Electromagnetic radiation of hot and dense matter

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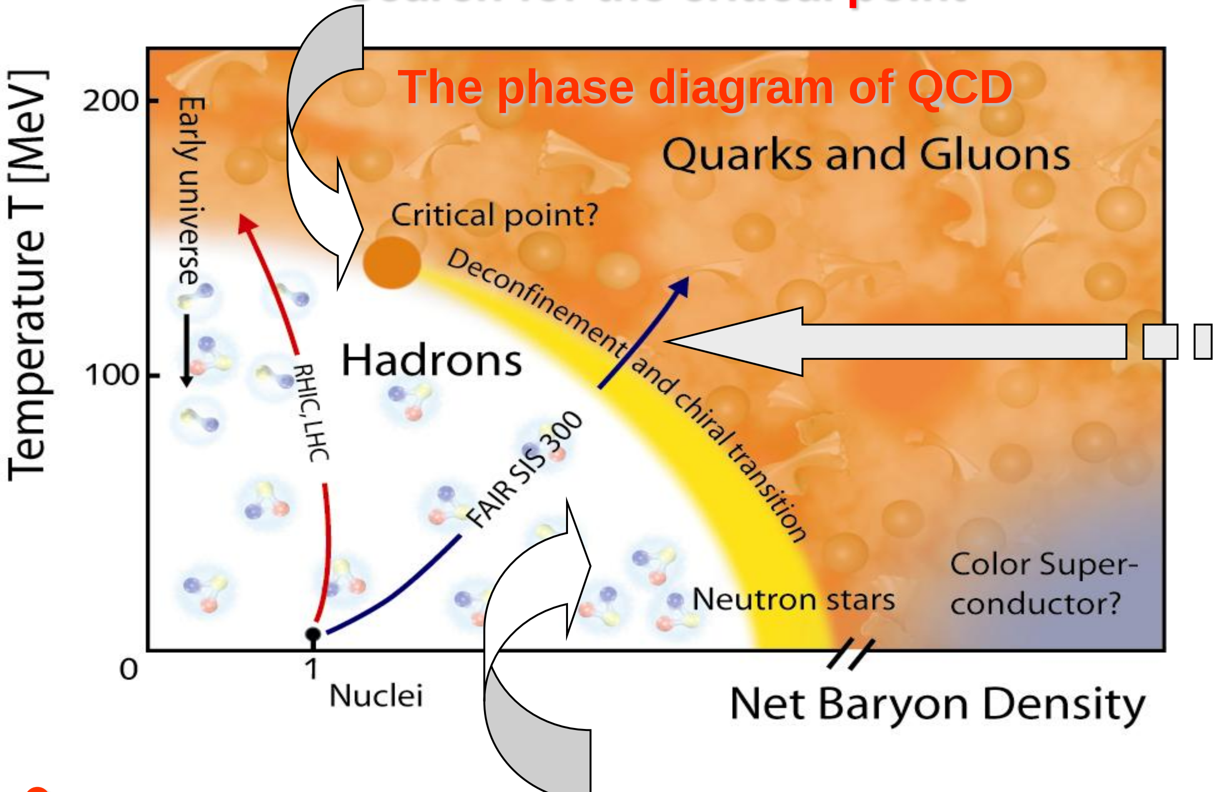
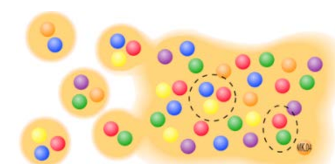
EMMI workshop "Constraining the QCD Phase Boundary with data from Heavy-Ion Collisions",
GSI, Darmstadt, Germany, February 12-14, 2018

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

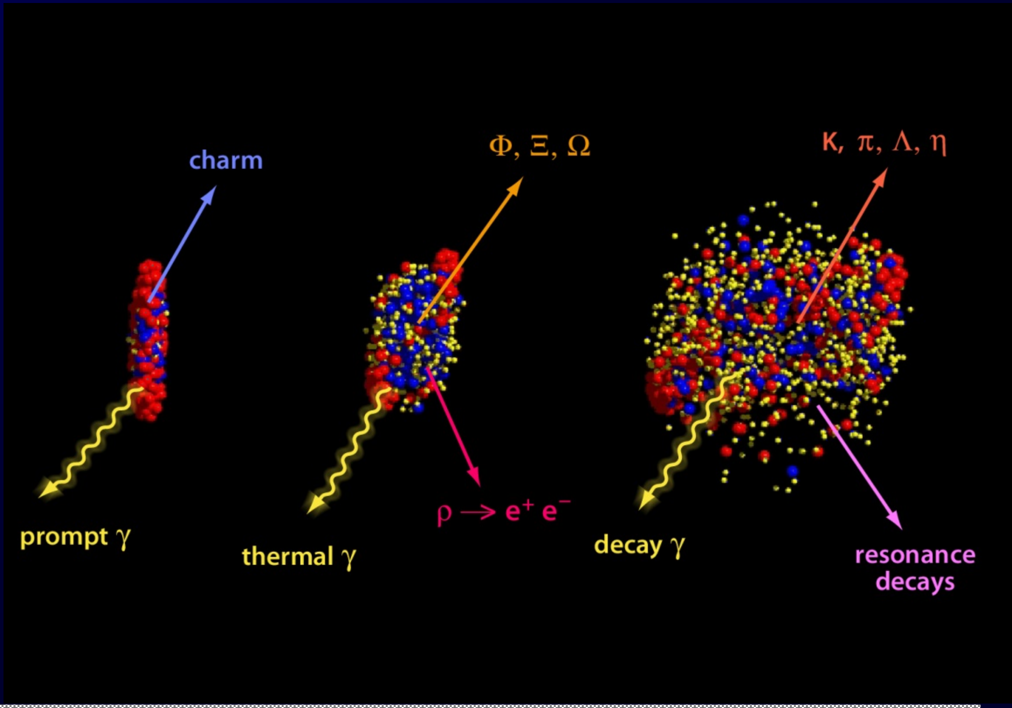
✓ provide undistorted information about their production channels

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

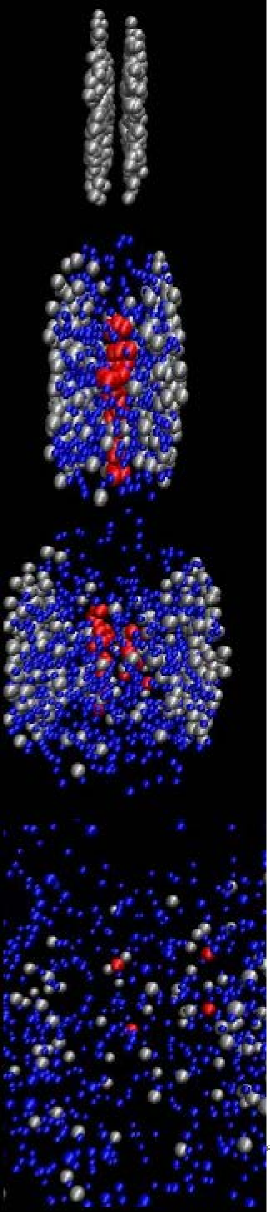
➔ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

Disadvantages:

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



Parton-Hadron-String-Dynamics (PHSD)



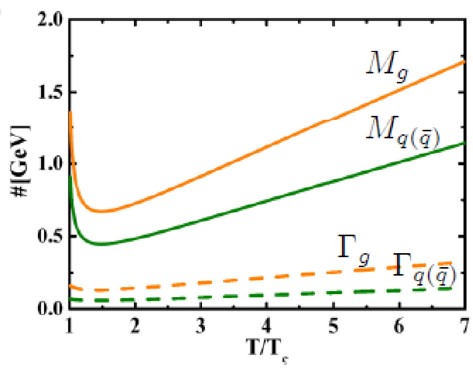
PHSD is a **non-equilibrium transport approach** with

