Electromagnetic emissivity of hot and dense matter

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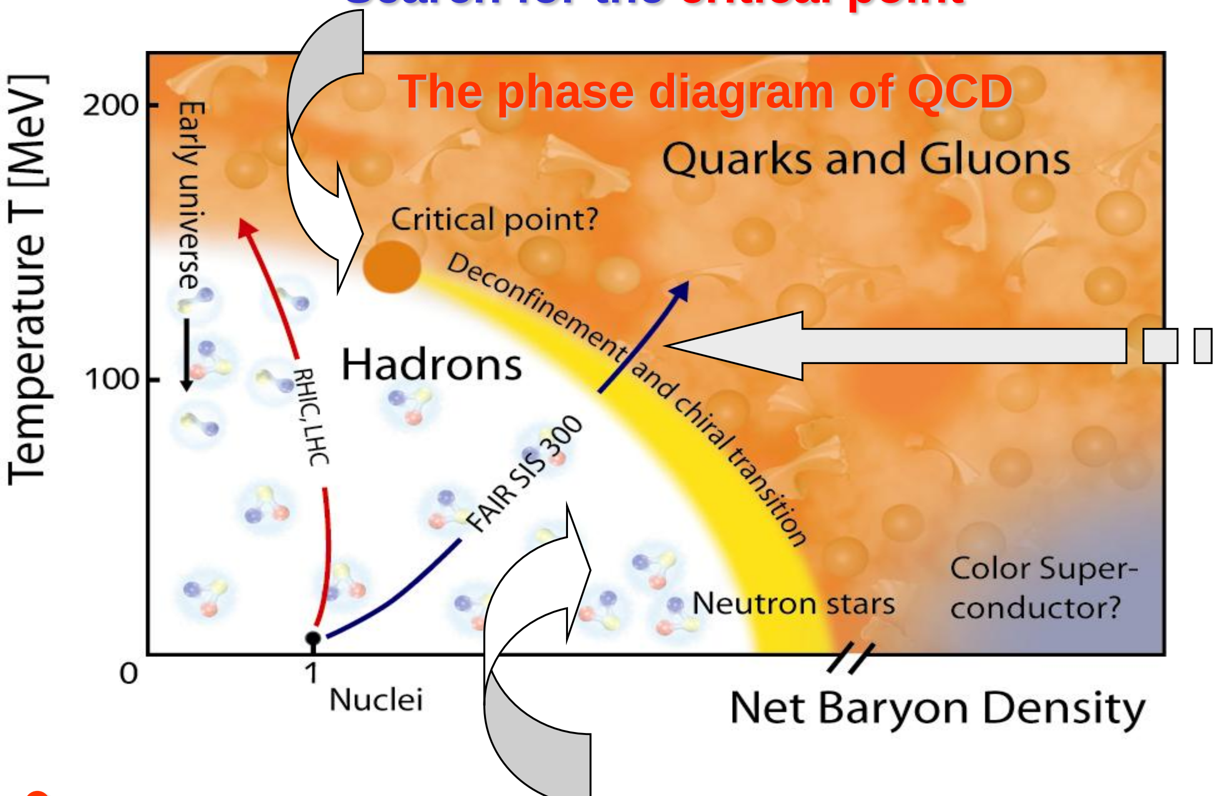
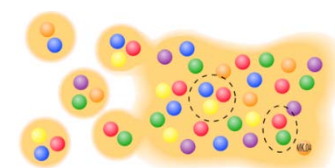
The ‚holy grail‘ of heavy-ion physics:

- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma



- Study of the in-medium properties of hadrons at high baryon density and temperature

Electromagnetic probes: photons and dileptons

Feinberg (76), Shuryak (78)

Advantages:

✓ dileptons and real photons are emitted from different stages of the reaction and not effected by final-state interactions

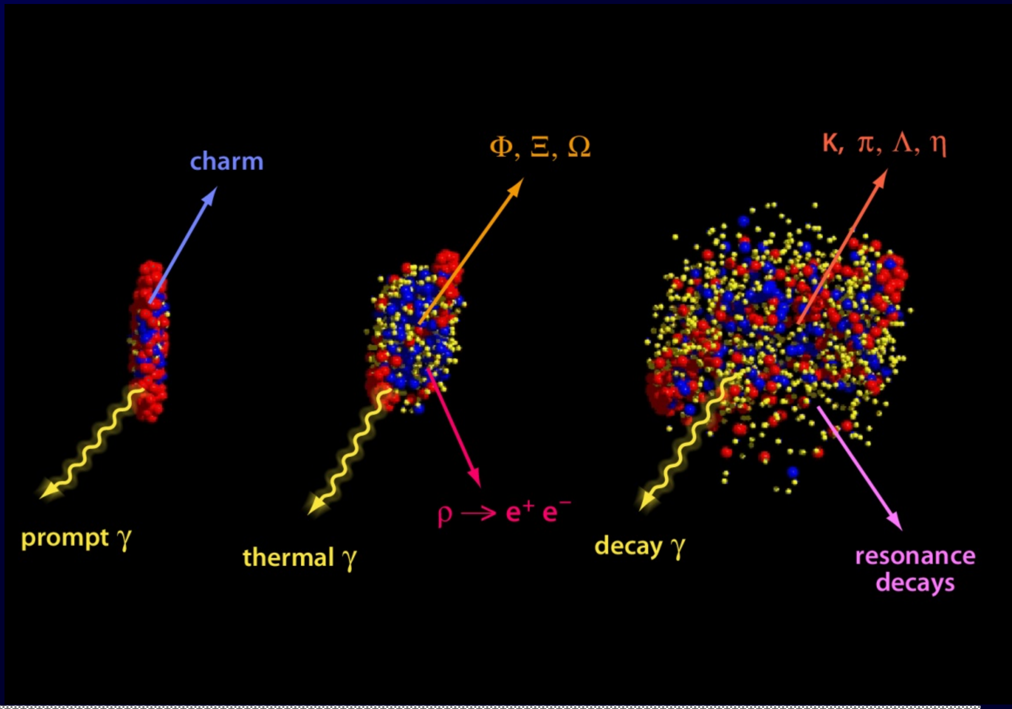
✓ provide undistorted information about their production channels

✓ promising signal of QGP – ‚thermal' photons and dileptons

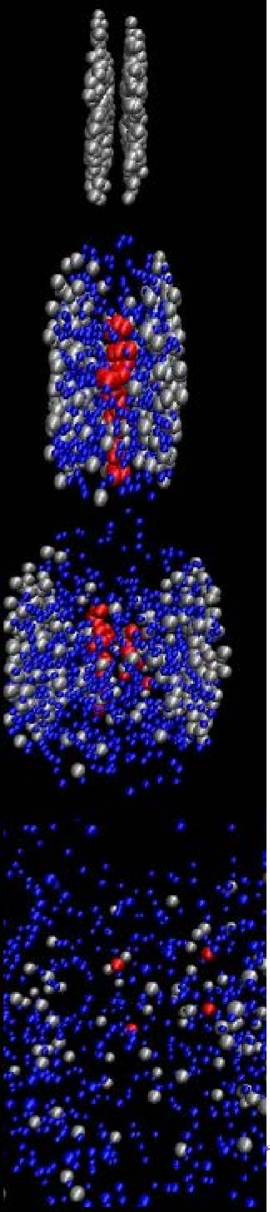
➔ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

Disadvantages:

- low emission rate
- production from hadronic corona
- many production sources which cannot be individually disentangled by experimental data



Parton-Hadron-String-Dynamics (PHSD)



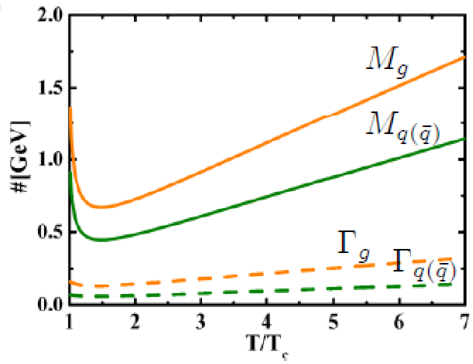
PHSD is a **non-equilibrium transport approach** with

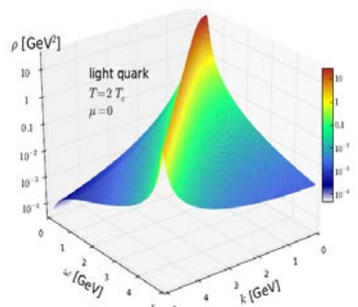
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for the partonic phase (‚crossover' at low μ_q)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

❑ **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 791 (2007) 365: NPA 793 (2007)

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





- **Spectral functions:**

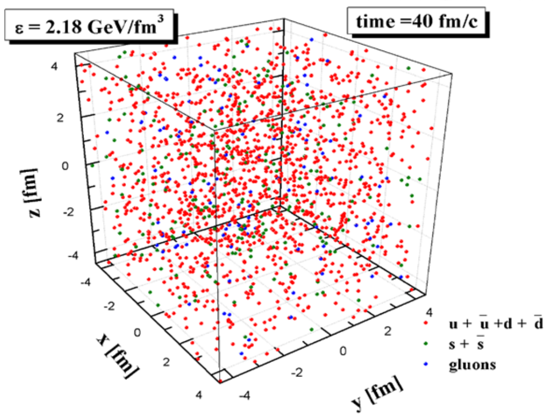
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \quad (i = q,\bar{q},g)$$

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

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

QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

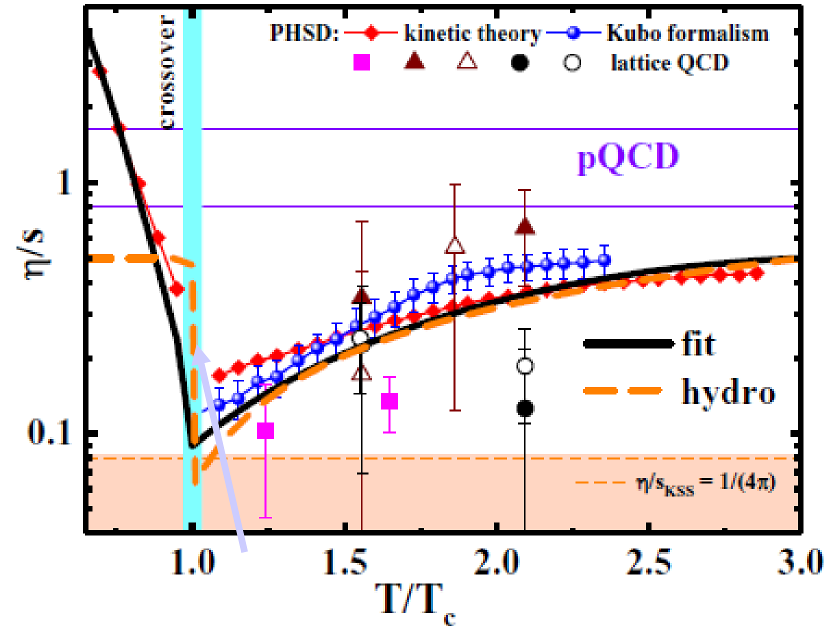
Infinite hot/dense matter = PHSD in a box:



