Measurement of Quarkonium Production and Polarization in Heavy-Ion Collisions

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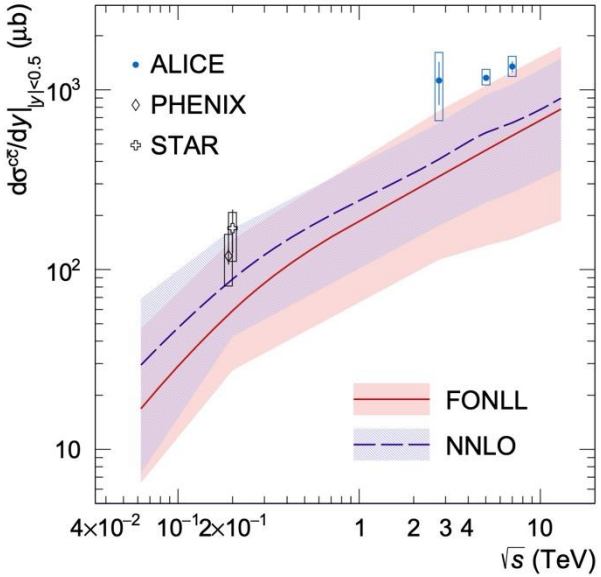
Guilin, 2025.10.26

ALICE

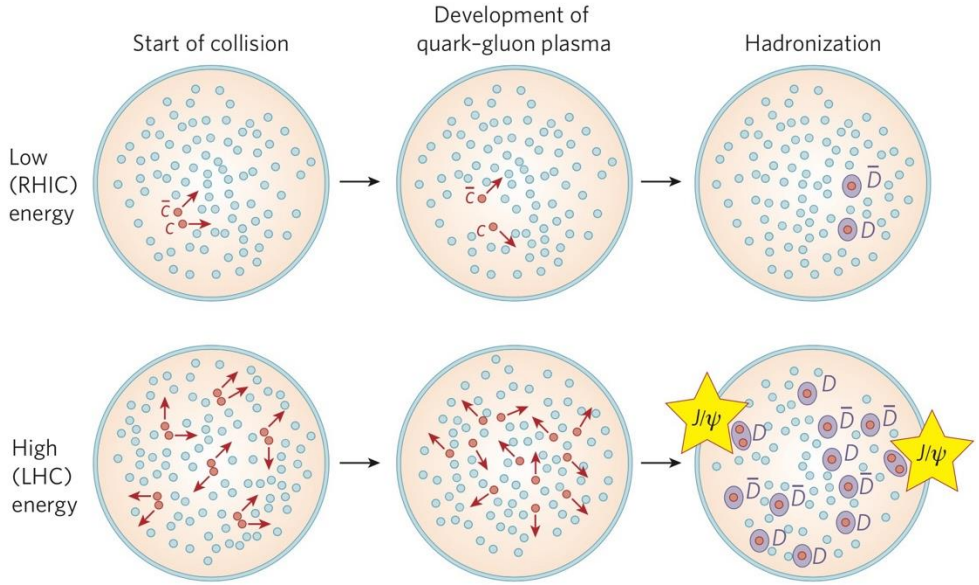
1958 University of Science and Technology of China

Charmonium production in heavy-ion collisions

ALICE, Phys. Rev. D 105, 011103 (2022)

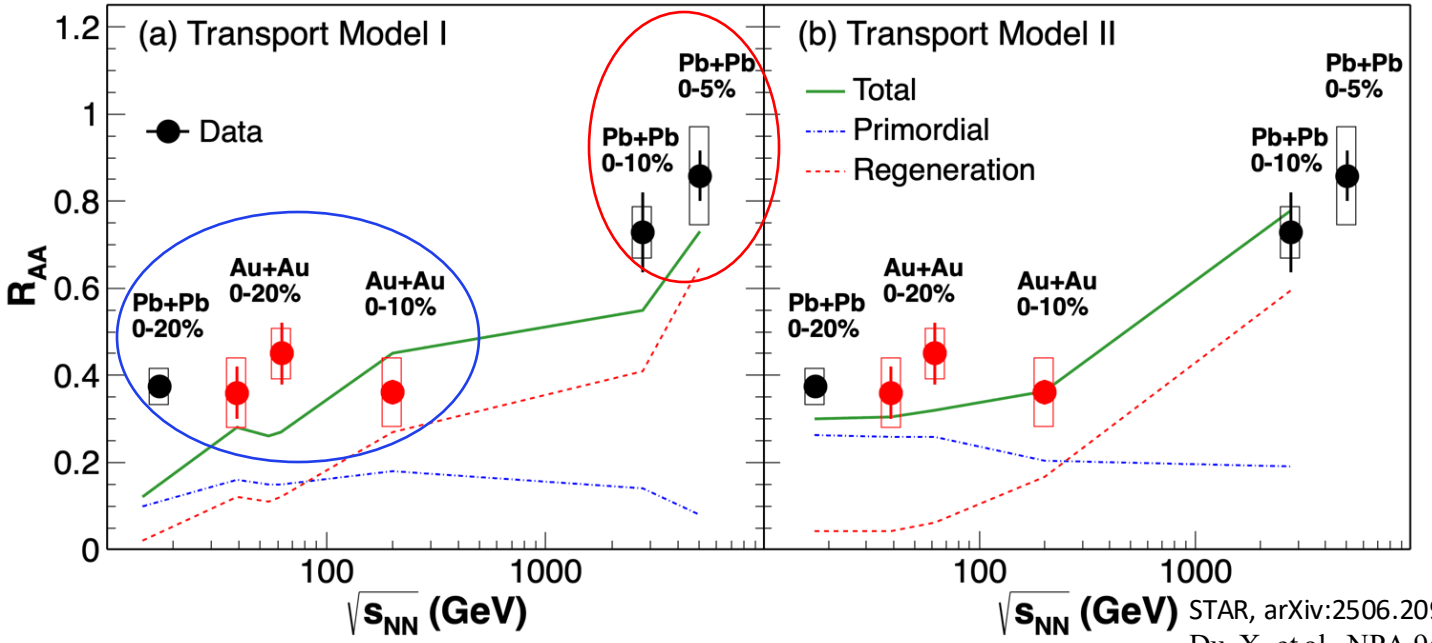


P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302



- Charm quark production cross section at the LHC is much larger compared to RHIC energies
- The (re)generation contribution to J/ψ production is dominant at LHC energies

