A fresh look at the radiation from the QGP

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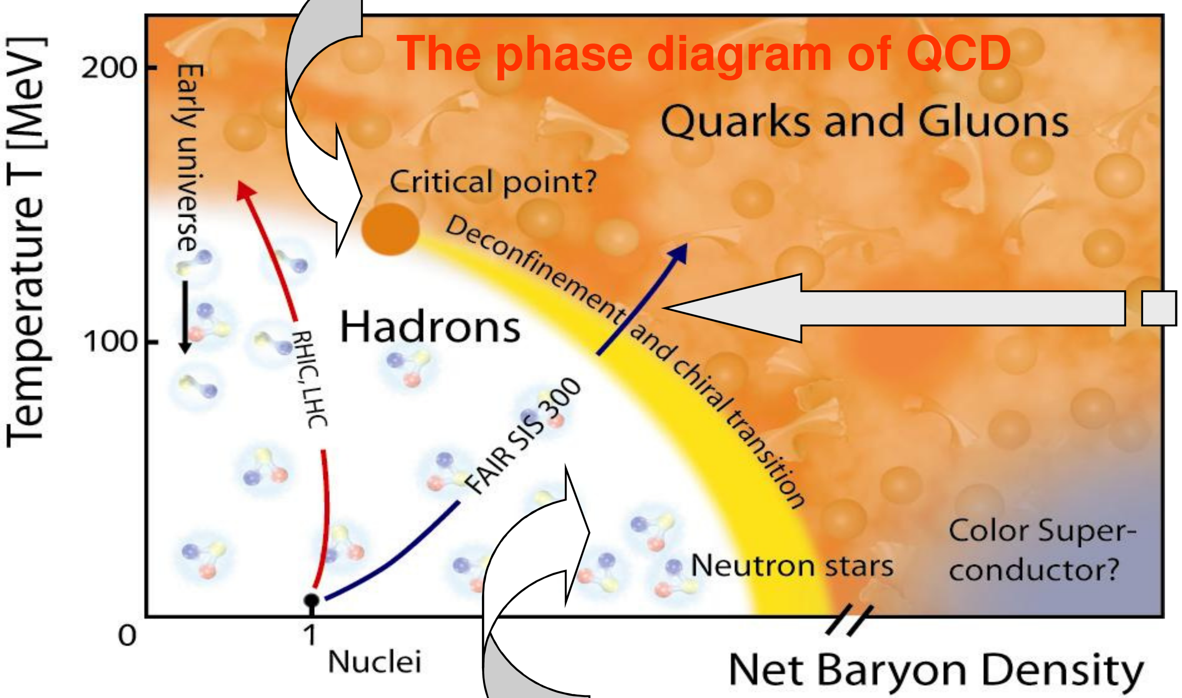
The Erice School on Nuclear Physics 2018

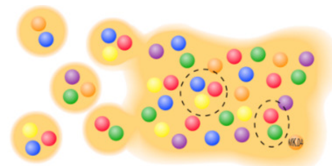
The Strong Interaction: From Quarks and Gluons to Nuclei and Stars

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

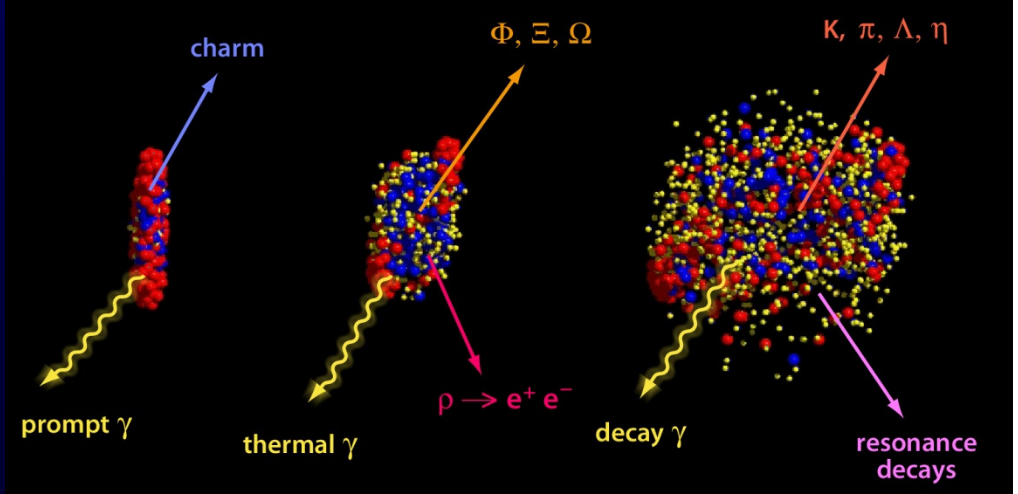
✓ provide undistorted information about their production channels

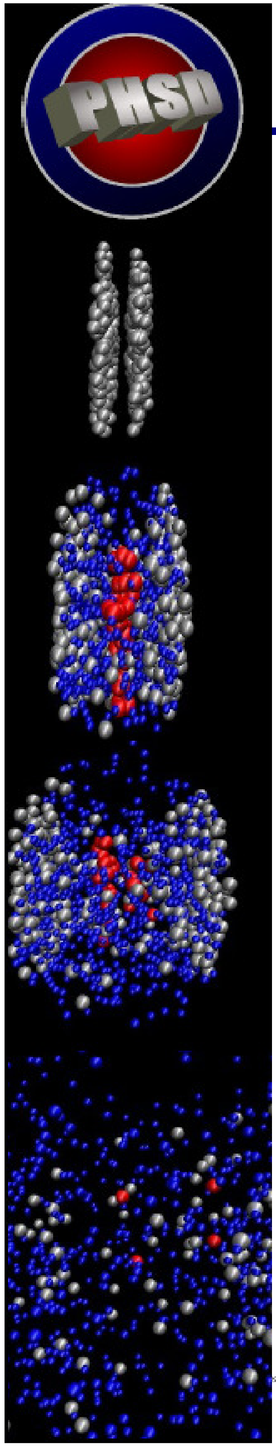
✓ promising signal of QGP – ‚thermal' photons and dileptons

➔ 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

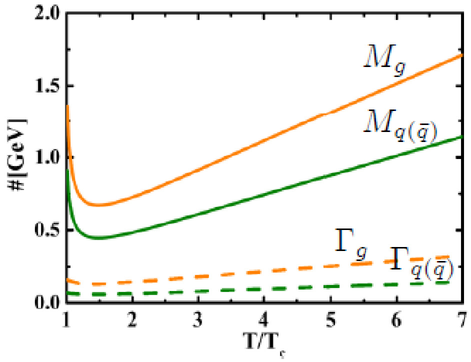
- **explicit phase transition from hadronic to partonic degrees of freedom**
- **lQCD EoS for the partonic phase (‚crossover‘ at low μ_q)**
- **explicit parton-parton interactions - between quarks and gluons**
- **dynamical hadronization**

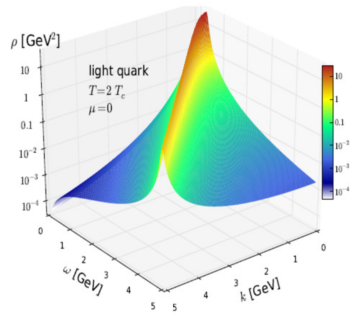
❑ **QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD**

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:**

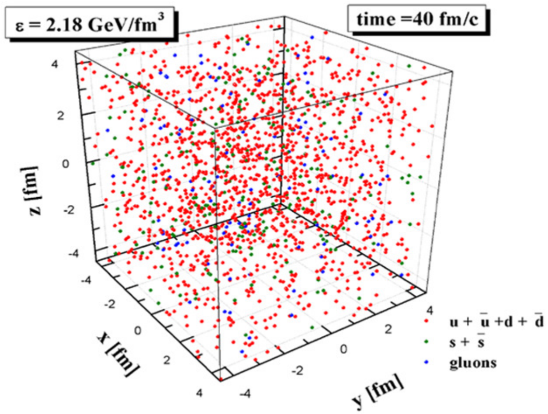
$$\rho_i(\omega,T)=\frac{4\omega\Gamma_i(T)}{\left(\omega^2-\vec{p}^2-M_i^2(T)\right)^2+4\omega^2\Gamma_i^2(T)} \quad (i=q,\bar{q},g)$$

❑ **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

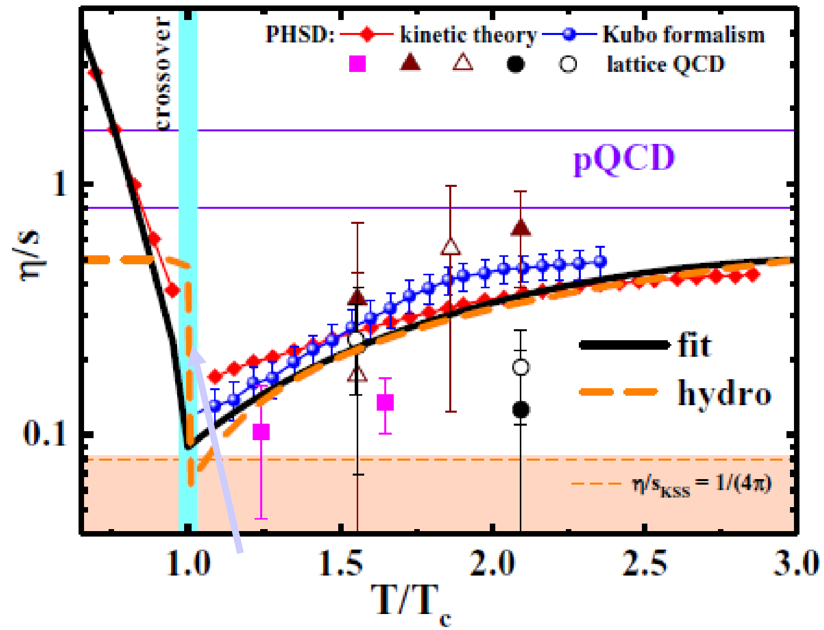
Infinite hot/dense matter = PHSD in a box:



