Tomography of the Quark-Gluon-Plasma by Charm Quarks

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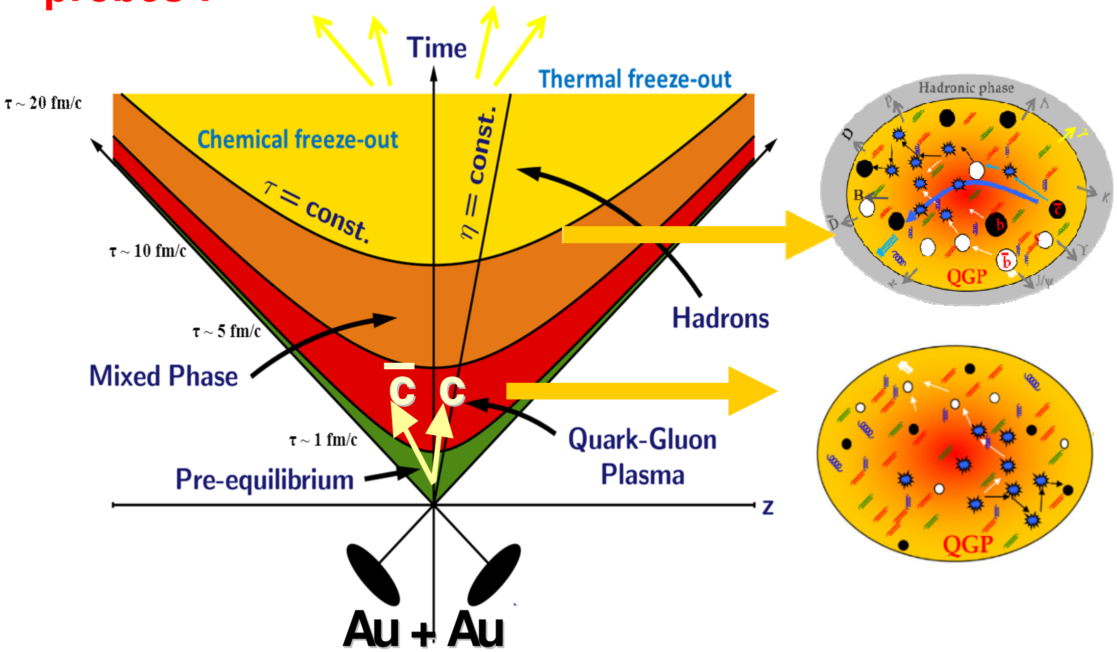
DAAD

DFG Deutsche Forschungsgemeinschaft

Motivation

❑ study of the properties of hot and dense nuclear and partonic matter by ‚charm probes‘:



The advantages of the 'charm probes':

❑ dominantly produced in the very early stages of the reactions in initial binary collisions with large energy-momentum transfer

❑ initial charm production is well described by pQCD – FONLL

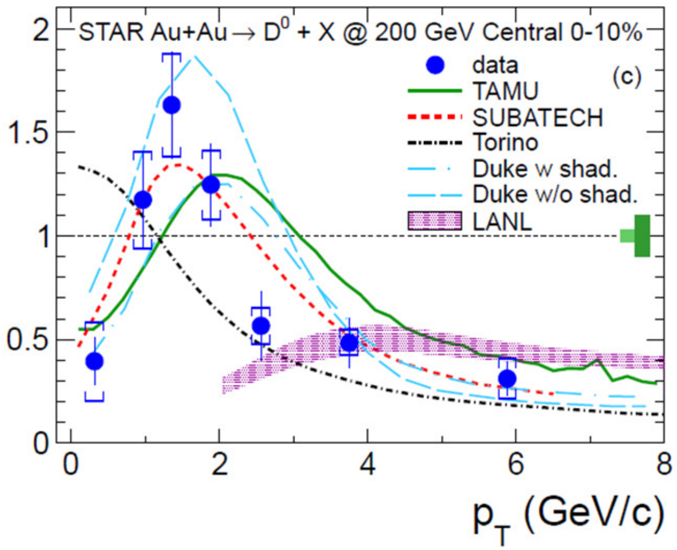
❑ scattering cross sections are small (compared to the light quarks) ➔ not in an equilibrium with the surrounding matter

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

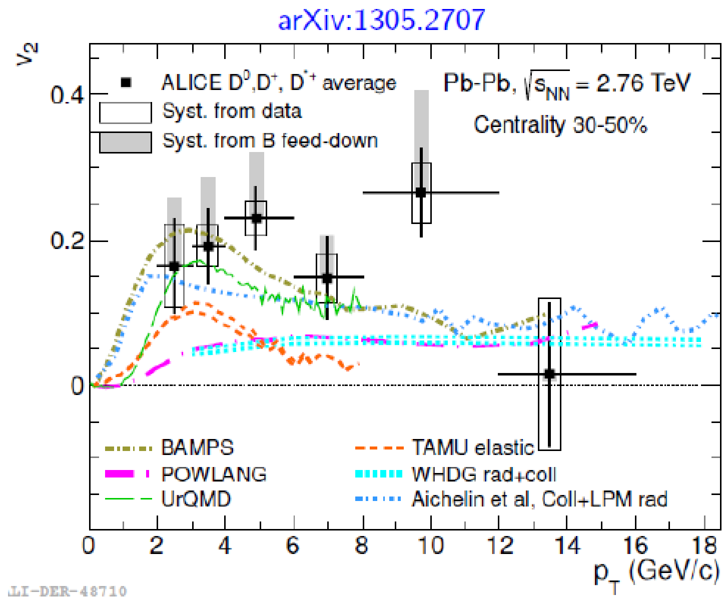
Charm: experimental signals

1. Nuclear modification factor:

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



2. Elliptic flow v_2:



❑ **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 v_2 !**

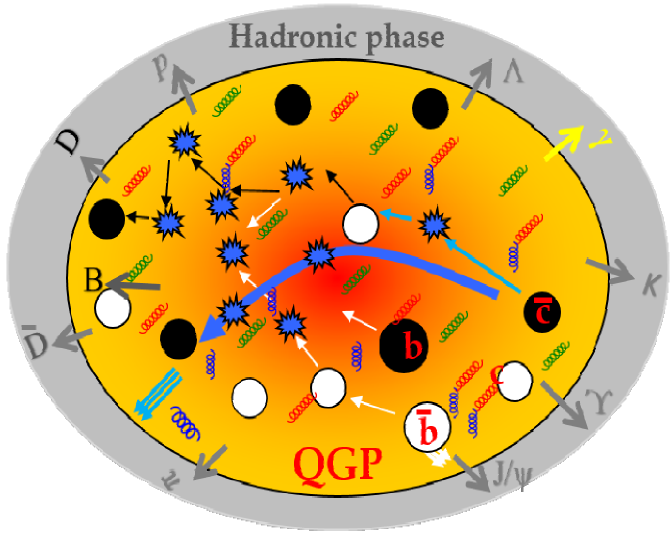
Dynamics of charm quarks in A+A

1. **Production** of charm quarks in initial binary collisions

2. **Interactions in the QGP**:
   elastic scattering Q+q→Q+q → collisional energy loss
   gluon bremsstrahlung Q+q→Q+q+g → radiative energy loss

3. **Hadronization: c/cbar quarks →D(D*)-mesons:**
   coalescence vs fragmentation

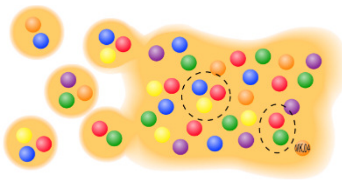
4. **Hadronic interactions:**
   D+baryons; D+mesons



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

The tool: PHSD approach

From SIS to LHC: from hadrons to partons



The goal: to **study of the phase transition** from hadronic to partonic matter and properties of the Quark-Gluon-Plasma on a **microscopic level**

➔ need a **consistent non-equilibrium transport model**

- ❑ with explicit **parton-parton interactions** (i.e. between quarks and gluons)
- ❑ explicit **phase transition** from hadronic to partonic degrees of freedom
- ❑ **lQCD EoS** for partonic phase (‚cross over‘ at μ_q=0)

❑ **Transport theory for strongly interacting systems: off-shell Kadanoff-Baym equations** for the Green-functions $S^<_h(x,p)$ in phase-space representation for the **partonic** and **hadronic phase**

⇨ **Parton-Hadron-String-Dynamics (PHSD)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

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

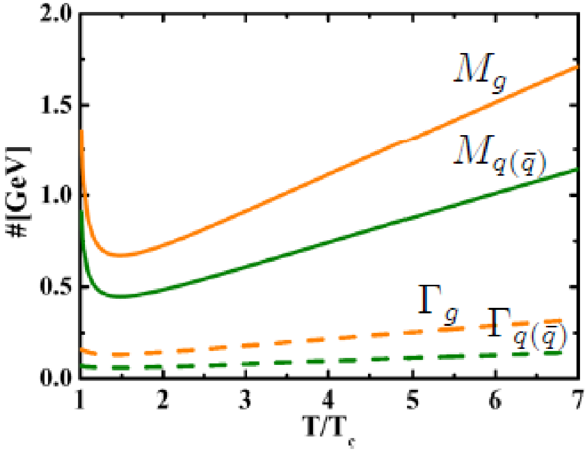
The Dynamical QuasiParticle Model (DQPM)

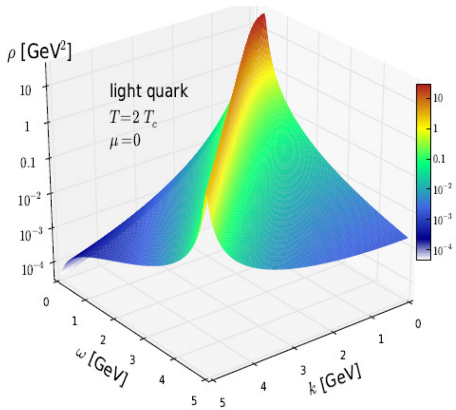
- **Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :**

