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Tomography of the Quark-Gluon-Plasma by Charm Quarks

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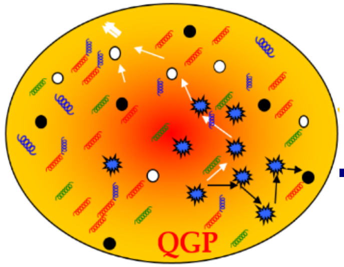
In collaboration with Taesoo Song, Hamza Berrehrah, Daniel Cabrera, Juan Torres-Rincon, Laura Tolos, Wolfgang Cassing, Jörg Aichelin and Pol-Bernard Gossiaux

DFG Deutsche Forschungsgemeinschaft

PHSD

JOINT INSTITUTE FOR NUCLEAR RESEARCH
Strangeness in Quark Matter
06 July - 11 July 2015
SQM DUBNA 2015



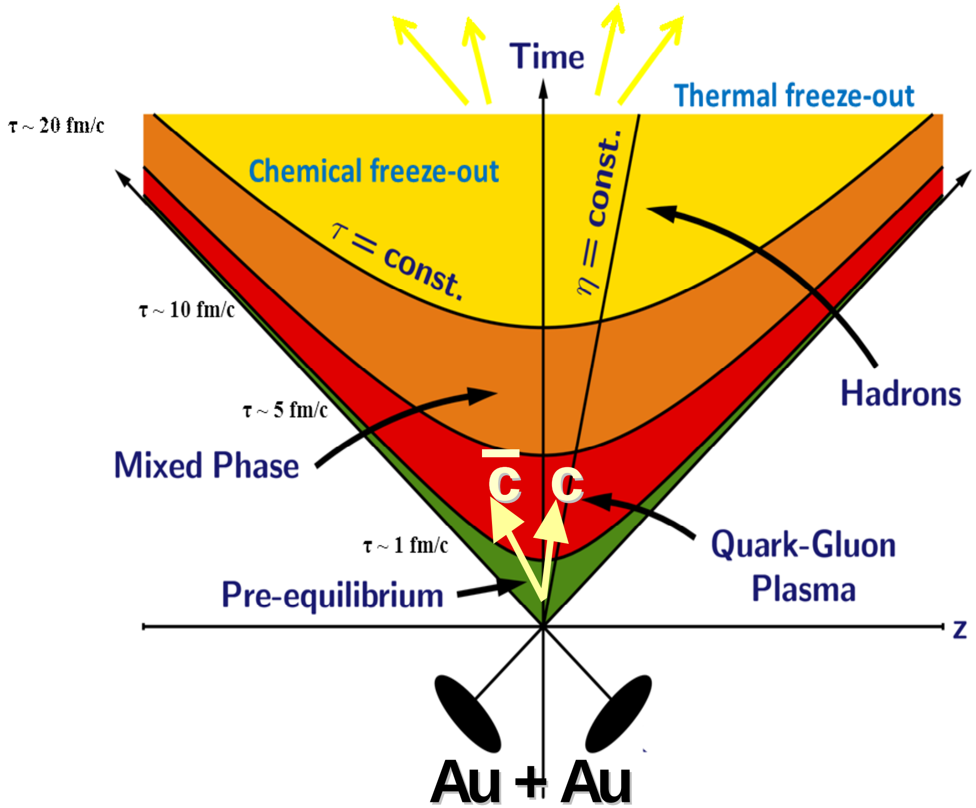
Tomography of the QGP by Charm Quarks

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**



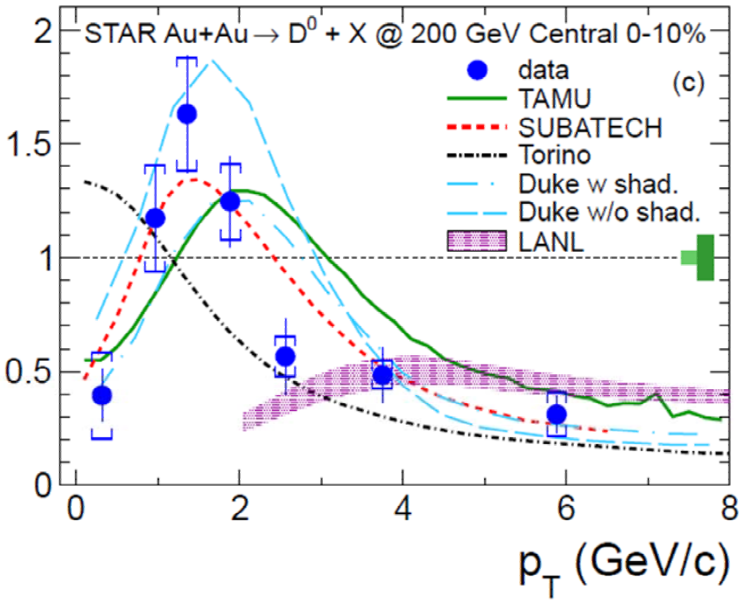
➔ Hope to use 'charm probes' for an early tomography of the QGP

Cf. talk by Marlene Nahrgang, Wed, 9:30

Charm: experimental signals

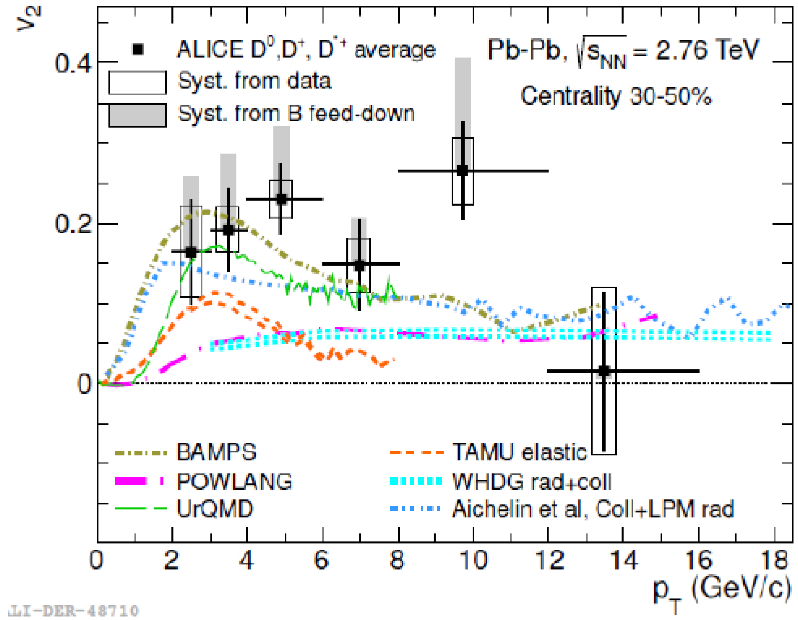
1. Nuclear modification factor:

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



2. Elliptic flow v_2:

arXiv:1305.2707



❑ **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 !**

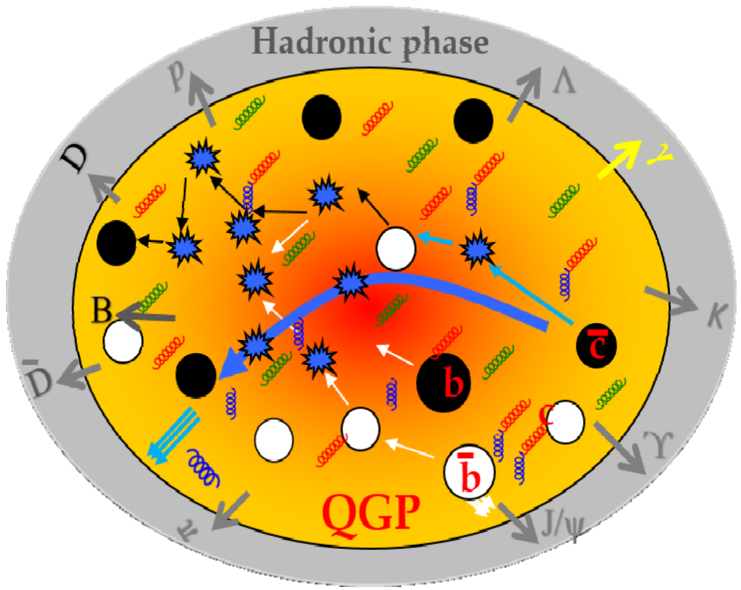
Dynamics of charm quarks in A+A

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 from a microscopic origin

➔ 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)

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions – in the sense of a two-particle irreducible (2PI) approach:

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)
- 2PI framework guaranties a consistent description of the system in- and out-off equilibrium on the basis of Kadanoff-Baym equations with proper states in equilibrium

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 :**

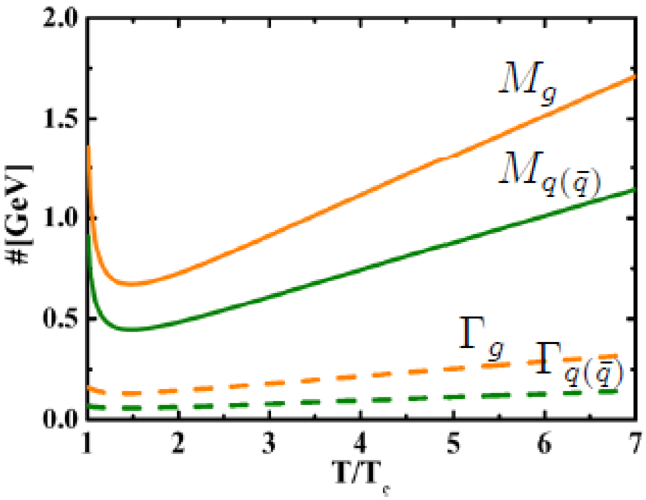
$$\rho_i(\omega,T)=\frac{4\omega\Gamma_i(T)}{\left(\omega^2-\vec{p}^2-M_i^2(T)\right)^2+4\omega^2\Gamma_i^2(T)} \qquad (i=q,\bar{q},g)$$

