EMMI Rapid Reaction Task Force

TAMU Approach

Part.3: Off-Equilibrium Effects

Xiaojian Du, Ralf Rapp

Texas A&M University

GSI
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Outline

- QGP Thermalization
- Initial fireball temperature
- Sensitivity

- Quarkonium Formation
- Quarkonium protection at high-Temperature
- High-pT spectra

- Heavy Quark Relaxation
- Relaxation time factor
- Off-/equilibrium pT-spectra for bottom-/charmonium

QGP Thermalization

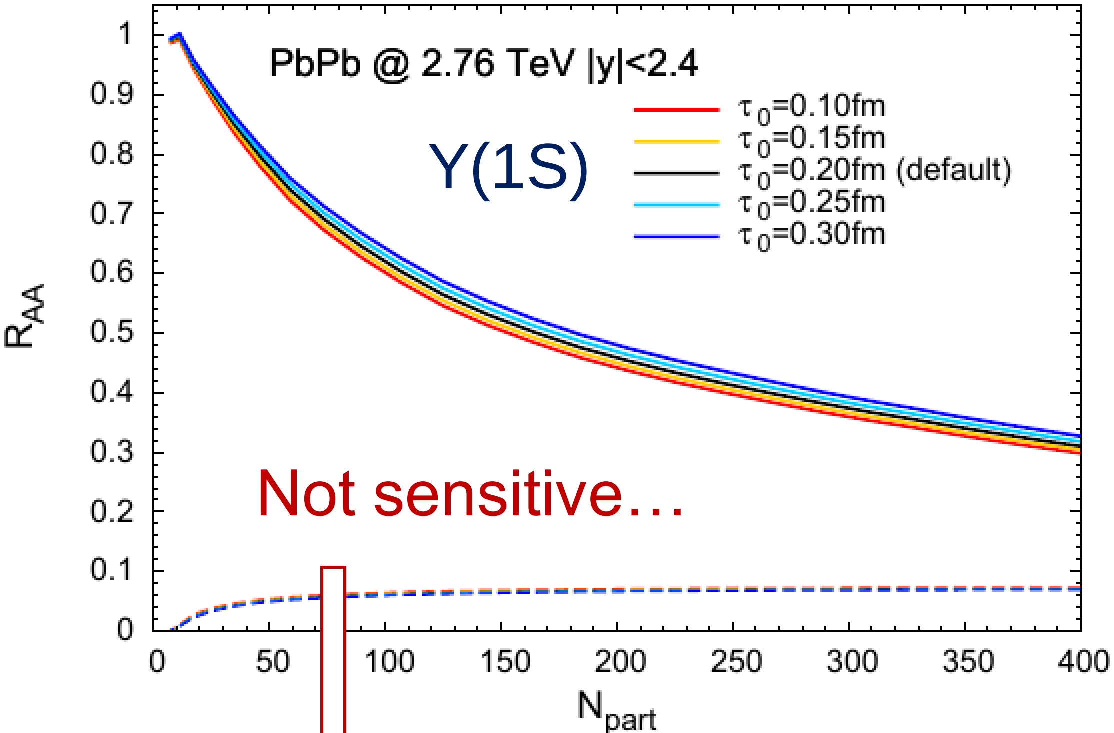
- QGP Thermalization time τ_0

- $V_{\mathrm{FB}}(\tau_0) = R_\perp^2 \tau_0 \Delta y$

- $S_{\mathrm{tot}} = V_{\mathrm{FB}}(t) s(T)$

- τ_0 affects initial-T

$$T \propto \left(\frac{1}{\tau_0}\right)^{\frac{1}{3}}$$



