Heavy quarks in deconfined quark-gluon matter

A. Andronic – GSI Darmstadt

- Intoduction / Motivation
- Open charm and bottom
- Quarkonia
- Summary and outlook

(focus on recent LHC results)

Heavy quarks and deconfined matter

$q - \bar{q}$ pairs produced early in pQCD processes

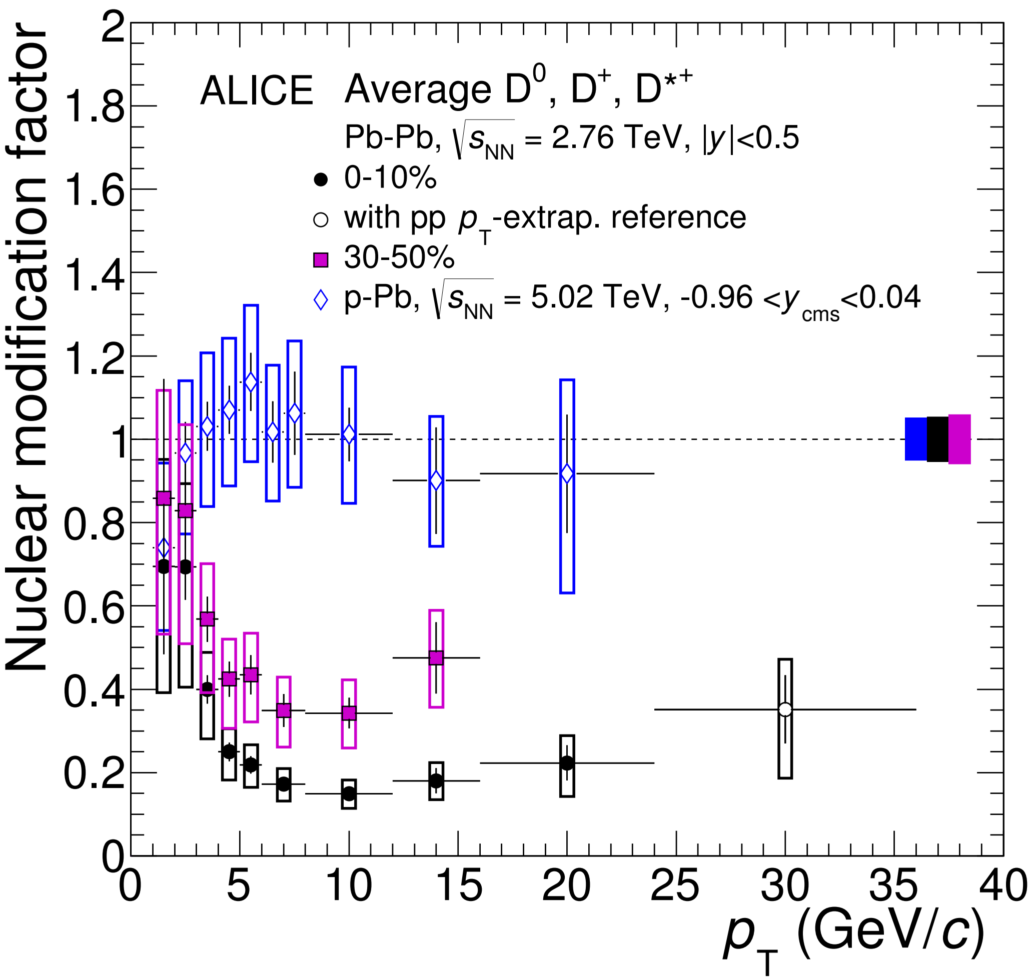
- Open heavy-flavor hadrons are at high energies abundant probes of high density stages (thermalization and energy loss)
- Quarkonium formation is hindered with a screened potential
  Matsui & Satz, Phys. Lett. B 178 (1986) 178

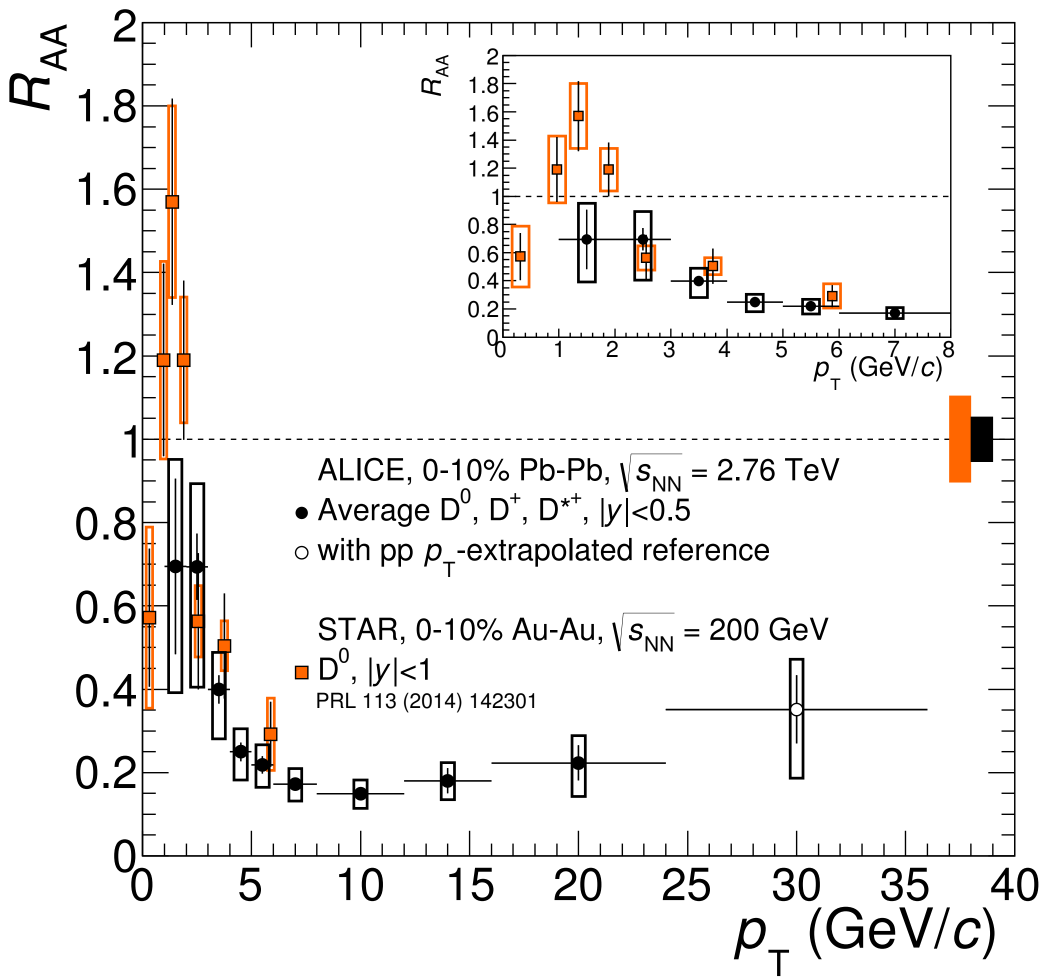
  "If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

  no $q\bar{q}$ state if $r_{q\bar{q}}(T) > \lambda_D \simeq 1/(g(T)T)$ (Debye length in QGP)
  (quarkonia constitute a "thermometer" of QGP)

Main observables (vs. N_{part} and p_T):
- The nuclear modification factor, $R_{AA} =$ "hot QCD" / "binary-scaled pp"
- Elliptic flow, v_2

D-meson production





ALICE, JHEP 03 (2016) 081

large suppression of charmed mesons (first observed at RHIC with decay e)

D-meson nuclear modification

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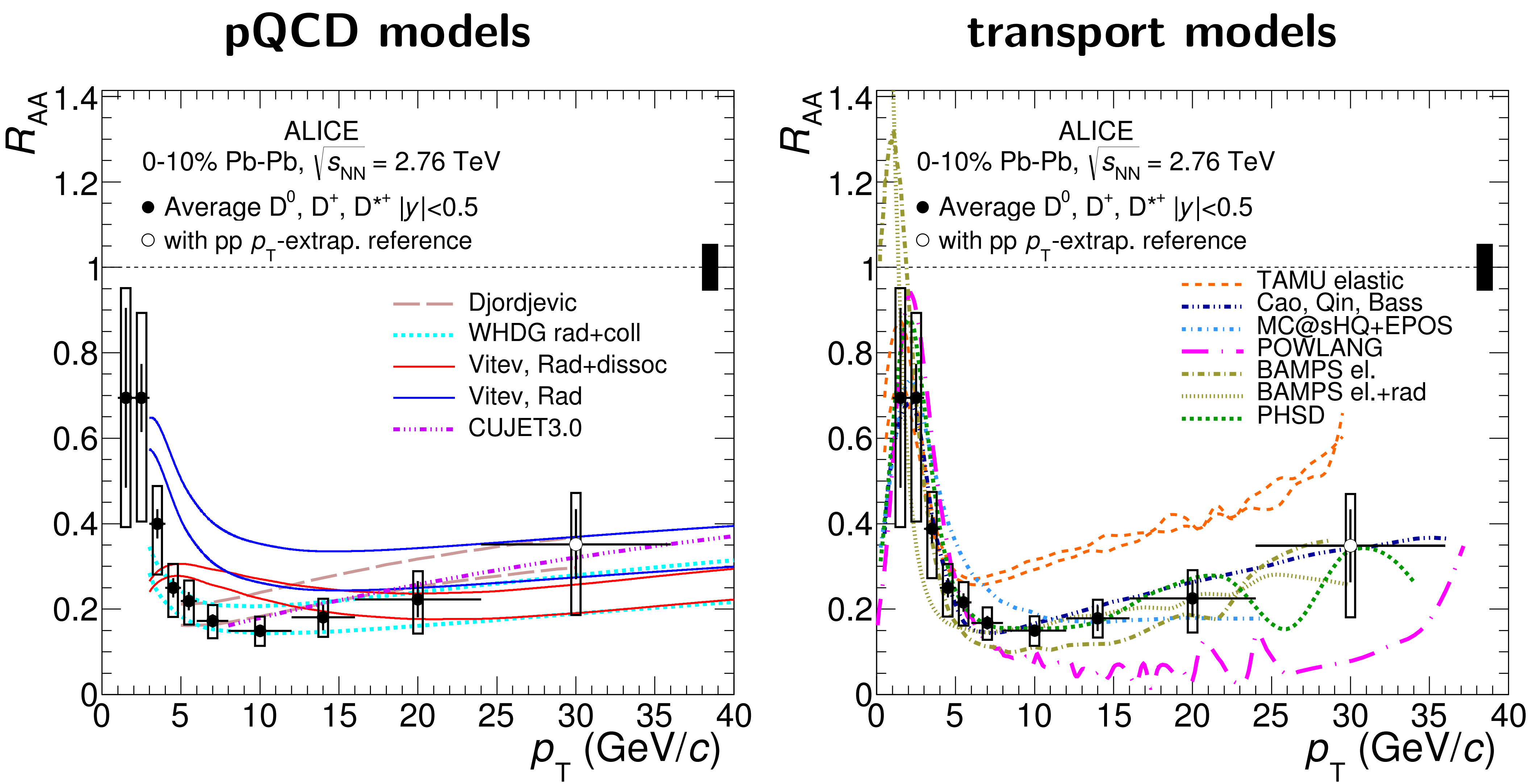

ALICE, JHEP 03 (2016) 081

good description of data in theoretical models

D-meson nuclear modification

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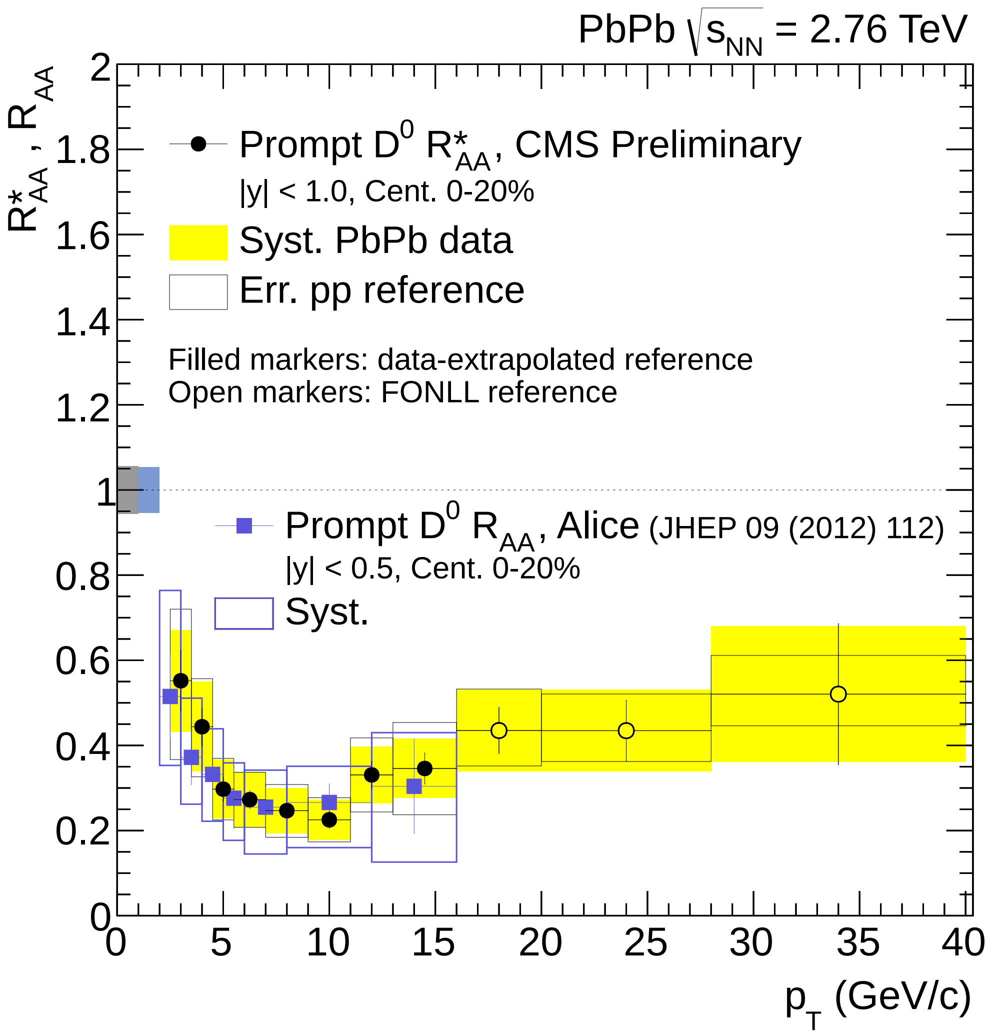

