Electromagnetic emissivity of hot and dense matter

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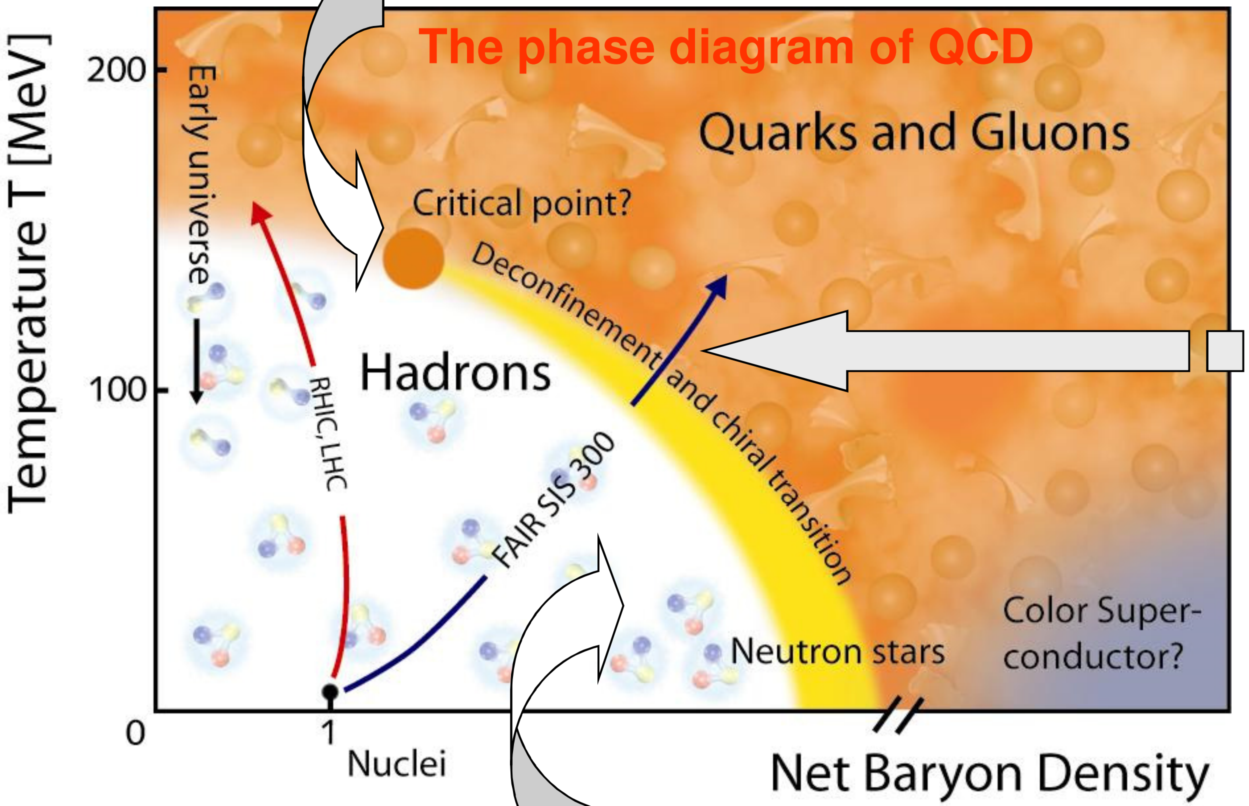
23-28 November 2015, Makutsi Safari Farm, South Africa

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

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 from a microscopic origin

➔ need a consistent non-equilibrium transport model

- ❑ with explicit parton-parton interactions (i.e. between quarks and gluons)
- ❑ explicit phase transition from hadronic to partonic degrees of freedom
- ❑ lQCD EoS for partonic phase (‚cross over‘ at μ_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

PHSD

⇒ **Parton-Hadron-String-Dynamics (PHSD)**

QGP phase 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)

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions – in the sense of a two-particle irreducible (2PI) approach:

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the resummed properties are specified by complex self-energies which depend on temperature:
  - the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  - the imaginary part describes the interaction width of partons (Γ_q, Γ_g)

- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons (U_q, U_g)

- 2PI framework guaranties a consistent description of the system in- and out-off equilibrium on the basis of Kadanoff-Baym equations with proper states in equilibrium

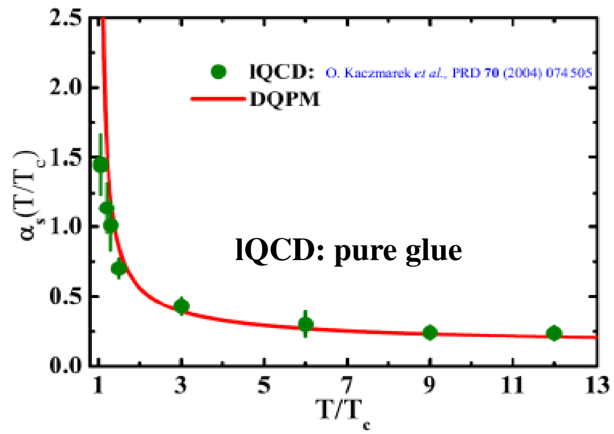
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

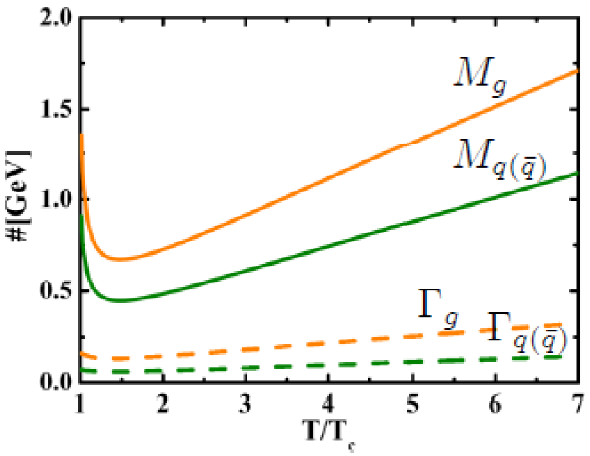
- **Basic idea: interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :**

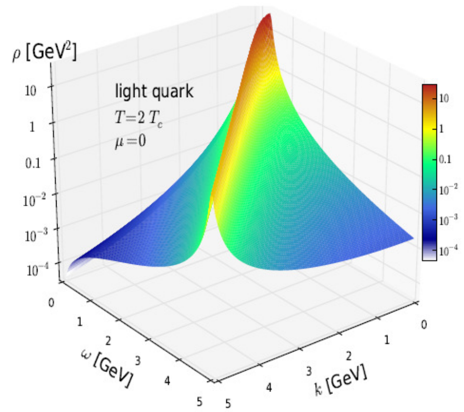
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

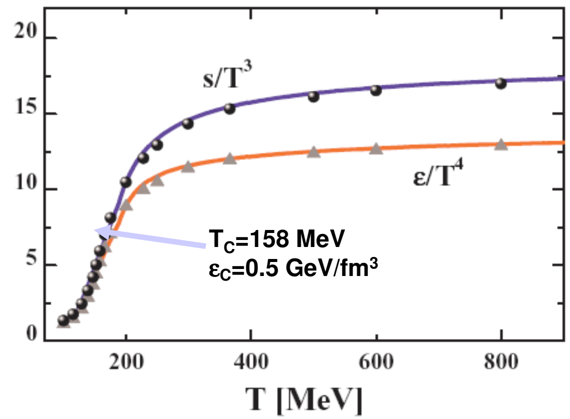
- **fit to lattice (lQCD) results**
  (e.g. entropy density) with 3 parameters



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

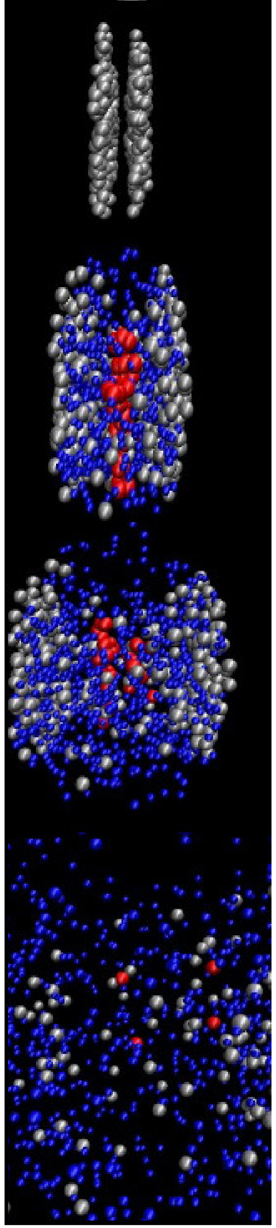






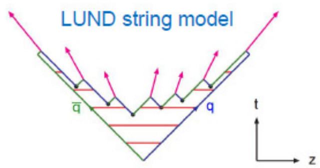
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

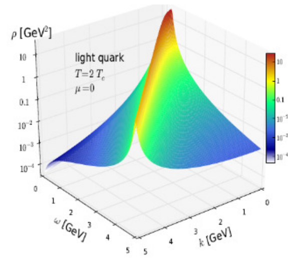


Parton-Hadron-String-Dynamics (PHSD)

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



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



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

  - (quasi-) elastic collisions:

    $q+q \to q+q \qquad g+q \to g+q$

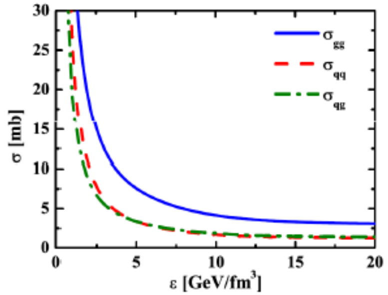
    $q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$

    $\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$

  - inelastic collisions:

    $q+\bar{q} \to g \qquad q+\bar{q} \to g+g$

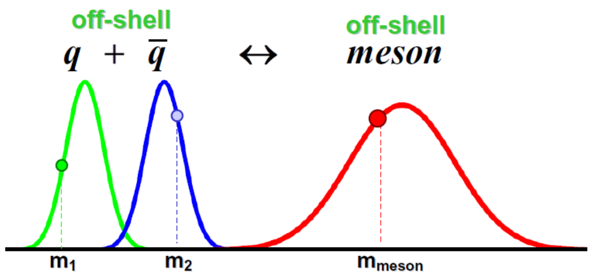
    $g \to q+\bar{q} \qquad g \to g+g$



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

$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson \;\; (or\;'string\;')$$

$$q+q+q \leftrightarrow baryon \;\; (or\;'string\;')$$

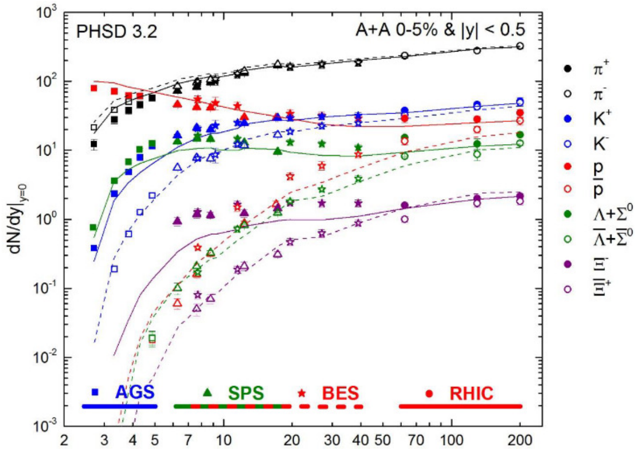


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

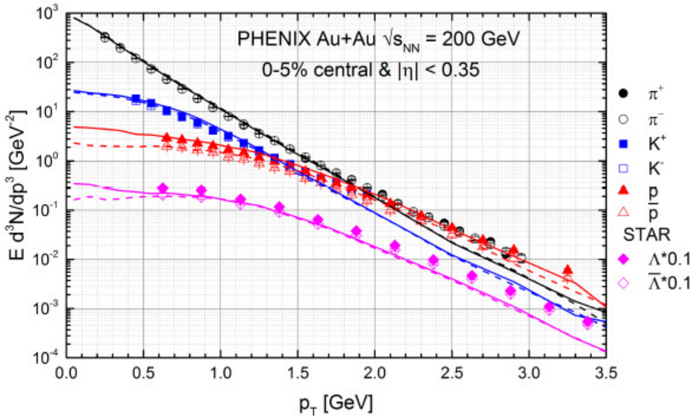
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

