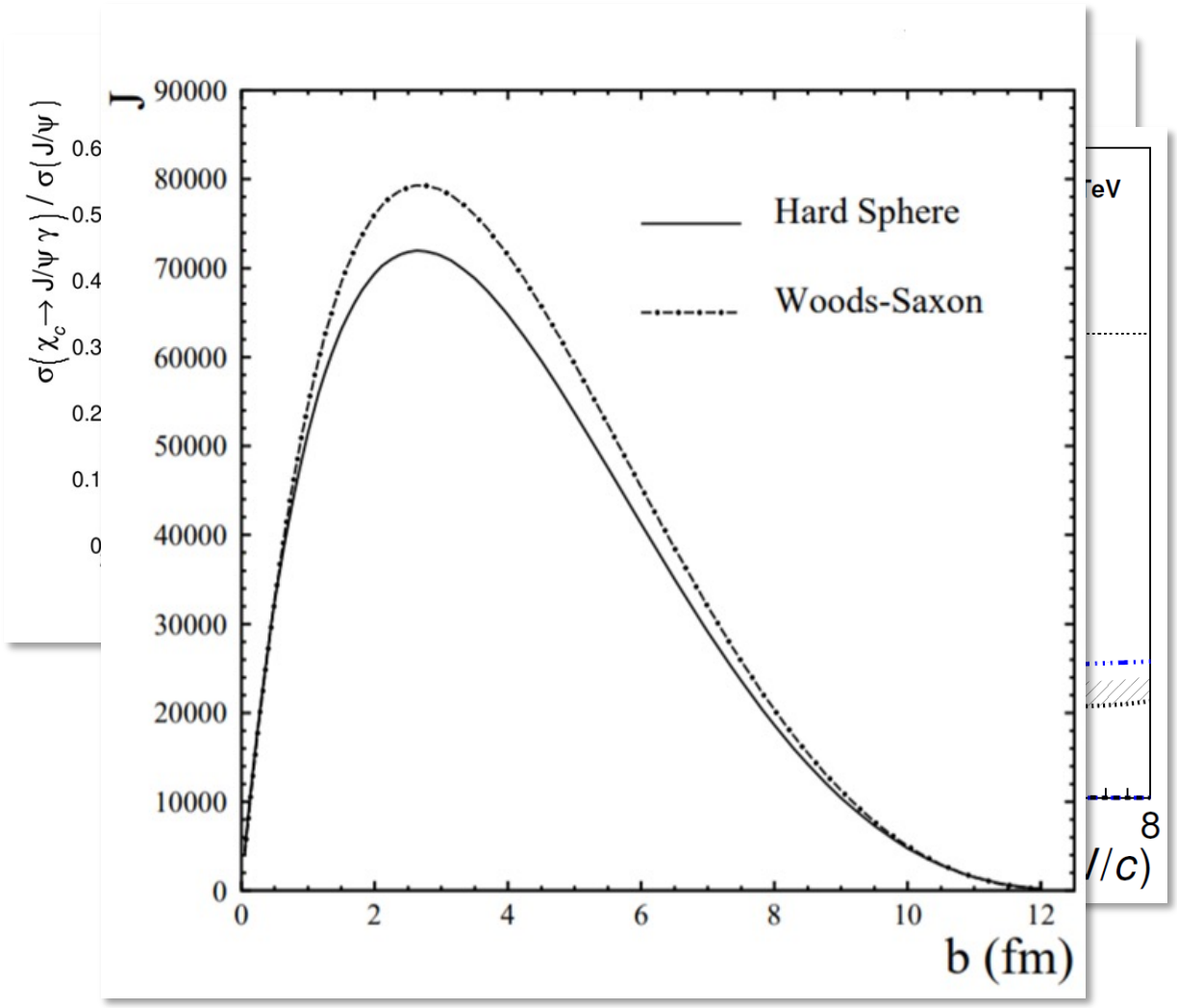
$$J/\psi^{\text{Prompt}} : (60\%)^{\text{Direct}} + (30\%)^{\chi_c} + (10\%)^{\psi(2S)}$$

- contribution from charmonium **(re)generation** plays an important role at the LHC energies in central Pb–Pb collisions at low p_T

