Electromagnetic probes of the QGP

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Workshop "Opportunities from FAIR to other low energy facilities"

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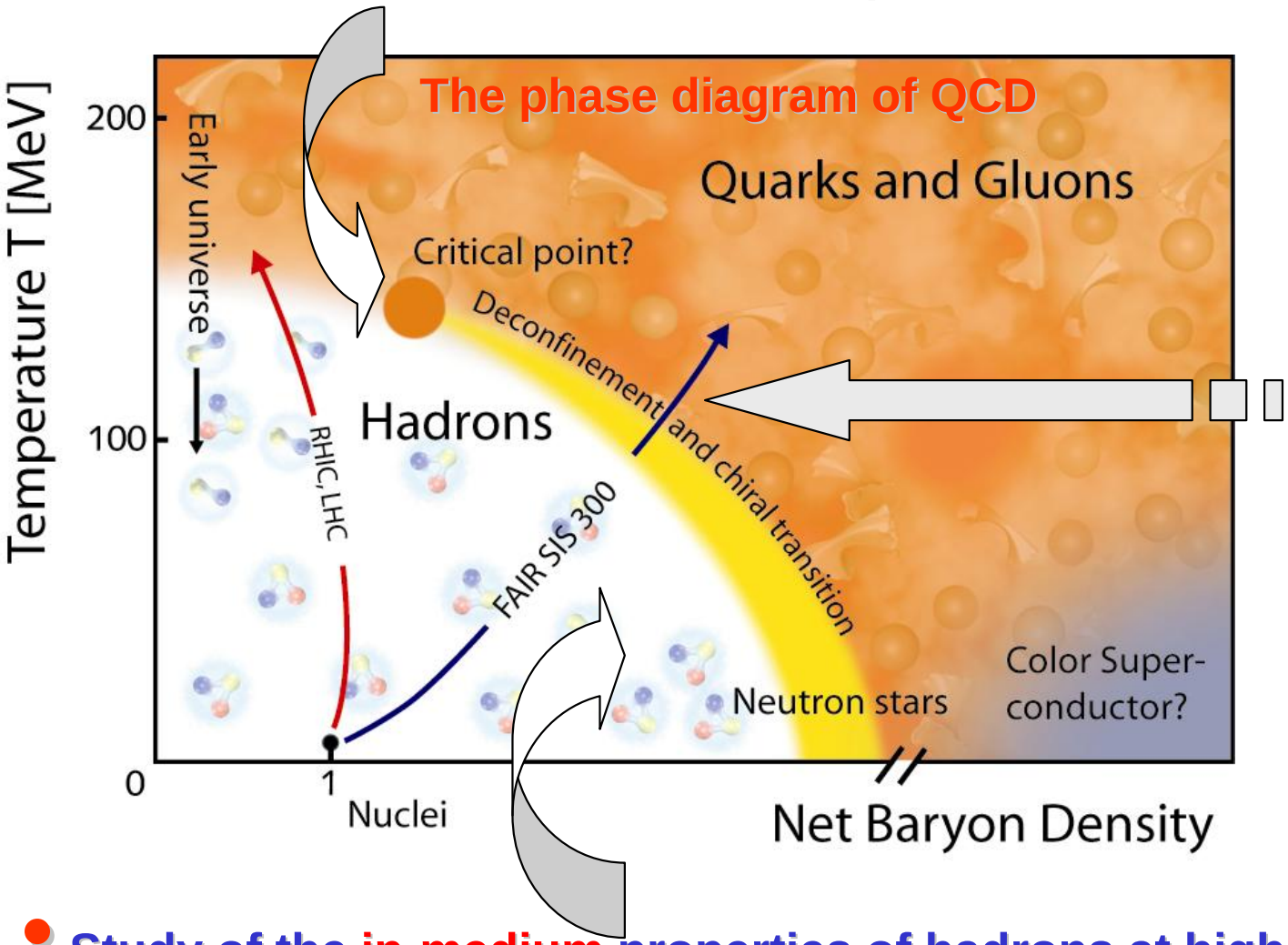
The holy grail of heavy-ion physics:

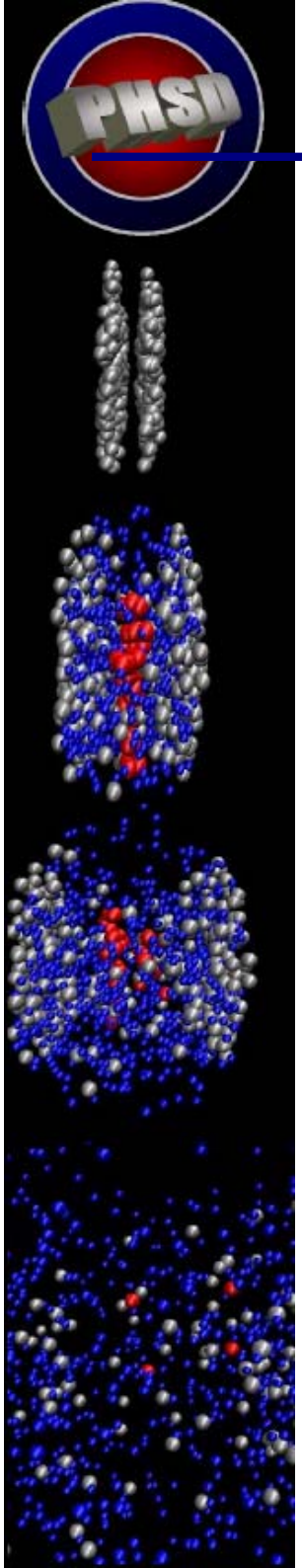
- Search for the critical point



- 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

Parton-Hadron-String-Dynamics (PHSD)



PHSD is a non-equilibrium transport model with

- **explicit phase transition from hadronic to partonic degrees of freedom**
- **lQCD EoS for the partonic phase**
- **explicit parton-parton interactions - between quarks and gluons**
- **dynamical hadronization**

❑ QGP phase is described by the Dynamical QuasiParticle Model (DQPM)

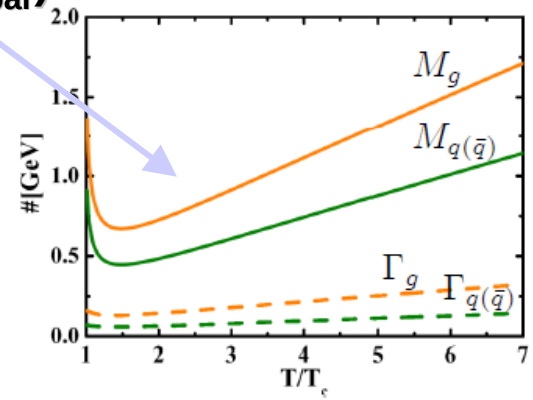
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

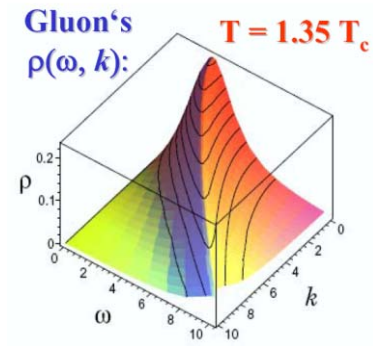
- **strongly interacting quasi-particles**

- massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in 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 system!)

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

Direct photon flow puzzle

?

EMMI Rapid Reaction Task Force

Direct-Photon Flow Puzzle

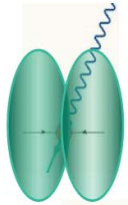
February 24-28, 2014, GSI, Darmstadt, Germany

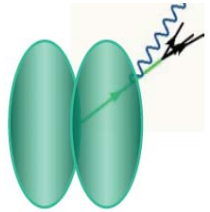
Production sources of photons in p+p and A+A

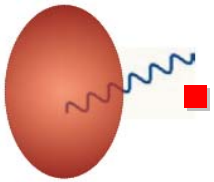
- **Decay photons (in pp and AA):**

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

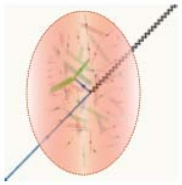
- **Direct photons: (inclusive(=total) – decay) – measured experimentally**
  - **hard photons:** (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)



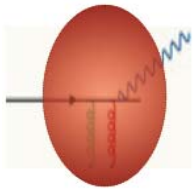




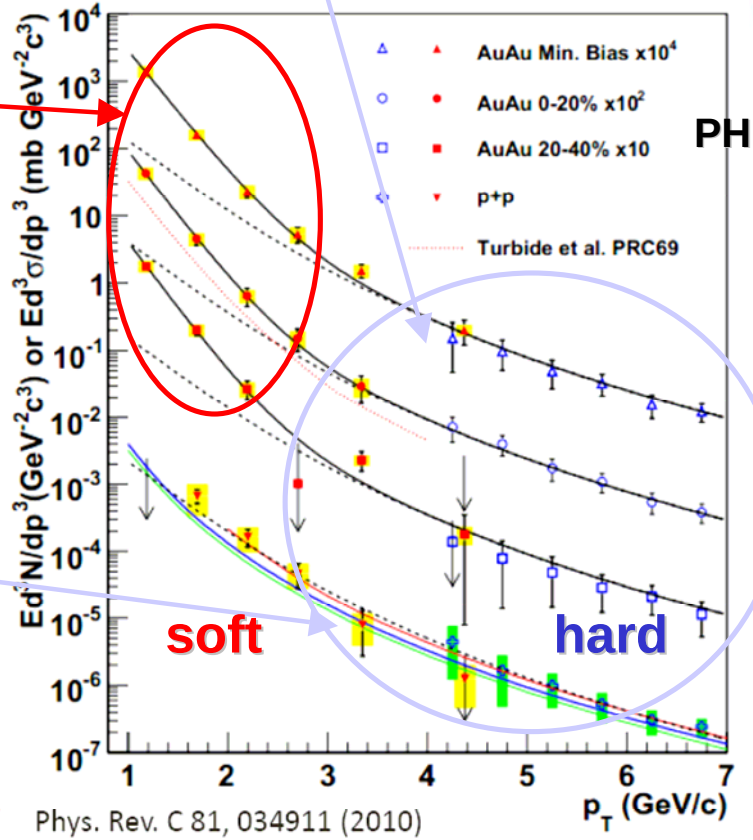
  - **thermal photons:** (low p_T, in AA)
    - **QGP**
    - **Hadron gas**



  - **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 $q_{hard}+g_{QGP} \rightarrow \gamma+q$, $q_{hard}+qbar_{QGP} \rightarrow \gamma+q$



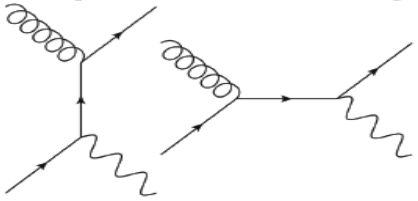
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

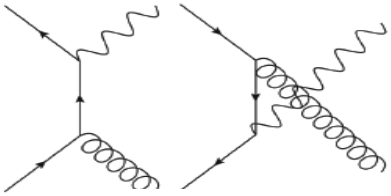
Thermal QGP:

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

Compton scattering **q-qbar annihilation**



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



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

+ soft …

- **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:

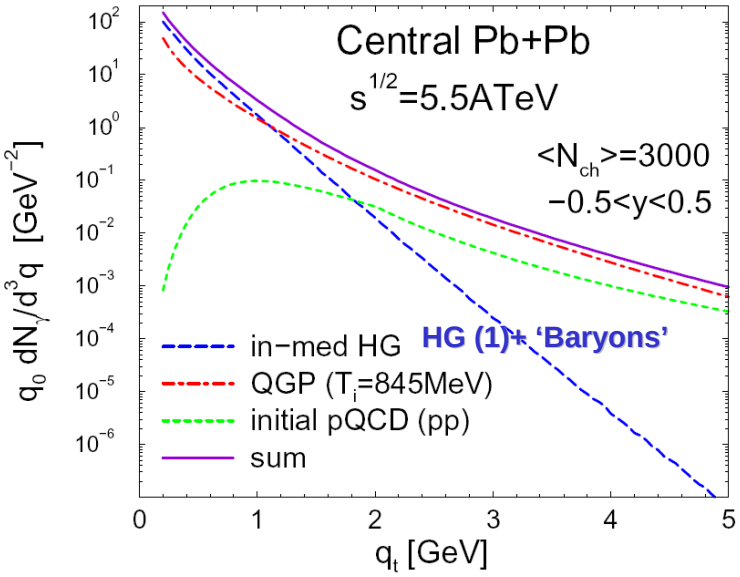
(1) secondary mesonic interactions:

