Dynamical description of heavy quarks and electromagnetic probes in heavy-ion collisions at ultra-relativistic energies

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contents

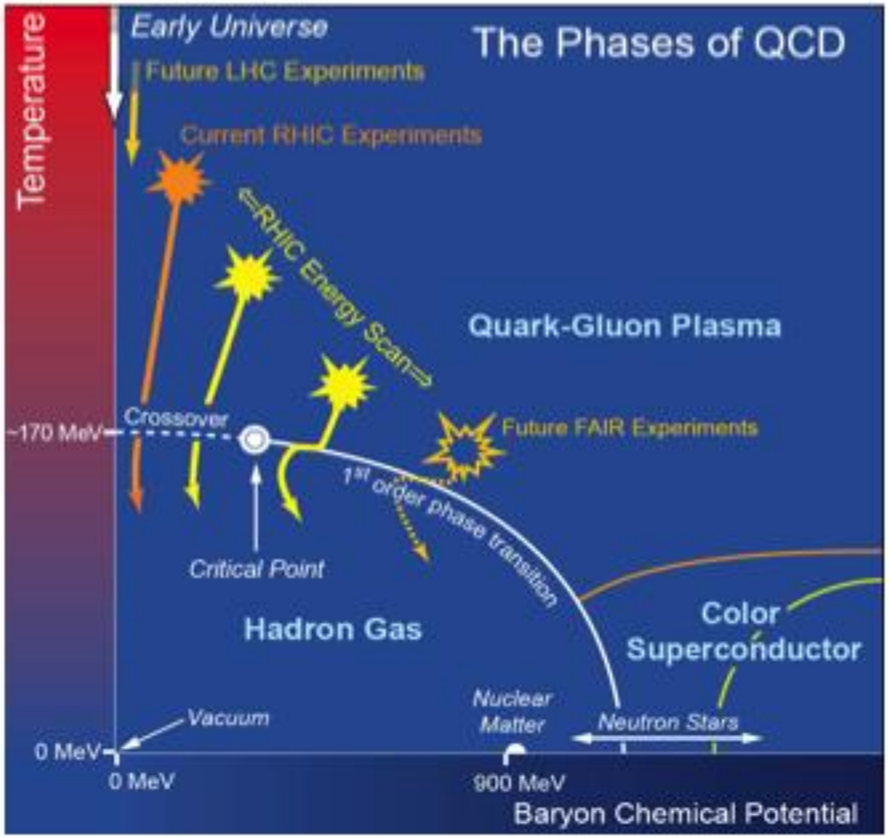
1. Introduction
2. Parton-Hadron-String Dynamics (PHSD)
3. Heavy flavor production in HIC
4. Dilepton production in HIC
5. Summary

1. introduction

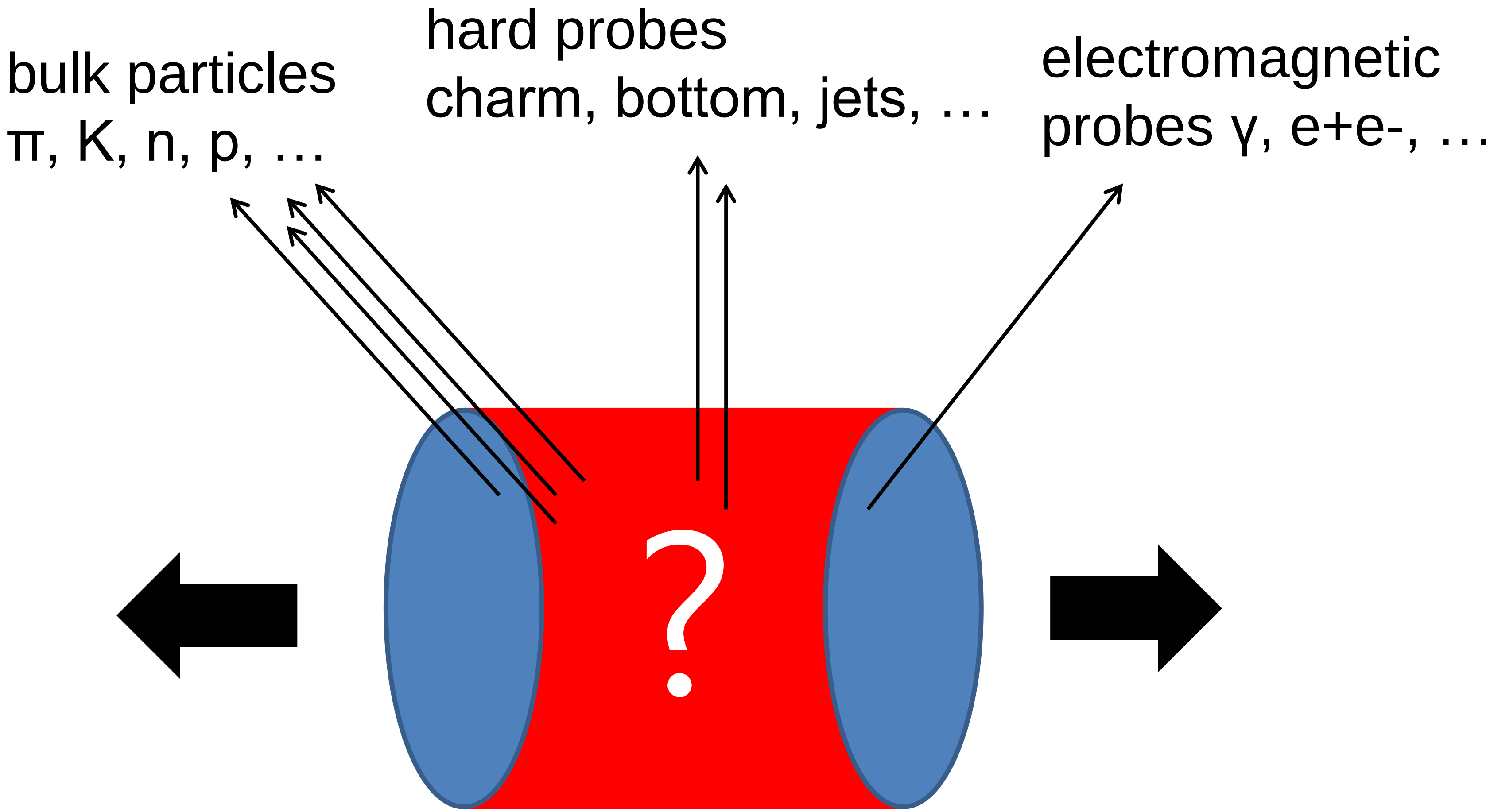
Relativistic heavy-ion collisions produce nuclear matter in extreme conditions

Beam Energy Scan, FAIR : baryon rich matter

top energies of RHIC, LHC : almost baryon free, hot matter



investigate the properties of the matter through produced particles

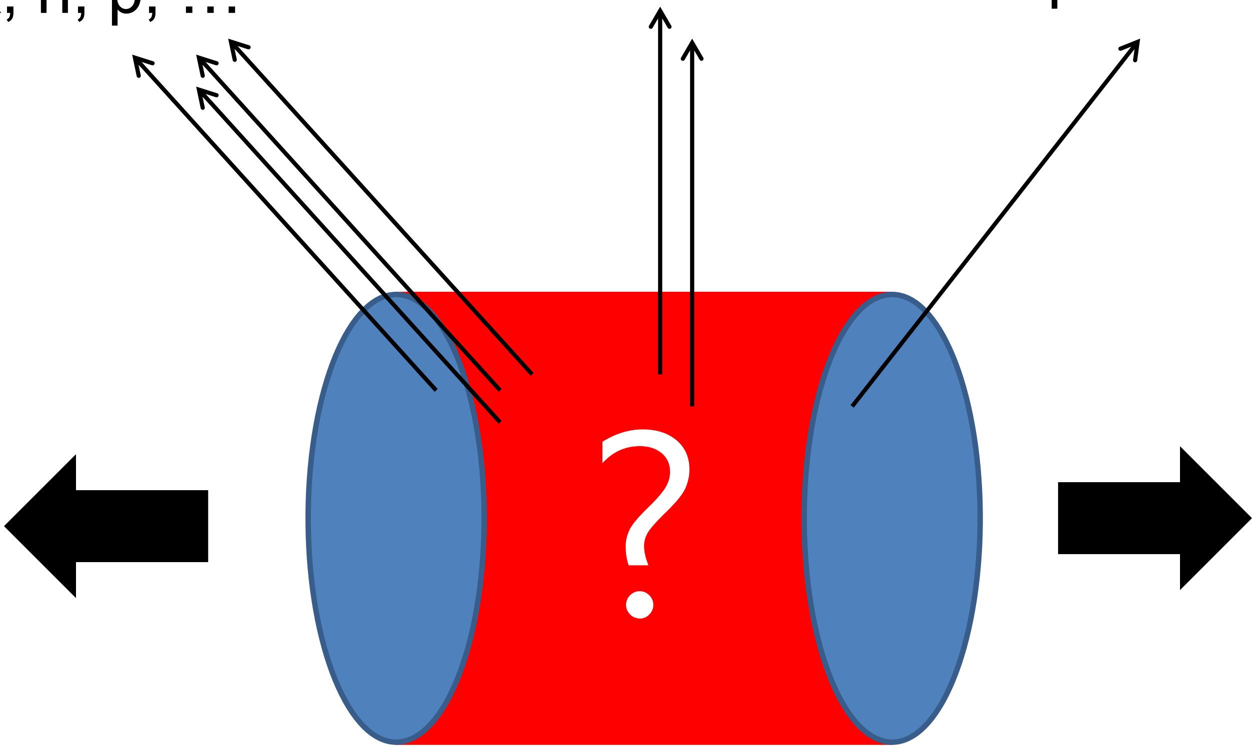


investigate the properties of the matter through produced particles

bulk particles
π, K, n, p, …

hard probes
charm, bottom, jets, …

electromagnetic
probes γ, **e+e- (γ*)**



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
- …

Some characteristics of dilepon

- advantages

1. no color charge → no further interactions in nuclear matter after its production
2. one more dimension (invariant mass) compared to real photons

Low mass dilepton :

dominated by hadronic sources

One can study the modification of hadron spectral functions in nuclear matter (mass shift and/or width broadening due to chiral symmetry restoration and interactions in the medium)

Intermediate mass dileptons :

dominated by partonic sources & heavy flavor decays

One can possibly study QGP matter

- disadvantage

1. small yield because of electromagnetic coupling ($\alpha = 1/137$)

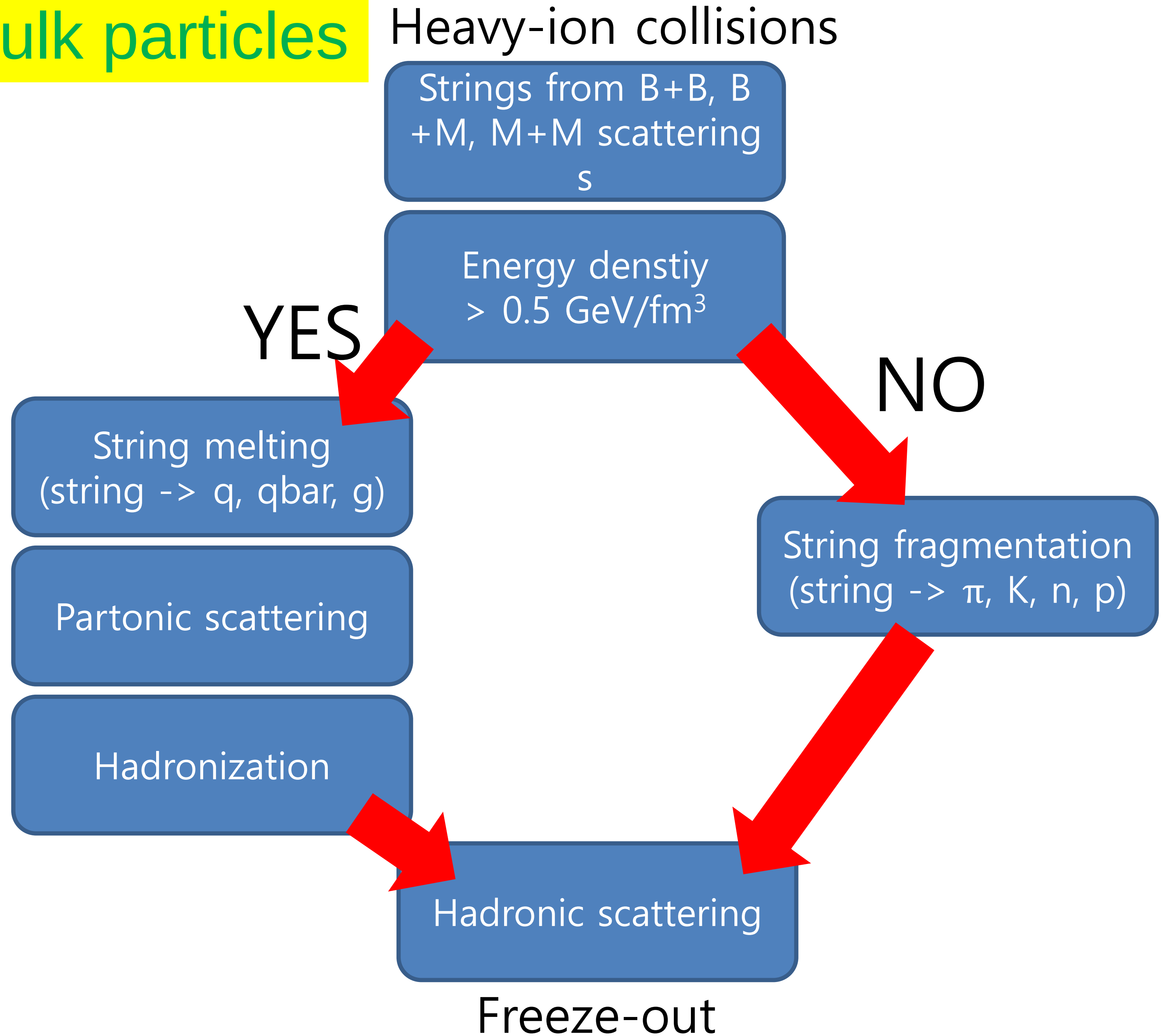
- One special feature

Dileptons are produced continuously from the initial hard scatterings to the freeze-out in heavy-ion collisions

