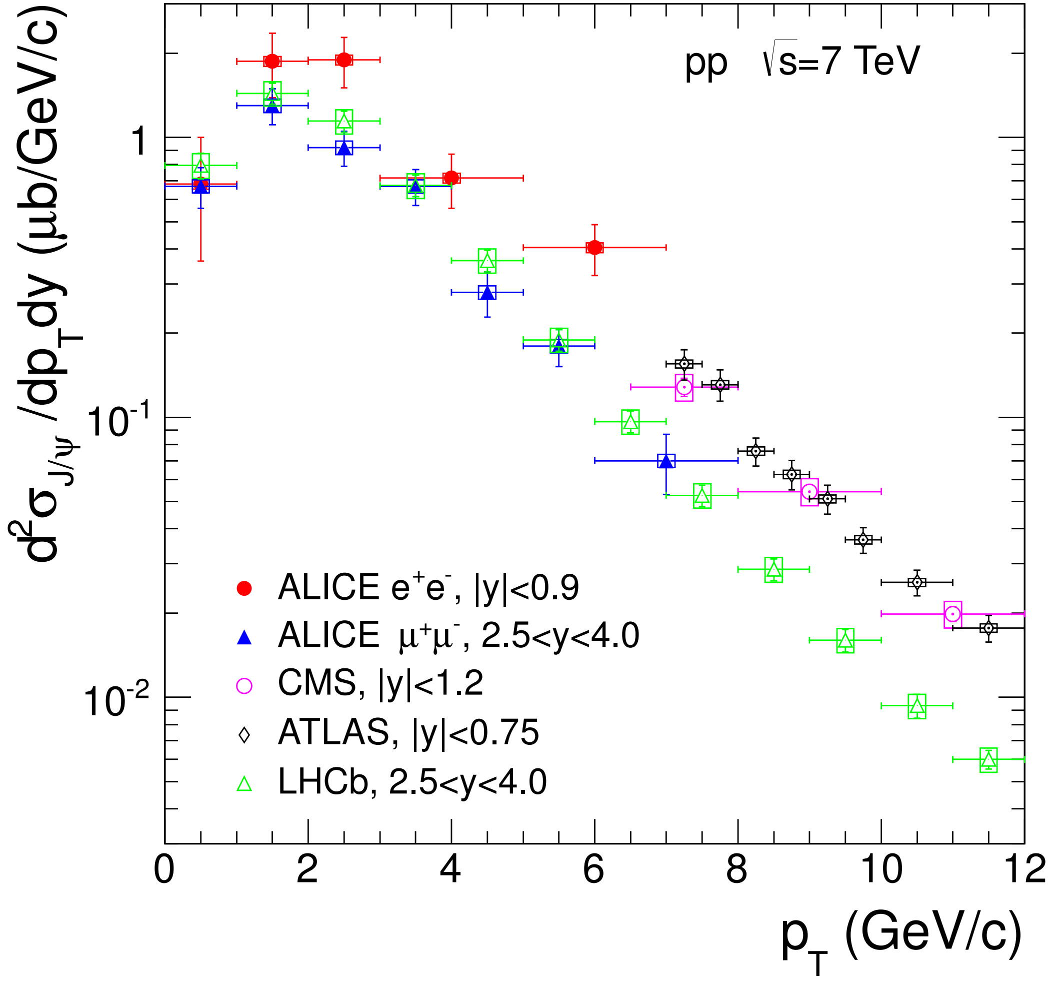
Measurement of quarkonium production at the LHC: from pp to Pb–Pb collisions with insight into the Quark-Gluon Plasma

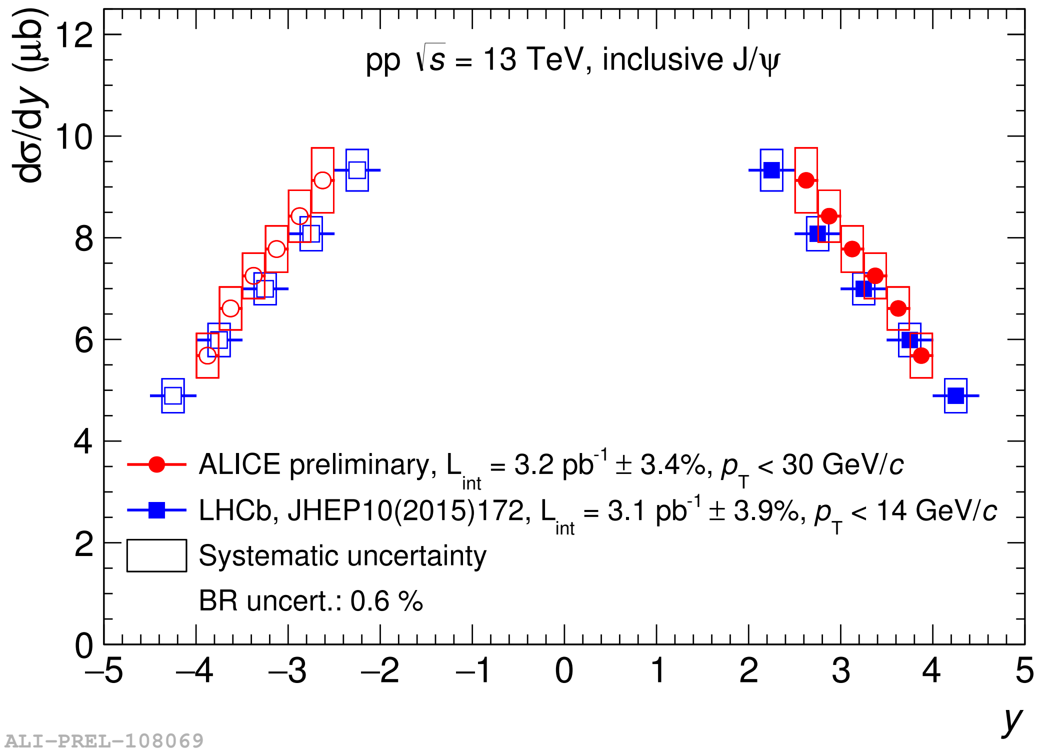
A. Andronic – GSI Darmstadt

- Quarkonium production in pp and p–Pb collisions
- Quarkonium production in Pb–Pb collisions
- Summary and outlook

Charmonium production in pp collisions



ALICE, PLB 704 (2011) 442

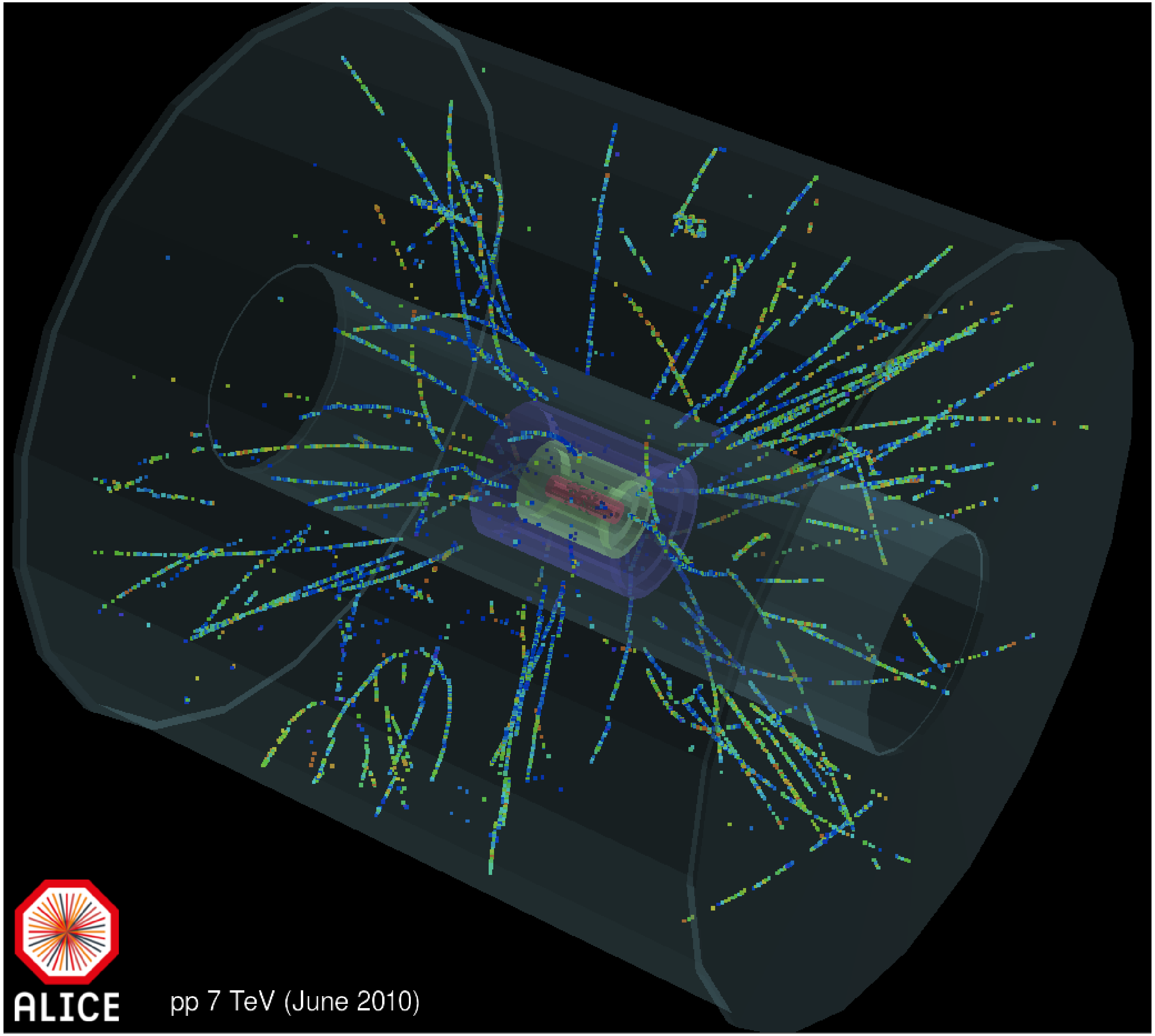


Observable to test models (non-perturbative QCD)

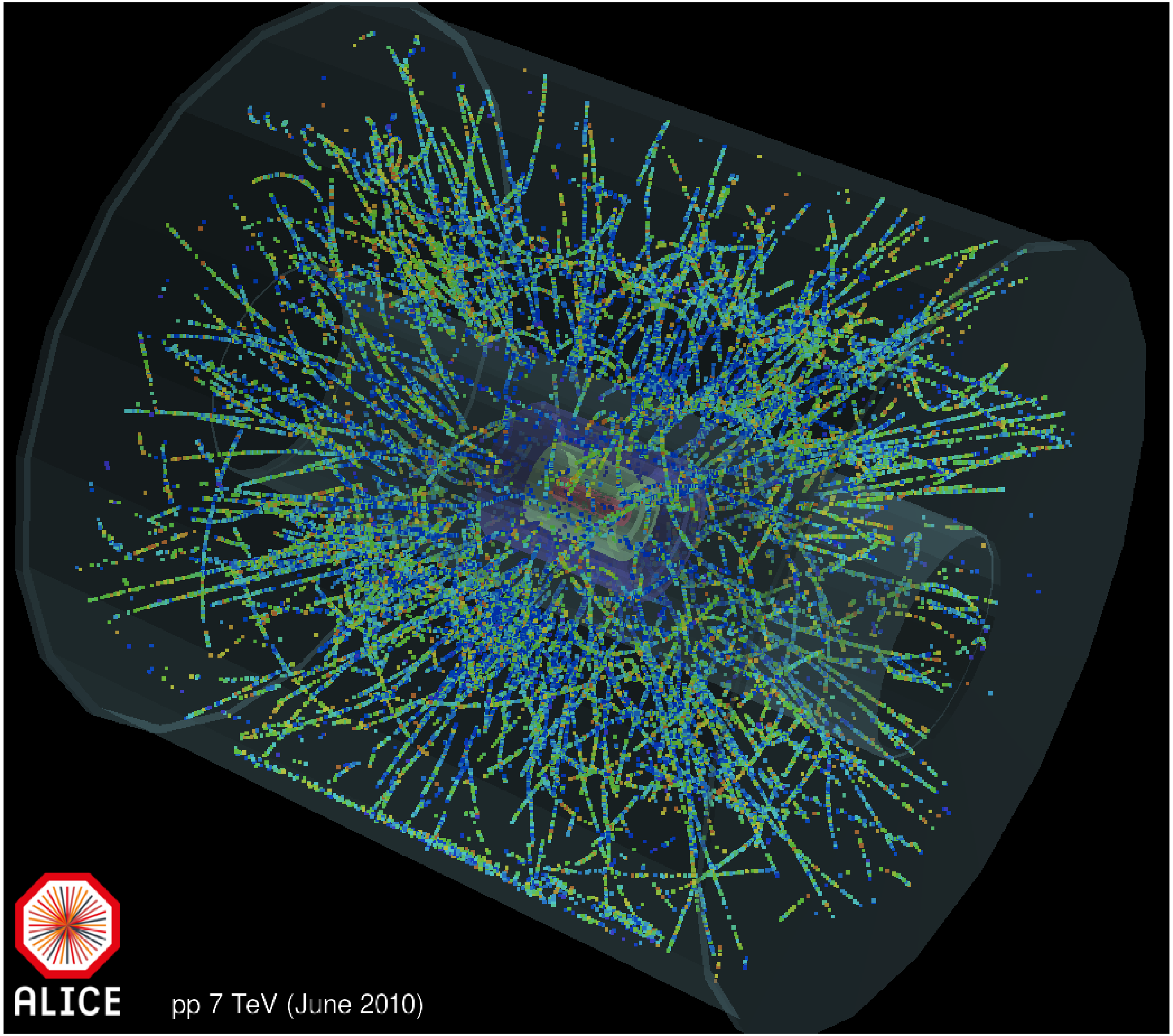
Reference for measurements in p–Pb, Pb–Pb collisions

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}{N_{coll}^{AA}\cdot\mathrm{d}N_{pp}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}$$