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

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

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

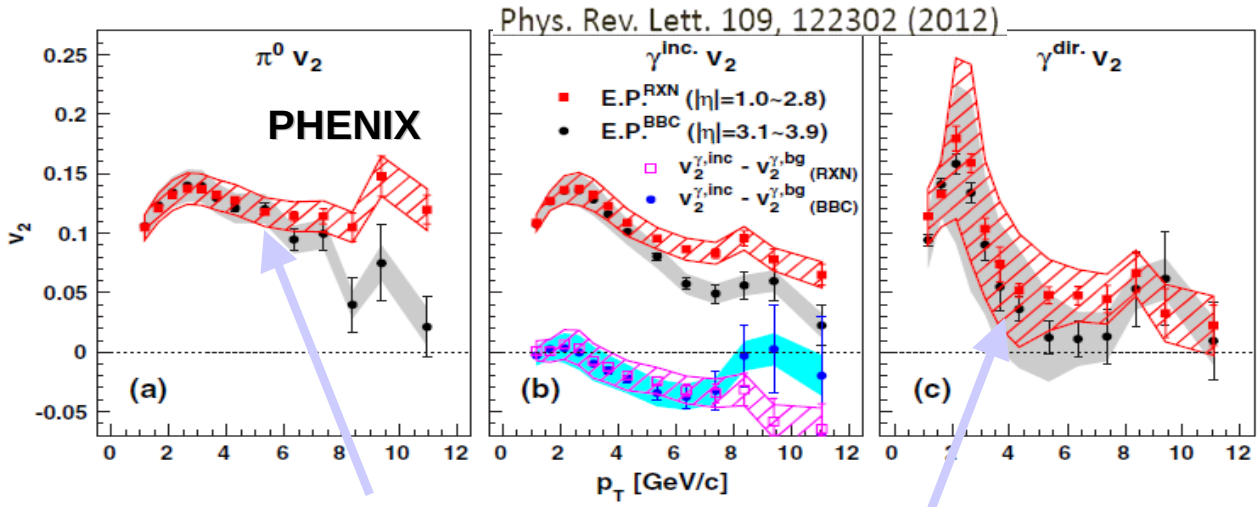
$m=\pi,\eta,\rho,\omega,K,K^*,\ldots,\ B=p,\Delta,\ldots$



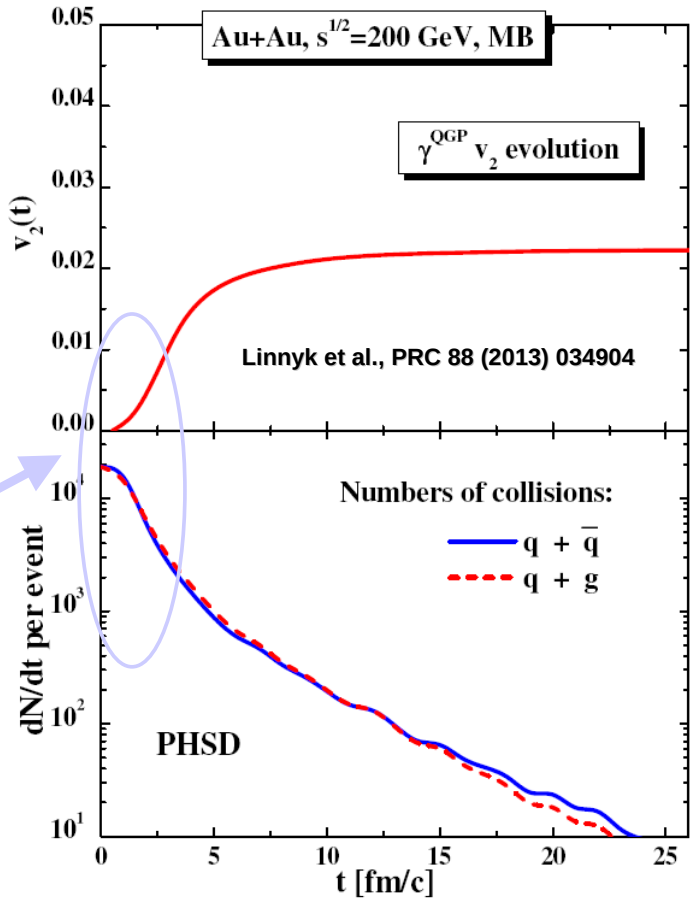
Models: **chiral models, OBE, SPA …**
Kapusta, Gale, Haglin (91), Rapp (07), …

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

PHENIX: Photon v_2 puzzle



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



- **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** $v_2(\gamma^{QGP})$

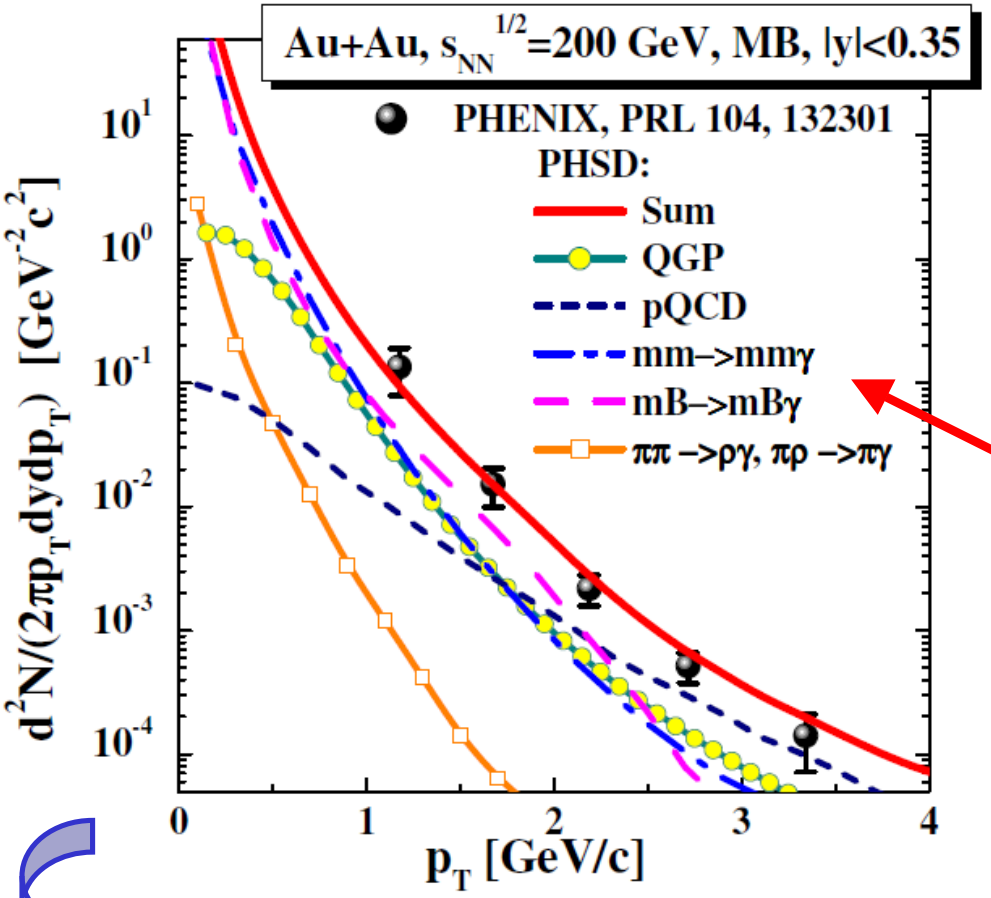
- **NEW (QM'2014): PHENIX, ALICE experiments - large photon v_3 !**

➡ **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:

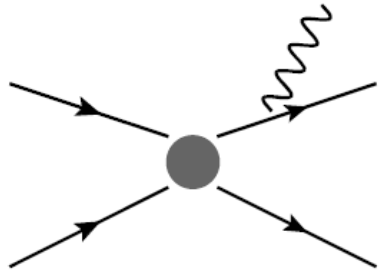
- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

! 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	$233 \pm 14 \pm 19$

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

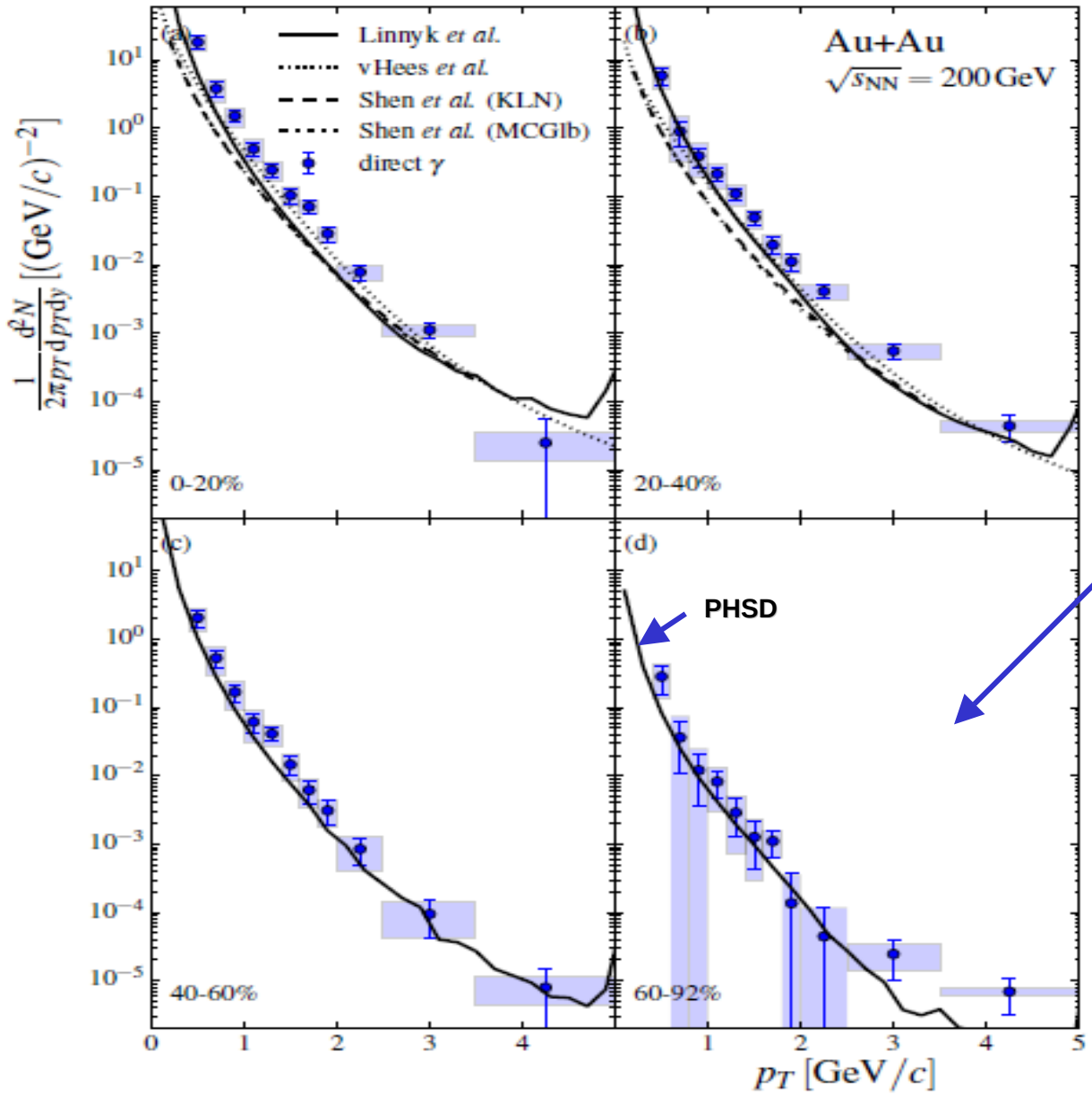
Measured Teff > ‚true' T → ‚blue shift' due to the radial flow!

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 !

Bremsstrahlung – trivial ‚background'?