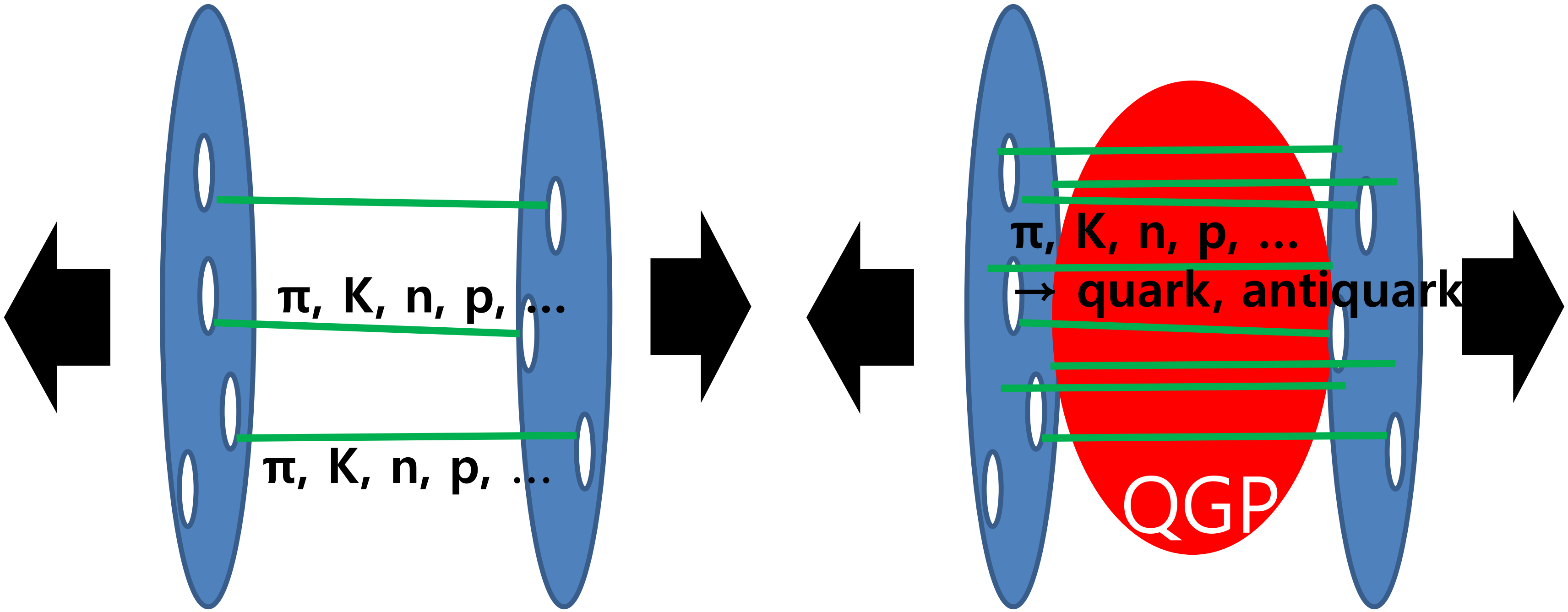
Therefore, we need a model well describing heavy-ion collisions from beginning to the end.

2. Parton-Hadron-String Dynamics (PHSD)

for bulk particles



- String fragmentation (low energy density)
- String melting (high energy density)



A partonic matter is produced throgh string melting

Partonic matter described by the
Dynamical Quasi-Particle Model (DQPM)

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

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

Mass and width from HTL at high T

- quarks:

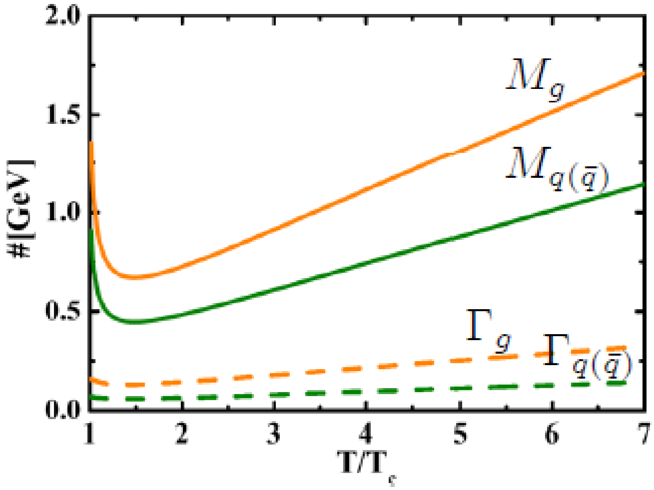
mass: $M^2_{q(\bar{q})}(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$

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

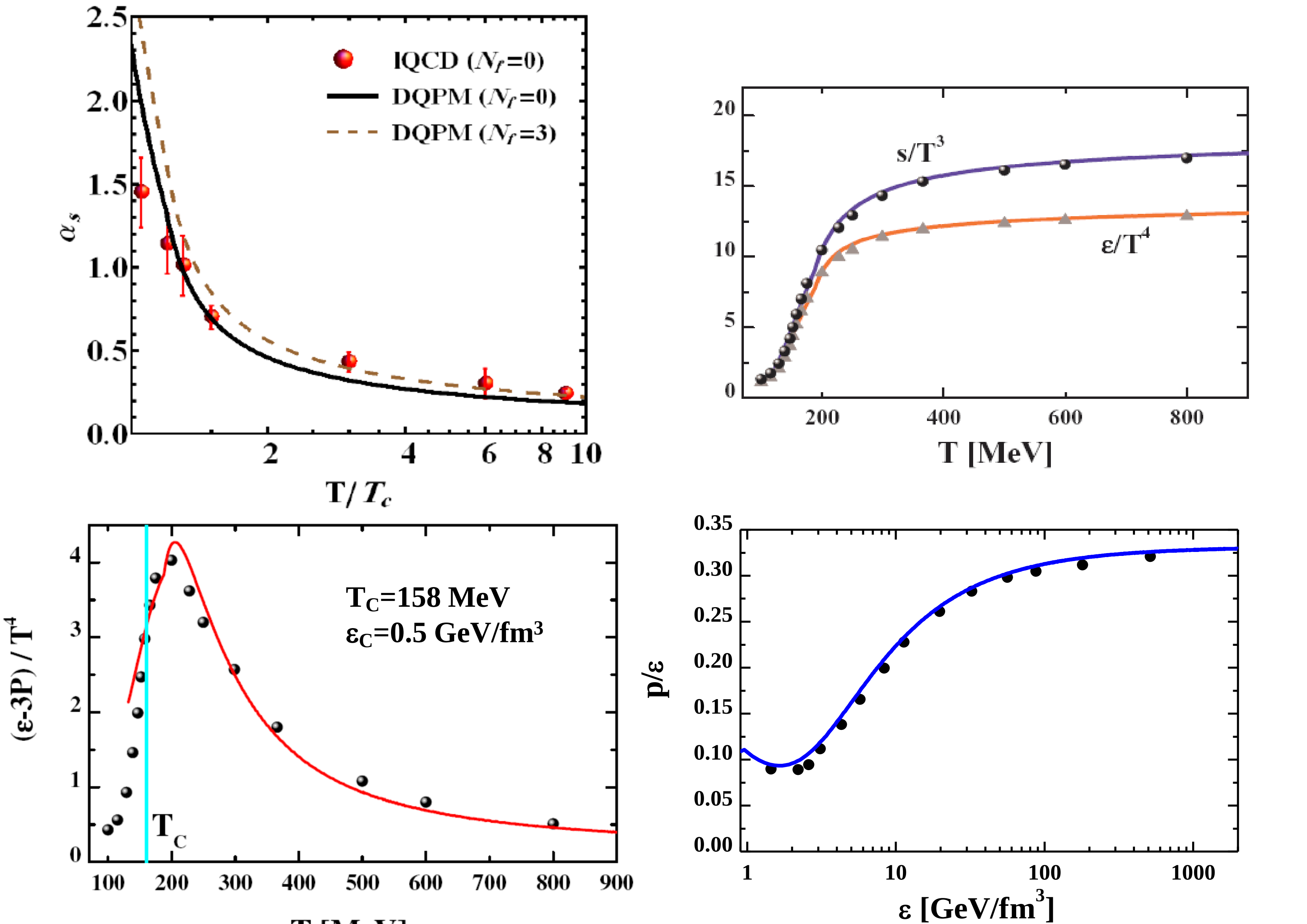
width: $\Gamma_g(T) = \frac{1}{3}N_c \frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2} + 1\right)$



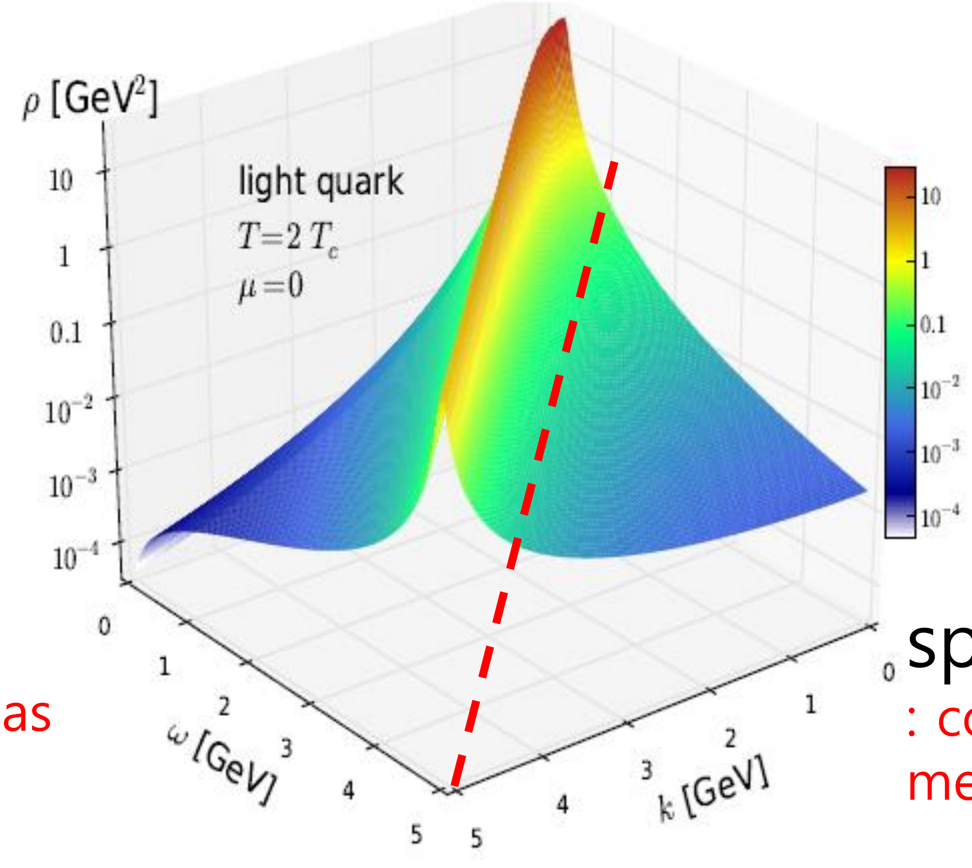
$N_c = 3$, $N_f=3$

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

quark/gluon spectral function



time-like

: propagate as a particle

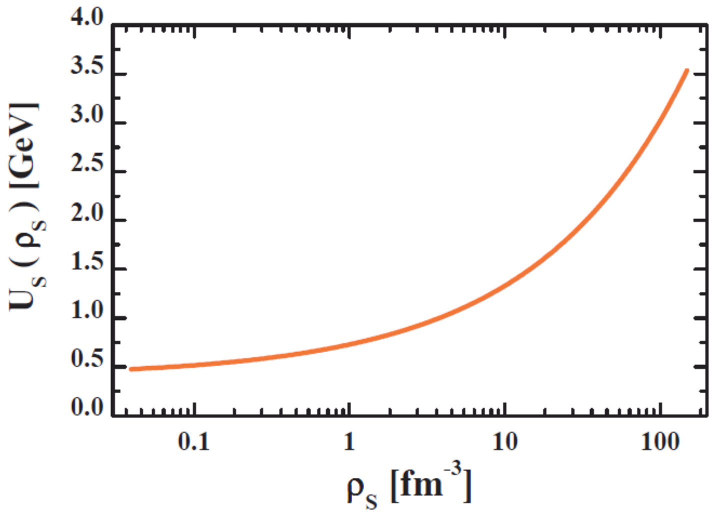
space-like

: 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 stems from the space-like part of parton spectral function.



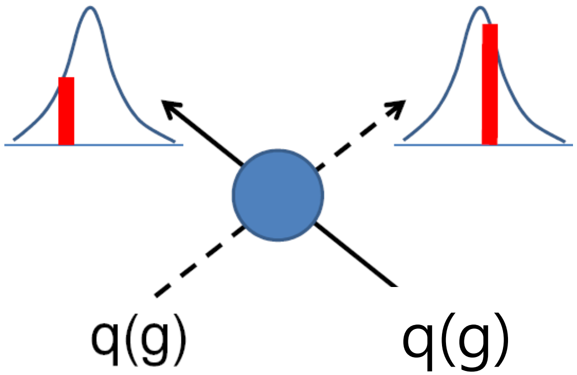
U_s increases with ρ_S

→ partons are outwardly accelerated in heavy ion-collisions.

