Heavy flavor and quarkonium production in the PHSD transport

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outline

- Introduction
- PHSD (Parton-Hadron-String Dynamics)
- Charm production in heavy-ion collisions
- Single electron production in HIC
- J/ψ production in HIC (in progress)
- Summary

1. introduction

- Relativistic heavy-ion collisions produce extremely hot dense nuclear matter.
- It is very interesting to know the properties of the hot dense matter.
- Heavy flavor is one of promising probes for the properties.
- Heavy flavor has a couple of characteristics:

1. Its production is well described by pQCD.
2. It is produced in a very early stage of HIC-> possibly has the information of the early stage of HIC.
3. …

2. PHSD

(Parton-Hadron-String Dynamics)

Heavy-ion collisions in the PHSD

- High-energy BB and BM collisions produce strings (Lund string model).
- The strings fragment into hadrons or melt into quarks and antiquarks at high energy density.
- The melted quarks and antiquarks are off-shell and form off-shell gluons by their fusion.
- Partons interact in Dynamical Quasi-Particle Model (DQPM) and are hadronized into off-shell hadrons at the critical temperature (~158 MeV).
- Hadrons interact with each other, and then freeze out.

Dynamical Quasi-Particle Model for QGP

gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$
quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q, M_g)
- the imaginary part describes the interaction width of partons (G_q, G_g)
- QGP is composed of interacting Quasi-Particles.

Mass and width from HTL at high T

- quarks:

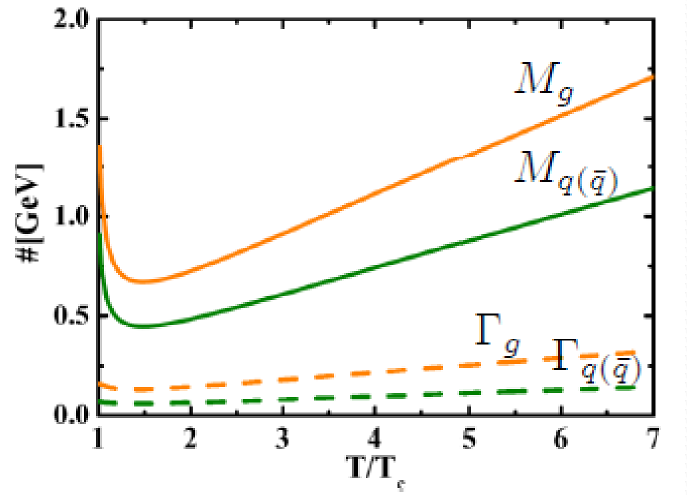
mass: $M^2_{q(\bar{q})}(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$

width: $\Gamma_{q(\bar{q})}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

- gluons:

mass: $M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

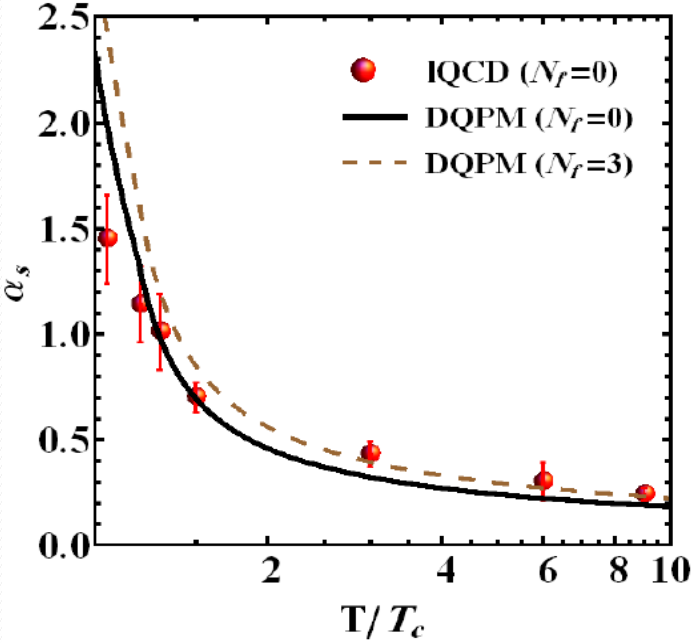
width: $\Gamma_g(T) = \frac{1}{3}N_c \frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$



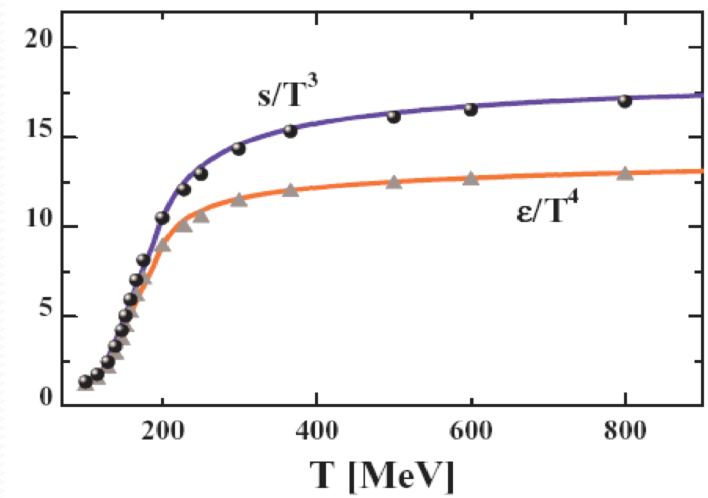
$N_c = 3, N_f=3$

- g(T) is fitted to the lattice calculations on running coupling and EoS.

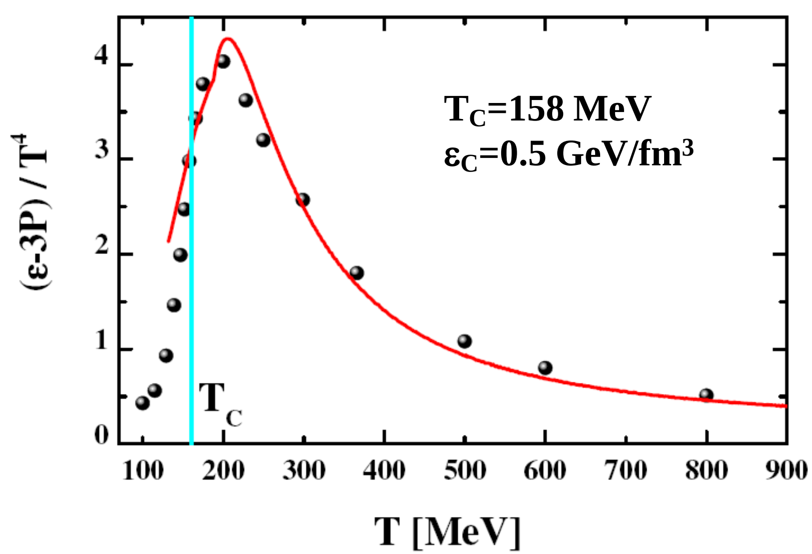
$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



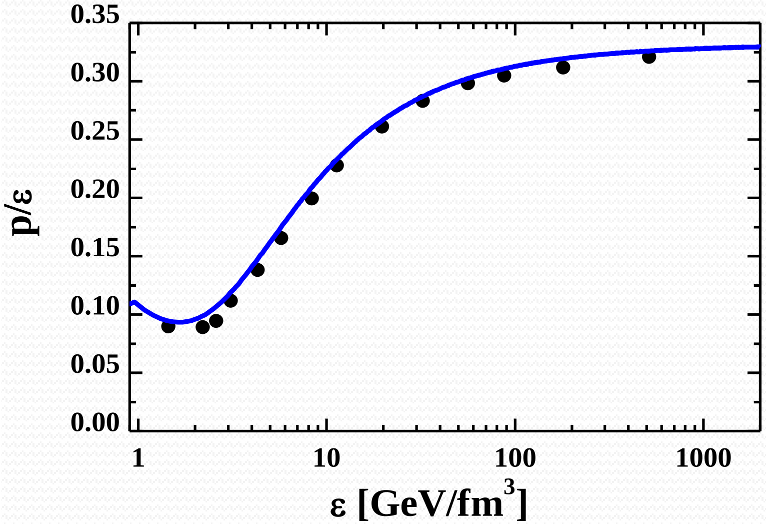
lQCD (N_f=0)
DQPM (N_f=0)
DQPM (N_f=3)
α_s
T/ T_c



s/T^3
ε/T^4
T [MeV]

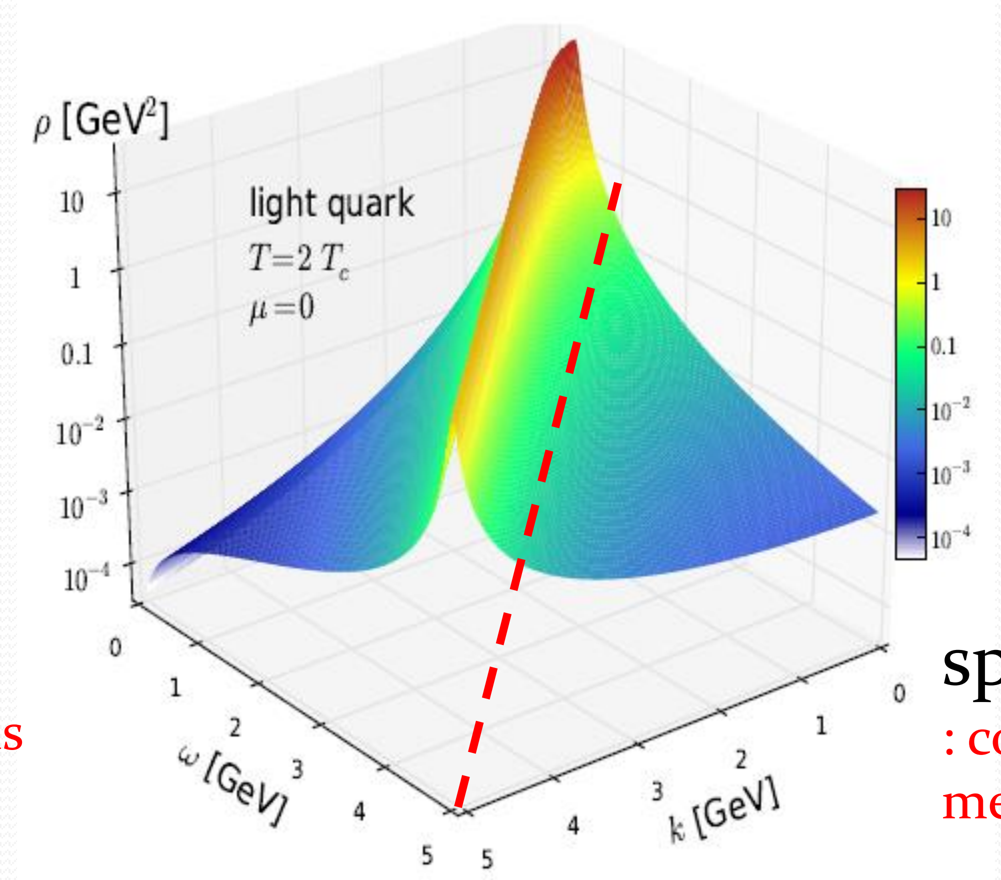


T_C=158 MeV
ε_C=0.5 GeV/fm^3
T_C
(ε-3P) / T^4
T [MeV]



p/ε
ε [GeV/fm^3]

Quark/gluon with Lorentzian spectral function



time-like

: propagate as a particle

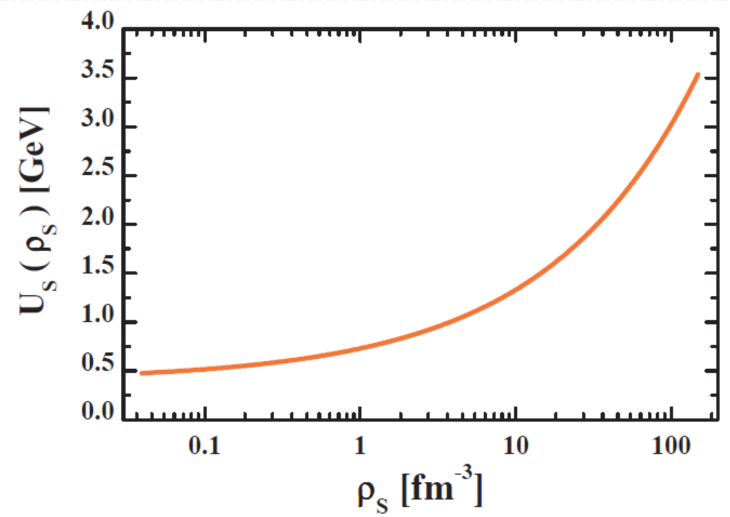
space-like

: contribute to scalar-mean-field potential

mean-field scalar potential

$$U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s}$$

where ρ_S is scalar density, and V_p is the potential energy density, which is the energy density contributed by the space-like part of parton spectral function.



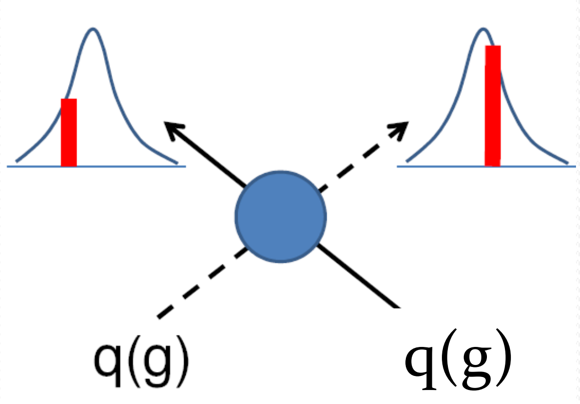
U_s increases with increasing ρ_S

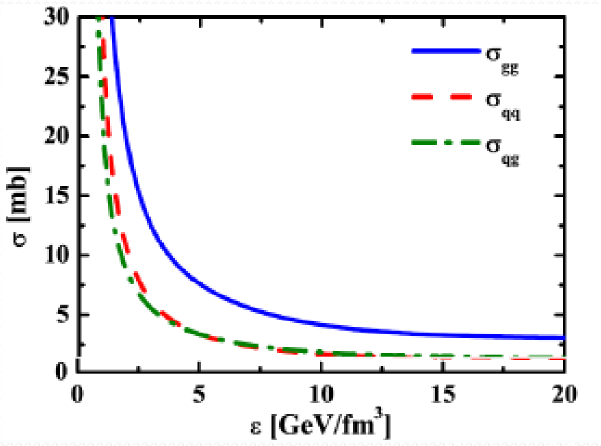
→ Particles are outwardly accelerated in heavy ion-collisions.