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

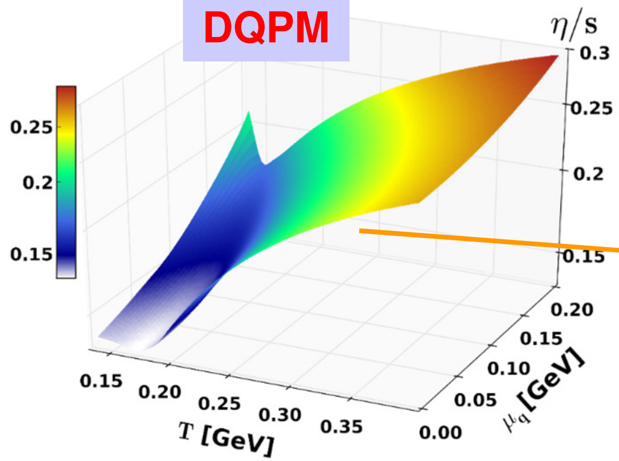


QGP in PHSD = strongly-interacting liquid-like system

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

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

DQPM



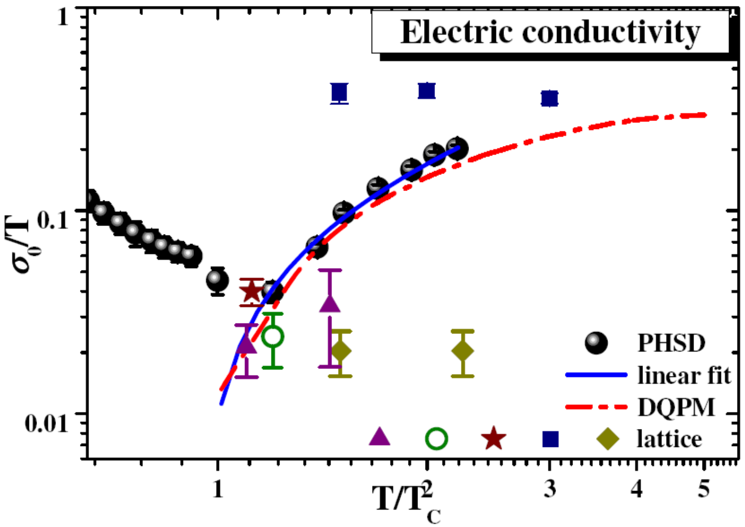
η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

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

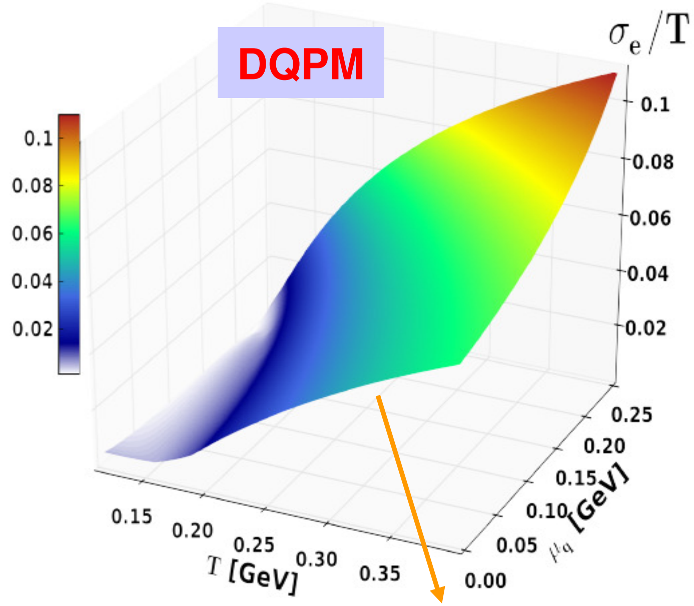
W. Cassing et al., PRL 110(2013)182301



- 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)

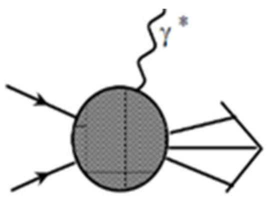
H. Berrehrah et al. , PRC93 (2016) 044914



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

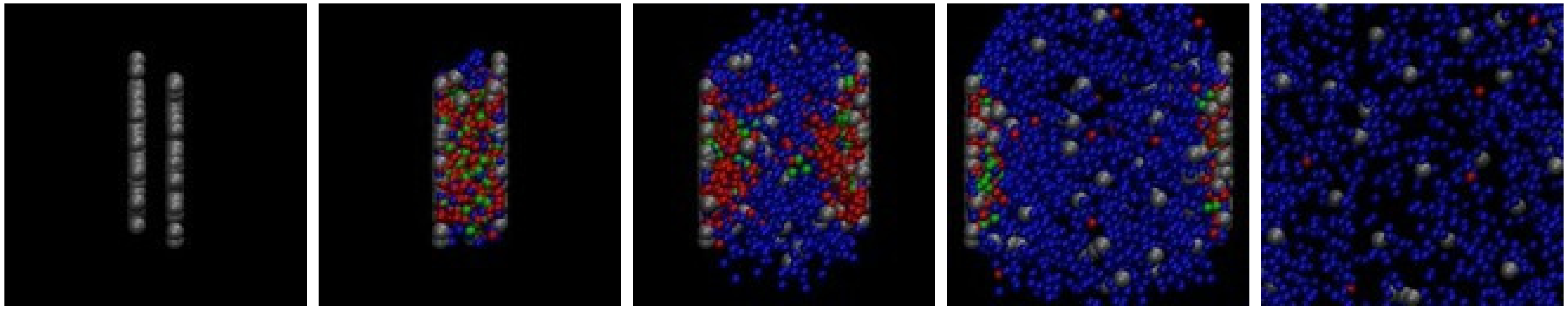
❑ Photon emission: rates at $q_0 \to 0$ are related to electric conductivity σ_0

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



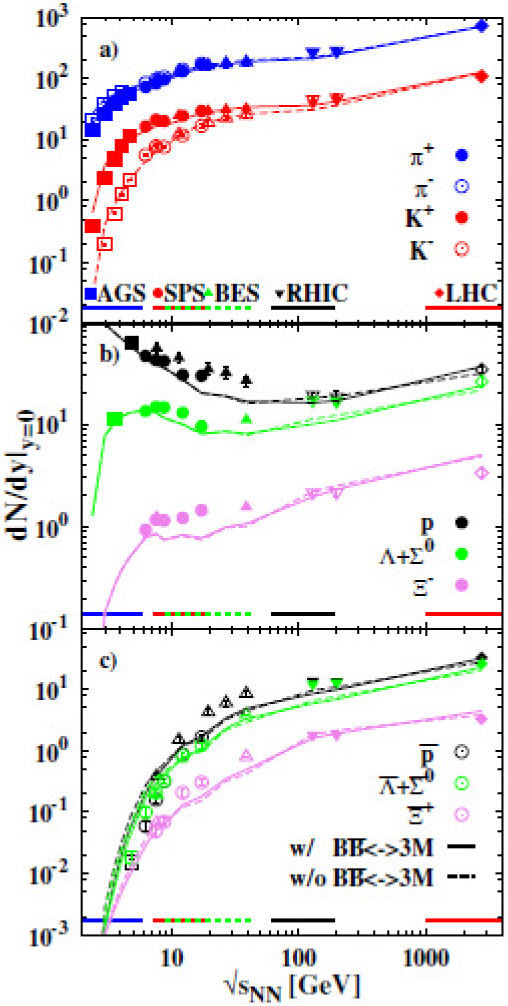
$\boxed{\sigma_0 \text{ ➔ Probe of electromagnetic properties of the QGP}}$

‚Bulk‘ properties
in Au+Au collisions

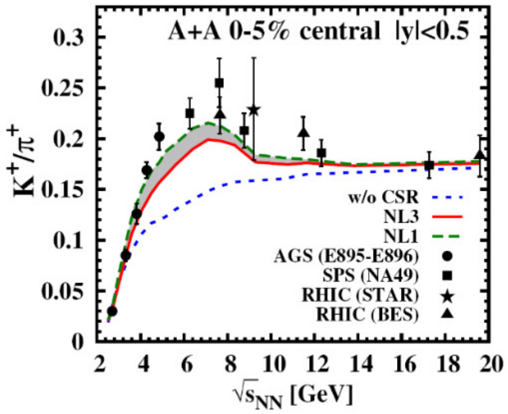


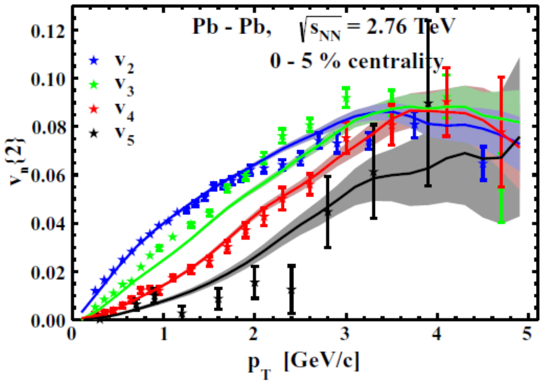
Non-equilibrium dynamics: description of A+A with PHSD

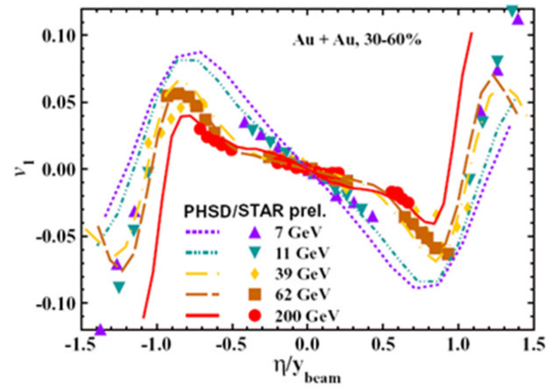
❑ PHSD: highlights

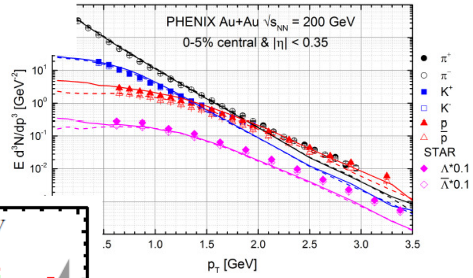


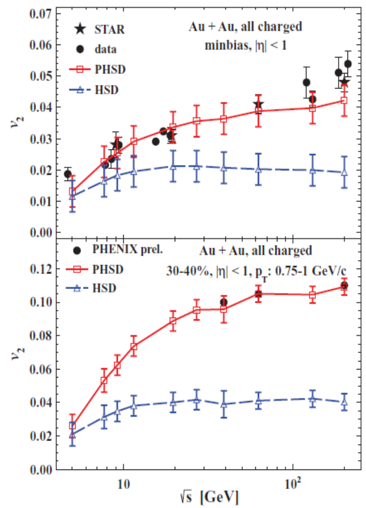
PRC 97 (2018) 044907







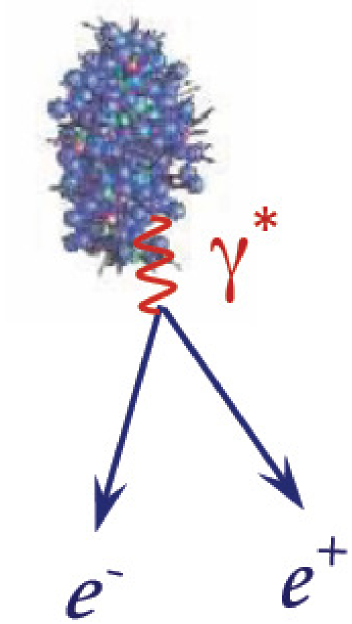




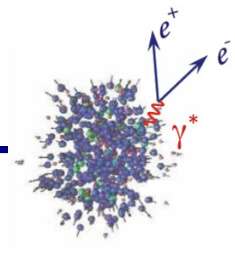
PRC 85 (2012) 011902; JPG42 (2015) 055106

