Quarkonia production (with a focus on bottomonia)

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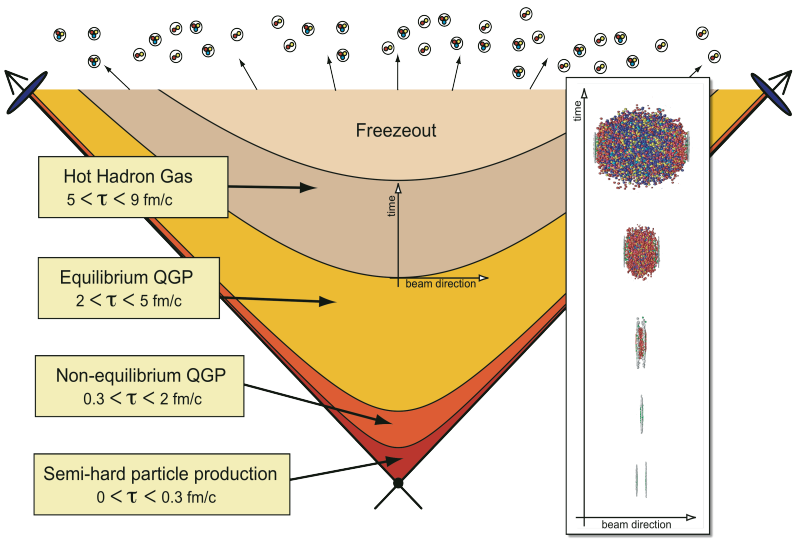
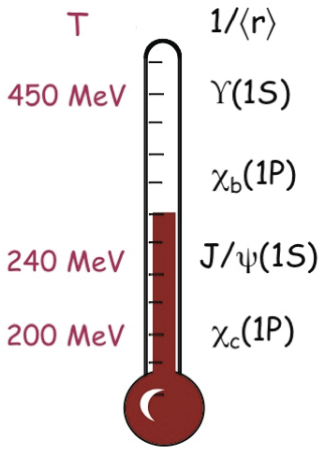
Why heavy quarkonia in AA?

- Ground state charmonium and bottomonium have vacuum binding energies on the order of 0.5 – 1 GeV, implying formation times that are less than ~ 0.5 fm/c
- They are rare probes
- Quarkonia masses are higher than the QGP temperature; therefore, thermal production is strongly suppressed
- From a theoretical perspective, one can make use of heavy quark effective theory to approach the problem systematically both (vacuum and finite T)





This cartoon is too simplistic! There are <u>no discrete thresholds in T</u>. More on this later…

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

Heavy Quarkonia Suppression

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

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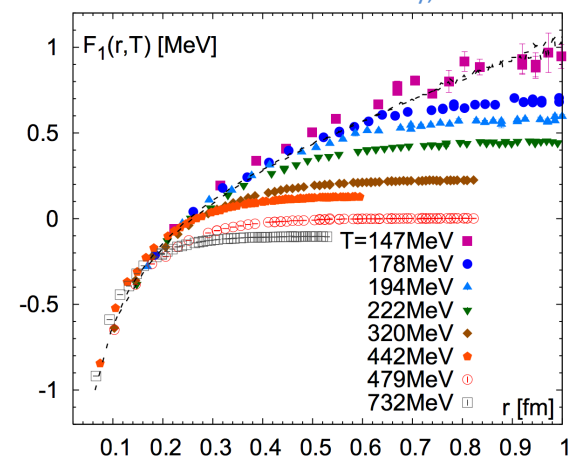
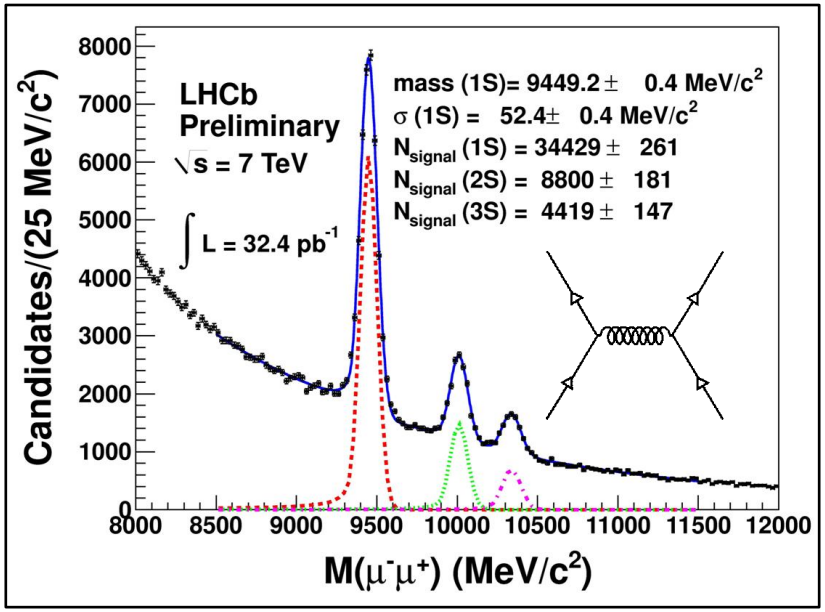
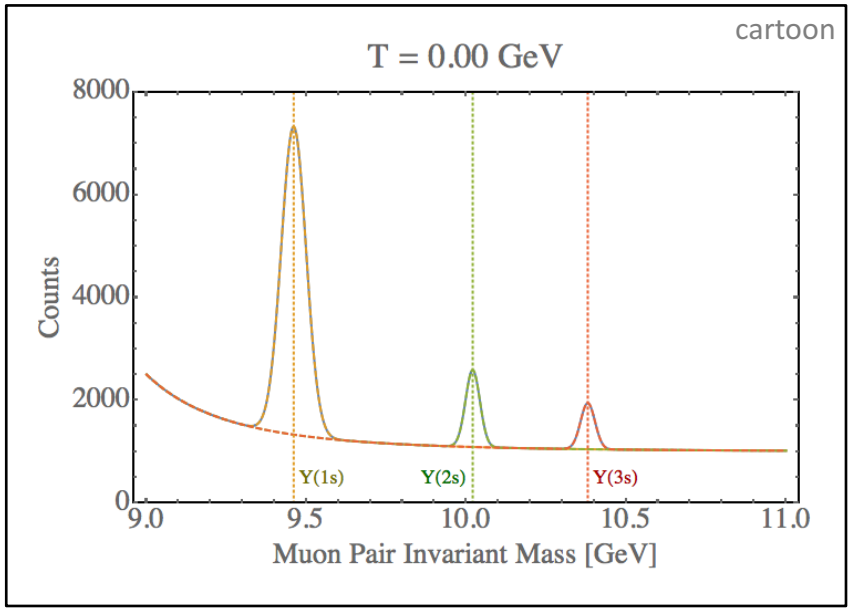
- Also, high energy plasma particles which slam into the bound states cause them to have shorter lifetimes → **larger spectral widths**

A. Bazavov and P. Petreczky, 1211.5638







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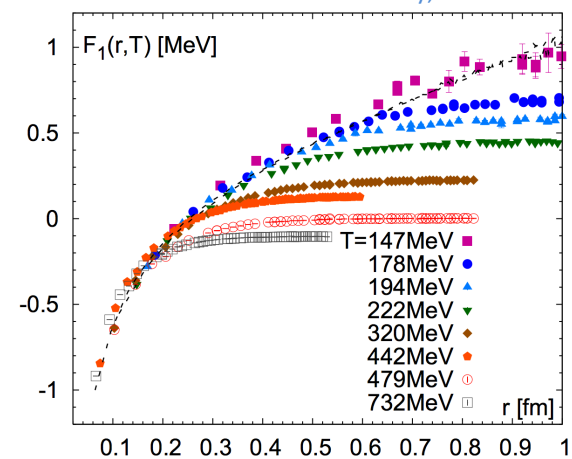

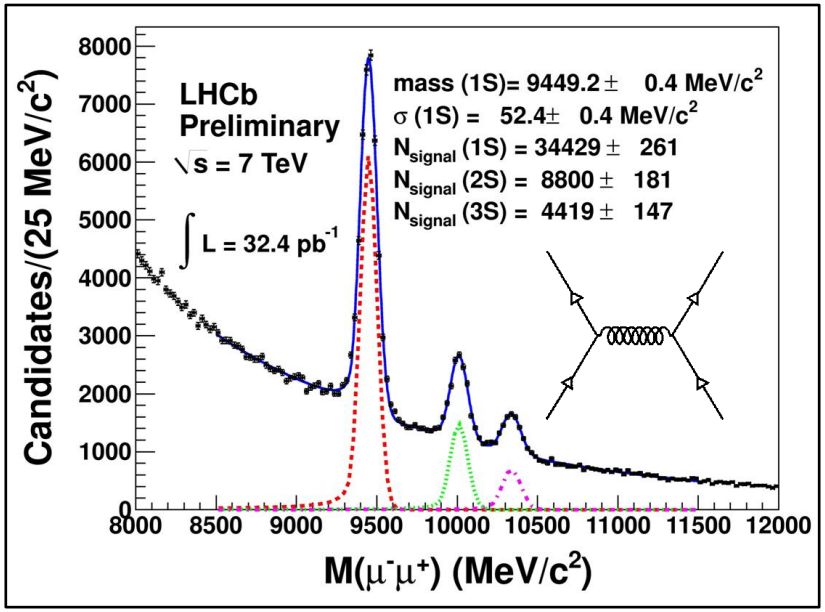

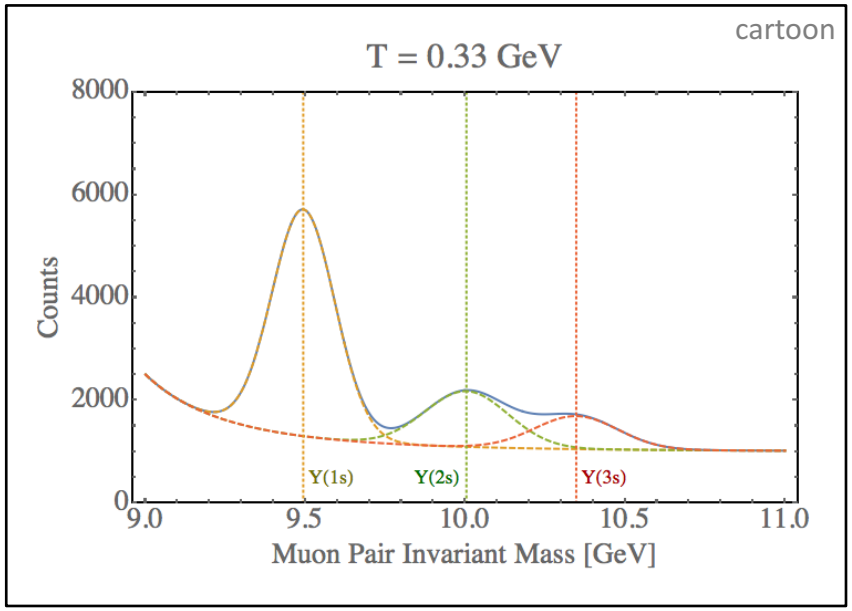

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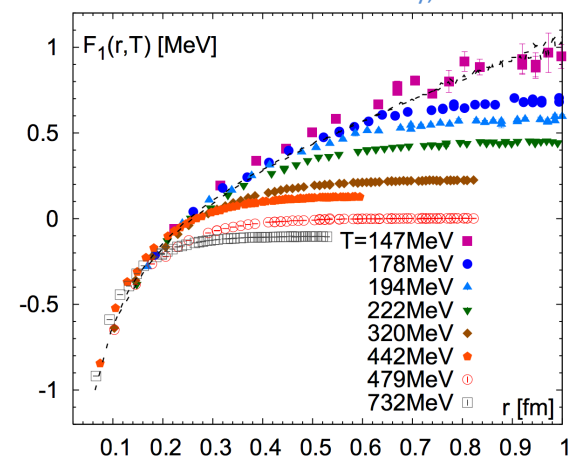

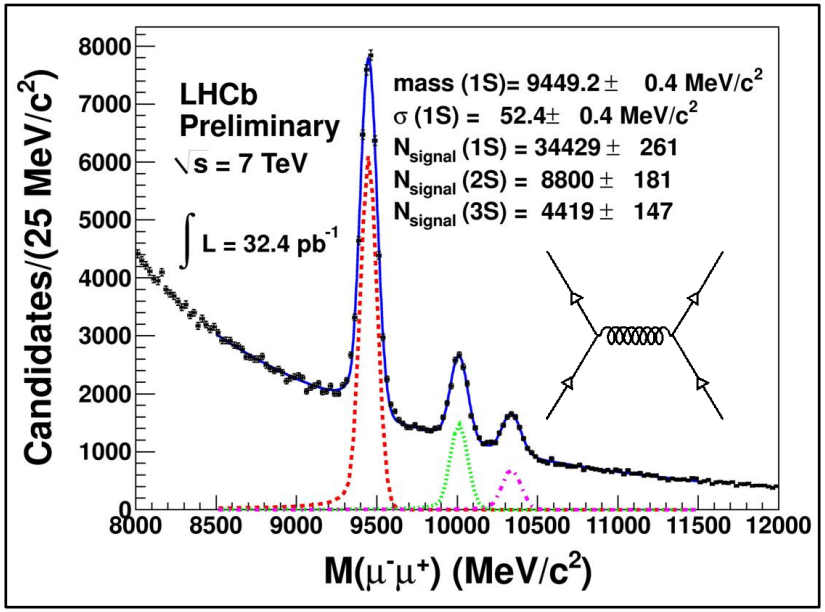

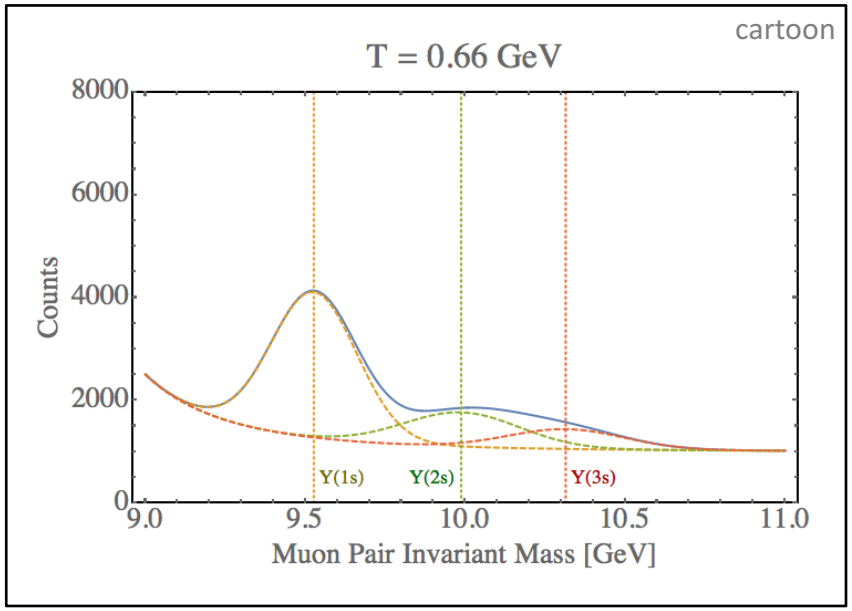

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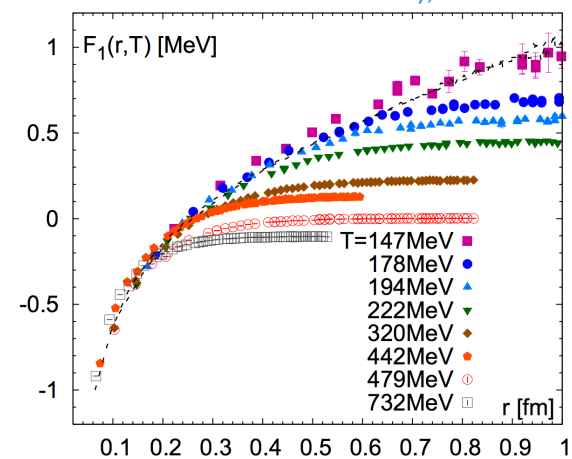

