RHIC-BES seminar – 09/05/2023

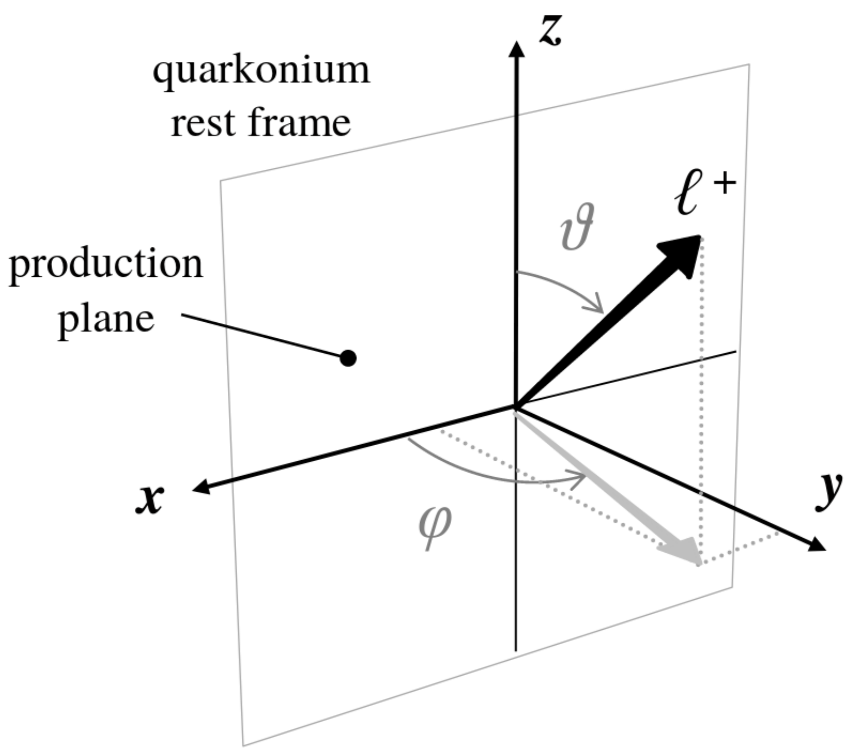
Vector meson polarization from pp to Pb-Pb collisions at the LHC

Luca Micheletti (INFN Torino)

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Polarization: an introduction

For a vector meson (ν) the total angular momentum ($\mathrm{J}, \mathrm{J_z}$) state can be expressed as:



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

Polarization ⇔ decay products angular distribution

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

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

- θ and ϕ: polar and azimuthal angle of the daughter particle with respect to the **quantization axis**

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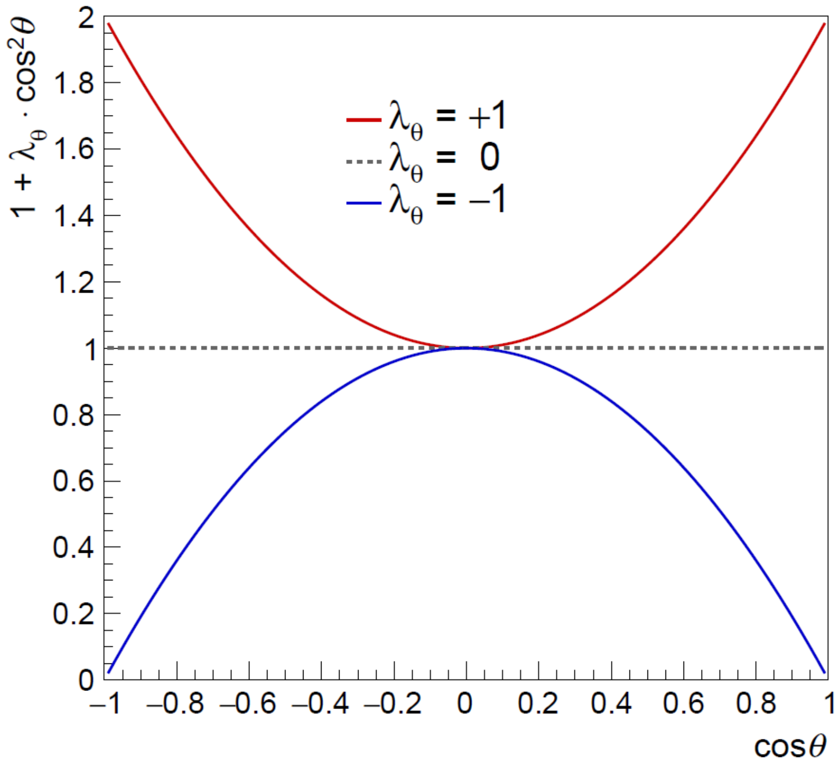

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- θ and ϕ: polar and azimuthal angle of the daughter particle with respect to the **quantization axis**

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$: **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

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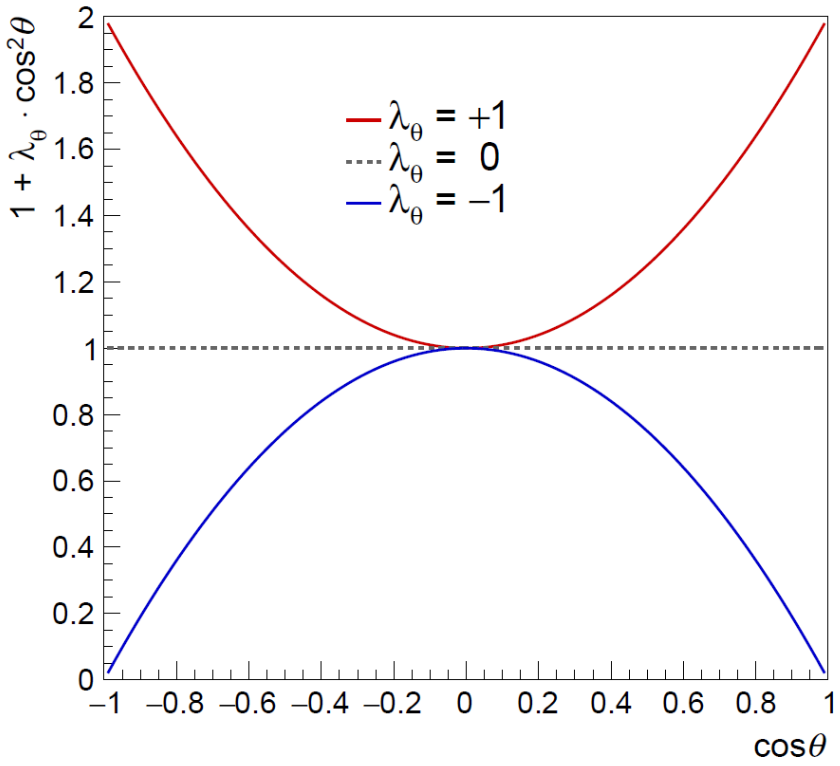

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  Spin alignment ⇔ decay products angular distribution

- $W(\cos\theta) \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta$

  ρ_{00} = spin density matrix element

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

Polarization: an introduction

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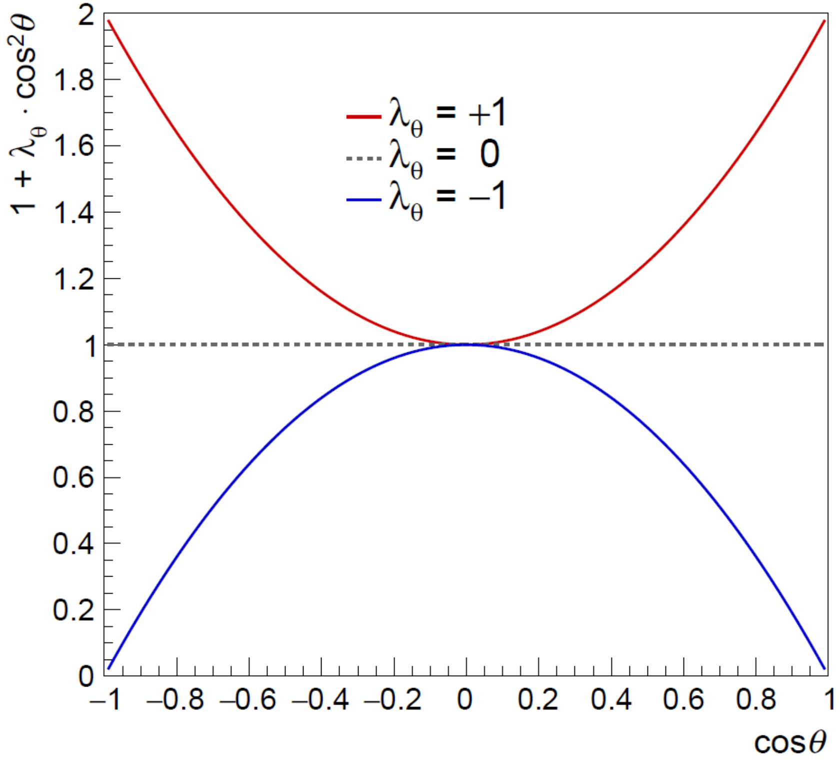

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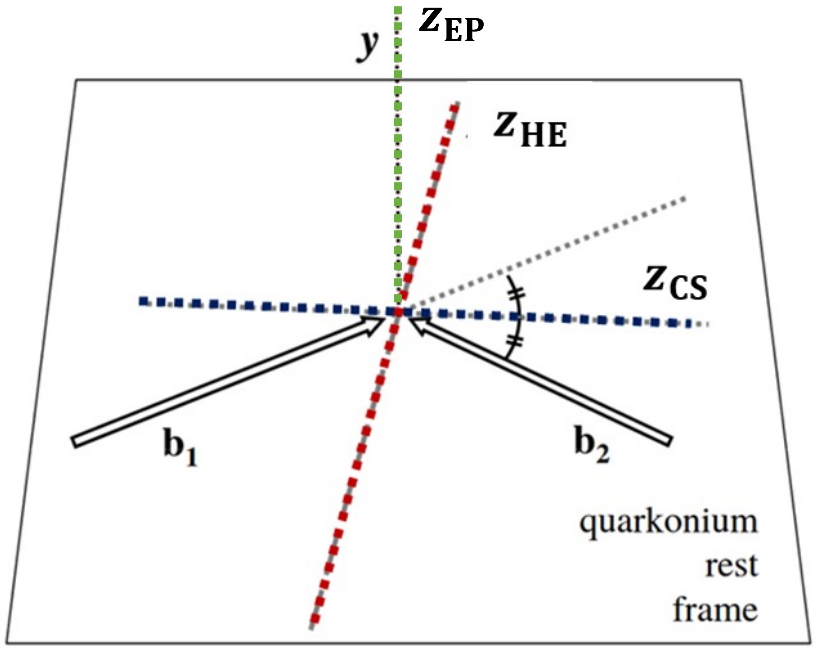
ρ_{00} = 1/3 no spin alignment

!

The connection among ρ_{00} and λ_θ depends on the spin state of the daughter particle system

Polarization: reference frames

- Crucial to define the polarization axis according the physics goal (production, QGP like effects, ecc…)



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.

