Bottomonium suppression at LHC

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Recent references:
1507.03951 (Krouppa, Ryblewski, and MS)
1605.03561 (Krouppa and MS)

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Heavy Quarkonia Suppression

- In a high temperature quark-gluon plasma we expect **weaker color binding** (Debye screening)

  E. V. Shuryak, Phys. Rept. 61, 71–158 (1980)
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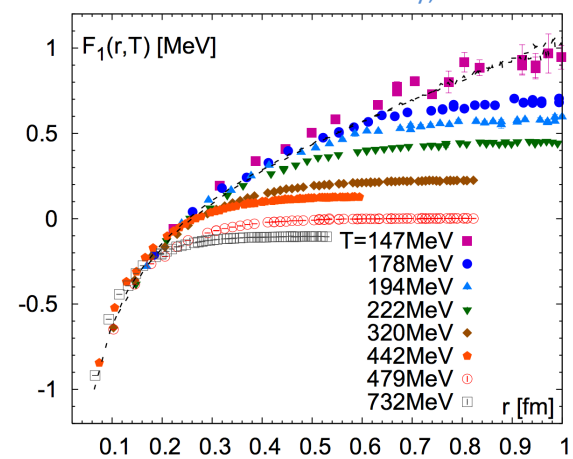
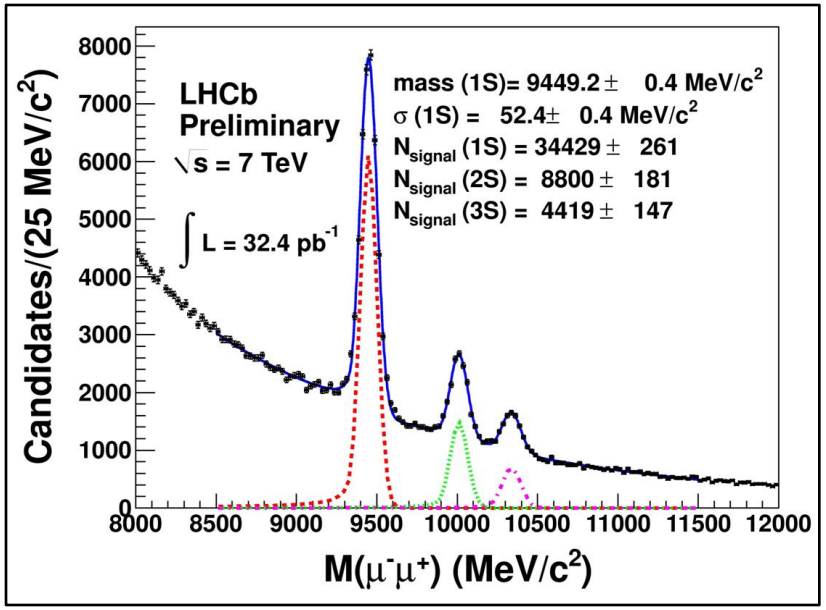
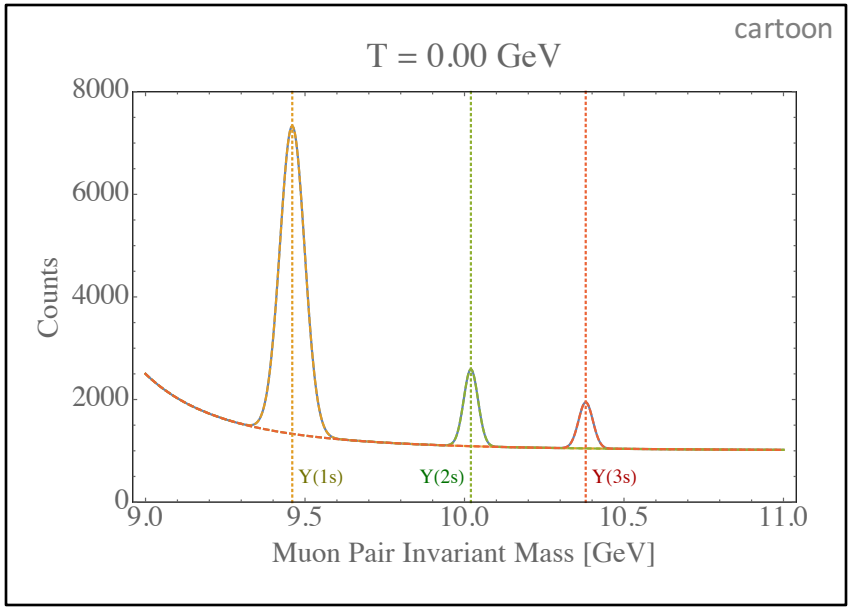
A. Bazavov and P. Petreczky, 1211.5638







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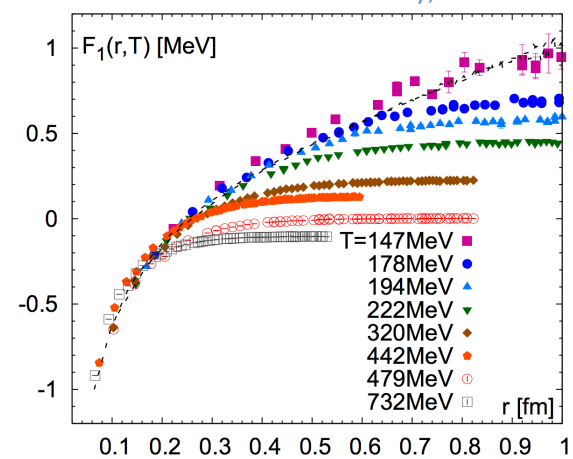

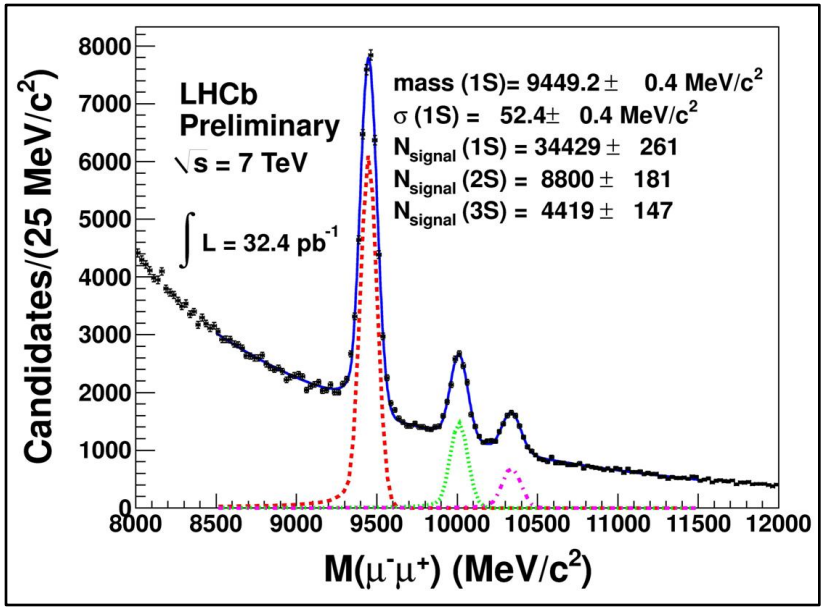

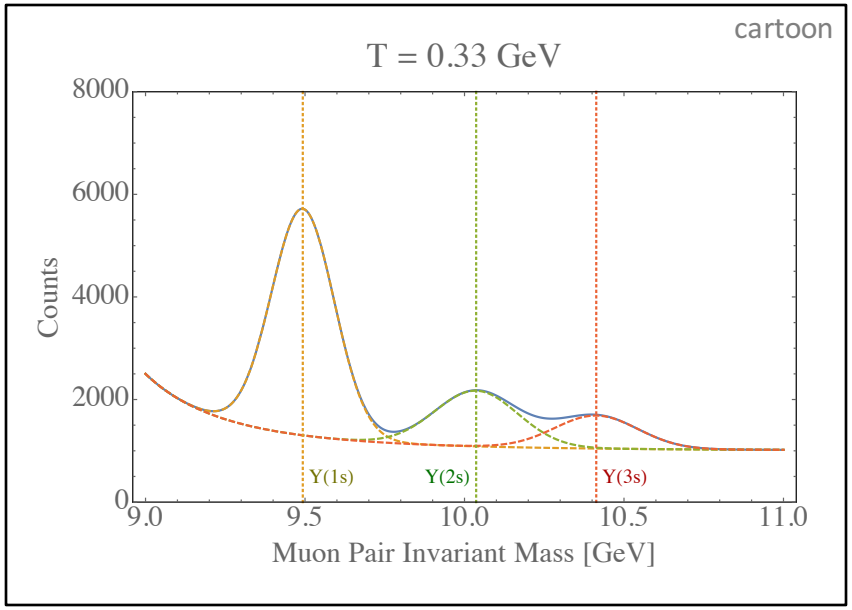

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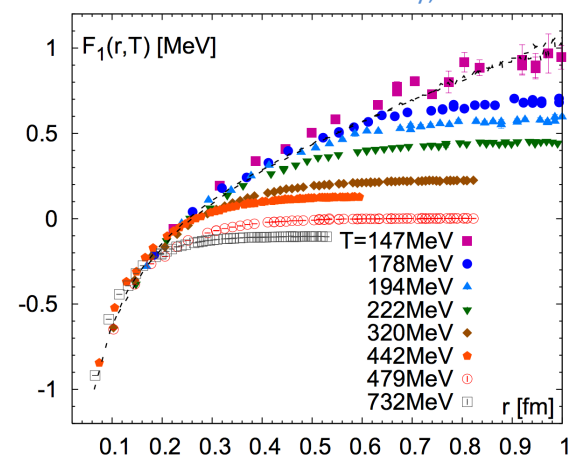

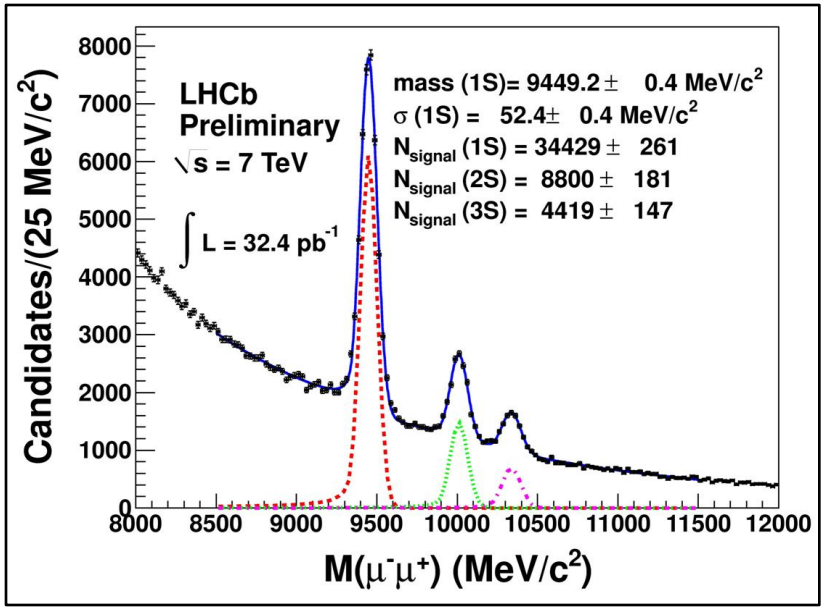

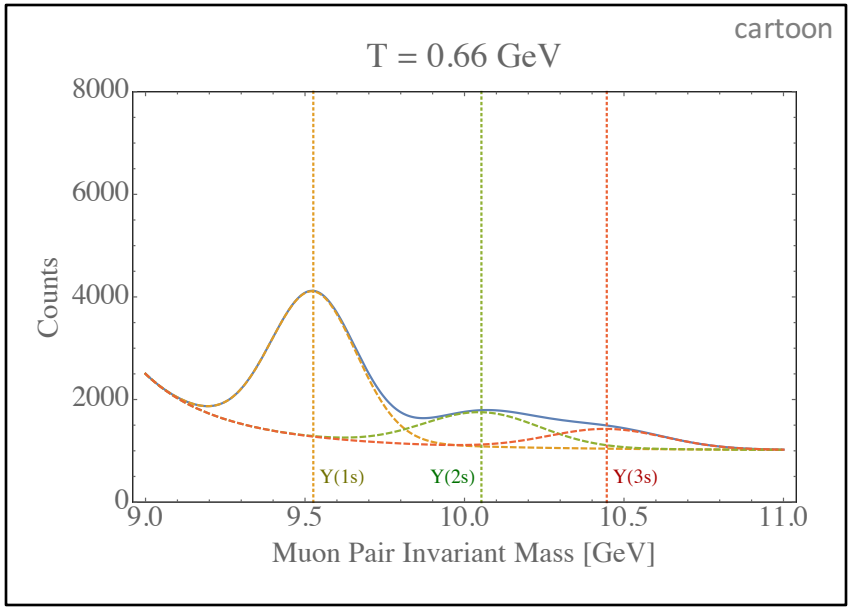

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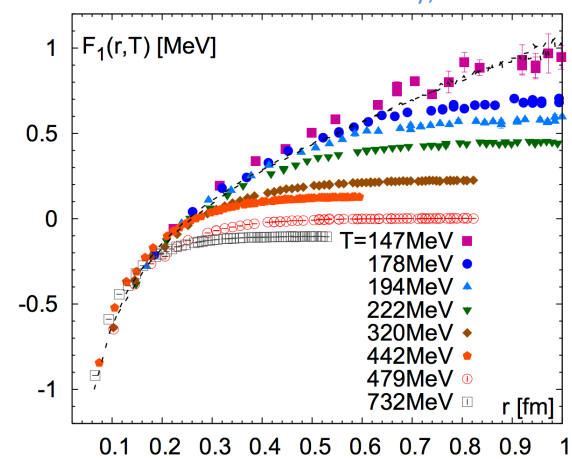
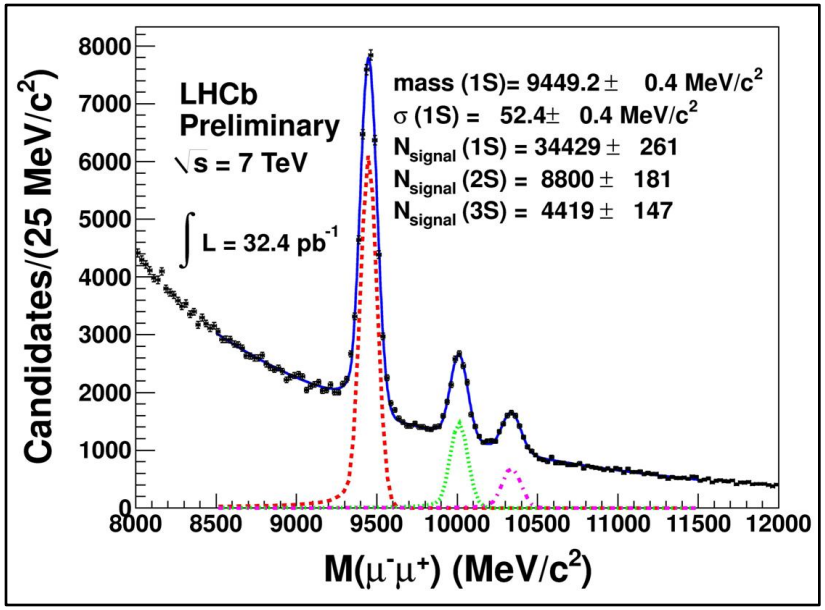
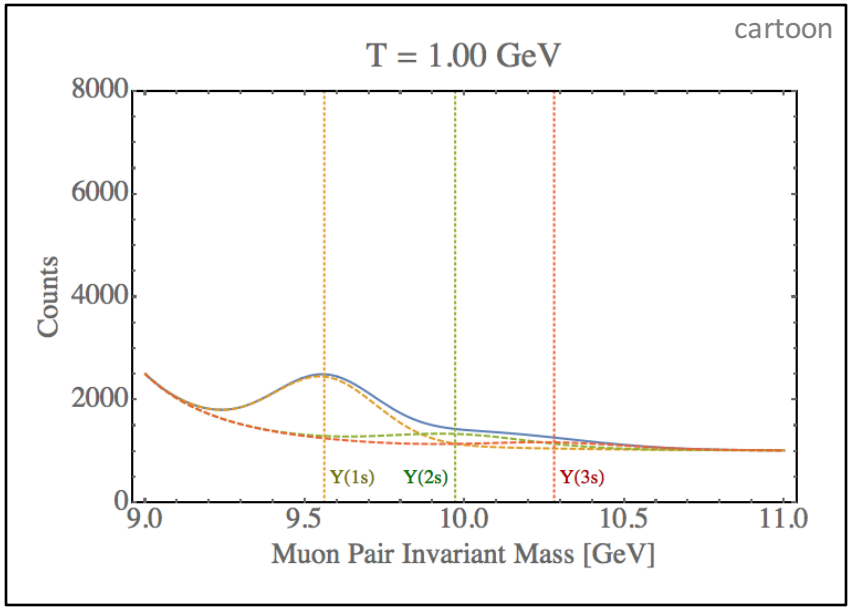