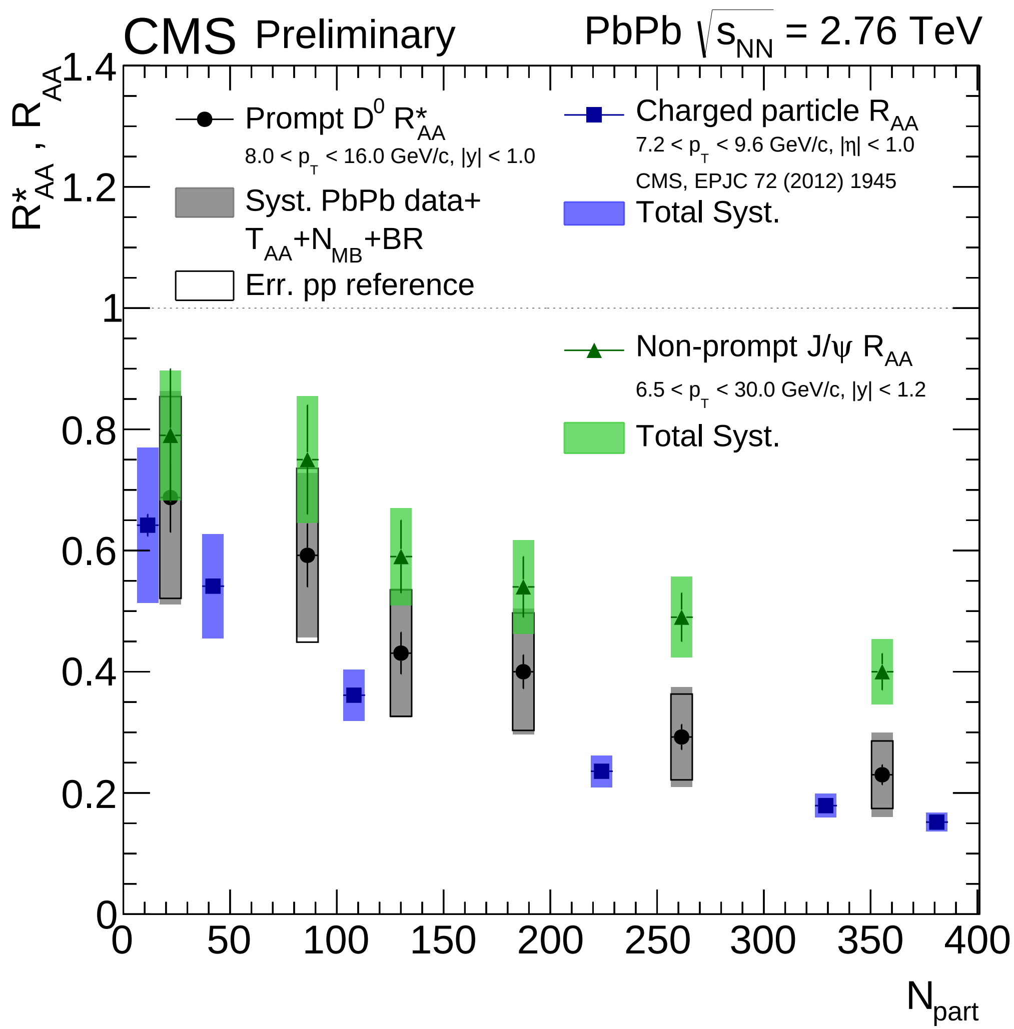

CMS-PAS-HIN-15-005

expected parton / flavor ordering observed (not all details clear yet, though)

D mesons - fresh results at 5 TeV

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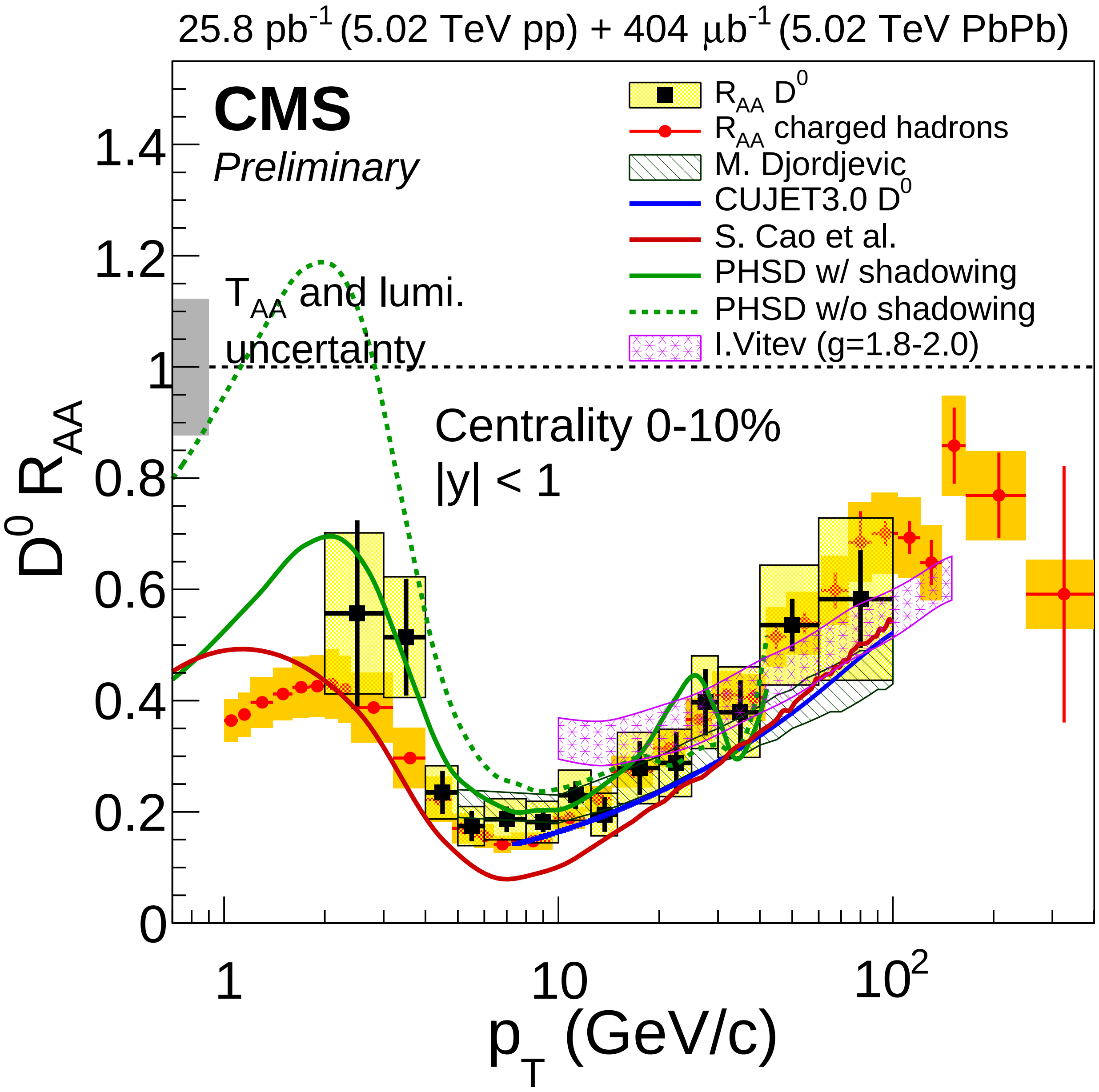

CMS-PAS-HIN-16-001

D-meson flow

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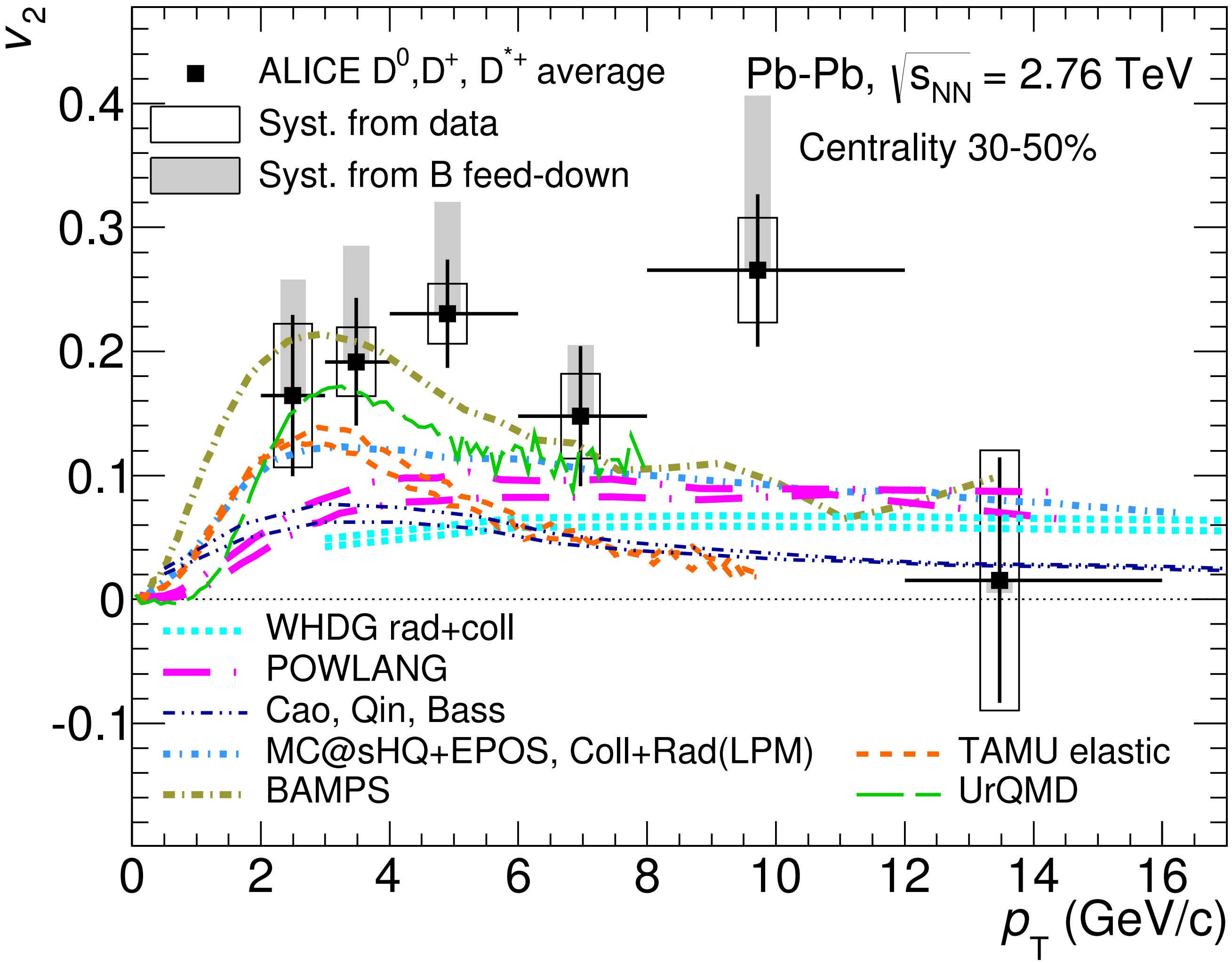

