



2023



Vector meson polarization in pp and Pb–Pb collisions with ALICE at the LHC

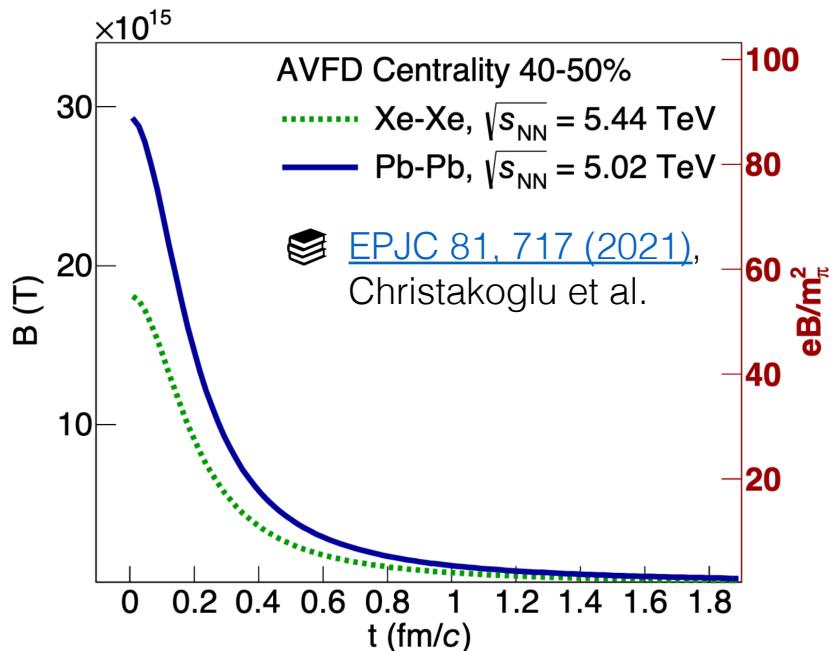
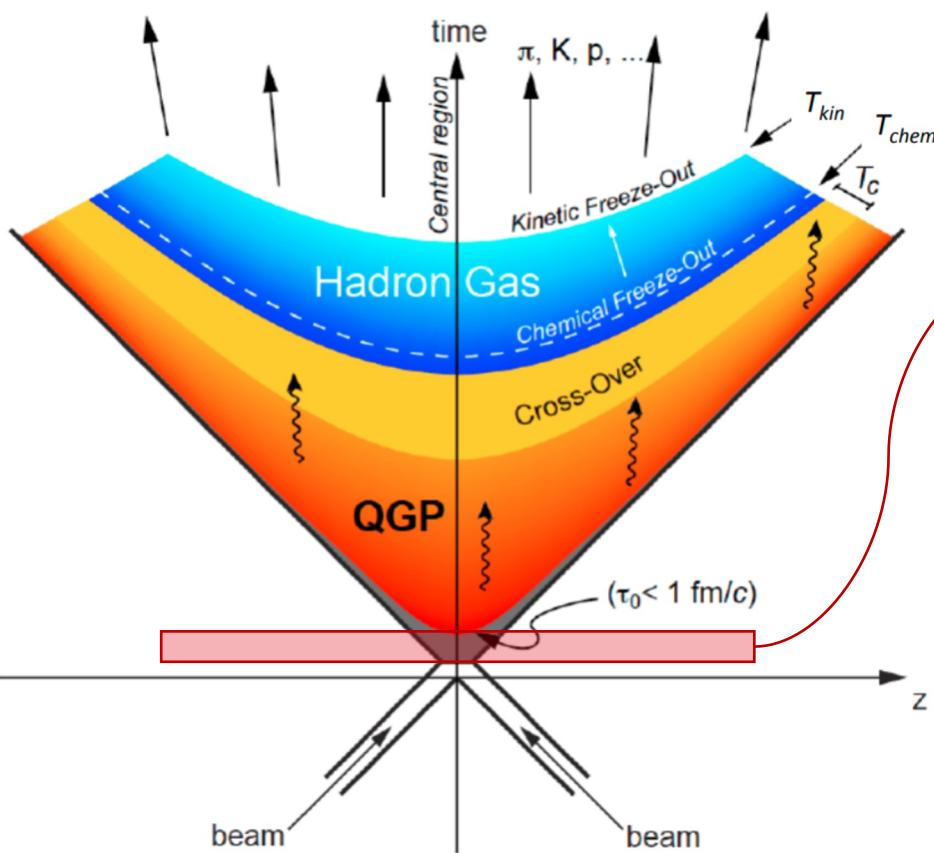
Luca Micheletti (CERN)
on behalf of the ALICE Collaboration



ALICE

Physics motivations

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05/09/2023
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	B (T)
HICs	10^{16}
Pulsar	10^{11}
Earth	10^{-5}

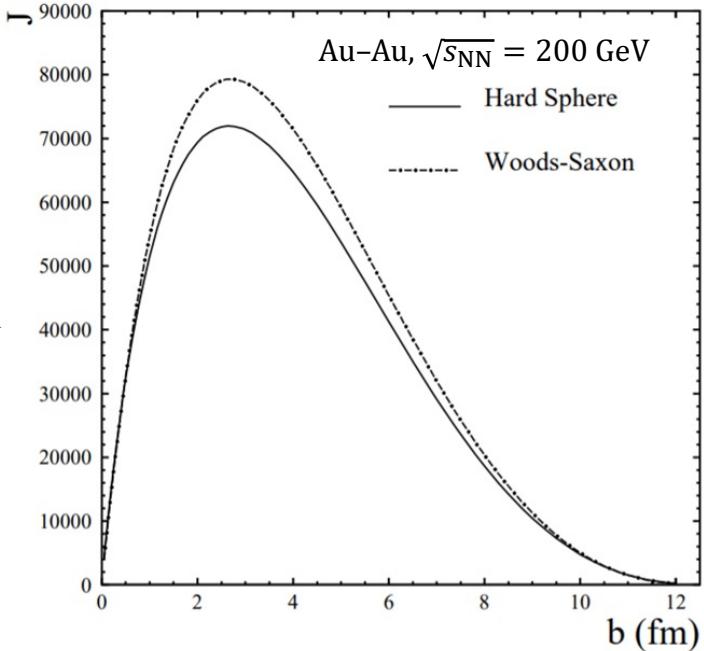
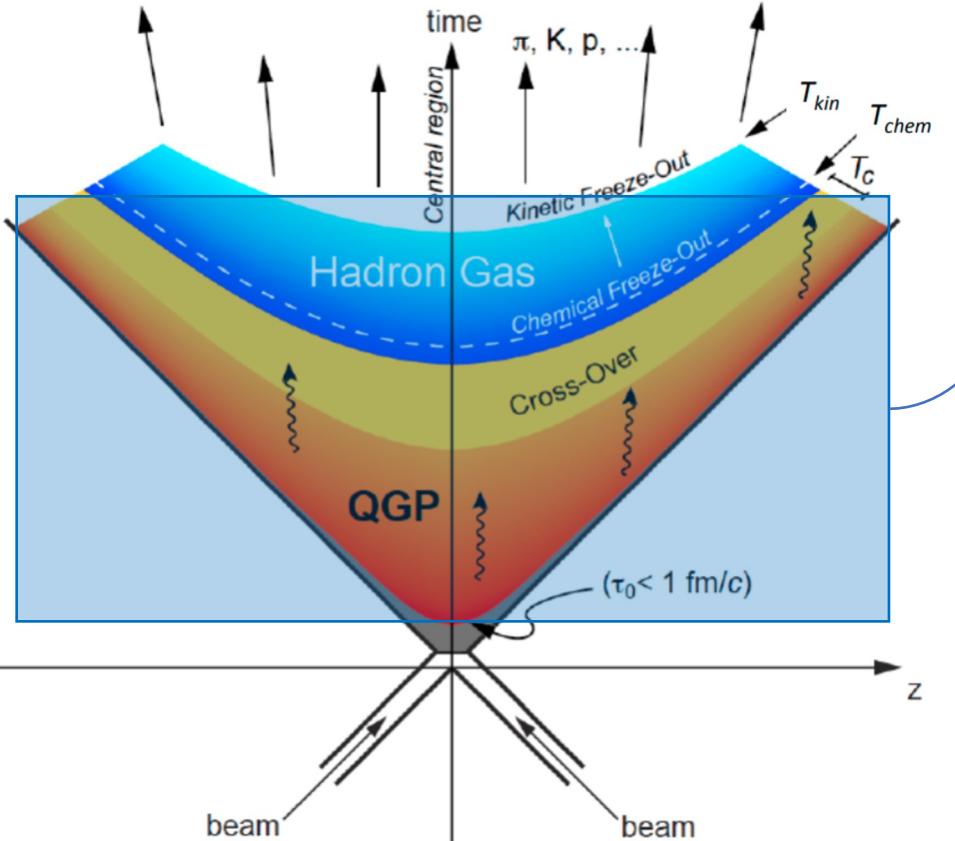
• Magnetic field

- The **most intense magnetic field** in nature!
- No strong b dependence [NPA 803 \(2008\)](#), Kharzeev et al.
- Lifetime increases from mid to **forward rapidity**

[PLB 768 \(2017\) 260](#), Das et al.

