Quarkonium production in pp and heavy-ion collisions

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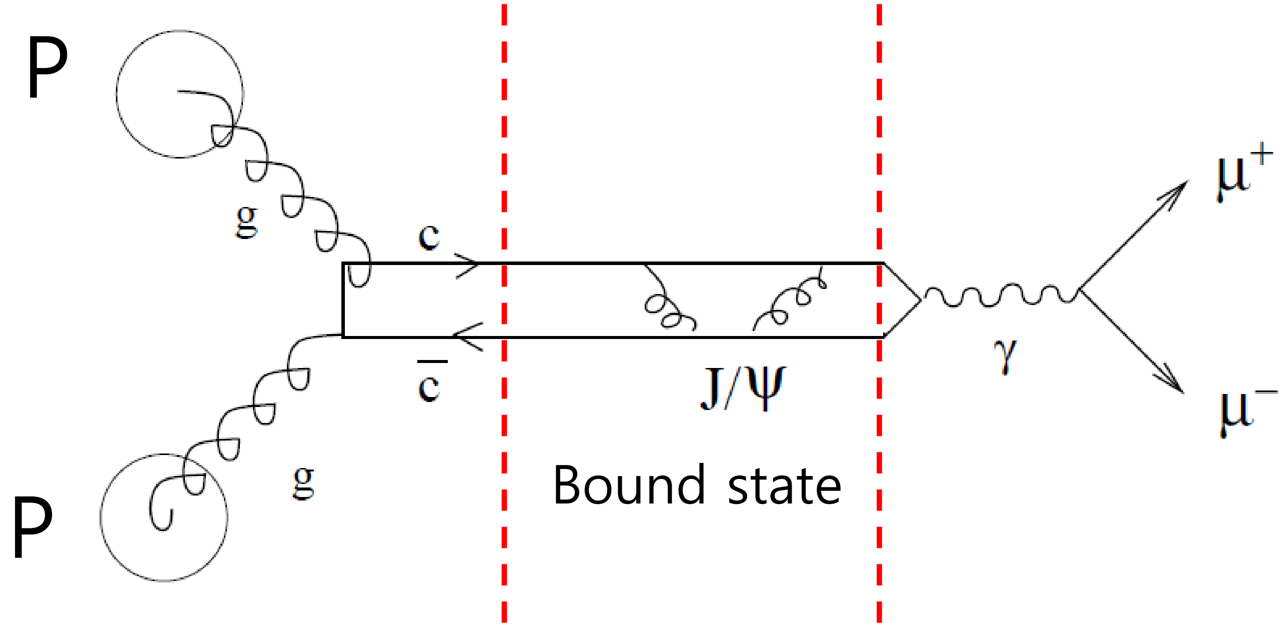
outline

- Introduction
- Quarkonium production in pp collision
- Quarkonium production in AA collision
- Summary

quarkonium production in p+p collisions



Heavy quark pair production
(pQCD process)
momentum from PYTHIA
relative distance from uncertainty principle

Quarkonium formation
(non-pQCD process)
depends on model
We use the Wigner projection

Wigner projection

- Wigner density of S- & P-wave states: $\langle p, r | p_1, r_1; p_2, r_2 \rangle$

$$\Phi_S^W(\mathbf{r},\mathbf{p}) = 8\frac{D}{d_1 d_2}\exp\left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2\right],$$

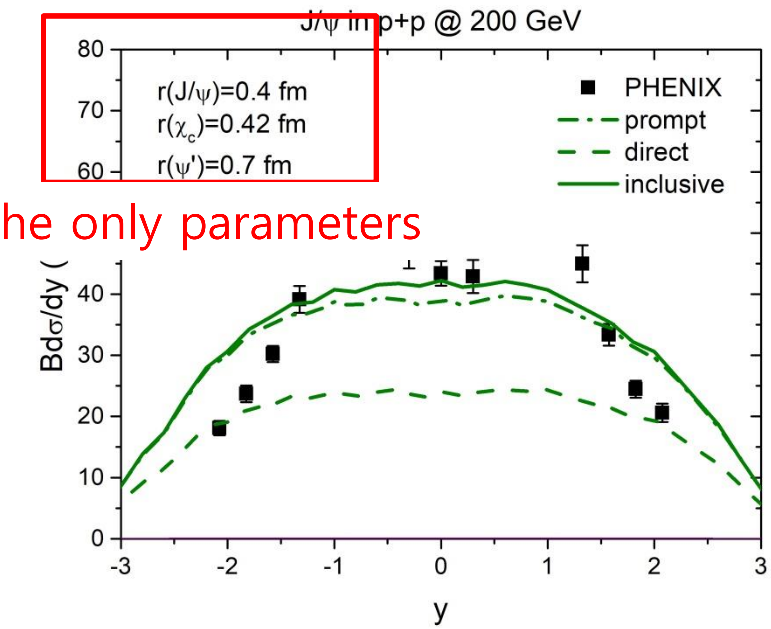
$$\Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}\left(\frac{r^2}{\sigma^2} - \frac{3}{2} + \sigma^2 p^2\right) \times \exp\left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2\right],$$

- D, d1, d2: color-spin degeneracy of quarkonium, heavy quark and antiquark
- r, p: relative distance and momentum in center-of-mass frame
- **σ**: the only parameter ~ quarkonium radius