It helps to reproduce experimental data

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

Parton scattering in the PHSD



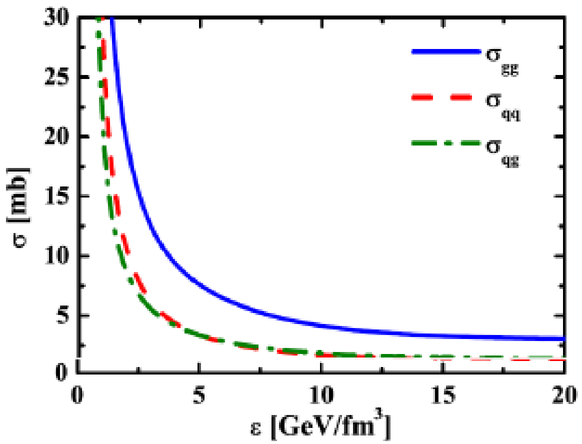
- (quasi-)elastic scattering :
- masses change in scattering

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

- inelastic scattering :

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

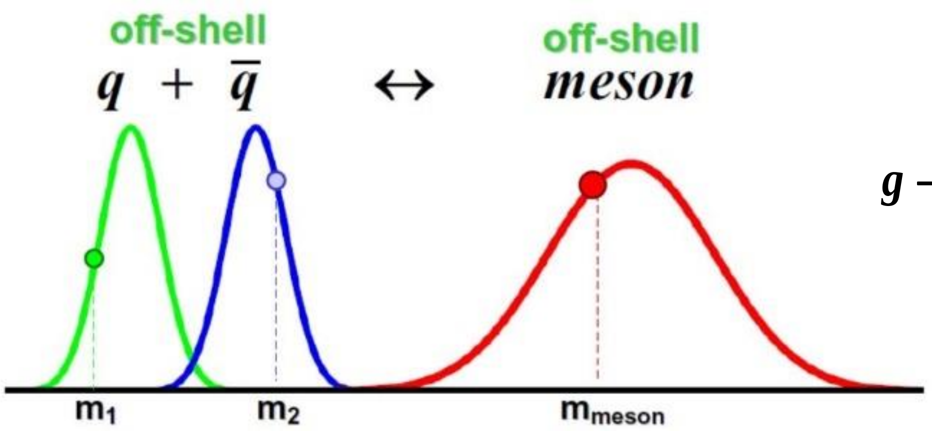
suppressed due to large gluon mass



Scattering cross sections based on spectral widths

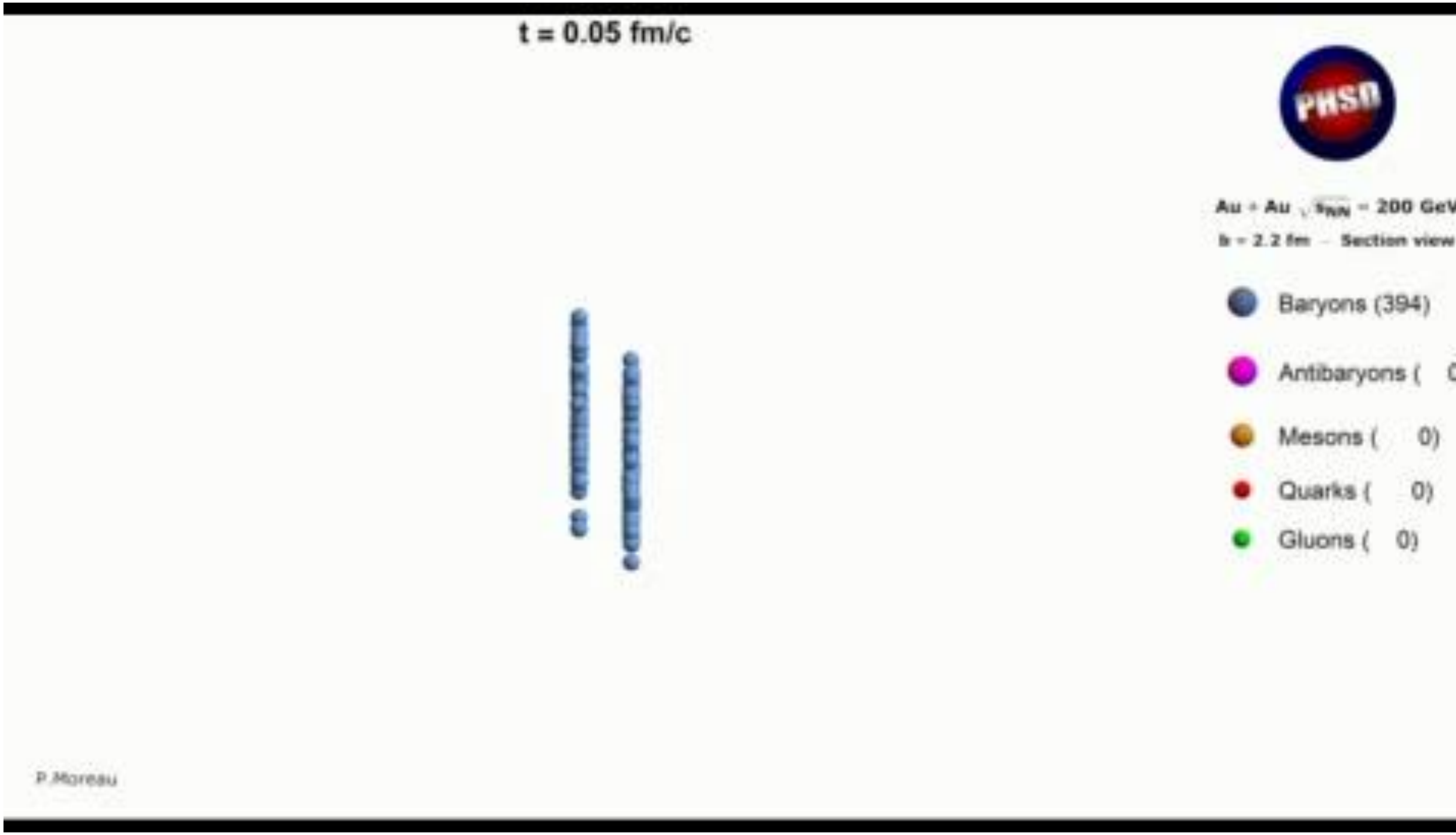
Hadronization in the PHSD

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



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

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


t = 0.05 fm/c
PHSD
Au + Au √sNN = 200 GeV
b = 2.2 fm – Section view
Baryons (394)
Antibaryons (0)
Mesons (0)
Quarks (0)
Gluons (0)
P.Moreau

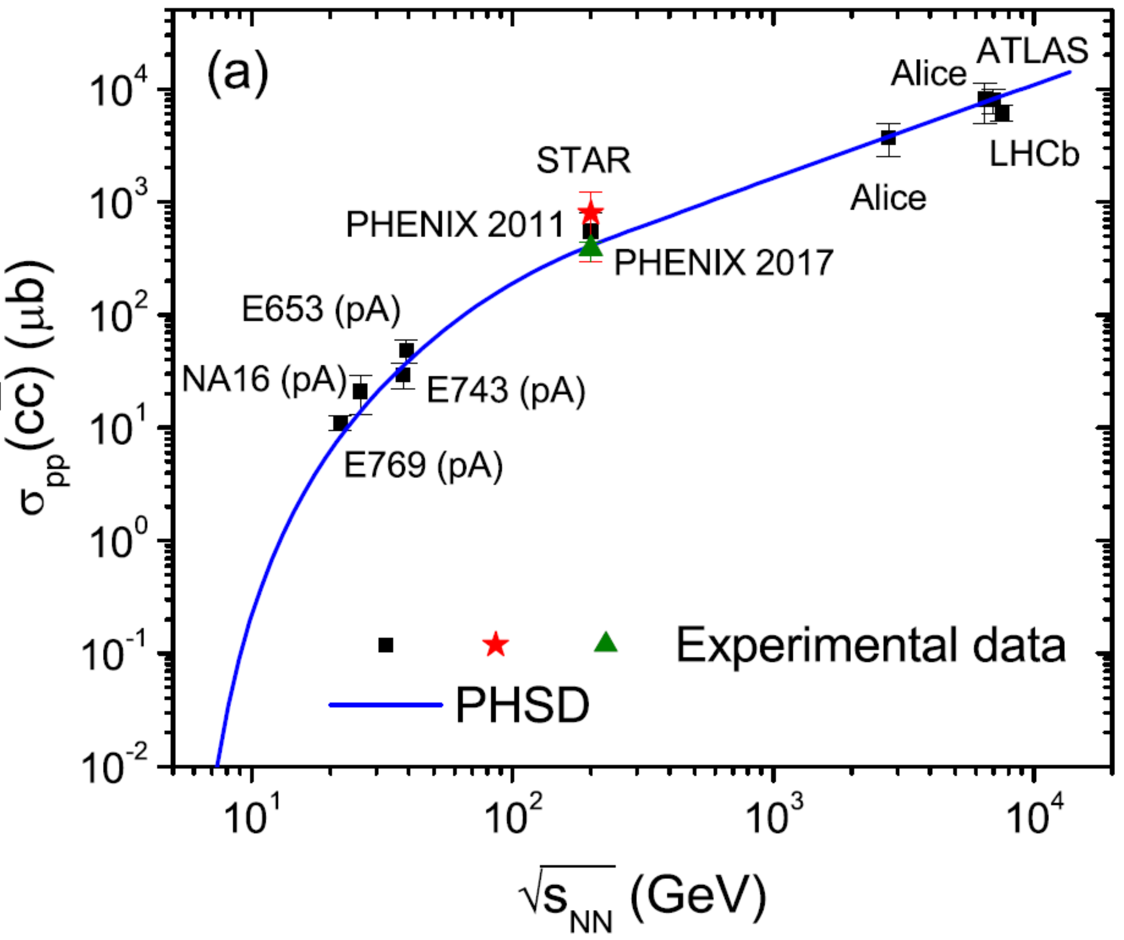
3. Heavy flavor production in HIC

3.1. p+p collisions

3.2. d+A collisions

3.3. A+A collisions

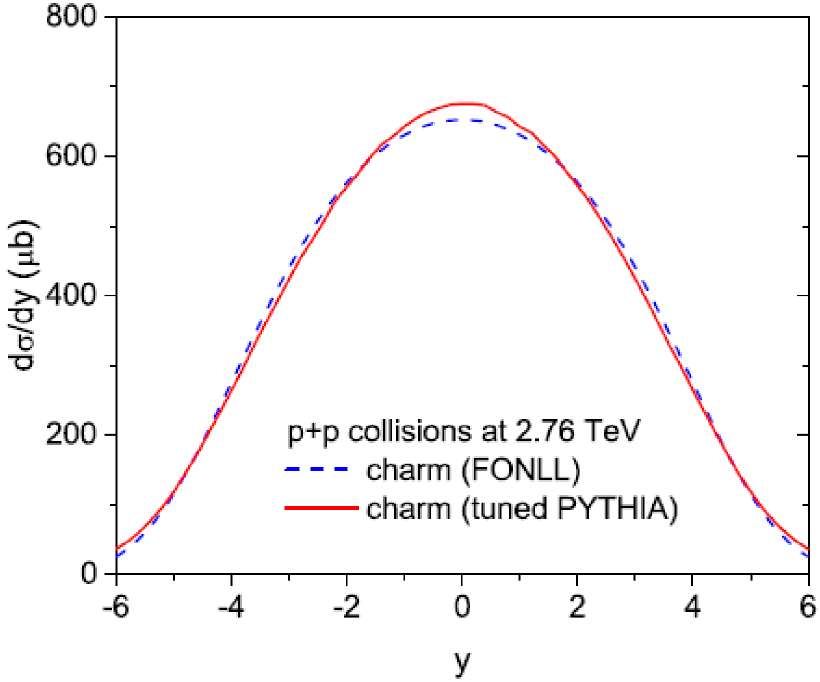
3.1. total cross section for charm production in p+p



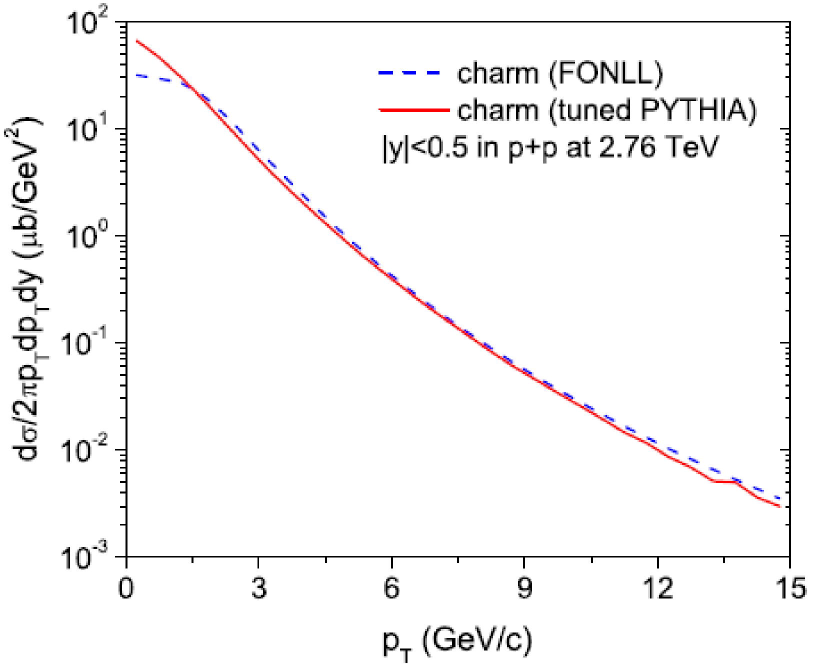
generate charm by using PYTHIA tuned to FONLL

Initial heavy flavors are generated by PYTHIA with rapidity and p_T rescaled to produce FONLL-shaped distributions

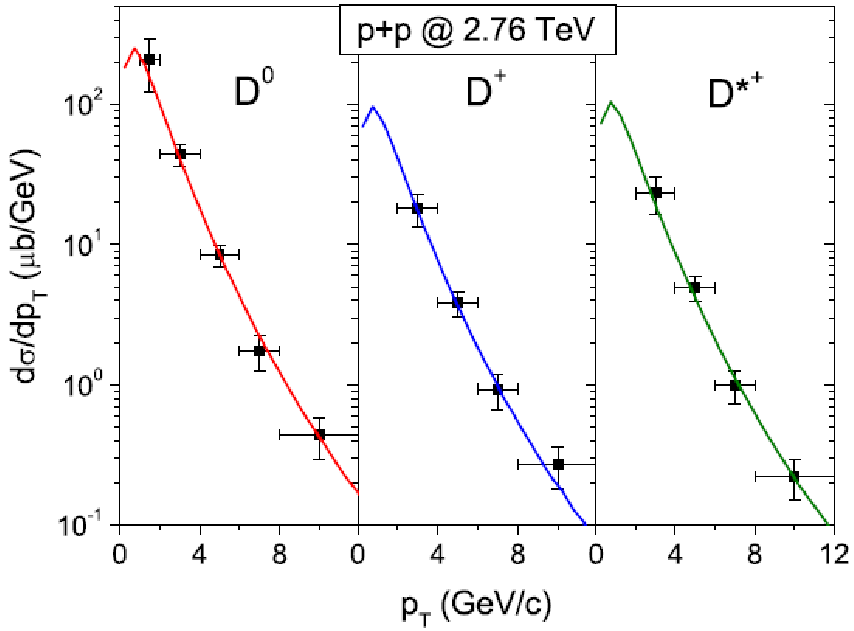
Rapidity distribution



p_T spectrum

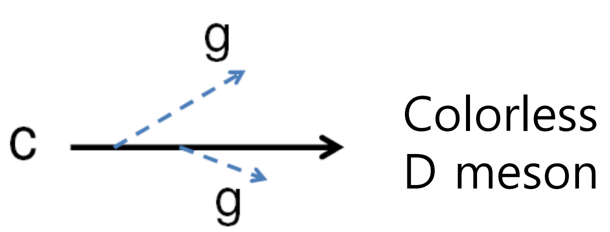


charm quark hadronizes through fragmentation in p+p



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

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



3.2. Charm production in p+A collisions (cold nuclear matter effects)

1. Shadowing

: Parton distribution function (PDF) modified in nucleus,
for which EPS09 is used.