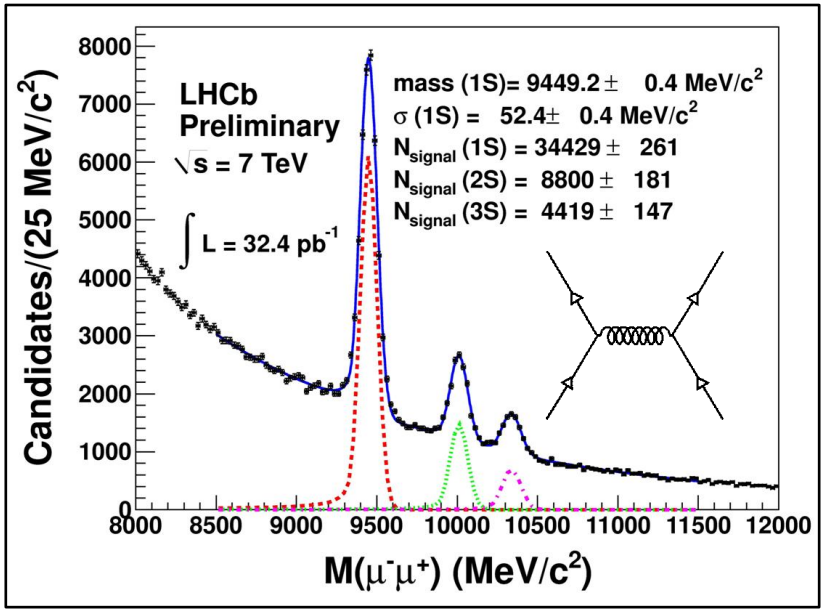

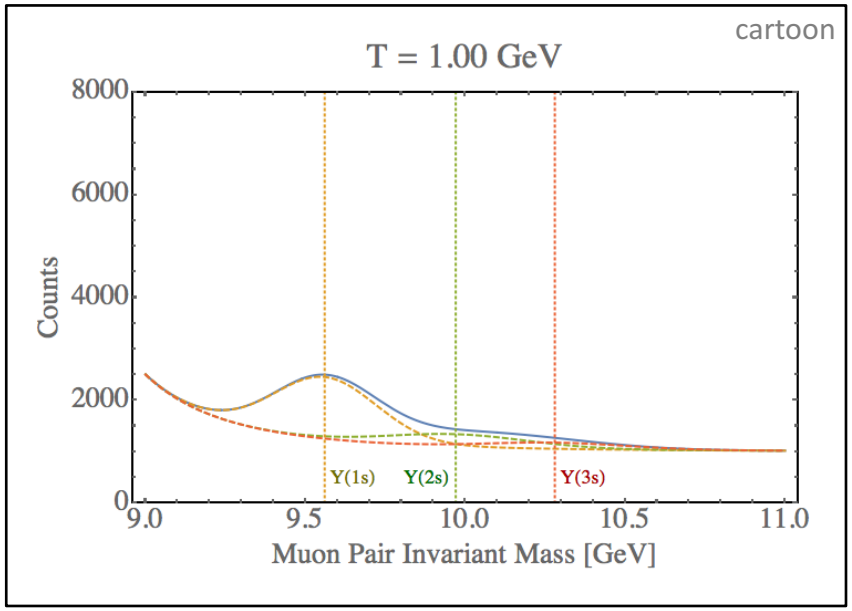

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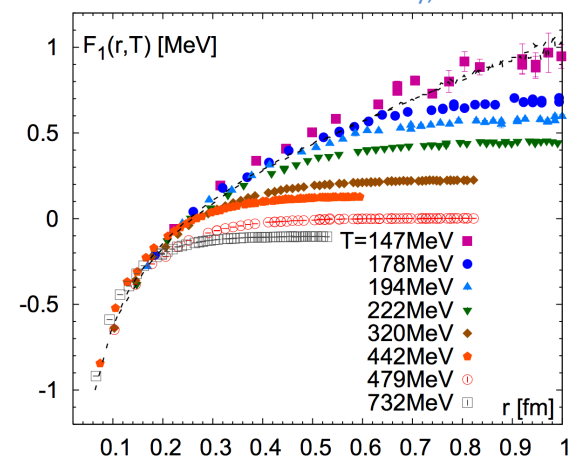
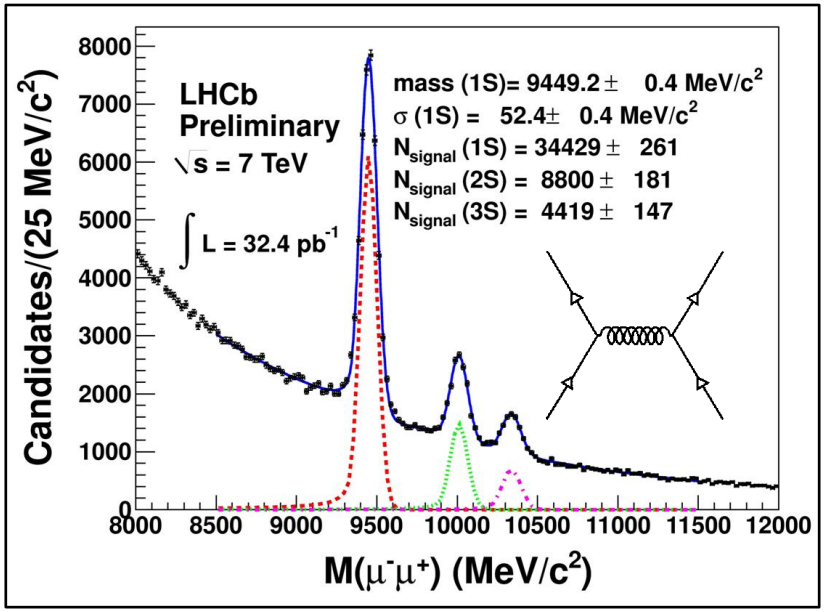
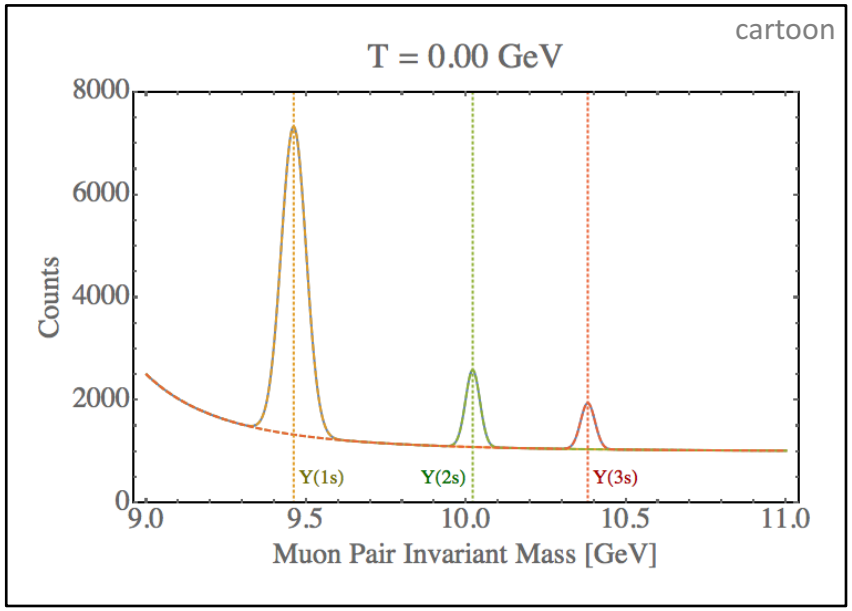
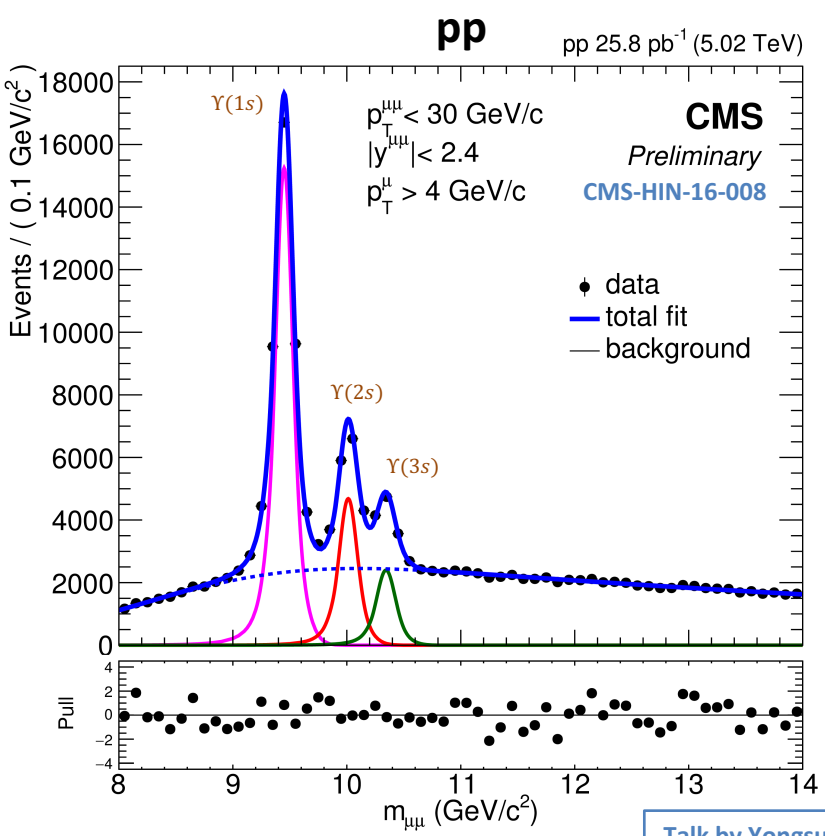


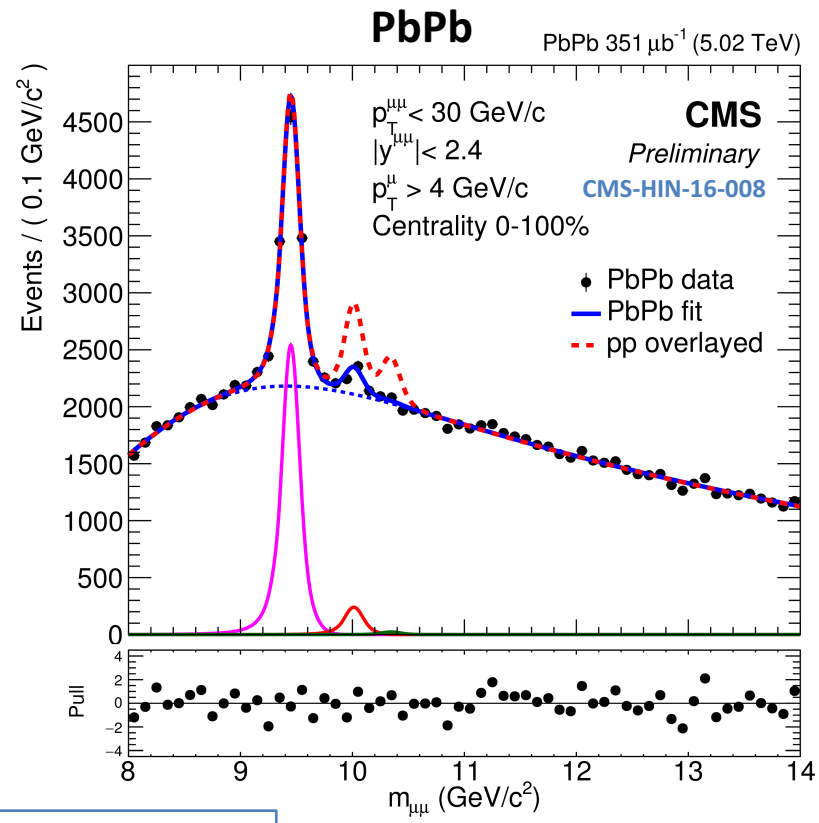




2016 CMS Data – 5.02 TeV Dimuon Spectra

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.

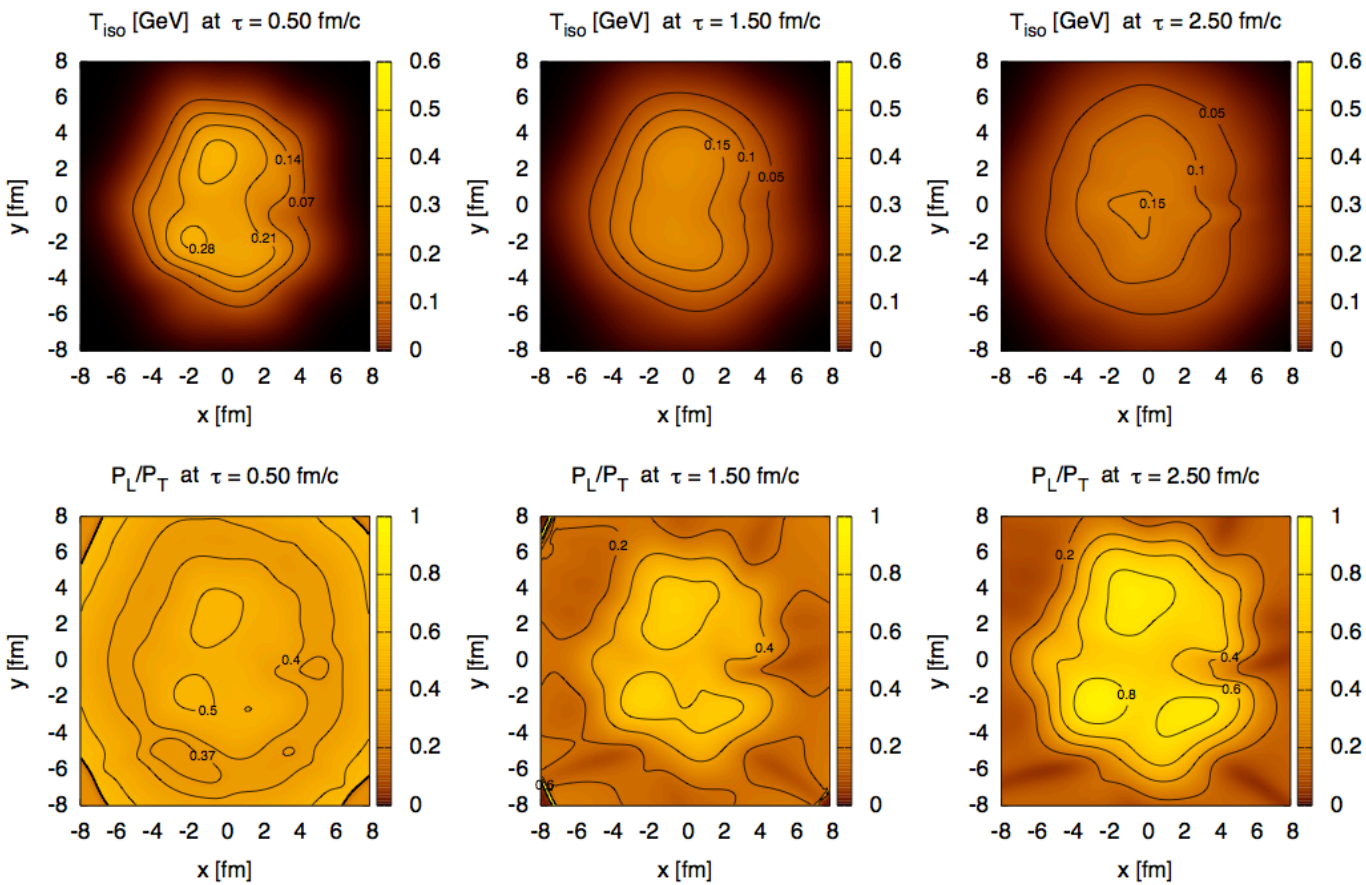




Talk by Yongsun Kim in this conference

Conceptually simple calculation

For in-medium suppression, 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

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 co-movers** which can 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.