It helps to reproduce experimental data

Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Partonic scattering in the PHSD





Scattering cross sections based on spectral width

- (quasi-)elastic collisions :
- Masses change by collision

$$q+q \rightarrow q+q \qquad g+q \rightarrow g+q$$
$$q+\bar{q} \rightarrow q+\bar{q} \qquad g+\bar{q} \rightarrow g+\bar{q}$$
$$\bar{q}+\bar{q} \rightarrow \bar{q}+\bar{q} \qquad g+g \rightarrow g+g$$

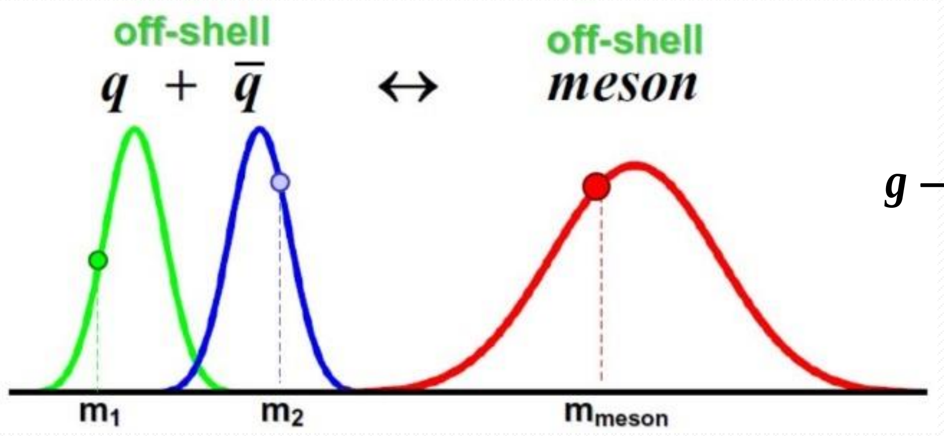
- inelastic collisions :

$$q+\bar{q} \rightarrow g \qquad q+\bar{q} \rightarrow g+g$$
$$g \rightarrow q+\bar{q} \qquad g \rightarrow g+g$$

Suppressed due to the large gluon mass

Hadronization in the PHSD

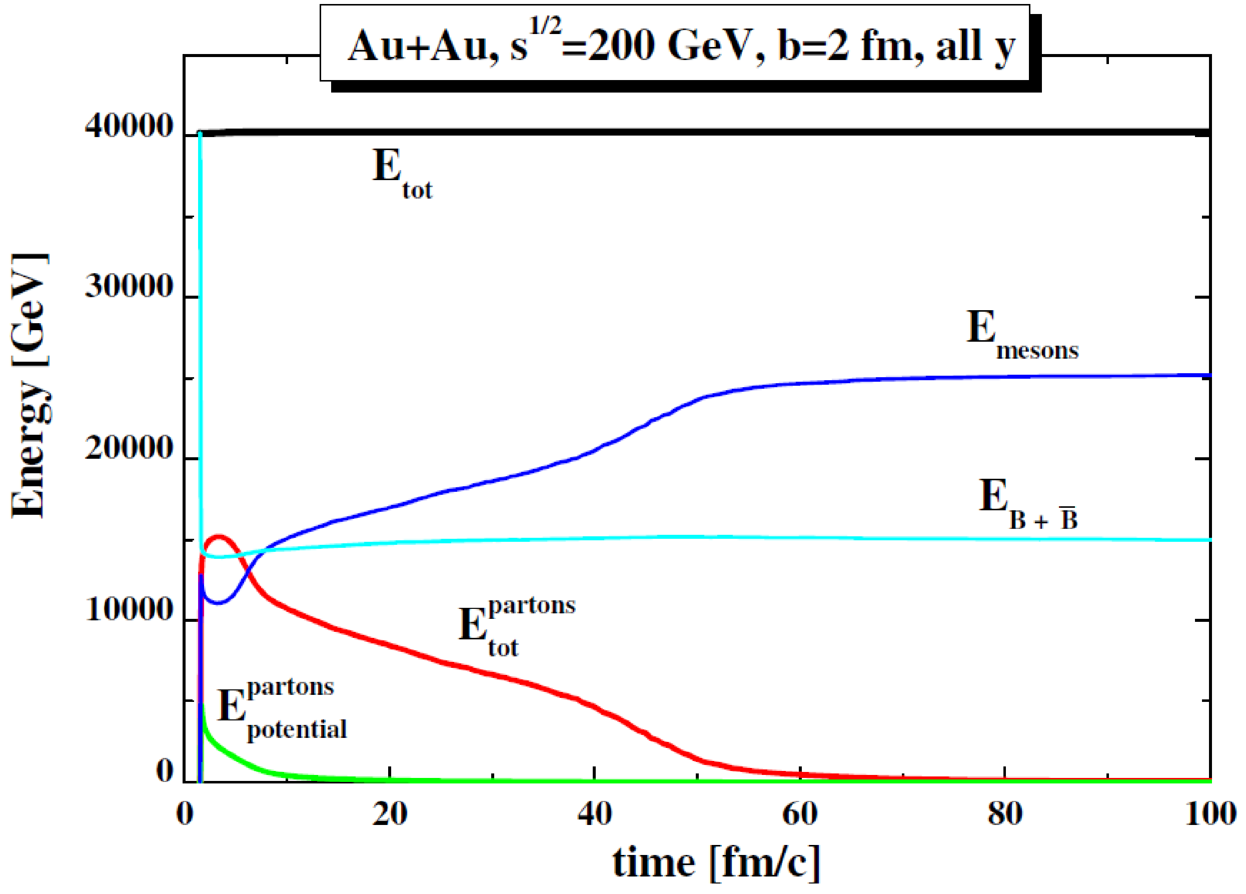
- Massive colored off-shell (anti)quarks are hadronized into colorless off-shell mesons and (anti)baryons.



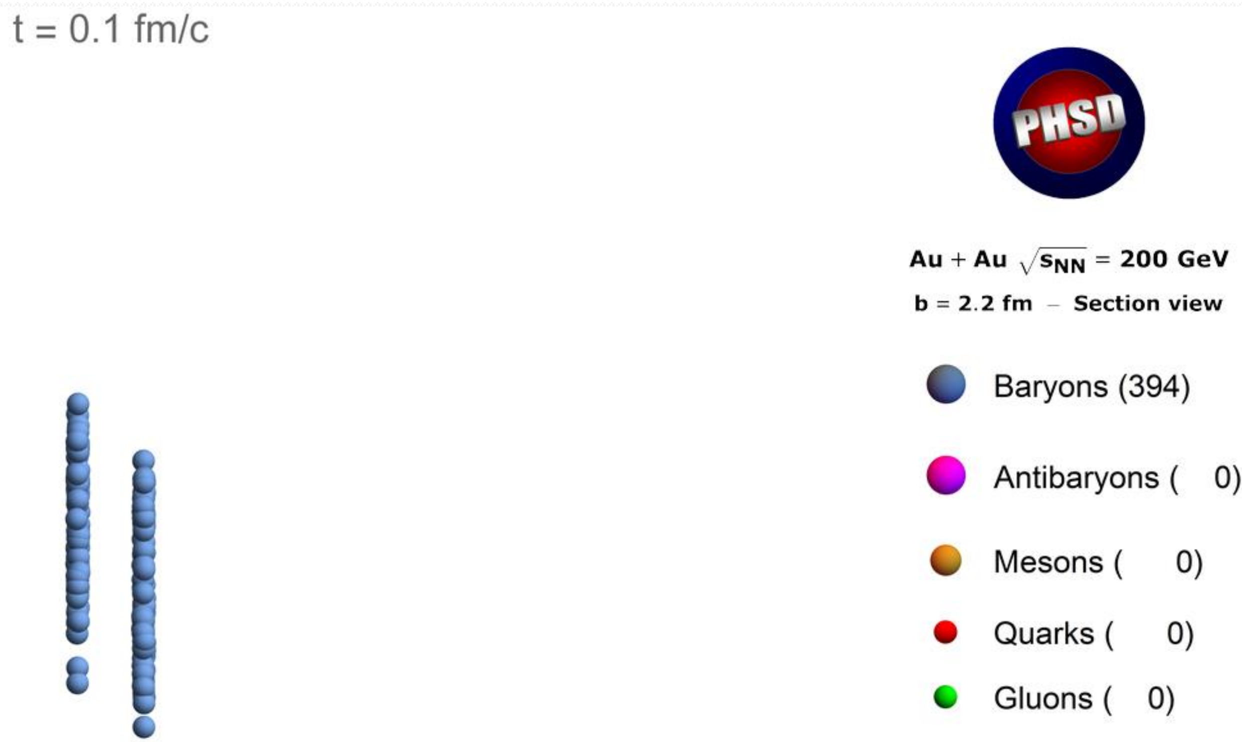
$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow meson \ ('string')$$

$$q + q + q \leftrightarrow baryon \ ('string')$$

Energy decomposition with time

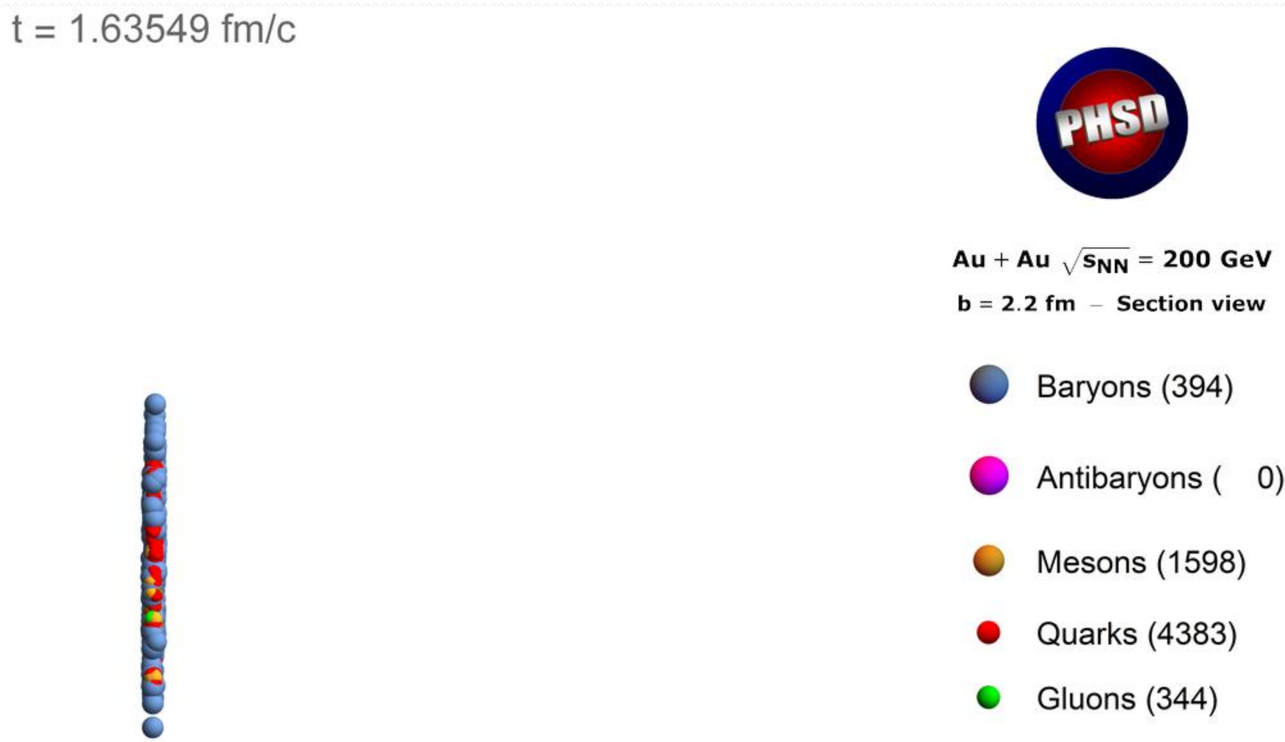


Stages of a collision in PHSD



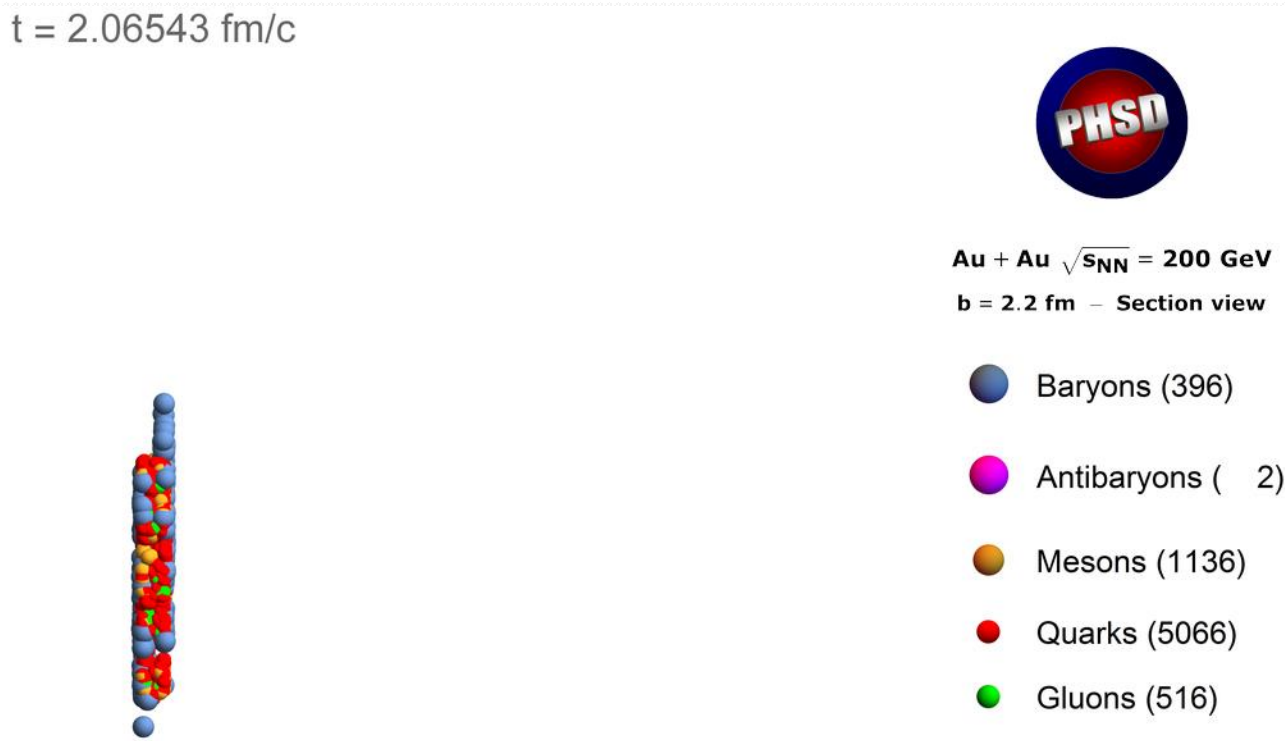
P.Moreau

Stages of a collision in PHSD



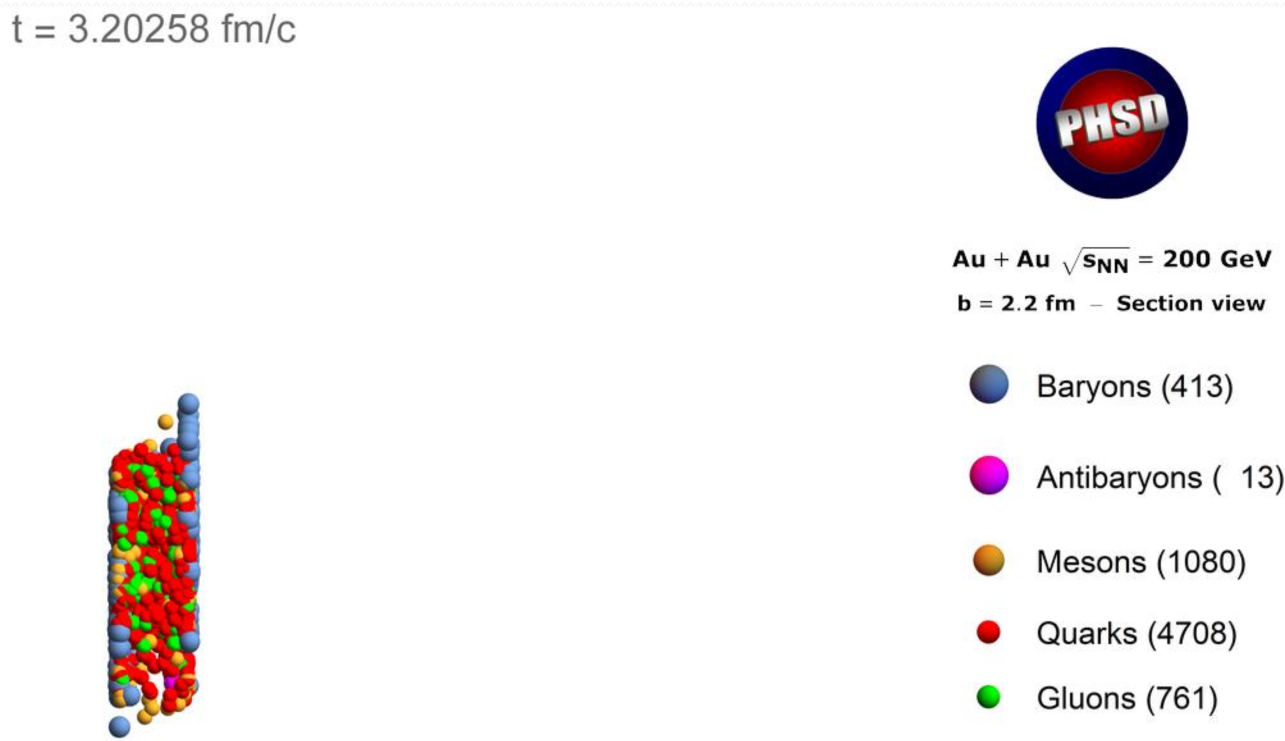
P.Moreau

Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD



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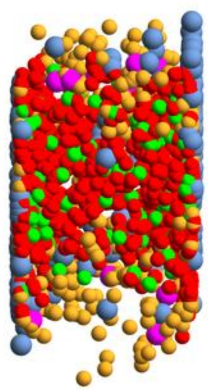
Stages of a collision in PHSD

t = 5.56921 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (472)

Antibaryons (70)

Mesons (1724)

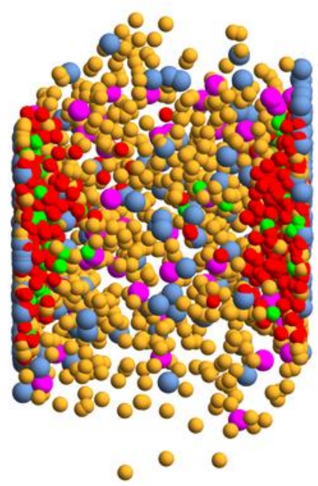
Quarks (3843)

Gluons (652)

P.Moreau

Stages of a collision in PHSD

t = 8.06922 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

- Baryons (559)
- Antibaryons (139)
- Mesons (2686)
- Quarks (2628)
- Gluons (442)

