Open charm and dileptons from relativistic heavy-ion collisions

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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

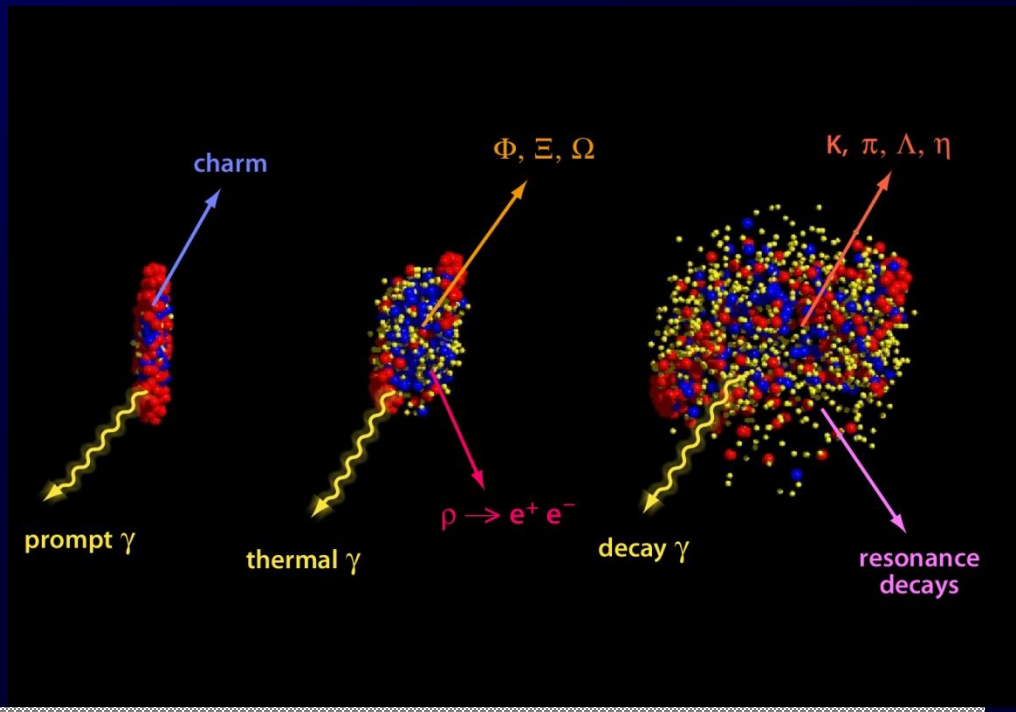
❑ Heavy quarks (charm, bottom):

- 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

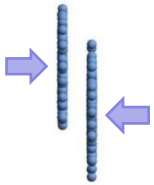


Parton-Hadron-String-Dynamics (PHSD)

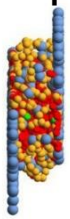
PHSD is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

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

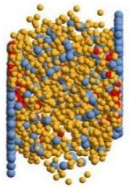
Initial A+A collision



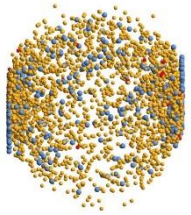
Partonic phase



Hadronization

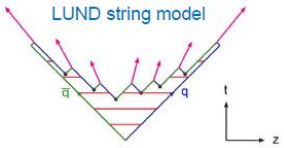


Hadronic phase

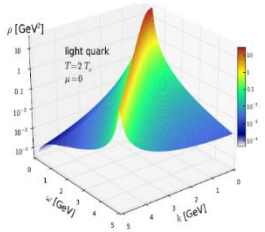


P.Moreau

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

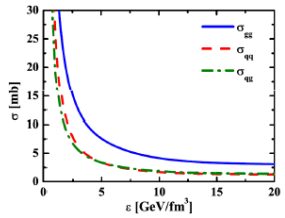


- **Formation of QGP stage if local $\varepsilon > \varepsilon_{critical}$ =0.5 GeV/fm^3:**
  dissolution of pre-hadrons → partons



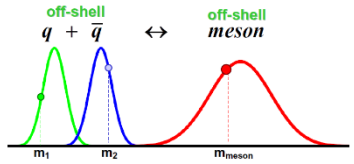
- **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)

- 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**

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

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

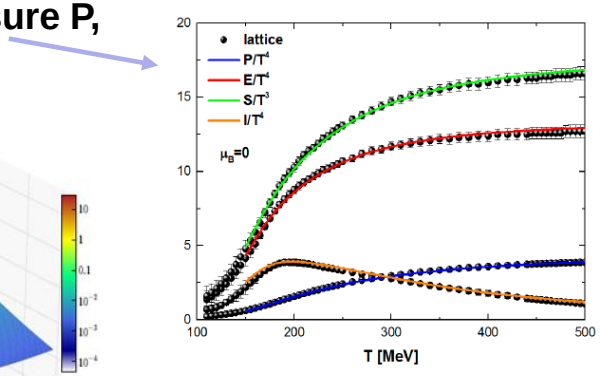
Theoretical basis :

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

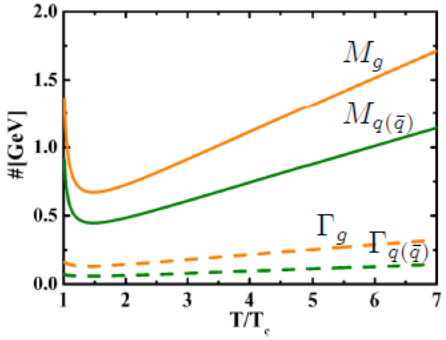
Properties of the quasiparticles are specified by scalar complex self-energies: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

