Measurement of Quarkonium Production and Polarization with ALICE at LHC

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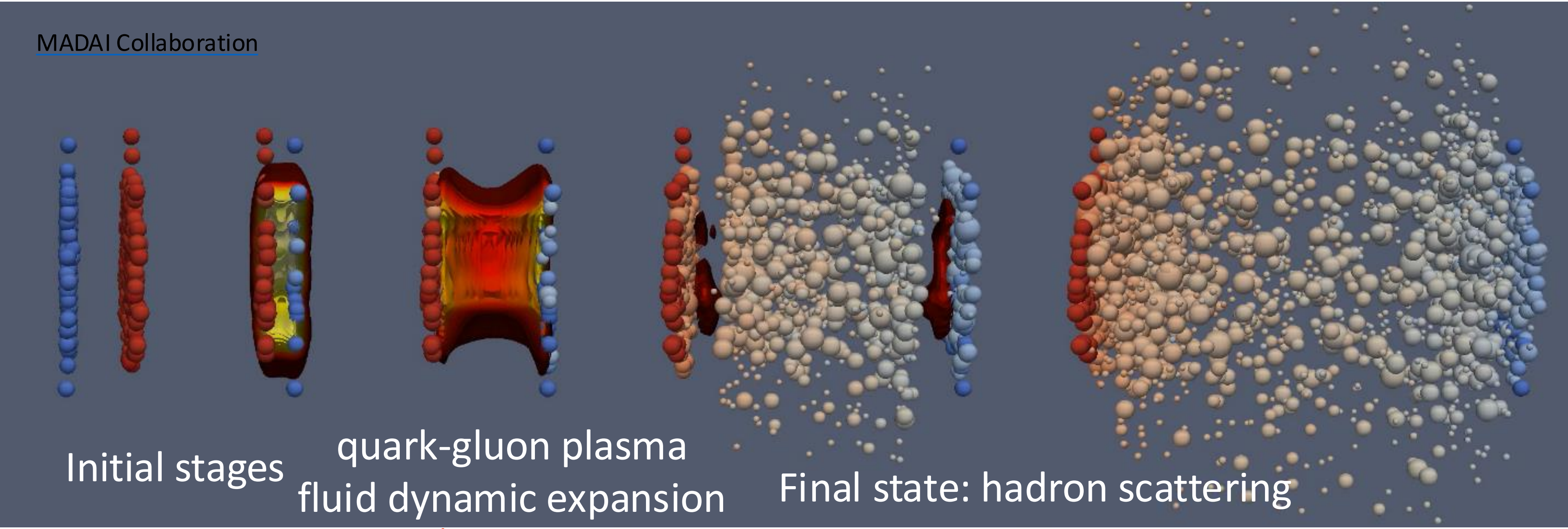
2025.09.19, 中国科学院大学

The history of the Pb-Pb collision



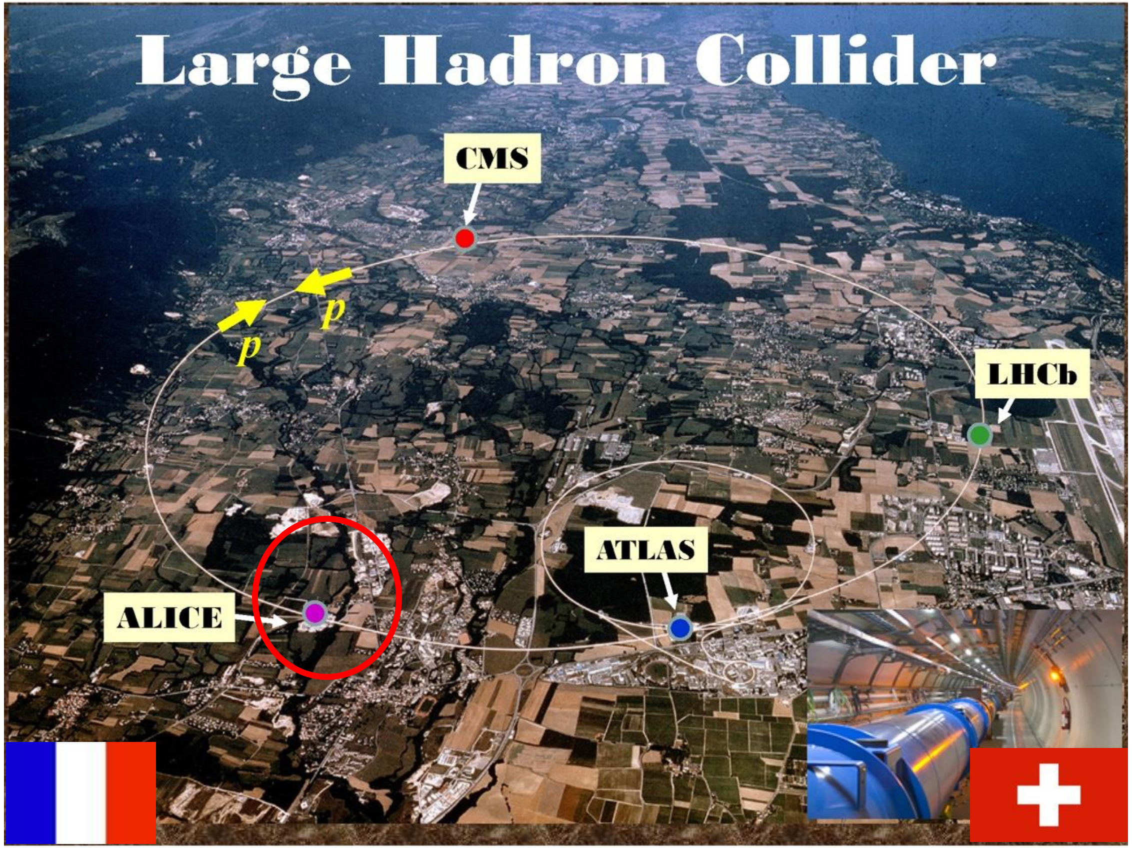
Emission of thermal radiation $\propto T^2$

geometry
gluon density
saturation?

parton energy loss, collectivity
transport coefficients, temperature

scattering lengths

The large hadron collider at CERN



ALICE collaboration

40 countries, 167 institutes

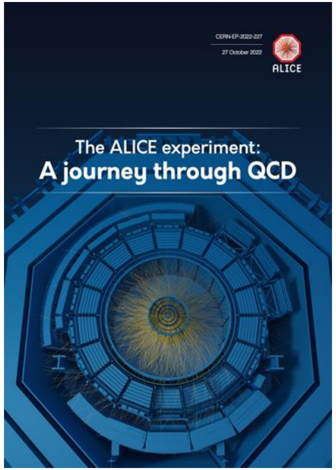
1989 members, 1071 scientific authors
377 doctoral students, 124 postdocs

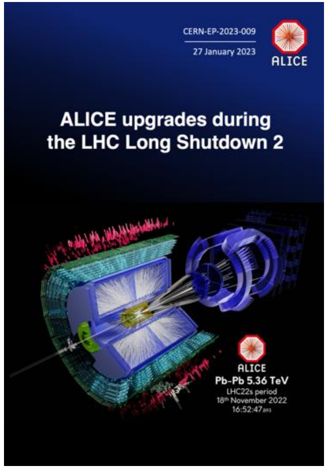
Run 1 | Run 2

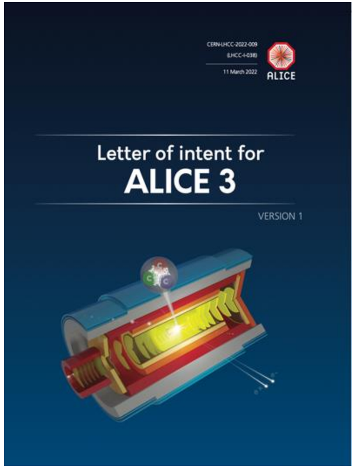
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} ~36 pb^{-1}

The outline of the ALICE

- ALICE 1 (2009 - 2018)
- ALICE 2 (2022 - 2033)
- ALICE 3 (2035 - 2041)





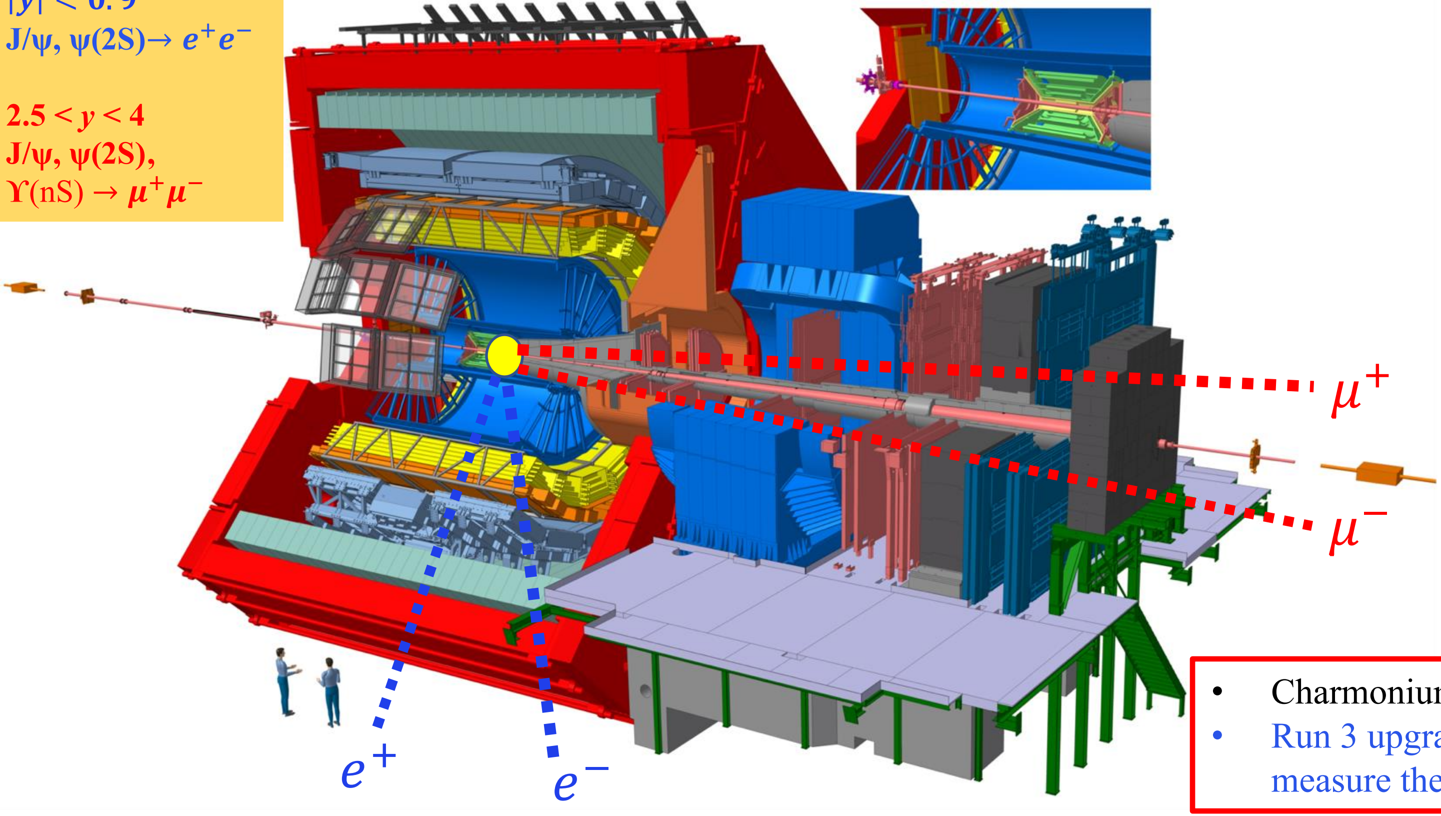


LHC LS2	LHC RUN 3	LHC LS3	LHC RUN 4	LHC LS4	LHC RUN 5 and RUN 6
2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

