第一届强相互作用自旋物理会议

Measurement of Spin Alignment of Heavy-Flavor Vector Mesons with ALICE

Xiaozhi Bai (白晓智)

Central China Normal University

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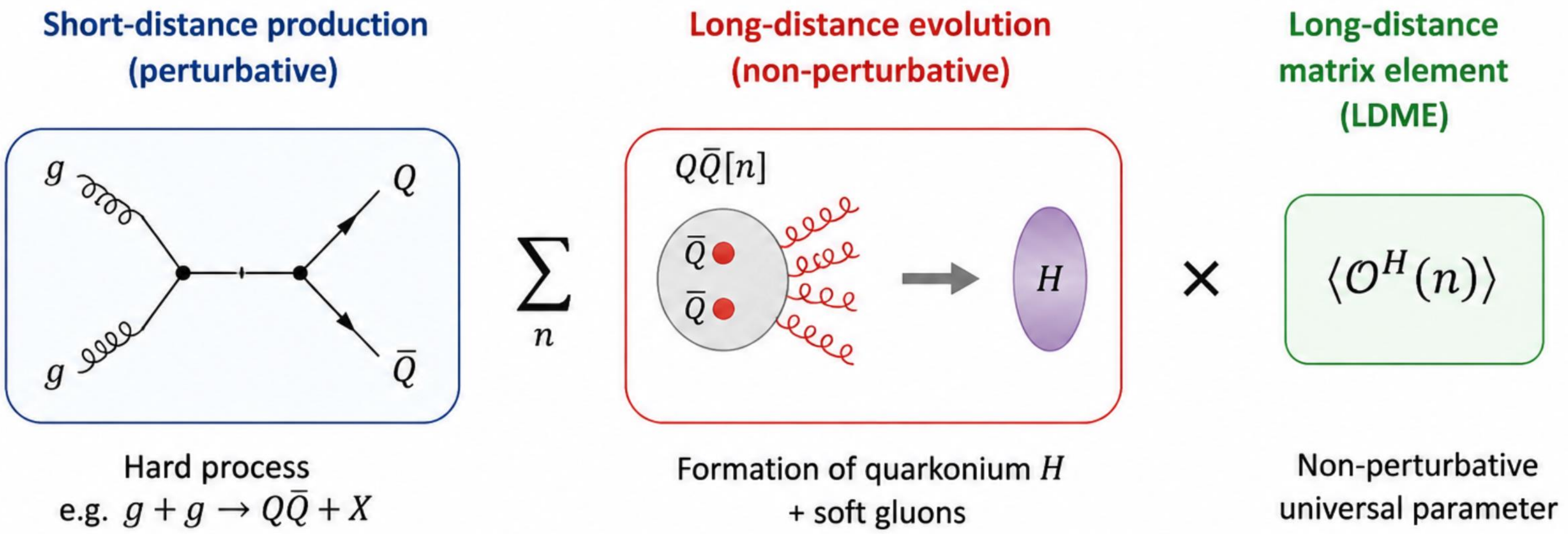
Quarkonium production in pp collisions (NRQCD)

$$\sigma(H+X)=\sum_{i,j,n}\int dx_1 dx_2 f_{i/p}(x_1,\mu_F) f_{j/p}(x_2,\mu_F)\hat{\sigma}\left(ij\to Q\bar{Q}[n]+X;\mu_F,\mu_R\right)\langle\mathcal{O}^H(n)\rangle$$



Quarkonium production in pp collisions (NRQCD)

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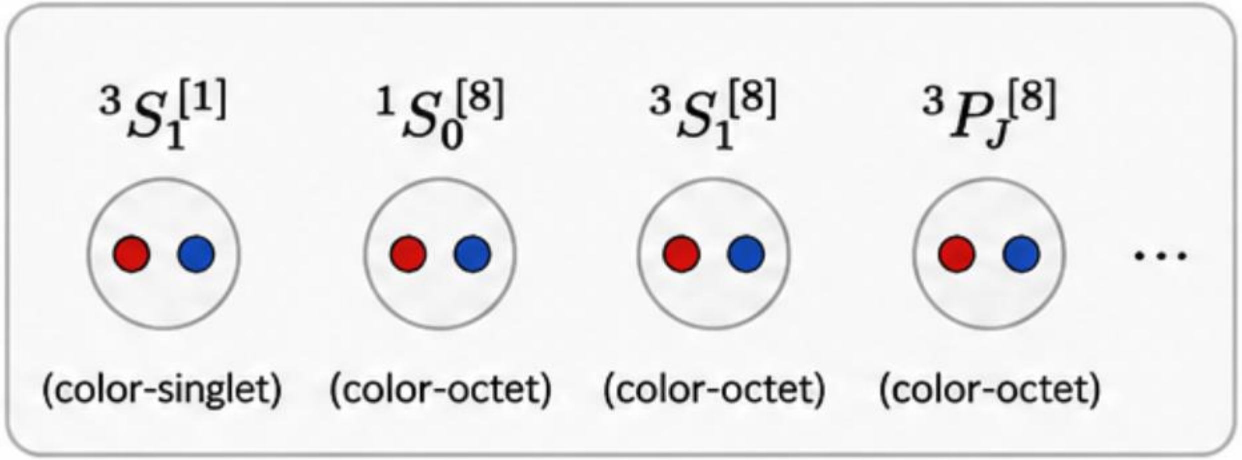
- Non-perturbative
- Universal