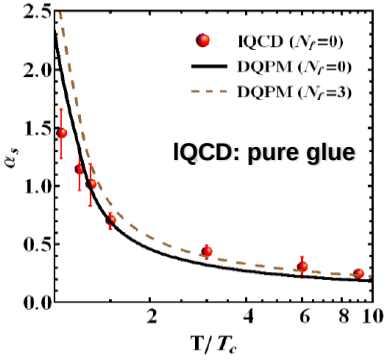
$Re\Sigma_q$: thermal masses (M_g, M_q); $Im\Sigma_q$: interaction widths (γ_g, γ_q) ➔ spectral functions $\rho_q = -2ImG_q$

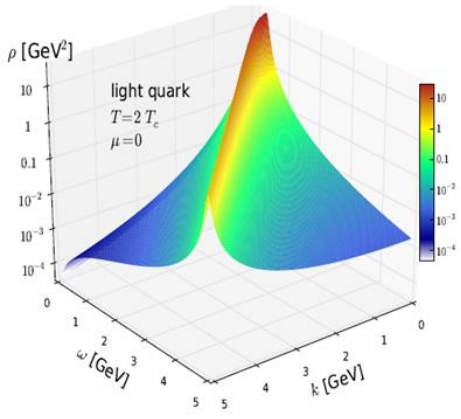
- introduce an ansatz (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the QGP thermodynamics in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison to the entropy density s, pressure P, energy density ε from DQPM to lQCD at $\mu_B = 0$



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



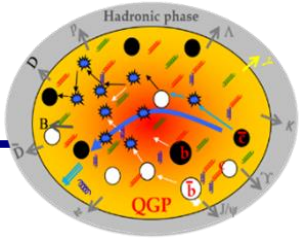




- **DQPM provides mean-fields (1PI) for q,g and effective 2-body partonic interactions (2PI); gives transition rates for the formation of hadrons ➔ QGP in PHSD**

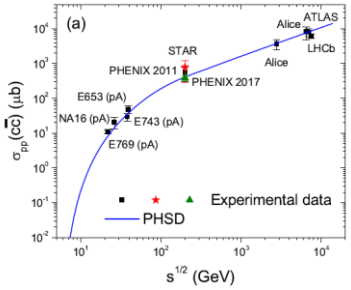
A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

Charm dynamics in PHSD



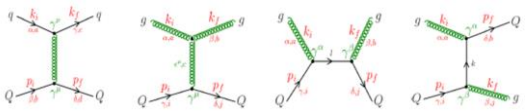
In order to get information about the QGP in HIC via dileptons, the charm dynamics must be under control

Dynamics of heavy quarks in A+A :



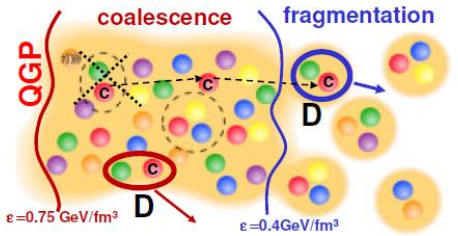
1. **Production of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects**

2. **Interactions in the non-perturbative QGP – according to the DQPM: elastic scattering with off-shell massive partons Q+q→Q+q**
   ➔ collisional energy loss

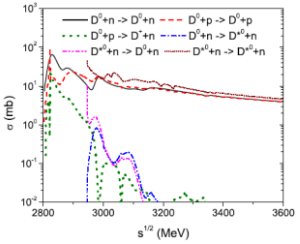


3. **Hadronization: c/cbar quarks →D(D*)-mesons:**

   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:**

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

PHSD vs charm observables at RHIC (highlights)

STAR

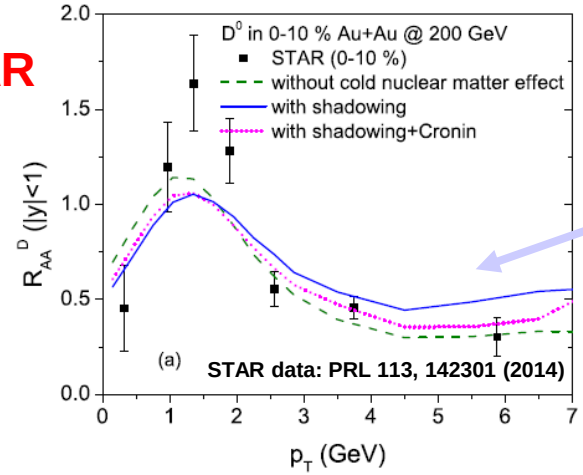
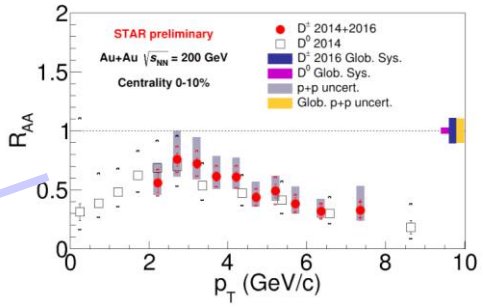
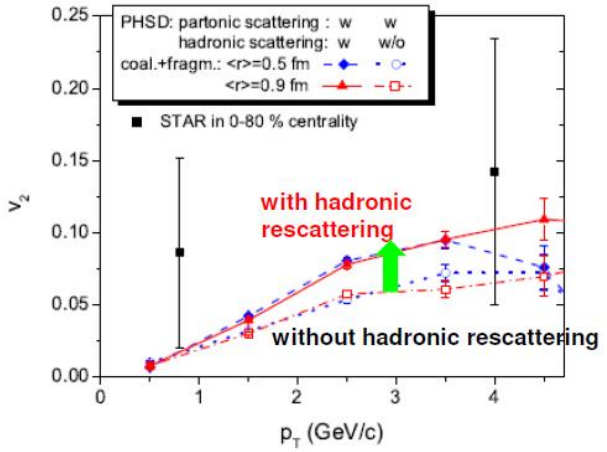


