Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

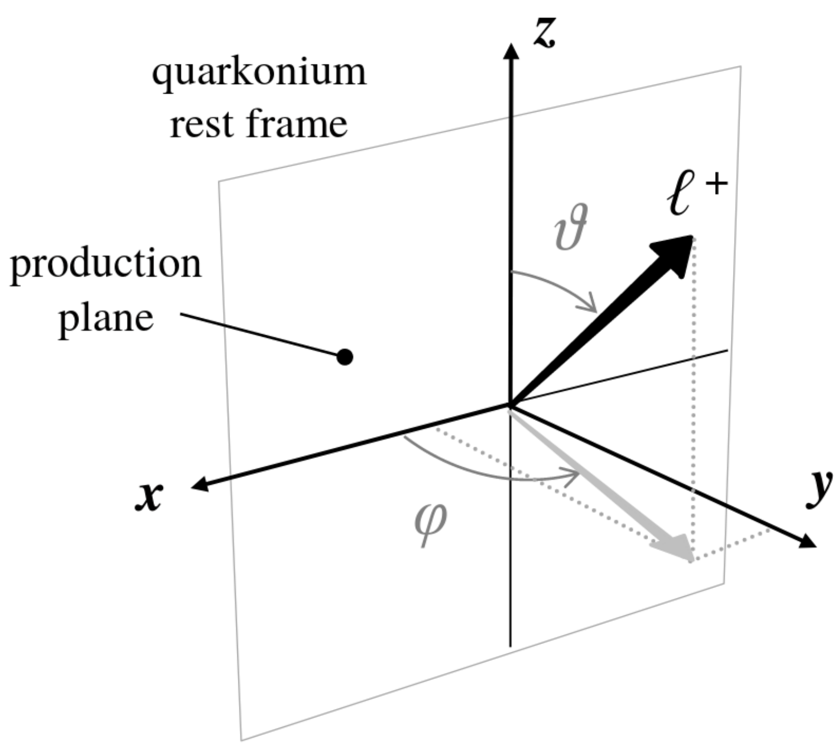
2 – 4 December 2022, UCLA

Quarkonia and heavy flavor polarization: recent results and future perspectives

Luca Micheletti (INFN Torino)

Polarization: an introduction

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



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

<u>Spin-alignment ⇔ decay products angular distribution</u>

<u>EPJC 69 (657-673), 2010</u>, Faccioli et al.

Dilepton decay angular distribution

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

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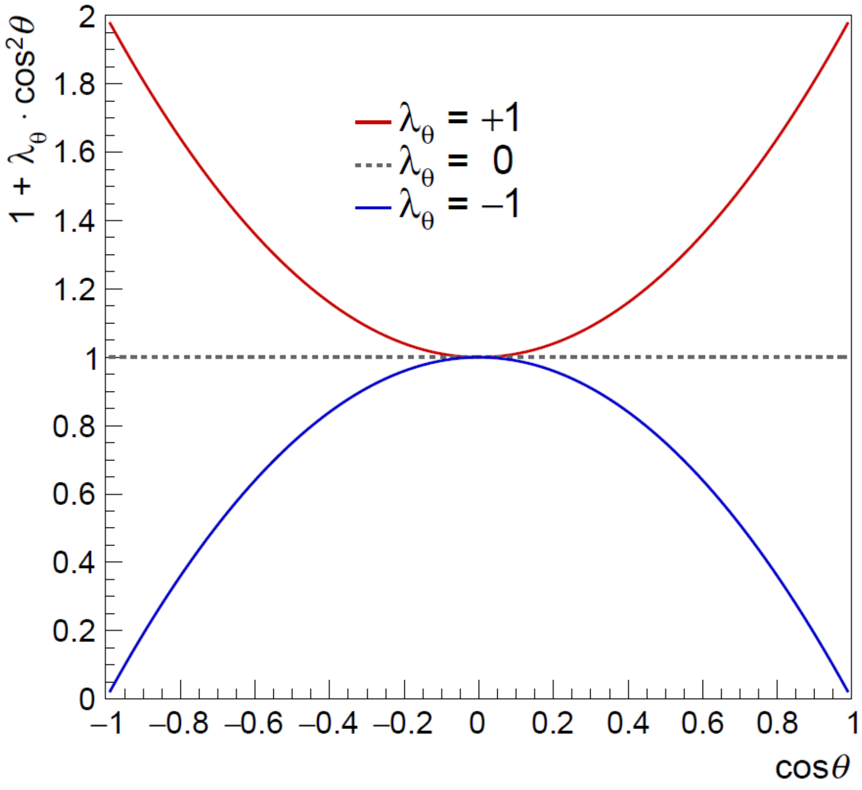

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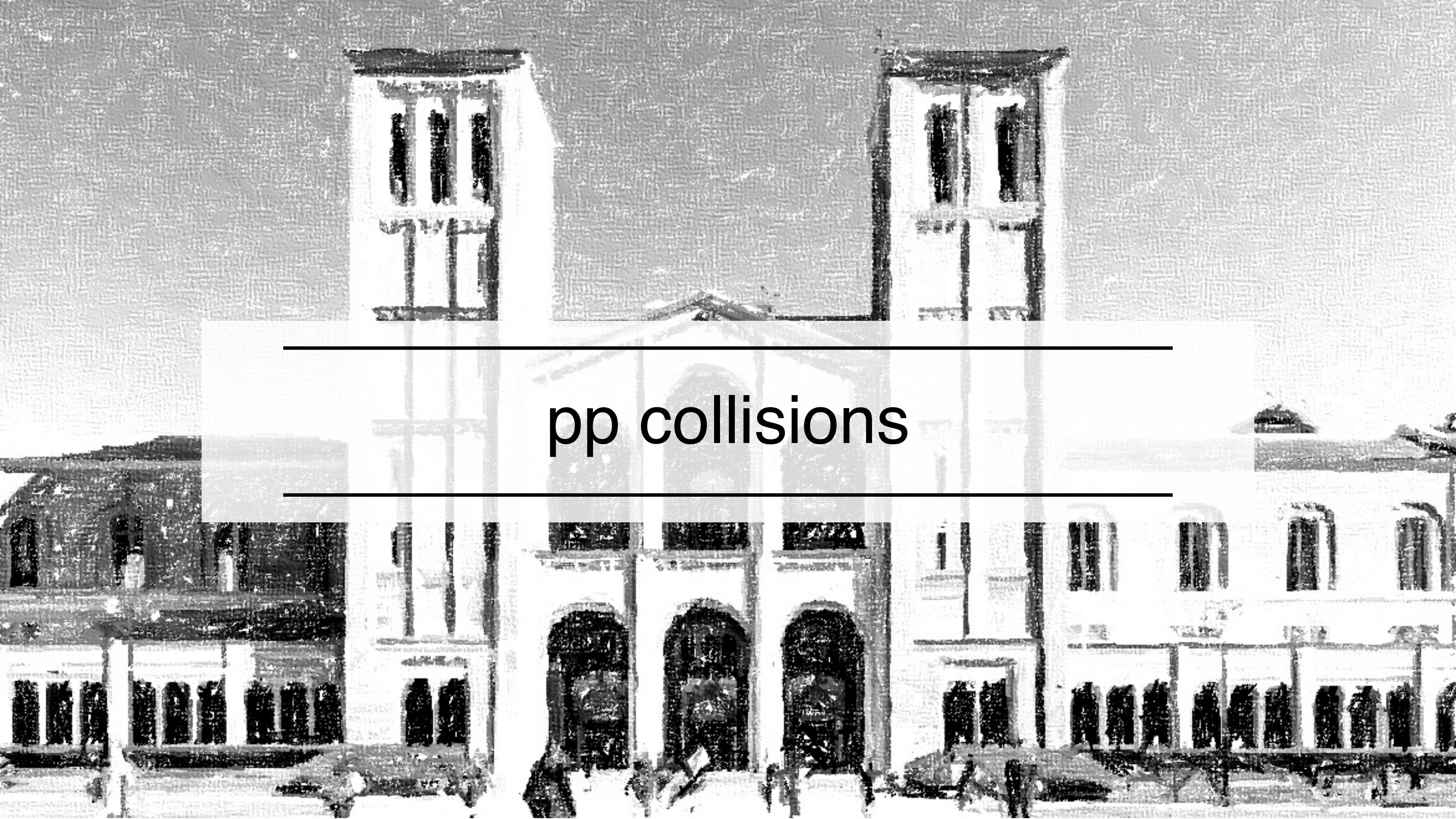
❑ Polarization parameters

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

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

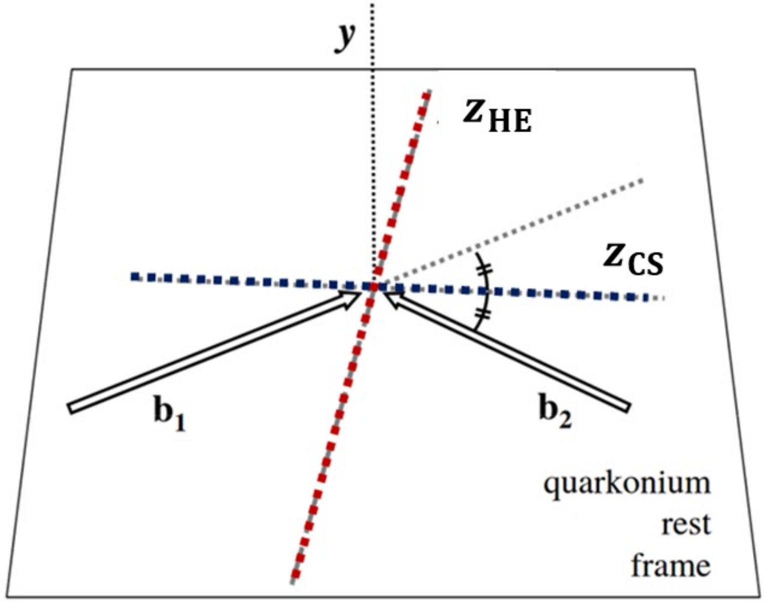
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0)$ ⟹ Longitudinal polarization