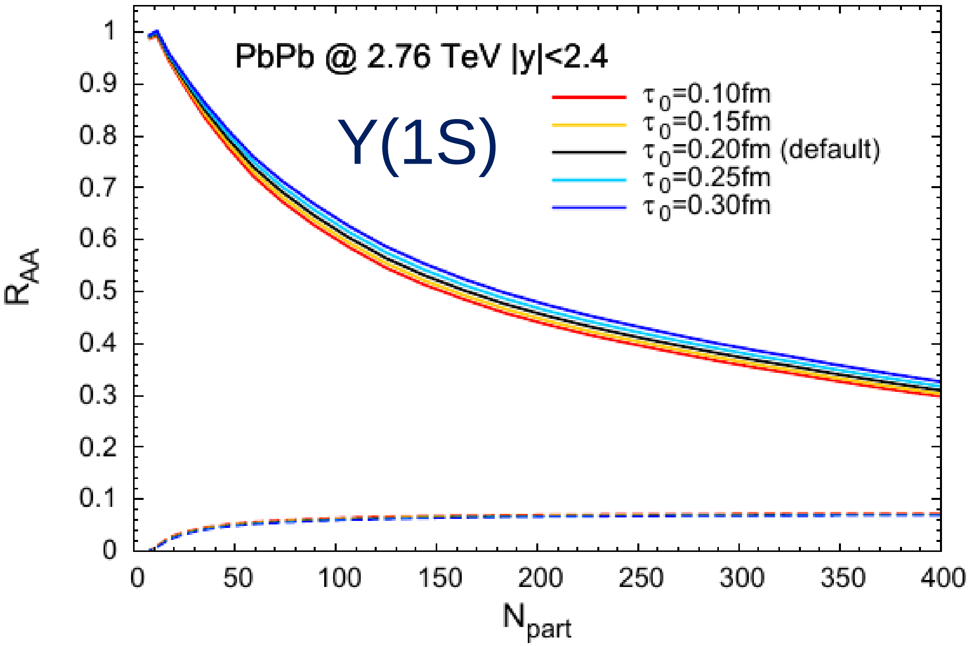
Not sensitive…

Quarkonium formation time

Quarkonium Formation Time

- Quarkonium Formation Time $\tau_\Psi^{\mathrm{form}}$
- Early time formation of quarkonium
- Suppress the quarkonium dissociation width at early time

$$\tilde{\Gamma}_\Psi(p_T,T) = \Gamma_\Psi(p_T,T)\frac{\tau}{\tau_\Psi^{\mathrm{form}}}\frac{m_\Psi}{\sqrt{p_T^2+m_\Psi^2}},\ \text{for } \tau < \tau_\Psi^{\mathrm{form}}\frac{\sqrt{p_T^2+m_\Psi^2}}{m_\Psi}$$



Protecting quarkonium from dissociation at early time

⇩

QGP-thermalization time not sensitive

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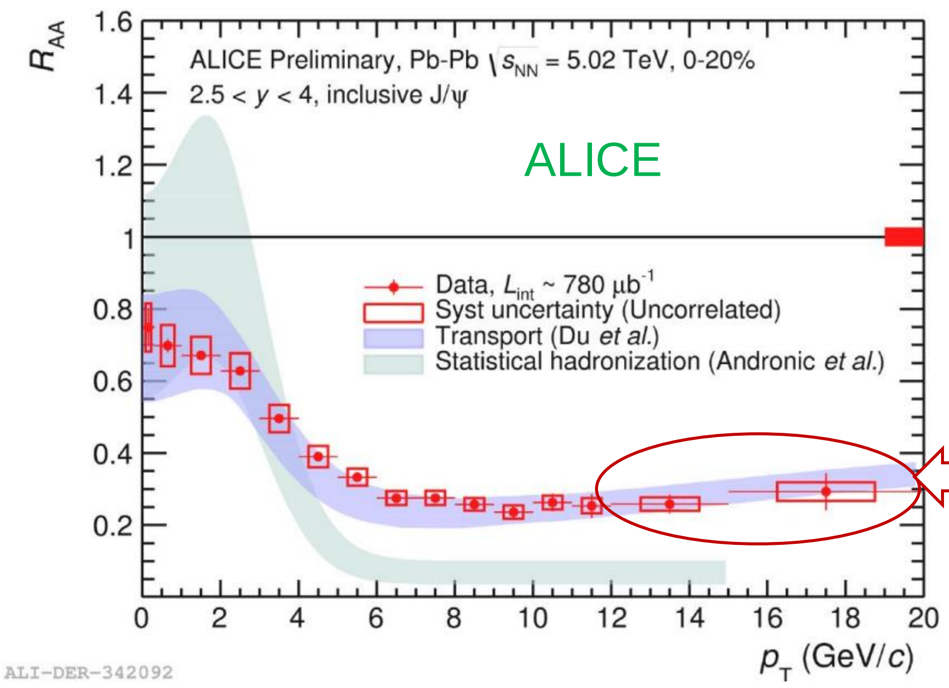
Quarkonium Formation Time

