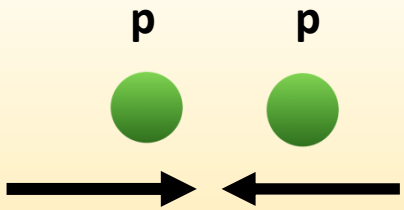
The 1st Workshop on Jet and Heavy Quark Physics
首届喷注与重夸克物理研讨会

Experimental overview of heavy quarks in heavy-ion collisions

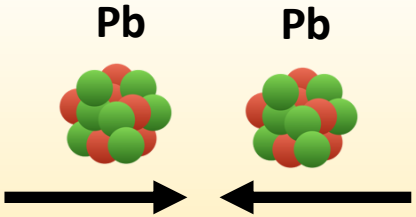
Xiaozhi Bai (CCNU/USTC)

Wuhan, Jan. 25 2026

Motivation of heavy-flavor measurements

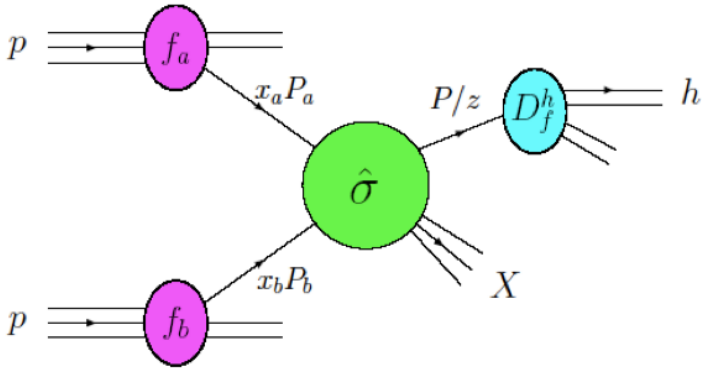


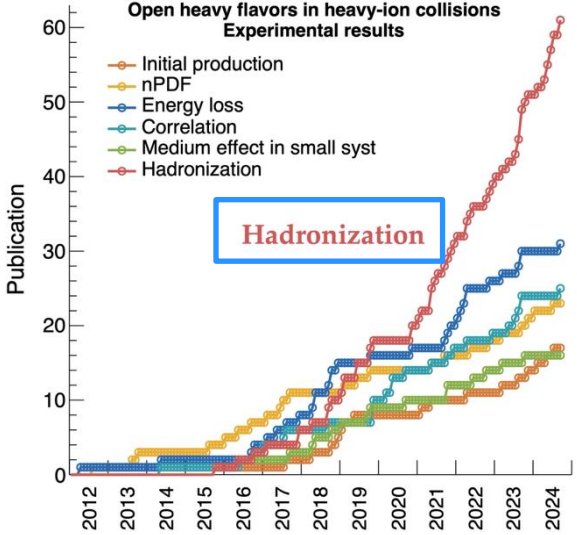
- Test the perturbative and non-perturbative QCD theory
- Hadronization in “vacuum”
- Baseline for pA and AA Collisions



- Probe the Quark-Gluon Plasma (QGP)
- Study parton medium interaction (transport, energy loss, thermalization)
- Hadronization mechanisms

Open heavy-flavor production in pp collisions





$$\frac{\mathrm{d}\sigma^{\mathrm{D}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{D}}}(p_{\mathrm{T}};\mu_{\mathrm{F}};\mu_{\mathrm{R}}) = PDF\,(x_{\mathrm{a}},\mu_{\mathrm{F}})PDF\,(x_{\mathrm{b}},\mu_{\mathrm{F}}) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_{\mathrm{a}},x_{\mathrm{b}},\mu_{\mathrm{R}},\mu_{\mathrm{F}}) \otimes D_{\mathrm{c}\to\mathrm{D}}\,(z=p_{\mathrm{D}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$

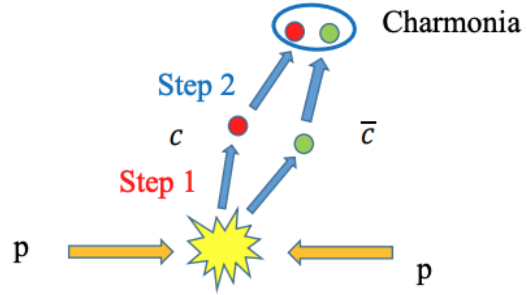
Heavy-flavor production is not fully understood, particularly baryon hadronization

Quarkonium production in pp collisions

- Quarkonia: bound states of heavy quark and heavy anti-quark pairs.

  Charmonia: J/ψ, ψ(2S)…

  Bottomonia: **ϒ**(nS)



- The production mechanism of quarkonia remains as challenge

  (1) Heavy-Quark production (perturbative QCD)

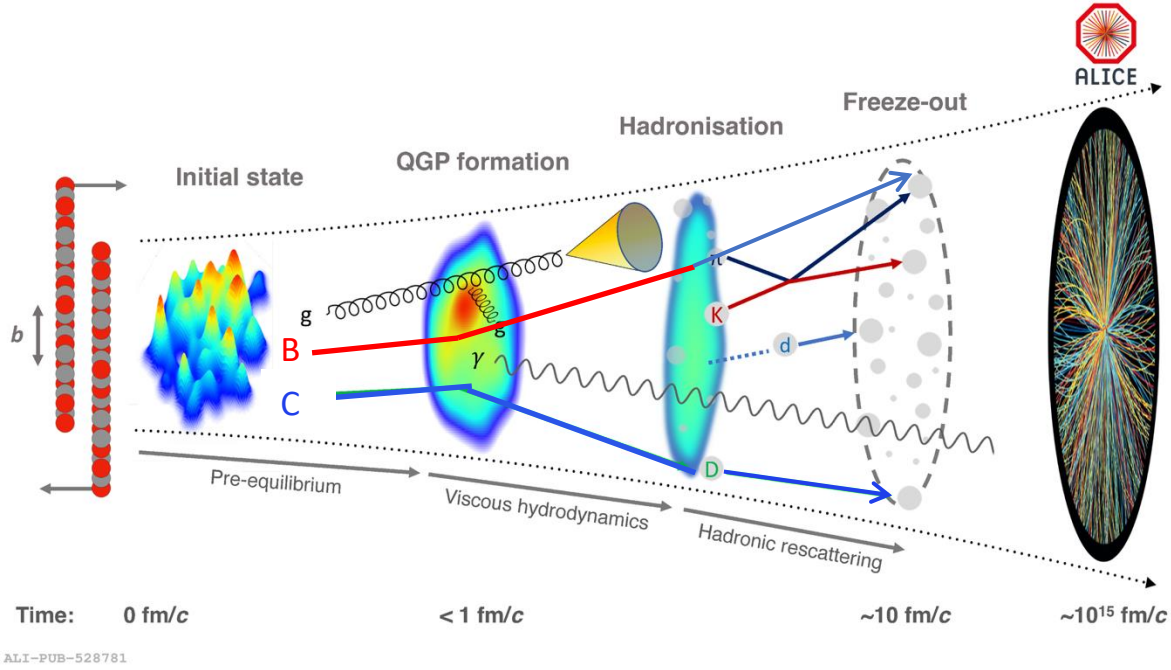
  (2) Formation of the quarkonium states (non-perturbative QCD)

- Non-Relativistic QCD (NRQCD) approach, long-distance effects are described by long distance matrix elements (**LDMEs**) in an effective field theory.

Phys.Rev.D51(1995)1125-1171

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} = \sum d\hat{\sigma}_n(P_H)\langle \mathcal{O}_n^H \rangle$$

Introduction to heavy-ion collisions



Heavy flavor and quarkonium, are excellent **hard probes** to study the **initial state**, **QGP properties** and **hadronisation mechanisms in heavy-ion collisions**

ALICE, Eur. Phys. J. C 84 (2024) 813

Quarkonium suppression is the “smoking gun” of QGP

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86-9-102
高工研図書室

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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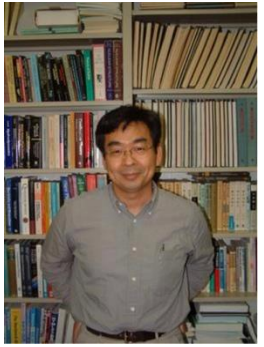
- Heavy quarks produced in the early collision stages
- Quarkonium production is one of the “smoking guns” of QGP formation
- Quarkonium production suppressed sequentially via colour screening in QGP