Intermediate $Q\bar{Q}$ states n

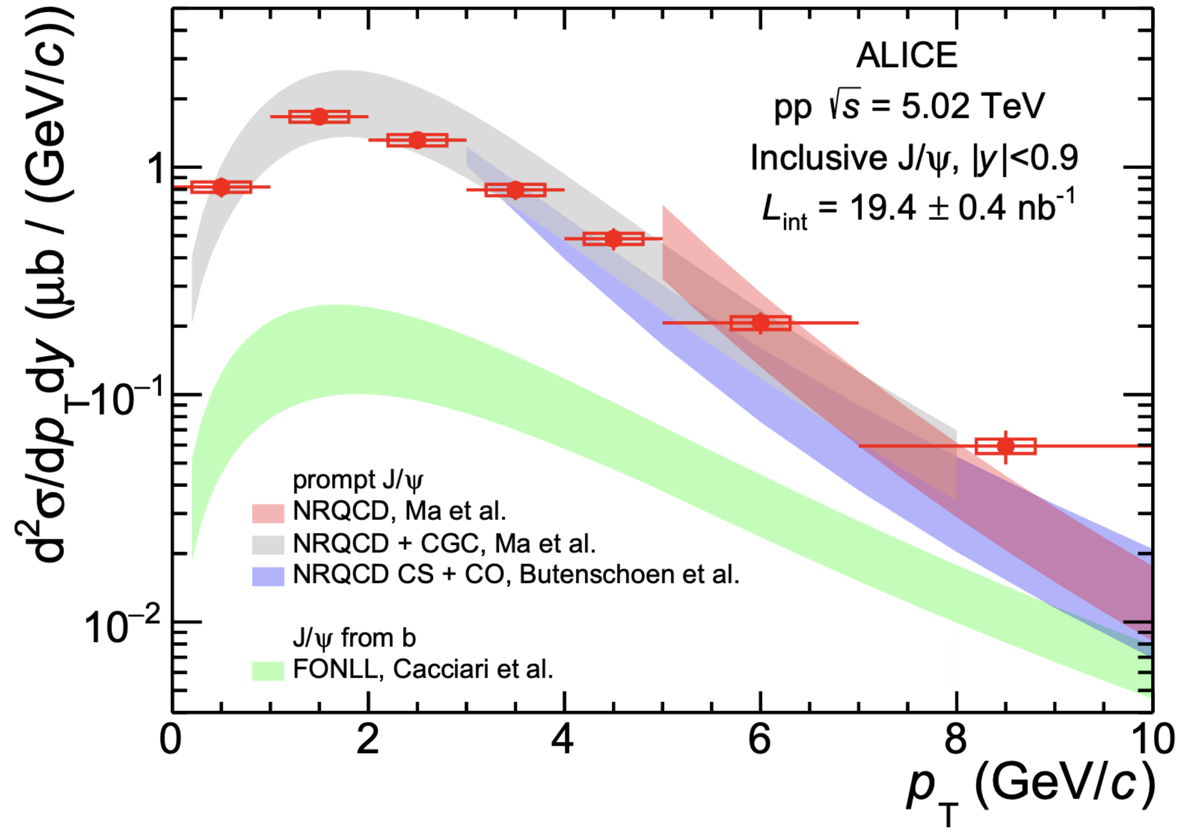


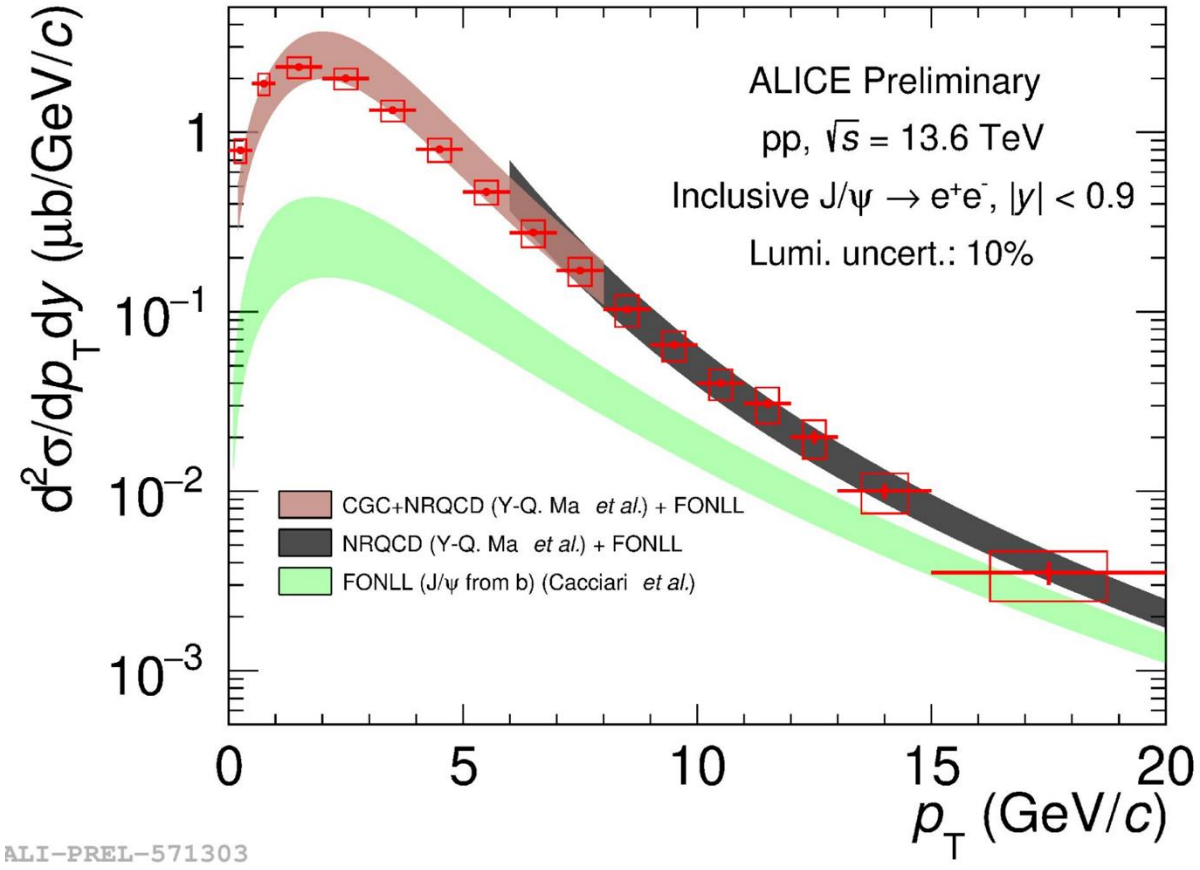
- Perturbative process
- calculated by pQCD

Global fit to data and extract the Long-distance matrix element (LDME)

NRQCD factorization was established in 1995 by **B**odwin, **B**raaten, and **L**epage (BBL), Phys. Rev. D **51**, 1125 (1995), Citation> 4800

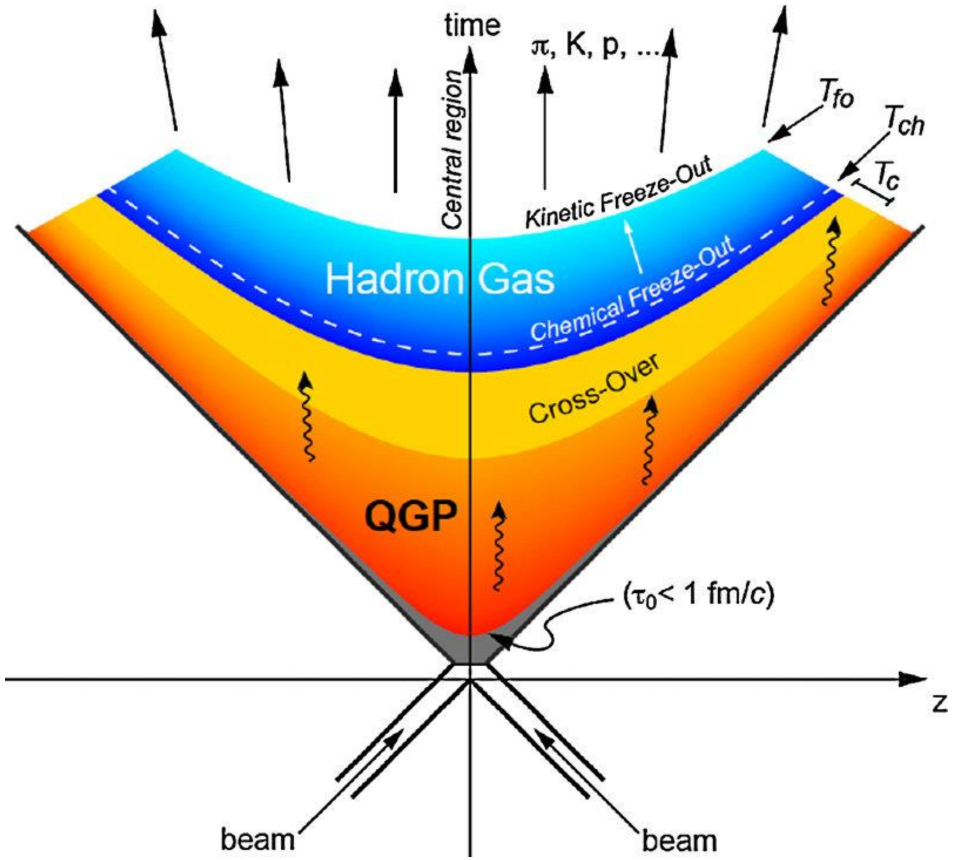
Spin alignment as a probe of quarkonium production mechanism

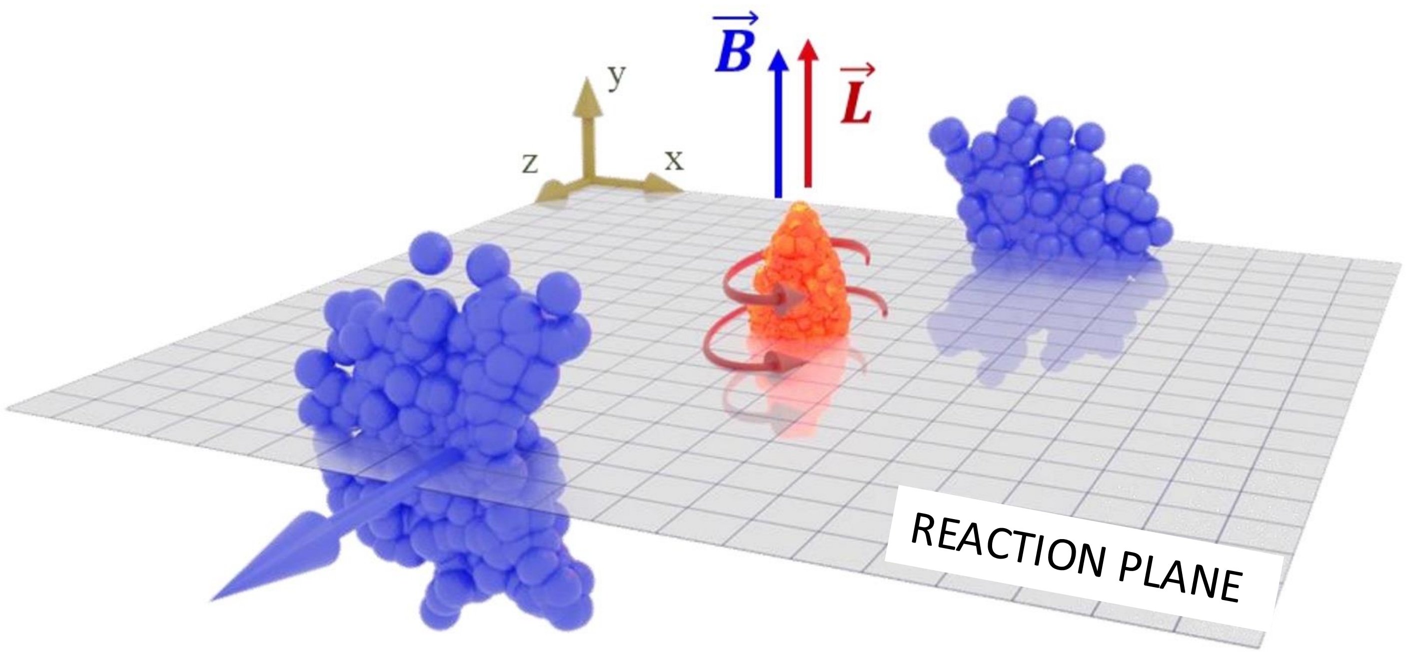




- NRQCD can describe the quarkonium production cross section.
- How are **spin alignment** measurements described by NRQCD? Can polarization observables provide additional constraints on the LDMEs?