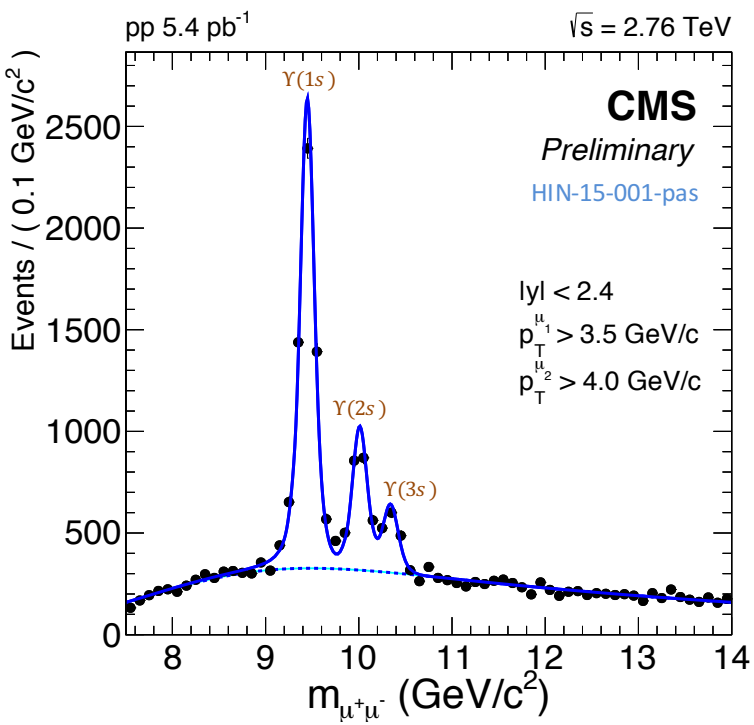




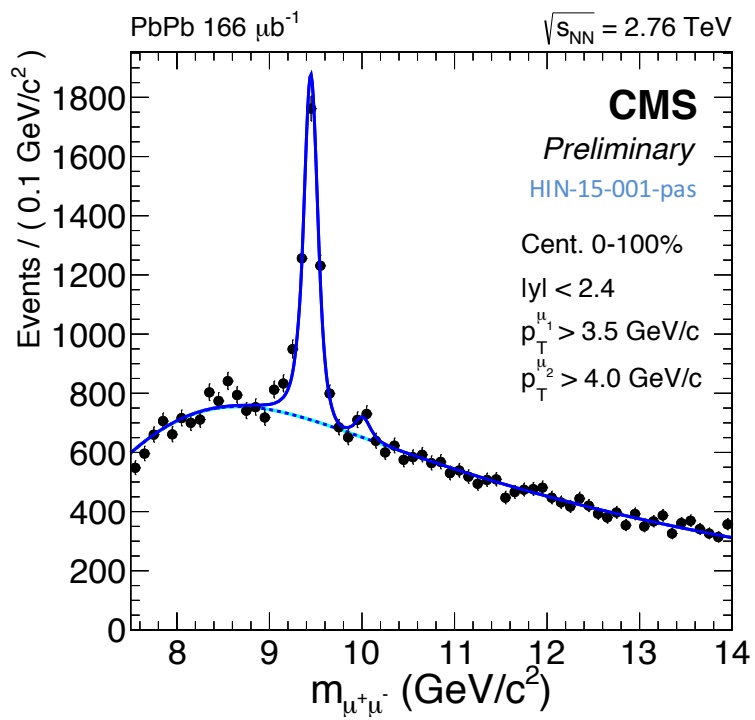
2015 Preliminary CMS Data

The **CMS** (Compact Muon Solenoid) experiment has measured bottomonium spectra for both pp and Pb-Pb collisions. With this we can extract R_{AA} experimentally.

p-p

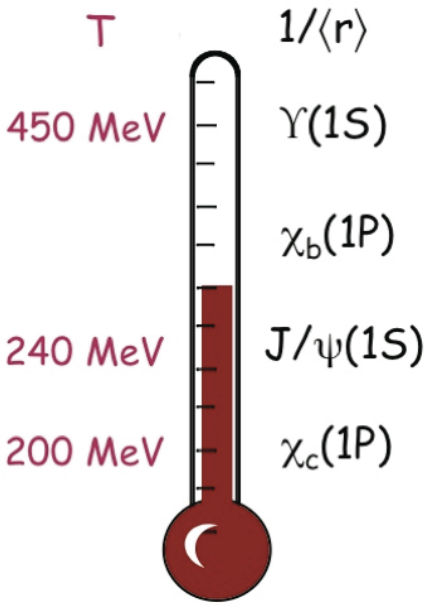


Pb-Pb



Why Bottomonia in AA?

- Heavy quark effective theory on surer footing than for charmonia
- Cold nuclear matter (CNM) effects are much smaller than for the charmonia
- The masses of bottomonia are much higher than the temperature (T < 1 GeV) generated in HICs → bottomonia production dominated by initial hard scatterings
- Since bottom quarks and anti-quarks are relatively rare (1 pair per 10 billion events), the probability for regeneration of bottomonia through recombination is much smaller than for charm quarks [see e.g. E. Emerick, X. Zhao, and R. Rapp, arXiv:1111.6537]



A. Mocsy, P. Petreczky, and MS, 1302.2180

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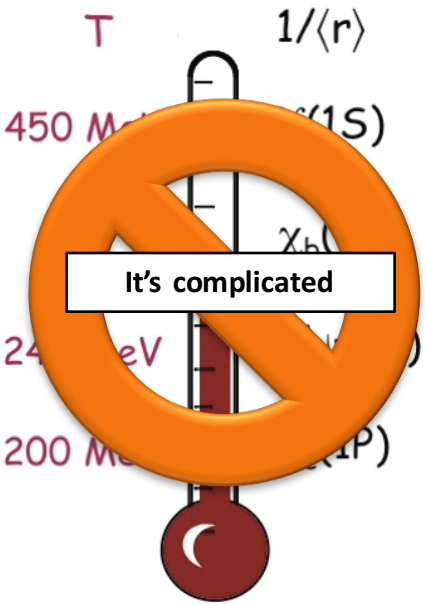

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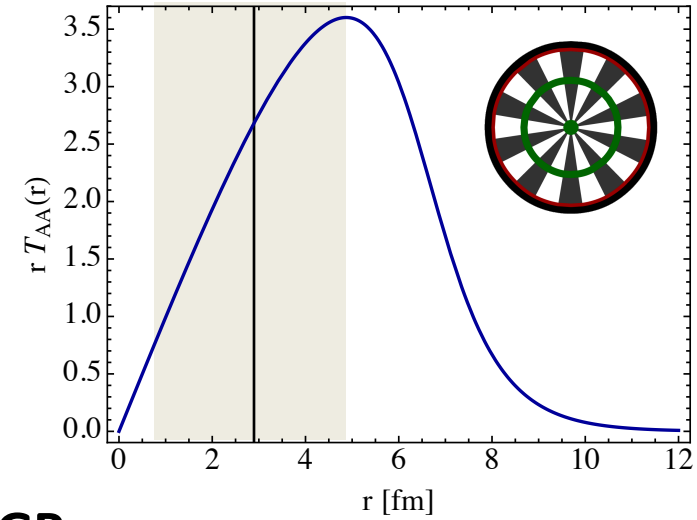
Good news and bad news

- Large binding energies → short formation times
- Formation time for Υ(1s), for example, is ≈ 0.2 fm/c
- This comes at a cost: **We need to reliably model the early-time dynamics since quarkonia are born into it**
- In addition, production vertices can be anywhere in the transverse plane, not just the central hottest region
- For example, for a central collision <r> ~ 3.2 fm and the most probable r is ~ 5 fm

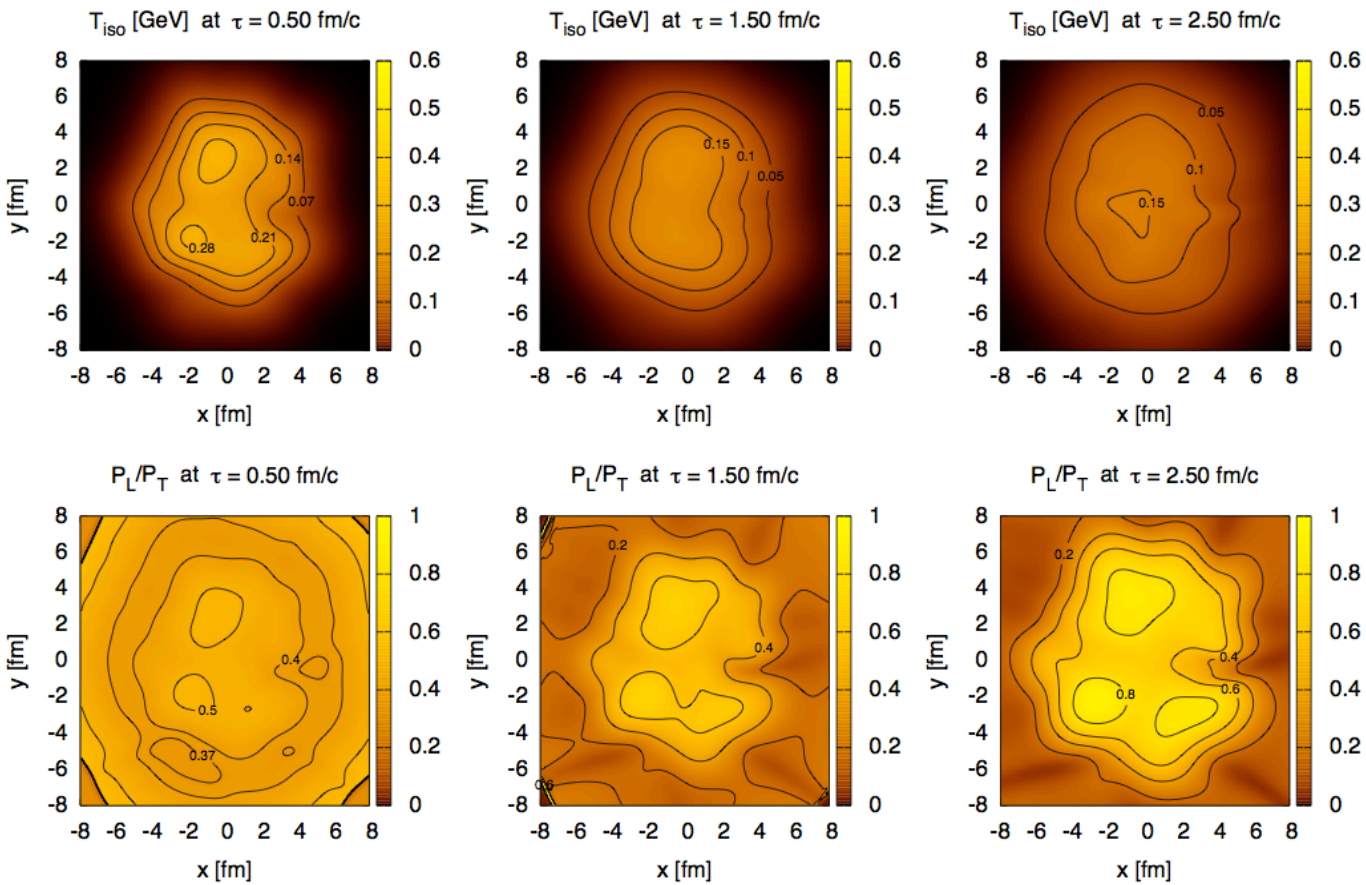


- Therefore, we also **need to reliably describe the 3+1d dynamics of the QGP**
- For this purpose, we will use a framework called **anisotropic hydrodynamics**

Anisotropic hydrodynamics

Anisotropic hydrodynamics

Given the population of quarkonia states at some τ_0, we can simply integrate the instantaneous decay/regeneration rate of the state $\Gamma(\tau,x,y,\eta)$ over the QGP spatiotemporal evolution to obtain the **survival probability**.