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

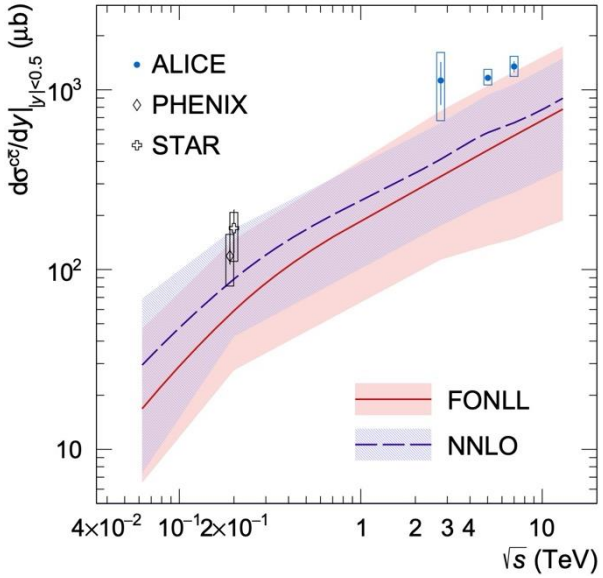
> 5700 citations



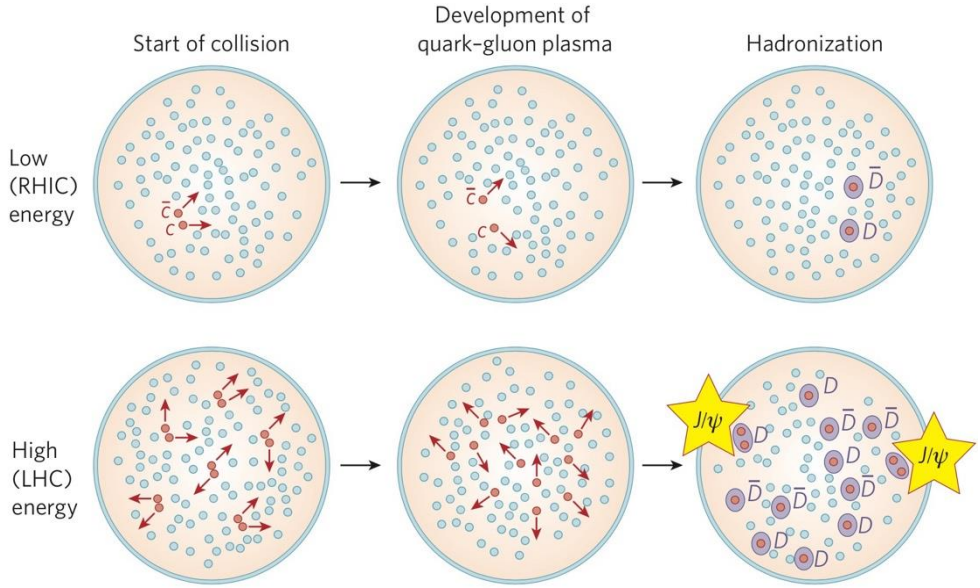
Tetsuo Matsui (1953-2025)

Charmonium production in heavy-ion collisions

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



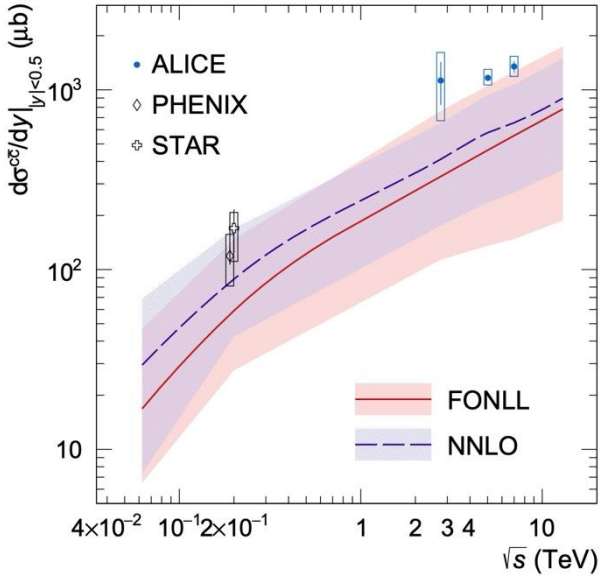
P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302



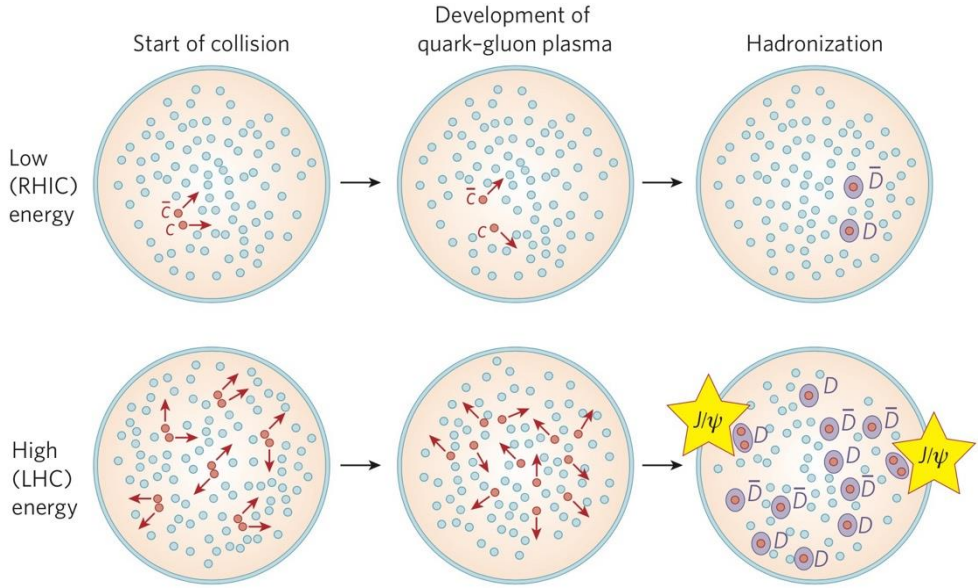
- Charm quark production cross section at the LHC is much larger compared to RHIC energies
- The (re)generation contribution to J/ψ production is dominant at LHC energies

Charmonium production in heavy-ion collisions

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



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



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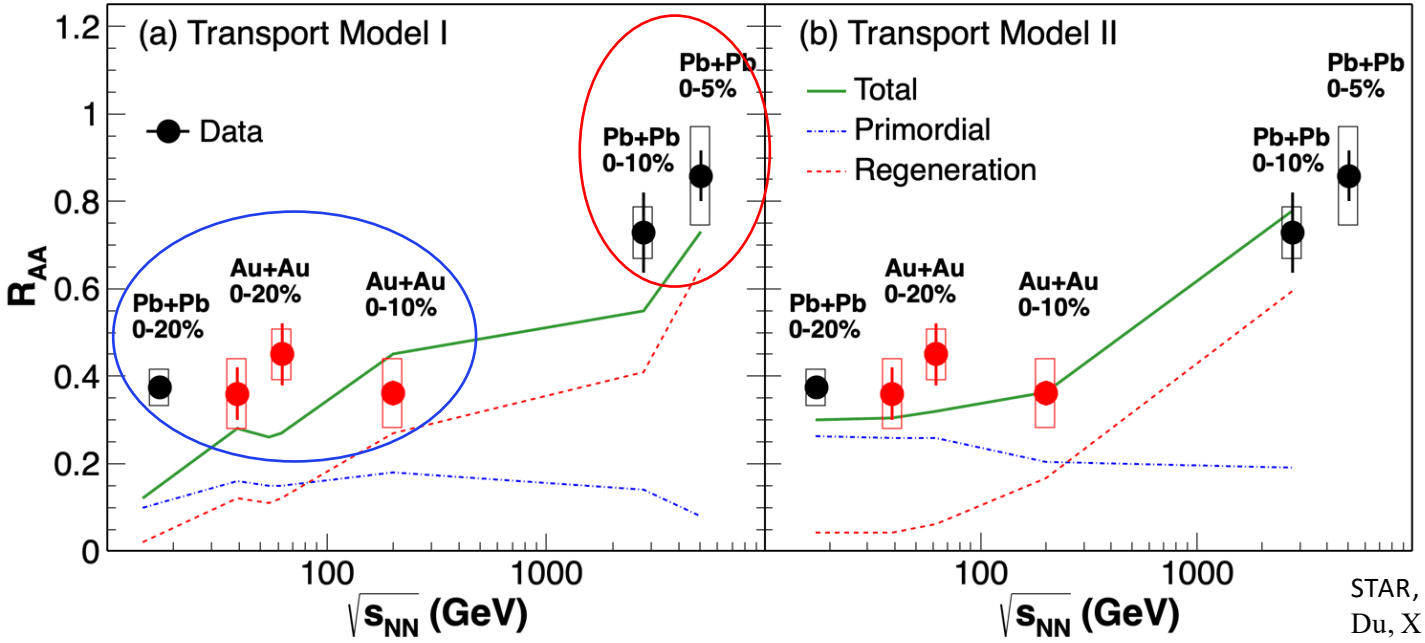
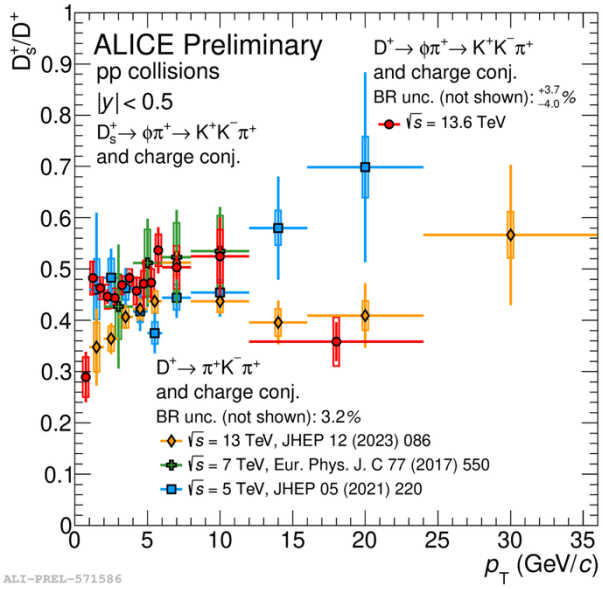
Charmonium production in RHIC and LHC

