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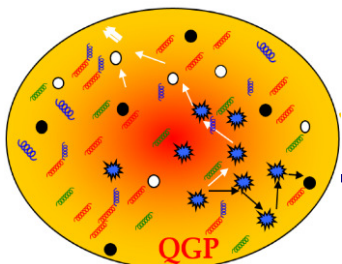
Charm dynamics in heavy-ion collisions

Taesoo Song

In collaboration with Elena Bratkovskaya, Hamza Berrehrah, Daniel Cabrera, Juan Torres-Rincon, Laura Tolos, Wolfgang Cassing, Jörg Aichelin and Pol-Bernard Gossiaux

DFG Deutsche
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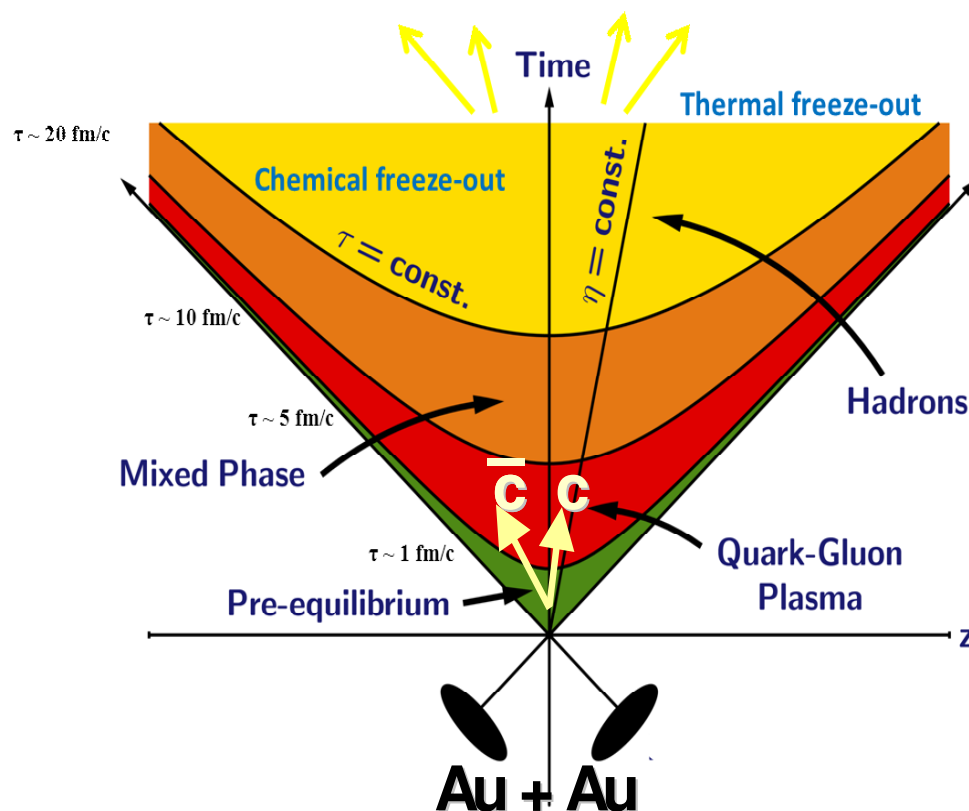




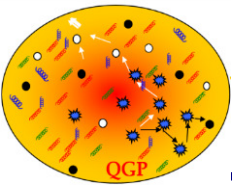
Tomography of the QGP by Charm Quarks

The **advantages** of the 'charm probes':

- ❑ dominantly produced in very early stage of reactions through **initial N+N binary collisions** with large energy-momentum transfer
- ❑ initial charm production is well described by **pQCD** (FONLL)
- ❑ scattering cross sections are small & heavy (compared to light quarks) → **not in equilibrium** with surrounding matter



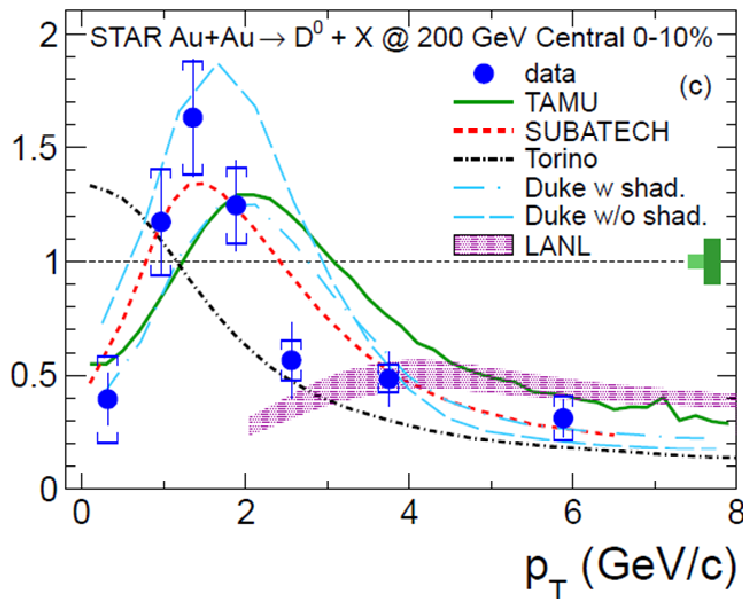
→ Hope to use 'charm probes' for an **early tomography of the QGP**



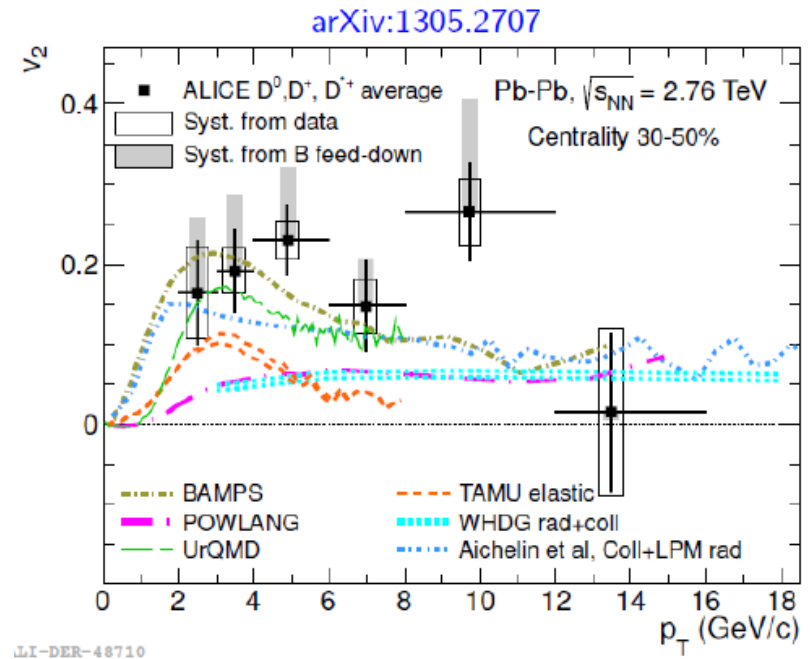
Charm: experimental signals

1. Nuclear modification factor:

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



2. Elliptic flow v₂:



❑ What is the origin for the “energy loss” of charm at large p_T?

Collisional energy loss (elastic scattering Q+q→Q+q)
vs **radiative** (gluon bremsstrahlung Q+q→Q+q+g) ?

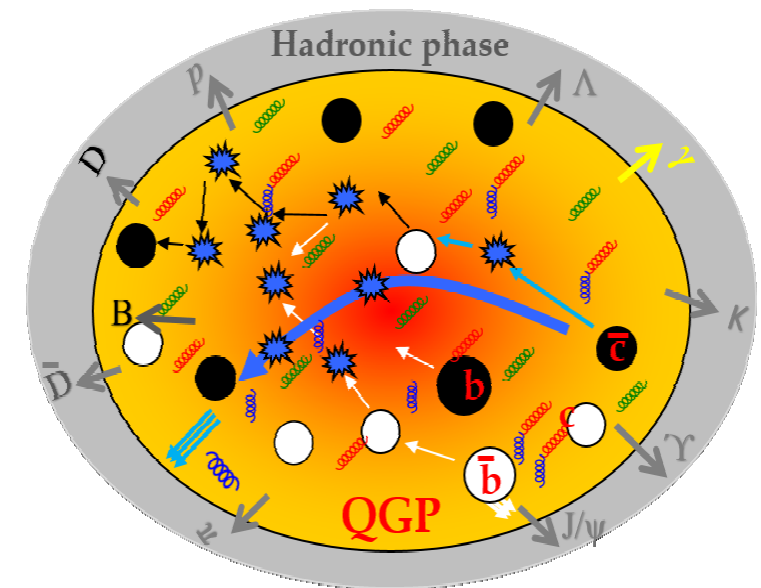
➔ **Challenge for theory:** simultaneous description of R_{AA} and v₂ !

Charm dynamics in A+A

1. **Production** of charm quarks in initial binary collisions
2. **Interactions in QGP:**
elastic scattering $Q+q \rightarrow Q+q$ → collisional energy loss
gluon bremsstrahlung $Q+q \rightarrow Q+q+g$ → radiative energy loss
3. **Hadronization:** c/\bar{c} quarks → $D(D^*)$ -mesons:
coalescence vs fragmentation
4. **Hadronic interactions:**
 D +baryons; D +mesons

The goal: to model the dynamics of charm quarks/mesons in all phases on a **microscopic basis**

The tool: PHSD approach





Parton-Hadron-String-Dynamics (PHSD)

Initial A+A collisions – HSD:

$N+N \rightarrow$ string formation \rightarrow decay to pre-hadrons

Formation of QGP stage if $\epsilon > \epsilon_{\text{critical}}$:

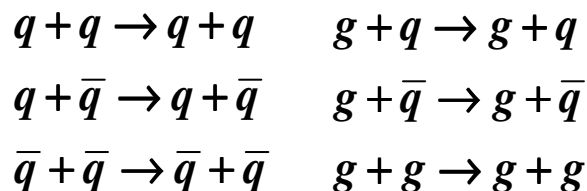
dissolution of pre-hadrons \rightarrow (DQPM) \rightarrow

\rightarrow massive quarks/gluons + mean-field potential U_q

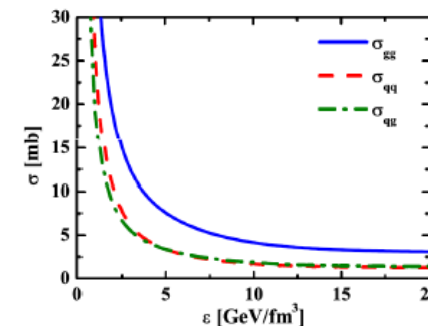
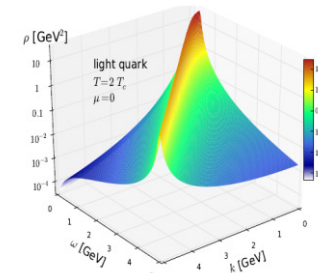
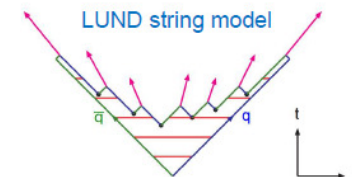
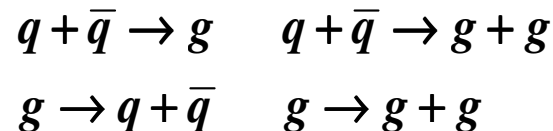
Partonic stage – QGP:

based on the Dynamical Quasi-Particle Model (DQPM)

(quasi-) elastic collisions:



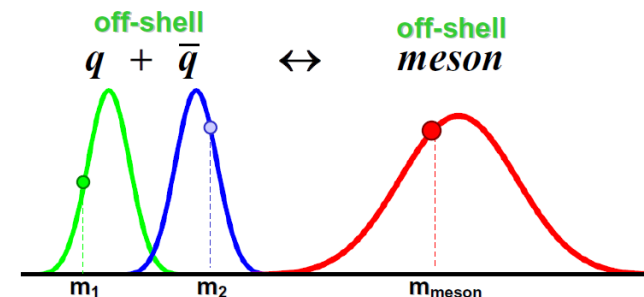
inelastic collisions:



Hadronization (based on DQPM):

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

$$q + q + q \leftrightarrow \text{baryon (or 'string')}$$



Hadronic phase: hadron-hadron interactions – off-shell HSD

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes **QCD** properties in terms of **,resummed' single-particle Green's functions**