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

Quarkonium suppression is the "smoking gun" of QGP

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
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Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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- Heavy quarks produced in the early collision stages
- Quarkonium production is one of the "smoking guns" of QGP formation
- Quarkonium production suppressed sequentially via colour screening in QGP

T. Matsui, H. Satz, PLB178 (1986) 416

> 5700 citations

Quarkonium suppression is the “smoking gun” of QGP

PHYS. LETT. B, in press

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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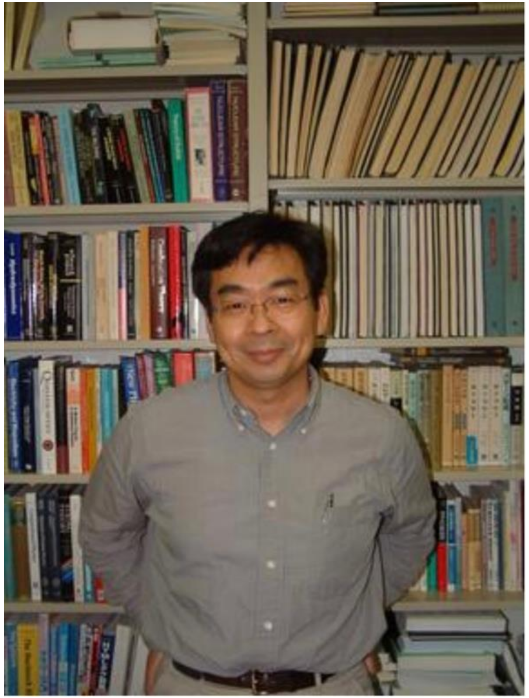
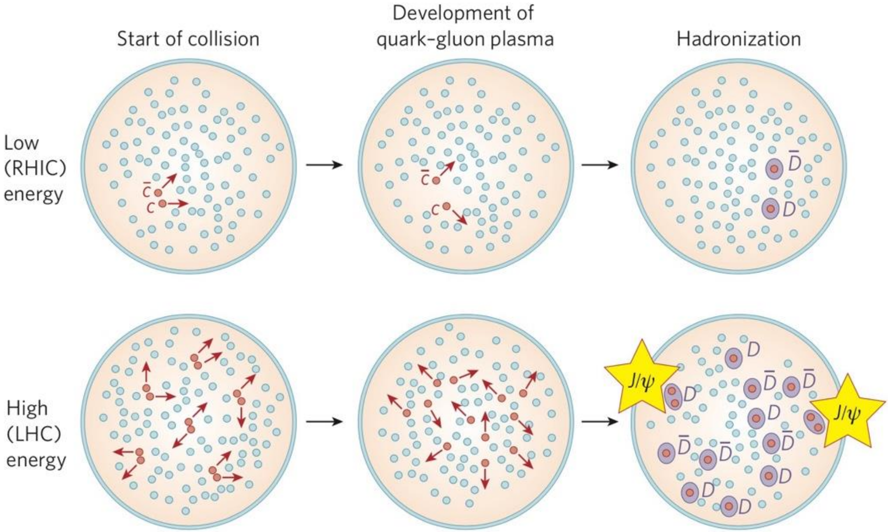


Tetsuo Matsui (1953-2025)

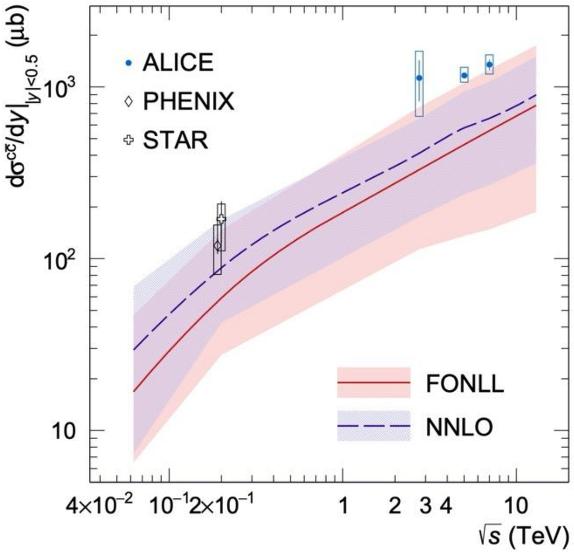
T. Matsui, H. Satz, PLB178 (1986) 416 > 5700 citations

Charmonium (re)generation production

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



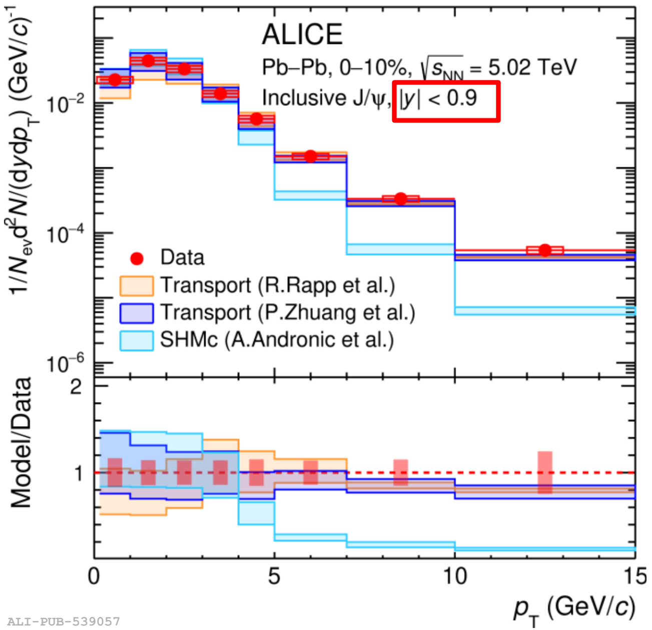
Phys. Rev. D 105, 011103 (2022)

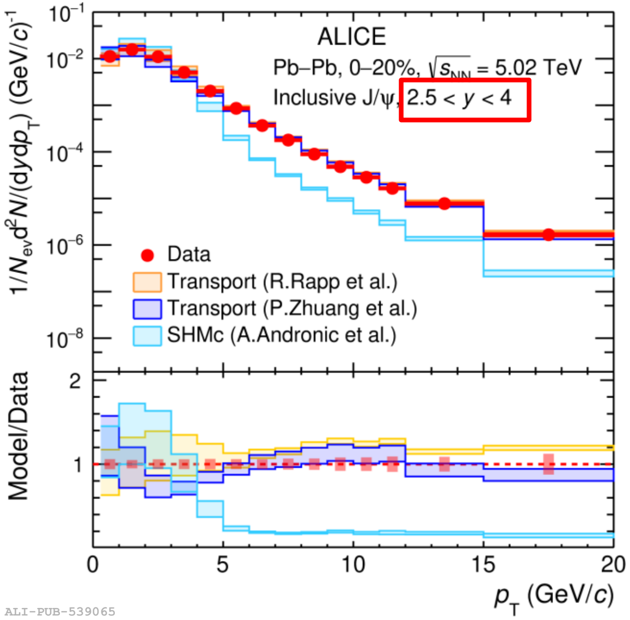


- Suppression of the charmonia due to colour screening and the dynamic dissociation
- Charm quark production cross section at the LHC is much larger compared to RHIC energies, and the **(re)generation** contribution to the J/ψ is significantly higher than at RHIC

Inclusive J/ψ yield

ALICE, PLB 849 (2024) 138451



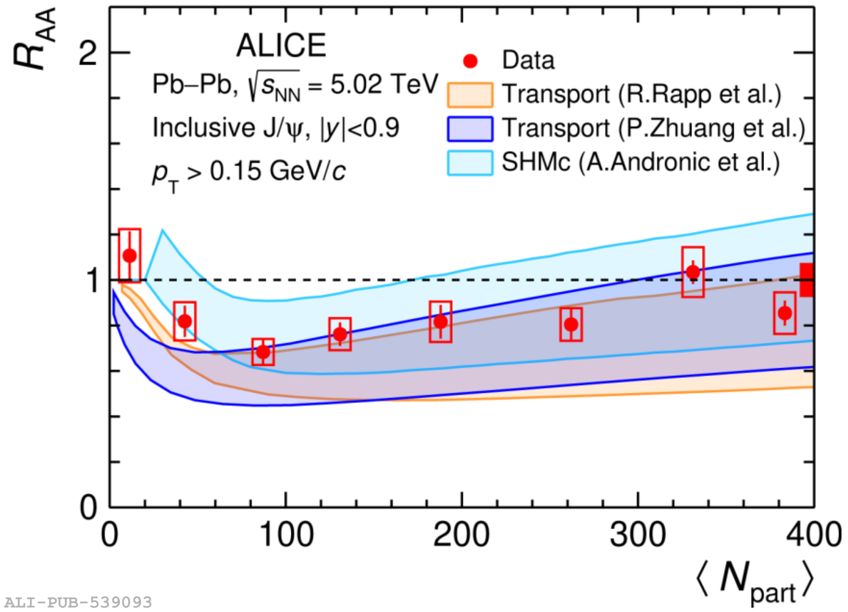


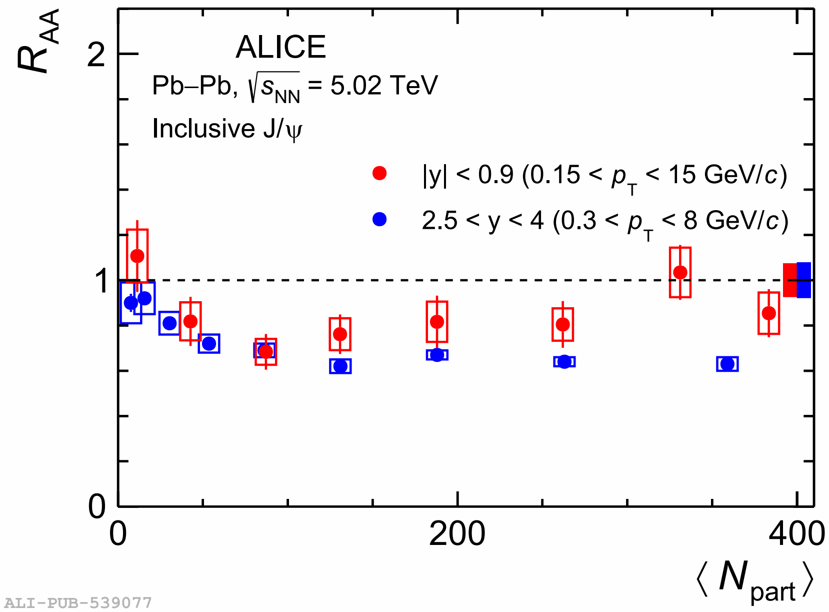
- Inclusive J/ψ yields are shown as a function of p_T at **mid- (left) and forward (right)** rapidity in central collisions
- Two transport models describe the data within uncertainties
- SHMc agrees with data at low p_T, and underestimates the measurement at high p_T

