Tomography of the QGP by Charm Quarks

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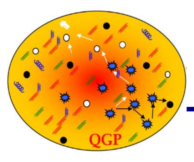
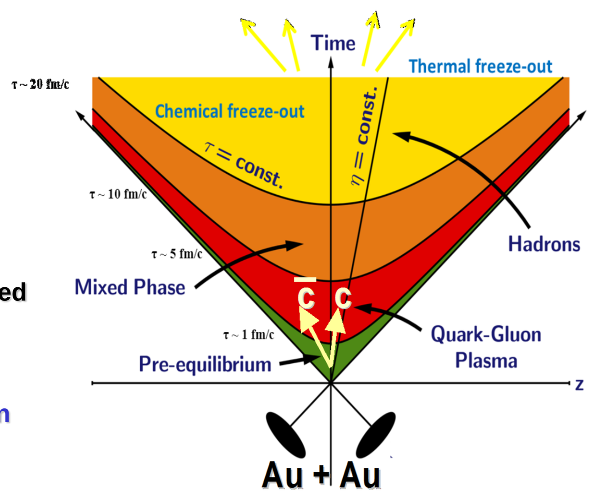
Motivation



The advantages of the 'charm probes':

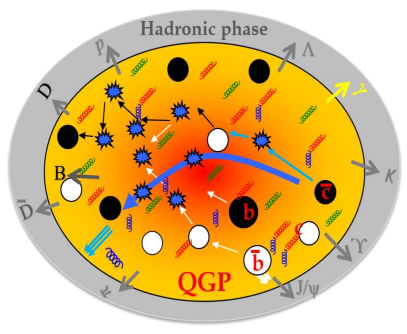
- dominantly produced in the very early stages of the reactions in initial binary collisions with large energy-momentum transfer
- initial charm production is well described by pQCD – FONLL
- scattering cross sections are small (compared to the light quarks) ➔ not in an equilibrium with the surrounding matter



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

Dynamics of charm quarks in A+A

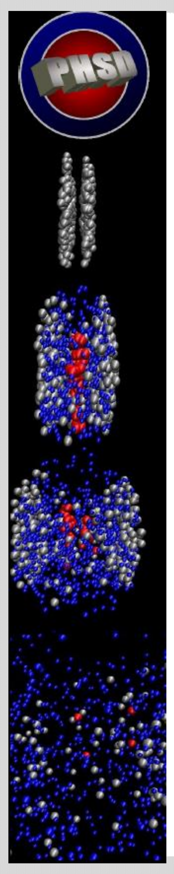
1. Production of charm quarks in initial binary collisions
2. Interactions in the QGP:
   elastic scattering Q+q➔Q+q ➔ collisional energy loss
   gluon bremsstrahlung Q+q➔Q+q+g ➔ radiative energy loss
3. Hadronization: c/cbar quarks ➔D(D*)-mesons: coalescence vs fragmentation
4. Hadronic interactions: 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

Parton-Hadron-String-Dynamics (PHSD)



PHSD is a non-equilibrium transport model with

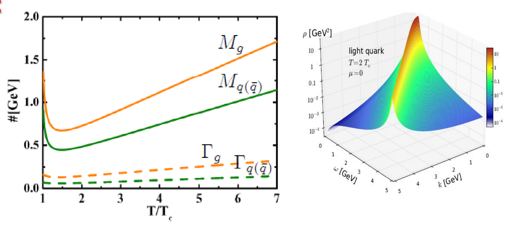
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for the partonic phase ('crossover' at μ_q=0)
- explicit parton-parton interactions - between quarks and gluons
- dynamical hadronization

QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD

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

- strongly interacting quasi-particles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in self-generated mean-field potential
- Spectral functions:

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



Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting system!)

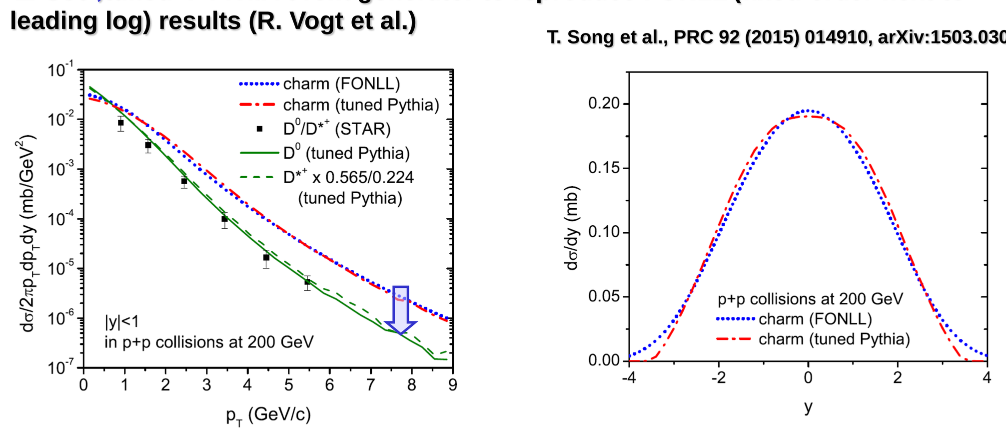
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