Polarization in AA: motivations

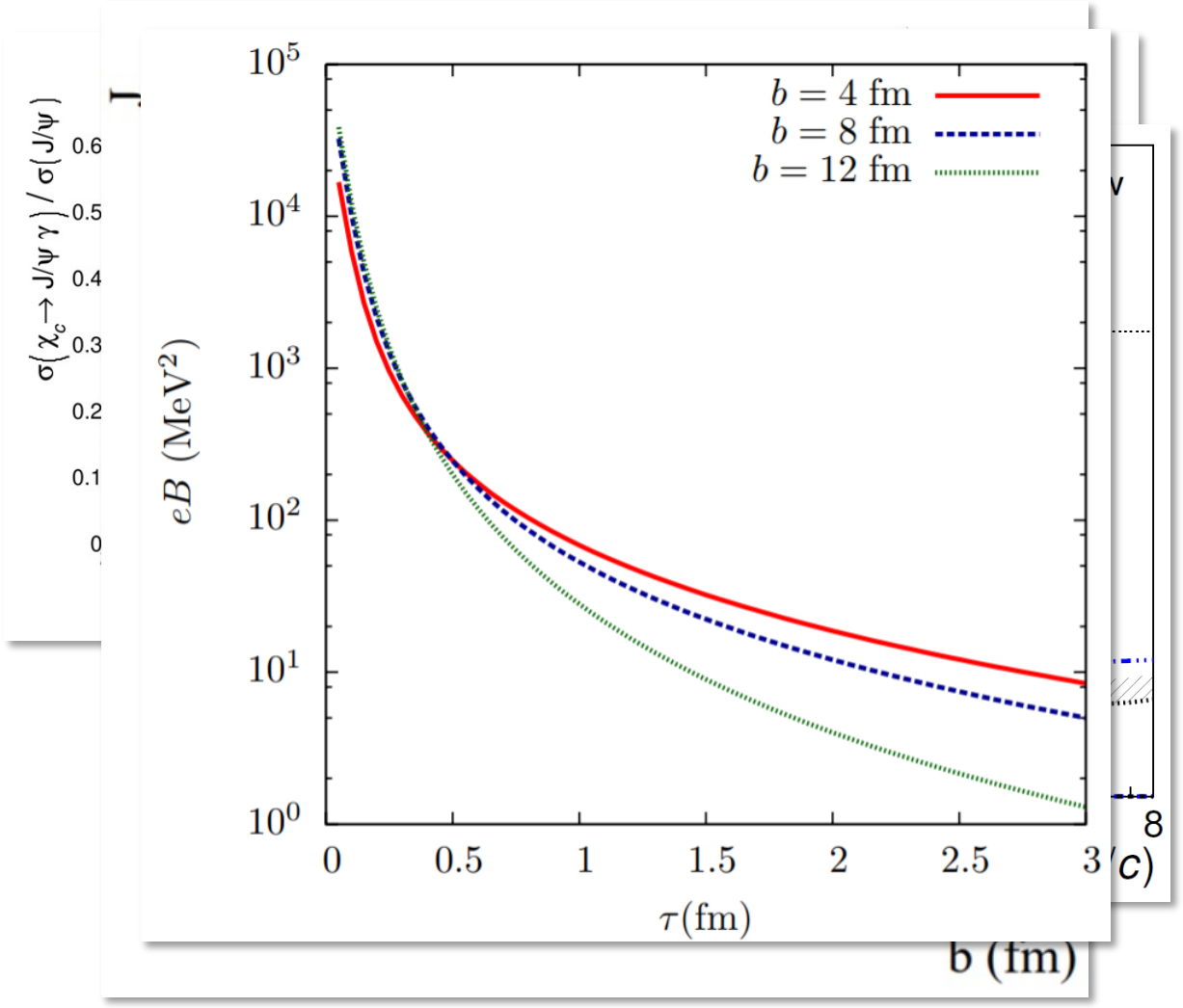


In non-central HICs…

- **Large angular momentum** due to the medium rotation is predicted

PRC 77 (2008) 024906, Becattini et al.

