Quarkonium production in PHSD

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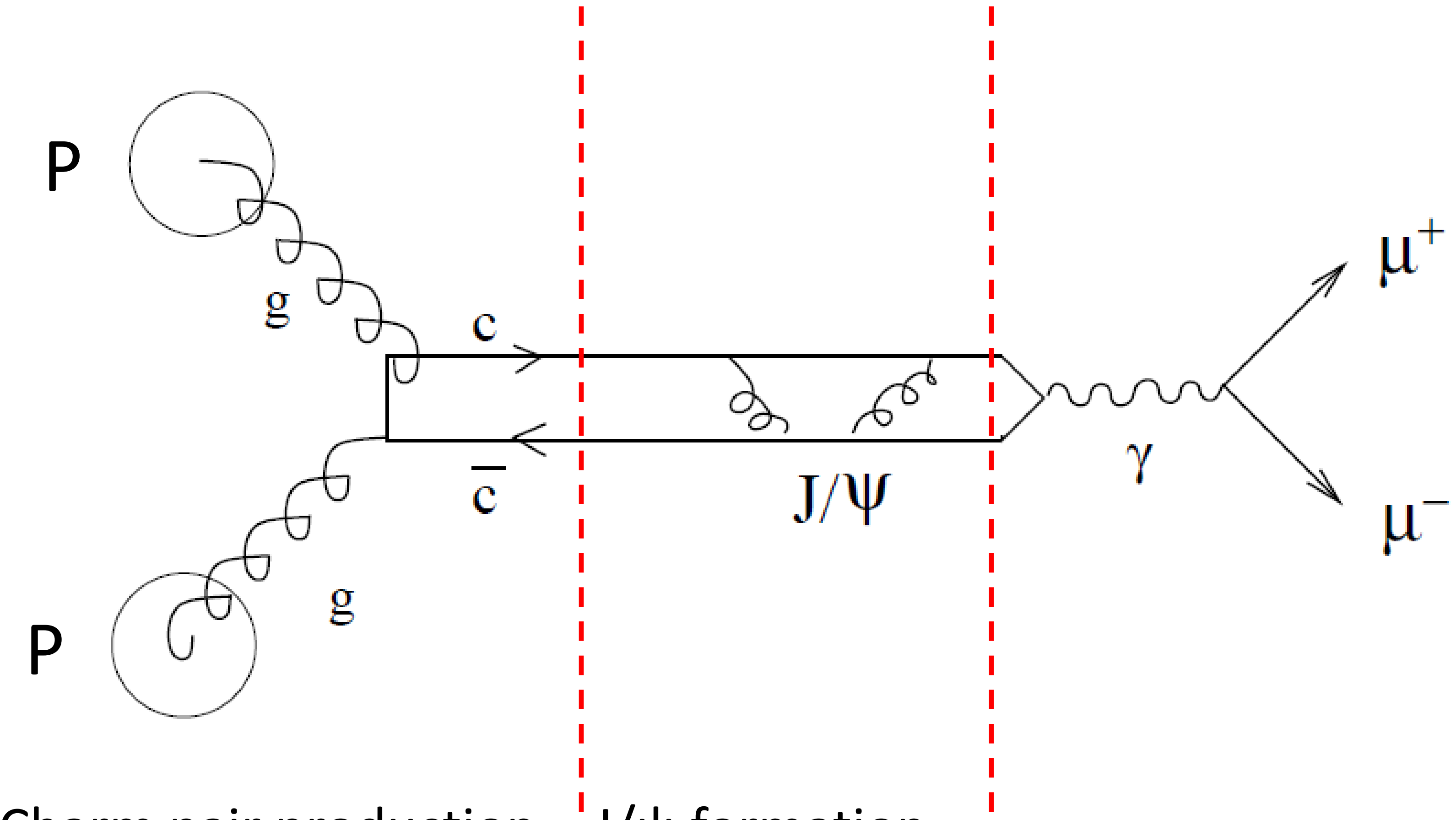
1. Quarkonium production in p+p