Charmonium production in RHIC and LHC



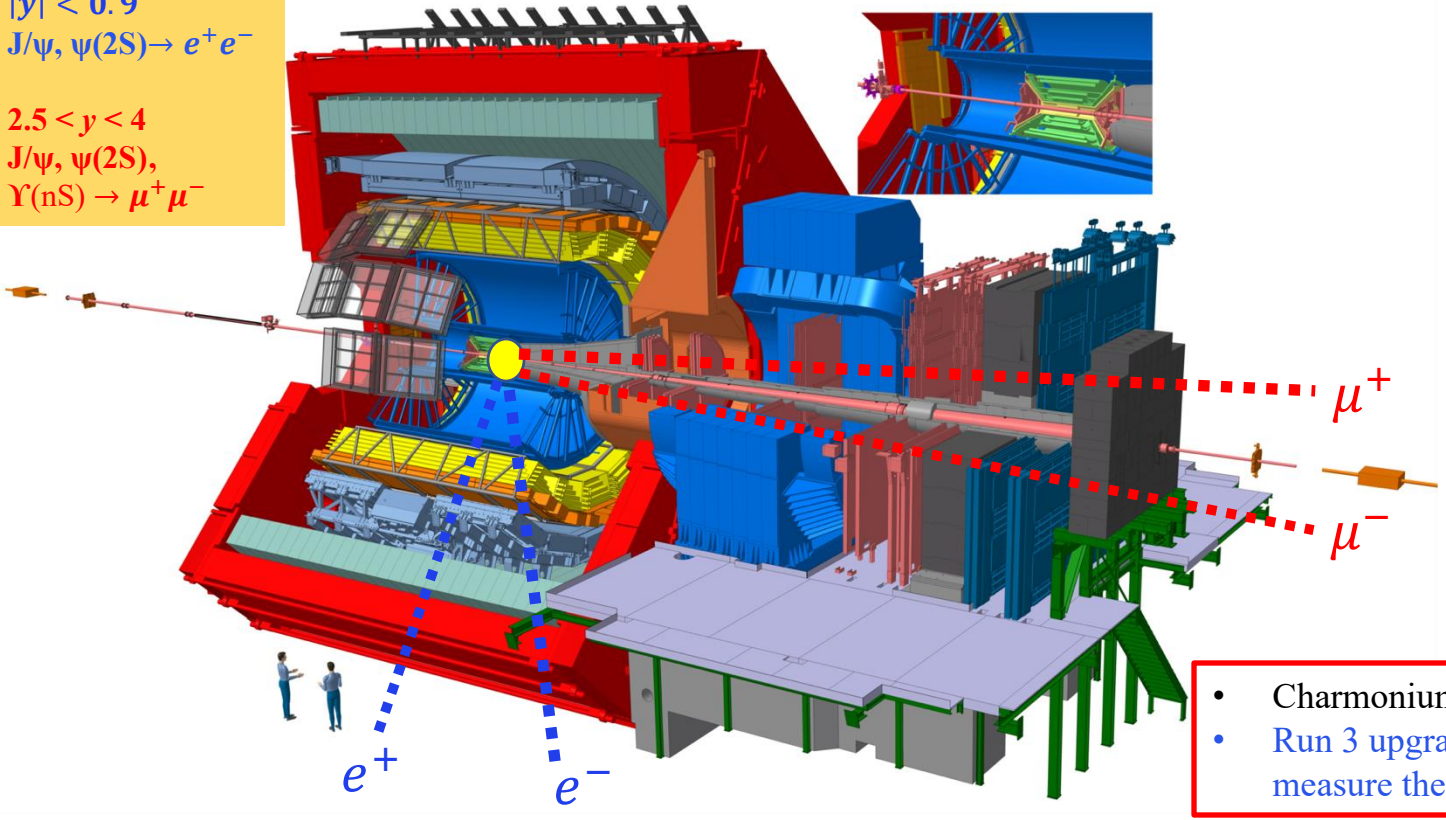
STAR, arXiv:2506.20962
Du, X. et al., NPA 943, 147–158 (2015)
Zhou, K., et al., PRC 89, 054911 (2014)

- Suppression of the charmonia due to colour screening and the dynamic dissociation
- The **(re)generation** contribution to the J/ψ is significantly higher than at RHIC

Quarkonium measurements with the ALICE

$|y| < 0.9$
J/ψ, ψ(2S)→ e^+e^-

$2.5 < y < 4$
J/ψ, ψ(2S),
ϒ(nS) → $\mu^+\mu^-$



Time Projection Chamber
Tracking, particle identification

Inner Tracking System
Tracking, vertex reconstruction, Event plane determination

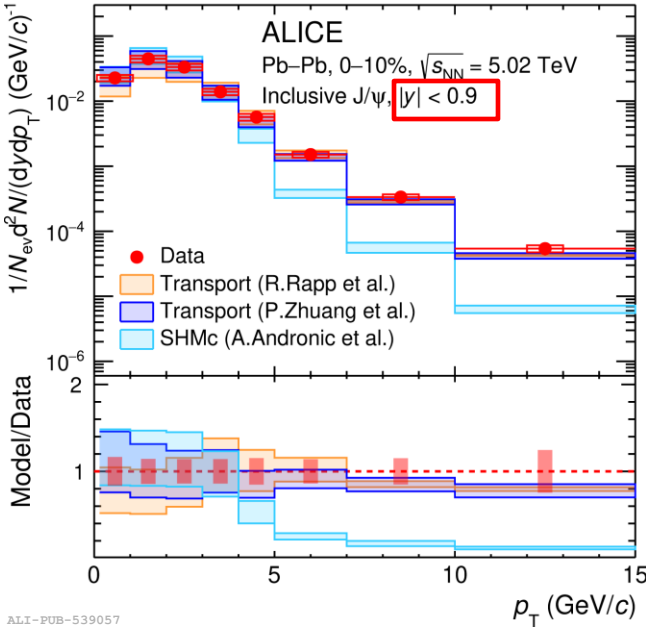
V0 Detector
Centrality determination, triggering, event plane determination, and background rejection

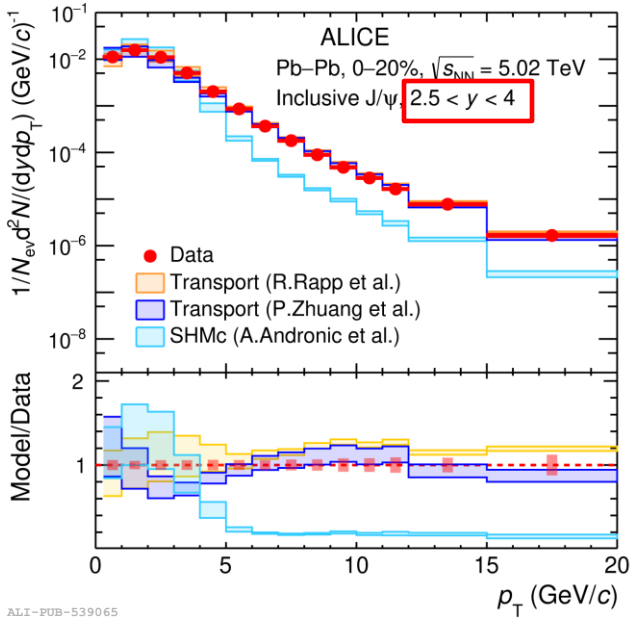
Muon spectrometer
Trigger and tracking for muons

- Charmonium measurement down to $p_T = 0$
- Run 3 upgraded detectors allow to measure the **ψ(2S), ϒ(nS)** at midrapidty