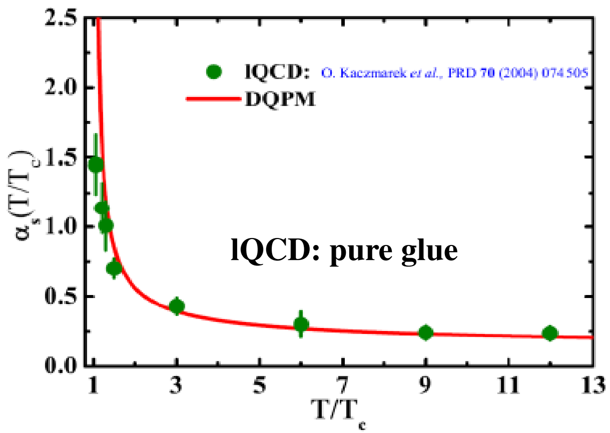
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

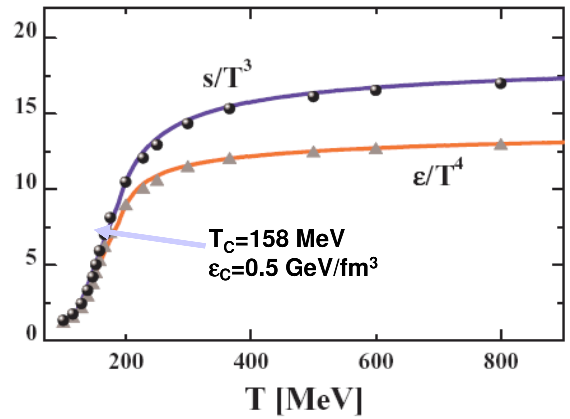
- **fit to lattice (lQCD) results (e.g. entropy density) with 3 parameters**

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





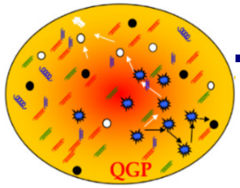




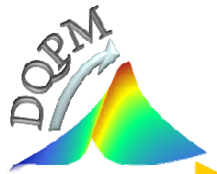
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

Basic idea of PHSD



QGP in equilibrium



Dynamical QuasiParticle Model (DQPM):

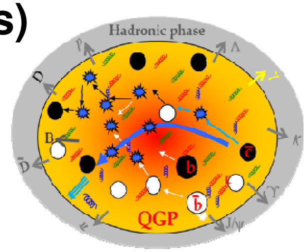
fitted to → **lQCD**

controled by lQCD!

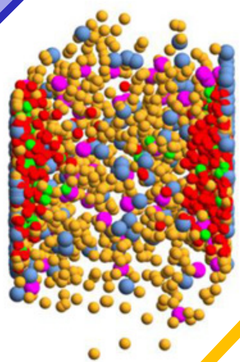
Quasiparticle properties:
‚resummed' self-energies, propagators
→ Calculation of cross sections

⇒ Calculation of transport coefficients η, ζ, σ_0, ..

DQPM: consider all the effects of the nonperturbative nature of the strongly interacting quark-gluon plasma (sQGP) constituents (vs. pQCD models)

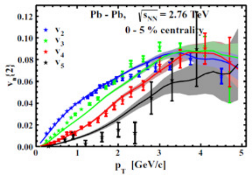


QGP out-of equilibrium ←→ HIC



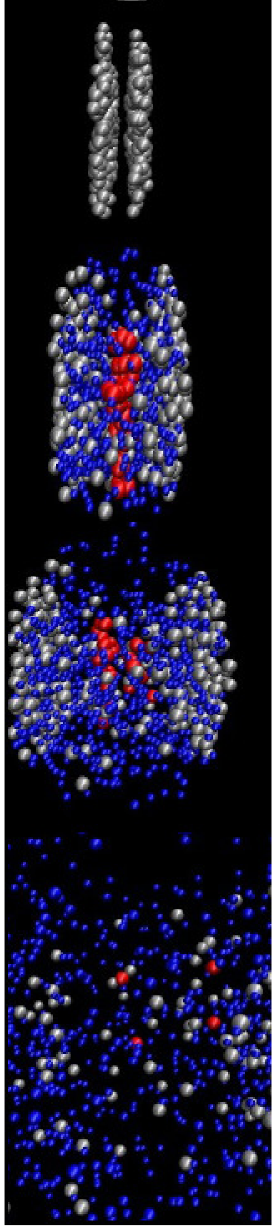
Parton-Hadron-String-Dynamics (PHSD)

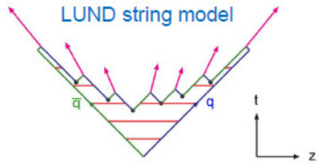
controled by → **experimental data**



Partonic interactions → DQPM
hadronic interactions → hadron physics
* In-medium hadronic interactions → many-body physics: G-matrix

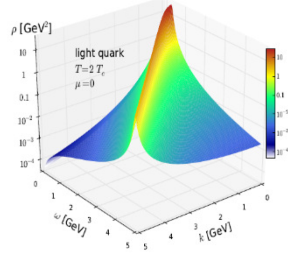
Parton-Hadron-String-Dynamics (PHSD)





- **Initial A+A collisions – HSD:**
  N+N → string formation → decay to pre-hadrons

- **Formation of QGP stage if $\varepsilon > \varepsilon_{critical}$:**
  dissolution of pre-hadrons → (DQPM) →
  → massive quarks/gluons + mean-field potential U_q



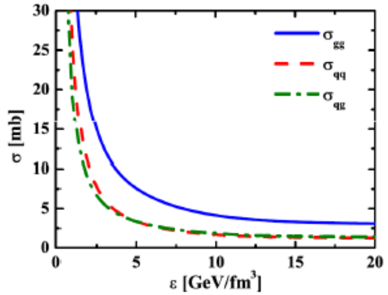
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

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

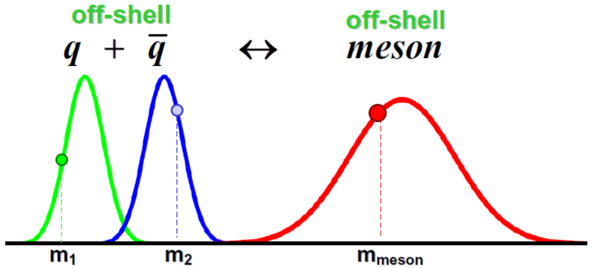
  - inelastic collisions:

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



- **Hadronization (based on DQPM):**

$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson\ \ (or\ 'string\ ')$$
$$q+q+q \leftrightarrow baryon\ \ (or\ 'string\ ')$$

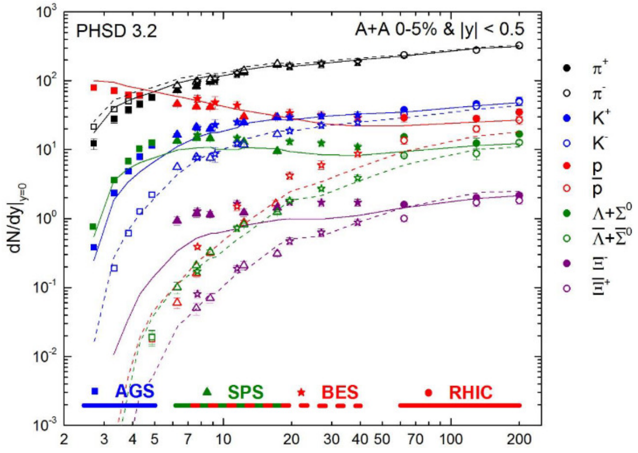


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

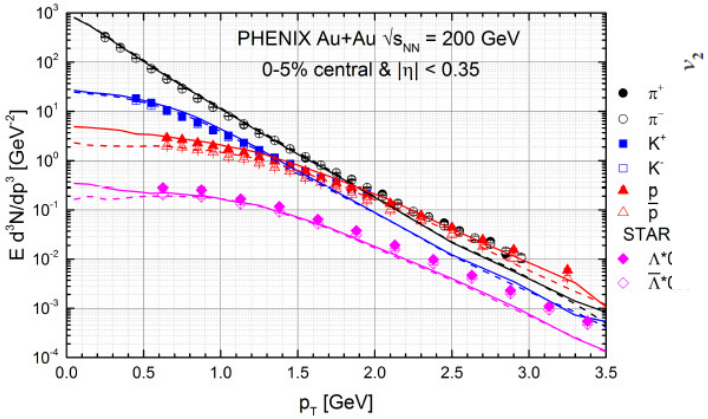
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

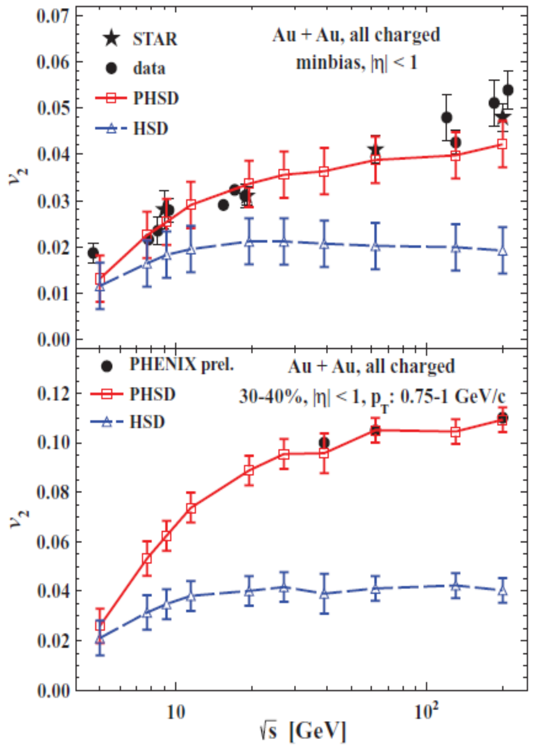
Non-equilibrium dynamics: description of A+A with PHSD

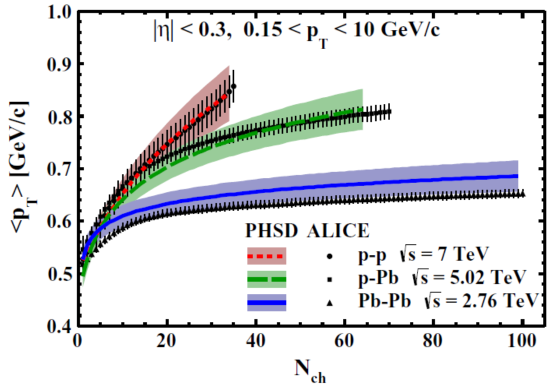
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