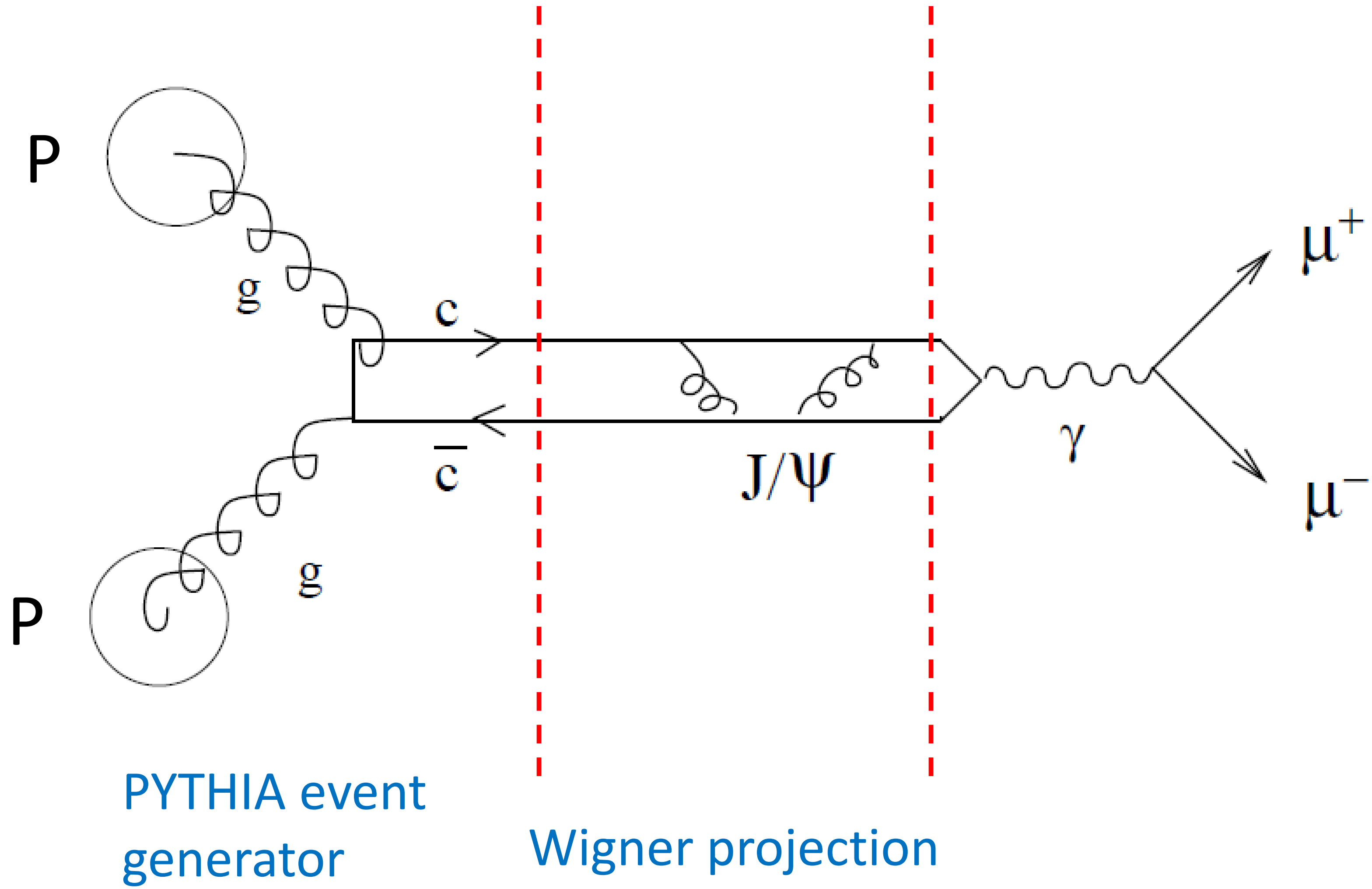
J/ψ production in p+p collisions



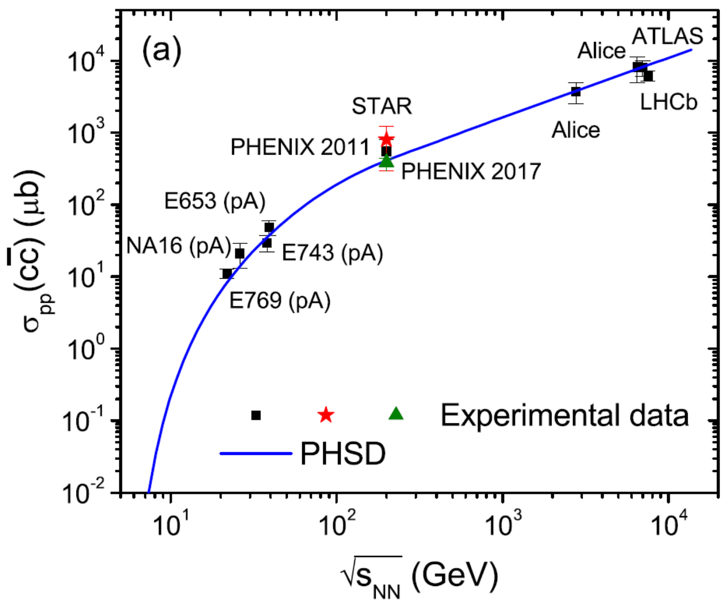
Charm pair production
(pQCD process)

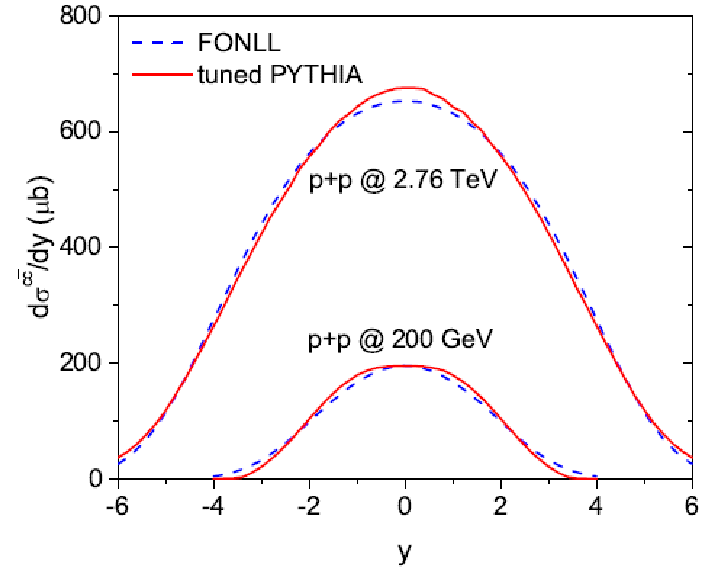
J/ψ formation
(non-pQCD process)
depends on model

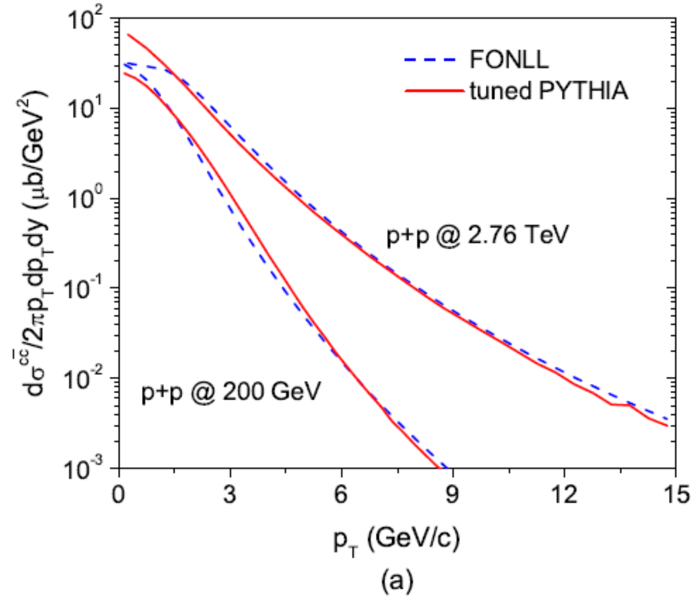
J/ψ production in p+p collisions



1.1. Charm from PYTHIA after tuning







1. Total cross section is parameterized from experimental data
2. PHYTHIA generates charm pairs
3. y, pt are rescaled to be similar to the FONLL calculations