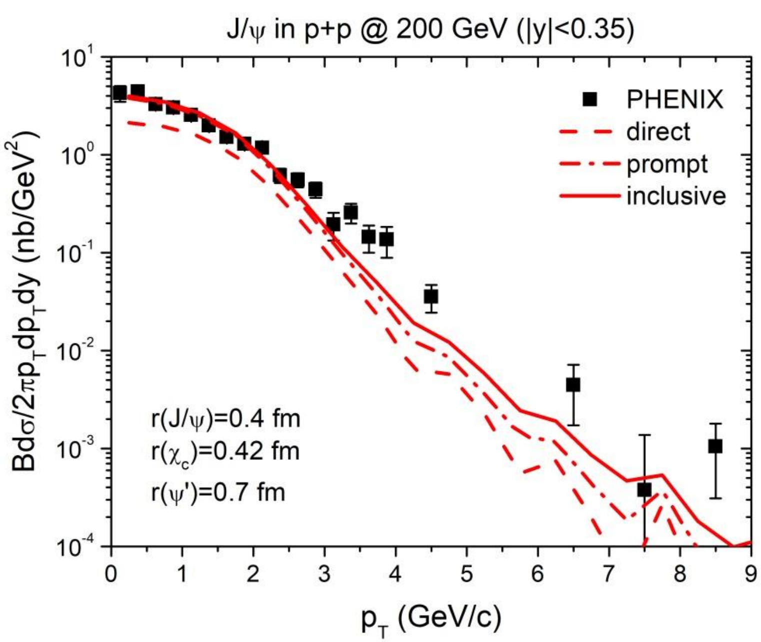
J/ψ in pp @ 200 GeV

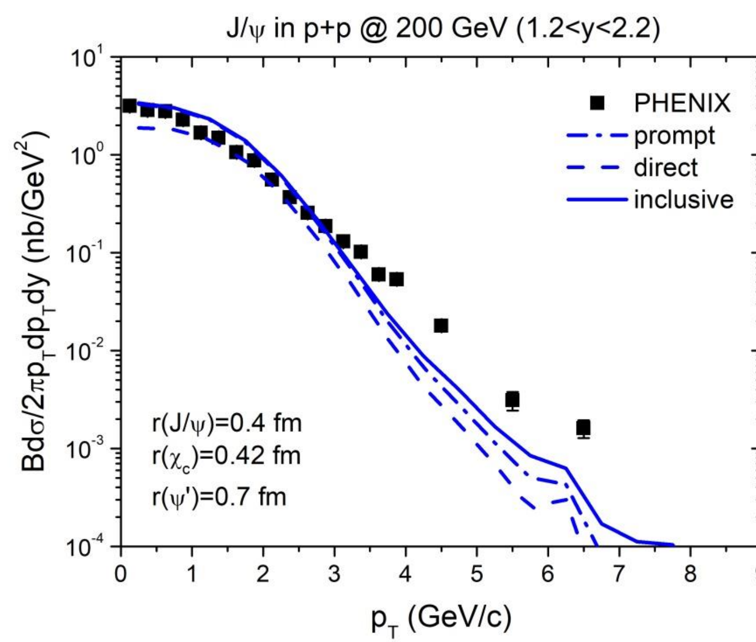
T. Song, J. Aichelin, E. Bratkovskaya, PRC96, 014907

direct: purely initial J/ψ
prompt: including the feed-down from χ_c, ψ′
Inclusive: including χ_c, ψ′ and B decay



The only parameters





J/ψ in pp @ 2.76 TeV

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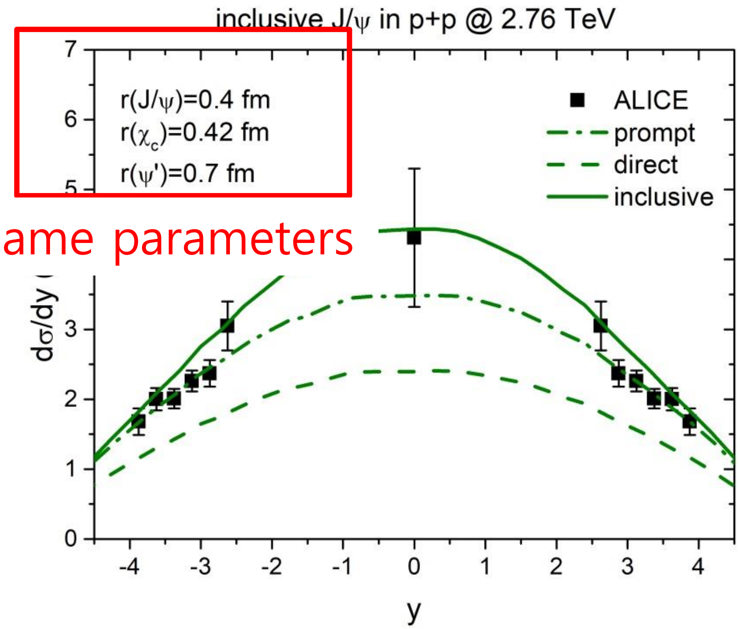
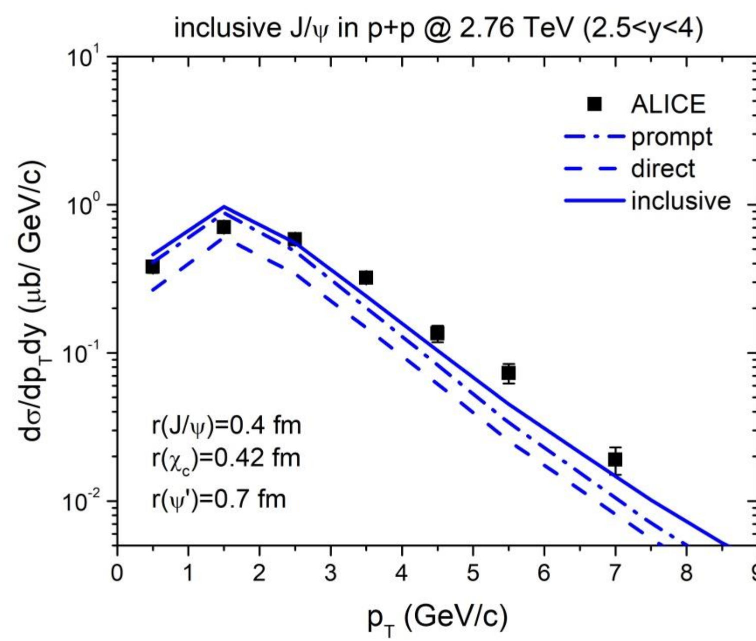
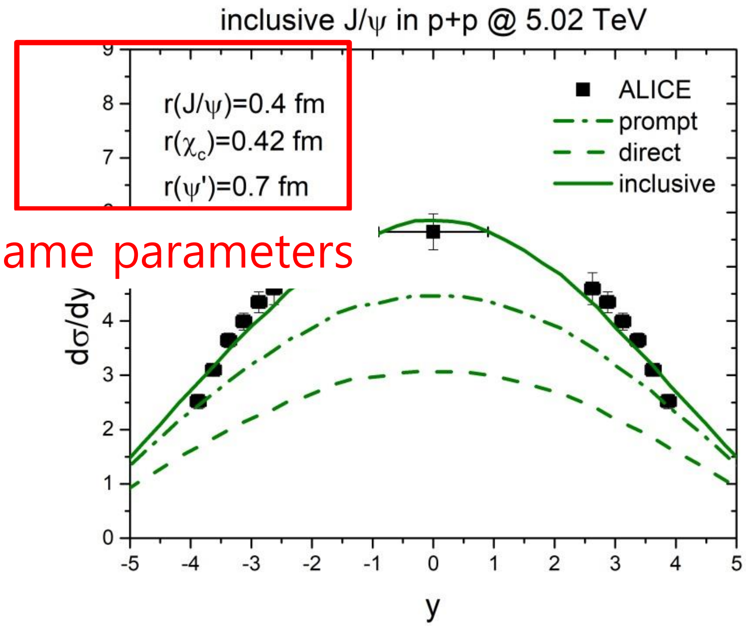


