Dileptons from PHSD

Elena Bratkovskaya

Institut für Theoretische Physik & FIAS, Uni. Frankfurt

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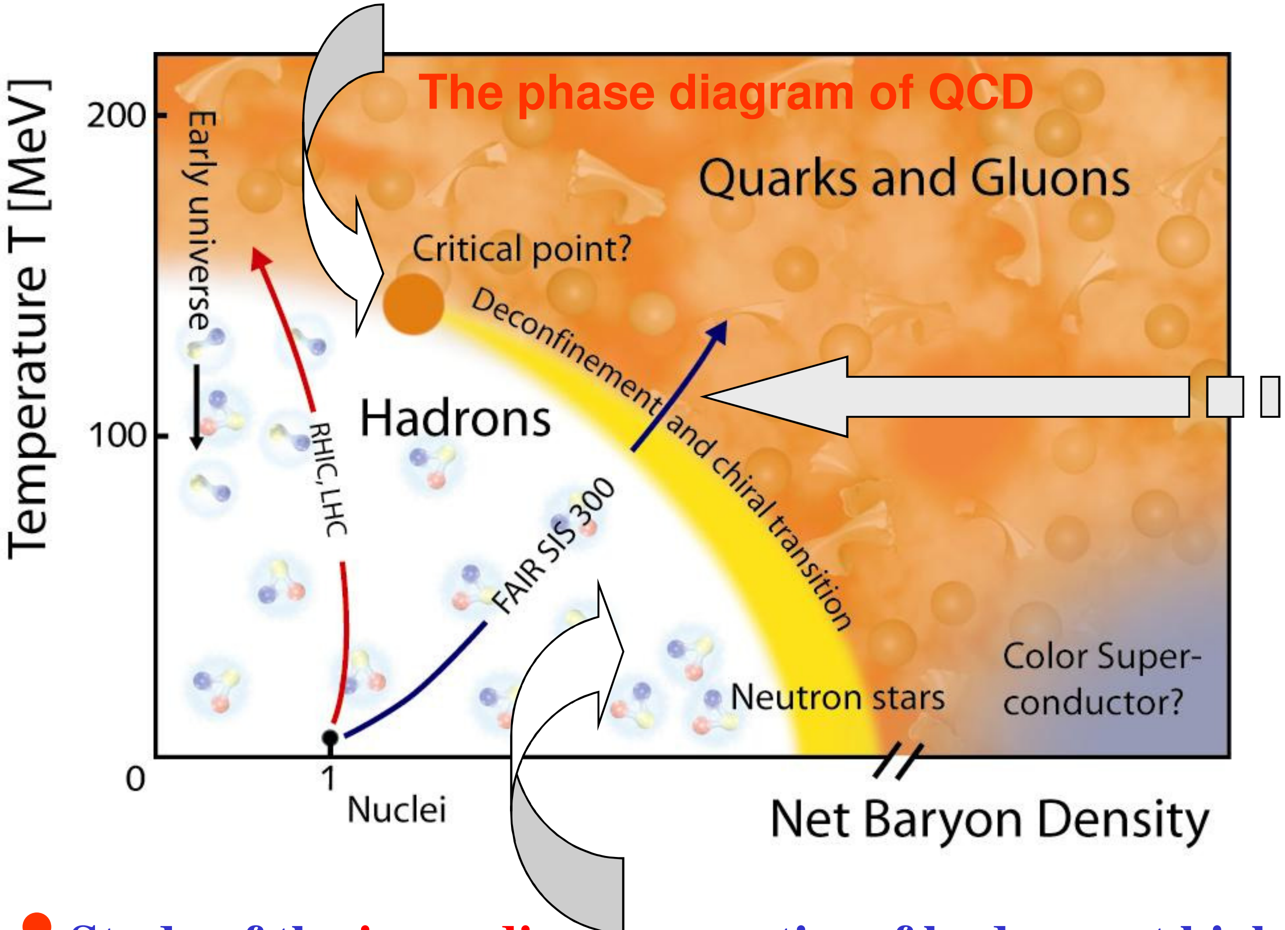
The holy grail:

- 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
- Study of the partonic medium beyond the phase boundary

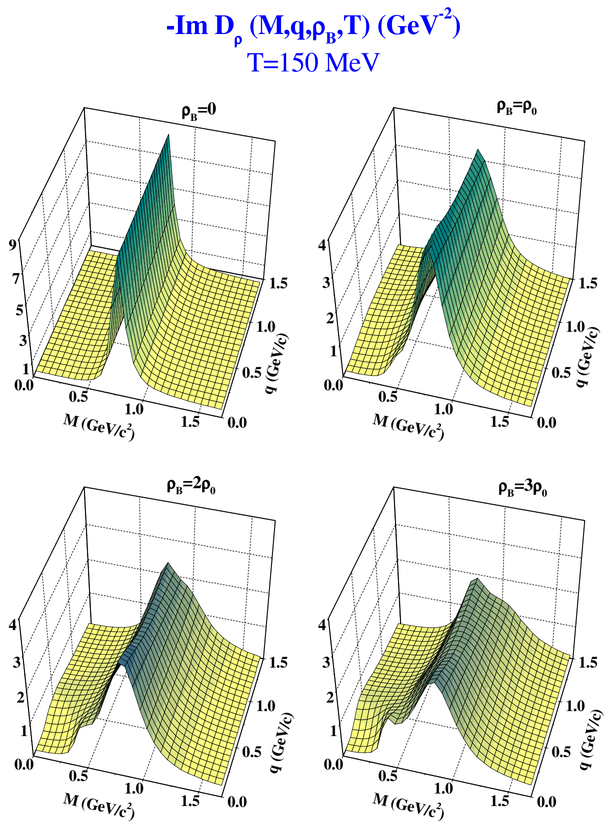
Study of in-medium effects within transport approaches

In-medium models:

- chiral perturbation theory
- chiral SU(3) model
- coupled-channel G-matrix approach
- chiral coupled-channel effective field theory

predict changes of the particle properties in the hot and dense medium, e.g. broadening of the spectral function

R. Rapp: ρ meson spectral function



● **Accounting for in-medium effects with medium-dependent spectral functions requires off-shell transport models !**

From Kadanoff-Baym equations to transport equations

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations:

drift term | **Vlasov term** | **backflow term** | **collision term = ‚loss' term - ‚gain' term**

$$\diamond\{\,P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\,\}\{\,S^<_{XP}\,\} - \diamond\{\,\Sigma^<_{XP}\,\}\{\,Re S^{ret}_{XP}\,\} = \frac{i}{2}\left[\,\Sigma^>_{XP}\, S^<_{XP} - \Sigma^<_{XP}\, S^>_{XP}\,\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation

! vanishes in the quasiparticle limit $A_{XP} = 2\,\pi\,\delta(p^2-M^2)$

➔‚on-shell' transport models (VUU, BUU, QMD, IQMD, UrQMD etc.)

Greens function $S^<$ characterizes the number of particles (N) and their properties (A – spectral function): $iS^<_{XP}=A_{XP}N_{XP}$

The imaginary part of the retarded propagator is given by the normalized spectral function:

$$A_{XP} = i\left[S^{ret}_{XP} - S^{adv}_{XP}\right] = -2\,Im\,S^{ret}_{XP}\,, \qquad \int \frac{dP_0^2}{4\pi}\,A_{XP} = 1$$

For bosons in first order gradient expansion:

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

Γ_{XP} – width of spectral function = reaction rate of particle (at phase-space position XP)

4-dimentional generalizaton of the Poisson-bracket:

$$\diamond\{\,F_1\,\}\{\,F_2\,\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

General testparticle off-shell equations of motion

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Employ testparticle Ansatz for the real valued quantity $i\, S^<_{XP}$ -

$$F_{XP} = A_{XP} N_{XP} = i\, S^<_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

General testparticle off-shell equations of motion:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

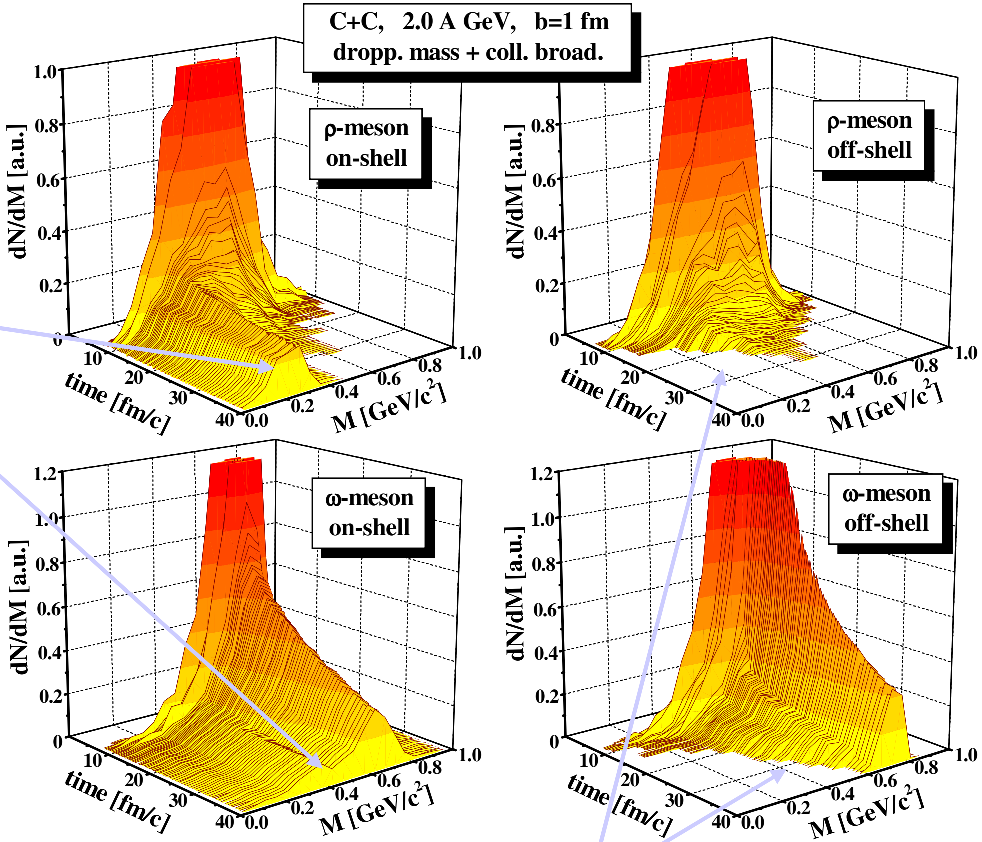
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

Off-shell vs. on-shell transport dynamics

Time evolution of the mass distribution of ρ and ω mesons for central C+C collisions (b=1 fm) at 2 A GeV for dropping mass + collisional broadening scenario

E.L.B. &W. Casssing, NPA 807 (2008) 214

On-shell model: low mass ρ and ω mesons live forever and shine dileptons!