Physics motivations

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	ω (s ⁻¹)
QGP	10^{22}
Pulsar	10^2
Tornado	10^{-1}



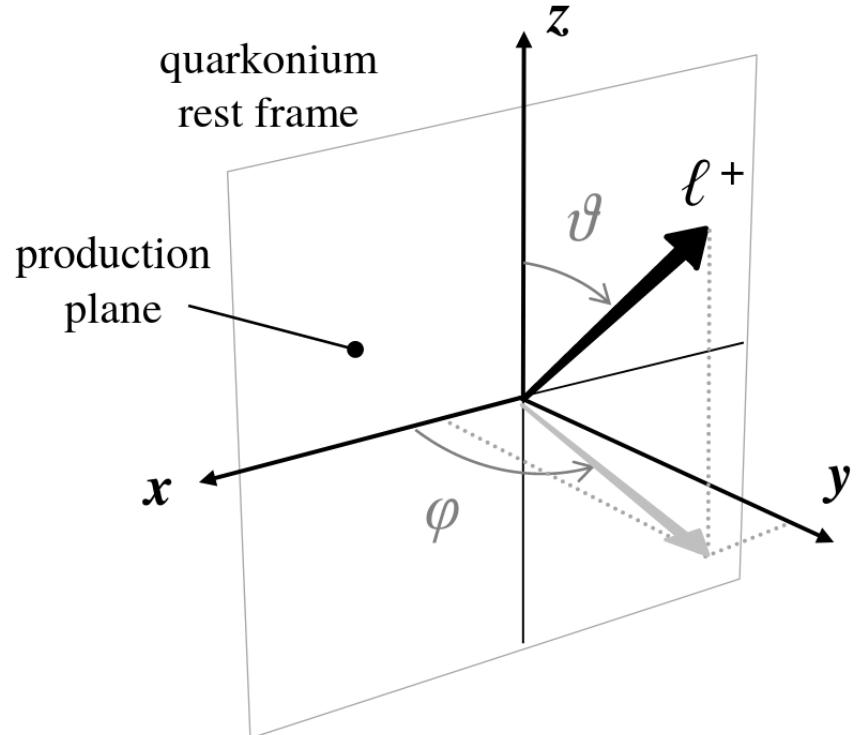
Angular momentum

- The **most vortical fluid in nature!** [Nature 548, 62 \(2017\)](#), STAR Collaboration
- Strong b dependence [PRC 77 \(2008\) 024906](#), Becattini et al.
- Affects **system evolution / hadronization**

Polarization: an introduction



spin alignment w.r.t. a chosen direction \Leftrightarrow angular distribution of the decay products



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

ρ_{00} = spin density matrix element

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

In quarkonia analyses:

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

λ_θ = polarization parameter

$\lambda_\theta = 0$ no spin alignment

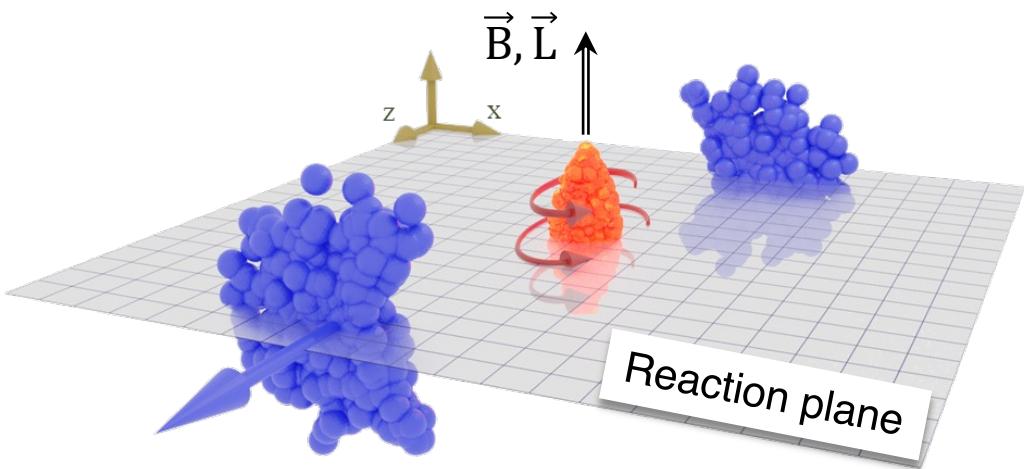
$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$$



[EPJC 69 \(657-673\), 2010](#), Faccioli et al.

Polarization: an introduction

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$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$$

- **Reaction plane based frame:** axis orthogonal to the reaction plane in the collision center of mass frame
- **Helicity frame:** direction of vector meson in the collision center-of-mass frame

Polarization: an introduction

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Vector meson production / polarization via 2 different mechanisms in HICs:

- Recombination of polarized quark (antiquark) in the QGP

$$\rho_{00} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} = \begin{cases} \leq 1/3^* \Rightarrow \vec{B} \\ < 1/3 \Rightarrow \vec{L} \end{cases}$$

* $> 1/3$ q=0, $< 1/3$ q \neq 0

- Polarized quark (antiquark) fragmentation

$$\rho_{00} = \frac{1 + \beta \cdot P_{\bar{q}}^2}{3 - \beta \cdot P_{\bar{q}}^2} > 1/3$$

Phys. Lett. B 629, 20 (2005), Liang et al.

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

? Recombination scenario at low p_T supported by light flavors (K^{*0}, ϕ), valid also for heavy flavors?

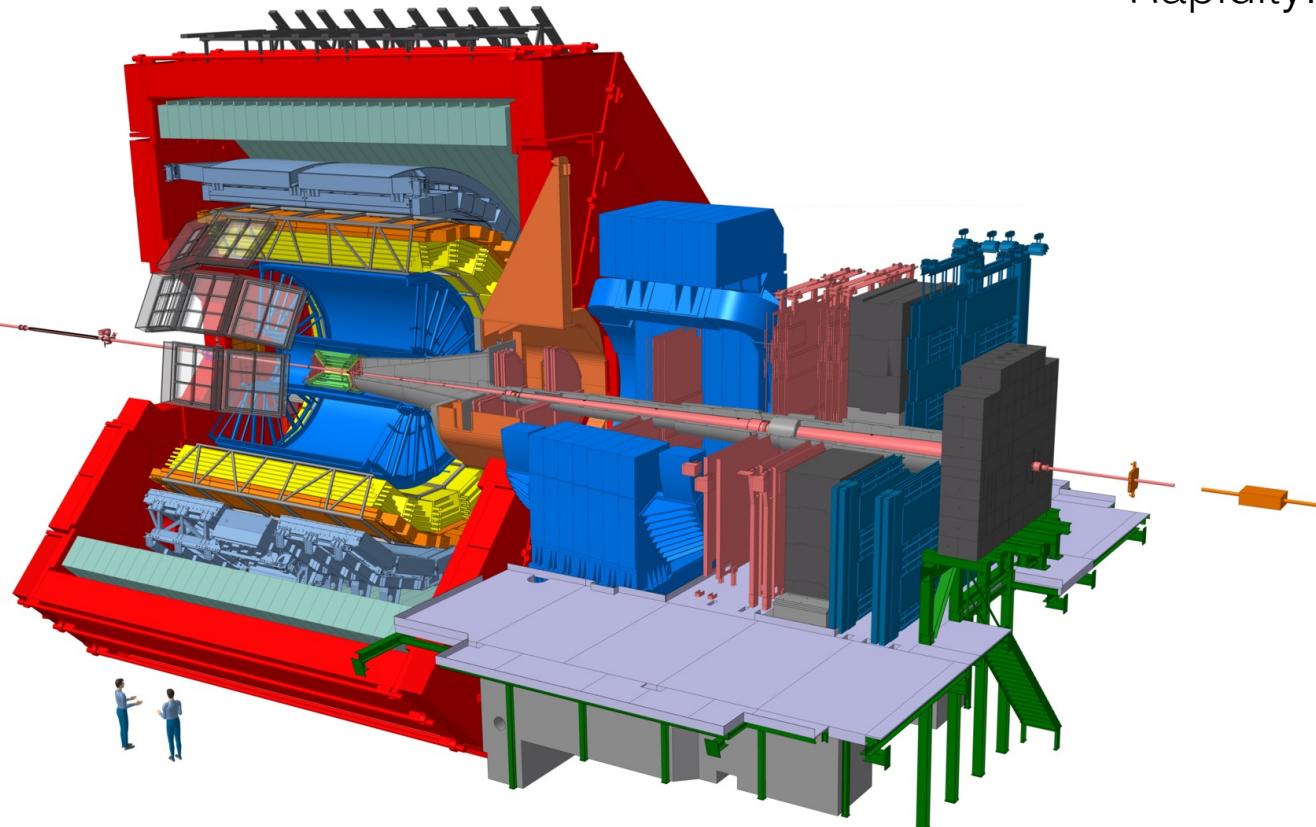
PRl 125 (2020) 012301, ALICE Collaboration

