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Charm dynamics in heavy-ion collisions

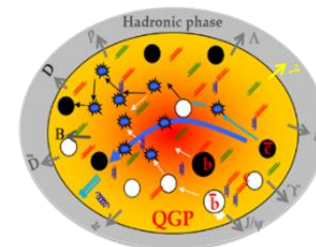
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In collaboration with **Taesoo Song**, Pierre Moreau, Wolfgang Cassing,
Hamza Berrehrah, Laura Tolos, Juan Torres-Rincon,
Jörg Aichelin, Pol-Bernard Gossiaux



Workshop “Quark-Gluon Plasma
Characterisation with Heavy Flavour Probes”
15-18 November 2021
ECT* - Trento, Italy



Motivation

The goal: study of the properties of hot and dense nuclear and partonic matter by **'charm probes'** (or heavy quark probes)

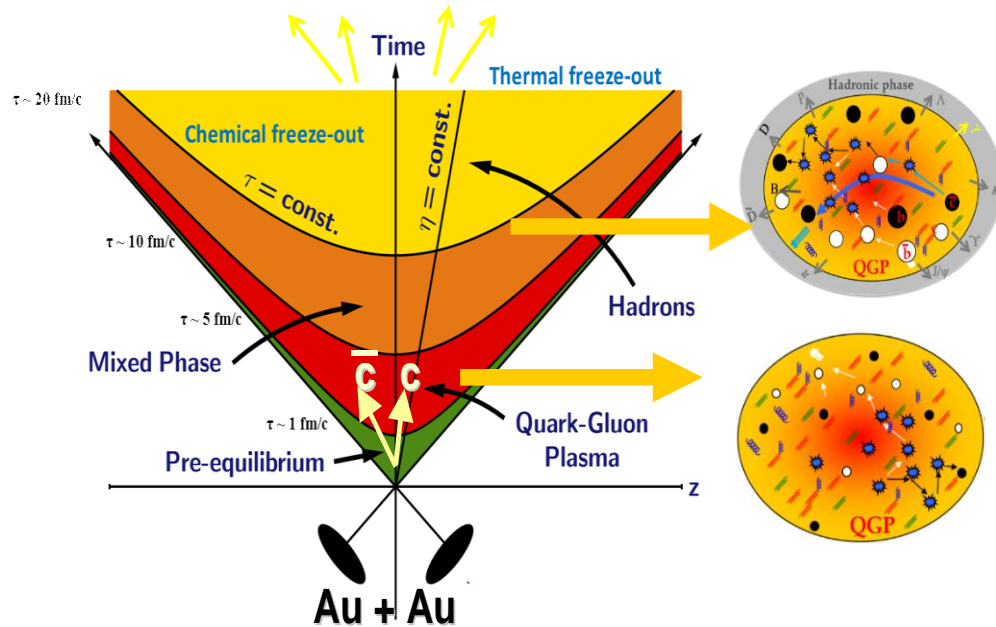
The **advantages** of the 'charm probes':

- 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

- heavy quark scattering cross sections are small (compared to the light quarks) → **not in an equilibrium** with the surrounding matter

- sensitive to the properties of the QGP during the expansion (and not only to its final state)

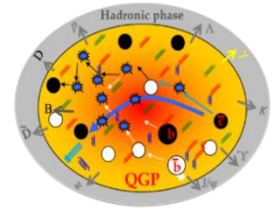


→ Hope to use 'charm probes' for an **early tomography of the QGP**

Dynamical description of hard probes

I. Modeling of time evolution of the ,medium‘ = system:

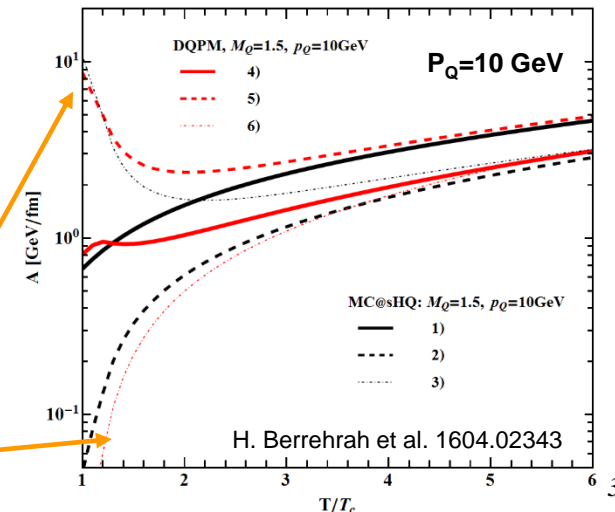
- ❑ expanding fireball models ← assumption of global equilibrium
- ❑ ideal or viscous hydrodynamical models ← assumption of local equilibrium
- ❑ microscopic transport models ← full non-equilibrium dynamics!



II. Modeling of the interaction of the hard probes with the ,medium‘:

- ❑ Fokker-Planck model, Langevin model ← transport coefficients $A = dp_L/dt, \hat{q} = dp_T^2/dt$
- ❑ linear Boltzmann models ← cross sections
- ❑ microscopic collision integral ← cross sections

	coupling	mass in gluon propagator	mass in external legs
1)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
2)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = m_{q,g}^{DQPM}$
3)	$\alpha(T)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
4)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$
5)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = 0$
6)	$\alpha(Q^2)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$



H. Berrehran et al. 1604.02343

Dynamical Models → PHSD

The goal:

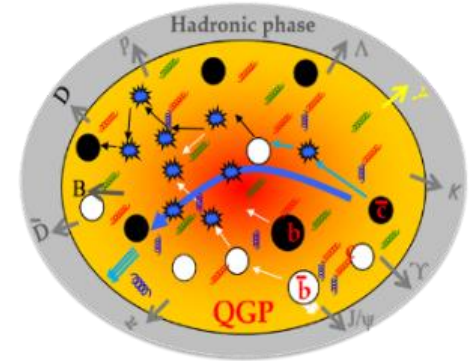
to describe the dynamics of charm quarks/mesons in all phases of HICs on a **microscopic basis**

Realization:

a **dynamical non-equilibrium transport approach**

- applicable for **strongly interacting systems**,
- which includes a **phase transition** from hadronic matter to QGP

The tool: PHSD approach

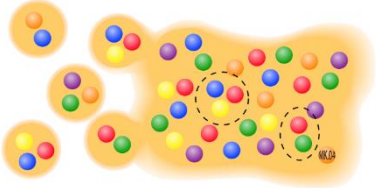


- Baryons
- Antibaryons
- Mesons
- Quarks
- Gluons

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

$b = 2.2 \text{ fm}$ – Section view





Degrees-of-freedom of QGP

For the microscopic transport description of the system one **needs to know all degrees of freedom** as well as their properties and interactions!

❖ IQCD gives QGP EoS at finite μ_B



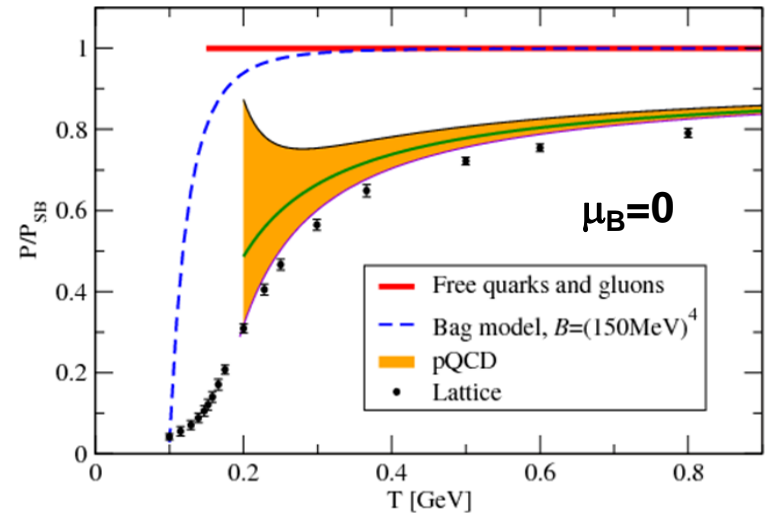
! need to be interpreted in terms of degrees-of-freedom

pQCD:

- weakly interacting system
- massless quarks and gluons

How to learn about the degrees-of-freedom of the QGP from HICs?