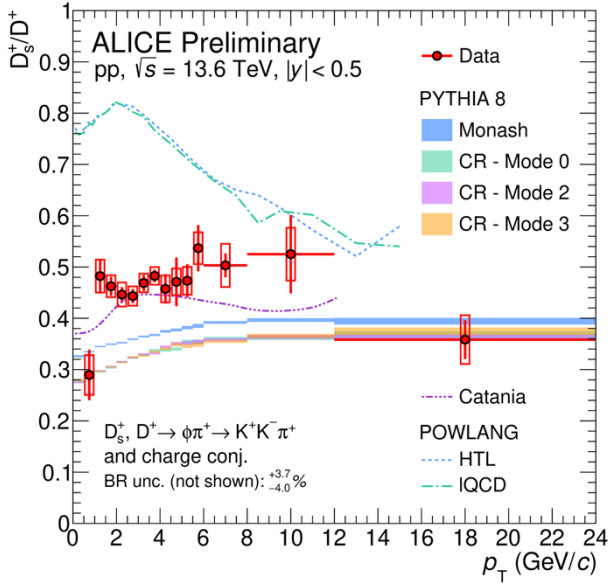


STAR, arXiv:2506.20962
Du, X. et al., NPA 943, 147–158 (2015)
Zhou, K., et al., PRC 89, 054911 (2014)

- 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

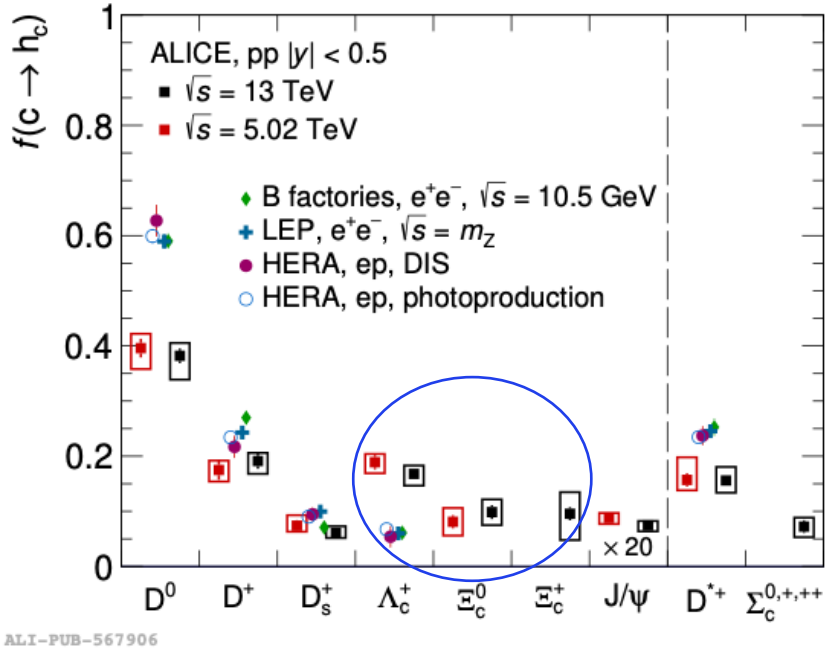
Prompt D_s^+ and D^+ in pp collisions at $\sqrt{s}$ = 13.6 TeV

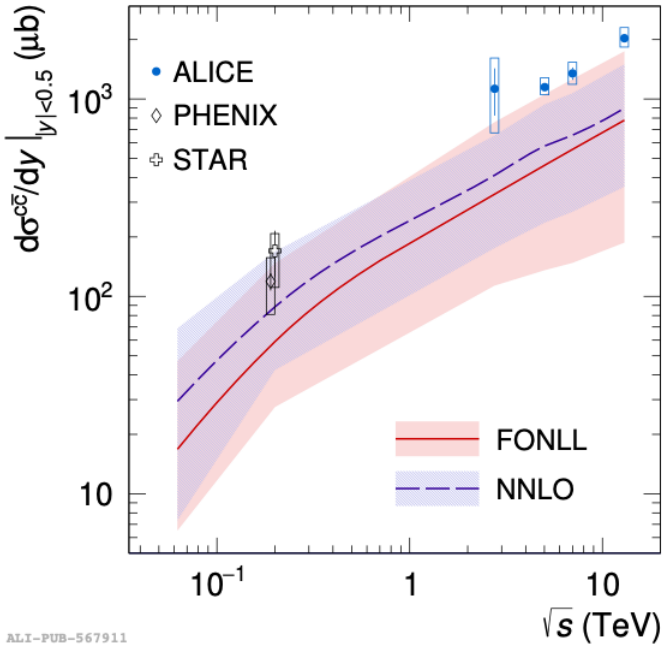




- Provide a better **baseline for Pb-Pb measurements,** tools to investigate the **strangeness enhancement in charm sector**
- Catania (coalescence) gives best description, while POWLANG (local color recombination) and PYTHIA (string fragmentation) can not describe the data

Charm production in pp collisions

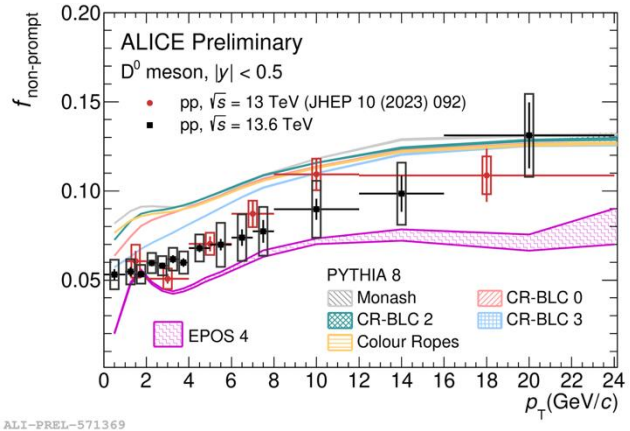




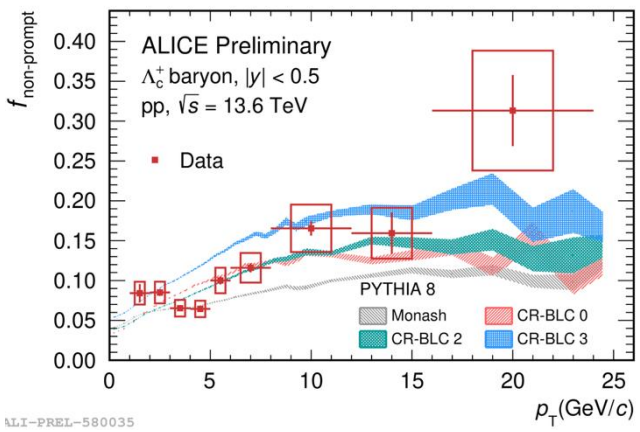
- Total charm production cross section: values on the upper limits of the FONLL prediction at midrapity
- **Charm production fractions in pp are different** w.r.t ee and ep collisions
- **Baryon production is not fully understood**

