Statistical hadronization and the phase boundary of QCD
- a journey of five flavors -

A. Andronic – GSI Darmstadt

- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Charmonium
- Bottomonium
- Outlook (to full energy LHC and FCC)

work in collaboration with P. Braun-Munzinger, K. Redlich, J. Stachel

Hadron yields - central collisions

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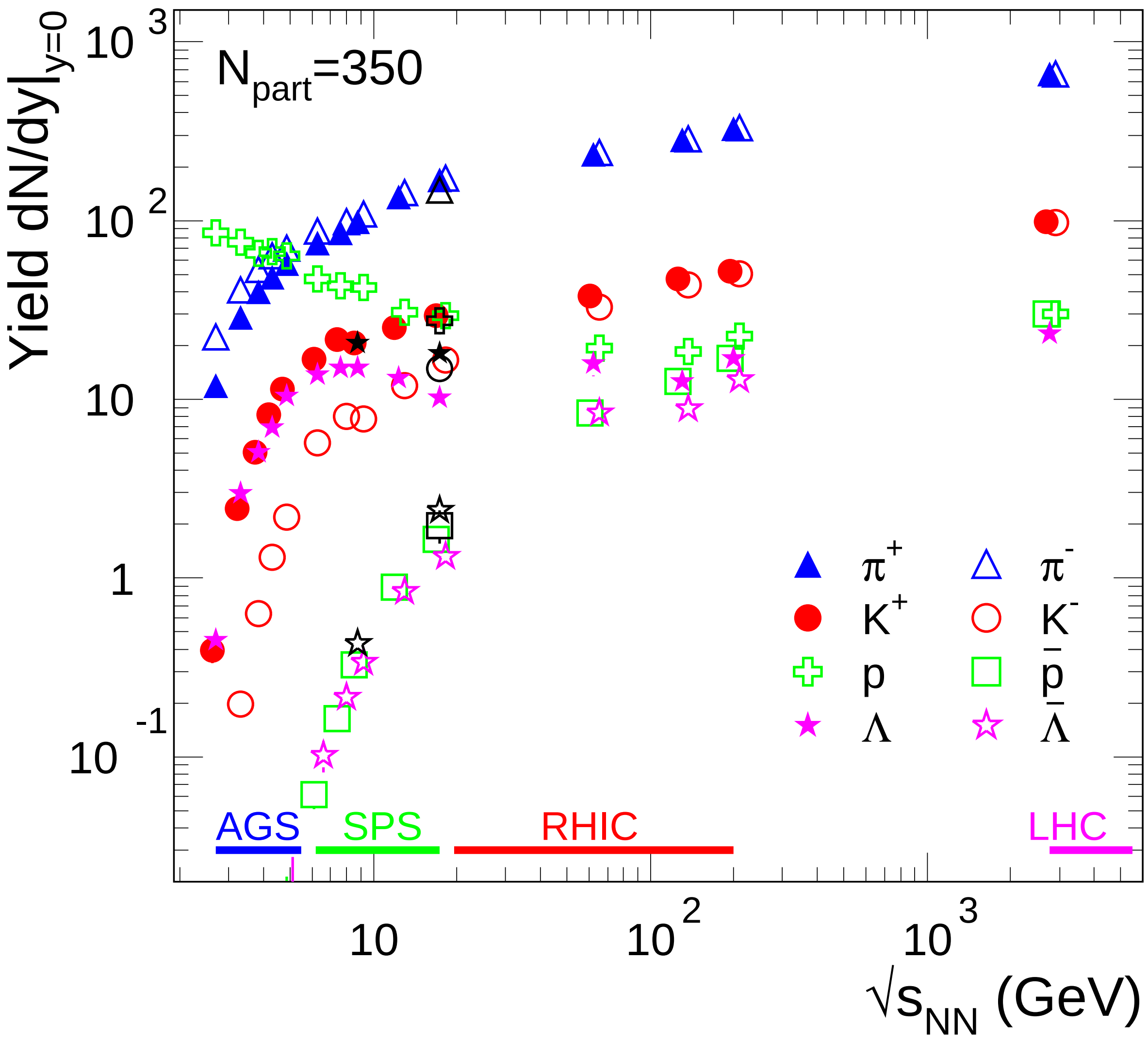

- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\ d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s},\ \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- 3 decades in energy and

  3 decades of experimental effort

mass hierarchy in production ...would a thermal model work?

The pioneering attempts

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Cleymans et al., PLB 242 (1990) 111; PLB 255 (1991) 105

Letessier, Tounsi, Rafelski, PLB 292 (1992) 417; PLB 328 (1994) 499

Braun-Munzinger, Stachel, Wessels, Xu

- Thermal equilibration and expansion in nucleus-nucleus collisions at the AGS
  nucl-th/9410026, PLB 344 (1995) 43
  T=120-140 MeV, μ_B=540 MeV

- Thermal and hadrochemical equilibration in nucleus-nucleus collisions at the SPS
  T=160-170 MeV, μ_B=170-180 MeV ; "phase boundary"
  nucl-th/9508020, PLB 365 (1996) 1

The statistical (thermal) model

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grand canonical partition function for specie i ($\hbar = c = 1$):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;
$E_i = \sqrt{p^2 + m_i^2}$ total energy; $+$ for fermions – for bosons
$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

i) isospin: $V_{cons} \sum_i n_i I_{3i} = I_3^{tot}$, with $V_{cons} = N_B^{tot} / \sum_i n_i B_i$
I_3^{tot}, N_B^{tot} isospin and baryon number of the system (=0 at high energies)
ii) strangeness: $\sum_i n_i S_i = 0$
iii) charm: $\sum_i n_i C_i = 0$.

canonical treatment whenever needed (small abundances)

Thermal fits of hadron abundances

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$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

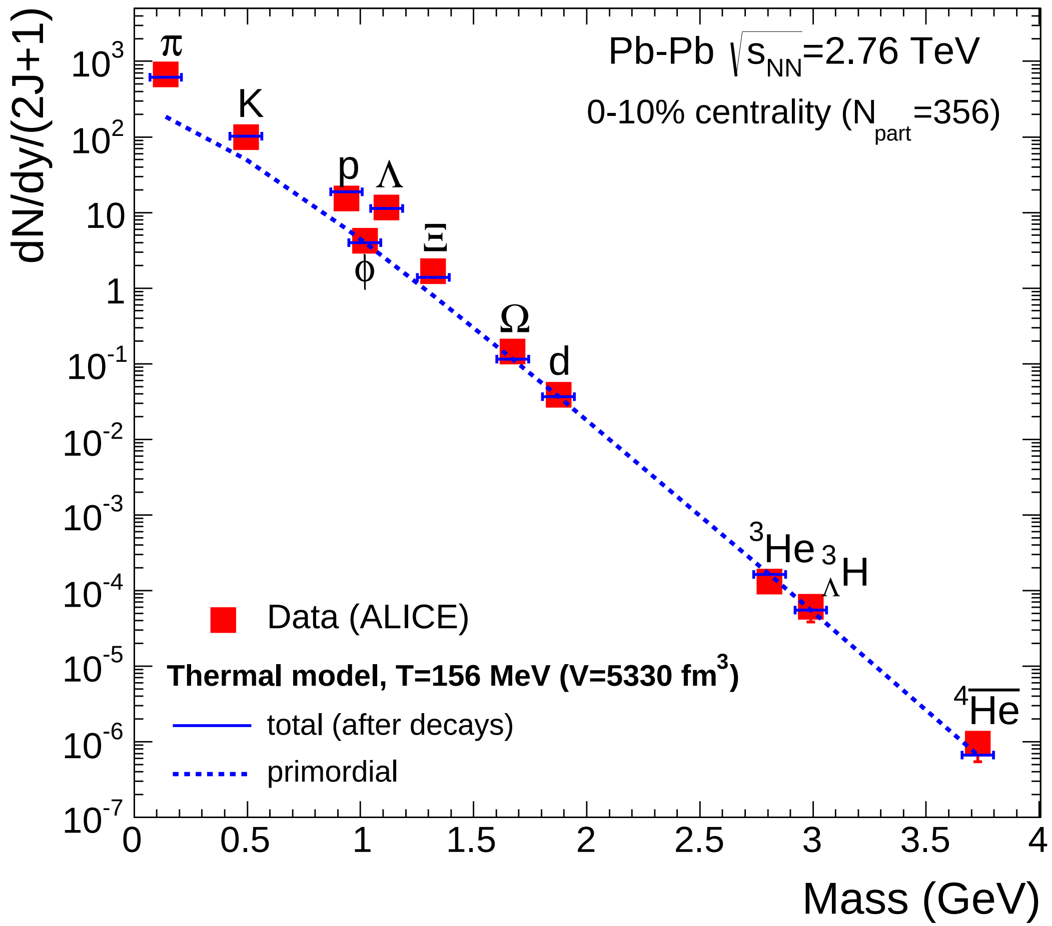
quantum no. conservation:

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$

Latest PDG hadron mass spectrum (up to 3 GeV, 485 species)

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i: hadron yield $\Rightarrow (T, \mu_B, V)$



Hadron abundances consistent with a thermally equilibrated system

Thermal fits – LHC, Pb–Pb, 0-10%

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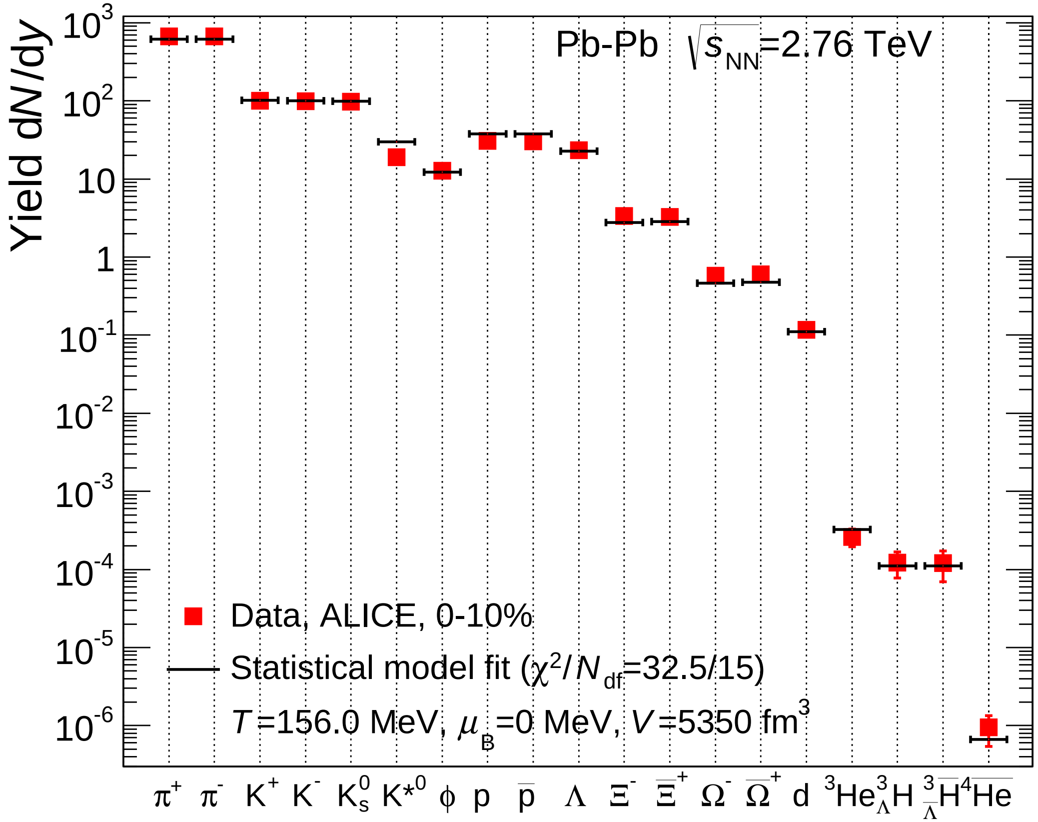

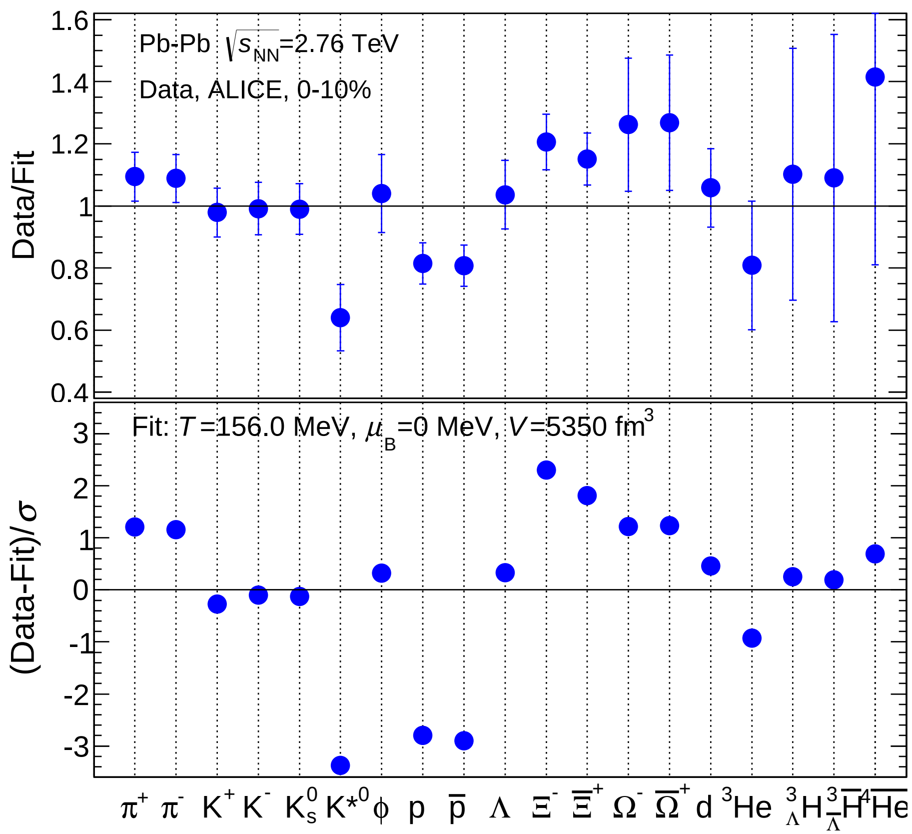

K^* not in fit

$$T = 156.0^{+1.0}_{-2.0}\ \text{MeV},\ \mu_B = 0 \pm 3\ \text{MeV},\ V = 5350^{+340}_{-670}\ \text{fm}^3$$

model-systematic effects under investigation (T robust against hadron spectrum)

Energy dependence of T, μ_B (central collisions)

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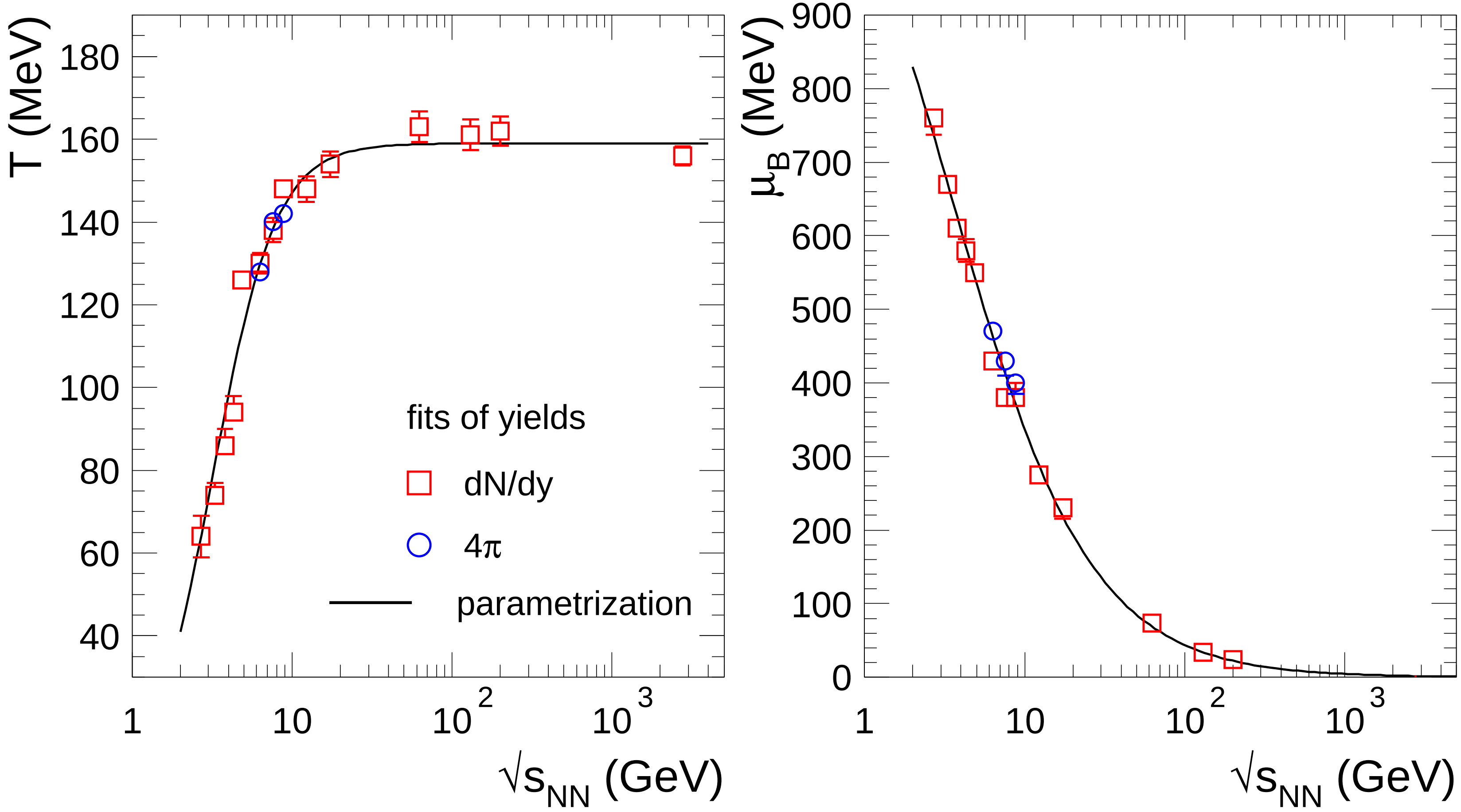

thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2$ MeV

$$T = T_{lim} \frac{1}{1+\exp(2.60 - \ln(\sqrt{s_{NN}(\mathrm{GeV})})/0.45)}, \qquad \mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

NPA 772 (2006) 167, PLB 673 (2009) 142 ...with updates

A "global" look (ratios)

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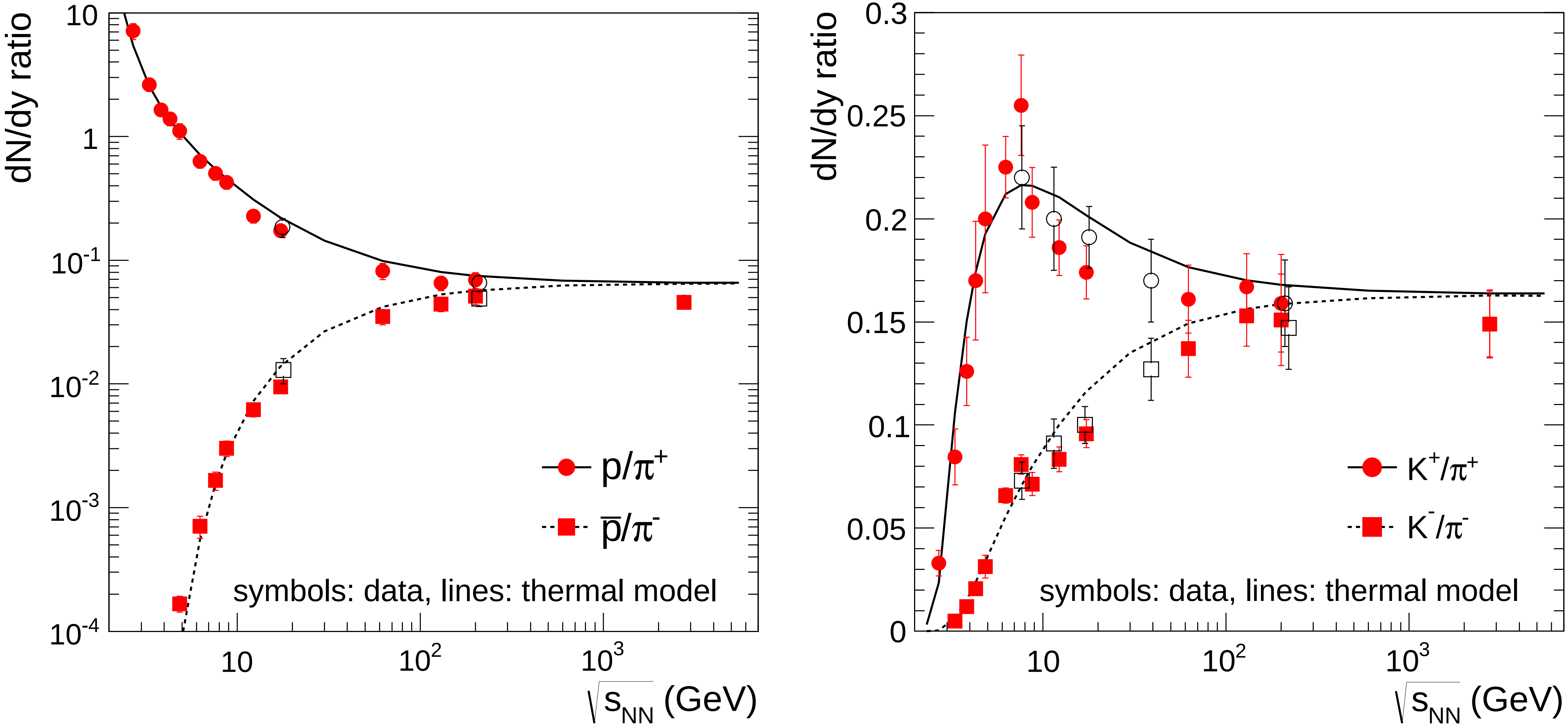

full: NA49 & STAR (p, $\bar{p}$ from w.d. subtracted); at 17 GeV open symbols NA44; at 200 GeV open symbols BRAHMS, lower energies STAR BES (prel.)

