2022 RHIC/AGS ANNUAL USERS' MEETING
From RHIC to EIC
At the QCD Frontiers
This meeting will be held virtually.
June 7–10, 2022

Recent measurements of heavy flavor and jet production at LHC

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ALICE

Motivation

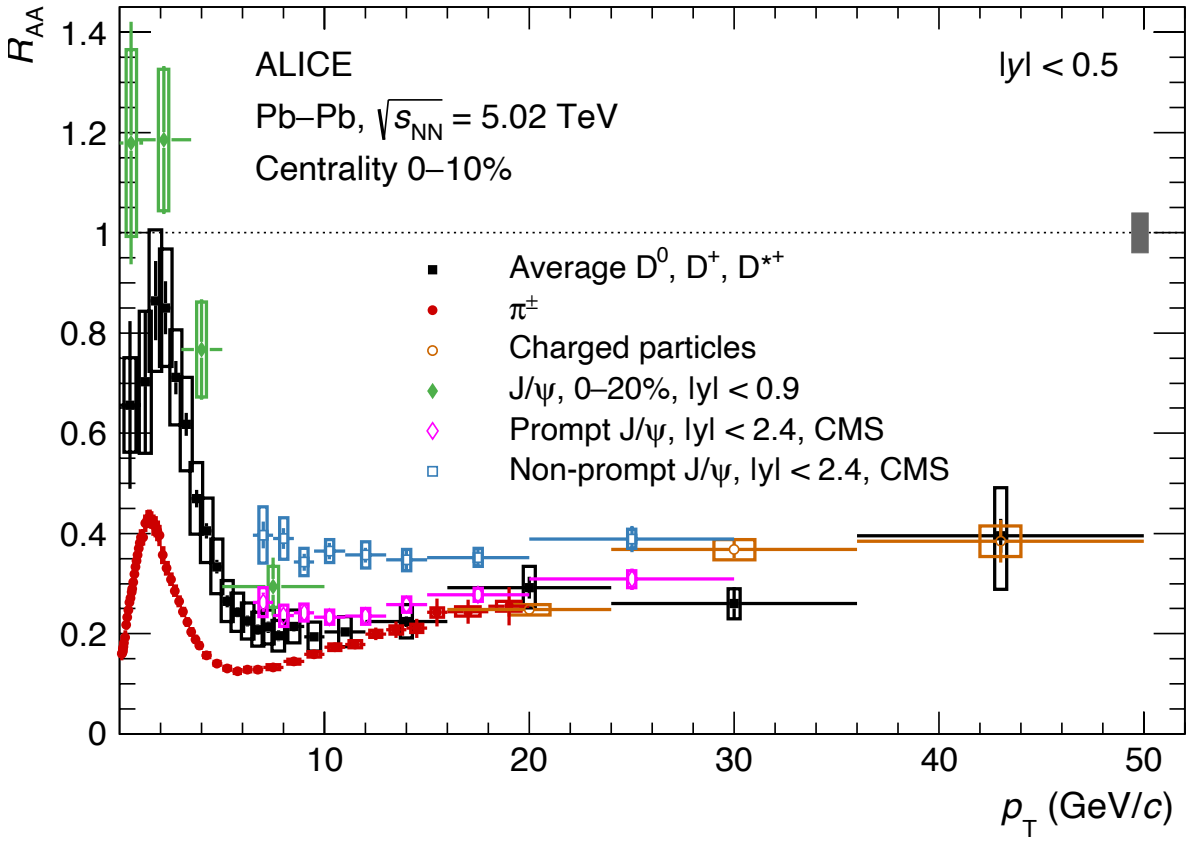
- **pp collisions:**
  - Test QCD calculations
  - Provide reference for p-Pb and Pb-Pb collisions

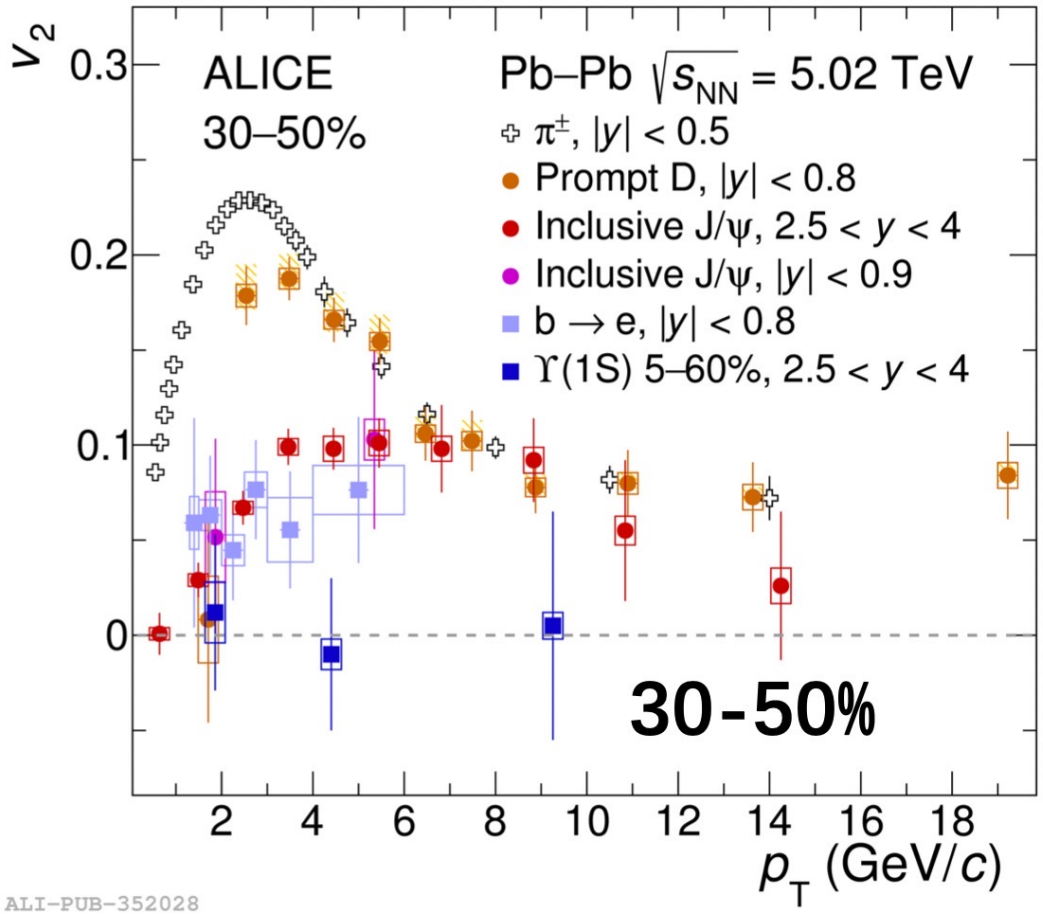
- **p-Pb collisions:**
  - Investigate the cold nuclear matter
  - Study the potential collective and energy loss effects

- **Pb-Pb collisions:**
  - Heavy quark energy loss
  - Hadronization mechanisms in presence of a medium
  - Quarkonium dissociation and (re-)generation in the medium

Heavy flavor production in AA collisions

ALICE, JHEP 01 (2022) 174, PRL 126 (2021) 162001

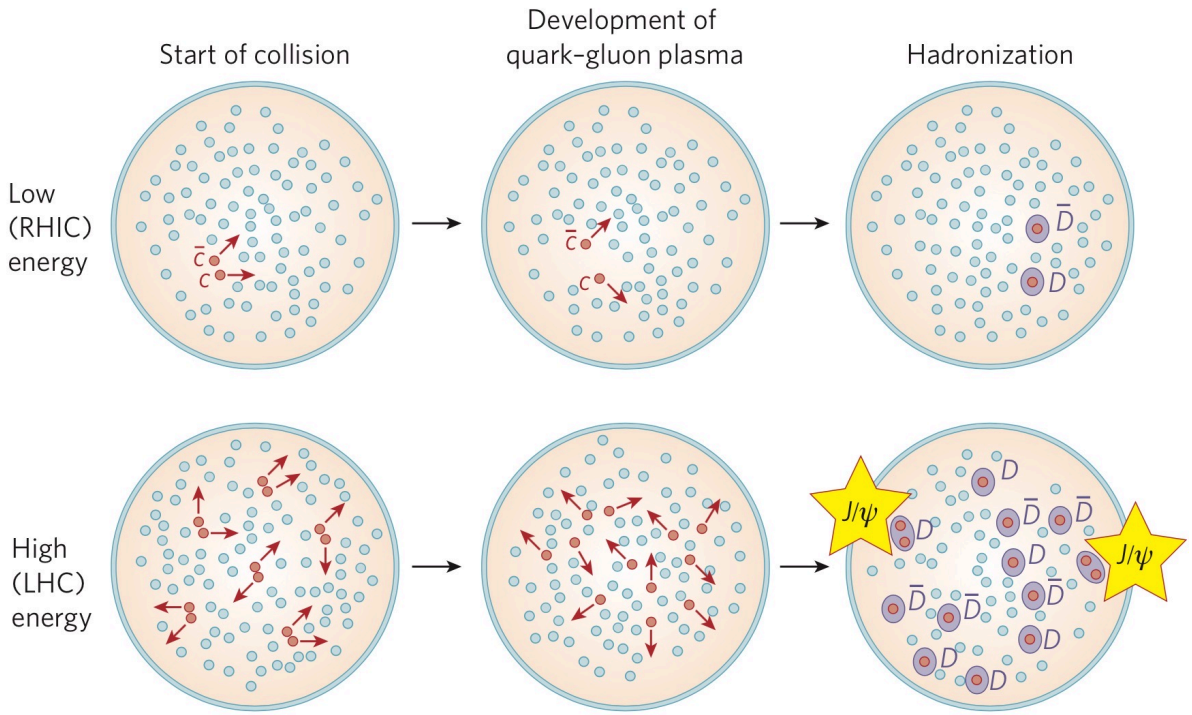


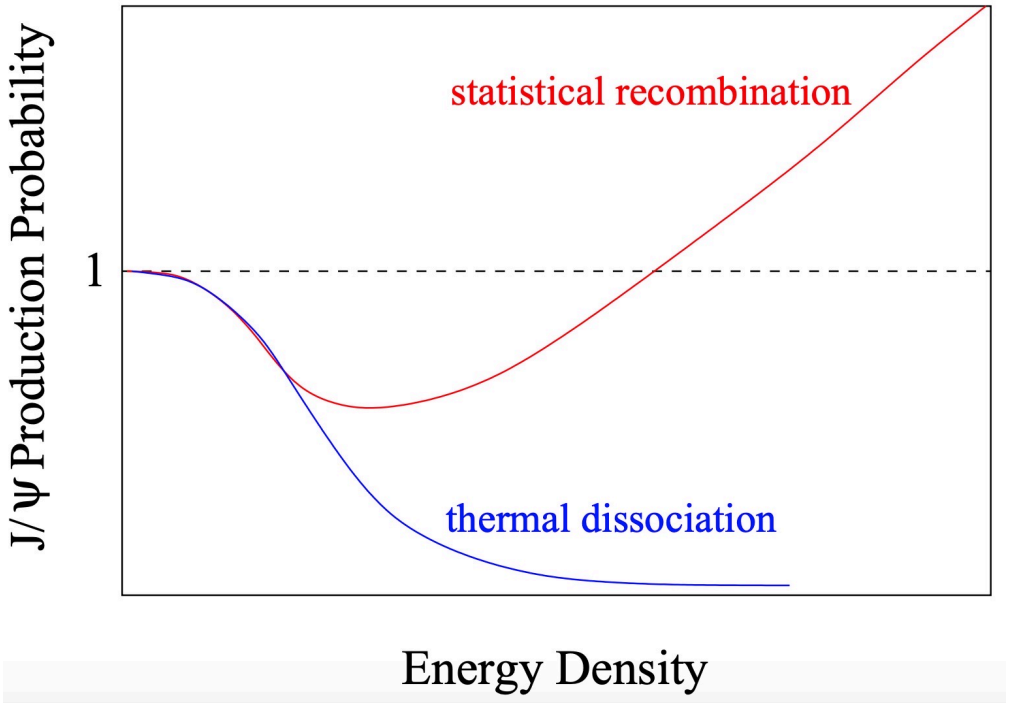


- Heavy quarks produced in hard scattering processes in initial stages of the heavy-ion collisions, experienced the full system evolution
- Beauty and charm quarks production in Pb-Pb collisions, study the mass dependent parton medium interaction

Quarkonium production in AA collisions

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



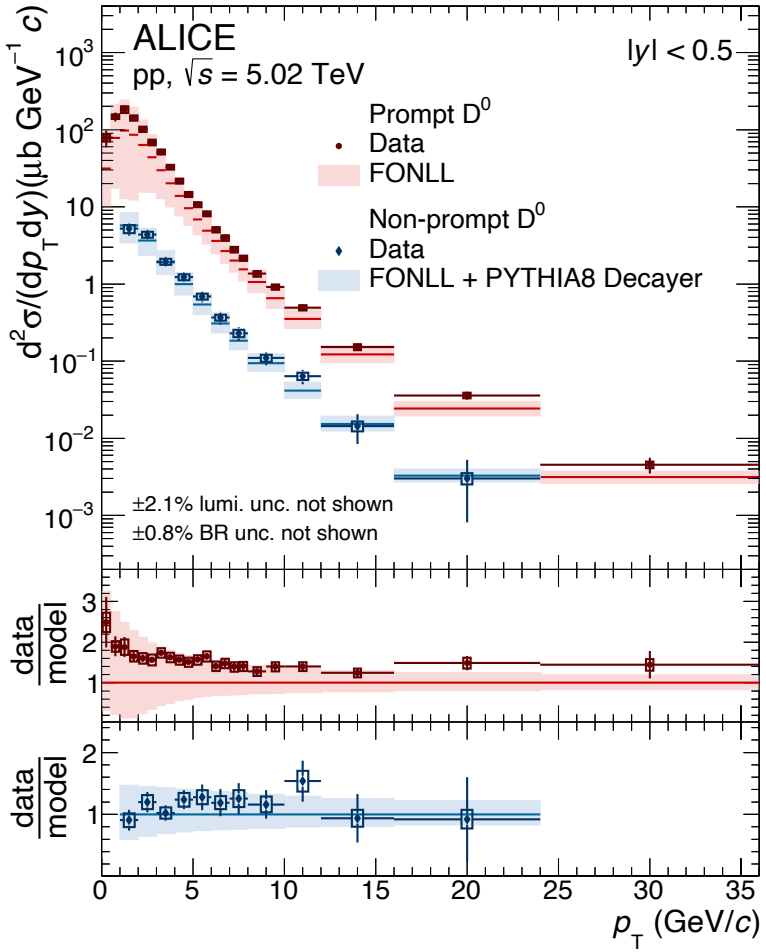


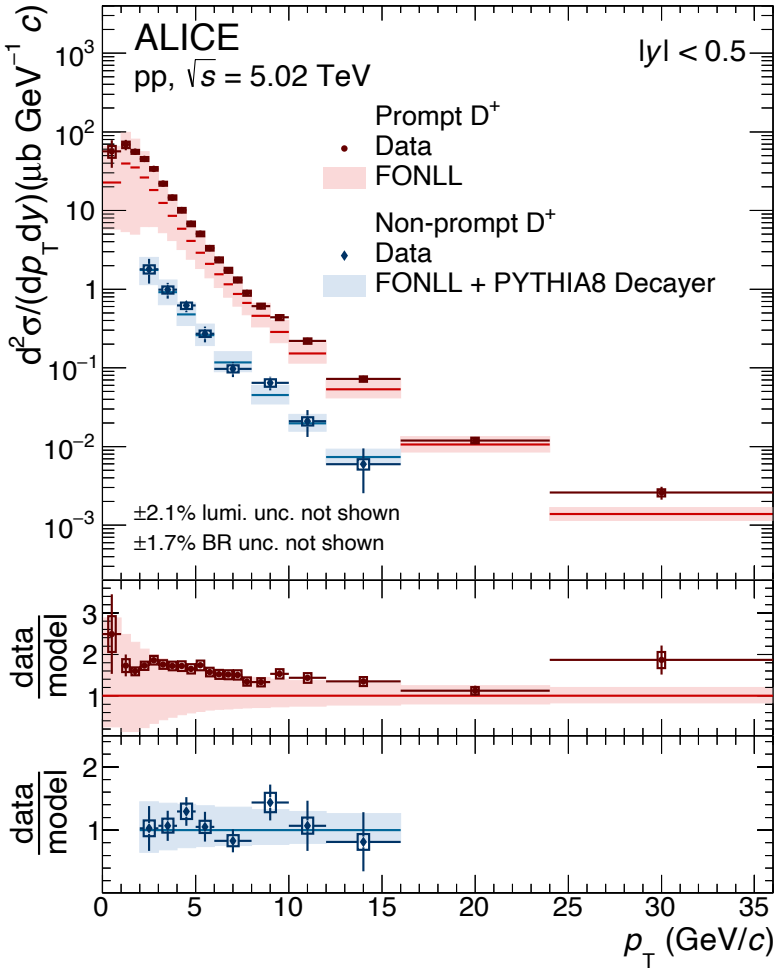
P. Braun Muzinger, J.Stachel, PLB 490 (2000) 196
R. Thews et al, Phys.Rev.C 63:054905 (2001)
Kluberg, Satz, arXiv:0901.3831

