Electromagnetic probes of the QGP

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Electromagnetic probes: photons and dileptons

Feinberg (76), Shuryak (78)

Advantages:

✓ dileptons and real photons are emitted from different stages of the reaction and not effected by final-state interactions

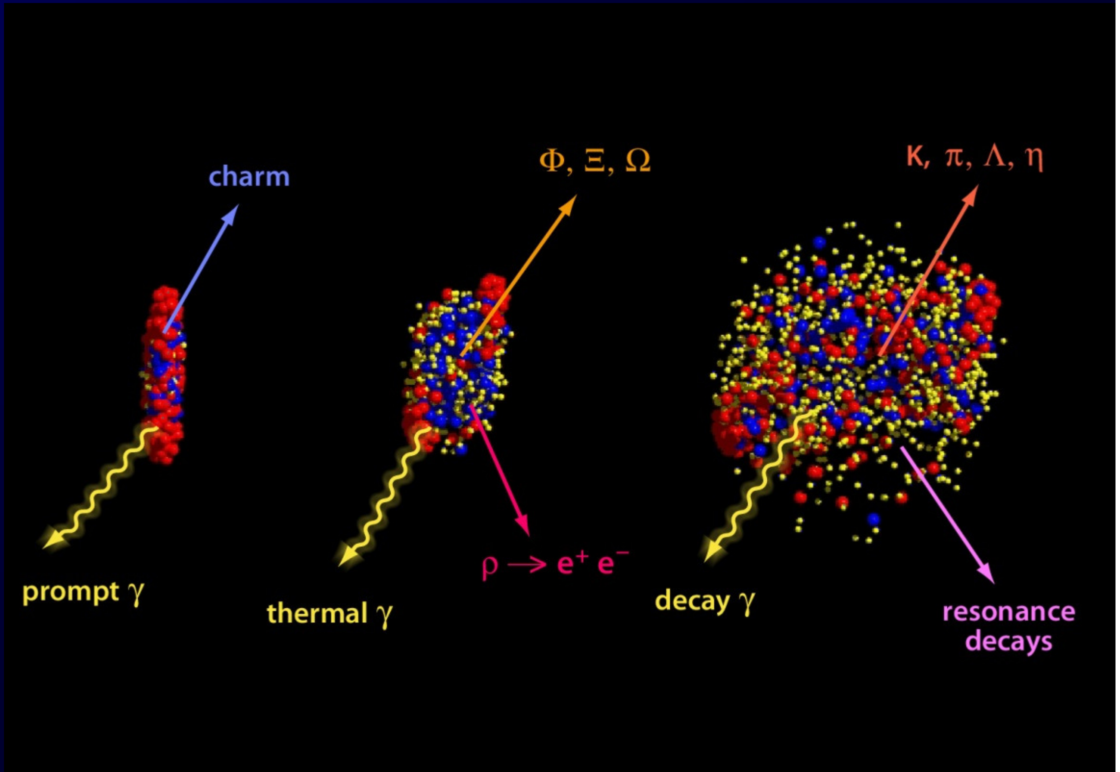
✓ provide undistorted information about their production channels

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

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

Disadvantages:

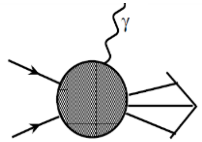
- low emission rate
- production from hadronic corona
- many production sources which cannot be individually disentangled by experimental data



Modeling of photon/dilepton emission

I. Emission rate from thermal field theory:

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

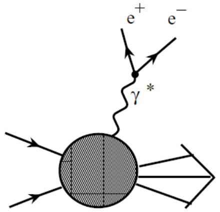


- **Photons:**

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

- **Bose distribution:**

$$f(q_0,T) = \frac{1}{e^{q_0/T} - 1}$$



- **Dileptons:**

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

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

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

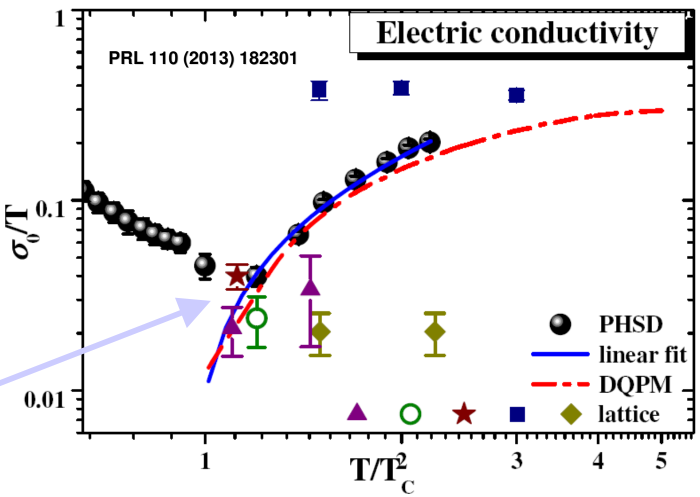
❑ **Hadron phase:** using **VDM**: *ImΠ ~> ImD*$^\rho$ in-medium **ρ-meson spectral function** from many-body approach (cf. Rapp, Chanfrey, Wambach, NPA 617 (1997) 472)