Open beauty production in pp collisions

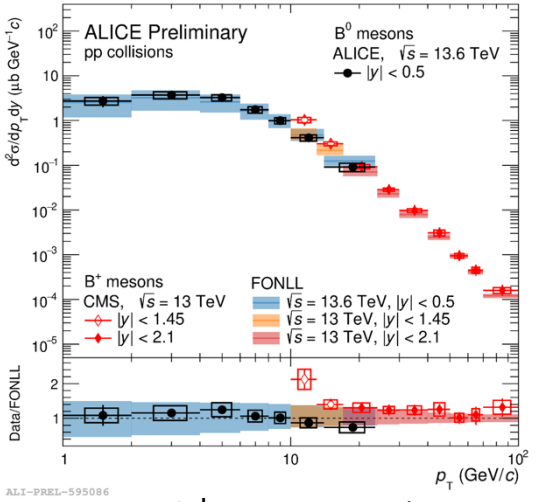
Non-prompt D⁰



Non-prompt Λ_c^+

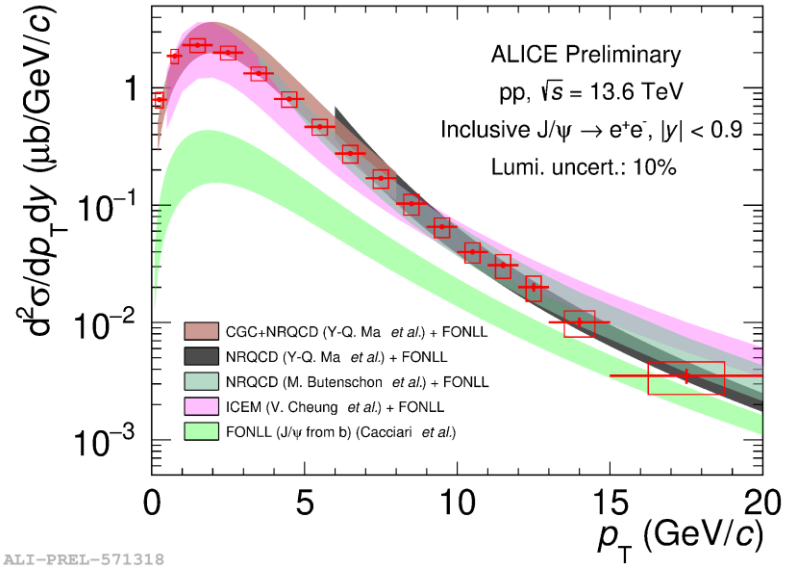


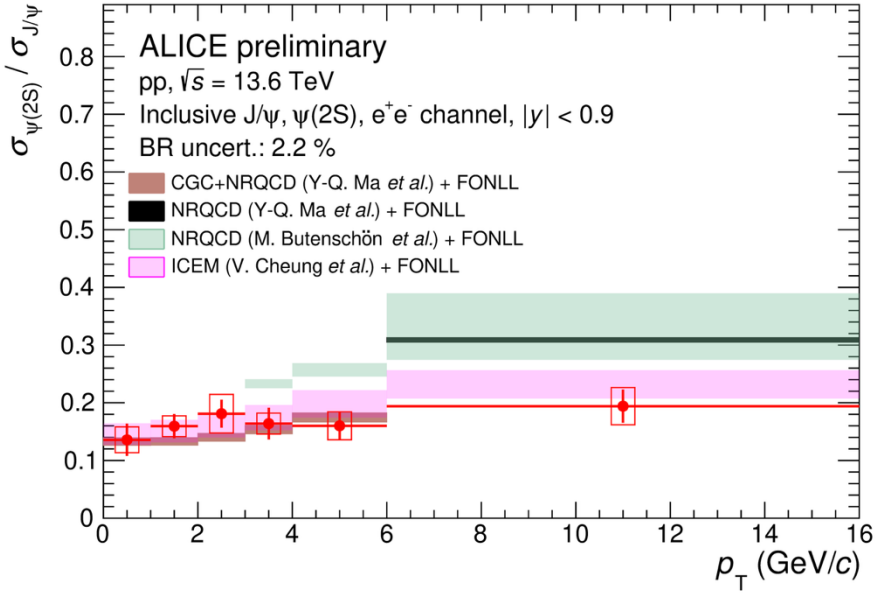
B⁰ meson



- Non-prompt D⁰ fraction measured extended down to $p_T = 0$, non-prompt Λ_c^+ measured p_T down to 1 GeV/c
- **First direct observation of B⁰ meson in ALICE**, measured down to $p_T = 1$ GeV/c
  - Better constraint of the open beauty production

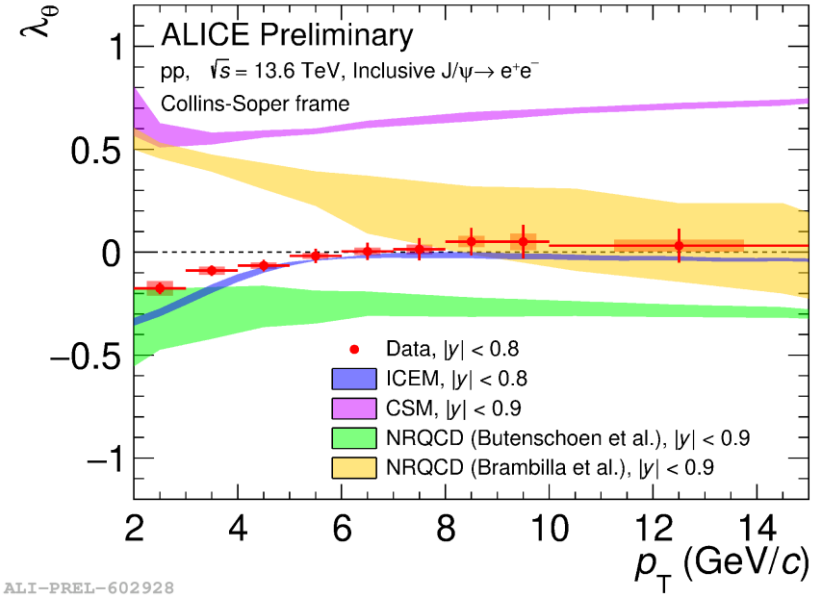
Charmonia in pp collisions at $\sqrt{s}$ = 13.6 TeV

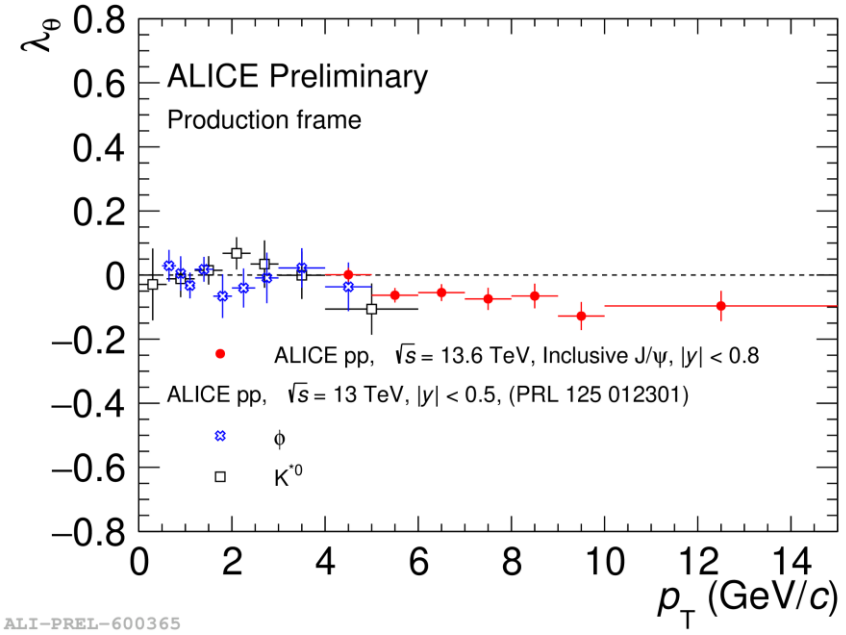




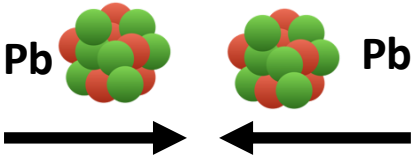
- The new J/ψ cross section is described by ICEM and NRQCD based models, the CGC + NRQCD and ICEM can describe the data at low p_T
- FONLL to account for the non-prompt J/ψ contribution

