Heavy flavor production in PHSD
(Parton-Hadron-String Dynamics)

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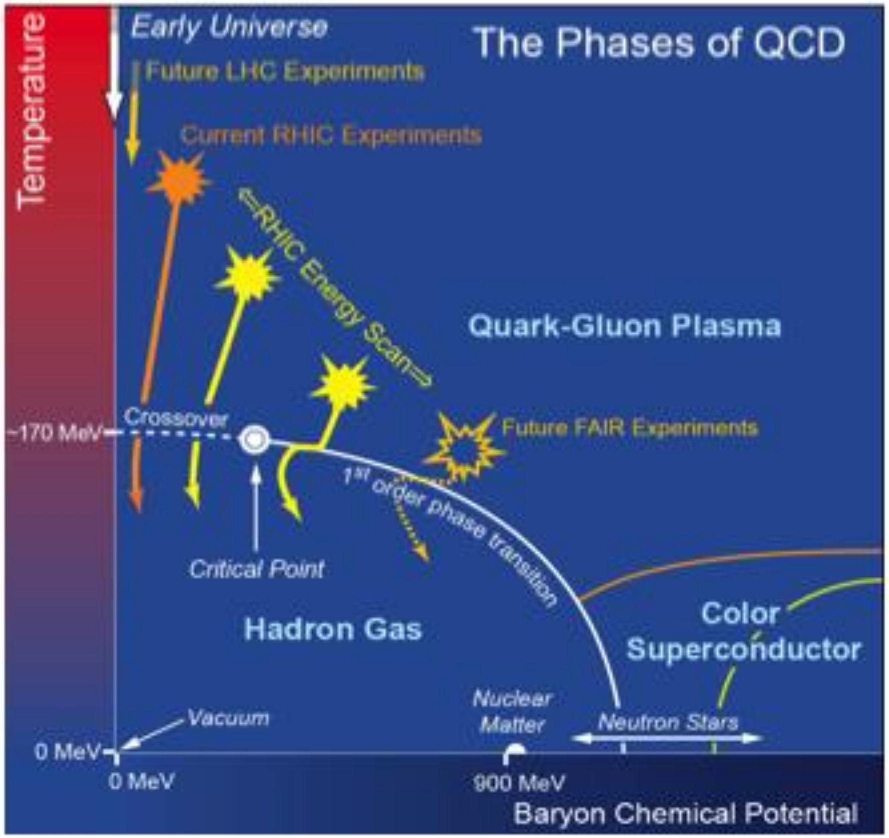
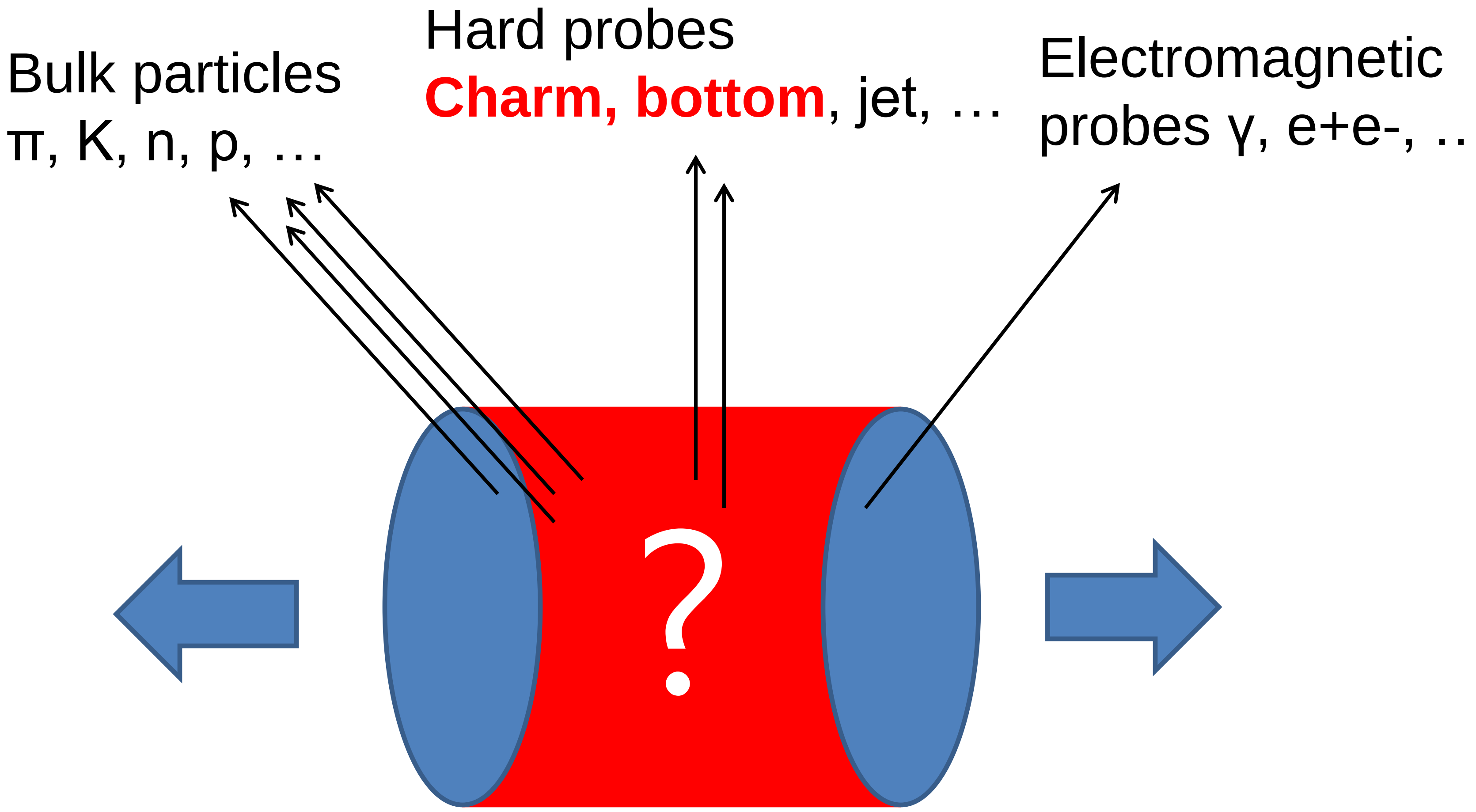
1. introduction

Relativistic heavy-ion collisions to produce a nuclear matter in extreme conditions



Hot dense nuclear matter produced in relativistic heavy-ion collisions

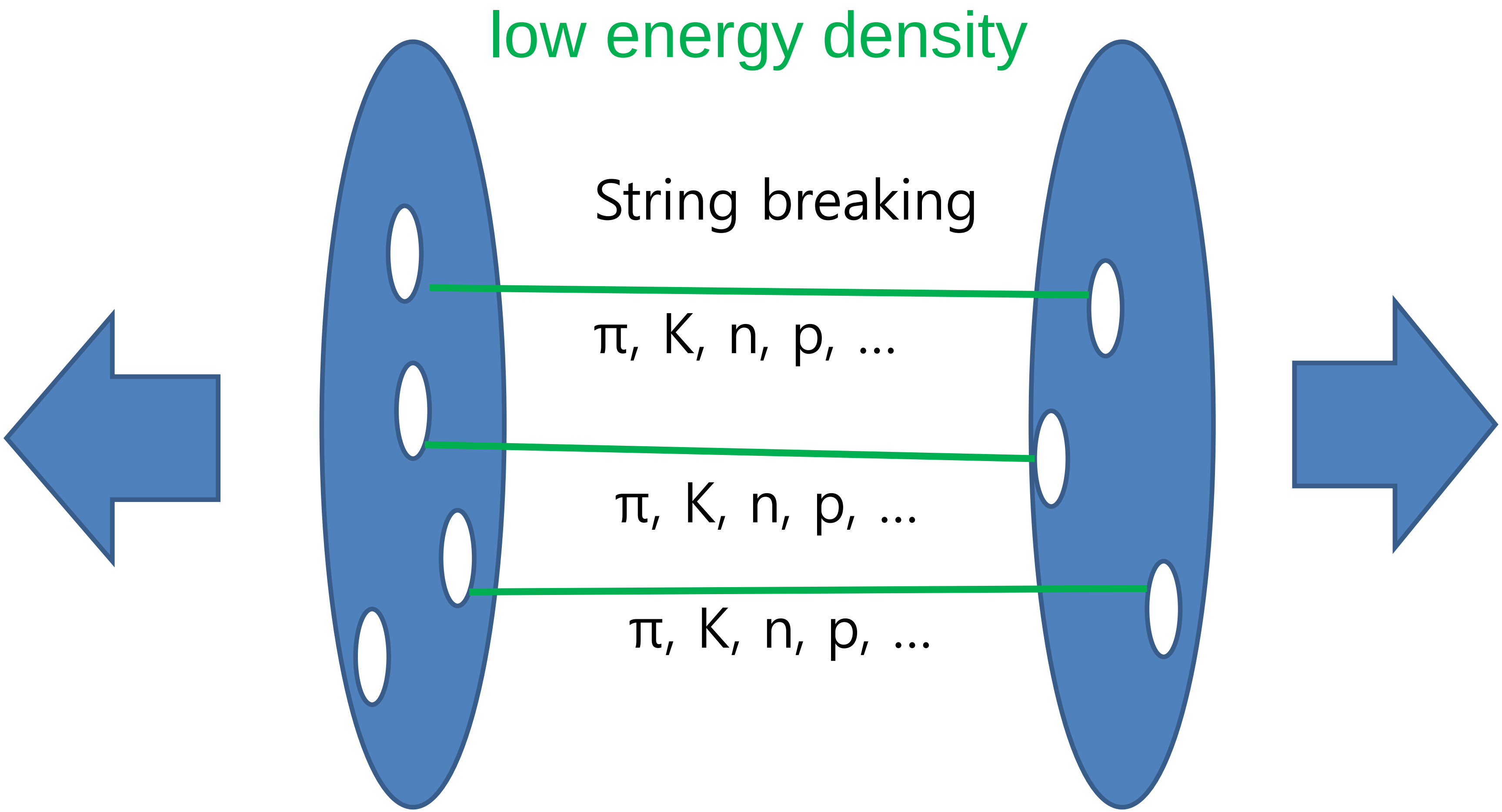


Some characteristics of heavy flavors

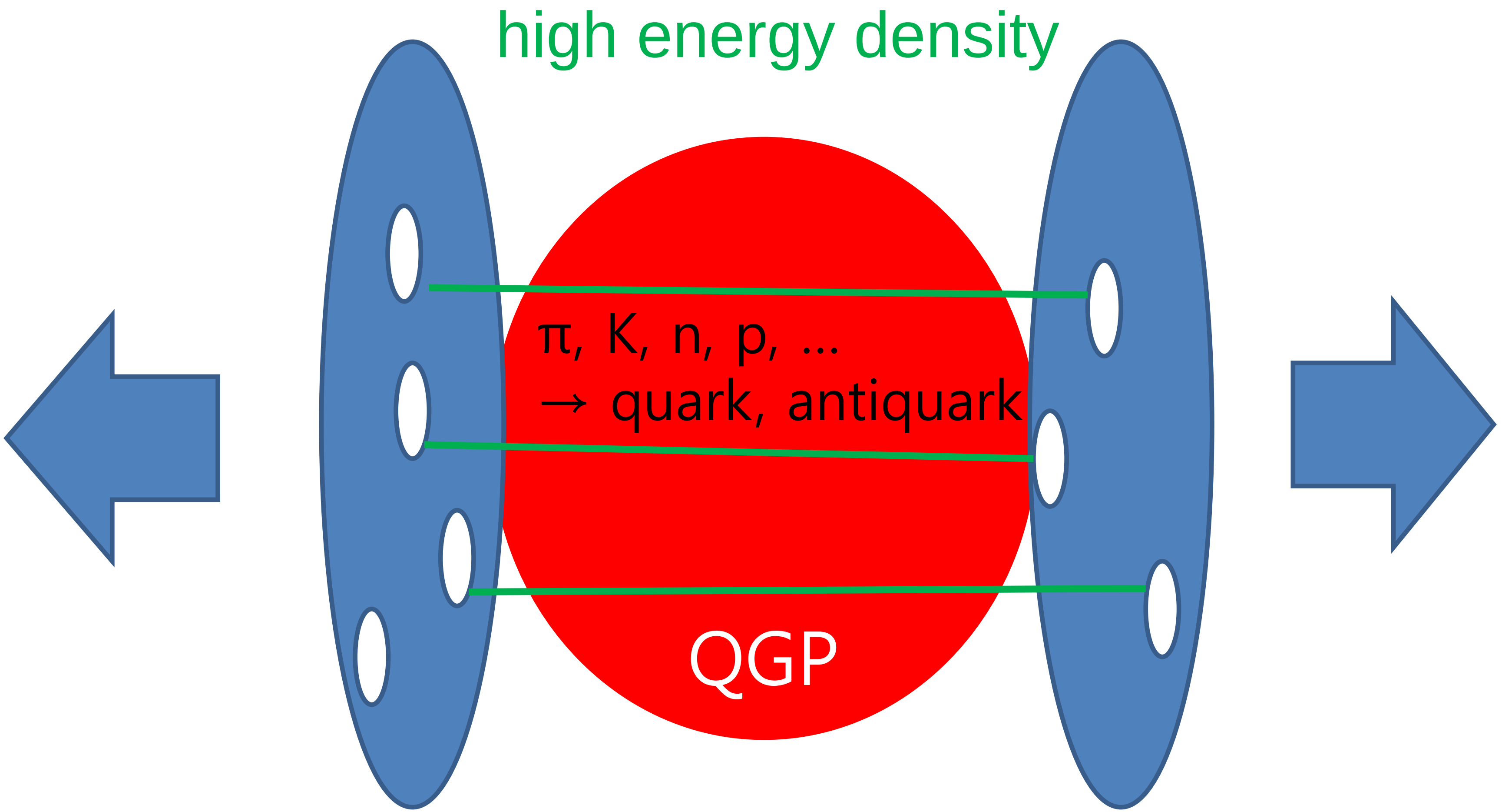
- Because they are heavy (m_c~1.5 GeV, m_b~5 GeV),
- large energy-momentum transfer is required for the production
- early produced in Ultra-relativistic heavy-ion collisions (URHIC)
- pQCD is applicable
- incomplete thermalization in URHIC
- …

