Bottomonium Production in Heavy-Ion Collisions

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Outline

- Introduction
  - Heavy-Ion Collisions and Quarkonium as Probe
- Bottomonium Transport Approach
  - Boltzmann and Rate Equation
  - Transport Coefficients:
    - In-Medium Binding and Reaction Rates
    - Equilibrium Limit
- Comparison with Data: R_{AA} and v_2
  - Centrality Dependence and p_T-Dependence of R_{AA}
  - Excitation Function (Energy dependence)
- Conclusion

Heavy-ion Collisions and Quarkonium

Why quarkonium in HIC?

- Can survive in QGP with large binding energy
- Large mass makes nonrelativistic EFT suitable
- Not in equilibrium during medium evolution
- Quarkonia decay after medium evolution
- Various species enable fruitful phenomenology
- Help to study the in-medium heavy quark potential

→ Learn about the medium

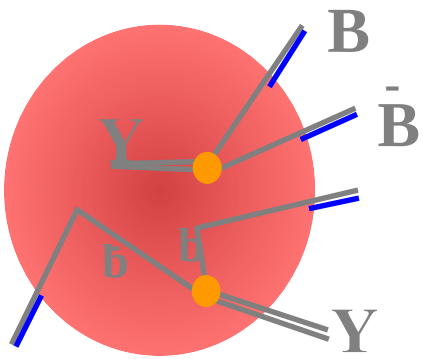
Quarkonium Transport in Medium

- Initial quarkonium from hard production not in equilibrium
- Simulate quarkonium time evolution towards equilibrium limit

Need a transport model quantifying

How fast the evolution is → reaction rate

Number of quarkonium in equilibrium → equilibrium limit



Quarkonium distribution evolution: Boltzmann equation:

$$\frac{\partial f_Y(x,p,\tau)}{\partial \tau} + v \cdot \frac{\partial f_Y(x,p,\tau)}{\partial x} = -\alpha_Y(T,p)\, f_Y(x,p,\tau) + \beta_Y(T,p)$$

loss primordial

gain regeneration

Transport: Rate Equation

Total quarkonium number evolution

primordial regeneration

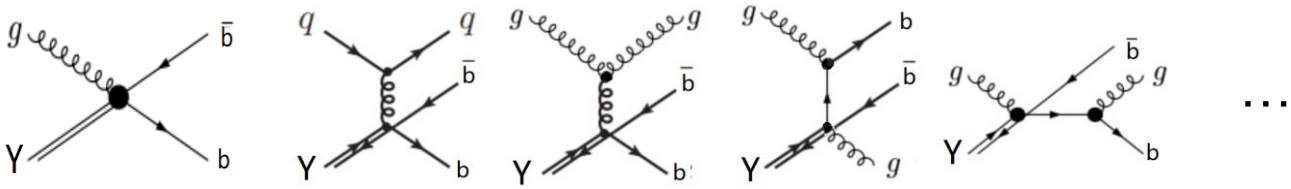
Kinetic Rate Equation

$$\frac{\mathrm{d}N_Y(\tau)}{\mathrm{d}\tau} = -\Gamma_Y(T(\tau))\left[N_Y(\tau) - N_Y^{\mathrm{eq}}(T(\tau))\right]$$