why spin alignment are important in AA collisions

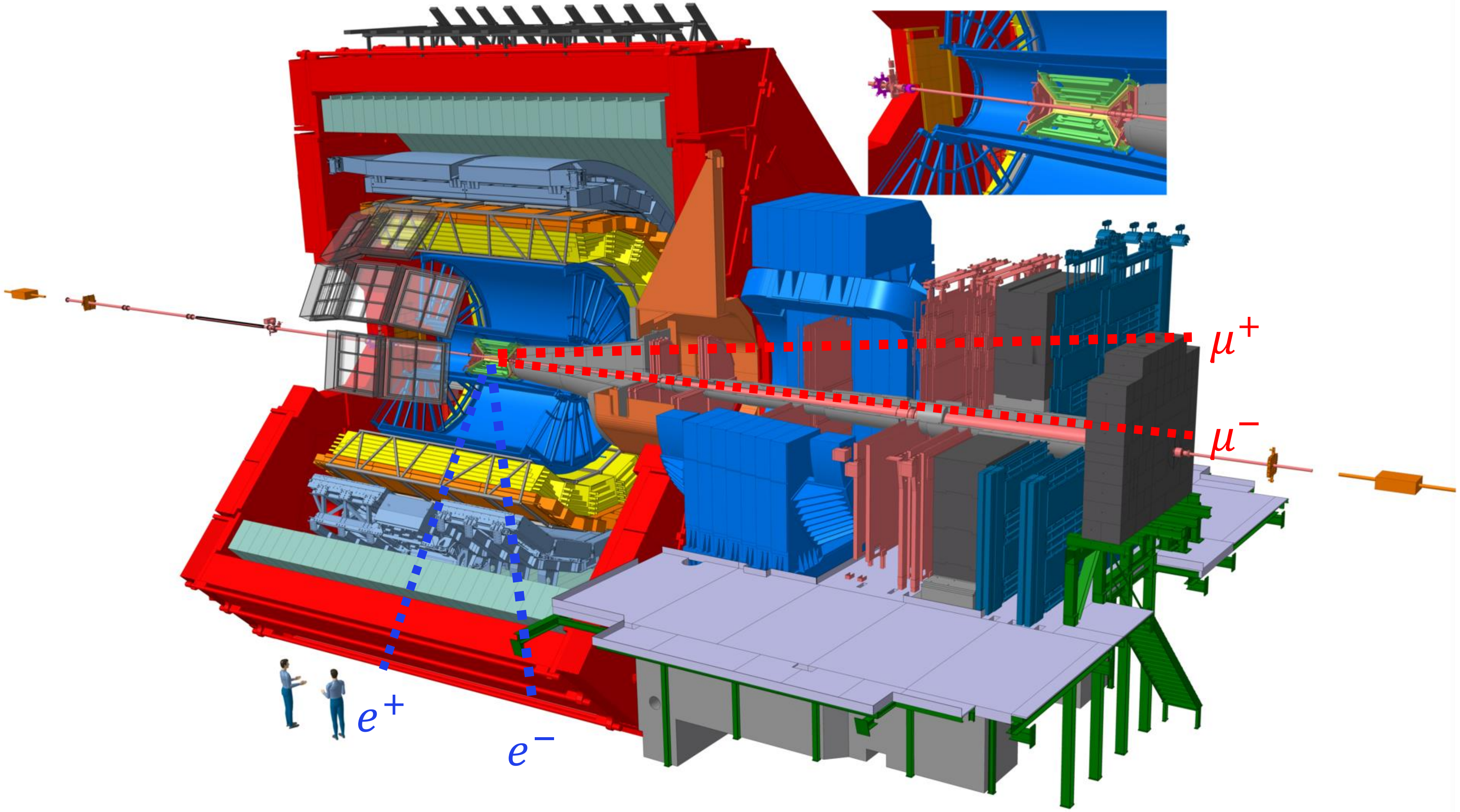




Z.-T. Liang and X.-N. Wang, *PRL* 94 (2005) 102301
Z.-T. Liang and X.-N. Wang, *PLB* 629 (2005) 20-26

- In non-central heavy-ion collisions, short-lived magnetic fields (***B***) and very strong orbital momentum (***L***) are expected to be produced, The spin alignment can serve as a probe of these effects.
- Are there other mechanisms that may contribute to vector meson spin alignment?

ALICE detector



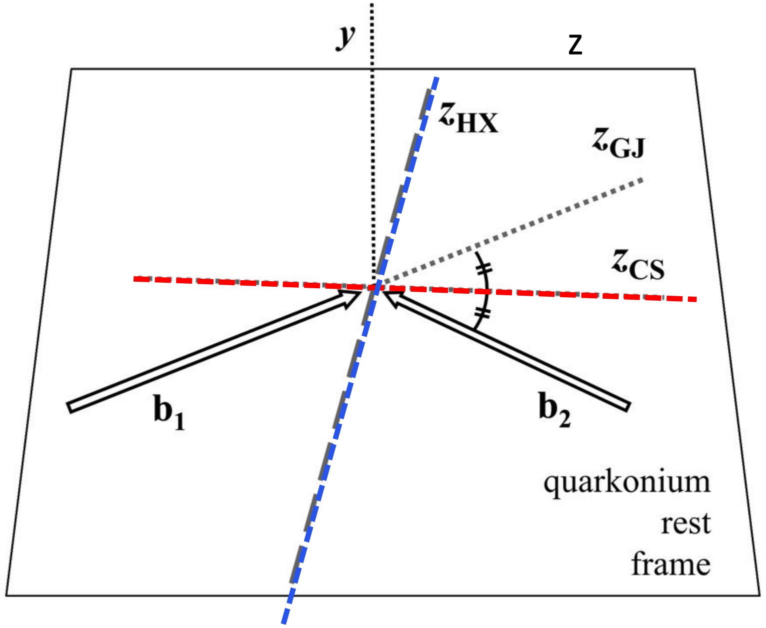
Time Projection Chamber
Tracking, particle identification

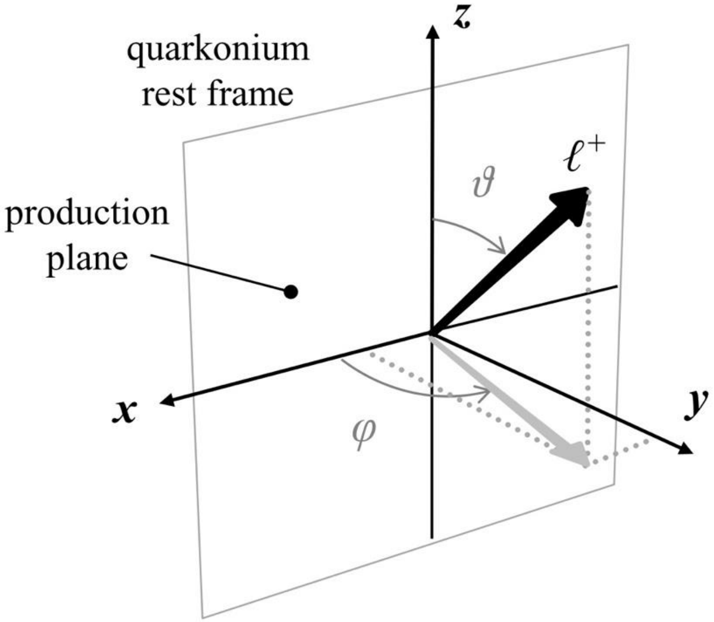
Inner Tracking System
Tracking, vertex reconstruction, Event plane determination

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

Muon spectrometer
Trigger and tracking for muons

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

Introduction to the polarization measurements

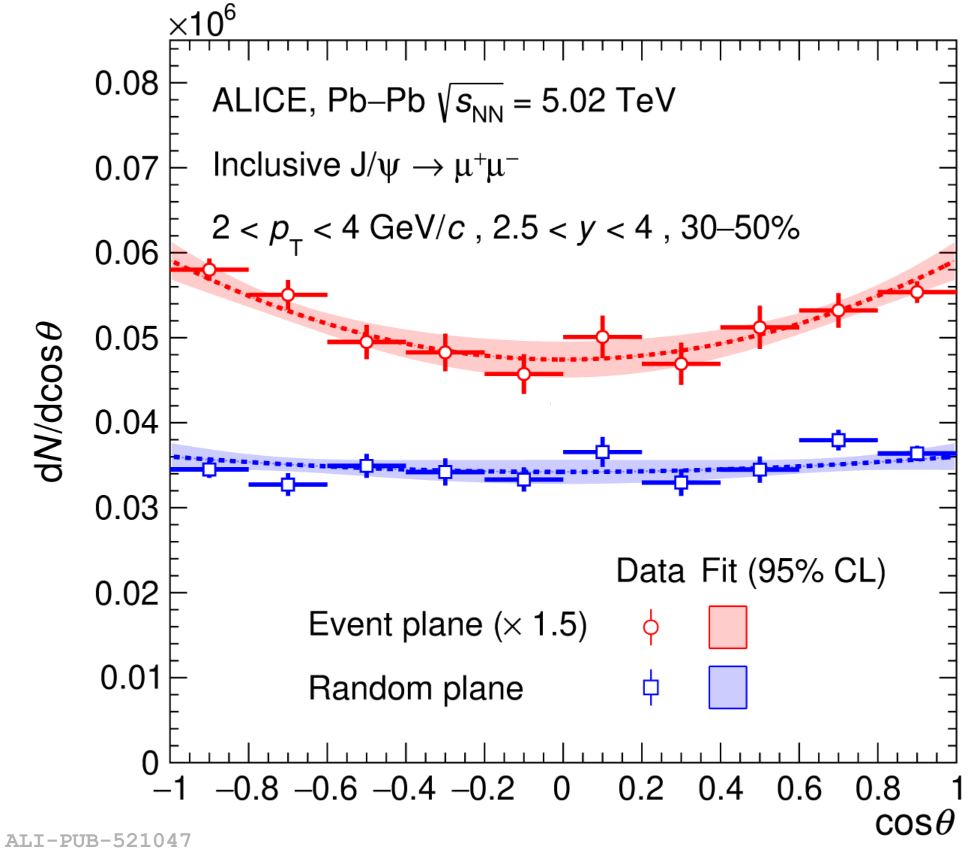
$$W(\cos\theta) \propto (1 - \boxed{\rho_{00}}) + (3\rho_{00} - 1)\cos^2\theta$$

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

ρ_{00} (λ_θ) spin density matrix element (polarization parameter)
$\rho_{00} = 1/3$ ($\lambda_\theta = 0$) no spin alignment

Quarkonium decay to dilepton:

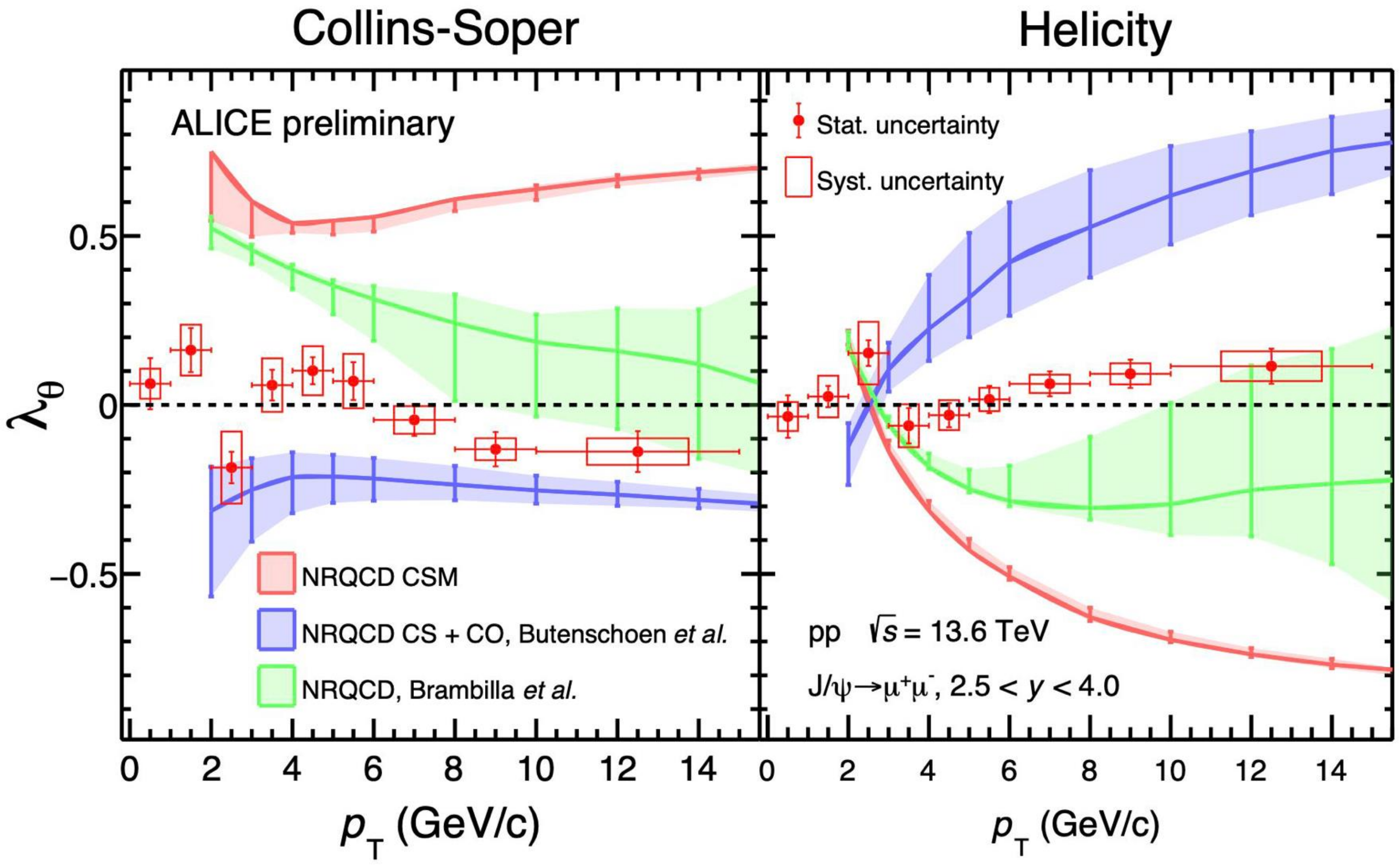
$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}} \quad \begin{cases} \lambda_\theta > 0 \rightarrow \rho_{00} < 1/3 \\ \lambda_\theta < 0 \rightarrow \rho_{00} > 1/3 \end{cases}$$



ALI-PUB-521047

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

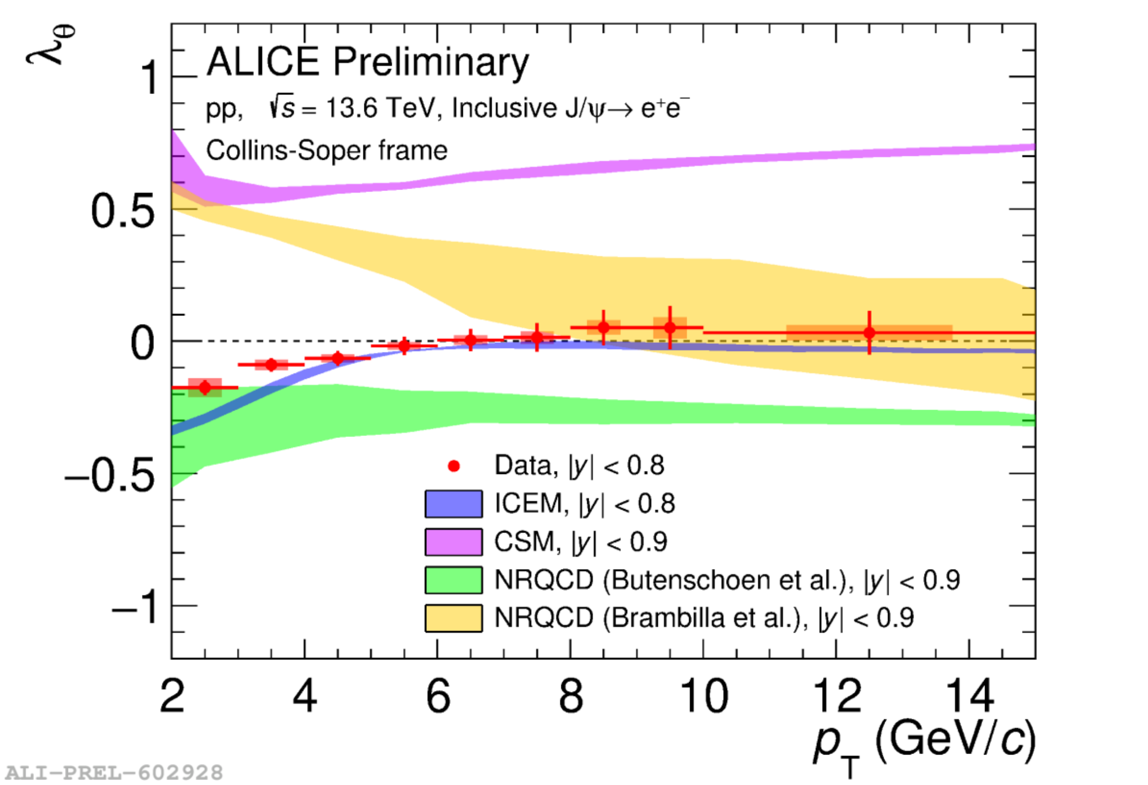
Charmonia spin alignment at forward rapidity in pp collisions



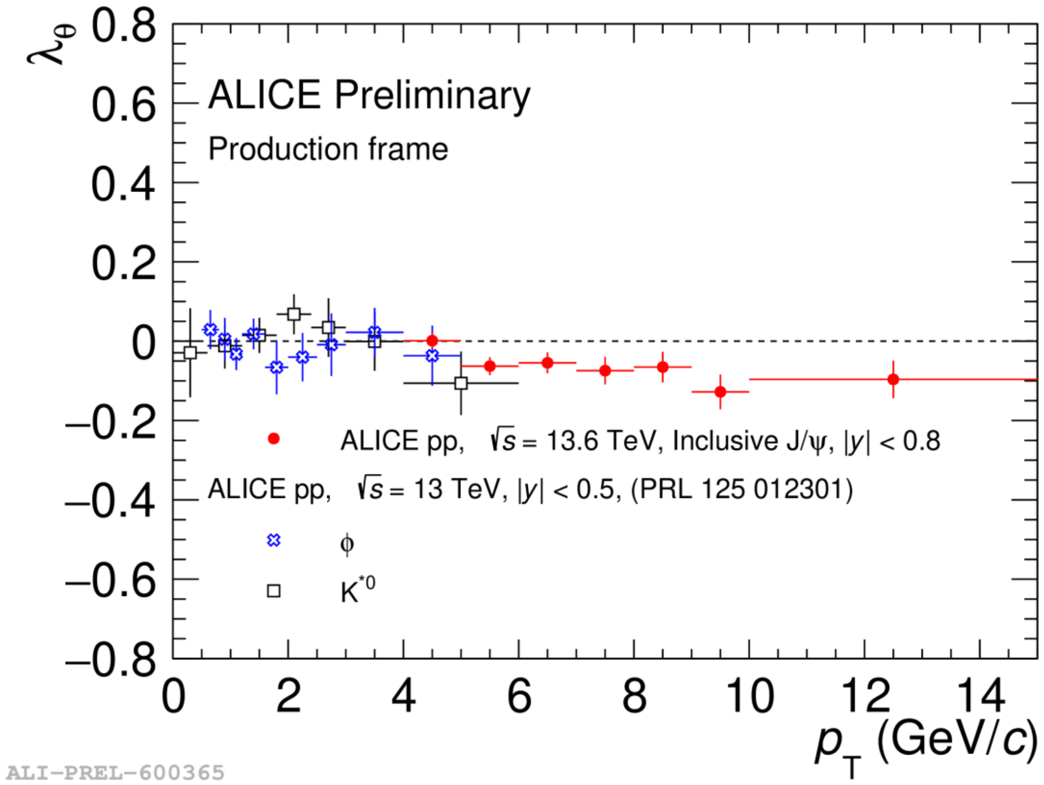
- NRQCD can describe the cross section but fails to describe the spin alignment.
- Different LDME sets predict similar cross section significantly different polarization patterns, the LDMEs are very sensitive to spin alignment and can be used as an additional constraint on the LDME extraction

