Open/hidden charm transport in nuclear collisions at SPS/FAIR energies

Taesoo Song (GSI, Darmstadt)

in collaboration with Jiaxing Zhao, Joerg Aichelin, Pol Gossiaux and Elena Bratkovskaya

FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Penetrating Probes of Hot High-mu_B Matter: Theory Meets Experiment

Contents

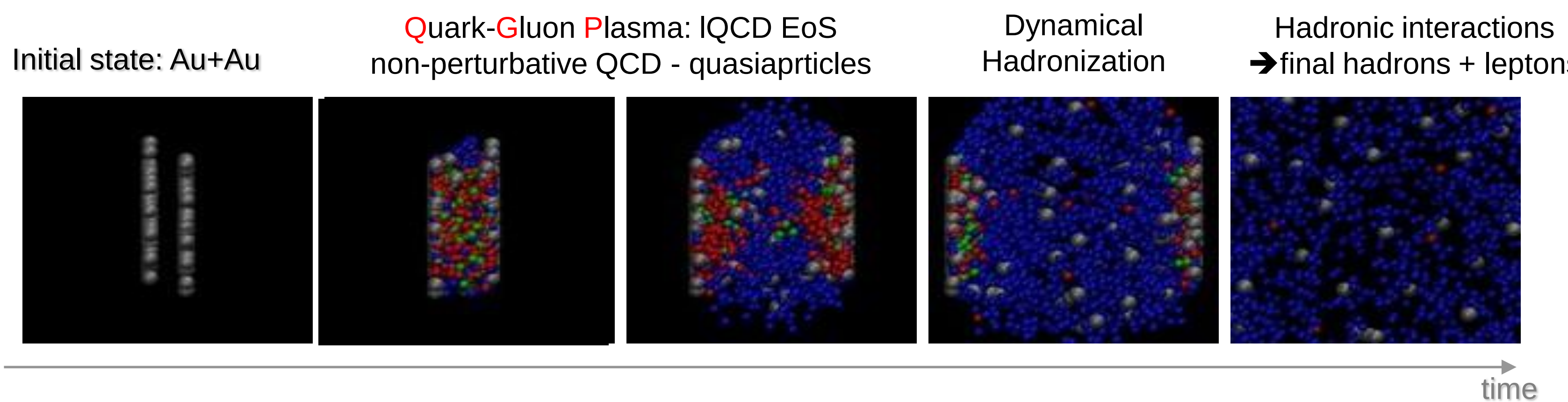
- Bulk dynamics in HIC
- Open charm
- Hidden charm
- summary

1. Bulk dynamics in HIC

For the simulation of heavy ion collisions

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

Dynamics: based on the **Kadanoff-Baym many-body theory** (beyond semi-classical BUU)

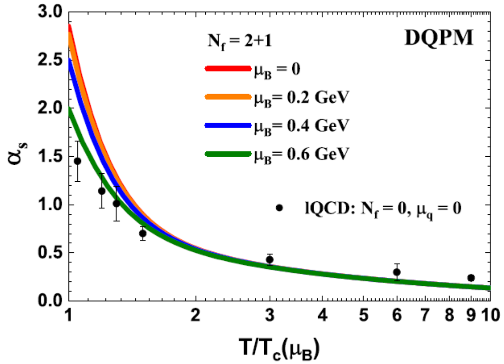


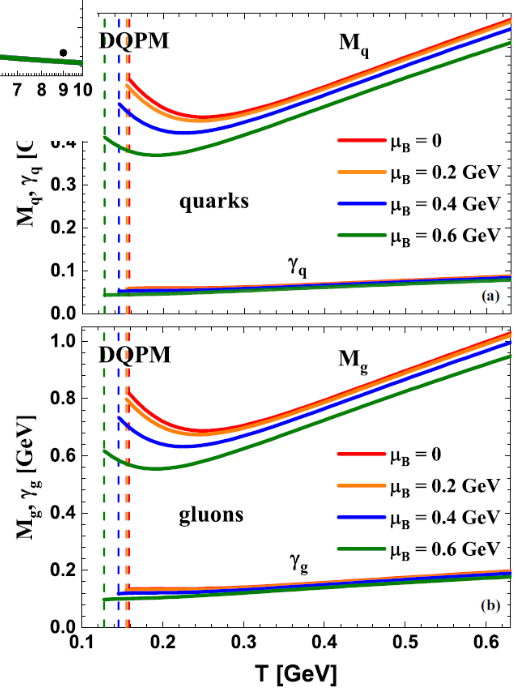
PHSD provides a good description of ‘bulk’ hadronic and electromagnetic observables from SIS to LHC energies

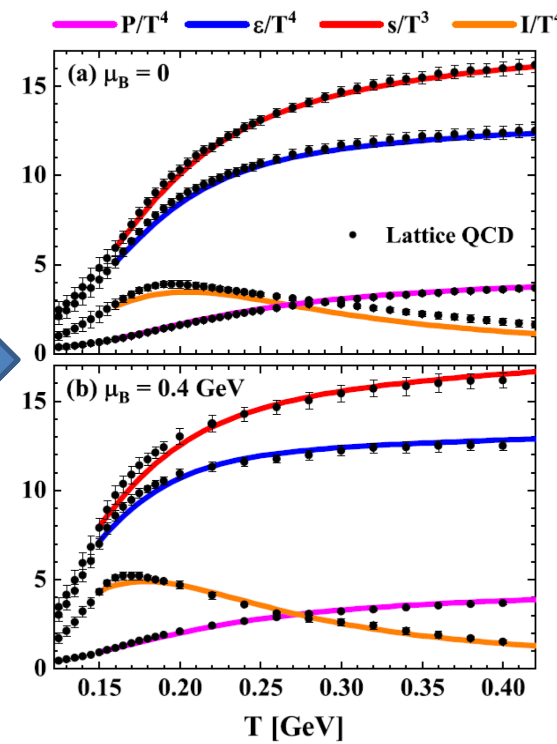
PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; P. Moreau et al., PRC100 (2019) 014911

Dynamical Quasi-Particle Model
for QGP at **(non)zero μ_B**

- QGP is composed of massive off-shell partons
- α_s & pole mass, width of parton from lattice EoS





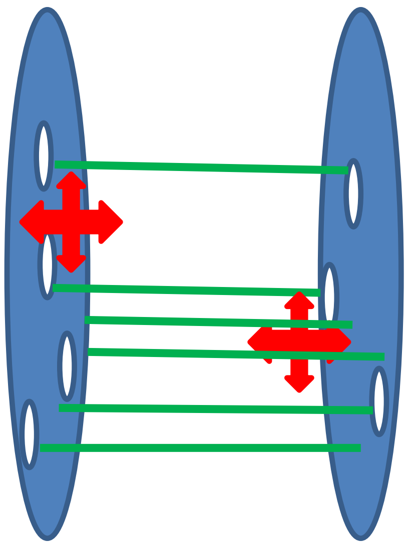


P. Moreau et al., PRC100, 014911 (2019)

2. Open charm

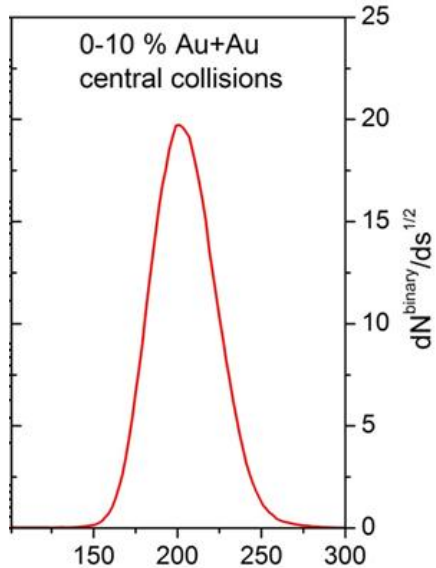
Initial production 1

How many charms are produced?



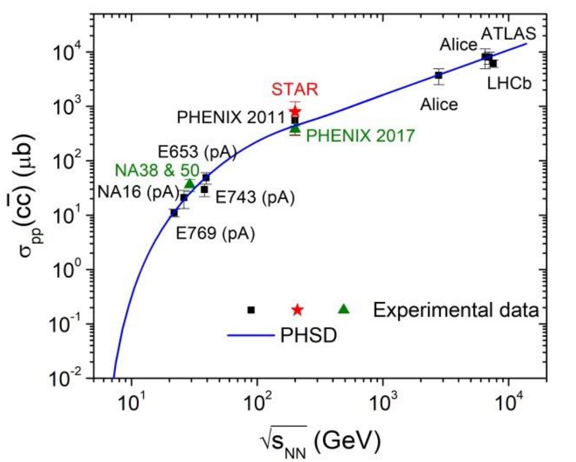
Fermi motion is important in low E collision

1. **Simulate NN collisions in AA**



2. $\sqrt{s}$ **of NN**

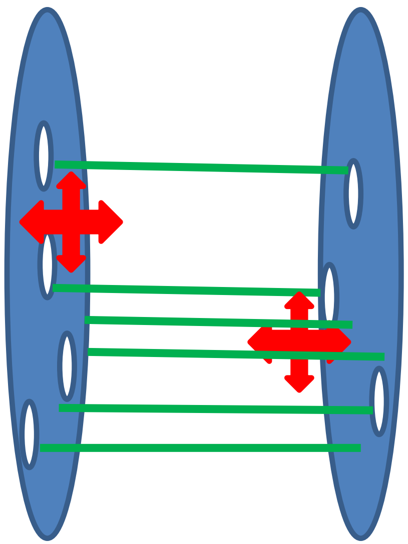
3. **Charm is produced with the ratio** $\sigma_{c\bar{c}}/\sigma_{NN}$

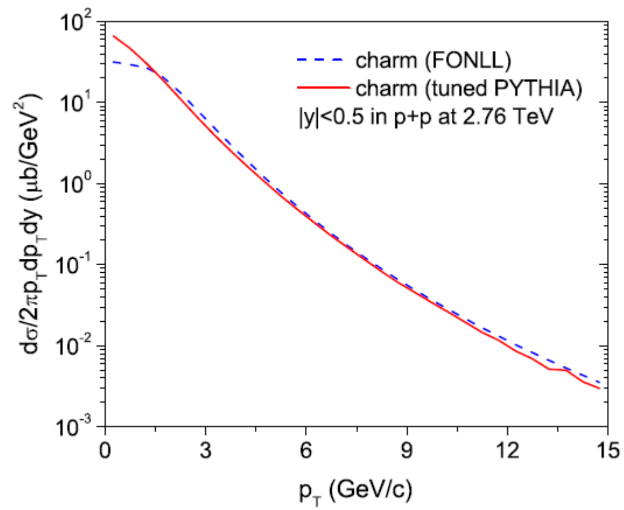


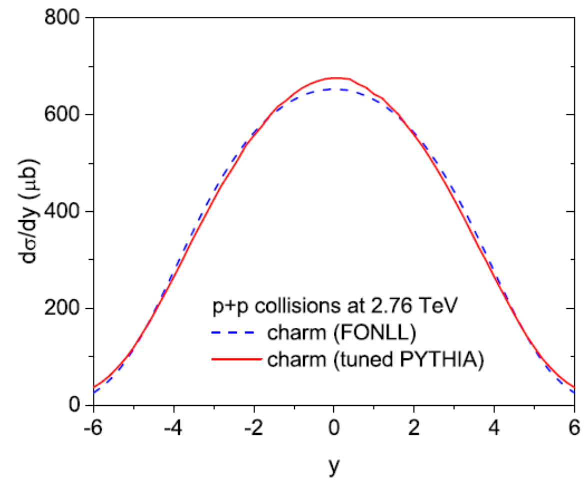
T. Song et al., PRC92, 014910 (2015)

Initial production 2

Charm position & momentum?