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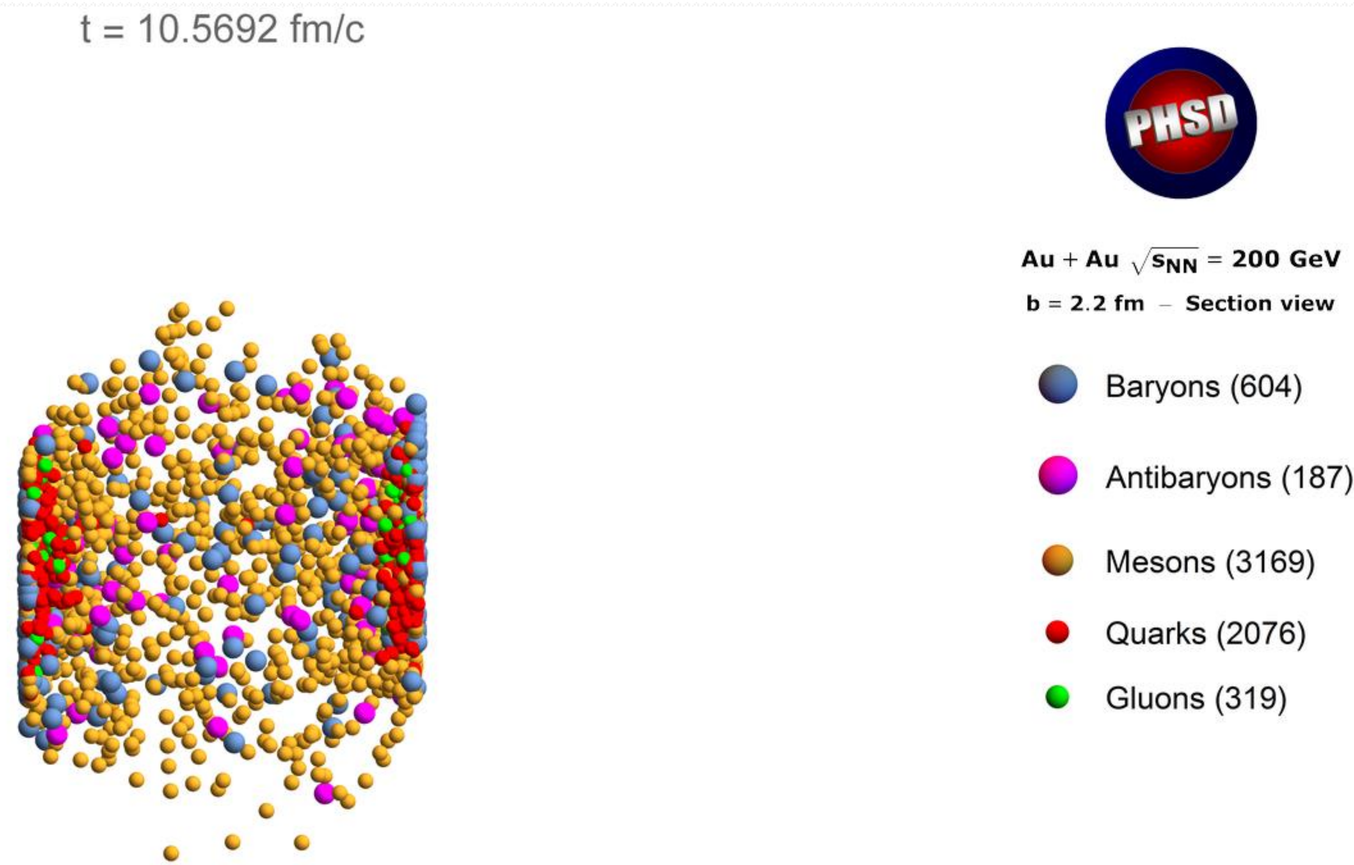
Stages of a collision in PHSD



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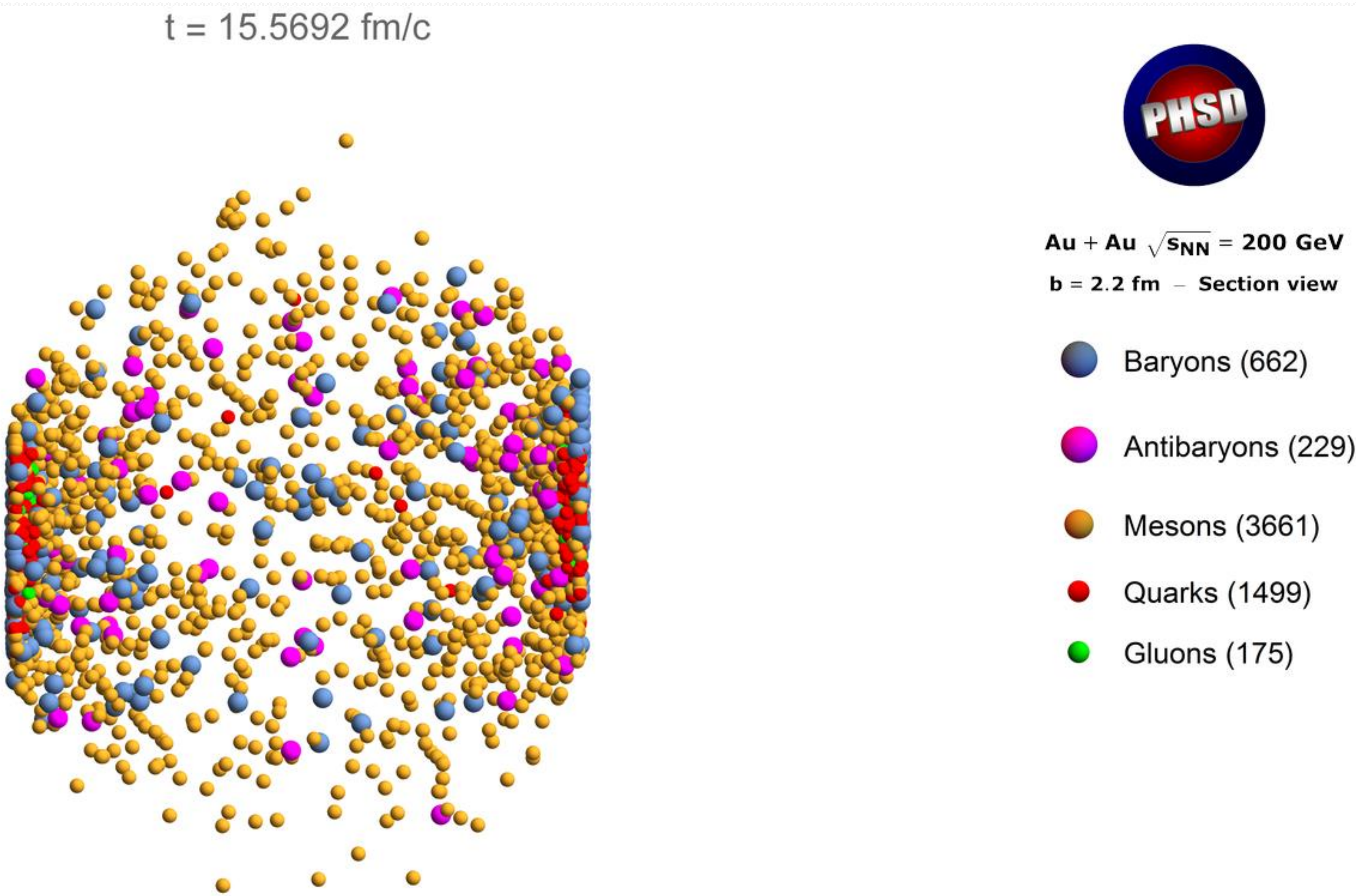
Stages of a collision in PHSD



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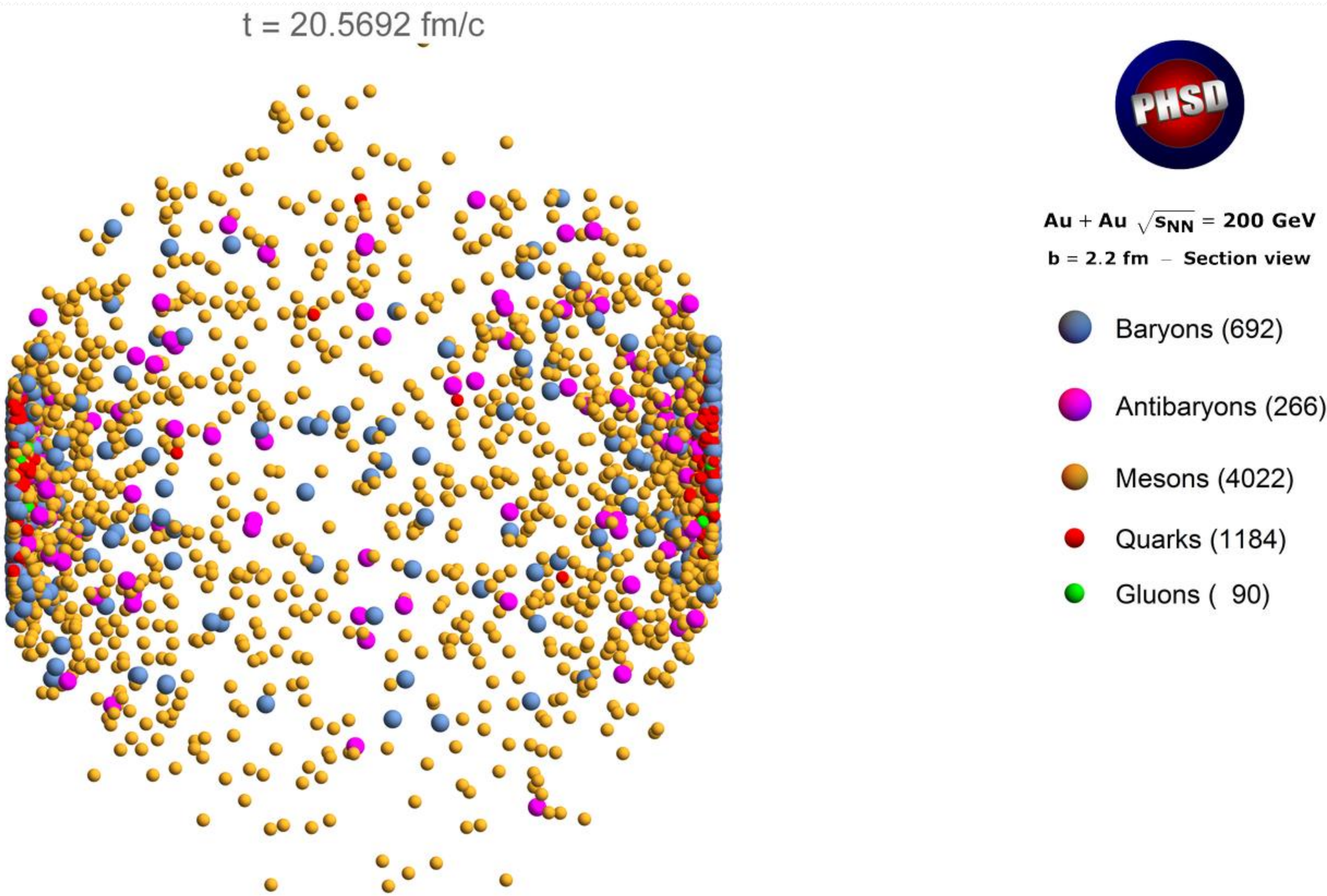
Stages of a collision in PHSD

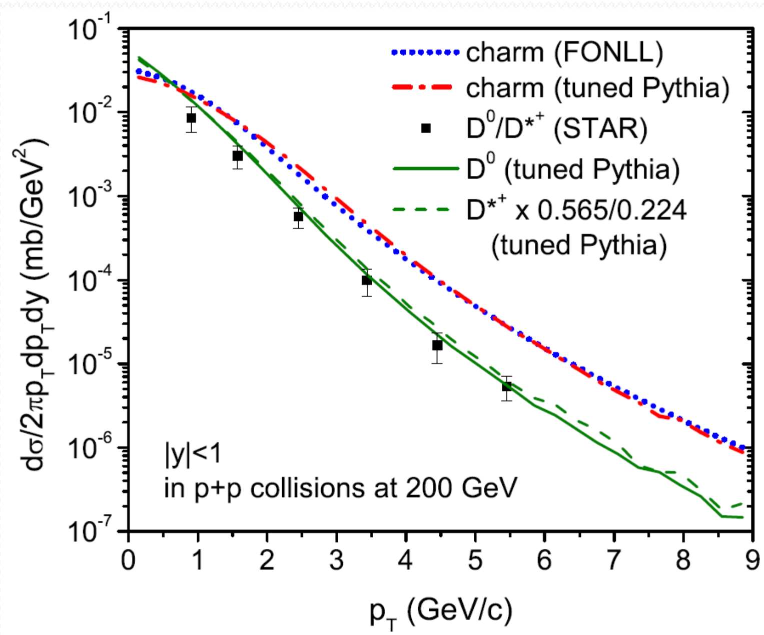


P.Moreau

3. Charm production in HIC

Initial production of charm

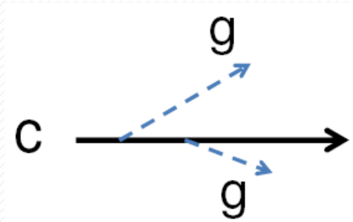
- Initial charm pairs are produced by using PYTHIA which is then tuned (e.g. y*0.9, p_T*0.84 for E=200 GeV) to reproduce FONLL (fixed-order next-to-leading log) results.



In p+p collisions produced charm quark is fragmented into D meson by emitting soft gluons:

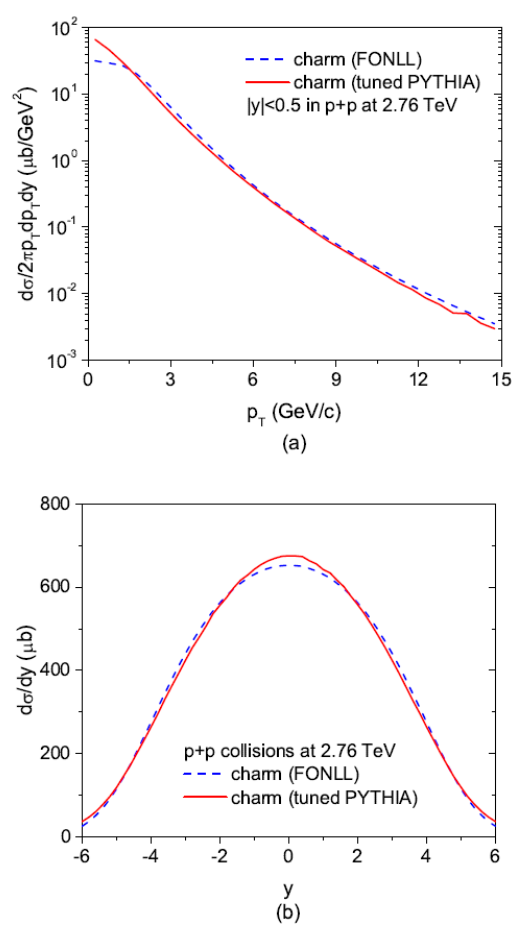
Peterson's fragmentation function

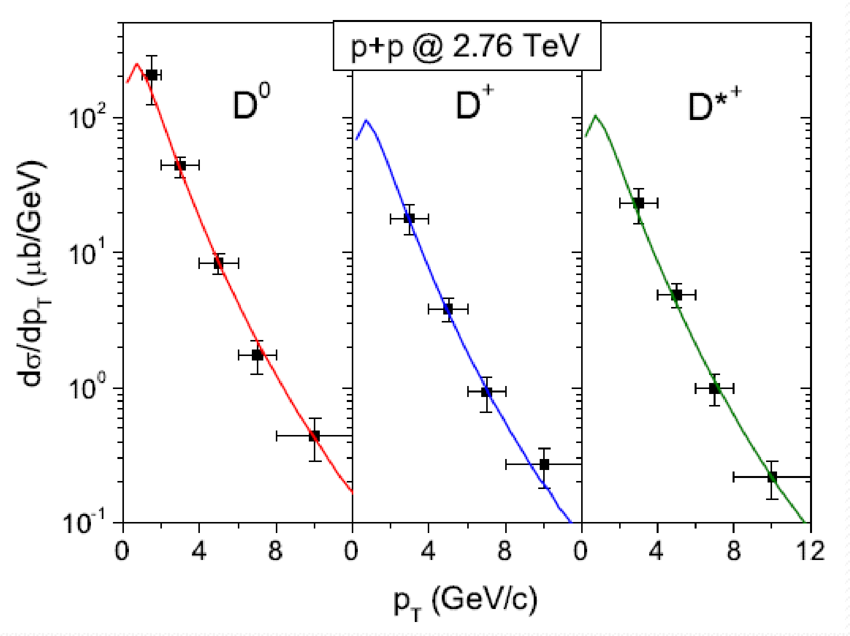
$$D_Q^H(z) \sim \frac{1}{z[1 - 1/z - \epsilon_Q/(1-z)]^2}$$



