25th International Spin Symposium(SPIN 2023)

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

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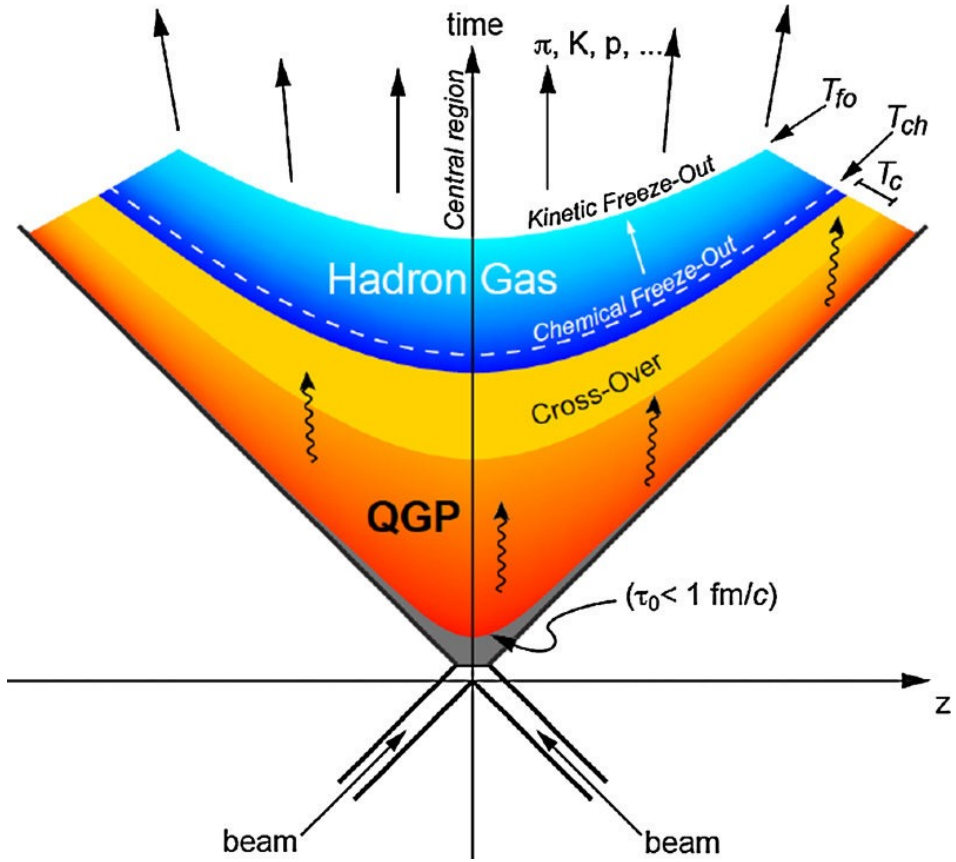
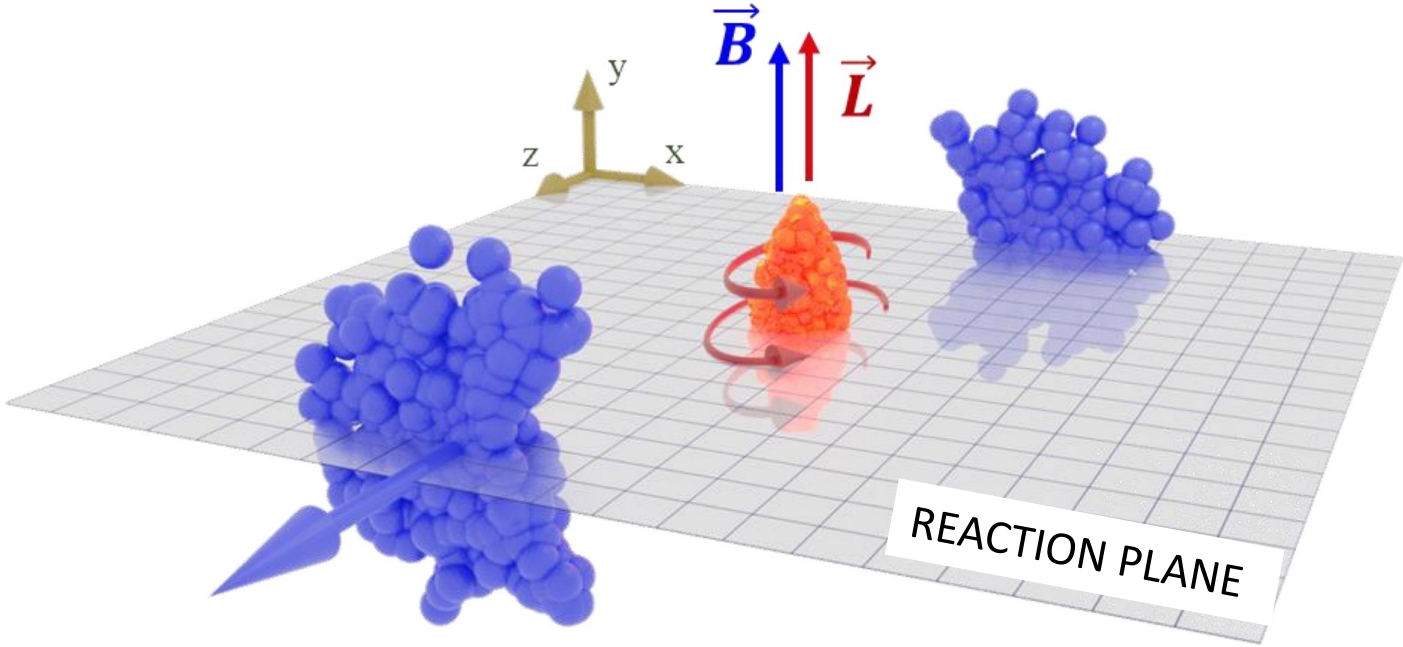
University of Science and Technology of China

Durham US, 24-29 Sep. 2023

ALICE

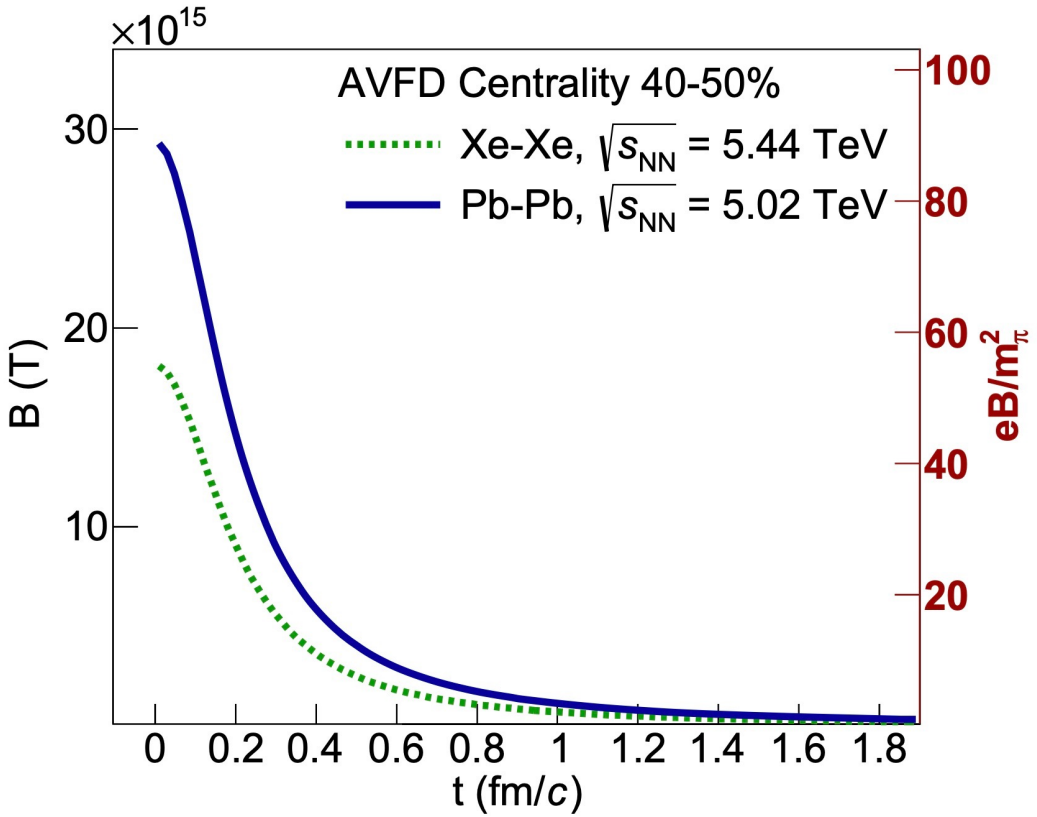
Introduction to heavy-ion collisions



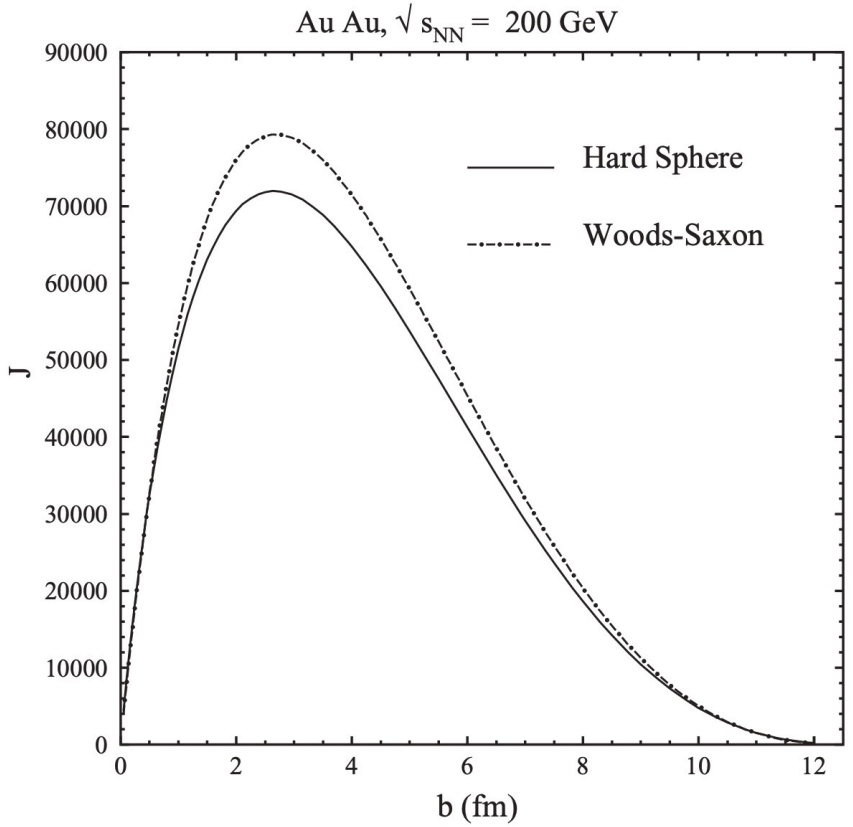


- In non-central heavy-ion collisions, short-lived magnetic fields (***B***) and very strong orbital momentum (***L***) are expected to be produced.
- They can influence the global polarization of the produced particles.