❑ **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

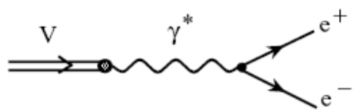


- **from the QGP via partonic (q,qbar, g) interactions:**

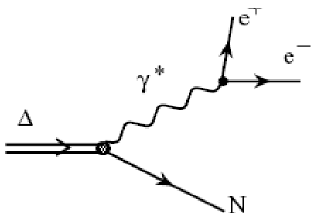
- **from hadronic sources:**

in-medium effects

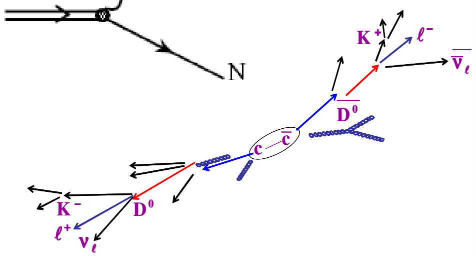
•**direct decay of vector mesons** ($\rho,\omega,\phi,J/\Psi,\Psi'$)



•**Dalitz decay of mesons and baryons** ($\pi^0,\eta,\Delta,\ldots$)

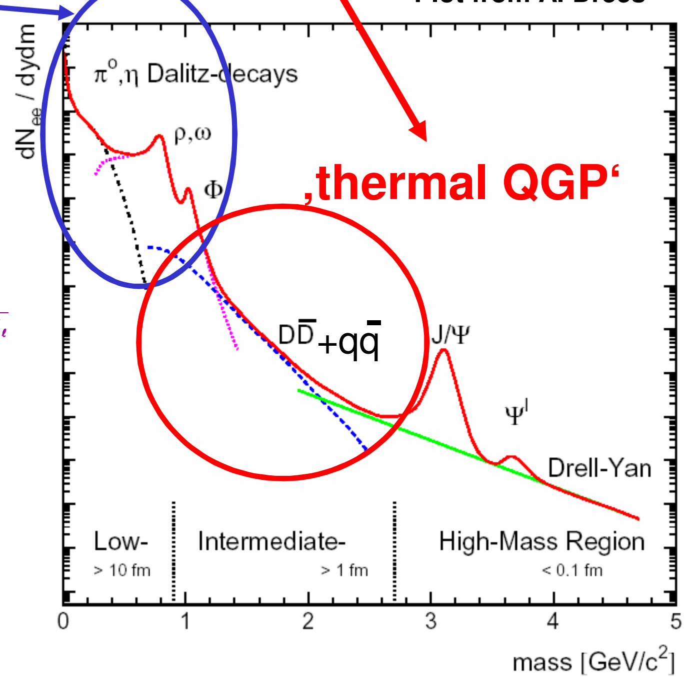


•**correlated D+Dbar pairs**



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

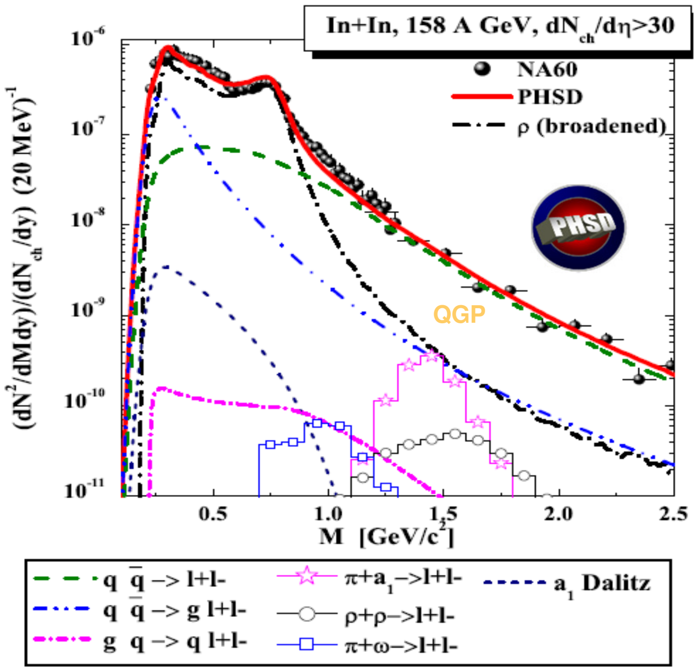
Plot from A. Drees



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

Lessons from SPS: NA60

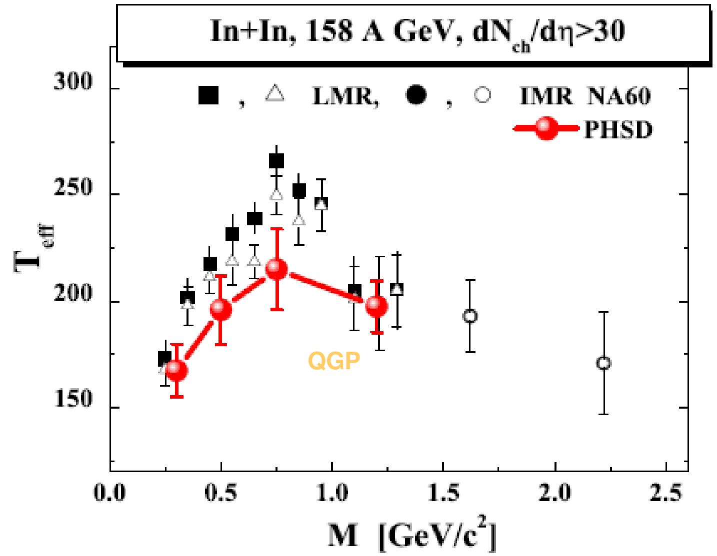
❑ Dilepton invariant mass spectra:



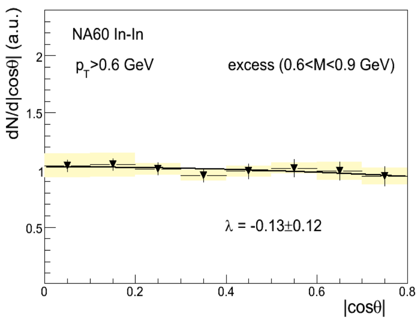
NA60: Eur. Phys. J. C 59 (2009) 607

❑ 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



PRL 102 (2009) 222301

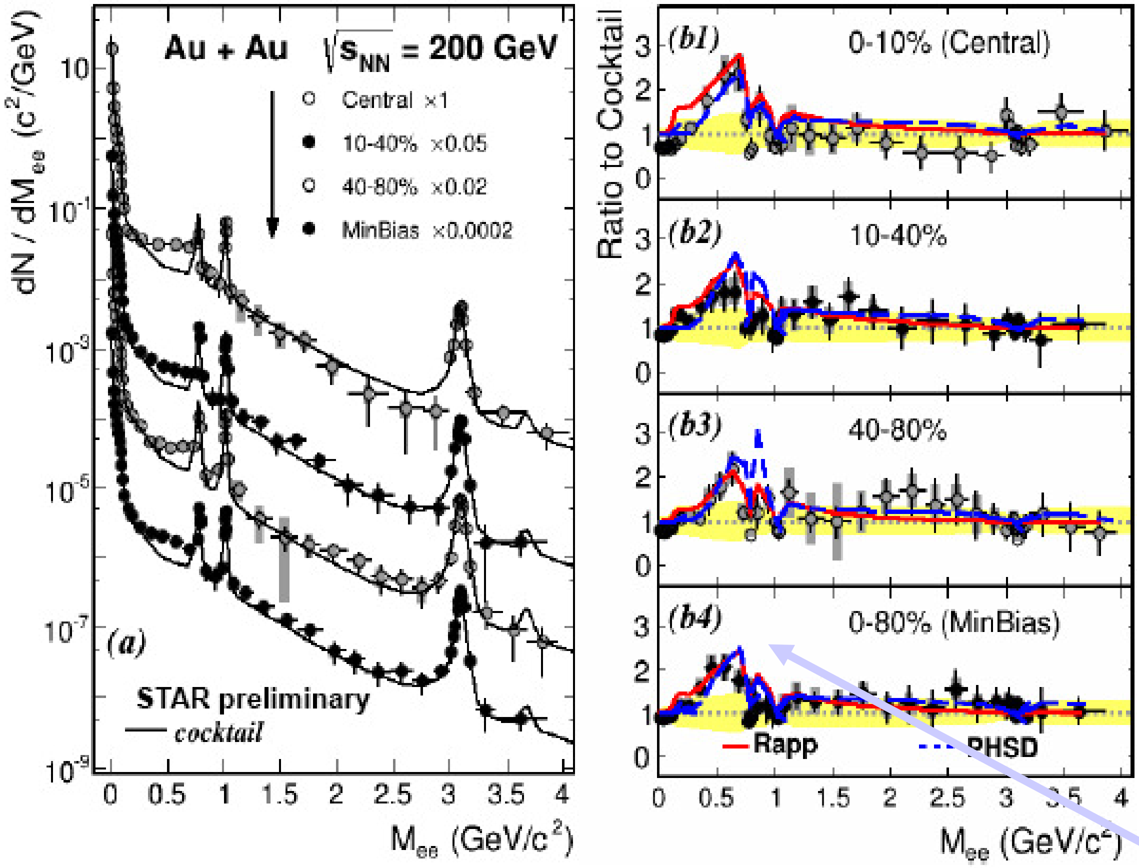
Message from SPS: (based on NA60 and CERES data)

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

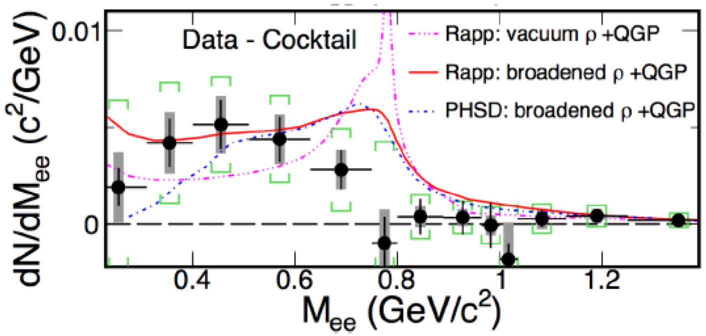
Dileptons at RHIC: STAR data vs model predictions

