

Dileptons from heavy-ion collisions at SIS and FAIR/NICA energies

Wolfgang Cassing
for the PHSD group

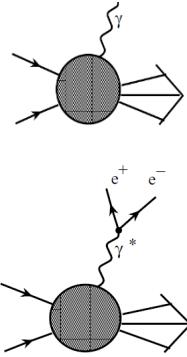


Tel Aviv
March 28th 2017

Modelling of photon/dilepton emission

I. Emission rate from thermal field theory:

Feinberg (76), McLerran, Toimela (85),
Weldon (90), Gale, Kapusta (91)



- **Photons:** $q_0 \frac{d^3 R}{d^3 q} = -\frac{g_{\mu\nu}}{(2\pi)^3} \text{Im } \Pi^{\mu\nu}(q_0 = |\vec{q}|) f(q_0, T)$

- **Dileptons:** $E_+ E_- \frac{d^3 R}{d^3 p_+ d^3 p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{q^4} L_{\mu\nu} \text{Im } \Pi^{\mu\nu}(q_0, \vec{q}) f(q_0, T)$

- $L_{\mu\nu}$ is the electromagnetic leptonic tensor

- $\Pi_{\mu\nu}$ is the retarded photon self energy at finite T : $\Pi_{\mu\nu} \sim i \int d^4 x e^{ipx} \langle [J_\mu(x), J_\nu(0)] \rangle_T$

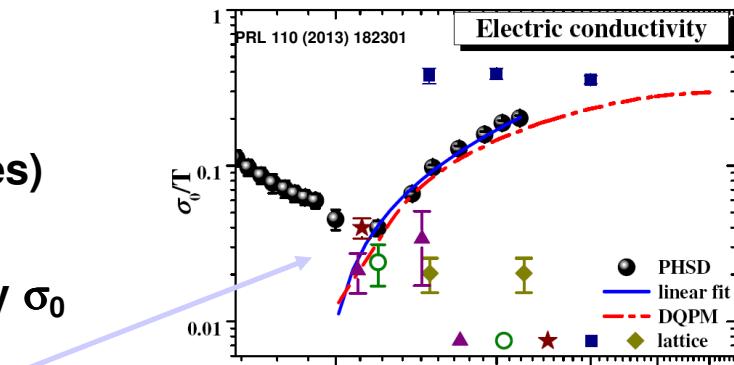
□ Hadron phase: using VDM: $\text{Im}\Pi \sim \text{Im}D^\rho$ in-medium ρ -meson spectral function from many-body approach (cf. Rapp, Chanfrey, Wambach, NPA 617 (1997) 472)

→ study of the in-medium properties of hadrons at high baryon density and T

→ restoration of chiral symmetry (ρ -a₁):
 $\text{Im}D^\rho \sim$ chiral condensate (by Weinberg sum rules)
 (cf. Hohler, Rapp, arXiv:1311.2921)

□ Rates at $q_0 \rightarrow 0$ are related to electric conductivity σ_0
 → Probe of electric properties of the QGP

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

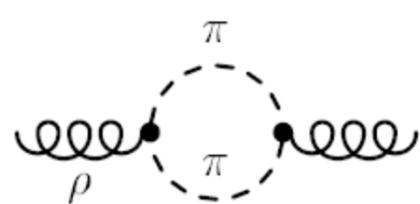


PHSD plot from Cassing et al., PRL 110 (2013) 182301;
 cf. also NJL: Marty et al., PRC87 (2013) 3, 034912

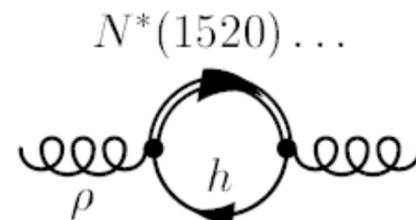
The in-medium rho-meson propagator

$$D_{\rho}^{L,T}(q_0, q; \mu_B, T) = \frac{1}{M^2 - m_V^2 - \Sigma_{\rho\pi\pi}^{L,T} - \Sigma_{\rho M}^{L,T} - \Sigma_{\rho B}^{L,T}}$$

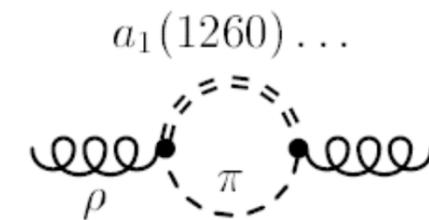
depends on medium-dependent selfenergies that include



(a)



(b)



(c)

modifications of the 2-pion decay, scatterings with baryons and mesons

cf. talk by Ralf

Modelling of the space-time evolution

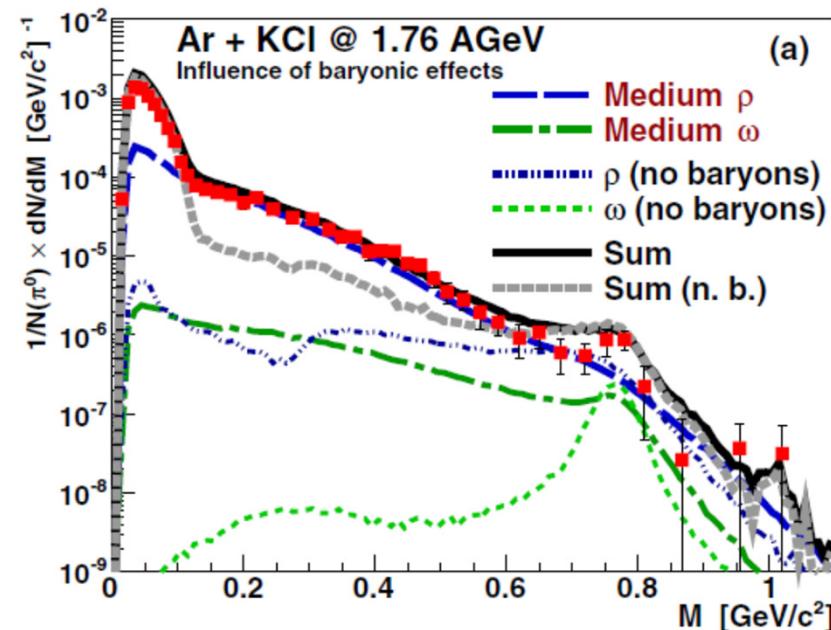
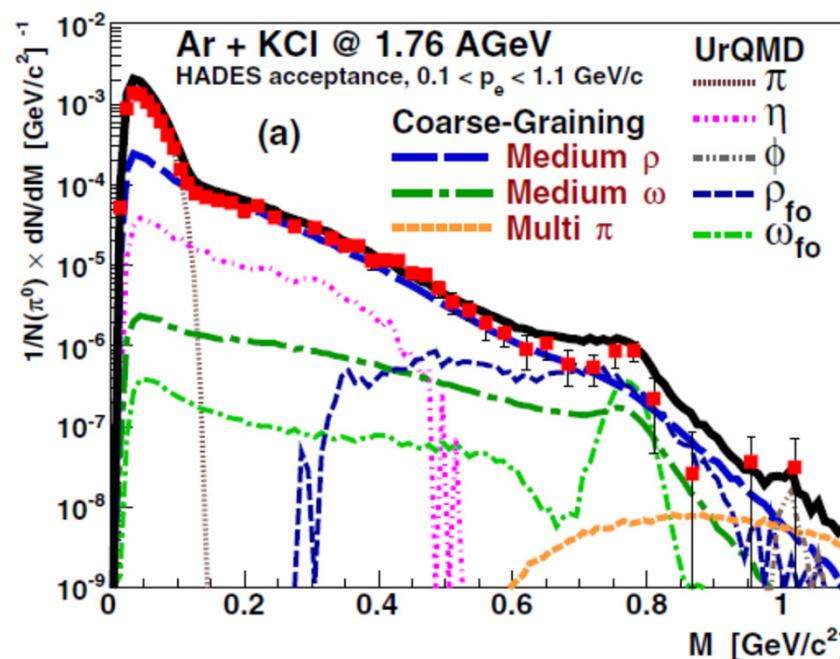
- a) Fit a **fireball evolution** to asymptotic particle spectra and integrate the microscopic dilepton rate in space-time over the fireball evolution; **open question:** is the assumption of thermal and chemical equilibrium justified?
- b) **Coarse-grained transport models:** calculate energy-momentum tensor and charge current in local cells by averaging over many events:

$$T^{\mu\nu} = \int d^3 p \frac{p^\mu p^\nu}{p^0} f(\vec{x}, \vec{p}, t) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_h \in \Delta V} \frac{p_i^\mu \cdot p_i^\nu}{p_i^0} \right\rangle,$$

$$j_B^\mu = \int d^3 p \frac{p^\mu}{p^0} f_B(\vec{x}, \vec{p}, t) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_{B/B} \in \Delta V} \pm \frac{p_i^\mu}{p_i^0} \right\rangle.$$

This defines a local 'temperature' and chemical potential assuming chemical equilibrium; then integrate a microscopic dilepton rate in space-time

Results from UrQMD at SIS energies



Large effect of a finite baryon density on the low-mass dilepton spectra!

Baryon-hole loops or meson-baryon scatterings drive the enhancement!

Modelling of photon/dilepton emission

II. Emission rate from relativistic kinetic theory:
(e.g. for $1+2 \rightarrow \gamma+3$)

Applicable also for
non-equilibrium
systems !