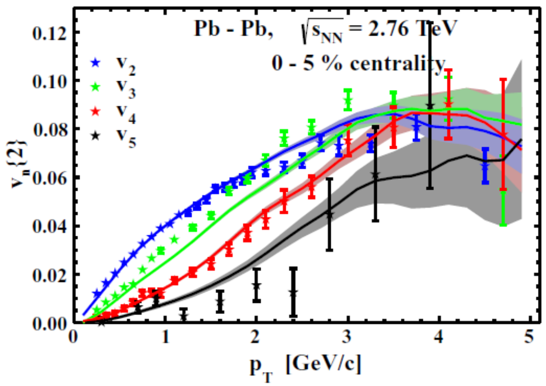


PHSD: P. Moreau







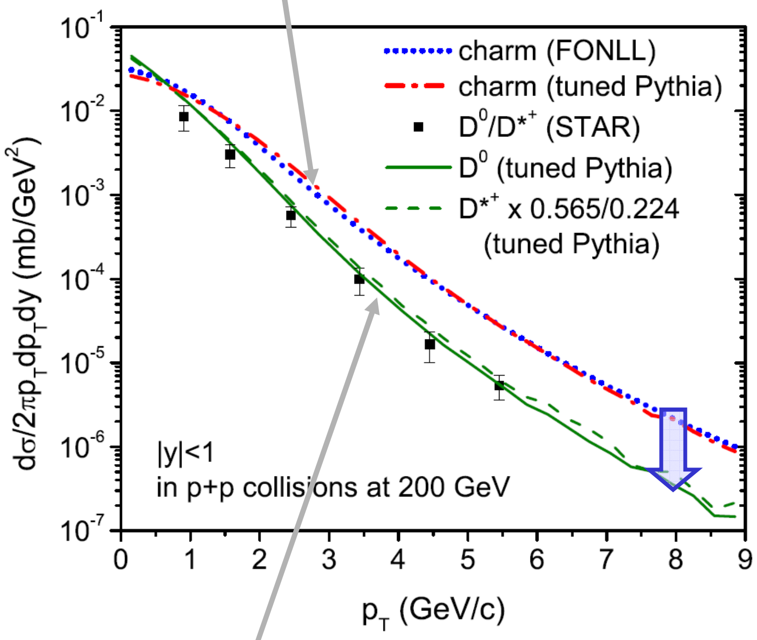


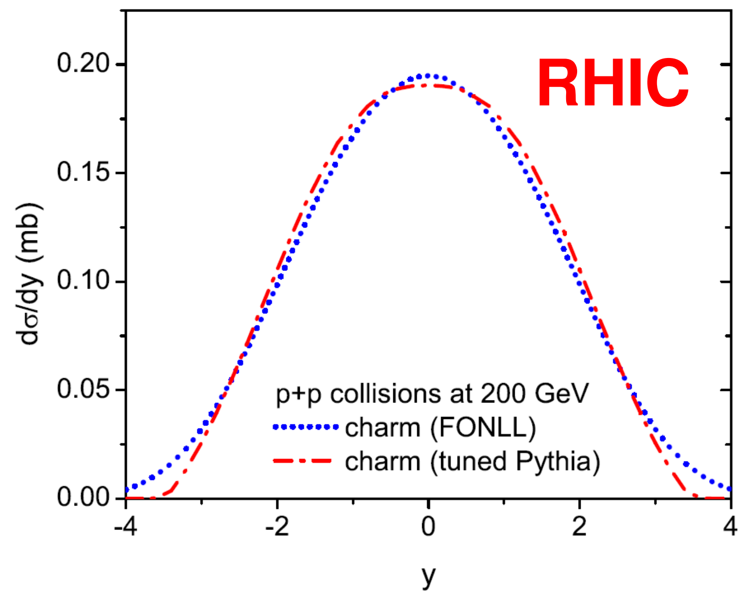
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

❑ **PHSD** provides a **good description of ‚bulk‘ observables** (y-, p_T-distributions, flow coeficients v_n, …) from SPS to LHC

Charm quark/hadrons production in p+p collisions

1) Momentum distribution of charm quark: use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)





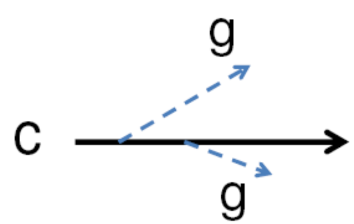
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

2) Charm hadron production by c-quark fragmentation:

D^0 20 %
D^+ 17.4 %
D^{*0} 21.3 %
D^{*+} 22.4 %
Ds^+ 8 %
Λ_c 9.4 %

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

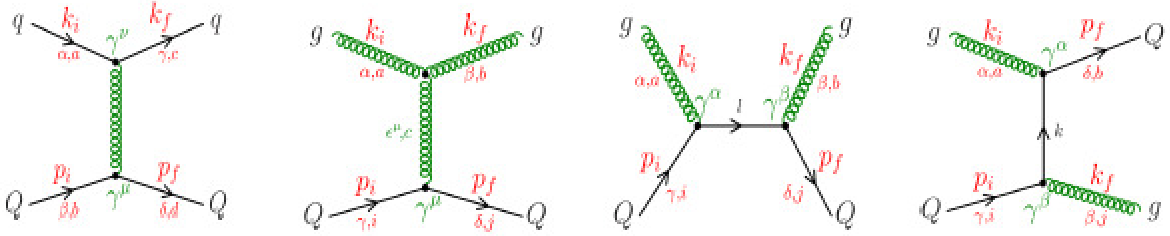
From C. Peterson et al., PRD27 (1983) 105



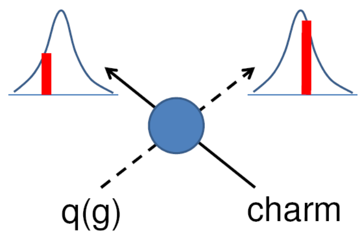
- **z : momentum fraction of hadron H in heavy quark Q**
- **ϵ_Q=0.01 for Q=charm**

Charm quark scattering in the QGP (DQPM)

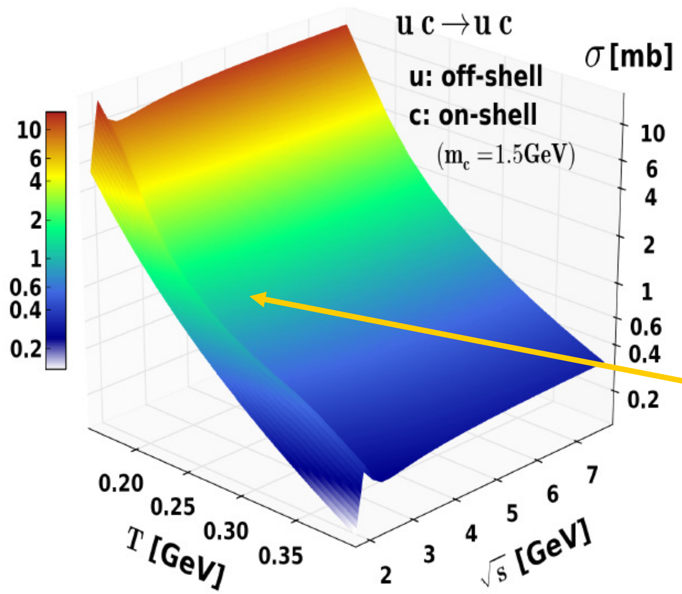
❑ **Elastic scattering with off-shell massive partons Q+q(g)→Q+q(g)**



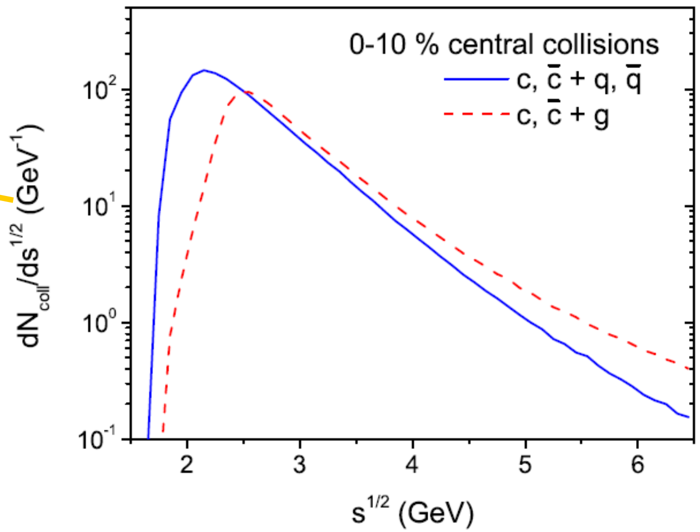
Non-perturbative QGP!



❑ **Elastic cross section uc→uc**



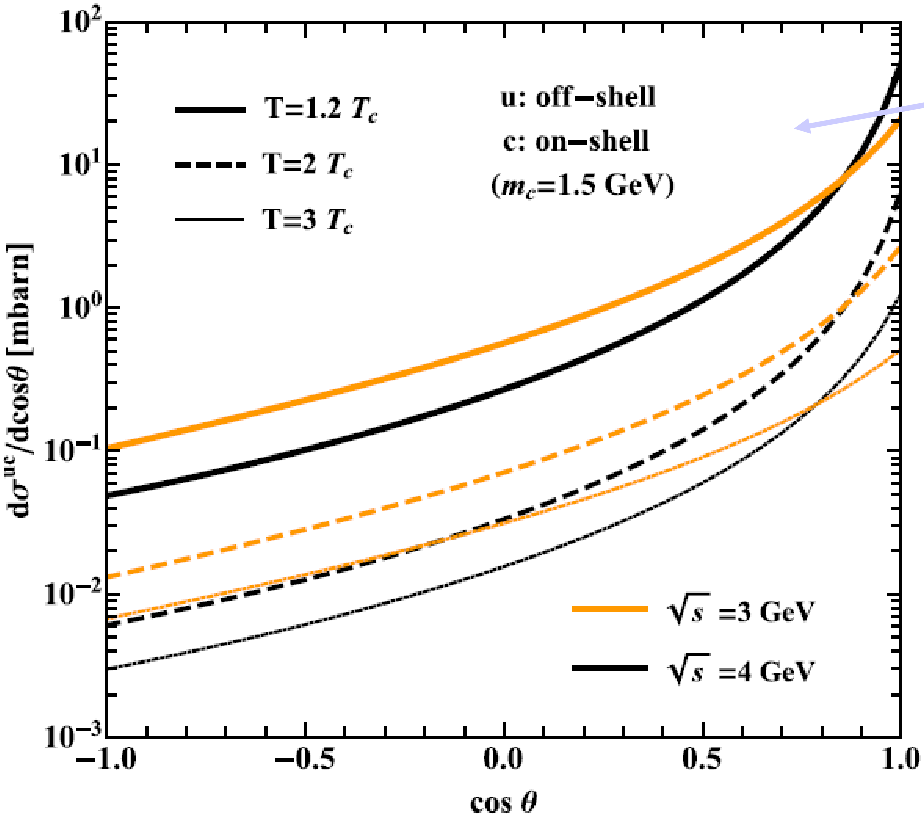
❑ **Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 10% central**