Colorless D meson

By using the same fragmentation function for LHC energy





Cold nuclear matter effects (shadowing effect)

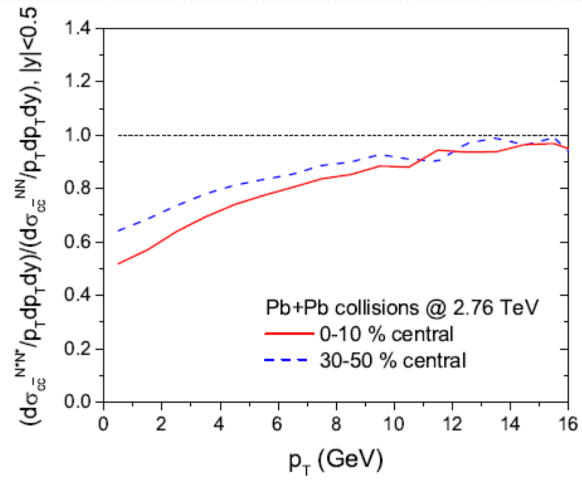
Charm production cross section in N*N* in HIC:

$$\sigma_{c\bar{c}}^{N^*N^*}(s) = \sum_{i,j} \int dx_1 dx_2 R_i^A(x_1,Q) R_j^A(x_2,Q) \times f_i^N(x_1,Q) f_j^N(x_2,Q) \sigma_{c\bar{c}}^{ij}(x_1 x_2 s, Q).$$

$$x_1 = \frac{M_T}{E_{\rm cm}} e^{y},$$
$$x_2 = \frac{M_T}{E_{\rm cm}} e^{-y},$$

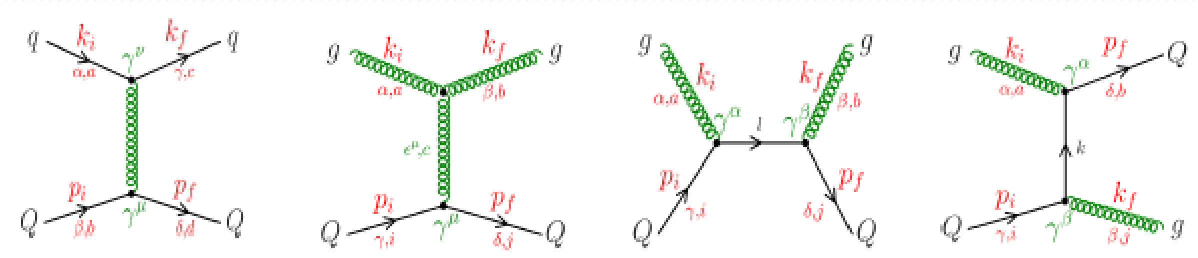
Scale $Q = (M_{T_1}+M_{T_2})/2$

$R_i^A(x_1,Q)$, $R_i^A(x_2,Q)$ for *i=j=gluon* are obtained from the EPS09 using that charm production is dominated by gluon fusion:

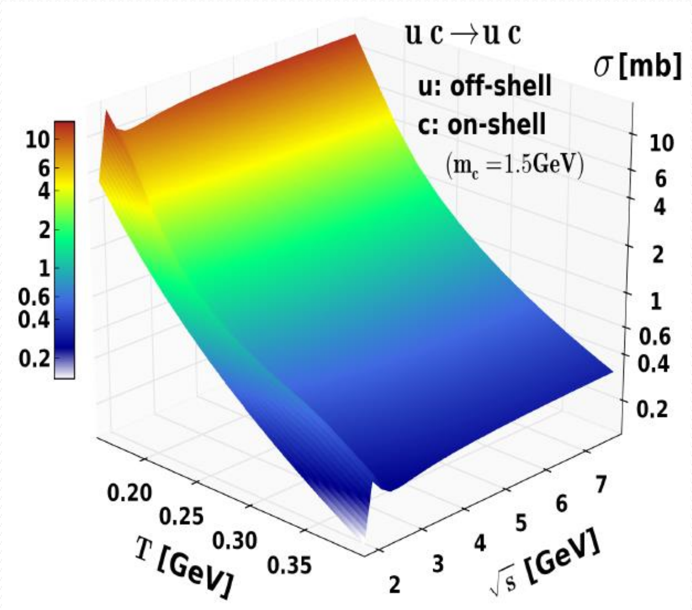


Charm scattering in QGP (DQPM)

- Elastic scattering with off-shell massive partons Q+q(g)→Q+q(g)

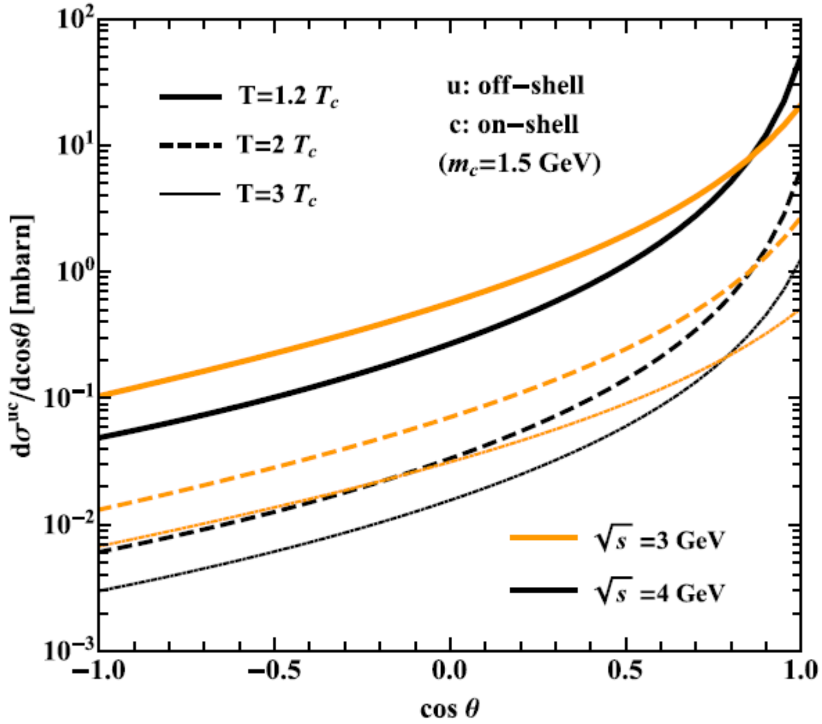


- massive gluon with a finite width is exchanged: it plays the role of the regulator which removes divergence

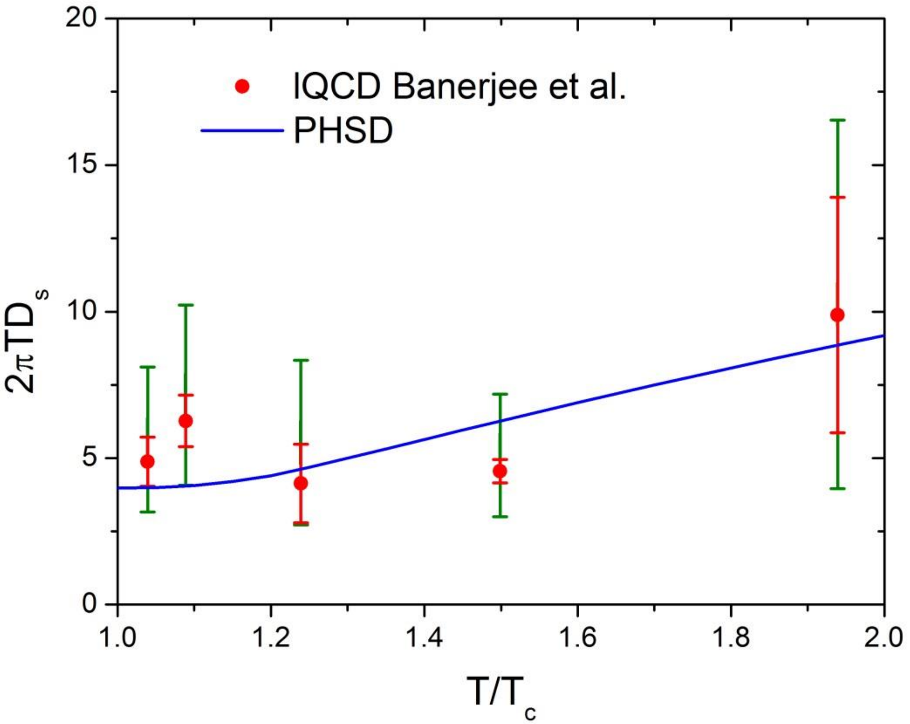


- scattering cross section rapidly increases near T_c due to g(T)

Massive quark/gluon→
less number of scattering,
but less forward scattering,
compared to massless pQCD



the scattering cross sections are multiplied by 2 in PHSD

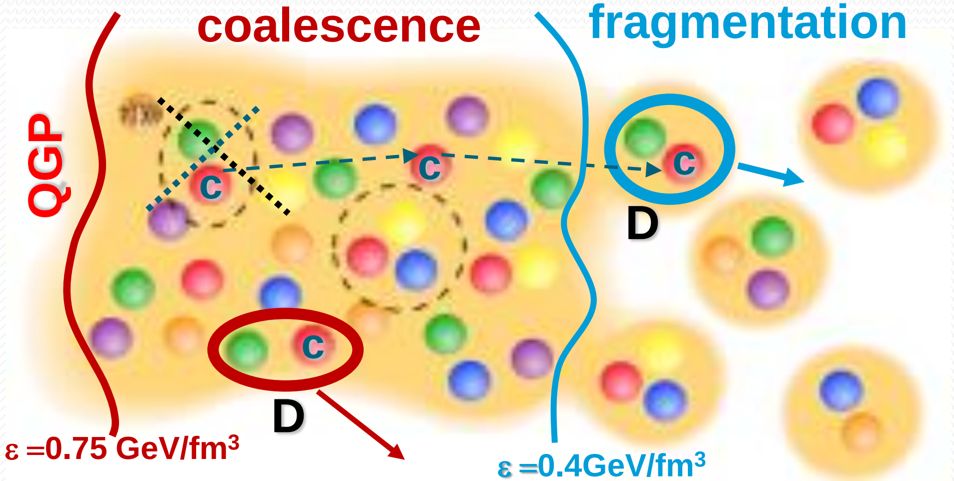


Hadronization of charm quark in HIC

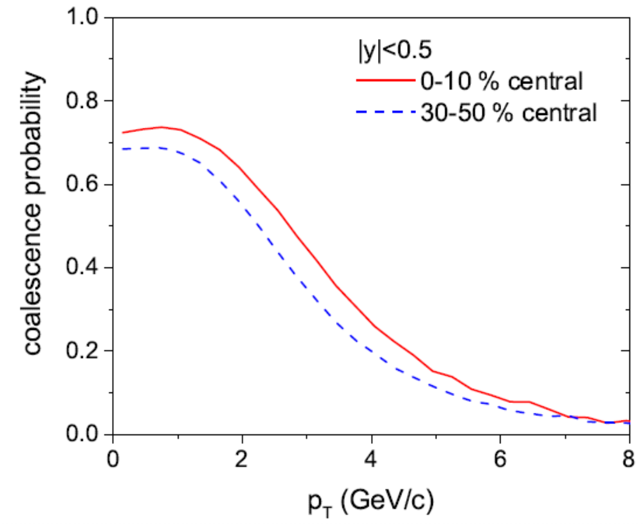
- Coalescence probability

$$f(\boldsymbol{\rho}, \mathbf{k}_\rho) = \frac{8g_M}{6^2} \exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2} - \mathbf{k}_\rho^2 \delta^2\right]$$

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2), \quad \mathbf{k}_\rho = \sqrt{2}\,\frac{m_2\mathbf{k}_1 - m_1\mathbf{k}_2}{m_1 + m_2}$$



Coalescence probability in Pb+Pb at 2.76 TeV



Hadronic scattering of D mesons

1. **D-meson scattering with mesons**

Model: effective Lagrangian approach with heavy-quark spin symmetry

L. M. Abreu, D. Cabrera, F. J. Llanes-Estrada, J. M. Torres-Rincon, Annals Phys. 326, 2737 (2011)

Interaction of D=(D^0,D^+,D^+_s) and D*=(D^{*0},D^{*+},D^{*+}_s) with octet (π,K,Kbar,η) :

$$\begin{aligned}\mathcal{L}_{LO} &= \langle \nabla^\mu D \nabla_\mu D^\dagger \rangle - m_D^2 \langle D D^\dagger \rangle - \langle \nabla^\mu D^{*\nu} \nabla_\mu D^{*\dagger}_\nu \rangle \\ &+ m_D^2 \langle D^{*\mu} D^{*\dagger}_\mu \rangle + ig \langle D^{*\mu} u_\mu D^\dagger - D u^\mu D^{*\dagger}_\mu \rangle \\ &+ \frac{g}{2m_D} \langle D^*_\mu u_\alpha \nabla_\beta D^{*\dagger}_\nu - \nabla_\beta D^*_\mu u_\alpha D^{*\dagger}_\nu \rangle \epsilon^{\mu\nu\alpha\beta}\end{aligned}$$

$$u_\mu = i\left(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger\right)$$

$$U = u^2 = \exp\left(\frac{\sqrt{2} i \Phi}{f}\right)$$

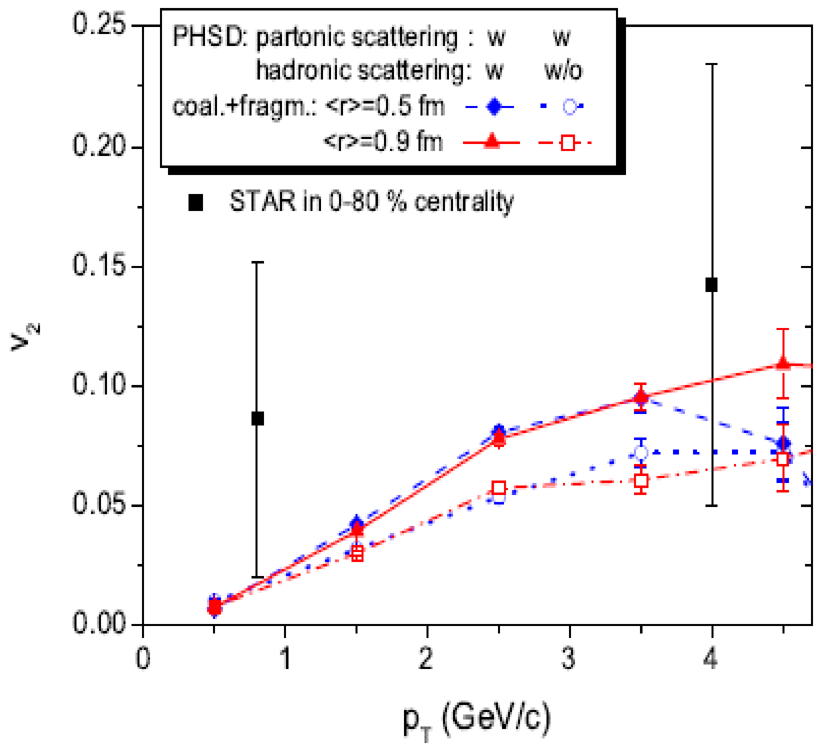
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