Shear viscosity η/s at finite T

PHSD: V. Ozvenchuk et al., PRC 87 (2013) 064903

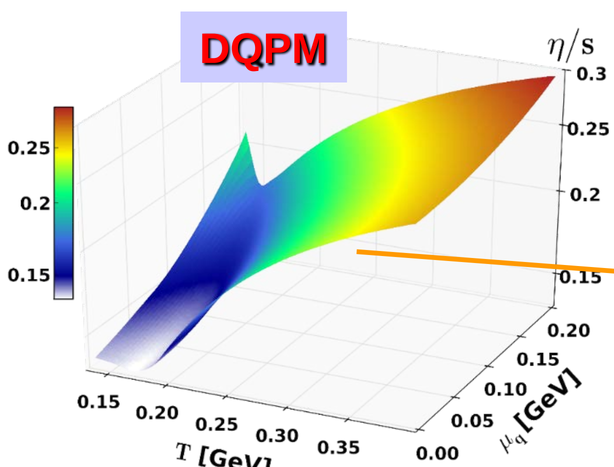
Hydro: Bayesian analysis, S. Bass et al. ,1704.07671



Shear viscosity η/s at finite (T, μ_q)

lQCD:

$$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1-\alpha/2\,\mu_q^2 + \cdots$$



QGP in PHSD = strongly-interacting liquid-like system

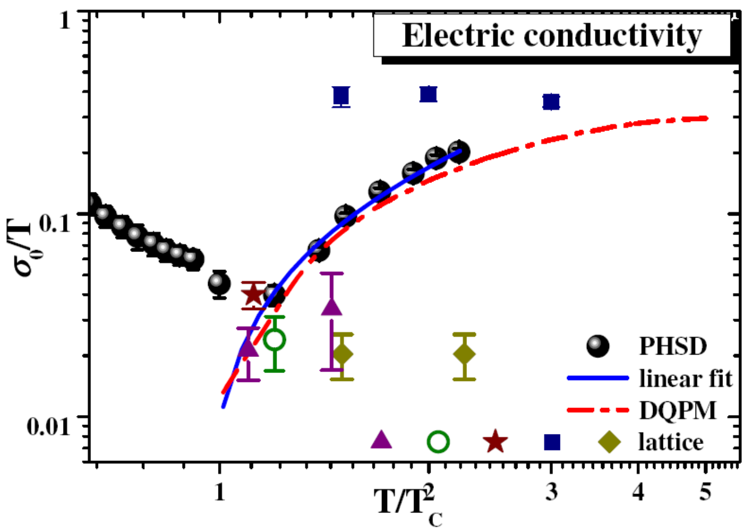
η/s: $\mu_q=0$ ➔ finite μ_q: smooth increase as a function of (T, μ_q)

Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

Transport properties at finite (T, μ_q): σ_e/T

PHSD in a box:
Electric conductivity σ_e/T at finite T

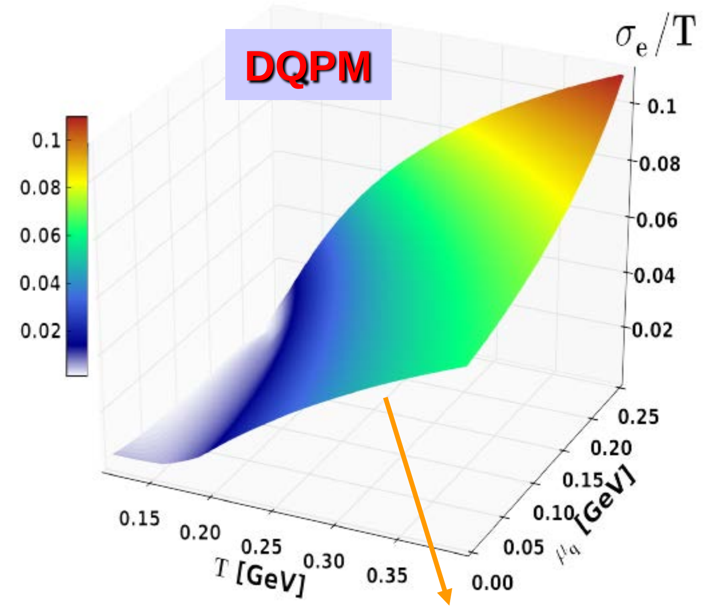
W. Cassing et al., PRL 110(2013)182301



- the QCD matter even at T~ T_c is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !

Electric conductivity σ_e/T at finite (T, μ_q)

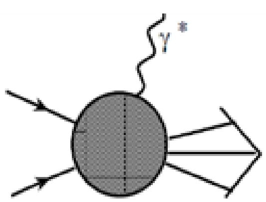
H. Berrehrah et al. , PRC93 (2016) 044914



σ_e/T : μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

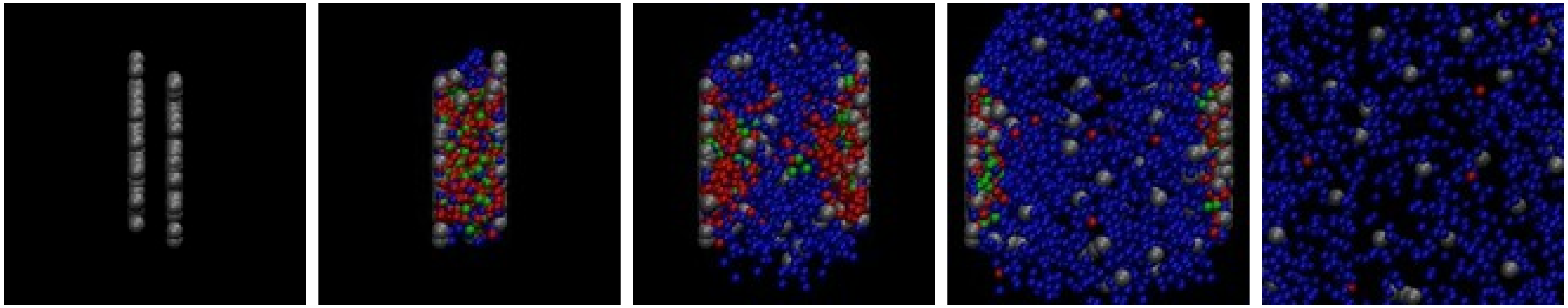
- **Photon emission:** rates at $q_0 \to 0$ are related to electric conductivity σ_0

$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0\to 0} = \frac{T}{4\pi^3}\sigma_0$$



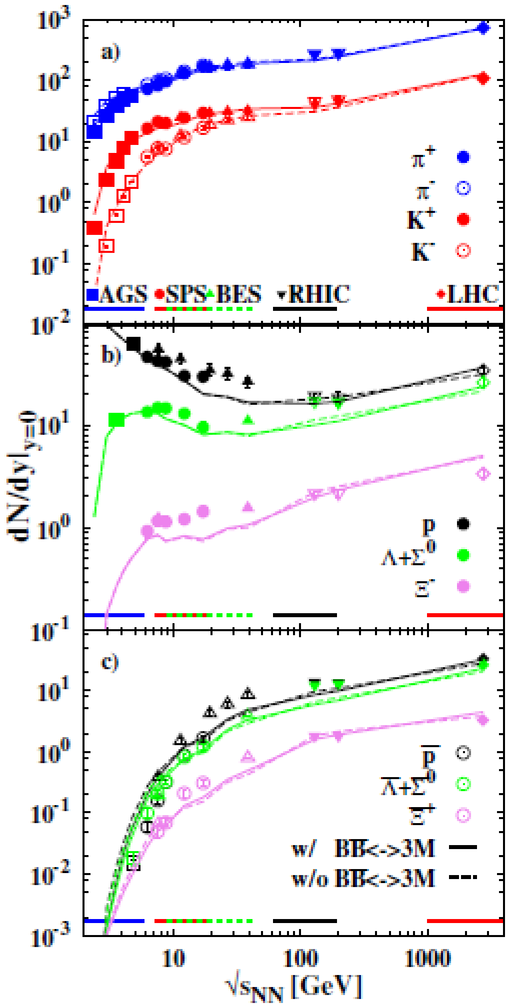
σ_0 ➔ Probe of electromagnetic properties of the QGP

‚Bulk' properties
in Au+Au collisions

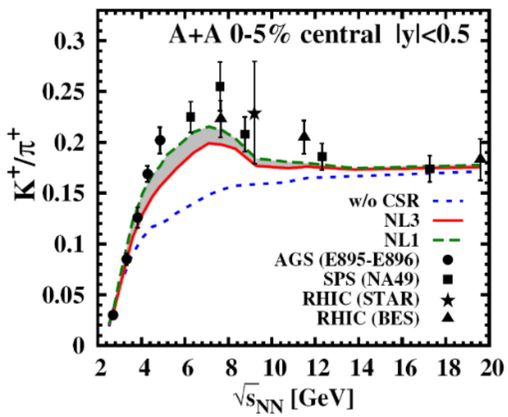


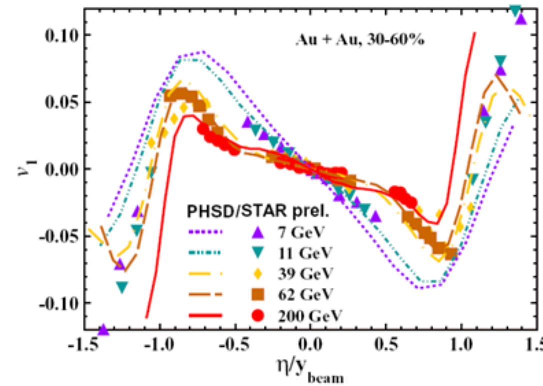
Non-equilibrium dynamics: description of A+A with PHSD

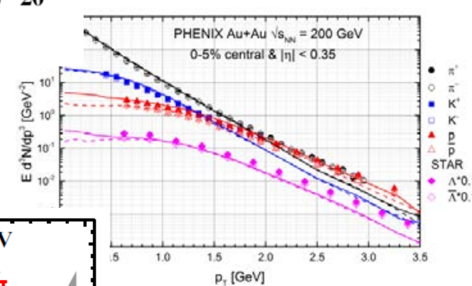
❑ PHSD: highlights

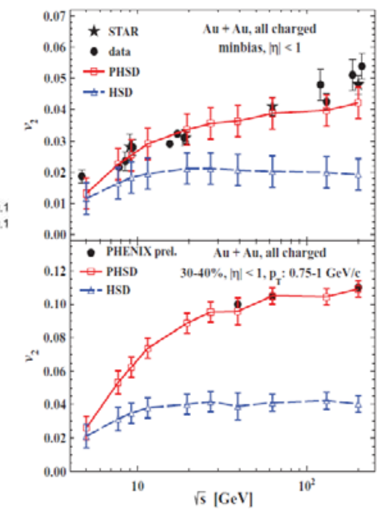


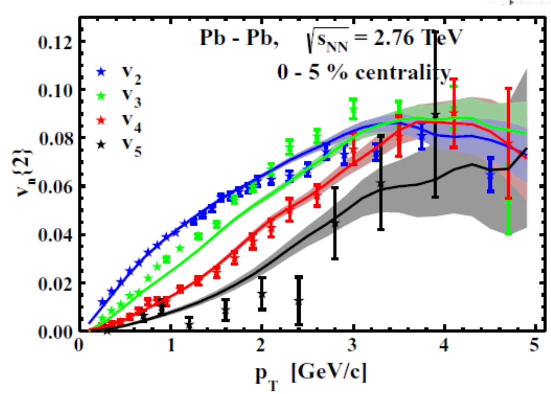
arXiv:1801.07557







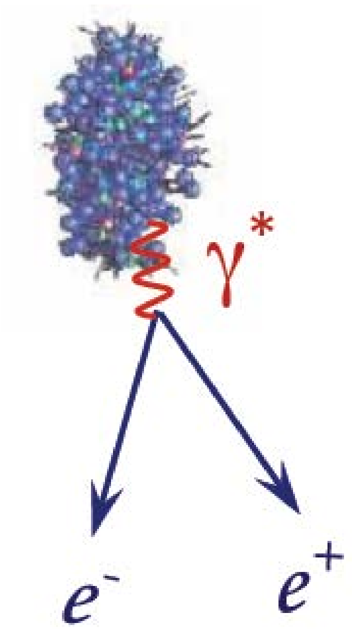




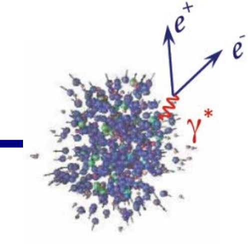
PRC 85 (2012) 011902; JPG42 (2015) 055106