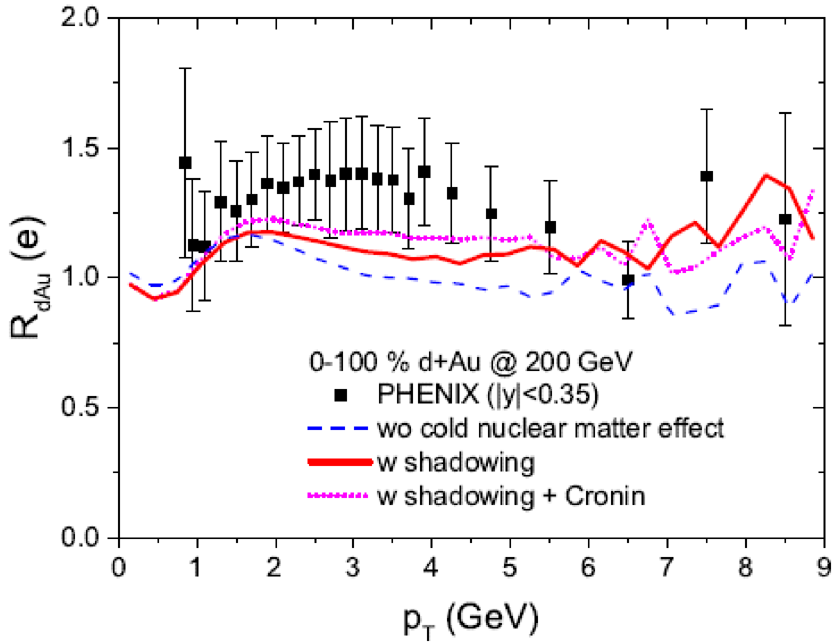
$$g + g \rightarrow h + \bar{h}, \qquad q + \bar{q} \rightarrow h + \bar{h}$$

2. Cronin effect

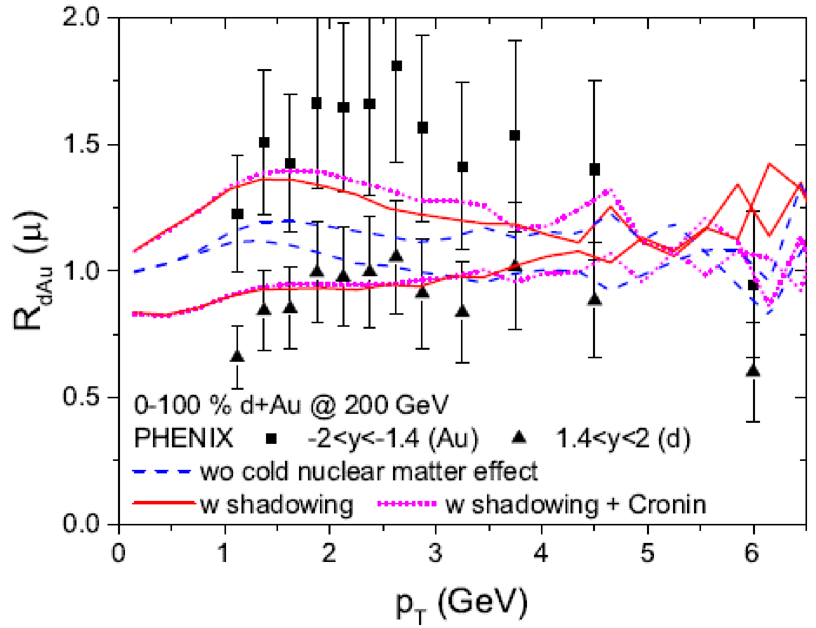
: Because of parton+N scattering in A(p)+A collisions,
p_T of produced particle is enhanced.

It is controversial whether the Cronin effect is include d in the shadowing effect or not.

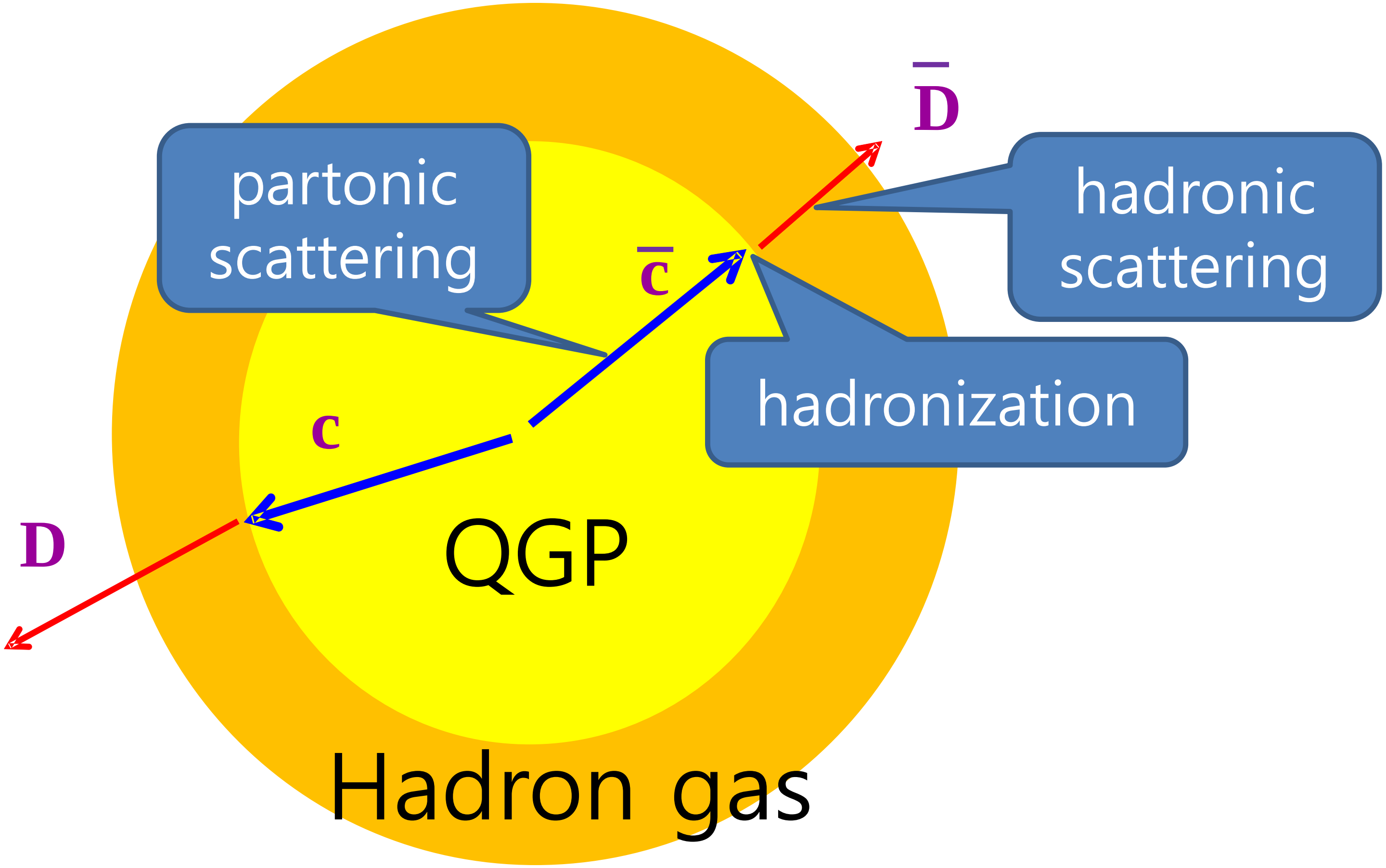
Mid-rapidity (e)
d+Au @ 200 GeV



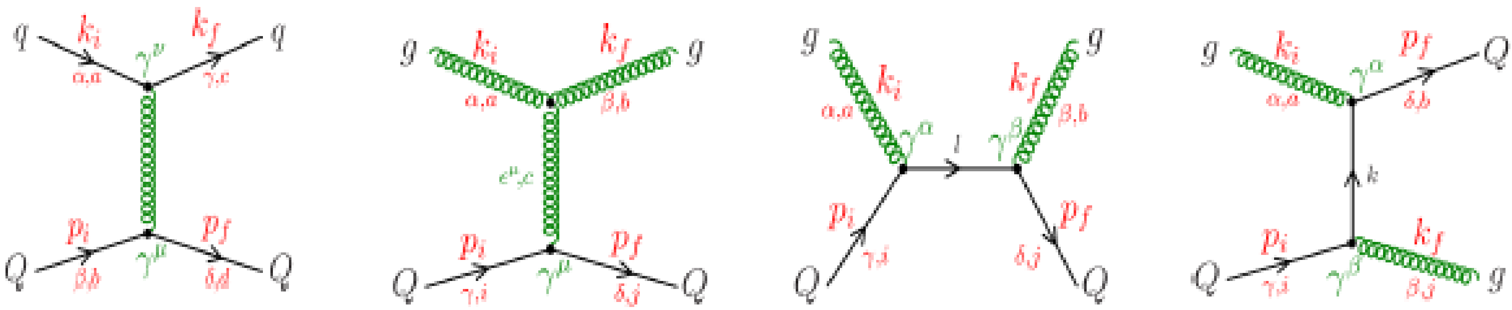
Forward/backward-rapidites (μ)
d+Au @ 200 GeV



3.3. Charm production in A+A (cold & hot nuclear matter effects)



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

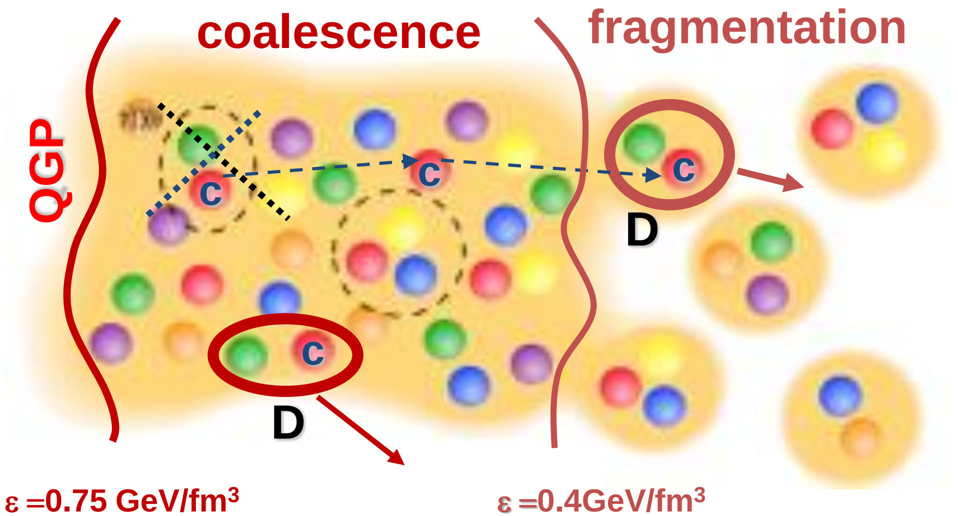


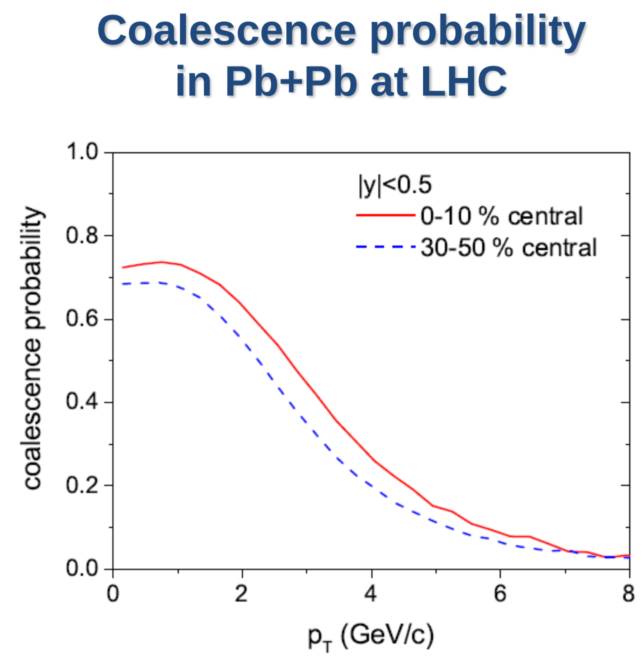
elastic scattering with off-shell massive partons

$Q+q(g) \rightarrow Q+q(g)$

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

Hadronization of heavy quarks





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

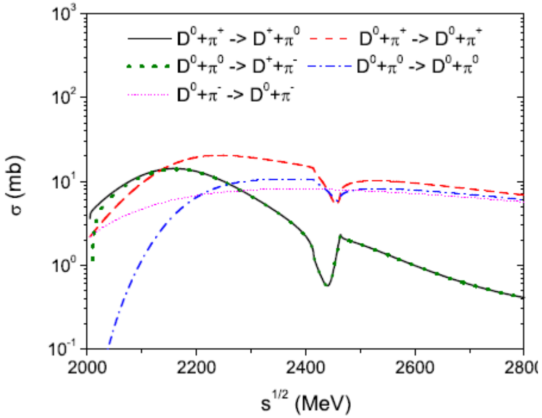
$$f(\boldsymbol{\rho},\mathbf{k}_\rho)=\frac{8g_M}{6^2}\exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2}-\mathbf{k}_\rho^2\delta^2\right]$$

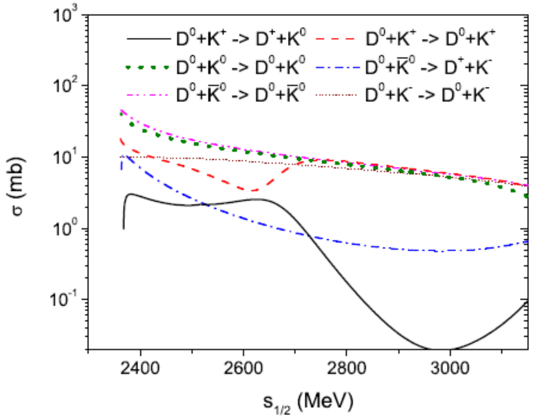
where $\boldsymbol{\rho}=\frac{1}{\sqrt{2}}(\mathbf{r}_1-\mathbf{r}_2),\quad \mathbf{k}_\rho=\sqrt{2}\,\frac{m_2\mathbf{k}_1-m_1\mathbf{k}_2}{m_1+m_2}$