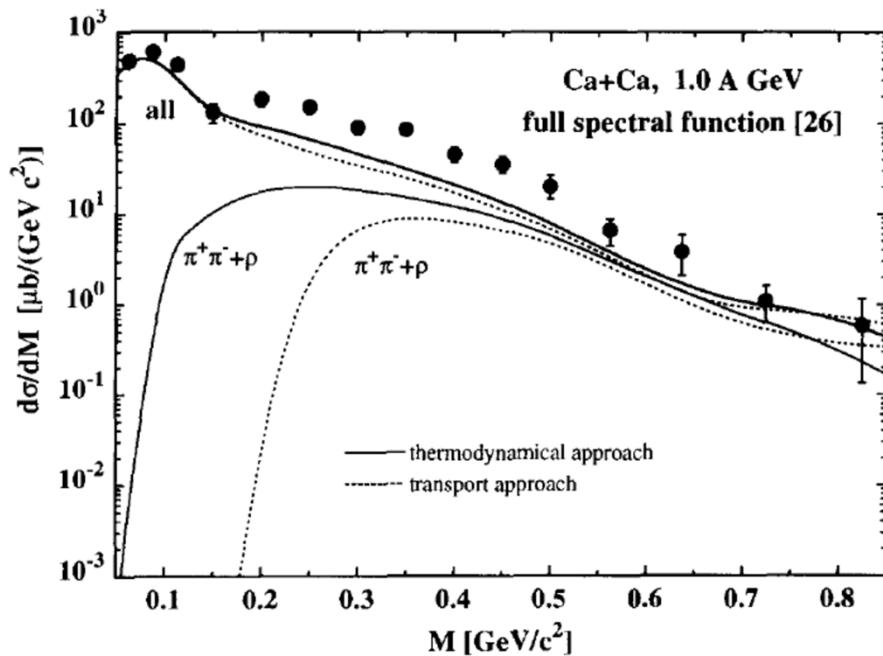
$$q_0 \frac{d^3 R}{d^3 q} = \int \frac{d^3 p_1}{2(2\pi)^3 E_1} \frac{d^3 p_2}{2(2\pi)^3 E_2} \frac{d^3 p_3}{2(2\pi)^3 E_3} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - q) \\ \times |M|^2 \frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}$$

■ $f(E)$ - distribution function

- M – invariant scattering matrix element from microscopic models
- Modelling of hadronic elementary reactions:
Chiral models, OBE models,... (Born-type diagrams)
- Problems:
 - very limited experimental information on mm, mB elementary reactions
 - Hadrons change their properties in the hot and dense medium:
→ from vacuum cross sections to in-medium, i.e.
from 'T-matrix' to 'G-matrix' approaches (many-body theory)

E.g. : ρ -meson collisional broadening – important for dilepton studies!

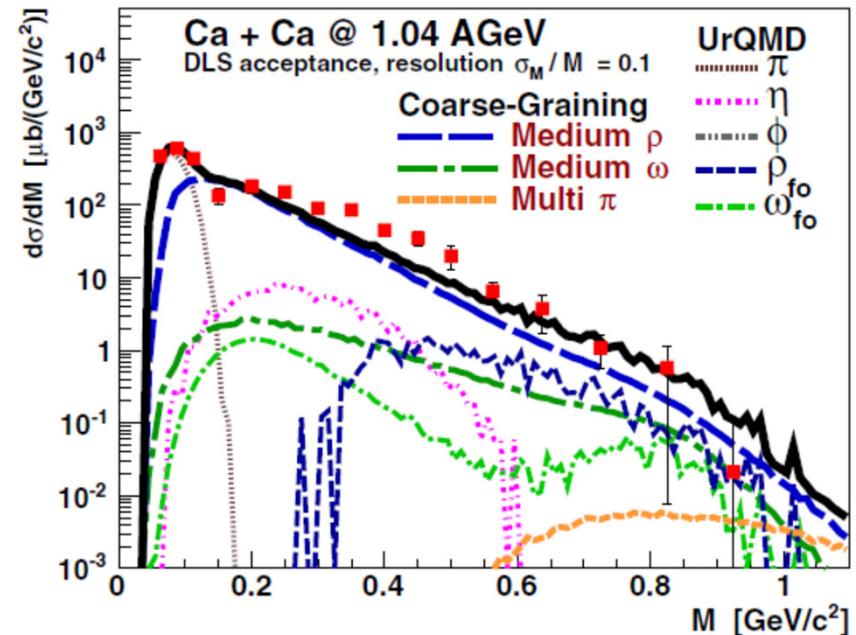
HSD coarse-grained with a microscopic dilepton rate



Dilepton production and m_T -scaling
at BEVALAC/SIS energies *

E.L. Bratkovskaya^a, W. Cassing^a, R. Rapp^b, J. Wambach^c

Nuclear Physics A 634 (1998) 168–189

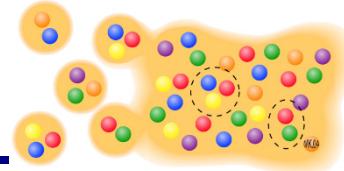


S. Endres et al., PRC 92 (2015) 014911

Only small differences between old
on-shell transport (HSD) and
coarse-grained microscopic spectra

What about a full off-shell quantum transport?

From SIS to LHC: from hadrons to partons



The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma on a **microscopic level**

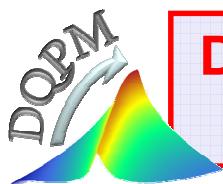
→ need a **consistent non-equilibrium transport approach on the level of propagators to incorporate dynamical spectral functions!**

- with explicit **parton-parton interactions** (i.e. between quarks and gluons)
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **IQCD EoS** for partonic phase (‘cross over’ at $\mu_q=0$)
- **Transport theory for strongly interacting systems:** off-shell Kadanoff-Baym equations for the Green-functions $S_h^<(x,p)$ in phase-space representation for the **partonic** and **hadronic phase**



Parton-Hadron-String-Dynamics (PHSD)

QGP phase is described by



**Dynamical QuasiParticle Model
(DQPM)**

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

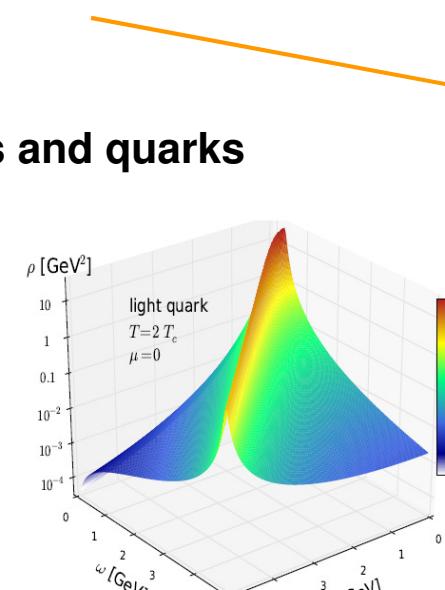
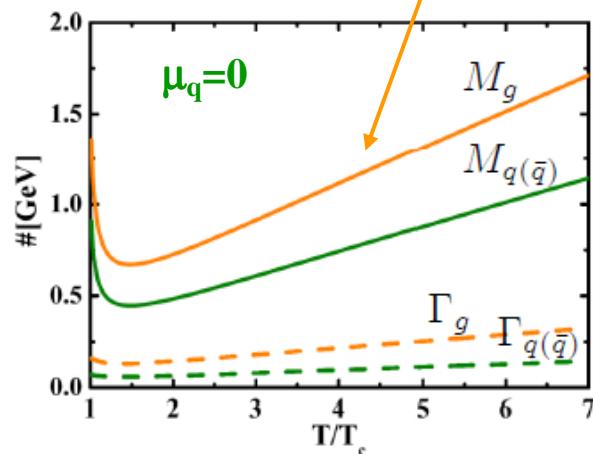
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365; NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

- Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, \bar{q}) with Lorentzian spectral functions :

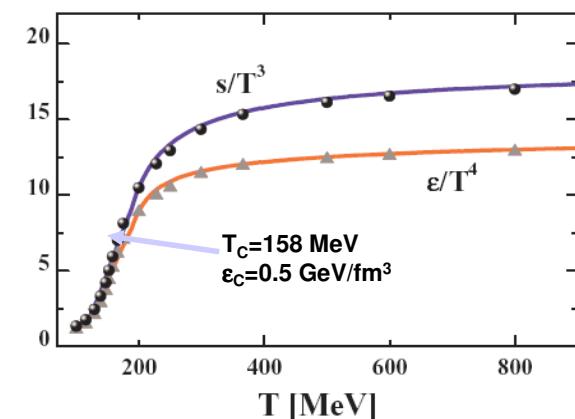
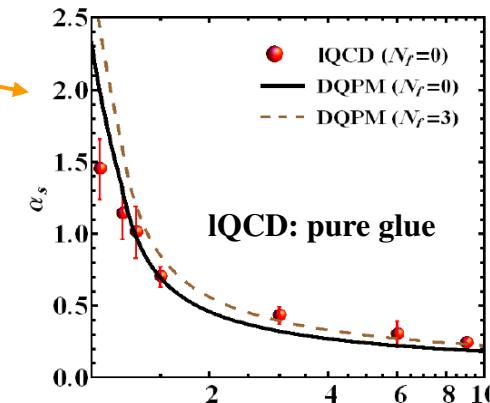
- fit to lattice (IQCD) results
(e.g. entropy density) with 3 parameters
- T-dependent $\alpha_s(T)$

→ Quasi-particle properties:
large width and mass for gluons and quarks

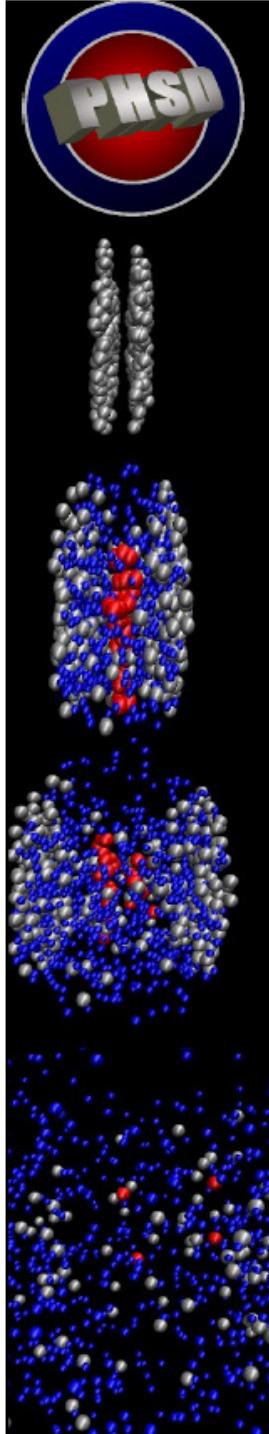


$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

$(i = q, \bar{q}, g)$

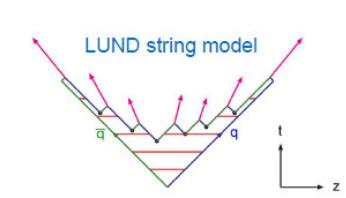


- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons
→ PHSD

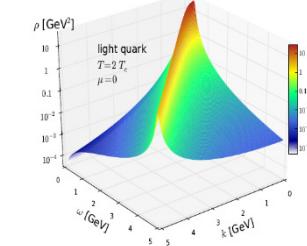


Parton-Hadron-String-Dynamics (PHSD)

- **Initial A+A collisions – HSD:**
 $N+N \rightarrow$ string formation \rightarrow decay to ‘pre-hadrons’