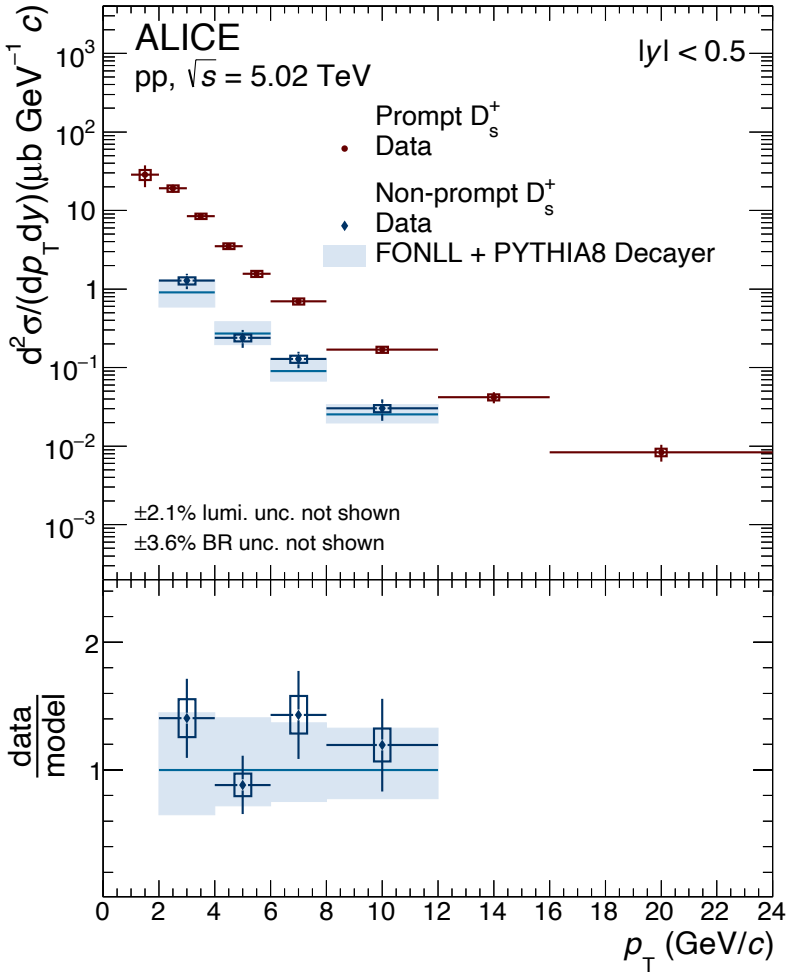
- Charm quark (c and $\bar{c}$) production cross section in LHC is larger compared to RHIC energies
- The J/ψ (re-)generation contribution is significantly higher than RHIC

Open heavy flavor production

Open charm and beauty mesons production



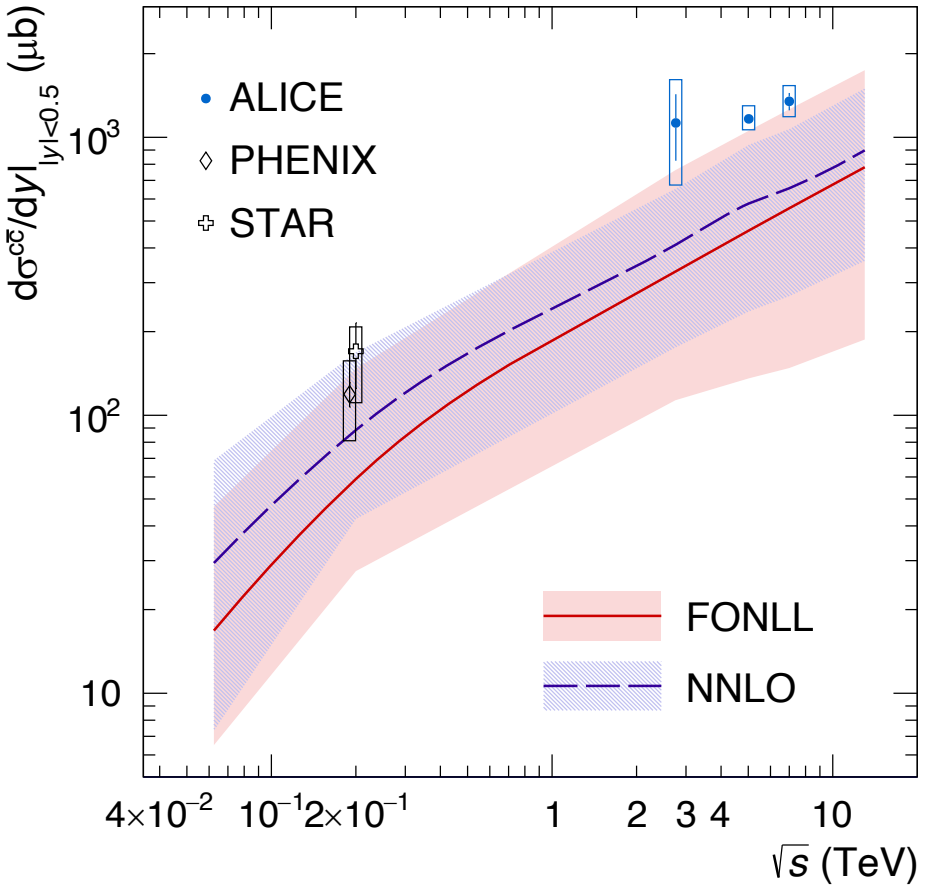


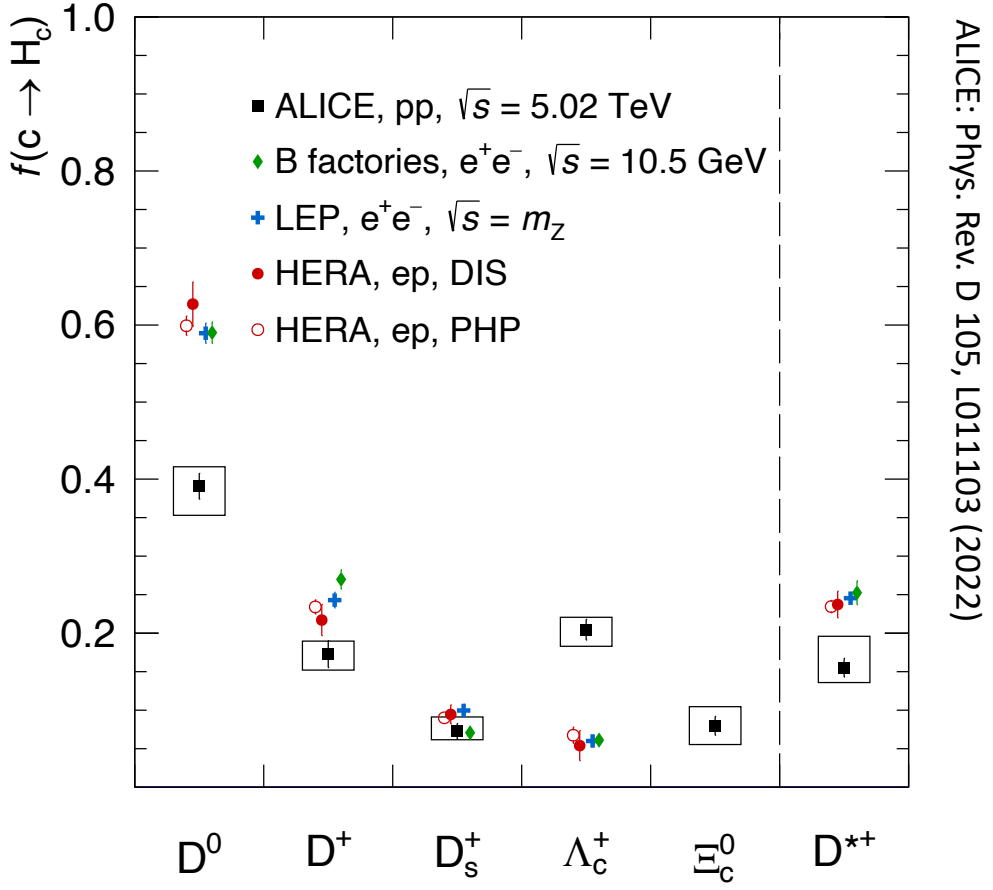


- Wide p_T range cross section measured down to $p_T = 0$ for D^0 and D^+ meson
- NLO pQCD calculations describe cross sections down to low p_T

ALICE: JHEP 05 (2021) 220
FONNL: JHEP 1210 (2012) 137

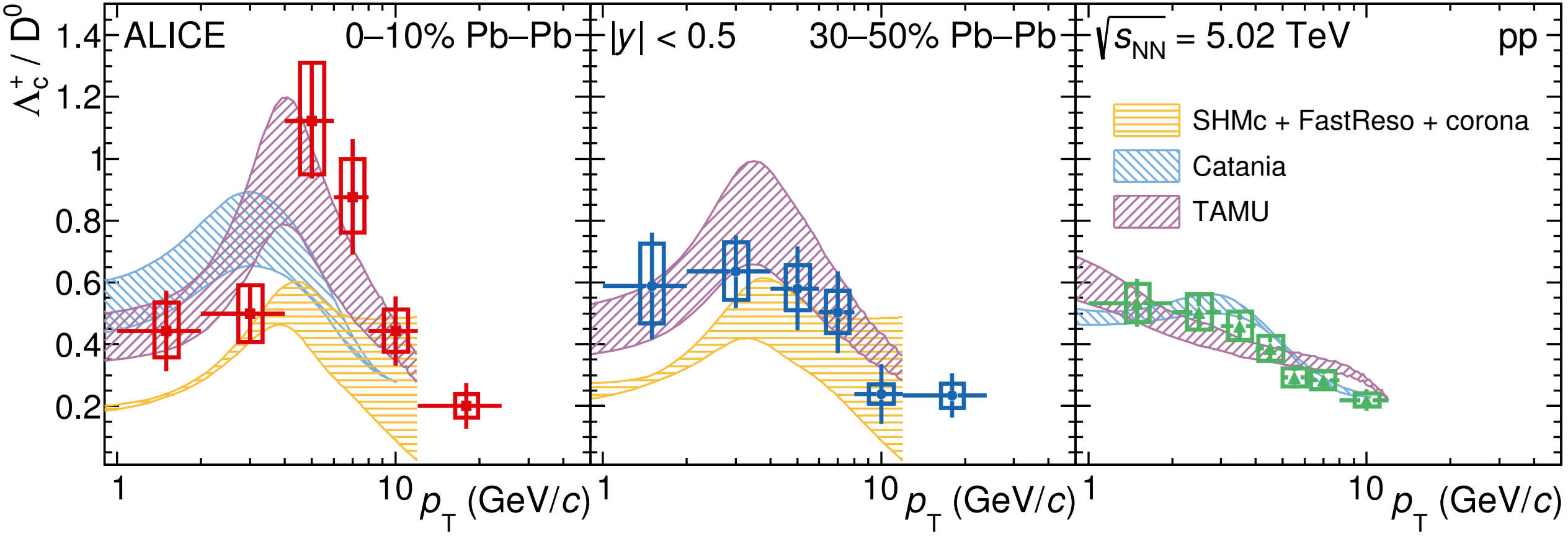
Charm production cross section and fragmentation fractions





- Charm fragmentation is not universal!
- First midrapidity charm production cross section measurement in pp collisions at 5.02 TeV
- Update the charm cross section measurements previously published at 7 and 2.76 TeV → 40% higher

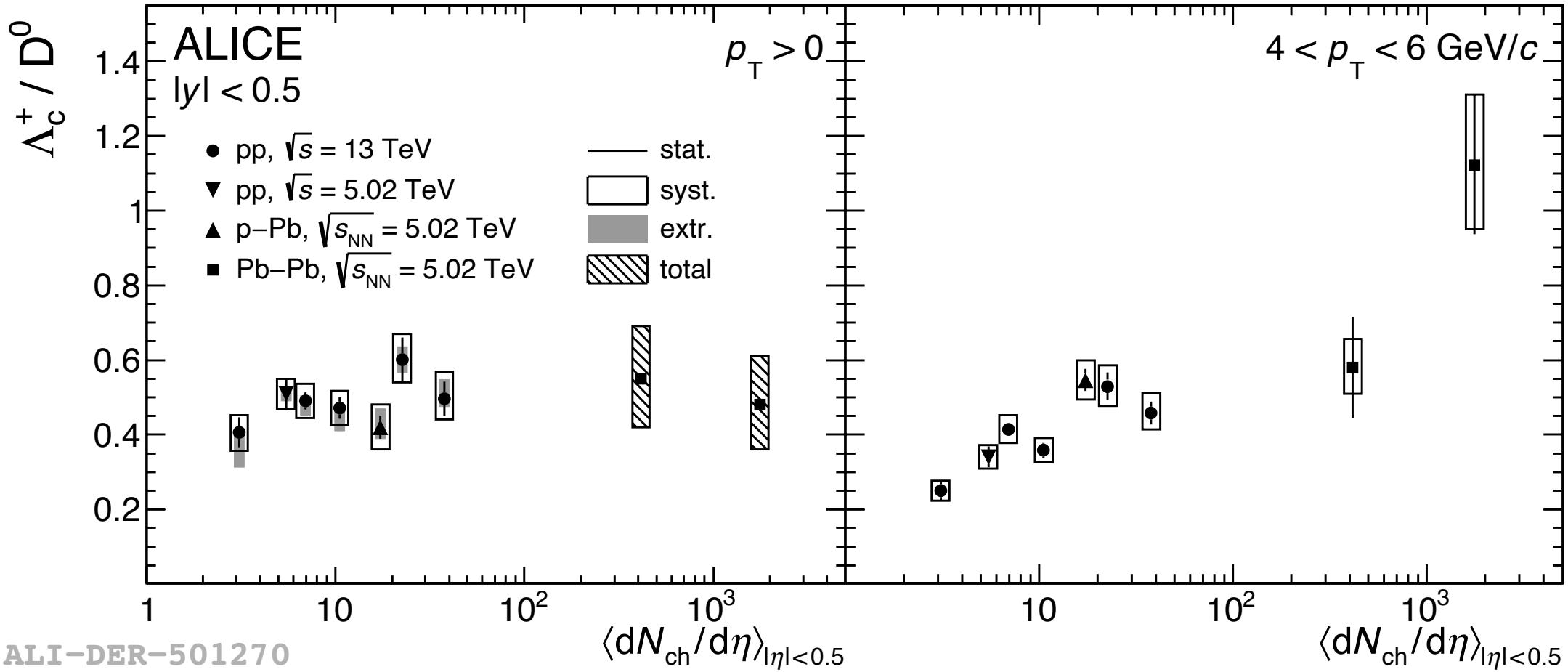
Charm baryon to probe hadronisation



- The Λ_c^+/D^0 ratios increase from pp to central Pb–Pb collisions for $4 < p_T < 8$ GeV/c with a significance of 3.7σ
- The measurements are described by theoretical calculations that include both coalescence and fragmentation