Connection to the phase diagram of QCD

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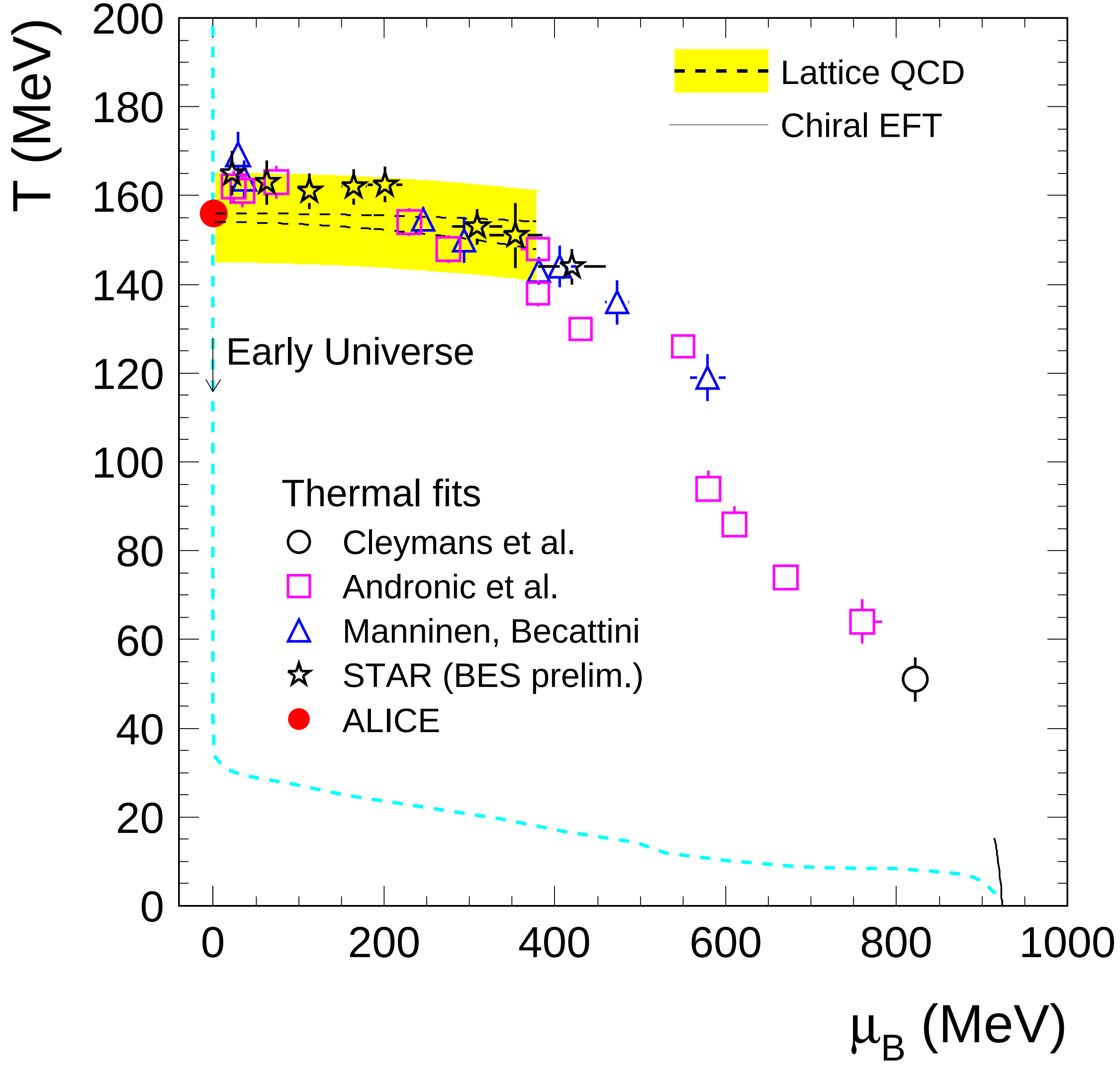

(as $T \to T_{lim}$) is chemical freeze-out a determination of the phase boundary? ...Yes (at low μ_B)

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

BW, JHEP 1009 (2010) 073

HotQCD, PRD 90 (2014) 094503

...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

We turn now to quarkonium

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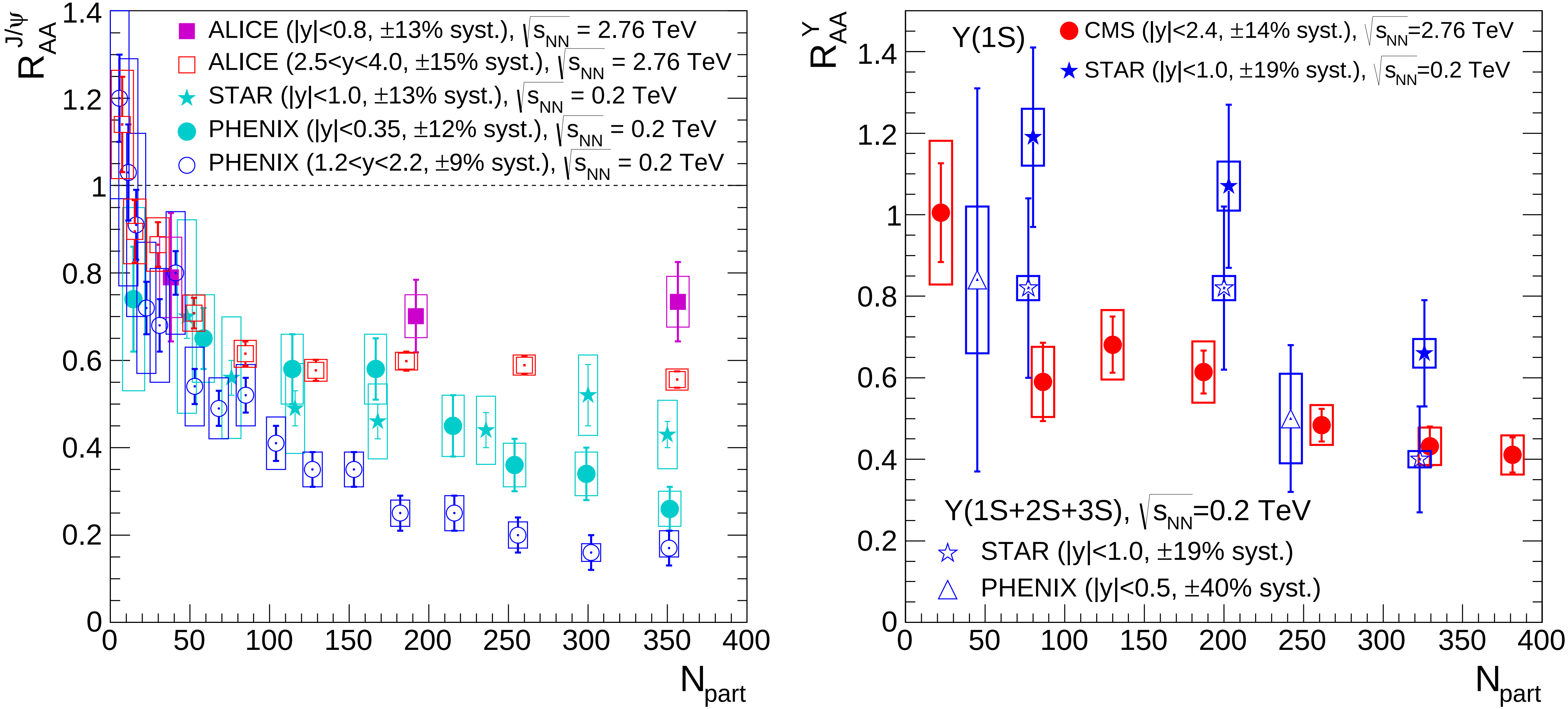

arXiv:1409.5778

Statistical hadronization of heavy quarks: assumptions

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P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

- all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)
- survive and thermalize **in QGP** (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons
  statistical laws, quantum no. conservation; stat. hadronization $\neq$ coalescence

  is freeze-out at(/the?) phase boundary?

  ...we believe yes ...based on data in the light-quark sector (support from LQCD)
- no J/ψ survival in QGP (full screening; Matsui, Satz)

  can J/ψ survive above T$_c$? ...yet to be settled (LQCD)

  Asakawa, Hatsuda, PRL 92 (2004) 012001; Mocsy, Petreczky, PRL 99 (2007) 211602; etc.

Statistical hadronization of heavy quarks: assumptions

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if all this is supported by data, J/ψ looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Statistical hadronization of charm: method and inputs

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- 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):

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

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

Inputs: T, μ_B, $V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{d}y)/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (pQCD or exp.)

Minimal volume for QGP: V_{QGP}^{min}=400 fm^3

Charmonium in the statistical hadronization model

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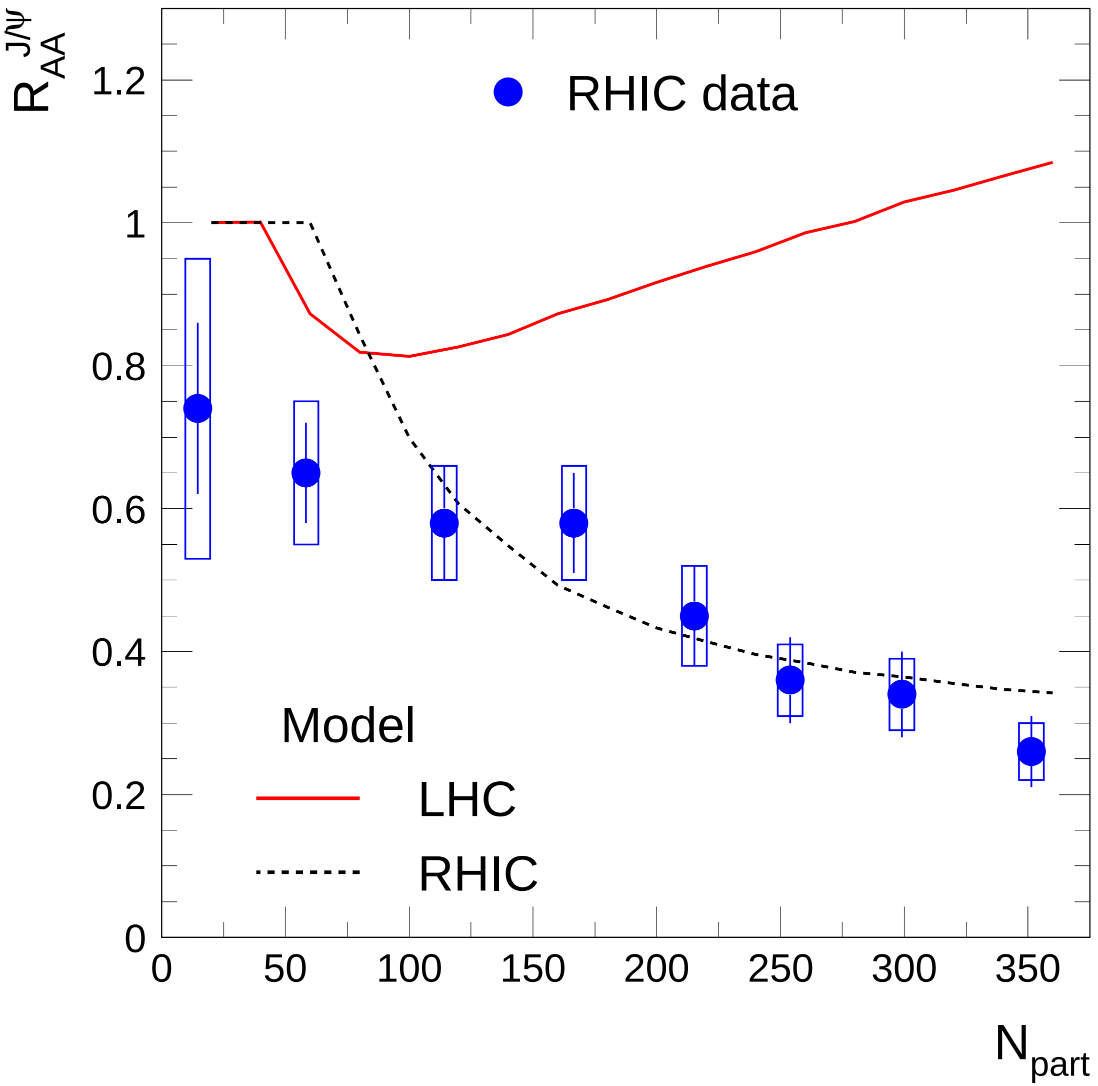

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AA}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- "suppression" at RHIC
- "enhancement" at the LHC

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

What is so different at LHC?

(compared to RHIC)

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

PLB 571 (2003) 36, NPA 789 (2007) 334, PLB 652 (2007) 259

this was for full LHC energy ... but is a generic prediction of the model

Charmonium in the statistical hadronization model at LHC

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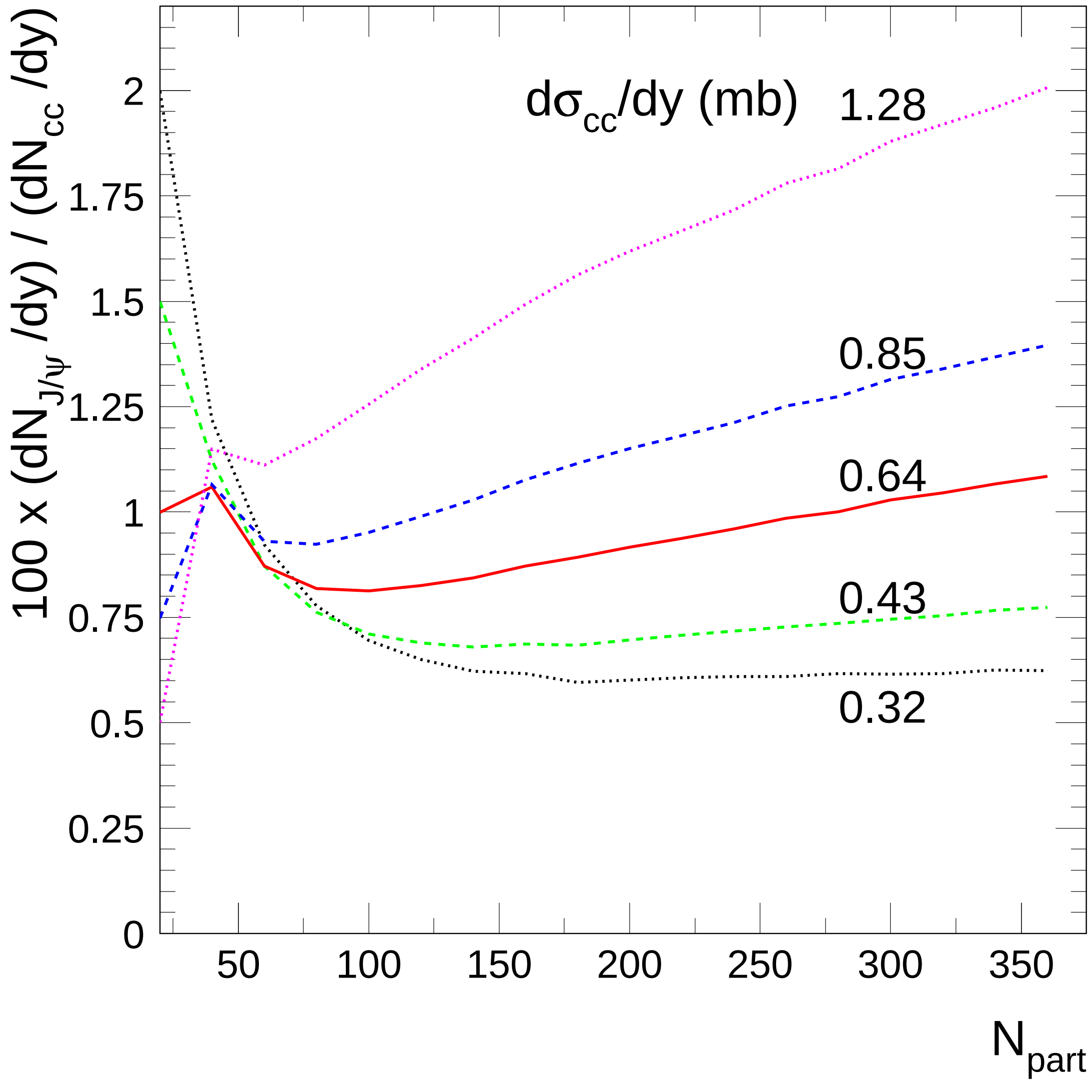

$$\frac{\mathrm{d}N^{AA}_{J/\psi}/\mathrm{d}y}{\mathrm{d}N^{AA}_{c\bar{c}}/\mathrm{d}y}$$

(“proxy” for R_{AA})