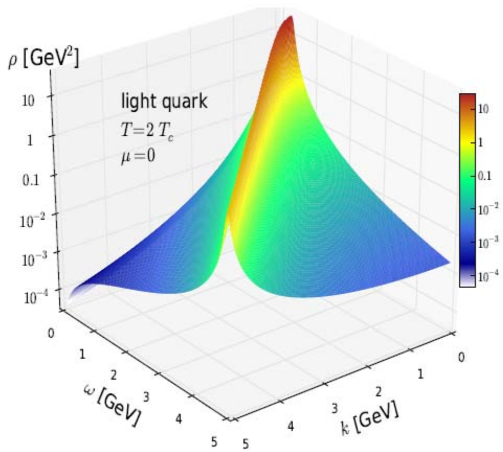
- **fit to lattice (lQCD) results**

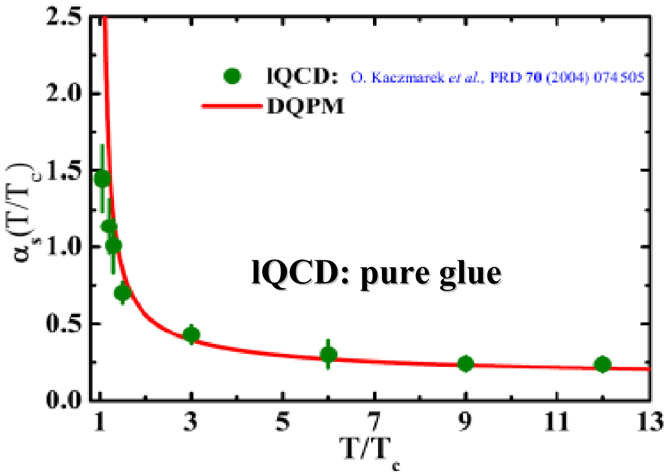
(e.g. entropy density) with 3 parameters

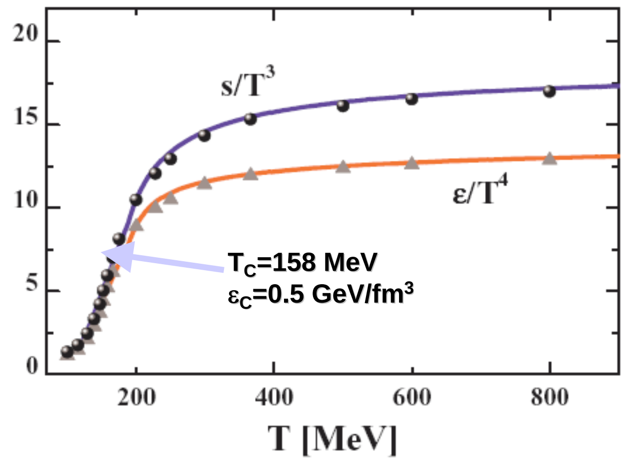
➔ Quasi-particle properties:

large width and mass for gluons and quarks







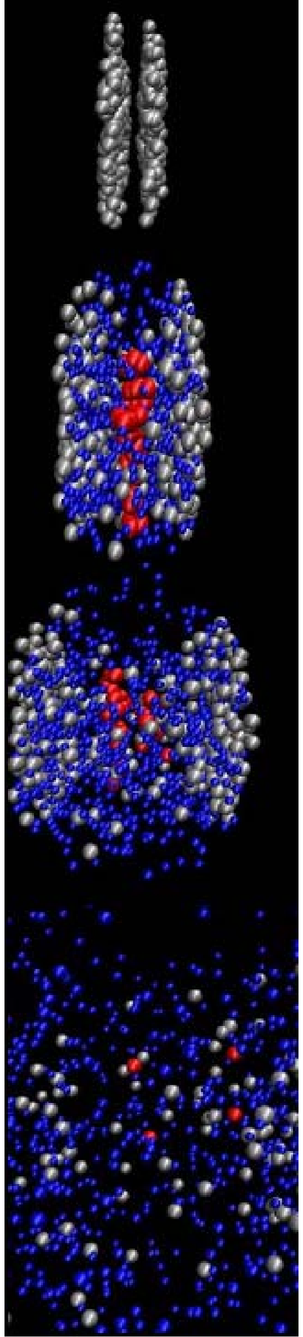


- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons**

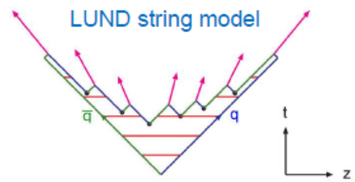
→ PHSD

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

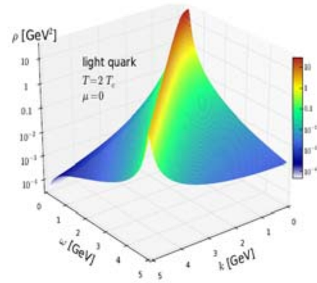
Parton-Hadron-String-Dynamics (PHSD)



- **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



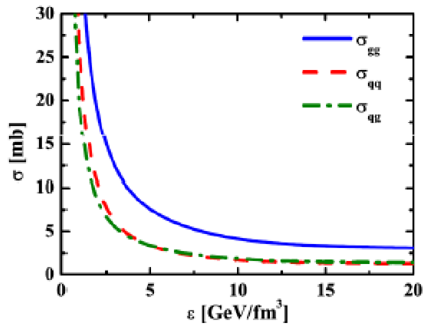
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - **(quasi-) elastic collisions:**

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

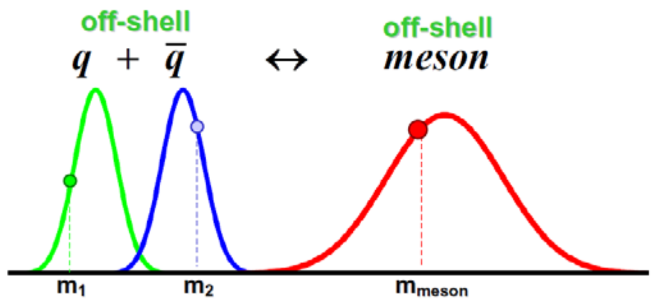
  - **inelastic collisions:**

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



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

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



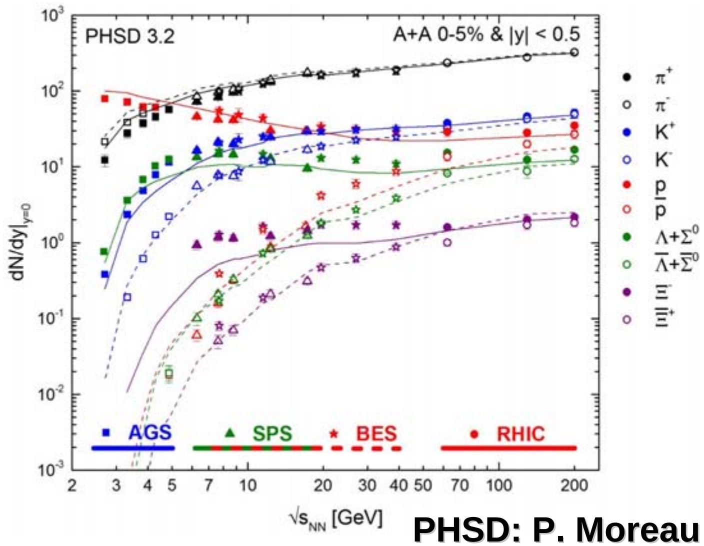
- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

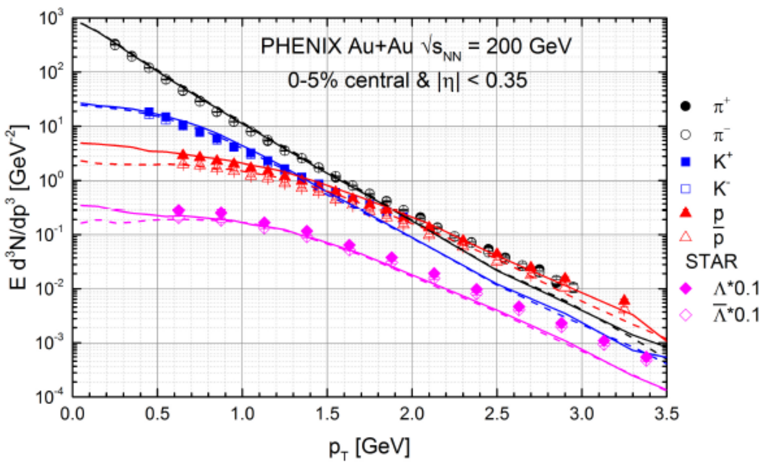
Description of A+A with PHSD

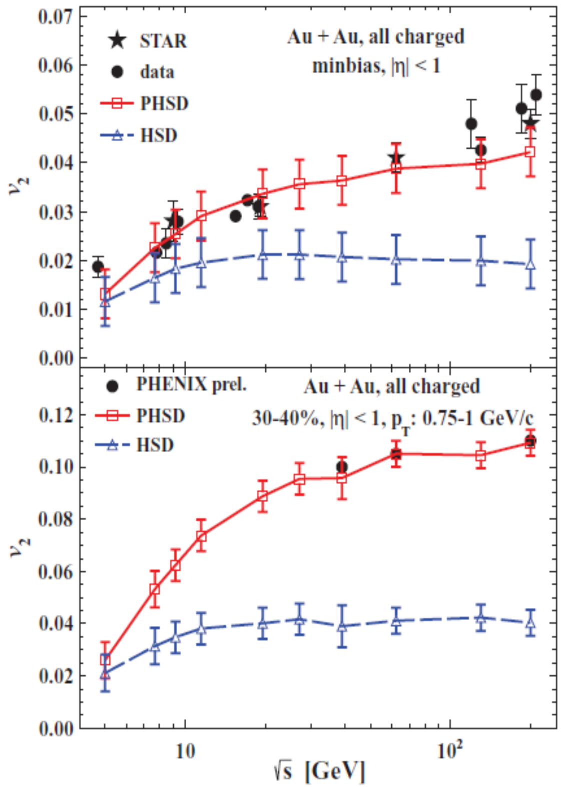
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