2. Parton-Hadron-String Dynamics (PHSD)

String fragmentation



String melt into partons



Dynamical Quasi-Particle Model (DQPM)

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

- 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:

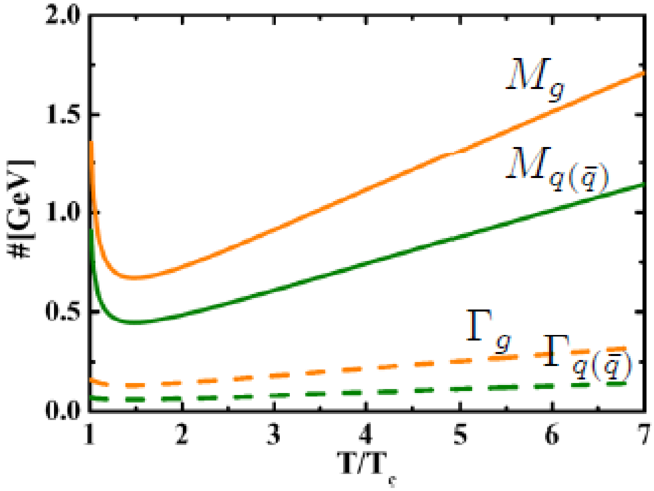
mass: $M^2_{q(\bar{q})}(T) = \frac{N_c^2-1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2} \right)$

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

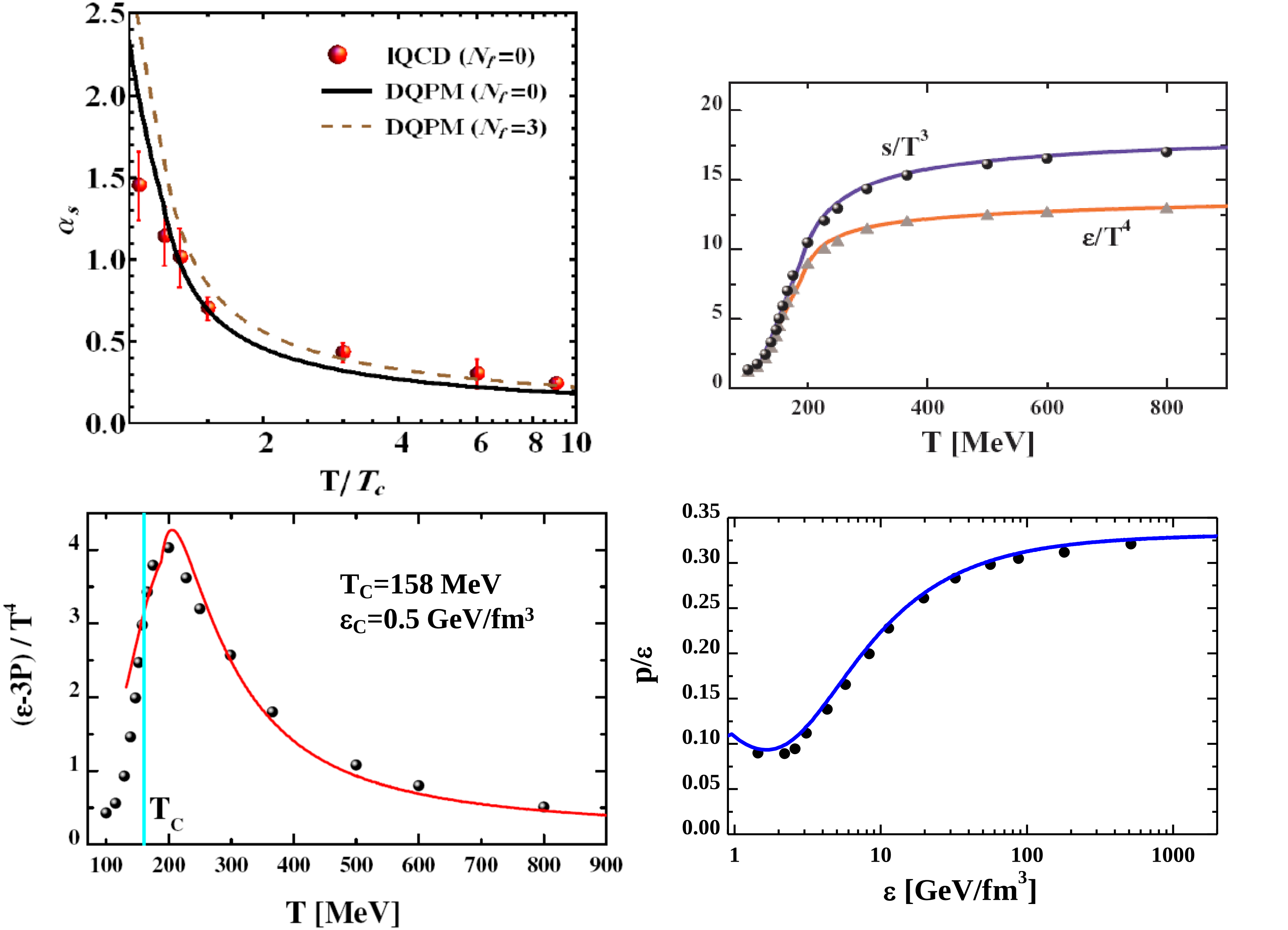
width: $\Gamma_g(T) = \frac{1}{3} N_c \frac{g^2 T}{8\pi} \ln\left(\frac{2c}{g^2} + 1 \right)$



$N_c = 3, N_f=3$

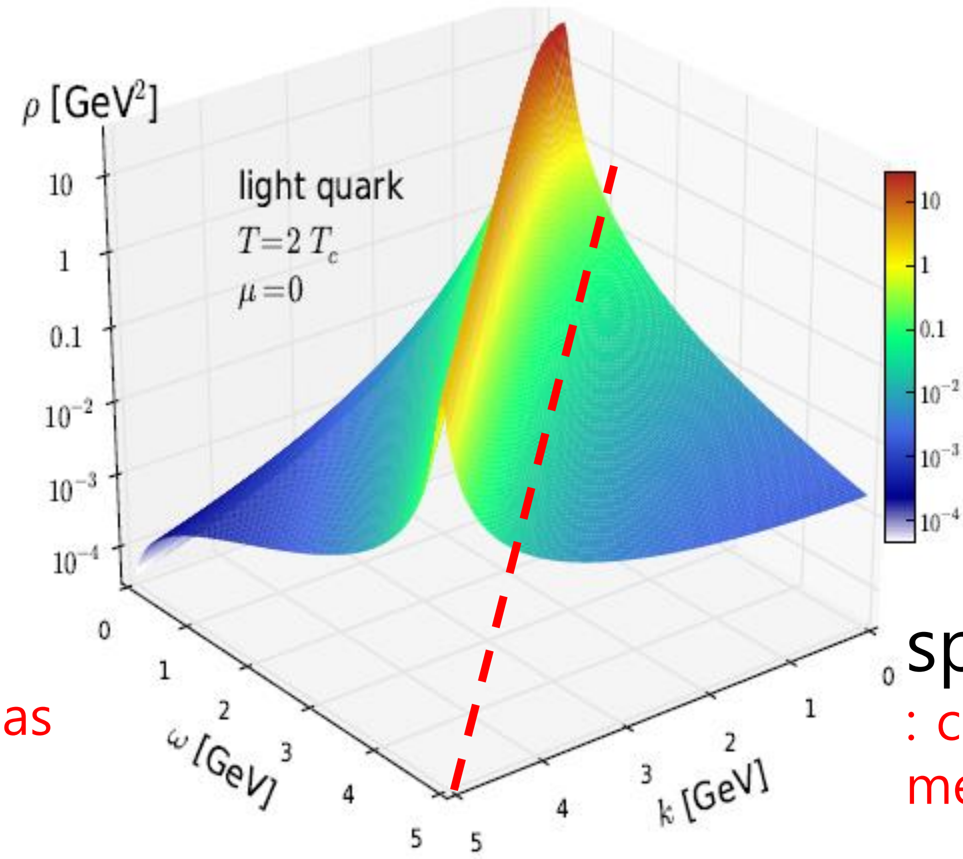
- g(T) is fitted to the lattice calculations on running couplin g and EoS.

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



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
(ε-3P) / T^4
T$_C$
T [MeV]
p/ε
ε [GeV/fm^3]

Quark/gluon spectral function



time-like

: propagate as a particle

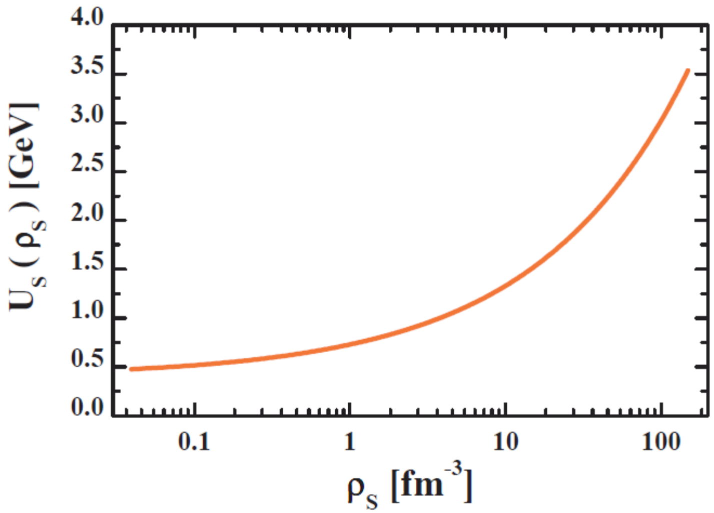
space-like

: 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 contributed by the space-like part of parton spectral func tion.



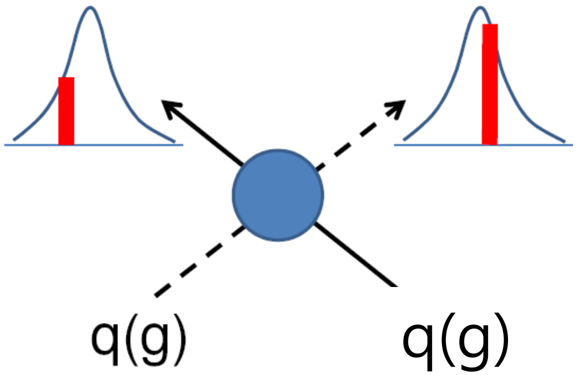
U_s increases with ρ_S

→ Partons are outwardly accelerated in heavy ion-collisions.

It helps to reproduce experimental data

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

Parton scattering in the PHSD



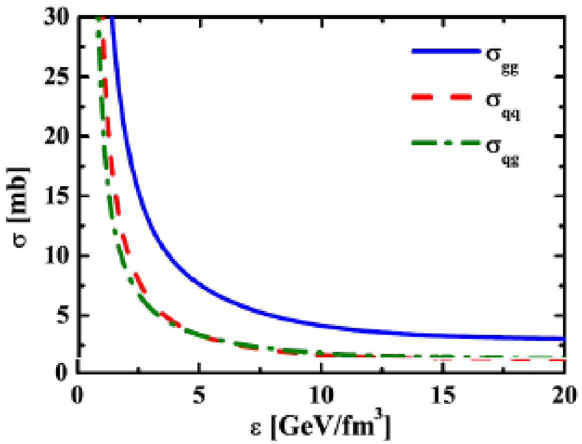
- (quasi-)elastic collisions :
- Masses change by collision

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

- inelastic collisions :

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

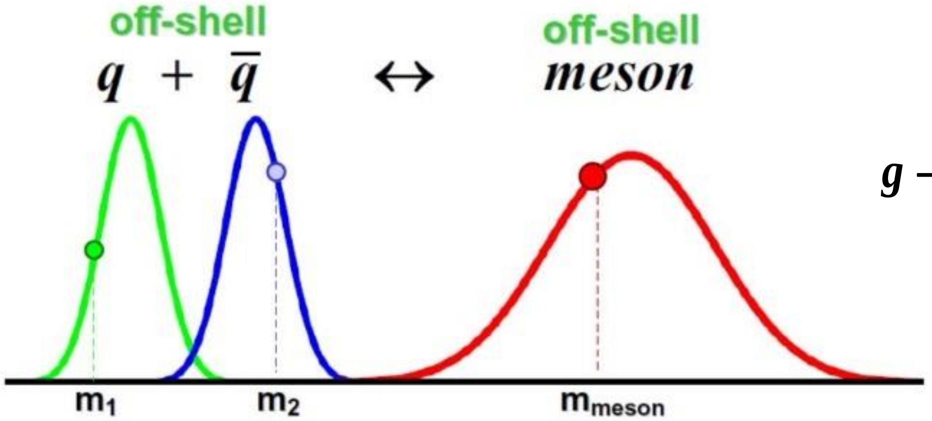
Suppressed due to the large gluon mass



Scattering cross sections based on spectral widths

Hadronization in the PHSD

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

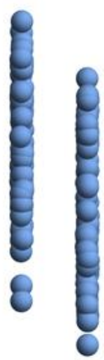


$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow meson \ \ ('\,string\,')$$

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

Stages of a collision in PHSD

t = 0.1 fm/c



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

b = 2.2 fm – Section view

Baryons (394)

Antibaryons (0)