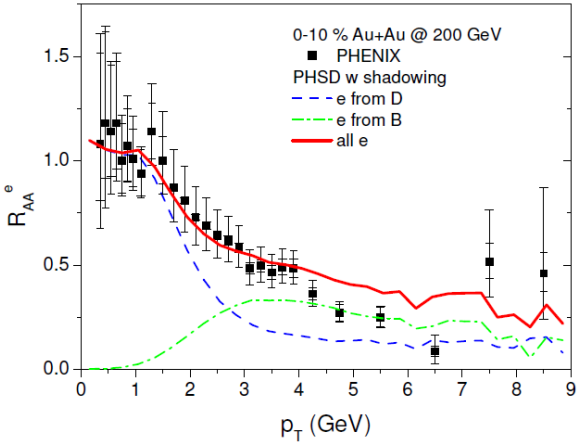
Fig. from the talk by Jan Vanek

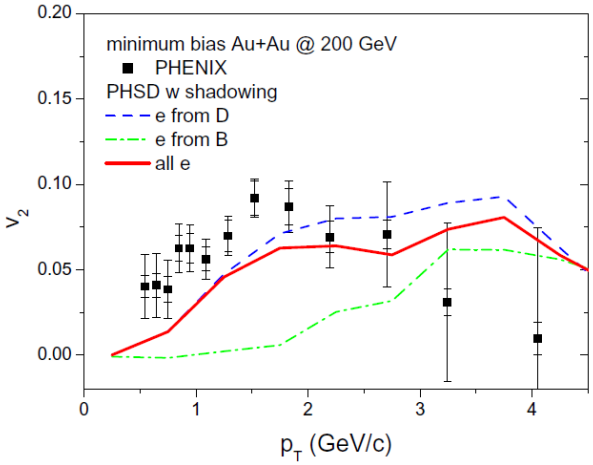




PHENIX

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





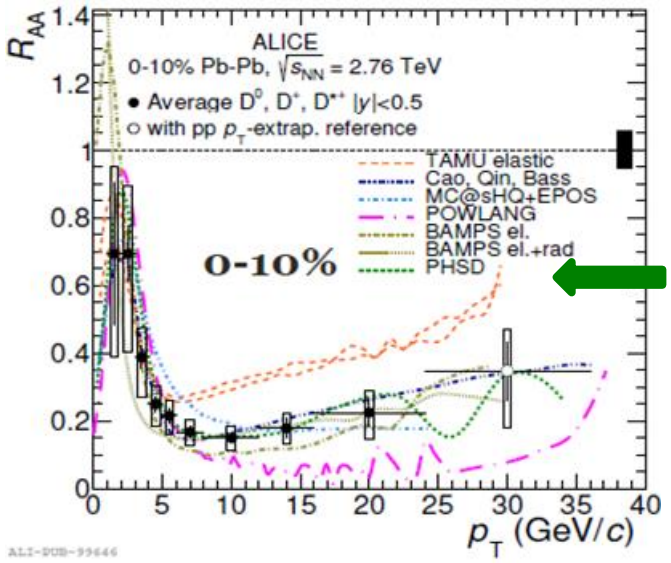
- The exp. data for the R_{AA} and v_2 are described in the PHSD by QGP collisional energy loss due to elastic scattering of charm quarks with massive quarks and gluons in the QGP

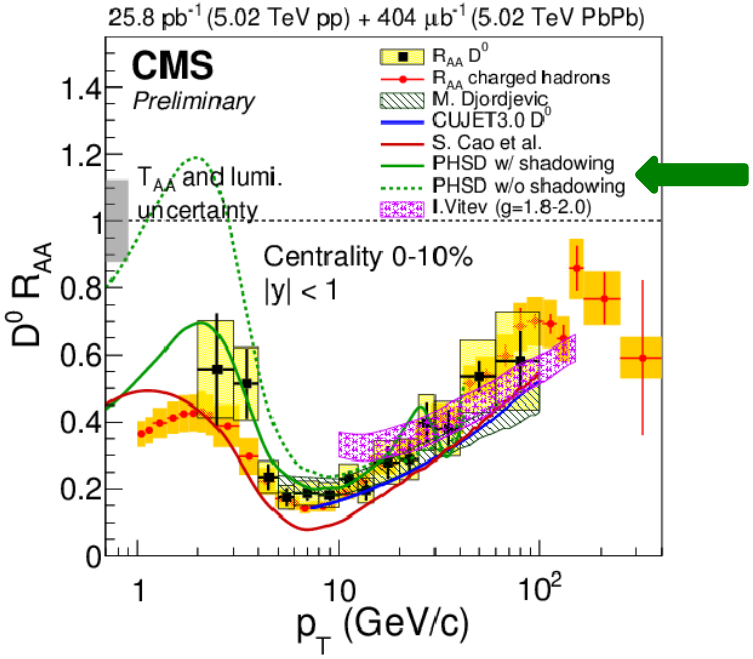
+ by the dynamical hadronization scenario „coalescence & fragmentation“

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

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

PHSD vs charm observables at LHC (highlights)