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ **gluon self-energy:** $\Pi = M_g^2 - i2\Gamma_g \omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ **quark self-energy:** $\Sigma_q = M_q^2 - i2\Gamma_q \omega$

- the resummed properties are specified by **complex self-energies** which depend on temperature:
 - 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 (Γ_q, Γ_g)
- **space-like part of energy-momentum tensor** $T_{\mu\nu}$ defines the potential energy density and the **mean-field potential** (1PI) for quarks and gluons (U_q, U_g)

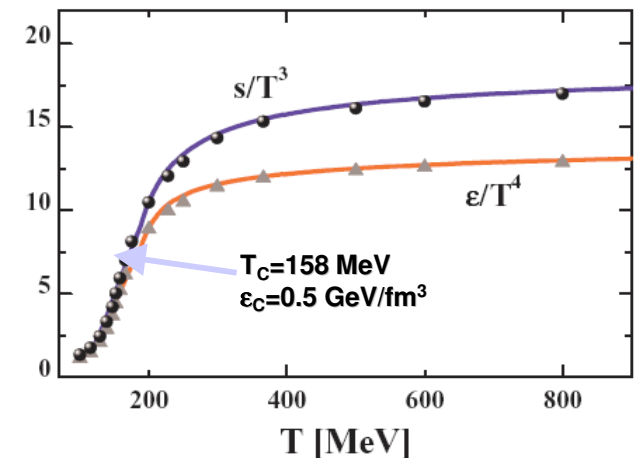
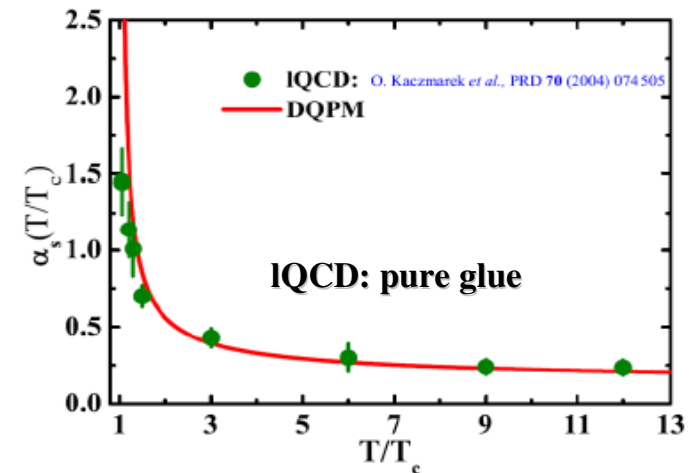
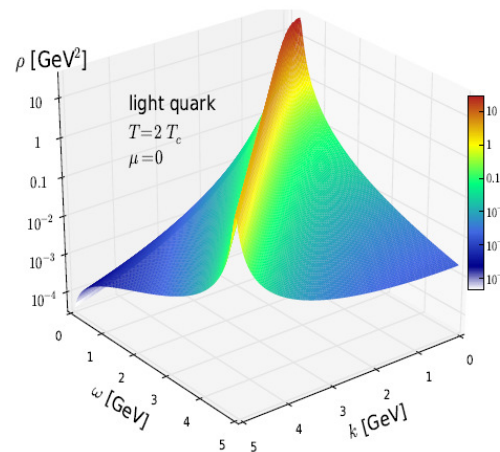
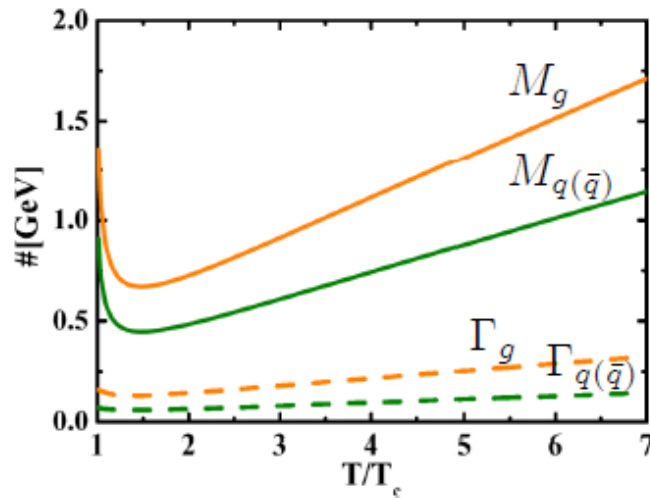
The Dynamical QuasiParticle Model (DQPM)

- Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, \bar{q}) with Lorentzian spectral functions :

$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \bar{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)} \quad (i = q, \bar{q}, g)$$

- fit to lattice (IQCD) results (e.g. entropy density) with 3 parameters

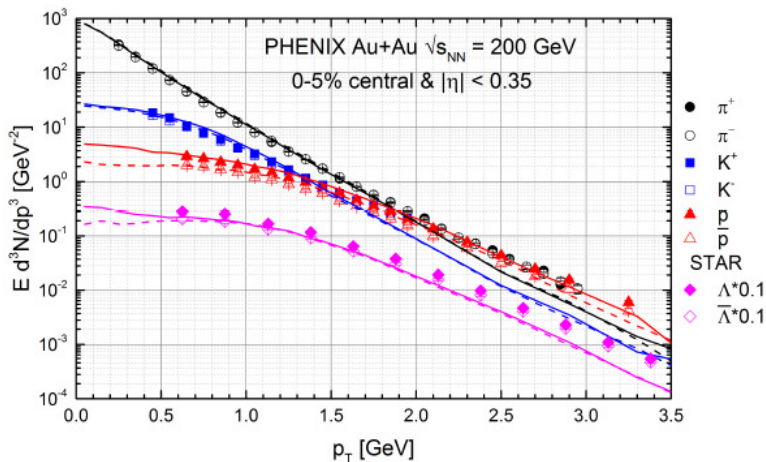
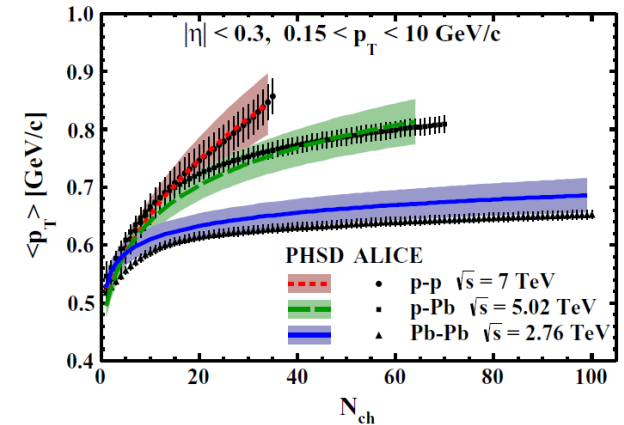
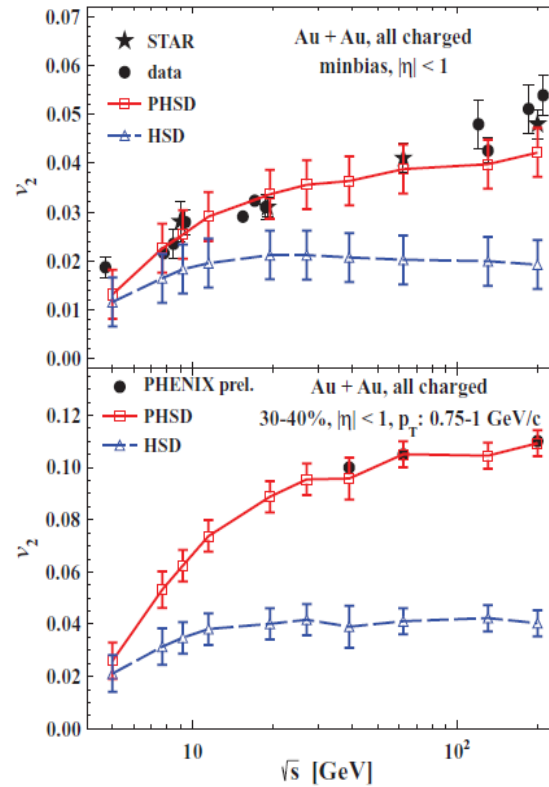
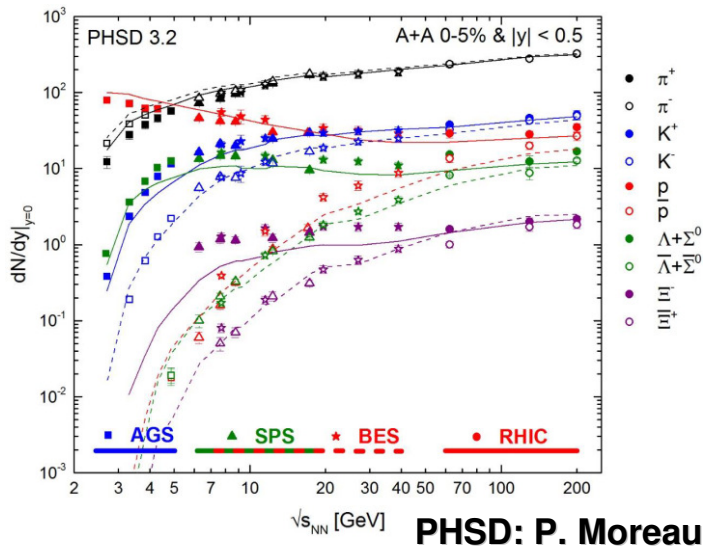
→ Quasi-particle properties: large width and mass for gluons and quarks



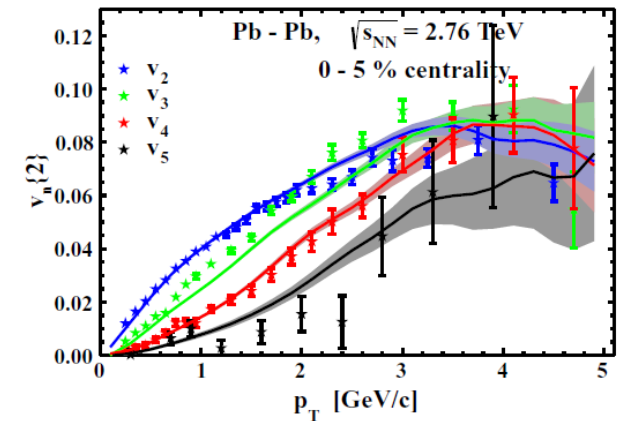


Description of A+A with PHSD

Important: to be conclusive on charm observables, the **light quark dynamics** must be well under control!