Strong magnetic field and orbital momentum



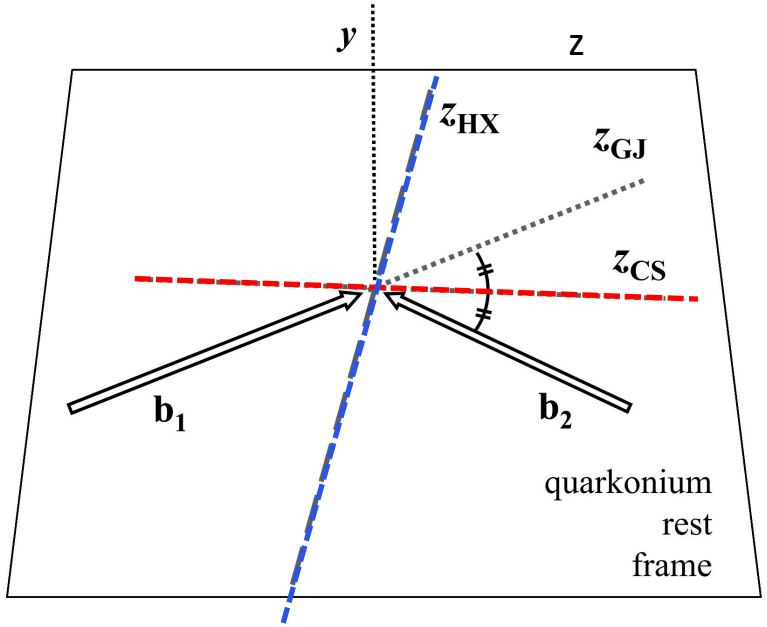
Christakoglu et al., EPJC (2021) **81**: 717

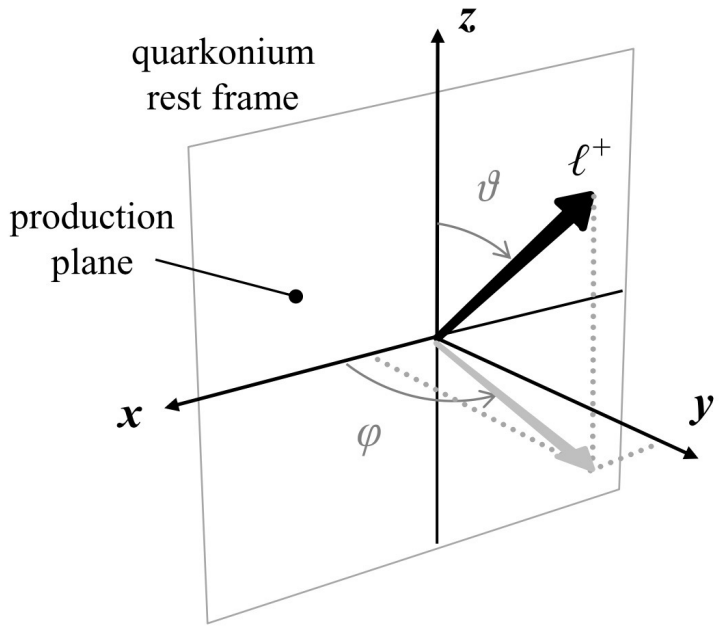


F. Becattini et al., PRC 77 (2008)

- The most intense magnetic field in nature! [STAR Collaboration, Nature 548, 62 (2017)]
- Lifetime increases from mid to forward rapidity [Das et al., PLB 768 (2017) 260]
- Angular momentum strongly dependents on impact parameter (b)

Introduction to polarization measurements





Polarization is studied via measurement of angular distribution of particle decay products

Polarization axis:

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

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

Motivation for polarization measurements

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

- **Recombination** of polarized quark (antiquark) during the hadronization

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

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

P_{q} is global quark polarization

- Polarized quark (antiquark) **fragmentation**

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

Quarkonia measurements:

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

$\lambda_\theta =$ polarization parameter

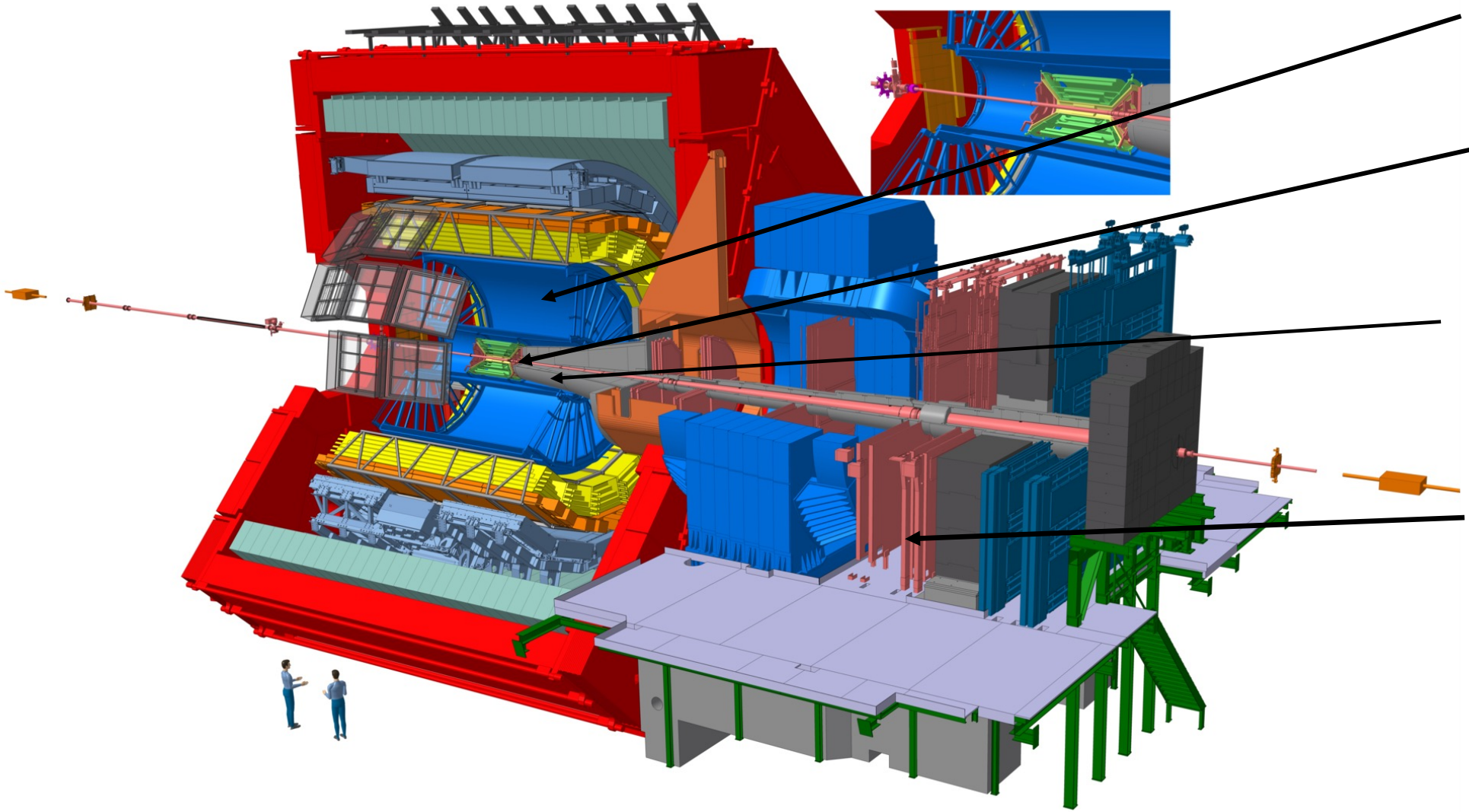
$\lambda_\theta = 0$ no spin alignment

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

Z. Liang, X. Wang, PLB 629 (2005) 20-26
Y. Yang, et al. ,Phys. Rev. C **97**, (2018)034917
P. Faccioli et al. EPJ C69 (2010) 657-673
X. Sheng, et al., PRL 131 (2023) 4, 042304

- **pp collisions**: Important to constrain quarkonium production mechanisms in hadronic collisions
- **AA collisions**: Polarization measurements gives access to different time scales and mechanisms, like the early-produced magnetic field, angular momentum, and hadronization mechanisms.