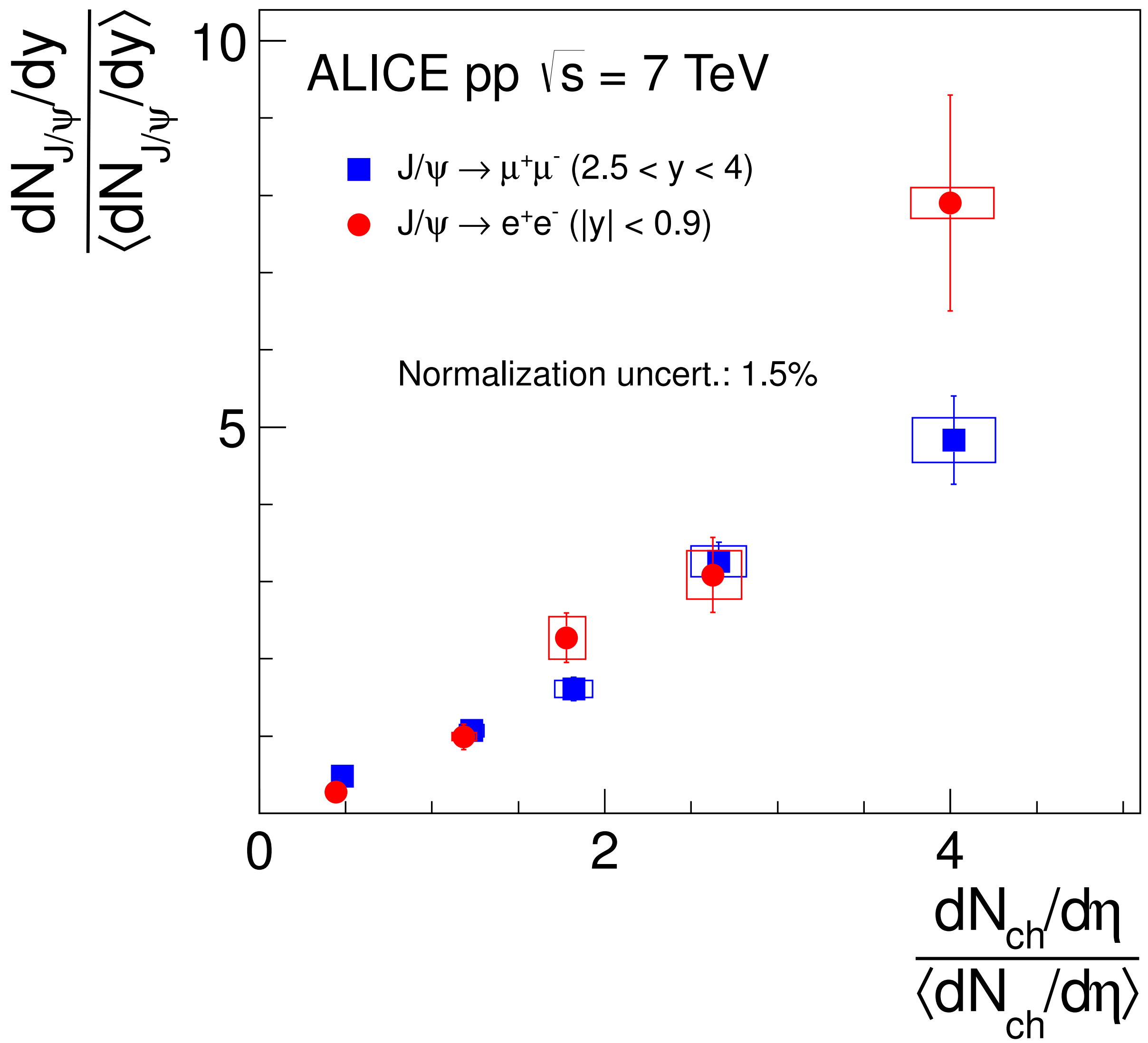
pp collisions



pp collisions

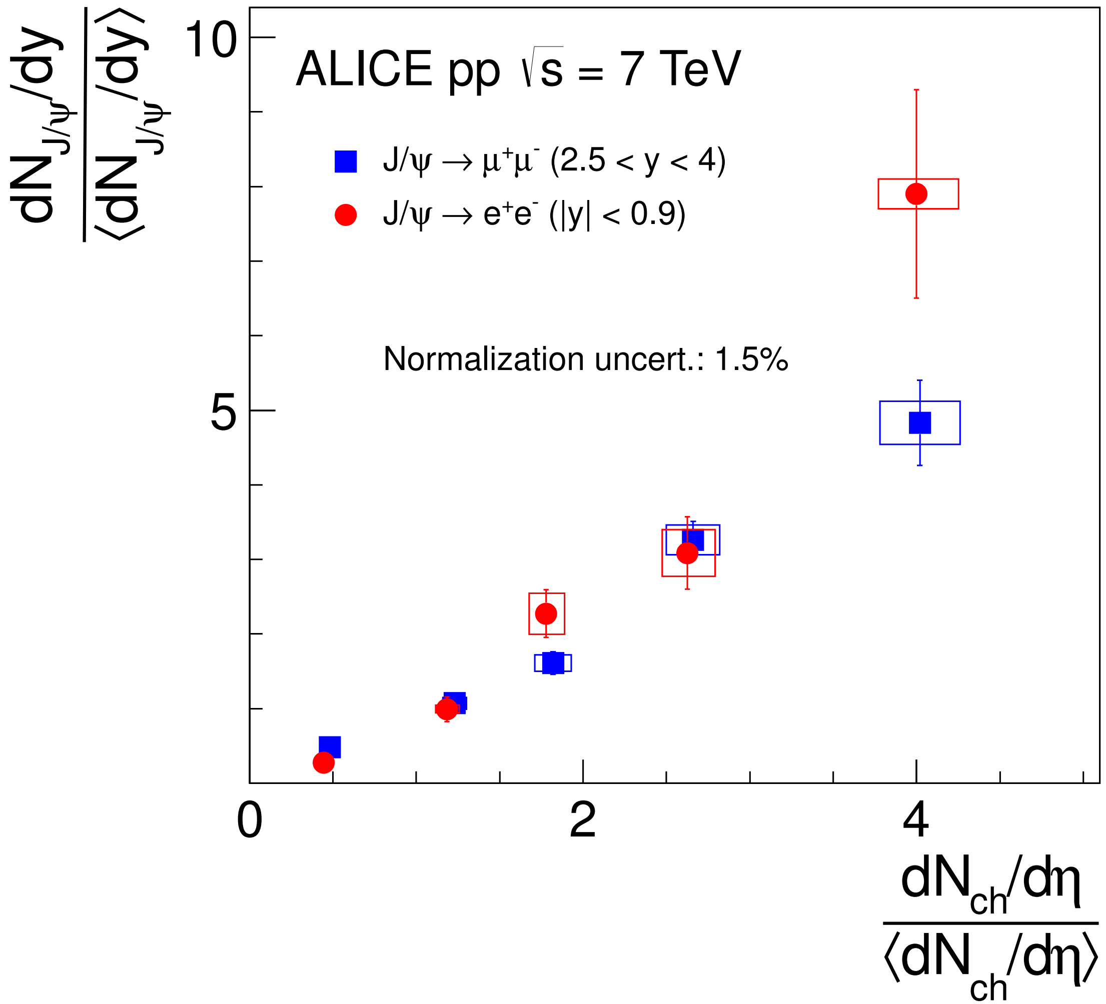


J/ψ production vs. multiplicity

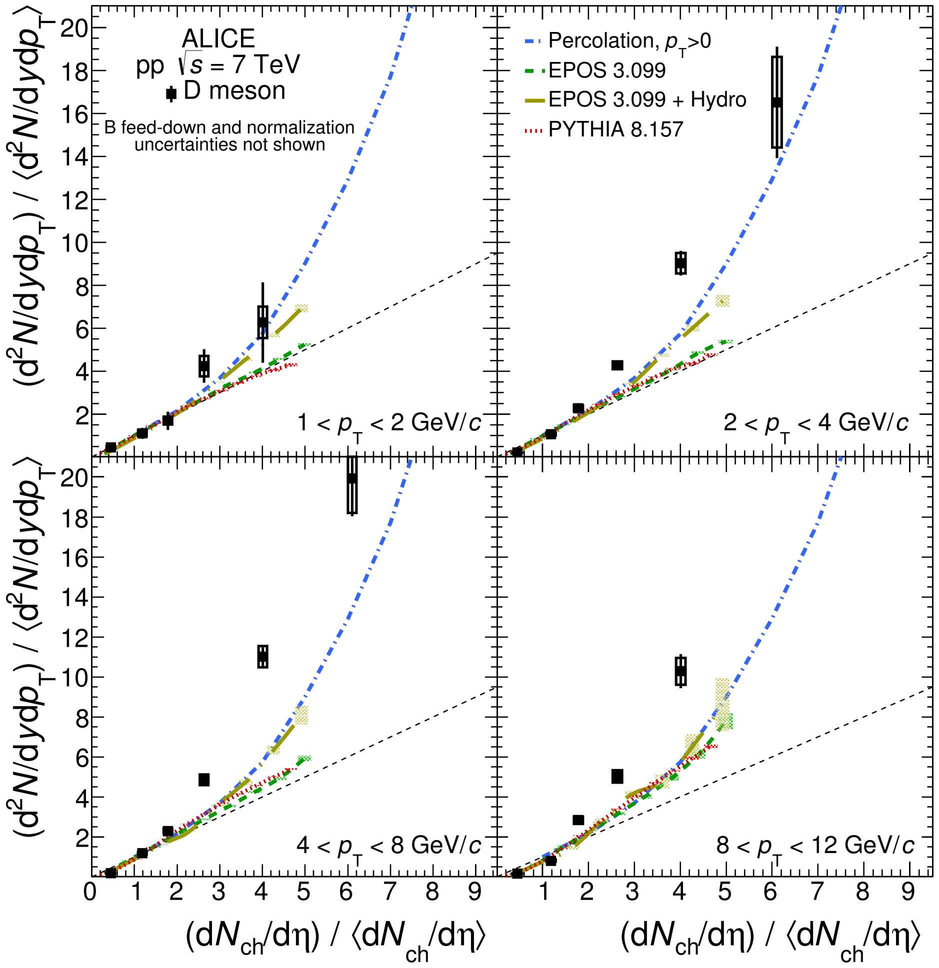


ALICE, PLB 712 (2012) 165

J/ψ production vs. multiplicity

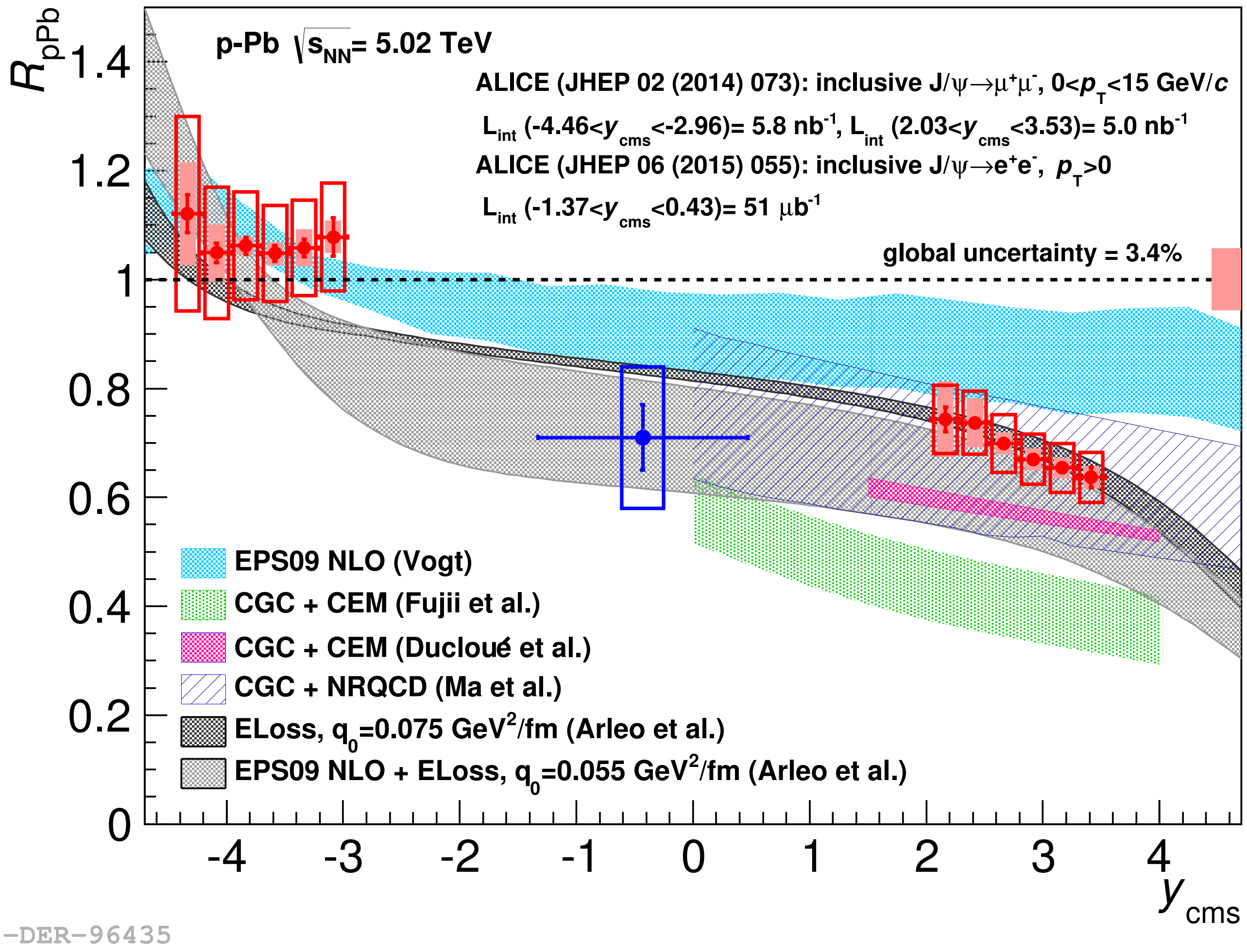


ALICE, PLB 712 (2012) 165



ALICE, JHEP 09 (2015) 148

J/ψ production in p–Pb collisions

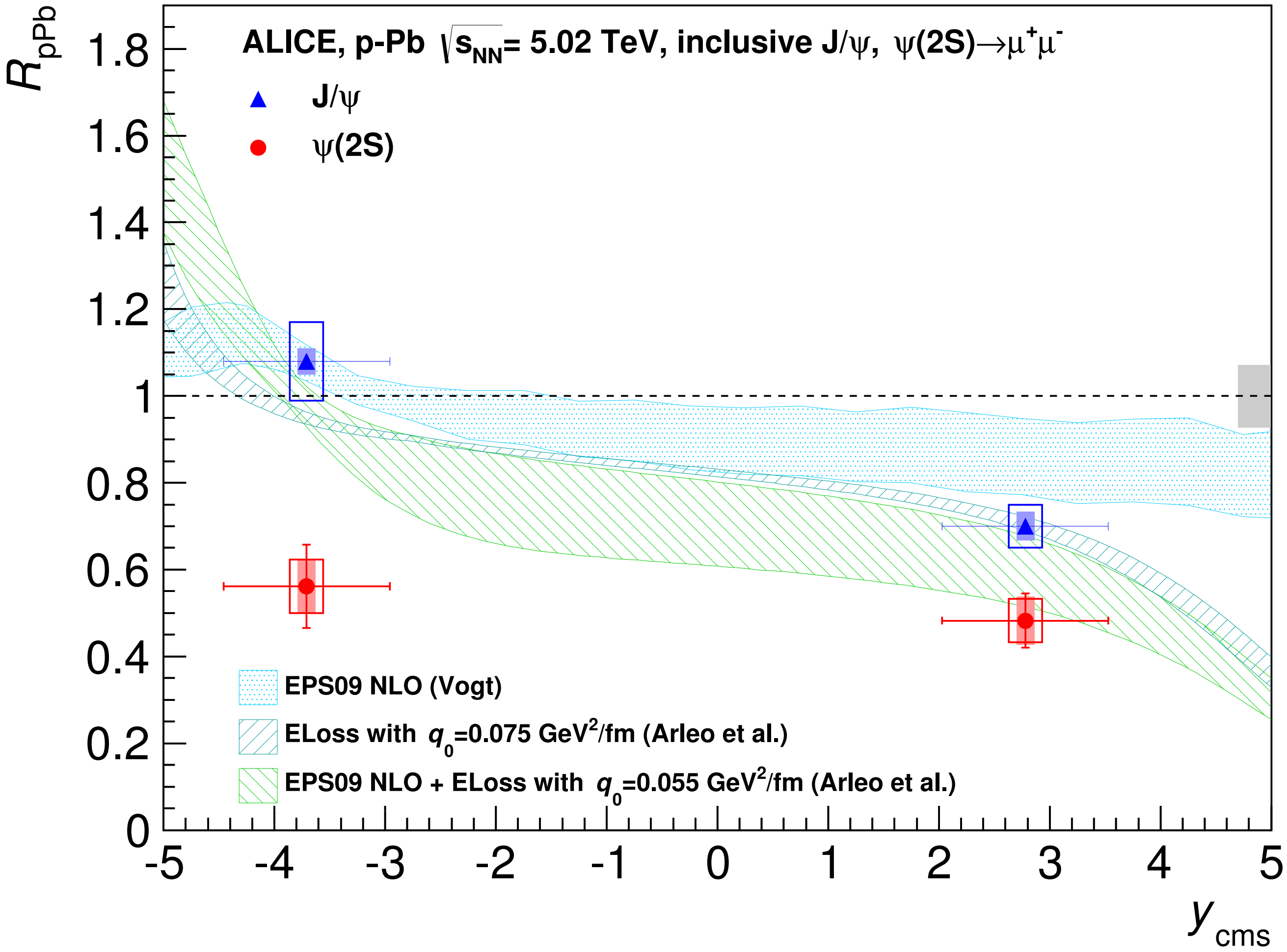


ALICE, JHEP 02 (2014) 073, 06 (2015) 55

Shadowing describes data, not that well though ...more sophistications needed?

Precision to improve significantly with data just acquired (Nov.-Dec. 2016)

$\psi(2S)$ production in p–Pb collisions

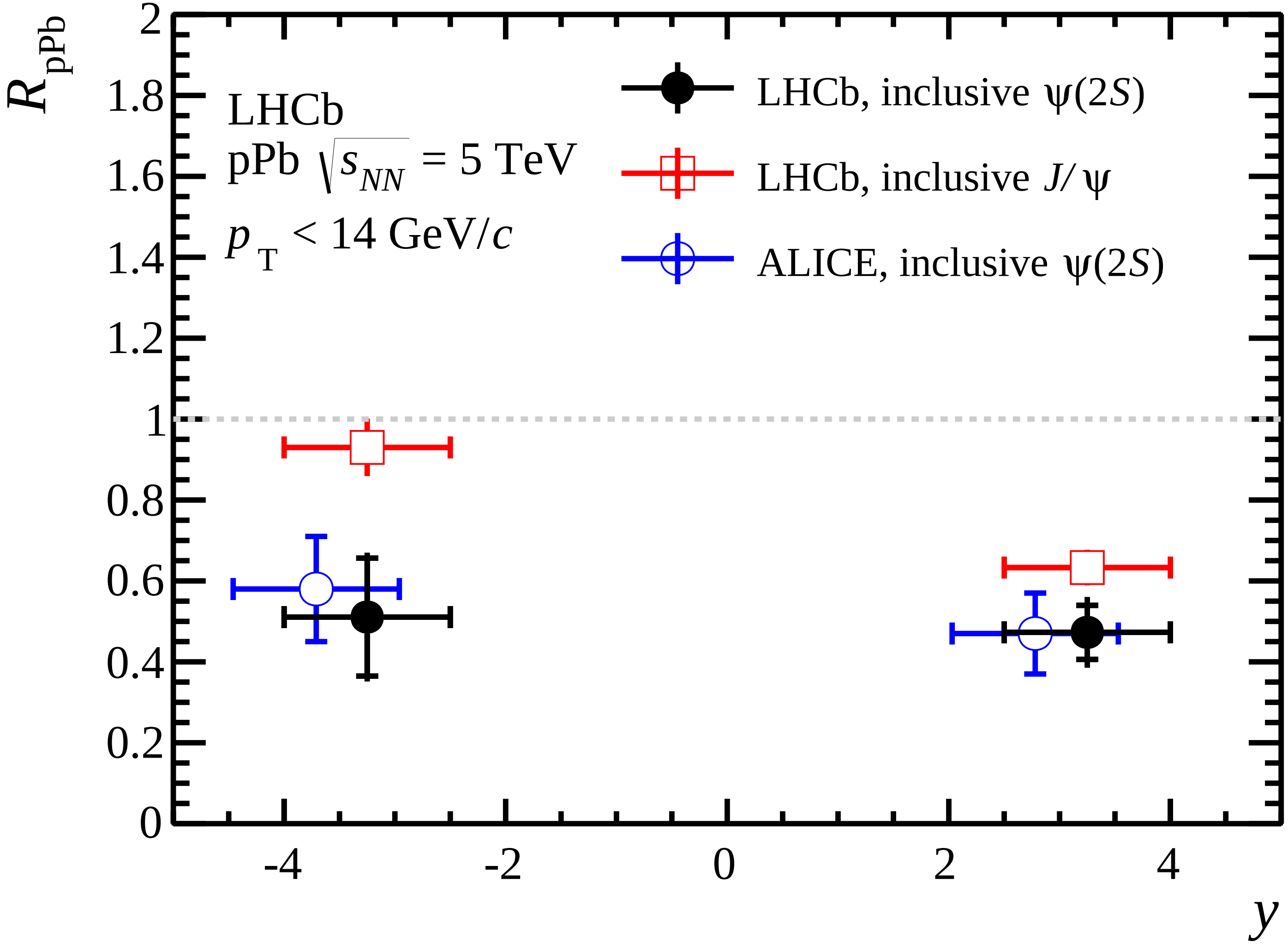


ALICE, JHEP 12 (2014) 073

(at least in first order) models give same result for $\psi(2S)$ as for J/ψ