The off-shell spectral function becomes on-shell in the vacuum dynamically by propagation through the medium!

The baseline concepts of HSD

HSD – Hadron-String-Dynamics transport approach:

- for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the generalized transport equations

  with collision terms I_{coll} describing:

  - elastic and inelastic hadronic reactions:

    baryon-baryon, meson-baryon, meson-meson

    BB <–> B´B´, BB <–> B´B´m
    mB <–> m´B´, mB <–> B´

  - formation and decay of

    baryonic and mesonic resonances

    and strings - excited color singlet states *(qq - q)* or *(q – qbar)* -

    (for inclusive particle production: BB –> X , mB –>X, X =many particles)

  Baryons:
  B=(p, n, Δ(1232),
  N(1440), N(1535), ...)
  Mesons:
  m=(π, η, ρ, ω, ϕ, ...)

- implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-particle reactions in HSD !)

- off-shell dynamics for short-lived states

HSD is an open code: http://www.th.physik.uni-frankfurt.de/~brat/hsd.html

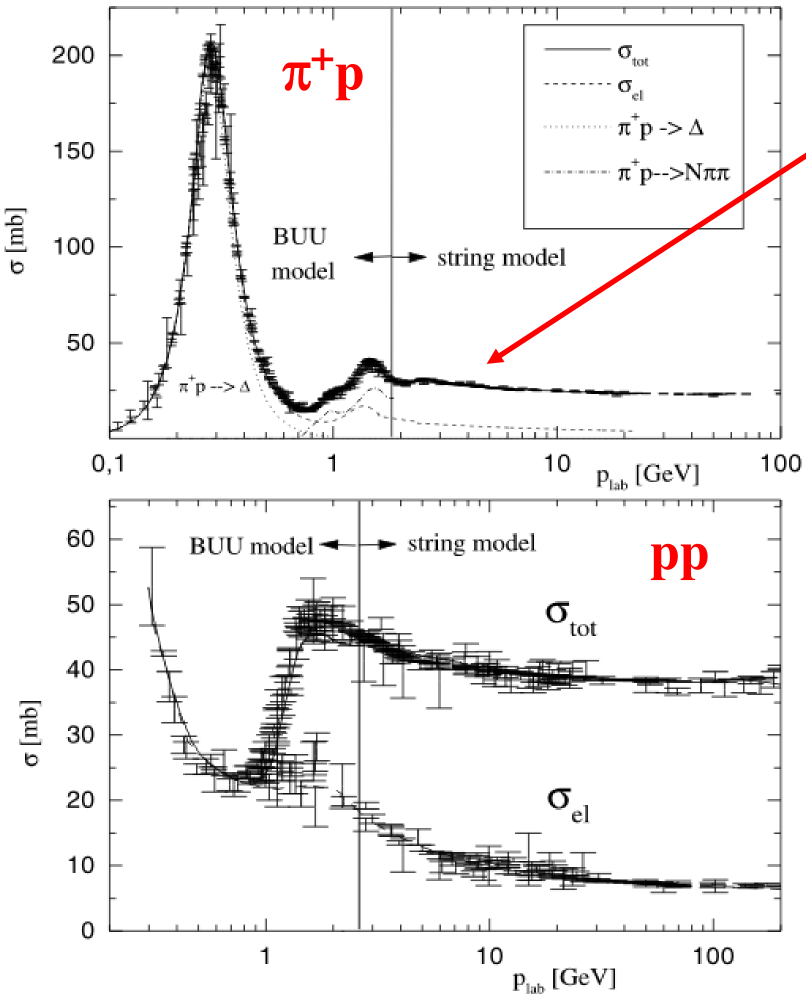
(Collision term) Description of elementary reactions in HSD

Low energy collisions:

- binary 2<–>2 and 2<–>3 reactions
- formation and decay of baryonic and mesonic resonances

BB <–> B´B´
BB <–> B´B´m
mB <–> m´B´
mB <–> B´
mm <–> m´m´
mm <–> m´
. . .

Baryons:
B=(p, n, Δ(1232), N(1440), N(1535), ...)
Mesons:
m=(π, η, ρ, ω, ϕ, ...)

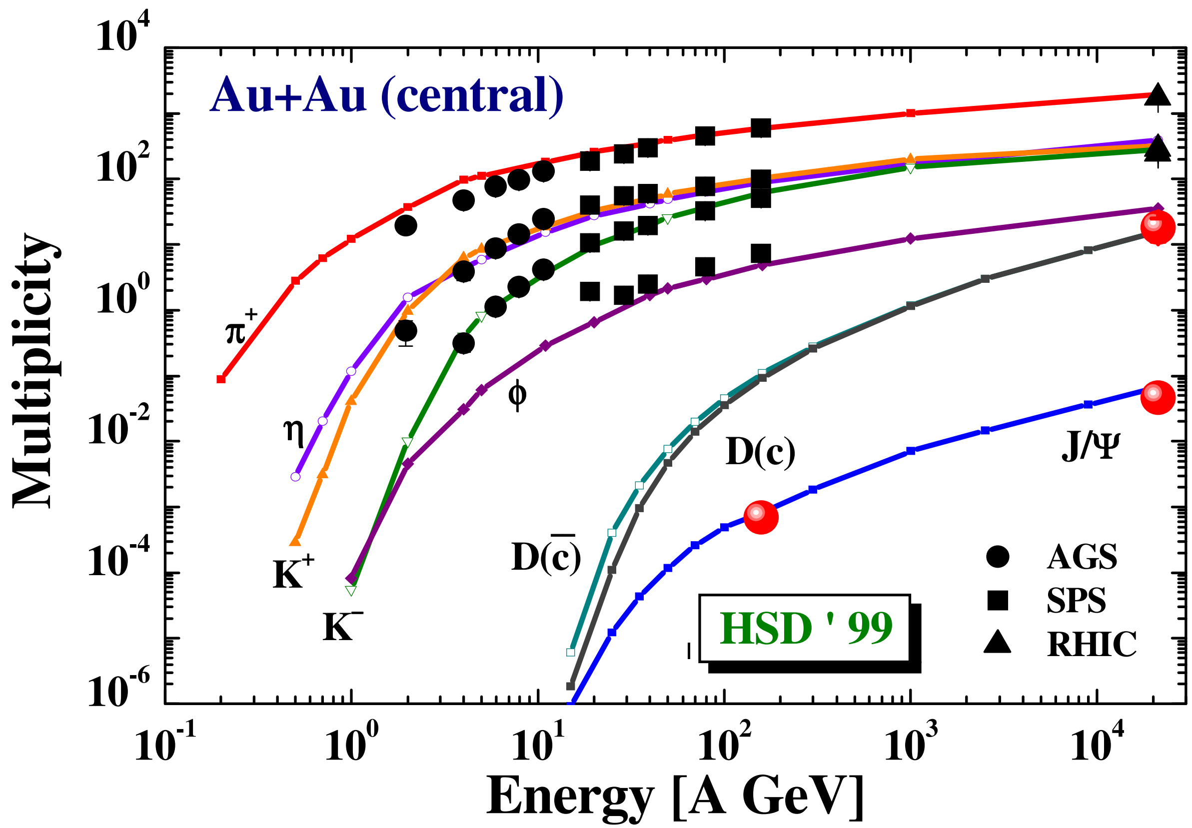


High energy collisions:
(above $s^{1/2}$~2.5 GeV)

Inclusive particle production:
BB –> X , mB –>X
X =many particles
described by
strings (= excited color singlet states *q-qq*, *q-qbar*) **formation and decay**

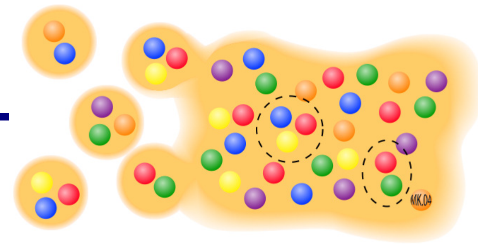
HSD – a microscopic model for heavy-ion reactions

- very good description of particle production in pp, pA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (>20 TeV) energies



HSD predictions from 1999; data from the new millenium

From hadrons to partons



In order to study the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- **explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!**
- **explicit phase transition from hadronic to partonic degrees of freedom**
- **lQCD EoS for partonic phase**

Transport theory: 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)**

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

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

The Dynamical QuasiParticle Model (DQPM)