ALICE detector (Run 2)



Time Projection Chamber
Tracking, particle identification

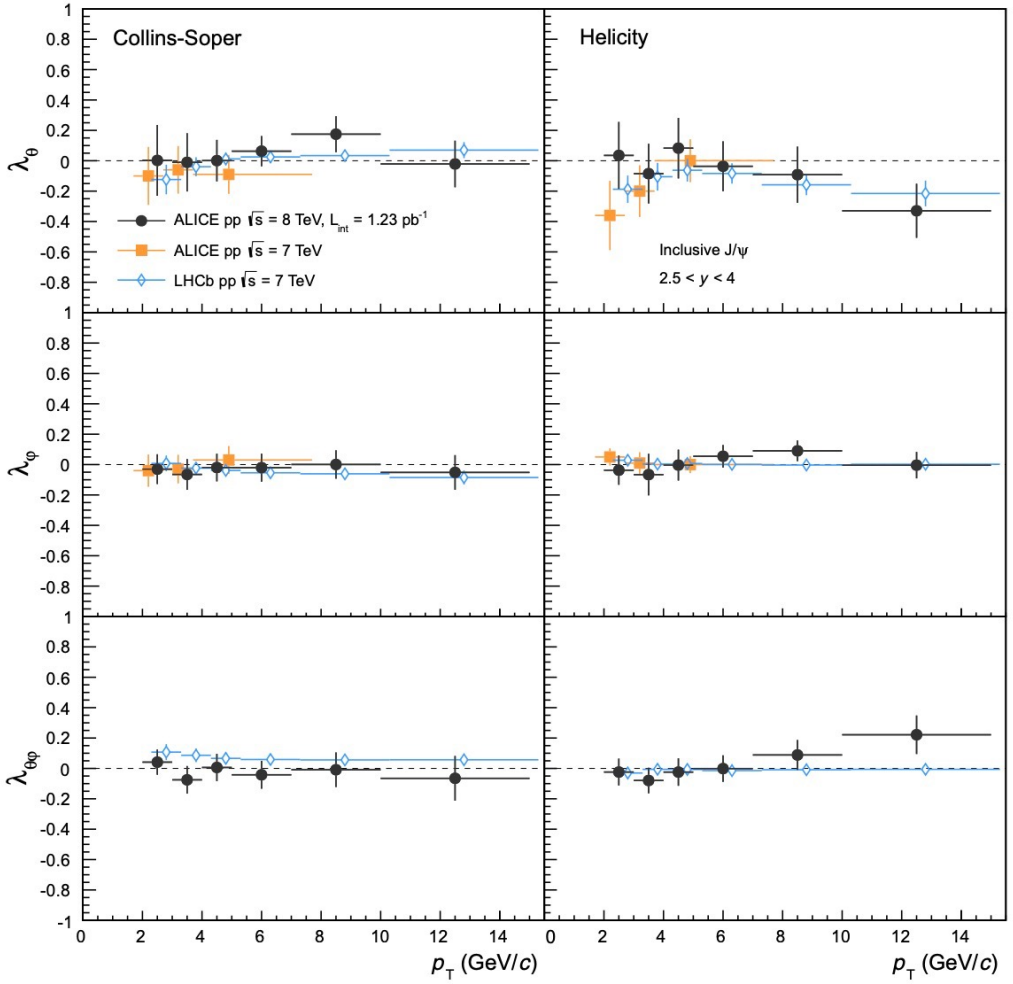
Inner Tracking System
Tracking, vertex reconstruction, event plane determination

V0 Detector
Centrality determination, triggering, event plane determination, and background rejection

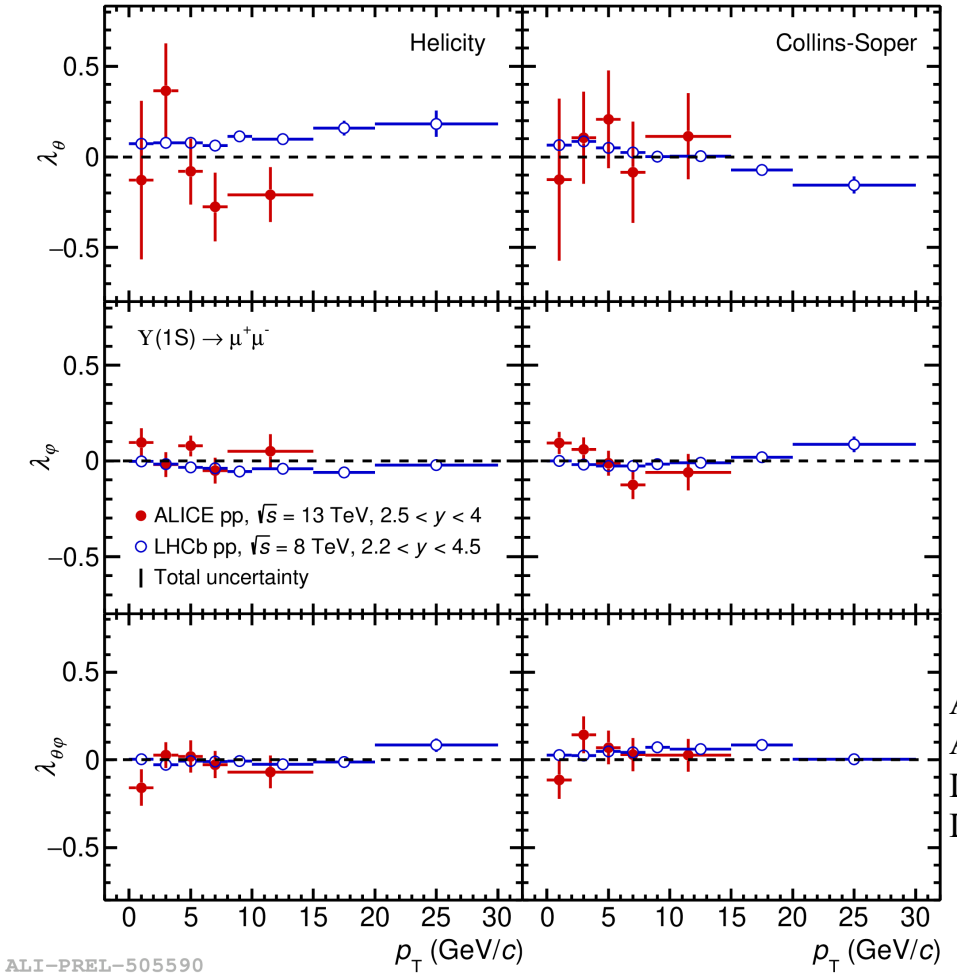
Muon spectrometer
Trigger and tracking for muons