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

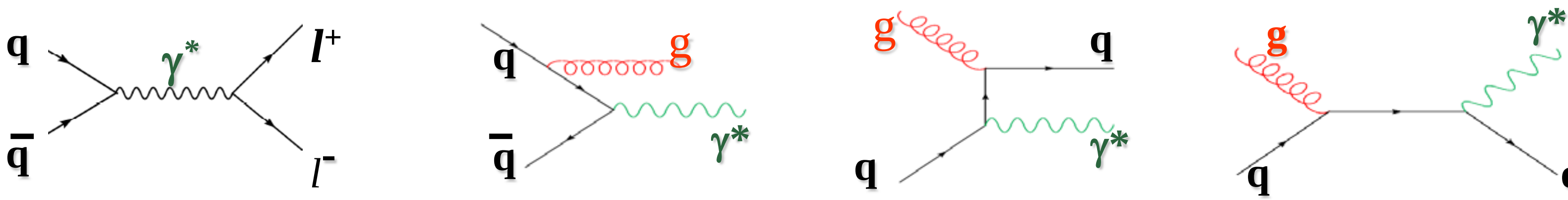
Dileptons as a probe of the QGP and in-medium effects



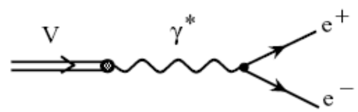
Dilepton sources

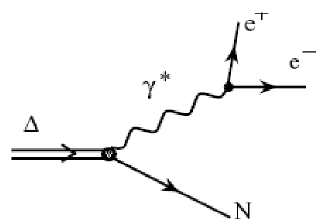


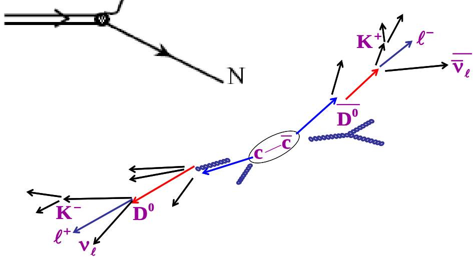
- **from the QGP via partonic (q,qbar, g) interactions:**



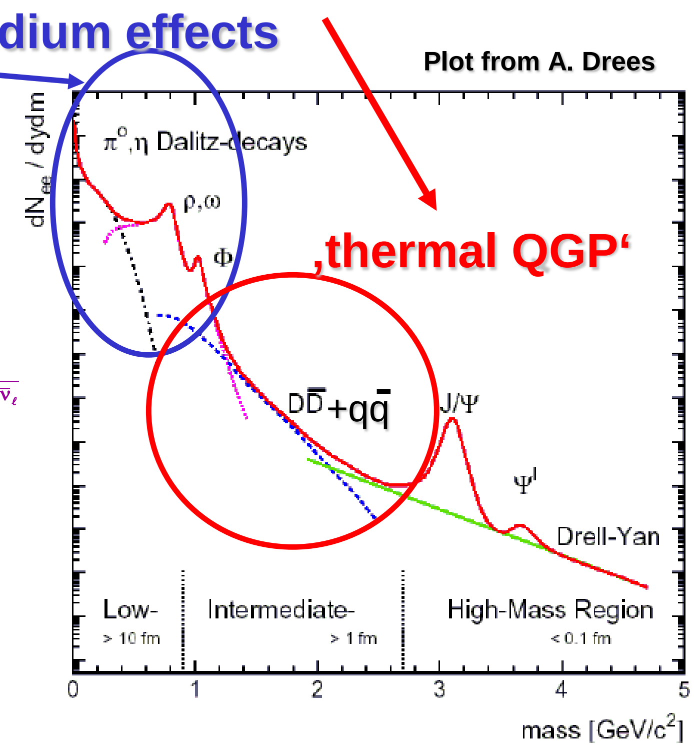
- **from hadronic sources:**







Plot from A. Drees

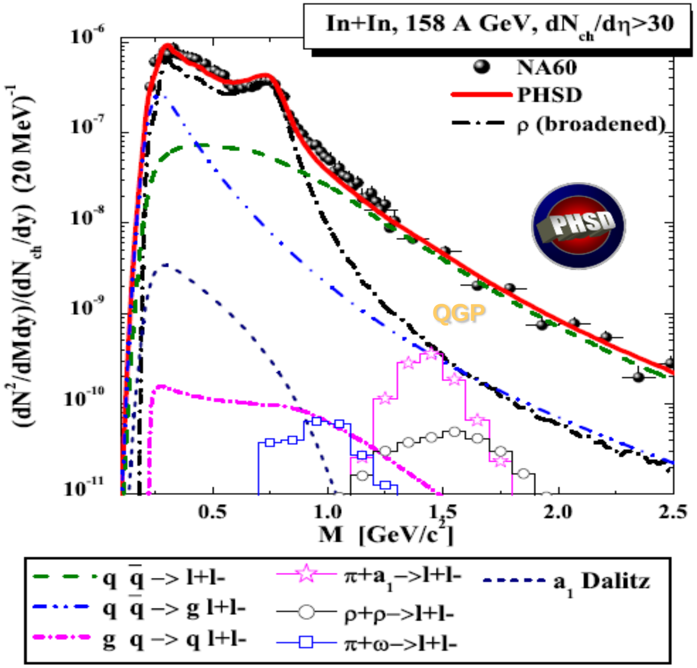


- **direct decay** of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ')
- **Dalitz decay** of mesons and baryons (π^0,η, Δ,…)
- **correlated D+Dbar pairs**
- **radiation from multi-meson reactions** (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - ‚4π'

! Advantage of dileptons:
additional „degree of freedom" (*M*) allows to disentangle various sources

Lessons from SPS: NA60

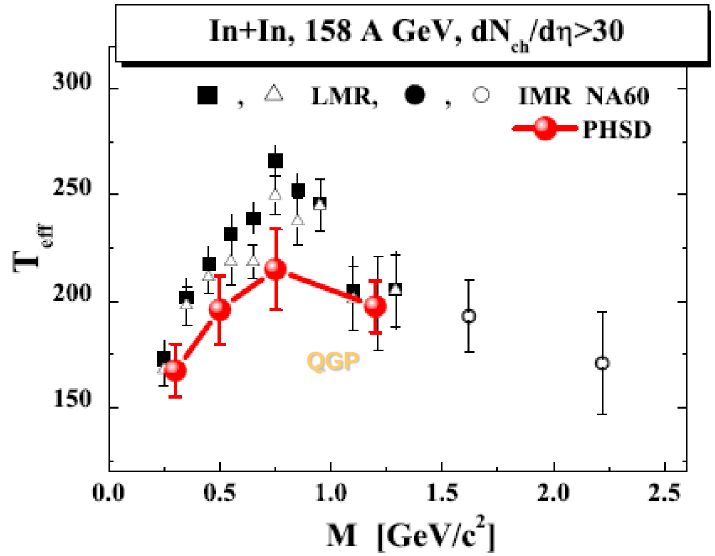
❑ Dilepton invariant mass spectra:



NA60: Eur. Phys. J. C 59 (2009) 607

❑ Inverse slope parameter T_{eff}:

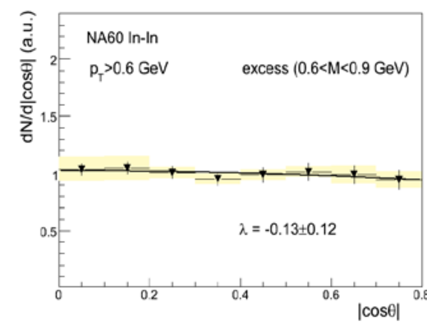
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed



PHSD:
Linnyk et al, PRC 84 (2011) 054917

Message from SPS: (based on NA60 and CERES data)

1) **Low mass spectra** - evidence for the **in-medium broadening of ρ-mesons**
2) **Intermediate mass spectra above 1 GeV** - dominated by **partonic radiation**
3) **The rise and fall of T_{eff}** – evidence for the thermal **QGP radiation**
4) **Isotropic angular distribution** – indication for a **thermal origin of dimuons**

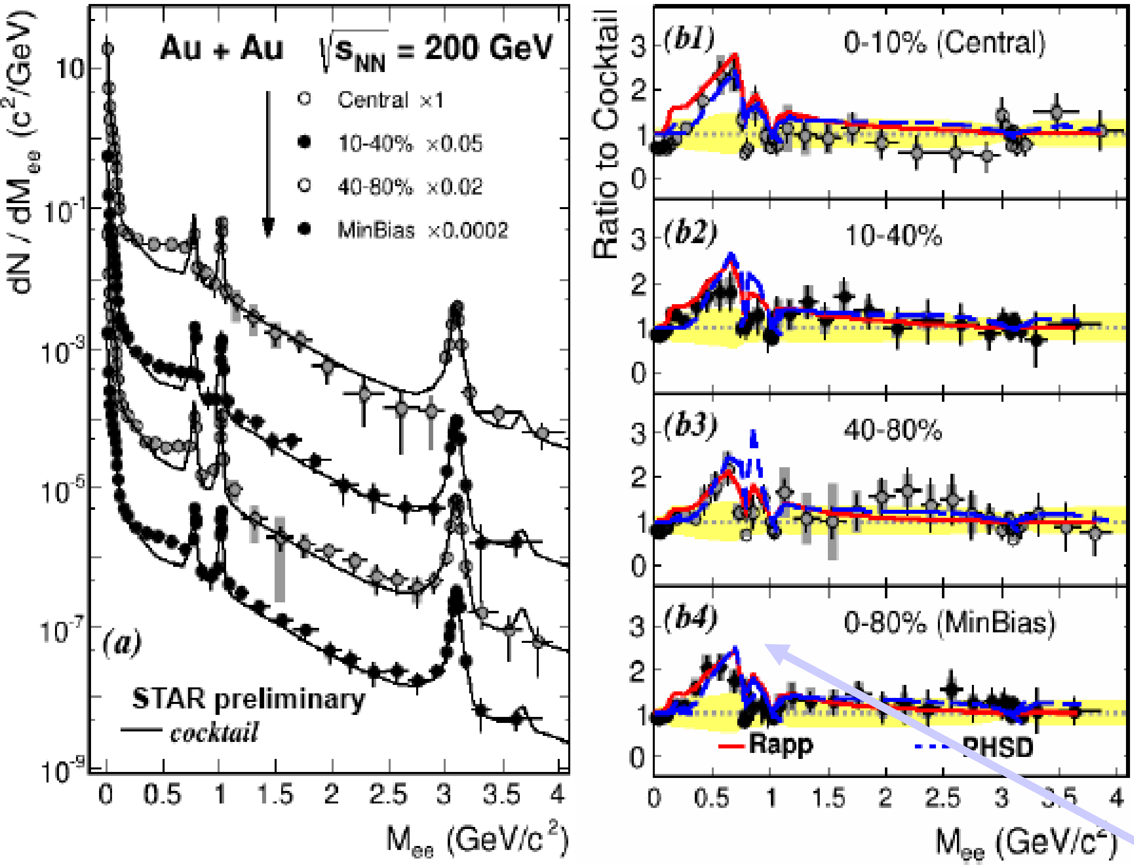


PRL 102 (2009) 222301

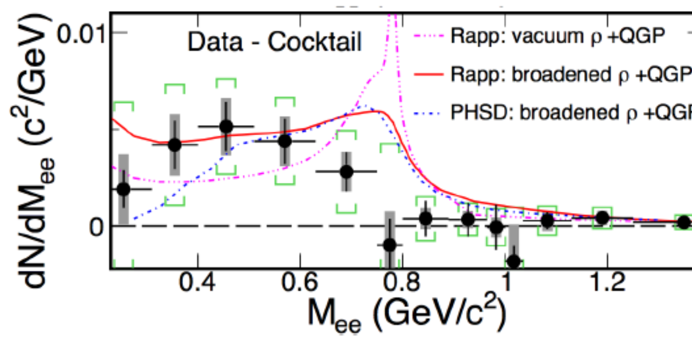
Dileptons at RHIC: STAR data vs model predictions