Charmonia spin alignment at midrapidity in pp collisions

Collins-Soper frame



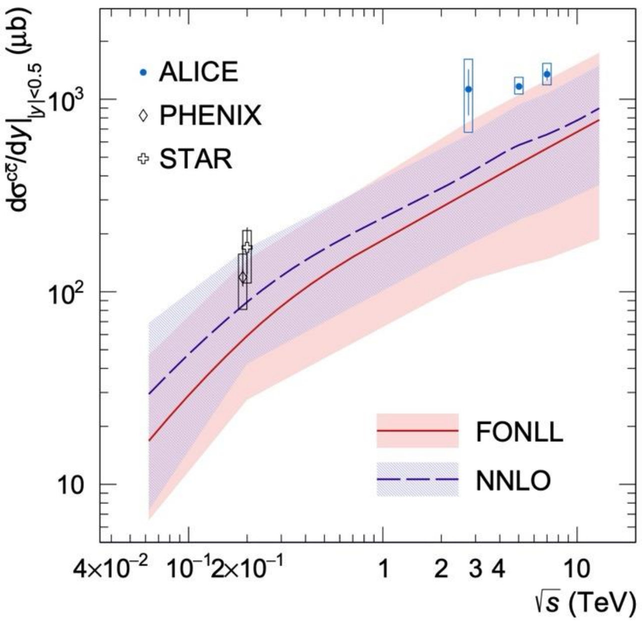
Production plane frame



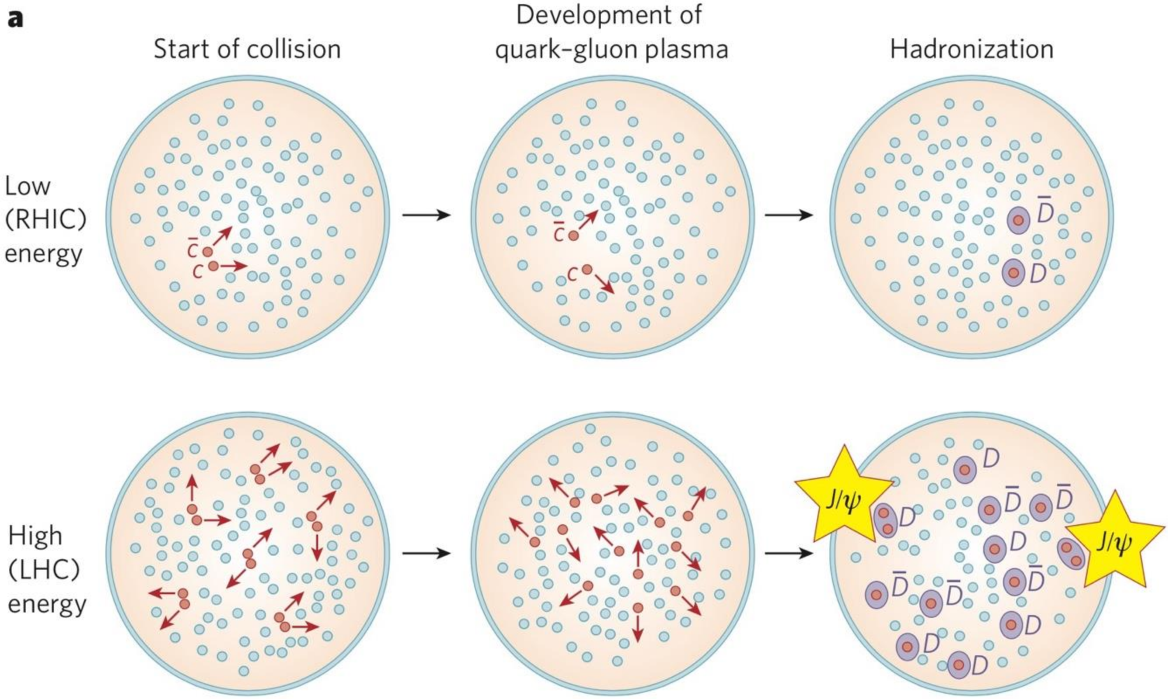
- Different LDME sets predict similar cross section significantly different polarization patterns, the LDMEs are very sensitive to spin alignment and can be used as an additional constraint on the LDME extraction
- **This may provide new insights into the long-standing (1995) question of quarkonium production mechanisms**

J/ψ production in heavy-ion collisions at LHC energies

Phys. Rev. D 105, 011103 (2022)



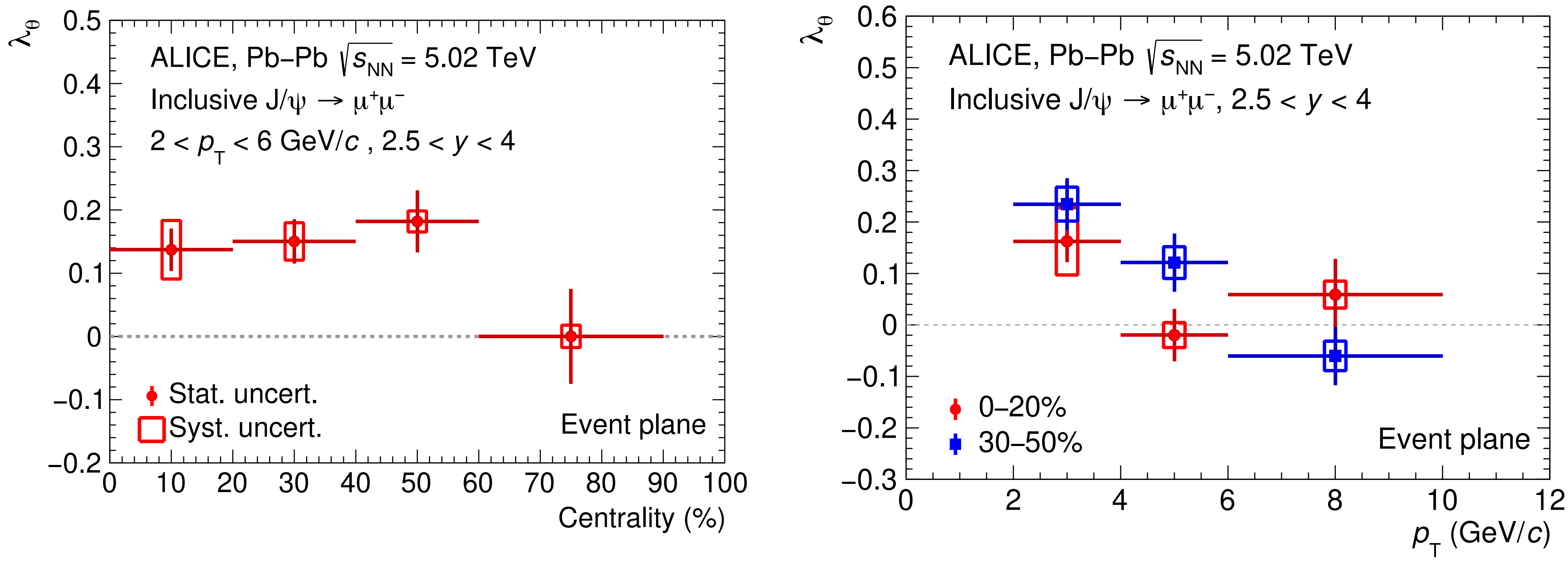
P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302



- The charm quark production cross section at the LHC is significantly larger than at RHIC energies, resulting in a higher charm quark density in the medium.
- J/ψ production is dominated by the coalescence of uncorrelated charm and anticharm quarks at the phase boundary.
- "Similar" hadronization and medium-interaction mechanisms are expected to vector mesons (K^{*0}, ϕ and D^{*+}).