Quarkonia polarization measurements in pp collisions

J/ψ polarization



ϒ(1S) polarization

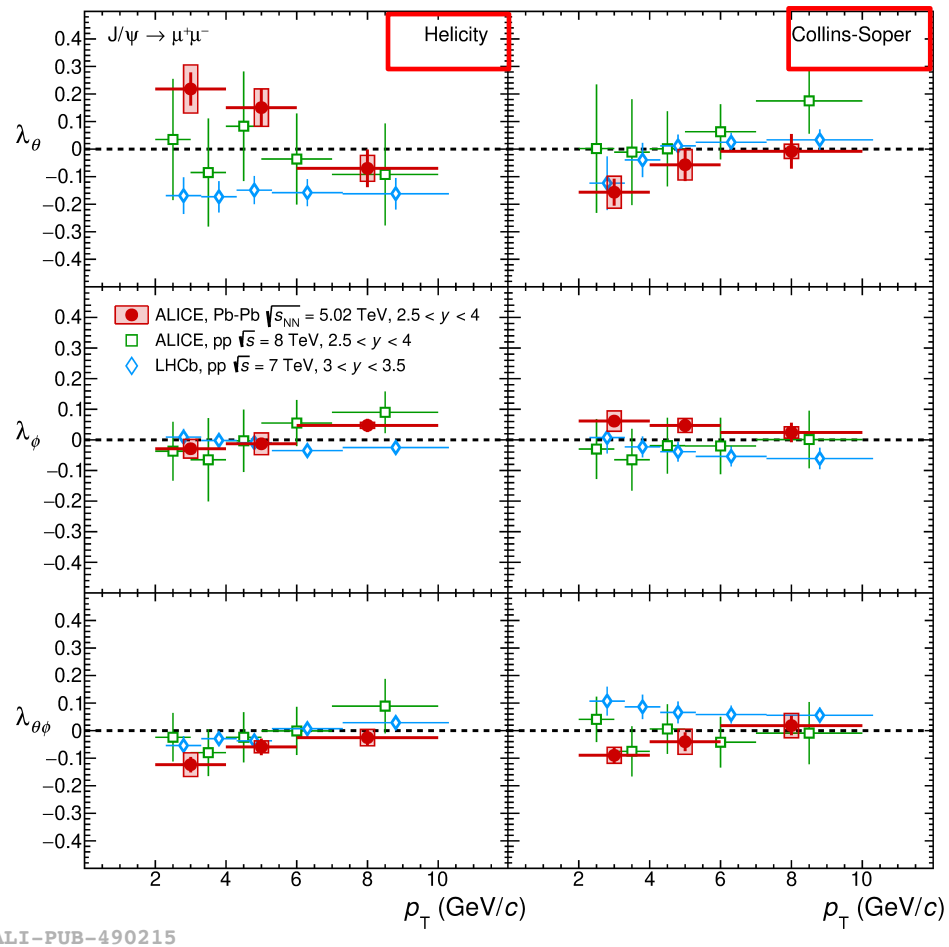


ALICE, PRL 108 (2012) 082001
ALICE, EPJC 78 (2018) 562
LHCb, JHEP,12(2017) 110
LHCb: JHEP 12 (2017) 110

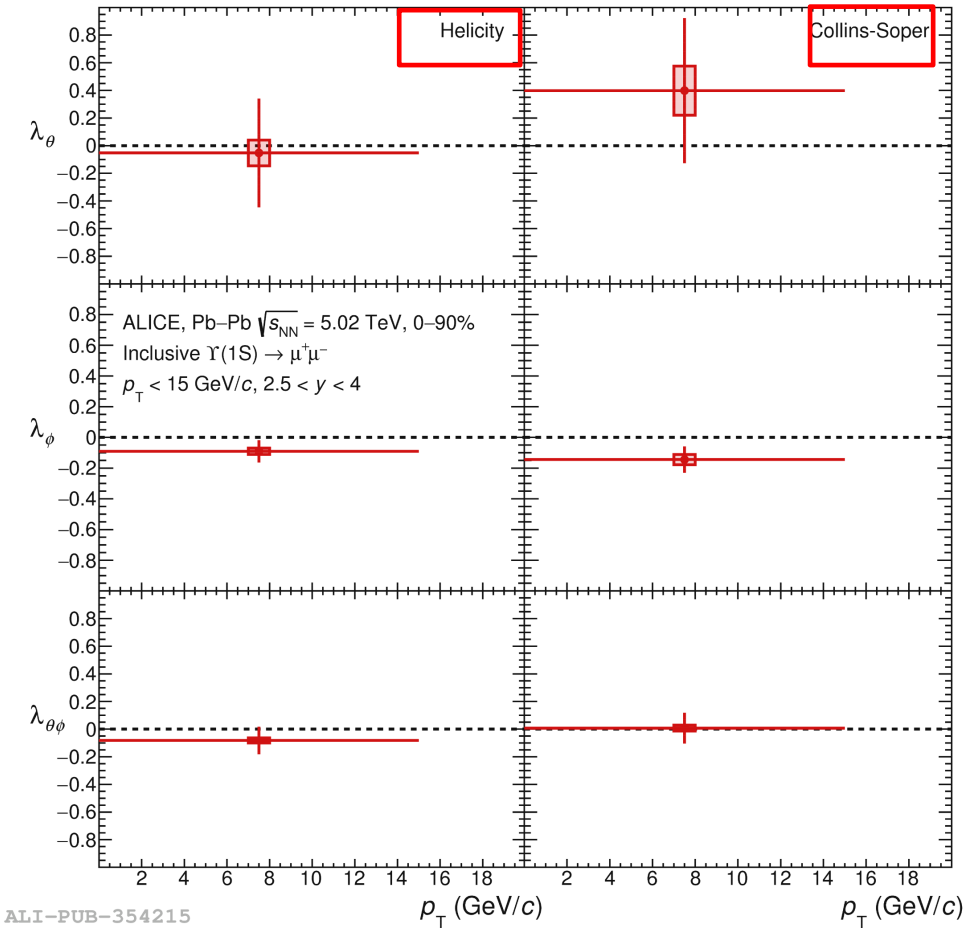
No strong polarization is observed for **J/ψ and ϒ(1S)** by ALICE at forward rapidity up to p_T = 15 GeV/c

Quarkonia polarization measurements in heavy-ion collisions

J/ψ polarization



Υ(1S) polarization

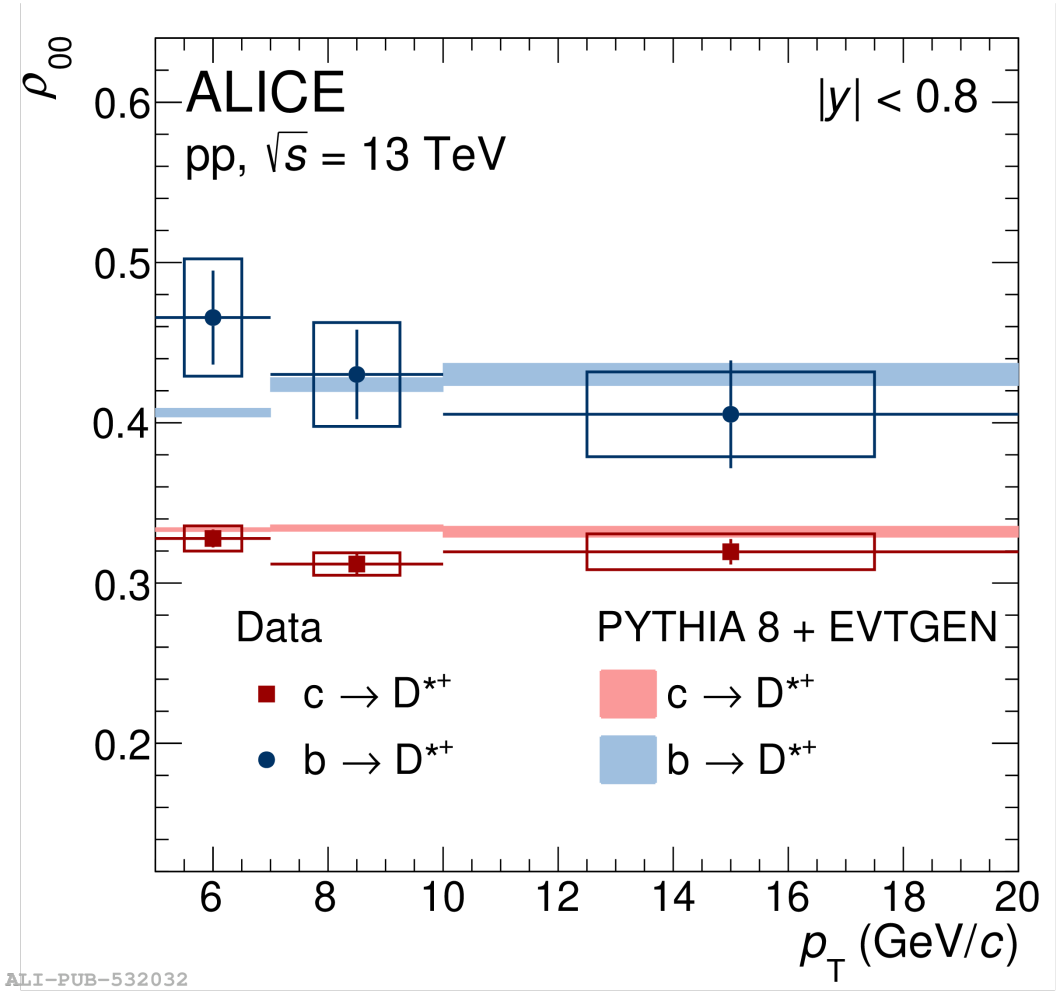


- **No strong polarization** is observed for **Υ(1S)** although there are substantial uncertainties.
- Maximum deviation from zero is 2.1σ in the low p_T bin for J/ψ in Helicity reference frame

ALICE, PLB 815 (2021) 136146
LHCb, JHEP12 (2017) 110
ALICE, PLB 815 (2021) 136146

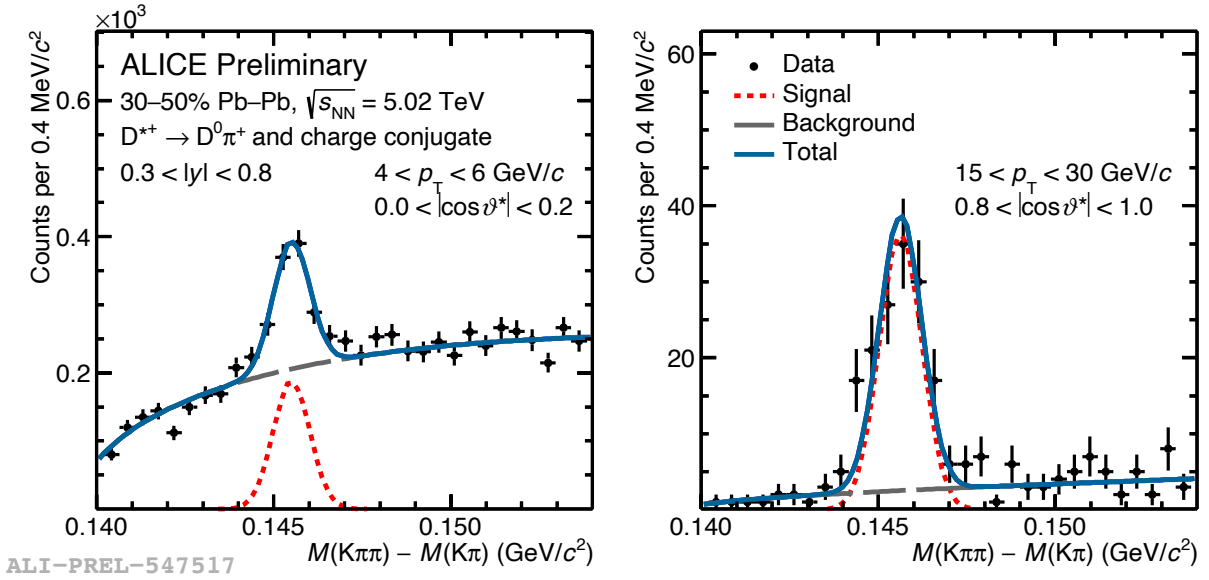
The prompt and non-prompt D^{*+} polarization in pp collisions

ALICE, arxiv:2212.06588, accepted by PLB



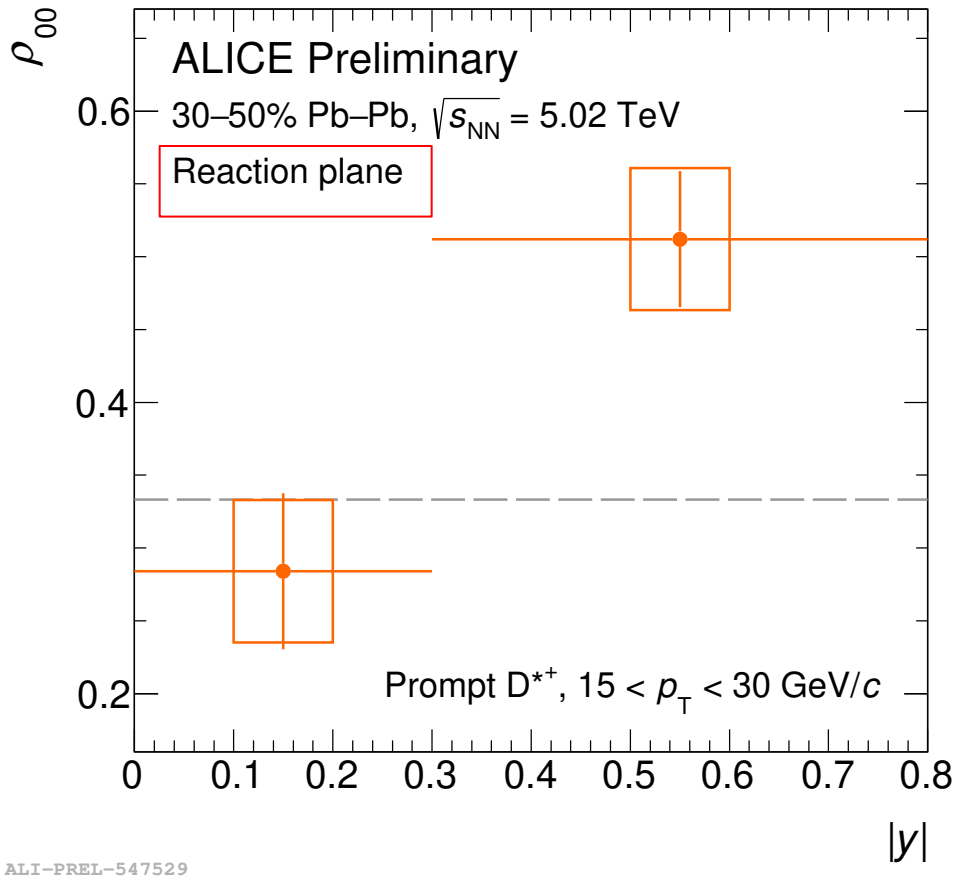
- Measurement performed with respect to the helicity reference frame
- Prompt $\mathbf{D}^{*+}$ ρ_{00} compatible with 1/3 within uncertainties (no polarization)
- Non-prompt $\mathbf{D}^{*+}$ $\rho_{00} > 1/3$ due to the helicity conservation of the beauty hadrons decay
- The charm quarks are either produced unpolarised or their polarization is washed out during the hadronization process
- An important baseline for future spin alignment measurements of D^{*+} vector mesons in heavy-ion collisions