- ➔ microscopic transport approaches
- ➔ comparison to HIC experiments



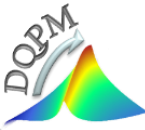
Non-perturbative QCD ← pQCD

Thermal QCD

= QCD at high parton densities:

- strongly interacting system
- massive quarks and gluons
- ➔ quasiparticles
- = effective degrees-of-freedom

Dynamical QuasiParticle Model (DQPM)



DQPM – effective model for the description of **non-perturbative** (strongly interacting) QCD based on **IQCD EoS**

Degrees-of-freedom: strongly interacting **dynamical quasiparticles** - quarks and gluons

Theoretical basis :

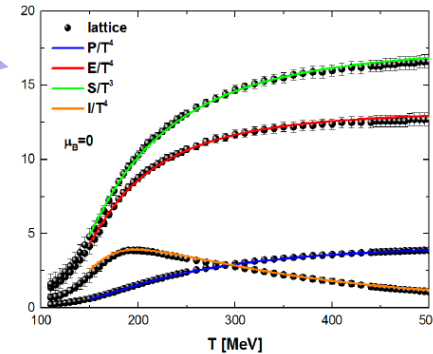
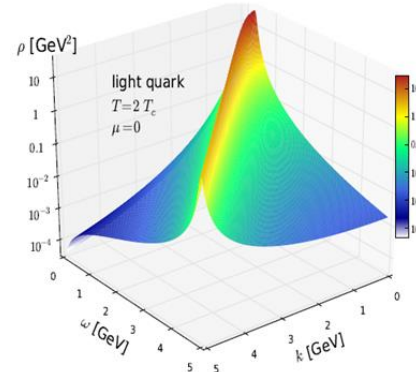
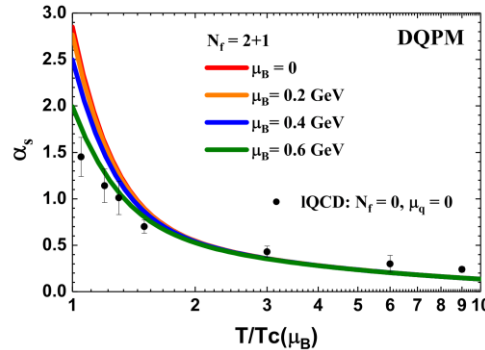
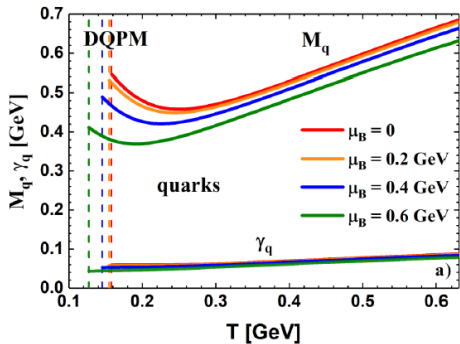
□ ,resummed' single-particle Green's functions → quark (gluon) propagator (2PI) : $G_q^{-1} = P^2 - \Sigma_q$

Properties of the quasiparticles are specified by scalar complex self-energies: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

$Re\Sigma_q$: **thermal masses** (M_g, M_q); $Im\Sigma_q$: **interaction widths** (γ_g, γ_q) → spectral functions $\rho_q = -2ImG_q$

- introduce an **ansatz** (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the **QGP thermodynamics** in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison to the entropy density s , pressure P , energy density ε from DQPM to **IQCD** at $\mu_B = 0$

→ **Quasi-particle properties at (T, μ_B) :**



• **DQPM** provides **mean-fields** (1PI) for q, g and **effective 2-body partonic interactions** (2PI); gives **transition rates** for the formation of hadrons → **sQGP in PHSD**



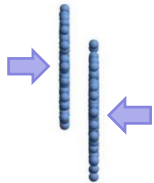
Parton-Hadron-String-Dynamics (PHSD)



PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

Dynamics: based on the solution of **generalized off-shell transport equations** derived from Kadanoff-Baym many-body theory

Initial A+A collision

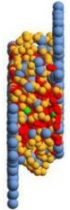


□ **Initial A+A collisions** :
 $N+N \rightarrow$ **string formation** \rightarrow decay to pre-hadrons + leading hadrons

□ **Formation of QGP stage** if local $\varepsilon > \varepsilon_{\text{critical}}$:
 dissolution of **pre-hadrons** \rightarrow partons

□ **Partonic phase - QGP:**
 QGP is described by the **Dynamical QuasiParticle Model (DQPM)** matched to reproduce **lattice QCD EoS** for finite T and μ_B (crossover)

Partonic phase



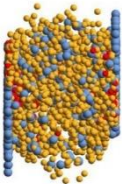
- **Degrees-of-freedom:** strongly interacting quasiparticles: **massive quarks and gluons (g, q, q_{bar})** with sizeable collisional widths in a self-generated mean-field potential

- **Interactions:** (quasi-)elastic and inelastic collisions of partons

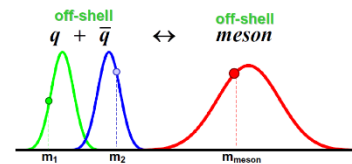
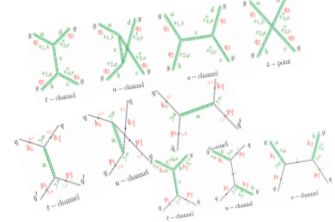
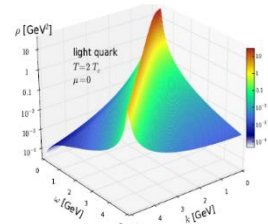
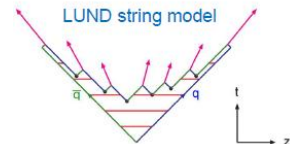
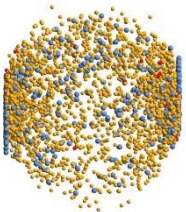
□ **Hadronization** to colorless **off-shell mesons and baryons:**
 Strict 4-momentum and quantum number conservation

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

Hadronization



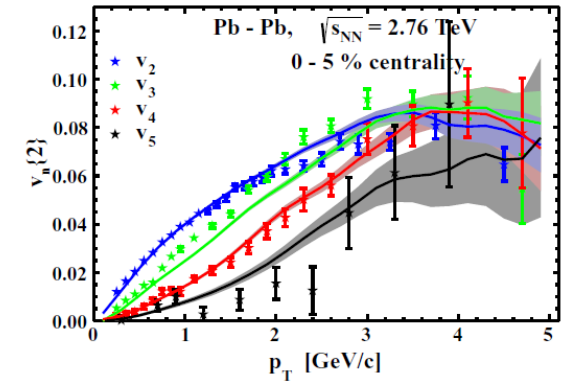
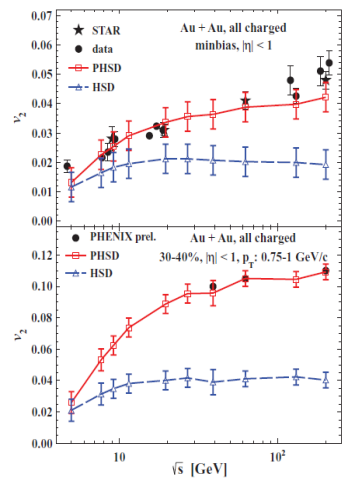
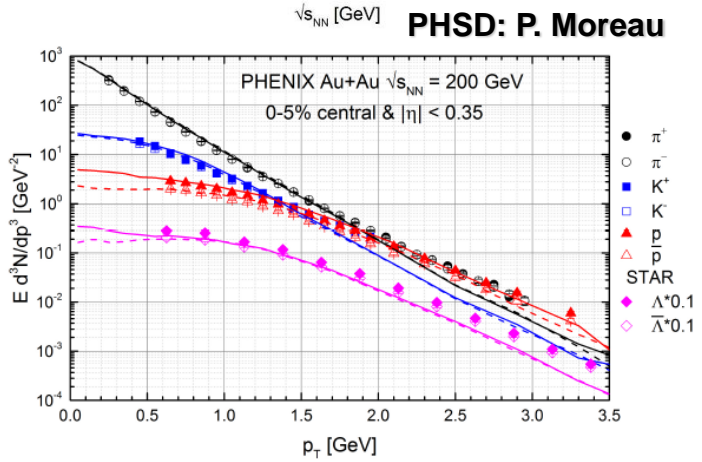
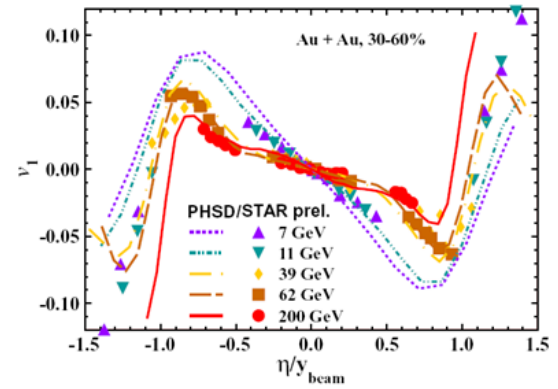
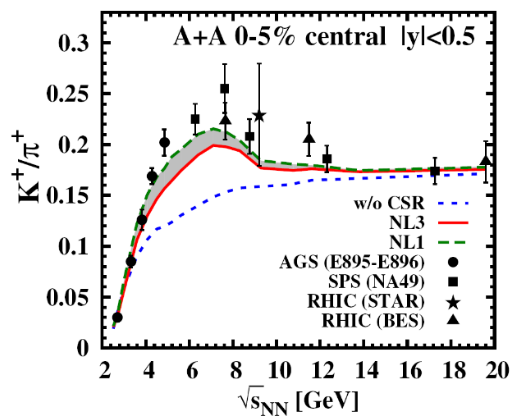
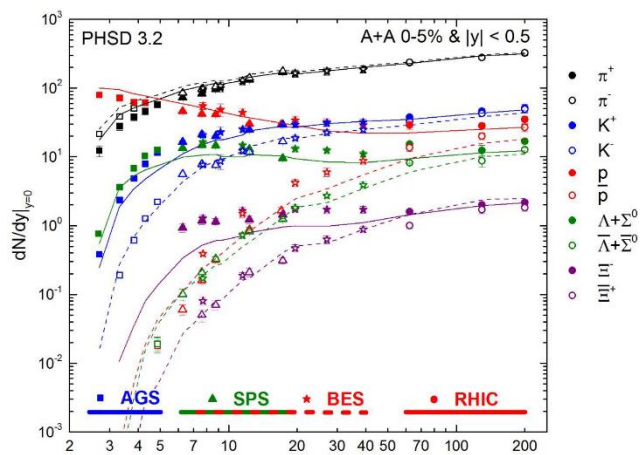
Hadronic phase