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 centrality

ALICE, PLB 849 (2024) 138451



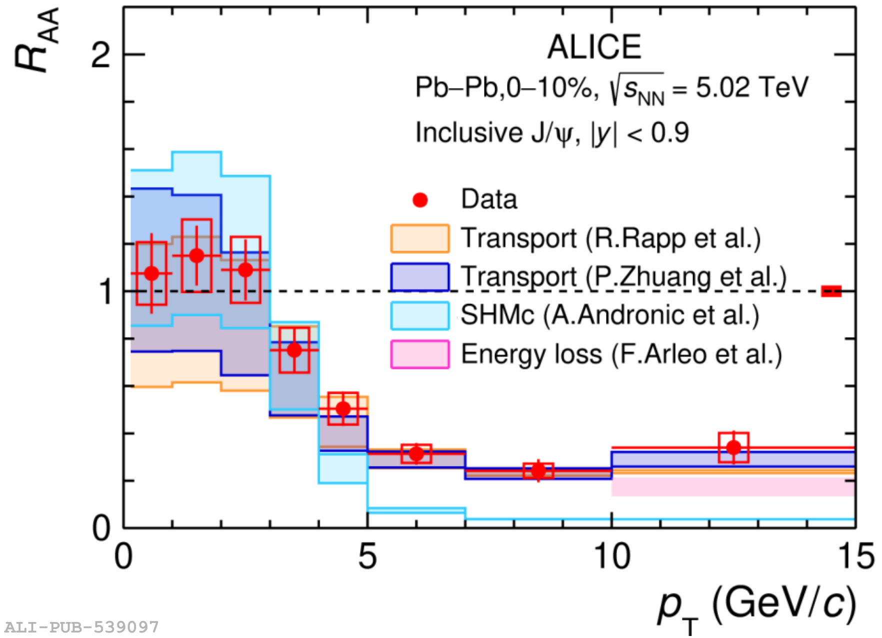


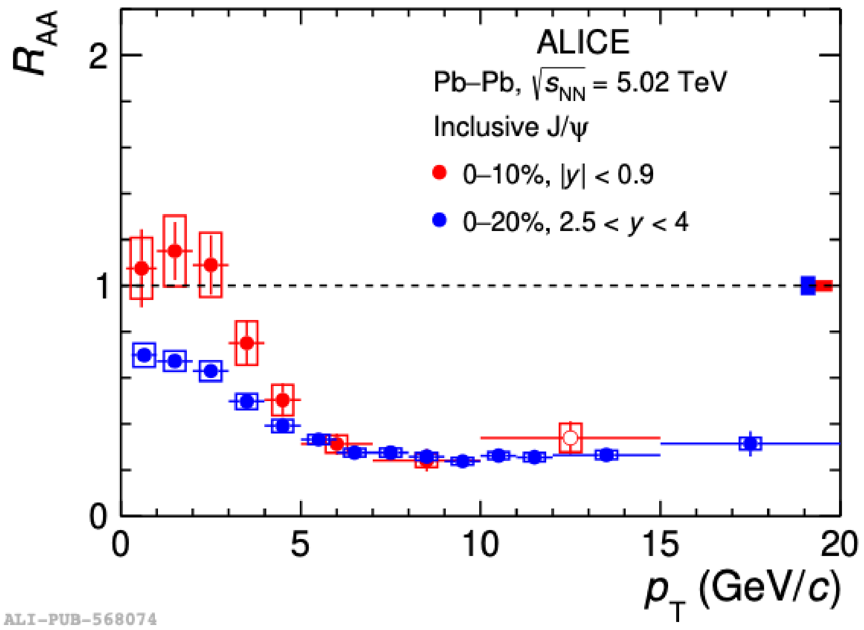
- **Evidence for J/ψ (re-)generation in central collisions, with a larger contribution at midrapidity compared to forward rapidity**
- All models can describe the data but suffer from large uncertainties related to inputs used in calculations (eg. charm cross section, shadowing).

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



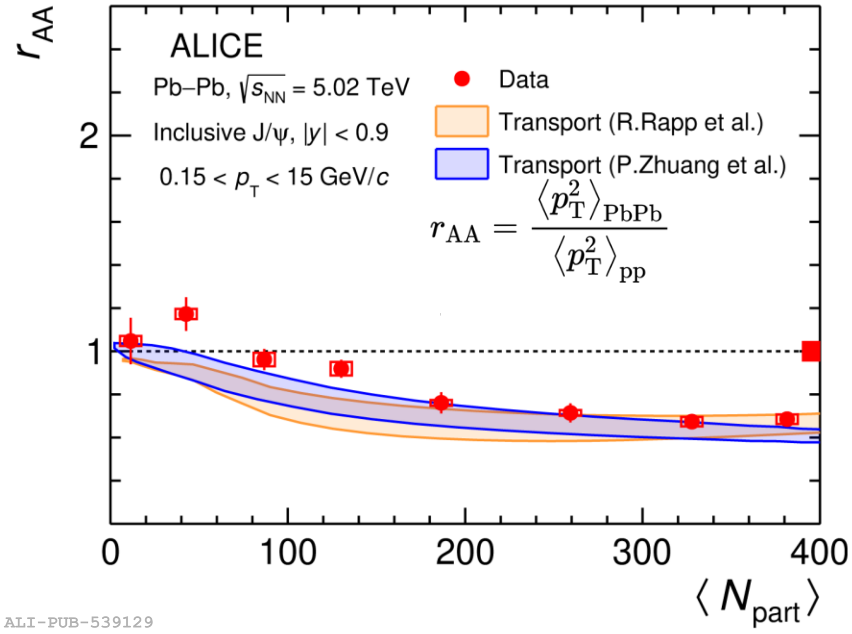


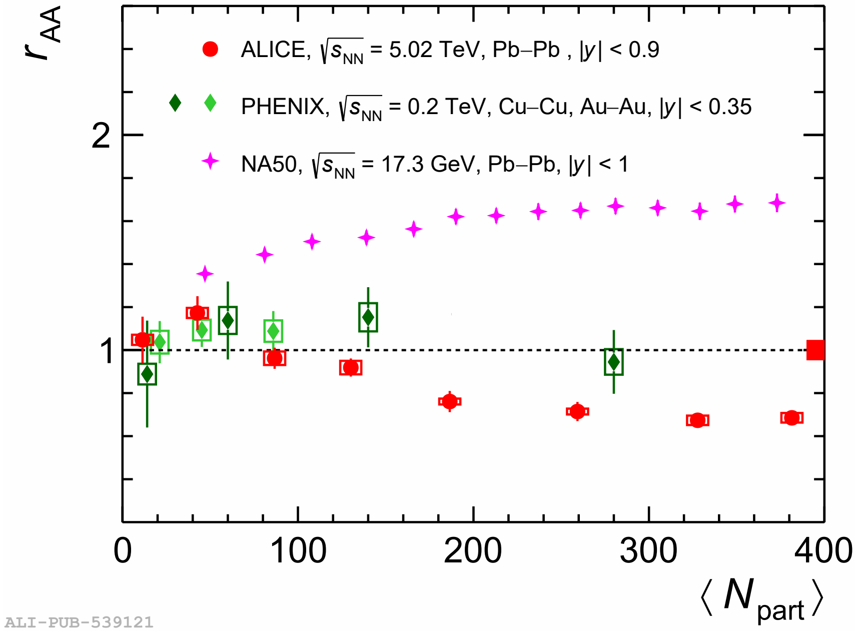
- Transport and SHMc models describe data at low p_T, while SHMc underestimates the measurement at high p_T, the energy loss model agrees with data at high p_T
- **Evidence for the (re)generation and demonstration of deconfinement at LHC**

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



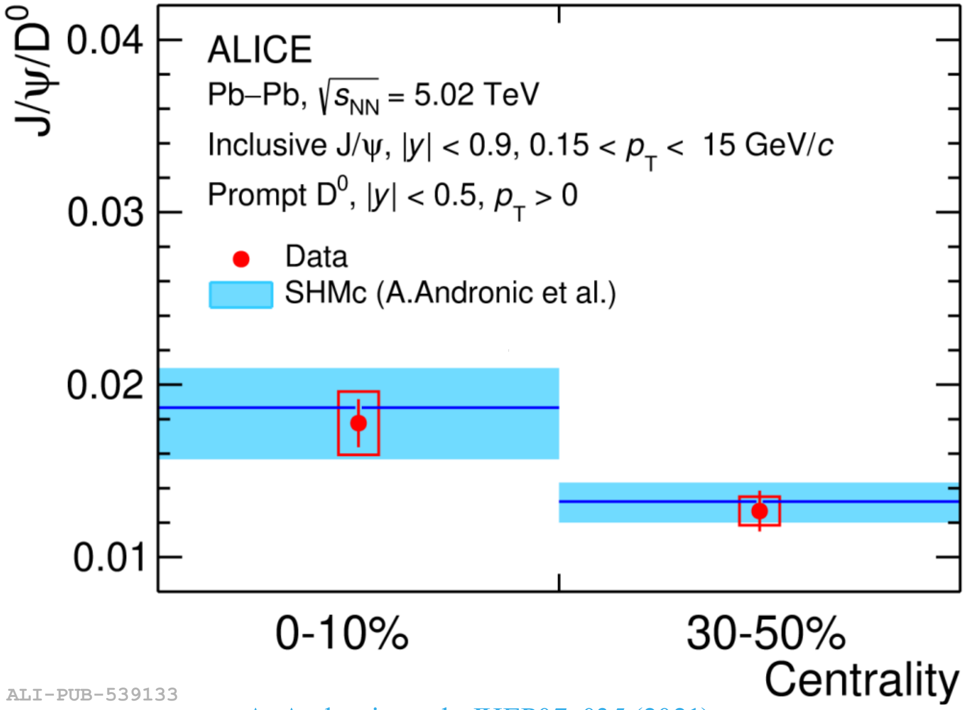


Du, X. et al., NPA 943, 147–158 (2015)
Zhou, K., et al., PRC 89, 054911 (2014)

- 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

J/ψ-to-D^0 ratio in Pb–Pb collisions

ALICE, PLB 849 (2024) 138451

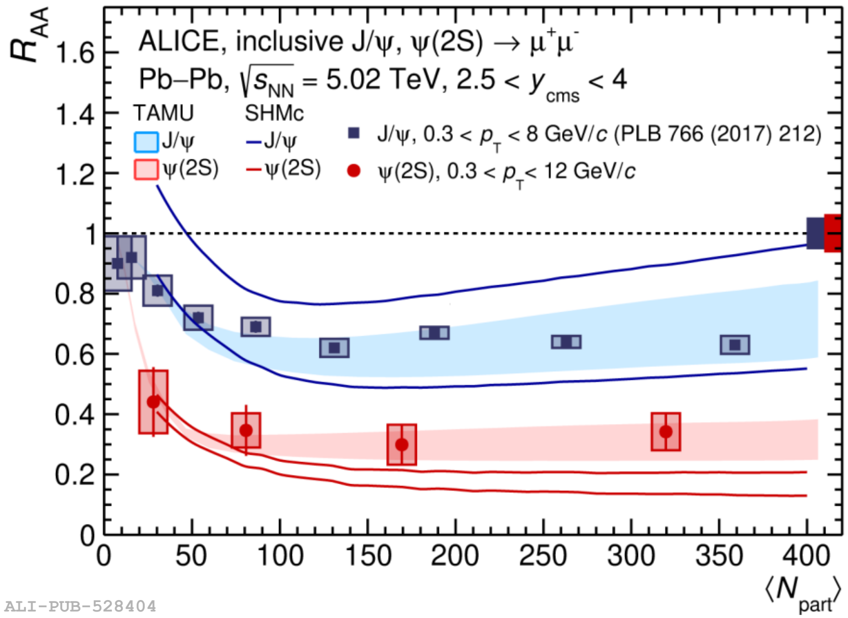


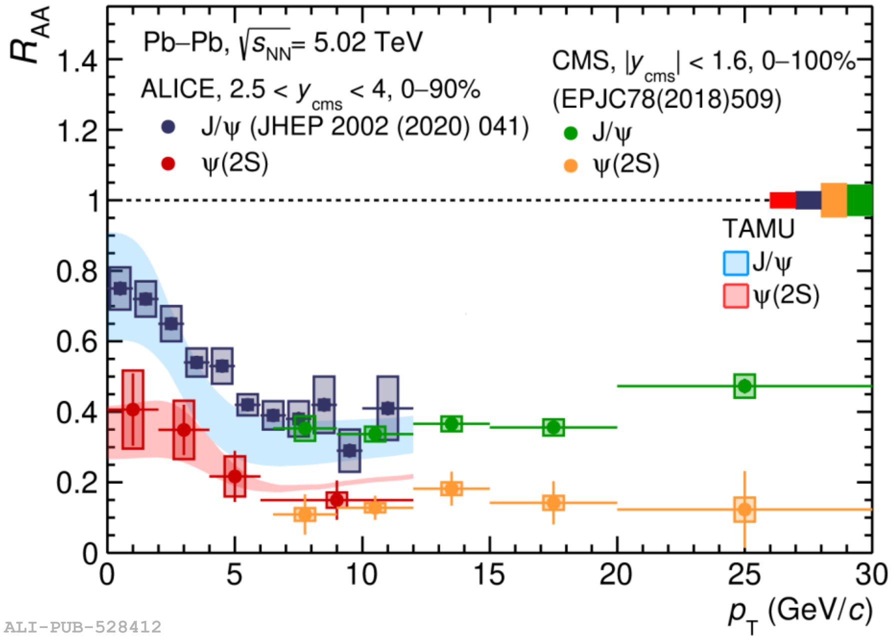
A. Andronic et al., JHEP07, 035 (2021)