- **Uncertainties in the Bremsstrahlung channels in the present PHSD results :**

1) based on the Soft-Photon-Approximation (SPA) (factorization = strong x EM)

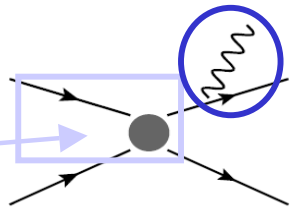
- **Soft Photon Approximation (SPA):**

$m_1+m_2 \rightarrow m_1+m_2+\gamma$

C. Gale, J. Kapusta, Phys. Rev. C 35 (1987) 2107

$$q_0 \frac{d^3\sigma^\gamma}{d^3q} = \frac{\alpha}{4\pi}\frac{\bar{\sigma}(s)}{q_0^2}$$

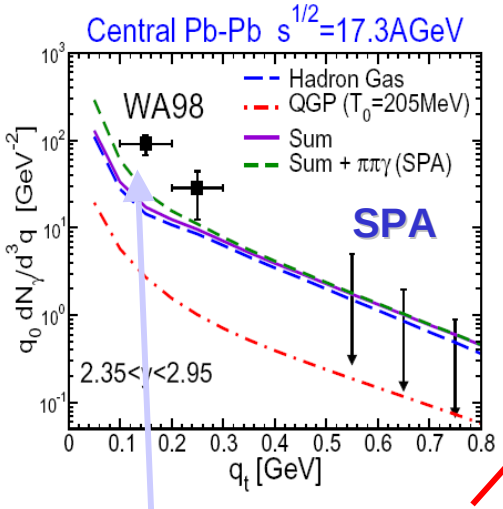
$$\bar{\sigma}(s) = \frac{s-(M_1+M_2)^2}{2M_1^2}\sigma(s),$$

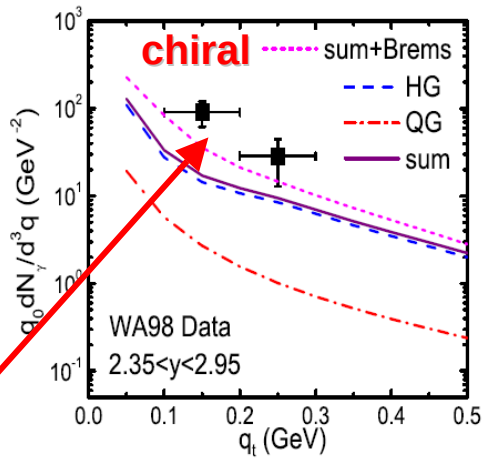


2) little experimental constraint on many m+m and m+B elastic cross sections

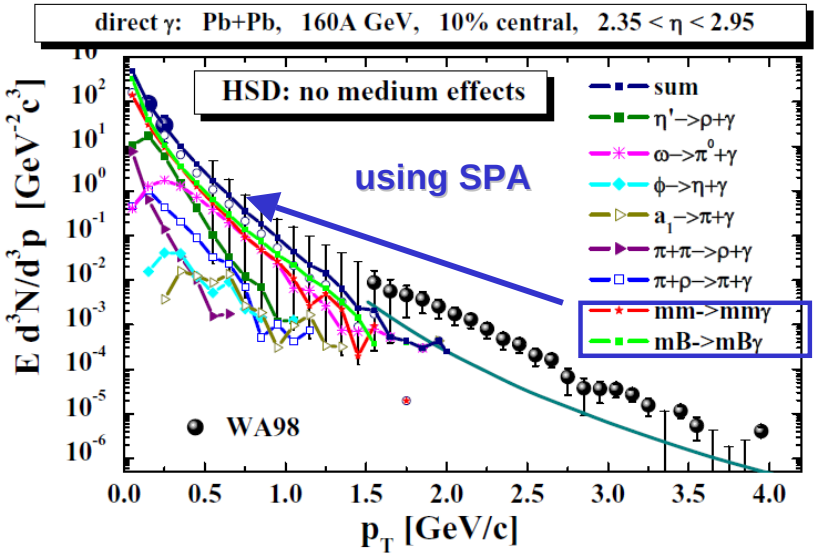
- **Bremsstrahlung: seen at SPS - WA98**

Firebal model: Liu, Rapp, Nucl. Phys. A 96 (2007) 101





HSD: E. B., Kiselev, Sharkov, PR C78 (2008) 034905



- **effective chiral model for ππ→ππγ, πK→πKγ bremsstrahlung gives larger contribution than SPA**

➔ Bremsstrahlung has been an important source of soft photons at SPS!

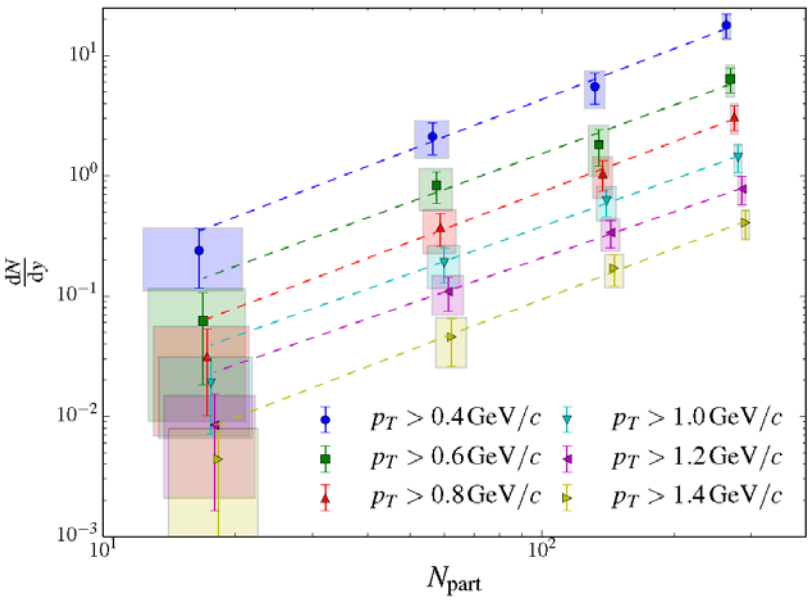
Centrality dependence of the ‚thermal' photon yield

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

PHENIX (arXiv:1405.3940):

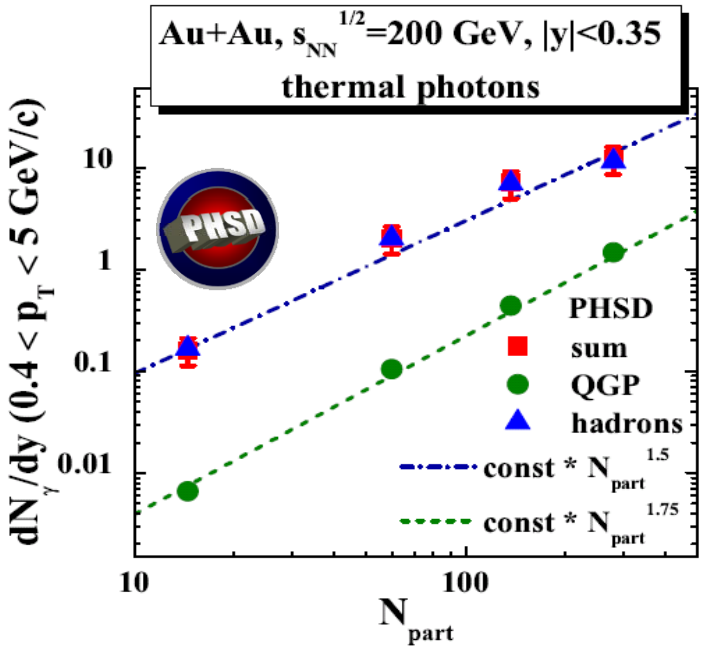
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

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



PHSD predictions:

- **Hadronic channels scale as $\sim N_{part}^{1.5}$**
- **Partonic channels scale as $\sim N_{part}^{1.75}$**



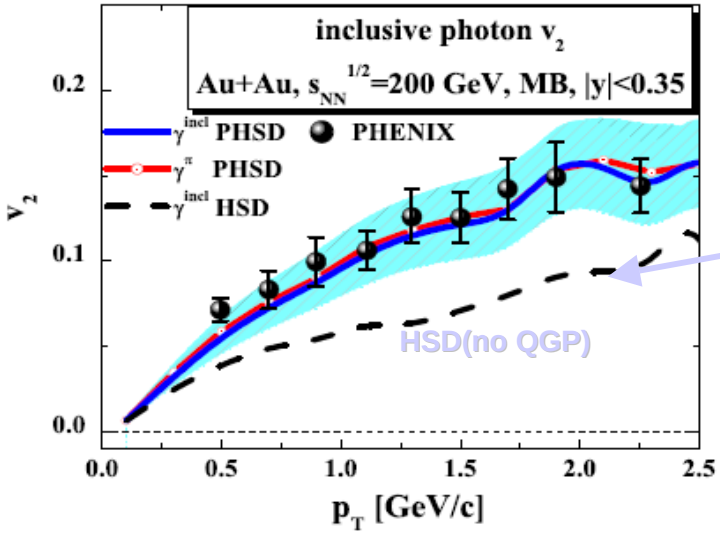
- **PHSD: scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$**
- **similar results from viscous hydro:**
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

➔ 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?

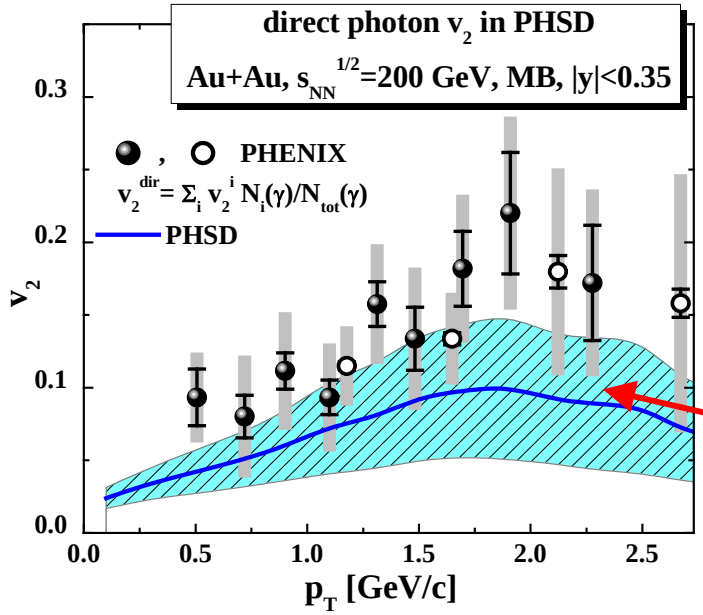
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



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



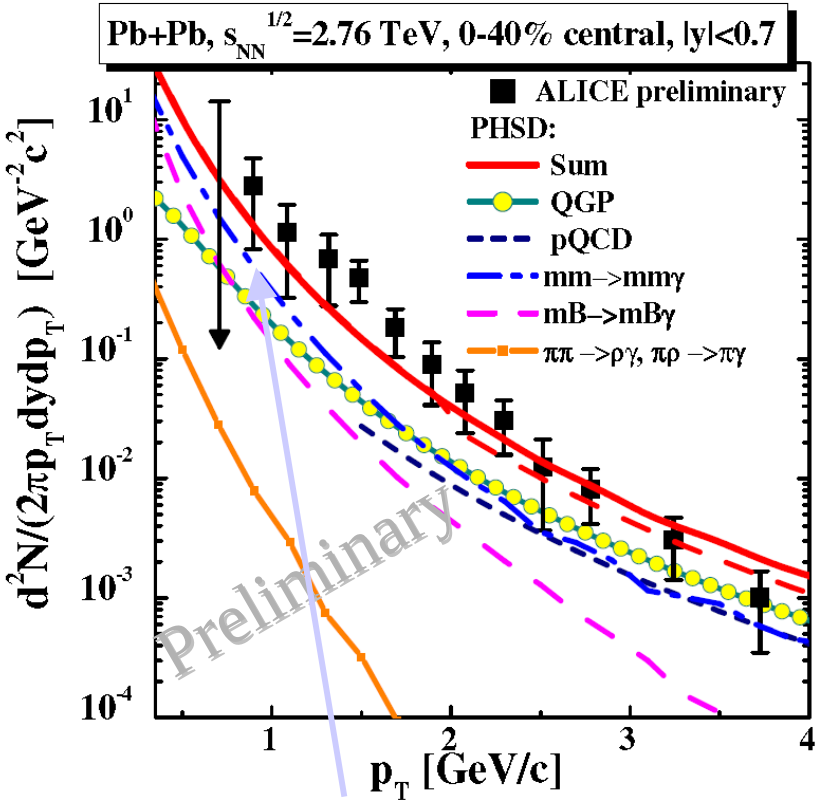
Direct photons (inclusive(=total) – decay):

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

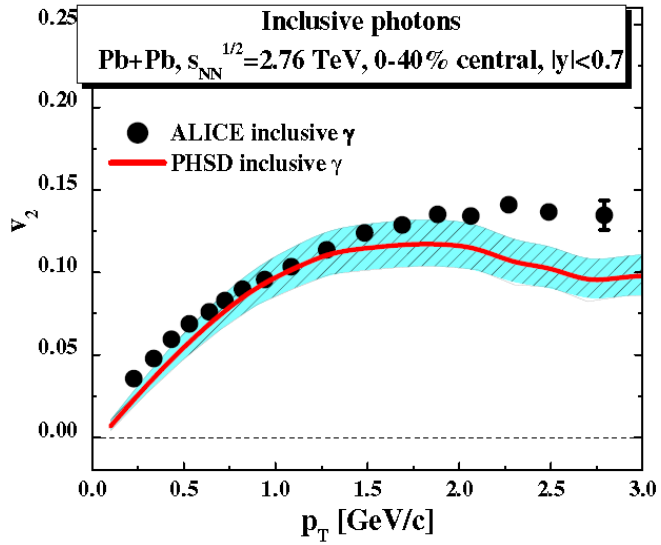
➔PHSD: $v_2(\gamma^{dir})$ comes from mm and mB bremsstrahlung !