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 the hadron gas

D-meson scattering with mesons

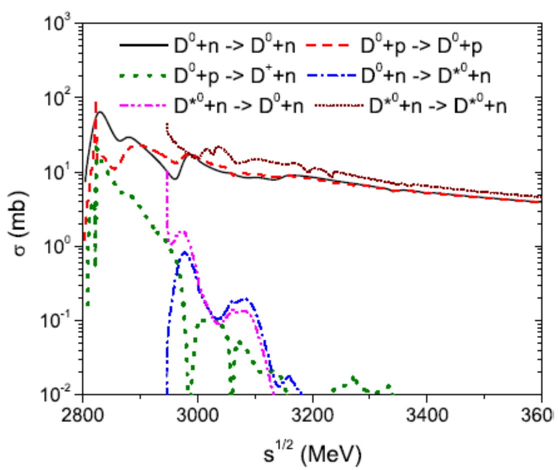


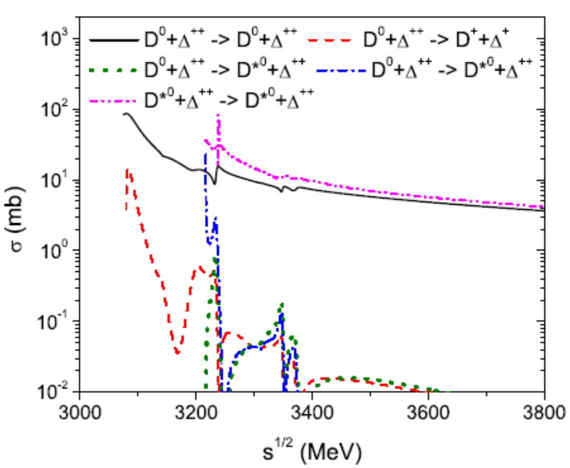


Calculated in effective Lagrangian with heavy-quark spin symmetry

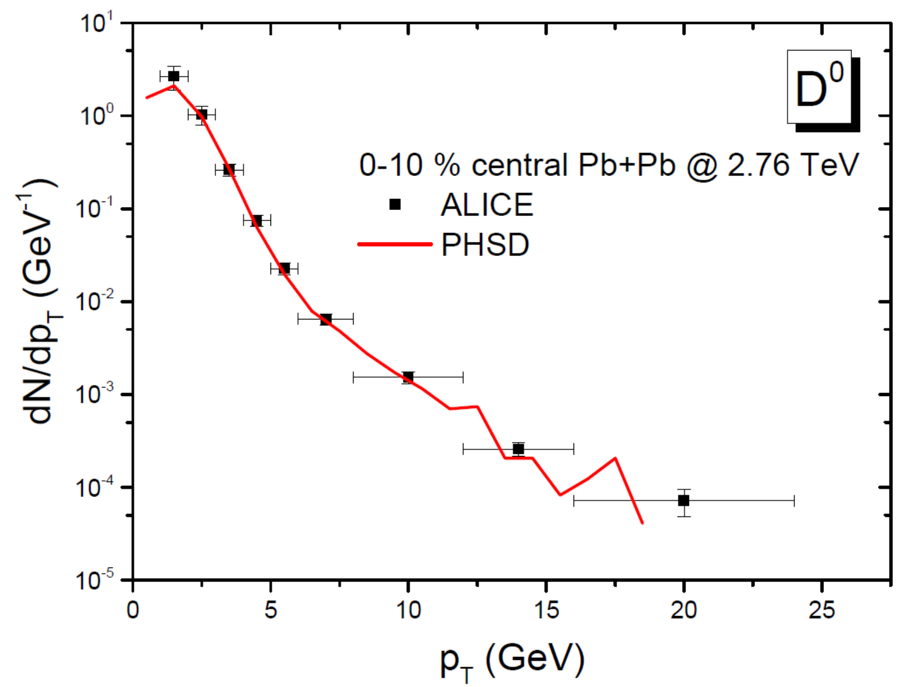
L. M. Abreu, D. Cabrera, F. J. Llanes-Estrada, J. M. Torres-Rincon, Annals Phys. 326, 2737 (2011)

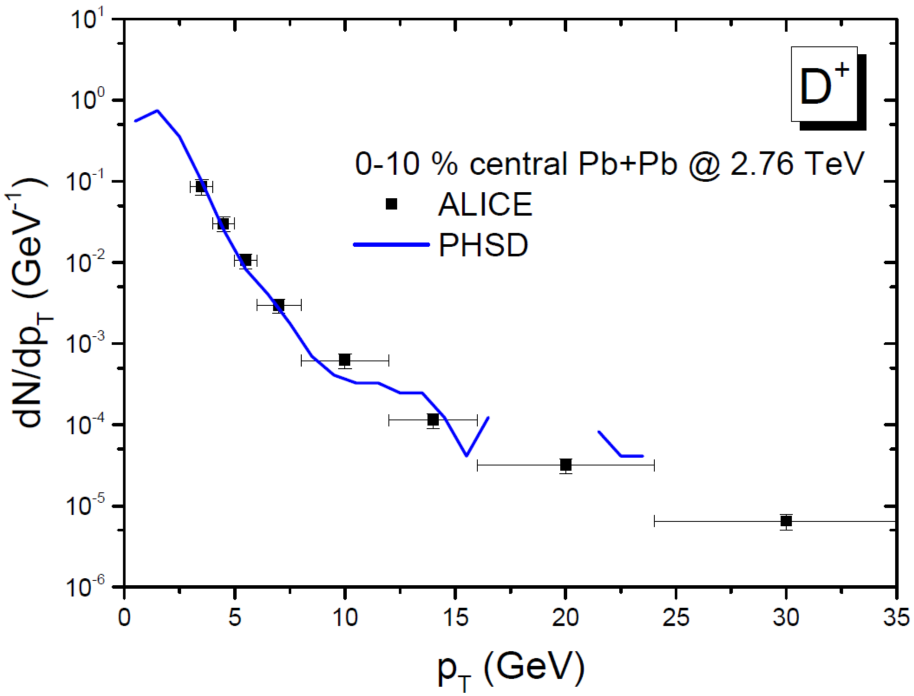
D-meson scattering with baryons

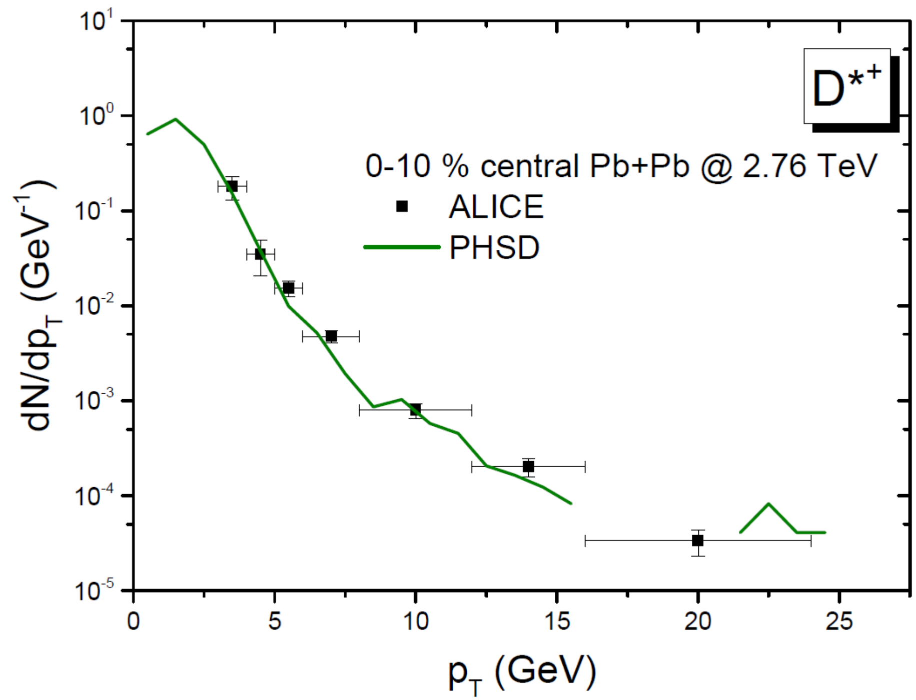




D meson spectra in Pb+Pb collisions at 2.76 TeV

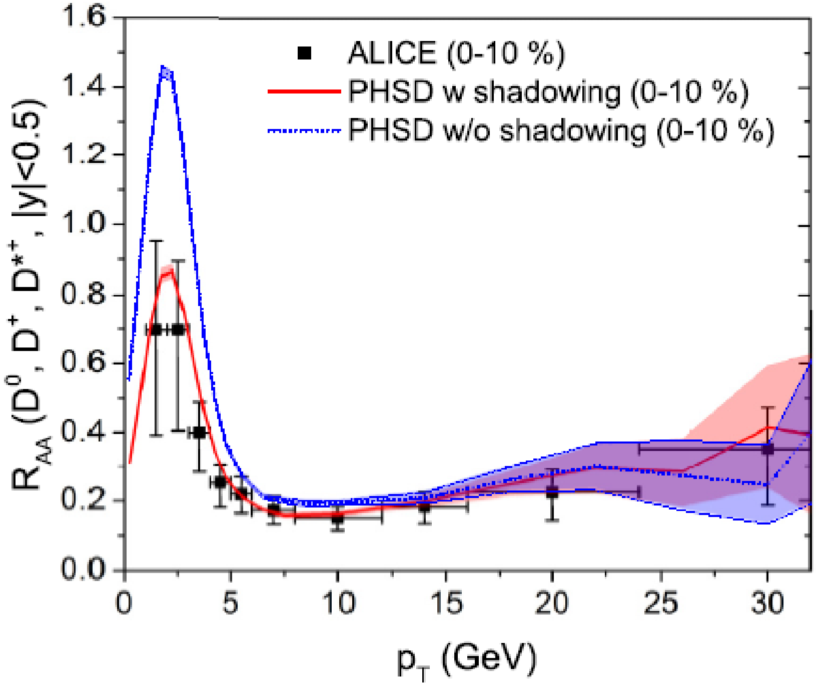




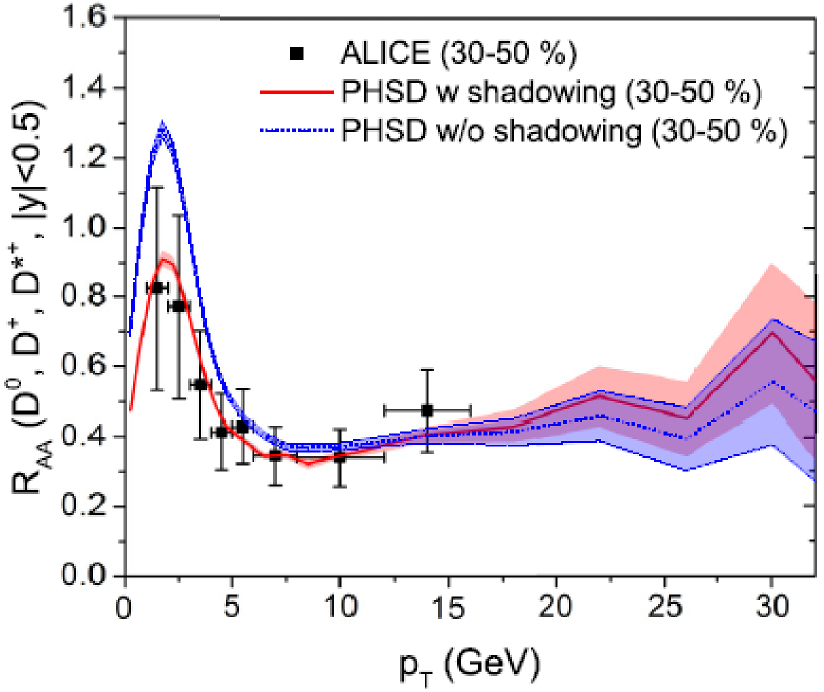


Nuclear modification factors (R_{AA})

0-10 % Pb+Pb @ 2.76 TeV



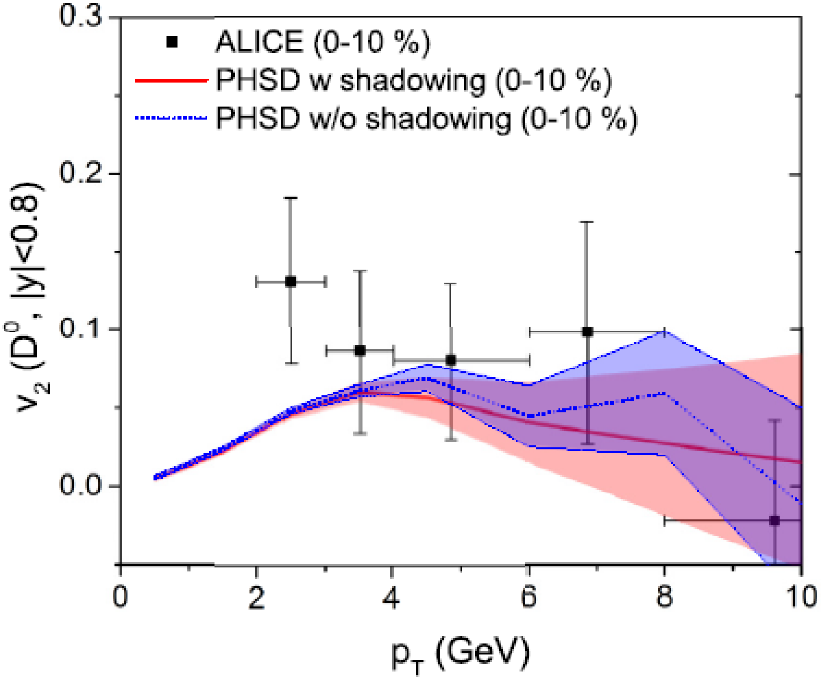
30-50 % Pb+Pb @ 2.76 TeV



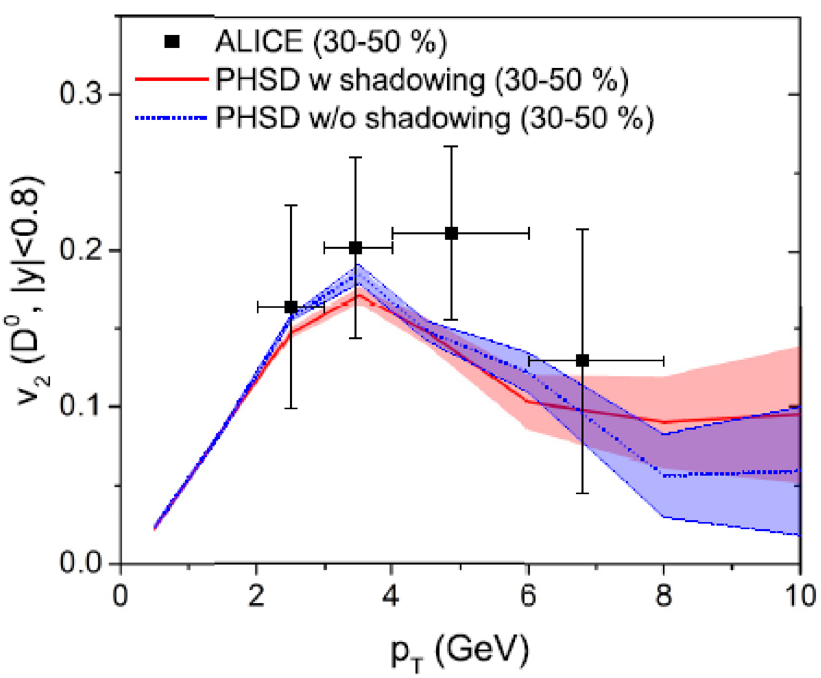
$$R_{AA}(p_T) \equiv \frac{dN_D^{\text{Au+Au}}/dp_T}{N_{\text{binary}}^{\text{Au+Au}} \times dN_D^{p+p}/dp_T}$$