- ”enhancement” at the LHC

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

canonical suppression (mostly) lifted, quadratic term dominant

it can be more dramatic at FHC

AA et al., in N. Armesto et al., “Last Call...”, JPG 35 (2008) 054001

this was for full LHC energy ... but is a generic prediction of the model

Charmonium in the statistical hadronization model

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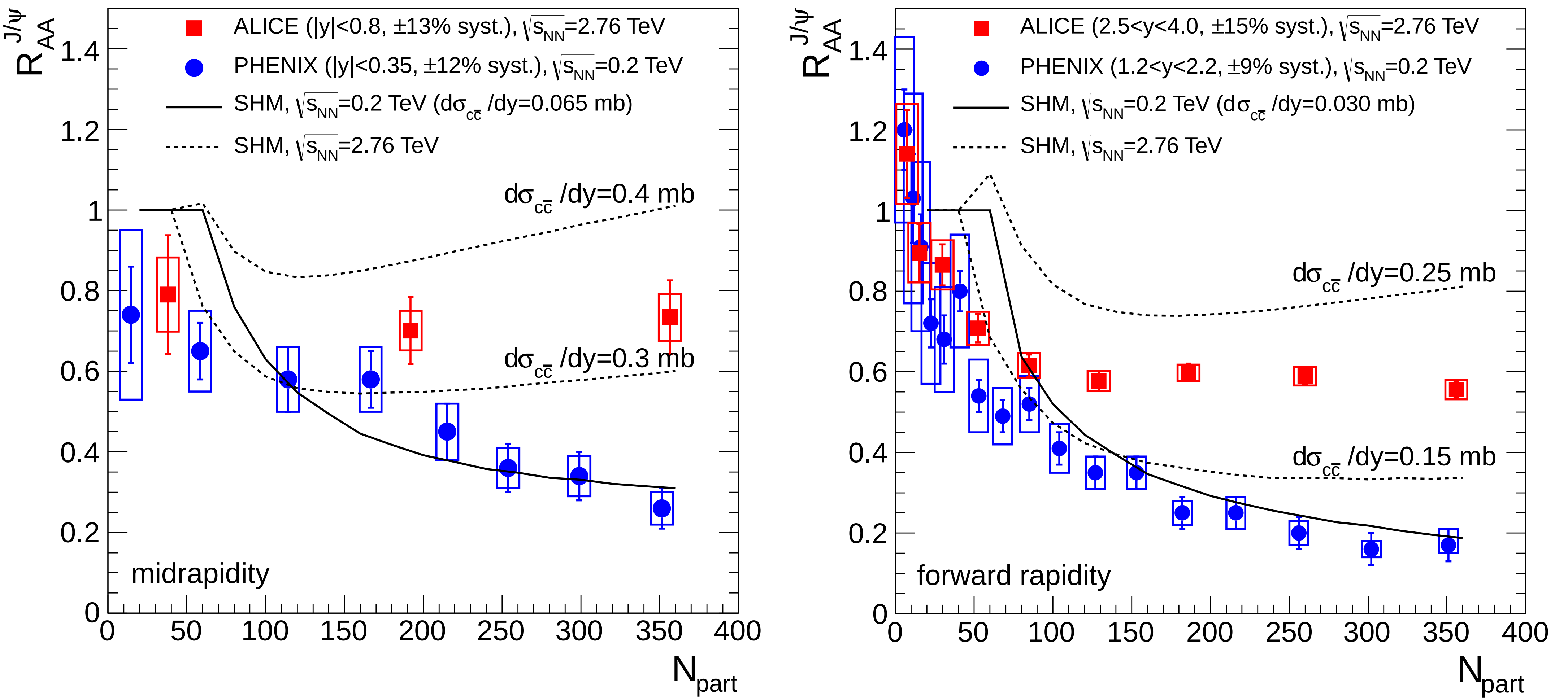

the generic prediction by the model is confirmed by data ALICE, PLB 734 (2014) 314

establishes charmonium as an ultimate observable of the phase boundary

More model comparisons (LHC)

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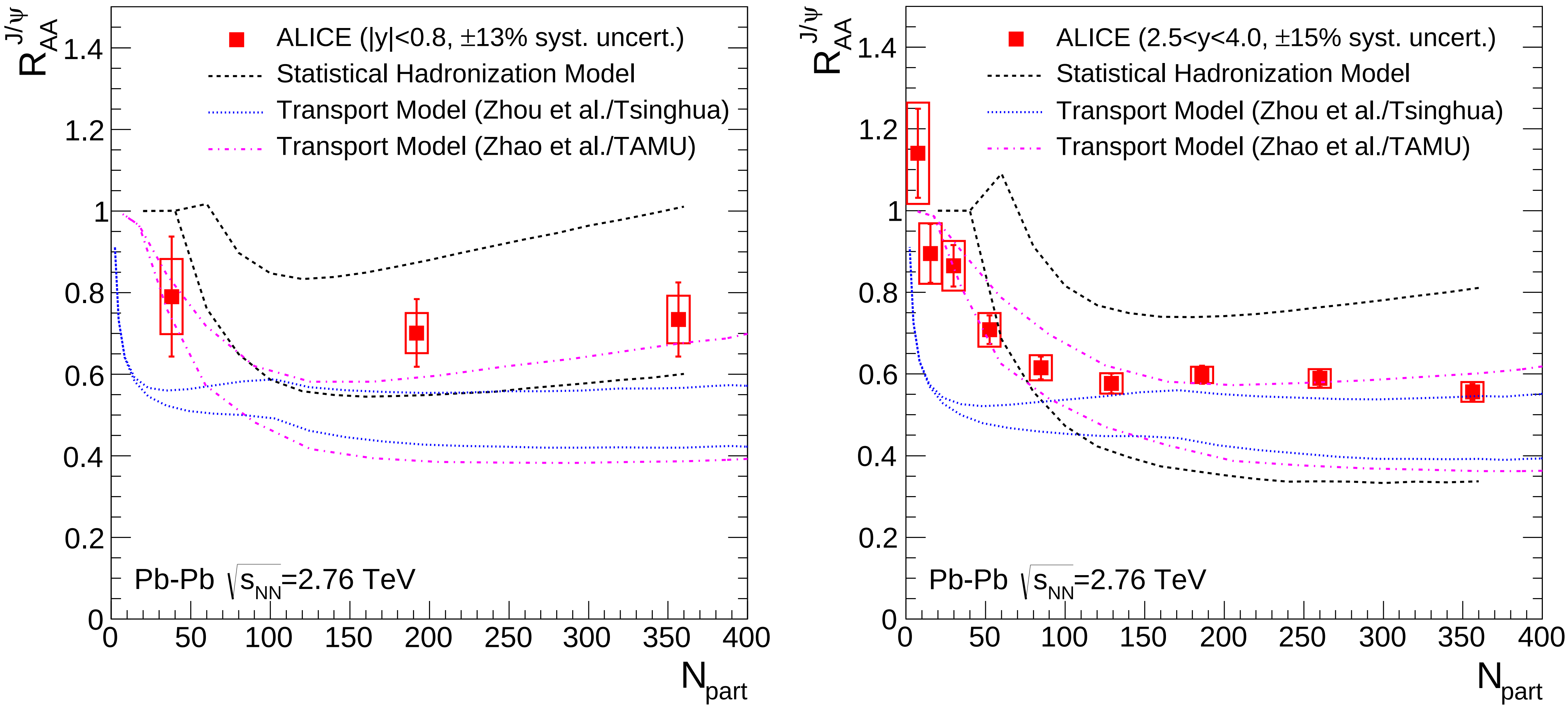
midrapidity   forward rapidity



Both model categories reproduce the data ...$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different:

midrapidity: Stat. Hadr.: 0.3-0.4 mb (will go up with incl. of more open charm states)

Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)

Fractions primordial, (re)generated

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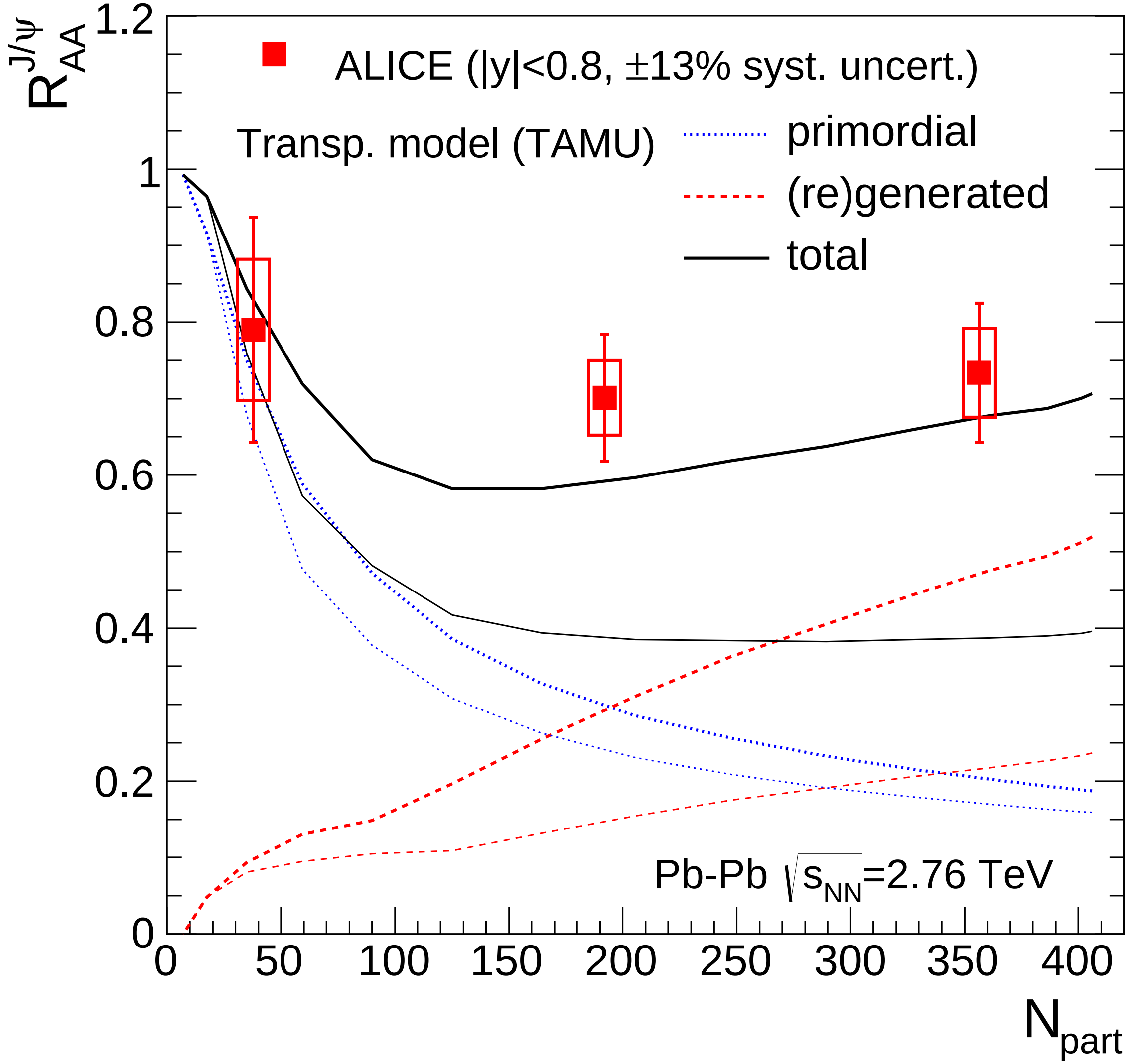

TAMU transport model:

Zhao et al., NPA 859 (2011) 114 and priv. comm.

similar fractions in the Tsinghua model

NB: not only regeneration but also generation

J/ψ vs. p_T - data

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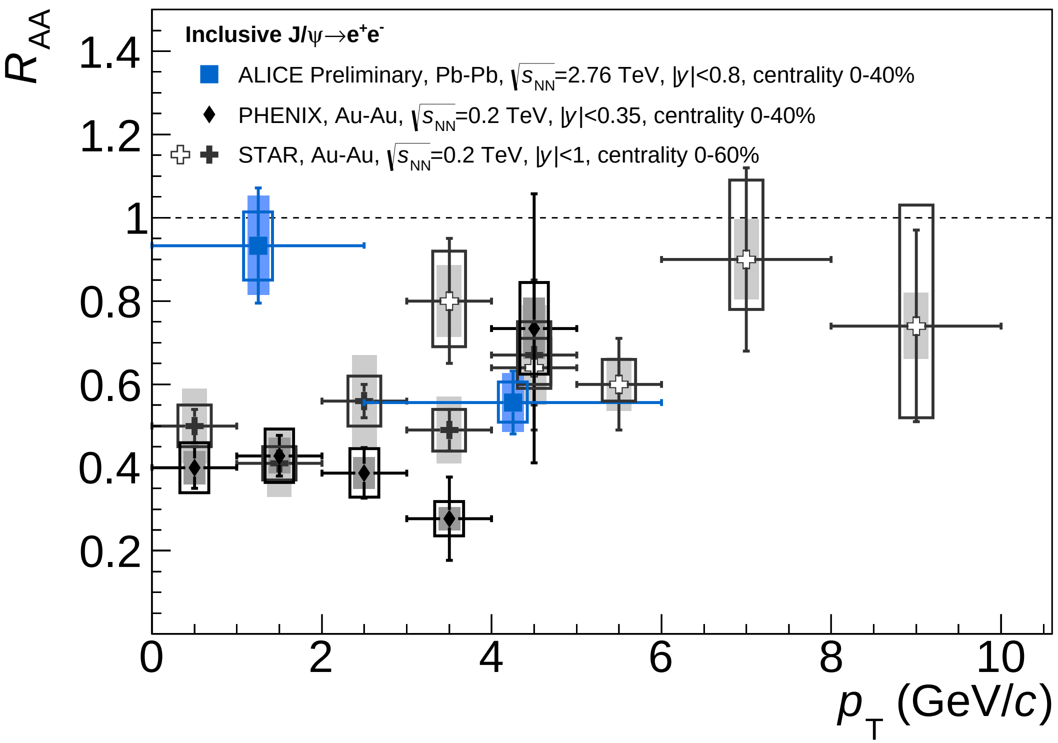
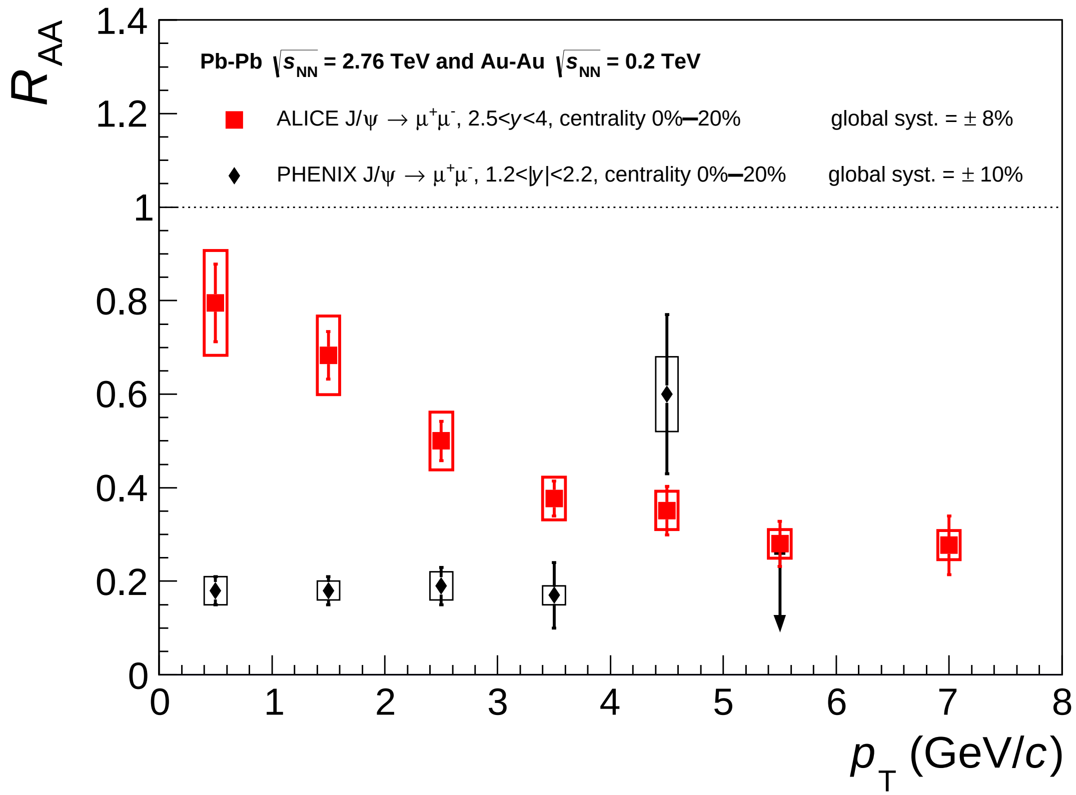
midrapidity



forward rapidity



further support of (dominance of) a new production mechanism: "(re)generation"
(re)generation in QGP or generation at chemical freeze-out (hadronization)

ALICE, PLB 734 (2014) 314 (& prelim., QM'14)

J/ψ Pb–Pb in context (p–Pb)

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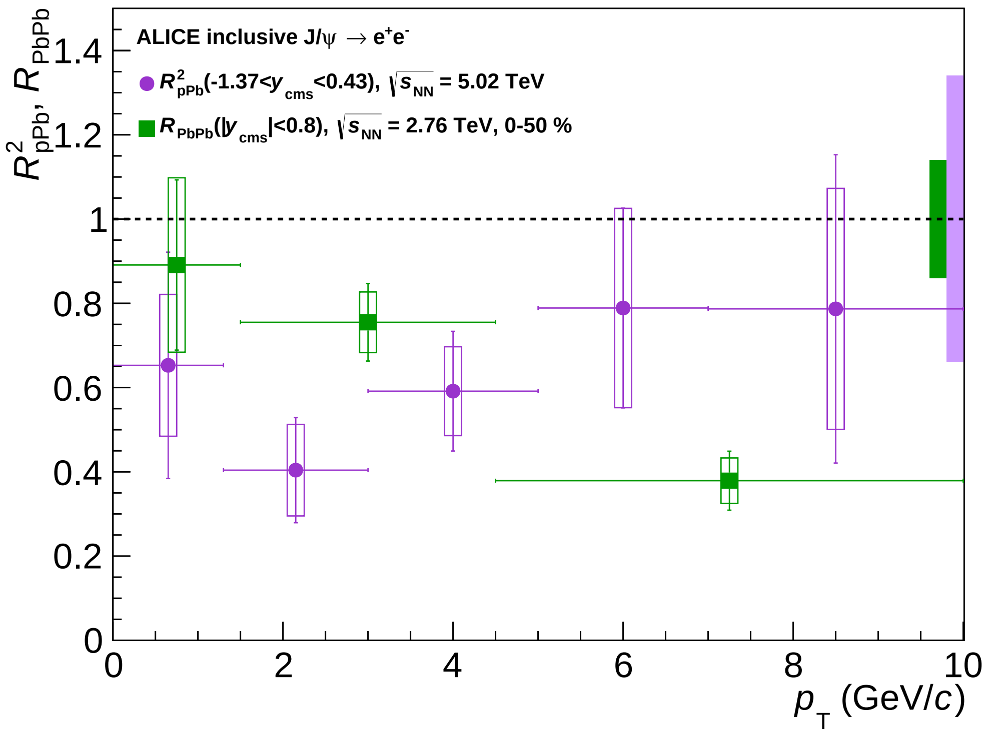
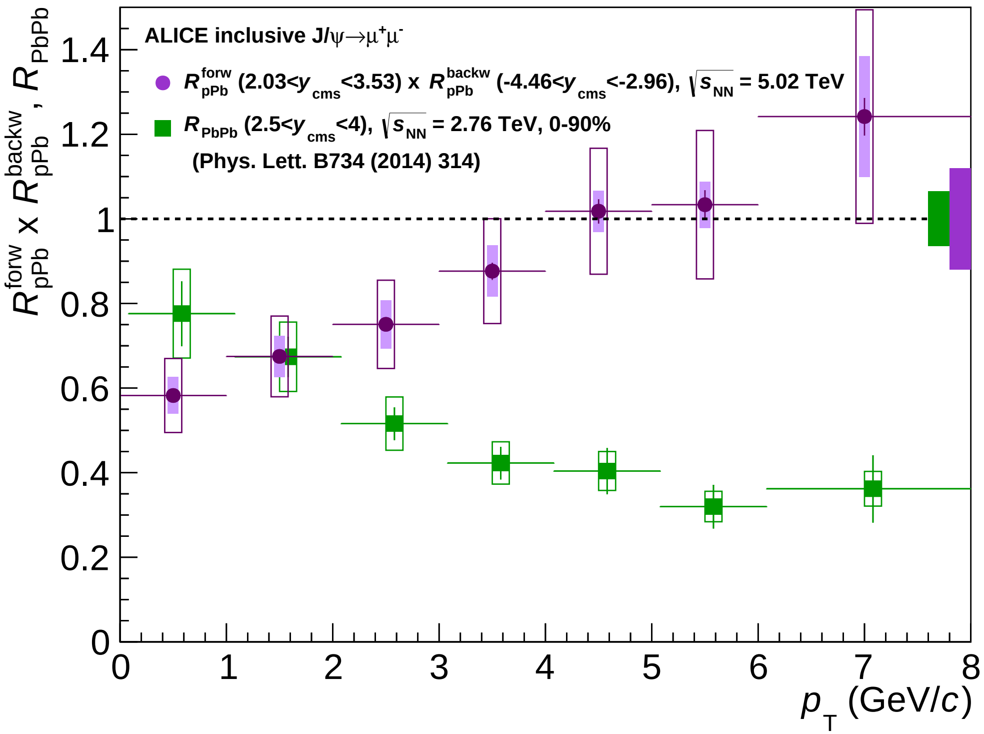
ALICE, arXiv:1503.07179