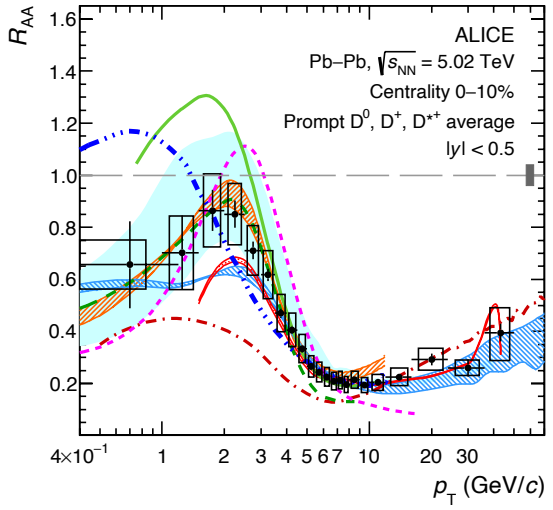
arXiv:2112.08156

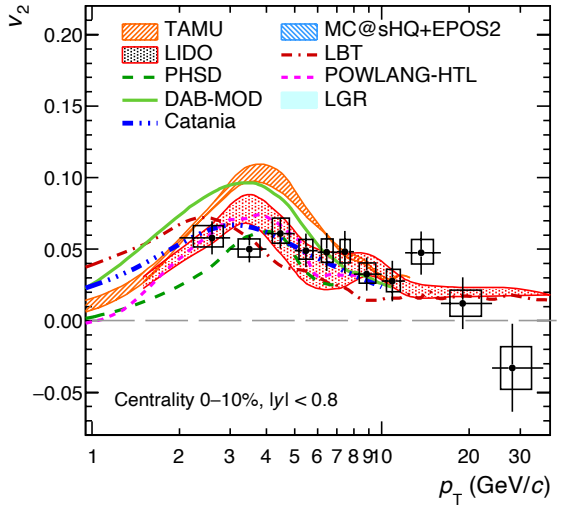
Λ_c^+/D^0 ratio vs. multiplicity for integrated and intermediate p_T

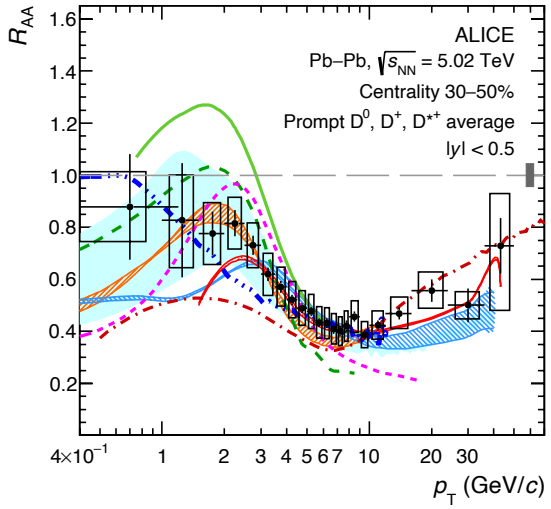


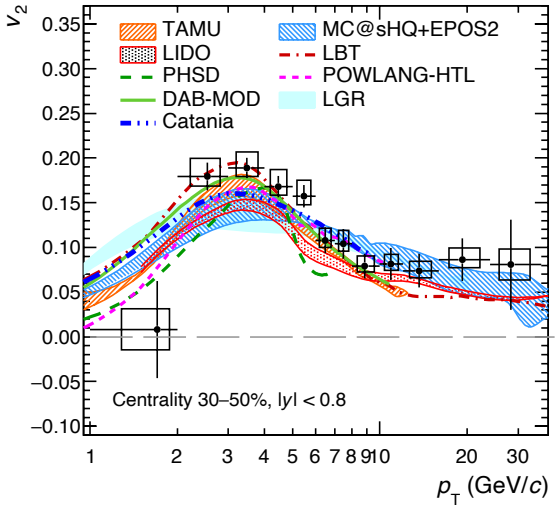
- p_T -integrated ratio compatible with a flat behaviour versus event multiplicity
- Re-distribution of p_T for baryons and mesons, no modification of overall p_T -integrated yields

Prompt D-mesons R_{AA} in Pb−Pb collisions







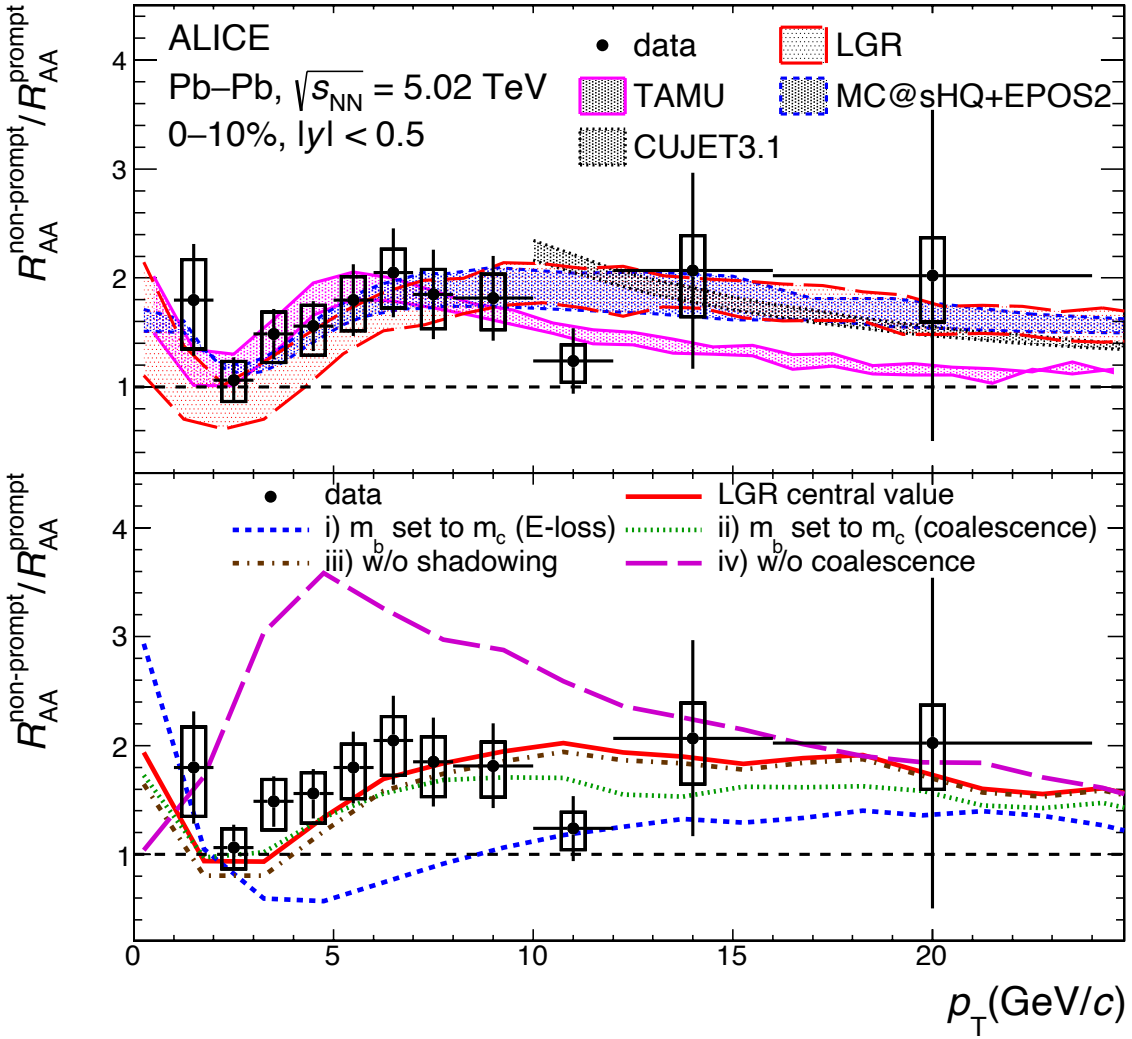


- The average prompt D-mesons R_{AA} compared with different transport model calculations
  - Some of the models only include the collisional energy loss, others coll. + rad.
  - All models include the hadronization via frag.+reco.

- $p_T < 5$ GeV/c sensitive not only to charm-quark interaction with the medium
  - Cold nuclear matter effects
  - Hydrodynamics

TAMU: PRL 124.042301(2020); MC@sHQ+EPOS:PRC 91,014904(2015)
PHSD: PRC 93, 034906(2016); LIDO: PRC 98 064901(2018)
POWLANG: EPJC 75, 121(2015); LBT: PLB 777255-259(2018)
CATANIA: PRC 96 044905(2017); LGR: EPJC 807,671 (2020)
DAB-MODM&T PRC96 064903(2017)

Non-prompt D^0 R_{AA} in Pb−Pb collisions

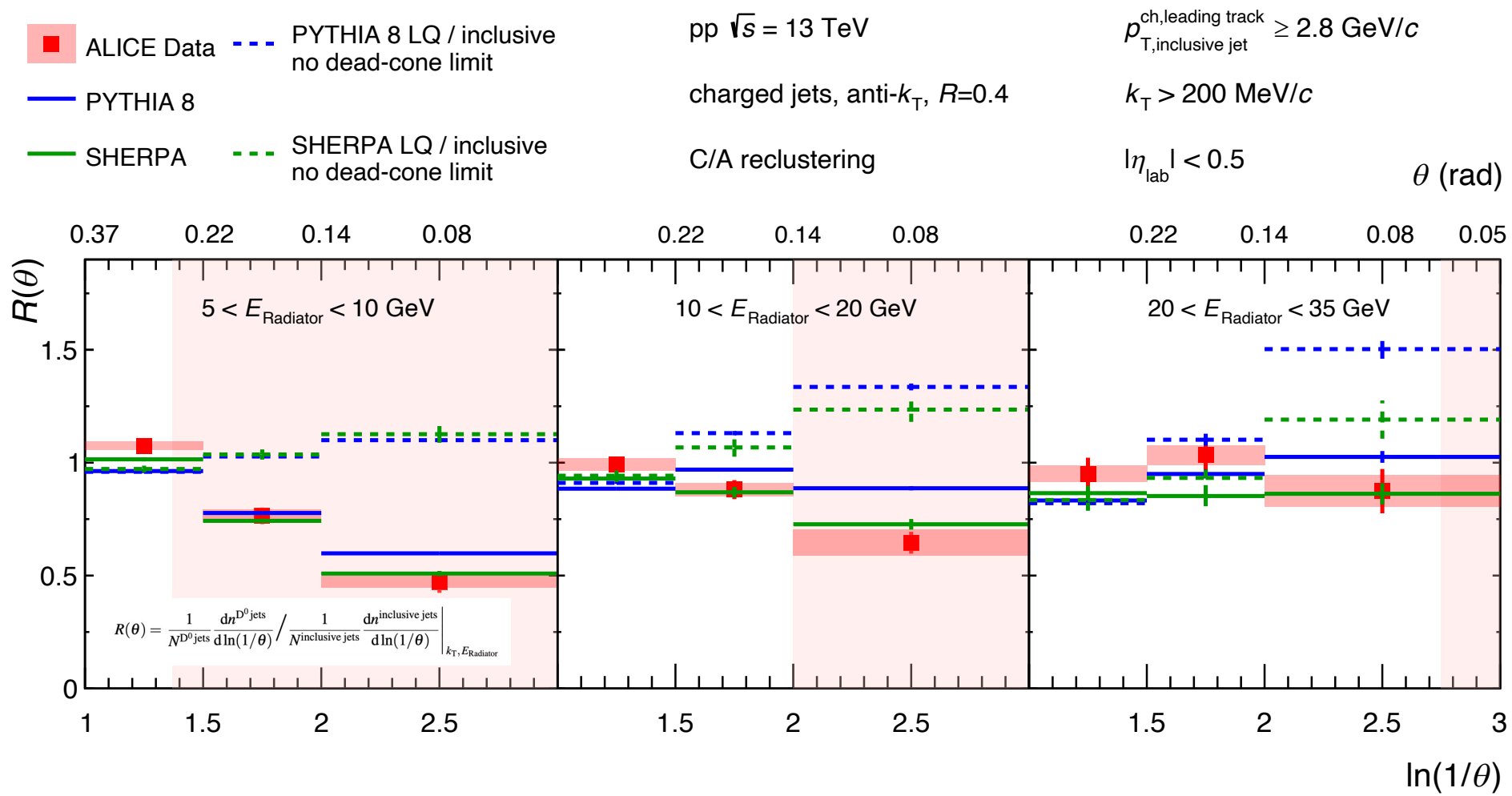


arXiv:2202.00815

- R_{AA} (non-prompt $\mathbf{D^0}$)/ R_{AA} (prompt $\mathbf{D^0}$)/ in Pb−Pb collisions central collisions, larger than unity for $p_T > 5$ GeV/c with significance $\mathbf{3.9\sigma}$
- Parton mass-dependent energy loss (dead cone effect), described by the models including the collision and radiative energy loss

LGR:EPJC 807,671(2020)
TAMU: PLB 735,445-450(2014)
CUTJET 3.1: CPC 43,044101(2019)
MC@sHQ+EPOS PRC 89,014905(2015)

