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# Calibrating the In-Medium Behavior of Quarkonia


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**general:**

**Use in-medium charmonium behavior to probe quark-gluon plasma**

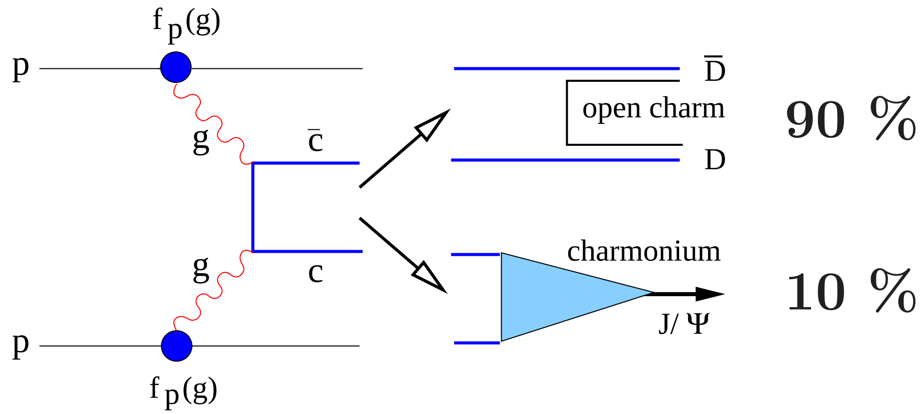
**specific:**

**Use charmonium production in nuclear collisions to probe QGP formation**

**basis:**

**Presence of produced medium modifies $c\bar{c}$ binding to charmonia**

**charmonium production in $pp$ collisions**




**$c\bar{c}$ production: PDF's $f_p(g)$ + perturbative QCD**

**$J/\psi$ binding ? ...CEM, CSM, COM, ...**

**color evaporation "works"**

$$\sigma_{hh \to J/\psi}(s) = g_{c\bar{c} \to J/\psi}\, \sigma_{hh \to c\bar{c}}(s),$$

**partitioning of $c\bar{c}$ cake among eaters is energy-independent**

**Further consequence: energy-independent feed-down fractions**

**$J/\psi$ measured in $pp$ collisions is approximately**

**60 % direct $J/\psi$(1S), 30 % $\chi_c$(1P) & 10 % $\psi'$ (2S)feed-down**

**narrow resonances $\longrightarrow$ decay outside interaction region**

**medium sees traversal of higher resonances**

- **crucial question:**

**are these features**

**(hidden/open, relative quarkonium fractions)**

**changed in nuclear collisions?**

**NB:**

**the production dynamics in $AA$ collisions is different from that in $pp$ collisions !**

## modifications in nuclear collisions:

- **initial state effects**

  **pdf modification (shadowing, antishadowing)**

  **energy loss of incident parton (gluon)**

- **final state effects**

  **energy loss of primary $c\bar{c}$**

  **cold nuclear matter effect on (nascent) charmonium**

  **secondary matter effect on (nascent) charmonium**

## previous analysis procedure:

- **measure production in $pp$ and $pA$**

  **determine pdf modification (shadowing, antishadowing)**

  **determine parton energy loss**

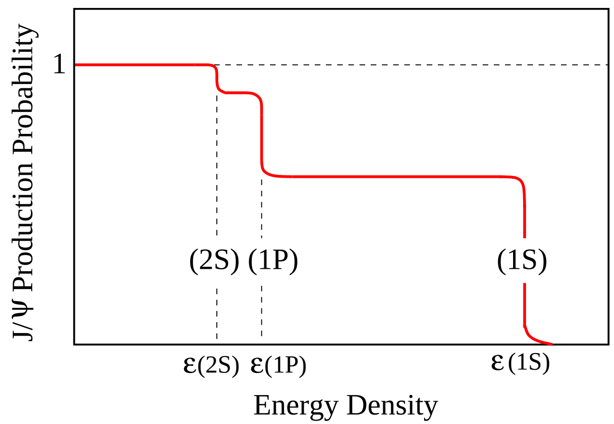
  **determine cold nuclear matter effect**

- construct model for $AA$
  - scale $pp$ by number of collisions
  - incorporate initial & cnm final state modifications
- compare to $AA$ data: is there *anomalous behavior?*
  i.e., something not accounted for by model $\longrightarrow$ **inconclusive**