- Sensitive to hadronization mechanisms for open and hidden charm hadrons
- The centrality-dependent trend of the D^0 to J/ψ ratio can be explained by the increase of charm fugacity towards most central collisions according to SHMc prediction

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

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

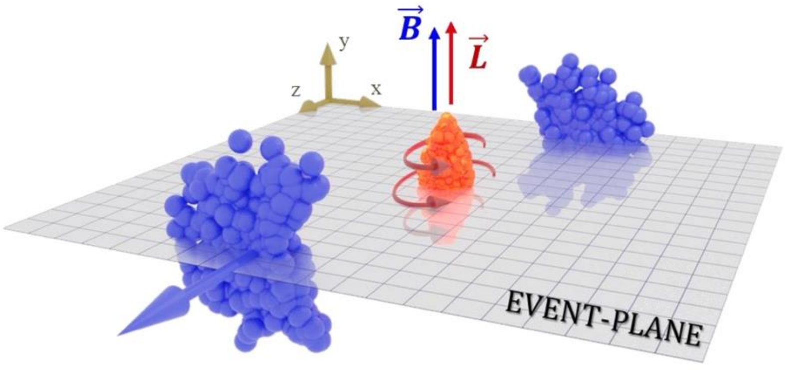


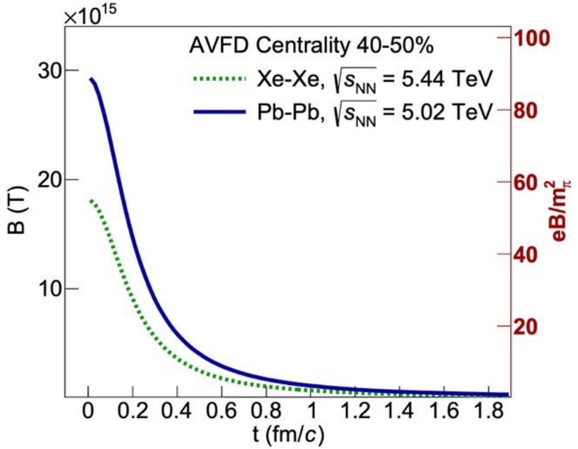


- A **larger suppression** of the ψ(2S) w.r.t the J/ψ is observed
- The ψ(2S) R_{AA} increases at low p_T , which is a hint of ψ(2S) regeneration
- The TAMU model describes data better than SHMc in central collisions

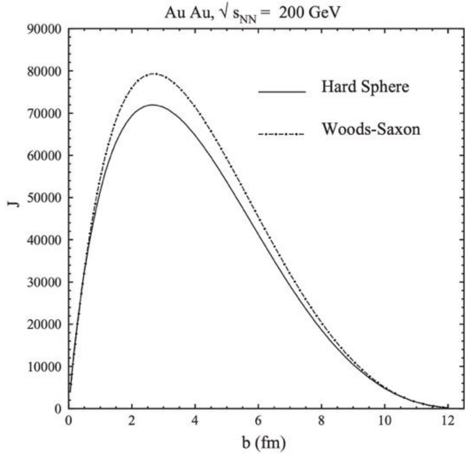
(TAMU) X. Du, et al.,NPA943,147-158(2015)
(SHMc) A. Andronic, et al.,PLB797,134836(2019)

Charmonium polarization





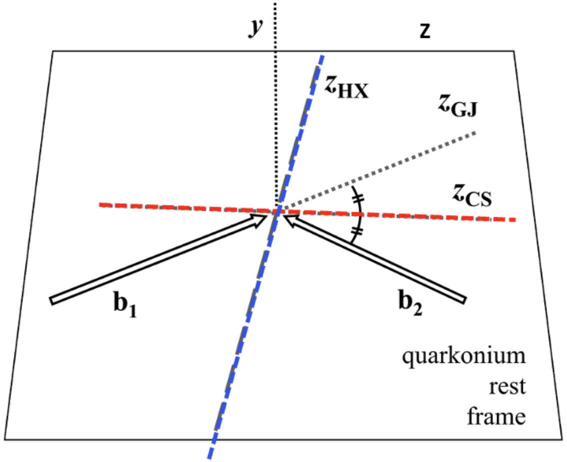
Christakoglu et al., EPJC (2021) **81**: 717

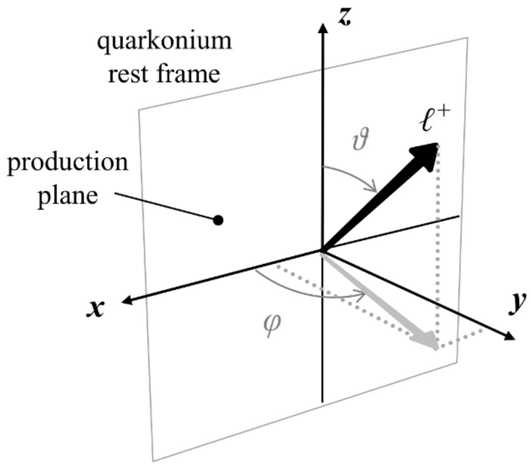


F. Becattini et al., PRC 77 (2008)

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.

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

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

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

$\lambda_\theta =$ polarization parameter

$\lambda_\theta = 0$ no spin alignment

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

- **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.

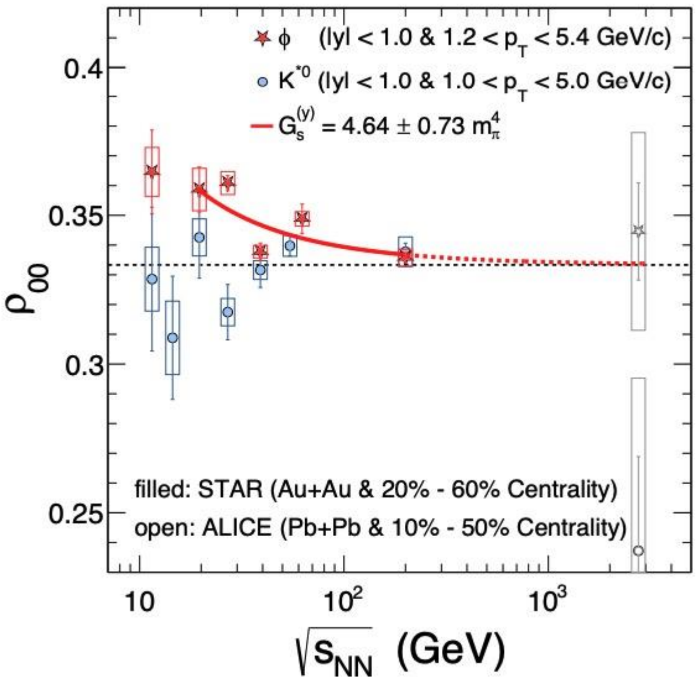
Z. Liang, X. Wang, PLB 629 (2005) 20-26

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

Vector meson spin alignment

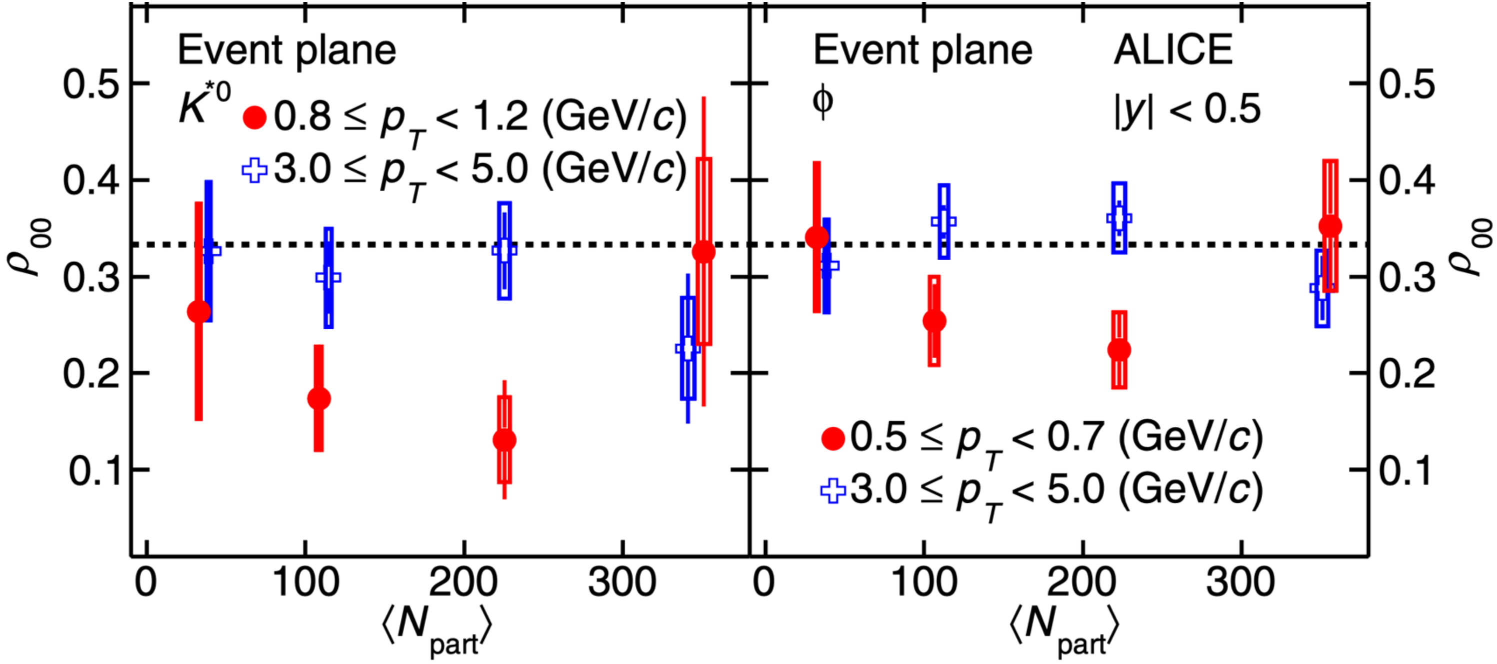


STAR, Nature 614 244 (2023)

- Vector meson spin alignment measures field square, which corresponds to the local correlation and fluctuation of the strong force field
- The vector field is induced during the hadronization process
- This mechanism will open a new window for the strong force field study once it is confirmed!