Pb-Pb @ 2.76 TeV
T_0 = 600 MeV
τ_0 = 0.25 fm/c
b = 7 fm

M. Martinez, R. Ryblewski, MS, arXiv:1204.1473

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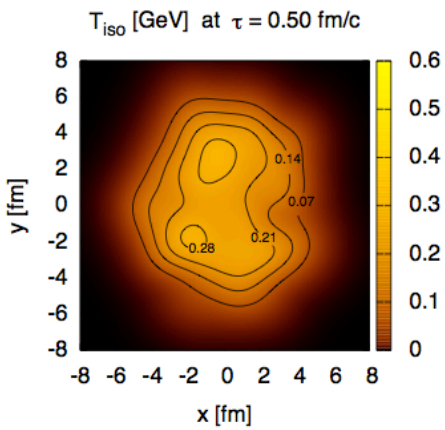

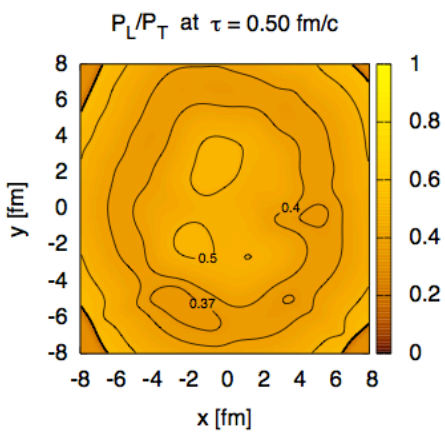

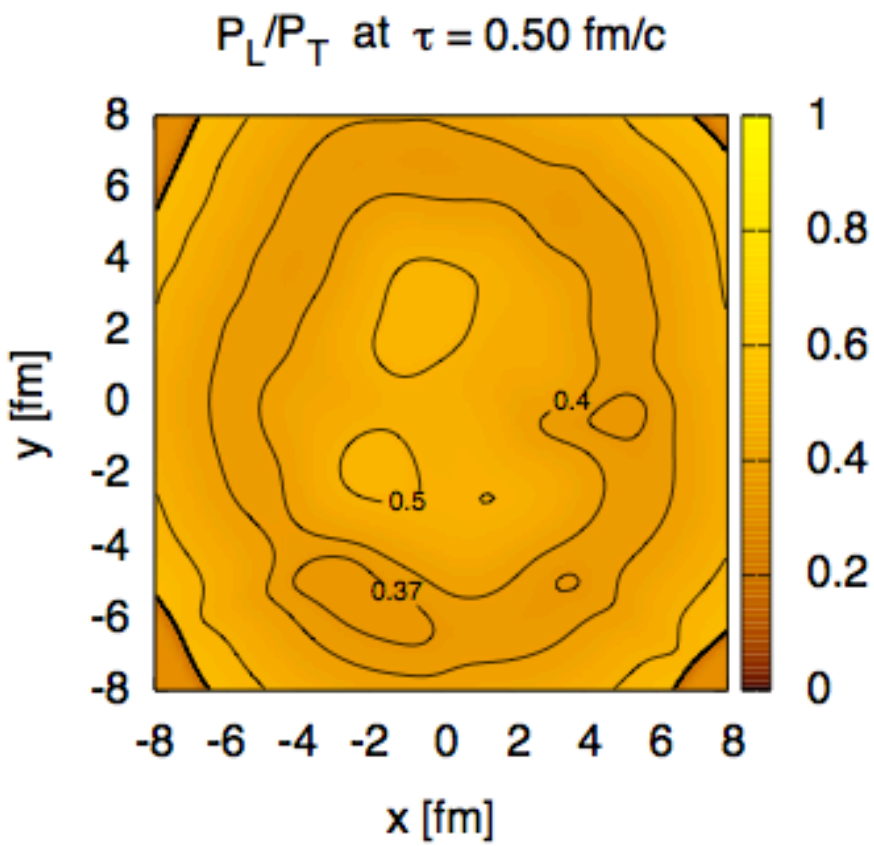

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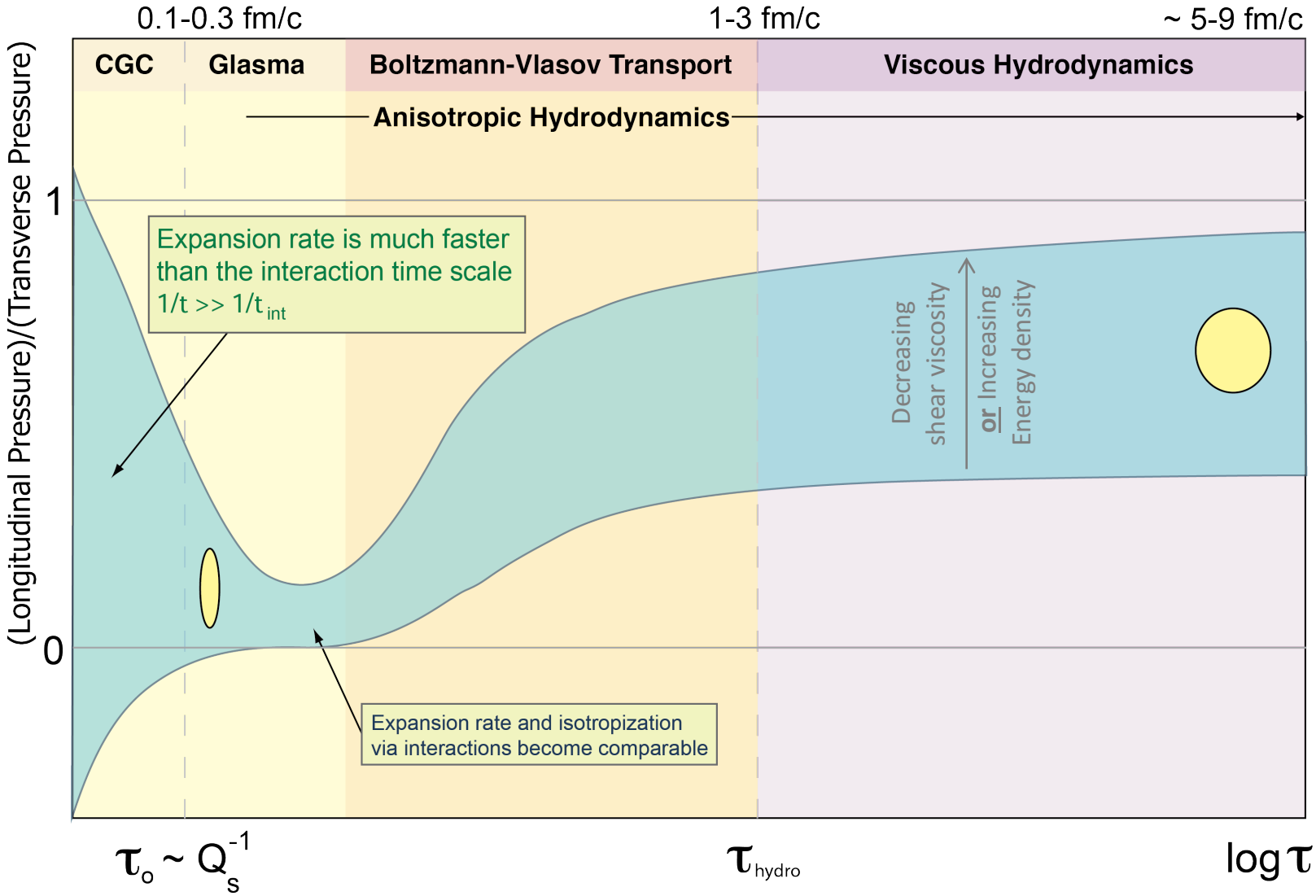
QGP momentum anisotropy cartoon



Model potential

Complex-valued Potential

- Anisotropic potential can be parameterized as a Debye-screened potential with a direction-dependent Debye mass

$$V_{\rm screened}(r,\theta,\xi,\Lambda) = -C_F \alpha_s \frac{e^{-\mu(\theta,\xi,\Lambda) r}}{r}$$

D Bazow and MS, 1112.2761; MS, 1106.2571.

- The potential also has an imaginary part coming from the Landau damping of the exchanged gluon

Internal Energy

$$V_{\rm R}(\mathbf{r}) = -\frac{\alpha}{r}\,(1+\mu\, r)\exp\left(-\mu\, r\right) + \frac{2\sigma}{\mu}\left[1-\exp\left(-\mu\, r\right)\right] - \sigma\, r\, \exp(-\mu\, r) - \frac{0.8\,\sigma}{m_Q^2\, r}$$

Dumitru, Guo, Mocsy, and MS, 0901.1998

- This imaginary part also exists in the isotropic case

Laine et al hep-ph/0611300
Brambilla et al 0804.0993

- Used this as a model for the free energy (F) and also obtained internal energy (U) from this

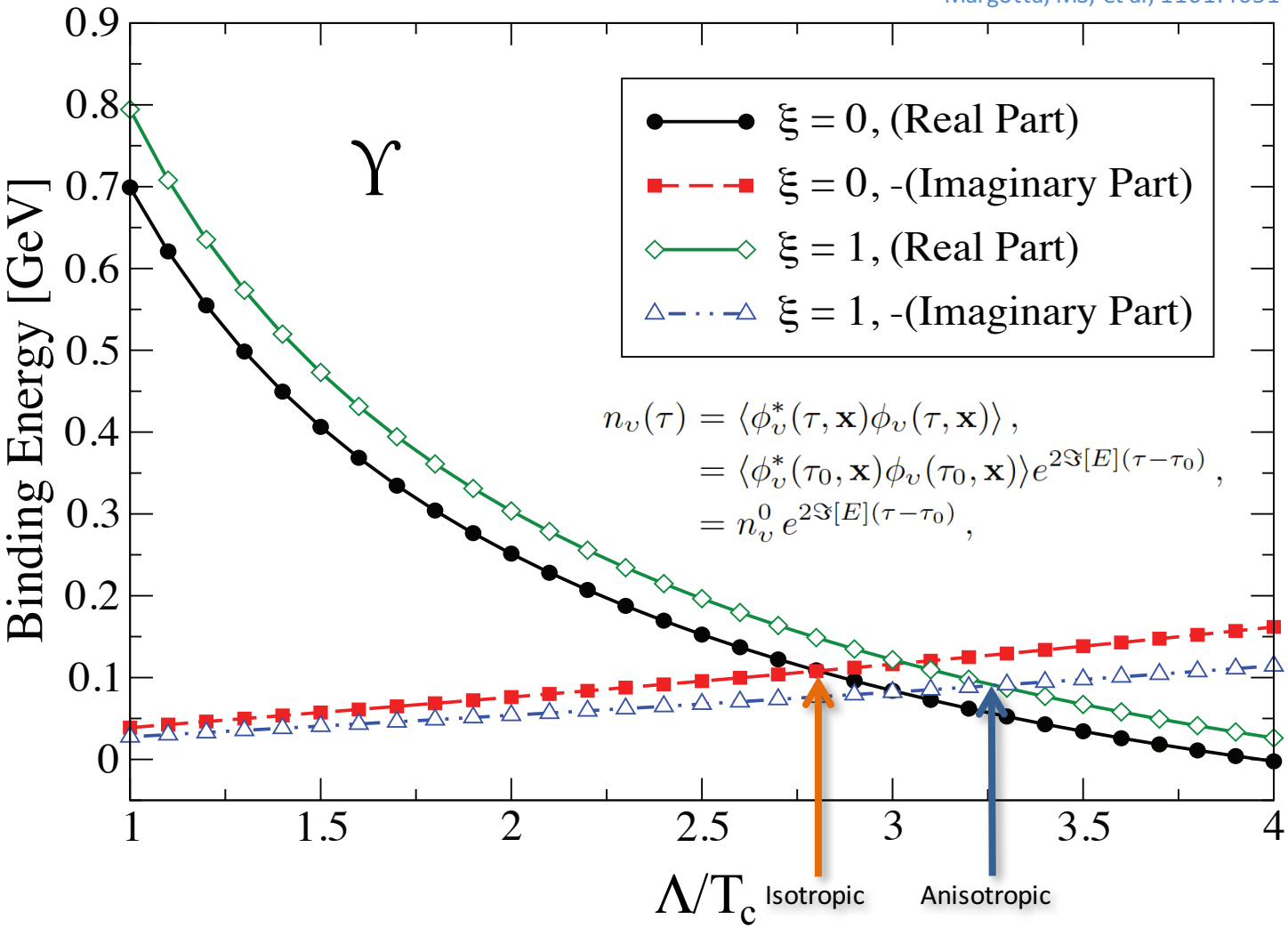
$$V_{\rm I}(\mathbf{r}) = -C_F \alpha_s p_{\rm hard}\left[\phi(\hat{r}) - \xi\left(\psi_1(\hat{r},\theta)+\psi_2(\hat{r},\theta)\right)\right]$$

Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Burnier, Laine, Vepsalainen, arXiv:0903.3467 (aniso)

For more discussion, see the talk by M. Escobedo in the next session

Results for the ϒ(1s) binding energy

Margotta, MS, et al, 1101.4651



Fold together with dynamical evolution

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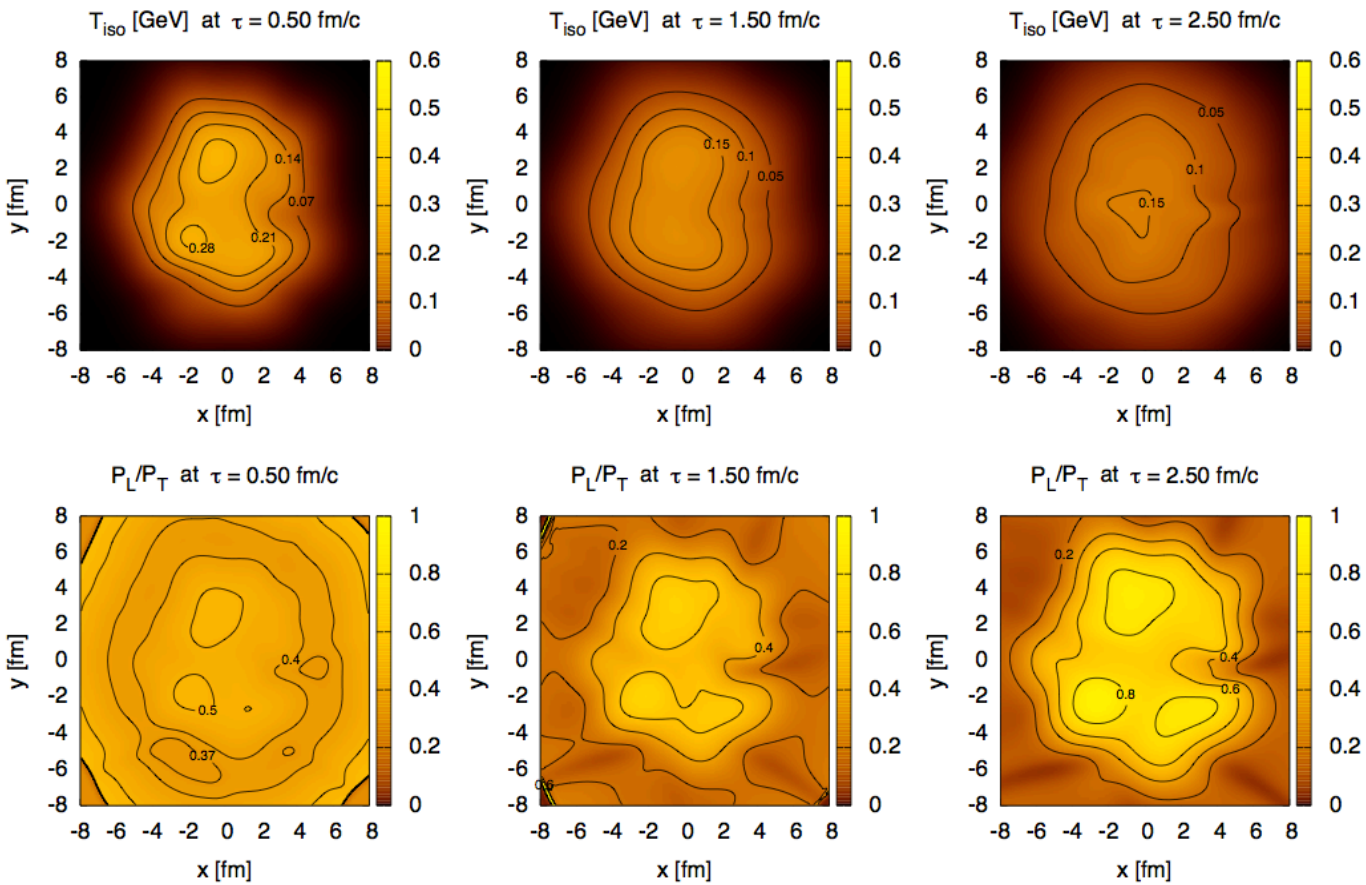