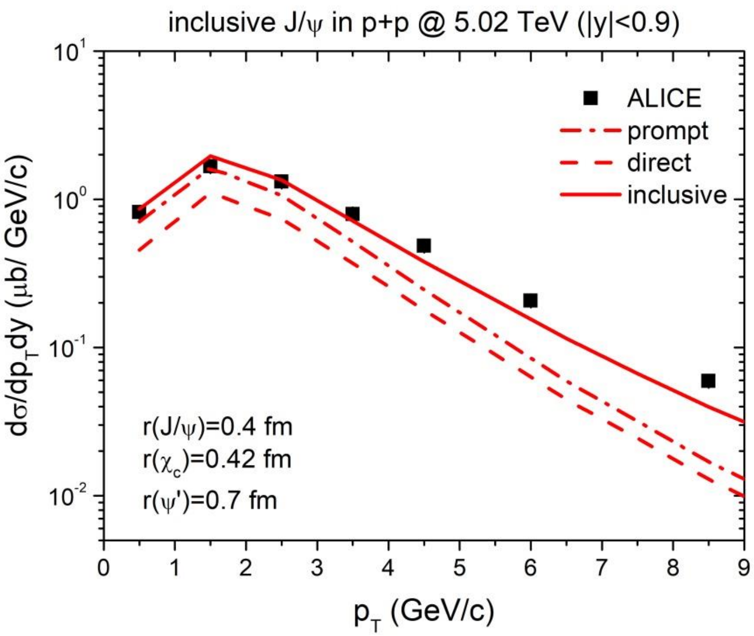


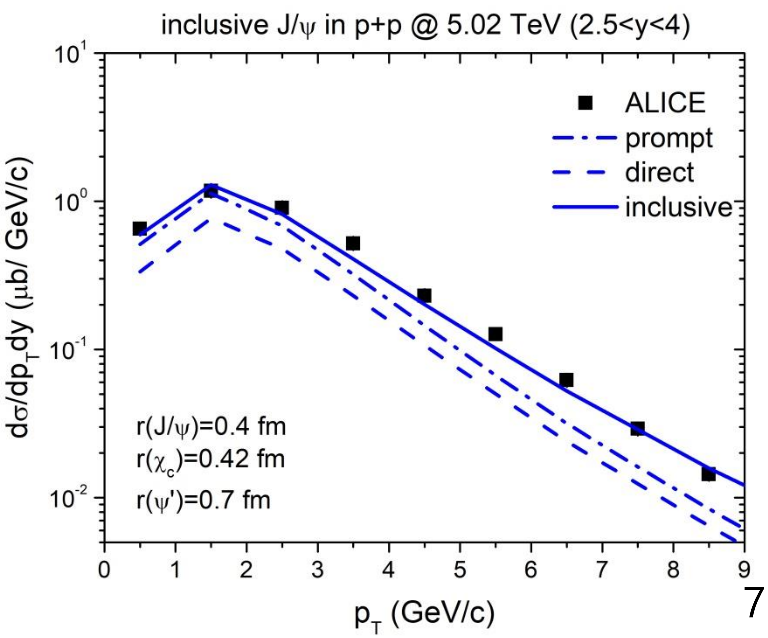
J/ψ in pp @ 5.02 TeV

T. Song, J. Aichelin, E. Bratkovskaya, PRC96, 014907

The same parameters







Υ(nS) @ 5.02 TeV

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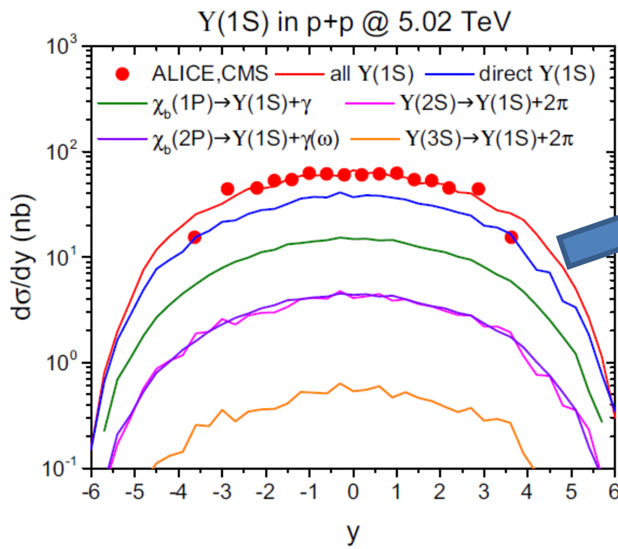
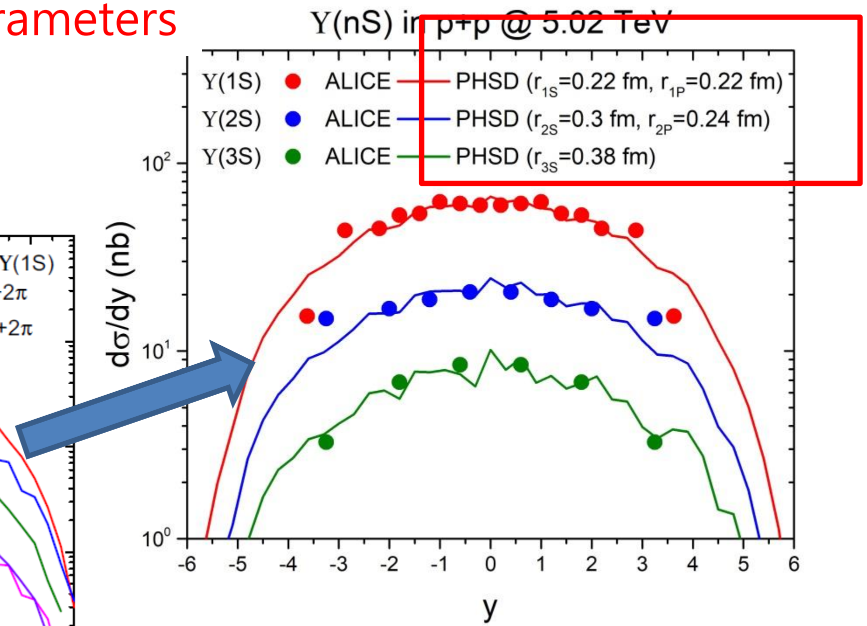
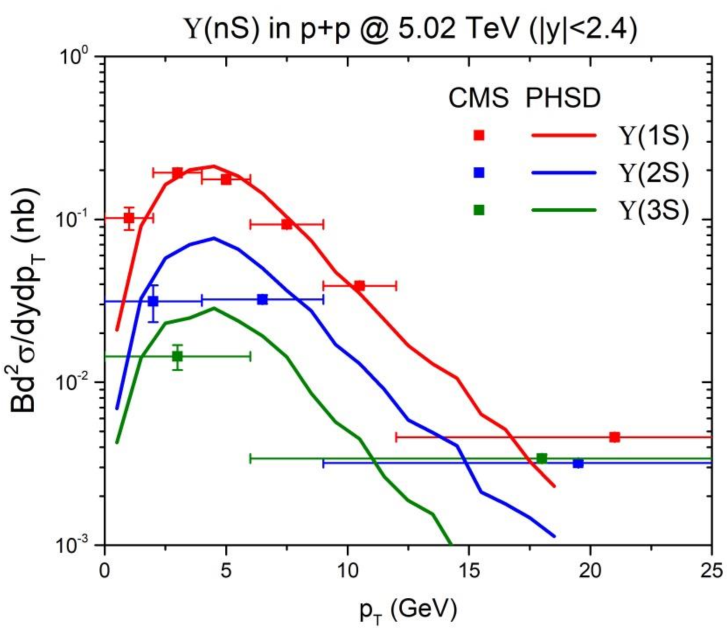
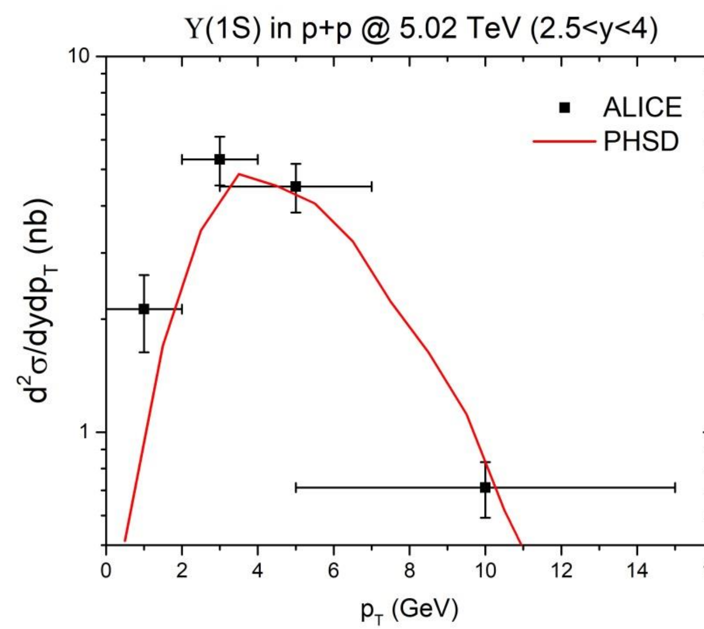
J. Zhao, P. Gossiaux,
E. Bratkovskaya,
PRC108, 054908