Elliptic flow (v_2)

0-10 % Pb+Pb @ 2.76 TeV



30-50 % Pb+Pb @ 2.76 TeV



$$v_2(p_T) \equiv \frac{\int d\phi \cos 2\phi \left(dN_D^{\mathrm{Pb+Pb}}/dp_T d\phi\right)}{dN_D^{\mathrm{Pb+Pb}}/dp_T},$$

4. Dilepton production in HIC

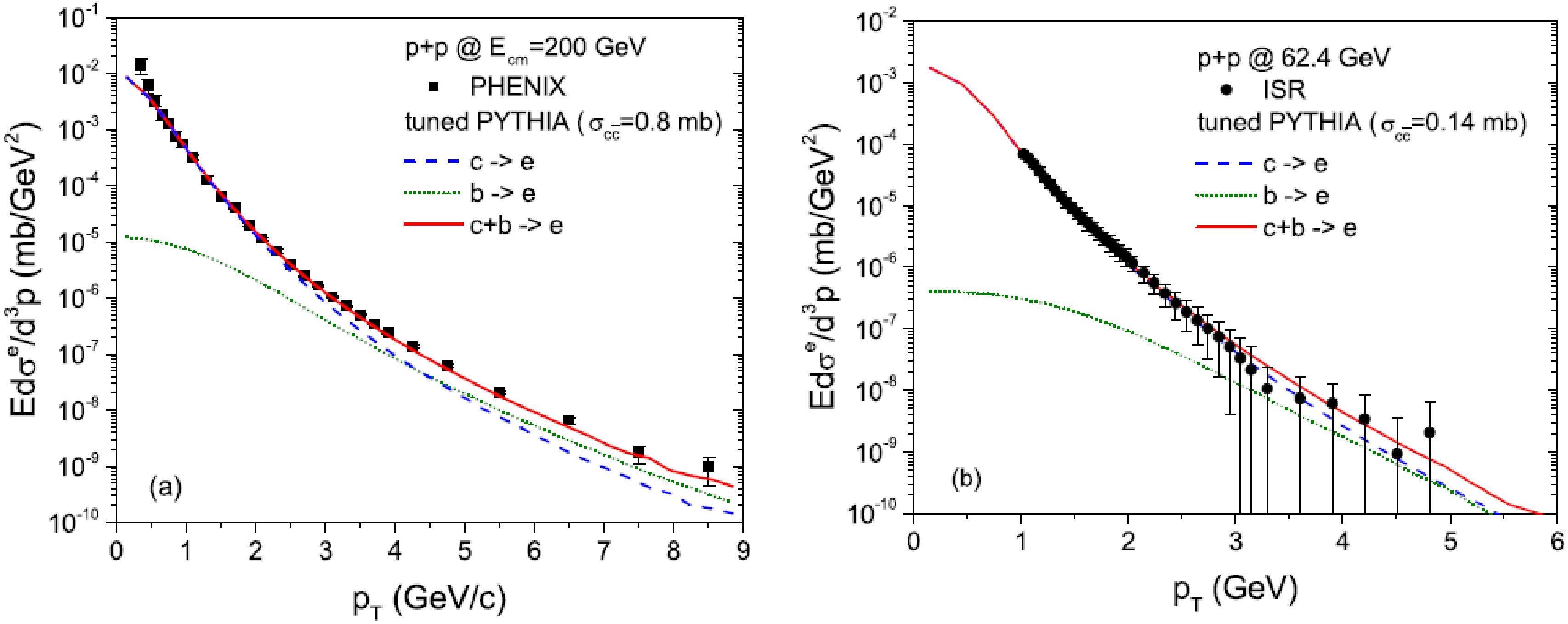
4.1. heavy flavor pair

4.2. partonic scattering

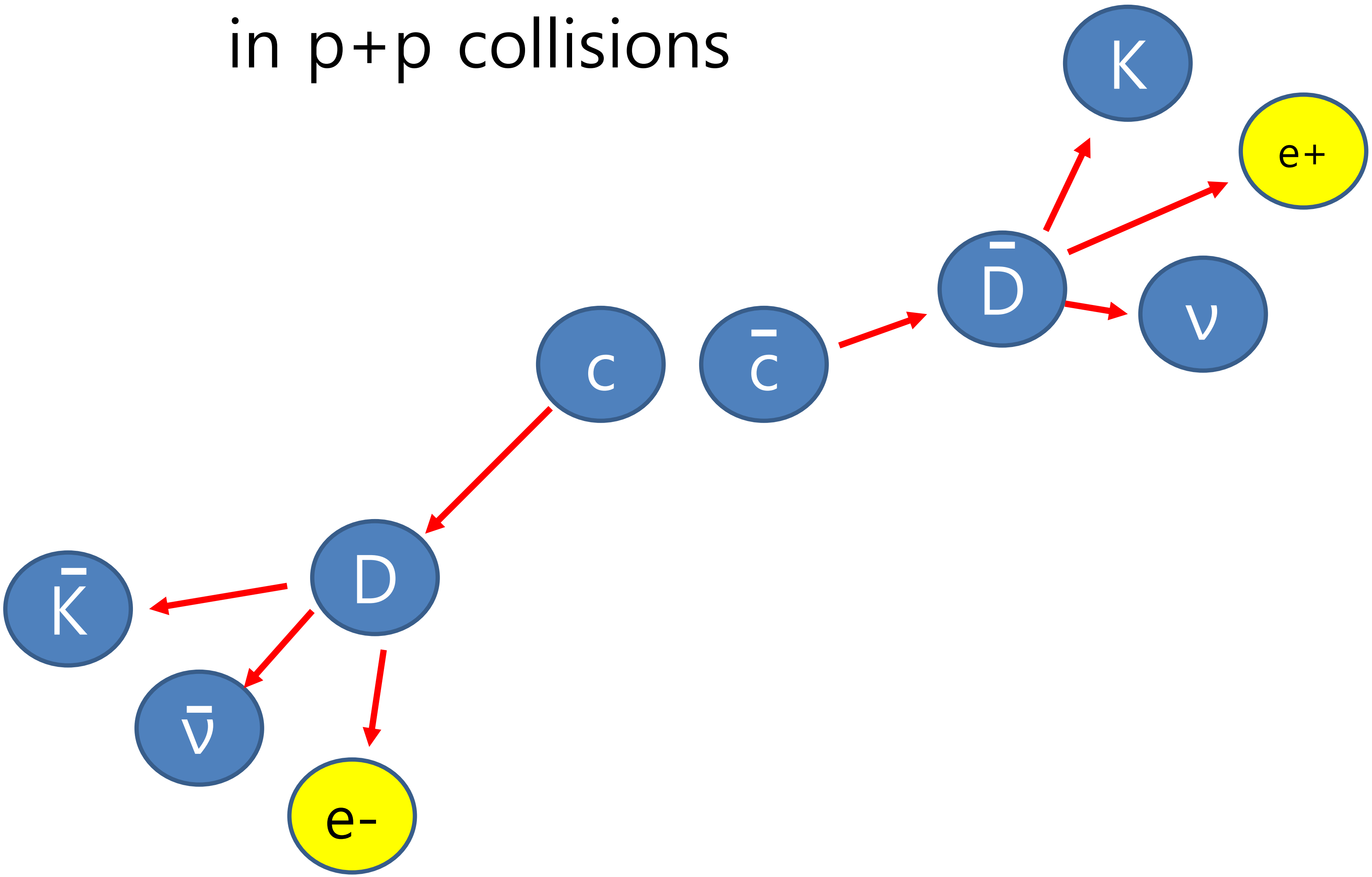
4.3. hadronic scattering

4.1. dilepton from heavy flavor pair

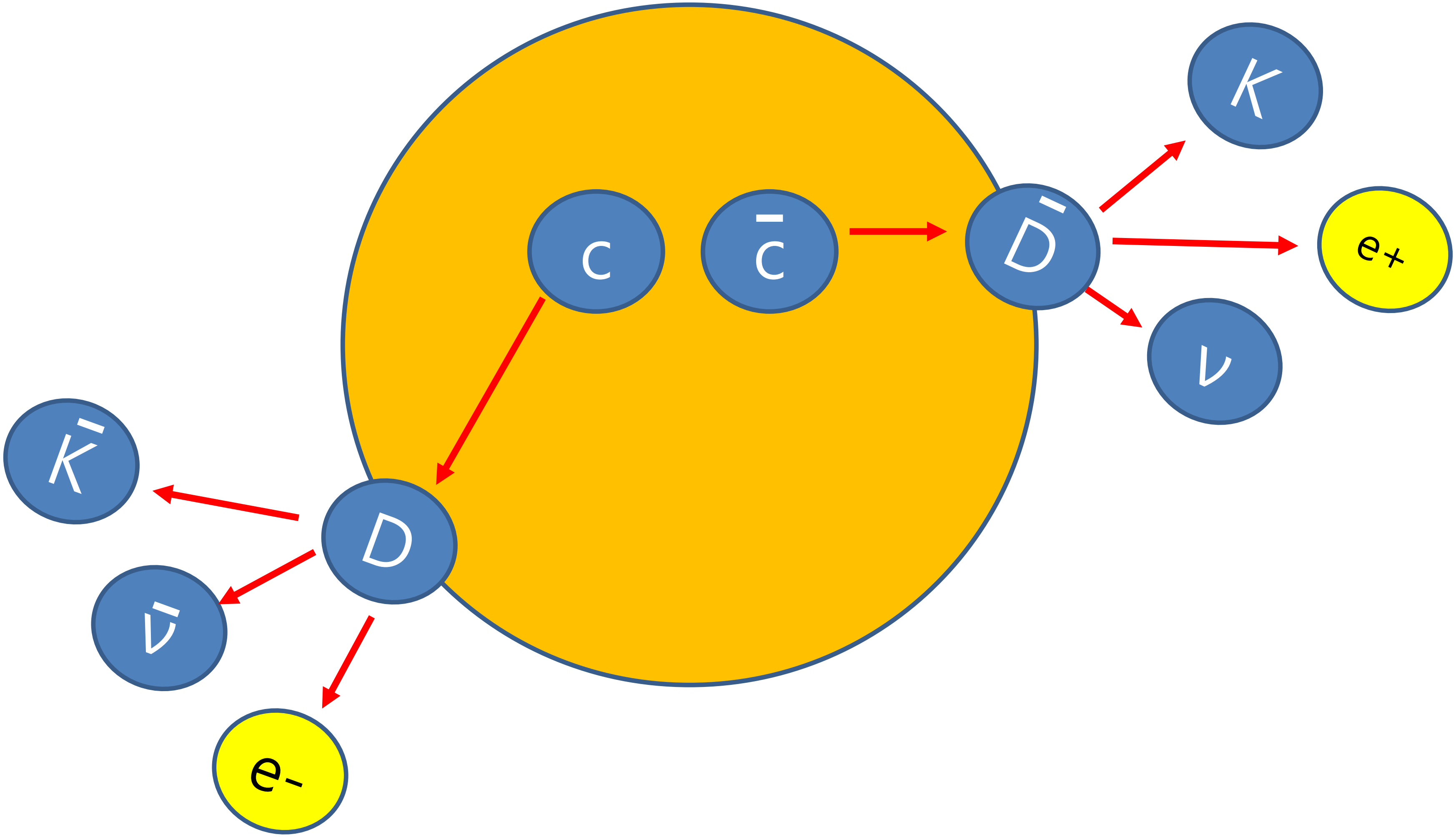
- $D(B) \rightarrow \bar{K}(\bar{D}) + e^{-} + \bar{\nu},$
- $\bar{D}(\bar{B}) \rightarrow K(D) + e^{+} + \nu$
- Single electrons from heavy flavor in p+p



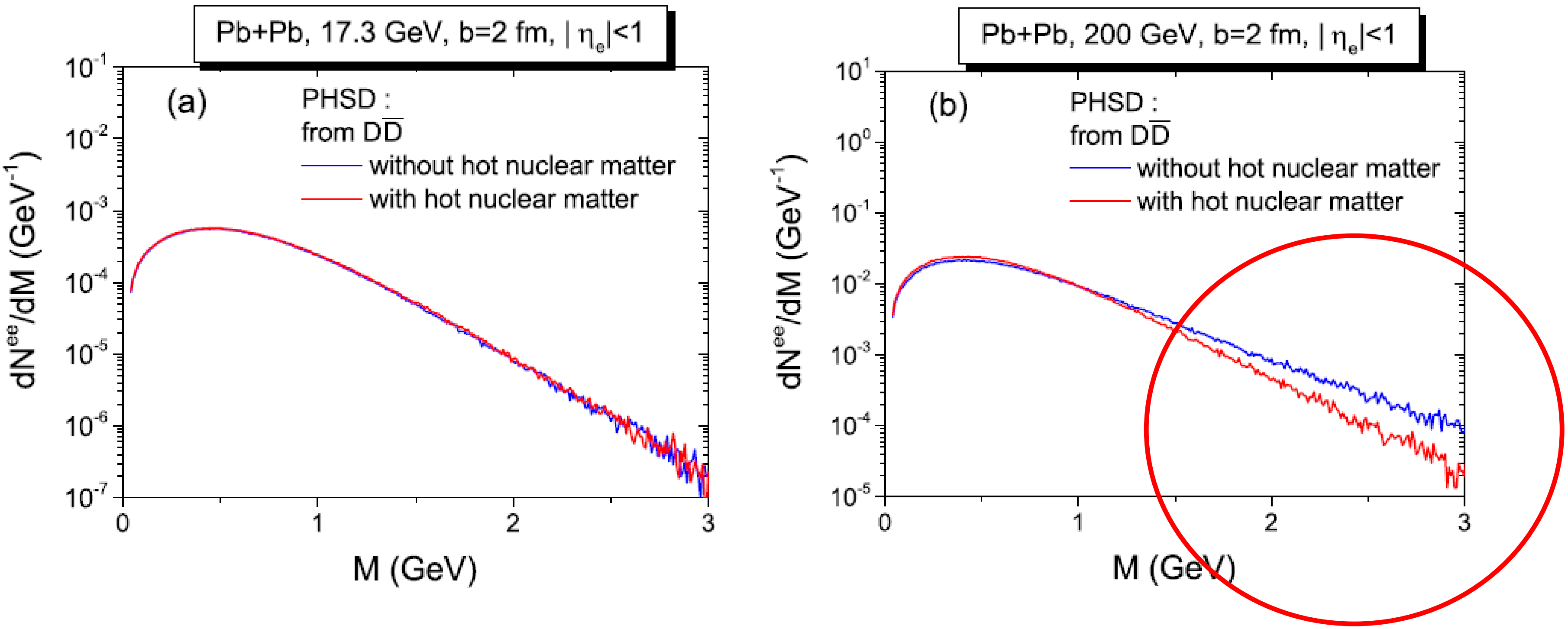
in p+p collisions



in A+A collisions



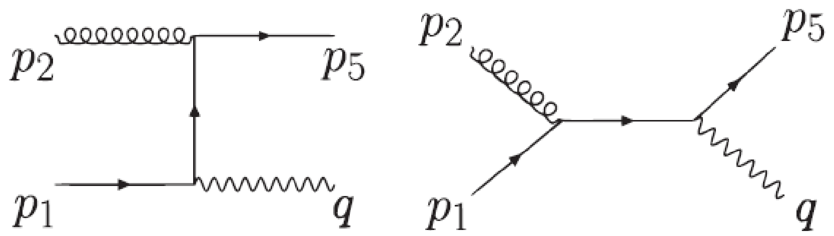
Nuclear modification of dileptons in heavy-ion collisions