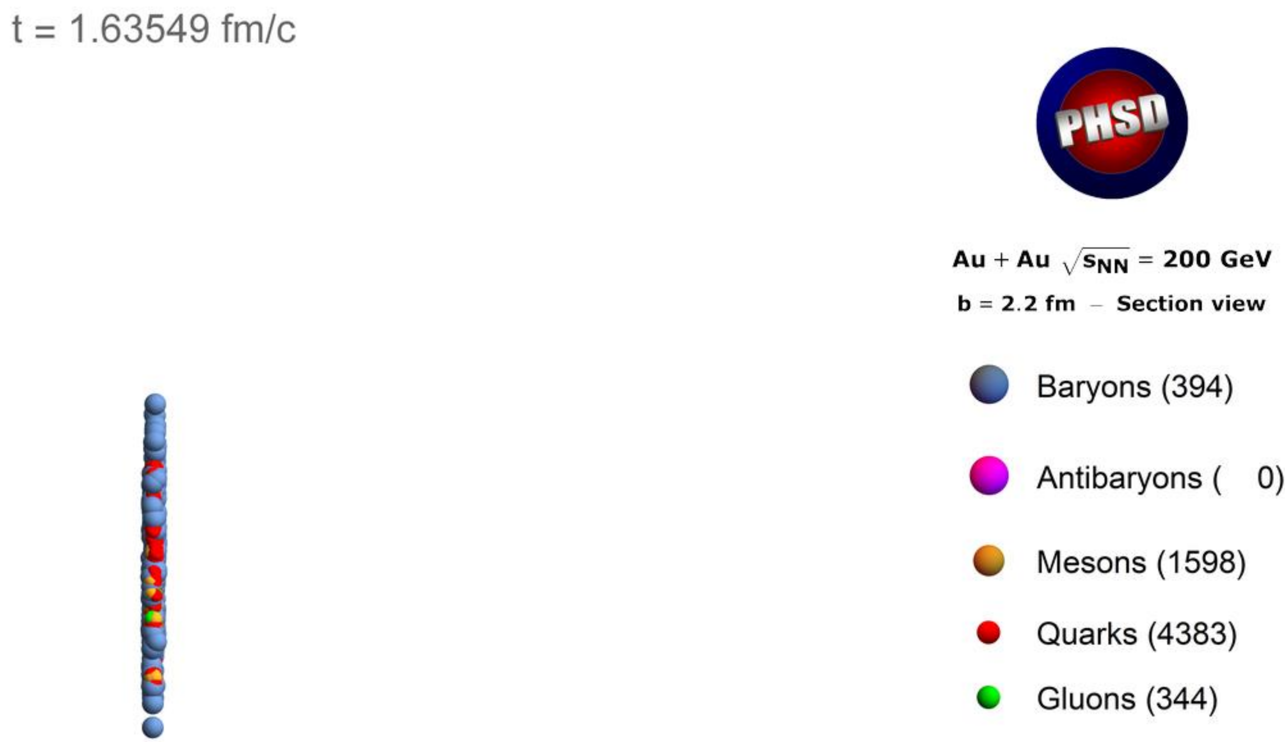
Mesons (0)

Quarks (0)

Gluons (0)

P.Moreau

Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD

t = 2.06543 fm/c

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

b = 2.2 fm – Section view

Baryons (396)

Antibaryons (2)

Mesons (1136)

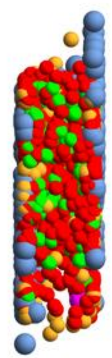
Quarks (5066)

Gluons (516)

P.Moreau

Stages of a collision in PHSD

t = 3.20258 fm/c



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

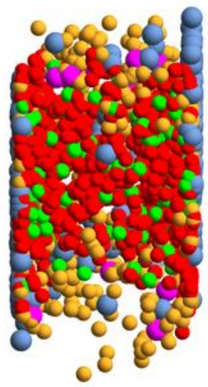
b = 2.2 fm – Section view

- Baryons (413)
- Antibaryons (13)
- Mesons (1080)
- Quarks (4708)
- Gluons (761)

P.Moreau

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)

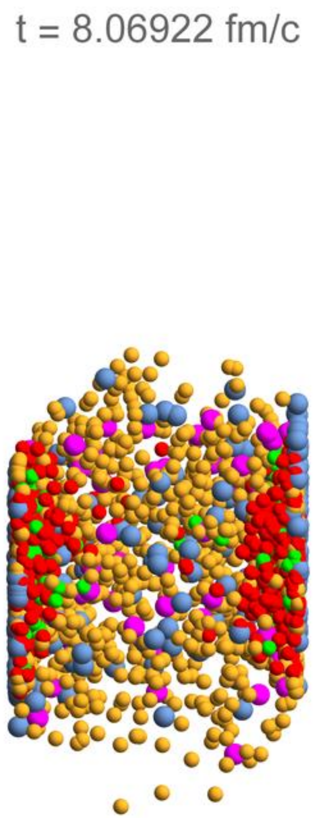
Mesons (1724)

Quarks (3843)

Gluons (652)

P.Moreau

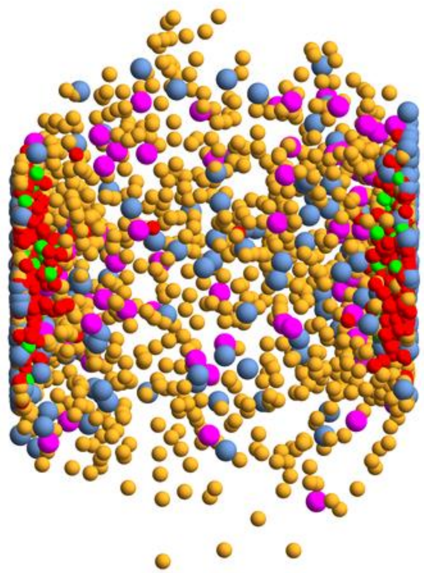
Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD

t = 10.5692 fm/c



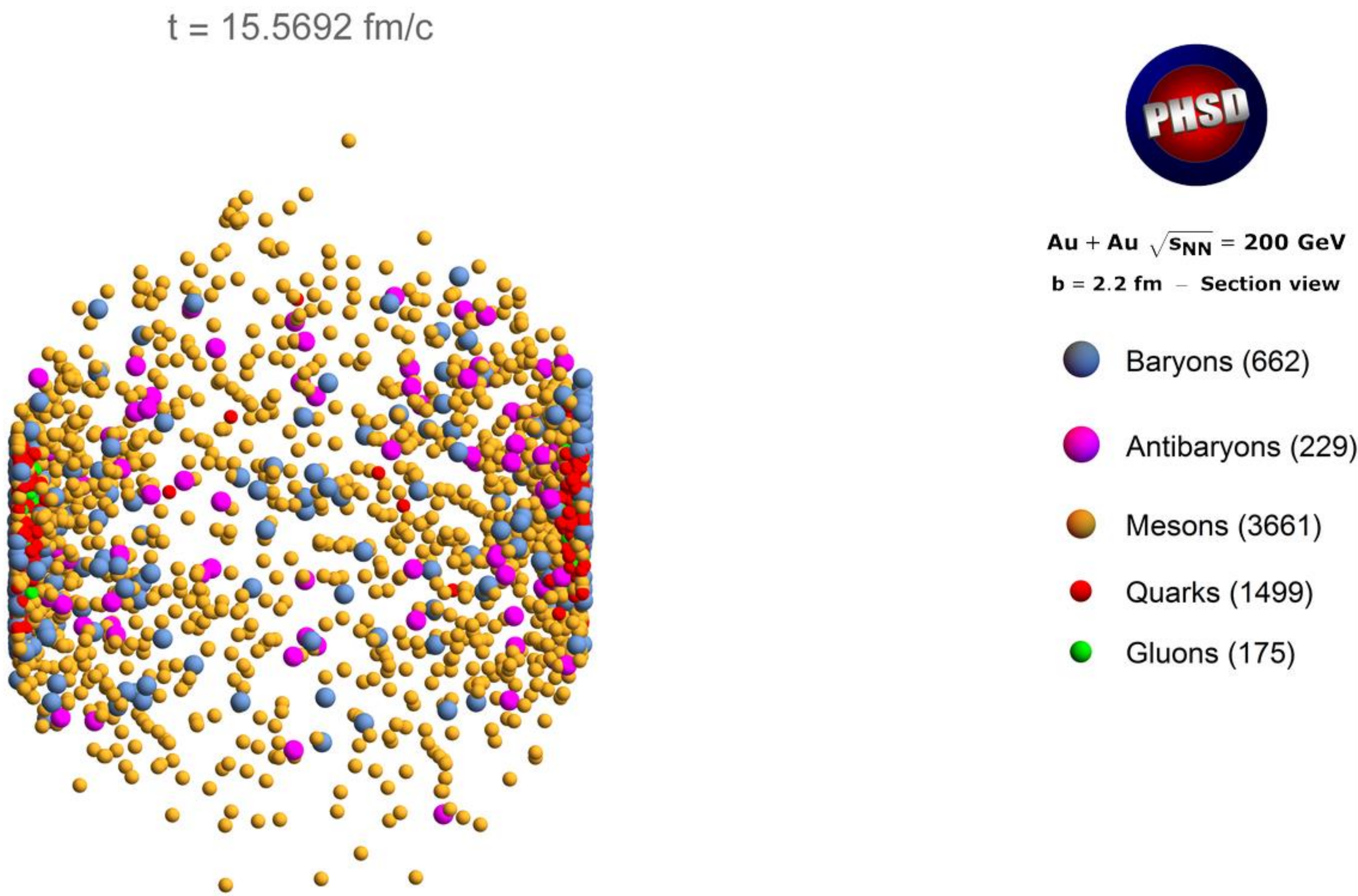
Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

- Baryons (604)
- Antibaryons (187)
- Mesons (3169)
- Quarks (2076)
- Gluons (319)