rates equilibrium limit

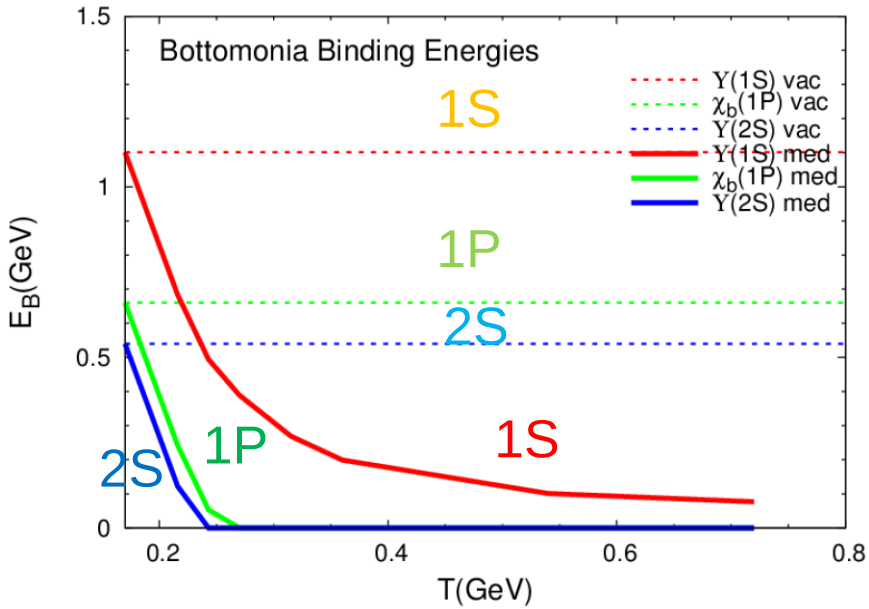
Transport Coefficients

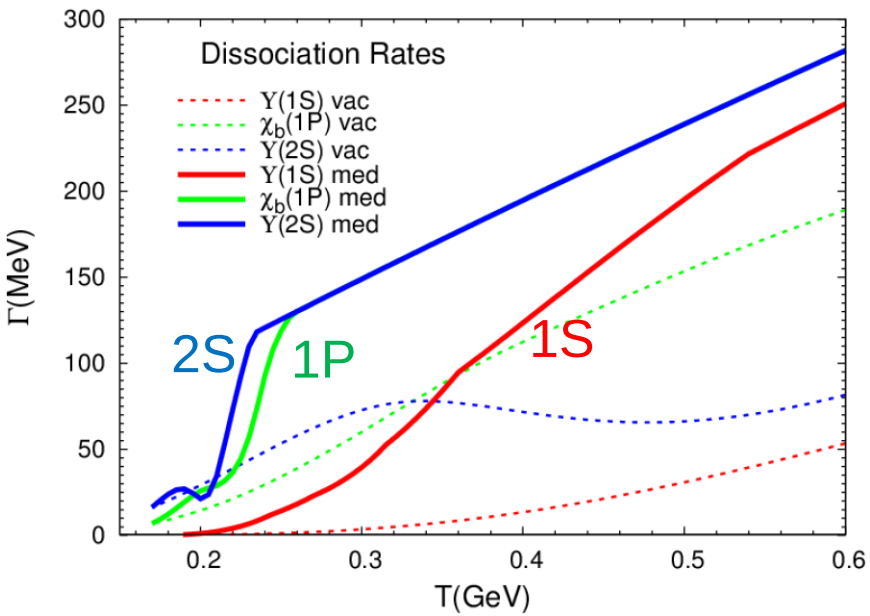
- Reaction Rates $\Gamma_Y(T) = \langle \alpha(T,p) \rangle_p$



- Equilibrium Limits $N_Y^{eq} = V n_Y^{eq} \approx V \int \gamma_b^2 d_Y e^{-E/T} \frac{d^3p}{(2\pi)^3}$

Transport Coefficient: Reaction Rates





In-medium binding energy:
In-medium potential based
T-matrix approach in strongly
interacting medium (solid)

F. Riek, R. Rapp, PRC 82 (2010)

- In-medium binding energy severely enhance the reaction rates
- Excited state rates much larger than ground state because of smaller binding

Transport Coefficient: Equilibrium Limit

Heavy quark conservation

$$N_{b\bar{b}} = \frac{1}{2}\gamma_b n_{\rm op} V_{\rm FB} \frac{I_1(\gamma_b n_{\rm op} V_{\rm FB})}{I_0(\gamma_b n_{\rm op} V_{\rm FB})} + \gamma_b^2 n_{\rm hid} V_{\rm FB}$$

total $b\bar{b}$ pairs

b-quarks

bottomonia

$N_{b\bar{b}}$ Initial produced $b\bar{b}$ pairs

V_{FB} Relativistic expanding fireball volume

fugacity factor γ_b

Bottomonium number in equilibrium $N_Y^{\rm eq}(T) = V_{\rm FB}\gamma_b^2(T) n_Y(m_Y;T)$

Bottomonium density

Fireball Model

Need temperature evolution to solve the rate equation...

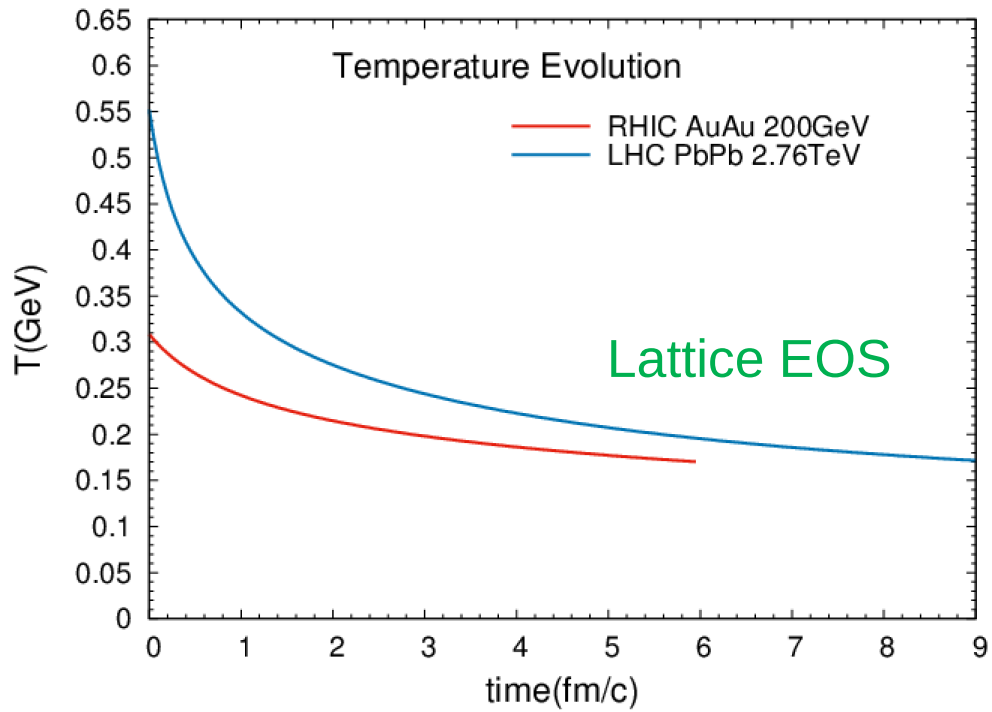
$$\frac{\mathrm{d}N_Y(\tau)}{\mathrm{d}\tau} = -\Gamma_Y(T(\tau))\left[N_Y(\tau) - N_Y^{\mathrm{eq}}(T(\tau))\right]$$

Total entropy conserved:

$$S_{total} = s_{QGP}(T)V_{FB}(\tau) \rightarrow T(\tau)$$

Constructed from measured charged hadron numbers

Temperature Evolution



From Transport to Observables

Initial Production (cross sections)
Cold Nuclear Matter Effects (Shadowing, Nuclear Absorption …)

Transport Equation → Final Quarkonium Numbers N_Y^{AA}(1S,1P,2S,..)