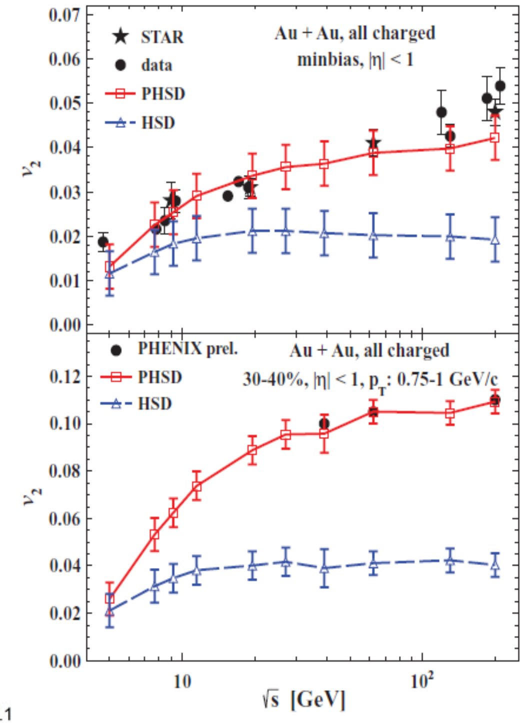
Description of A+A with PHSD

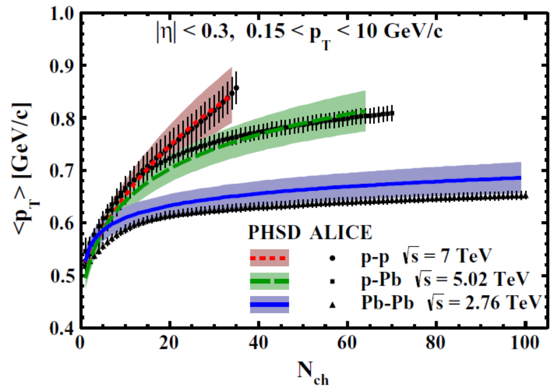
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

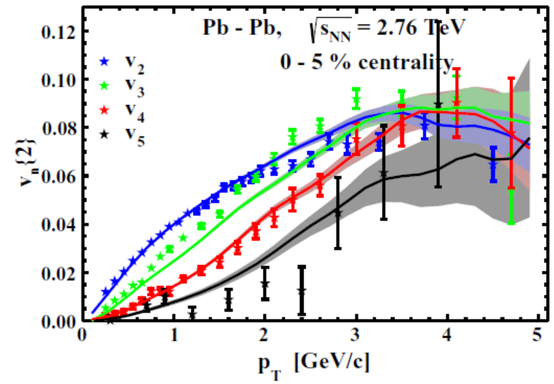


PHSD: P. Moreau







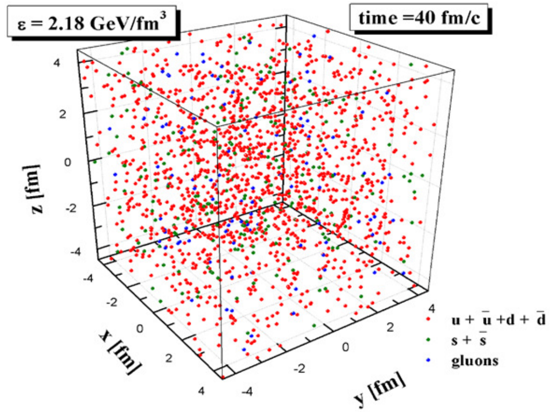


V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

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

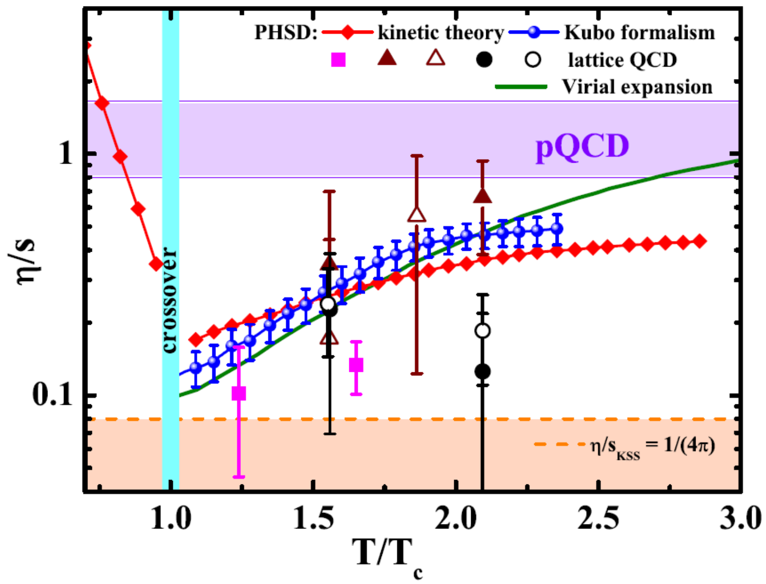
I. Transport properties at finite (T, μ_q) : η/s

PHSD in a box:

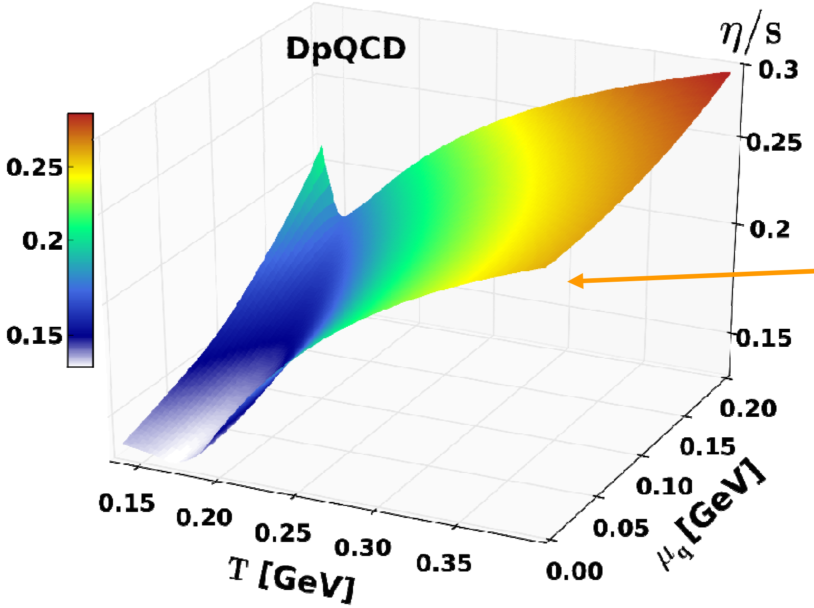


PHSD: shear viscosity η/s at finite T

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



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



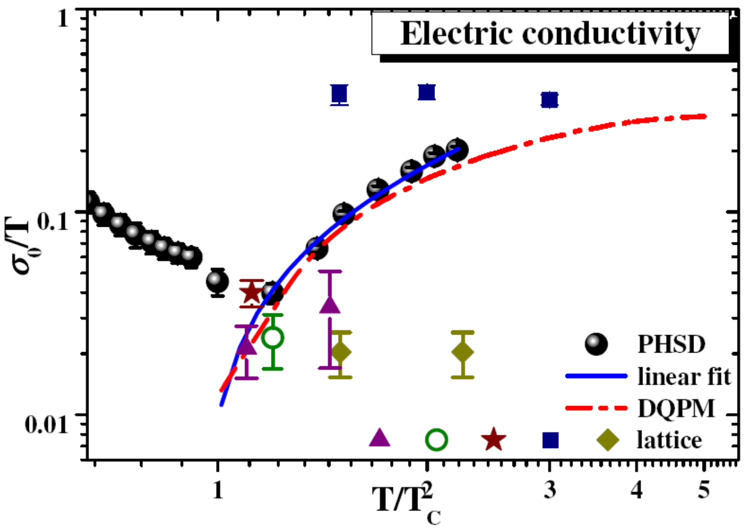
η/s: μ_q=0 ➔ finite μ_q:
smooth increase as a function of (T, μ_q)

H. Berrehrah et al. arXiv:1412.1017

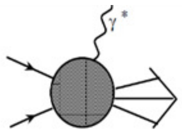
II. Transport properties at finite (T, μ_q): σ_e/T

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

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



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

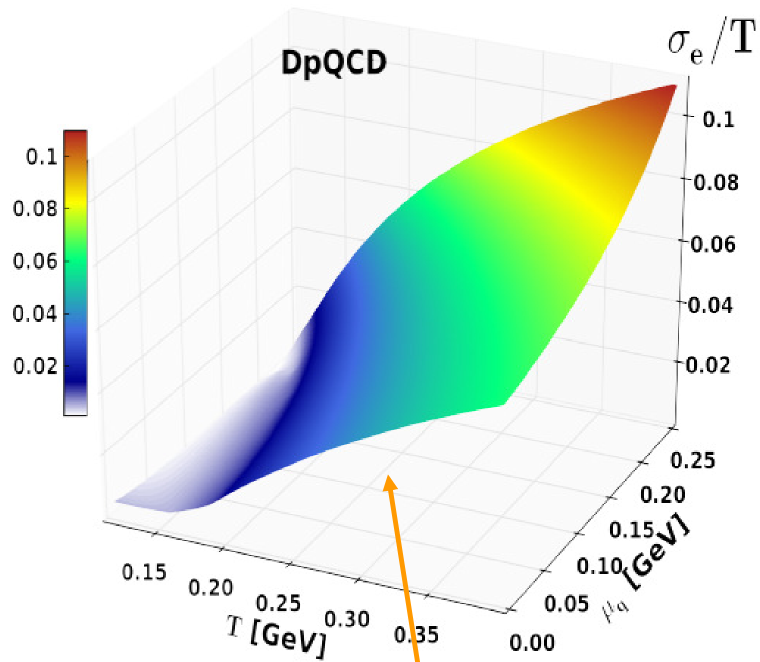


$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0\to 0} = \frac{T}{4\pi^3}\sigma_0$$

➔ Probe of electric properties of the QGP

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

H. Berrehrah et al. arXiv:1412.1017



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

Direct photon flow puzzle

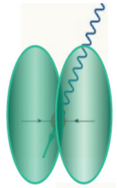
?