The only parameters







Quarkonium production in heavy-ion collisions

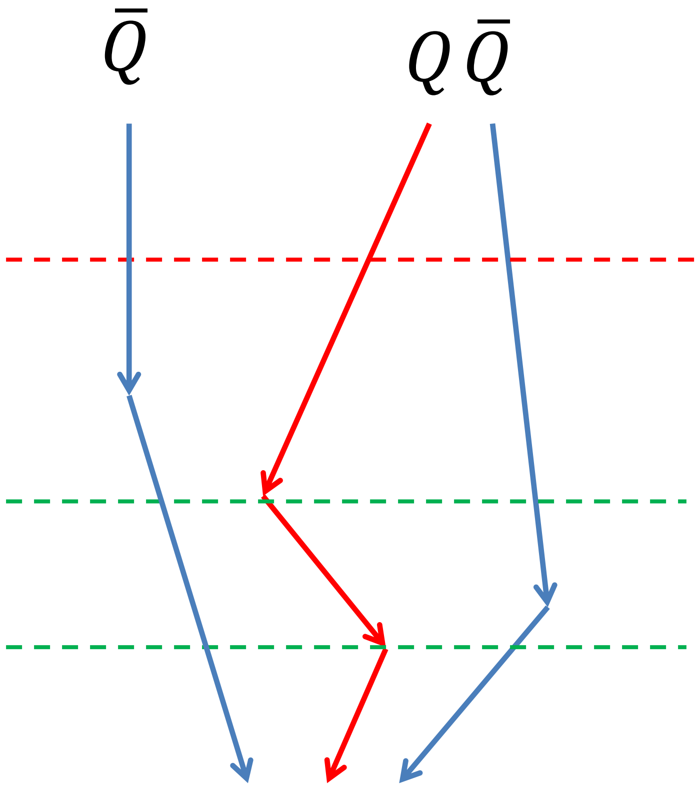
- Different from in p+p collisions,
- Quarkonium cannot be formed above the dissociation temperature
- Quarkonium radius changes with time (temperature)
- Quarkonium dissociation and regeneration take place
- …
- We use the Remler formalism

E. A. Remler and A. P. Sathe, Ann. Phys. **91**, 295 (1975).
E. A. Remler, Ann. Phys. **95**, 455 (1975).
E. A. Remler, Ann. Phys. **136**, 293 (1981).

D. Y. A. Villar, J. Zhao, J. Aichelin, and P. B. Gossiaux, arXiv:2206.01308 (2022).

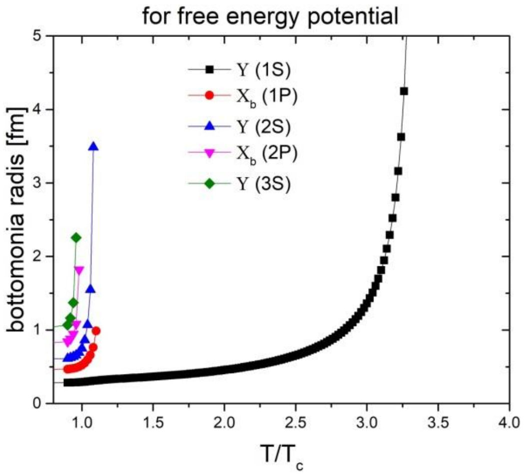
T. Song, J. Aichelin, and E. Bratkovskaya, Phys. Rev. C **96**, 014907 (2017), 1705.00046.