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

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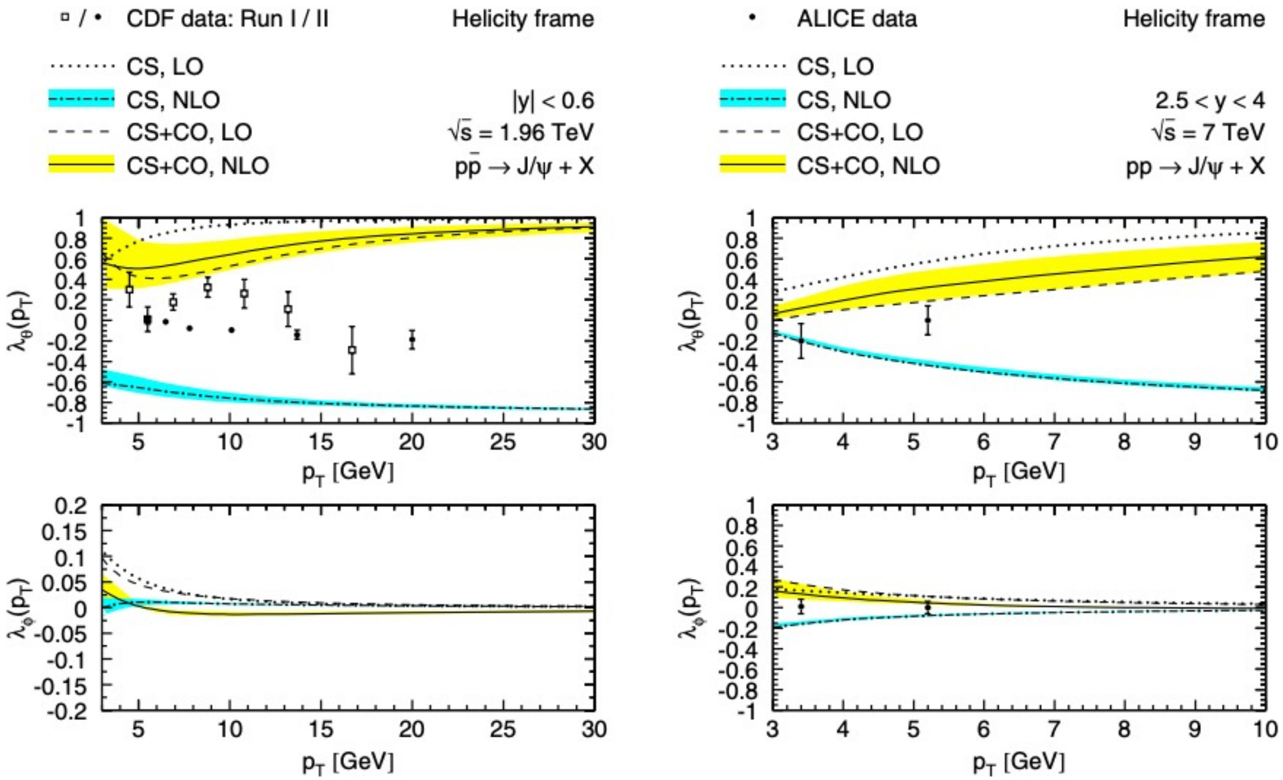

Phys. Rev. Lett. 108, 172002, Butenschoen et al.

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

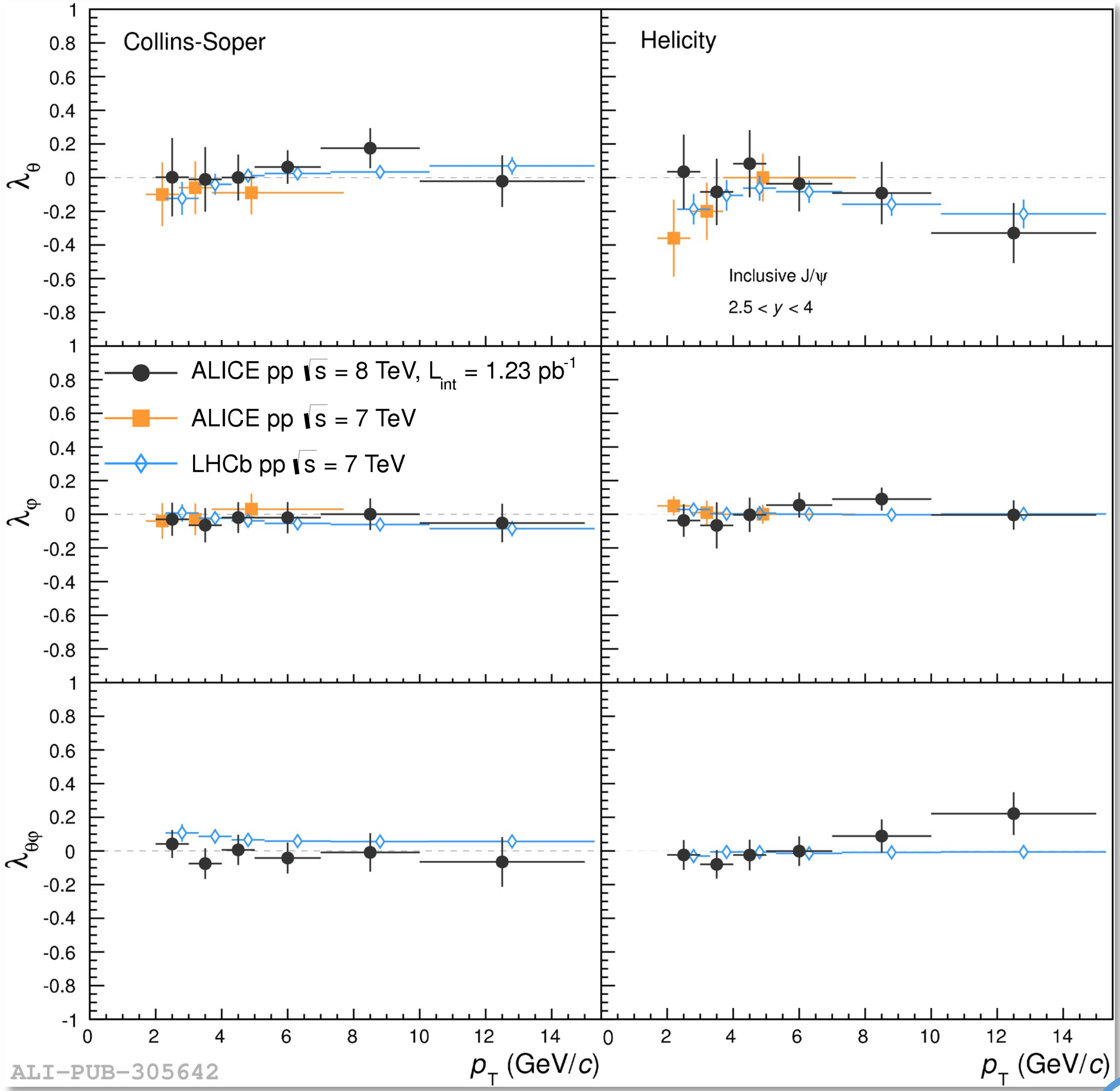
- …models provide different predictions for quarkonium polarization according to their **production mechanism**
  - **Color Singlet**: Longitudinal polarization
  - **NRQCD**: Transverse polarization

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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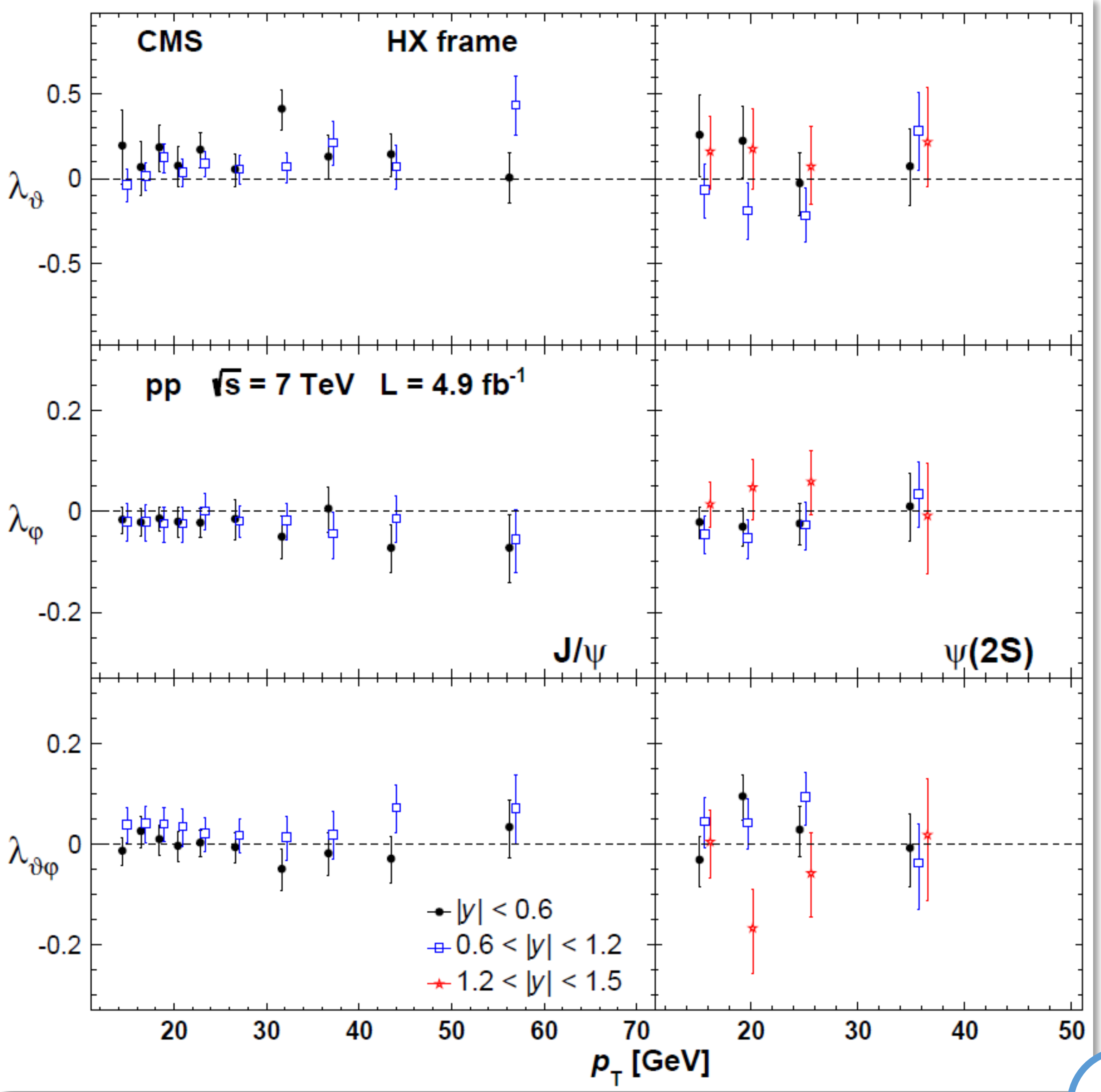
- No significant prompt J/ψ and $\psi(2S)$ polarization observed by **CMS** at midrapidity and up to p_T = 70 GeV/c (valid also for $\Upsilon(1S)$)