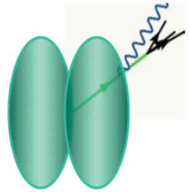
Production sources of photons in p+p and A+A

- **Decay photons** (in pp and AA):

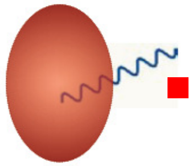
$$m \rightarrow \gamma + X, \;\; m = \pi^0, \eta, \omega, \eta', a_1, \ldots$$

- **Direct photons:** (inclusive(=total) – decay) – measured experimentally

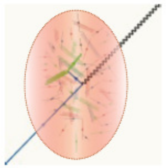




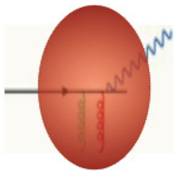
- **hard photons**: (large p_T, in pp and AA)
  - **prompt** (pQCD; initial hard N+N scattering)
  - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)



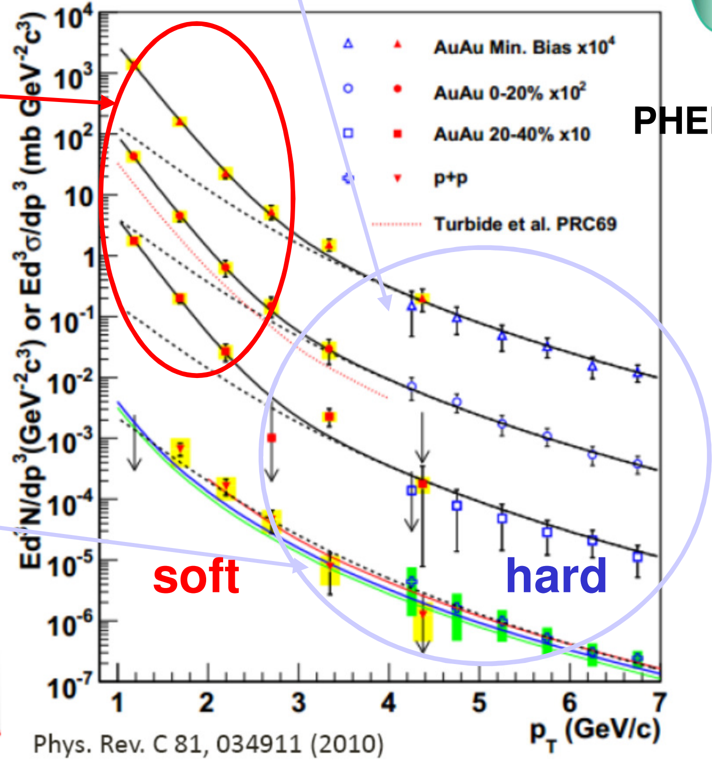
- **thermal photons**: (low p_T, in AA)
  - QGP
  - Hadron gas



- **jet-γ-conversion** in plasma (large p_T, in AA)



- **jet-medium photons** (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP} \rightarrow \gamma+q$,
  $q_{hard}+\bar{q}_{QGP} \rightarrow \gamma+q$



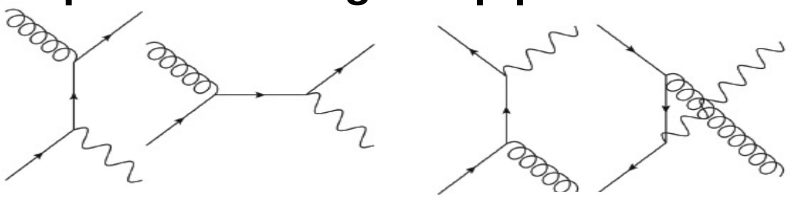
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

Thermal QGP:

HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990), …)

Compton scattering **q-qbar annihilation**

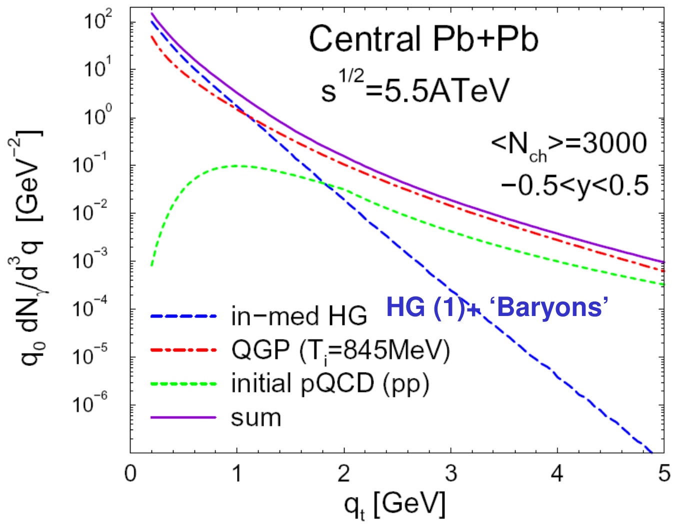


+ soft …

$q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma$ $q + \bar{q} \rightarrow g + \gamma$

- **Rates beyond pQCD:**
  off-shell massive q, g
  (used in PHSD)
  O. Linnyk, JPG 38 (2011) 025105;
  Poster by O. Linnyk & QM'2014

- **pQCD LO: 'AMY'** Arnold, Moore, Yaffe, JHEP 12, 009 (2001) ← **QGP rates used in hydro !**
- **pQCD NLO:** Gale, Ghiglieri (2014)



Hadronic sources:

(1) secondary mesonic interactions:

$\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma,\ \pi + K \rightarrow \rho + \gamma, \ldots$

(2) meson-meson and meson-baryon bremsstrahlung:

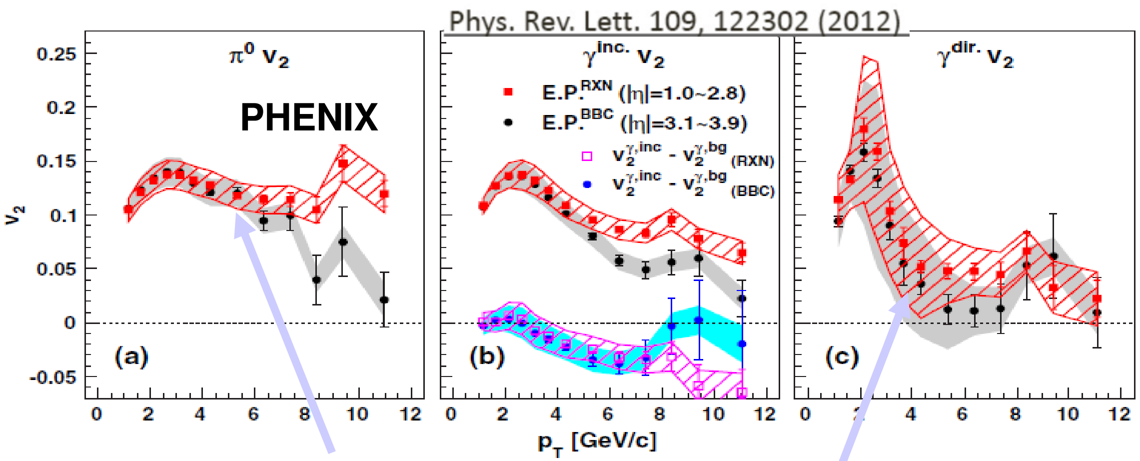
$m + m \rightarrow m + m + \gamma, \quad m + B \rightarrow m + B + \gamma,$

$m = \pi, \eta, \rho, \omega, K, K^*, \ldots, \quad B = p, \Delta, \ldots$

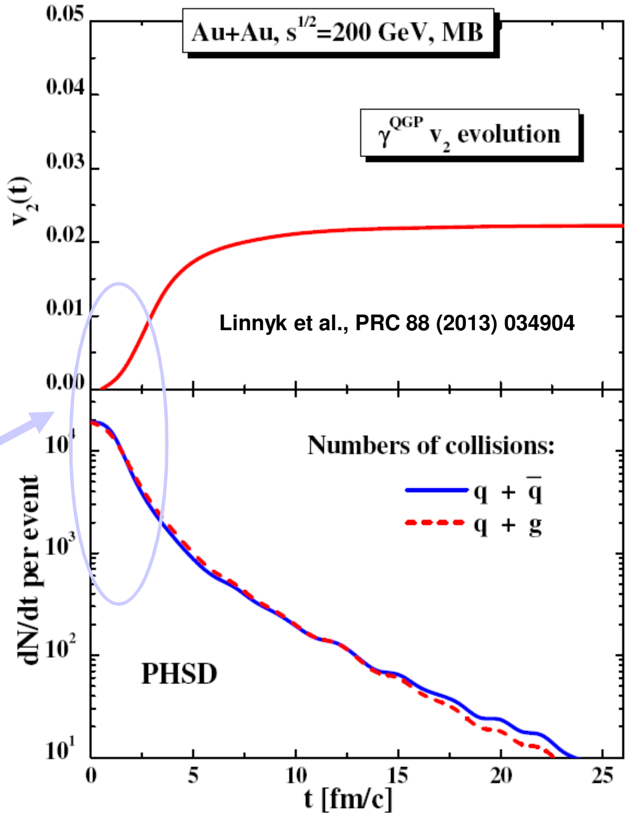
Models: chiral models, OBE, SPA …
Kapusta, Gale, Haglin (91), Rapp (07), …

HG rates (1) used in hydro ('TRG' model) - massive Yang-Mills approach:
Turbide, Rapp, Gale, PRC 69, 014903 (2004)

PHENIX: Photon v_2 puzzle



$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \Psi_n^{RP}))\right)$$



!

- **PHENIX (also now ALICE):**
  strong elliptic flow of photons $v_2(\gamma^{dir}) \sim v_2(\pi)$
- **Result from a variety of models:** $v_2(\gamma^{dir}) << v_2(\pi)$
- **Problem:** QGP radiation occurs at **early times** when elliptic flow is not yet developed ➔ expected $v_2(\gamma^{QGP}) \rightarrow 0$
- v_2 = weighted average $v_2 = \frac{\sum_i N^i \cdot v_2^i}{\sum_i N^i}$ ➔ **a large QGP contribution gives small** $v_2(\gamma^{QGP})^i$

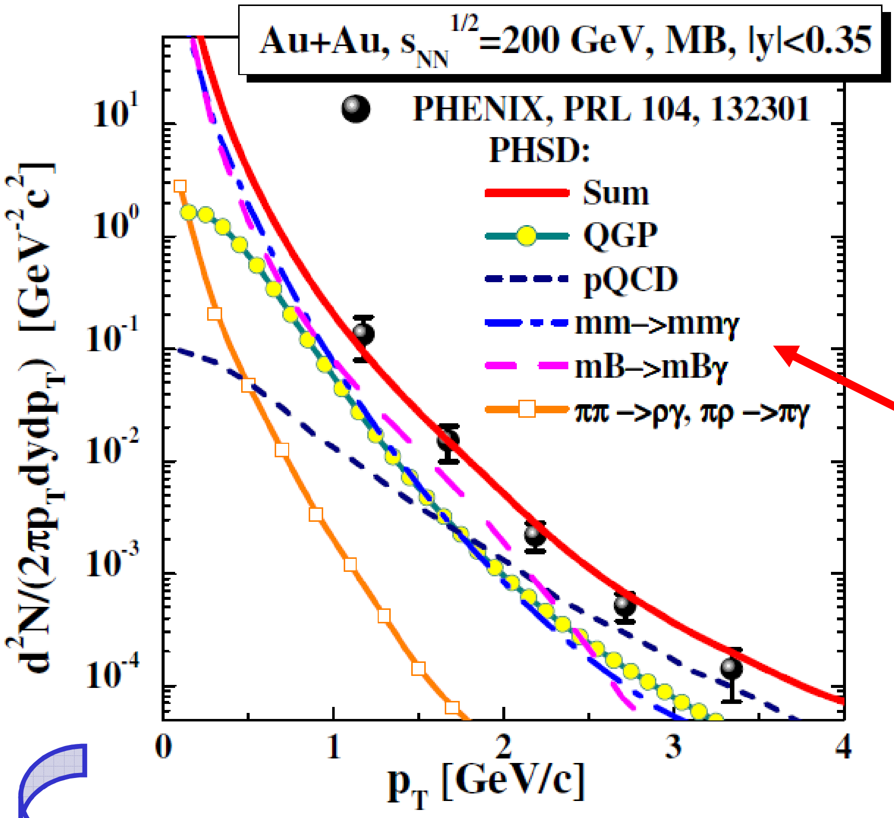
- **PHENIX, ALICE experiments - large photon v_3 !**

➔ **Challenge for theory – to describe spectra, v_2, v_3 simultaneously !**

PHSD: photon spectra at RHIC: QGP vs. HG ?