Direct observation of the dead-cone effect

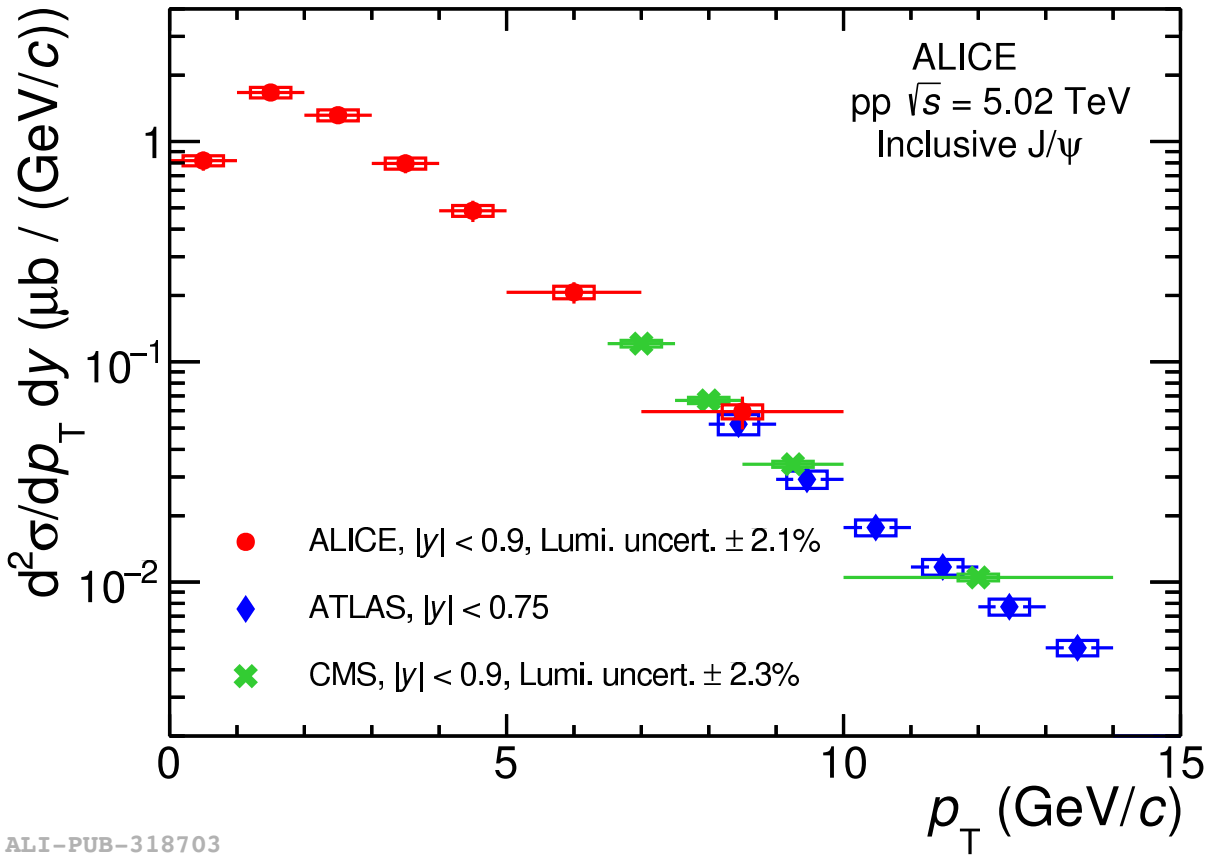


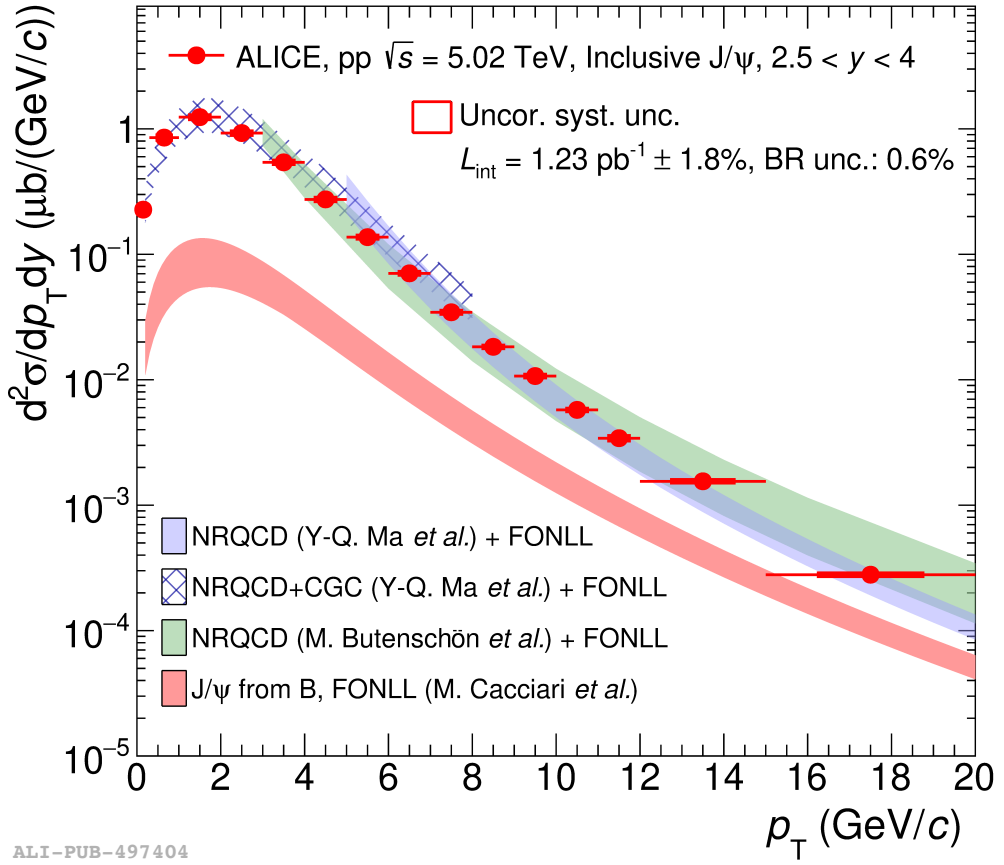
- The first direct measured dead-cone effect via the D^0 tagged jet in quantum chromodynamics
- This measurement provides insight into the influence of mass effects on jet properties

ALICE: nature 605, 440–446 (2022)

Quarkonium production

pp reference for inclusive J/ψ production at $\sqrt{s} = 5.02$ TeV

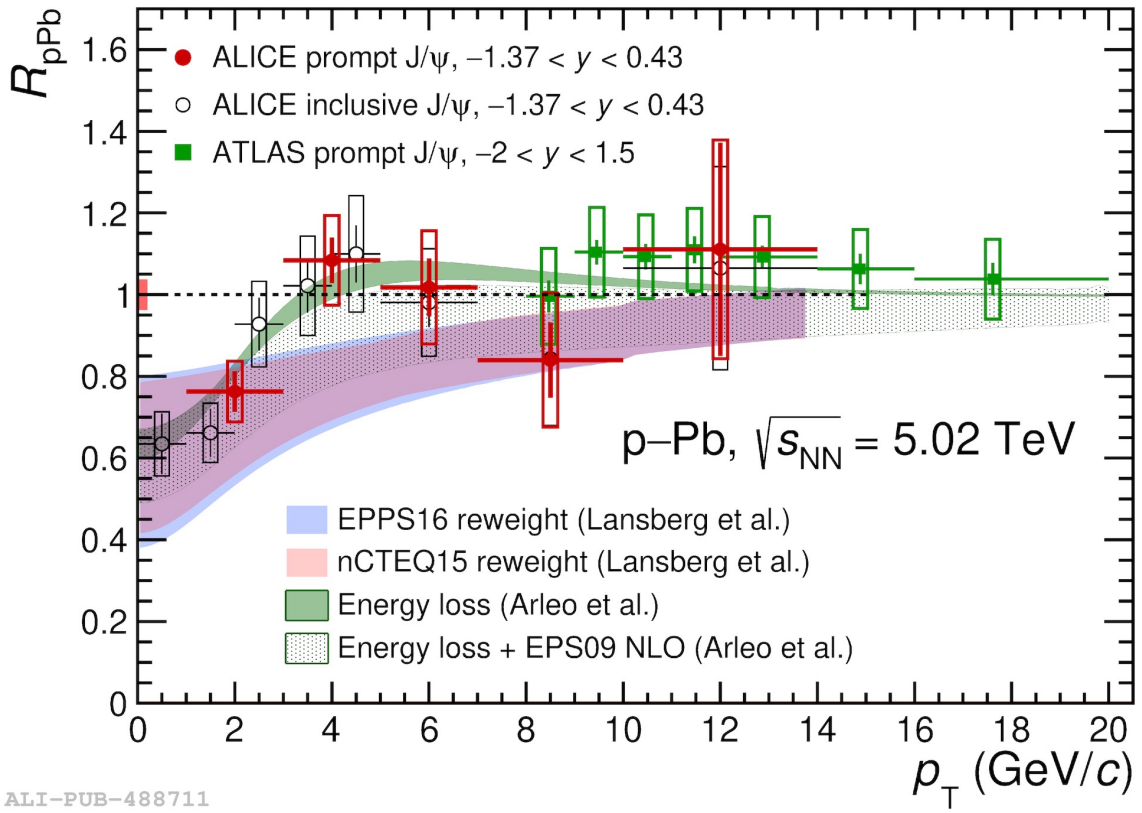


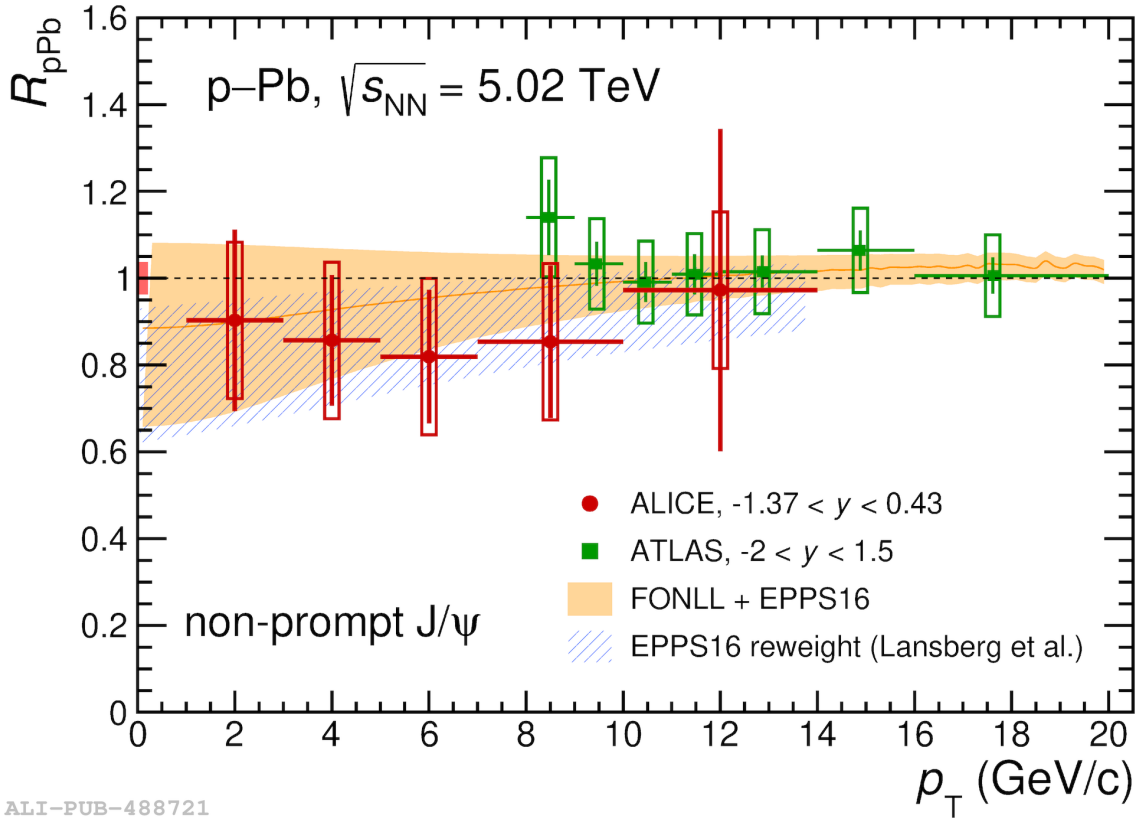


Eur. Phys. J. C 78 (2018) 171 (ATLAS)
Eur. Phys. J. C 77 (2017) 269 (CMS)
Phys. Rev. Lett. 113 (2014) 192301
JHEP10 (2019) 084 (ALICE)
arXiv, 2109.15240 (ALICE)

- First measurement of inclusive J/ψ production at pp 5.02 TeV, p_T down to 0
- New measurement consistent with ATLAS and CMS in overlapping p_T
- The measurements reach p_T to 20 GeV/c at forward rapidity

Prompt and non-prompt J/ψ R_{AA} in p−Pb collisions

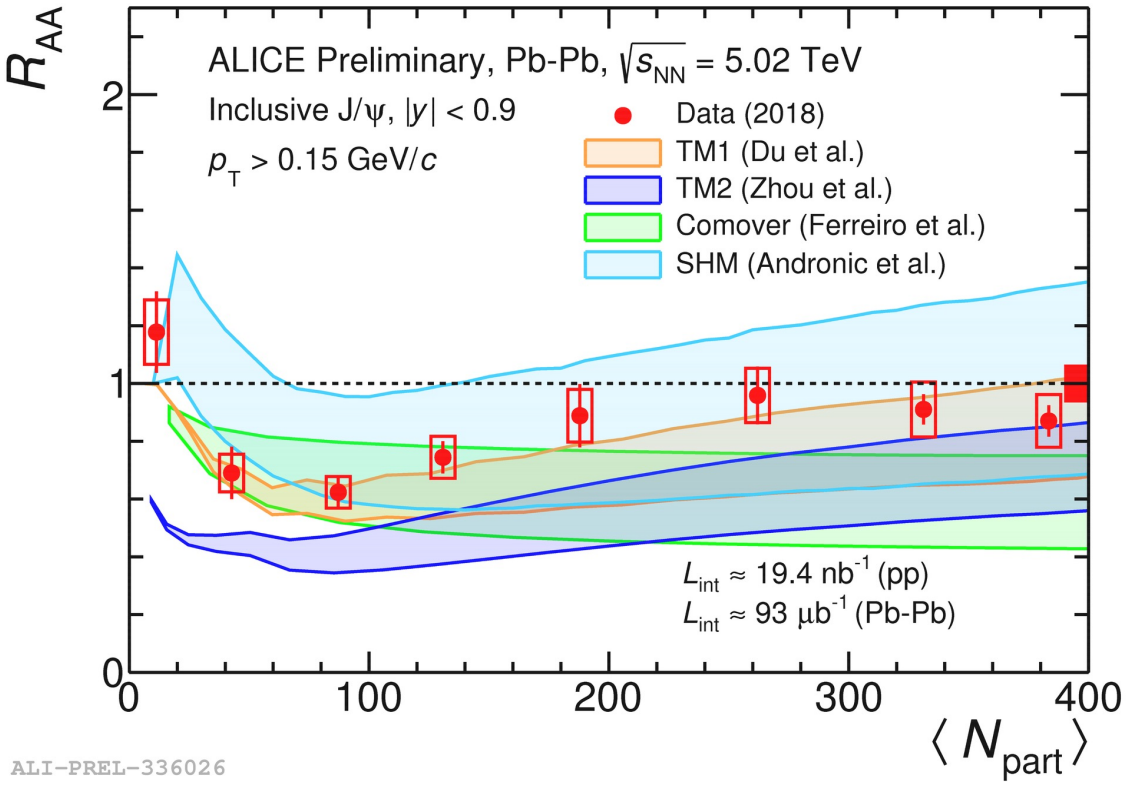


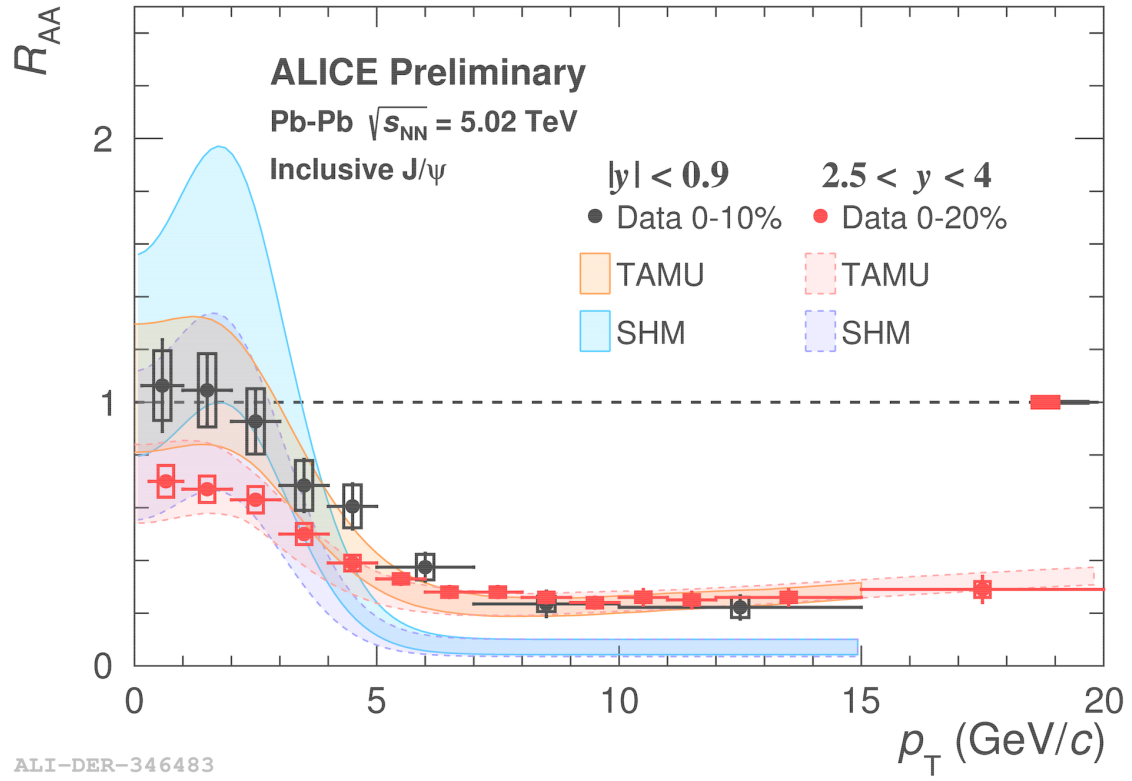


- Significant suppression for prompt J/ψ at $p_T < 3$ GeV/c, the energy loss model can describe the data
- No strong p_T dependence for non-prompt J/ψ