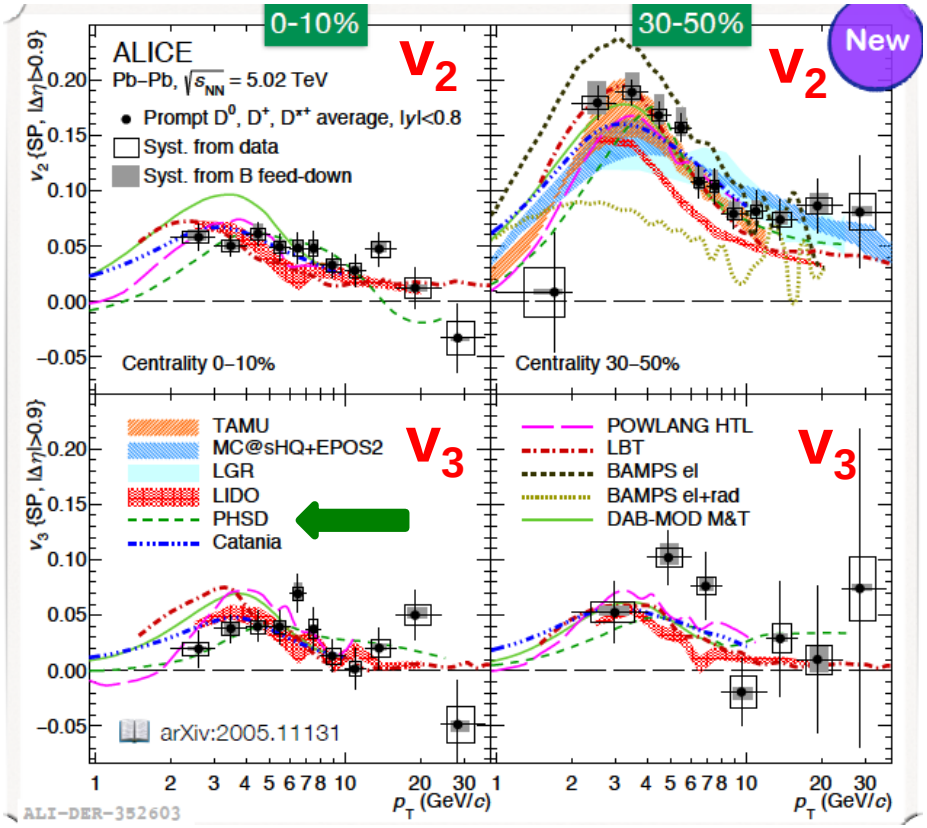
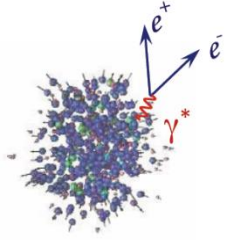


Fig. from the talk by Stefano Trogolo

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

Dilepton sources



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

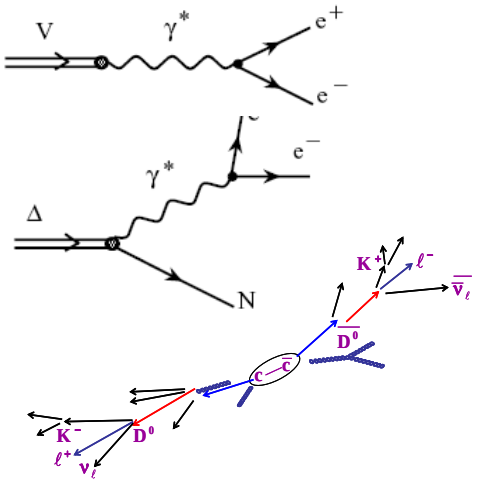
PHSD: non-perturbative QGP → DQPM

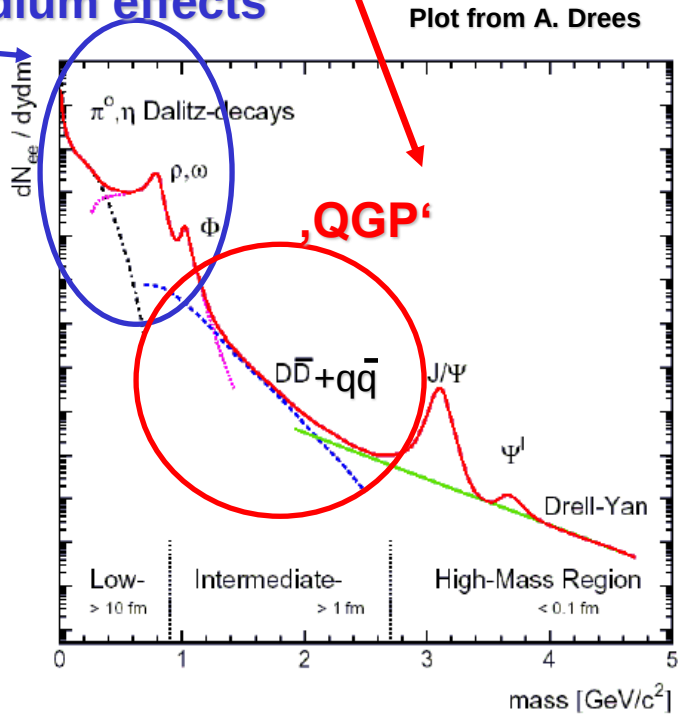
- **from hadronic sources:**

in-medium effects

Plot from A. Drees

- direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)
- Dalitz decay of mesons and baryons (π^0,η, Δ,…)
- correlated D+Dbar pairs