1.2. models for quarkonium formation

- Color singlet model

Charm pair forms charmonium with the same quantum number

- Non-Relativistic QCD (NRQCD) : Color octet model

QCD Lagrangian is expanded in power of $1/M_Q$

Both color singlet and octet contribute to charmonium formation

- Color evaporation model

Color charge evaporates during the process of charmonium formation

- new approach, PRC 96, 014907

Transition amplitude for charmonia formation

- $\Phi = J/\psi(1S),\ \ \chi_c(1P),\ \ \psi'(2S)$
- $\lim_{t\to\infty}\langle\Phi(t)|c\bar{c}(-t)\rangle \approx \langle\Phi|c\bar{c}\rangle$: sudden approximation
- $|\langle\Phi|c\bar{c}\rangle|^2 \sim$ Wigner function, Phys.Rev. C94 (2016) 034901

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

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

$$r = r_c - r_{\bar{c}}$$

$$p = \frac{p_c - p_{\bar{c}}}{2}$$

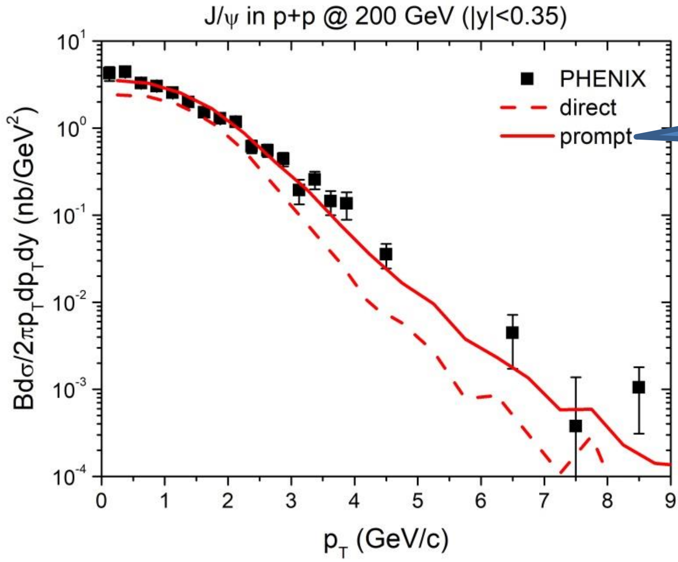
D : degeneracy of Φ
d_1 : degeneracy of c
d_2 : degeneracy of anti-c
σ ~ radius of Φ

- Smearing distance between c & cbar according to

$$W_\Psi(\mathbf{r},\mathbf{p}) \sim r^2 \exp\left(-\frac{r^2}{2\delta^2}\right),$$

where $\delta^2 = \langle r^2\rangle/3 = 4/(3m_c^2)$ such that $\sqrt{\langle r^2\rangle}/2 = 1/m_c$

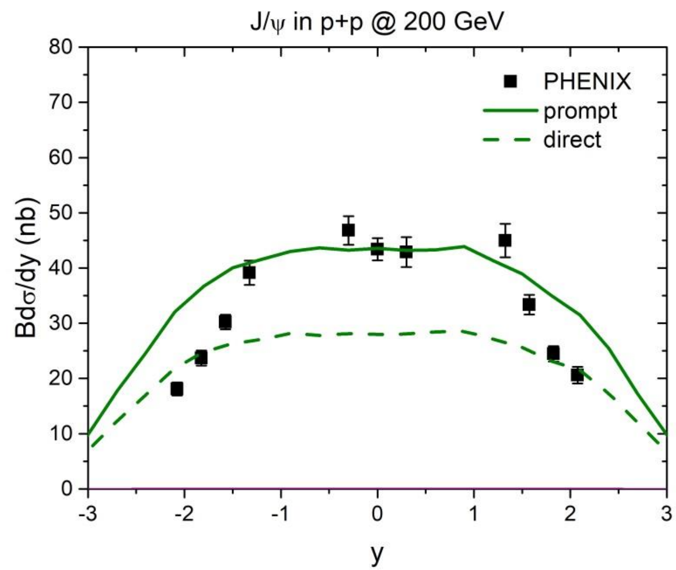
J/ψ in p+p @ 200 GeV (PHENIX)

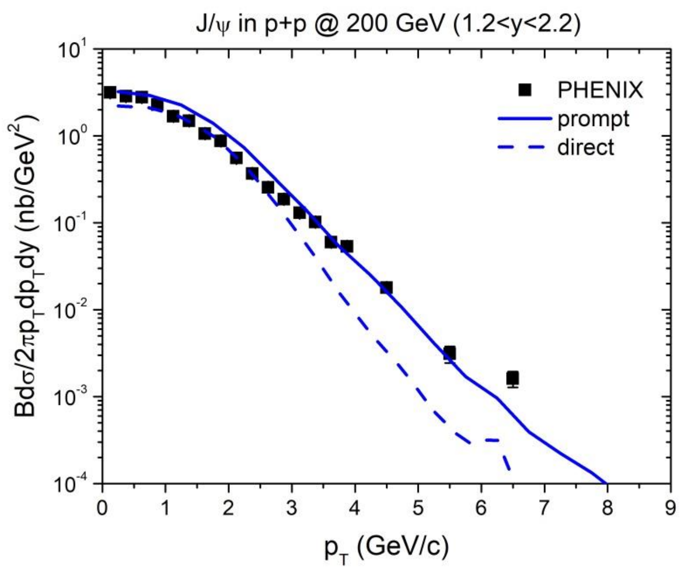


Including feed-down from χ_c, ψ'