midrapidity



forward rapidity

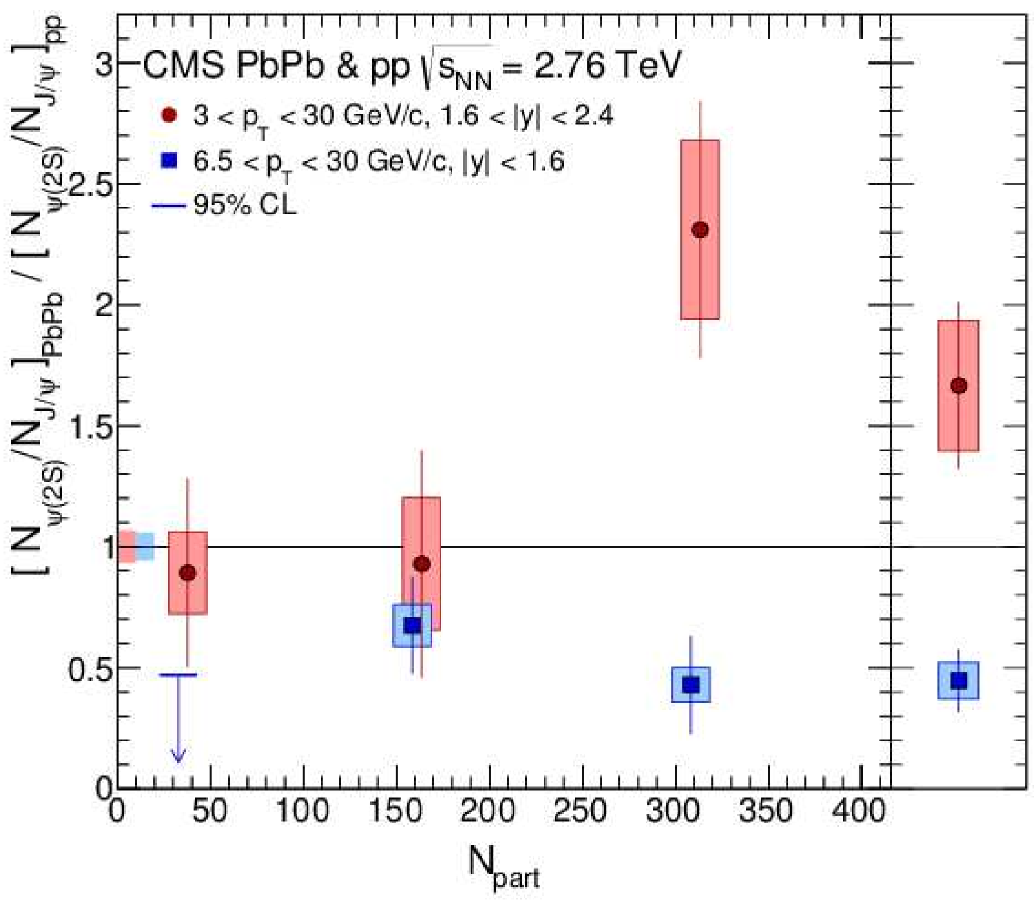


distinct differences between Pb–Pb and p–Pb, further support that low-p_T J/ψ are from (re)generation (while high-p_T is result of charm energy loss)

tantalizing implication for Pb–Pb: $R_{AA} > 1$ (at low $p_{\rm T}$) *if-more-charm*

...cannot turn off shadowing, but means we may see this at the top LHC energy

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



$$R = \frac{N^{\psi(2S)}_{\mathrm{Pb-Pb}}/N^{J/\psi}_{\mathrm{Pb-Pb}}}{N^{\psi(2S)}_{\mathrm{pp}}/N^{J/\psi}_{\mathrm{pp}}} = \frac{R^{\psi(2S)}_{\mathrm{AA}}}{R^{J/\psi}_{\mathrm{AA}}}$$

N - production yields

mind p_T ranges

CMS, PRL 113 (2014) 262301

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

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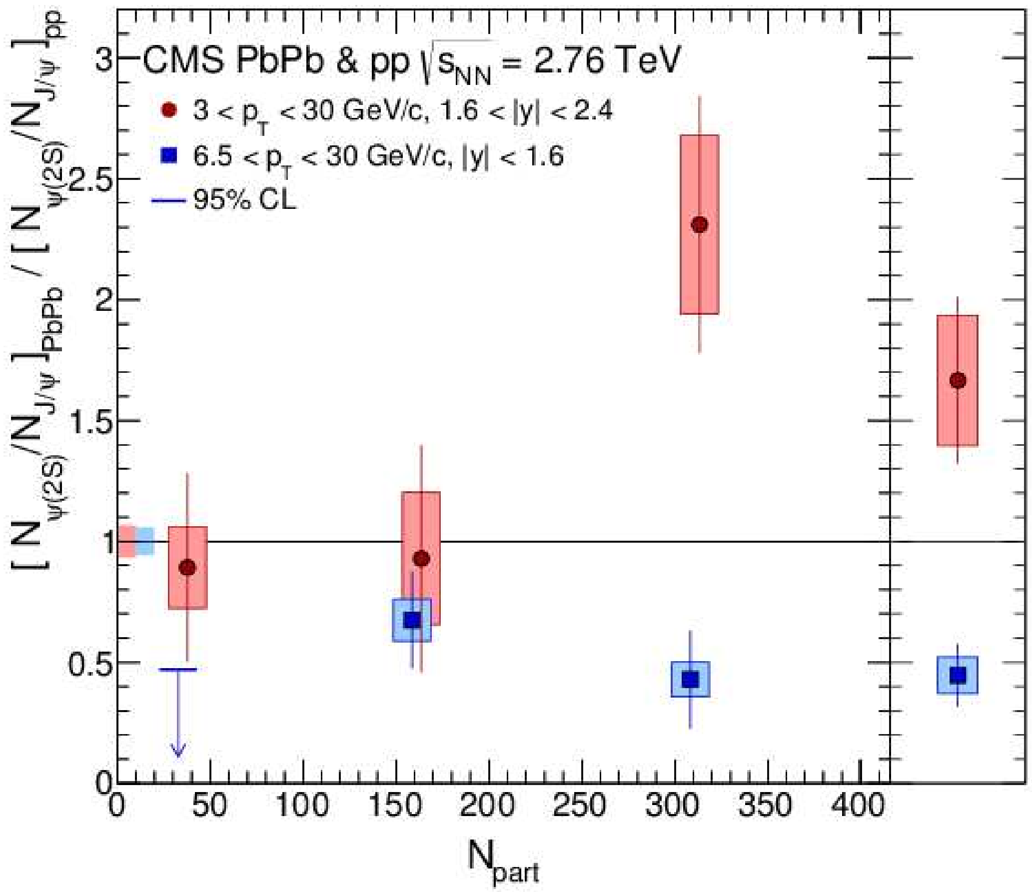
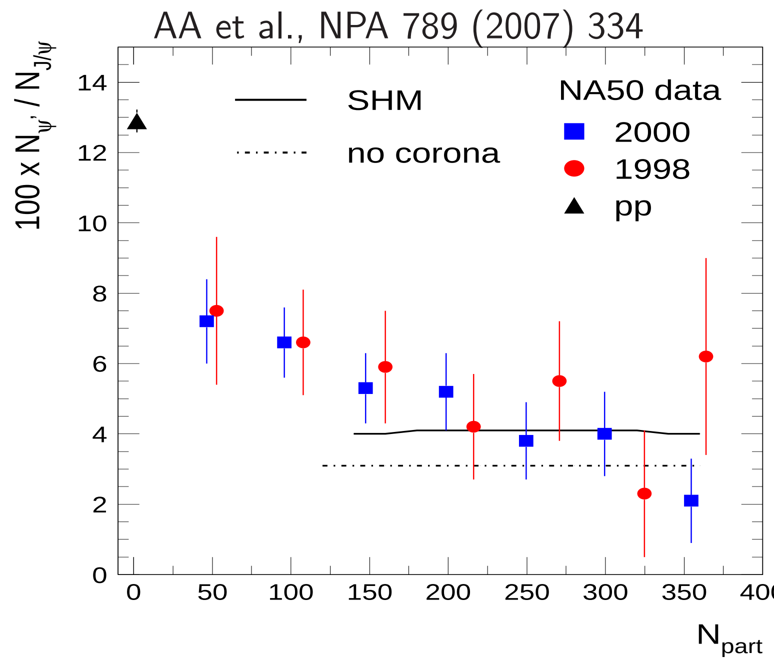


CMS, PRL 113 (2014) 262301



at SPS: $R \simeq$0.24 (p_T-integrated)

...evidence against sequential dissociation?

Data on other charmonium states is crucial ...$\psi(2S)$ is the focus

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

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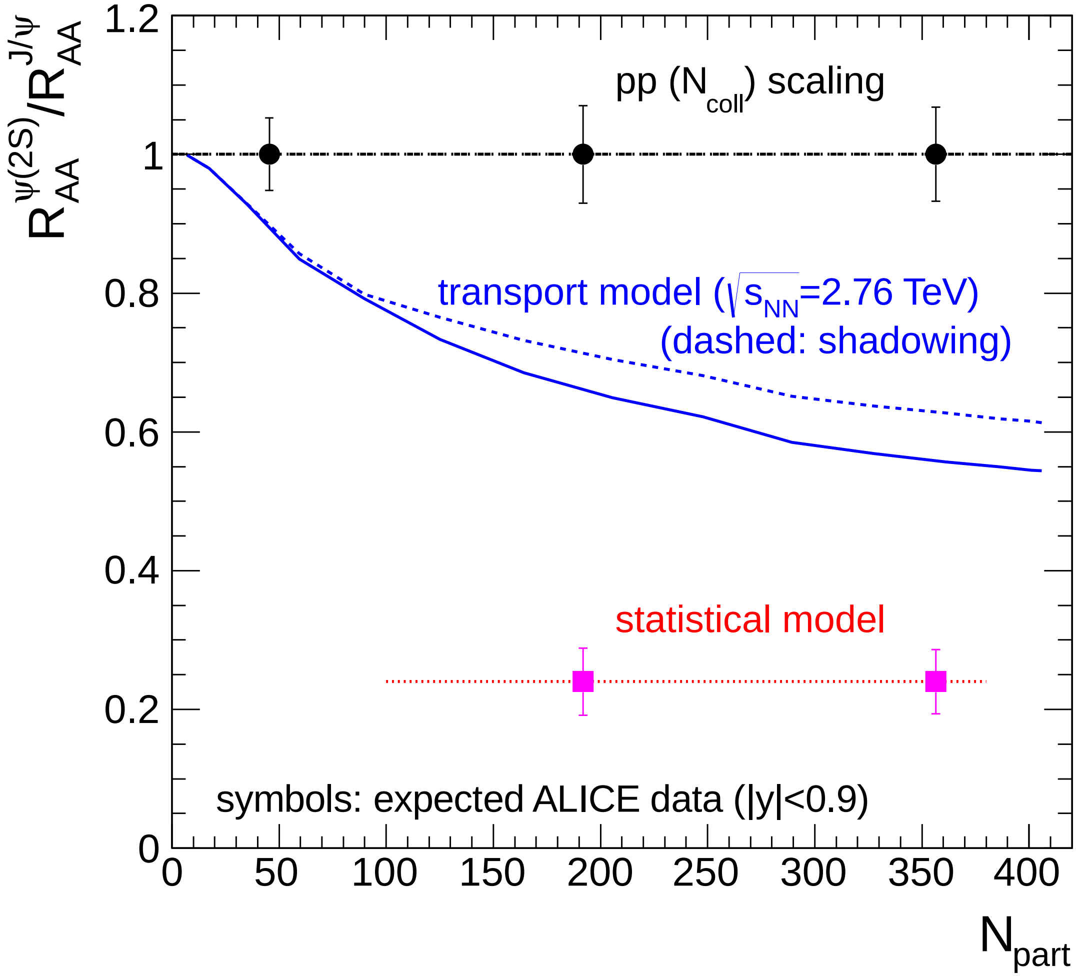
$R < 1$ expected in both models, different magnitudes predicted (p_{T}-integrated)

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



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 upgrade

ALICE, JPG 41 (2014) 087001

Outlook for J/ψ

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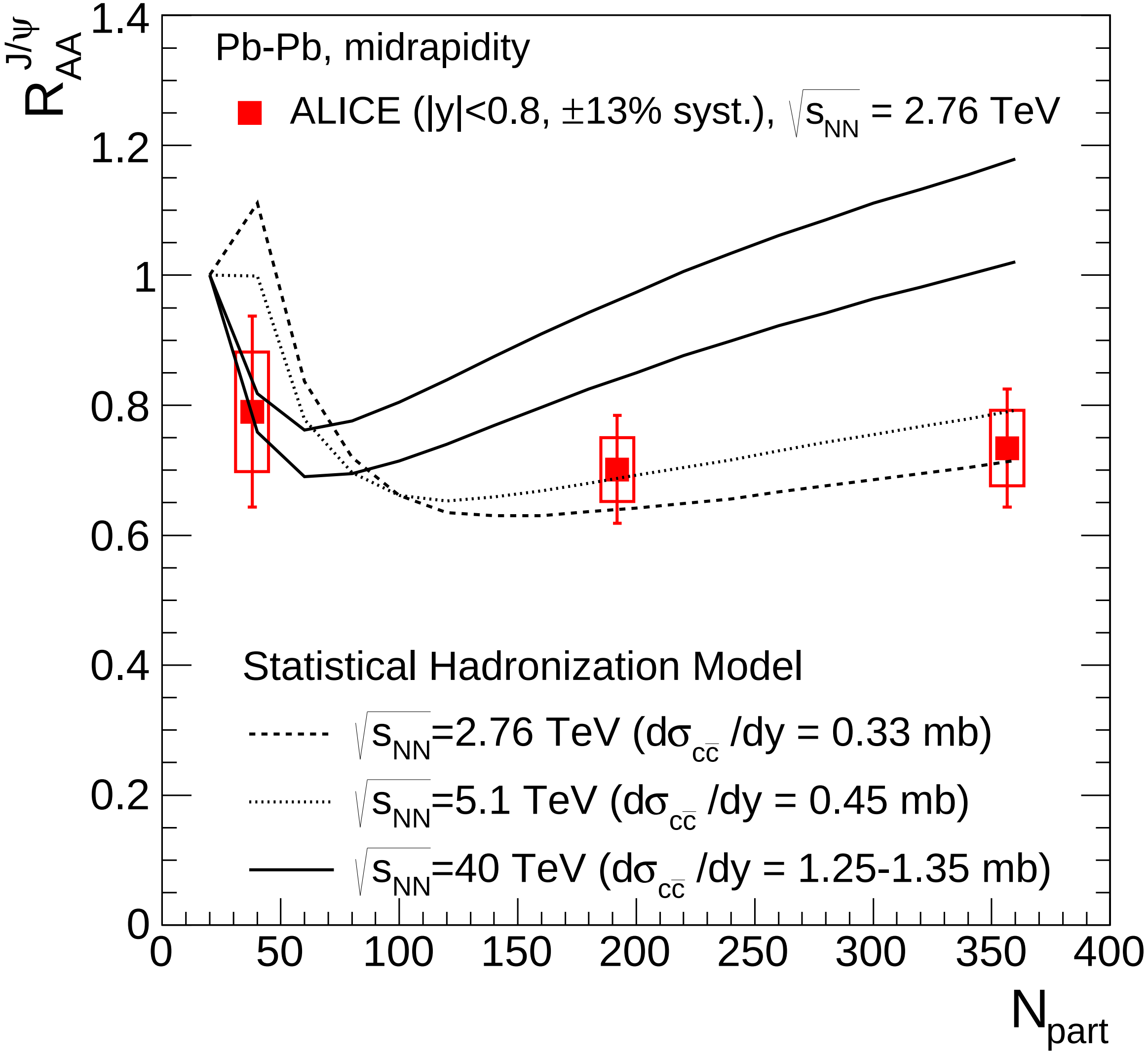

modest increase for 5.1 TeV

...due to modest increase in $\sigma c\bar{c}$

(slightly larger at forward y)

increasing trend vs. N_{part} at FCC

Bottomonium at the LHC

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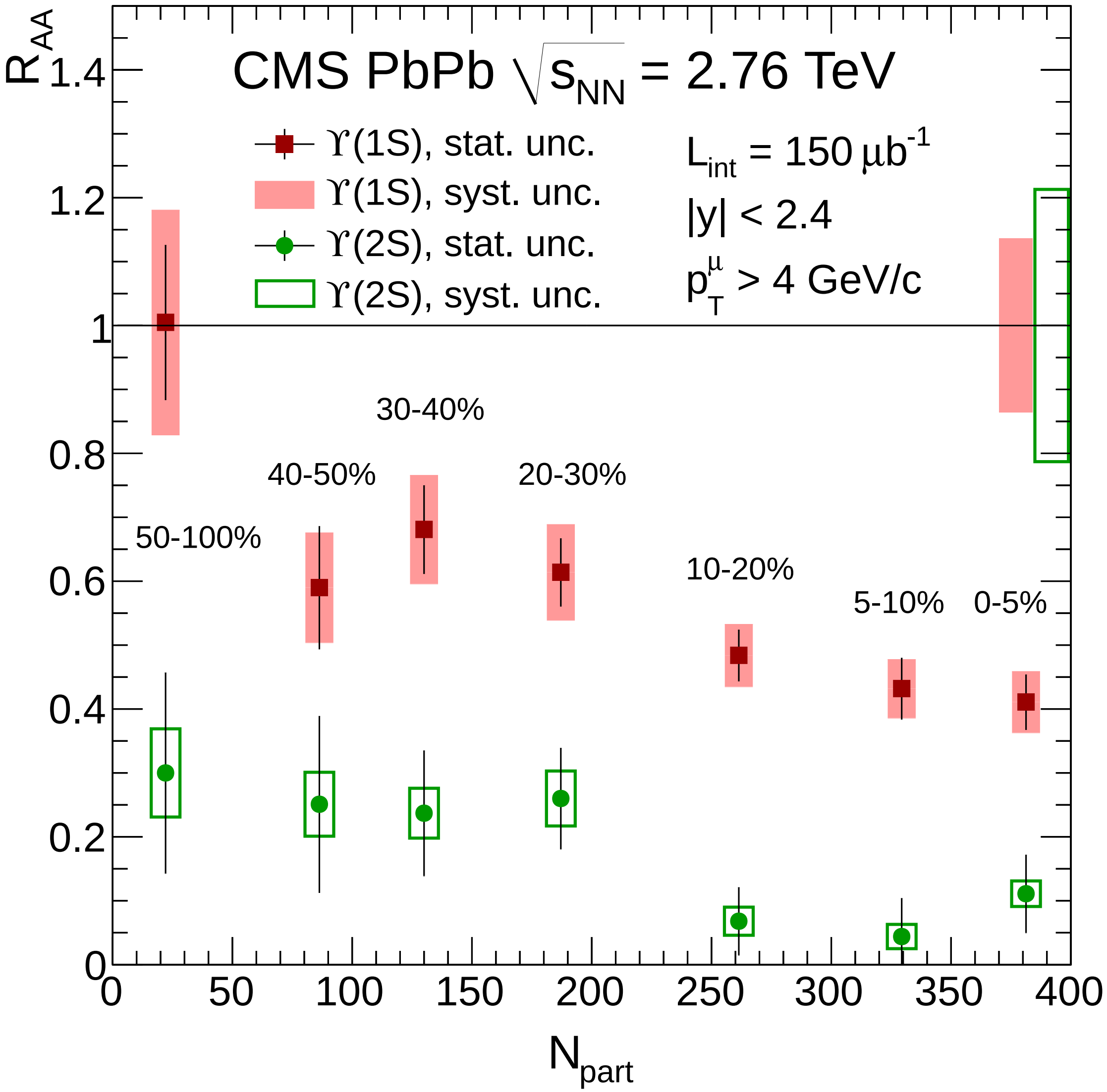