Polarization in AA: motivations



In non-central HICs…

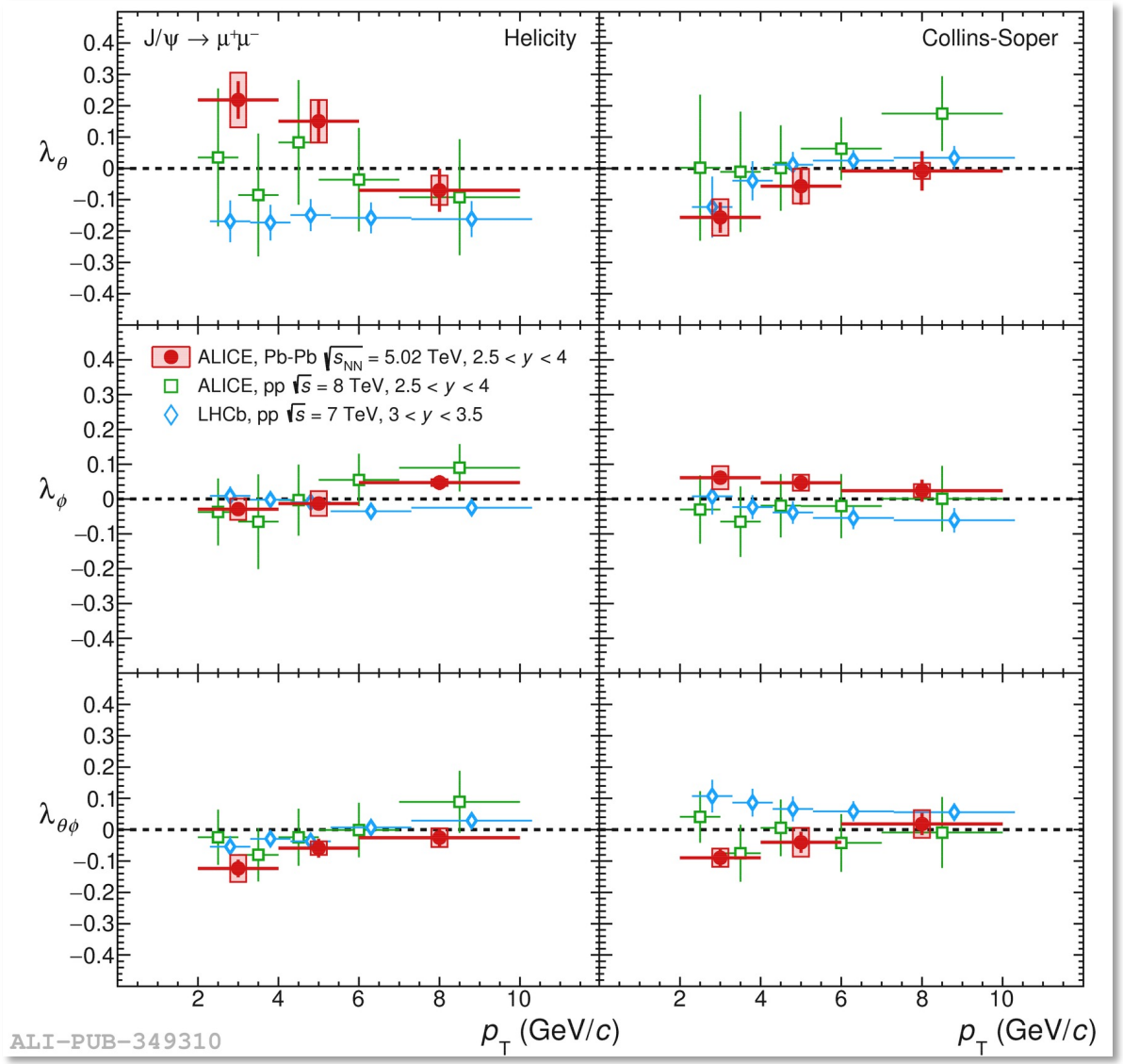
- **Large angular momentum** due to the medium rotation is predicted

  PRC 77 (2008) 024906, Becattini 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.

Polarization in AA: charmonia



- ALICE measured J/ψ polarization in Pb-Pb collisions

  PLB 815 (2021) 136146

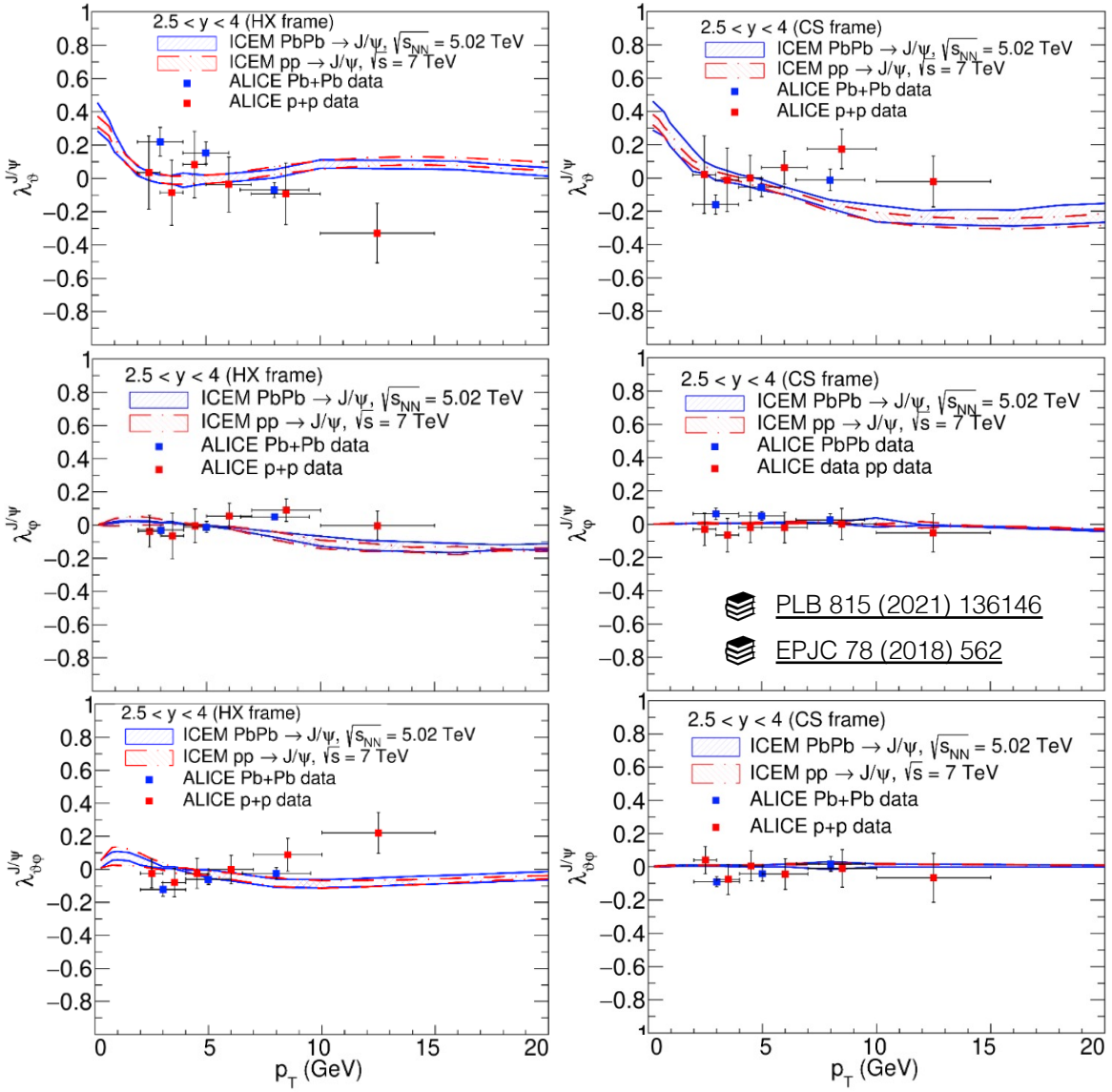
  - ❑ λ_θ shows a maximum 2σ deviation w.r.t zero in HE and CS for $2 < p_T < 4$ GeV/c
    - □ Compatible within the large uncertainties with ALICE results in pp collisions