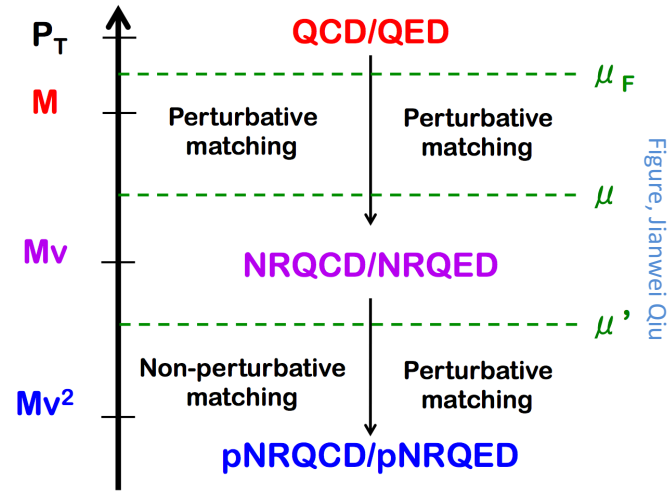
Viscous QGP modeling

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 pp

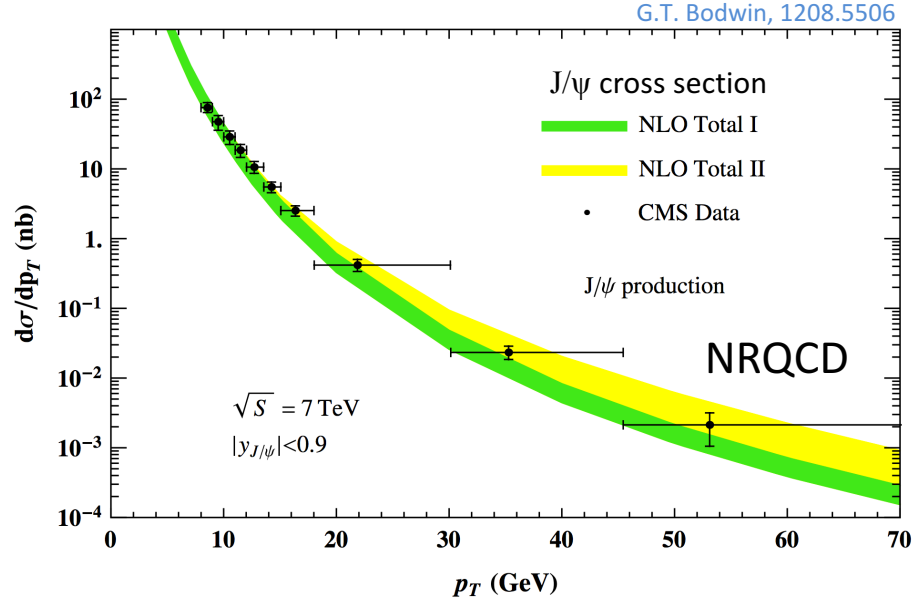
Quarkonia in pp collisions

- Produced in initial hard collisions
- Different theoretical approaches
  - **NRQCD factorization approach**
    Bodwin, Braaten, and Lepage
  - **Fragmentation approach**
    Kang, Qiu, and Sterman
  - **Color-singlet model (CSM)**
    Kartvelishvili, Likhoded, Slabospitsky, Chang, Baier, ...
  - **Color-evaporation model (CEM)**
    Fritzsch, Halzen, Amundson, Eboli, Gregores, Vogt, ...
  - **k_T - factorization approach**
    Yuan, Chao, Baranov, Zotov, and Szczurek



Figure, Jianwei Qiu

G.T. Bodwin, 1208.5506



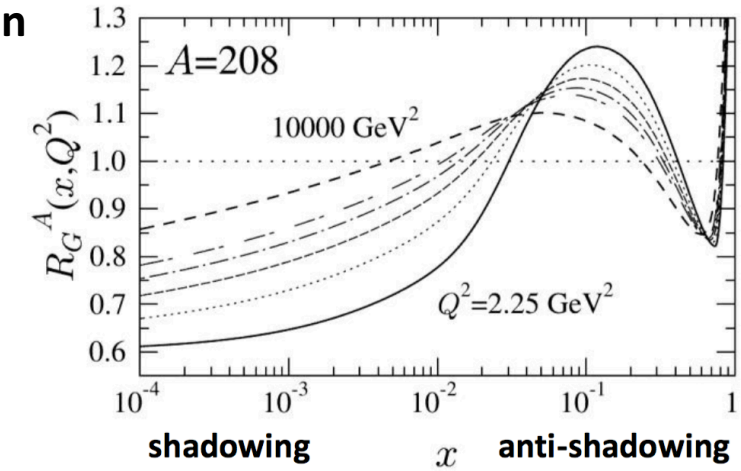
- <u>NRQCD factorization approach is the most successful</u>; in agreement with most of the inclusive production data (<u>polarized production still a problem</u>)
- Predictions of the color-singlet model fail to describe the data

For more details see talk of E.G. Ferreiro

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 (includes some of the other effects listed automatically)
  - **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
  - **Co-mover 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 Y(1S)

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

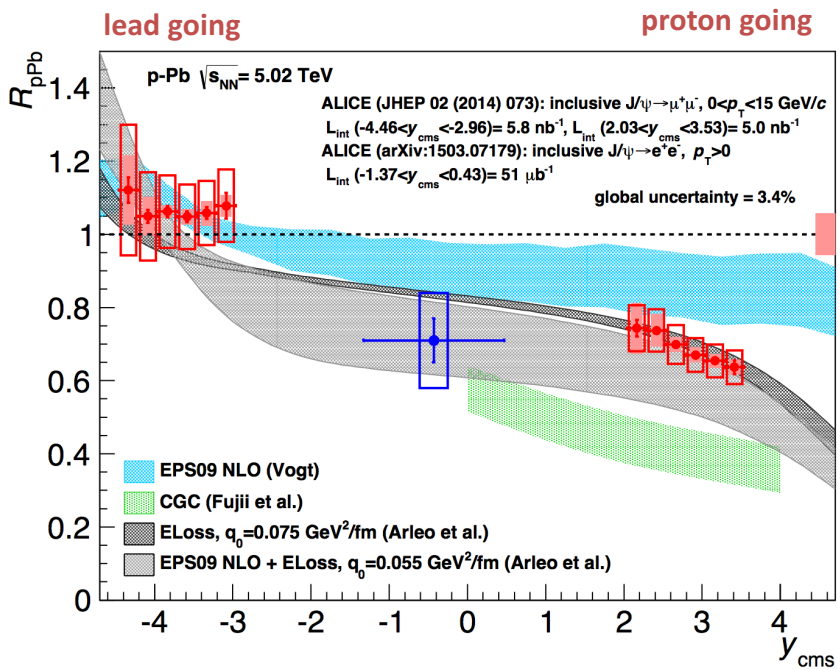
$$x_{1,2} = \frac{M}{\sqrt{s_{NN}}} e^{\pm y_{CM}}$$

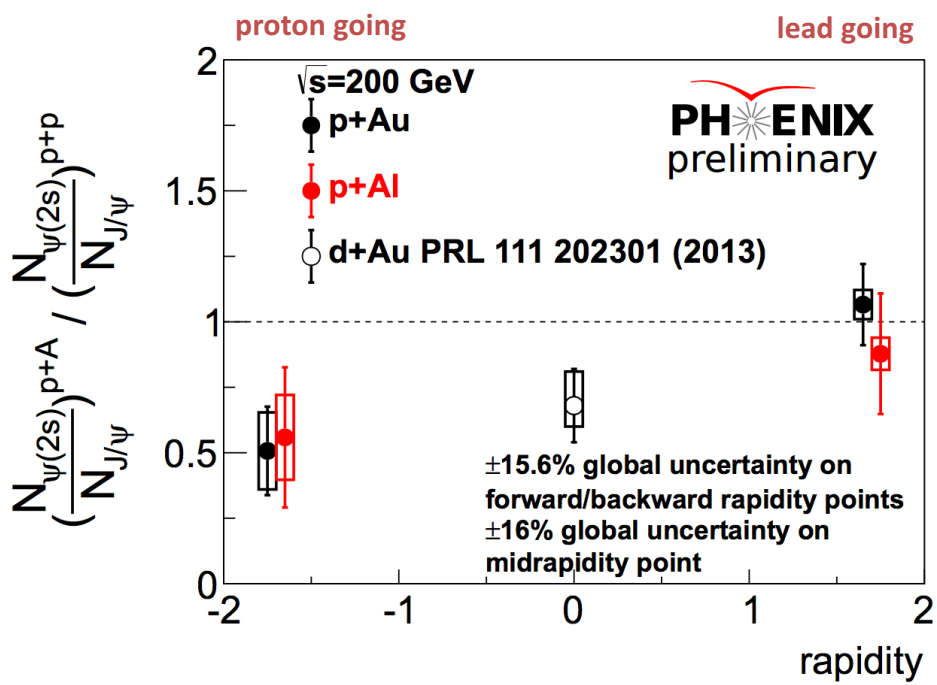
p going
$5 \times 10^{-5} < x < 2 \times 10^{-4}$ → shadowing

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

For more details see talk of F. Arleo and E.G. Ferreiro

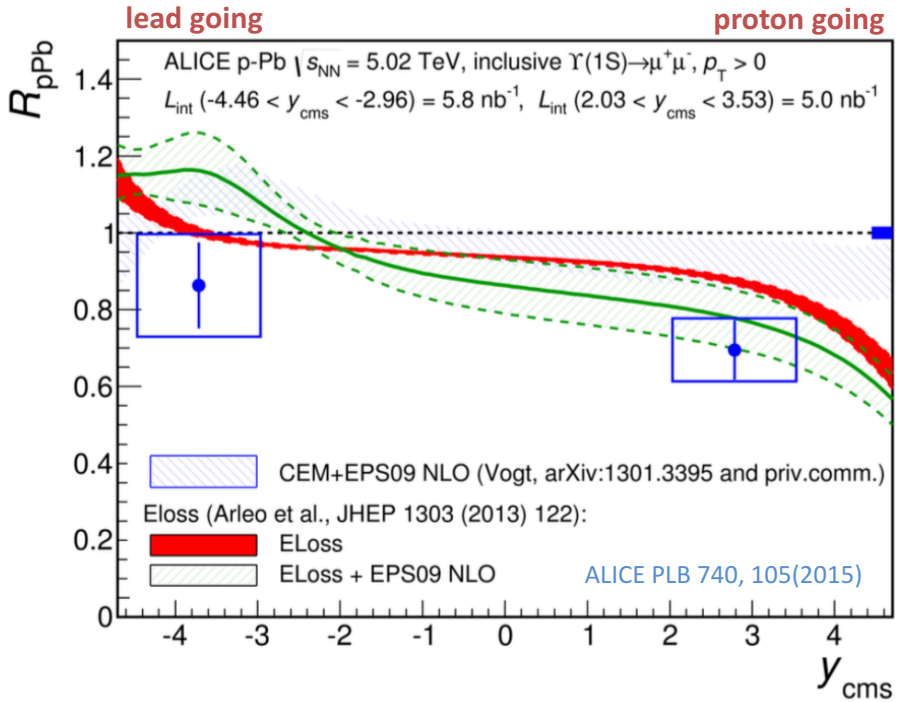
pA - Charmonia states

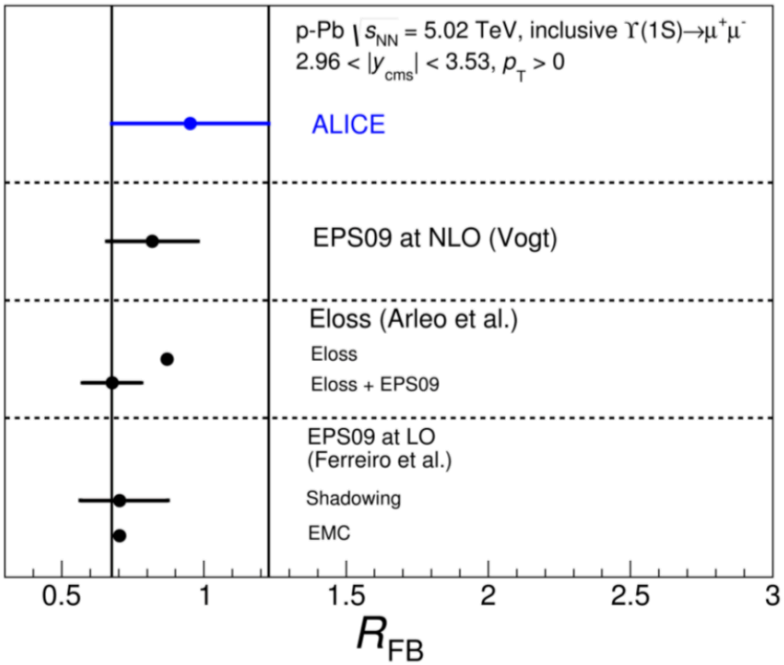




- Coherent energy loss and shadowing can explain the main characteristics of J/ψ production due to CNM.
- As a result, for charmonia, CNM effects must be taken into account in order to properly interpret the AA suppression data
- In most models shadowing and energy loss are expected to be almost identical
- However, this alone cannot describe the large ψ(2s) suppression; need enhanced suppression from **co-movers**?

pA - Bottomonia states

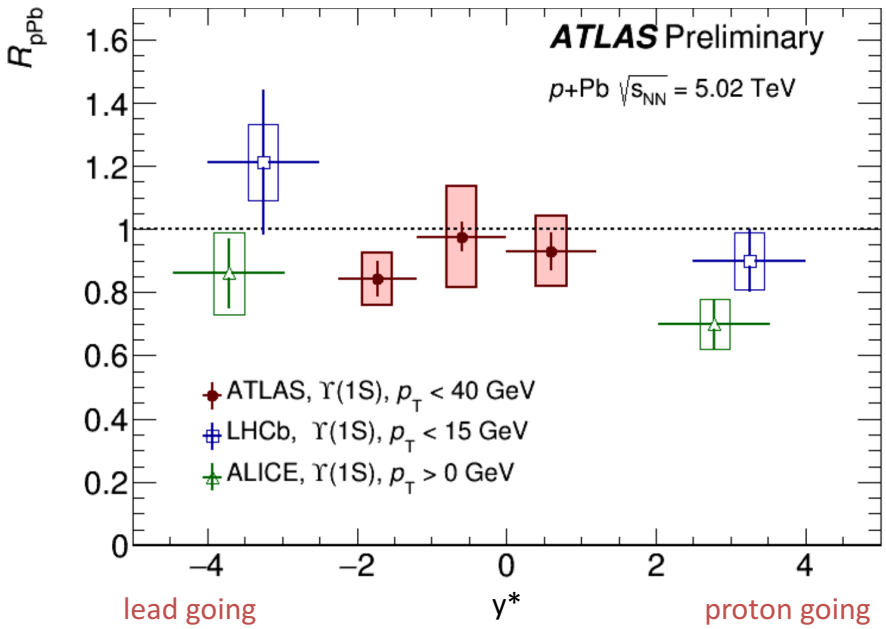


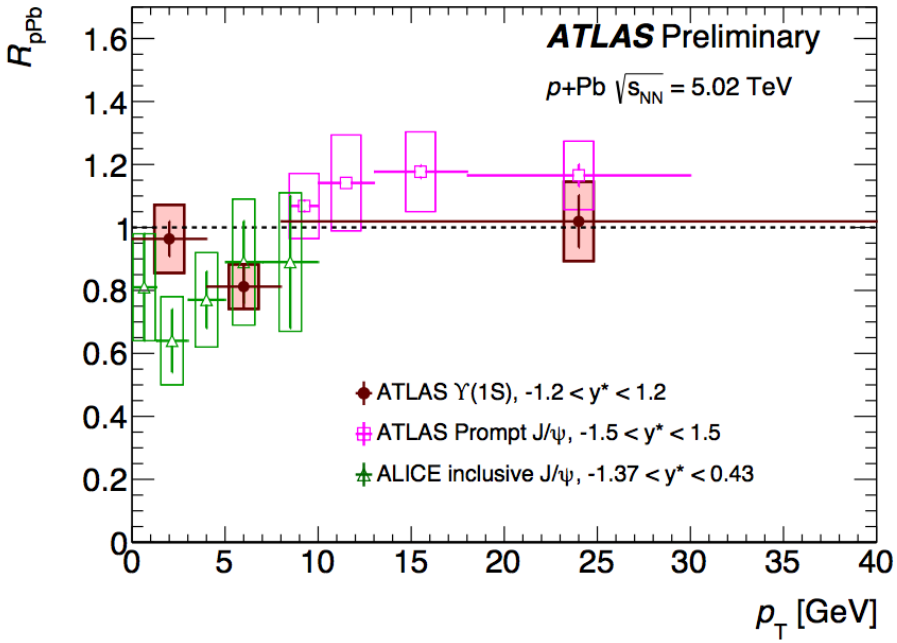


- No significant rapidity dependence of ϒ(1s) R_{pPb}
- Suppression at forward rapidity and R_{pPb} is consistent with unity at backward rapidity
- Models predict maximal CNM effect ~ 10-20% at central rapidity