p_T spectrum in mid-y

Rapidity distribution



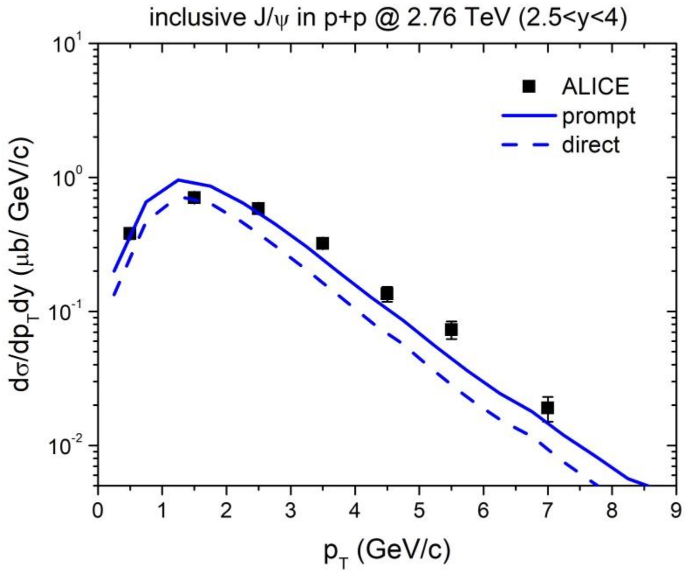


p_T spectrum in forward-y

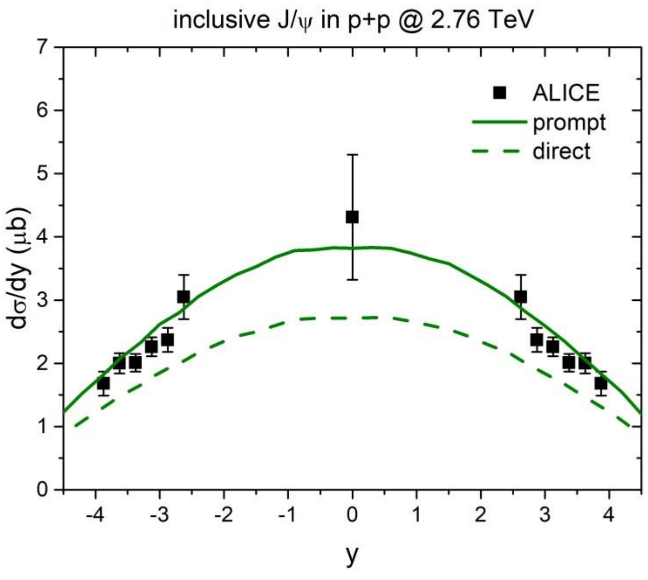
$$r_{J/\psi} = 0.38\ fm$$
$$r_{\chi c} = 0.42\ fm$$
$$r_{\psi'} = 0.68\ fm$$

J/ψ in p+p @ 2.76 TeV (ALICE)

p_T spectrum in forward-y



Rapidity distribution

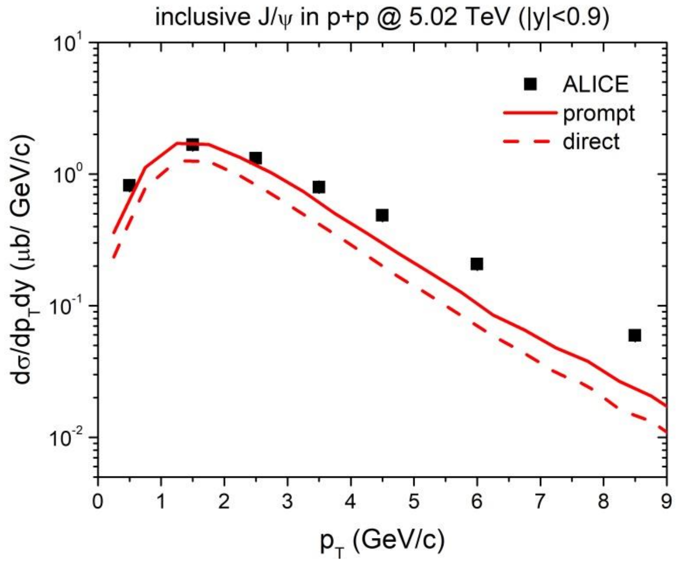


$r_{J/\psi} = 0.38\ fm$

$r_{\chi c} = 0.42\ fm$

$r_{\psi'} = 0.68\ fm$

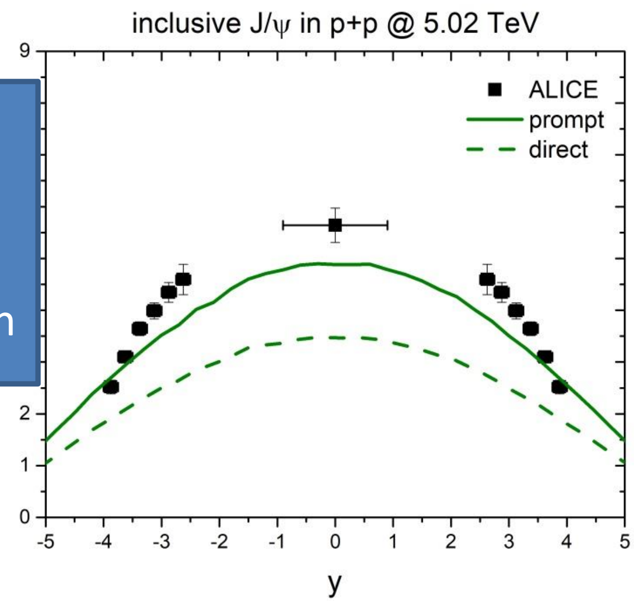
J/ψ in p+p @ 5.02 TeV (ALICE)