      EPJC 78 (2018) 562, ALICE collaboration
    - ◇ 3σ difference with LHCb in pp collisions in HE

      EPJC 73 (2013) 11, LHCb collaboration

- ➢ Difference due to suppression/regeneration effect in Pb–Pb w.r.t. pp collisions?
- ➢ What is the role of the angular momentum ($\vec{L}$) and the magnetic fields ($\vec{B}$)?

Polarization in AA: charmonia



- Can **Cold Nuclear Matter** (CNM) effects modify J/ψ polarization in Pb-Pb collisions?

- **Improved Color Evaporation Model (ICEM)**
  - **Direct J/ψ** polarization (no feed-down)
  - **CNM** effects only in Pb-Pb
  - No **Hot Nuclear Matter** effects

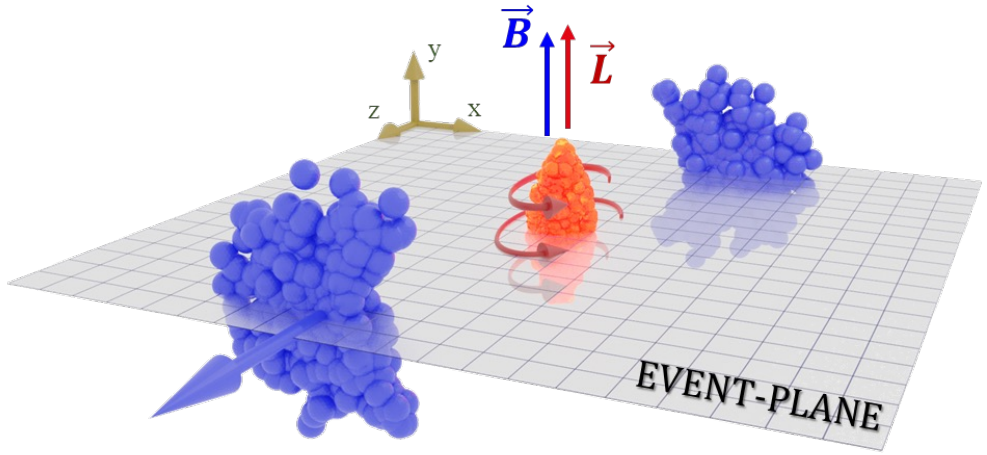
  PRC 105, 055202, Cheung, Vogt

- ICEM predicts small difference among pp and Pb-Pb results (assuming no QGP formation)
- CNM effects are not expected to modify significantly the polarization
- Impact of feed-down from excited states to be investigated

  - See Vincent Cheung talk

Polarization in AA: charmonia

Possibility to investigate the role of $\vec{L}$ and $\vec{B}$ with an ad hoc reference frame



Reference frame

- Event Plane based frame (EP): axis orthogonal to the event plane in the collision center of mass frame