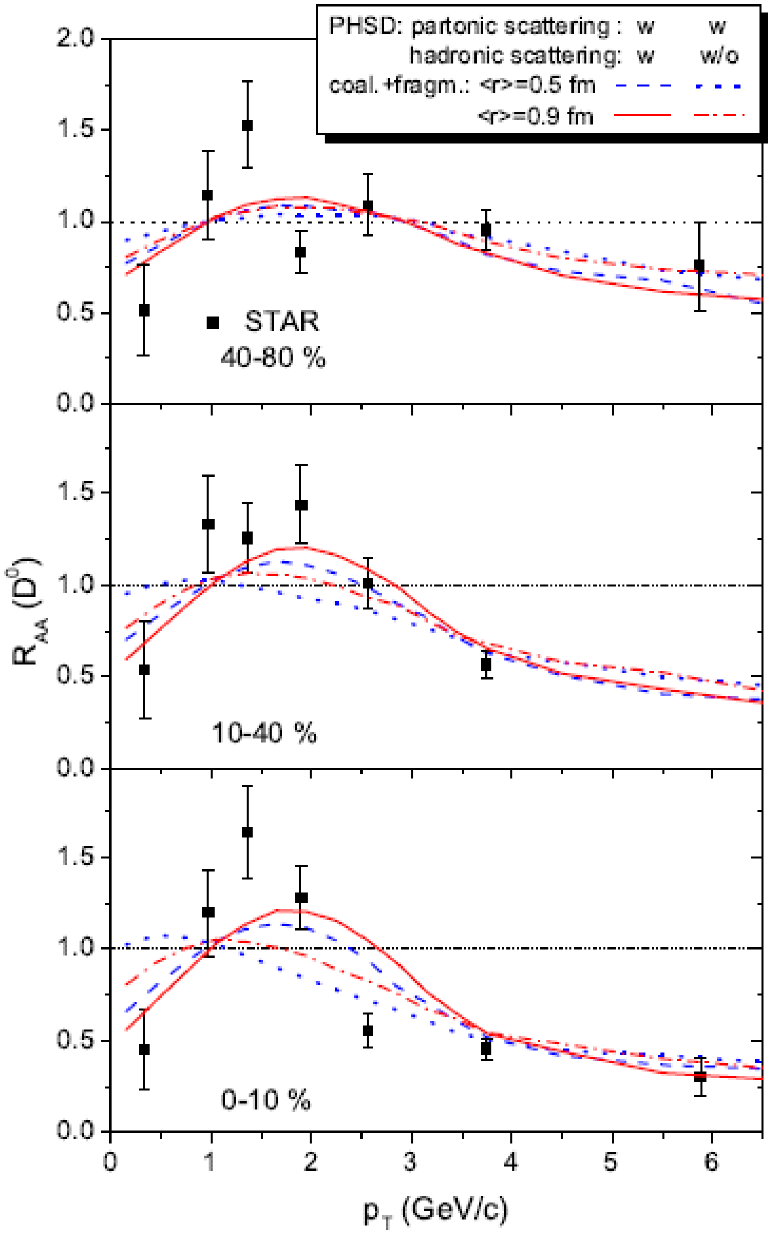
2. **D-meson scattering with baryons**

Model: G-matrix approach: interactions of D=(D^0,D^+,D^+_s) and D*=(D^{*0},D^{*+},D^{*+}_s) with nucleon octet $J^P=1/2^+$ and Delta decuplet $J^P=3/2^+$

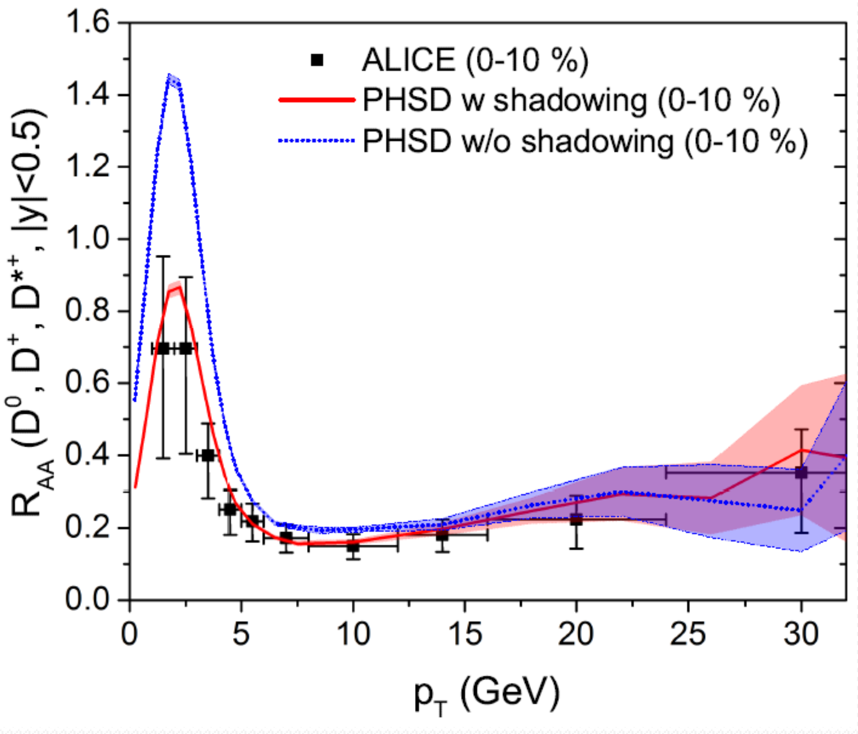
C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, L. Tolos, Phys. Rev. D 87, 074034 (2013)

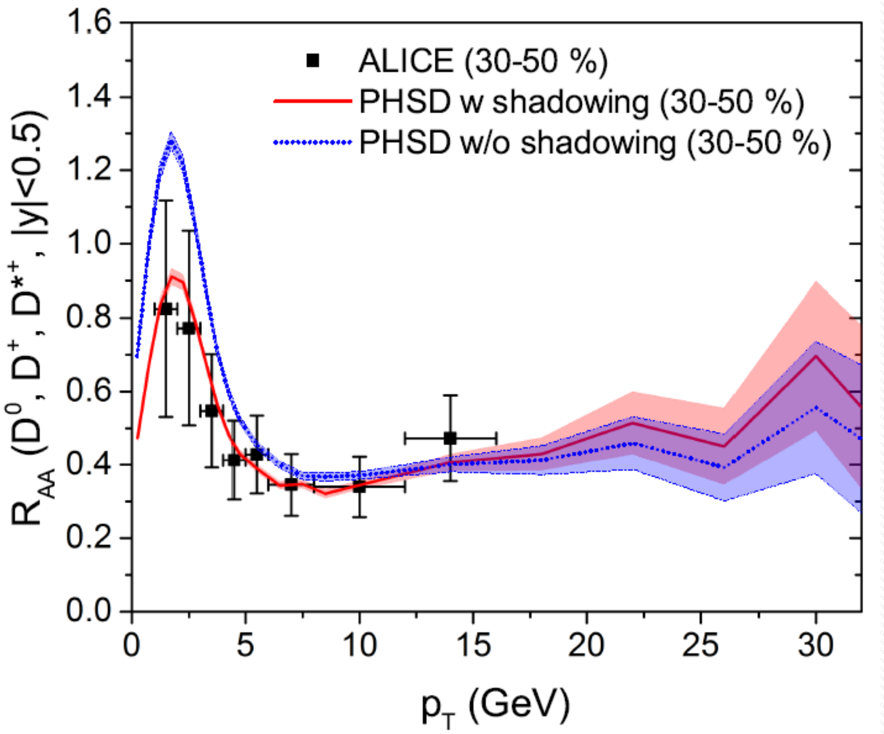
Results at RHIC





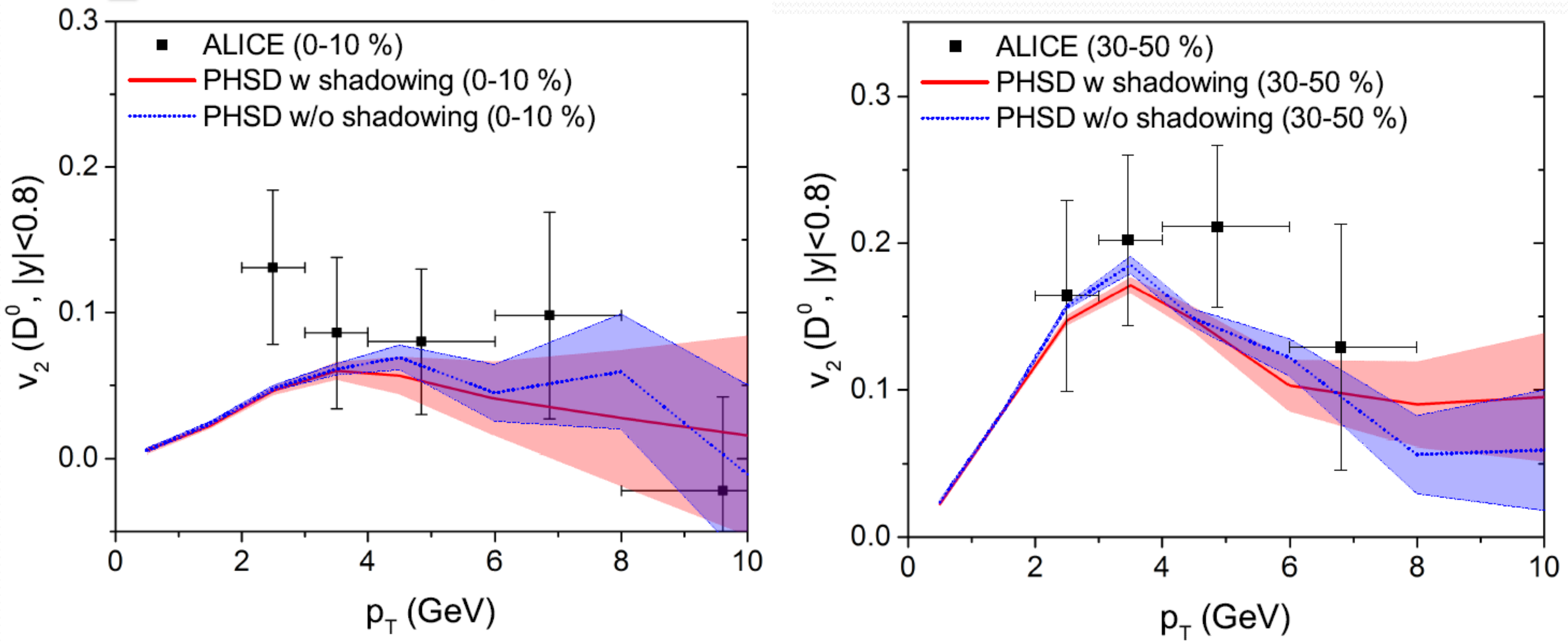
R_{AA} at LHC (2.76 TeV)





- Shadowing effect is important
- It suppresses the low p_T and slightly enhances the high p_T part of R_{AA}

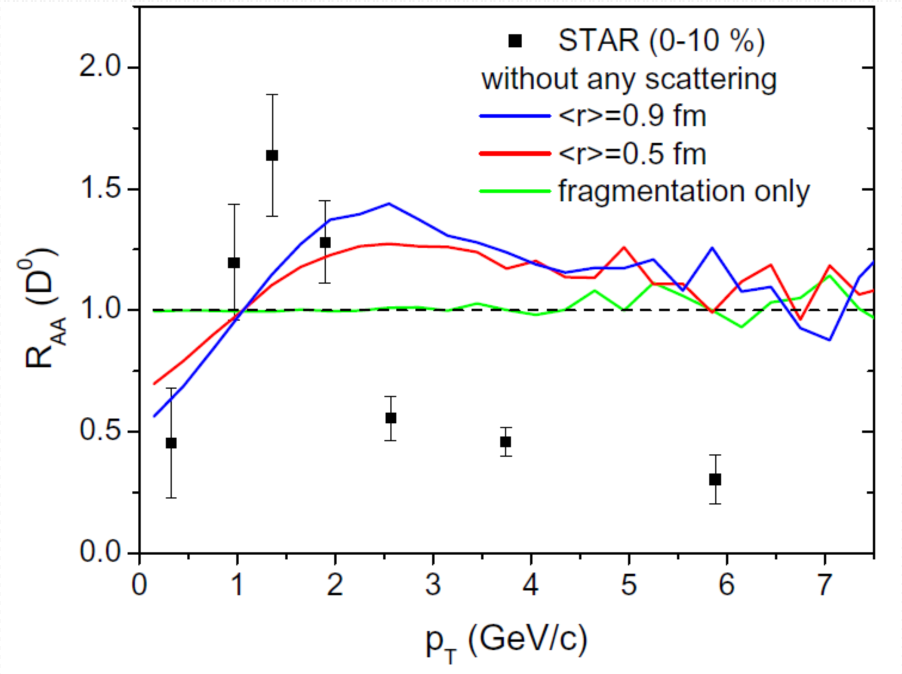
v_2 at LHC (2.76 TeV)



- **Shadowing effect has small impact on v_2**

How to be hadronized is important!
(coalescence vs fragmentation)

without any rescattering (partonic and hadronic)



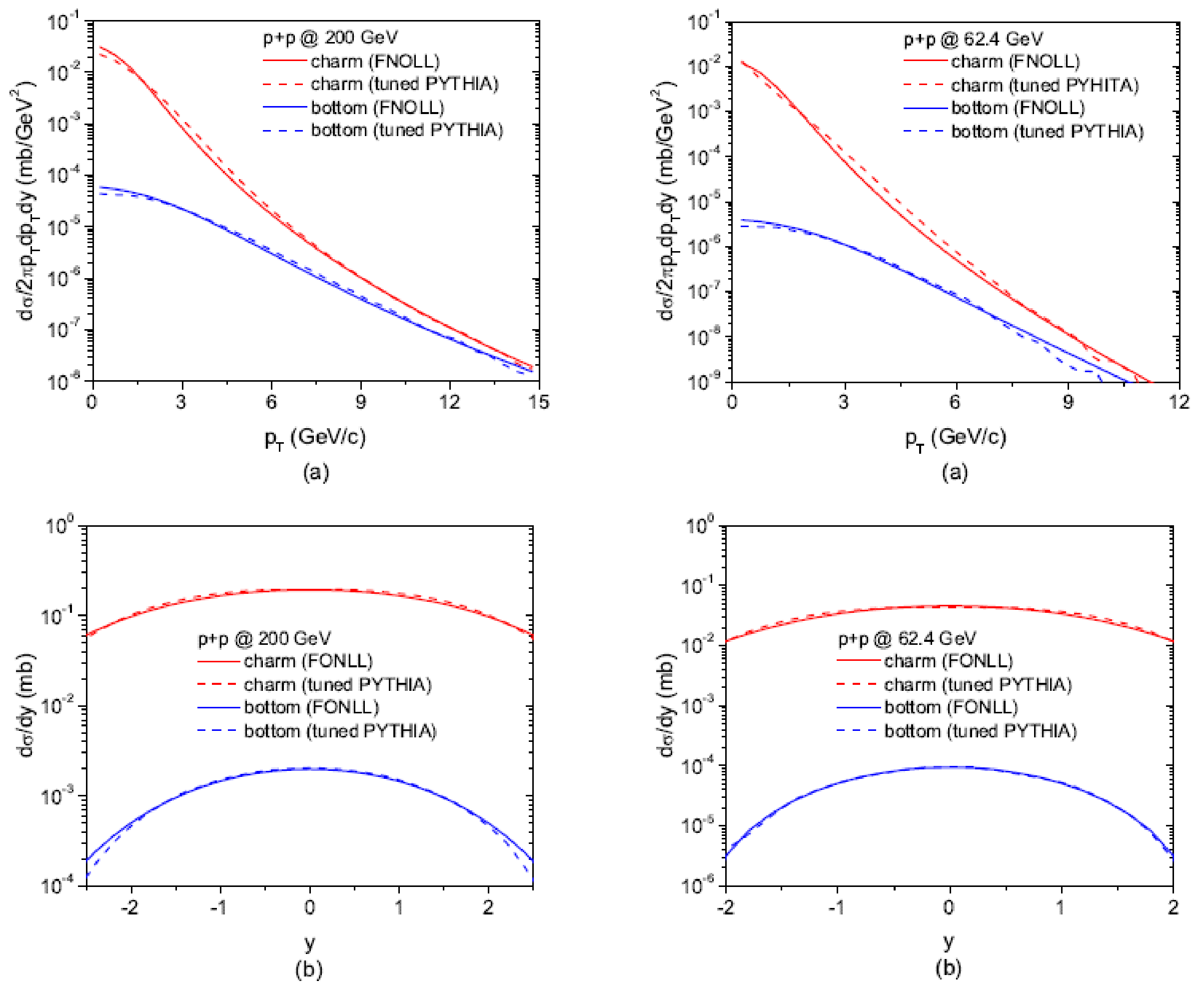
- **Hadronization by fragmentation only (as in pp) → R_{AA}=1**
- **Coalescence (not in pp!) shifts R_{AA} to larger p_T → ‚nuclear matter‘ effect**

4. Single electron production in HIC

(both charm and bottom contribute)

Charm & bottom production in p+p
(tuned Pythia vs. FONLL)

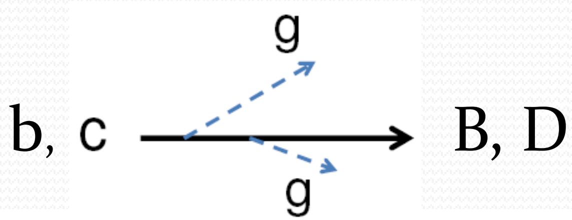
200 GeV
c (red)
b (blue)