V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

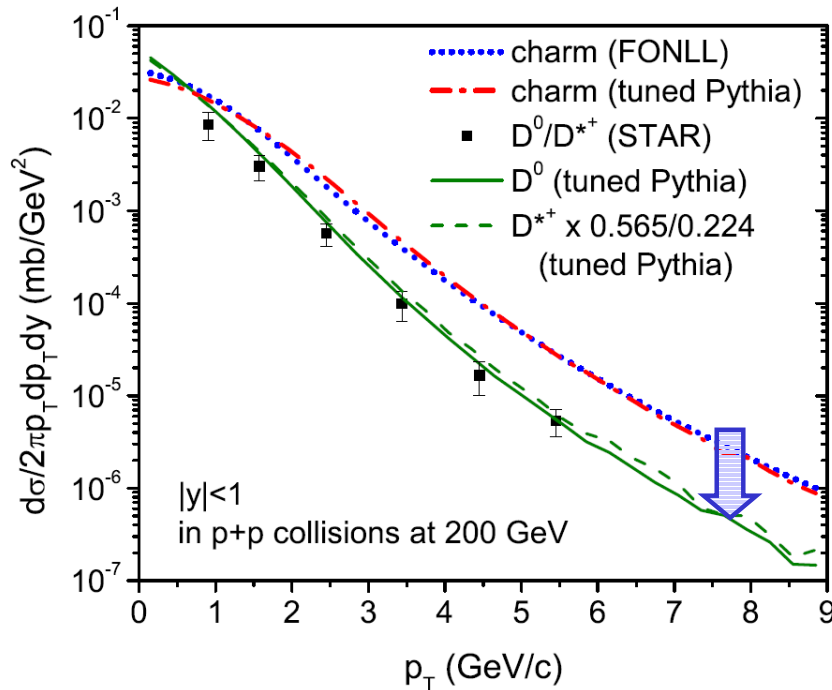


PHSD provides a **good description of ,bulk‘ observables** (y -, p_T -distributions, flow coefficients v_n , ...) from SPS to LHC

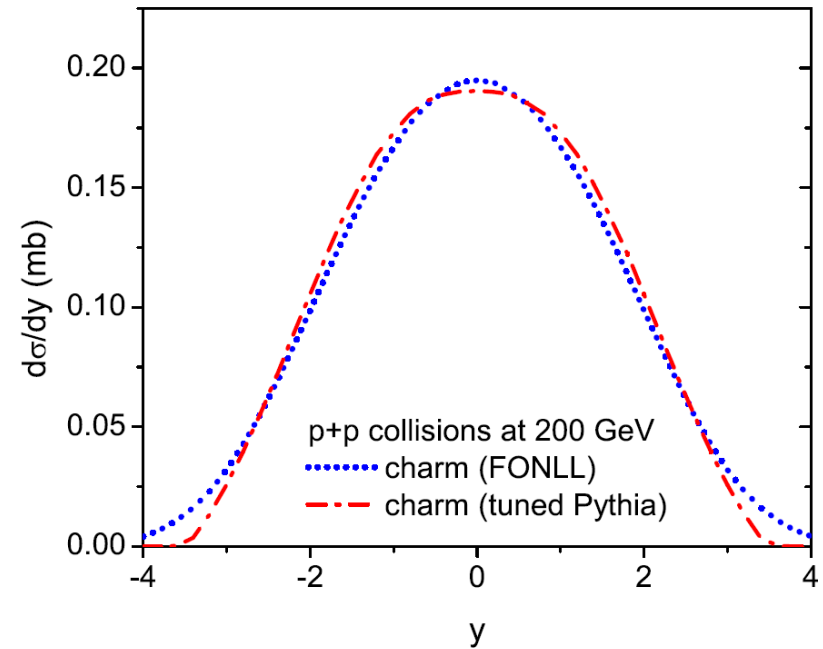


Charm quark production in p+p collisions

- Use **tuned** PYTHIA event generator to reproduce **FONLL** (fixed-order next-to-leading log) results (R. Vogt et al.)

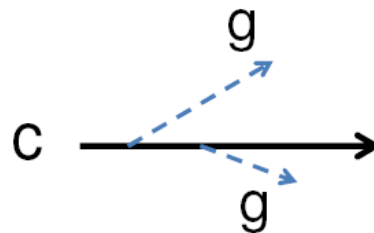


T. Song et al., PRC (2015), arXiv:1503.03039



Charm fragmentation

- D^+ : 22.6 %
- D^0 : 55.7 %
- D^{*+} : 23.8 %
- D^{*0} : 25.9 %



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

- z : momentum fraction of hadron H in heavy quark Q
- $\epsilon_Q=0.01$ for Q=charm

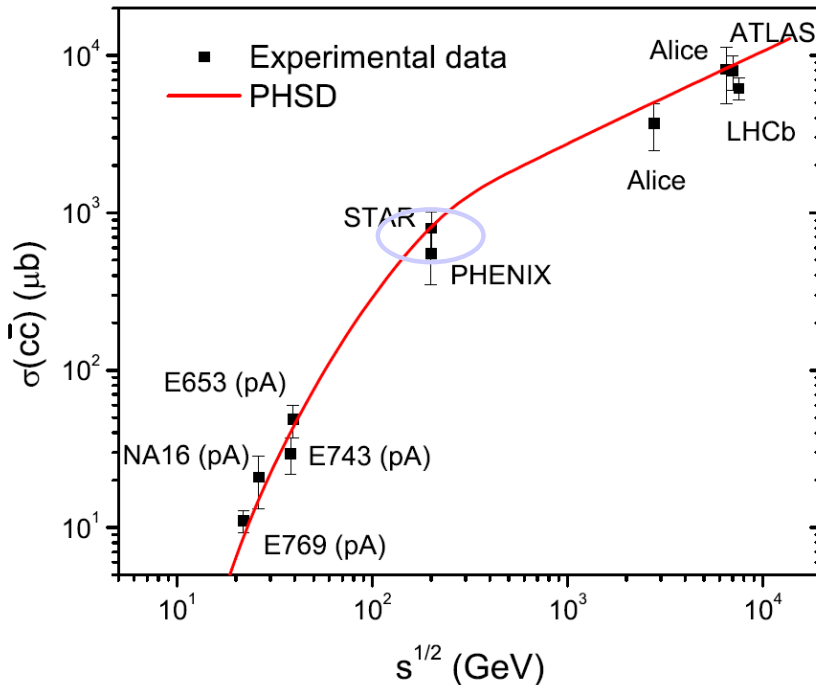
From C. Peterson et al., PRD27 (1983) 105



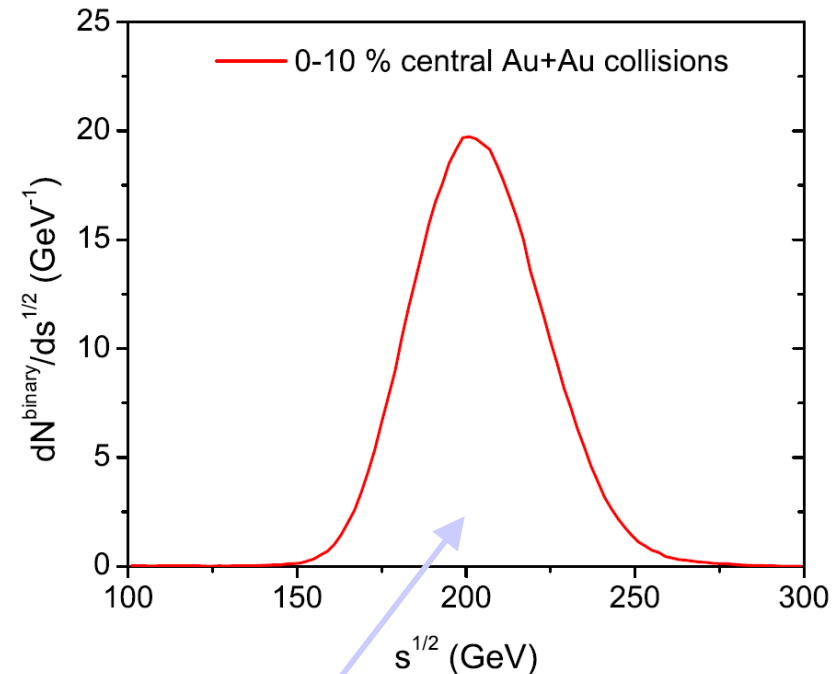
Charm quark production in A+A

□ A+A: charm production in **initial NN binary collisions**: probability $P = \frac{\sigma(cc\bar{c})}{\sigma_{NN}^{inel}}$

□ The **total cross section** for charm production in **p+p collisions** $\sigma(cc\bar{c})$



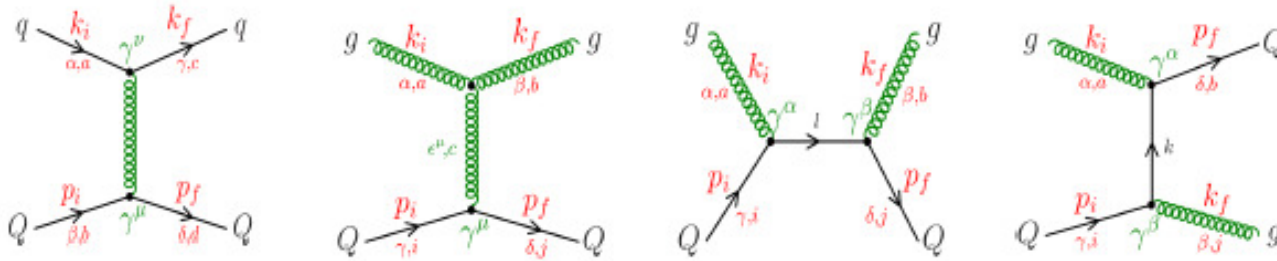
□ The energy distribution of binary NN collisions **including Fermi motion** in 0-10% central Au+Au collisions @ 200 GeV



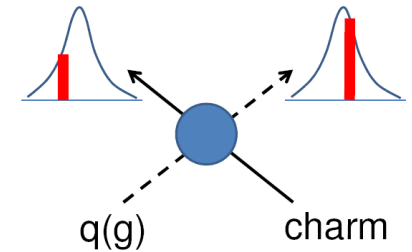
Collision energy smears due to the Fermi motion

Charm quark scattering in the QGP (DQPM)

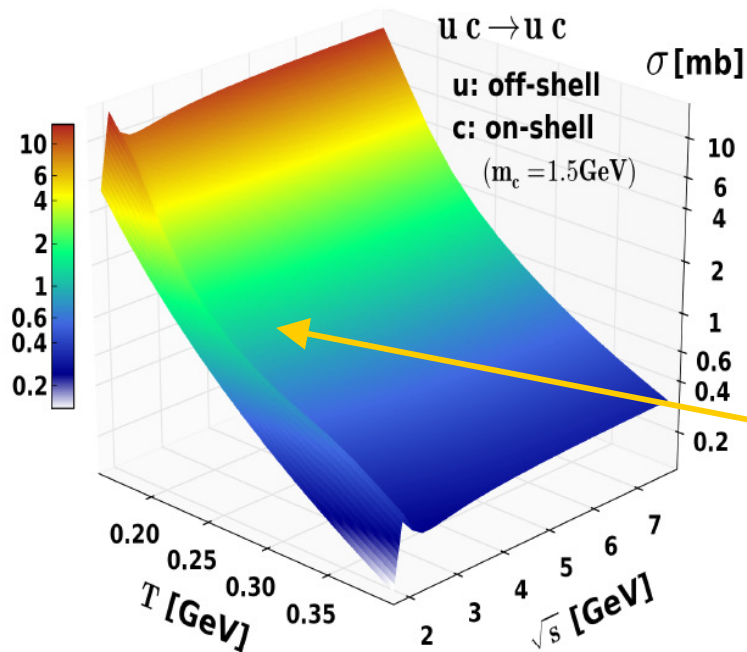
- Elastic scattering with **off-shell massive partons** $Q+q(g) \rightarrow Q+q(g)$



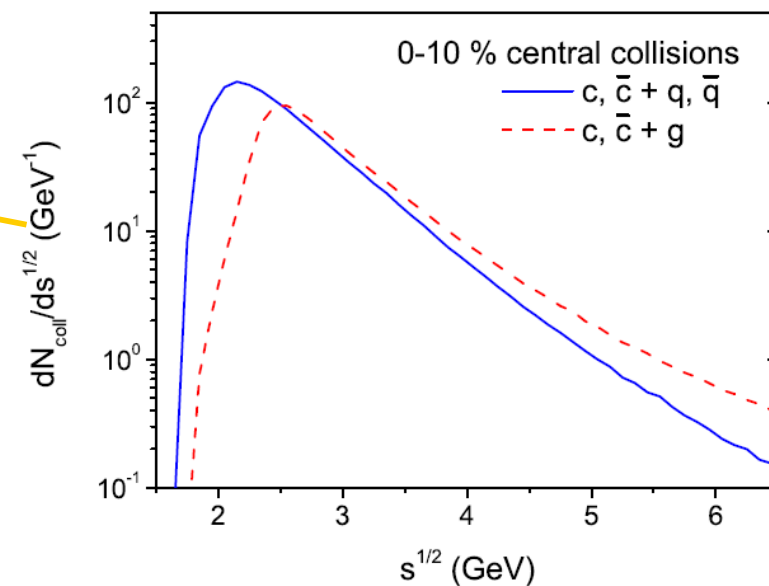
Non-perturbative QGP!