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



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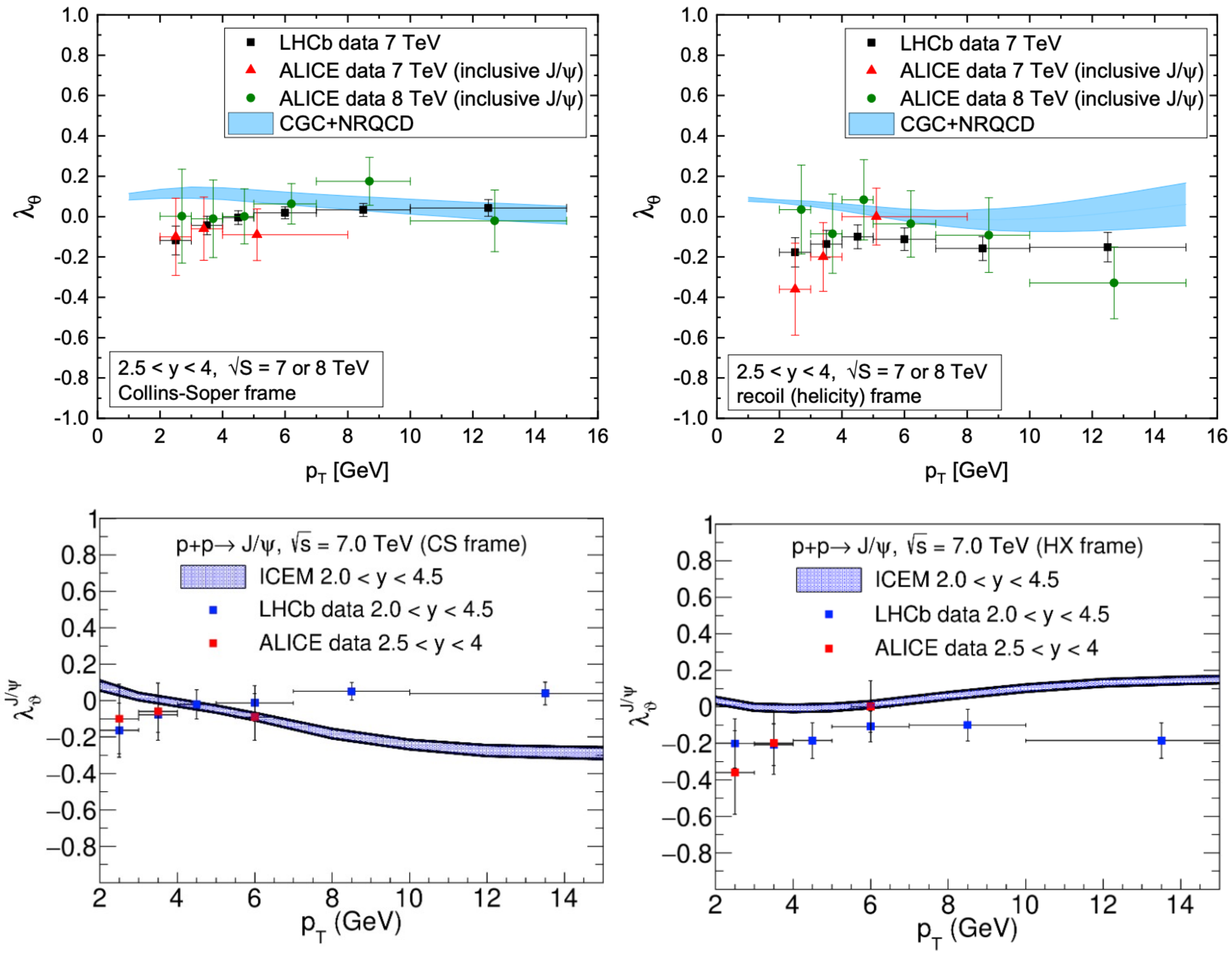
  PLB 727 (2013) 381 PLB 761 (2016) 31

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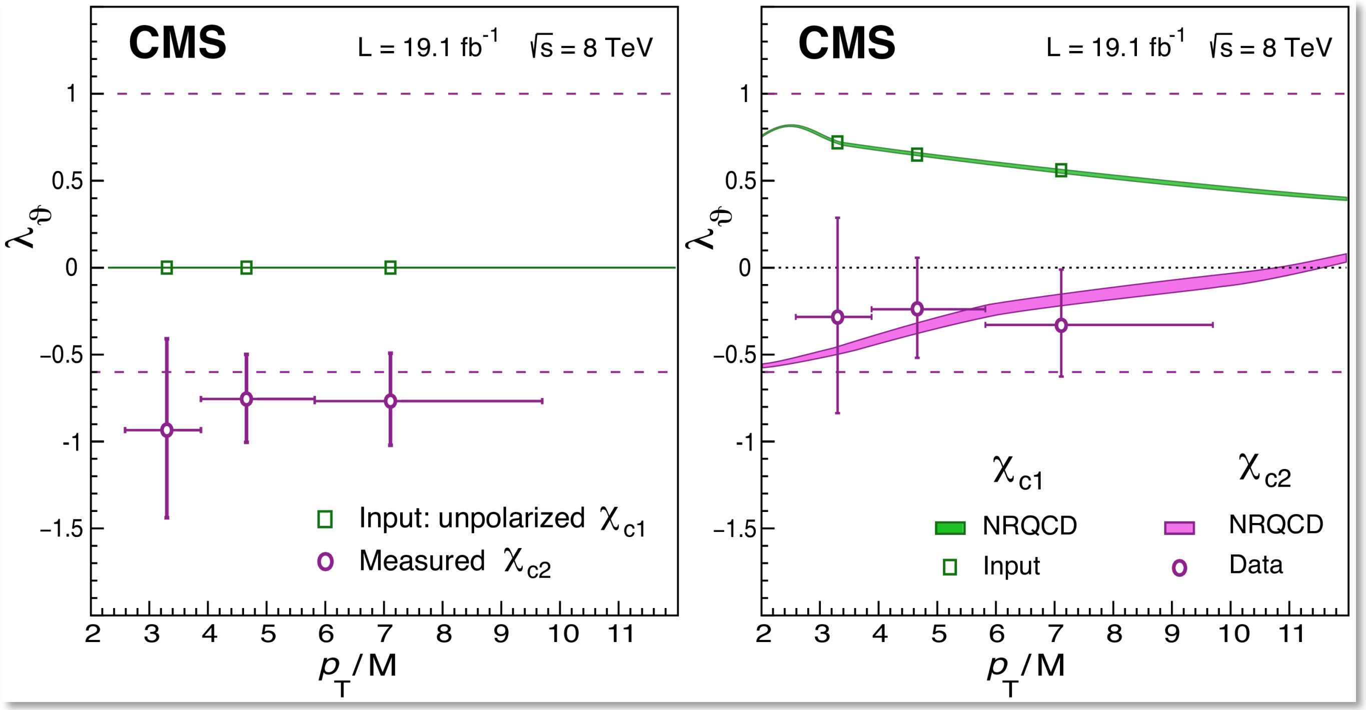
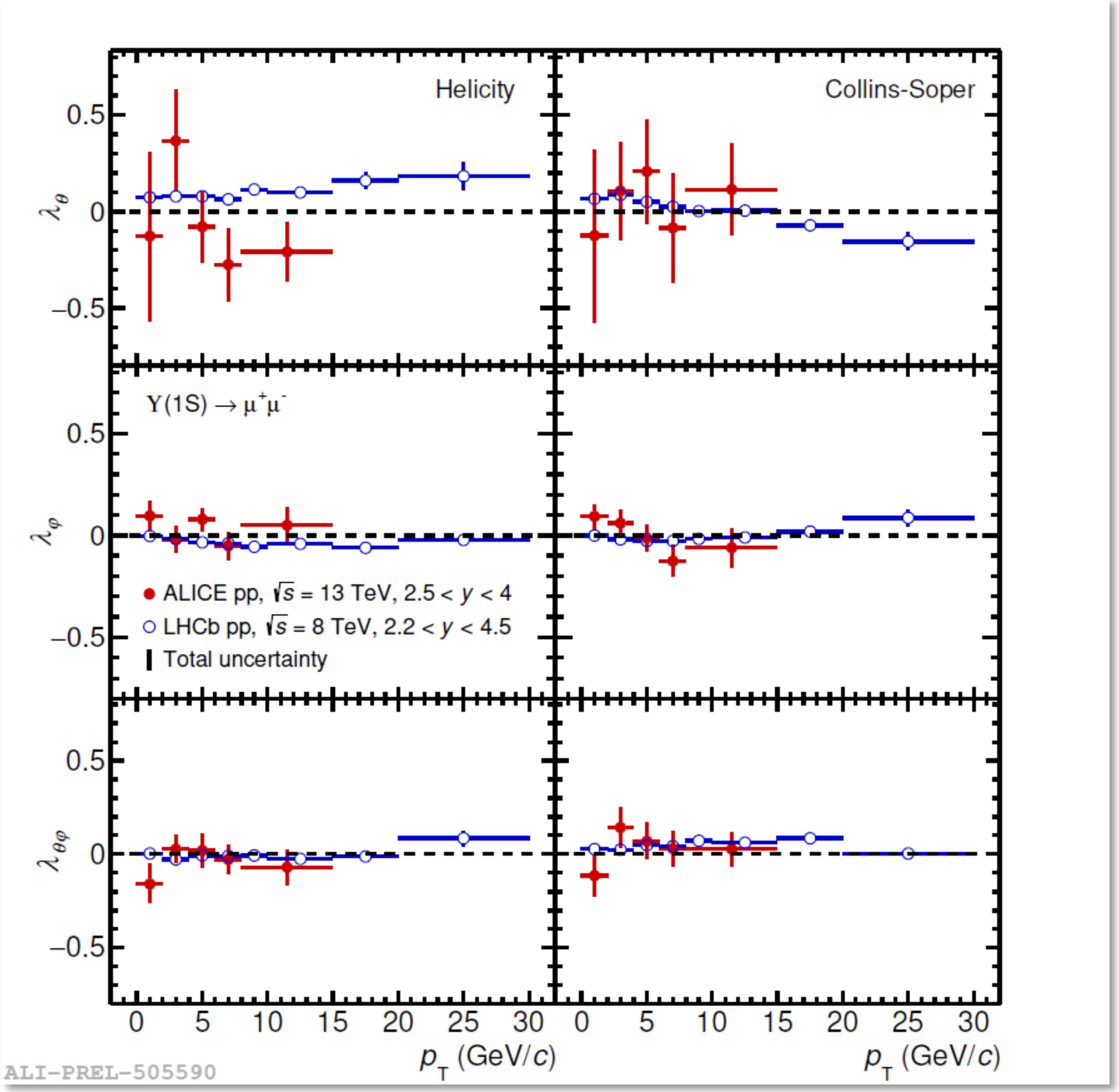
- Interestingly **CMS** observed a sizeable relative polarization between χ_{c1} and χ_{c2}, reproduced by NRQCD