pA - Bottomonia states

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

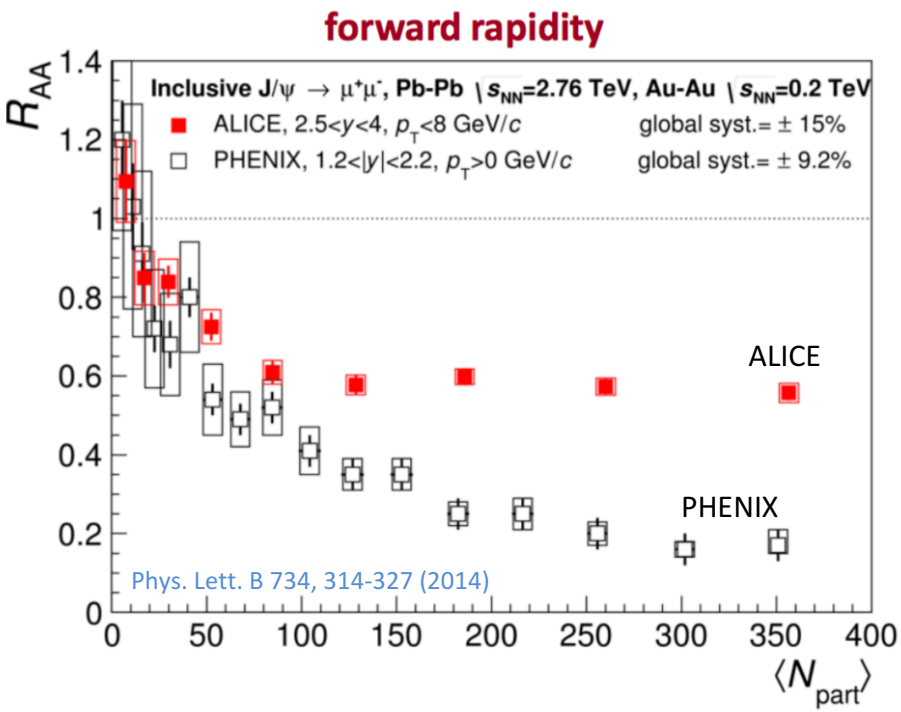


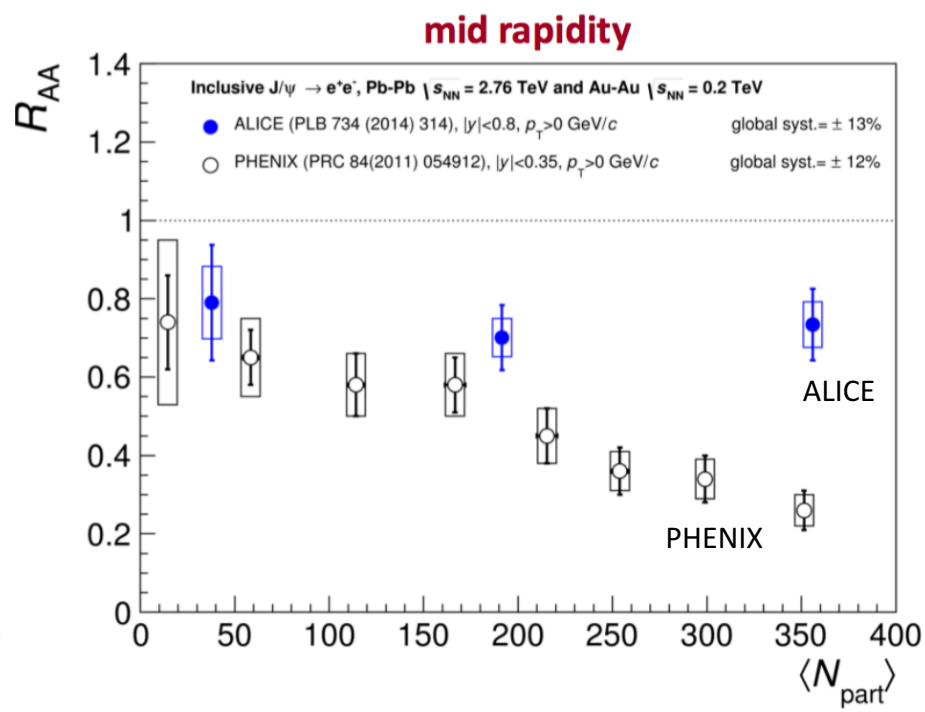


- The transverse momentum dependence is also rather flat.
- R_{pPb} is consistent with unity, indicating weak cold nuclear matter effects on ϒ(1s) production.
- Note, however, that the excited ϒ states measured by CMS show a stronger suppression with respect to the ϒ(1s), suggesting final state interactions or co-mover effect. Or is this perhaps a QGP droplet?

Quarkonia production in AA

AA – Charmonia states

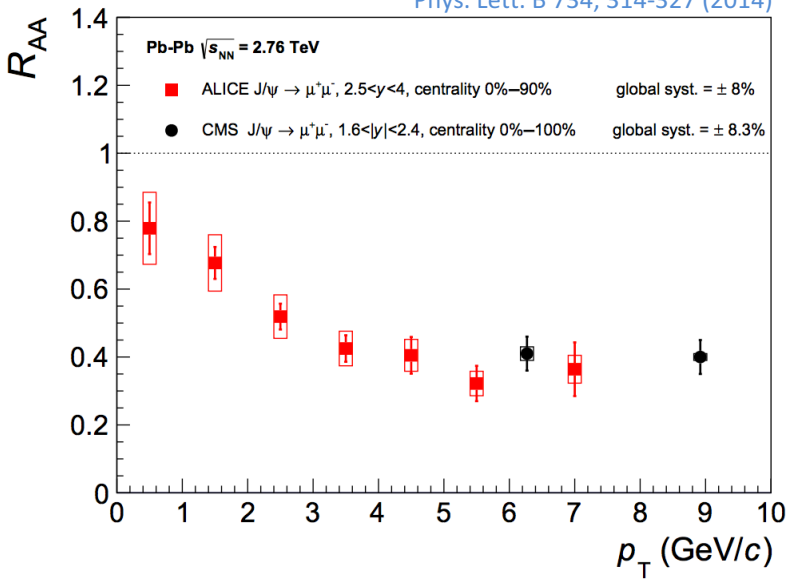


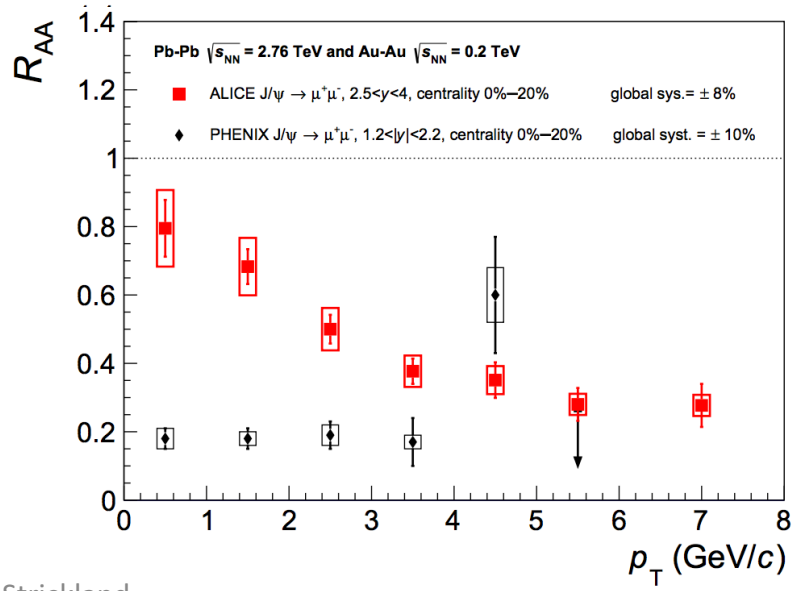


- Stronger J/ψ suppression at RHIC at both forward and mid rapidity!
- No significant centrality dependence for $N_{part} > 70$
- Evidence of regeneration of charmonia states?
- What about the p_T dependence?

AA – Charmonia states

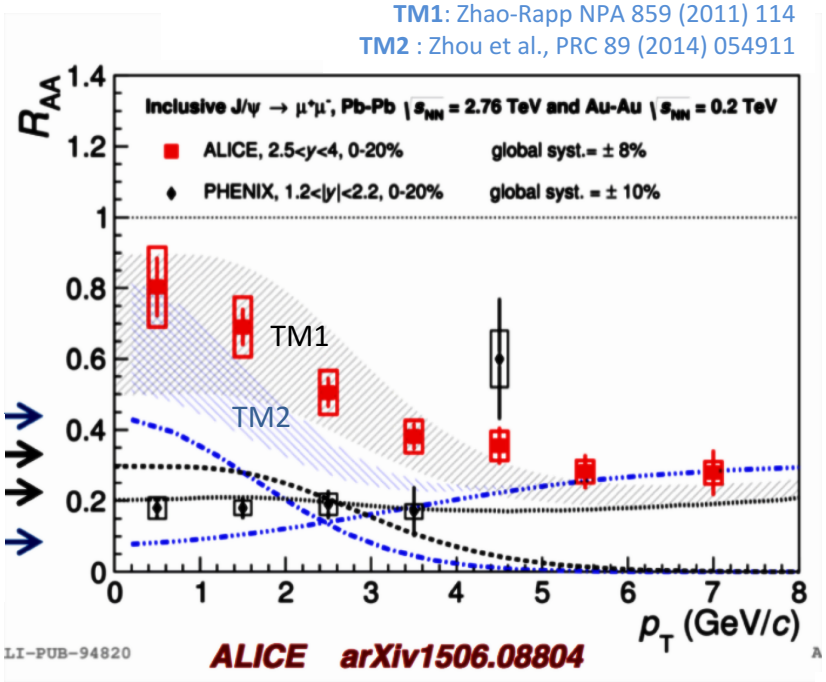
Phys. Lett. B 734, 314-327 (2014)





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

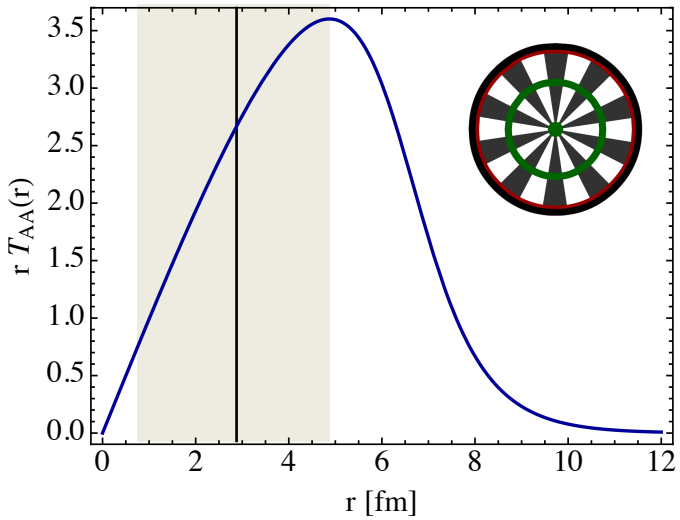
Models
TM1: Zhao-Rapp NPA 859 (2011) 114
TM2 : Zhou et al., PRC 89 (2014) 054911



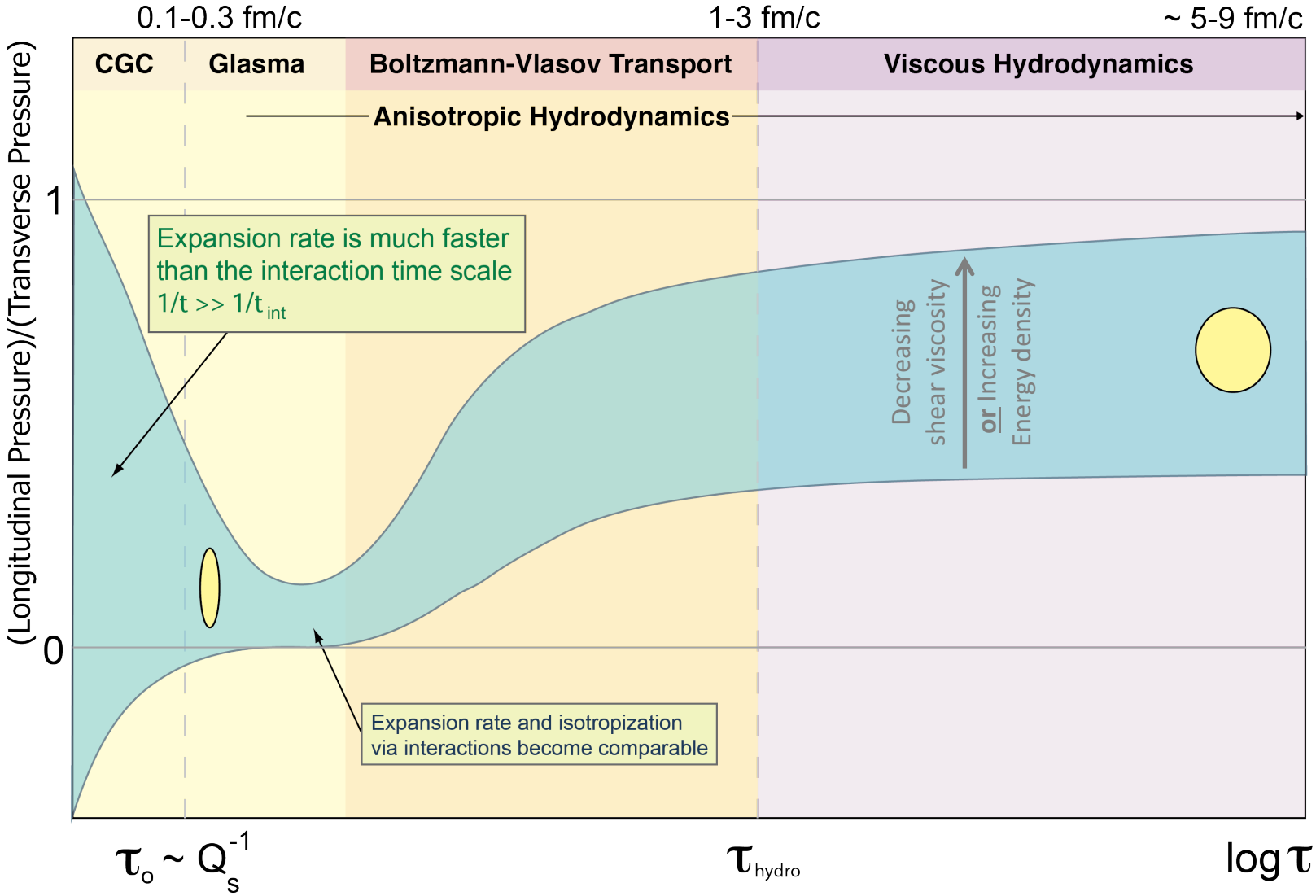
Bottomonia in AA
with some model details

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.
- **We need to reliably describe the dynamics in the full 3+1d volume.**



QGP momentum anisotropy cartoon



Complex-valued Potential

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

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

MS, 1106.2571; Bazow and MS, 1112.2761

- 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

- 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)

Summary of the method

Solve the 3d Schrödinger EQ with complex-valued potential

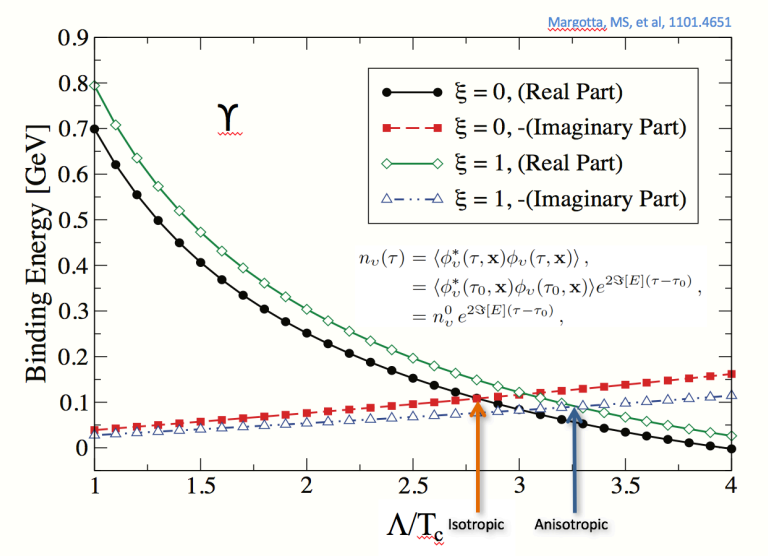
↓

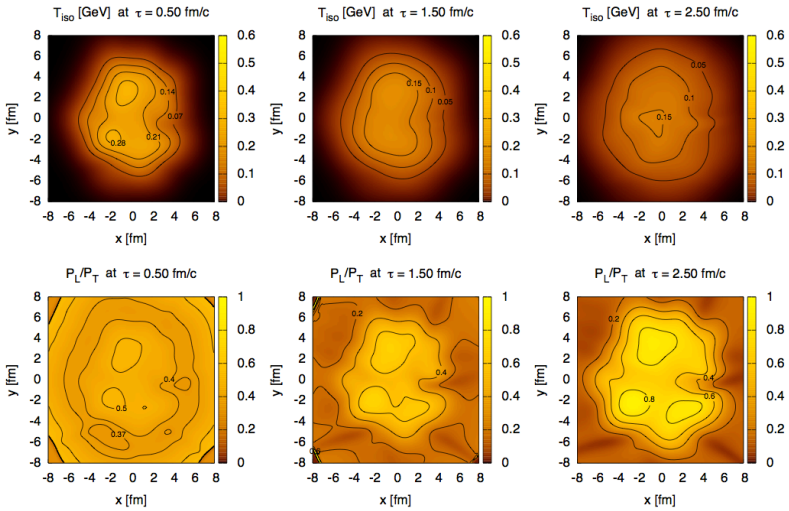
Obtain real and imaginary parts of the binding energies for the ϒ(1s), ϒ(2s), ϒ(3s), χ_{b1}, and χ_{b2} as function of energy density and anisotropy.

Yager-Elorriaga and MS, 0901.1998; Margotta, MS, et al, 1101.4651

↓

Fold together with the non-EQ spatiotemporal evolution to obtain the **survival probability**.