- Quarkonium Formation Time $\tau_\Psi^{\mathrm{form}}$
- Time dilation for high momentum quarkonium
- Suppress the quarkonium dissociation width at high-pT

$$\tilde{\Gamma}_\Psi(p_T,T) = \Gamma_\Psi(p_T,T)\frac{\tau}{\tau_\Psi^{\mathrm{form}}}\frac{m_\Psi}{\sqrt{p_T^2+m_\Psi^2}}, \text{ for } \tau < \tau_\Psi^{\mathrm{form}}\frac{\sqrt{p_T^2+m_\Psi^2}}{m_\Psi}$$



High-pT quarkonium forms slower

Less high-pT suppression

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Heavy Quark Relaxation

Equilibrium Limit and "Relaxation Factor"

$$\tilde{N}^{\mathrm{eq}}(T(t)) = N^{\mathrm{eq}}(T(t))R(t)$$

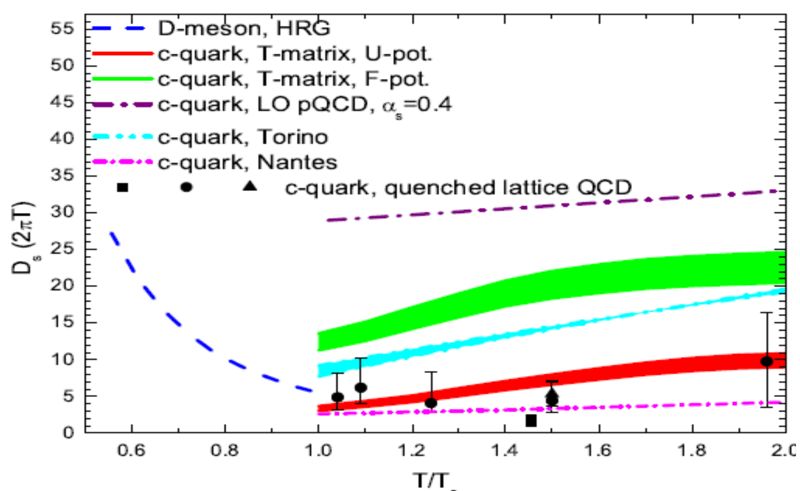
$$R(t) = 1 - \exp\left(-\int_0^t \frac{dt'}{\tau_Q(T(t'))}\right)$$

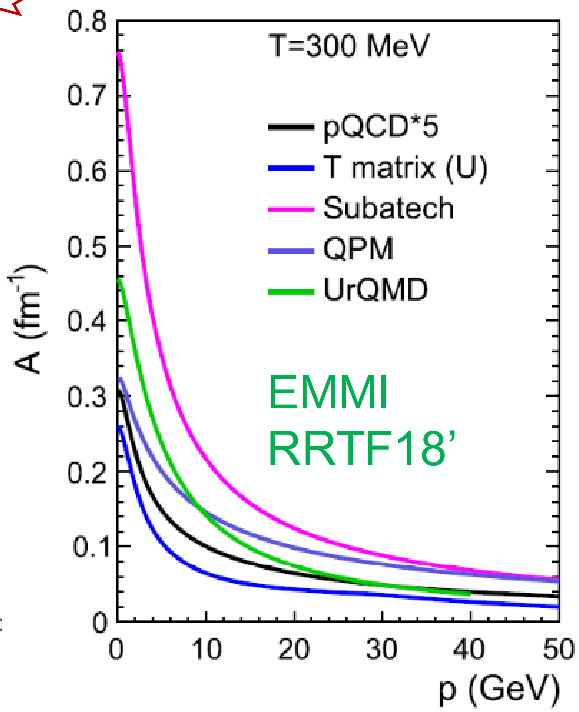
- Heavy quark relaxation time
- From T-matrix calculation & HF phenomenology