  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 pp: open charm

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

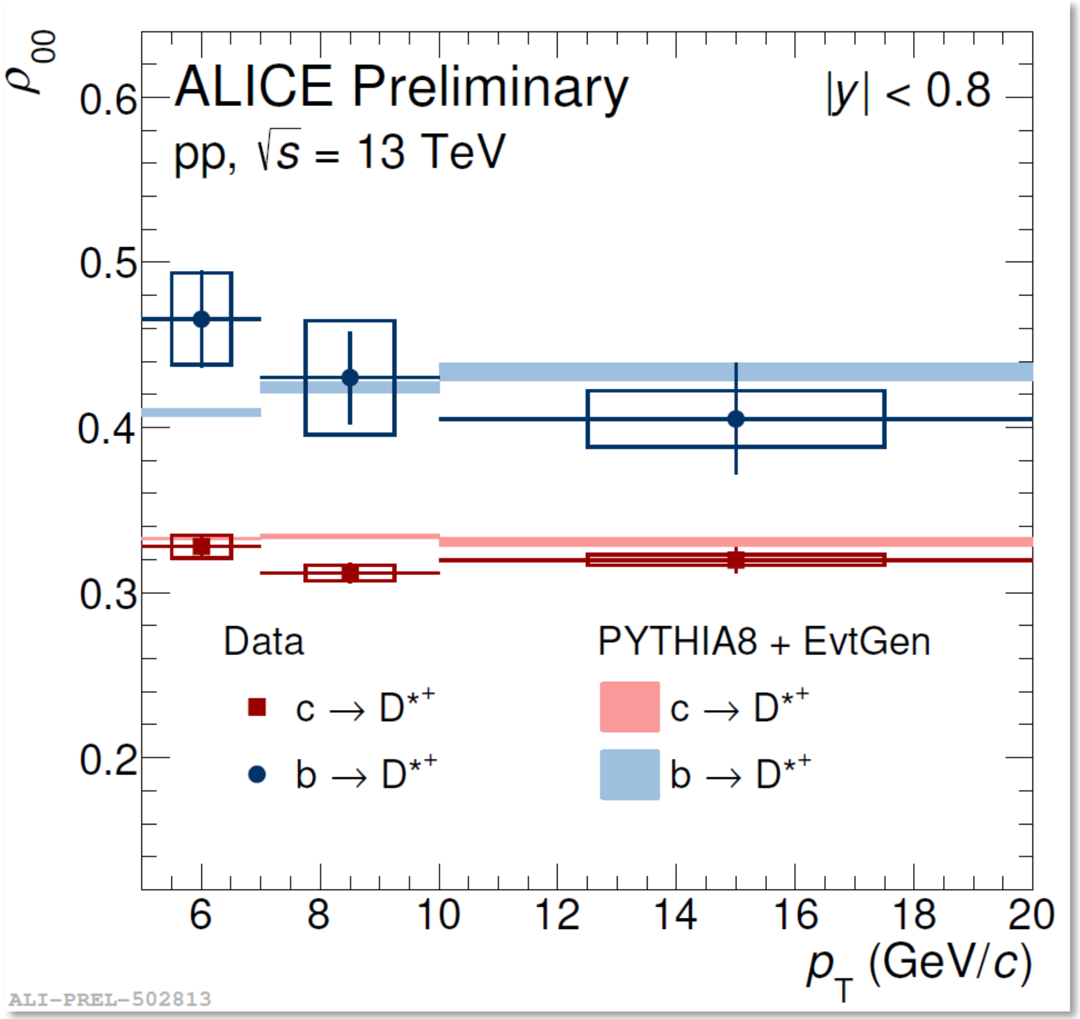
  - $\frac{dN}{d\cos\theta} \propto (1-\boldsymbol{\rho_{00}}) + (3\boldsymbol{\rho_{00}} - 1)\cos^2\theta$

    - Spin density matrix element

      $\rho_{00} = {}^{1}/_{3}$ $\Rightarrow$ No spin alignment

      $\rho_{00} \neq {}^{1}/_{3}$ $\Rightarrow$ 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 $(B(S=0) \rightarrow D^{*+}(S=1) + X)$



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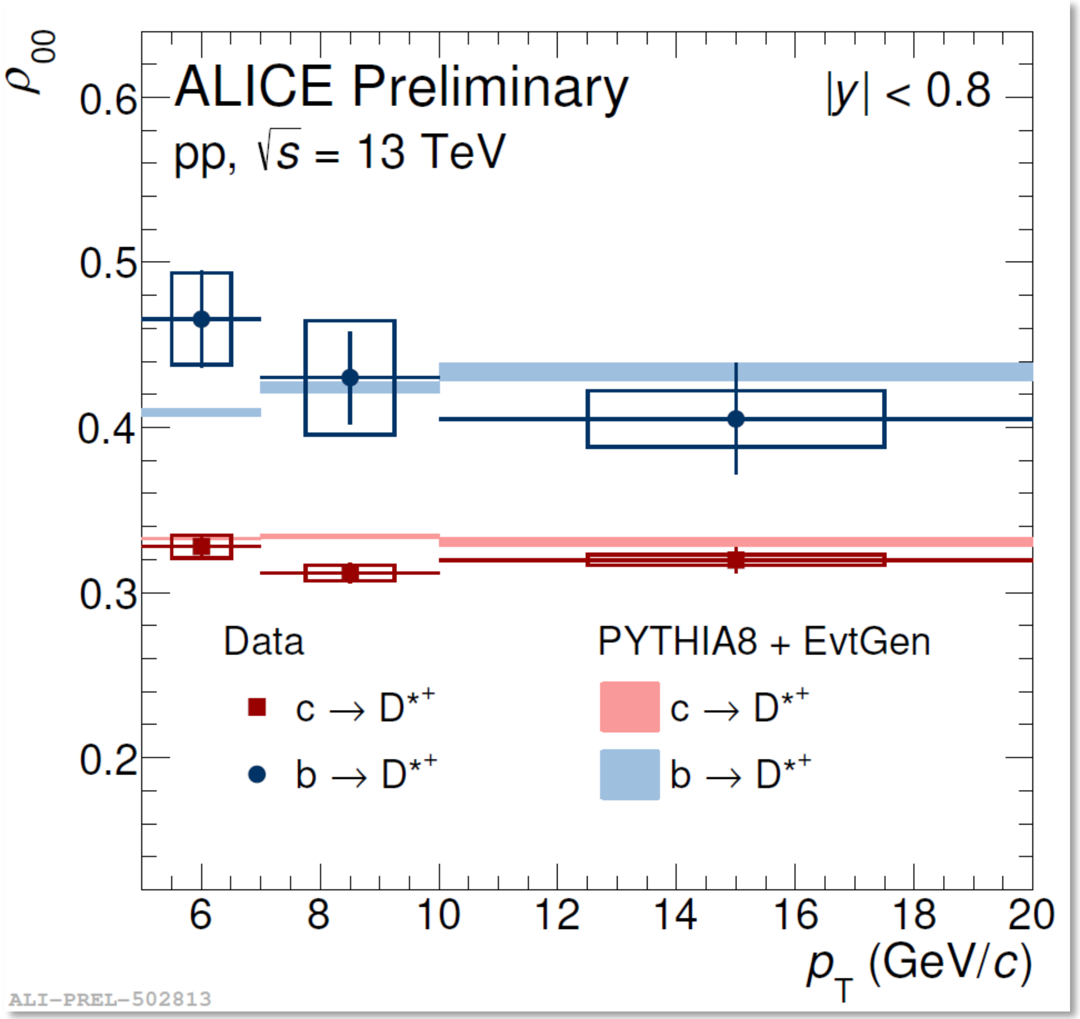
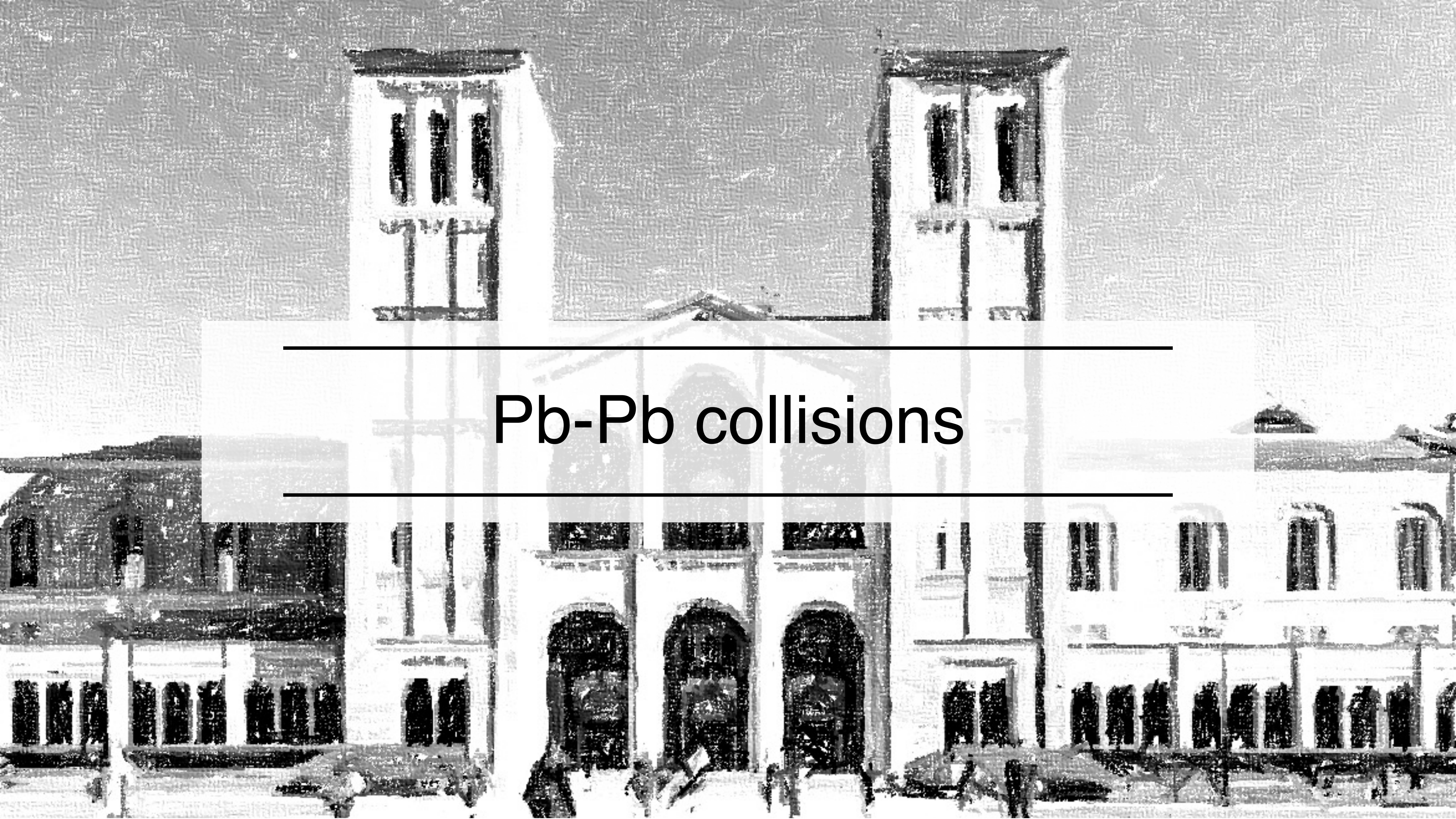
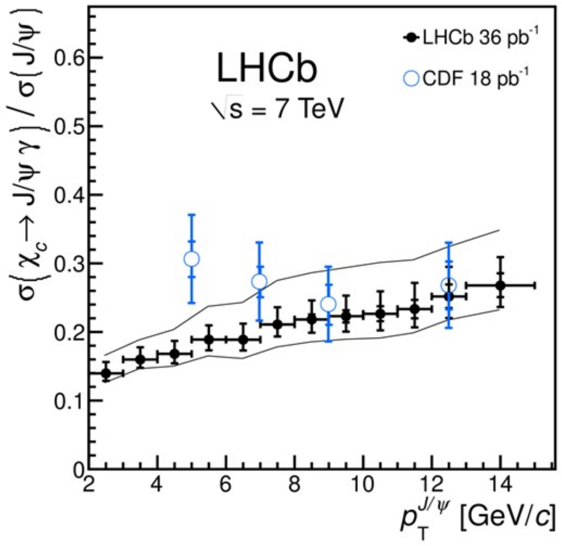
- PYTHIA8 + EvtGen manages to describe both the components
- Important baseline for the measurement in nucleus-nucleus collisions