Inclusive J/ψ yield

ALICE, PLB 849 (2024) 138451



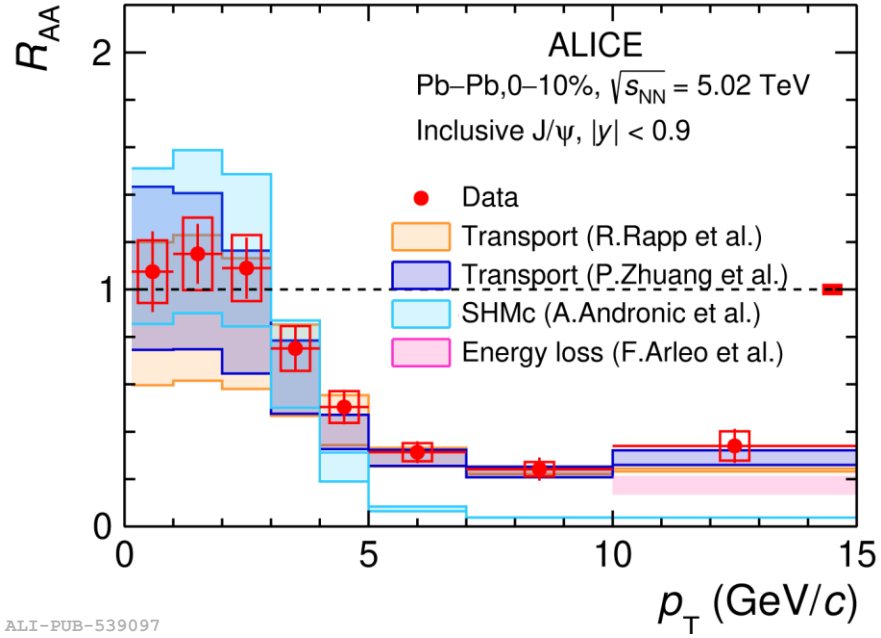


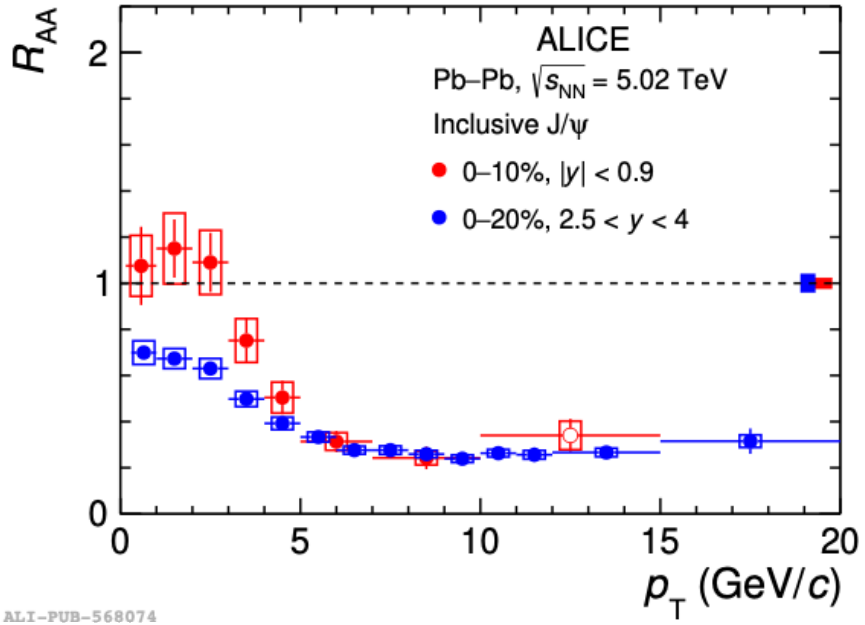
- Inclusive J/ψ yields are shown as a function of p_T at **mid- (left) and forward (right)** rapidity in central collisions
- Two transport models describe the data within uncertainties
- SHMc agrees with data at low p_T, and underestimates the measurement at high p_T

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)

Inclusive J/ψ R_{AA} vs p_T

ALICE, PLB 849 (2024) 138451



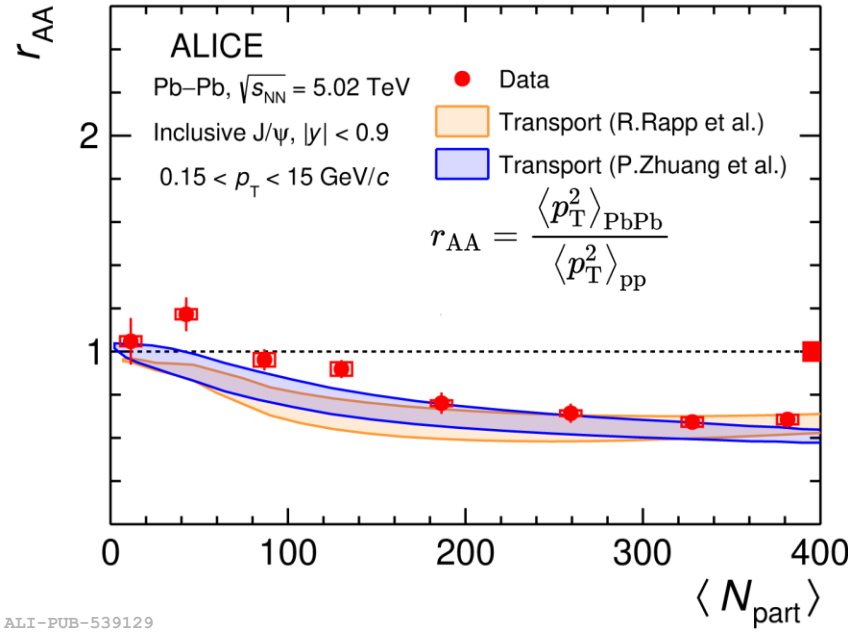


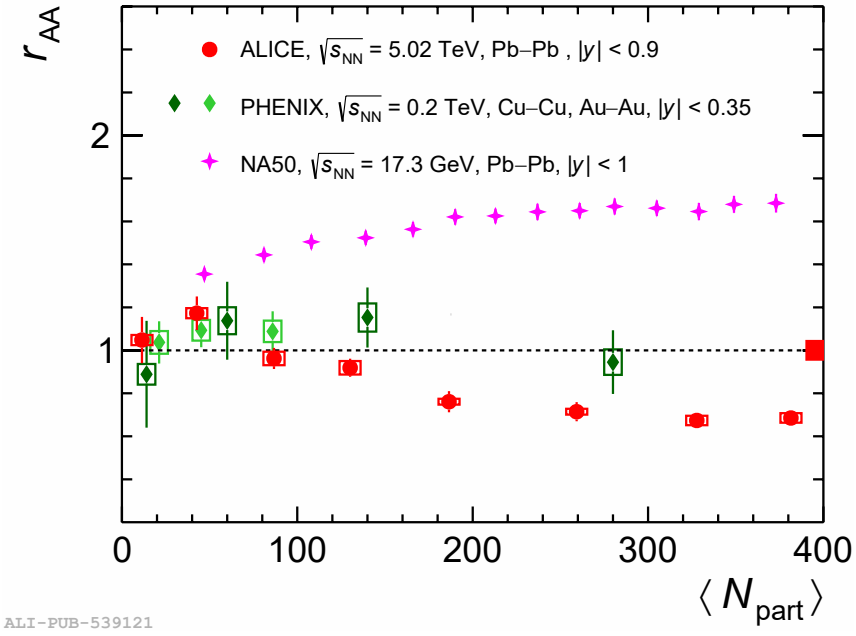
- Transport and SHMc models describe data at low p_T, while SHMc underestimates the measurement at high p_T, the energy loss model agrees with data at high p_T
- **Evidence for the (re)generation and demonstration of deconfinement at LHC**

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)