Charmonia polarization in pp collisions



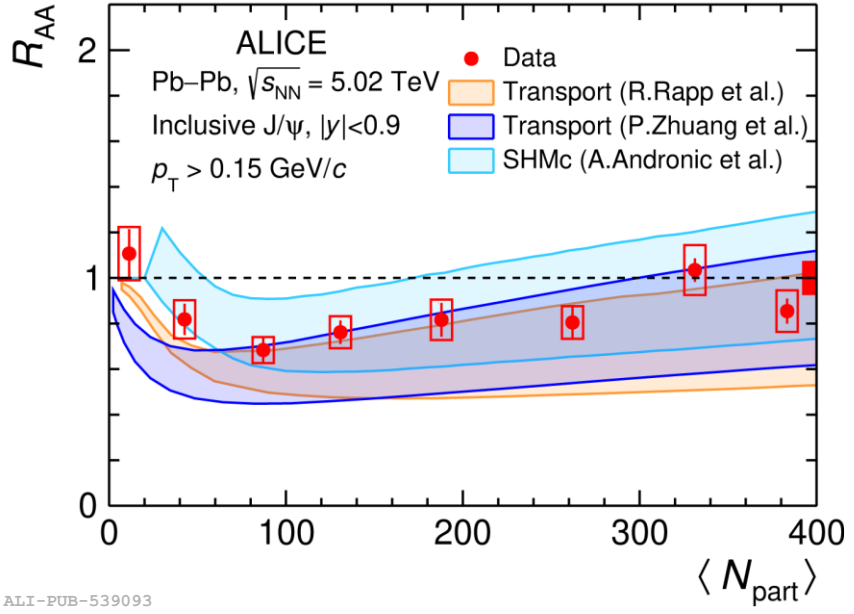


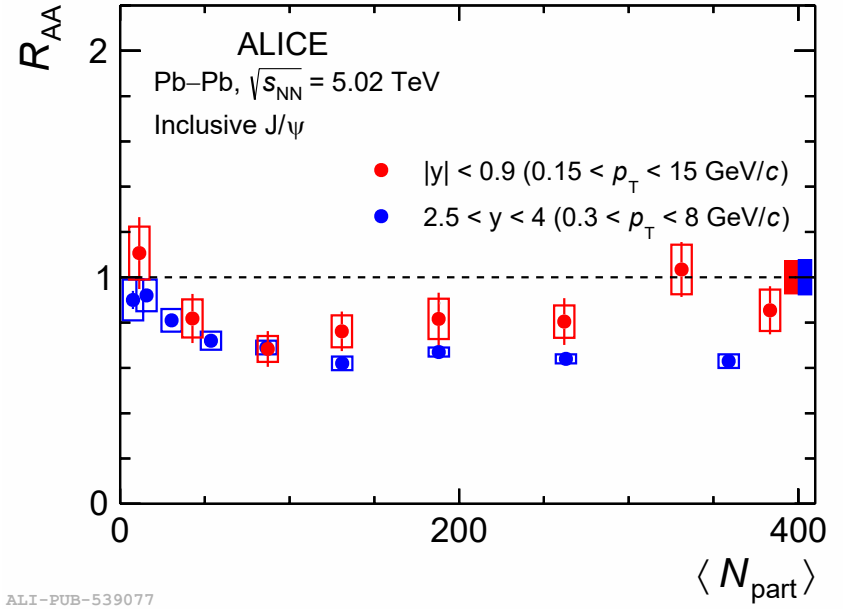
- The measurement of J/ψ polarization in pp collisions at midrapidity. The measurements in Pb–Pb collisions is ongoing
- The data can be described by the ICEM calculations.


Pb
Pb

Inclusive J/ψ R_{AA} vs centrality

ALICE, PLB 849 (2024) 138451



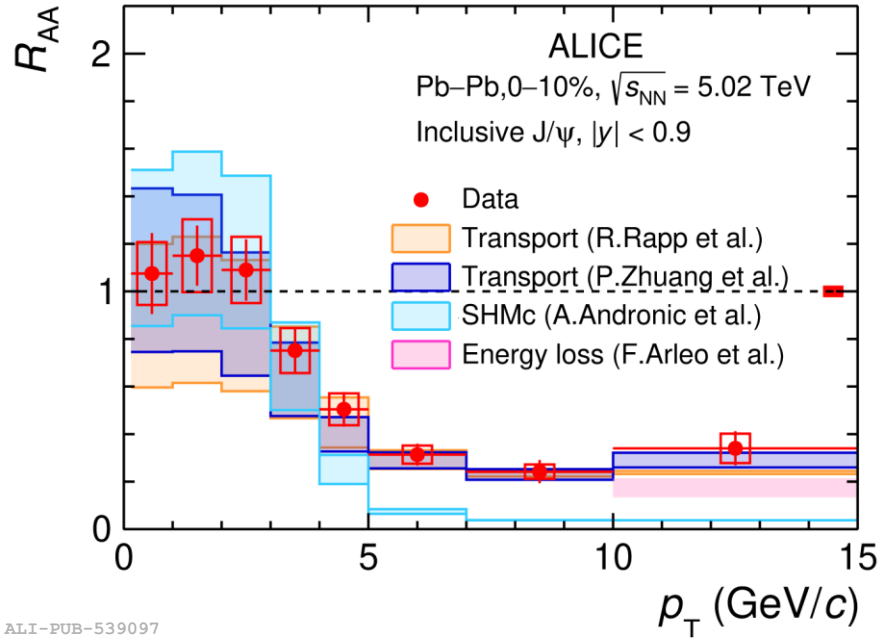


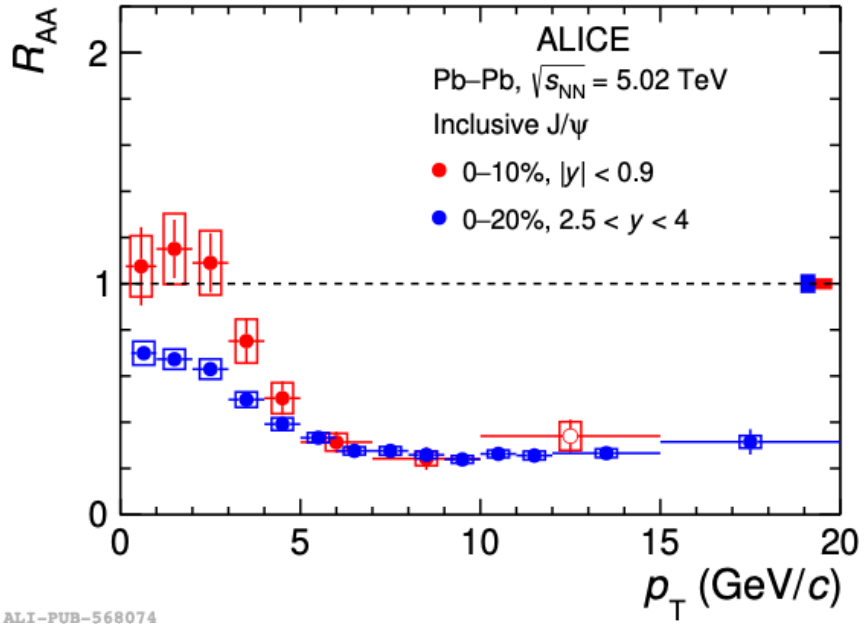
- **Evidence for J/ψ (re-)generation in central collisions, with a larger contribution at midrapidity compared to forward rapidity**
- All models can describe the data but suffer from large uncertainties related to inputs used in calculations (eg. charm cross section, shadowing).

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



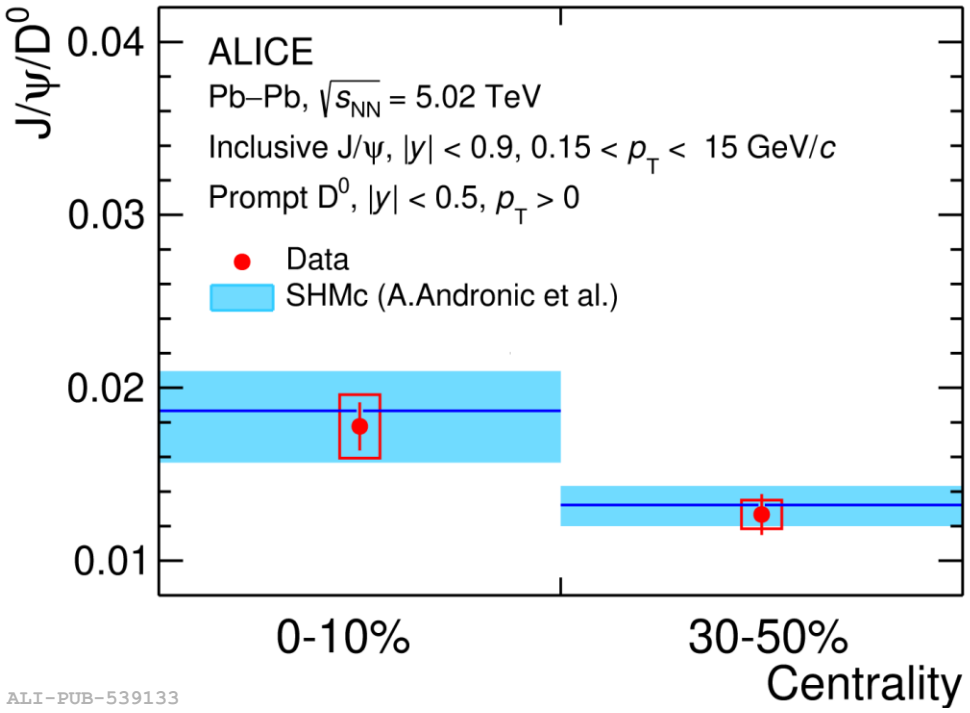


- Transport and SHMc models describe data at low p_T, while SHMc underestimates the measurement at high p_T, the energy loss model agrees with data at high p_T
- **Evidence for the (re)generation and demonstration of deconfinement at LHC**