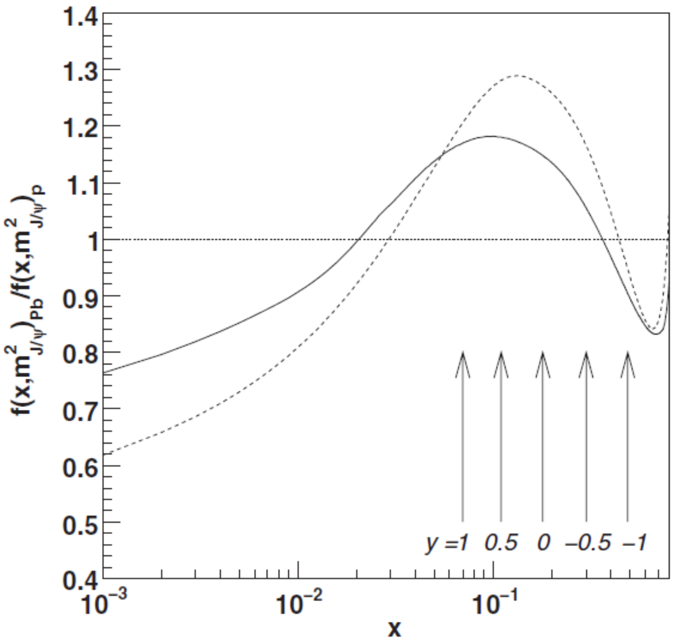
Charm production points are given from Glauber modeling of nuclei

Charm momentum is given by PYTHIA after rescaling p_T, y to imitate FONLL distributions

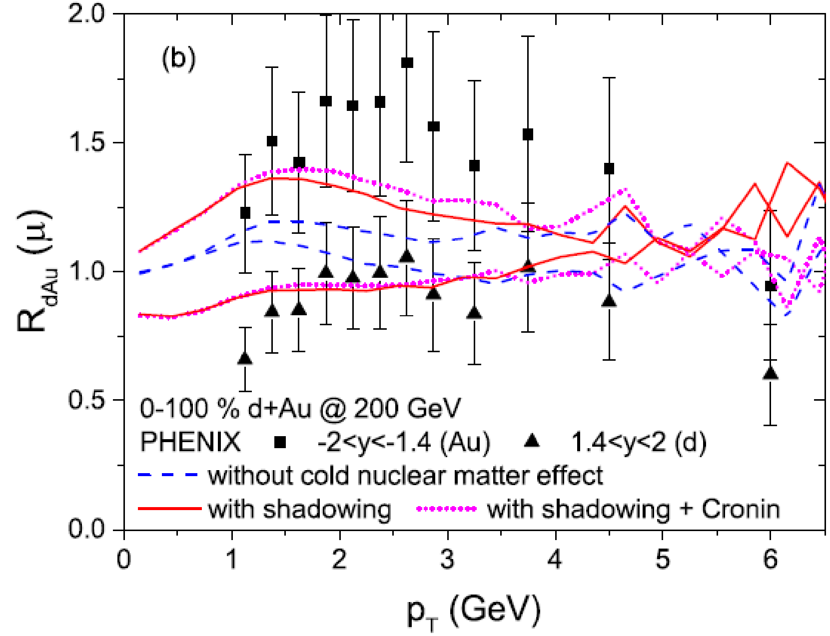
T. Song et al., PRC92, 014910 (2015)

Initial production 3

(anti)shadowing effects with EPS09



Parton distribution function changes in nucleus

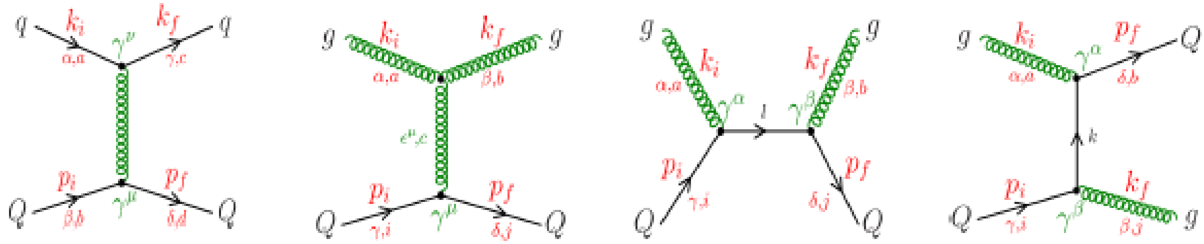


It affects charm production, depending on collision energy, centrality and mass number of nucleus

T. Song et al., PRC96, 014905 (2017)

Charm interaction in QGP

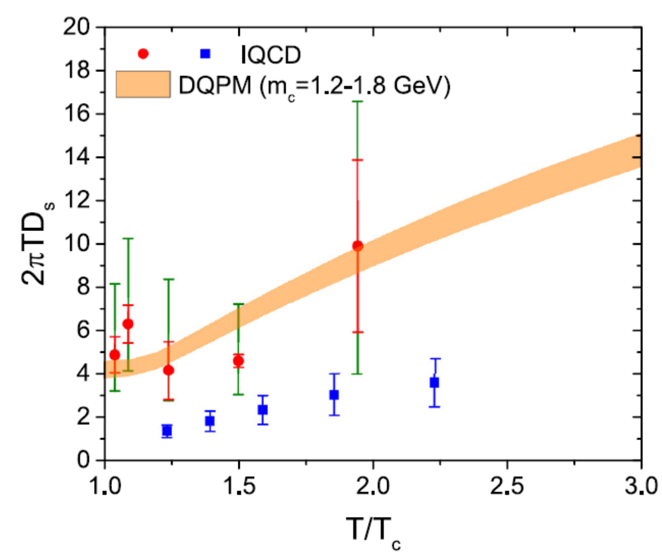
- Charm quark interacts with massive off-shell partons



H. Berrehrah et al., PRC89, 054901 (2014)
I. Grishmanovskii et al., 2503.22311 (2025)
including radiative interactions

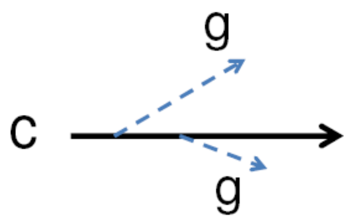
- It is consistent with the spatial diffusion coefficients from lQCD

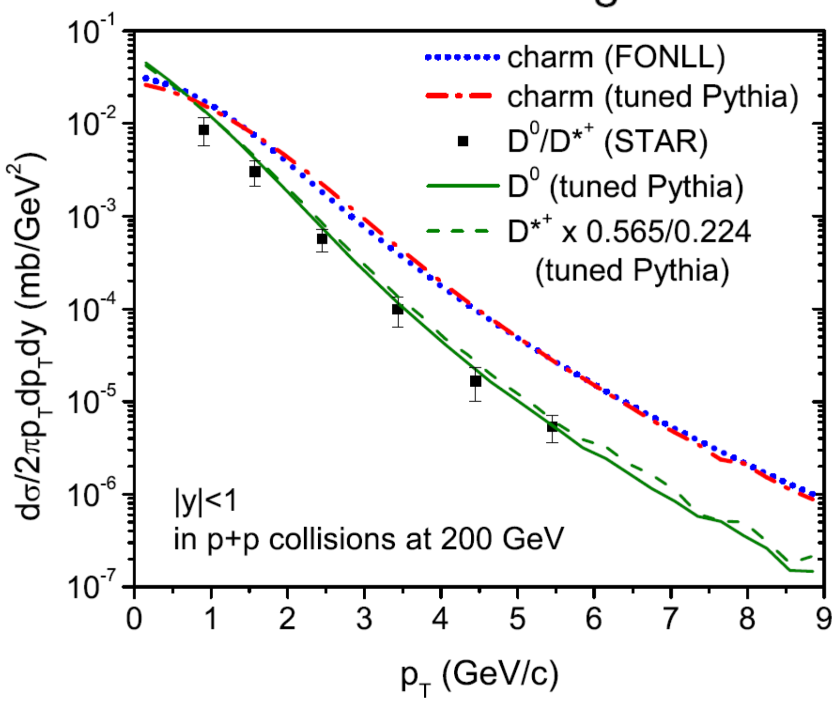
T. Song et al., PRC110, 034906 (2024)



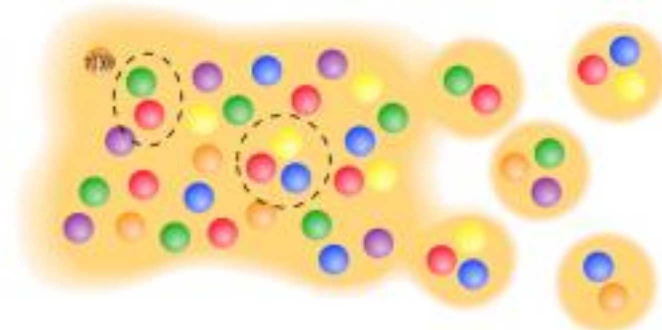
Hadronization

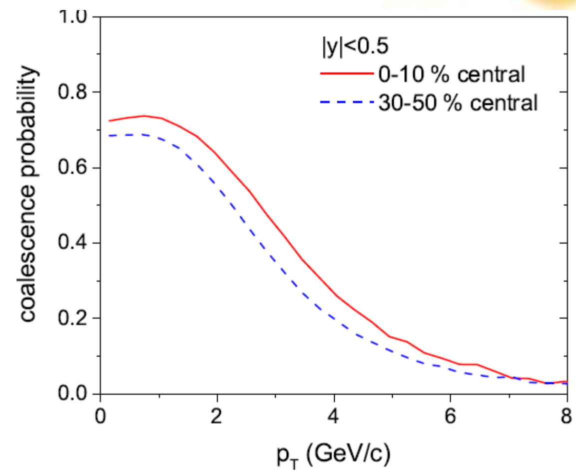
fragmentation





coalescence





Coalescence probability decreases with centrality and p_T

T. Song et al., PRC93, 034906 (2016)

D meson interactions

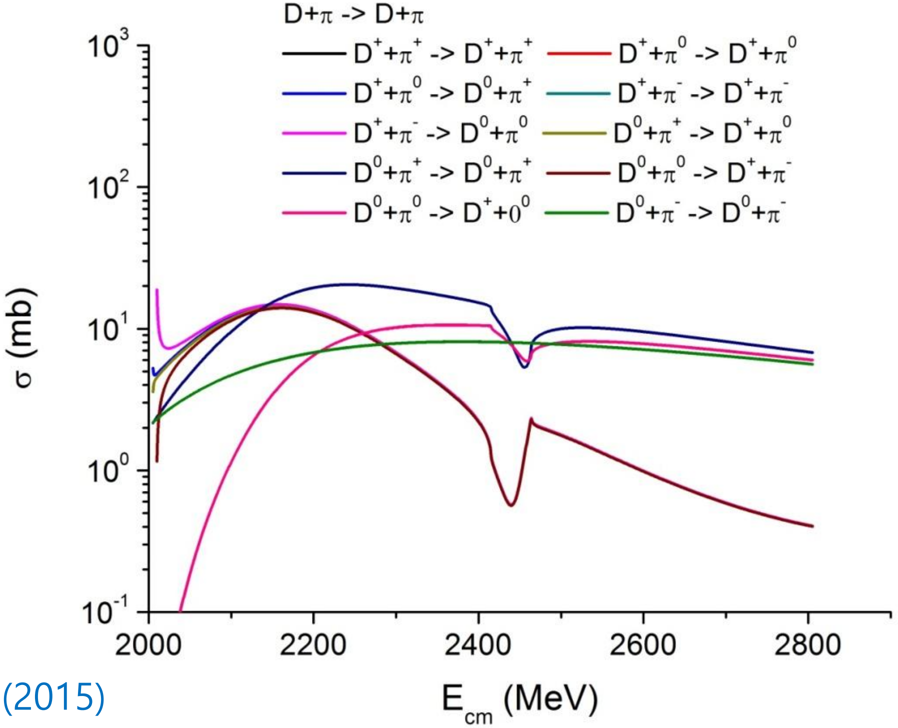
- Effective chiral Lagrangian + unitarization

L. M. Abreu et al., Ann.Phys.,326, 2737 (2011);
C. Garcia-Recio et al., PRD87, 074034 (2013)

$$\boldsymbol{T = T + VGT}$$

- $D+\pi \rightarrow D+\pi$

(10 cross sections)



T. Song et al., PRC92, 014910 (2015)

In total 256 hadronic reactions are considered

- D+K→D+K (6 cross sections)
- D+$\bar{K}$→D+ $\bar{K}$ (6 cross sections)
- D+η→ D+η (2 cross sections)
- D*+π→D*+π (10 cross sections)
- D*+K→D*+K (6 cross sections)
- D*+$\bar{K}$ → D*+$\bar{K}$ (6 cross sections)
- D*+η→ D*+η (2 cross sections)

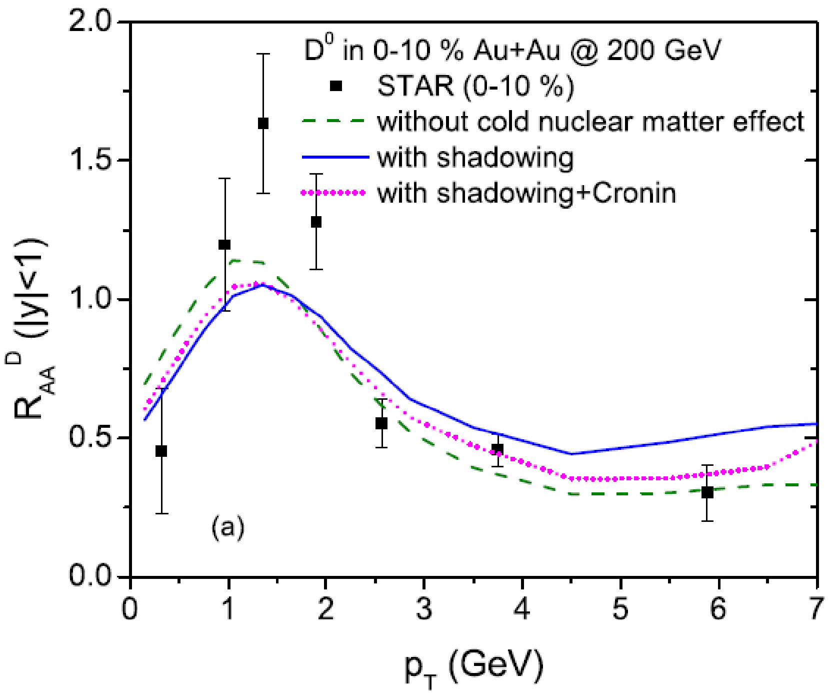
- D+N→D+N (6 cross sections)
- D+N→D*+N (6 cross sections)
- D*+N→D+N (6 cross sections)
- D*+N→D*+N (6 cross sections)
- $\bar{D}$+N→$\bar{D}$+N (6 cross sections)
- $\bar{D}$+N→$\bar{D}$*+N (6 cross sections)
- $\bar{D}$*+N→$\bar{D}$+N (6 cross sections)
- $\bar{D}$*+N→$\bar{D}$*+N (6 cross sections)