- Elastic cross section $uc \rightarrow uc$



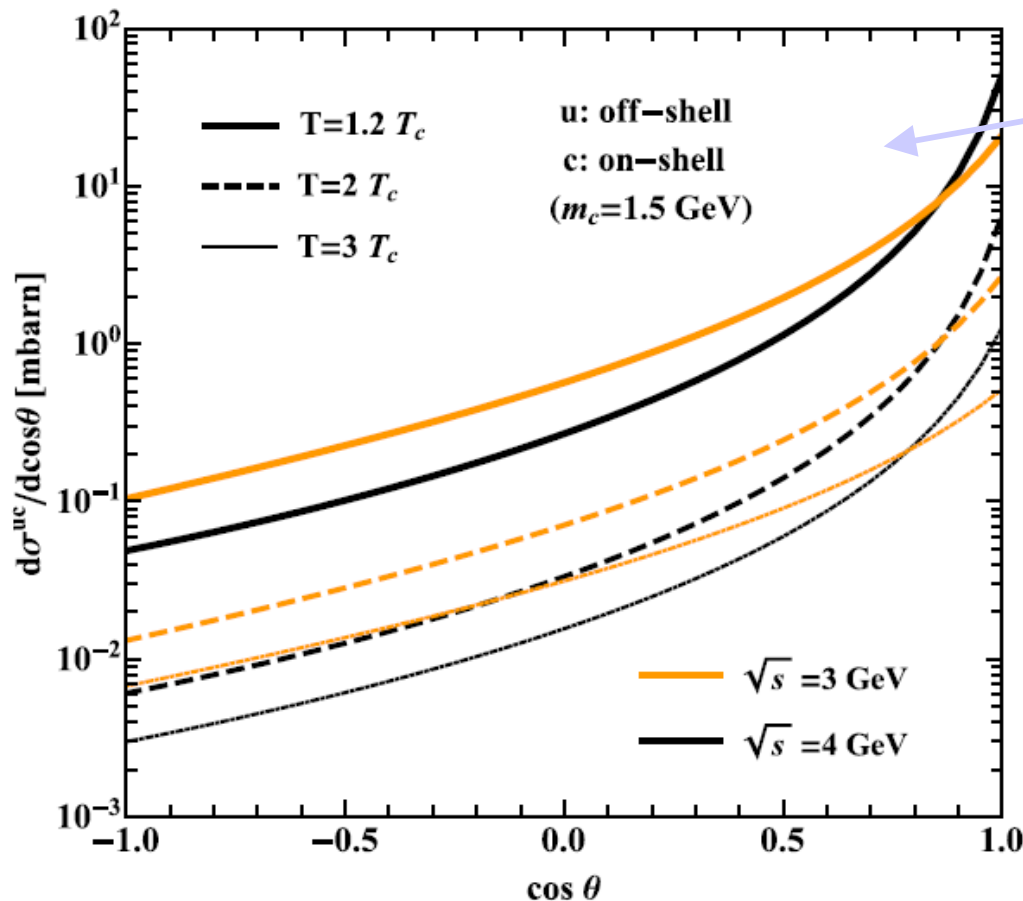
- Distributions of $Q+q, Q+g$ scatterings vs $s^{1/2}$ in 0-10% central Au+Au collisions





Charm quark scattering in QGP

□ **Differential cross section** for $uc \rightarrow uc$ for $s^{1/2} = 3$ and 4 GeV at $1.2T_c$, $2T_c$ and $3T_c$



□ **DQPM - anisotropic angular distribution**

Note: pQCD - strongly forward peaked,
DQPM - less forward peaked :
Less forward peaked angular distribution
leads to **more efficient momentum transfer**

□ **N(cc) ~ 19 pairs,**
N(Q+q) ~ 130, N(Q+g) ~ 85 collisions

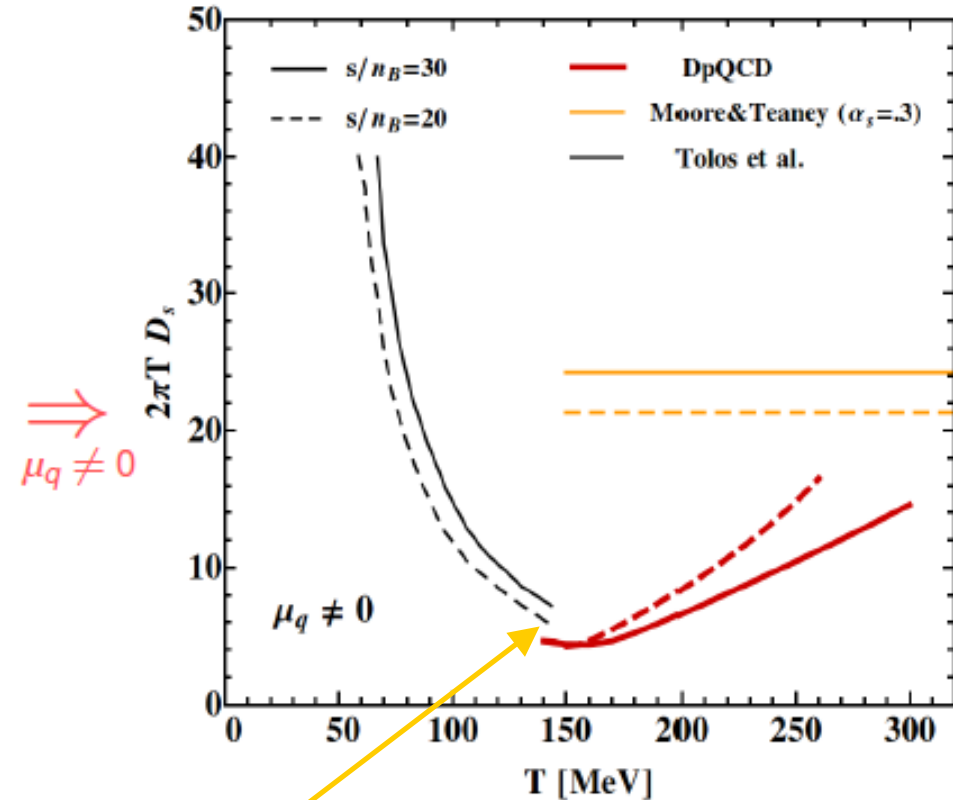
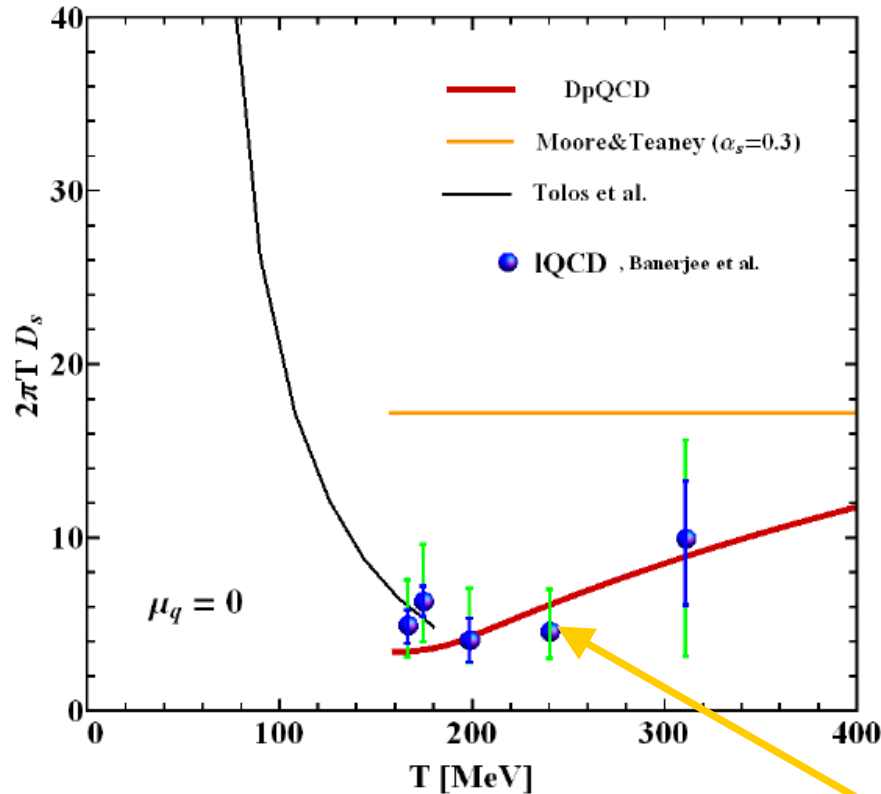
→ **each charm quark makes**
~ 6 elastic collisions

→ **Smaller number** (compared to pQCD)
of elastic scatterings with **massive**
partons leads to a **large energy loss**

! Note: radiative energy loss is NOT included yet in PHSD (work in progress);
expected to be **small** due to the large gluon mass in the DQPM

Charm spatial diffusion coefficient D_s in the hot medium

- D_s for heavy quarks as a function of T for $\mu_q=0$ and finite μ_q



□ $T < T_c$: hadronic D_s

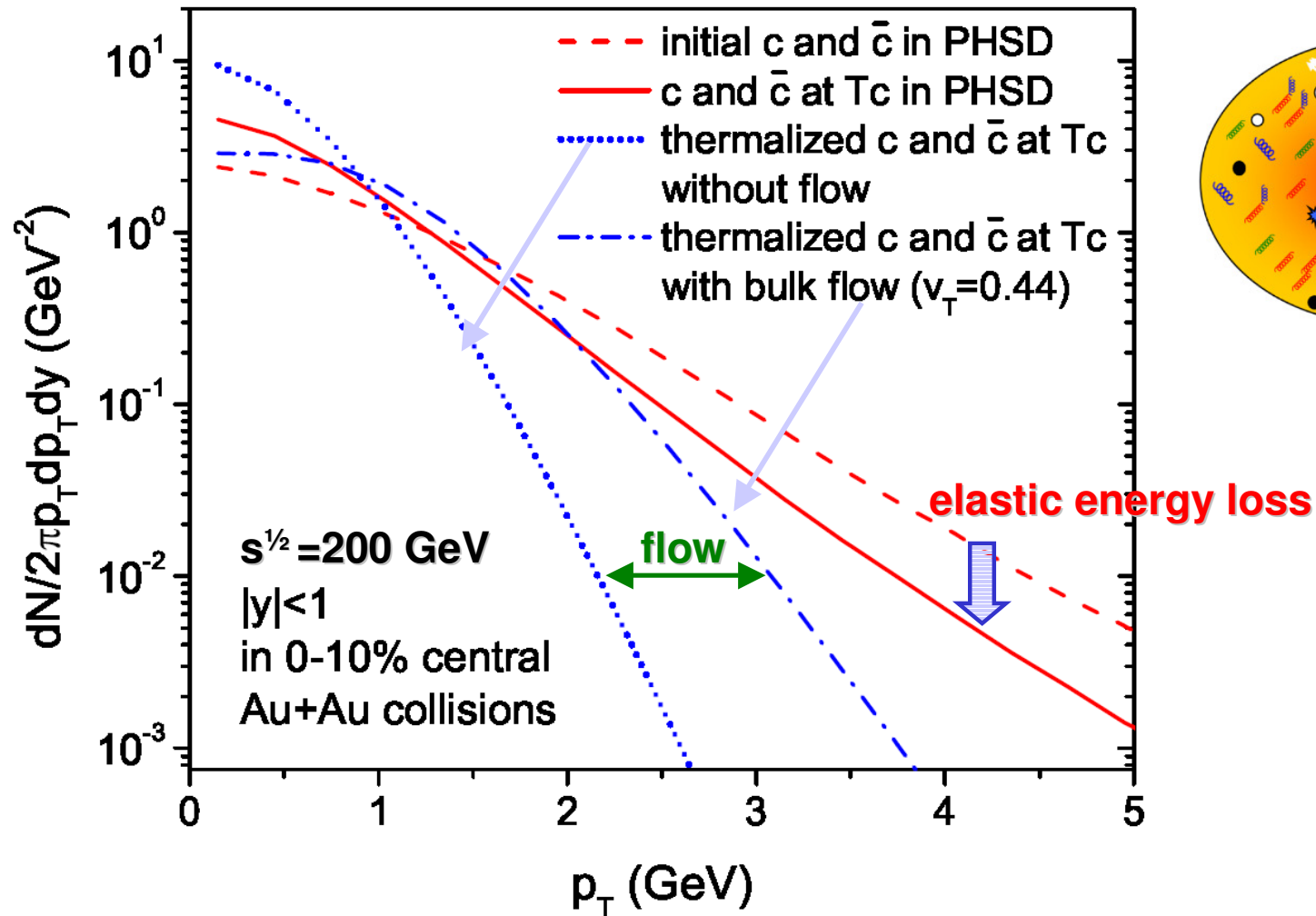
→ Continuous transition at T_c !

L. Tolos, J. M. Torres-Rincon, PRD 88 (2013) 074019

V. Ozvenchuk et al., PRC90 (2014) 054909

H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322

Thermalization of charm quarks in A+A ?