Photons from PHSD at LHC

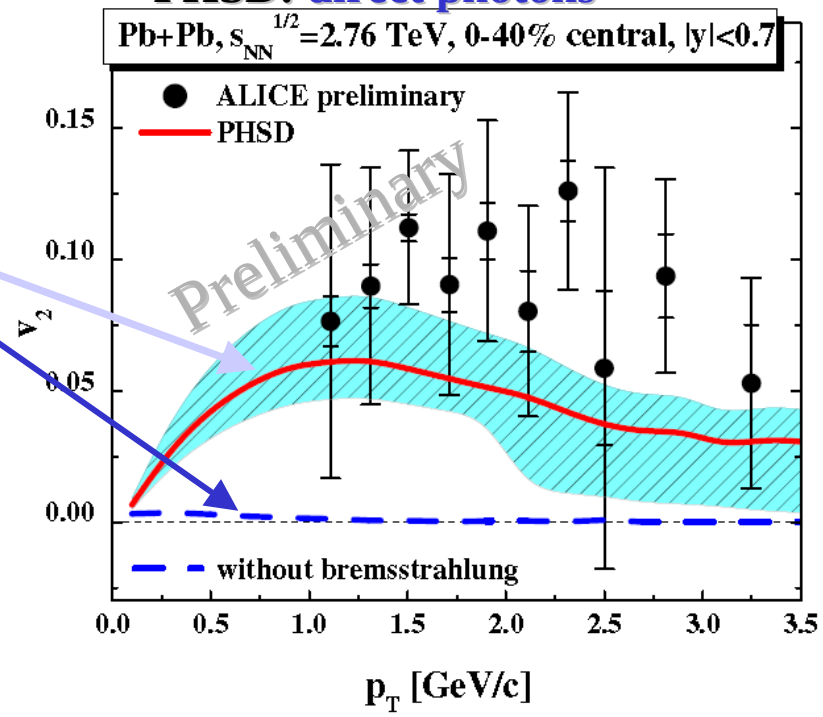
PHSD- preliminary: Olena Linnyk



PHSD: v_2 of inclusive photons



PHSD: direct photons



- 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.

➔ LHC (similar to RHIC): hadronic photons dominate spectra and v_2

Towards the solution of the v_2 puzzle

- Is hadronic bremsstrahlung a ‚solution'?

Other scenarios:

- Early-time magnetic field effects ?

(Basar, Kharzeev, Skokov, PRL109 (2012) 202303; Basar, Kharzeev, Shuryak, arXiv:1402.2286)

„ … a novel photon production mechanism stemming from the conformal anomaly of QCD-QED and the existence of strong (electro)magnetic fields in heavy ion collisions."
Exp. checks: v_3 , centrality dependence of photon yield (PHENIX: arXiv:1405.3940)

- Glasma effects ?

(L. McLerran, B. Schenke, arXiv: 1403.7462)

„ … Photon distributions from the Glasma are steeper than those computed in the Thermalized Quark Gluon Plasma (TQGP). Both the delayed equilibration of the Glasma and a possible anisotropy in the pressure lead to a slower expansion and mean times of photon emission of fixed energy are increased."

- Pseudo-Critical Enhancement of thermal photons near T_C ?

(H. van Hees, M. He, R. Rapp, arXiv:1404.2846. cf. talk by R. Rapp at QM*20140)

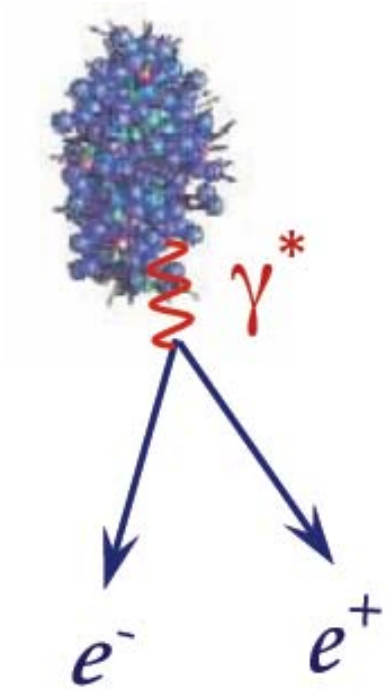
- non-perturbative effects?

semi-QGP - cf. talk by S. Lin at QM'2014

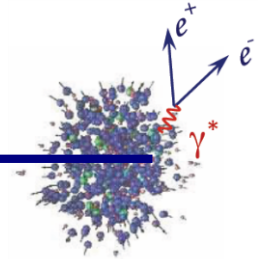
?

Photons – one of the most sensitive probes for the dynamics of HIC!

Dileptons

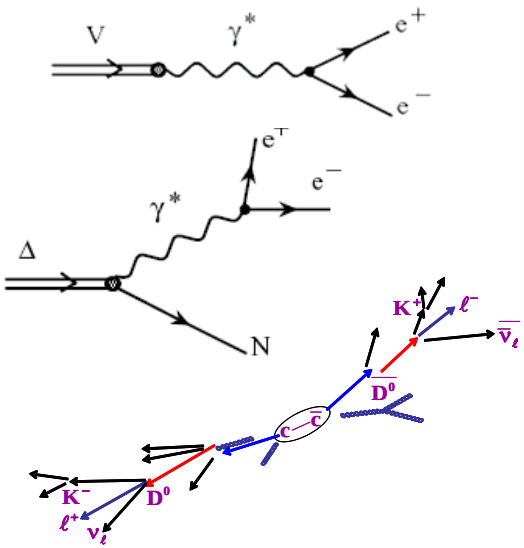


Dilepton sources



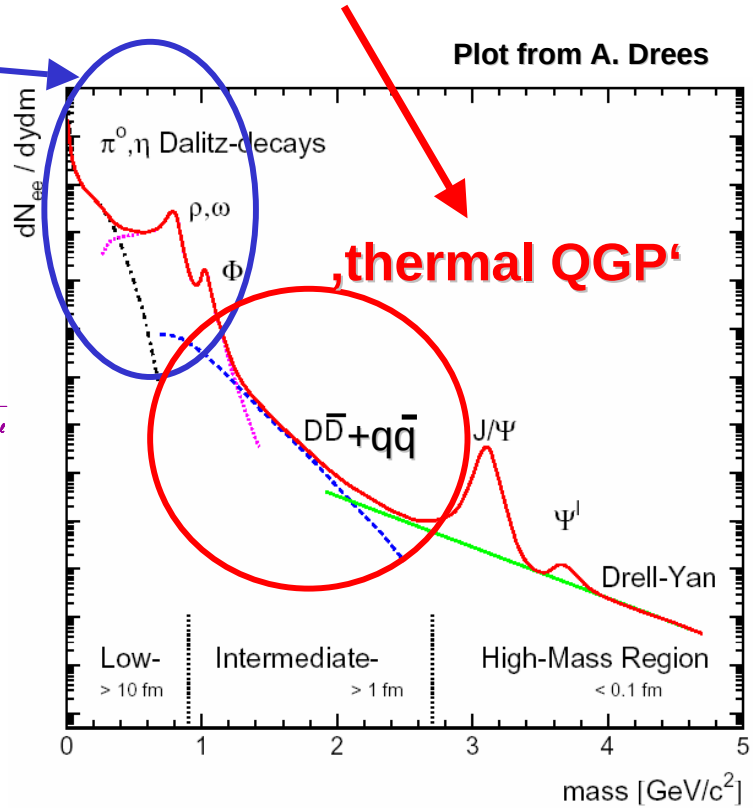
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**



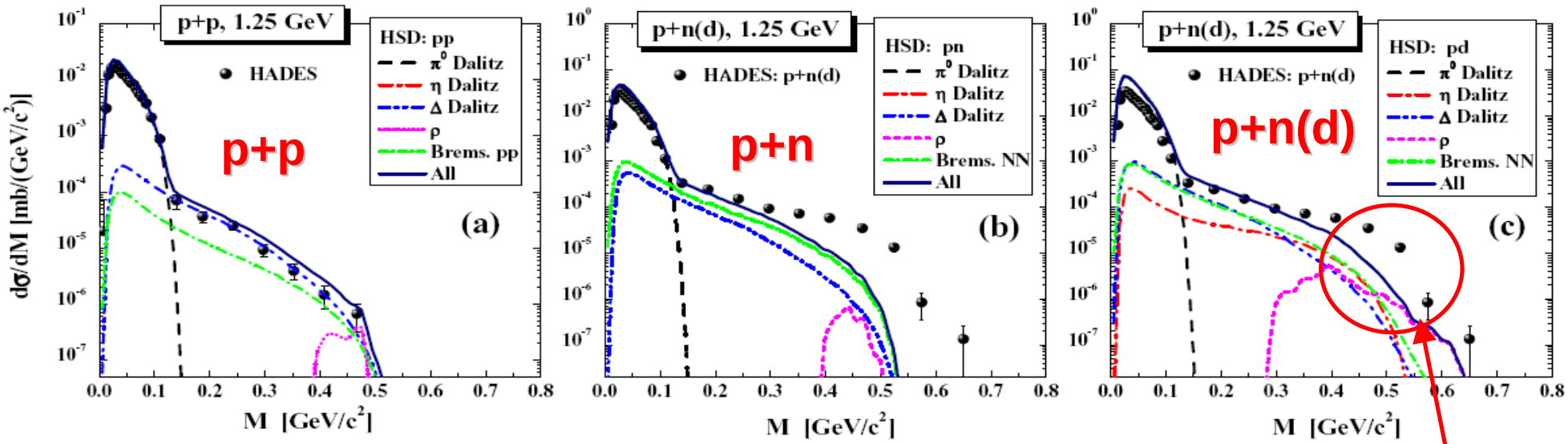
- **direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)**
- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**
- **correlated D+Dbar pairs**
- **radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π‘**