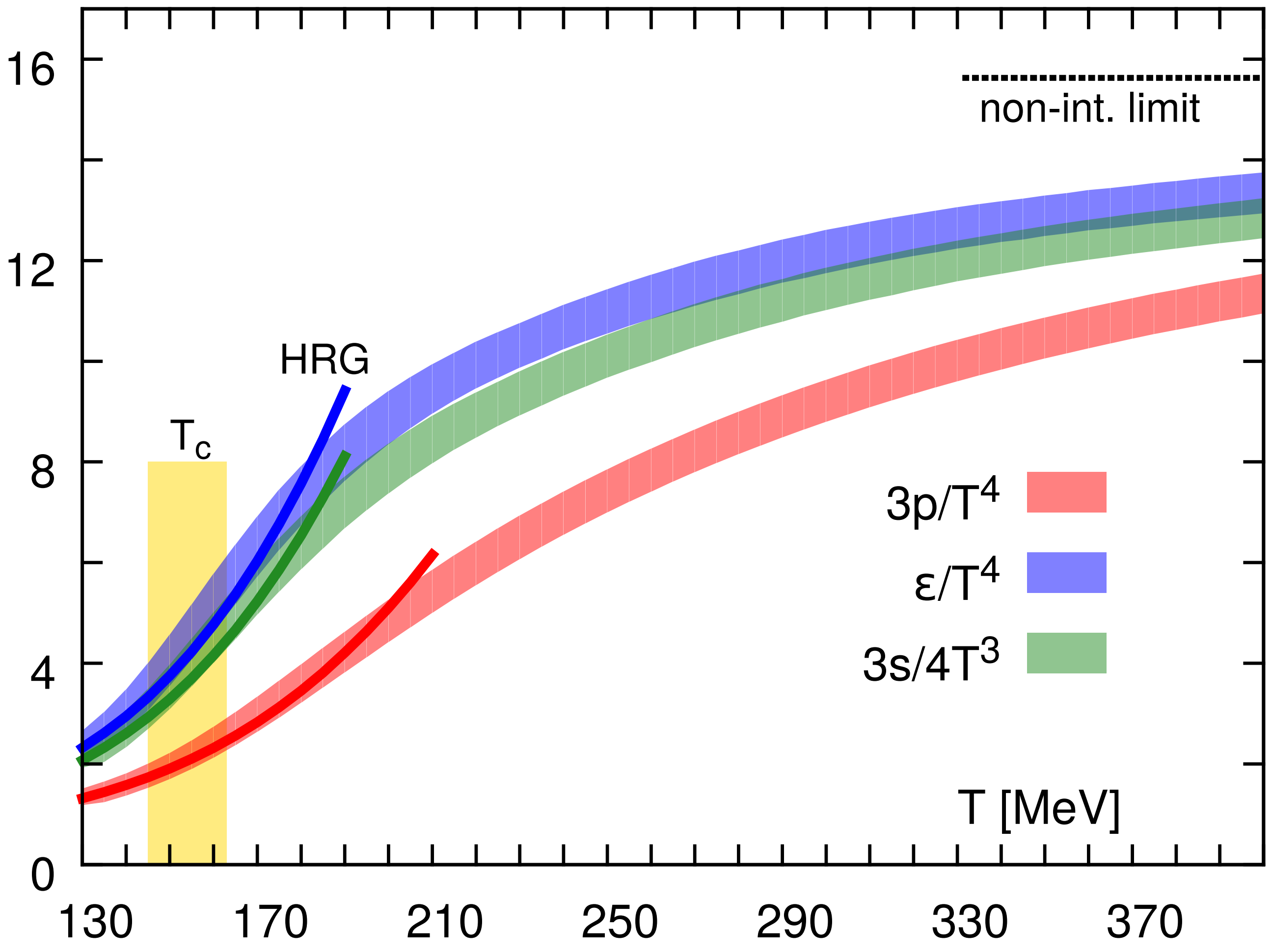
difference predominant at low p_T

$\psi(2S)$ production in p–Pb collisions



LHCb, arXiv:1601.07878

Lattice QCD predicts a phase transition (at μ_B=0)



(ideal gas)

quarks and gluons

$\varepsilon_{qg}/T^4 = (32 + 21N_f)\frac{\pi^2}{60}$

hadrons (pions)

$\varepsilon_{had}/T^4 = \frac{\pi^2}{10}$

...of crossover type, Y. Aoki et al., `Nature 443 (2006) 675`

$T_c \simeq$145-164 MeV, $\varepsilon_c \simeq (0.18 - 0.5)$ GeV/fm^3, or (1.2-3.1)$\varepsilon_{nuclear}$

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."

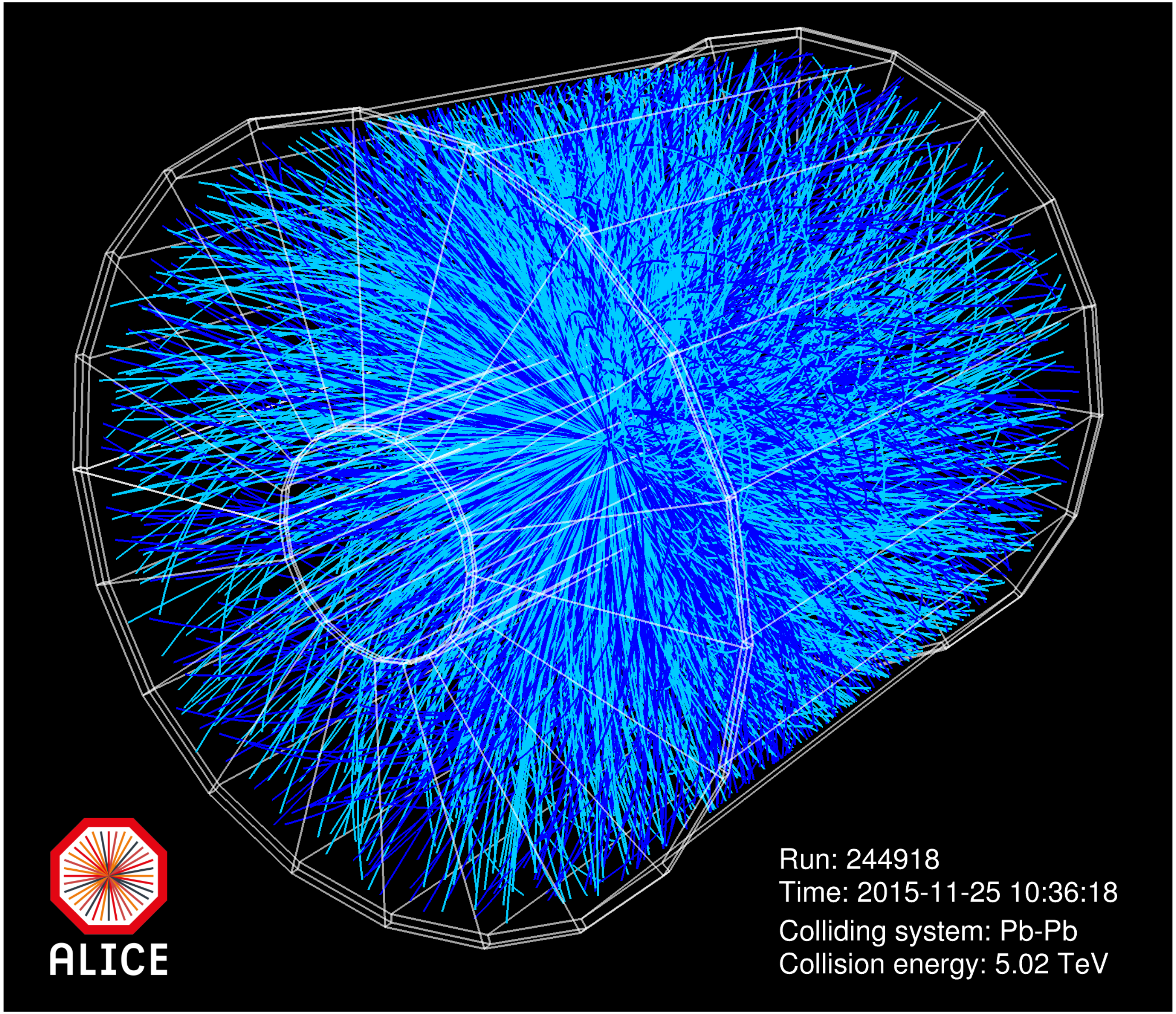
  no $q\bar{q}$ state if $r_{q\bar{q}}(T) > \lambda_D \simeq 1/(g(T)T)$ (Debye length in QGP)

  via binding E of different states, quarkonia constitute a "thermometer" of deconfined medium