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

➔ **restoration of chiral symmetry (ρ-a$_1$):**
ImD$^\rho$ ~> chiral condensate (by Weinberg sum rules)
(cf. Hohler, Rapp, arXiv:1311.2921)

❑ Rates at $q_0 \to 0$ are related to electric conductivity σ_0
➔ Probe of **electric properties of the QGP**

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



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

Modeling of photon/dilepton emission

Applicable also for **non-equilibrium** system !

II. Emission rate from relativistic kinetic theory:
(e.g. for 1+2 → γ+3)

$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - q)$$

$$\times |M|^2 \frac{f(E_1) f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}$$

- *f(E)* - distribution function

- M – invariant scattering matrix element from microscopic models

- **Modeling of hadronic elementary reactions:**
  Chiral models, OBE models,… (Born-type diagrams)

- **Problems:**

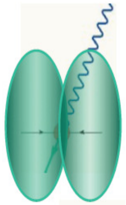
❑ very limited experimental information on mm, mB elementary reactions

❑ 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)

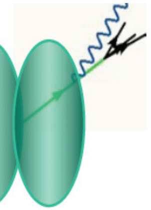
E.g. : ρ-meson collisional broadening – important for dilepton studies!

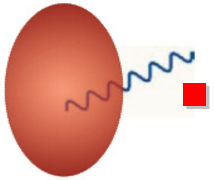
Production sources of photons in p+p and A+A

- **Decay photons** (in pp and AA):
  $m \rightarrow \gamma + X,\ \ m = \pi^0, \eta, \omega, \eta', a_1, \ldots$

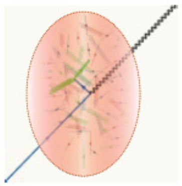


- **Direct photons:** (inclusive(=total) – decay) – measured experimentally
  - **hard photons**: (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)

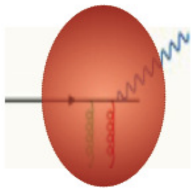




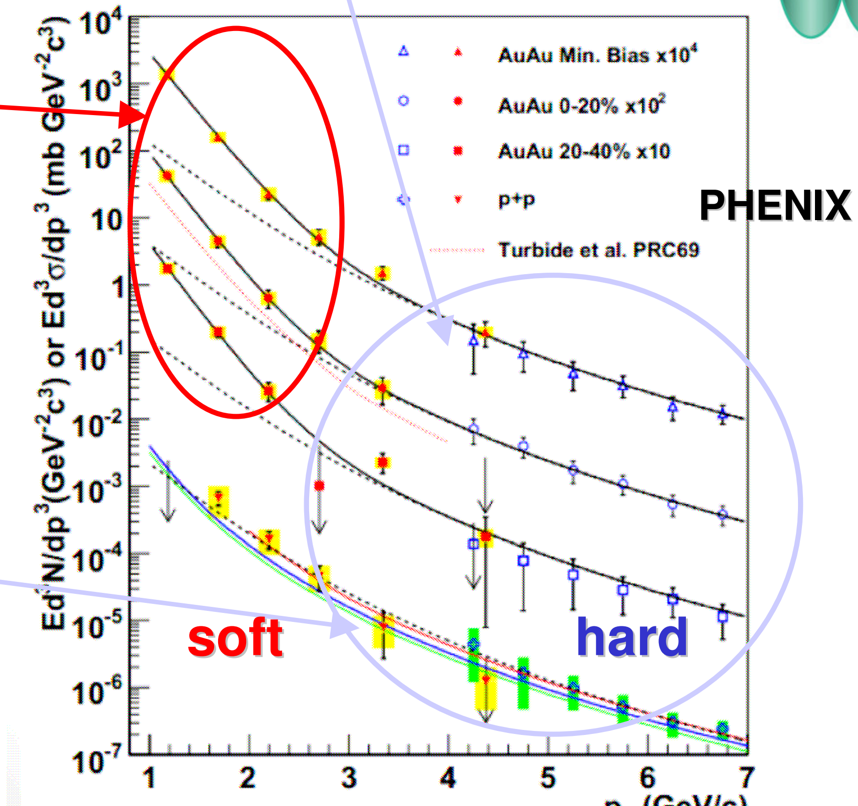
  - **thermal photons**: (low p_T, in AA)
    - QGP
    - Hadron gas