## Theoretical Scenarios

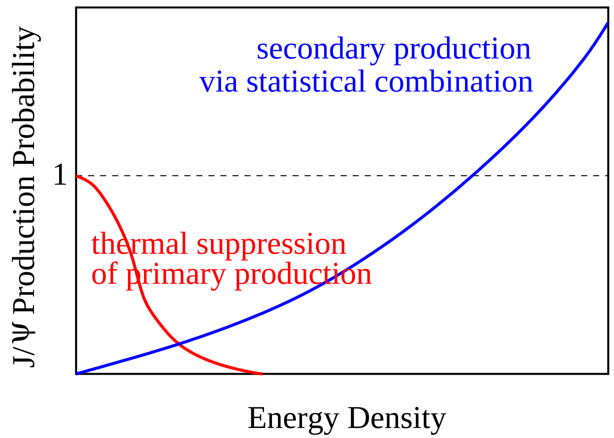
- sequential suppression

  color screening dissociates charmonium states in QGP first higher excited states (2S), (1P), then ground state (1S)



- <u>statistical enhancement</u>

  all primary charmonia dissociated
  at high collision energy,
  overabundance of charm quarks
  equilibration, $c\bar{c}$ excess survives
  hadronisation by statistical
  combination




## <u>How to calibrate $J/\psi$ survival probability?</u>

both scenarios claim that presence of medium modifies the relative fraction of $c\bar{c}$ going into charmonia

neither says anything about how many $c\bar{c}$ pairs are produced in $AA$ relative to scaled $pp$

more explicitly:

if the total number of $c\bar{c}$ pairs produced in $AA$ collisions is reduced by a factor two relative to scaled $pp$ rates, but as before, 90 % go into open charm, 10 % into charmonia (with same distribution among states), then

- the medium formed in $AA$ collisions leads neither to suppression nor to enhancement of $J/\psi$ production;
- the crucial question is what happens to the produced $c\bar{c}$ pairs, not how many there are to begin with; the medium can only affect those that are there.
- the quantity

$$R_{AA}(J/\psi) = \frac{N_{AA}(J/\psi)}{n_c N_{pp}(J/\psi)}$$

is reduced by a factor two.

**Conclude:**

**the correct calibration is hidden to open charm, so that the relevant observable is**

$$S_{J/\psi} = \left(\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})}\right) \Big/ \left(\frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})}\right) = \frac{1}{g_{c\bar{c}\to J/\psi}} \left(\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})}\right)$$

**In the observable**

$$N_{AA}(J/\psi)/N_{AA}(c\bar{c}),$$

**if measured over all phase space, initial state effects cancel out, and one can check if the result is different from**

$$N_{pp}(J/\psi)/N_{pp}(c\bar{c}) = g_{c\bar{c}\to J/\psi}.$$

**i.e., if the medium has had an effect on charmonium binding.**

**NB: the often used observable $R_{AA}(J/\psi)$ alone**
**is at best inconclusive, at worst misleading**

**need to compare hidden to open charm,**
**so must compare $R_{AA}(J/\psi)$ to $R_{AA}(c\bar{c})$;**
**if they are equal: neither suppression nor enhancement**

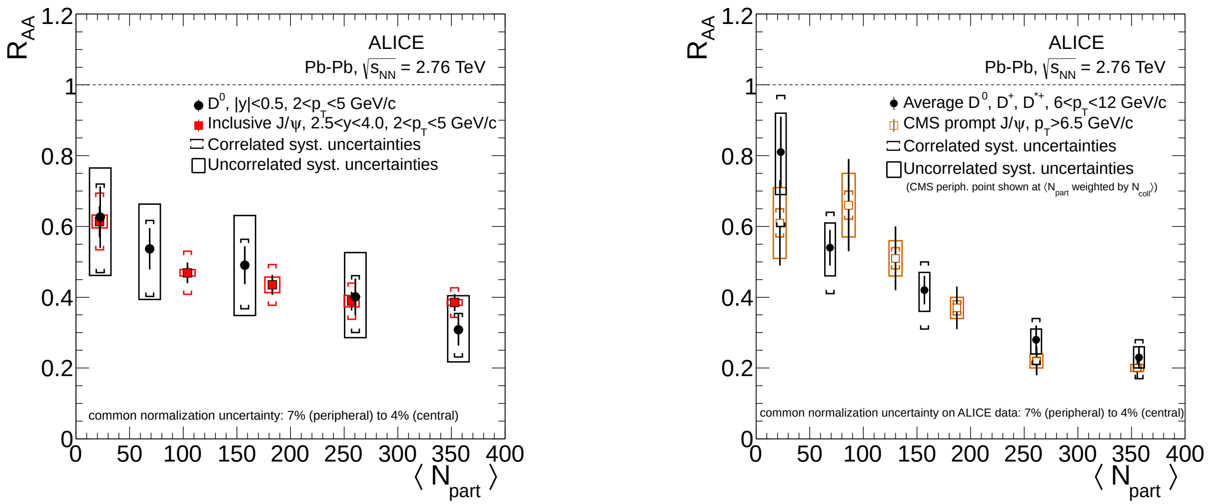
**specifically, use double ratio**

$$\frac{R_{AA}(J/\psi)}{R_{AA}(c\bar{c})} = \frac{N_{AA}(J/\psi)}{n_c N_{pp}(J/\psi)} \Big/ \frac{N_{AA}(c\bar{c})}{n_c N_{pp}(c\bar{c})} = S_{J/\psi}$$