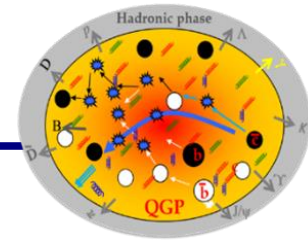
Non-equilibrium dynamics: description of A+A with PHSD

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



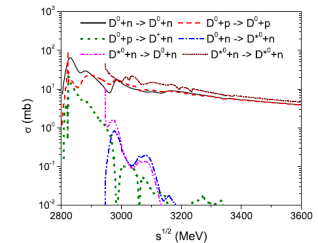
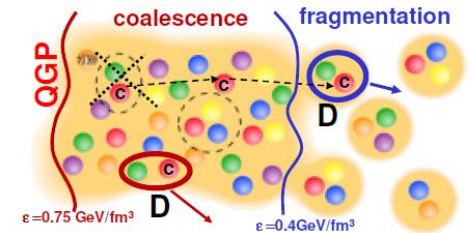
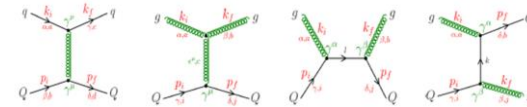
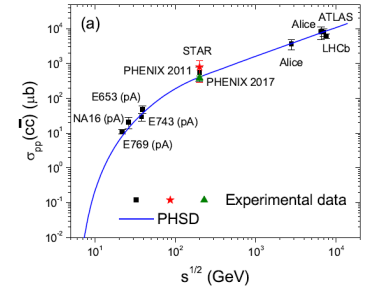
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

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



Dynamics of heavy quarks in A+A :

- 1. Production of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects**
- 2. Interactions in the non-perturbative QGP – according to the DQPM:**
 elastic scattering with off-shell massive partons $Q+q \rightarrow Q+q$
 \rightarrow collisional energy loss
- 3. Hadronization:** c/\bar{c} quarks \rightarrow $D(D^*)$ -mesons:
 Dynamical hadronization scenario for heavy quarks :
 coalescence with $\langle r \rangle = 0.9$ fm & fragmentation
 $0.4 < \varepsilon < 0.75$ GeV/fm³ $\varepsilon < 0.4$ GeV/fm³
- 4. Hadronic interactions:**
 D +baryons; D +mesons based on G-matrix and effective chiral Lagrangian approach with heavy-quark spin symmetry (>200 channels)
 (Juan Torres-Rincon, Laura Tolos)



* PHSD references on charm dynamics:

Taesoo Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

PRC 97 (2018) 064907; PRC 101 (2020) 044901; PRC 101 (2020) 044903

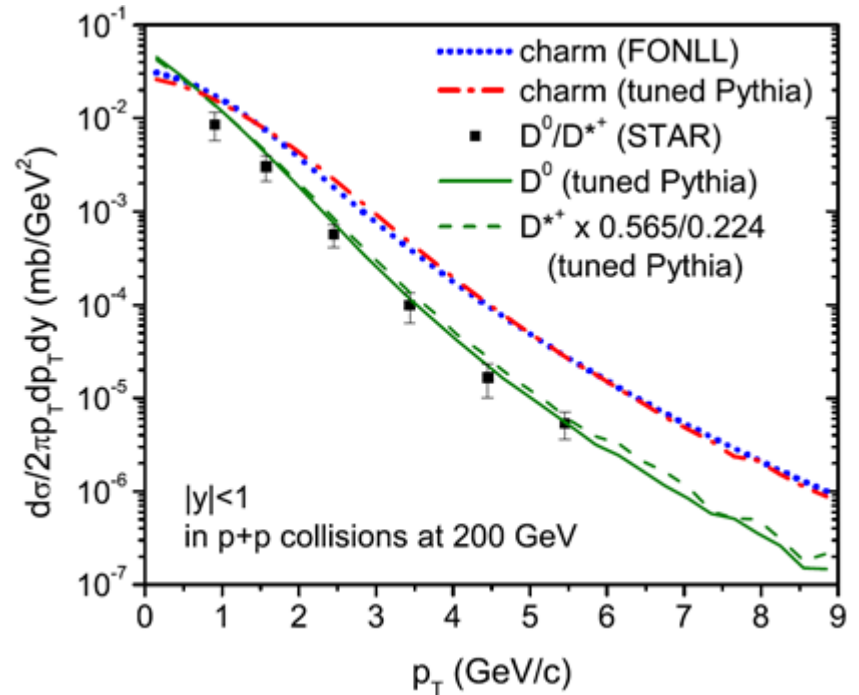
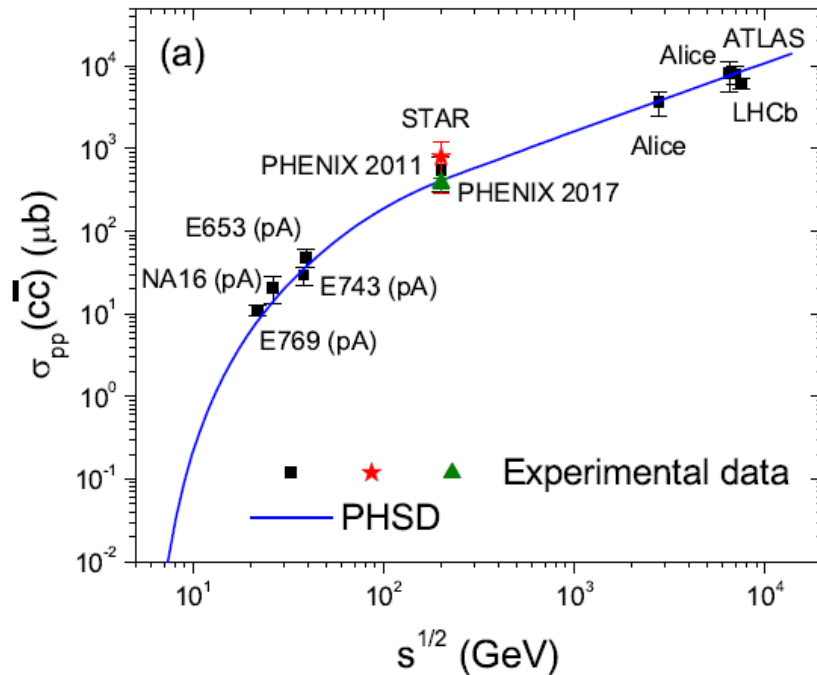


Charm production in NN collisions

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

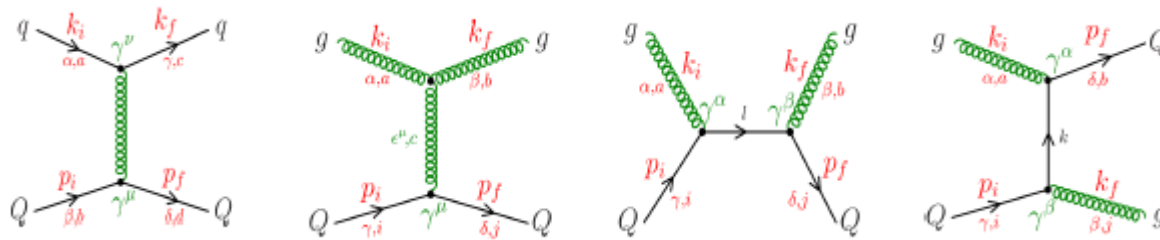
The **total cross section** for charm production in **p+p collisions** $\sigma(cc)$