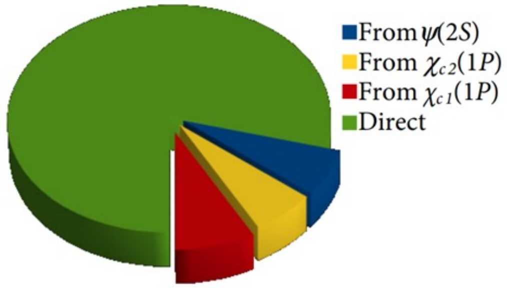




Pb-Pb collisions

Polarization in AA: motivations





PLB 718 (2012) 431

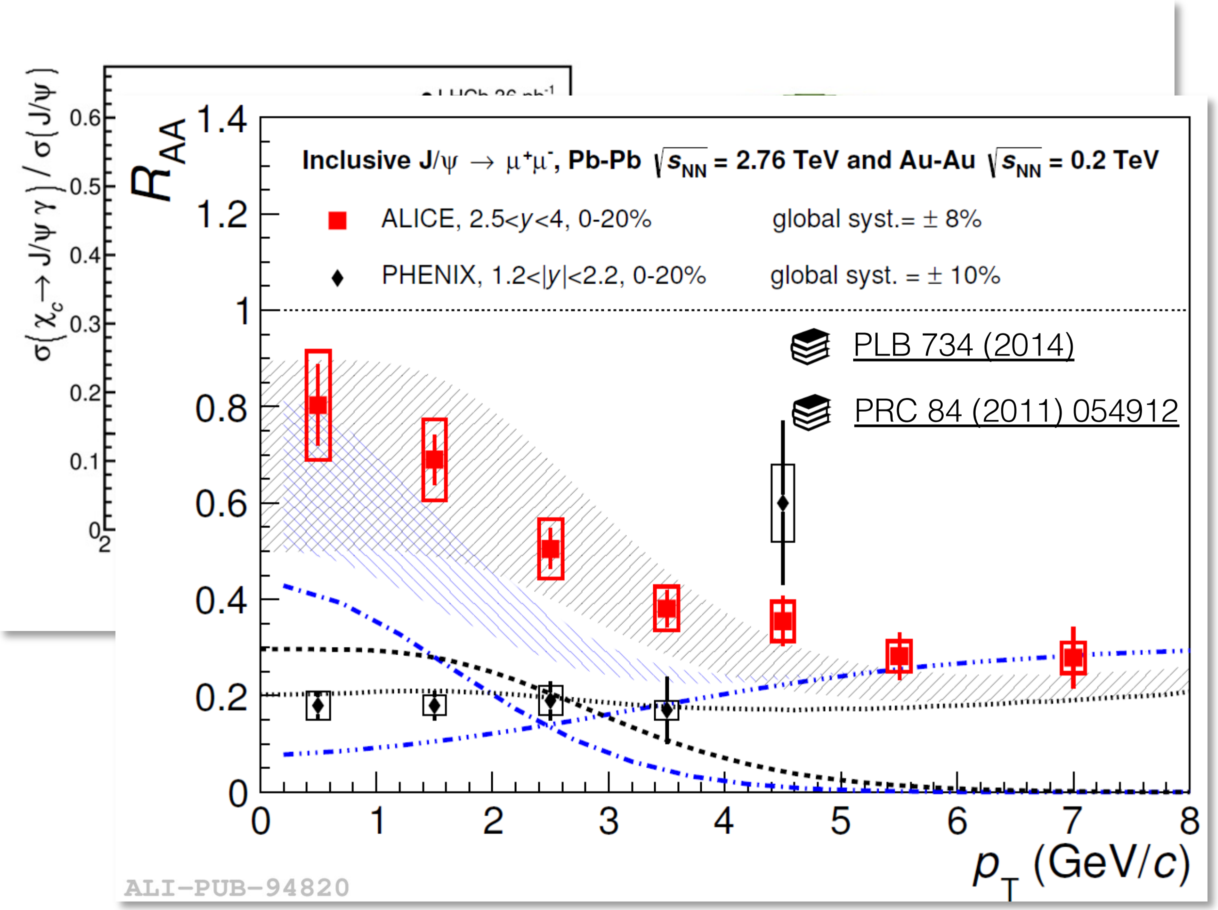
Phys.Rept. 889 (2020)

In central HICs…

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

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

Polarization in AA: motivations



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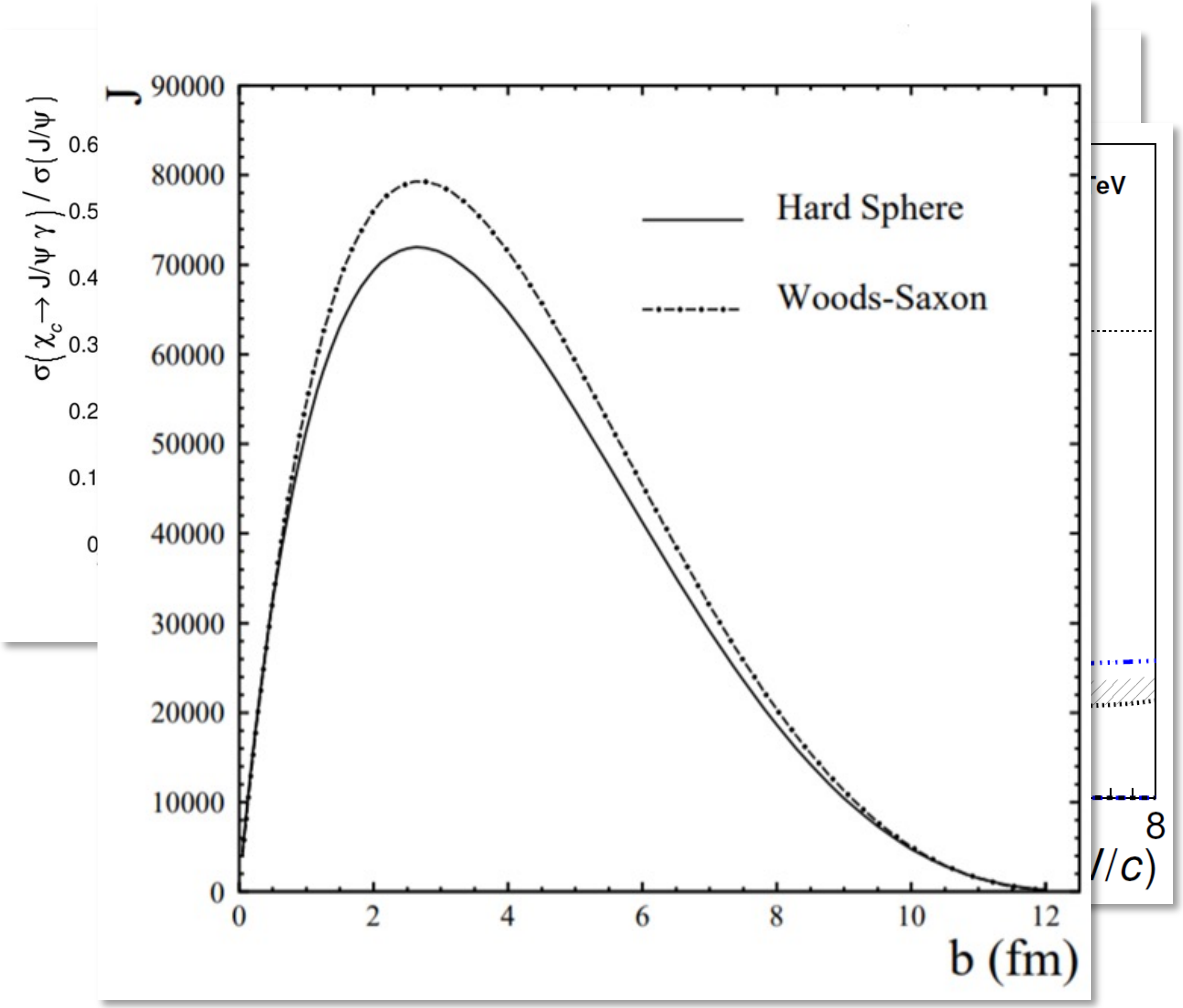
$$J/\psi^{\text{Prompt}} : (60\%)^{\text{Direct}} + (30\%)^{\chi_c} + (10\%)^{\psi(2S)}$$