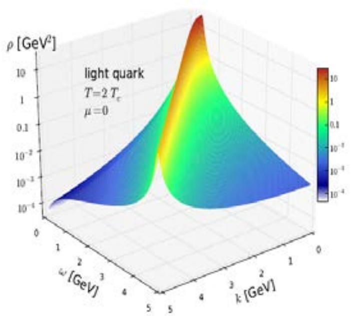
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for the partonic phase (‚crossover' at low μ_q)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

❑ **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:**

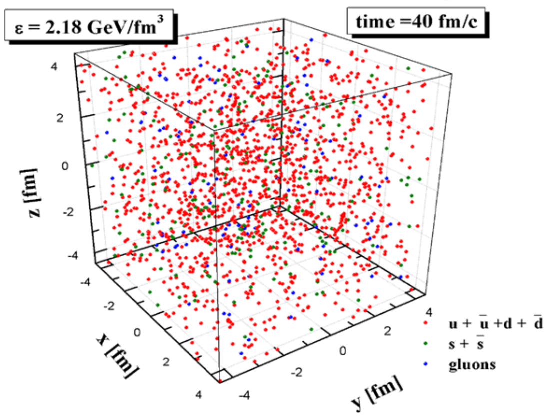
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

❑ **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

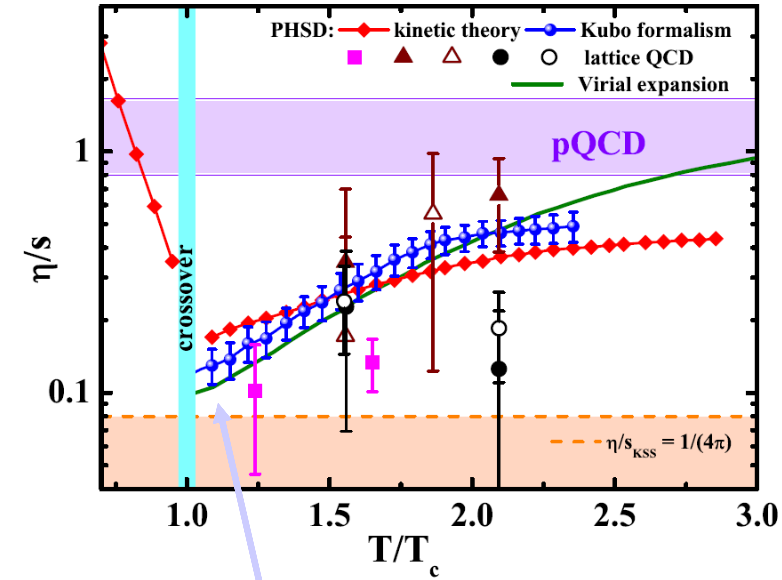
QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

Infinite hot/dense matter = PHSD in a box:



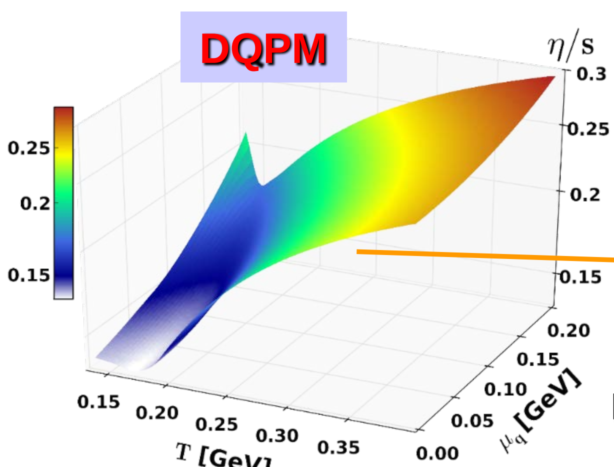
Shear viscosity η/s at finite T

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



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

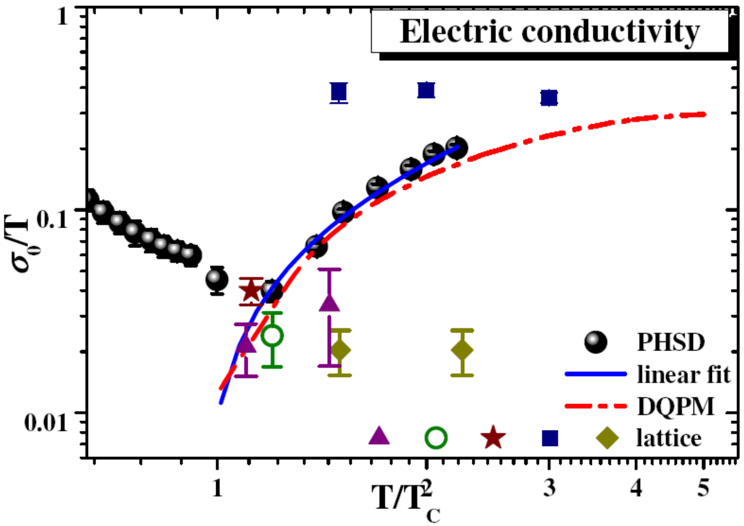
η/s: $\mu_q=0$ ➔ finite μ_q: smooth increase as a function of (T, μ_q)

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

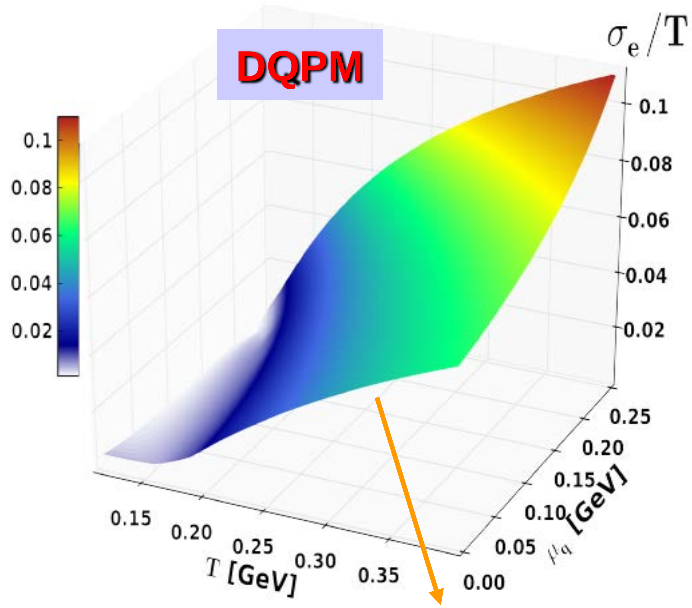
W. Cassing et al., PRL 110(2013)182301



- 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)

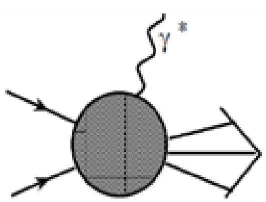
H. Berrehrah et al. , PRC93 (2016) 044914



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

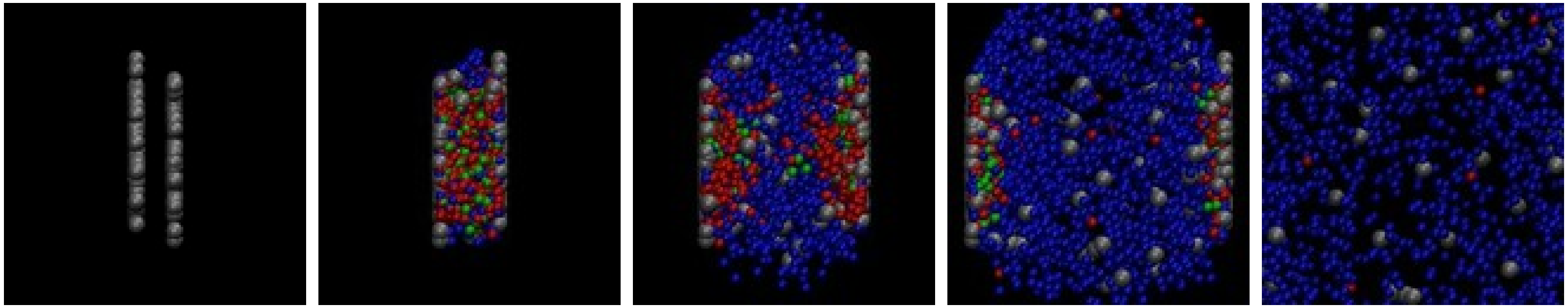
❑ Photon emission: rates at q_0→0 are related to electric conductivity σ_0