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

Charm quark scattering in the QGP

- **Differential elastic cross section** for uc→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
➔ Differences between DQPM and pQCD : 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

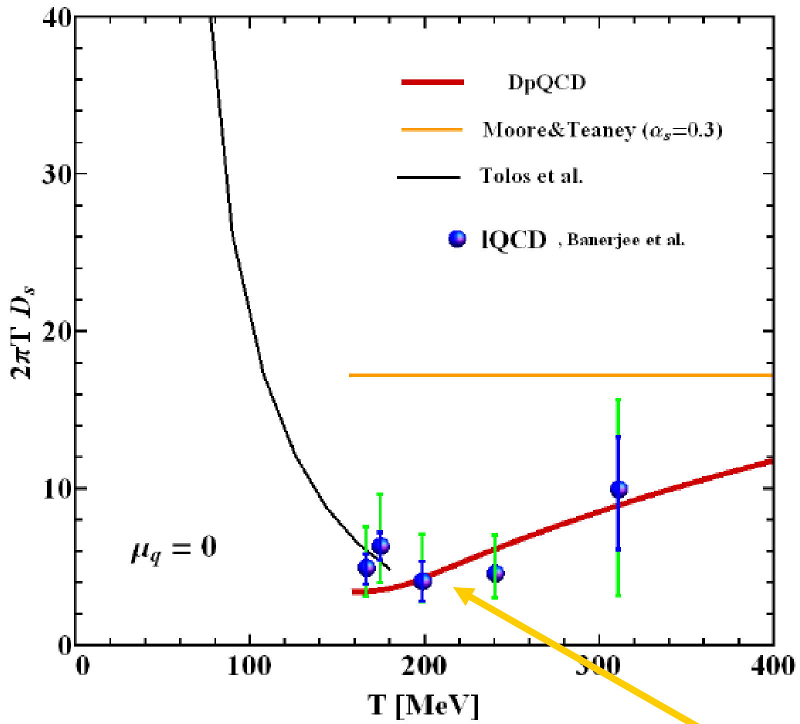
➔ Smaller number (compared to pQCD) of elastic scatterings with massive partons leads to a large energy loss

! 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

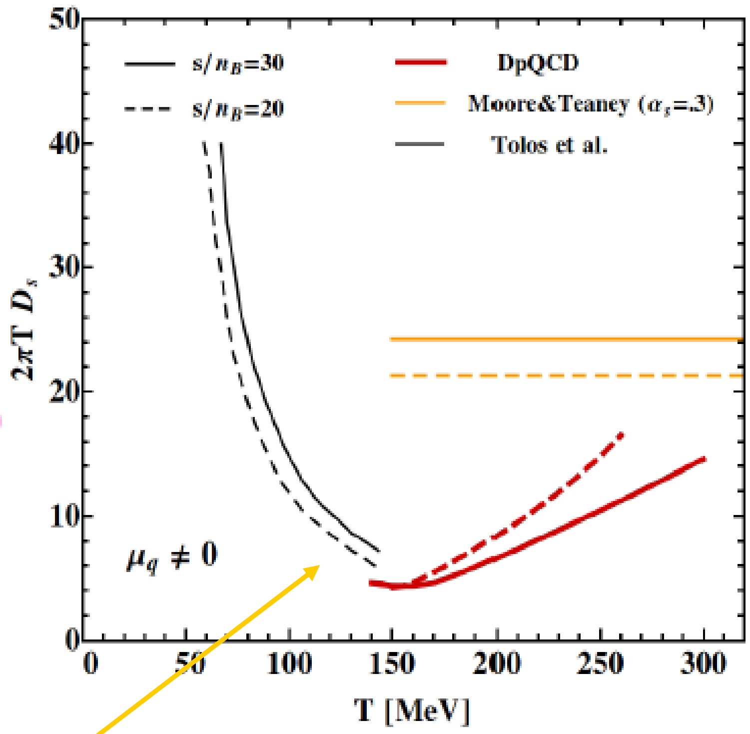
H. Berrehrah et al, PRC 89 (2014) 054901; PRC 90 (2014) 051901; PRC90 (2014) 064906

Charm spatial diffusion coefficient D_s in the hot medium

▪ D_s for heavy quarks as a function of T for μ_q=0 and finite μ_q assuming adiabatic trajectories (constant entropy per net baryon s/n_B) for the expansion



$\Rightarrow$ $\mu_q \neq 0$



❑ T < T_c : hadronic D_s

L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

➔ Continuous transition at T_C!

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

Hadronization of charm quarks in A+A

- PHSD: if the local energy density $\varepsilon < \varepsilon_C$ ➔ hadronization of charm quarks to hadrons:

ε_C =0.5 GeV/fm^3

1. Dynamical coalescence model

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

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

Degeneracy factor:
g_M = 1 for D
g_M = 3 for D*

D*:
D*$_0$(2400)^0
D*$_1$(2420)^0
D*$_2$(2460)$^{0\pm}$

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

Width δ ← from root-mean-square radius of meson:

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

Hadronization scenarios :

1: only fragmentation
2. coalescence with <r>=0.5 fm + fragmentation
3: coalescence with <r>=0.9 fm + fragmentation

2. Fragmentation (as in pp)

- if NOT hadronized by coalescence

Note: large <r> used also in Refs:
S. Cao, G. Y. Qin and S. A. Bass, PRC 88, 044907 (2013).
Y. Oh, C. M. Ko, S. H. Lee and S. Yasui, PRC 79, 044905 (2009)

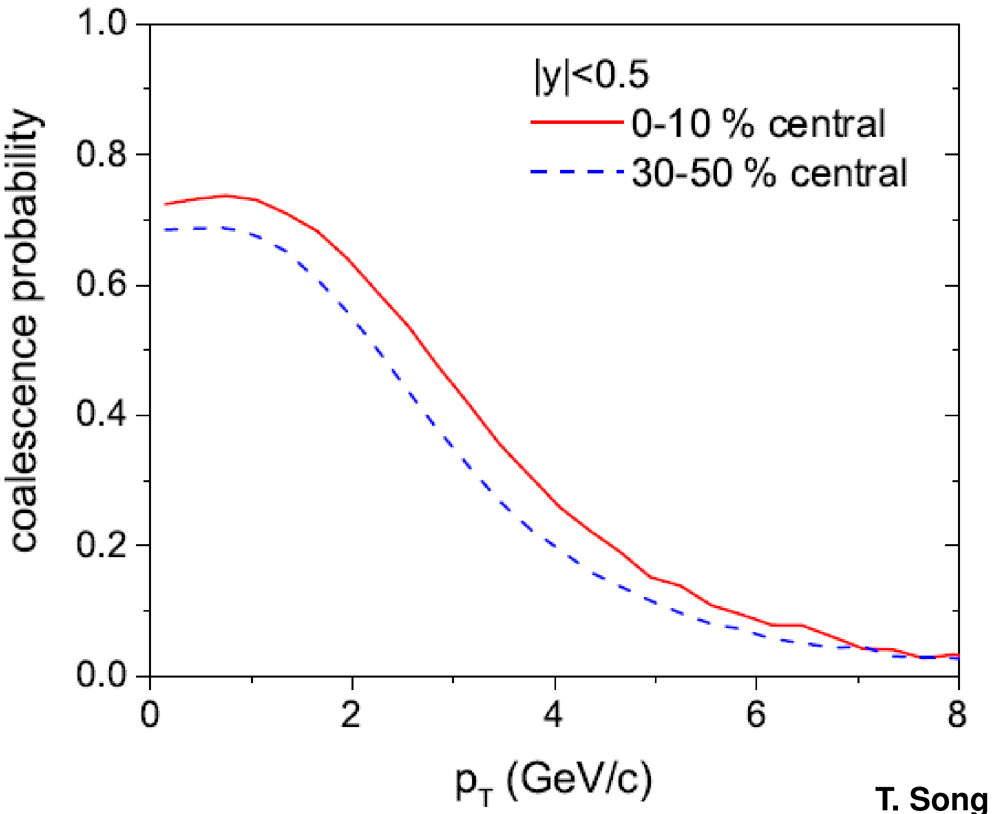
Hadronization of charm quarks in A+A : LHC

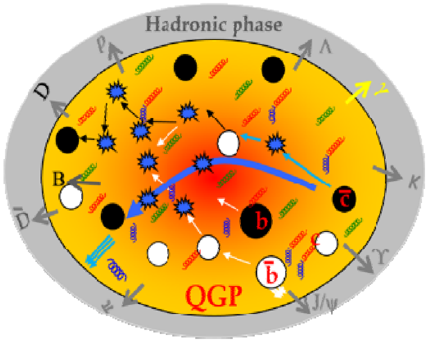
Dynamical Hadronization scenarios :