? Heavy quarks are produced in the first stages of the collision ($\tau_{\bar{c}c} \sim 0.1 \text{ fm}/c$)

Possibly affected by the magnetic field!

The ALICE detector (Run 2)

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Central Barrel

- Rapidity: $|y| < 0.9$

- I. Inner Tracking System
- II. Time Projection Chamber
- III. Time-Of-Flight detector
- IV. V0 detectors

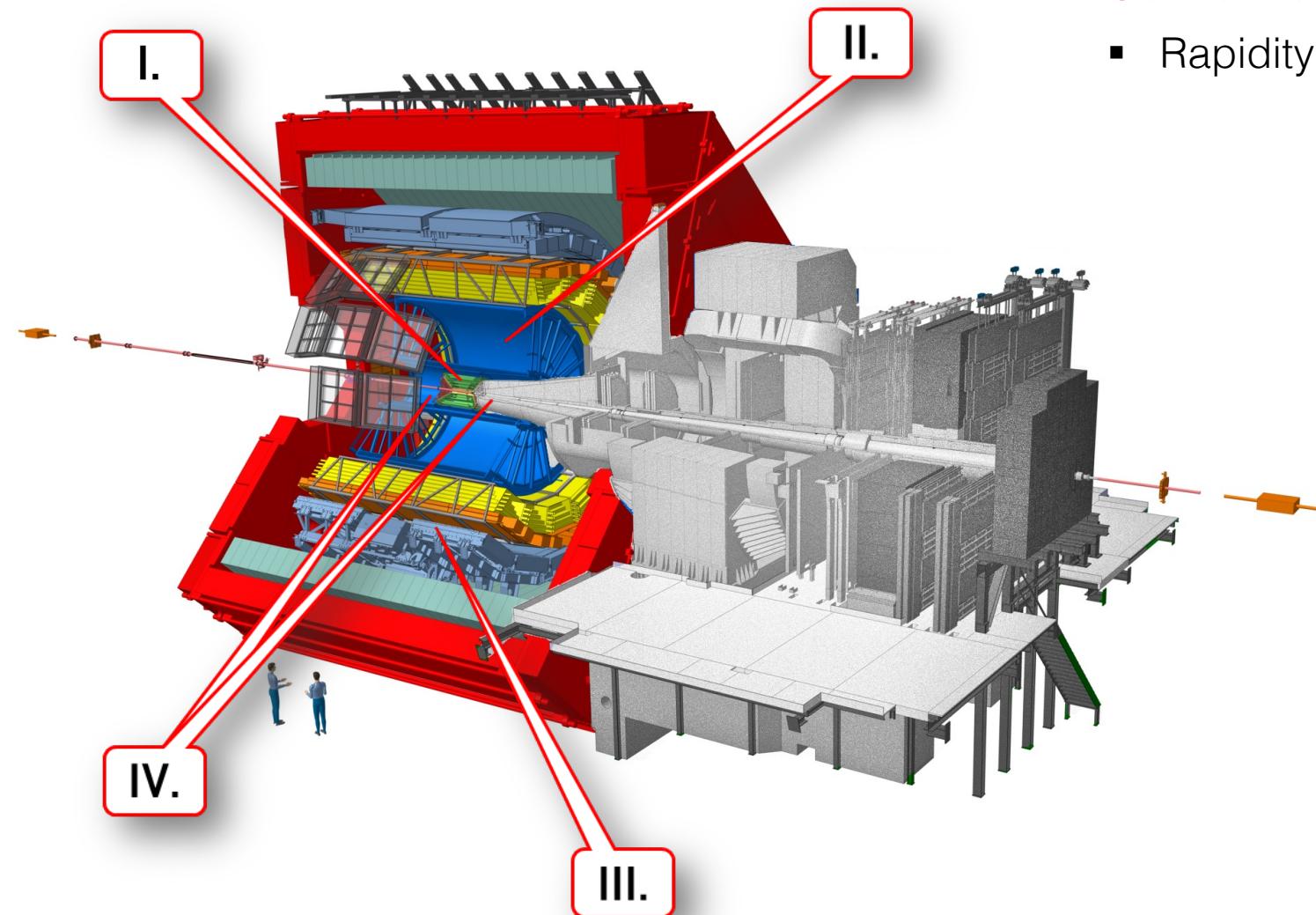
Muon Spectrometer

- Rapidity: $2.5 < y < 4$

- I. Front absorber
- II. Tracking system
- III. Dipole magnet
- IV. Trigger system

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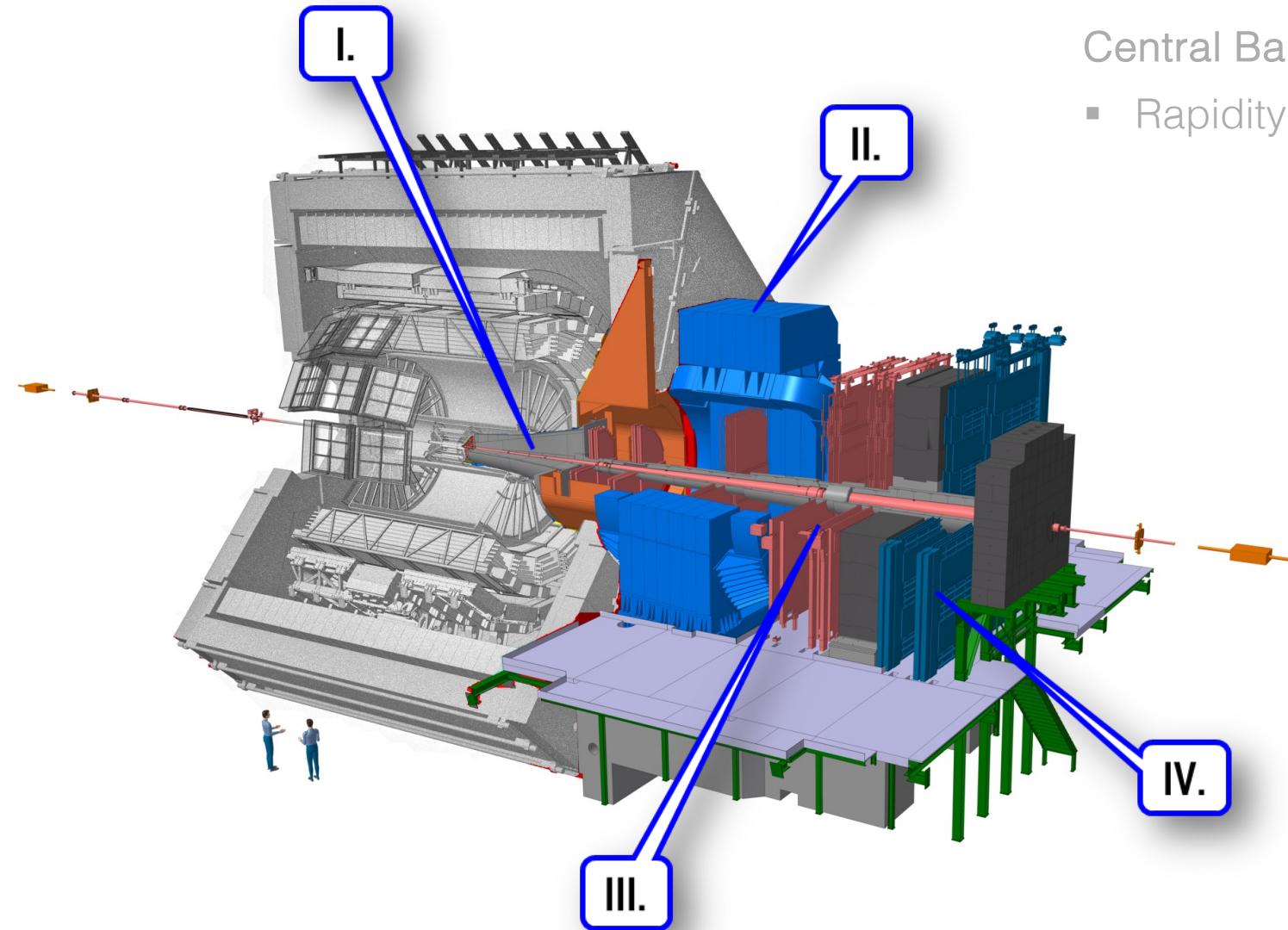
II. Tracking system