PRC 90 (2014) 034904

D-meson flow similar in magnitude with that of light quarks

Theoretical description is good in some models, challenging for others

Charm transport coefficient

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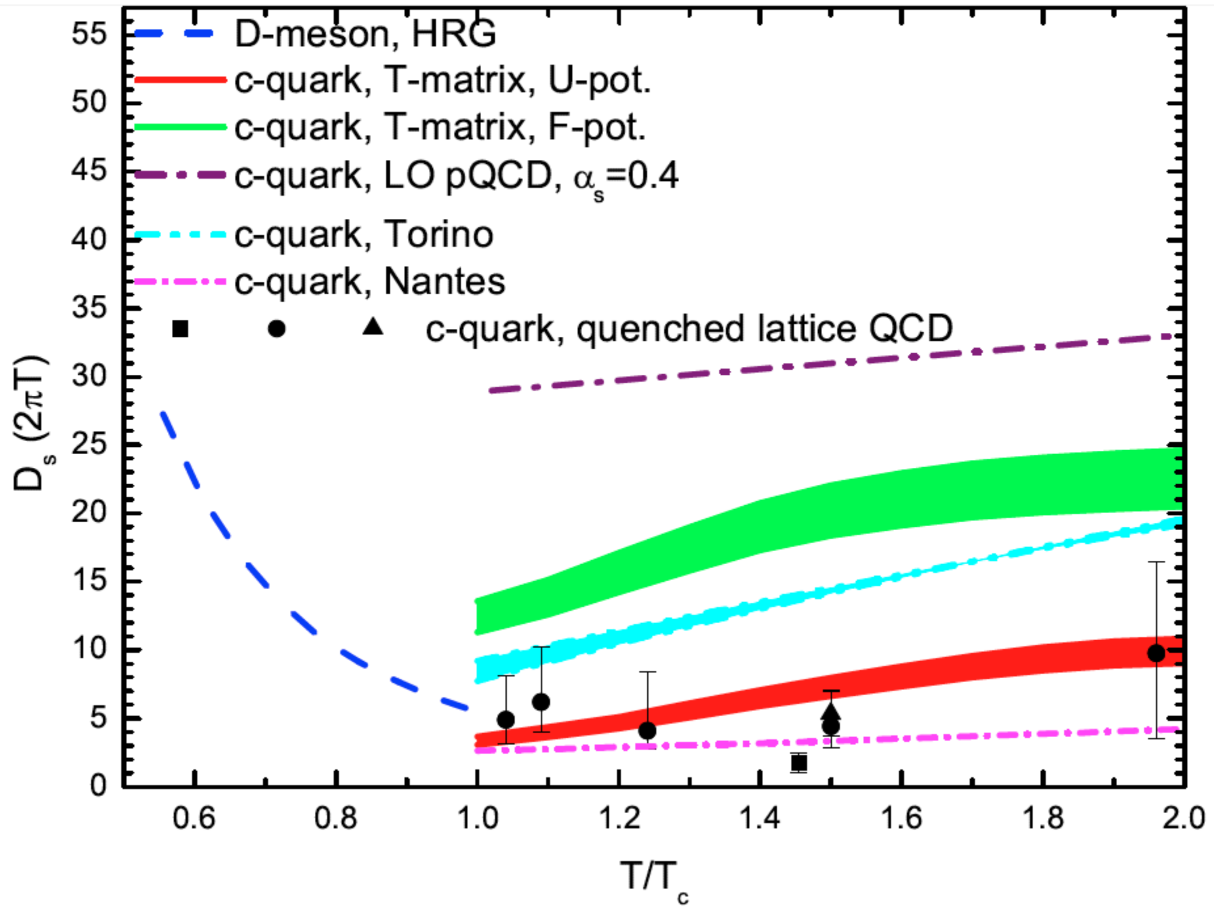

D_s spatial diffusion coefficient

$\langle r^2 \rangle = (2d) D_s t$

$D_s(2\pi T) \sim \frac{\eta}{s}(4\pi)$

relaxation time: $\tau_q = \frac{m_q}{T} D_s$

T-matrix: TAMU

Torino: POWLANG

Nantes: MC@sHQ+EPOS

Prino, Rapp, arXiv:1603.00529

spread of model predictions large; efforts to reduce it are under way

simultaneous description of R_{AA} and v_2 crucial ("unification" of inputs too)

D-meson production vs. multiplicity

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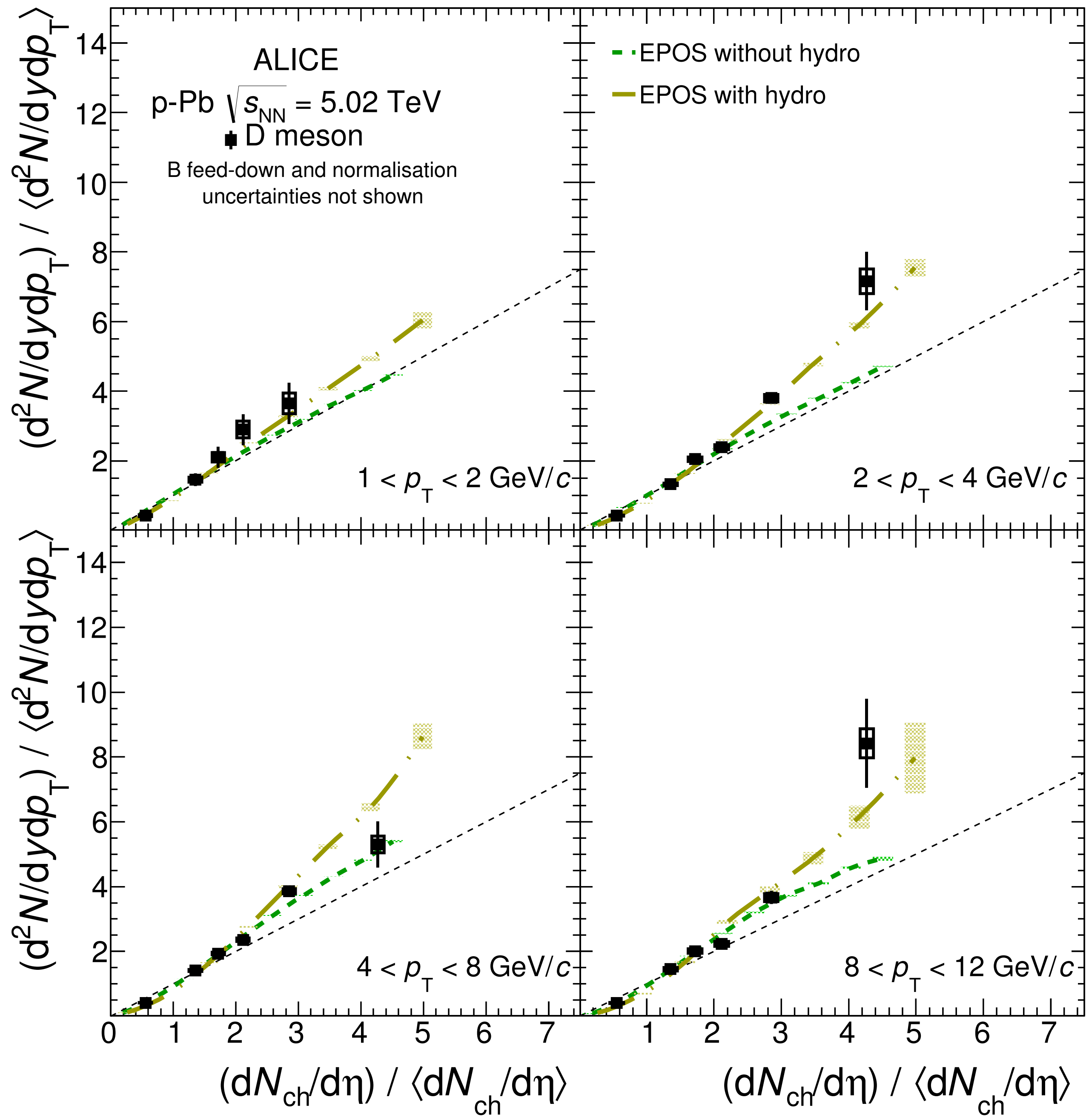
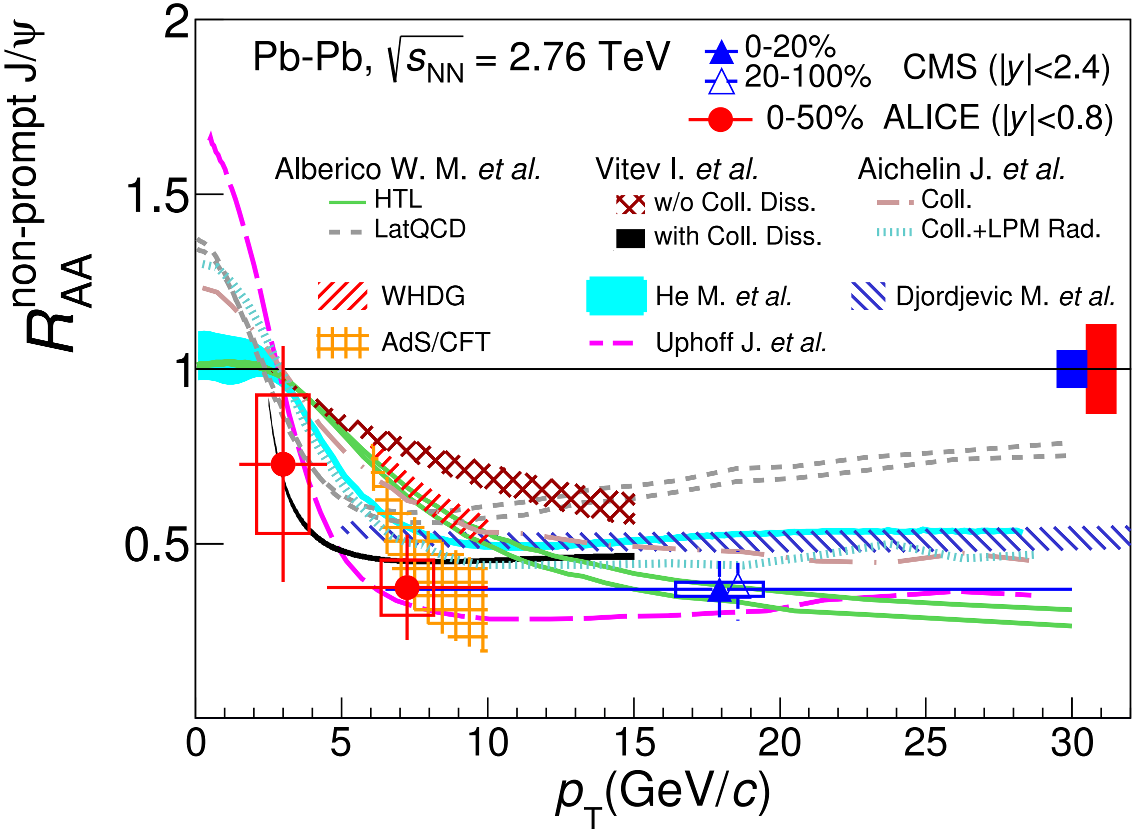


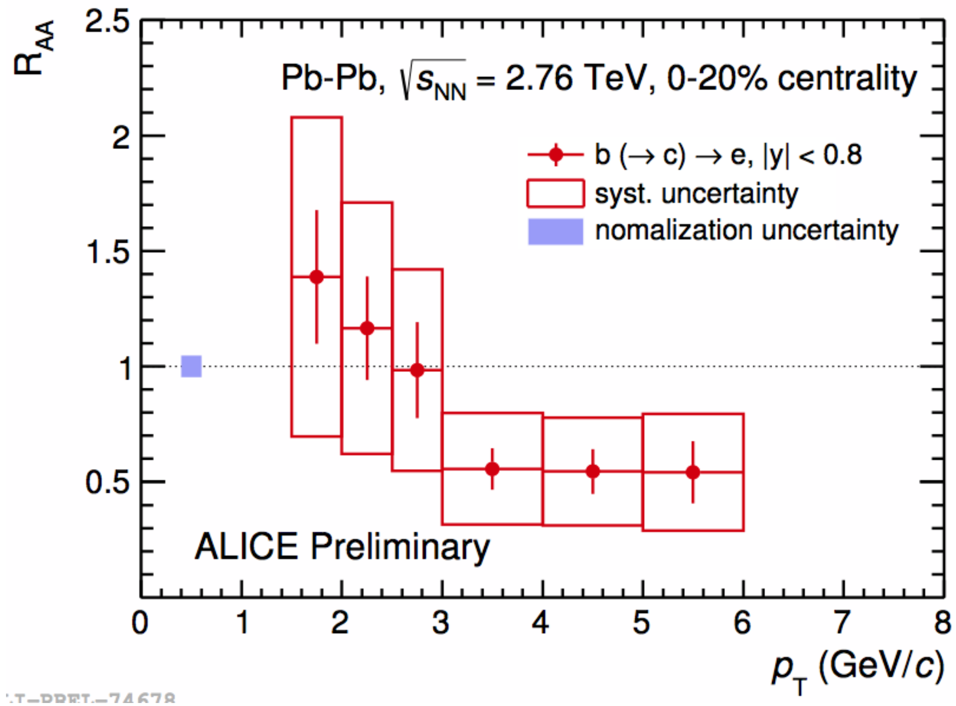
ALICE, JHEP 08 (2016) 1

data better described with inclusion of a hydrodynamical stage in EPOS

similar trend observed in pp (ALICE, JHEP 09 (2015) 148)

...also for J/ψ (p–Pb in prep.)





poster, MinJung Kim

ALICE, JHEP 07 (2015) 51

uncertainties still quite large (improvements expected in Run 2)