- D+Δ→ D+Δ (14 cross sections)
- D+Δ→ D*+Δ (14 cross sections)
- D*+Δ→ D+Δ (14 cross sections)
- D*+Δ→ D*+Δ (14 cross sections)
- $\bar{D}$+Δ→ $\bar{D}$+Δ (14 cross sections)
- $\bar{D}$+Δ→ $\bar{D}$*+Δ (14 cross sections)
- $\bar{D}$*+Δ→ $\bar{D}$+Δ (14 cross sections)
- $\bar{D}$*+Δ→ $\bar{D}$*+Δ (14 cross sections)

- D+N→ D*+Δ (8 cross sections)
- D*+N→ D+Δ (8 cross sections)
- D*+N→ D*+Δ (8 cross sections)
- D*+Δ→ D+N (8 cross sections)
- D+Δ→ D*+N (8 cross sections)
- D*+Δ→ D*+N (8 cross sections)

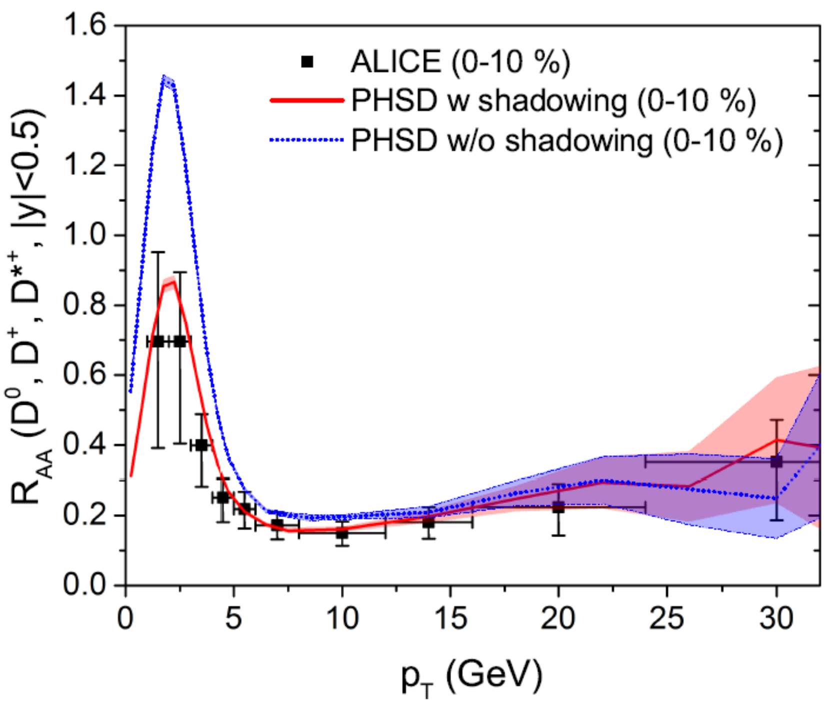
PHSD approach has been successful

at RHIC



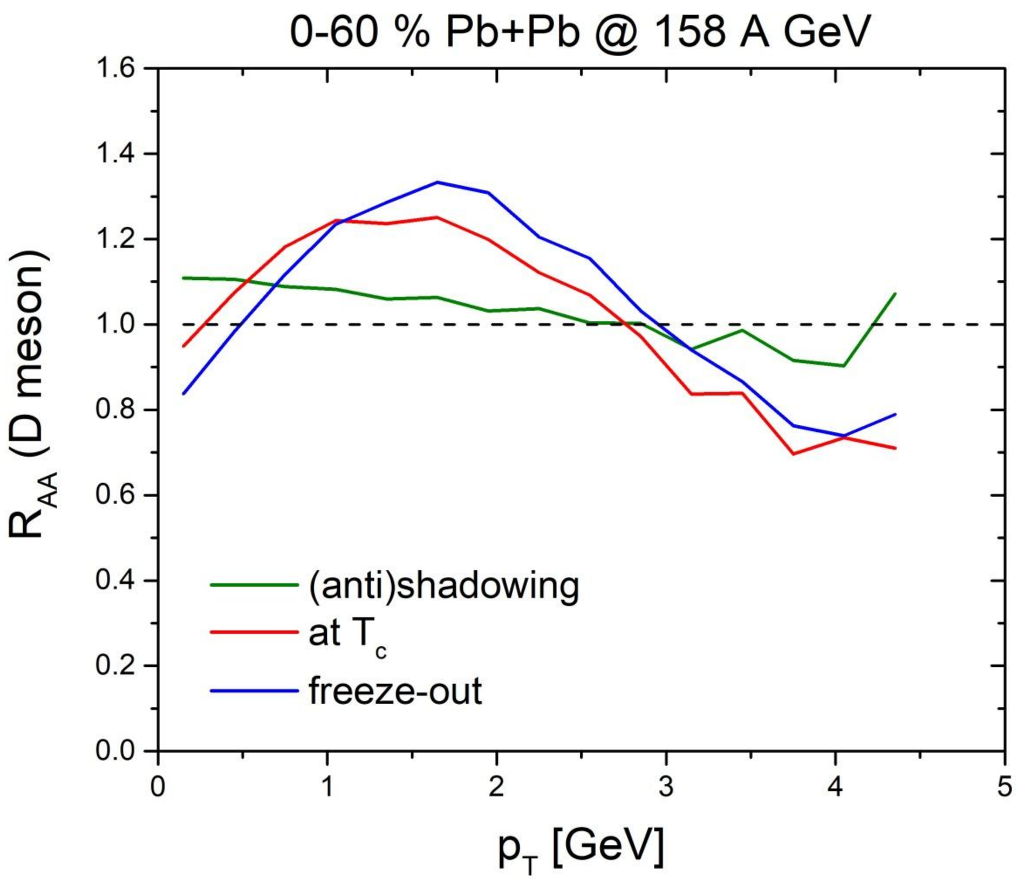
T. Song et al., PRC92, 014910 (2015)

at LHC



T. Song et al., PRC93, 034906 (2016)

at SPS energy (158 A GeV)



1. non-negligible effect from (anti)shadowing

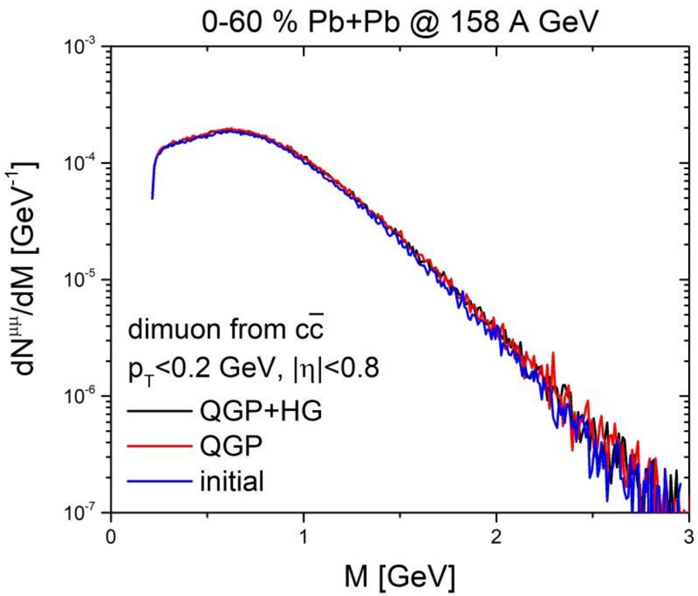
2. A bump appears due to the flow, same as at RHIC and LHC

3. Hadronic scattering shifts the peak of R_{AA} to higher p_T

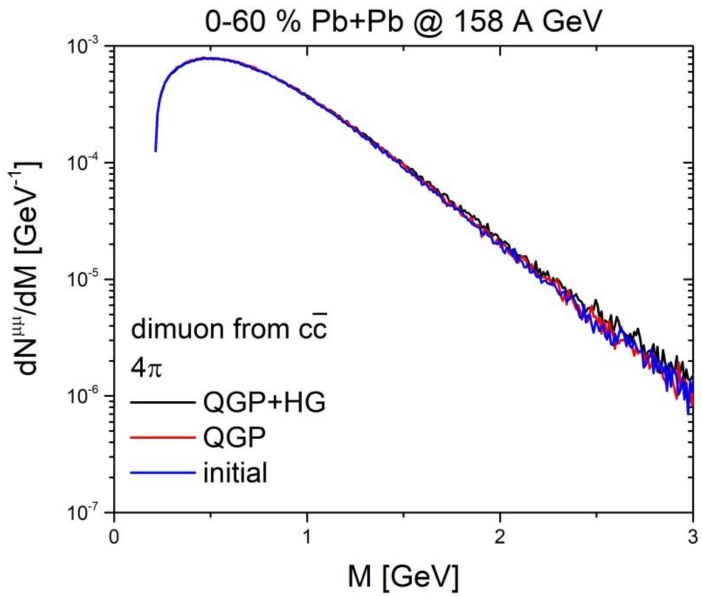
4. Weaker suppression of R_{AA} at high p_T

Dimuon production from charm pair at SPS

$p_T^e > 0.2$ GeV, $|\eta^e| < 0.8$



4π



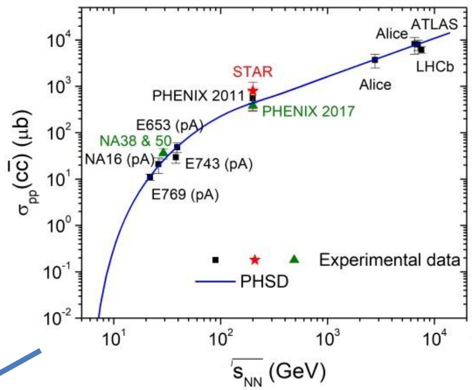
Dimuon from charm is not sensitive to QGP, HG interactions at SPS energies

at FAIR energies
Fermi momentum (FM) is important

SPS – little increase

$\sigma_{c\bar{c}}^{NN} = 5.26\ \mu b$ w/o FM

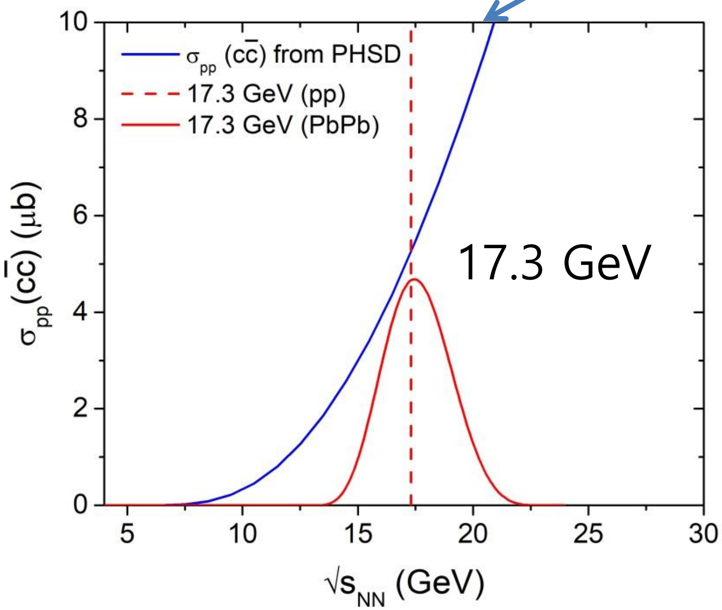
$\sigma_{c\bar{c}}^{NN} = 5.7\ \mu b$ with FM