**to get $J/\psi$ survival probability.**

**apply to data – illustration only so far, kinematics...**

# LHC Data

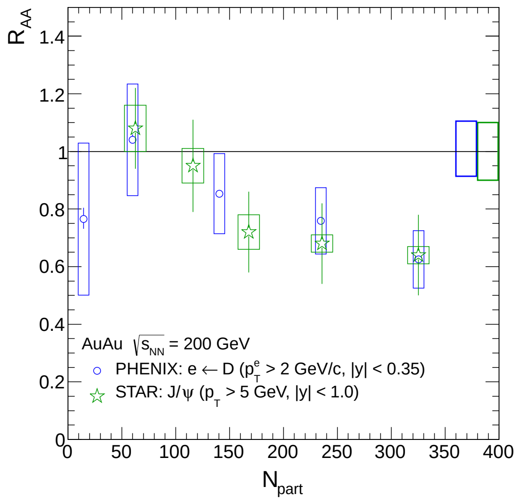


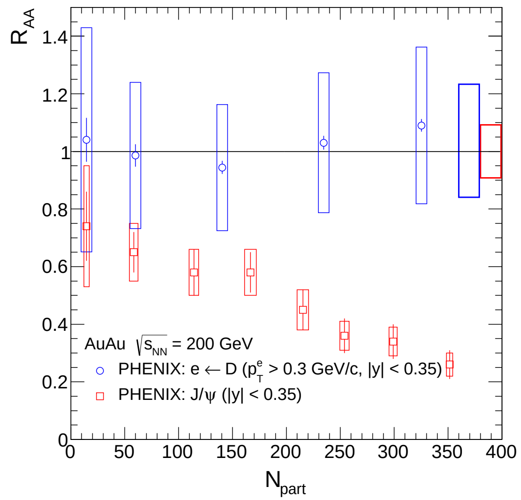

Data from ALICE & CMS: $\boldsymbol{J/\psi}$ vs. open charm production at intermediate & high transverse momenta (thanks to Zaida Conesa del Valle)

**in $\boldsymbol{AA}$, as many $\boldsymbol{c\bar{c}}$ pairs make $\boldsymbol{J/\psi}$ as in scaled $\boldsymbol{pp}$,**
**but there just are fewer now to begin with**

**here neither $\boldsymbol{J/\psi}$ suppression nor enhancement; low $\boldsymbol{P_T}$?**

# RHIC Data



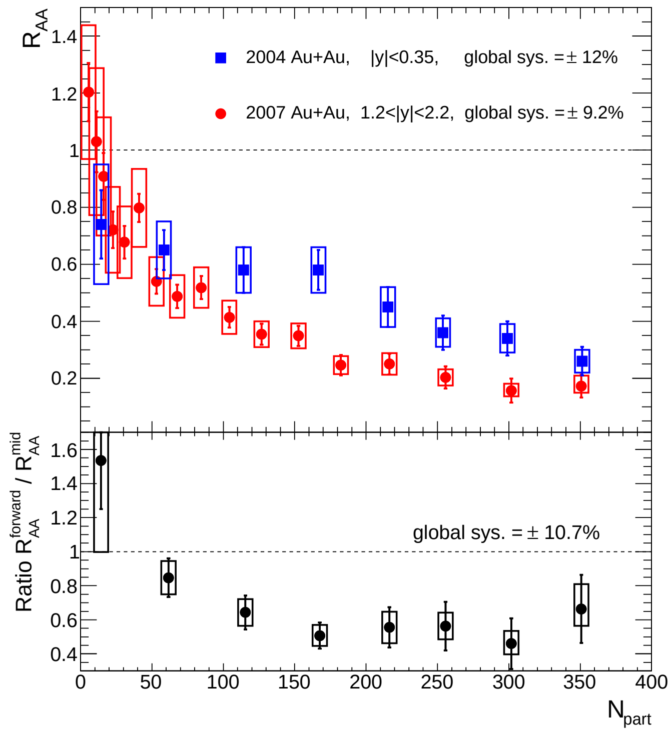




Data from PHENIX & STAR: $J/\psi$ vs. open charm production at high & low transverse momenta
(thanks to Torsten Dahms)

**at high $p_T$, as at LHC;**
**at low $p_T$, up to 80 % $J/\psi$ suppression:**
**here ∃ no medium effect on $c\bar{c}$ production,**
**only on charmonium binding.**