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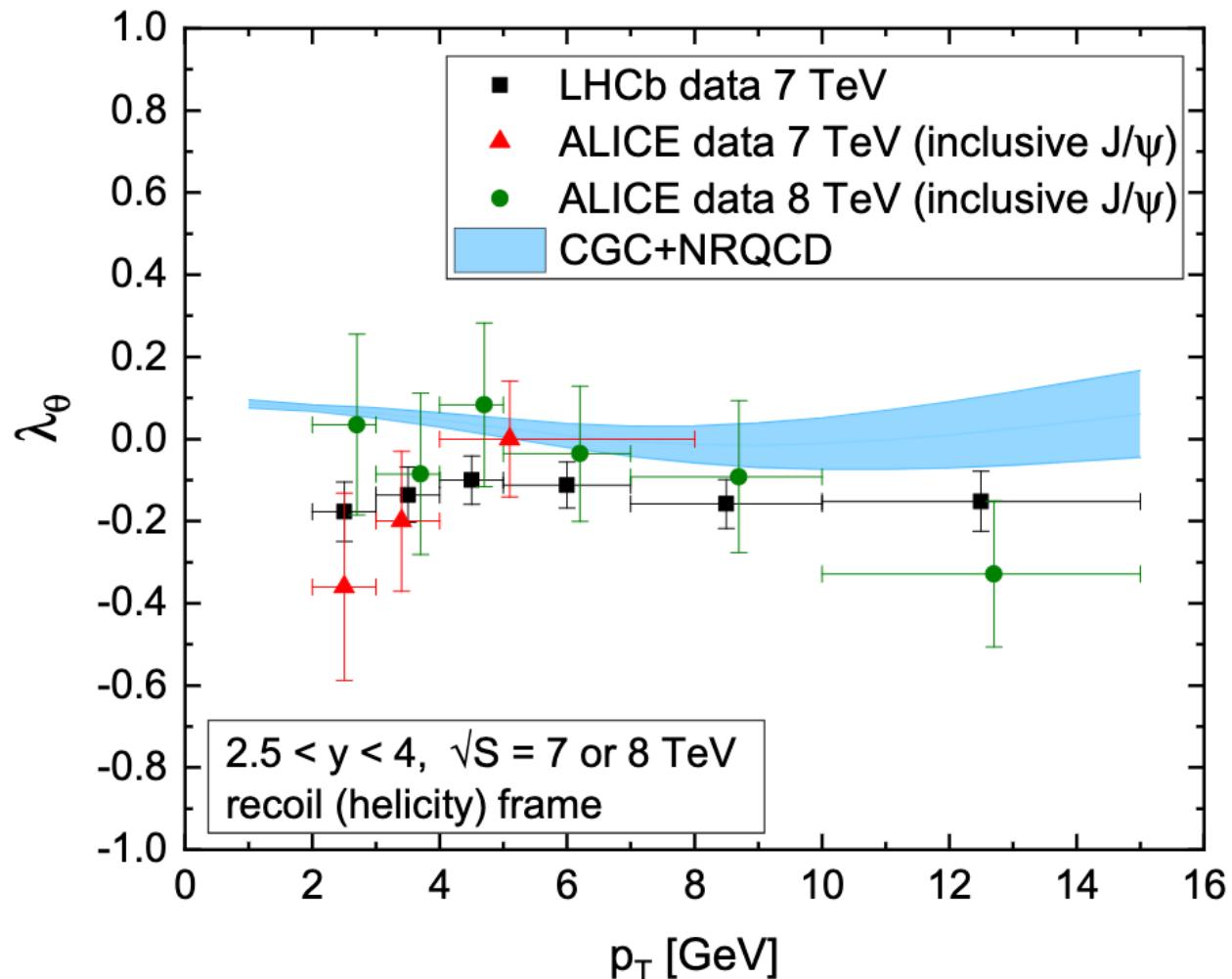
III. Dipole magnet

IV. Trigger system

Polarization in pp collisions: baseline

J/ ψ polarization in pp collisions

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Important to constrain charmonium production mechanisms in hadronic collisions

[PRL 108 \(2012\) 082001](#) [EPJC 78 \(2018\) 562](#)

[EPJC 73 \(2013\) 11](#) [JHEP 12 \(2017\) 110](#)

- 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

D^{*} polarization in pp collisions

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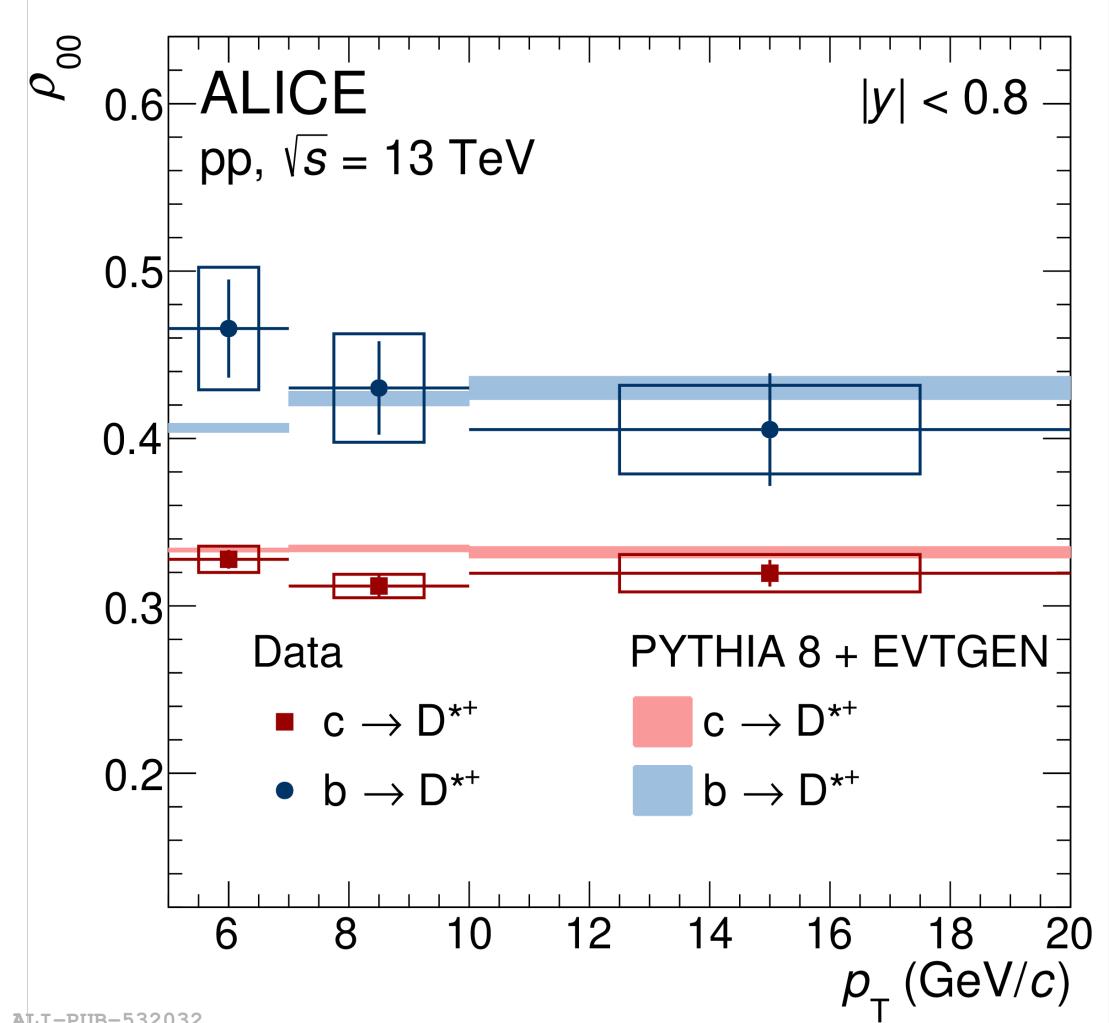