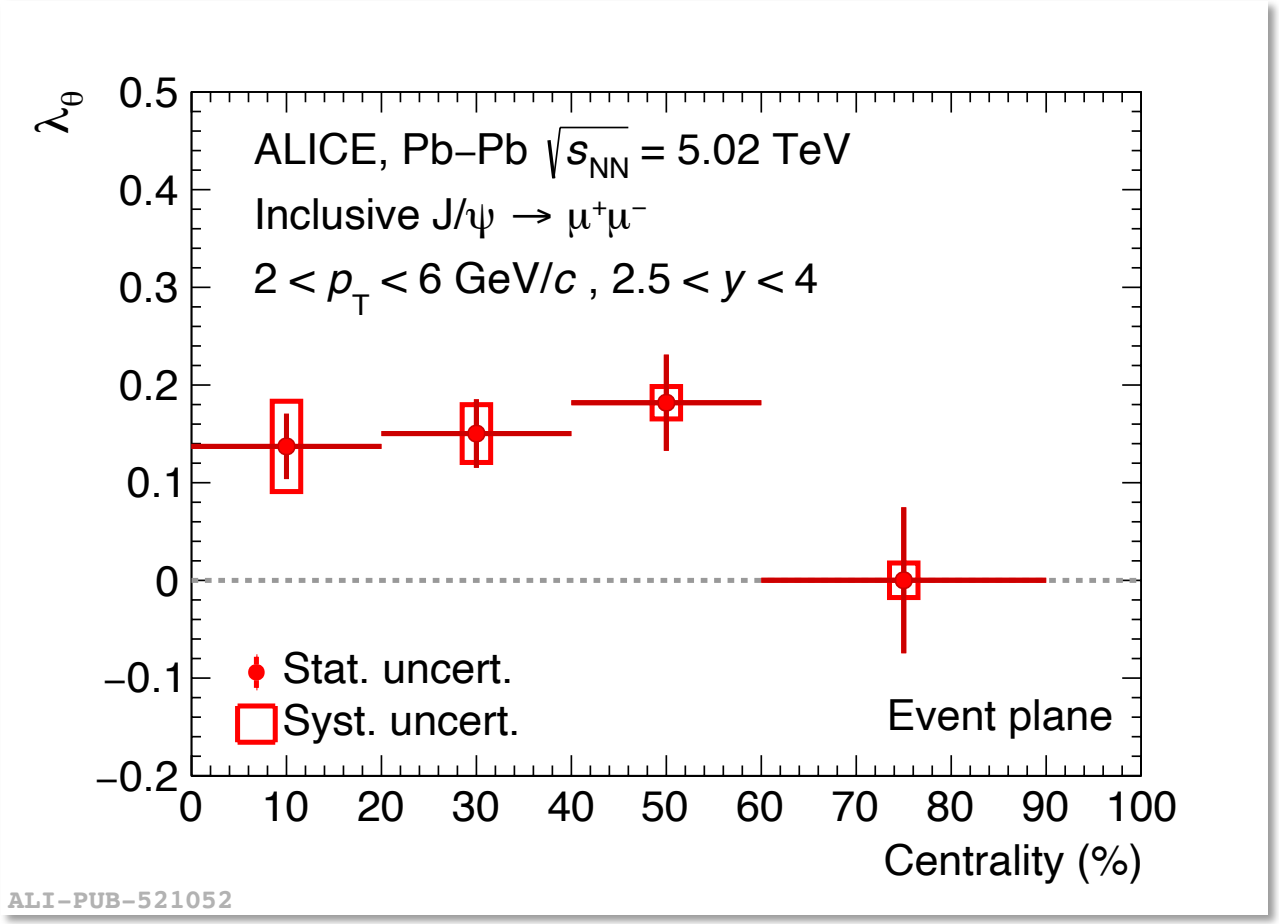
  - Event Plane normal to $\vec{B}$ and $\vec{L}$

  - Significant spin alignment observed for light vector mesons (K^{*0}, ϕ)

PRL 125 (2020) 012301

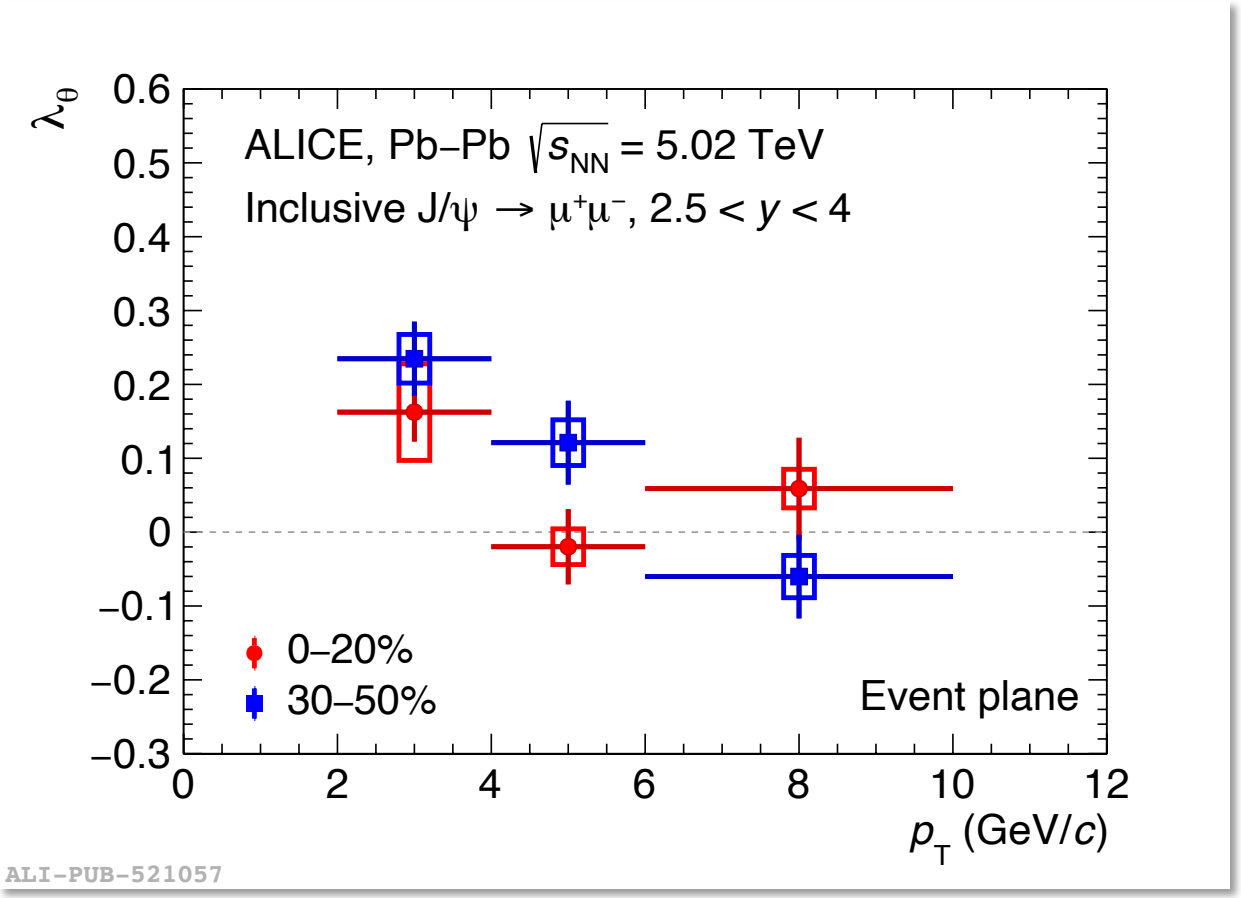
- Heavy quark pair production occurs early in the collision ($t \sim 0.1$ fm/c) and can experience both the short living $\vec{B}$ and the $\vec{L}$ of the rotating medium