CMS, PRL 109 (2012) 222301

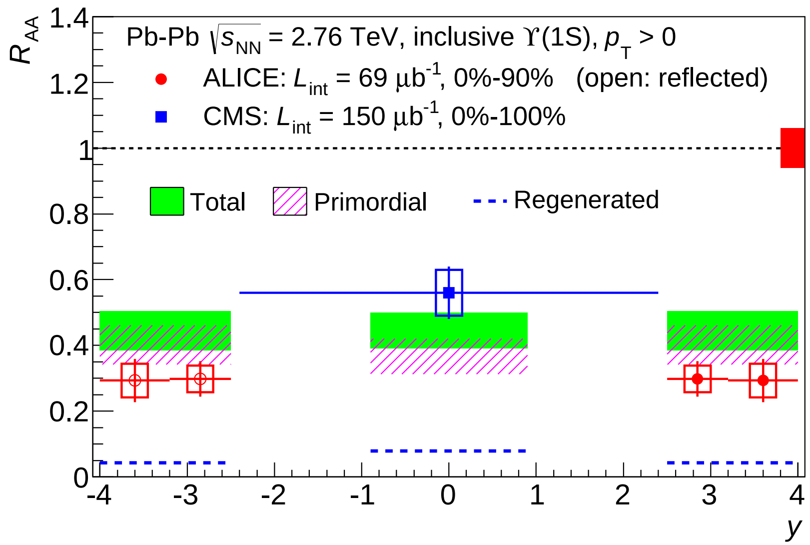
interpreted as effect of (almost:) full dissoc. of $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

Transport models:

Emerick et al./TAMU, EPJA 48 (2012) 72

Zhuang, arXiv:1408.3900

(re)gen. component small ($\lesssim$10%)



ALICE, arXiv:1405.4493

Bottomonium at the LHC in SHM

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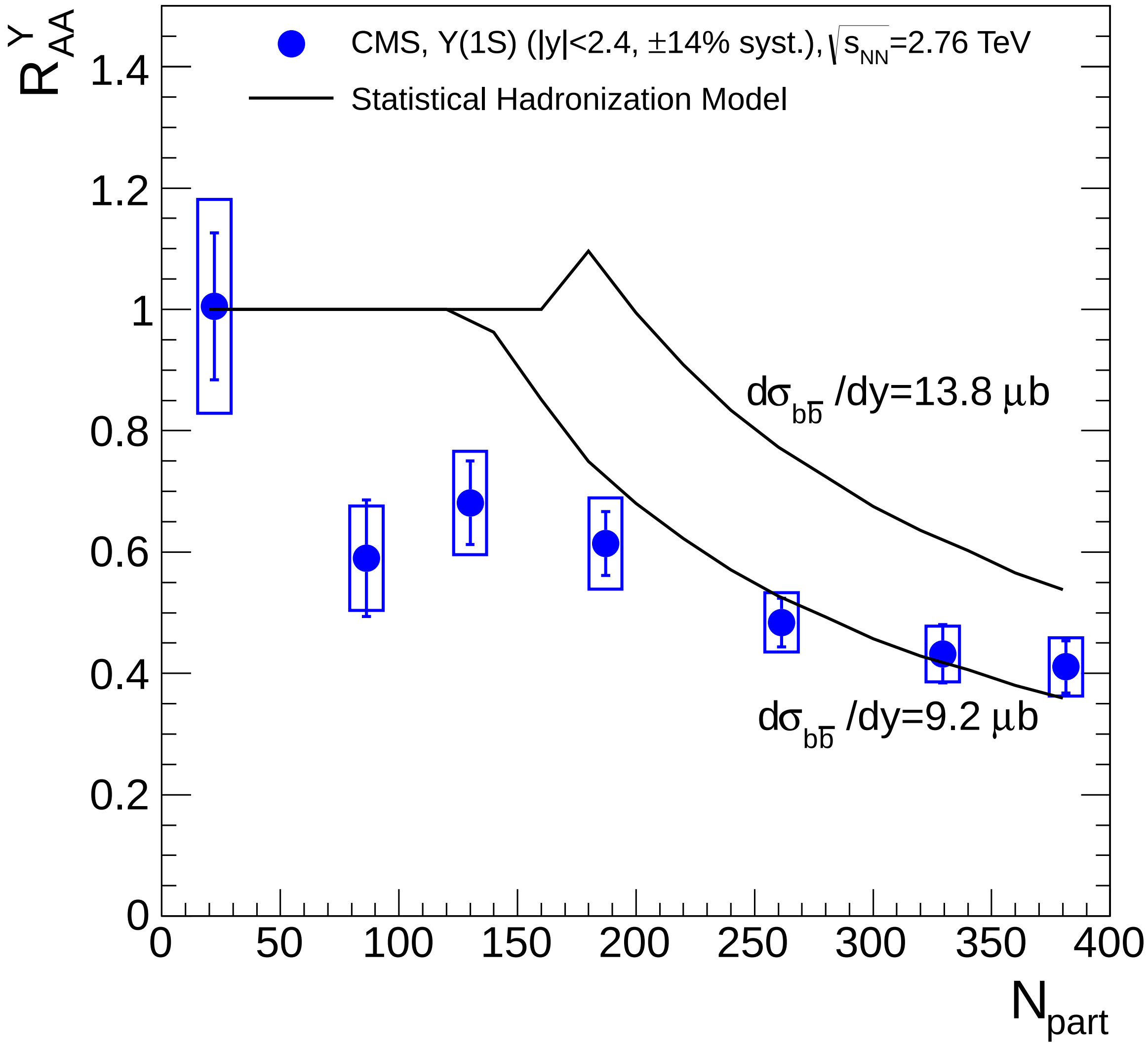

$$\frac{d\sigma_{b\bar{b}}}{dy} = 13.8\ \mu\text{b (MNR x0.8 shad.)}$$

fair description by model

CMS, PRL 109 (2012) 222301

Bottomonium ratios

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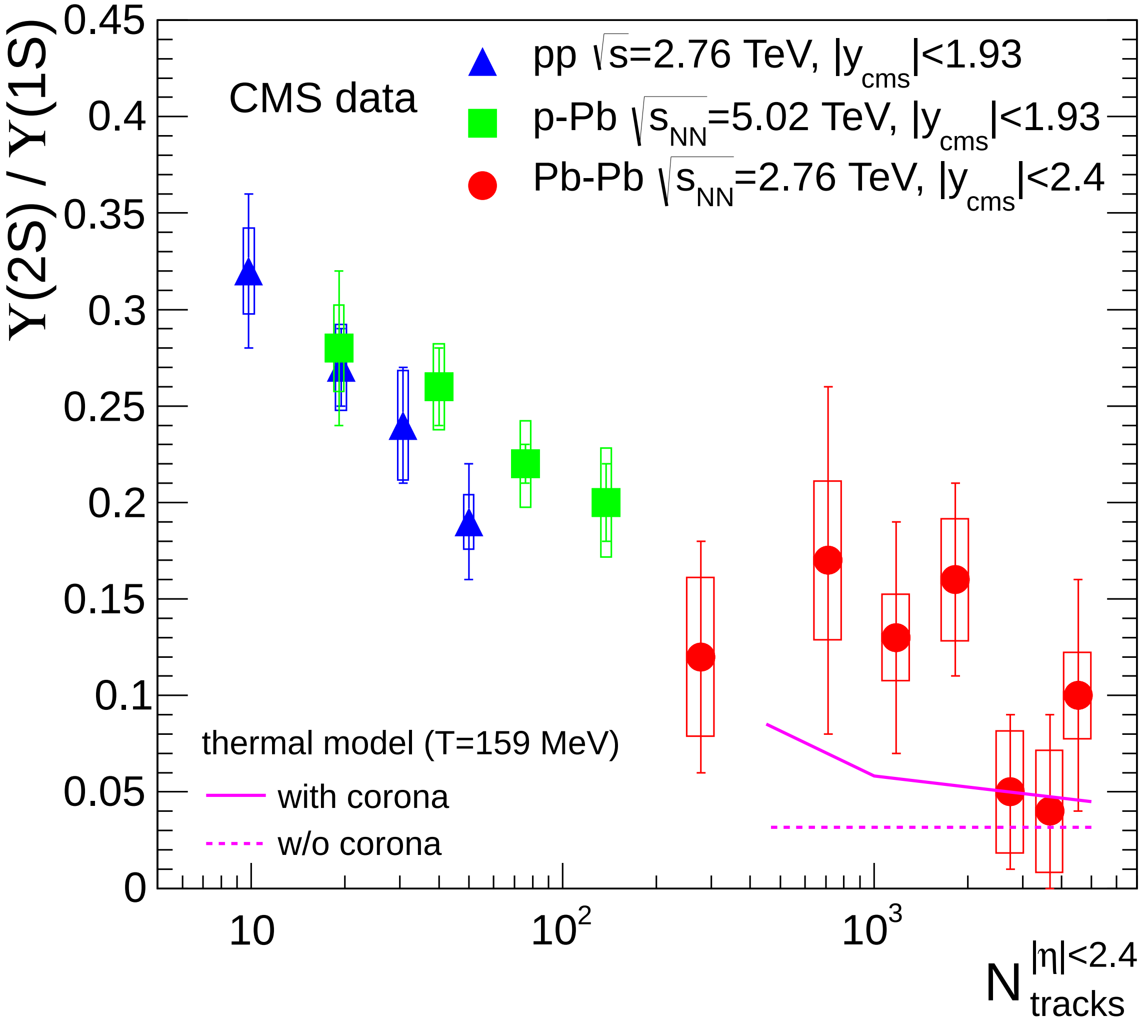

statistical model describes central Pb–Pb data

CMS, JHEP 1404 (2014) 103

Bottomonium at the FCC in SHM

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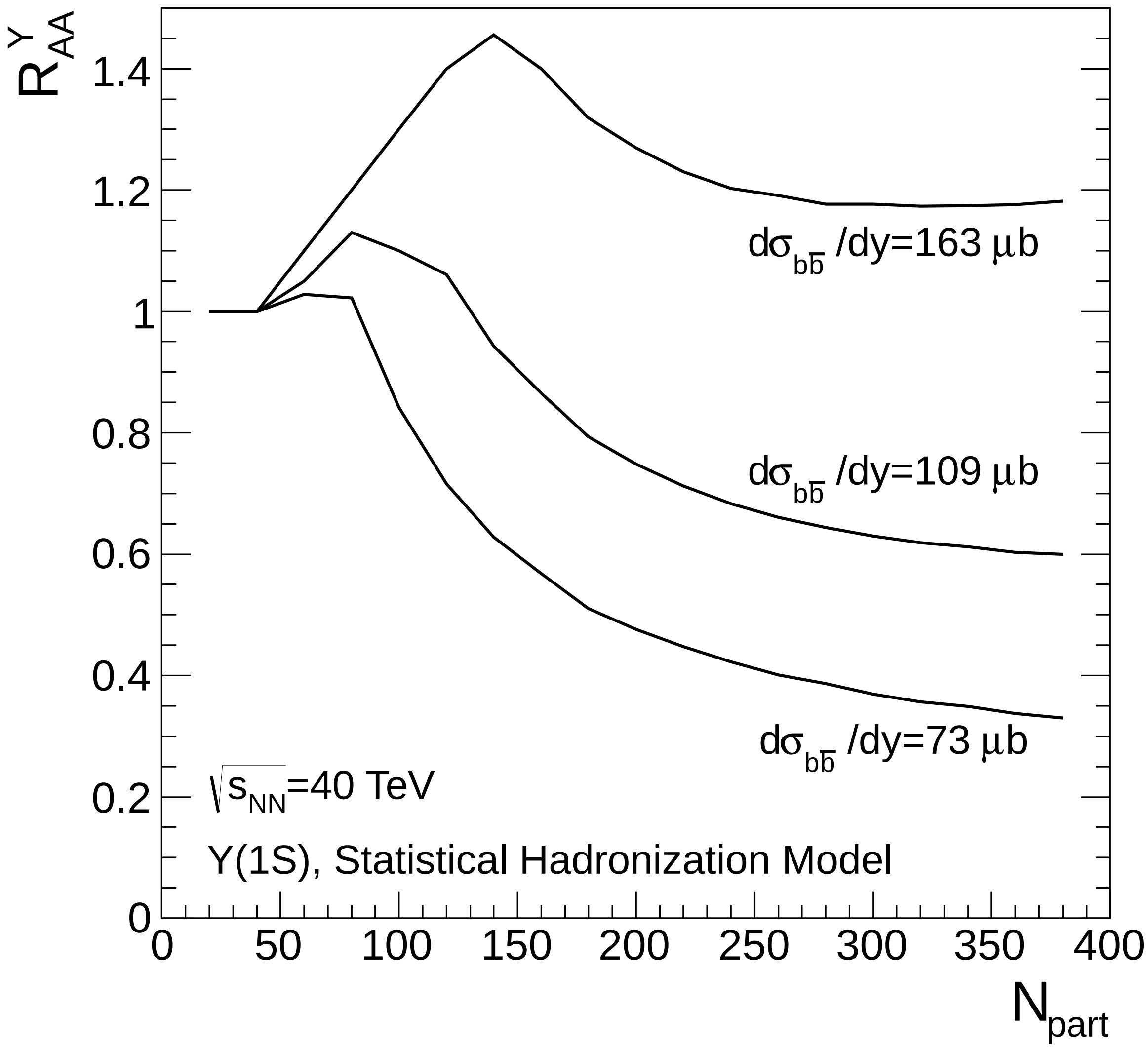


$\frac{\mathrm{d}\sigma_{b\bar{b}}}{\mathrm{d}y} = 109\ \mu$b (MNR x0.7 shad.)

$V = 12000$ fm^3

$Y(1S)$ in pp: 7 TeV data scaled by MNR factor of $\sigma_{b\bar{b}}$

the story of quarkonium as a “golden probe” for QGP is rather intricate

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

...(in QGP and/or) at the phase boundary ...maybe similar at RHIC (SPS?)

model results dependent on $\sigma_{c\bar{c}}$, to be better constrained by measurements

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?

a wealth of data (and puzzling too) in d-Au (RHIC) and p-Pb (LHC) awaits better understanding

while measurements at the LHC at 5.1 TeV are eagerly awaited
...strong bet: $R_{AA}^{J/\psi}$ will increase

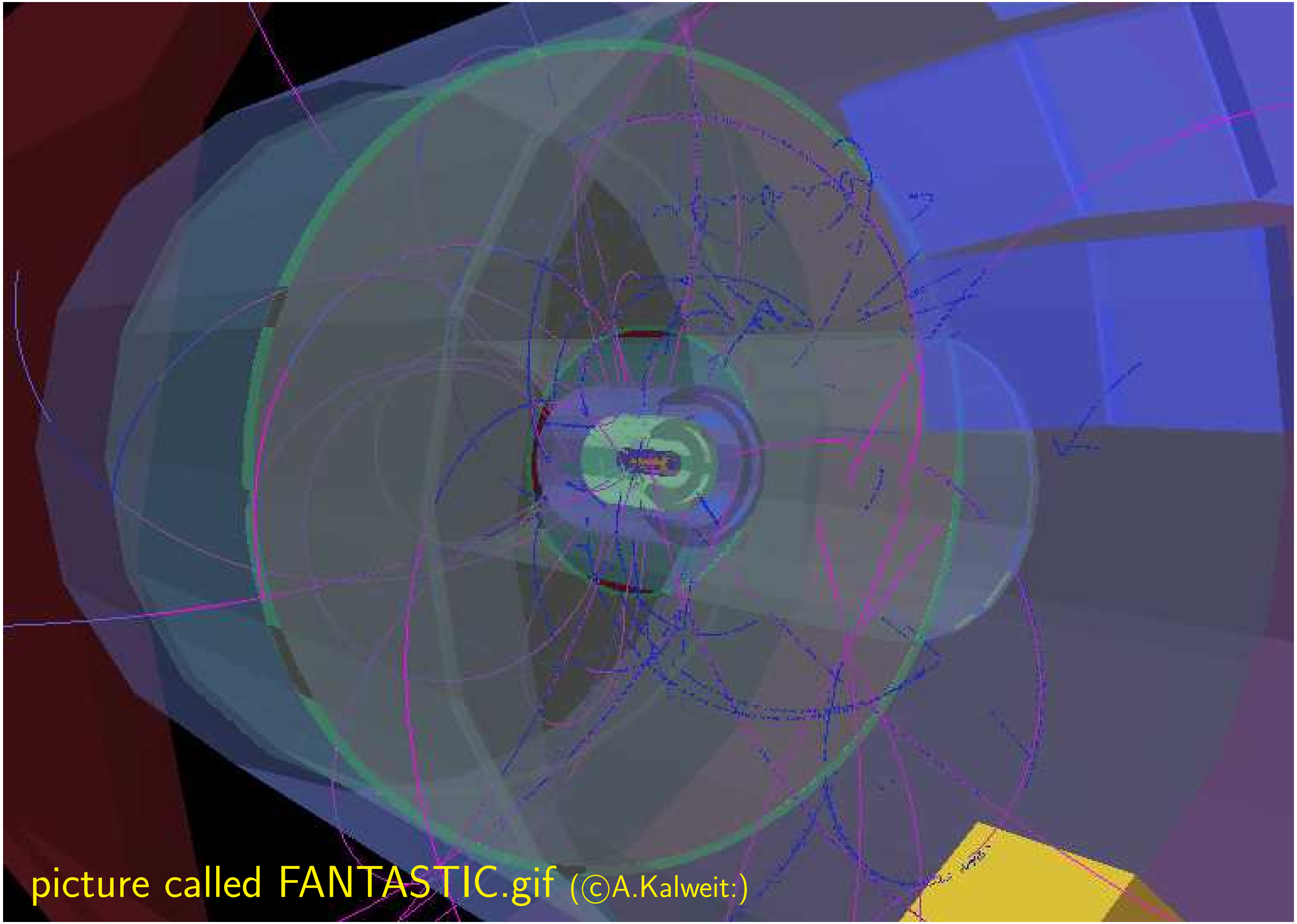
...and the last flavor

“getting hands dirty” ...by doing (transition radiation) detectors

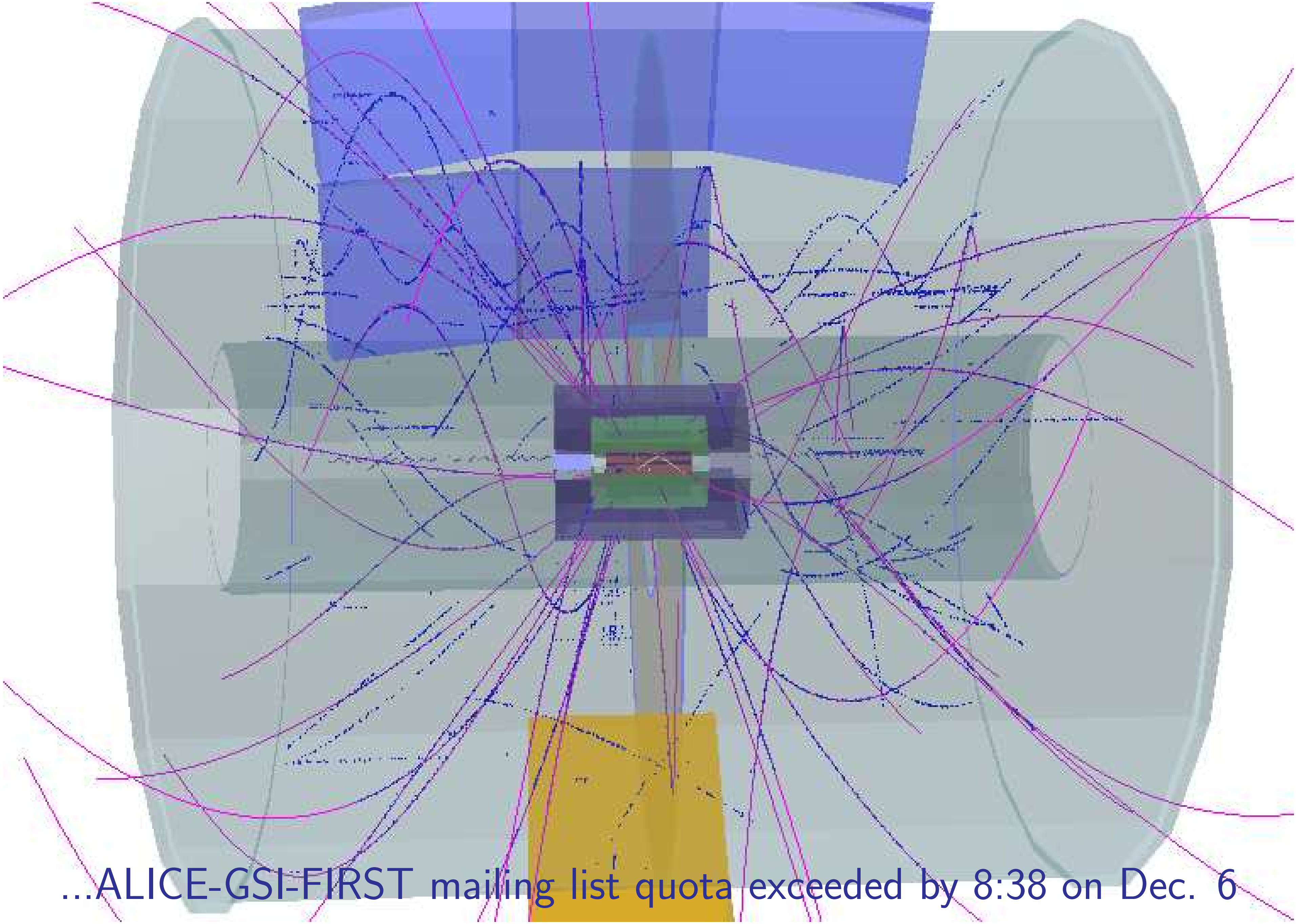
The 3rd “transition” in Johanna’s scientific career (she’s its Project Leader)