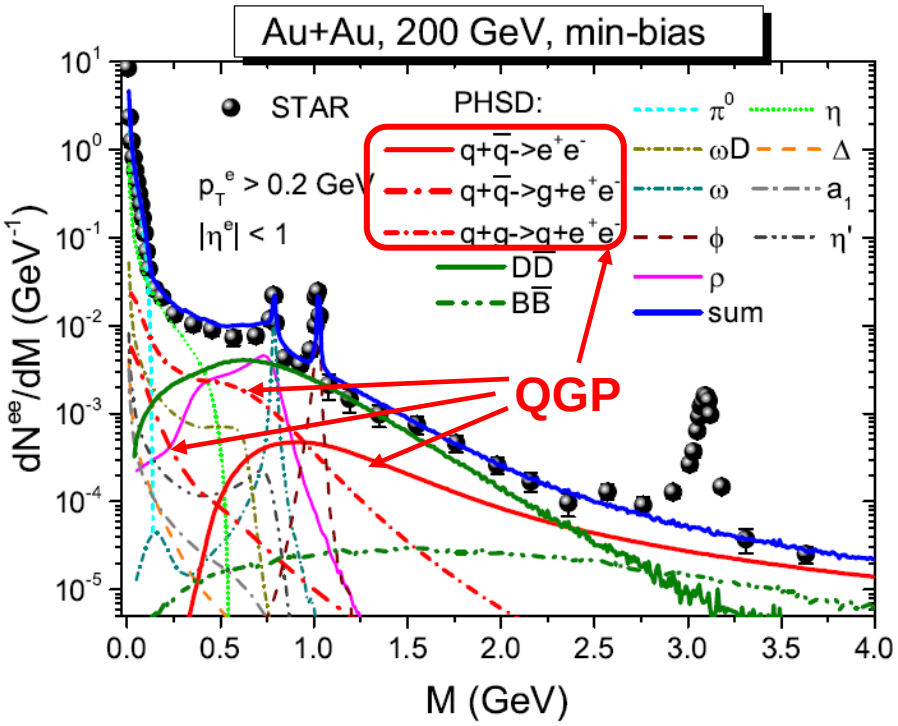


- radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π‘

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

Dileptons at RHIC and LHC

RHIC



LHC

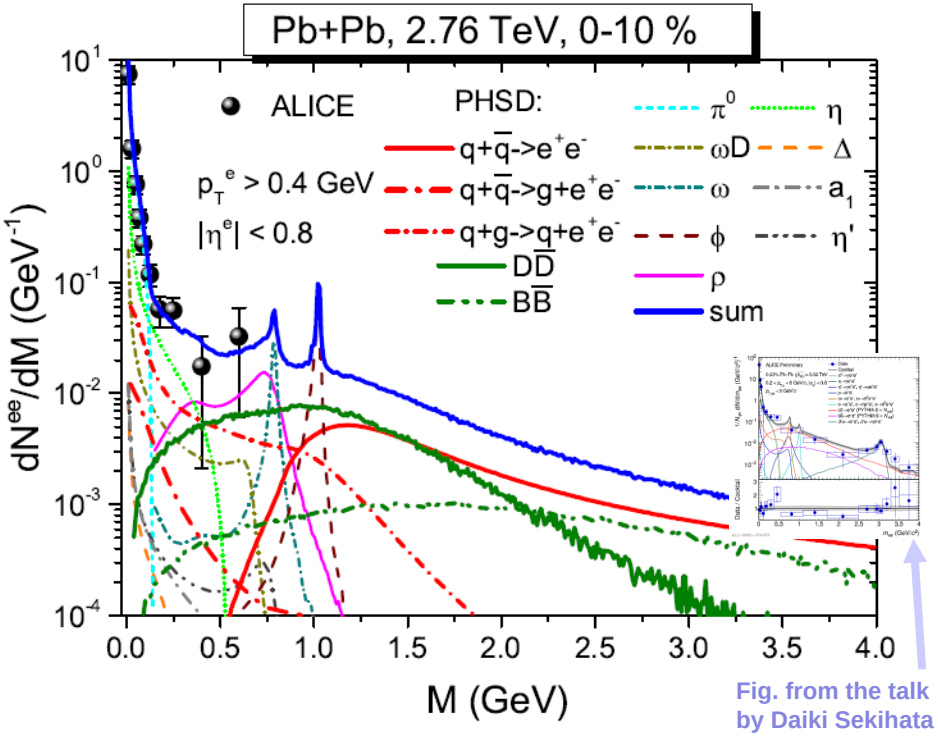


Fig. from the talk by Daiki Sekihata

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

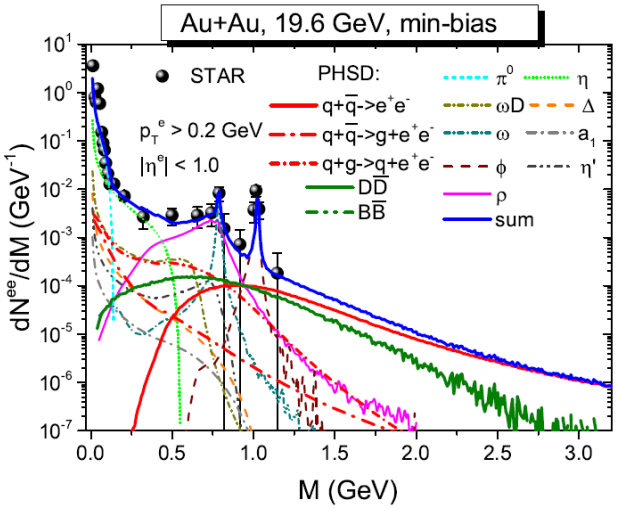
2) Charm contribution is dominant for 1.2 < M < 2.5 GeV