PRC 92 (2015) 024912

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models:

- **Fireball model – R. Rapp**
- **PHSD**

Low masses:

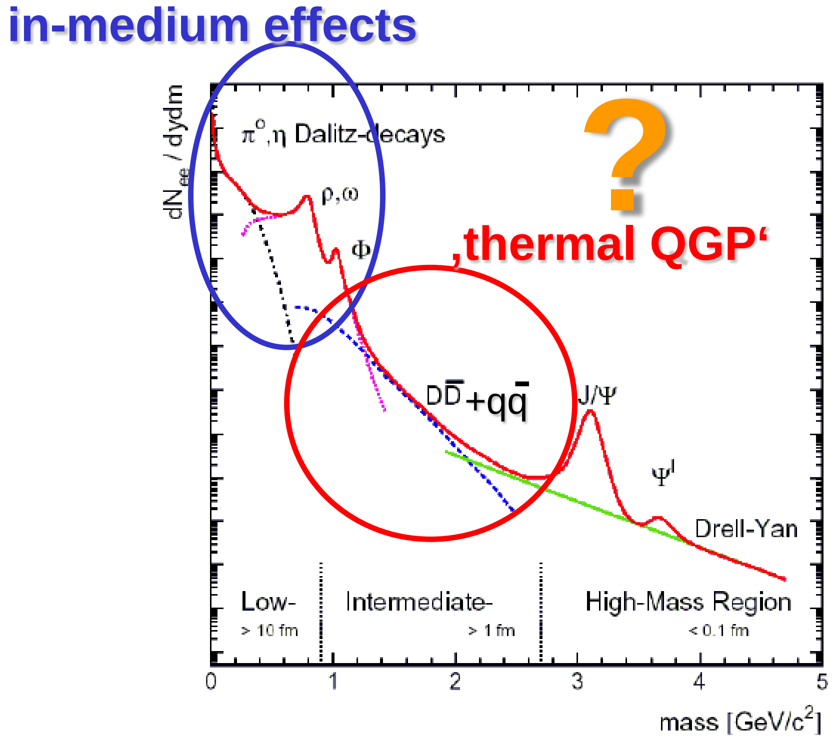
collisional broadening of ρ

Intermediate masses:

QGP dominant

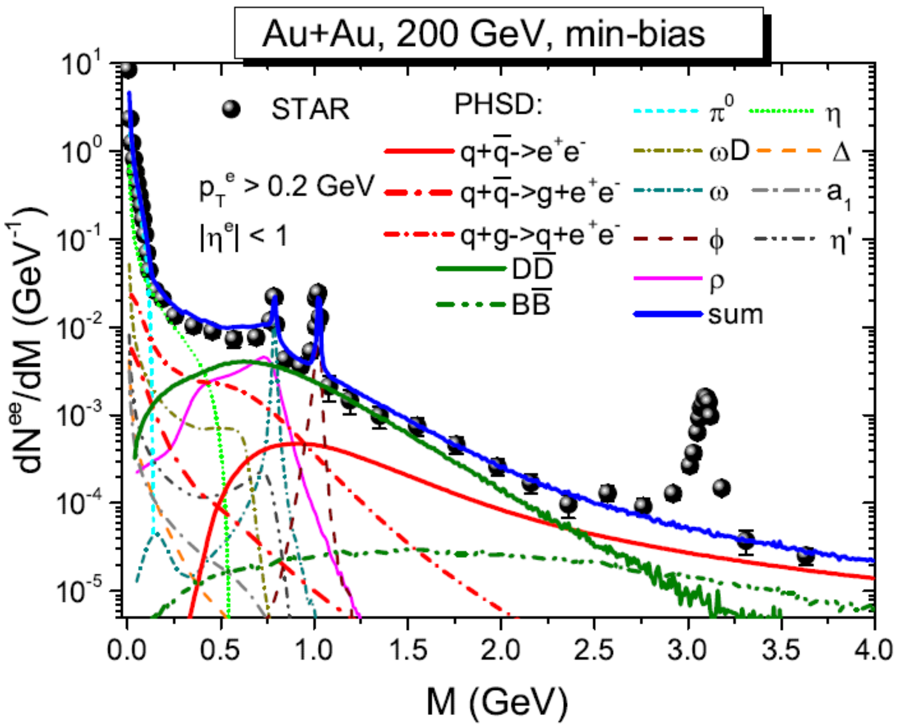
Message: **STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP**

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

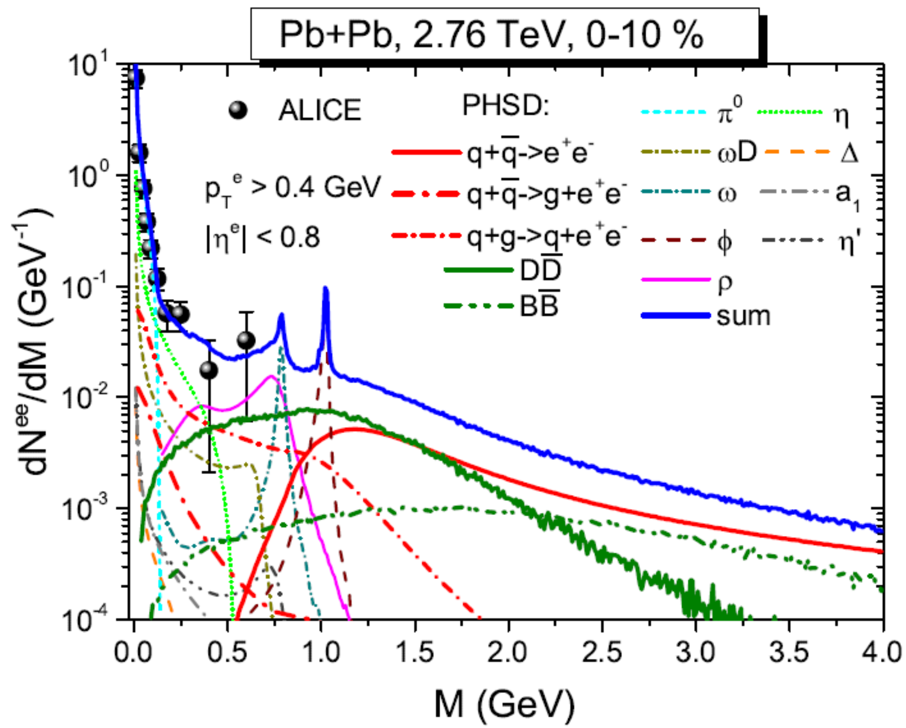


Dileptons at RHIC and LHC

RHIC



LHC



Message:

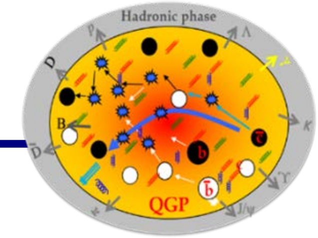
STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within

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, arXiv:1803.02698

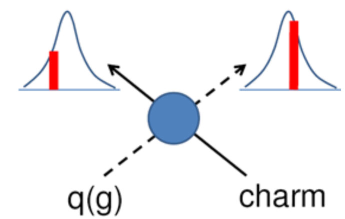
Charm dynamics in PHSD



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 :

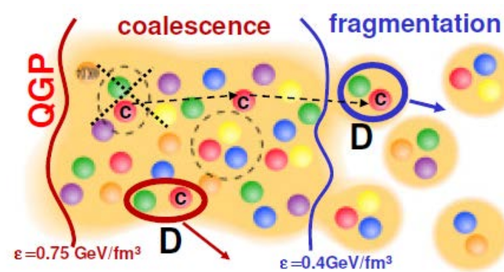
1. **Production** of heavy (charm and bottom) quarks
in initial binary collisions + shadowing and Cronin effects



2. **Interactions in the 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



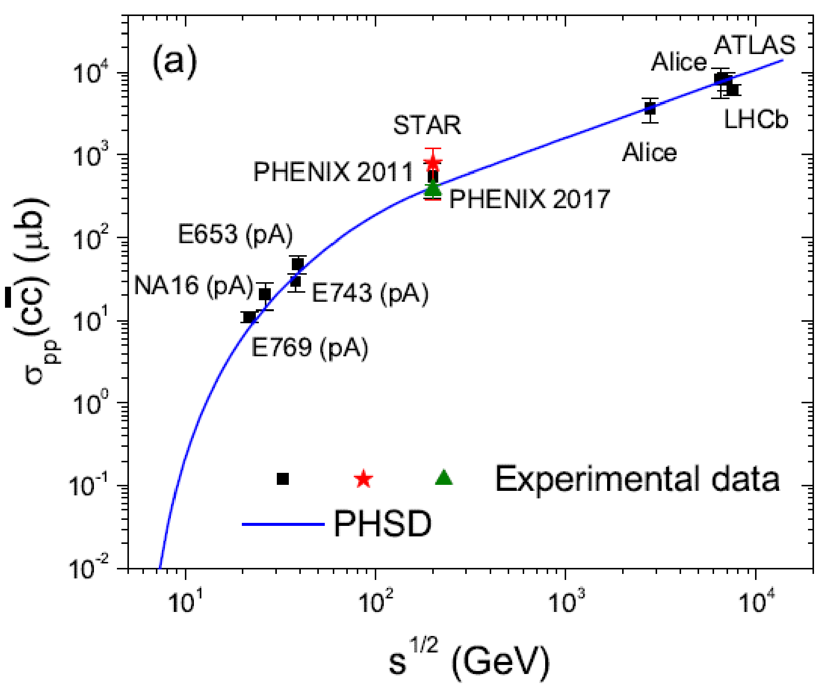
4. **Hadronic interactions**:
D+baryons; D+mesons with G-matrix and effective chiral Lagrangian approach with heavy-quark spin symmetry

T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905
T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