Modeling of charm dynamics in A+A :

I. Charm quark production in binary N+N collisions

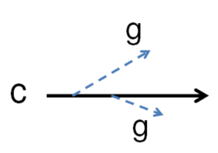
Use 'tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)

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



Charm fragmentation

D⁰ 20 %
D⁺ 17.4 %
D*⁰ 21.3 %
D*⁺ 22.4 %
Ds⁺ 8 %
Λc 9.4 %



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

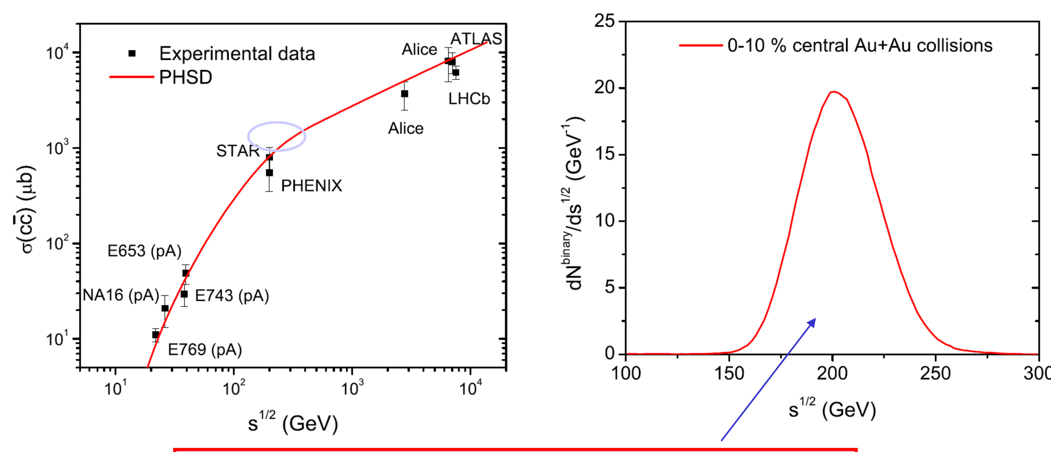
- z : momentum fraction of hadron H in heavy quark Q
- ϵ_Q=0.01 for Q=charm

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

II. Charm quark production in A+A

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

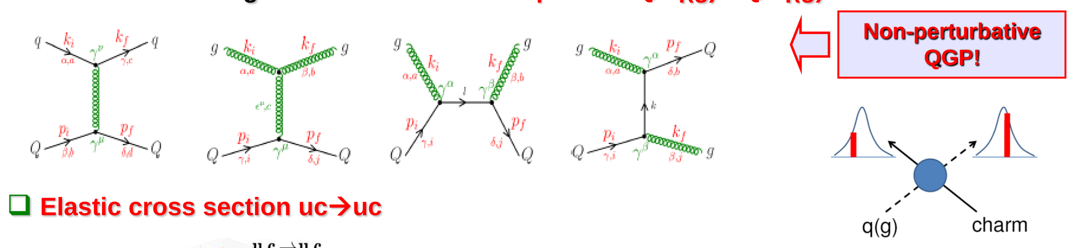
The total cross section for charm production in p+p collisions σ(cc)



Collision energy smearing due to the Fermi motion

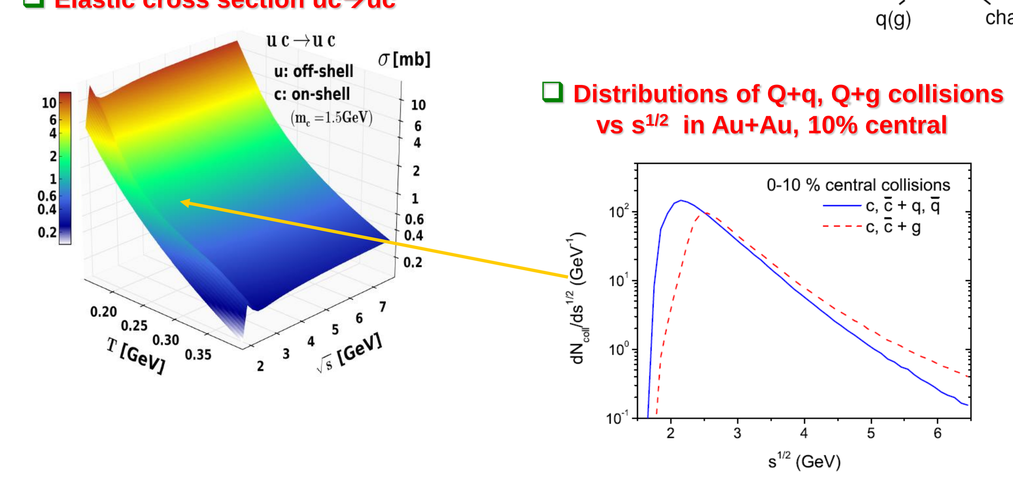
III. Charm quark scattering in the QGP (DQPM)