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

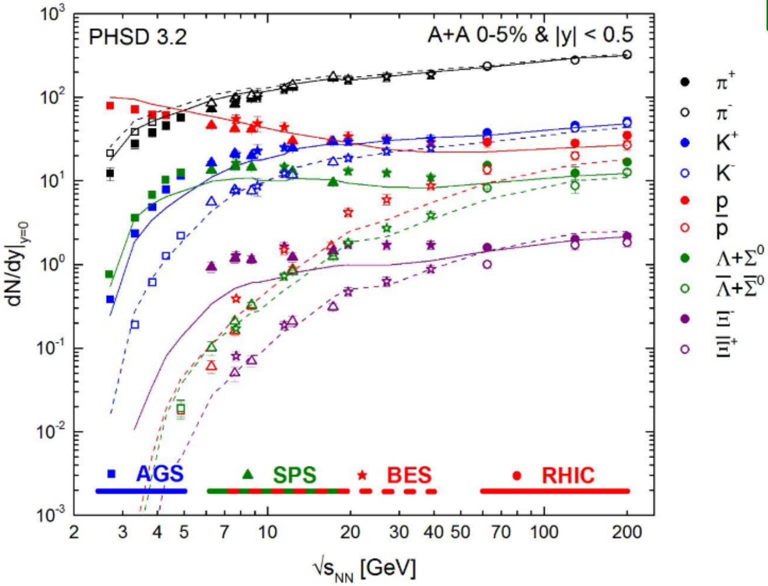


σ_0 ➔ Probe of electromagnetic properties of the QGP

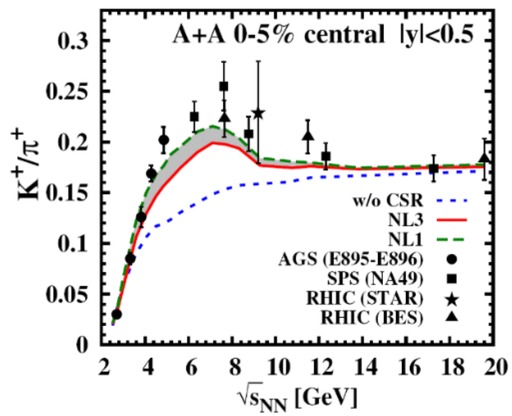
‚Bulk‘ properties
in Au+Au collisions

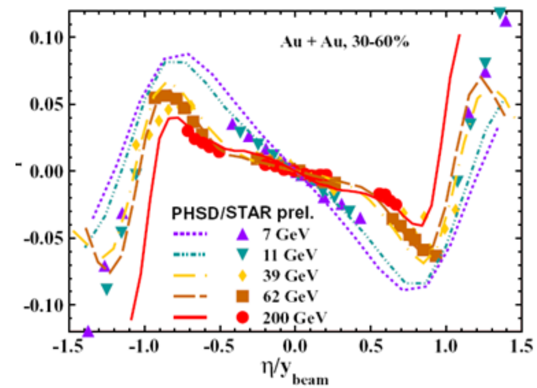


Non-equilibrium dynamics: description of A+A with PHSD

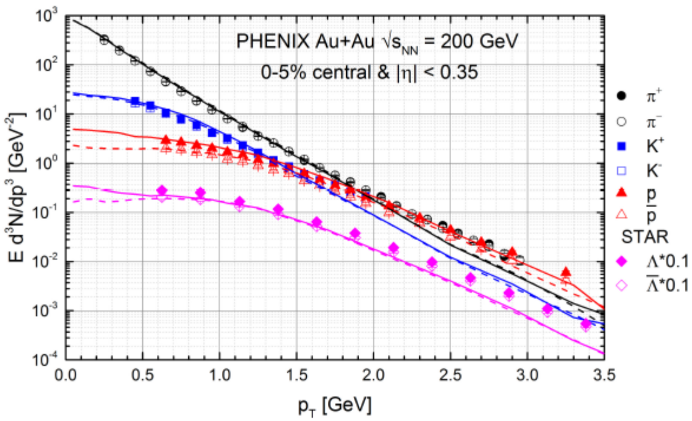


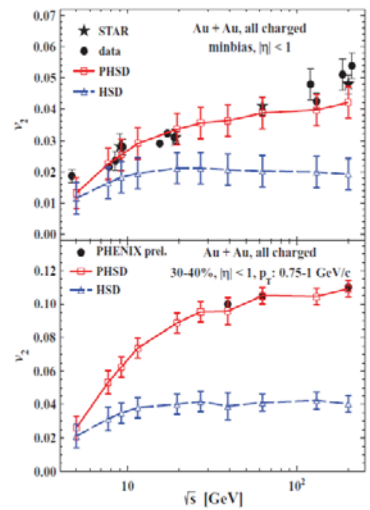
❑ PHSD: highlights

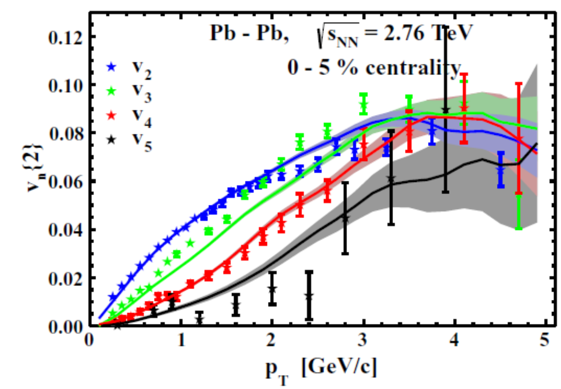




PHSD: P. Moreau



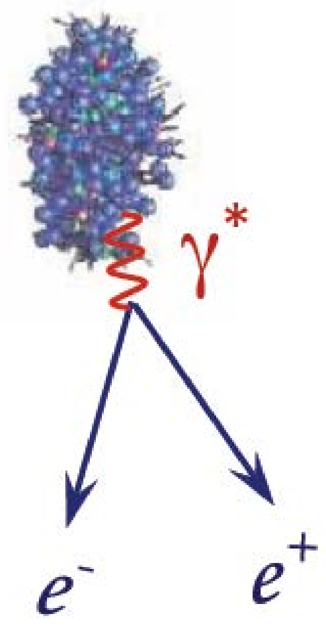




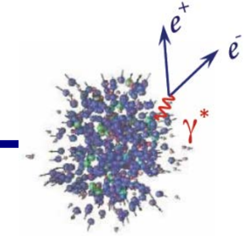
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

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

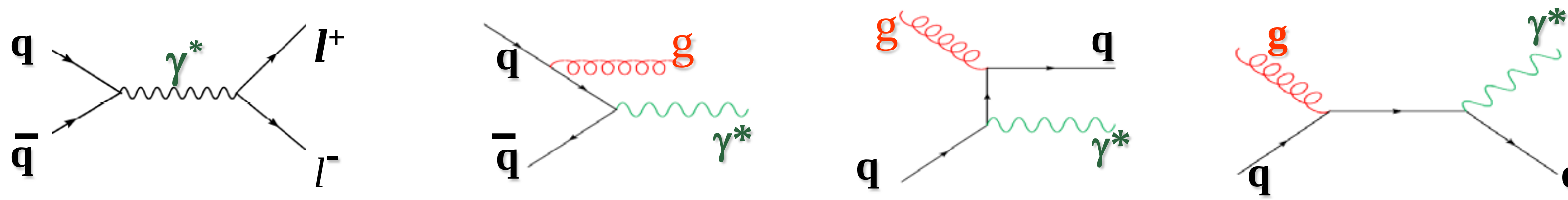
Dileptons as a probe of the QGP and in-medium effects