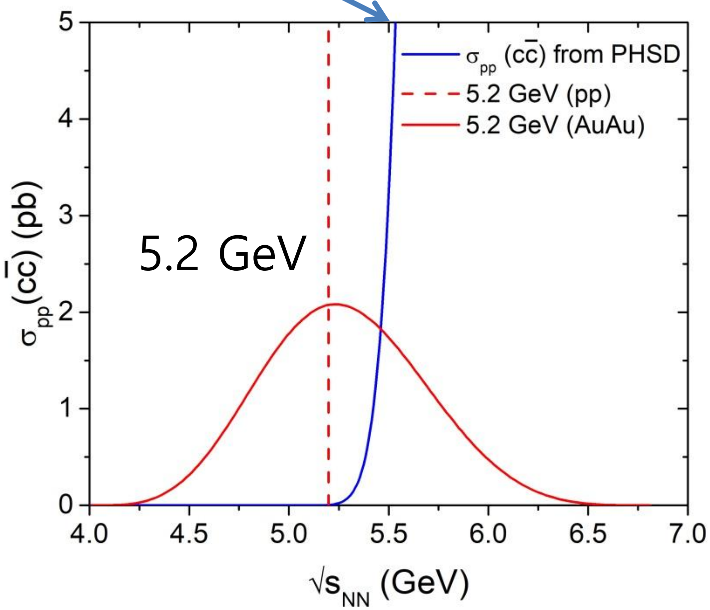


FAIR – huge increase

$\sigma_{c\bar{c}}^{NN} = 0.0038\ pb$ w/o FM

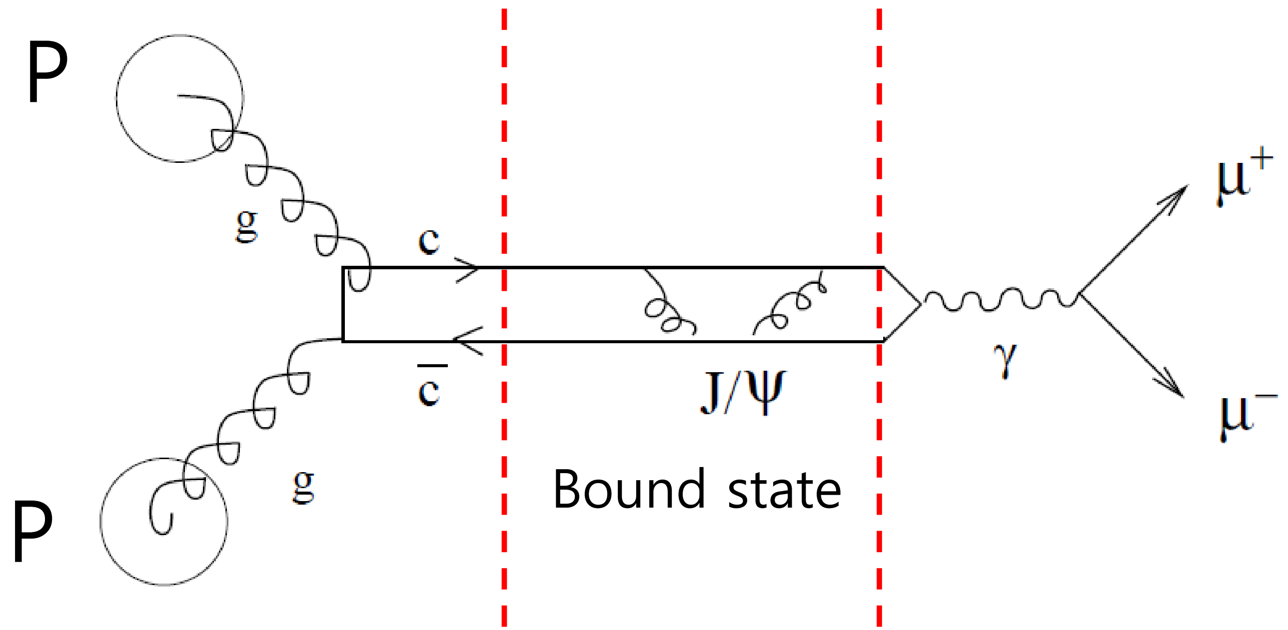
$\sigma_{c\bar{c}}^{NN} = 3.04\ pb$ with FM





3. Hidden charm

3.1 quarkonium production in p+p



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

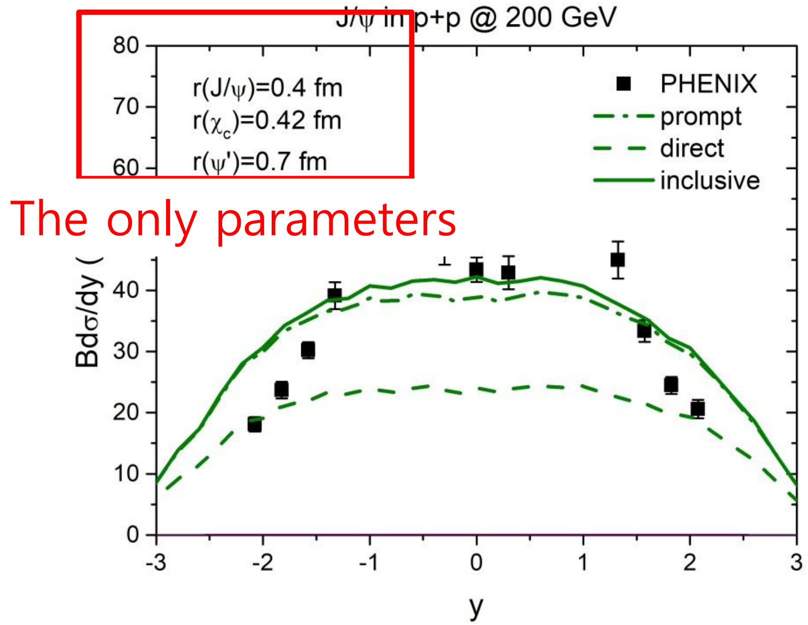
- Wigner density of S- & P-wave states: $\langle p, r | p_1, r_1; p_2, r_2 \rangle$

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

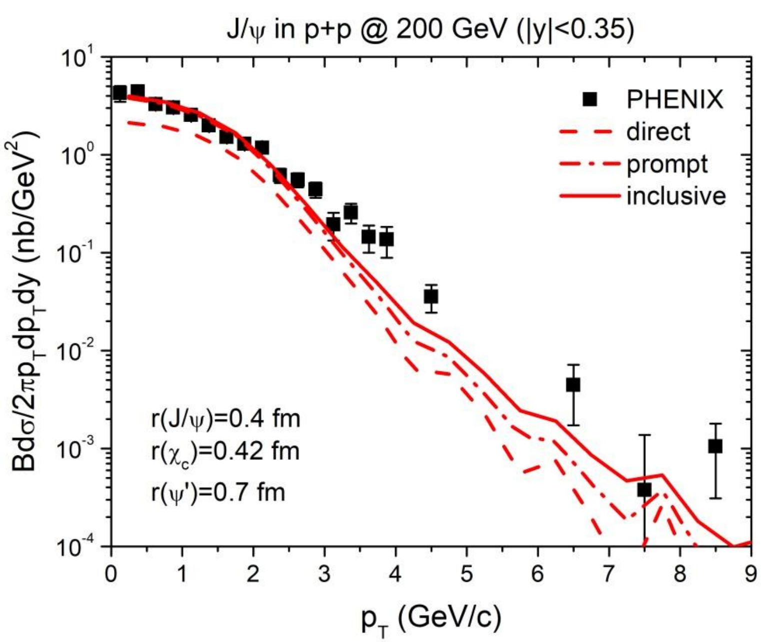
$$\Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}\left(\frac{r^2}{\sigma^2} - \frac{3}{2} + \sigma^2 p^2\right) \times \exp\left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2\right],$$

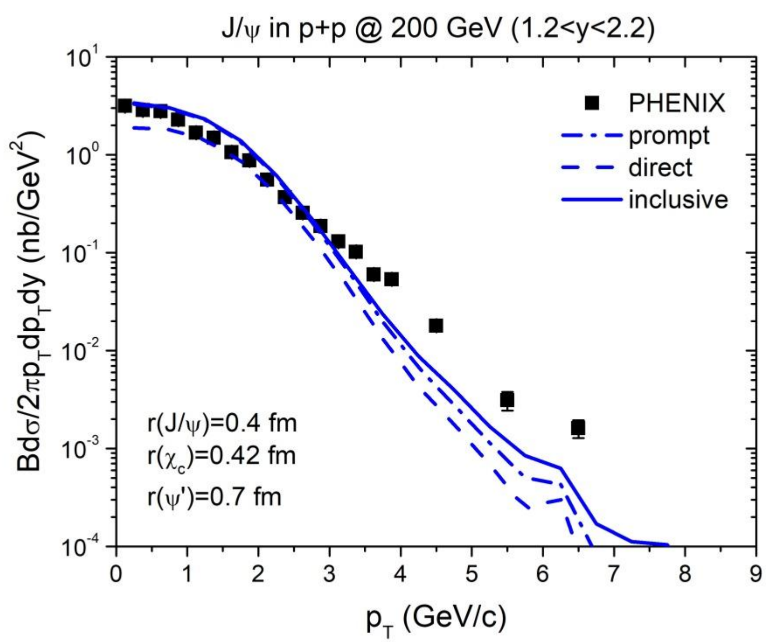
- D, d1, d2: color-spin degeneracies of quarkonium, heavy quark and antiquark
- r, p: relative distance and momentum in center-of-mass frame
- **σ**: the only parameter ~ quarkonium radius

J/ψ in pp @ 200 GeV

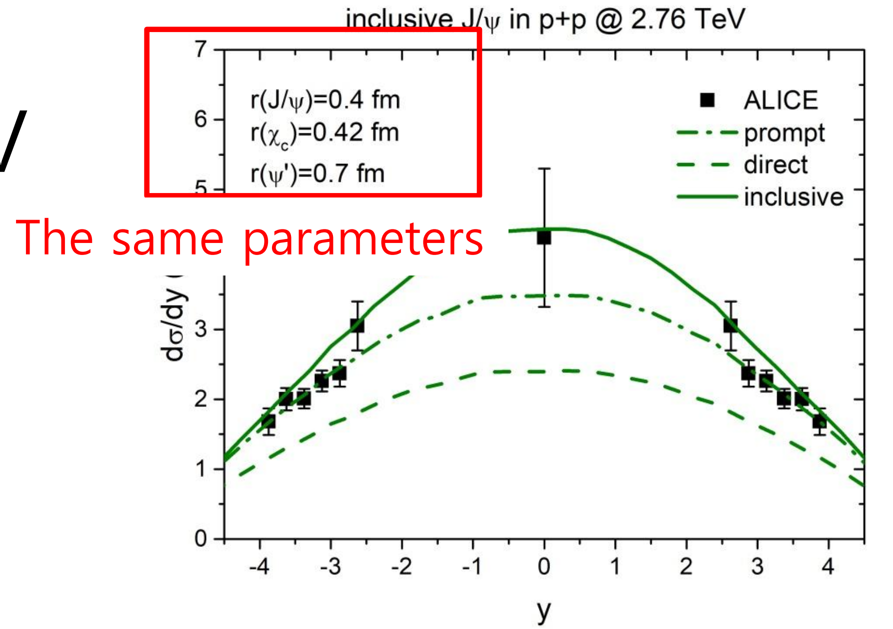


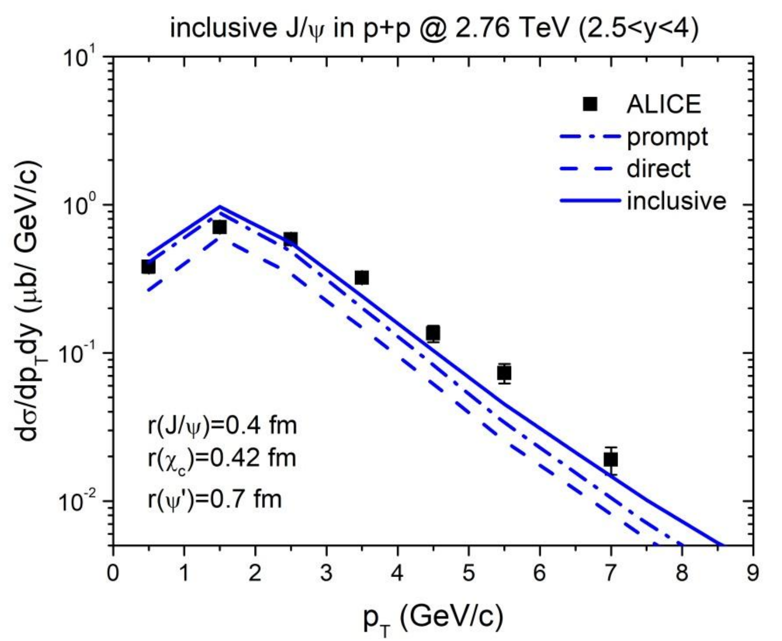
prompt: purely initial J/ψ
direct: including the feed-down from χ_c, ψ′
Inclusive: including χ_c, ψ′ and B decay