$$D_s = \frac{T}{m_Q \gamma_Q}$$

$$\tau_Q = \frac{1}{\gamma_Q}$$

$$\tau_b \simeq \frac{m_b}{m_c}\tau_c$$





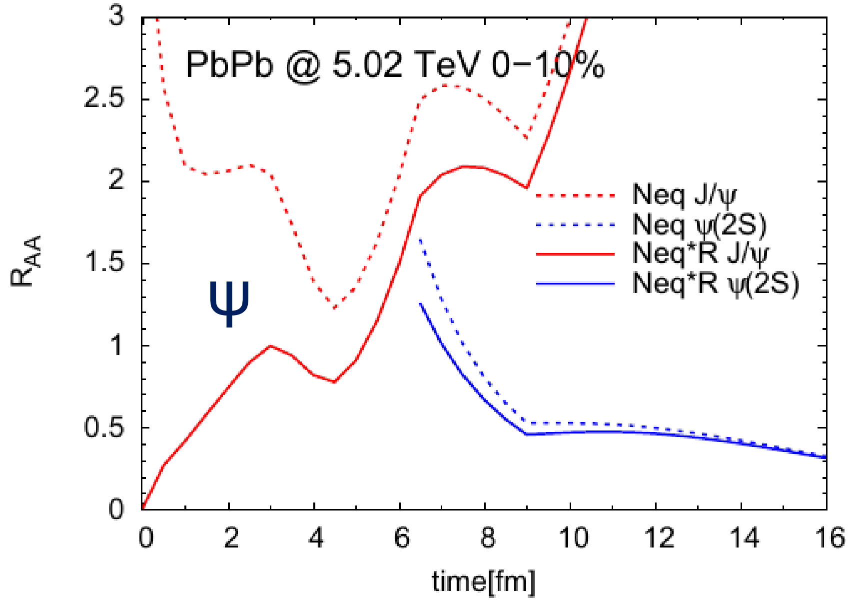
Heavy Quark Relaxation

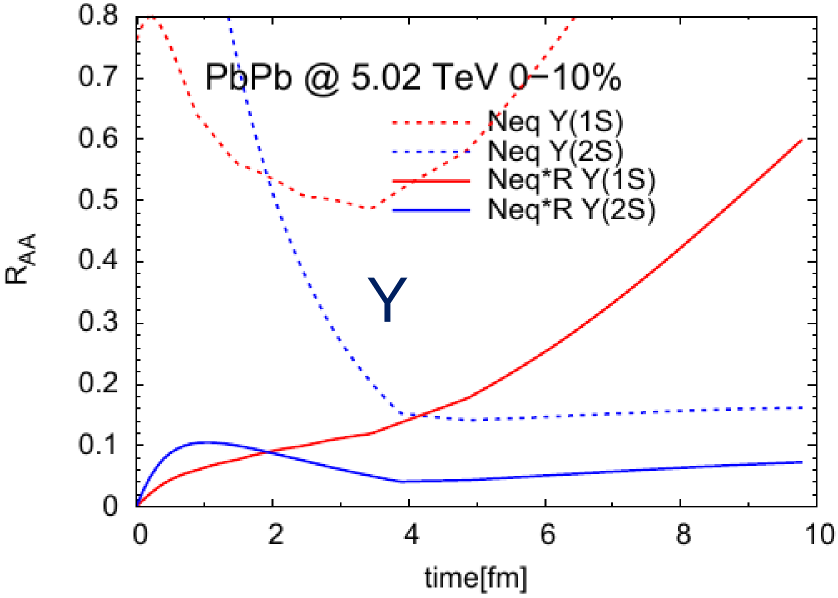
- Equilibrium Limit and "Relaxation Factor"

$$\tilde{N}^{\rm eq}(T(t)) = N^{\rm eq}(T(t))R(t)$$

$$R(t) = 1 - \exp\left(-\int_0^t \frac{dt'}{\tau_Q(T(t'))}\right)$$

- Suppress the equilibrium limit of quarkonium





$$\tau_b \simeq \frac{m_b}{m_c}\tau_c$$

- Charm: small relaxation, close to equilibrium
- Bottom: large relaxation, far from equilibrium