4. coalescence with <r>=0.9 fm... + fragmentation

0.4< ε < **0.75 GeV/fm³** ε < **0.4 GeV/fm³**

Coalescence probability in Au+Au



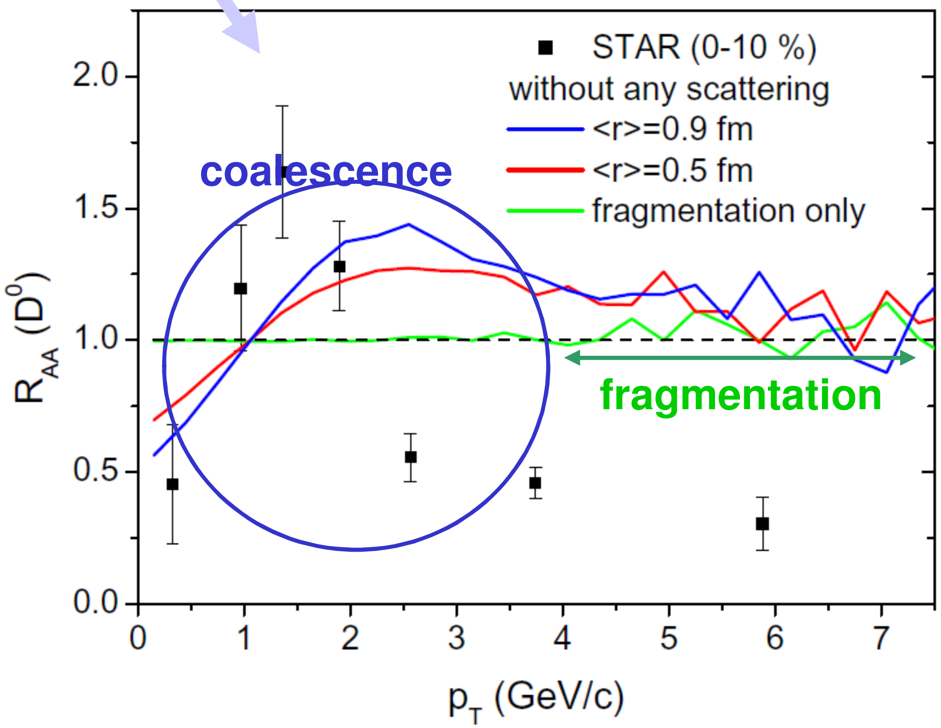


T. Song et al., PRC (2016), arXiv:1512.0089

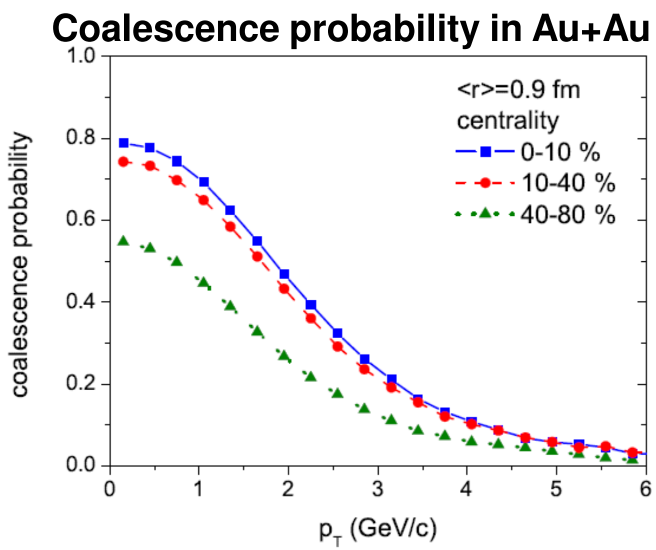
R_{AA} at RHIC - coalescence vs fragmentation

1. **Influence of hadronization scenarios: coalescence vs fragmentation**

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



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

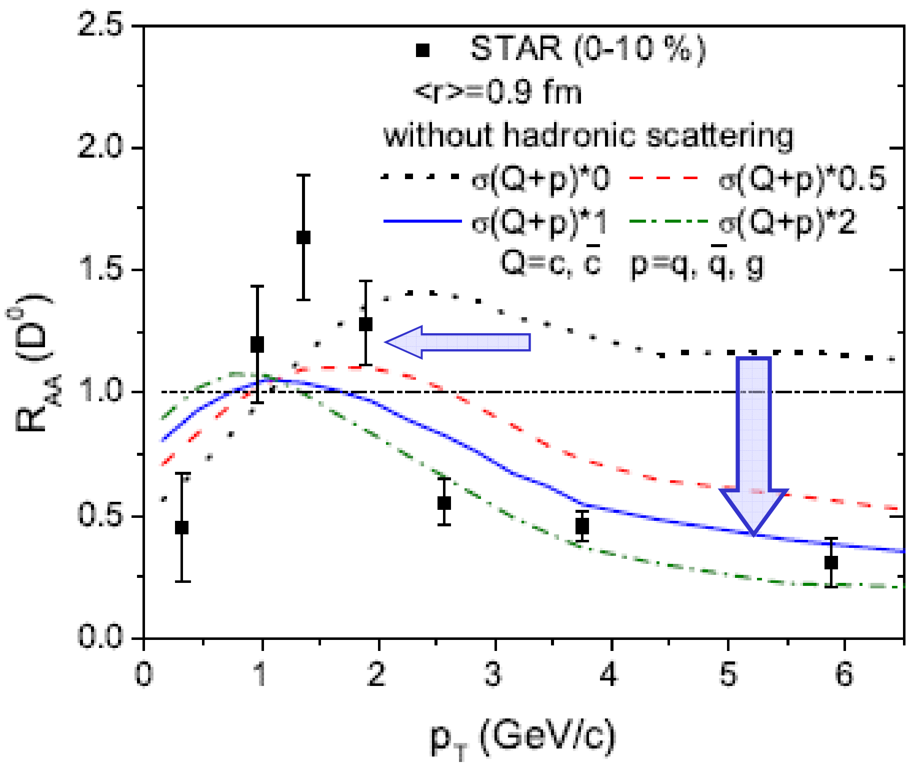


- Expect: no scattering: R_{AA}=1
- Hadronization by fragmentation only (as in pp) → R_{AA}=1
- Coalescence (not in pp!) shifts R_{AA} to larger p_T → ‚nuclear matter' effect
- The hight of the R_{AA} peak depends on the balance: coalescence vs. fragmentation

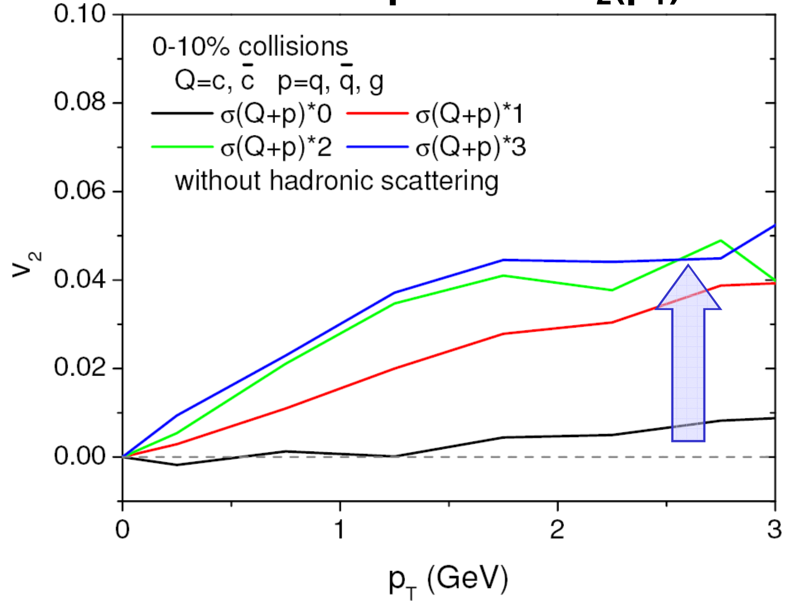
R_{AA} at RHIC: partonic scattering

2. Influence of partonic rescattering

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



Elliptic flow $v_2(p_T)$



Elastic partonic rescattering

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

Central Au+Au at $s^{1/2}$ =200 GeV :
N(cc) ~19 pairs,
N(Q+q)~130 collisions
N(Q+g) ~85 collisions

➔ **<u>each charm quark makes ~ 6 elastic collisions</u>**

Modelling of D-meson scattering in the hadronic gas

1. D-meson scattering with mesons

Model: effective chiral 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) :

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

with

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

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

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

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)

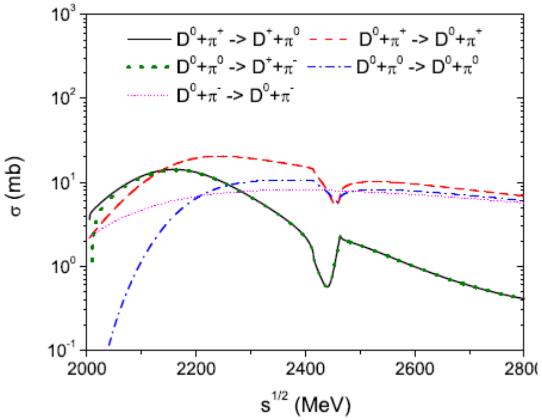
Unitarized scattering amplitude ➔ from solution of coupled-channel Bethe-Salpeter equations:

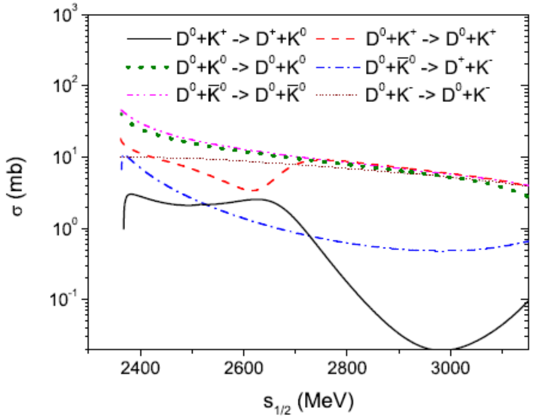
$$T = T + VGT$$

T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

D-meson scattering in the hadron gas

1. D-meson scattering with mesons

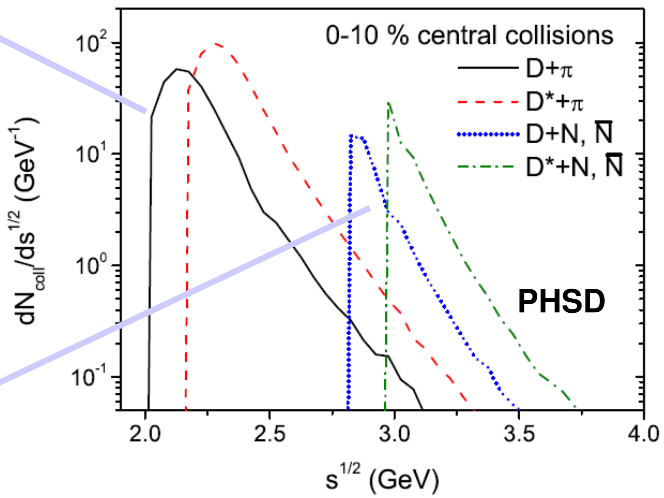




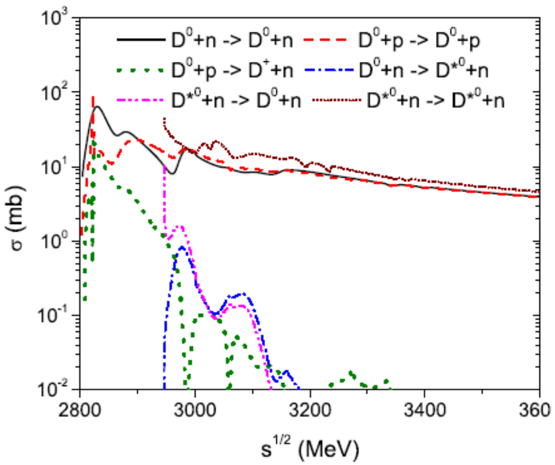
1a) cross sections with *m=ρ,ω,ϕ,K*,...* taken as