Momentum distribution of heavy quarks: use **'tuned' PYTHIA** event generator to reproduce **FONLL** (fixed-order next-to-leading log) results

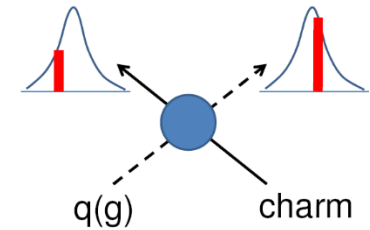


Heavy quark scattering in the QGP (DQPM)

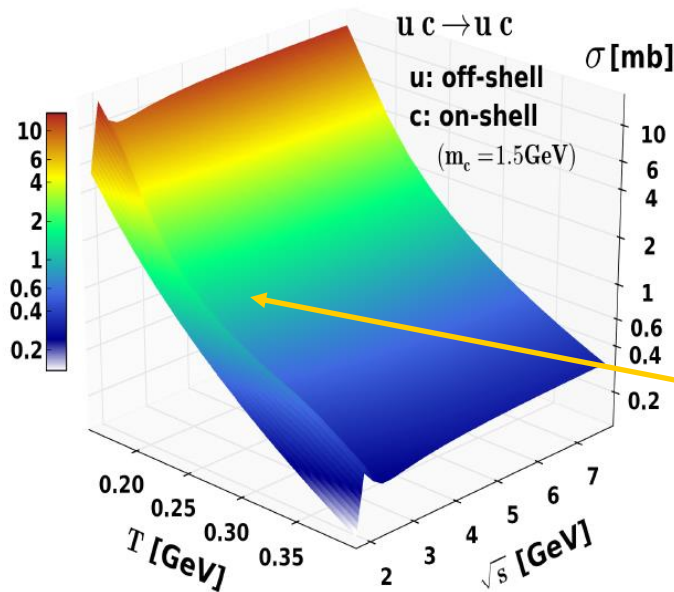
□ Elastic scattering with off-shell massive partons $Q+q(g) \rightarrow Q+q(g)$



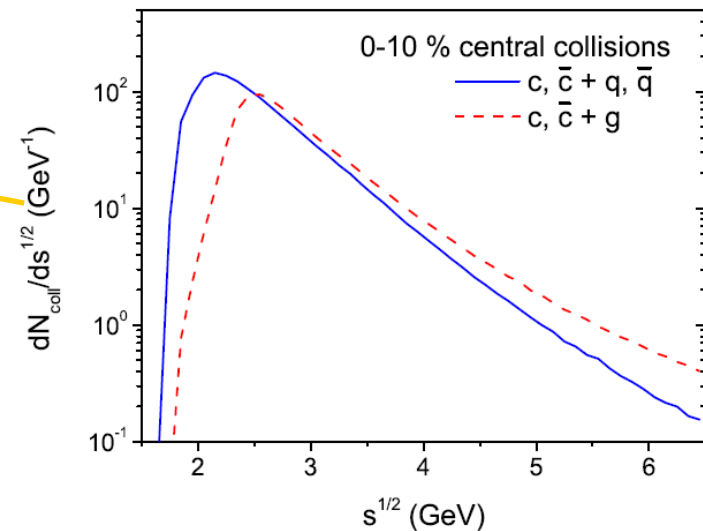
Non-perturbative QGP!

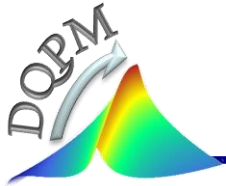


□ Elastic cross section $uc \rightarrow uc$



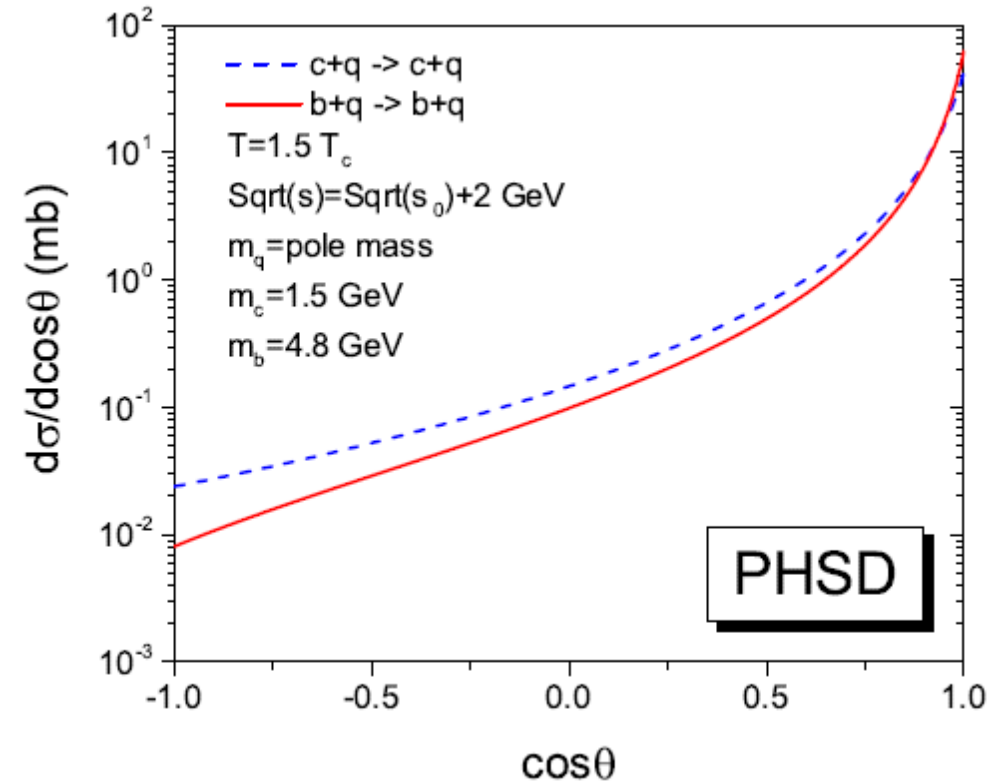
□ Distributions of $Q+q$, $Q+g$ collisions vs $s^{1/2}$ in Au+Au, 10% central





Heavy quark scattering in the QGP

□ **Differential elastic cross section** for $cq \rightarrow cq$, $bq \rightarrow bq$ for $s^{1/2} = s_0^{1/2} + 2\text{GeV}$ at $1.5T_c$



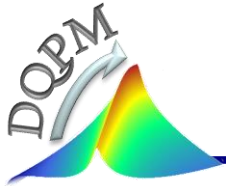
□ **DQPM - anisotropic angular distribution**

Note: pQCD - strongly forward peaked

→ Differences between DQPM and pQCD :
less forward peaked angular distribution
leads to **more efficient momentum transfer**

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

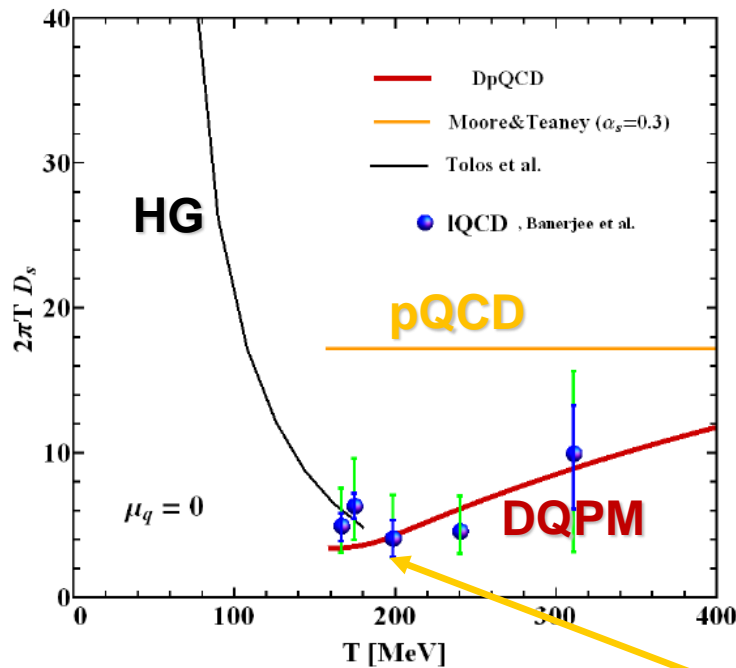
! Note: **radiative energy loss** is **NOT** included yet in PHSD,
it is expected to be **small** (at low p_T) due to the large gluon mass in the DQPM