The suppression factor

- Resulting decay rate $\Gamma_T = -2\ \mathrm{Im}[E_{bind}]$ 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}

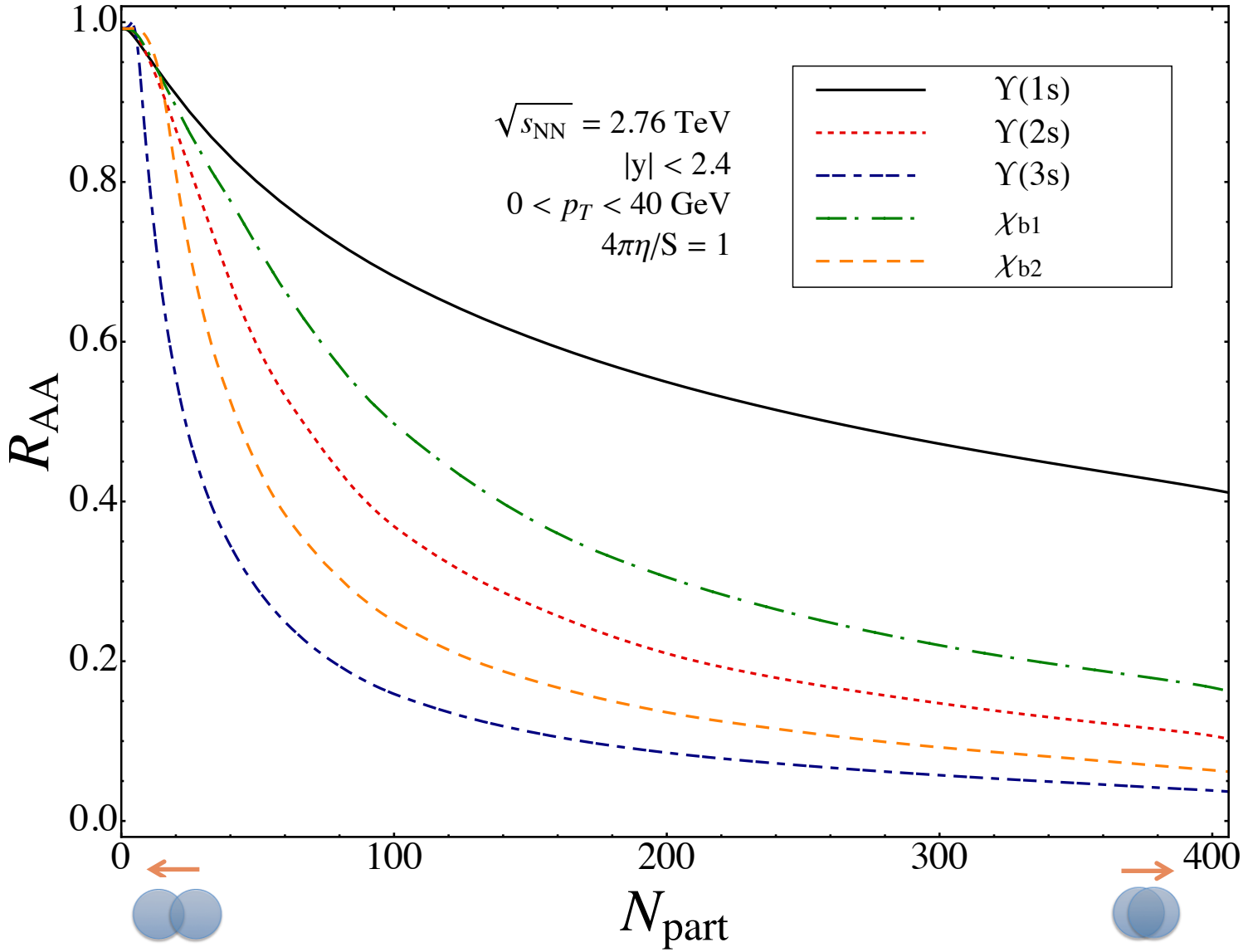
$$R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b) = \exp(-\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b))$$

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

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

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

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



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

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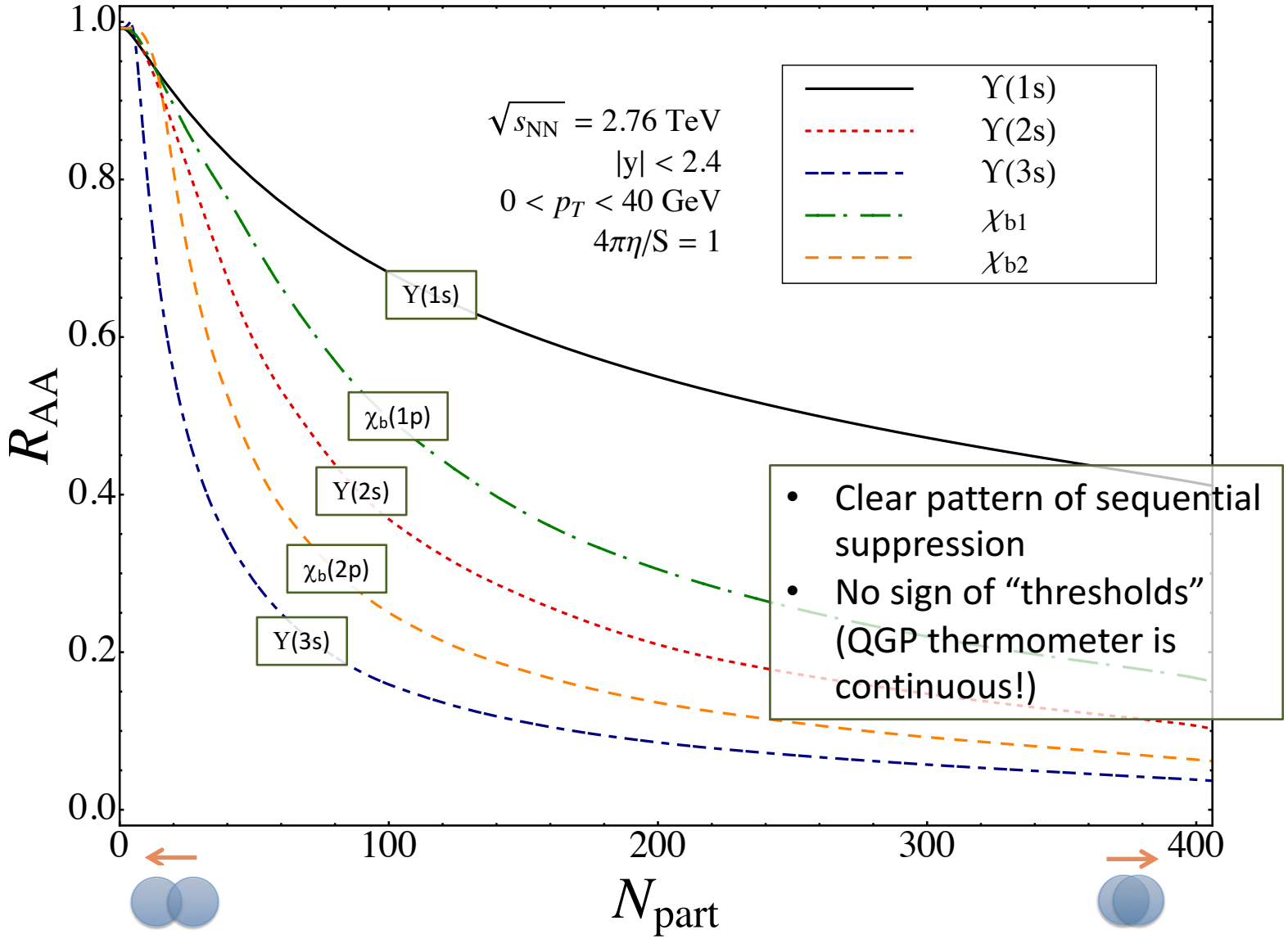
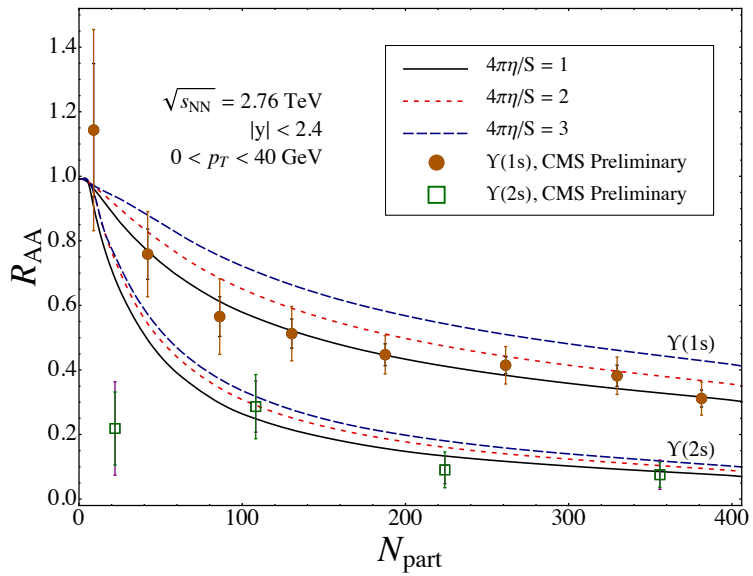


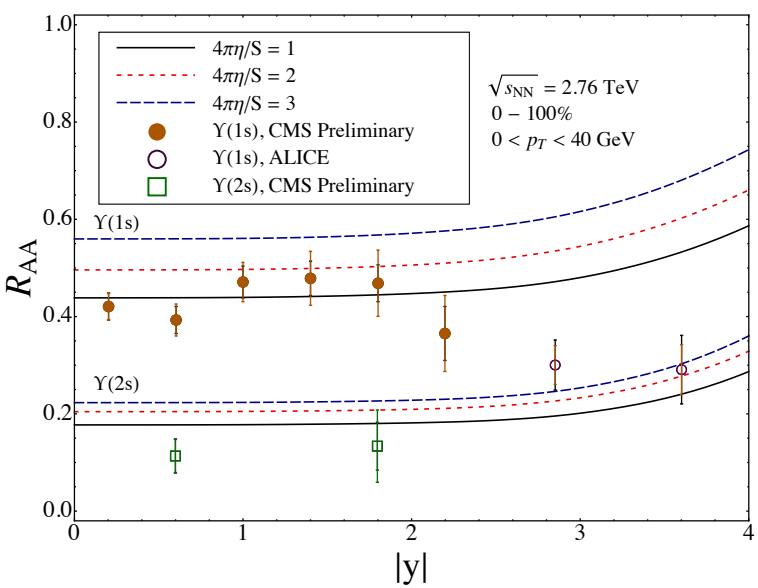
- Clear pattern of sequential suppression
- No sign of "thresholds" (QGP thermometer is continuous!)

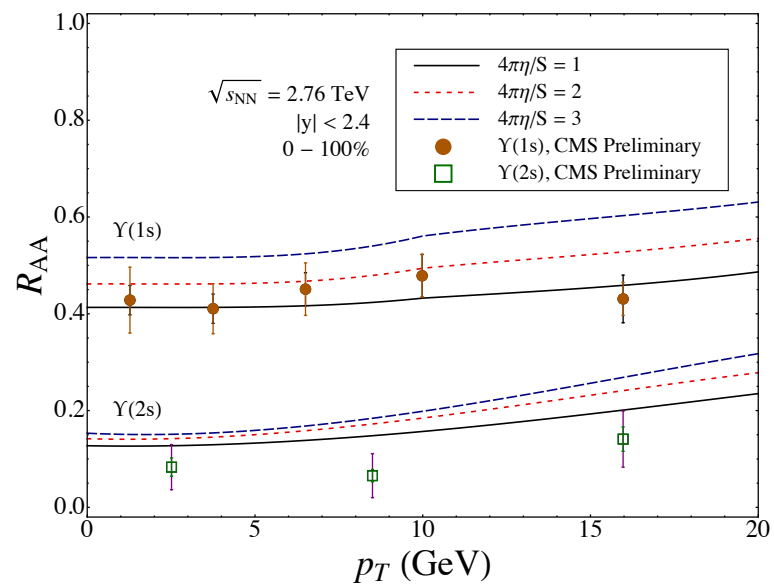
Inclusive Bottomonium Suppression @ 2.76 TeV

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



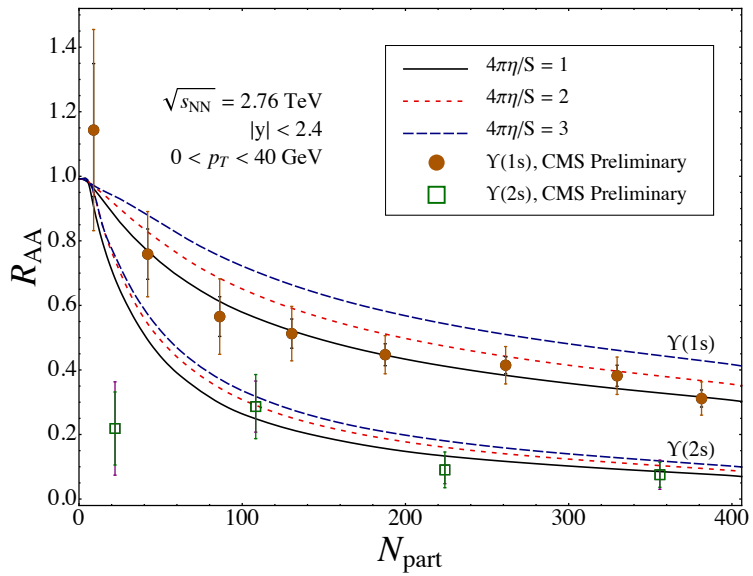
- Compare model to 2.76 TeV data from CMS and ALICE
- Reasonable agreement with CMS data but not perfect
- Disagreement with ALICE data in rapidity range 2.5 < y < 4
- Model under predicts Υ(2s) suppression