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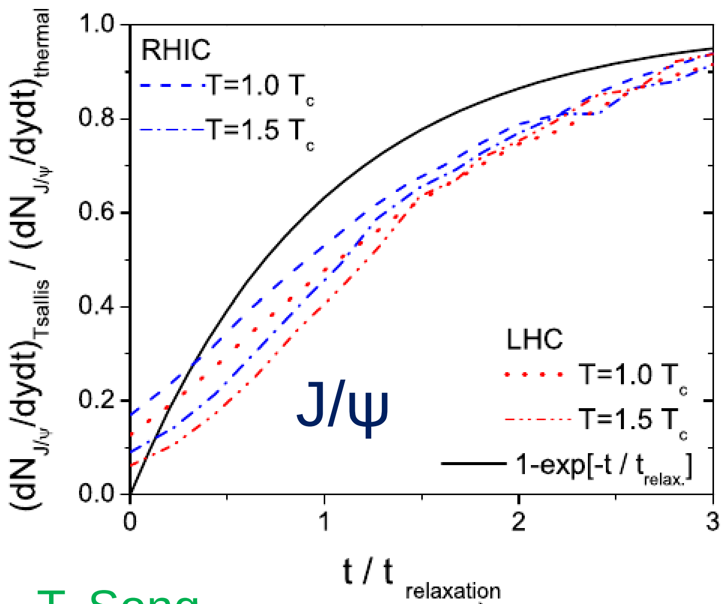
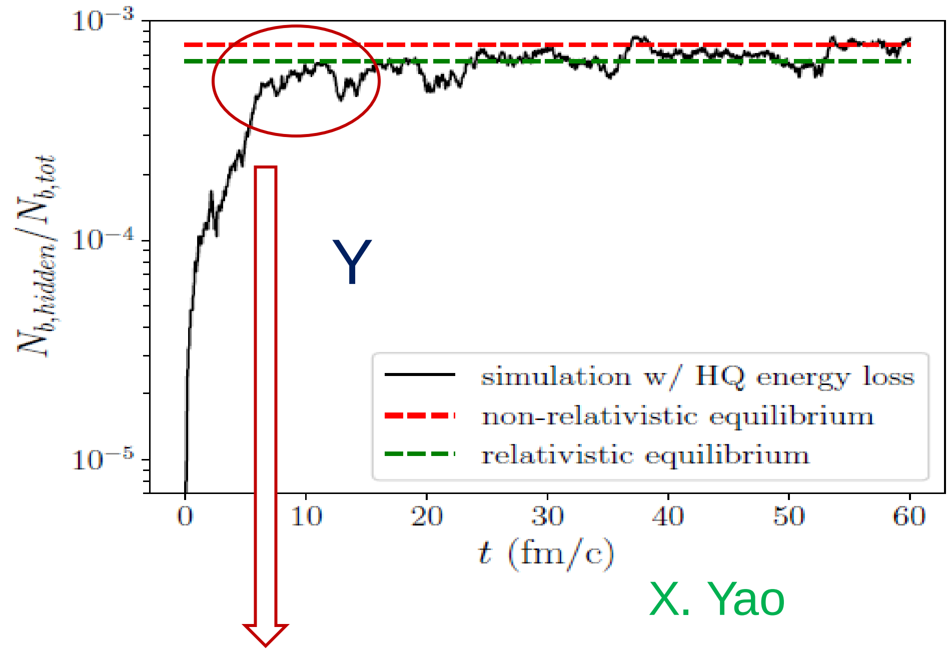
Heavy Quark Relaxation