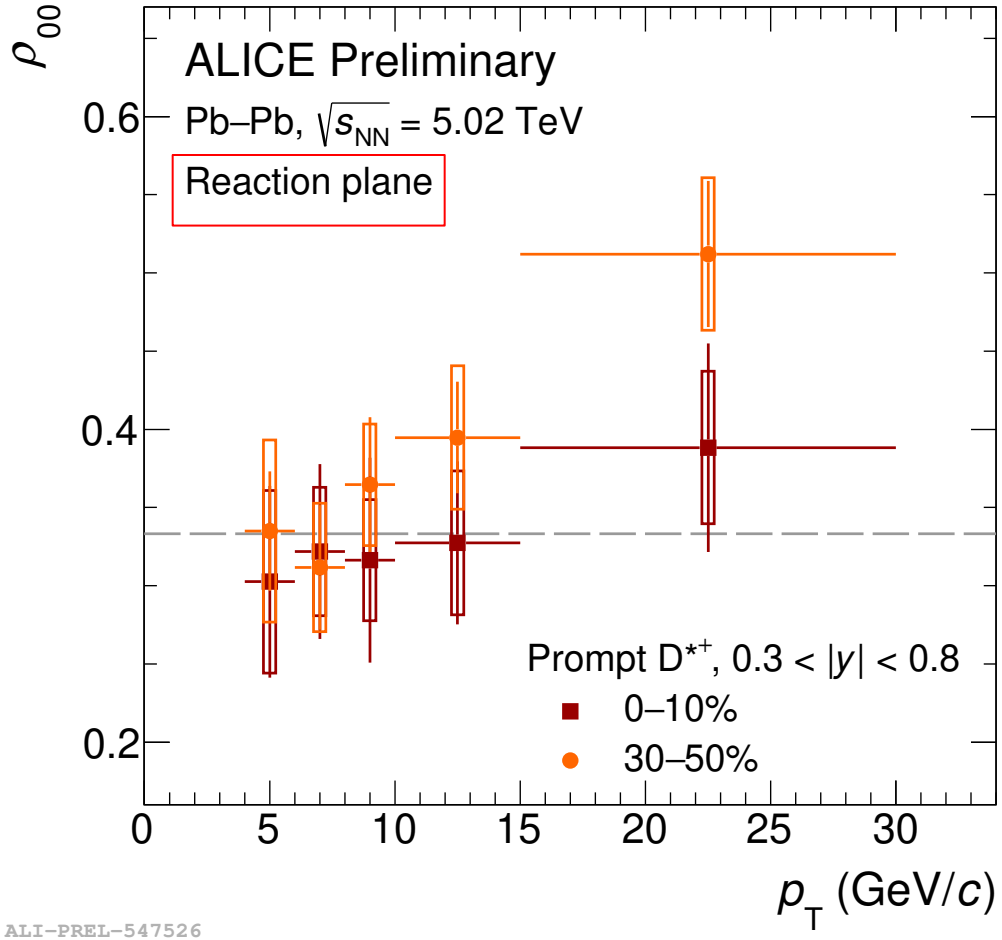
D^{*+} global polarization in Pb–Pb collisions



- First measurement of D^{*+} polarization with respect to the reaction plane
- Multiclass classification algorithm based on BDT used to reduce the combinatorial background and distinguish among prompt and non-prompt components
- ρ_{00} extracted taking into account:
  - Event plane finite resolution
  - B-hadron feed-down contribution

D^* global polarization in Pb–Pb collisions

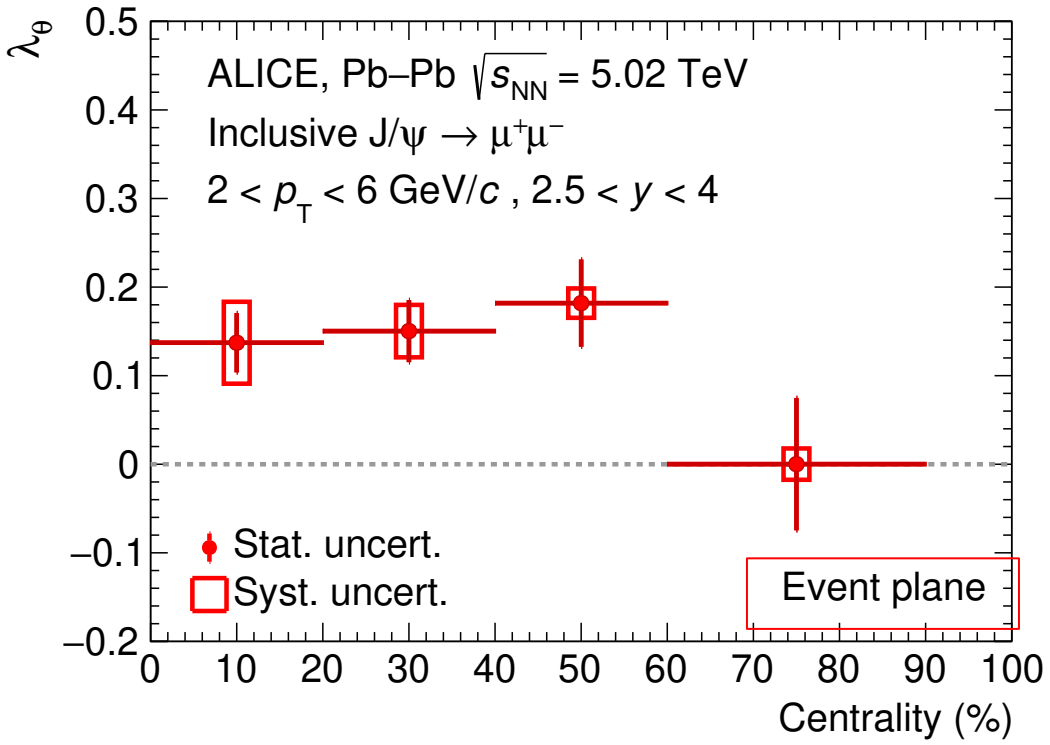


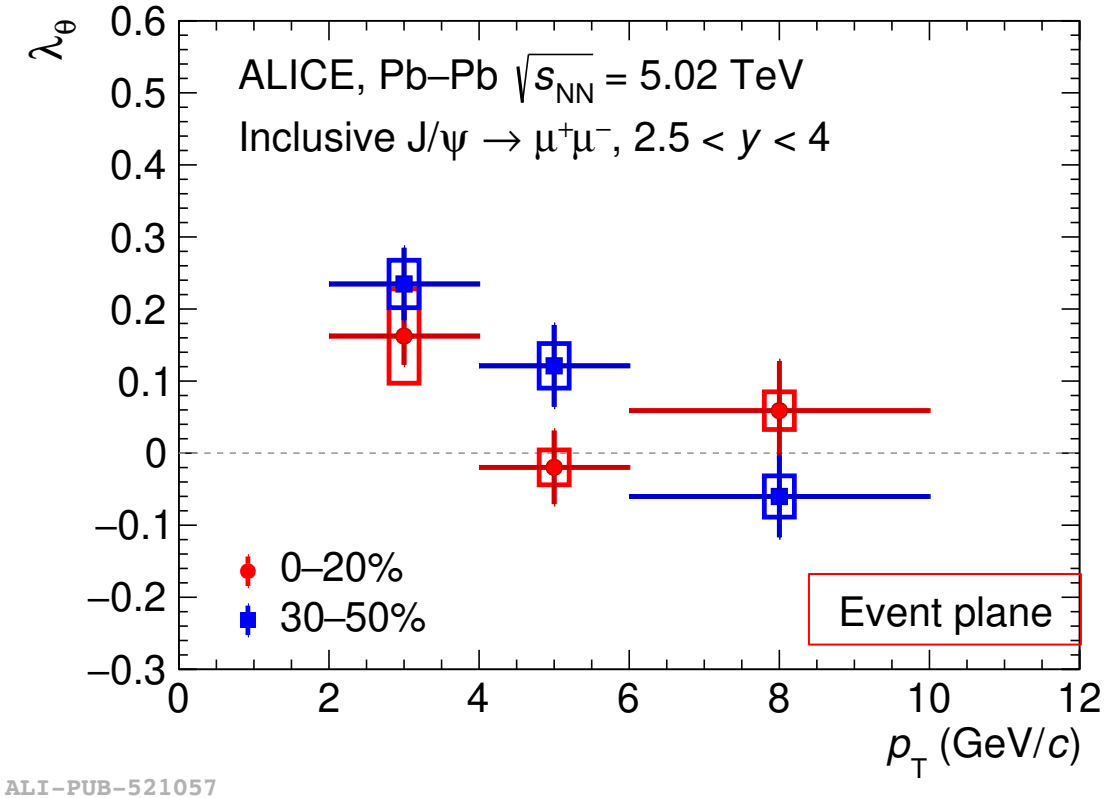


- 0 – 10% : ρ_{00} compatible with 1/3 , 30 – 50% : $\boldsymbol{\rho_{00}}$ > 1/3 at high p_T
- Significant deviation at larger rapidity (0.3 < |y| < 0.8) than at midrapidity (|y| < 0.3)