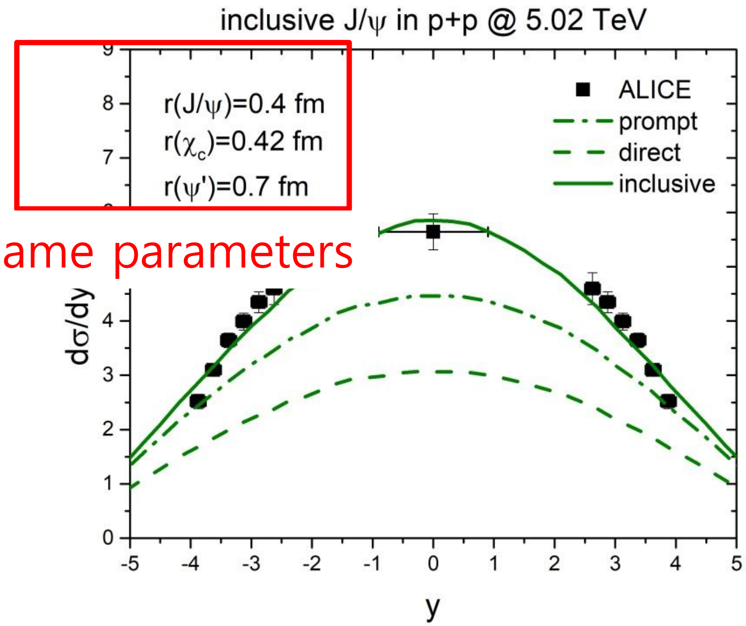


J/ψ in pp @ 2.76 TeV

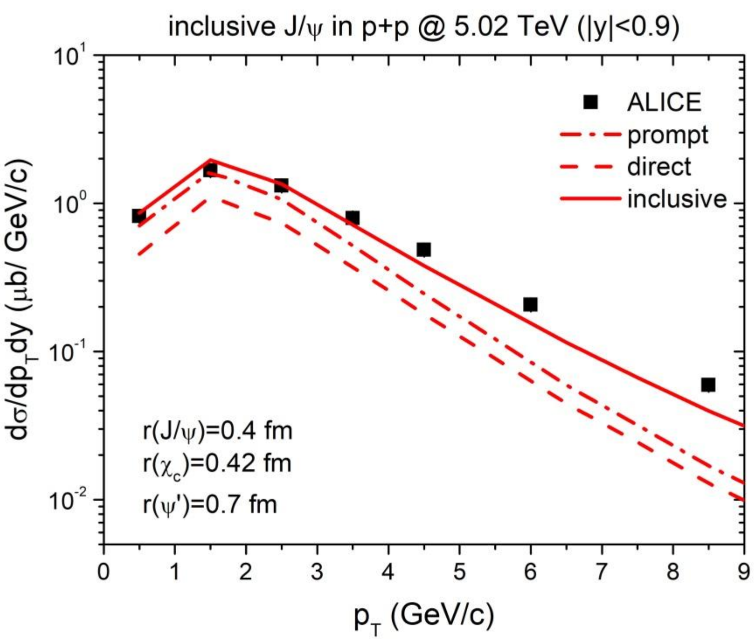


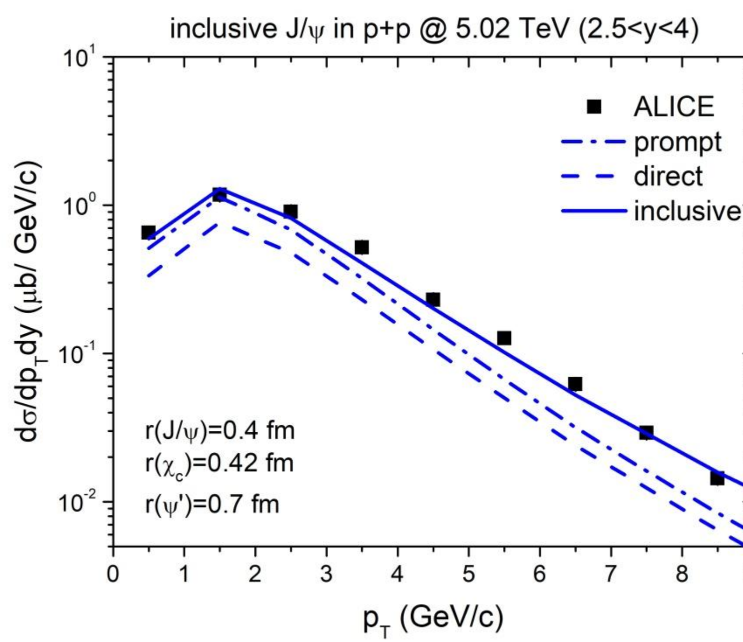


J/ψ in pp @ 5.02 TeV



The same parameters

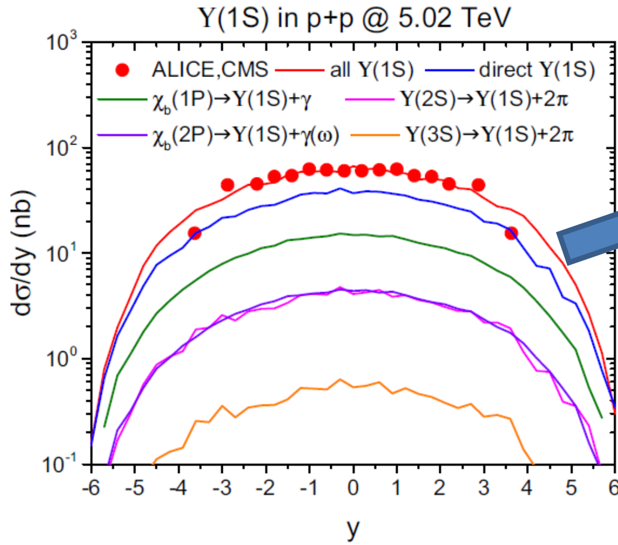


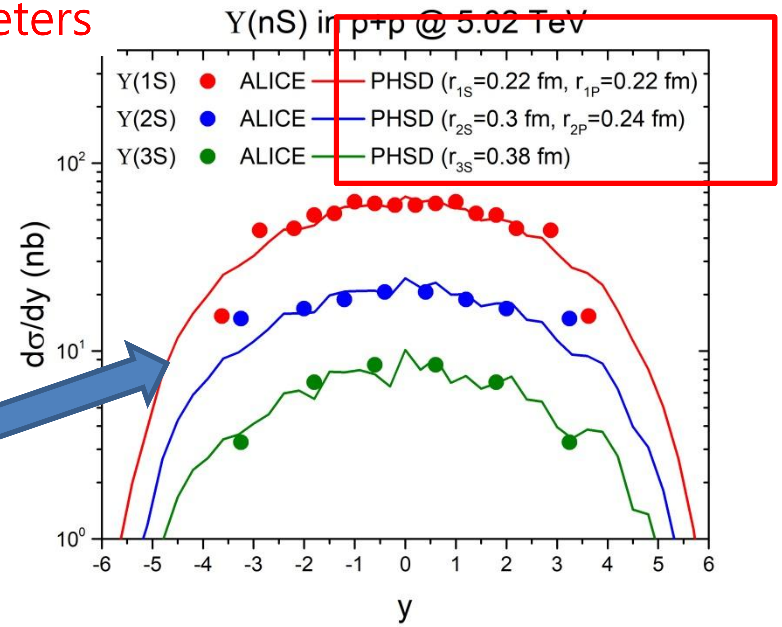


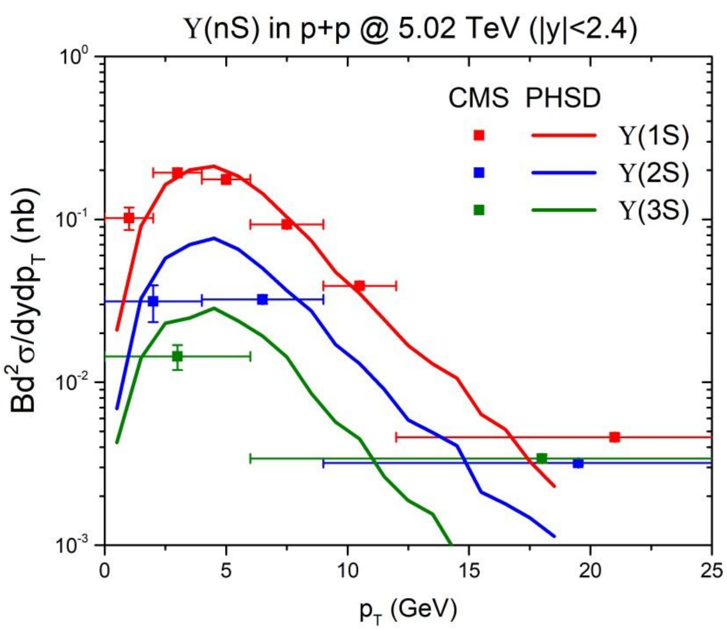
The only parameters

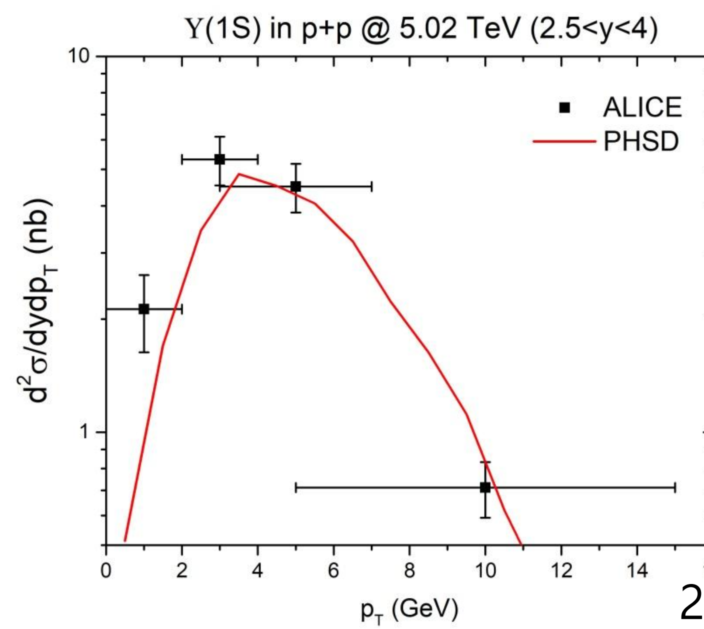
Υ(nS) in pp @ 5.02 TeV

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







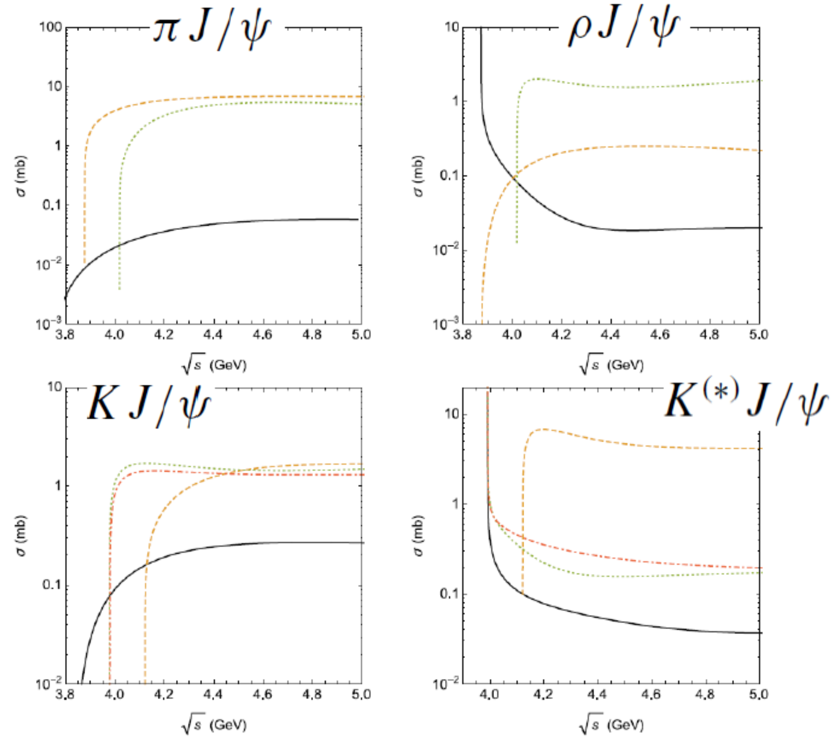


3.2 quarkonium production in p+A

Nuclear absorption (J/ψ+nucleon interaction)

- A constant cross section is introduced as a parameter to fit the experimental data