Charmonium data at RHIC and the LHC

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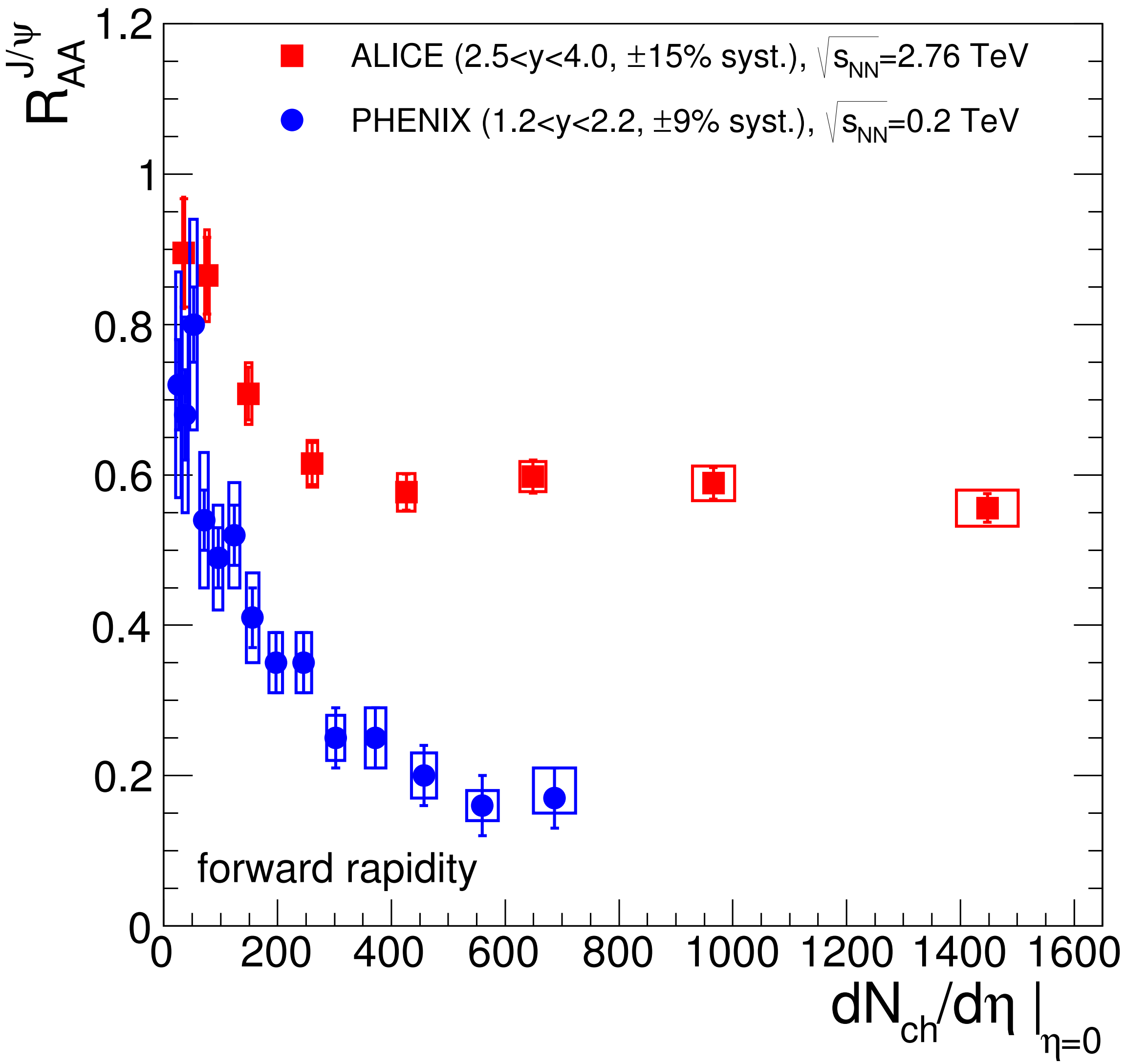

- "suppression" at RHIC
- dramatically different at the LHC

$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$ (>16 GeV/fm^3, for $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq 1500$)

...

Charmonium data at RHIC and the LHC

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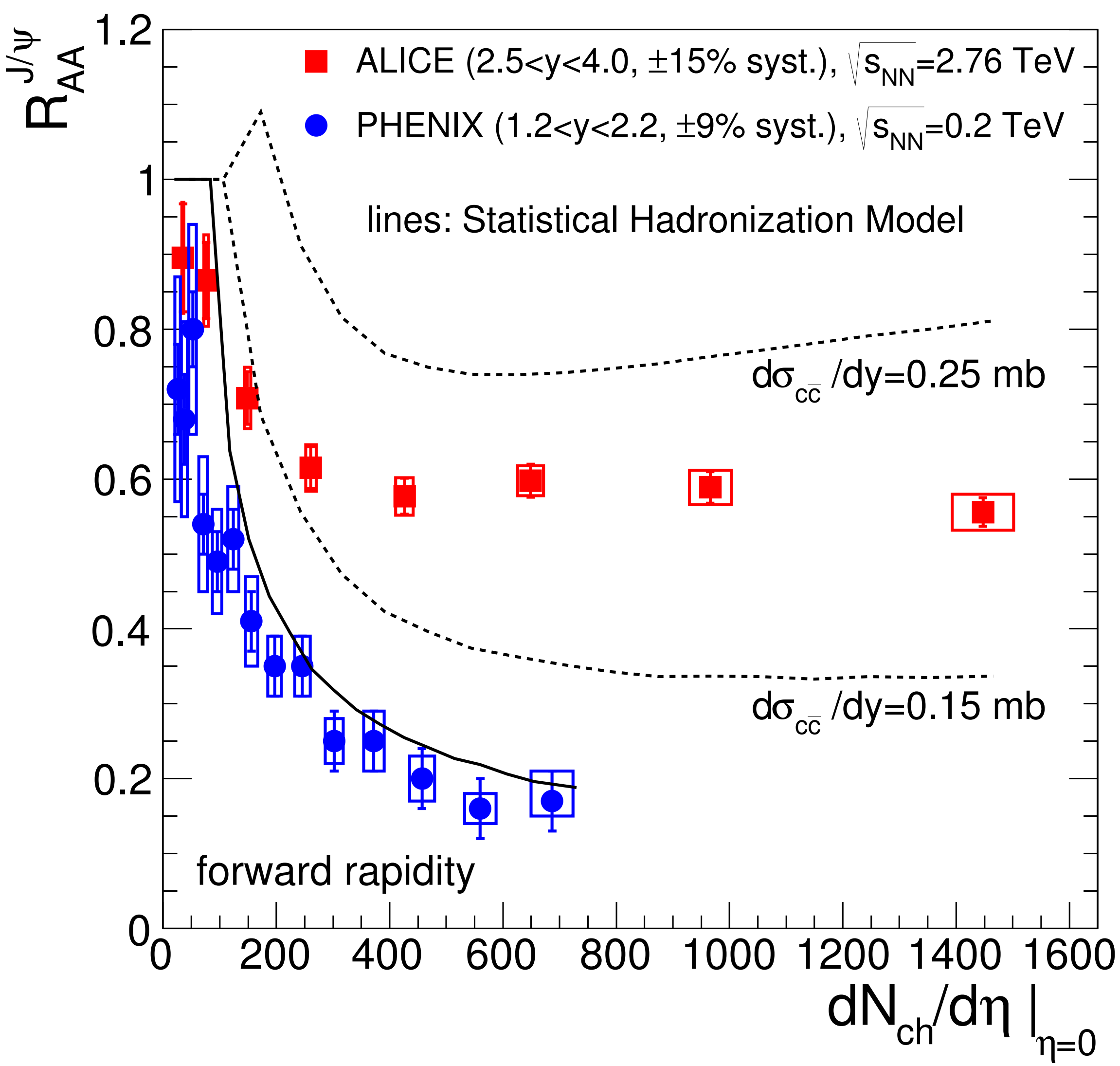

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Statistical Hadronization Model

$N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

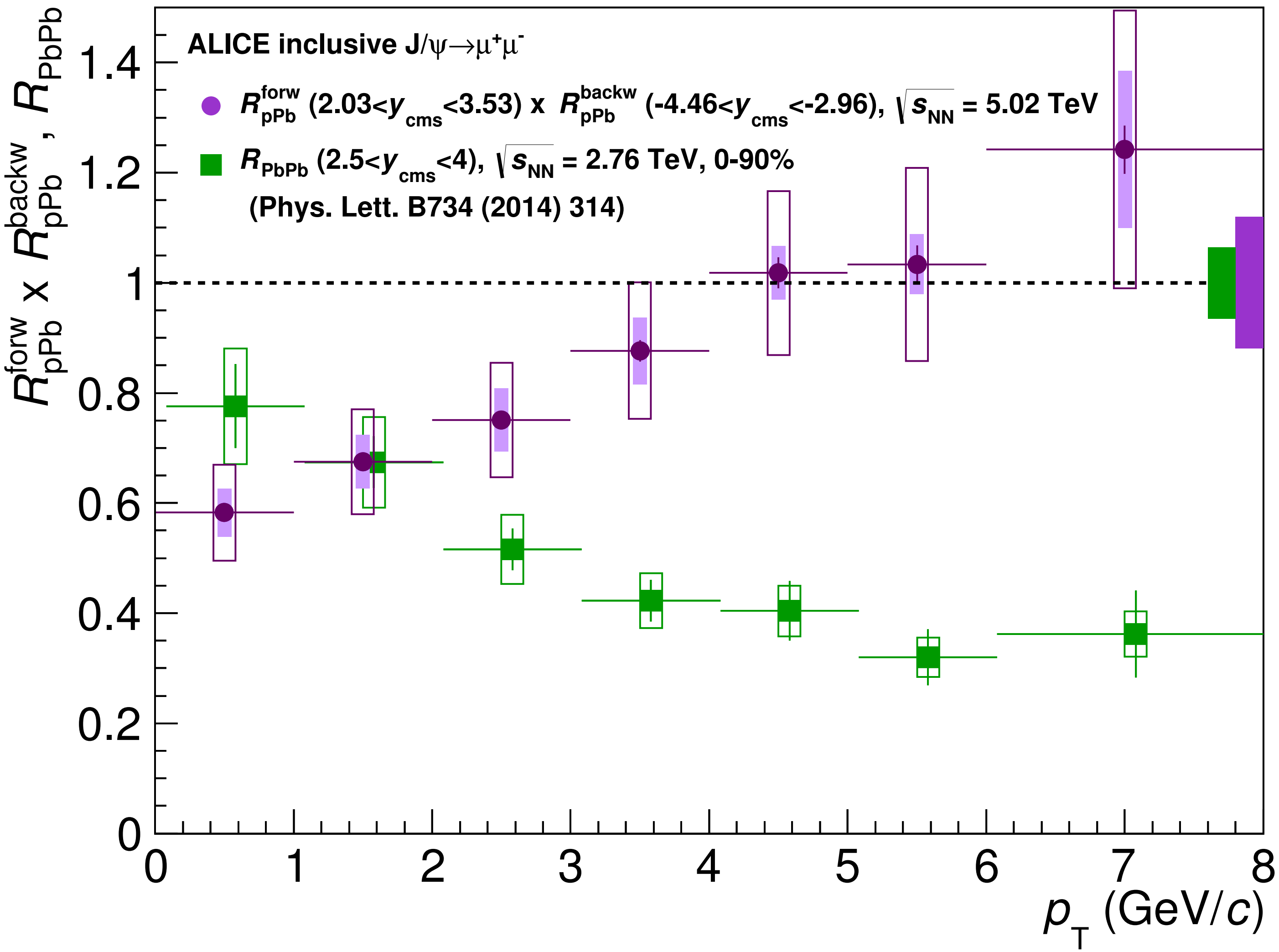
Predictions: AA et al., PLB 652 (2007) 259

What is so different at the LHC? (compared to RHIC)

$\sigma_{c\bar{c}}$: ∼10x, Volume: ∼2.2x

J/ψ is another observable (charm) for the phase boundary

calculations are for T=156 MeV



ALICE,

JHEP 06 (2015) 055

distinct differences between Pb–Pb and p–Pb, further support that low-p_T J/ψ are from (re)generation (while at high-p_T outcome of charm energy loss)

Connection to the phase diagram of QCD

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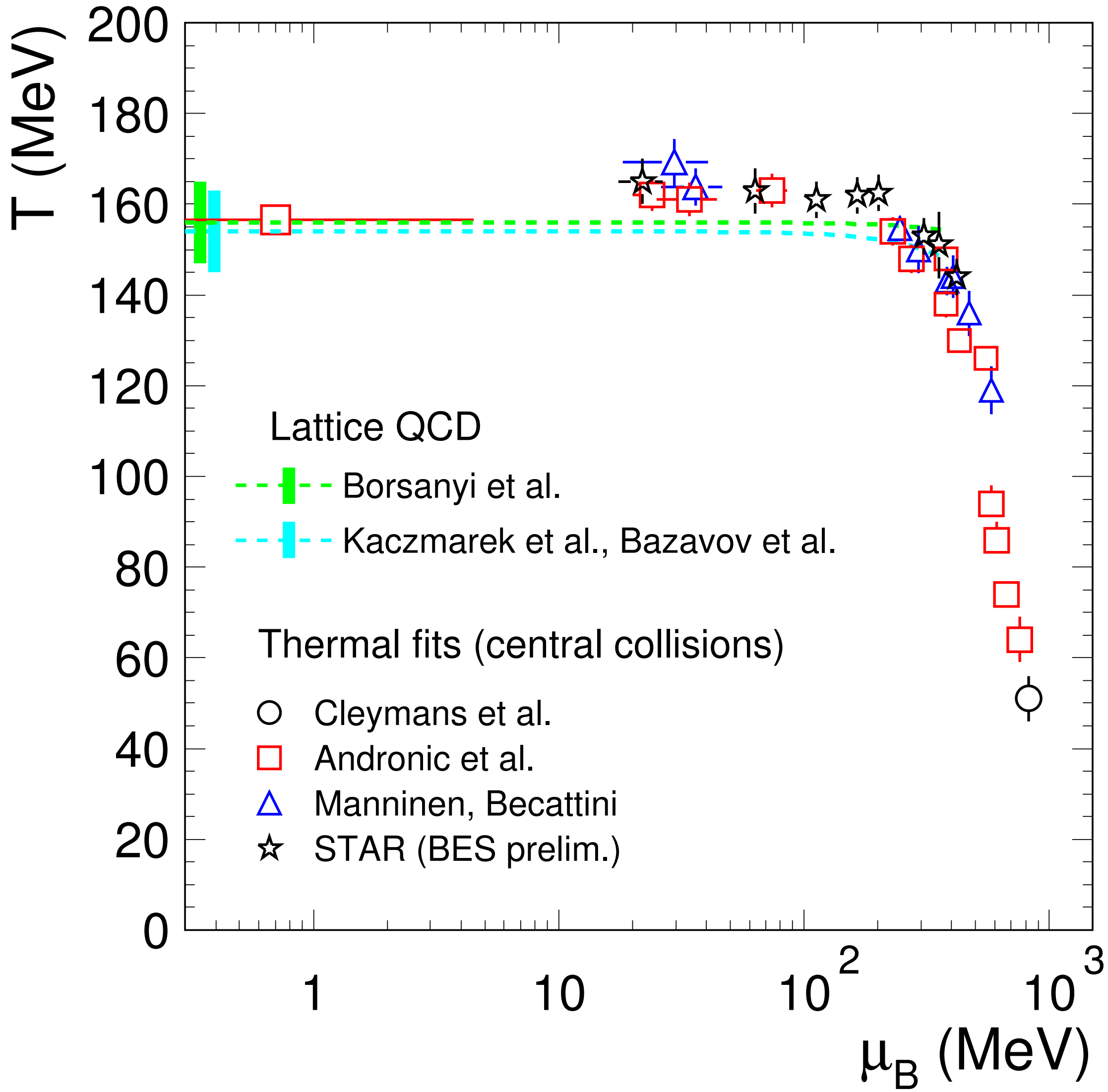
(as $T \to T_{lim}$) is chemical freeze-out a determination of the phase boundary?