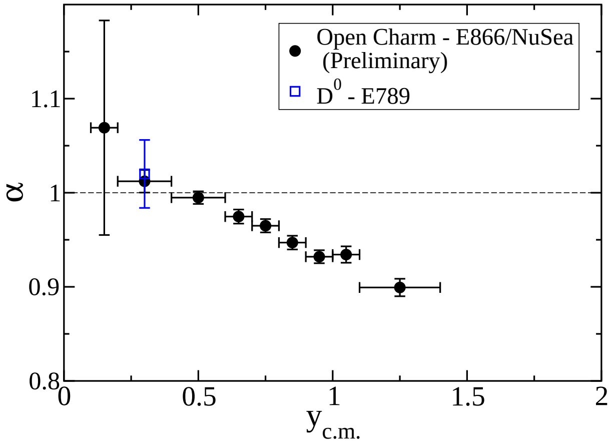
## Complementary aspect: so-called “RHIC puzzle”

**“more $J/\psi$ suppression” in forward than in central production, based on $R_{AA}$**




**Could it be that there are just fewer $c\bar{c}$ pairs produced at forward than at mid rapidity?**

## Check by looking at open charm production in $pA$ collisions

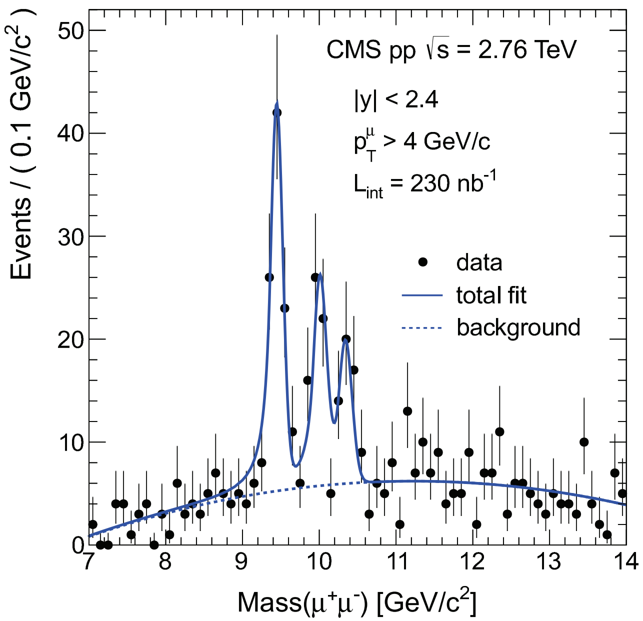


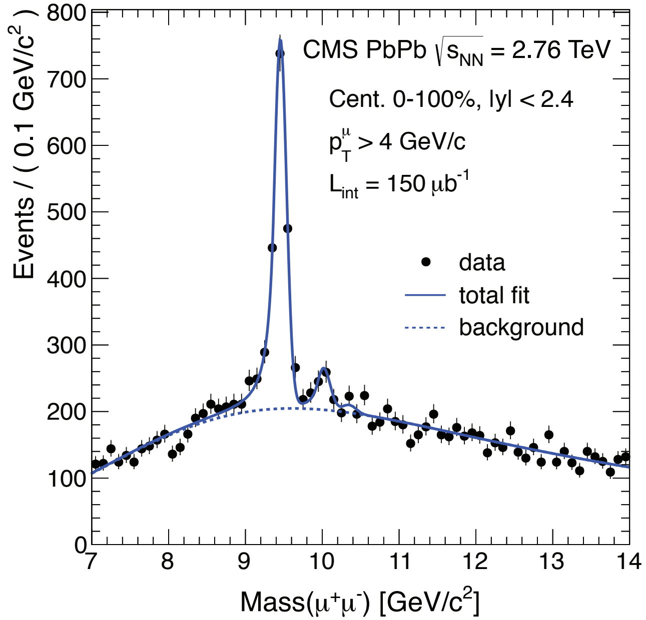

Rapidity dependence of open charm production in $pA$ at 800 GeV, with parametriztion $\sigma_{pA} = A^{\alpha}\sigma_{pp}$.
(thanks to Mike Leitch)

## The puzzle seems not so puzzling with correct calibration; but need to check quantitatively

# Additional Probe

**ratio of excited to ground state in $AA$: $\Upsilon(1S) : \Upsilon(2S) : \Upsilon(3S)$**
**does the presence of a medium change this from $pp$?**
**initial state effects cancel here as well; example**




**Seems evidence of sequential suppression...see CMS paper.**

## Conclusions

**Only measurements of hidden/open heavy flavor production,**

**measurements of excited/ground state quarkonium production**

**in $pp$, $pA$, $AA$**

**can provide model-independent answers**

**to model-independent questions.**