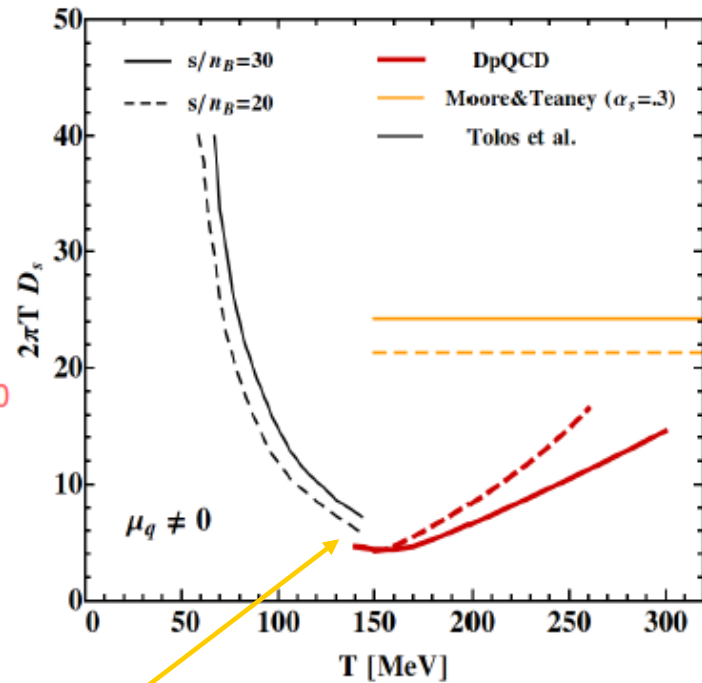
Charm spatial diffusion coefficient D_s in the hot medium

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

$$D_s = \lim(\vec{p} \rightarrow 0) \frac{T}{M\eta_D} \quad \text{where } \eta_D = A/p ; A(p,T) = \text{drag coefficient}$$



\Rightarrow
 $\mu_q \neq 0$



□ $T < T_c$: hadronic D_s

L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019;
2109.08204

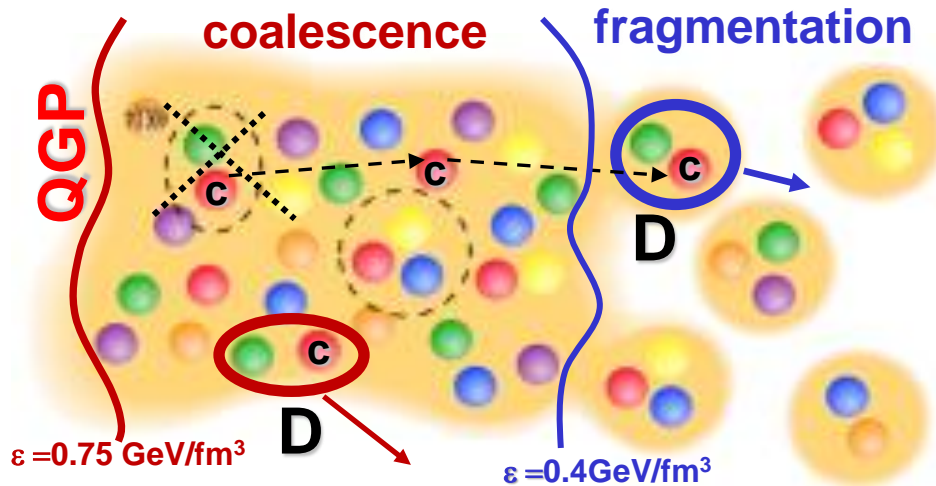
→ Continuous transition at T_c !

PHSD: if the local energy density $\varepsilon \rightarrow \varepsilon_c \rightarrow$ hadronization of heavy quarks to hadrons

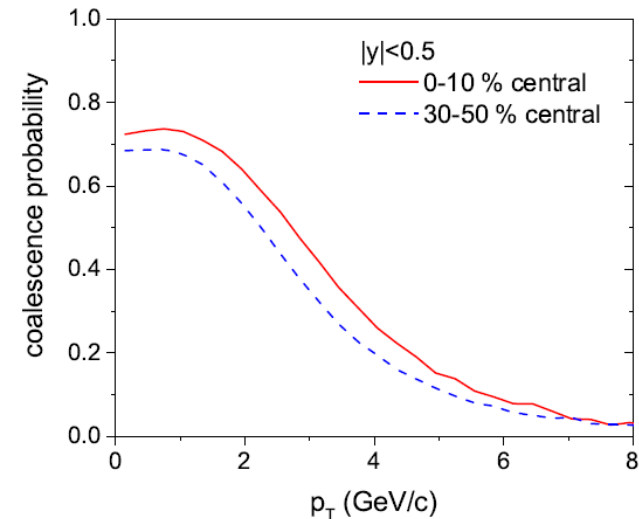
T. Song et al., PRC 93 (2016) 034906

Dynamical hadronization scenario for heavy quarks :

coalescence with $\langle r \rangle = 0.9$ fm & fragmentation
 $0.4 < \varepsilon < 0.75$ GeV/fm³ $\varepsilon < 0.4$ GeV/fm³



Coalescence probability in Au+Au at LHC



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

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

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 $\langle r \rangle$:

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

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



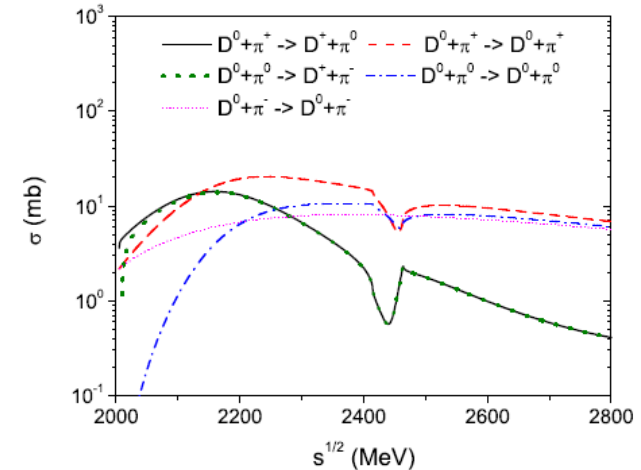
D-meson scattering in the hadronic phase

1. D-meson scattering with mesons

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

Model: effective chiral Lagrangian approach with heavy-quark spin symmetry

Interaction of $D=(D^0, D^+, D^+_s)$ and $D^*=(D^{*0}, D^{*+}, D^{*+}_s)$ with octet $(\pi, K, Kbar, \eta)$



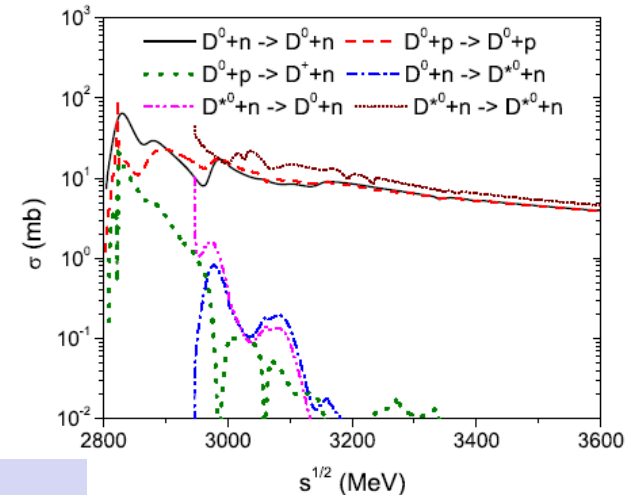
2. D-meson scattering with baryons

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

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 $J^P=3/2^+$

Unitarized scattering amplitude \rightarrow solution of coupled-channel **Bethe-Salpeter equations:**

$$T = T + VGT$$



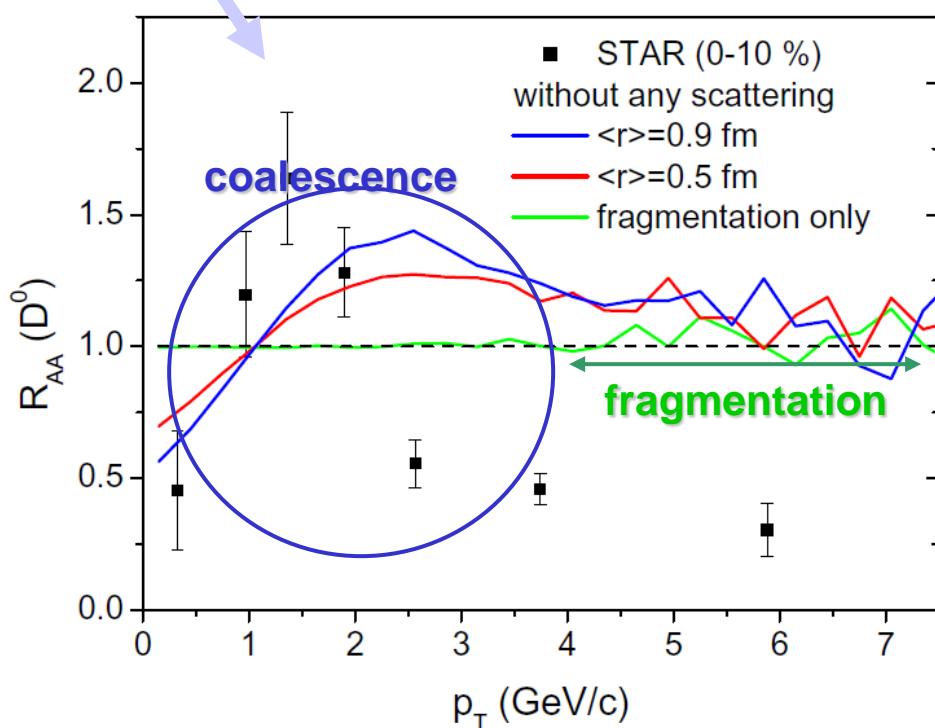
\rightarrow Strong **isospin dependence** and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!