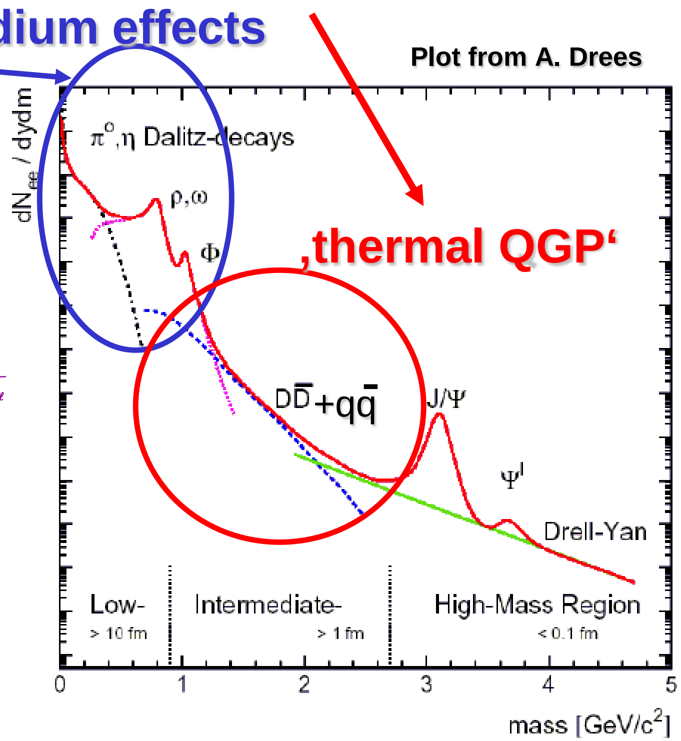
Dilepton sources



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



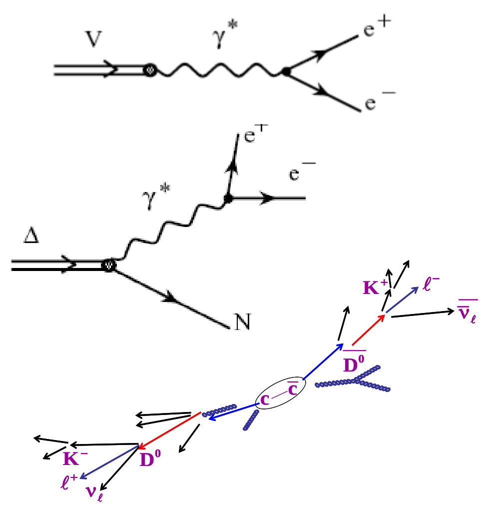
- **from hadronic sources:**



•**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'

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

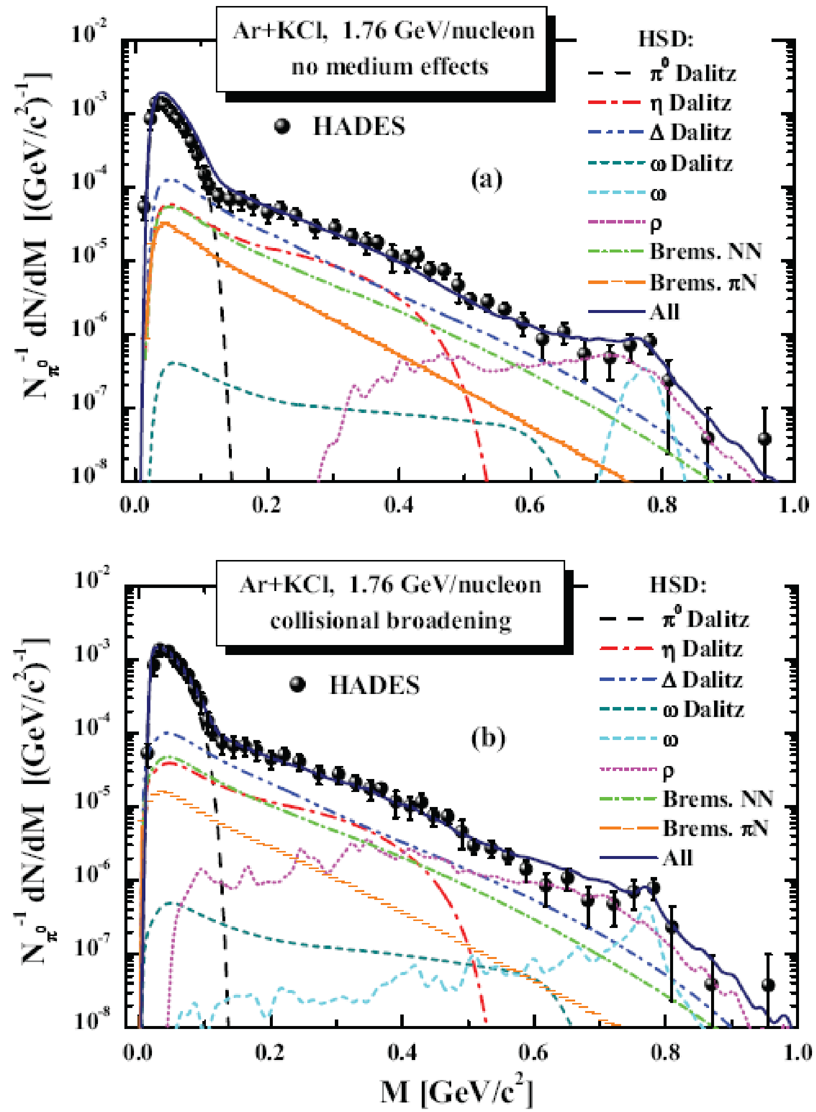
Dileptons at SIS energies - HADES

- **HADES:** dilepton yield dN/dM scaled with the number of pions $N_{\pi 0}$

- **Dominant hadronic sources at $M>m_\pi$:**
  - η, Δ Dalitz decays
  - NN bremsstrahlung
  - direct ρ decay

➢ **ρ meson = strongly interacting resonance**
strong collisional broadening of the ρ width

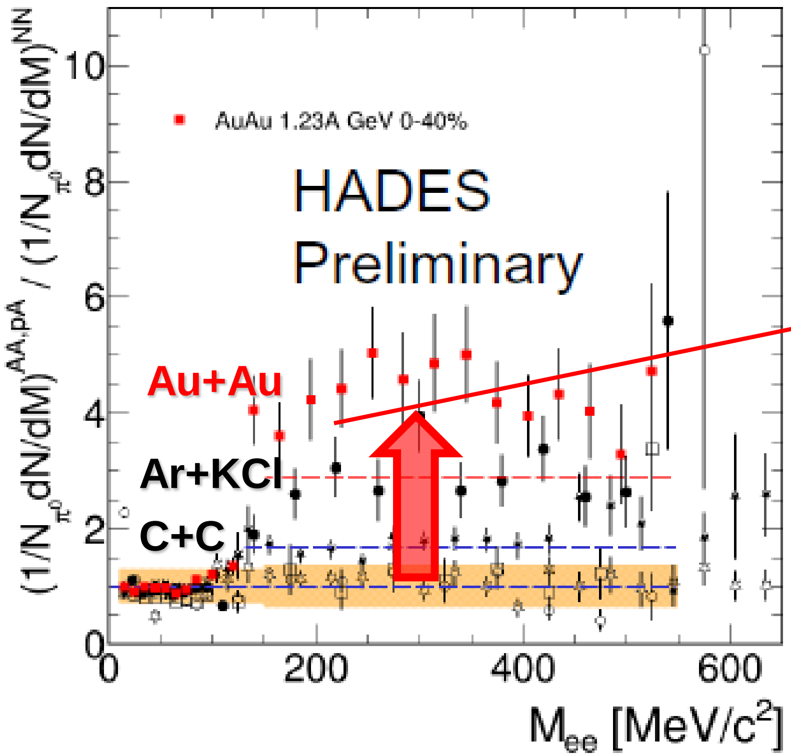
- In-medium effects are more pronounced for heavy systems such as Ar+KCl than C+C
- The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum



