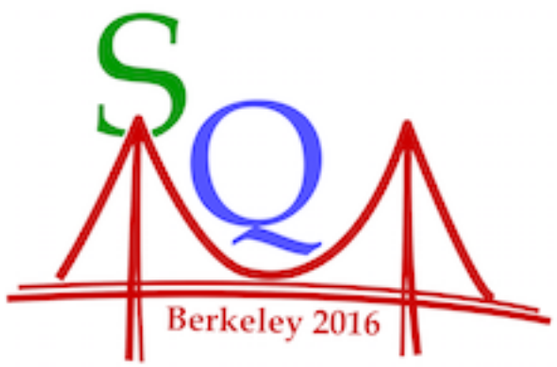
ALICE results on open heavy flavour and quarkonium production

Javier Castillo
for the
ALICE Collaboration



Outline

- Introduction
- ALICE
- Measurements in pp and p-Pb collisions
  - New results from LHC run2
  - More multi-differential analyses
  - Stress test of production models
- Measurements in Pb-Pb collisions
  - New results from LHC run2
  - Probing interactions of c and b quarks with the medium
- Summary

Introduction

- Heavy quarks (c, b) are produced in initial high-Q^2 scattering processes
  - Production is calculable with pQCD
  - The bulk of heavy-flavour results in pp collisions is well described by pQCD based models
- pp and p-Pb collisions
  - pp collisions are the reference for p-Pb and Pb-Pb collisions
  - p-Pb collisions provide the control experiment to study Cold Nuclear Matter (CNM) effects
  - Multi-differential measurements impose stronger constraints to the models and could address specific mechanisms such as
    - multi-parton interactions (MPI)
    - charm fragmentation and jet properties
    - collectivity in small systems
- Pb-Pb collisions
  - heavy quarks propagate and interact with the medium constituents
    - study energy loss mechanisms
    - address colour-charge and mass dependence of parton energy loss
    - do c and b quarks participate in the collective expansion of the system?

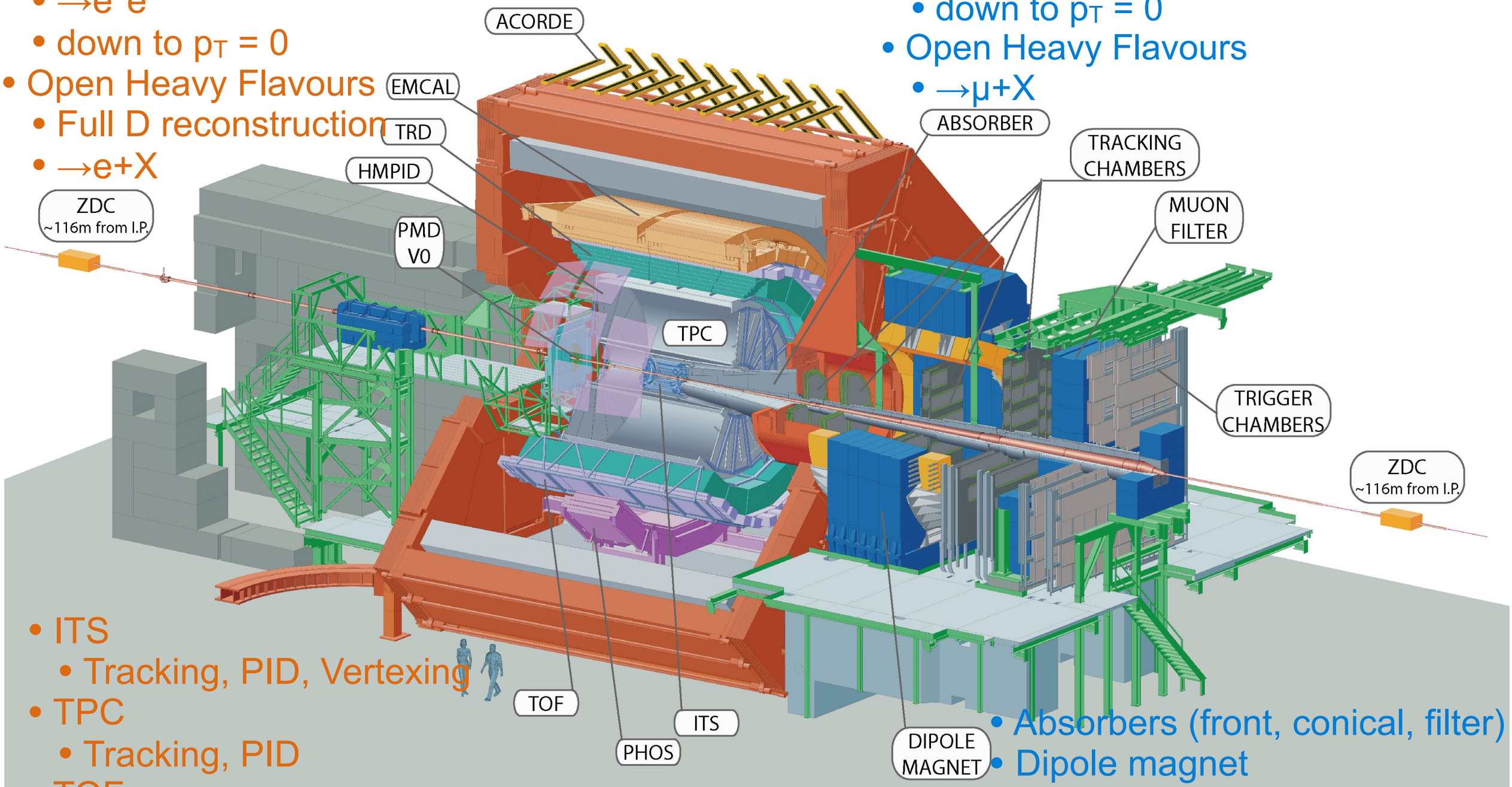
Introduction

- Quarkonia (c-cbar and b-bbar bound states) are important probes of QCD matter
  - Heavy-quark pair production is a perturbative process
  - Their binding is non-perturbative
  - Produced early in the collision
    - Sensitive to the properties of the surrounding medium
- In pp and p-Pb collisions
  - Test of production models
  - Reference for p-Pb and Pb-Pb studies
  - Study Cold Nuclear Matter effects
- In Pb-Pb collisions
  - Quarkonia could be suppressed in the QGP by colour screening
    - Different binding energies mean that sequential suppression of different quarkonium states is expected
  - Quarkonia could be regenerated in the QGP or at the phase boundary
    - Regeneration is expected to be more important for charmonia than for bottomonia due to the larger number of initially produced c-cbar pairs

ALICE

Central Barrel ($|\eta_{lab}| < 0.9$)

- Quarkonia
  - $\rightarrow e^+e^-$
  - down to $p_T = 0$
- Open Heavy Flavours
  - Full D reconstruction
  - $\rightarrow e+X$



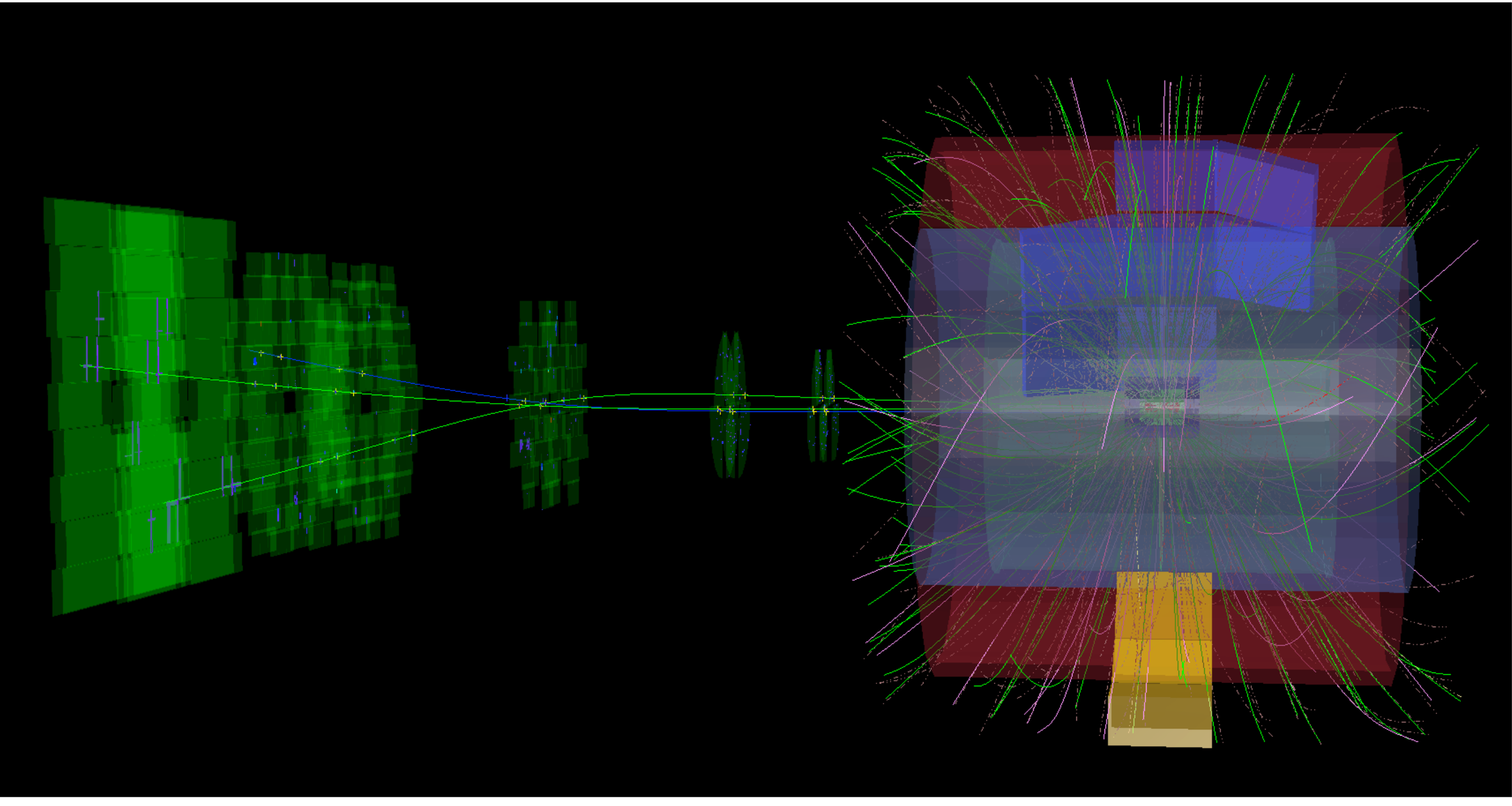
- ITS
  - Tracking, PID, Vertexing
- TPC
  - Tracking, PID
- TOF
  - PID

Muon spectrometer ($-4.0 < \eta_{lab} < -2.5$)

- Quarkonia
  - $\rightarrow \mu^+\mu^-$
  - down to $p_T = 0$
- Open Heavy Flavours
  - $\rightarrow \mu+X$

- Absorbers (front, conical, filter)
- Dipole magnet
- Tracking chambers
- Trigger system

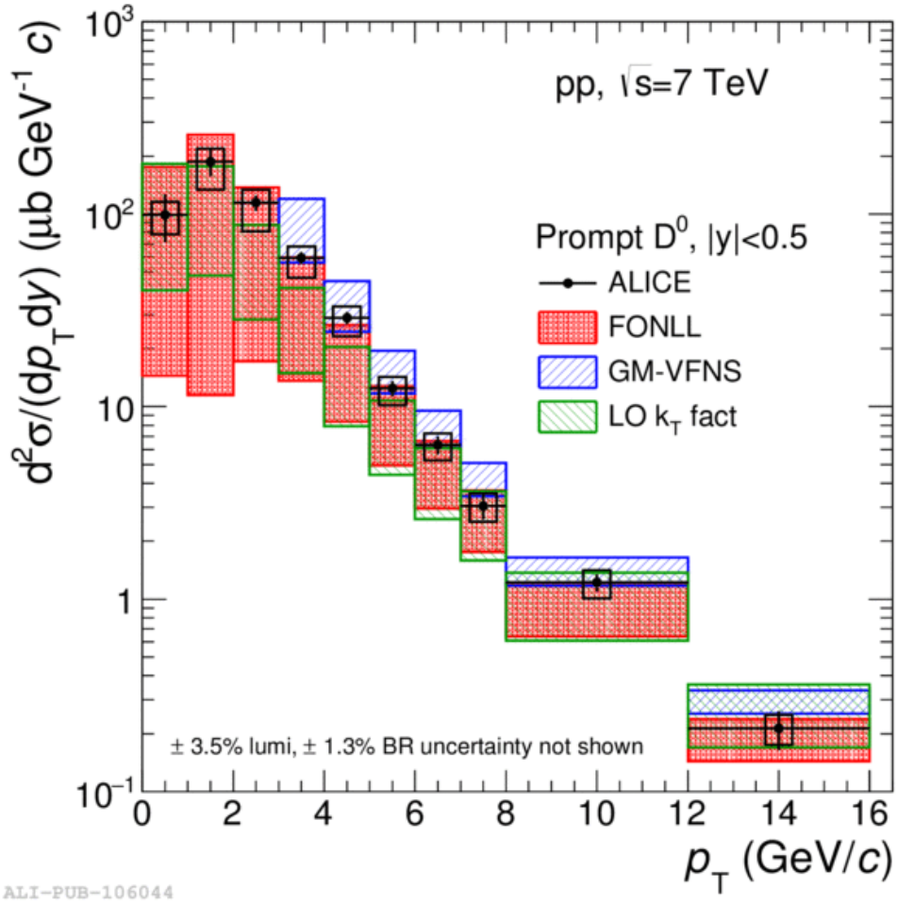
pp and p-Pb collisions

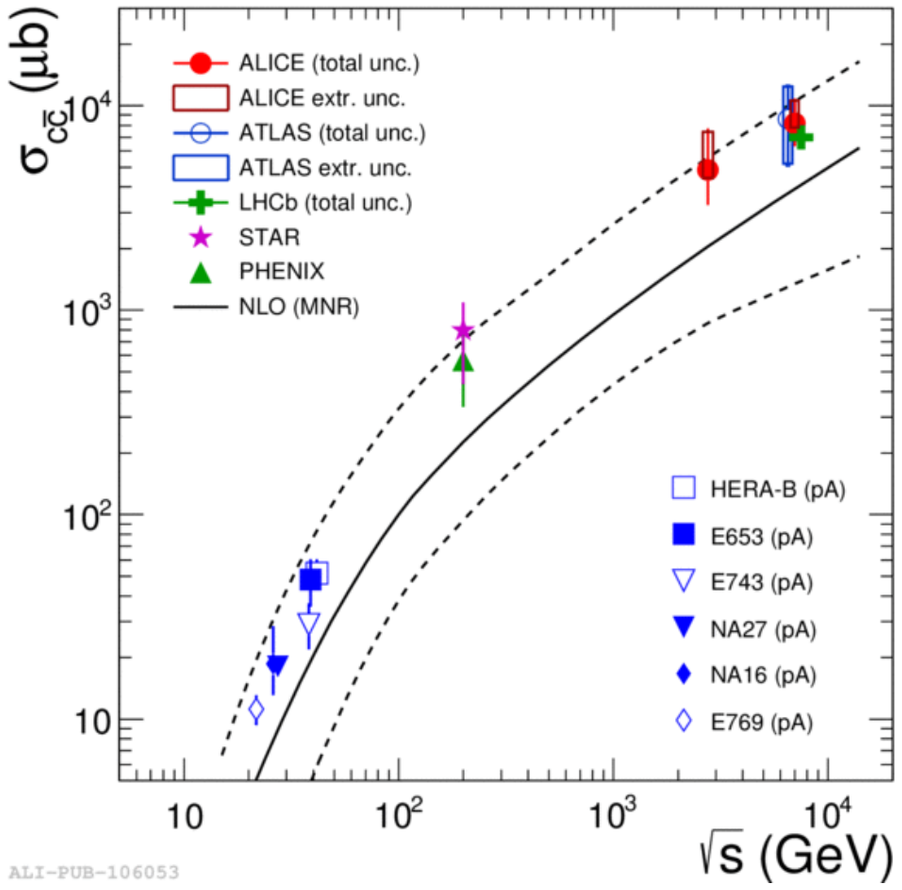


D mesons in pp collisions

arXiv:1605.07569

- New D^0-meson measurement down to $p_T = 0$ in pp collisions at 7 TeV
  - No secondary vertex reconstruction nor topological selections
  - Background subtraction by event-mixing, like-sign or rotation methods





- Reproduced by theoretical calculations
  - FONLL: JHEP 0407 (2004) 033, JHEP 1210 (2012) 137
  - GM-VFNS: EPJC 72 (2012) 2082
  - LO k_T fact: PRD 87 (2013) 094022
- Reduced uncertainty on total charm production cross section