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)

J/ψ-to-D^0 ratio in Pb–Pb collisions

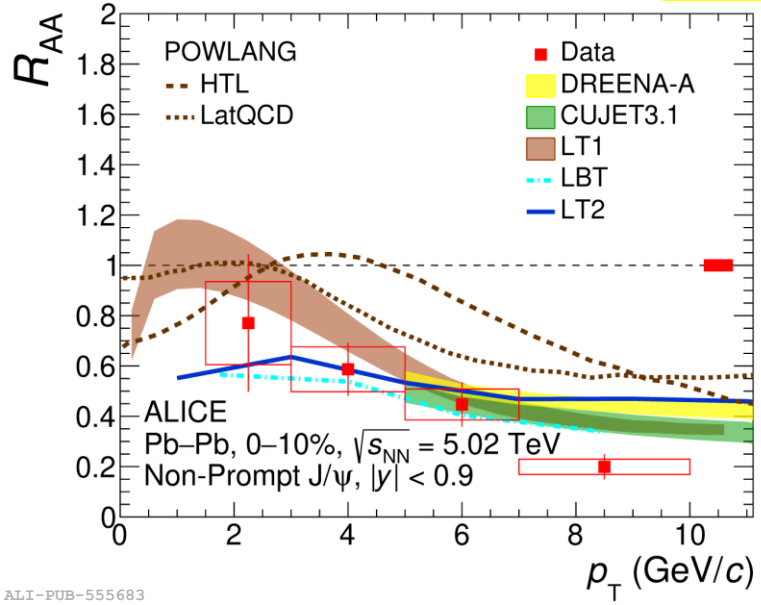
ALICE, PLB 849 (2024) 138451

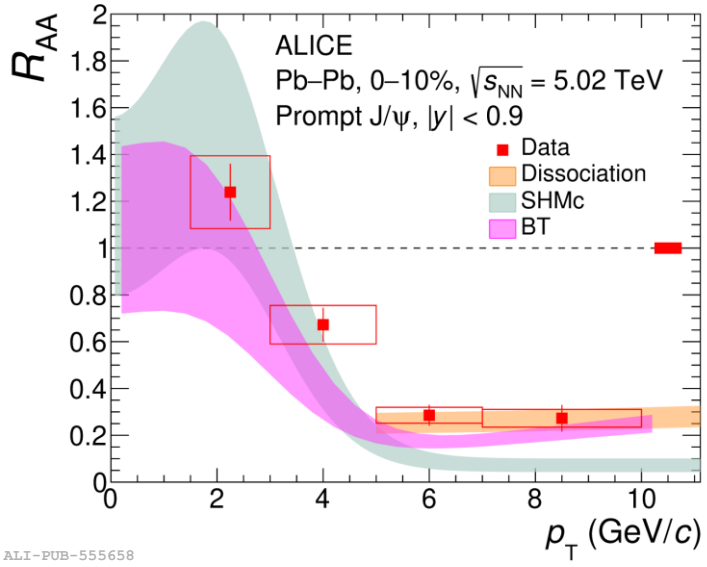


- Sensitive to hadronization mechanisms for open and hidden charm hadrons
- The centrality-dependent trend of the D^0 to J/ψ ratio can be explained by the increase of charm fugacity towards most central collisions
- **Evidence of charm deconfinement at LHC**

Non-prompt and prompt J/ψ R_{AA}

ALICE, JHEP 02 (2024) 066



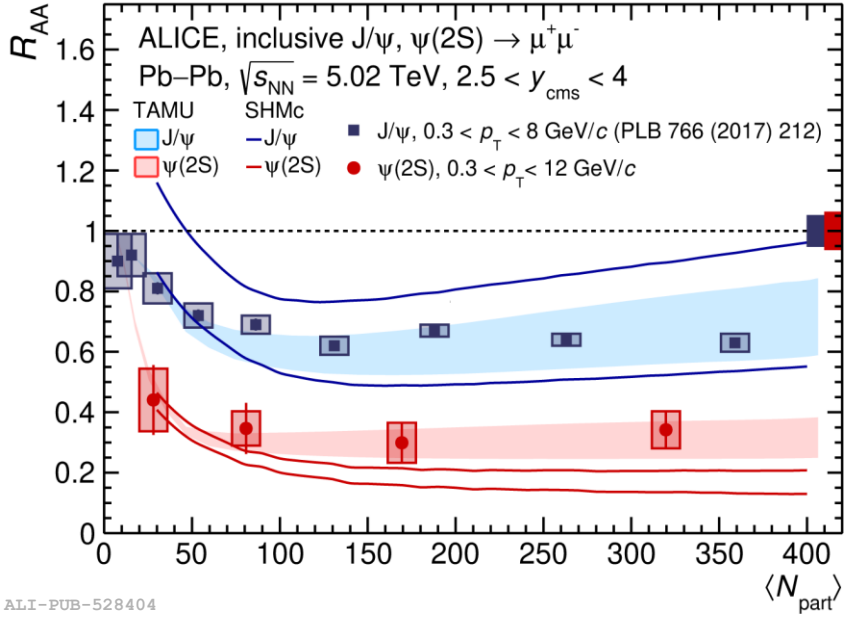


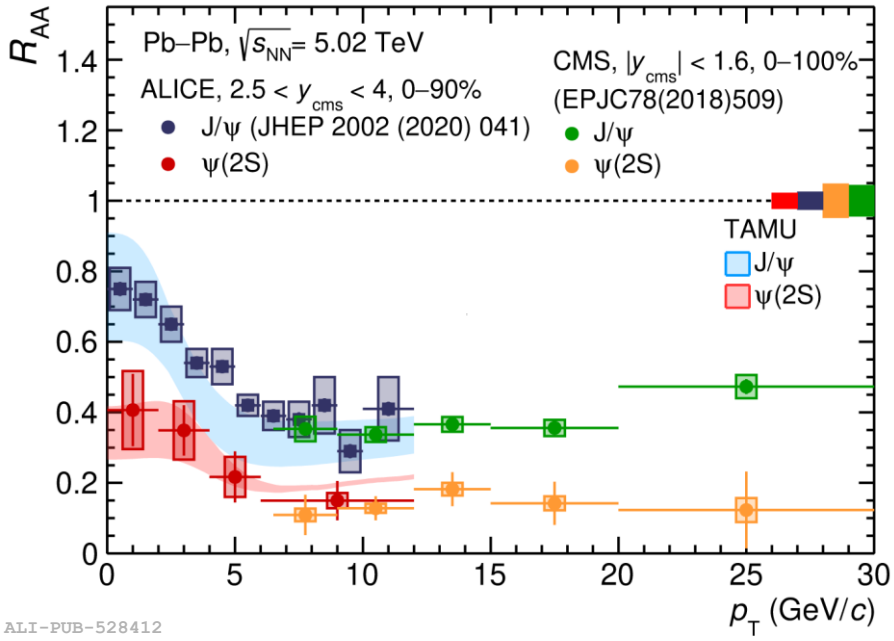
DREENA-A:
Front. Phys. 10:957019 (2022),
Phys. Rev. C 105, L021901
CUJJET3.1: CPC 43 (2019) 044101
LT1: PRC107, 054917(2023)
LBT: PLB838(2023) 137733
LBT2: EPJC 81 848 (2021) 1035
Dissociation:
PLB 778 (2018) 384-391
SHMc: PLB 797 (2019) 134836
BT: CPC43 (2019) 124101