...Yes (at low μ_B)

Lattice QCD, $\mu_B = 0$:
crossover T=145-165 MeV

Borsanyi et al.,
JHEP 1009 (2010) 073, JHEP 1208 (2012) 053

HotQCD, PRD 90 (2014) 094503, PRD 83, 014504 (2011)

...for entire μ_B range?

PBM, Stachel, Wetterich, PLB 596 (2004) 61
McLerran, Pisarski, NPA 796 (2007) 83
AA et al., NPA 837 (2010) 65
Floerchinger, Wetterich, NPA 890 (2012) 11

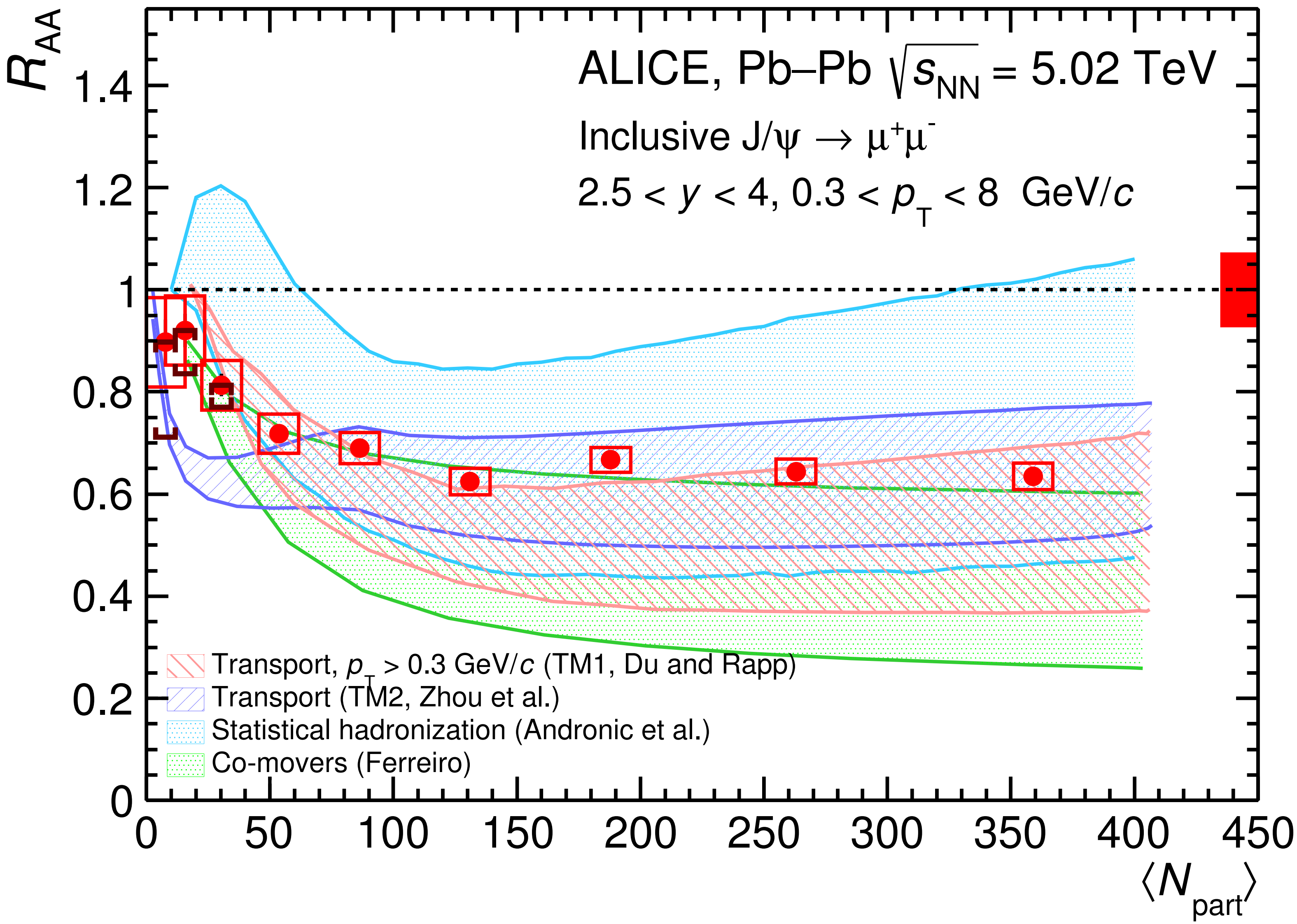
Are the larger T values at RHIC significant (physics)?

...an important connection, but not decisive (yet)

(recall that only $\sigma_{c\bar{c}}$ *is a new parameter in the statistical model, besides* T, V*)*

...as transport models describe data equally well (and predict $R_{AA}(p_T)$ and v_2) assuming continuous dissociation and formation during the whole lifetime of QGP

is there a way to make the distinction?



ALICE, arXiv:1606.08197

J/ψ production at 5 TeV

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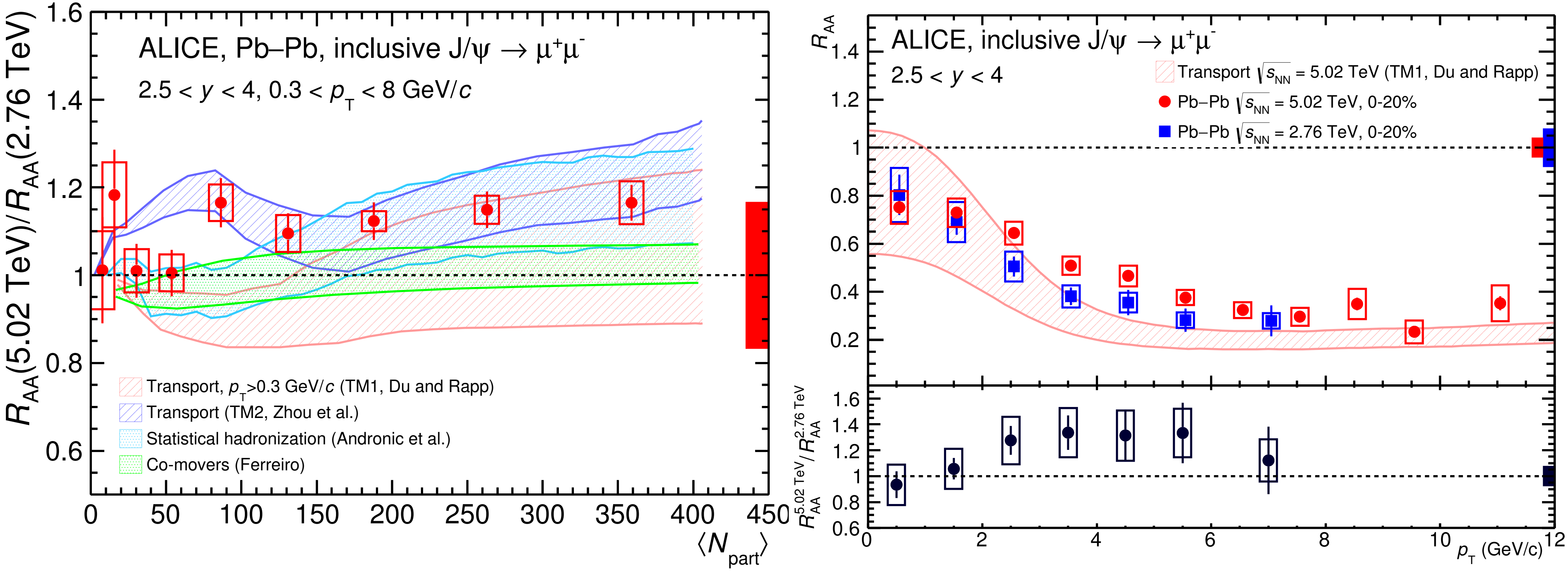
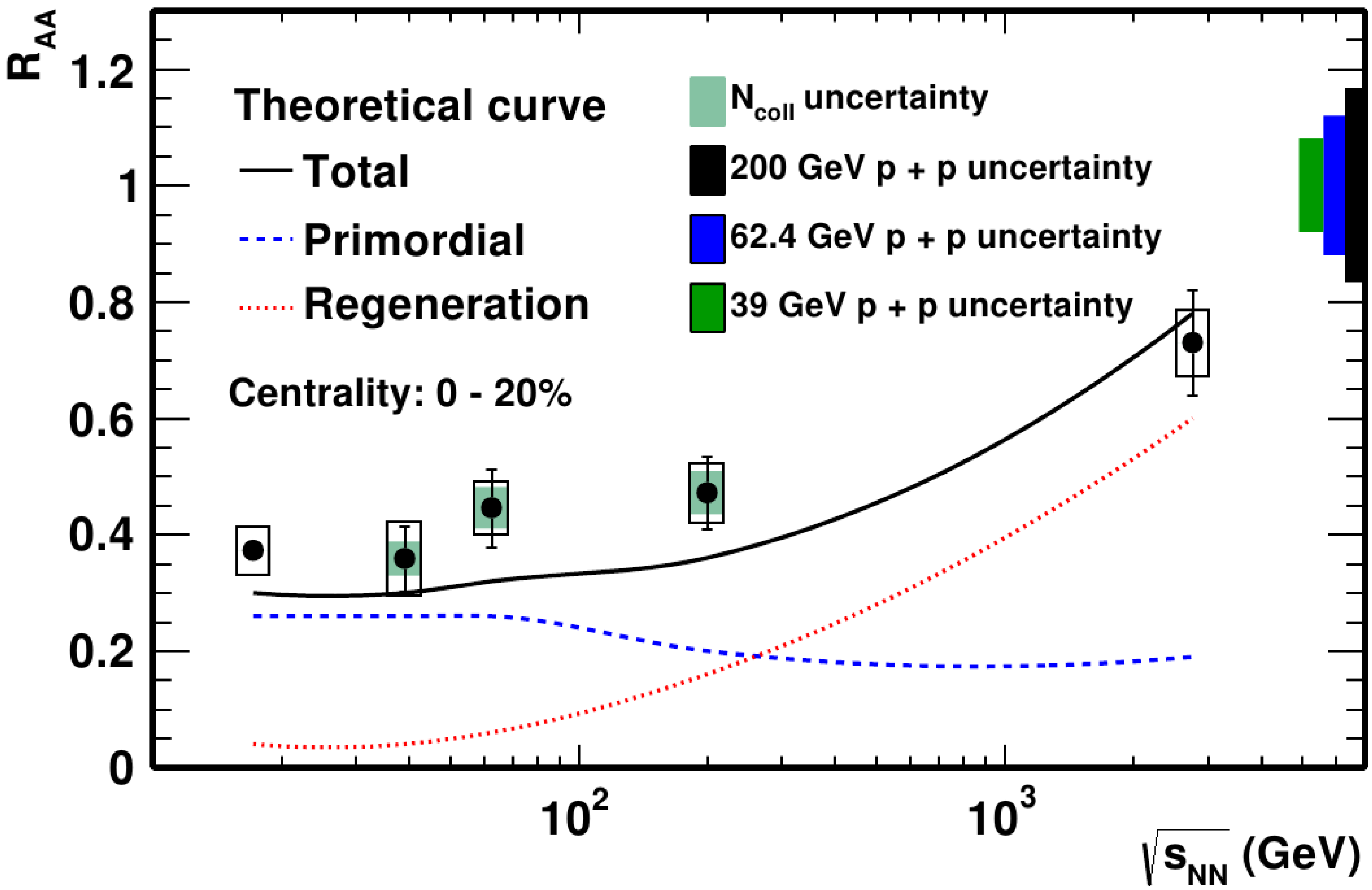


ALICE, arXiv:1606.08197

The current (syst.) uncertainties prevent a firm conclusion, but trend generically predicted by (re)generation models (uncertainties determined by $\sigma_{c\bar{c}}$, 5% here)

J/ψ vs. energy



STAR collab., arXiv:1607.07517

Theory: transport model (Tsinghua Univ.)