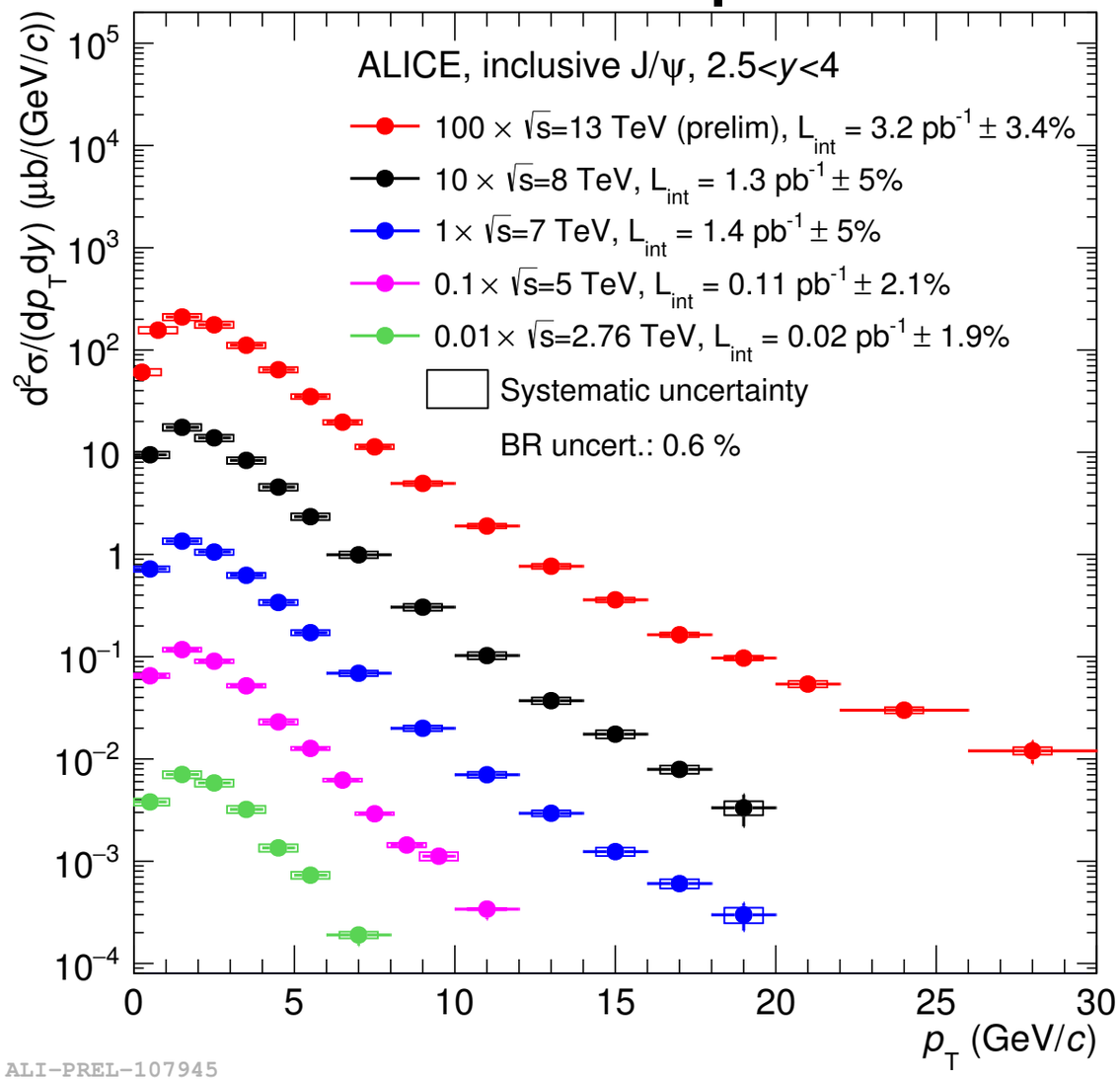
F. Colomaria, Tu. 16:00

Charmonia in pp collisions

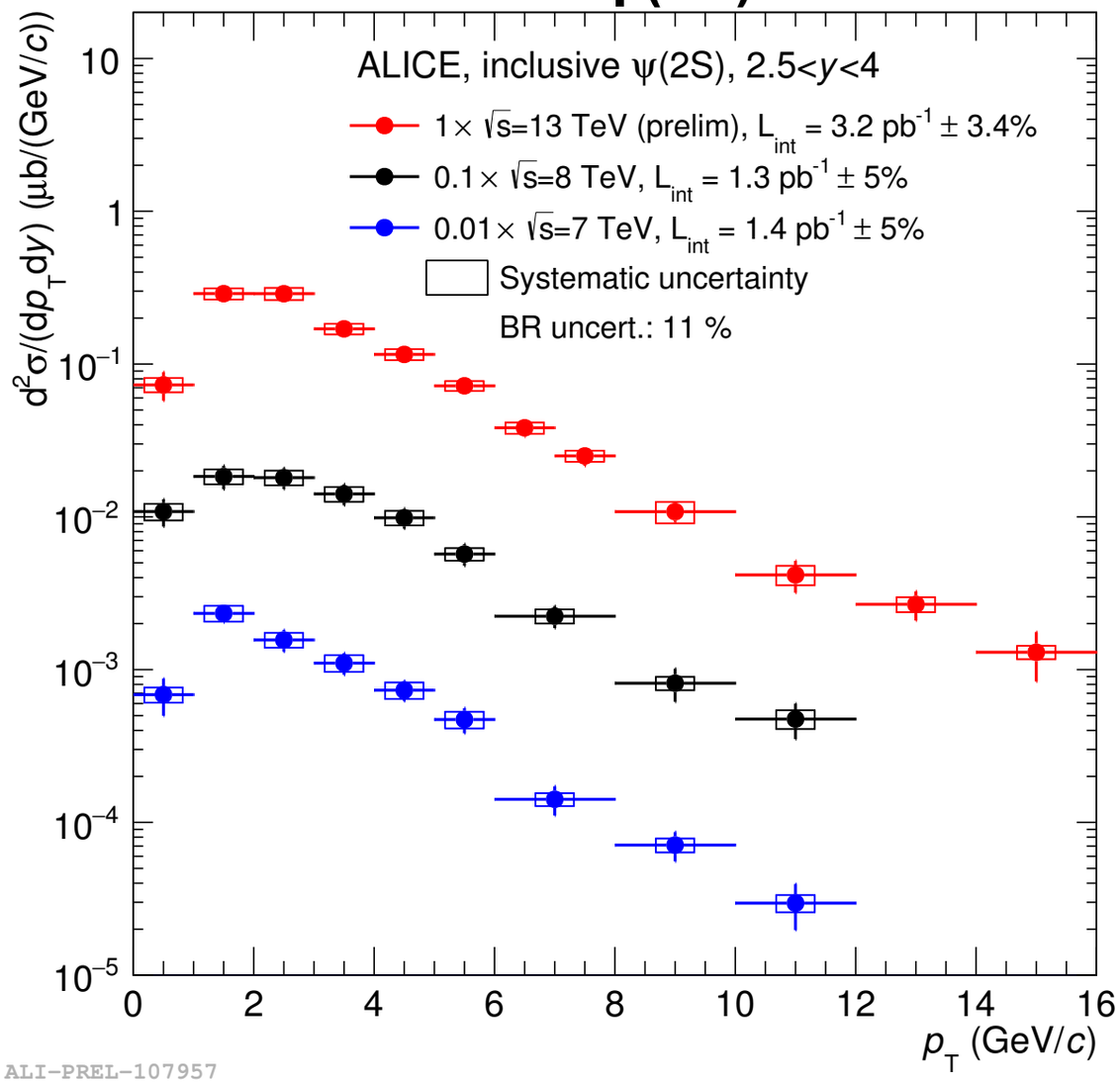
PLB 718 (2012) 2, CERN-EP-2016-162, EPJC 74 (2014) 29744, EPJC 76 (2016) 184

- New charmonium measurements in pp collisions at 5 and 13 TeV

inclusive J/ψ



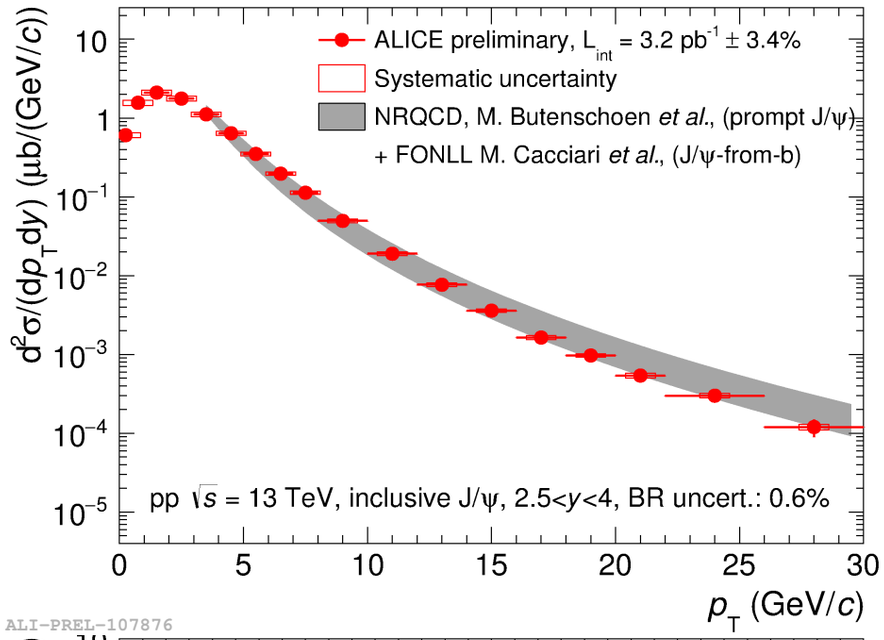
inclusive ψ(2S)

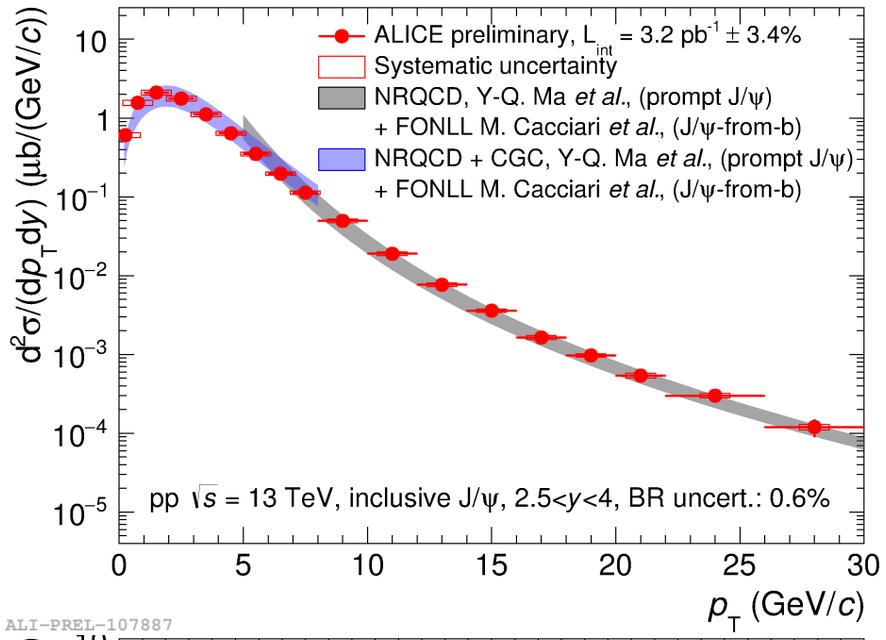


- J/ψ and ψ(2S) measured at five and three collision energies, respectively
  - Up to p_T = 30 GeV/c at 13 TeV
  - Only ψ(2S) measurement at forward-y at 8 and 13 TeV

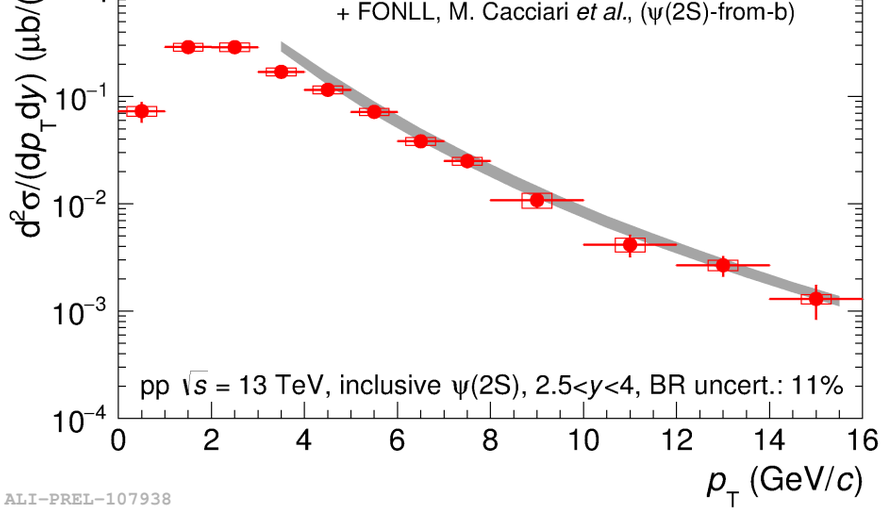
H. Pereira Da Costa, Tu. 16:00

Charmonia in pp collisions at 13 TeV



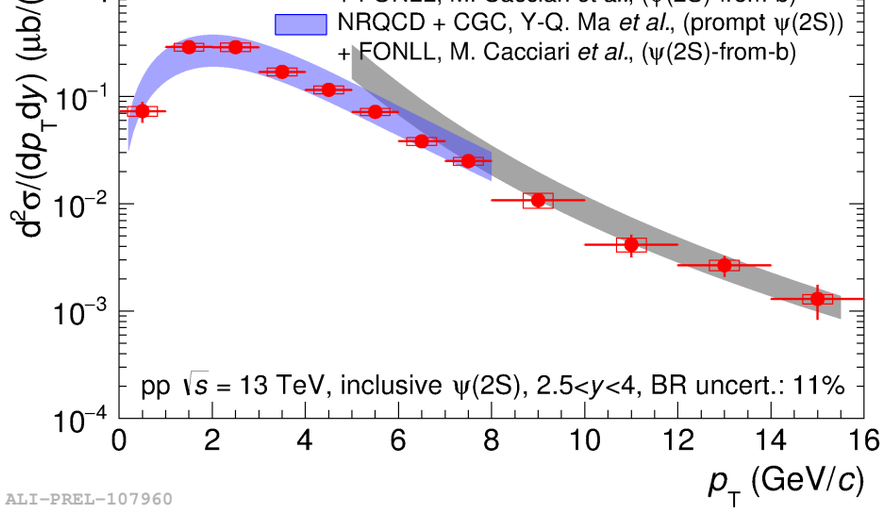


ALI-PREL-107876



ALI-PREL-107938

ALI-PREL-107887



ALI-PREL-107960

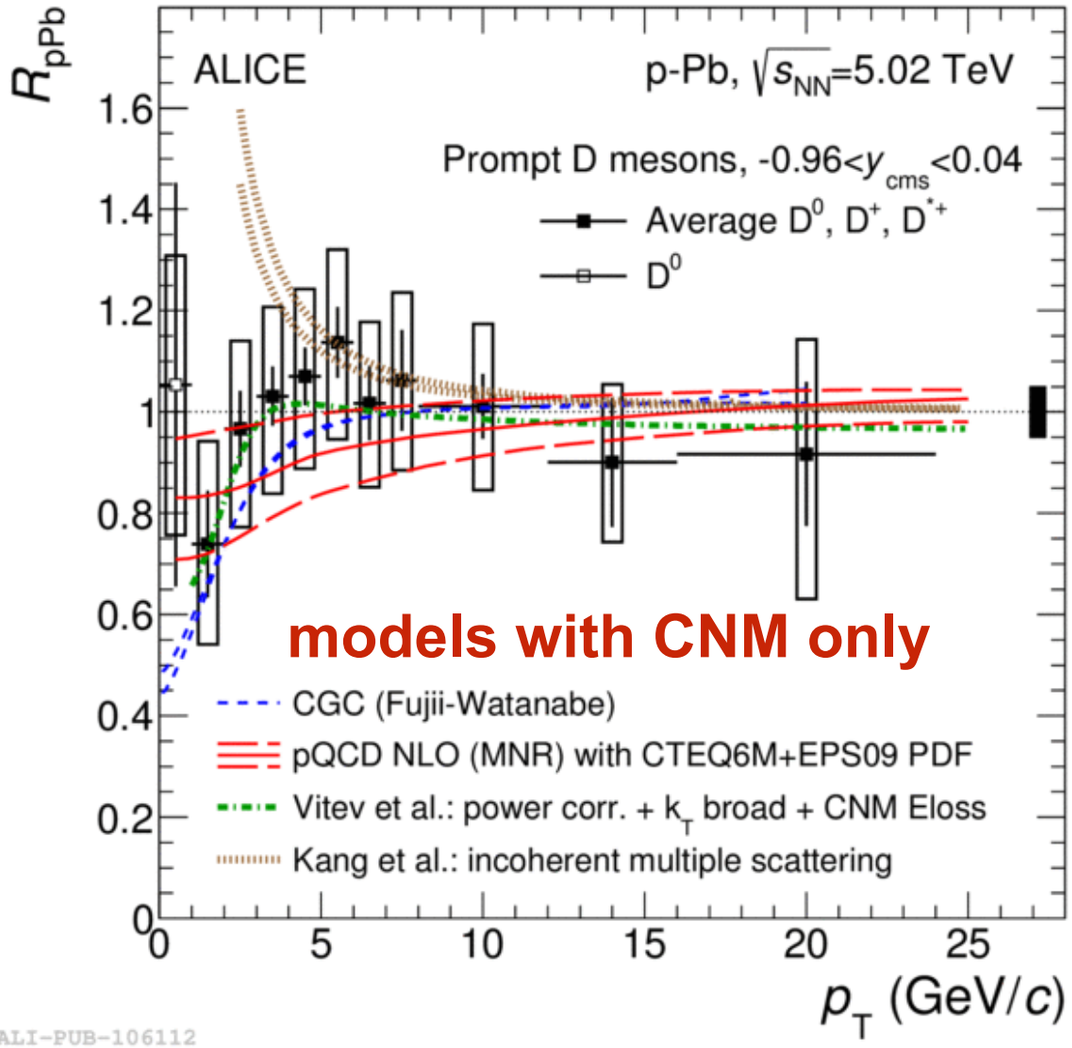
- NRQCD calculations for prompt J/ψ (ψ(2S)) + FONLL calculations for non-prompt J/ψ (ψ(2S)) reproduce the p_T-differential cross section at high p_T
- NRQCD + CGC reproduces the low p_T region