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

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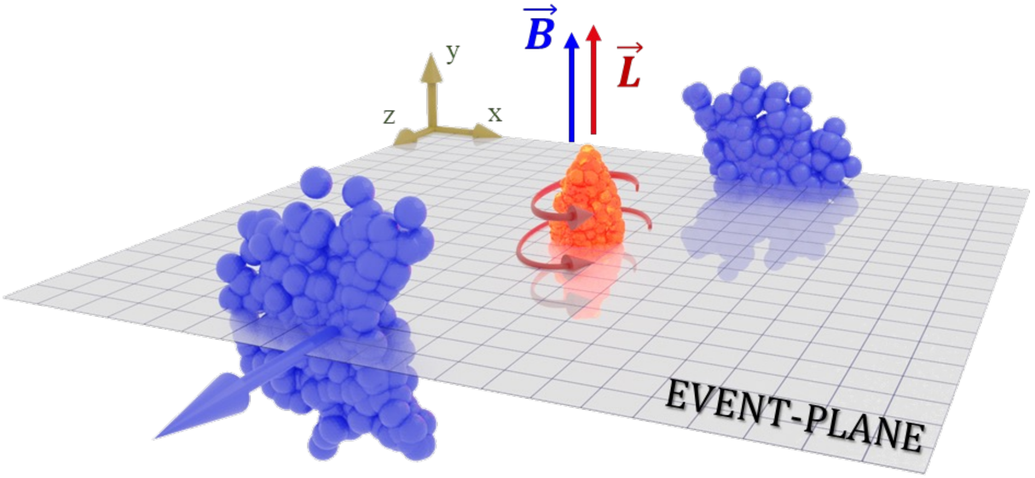

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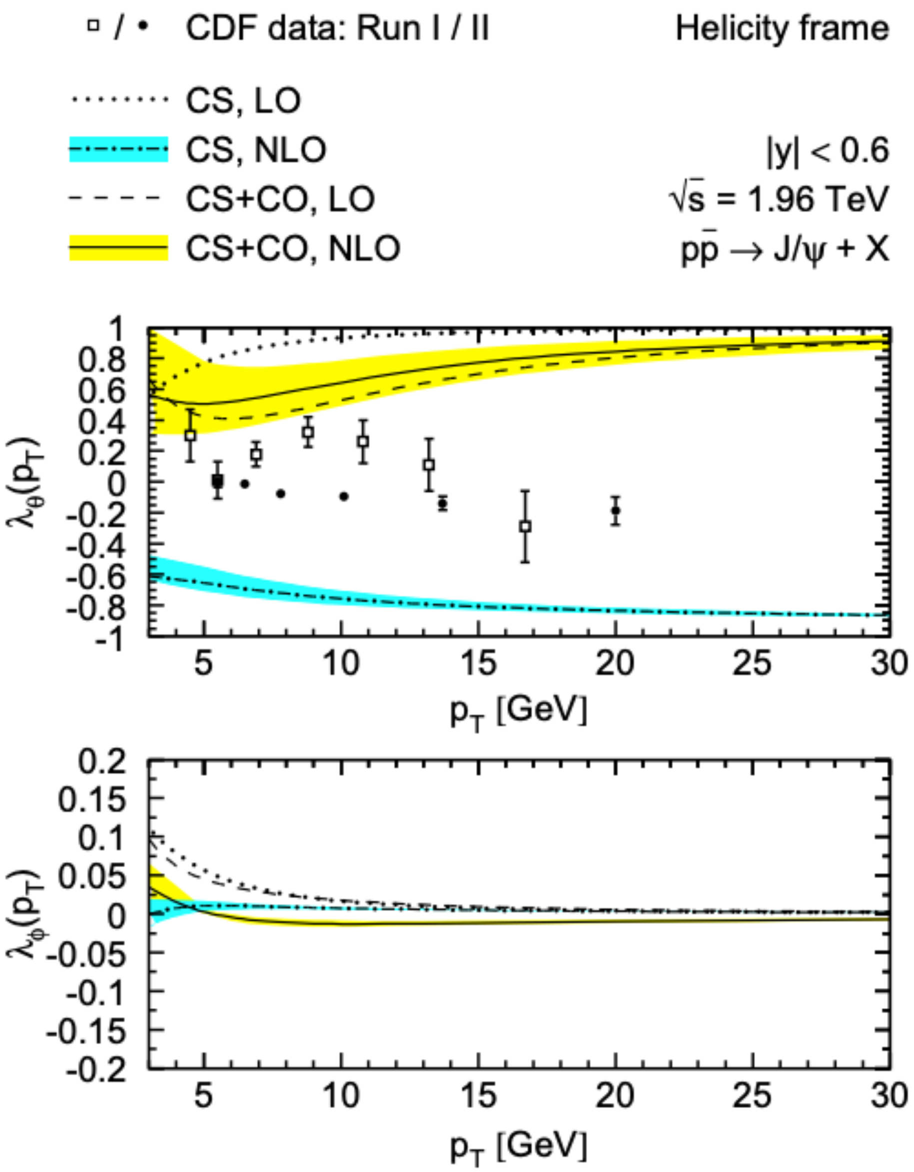
* The **Normal to the Event Plane** is by definition parallel to the to $\vec{B}$ and $\vec{L}$ vectors

Polarization in pp collisions

Polarization in pp: motivations



Important to constrain **quarkonium production** mechanisms in hadronic collisions

- …Before LHC model provided different predictions for quarkonium polarization according to the **production mechanism**
  - **Color Singlet**: Longitudinal polarization
  - **NRQCD**: Transverse polarization
- Some inconsistencies among different experimental results (CDF, D0)
- LHC measurements expected to help in the discrimination among different models

Polarization in pp: charmonia

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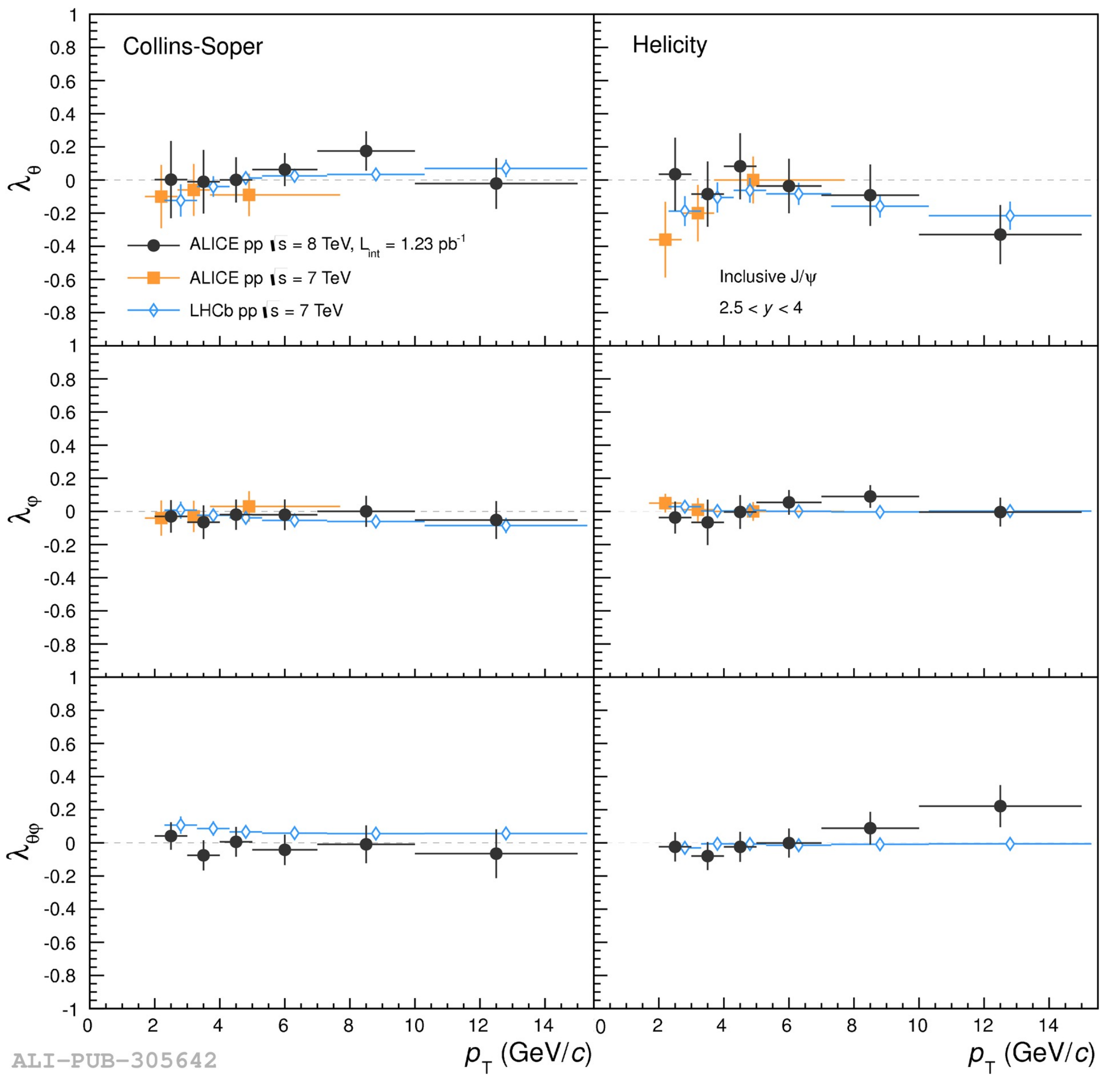


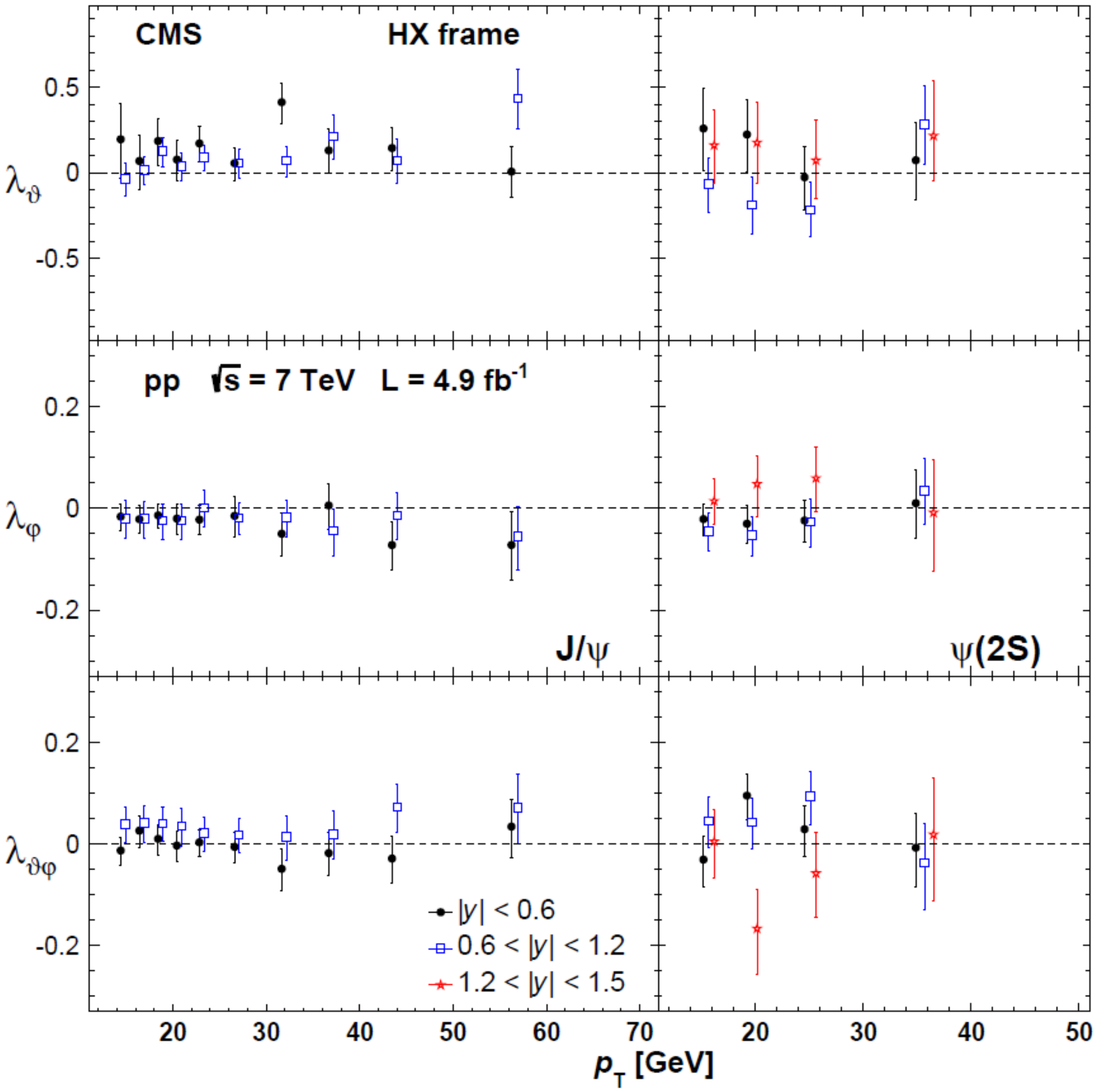
Important to constrain **quarkonium production** mechanisms in hadronic collisions