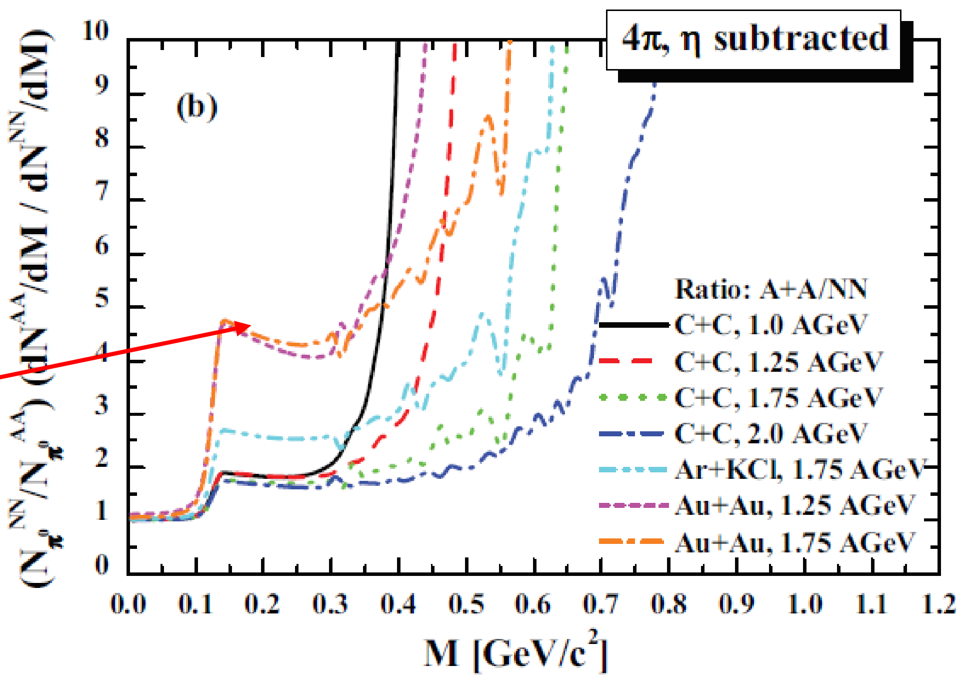
E.Bratkovskaya., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

Dileptons at SIS (HADES): Au+Au

CPOD-2016:
HADES preliminary: Au+Au, 1.23 A GeV



▪ **HSD predictions (2013)**



❑ **Strong in-medium enhancement of dilepton yield in Au+Au vs. NN :**

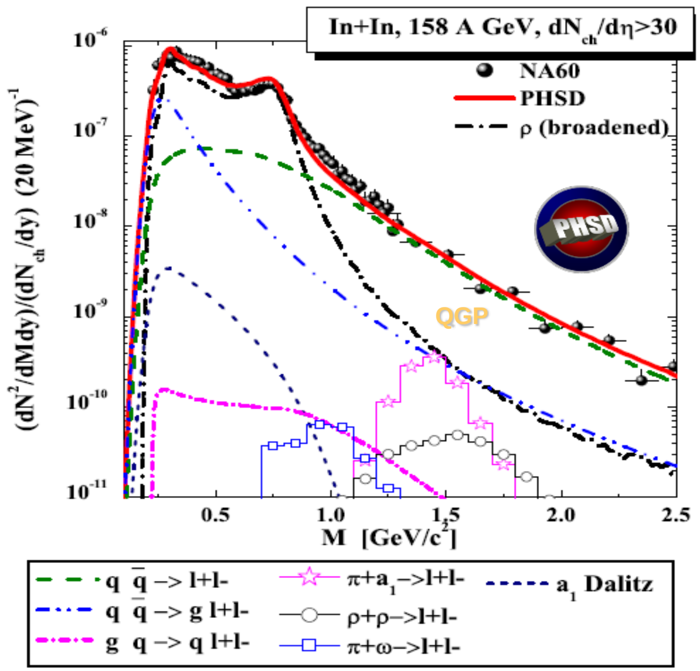
1) the **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

2) the **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions;

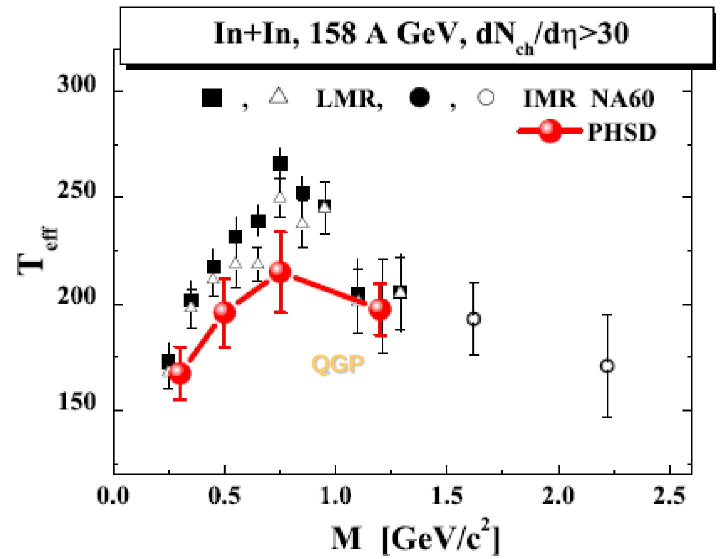
E.B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