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



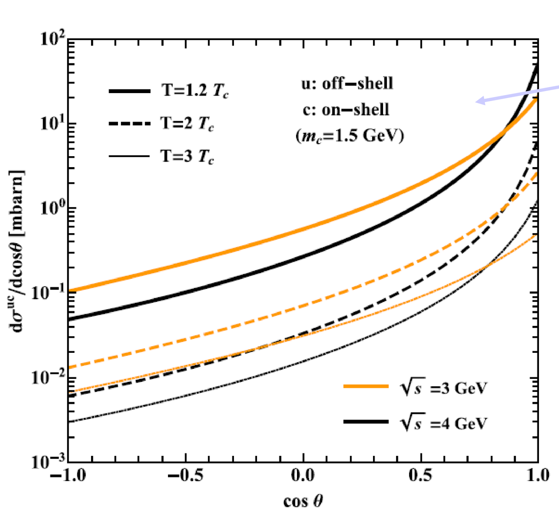
Elastic cross section uc➔uc

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



Charm quark scattering in the QGP: DQPM vs. PQCD

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

IV. 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) :

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

with

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

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

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⁺

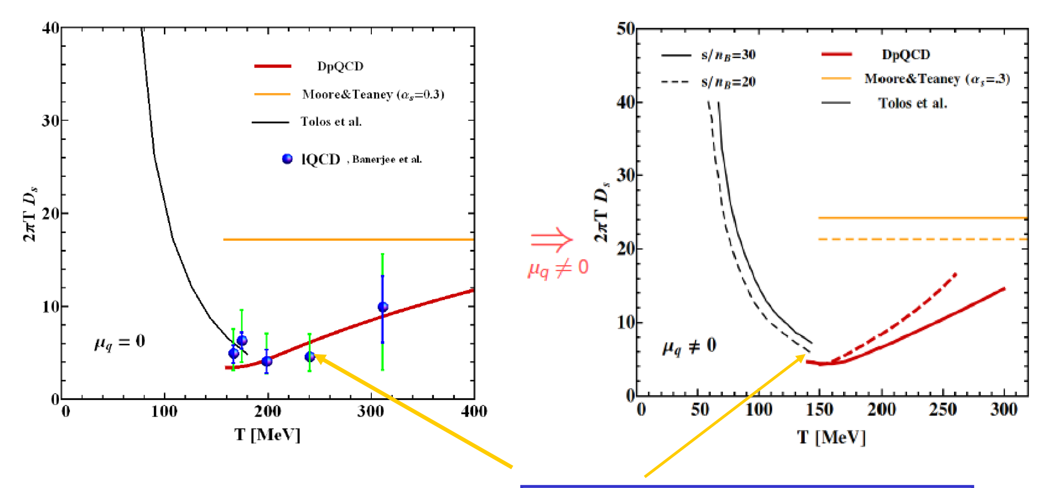
C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, L. Tolos, Phys. Rev. D 87, 074034 (2013)

Unitarized scattering amplitude ➔ from solution of coupled-channel Bethe-Salpeter equations: $T = T + VGT$

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

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!