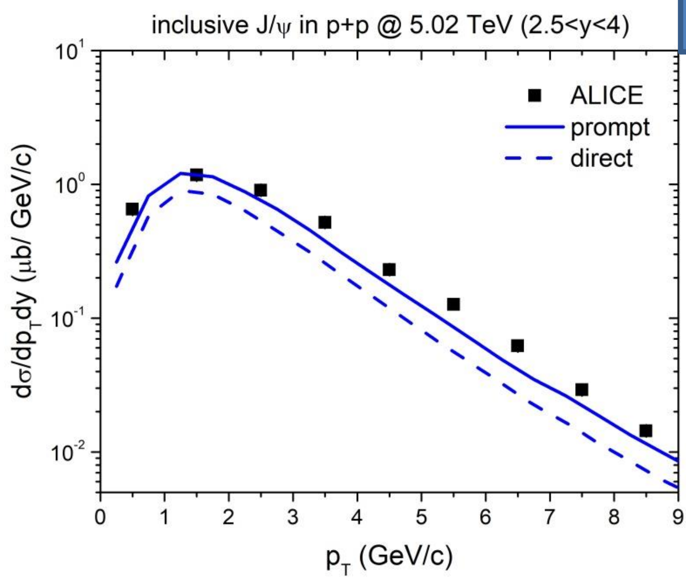


p_T spectrum in mid-y

A bit deficiency probably from non-prompt decay of B meson

Rapidity distribution



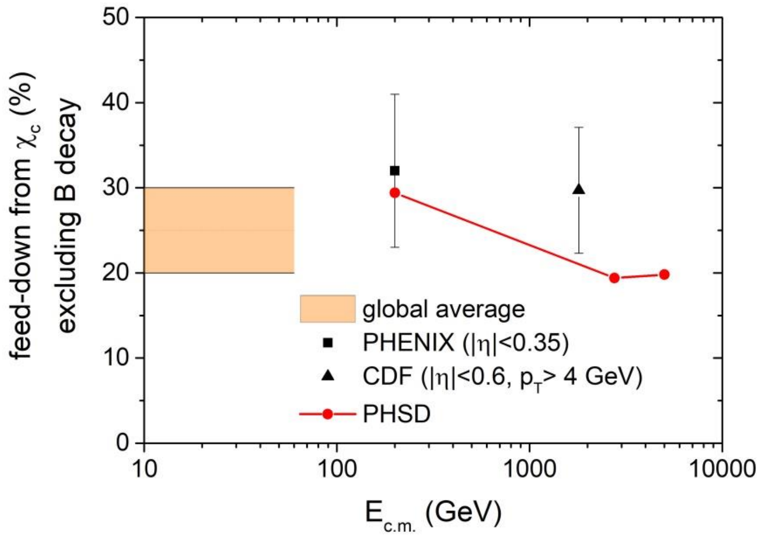


p_T spectrum in forward-y

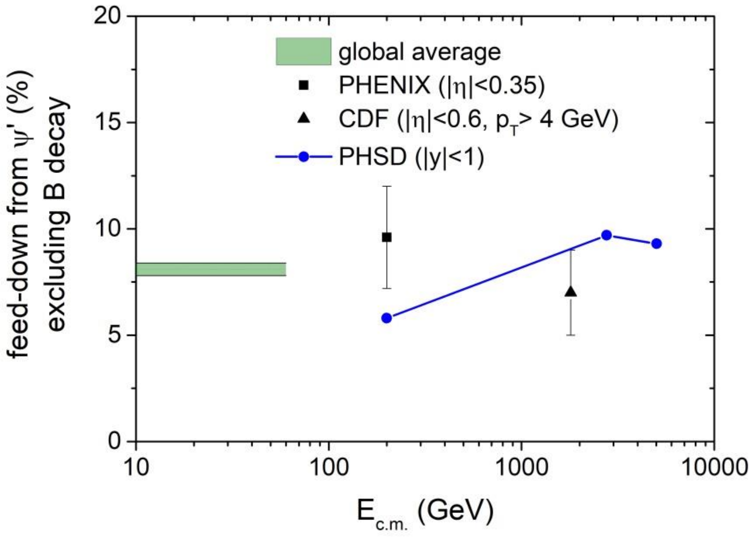
$r_{J/\psi} = 0.38\ fm$
$r_{\chi c} = 0.42\ fm$
$r_{\psi'} = 0.68\ fm$