Inclusive J/ψ mean p_T

ALICE, PLB 849 (2024) 138451



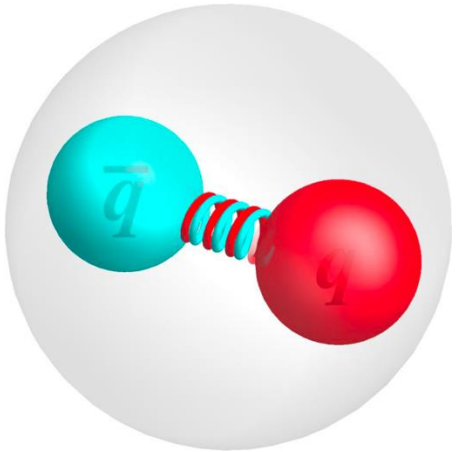


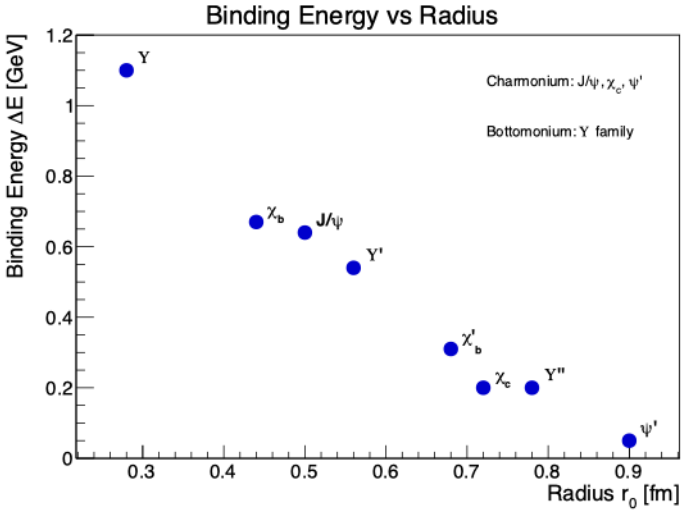
- Decreasing trend for r_{AA} from semicentral toward central collisions
- r_{AA} below unity indicates a softening of the J/ψ p_T shape in Pb−Pb collisions compared to pp collisions, the behavior is different from the lower center-of-mass energies

Du, X. et al., NPA 943, 147–158 (2015)
Zhou, K., et al., PRC 89, 054911 (2014)

The interaction of the quarkonium and QGP

State	J/ψ	χc	ψ′	Υ	χb	Υ′	χb′	Υ″
Mass [GeV]	3.1	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.5	0.72	0.9	0.28	0.44	0.56	0.68	0.78

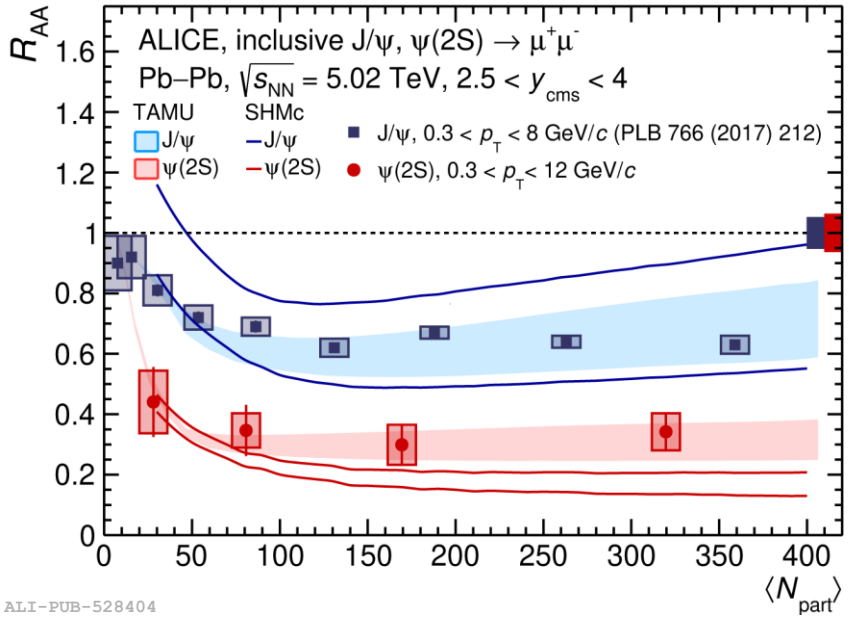


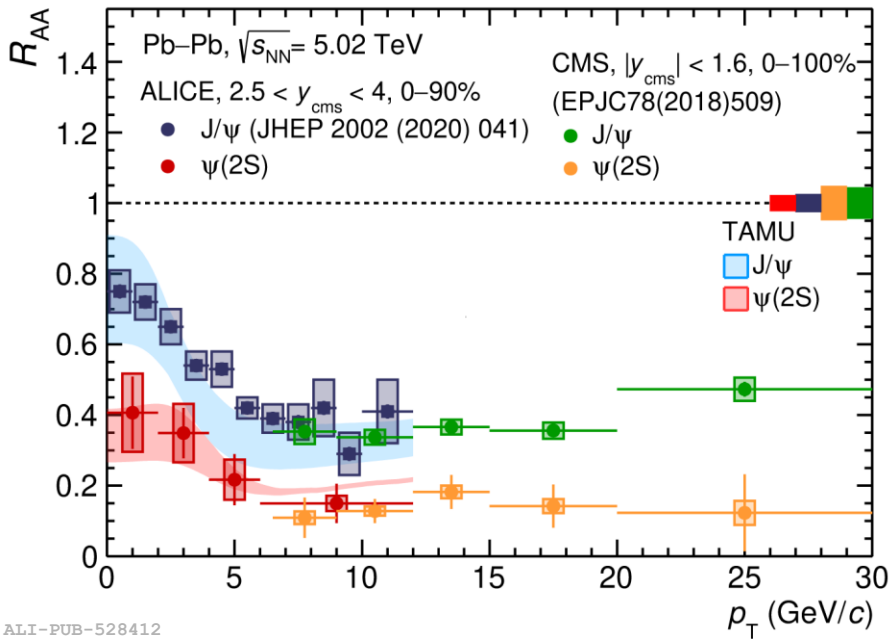


- Bound state will be dissociated into open heavy flavor hadrons when the debye radius is smaller than the size of the bound state
- Suppression of quarkonium in relativistic heavy ion collisions should provide a “smoking-gun” signature of QGP formation

ψ(2S) R_{AA} in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, PRL **132**, 042301(2024)



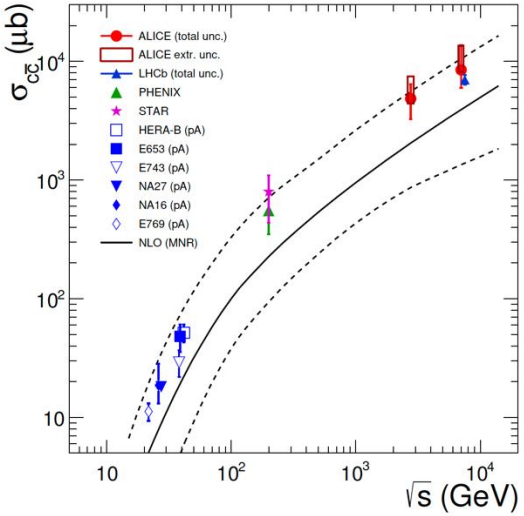


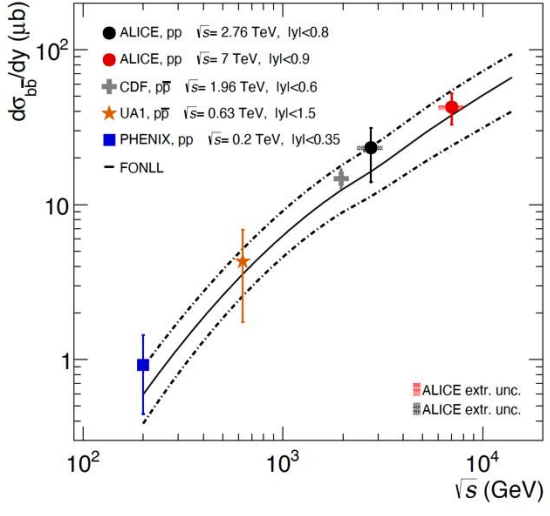
- A **larger suppression** of the ψ(2S) w.r.t the J/ψ is observed
- The ψ(2S) R_{AA} increases at low p_T , which is a hint of ψ(2S) regeneration
- The TAMU model describes data better than SHMc in central collisions