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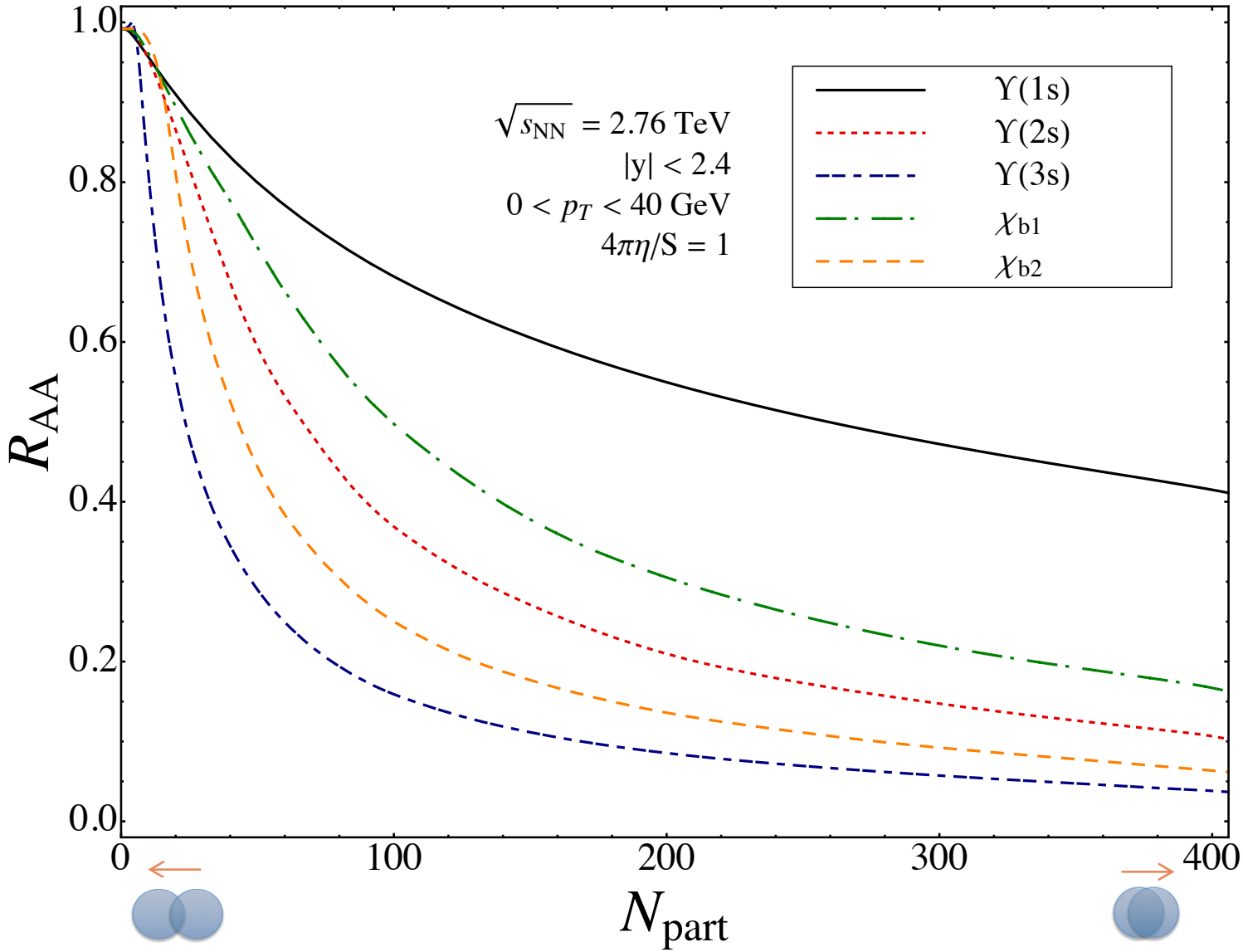
State Suppression Factors, $R_{AA}{}^{i}$

B. Krouppa, R. Ryblewski, and MS, Phys. Rev. C 92, 061901(R)(2015).



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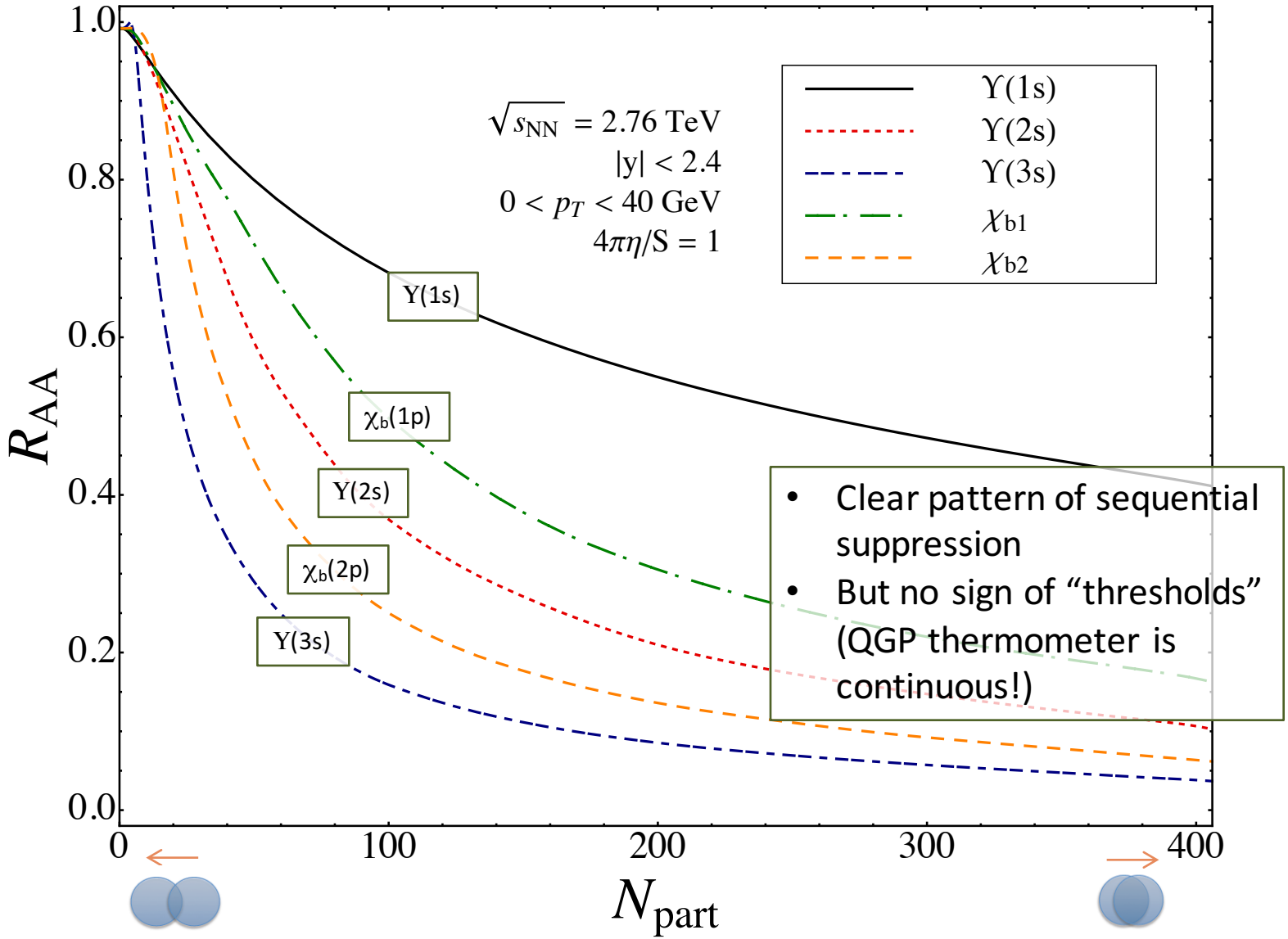

- Clear pattern of sequential suppression
- But no sign of "thresholds" (QGP thermometer is continuous!)

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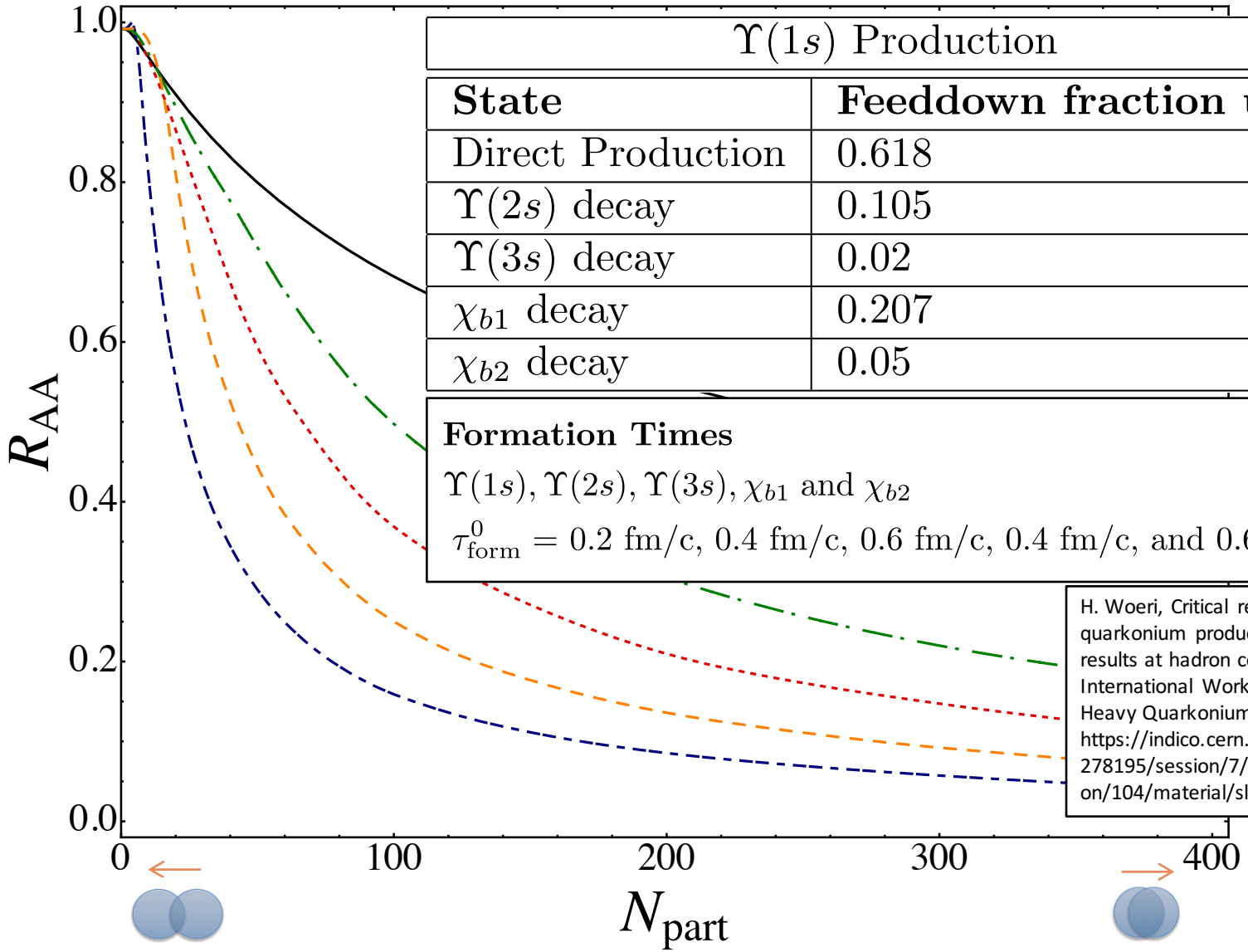

$\Upsilon(1s)$ Production	
State	**Feeddown fraction used**
Direct Production	0.618
$\Upsilon(2s)$ decay	0.105
$\Upsilon(3s)$ decay	0.02
χ_{b1} decay	0.207
χ_{b2} decay	0.05

Formation Times

$\Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_{b1}$ and χ_{b2}

$\tau^0_{\rm form} = 0.2$ fm/c, 0.4 fm/c, 0.6 fm/c, 0.4 fm/c, and 0.6 fm/c

H. Woeri, Critical review of quarkonium production results at hadron colliders, International Workshop on Heavy Quarkonium 2014, https://indico.cern.ch/event/278195/session/7/contribution/104/material/slides/0.pdf

Inclusive Bottomonium Suppression

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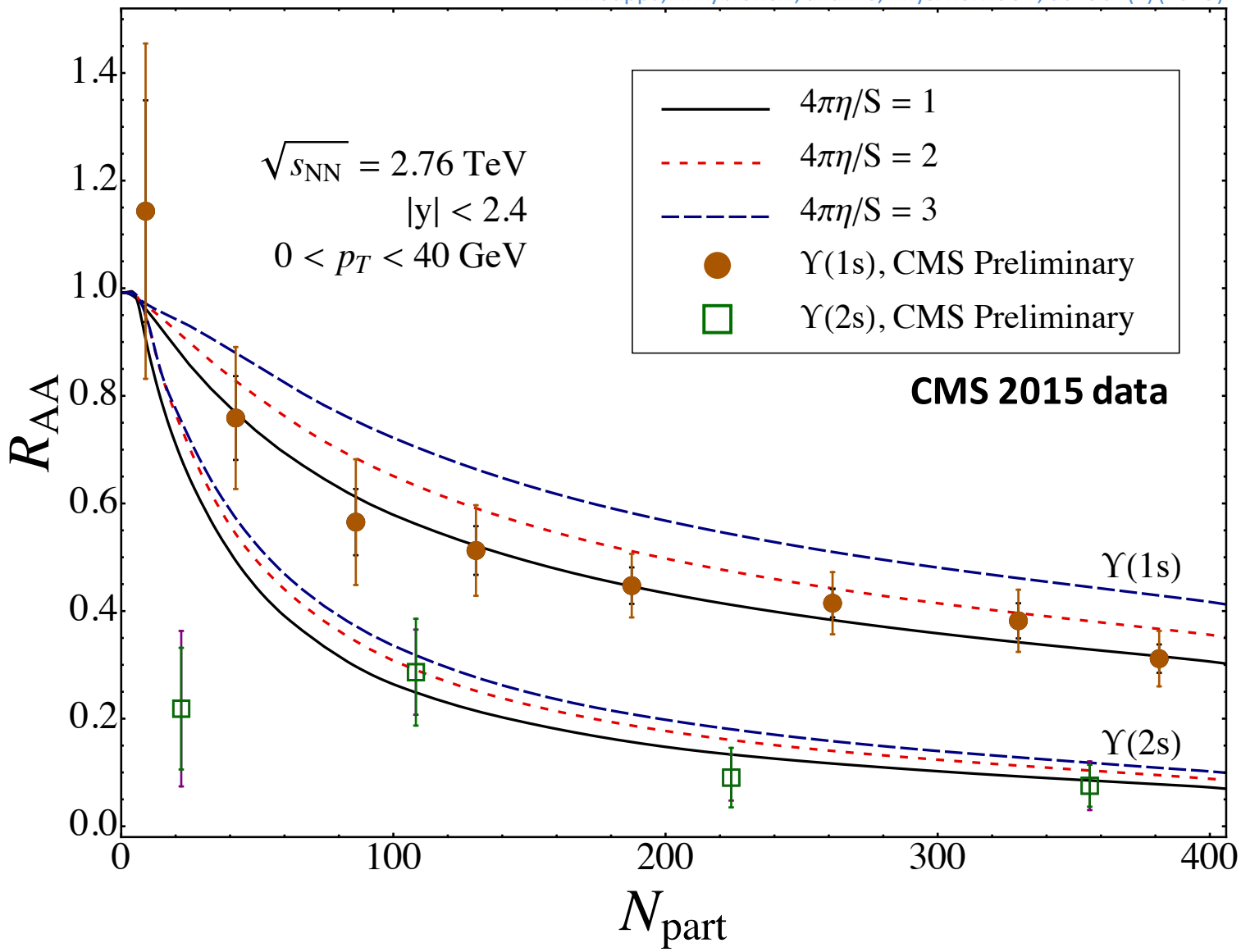