GSI, Dec. 2008 (chamber completion)

First events (Sun, 6 Dec 2009 08:05)

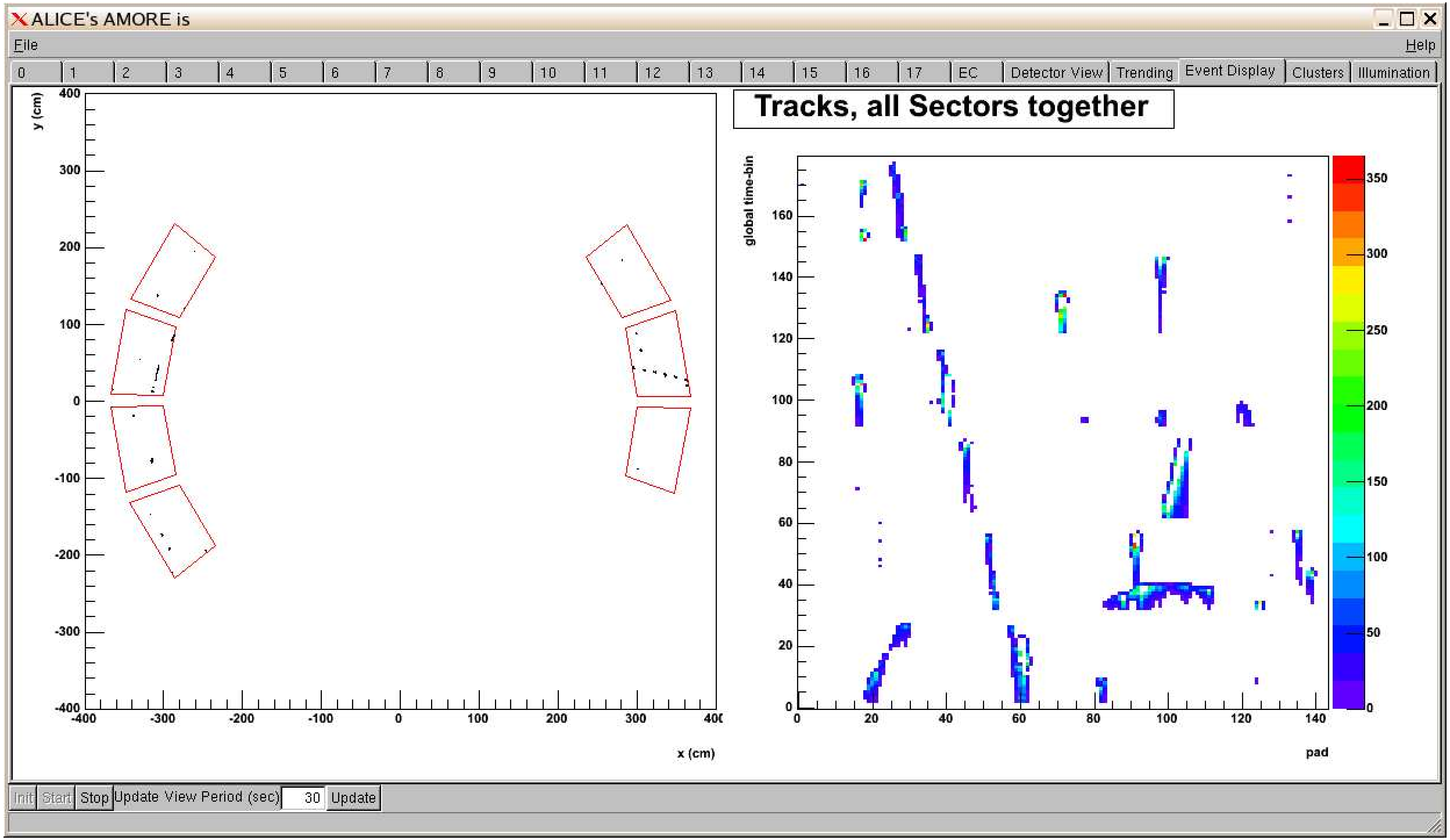


Another Fantastic event (Mail subject, Sun, 6 Dec 2009 08:38)



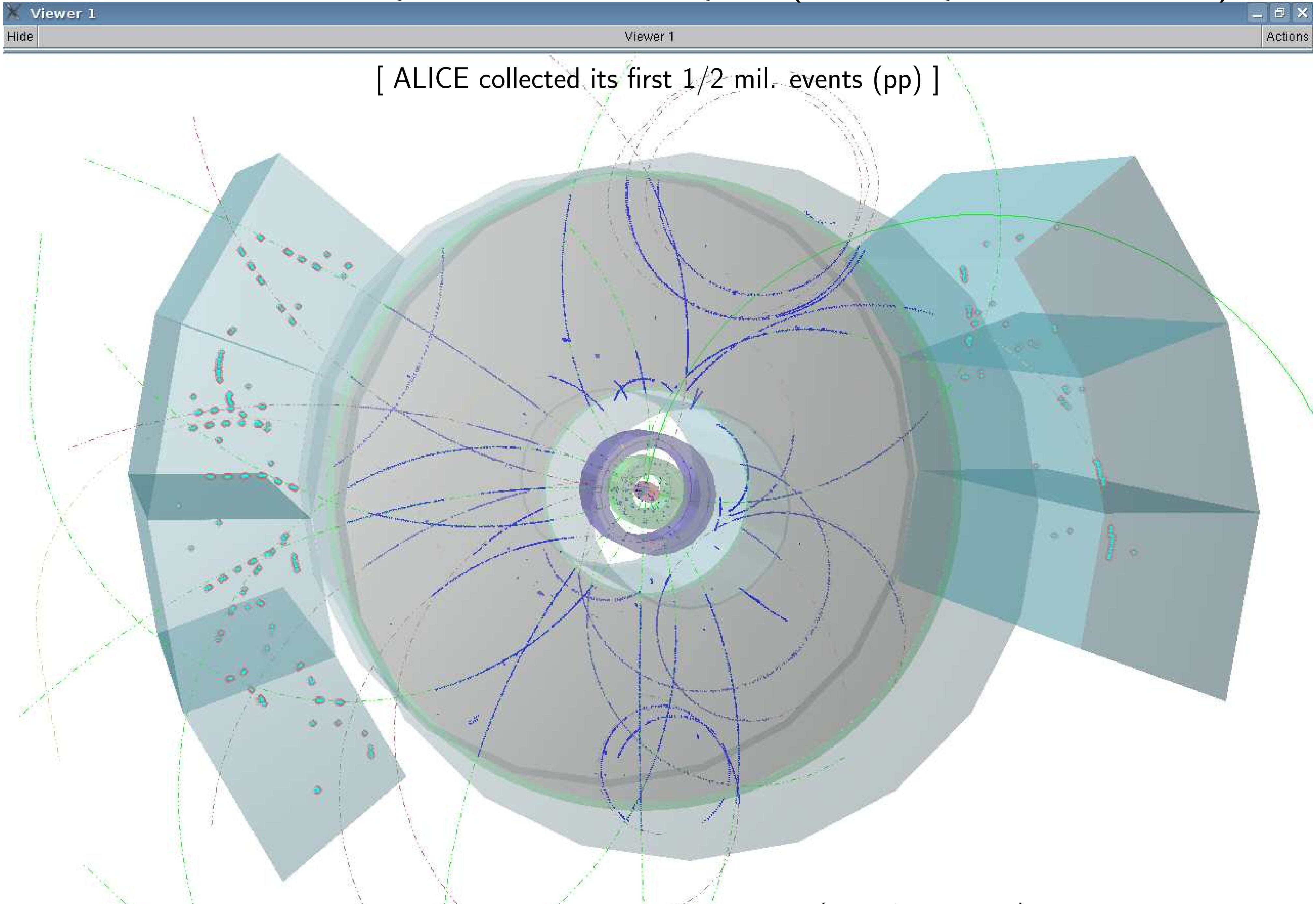
...ALICE-GSI-FIRST mailing list quota exceeded by 8:38 on Dec. 6

Transition Radiation Detector (Sun, 6 Dec 2009 08:53)



Johanna's energy pushed it through LoI, Sept. 1998; TDR, Oct. 2001; completion, Dec. 2014

"It has been a truly remakable 24 days." (Steve Myers, 18.12.2009)



for me, it's been a truly remarkable last 17 years of working together (exp. & phenom.) ...thank you, Johanna!

Backup slides

Volume in central collisions

x0

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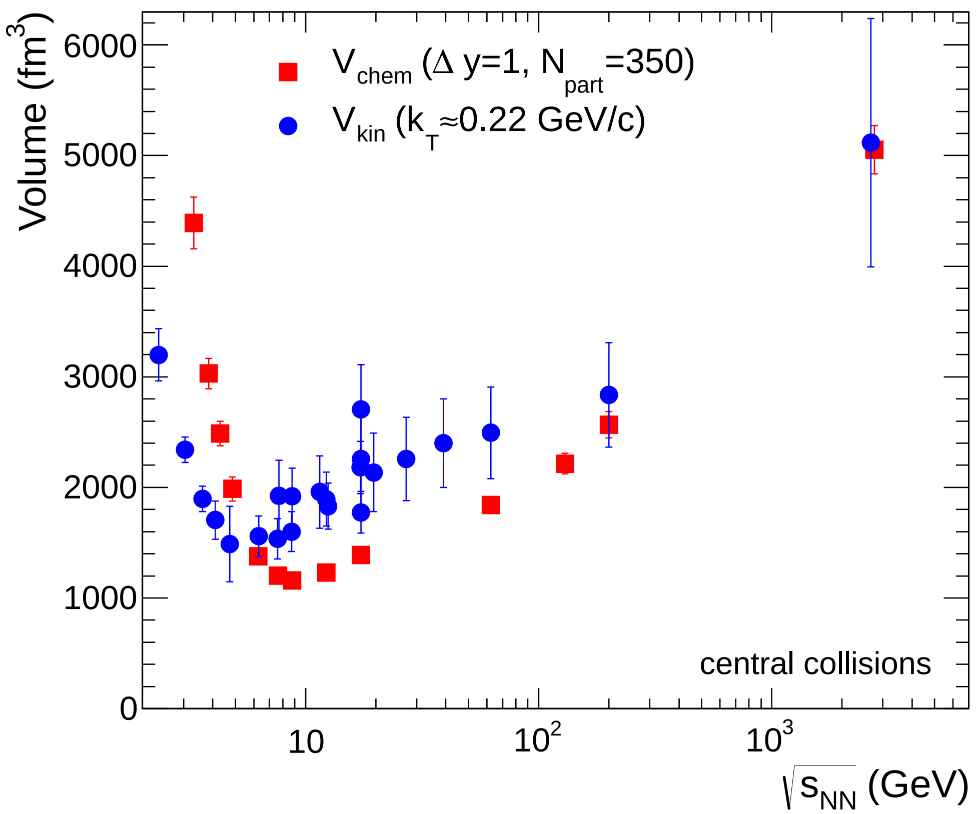
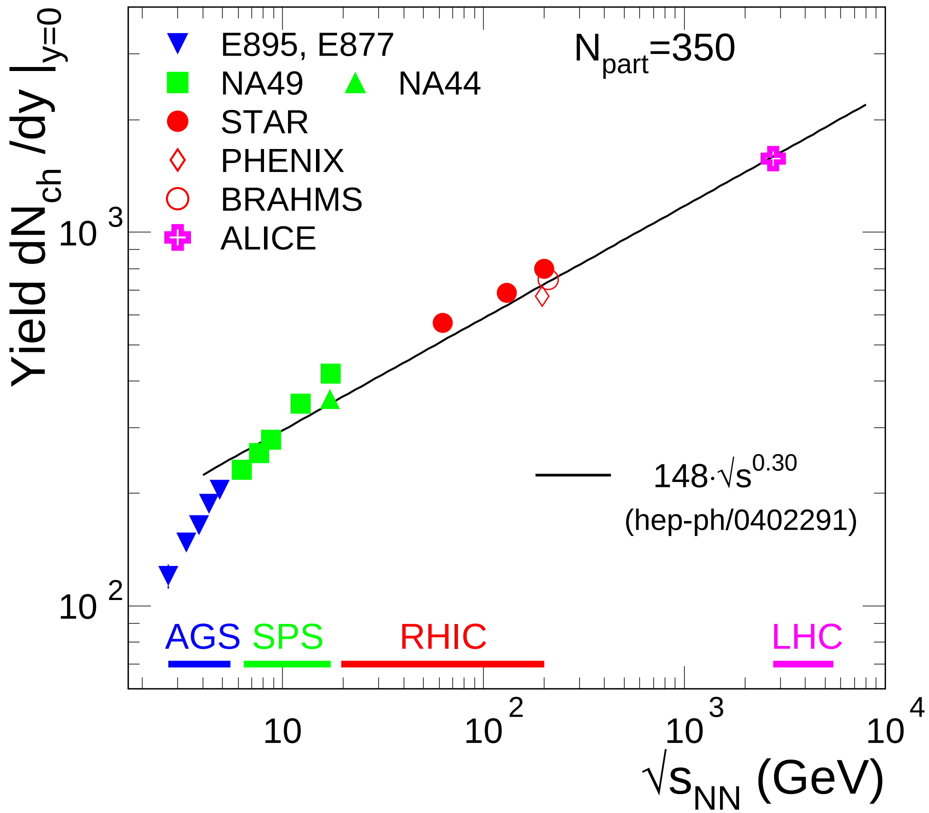
$$V_{chem}(\Delta y=1) = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$





$$V_{kin} = V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$$

HBT data: ALICE, PLB 696, 328 (2011)

5.1 TeV: $V = 6400$ fm^3

40 TeV: $V = 12000$ fm^3 (2.2x $V_{2.76}$)

Charmonium data at RHIC and the LHC

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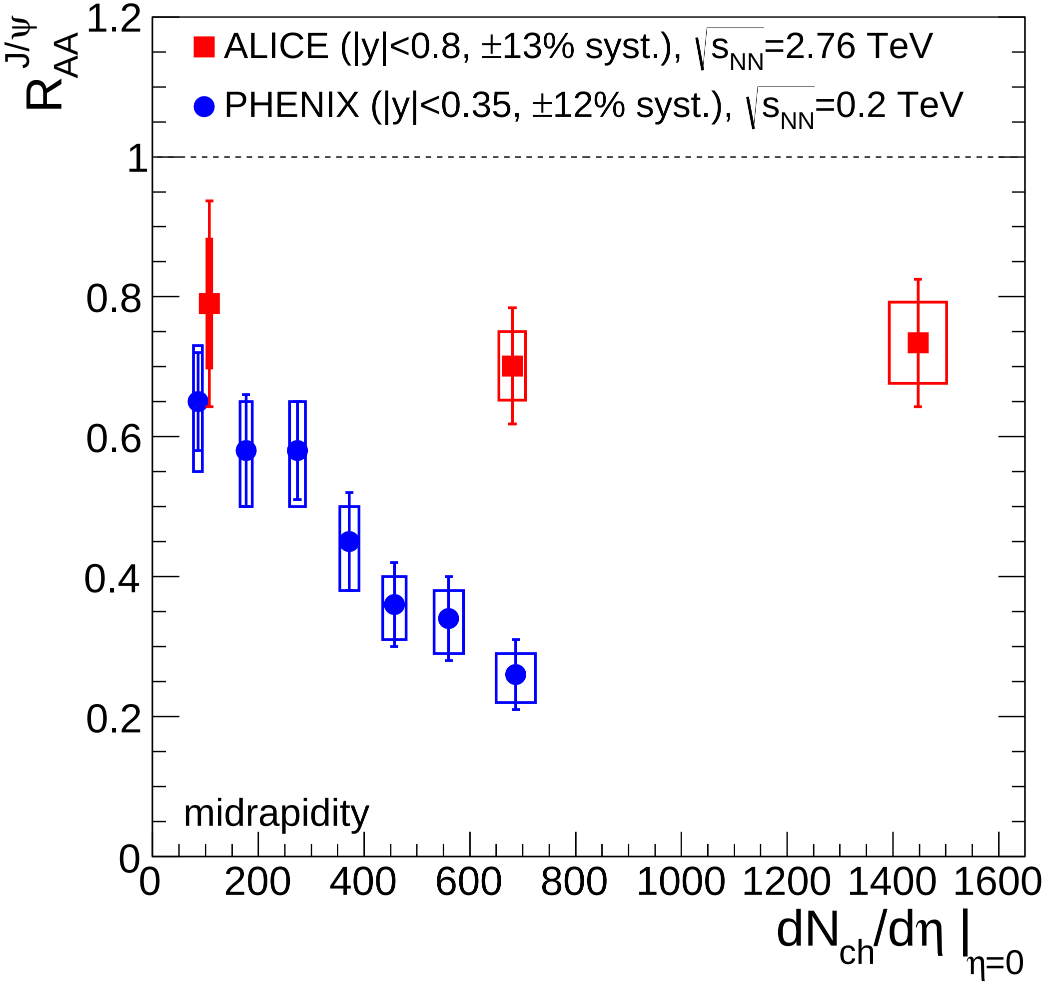
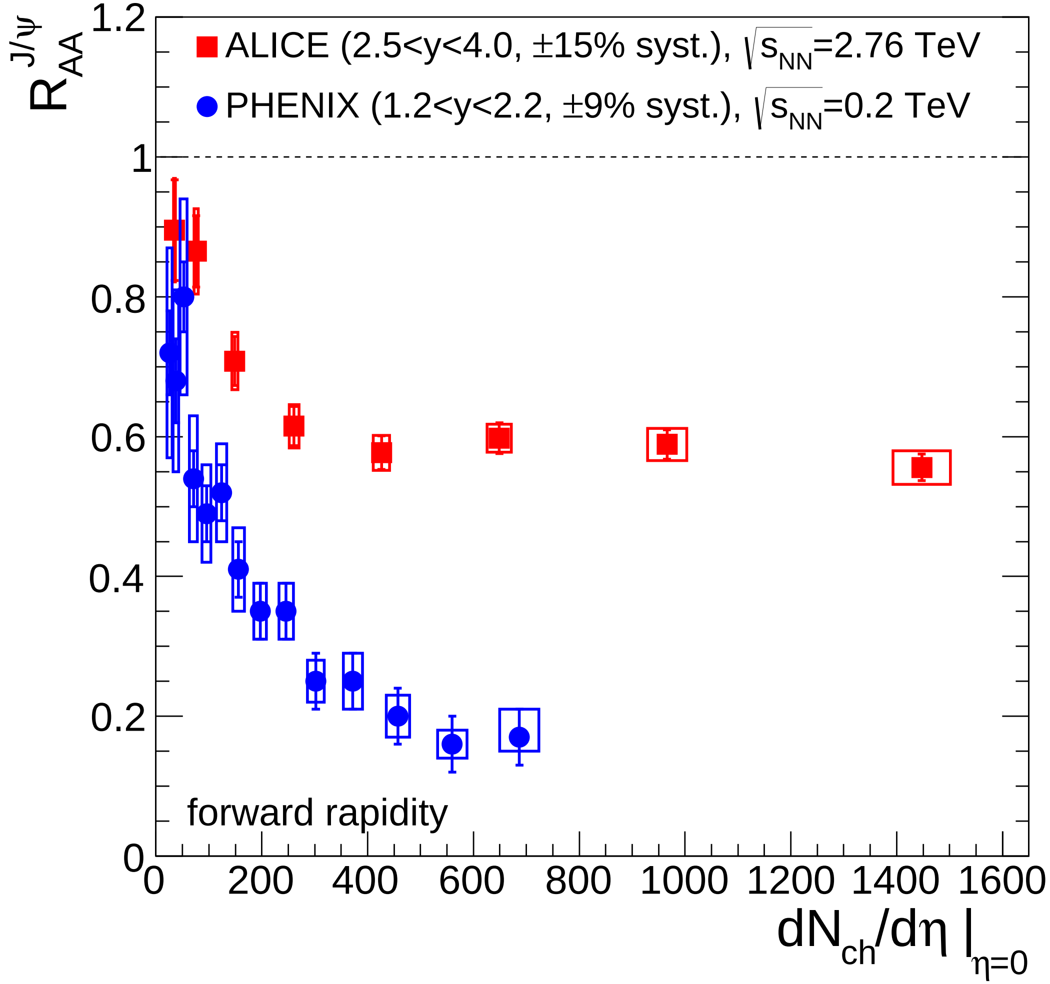
midrapidity