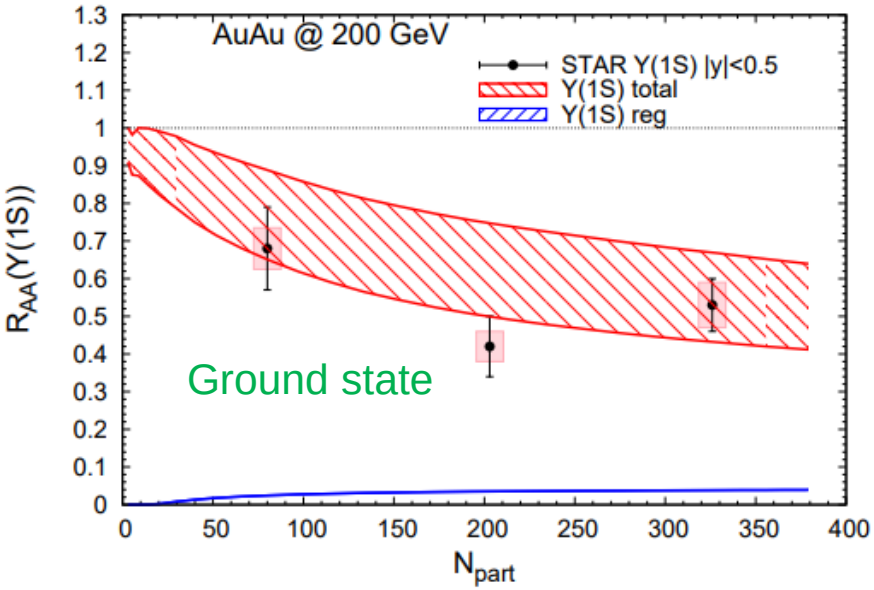
Direct $N_Y^{AA}(1S)$

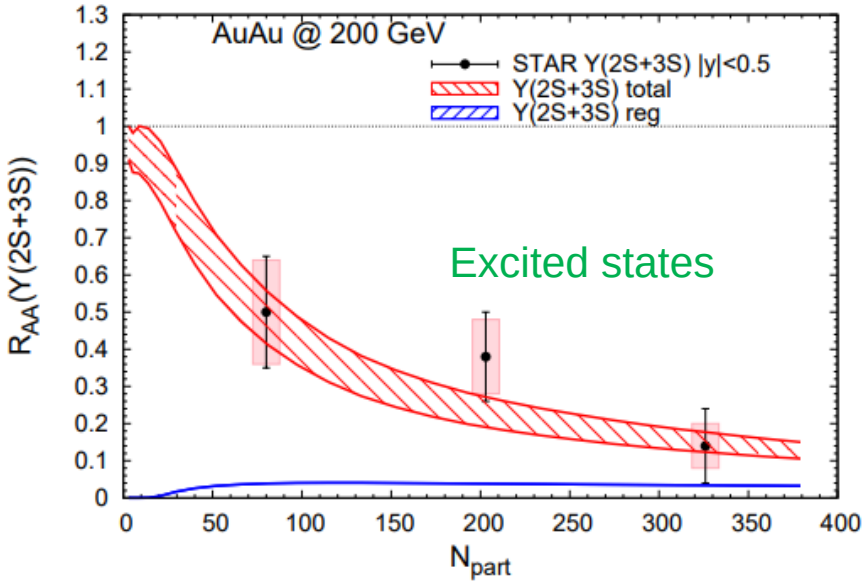
Feeddowns $N_Y^{AA}(1P)$ $N_Y^{AA}(2S)$ $N_Y^{AA}(2P)$ $N_Y^{AA}(3S)$

→ Inclusive $N_Y^{AA}(1S)$

Nuclear Modification Factor R_{AA}: $R_{AA} = \frac{N_Y^{AA}}{N_{coll} N_Y^{pp}}$