PRC 92 (2015) 024912

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models:

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

Low masses:

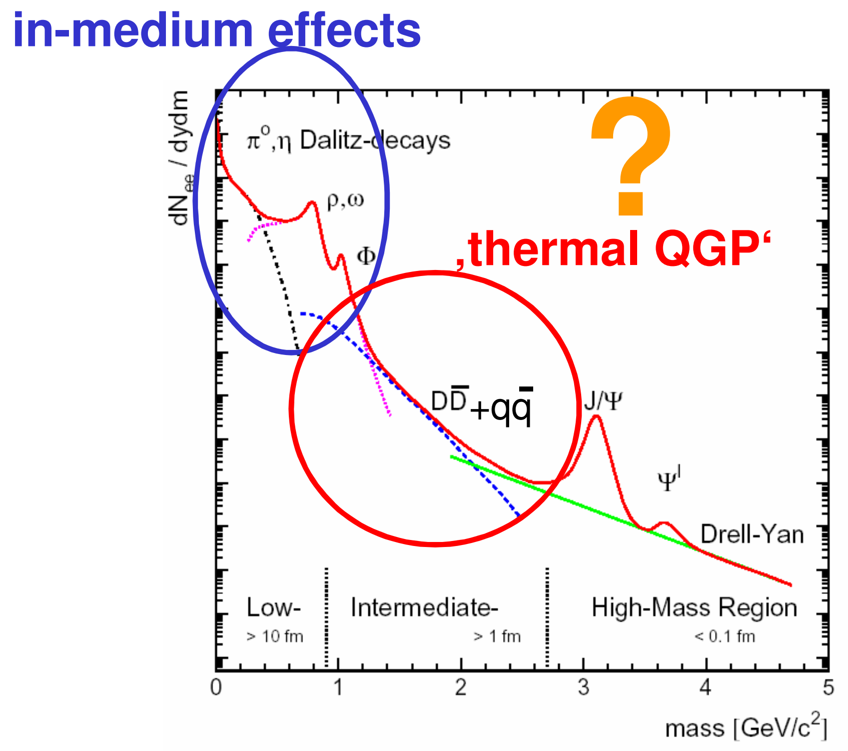
collisional broadening of ρ

Intermediate masses:

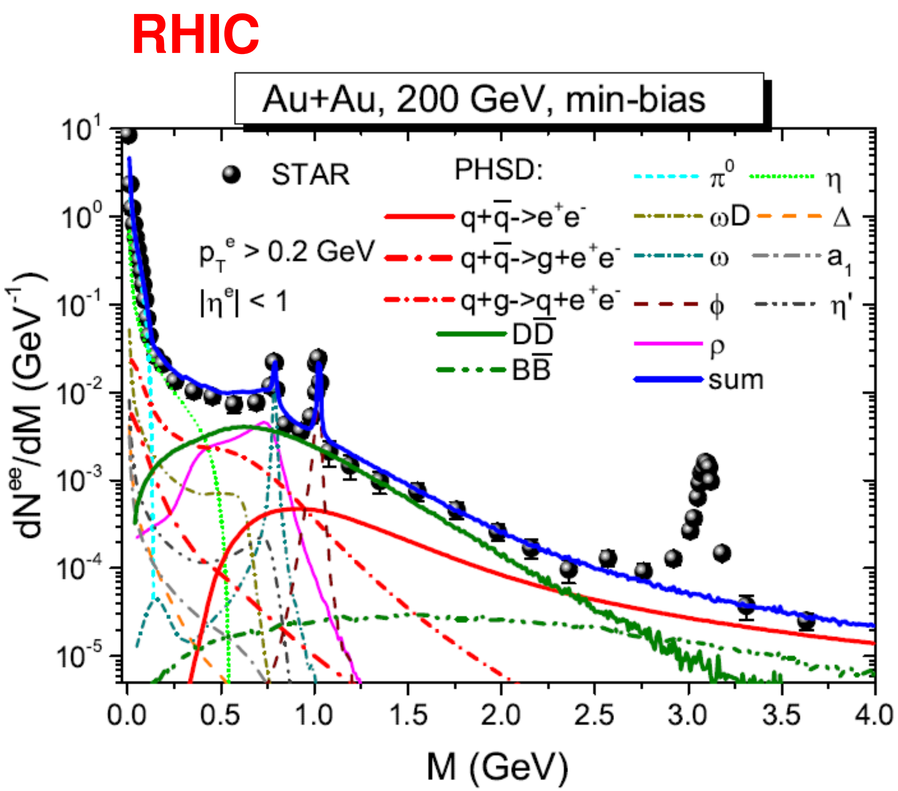
QGP dominant

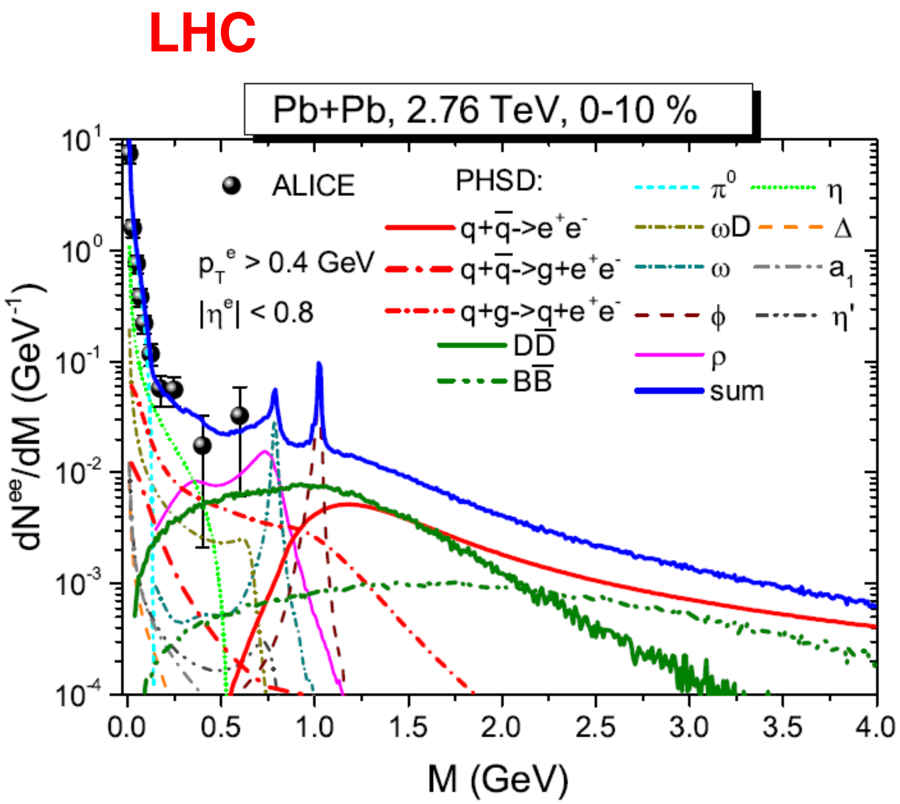
Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

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



Dileptons at RHIC and LHC





Message:

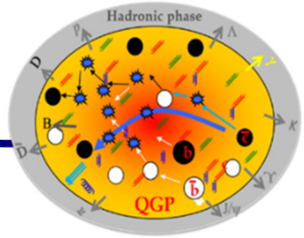
STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within

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, Phys.Rev. C97 (2018) 064907

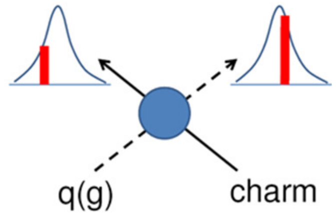
Charm dynamics in PHSD



➡ 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 :

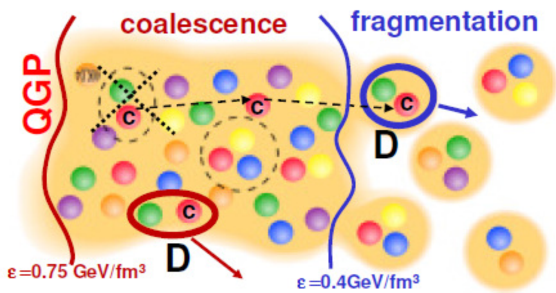
1. **Production** of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects



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

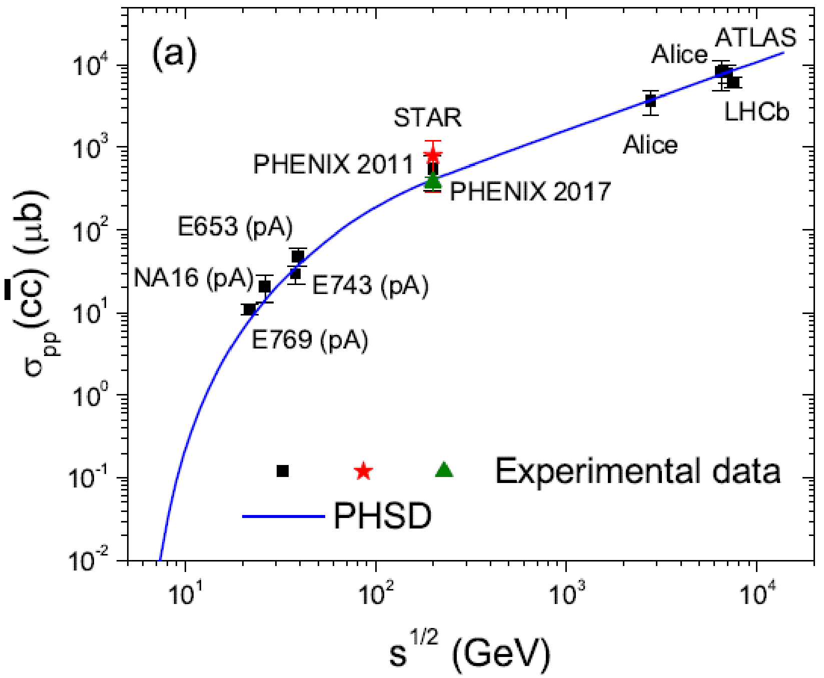
T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