Basic idea: Interacting quasiparticles

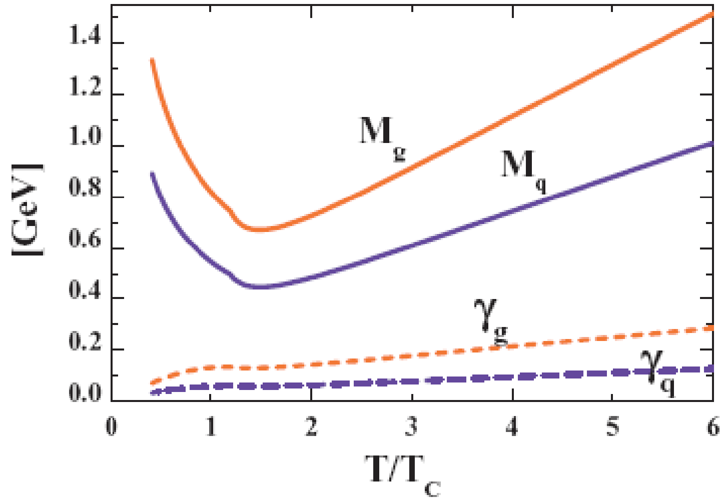
- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

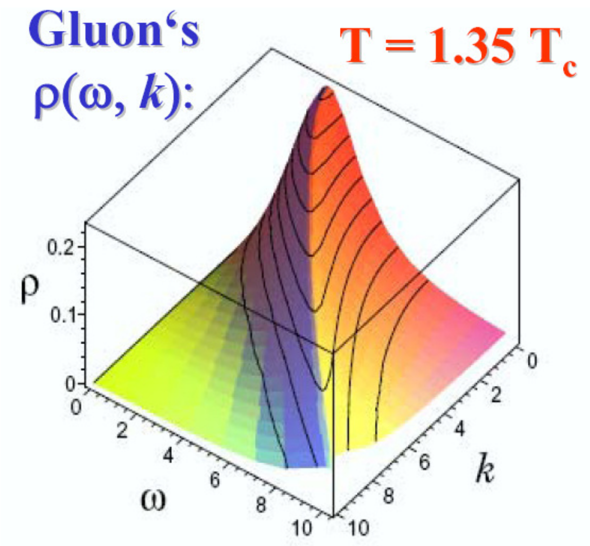
➢ fit to lattice (lQCD) results (e.g. entropy density)

$$\rho(\omega) = \frac{\gamma}{E}\left(\frac{1}{(\omega-E)^2+\gamma^2} - \frac{1}{(\omega+E)^2+\gamma^2}\right)$$

➔ Quasiparticle properties:

- large width and mass for gluons and quarks

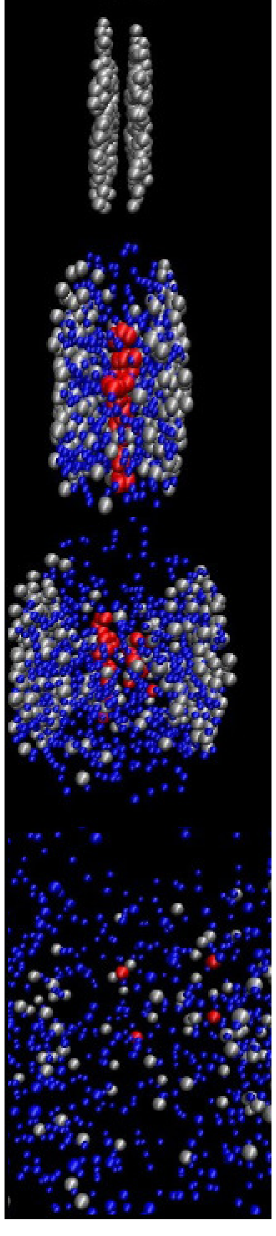




- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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

PHSD - basic concept



Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) - approximation to QCD

Partonic phase: quarks and gluons (= ‚dynamical quasiparticles‘) with off-shell spectral functions (width, mass) defined by the DQPM

- ❑ **elastic and inelastic parton-parton interactions:**
  using the effective cross sections from the DQPM
  - ✓ **q + qbar (flavor neutral) <=> gluon (colored)**
  - ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
  - ✓ **q + qbar (color neutral) <=> hadron resonances**
- ❑ **self-generated mean-field potential for quarks and gluons !**

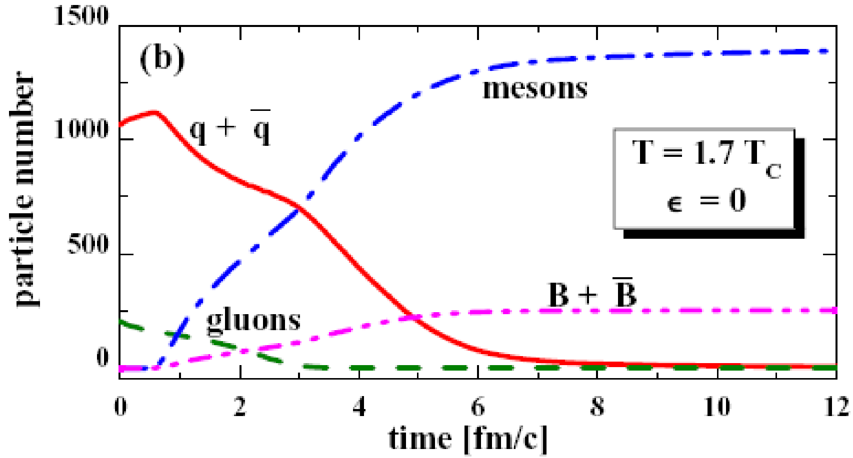
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states‘ for hadrons)

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

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

PHSD: hadronization of a partonic fireball

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at μ_q=0



Consequences:

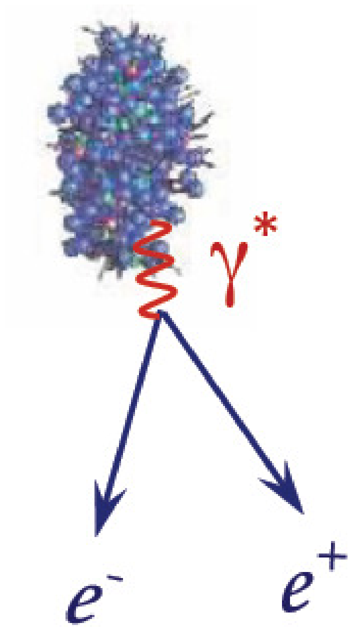
- **Hadronization: $q+q_{bar}$ or $3q$ or $3q_{bar}$ fuse to color neutral hadrons (or strings) which subsequently decay into hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!**

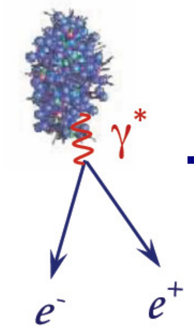
- **Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!**

- **Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system**

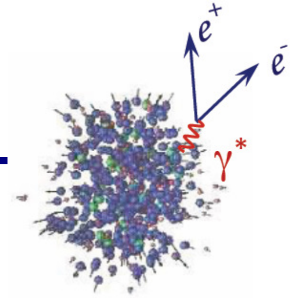
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

Dileptons





Electromagnetic probes: dileptons and photons



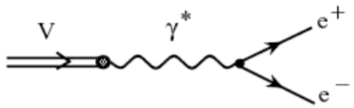
➢ Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions

Dilepton sources:

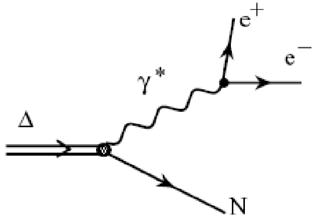
- from the QGP via partonic (q,qbar, g) interactions:

- from hadronic sources:

•direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ')

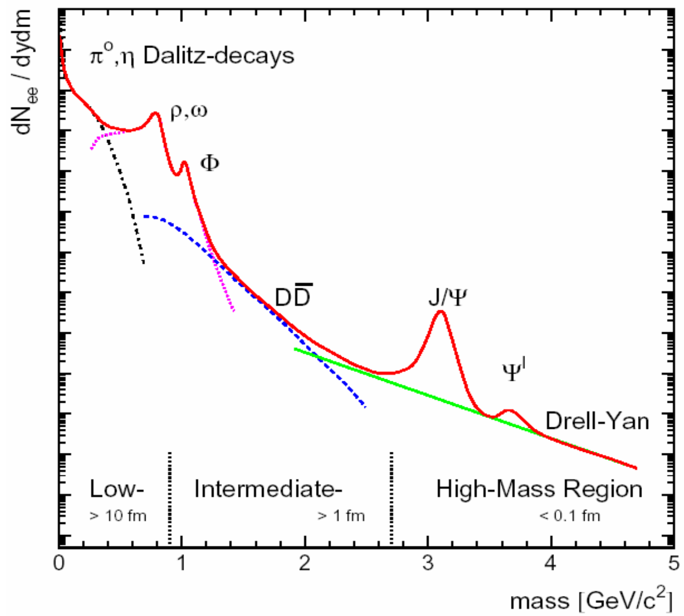


•Dalitz decay of mesons and baryons (π^0,η, Δ,…)