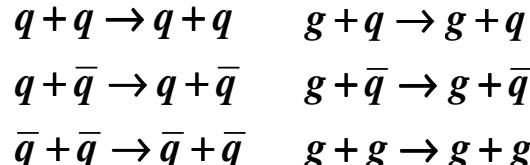


- **Formation of QGP stage if $\varepsilon > \varepsilon_{\text{critical}}$:**
dissolution of pre-hadrons \rightarrow (DQPM) \rightarrow
→ massive quarks/gluons + mean-field potential U_q

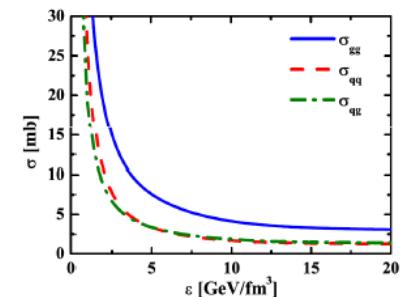
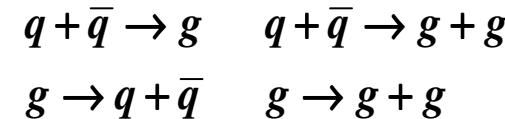


- **Partonic stage – QGP :**
based on the **Dynamical Quasi-Particle Model (DQPM)**

▪ **(quasi-) elastic collisions:**

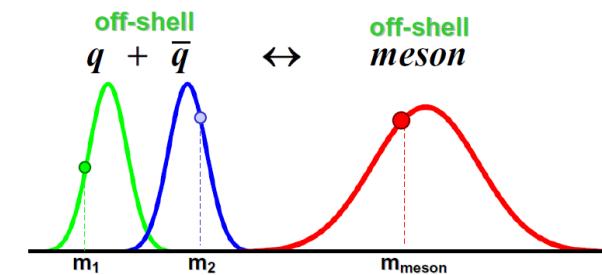


▪ **inelastic collisions:**



- **Hadronization (based on DQPM):**

$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow \text{meson (or 'string')} \\ q + q + q \leftrightarrow \text{baryon (or 'string')}$$

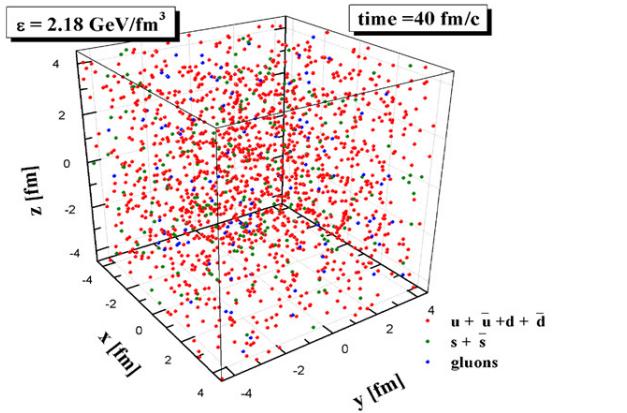


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**



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

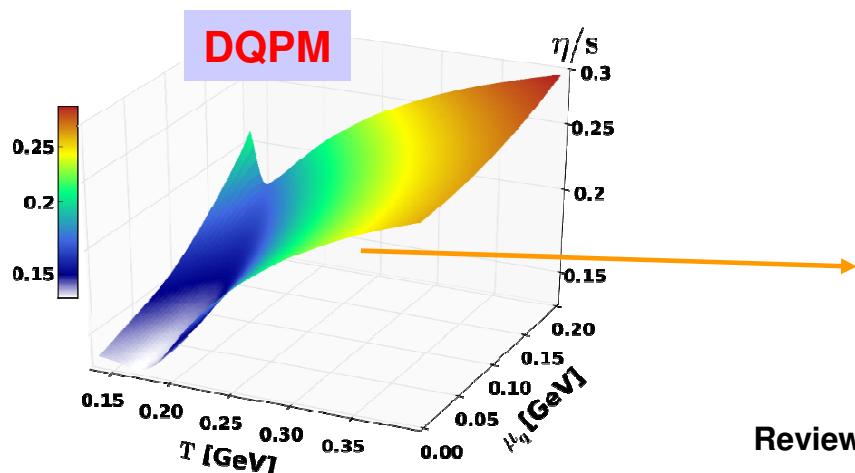
Infinite hot/dense matter =
PHSD in a box:



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

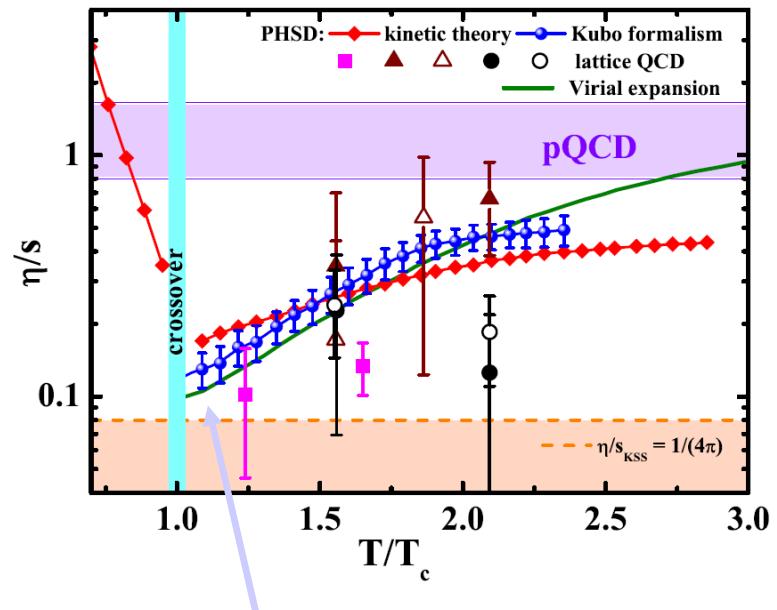
IQCD:

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



Shear viscosity η/s at finite T

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



QGP in PHSD = strongly-interacting partonic system

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

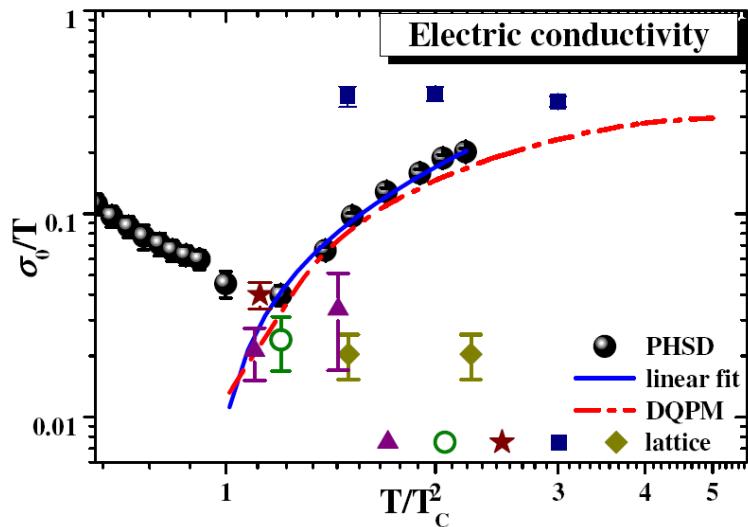
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003 ₁₁

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

PHSD in a box:

Electric conductivity σ_e/T at finite T

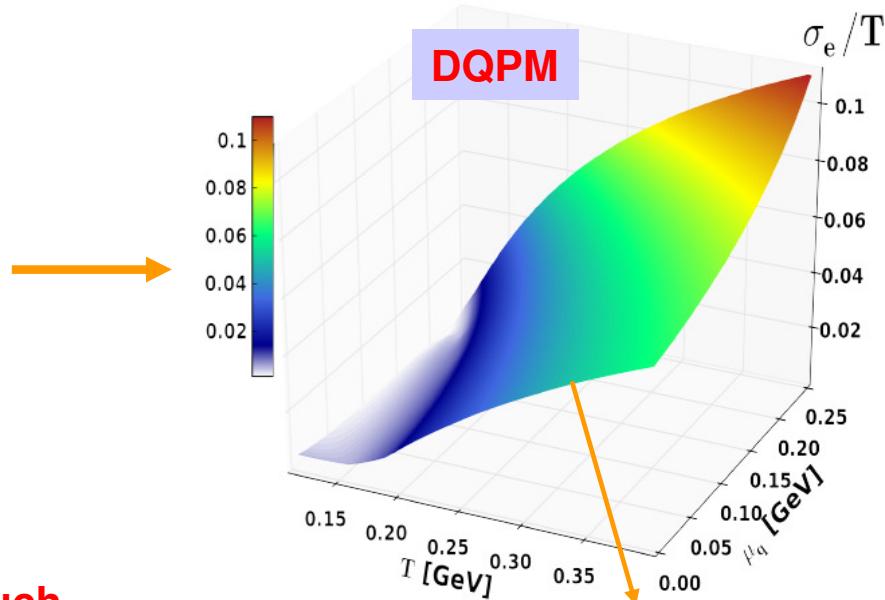
W. Cassing et al., PRL 110(2013)182301



- the QCD matter even at $T \sim T_c$ 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. arXiv:1412.1017

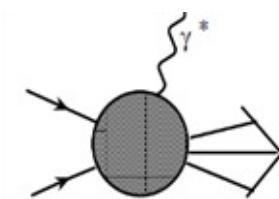


$\sigma_e/T : \mu_q=0 \rightarrow$ finite μ_q : smooth increase as a function of (T, μ_q)

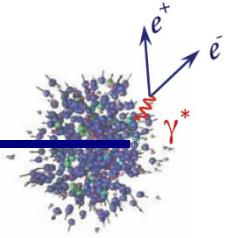
- Photon emission: rates at $q_0 \rightarrow 0$ are related to electric conductivity σ_0