- 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

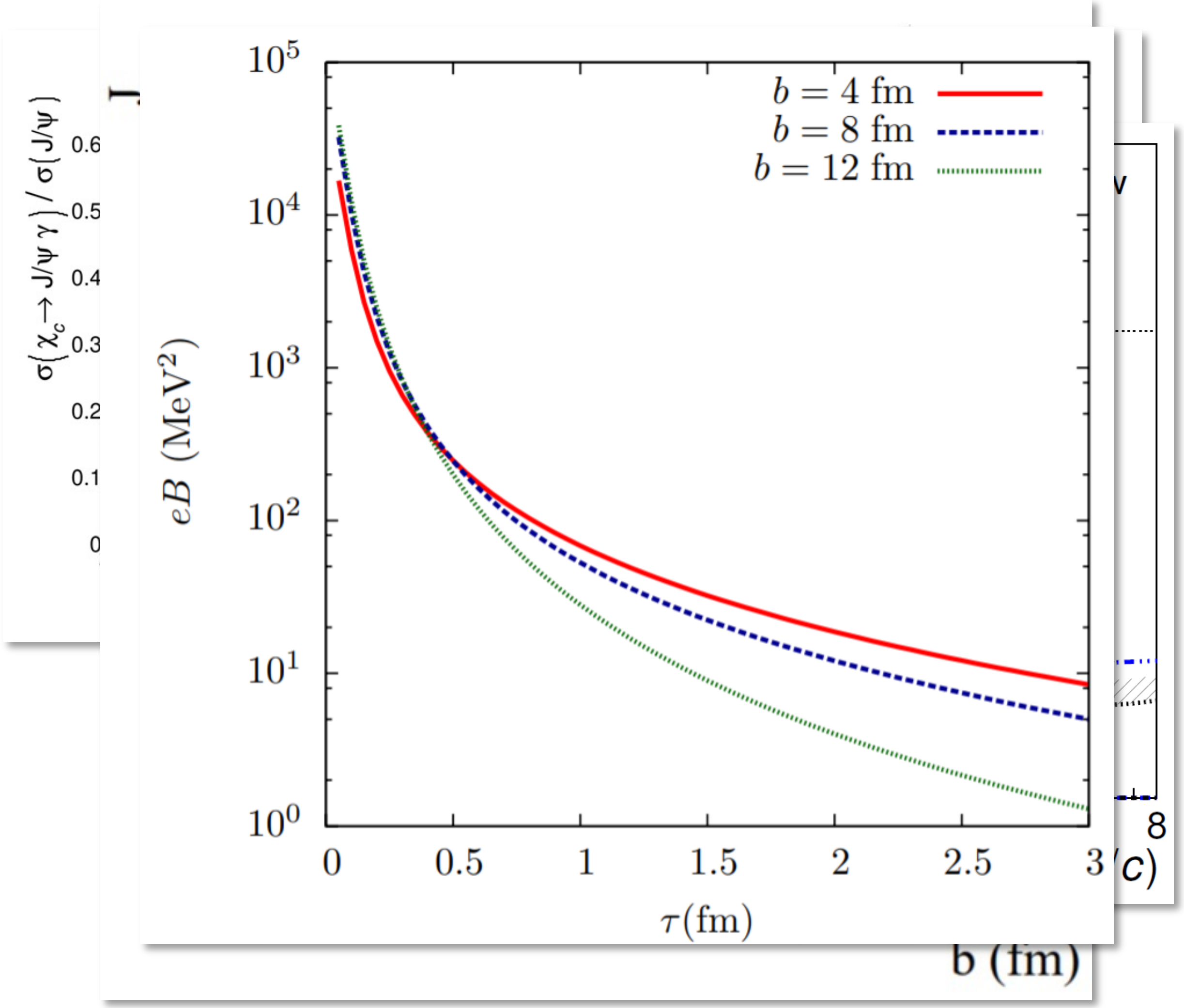


In non-central HICs…

- 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…

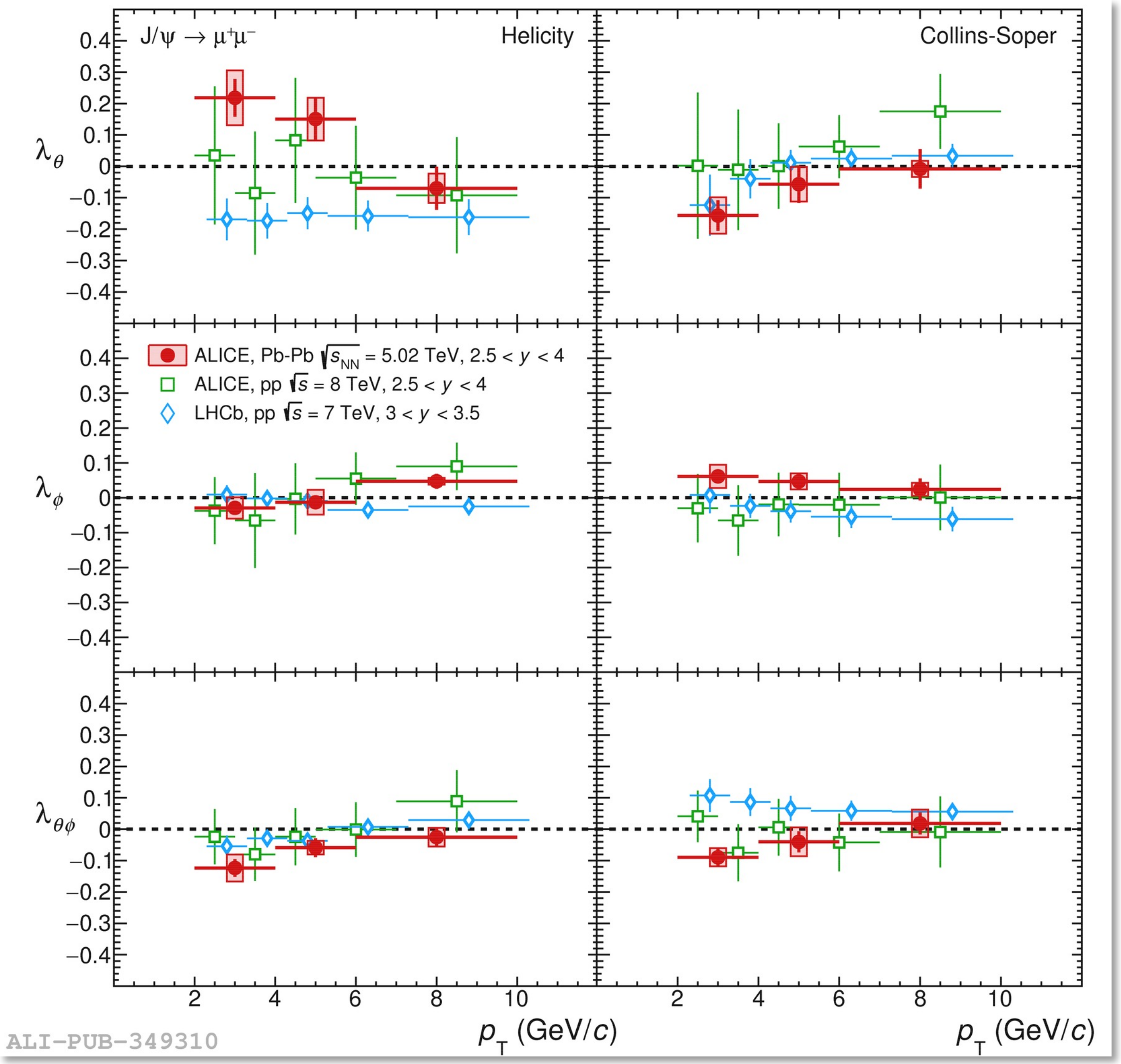
- ❑ **Large angular momentum** due to the medium rotation is predicted

  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

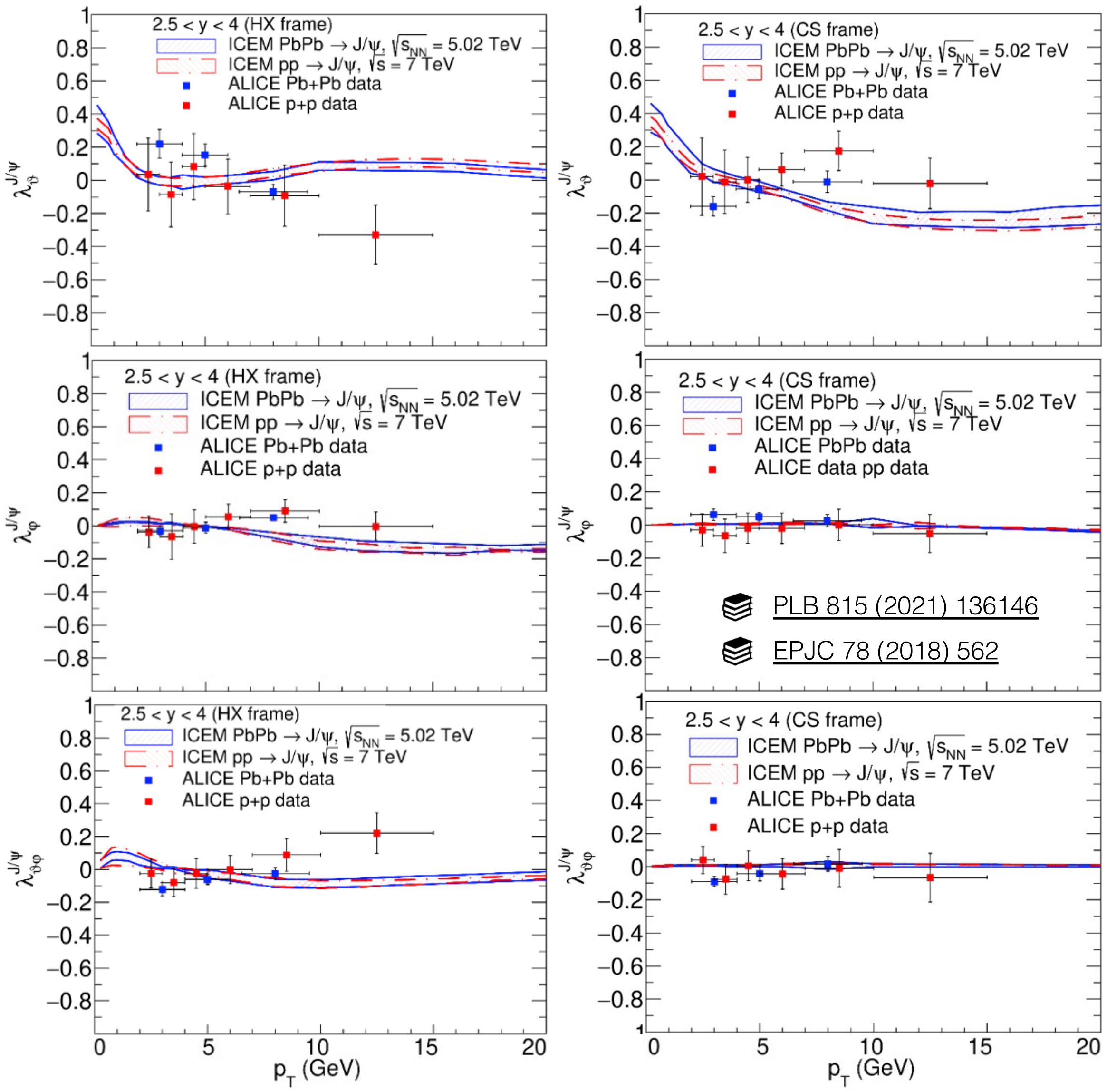
  - ◇ 3σ difference with LHCb in pp collisions in HE

    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?