- Direct photon spectrum (min. bias)

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



PHSD:

- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

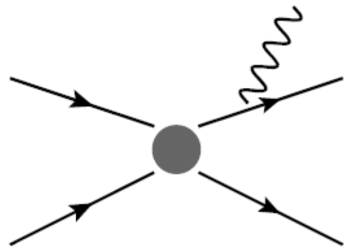
! sizeable contribution from hadronic sources – meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$m+m \rightarrow m+m+\gamma,$

$m+B \rightarrow m+B+\gamma,$

$m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

$B=p$



The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

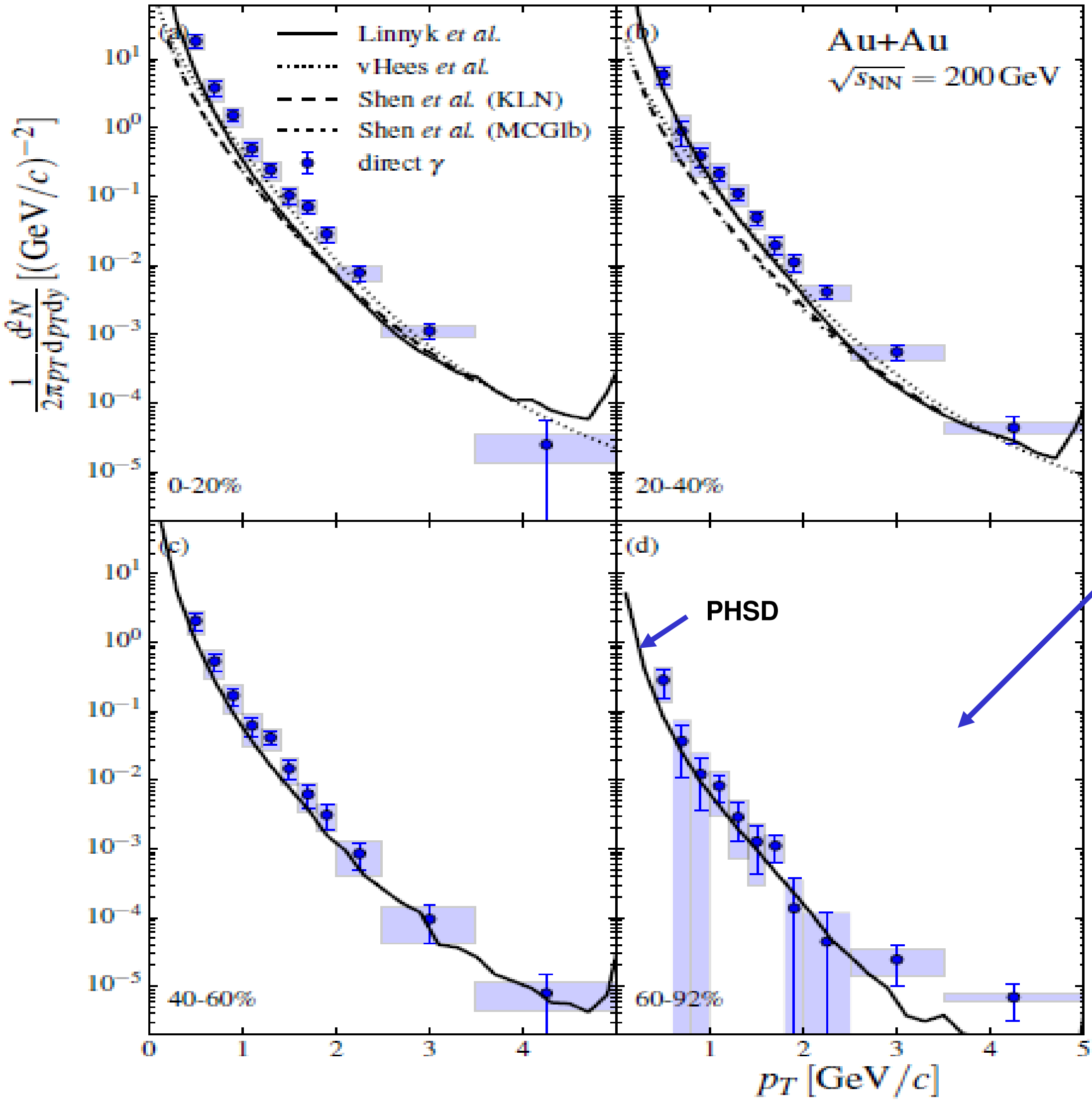
Measured Teff > ‚true' T → ‚blue shift' due to the radial flow!

Photon p_T spectra at RHIC for different centralities

from talk by S. Mizuno at QM'2014

PHENIX data - arXiv:1405.3940

PHSD predictions:
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908



- PHSD approximately reproduces the centrality dependence

- mm and mB bremsstrahlung is dominant at peripheral collisions

!!! Warning:
large uncertainties in the Bremsstrahlung channels in the present PHSD results !

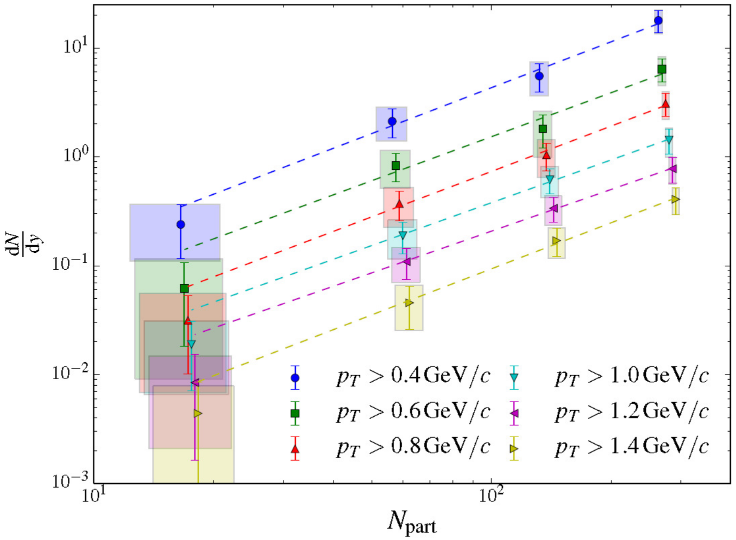
Centrality dependence of the ‚thermal' photon yield

O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

PHENIX (arXiv:1405.3940):

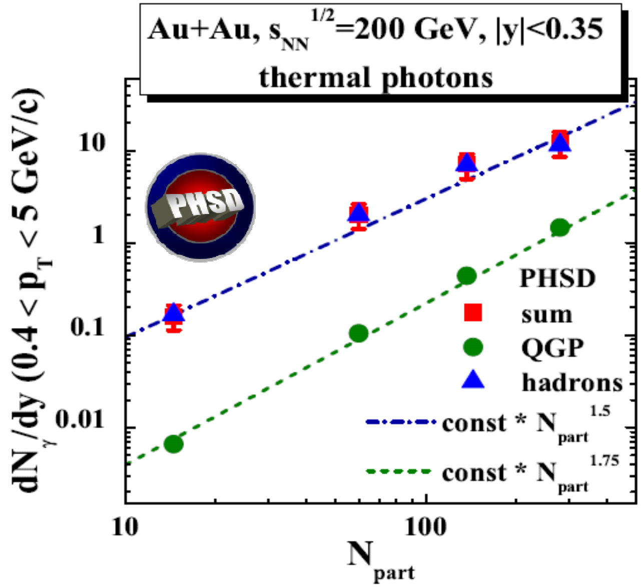
scaling of thermal photon yield vs centrality:
dN/dy ~ N_{part}^{α} with α~1.48±0.08

('Thermal' photon yield = direct photons - pQCD)



PHSD predictions:

- Hadronic channels scale as ~ $N_{part}^{1.5}$
- Partonic channels scale as ~$N_{part}^{1.75}$



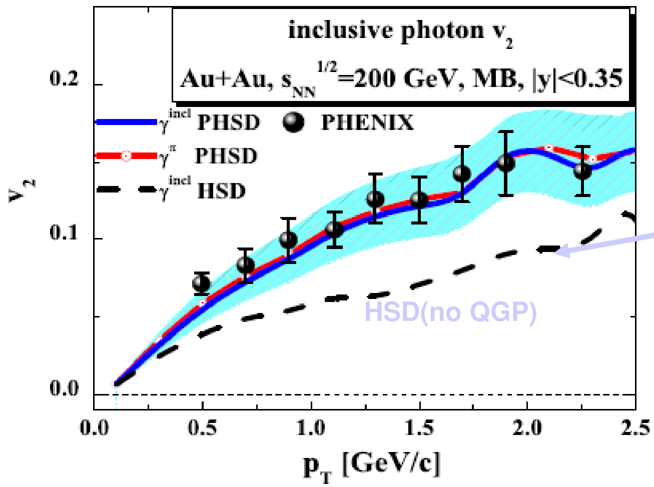
- **PHSD:** scaling of the thermal photon yield with N_{part}^{α} with α~1.5
- similar results from viscous hydro:
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

→ What do we learn?
Indications for a dominant hadronic origin of thermal photon production?!

Are the direct photons a barometer of the QGP?

❑ Do we see the QGP pressure in $v_2(\gamma)$ if the photon productions is dominated by hadronic sources?