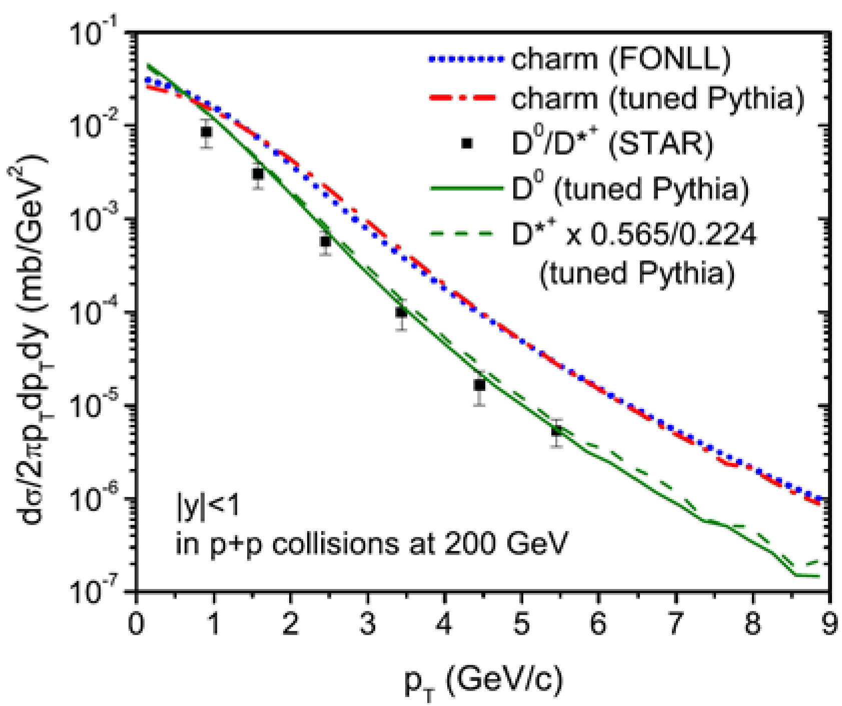
Charm production in NN collisions

- **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)



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

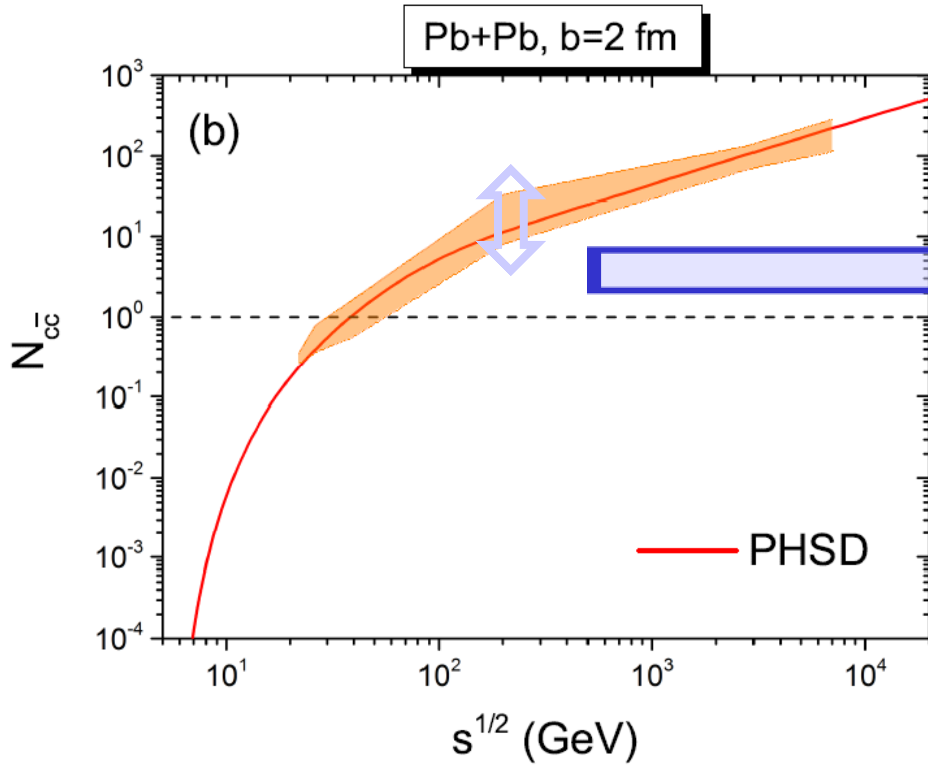


T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

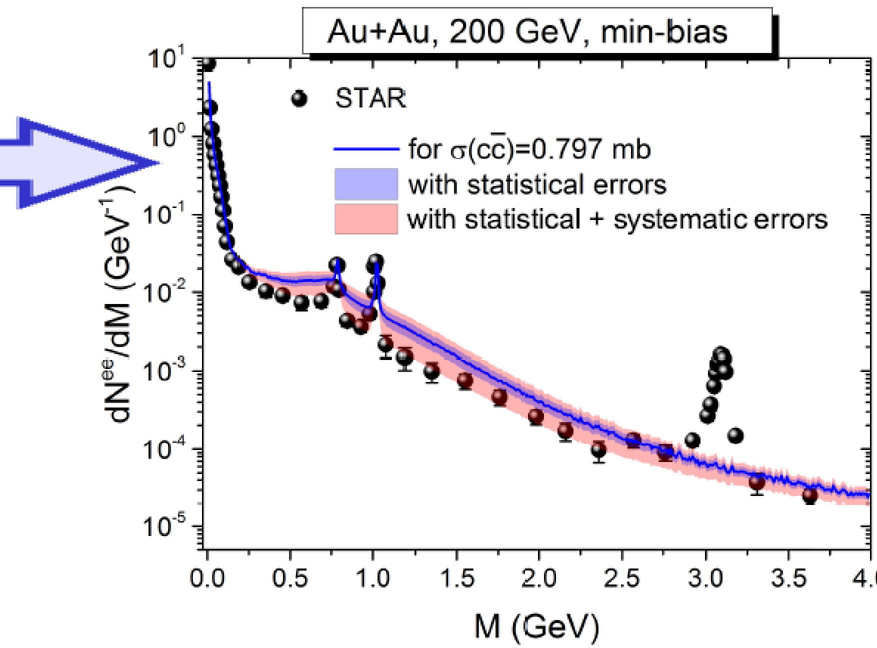
T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

Charm at RHIC and LHC

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



The invariant mass spectra of dielectrons for min-bias Au+Au at 200 GeV with the σ(cc) from the STAR with statistical and systematic errors



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

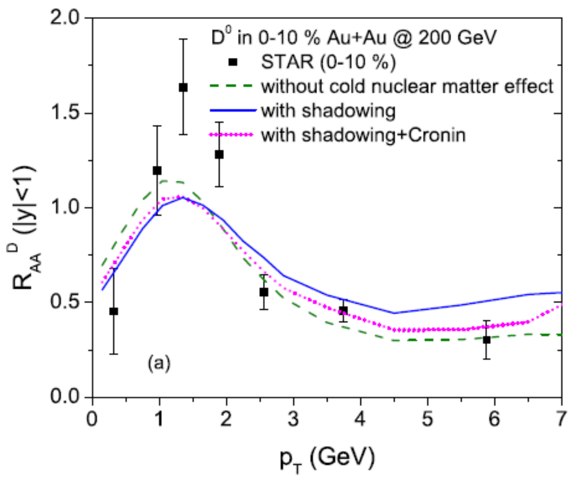
- **Uncertainty in σ(cc) from pp leads to the uncertainty in the charm production in AA and in the dilepton spectra!**

➔ **Reliable data for σ(cc) from pp are needed!**

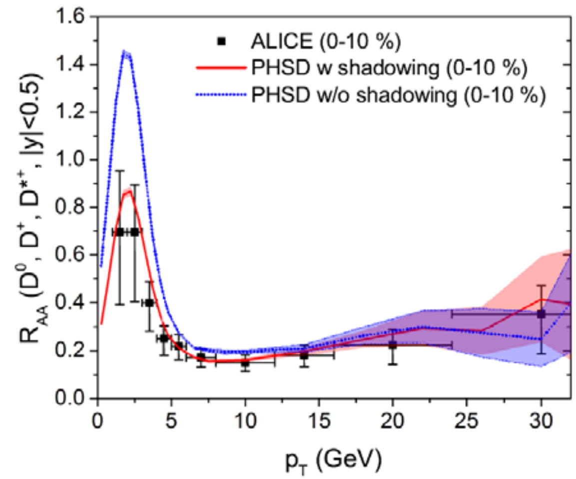
T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

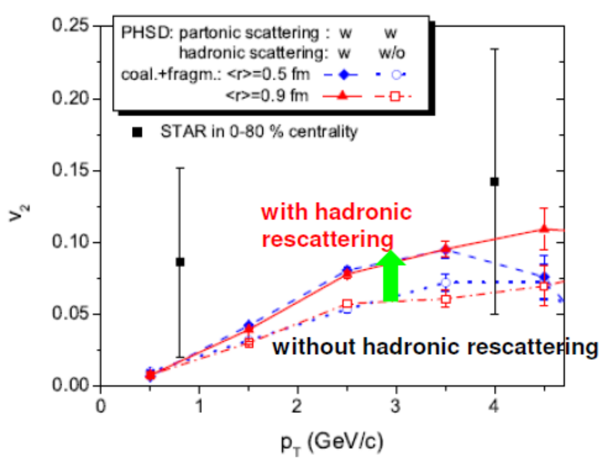
PHSD vs charm observables at RHIC and LHC