X.-L. Sheng, L. Oliva, Z.-T Liang et al, PRL131 (2023)4,042304
X.-L. Sheng, L. Oliva, Z.-T Liang et al, PRD109 (2024)3, 036004

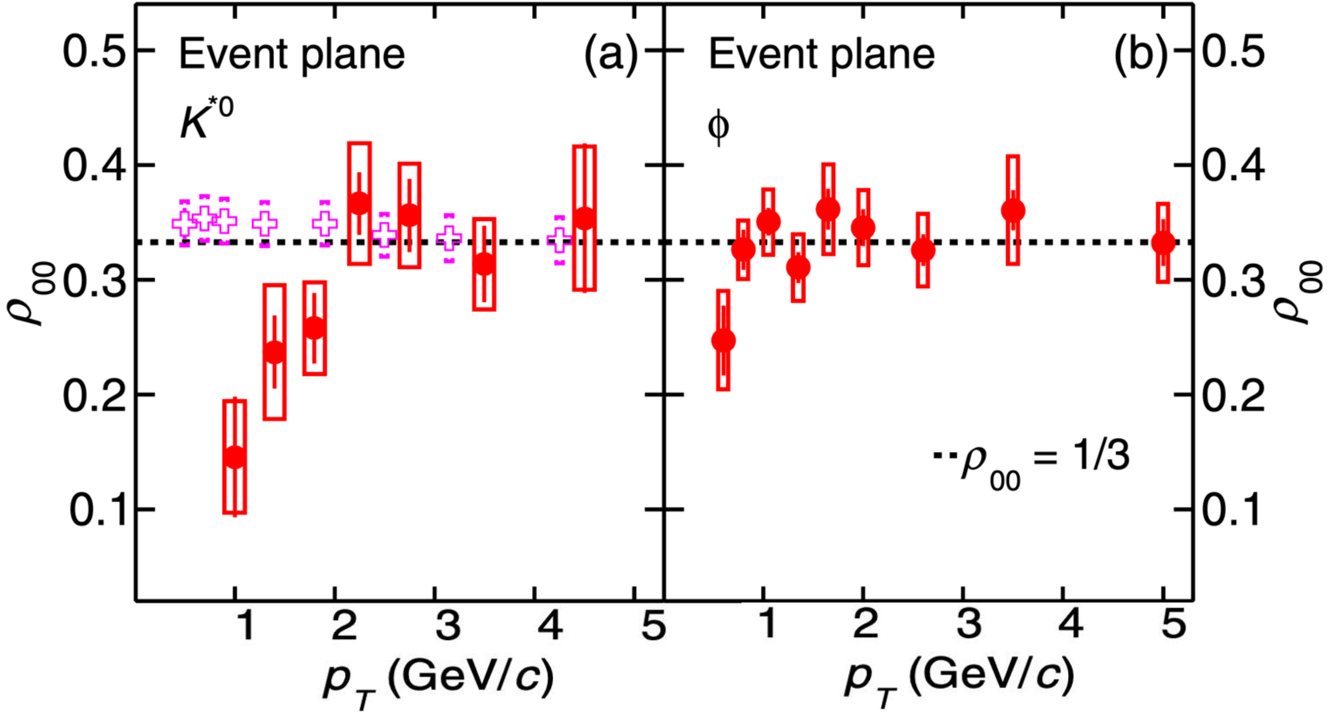
K^{*0} and ϕ spin alignment vs. centrality



- 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

ALICE, PRL 125(2020) 012301

K^{*0} and ϕ spin alignment Vs p_T

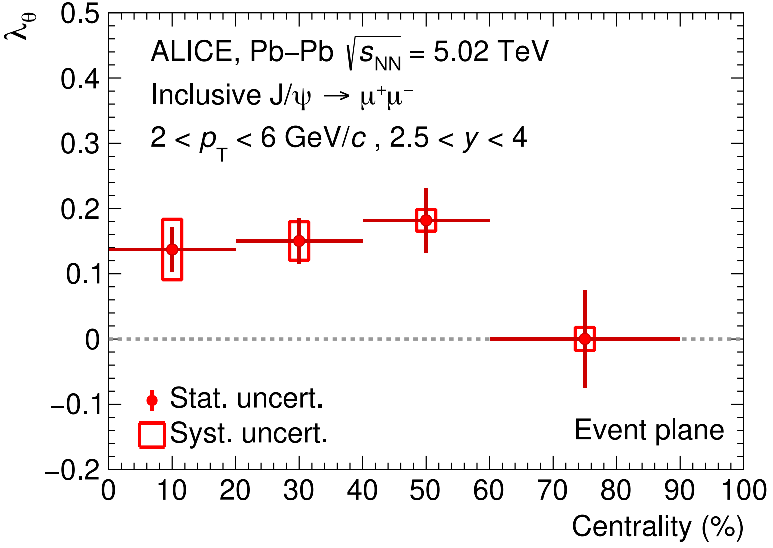


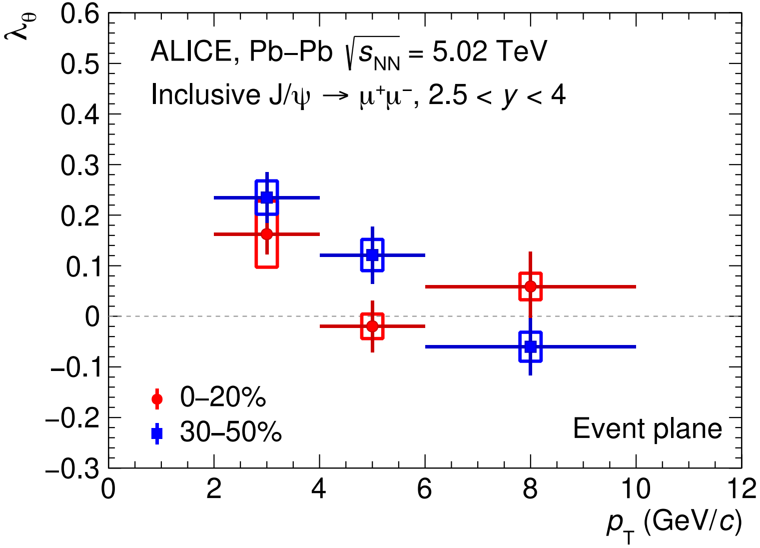
- $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T, ρ_{00} consistent with 1/3 at high p_T
- ρ_{00} for K_s^0 (spin=0) consistent with 1/3

ALICE, PRL 125(2020) 012301

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

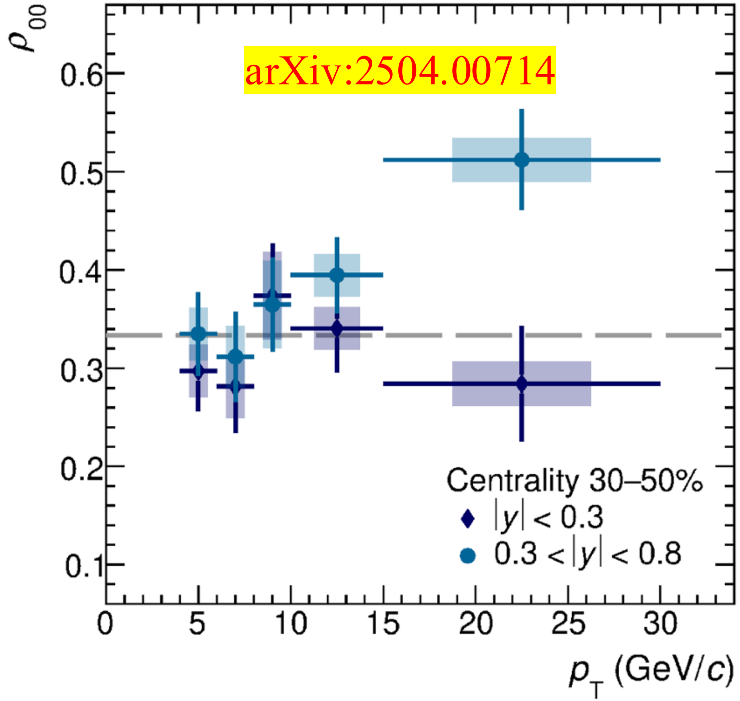
ALICE, PRL 131 (2024) 4, 042303



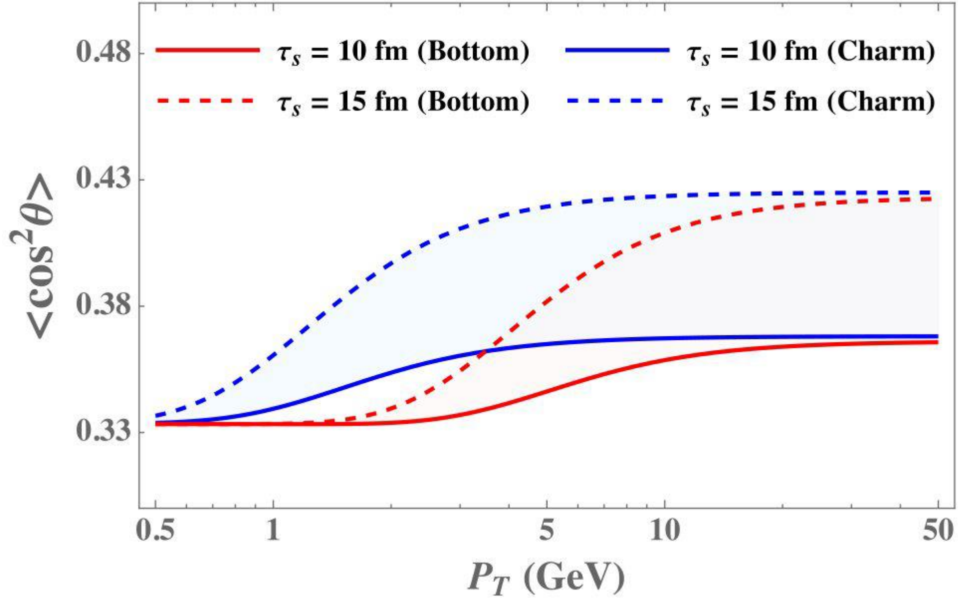


- First measurement of quarkonium polarization **w.r.t the event plane**
- **Significant polarization (~3.5σ)** observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The significance of the polarization reaches **~3.9σ** at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results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

D*$^+$ polarization

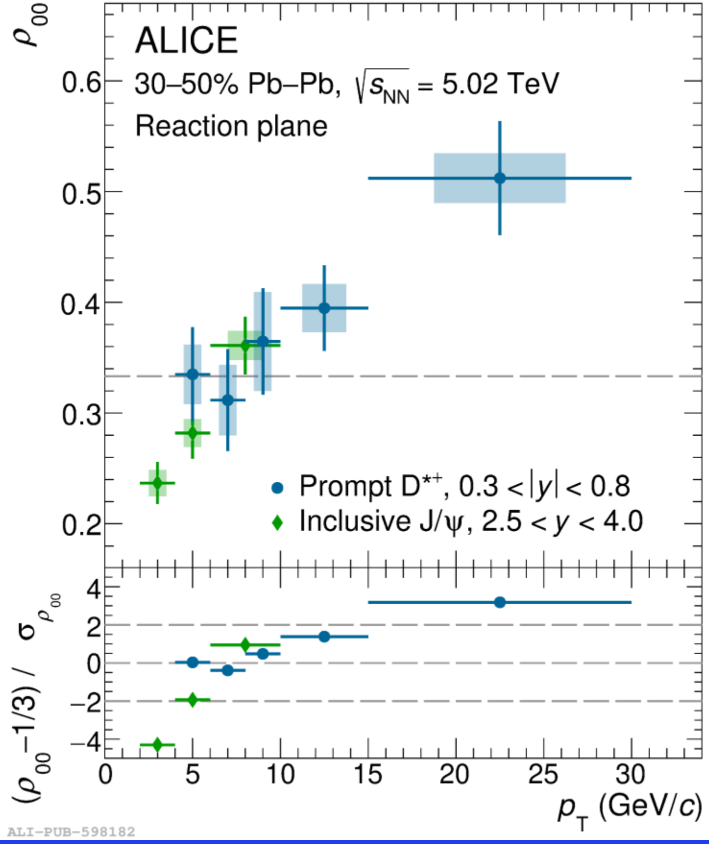


S. Dey, A. Jaiswal, arXiv:2502.20352v2



- Evidence (3.1σ) of spin alignment ρ00 > 1/3 at $p_T > 15$ GeV/c
- The D*$^+$ spin alignment is suppressed by the charm quark thermalization at low pT