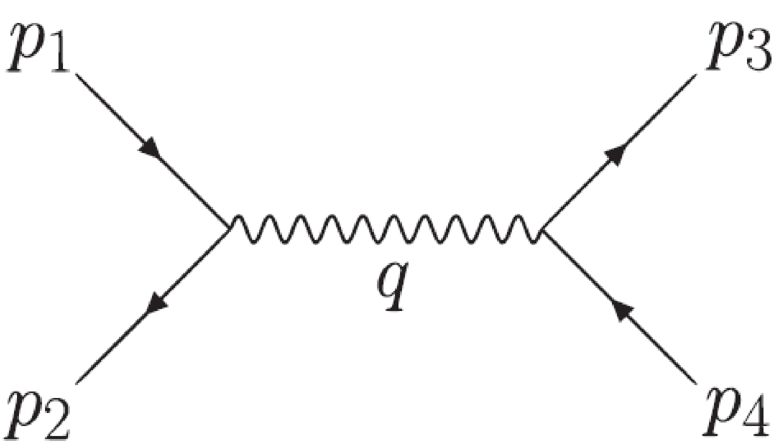
Nuclear matter makes invariant mass spectrum of dileptons softer

4.2. partonic scattering

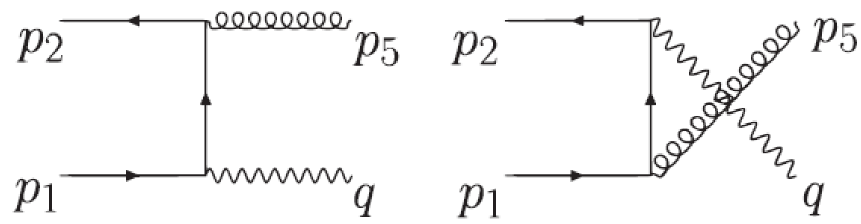
$q(\bar{q}) + g \rightarrow q(\bar{q}) + e^{+} + e^{-}$



$q + \bar{q} \rightarrow e^{+} + e^{-}$



$q + \bar{q} \rightarrow g + e^{+} + e^{-}$

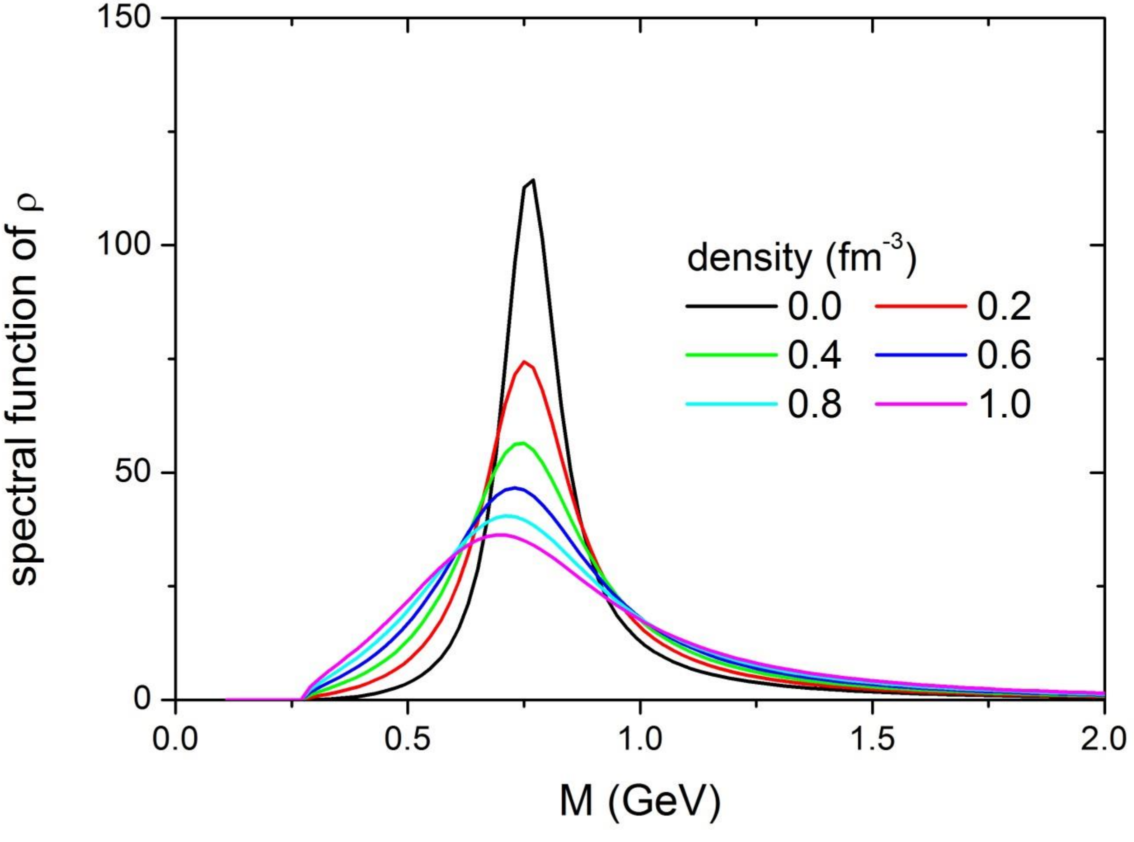


Interactions of massive off-shell partons
with a temperature-dependent strong coupling

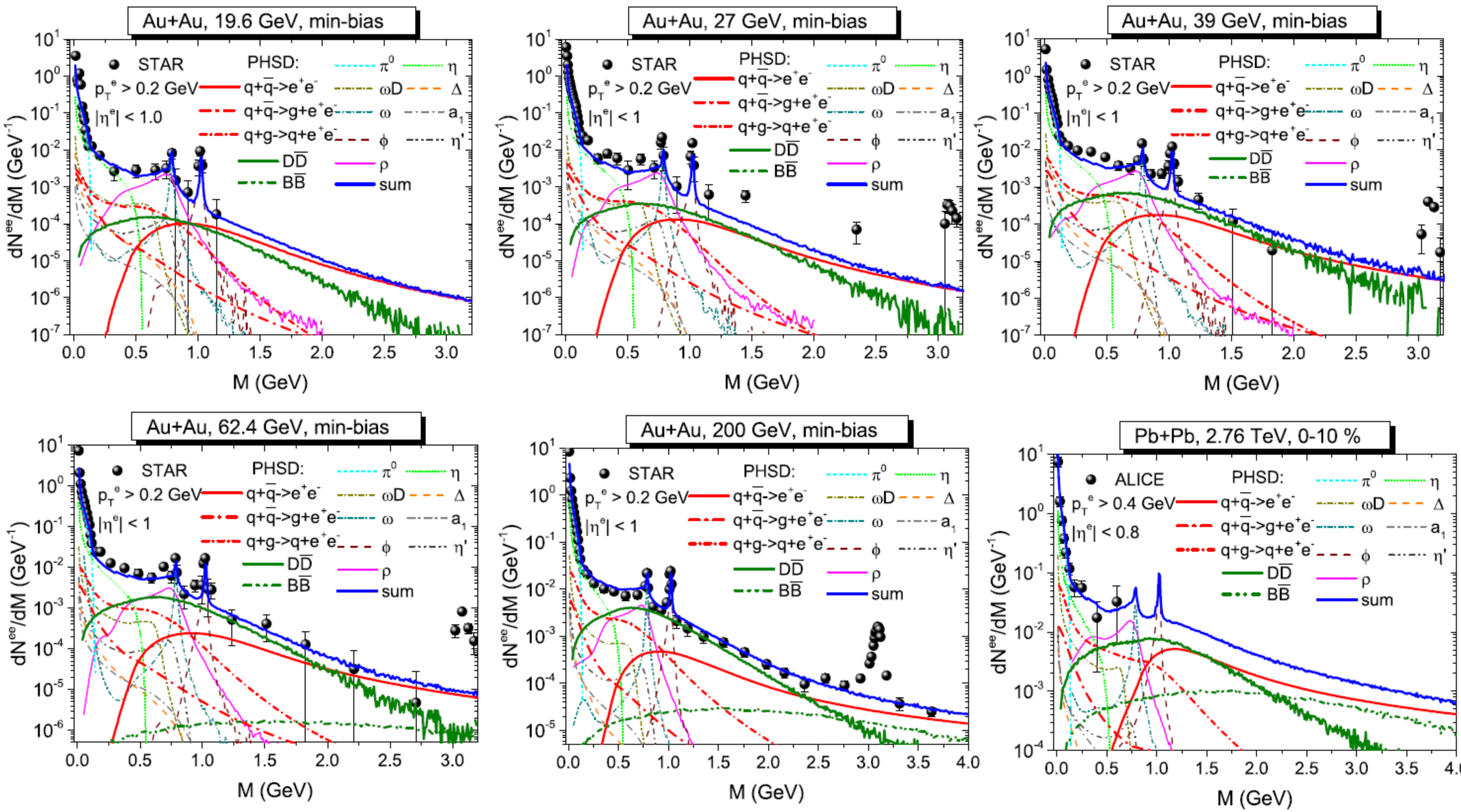
4.3. hadronic scattering

	Direct	Dalitz	Other
π^0	–	$\pi^0 \to \gamma\, e^+ e^-$	–
η^0	–	$\eta^0 \to \gamma\, e^+ e^-$	
η'	–	$\eta^0 \to \gamma\, e^+ e^-$	
ρ^0	$\rho^0 \to e^+ e^-$	–	–
ω^0	$\omega^0 \to e^+ e^-$	$\omega^0 \to \pi^0\, e^+ e^-$	–
ϕ^0	$\phi^0 \to e^+ e^-$		–
			–
			–
D	–	–	$D^\pm \to e^\pm \nu_e + X$
B	–	–	$B^\pm \to e^\pm \nu_e + X$

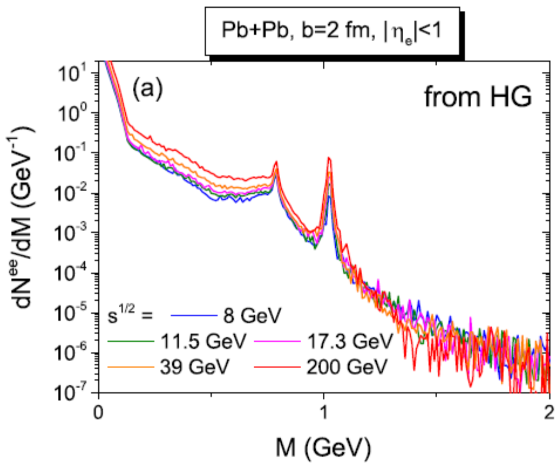
ρ meson spectrum in nuclear matter

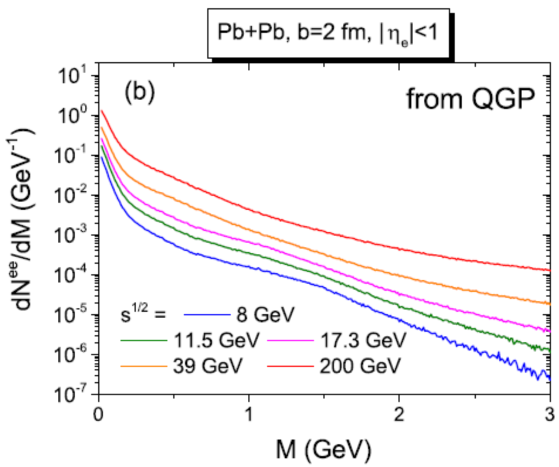


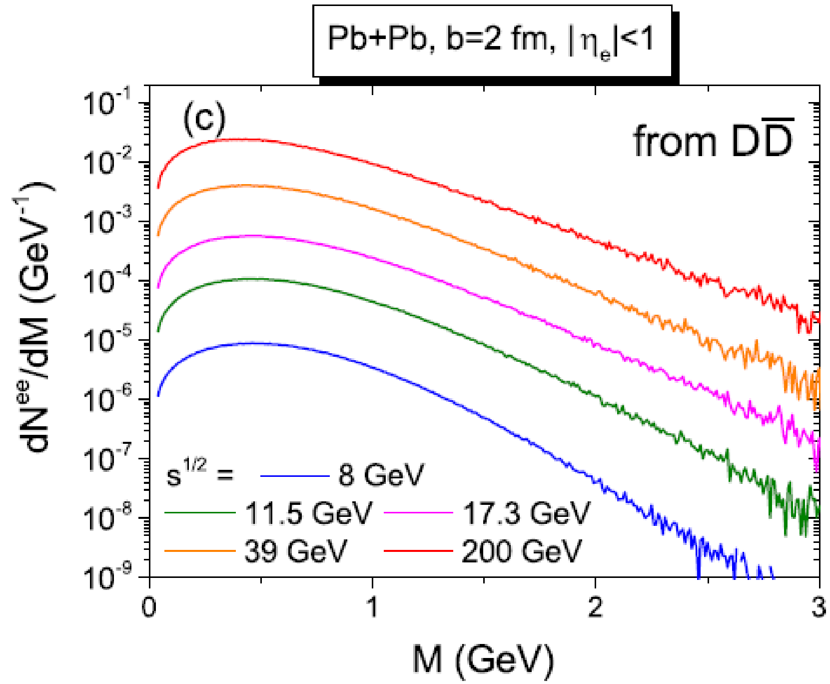
Comparison to experimental data (19.6 GeV ~ 2.76 TeV)