arXiv:2105.04957

J/ψ R_{AA} in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

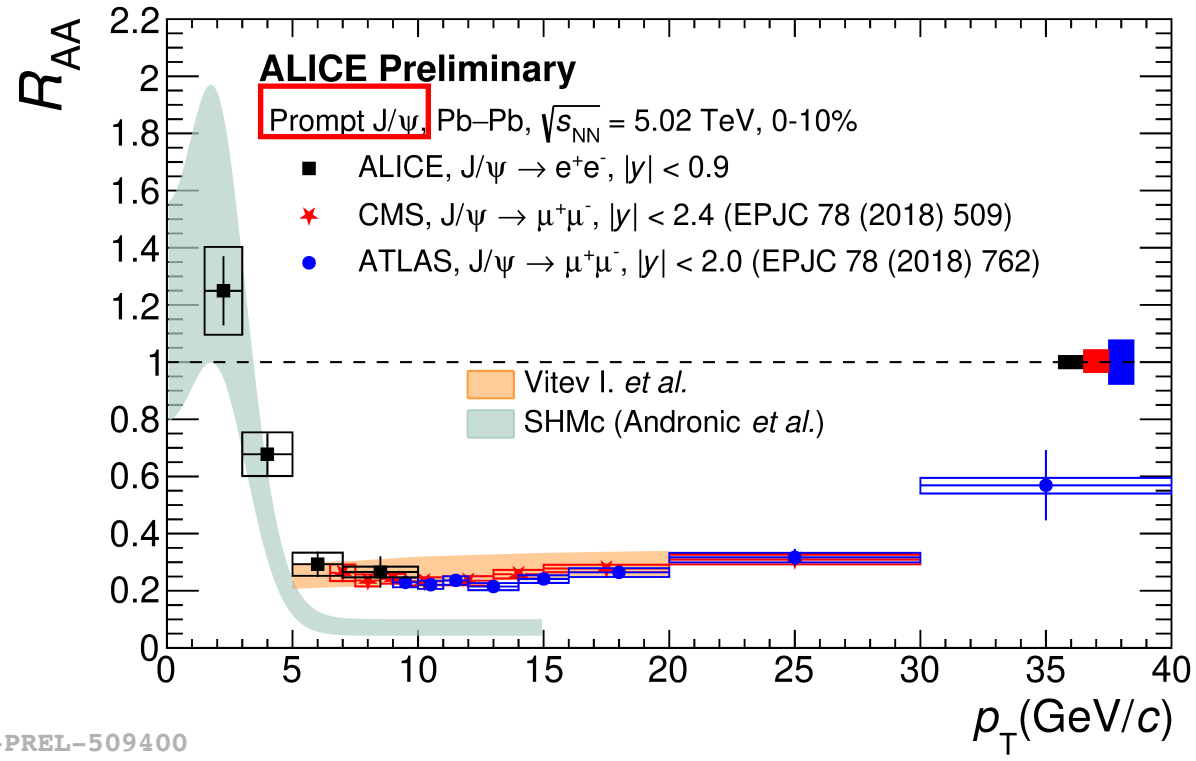




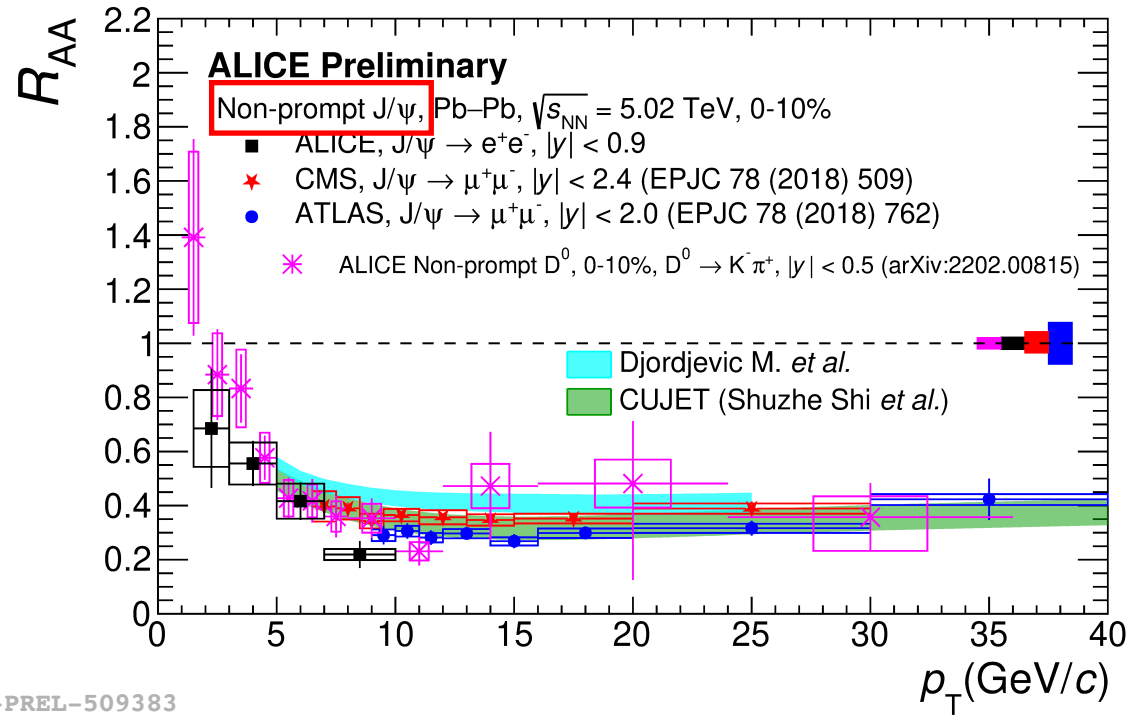
TM1: Du X. and Rapp R., NPA 943 (2015) 147-158
TM2: Zhou et al., PRC 89, 054911 (21 May 2014)
SHM: Andronic A. et al., PLB 797 (2019) 134836
Comover: Ferreiro E. et al., PLB 731 (2014) 57

- The evidence the regeneration contribution mainly at the central collisions and low p_T
- The statistical hadronization model can describe the data at low p_T, while the transport model agree with data in whole measured p_T regies

J/ψ R_{AA} comparison with the models



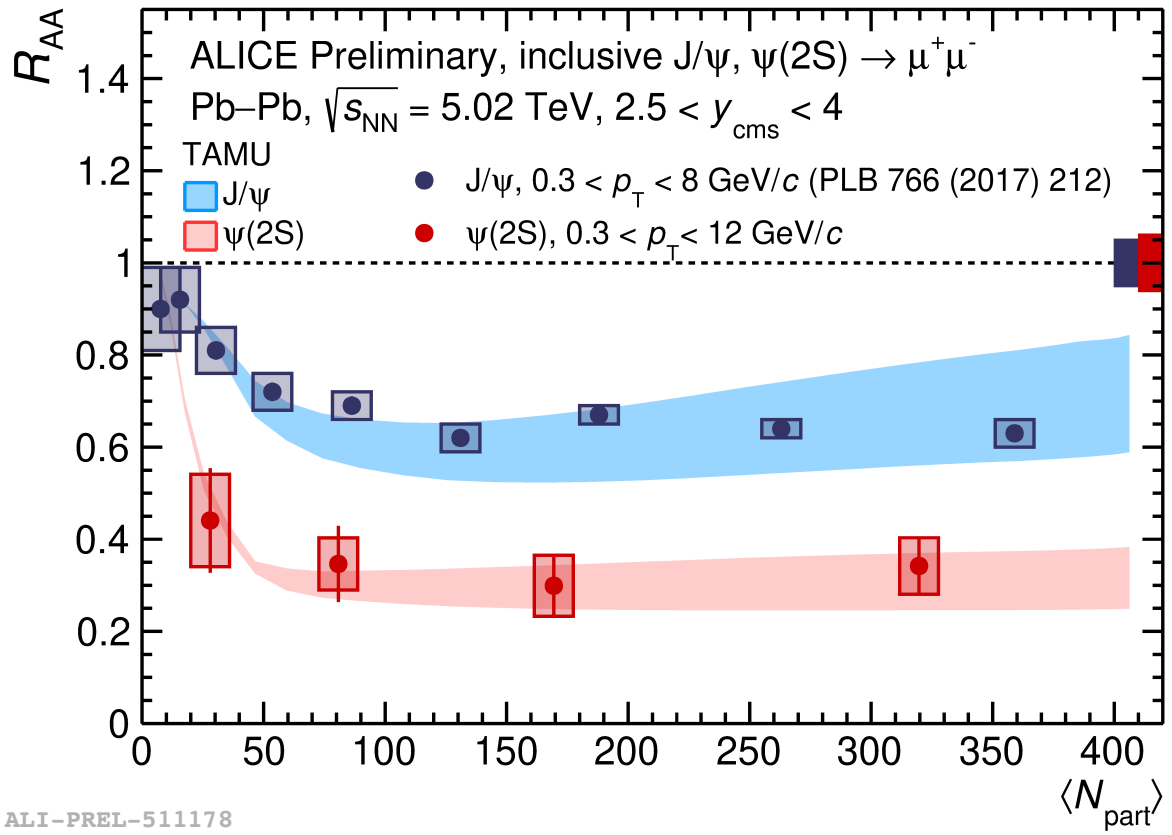
ALI-PREL-509400

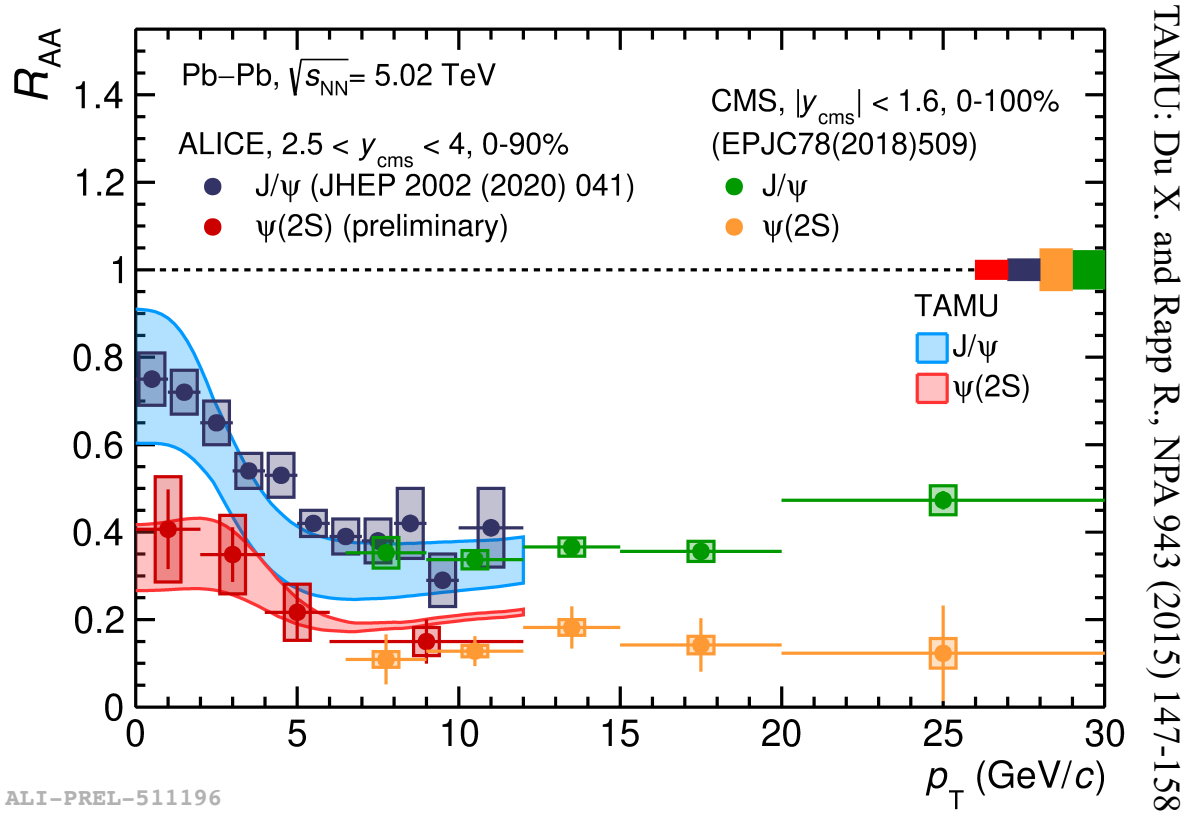


ALI-PREL-509383

- R_{AA} extended down to p_T =1.5 GeV/c and was compatible with ATLAS and CMS measurements in the overlapping p_T range.
- Similar trends for non-prompt J/ψ and non-prompt D^0 R_{AA} (small difference could arise from the different decay kinematics)
- Non-prompt J/ψ R_{AA} described by models implementing collisional and radiative energy loss for p_T > 5 GeV/c