- First measurement of the **prompt** and **non-prompt** D^{*+} spin alignment at the LHC

[arxiv:2212.06588](https://arxiv.org/abs/2212.06588), accepted by PLB

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

- ✓ Measurement in agreement with the prediction of PYTHIA 8 + EVTGEN
- ✓ Baseline for studies in Pb–Pb collisions

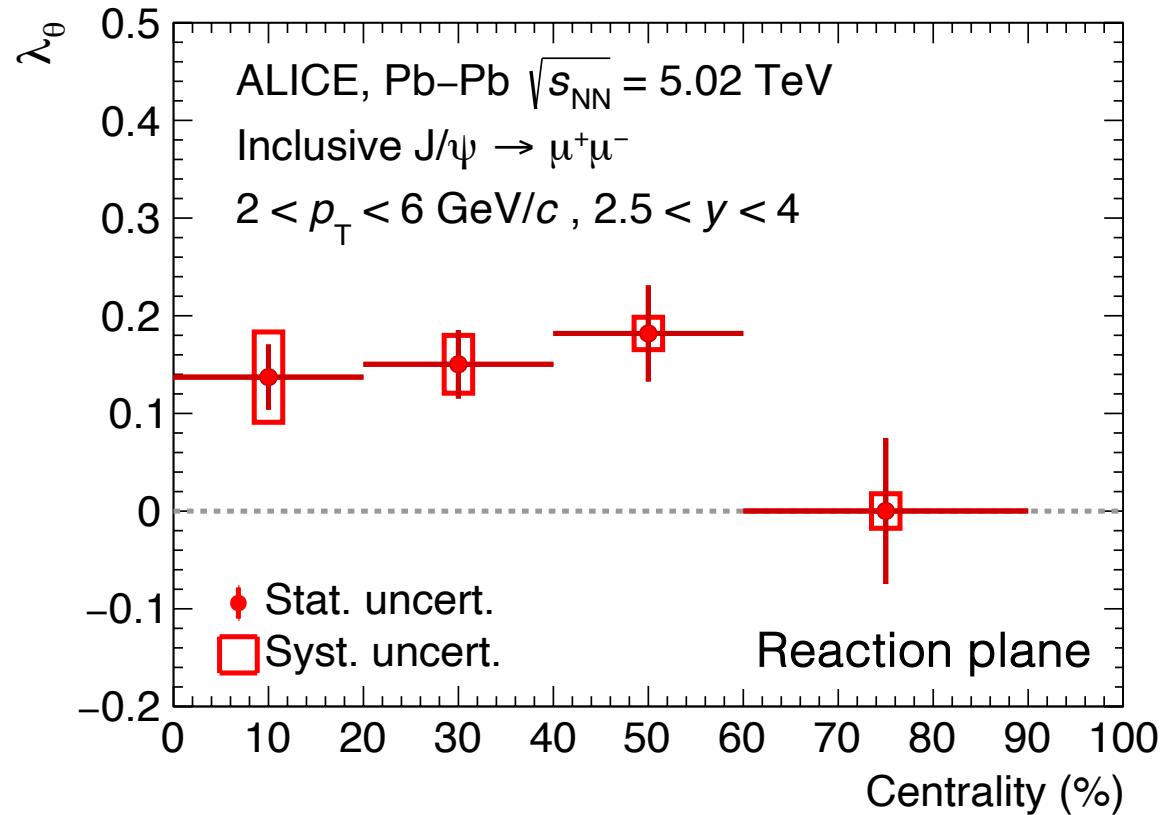


ALI-PUB-532032

Polarization in Pb–Pb collisions

J/ψ polarization in Pb–Pb collisions

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ALI-PUB-521052

- First measurement of quarkonium polarization with respect to the **Reaction plane**

[PRL 131 \(2023\) 042303](#), ALICE Collaboration

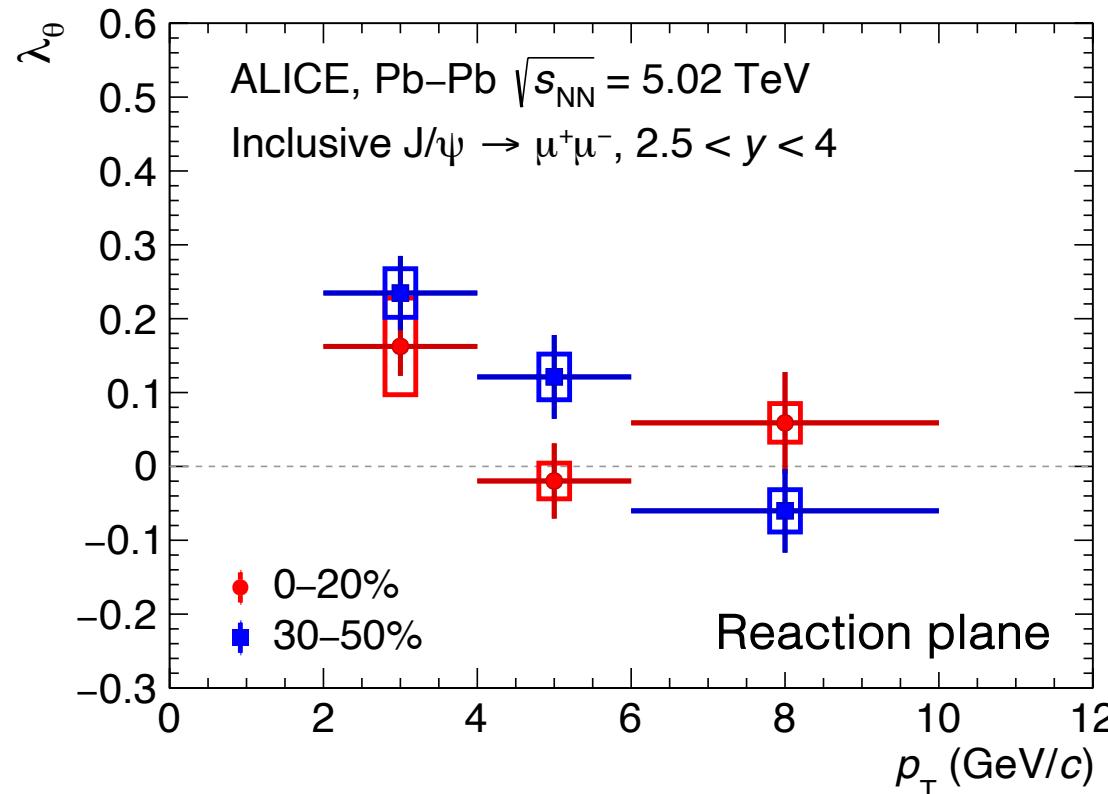
- **Centrality** dependence:
Small but significant (3.5σ) polarization observed in 40-60% centrality class and $2 < p_T < 6 \text{ GeV}/c$

- In the dilepton channel:

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

J/ψ polarization in Pb–Pb collisions

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- In the dilepton channel:

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

- First measurement of quarkonium polarization with respect to the **Reaction plane**
 [PRL 131 \(2023\) 042303](#), ALICE Collaboration
- Centrality** dependence:
Small but significant (3.5σ) polarization observed in 40-60% centrality class and $2 < p_T < 6 \text{ GeV}/c$
- p_T** dependence:
30-50%: significant deviation (3.9σ) at low transverse momentum ($2 < p_T < 4 \text{ GeV}/c$)
- ✓ Qualitatively in agreement with the scenario of **quark recombination**
- ✓ A comprehensive theory of quarkonium polarization in HICs is missing