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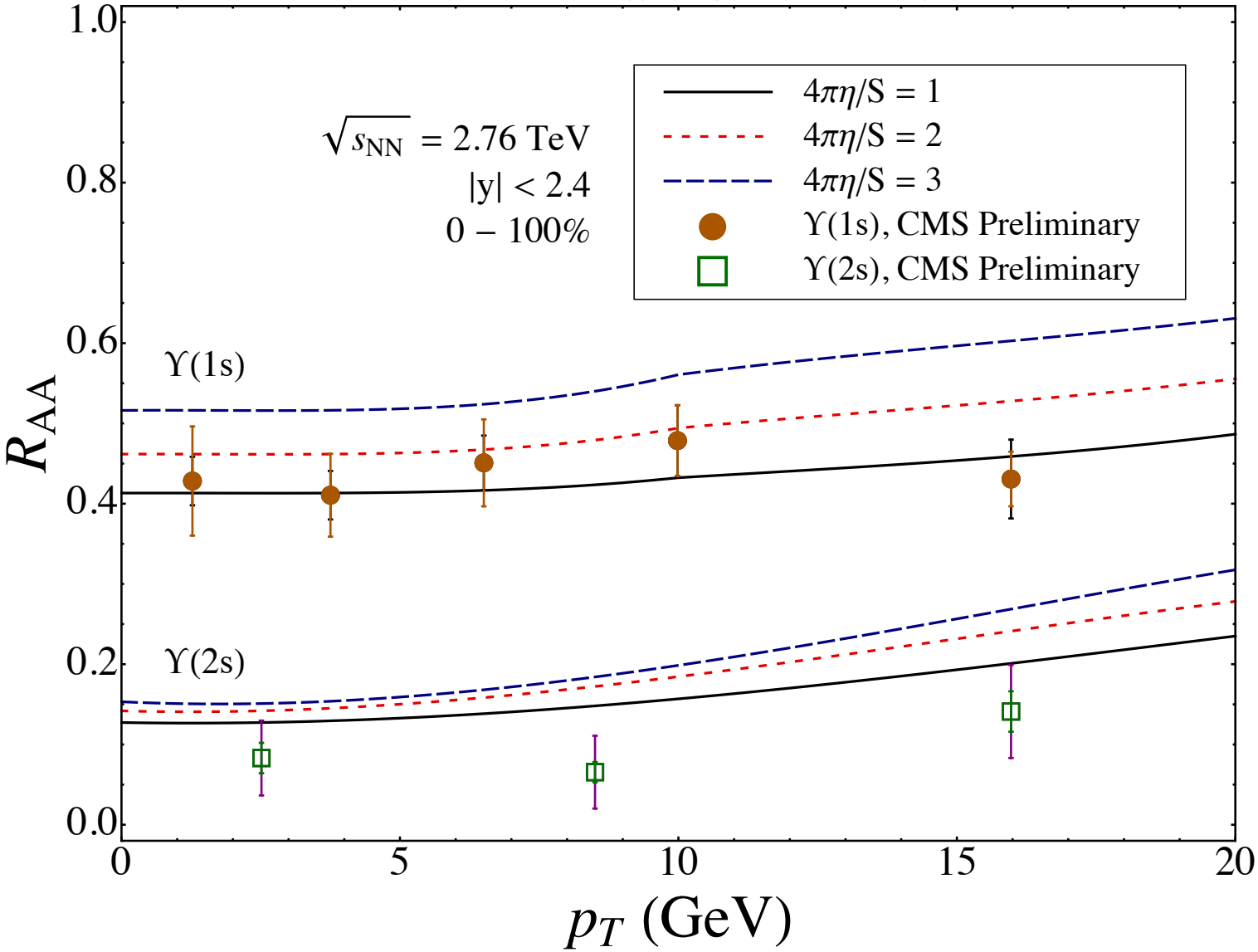

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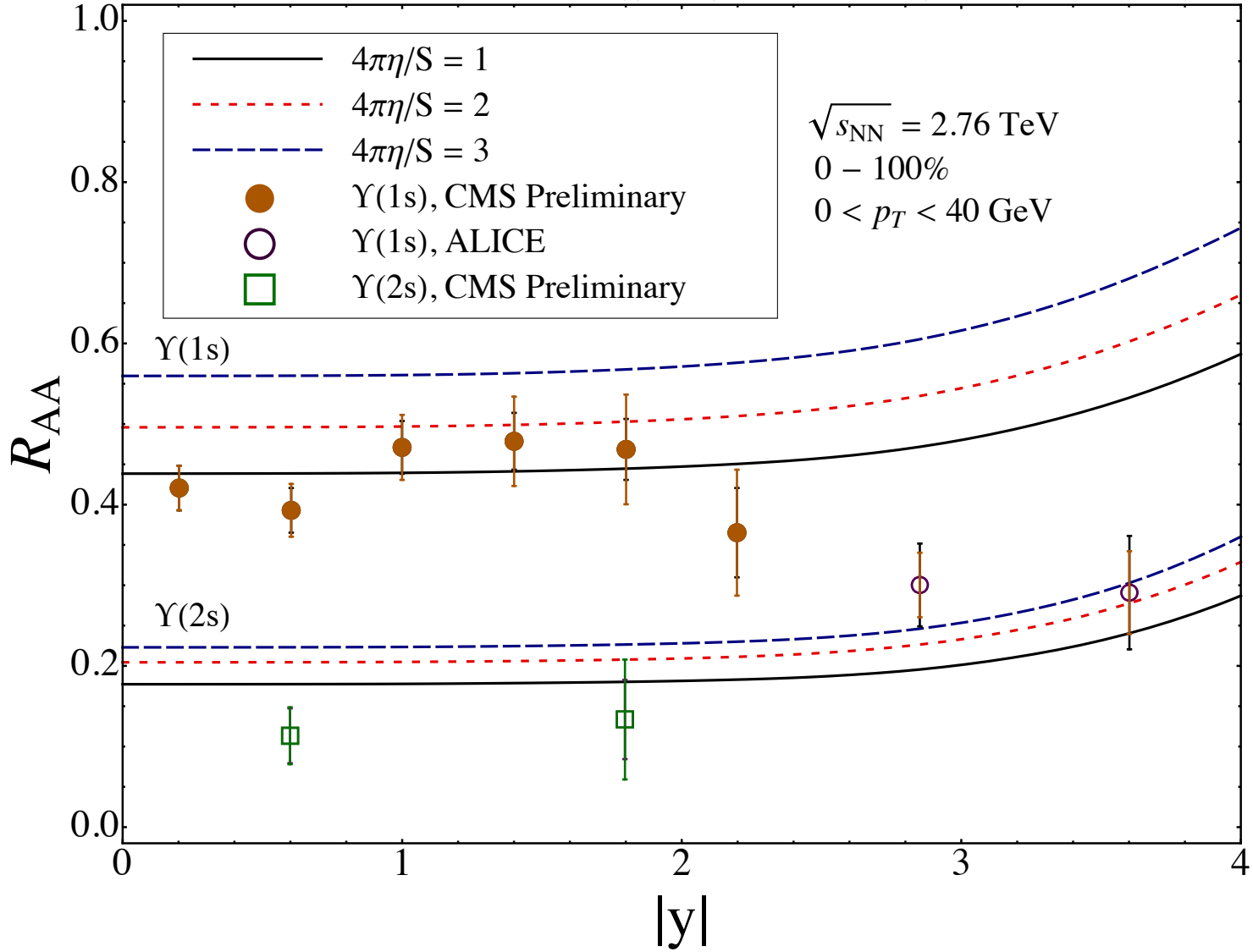

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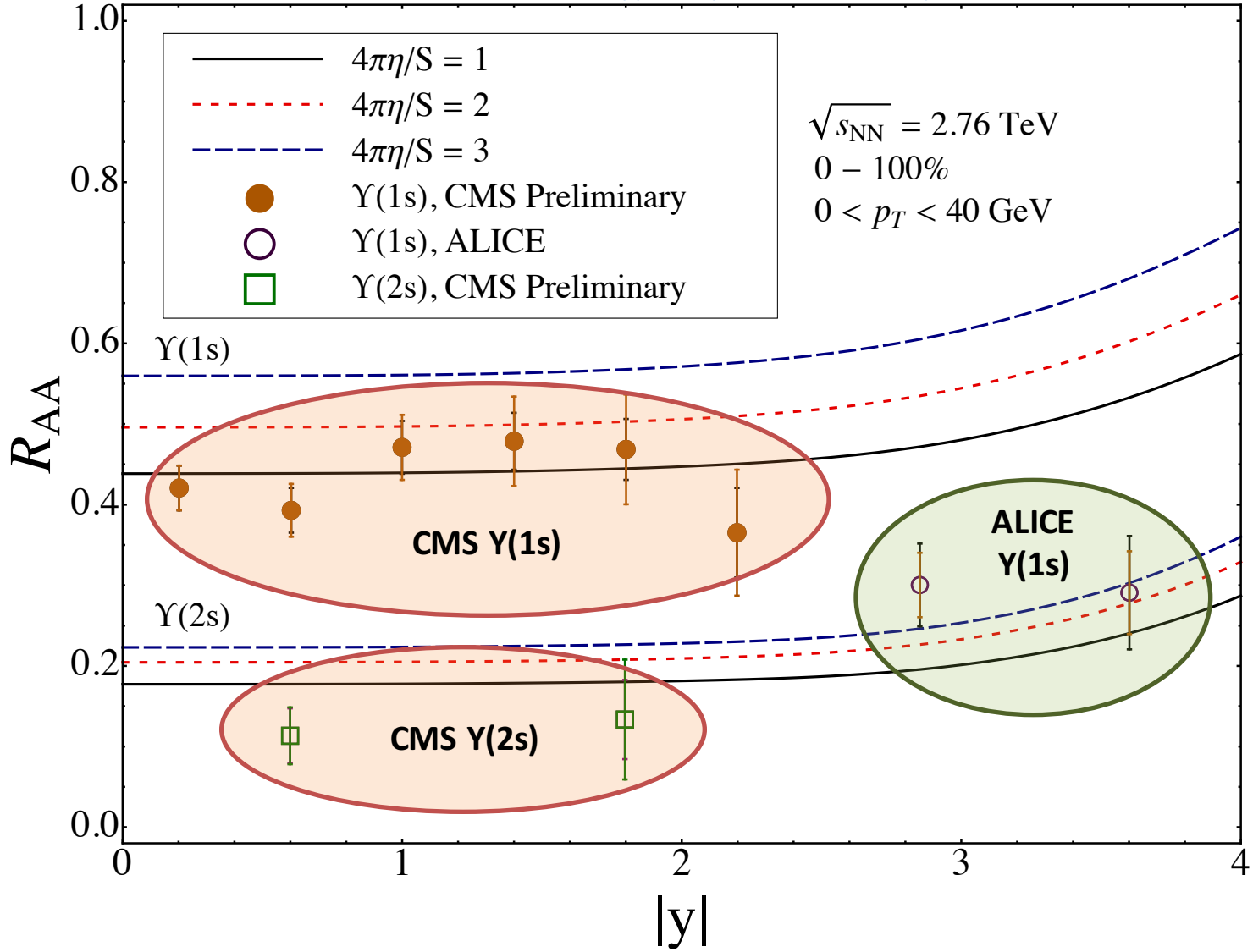
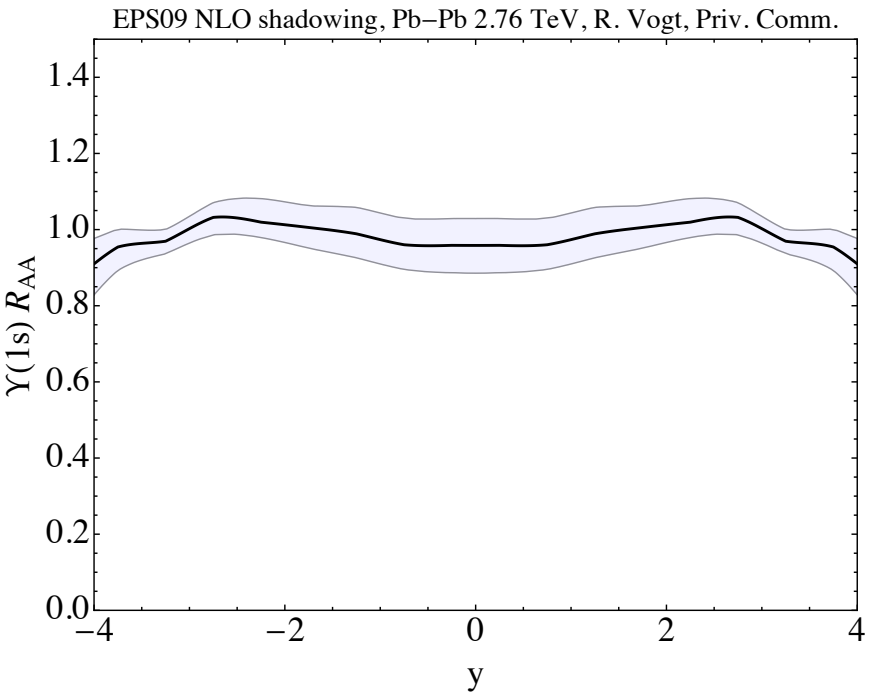
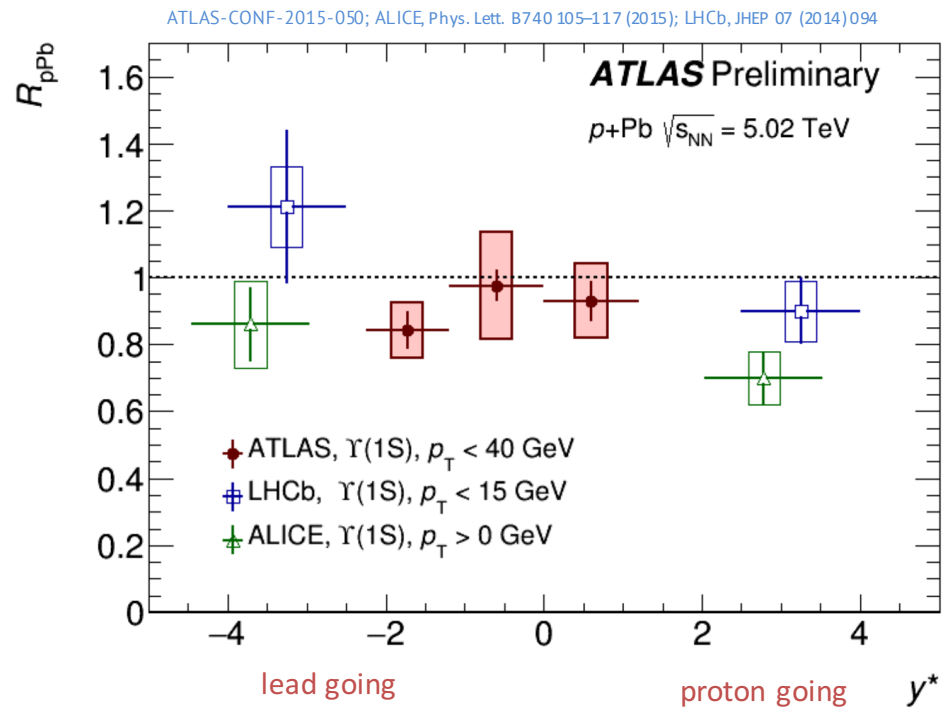