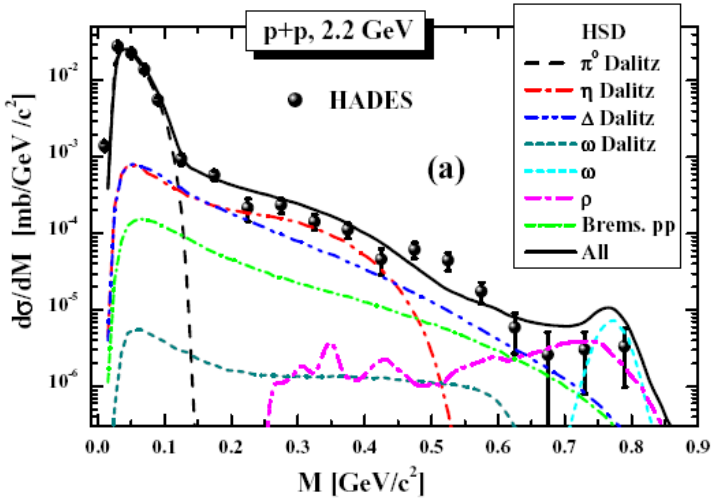
Plot from A. Drees

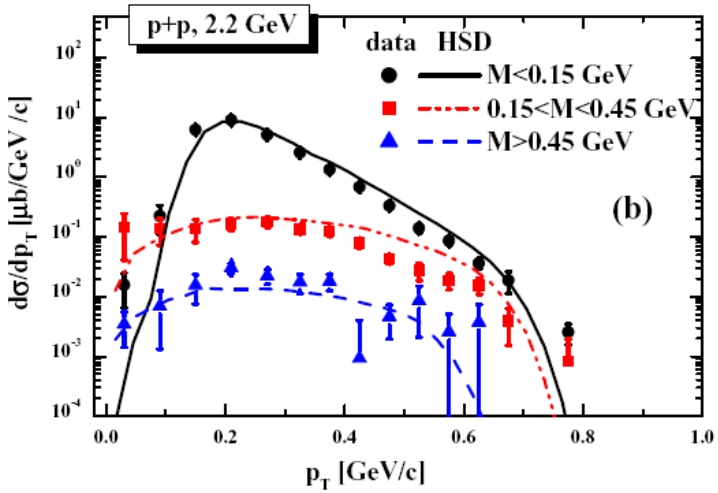


! Advantage of dileptons:
additional „degree of freedom“ (*M*) allows to disentangle various sources

Dileptons at SIS (HADES): p+p, p+n(d)



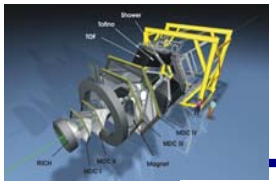




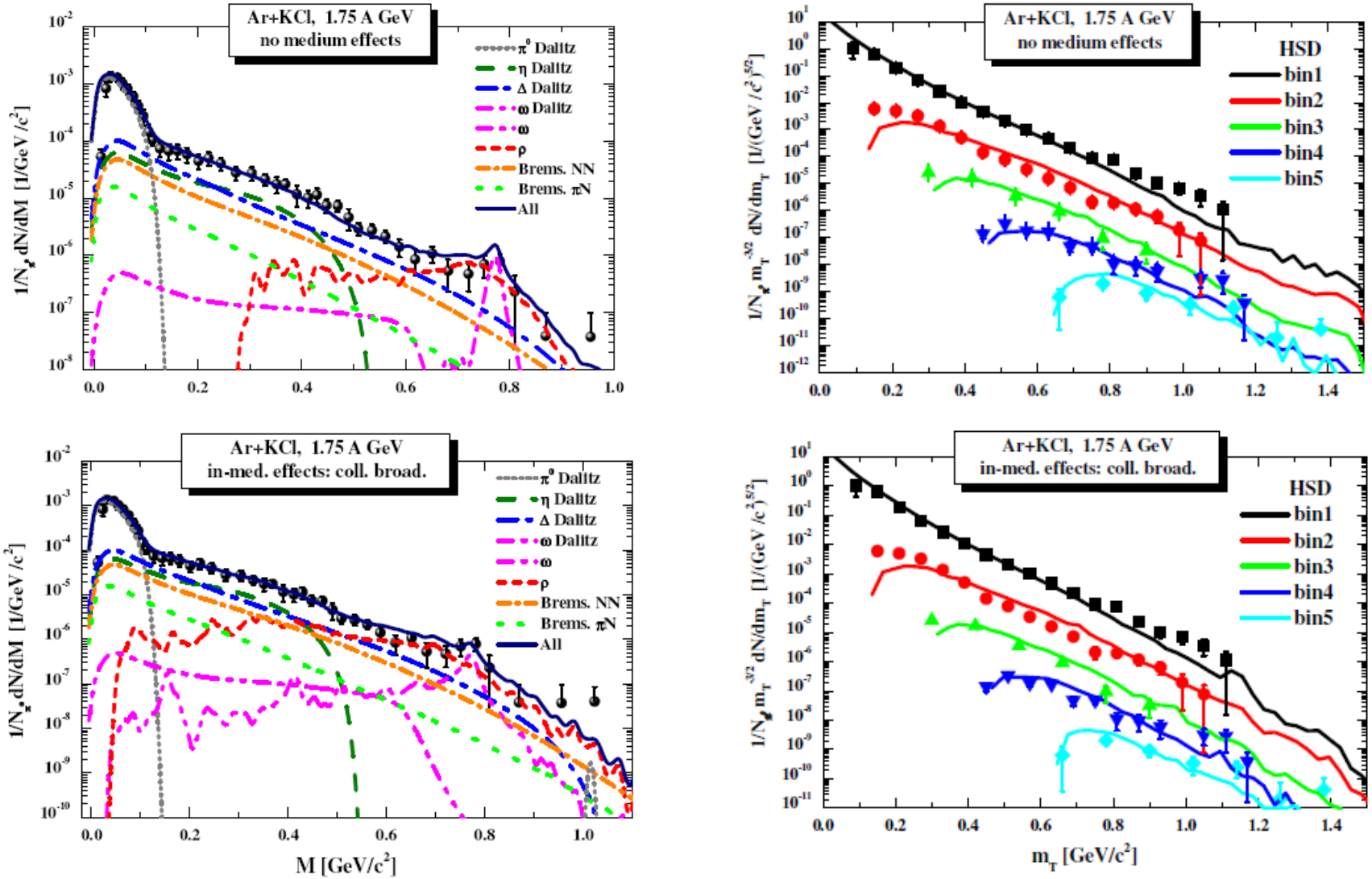
- **pn(d)@1.25 GeV-missing yield at M>0.35 GeV!**

➔ **Measurements of elementary reactions pp, pn and πN are very important for the interpretation of heavy-ion data!**

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



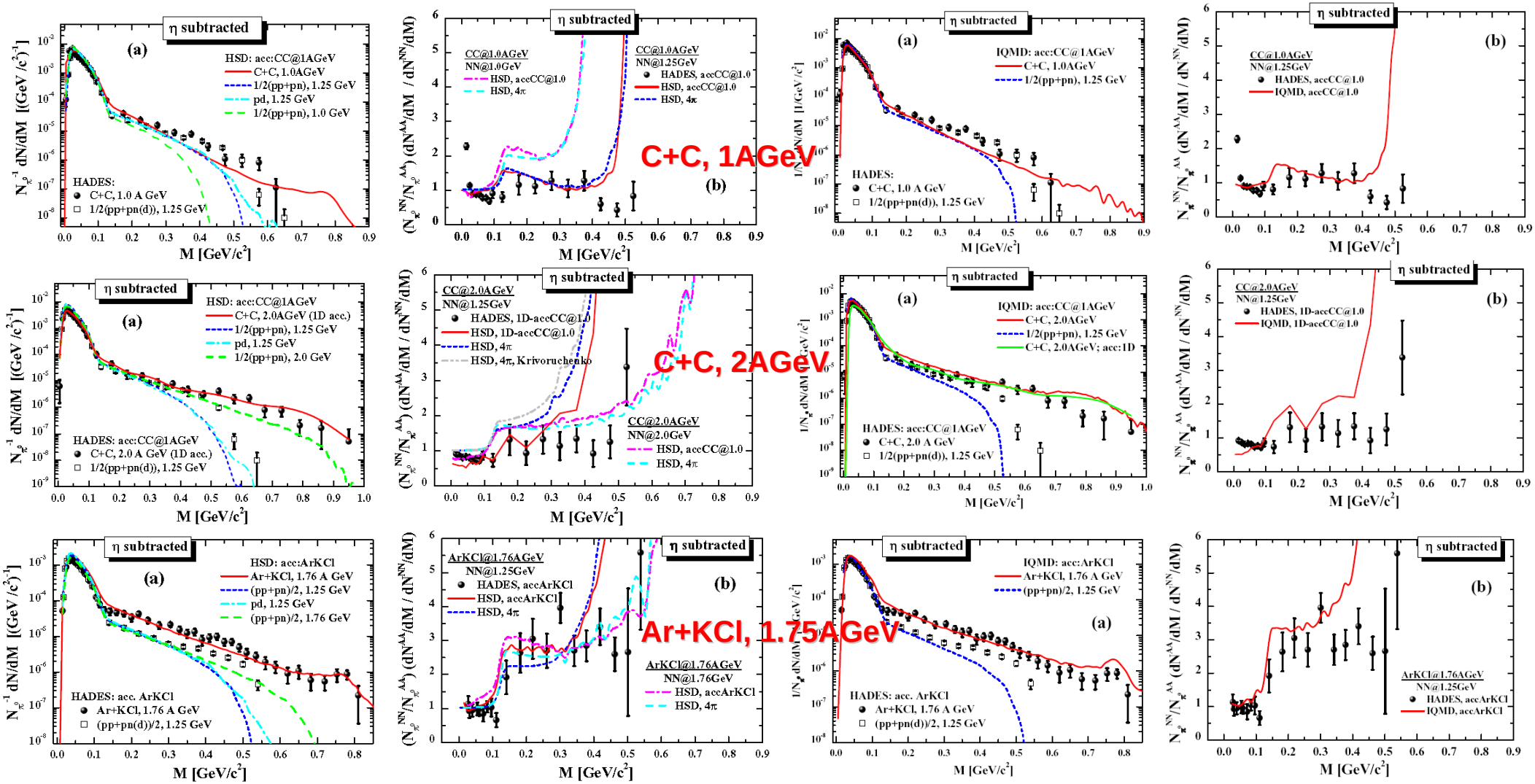
HSD: Dileptons from Ar+KCl at 1.75 A GeV - HADES



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

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

▪HSD ▪IQMD



➔ Strong enhancement of dilepton yield in A+A vs. NN is reproduced by HSD and IQMD!

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

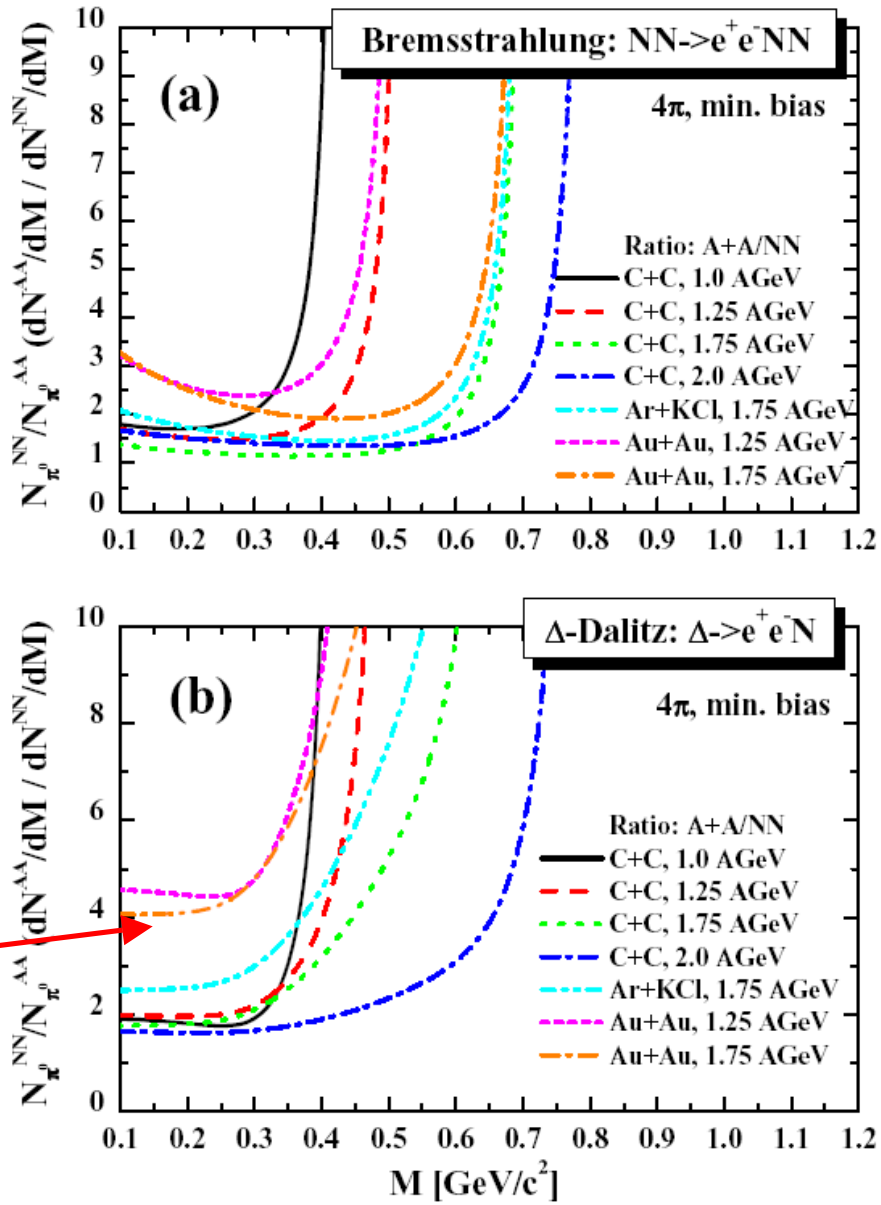
Dileptons at SIS (HADES): A+A vs NN

- 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!