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

Charm production in NN collisions

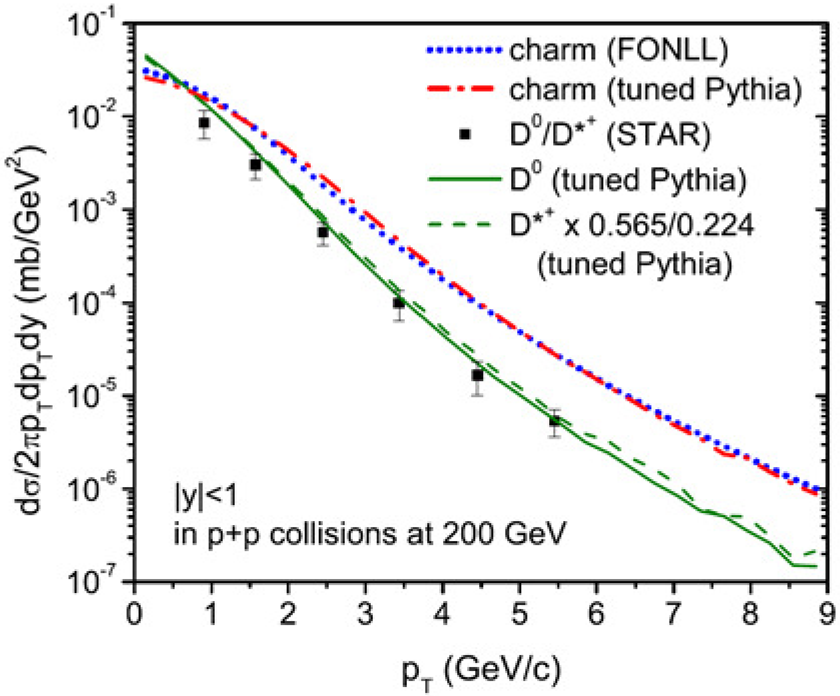
- A+A: charm production in initial NN binary collisions: probability $P = \frac{\sigma(c\bar{c})}{\sigma_{NN}^{inel}}$

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



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

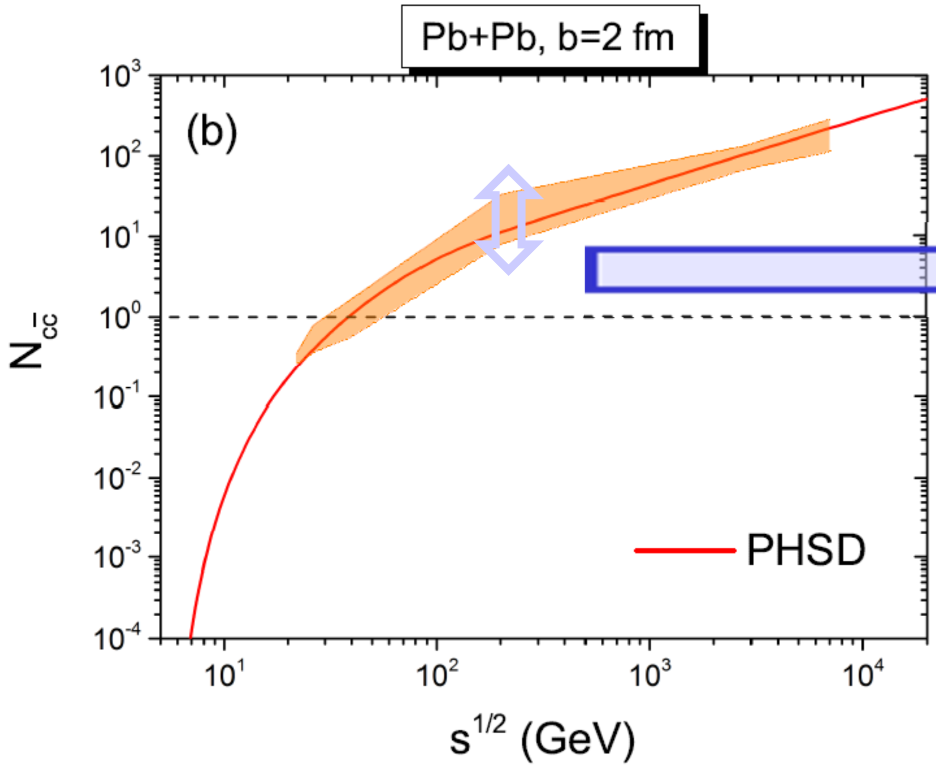
Momentum distribution of heavy quarks:
use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results



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

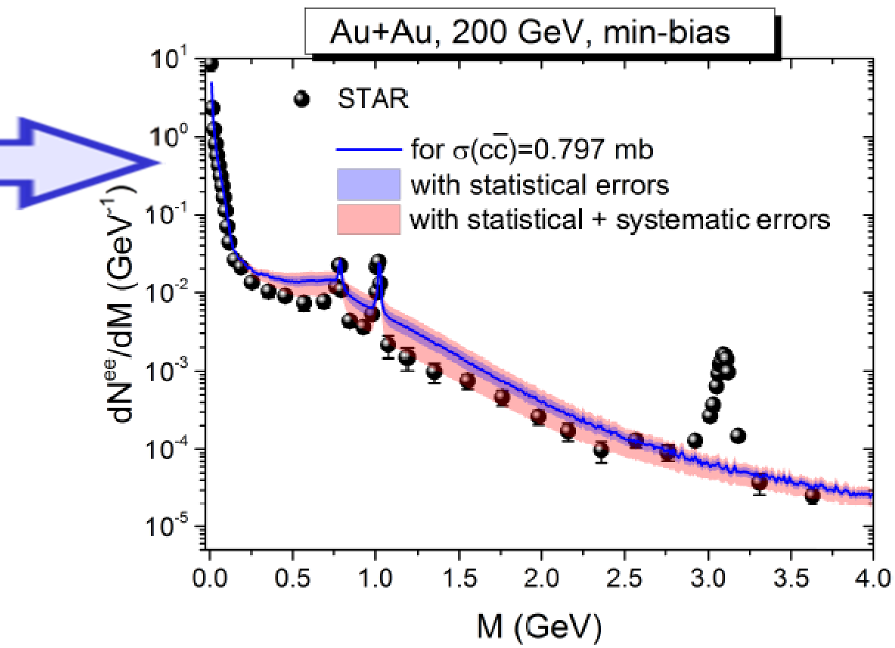
Charm at RHIC and LHC

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



* The 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

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



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

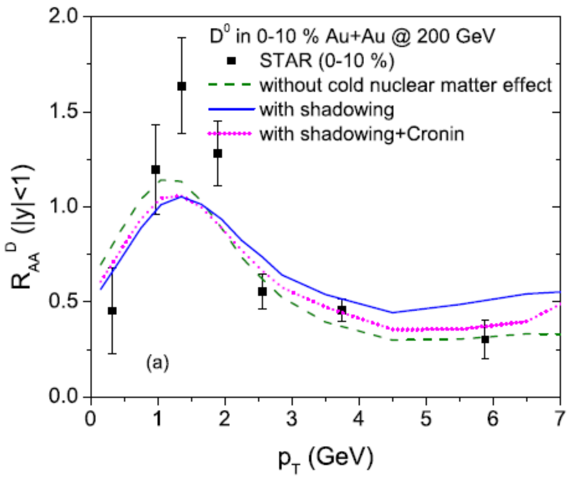
➔ **Reliable data for σ(cc) from pp are needed!**

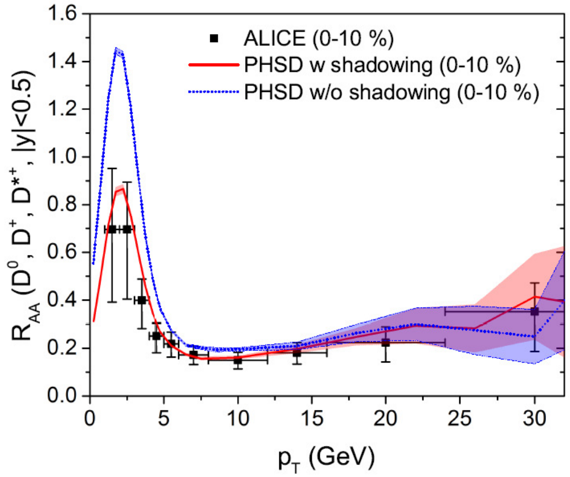
T. Song, W. Cassing, P. Moreau and E. Bratkovskaya, PRC 97 (2018) 064907

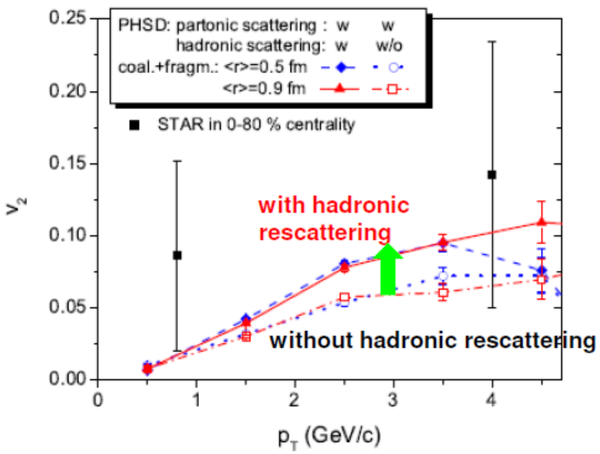
PHSD vs charm observables at RHIC and LHC