- Scattering of charm quarks with massive partons softens the p_T spectrum
 → elastic energy loss
- Charm quarks are close to thermal equilibrium at low $p_T < 2 \text{ GeV}/c$



Hadronization of charm quarks in A+A

□ PHSD: if local energy density $\varepsilon < 0.5 \text{ GeV/fm}^3 \rightarrow$ hadronization of charm quarks:

1. Dynamical coalescence model

Probability for charm quark/antiquark and the light quark/antiquark to form a meson:

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

g_M – degeneracy factor
(=1 for D and =3 for D*)

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

Width $\delta \leftarrow$ from **root-mean-square radius of meson:**

$$\langle r^2 \rangle = \frac{3}{2} \frac{m_1^2 + m_2^2}{(m_1 + m_2)^2} \delta^2$$

2. Fragmentation (as in pp)

- if NOT hadronized by coalescence

Hadronization scenarios :

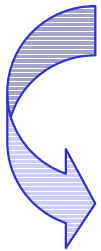
- 1: only fragmentation
2. coalescence with $\langle r \rangle = 0.5 \text{ fm}$ + fragmentation
- 3: coalescence with $\langle r \rangle = 0.9 \text{ fm}$ + fragmentation

Note: We take into account the coalescence into higher excited states: D*0(2400), D*1(2420), and D*2(2460). They are assumed to decay into D or D* and pion immediately after hadronization.

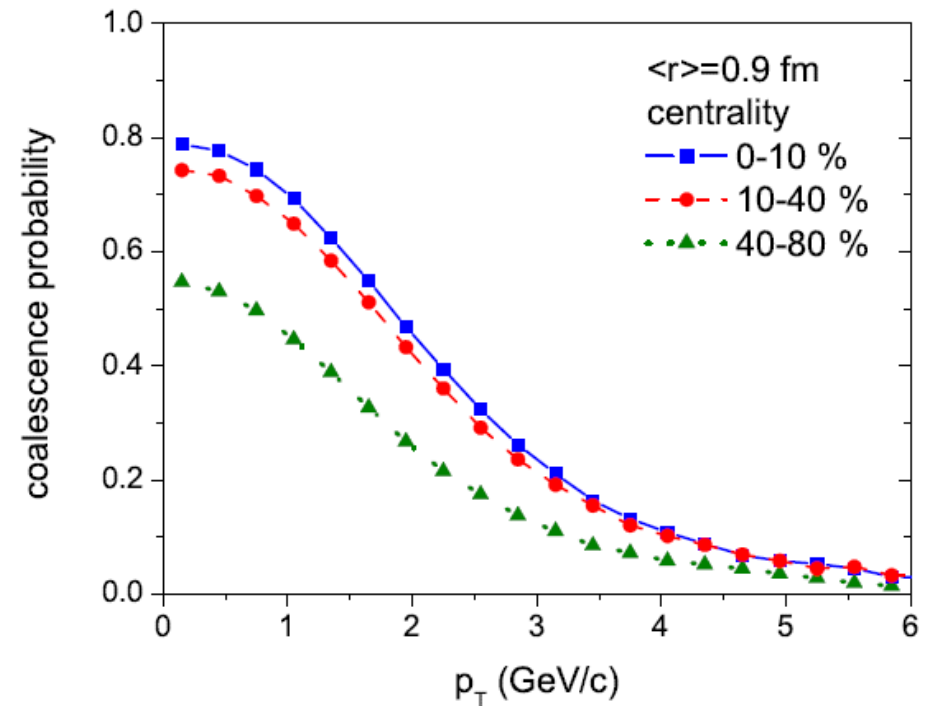
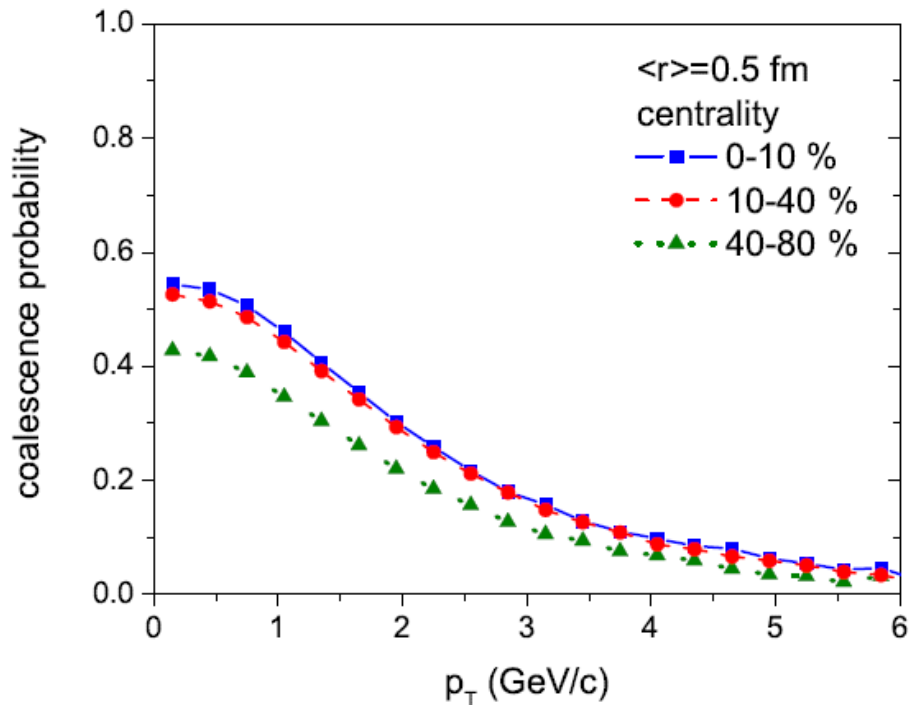
Hadronization of charm quarks in A+A

Hadronization scenarios :

- 1: only fragmentation
2. coalescence with $\langle r \rangle = 0.5$ fm + fragmentation
- 3: coalescence with $\langle r \rangle = 0.9$ fm + fragmentation



Coalescence probability in Au+Au





Modelling of D-meson scattering in the hadronic gas

1. D-meson scattering with mesons

Model: effective chiral Lagrangian 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 $(\pi, K, Kbar, \eta)$:

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

with

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

$$U = u^2 = \exp\left(\frac{\sqrt{2}i\Phi}{f}\right) \quad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

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 $J^P=3/2^+$

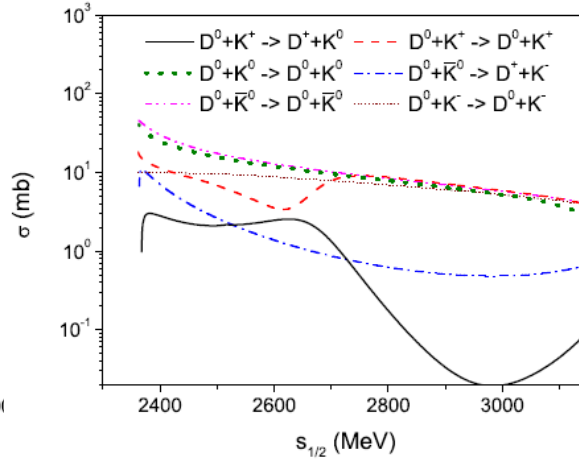
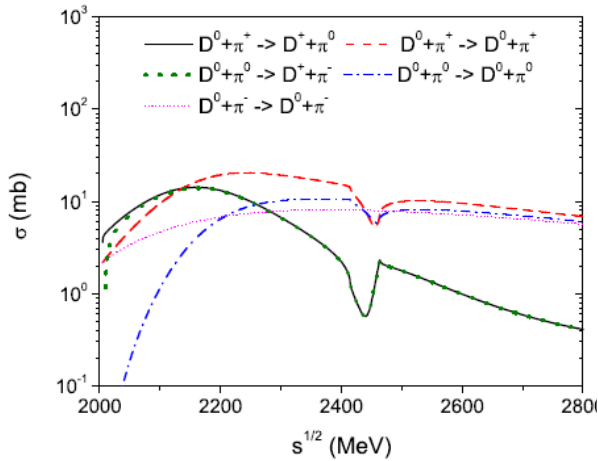
C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, L. Tolos, *Phys. Rev. D* 87, 074034 (2013)

Unitarized scattering amplitude \rightarrow from solution of coupled-channel

Bethe-Salpeter equations: $T = T + VGT$

D-meson scattering in the hadron gas

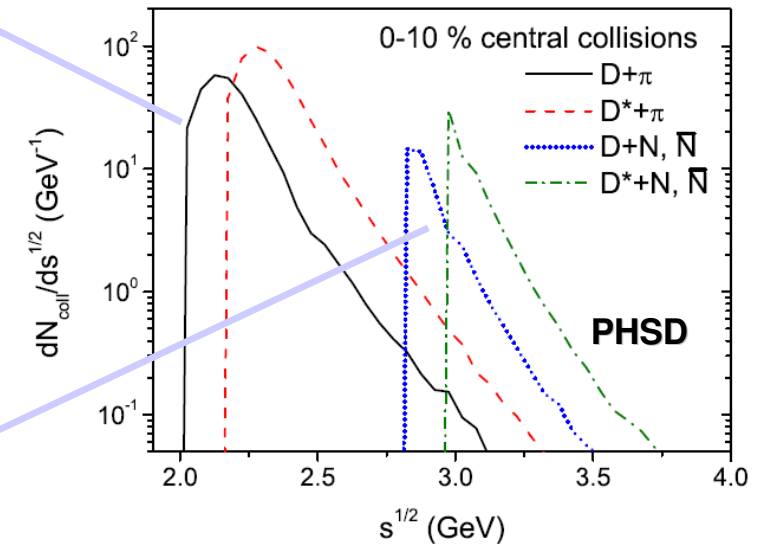
1. D-meson scattering σ with mesons



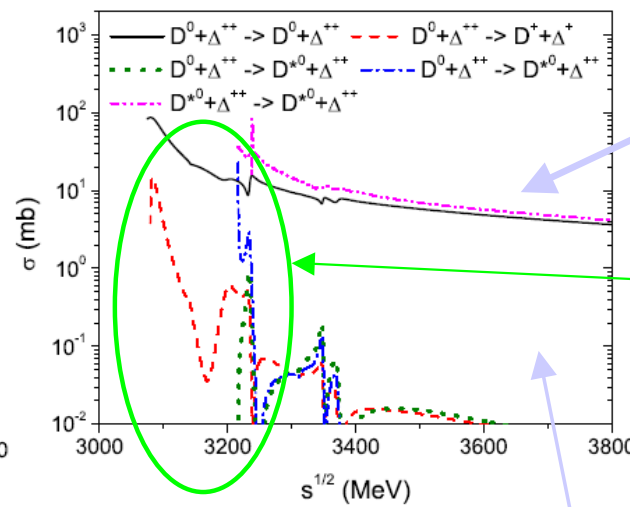
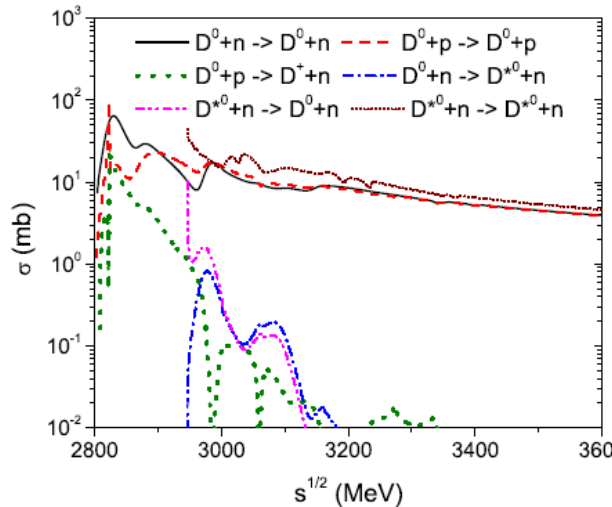
1a) cross sections with $m=\rho, \omega, \phi, K^*, \dots$ are taken to be

$$\sigma(D, D^* + m) = 10 \text{ mb}$$

Distribution $dN/ds^{1/2}$



2. D-meson scattering σ with baryons



→ Strong **isospin dependence** and complicated structure (due to the resonance coupling) of $D+m$, $D+B$ cross sections!