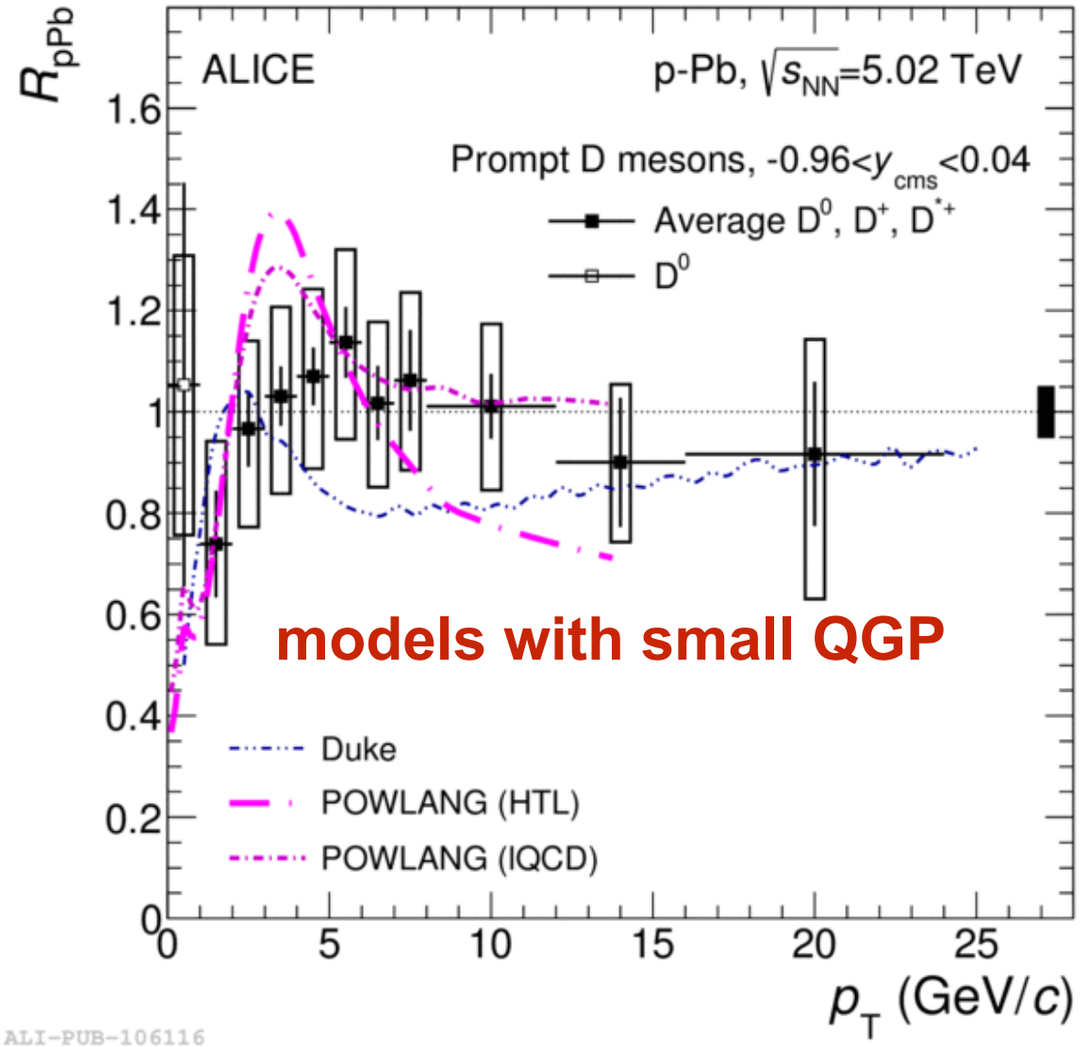
H. Pereira Da Costa, Tu. 16:00

D-meson R_{pPb}

arXiv:1605.07569

- D^0 measured down to zero p_T also in p-Pb collisions at 5 TeV





- R_{pPb} of D mesons consistent with unity
  - no indication for suppression at intermediate/high p_T
  - data do not favour a suppression larger than 20% at p_T ~ 5-10 GeV/c
- R_{pPb} described within uncertainties by models including initial- or final-state effects

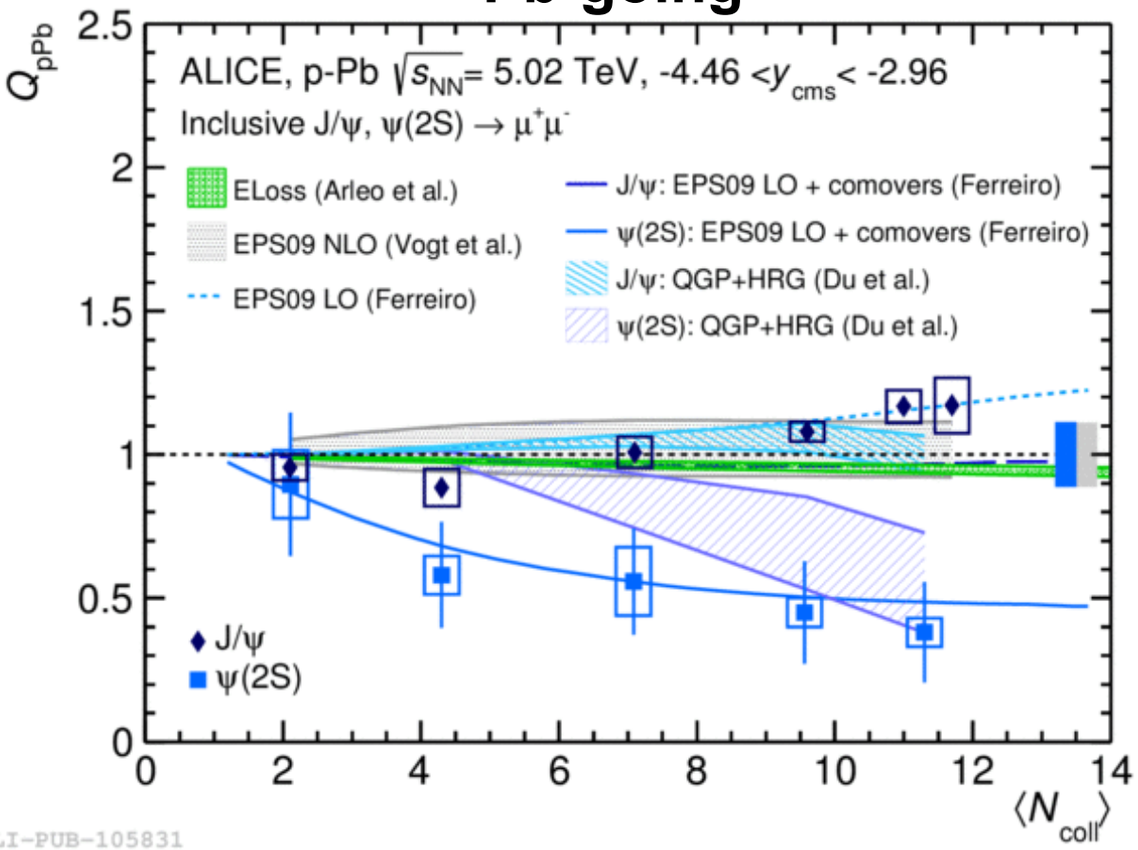
C. Terrevoli, Tu. 14:40

J/ψ and ψ(2S) in p-Pb collisions at 5.02 TeV

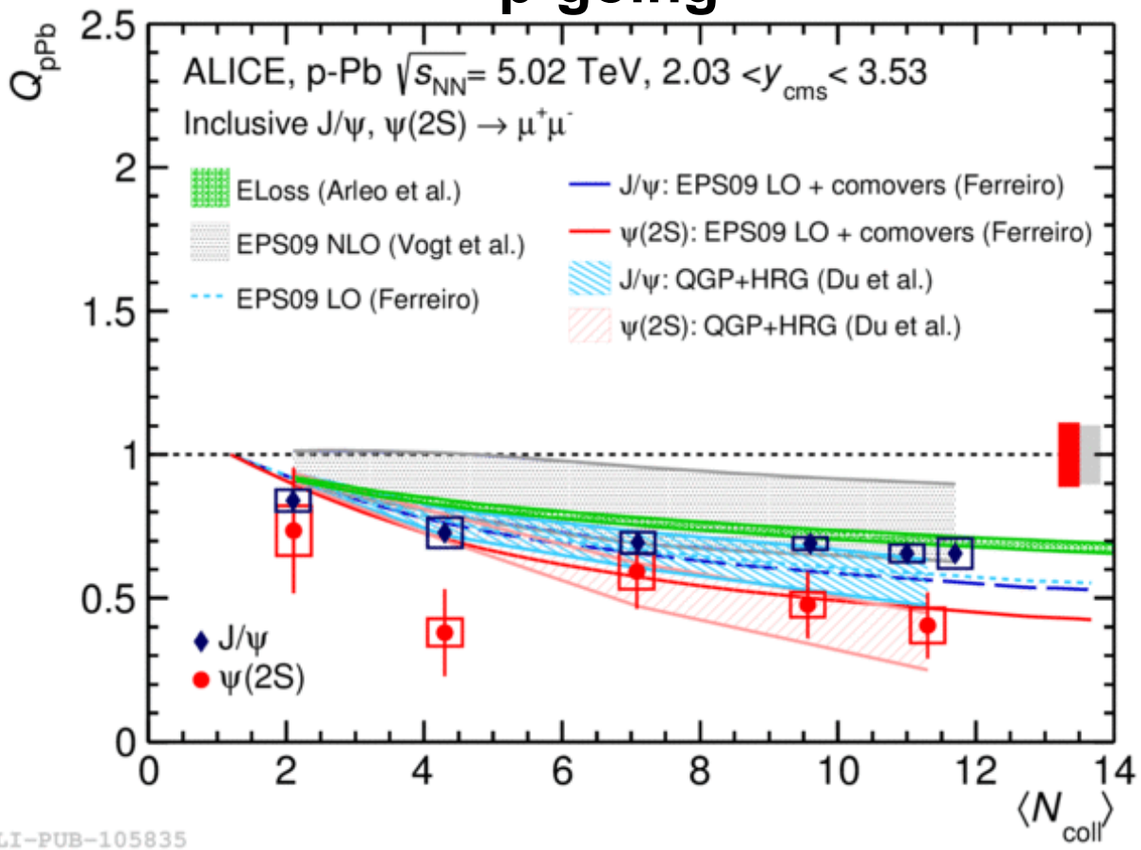
JHEP 1606 (2016) 050

- Centrality dependence of J/ψ and ψ(2S) in p-Pb collisions at 5.02 TeV

Pb-going



p-going

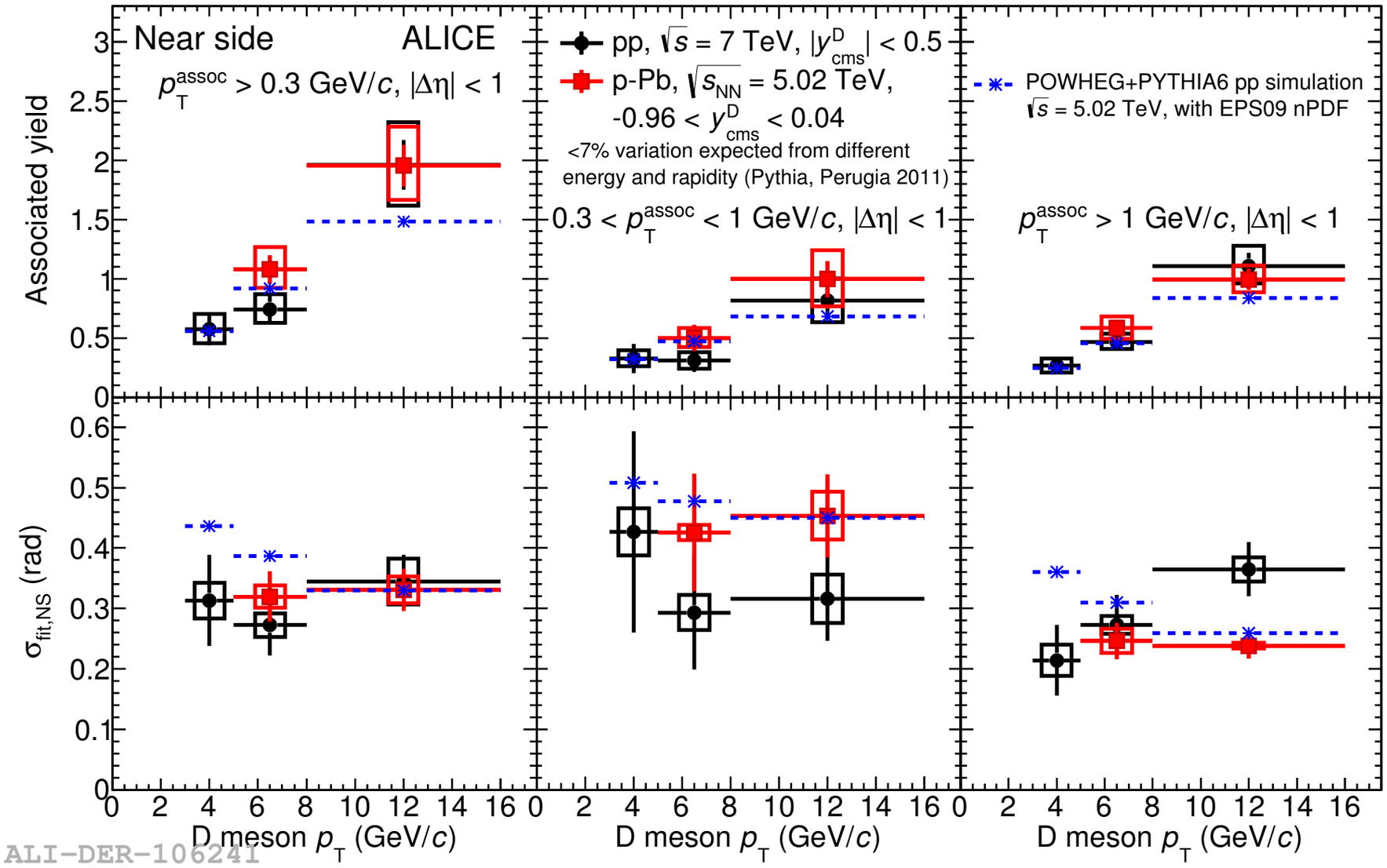


- J/ψ is suppressed in the p-going direction
  - Models including shadowing or energy loss mechanisms can describe the observed centrality dependence
- ψ(2S) is more suppressed than J/ψ
  - Stronger effect in the Pb-going than in the p-going direction
  - Effect increases with increasing centrality
  - Only models including some final-state interaction with co-moving medium reproduce the results

D-hadron correlations in pp and p-Pb

arXiv:1605.06963

- Azimuthal correlation between D mesons and charged hadrons
  - near-side Gaussian + away-side Gaussian + constant baseline
- Comparison of near-side yield and width in **pp (7 TeV)** and **p-Pb (5 TeV)** collisions



ALI-DER-106241

- Near-side peak properties compatible between the two collision systems
  - No signs of modifications due to initial-state or final-state effects are observed within uncertainties

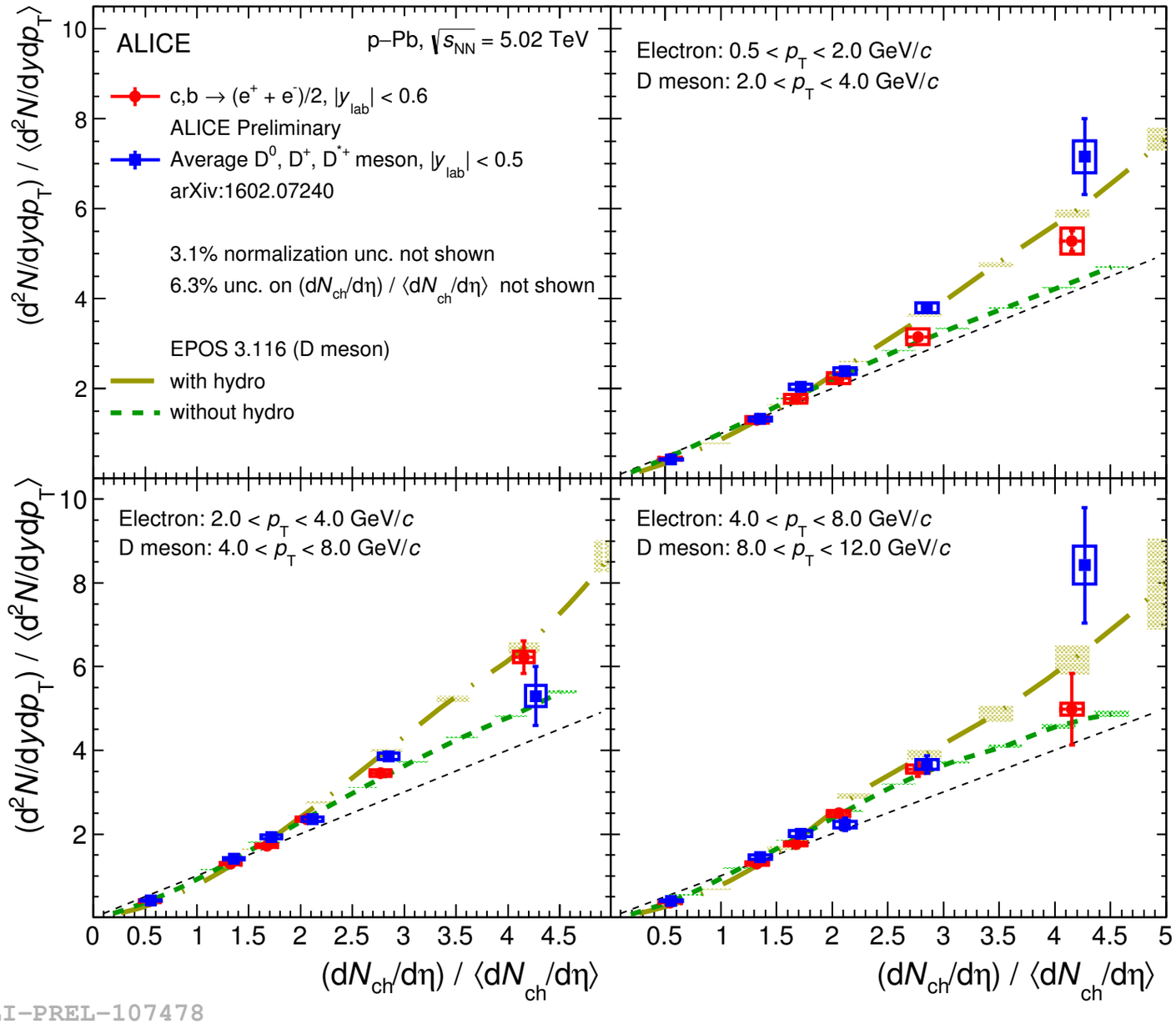
F. Colomaria, Tu. 16:00

HF production versus multiplicity

- Self-normalised yields vs relative charged-particle multiplicity at mid-rapidity in p-Pb collisions at 5 TeV