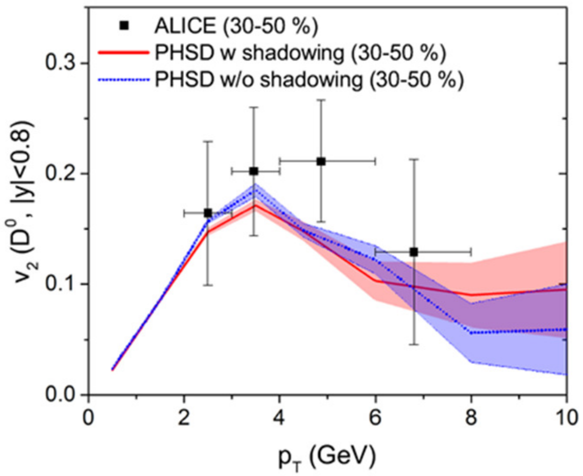
RHIC

LHC





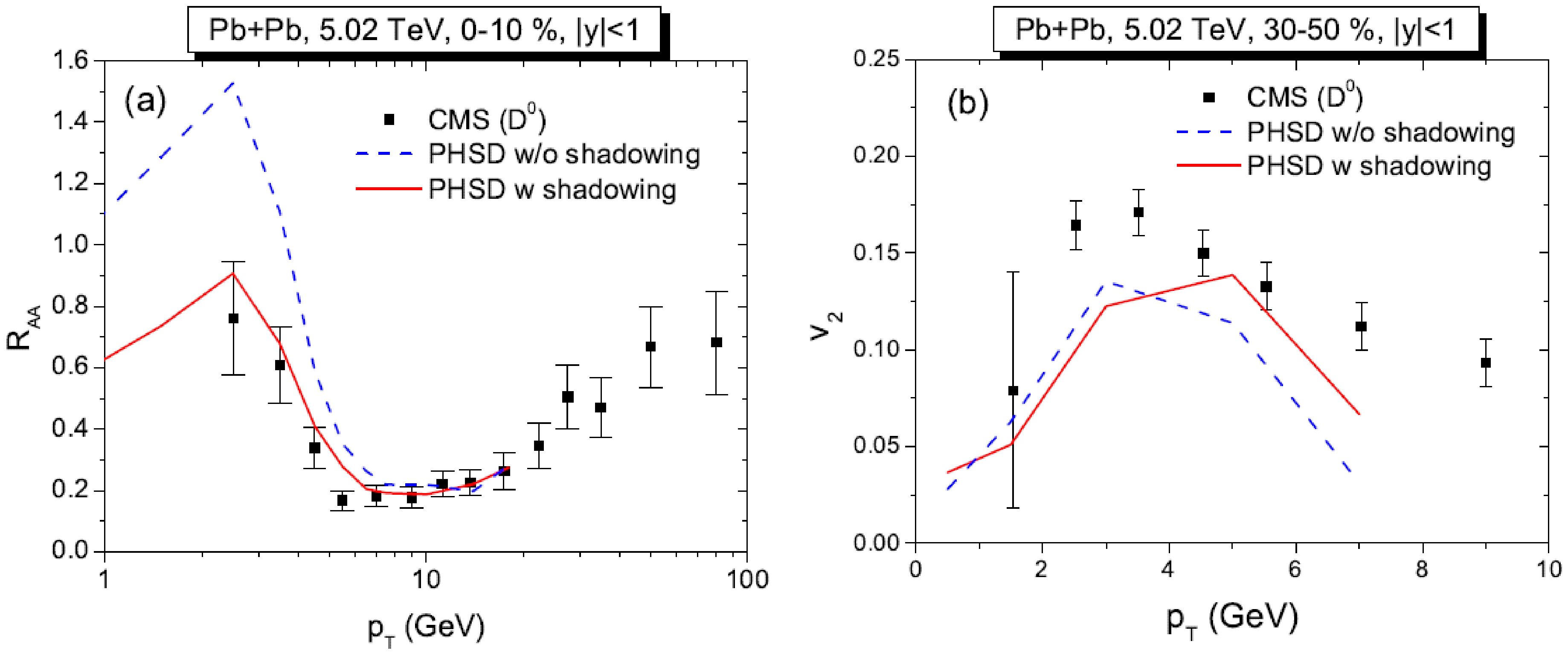




❑ **The exp. data for the R_{AA} and v_2 at RHIC and LHC are described in the PHSD by QGP collisional energy loss due to elastic scattering of charm quarks with massive quarks and gluons in the QGP**
+ by the dynamical hadronization scenario „coalescence & fragmentation“
+ by strong hadronic interactions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

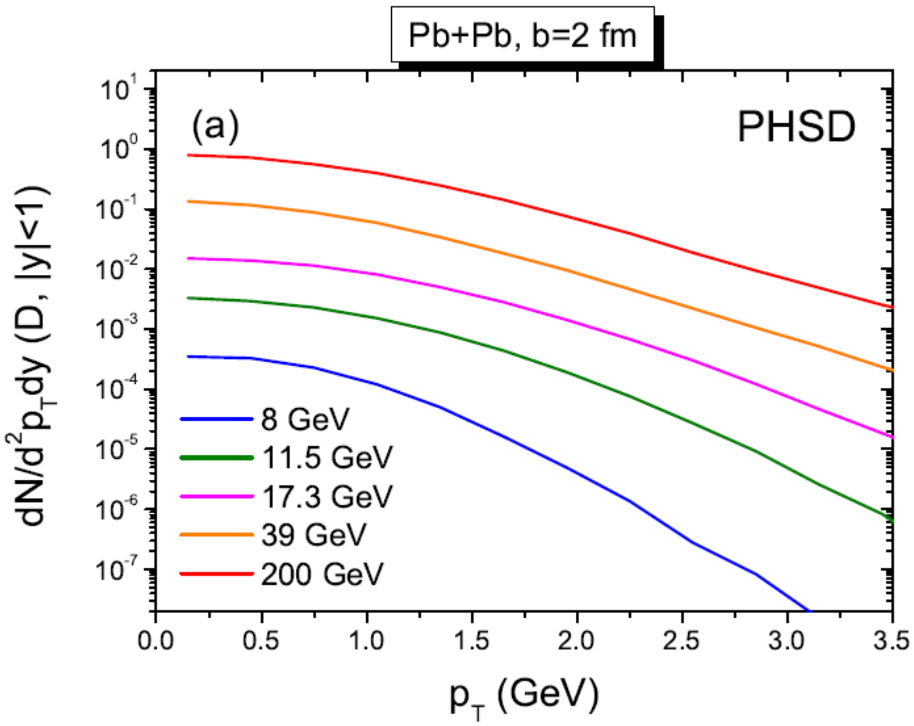
T. Song, W. Cassing, P. Moreau and E. Bratkovskaya, PRC 97 (2018) 064907

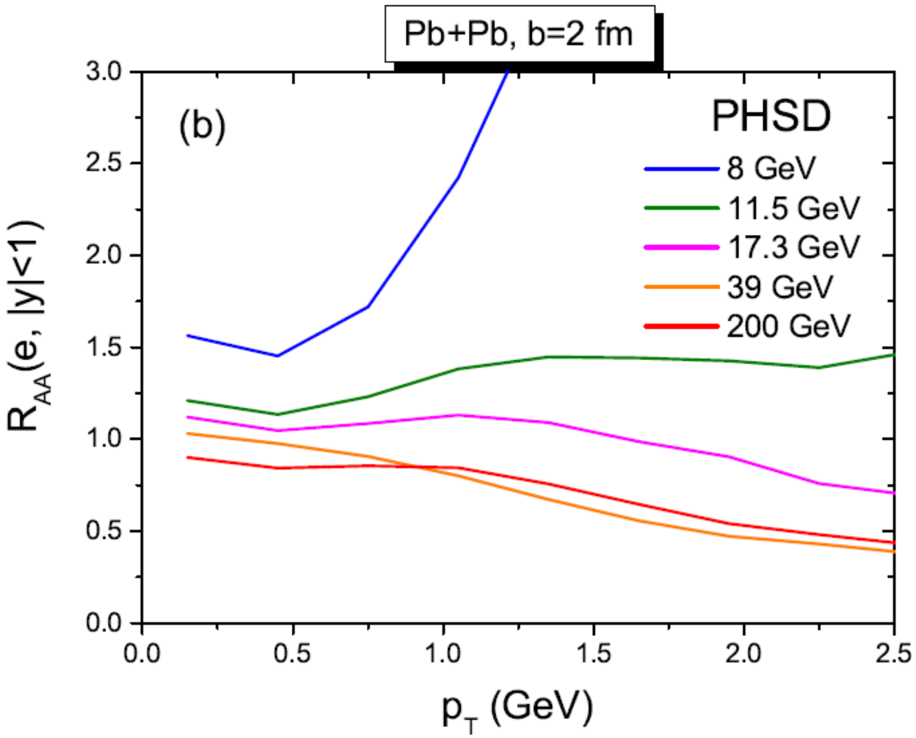
Nuclear modification of dielectrons from heavy flavor

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

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



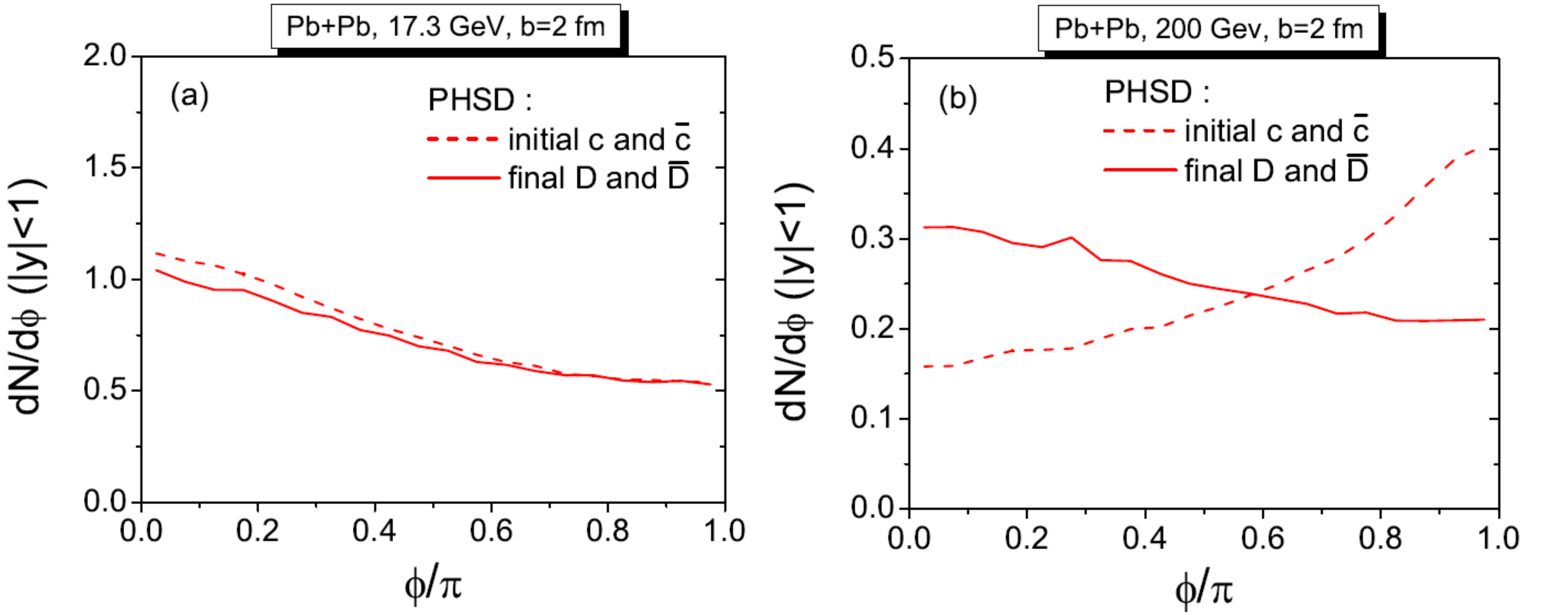


- **Hardening of the p_T spectra of D-mesons with increasing incoming energy**
- **$R_{AA}(p_T)$ of single electrons – from suppression at high energy to enhancement at low energy**