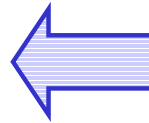
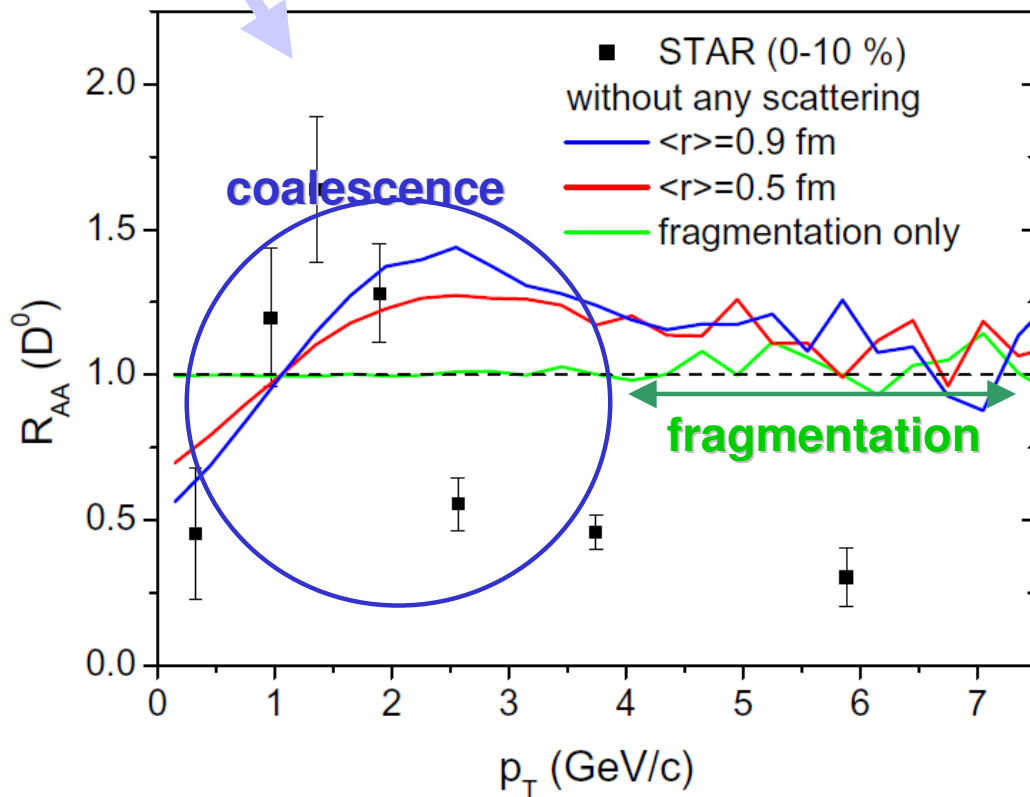
→ Hadronic interaction is ineffective for the energy loss of D, D^* mesons at high transverse momentum (i.e. large $s^{1/2}$)



R_{AA} at RHIC - coalescence vs fragmentation

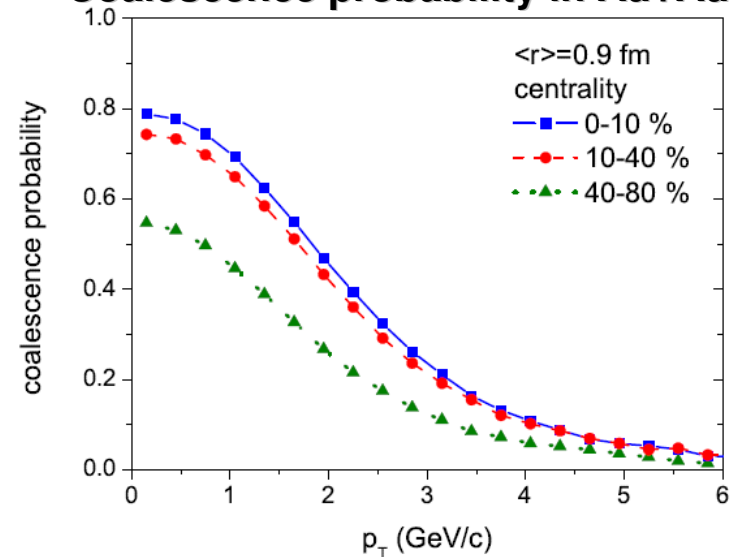
1. Influence of hadronization scenarios: coalescence vs fragmentation

! Model study: without any rescattering (partonic and hadronic)



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

Coalescence probability in Au+Au



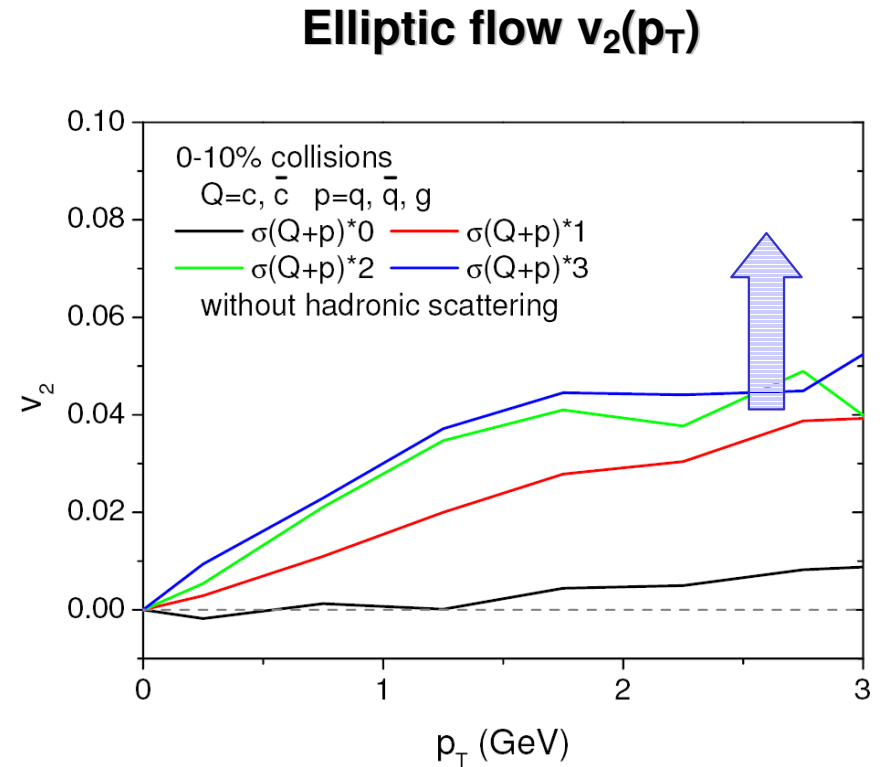
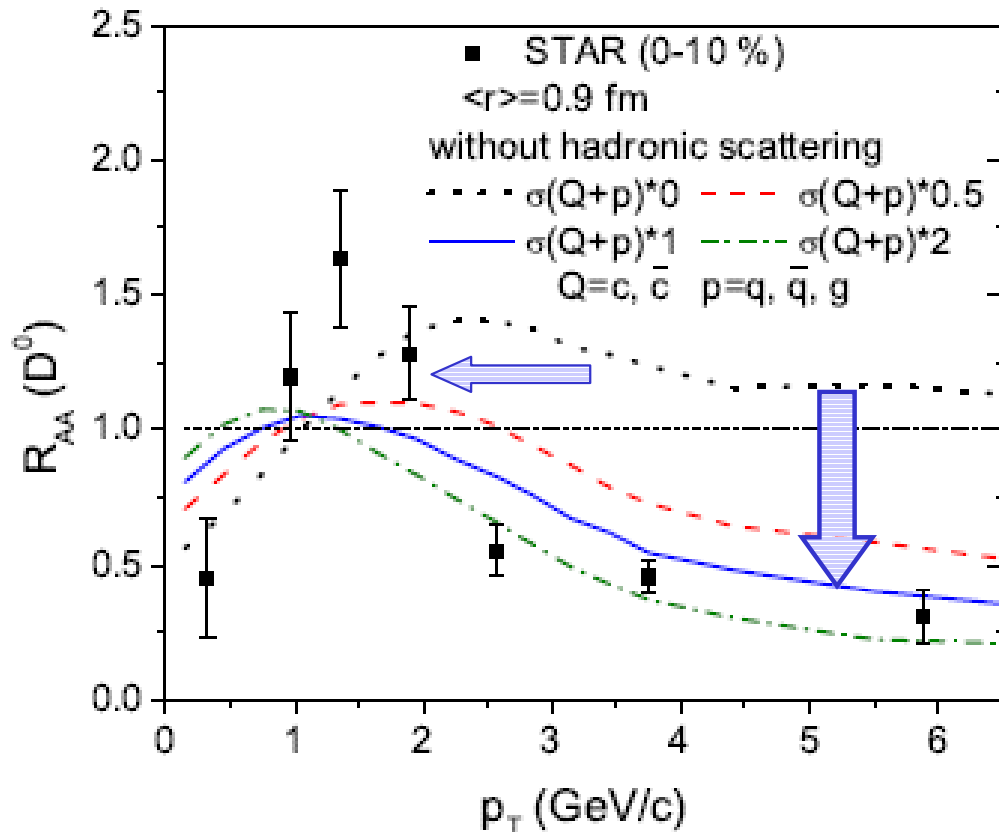
- Expect: no scattering: $R_{AA}=1$
- Hadronization by **fragmentation** only (as in pp) $\rightarrow R_{AA}=1$
- **Coalescence** (not in pp!) shifts R_{AA} to larger $p_T \rightarrow$ 'nuclear matter' effect
: coalescence (charm gains p_T) vs. Fragmentation (charm loses p_T)



R_{AA} at RHIC: partonic scattering

2. Influence of partonic rescattering

! Model study: by scaling of parton cross sections: $\sigma(Q+q(g))^*\alpha$ by $\alpha=0, 0.5, 1, 2$ (without hadronic rescattering)

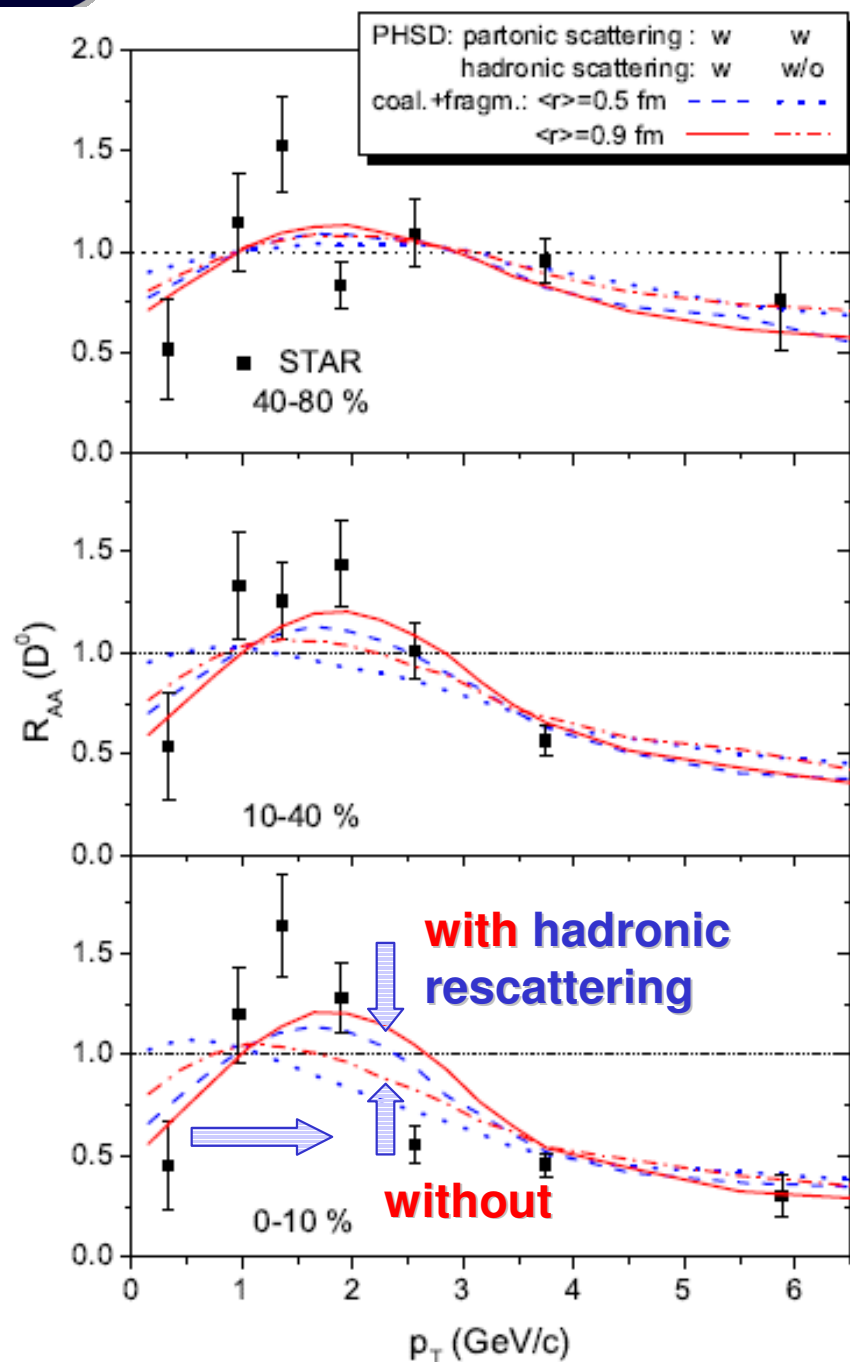


Elastic partonic rescattering

- moves R_{AA} to lower p_T and suppresses large p_T
- increases v_2



R_{AA} at RHIC: hadronic rescattering



3. Influence of hadronic rescattering

with partonic rescattering
 & **with / without** hadronic rescattering

In 0-10% Central Au+Au at $s^{1/2} = 200$ GeV :