- 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

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

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

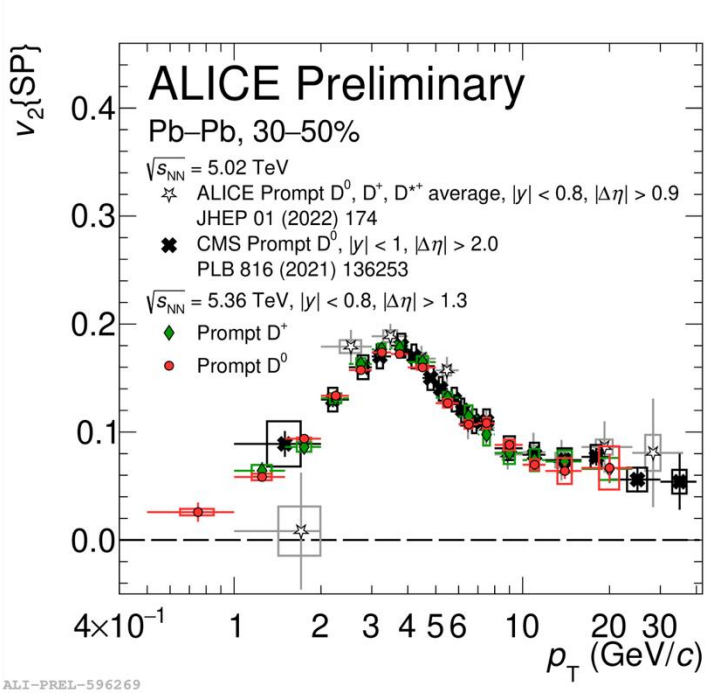


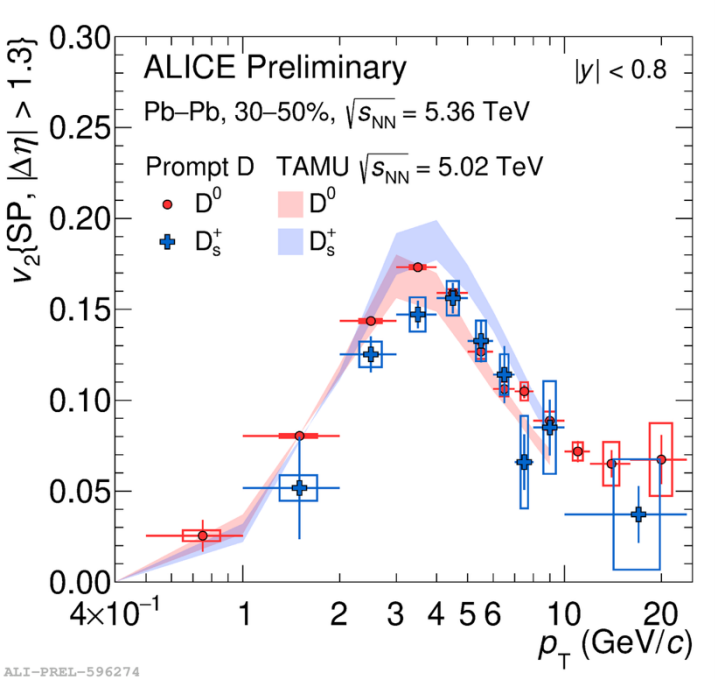


- A **larger suppression** of the ψ(2S) w.r.t the J/ψ is observed
- The ψ(2S) R_{AA} increases at low p_T , which is a hint of ψ(2S) regeneration
- The TAMU model describes data better than SHMc in central collisions

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

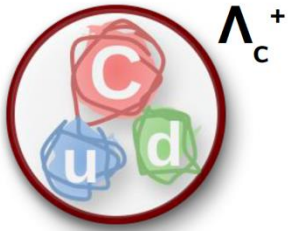
Strange and non-strange D-mesons elliptic flow

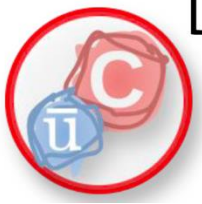


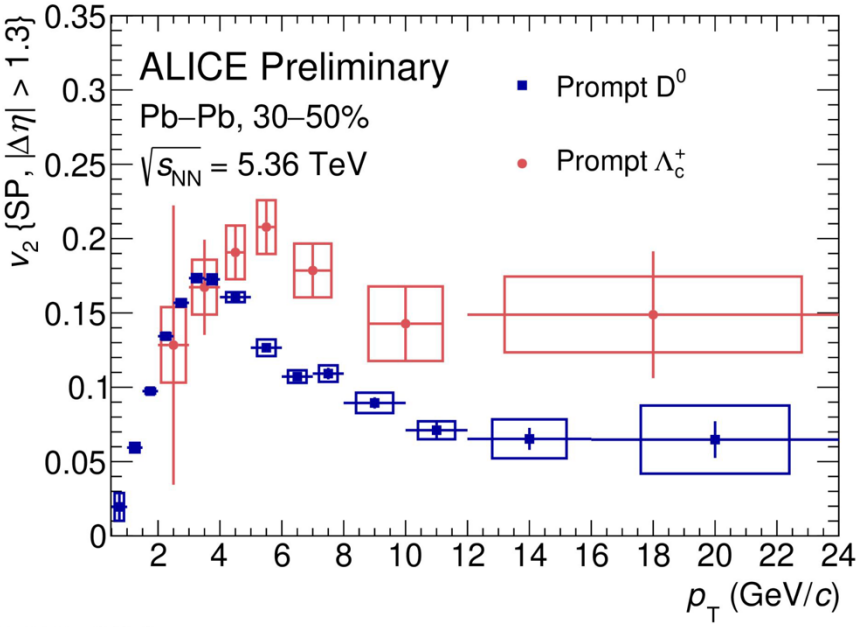


- No significant difference between strange and non-strange D mesons
- Data described by transport models with hydro evolution and hadronization **via coalescence**

Charm baryon/meson v_2 splitting



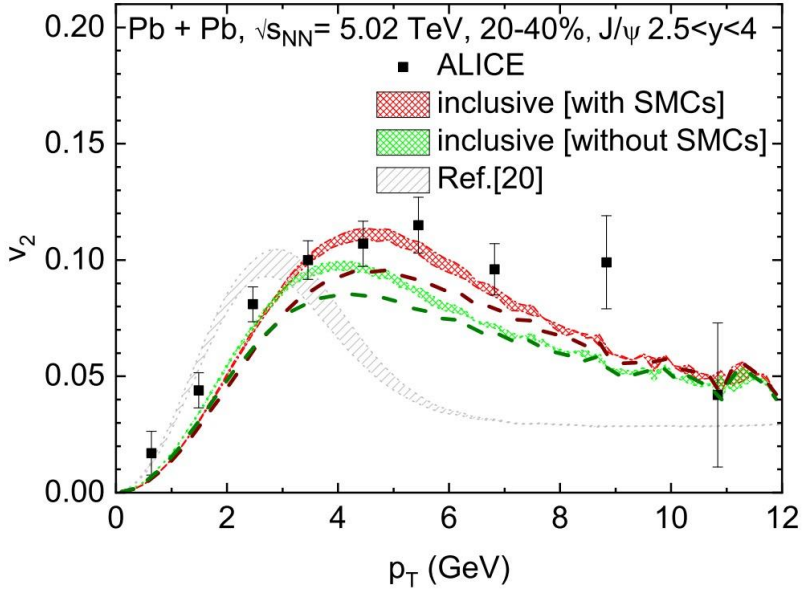




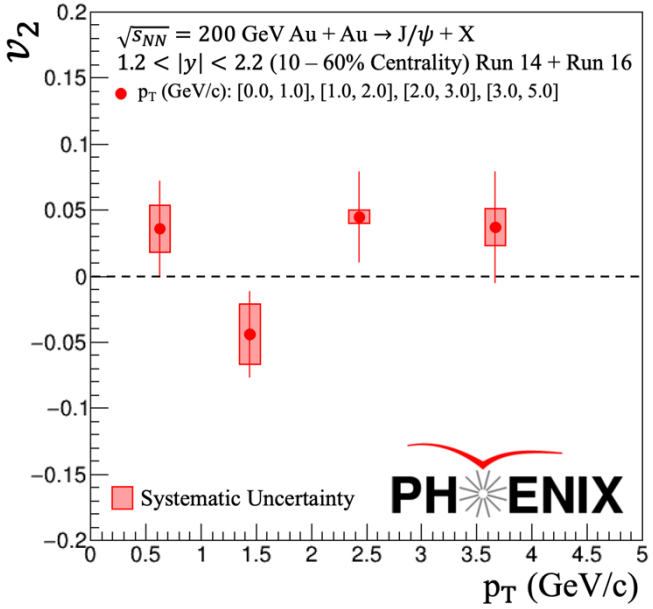
ALI-PREL-596373

- First prompt charm-baryon v_2 measurement in heavy-ion collisions
- Compatible within uncertainties with D^0 in the low p_T, $v_2(\Lambda c^+) > v_2(D^0)$ with 3.6σ in the intermediate p_T, evidence of charm baryon/meson splitting

Charmonium elliptic flow in Pb–Pb collisions

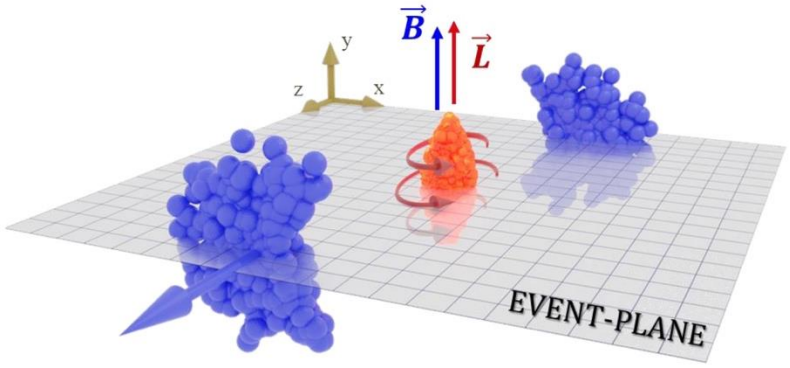


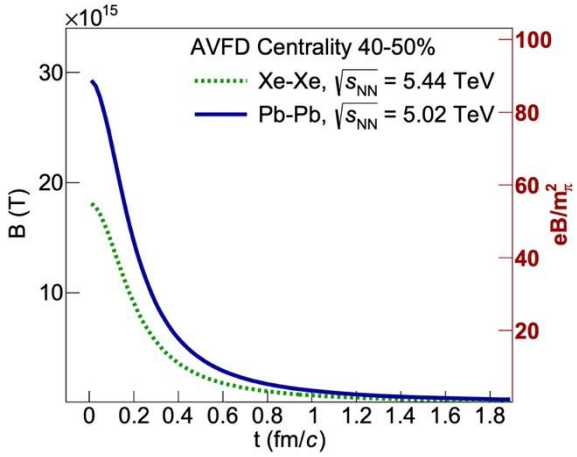
M. He, et al., PRL.128, 162301 (2022)