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



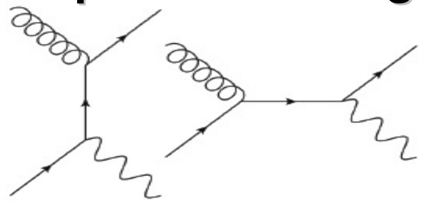
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

Thermal QGP:

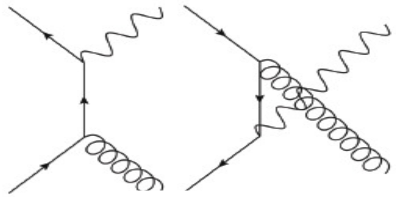
HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990), ...)

Compton scattering



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

q-qbar annihilation



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

+ soft ...

- **Rates beyond pQCD:**
  off-shell massive q, g
  (used in PHSD)
  O. Linnyk, JPG 38 (2011) 025105

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

Hadronic sources:

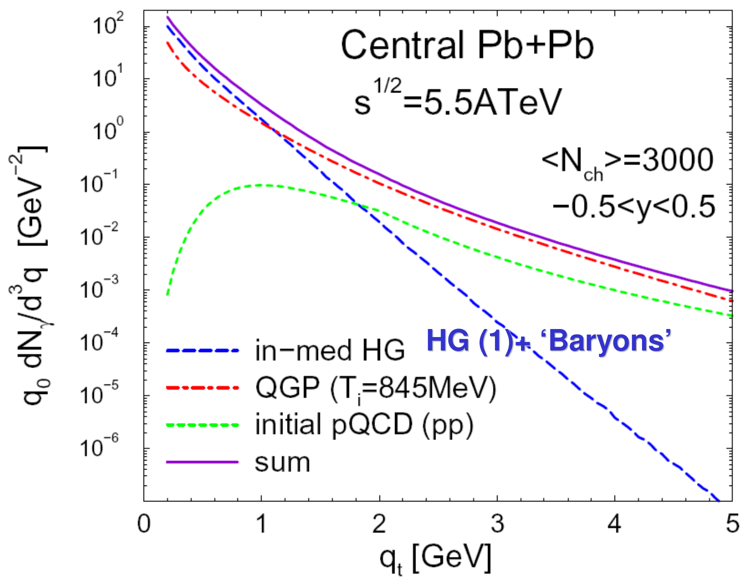
(1) secondary mesonic interactions:

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

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

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

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



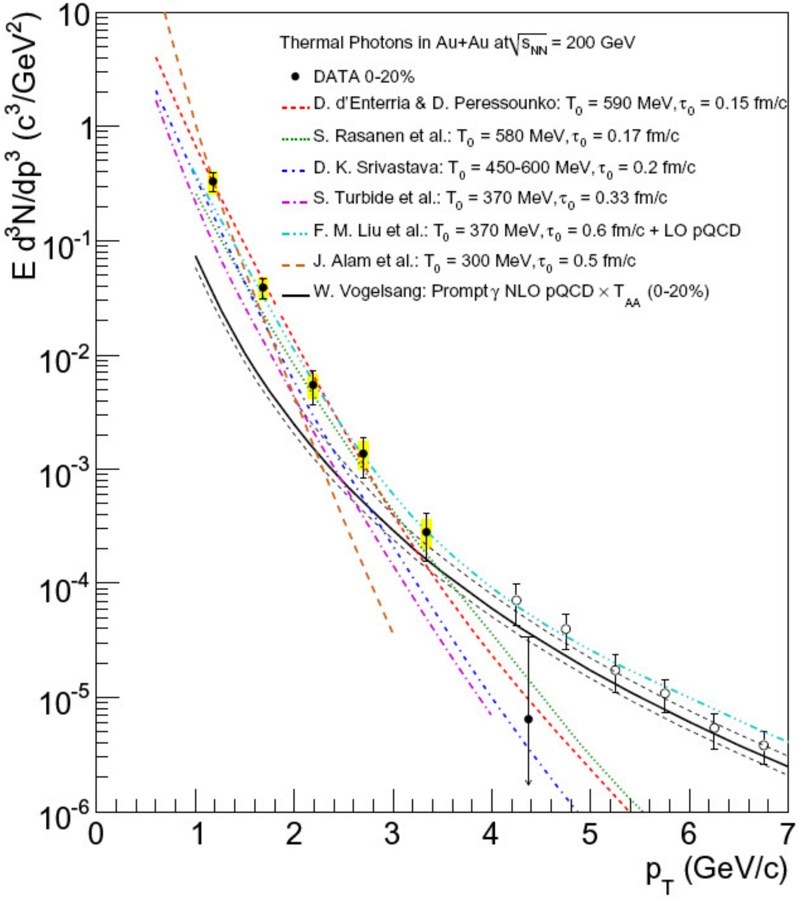
Models: chiral models, OBE, SPA ...
Kapusta, Gale, Haglin (91), Rapp (07), ...