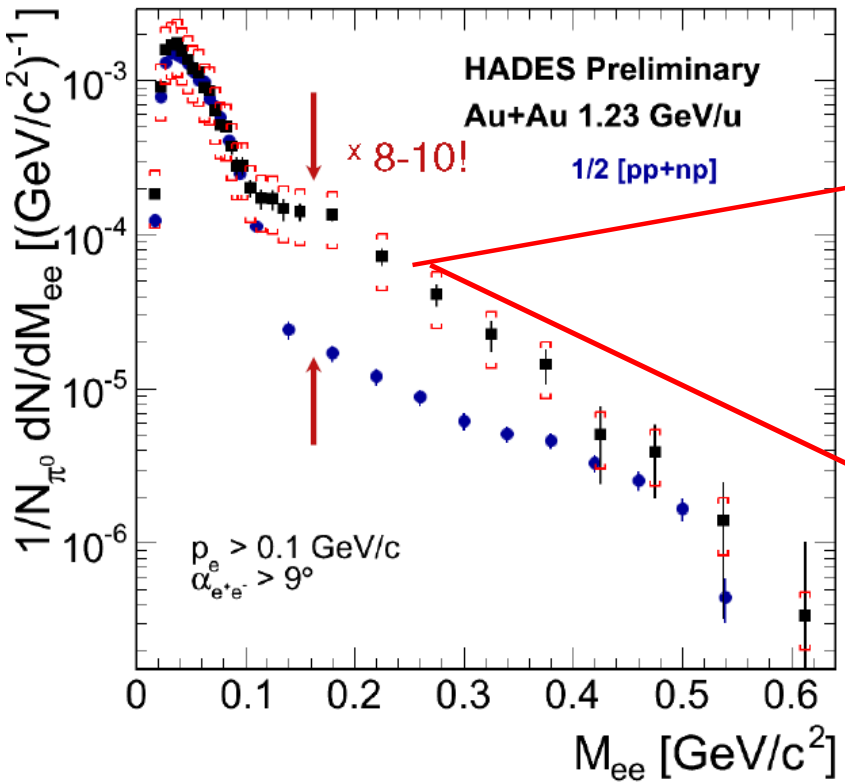


E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

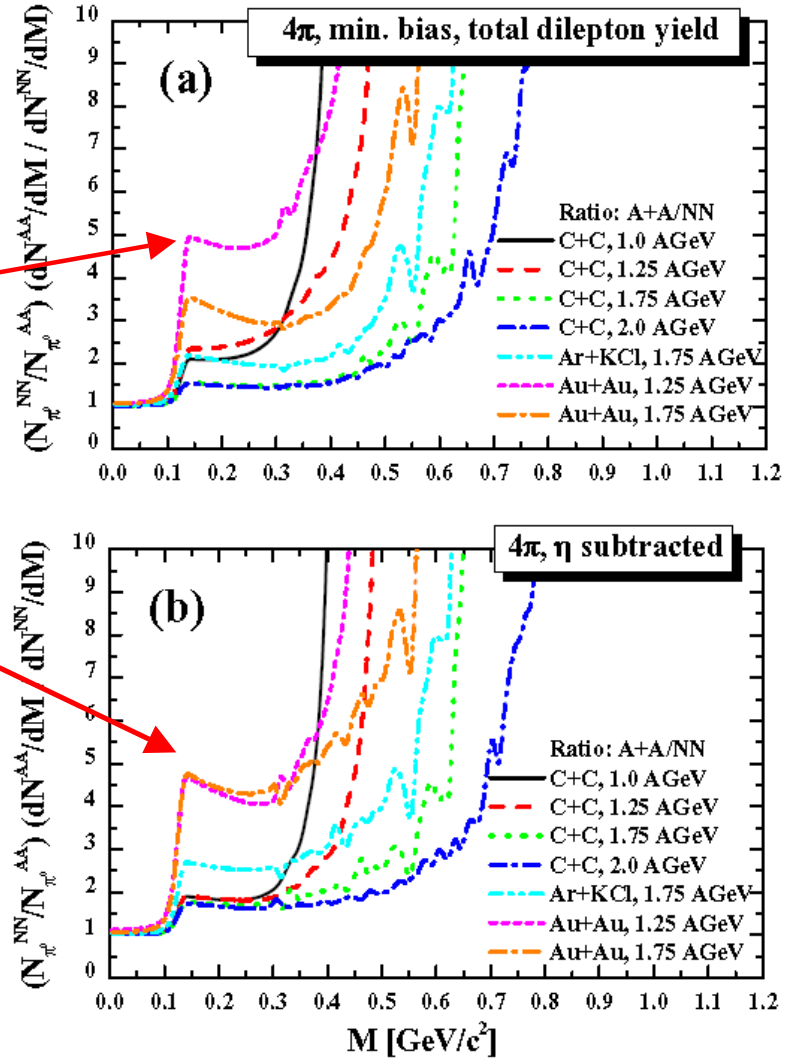
Dileptons at SIS (HADES): Au+Au

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**

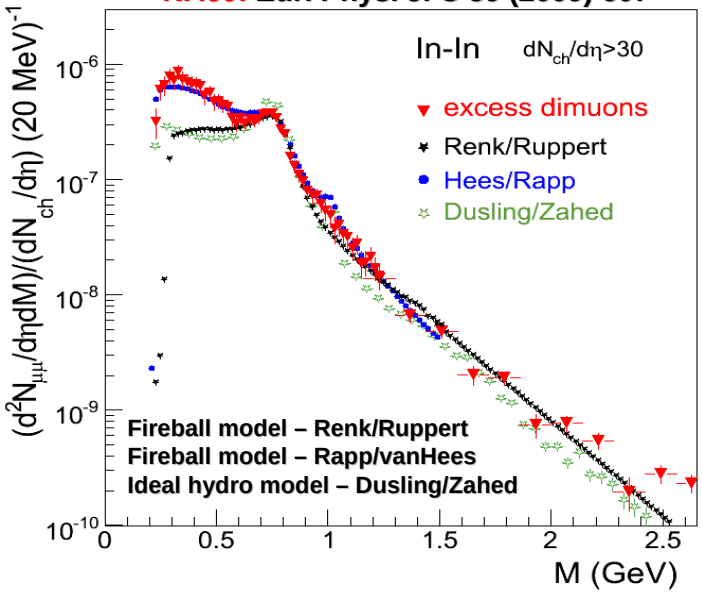
➔ **measurement of Δ regeneration by HADES!**

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

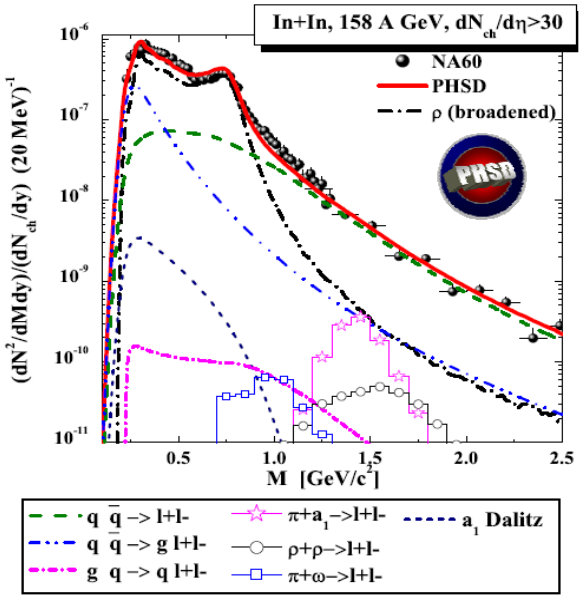
Lessons from SPS: NA60

❑ Dilepton invariant mass spectra:

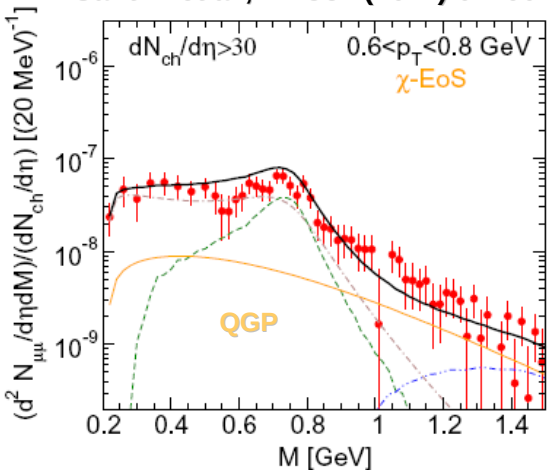
NA60: Eur. Phys. J. C 59 (2009) 607



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

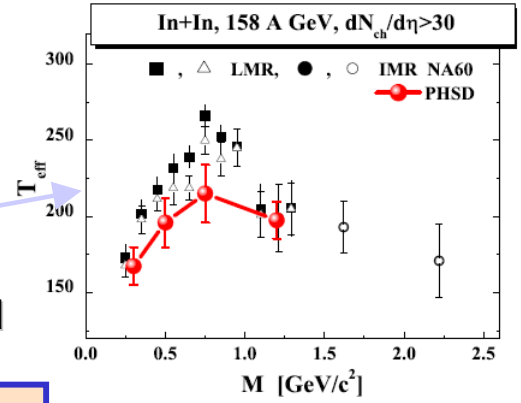


Hybrid-UrQMD:
Santini et al., PRC84 (2011) 014901



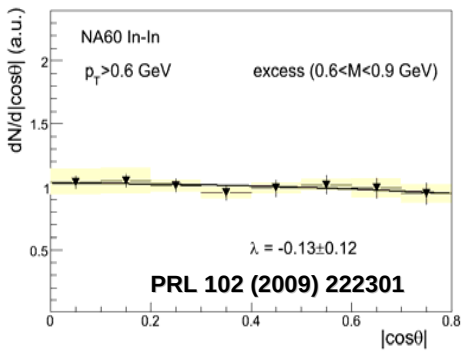
❑ Inverse slope parameter T_{eff}:

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

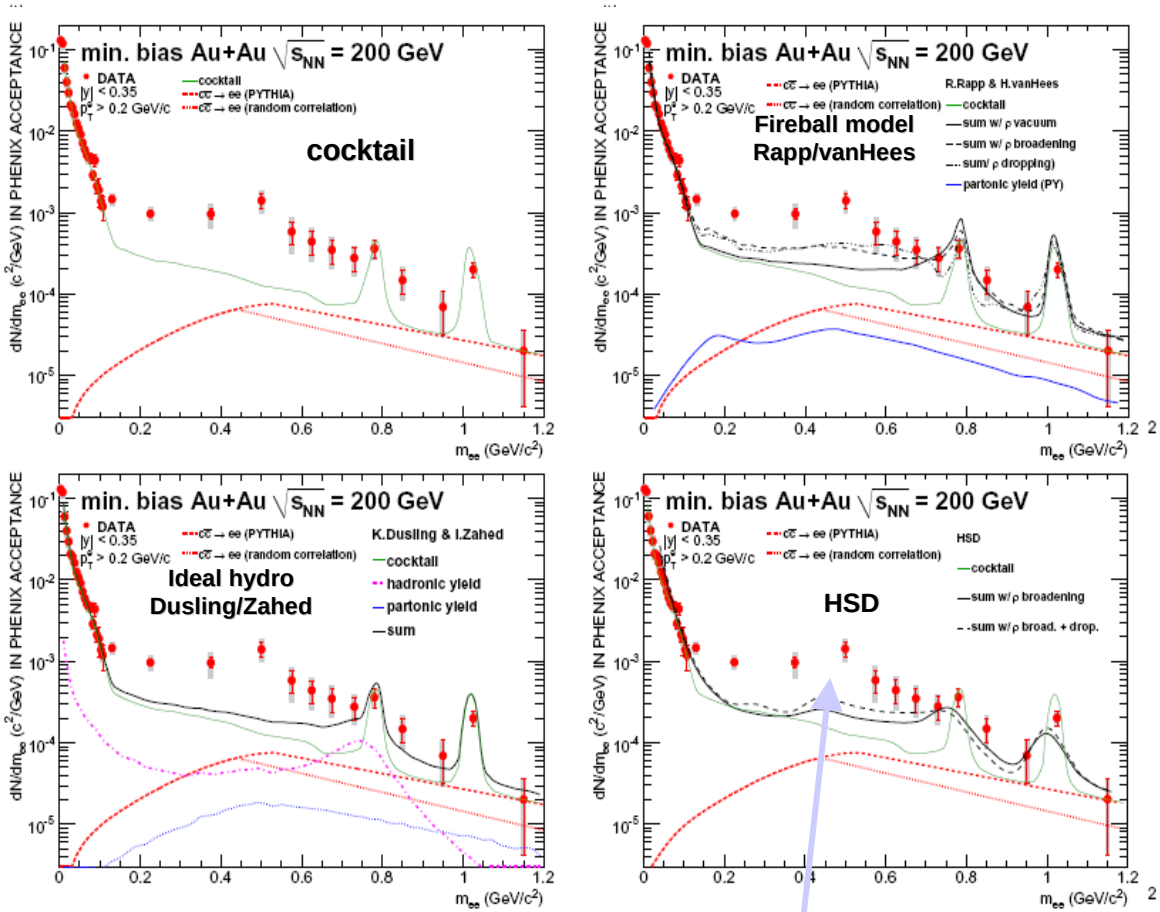


Message from SPS: (based on NA60 and CERES data)

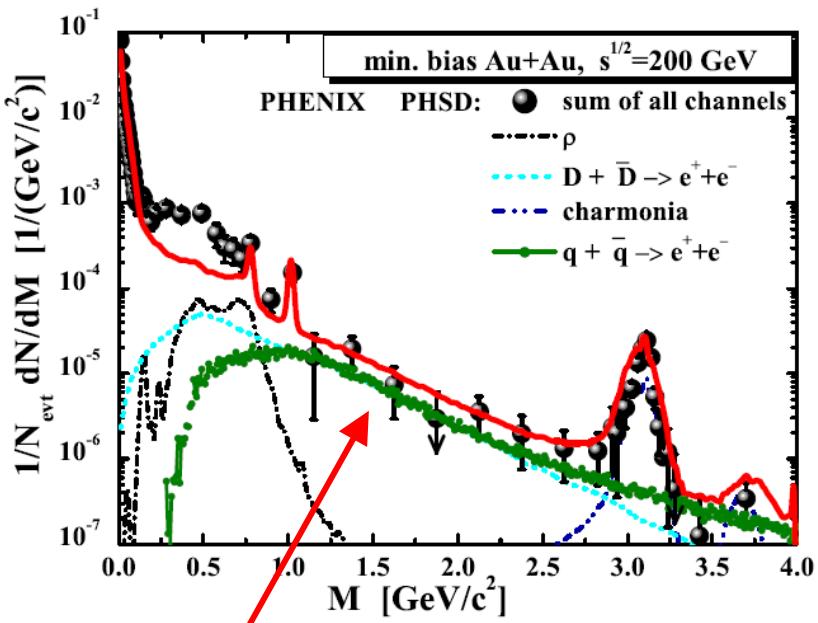
1) **Low mass spectra** - evidence for the **in-medium broadening of ρ-mesons**
2) Intermediate mass **spectra above 1 GeV** - dominated by **partonic radiation**
3) The rise and fall of **T_{eff}** – evidence for the thermal **QGP radiation**
4) **Isotropic angular distribution** – indication for a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



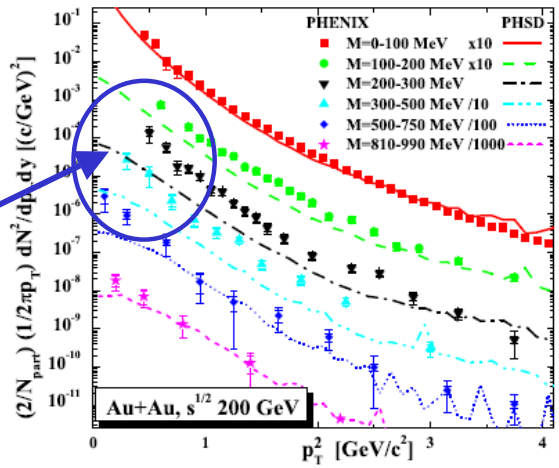
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



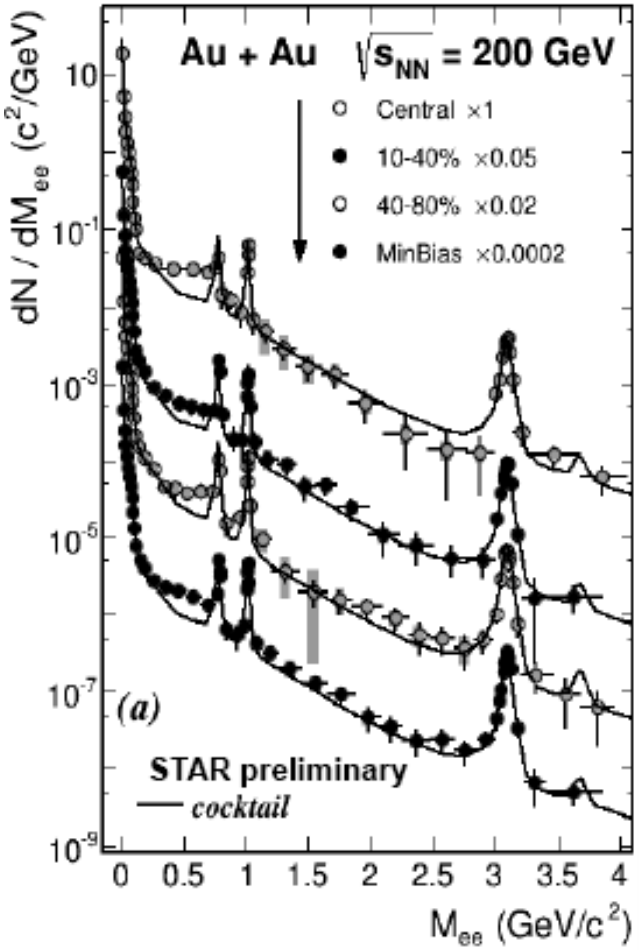
Message:

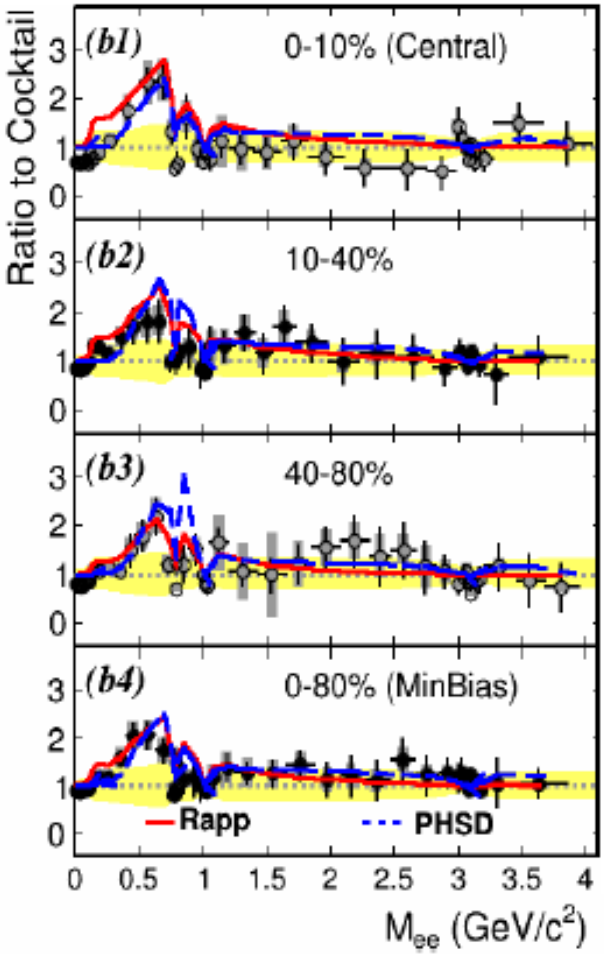
- **Models** provide a **good description of pp data** and **peripheral Au+Au** data, however, **fail in describing the excess for central collisions** even with **in-medium scenarios** for the vector meson spectral function
- The **'missing source'(?)** is located at **low p_T**
- **Intermediate mass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

Dileptons at RHIC: STAR data vs model predictions

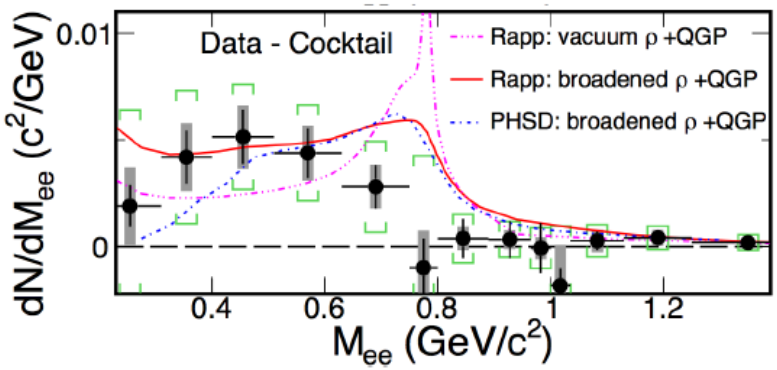
(STAR: arXiv:1407.6788)

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

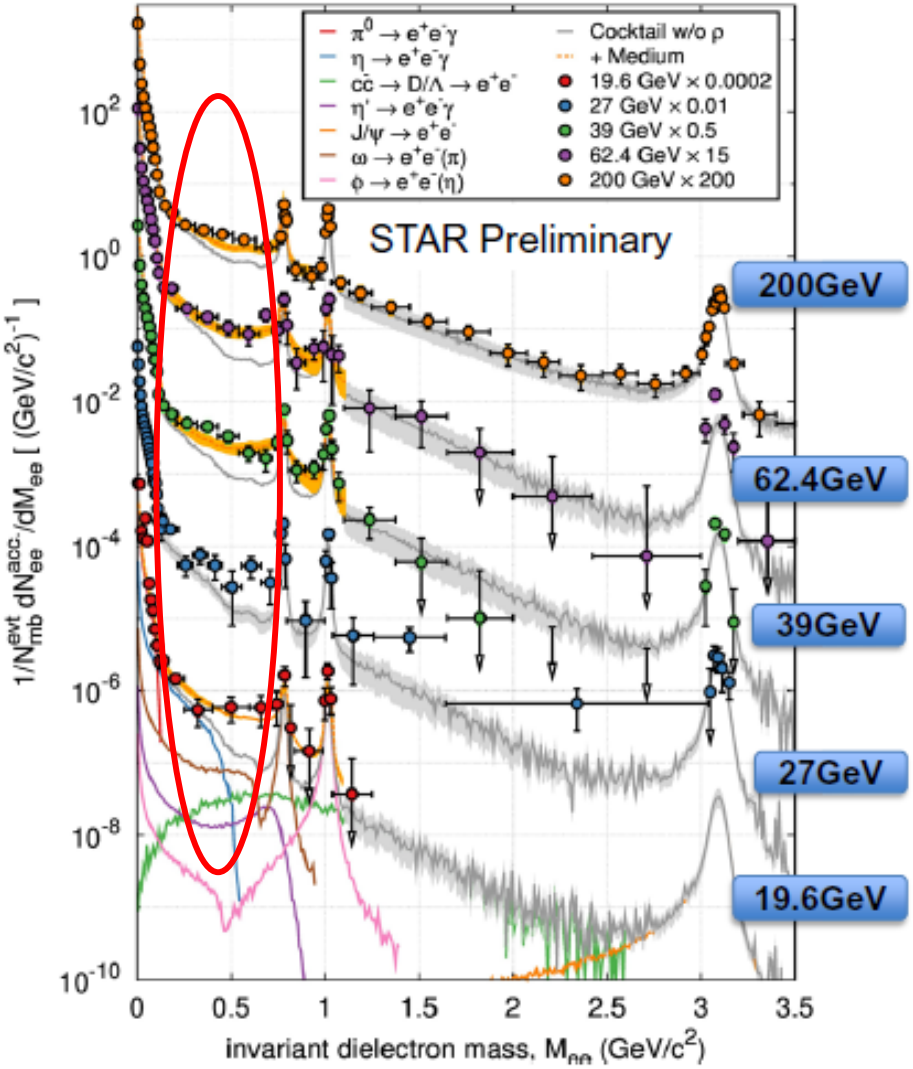
Intermediate masses:

QGP dominant

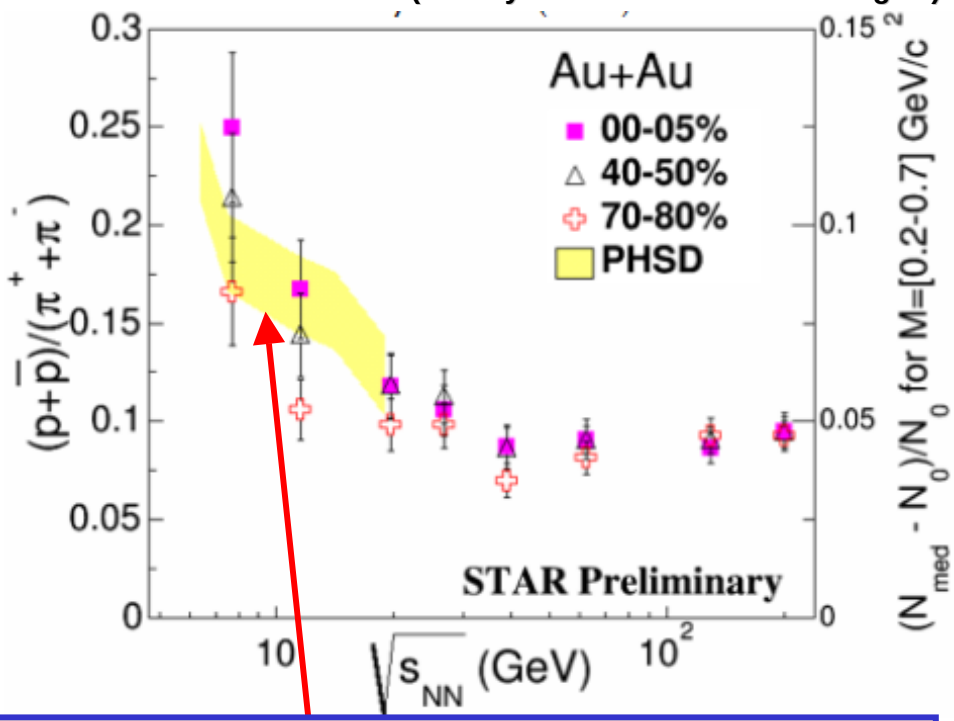
Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

Dileptons from RHIC BES: STAR

(Talk by Nu Xu at QM'2014)



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

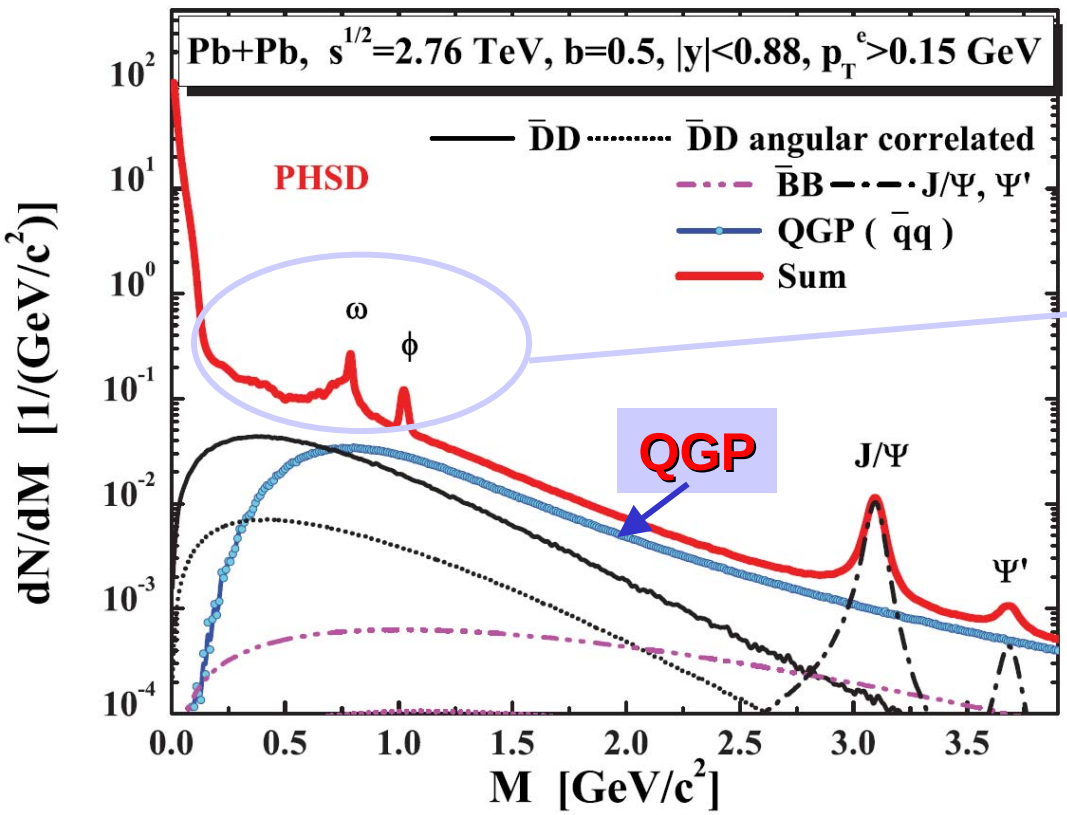


Message:

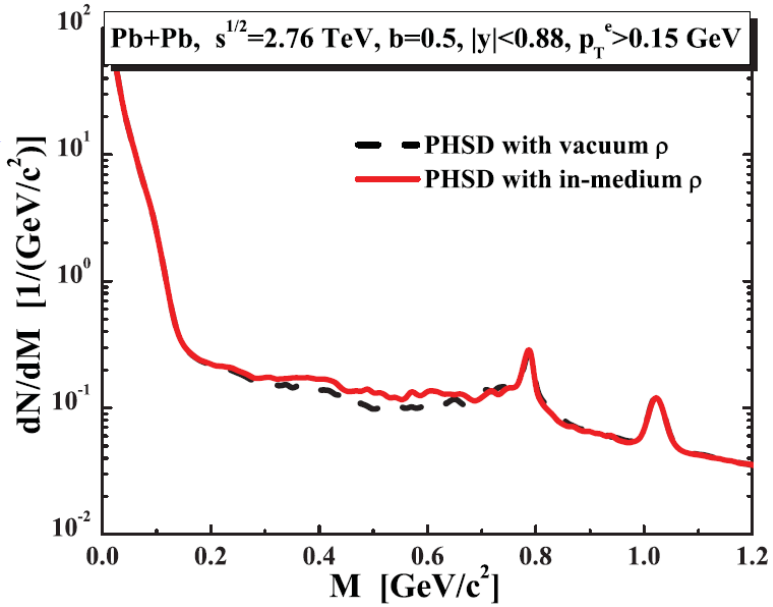
- **BES-STAR data** show a **constant low mass excess** (scaled with $N(\pi^0)$) within the measured energy range
- PHSD model: **excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon density phase

➔ 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!

Messages from dilepton data

- **Low dilepton masses:**

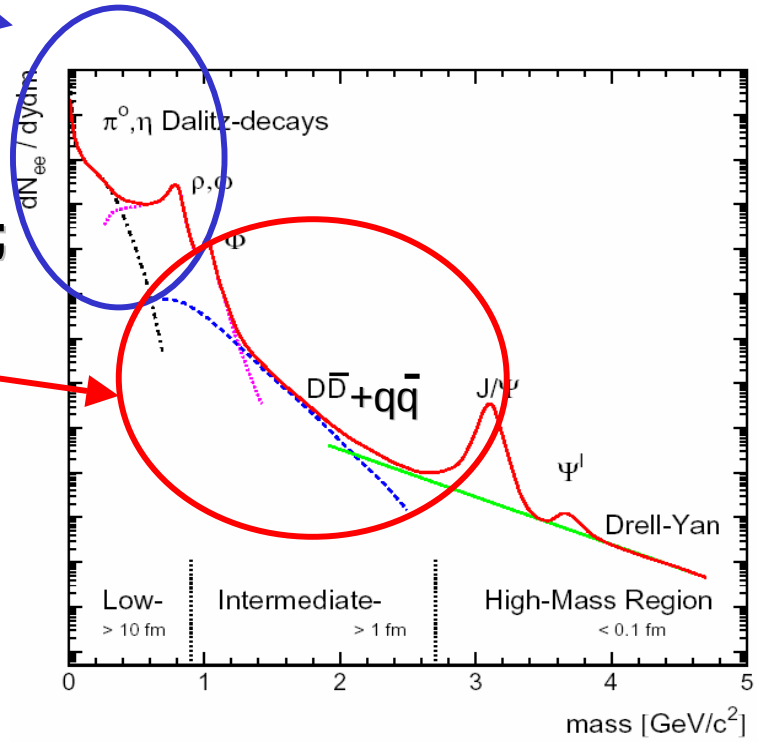
- **Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally**

- **In-medium effects can be observed at all energies from SIS to LHC**

- **Intermediate dilepton masses:**

- **The QGP (qbar-q) dominates for M>1.2 GeV**

- **Fraction of QGP grows with increasing energy; at the LHC it is dominant**



Outlook:

*** experimental energy scan**

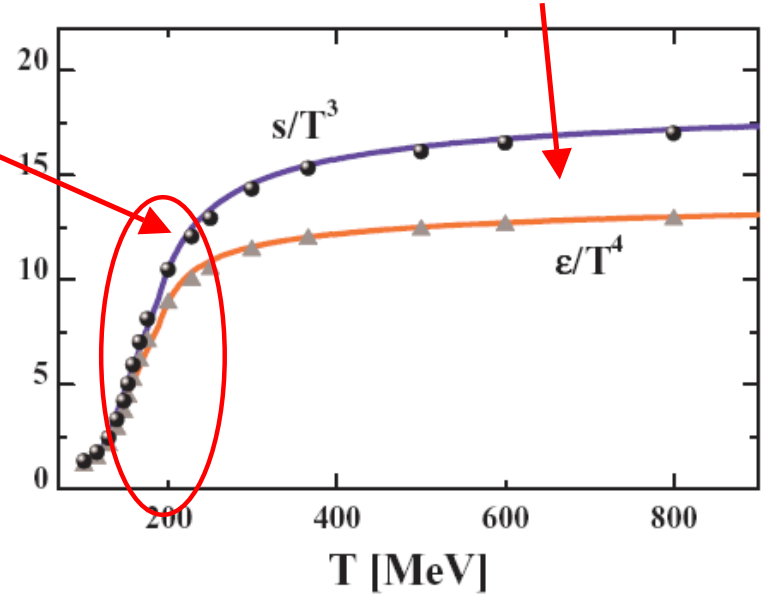
*** experimental measurements of dilepton's higher flow harmonics v_n**

Outlook - Perspectives

What is the stage of matter close to T_c and large μ:

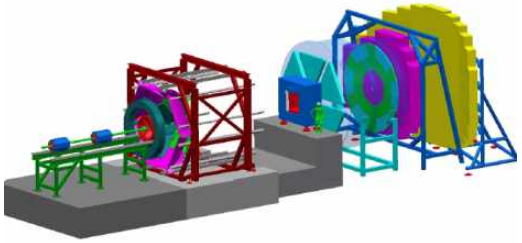
- ❑ 1st order phase transition?
- ❑ ‚Mixed' phase = interaction of partonic and hadronic degrees of freedom?

Lattice EQS for m=0
➔ ‚crossover' , $T > T_c$



Open problems:

- How to describe a first-order phase transition in transport models?
- How to describe parton-hadron interactions in a ‚mixed' phase?



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