Remler's formalism



Dissociation temperature (first projection)

Whenever Q ($\bar{Q}$) scatters, Wigner projection is updated, using temperature-dependent radius



1. This is carried out for all $Q\bar{Q}$ pairs for all physical states: J/ψ, χ_c, ψ′ for $c\bar{c}$ and ϒ(1S), ϒ(2S), ϒ(3S), χ_b(1P), χ_b(2P) for $b\bar{b}$
2. Heavy quark potential and scattering are closely related to quarkonium production/dissociation

2-dimensional table is prepared for all possible combinations of heavy quark and heavy antiquark whether charm or bottom

$$(Q_i, \bar{Q}_j) = (c, \bar{c}), (c, \bar{b}), (b, \bar{c}), (b, \bar{b})$$

	Q_1	Q_2	Q_3	Q_4	Q_5	…
$\bar{Q}_1$	d					
$\bar{Q}_2$		i		off	diag onal	
$\bar{Q}_3$			a			
$\bar{Q}_4$				g		
$\bar{Q}_5$					o	
…						nal

diagonal cells indicate initial $Q\bar{Q}$ pairs; off-diagonal cells recombination from two different initial $Q\bar{Q}$ pairs

Initially all cells are empty because of high temperature.
When the local temperature at the middle of $(Q_i, \bar{Q}_j)$ becomes lower than T_{diss}, the cell begins to be filled in → initial production

	Q_1	Q_2	Q_3	Q_4	Q_5	…
$\bar{Q}_1$	d					
$\bar{Q}_2$		i		off	diag onal	
$\bar{Q}_3$			a			
$\bar{Q}_4$				g		
$\bar{Q}_5$					o	
…						nal

When Q_2 scatters, Q_2 column is updated

	Q_1	Q_2	Q_3	Q_4	Q_5	…
$\bar{Q}_1$	d					
$\bar{Q}_2$		i		off	diag onal	
$\bar{Q}_3$			a			
$\bar{Q}_4$				g		
$\bar{Q}_5$					o	
…						nal

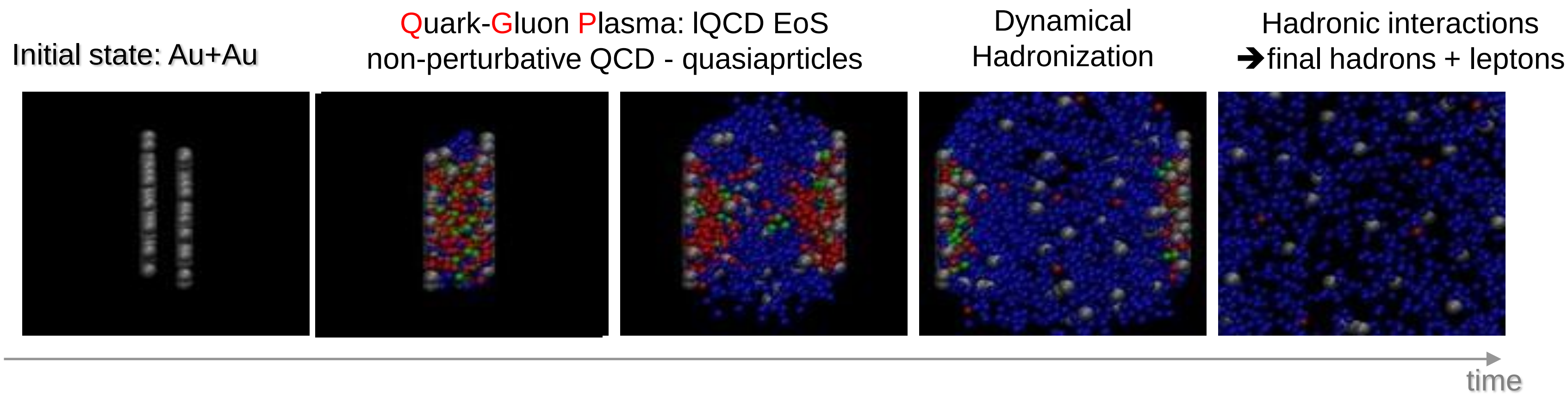
When $\bar{Q}_3$ scatters, $\bar{Q}_3$ row is updated

	Q_1	Q_2	Q_3	Q_4	Q_5	…
$\bar{Q}_1$	d					
$\bar{Q}_2$		i		off	diag onal	
$\bar{Q}_3$			a			
$\bar{Q}_4$				g		
$\bar{Q}_5$					o	
…						nal

Parton-Hadron-String-Dynamics (PHSD)

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of dynamics of **strongly-interacting hadronic and partonic matter** produced in heavy-ion collisions

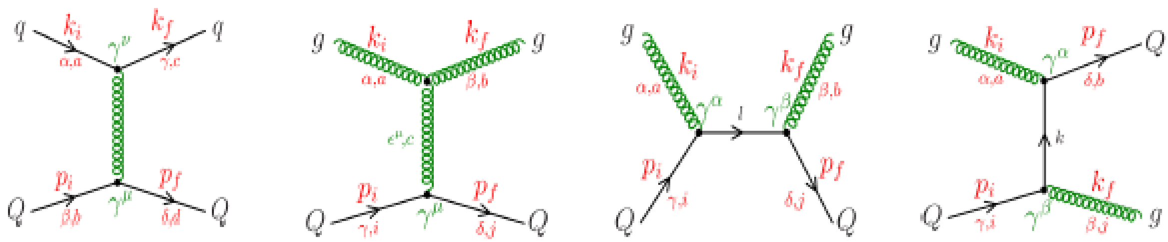
Dynamics: based on the solution of generalized off-shell transport equations derived from **Kadanoff-Baym many-body theory** (beyond semi-classical BUU)



PHSD provides a good description of ‘bulk’ hadronic and electromagnetic observables from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; P. Moreau et al., PRC100 (2019) 014911