J/ψ spin alignment in Pb−Pb collisions

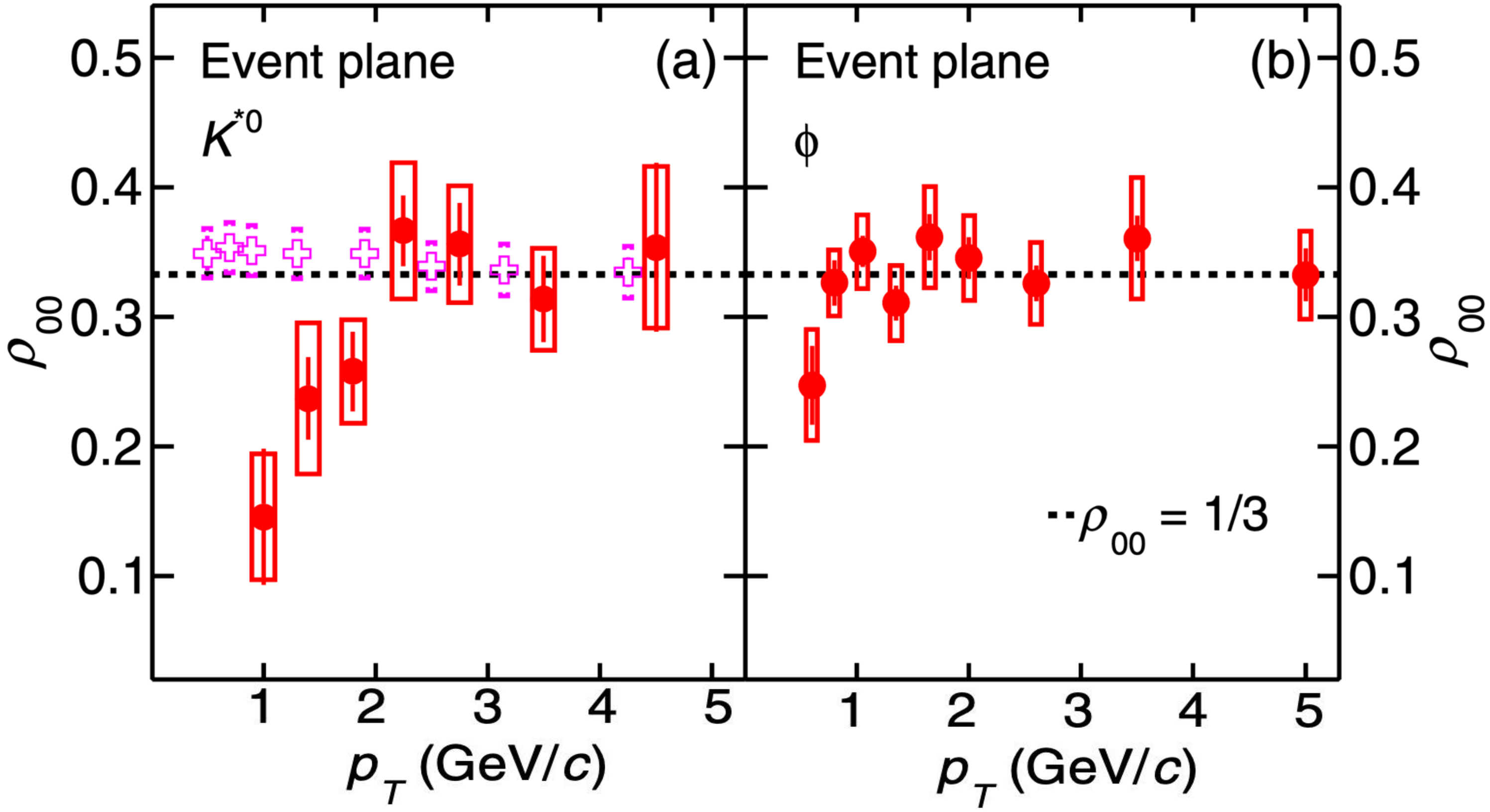
ALICE, PRL 131 (2023) 4, 042303



- ➢ 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%

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

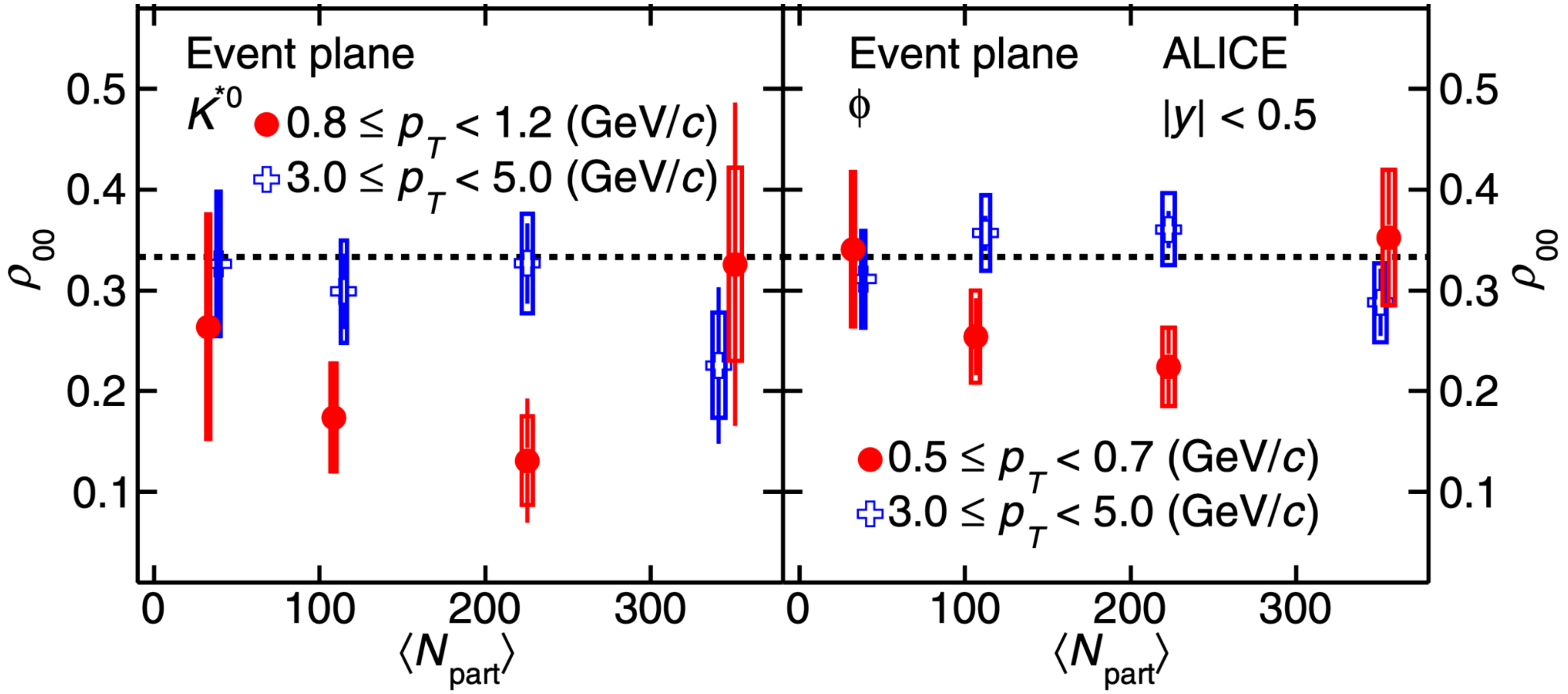
ALICE, PRL 125(2020) 012301



- $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T, ρ_{00} consistent with 1/3 at high p_T
- ρ_{00} for K_s^0 (spin=0) consistent with 1/3

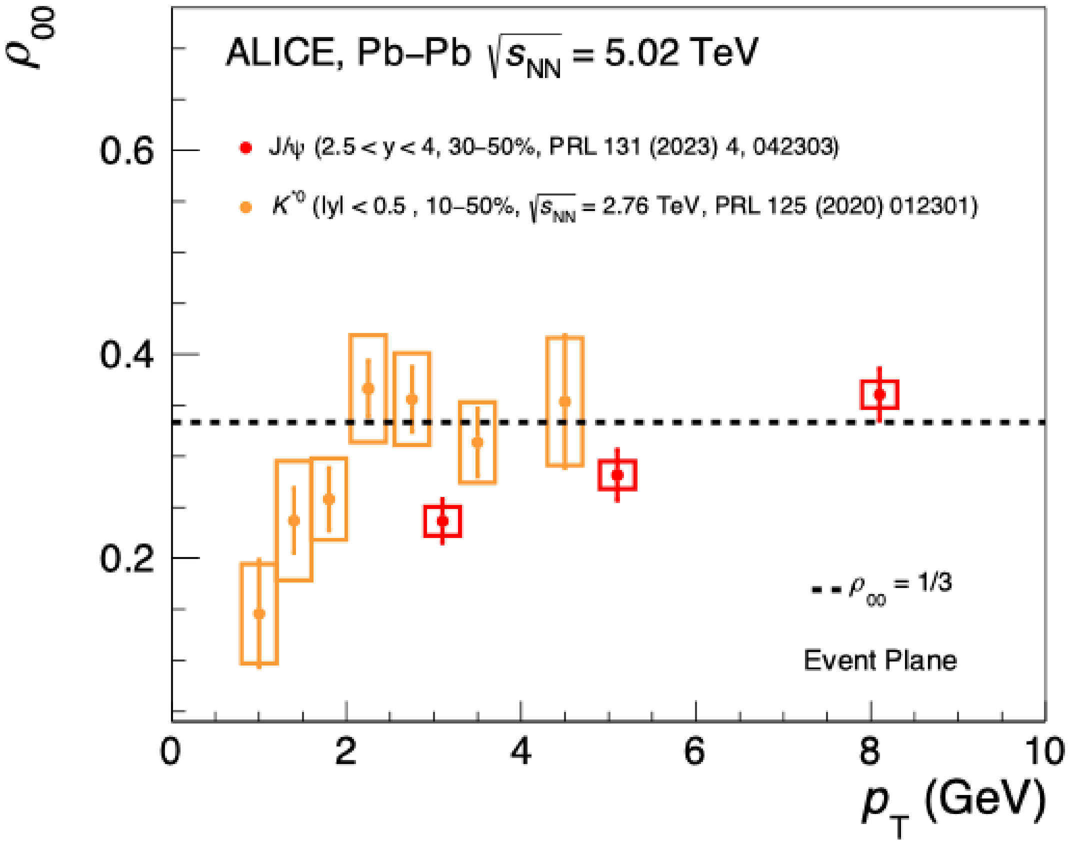
K^{*0} and ϕ spin alignment Pb−Pb collisions

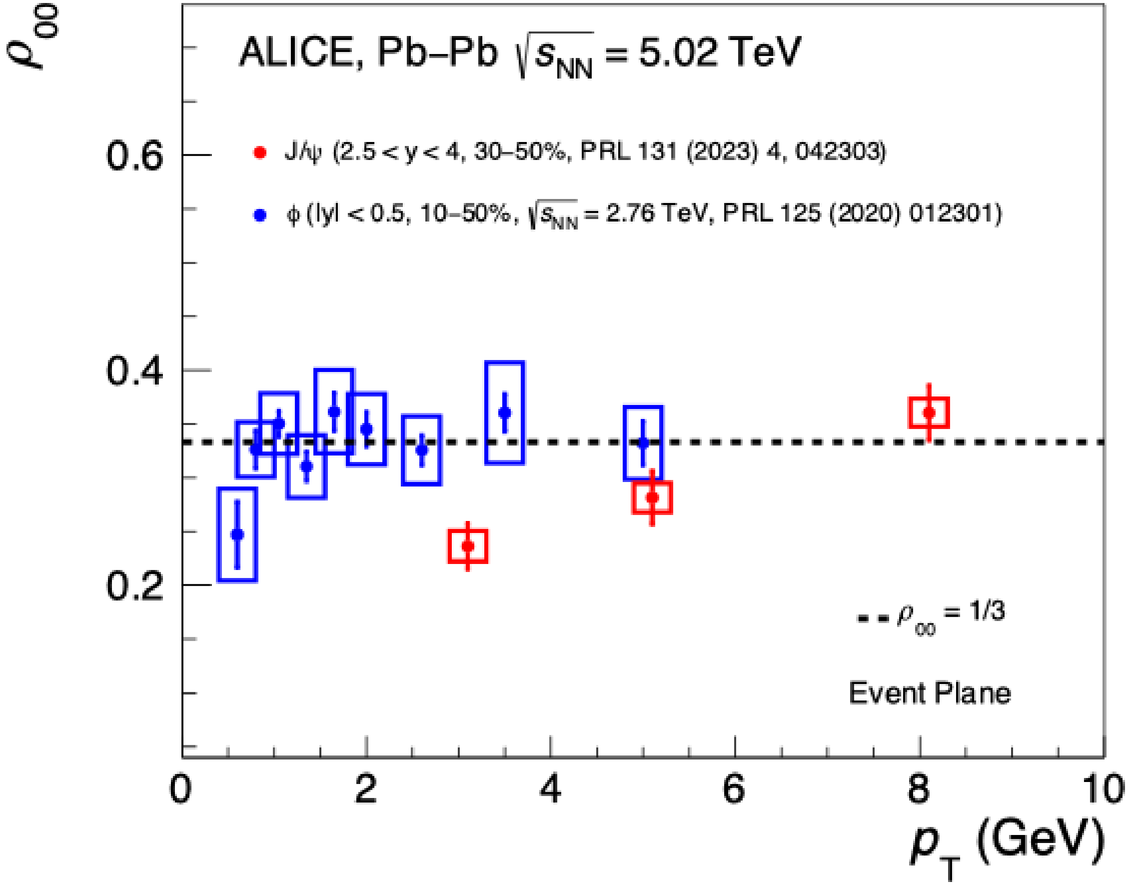
ALICE, PRL 125(2020) 012301



- Maximum deviation of ρ_{00} in semicentral collisions and low p_T
- Deviation w.r.t 1/3 are 2.6σ and 1.9σ for K^{*0} and ϕ, respectively