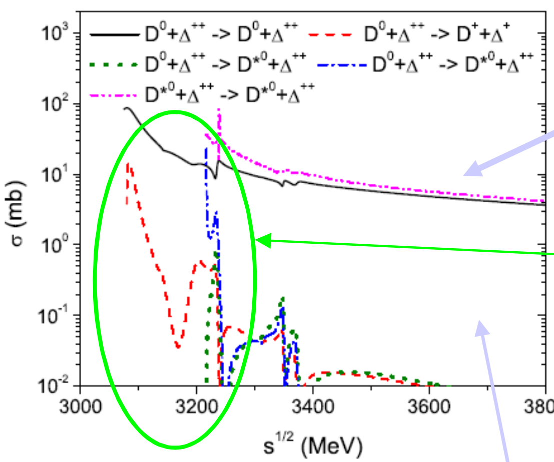
$$\sigma(D, D^* + m) = 10mb$$

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



2. D-meson scattering with baryons

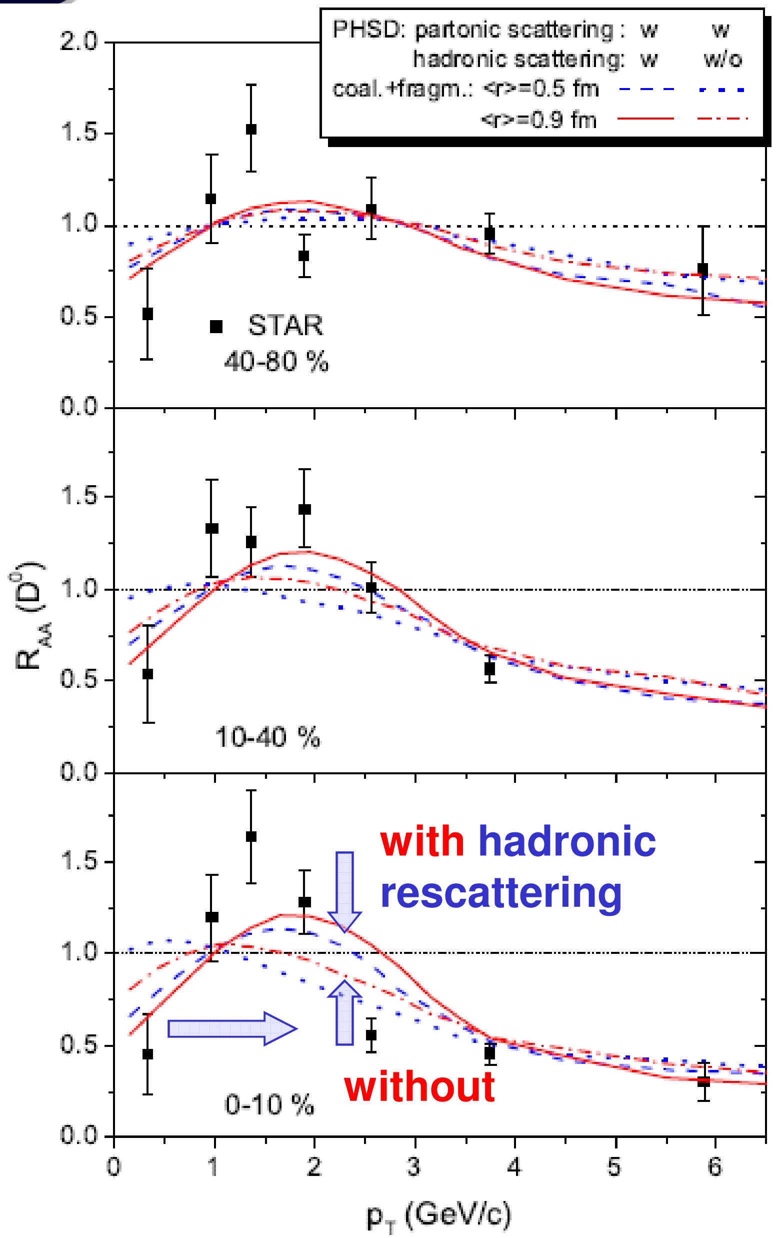




➔Strong isospin dependence and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!

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

R_{AA} at RHIC: hadronic rescattering



3. Influence of hadronic rescattering

! Model study: (with partonic rescattering)
with / without hadronic rescattering

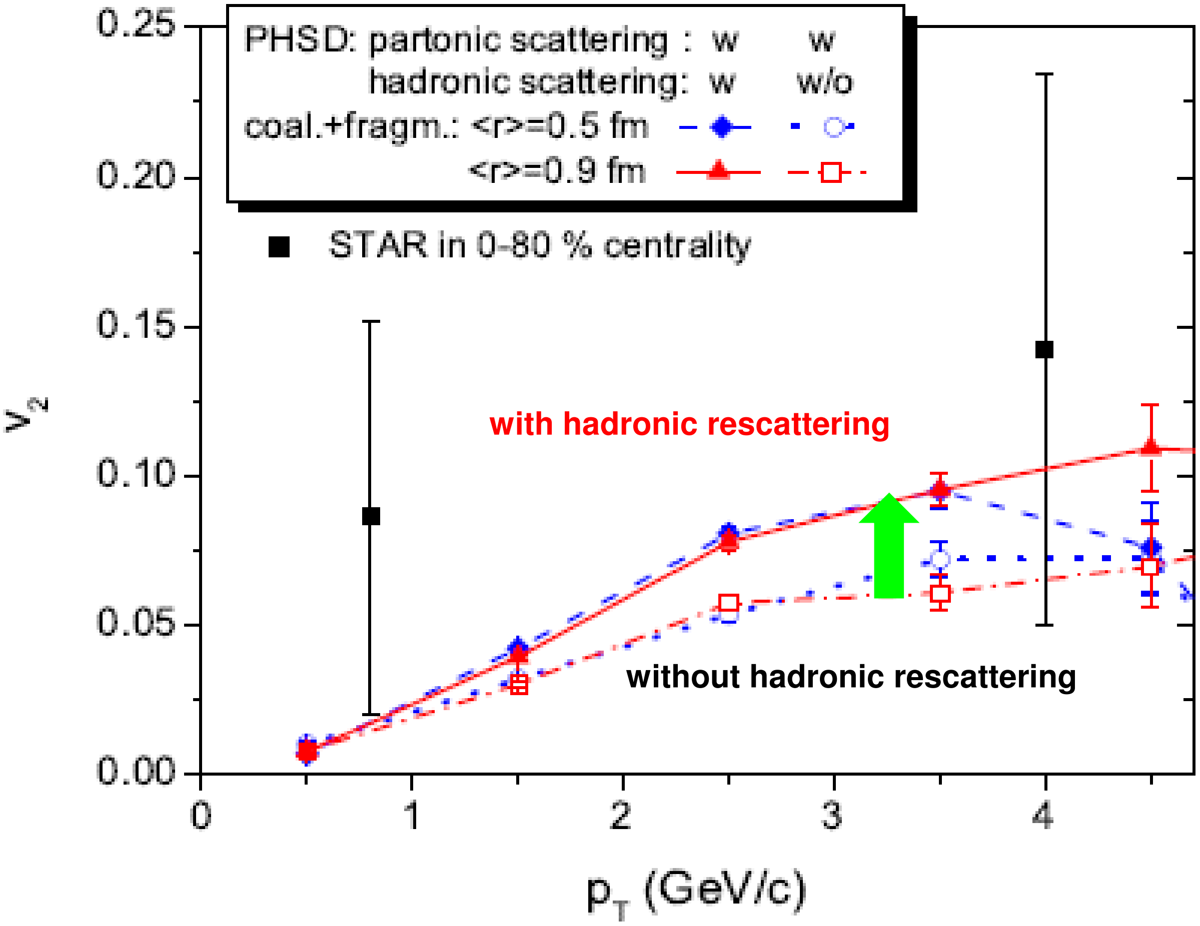
Central Au+Au at $s^{1/2}$=200 GeV :
N(D,D*) ~30
N(D,D*+m) ~56 collisions
N(D,D*+B,Bbar) ~10 collisions