$\psi(2S)$ production at the LHC

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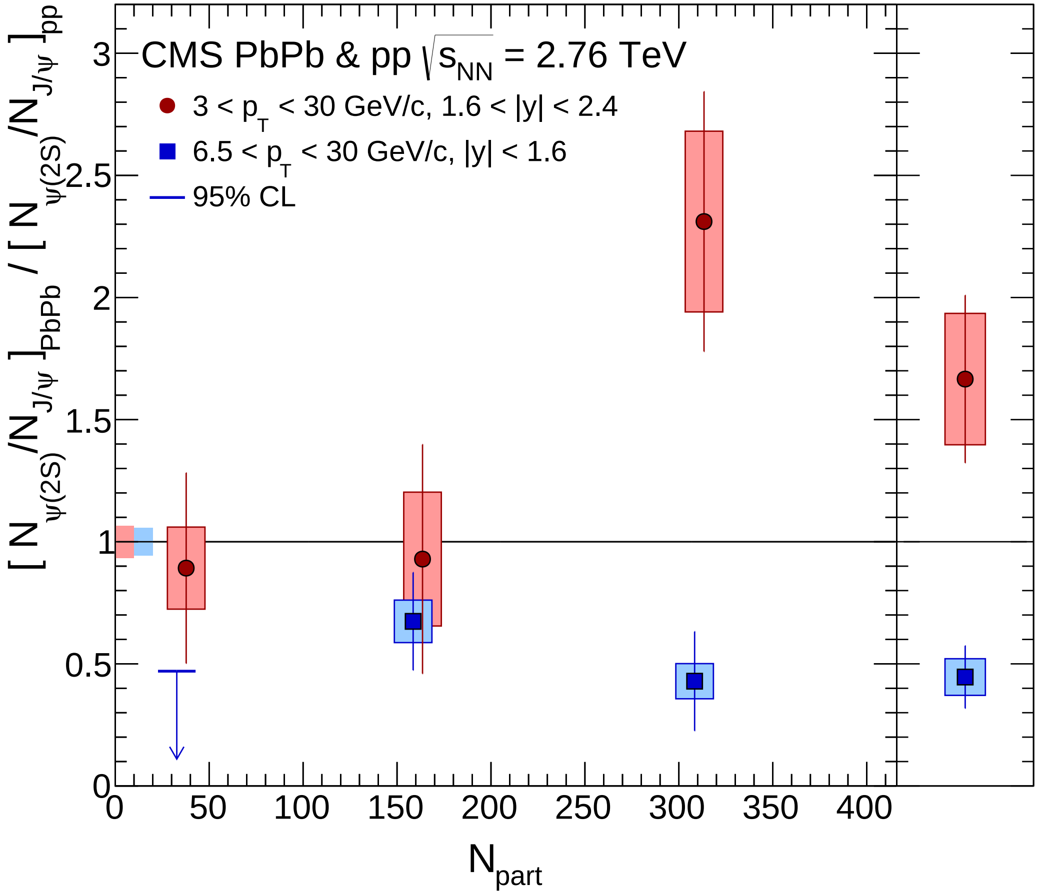
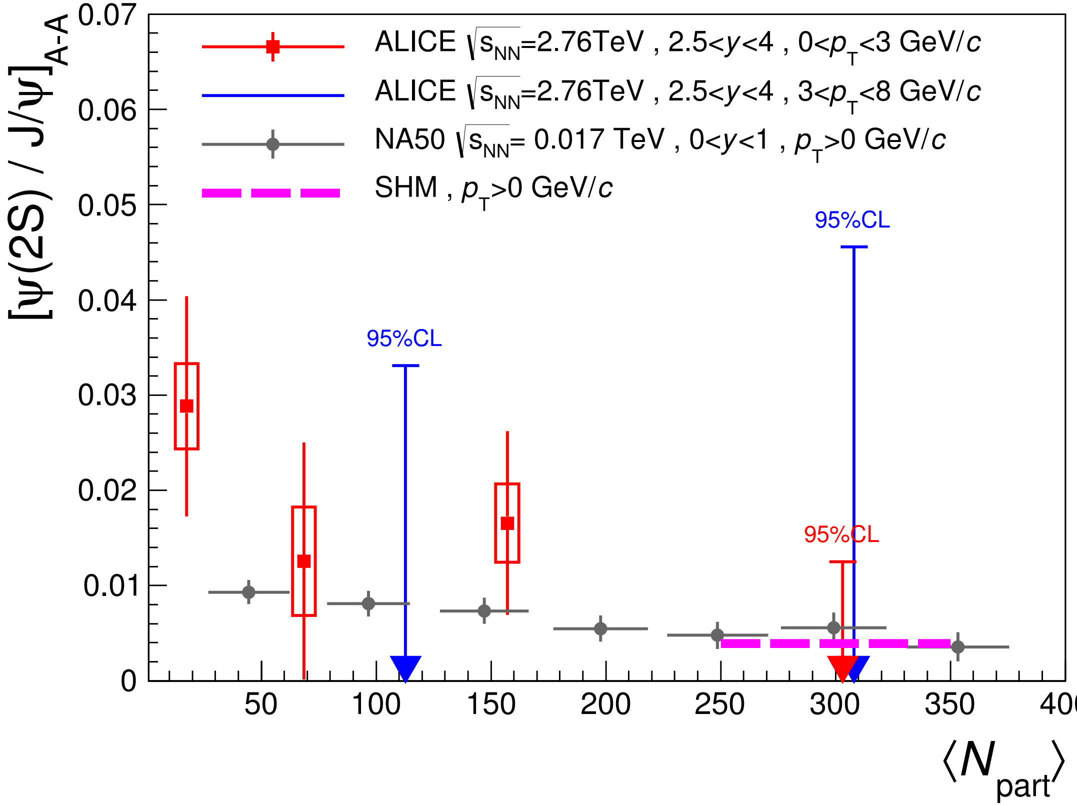


CMS, PRL 113 (2014) 262301



ALICE, JHEP 05 (2016) 179

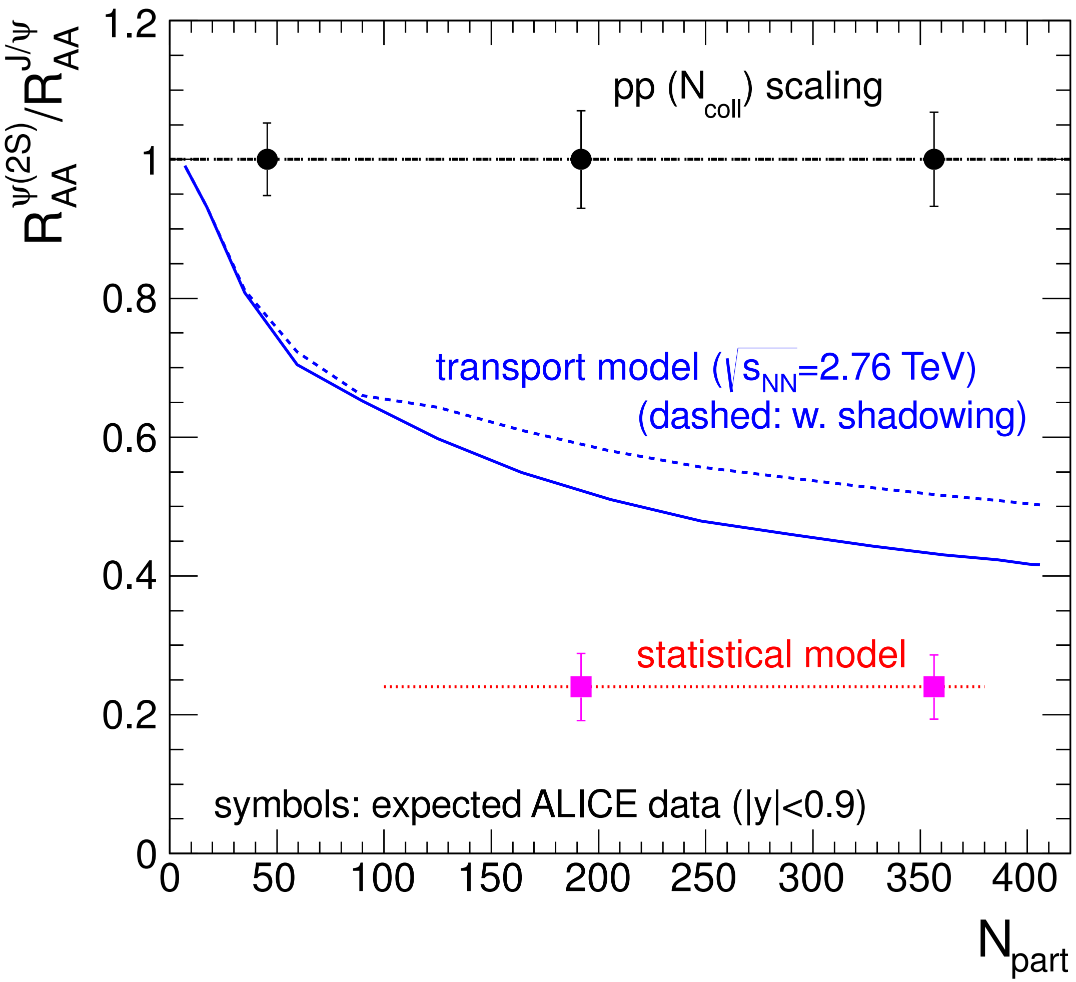
at the SPS, the thermal value (SHM) was reached for central Pb–Pb ($p_T > 0$)

LHC: uncertainties large, no conclusion yet ...but expected in Run 2 (and Run 3)

$R < 1$ expected in both models, different magnitudes predicted (p_{T}-integrated)

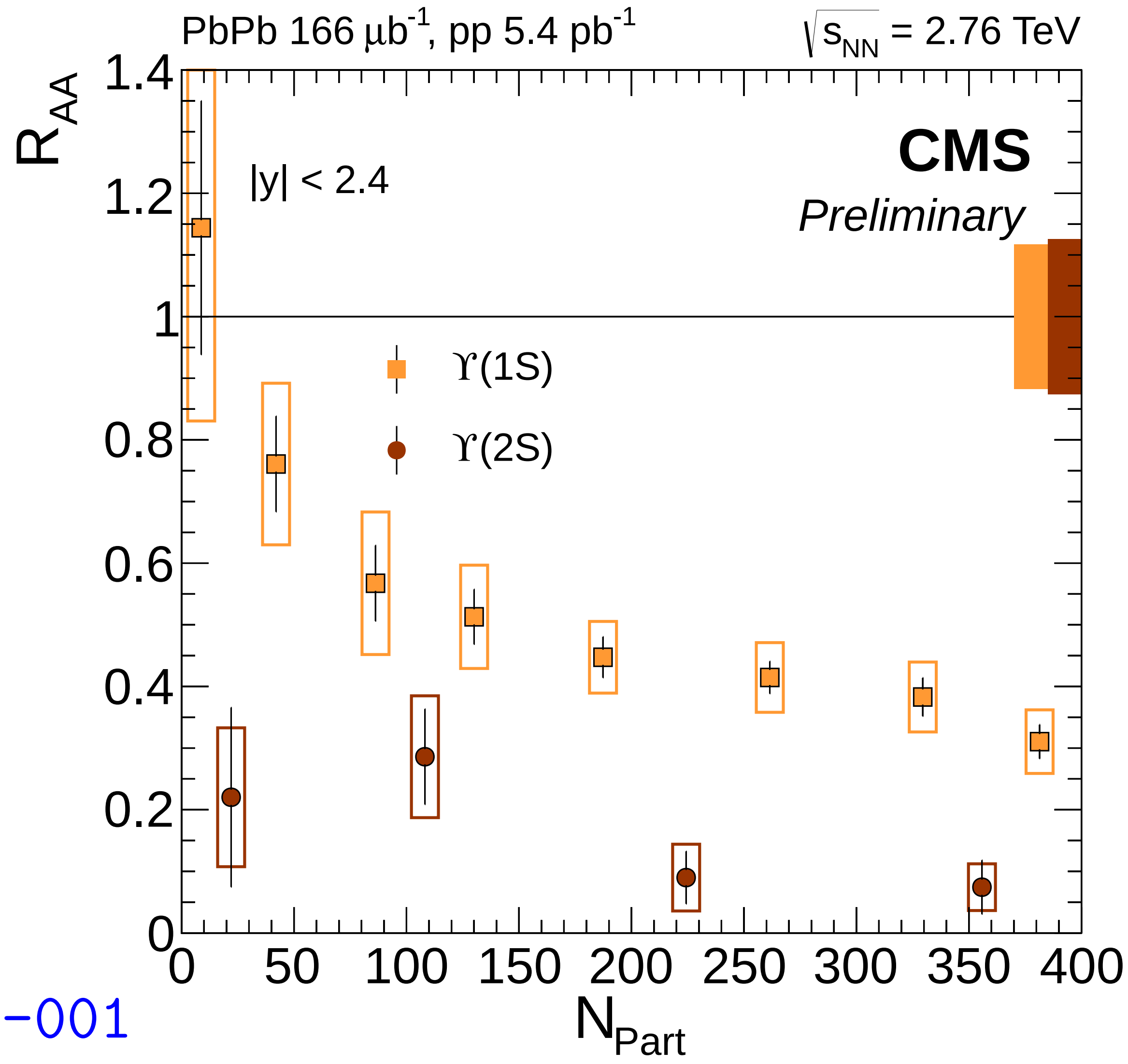
Transport model:
Zhao, Rapp, NPA 859 (2011) 114 and priv. comm.