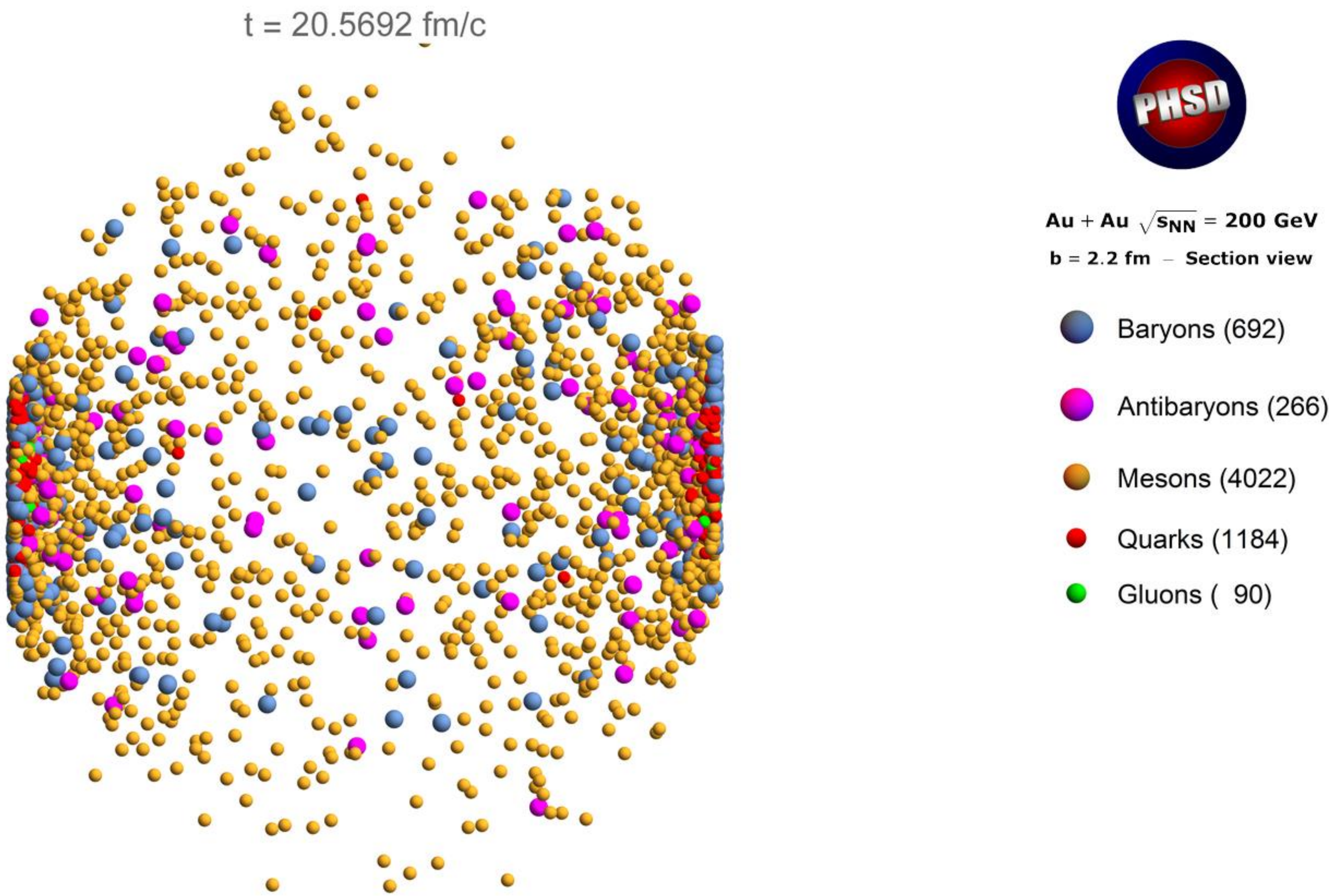
P.Moreau

Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD



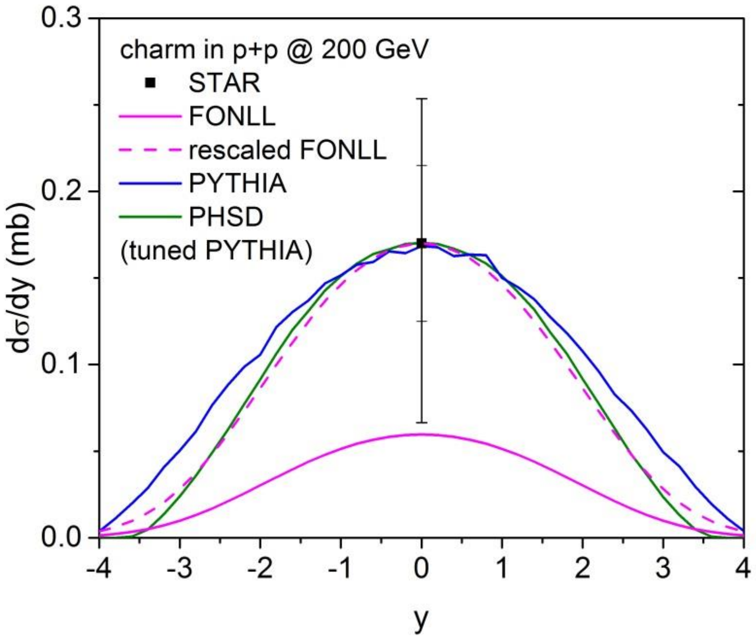
P.Moreau

3. Heavy flavor production in PHSD

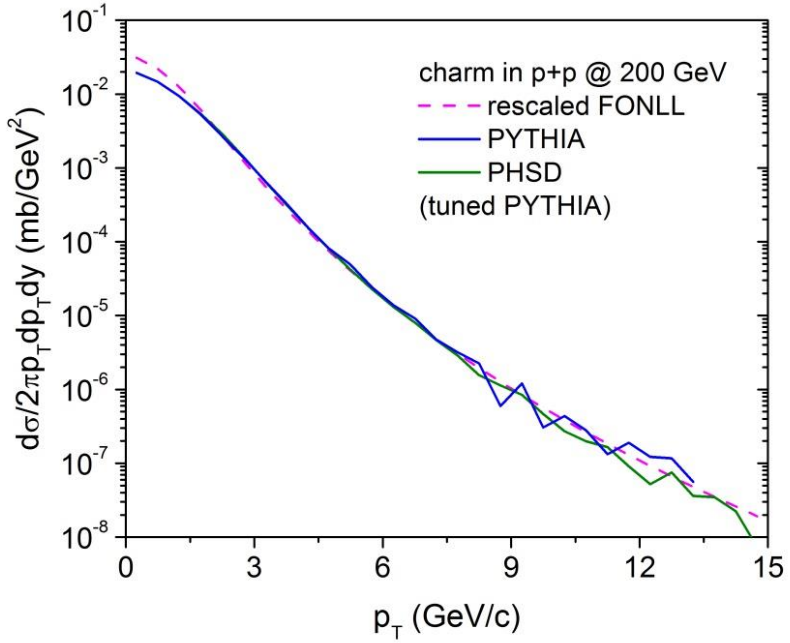
charm production in p+p collisions

Initial charm pairs are generated by the PYTHIA which is tuned (y*0.85, p_T*0.95) to produce FONLL-shape of distributions

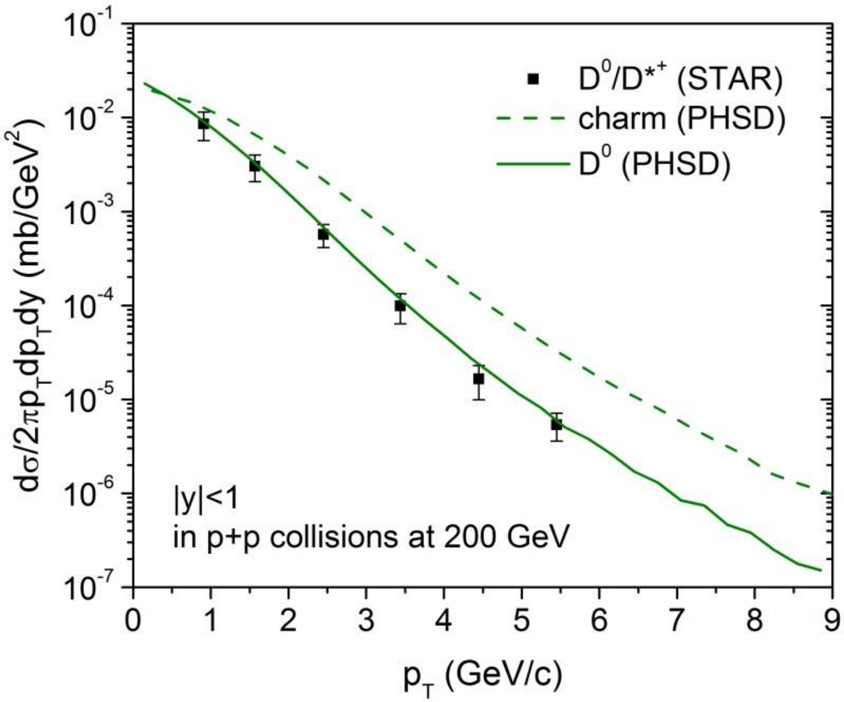
Rapidity distribution



p_T spectrum

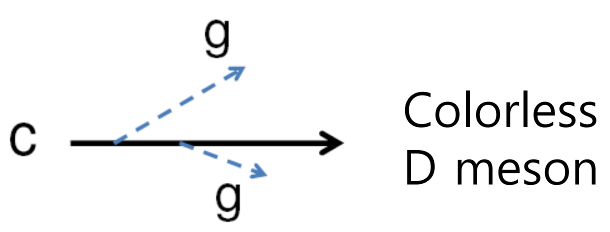


Charm is hadronized through fragmentation in p+p collisions



- In p+p collisions charm quark is hadronized by emitting soft gluons (fragmentation):
- Peterson's fragmentation function for p_T with rapidity unchanged

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



Charm production in A+A collisions

- Cold nuclear matter effects

1. Shadowing effect

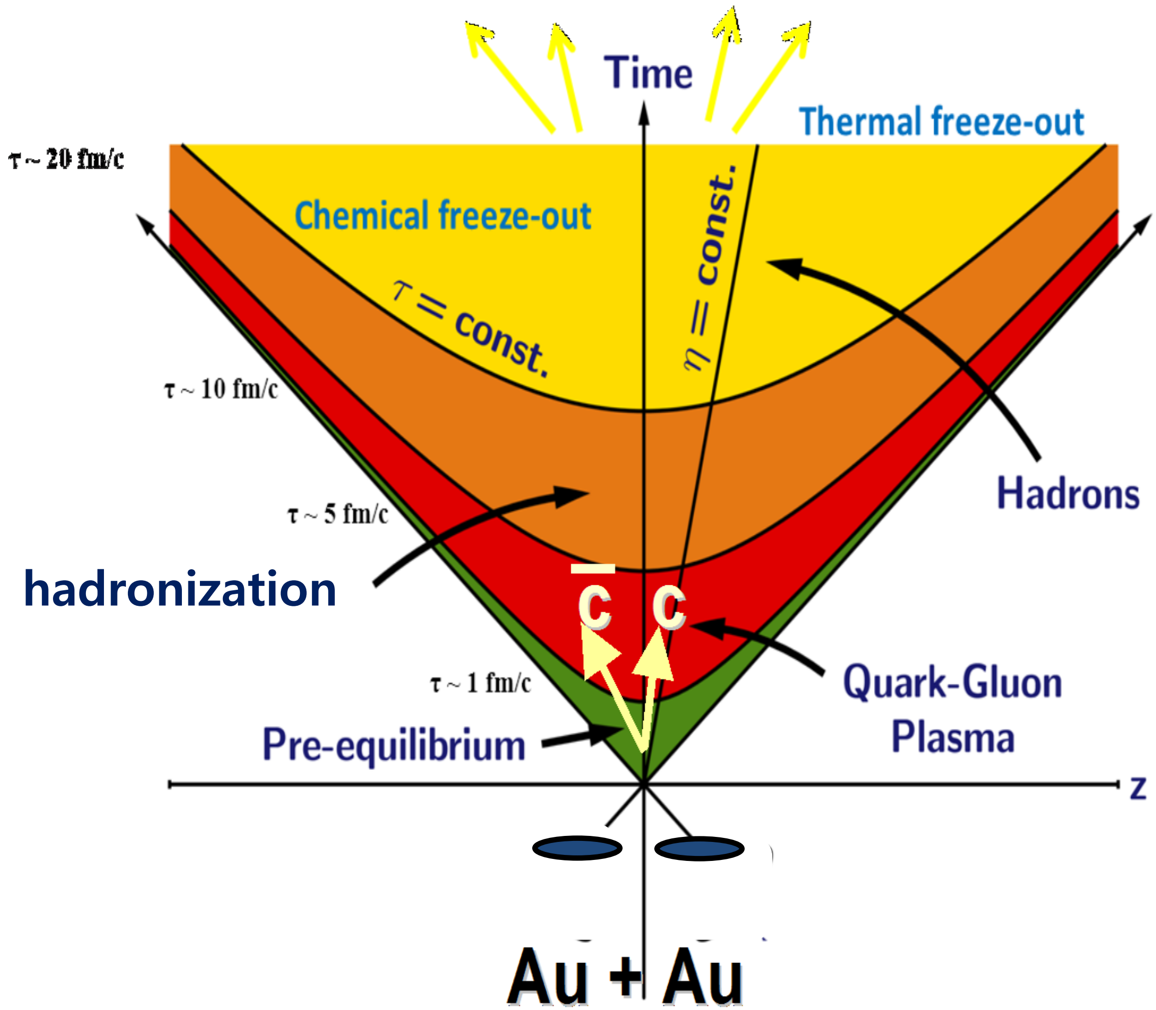
: PDF modifies in nucleus; EPS 09 is used.

2. Cronin effect

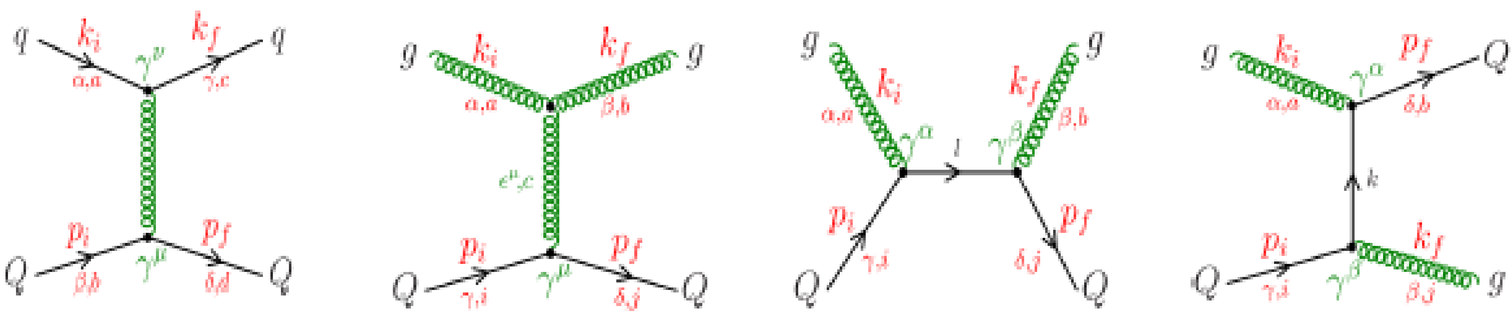
: Because of parton+N scattering in A(p)+A collisions, p_T of produced particle is enhanced.

- Hot nuclear matter effects

1. Partonic & hadronic rescattering
2. Hadronization in nuclear matter (coalescence)


Time
Thermal freeze-out
τ ~ 20 fm/c
Chemical freeze-out
τ = const.
η = const.
τ ~ 10 fm/c
τ ~ 5 fm/c
Hadrons
hadronization
c̄ c
τ ~ 1 fm/c
Quark-Gluon
Plasma
Pre-equilibrium
z
Au + Au

Heavy quark scattering in QGP (Dynamical Quasi-Particle Model)

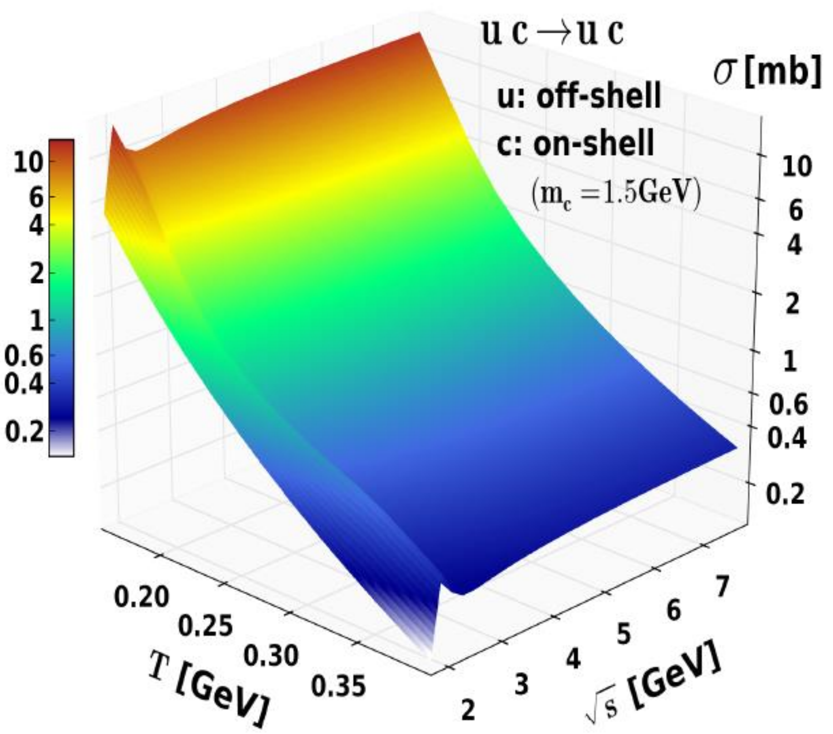


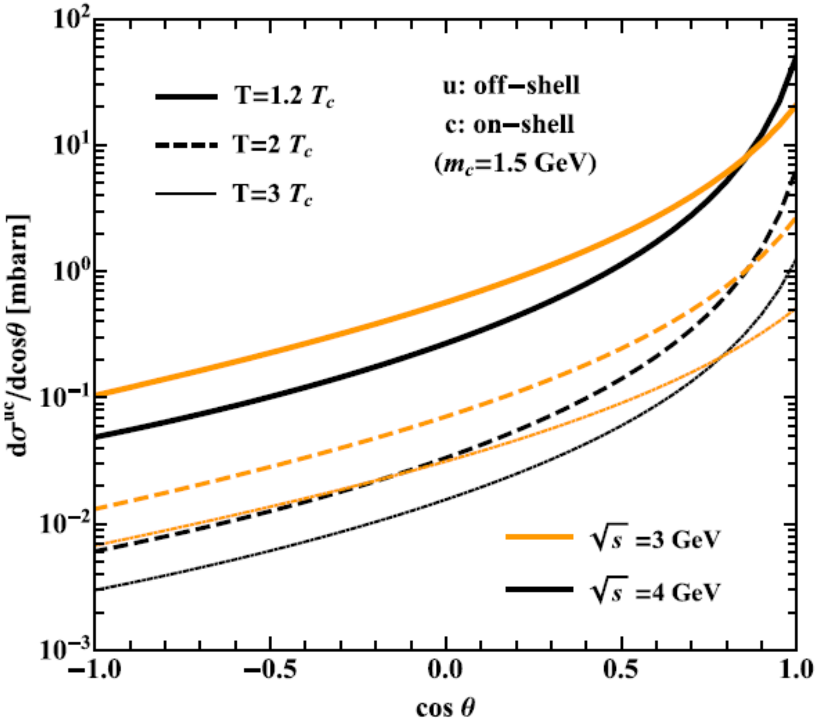
elastic scattering with off-shell massive partons