Feed-down of J/ψ from excited charmonia

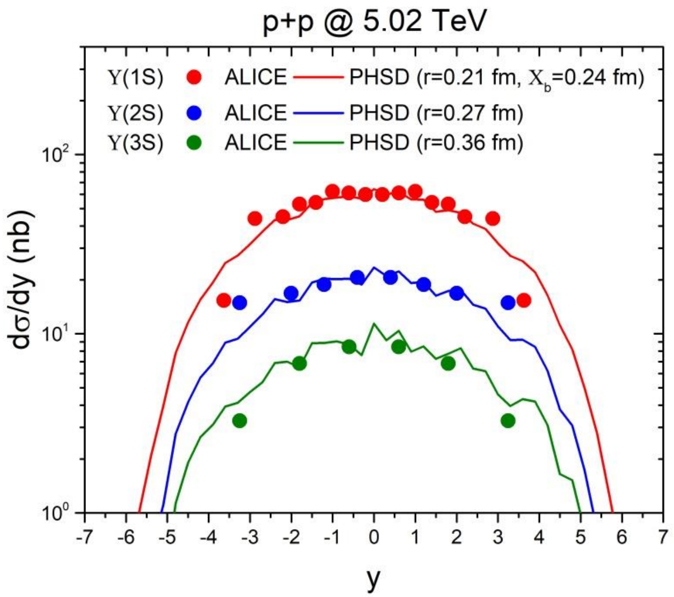
$\chi_c \rightarrow J/\psi + \gamma$



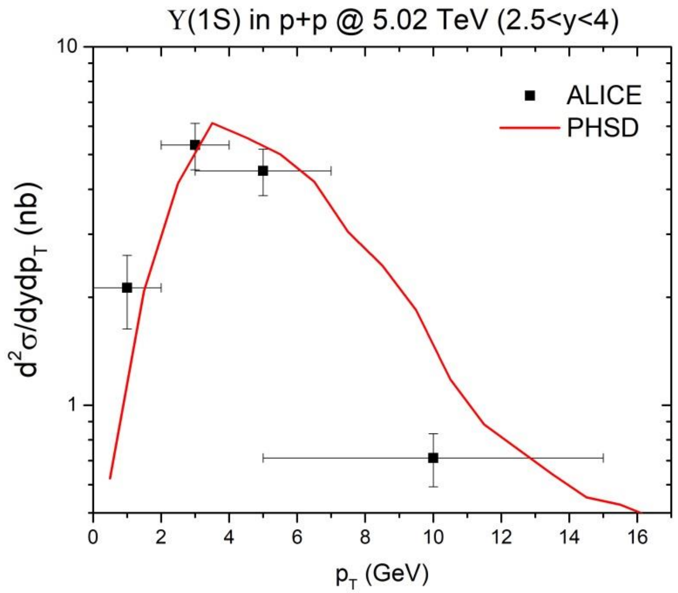
$\psi' \rightarrow J/\psi + \pi + \pi$



Υ in p+p @ 5.02 TeV (ALICE)



p_T spectrum in forward-y



$r_{1S} = 0.21\ fm$

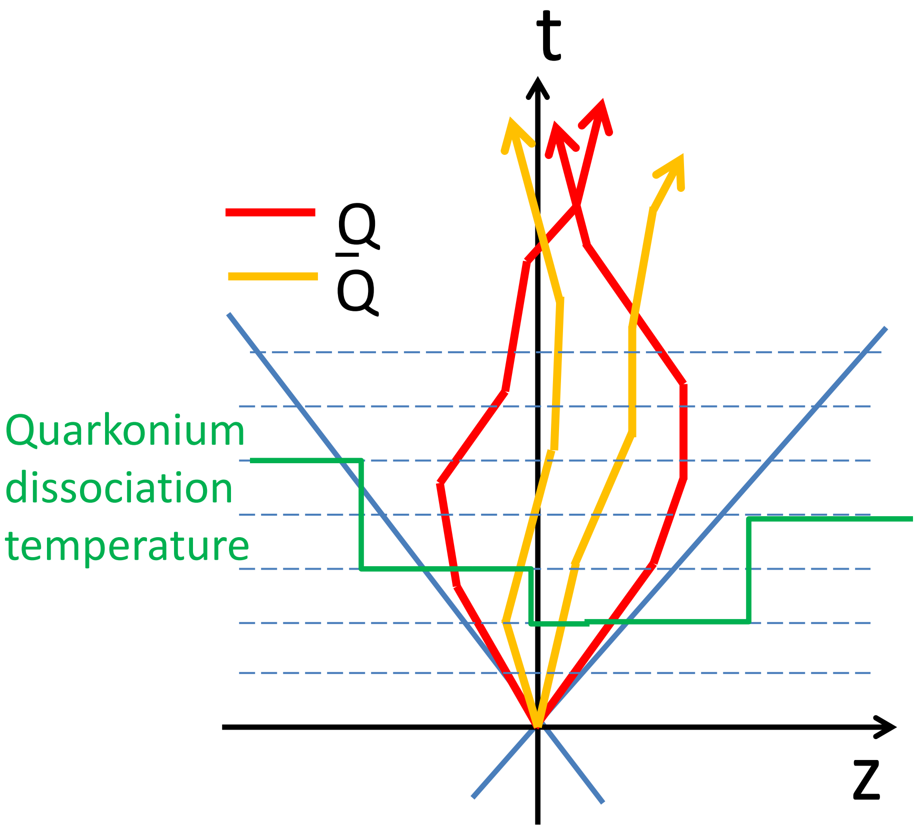
$r_{\chi b} = 0.24\ fm$

$r_{2S} = 0.27\ fm$

$r_{3S} = 0.36\ fm$

2. Quarkonium production in A+A

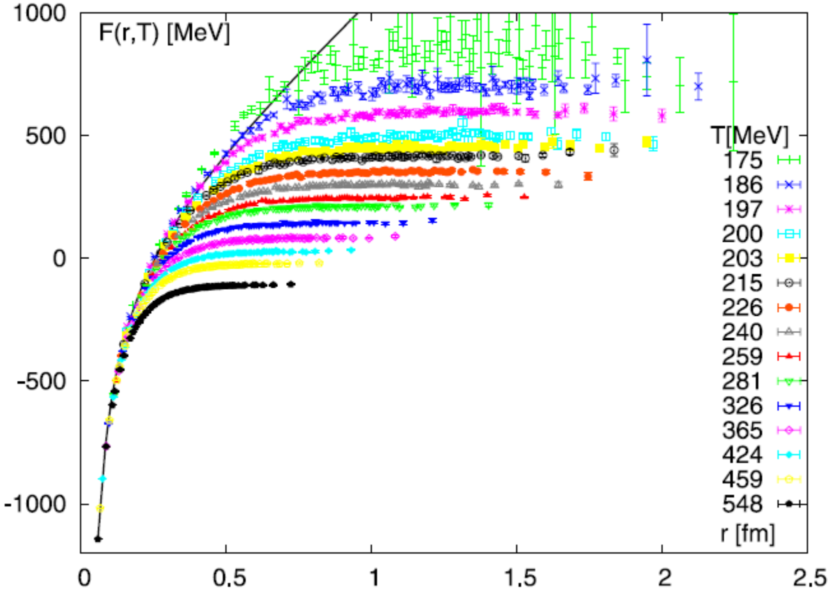
Based on Remler's formalism
e-Print: [2206.01308](2206.01308)
Denys, Joerg, Pol