J/ψ+meson interaction

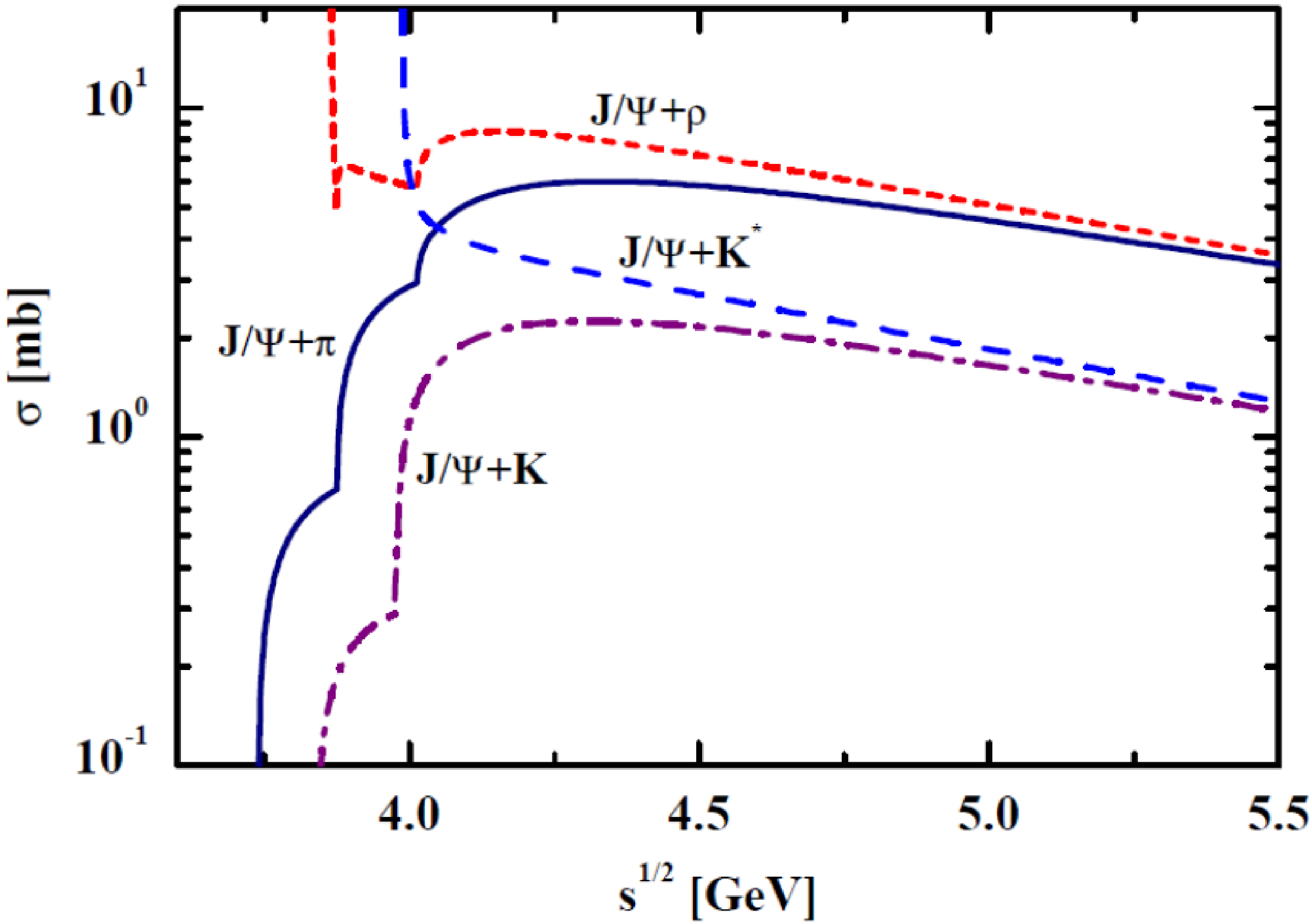


L. M. Abreu et al., PRC 97, 044902 (2018)

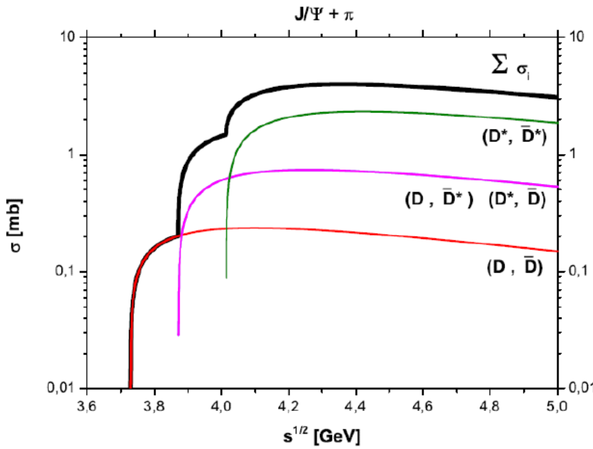
SU(4) effective model

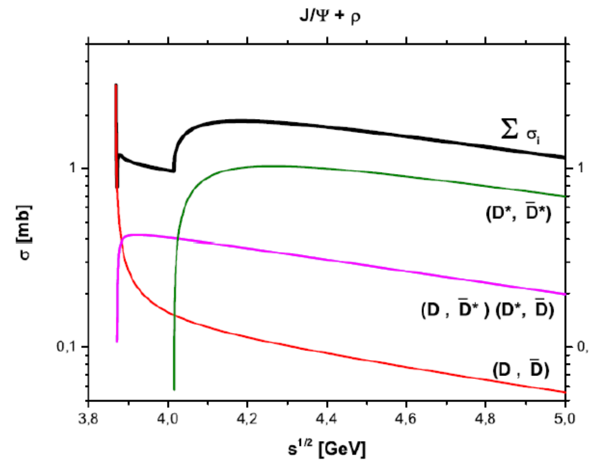
HSD: E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C 67, 054905 (2003), arXiv:nucl-th/0301083

J/Ψ+meson→ sum of ALL final channels (DDbar, D*Dbar* etc.)

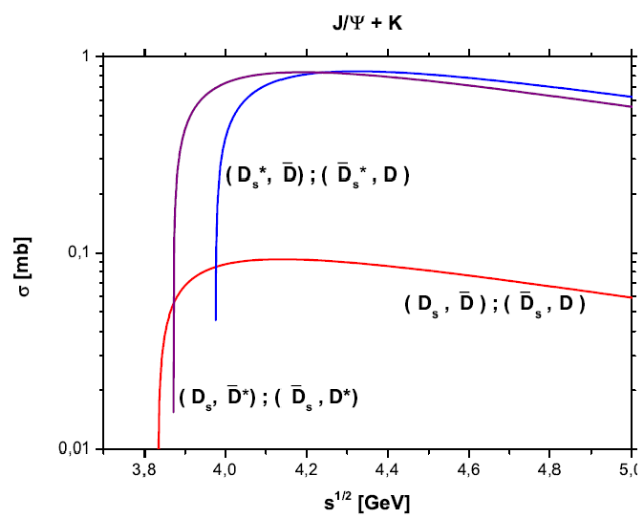


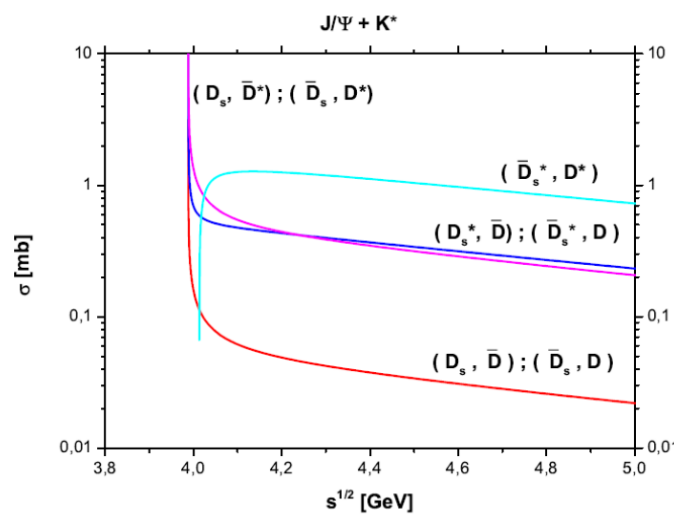
HSD: E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C 67, 054905 (2003), arXiv:nucl-th/0301083



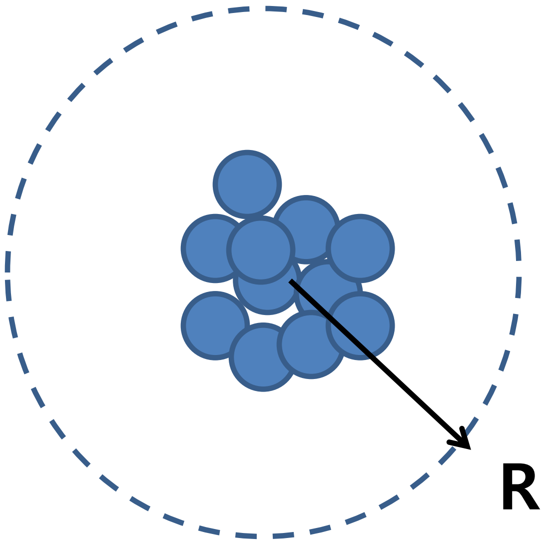


HSD: E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C 67, 054905 (2003), arXiv:nucl-th/0301083



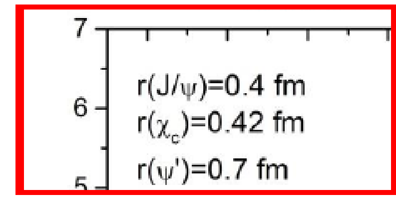


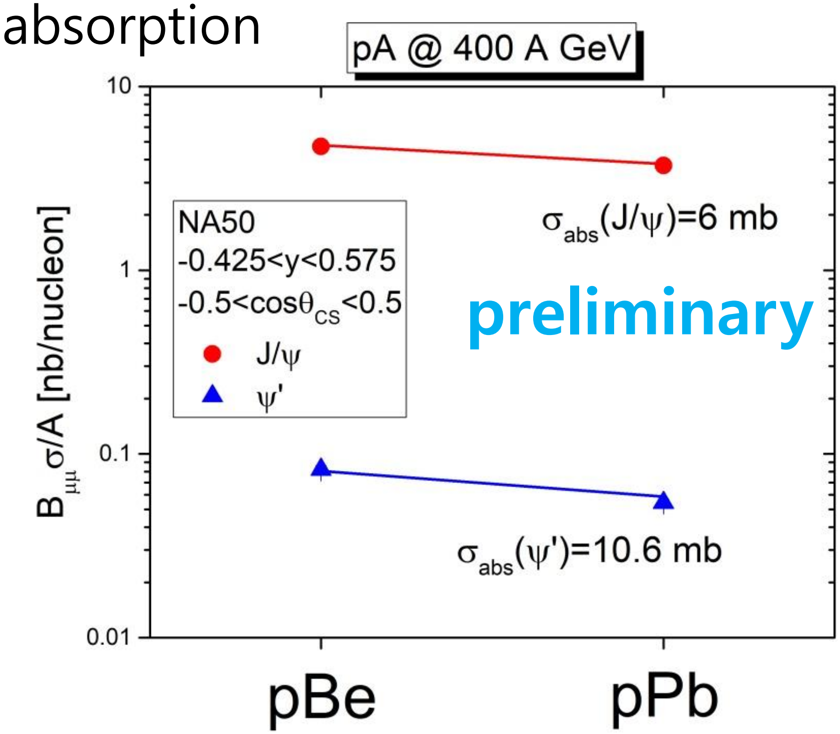
J/ψ and ψ' production in pA at SPS



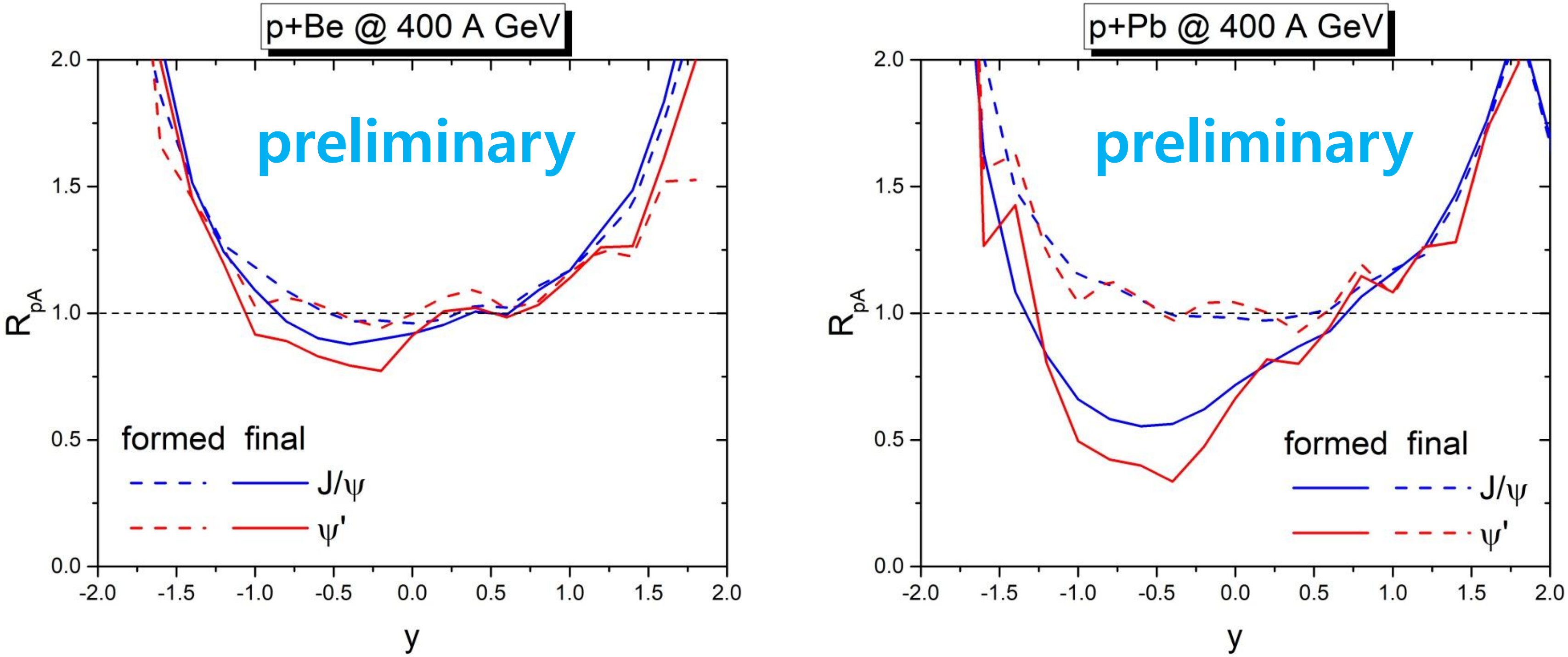
$$\sigma^{pA}_{J/\psi} = \frac{\pi R^2 N_{J/\psi}}{N_{p-beam}}$$