forward rapidity



$$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$$

J/ψ at RHIC, lower energies

x2

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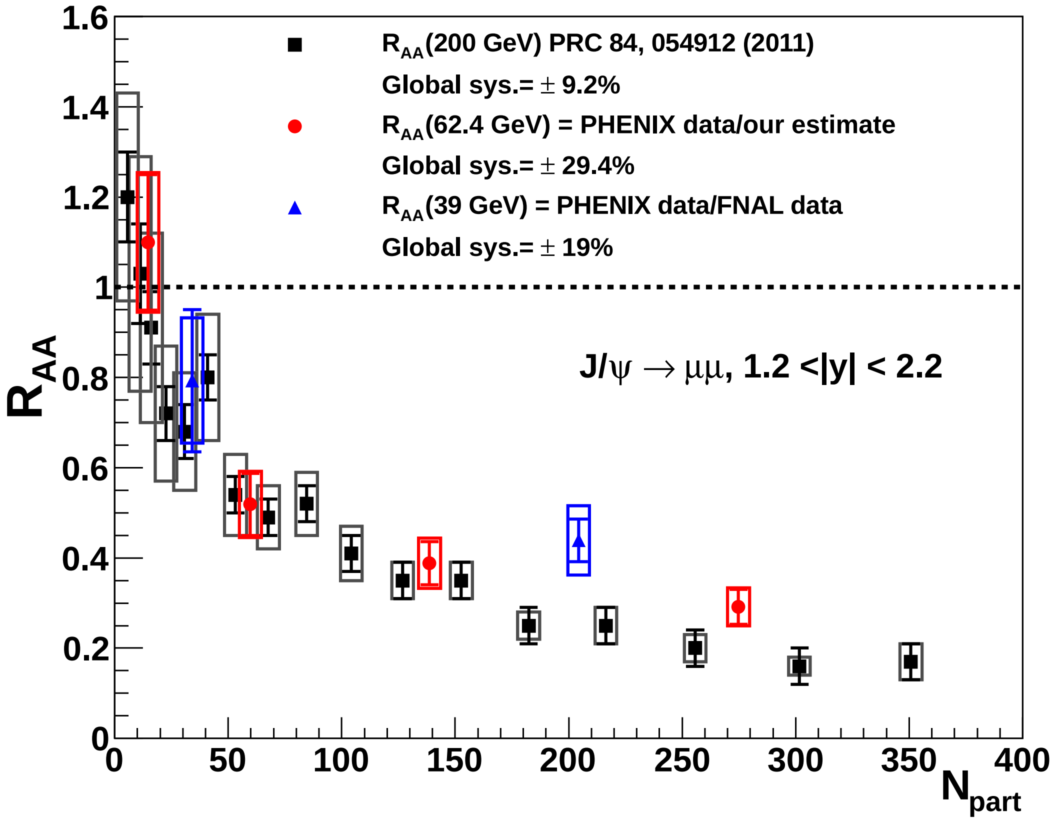
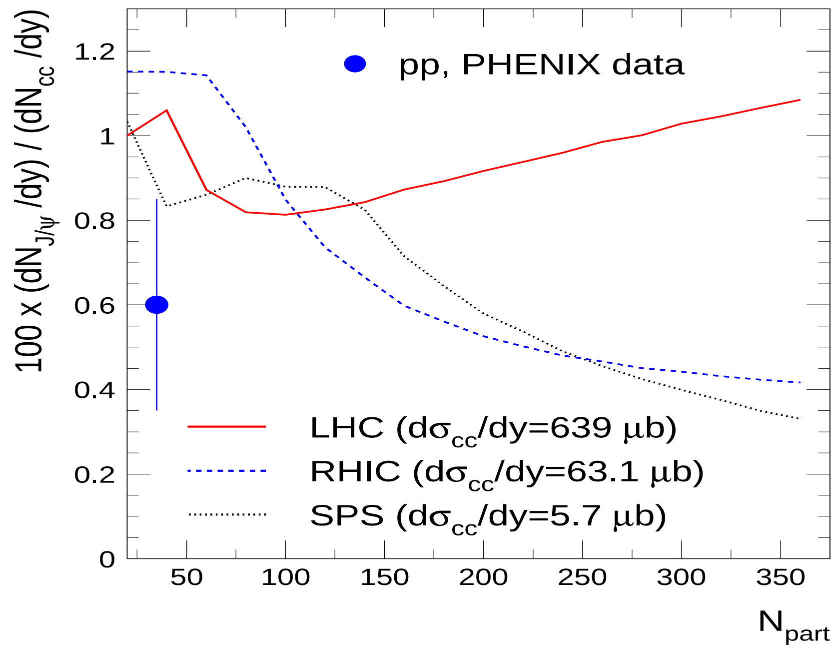


PHENIX, PRC 86 (2012) 064901

...not much "action"

seen already with the SPS data

...and "seen" in the stat. hadr. model



AA et al., NPA 789 (2007) 334

...and in transport models (TAMU)

J/ψ production relative to charm

x3

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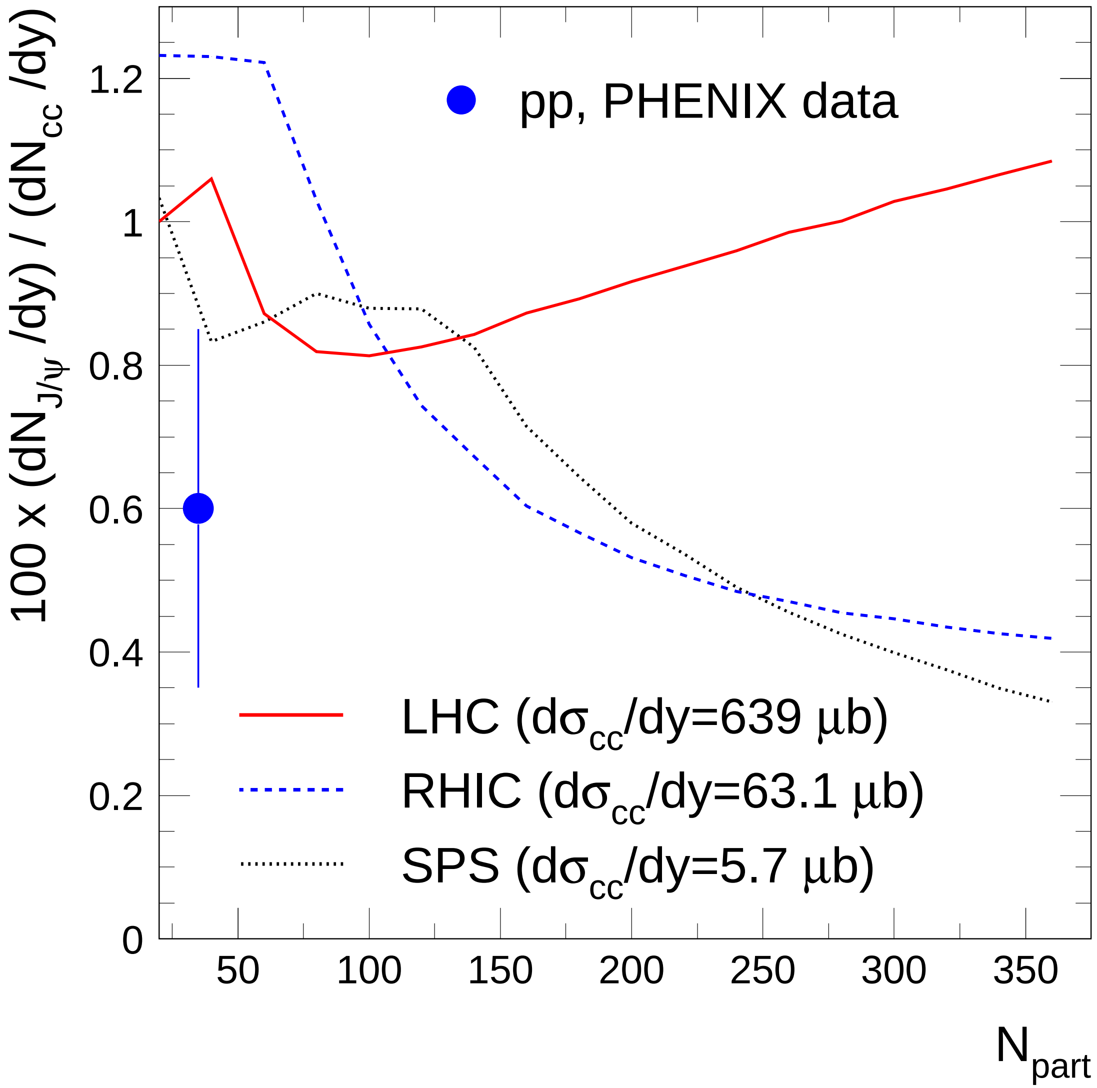
...the most "solid" observable ...with similar features as R_{AA}



AA, PBM, JS, NPA 789 (2007) 334

Satz, Adv.HEP 2013 (2013) 242918

- similar values at RHIC and SPS

  ...with differences in fine details

  ...determined by canonical suppression of open charm

  same with Υ at RHIC and LHC?

- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

J/ψ flow

x4

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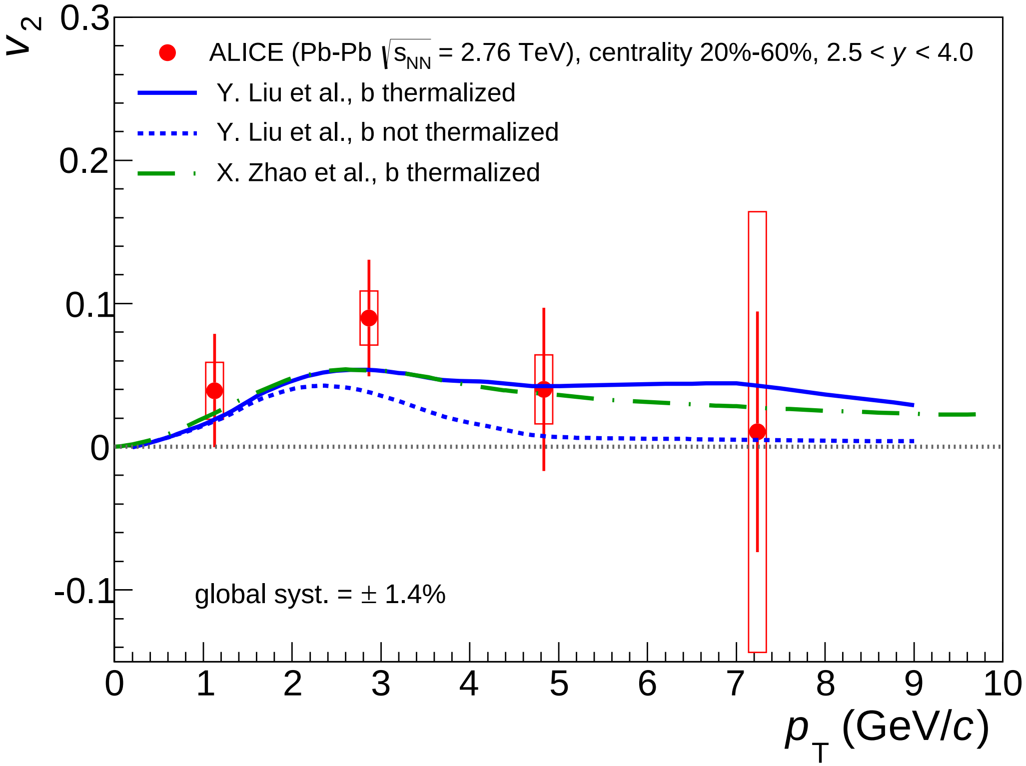
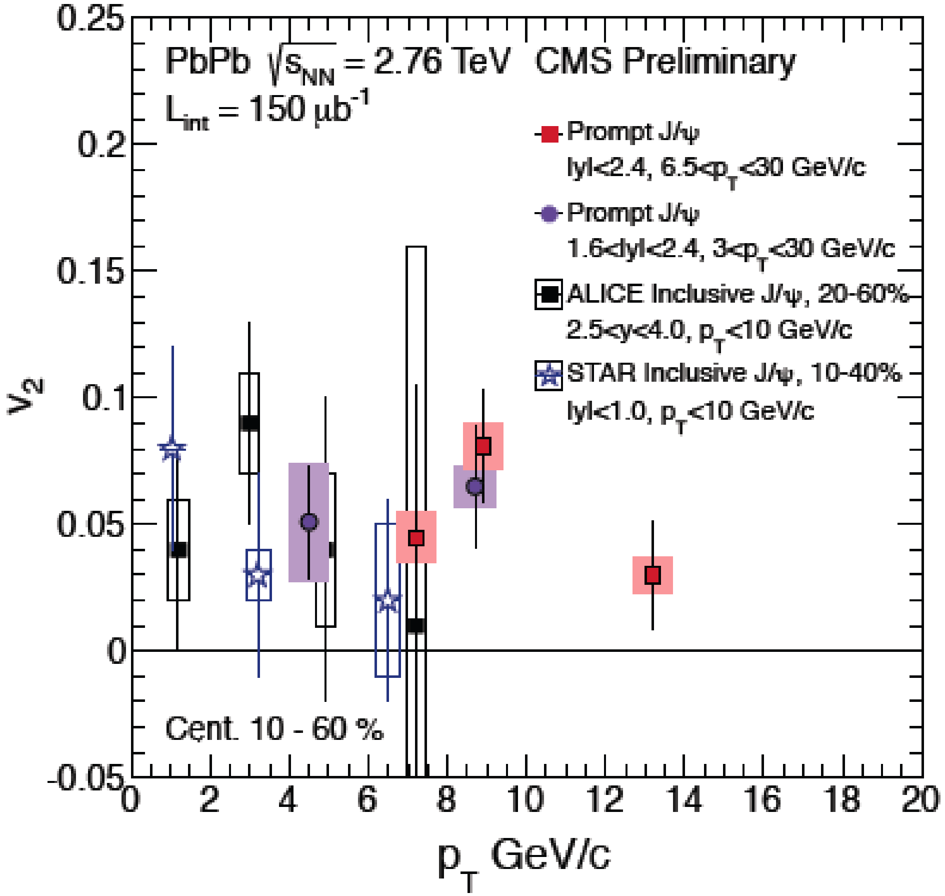
ALICE, PRL 111 (2013) 162301



CMS (Moon, QM'14)



further support of production in QGP or at chemical freeze-out at the LHC

(requiring thermalization of $c, \bar{c}$ and generically leading to flow)

Recall: non-zero v_2 was measured at SPS ("leakage effect")

...the RHIC case (STAR, $v_2 \sim 0$) remains open ...upcoming data will settle it

J/ψ at RHIC: rapidity dependence, R_{AA}

x5

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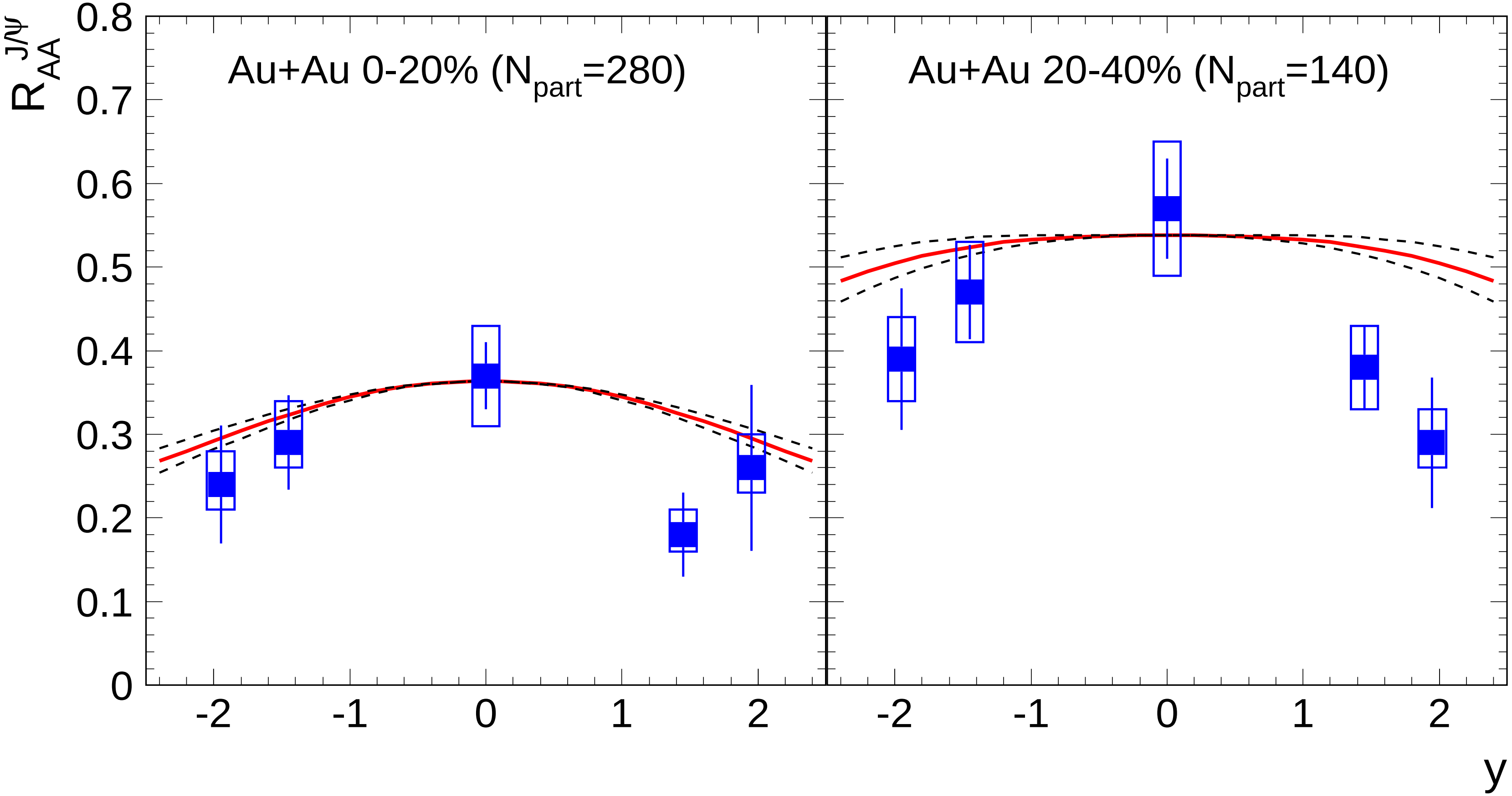

model reproduces data (PHENIX, nucl-ex/0611020) very well (pQCD $\sigma_{c\bar{c}}$)

direct indication of J/ψ generation at hadronization (enhanced at y=0)

(constant R_{AA} expected within Debye screening model)