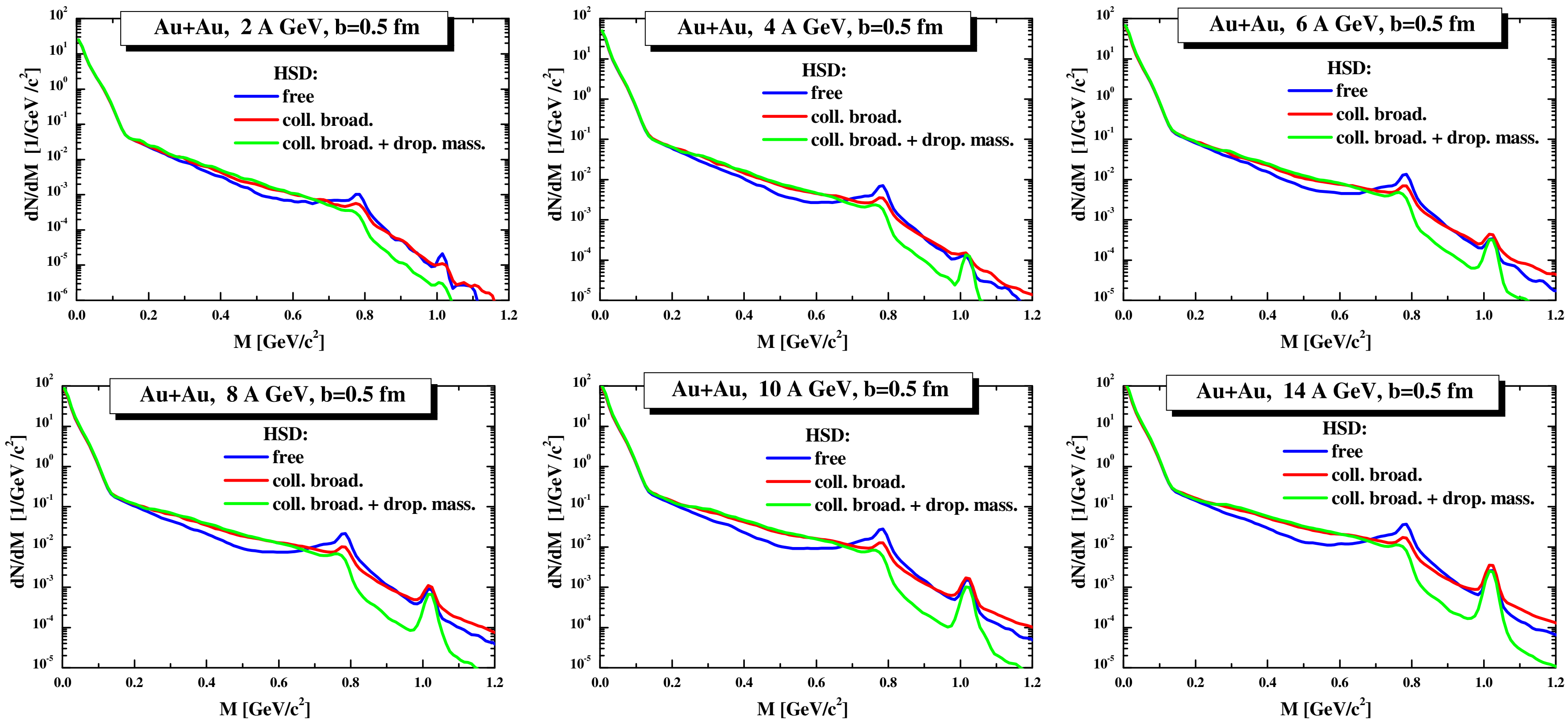
•correlated D+Dbar pairs

•radiation from multi-meson reactions (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - '4π'



➔ Dileptons are an ideal probe to study the properties of the hot and dense medium

Dileptons from SIS to FAIR/NICA

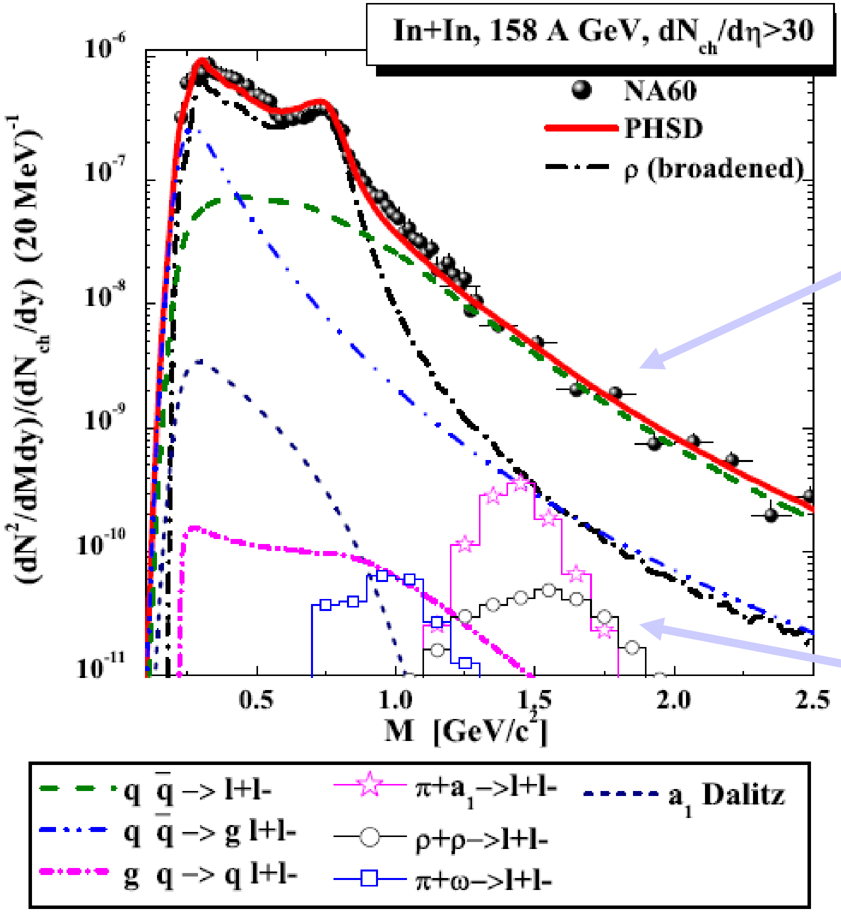


Dileptons : ‚free' vs. ‚in-medium' scenarios (collisional broadening , collisional broadening +dropping mass) for vector mesons (ρ,ω,ϕ)

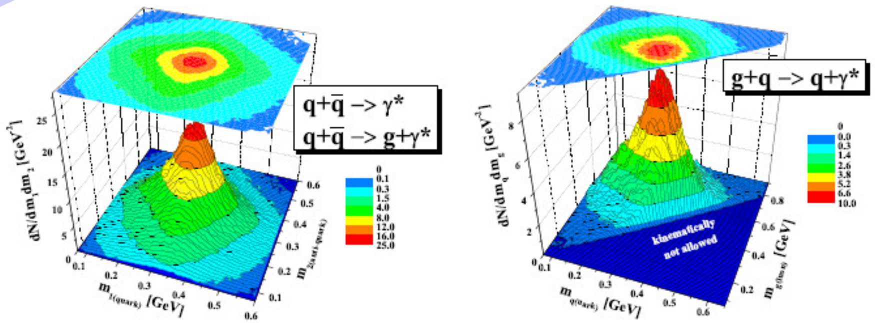
➔enhancement of dilepton yield for 0.2<M<0.7 GeV and
➔reduction at $M \sim m_{\rho/\omega}$ for all energies from SIS to FAIR/NICA!

Dileptons at SPS: NA60

Acceptance corrected NA60 data



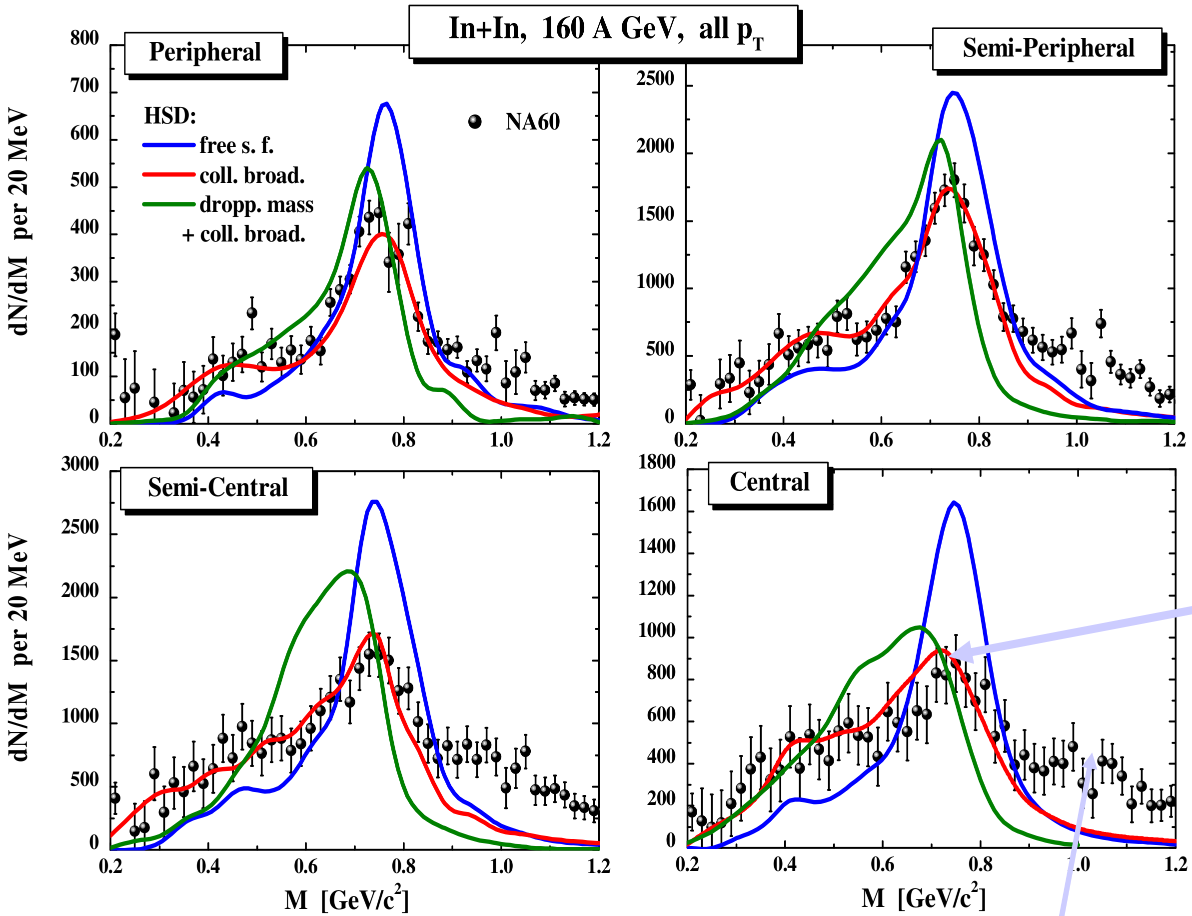
- Mass region above 1 GeV is dominated by **partonic radiation !**