First produce charm pair and do Wigner projection with The same parameters & consider nuclear absorption



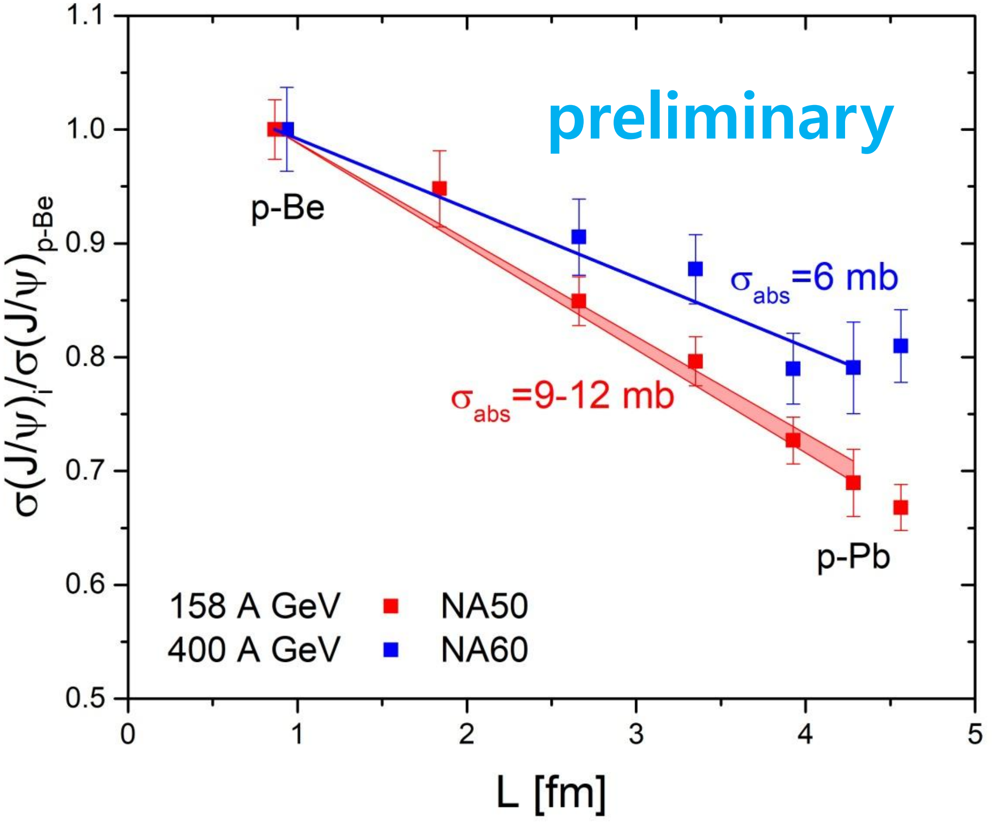


R_{pA} of J/ψ and ψ' at SPS



Even in p+Be collisions, nuclear absorption exists
Much larger nuclear absorption in p+Pb collisions

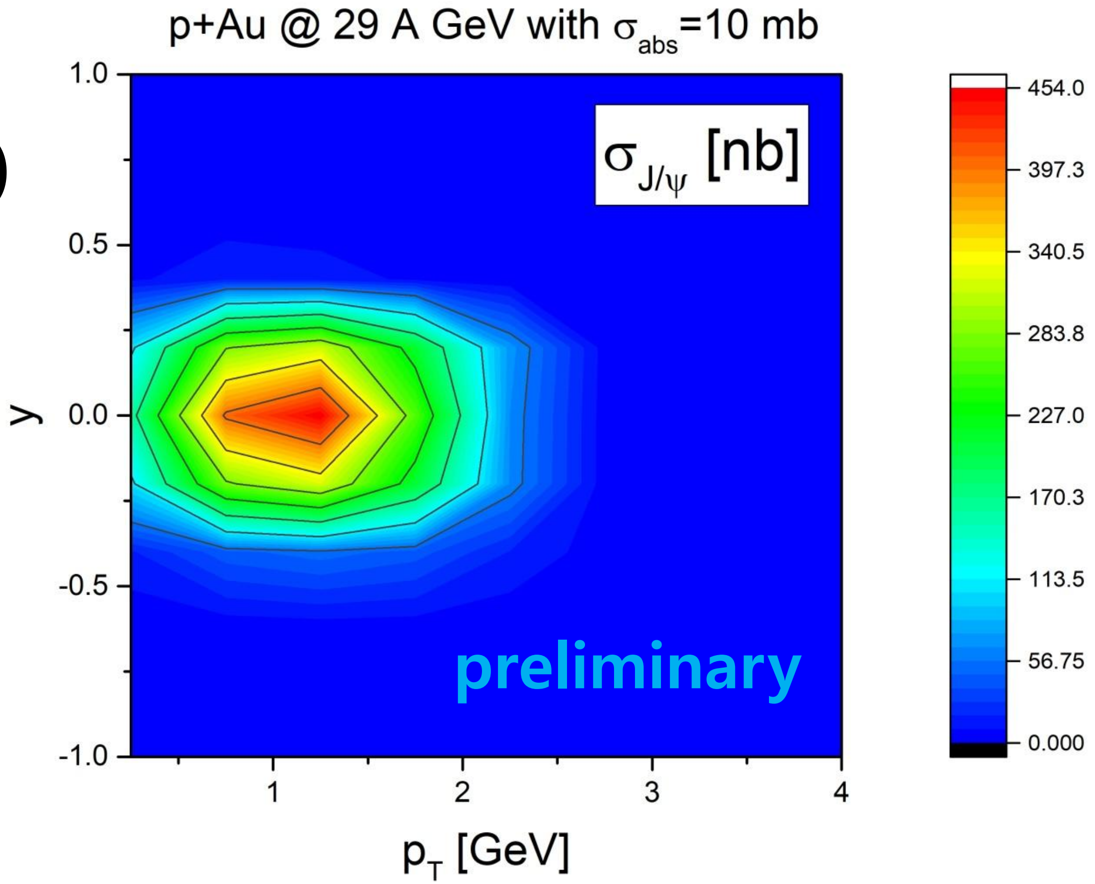
J/ψ at 400 A GeV vs. 158 A GeV



A larger absorption cross section is needed at 158 A GeV

J/ψ in p+Au @ FAIR (29 A GeV)

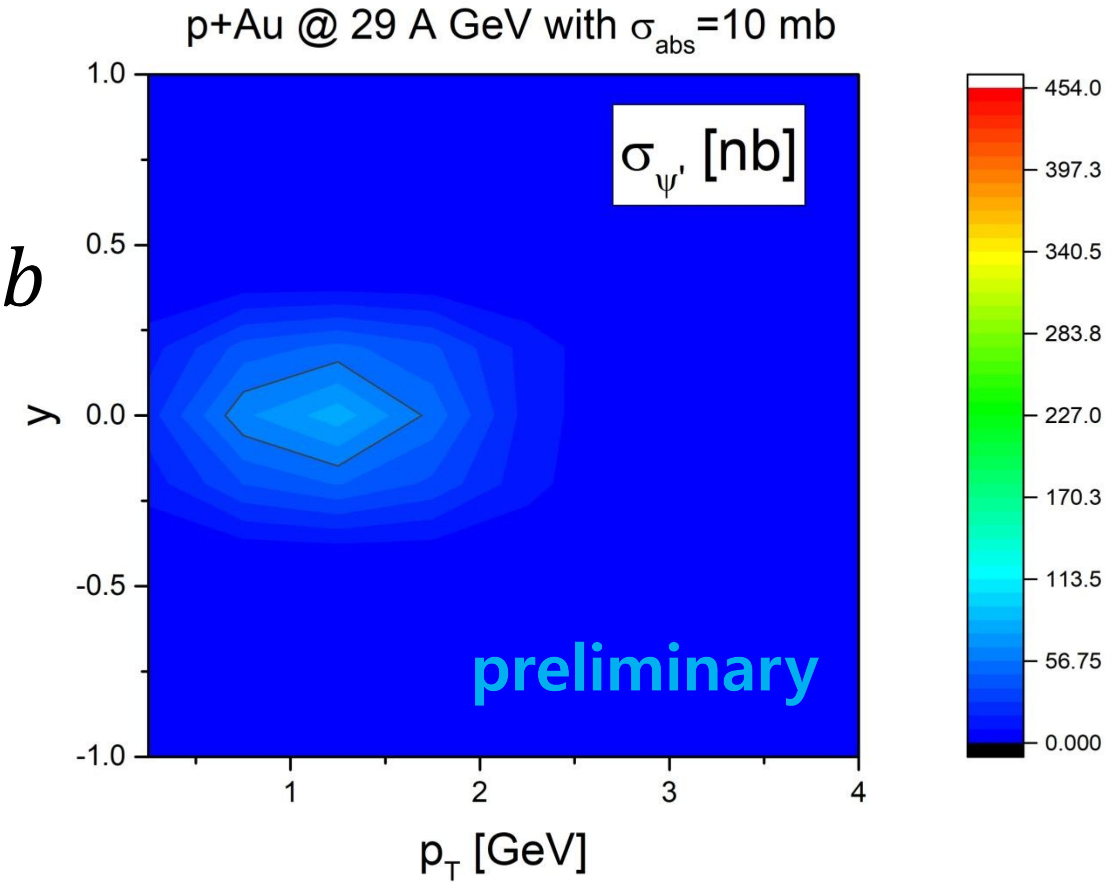
Total $\sigma_{J/\psi}$ (4π) $=0.36\mu b$



It decreases to 0.25 μb for $\sigma_{abs} = 20mb$

ψ' in p+Au @ FAIR (29 A GeV)

Total $\sigma_{\psi'}$ (4π) $=0.058\mu b$



It decreases to 0.039 μb for $\sigma_{abs} = 20mb$

3.3 Quarkonium production in AA

- Different from 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

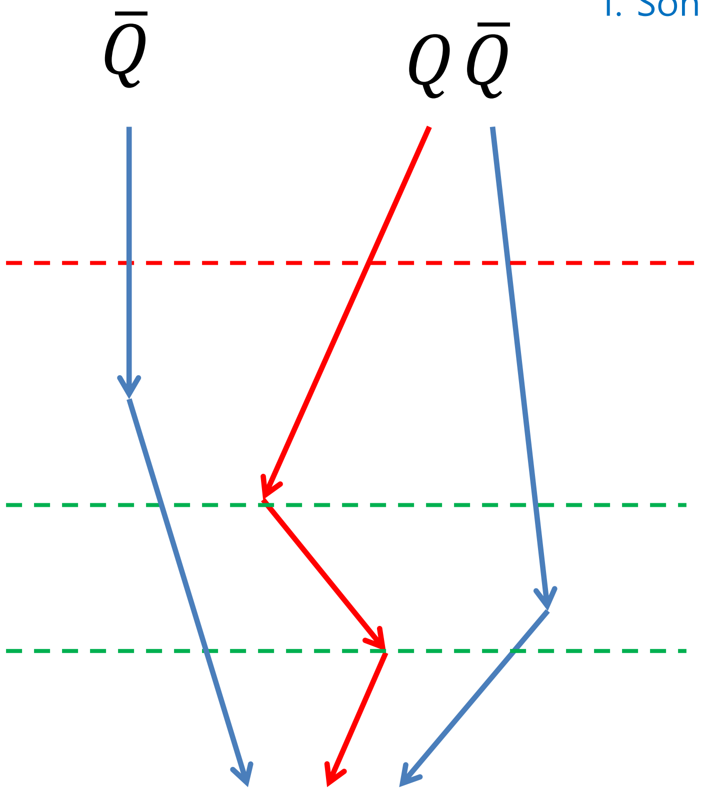
E. A. Remler and A. P. Sathe, Ann. Phys. **91**, 295 (1975).
E. A. Remler, Ann. Phys. **95**, 455 (1975).
E. A. Remler, Ann. Phys. **136**, 293 (1981).