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

Dileptons from RHIC BES: STAR

STAR data: NPA 931 (2014) 659; PRC 92 (2015) 024912

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907



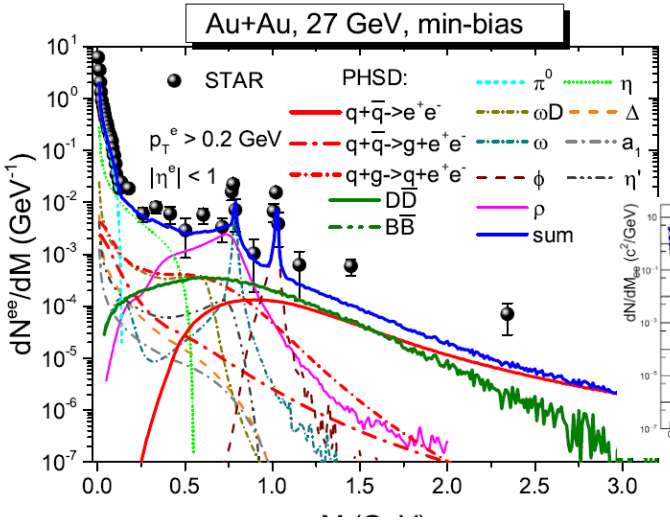
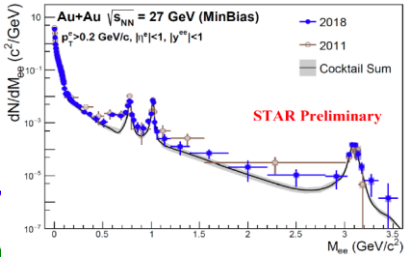
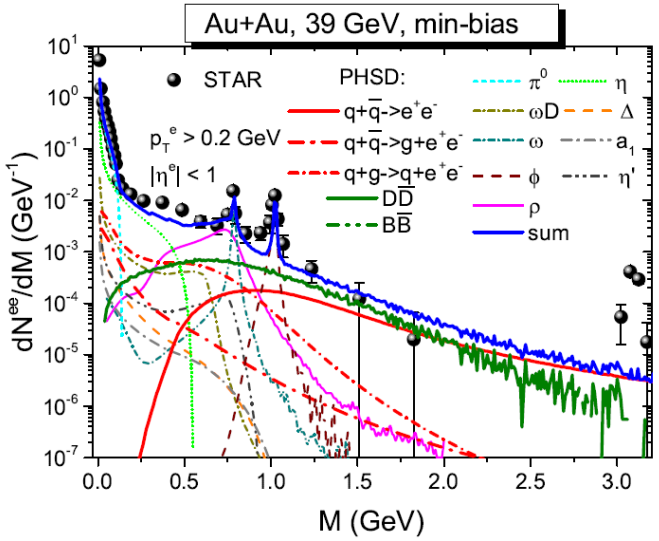
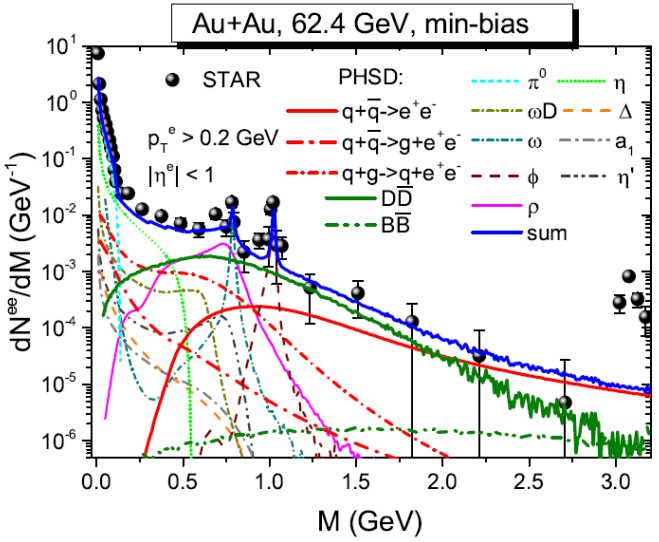


