Open charm and dileptons from relativistic heavy-ion collisions

Elena Bratkovskaya
(GSI, Darmstadt & Uni. Frankfurt)

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

The 10th edition of the Hard and Electromagnetic Probes
International Conference (HP-2020)
31 May - 5 June 2020
Online
Open charm and electromagnetic probes

- **Dileptons and real photons:**
  - emitted from different stages of the HIC
  - not effected by final-state partonic and hadronic interactions
  - promising signal of QGP – ’thermal‘ photons and dileptons

- **Heavy quarks (charm, bottom):**
  - produced at the early stage of the HIC
  - interact with QGP and hadronic matter

⇒ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

Microscopic transport approaches
**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:**
  - N+N → string formation → decay to pre-hadrons + leading hadrons

- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{\text{critical}} = 0.5$ GeV/fm$^3$:
  - dissolution of pre-hadrons → partons

- **Partonic phase - QGP:**
  - QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and $\mu_B$ (crossover)
  
  - Degrees-of-freedom: strongly interacting quasiparticles: massive quarks and gluons ($q, \bar{q}, q\bar{q}$) 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

---

Dynamical QuasiParticle Model (DQPM)

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

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

Theoretical basis:

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

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

- thermal masses \( (M_g, M_q) \)
- interaction widths \( (\gamma_g, \gamma_q) \)

- introduce an ansatz (HTL; with few parameters) for the \( (T, \mu_B) \) 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 \( \varepsilon \) from DQPM to lQCD at \( \mu_B = 0 \)

\( \Rightarrow \) Quasi-particle properties at \( (T, \mu_B) \):

- IQCD: pure glue

\( \bullet \) DQPM provides mean-fields (1PI) for q,g and effective 2-body partonic interactions (2PI); gives transition rates for the formation of hadrons

\( \Rightarrow \) QGP in PHSD

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 $<r> = 0.9$ fm & fragmentation
   $0.4 < \varepsilon < 0.75$ GeV/fm$^3$ & $\varepsilon < 0.4$ GeV/fm$^3$

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:
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.

PHSD vs charm observables at LHC (highlights)

Fig. from the talk by Stefano Trogolo

Dilepton sources

- **from the QGP via partonic (q, q̅, g) interactions:**

  PHSD: non-perturbative QGP → DQPM

  \[ \gamma^* \rightarrow q \bar{q} \]

- **from hadronic sources:**

  - **direct decay** of vector mesons (ρ, ω, φ, J/Ψ, Ψ′)
  
  - **Dalitz decay** of mesons and baryons (π⁰, η, Δ, ...)
  
  - **correlated D+D̅bar pairs**
  
  - **radiation from multi-meson reactions** (π+π, π+ρ, π+ω, ρ+ρ, π+a₁) - 4π′

---

What is the best energy range to observe dileptons from QGP?
**Message:**

STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within

1) a collisional broadening scenario for the vector meson spectral functions
   + QGP + correlated charm

2) Charm contribution is dominant for $1.2 < M < 2.5$ GeV
QGP and charm are dominant contributions for intermediate masses at BES RHIC ➔ measurements of charm at BES RHIC are needed to control charm production!
Dileptons at FAIR/NICA energies: predictions

Relative contribution of QGP versus charm increases with decreasing energy!

Excitation function of dilepton yield integrated for 1.2 < M < 3 GeV

mid-rapidity

The number of primary \( \text{cc} \) pairs in Pb+Pb collisions at \( b=2 \) fm as a function of \( s^{1/2} \)

* The shaded area shows the uncertainty in the number of \( \text{ccbar} \) pairs in Pb+Pb due to the uncertainty in the charm production cross section in p+p collisions

QGP contribution overshines charm with decreasing energy: \( \sqrt{s} \leq 30 \) GeV

Dilepton transverse mass spectra

The inverse slope parameter in the mass range $M=[1.75,2.95]$

- **Inverse slope parameter:** QGP contribution is harder than that from D-Dbar.
- **The excitation function** of the total inverse slope parameter shows characteristic changes at $s^{1/2}>20$ GeV.
Summary

- Charm quarks are sensitive to the history of the QGP evolution and retain information on the entire time evolution from initial stage up to the late stage of the HIC

  ➔ heavy quarks are a very suitable probe to study the QGP properties

- Intermediate dilepton masses $M > 1.2$ GeV:
  - Dominant sources: QGP ($q\bar{q}$) and correlated charm $D/D\bar{d}$
  - Fraction of QGP grows with increasing energy; however, the relative contribution of QGP dileptons to dileptons from charm pairs increases with decreasing energy

  ➔ QGP contribution overshines charm with decreasing energy
  Good perspectives for FAIR / NICA / BES RHIC!