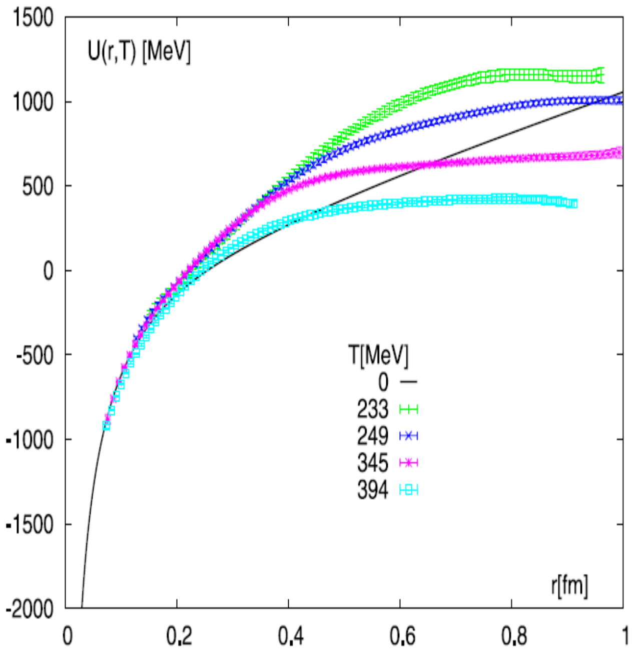


1. Once temperature drops below quarkonium dissociation temperature, Wigner function is calculated as in p+p collisions
2. Each time step whenever Q or Qbar scatters, Wigner function for the scattered Q and neighboring Qbar or for the scattered Qbar and neighboring Q is calculated before scattering and after scattering
3. The Wigner function before scattering is subtracted and that after scattering is added (The former is interpreted as the dissociation and the latter as the regeneration of quarkonium, respectively)
4. So roughly speaking, thermal decay rate of quarkonium is twice interaction rate of heavy quark

We need dissociation temperatures of quarkonia and T-dependent wavefunctions

Free & internal energies from lattice QCD as a heavy-quark potential





F (free energy)