Q+q(g)→Q+q(g)

1. temperature-dependent strong coupling g(T)
2. Off-shell mass plays the role of a regulator

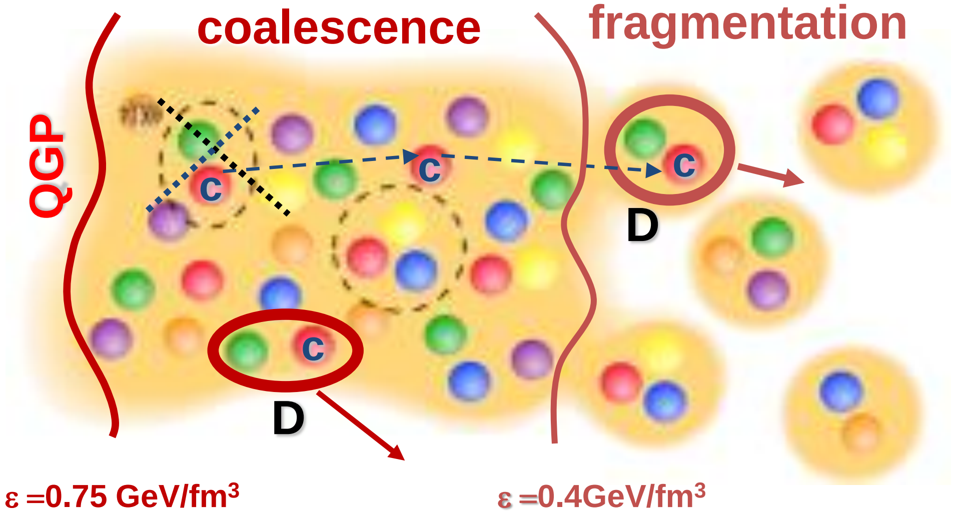
1. Cross sections rapidly increase near Tc
2. less forward peaked & less number of collisions, compared to in massless QGP



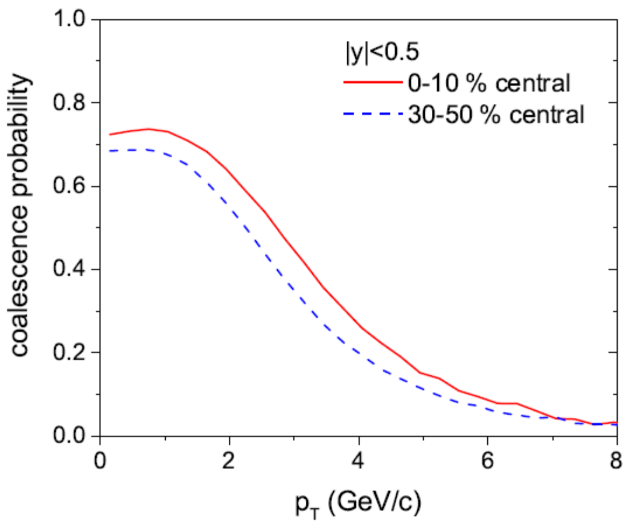


H. Berrehrah et al, PRC 89 (2014) 054901;
PRC 90 (2014) 051901; PRC90 (2014) 064906

Hadronization of heavy quark



Coalescence probability in Pb+Pb at LHC



Coalescence probability for $c + \bar{q} \rightarrow D$

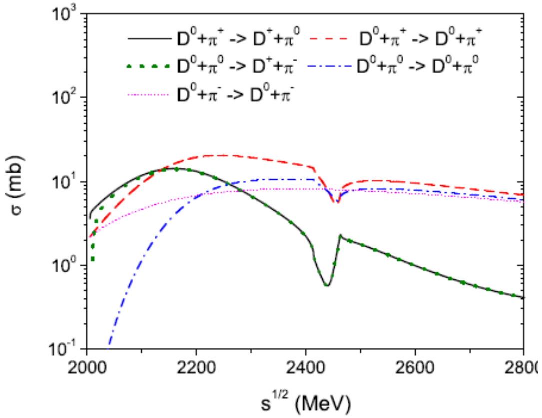
$$f(\boldsymbol{\rho}, \mathbf{k}_\rho) = \frac{8 g_M}{6^2} \exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2} - \mathbf{k}_\rho^2 \delta^2\right]$$

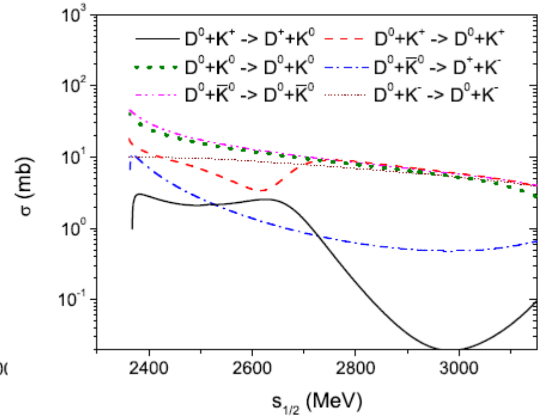
where $\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2), \quad \mathbf{k}_\rho = \sqrt{2}\, \frac{m_2 \mathbf{k}_1 - m_1 \mathbf{k}_2}{m_1 + m_2}$

Degeneracy factor : g_M = 1 for D, = 3 for $D^* = D^*_0(2400)^0$, $D^*_1(2420)^0$, $D^*_2(2460)^{0\pm}$

D meson scattering in hadron gas

D-meson scattering with mesons

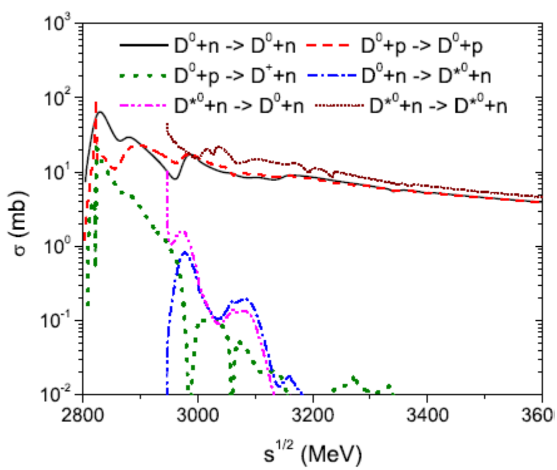


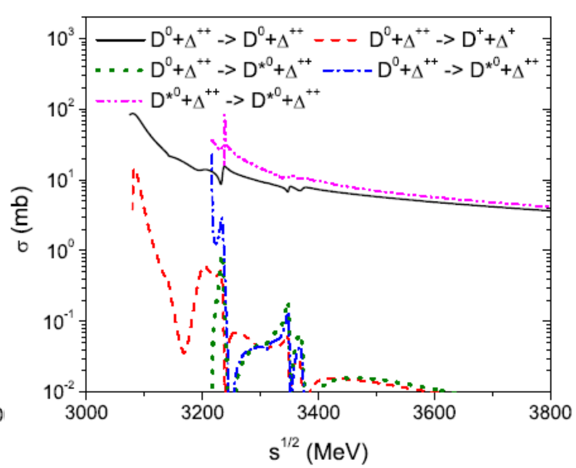


Calculated in effective Lagrangian with heavy-quark spin symmetry

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

D-meson scattering with baryons

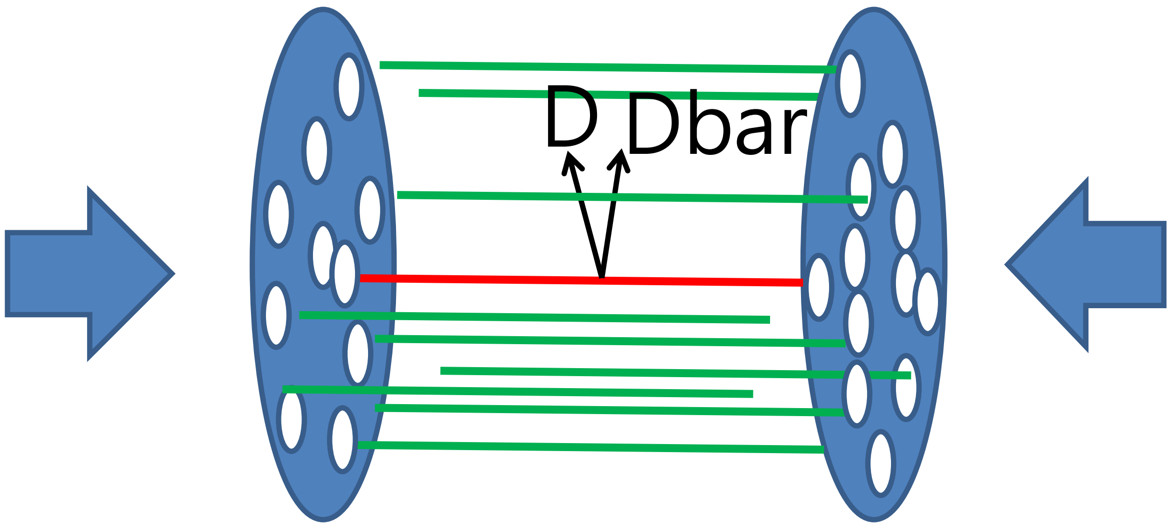




Experimental measurements

- R_{AA} (nuclear modification factor)
- V_2 (elliptic flow)
- Correlations

Nuclear modification factor (R_{AA})

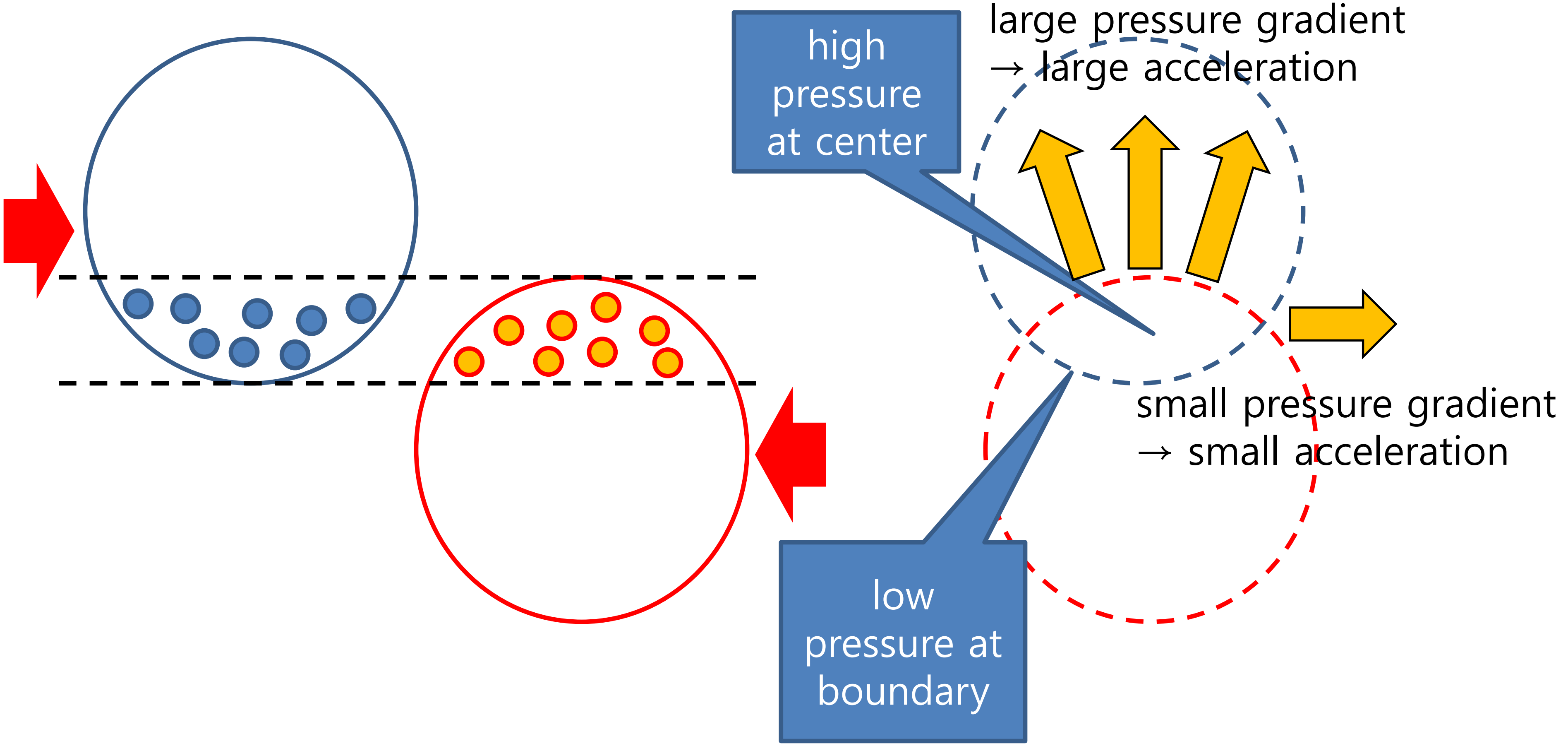


$$R_{AA} = \frac{N_D^{A+A}}{N_D^{N+N} \times (\#\ of\ N+N\ binary\ collisions)}$$