D^{*} polarization in Pb–Pb collisions

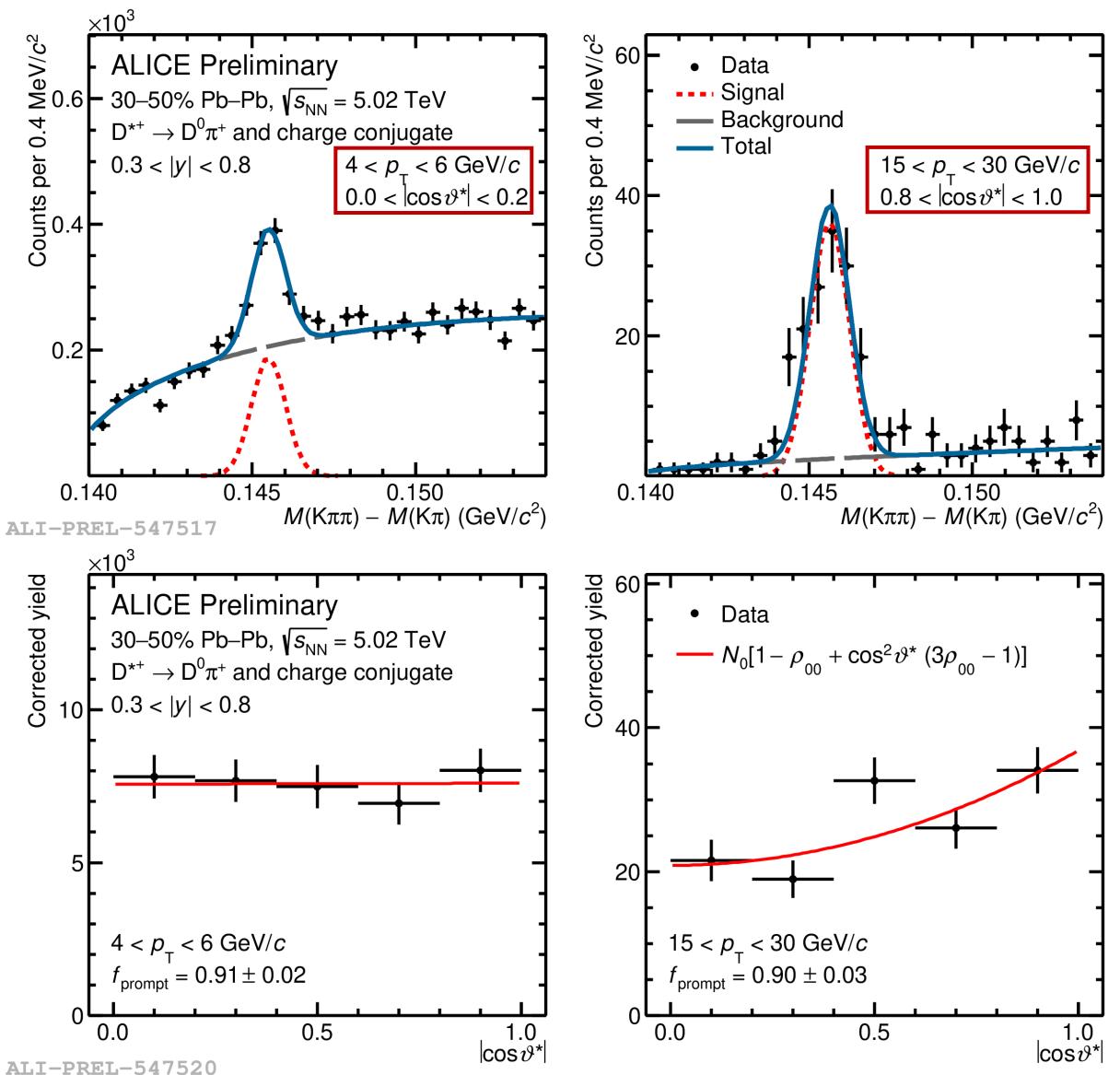
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New ALICE preliminary measurement!

First measurement of D⁺⁺ polarization with respect to the Reaction plane

- Multiclass classification algorithm based on BDT used to:
 - reduce **combinatorial background**
 - distinguish among **prompt** and **non-prompt** components
- ρ_{00} extracted taking into account:
 - Event plane finite resolution
 - Feed-down contribution



D^{*} polarization in Pb–Pb collisions

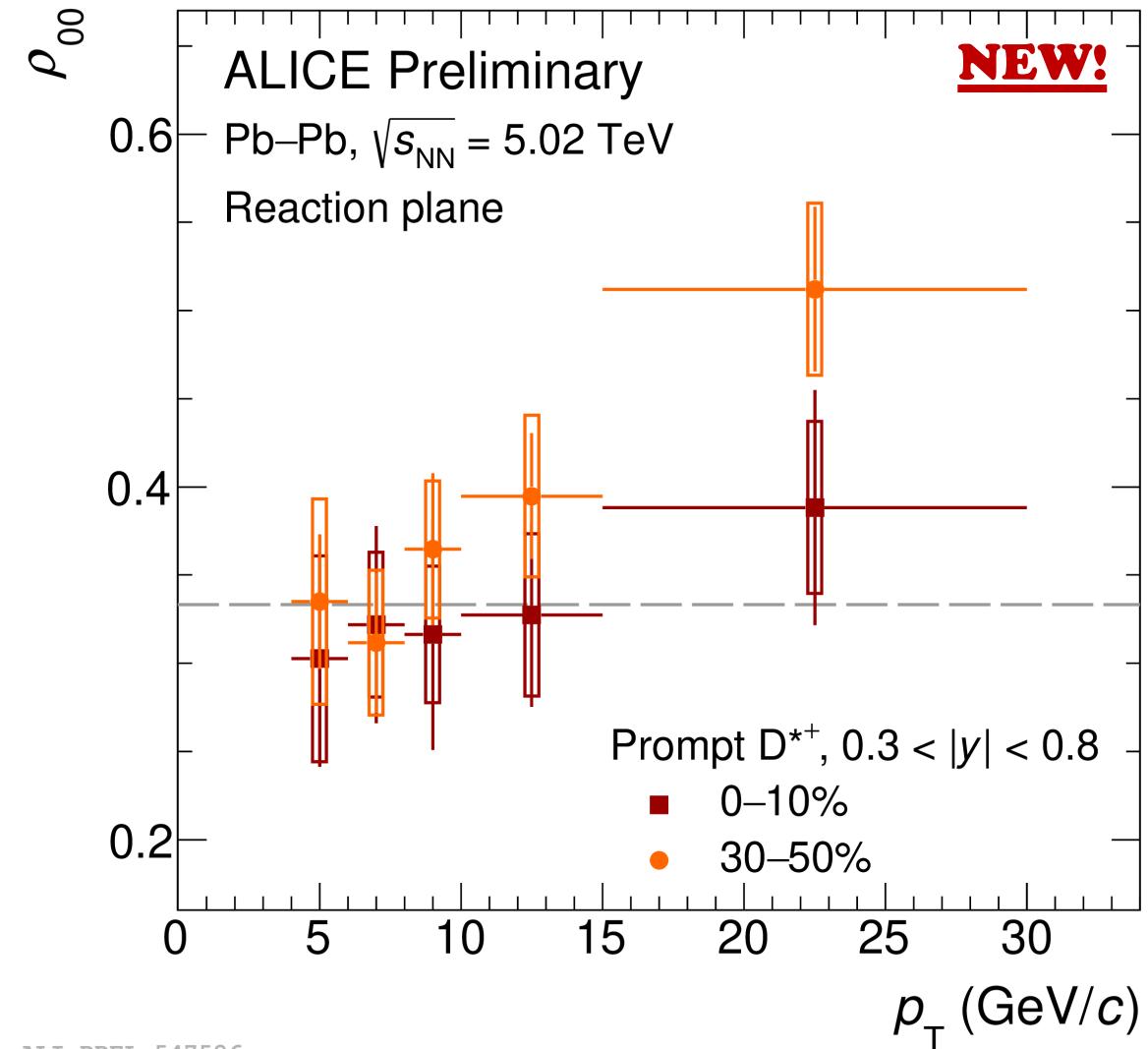
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New ALICE preliminary measurement!