J/ψ and D*+ polarization

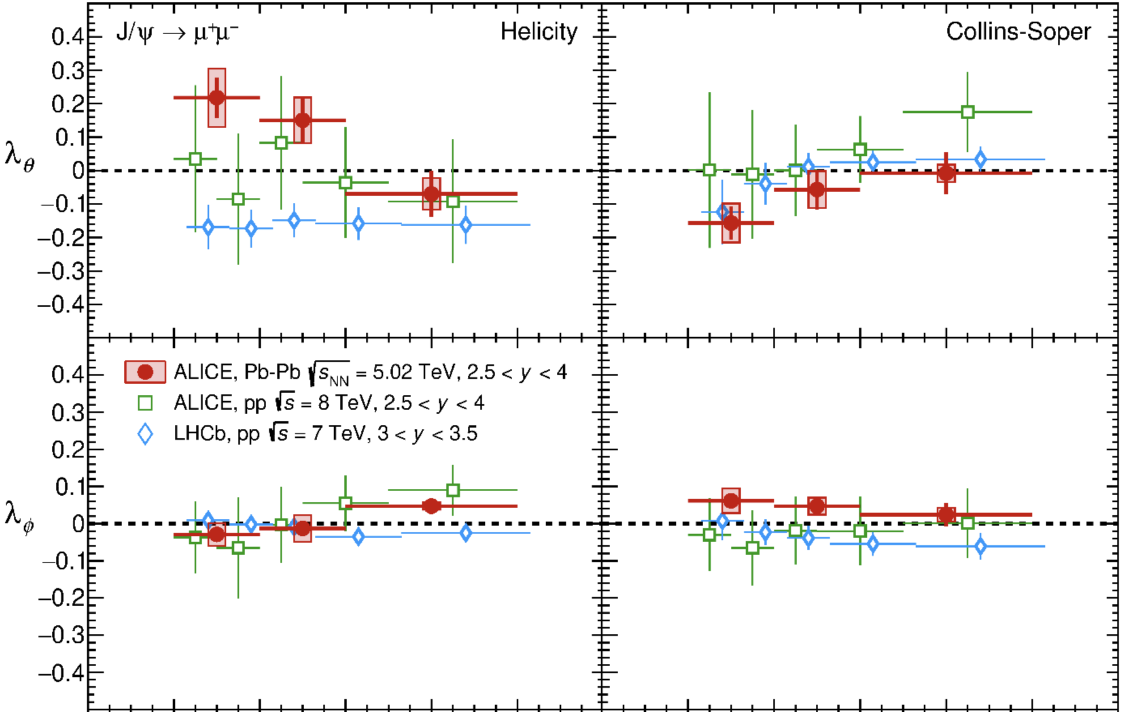


arXiv:2504.00714

- ➢Evidence (3.1σ) of spin alignment ρ00 > 1/3 at p_T > 15 GeV/*c* and 0.3 < |y| < 0.8

- ➢Inclusive J/ψ seems to feature a common increasing trend at the overlapping p_T (theoretical guidance is needed)

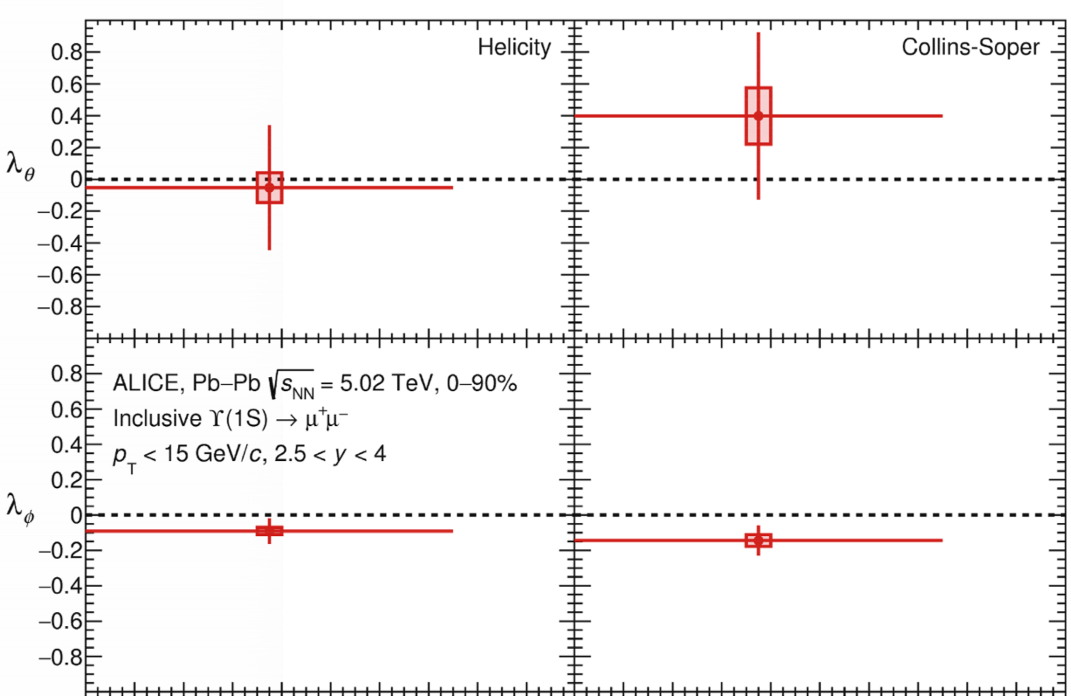
Charmonium polarization results in heavy-ion collisions



- λ_θ, λ_ϕ close to zero in Helicity and Collins-Soper reference frames
- Maximum deviation from zero is 2.1σ in the low p_T bin

ALICE, Phys.Lett.B 815 (2021) 136146
LHCb, JHEP 12 (2017) 110

Bottomonia polarization results in heavy-ion collisions

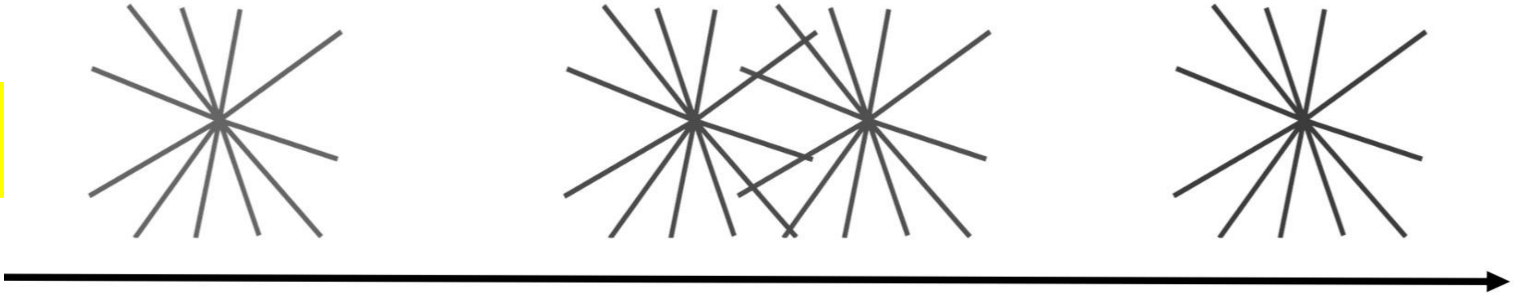


- The Υ(1s) polarization was measuremend in Helicity and Collins-Soper reference frames
- λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ all compatible with zero but the measurement is still strongly limited by the statistics

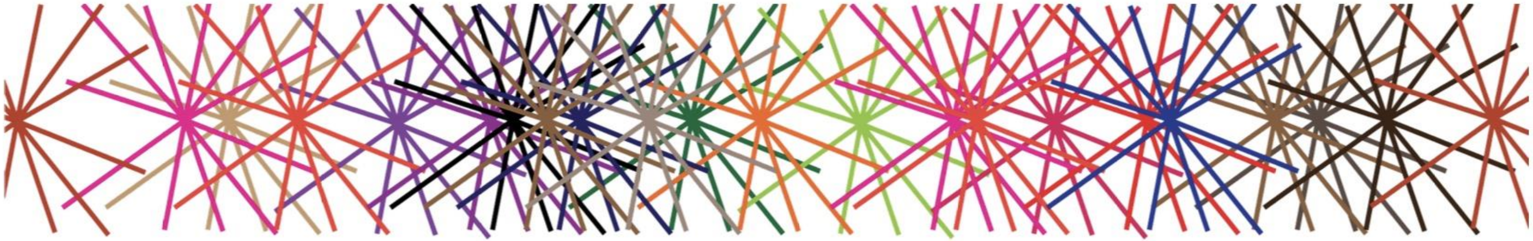
ALICE, Phys.Lett.B 815 (2021) 136146

ALICE in Run 3 (Ongoing)

Run 1 and Run 2 (2009-2018)

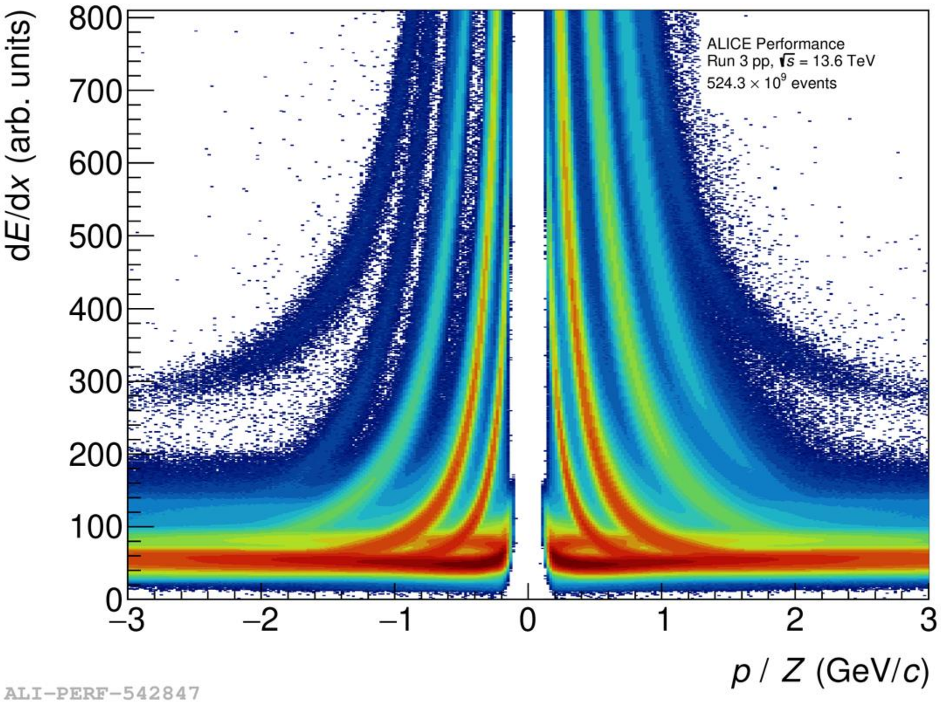


Run 3 and Run 4 (2022-2032)



LHC LS2	LHC RUN 3	LHC LS3	LHC RUN 4	LHC LS4	LHC RUN 5 and RUN 6
2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