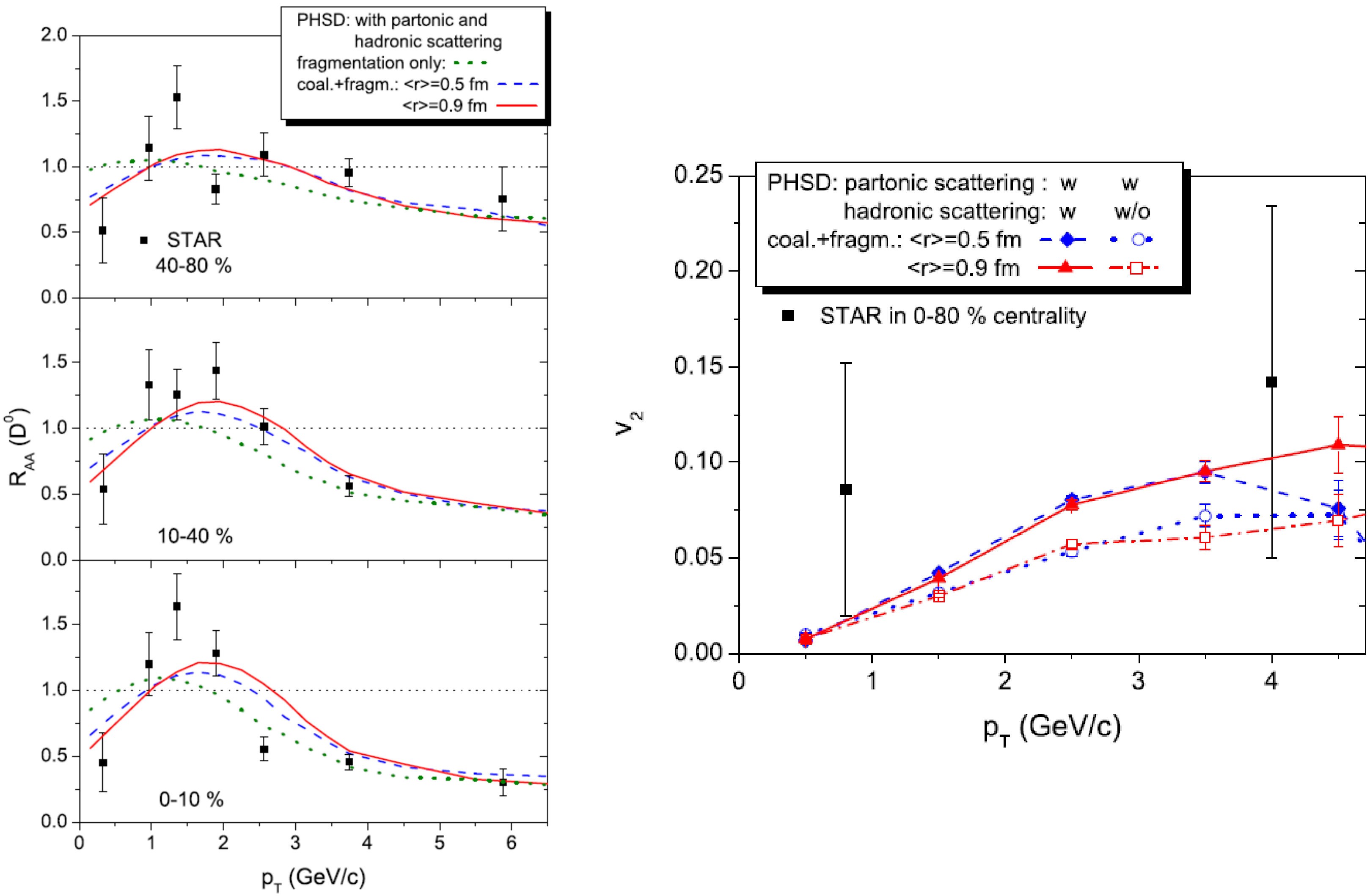
$R_{AA} = 1$: no nuclear modification
$R_{AA} < 1$: suppression
$R_{AA} > 1$: enhancement

elliptic flow (v_2)

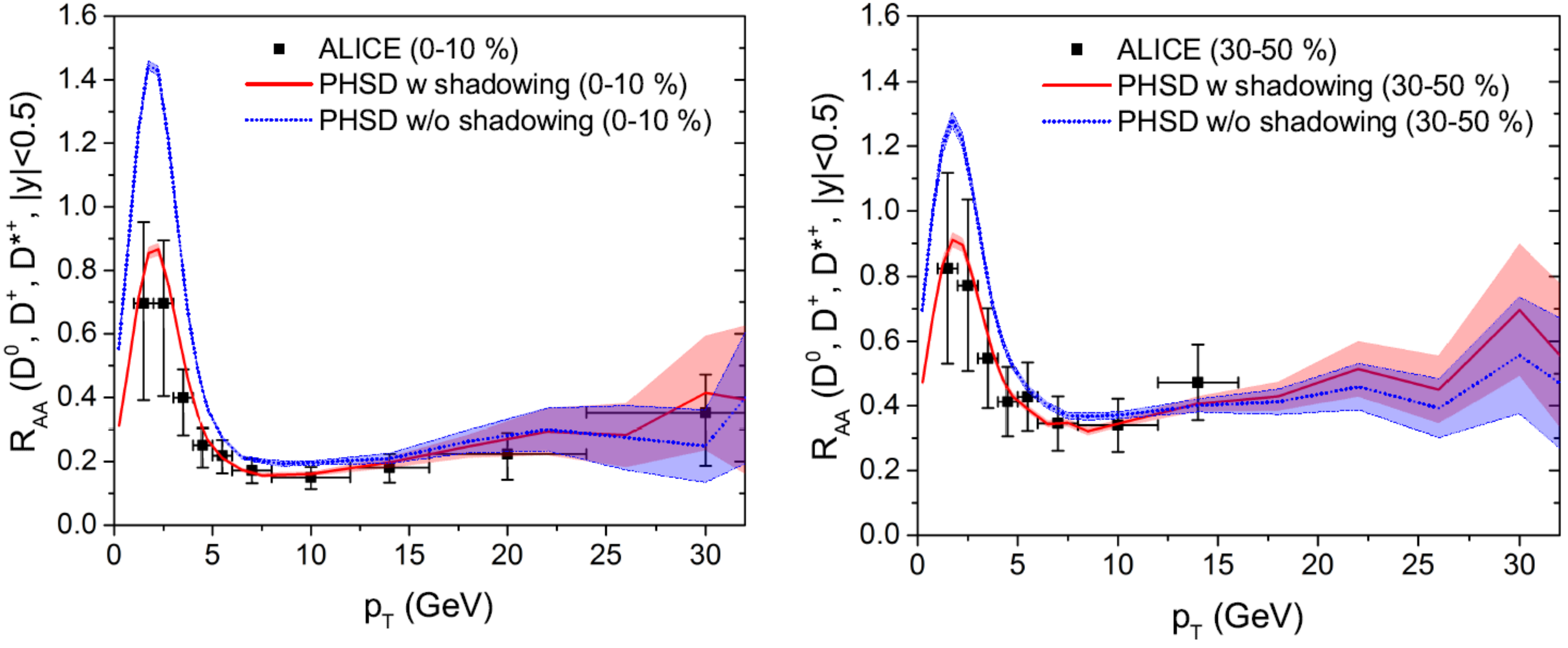
- In semi-central collisions,



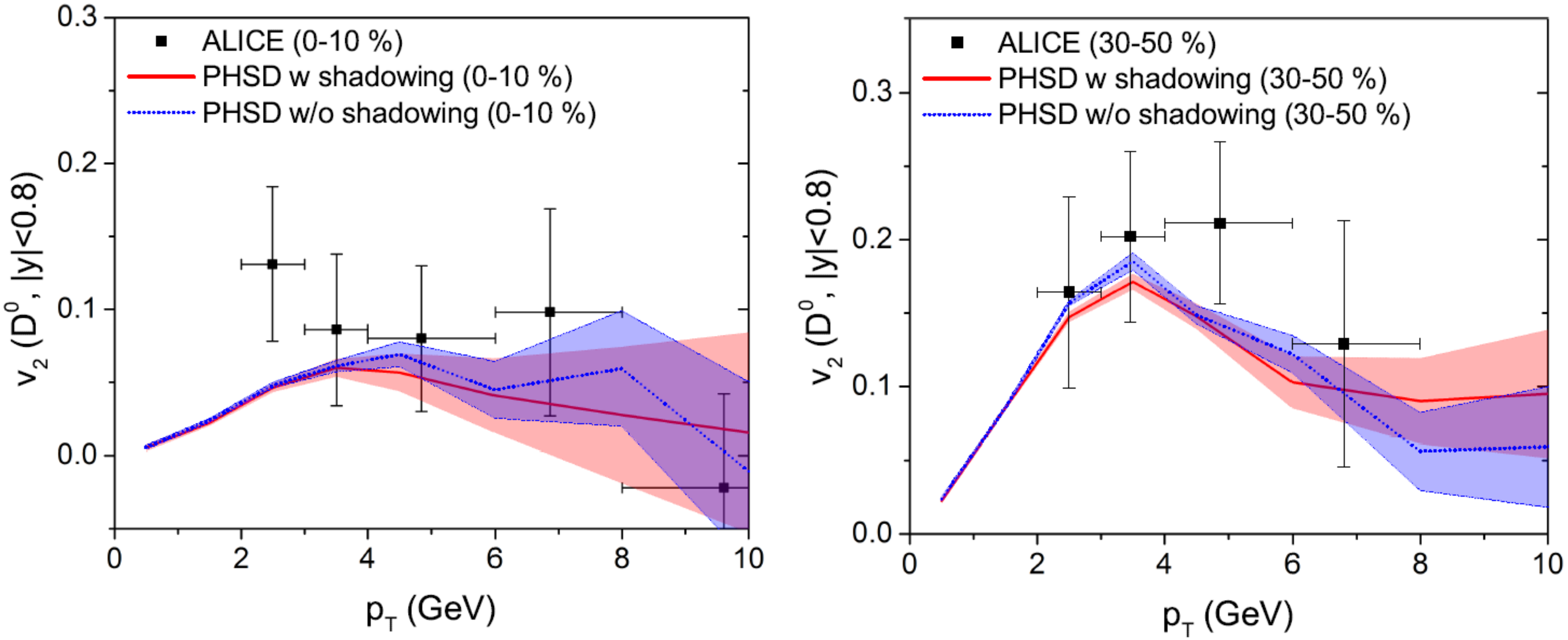
R_{AA} and v_2 of D^0 at RHIC (200 GeV)



R_{AA} of D^0, D^+, D^{+*} at LHC (2.76 TeV)



V_2 of D^0 at LHC (2.76 TeV)

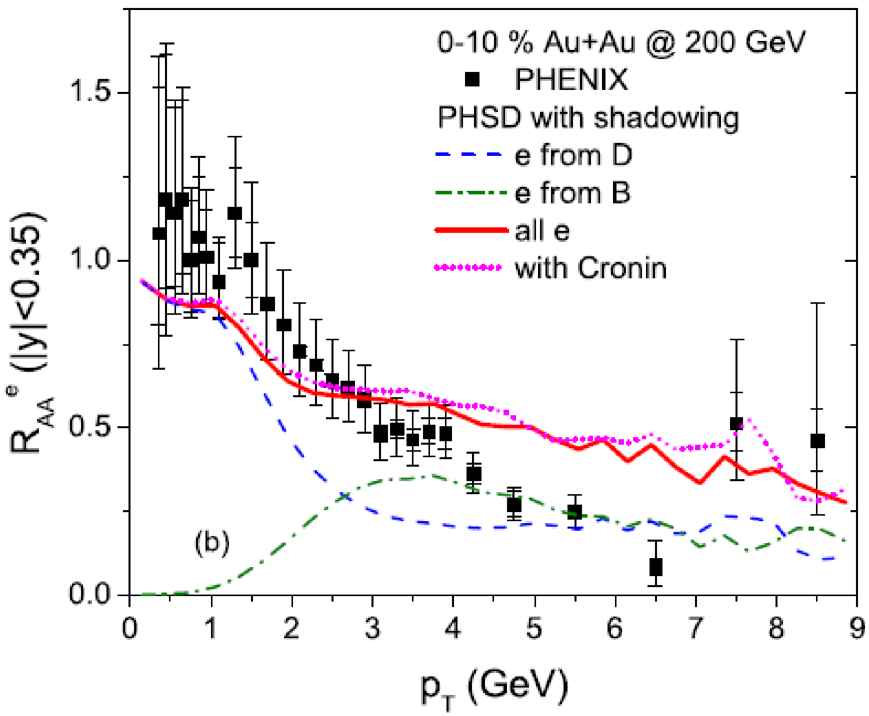


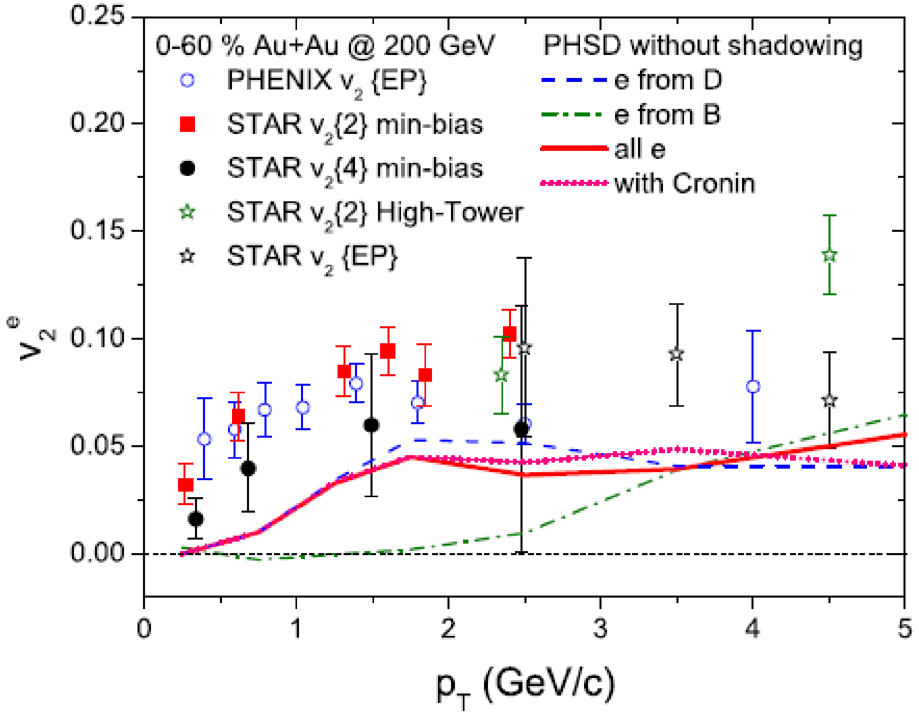
R_{AA} and v_2 of single-e at RHIC (200 GeV)