- Contributions of "4π" channels (radiation from multi-meson reactions) are small

O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60 data vs. HSD transport



HSD – full off-shell propagation of in-medium spectral functions through the hadronic medium

- models for ρ spectral function:

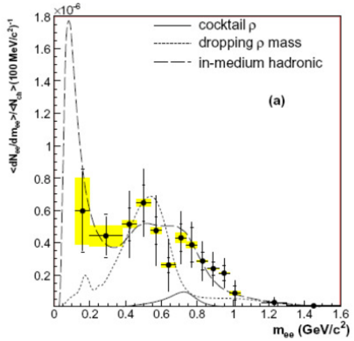
- **vacuum spectral function**
- **dropping mass (Brown/Rho)**
- **coll. broad. (Rapp/Wambach)**

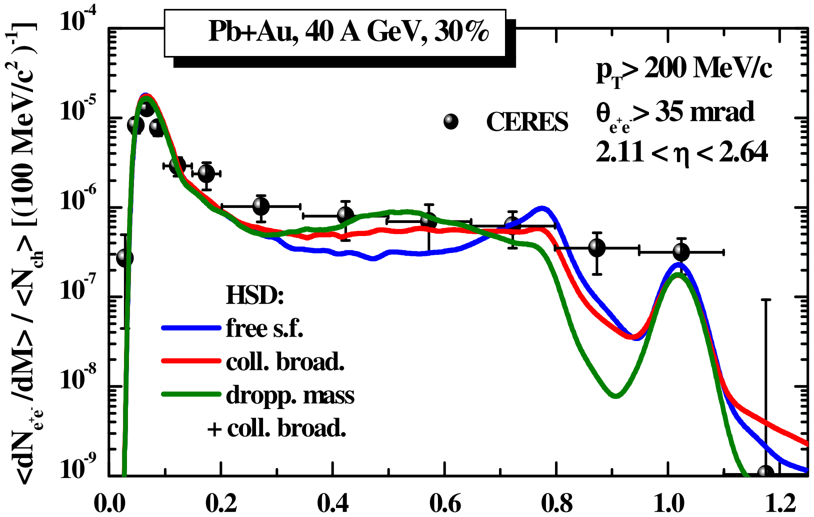
- **NA60 data are better described by in-medium scenario with collisional broadening**

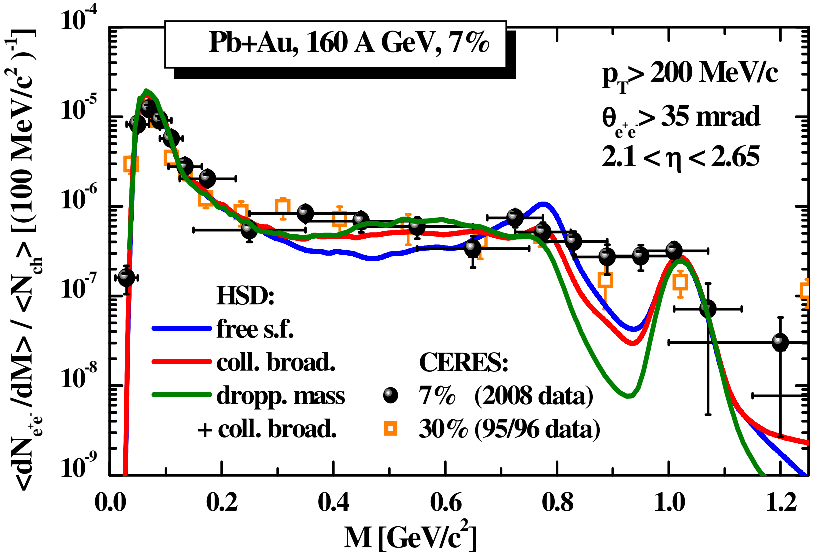
- **High M tail not reproduced in HSD ➔ Non-hadronic origin?**

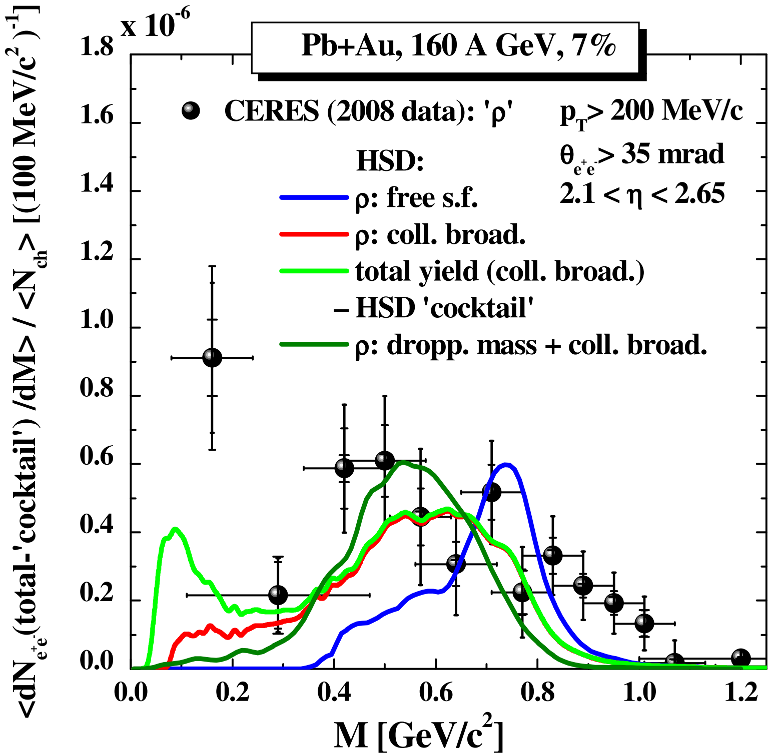
E. B., W. Cassing, O. Linnyk, PLB 670 (2009) 428

Dileptons at SPS: CERES





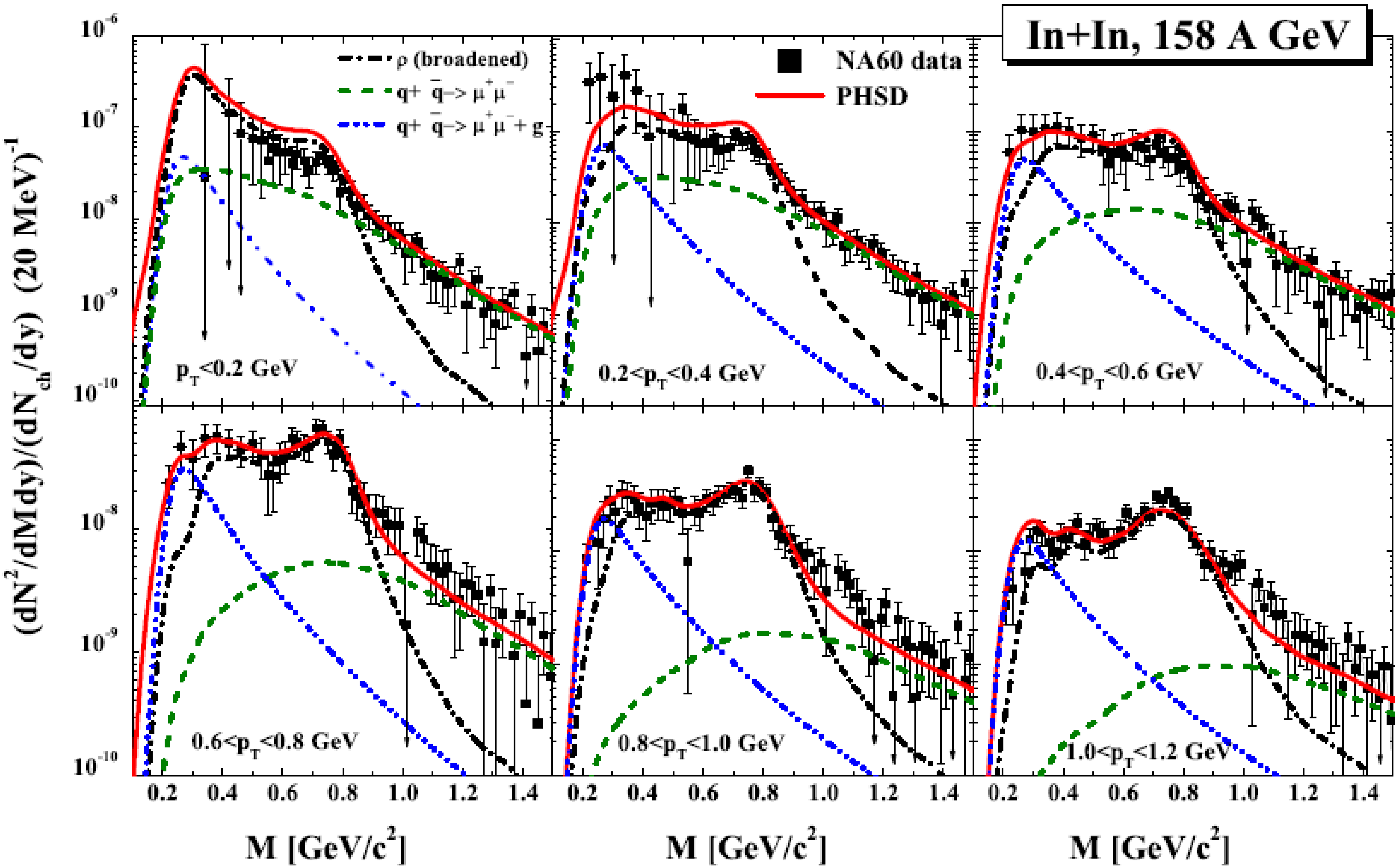




CERES data are better described by an in-medium scenario with collisional broadening