Estimate CNM effect on Bottomonium in A-A





- Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt (left)
- Experimental measurement of Upsion(1s) suppression in pA also suggest small CNM effects (right)
- CNM effects seem to be quite small for Upsilon(1s); could be more important for excited states though.
- This is good news for isolating the medium effect we are after, but doesn't help to explain the ALICE forward "anomaly"

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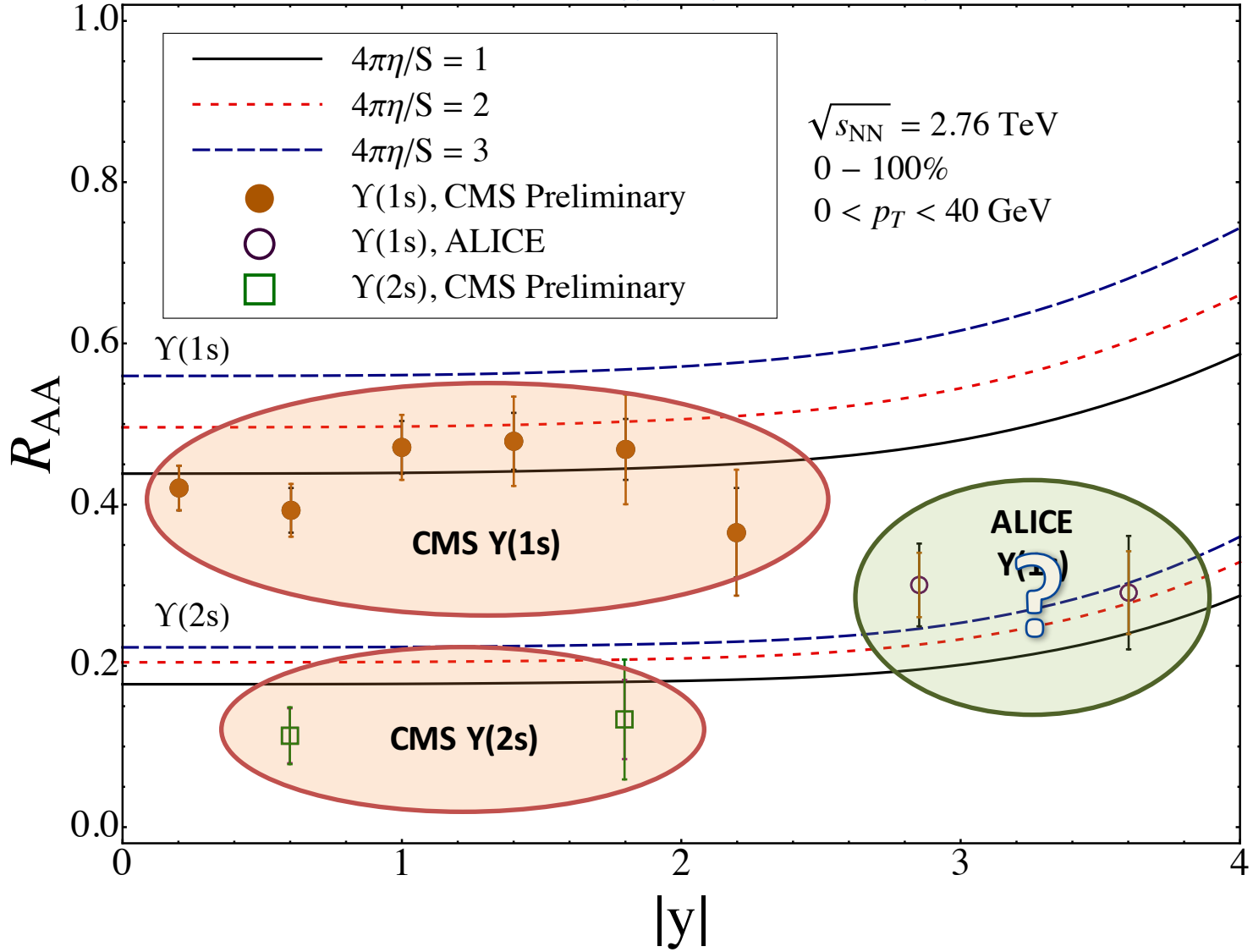
B. Krouppa, R. Ryblewski, and MS, Phys. Rev. C 92, 061901(R) (2015).



Conclusions and Outlook

- At central rapidities, the aHydro + anisotropic screening model works reasonably well, but (i) there is insufficient Y(2s) suppression and (ii) the forward ALICE points are in conflict with the model predictions.
- For the Y(2s) the resolution could be provided by CNM effects since these are expected to be larger for excited states
- Could also be sensitive to the precise form of the potential used. Work is under way to use a new lattice-based potential from Rothkopf and Burnier which shows more Y(2s) suppression.
- Not sure what to make of the ALICE points.
- In the kinematic region studied by ALICE, CNM effects are expected to be quite small.
- CGC? comovers? finite baryochemical potential? signs of regeneration?

Backup slides

The suppression factor

- Resulting decay rate Γ_T = -2 Im[E_{bind}] is a function of τ, $x_\perp$, and ς (spatial rapidity). First we need to integrate over proper time

$$\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b) \equiv \int_{\max(\tau_{\rm form}(p_T),\tau_0)}^{\tau_f} d\tau\, \Gamma_T(\tau, \mathbf{x}_\perp, \varsigma, b)$$

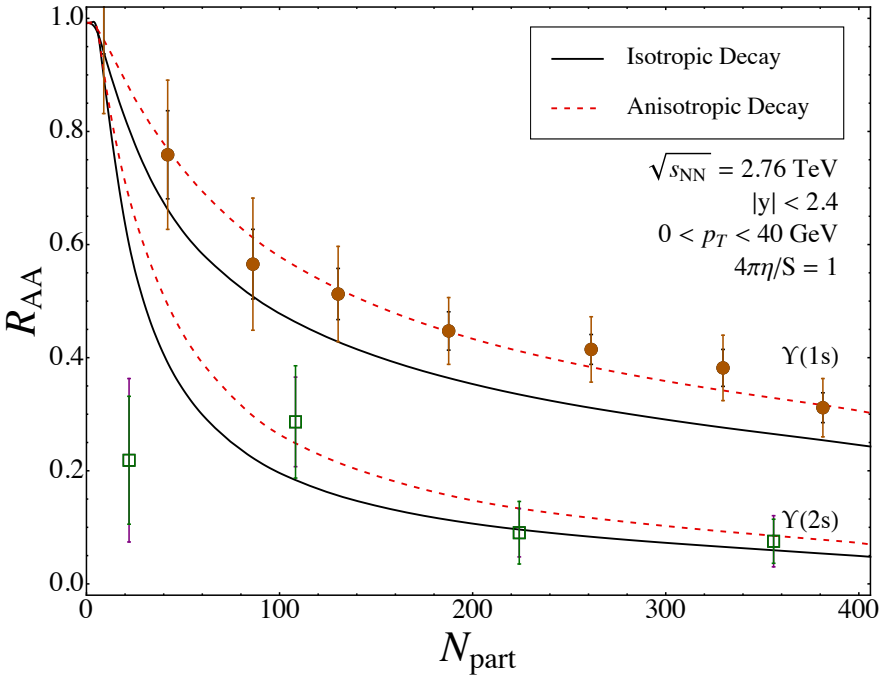
- From this we can extract R_{AA}

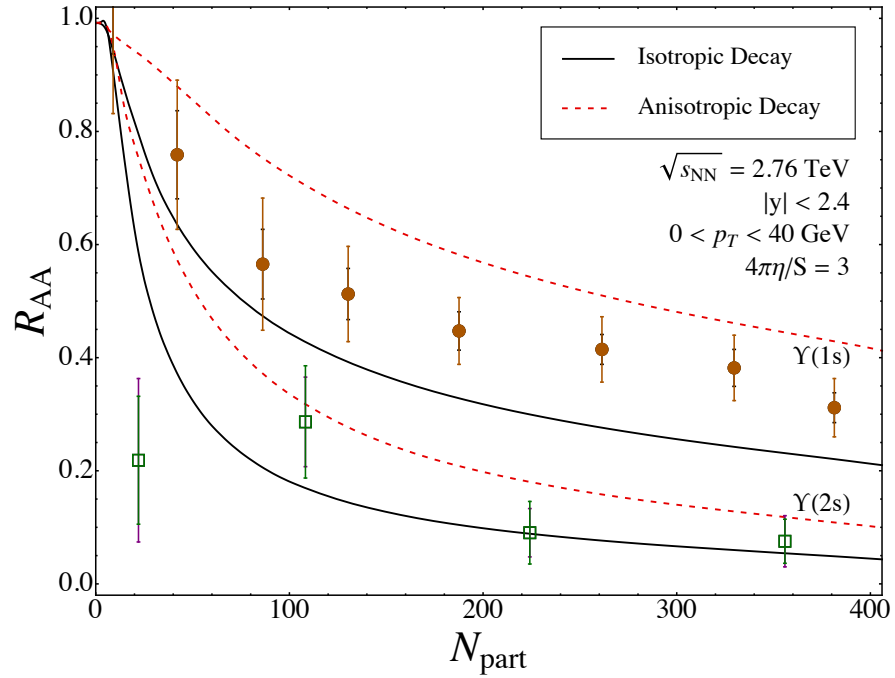
$$R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b) = \exp(-\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b))$$

- Use the overlap density as the probability distribution function for quarkonium production vertices and geometrically average

$$\langle R_{AA}(p_T, \varsigma, b)\rangle \equiv \frac{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)\, R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b)}{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)}$$

Anisotropy effect





- I argued in the beginning that including the anisotropy in the potential etc was important
- The two figures above show what happens if we simply use the isotropic potential with the local effective temperature determined from the energy density

Anisotropic hydrodynamics basics

[M. Martinez and MS, 1007.0889]
[W. Florkowski and R. Ryblewski, 1007.0130]

Viscous Hydrodynamics Expansion

$$f(\tau, \mathbf{x}, \mathbf{p}) = \underbrace{f_{\rm eq}(\mathbf{p}, T(\tau, \mathbf{x}))}_{\text{Isotropic in momentum space}} + \delta f$$

Anisotropic Hydrodynamics (aHydro) Expansion

Treat this term perturbatively
→ "NLO aHydro"

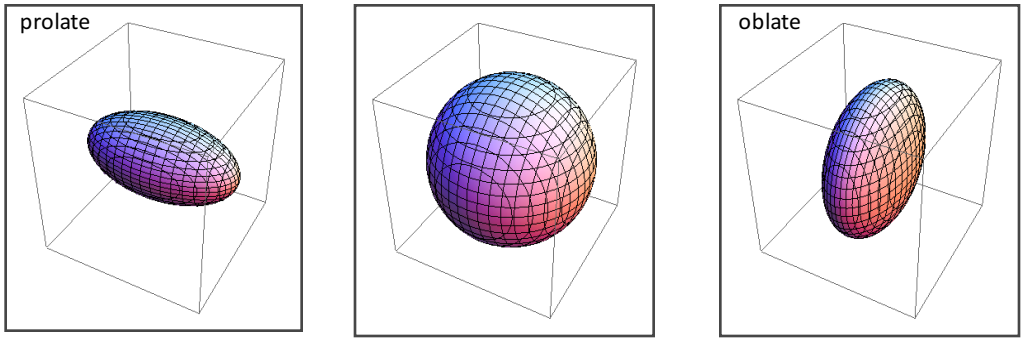
$$f(\tau, \mathbf{x}, \mathbf{p}) = f_{\rm aniso}(\mathbf{p}, \underbrace{\Lambda(\tau, \mathbf{x})}_{T_\perp}, \underbrace{\xi(\tau, \mathbf{x})}_{\text{anisotropy}}) + \delta\tilde{f}$$

D. Bazow, U. Heinz, and MS, 1311.6720
D. Bazow, U. Heinz, and M. Martinez, 1503.07443

→ "Romatschke-Strickland" form in LRF

$$f^{LRF}_{\rm aniso} = f_{\rm iso}\left(\frac{\sqrt{\mathbf{p}^2 + \xi(\mathbf{x},\tau)p_z^2}}{\Lambda(\mathbf{x},\tau)}\right)$$

$$\xi = \frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} - 1$$



$-1 < \xi < 0$ $\quad$ $\xi = 0$ $\quad$ $\xi > 0$

aHydro Executive Summary

- aHydro = improved viscous hydro framework ($\xi^{\mu\nu} \leftrightarrow \pi^{\mu\nu}$)
- The two frameworks agree perfectly in the limit of small eta/s and dense systems (central rapidity and small r)
- aHydro treats the dilute regions (large r and η) more accurately and allows one to reliably extend simulations to large eta/s and large initial anisotropies
- aHydro also allows us to more reliably describe small systems (e.g. pA) and lower energy AA collisions more reliably

In-medium heavy quark potential

Using the real-time formalism one can express the potential in terms of the *static* advanced, retarded, and Feynman propagators

$$\boxed{V(\mathbf{r},\xi) = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3}\left(e^{i\mathbf{p}\cdot\mathbf{r}}-1\right)\frac{1}{2}\left(D^{*}{}^{L}_{R} + D^{*}{}^{L}_{A} + D^{*}{}^{L}_{F}\right)}$$

Real part can be written as

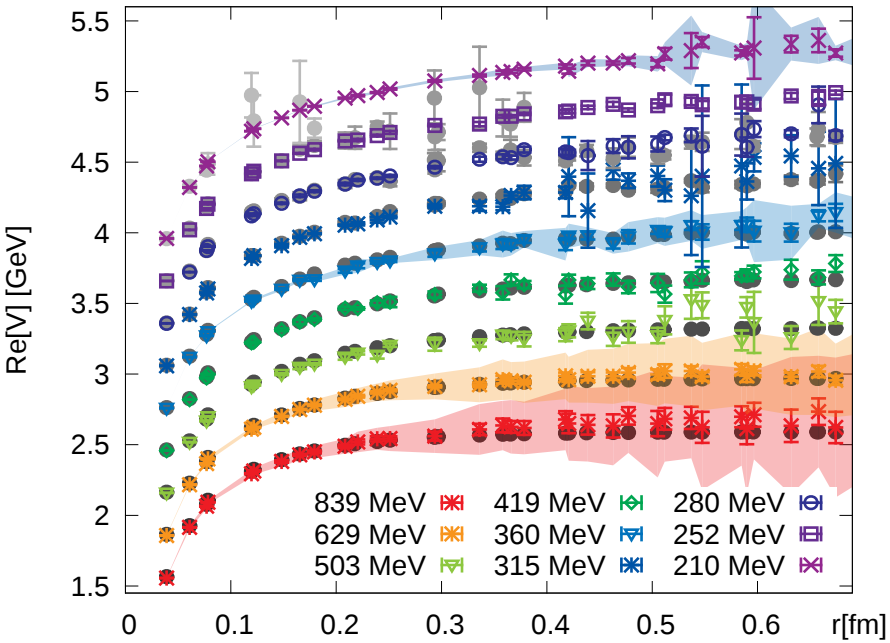
$$\mathrm{Re}[V(\mathbf{r},\xi)] = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, e^{i\mathbf{p}\cdot\mathbf{r}} \frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