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.

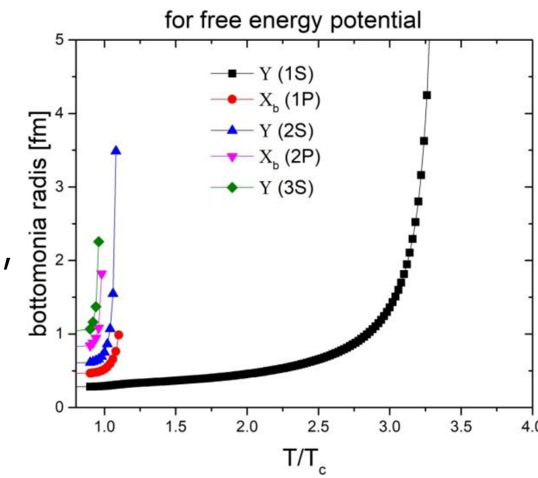
Remler's formalism

T. Song et al., PRC107, 054906 (2023)



Dissociation temperature (first projection)

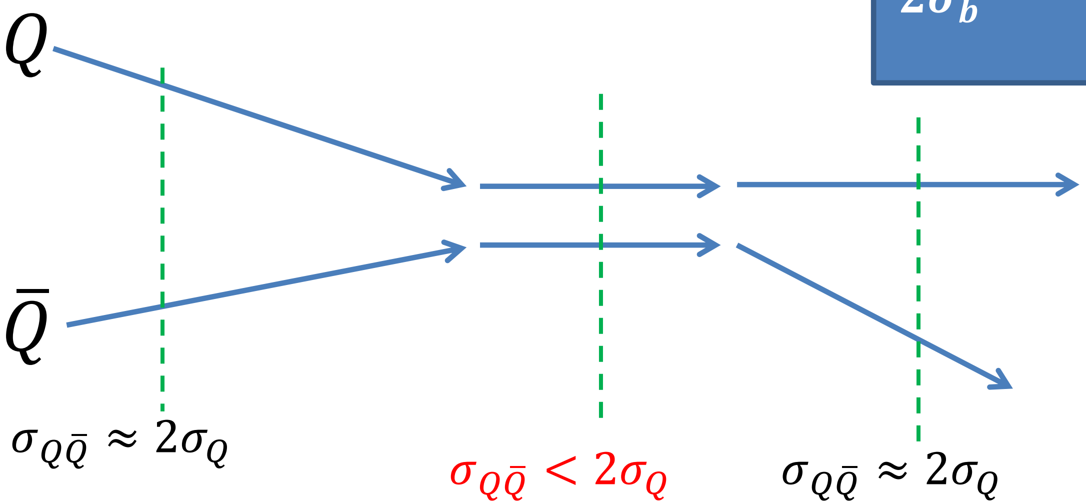
Whenever Q ($\bar{Q}$) scatters, Wigner projection is updated, using temperature-dependent radius

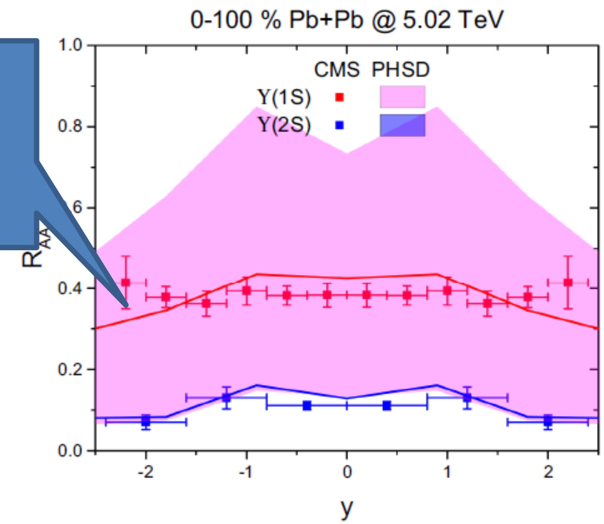


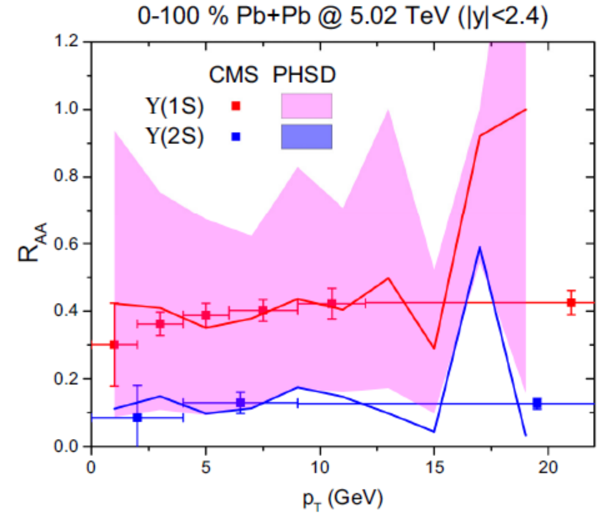
1. This is carried out for all $Q\bar{Q}$ pairs for all physical states: J/ψ, χ_c, ψ′ for $c\bar{c}$ and ϒ(1S), ϒ(2S), ϒ(3S), χ_b(1P), χ_b(2P) for $b\bar{b}$
2. Heavy quark potential and scattering are closely related to quarkonium production/dissociation

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

$$\frac{\sigma_\Upsilon}{2\sigma_b} = 0.1$$

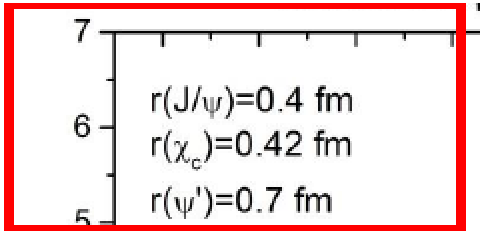




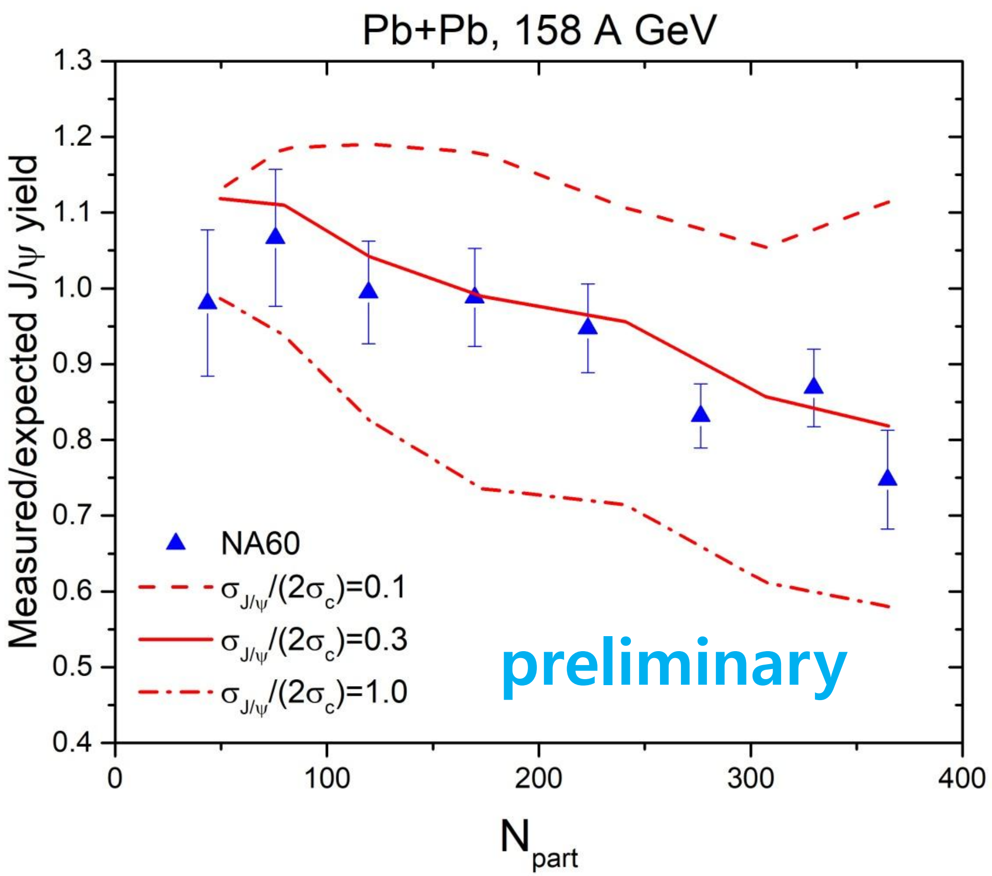


If $Q\bar{Q}$ form a color singlet, the size of $Q\bar{Q}$ pair will be small and the scattering cross section must be reduced due to interference

R_{AA} of J/ψ in Pb+Pb @ 158 A GeV



The same parameters



It suggests $\frac{\sigma_{J/\psi}}{2\sigma_c} = 0.3$

J/ψ in Au+Au at FAIR energies

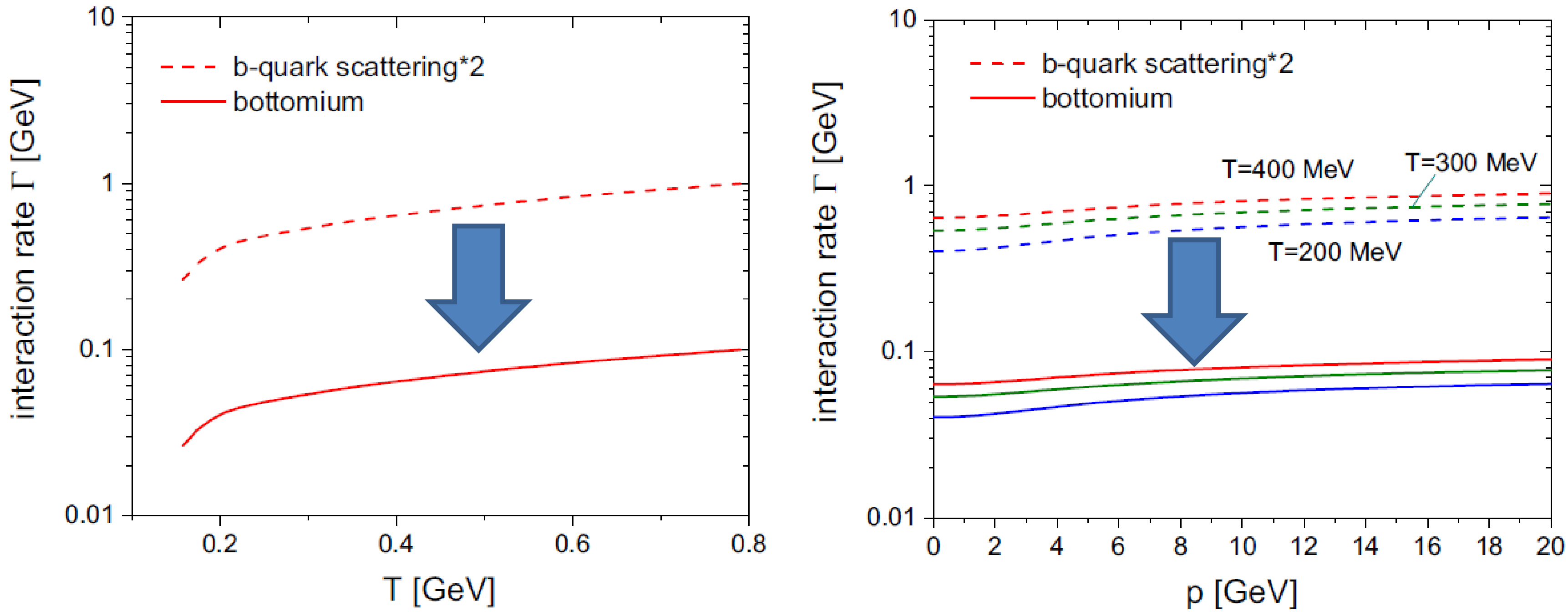
- in progress

Summary

- PHSD which has been successful for open/hidden charm at RHIC, LHC is applied to SPS, FAIR energies.
- Charm production is sensitive to the fermi momentum near the threshold energy (for example, Au+Au @ 5.2 GeV).
- Dimuon spectrum from charm is insensitive to partonic & hadronic interactions in heavy-ion collisions at SPS & FAIR energies.
- Based on the success of Remlar's formalism (Wigner projection) for J/ψ production in pp, we have extended it to p+A collisions at SPS/FAIR energies.
- J/ψ in Pb+Pb collisions at SPS suggests $\sigma_{J/\psi}=0.3(2\sigma_c)$ in QGP.

Thanks for your attention

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



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

Effects of hadronic scattering