- …But 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 JHEP 12 (2017) 110

Polarization in pp: charmonia



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

EPJC 73 (2013) 11 JHEP 12 (2017) 110

- No significant prompt J/ψ and $\psi(2S)$ polarization observed by **CMS** at mid rapidity and up to p_T = 70 GeV/c

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

Models not able to describe data

Polarization in pp: charmonia

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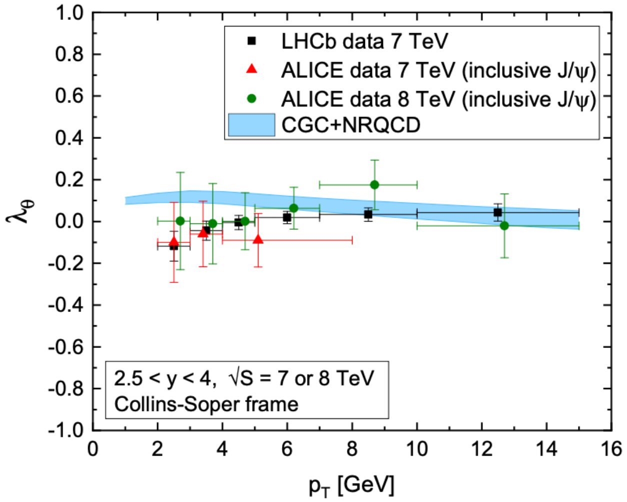

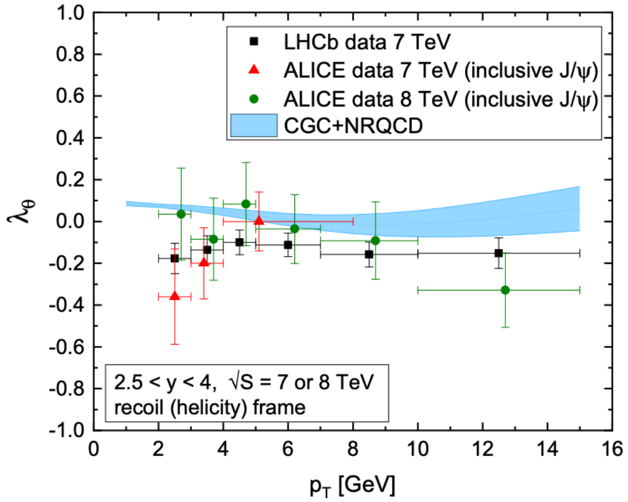

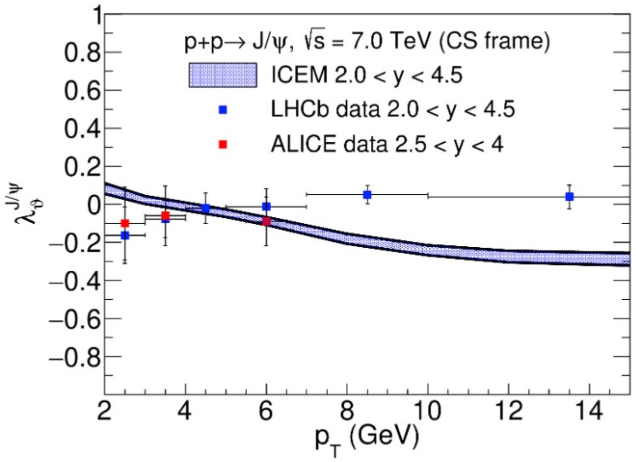

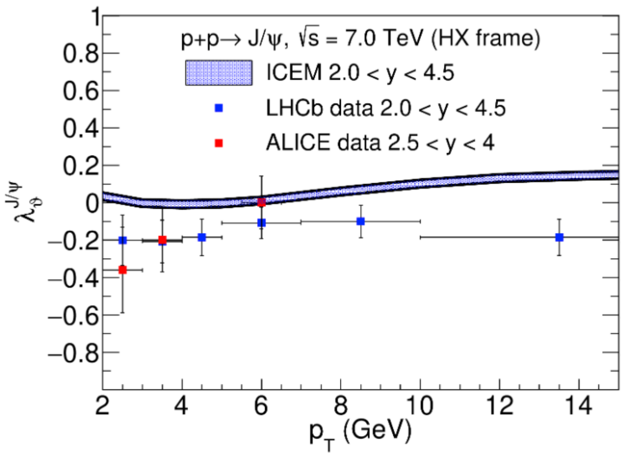

Important to constrain **quarkonium production** mechanisms in hadronic collisions

- Great theoretical effort to understand the difference among data and models
- 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

- ✓ General agreement among all results at LHC energies ($\lambda_\theta \sim 0$)
- ✓ Models reproduce a smooth trend vs p_T close to zero polarization

Polarization in pp: charmonia

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- Important to measure the polarization of all states contributing to J/ψ via **feed-down**
  - ➢ J/ψ ⟵ χ_c(nP) ~ 30%
  - ➢ J/ψ ⟵ ψ(2S) ~ 10%

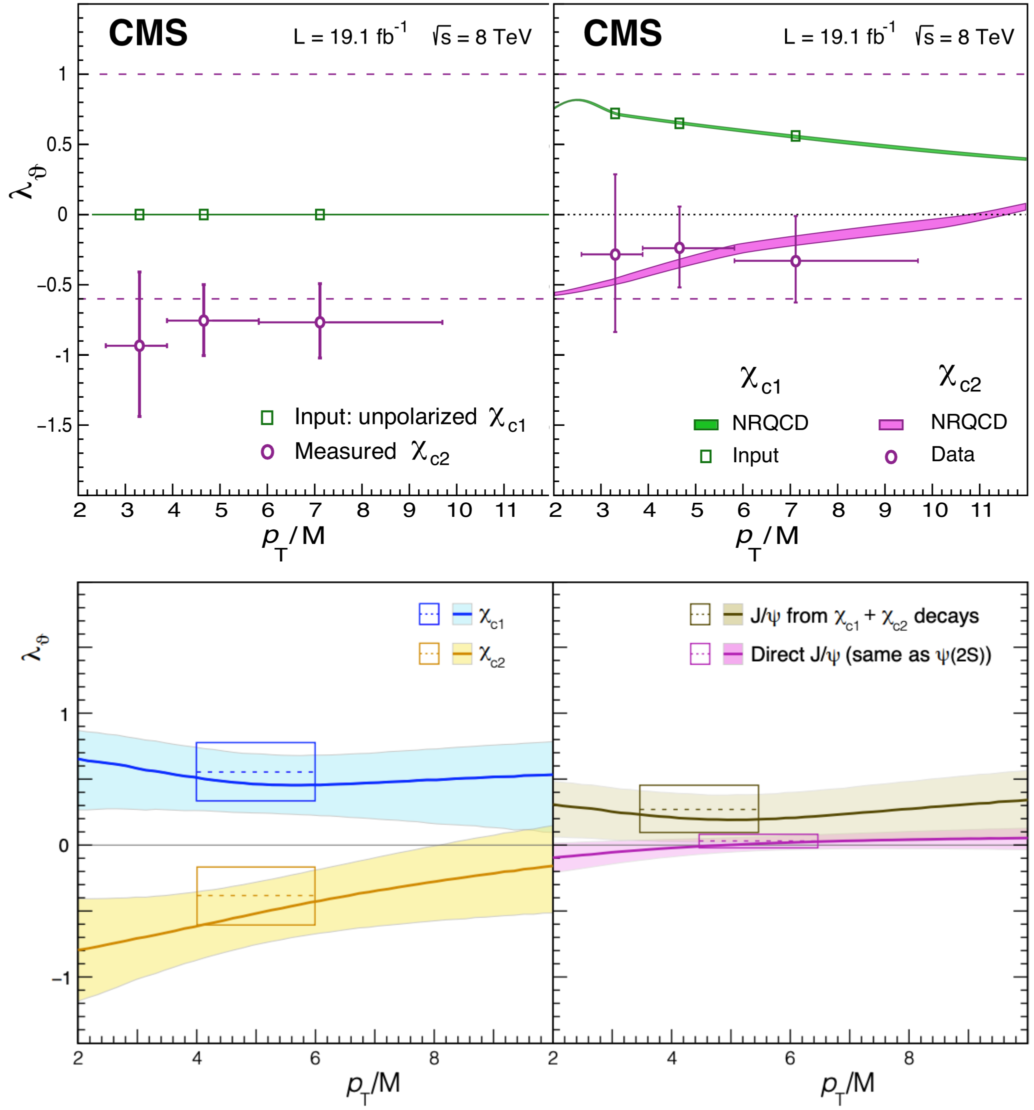
- For ψ(2S) all measurements give $\lambda_\theta \sim 0$

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

PRL 124, 162002 (2020), CMS collaboration

- Possibility to estimate contribution from χ_c to J/ψ polarization and to set better constraints to charmonia production

arxiv:2006.15446, Faccioli et al.