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

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**

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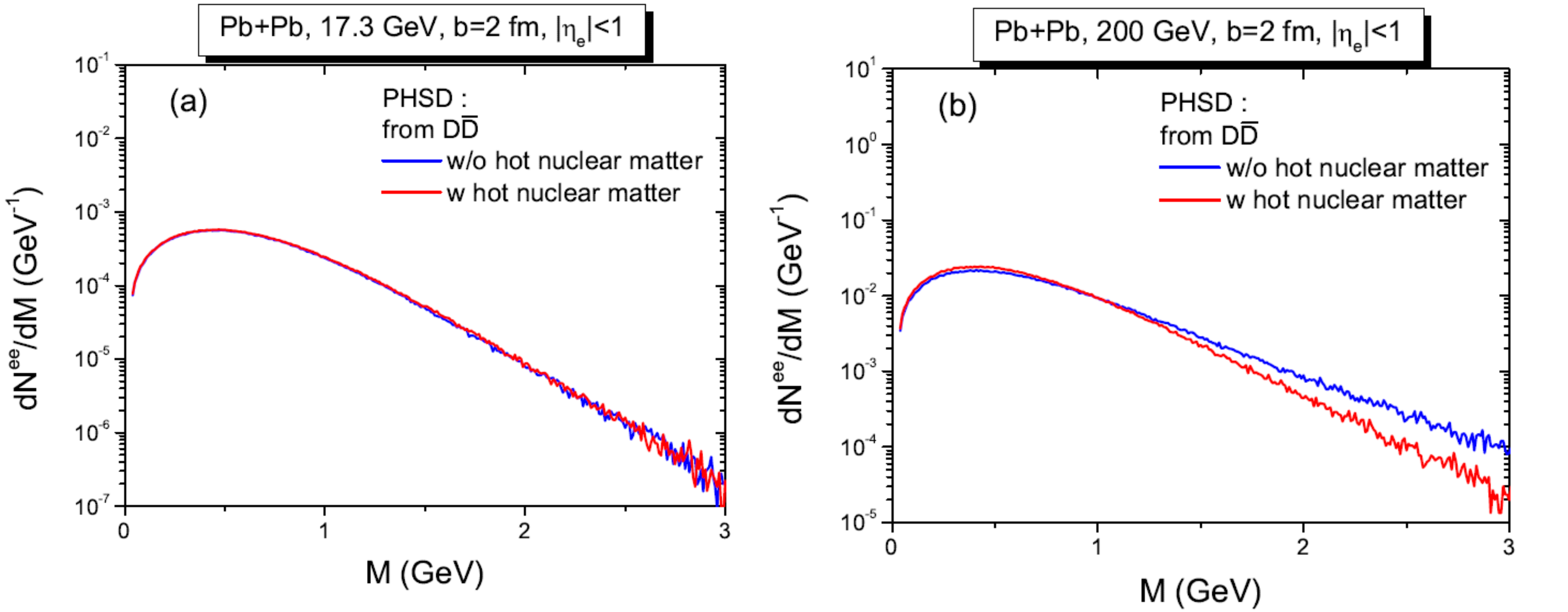
Modification of dielectron spectra due to the in-medium interaction of D-Dbar

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 $\sqrt{s}$= 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 $\sqrt{s}$ = 200 GeV

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Dileptons from RHIC BES: STAR

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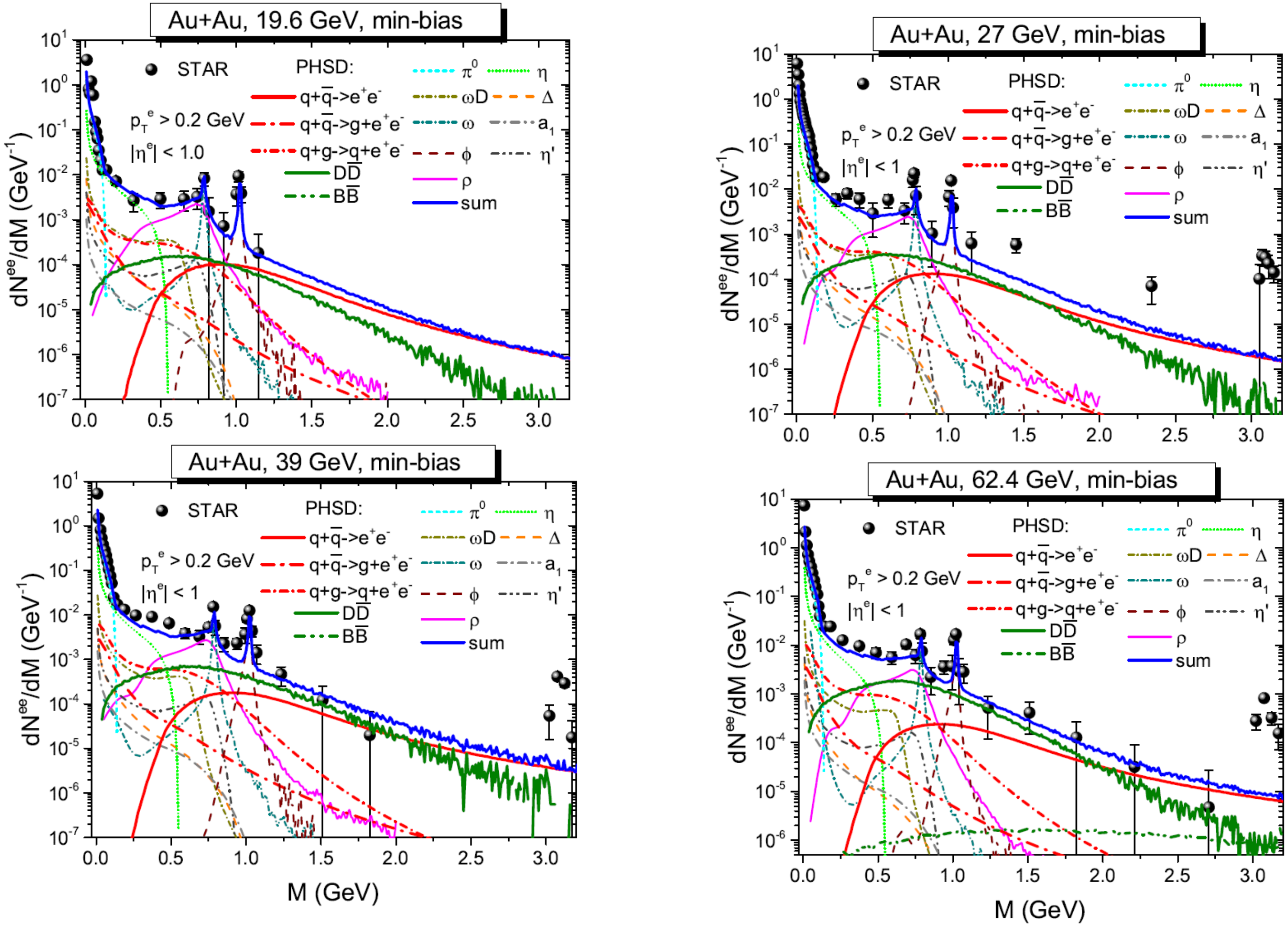
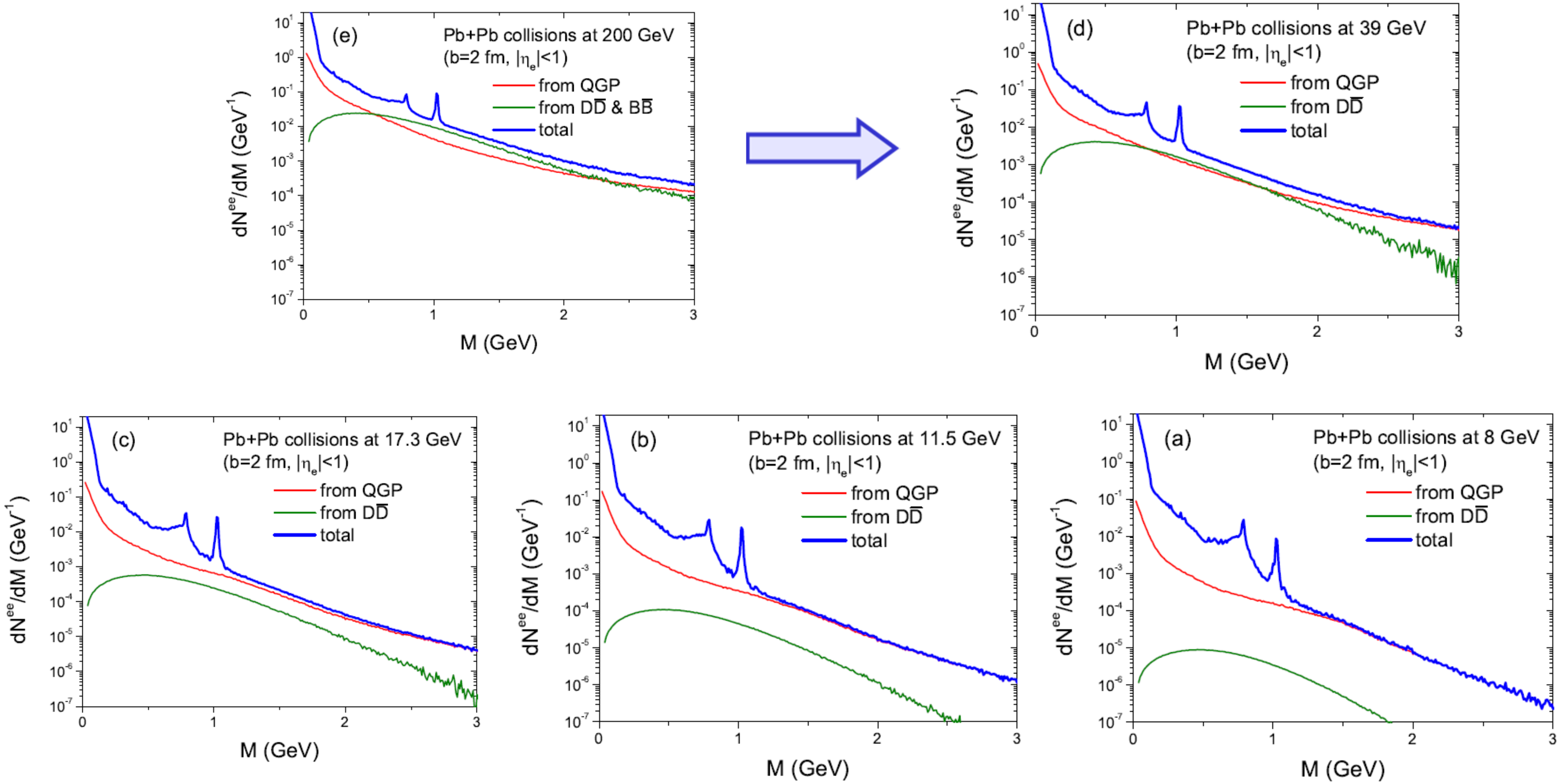


QGP and charm are dominant contributions for intermediate masses at BES RHIC
➔ measurements of charm at BES RHIC are needed to control charm production !