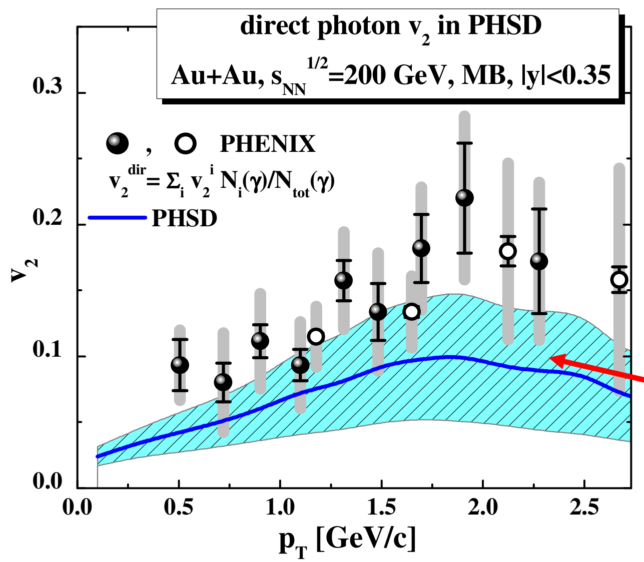
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - inclusive photons mainly come from π^0 decays

- HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, wheras the PHSD model with QGP is consistent with exp. data

➔ The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions



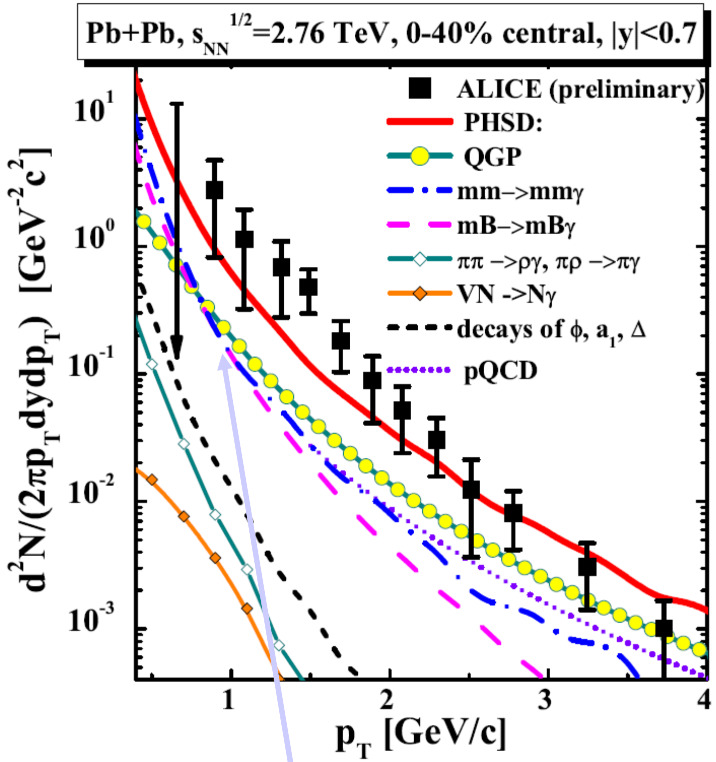
Direct photons (inclusive(=total) – decay):

2) $v_2(\gamma^{dir})$ of direct photons in PHSD underestimates the PHENIX data :

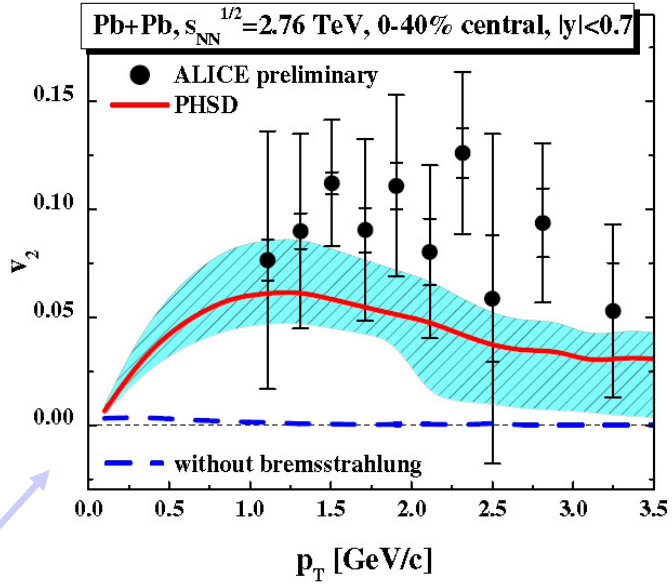
$v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield ➔ lowering flow

➔PHSD: $v_2(\gamma^{dir})$ comes from mm and mB bremsstrahlung !

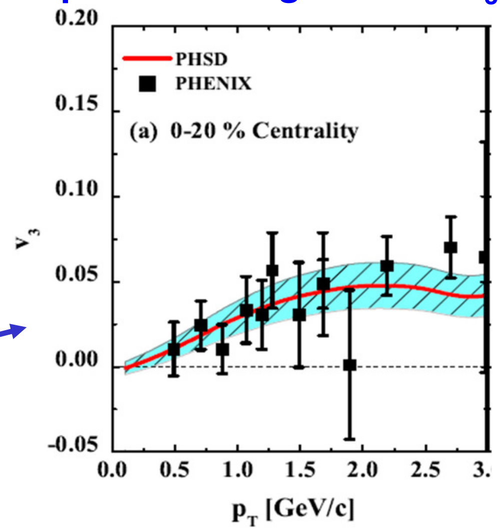
Photons from PHSD at LHC



Direct photon elliptic flow v2



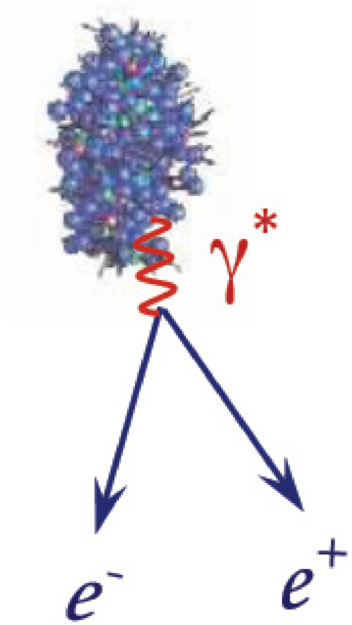
Direct photon triangular flow v_3



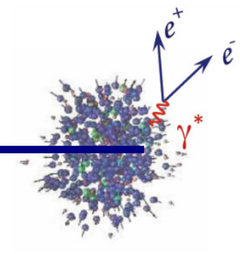
- Is the considerable elliptic flow of direct photons at the LHC also of hadronic origin as for RHIC?!
- The photon elliptic flow at LHC is lower than at RHIC due to a larger relative QGP contribution / longer QGP phase.
- Nonzero triangular flow v_3 of direct photon

Linnyk et al., PRC (2015) in press; arXiv: 1504.05699

Dileptons

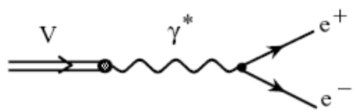


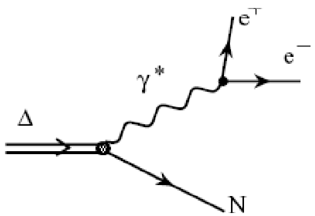
Dilepton sources

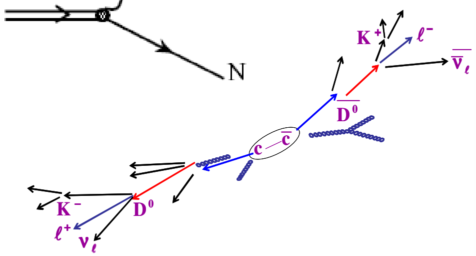


- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

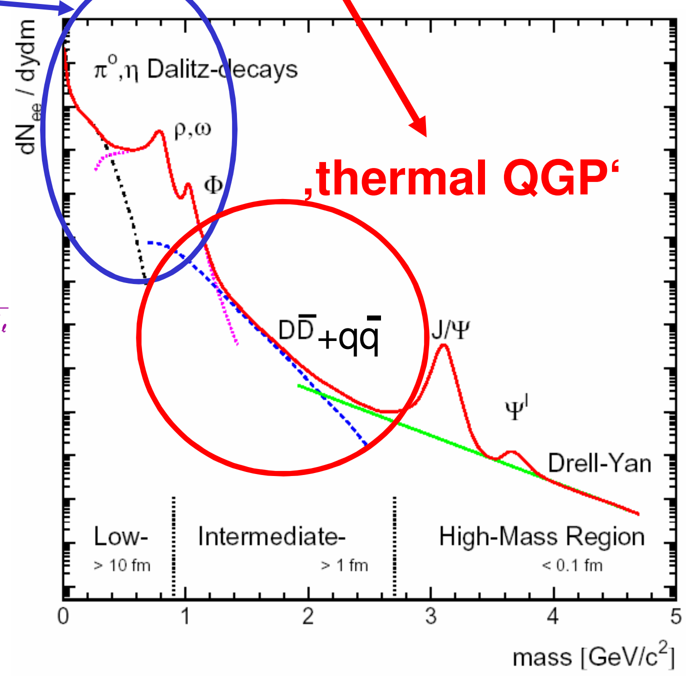




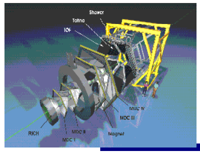


- **direct decay of vector mesons** (ρ,ω,φ,J/Ψ,Ψ‘)
- **Dalitz decay of mesons and baryons** (π^0,η, Δ,…)
- **correlated D+Dbar pairs**
- **radiation from multi-meson reactions** (π+π, π+ρ, π+ω, ρ+ρ , $\pi+a_1$) - ‚4π‘

Plot from A. Drees



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



Dileptons at SIS energies - HADES

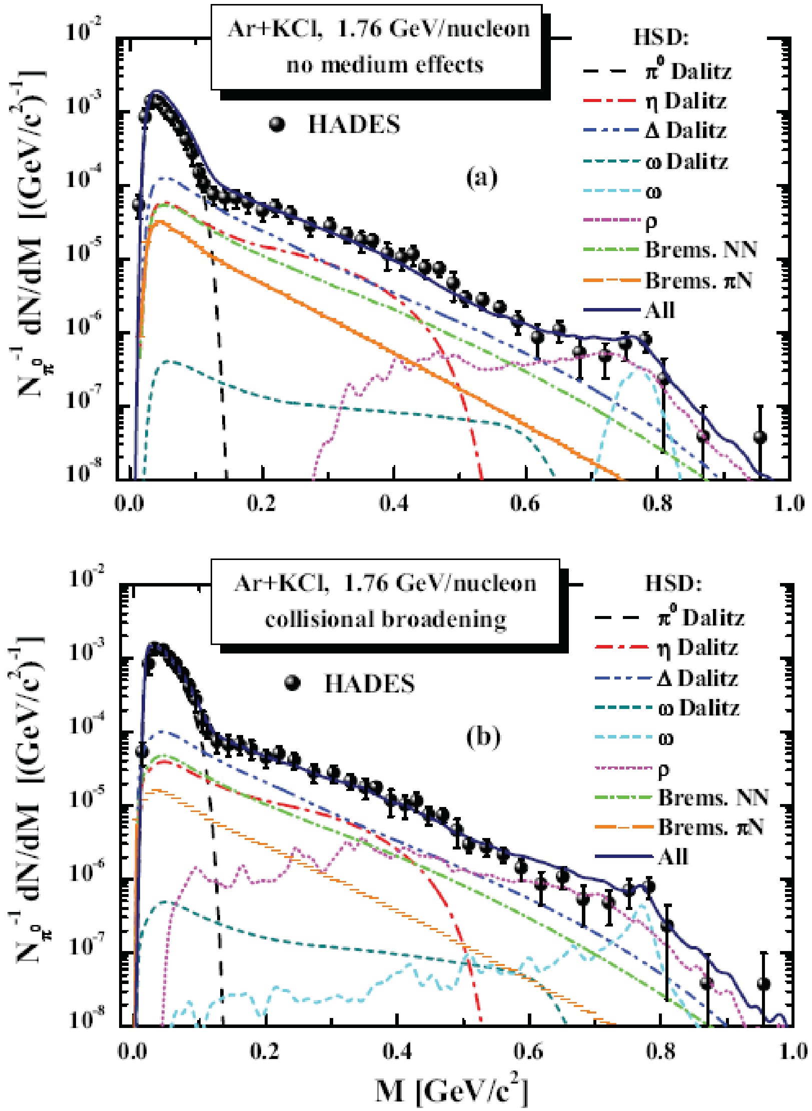
❑ **HADES: dilepton yield dN/dM scaled with the number of pions $N_{\pi 0}$**