Main observable (vs. N_{part} and p_T):

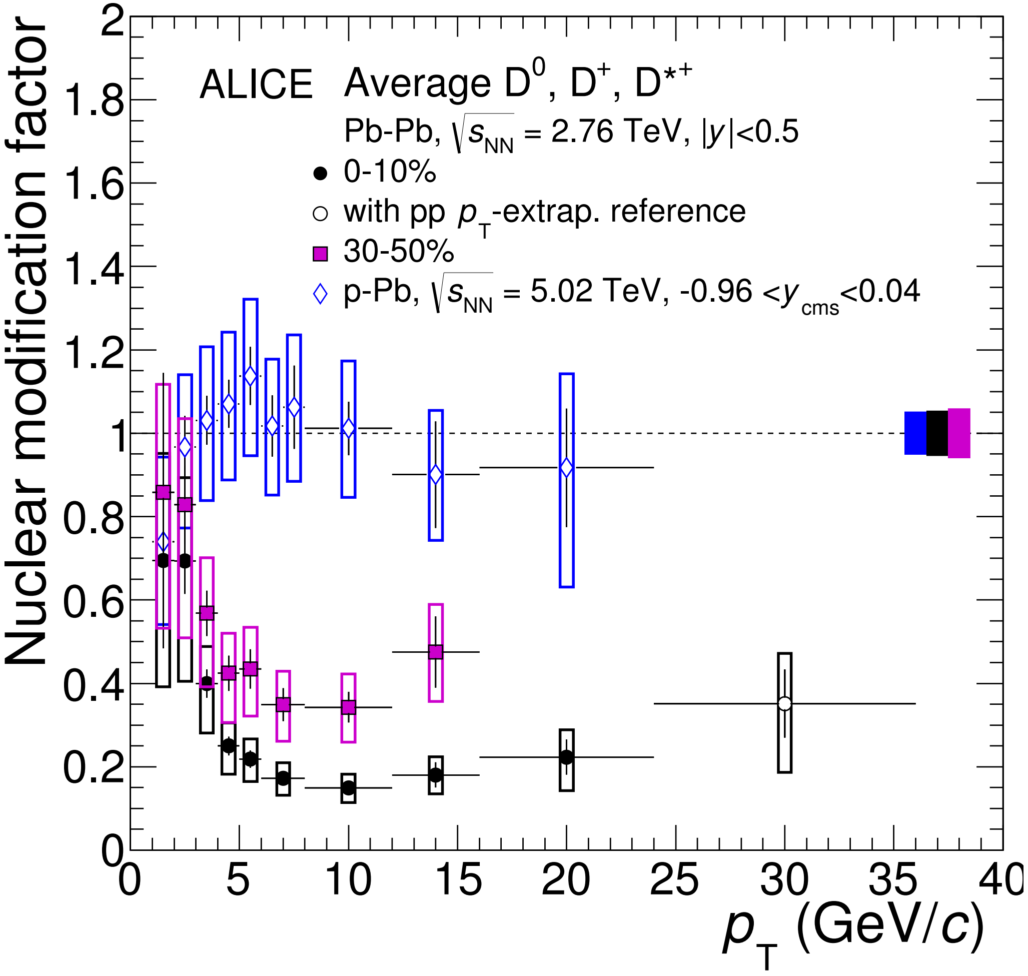
The nuclear modification factor, $R_{AA} =$ "hot QCD" / "binary-scaled pp"

Nucleus-nucleus collisions at the LHC

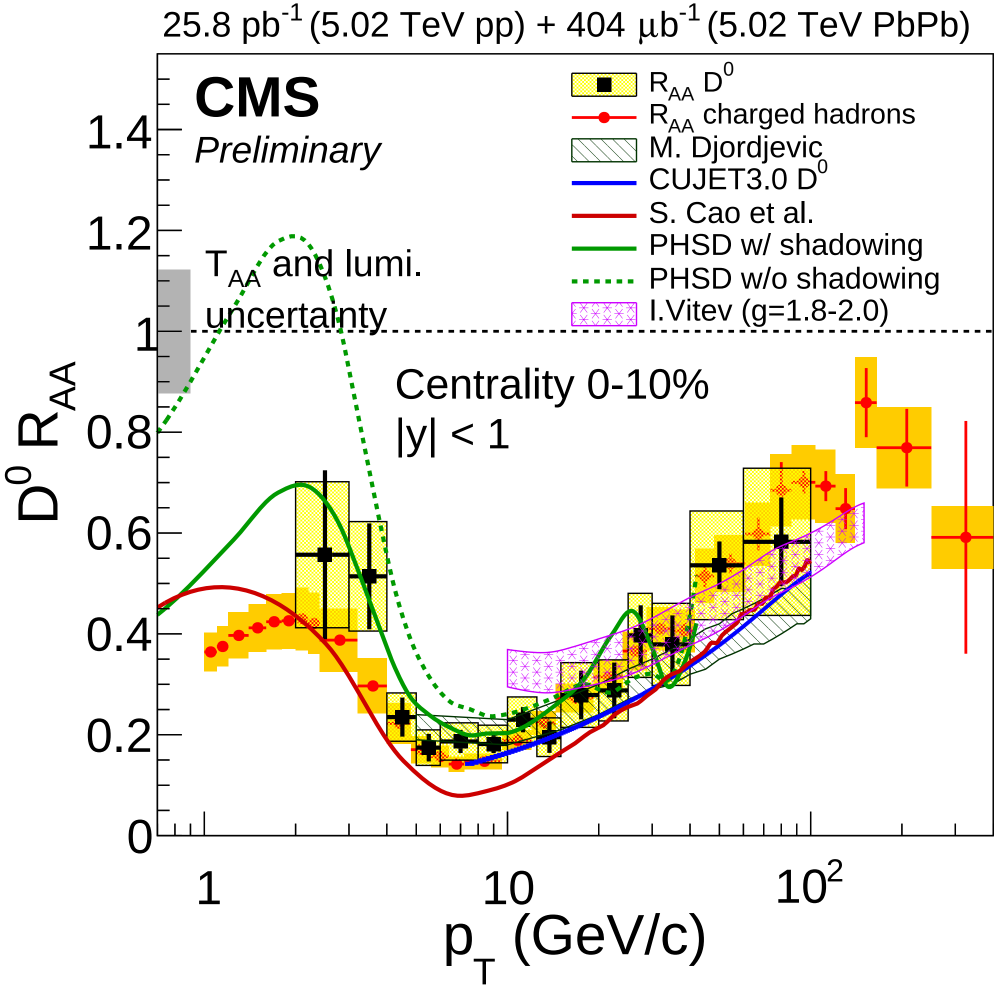


a picture (with 500 mil. pixels) of a central collision (about 3000 primary tracks)

D-meson production



ALICE, JHEP 03 (2016) 081

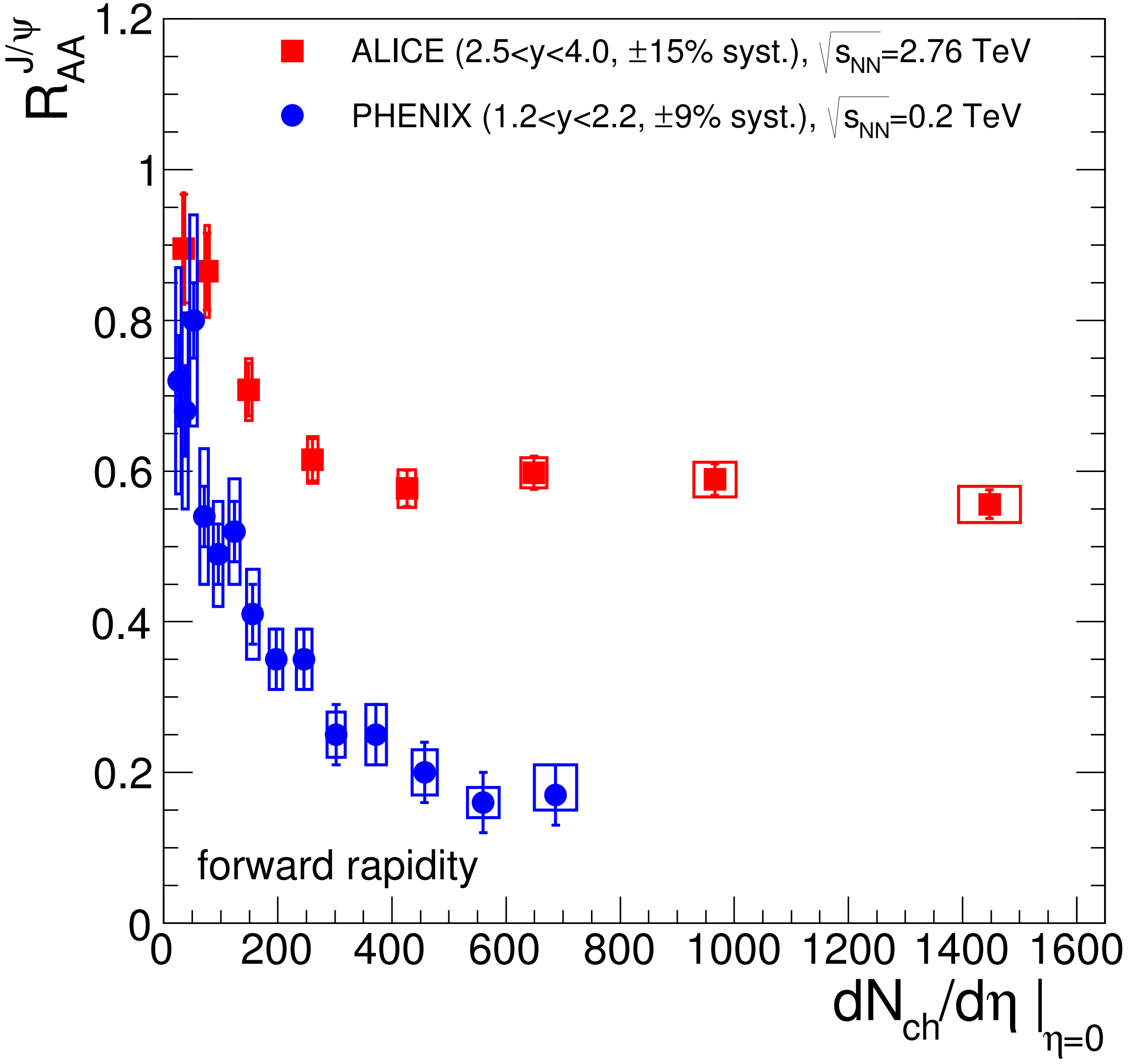


CMS, CMS-PAS-HIN-16-001

Large suppression of charmed mesons, due to quark energy loss in QGP

Heavy quarks also experience collective flow (similar magnitude as lighter siblings)

Charmonium data at RHIC and the LHC

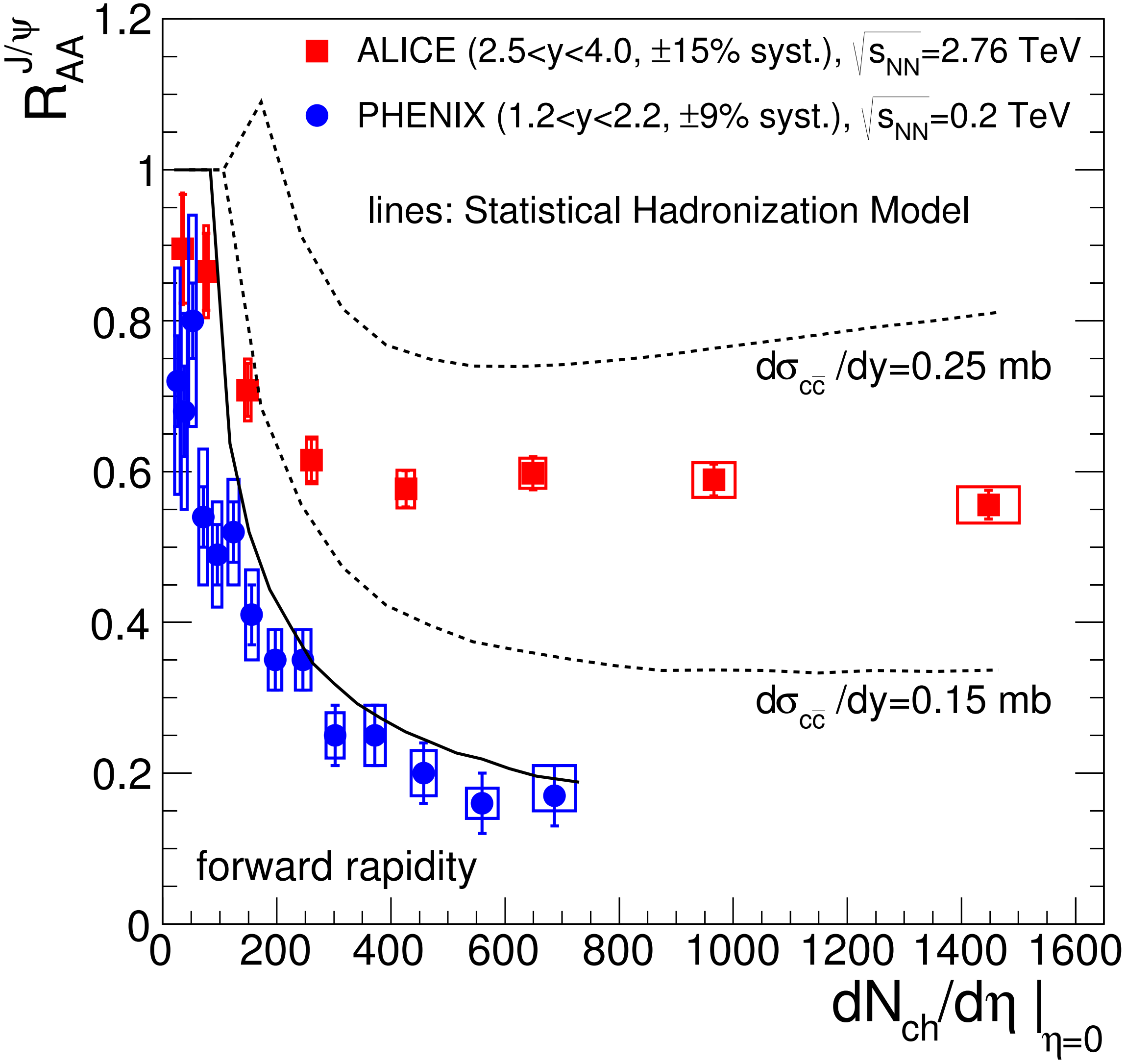


$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$ (>16 GeV/fm^3, for $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq 1500$)

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

...

