Statistical hadronization of heavy quarks

...and some facts on charmonium in pp/pPb

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Abstract

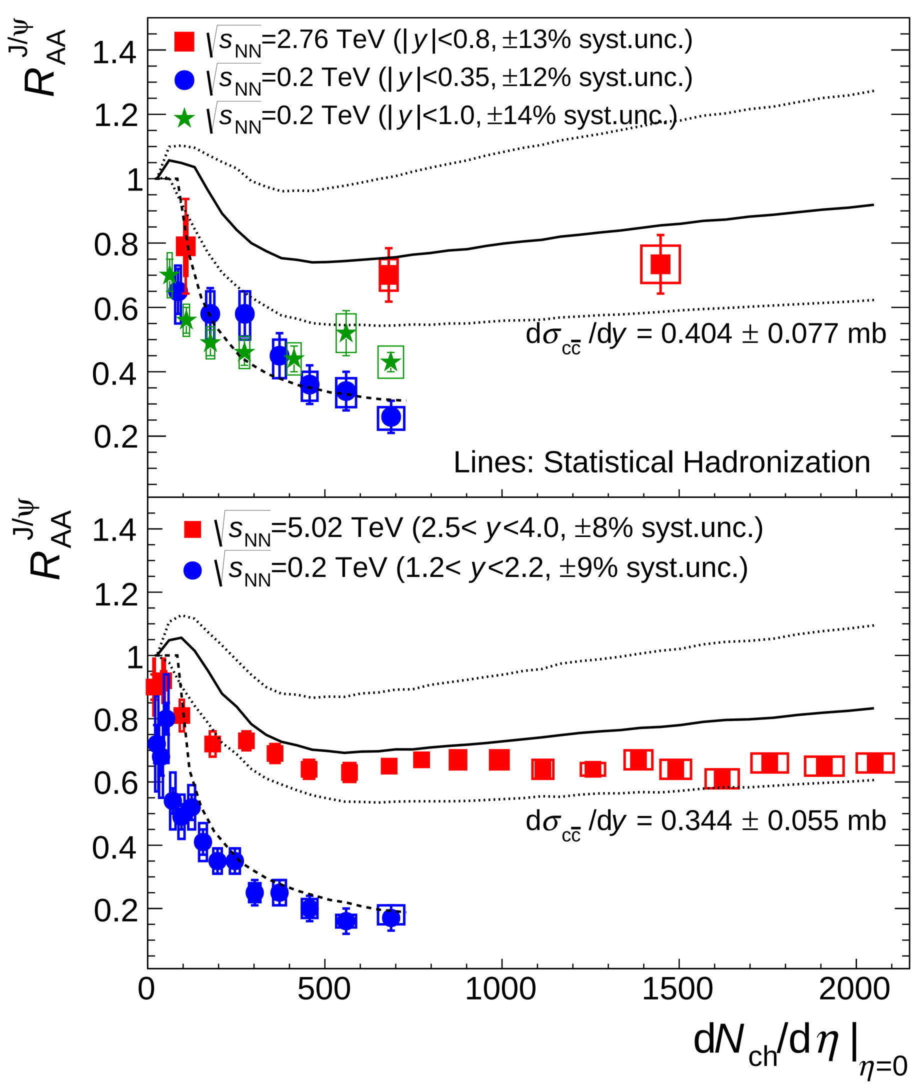
Production of hadrons in nucleus-nucleus collisions exhibits in its bulk aspects clear statistical features, over a broad range of collision energy. At the LHC production of heavy-quark hadrons, and in particular charmonium, also exhibits statistical features, indicating hadronization at the QCD phase (crossover) boundary. I discuss these aspects and add in the mix remarks on production in pp (and pA) collisions as a function of the event multiplicity.

Introduction

Quarkonium production in Pb–Pb collisions is a prominent probe for QGP, where color screening hinders formation. One (the?) most-significant of the discoveries at the LHC (2011, $\mu^+\mu^-$) was that (re)generation of J/ψ mesons is a dominat production mechanism.

(Re)generation could happen either throughout the QGP phase (hence the "re" particle) or is a production ("generation") at the QCD (crossover) phase boundary, this latter mechanism being addressed in the Statistical Hadronization Model (SHM) [2]. In fact, SHM predicted the significant increase of $R_{AA}^{J/\psi}$ from RHIC to the LHC, which was impressively confirmed by the LHC data [1].