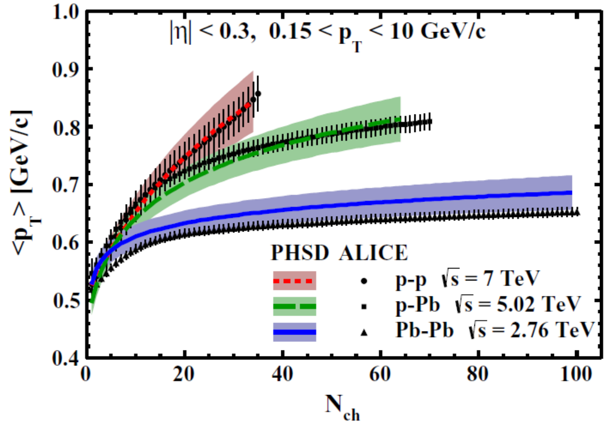
Cf. talk by Pierre Moreau, Tu, 16:20; Alessia Palmese, Fr, 16:00

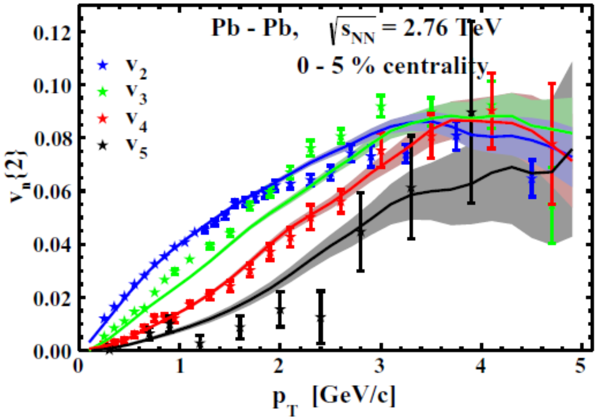


PHSD: P. Moreau









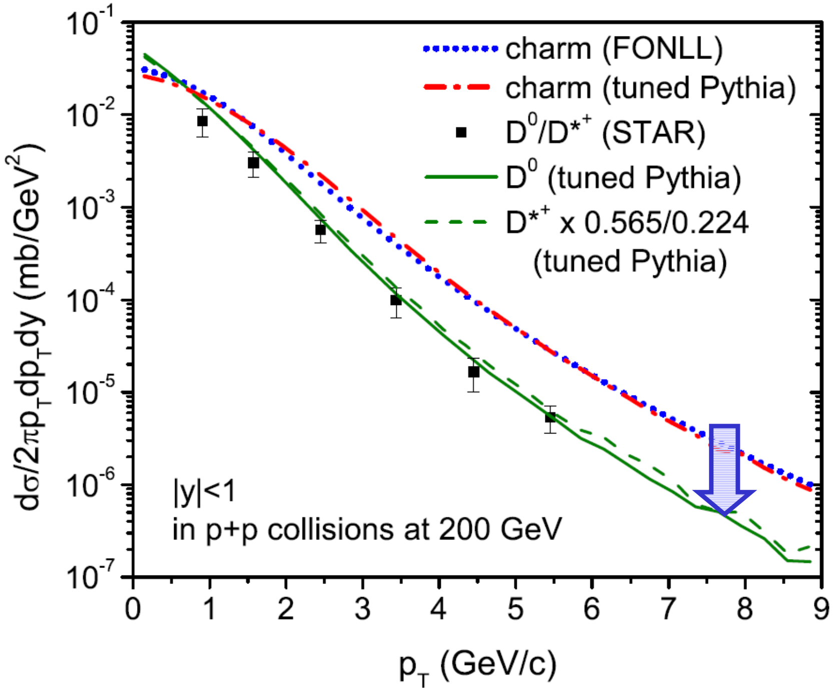
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

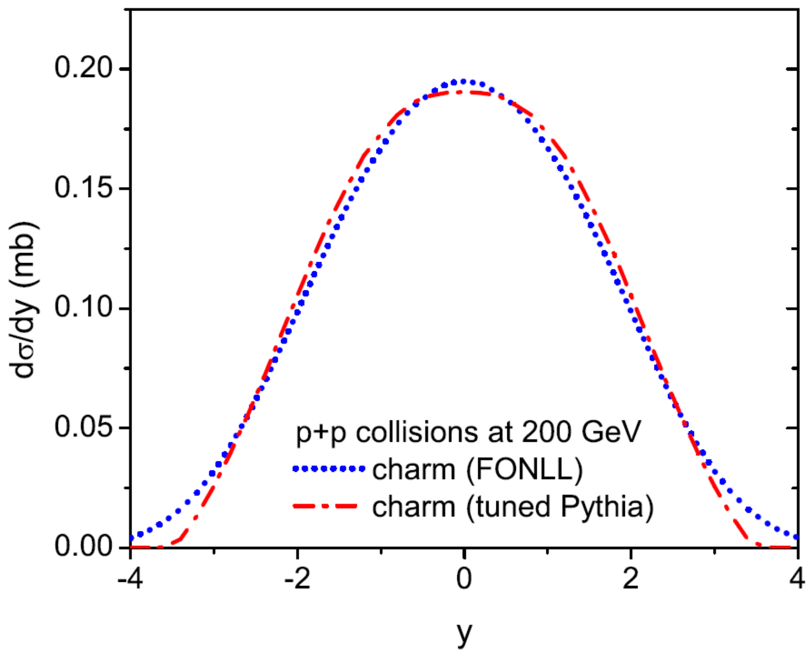
❑ **PHSD** provides a **good description of ‚bulk' observables** (y-, p_T-distributions, flow coeficients v_n, …) from SPS to LHC

Charm quark production in p+p collisions

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

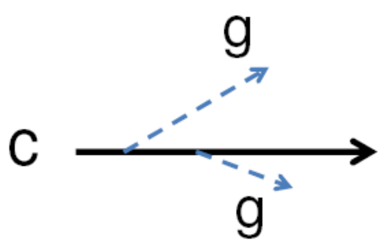
T. Song et al., PRC (2015), arXiv:1503.03039





- **Charm fragmentation**

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



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

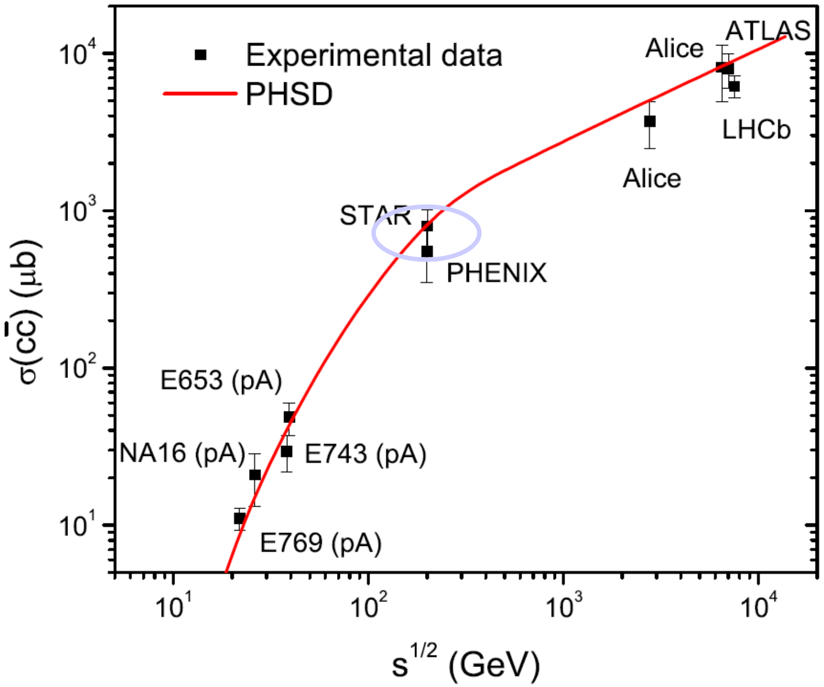
- z : momentum fraction of hadron H in heavy quark Q
- ϵ_Q=0.01 for Q=charm