First measurement of D⁺⁺ polarization with respect to the Reaction plane

- p_T & centrality dependence:
 - 0 – 10% : ρ_{00} compatible with 1/3
 - 30 – 50% : $\rho_{00} > 1/3$ at high p_T



D^{*} polarization in Pb–Pb collisions

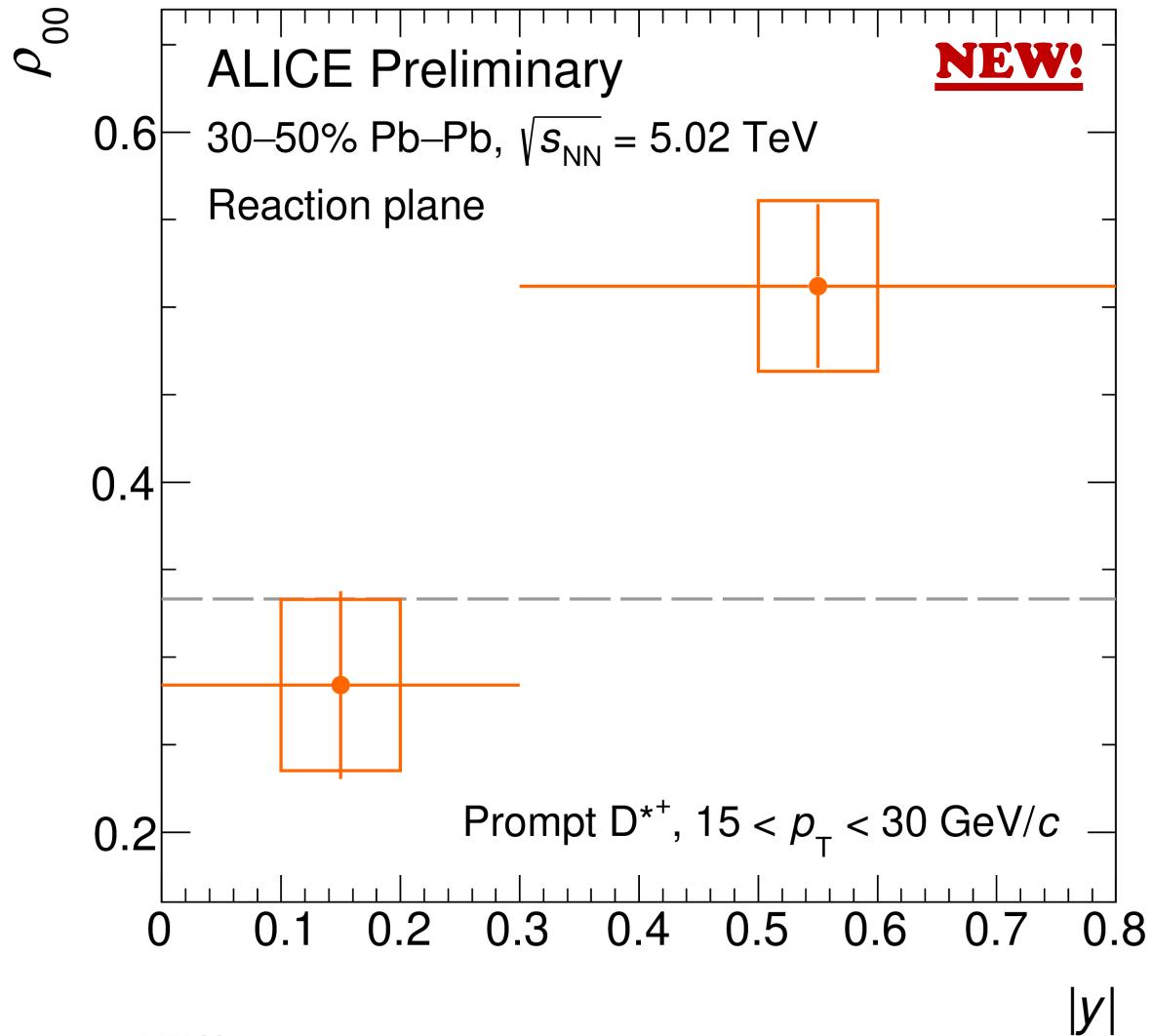
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New ALICE preliminary measurement!

First measurement of D^{*+} polarization with respect to the Reaction plane

- p_T & centrality dependence:
 - 0 – 10% : ρ_{00} compatible with 1/3
 - 30 – 50% : $\rho_{00} > 1/3$ at high p_T
- y dependence:
significant deviation at forward ($0.3 < |y| < 0.8$) than at mid ($|y| < 0.3$) rapidity



D^{*} polarization in Pb–Pb collisions

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New ALICE preliminary measurement!

First measurement of D^{*+} polarization with respect to the Reaction plane

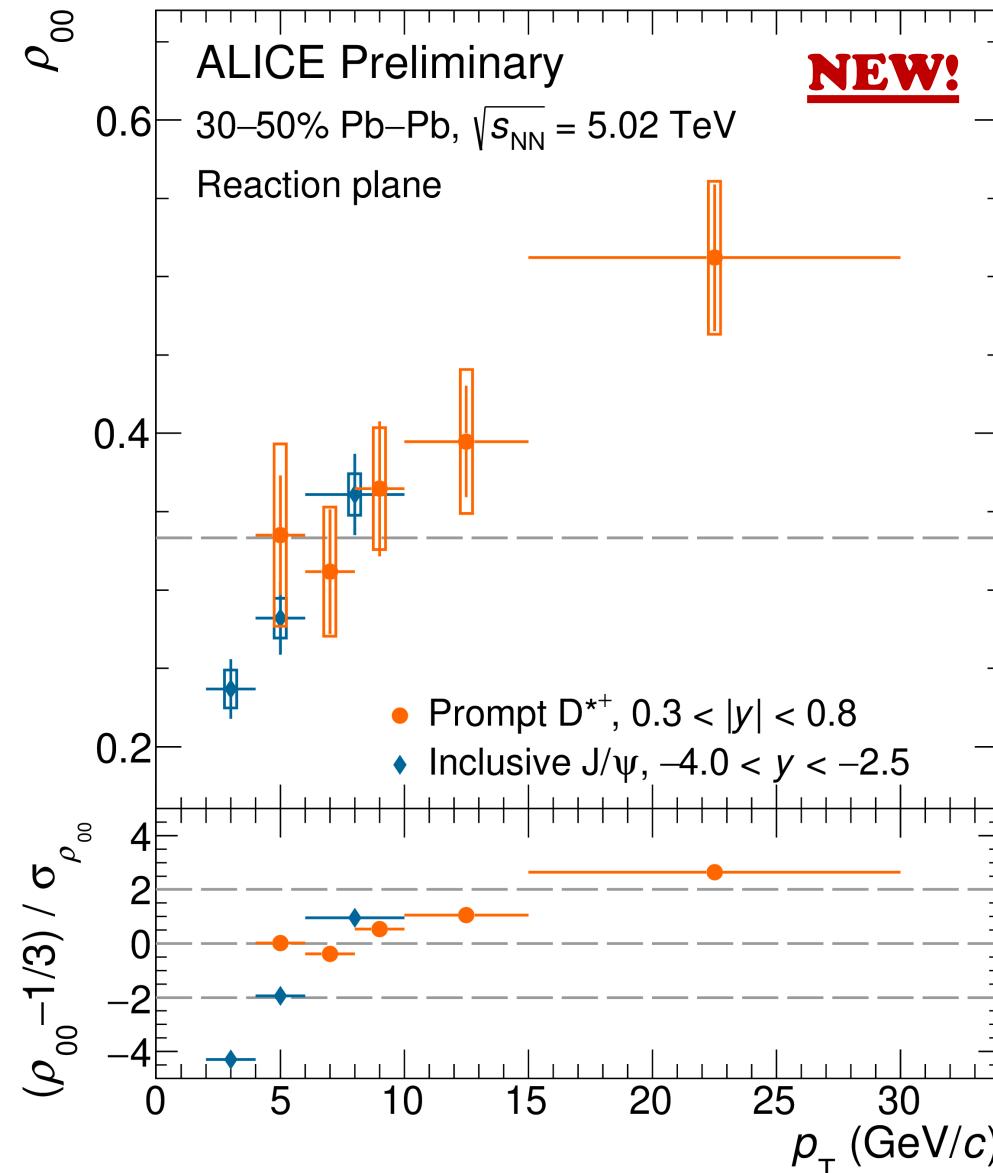
Qualitatively in agreement with:

$$\rho_{00} < \frac{1}{3} \quad \text{quark recombination at low } p_T$$

$$\rho_{00} > \frac{1}{3} \quad \text{quark fragmentation at high } p_T$$

- At high p_T the fragmentation of heavy quarks polarized by the magnetic field translates to $\rho_{00} > 1/3$?

➤ Theory guidance needed!