Charmonium data at RHIC and the LHC



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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

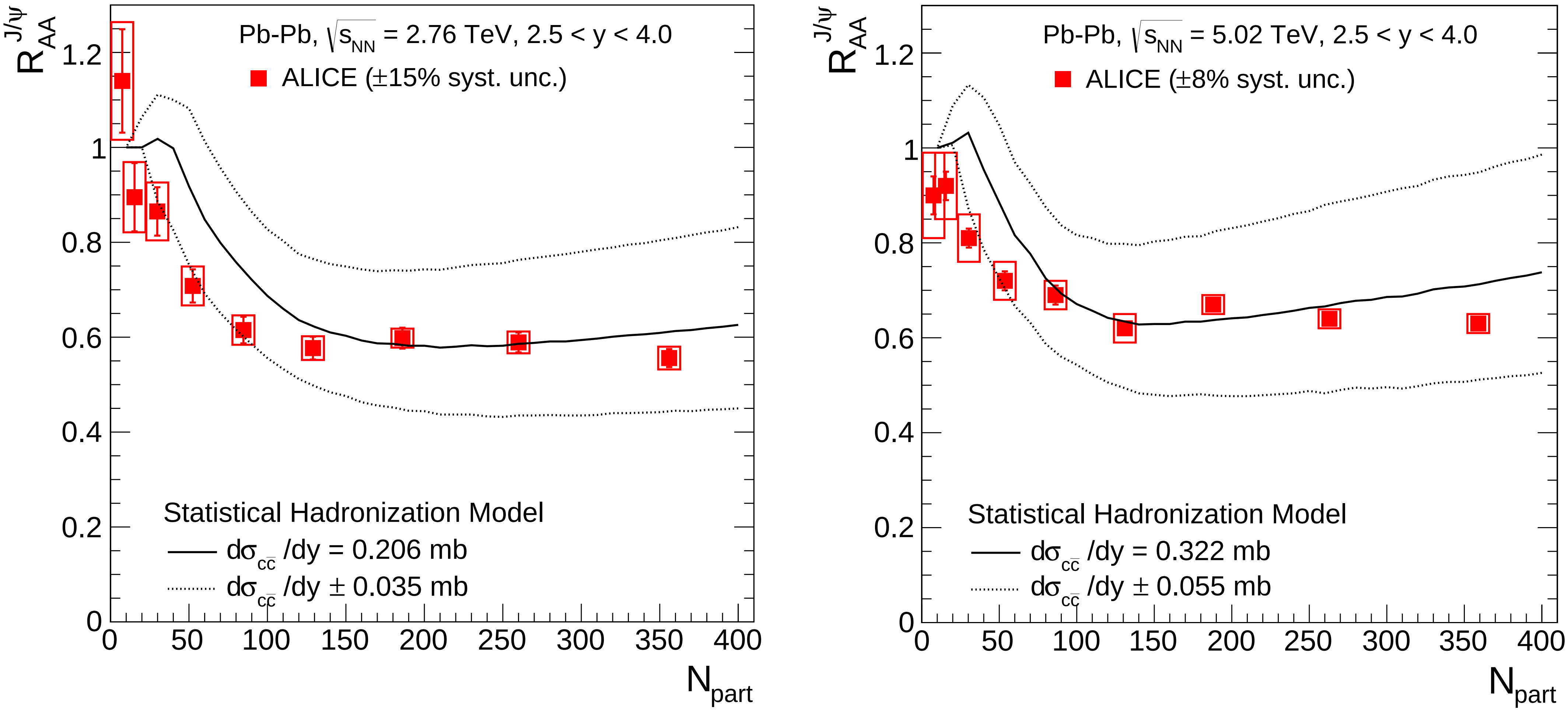
J/ψ is another observable (charm)

for the phase boundary

calculations are for T=156 MeV

Charmonium production at the LHC

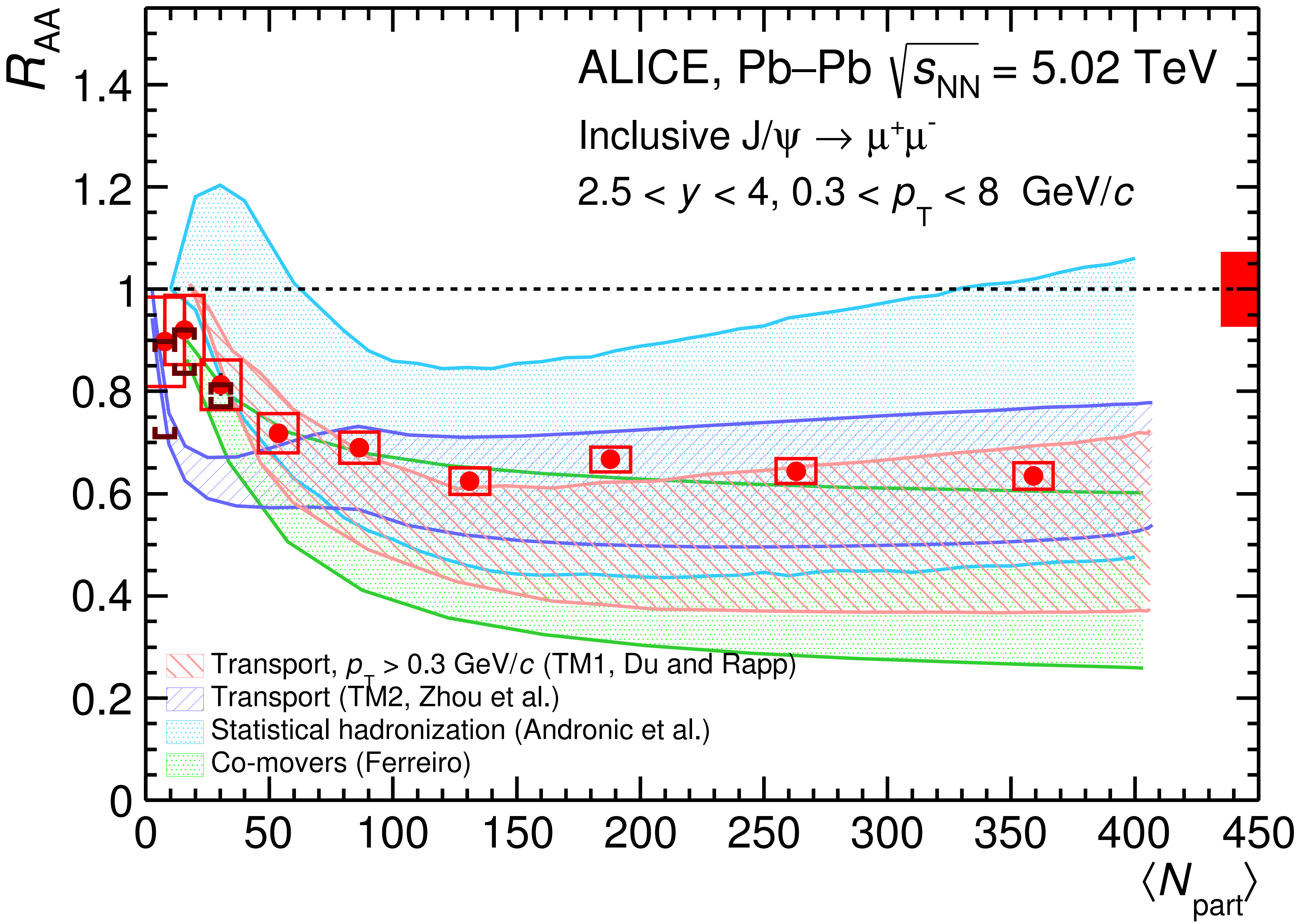
A.Andronic



the generic prediction by the model is confirmed by data arXiv:1606.08197

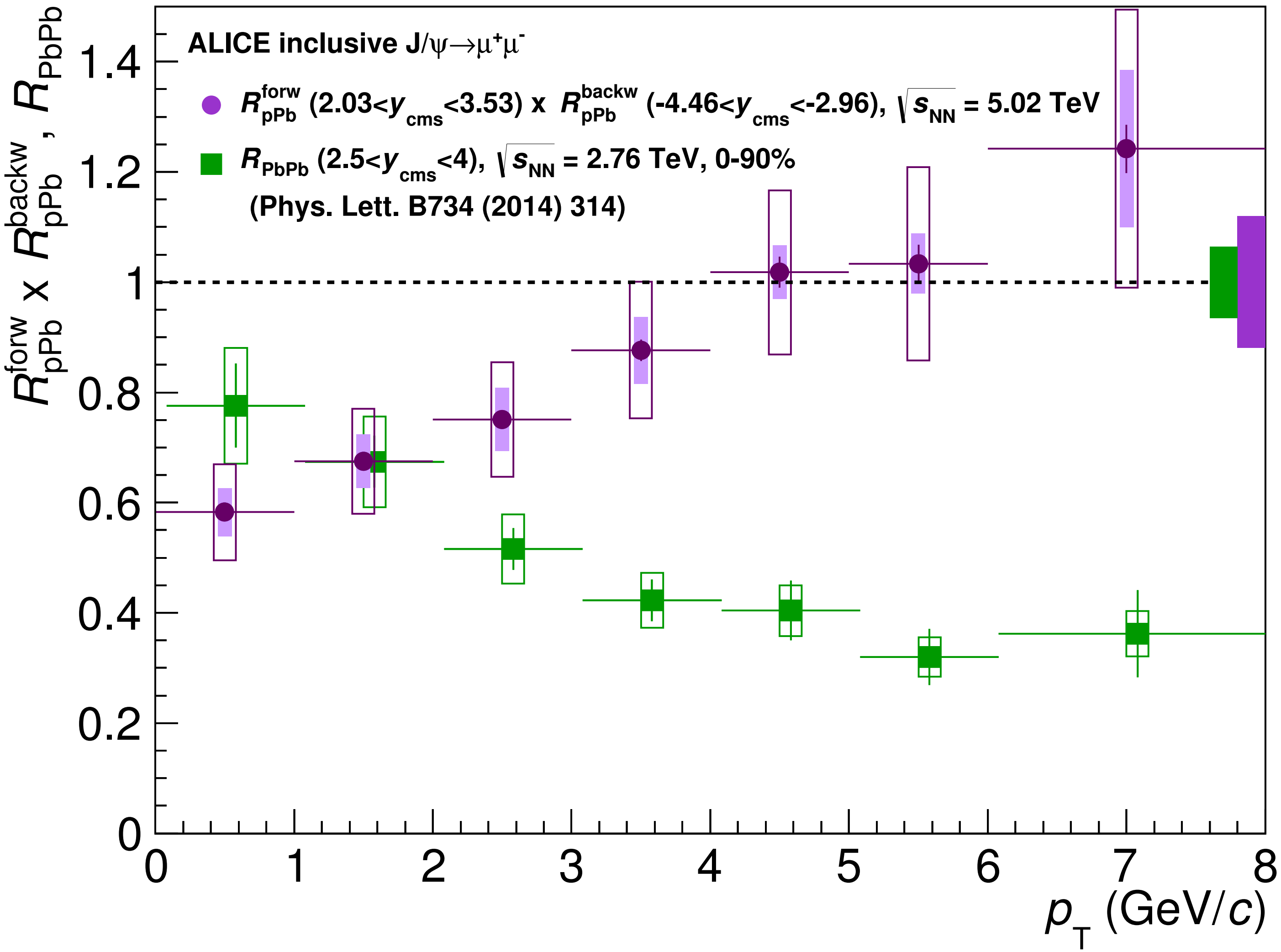
establishes charmonium as a powerful new observable of the phase boundary

J/ψ production at 5 TeV



ALICE, arXiv:1606.08197

J/ψ production vs. p_T



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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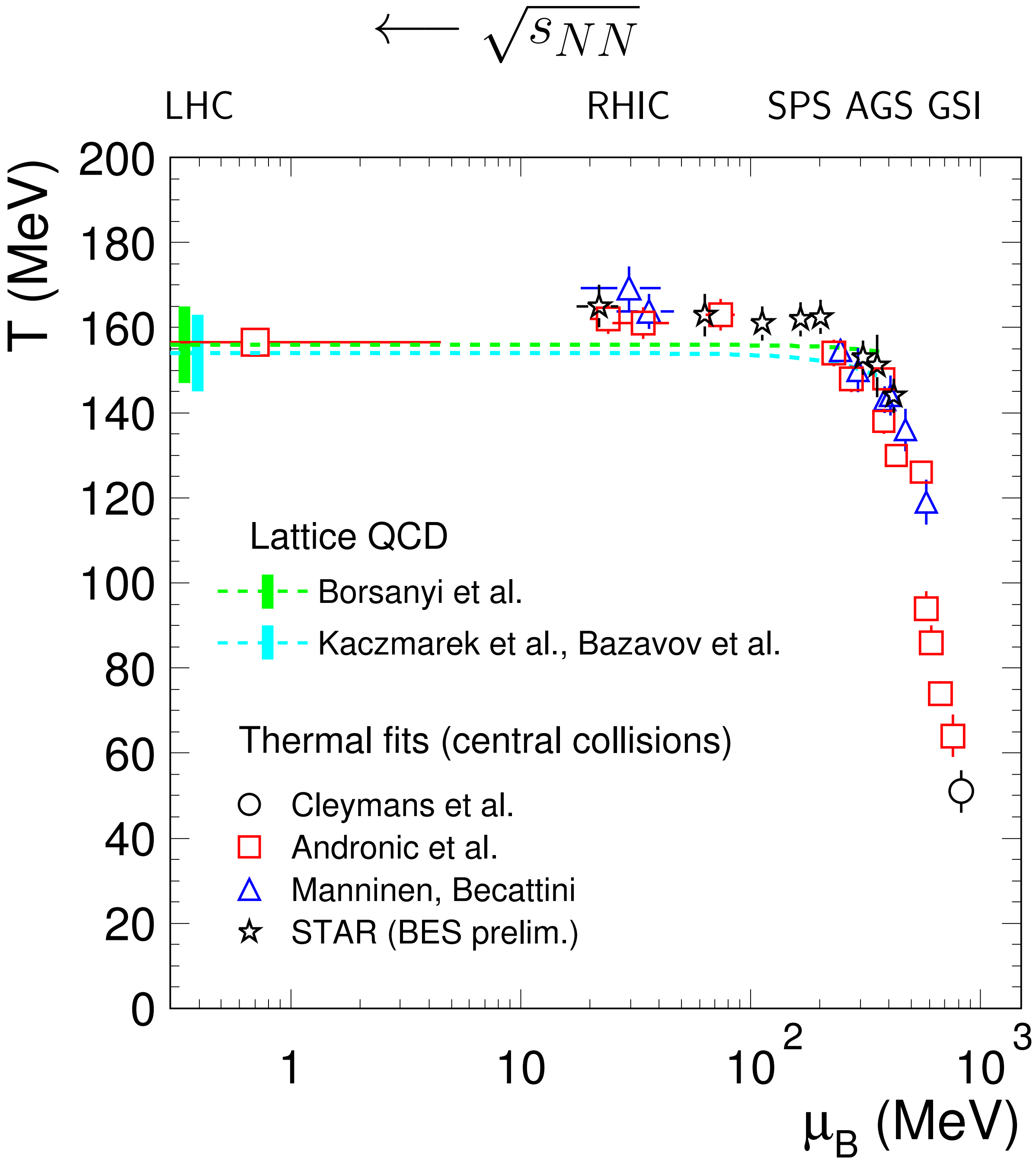


phenomenological link
(at low μ_B),
chemical freeze-out of u,d,s-hadrons

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)