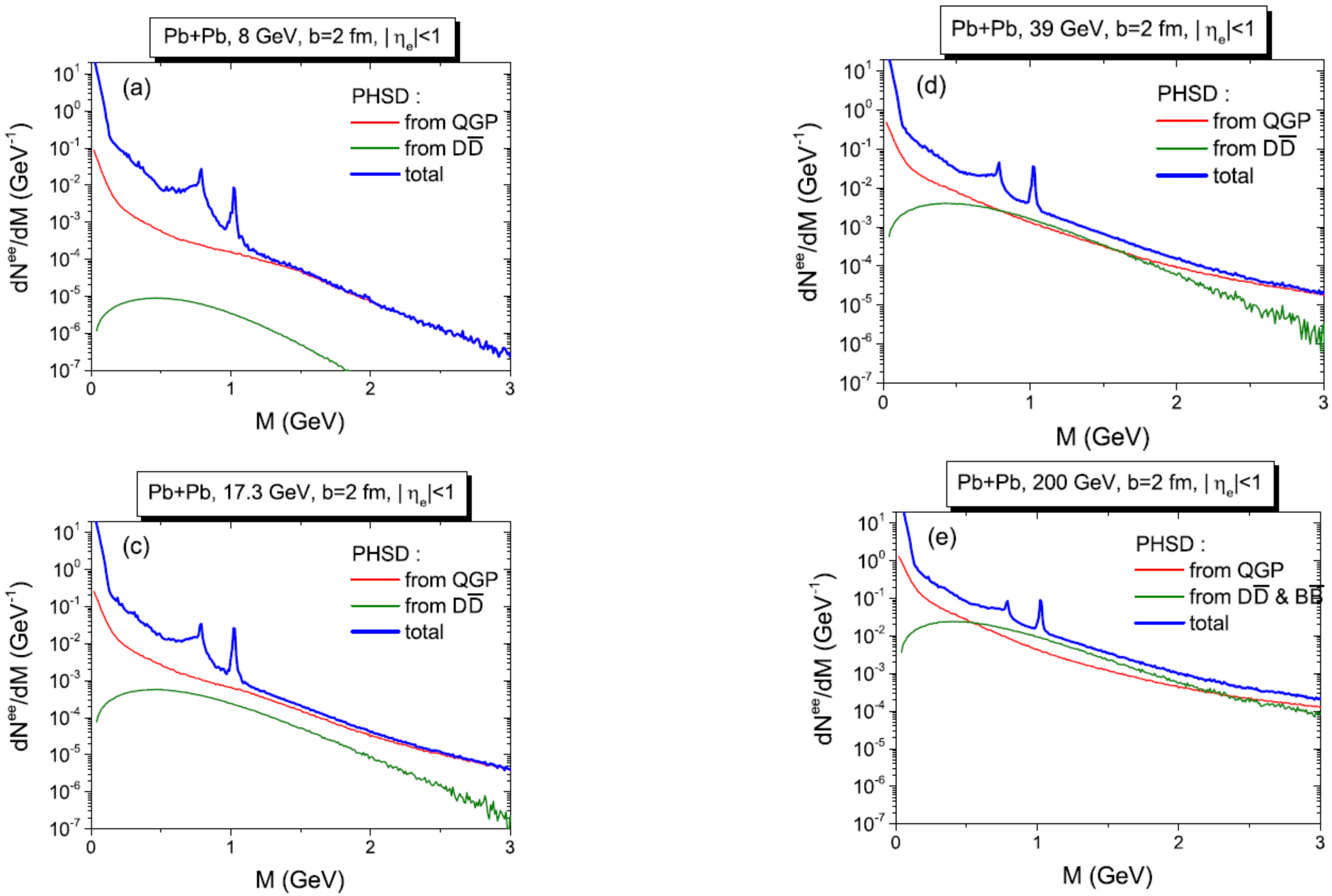
Three contributions at RHIC energies





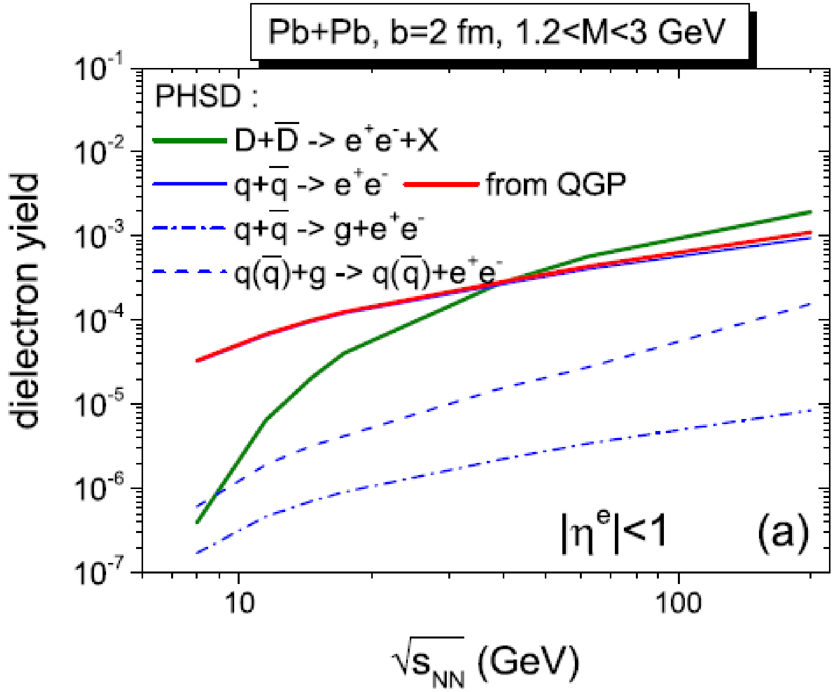


Comparison of contributions from QGP & heavy-flavor pairs

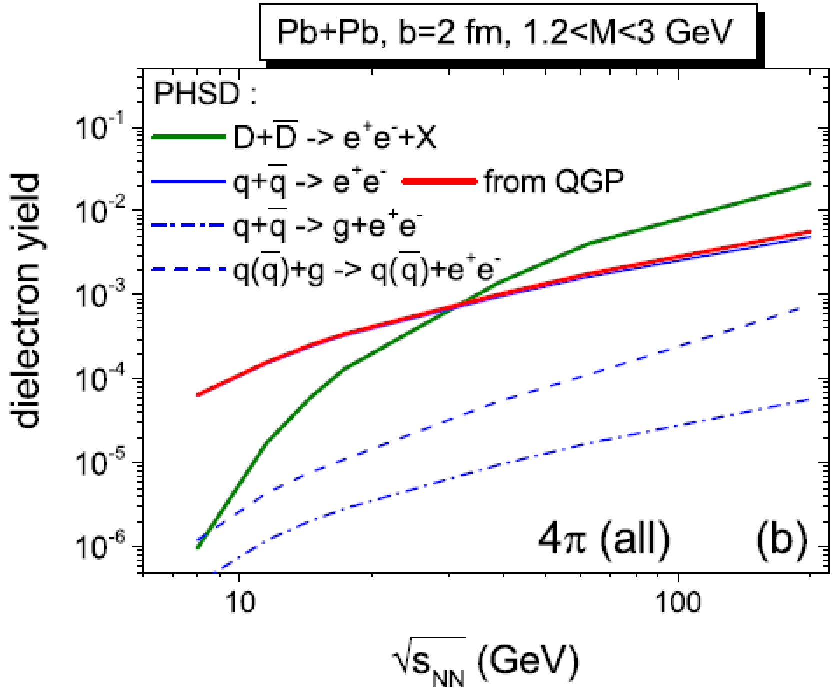


Integrated dielectron yield
(intermediate invariant mass 1.2<M<3 GeV)

In mid-rapidity



All rapidity range



5. Summary

5.1 PHSD

- Relativistic heavy-ion collisions produce strings.

- Strings melt into massive off-shell partons at high energy density according to the Dynamical Quasi-Particle Model where pole mass and spectral width of parton depends on temperature and are fitted to the lattice EoS of QGP.

- Massive off-shell partons interact with each other with the same temperature-dependent strong coupling and propagators down to the critical temperature.

- Massive off-shell partons hadronize into off-shell hadrons.

5.2 heavy flavor production

- Heavy flavor is generated by the PYTHIA event generator in PHSD.

- Rapidity distribution and transverse momentum spectrum are adjusted to be FONLL-like shapes.

- (Anti)shadowing effect is included by using EPS09.

- Heavy quark interacts with partons with the same temperature-dependent strong coupling and propagator mass.

- Heavy quarks hardonize into heavy hadrons through coalescence (at low pT) or through fragmentation (at high pT).

- Heavy mesons interact with light hadrons in according to an effective
- Lagrangian model.

5.3 Dileptons

- Low mass dileptons mainly stem from direct and Dalitz decays of hadrons.
- Intermediate mass dileptons stem from partonic interactions and heavy flavor pairs.
- The interactions of heavy flavor in nuclear matter soften the dilepton mass spectrum.
- Comparing the contribution from partonic interactions and that from heavy flavor pairs, the former is dominant in heavy-ion collisions at low energy (less then 30-40 GeV/nucleon)

Direct decay of vector mesons

$$\Gamma_V^*(M, |\vec{p}|, \rho_N) = \Gamma_V(M) + \Gamma_{coll}(M, |\vec{p}|, \rho_N).$$

$$\Gamma_\rho(M) \simeq \Gamma_{\rho\to\pi\pi}(M) = \Gamma_0 \left(\frac{M_0}{M}\right)^2 \left(\frac{q}{q_0}\right)^3 F(M)$$

$$q = \frac{(M^2 - 4m_\pi^2)^{1/2}}{2}, \quad q_0 = \frac{(M_0^2 - 4m_\pi^2)}{2}$$

$$F(M) = \left(\frac{2\Lambda^2 + M_0^2}{2\Lambda^2 + M^2}\right)^2$$

with a cut-off parameter $\Lambda = 3.1$ GeV.

$$\Gamma_{coll}(M, |\vec{p}|, \rho_N) = \gamma\ \rho_N < v\ \sigma_{VN}^{tot} > \approx\ \alpha_{coll}\ \frac{\rho_N}{\rho_0}.$$

$\alpha_{coll} = 0.08$ for ρ ; $= 0.04$ for ϖ

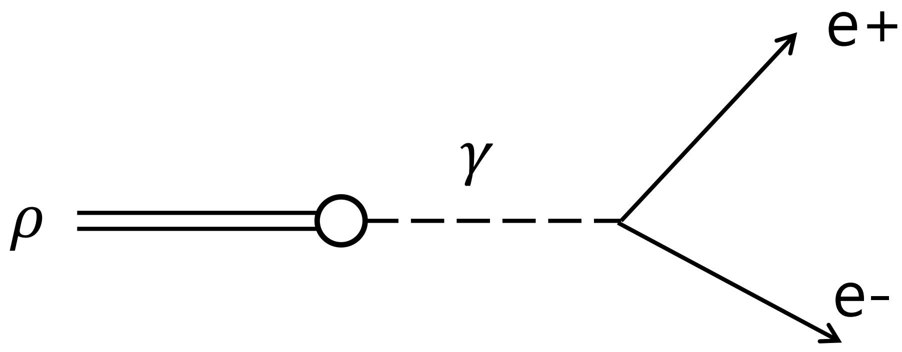
Electromagnetic decay width

$$\frac{dN^{\rho\to e^+e^-}}{dM} = \sum_{t=0}^{t_F} \Gamma^{\rho^0\to e^+e^-}(M) \cdot \frac{\Delta t}{\gamma(\hbar c)} \cdot \frac{1}{\Delta M}$$

$$\Gamma^{\rho^0\to e^+e^-}(M) = C_\rho \frac{M_0^{*4}}{M^3},$$

where $C_\rho = \Gamma^{\rho\to e^+e^-}(M_0)/M_0$.

E.L.Bratkovskaya, W.Cassing,
NPA 807 (2008) 214-250

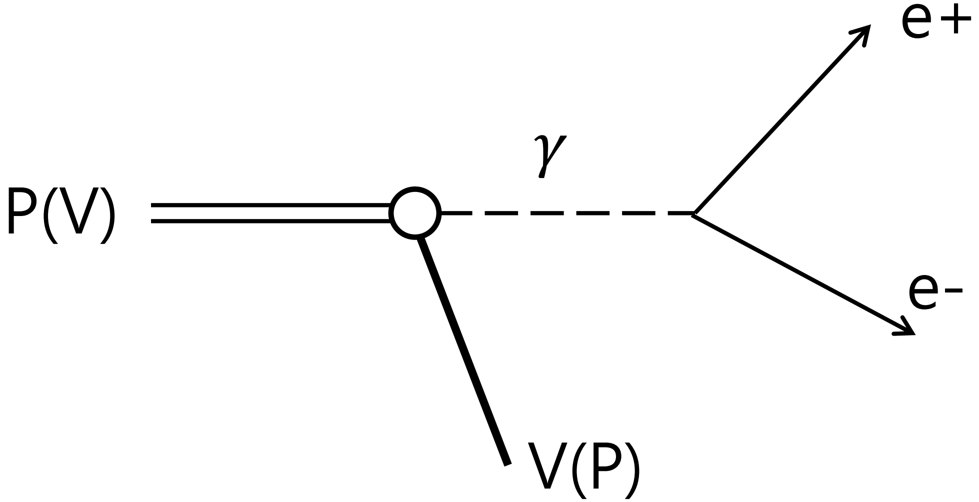


Dalitz decay (3body decay)

$$\frac{d\Gamma(A\to B\ell^+\ell^-)}{dq^2\cdot\Gamma(A\to B\gamma)} = \frac{\alpha}{3\pi}\left[1-\frac{4m_\ell^2}{q^2}\right]^{1/2}\left[1+2\frac{m_\ell^2}{q^2}\right]\frac{1}{q^2}$$

$$\times\left[\left(1+\frac{q^2}{m_A^2-m_B^2}\right)^2-\frac{4m_A^2q^2}{(m_A^2-m_B^2)^2}\right]^{3/2}\left|\frac{f_{AB}(q^2)}{f_{AB}(0)}\right|^2$$

L.G.Landsberg, PR 128 (1985) 301-376



P : Pseudoscalar particle
V : Vector particle including photon