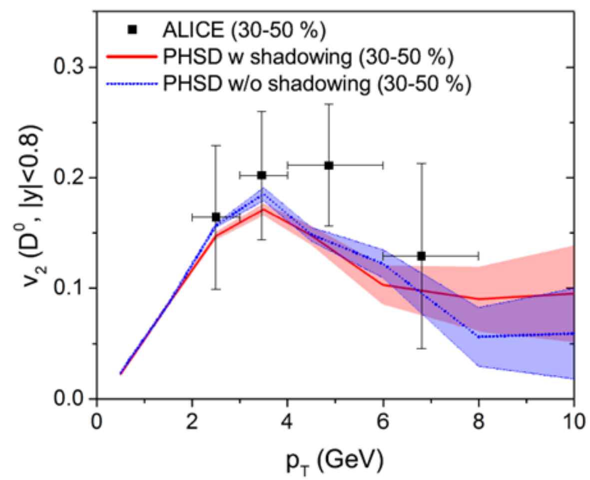
RHIC



LHC



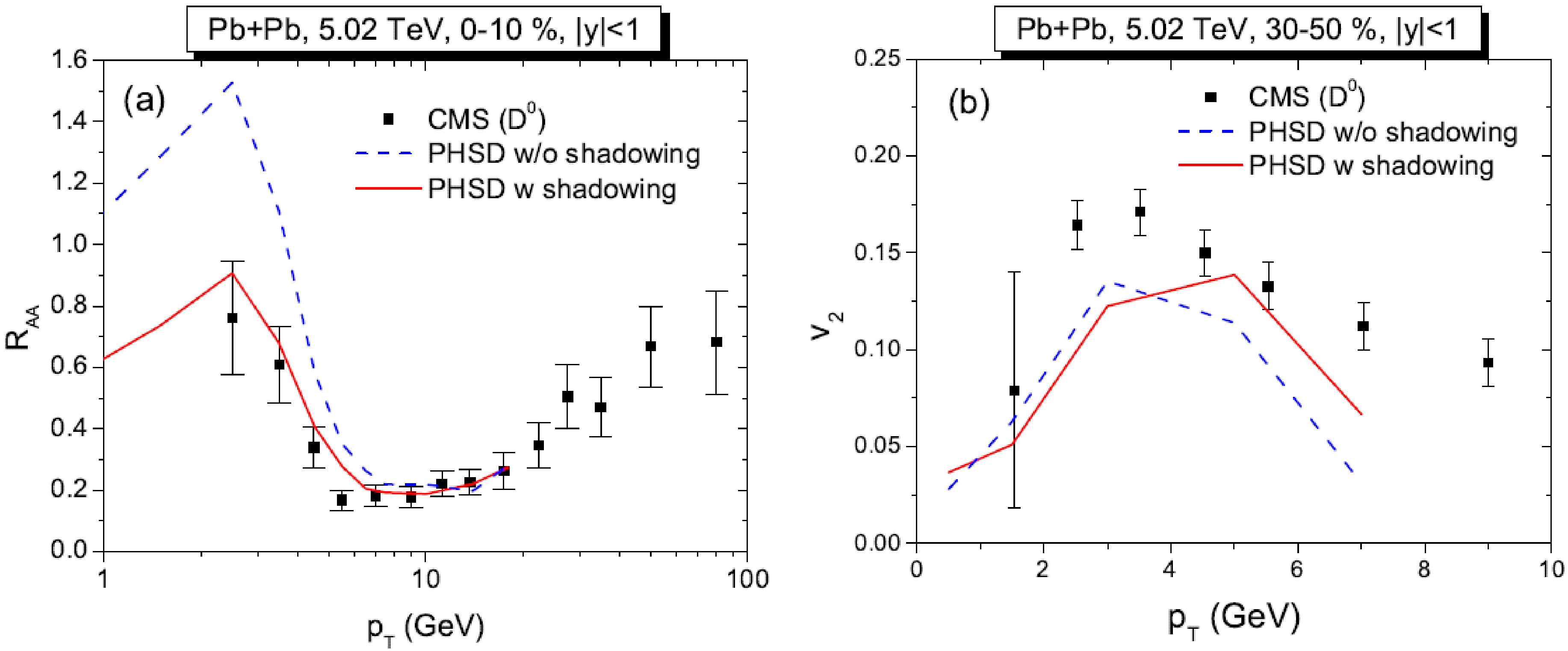




- The **exp. data** for the R_{AA} and v_2 at RHIC and LHC are described in the PHSD by **QGP collisional energy loss** due to **elastic scattering** of charm quarks with massive quarks and gluons in the QGP
+ by the **dynamical hadronization scenario** „coalescence & fragmentation“
+ by **strong hadronic 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

Charm at LHC: central Pb+Pb at 5.02 TeV



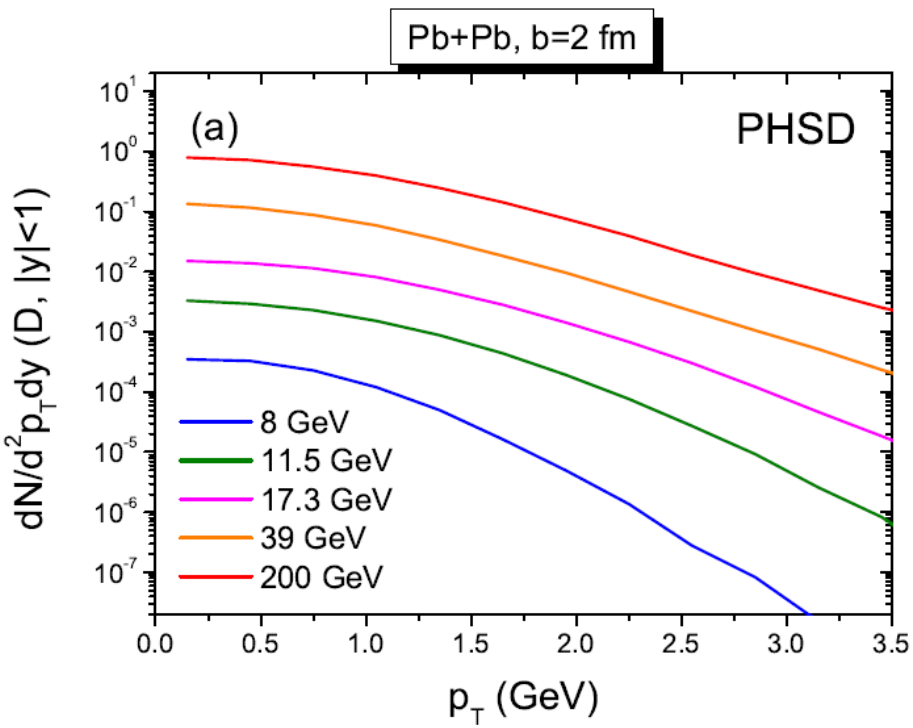
➔ **PHSD shows a good agreement with CMC data**

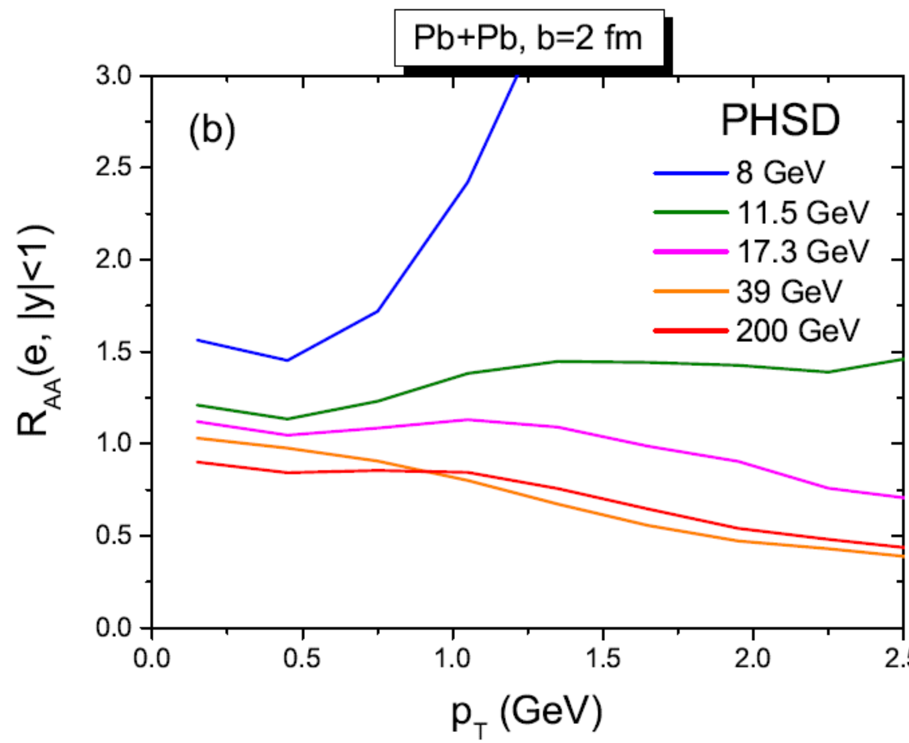
Nuclear modification of dielectrons from heavy flavor

The transverse momentum spectra of D-mesons at $s^{1/2}$ from 8 to 200 GeV at mid-rapidity

$R_{AA}(p_T)$ of single electrons from semi-leptonic decay of D-mesons

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N^{AA}_{binary} \times dN_{pp}/dp_T}$$



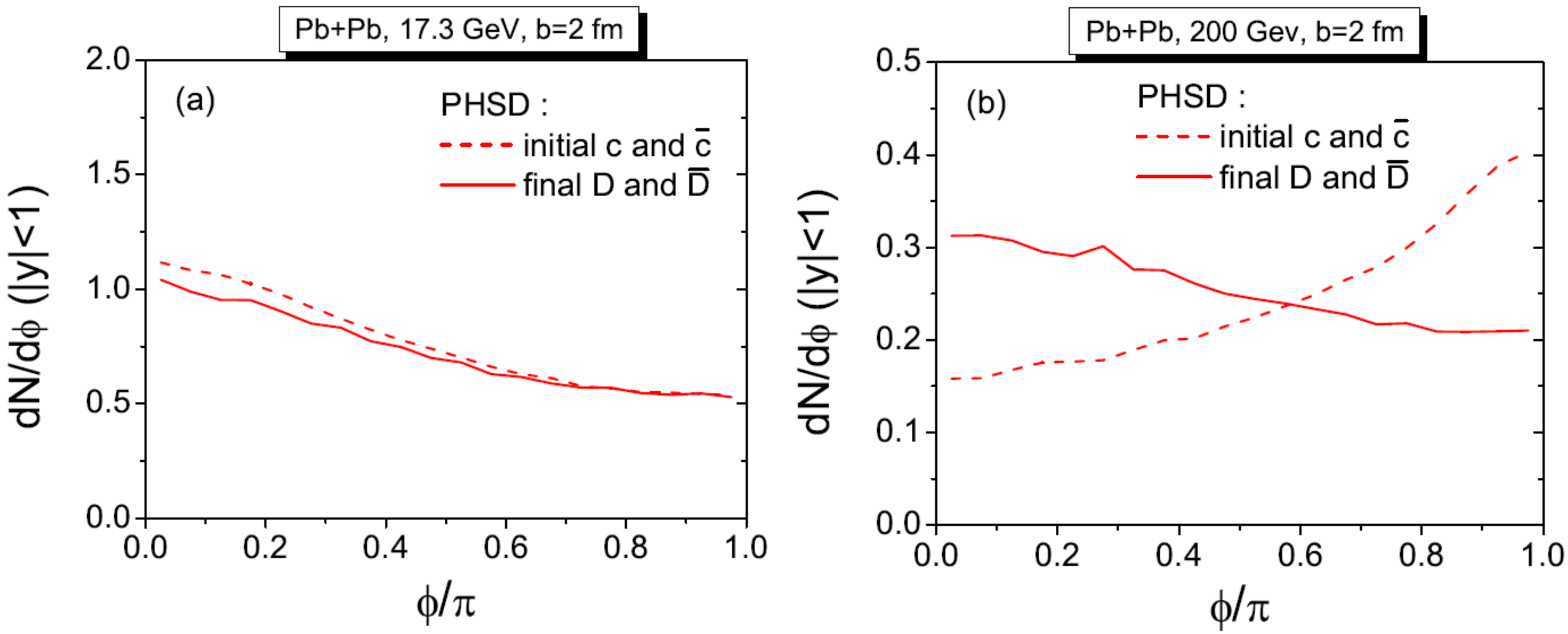


- **Hardening of the p_T spectra of D-mesons with increasing incoming energy**
- **$R_{AA}(p_T)$ of single electrons – from suppression at high energy to enhancement at low energy**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

Angular correlation between D-Dbar

Azimuthal angular distribution between the transverse momentum of D-Dbar at midrapidity (|y| < 1) before (dashed lines) and after the interactions with the medium (solid lines) in central Pb+Pb collisions at $s^{1/2}$ = 17.3 and 200 GeV