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

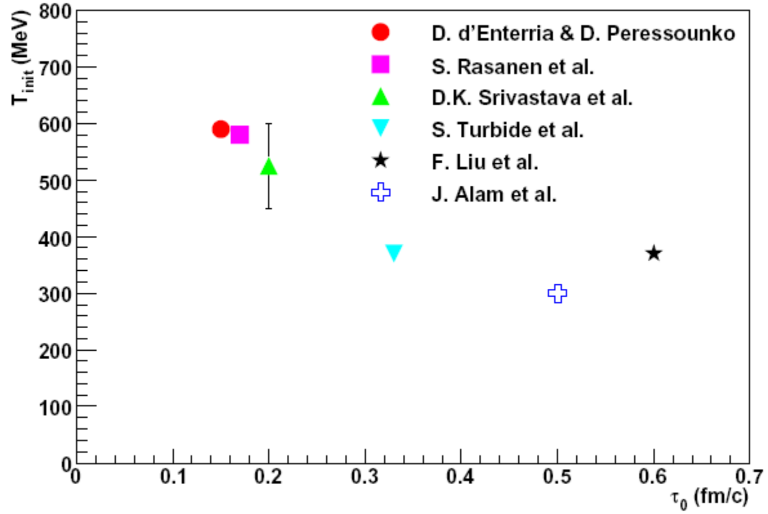
2010: Direct photon spectra for Au+Au at $s^{1/2}$=200 GeV

PHENIX, Phys. Rev. C81 (2010) 034911

Variety of model predictions:
fireball, 2+1 Bjorken hydro, 3+1 ideal hydro with different initial conditions and EoS



Models: **assume formation of a hot QGP with initial temperature T_{init} at thermalization time τ_0**