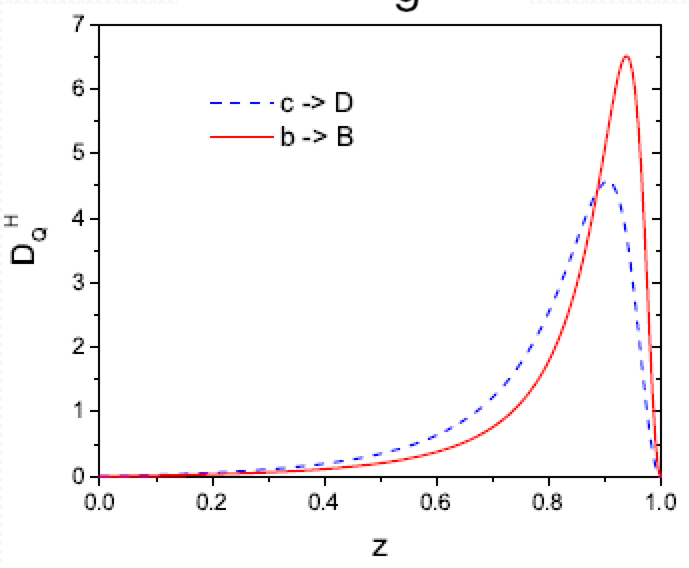


62.4 GeV
c (red)
b (blue)

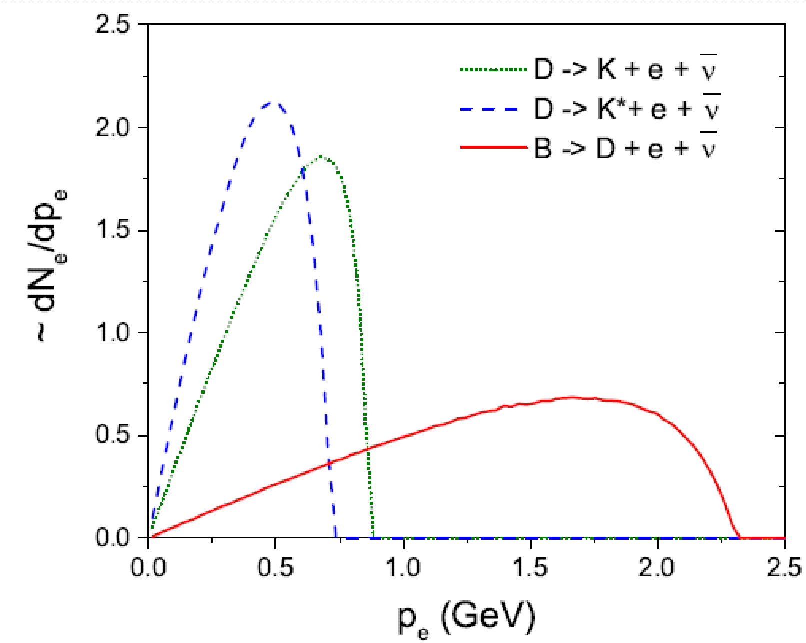
Fragmentation & semileptonic decay

- By using the same Peterson's fragmentation function

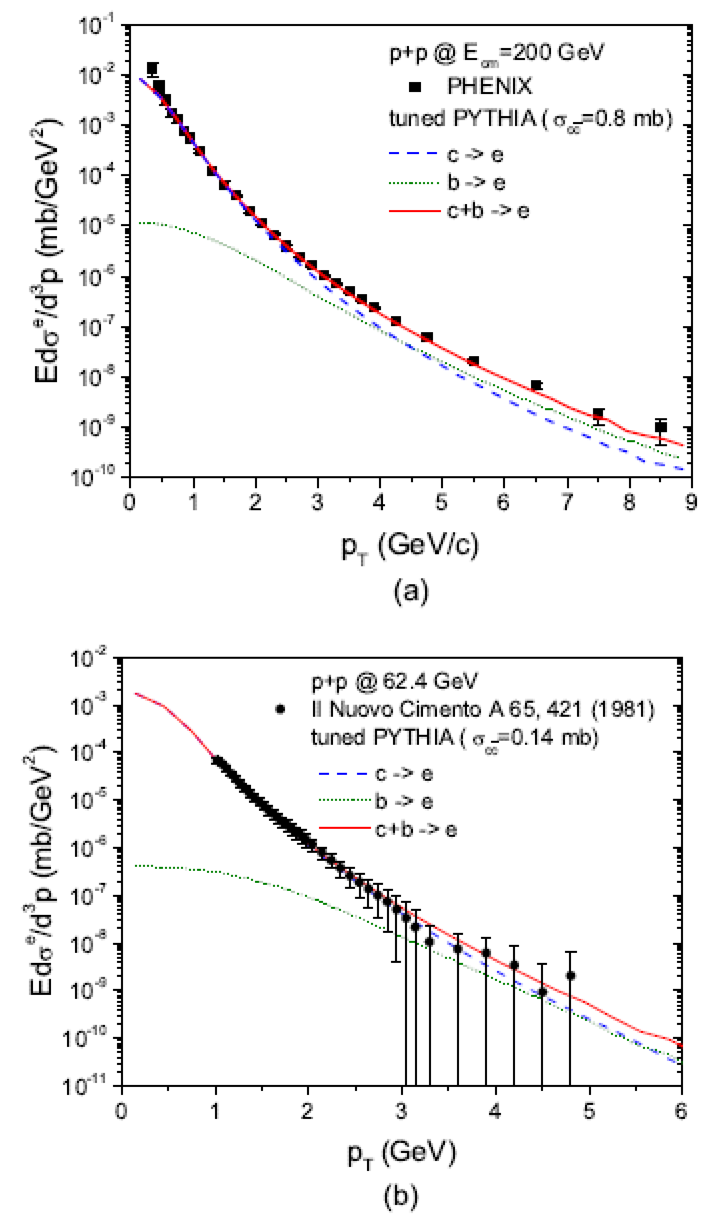




- $D \rightarrow K + e + \bar{\upsilon}_e$
- $B \rightarrow D + e + \bar{\upsilon}_e$
- Assuming constant transition amplitude,

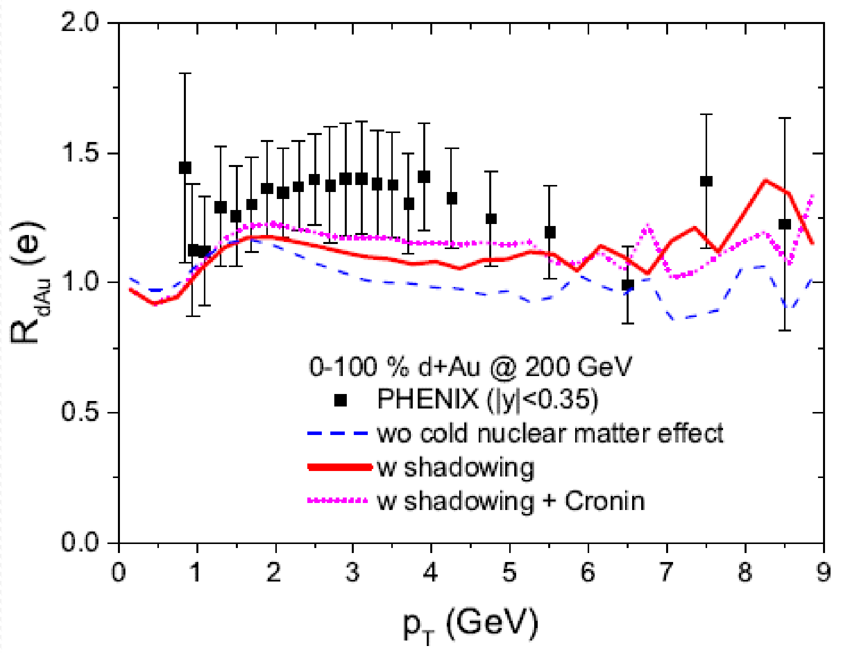


Comparison with experimental data in p+p @ 62.4 and 200 GeV

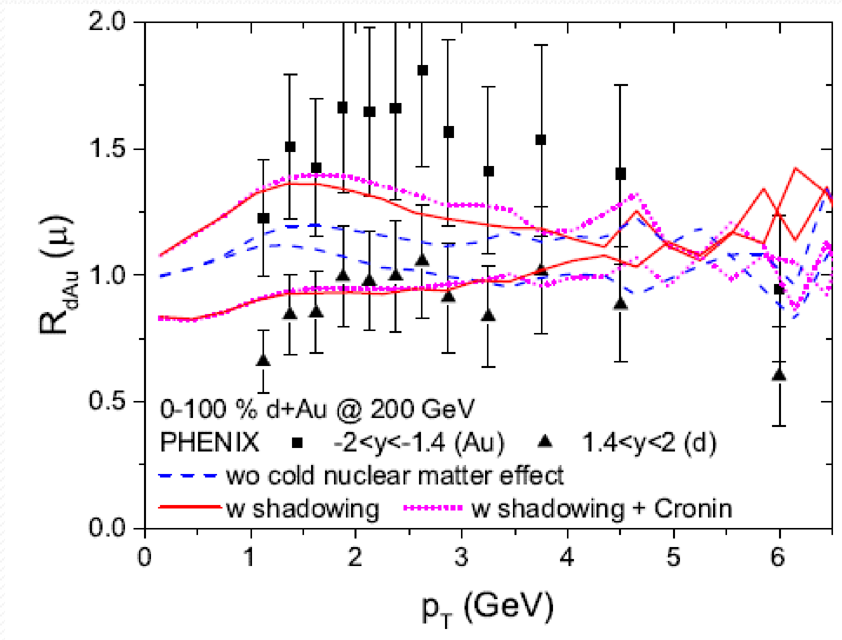


Cold nuclear matter effects (d+Au)

Mid-rapidity (e)

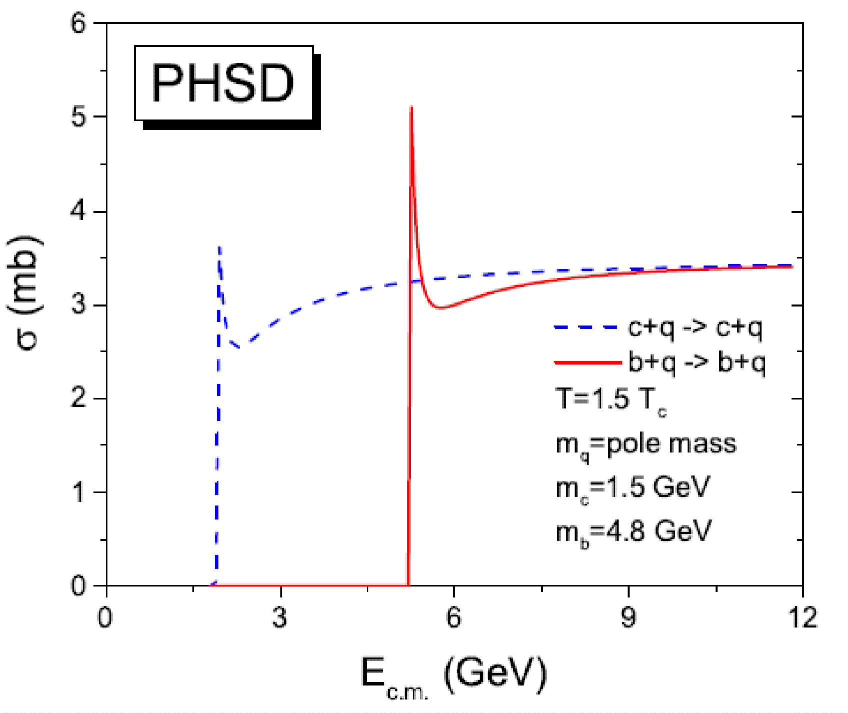


Forward/backward-rapidites (μ)

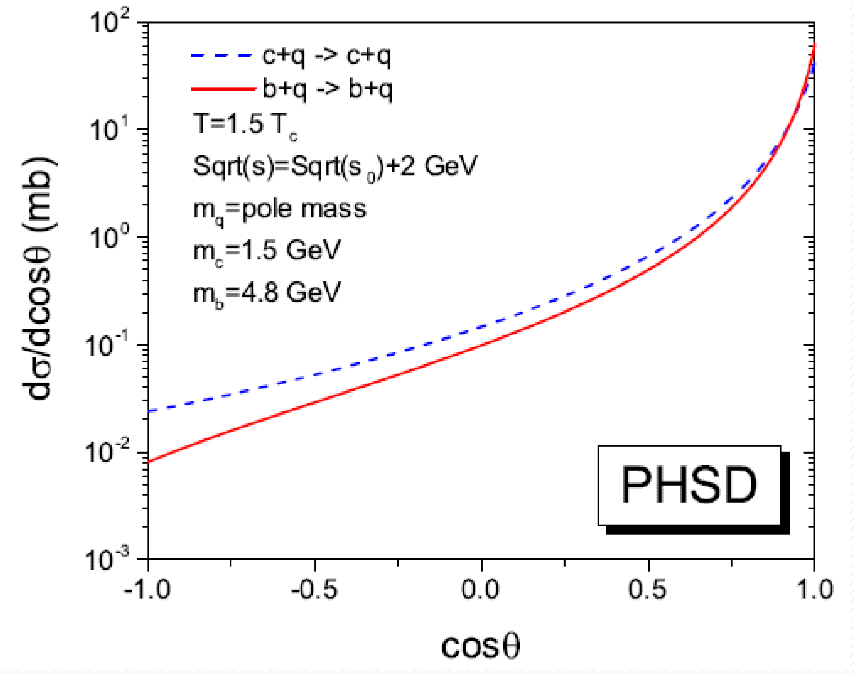


Charm & bottom quark interactions in QGP

Total cross sections

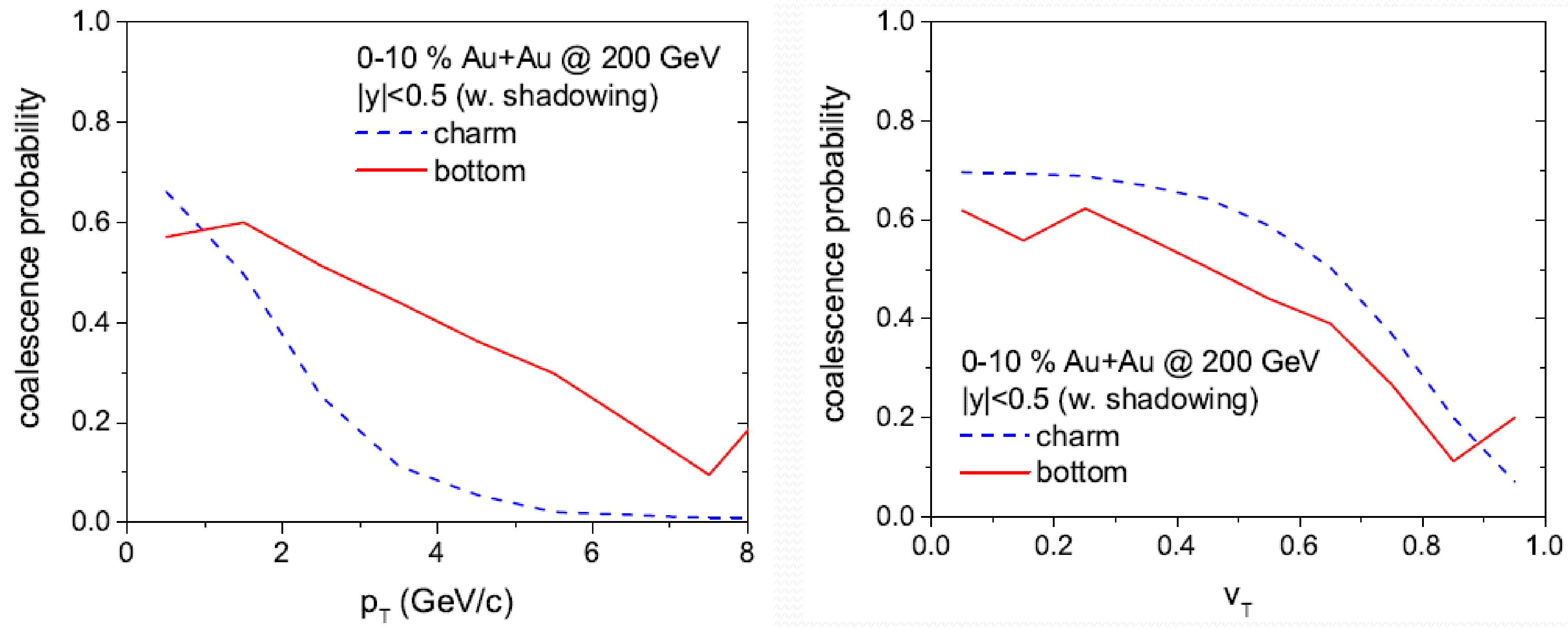


Differential cross sections



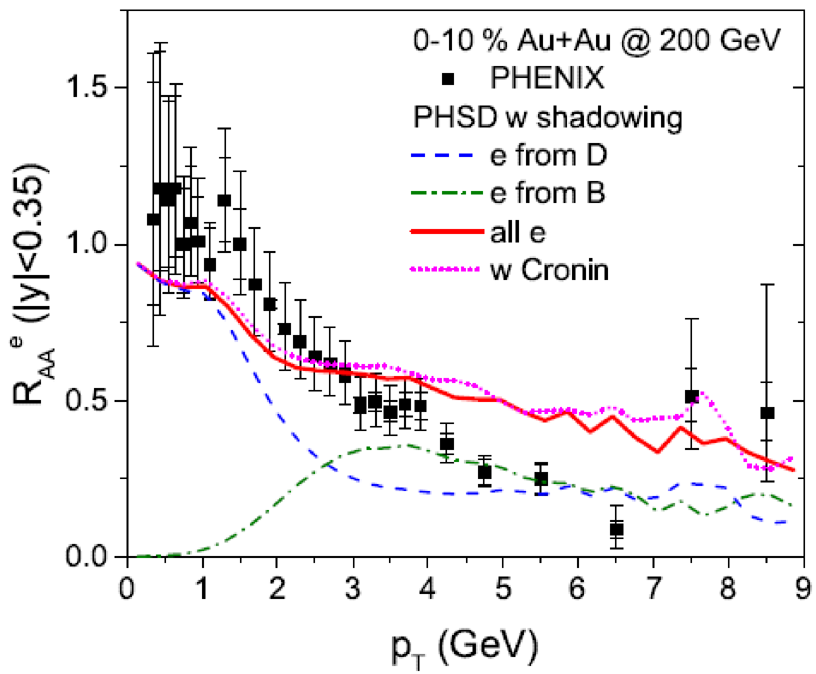
Total cross sections are similar, but bottom cross section is more highly forward peaked, because it is heavier.