- electrons from HF decays and D mesons
  - different p_T range for better kinematic comparability
  - compatible within uncertainties
  - increase faster than linear

- EPOS 3 with initial conditions and with or without hydrodynamic evolution (including MPIs):
  - D mesons more compatible with EPOS 3 with hydro

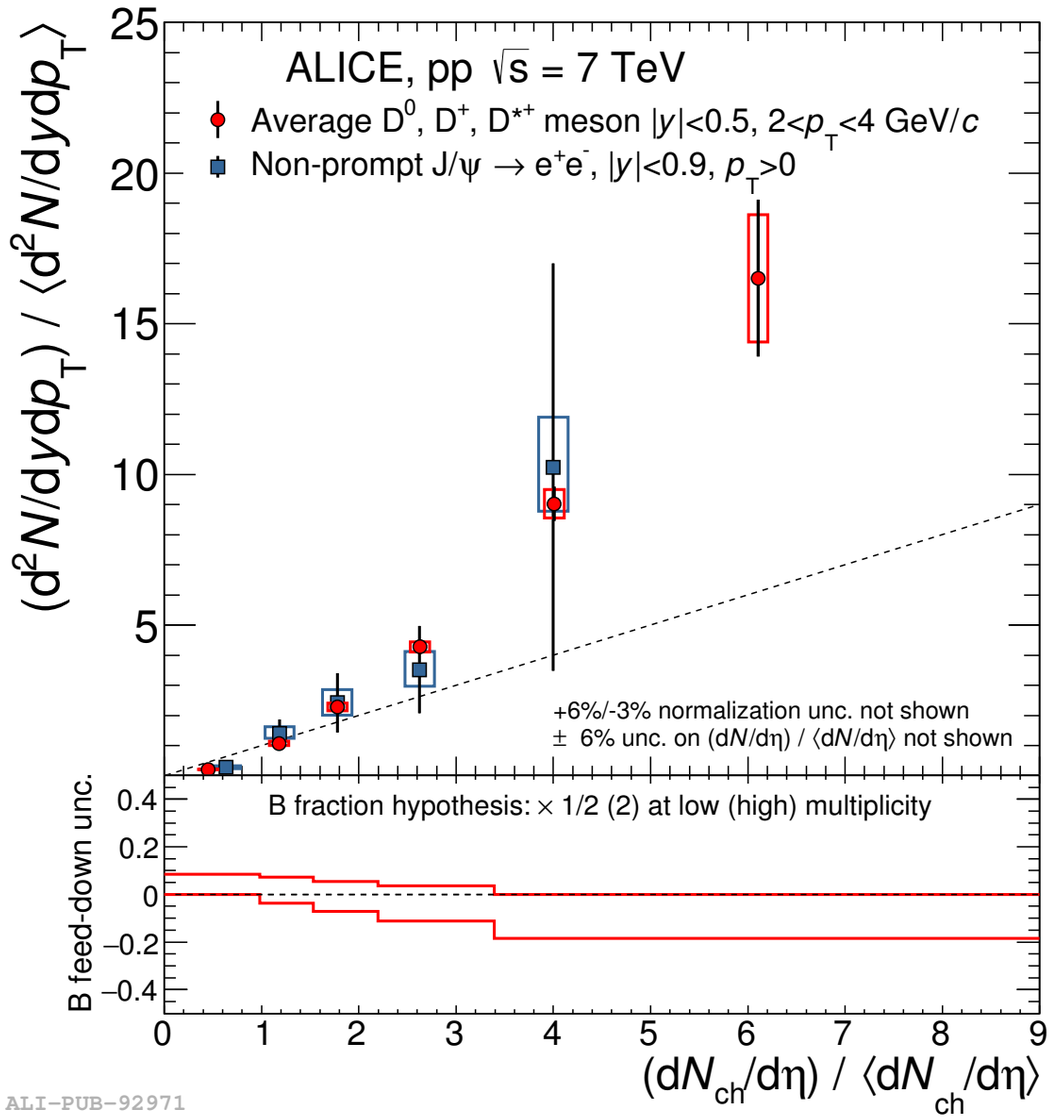


J. Wagner, Tu. 17:40

Charm vs Beauty

JHEP 1509 (2015) 148

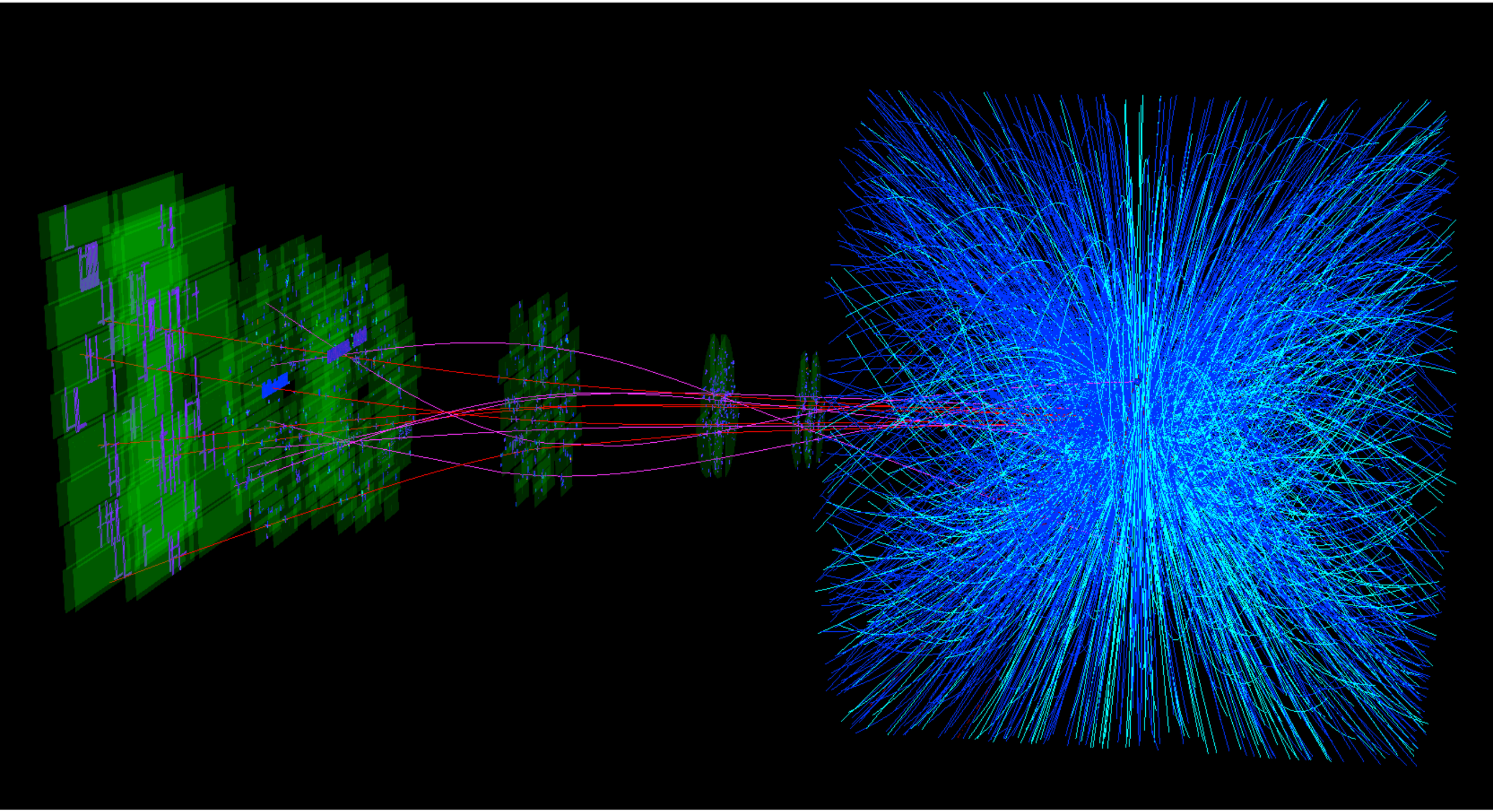
- Self-normalised yields vs relative charged-particle multiplicity at mid-rapidity in pp collisions at 7 TeV



- D mesons (charm) and non-prompt J/ψ (beauty)
  - compatible within uncertainties
  - increase faster than linear
  - similar behaviour for charm and beauty

J. Wagner, Tu. 17:40

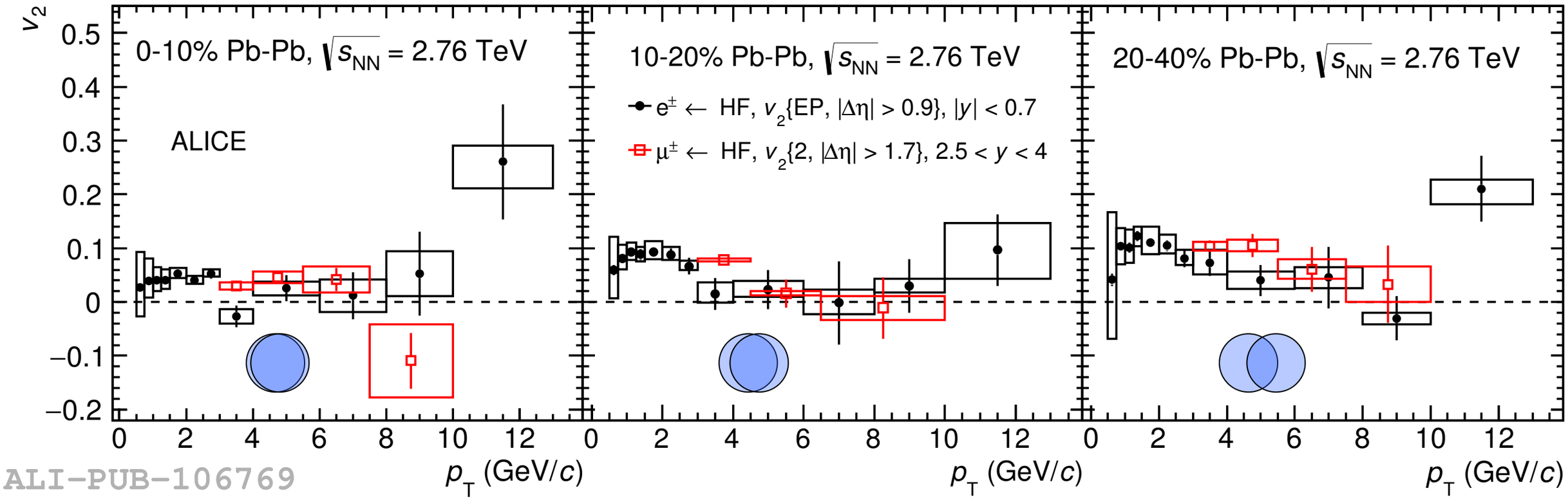
Pb-Pb collisions



v_2 of leptons from open heavy flavour decays

arXiv:1606.00321

- New results on the v_2 of electrons from heavy-flavour hadron decays
  - Using event plane method
  - v_2 of background electrons is subtracted
- Similar to v_2 of muons from heavy flavour-hadrons decays at forward-y



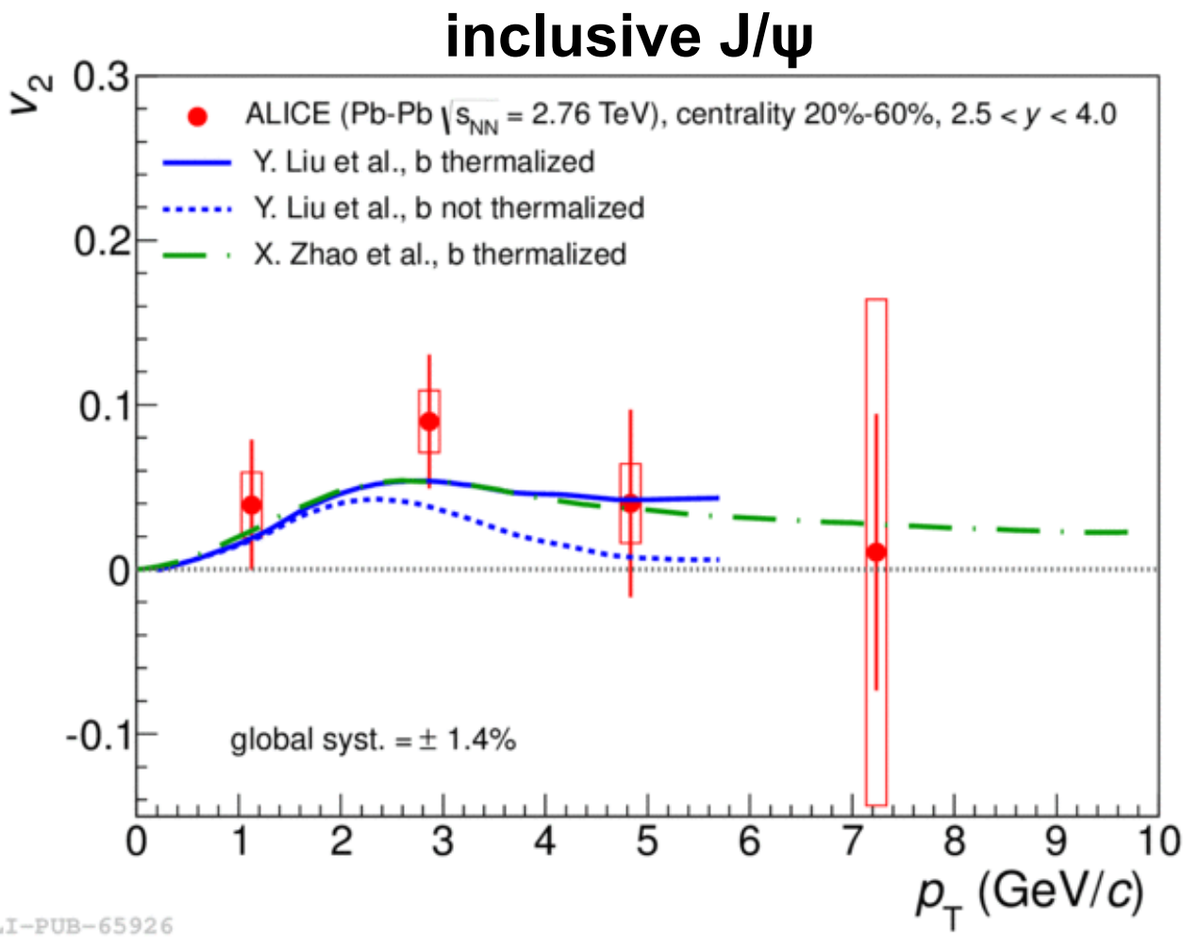
- Clear non-zero v_2 signal with a hint of an increase from central to semi-central collisions
- Suggest a significant participation of heavy quarks in the collective motion of the system

C. Terrevoli, Tu. 14:40

J/ψ elliptic flow

PRL 111 (2013) 162301

- If c quarks participate to the collective motion of the QGP, then they will acquire some elliptic flow
- Regenerated J/ψ will inherit the elliptic flow of the c quarks

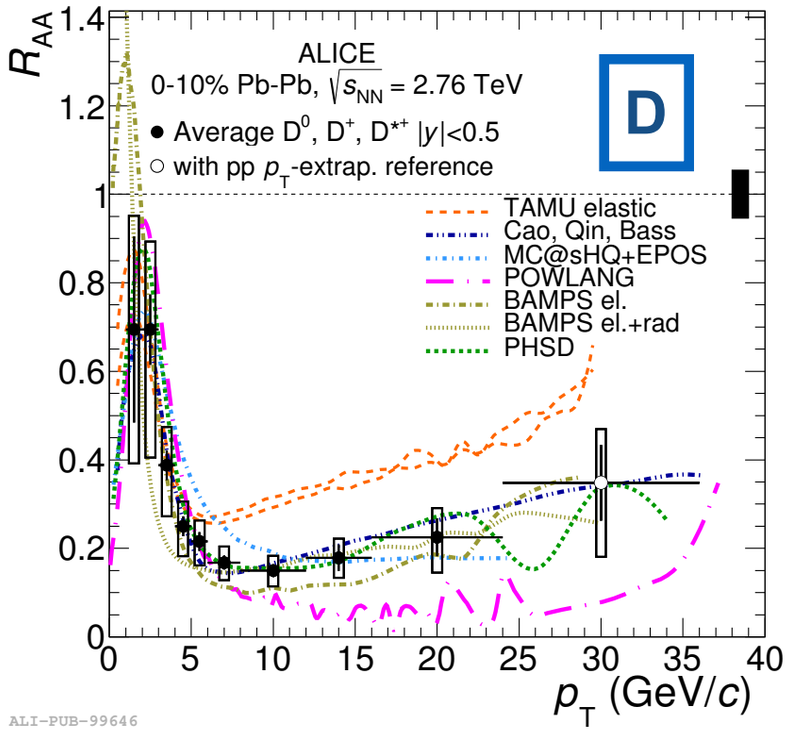


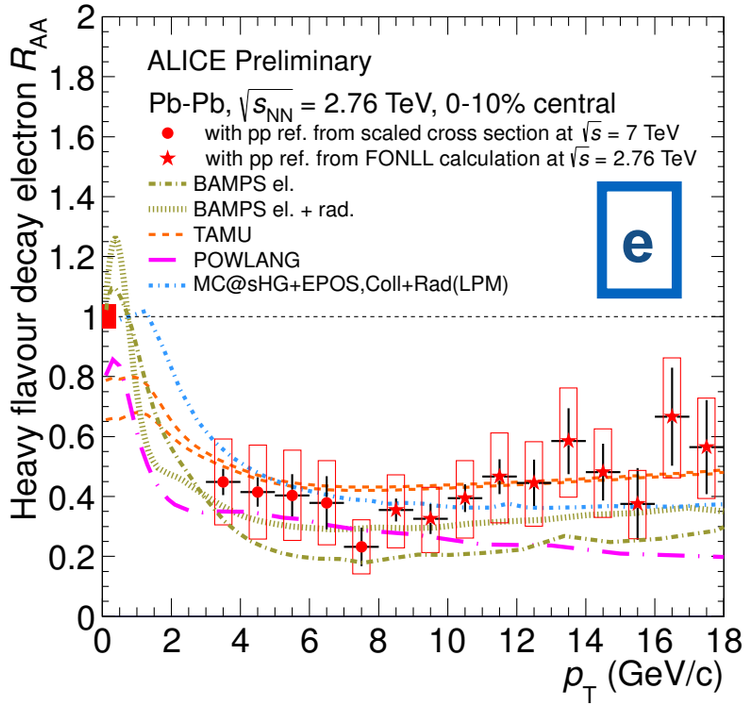
- Hint of non-zero J/ψ v_2 at intermediate p_T for semi-central collisions at the LHC
- Qualitatively described by models including regeneration
- Larger statistics of run 2 will help