Heavy quark scattering in PHSD

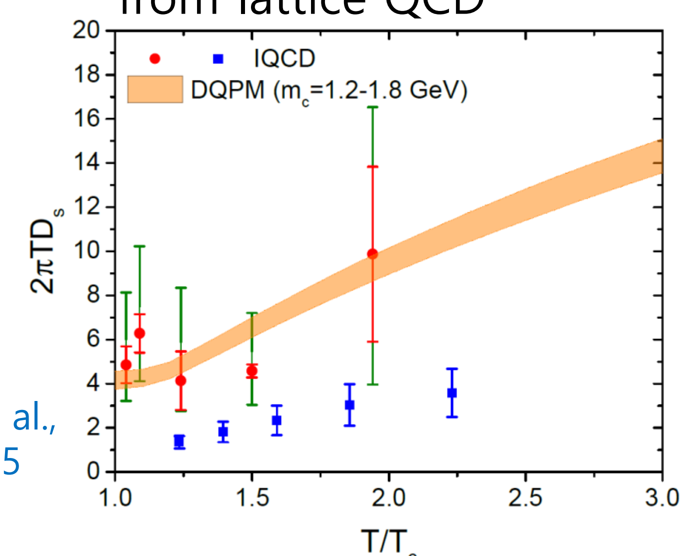


Dynamical Quasi-Particle Model

H. Berrehrah et al., PRC89, 054901

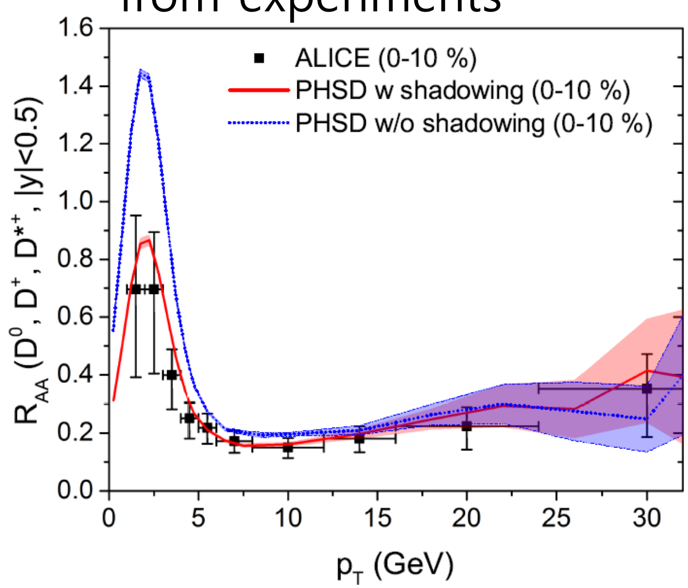
1. Heavy quark interacts with off-shell massive partons
2. T-dependent g_s from lattice EoS

Spatial diffusion coefficient from lattice QCD



T. Song et al., 2404.00425

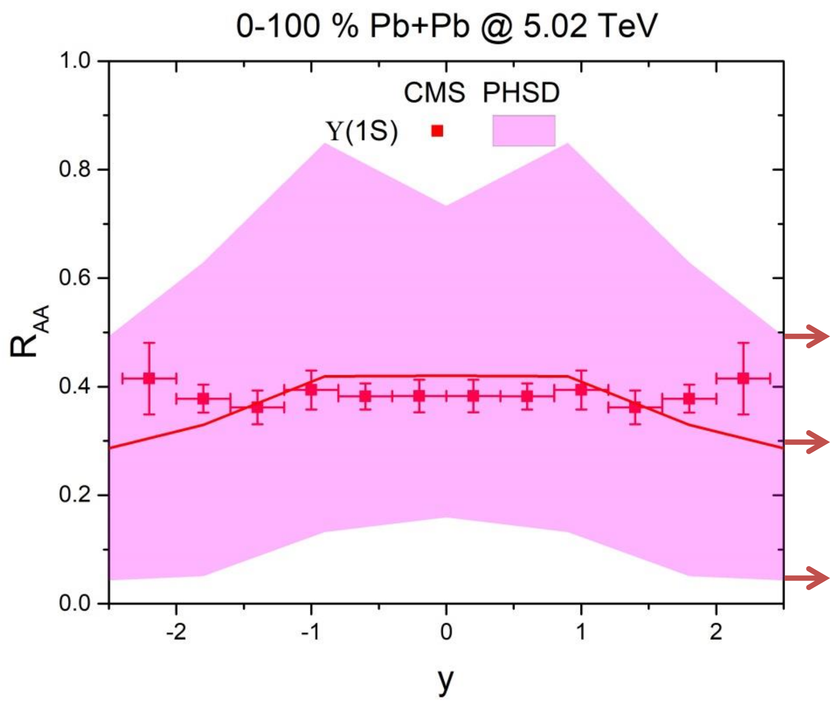
R_{AA} of heavy meson from experiments



T. Song et al., PRC93, 034906

$R_{AA}(y)$ of Y(1S)

T. Song, J. Aichelin, J. Zhao, P. Gossiaux, E. Bratkovskaya, PRC108, 054908



$$R_{AA} = \frac{\frac{dN^{AA}}{dydp_T}}{N_{coll}\left(\frac{dN^{pp}}{dydp_T}\right)}$$

Upper limit: Initial production at T_{diss} (Wigner projection at T_{diss})

Solid line: only 10 % of scatterings update the Wigner projection

Lower limit: final number at T_c (Wigner projection at T_c)

Because of the spatial diffusion of heavy (anti)quark, Wigner density normally decreases with time

$R_{AA}(p_T)$ of Υ(1S)

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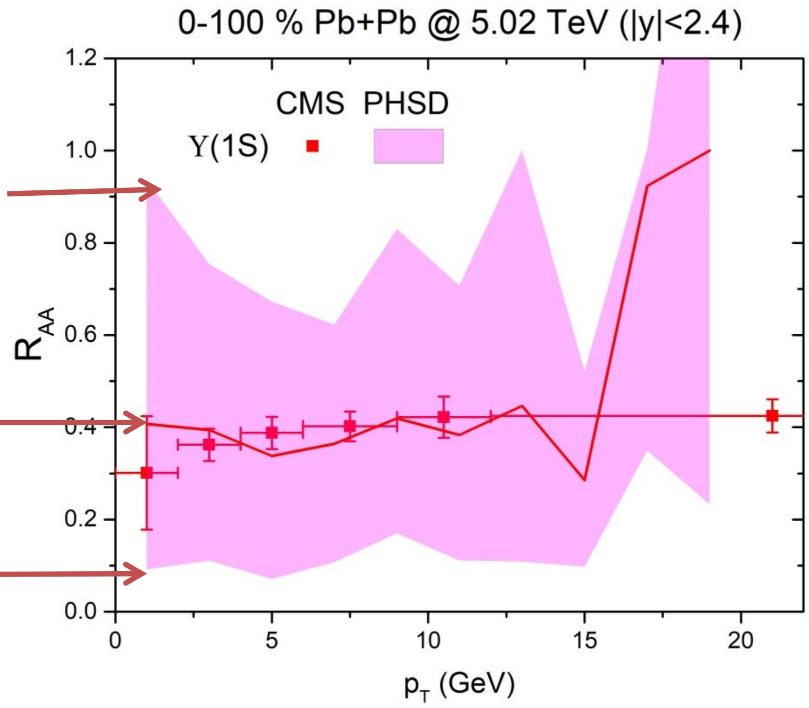
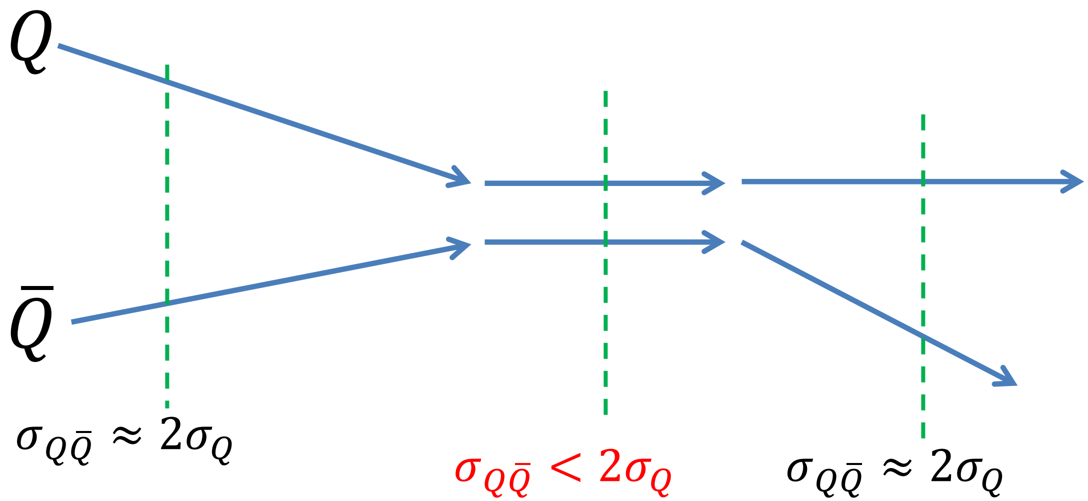
Upper limit: Initial production at T_{diss}
(Wigner projection at T_{diss})