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

$\sigma_0 \rightarrow$ Probe of electric properties of the QGP



Dilepton sources

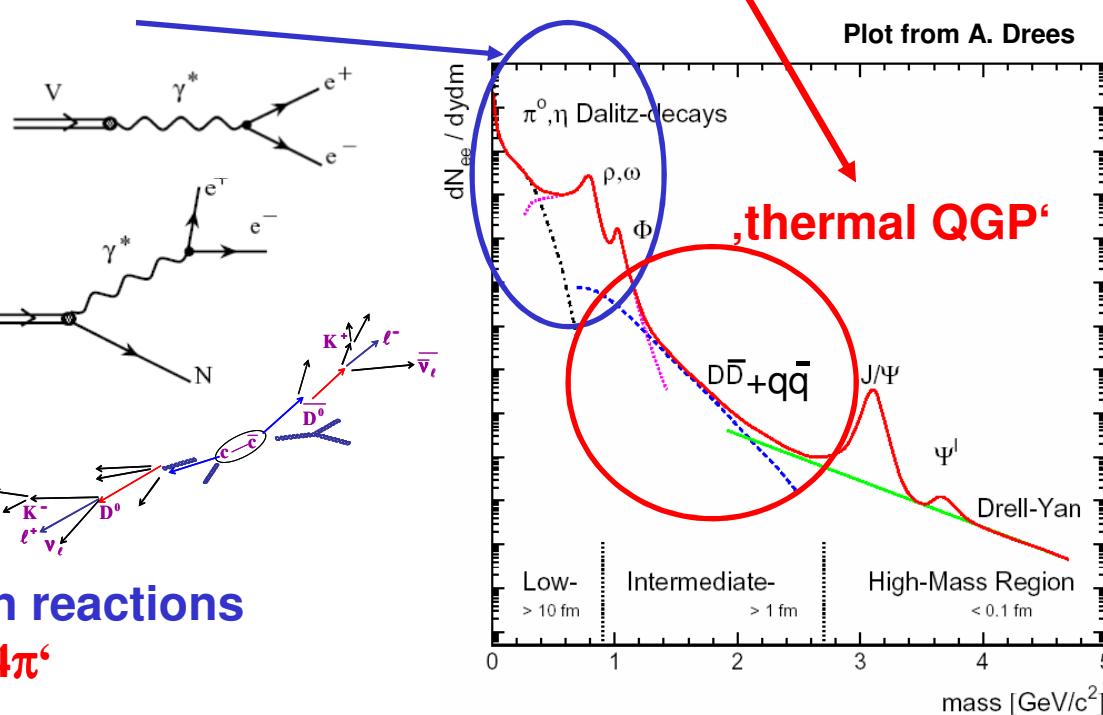


□ from the QGP via partonic (q, \bar{q}, g) interactions:

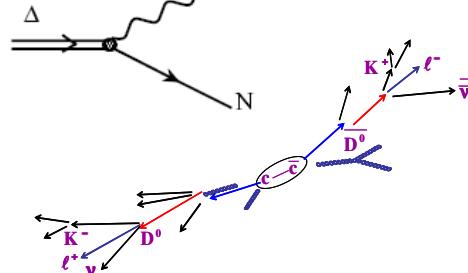


□ from hadronic sources:

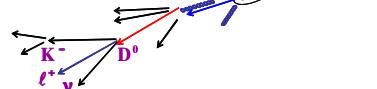
- direct decay of vector mesons ($\rho, \omega, \phi, J/\Psi, \Psi'$)



- Dalitz decay of mesons and baryons ($\pi^0, \eta, \Delta, \dots$)



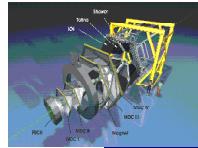
- correlated D+Dbar pairs



- 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

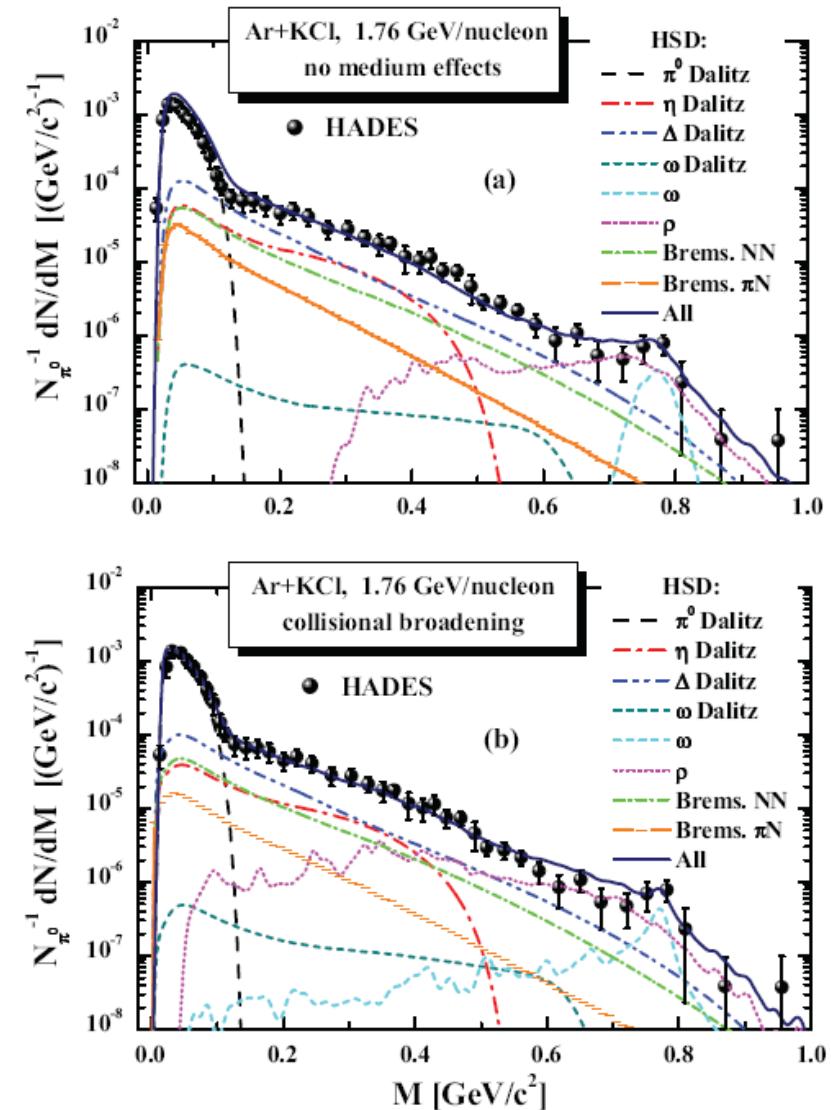
□ **HADES:** dilepton yield dN/dM scaled with the number of pions N_{π^0}

□ Dominant hadronic sources at $M > m_\pi$:

- η, Δ Dalitz decays
- NN bremsstrahlung
- direct ρ decay

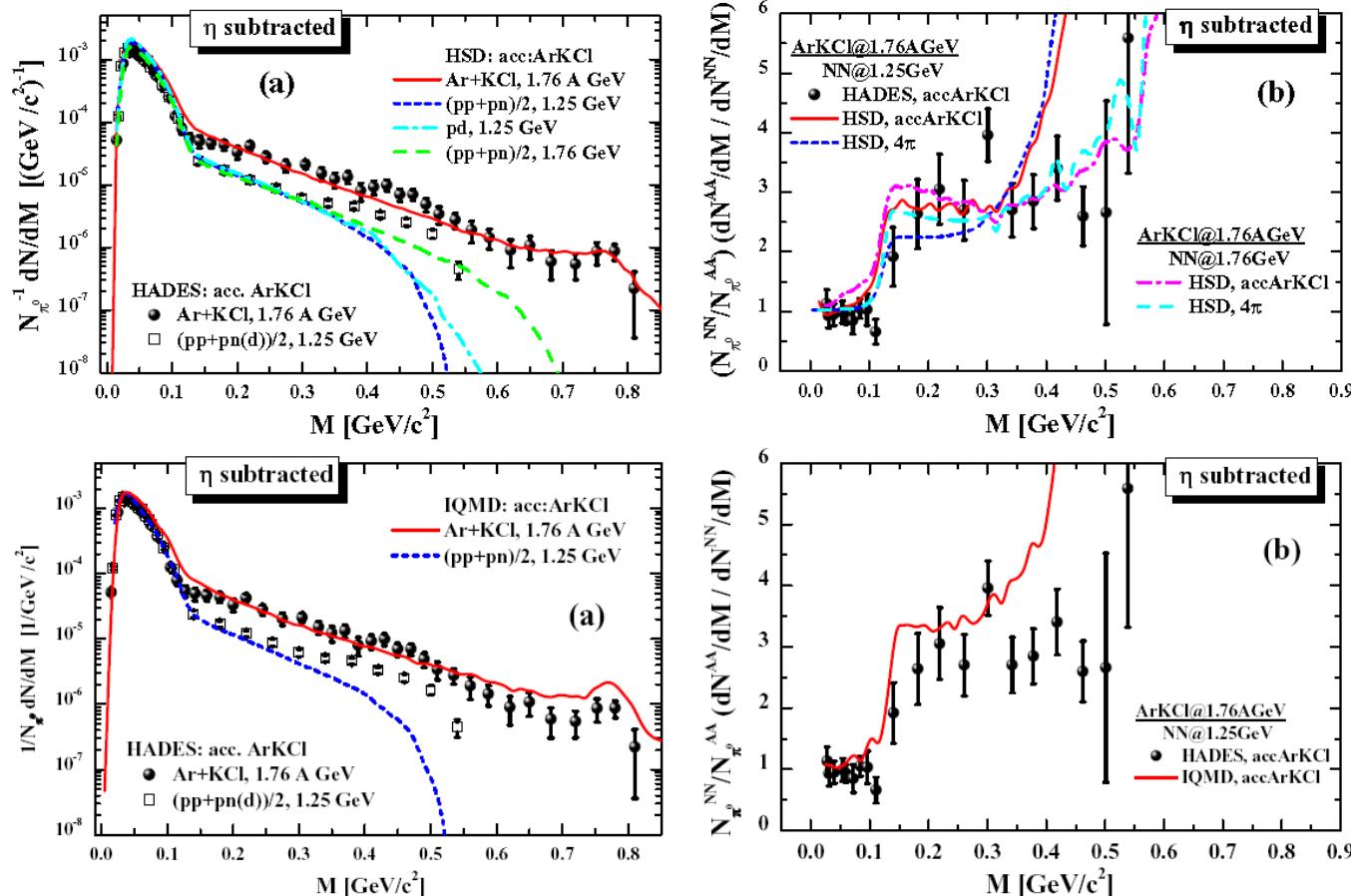
➤ ρ meson = strongly interacting resonance
strong collisional broadening of the ρ width

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



Dileptons at SIS energies: A+A vs. N+N

- ratio of AA/NN spectra (scaled by $N_{\pi0}$) after subtracted η contribution



▪ HSD

▪ IQMD

→ Strong enhancement of dilepton yield in A+A vs. NN is reproduced by HSD and IQMD for C+C at 1.0, 2.0 A GeV and Ar+KCl at 1.75 A GeV