Polarization in pp: bottomonia

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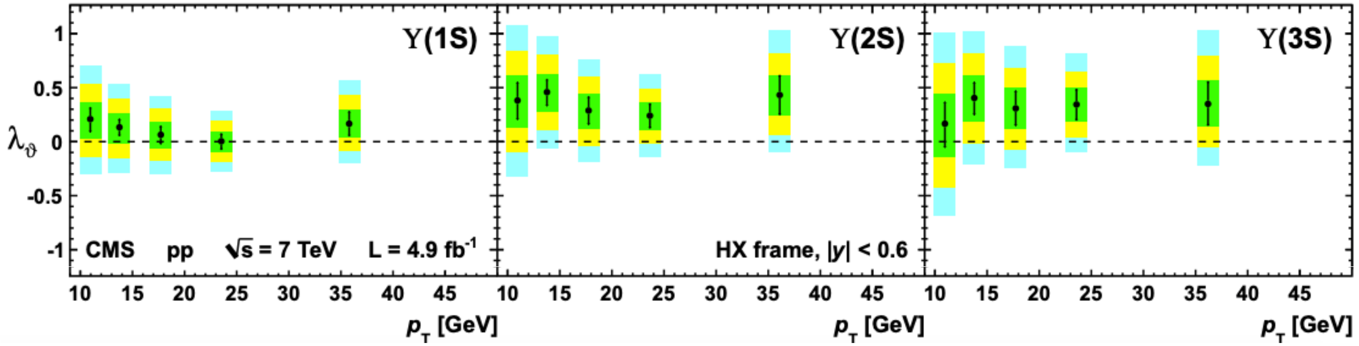
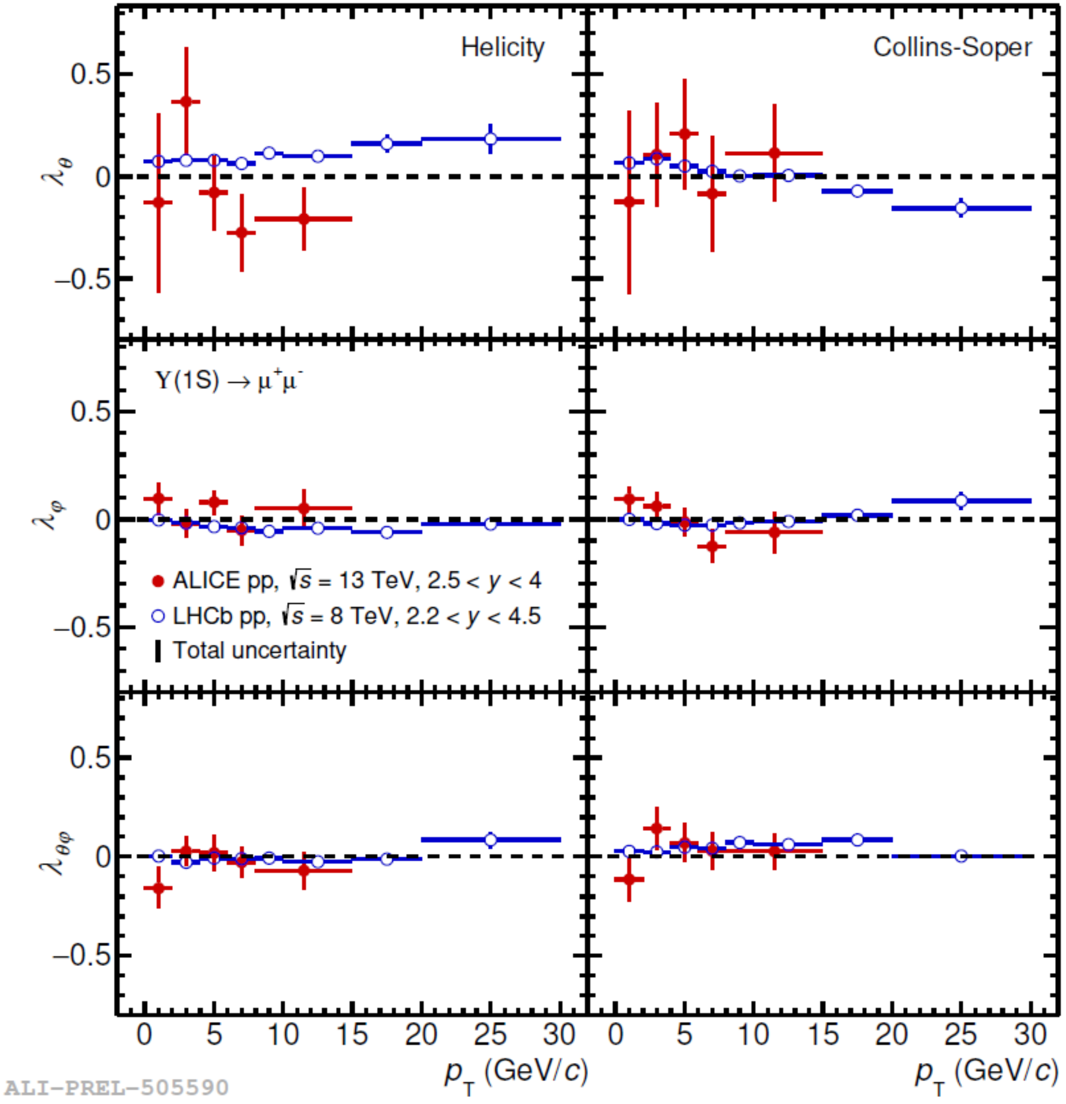
- Bottomonia polarization extensively explored at the LHC by many experiments
  - Measurements at mid (CMS) and forward (ALICE, LHCb) rapidity are all comparible with $\lambda_\theta \sim 0$

    JHEP 12 (2017) 110 PLB 727 (2013) 381

  - Also excited states are compatible with $\lambda_\theta \sim 0$
    - $\Upsilon(2S+3S)$ found $\lambda_\theta \sim +1$ by E866

    PRL 86 2529, E866 collaboration





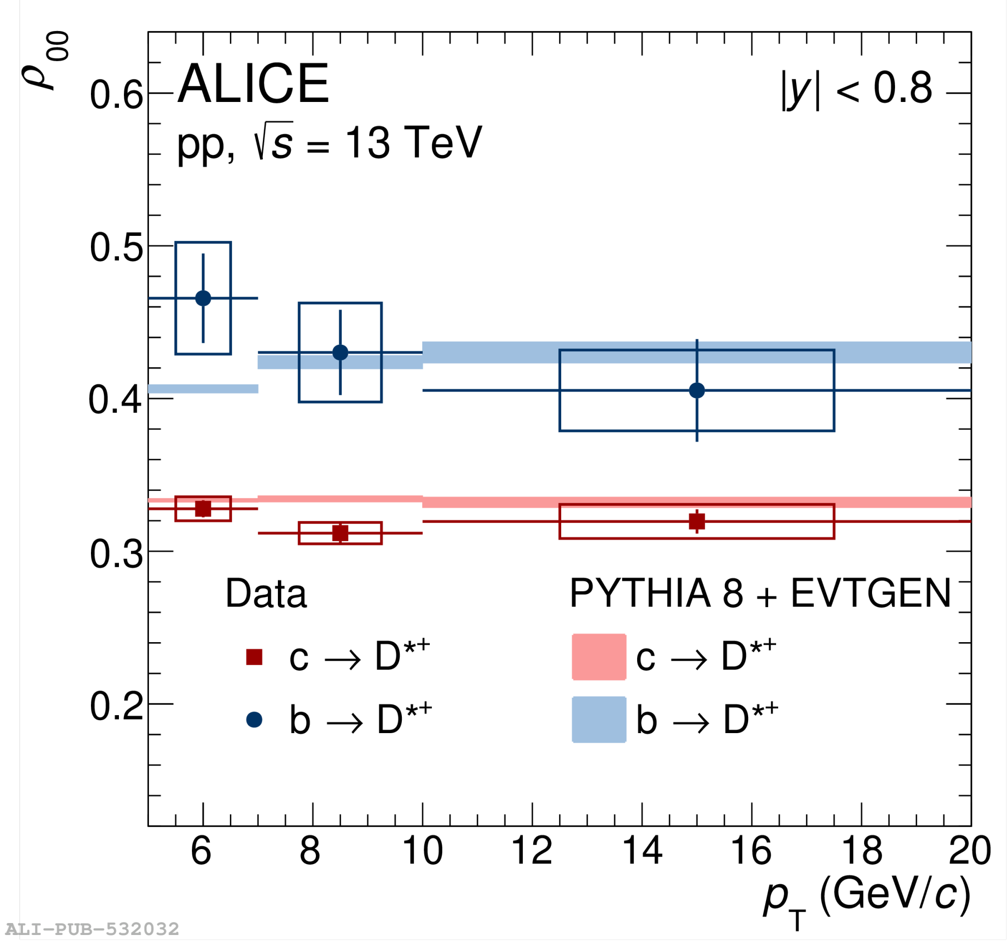
Polarization in pp: open charm

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

arxiv:2212.06588, accepted by PLB

- 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 $(B(S=0) \rightarrow D^{*+}(S=1) + X)$

- Important baseline for studies in Pb-Pb collisions!



Polarization in AA collisions

Polarization in AA: motivations

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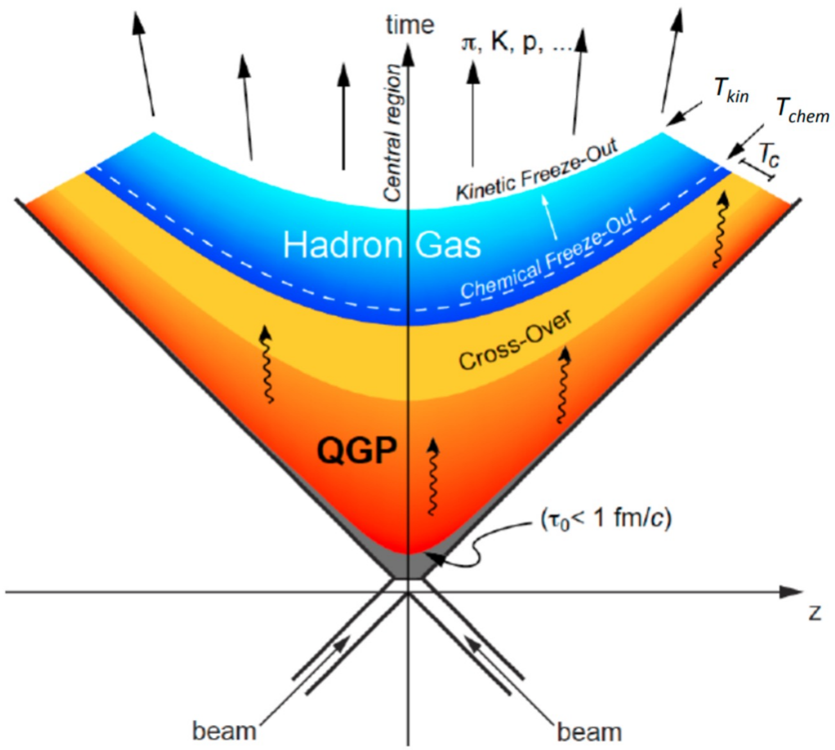

- Polarization gives access to different **time scales** and various **mechanisms**