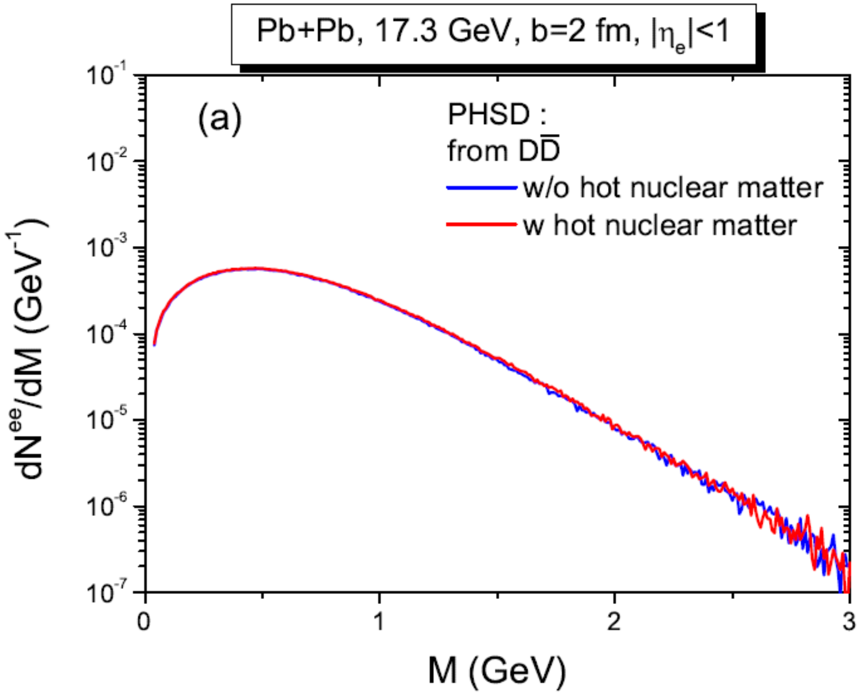


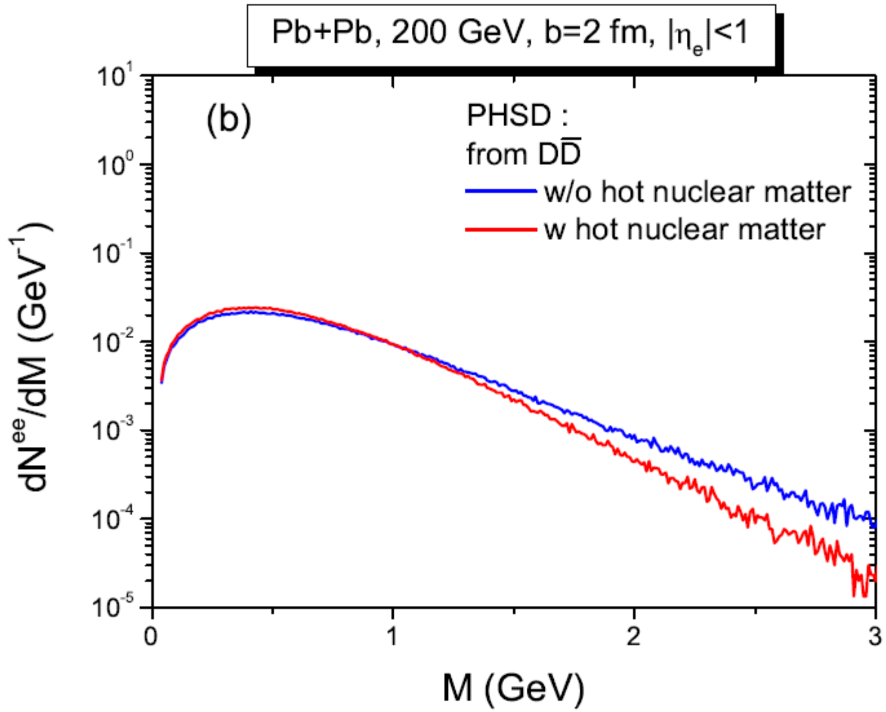
- **Initial correlations - from PYTHIA : peaks around $\phi = 0$ for $\sqrt{s}$ = 17.3 GeV, while around $\phi = \pi$ for $\sqrt{s}$= 200 GeV**
- **Final correlations: smeared at $\sqrt{s}$= 200 GeV due to the interaction of charm quarks in QGP**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

Modification of dielectron spectra due to the in-medium interaction of D-Dbar

The invariant mass spectra of dielectrons from charm pairs with (red lines) and without the interactions with the hot medium (blue lines) in central Pb+Pb collisions at $s^{1/2}$ = 17.3 and 200 GeV



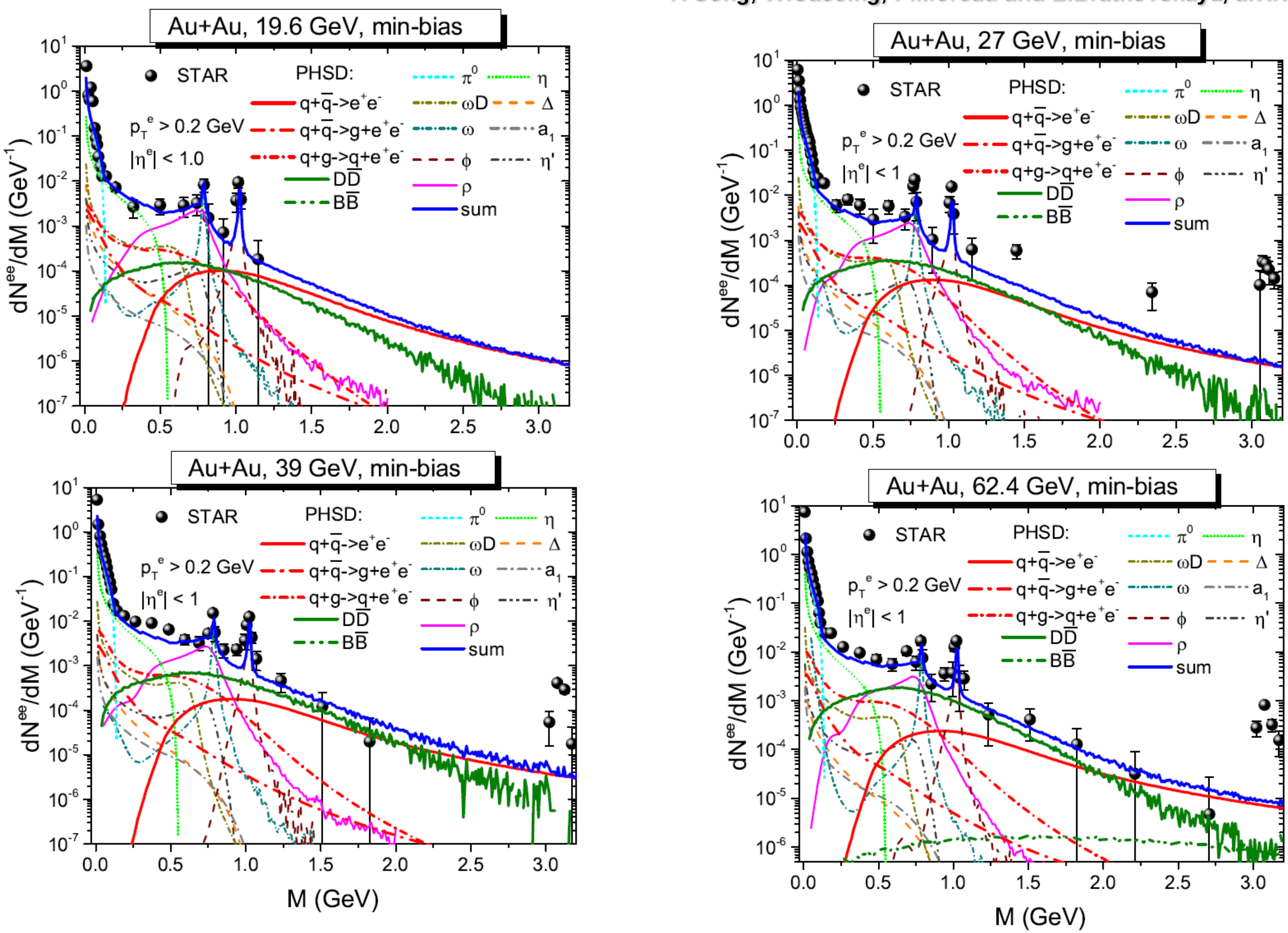


- **Softening of dN/dM at √s= 200 GeV due to the interaction of charm quarks in QGP**
- **Note: the invariant mass of the dielectrons depends on the momenta of e^+, e^- and also on the angle between them ➔$R_{AA}(p_T)$ shows that the momenta of e^+, e^- are suppressed and dN/dϕ shows that the azimuthal angle between them decreases at √s = 200 GeV**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