Inclusive Bottomonium Suppression @ 2.76 TeV

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



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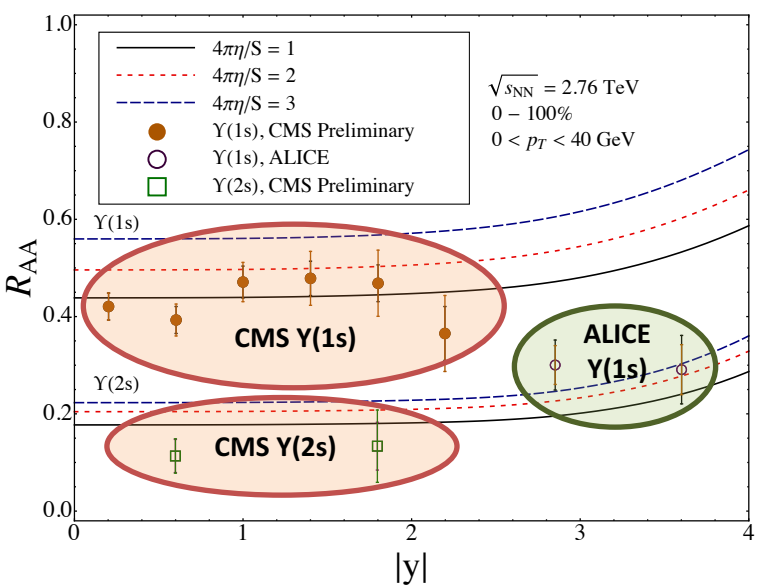
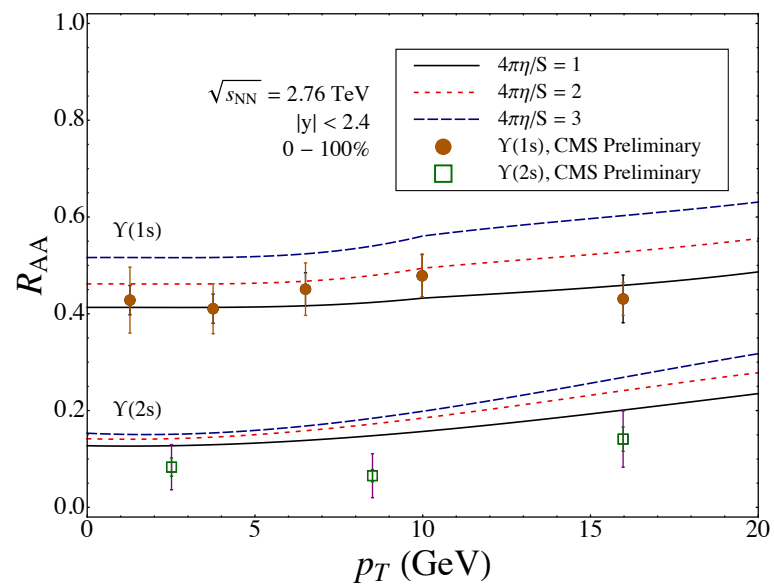
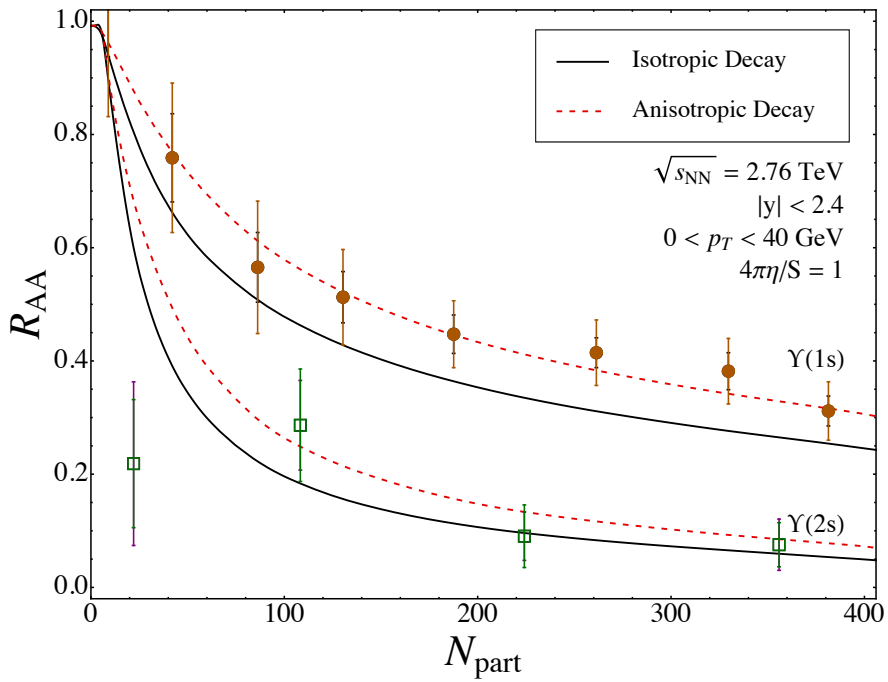
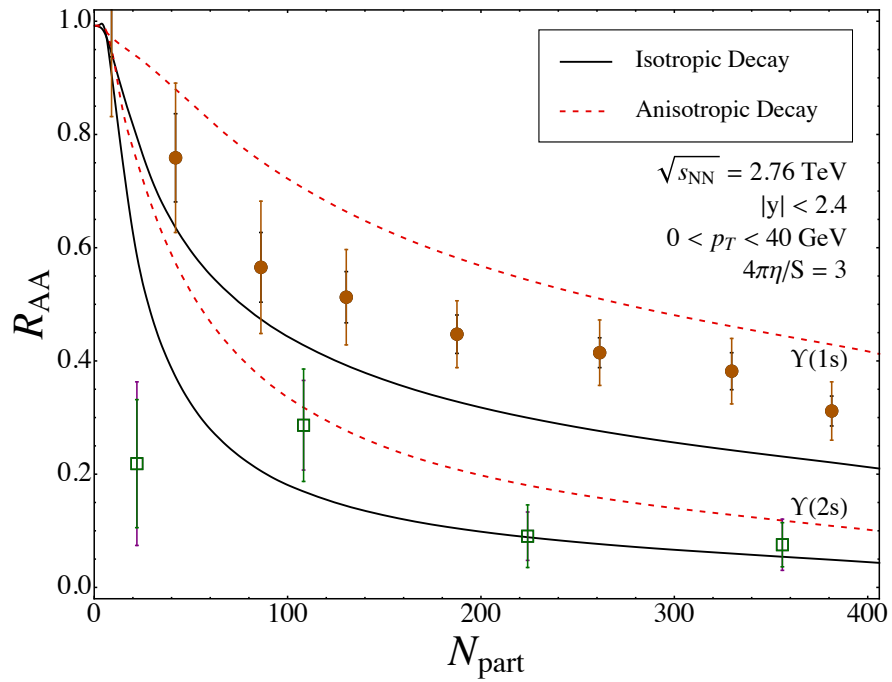




Anisotropy effect @ 2.76 TeV



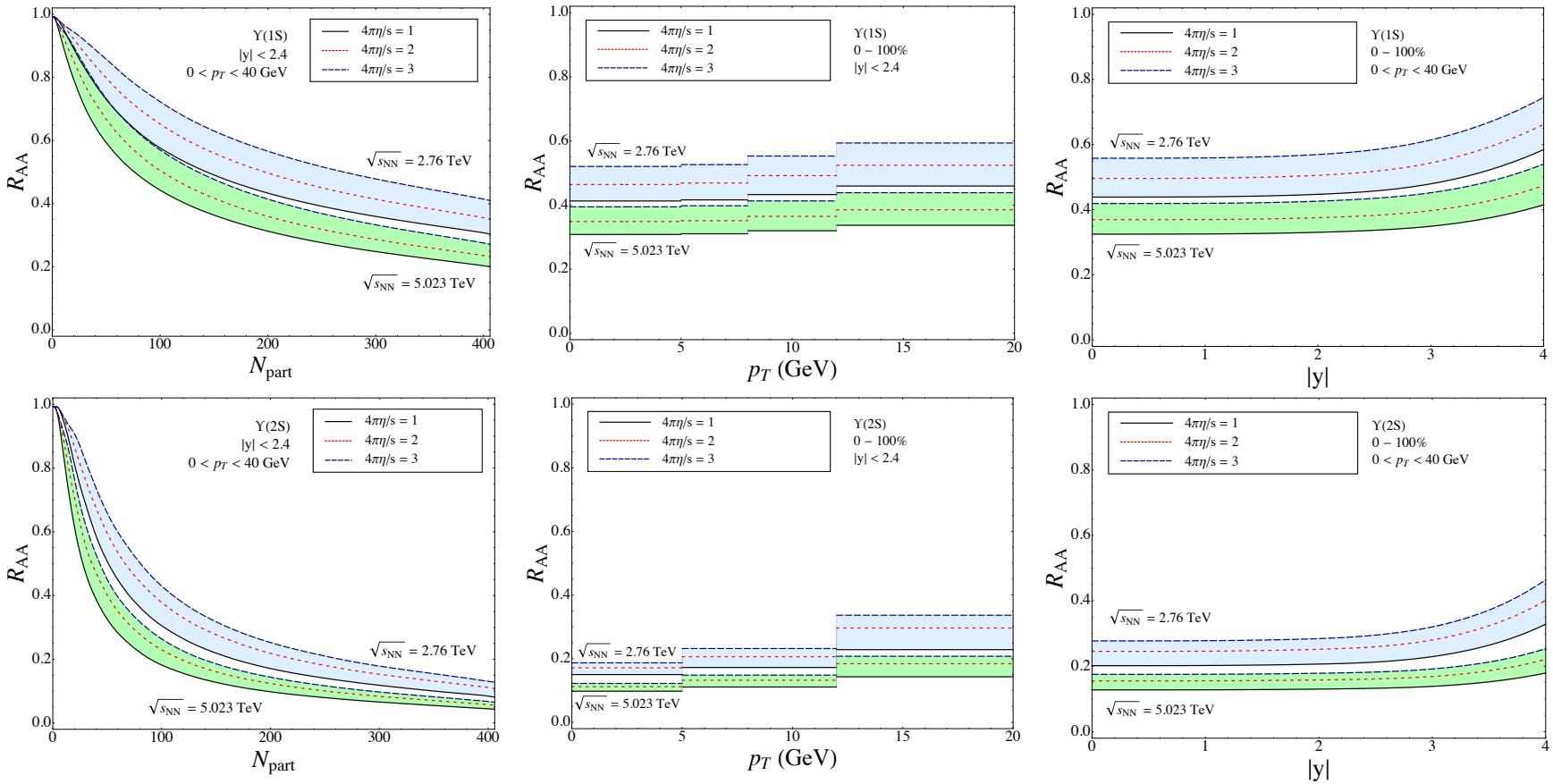


- I argued that including the anisotropy in the potential etc was important
- The two figures above show what happens if we simply use the isotropic potential with the local effective temperature determined from the energy density

Inclusive Bottomonium Suppression @ 5.02 TeV

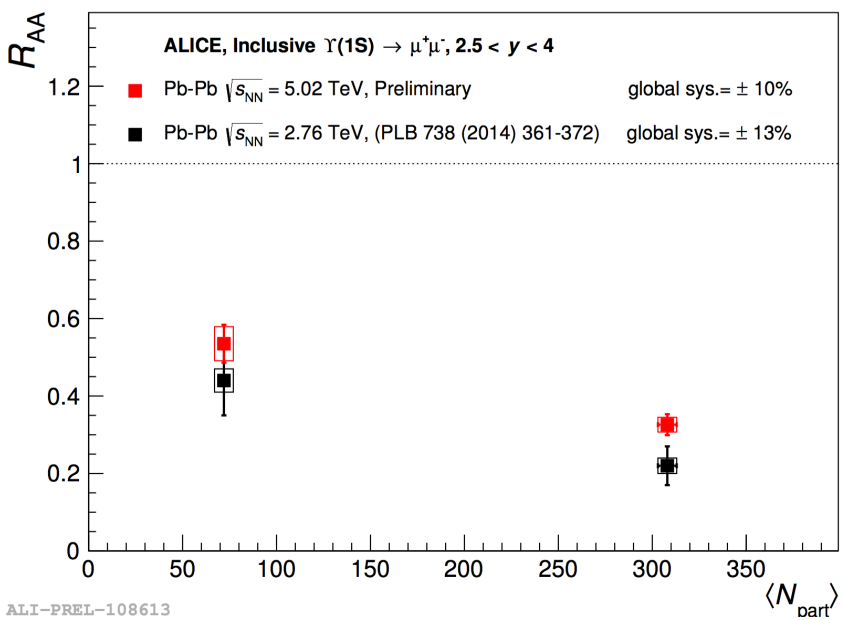
B. Krouppa, and MS, Universe 2016, 2(3), 16 (2016).

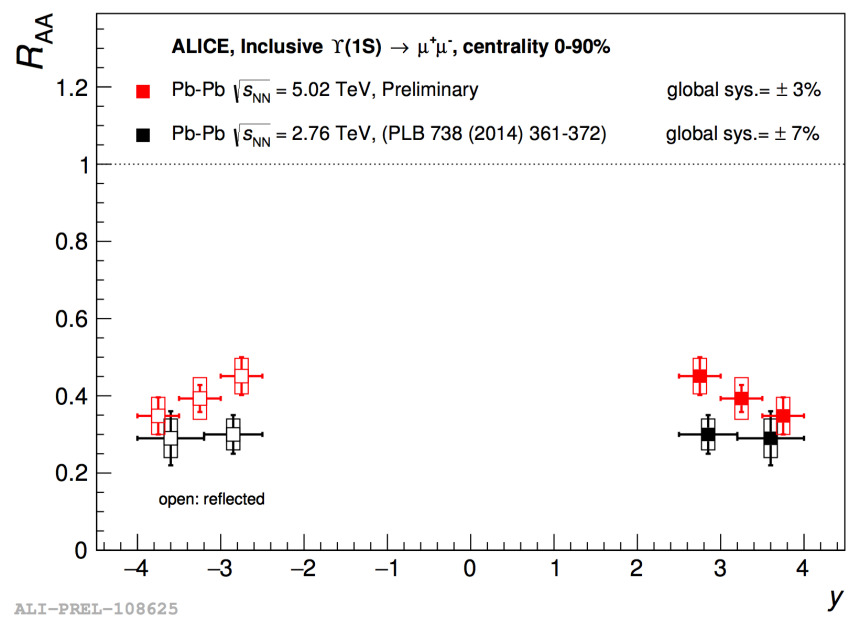
- We made predictions for 5.02 TeV in May 2016, then nervously waited for the data to appear…



Inclusive Bottomonium Suppression @ 5.02 TeV

- ALICE results show that at forward rapidities, the Y(1s) suppression increases (!) as one goes from 2.76 TeV to 5.02 TeV.