Centrality-dependent R_{AA} at RHIC

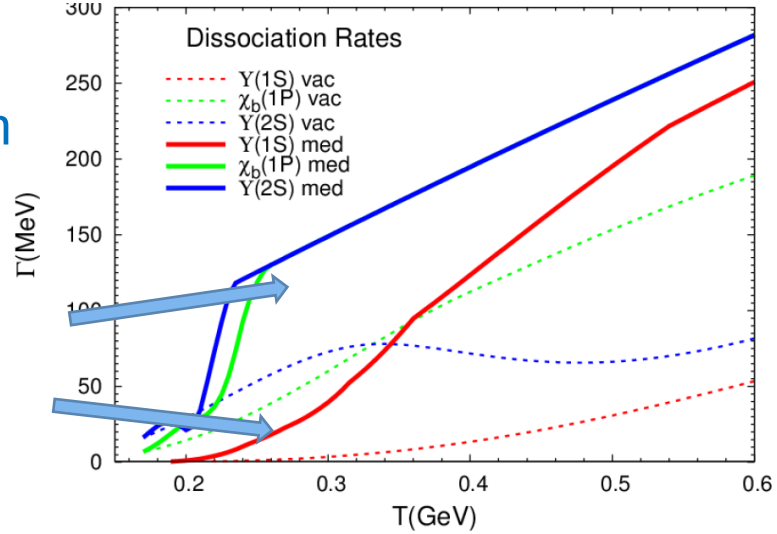


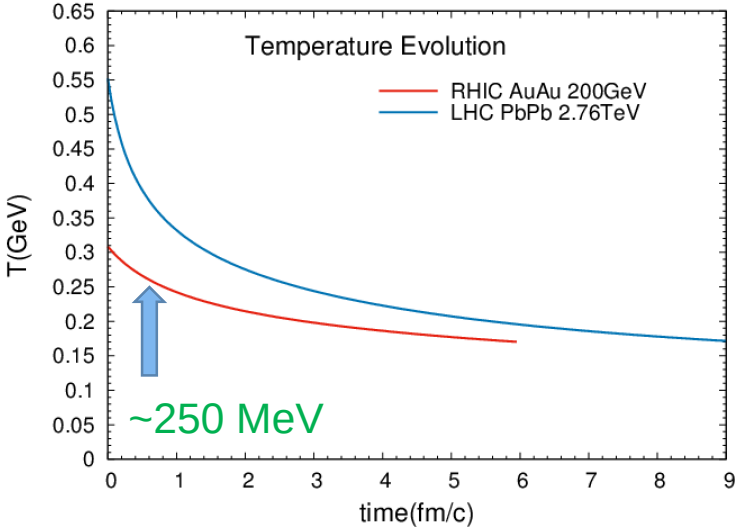


Sequential suppression

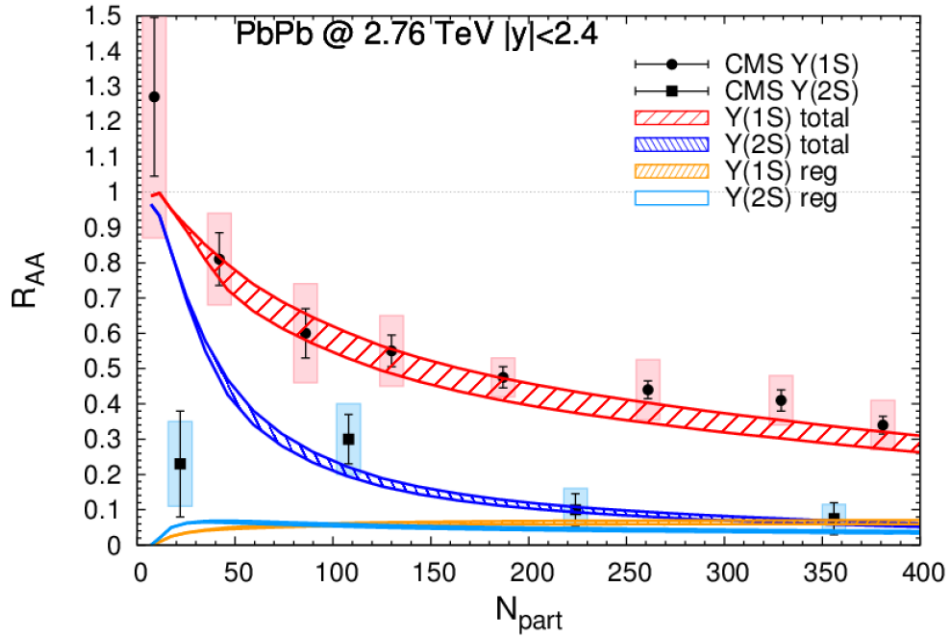
Excited states

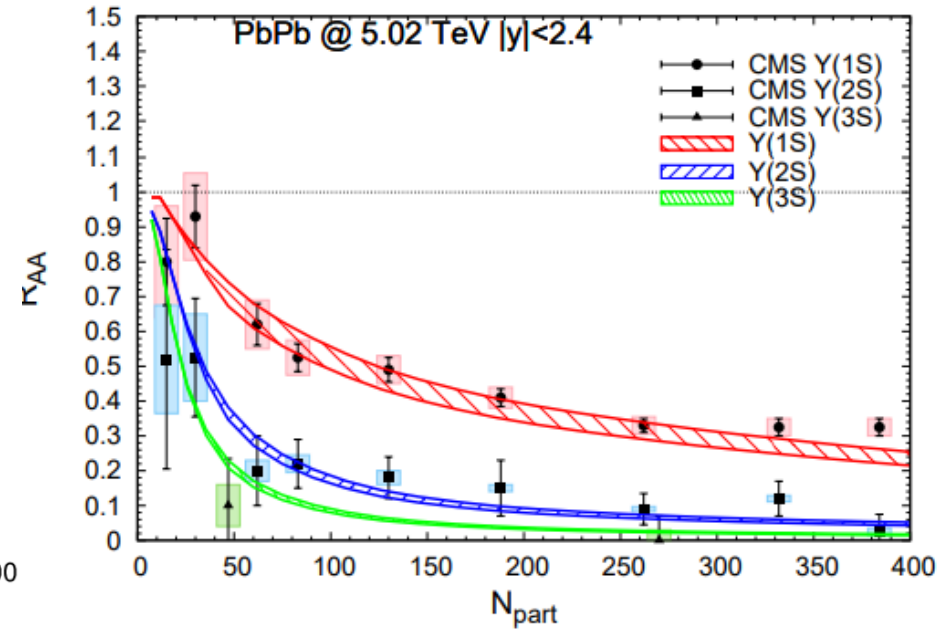
Ground state





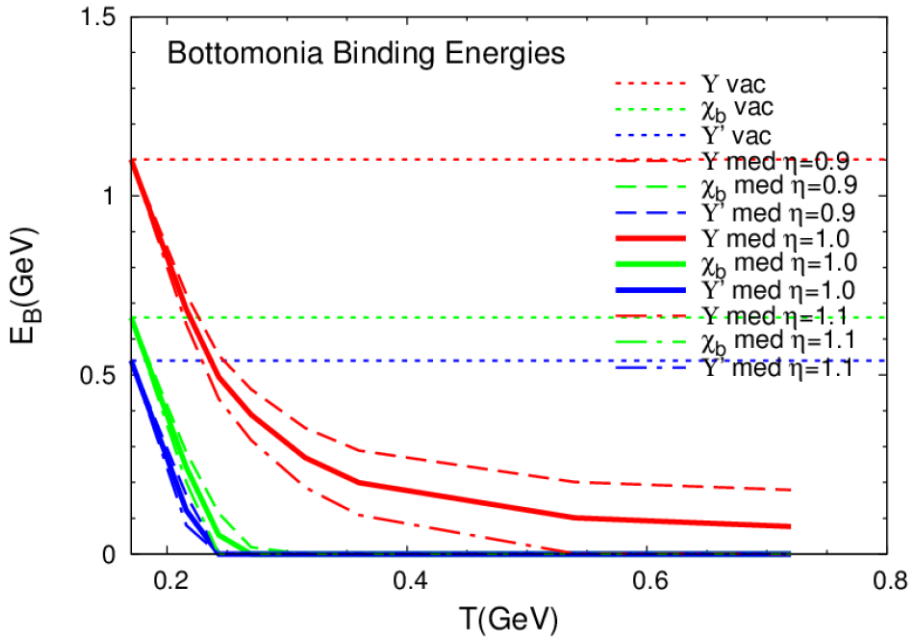
Centrality-dependent R_{AA} at the LHC

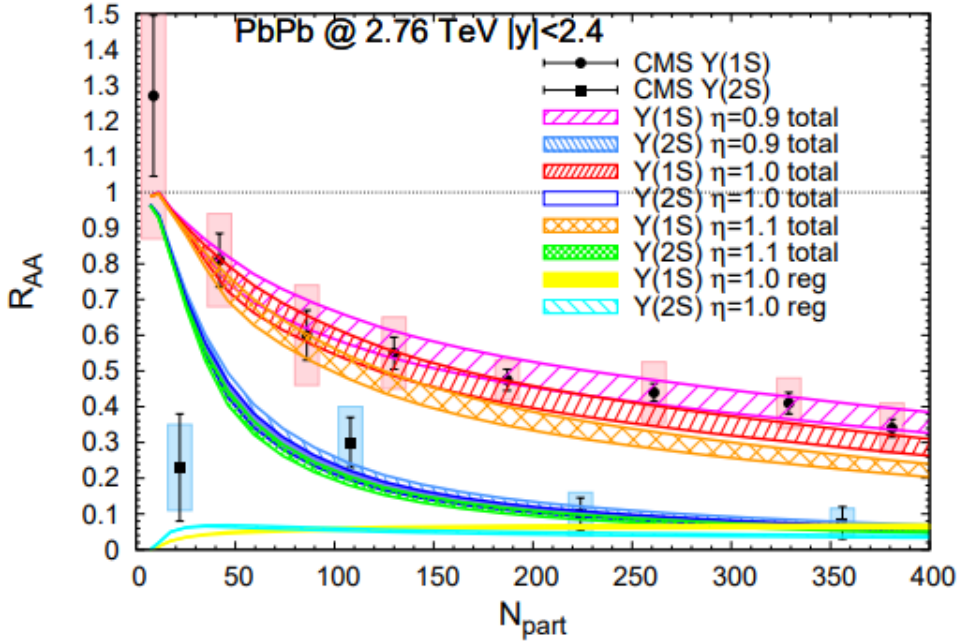




- Sequential suppression