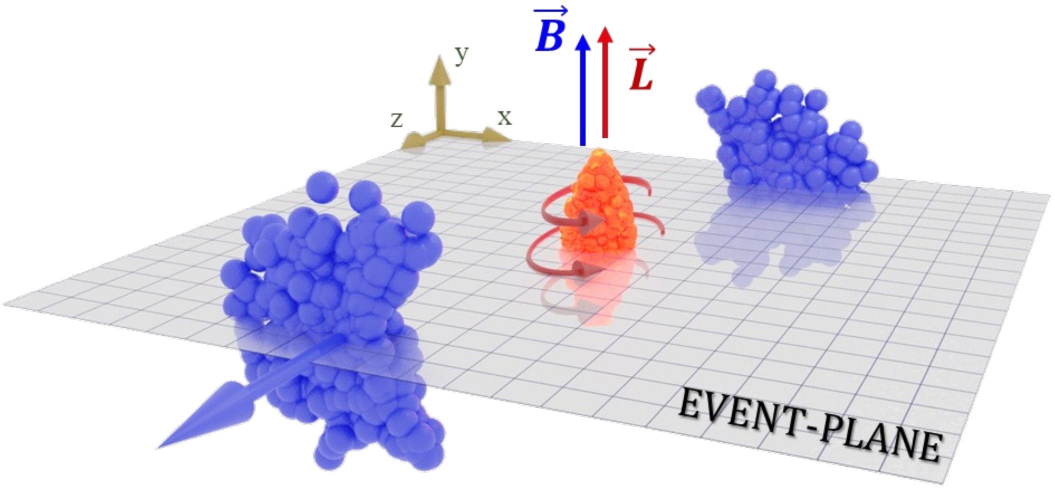
- **Improved Color Evaporation Model (ICEM)**
  - **Direct J/ψ** polarization (no feed-down)
  - **CNM** effects only in Pb-Pb
  - No **Hot Nuclear Matter** effects

  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

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

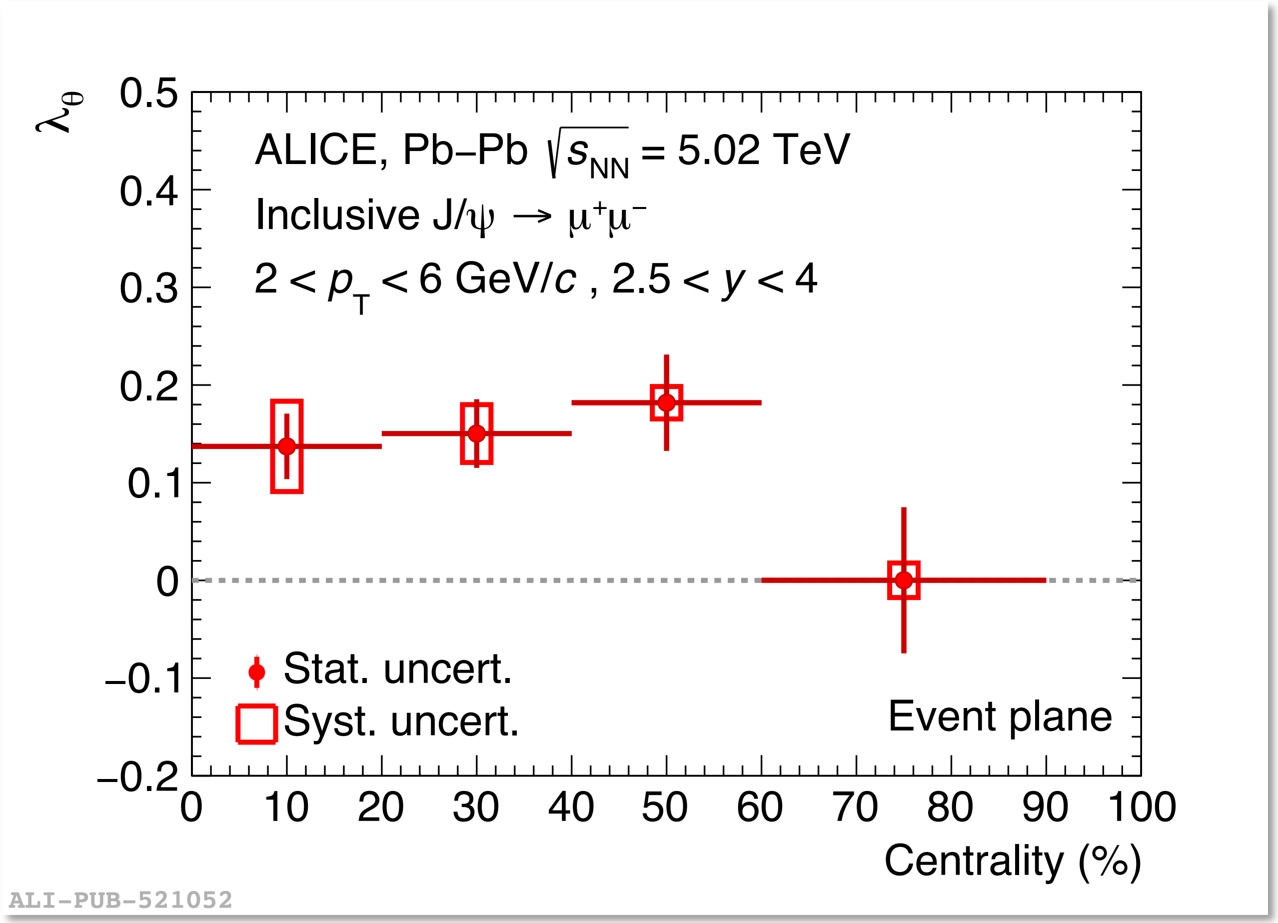
❑ Event Plane normal to $\vec{B}$ and $\vec{L}$

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

PRL 125 (2020) 012301

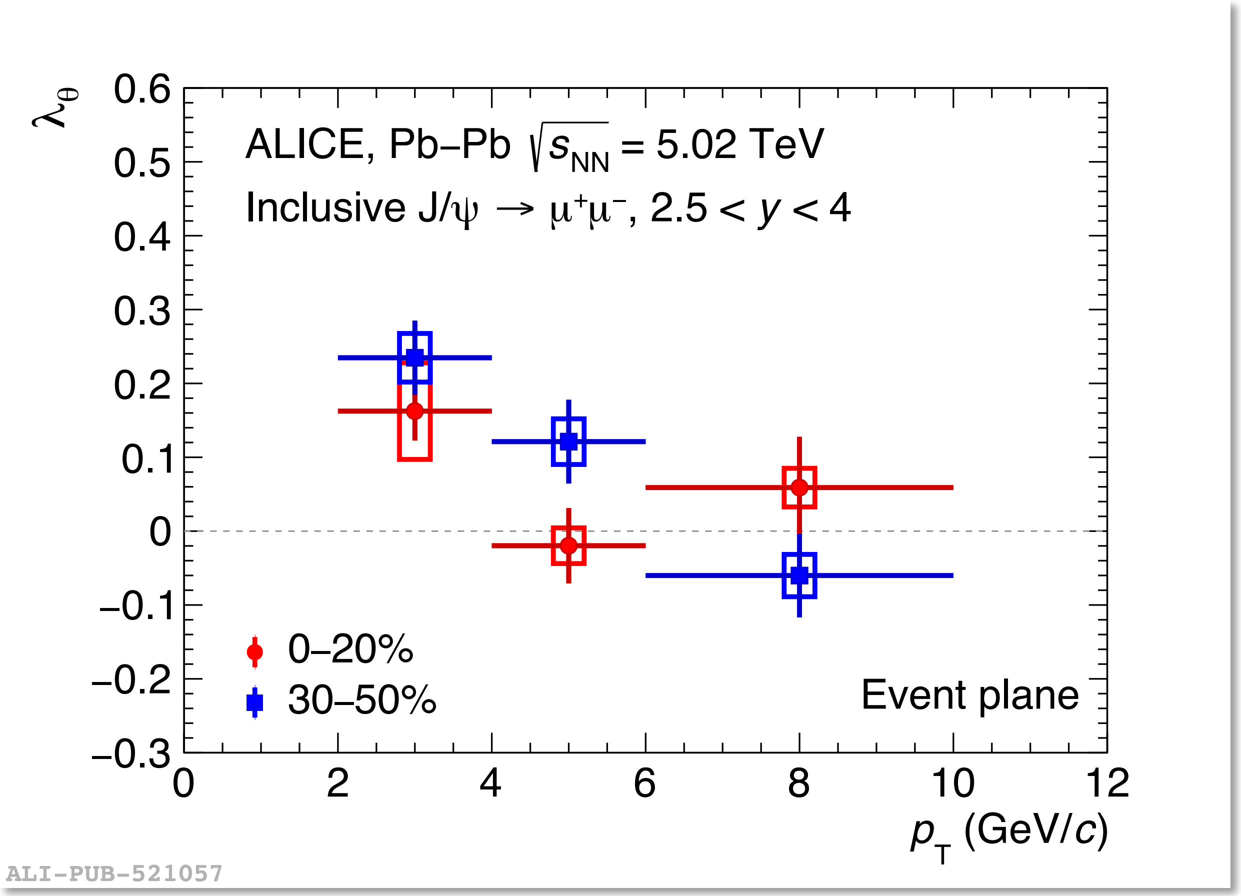
❑ Heavy quark pair production occurs early in the collision $(t \sim 0.1\ fm/c)$ and can experience both the short living $\vec{B}$ and the $\vec{L}$ of the rotating medium

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.

Perspectives

Perspectives

pp collisions

What we know?

Quarkonia:
- No strong polarization for J/ψ, $\psi(2S), \Upsilon(\mathrm{n}S)$
- Indication of strong (relative) polarization for χ_c

- Improved agreement among theoretical calculations and data with ICEM and NRQCD

Open charm:
- ρ_{00}~$1/3$ for prompt D^*
- $\rho_{00} > 1/3$ for non-prompt D^*

- PYTHIA + EvtGen in good agreement with data

What's next?

- Extend the measurement down to $\mathrm{p_T} = 0$ and for prompt and non-prompt
- Possibility to improve the precision of the χ_c measurement
- Extend the measurement to other species (important baseline for AA)

Perspectives

A-A collisions

What we know?