Dileptons at FAIR/NICA energies: predictions



Relative contribution of QGP versus charm increases with decreasing energy!

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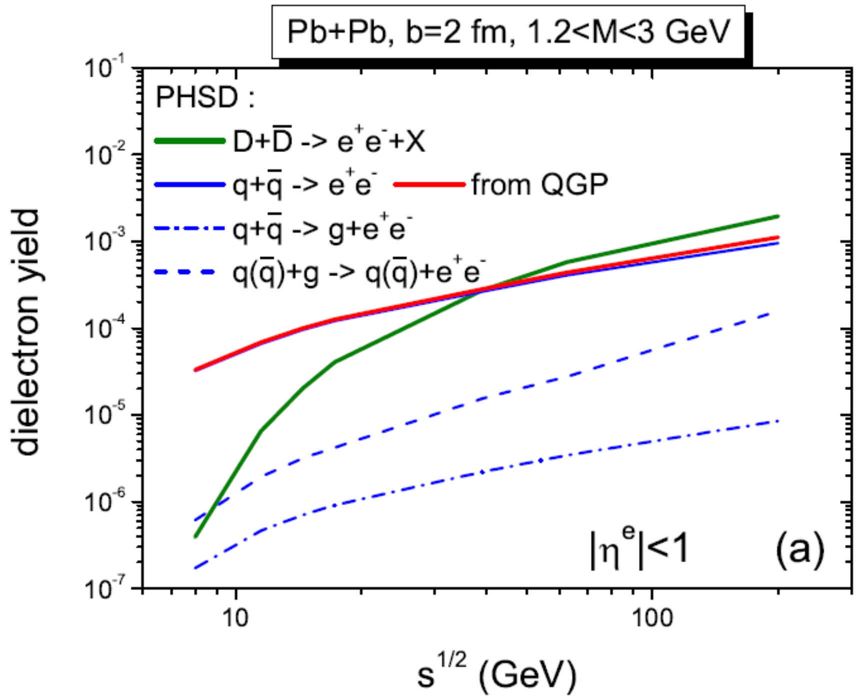
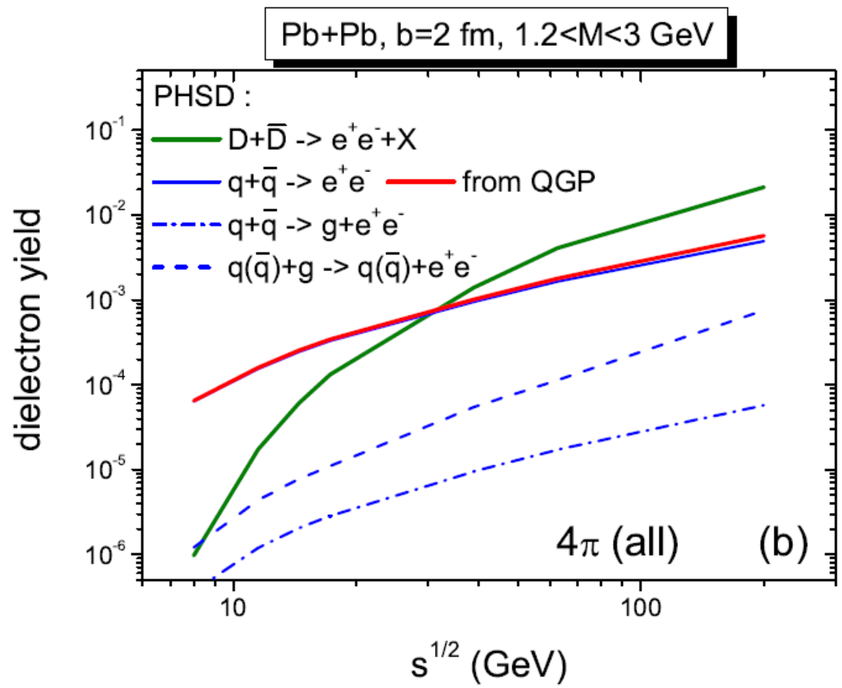
Dileptons: QGP vs charm

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!

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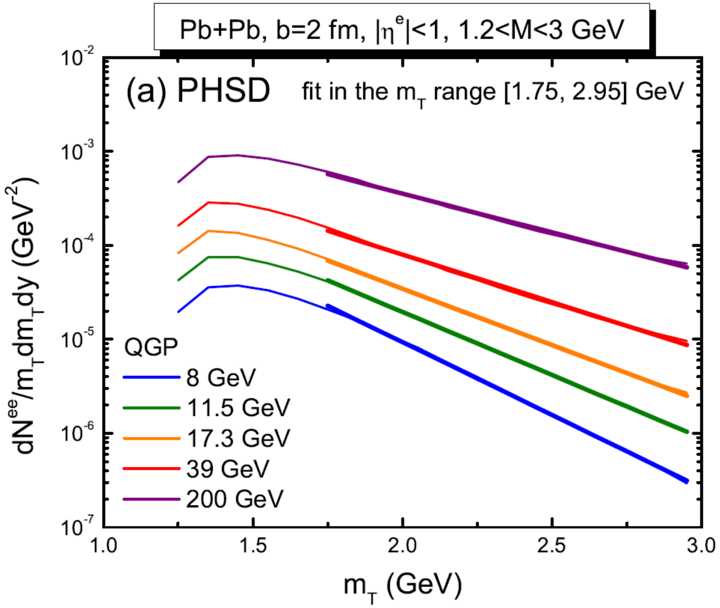
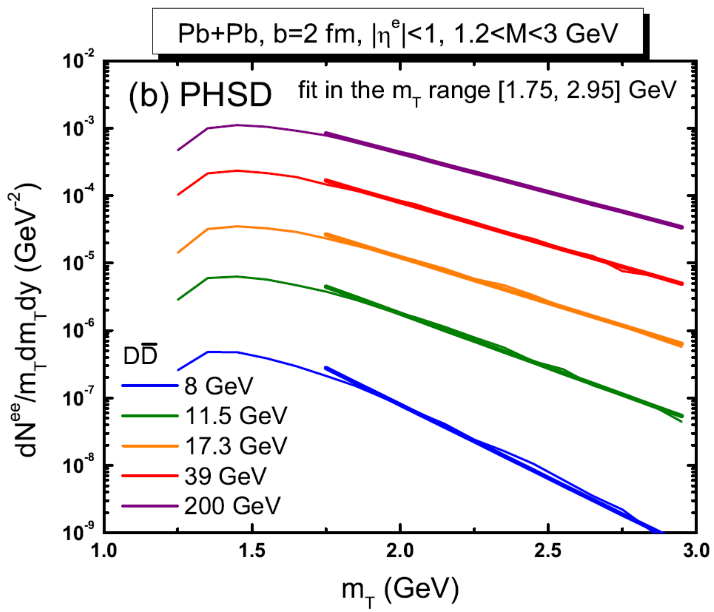
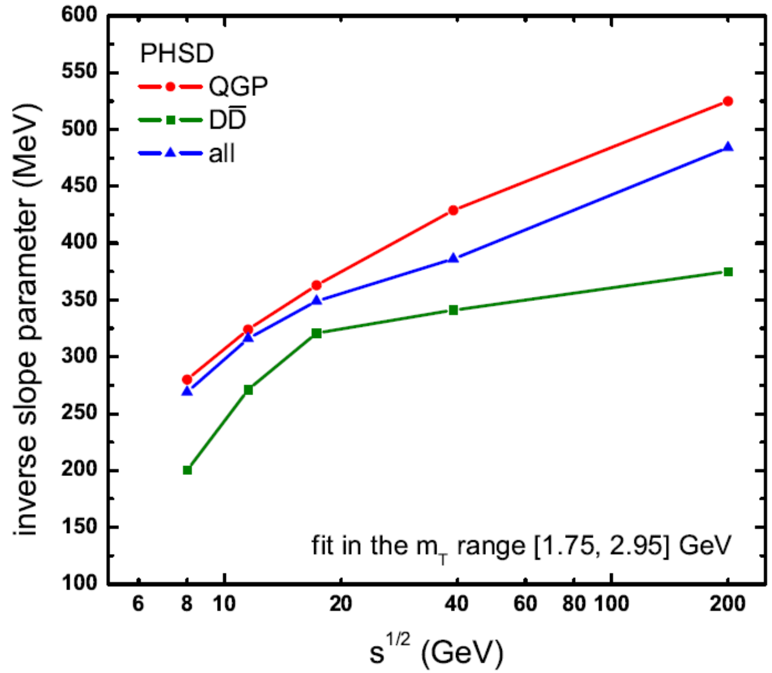
Dilepton transverse mass spectra





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**

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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

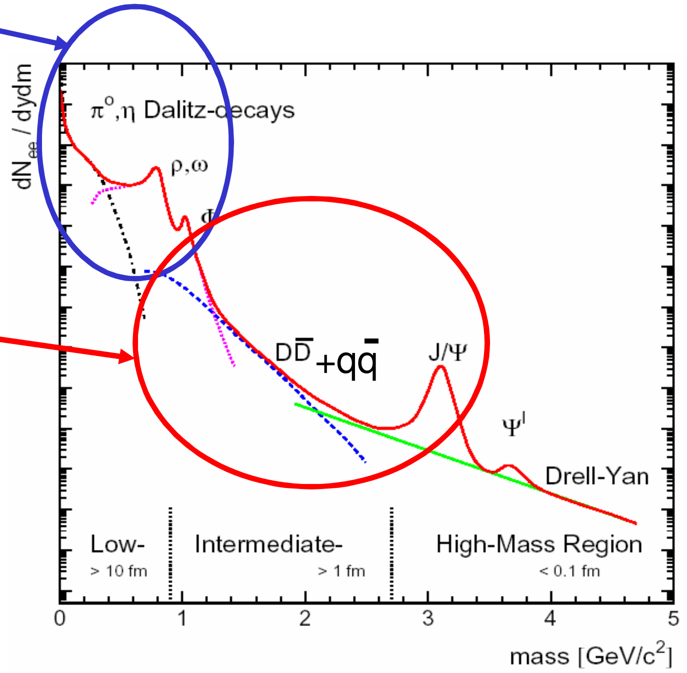
- **In-medium effects** can be observed at **all energies from SIS to LHC; excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon-density phase

❑ 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

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Thank you for your attention !

Erice-2018