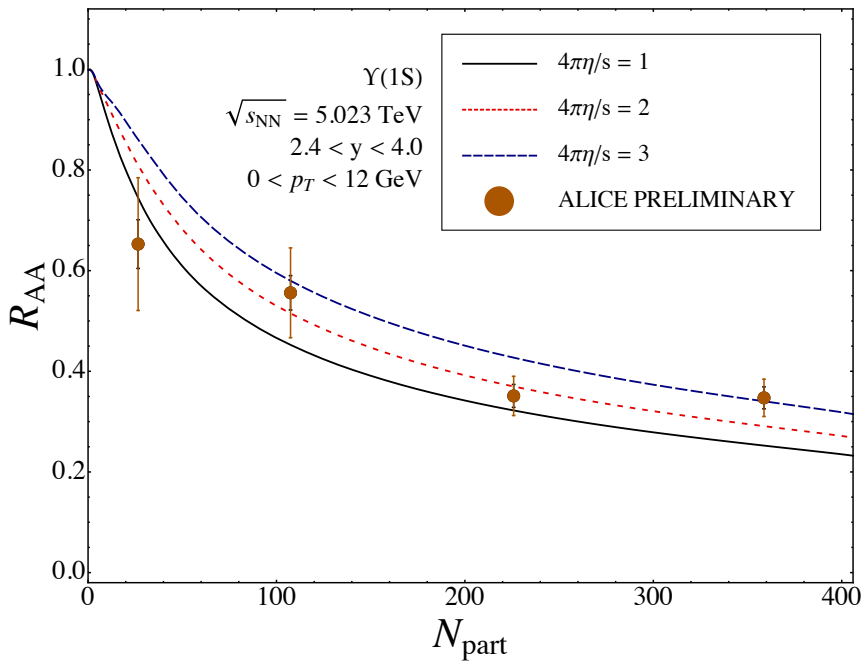


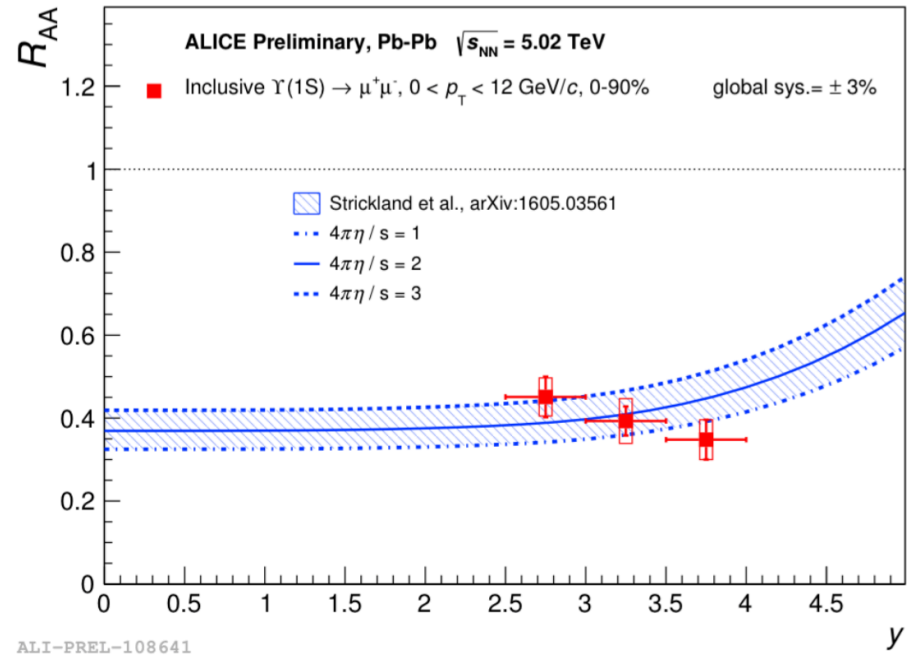


Inclusive Bottomonium Suppression @ 5.02 TeV

B. Krouppa, and MS, Universe 2016, 2(3), 16 (2016).

- Model predictions vs ALICE data

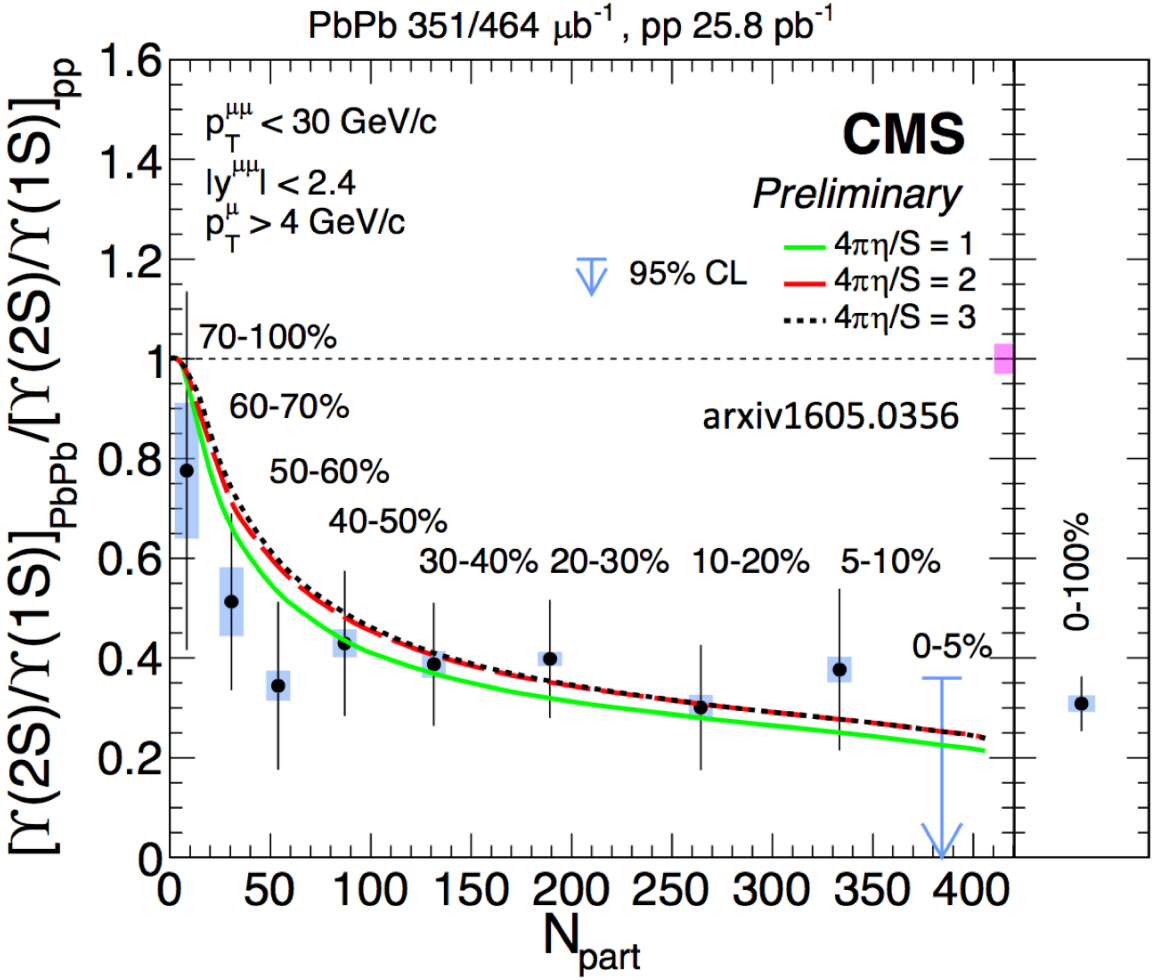




Inclusive Bottomonium Suppression @ 5.02 TeV

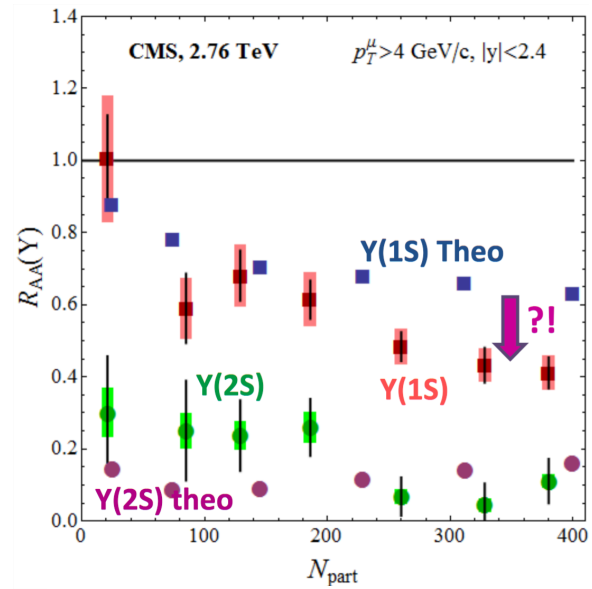
B. Krouppa, and MS, Universe 2016, 2(3), 16 (2016).

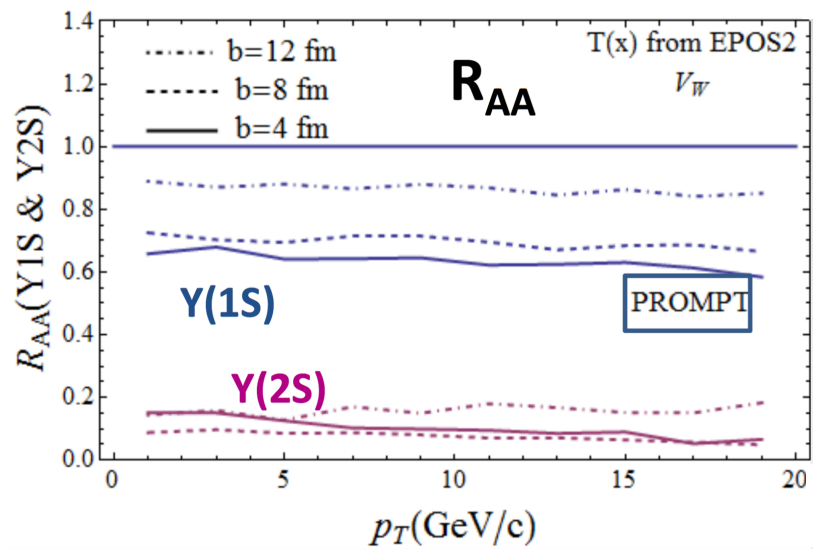
- Model predictions vs CMS double ratio data



But my model is too simple…

- My model presumes that we don't have to worry about details of quantum interference/evolution etc.
- An alternative approach is to try to realistically model the quantum/statistical evolution of the $Q\bar{Q}$ wave function in the presence of a mean field potential and then project onto the vacuum states at the end of the calculation and look for the overlap.
  [See talk by Pol Gossiaux in this conference]
- The model is able to reproduce the trends seen in the 2.76 TeV data. This is <u>very promising</u> since this method incorporates physics that my simple model completely throws out.

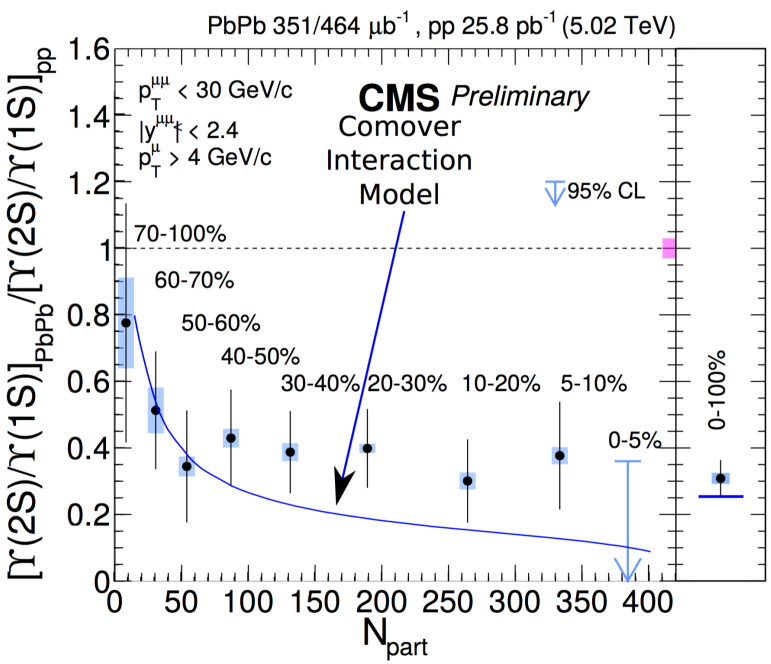


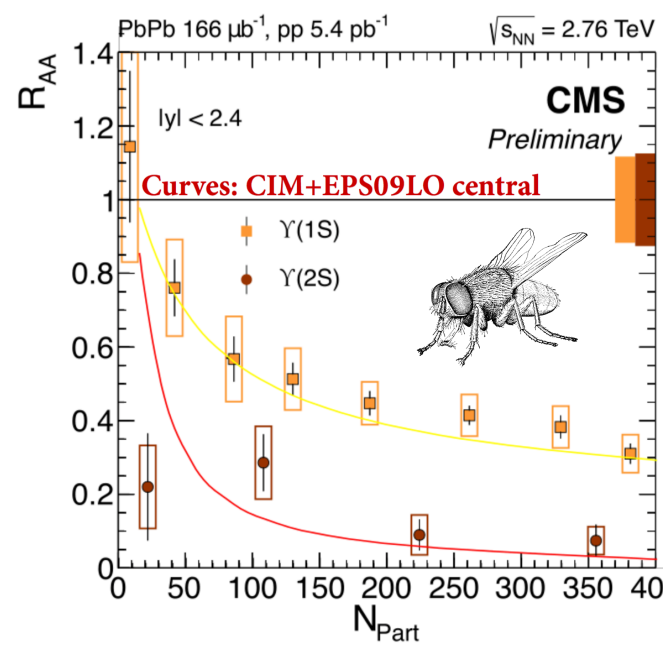


A fly in the ointment?

Definition: An irritation that spoils success or enjoyment of something.

- Results of J.P. Lansberg and E.G. Ferreiro [this conference] suggest that there are VERY LARGE effects from co-movers on bottomonia production
- But, temporal duration of the co-mover interactions is on the order 5 fm/c which is on the order of the typical QGP lifetime. Replace QGP with only hadronic scattering?
- Seems like the wrong degrees of freedom, but we must remain somewhat agnostic. Does the model fail to describe other basic observables? If not, we have to withdraw our claims of QGP discovery.





Conclusions and Outlook

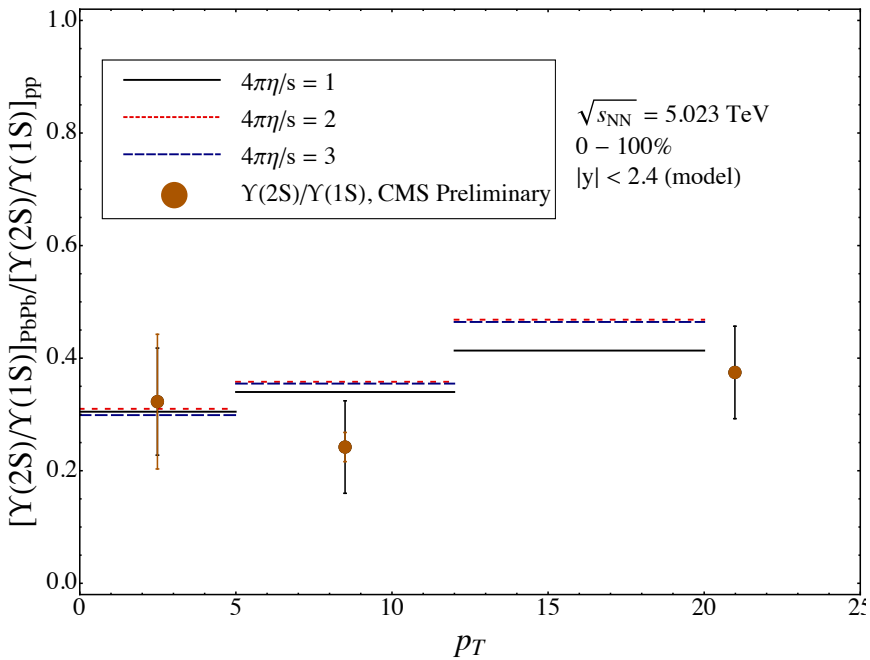
- For J/ψ, CNM effects are important.
- For J/ψ, we see signs of regeneration for p_T < 4-5 GeV; to see suppression directly we should apply p_T > 5 GeV cut.
- For Υ(1s), we might be able to get away with ignoring regeneration and/or CNM; however, going forward all effects should be included in a self-consistent manner (work in progress).
- Complex screening model works reasonably well to describe suppression seen at LHC and RHIC (not shown here).
- Other models presented at this conference are able to describe many features of the data. Some even with only hadronic DOFs!
- New ALICE results (2.76 vs 5.02 TeV) are quite confusing; is this sign of regeneration in the bottom sector?
- From CMS, we need R_{AA} for the the 1s and 2s independently, not just the double ratio. Maybe by Quark Matter 2017?

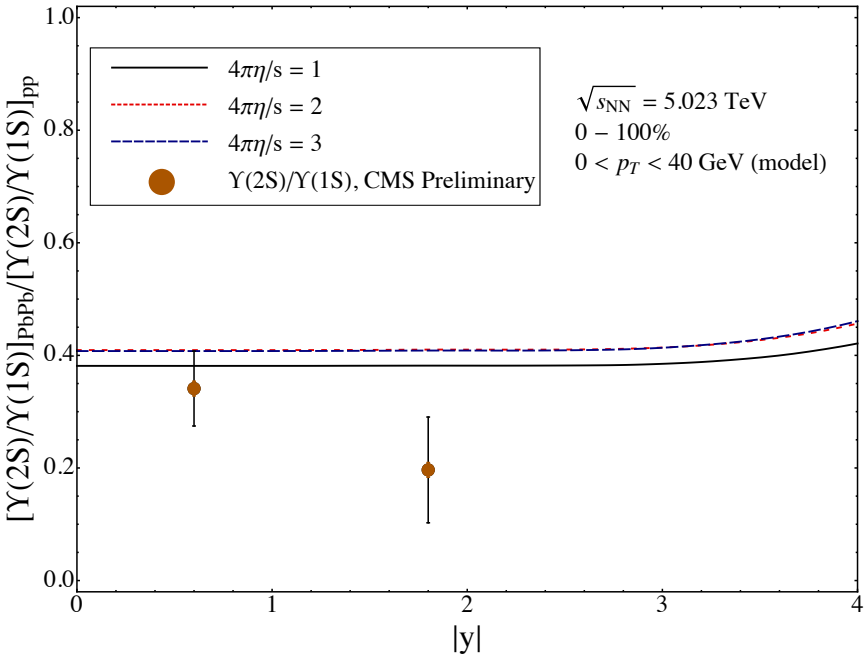
Backup slides

Inclusive Bottomonium Suppression @ 5.02 TeV

B. Krouppa, and MS, Universe 2016, 2(3), 16 (2016).

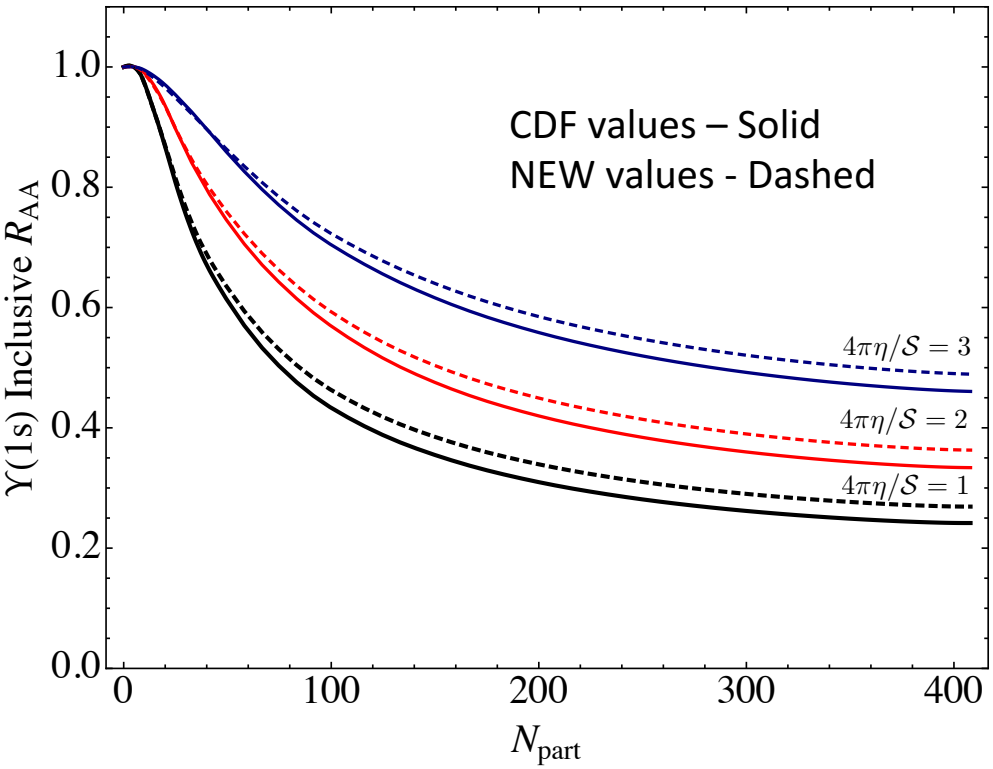
- Model predictions vs CMS double ratio data