ψ(2S) and J/ψ R_{AA} as a function of centrality and p_T

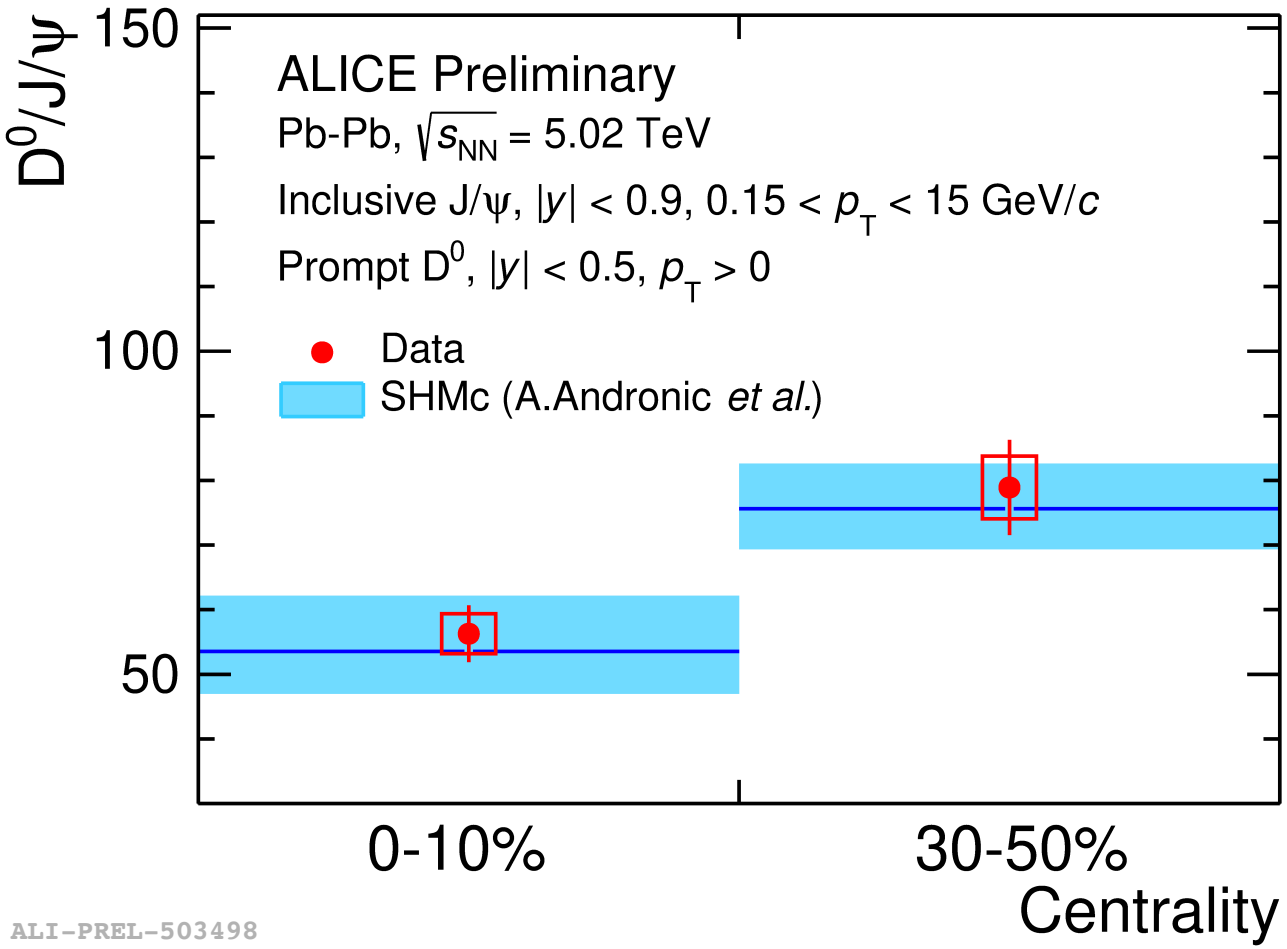




TAMU: Du X. and Rapp R., NPA 943 (2015) 147-158

- Higher suppression was observed for ψ(2S) compared to J/ψ
- Increasing trend of R_{AA} towards low p_T for both J/ψ and ψ(2S), hint of ψ(2S) production via (re-)generation!
- Centrality and p_T dependence are well reproduced by the TAMU model for both J/ψ and ψ(2S)

D^0-to-J/ψ ratio in Pb–Pb collisions

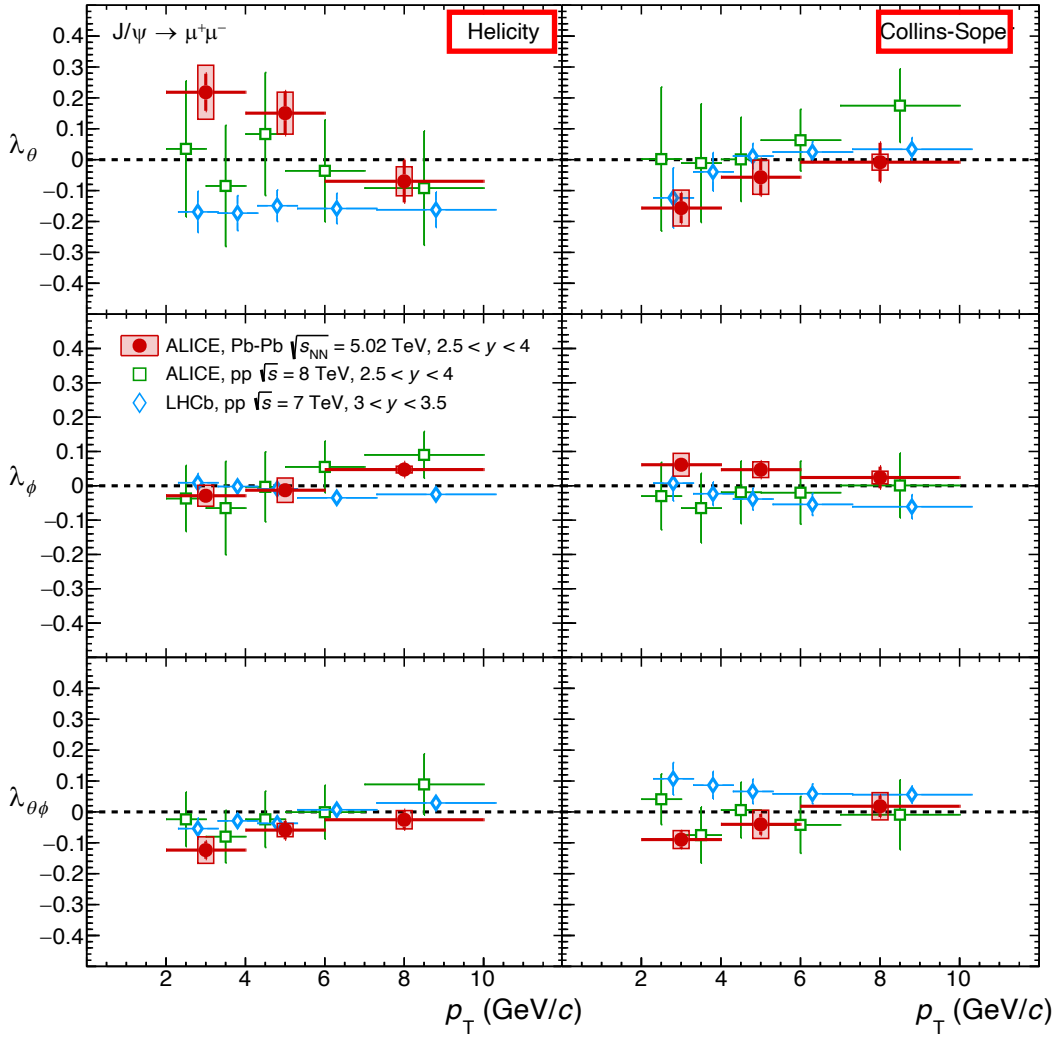


A. Andronic et al., JHEP07 (2021) 035

- 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

J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration, PLB 815 (2021) 136146

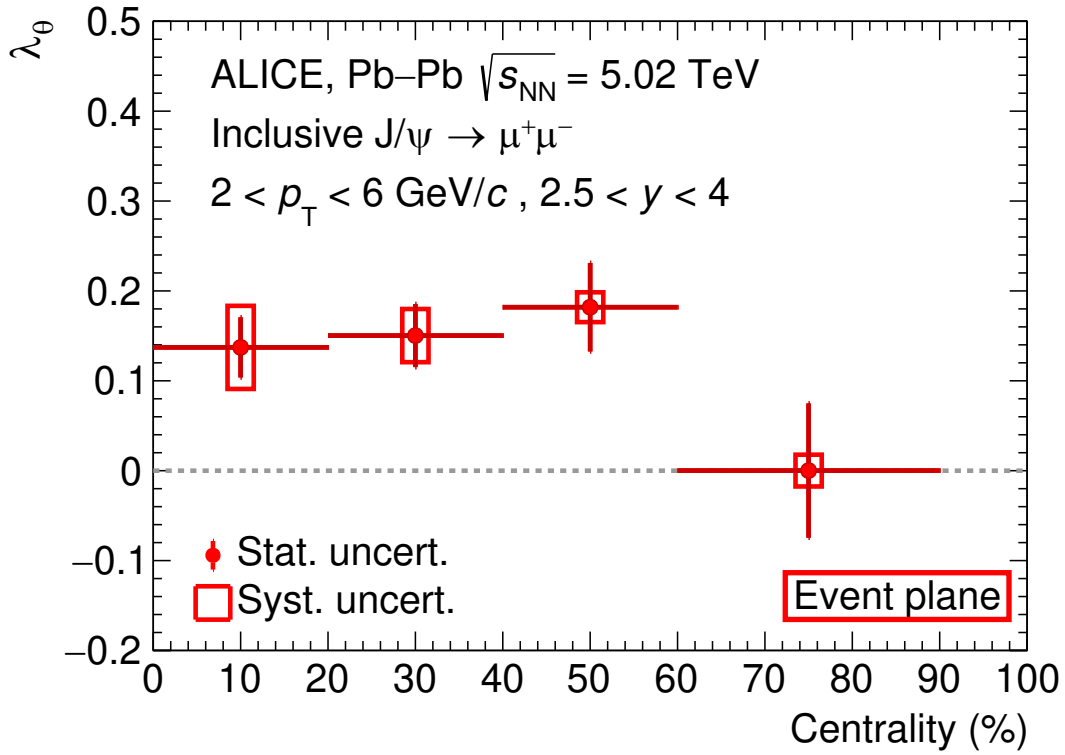


- First measurement of J/ψ polarization in Pb−Pb collisions at LHC
- λ_θ shows a maximum 2σ deviation w.r.t zero in HE and CS for $2 < p_T < 4$ GeV/c, 3σ difference w.r.t LHCb in pp collisions in the HE reference frame
- Different behaviours in Pb-Pb compared to pp collisions due to the suppression/regeneration?

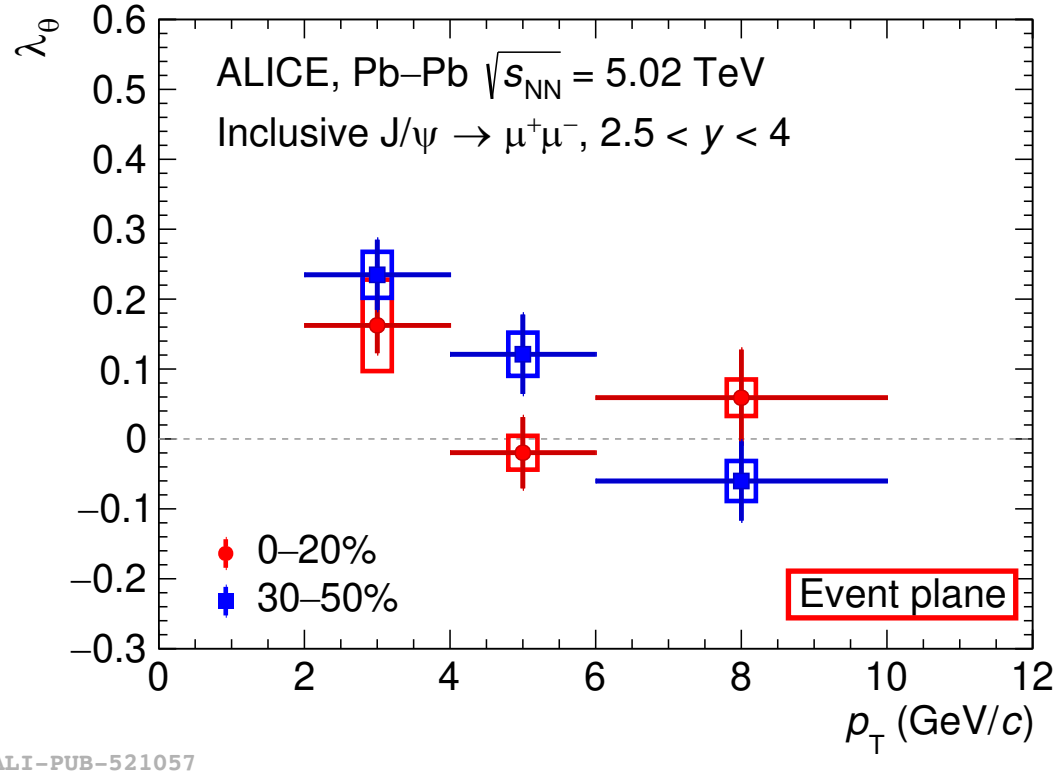
LHCb Collaboration, EPJC 73 (2013) 11
ALICE Collaboration, EPJC 78 (2018) 562