❑ **Dominant hadronic sourses at $M>m_{\pi}$:**

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

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

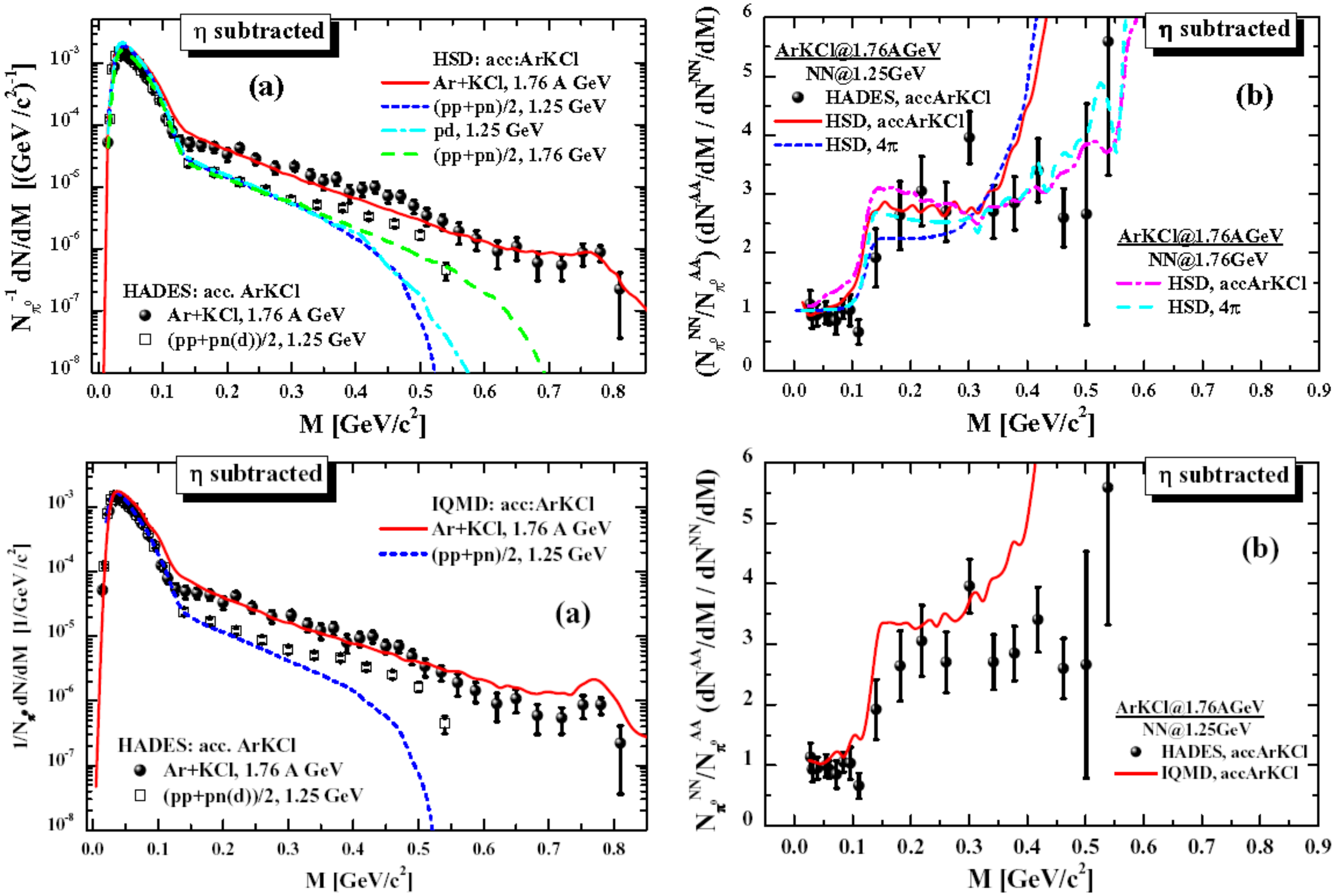
- **In-medium effects are more pronounced for heavy systems such as Ar+KCl then C+C**
- **The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum**



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

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

- **ratio of AA/NN spectra** (scaled by $N_{\pi 0}$) 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

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

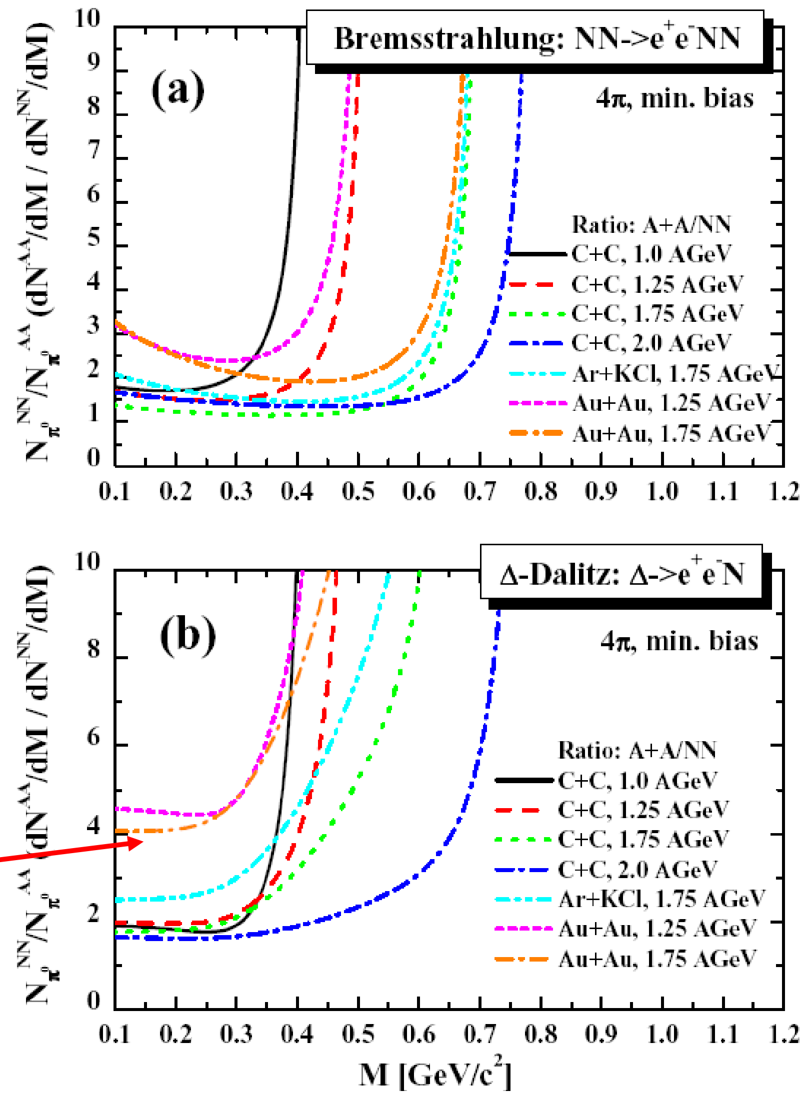
Dileptons at SIS (HADES): A+A vs NN

- 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 Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

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

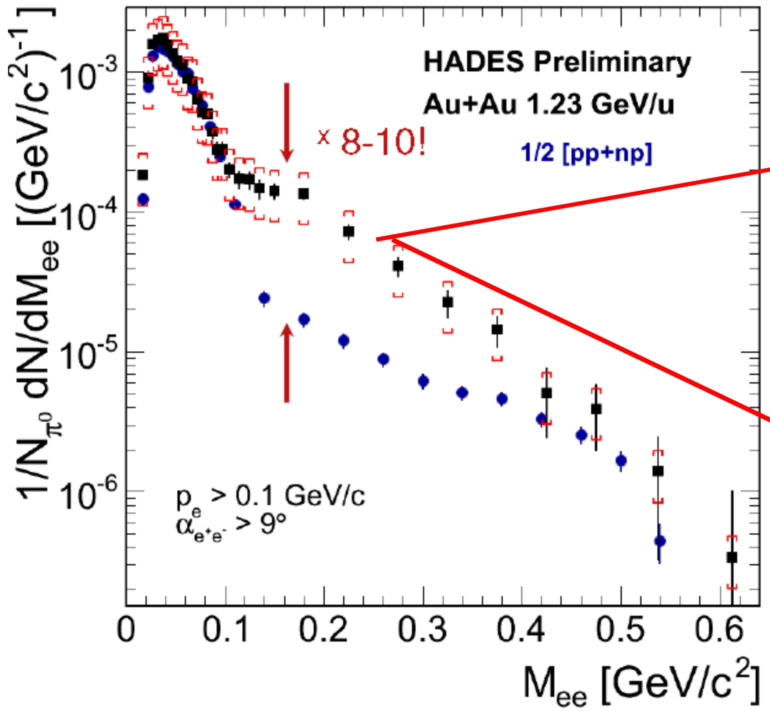


E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

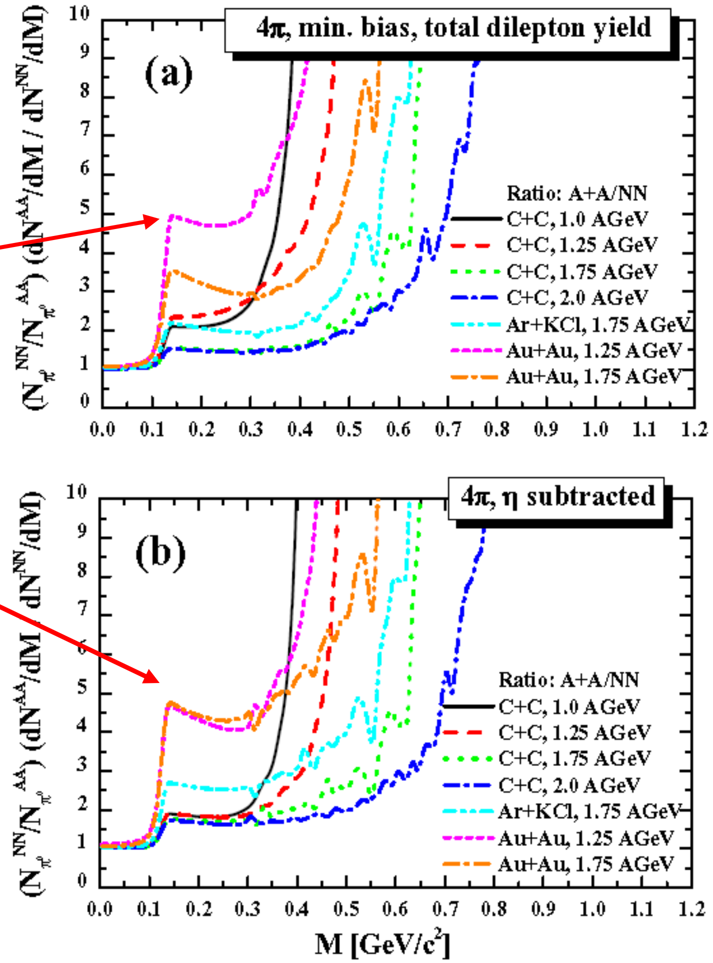
Dileptons at SIS (HADES): Au+Au

HADES preliminary: Au+Au, 1.23 A GeV

T. Galatyuk, QM'2014



- **HSD predictions (2013)**



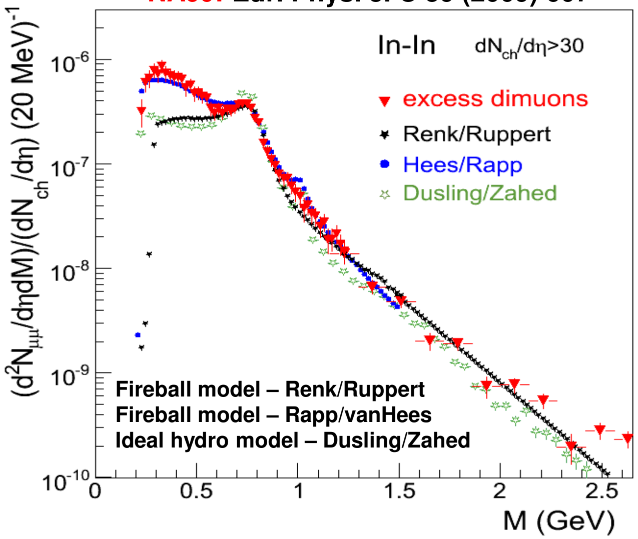
❑ **Strong in-medium enhancement of dilepton yield in Au+Au vs. NN**
➔ measurement of Δ regeneration by HADES!