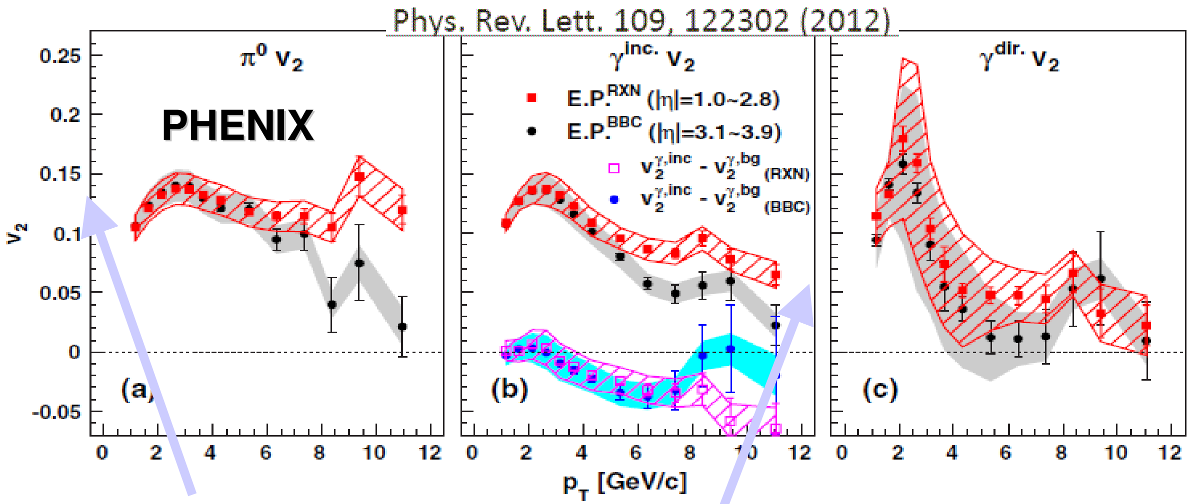


➔ **Huge variations in T_{init} and τ_0!**

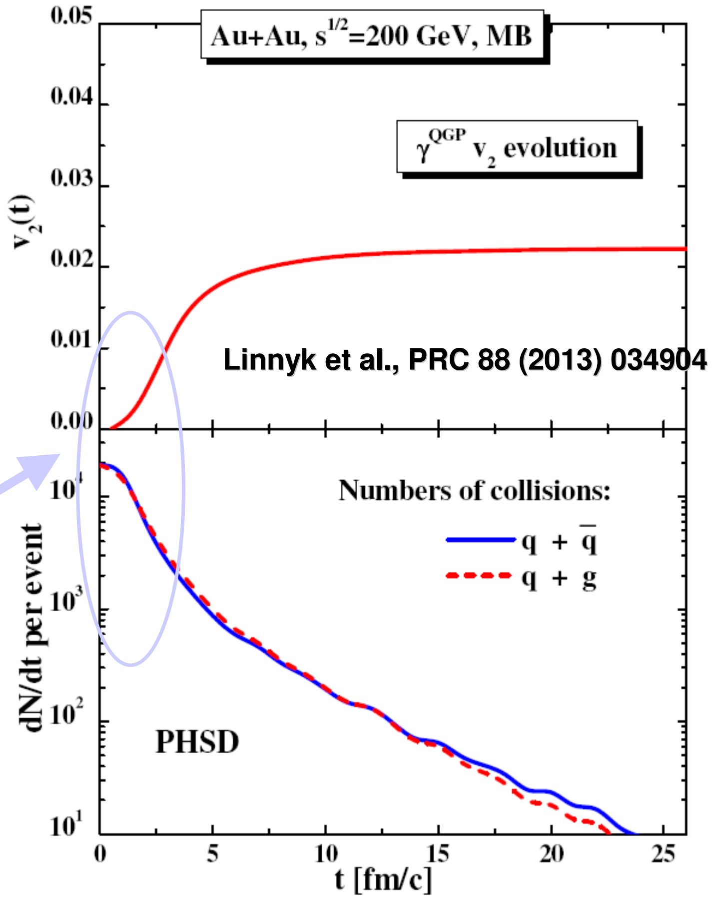
Warning: some model evolution was not fitted to the final hadron spectra!

❑ **Photon spectra show sensitivity to the dynamical evolution!**

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 flow is not yet developed → expected $v_2(\gamma^{QGP}) \to 0$

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 !**

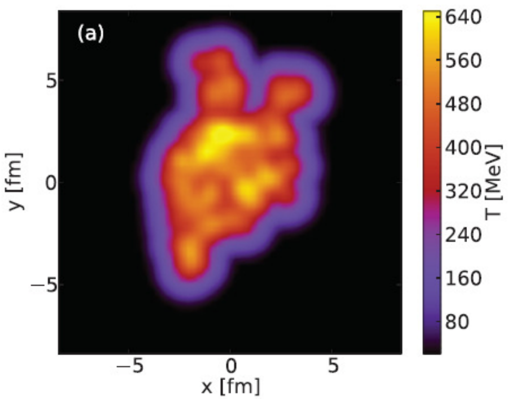
1. Hydro: Influence of e-b-e fluctuating initial conditions

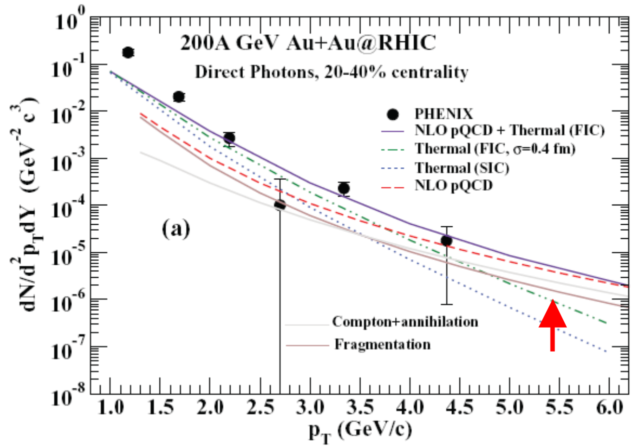
➔ **From smooth Glauber initial conditions**
to event-by-event hydro with fluctuating initial conditions