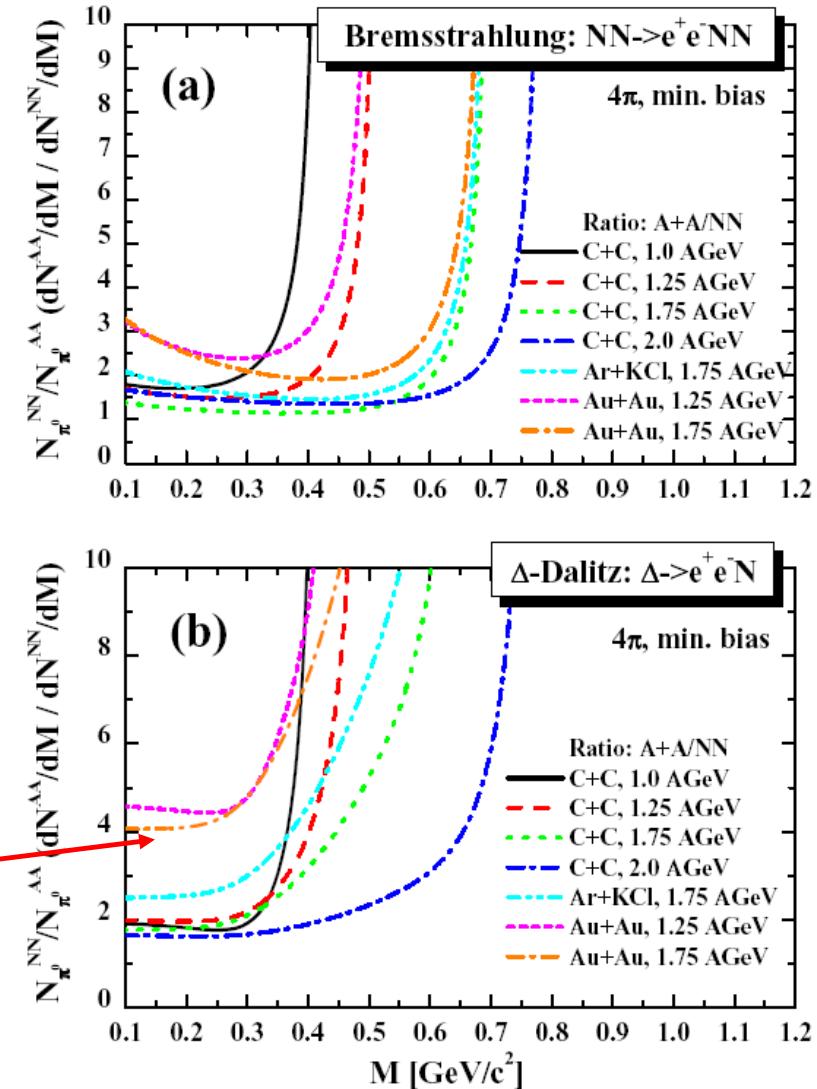
Dileptons at SIS (HADES): A+A vs NN

- Two contributions to the enhancement of dilepton yield in A+A vs. NN

1) the **pN bremsstrahlung** which scales with the number of collisions and not with the number of participants, i.e. pions;

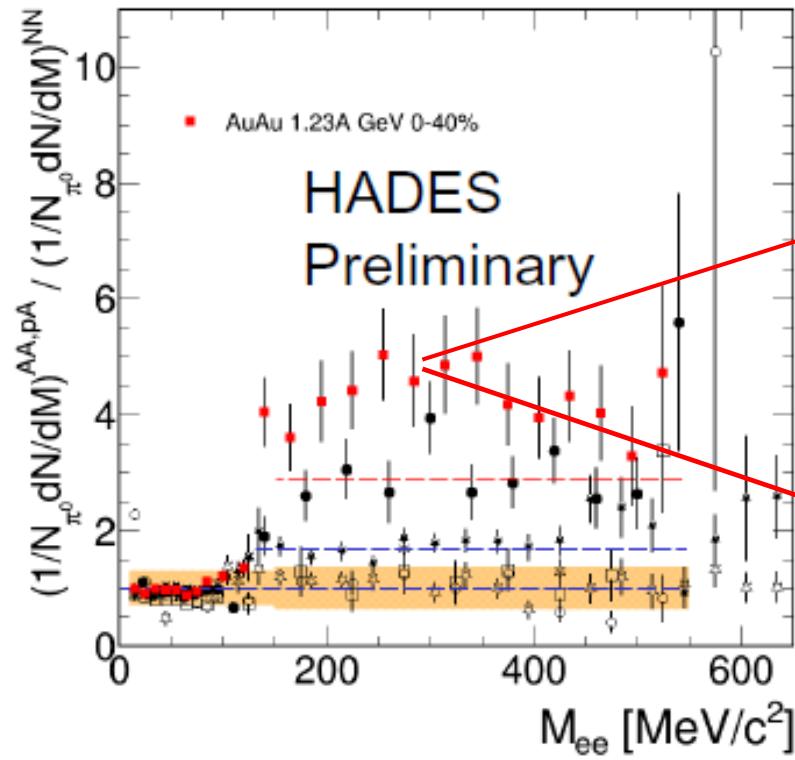
2) the **multiple Δ regeneration** – dilepton emission from intermediate Δ 's which are part of the reaction cycles $\Delta \rightarrow \pi N$; $\pi N \rightarrow \Delta$ and $NN \rightarrow N\Delta$; $N\Delta \rightarrow NN$

- Enhancement of dilepton yield in A+A vs. NN increases with the system size!



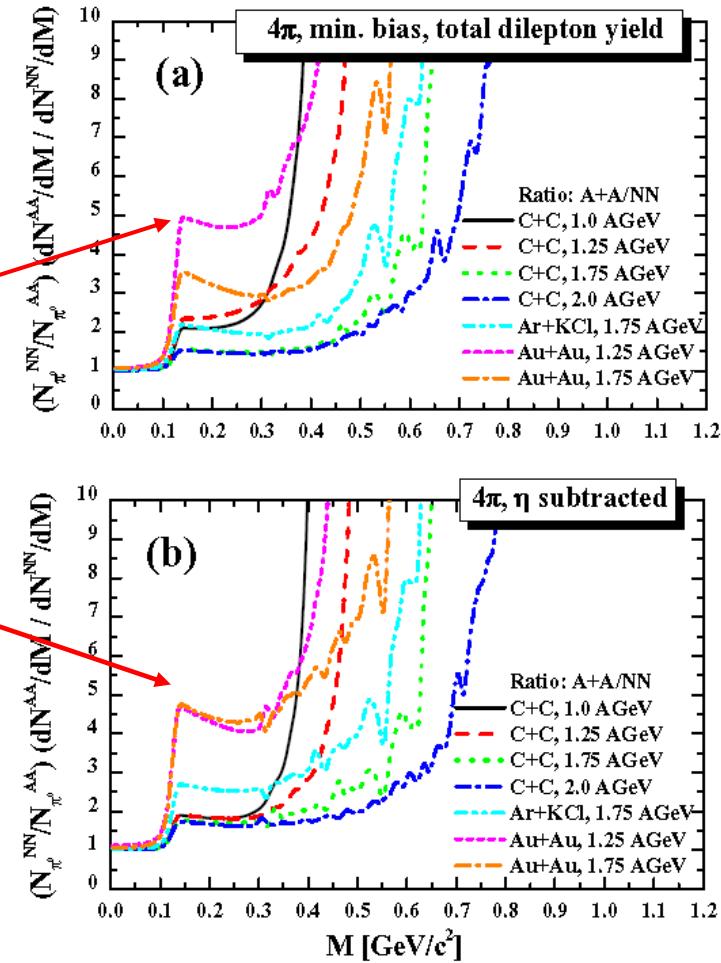
Dileptons at SIS (HADES): Au+Au

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

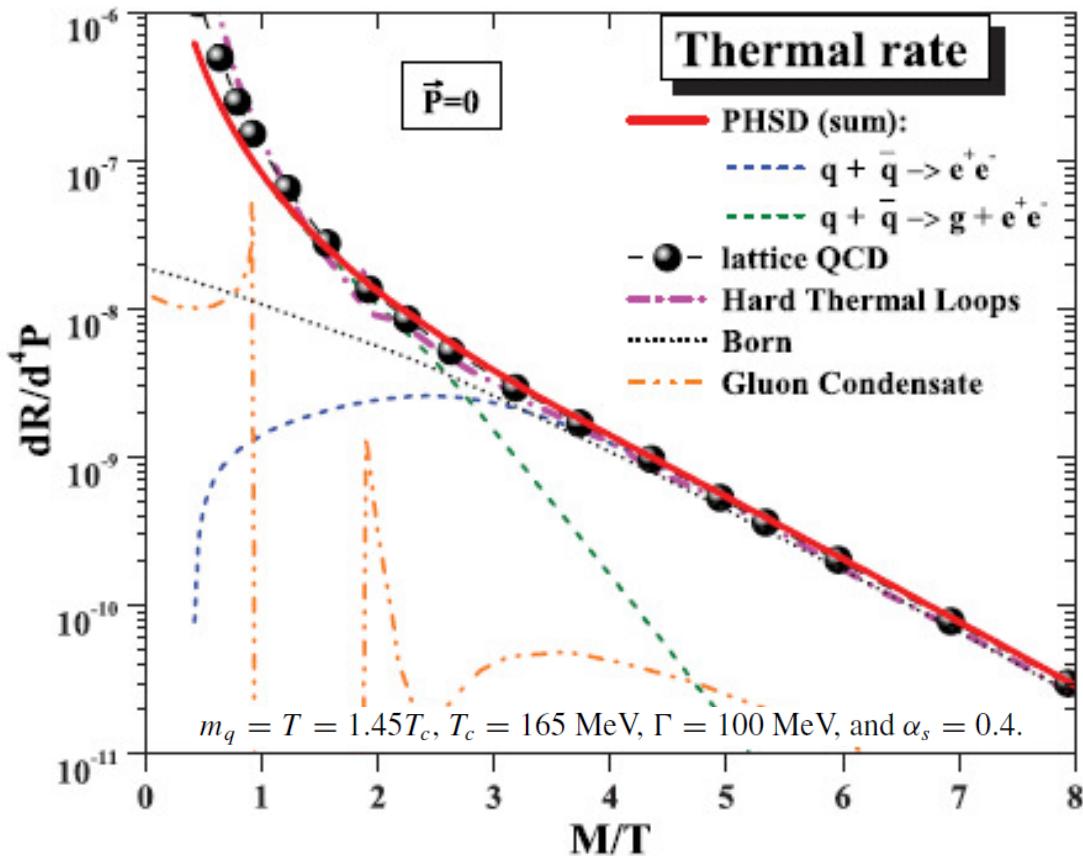


- Strong in-medium enhancement of dilepton yield in Au+Au vs. NN
- related to Δ regeneration !