- Direct Υ(1S) suppression, small regeneration
- Regeneration significant for Υ(2S)

Sensitivity to Binding Energy





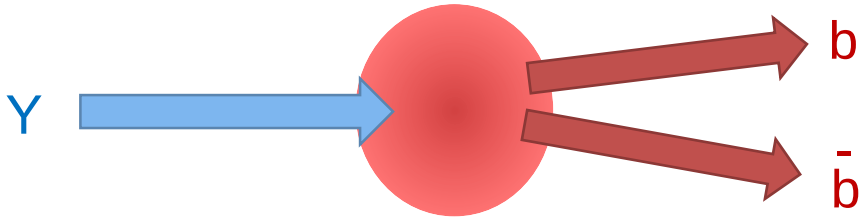
Binding Energies → Reaction Rates → R_{AA} Observables

- Significant binding energy dependence of the $\Upsilon(1S)$ R_{AA}

Calculation of p_T-Spectra

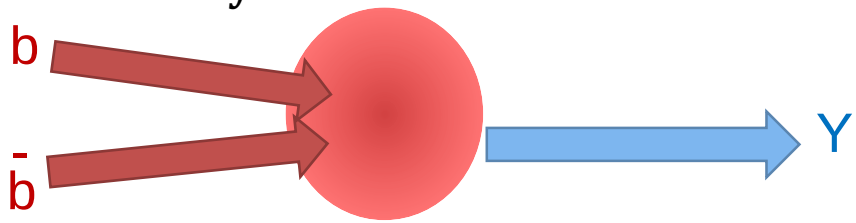
Primordial component: Boltzmann Equation