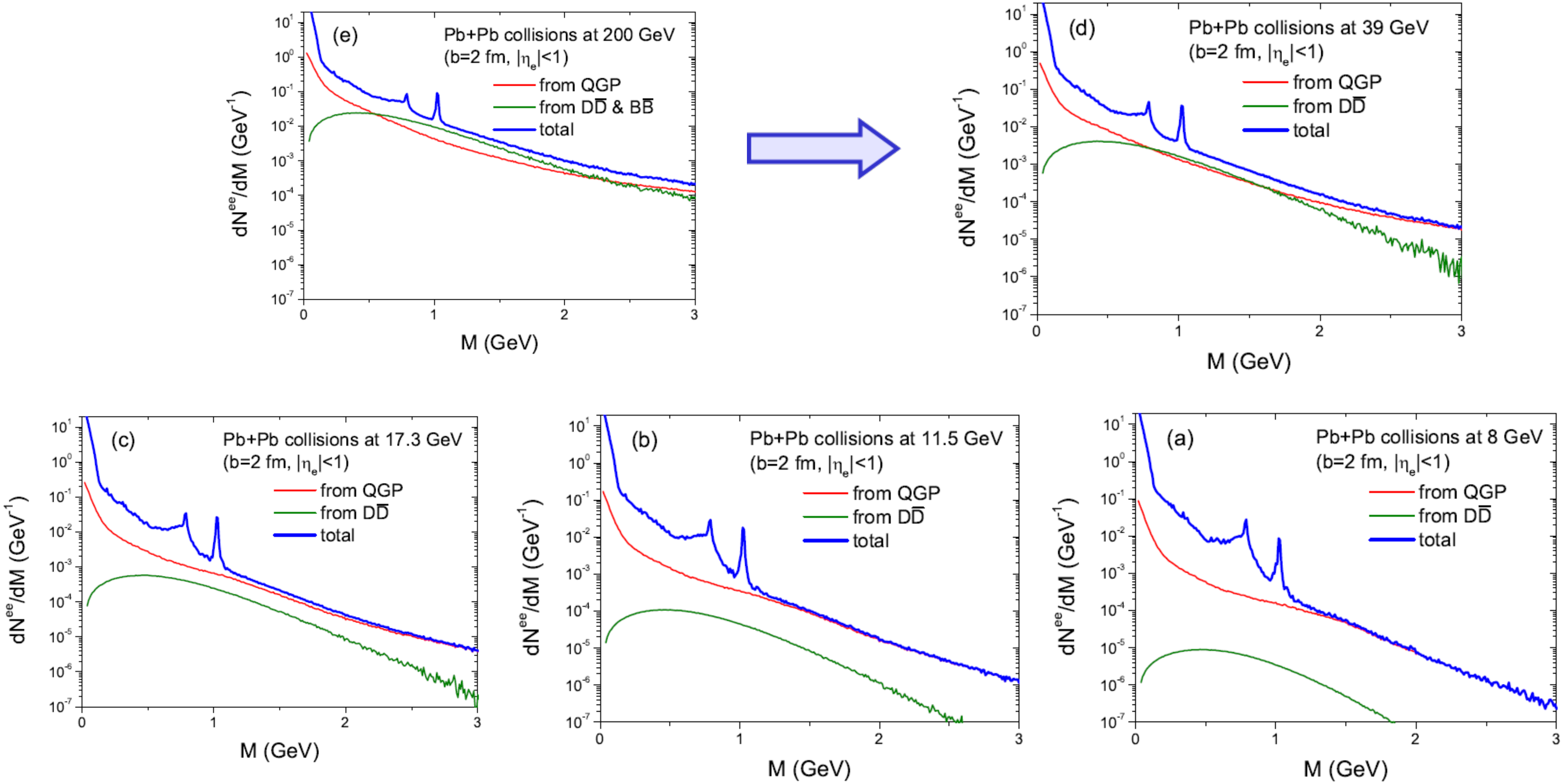
Dileptons from RHIC BES: STAR

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698



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



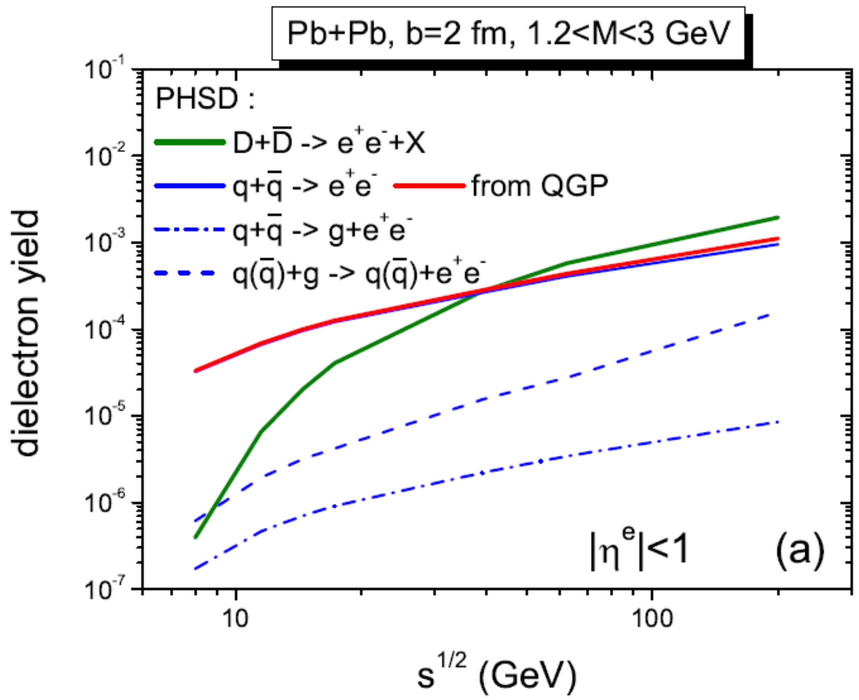
Relative contribution of QGP versus charm increases with decreasing energy!

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

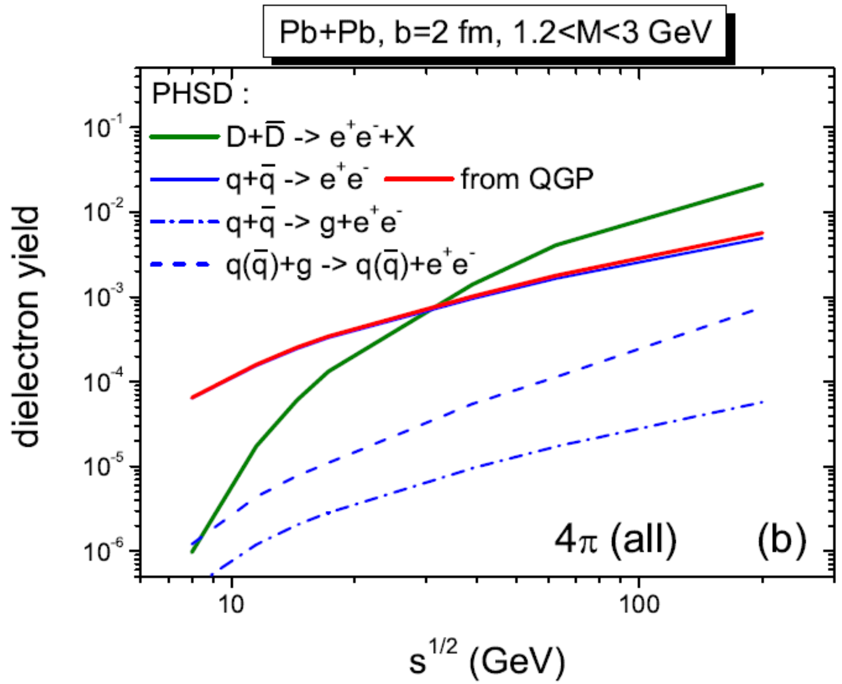
Dileptons: QGP vs charm

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

mid-rapidity



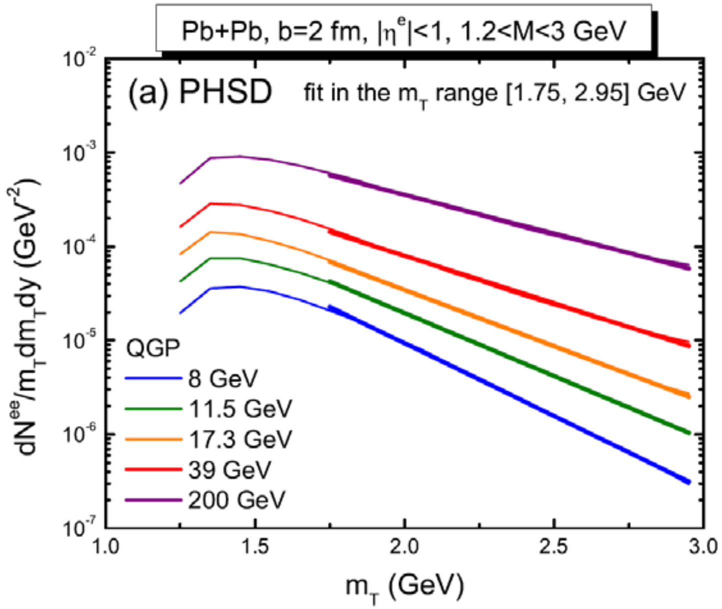
all rapidities (4π)

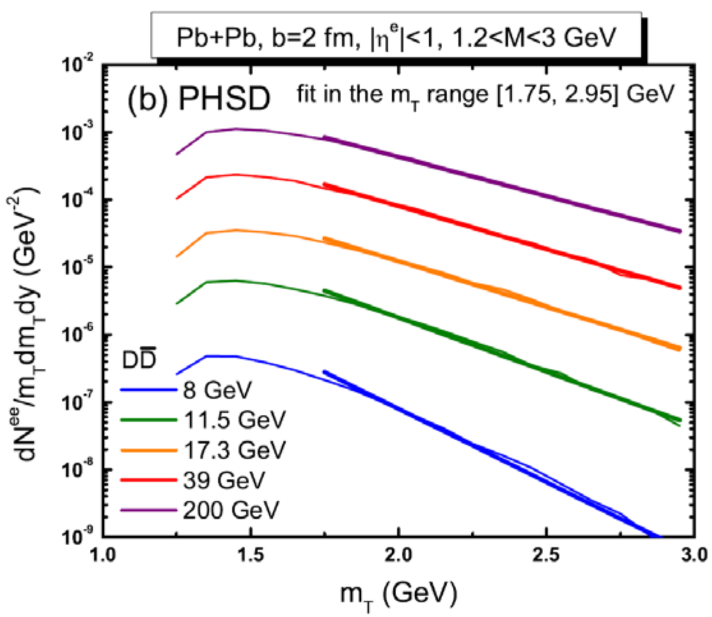


QGP contribution overshines charm with decreasing energy!
➔ Good perspectives for FAIR/NICA and BES RHIC!

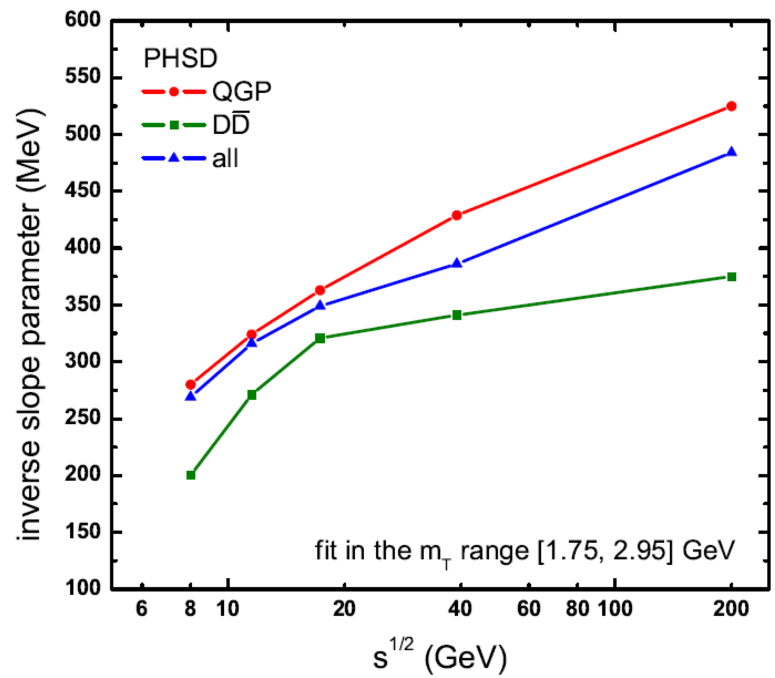
T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

Dilepton transverse mass spectra





The inverse slope parameter in the mass range [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, arXiv:1803.02698

Messages from the dilepton study

❑ Low dilepton masses:

- Dilepton spectra show **sizeable changes due to the in-medium effects – modification of the properties of vector mesons** (as collisional broadening) – which are observed experimentally

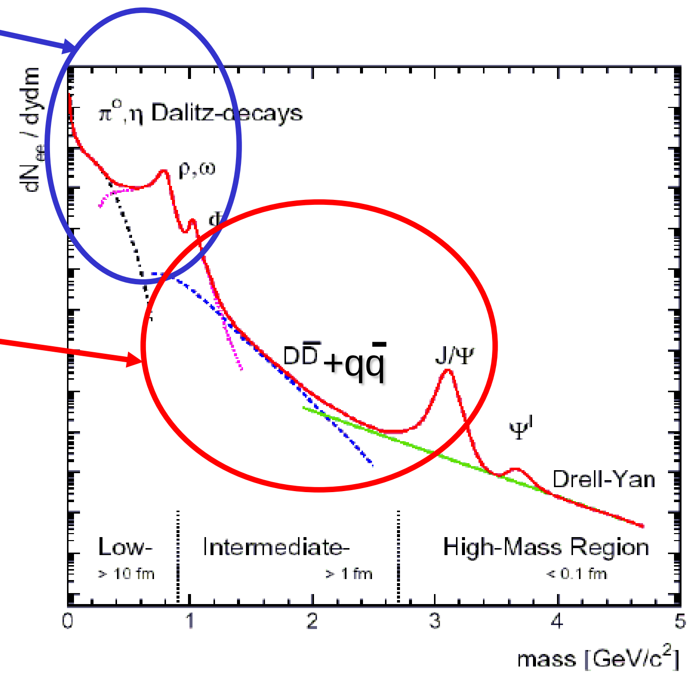
- **In-medium effects** can be observed at **all energies from SIS to LHC; excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon-density phase

❑ Intermediate dilepton masses M>1.2 GeV :

- Dominant sources : **QGP** (qbar-q) , correlated charm D/Dbar

- Fraction of QGP **grows** with increasing energy; however, the relative contribution of QGP to dileptons from charm pairs increases with decreasing energy

→ Good perspectives for **FAIR/NICA**



Review: O. Linnyk et al., Prog. Part. Nucl. Phys. 89 (2016) 50

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, arXiv:1803.02698

Thank you for your attention !

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