Solid line: only 10 % of scatterings update the Wigner projection

Lower limit: final number at T_c
(Wigner projection at T_c)

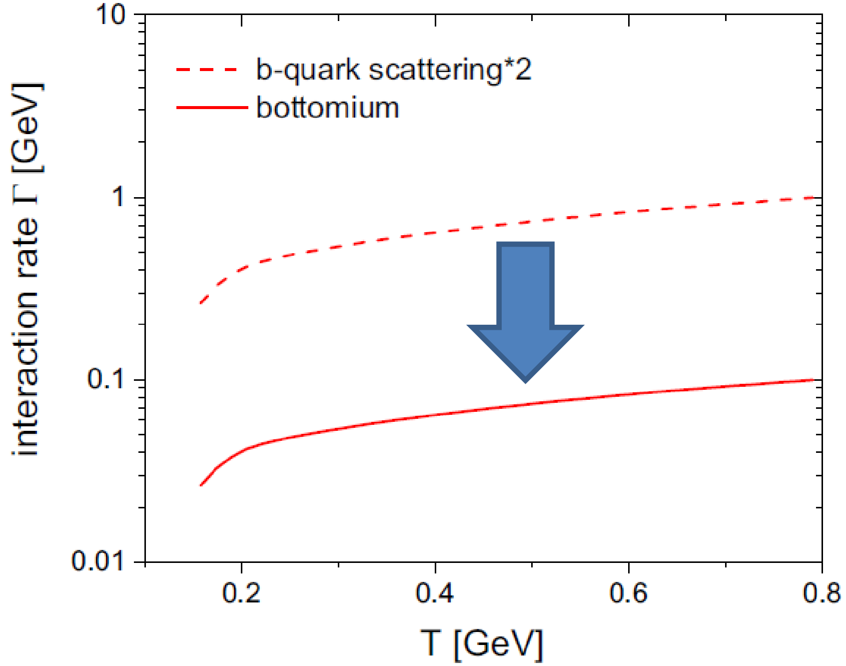


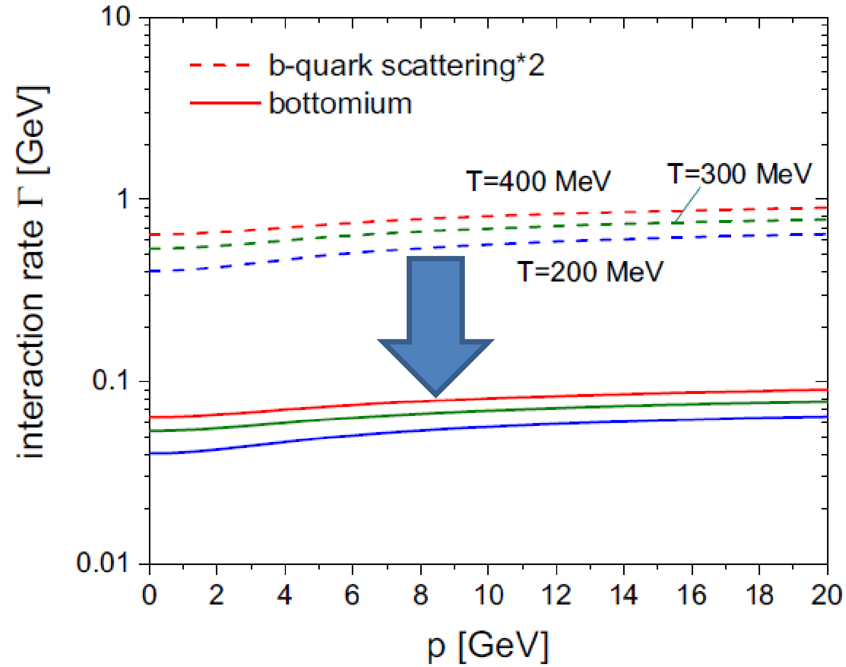
There must be a suppression of heavy (anti)quark scattering, if it is bound



If $Q\bar{Q}$ form a color singlet, the size of $Q\bar{Q}$ pair will be small and the scattering cross section must be reduced due to interference

Υ(1S) interaction rate ≈ interaction rate of b and $\bar{b}$ quarks/10





T. Song, J. Aichelin, J. Zhao, P. Gossiaux, E. Bratkovskaya, PRC108, 054908

$R_{AA}(y)$ of Υ(2S)

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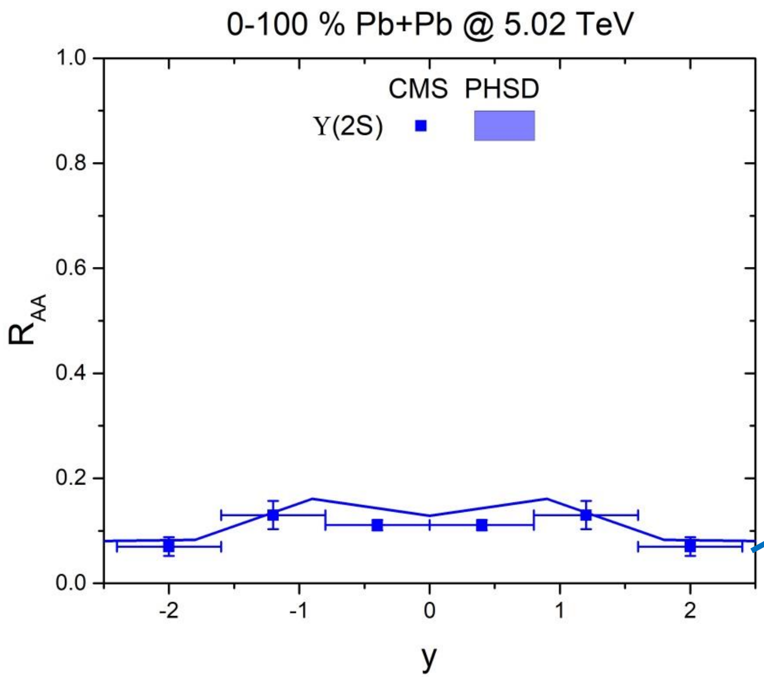