Largest uncertainty in the model : the $c\bar{c}$ production cross section.



Statistical hadronization of heavy quarks

Assumptions:

- 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)
  this was in the early years debated, but now we do see large flow of charm (D, J/ψ)
- 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, at LHC T=156.5±1.5 MeV.
  ...based on statistical hadronization in the light-quark sector and Lattice QCD predictions
- no J/ψ survival in QGP (full screening)

  can J/ψ survive above T_c? ...yet to be fully settled (LQCD: rather yes, up to about 1.7T_c)

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.

Method and inputs:

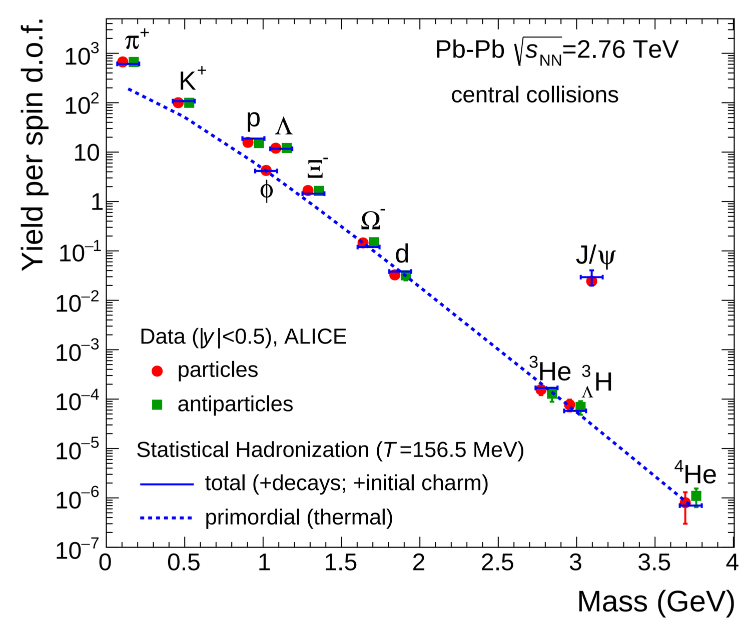
- Thermal model calculation (grand canonical) T, μ_B: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$

$\rightarrow g_c$ (charm fugacity)

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

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

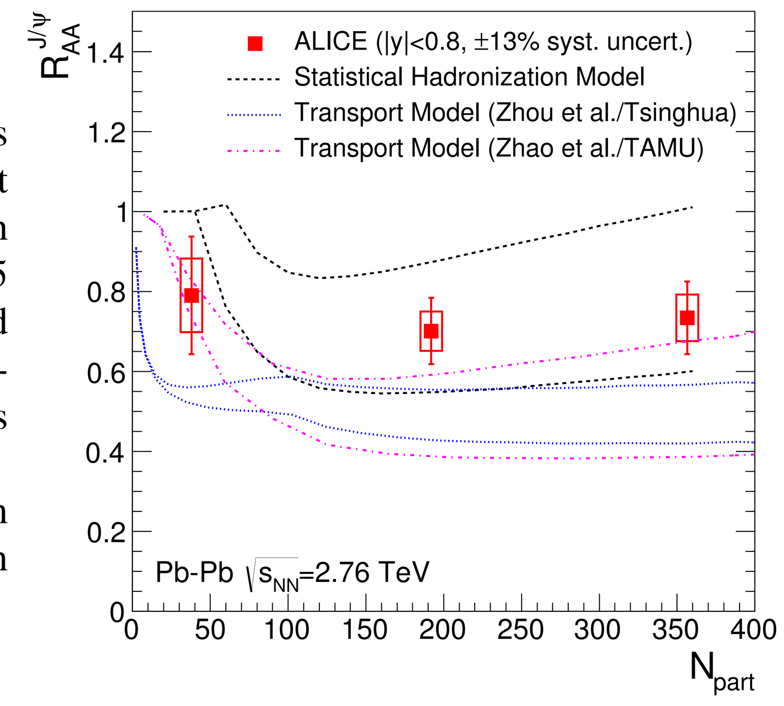
$V_{\Delta y=1} \simeq$5000 fm^3 (0-10% centr.) at the LHC.
(minimal volume for QGP: V_{QGP}^{min}=200 fm^3)
Corona contribution considered.