Lessons from SPS: NA60

❑ **Dilepton invariant mass spectra:**



❑ **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

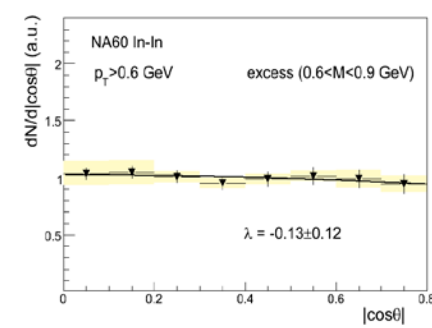


NA60: Eur. Phys. J. C 59 (2009) 607

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**

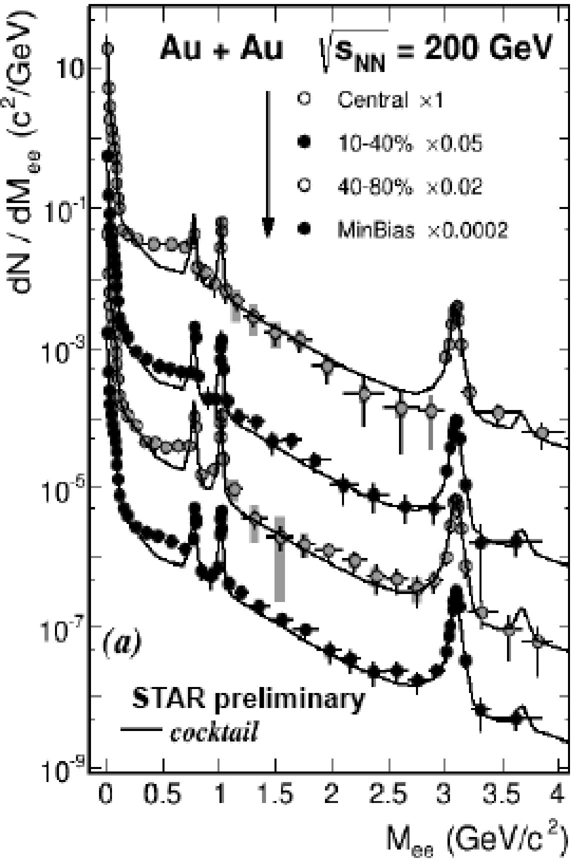


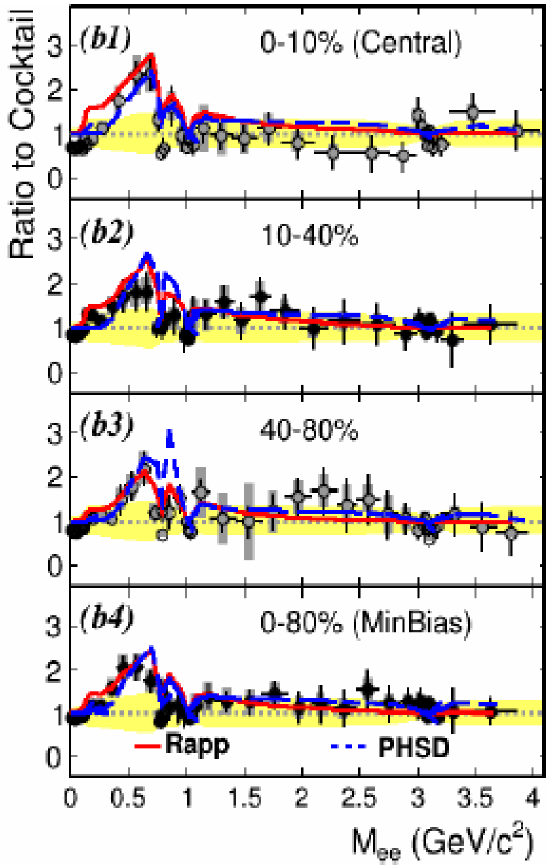
PRL 102 (2009) 222301

Dileptons at RHIC: STAR data vs model predictions

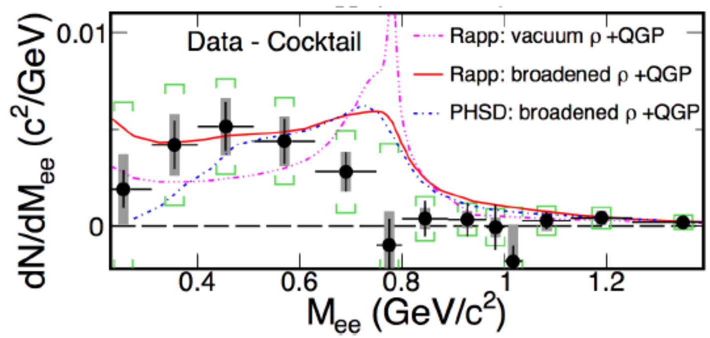
PRC 92 (2015) 024912

Centrality dependence of dilepton yield





Excess in low mass region, min. bias



Models:

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

Low masses:

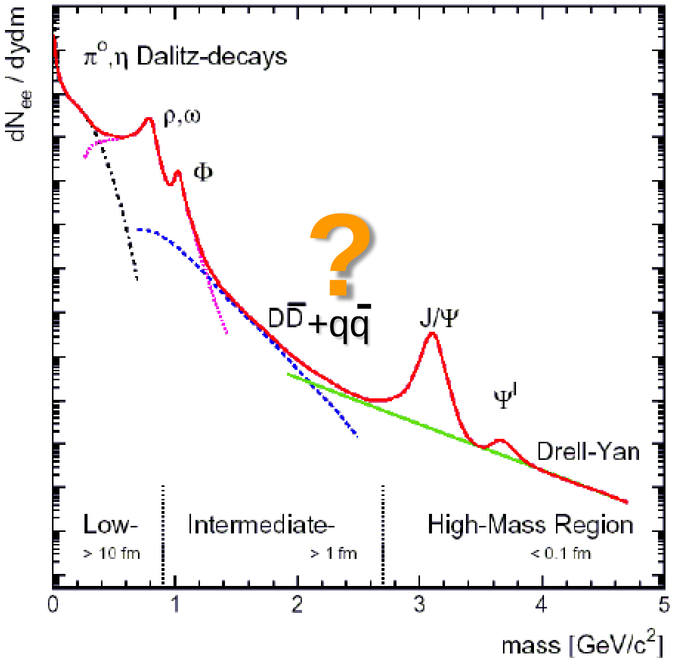
collisional broadening of ρ

Intermediate masses:

QGP dominant

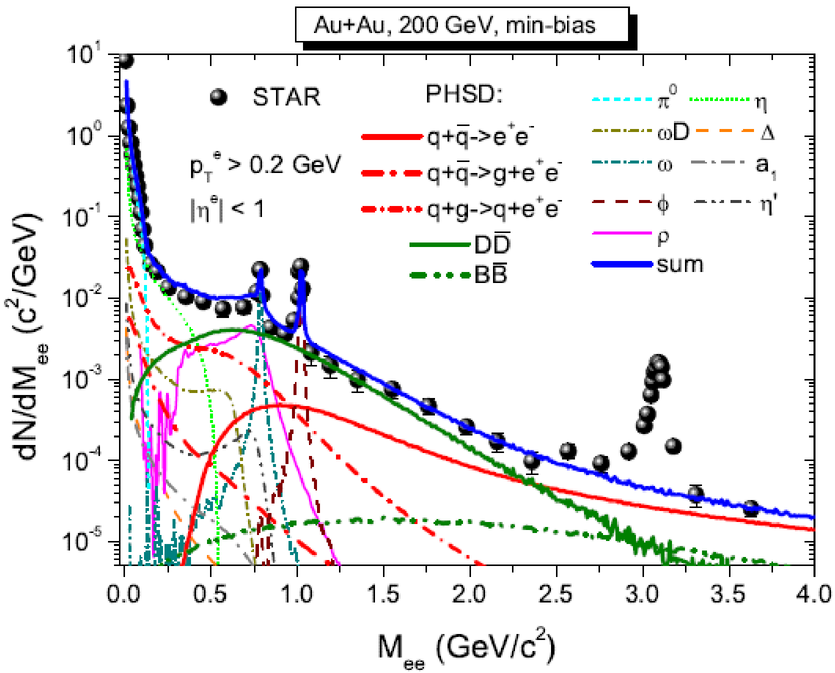
Message: **STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP**

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

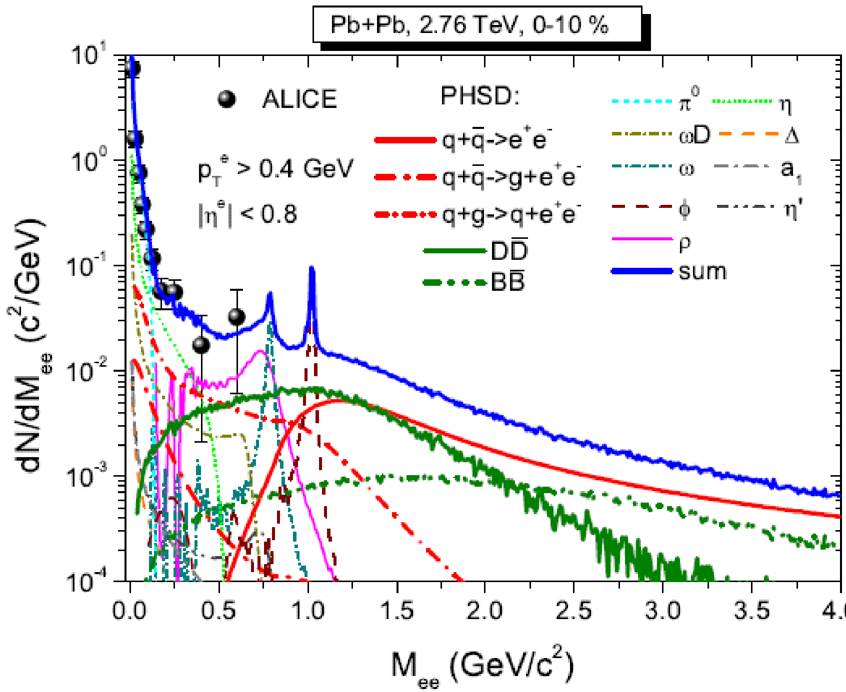


Dileptons at RHIC and LHC

RHIC



LHC



Message:

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

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

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

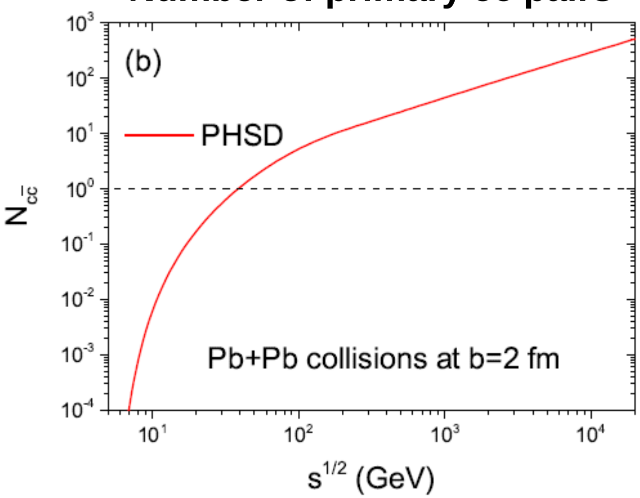
T. Song et al., 20018

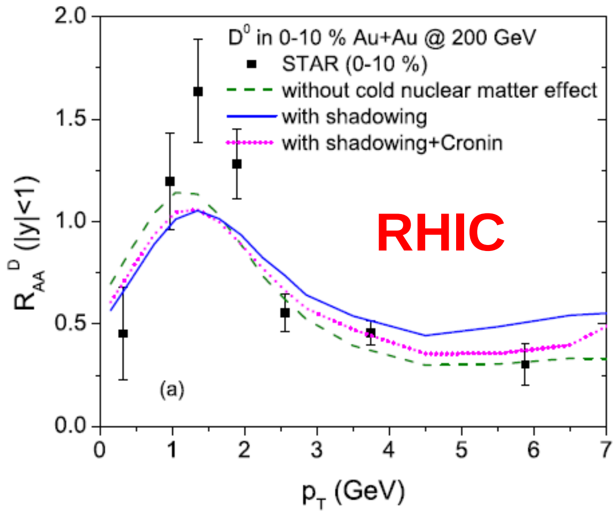
Charm at RHIC and LHC

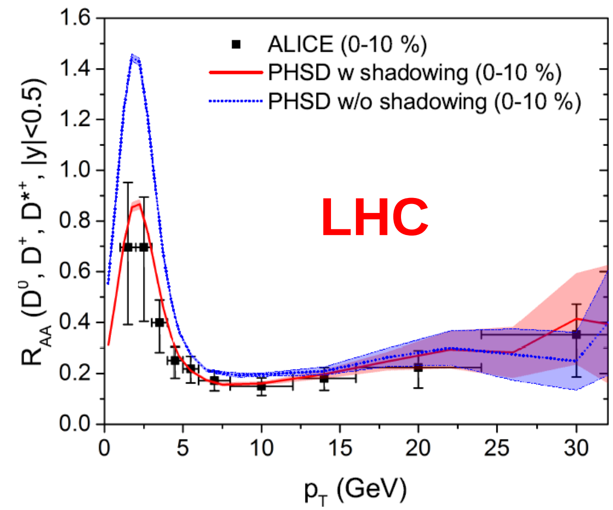
In order to get **information about the QGP in HIC via dileptons**, the **charm dynamics must be under control**

→ **PHSD vs charm observables at RHIC and LHC**

Number of primary cc pairs



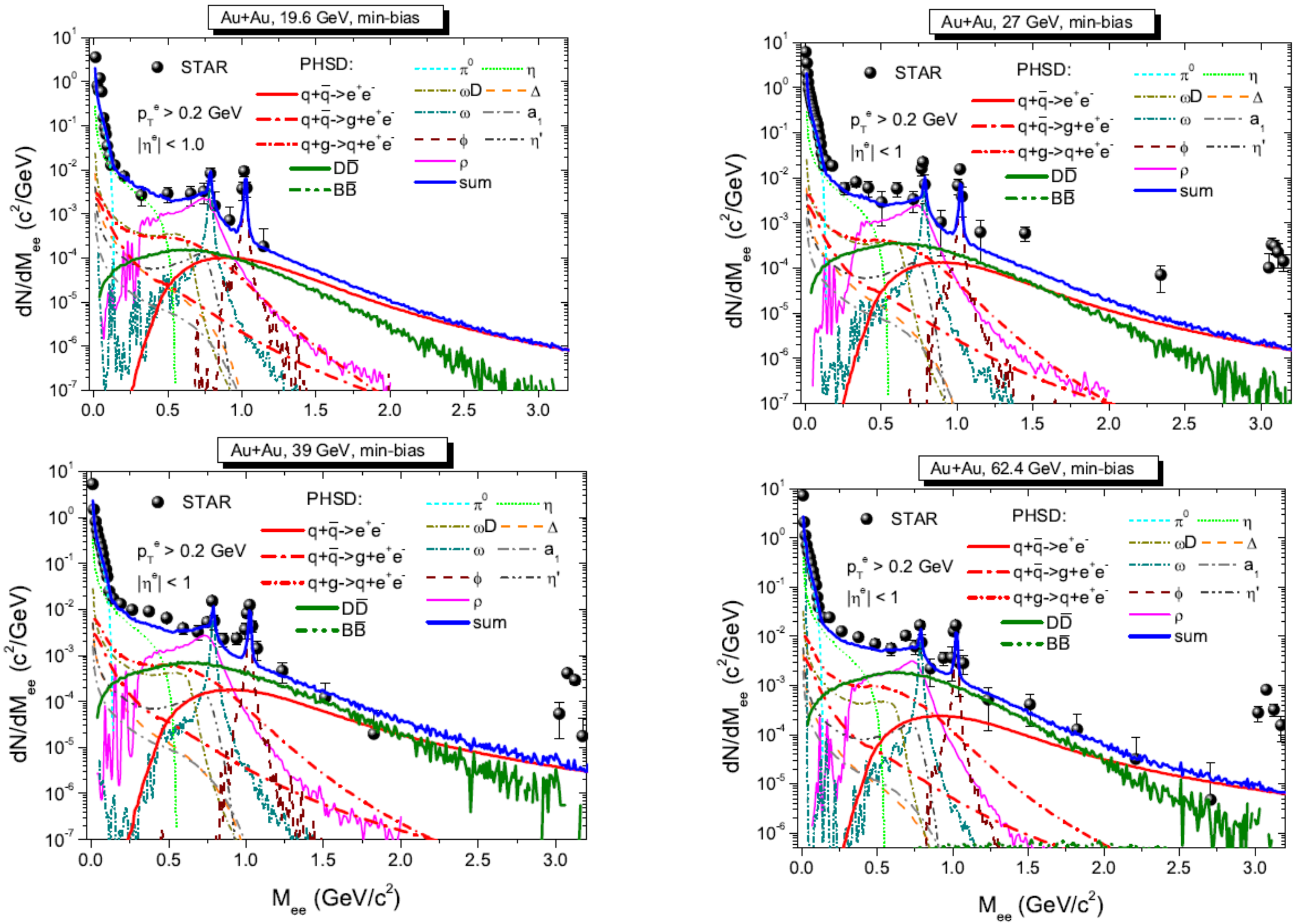




- The **exp. data** for the R_{AA} and v_2 at RHIC and LHC are described in the PHSD by **QGP collisional energy loss** due to **elastic scattering** of charm quarks with massive quarks and gluons in the QGP phase
  - \+ by the **dynamical hadronization scenario** „coalescence & fragmentation“
  - \+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