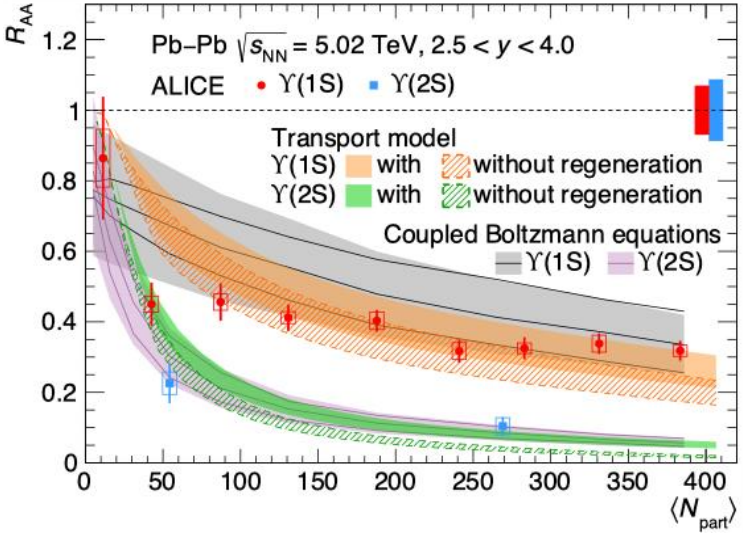
(TAMU) X. Du, et al.,NPA943,147-158(2015)
(SHMc) A. Andronic, et al.,PLB797,134836(2019)

Υ(nS) production in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, PLB 822 (2021) 136579



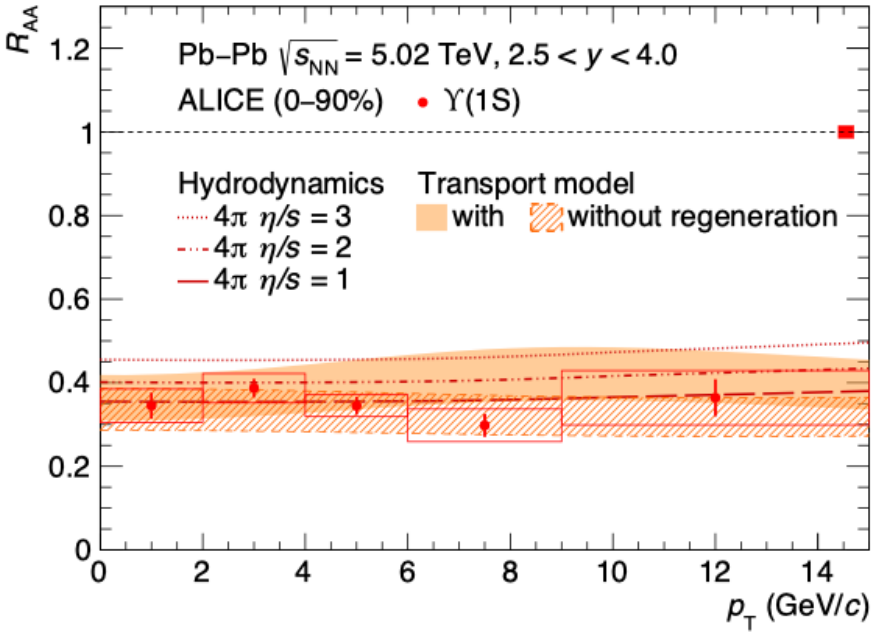


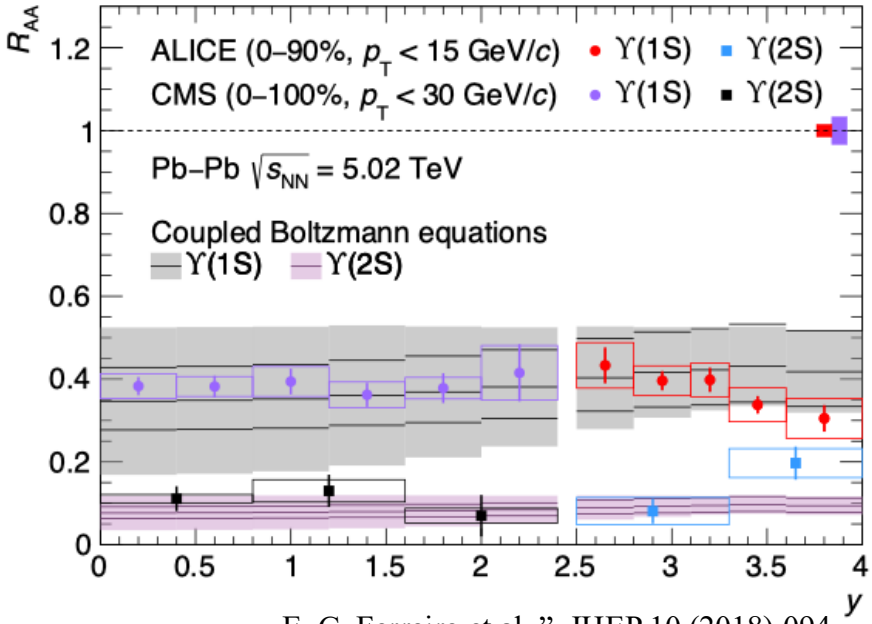


- The beauty production cross section is significantly lower than that of charm, and the contribution from Υ production is negligible.
- Slight centrality dependence for both Υ(1S) and Υ(2S) $R_{AA,}$ stronger suppression of Υ(2S) compared to Υ(1S)

Υ(nS) production in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, PLB 822 (2021) 136579