see Du, Rapp, arXiv:1504.00670



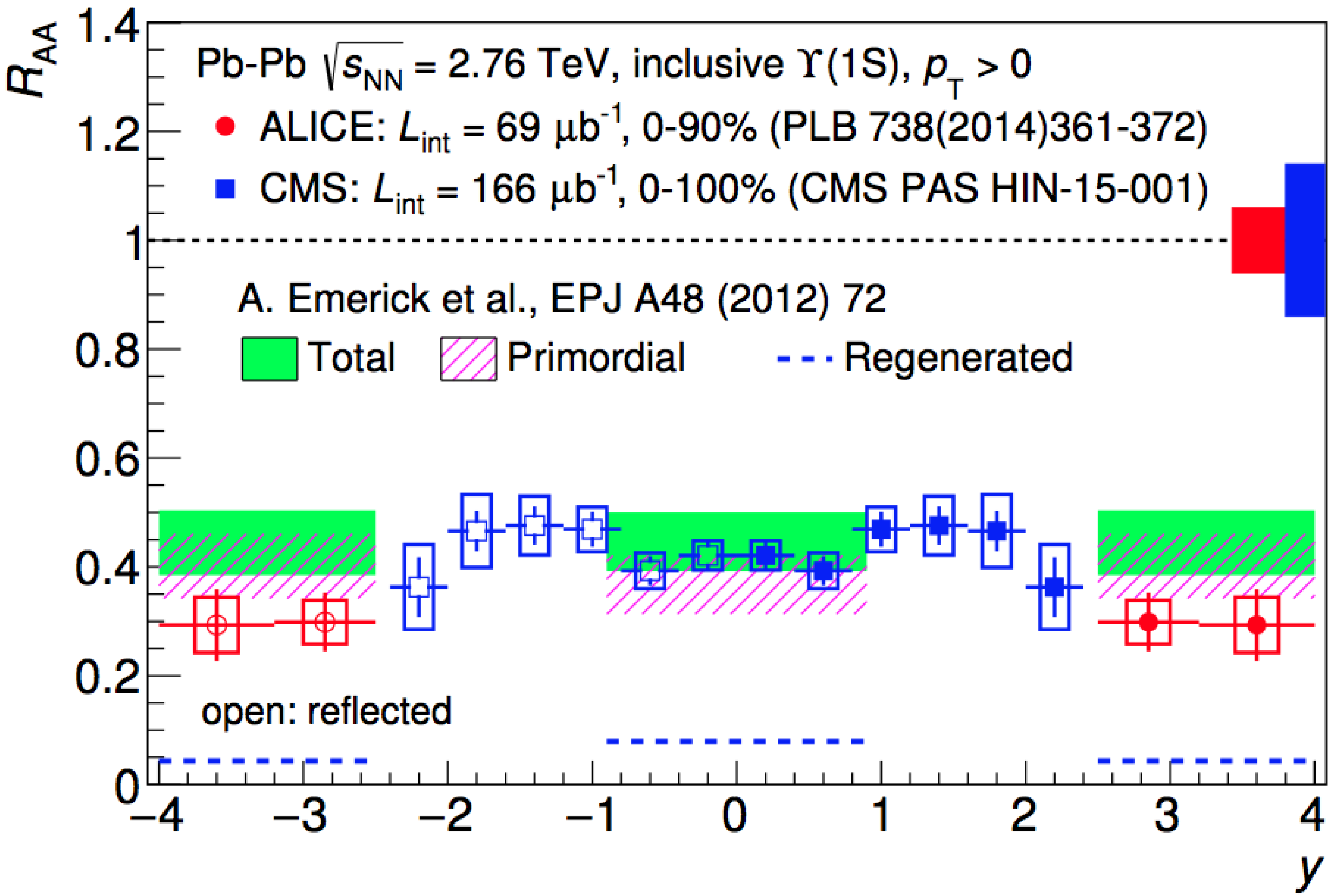
Central Barrel: measurement possible only with upgrade (10 nb^{-1})
Muon Spectrometer: a first glimpse with baseline data (1 nb^{-1}), a real measurement only with upgraded ALICE

ALICE, JPG 41 (2014) 087001

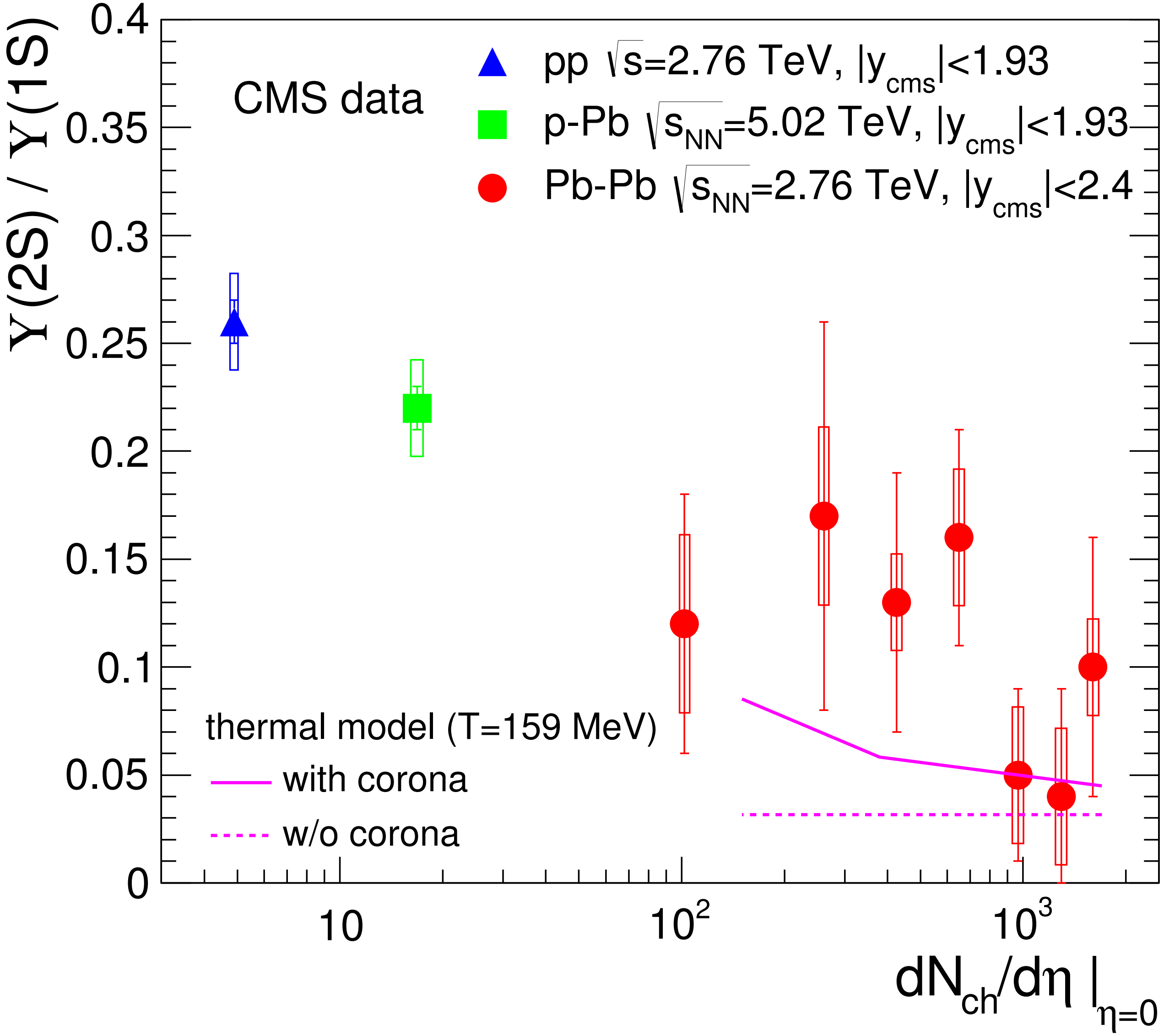


CMS-PAS-HIN-15-001

$\Upsilon(1S)$ supression interpreted as effect of feed-down from $\Upsilon(2S, 3S)$, which were fully dissociated ("sequential suppression")



Transport model predicts a small fraction of regenerated Υ



The data approach the thermal limit for central Pb-Pb coll.

(the trend itself is interesting and not well understood)

fair description by model

[also for R_{AA} of $\Upsilon(1S)$]

Summary

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- a wealth of data on hadrons with heavy quarks (mostly charm though) awaits a more precise model description and extraction of transport coefficients

  interesting observations on multiplicity dependence in pp and p–Pb collisions

- (I think:) everybody agrees that we see (re)combination of charm quarks at the LHC

  ...a new observable for the QCD phase boundary (...maybe similar at RHIC)

- interesting (sequential?) "disappearance" pattern in the bottom (Υ) sector

  do bottom quarks also thermalize at the LHC? (at RHIC?)

  will Υ add more weight to the phase boundary?

Backup slides

D meson production

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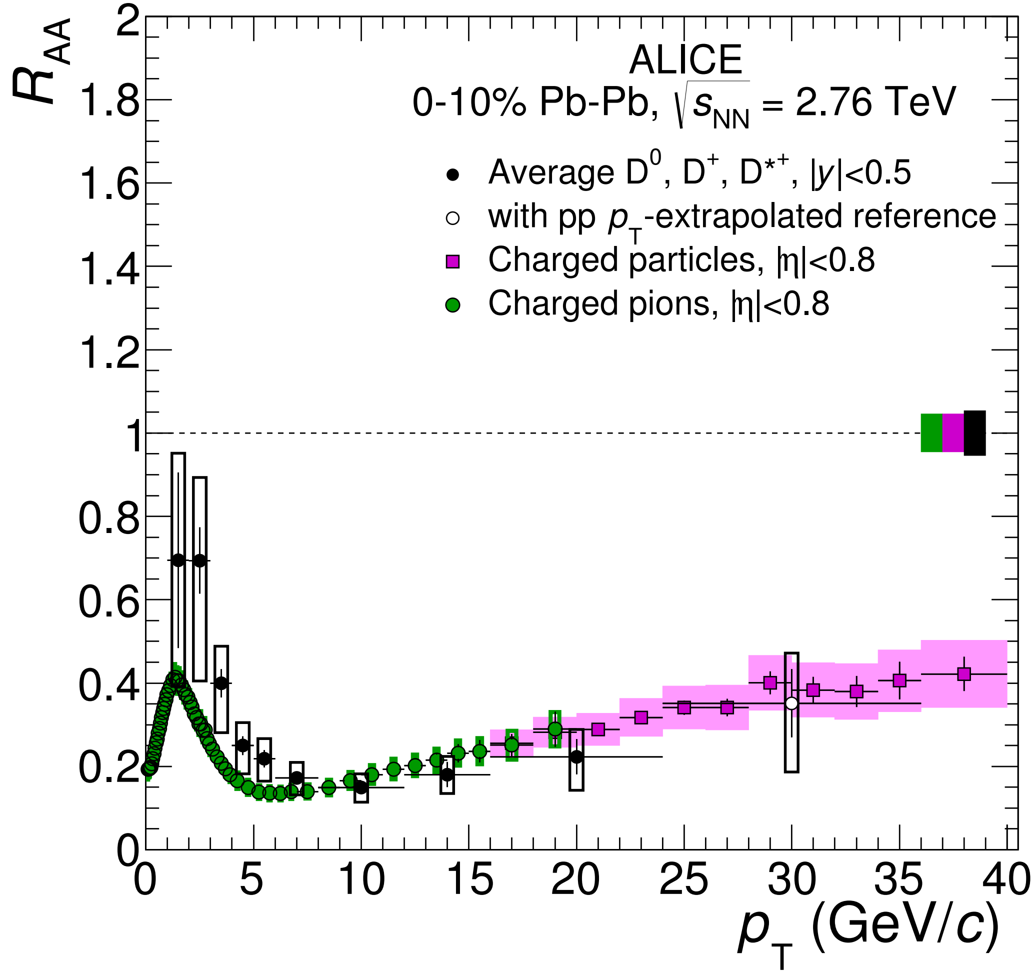
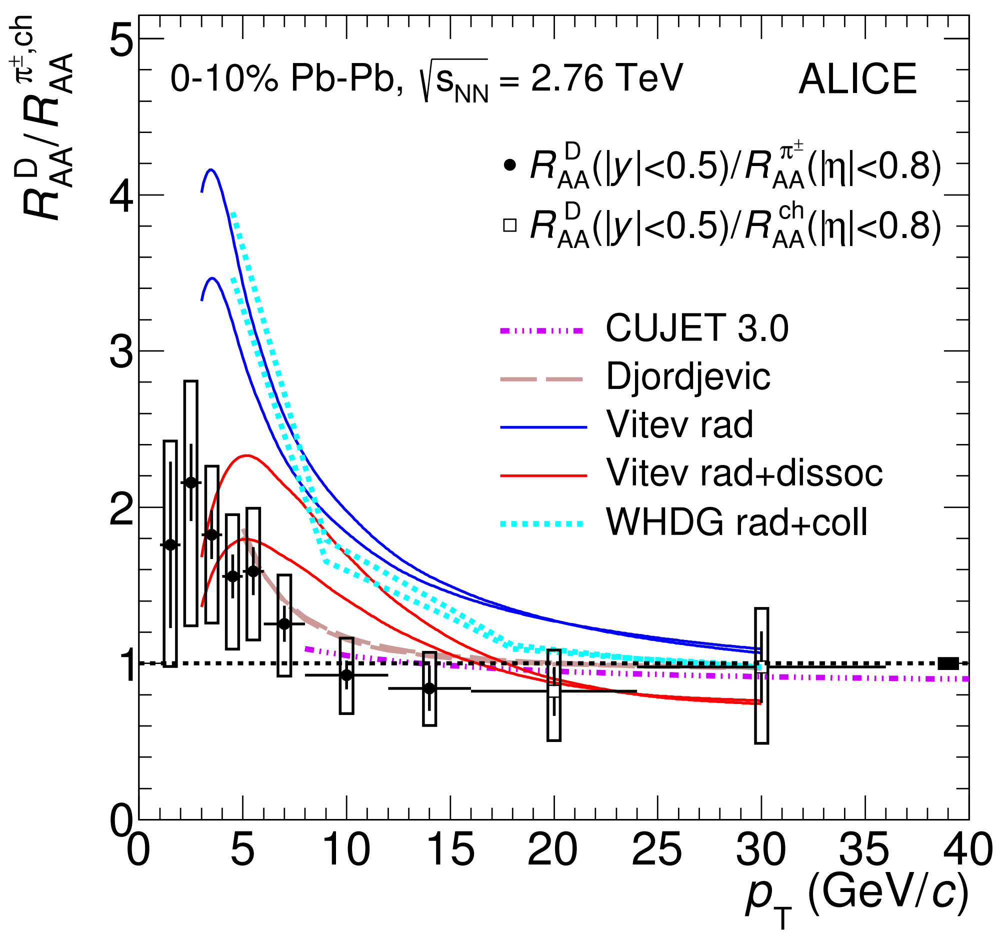
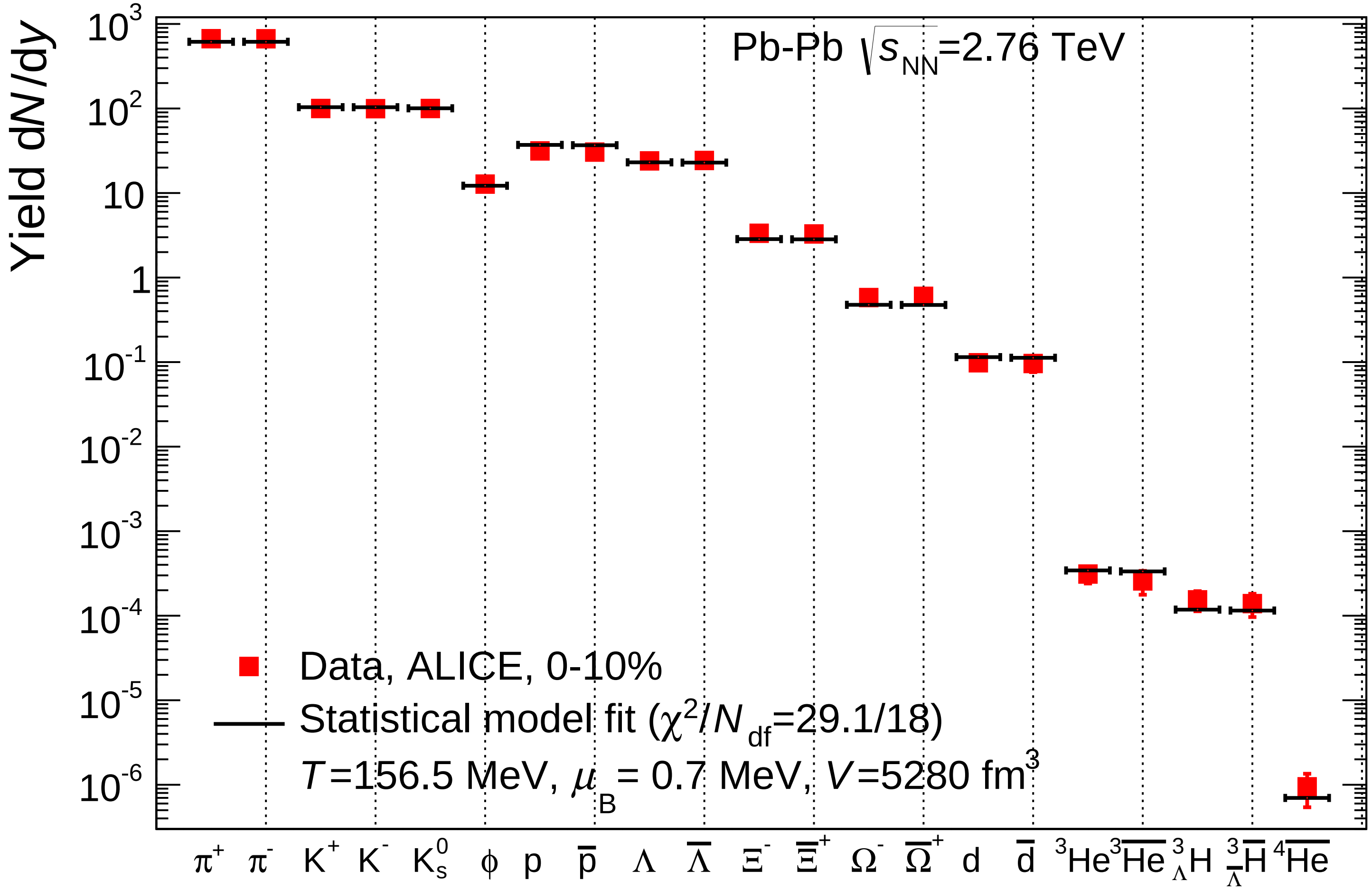