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

Charm quark production in A+A

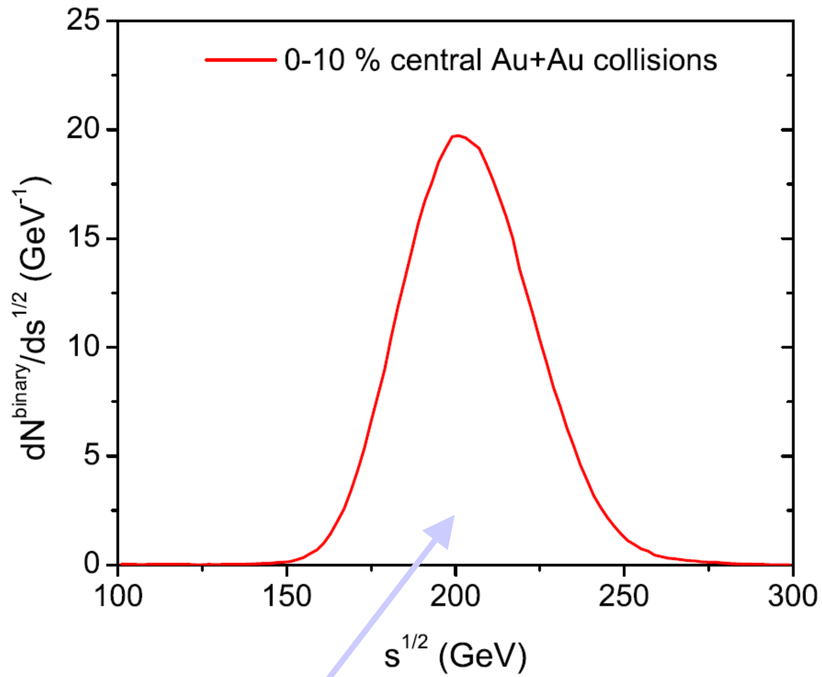
- A+A: charm production in **initial NN binary collisions:** probability $P = \frac{\sigma(c\bar{c})}{\sigma_{NN}^{inel}}$

- The **total cross section** for charm production in **p+p collisions σ(cc)**



- The energy distribution of binary NN collision including **Fermi smearing**

Au+Au, 0-10%, 200 GeV

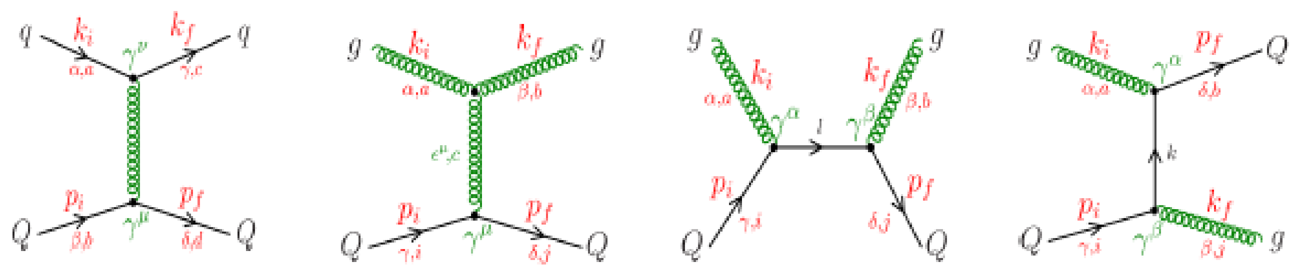


Collision energy smearing due to the Fermi motion

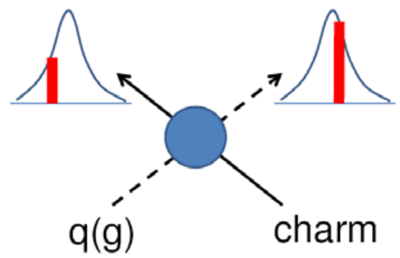
T. Song et al., PRC (2015), arXiv:1503.03039

Charm quark scattering in the QGP (DQPM)

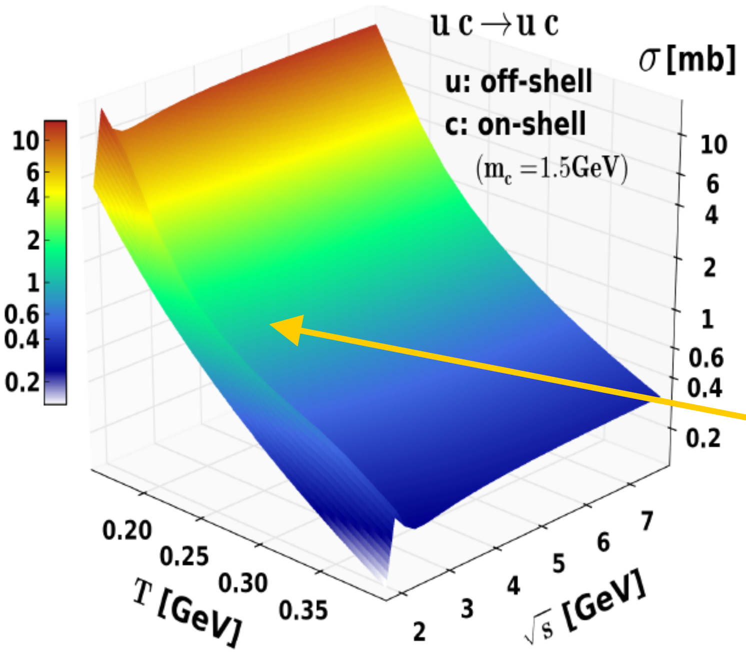
- Elastic scattering with off-shell massive partons Q+q(g)→Q+q(g)



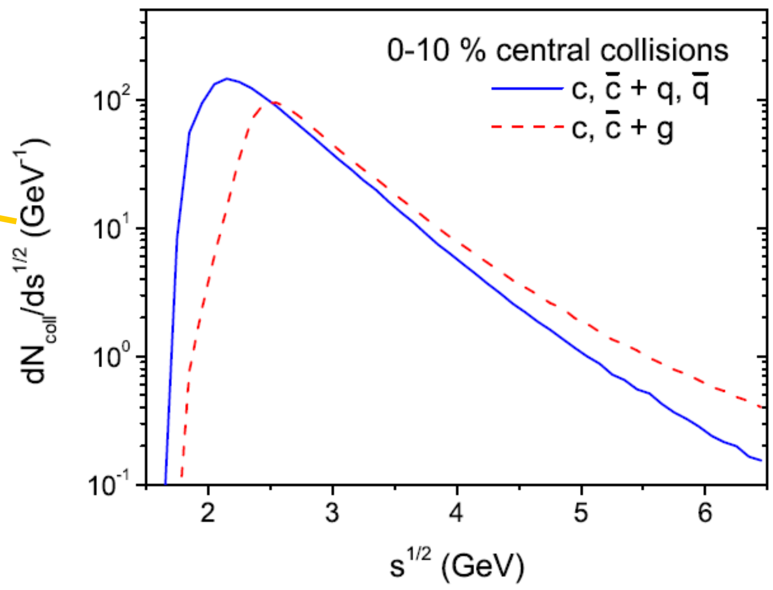
Non-perturbative QGP!



- Elastic cross section uc→uc



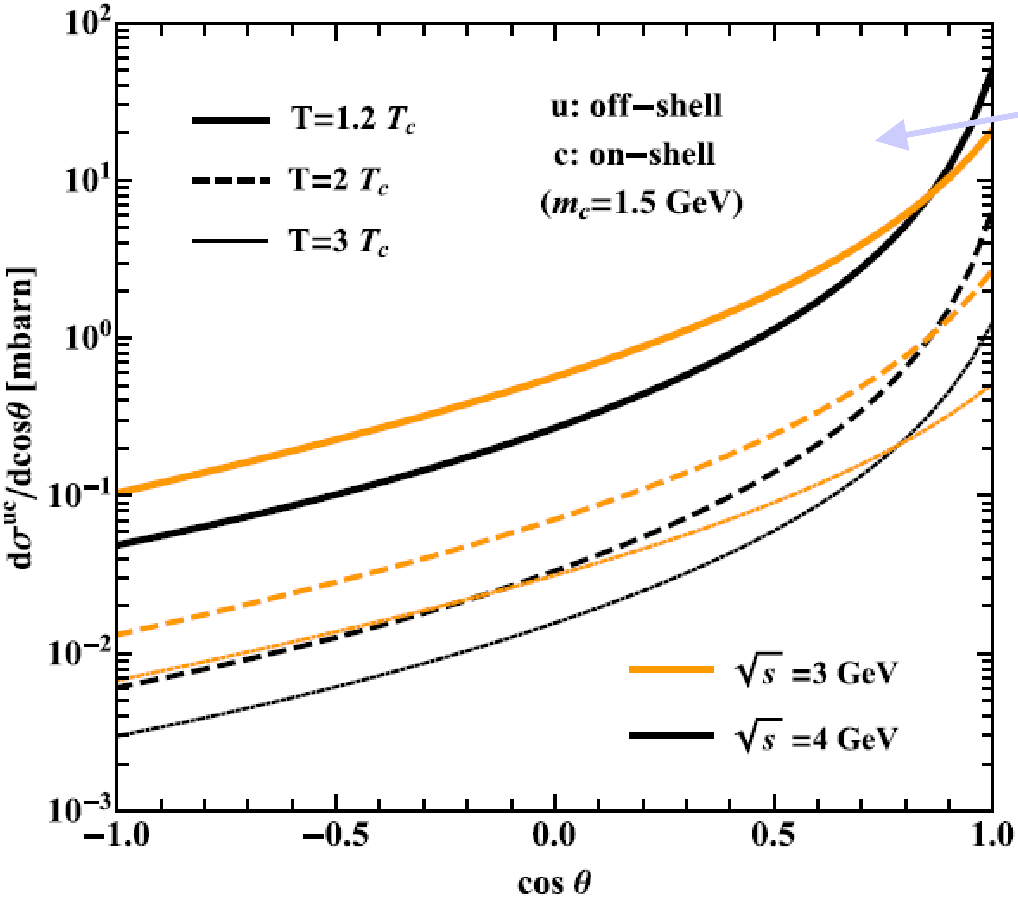
- Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 10% central