Polarization in AA: motivations

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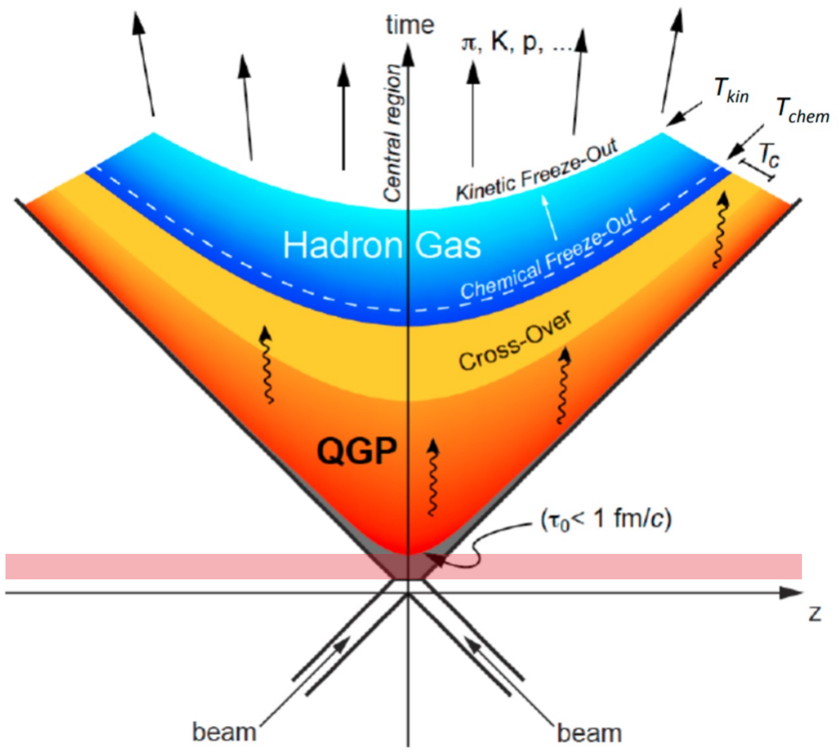
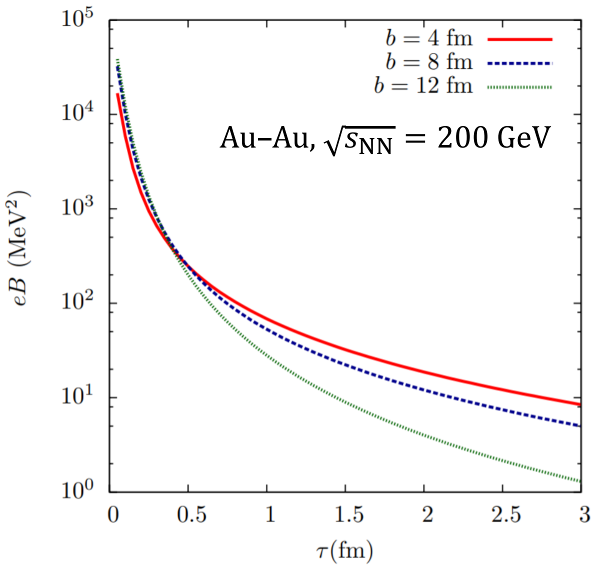


Polarization gives access to different **time scales** and various **mechanisms**

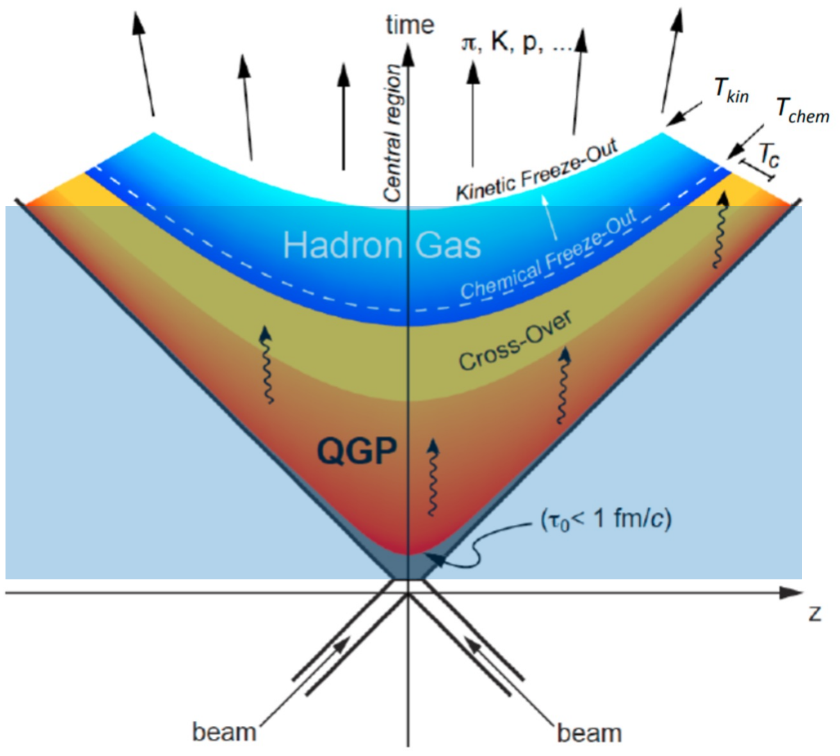
Magnetic field

- Huge intensity ($|\vec{B}| \sim 10^{14}$ T)
- Short-living ($\tau \sim 1$ fm/c)
- No strong *b* dependence

NPA 803 (2008), Kharzeev et al.



Polarization in AA: motivations



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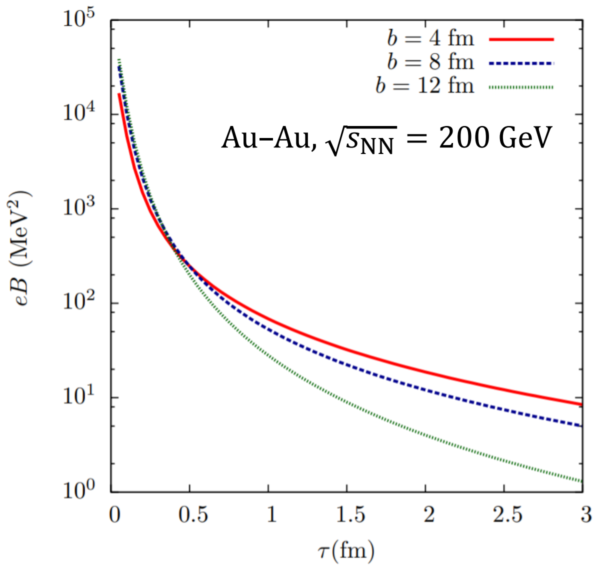
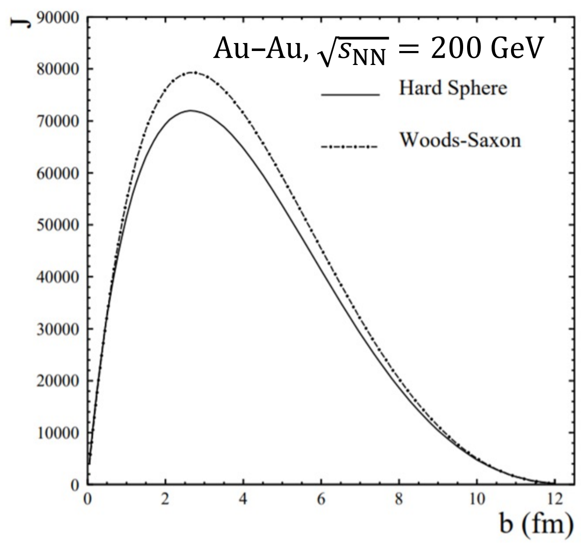


Angular momentum

- Fast rotating ($\sim 10^{22}$ s^{-1})
- Affects system evolution
- *b* dependence

PRC 77 (2008) 024906, Becattini et al.



Polarization in AA: motivations

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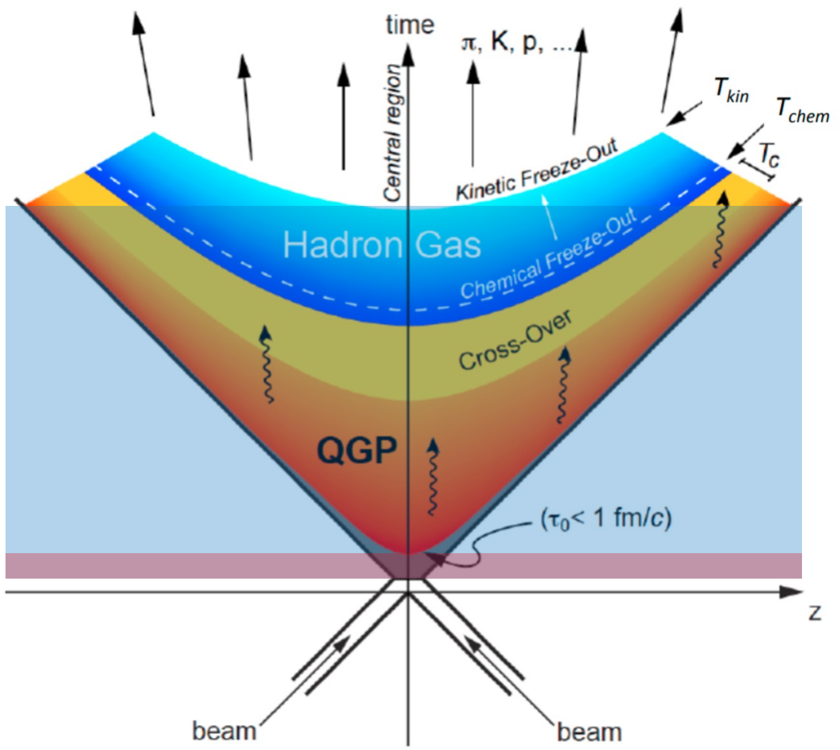


Polarization gives access to different **time scales** and various **mechanisms**

Magnetic field

- Huge intensity ($|\vec{B}| \sim 10^{14}$ T)
- Short-living ($\tau \sim 1$ fm/c)
- No strong b dependence

- Theory predictions:

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

- $\rho_{00} > \frac{1}{3}$ for K^{*0}, ρ^0 ecc..
- $\rho_{00} < \frac{1}{3}$ for K^{*+}, ρ^+ ecc..

PRC 97, 034917 (2018), Yang et al.

Angular momentum

- Fast rotating ($\sim 10^{22}\ s^{-1}$)
- Affects system evolution
- b dependence

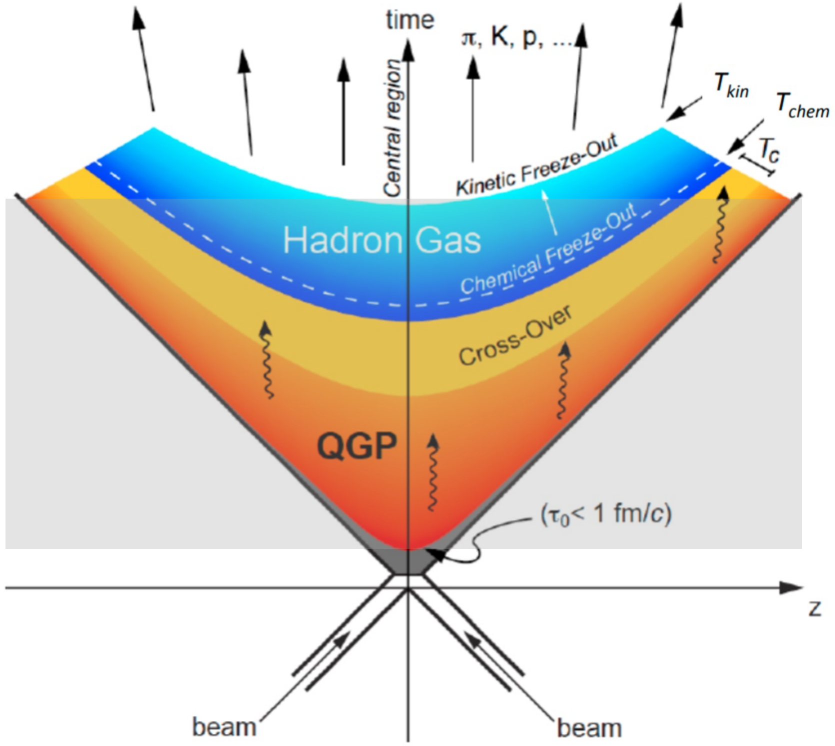
- Theory predictions:

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

- $\rho_{00} < \frac{1}{3}$ for all vectors

PRC 97, 034917 (2018), Yang et al.