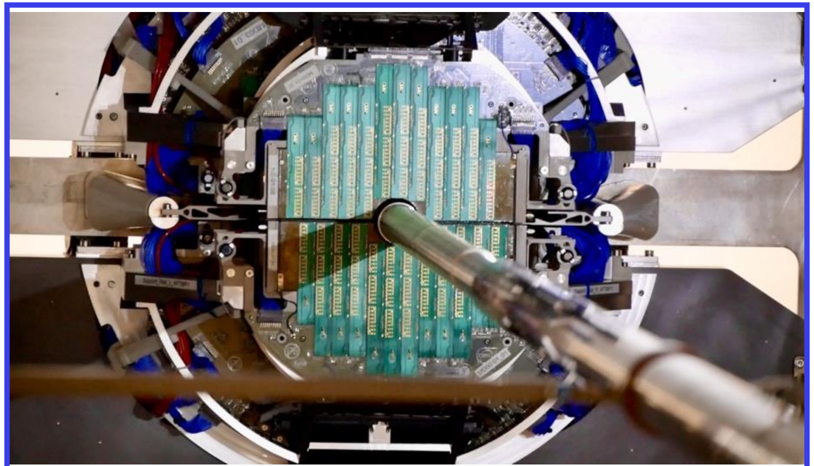
Upgraded Time Projection Chamber



TPC continuous readout (GEM)

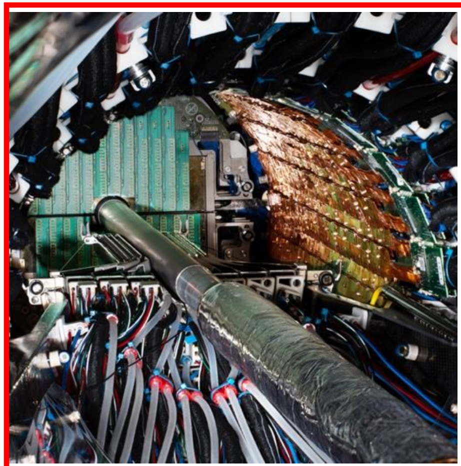
- pp data taking at 500 kHz
- Pb-Pb data taking at 50 kHz

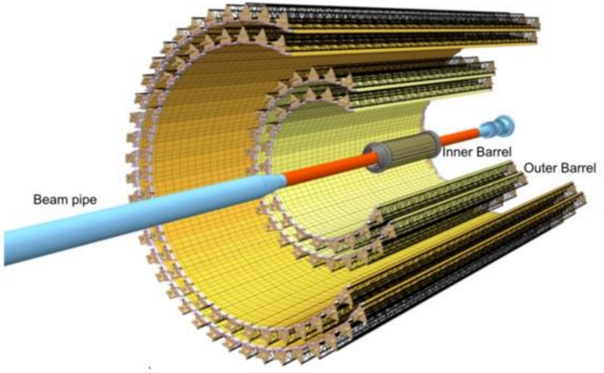
ALICE in Run 3 (MFT and ITS2)



New Muon Forward Tracker

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



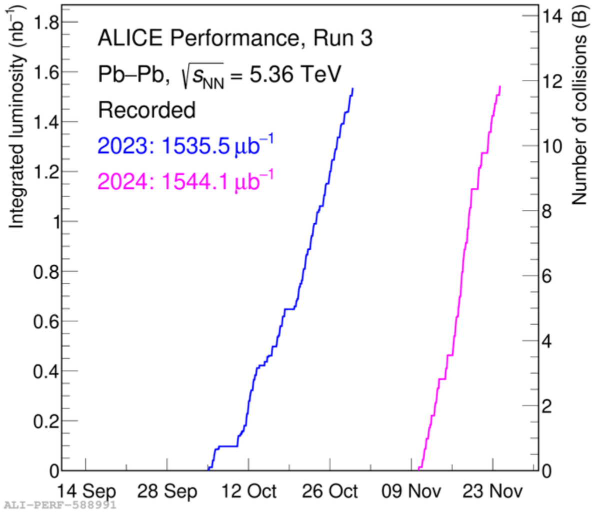


Upgraded Inner Tracking System

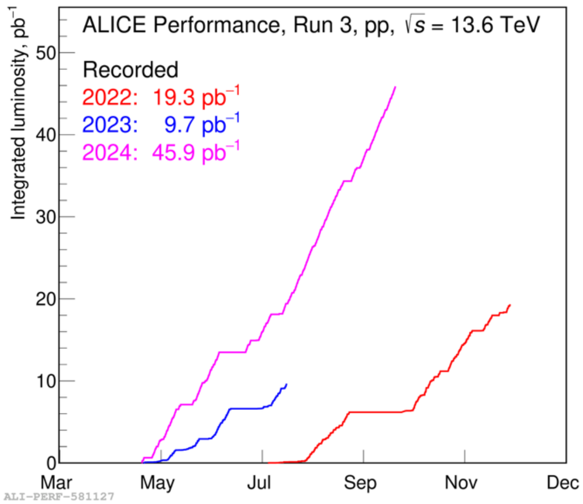
- 3 layers in inner barrel (IB), 4 in outer barrel (OB)
- Get closer to IP: from 39 mm to 23 mm
- Reduced material budget: from 1.14% X_0 to 0.36% X_0 per layer
- Reduced pixel size: from 50 x 425 μm^2 to 29 x 27 μm^2

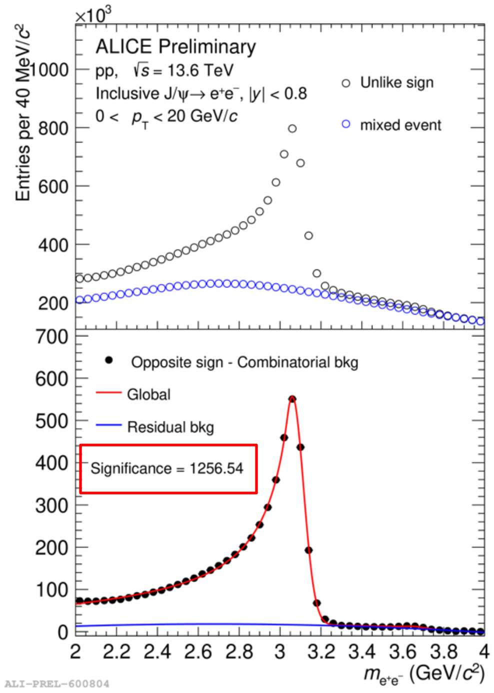
ALICE in Run 3 data taken

Pb-Pb @5.36 TeV



pp @13.6 TeV

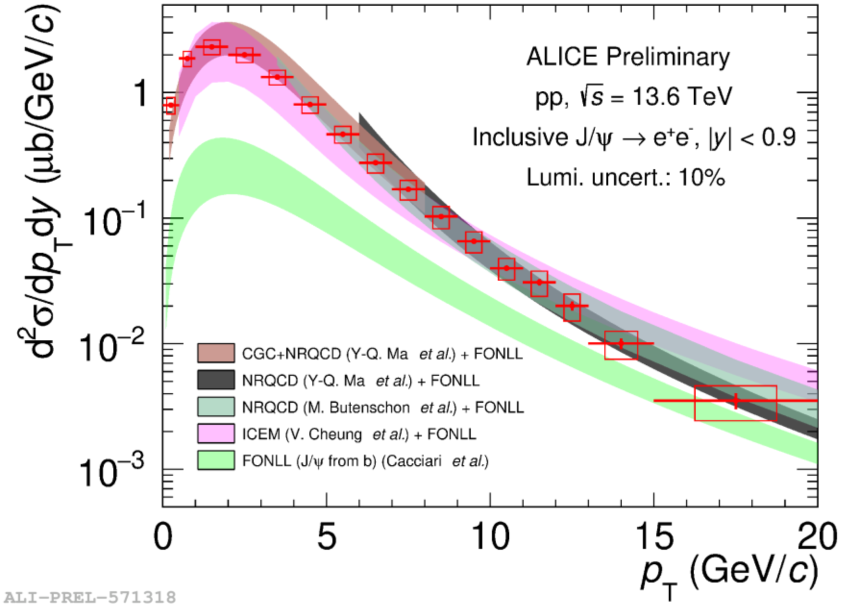


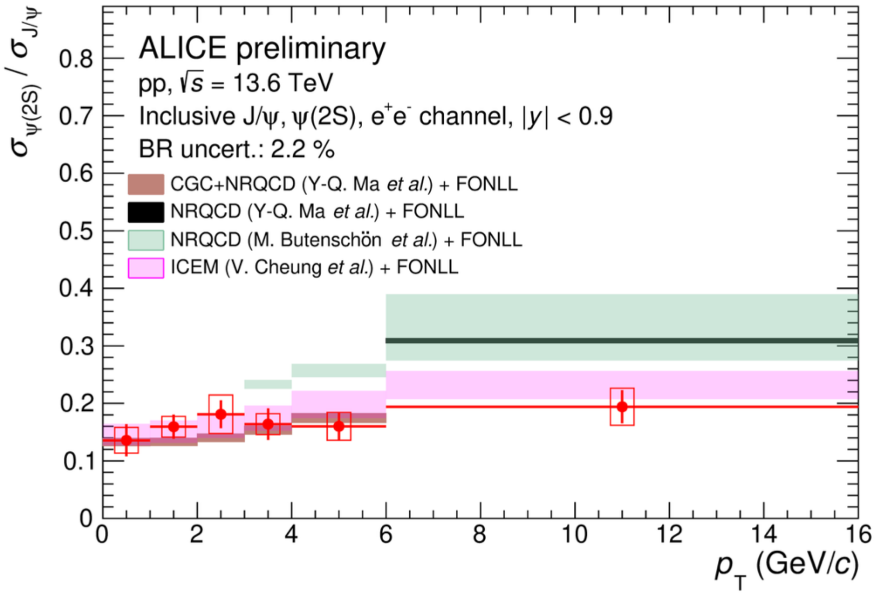


- ➢Record all the minimum bias （MB) events during the data taken
- ➢Collected approx. **24B and 2000B MB** events **in Pb-Pb and pp** collisions, respectively
- ➢The reconstructed J/ψ significance is **greater than 1200**

Charmonia in pp collisions at √s = 13.6 TeV

New Preliminary

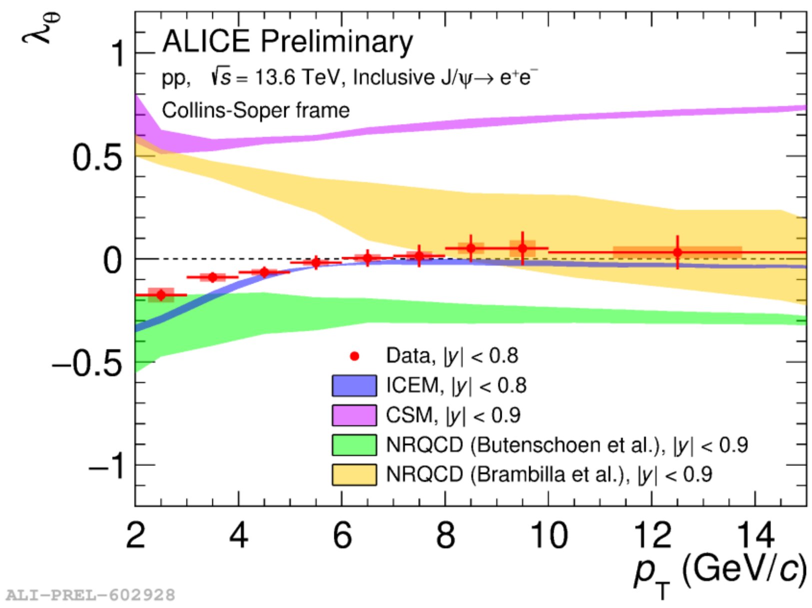


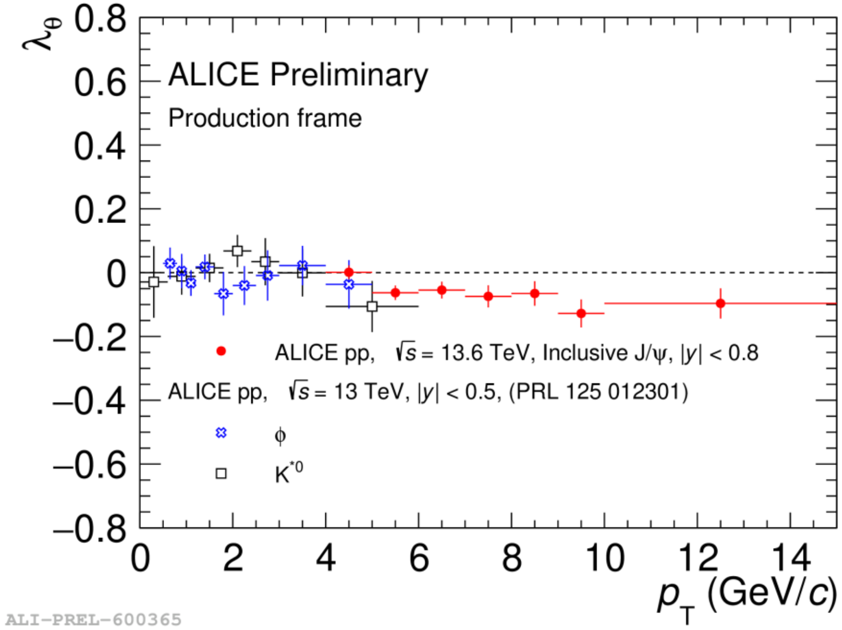


- With the significantly increased statistics allow to reconstruct ψ(2S) via dielectron decays
- The CGC + NRQCD and ICEM can describe the data at low p_T