R_{AA} at RHIC - coalescence vs fragmentation

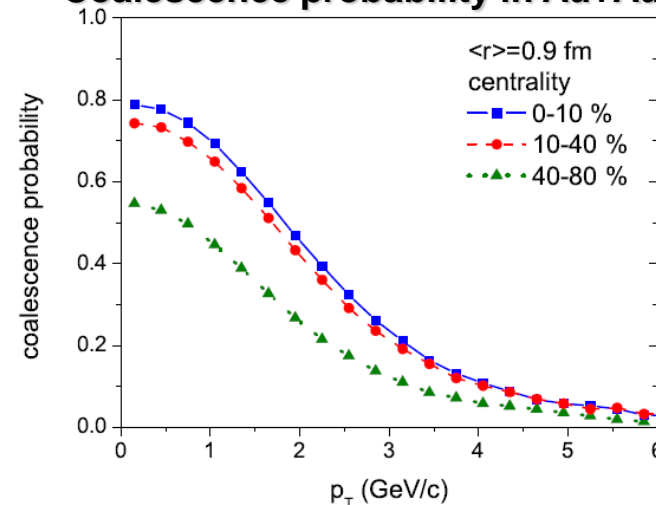
Influence of hadronization scenarios: coalescence vs fragmentation

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



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

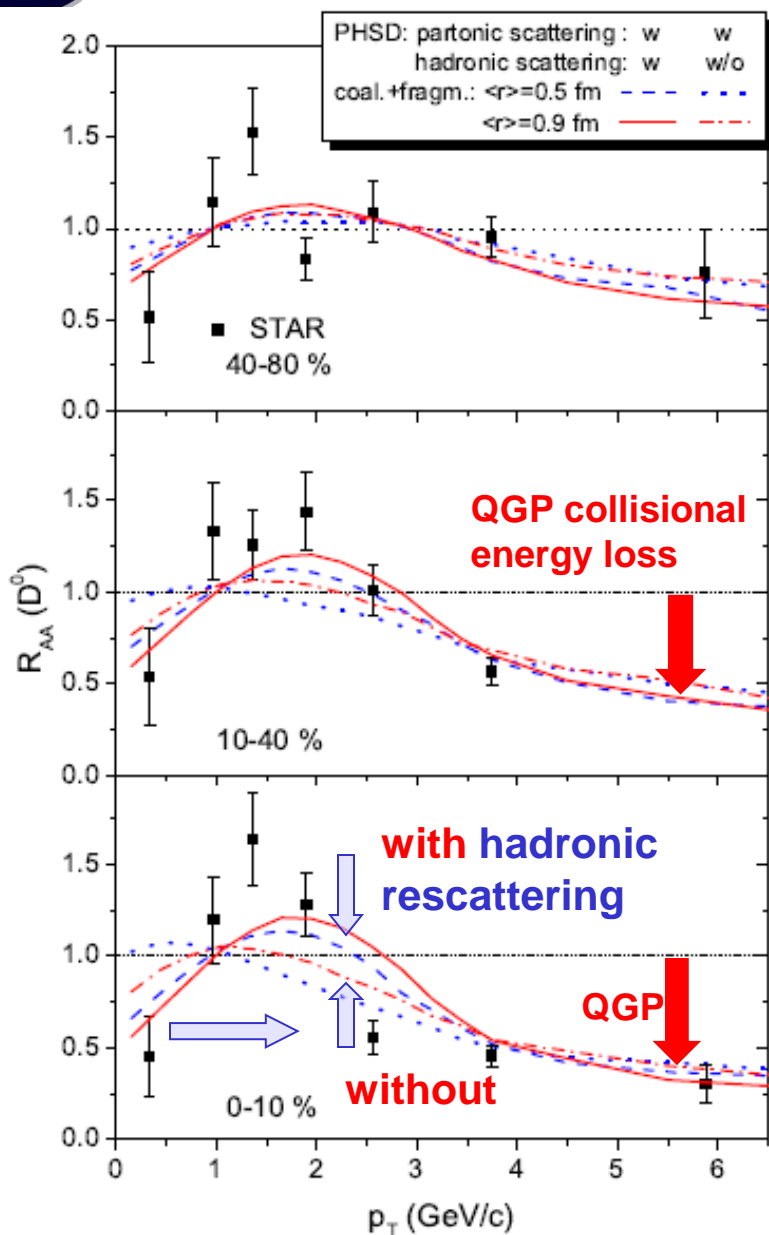
Coalescence probability in Au+Au



- 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
- The height of the R_{AA} peak depends on the balance: coalescence vs. fragmentation



R_{AA} at RHIC: hadronic rescattering



Influence of hadronic rescattering:

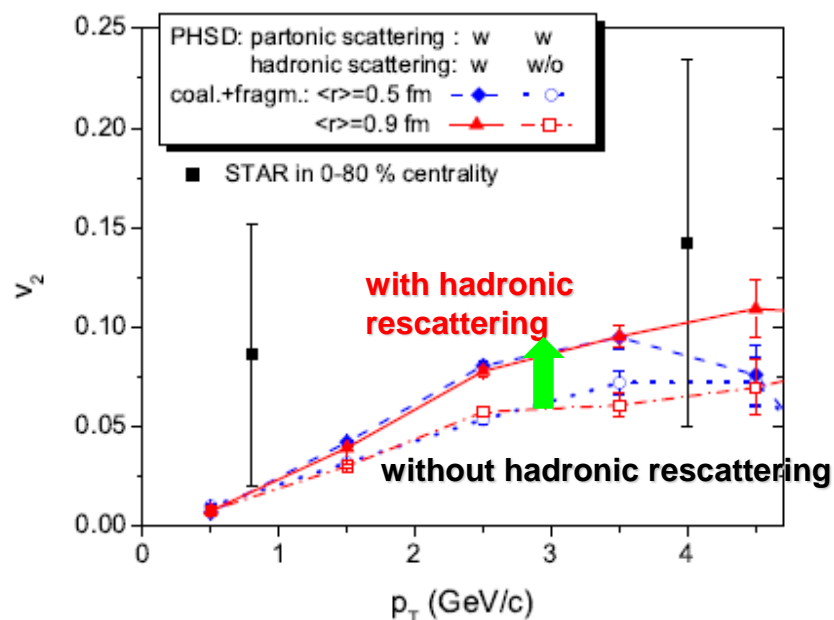
Central Au+Au at $s^{1/2} = 200$ GeV :

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

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

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

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



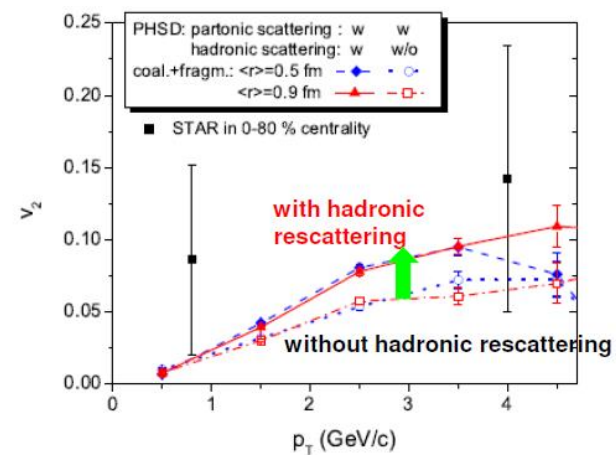
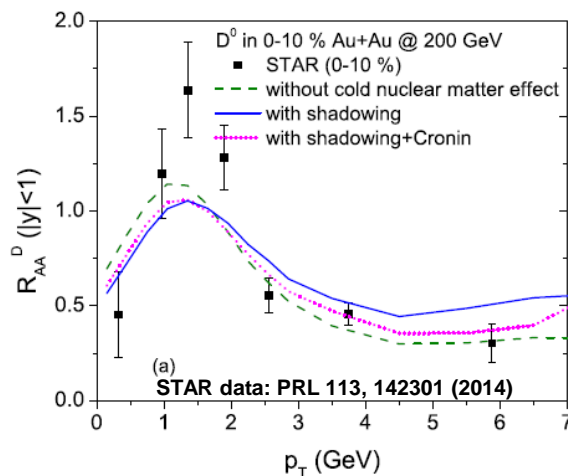
- Hadronic rescattering moves R_{AA} peak to higher p_T !
- substantially increases v_2 at larger p_T