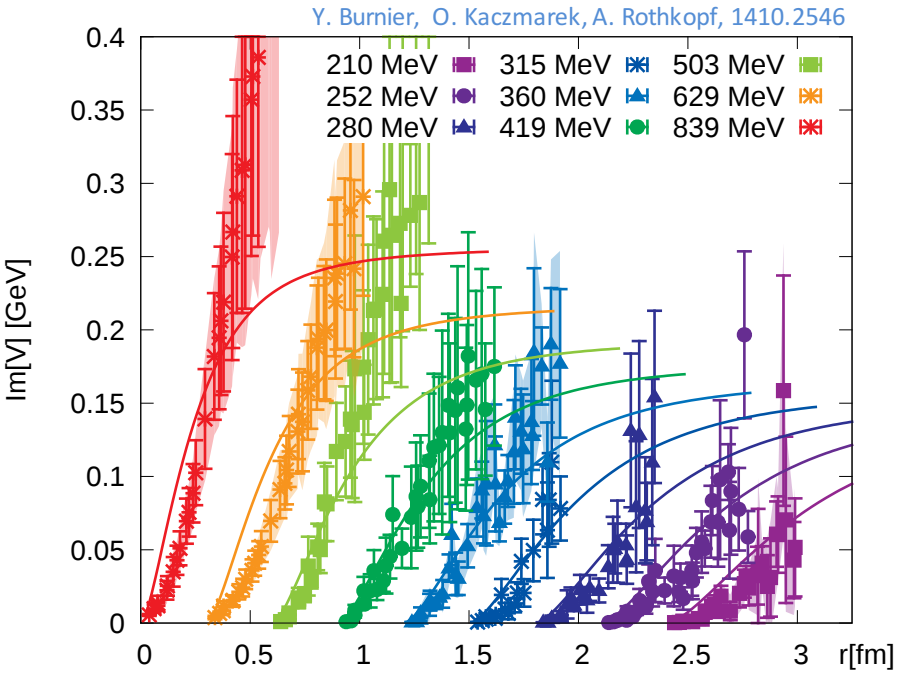
With <u>direction-dependent masses</u>, e.g.

$$m_\alpha^2 = -\frac{m_D^2}{2p_\perp^2\sqrt{\xi}}\left(p_z^2 \arctan\sqrt{\xi} - \frac{p_z \mathbf{p}^2}{\sqrt{\mathbf{p}^2+\xi p_\perp^2}}\arctan\frac{\sqrt{\xi}p_z}{\sqrt{\mathbf{p}^2+\xi p_\perp^2}}\right)$$

Anisotropic potential calculation: Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Gluon propagator in an anisotropic plasma: Romatschke and MS, hep-ph/0304092

Sanity check





- Results above are the real and imaginary part of the heavy quark potential extracted from the lattice.
- For the imaginary part, the authors also compare with the isotropic Im[V] indicated on the previous slide.

Other pieces of the puzzle

pp reference

Experimental measurements rely on R_{AA} which is **defined relative to the pp cross section**; therefore, we need reliable pp reference data and a firm theoretical understanding of open- and closed-charm production in pp collisions

Cold nuclear matter effects

Quarkonia production is also affected by **nuclear-modified PDFs, Cronin effect, and comovers** which result in enhancement or suppression of quarkonia production depending on the kinematic window.

Regeneration

If the population of open and closed-charm states is high, then it is possible for quarkonia to be regenerated through **recombination of open heavy flavor with a liberated heavy flavor**. There can also be local recombination of an individual bound state due to medium interactions.

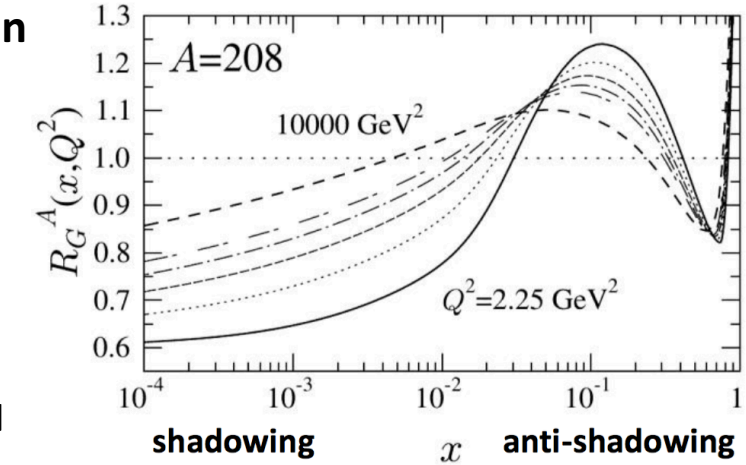
Viscous QGP modeling

Quarkonia are sensitive to the full spatio-temporal evolution of the QGP. Need to compute dynamical processes including non-equilibrium corrections. **Should use codes that reproduce experimental data for bulk observables** such as particle spectra and azimuthal flow.

Quarkonia production in pA

Cold nuclear matter effects

- **Can enhance or suppress quarkonium production**
  - **Nuclear PDFs:**
    - Shadowing: decreases production
    - Anti-shadowing: increases production
  - **Color Glass Condensate (CGC):** high gluon occupation numbers can affect production
  - **Cronin effect:** broadening of p_T spectra due to NN interactions in nucleus
  - **Nuclear absorption:** disassociation of a bound state passing through a nucleus
  - **Parton energy loss:** elastic scattering when moving through the nucleus before hard scattering
  - **Comover absorption:** hadrons propagating together with the bound state interact with it, e.g. $J/\psi + \pi \rightarrow D + D + X$
- Cold nuclear matter effects present in pA and AA collisions; **less important for bottomonia**



Bjorken x for Υ(1S)

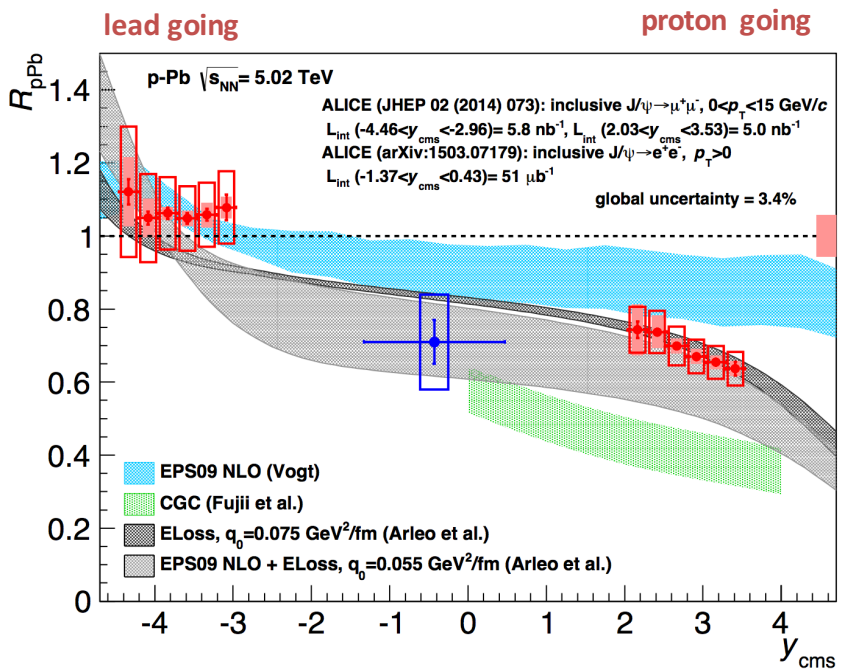
Ballpark estimate for $g + g \rightarrow \Upsilon(1s)$

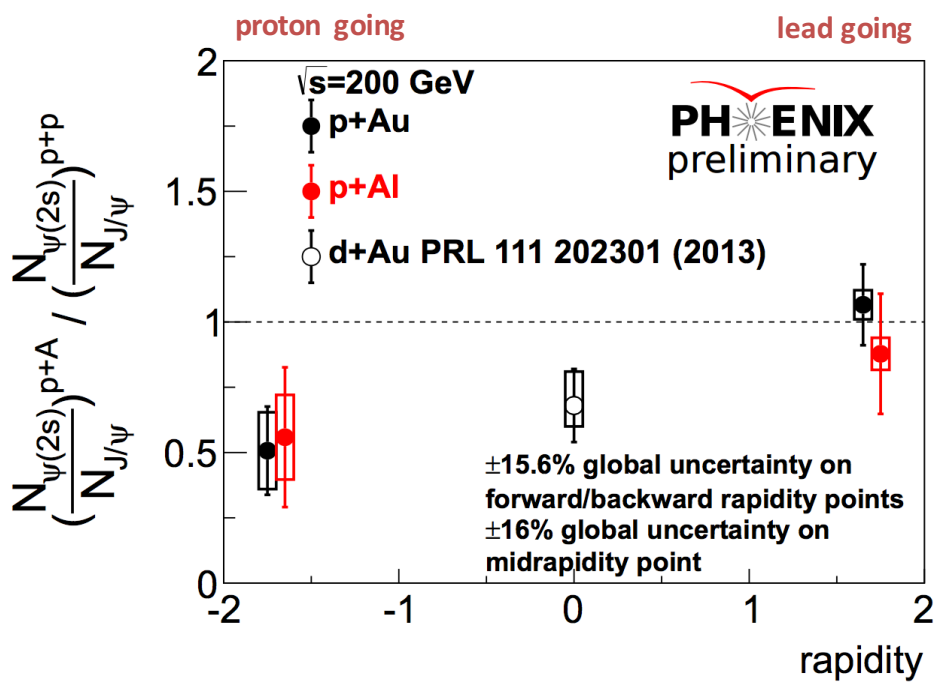
$$x_{1,2} = \frac{M}{\sqrt{s_{NN}}} e^{\pm y_{CM}}$$

p going
$5 \times 10^{-5} < x < 2 \times 10^{-4}$ → shadowing

Pb going
$4 \times 10^{-2} < x < 2 \times 10^{-1}$ → anti-shadowing

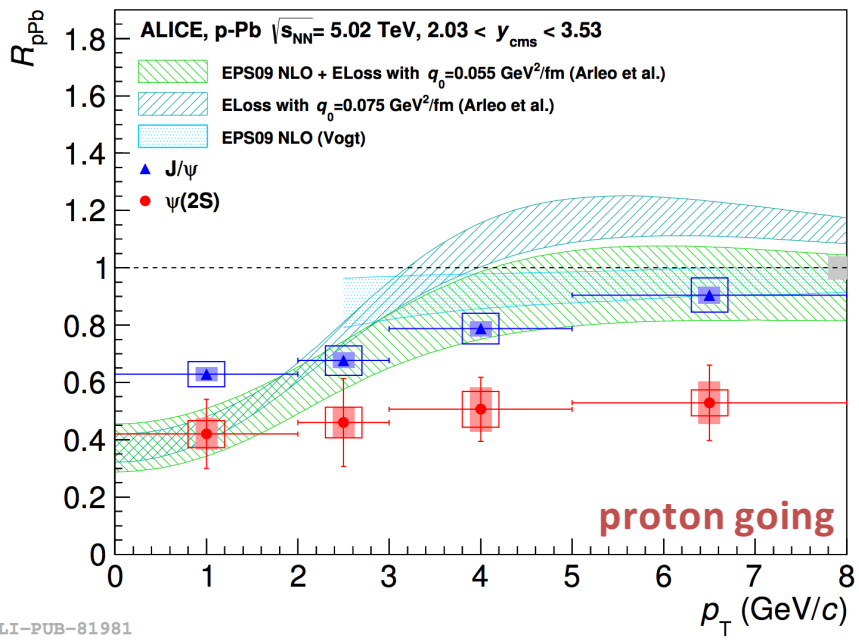
pA - Charmonia states

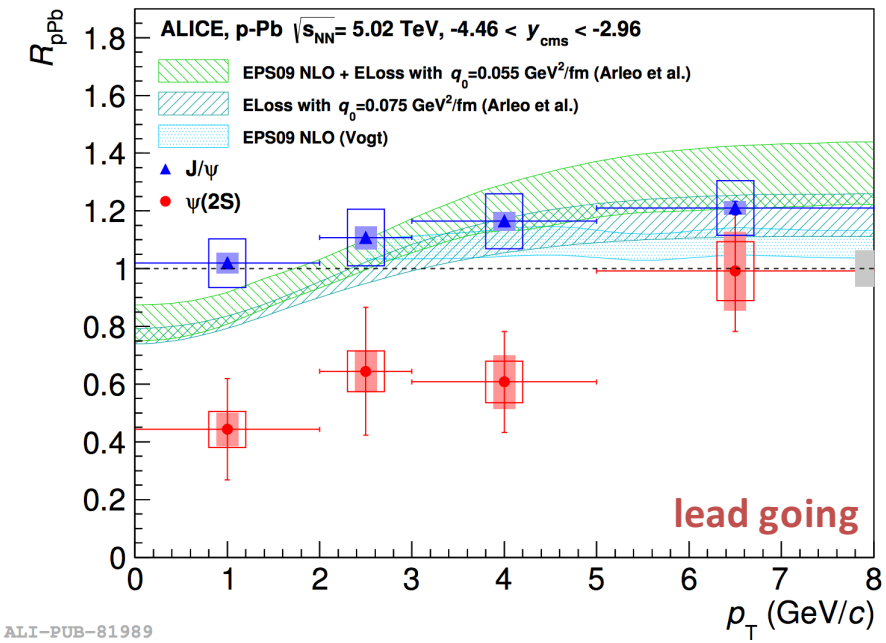




- Coherent energy loss and shadowing can explain the main characteristics of J/ψ production due to CNM.
- For charmonia, CNM effects must be taken into account in order to properly interpret the AA suppression data

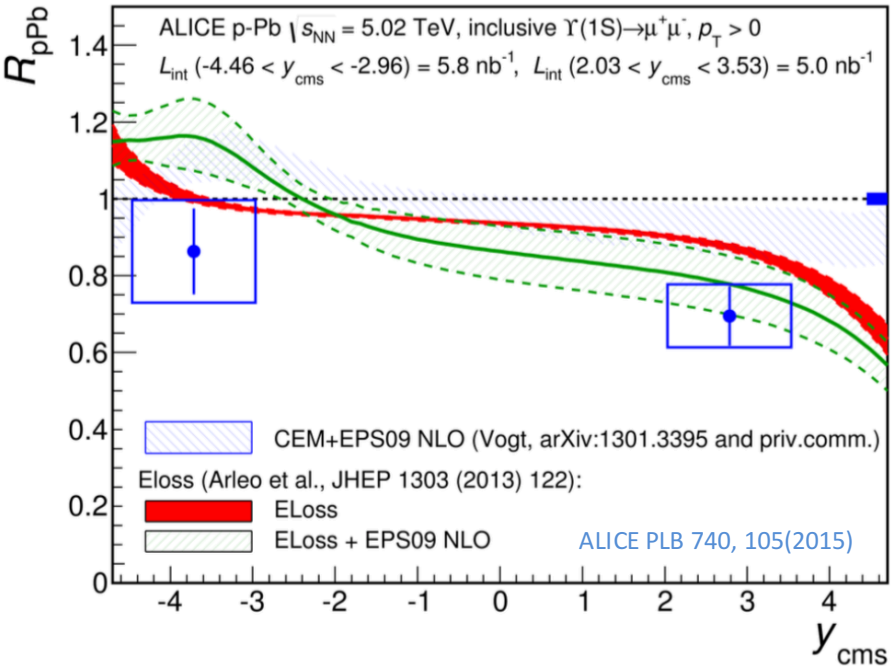
pA - Charmonia states

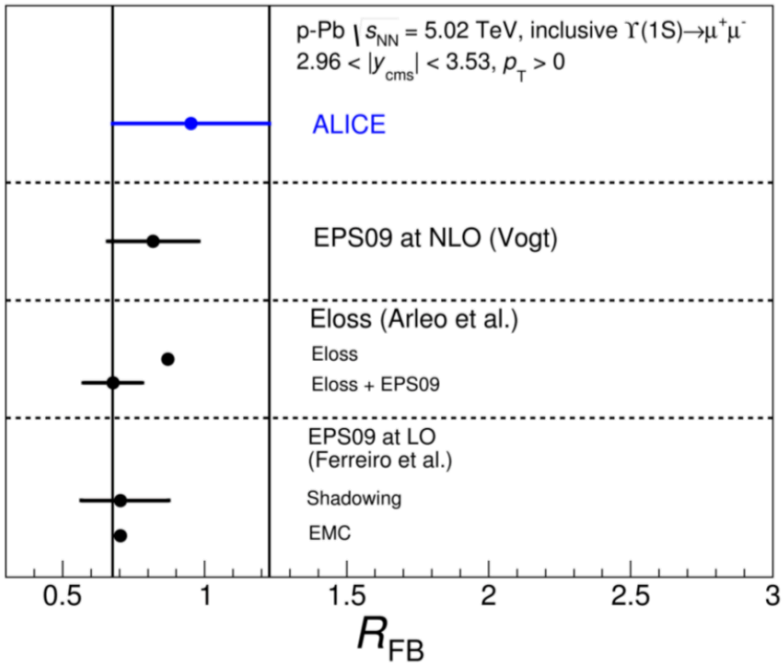




- Backward and forward rapidity: larger ψ(2s) suppression relative to the J/ψ
- R_{pPb} increases with p_T
- In most models shadowing and energy loss are expected to be almost identical; cannot describe the large ψ(2s) suppression; need enhanced suppression from comovers?