$N(D, D^*) \sim 30$

$N(D, D^* + m) \sim 56$ collisions

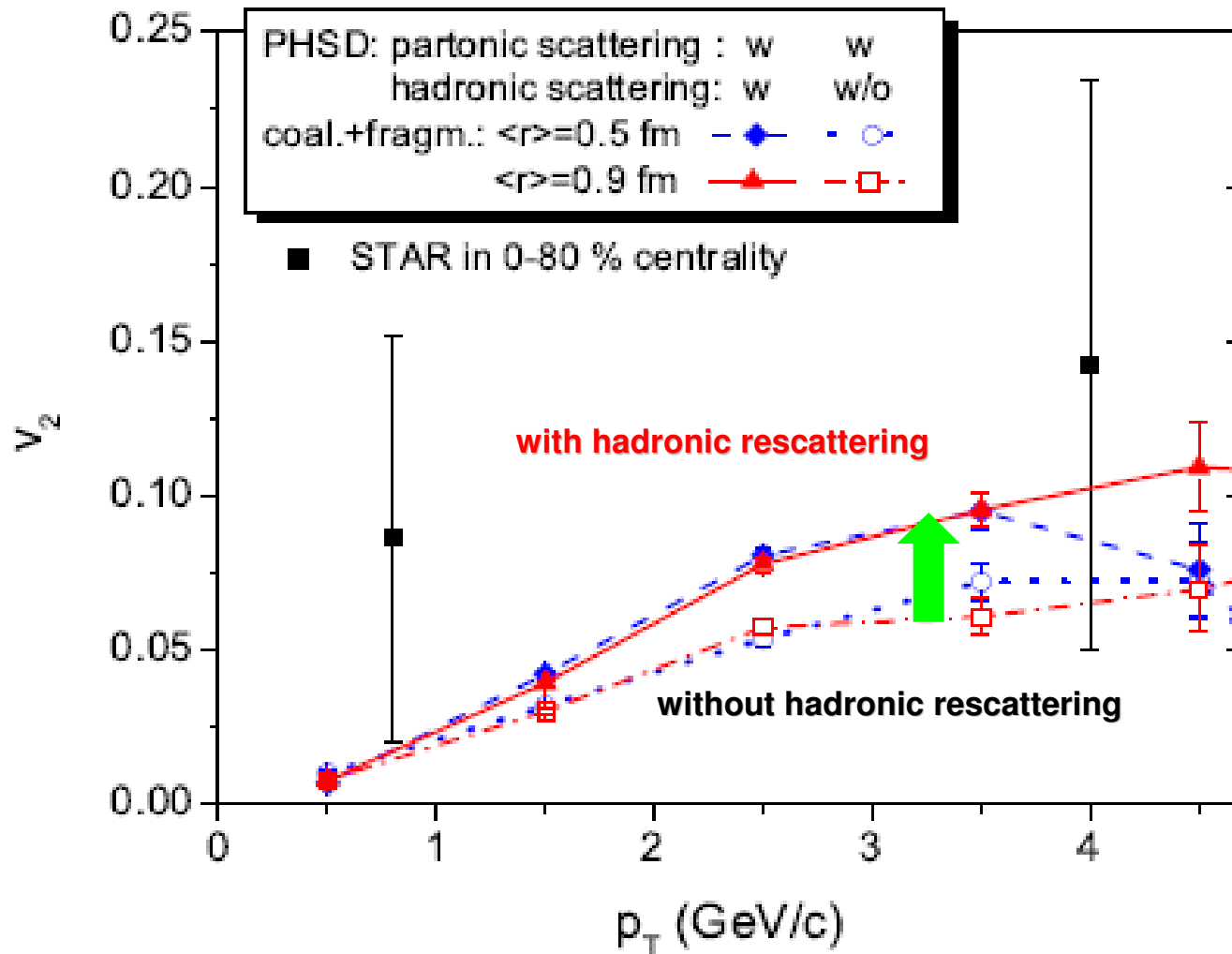
$N(D, D^* + B, Bbar) \sim 10$ collisions

→ each D, D^* makes
~ 2 scatterings with hadrons

□ **Hadronic rescattering** moves
 R_{AA} peak to higher p_T !



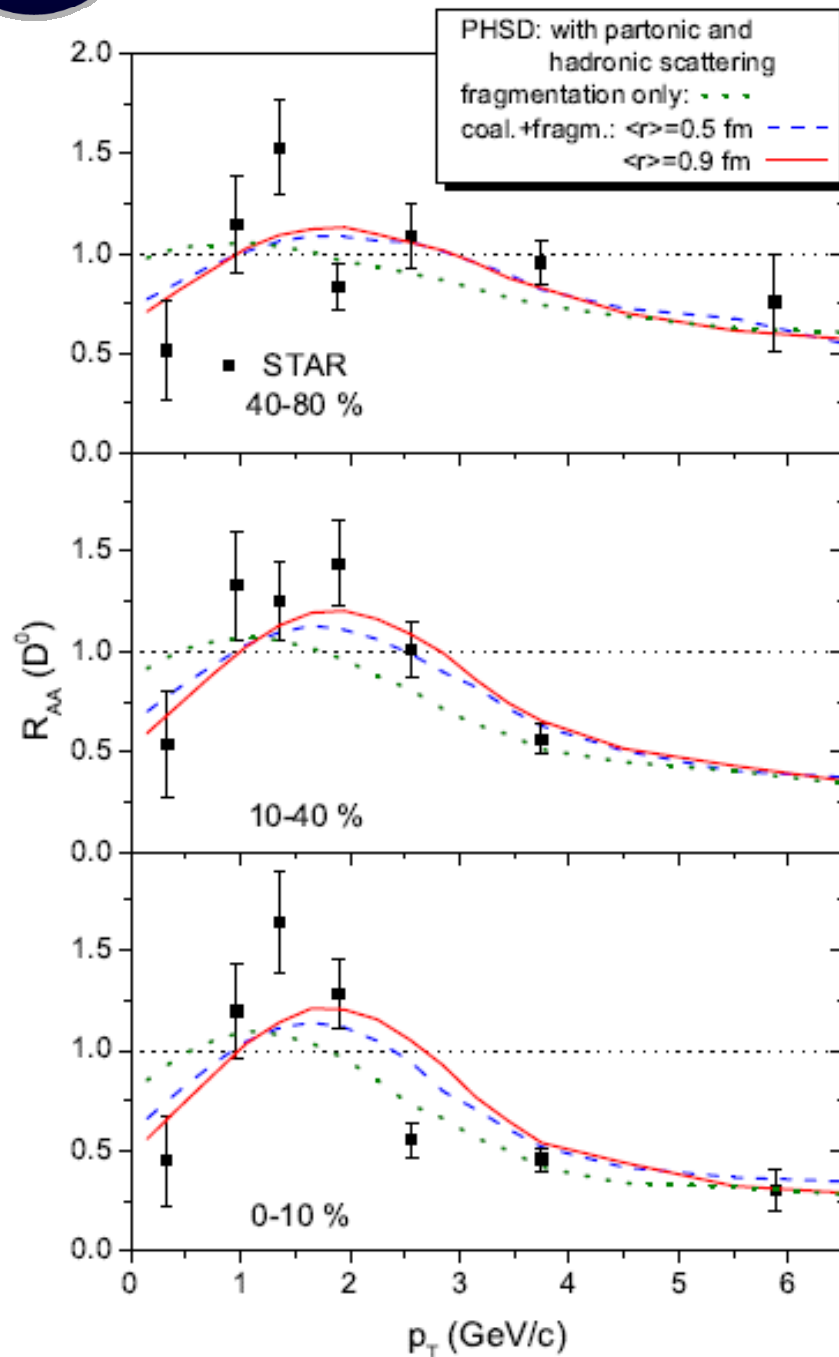
D-meson elliptic flow v_2 at RHIC



- **Hadronic rescattering** substantially **increases v_2**
- v_2 is less sensitive to the hadronization scenarios than R_{AA}



R_{AA} at RHIC



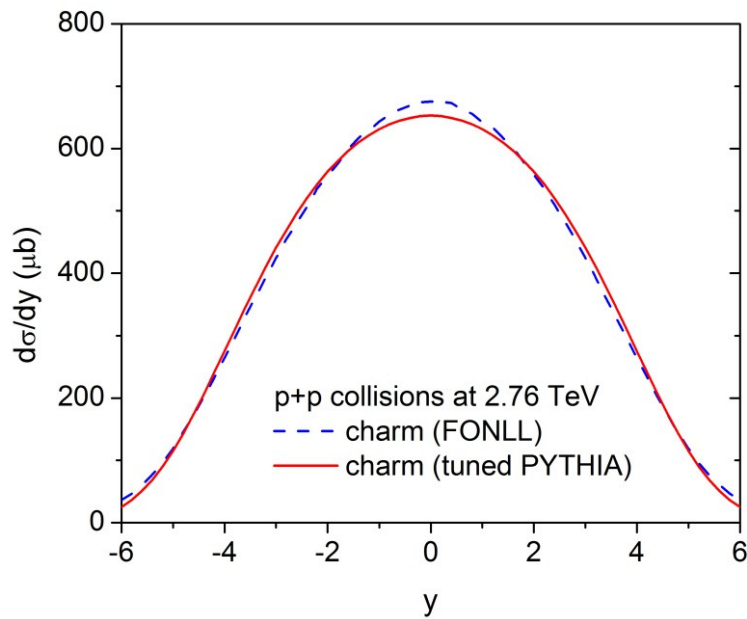
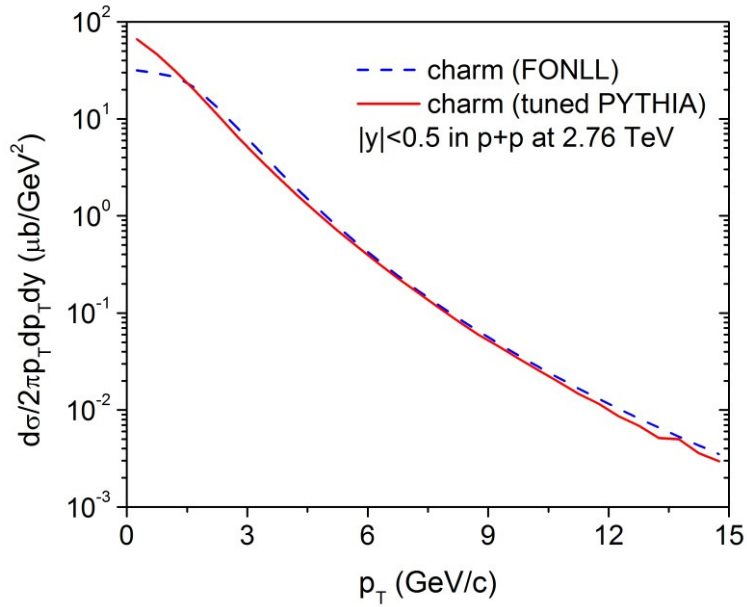
PHSD results:
with all rescattering (partonic and hadronic)

□ The height and position of the R_{AA} peak depends on the hadronization scenario: coalescence/fragmentation!