- Compatible with non-equilibrium calculations

$$R(t) = 1 - \exp\left(-\int_0^t \frac{dt'}{\tau_Q(T(t'))}\right)$$



T. Song

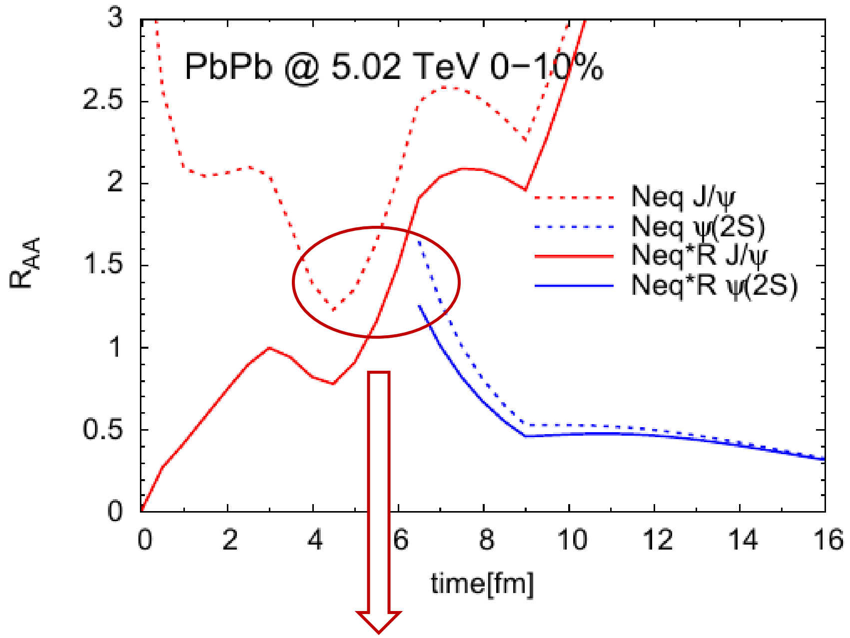


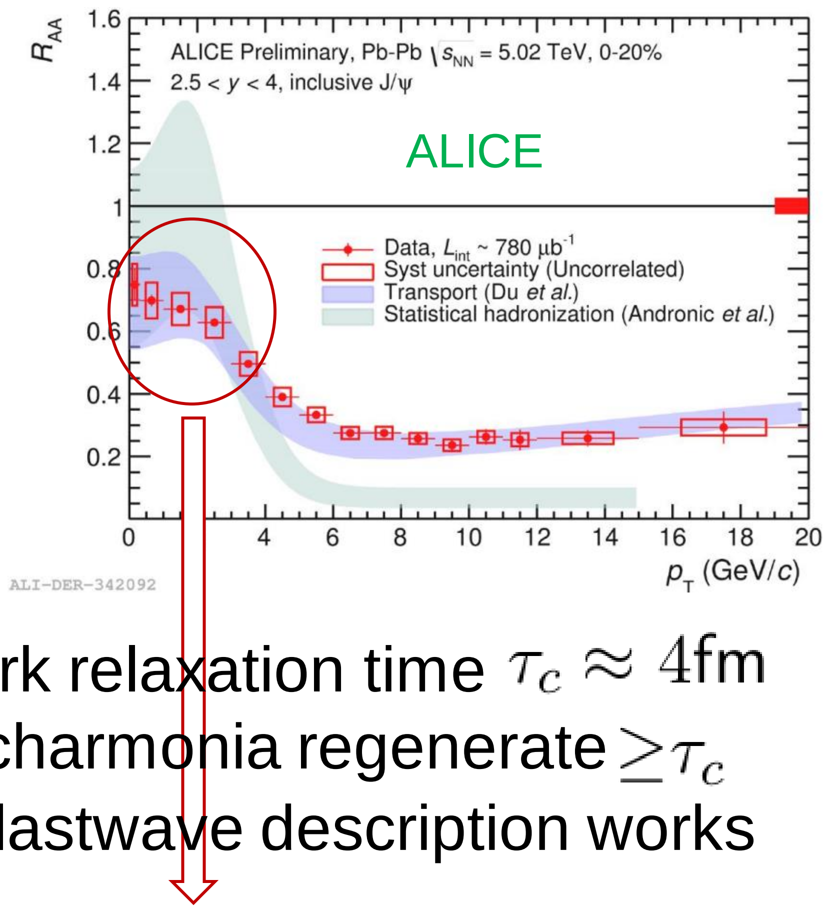
X. Yao

$\tau_Q(T(t'))$

- Charm: 3~5 fm
- Bottom: 10~12 fm

Charmonium Momentum Spectra



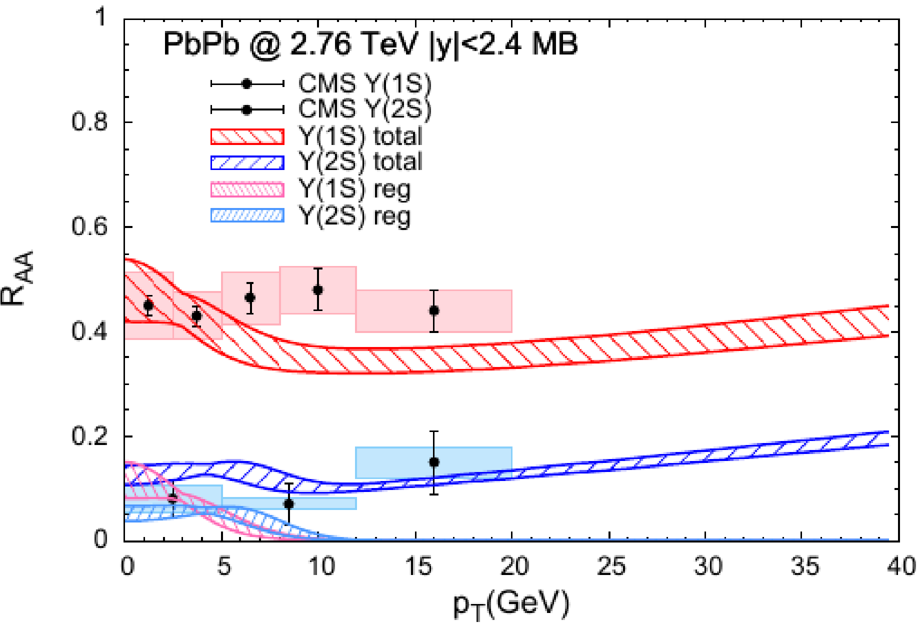


- Small charm mass: Charm quark relaxation time $\tau_c \approx 4\text{fm}$
- Small binding energy: Most of charmonia regenerate $\geq \tau_c$
- Close to thermal equilibrium: Blastwave description works