- Quarkonia:
  - J/ψ does not exhibit strong polarization but some differences w.r.t. pp collisions
  - J/ψ exhibits a significant polarization when measured w.r.t. the event plane
- First predictions available (no suppression and regeneration included in the model)

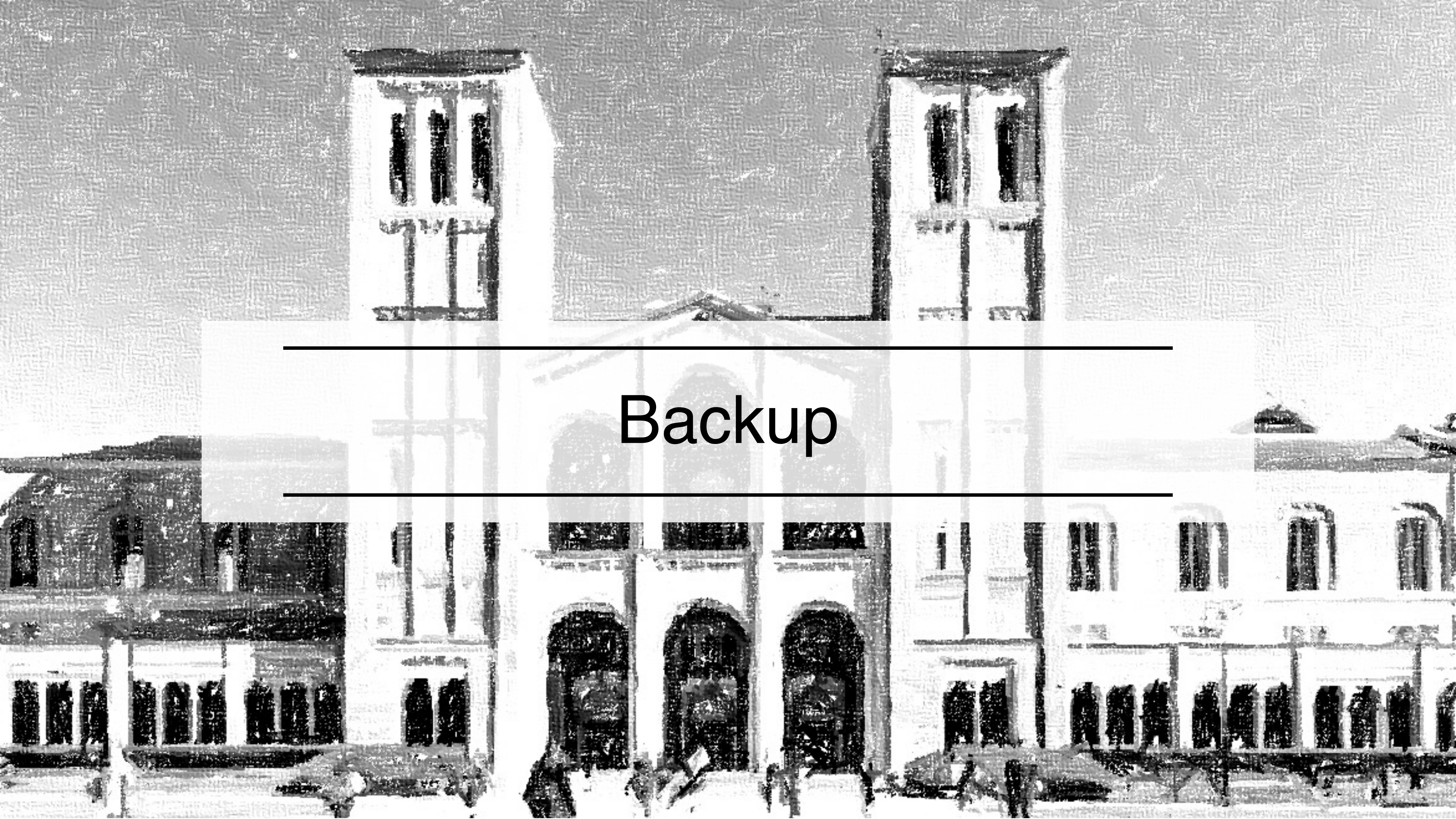
- Open charm:
  - No measurement available for the moment

What's next?

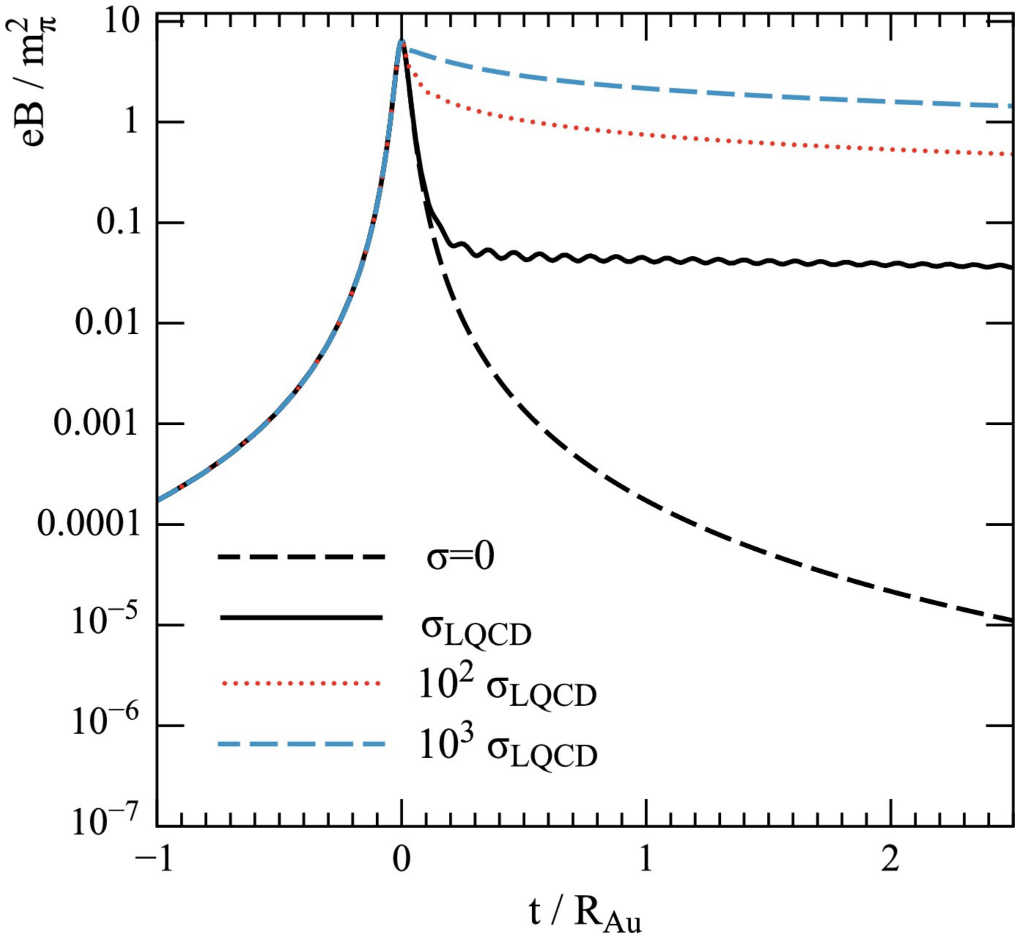
- Perform the same measurement at central rapidities for J/ψ
- Perform a precise measurement of the $\Upsilon(1S)$
  - b quarks produced before c quarks
  - no significant regeneration observed

- Evaluate ρ_{00} for D^{*} in Pb-Pb collisions
- Evaluate ρ_{00} for D^{*0} could help in disentangling magnetic field and vorticity effects

Backup

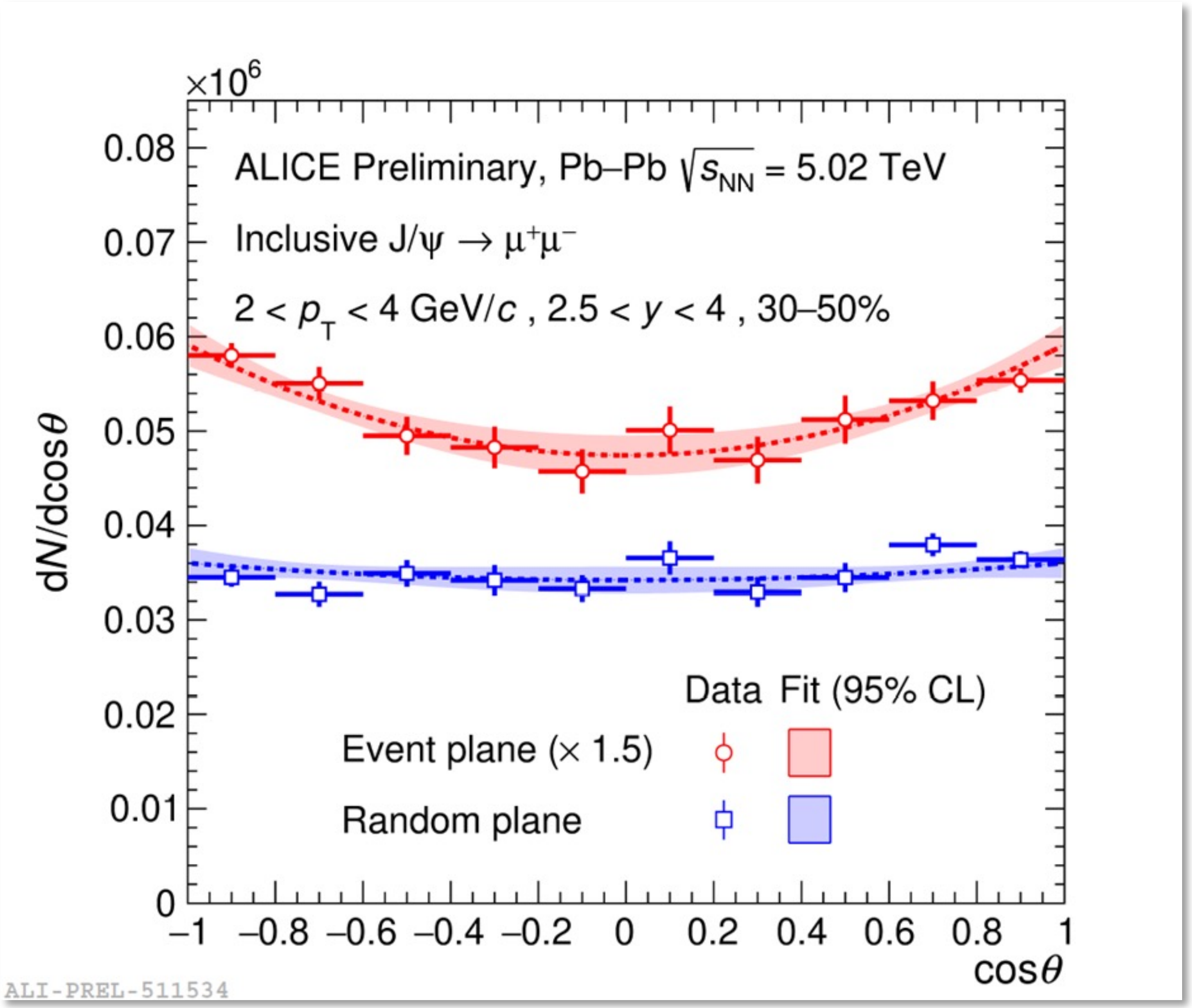


Magnetic field



Nuclear Physics A 929 (2014) 184–190

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



Quark coalescence model

PHYSICAL REVIEW C 97, 034917 (2018)

$$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2 < \frac{1}{3}$$

$$\rho_{00}(B) \sim \frac{1}{3} - \frac{1}{9}\beta^2 \frac{Q_1 Q_2}{m_1 m_2} B^2$$

- **Vorticity contribution**: independent of quark flavor and always negative
- **Magnetic field contribution**: depends on the quark electric charges

➢ ρ_{00} for vector mesons depends on the competing effects of vorticity and magnetic field