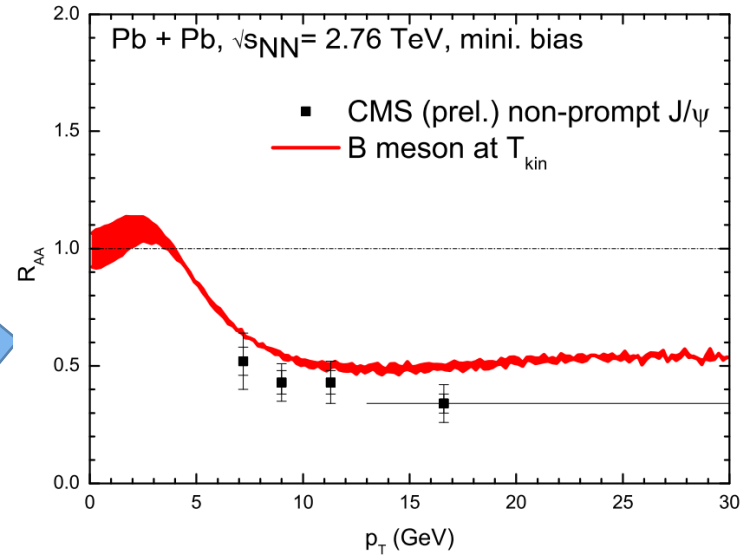
$$\frac{\partial f_Y^{prim}(x,p,\tau)}{\partial \tau} + v \cdot \frac{\partial f_Y^{prim}(x,p,\tau)}{\partial x} = -\alpha(T,p) f_Y^{prim}(x,p,\tau)$$