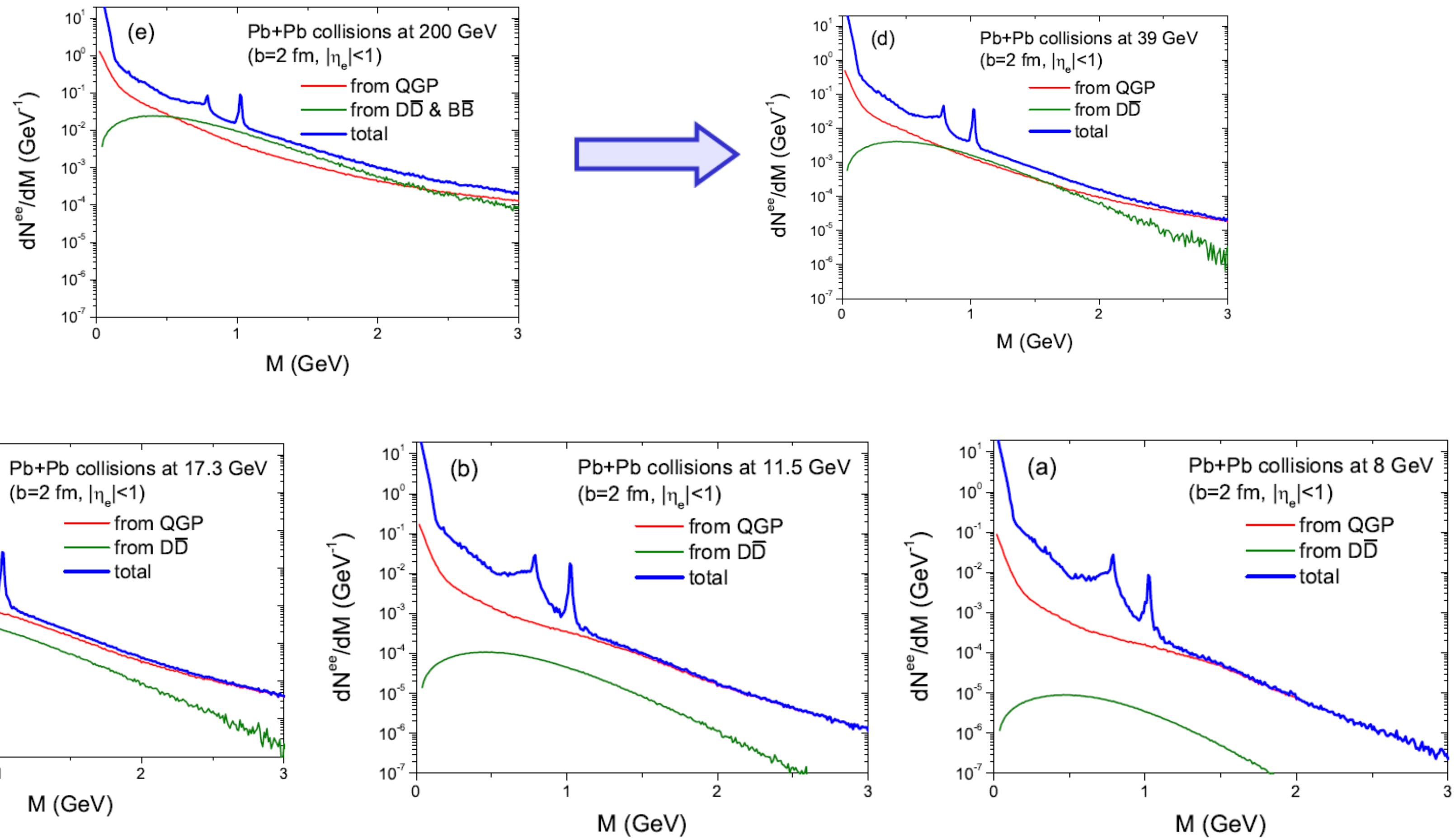
T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

Dileptons from RHIC BES: STAR



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

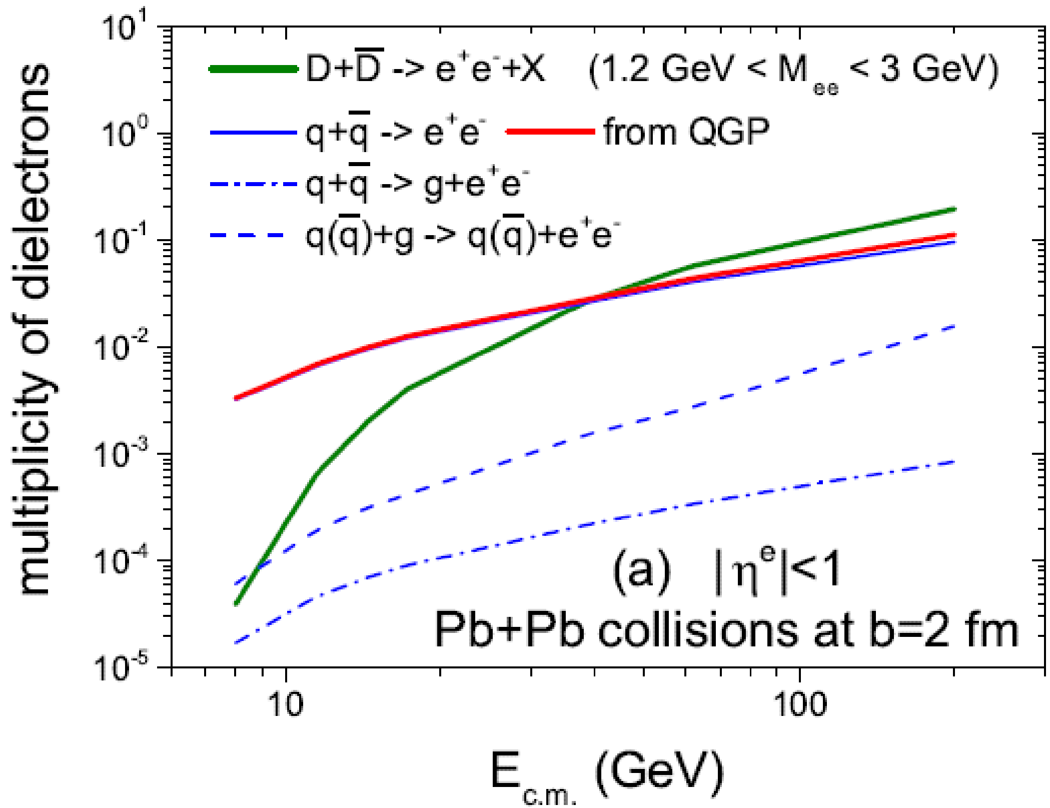


Relative contribution of QGP versus charm increases with decreasing energy!

Dileptons: QGP vs charm

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

mid-rapidity $|\eta_e|<1$



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

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

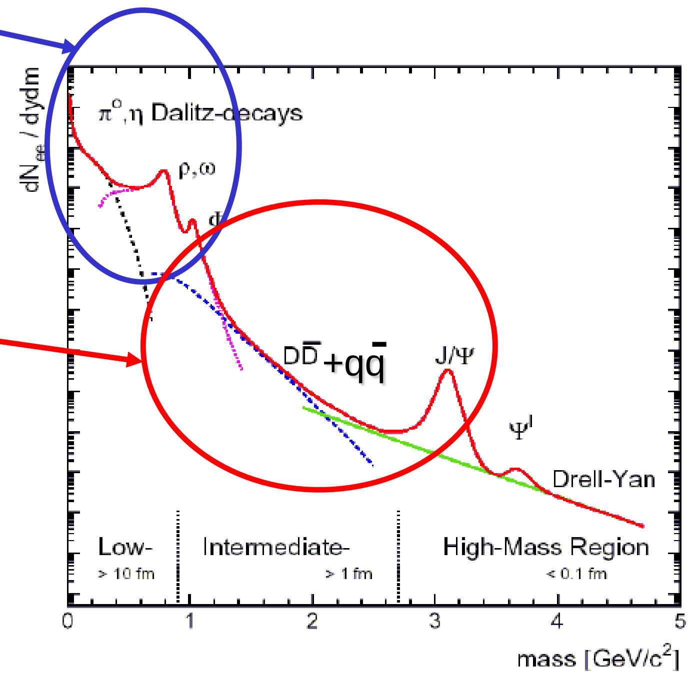
- **In-medium effects** can be observed at **all energies from SIS to LHC; excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon-density phase

❑ 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 the 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 et al., in preparation, 2018