Summary: before QM2023

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QM 2023



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

Summary: before QM2023

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QM 2023



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

👉 pp collisions: light flavors, D^{*+} and J/ψ are compatible with zero polarization

Summary: new at QM2023

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QM 2023



	K [*] 0	Φ	D ⁺	J/ψ	ψ(2S)	χ _c	Υ(nS)
pp	$\rho_{00} \sim 1/3$	$\rho_{00} \sim 1/3$	$\rho_{00} \sim 1/3$	$\rho_{00} \sim 1/3$	$\rho_{00} \sim 1/3$	$\rho_{00} \sim 1/3$	$\rho_{00} \neq 1/3$
Pb–Pb	$\rho_{00} < 1/3$ <small>low p_T</small>	$\rho_{00} < 1/3$ <small>low p_T</small>	NEW! $\rho_{00} > 1/3$ <small>high p_T</small>	$\rho_{00} < 1/3$ <small>low p_T</small>	?	?	$\rho_{00} \sim 1/3$

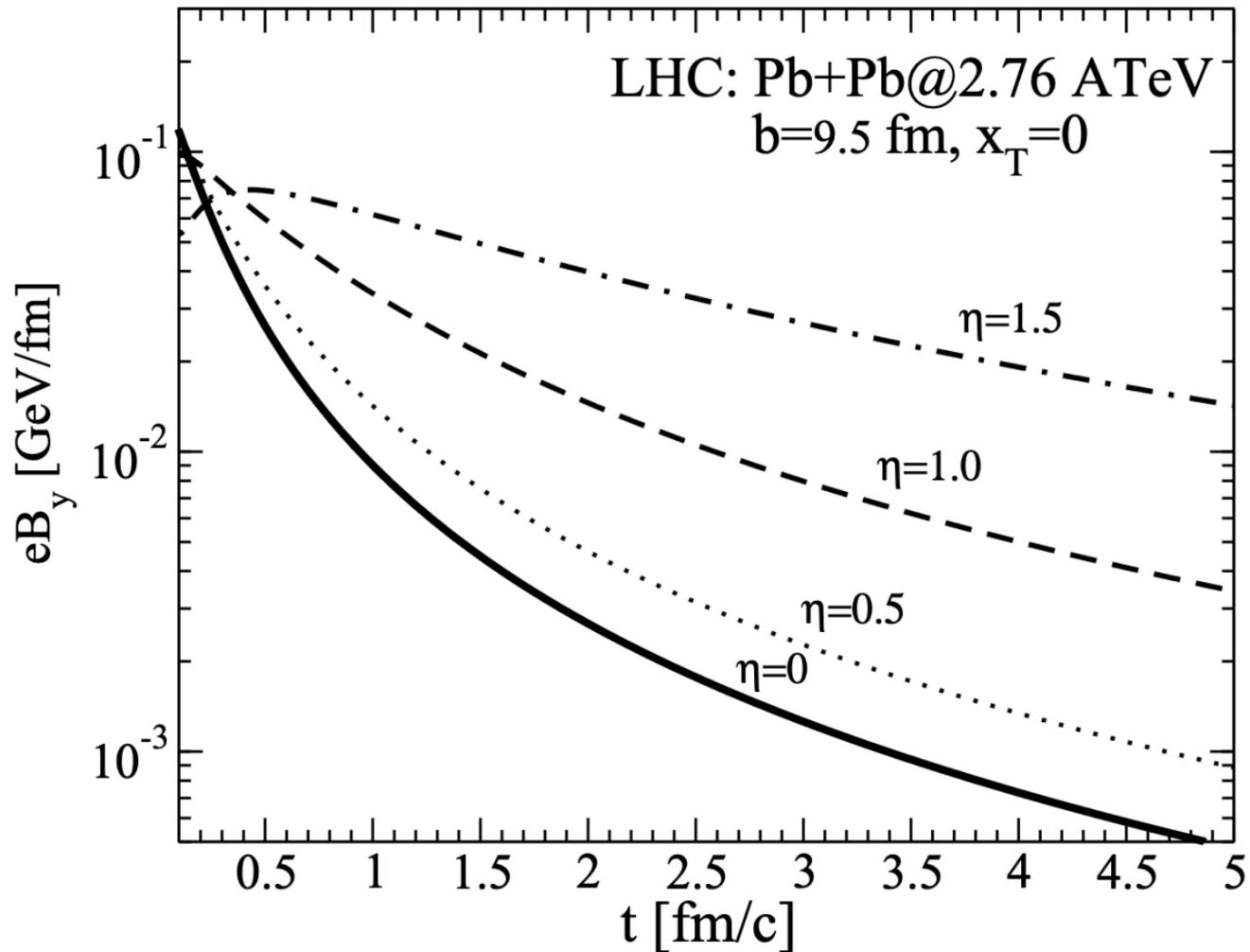
● pp collisions: light flavors, D⁺ and J/ψ are compatible with zero polarization

● Pb–Pb collisions:

- $\rho_{00} < 1/3$ for light flavors, J/ψ at low p_T ⇒ recombination scenario
- $\rho_{00} > 1/3$ for D⁺ at high p_T & fwd rapidity ⇒ quark fragmentation scenario

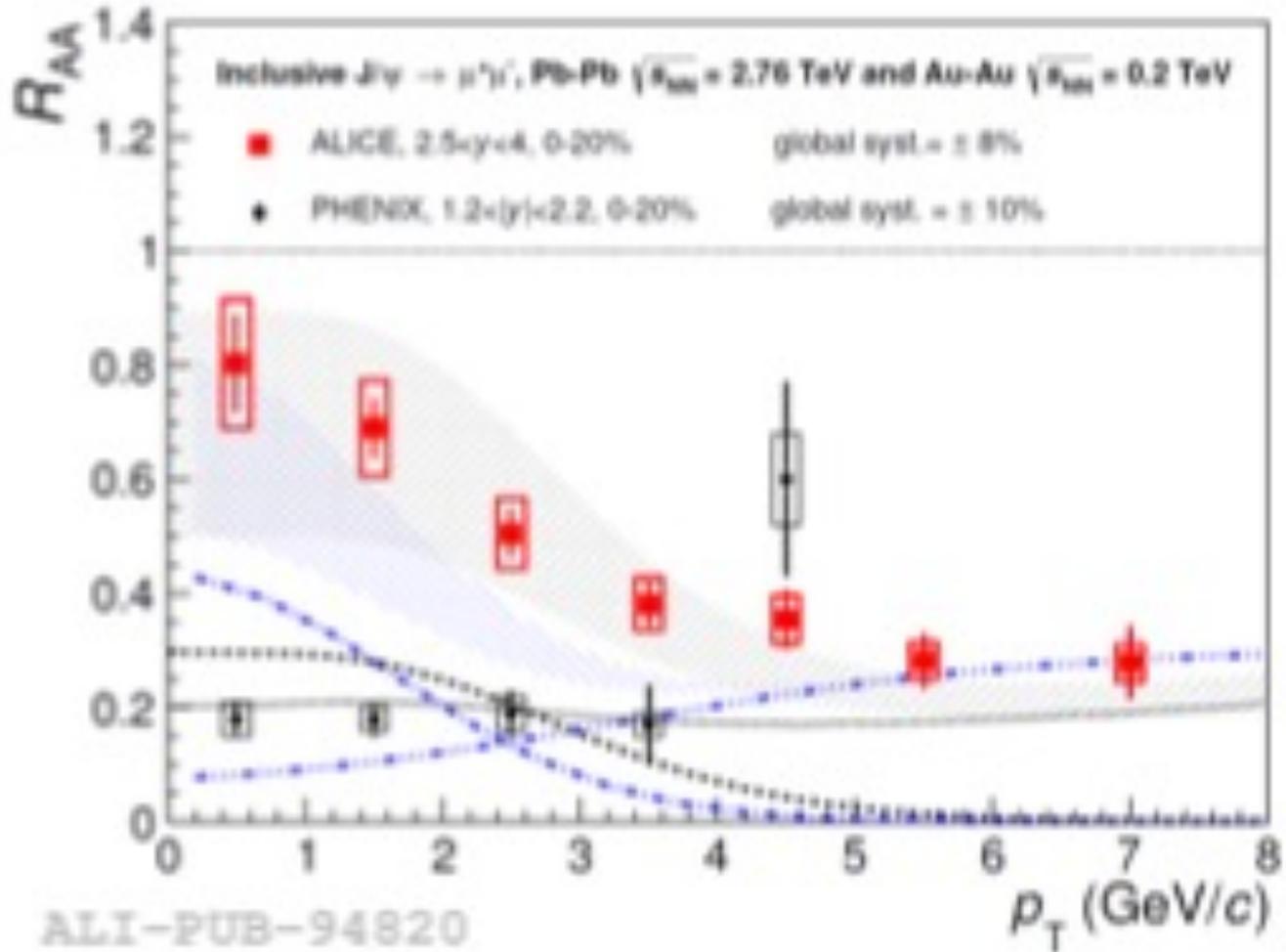
Backup

Magnetic field



Charmonia at LHC and RHIC

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[PLB 734 \(2014\)](#), ALICE collaboration

D^{*} polarization: random plane

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