Fig. from the talk by Zhen Wang



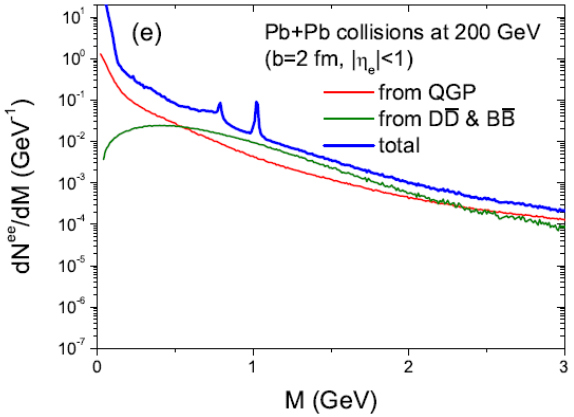


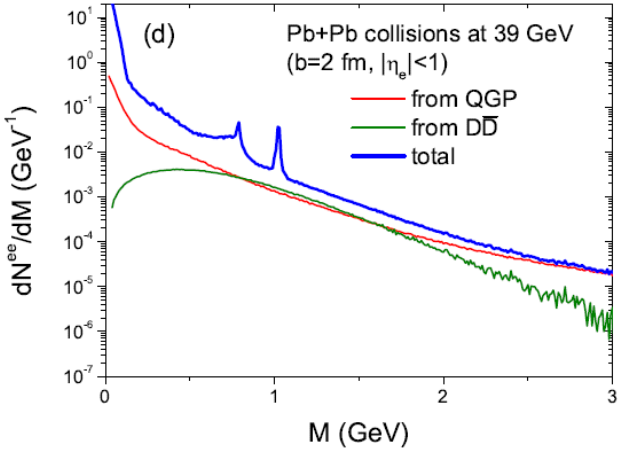


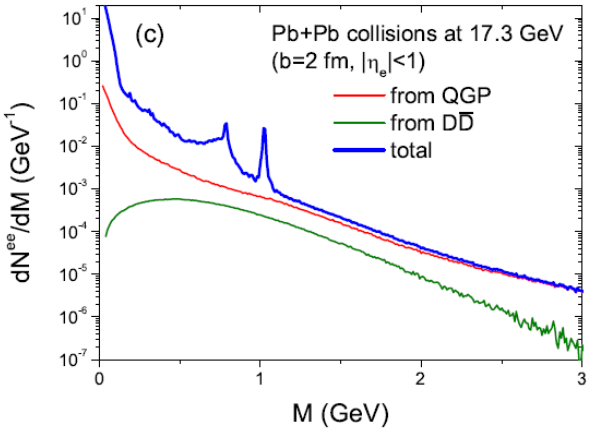
QGP and charm are dominant contributions for intermediate masses at BES RHIC

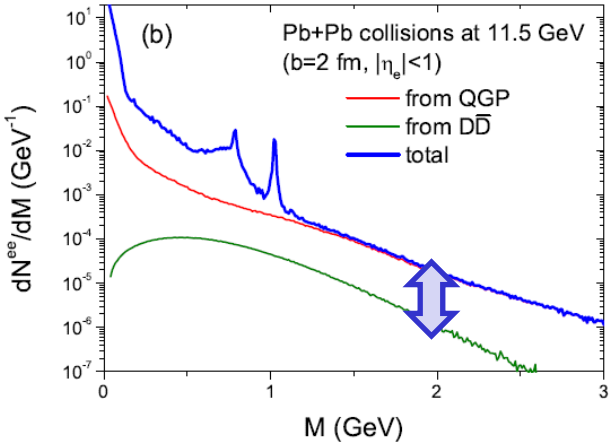
➔ measurements of charm at BES RHIC are needed to control charm production !

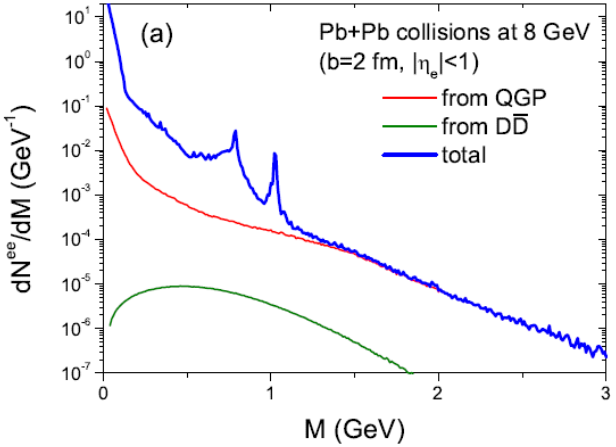
Dileptons at FAIR/NICA energies: predictions











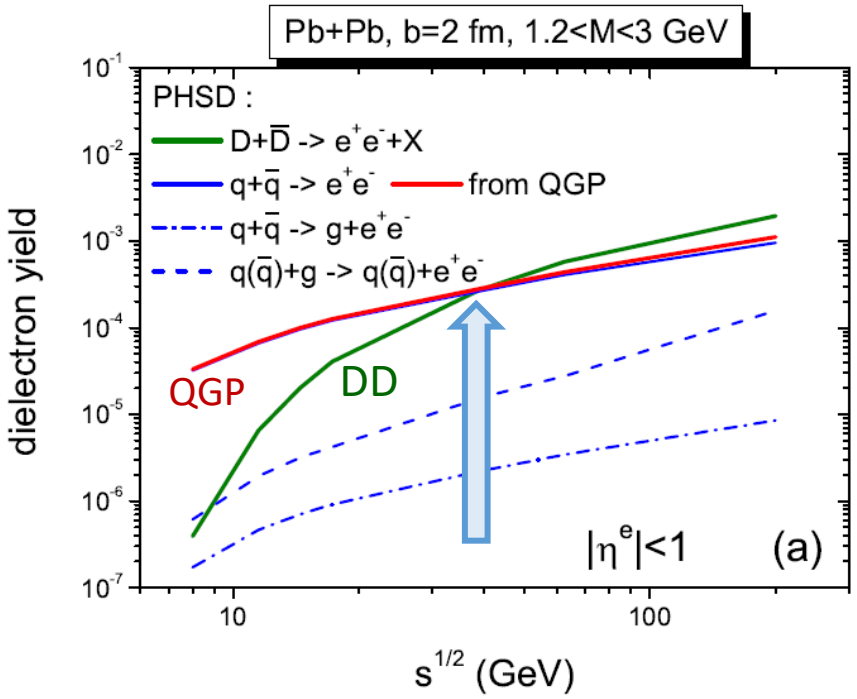
Relative contribution of QGP versus charm increases with decreasing energy!