Regeneration component: Coalescence with off-equilibrium b-quark spectra

$$f_Y^{coal}(p) = \int f_b(p_1) f_{\bar{b}}(p_2) W_Y(\Delta p) d^2p_1 d^2p_2$$



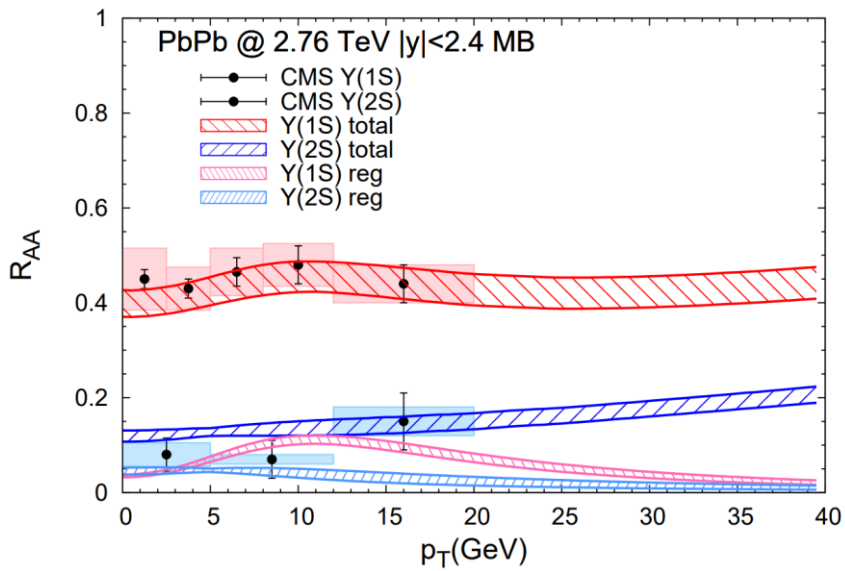


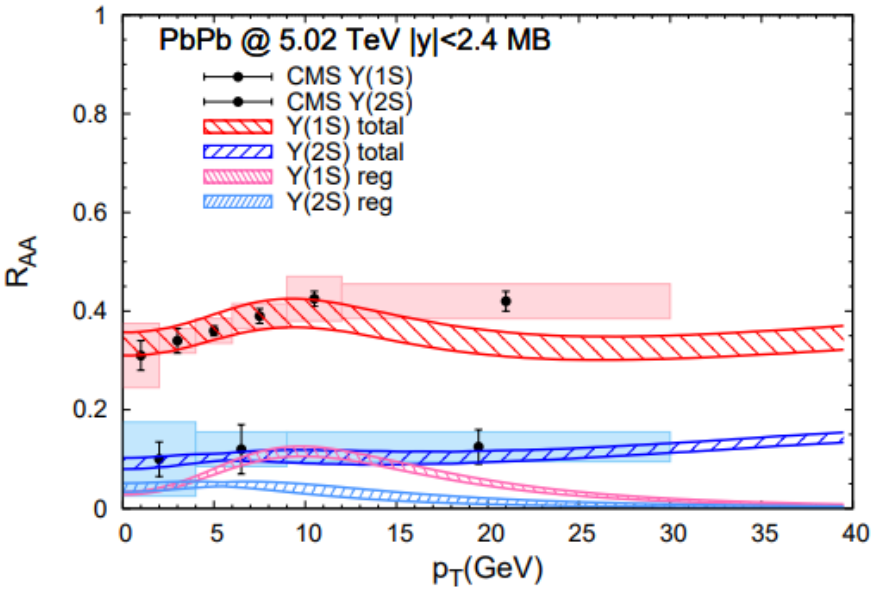
Langevin simulation

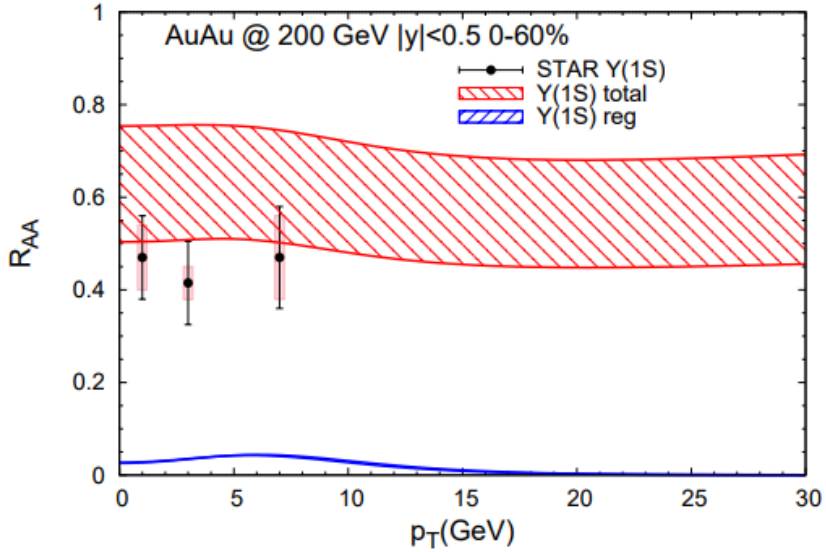
M. He, R. Fries, R. Rapp, PLB 735 (2014)

Coalescence at average regeneration temperature

p_T-dependent R_{AA} at RHIC and the LHC

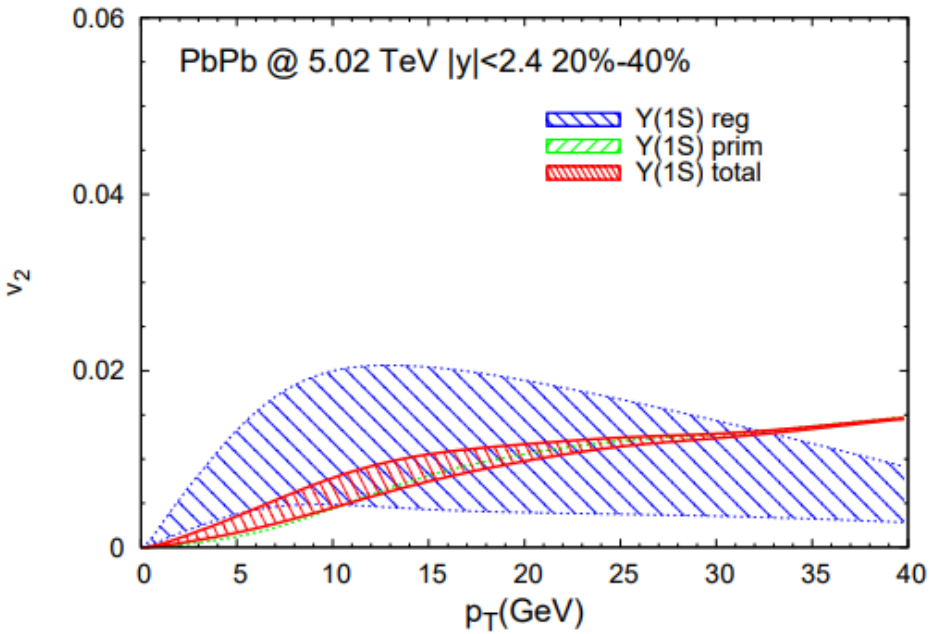


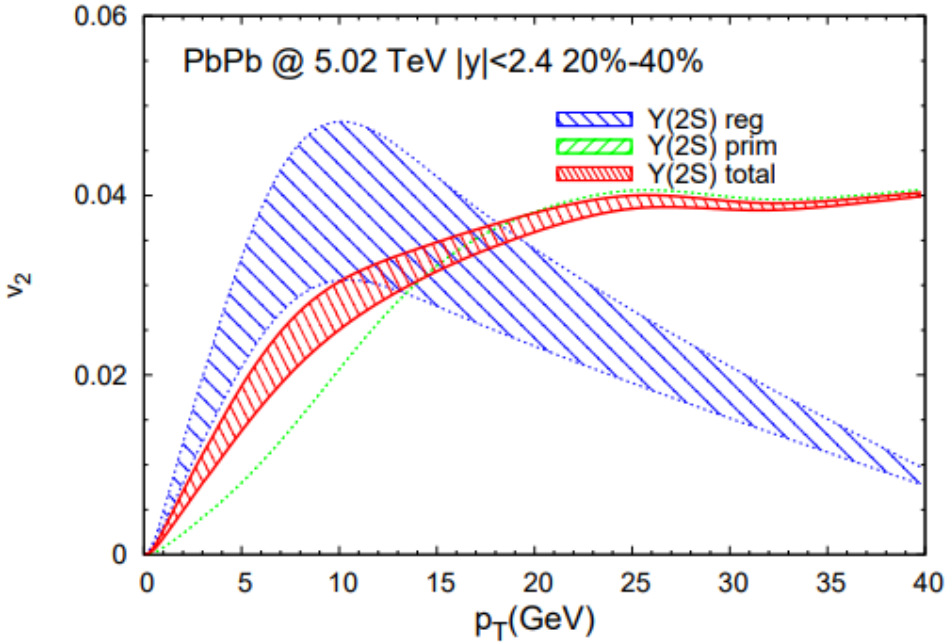




- Coalescence from non-thermalized b-quarks induces small p_T-dependence for bottomonium

v_2 at LHC

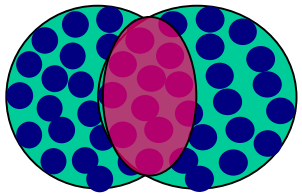




elliptic flow v_2:

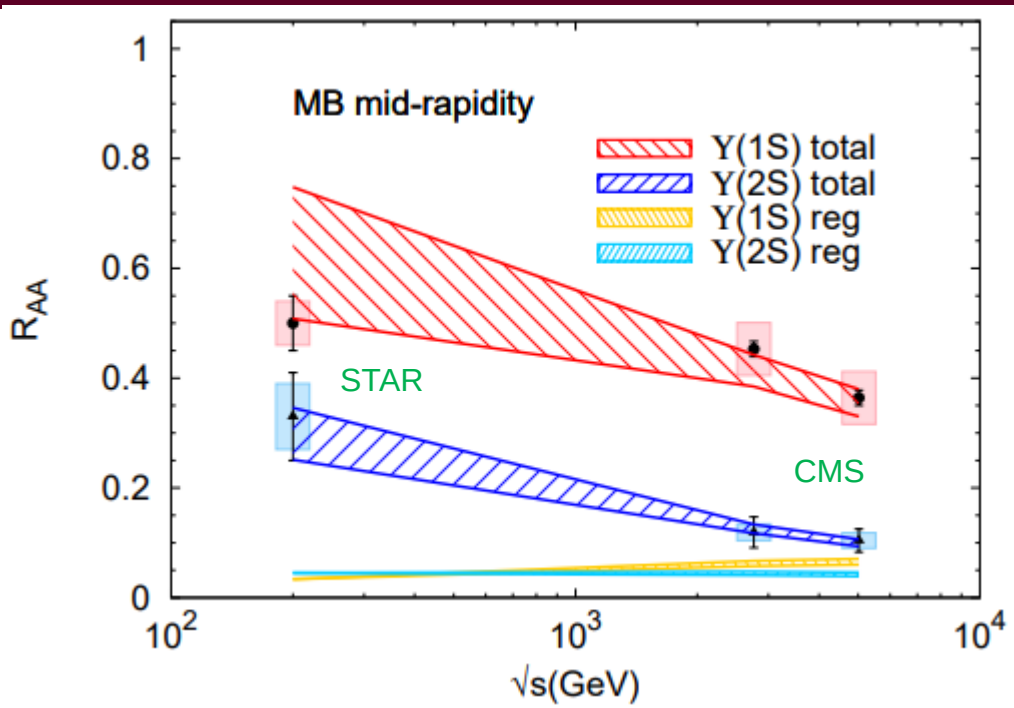
Anisotropy of production

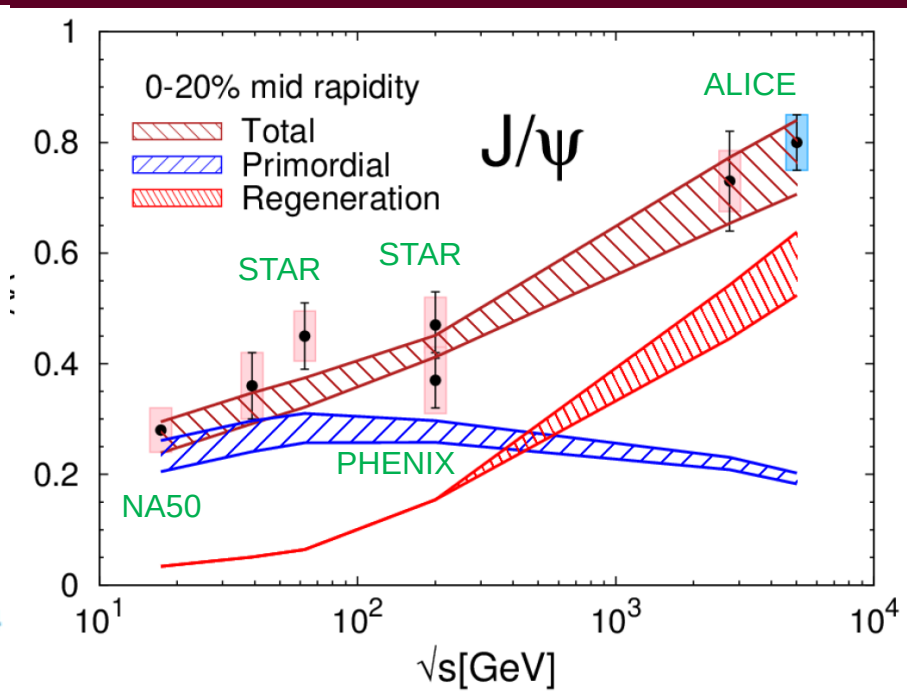
$$\frac{d^2N}{d^2p_T} = \frac{1}{2\pi}\frac{dN(p_T)}{p_T dp_T}(1 + 2v_2(p_T)\cos(2\phi) + \dots)$$



Both destruction and coalescence occurs early for Υ(1S), later for Υ(2S)

Excitation Function





Energy dependence of R_{AA}:
Suppression at higher energy for bottomonium
-> Significant regeneration contribution for excited states
Enhancement at higher energy for charmonium:
-> Interplay of primordial and regeneration component

Conclusion

- Learn about in-medium heavy quark anti-quark QCD force using bottomonium in heavy-ion collision
  → Significance of in-medium binding energies

- Sequential suppression for bottomonium, regeneration essential for excited state excitation function

- More suppression for bottomonium at higher energy vs. enhancement for charmonium at higher energy (regeneration).

- Υ v_2 as a probe of suppression/recombination temperature