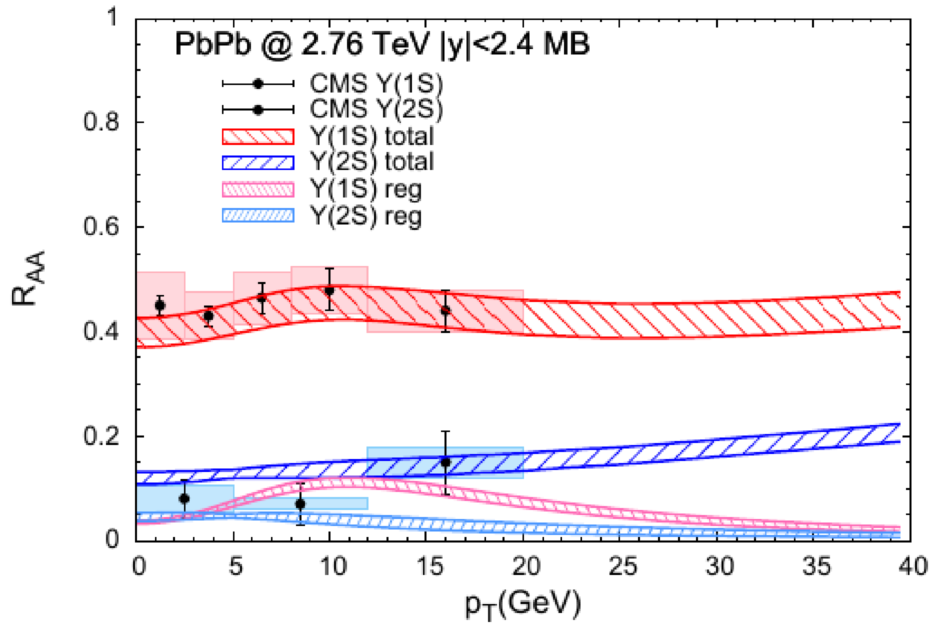
$$\frac{dN_{\Psi}^{\text{reg}}(p_T)}{p_T dp_T} \propto m_T \int_0^R r dr K_1\left(\frac{m_T \cosh(\rho(r))}{T}\right) I_0\left(\frac{p_T \sinh(\rho(r))}{T}\right)$$

Bottomonium Momentum Spectra

- Large bottom mass: Bottom quark relaxation time $\tau_b \geq 10\text{fm}$
- Large binding energy: Regenerate during whole evolution
- Far from equilibrium: Blastwave description fails
- Coalescence with Langevin simulated bottom quark spectra



- blastwave (thermal)



- Coalescence (non-thermal)