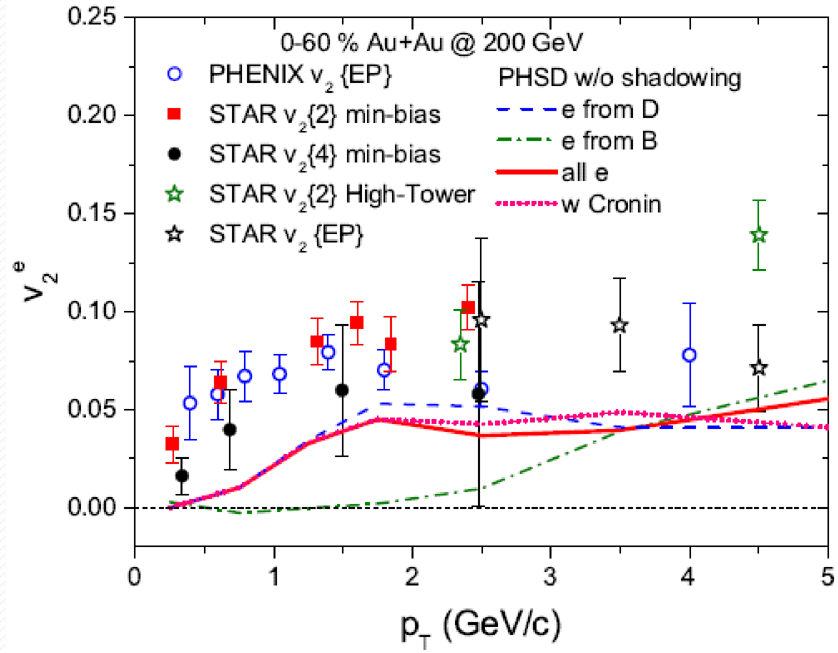
Hadronization of c and b quarks



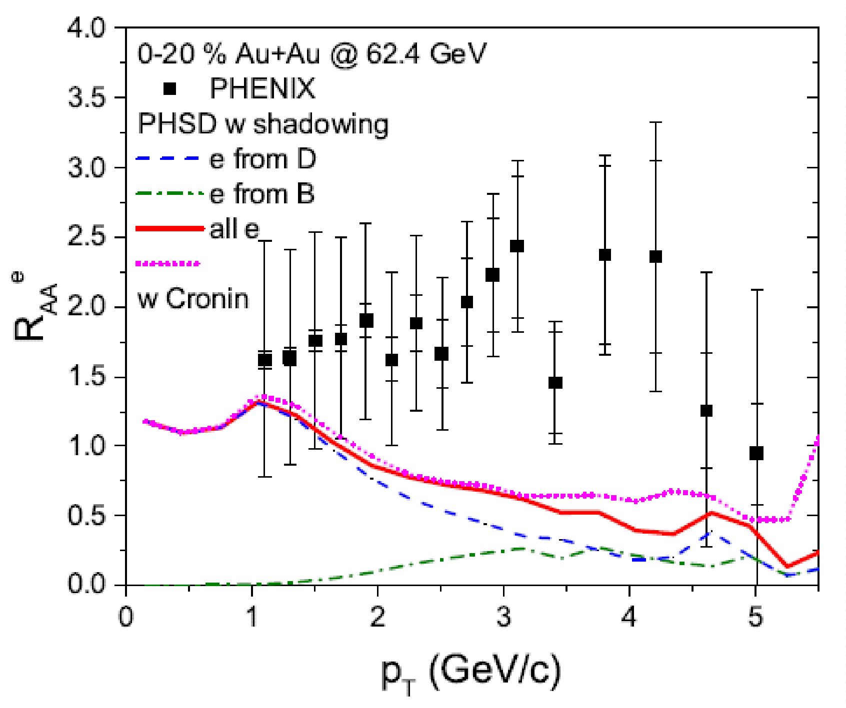
Coalescence probability of bottom seems larger at high pt, but it becomes similar expressed in term of transverse velocity.

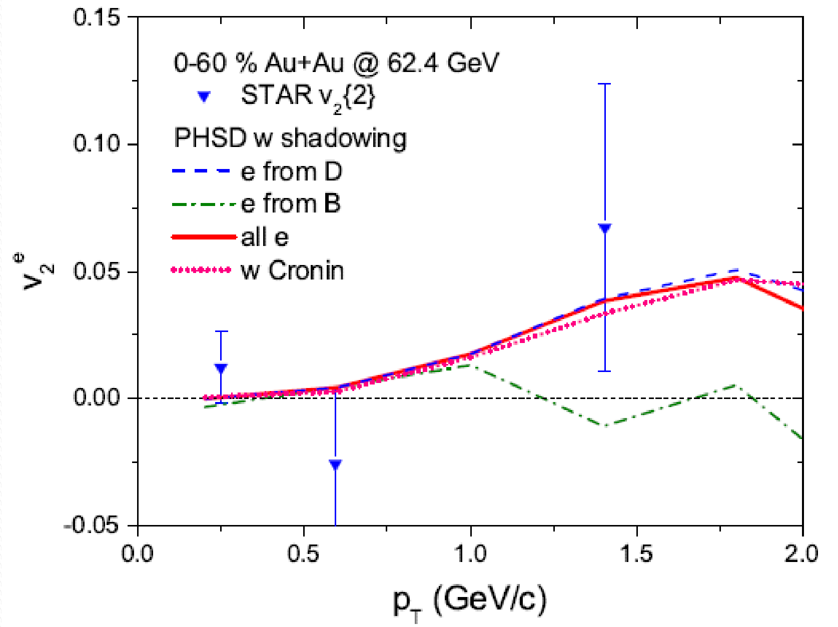
Comparison with Exp. data at 200 GeV





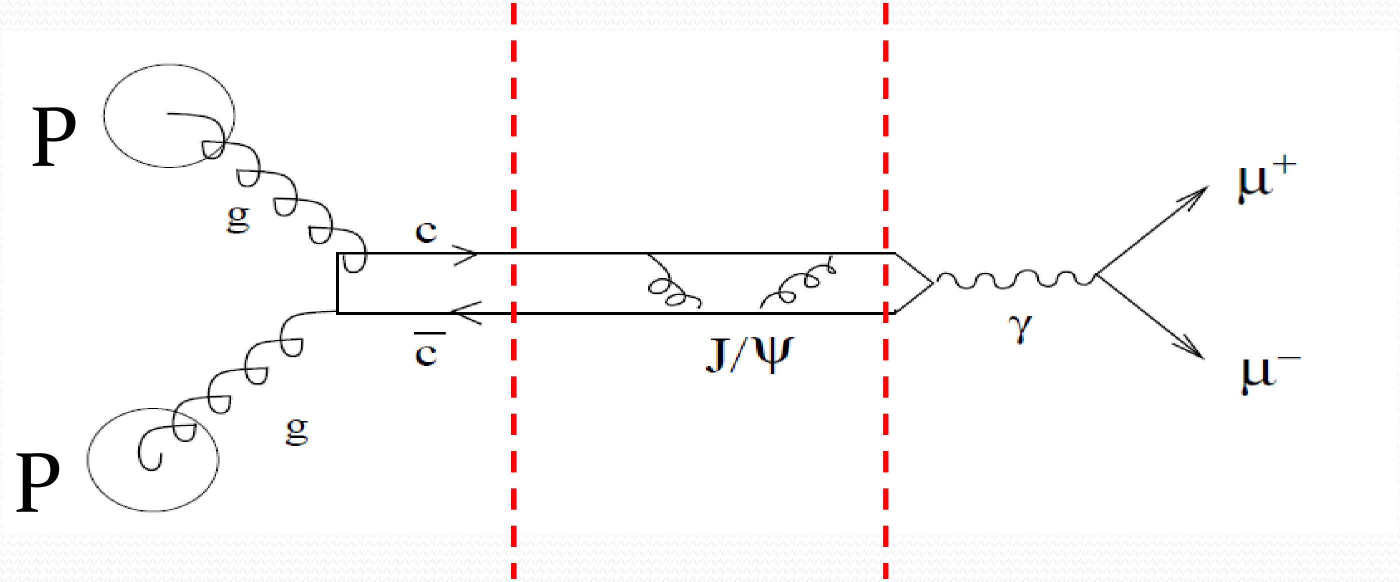
Comparison with Exp. data at 62.4 GeV





5. J/ψ production in HIC (in progress)

J/ψ production in p+p collisions



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

models

- **Color singlet model**

Only charm pair with the same quantum number as a charmonium can form a bound state

- **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**

Sudden approximation

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

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

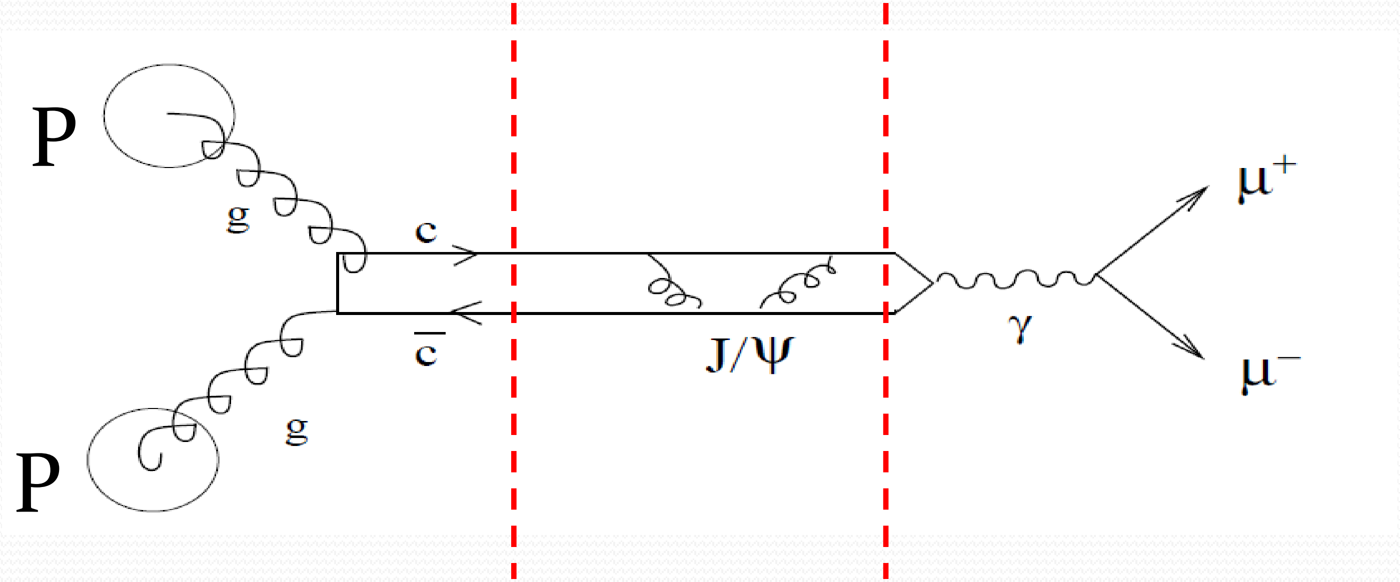
$$\Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}\left(\frac{r^2}{\sigma^2}-\frac{3}{2}+\sigma^2 p^2\right) \times \exp\left[-\frac{r^2}{\sigma^2}-\sigma^2 p^2\right],$$

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

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

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

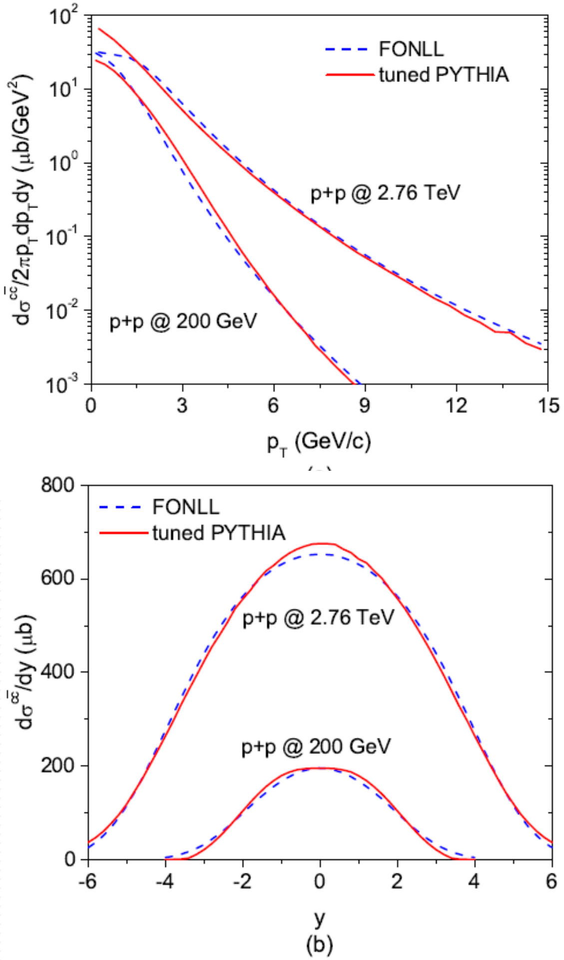
J/ψ production in p+p collisions



PYTHIA event generator

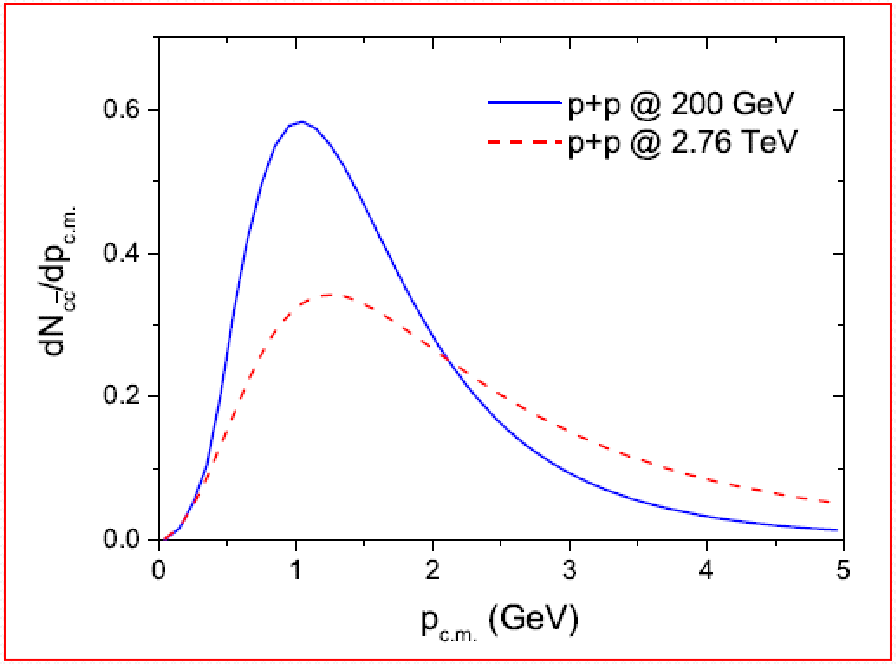
Wigner projection

Charm from PYTHIA after tuning

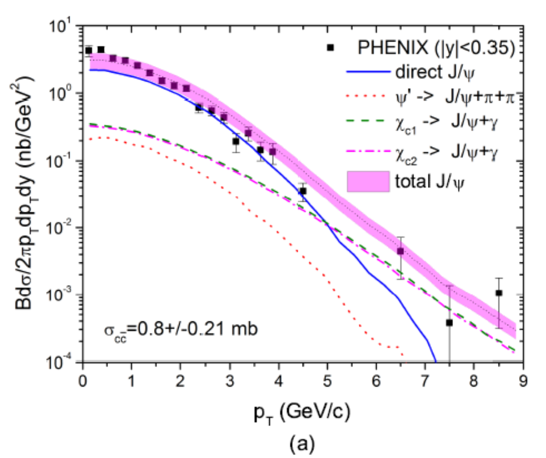


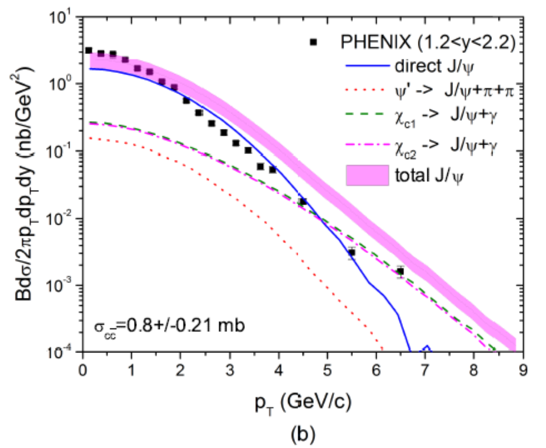
in good agreement with FONLL calculations at RHIC and LHC