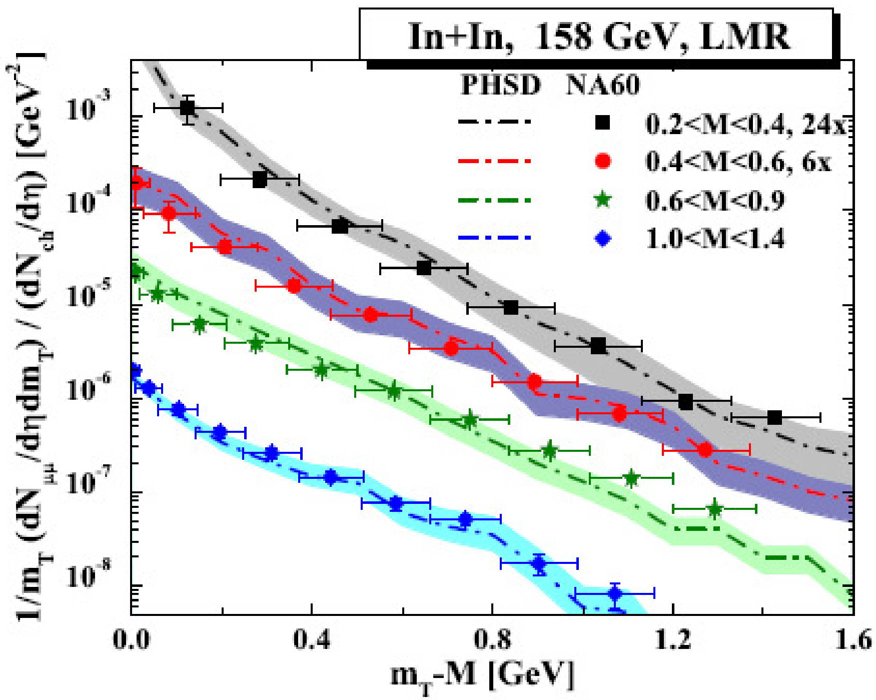
E. Bratkovskaya, W. Cassing, O. Linnyk, PLB 670 (2009) 428

Dileptons at SPS: NA60

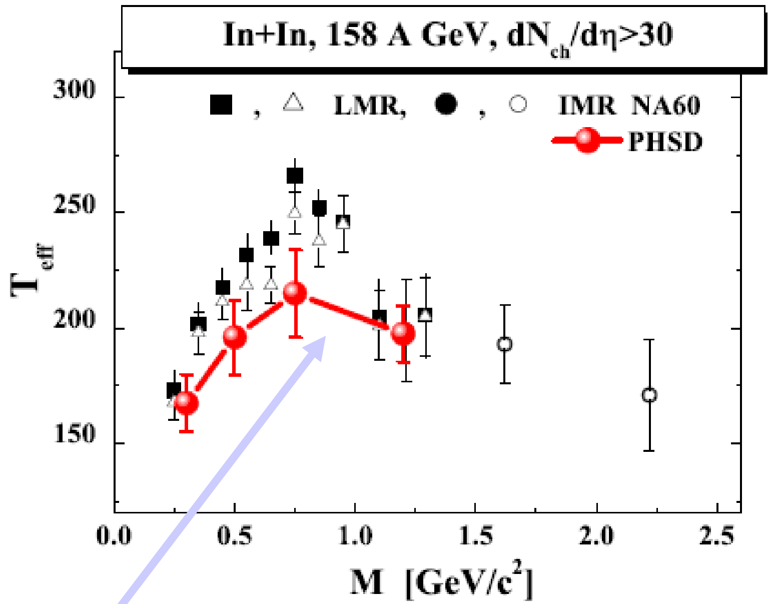


O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60: m_T spectra



- Inverse slope parameter T_{eff} for dilepton spectra vs NA60 data



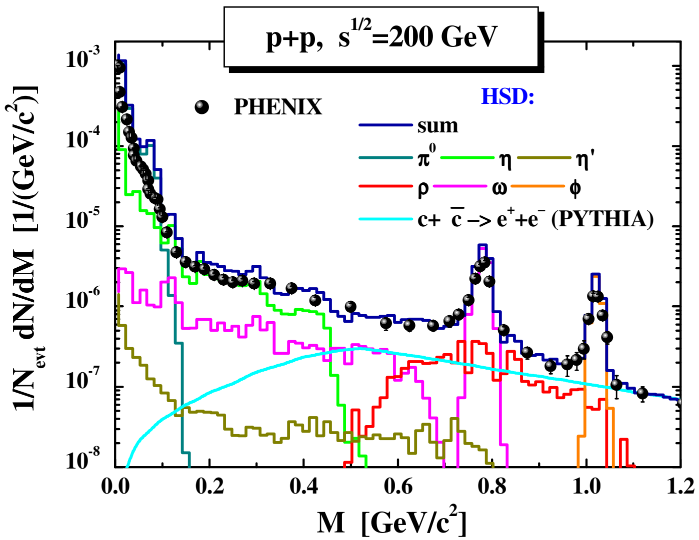
Conjecture:

- spectrum from sQGP is softer than from hadronic phase since quark-antiquark annihilation occurs dominantly before the collective radial flow has developed (cf. NA60)

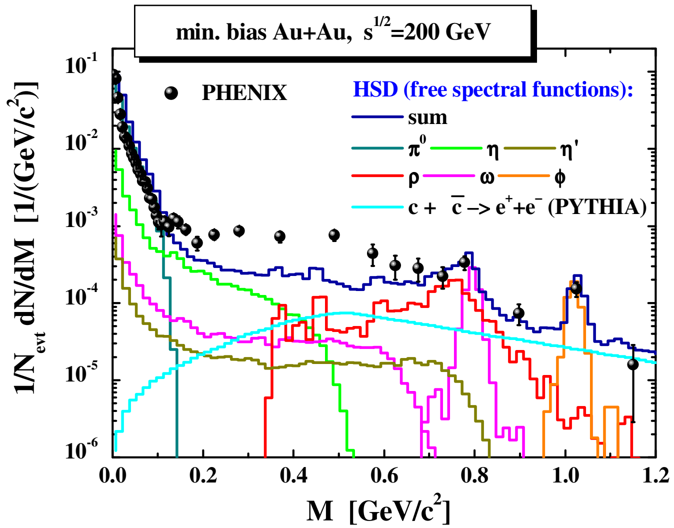
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