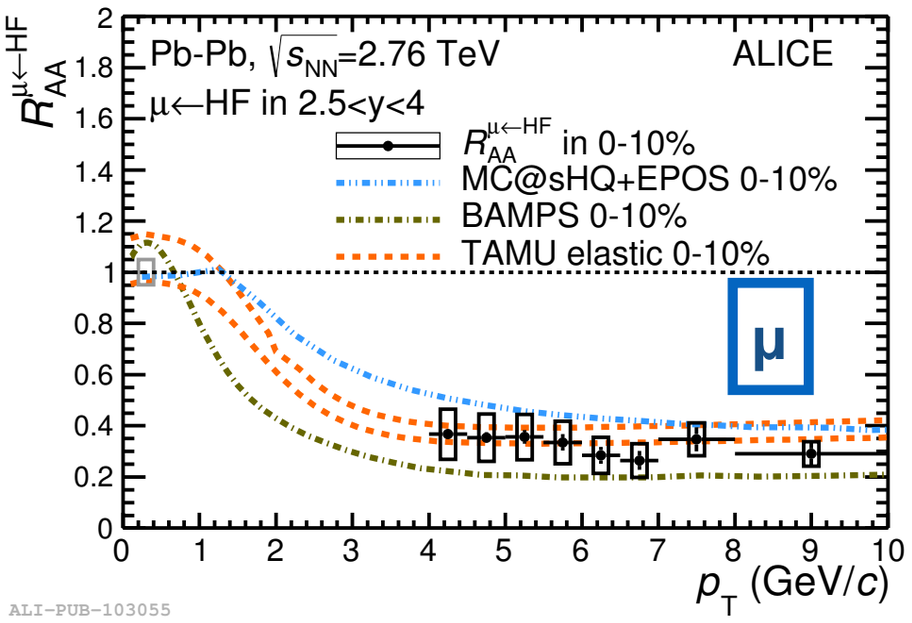
R_{AA} and v_2 of open Heavy Flavours

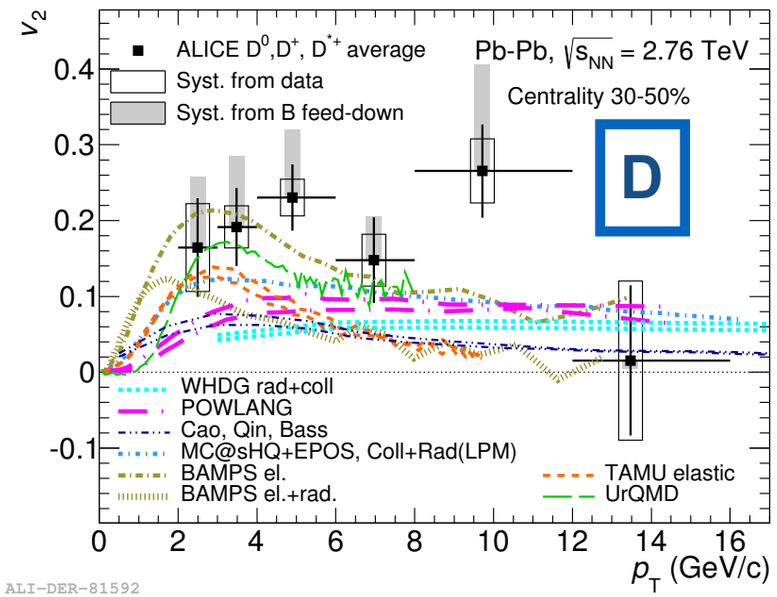
PRC 90 (2014) 034904, arXiv:1606.00321, PLB 753 (2016) 41, PRL 109 (2012) 112301

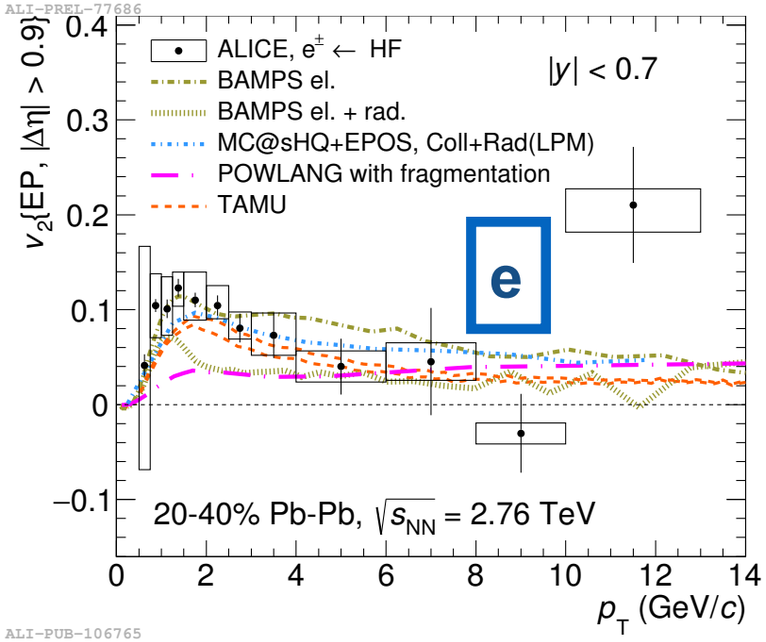
- Complete and coherent wealth of HF results in Pb-Pb collisions

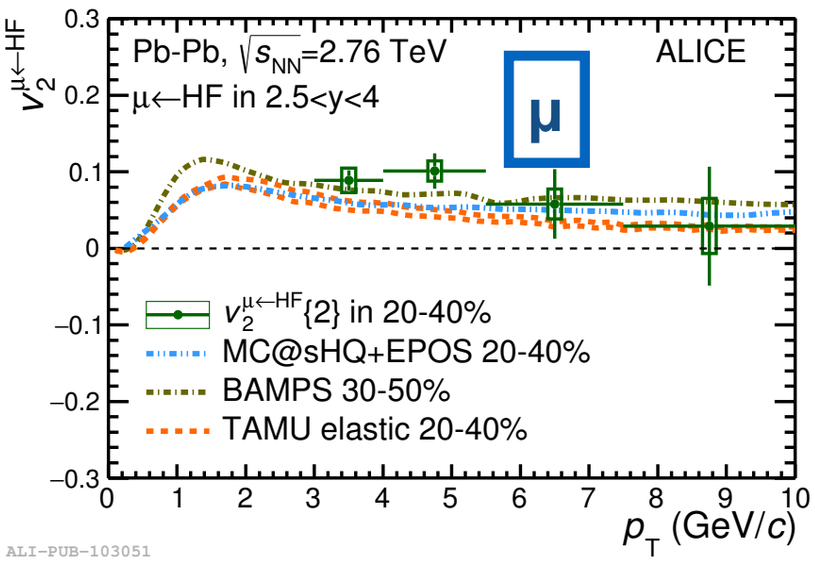












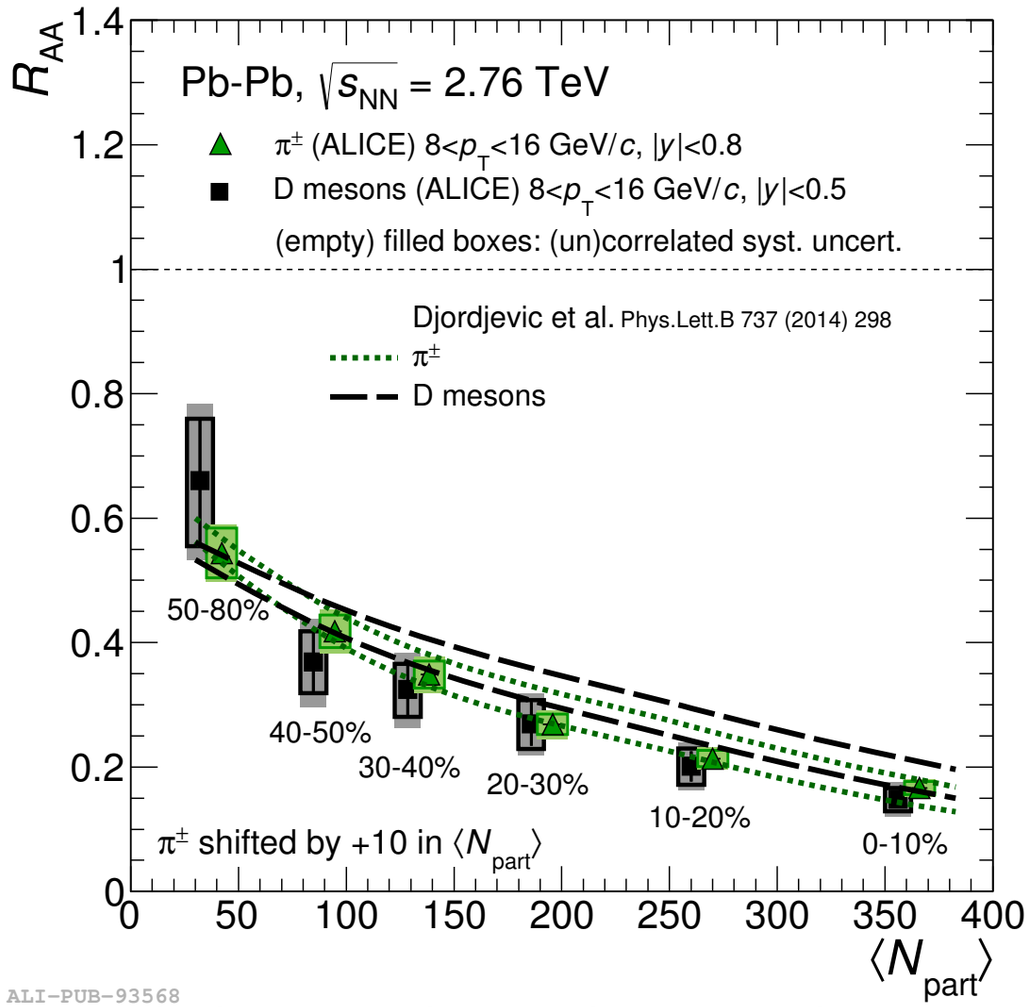
- Simultaneous description of v_2 and R_{AA} is challenging for the models

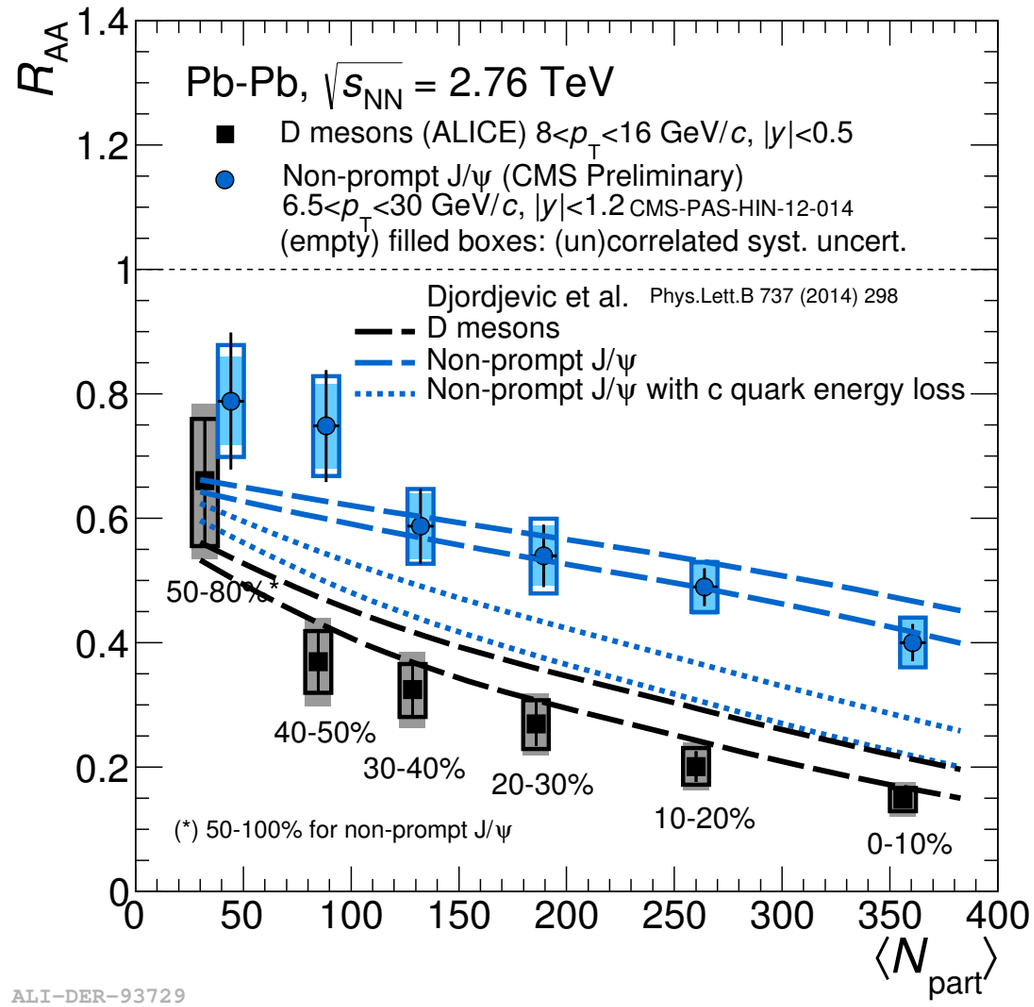
C. Terrevoli, Tu. 14:40

Mass dependence of R_{AA}

JHEP 1511 (2015) 205

- Comparison of pions, D-mesons and non-prompt J/ψ R_{AA}





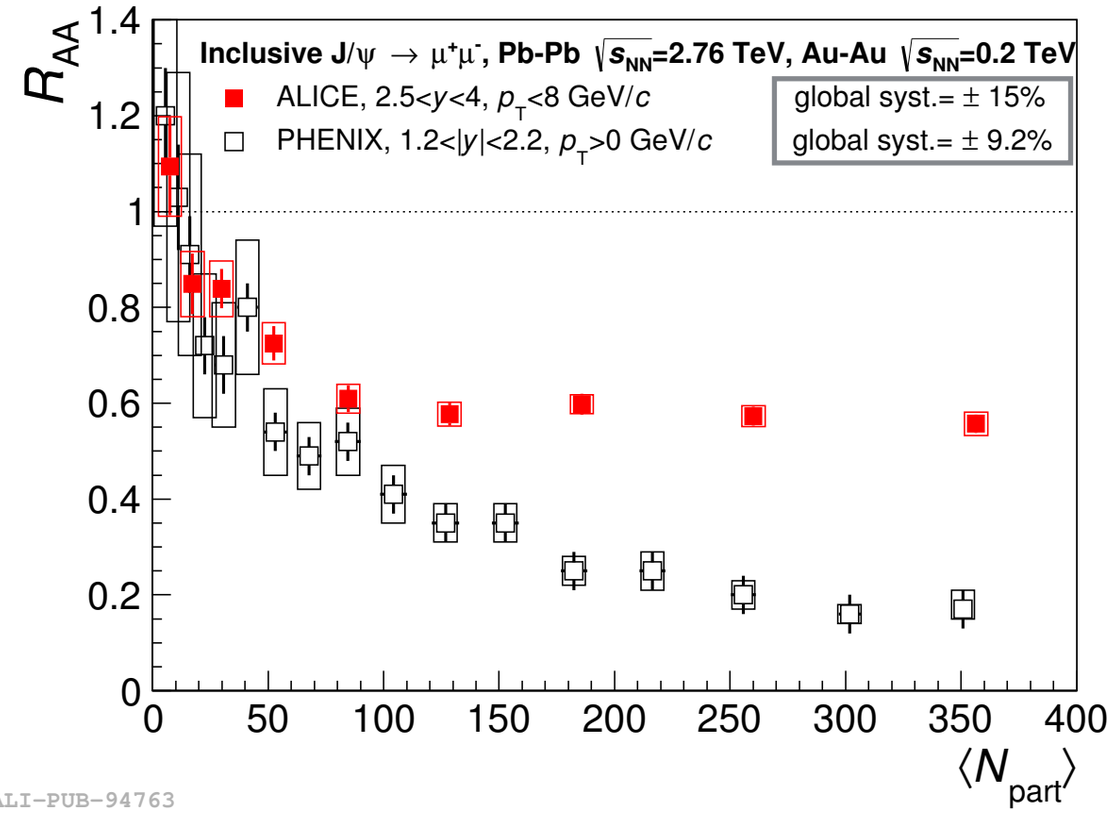
- R_{AA}(D) ~ R_{AA}(light flavours)
  - described by models that take into account colour-charge dependence of energy loss and softer fragmentation and p_T spectrum of gluons w.r.t. c quarks
- R_{AA}(D) < R_{AA}(B→J/ψ)
  - hint for mass hierarchy of the R_{AA}
  - described by a model including mass-dependent radiative and collisional energy loss