Semi-leptonic decay

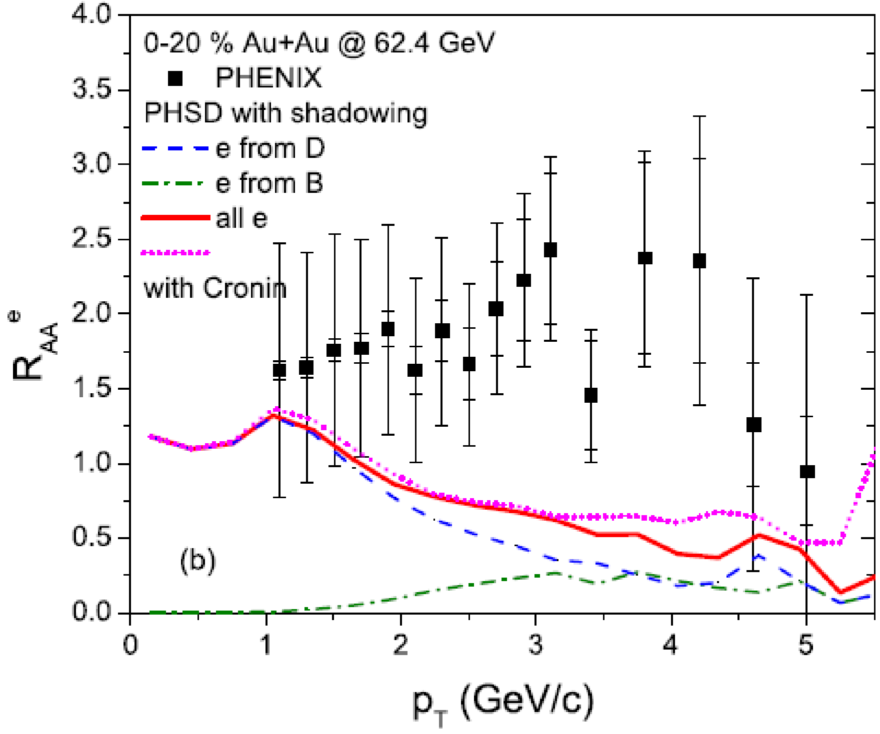
$$D \rightarrow K + \bar{\nu}_e + e$$

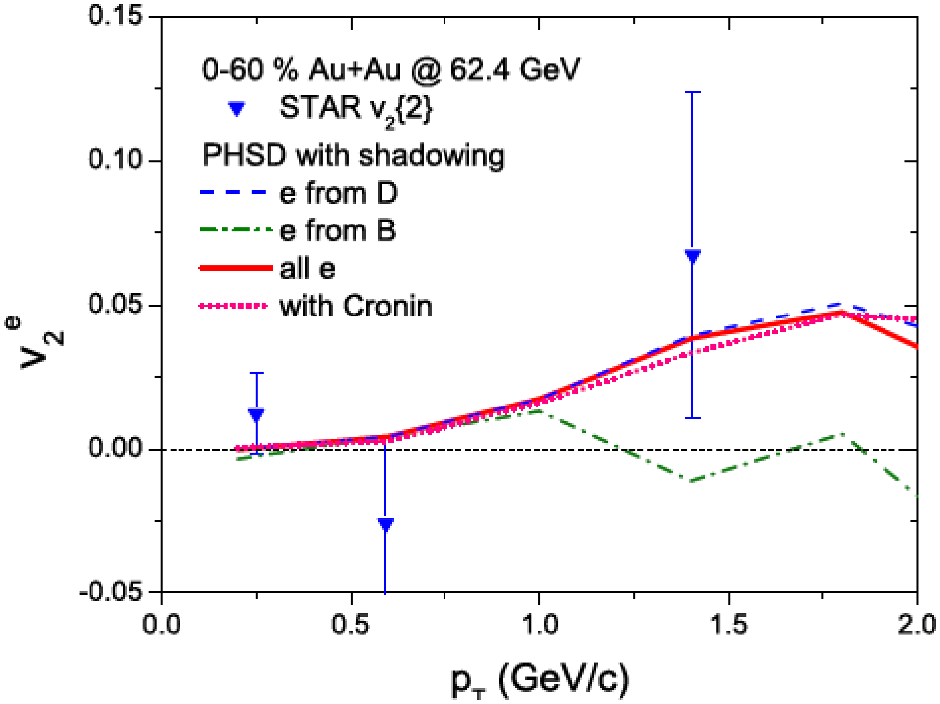
$$B \rightarrow D + \bar{\nu}_e + e$$



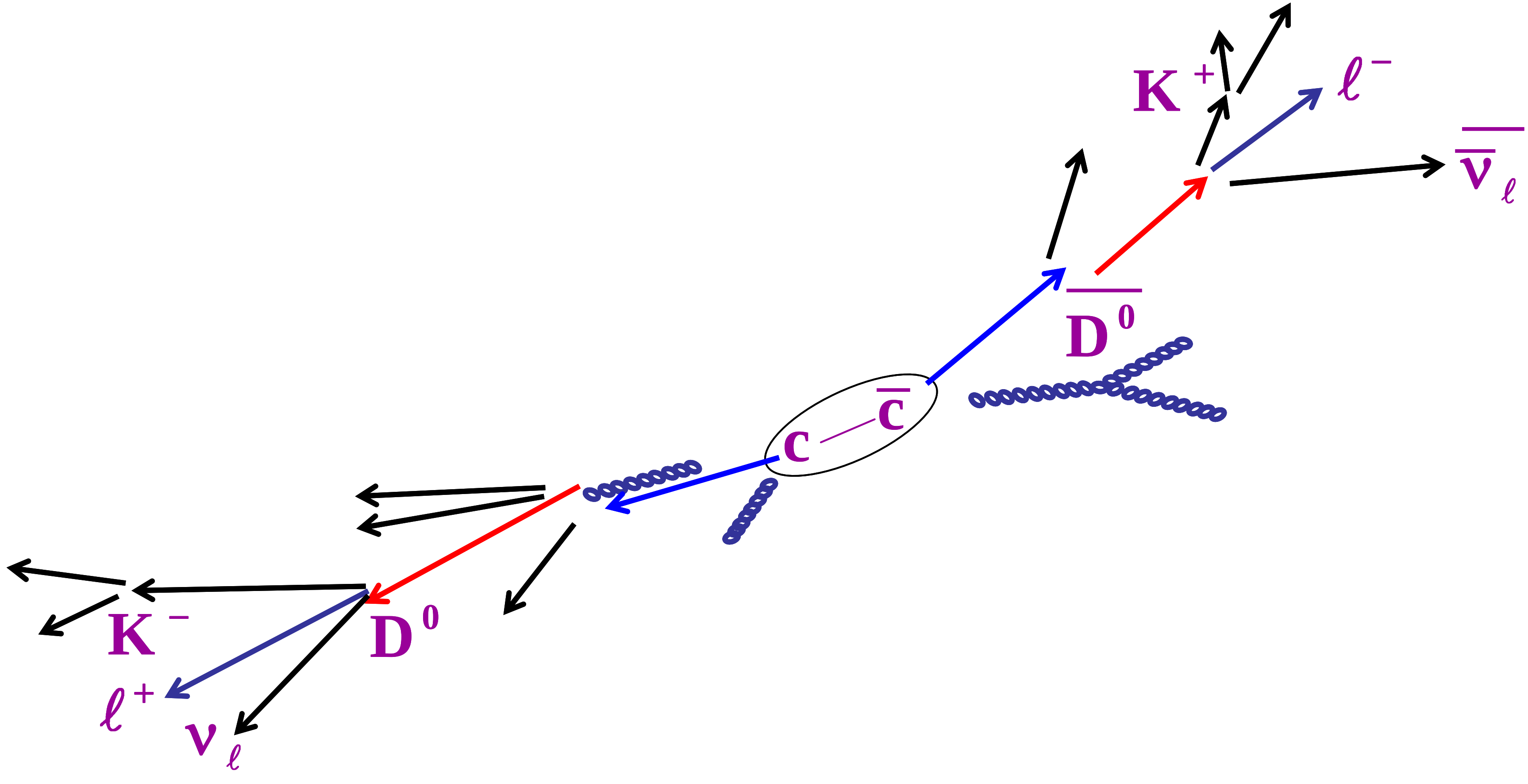


R_{AA} and v_2 of single-e at BES (62.4 GeV)