Dileptons at RHIC: PHENIX

PHENIX: pp

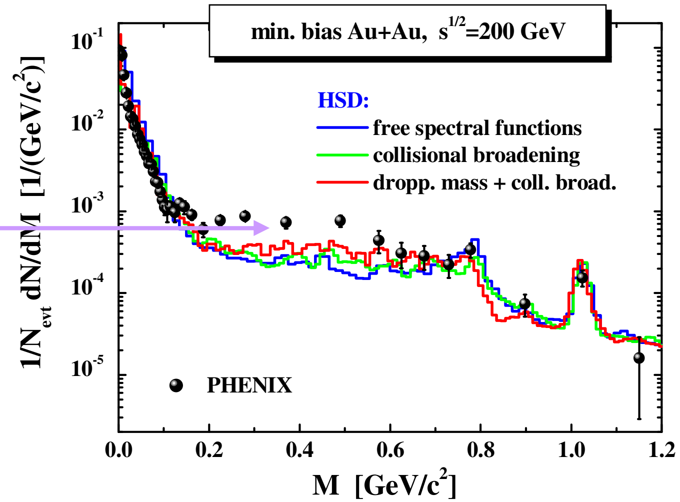


PHENIX: Au+Au



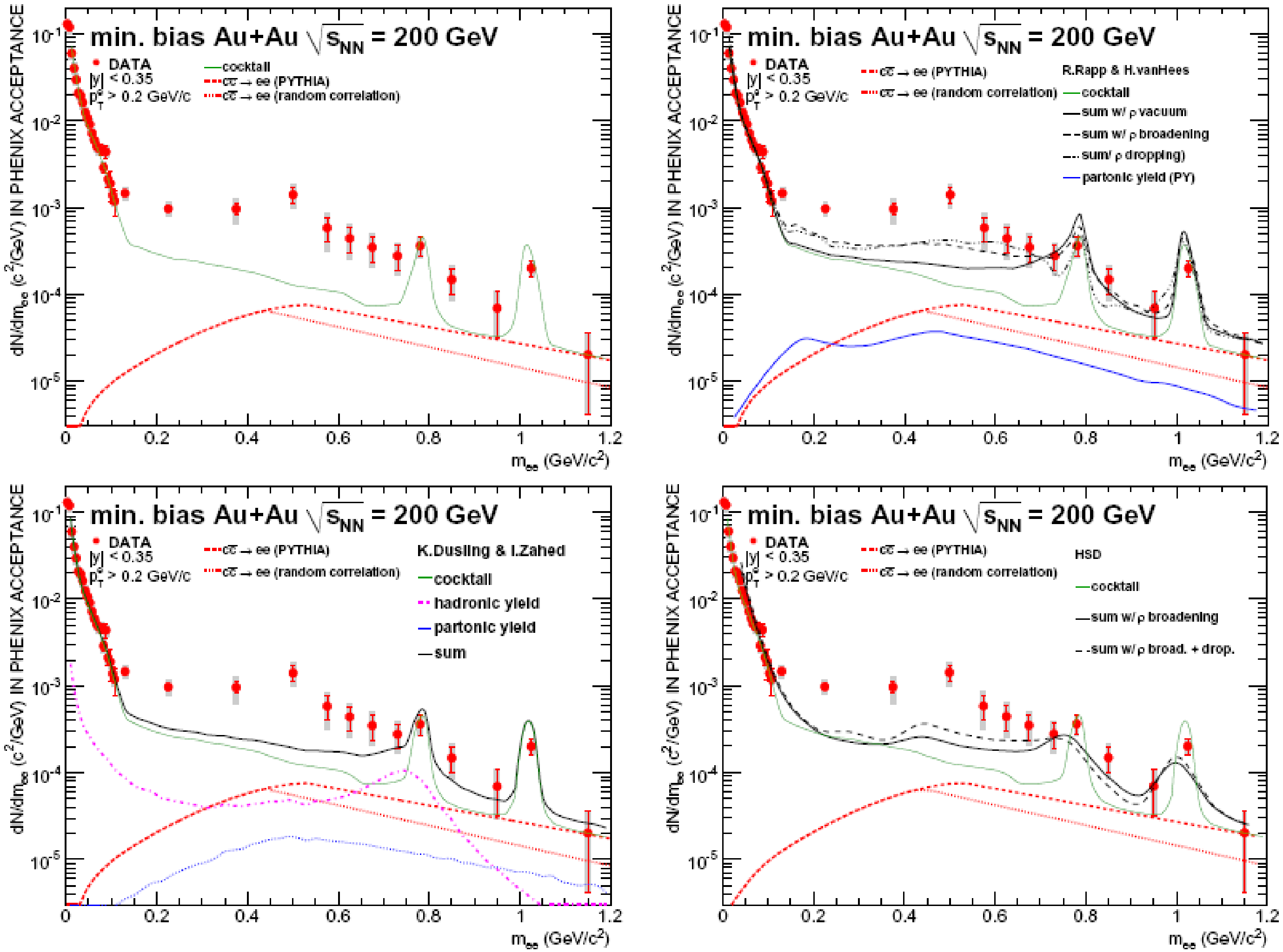
- HSD provides a good description of pp data

- Standard in-medium effects of vector mesons -- compatible with the NA60 and CERES data at SPS – do not explain the large enhancement observed by PHENIX in the invariant mass from 0.2 to 0.5 GeV in Au+Au collisions at $s^{1/2}$=200 GeV (relative to pp collisions)



E. B., W. Cassing, O. Linnyk, PLB 670 (2009) 428

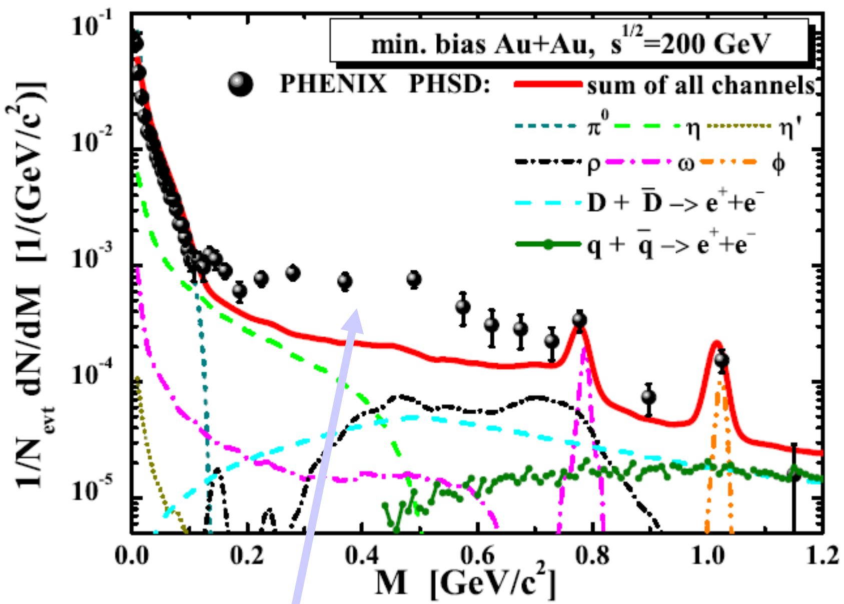
Dileptons at RHIC: data vs. theor. models

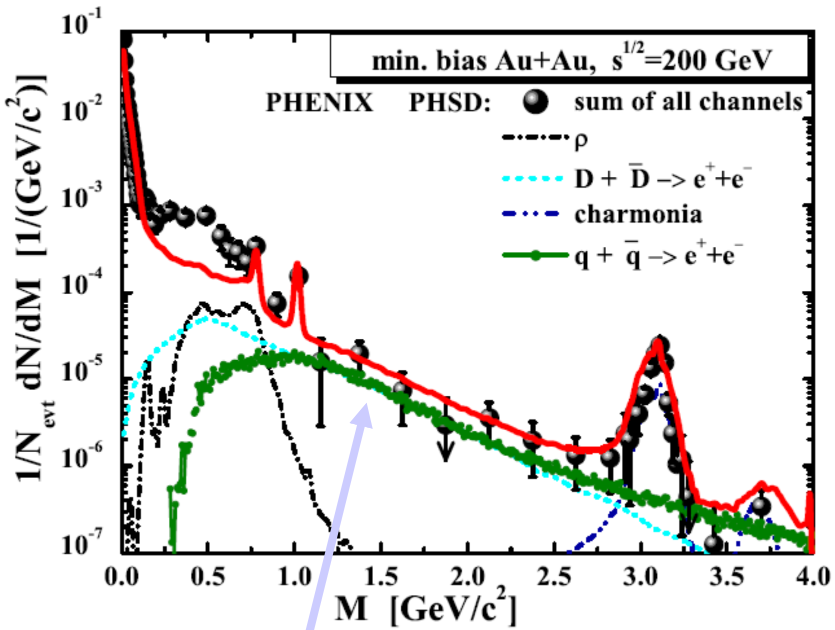


PHENIX: Au+Au

➔ PHENIX dilepton puzzle ?!

PHENIX: dileptons from partonic channels



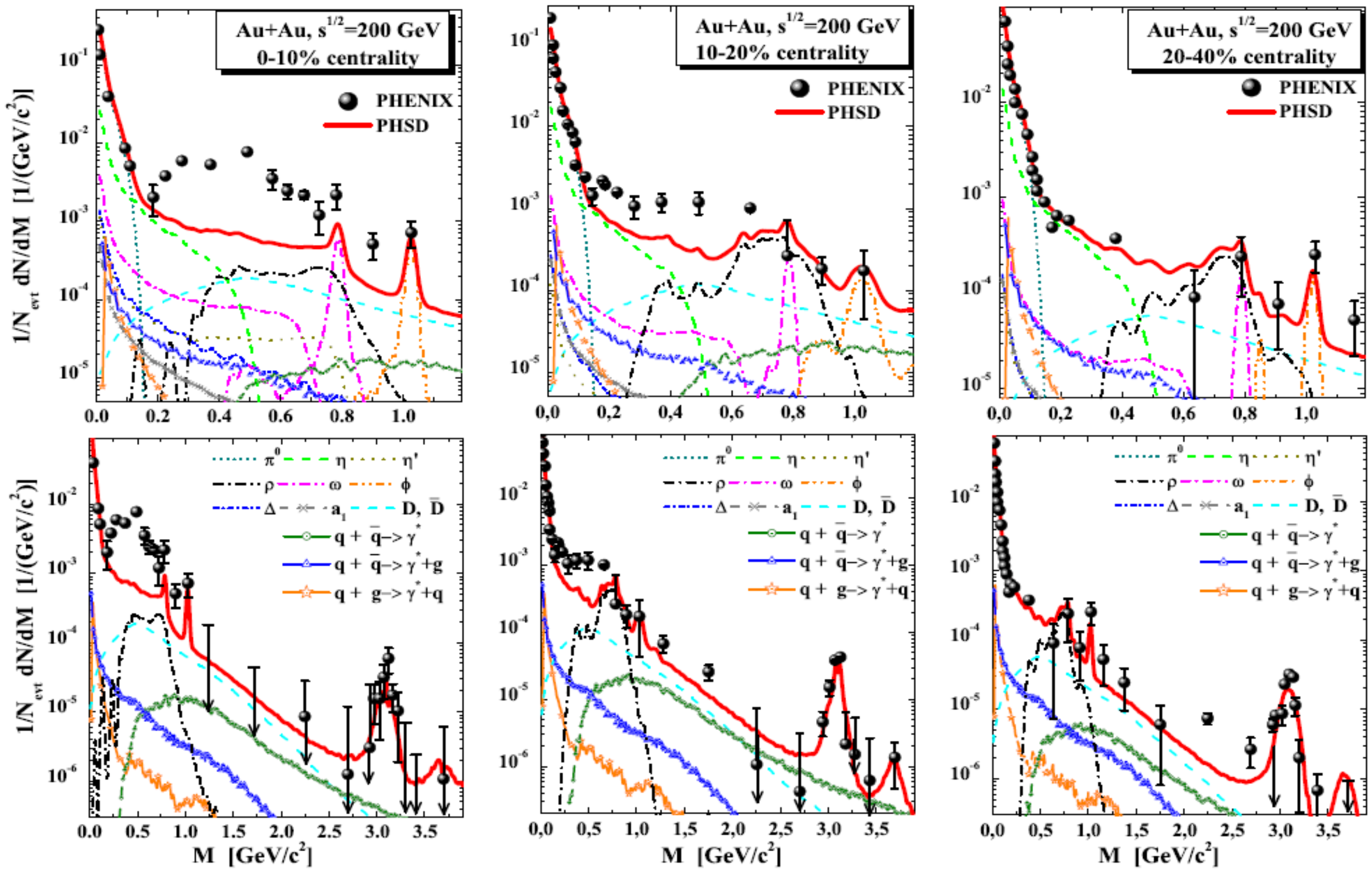


- The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD

- The partonic channels fill up the discrepancy between the hadronic contributions and the data for M>1 GeV