J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration, arXiv:2204.10171

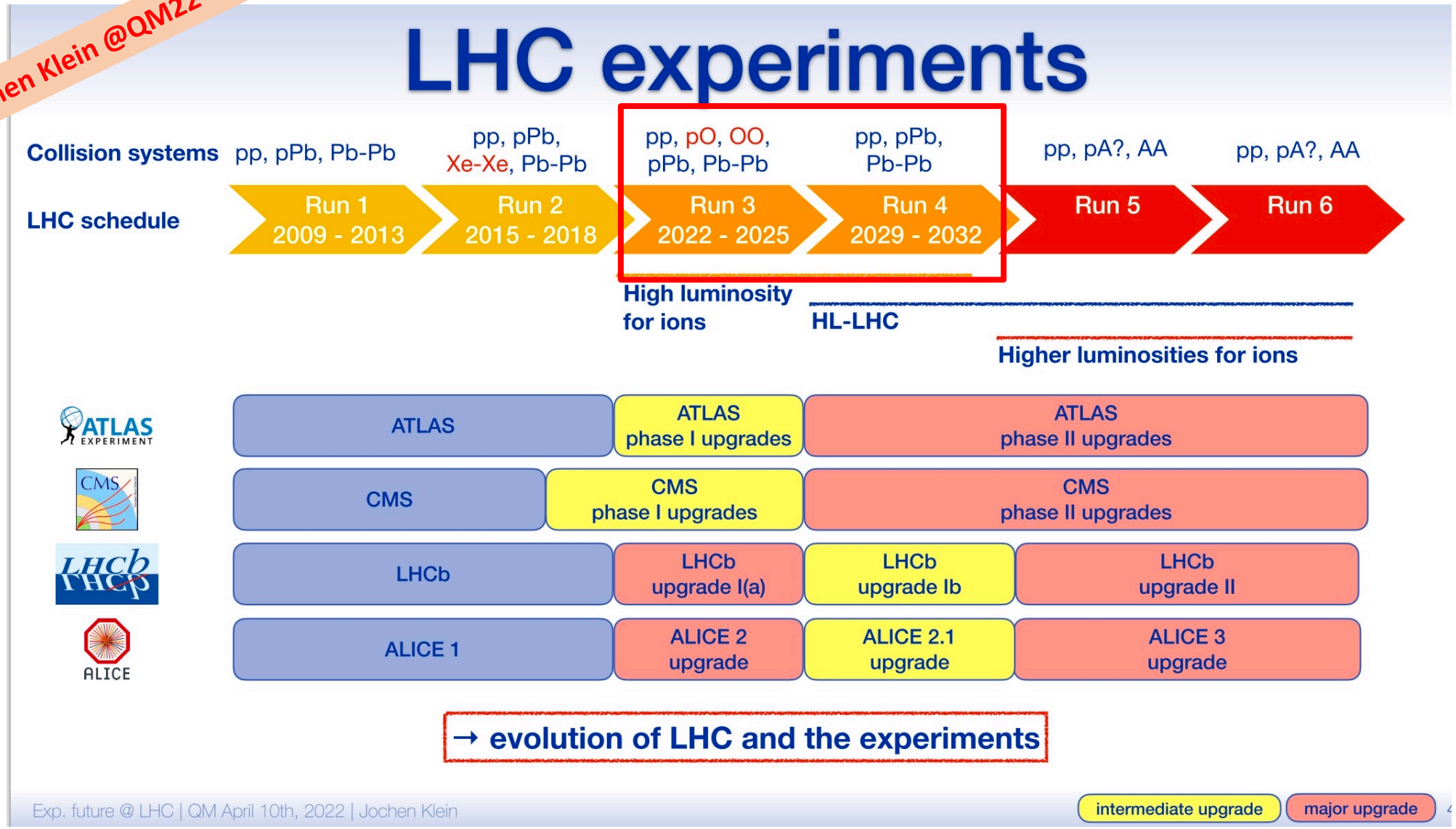


NEW



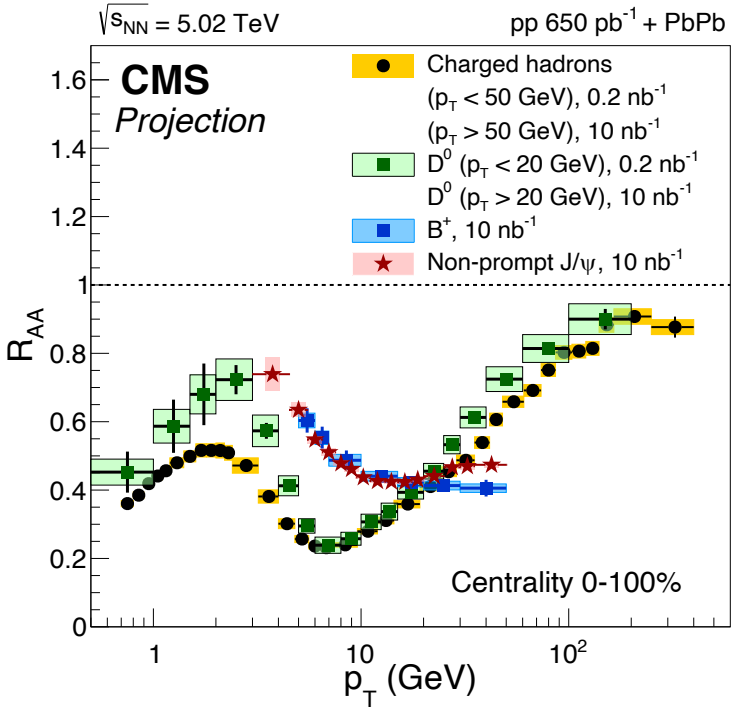
- First measurement of quarkonium polarization w.r.t the event plane
- Significant polarization (~**3.5σ**) observed in semicentral collisions (40-60%) in 2 < p_T < 6 GeV/c
- The deviation reaches (~**3.9σ**) at low p_T (2 < p_T < 4 GeV/c) in 30-50%
- Interpretation of results requires inputs from theoretical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

LHC experiments

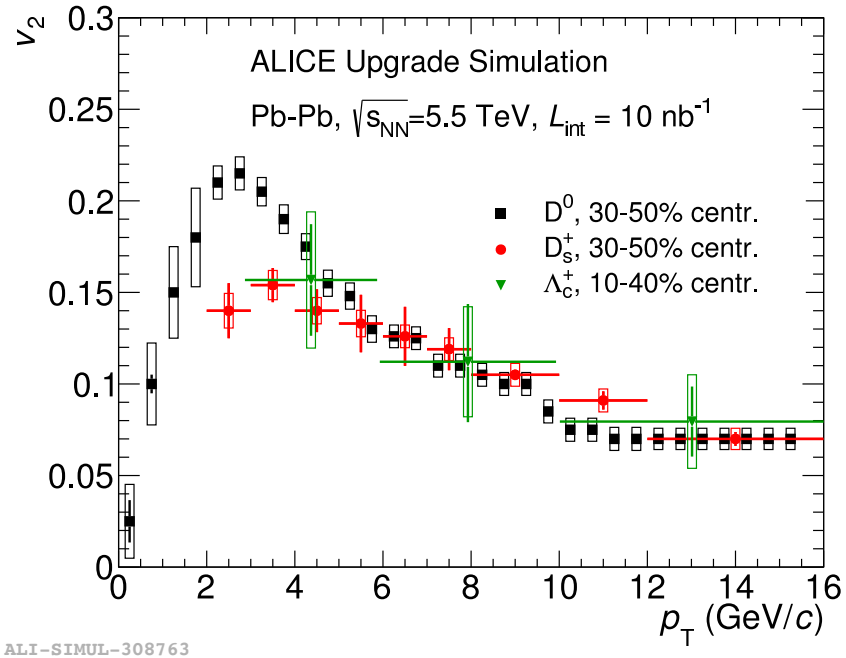


Heavy flavor transport (Run 3 & 4)

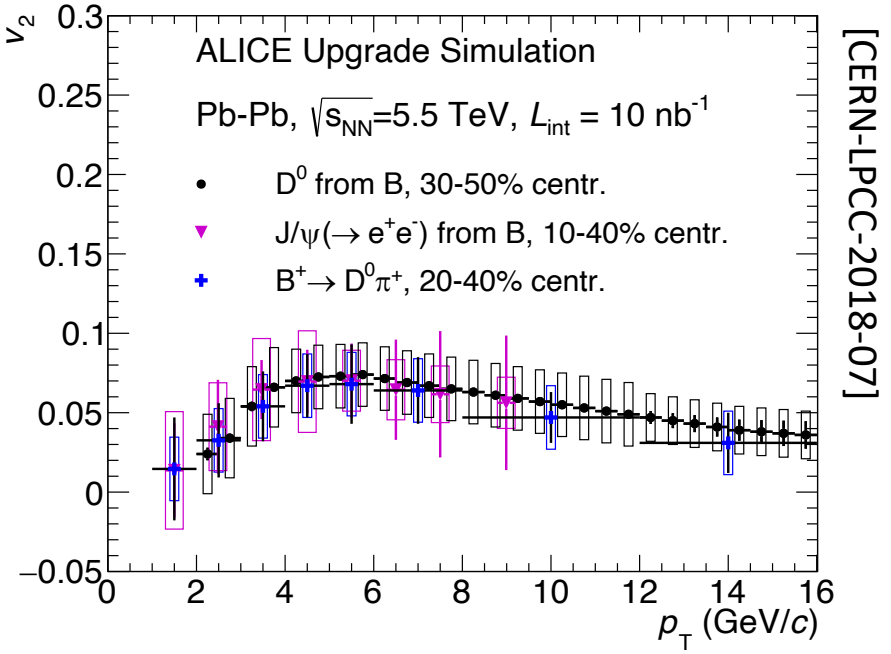
Precise R_{AA} for c and b mesons



v_2 for charm hadrons



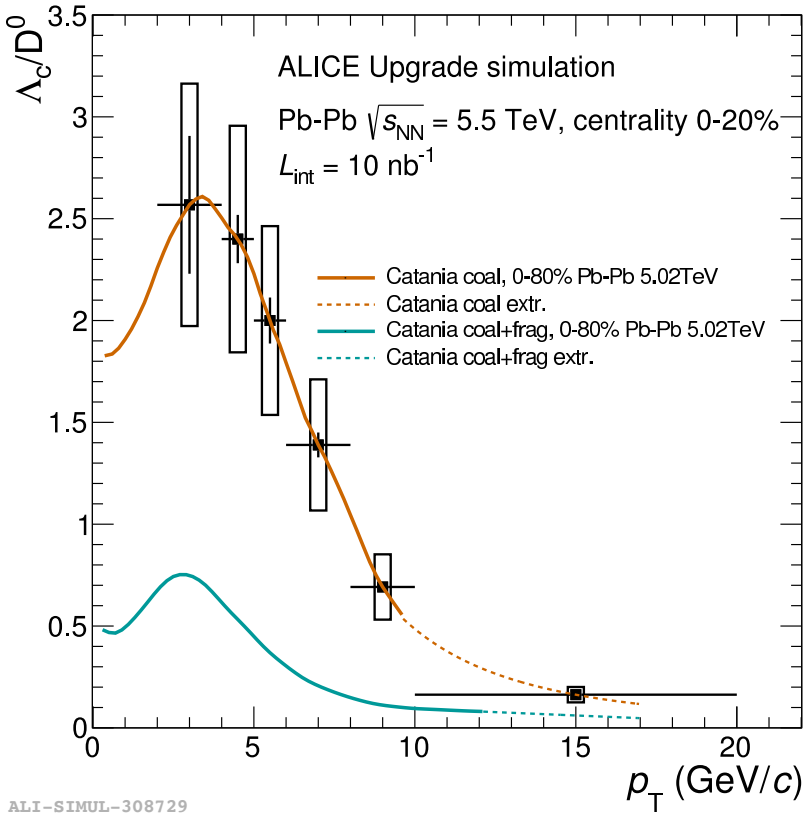
v_2 for beauty hadrons

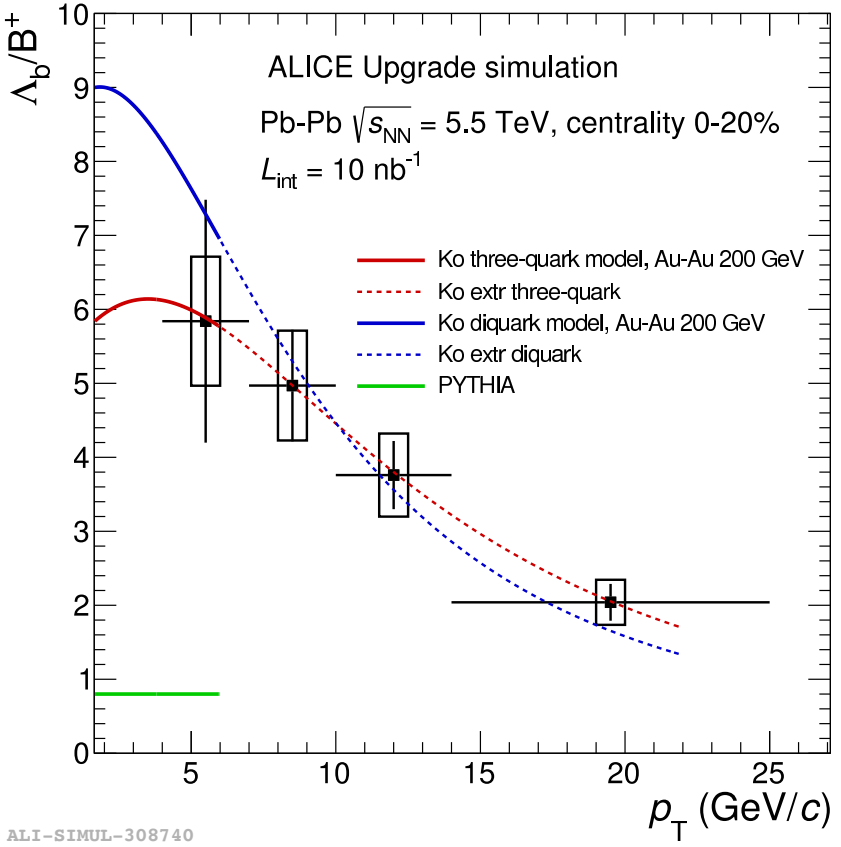


Measure spatial heavy flavour diffusion coefficient in the QGP

- Precision measurements of R_{AA} and v_2 for charm and beauty
- High statistics and improved vertexing detector

Heavy flavor hadronisation (Run 3 & 4)





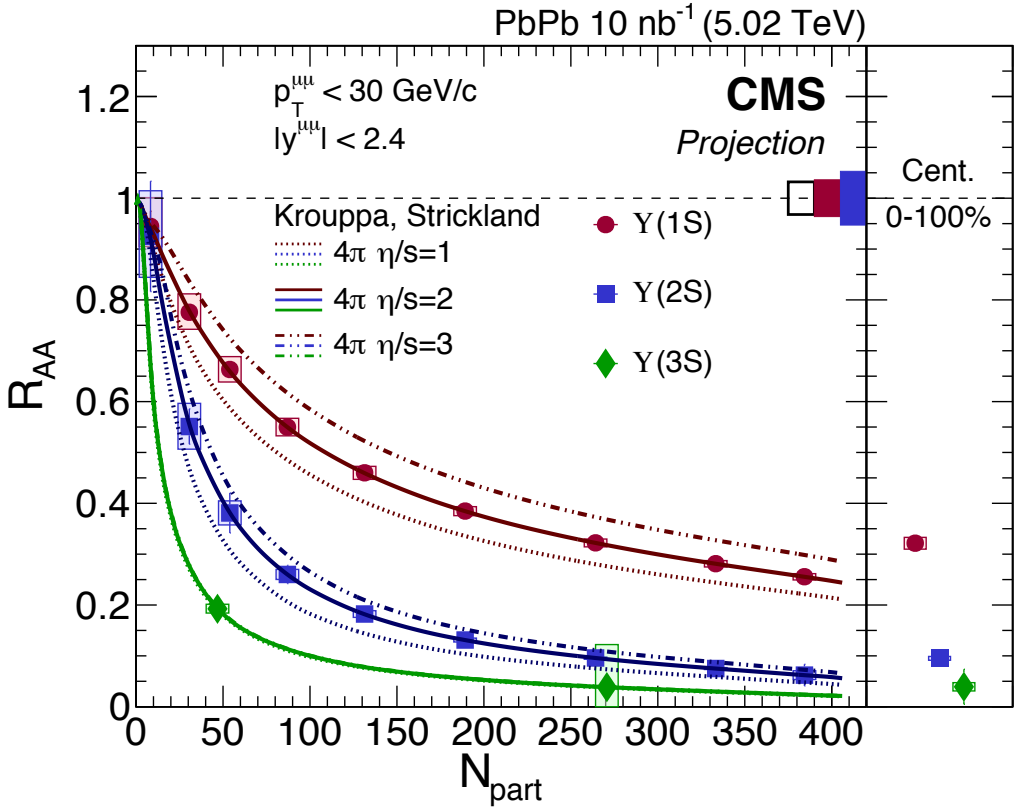
[CERN-LPCC-2018-07]