Polarization in AA: motivations



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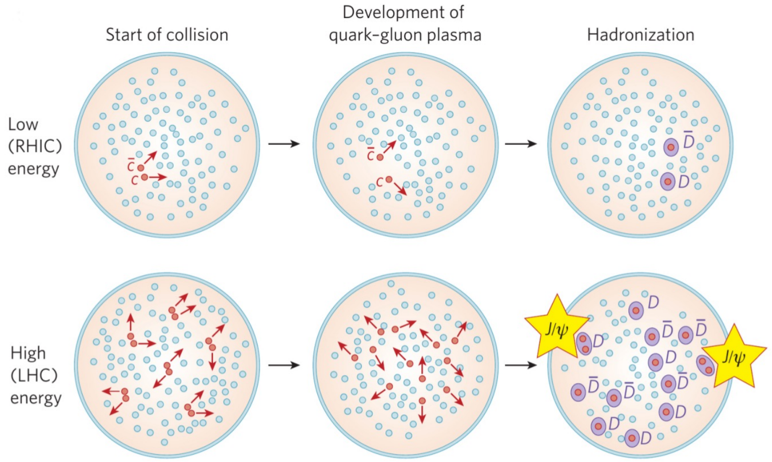

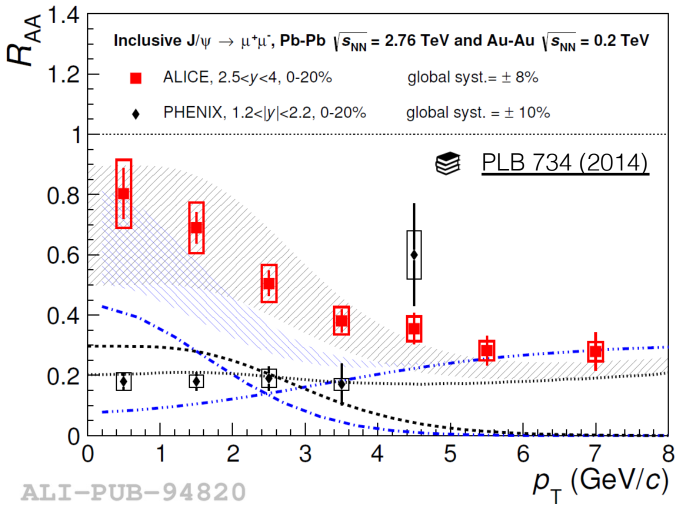

- **Quarkonia suppression / (re)generation**
  - quarkonium states dissociated via a **color screening effect**

    PLB 178 (1986) 416   PR 858 (2020) 1-117

  - Statistical **(re)combination** of uncorrelated $c\bar{c}$ pairs

    PLB 490 (2000) 196-202   PRC 63 (2001) 054905

K^{*0} & ϕ polarization in Pb-Pb

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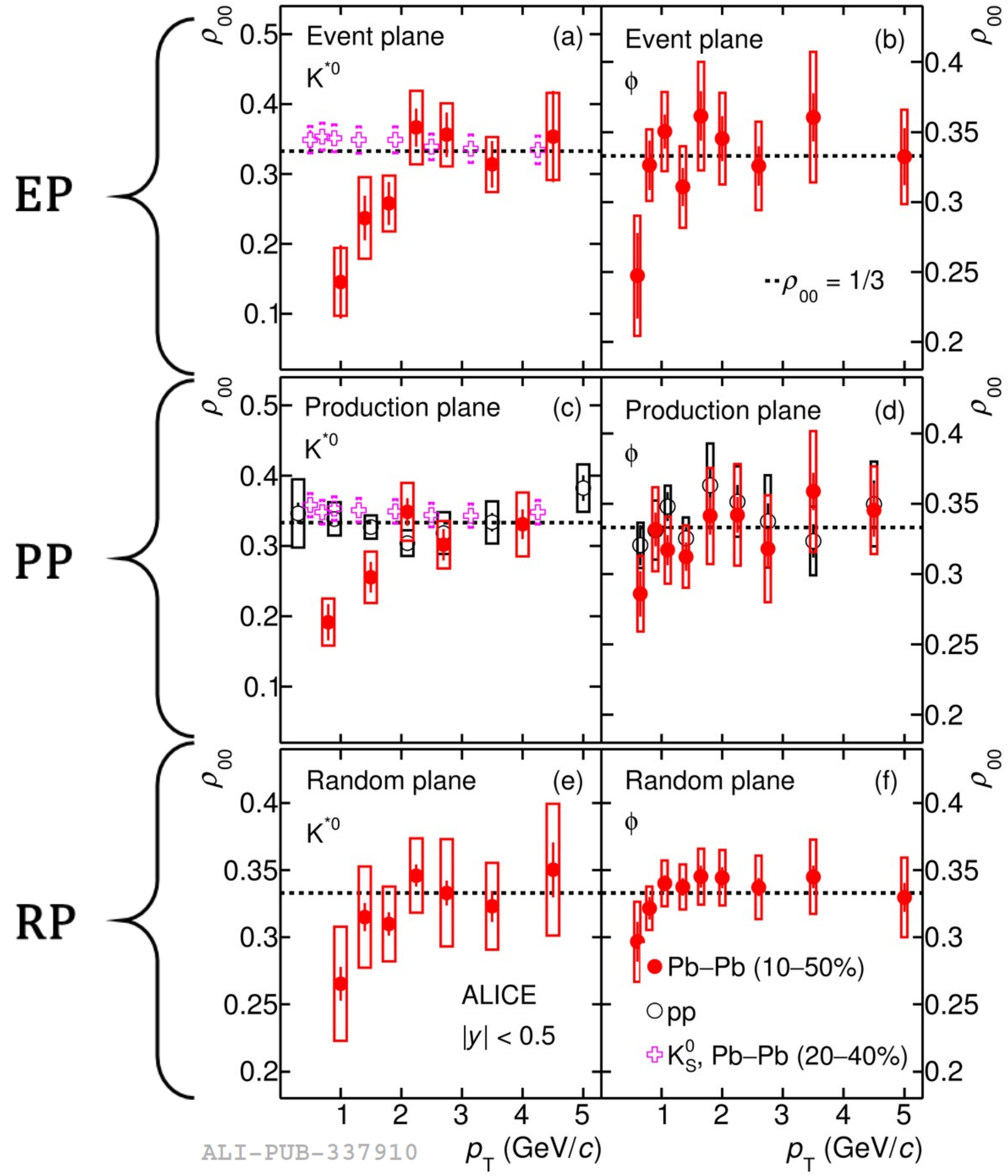

- p_{T} – dependence
  - $\rho_{00} < 1/3$ for K^{*0} and ϕ in Pb–Pb collisions at low p_{T}
  - $\rho_{00} \sim 1/3$ for:
    - ● $p_{\mathrm{T}}^{K^{*0}} > 2\ \mathrm{GeV}/c$ and $p_{\mathrm{T}}^{\phi} > 0.8\ \mathrm{GeV}/c$
    - ● a randomized event plane (RP)
    - ✚ K_S^0 (Spin = 0) in Pb–Pb
    - ○ K^{*0} and ϕ in proton–proton collisions

K^{*0} & ϕ polarization in Pb-Pb

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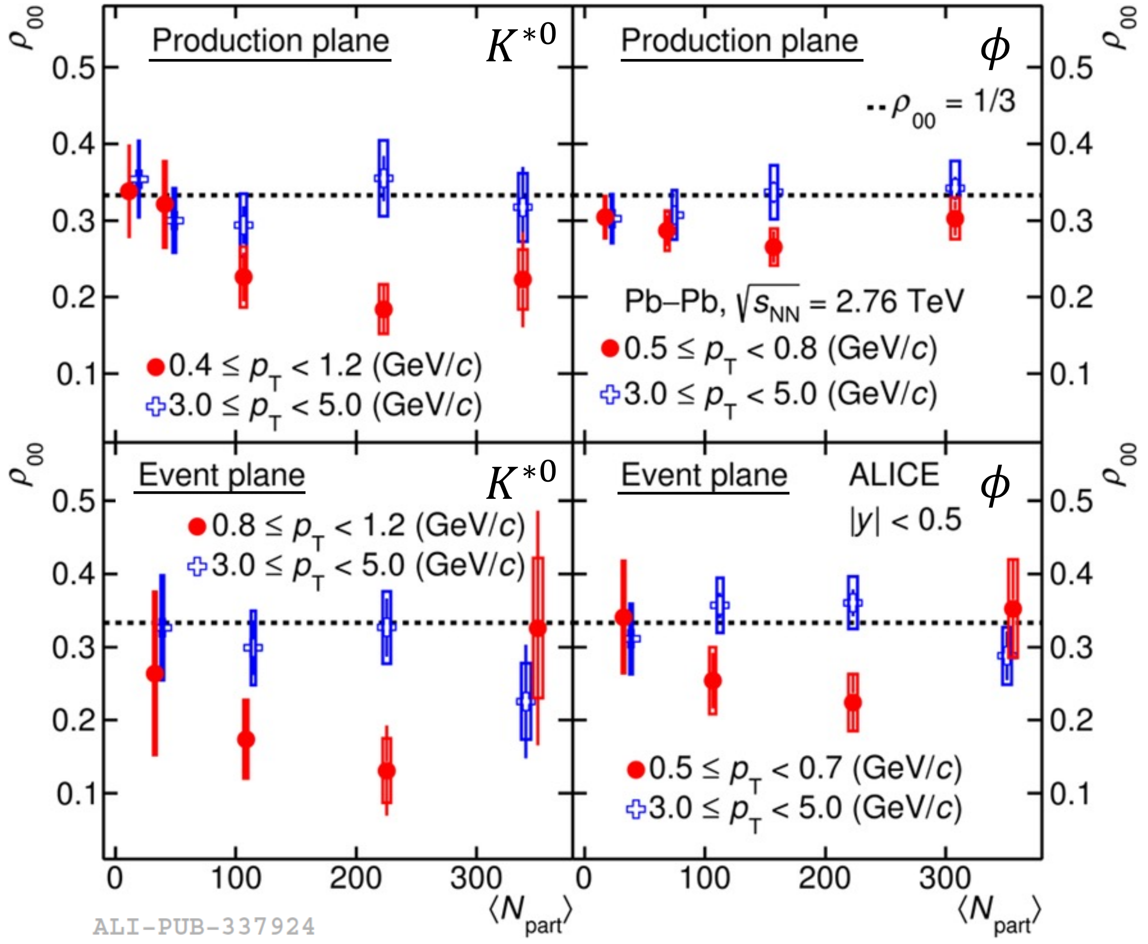

- p_T – dependence
  - $\rho_{00} < 1/3$ for K^{*0} and ϕ in Pb–Pb collisions at low p_T
- Centrality – dependence
  - ρ_{00} deviates w.r.t. $1/3$ at low p_T in semi-central collisions
    - K^{*0}: 3.2σ (PP), 2.6σ (EP)
    - ϕ: 2.1σ (PP), 1.9σ (EP)
  - No centrality dependence ($\rho_{00} \sim 1/3$) of ρ_{00} at high p_T
- Results consistent with expectations from **quark recombination** at the phase boundary