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

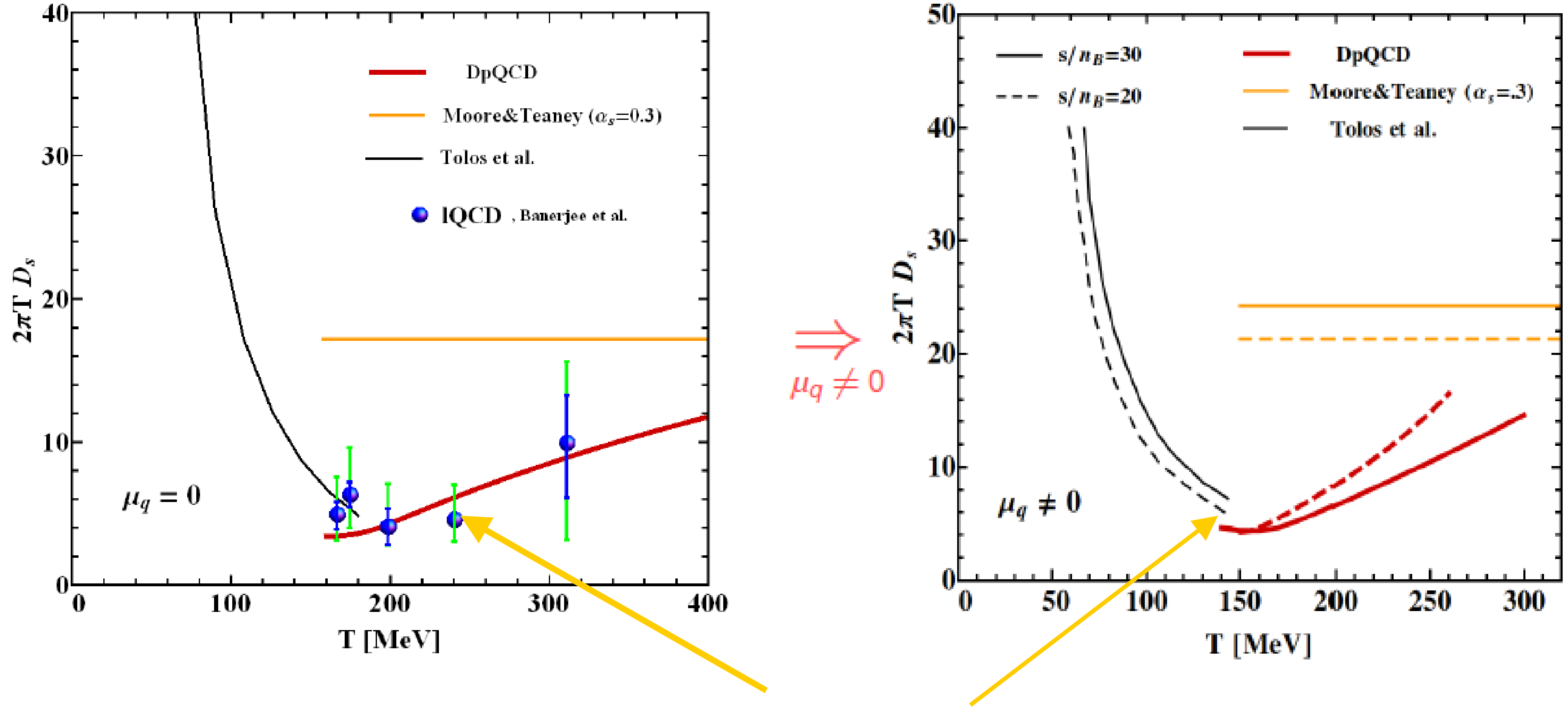
➔ Smaller number (compared to pQCD) of elastic scatterings with massive partons leads to a large energy loss

! 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



→ Continuous transition at T_C!

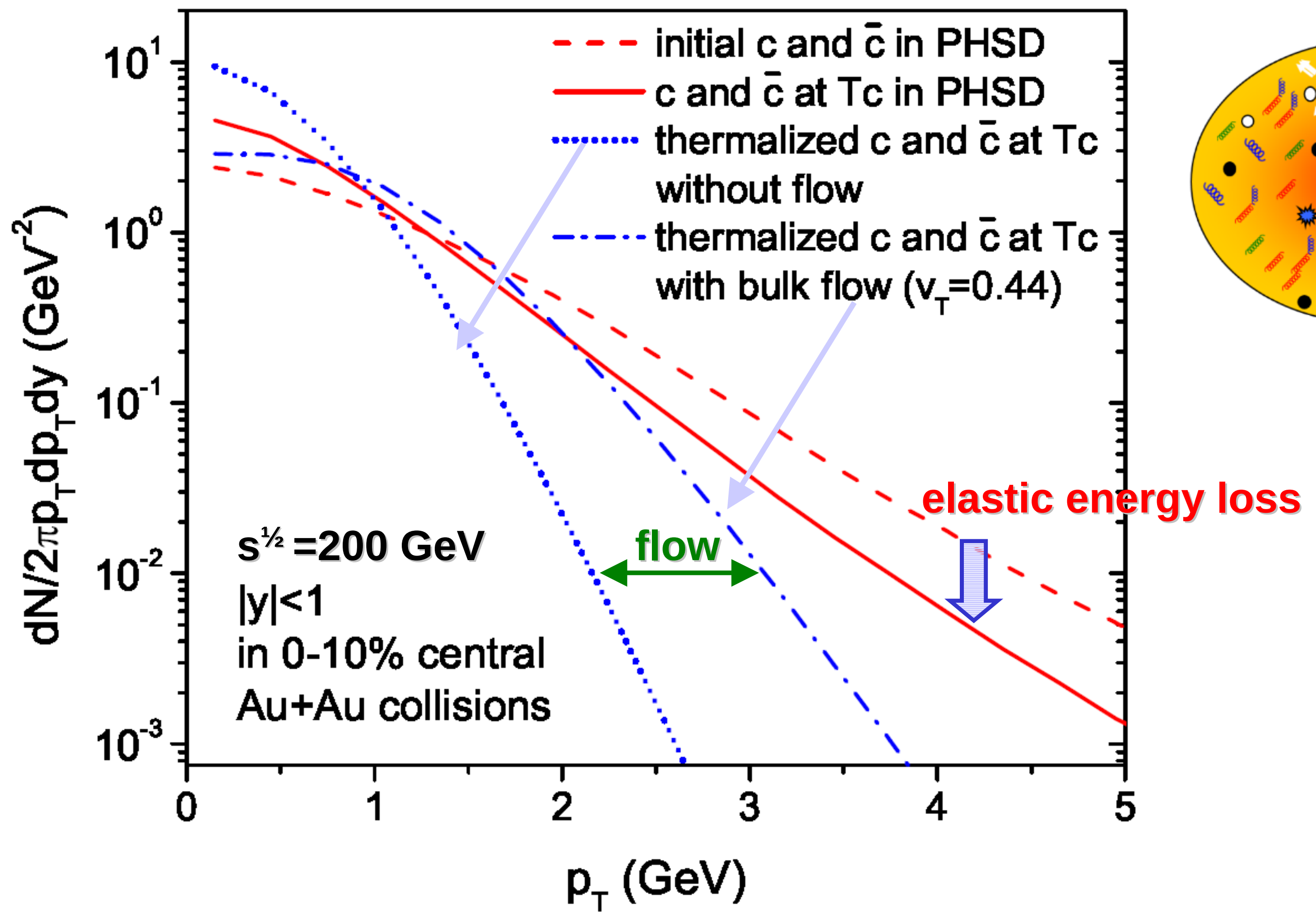
❑ $T < T_c$: hadronic D_s

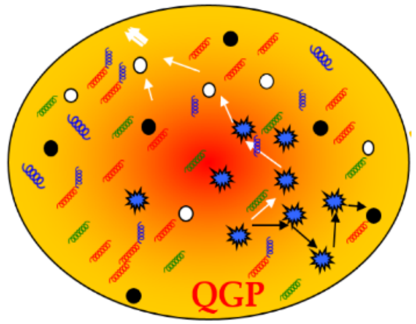
L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

Cf. talk by Laura Tolos, Tu, 17:00

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 spectra
  → elastic energy loss
- Charm quarks are close to thermal equilibrium at low p_T < 2 GeV/c

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

Hadronization of charm quarks in A+A

- **PHSD:** if the local energy density $\varepsilon < 0.5$ GeV/fm^3 ➔ hadronization of charm quarks:

1. Dynamical coalescence model

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

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

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

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:

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

2. Fragmentation (as in pp)
- if NOT hadronized by coalescence

Hadronization scenarios :