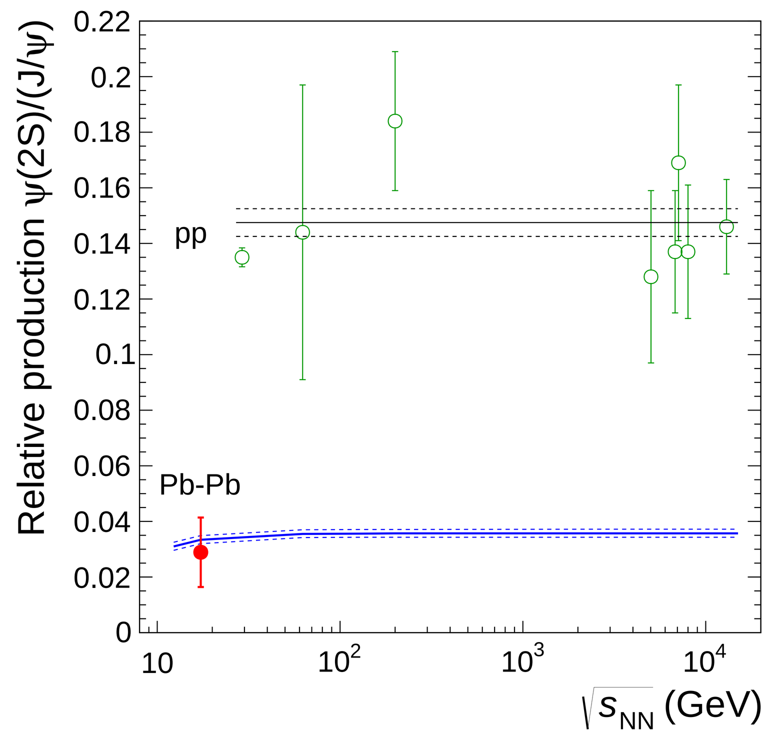


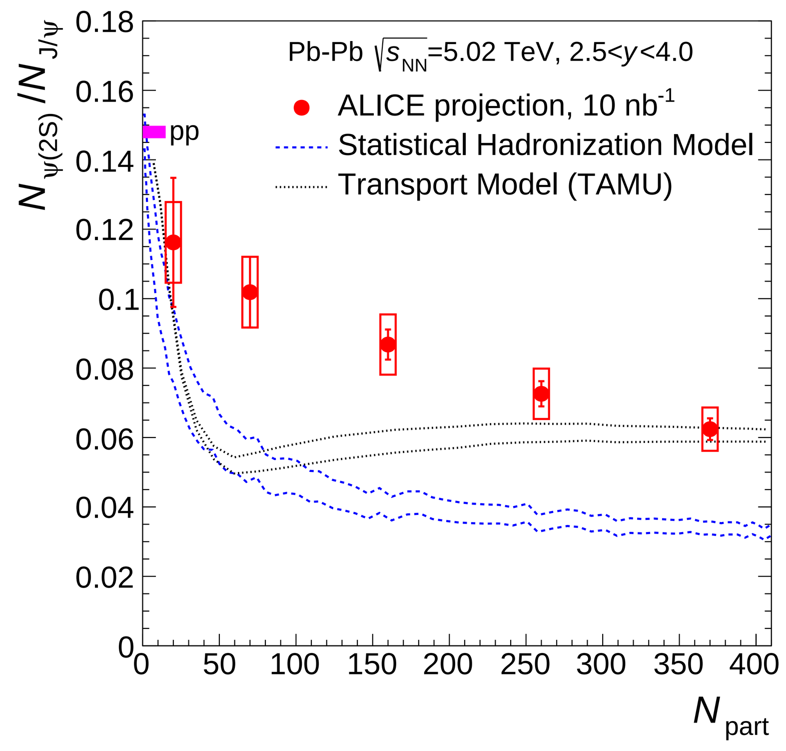
The dilemma

Can I declare victory and add J/ψ as the qualitatively-new observable of the QCD phase boundary?