PLB 652 (2007) 259

J/ψ at RHIC: effect of shadowing

x6

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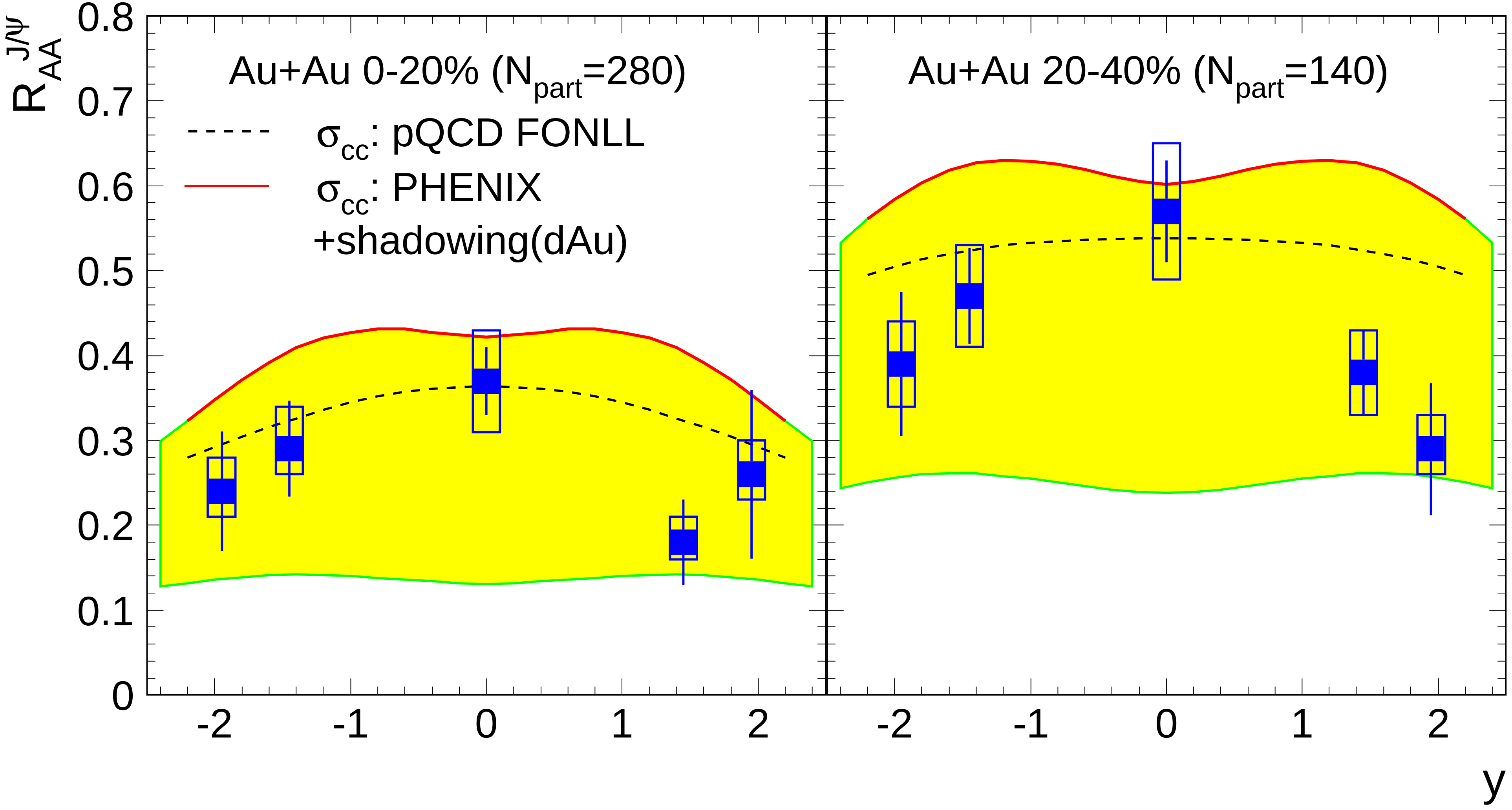

model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

JPG 35 (2008) 104155

The "null hypothesis"

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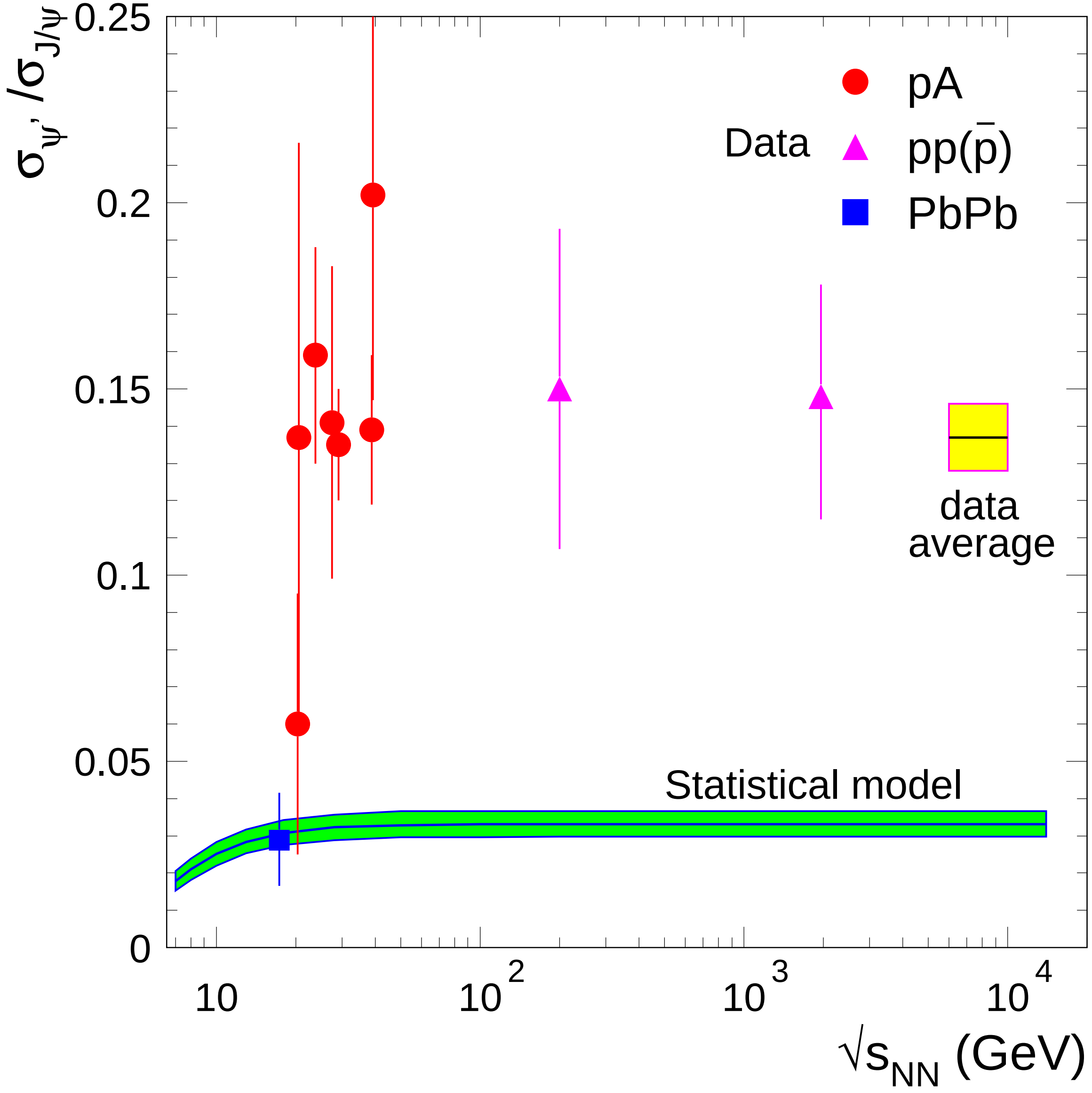

charmonium in pp(A) collisions

...is far from thermalized
(model is for AA)

...while a thermal value is reached in central PbPb (NA50, SPS)

PLB 678 (2009) 350

The "null hypothesis" for bottomonium

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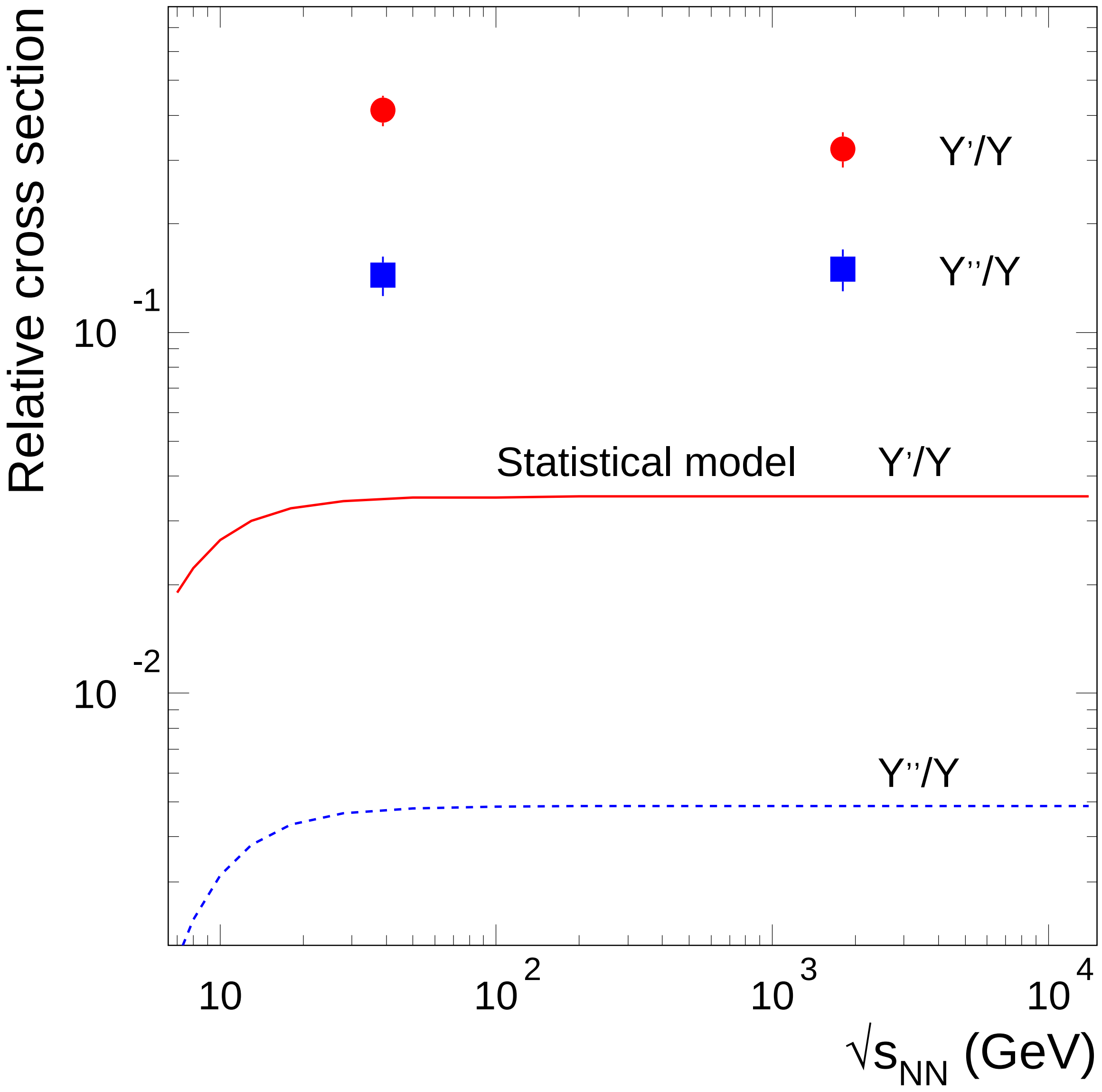

bottonium in pp(A) collisions

...is far from thermalized (model is for AA)

...will we find a thermal value at LHC? ...it seem to look so

PLB 678 (2009) 350

Charmonium ratios in p(d)-A collisions

x8

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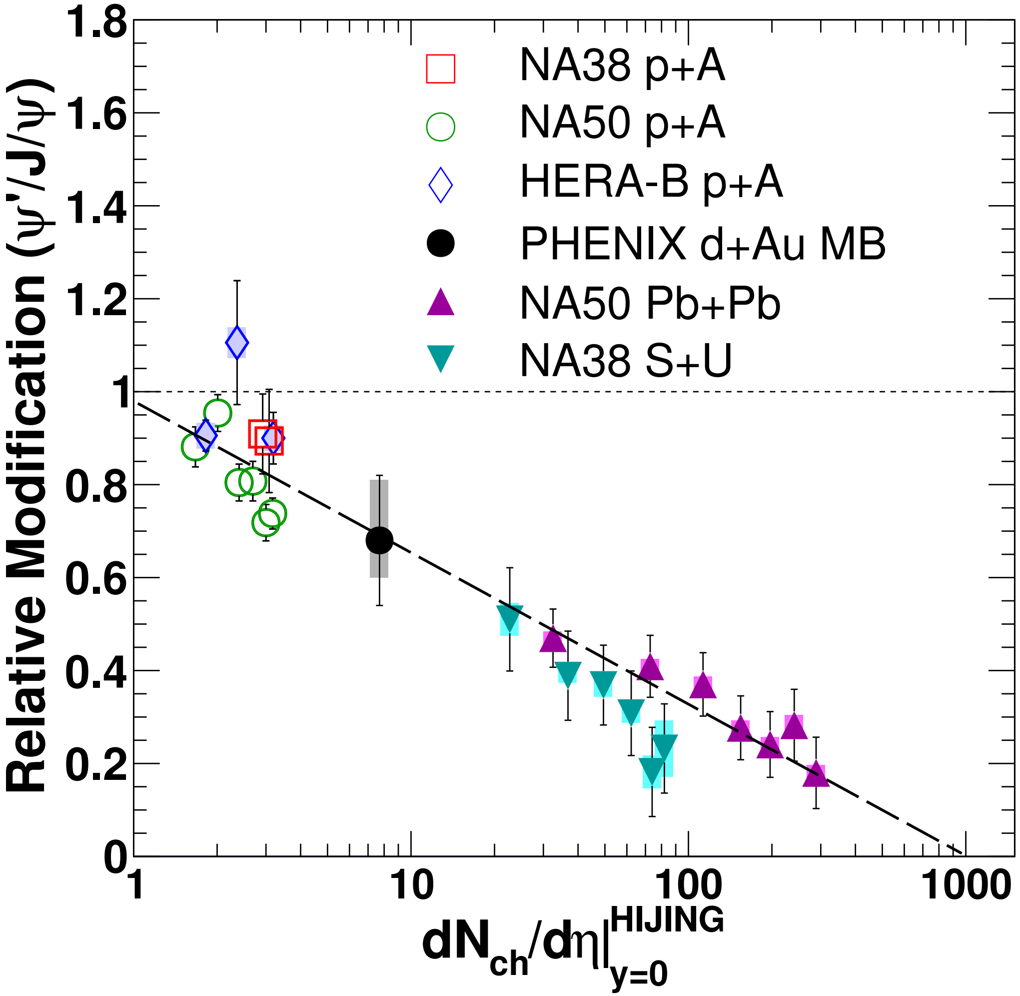
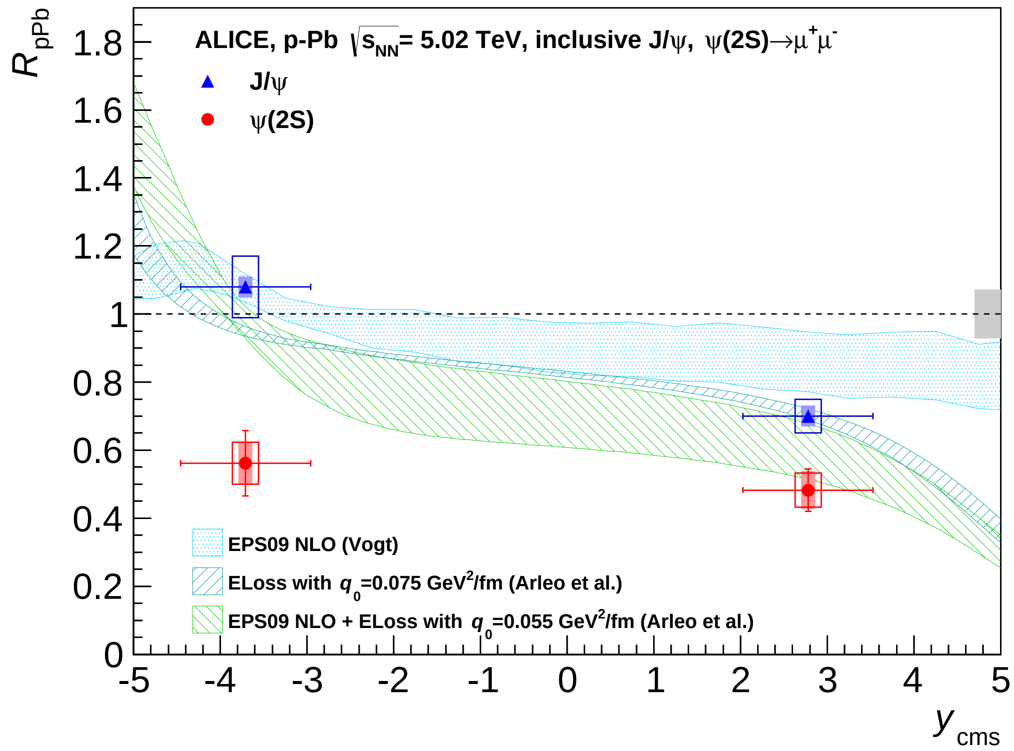
PHENIX, PRL 111 (2013) 202301



ALICE, arXiv:1405.3796



abs. cross sect. depends on time spent in the nucleus

(McGlinchey et al., PRC 87 (2013) 054910)

at the LHC, the strong $\psi(2S)$ suppression in Pb-side remains puzzling

indication for final-state effects?

Bottomonium in p–Pb collisions

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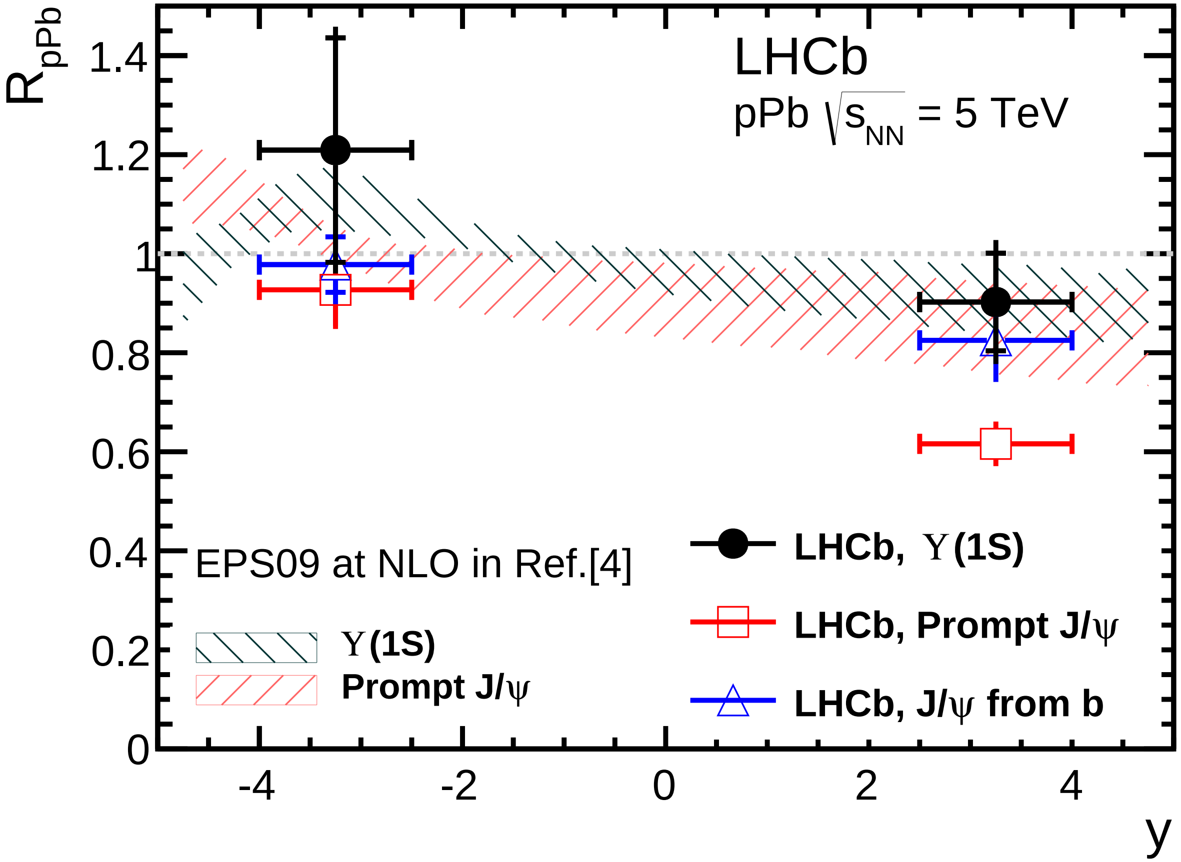

LHCb, JHEP 1407 (2014) 094