PHSD vs charm observables at RHIC

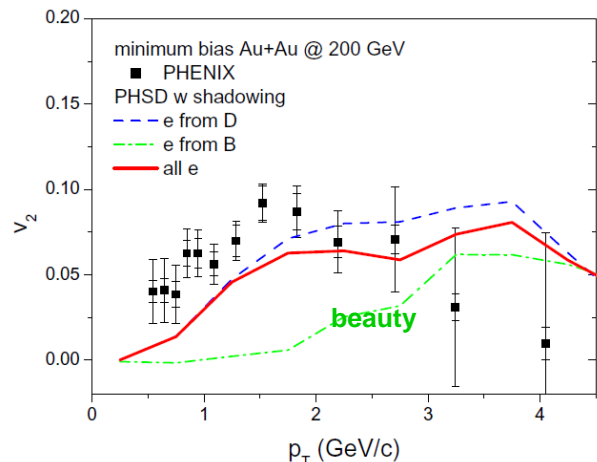
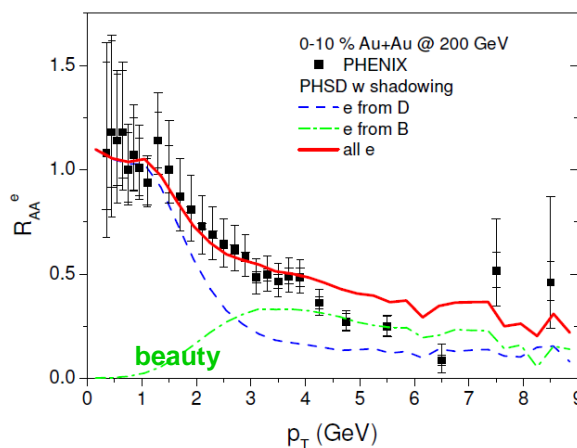
STAR

R_{AA} and v_2 vs p_T
from D^0 -mesons
in Au+Au @ 200 GeV →



PHENIX

R_{AA} and v_2 vs p_T
from single electrons
in Au+Au @ 200 GeV →

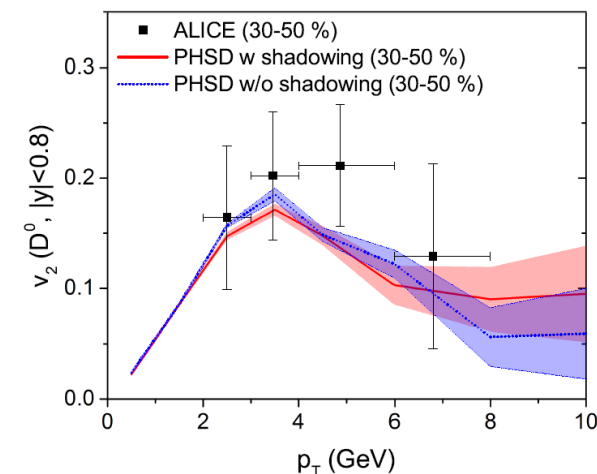
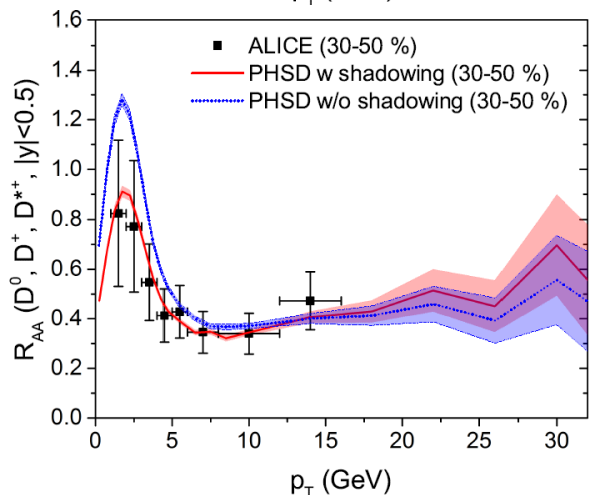
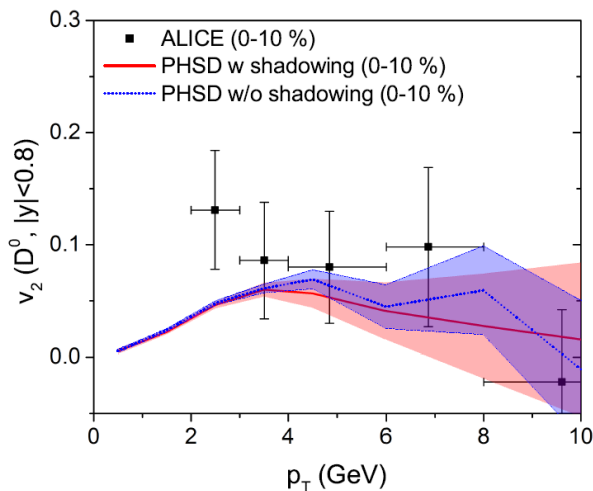
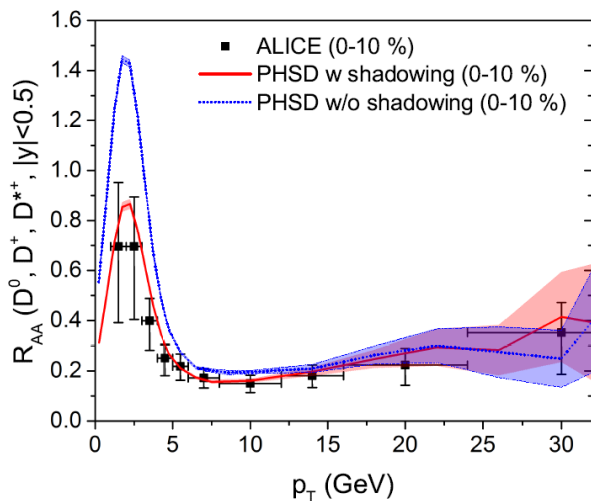


cf. talk by T. Song
on Wed. 17 Nov.

- The exp. data for the R_{AA} and v_2 are described in the PHSD by **QGP collisional energy loss** due to elastic scattering of charm quarks with massive quarks and gluons in the QGP
- + by the **dynamical hadronization scenario** „coalescence & fragmentation“
- + by **strong hadronic interactions** due to resonant elastic scattering of D, D^* with mesons and baryons
- Feed back from **beauty** contribution becomes dominant for single electrons R_{AA} and v_2 at $p_T > 3$ GeV



Charm R_{AA} at LHC: PHSD vs ALICE



- 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 ; increases v_2



PHSD vs charm observables at LHC (predictions)