ALICE, JHEP 03 (2016) 081

simultaneous description of LQ and charm challenging in some models

Thermal fit at the LHC (Pb–Pb, 0-10%)



π, $K^{\pm}$, K^0 from charm included (0.7%, 2.9%, 3.1% for the best fit)

$$T = 156.5 \pm 1.5 \text{ MeV}, \quad \mu_B = 0.7 \pm 3.8 \text{ MeV}, \quad V_{\Delta y=1} = 5280 \pm 410 \text{ fm}^3$$

- Thermal model calculation (grand canonical) T,μ_B: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c$$ (charm fugacity)

Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

The only new input parameter: $N_{c\bar{c}}^{dir}$ (from experiment or pQCd)

Minimal volume for QGP: V_{QGP}^{min}=100 fm^3

Charmonium in the statistical hadronization model

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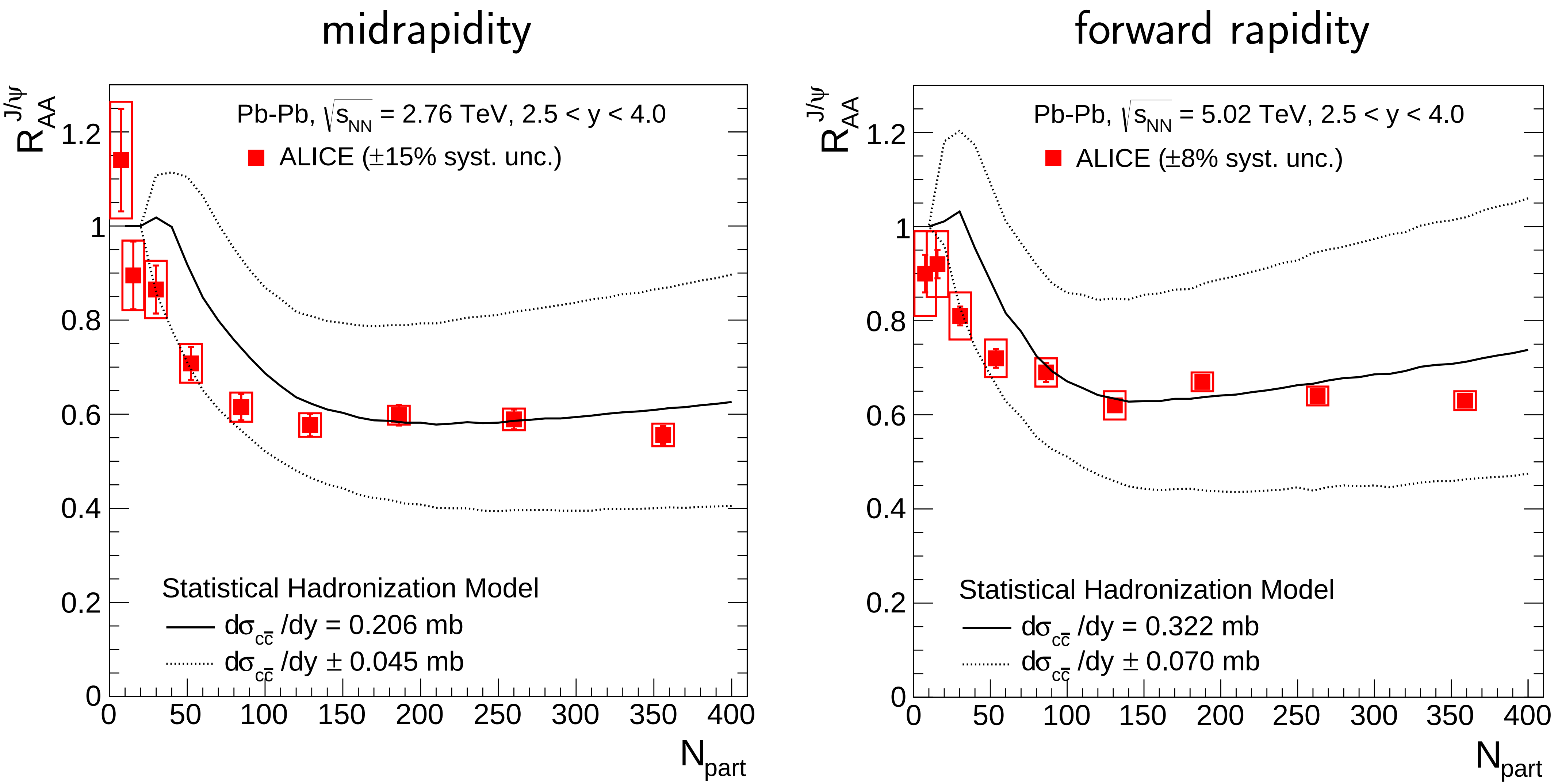
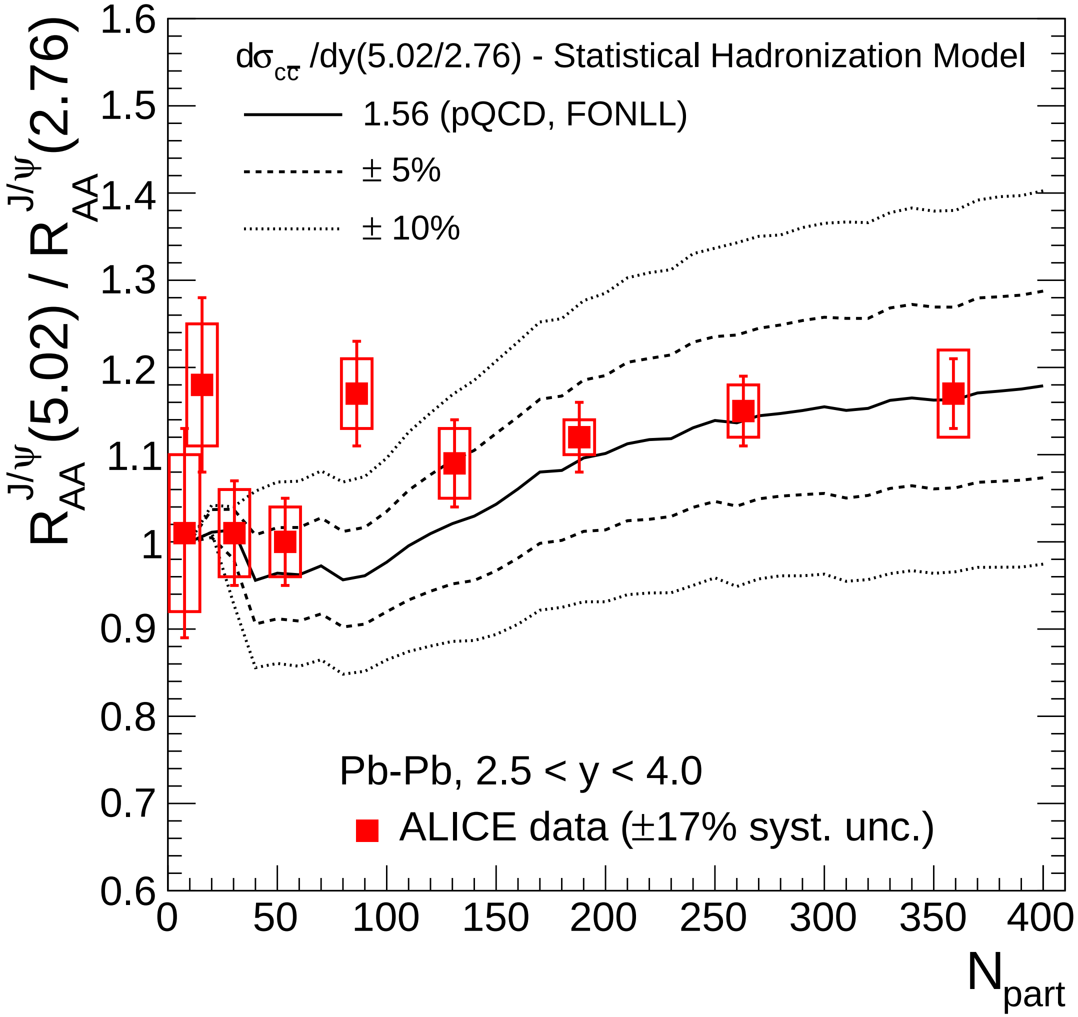


the generic prediction by the model is confirmed by data (ALICE, arXiv:1606.08197)

establishes charmonium as a powerful new observable of the phase boundary the model predicts absolute yields (R_{AA} is calculated with the pp reference as for data)



$2.5 < y < 4.0$

$\sigma_{c\bar{c}}$ from pp, $\sqrt{s}$=7 TeV, LHCb, NPB 871 (2013) 1

$p_T < 8\,GeV/c, 2.0 < y < 4.5$

$\sigma_{c\bar{c}} = 1419 \pm 12(stat) \pm 116(syst) \pm 65(frag)\,\mu$b

energy scaling via FONLL pQCD

shadowing calculations (R.Vogt): 0.71±0.10

$V_{\Delta y=1}$: 2.76 TeV: 4120 fm^3; 5.02 TeV: 5150 fm^3

Syst. uncert. of data apply fully-correlated to the model calculations