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

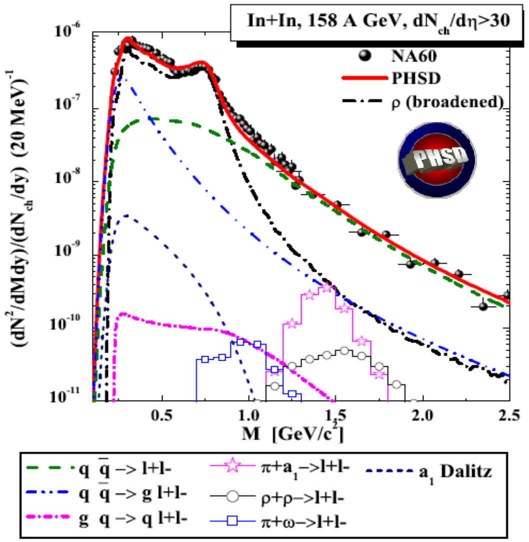
Lessons from SPS: NA60

❑ Dilepton invariant mass spectra:

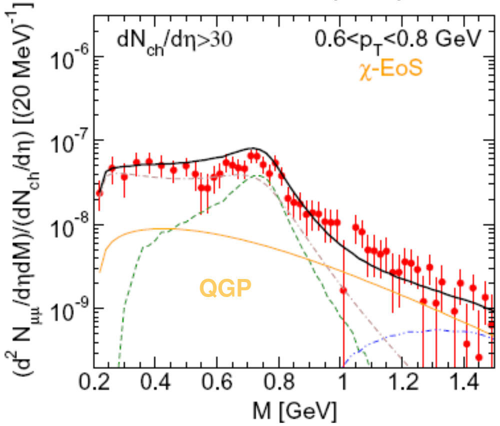
NA60: Eur. Phys. J. C 59 (2009) 607

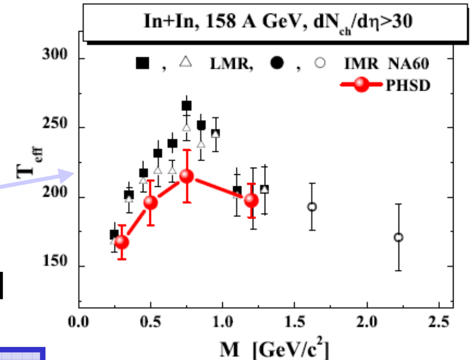


PHSD:
Linnyk et al, PRC 84 (2011) 054917



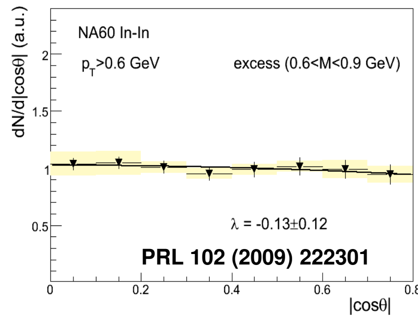
Hybrid-UrQMD:
Santini et al., PRC84 (2011) 014901





❑ Inverse slope parameter T_{eff}:

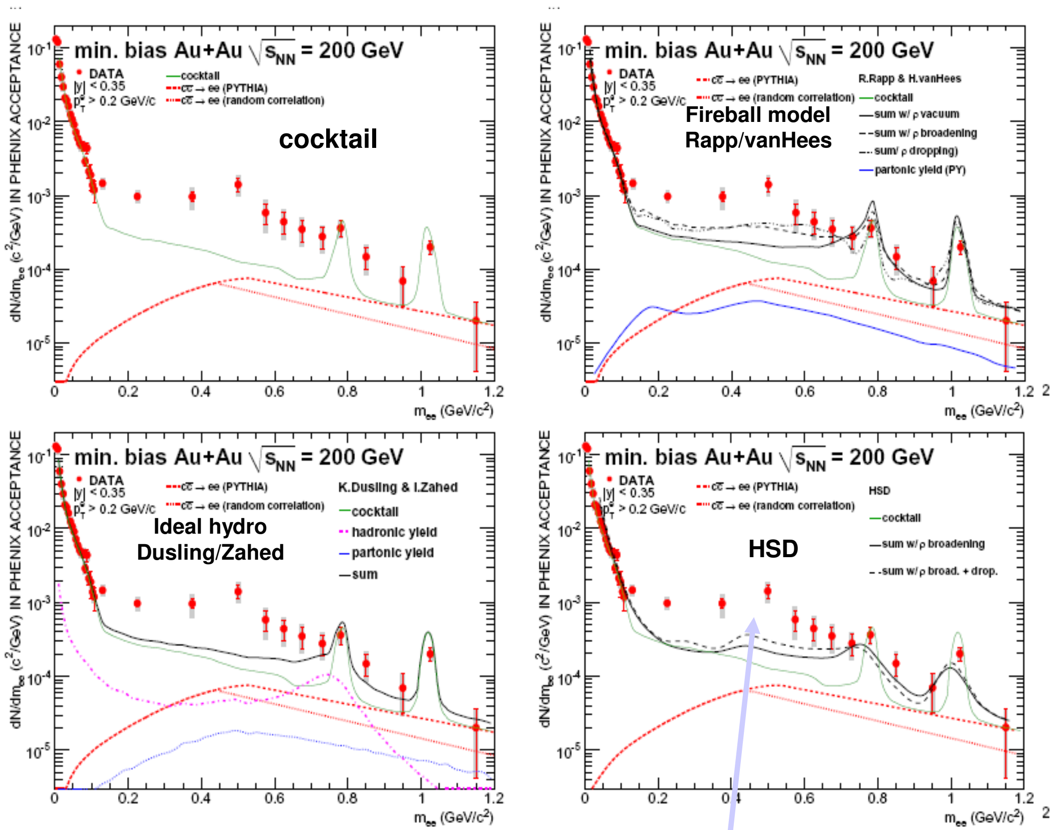
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed



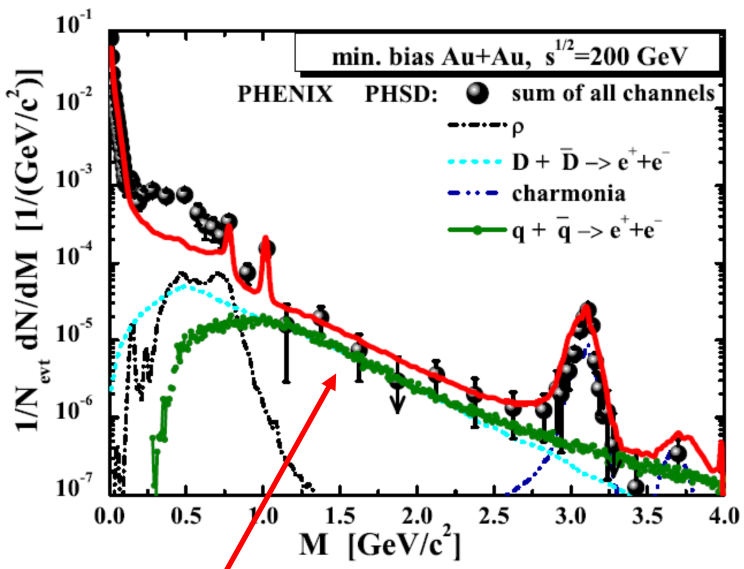
Message from SPS: (based on NA60 and CERES data)

1) Low mass spectra - evidence for the in-medium broadening of 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

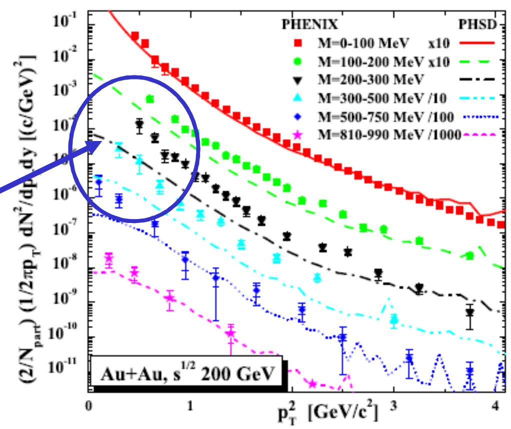
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



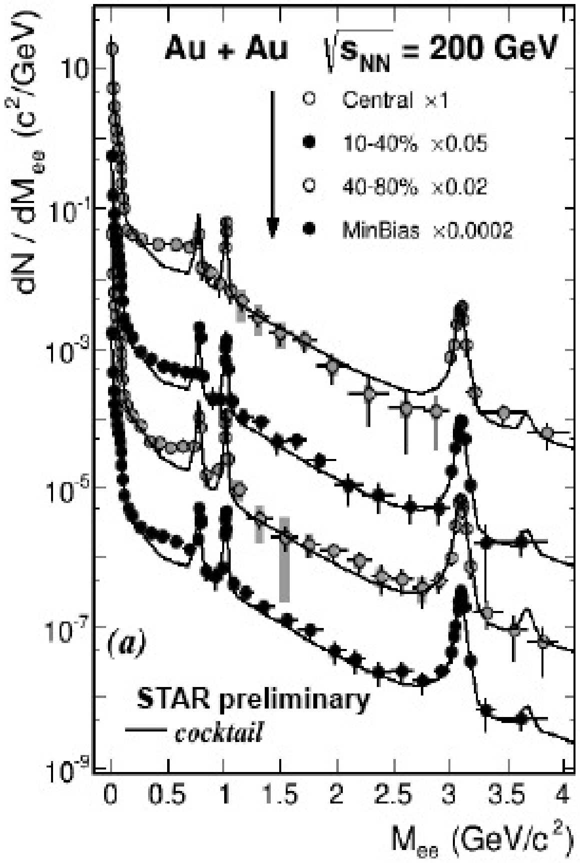
Message:

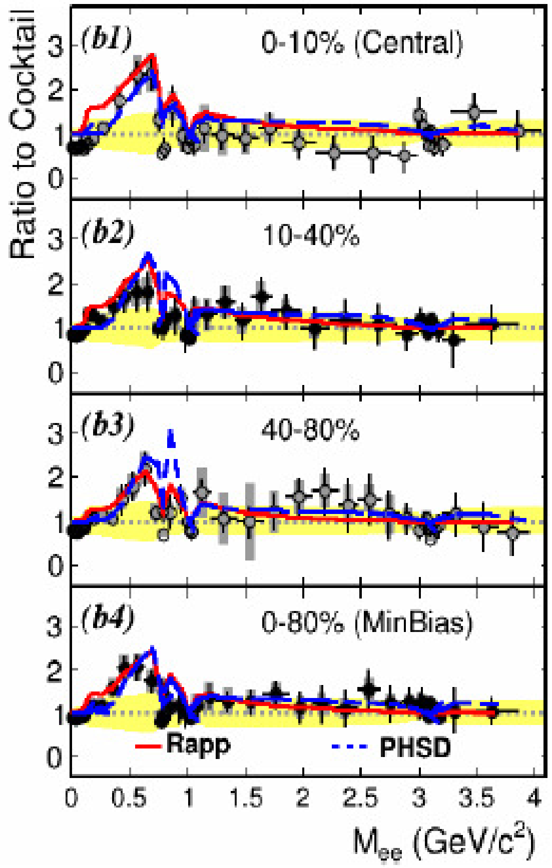
- **Models** provide a **good description of pp data** and **peripheral Au+Au** data, however, **fail in describing the excess for central collisions** even with **in-medium scenarios** for the vector meson spectral function
- The **'missing source'(?)** is located at **low p_T**
- **Intermediate mass spectra – dominant QGP contribution**