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

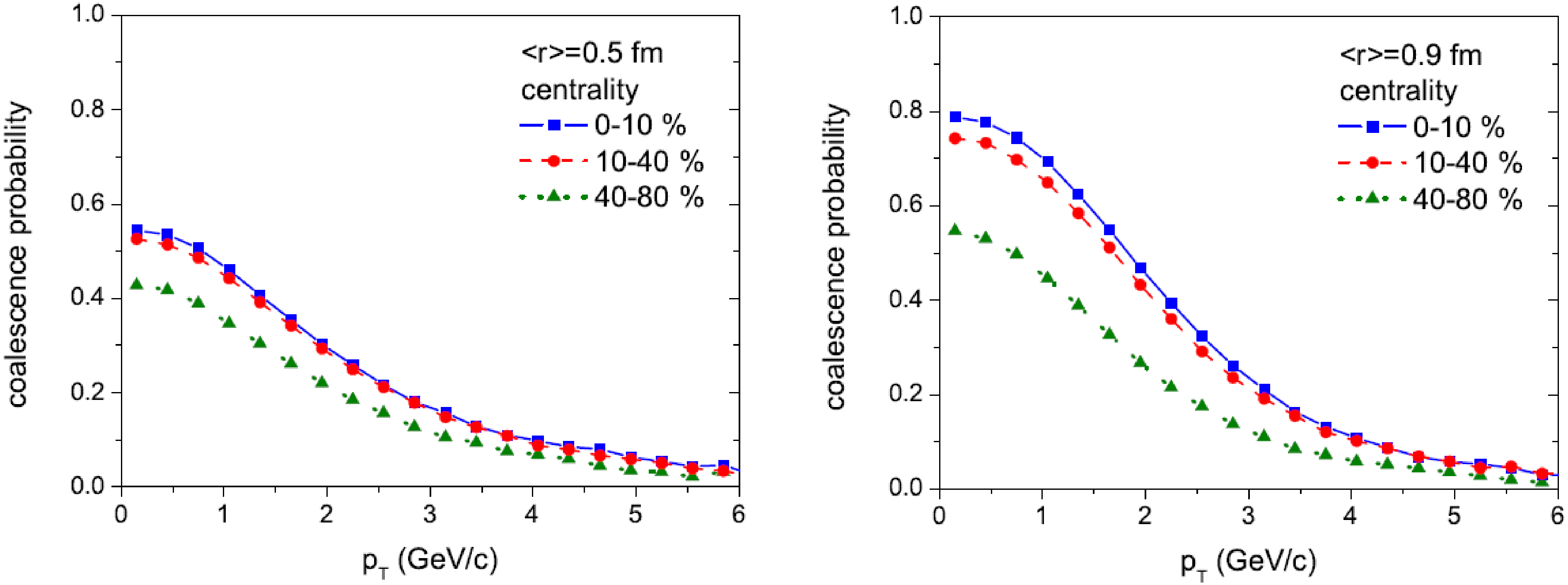
Note: large <r> used also in Refs:
S. Cao, G. Y. Qin and S. A. Bass, PRC 88, 044907 (2013).
Y. Oh, C. M. Ko, S. H. Lee and S. Yasui, PRC 79, 044905 (2009)

Hadronization of charm quarks in A+A

Hadronization scenarios :

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

Coalescence probability in Au+Au



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

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)

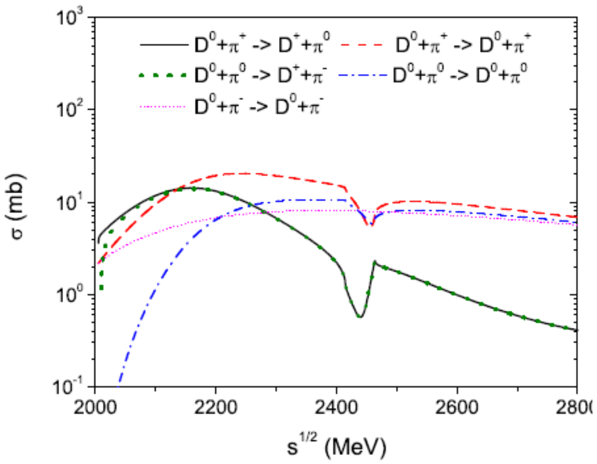
Unitarized scattering amplitude ➔ from solution of coupled-channel Bethe-Salpeter equations:

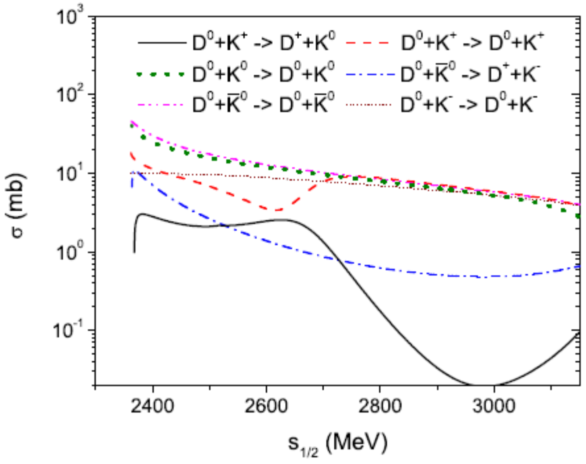
$$T = T + VGT$$

Cf. talk by Juan Torres-Rincon, Thu, 17:40

D-meson scattering in the hadron gas

1. D-meson scattering with mesons

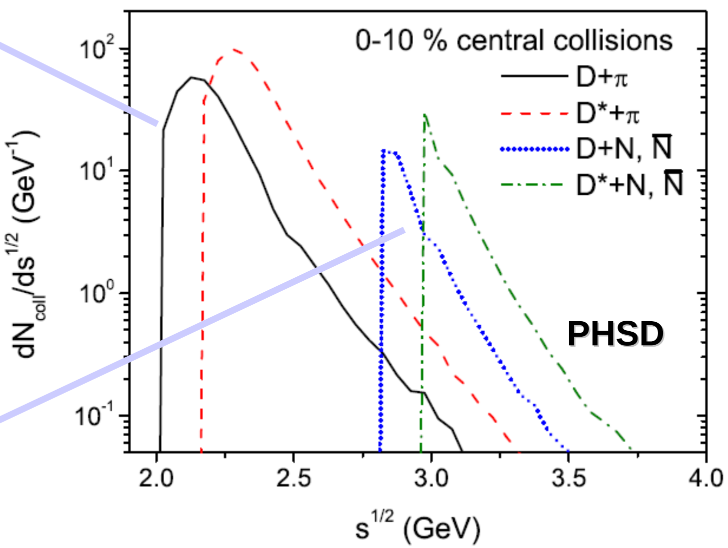




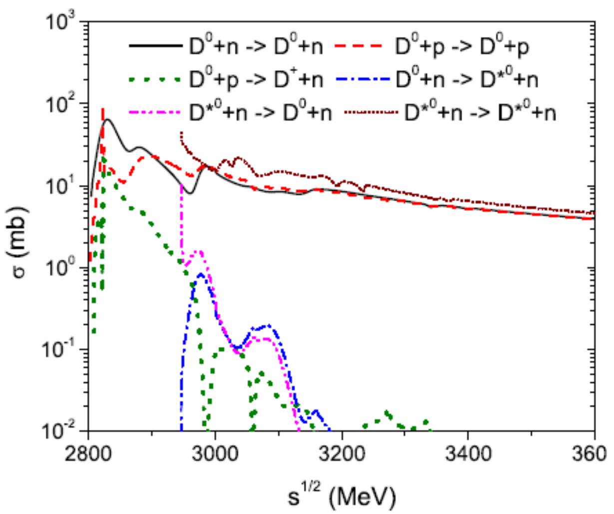
1a) cross sections with ***m=ρ,ω,ϕ,K*,...*** **taken as**

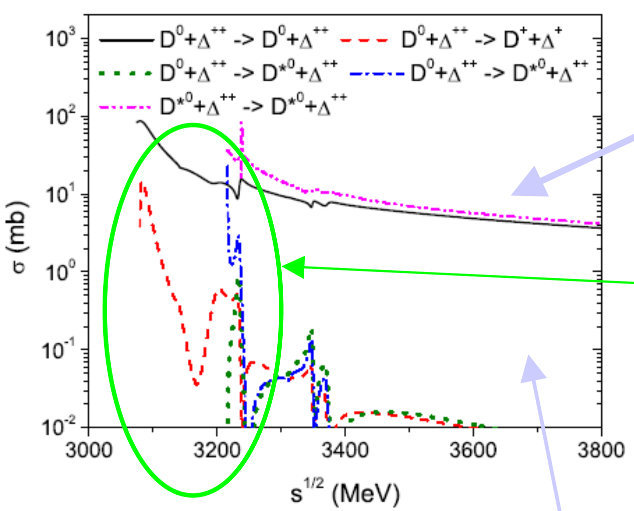
$$\sigma(D,D^*+m)=10mb$$

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



2. D-meson scattering with baryons





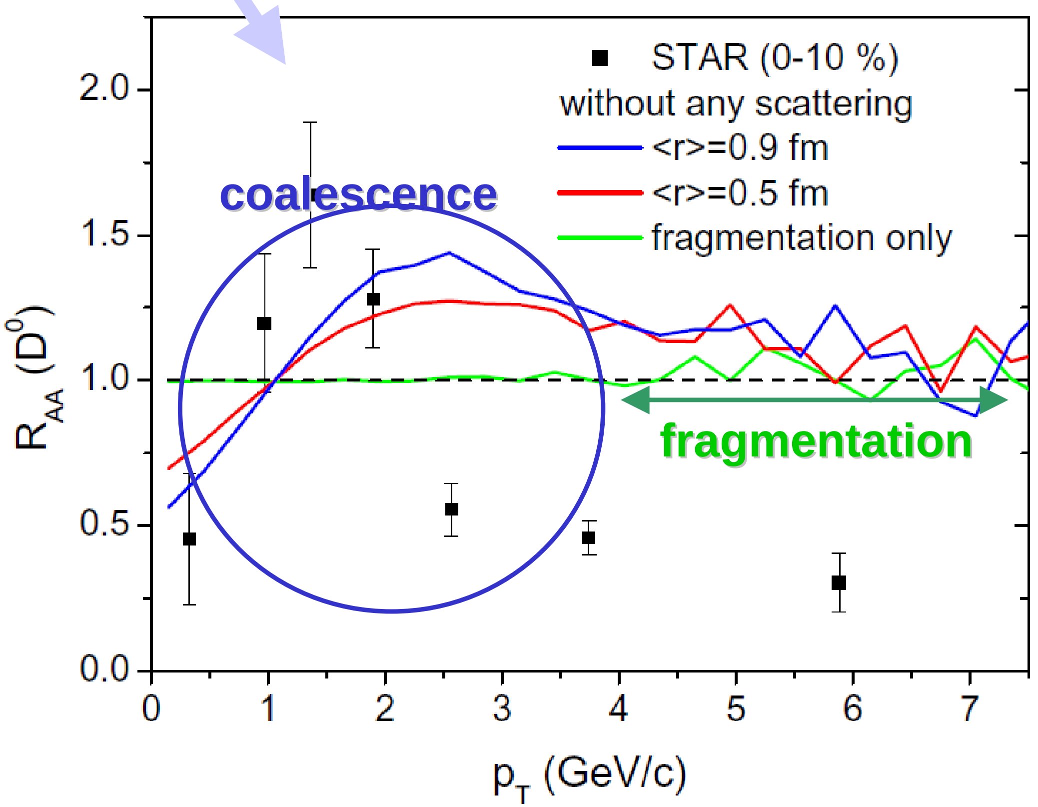
➔**Strong isospin dependence and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!**