▪ HSD predictions (2013)



Thermal dilepton rates in lattice QCD



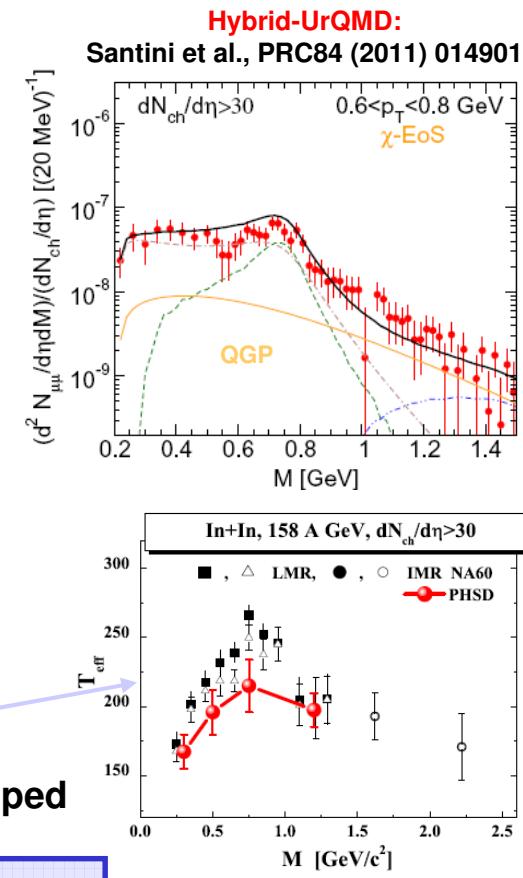
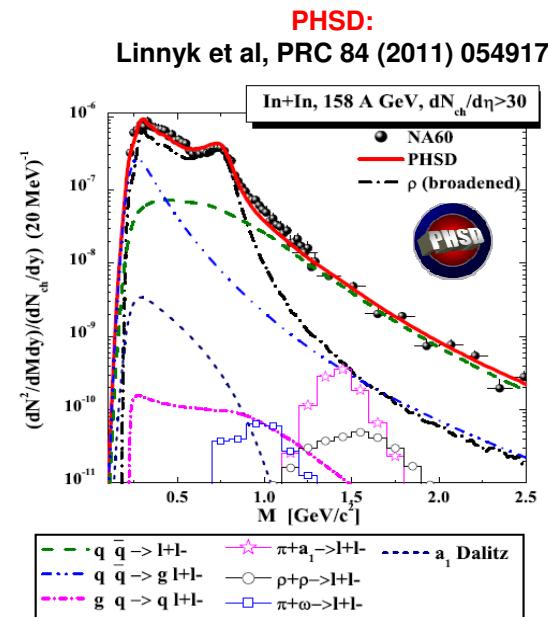
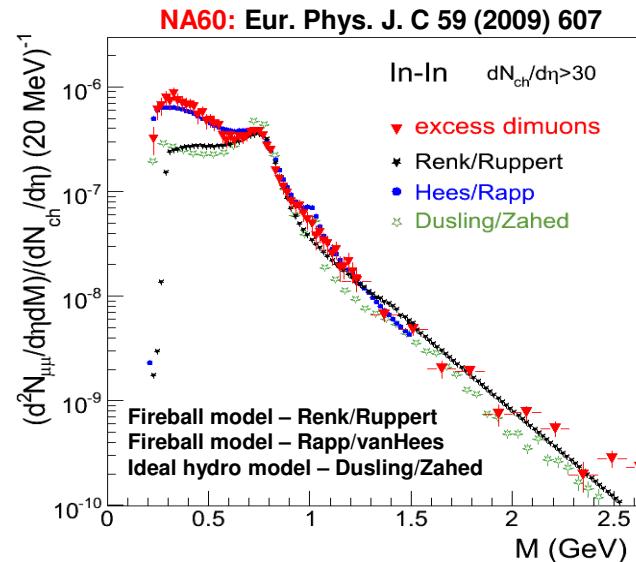
Dileptons from dynamical off-shell quark and gluon interactions,
LO and NLO in the coupling

- LQCD: H.-T.Ding, A. Francis, O. Kaczmarek, F. Karsch, E. Laermann, W. Soeldner, Phys. Rev. D 83, 034504 (2011).
- HTL: E. Braaten, R. D. Pisarski, T.-C. Yuan, Phys. Rev. Lett. 64, 2242 (1990)
- Born: J. Cleymans, J. Fingberg, K. Redlich, Phys. Rev. D 35, 2153 (1987)
- Gluon Condensate: C. Greiner, N. Haque,M. G.Mustafa, M. H. Thoma, Phys. Rev. C 83, 014908 (2011).

- Quantitative agreement of DQPM, lattice QCD and HTL

Lessons from SPS: NA60

□ Dilepton invariant mass spectra:

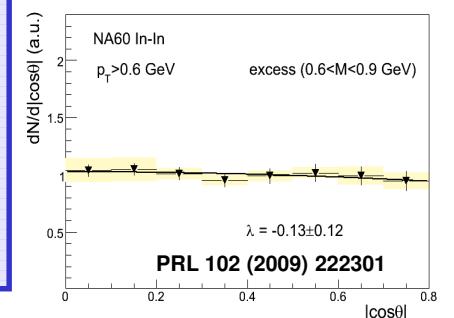


□ Inverse slope parameter T_{eff} :

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

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

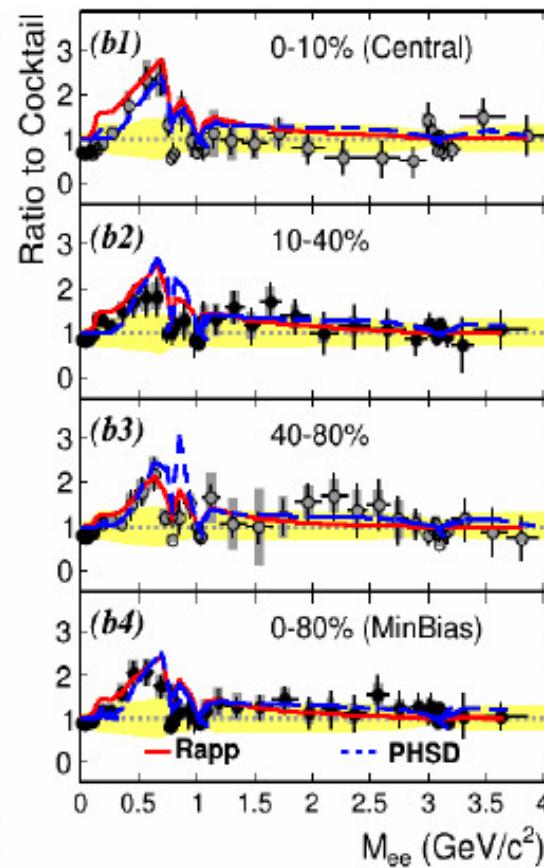
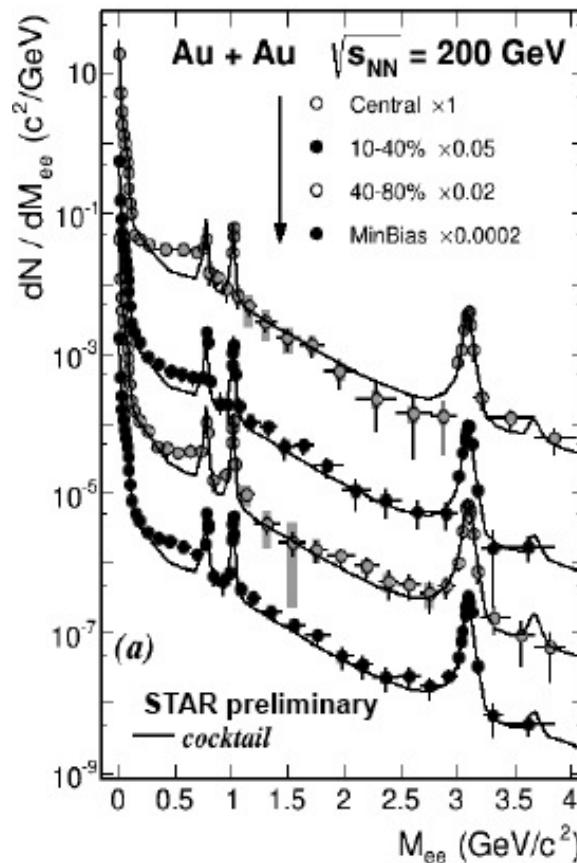
- 1) Low mass spectra - evidence for the **in-medium broadening of rho-mesons**
- 2) Intermediate mass spectra above 1 GeV - dominated by **partonic radiation**
- 3) The rise and fall of T_{eff} – evidence for the thermal **QGP radiation**
- 4) Isotropic angular distribution – indication for a **thermal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



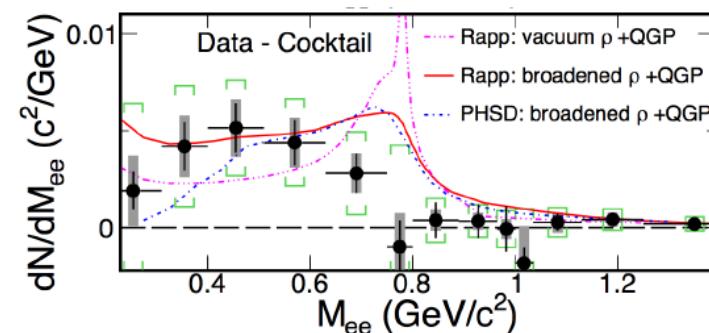
Dileptons at RHIC: STAR data vs model predictions