PLB 629 (2005), Liang, Wang

Quarkonium polarization in Pb-Pb

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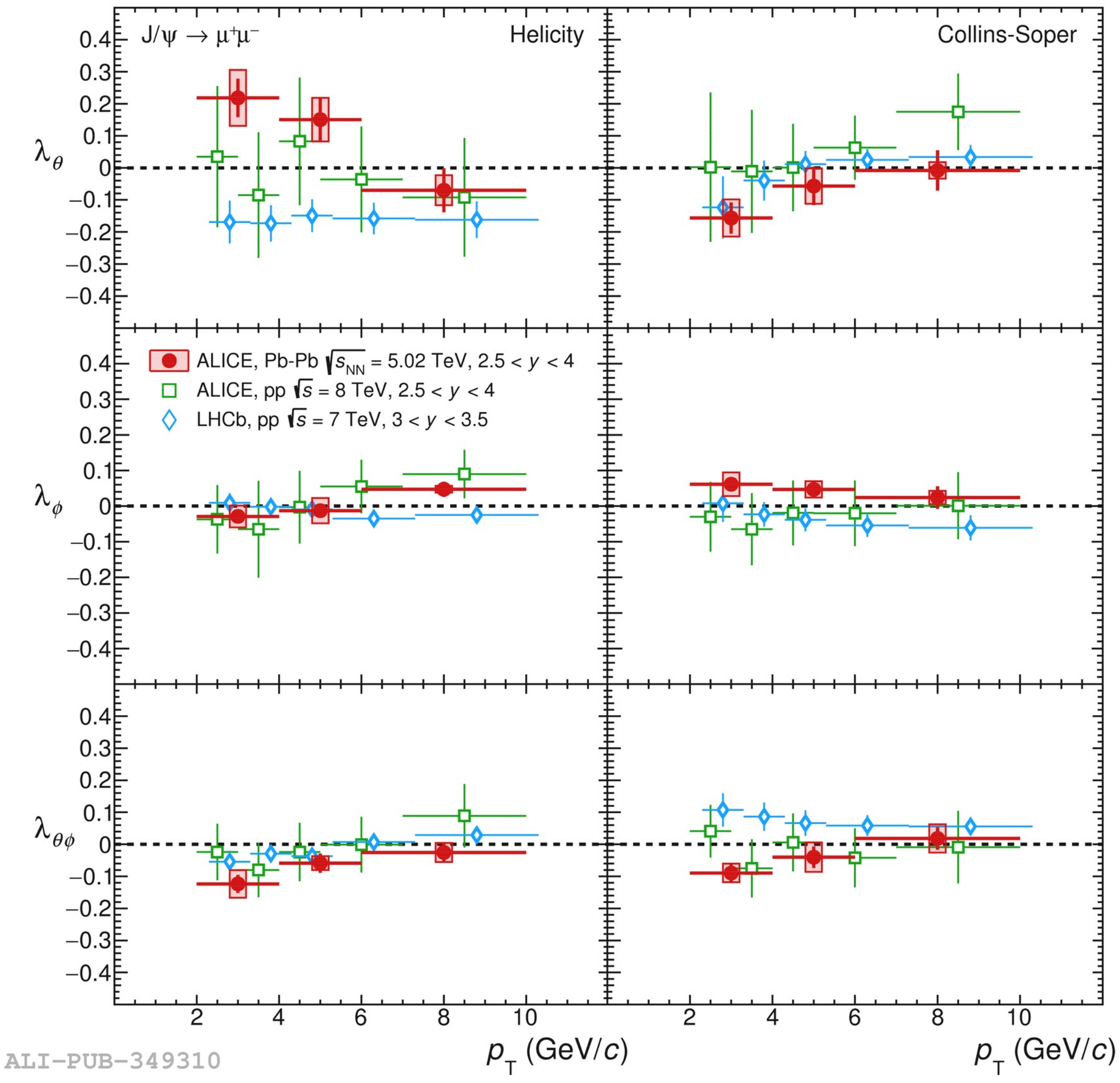


- ALICE measured J/ψ polarization in Pb-Pb

  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

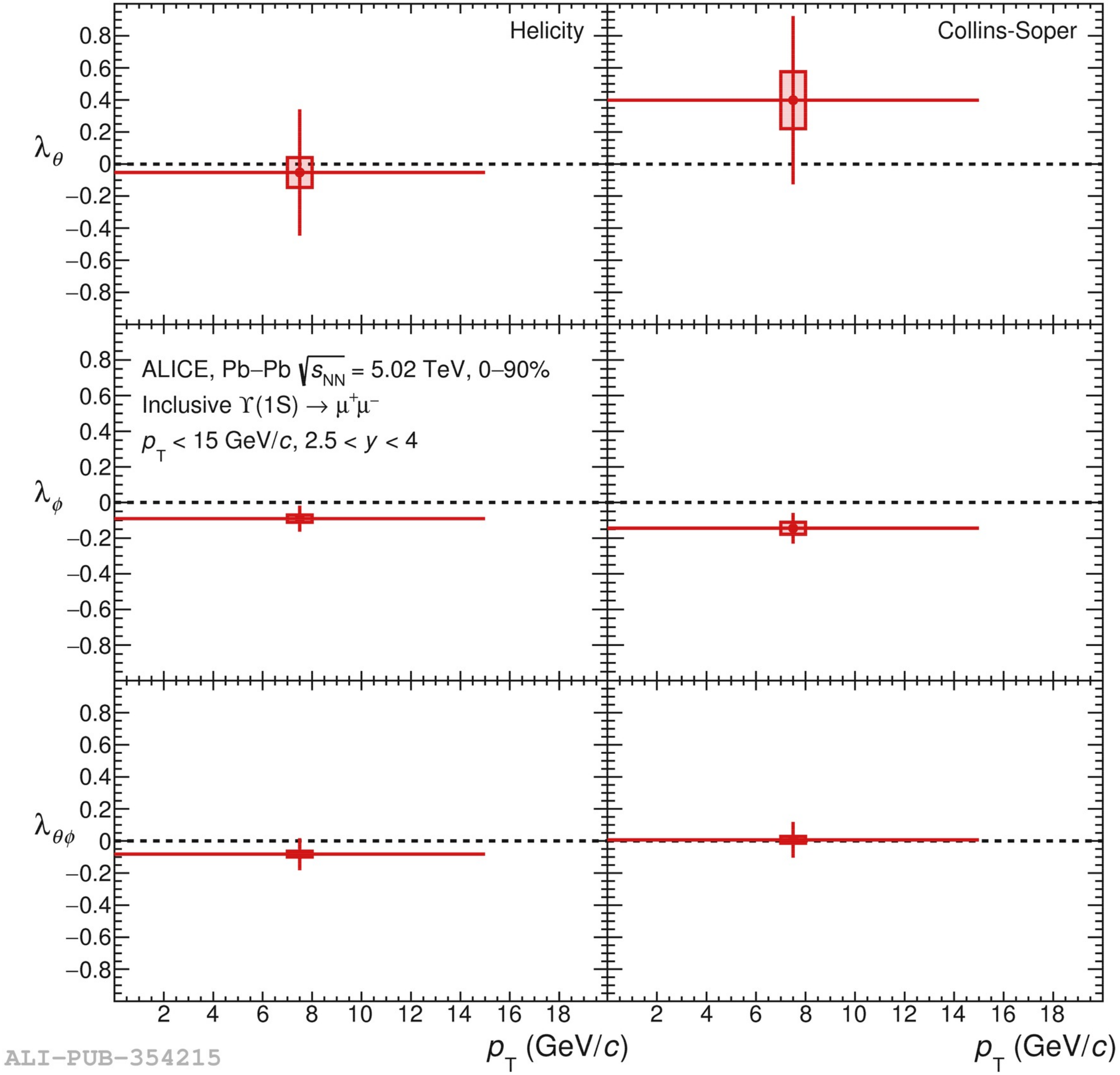
  □ Compatible within the large uncertainties with ALICE results in pp collisions

  EPJC 78 (2018) 562, ALICE collaboration

  ◊ 3σ difference with LHCb in pp collisions in HE

  EPJC 73 (2013) 11, LHCb collaboration

Quarkonium polarization in Pb-Pb



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

      EPJC 73 (2013) 11, LHCb collaboration

- ALICE measured $\Upsilon(1S)$ polarization in Pb-Pb
  - λ_θ compatible with zero but the measurement is still strongly limited by the statistics

Quarkonium polarization in Pb-Pb

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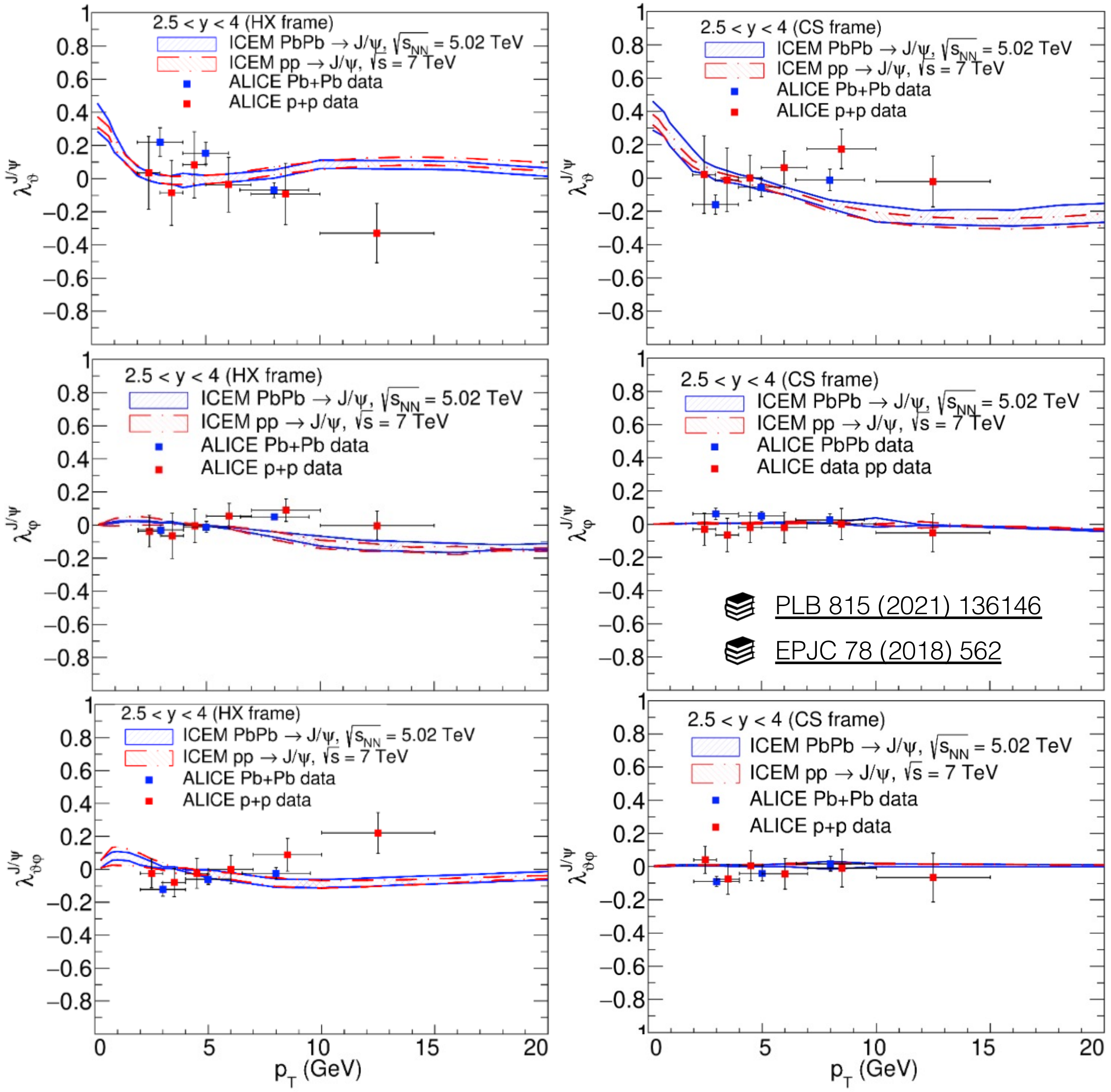

Can **Cold Nuclear Matter** (CNM) effects affect J/ψ polarization in Pb-Pb collisions?