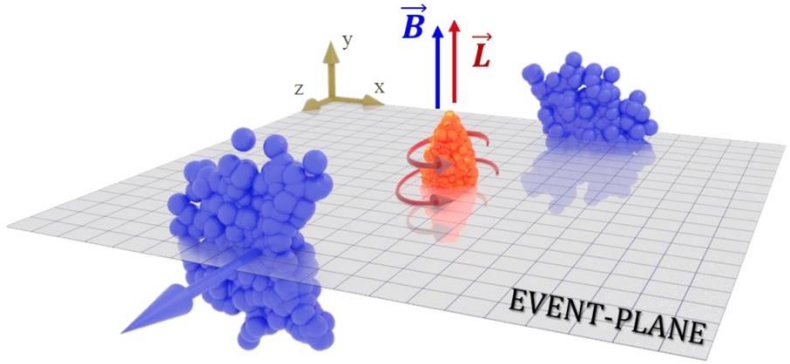


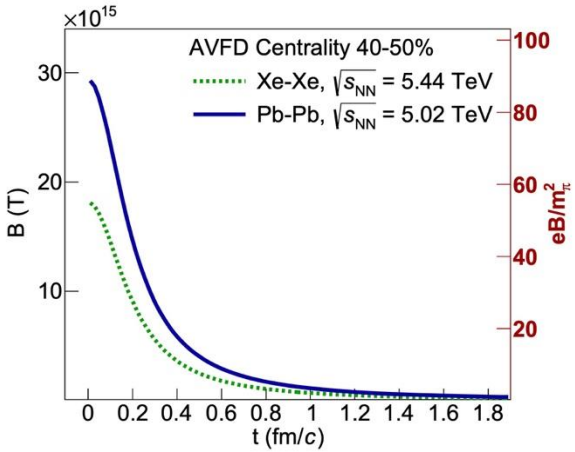


E. G. Ferreiro et al, ", JHEP 10 (2018) 094
X. Yao eta al, JHEP 21 (2020) 046

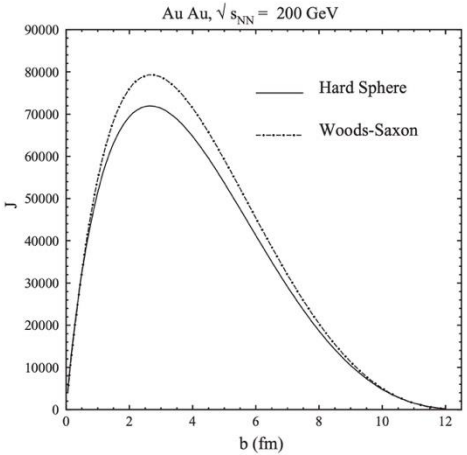
- Slight rapidity dependence, the trend is different from the model calculation
- No p_T dependence which in strong contrast to the J/ψ R_{AA}

Charmonium polarization





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



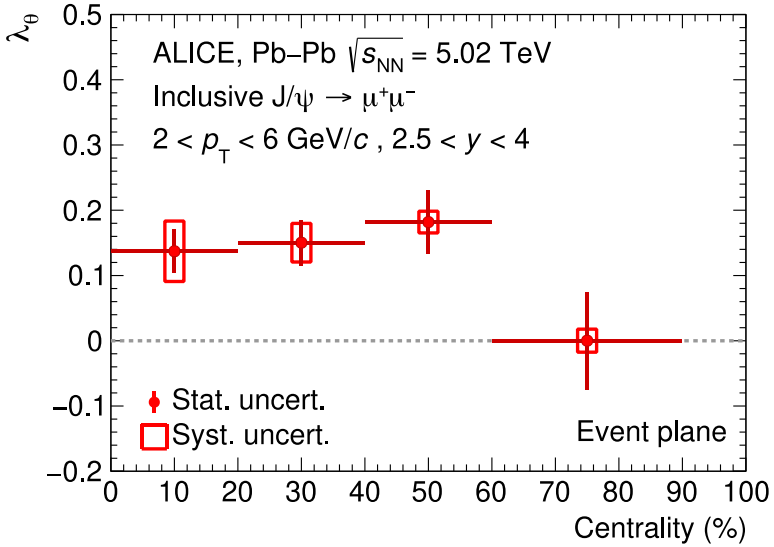
F. Becattini et al., PRC 77 (2008)

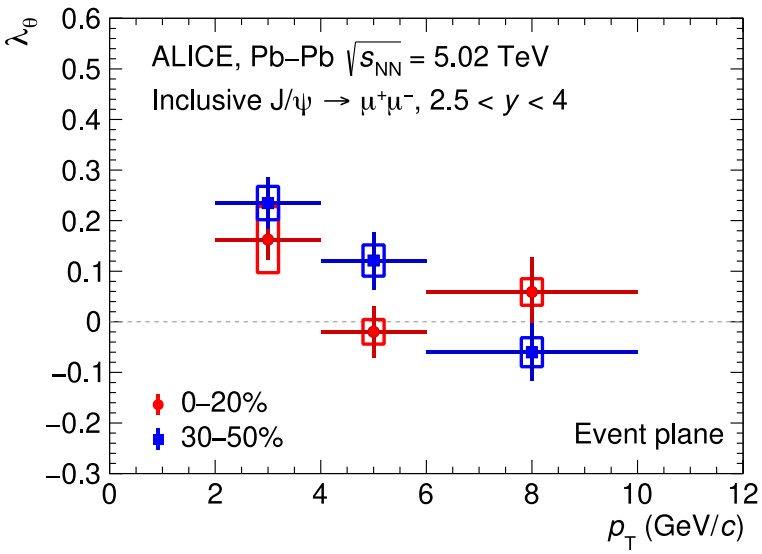
Heavy-quark pairs are produced in the early stage of AA collision and can experience both the **short living *B* and the *L* of the rotating medium**, polarization w.r.t. an axis orthogonal to the event plane can be affected.

X. Wang, Z. Liang, Phys.Lett.B 629:20-26,2005

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

ALICE, PRL 131 (2024) 4, 042303

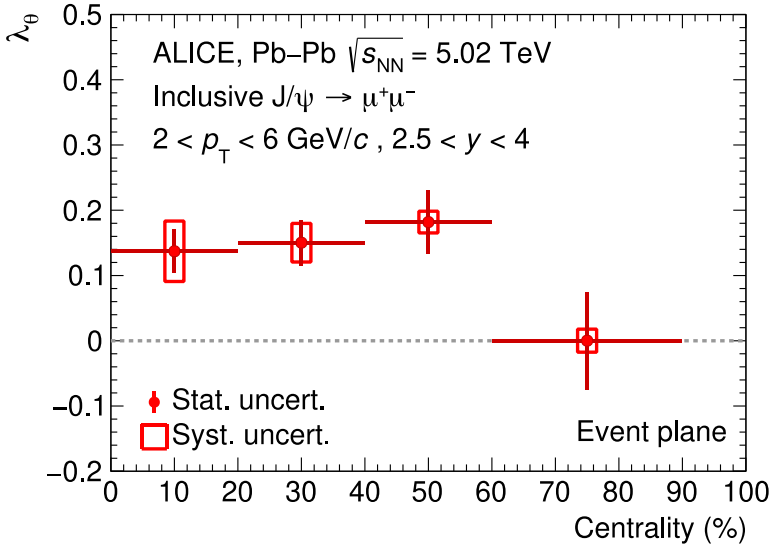


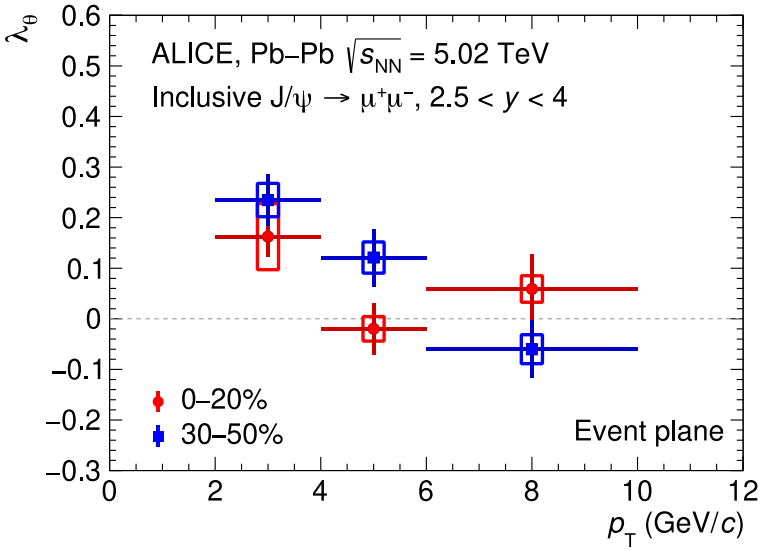


- First measurement of quarkonium polarization **w.r.t the event plane**
- **Significant polarization (~3.5σ)** observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The significance of the polarization reaches **~3.9σ** at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results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