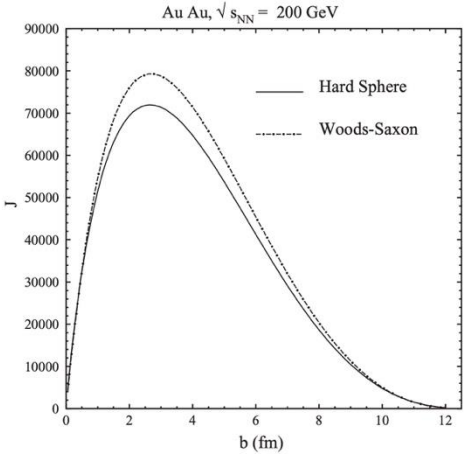
- A significant J/ψ v_2 is observed at LHC energy, while it consistent with 0 at RHIC energy
- Suggest the charm quark thermalization

Charmonium polarization





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

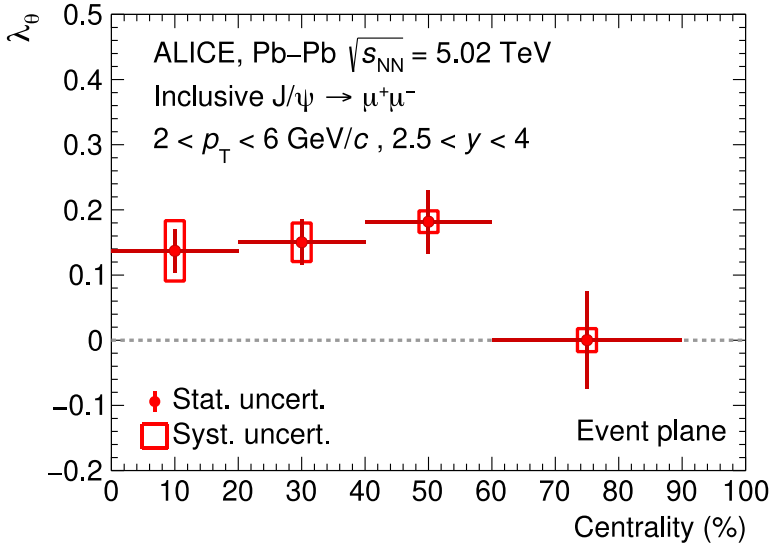


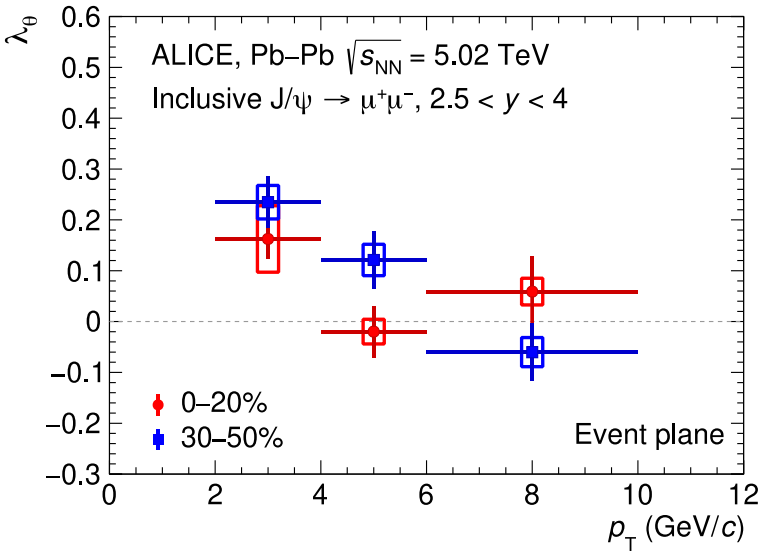
F. Becattini et al., PRC 77 (2008)

Heavy-quark 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.

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

ALICE, PRL 131 (2024) 4, 042303

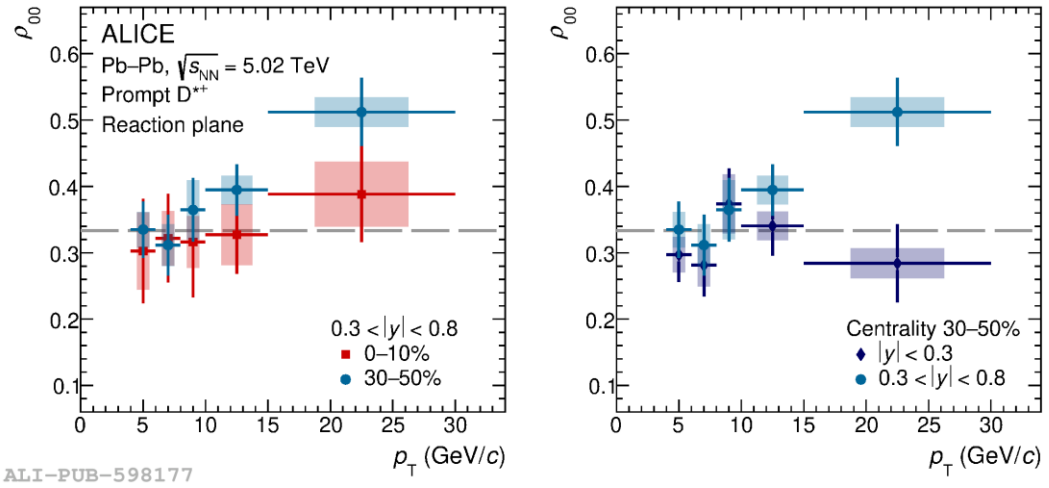


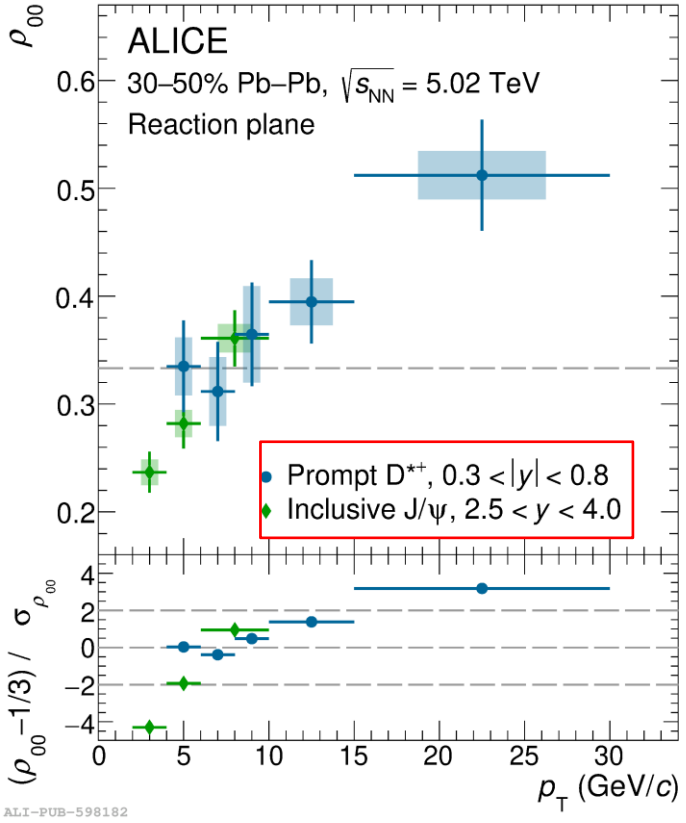


- First measurement of quarkonium polarization **w.r.t the event plane**
- **Significant polarization (~3.5σ)** observed in semicentral collisions (40-60%) in 2 < p_T < 6 GeV/c
- The significance of the polarization reaches **~3.9σ** at low p_T (2 < p_T < 4 GeV/c) in 30-50%
- Interpretation of results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

D*+ polarization spin alignment

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)

Summary

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

  Evidence of the charm deconfinement at LHC

- Significant non-zero polarization and v_2 are observed, for charm baryon, meson and J/ψ.

  Charm quarks thermalized at LHC energies (?)

Thanks