Upper limit: Initial production at T_{diss}

Lower limit: final number at T_c

The band is too thin, because $T_{diss} \approx T_c$ for Υ(2S)

$R_{AA}(p_T)$ of Υ(2S)

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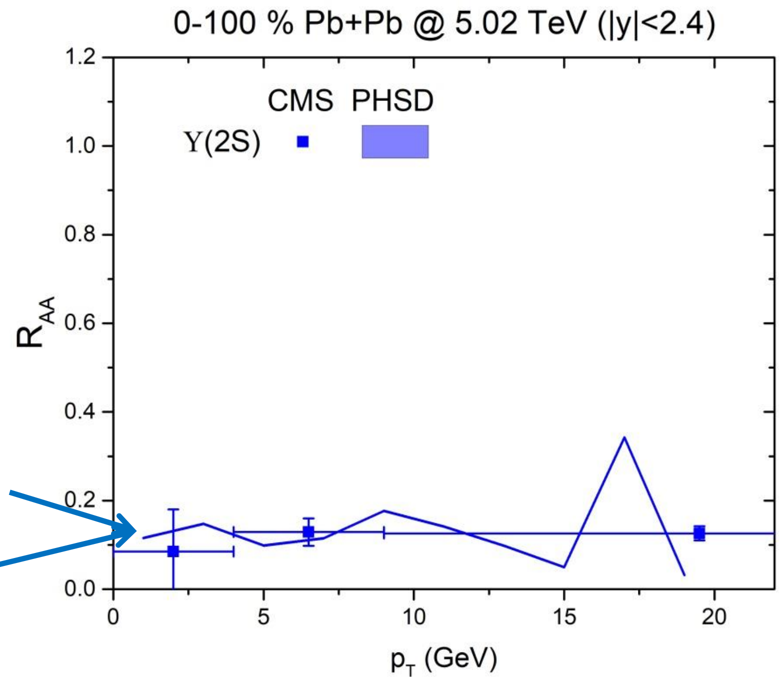
Upper limit: Initial production at T_{diss}

Lower limit: final number at T_c



The band is too thin, because $T_{diss} \approx T_c$ for Υ(2S)

R_{AA} vs N_{part}

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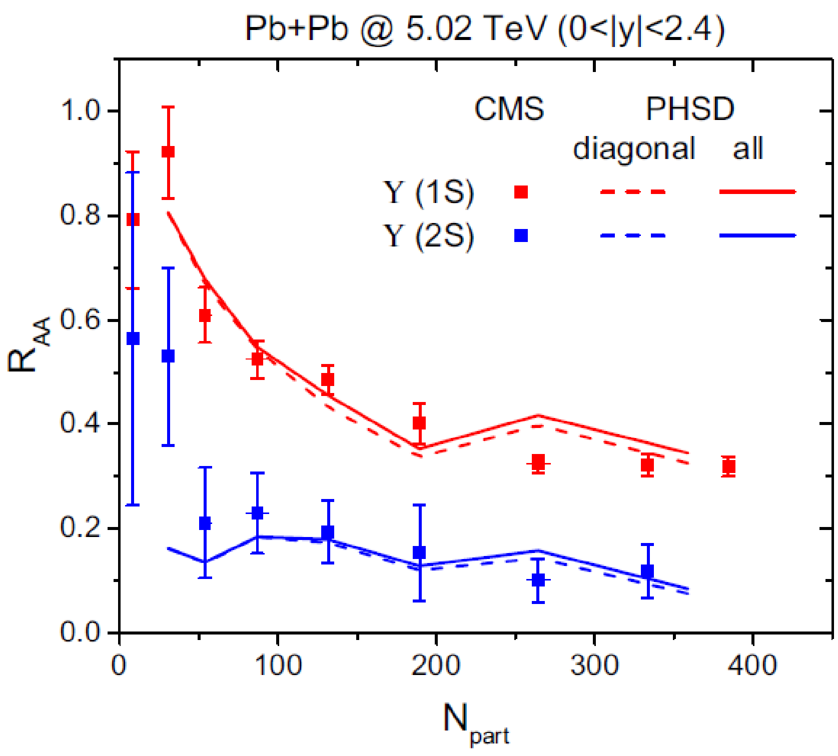
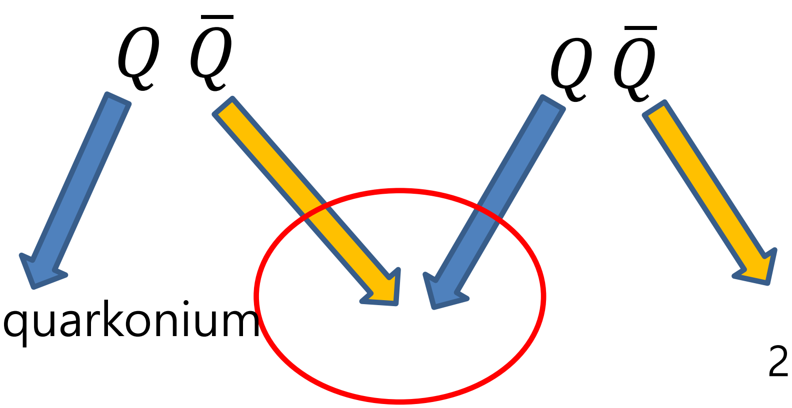


- Diagonal: Upsilon only from initial pairs
- All: include upsilon from initial other pairs
- The contribution from off-diagonal is little, because b quark pairs are rare even at LHC



Off-diagonal quarkonium

Summary

- Relmer formalism is applied to quarkonium production in pp and AA collisions
- In pp collisions, only initial Wigner projection is carried out
- In AA collisions, the initial Wigner projection starts at T_{diss} and then Wigner density is updated whenever Q or $\bar{Q}$ scatters until T_c
- Since the scattering cross section of color singlet (quarkonium) is smaller than that of separate Q and $\bar{Q}$, there must be a suppression of scattering
- R_{AA} (y), R_{AA} (p_T), R_{AA} (N_{part}) of Υ(1S), Υ(2S) in Pb+Pb collisions at LHC are well reproduced by the PHSD using free energy for heavy quark potential and applying that the quarkonium interaction rate ≈ 10 % interaction rate of separate Q and $\bar{Q}$
- Off-diagonal bottomonium is little even at LHC

Thank you for your attention