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

ALICE, PRL 131 (2024) 4, 042303





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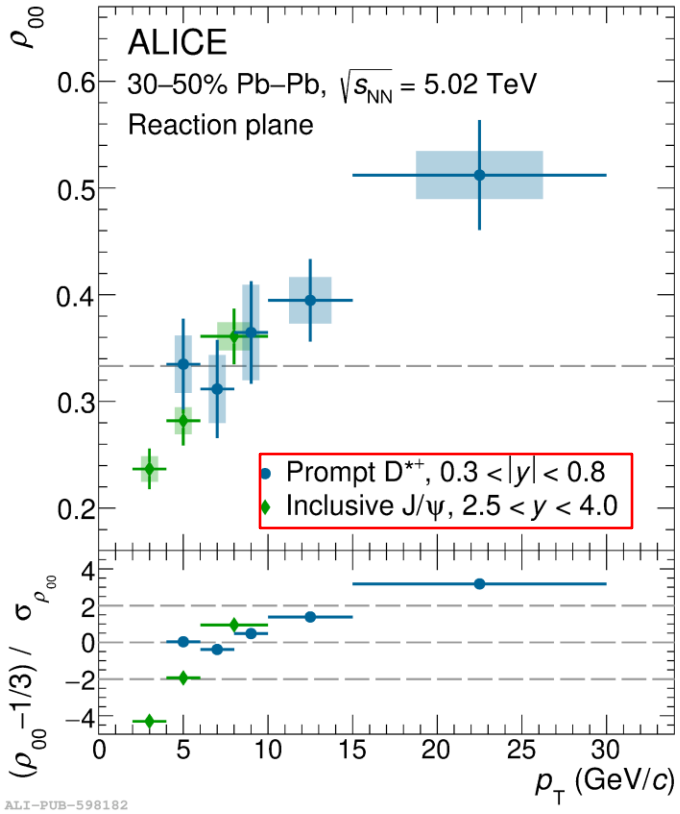
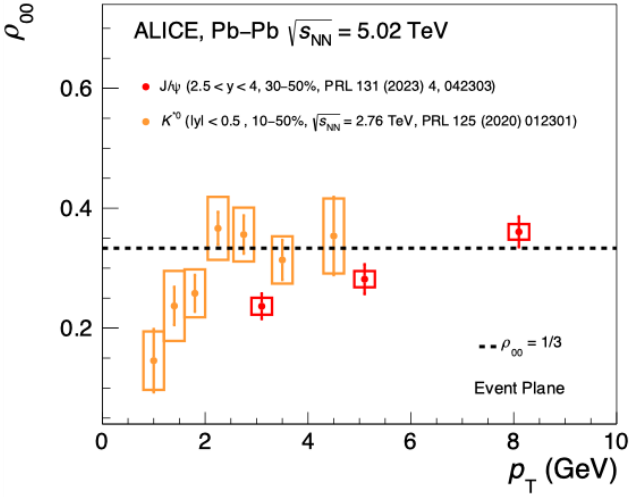
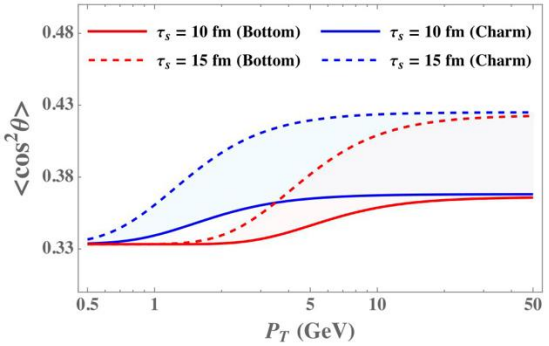
J/ψ polarization compared with model





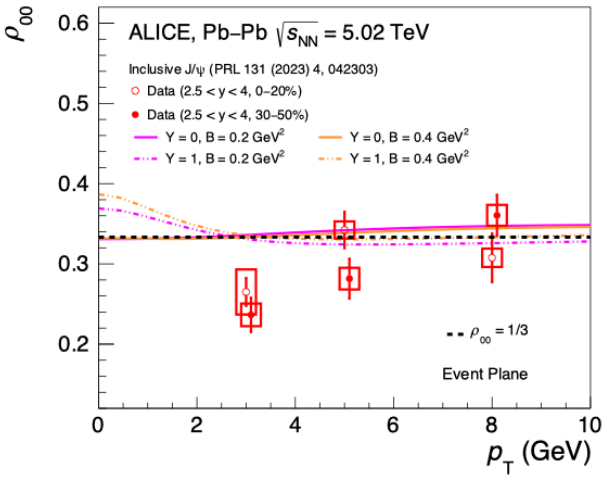


S. Dey et. al , arXiv:2502.20352v2

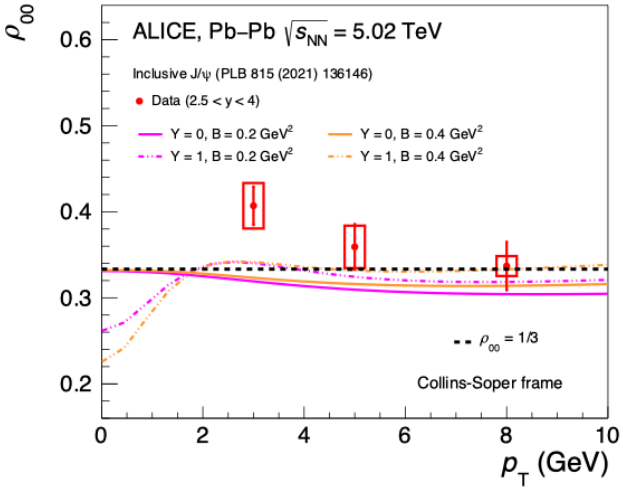
- The trend of the J/ψ polarization and K^{0*} and D^{*+} are similar
- The magnetic field plays a more important role in polarization, particularly for charm vector mesons at LHC (?)
- Interpretation of results requires inputs from theoretical models