Dileptons at RHIC: STAR data vs model predictions

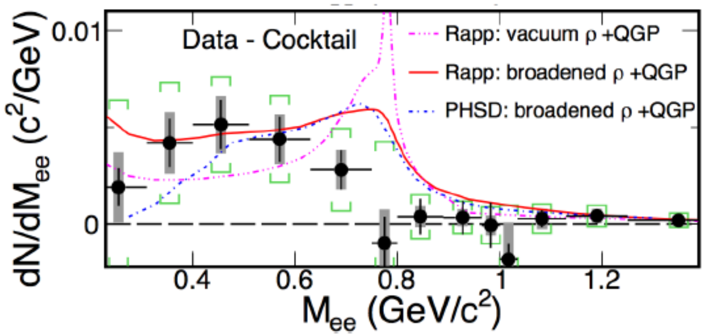
(STAR: arXiv:1407.6788)

Centrality dependence of dilepton yield





Excess in low mass region, min. bias



Models (predictions):

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

Low masses:

collisional broadening of ρ

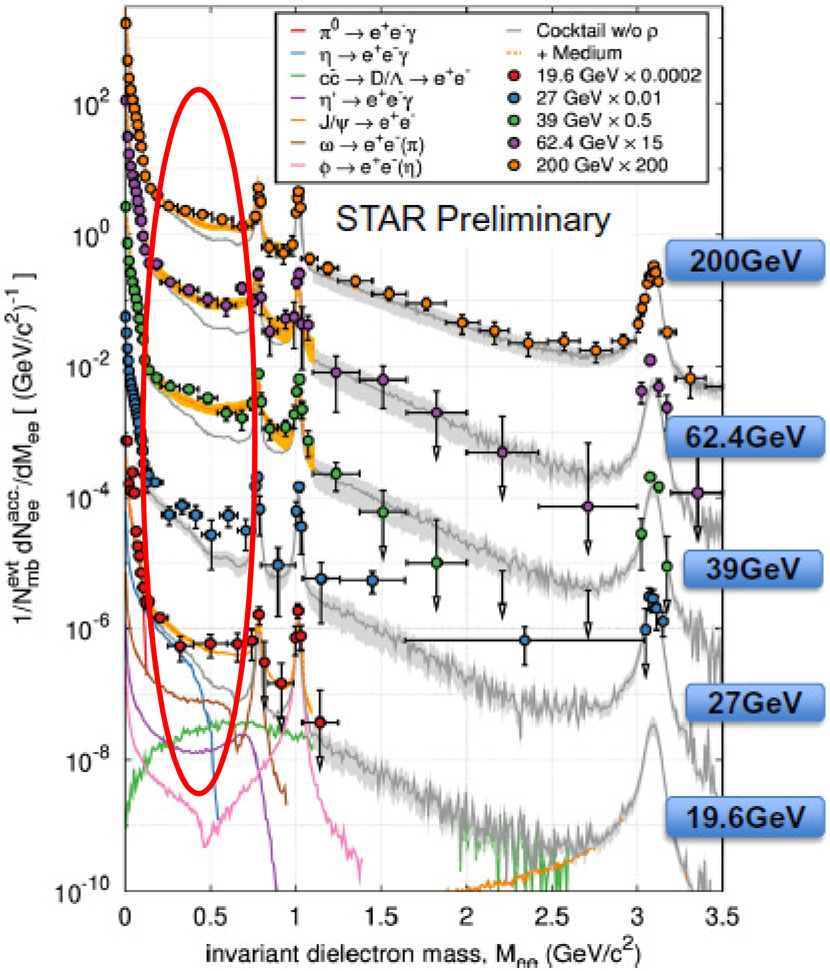
Intermediate masses:

QGP dominant

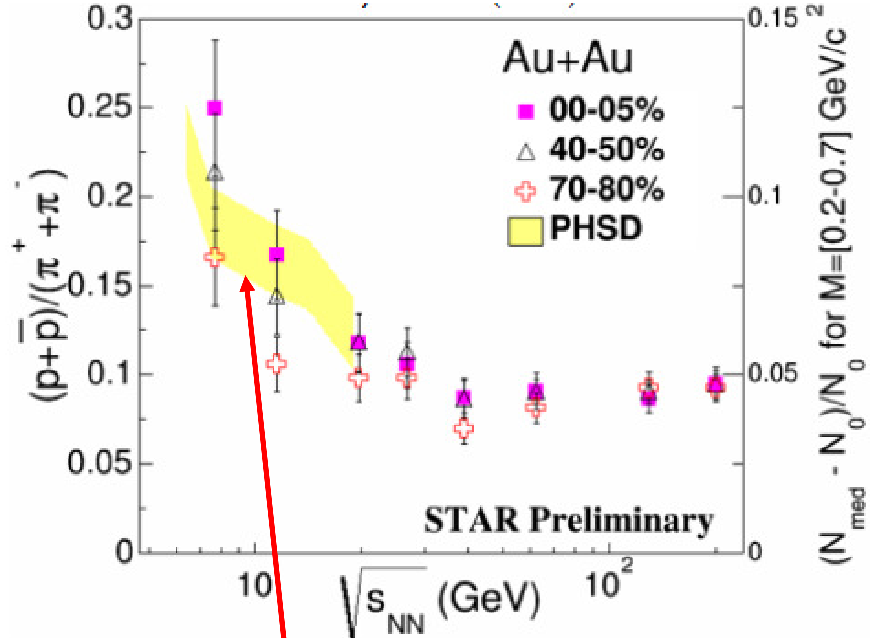
Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

Dileptons from RHIC BES: STAR

(Talk by Nu Xu at QM'2014)



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

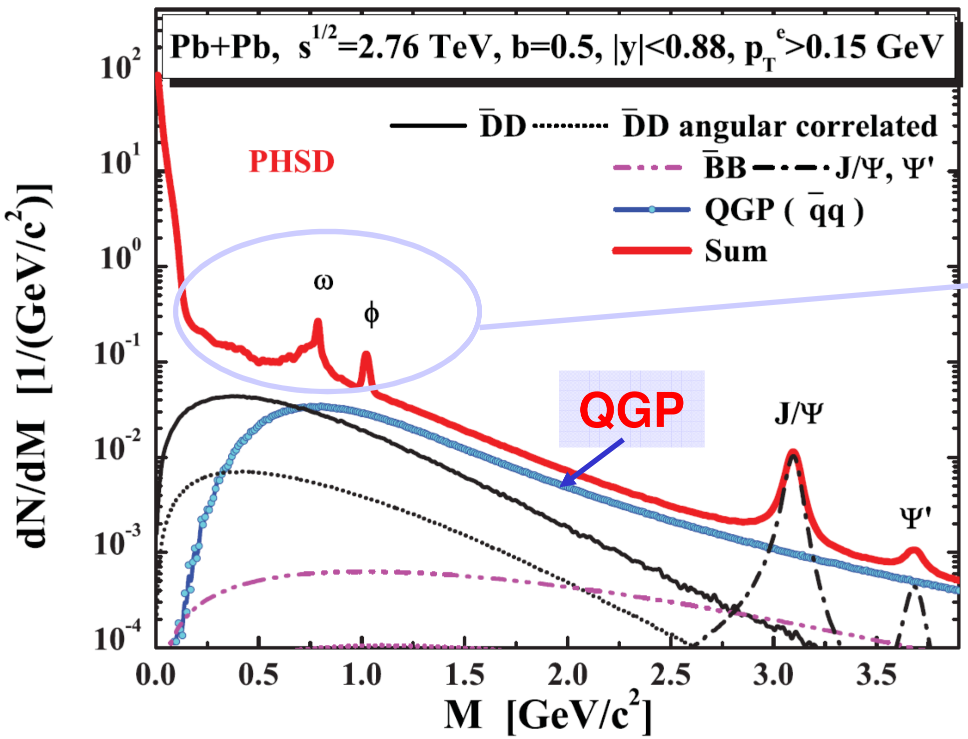


Message:

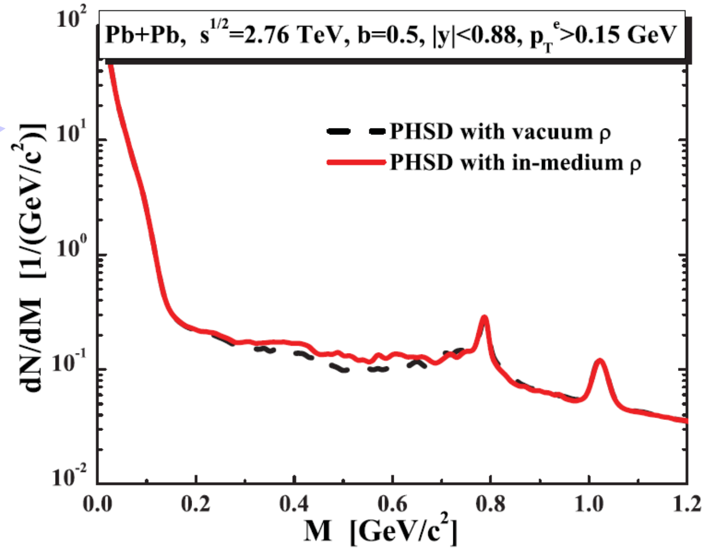
- **BES-STAR data** show a **constant low mass excess** (scaled with N(π^0)) within the measured energy range
- **PHSD model: excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon density phase

➔ **Good perspectives for future experiments – CBM(FAIR) / MPD(NICA)**

Dileptons at LHC



O. Linnyk, W. Cassing, J. Manninen, E.B., P.B. Gossiaux, J. Aichelin, T. Song, C.-M. Ko, Phys.Rev. C87 (2013) 014905; arXiv:1208.1279



Message:

- low masses - hadronic sources: in-medium effects for ρ mesons are small
- intermediate masses: QGP + D/Dbar
  - charm ‘background’ is smaller than thermal QGP yield
  - QGP(qbar-q) dominates at M>1.2 GeV ➔ clean signal of QGP at LHC!

Summary

I. Direct photons - the photons produced in the QGP contribute up to 50% to the observed spectrum, but have small v_2

- **Large direct photon v_2 – comparable to that of hadrons – is attributed to the intermediate hadronic bremsstrahlung and hadronic scattering channels not subtracted from the data**

- **The QGP phase causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interaction in terms of explicit parton collisions and the partonic mean-field potentials**

II. Dilepton spectra - according to the PHSD predictions - show sizeable changes due to the different in-medium scenarios (as collisional broadening and dropping mass) which can be observed experimentally

- **In-medium effects can be observed at all energies from SIS to LHC**
- **At SPS, RHIC and LHC the QGP (qbar-q) dominates at M>1.2 GeV**

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

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Thank you!