Yes, but...
Not only SHM is successful, transport models (TM) also describe the data well (predicted that (re)generation is predominant at low-p_T) ...but with $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different (Transport: 0.5-0.75 mb TAMU; 0.65-0.8 mb Tsinghua). This is in need of clarification, it is not possible that the two approaches give quasi-identical results (one model is the full-equilibrium limit of the other).
A way forward: measure $\psi(2S)$ production (data in HI collisions are very scarce to date); envisaged in Run 3,4 at the LHC with the ALICE detector.



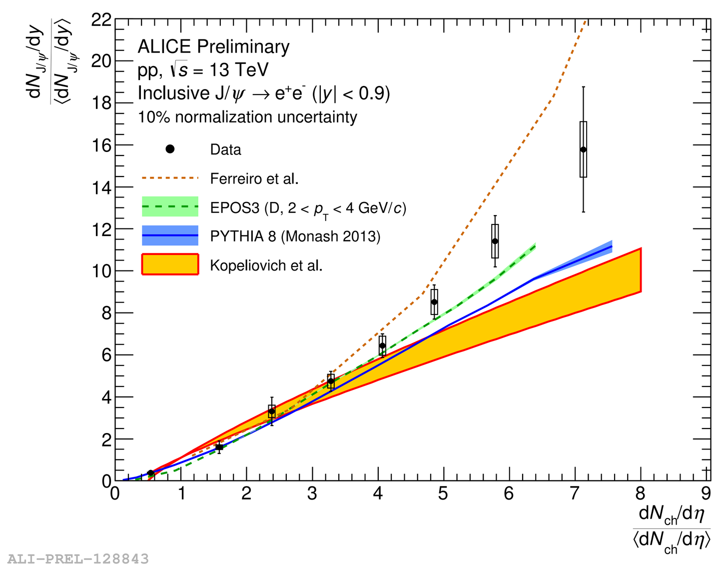


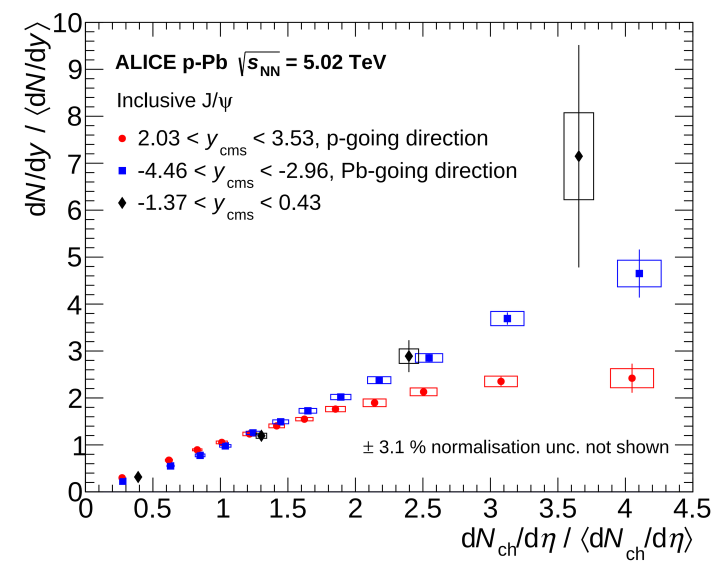


Charmonium family has the great appeal, alongside the bottomonium, to help determining the QCD heavy-quark potential [3].

Charmonium in high-multiplicity pp/pPb events

A strong relative increase in production is seen experimentally vs. event multiplicity in pp and p–Pb collisions. For pp, various models (too various?) describe the trend, quasi-quantitatively.





We hope to learn (significantly?) from such measurements about quarkonium production (hadronization). One other fact in the mix: $v_2 > 0$ was measured in high-mult. p–Pb events.

References

[1] Betty Bezverkhny Abelev et al. Centrality, rapidity and transverse momentum dependence of J/ψ suppression in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. *Phys. Lett.*, B734:314–327, 2014.

[2] Anton Andronic, Peter Braun-Munzinger, Krzysztof Redlich, and Johanna Stachel. Decoding the phase structure of QCD via particle production at high energy. *Nature*, 561(7723):321–330, 2018.

[3] Xiaojian Du, Shuai Y. F. Liu, and Ralf Rapp. Extraction of the Heavy-Quark Potential from Bottomonium Observables in Heavy-Ion Collisions. *Phys. Lett.*, B796:20–25, 2019.