J/ψ polarization in Pb−Pb collisions

PRL 131 (2023) 4, 042303

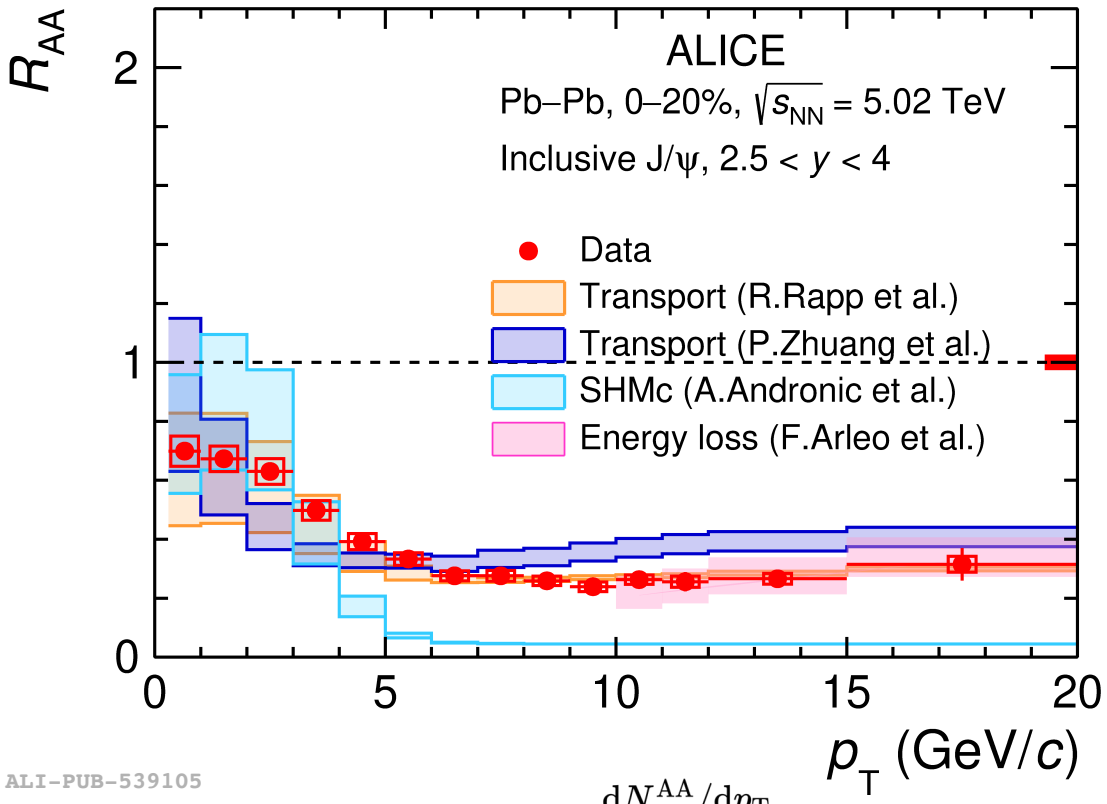




- First measurement of quarkonium polarization **with respect to the event plane**
- **Significant polarization (~3.5σ)** observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The significance of the polarization reaches **~3.9σ** at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results requires inputs from theoretical models

J/ψ polarization in Pb−Pb collisions

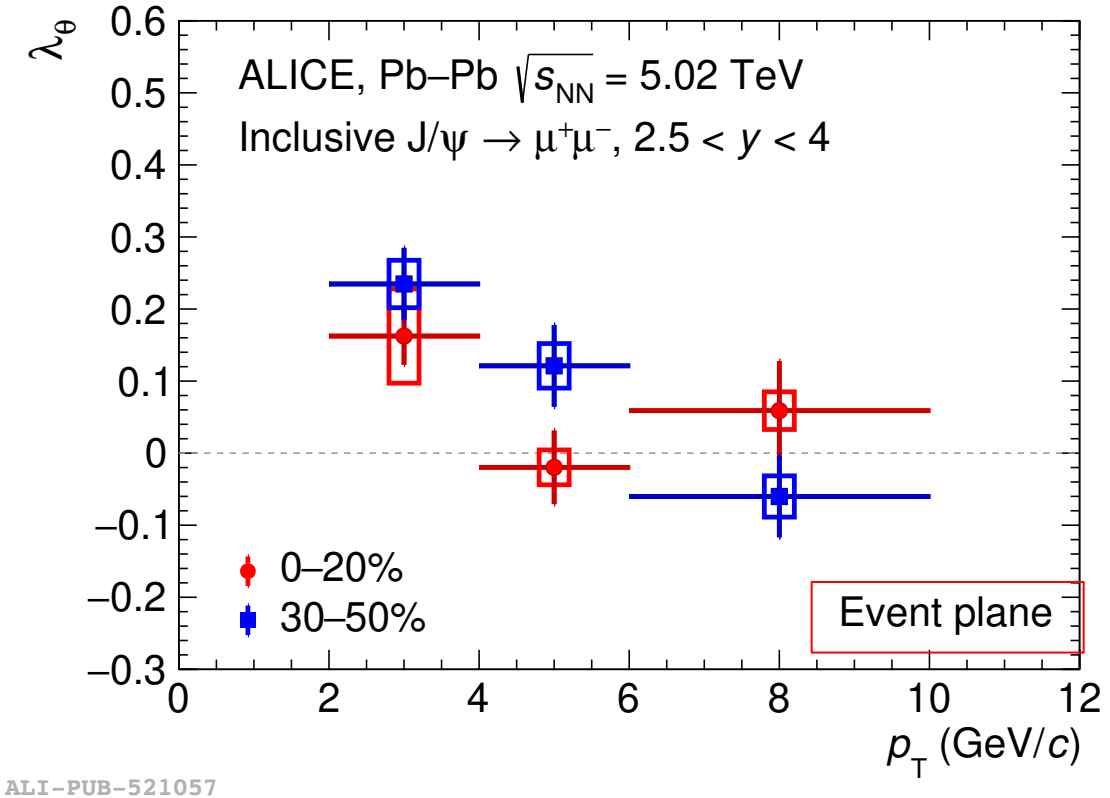
arXiv:2303.13361



ALI-PUB-539105

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dNpp/dp_T}$$

PRL 131 (2023) 4, 042303

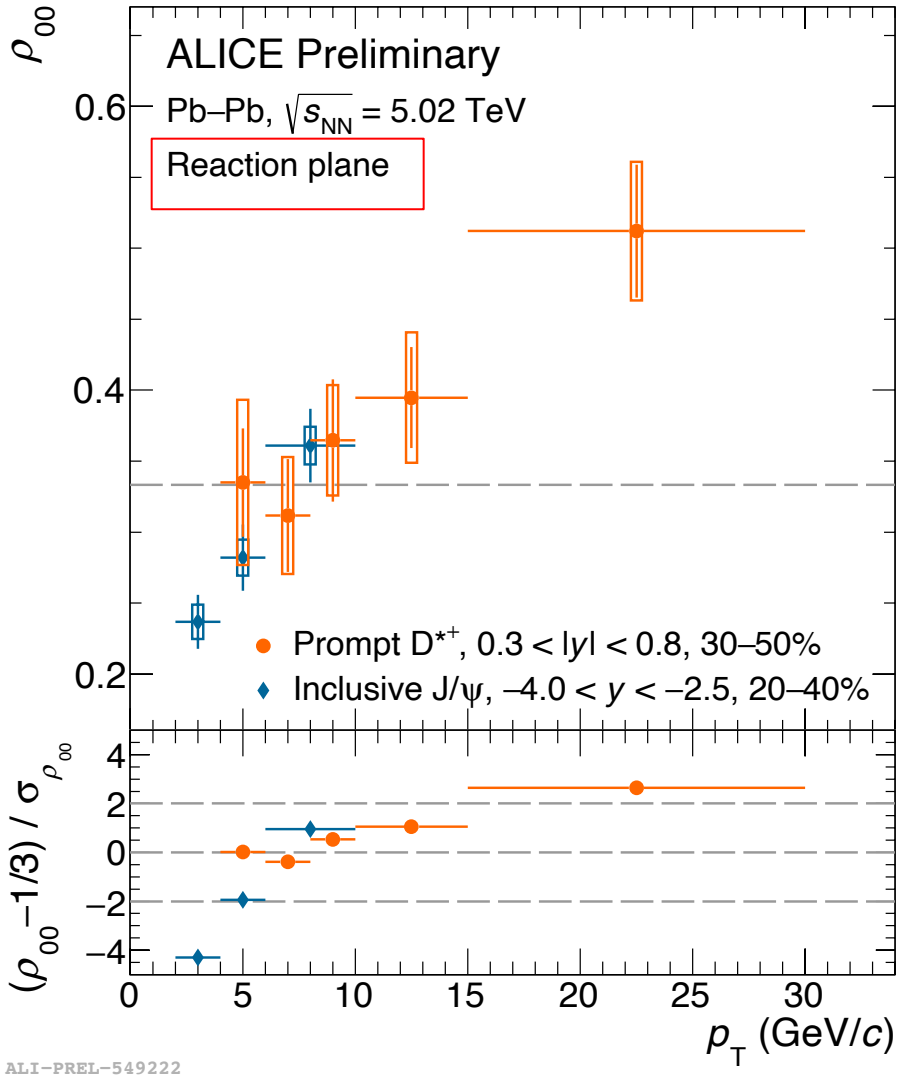


ALI-PUB-521057

Du, X. et al., NPA 943, 147–158 (2015)
Zhou, K., et al., PRC 89, 054911 (2014)
Andronic, A, et al, PLB 797, 134836 (2019)
Arleo. F, PRL119, 062302 (2017)