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

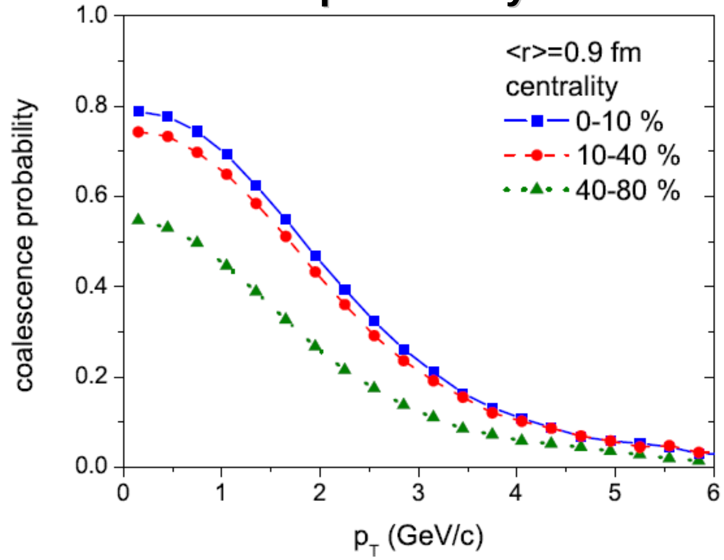
R_{AA} at RHIC - coalescence vs fragmentation

1. Influence of hadronization scenarios: coalescence vs fragmentation

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



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

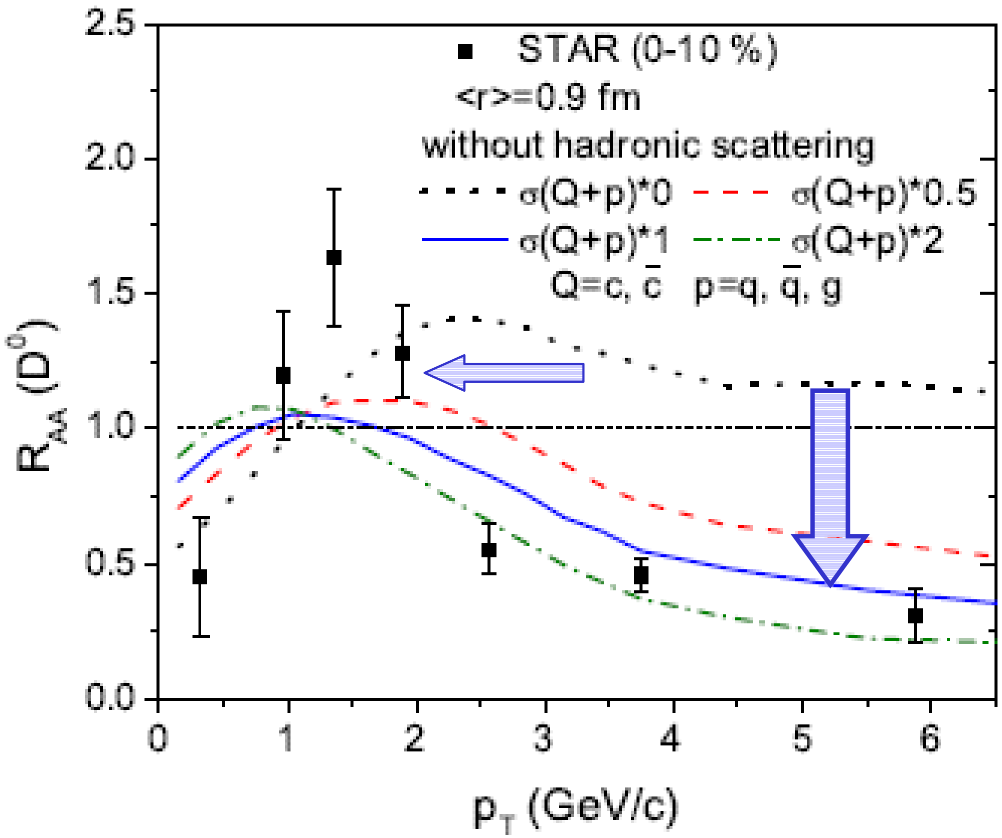


- Expect: no scattering: R_{AA}=1
- Hadronization by fragmentation only (as in pp) → R_{AA}=1
- Coalescence (not in pp!) shifts R_{AA} to larger p_T → ‚nuclear matter' effect
- The hight of the R_{AA} peak depends on the balance: coalescence vs. fragmentation

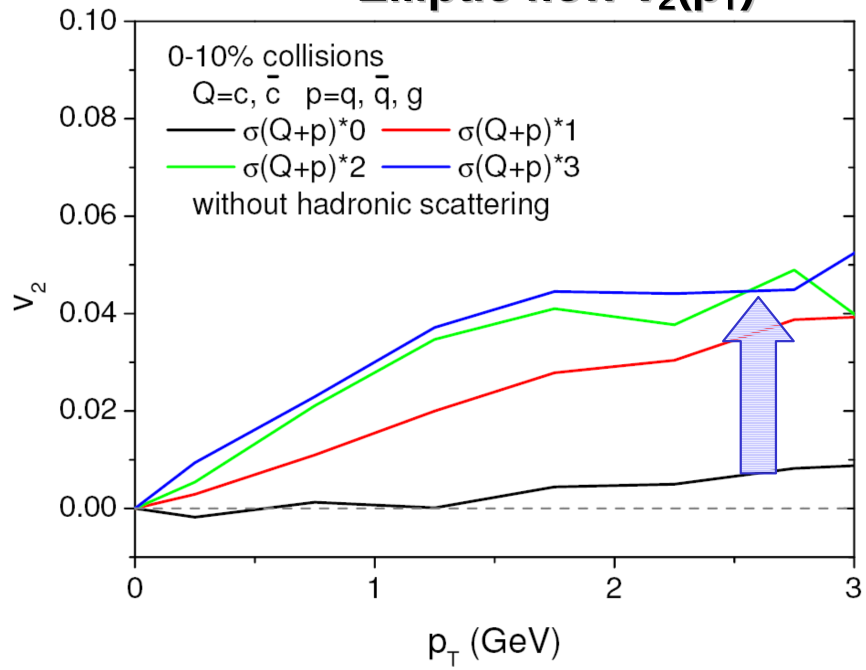
R_{AA} at RHIC: partonic scattering

2. Influence of partonic rescattering

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



Elliptic flow $v_2(p_T)$



Central Au+Au at $s^{1/2}$ =200 GeV :