J/ψ spin alignment compare with light-flavor vector mesons

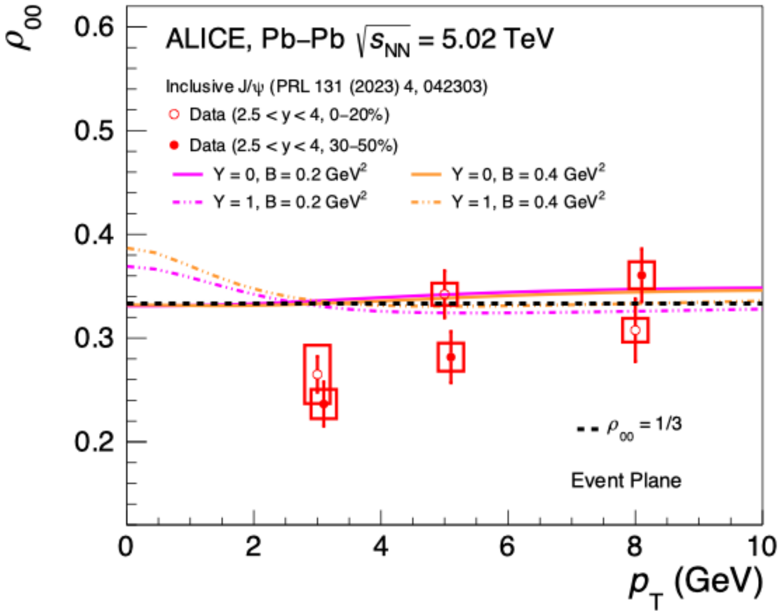




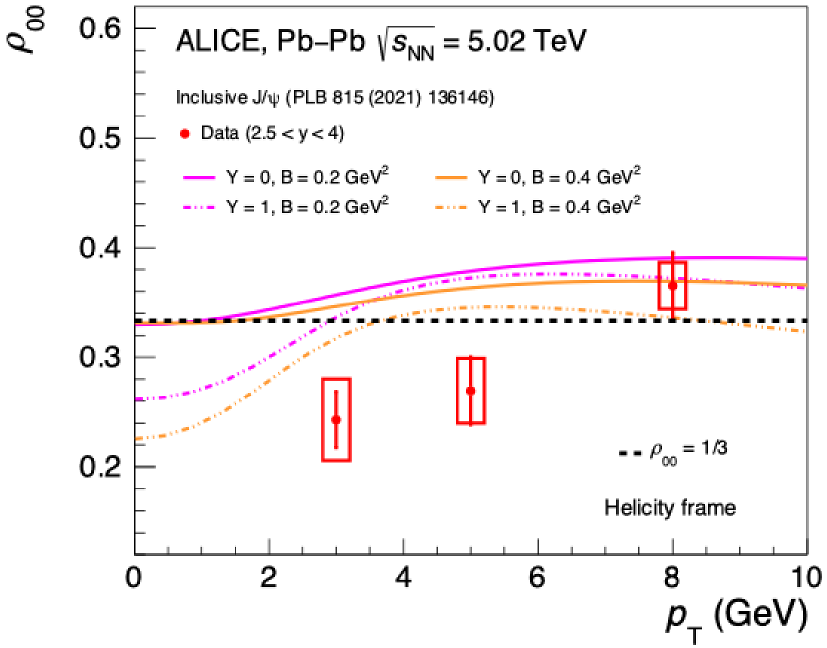
- A similar trend of J/ψ spin alignment to that observed for light-flavor vector mesons is found with ALICE, which is opposite to the STAR measurements.
- A significantly stronger spin-alignment signal is observed for J/ψ than light-flavor vector mesons

Comparison of the J/ψ spin alignment with theoretical predictions

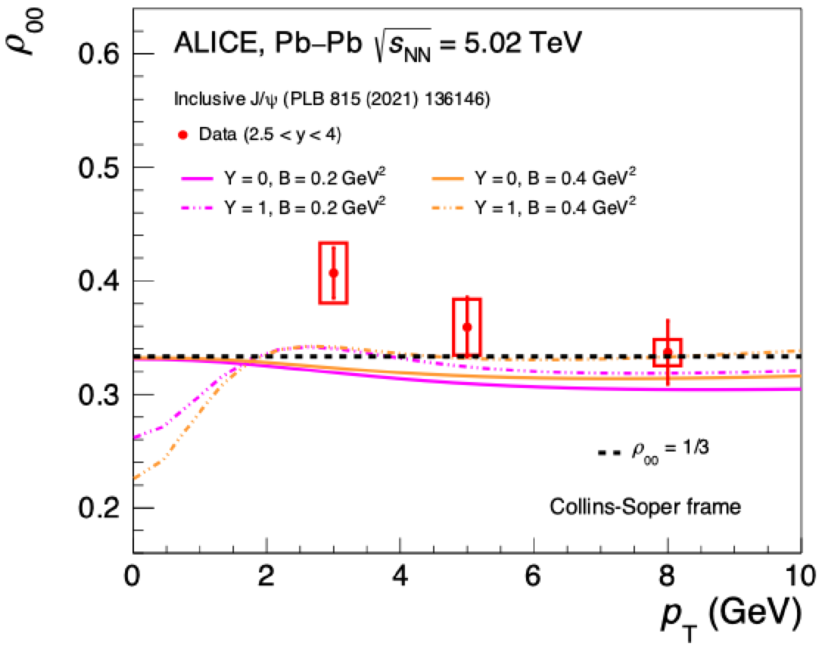
Event plane frame



Helicity frame



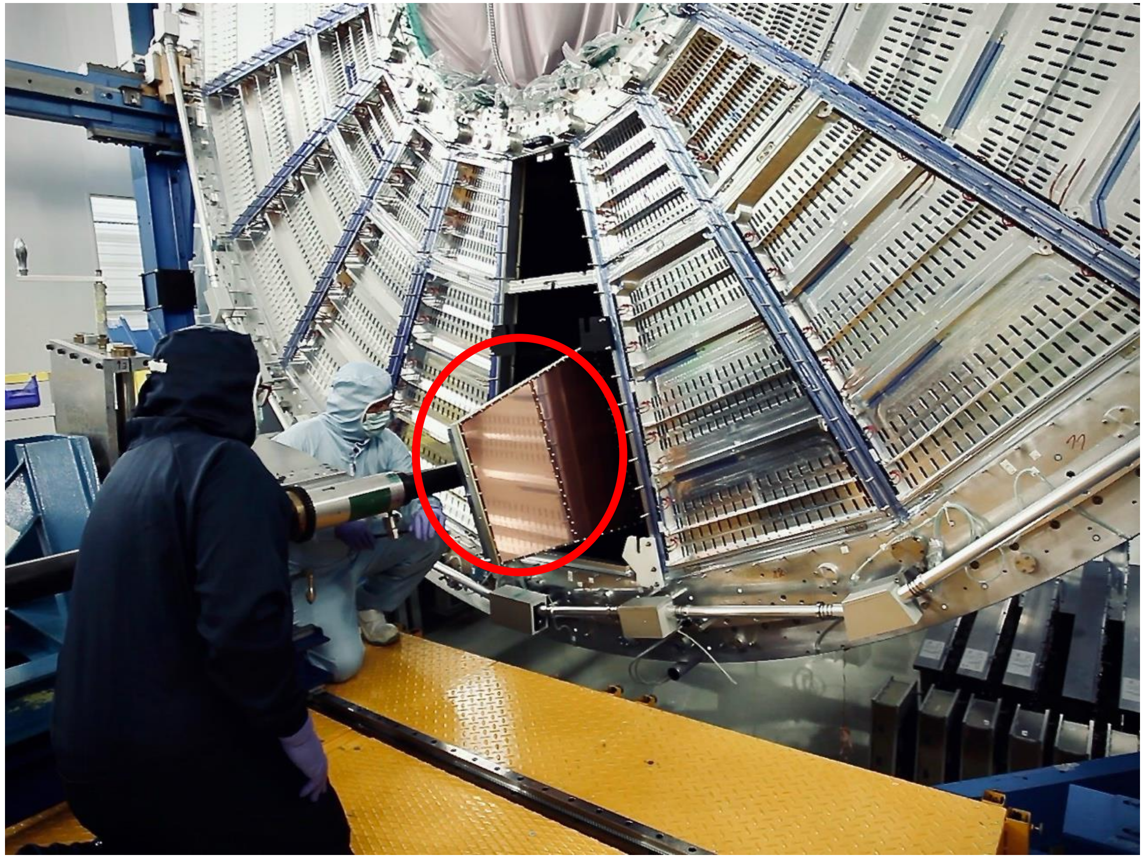
Collins–Soper frame



- Existing theoretical calculations do not yet provide a consistent description of the measured J/ψ spin alignment
- Interpretation of the measurements requires guidance from theoretical calculations