➔ each D,D* makes
~ 2 scatterings with hadrons

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

T. Song et al., PRC (2015), arXiv:1503.03039
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

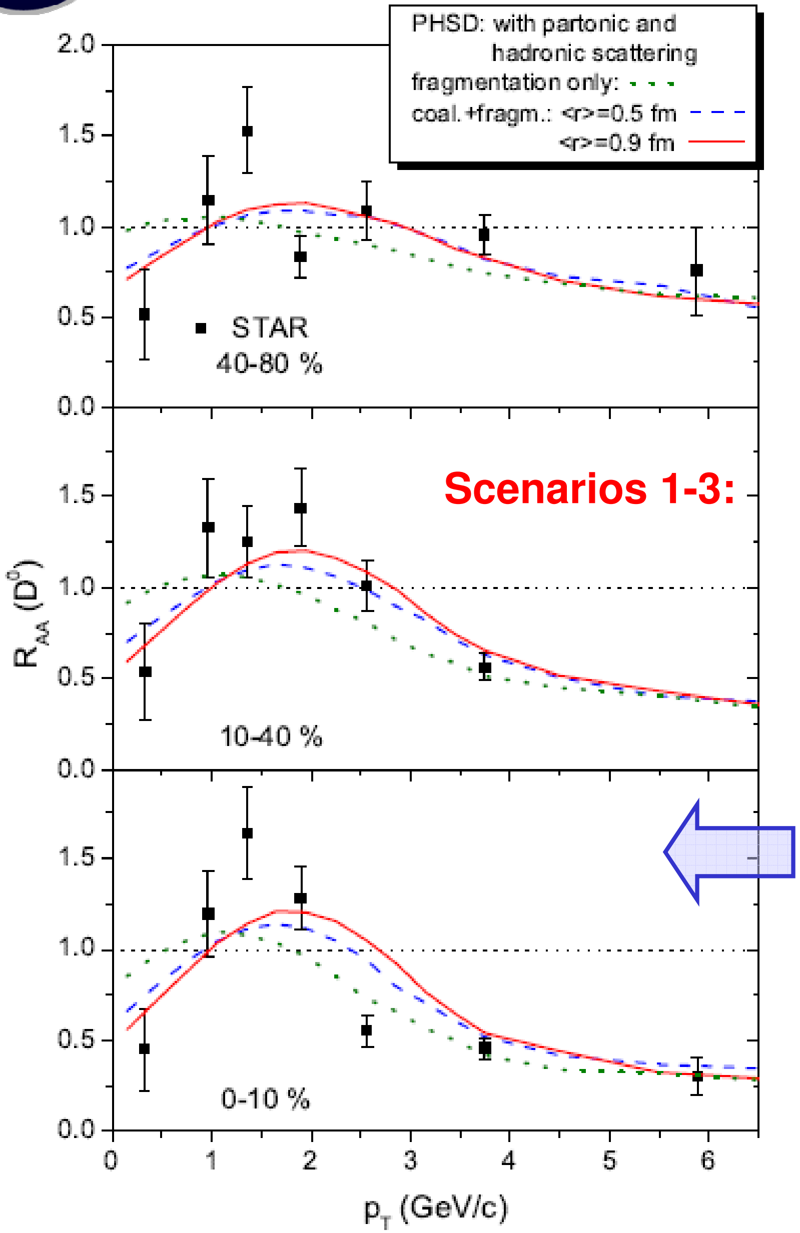
D-meson elliptic flow v_2 at RHIC



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

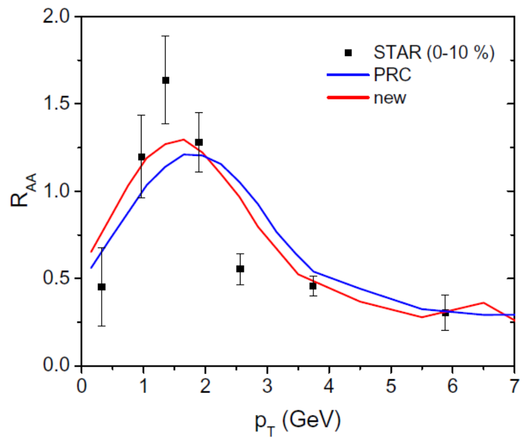
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

R_{AA} at RHIC



PHSD results:
with all rescattering (partonic and hadronic)

4: Dynamical Hadronization scenario



❑ **The hight and position of the R_{AA} peak at low p_T depends on the hadronization scenario: coalescence/fragmentation!**

➔**PHSD: the STAR data are better described within scenario „coalescence with <r>=0.9 fm + fragmentation“ and dynamical hadronization scenario**

T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

Shadowing effect

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

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

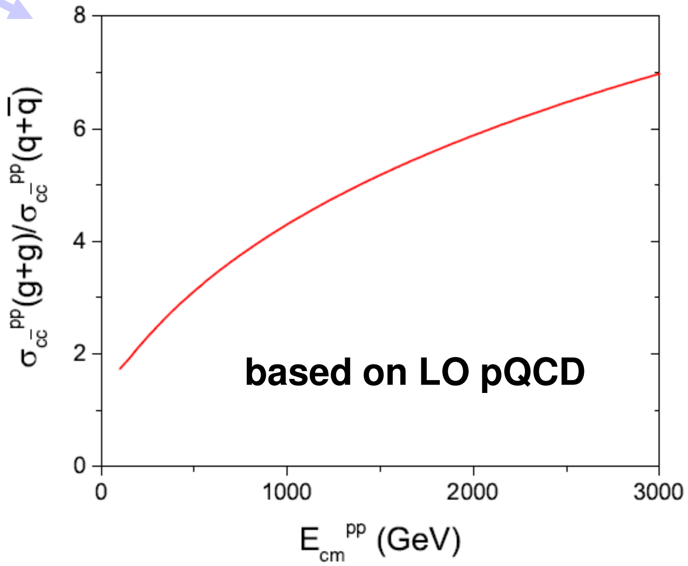
$$x_1 = \frac{M_T}{E_{\rm cm}} e^{y}, \qquad x_2 = \frac{M_T}{E_{\rm cm}} e^{-y},$$

$$\sigma_{c\bar{c}}^{N^*N^*}(s) = \langle R_g^{Pb}(x_1,Q) R_g^{Pb}(x_2,Q)\rangle \; \sigma_{c\bar{c}}^{NN}(s)$$

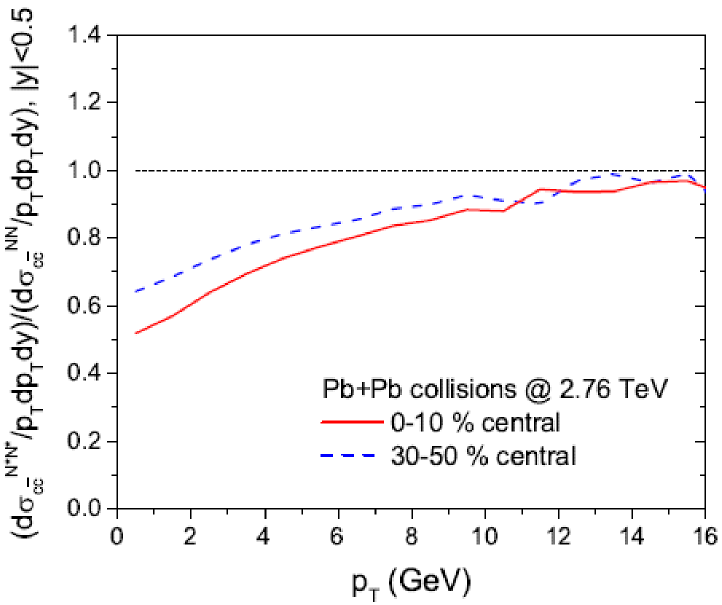
Scale Q = $(M_T^1+M_T^2)/2$

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

$$\sigma(g+g \rightarrow c+\bar{c}) / \sigma(q+\bar{q} \rightarrow c+\bar{c})$$

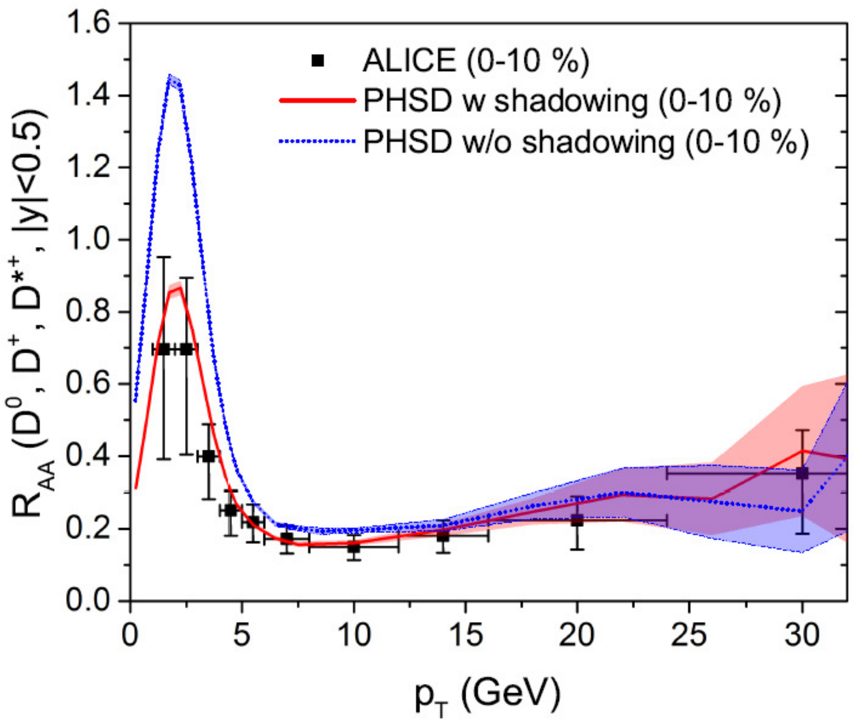


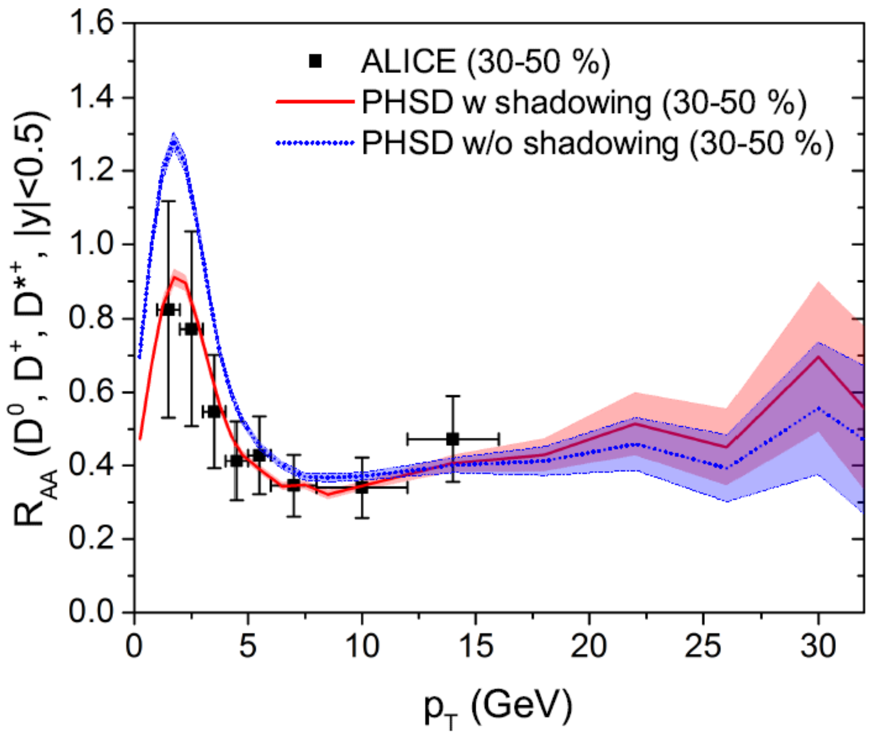
- **The (anti-)shadowing effect depends on the impact parameter in HIC:**