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

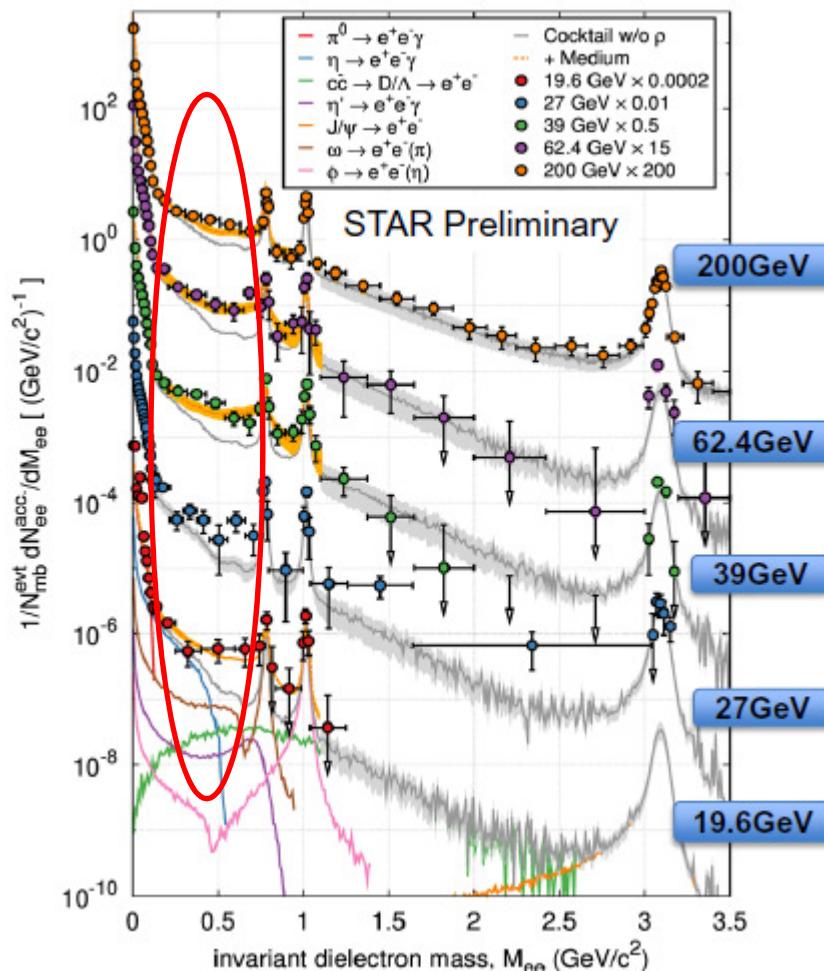
Intermediate masses:

QGP dominant

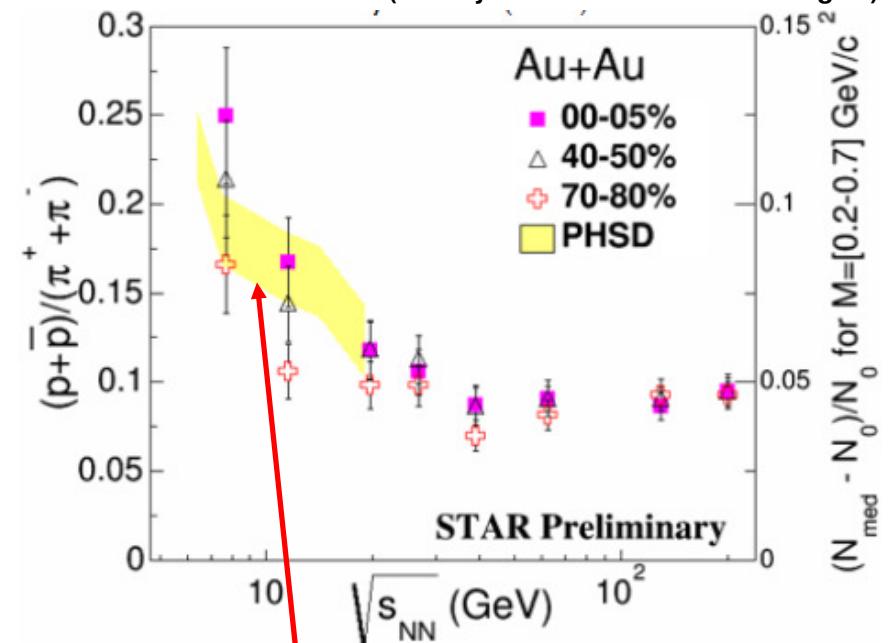
Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

Dileptons from RHIC BES: STAR

(Nu Xu in 2014)



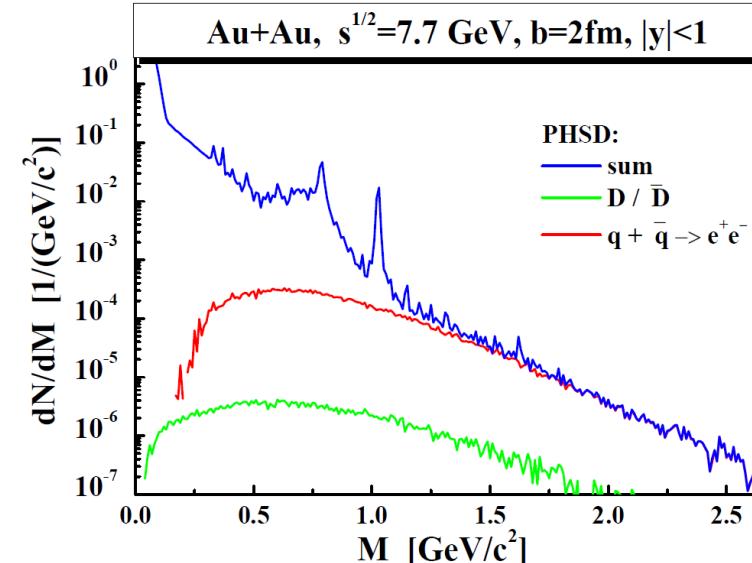
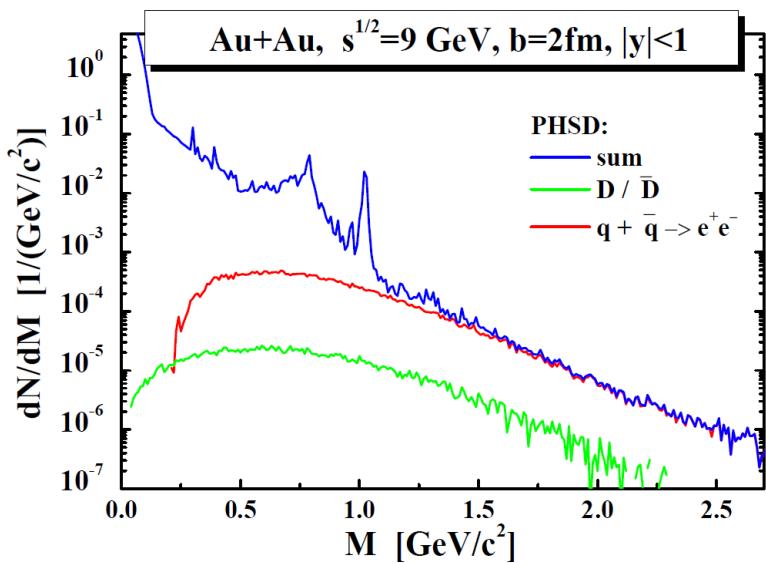
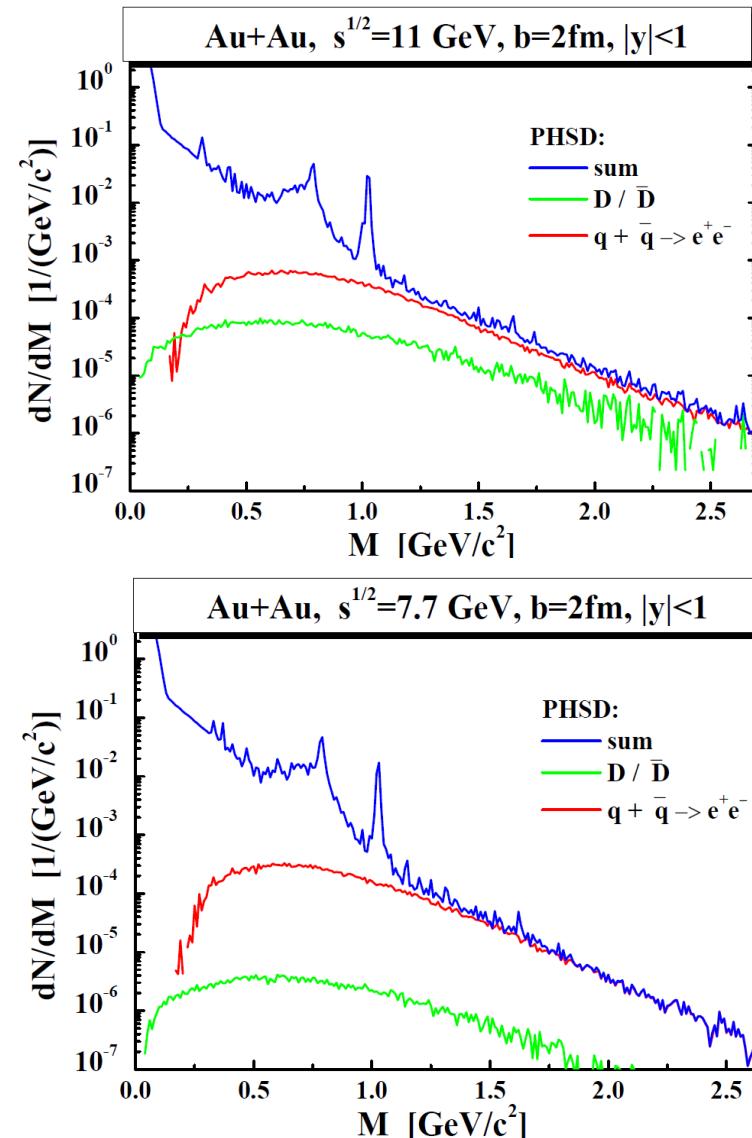
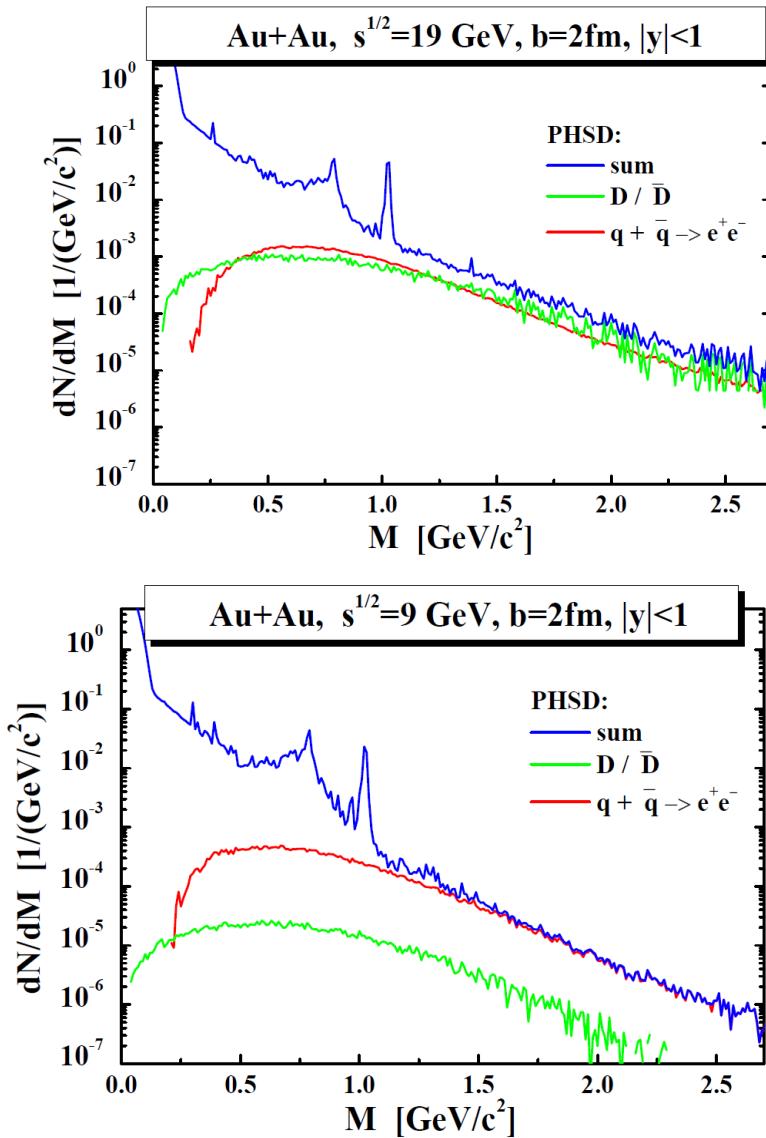
(Talk by Nu Xu at 23d CBM Meeting'14)