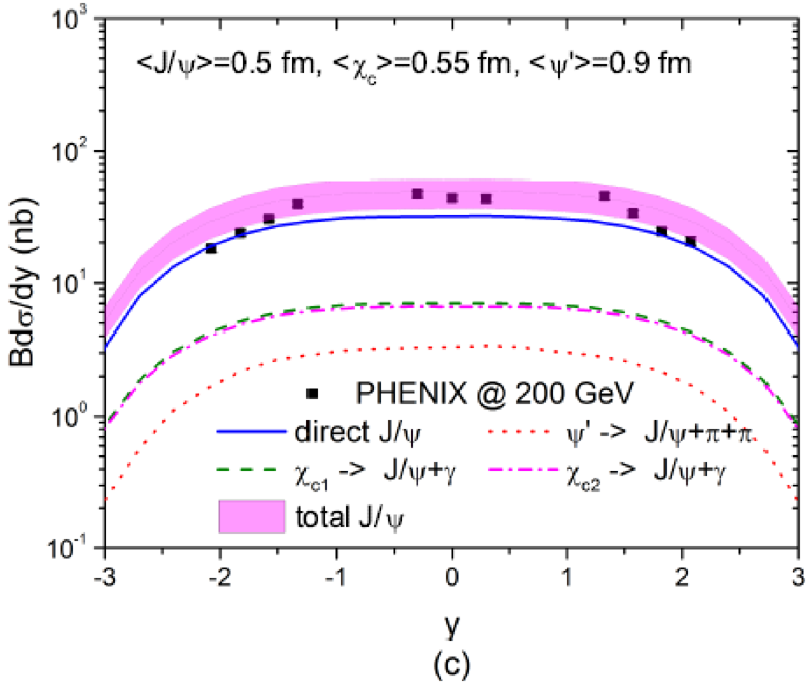
Relative momentum distribution in c.m. frame



Comparison with PHENIX data



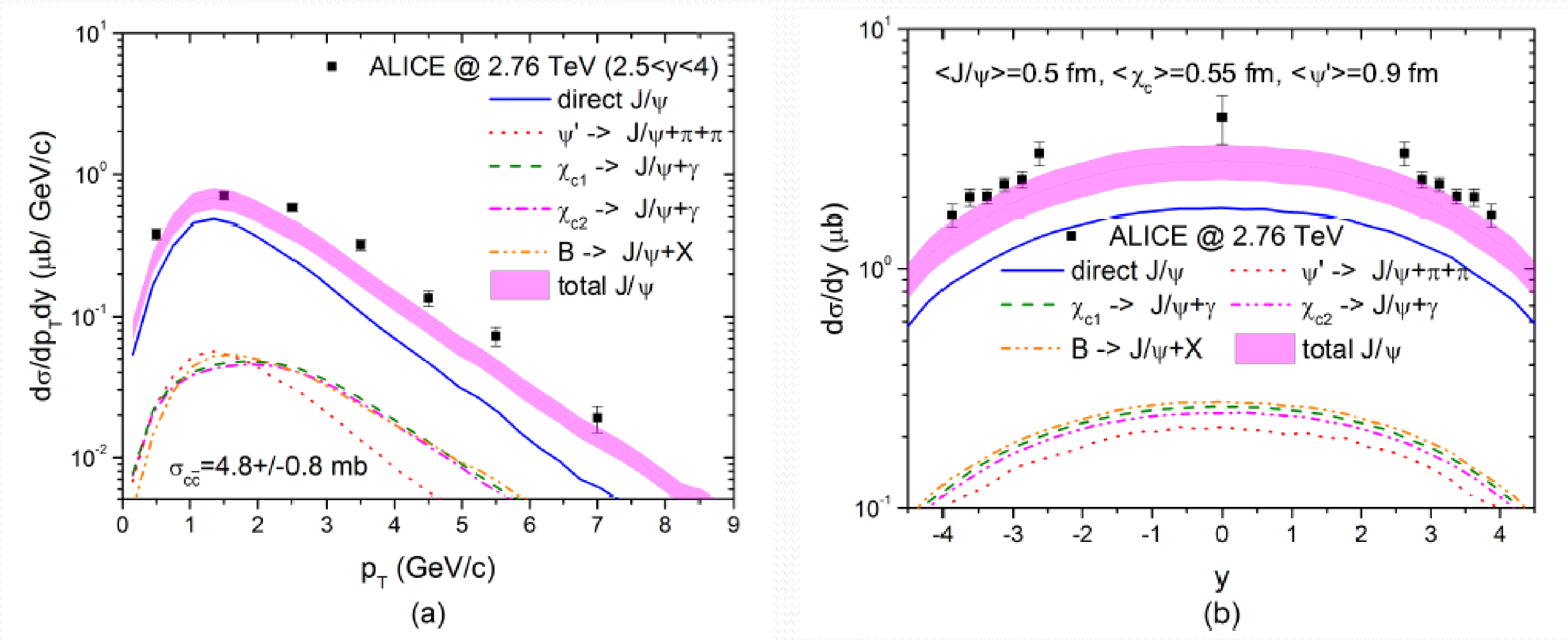




Only paramters:
$r_{J/\psi} = 0.5\ fm\ , r_{\chi c} = 0.55\ fm, r_{\psi'} = 0.9\ fm$
similar to the radii from potential model

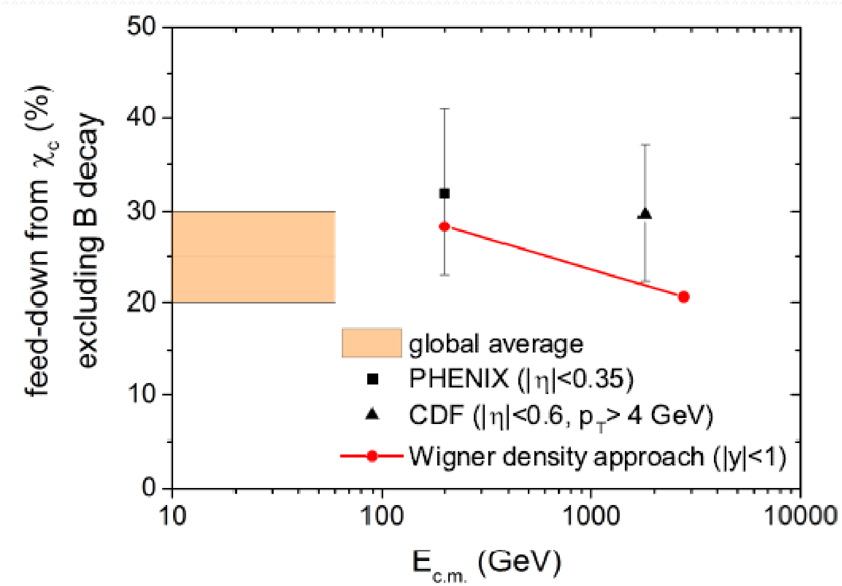
Comparison with ALICE data

we use the same charmonia radii as at RHIC

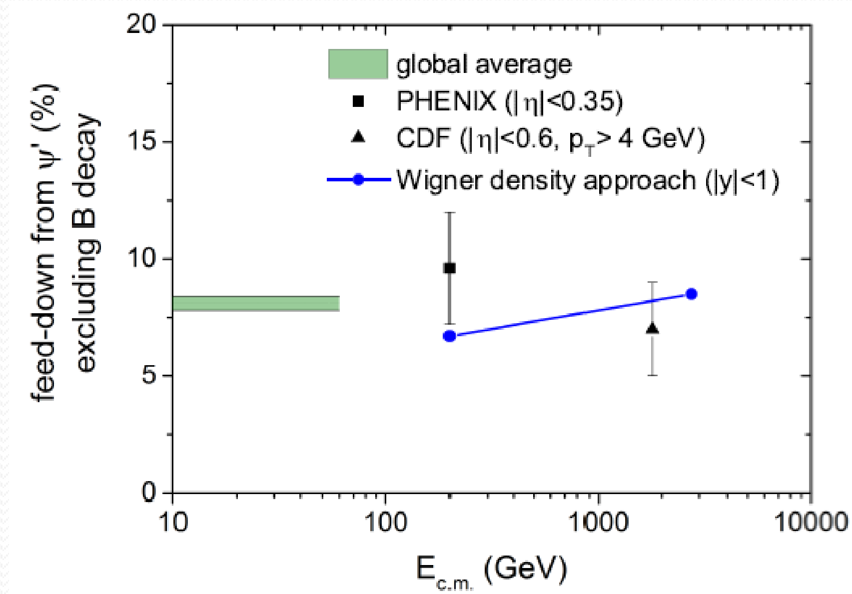


Feed-down from excited charmonia

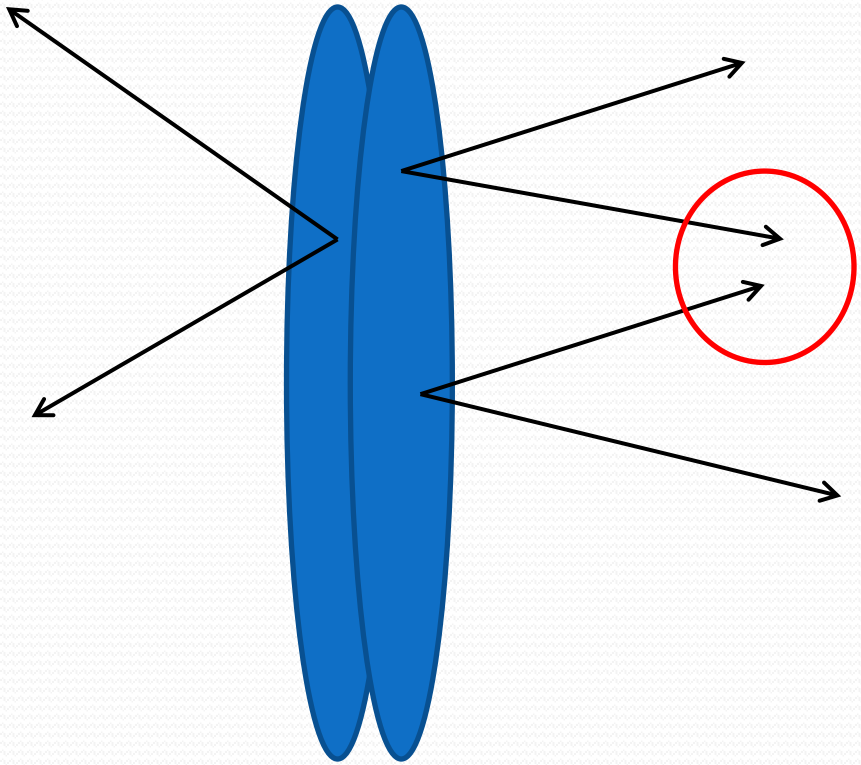
χc→J/ψ+γ



ψ'→J/ψ+π+π

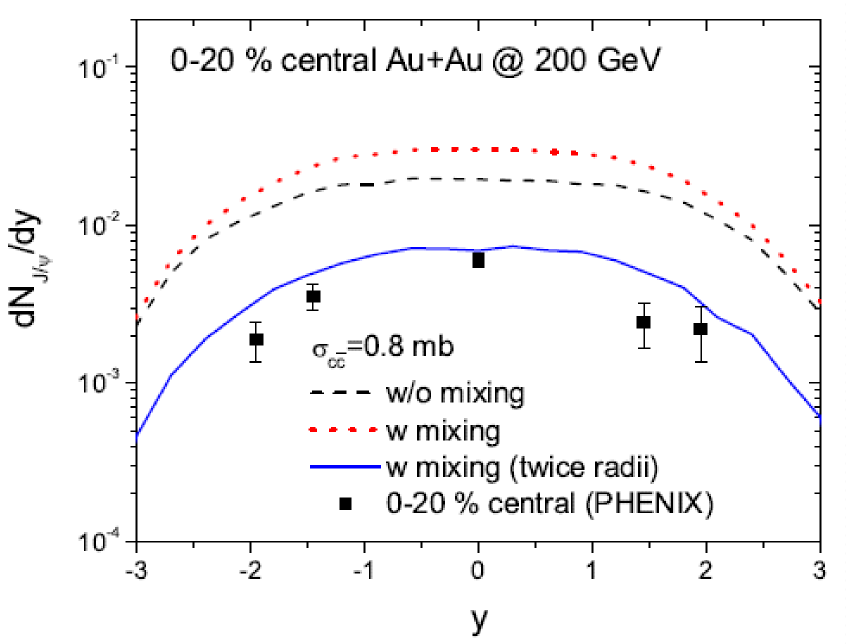


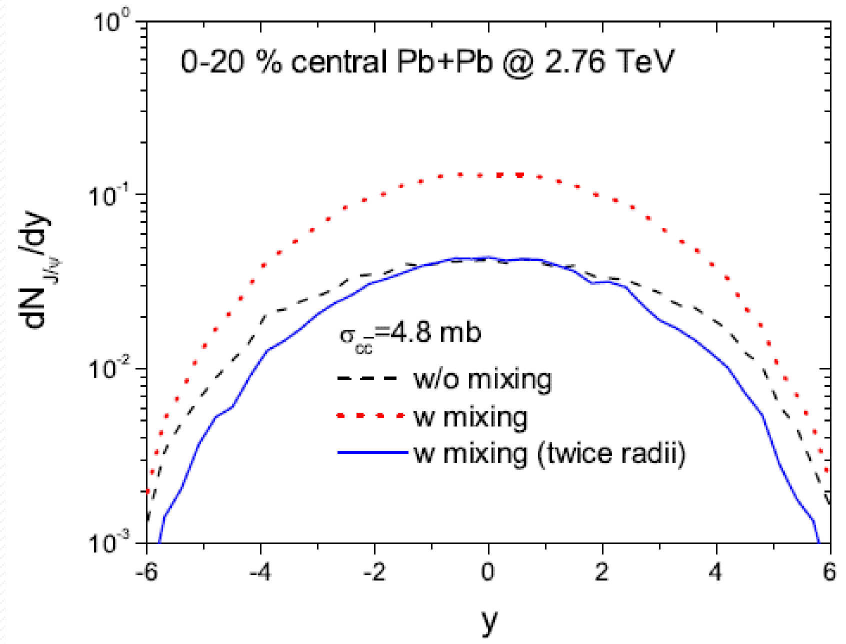
In relativistic heavy-ion collisions



- (without considering the shadowing effect)
- About **20 pairs** of charm and **120 pairs** of charm are produced in a small volume in central heavy-ion collisions at RHIC and LHC, respectively.
- There might be mixing between two different charm pairs in charmonium formation.

Without any nuclear matter effect





1. Charmonium production from two different charm quark pairs enhances total J/ψ
2. According to lattice QCD, the radii of charmonia increase (weakly binding) at high T. It suppresses total J/ψ

To be more realistic

- Charm quarks strongly interact in the nuclear matter

(charm momentum-position and the formation times of charmonia might change)

- The existence of bound states in QGP?
- Cold nuclear matter effect (shadowing …)

6. summary

- Parton-Hadron-String Dynamics (PHSD) with heavy flavor works reasonably well from BES to LHC energies.
- In PHSD initial heavy quarks are generated by PYTHIA and tuned to FONLL calculations.
- Cold nuclear matter (shadowing) effect is implemented by EPS09.
- In QGP, partonic scattering cross sections are calculated in the Dynamical Quasi-Particle Model (DQPM).
- Heavy flavor is hadronized through either coalescence or fragmentation.
- In HG, hadronic scattering cross sections are calculated in effective lagrangian with heavy quark spin symmetry.

- Quarkonium (J/ψ) production in p+p collisions can be described by the Wigner projection in space+momentum.
- The same method applied to HIC, J/ψ production is enhanced due to the dense population of ccbar pairs in a small volume even without any nuclear matter effect.
- Now it is in progress to take into account the nuclear matter effect.