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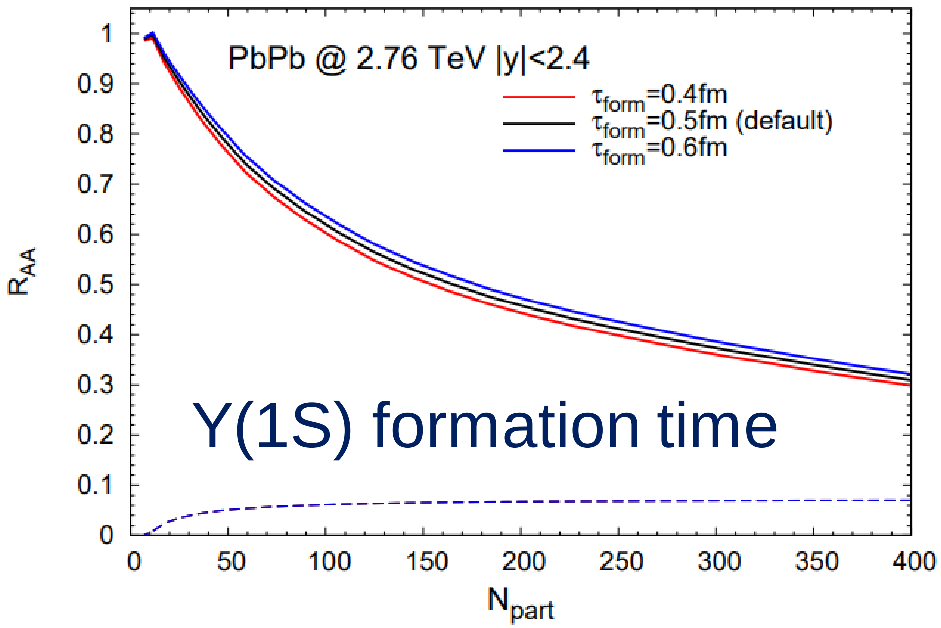
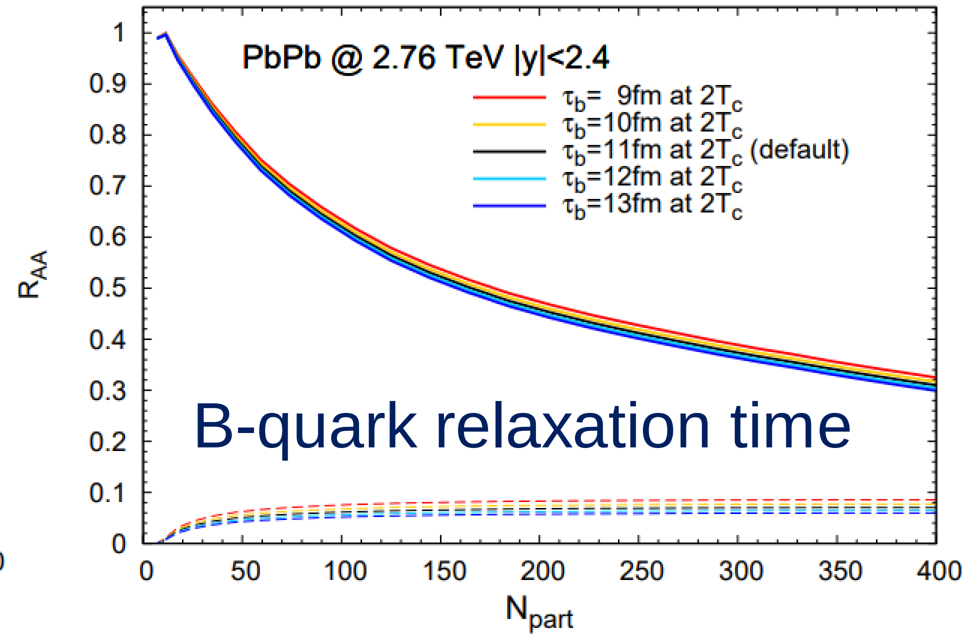
Formation/Relaxation Time Sensitivity





- QGP Thermalization/B-quark Relaxation:
  Constrained by hydro/HF phenomenology
- Quarkonium formation time:
  Need quantum treatment of the quarkonium formation

Correlation Volume Sensitivity

■ Another item related with quark/antiquark correlation:

Correlation Volume $V_{\rm corr} = \frac{4}{3}\pi(r_0 + \langle v_Q \rangle\, t)^3$

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

■ r_0 :0.8~1.2 fm, minimum radius for strong interaction

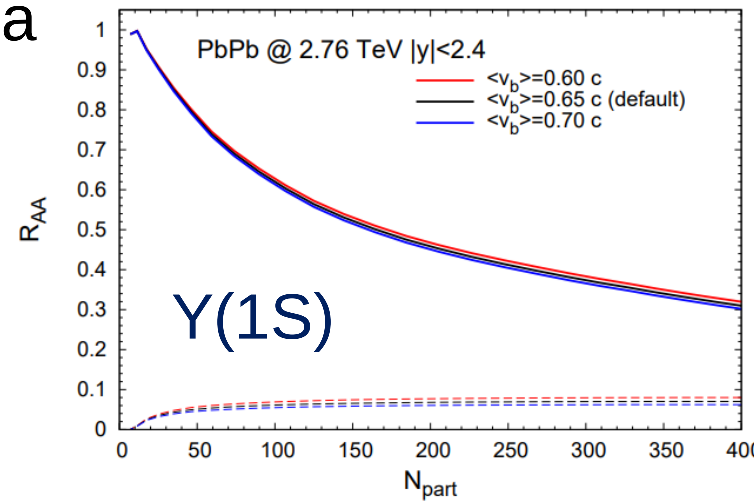
L. Grandchamp, R. Rapp PRL 92'

■ v_Q : 0.6~0.7fm, heavy quark spectra

Not sensitive:

(1) Bottomonium: Small regeneration

(2) Charmonium: Grand-canonical region, correlation volumes merge.



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