Defu Hou, Xing-Sheng Li, *et al*, JHEP 08 (2024) 070

Detector Upgraded for ALICE Run 3

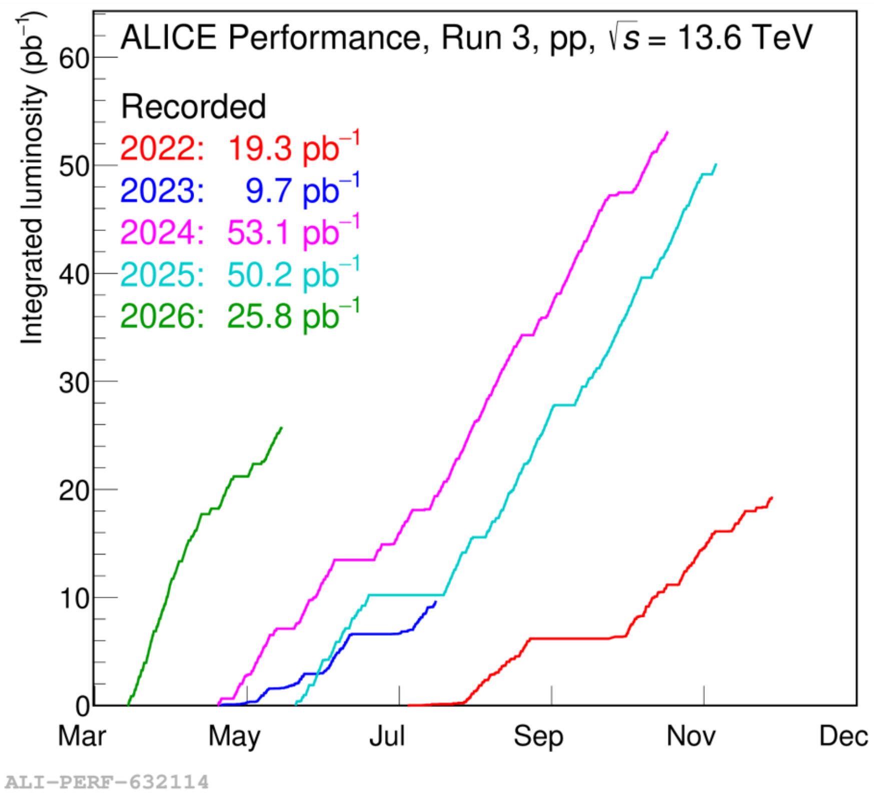


TPC continuous readout (GEM)

- ➢ pp data taking at 500 kHz
- ➢ Pb-Pb data taking at 50 kHz

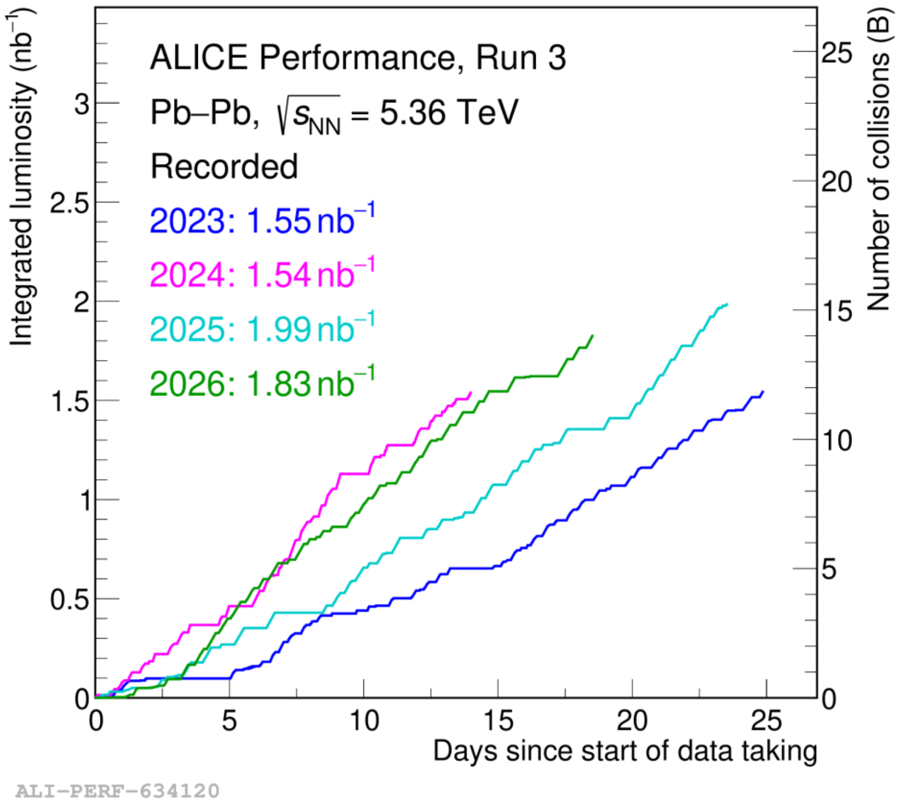
ALICE data taking in Run 3

pp collision



~8 trillion MB events
×**2000** more than Run 1+2

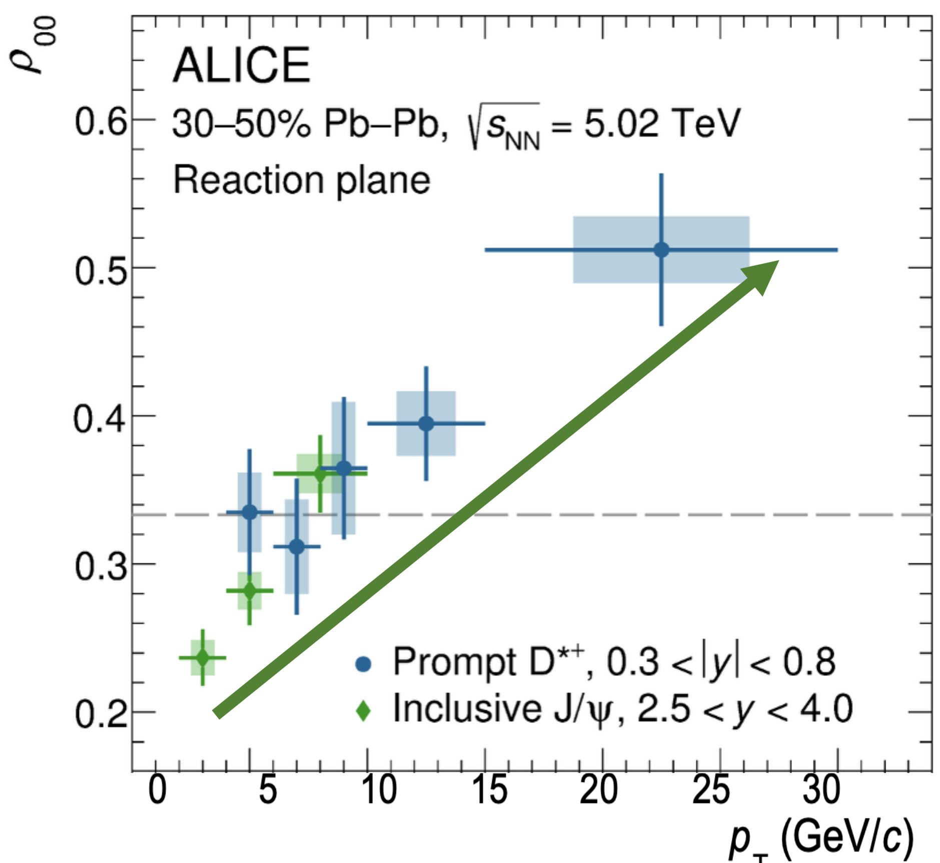
Pb-Pb collision

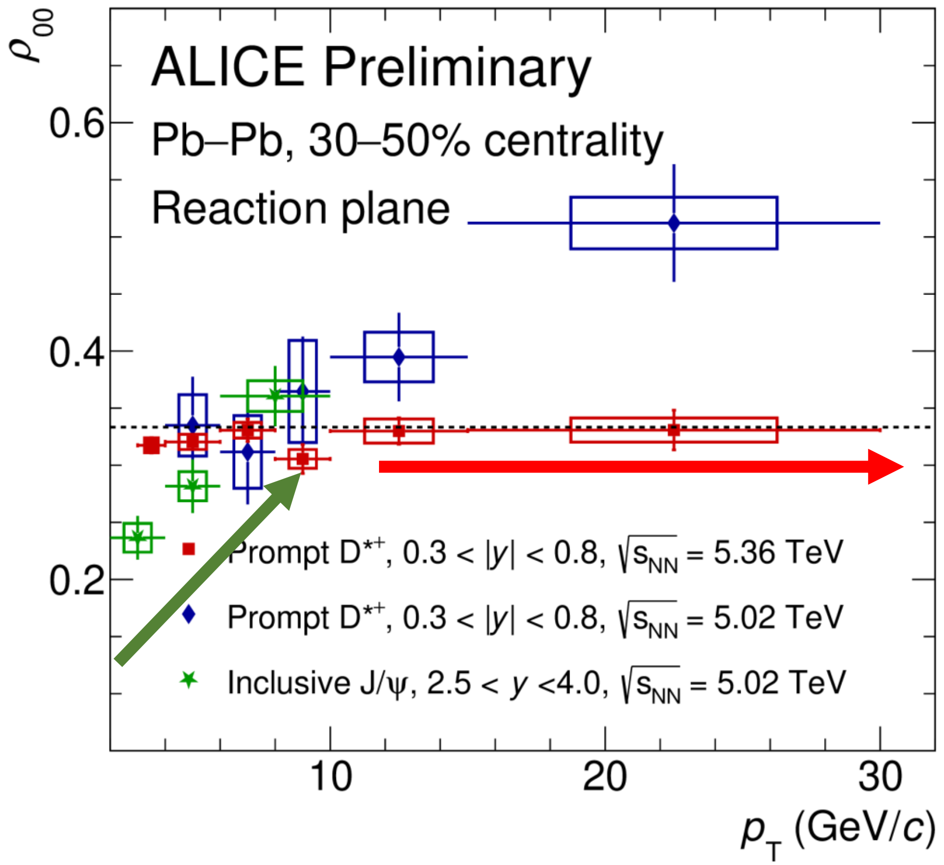


~52 billion MB events
×**160 more** than Run 1+2

J/ψ spin alignment compare with heavy-flavor vector mesons

ALICE, JHEP 10 (2025) 094





- J/ψ spin alignment shows an increasing trend with p_T in the measured kinematic range, similar trend was also for light-flavor vector mesons
- D*+ spin alignment is consistent with 1/3 within the improved statistical precision, the deviation in the highest p_T bin is due to statistical fluctuations

Summary and outlook

➢ In pp collisions

- NRQCD can describe the cross section but fails to describe the spin alignment.
- The LDMEs are sensitive to spin alignment and can be used as an additional constraint on the LDME

➢ In AA collisions

- Significant J/ψ spin alignment (~**3**.9$\boldsymbol{\sigma}$) observed w.r.t the reaction plane
- Theory guidance is needed to interpret the data

➢ Run 3 data will enable precision measurements of heavy-flavor vector meson spin alignment

Thanks