pA - Bottomonia states

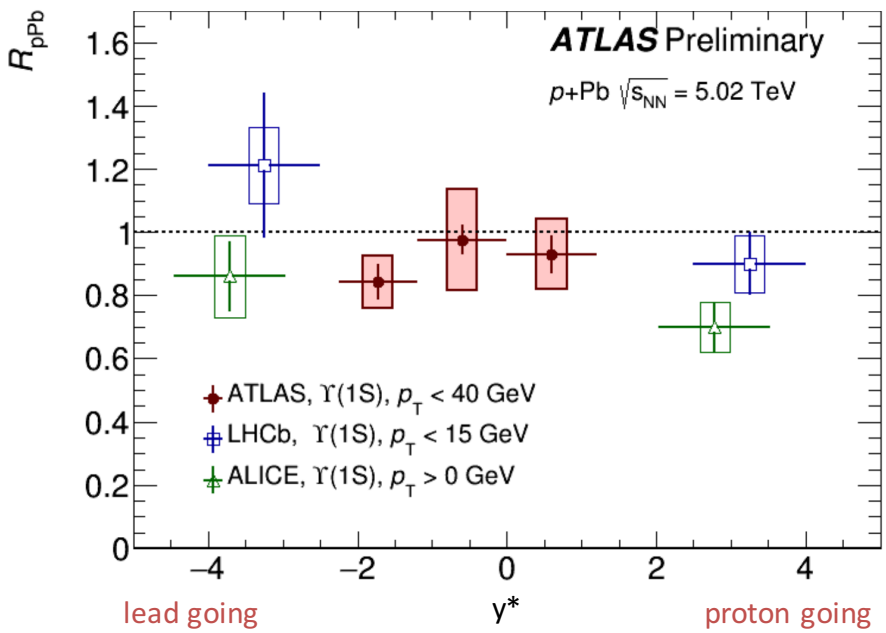


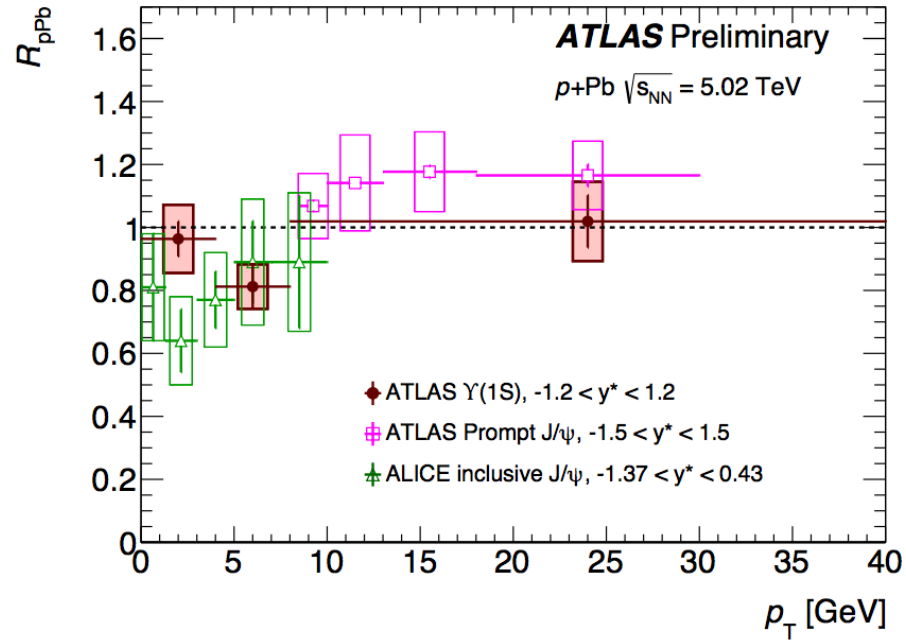


- No significant rapidity dependence of ϒ(1s) R_{pPb}
- Suppression at forward rapidity and R_{pPb} is consistent with unity at backward rapidity
- Models predict maximal CNM effect ~ 10-20% at central rapidity

pA - Bottomonia states

ATLAS-CONF-2015-050; ALICE, Phys. Lett. B740 105–117 (2015); LHCb, JHEP 07 (2014) 094

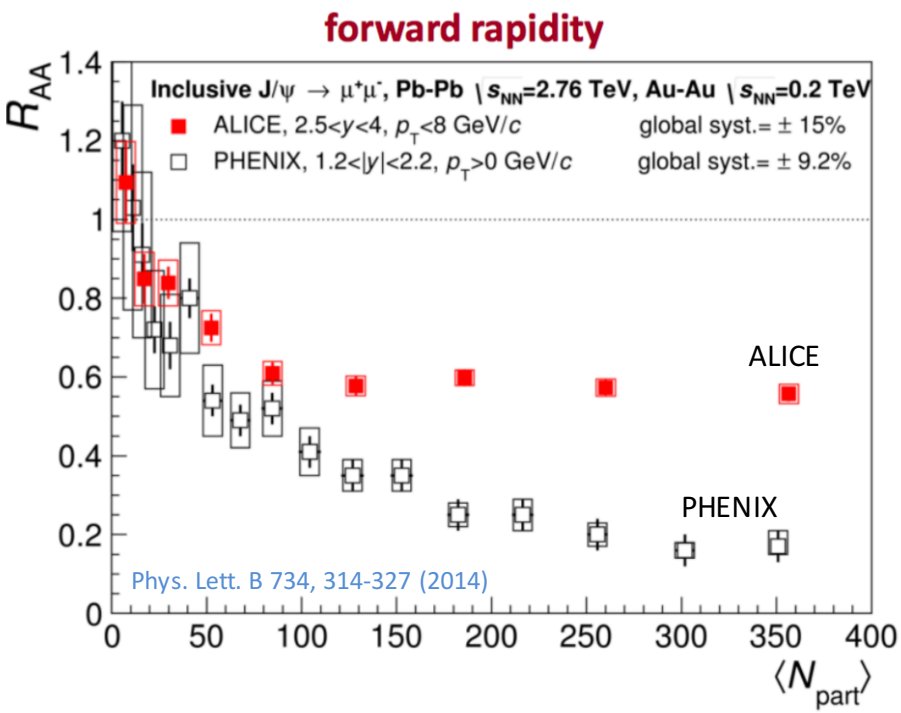


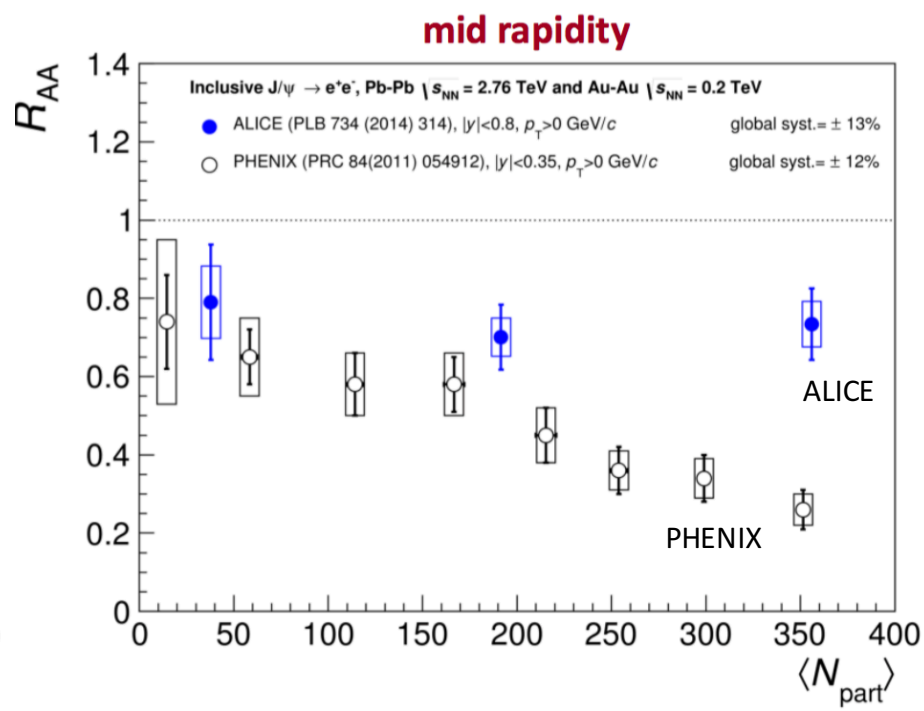


- The centrality dependence found is also rather flat
- R_{pPb} is consistent with unity, indicating weak cold nuclear matter effects on ϒ(1s) production
- Note, however, that the excited ϒ states measured by CMS show a stronger suppression with respect to the ϒ(1s), suggesting final state interactions or comover effect

Quarkonia production in AA

AA – Charmonia states

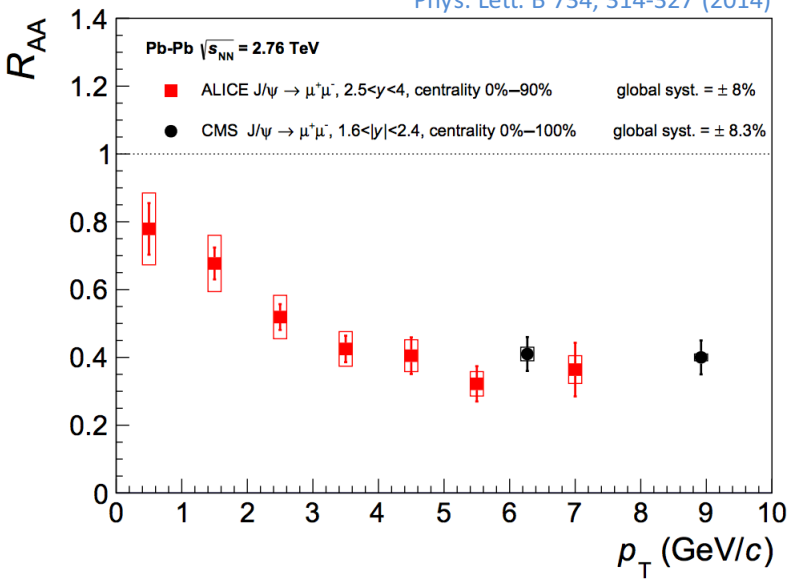


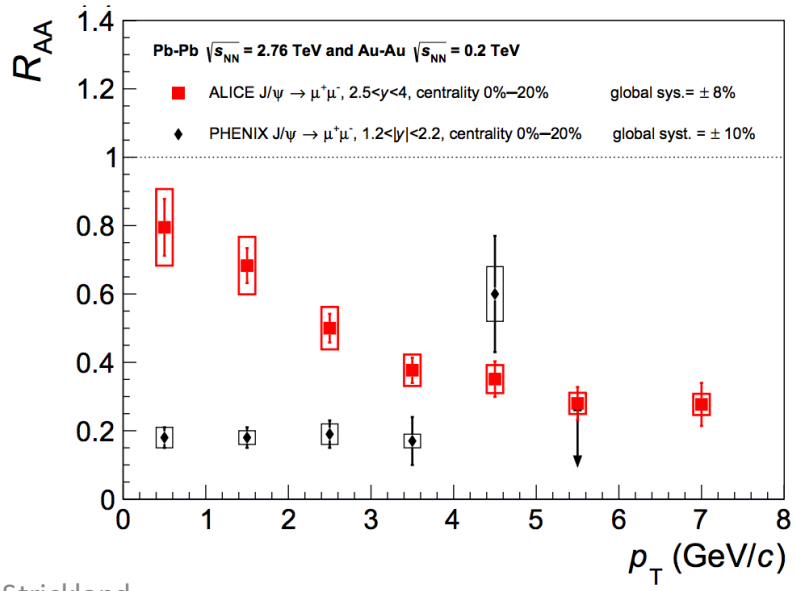


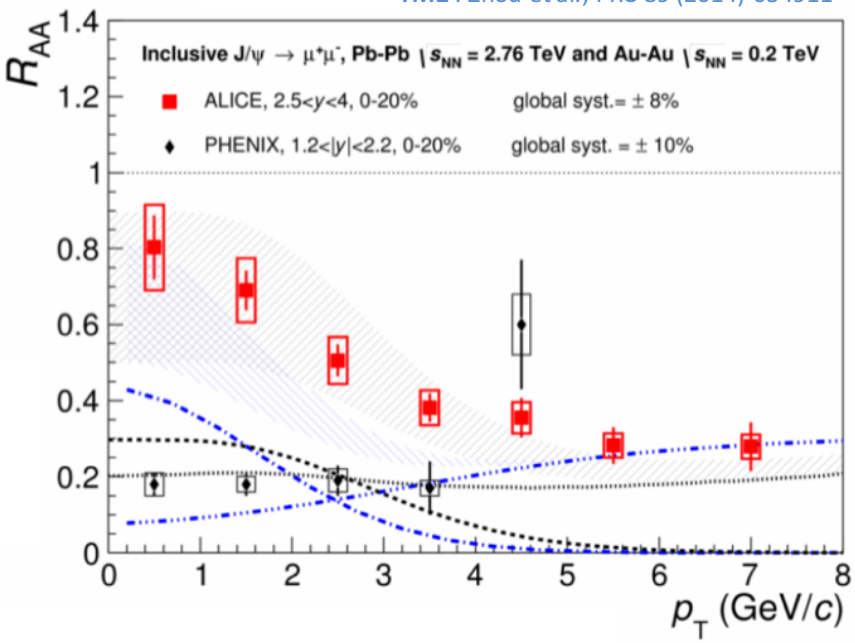
- Stronger J/ψ suppression at RHIC at both forward and mid rapidity!
- No significant centrality dependence for $N_{part} > 70$
- Evidence of regeneration of charmonia states?
- What about the p_T dependence?

AA – Charmonia states

Phys. Lett. B 734, 314-327 (2014)





- Dependence on p_T opposite from what is expected from QGP dissociation
- Models which include statistical regeneration explain the qualitative features well

Models
TM1: Zhao-Rapp NPA 859 (2011) 114
TM2 : Zhou et al., PRC 89 (2014) 054911