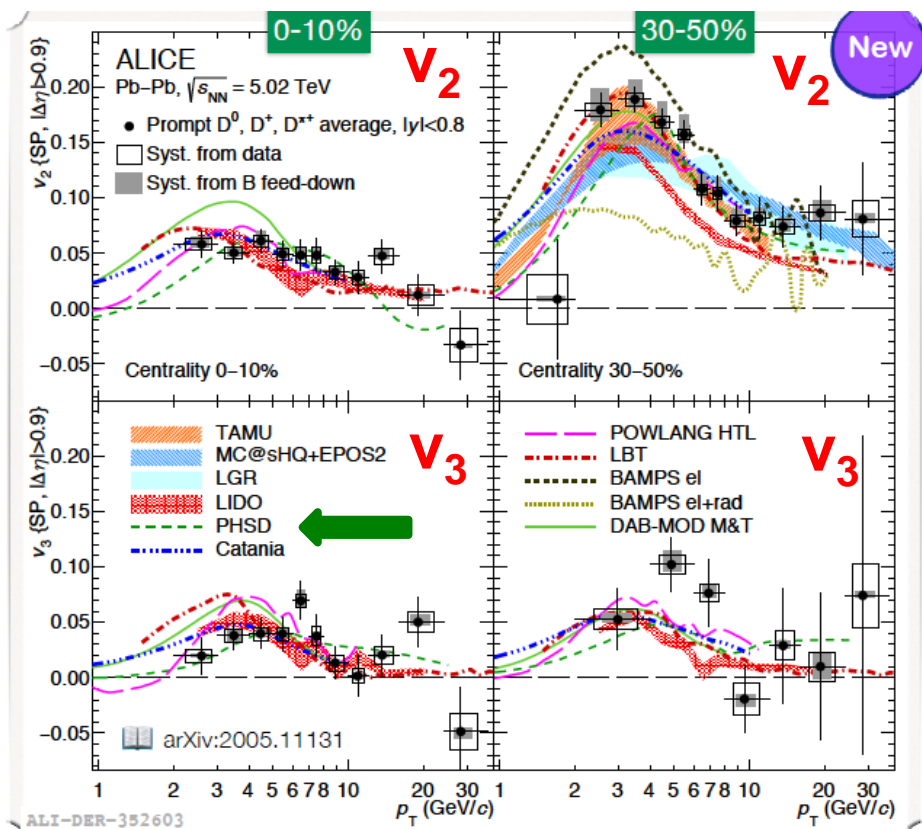
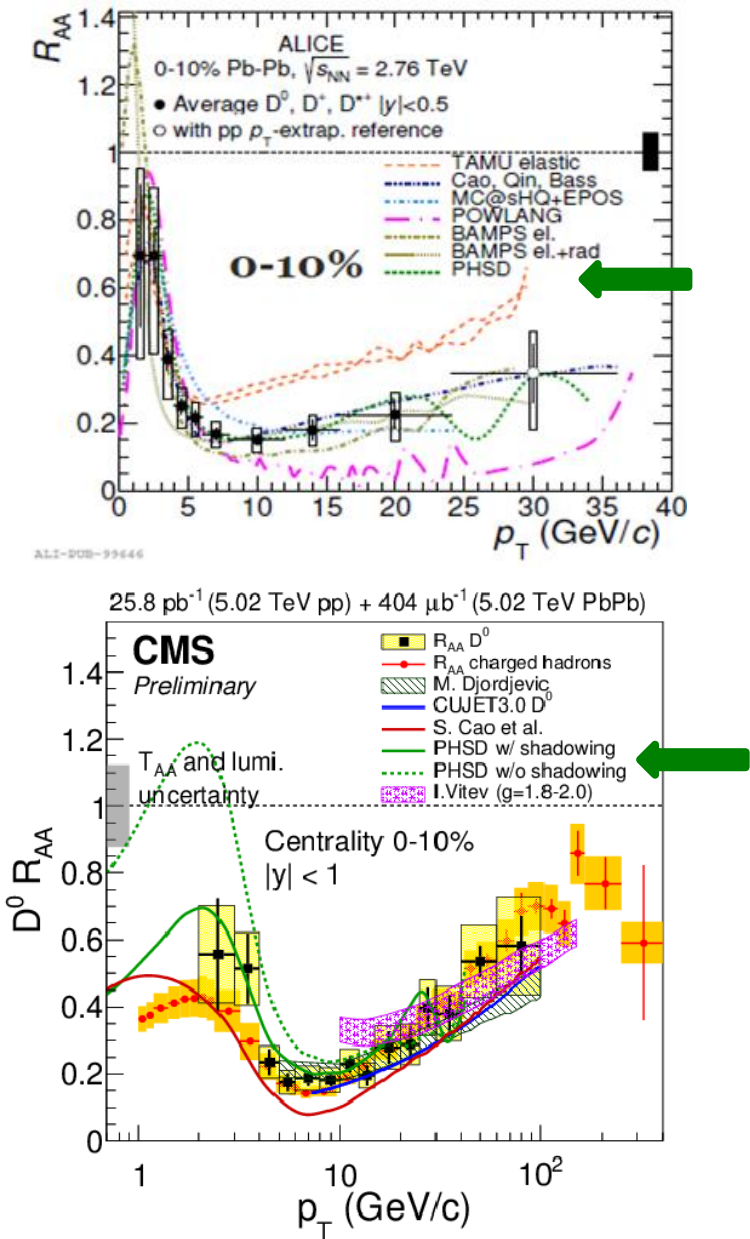
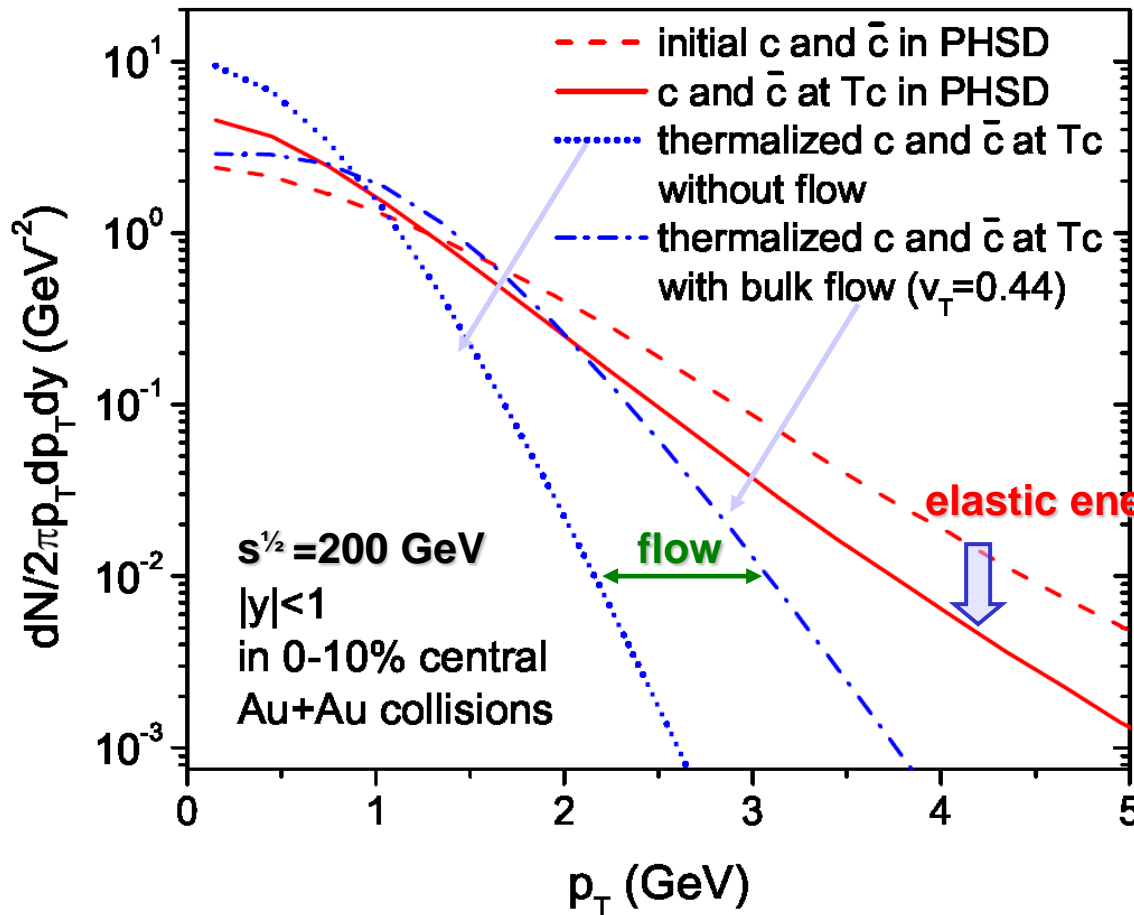


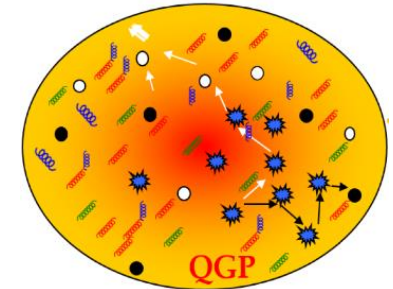
Fig. from the talk by Stefano Trogolo at HP-2020

T. Song et al., PRC 92 (2015) 014910,
PRC 93 (2016) 034906, PRC 96 (2017) 014905

Thermalization of charm quarks in A+A ?



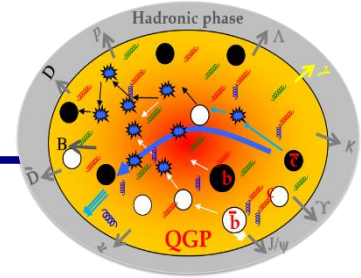
Model study



- 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



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} , generates 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 effects** suppress R_{AA} at LHC at low transverse momenta, **Cronin effect** slightly increases R_{AA} above $p_T > 1$ GeV
- The **exp. data** for the R_{AA} and v_2 at RHIC and LHC are 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 **dynamical hadronization scenario** „coalescence & fragmentation“
 - + by **strong hadronic interactions** due to resonant elastic scattering of D, D^* with mesons and baryons
- Feed back from **beauty contribution** for R_{AA}^e and v_2^e from single electrons for Au+Au at 200 GeV becomes dominant for $p_T > 3$ GeV