Constrain hadronisation models

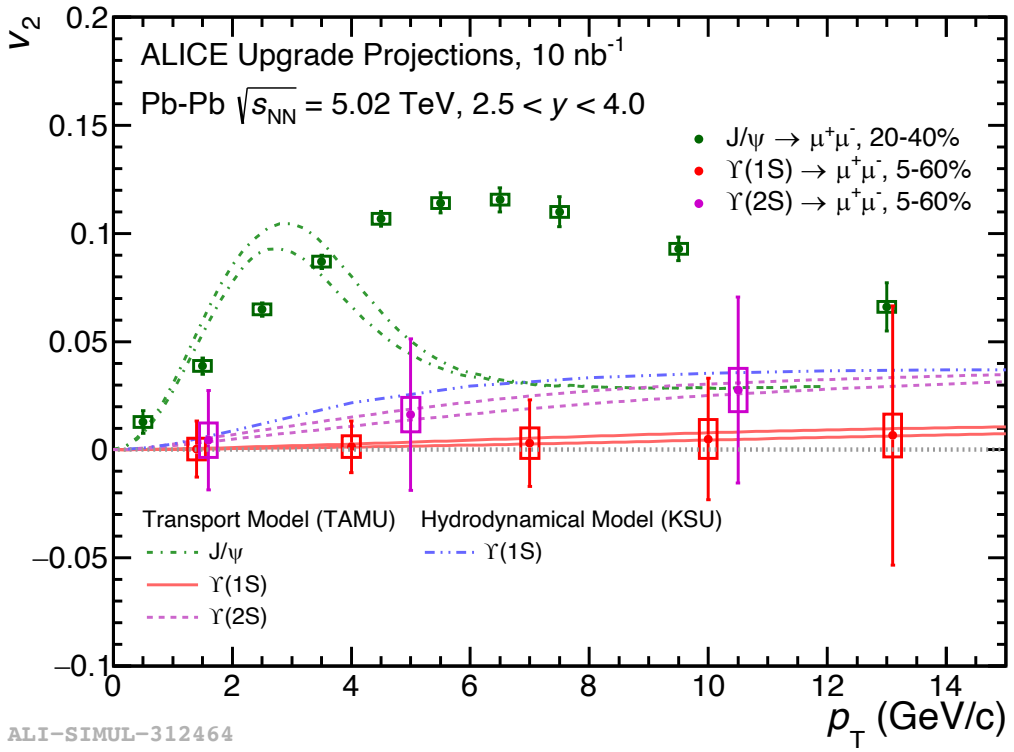
- measurements of baryon/meson ratios, nuclear suppression
- luminosity, vertexing, PID

Quarkonia production (Run 3 & 4)

R_{AA} for Y states



v_2 for J/ψ, Υ v_2

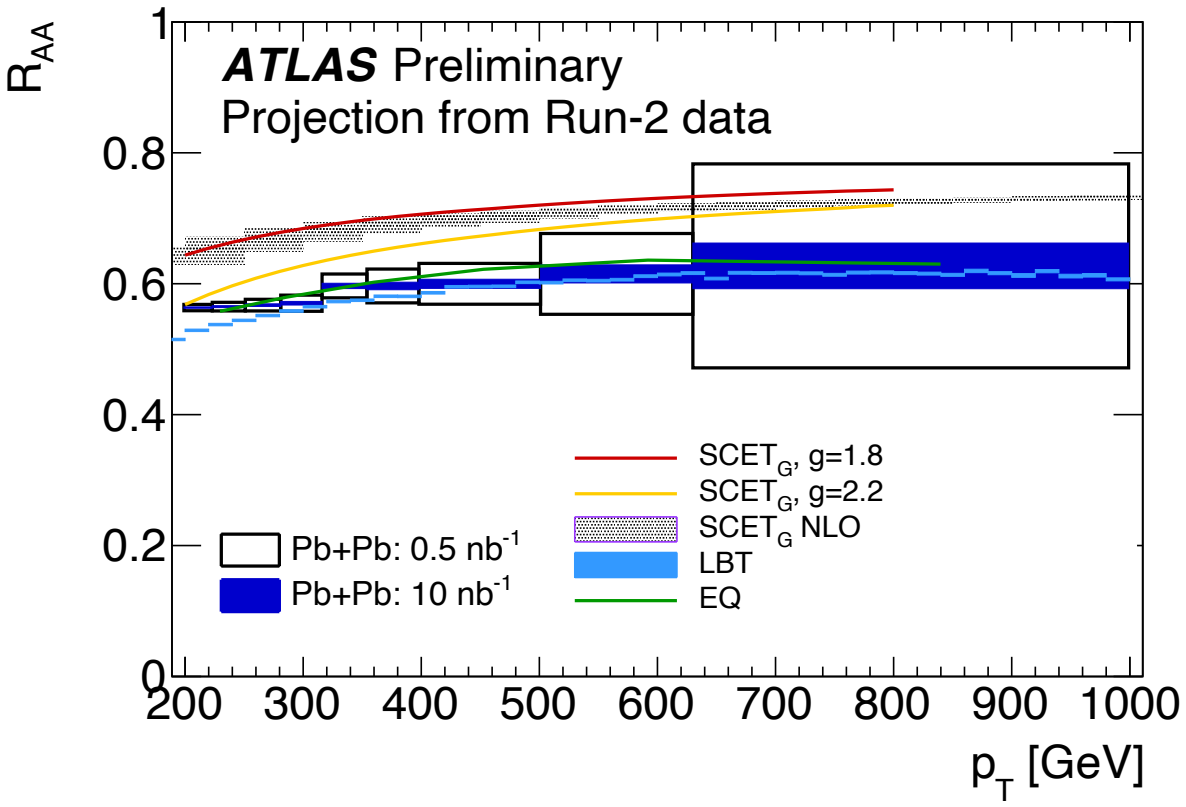


Understand heavy-quark dynamics in the QGP

- precision measurements of charmonium and bottomonium different states
- luminosity and PID

arXiv:1812.06772 ; CERN-LPCC-2018-07

Precise jet R_{AA} measurement up to high p_T (Run 3 & 4)



Large samples allow us to look at tagged jets, substructure…

- Understand mass and time dependence
- High statistics and new collision systems (OO, pO, also high-multiplicity pp)

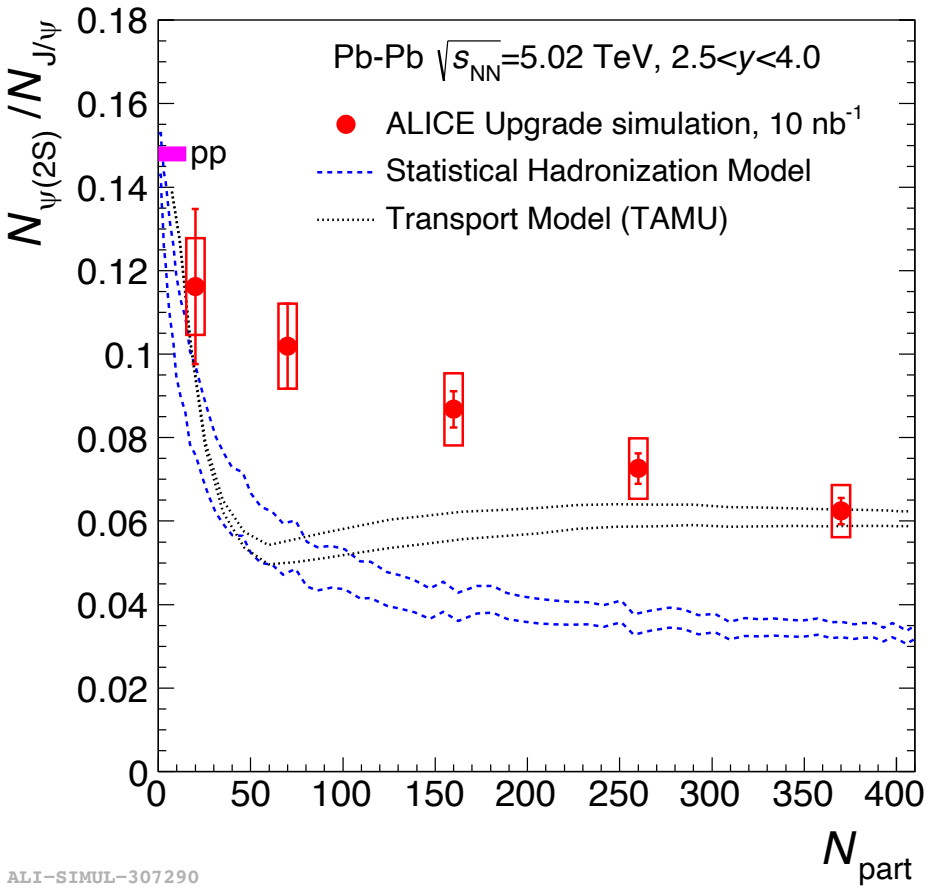
arXiv:1812.06772 ; CERN-LPCC-2018-07

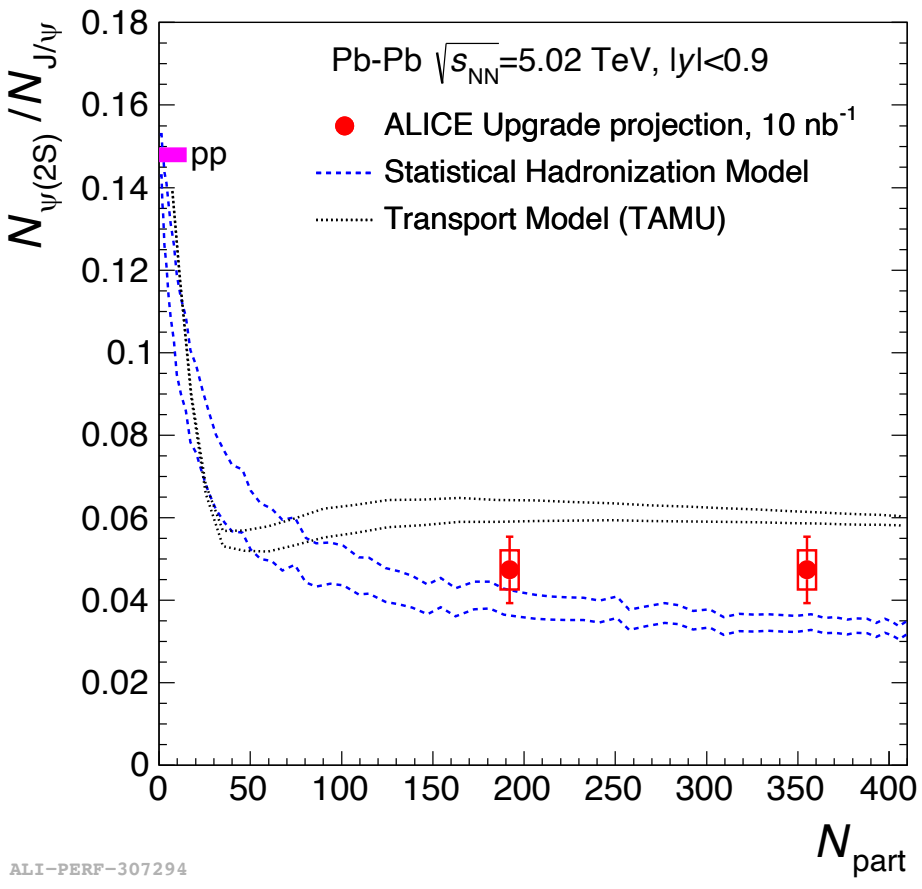
Summary and outlook

- **Recent measurements of open heavy flavour and quarkonium production at ALICE with LHC are presented**
  - Non-universal charm hadronisation process
  - Mass-dependent energy loss was observed in central Pb-Pb collisions
  - J/ψ (re-)generation dominant at low p_T
  - Significant non-zero polarization observed w.r.t event plane in semicentral at low p_T
- **LHC upgrade program for Run 3 and 4 crucial for heavy flavour and jet measurements**

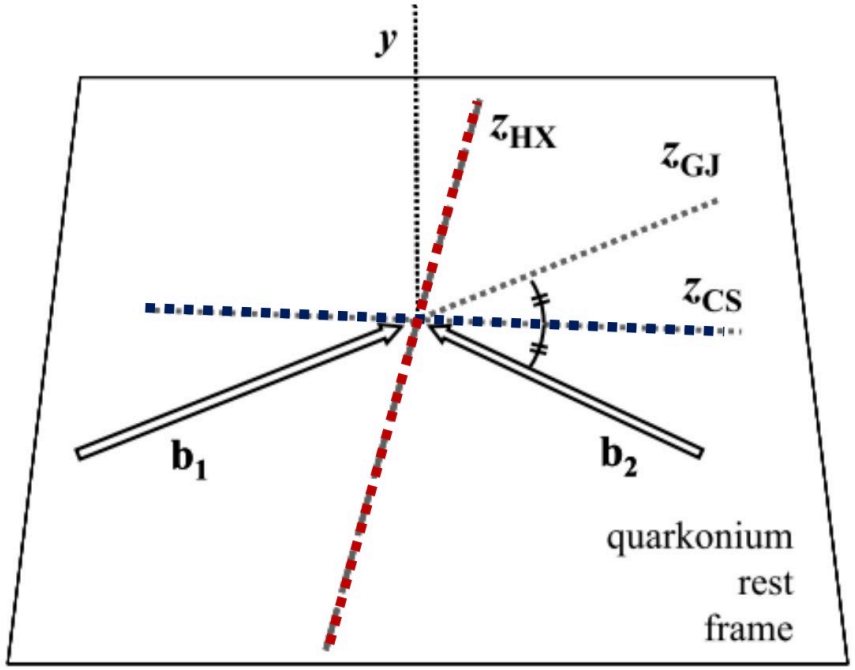
Thanks

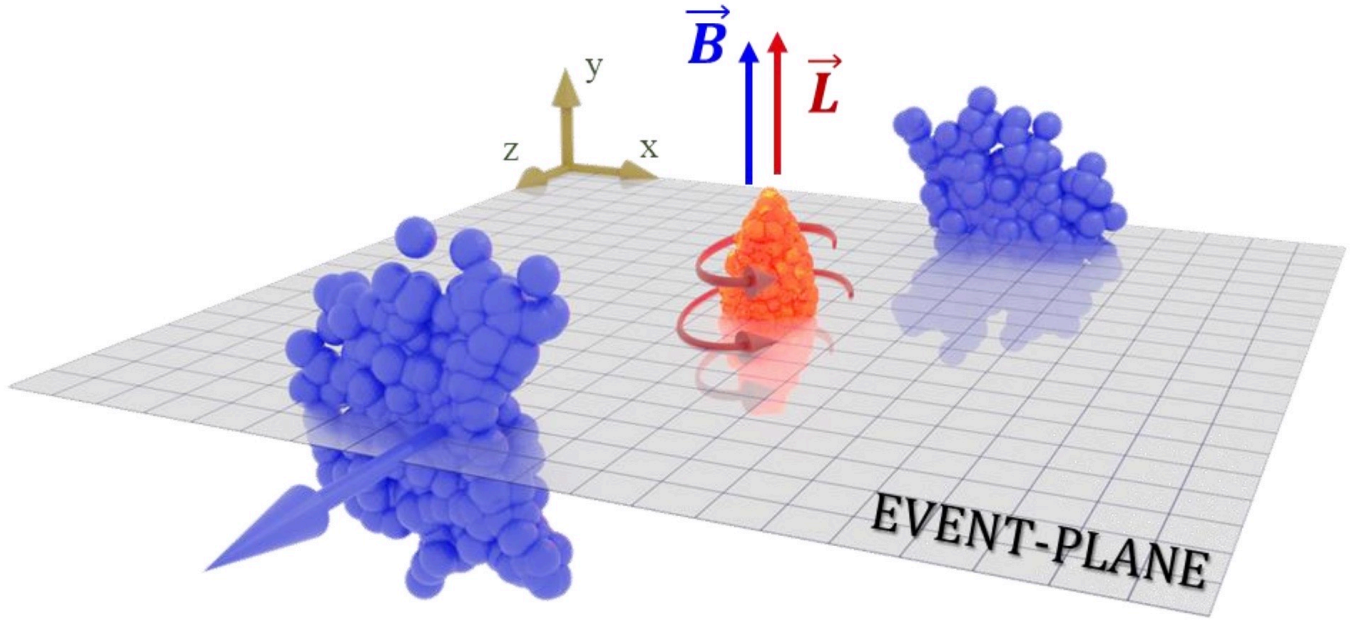
Quarkonia production **(Run 3 & 4)**





Quarkonium polarization





Figures from P. Faccioli et al. EPJ C69 (2010) 657-673

- Constrains quarkonium production mechanism in pp collisions.
- Heavy quark pairs are produced in the earlier stage of AA collision and can experience both the short living ***B*** and the ***L*** of the rotating medium, can access the spin alignment of w.r.t a chosen axis