Charmonium and the phase boundary

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

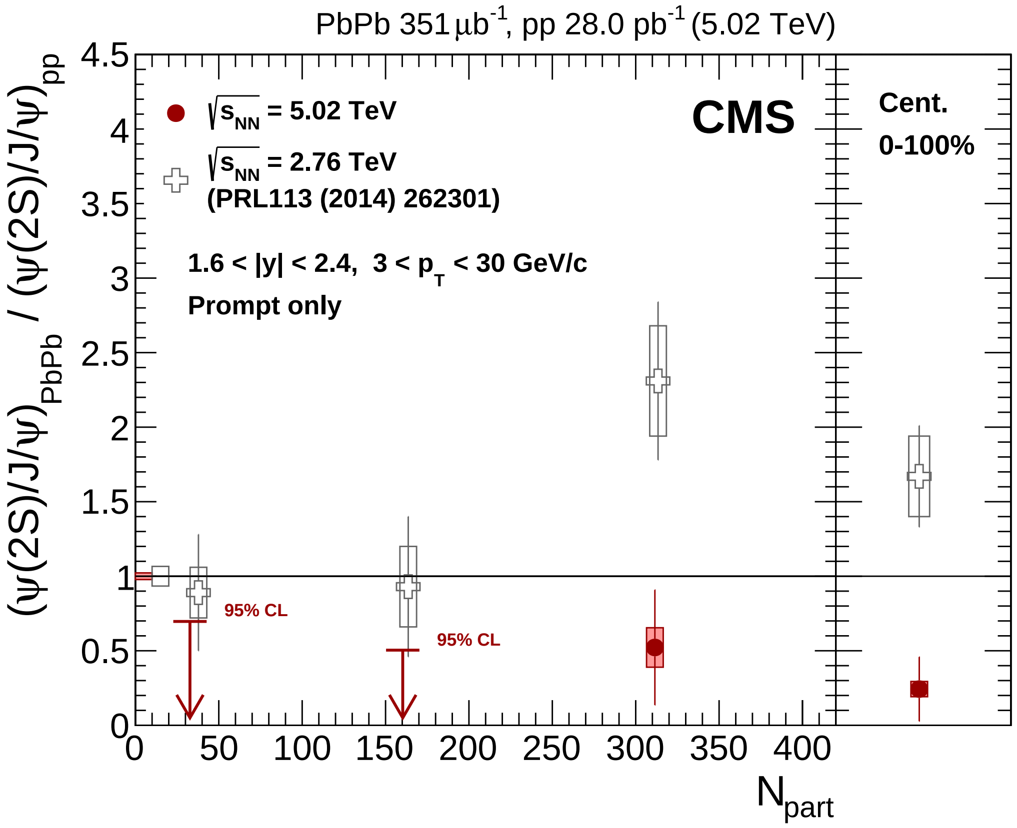
(recall that only $\sigma_{c\bar{c}}$ *is a new parameter in the statistical model, besides* T*,* V*)*

...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

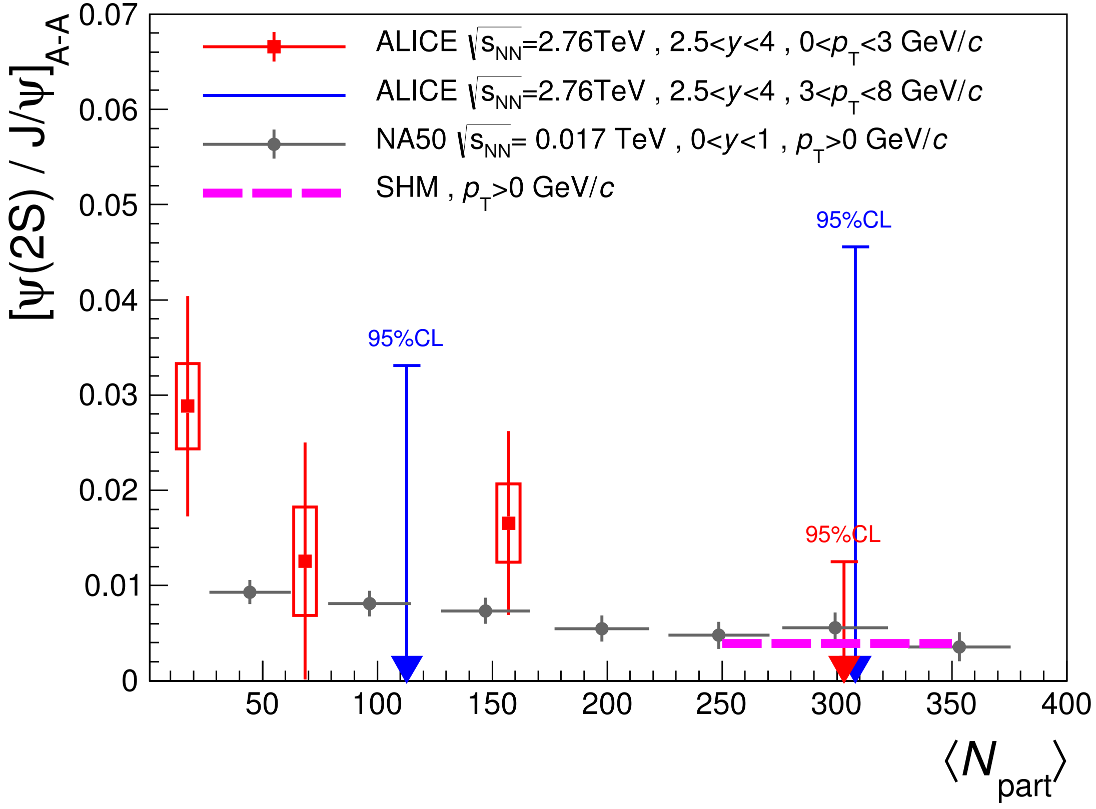
is there a way to make the distinction?

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

A.Andronic



CMS, arXiv:1611.01438



ALICE, JHEP 05 (2016) 179

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

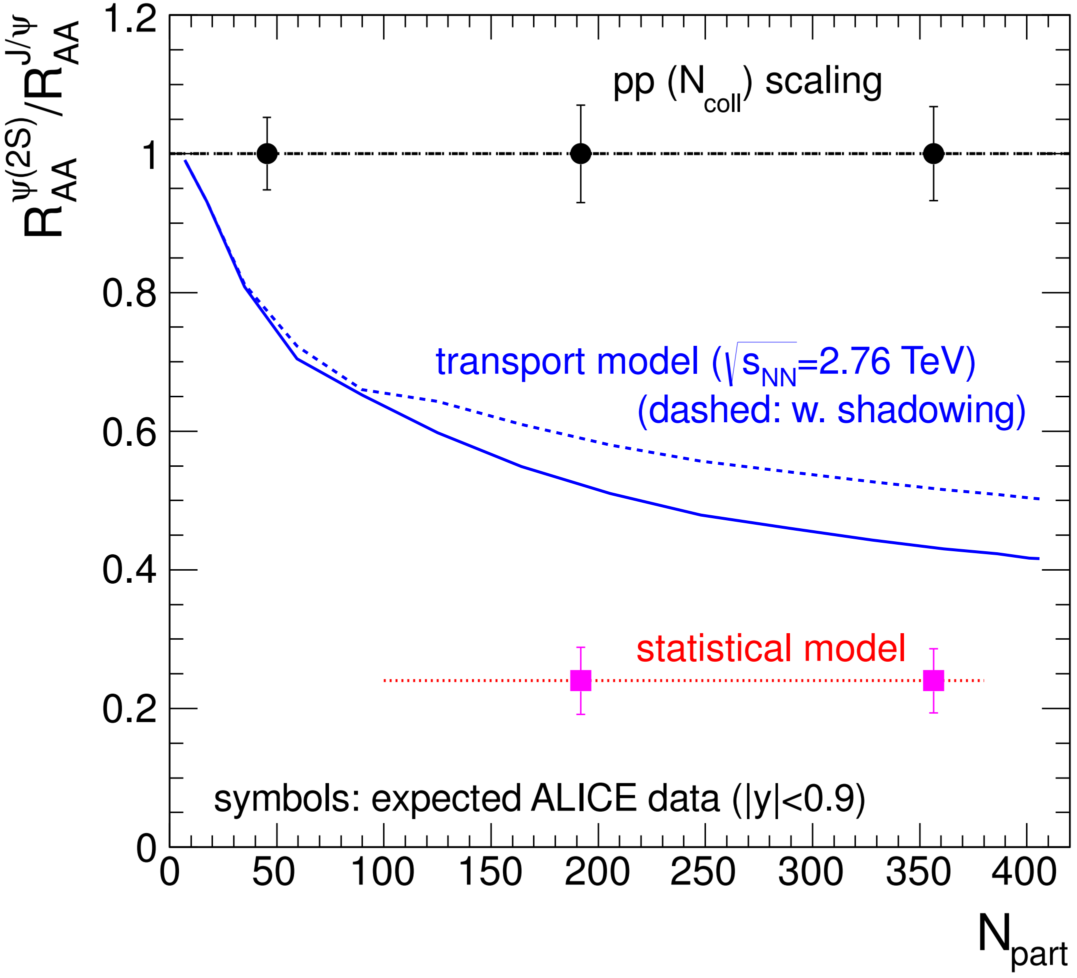
LHC: uncertainties large, no conclusion yet ...Run 2 and Run 3 data crucial