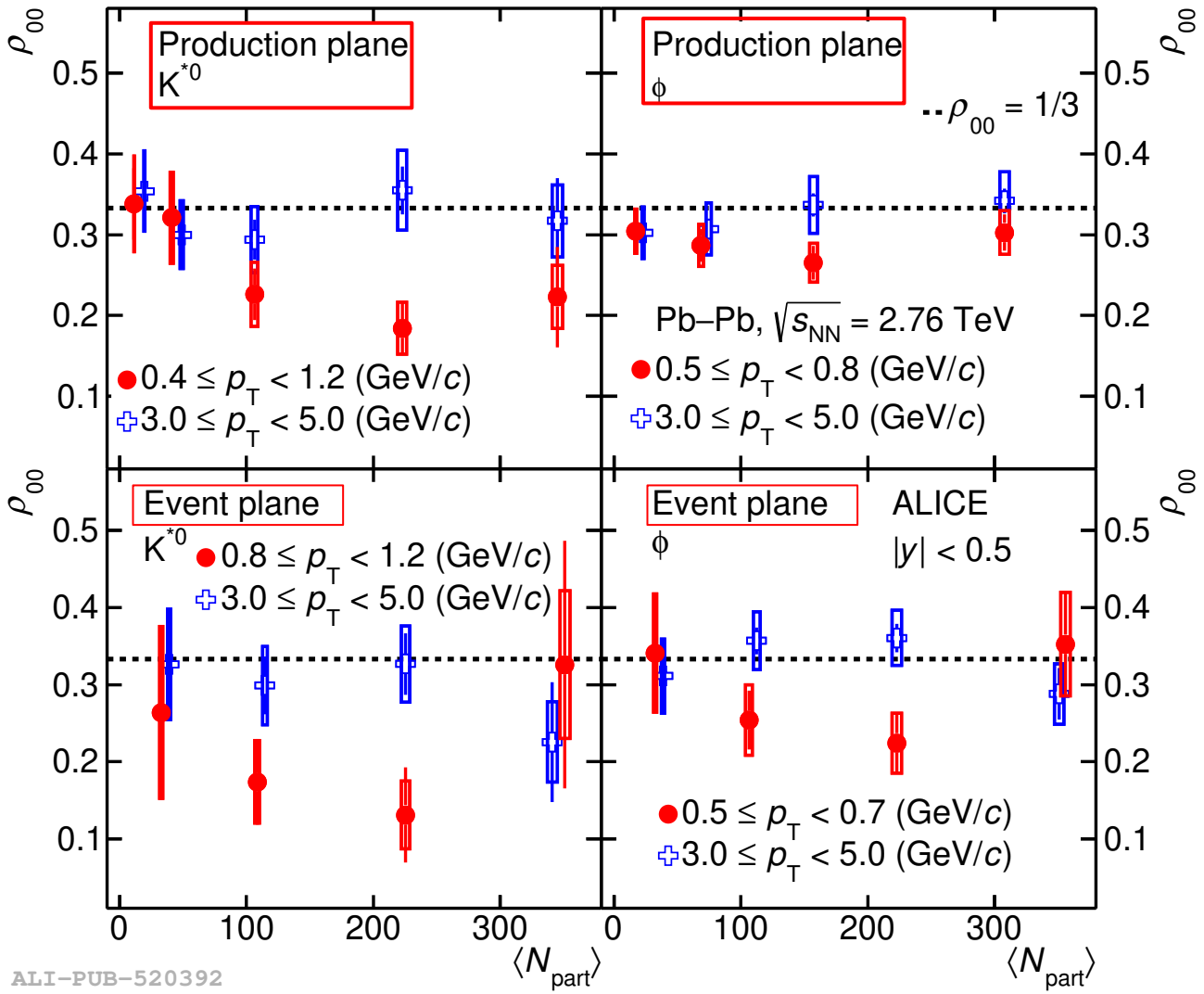
- The recombination is a dominate process for the J/ψ production at low p_T
- Is the J/ψ global polarization inherited from polarized charm quarks via uncorrelated charm and anticharm recombination?

Comparison of the D* and J/ψ polarization



- Agreement with the:
  - $\boldsymbol{\rho_{00}} < 1/3$ quark recombination at low p_T
  - $\boldsymbol{\rho_{00}} > 1/3$ quark fragmentation at high p_T
- At high p_T the fragmentation of heavy quarks polarized by the magnetic field translates to $\boldsymbol{\rho_{00}} > 1/3$?
- Theory guidance needed!

K^{*0} and ϕ polarization in Pb−Pb collisions



Low p_T

- Maximum deviation of ρ_{00} in semicentral collisions
- Deviation from 1/3

  K^{*0}: 3.2 σ (PP) and 2.6 σ (EP)

  ϕ : 2.1 σ (PP) and 1.9 σ (EP)
- Larger effect than observed in Λ polarization

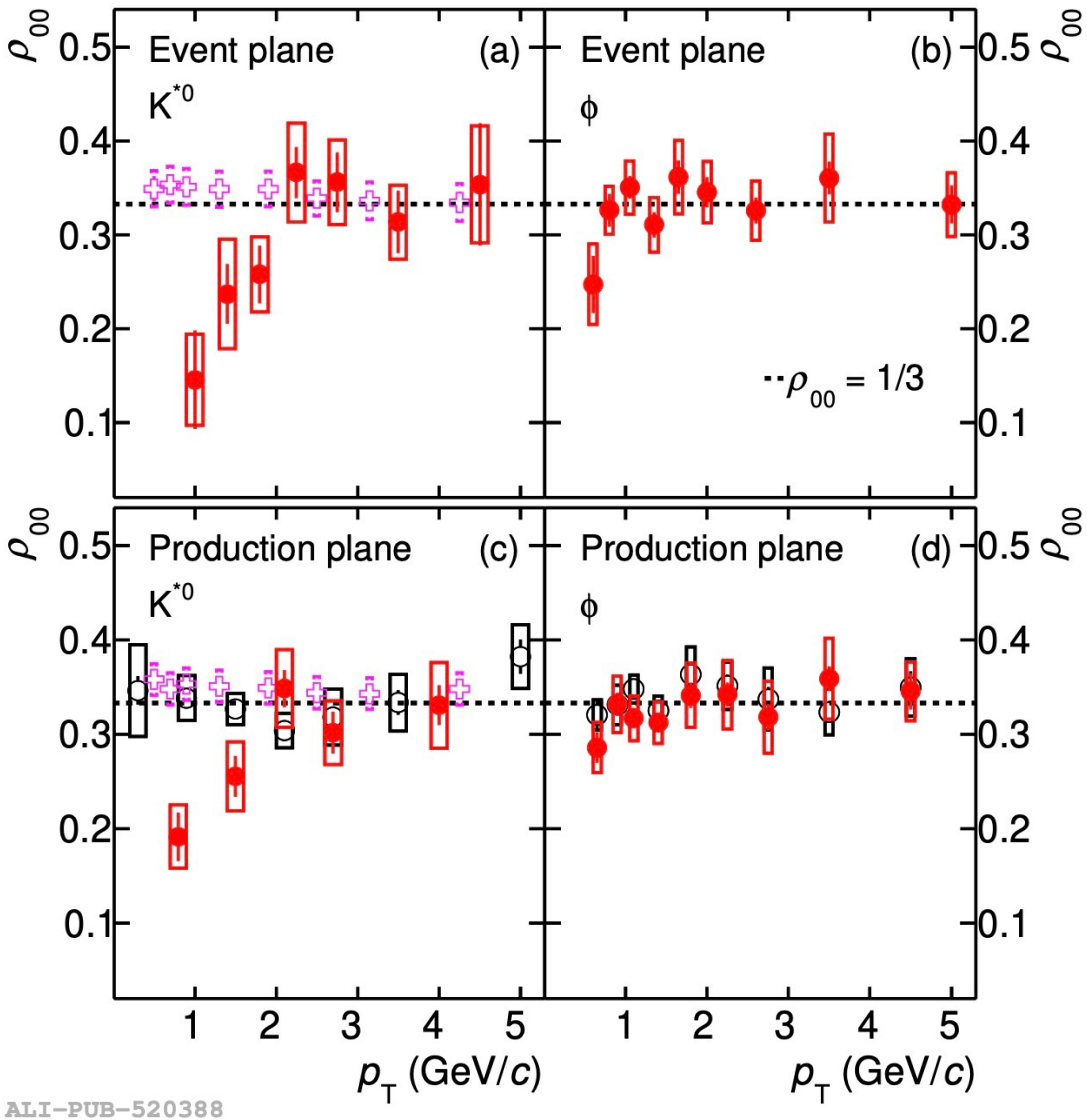
  [ALICE, *Phys.Rev.C* 105 (2022) 2, 029902]

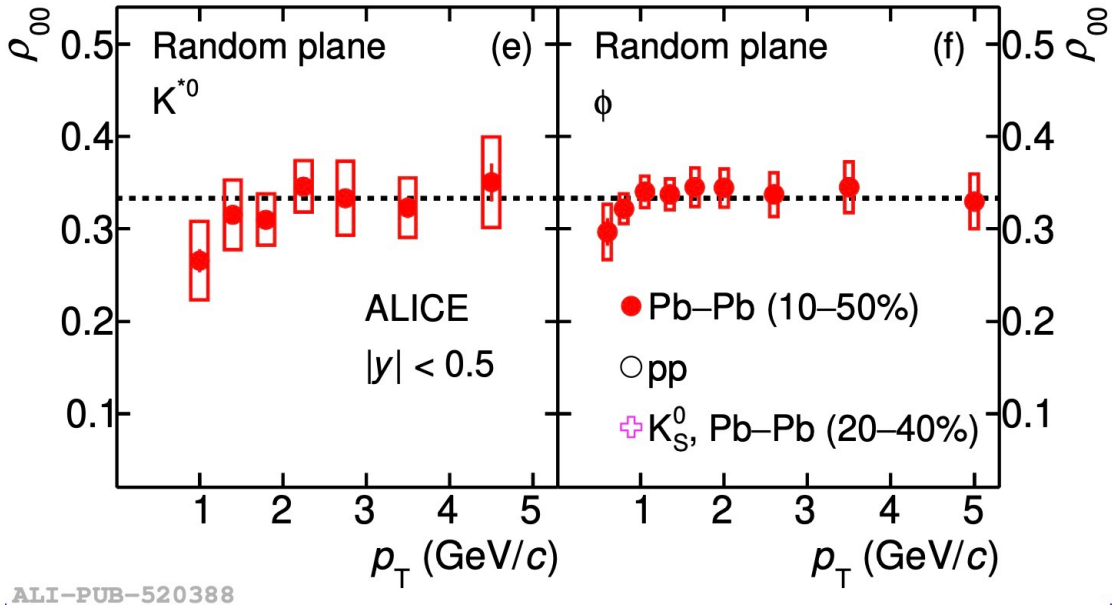
High p_T

No centrality dependence and results are consistent with 1/3

PRL 125(2020) 012301

K^{*0} and ϕ polarization in pp and Pb−Pb collisions





pp collisions:

- ρ_{00} consistent with 1/3 for both K^{*0} and ϕ in production plane in pp collisions

Pb-Pb collisions:

- ρ_{00} for K^0_s (spin=0) consistent with 1/3
- $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T
- ρ_{00} consistent with 1/3 at high p_T (K^{*0}: $p_T > 2$ GeV/c, ϕ: $p_T > 0.8$ GeV/c

ALICE, PRL 125(2020) 012301

Vector mesons polarization measurements with ALICE

	K^{*0}	ϕ	D^{*+}	J/ψ	ϒ(1S)
pp	$\rho_{00} \sim 1/3$ (production plane)	$\rho_{00} \sim 1/3$ (production plane)	$\rho_{00} \sim 1/3$ (HX)	$\rho_{00} \sim 1/3$ (HX and CS)	$\rho_{00} \sim 1/3$ (HX and CS)
Pb-Pb	$\rho_{00} < 1/3$ low p_T (RP)	$\rho_{00} < 1/3$ low p_T (RP)	$\rho_{00} > 1/3$ high p_T (RP)	$\rho_{00} < 1/3$ (low p_T) (RP)	$\rho_{00} \sim 1/3$ (HX and CS)

Summary

➢ pp collisions:

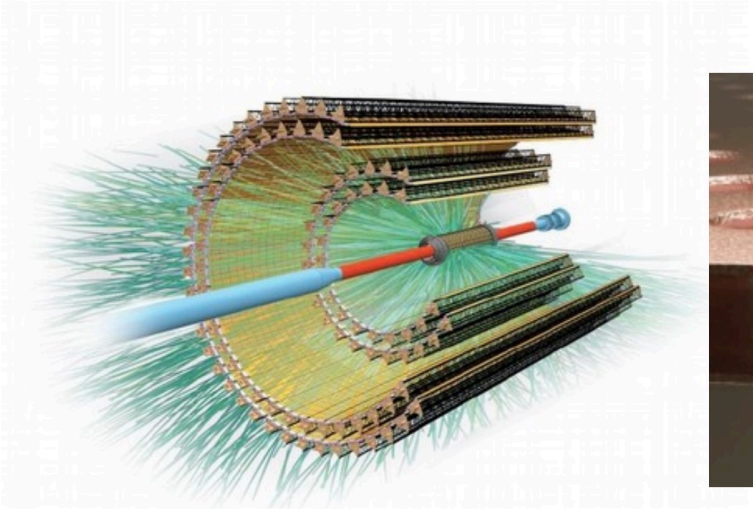
- The measured **J/ψ, Y(1S) , D^{*+} , K^{*0} and ϕ** , do not exhibit strong polarization

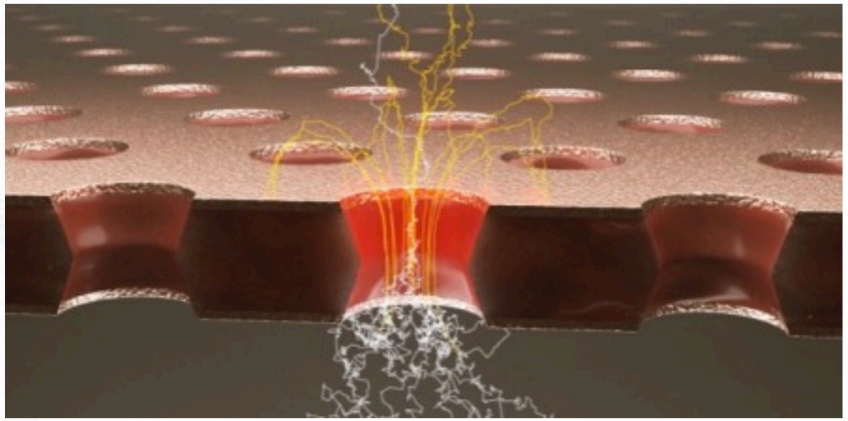
➢ Pb−Pb collisions

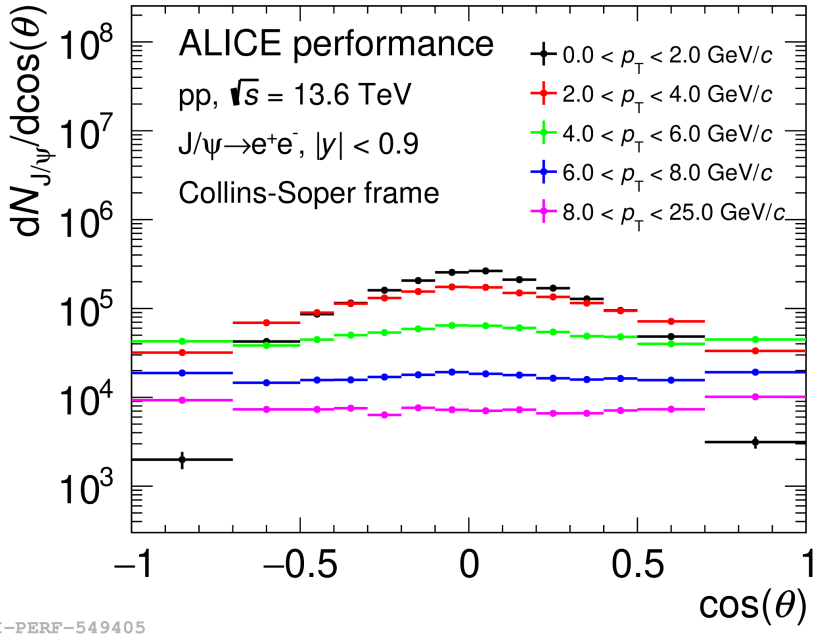
- J/ψ and Y(1S) do not show strong polarization in Helicity and Collins-Soper reference frames, but significant polarization (~**3**.9$\boldsymbol{\sigma}$) observed w.r.t the reaction plane for J/ψ
- The measured ρ_{00} of light flavor vector meson K^{*0} and ϕ are less than 1/3 at low p_T
- D^{*+} ρ_{00} depends on the centrality, p_T and rapidity
- **Theory guidance is needed to interpret the data.**

Outlook

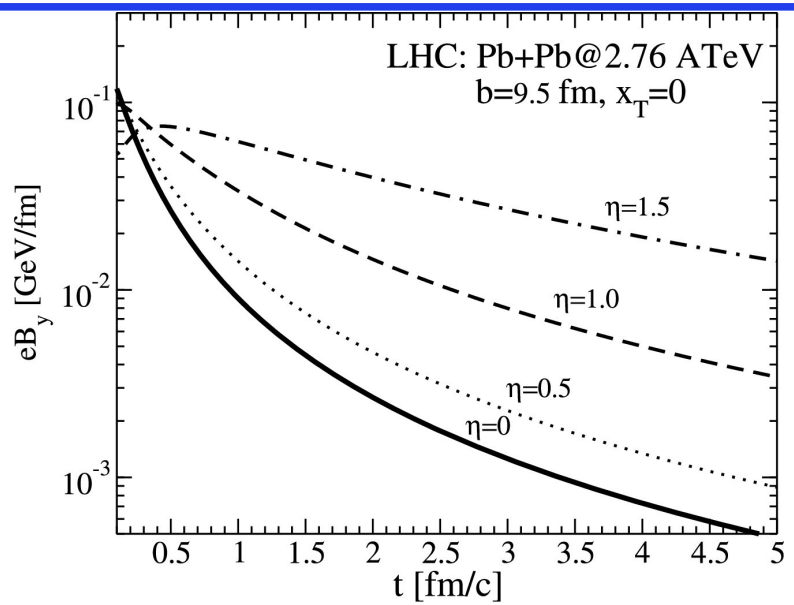
- More precise measurements can be expected from the upgraded detector and higher statistics
- The J/ψ global polarization will be measured via dielectron decay channel at midrapidity
- The newly installed MFT enables the separation between prompt and non-prompt charmonium at forward rapidity

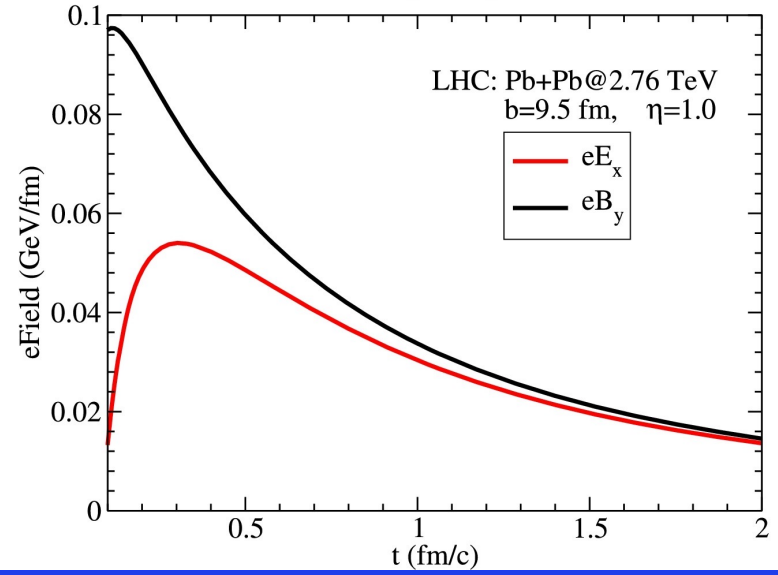






Thanks


LHC: Pb+Pb@2.76 ATeV
b=9.5 fm, x_T=0
eB_y [GeV/fm]
t [fm/c]
η=1.5
η=1.0
η=0.5
η=0


LHC: Pb+Pb@2.76 TeV
b=9.5 fm, η=1.0
eE_x
eB_y
eField (GeV/fm)
t (fm/c)