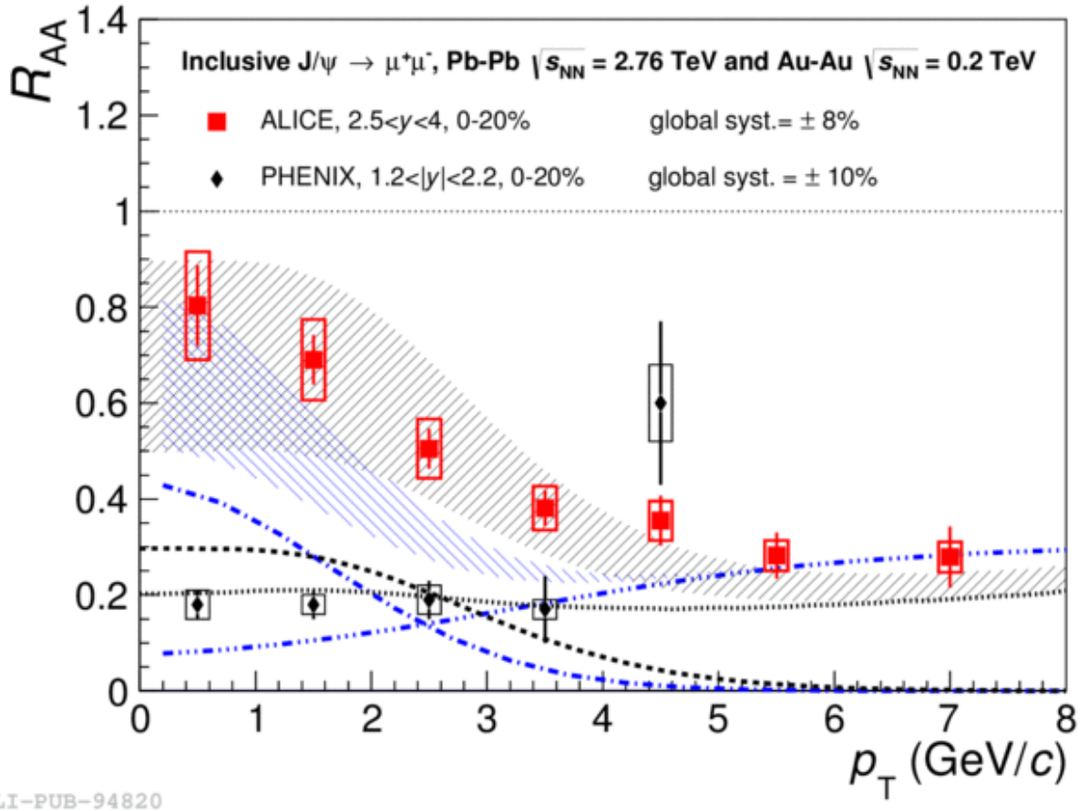
C. Terrevoli, Tu. 14:40

J/ψ suppression in Pb-Pb collisions at 2.76 TeV

JHEP 1605 (2016) 179

- At 2.76 TeV
  - Flat J/ψ R_{AA} for $N_{part} > 70$
  - Higher J/ψ R_{AA} for central collisions at the LHC than at RHIC
  - J/ψ R_{AA} increases with decreasing p_T





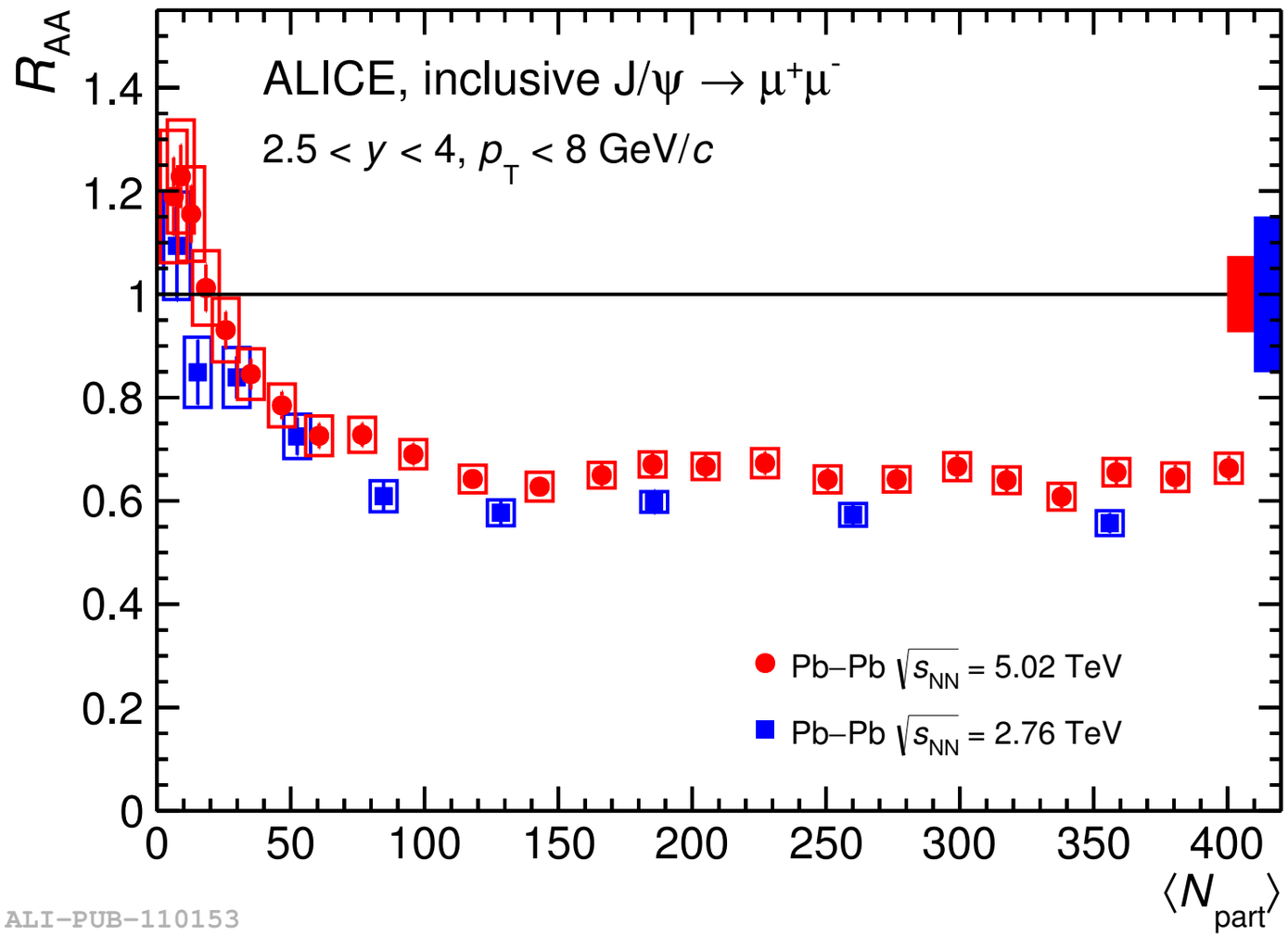
- Well described by models including partial or full regeneration of J/ψ in the QGP or at hadronisation

- Confirmed at 5 TeV?

J/ψ R_{AA} in Pb-Pb 5 TeV

CERN-EP-2016-162

- R_{AA} versus centrality
  - Similar trend at 5 TeV and at 2.76 TeV
  - Increased statistics and reduced uncertainties



ALI-PUB-110153

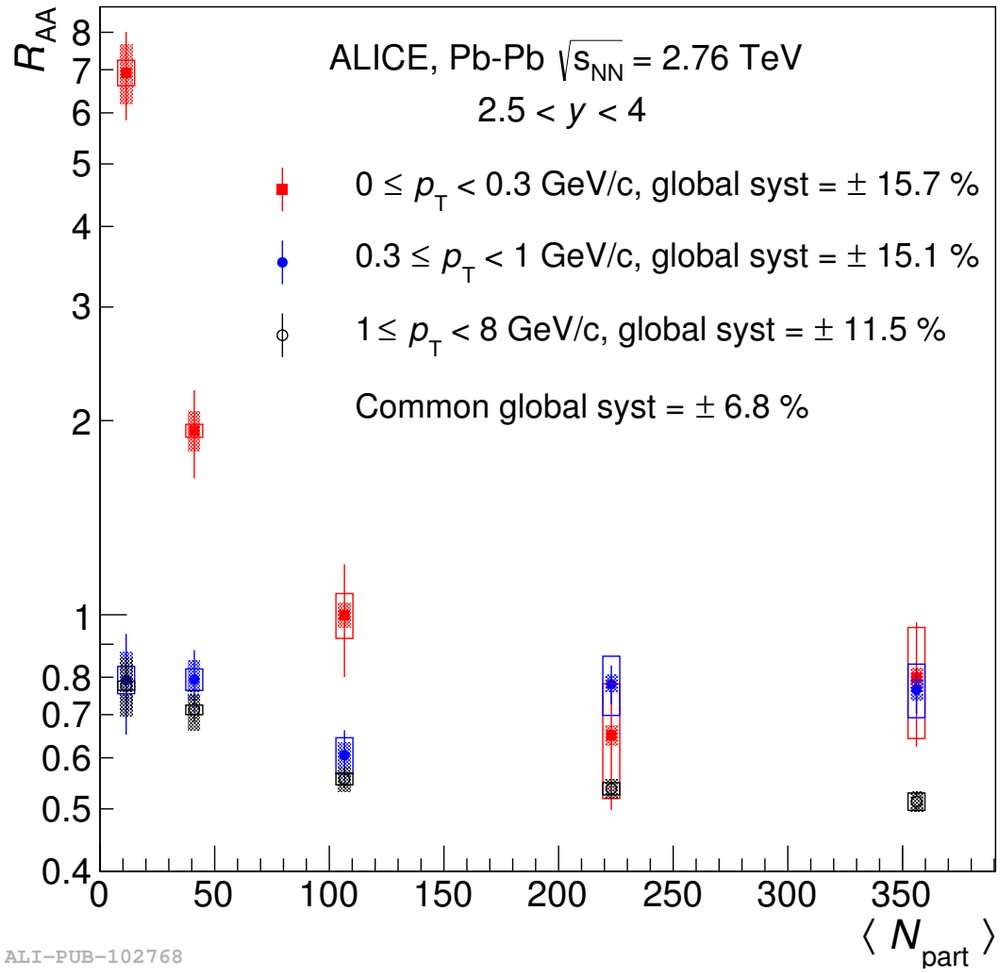
- $R_{AA}^{0\text{-}90\%}$(5.02 TeV, p_T < 8 GeV/c) = 0.66 ± 0.01(stat) ± 0.05(syst)
- $R_{AA}^{0\text{-}90\%}$(2.76 TeV, p_T < 8 GeV/c) = 0.58 ± 0.01(stat) ± 0.09(syst)
- $R_{AA}^{0\text{-}90\%}$(5.02 TeV) / $R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 1.13 ± 0.02(stat) ± 0.18(syst)

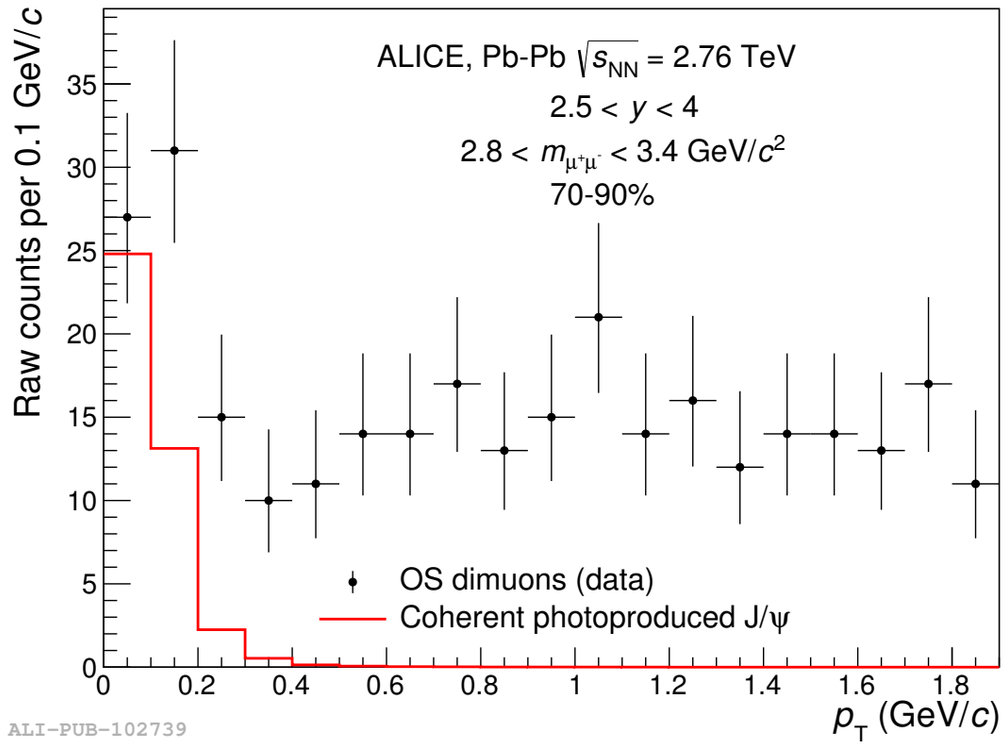
B. Paul, Tu. 17:00

Excess of very-low-p_T J/ψ

PRL 116 (2016) 222301

- Very-low-p_T J/ψ excess
  - Seen in peripheral Pb-Pb collisions at 2.76 TeV
  - Presumably of EM origin





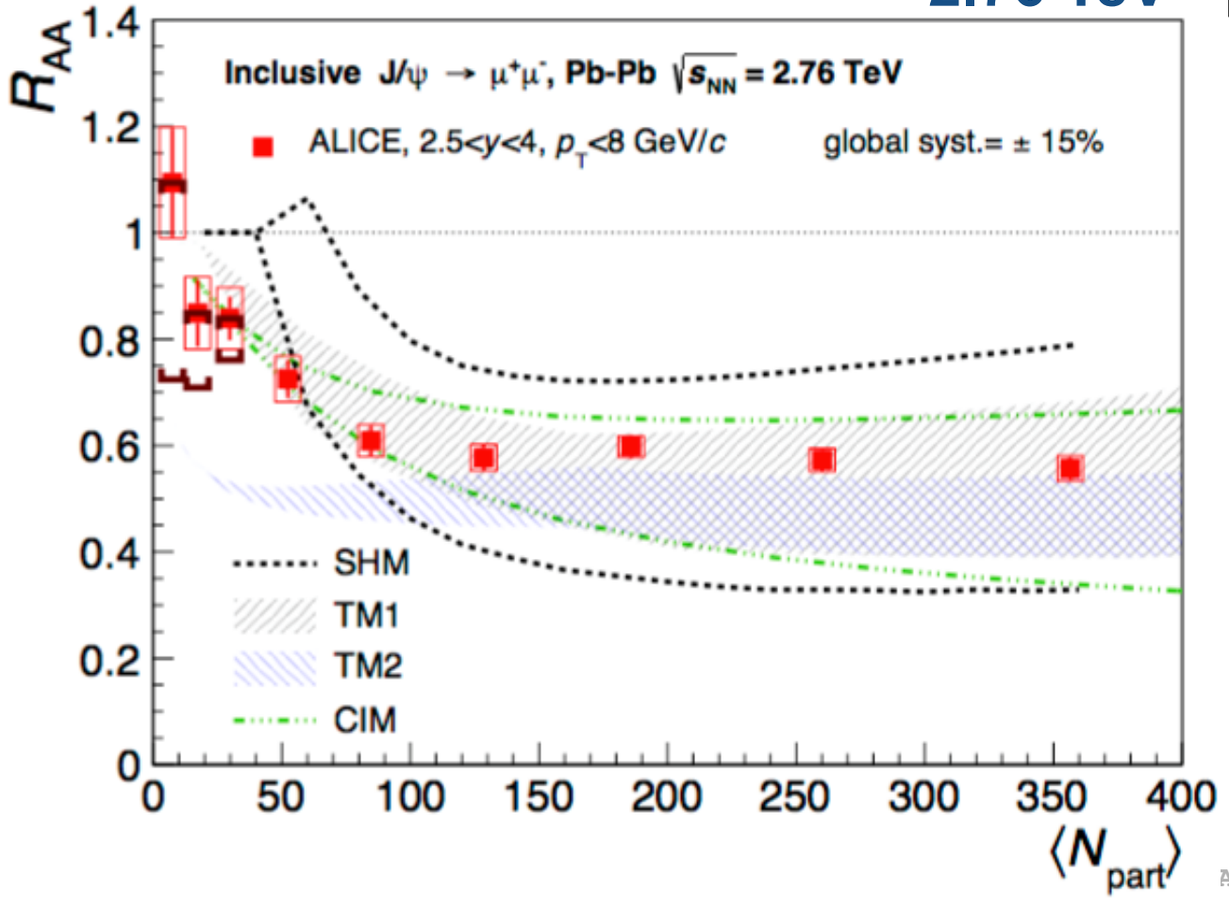
  - Due to the very specific origin and kinematics, photo-produced J/ψ could become an useful probe of the QGP
  - In the mean time, it constitutes a "contamination" to the hadronic R_{AA}
    - Apply a cut p_T > 0.3 GeV to reduce photo-production contribution