→ weakly bound

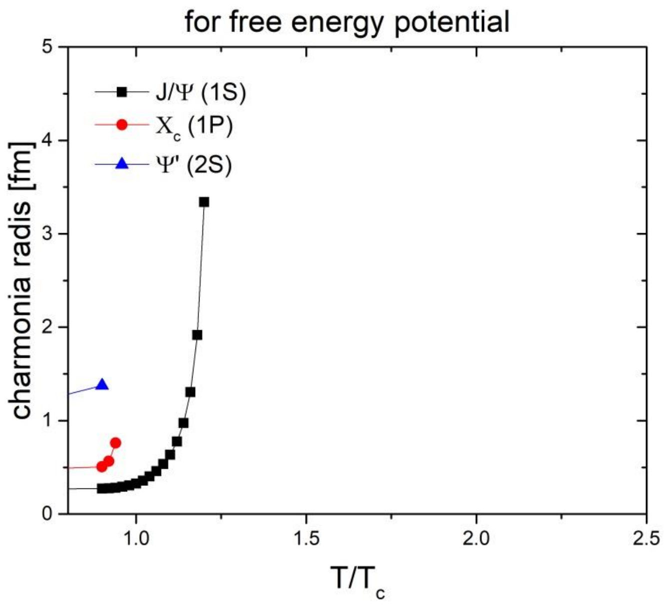
U (internal energy) = F+TS

Eur.Phys.J.C(2009)61:811

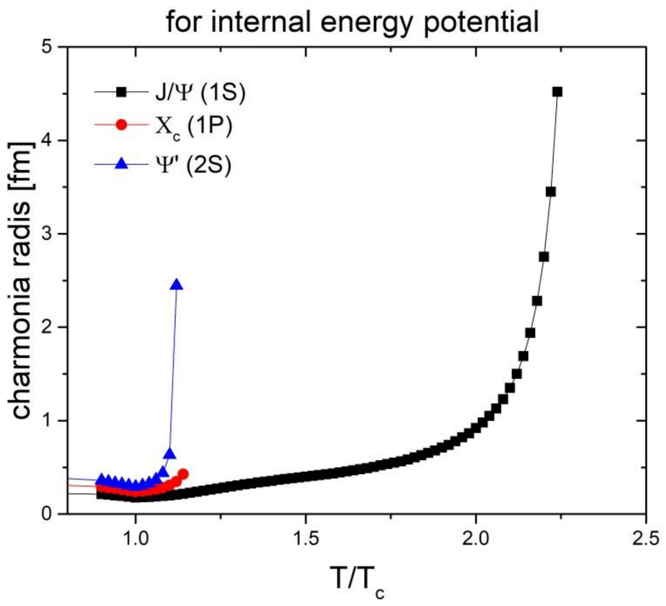
→ strongly bound

Solving the Schrödinger Eq. for **charmonia**

Free energy potential

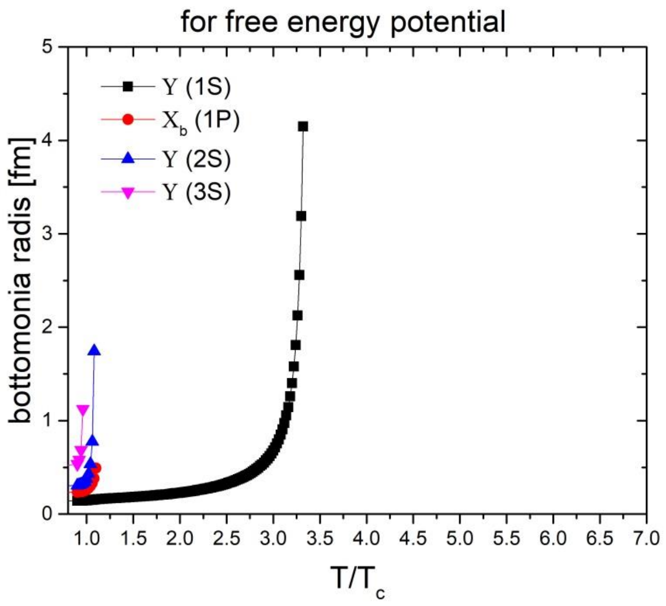


Internal energy potential

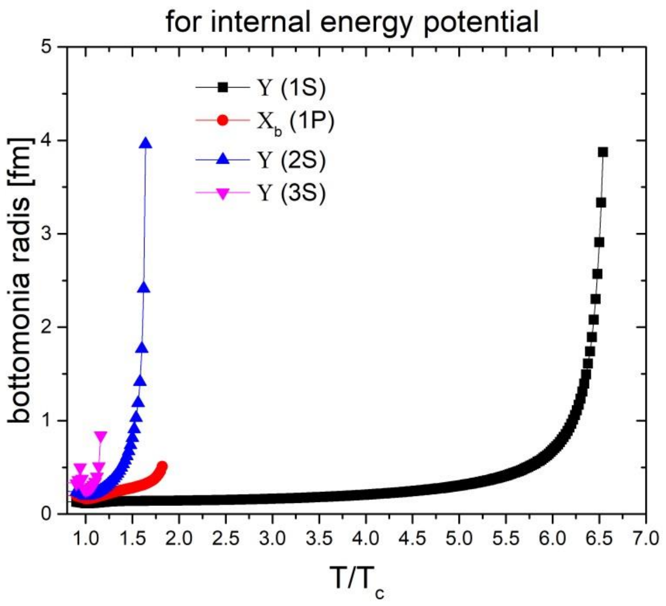


Solving the Schrödinger Eq. for **bottomonia**

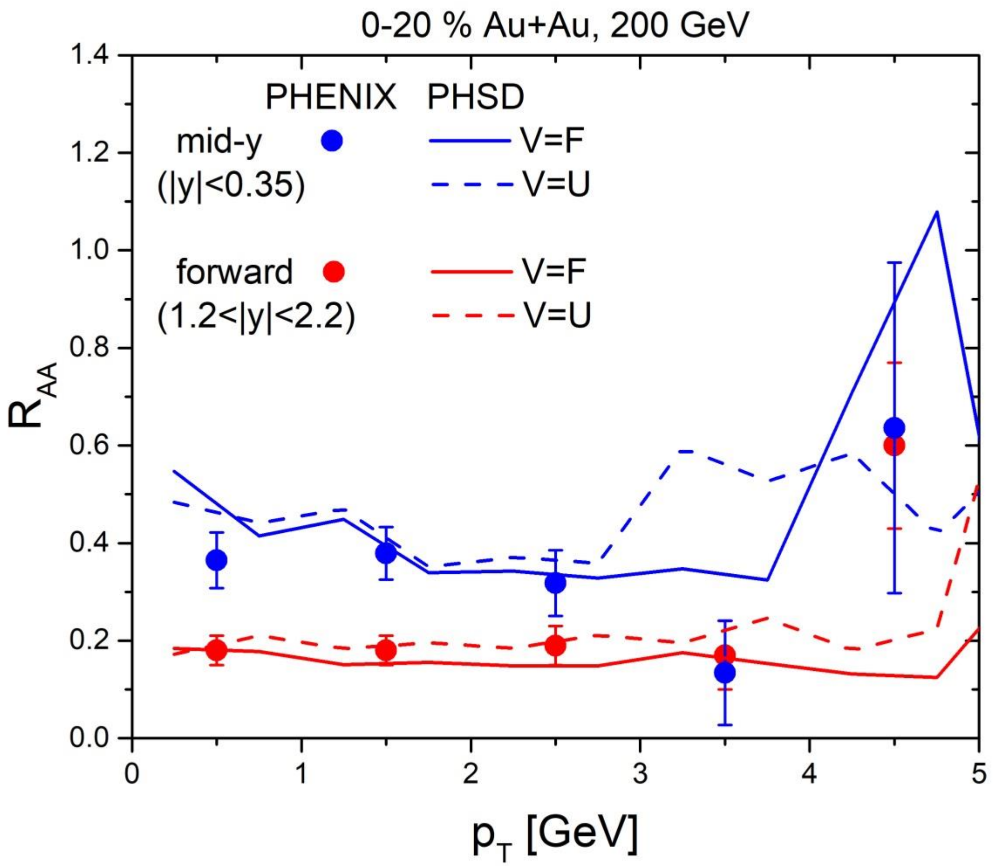
Free energy potential



Internal energy potential



Preliminary results in Au+Au @ 200 GeV



still in progress

Summary

- Quarkonium production is the combination of pQCD+non-pQCD.
- Initial heavy quark pairs are produced by PYTHIA event generator and then y and pt are tuned.
- In p+p collisions the heavy quark pairs are projected into quarkonia (Wigner functions), including position smearing.
- It can reproduce the experimental data on J/ψ production and the feed-down from excited states in p+p collisions at RHIC and LHC.

- In heavy-ion collisions, temperature changes with time.
- Solving Schrödinger Eq. with heavy quark potential, dissociation temperatures and radii of quarkonia are obtained.
- Quarkonia are produced below dissociation temperatures as in p+p collisions but with different radii.
- For the dissociation and regeneration, the Remler's formalism is adopted