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

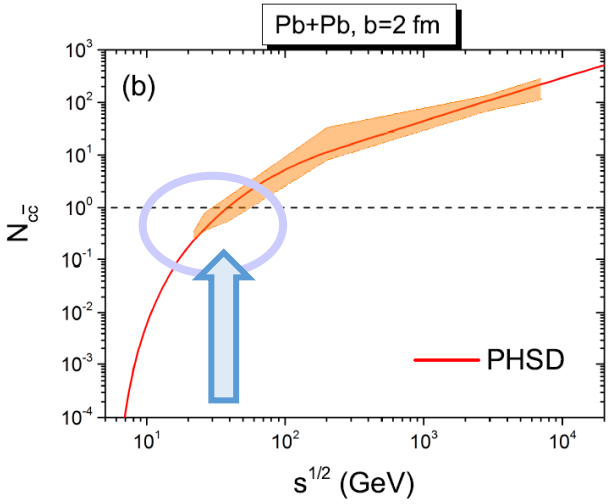
Dileptons: QGP vs charm

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

mid-rapidity



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

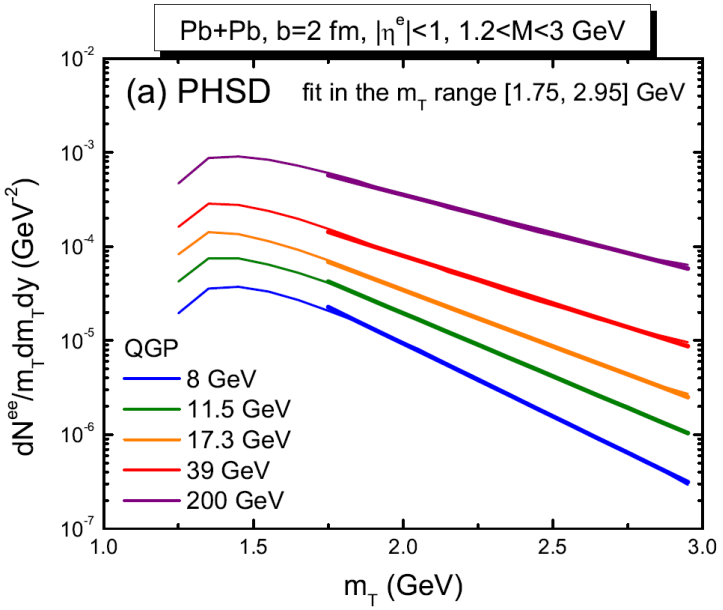


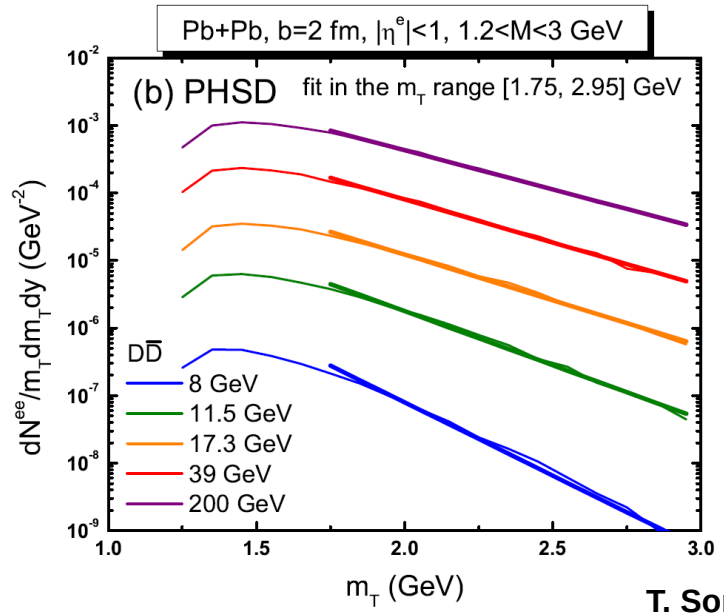
* The shaded area shows the uncertainty in the number of ccbar pairs in Pb+Pb due to the uncertainty in the charm production cross section in p+p collisions

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

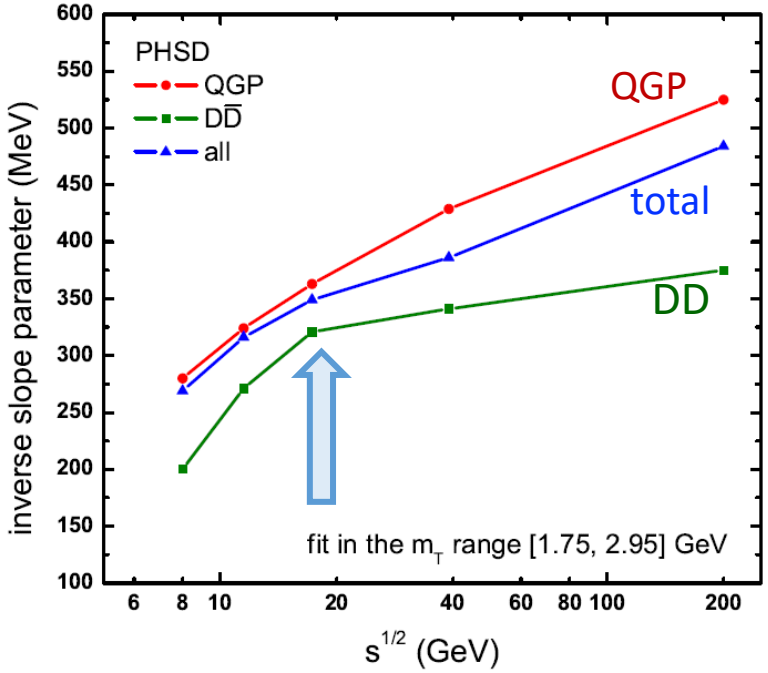
T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

Dilepton transverse mass spectra





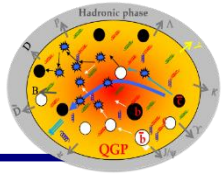
The inverse slope parameter in the mass range M=[1.75,2.95]



- **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**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

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 (qbar-q) and correlated charm D/Dbar**
  - **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 !