J/ψ R_{AA} – model comparison

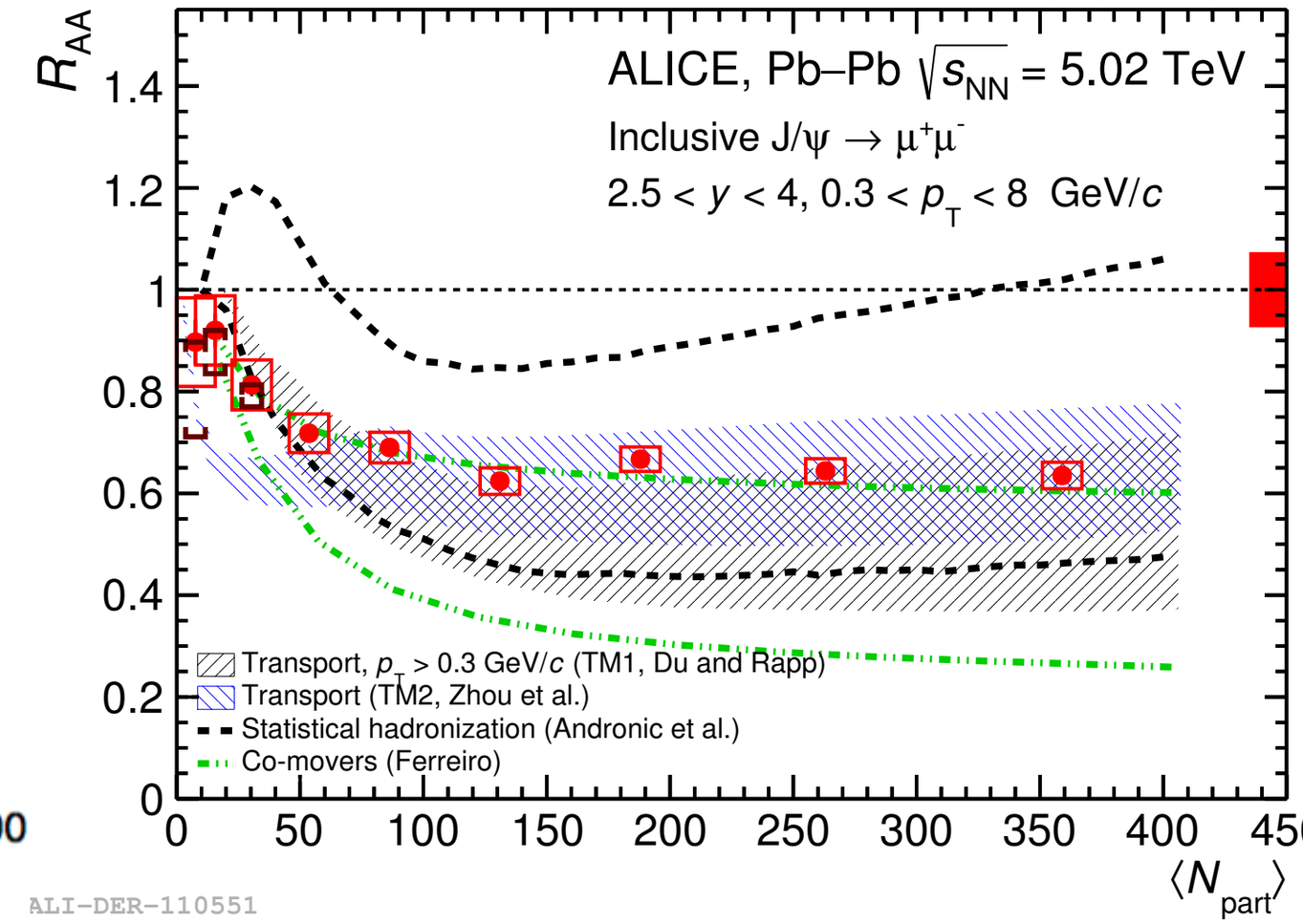
CERN-EP-2016-162

- J/ψ R_{AA} versus centrality
  - Brackets indicate the possible range of variation of the hadronic R_{AA}

2.76 TeV



5.02 TeV



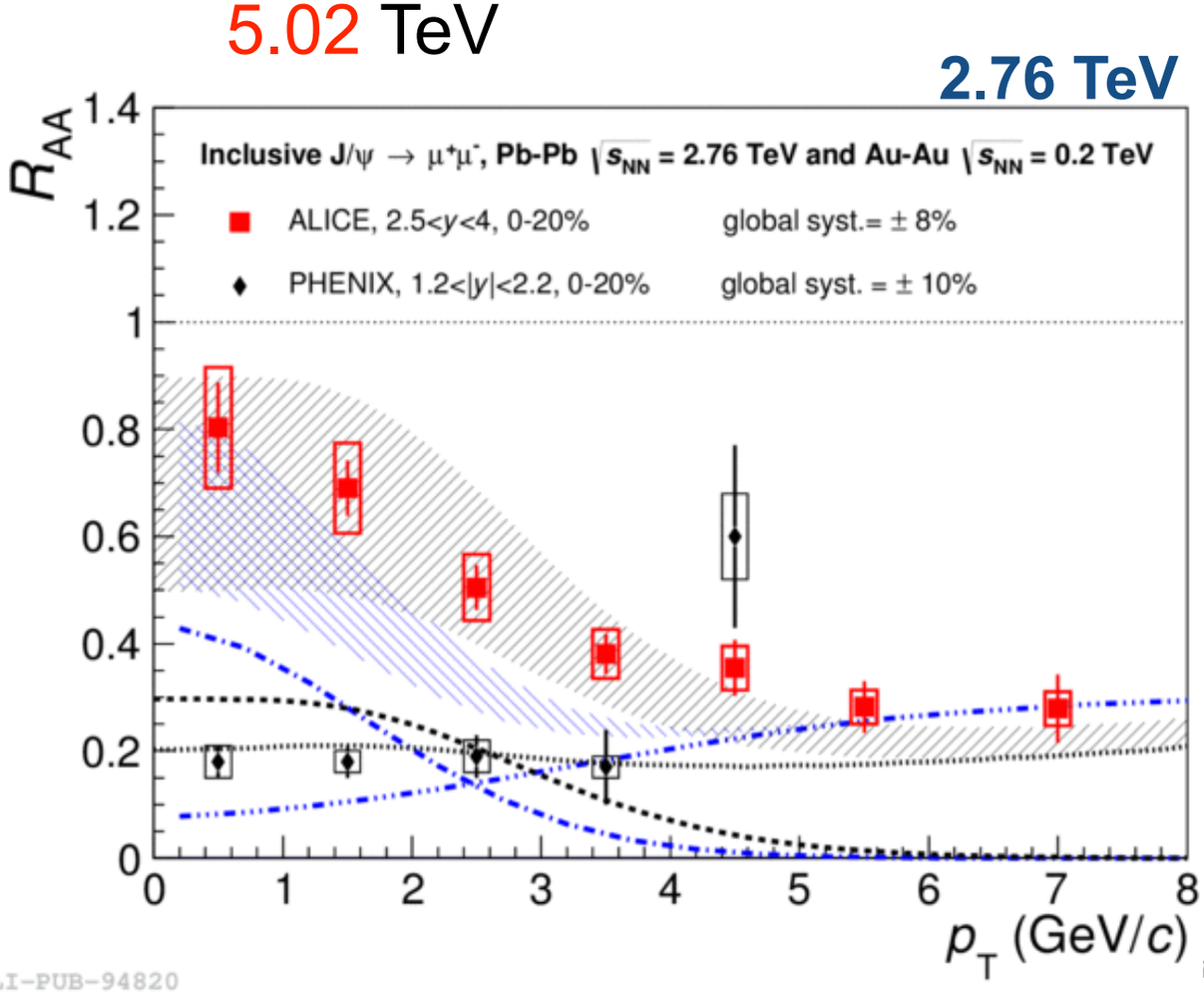
- Compared to the same models at both energies
  - SHM (Andronic *et al.*): all J/ψ produced by statistical hadronisation at the QGP phase boundary
  - TM (Du *et al.* and Zhou *et al.*): rate equation of suppression and regeneration by/in the QGP
  - CIM (Ferreiro): suppression by the co-moving partonic medium and regeneration
- Good description at both energies

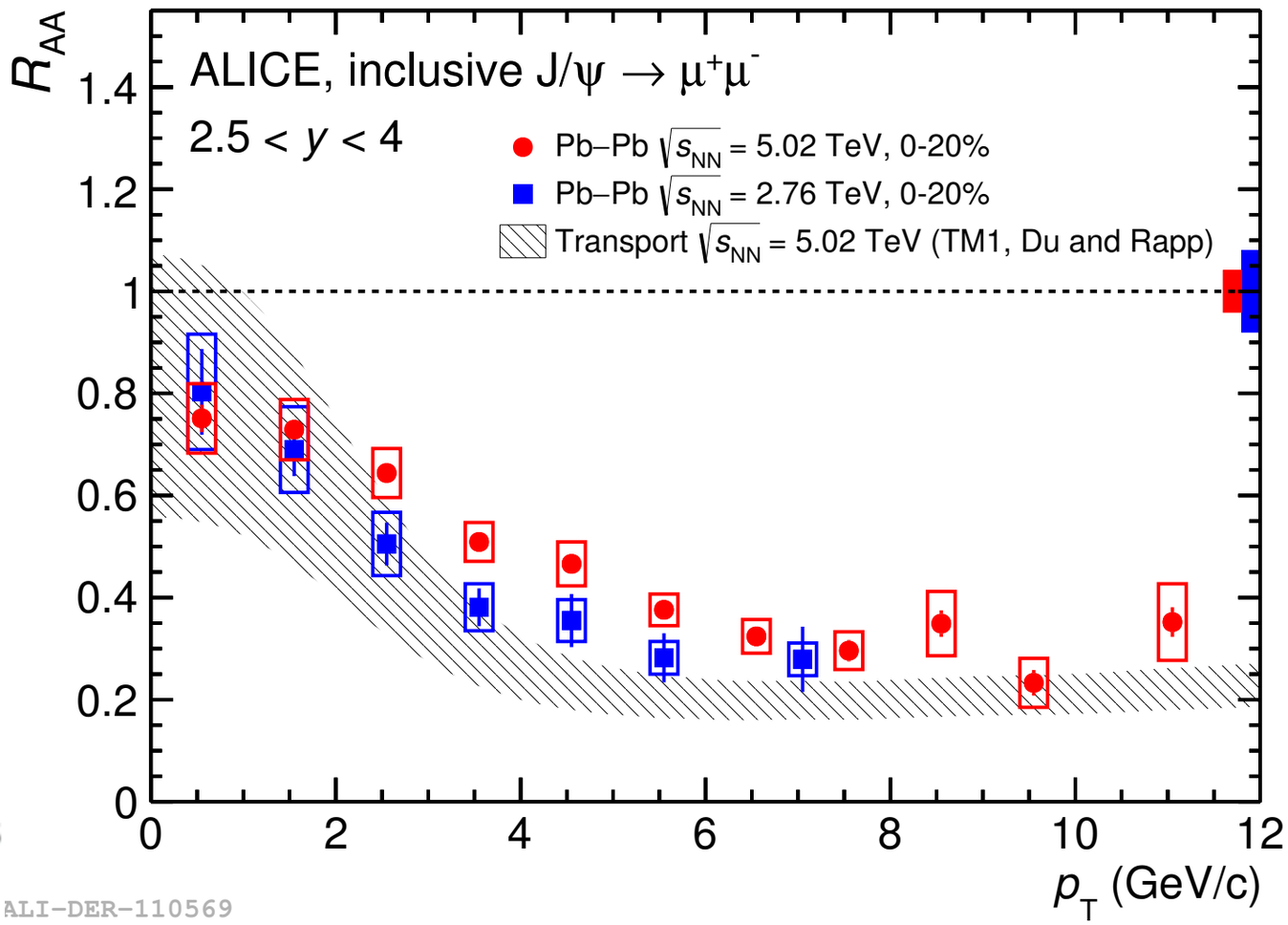
B. Paul, Tu. 17:00

J/ψ R_{AA} – p_T dependence

CERN-EP-2016-162

- R_{AA} vs transverse momentum
  - Similar decreasing trend of R_{AA} with increasing p_T at both 2.76 and 5.02 TeV



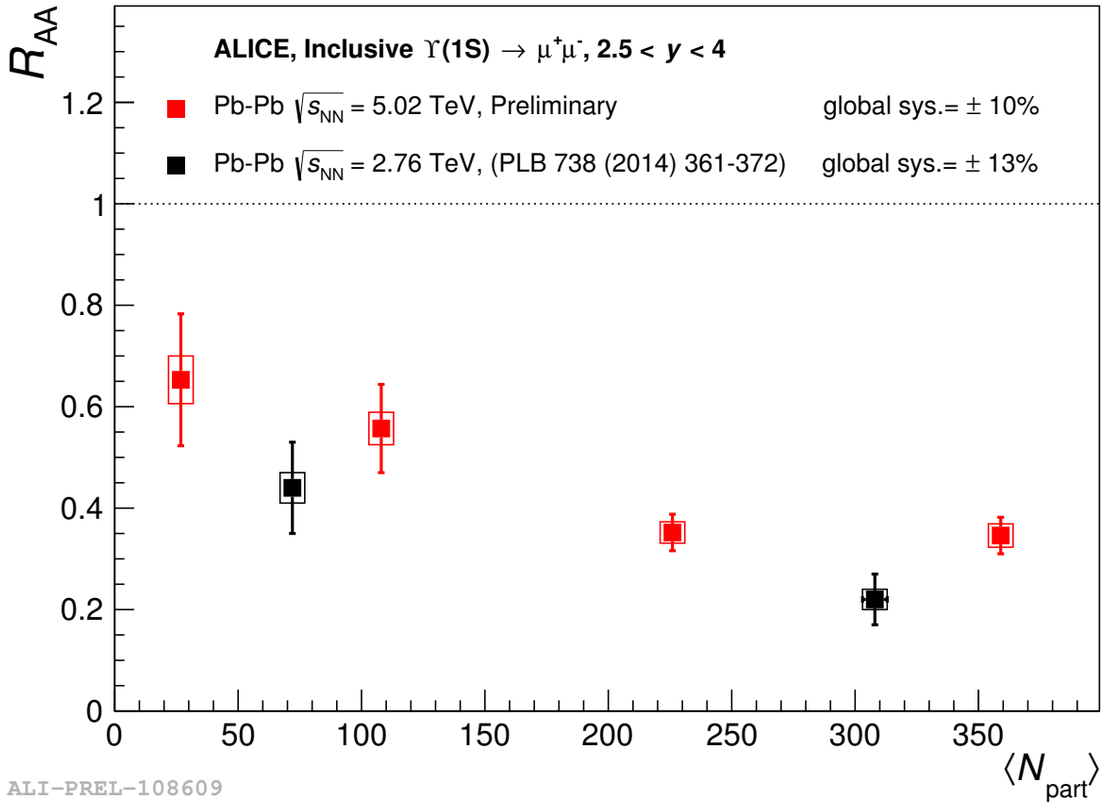


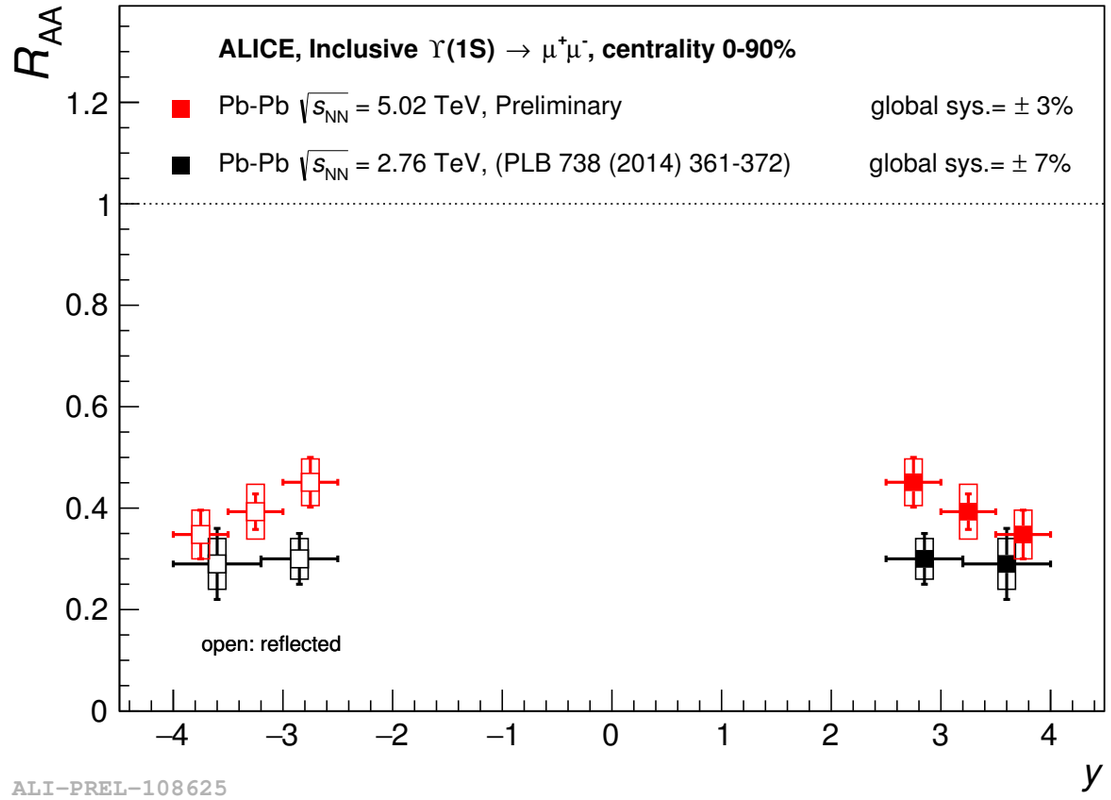
- R_{AA}(5.02 TeV) vs R_{AA}(2.76 TeV)
  - Broader R_{AA} versus p_T at 5.02 TeV than at 2.76 TeV?
  - Better model agreement at 2.76 TeV?

B. Paul, Tu. 17:00

Y(1S) R_{AA} in Pb-Pb at 5 TeV

- Integrated Y(1S) R_{AA}
  - $R_{AA}^{0\text{-}90\%}$(5.02 TeV) = 0.40 ± 0.03(stat) ± 0.04(syst)
  - $R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 0.30 ± 0.05(stat) ± 0.04(syst)
  - $R_{AA}^{0\text{-}90\%}$(5.02 TeV) / $R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 1.3 ± 0.2(stat) ± 0.2(syst)





- At both energies the Y(1S) suppression is stronger for central than for peripheral collisions
- No firm conclusion on the energy dependence possible with the current uncertainties

A. Lardeux, Th. 11:20

Summary

- pp and p-Pb collisions
  - open heavy flavour and quarkonium production cross sections are well described by pQCD based calculations
  - R_{pPb} results are well reproduced by models including initial- or final-state effects
    - ψ(2S) results require final-state interactions
  - Relative yields increase with charged-particle multiplicity
    - models including multiple parton and nucleon-nucleon interactions can describe the measurements
  - D-mesons to hadrons azimuthal correlations in pp and p-Pb collisions
    - similar near-side peak properties and good agreement with Monte Carlo generators
- Pb-Pb collisions
  - Strong open heavy-flavour suppression for p_T > 3 GeV/c
    - due to final-state effects and consistent with collisional and radiative energy loss mechanisms
    - signs of mass dependent parton energy loss at high-p_T
  - Quarkonia are suppressed in Pb-Pb collisions at the LHC
    - Consistent with strong regeneration component for J/ψ
      - less suppression at the LHC than at RHIC
      - less suppression at low than at high p_T
    - Υ(1S) suppression is stronger for central than peripheral collisions
  - c quarks participate in the collective motion of the QGP
- Stay tuned for more run 2 results!