J/ψ polarization compared with model

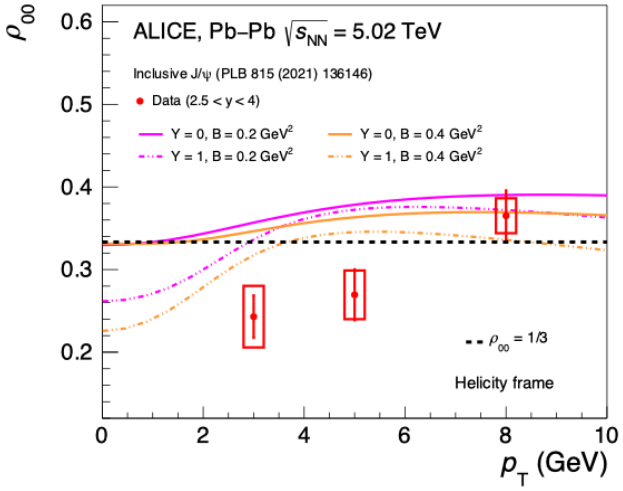
Event plane frame



Collions-Soper frame



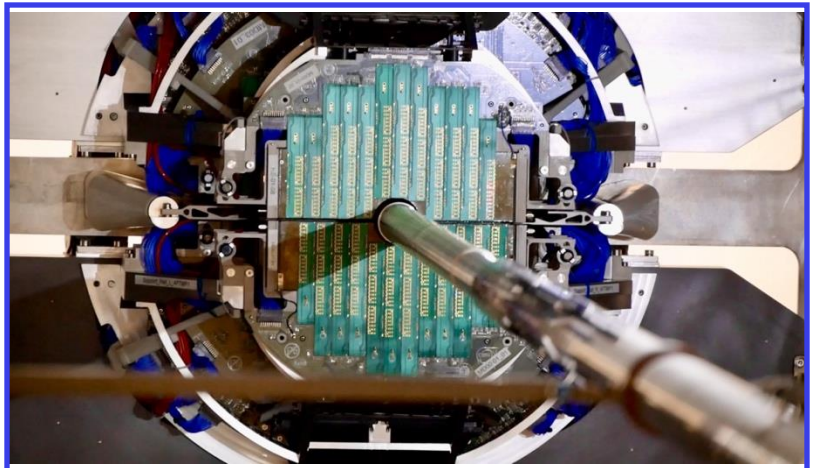
Helicity frame



The observed trend of the J/ψ polarization is inconsistent with the holographic theoretical predictions in the event-plane and Collins–Soper frames

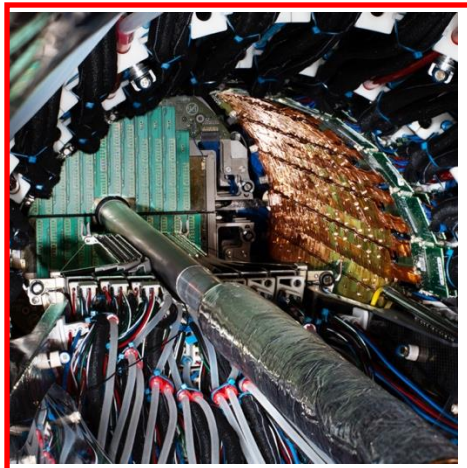
Y. Zhao et al. JHEP 08 (2024) 070

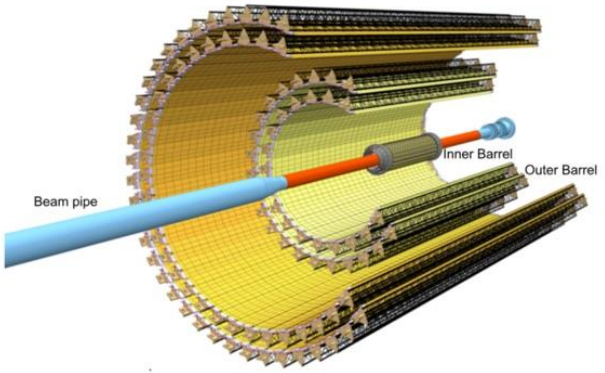
ALICE in Run 3 (MFT and ITS2)



New Muon Forward Tracker

- Monolithic Active Pixel Sensor technology
- Spatial resolution: 5 µm
- Pixel size: 27 µm x 29 µm
- Integration time: 5 µs



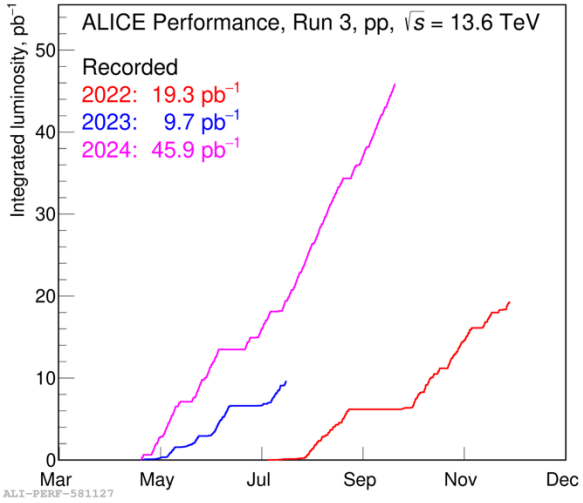


Upgraded Inner Tracking System

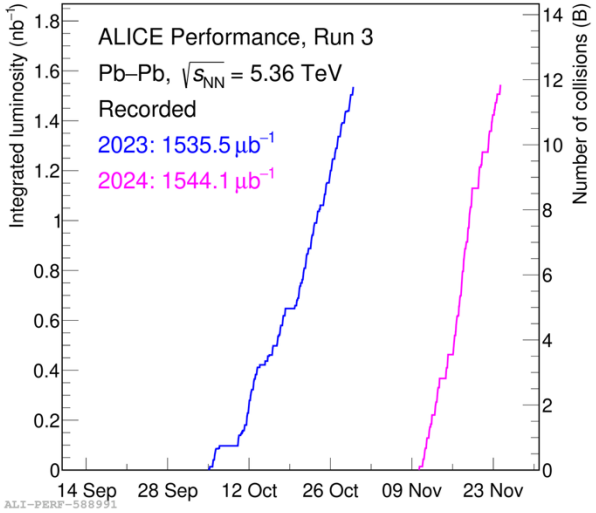
- 3 layers in inner barrel (IB), 4 in outer barrel (OB)
- Get closer to IP: from 39 mm to 23 mm
- Reduced material budget: from 1.14% X_0 to 0.36% X_0 per layer
- Reduced pixel size: from 50 x 425 µm^2 to 29 x 27 µm^2

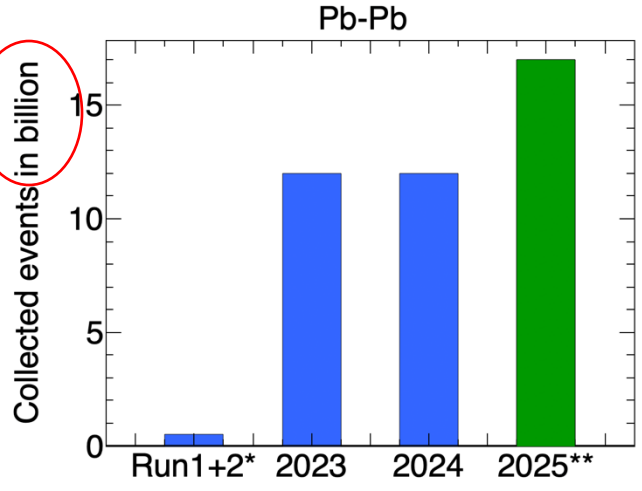
Statistics collected in LHC Run 3 (so far)

pp @13.6 TeV



Pb-Pb @5.36 TeV





- Record all the minimum bias （MB) events during the data taken
- Collected approx. **24B and 2000B MB** events **in Pb-Pb and pp** collisions, respectively
- The reconstructed J/ψ significance is **greater than 1200**

Summary

- **Charmonium**
  - Dominant contribution from (re-)generation for J/ψ
  - First measurement of quarkonium **significant polarization w.r.t the event plane**
- **Bottomonium**
  - Strong suppression for all centrality and p_T, stronger suppression of ϒ(2S) compared to the ϒ(1S)
  - No p_T dependence which in **strong contrast to the J/ψ R_{AA}**
- **Stay tuned with Run 3**

Thanks