The weight of the $\psi(2S)$ measurement

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

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

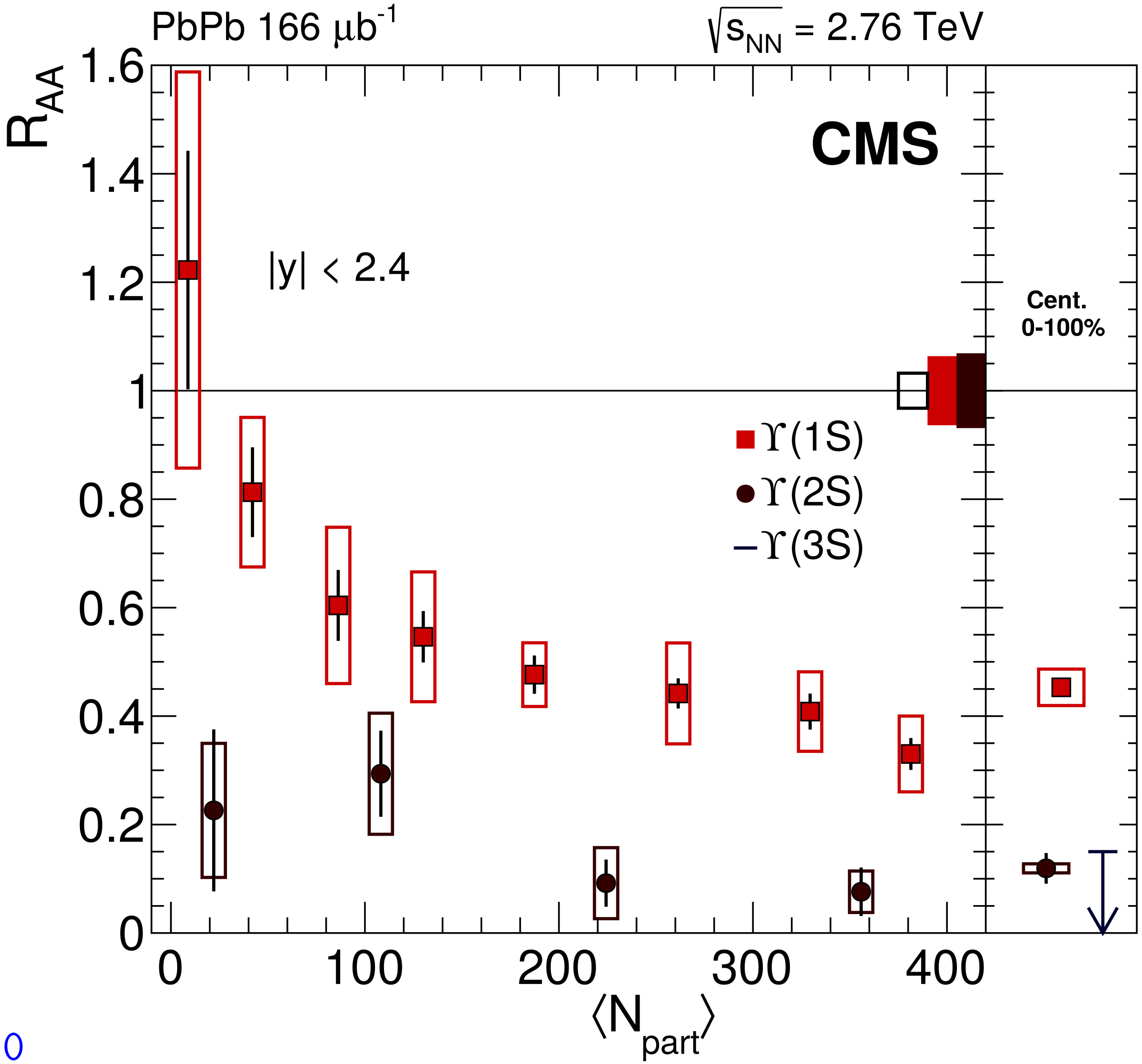
see Du, Rapp, arXiv:1504.00670



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

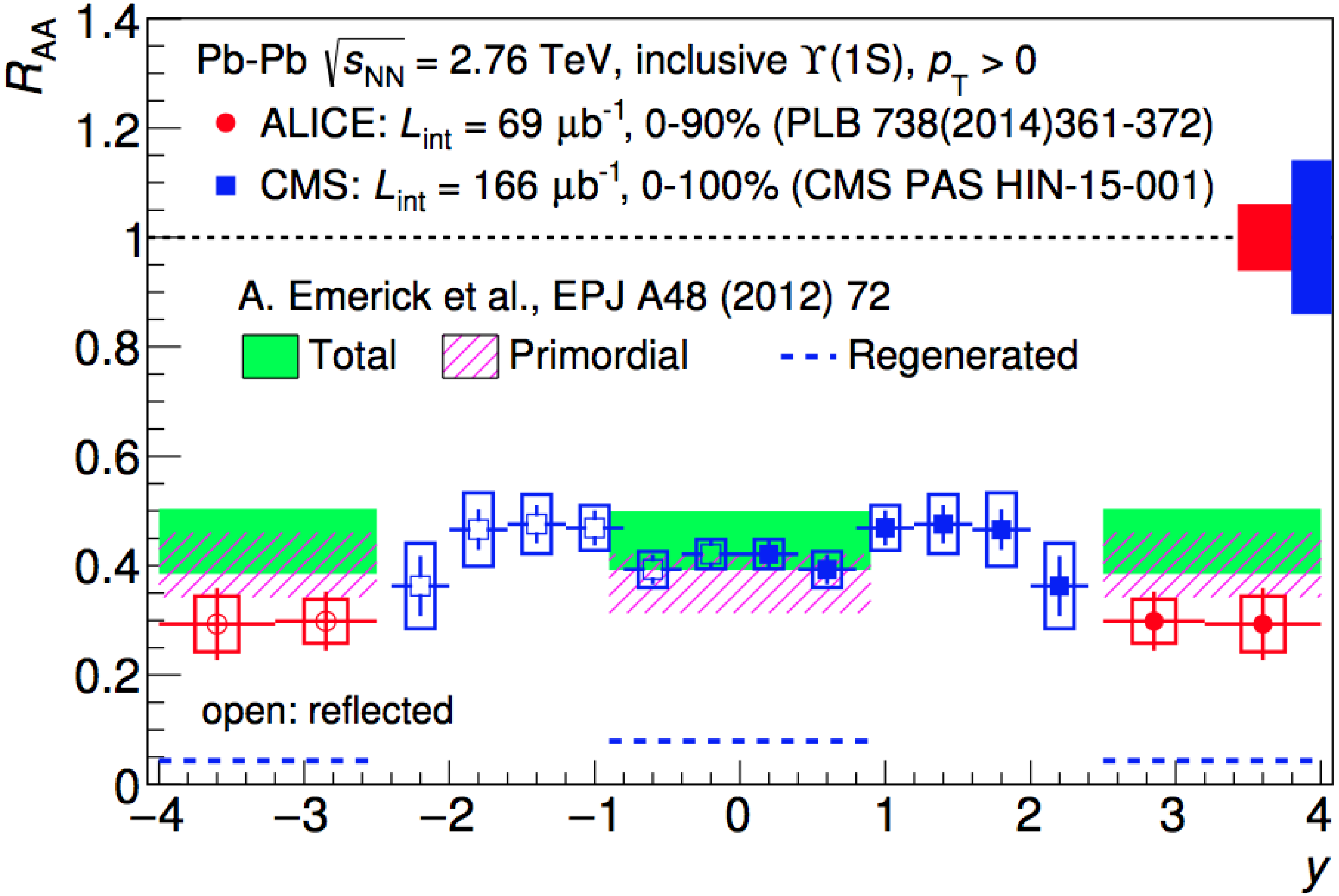
Υ production



CMS, arXiv:1611.01510

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

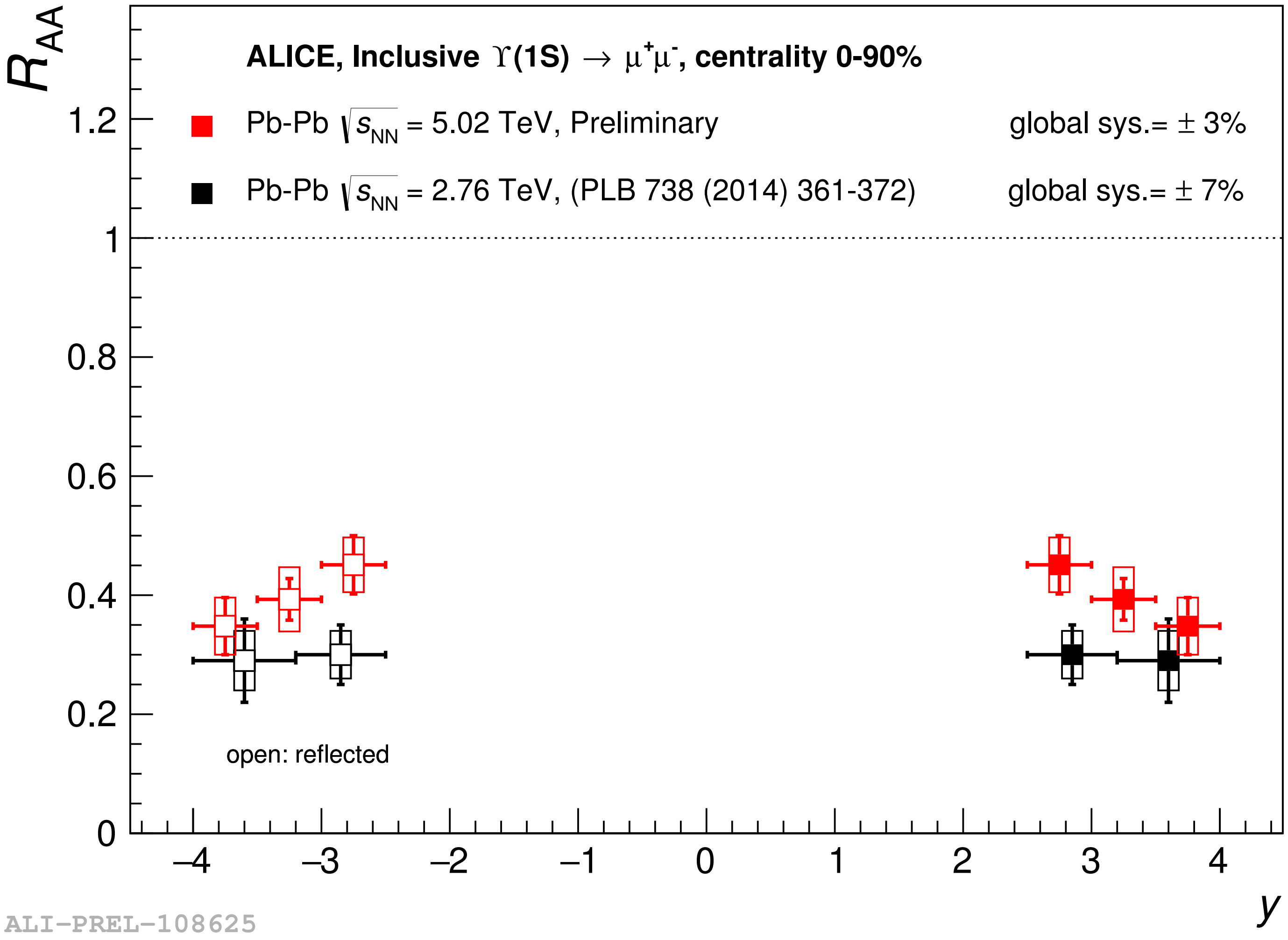
Υ production



Transport model predicts a small fraction of regenerated Υ (more at $y = 0$)

"Primordial": assumes that 60% of $\Upsilon(1S)$ originates from feed-down

Υ production

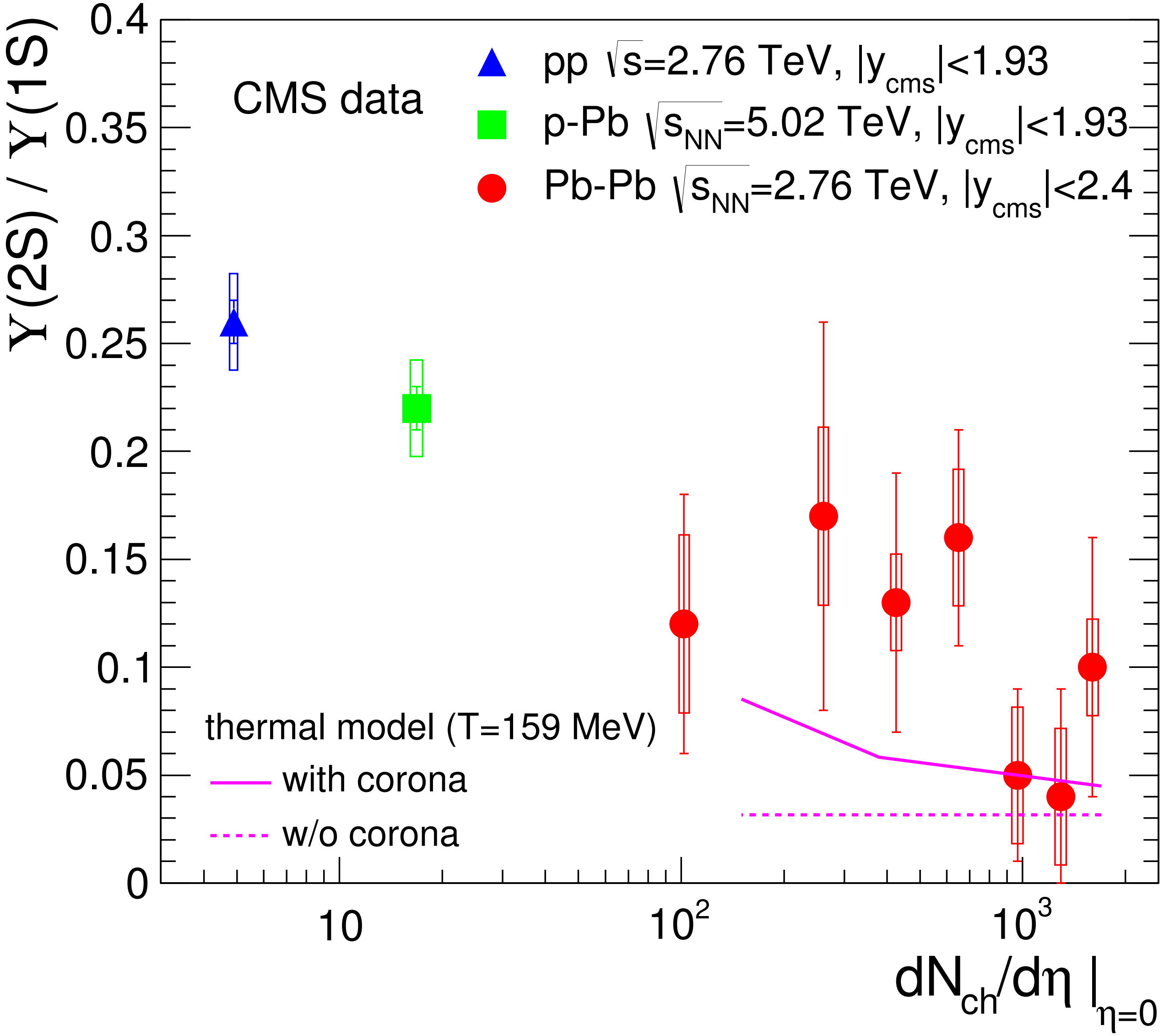


an intriguing result ...even if, considering uncertainties, not a large effect

expectation from the sequential "melting" (Debye screening): $R_{\rm AA}^{5.02} \leq R_{\rm AA}^{2.76}$

do we see *substantial* (re)generation? (in QGP/at phase boundary?)

Υ production (relative)



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 and outlook

- A wealth of data on quarkonium production in pp and p–Pb collisions

  interesting observations on multiplicity dependence
- Everybody agrees that we see (re)combination of charm quarks at the LHC

  ...a new observable for the QCD phase boundary
- Interesting (sequential?) "disappearance" pattern in the bottom (Υ) sector

  do bottom quarks also thermalize at the LHC?

  will Υ add more weight to the phase boundary?

A larger data sample available in Pb–Pb (5 TeV) and p-Pb (5, 8 TeV) in Run 2

Ambitious plans for Run 3, 4 ...characterization of deconfined medium
(ALICE and LHCb upgrades targeted/crucial for p/Pb–Pb)

Backup slides

Charmonium and deconfined matter

the original idea: 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."