T. Song et al., PRC (2016), arXiv:1512.0089

Charm R_{AA} at LHC

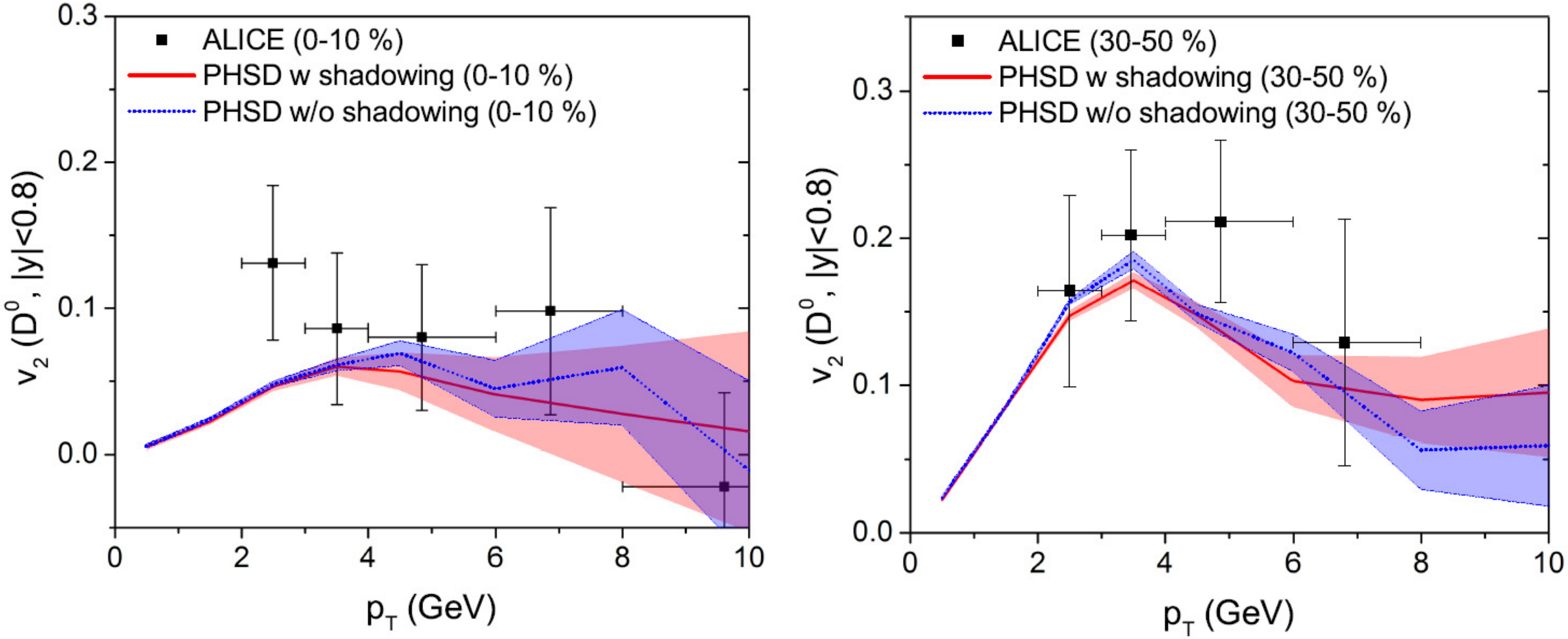




- in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering
- Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}
- Hadronic rescattering moves R_{AA} peak to higher p_T

T. Song et al., PRC (2016), arXiv:1512.0089

Charm v_2 at LHC

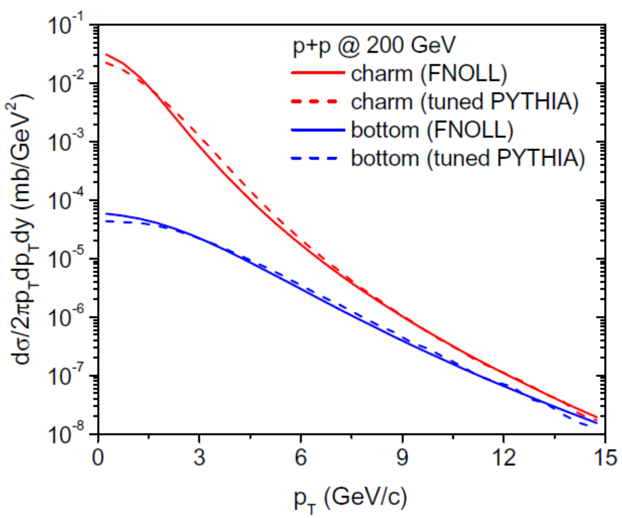


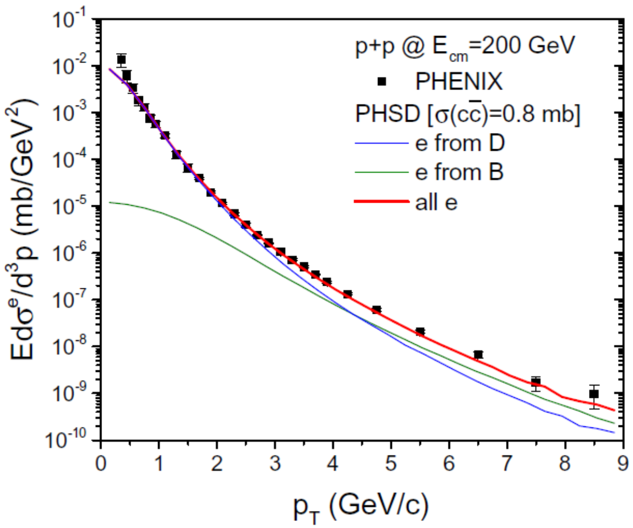
- Shadowing effect has small impact on v_2
- Hadronic rescattering increases v_2

T. Song et al., PRC (2016), arXiv:1512.0089

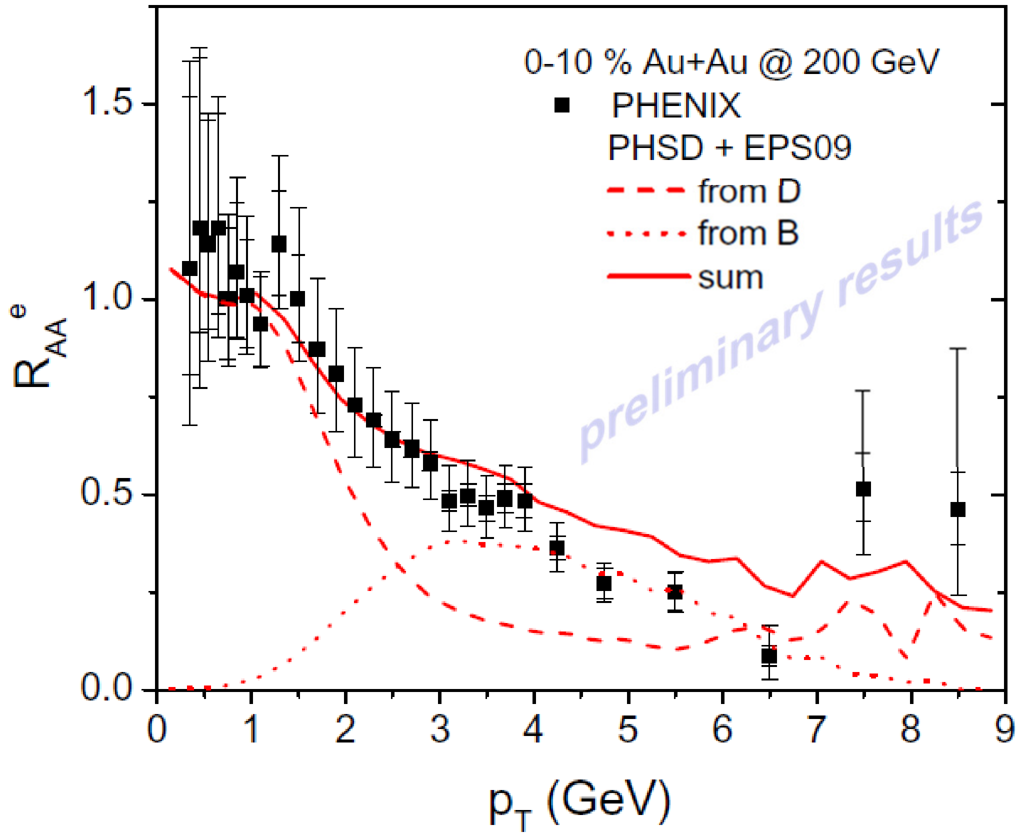
Beauty contribution

Beauty production in pp





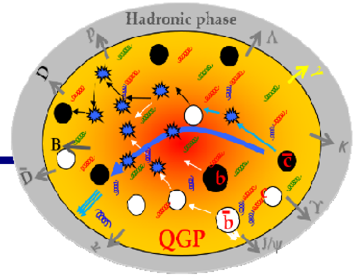
R_{AA} from single electrons in Au+Au @ 200 GeV



- ❑ **Feed back from beauty contribution becoms dominant at p_T >2.5 GeV**

T. Song et al., in progress

Summary



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

- Partonic rescattering suppresses the high p_T part of R_{AA}, increases v_2
- Hadronic rescattering moves R_{AA} peak to higher p_T, 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
- Shadowing effect supresses R_{AA}

- The exp data for the R_{AA} and v_2 at RHIC and LHC are better 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 <r>=0.9 fm + fragmentation"

  \+ by strong hadronic interactions due to the elastic scattering of D,D* mesons with mesons and baryons

Outlook

- the BES RHIC – in progress
- Influence of radiative energy loss at larger p_T ?

(expected to be strongly suppressed at lower transverse momenta in the PHSD due to the large mass of gluons for lower relative momenta)

Thank you!