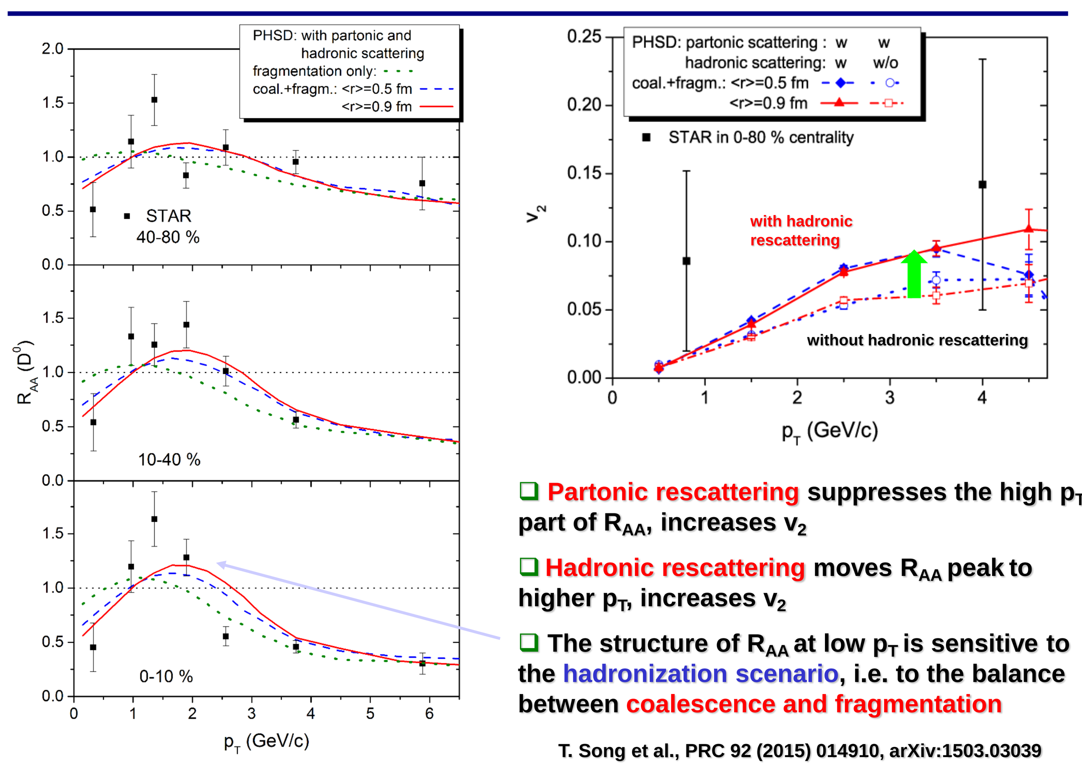
T < T_c : hadronic D_s

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

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

PHSD results :

PHSD: charm R_{AA} and v_2 at RHIC

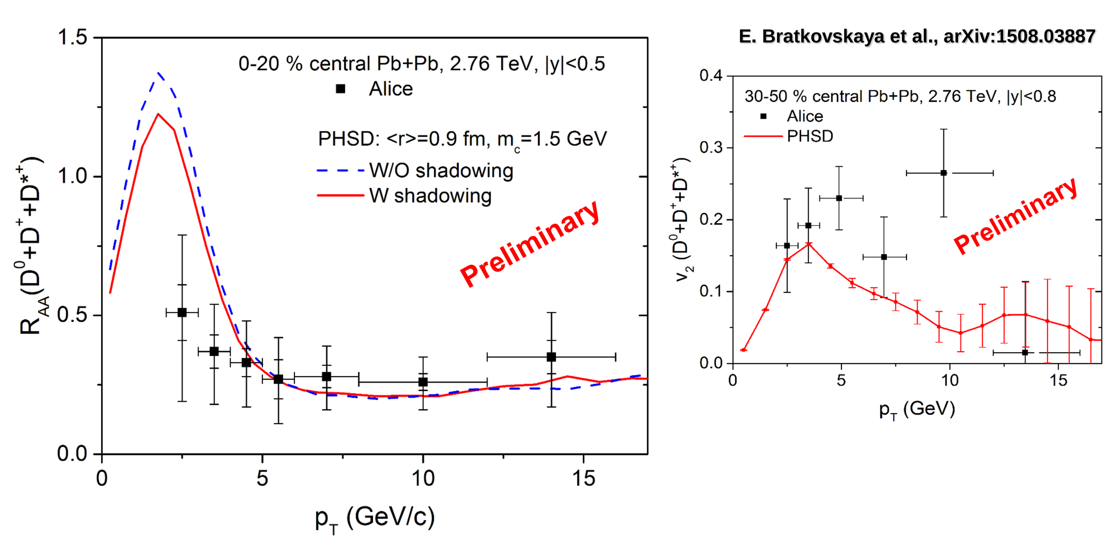


- Partonic rescattering suppresses the high p_T part of R_{AA}, increases v_2
- Hadronic rescattering moves R_{AA} peak to higher p_T, increases v_2
- The structure of R_{AA} at low p_T is sensitive to the hadronization scenario, i.e. the balance between coalescence and fragmentation

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

PHSD: charm R_{AA} and v_2 at LHC

E. Bratkovskaya et al., arXiv:1508.03887



- 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 enhances the high p_T part of R_{AA}

Summary

- PHSD provides a microscopic description of non-equilibrium charm dynamics in the partonic and hadronic phases
- The charm energy loss is mainly attributed to the partonic rescattering
- Hadronic rescattering moves R_{AA} peak to higher p_T, increases v_2
- Shadowing effect suppresses the low p_T and enhances the high p_T part of R_{AA}
- The structure of R_{AA} at low p_T is sensitive to the hadronization scenario, i.e. to the balance between coalescence and fragmentation
- Outlook: Influence of radiative energy loss at larger p_T ?

References

T. Song et al., Phys. Rev. C 92 (2015) 014910, arXiv:1503.03039

E. Bratkovskaya et al., arXiv:1508.03887

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

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