"Debye screening": no J/ψ if $r_{J/\psi} > \lambda_D$

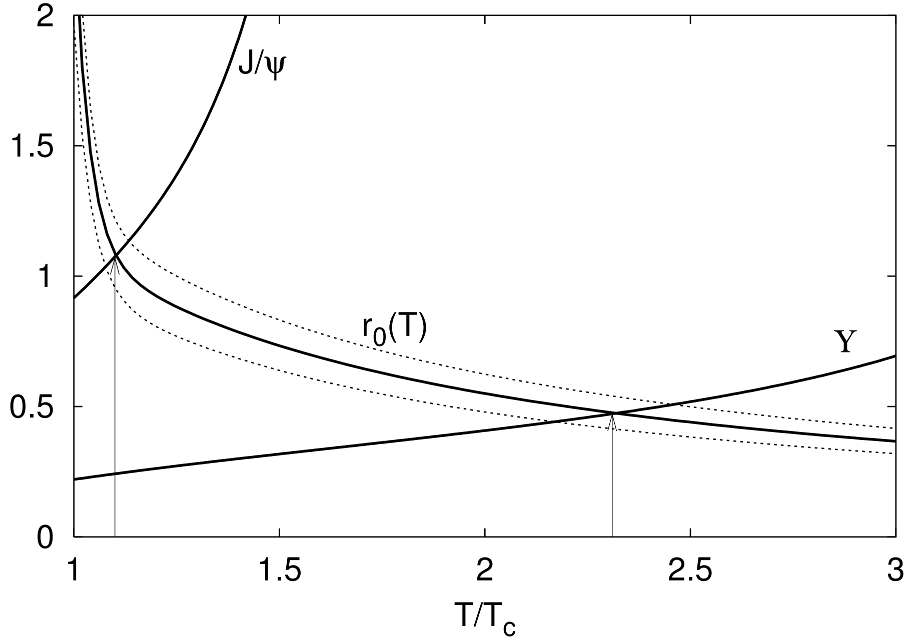
Refinements: "sequential suppression":

Digal et al., `PRD 64 (2001) 75`

Debye length in QGP: $\lambda_D \simeq 1/(g(T) \cdot T)$

$r_{q\bar{q}} = f(T)$ (Lattice QCD results)

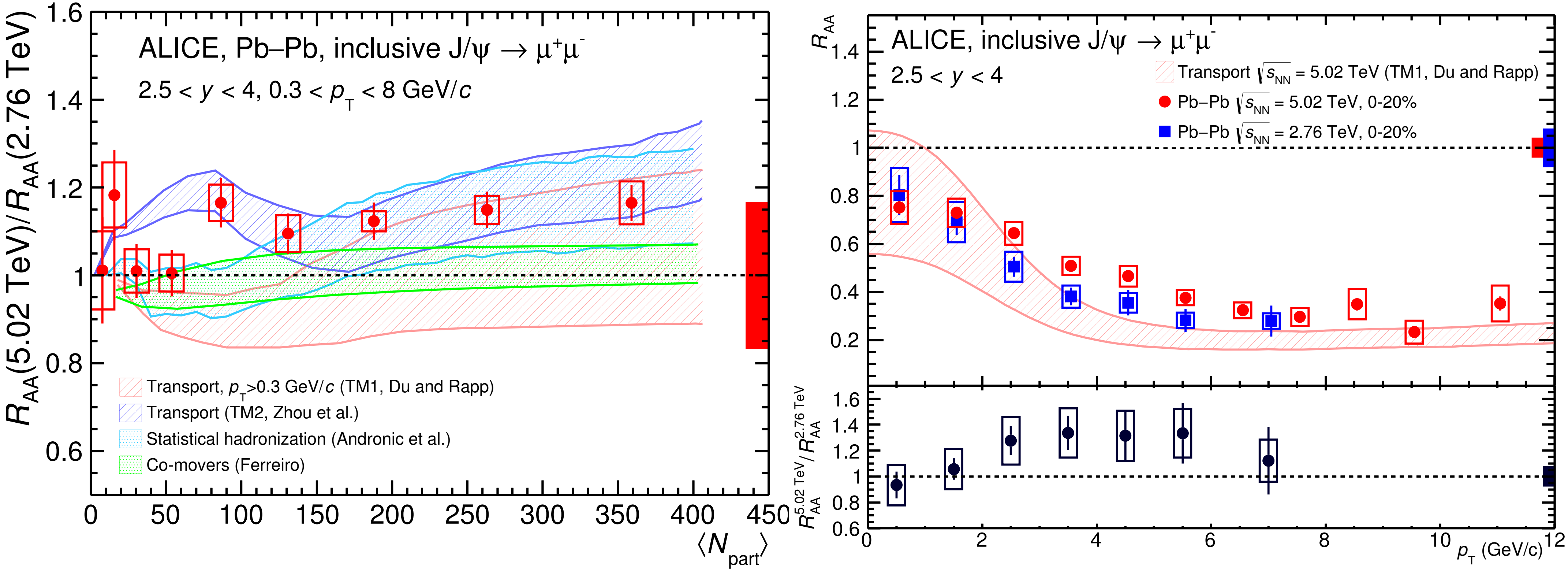
$\Rightarrow q\bar{q}$ "thermometer" of QGP



Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi}$

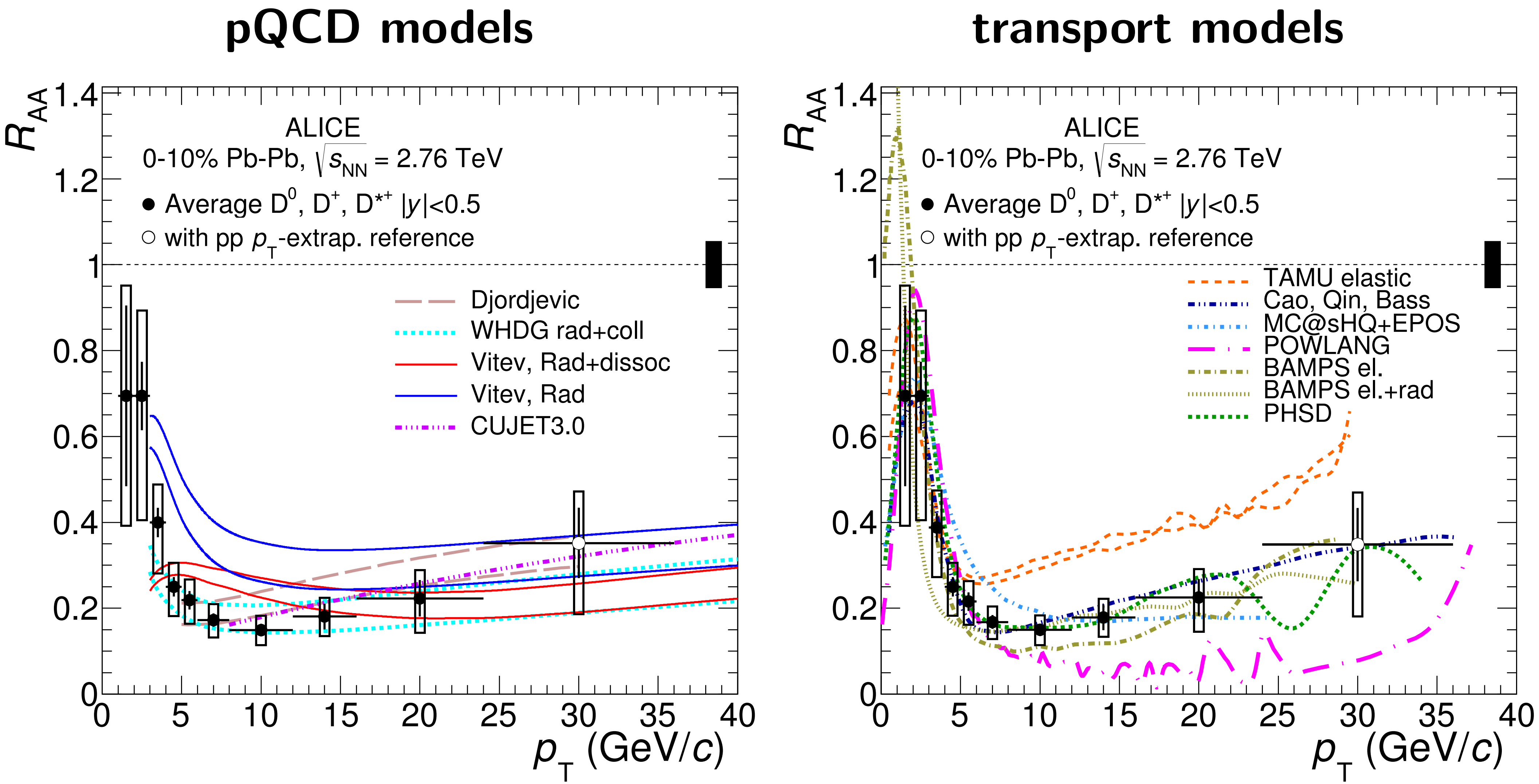
J/ψ production at 5 TeV



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)

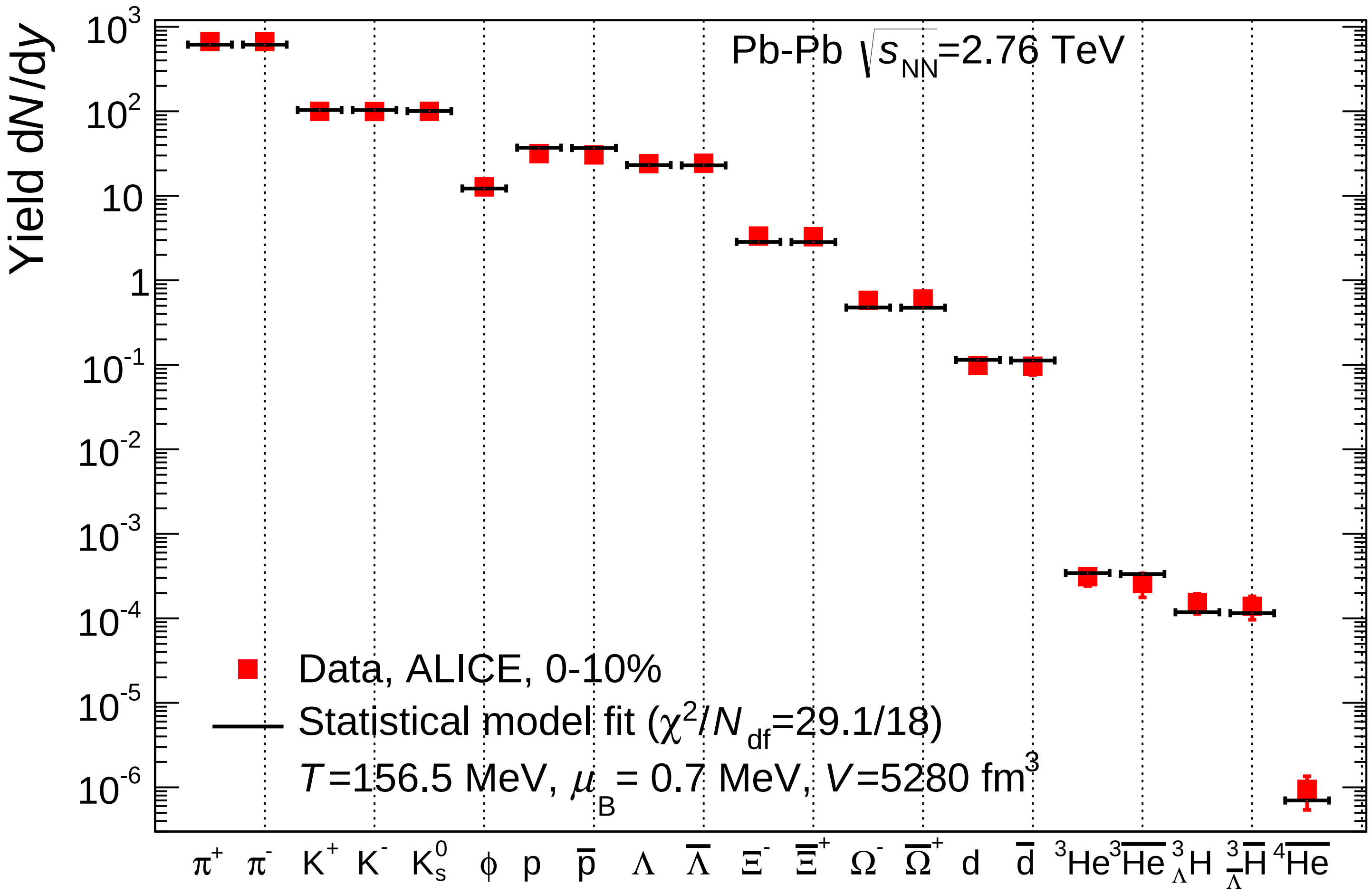
D-meson nuclear modification



ALICE, JHEP 03 (2016) 081

good description of data in theoretical 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)

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

Statistical hadronization of charm: method and inputs

A.Andronic

- 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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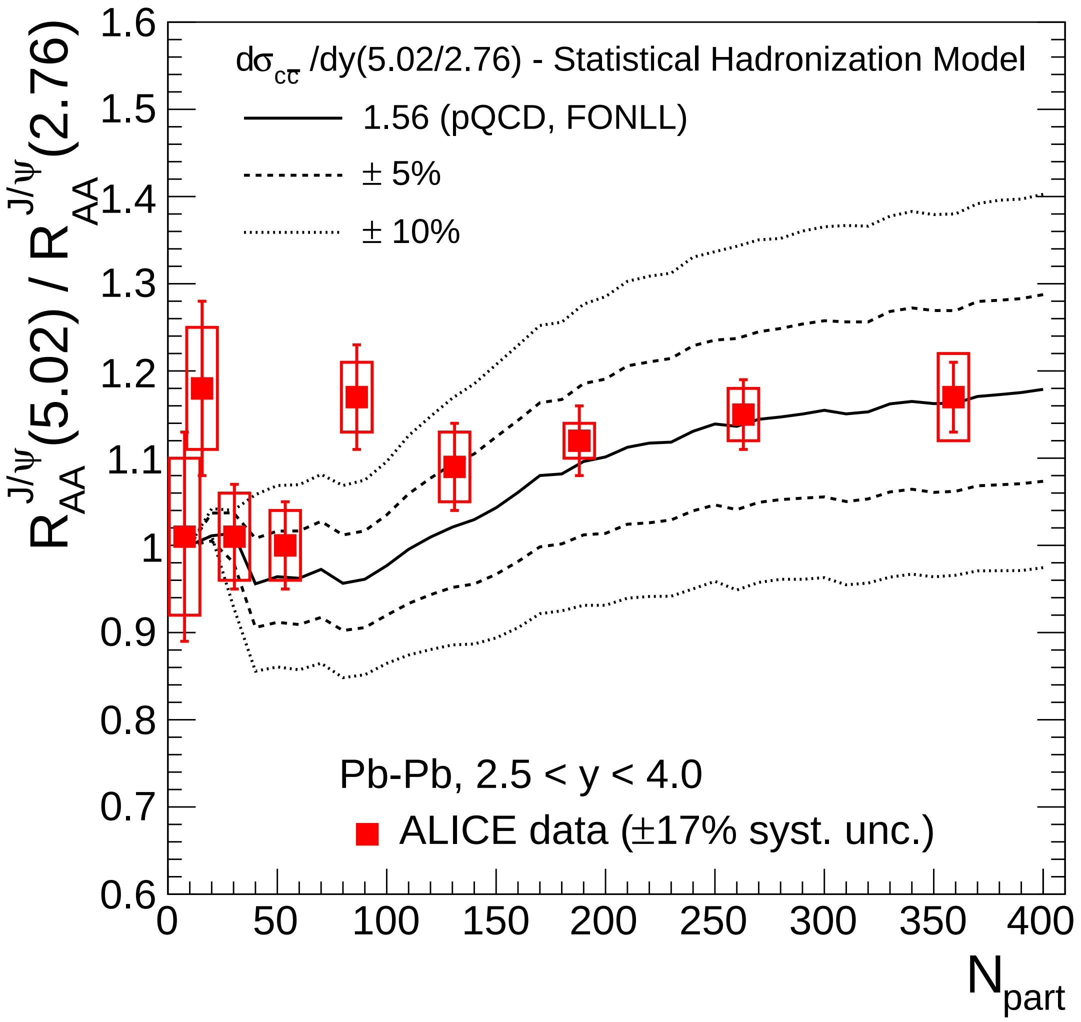
the model predicts absolute yields (R_{AA} is calculated with the pp reference as for data)



$2.5 < y < 4.0$

$\sigma_{c\bar{c}}$ 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

D-meson production vs. multiplicity