Polarization in AA: charmonia



- First measurement of quarkonium polarization with respect to the Event Plane
  - Centrality dependence:
    Small but significant (3.5σ) polarization observed in 40-60% and $2 < p_T < 6$ GeV/c

Polarization in AA: charmonia



- First measurement of quarkonium polarization with respect to the Event Plane
  - p_T dependence:
    30-50%: significant deviation (3.9σ) at low transverse momentum ($2 < p_T < 4$ GeV/c)

- Similarly to light flavors (K^{*0}, ϕ) maximum polarization for semicentral collisions at low p_T

  PRL 125 (2020) 012301

  BUT

- Not clear which contribution (**vorticity** and / or **magnetic field**) is the dominant one
- Can similar approach, used for ϕ meson, be extended to J/ψ?

  arXiv:2205.15689, Xin-Li Sheng et al.

Summary and conclusions

pp collisions

J/ψ and $\Upsilon(1S)$ do not exhibit strong polarization in pp collisions

- Improved agreement among theoretical calculations (ICEM and NRQCD) and data

Only χ_c exhibits an indication of a strong polarization in pp collisions, as seen by CMS

A–A collisions

J/ψ does not exhibit strong polarization but some differences w.r.t. pp collisions in helicity and Collins-Soper reference frames

- First predictions are now available

J/ψ significantly deviates from zero in the event plane based reference frame

- Possibly related to the magnetic field and large angular momentum in AA collisions

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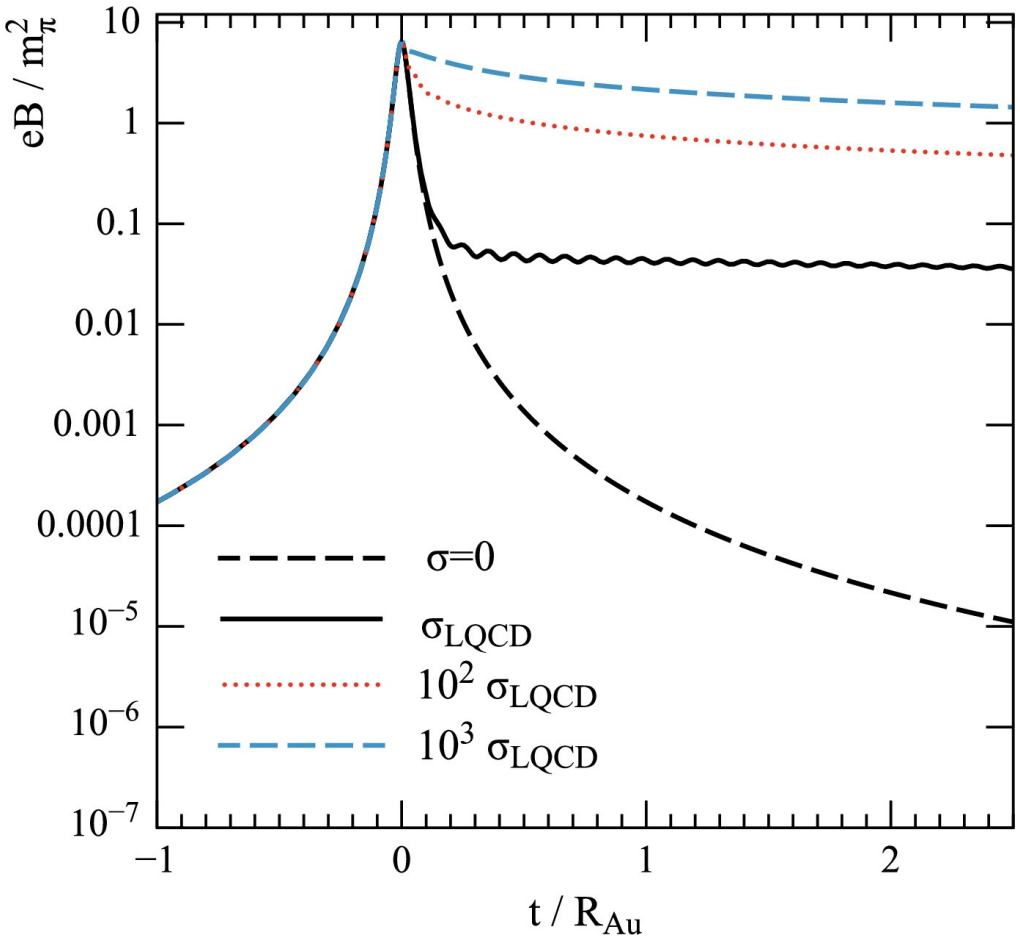
What's next?