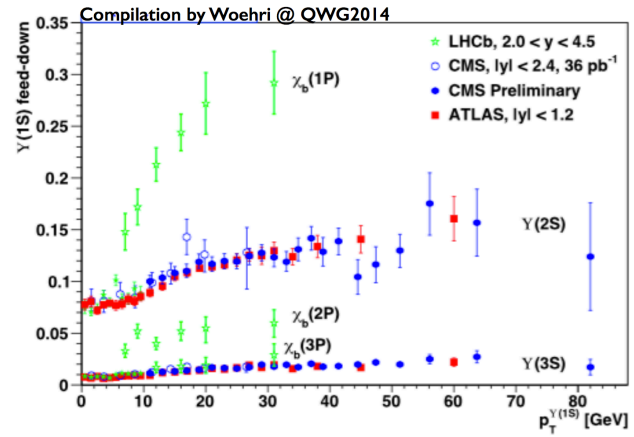




Updated feed down fractions

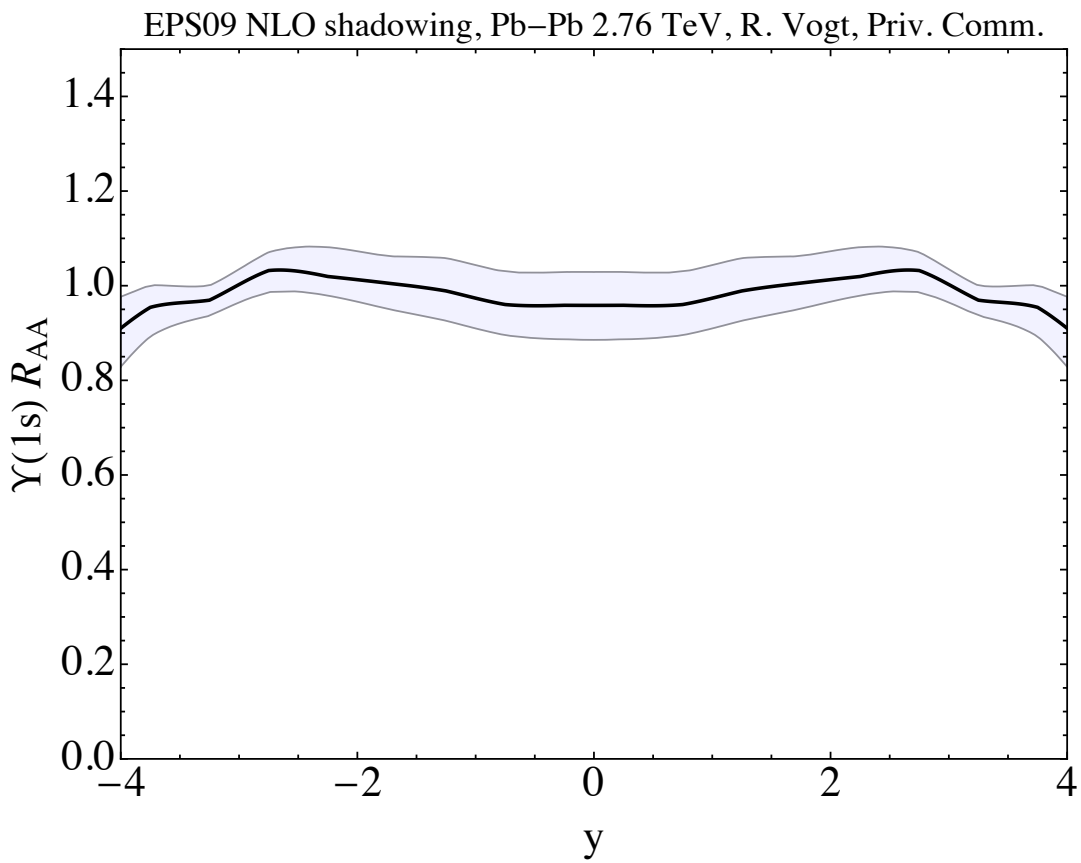
- Original feed down fractions came from CDF collaboration at Fermilab
- Better values avaliable (p_T-dependent); we compute average p_T ~ 8.9 GeV and use the values at this point





$\Upsilon(1S)$ Feed Down Fractions	
$\Upsilon(1S)$	0.668
$\Upsilon(2S)$	0.086
$\Upsilon(3S)$	0.010
$\chi_b(1P)$	0.170
$\chi_b(2P)$	0.051
$\chi_b(3P)$	0.015

Estimate CNM effect on Bottomonium in A-A

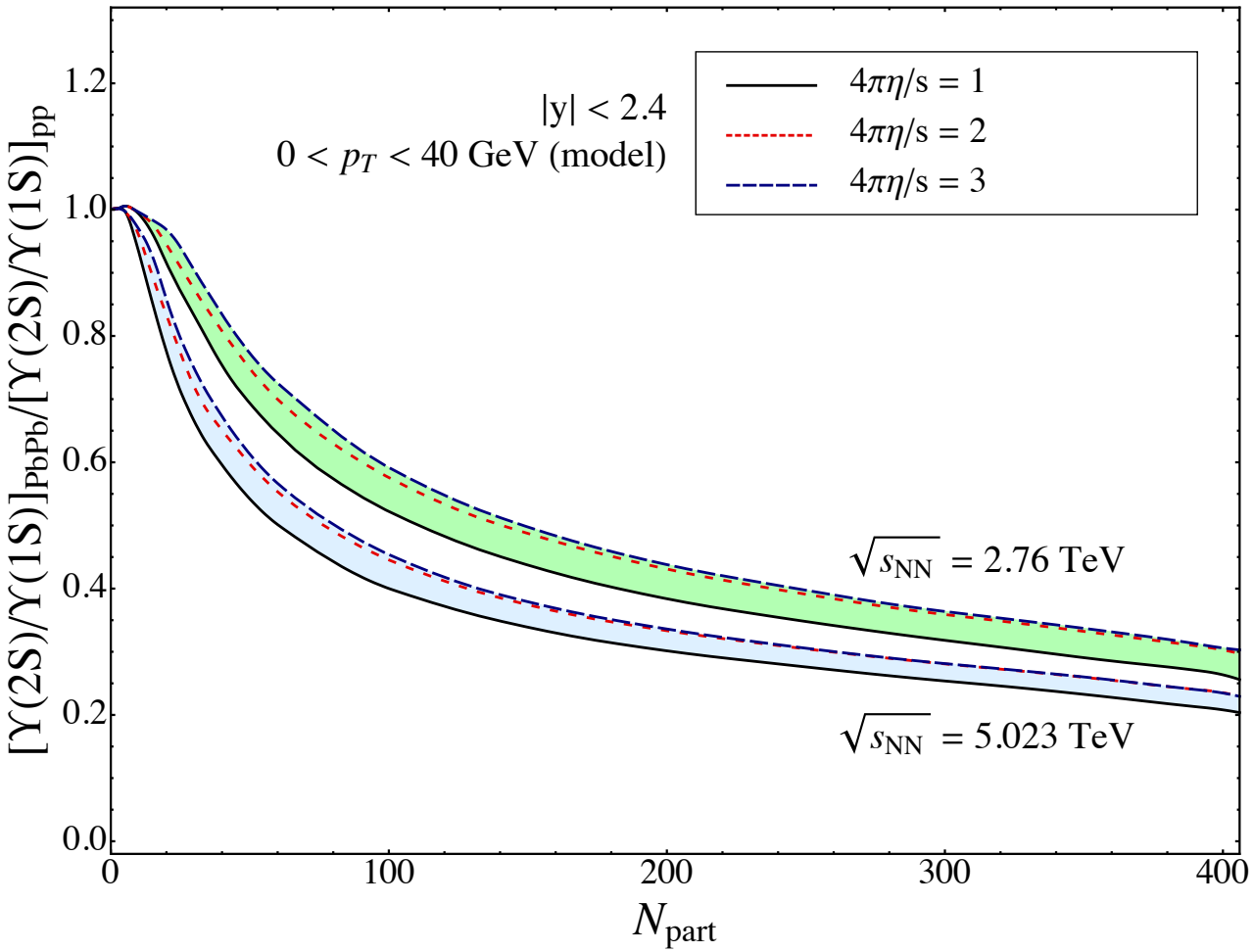


- Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt
- Effect seems to be quite small
- This is good news for isolating the medium effect we are after, but doesn't help to explain the ALICE forward "anomaly"

Inclusive Bottomonium Suppression @ 5.02 TeV

B. Krouppa, and MS, Universe 2016, 2(3), 16 (2016).

- Model predictions vs CMS double ratio data



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

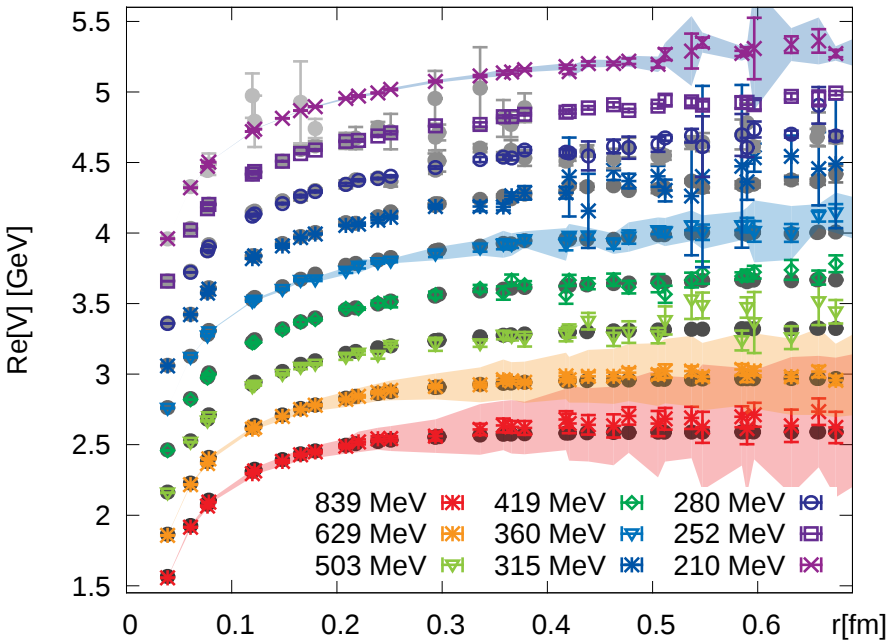
$$\mathrm{Re}[V(\mathbf{r},\xi)] = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3} e^{i\mathbf{p}\cdot\mathbf{r}} \frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

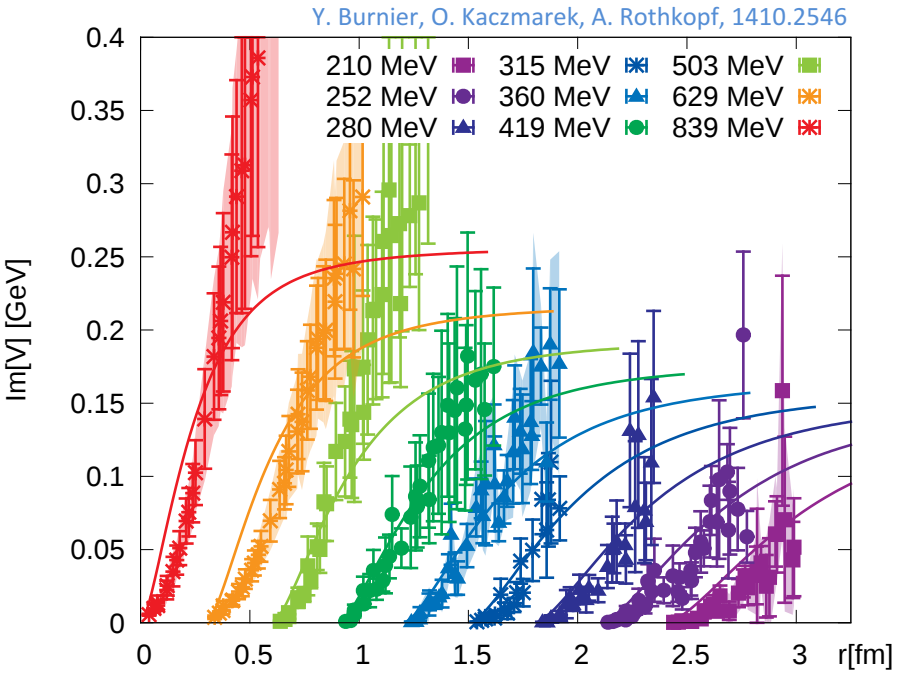
With <u>direction-dependent masses</u>, e.g.

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

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

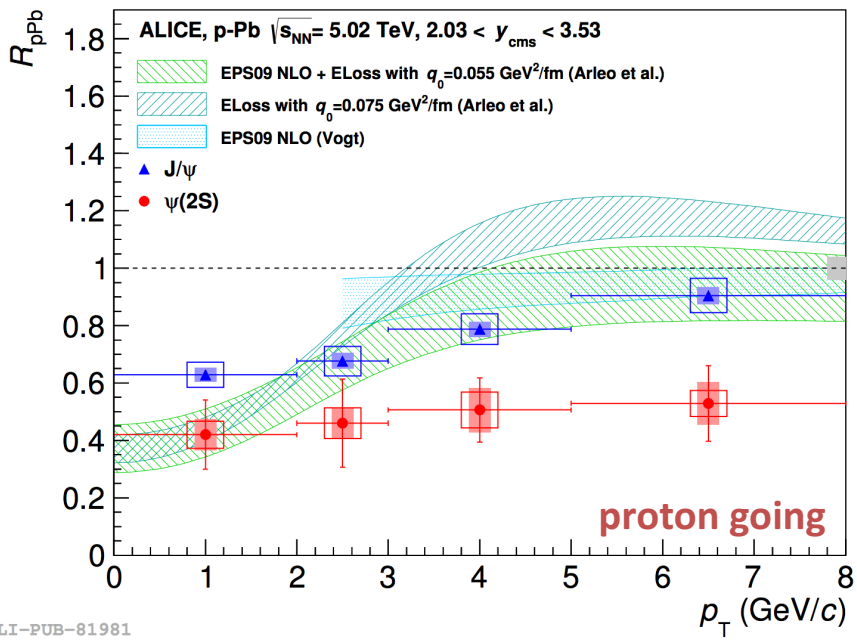
Sanity check

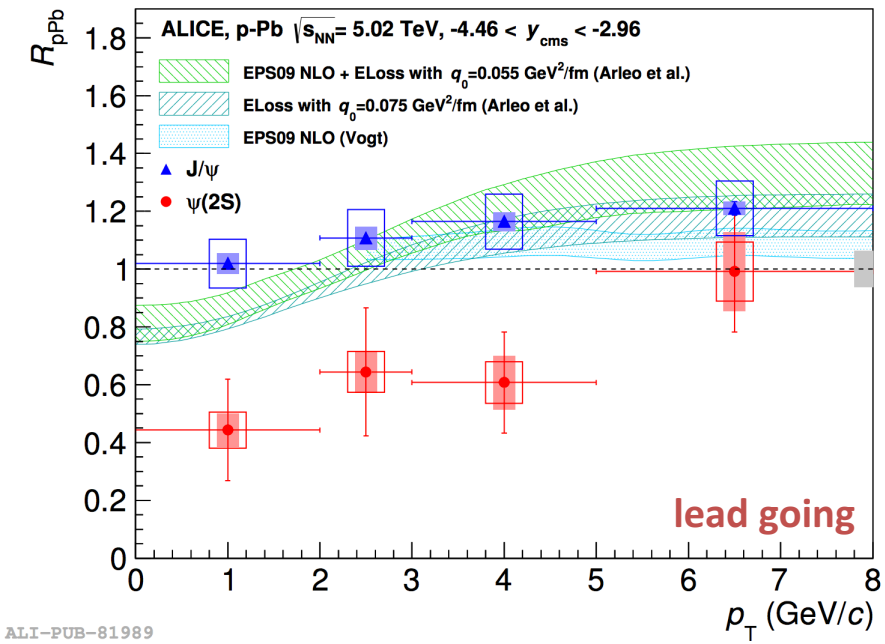




- Results above are the real and imaginary part of the heavy quark potential extracted from the lattice.
- For the imaginary part, the authors also compare with the isotropic Im[V] indicated on the previous slide.

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 co-movers**?

Anisotropic hydrodynamics basics

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

Viscous Hydrodynamics Expansion

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

Non-equilibrium corrections from e.g. shear stress

Anisotropic Hydrodynamics (aHydro) Expansion

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

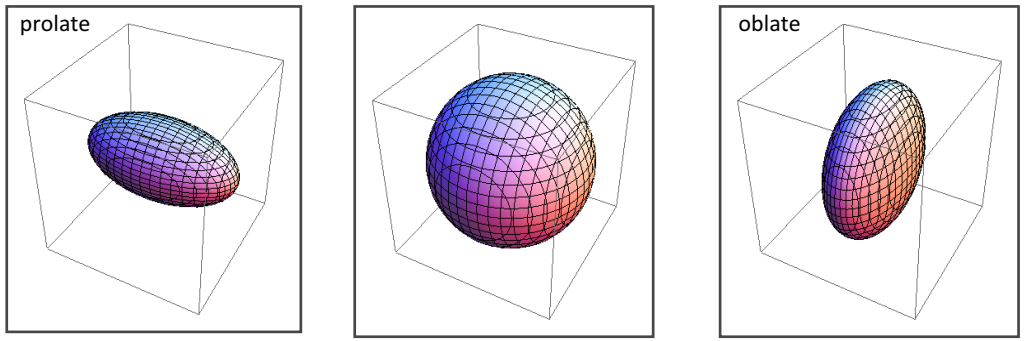
Treat this term perturbatively
→ "NLO aHydro"

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

→ "Romatschke-Strickland" form in LRF

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

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



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