Message:

- BES-STAR data show a constant low mass excess (scaled with $N(\pi^0)$) within the measured energy range
 - PHSD: excess increasing with decreasing energy due to a longer p -propagation in the high baryon density phase
- Good perspectives for future experiments – CBM(FAIR) / MPD(NICA)

Dileptons at FAIR/NICA energies: predictions



Messages from dilepton data

□ Low dilepton masses:

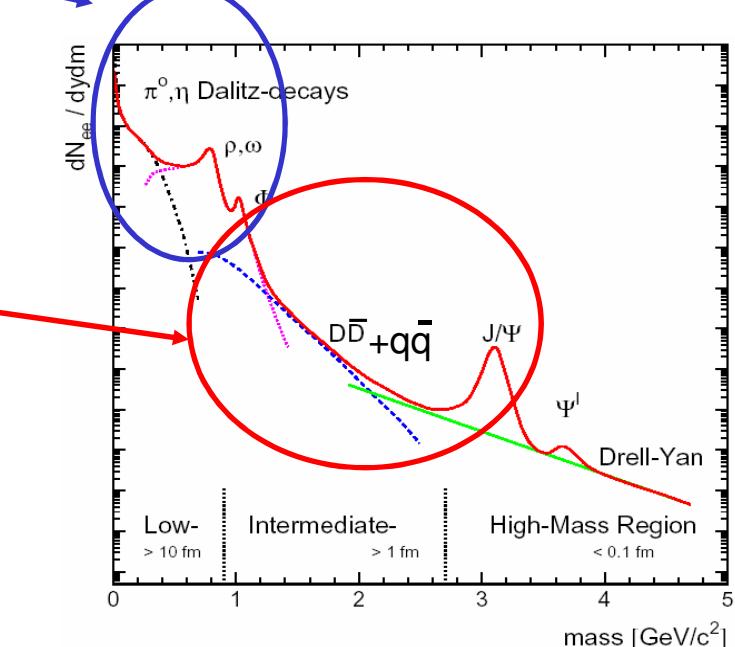
- Dilepton spectra show sizeable changes due to the in-medium effects
 - modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally
- In-medium effects can be observed at all energies from SIS to LHC

□ Intermediate dilepton masses at FAIR/NICA:

- The QGP ($\bar{q}q$) dominates for $M > 1.2$ GeV
- Fraction of QGP dominant over D/\bar{D}

Outlook:

- * experimental energy scan
- * experimental measurements of dilepton's higher flow harmonics v_n



Thanks to:

PHSD group (2016)



Bundesministerium
für Bildung
und Forschung



DAAD

FIAS & GSI
Elena Bratkovskaya
Taesoo Song
Pierre Moreau
Andrej Ilner

Giessen University
Wolfgang Cassing
Olena Linnyk
Thorsten Steinert
Alessia Palmese
Eduard Seifert



External Collaborations

SUBATECH, Nantes University:

Jörg Aichelin
Christoph Hartnack
Pol-Bernard Gossiaux

Texas A&M University:

Che-Ming Ko

JINR, Dubna:

Viacheslav Toneev
Vadim Voronyuk

Barcelona University:

Laura Tolos
Angel Ramos

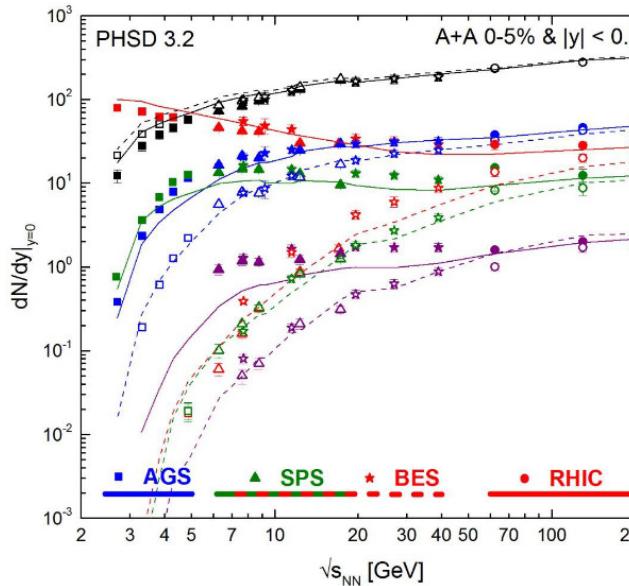
Duke University:

Steffen Bass
Marlene Nahrgang

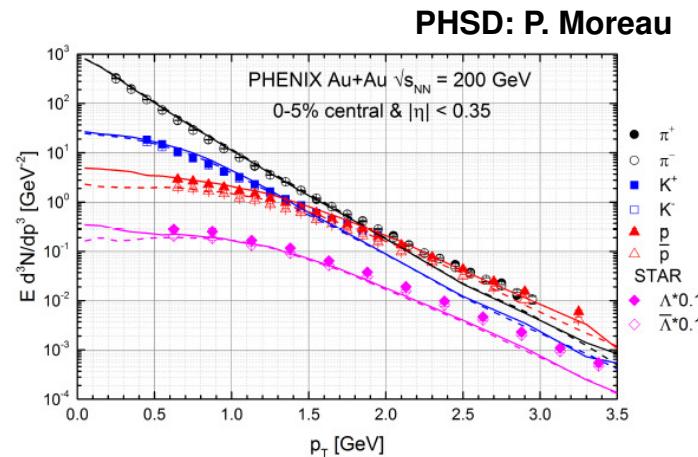
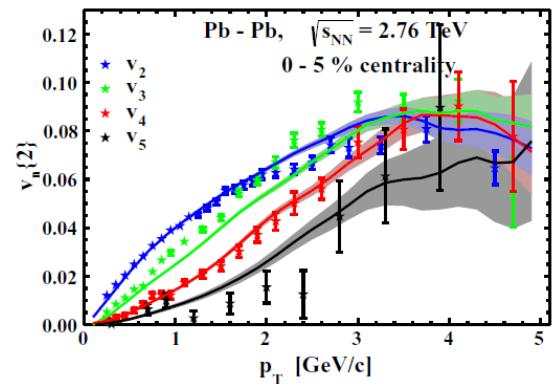
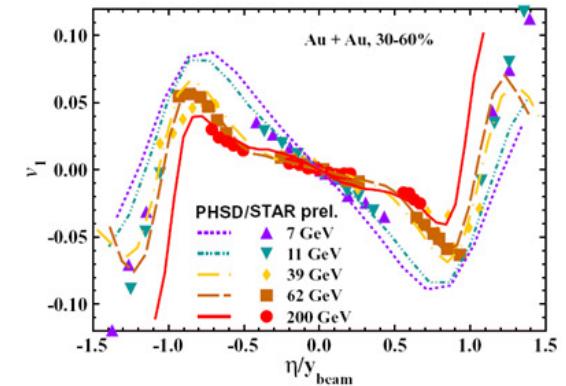
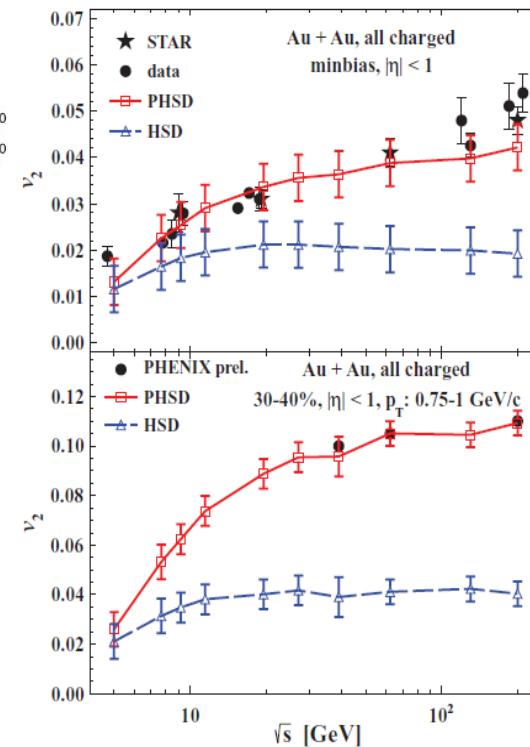




Non-equilibrium dynamics: description of A+A with PHSD



□ PHSD: highlights



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 SIS to LHC