Charmonia polarization in pp collisions

New Preliminary

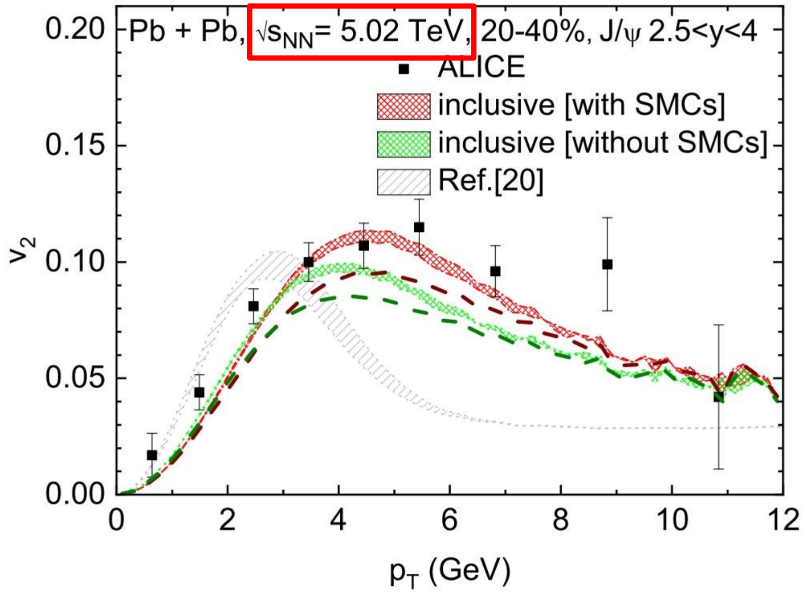


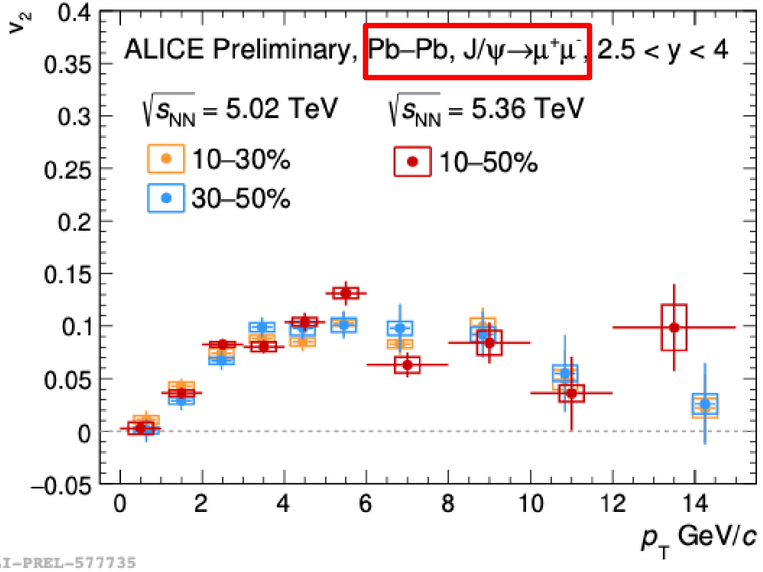


- ➢ The Run 3 statistics allow for the measurement of J/ψ polarization at midrapidity
- ➢ The measurement of J/ψ polarization in Pb–Pb collisions is ongoing

Charmonium elliptic flow in Pb–Pb collisions

New Preliminary





M. He, et al., PRL.128, 162301 (2022)

- The new result is consistent with Run 2, with statistical precision improved at low p_T at forward rapidity
- A significant J/ψ v_2 is observed at forward rapidity, consistent with the charm quark thermalization

Summary

- Dominant contribution from (re-)generation in central collisions and low p_T for prompt J/ψ

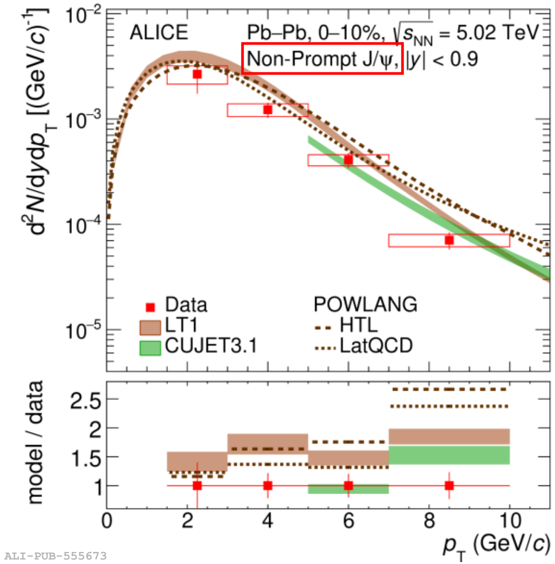
  Evidence of the deconfinement at LHC

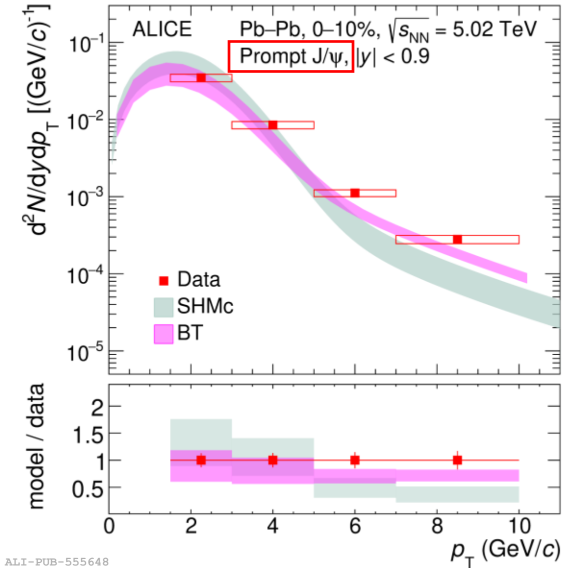
- A larger suppression of the ψ(2S) with respect to the J/ψ is observed
- Significant non-zero J/ψ polarization and v_2 are observed w.r.t the event plane
- Stay tuned with Run 3

Thanks

Non-prompt and prompt J/ψ p_T spectrum

ALICE, JHEP 02 (2024) 066





LT1: PRC107, 054917(2023)

POWLANG:
JHEP 05 (2021) 279,
EPJC 75 (2015) 121

CUJET3.1: CPC 43 (2019) 044101

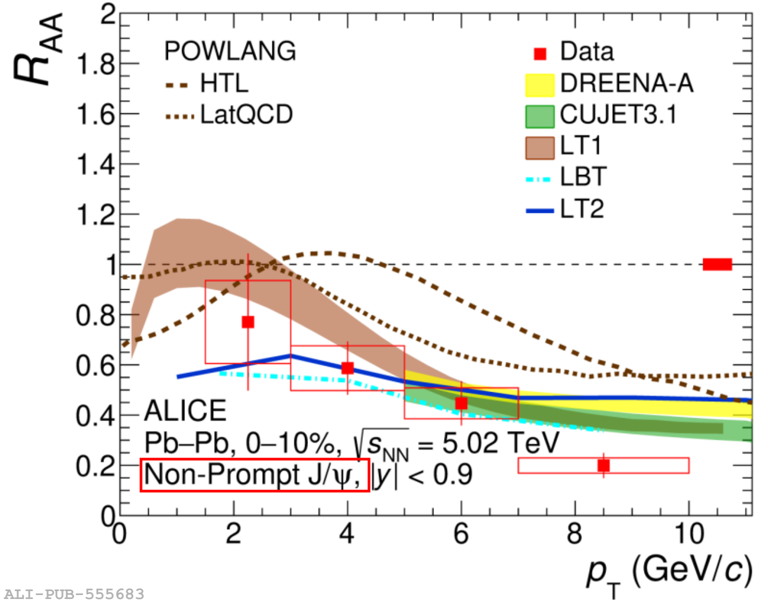
SHMc: PLB 797 (2019) 134836

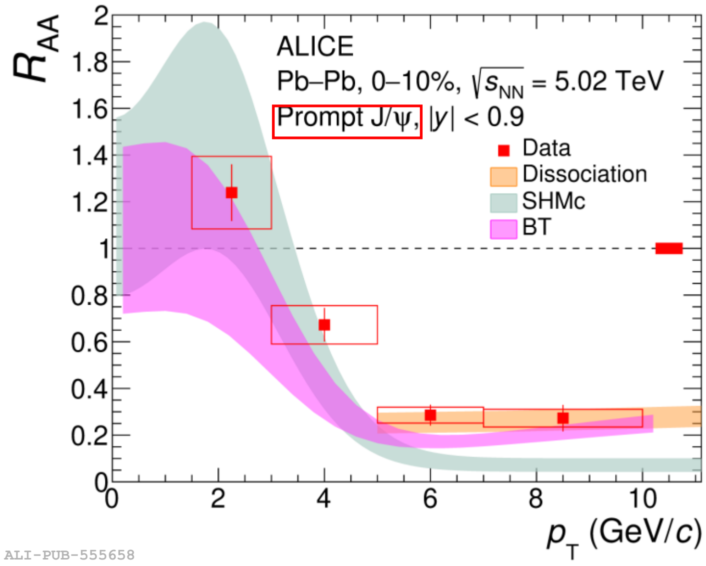
BT: CPC43 (2019) 124101

- Non-prompt (left) and prompt (right) J/ψ p_T spectrum are compared with several different models.
- All the models seem to over estimate measured data of non-prompt J/ψ, the SHMc and BT agree with data within uncertainties for the prompt J/ψ at low p_T

Non-prompt and prompt J/ψ R_{AA}

ALICE, JHEP 02 (2024) 066





DREENA-A: Front. Phys. 10:957019 (2022), Phys. Rev. C 105, L021901

CUJET3.1: CPC 43 (2019) 044101

LT1: PRC107, 054917(2023)

LBT: PLB838(2023) 137733

LBT2: EPJC 81 848 (2021) 1035

Dissociation: PLB 778 (2018) 384-391

SHMc: PLB 797 (2019) 134836

BT: CPC43 (2019) 124101

- The SHMc model and transport microscopic calculations that include a contribution from **regeneration** are compatible with the measured **prompt J/ψ R_{AA} at low p_T**
- **Non-prompt J/ψ R_{AA}** is described within uncertainties by models implementing **collisional and radiative energy loss** contributions
- POWLANG calculations, which include only collisional contributions, overestimate the R_{AA} at intermediate and high p_T