Enable χ_c polarization measurement, improving the existing results

Extend the measurement to more species (quarkonia and open heavy flavors)

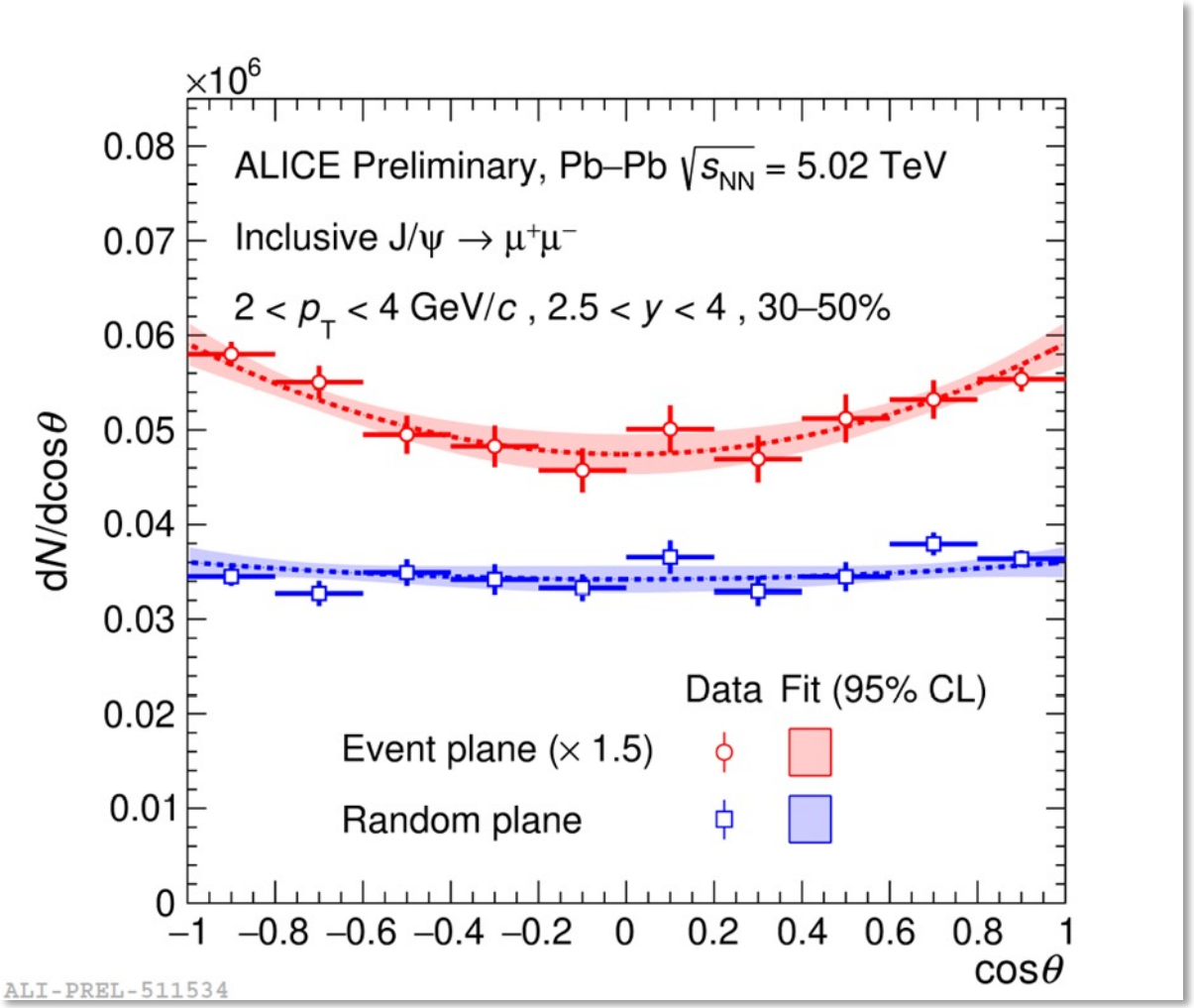
Backup

Magnetic field



Nuclear Physics A 929 (2014) 184–190

J/Ψ polarization w.r.t. the event plane



Polarization in pp: open charm

- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC

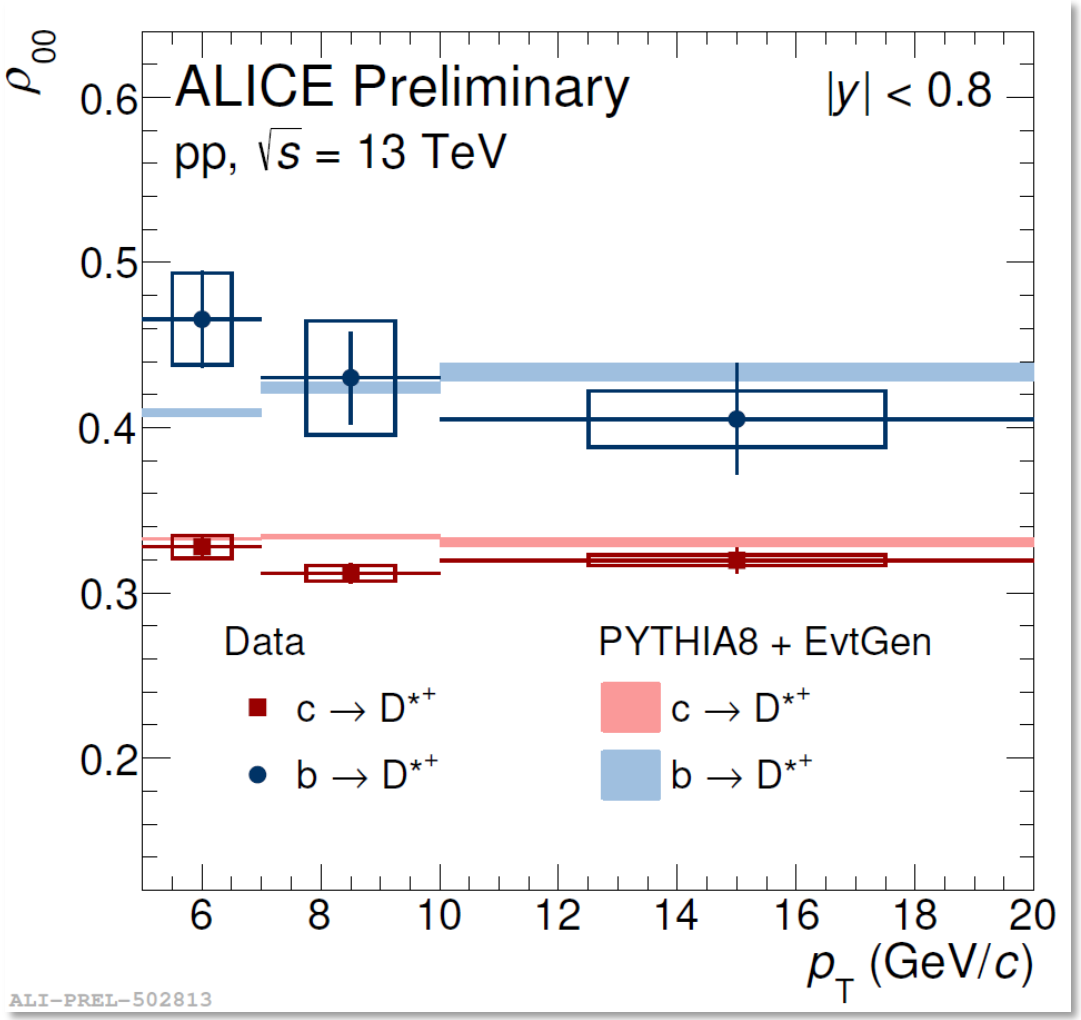
  - $\frac{dN}{d\cos\theta} \propto (1 - \boldsymbol{\rho_{00}}) + (3\boldsymbol{\rho_{00}} - 1)\cos^2\theta$

    - Spin density matrix element

      $\rho_{00} = 1/3 \implies$ No spin alignment

      $\rho_{00} \neq 1/3 \implies$ Spin alignment

- Measurement performed with respect to the helicity axis
- Prompt D^{*+} compatible with no polarization
- Non-prompt D^{*+} $\rho_{00} > 1/3$ due to the helicity conservation $(B(S = 0) \to D^{*+}(S = 1) + X)$



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      $\rho_{00} = {}^1/_3 \implies$ No spin alignment

      $\rho_{00} \neq {}^1/_3 \implies$ Spin alignment

- **PYTHIA8 + EvtGen** manages to describe both the components
- Important baseline for the measurement in nucleus-nucleus collisions