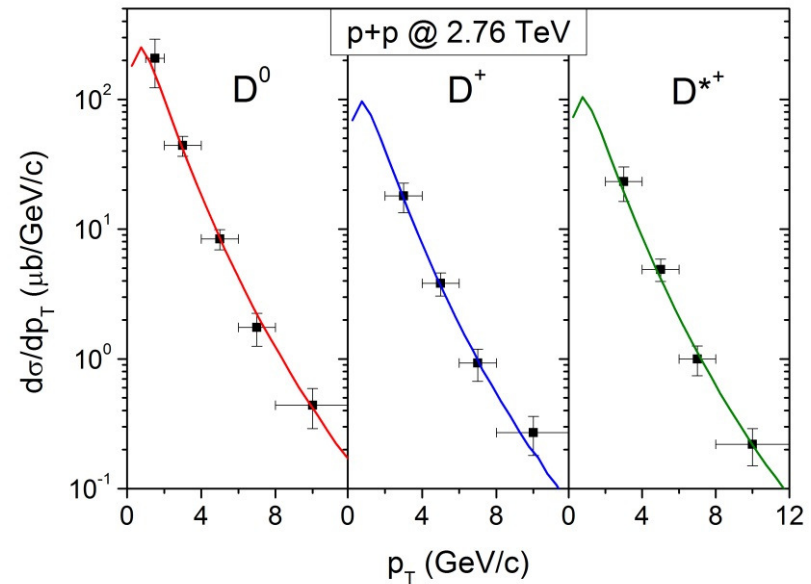
→ PHSD: the STAR data are better described in the scenario „coalescence with $\langle r \rangle = 0.9$ fm + fragmentation“



p+p collision @ 2.76 TeV



by using the same charm fragmentation function as in RHIC





(anti)shadowing effect

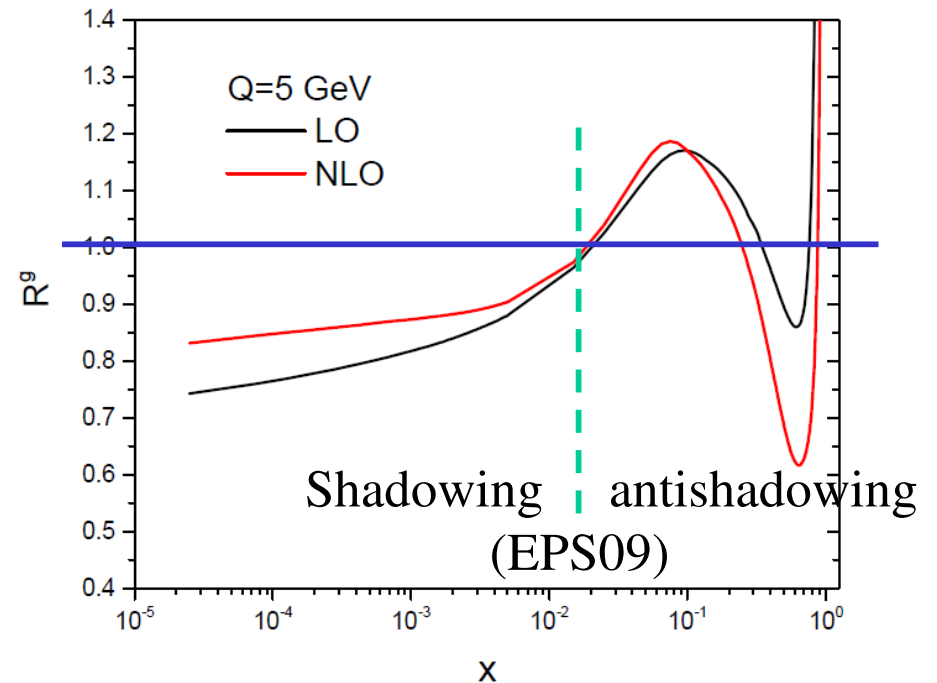
- Factorization formula (x_1, x_2 =energy fractions of parton 1 and 2, Q =factorization scale)

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

- Modified parton distribution function (PDF) in nucleus

$$f_i^{N^*}(x, Q) = R_i^A(x, Q) f_i^N(x, Q),$$

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





(anti)shadowing effect in PHSD

LO : $q+qbar \rightarrow c+cbar$, $g+g \rightarrow c+cbar$

NLO : $q+qbar \rightarrow c+cbar+g$, $g+g \rightarrow c+cbar+g$

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

M_T, y : the transverse mass, rapidity of final state
 E_{cm} : N+N collision energy in CM frame

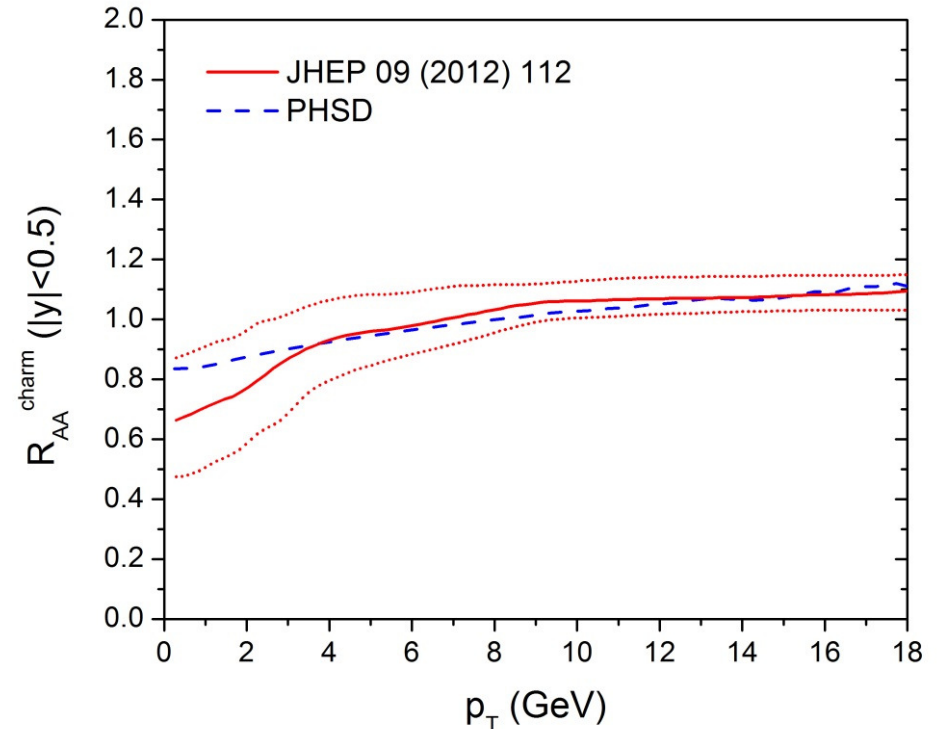
(E,p) of $c, cbar$ from PYTHIA

(E,p) of $gluon$ from the assumptions:

$$p_T(c+cbar) + p_T(g) = 0,$$

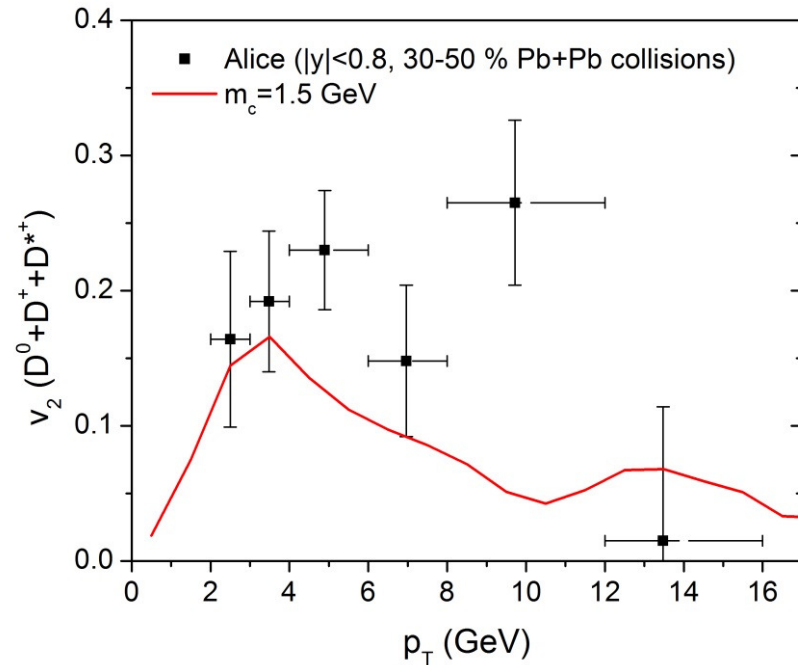
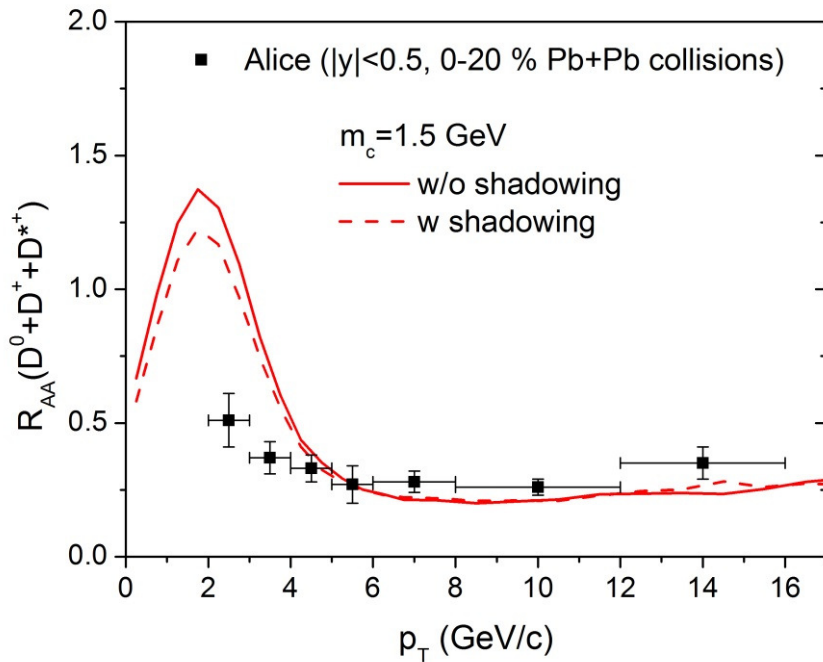
$$v_L(c+cbar) = v_L(g),$$

Factorization scale : $Q = M_T$



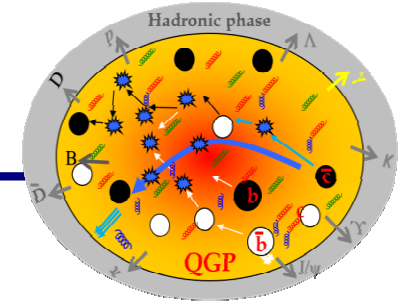


R_{AA} & v_2 of D^0 , D^+ , and D^{*+} using the same partonic & hadronic cross sections ($\langle r \rangle = 0.9$ fm)





Summary



- ❑ **PHSD** provides a **microscopic description** of non-equilibrium charm dynamics in partonic and hadronic phases

- ❑ **Partonic rescattering** suppresses R_{AA} at high p_T , and increases v_2
- ❑ **Hadronic rescattering** moves R_{AA} peak to higher p_T , and increases v_2

- ❑ The structure of R_{AA} at low p_T is sensitive to the **hadronization scenario**, i.e. to the balance between **coalescence and fragmentation**

- ❑ The **STAR & ALICE data** for the R_{AA} and v_2 at RHIC & LHC are well described in the PHSD:
 - by **QGP collisional energy loss** due to the **elastic scattering** of charm quarks with massive quarks and gluons in the QGP phase
 - + by the **hadronization scenario** „coalescence with $\langle r \rangle = 0.9$ fm + fragmentation“
 - + by **strong hadronic interactions** due to the (in)elastic scattering of D, D^* mesons with mesons and baryons

Thank you!