N(cc) ~19 pairs,

N(Q+q)~130 collisions

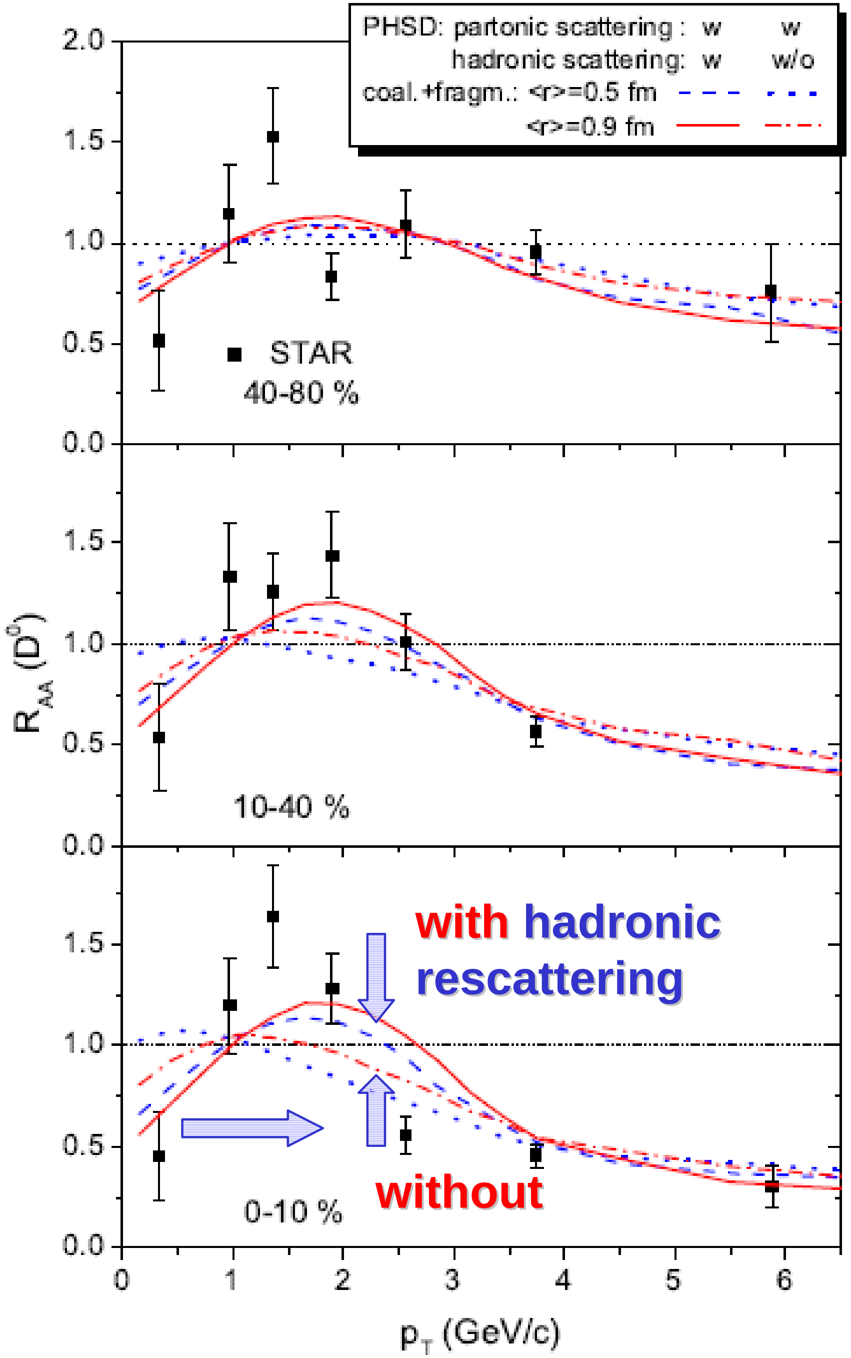
N(Q+g) ~85 collisions

Elastic partonic rescattering

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

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

R_{AA} at RHIC: hadronic rescattering



3. Influence of hadronic rescattering

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

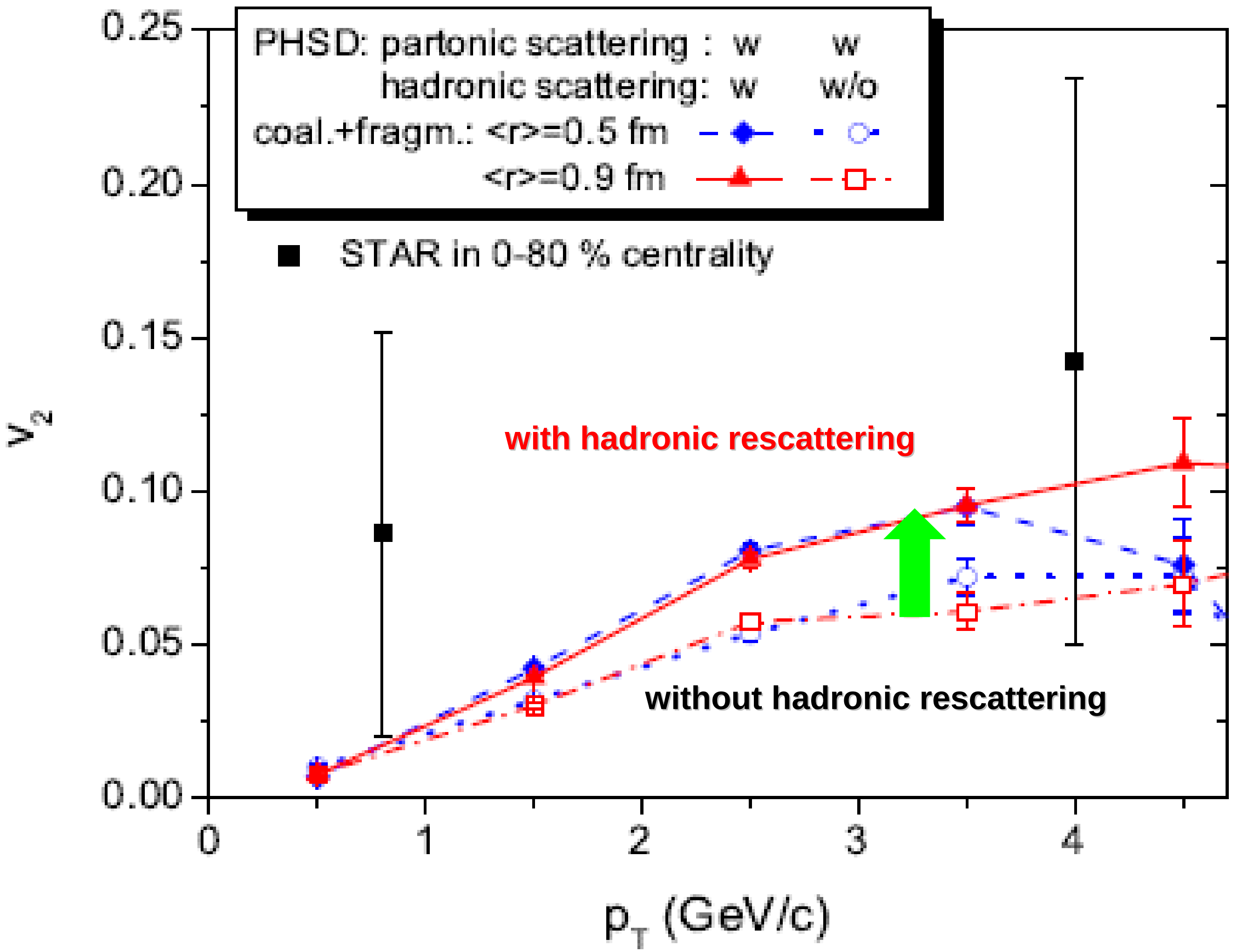
Central Au+Au at $s^{1/2}$ =200 GeV :
- N(D,D*) ~30
- N(D,D*+m) ~56 collisions
- N(D,D*+B,Bbar) ~10 collisions

➔ 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

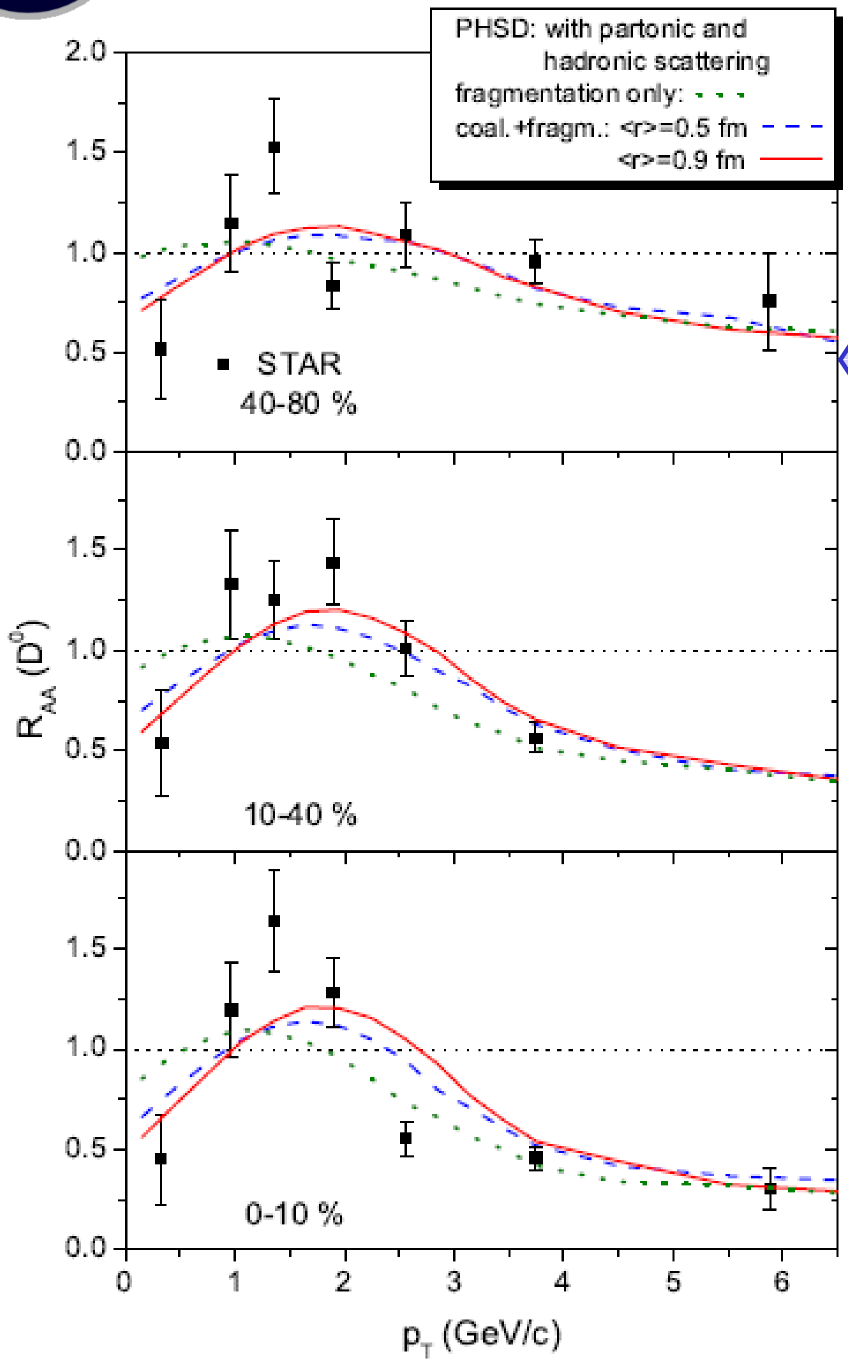
D-meson elliptic flow v_2 at RHIC



- **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 (2015), arXiv:1503.03039

R_{AA} at RHIC



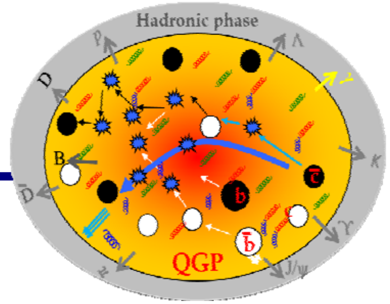
PHSD results:
with all rescattering (partonic and hadronic)

❑ **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“**

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

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

- The STAR data for the R_{AA} and v_2 at RHIC 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 LHC energies, 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!