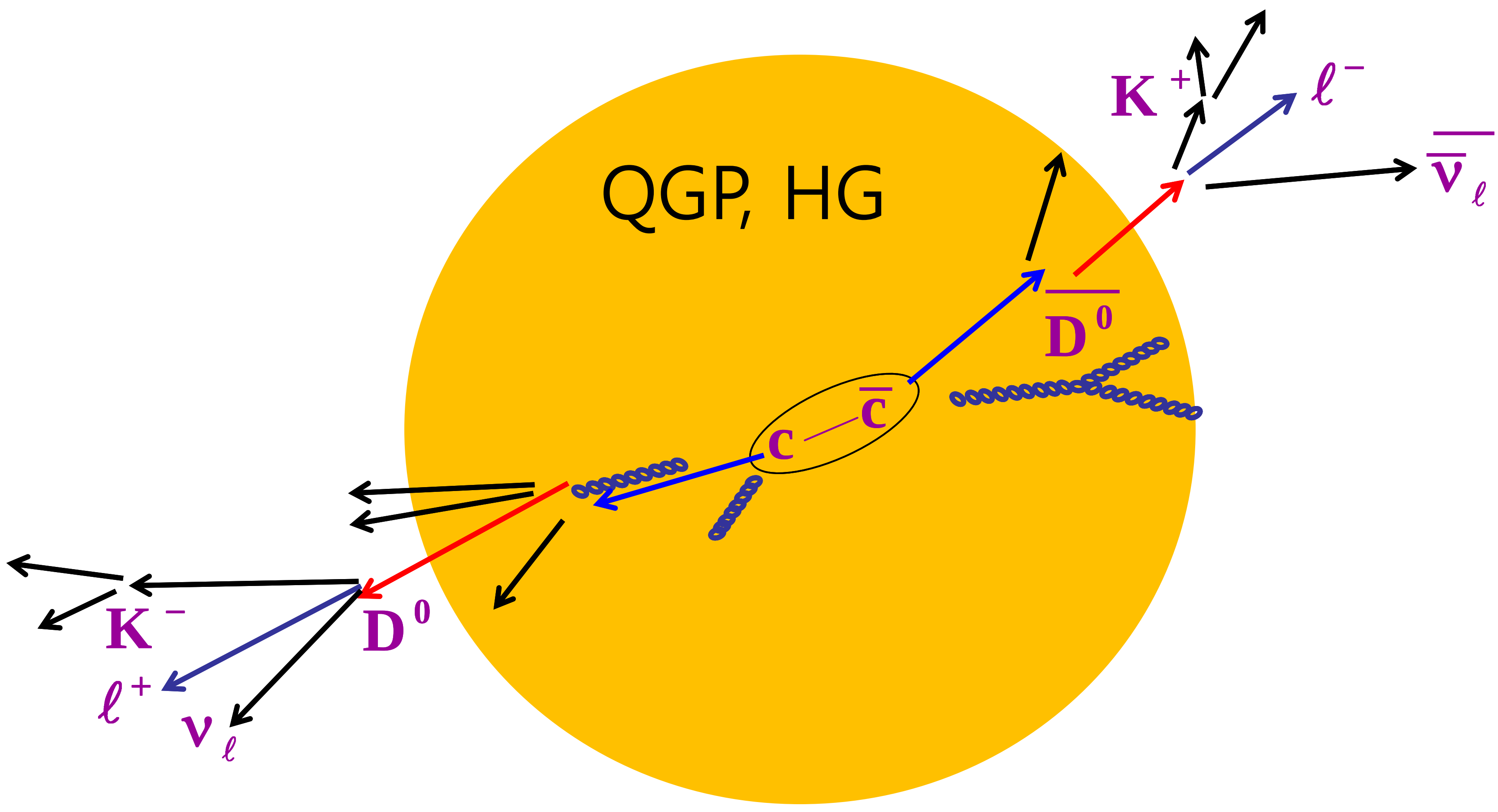




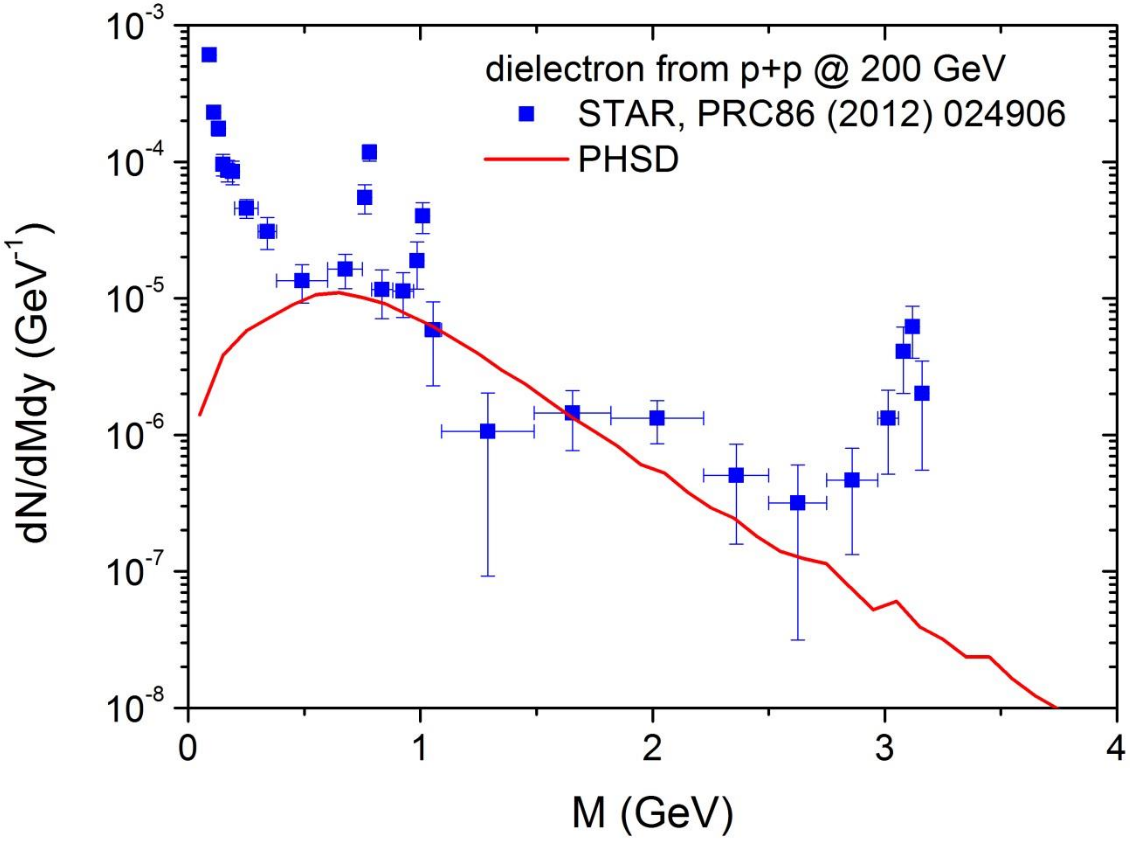
Electron-positron correlation



Electron-positron correlation



Dileptons from DD in p+p collisions



STAR acceptance

$|\eta(e^+)|<1$,

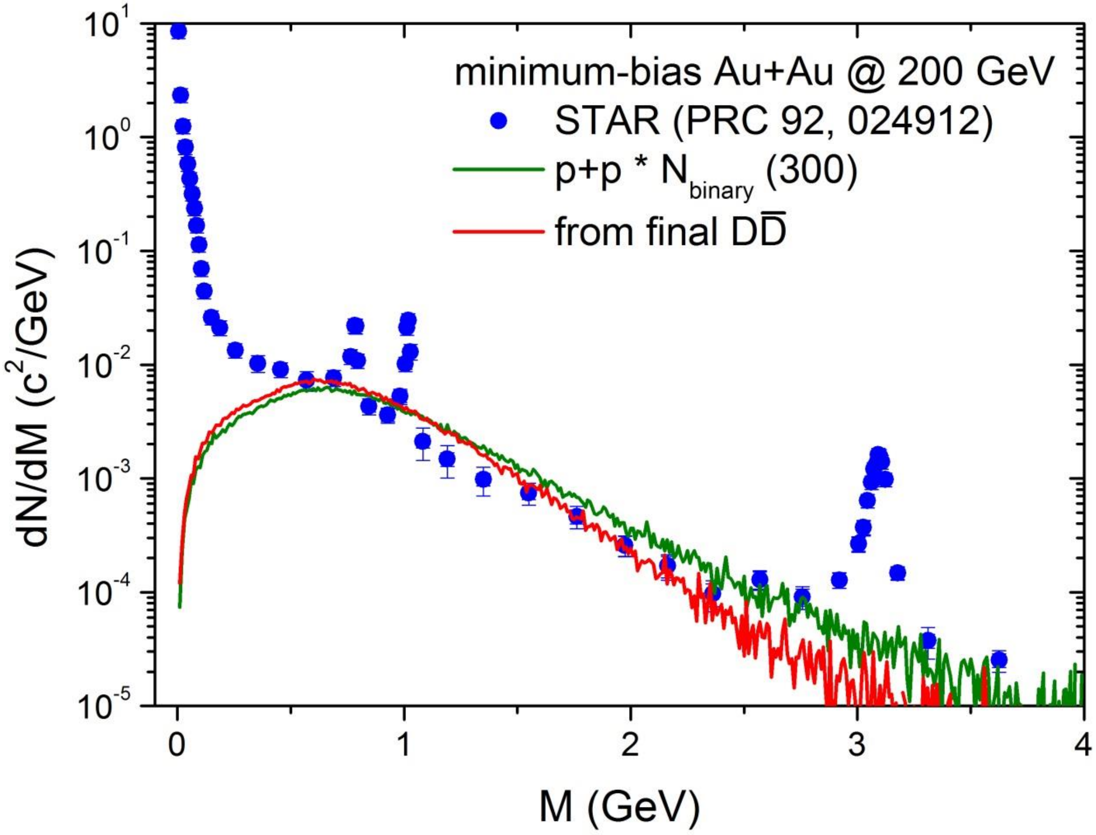
$|\eta(e^-)|<1$,

$p_T(e^+)>0.2$ GeV,

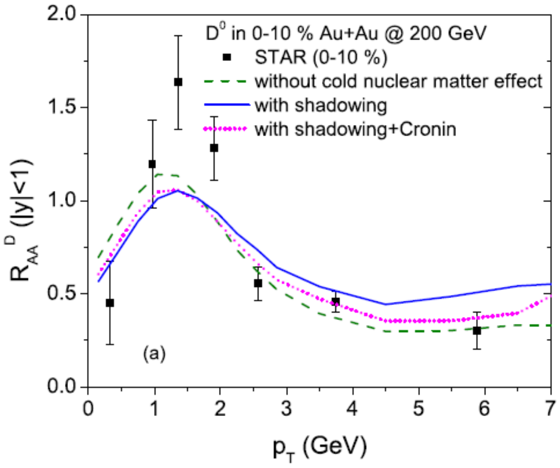
$p_T(e^-)>0.2$ GeV,

$|y(e^+e^-)|<1$

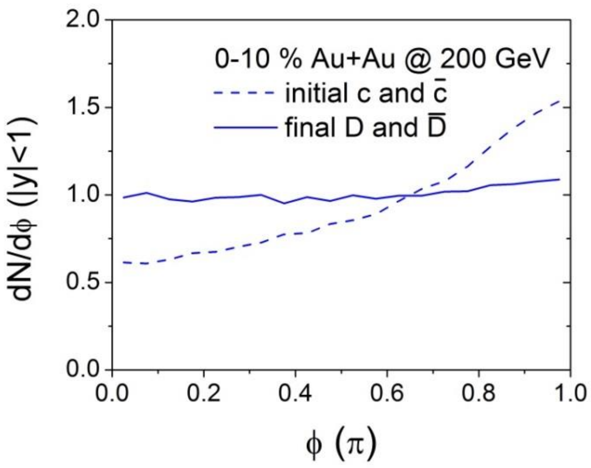
Nuclear matter effect on dileptons from DD in Au+Au @ 200 GeV



Heavy flavor energy loss

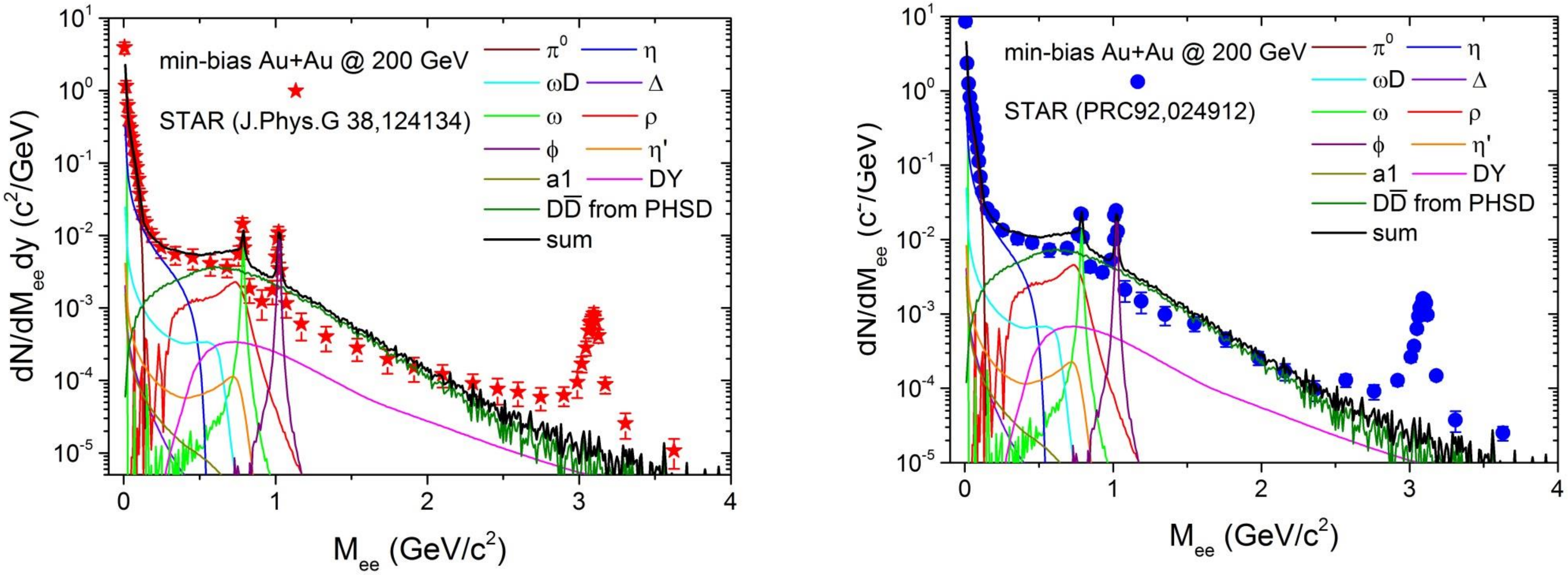


Change of angle correlation

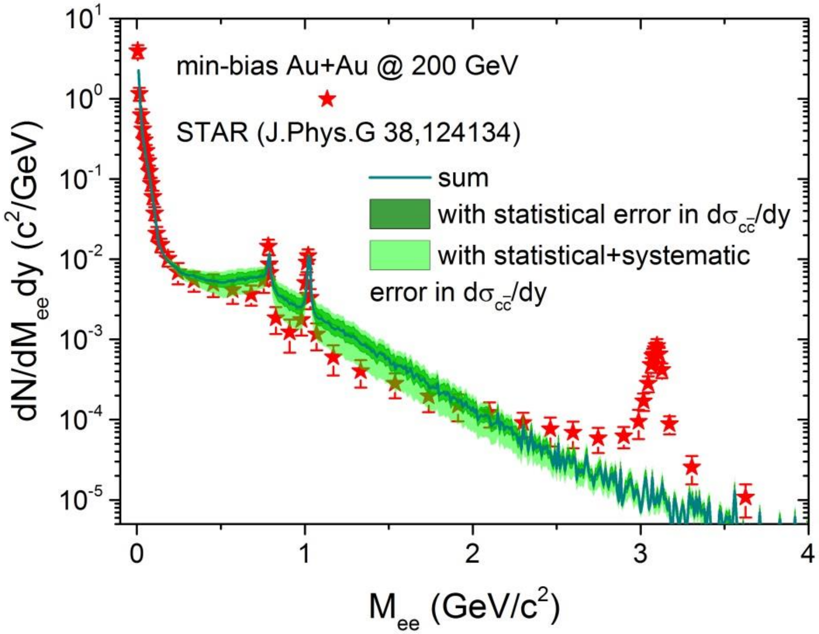


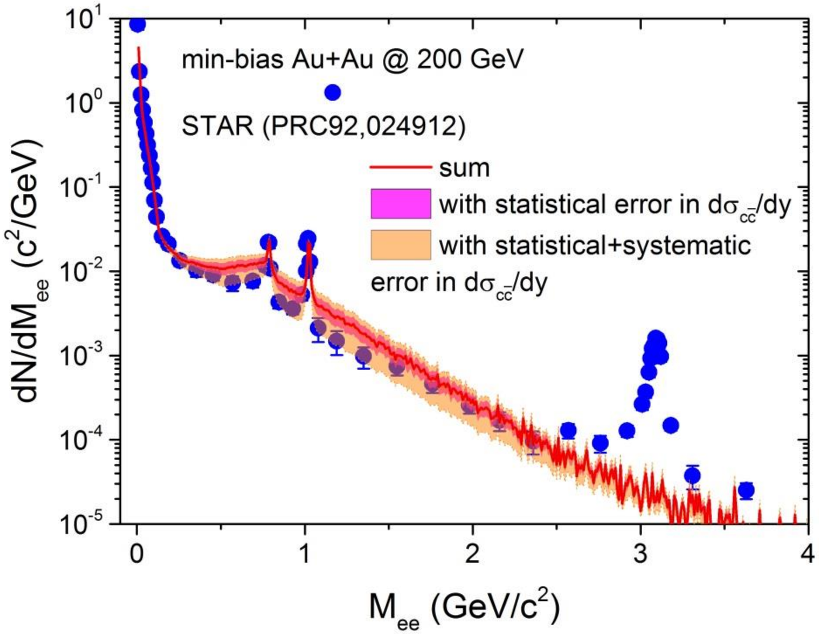
Dilepton with large M is suppressed & small M is a bit enhanced

Including all contributions



Considering the uncertainties in σ_{cc}





Summary

- Charm pair is produced by PYTHIA which is then tuned to get the FONLL-like p_T and y-distributions of charm.
- The shadowing effect from EPS09 and/or Cronin effect are implemented
- In QGP heavy quark interacts with the massive off-shell partons
- Heavy quark hadronizes either through coalescence or through fragmentation
- In hadron gas D meson interacts with light hadrons based on an effective Lagrangian with heavy quark spin-symmetry