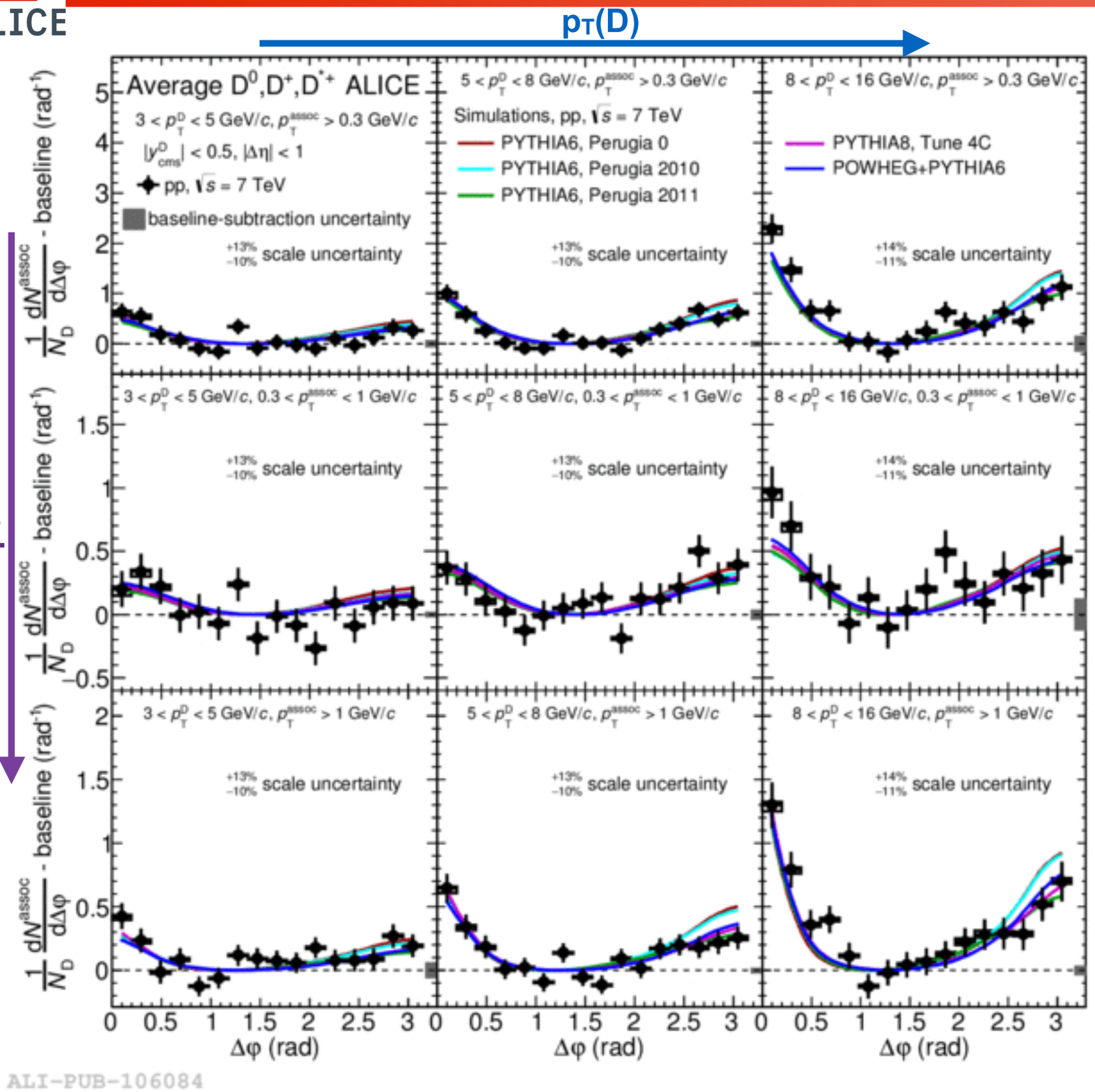
Do not miss them!

- D-meson measurements in p-Pb and Pb-Pb collisions with ALICE at the LHC
  - Cristina Terrevoli, 28 Jun 2016, 14:40 (Heavy Quark Production I)
- Heavy-flavour production in pp collisions and correlations in pp and p-Pb collisions with ALICE at the LHC
  - Fabio Colamaria, 28 Jun 2016, 16:00 (Heavy Quark Production: II)
- Heavy-flavour multiplicity dependence in p-Pb collisions with ALICE at the LHC
  - Jan Wagner, 28 Jun 2016, 17:40 (Heavy Quark Production: II)
- Measurement of charmonium production in pp collisions with ALICE
  - Hugo Pereira Da Costa, 28 Jun 2016, 16:00 (Quarkonia I: I)
- Charmonium production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV with ALICE
  - Biswarup Paul, 28 Jun 2016, 17:00 (Quarkonia I: I)
- Y production measurements in p-Pb and Pb-Pb collisions with ALICE at the LHC
  - Antoine Lardeux, 30 Jun 2016, 11:20 (Quarkonia II)

Backup

D-hadron correlations in pp at 7 TeV

arXiv:1605.06963



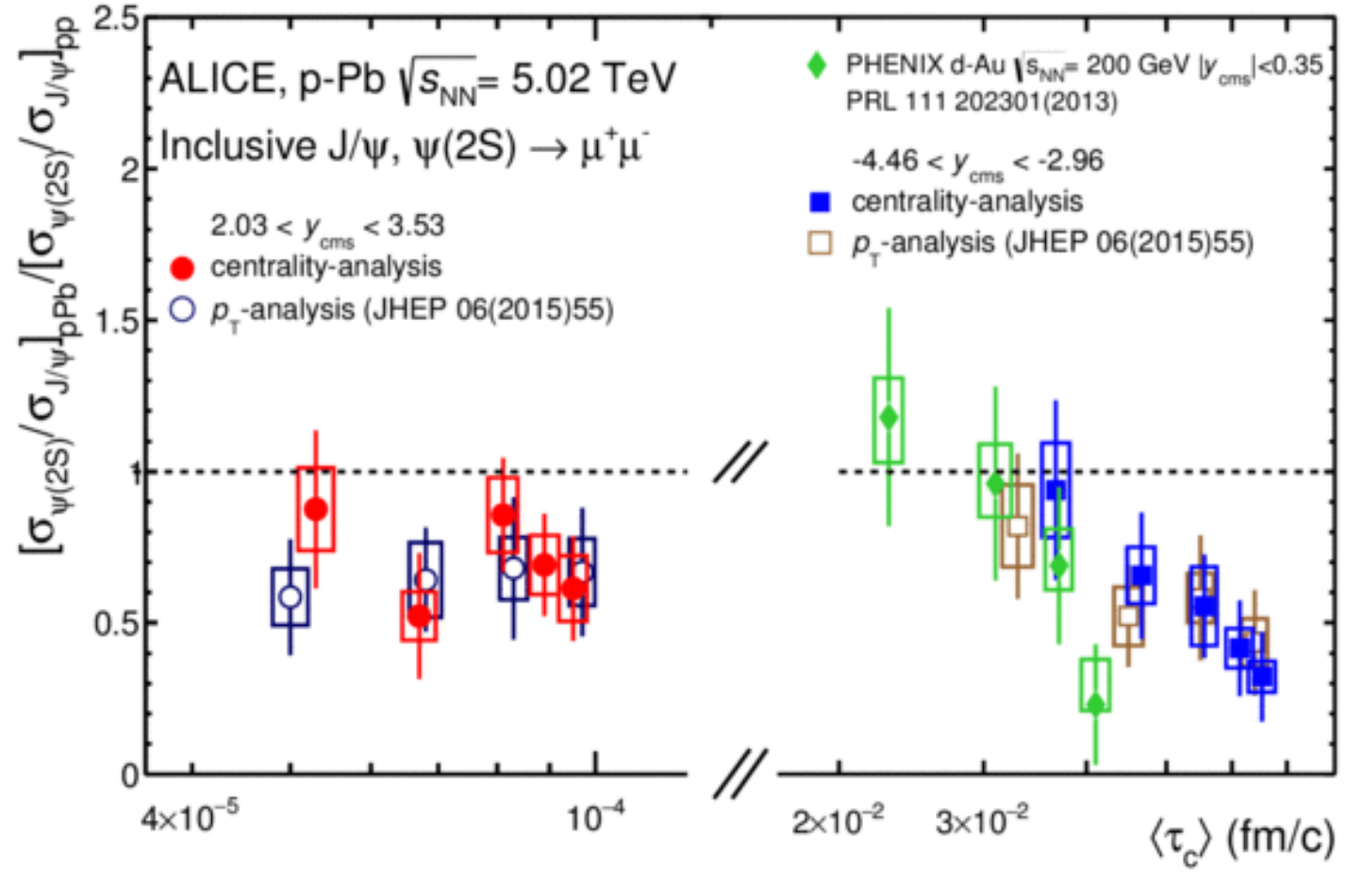
- D-hadron azimuthal correlation
  - – double Gaussian + constant baseline
- Baseline-subtracted correlation distributions
  - – well described by
    - PYTHIA6 (various tunes)
    - PYTHIA8
    - POWHEG+PYTHIA

  calculations

F. Colomaria, Tu. 16:00

J/ψ and ψ(2S) in p-Pb 5.02 TeV

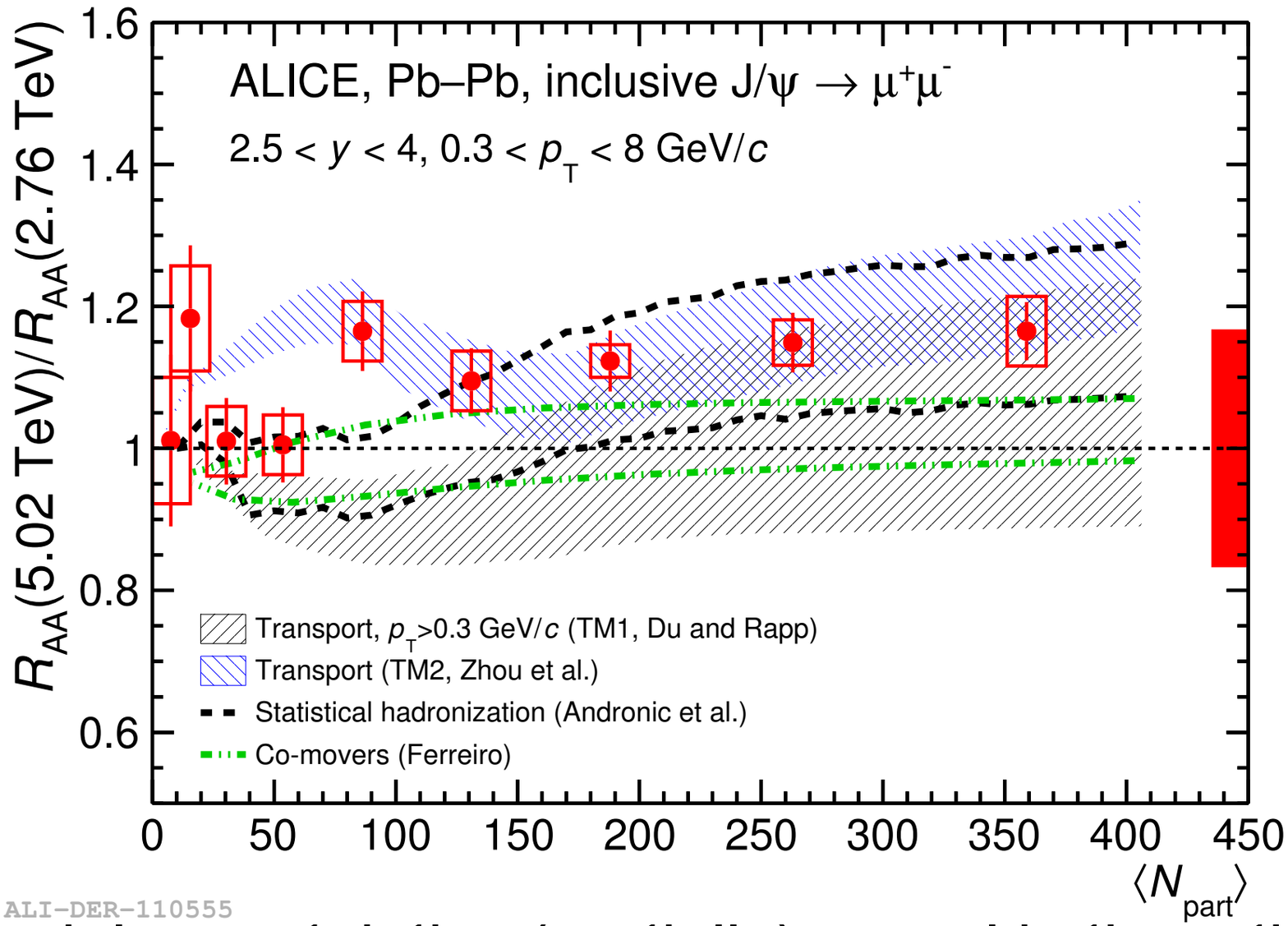
- Dependence with crossing-time
  - p-going direction: no time for in-nucleus dissociation
  - Pb-going direction: ψ(2S) dissociation in the nucleus?



ALI-PUB-105839

R_{AA}(5.02 TeV) / R_{AA}(2.76 TeV)

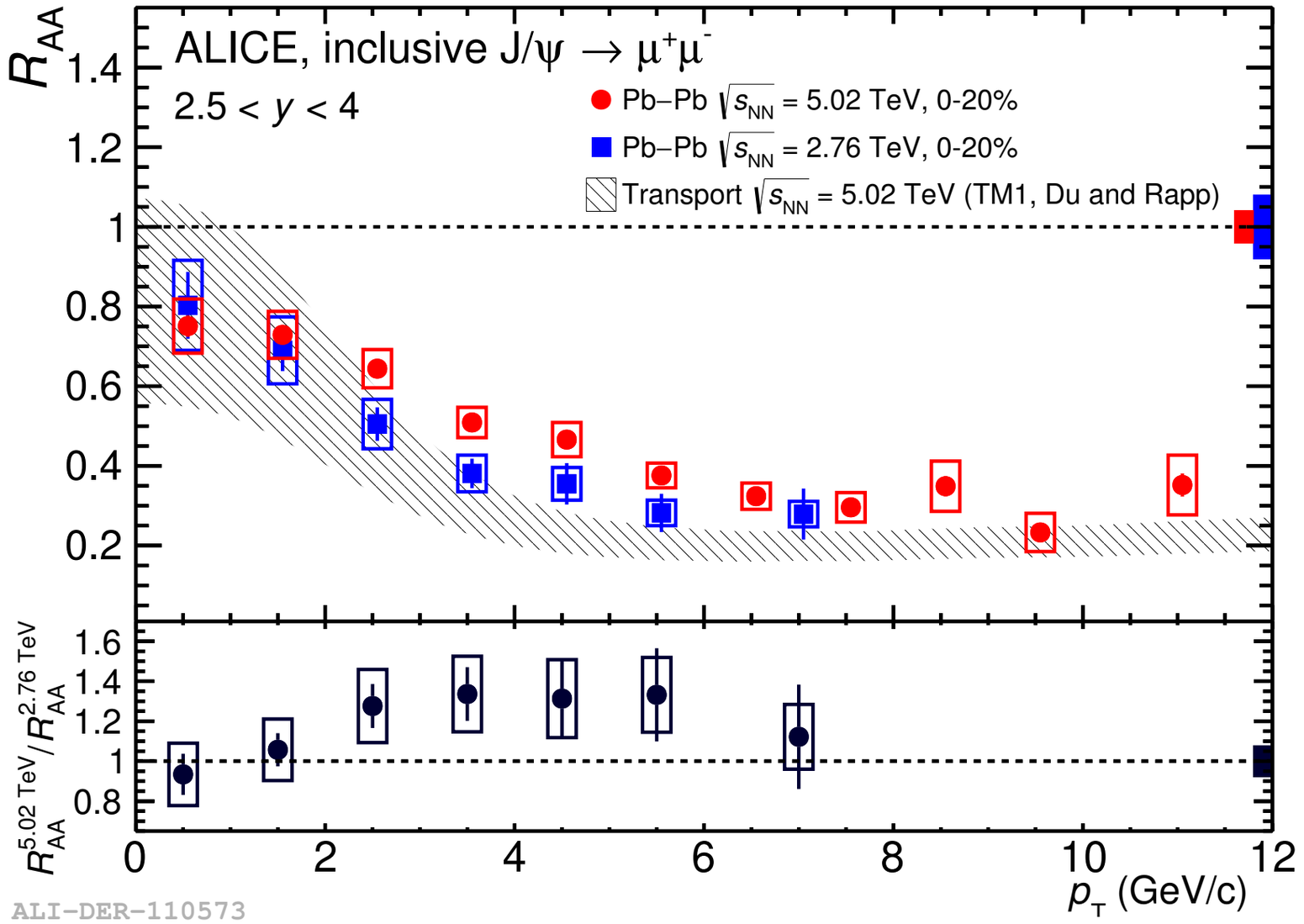
- R_{AA}(0-10%,5.02 TeV) / R_{AA}(0-10%,2.76 TeV) = 1.17±0.04±0.20
- No clear trend with centrality



- Some model uncertainties (partially) cancel in the ratio
- Model bands express a 5% uncertainty on c-cbar cross section

J/ψ in Pb-Pb 5 TeV – differential R_{AA}

- R_{AA} vs transverse momentum
  - Similar decreasing trend of R_{AA} with increasing p_T at both 5 and 2.76 TeV



- R_{AA}(5.02 TeV) vs R_{AA}(2.76 TeV)
  - Broader R_{AA} versus p_T at 5.02 TeV than at 2.76 TeV?

Y(1S) in Pb-Pb at 5 TeV – differential R_{AA}

- Differentially
  - versus centrality
  - versus rapidity