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

PHENIX: mass spectra

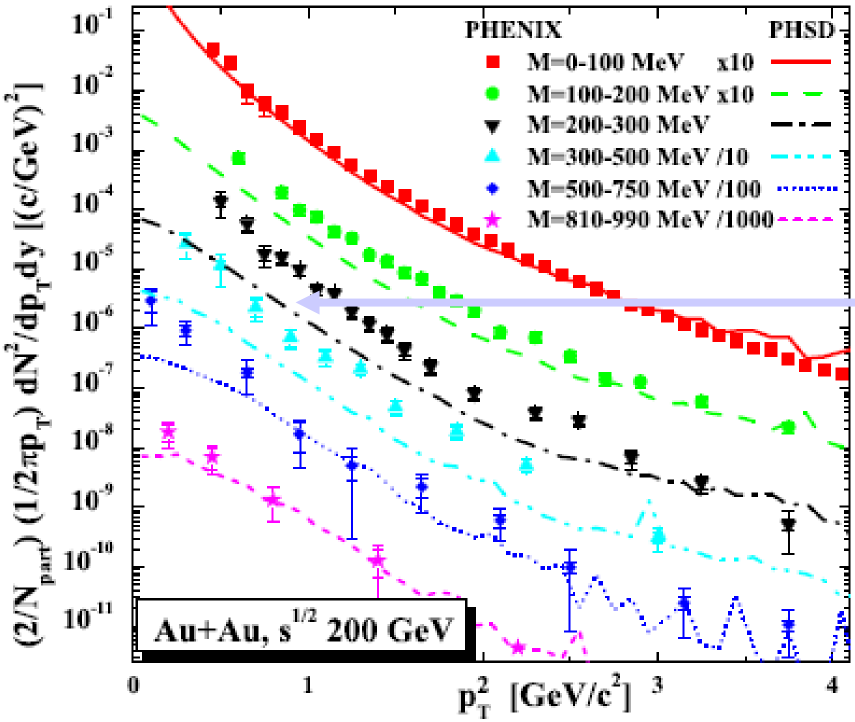


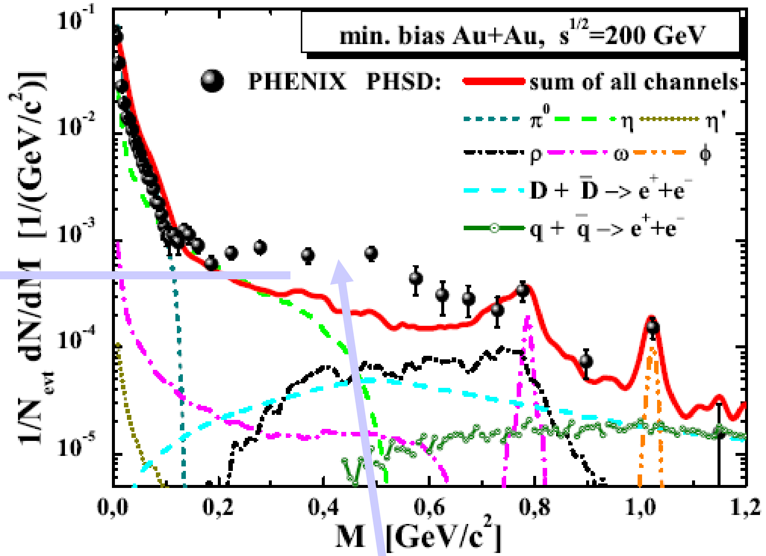
(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

- **Peripheral collisions are well described, however, central fail!**

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

PHENIX: p_T spectra





- The lowest and highest mass bins are described very well
- Underestimation of p_T data for 100<M<750 MeV bins consistent with dN/dM
- The 'missing source'(?) is located at low p_T !

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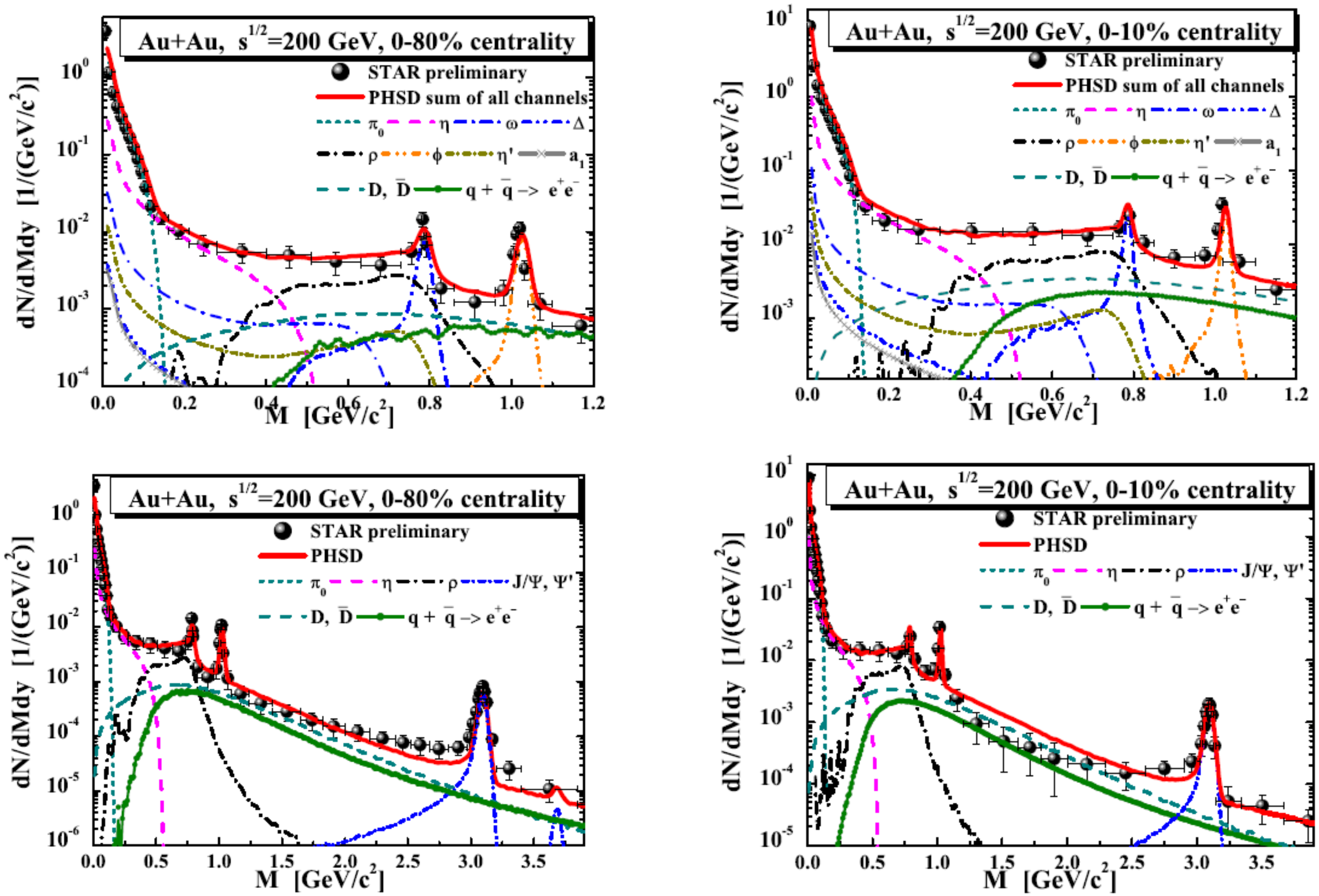
STAR: mass spectra



- **STAR data are well described!**

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Summary

- Parton-Hadron-String-Dynamics (PHSD) theory provides a consistent description of the phase transition to the QGP in heavy-ion collisions.

- In-medium effects can be observed in dilepton spectra at all energies from SIS to RHIC

- The dilepton data from NA60 at SPS energies are better described within off-shell HSD/PHSD, if a collisional broadening of vector mesons is assumed.

- The yield of dilepton pairs at masses above 1 GeV indicates the presence of the strongly interacting QGP and is described by the interactions of dynamical quasiparticles

- Neither the incorporated hadronic nor partonic sources account for the enhancement observed by PHENIX in the invariant mass from 0.2 to 0.6 GeV in Au+Au collisions at $s^{1/2}$=200 GeV (relative to pp collisions)

- STAR data are well reproduced by PHSD within the STAR acceptance

PHSD group

Wolfgang Cassing (Giessen Univ.)
Volodya Konchakovski (Giessen Univ.)
Olena Linnyk (Giessen Univ.)
Elena Bratkovskaya (FIAS & ITP Frankfurt Univ.)
Vitalii Ozvenchuk (HGS-HIRe, FIAS & ITP Frankfurt Univ.)
\+ **Rudy Marty** (SUBATECH→FIAS, Frankfurt Univ.)

External Collaborations:

SUBATECH, Nantes Univ. :
- Jörg Aichelin
- Christoph Hartnack
- Pol-Bernard Gossiaux

Texas A&M Univ.:
- Che-Ming Ko

JINR, Dubna:
- Vadim Voronyuk
- Viatcheslav Toneev

Kiev Univ.:
- Mark Gorenstein

Barcelona Univ.
- Laura Tolos, Angel Ramos