- **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

J/ψ polarization in Pb-Pb collisions

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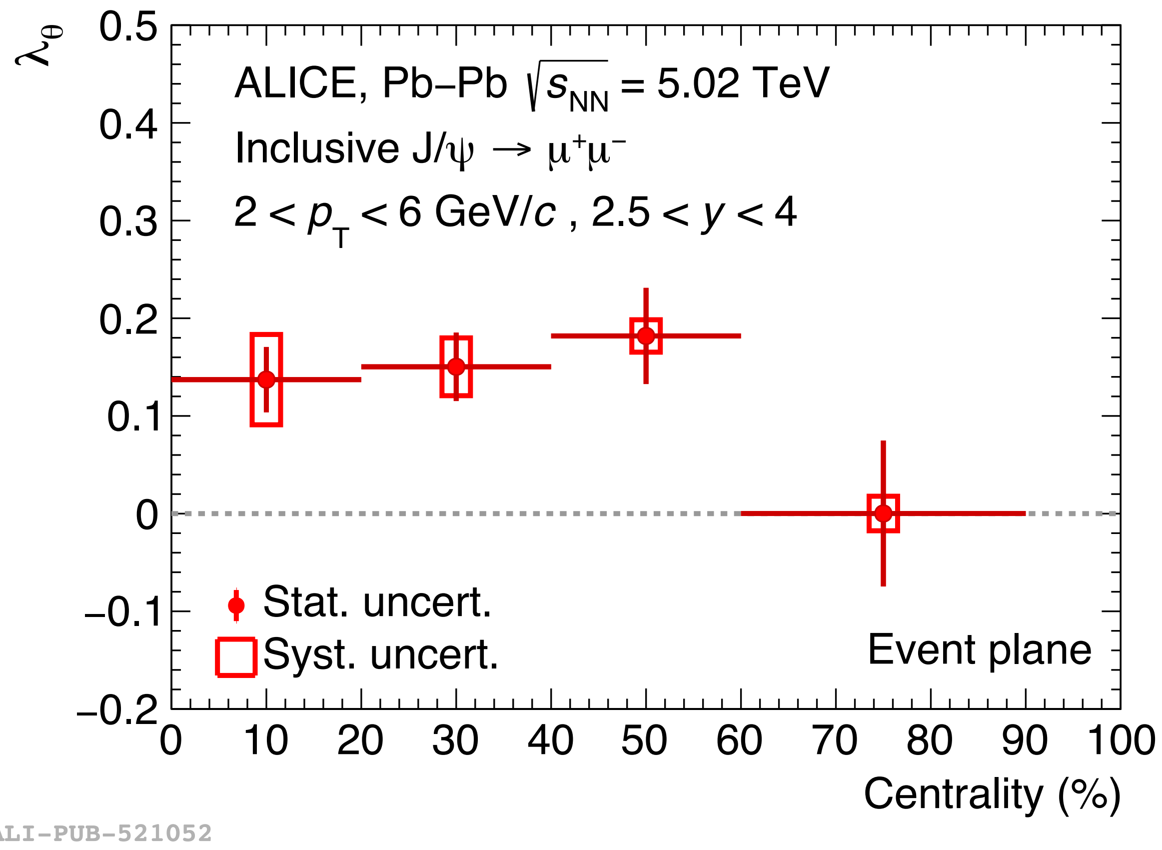


- First measurement of quarkonium polarization with respect to the **Event Plane**

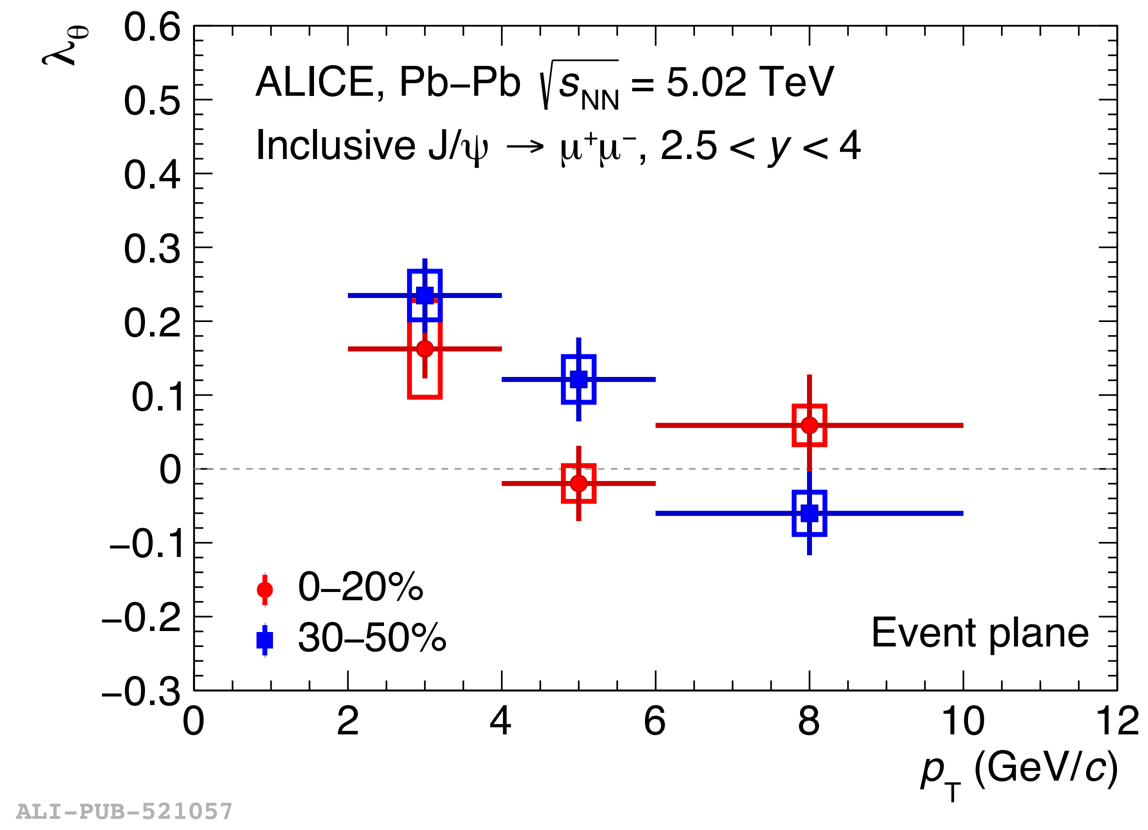
  arxiv:2204.10171, accepted by PRL

  - Centrality dependence:
    Small but significant (3.5σ) polarization observed in 40-60% and $2 < p_{\mathrm{T}} < 6\ \mathrm{GeV}/c$

- In the dilepton channel:

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}} \qquad \begin{cases} \lambda_\theta > 0 \rightarrow \rho_{00} < 1/3 \\ \lambda_\theta < 0 \rightarrow \rho_{00} > 1/3 \end{cases}$$

J/ψ polarization in Pb-Pb collisions



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  arxiv:2204.10171, accepted by PRL

  - p_T dependence:
    30-50%: significant deviation (3.9σ) at low transverse momentum ($2 < p_T < 4$ GeV/c)

- In the dilepton channel:

$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}} \qquad \begin{cases} \lambda_\theta > 0 \rightarrow \rho_{00} < 1/3 \\ \lambda_\theta < 0 \rightarrow \rho_{00} > 1/3 \end{cases}$$

- 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 perspectives

Summary and perspectives

Luca Micheletti
09/05/2023
RHIC-BES seminar

	K^{*0}	ϕ	D^{*+}	J/ψ	$\psi(2S)$	χ_c	$\Upsilon(nS)$
pp	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00} \neq 1/3$	$\rho_{00}\sim 1/3$
Pb-Pb	$\rho_{00} < 1/3$	$\rho_{00} < 1/3$	?	$\rho_{00} < 1/3$	?	?	$\rho_{00}\sim 1/3$

Summary and perspectives

	K^{*0}	ϕ	D^{*+}	J/ψ	$\psi(2S)$	χ_c	$\Upsilon(nS)$
pp	$\rho_{00}\sim1/3$	$\rho_{00}\sim1/3$	$\rho_{00}\sim1/3$	$\rho_{00}\sim1/3$	$\rho_{00}\sim1/3$	$\rho_{00}\neq1/3$	$\rho_{00}\sim1/3$
Pb-Pb	$\rho_{00}<1/3$	$\rho_{00}<1/3$	?	$\rho_{00}<1/3$	?	?	$\rho_{00}\sim1/3$

- Quark polarization via spin-orbit coupling
- Polarization transferred to the final state

Summary and perspectives

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	K^{*0}	ϕ	D^{*+}	J/ψ	ψ(2S)	χ_c	ϒ(nS)
pp	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	$\rho_{00} \neq 1/3$	ρ_{00}~1/3
Pb-Pb	$\rho_{00} < 1/3$	$\rho_{00} < 1/3$	?	$\rho_{00} < 1/3$	?	?	ρ_{00}~1/3

- Quark polarization via spin-orbit coupling
- Polarization transferred to the final state

- Important interplay among LF and quarkonia
- Measuring D^{*0} and D^{*+} polarization could help in the separation of vorticity / magnetic field effect

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

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

Summary and perspectives

	K^{*0}	ϕ	D^{*+}	J/ψ	$\psi(2S)$	χ_c	$\Upsilon(nS)$
pp	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00} \neq 1/3$	$\rho_{00}\sim 1/3$
Pb-Pb	$\rho_{00} < 1/3$	$\rho_{00} < 1/3$	?	$\rho_{00} < 1/3$	?	?	$\rho_{00}\sim 1/3$

- Quark polarization via spin-orbit coupling
- Polarization transferred to the final state

- Similar effect as LF, similar mechanism?
- $\tau_{\bar{c}c} \sim 0.1\ \mathrm{fm}/c$, sensitive to magnetic field
- Role of suppression / (re)generation?

- Important interplay among LF and quarkonia
- Measuring D^{*0} and D^{*+} polarization could help in the separation of vorticity / magnetic field effect

Summary and perspectives

	K^{*0}	ϕ	D^{*+}	J/ψ	ψ(2S)	χ_c	Υ(nS)
pp	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	$\rho_{00} \neq 1/3$	ρ_{00}~1/3
Pb-Pb	$\rho_{00} < 1/3$	$\rho_{00} < 1/3$	?	$\rho_{00} < 1/3$	?	?	ρ_{00}~1/3

K^{*0}, ϕ:
- Quark polarization via spin-orbit coupling
- Polarization transferred to the final state

D^{*+}:
- Important interplay among LF and quarkonia
- Measuring D^{*0} and D^{*+} polarization could help in the separation of vorticity / magnetic field effect

J/ψ:
- Similar effect as LF, similar mechanism?
- $\tau_{\bar{c}c} \sim 0.1$ fm/c, sensitive to magnetic field
- Role of suppression / (re)generation?

Υ(nS):
- No regeneration
- $\tau_{\bar{b}b} < \tau_{\bar{c}c}$, more sensitive to magnetic field

Backup