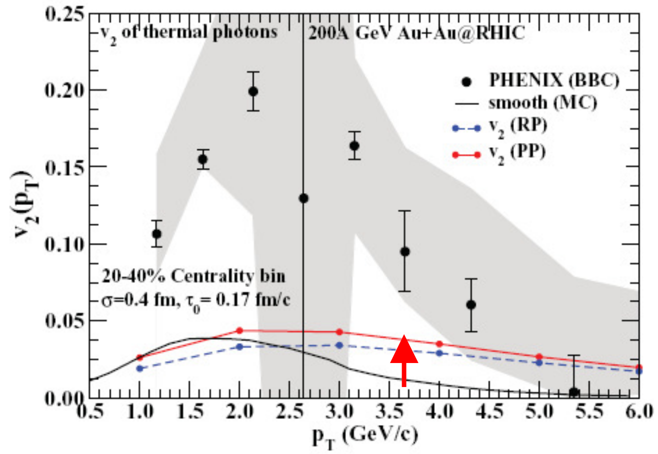
❑ **Jyväskylä ideal hydro**

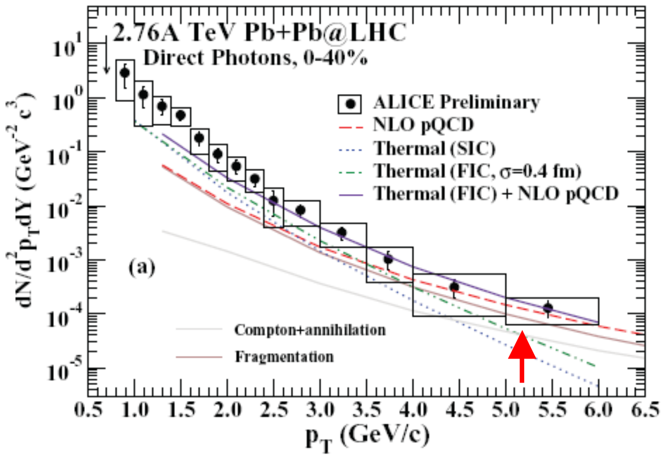
- **Ideal QGP and HG fluid**
- **Initial: ‚bumpy' ebe MC Glauber**
- **EoS: lQCD**

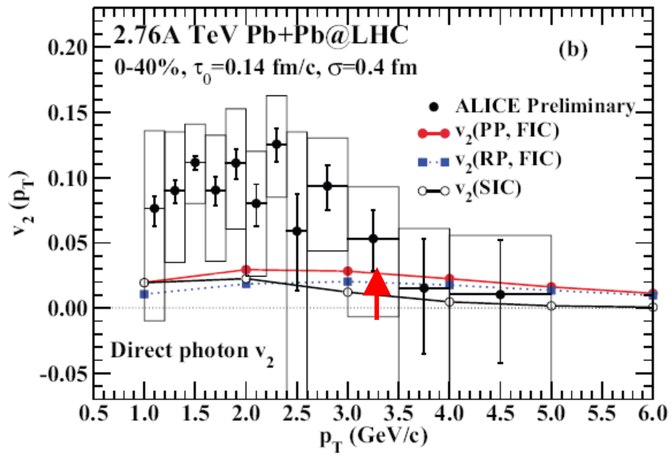
R. Chatterjee et al., PRC 88, 034901 (2013)











➔ **Fluctuating initial conditions:** slight increase at high p_T for yield and v_2
small effect, right direction!

2. From ideal to viscous hydro: direct photons as a QGP viscometer?

The thermal photon emission rates with viscous corrections:

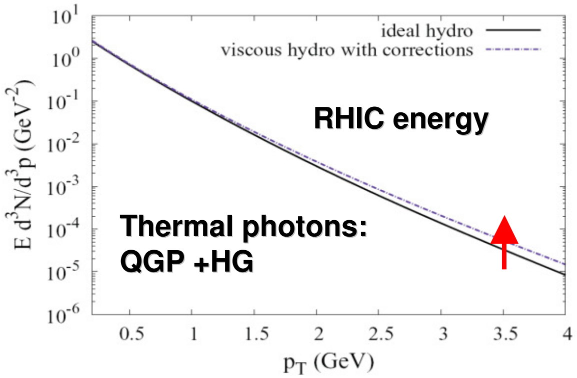
$$q\frac{dR}{d^3q}(q,T) = \Gamma_0(q,T) + \frac{\pi^{\mu\nu}}{2(e+P)}\Gamma_{\mu\nu}(q,T),$$

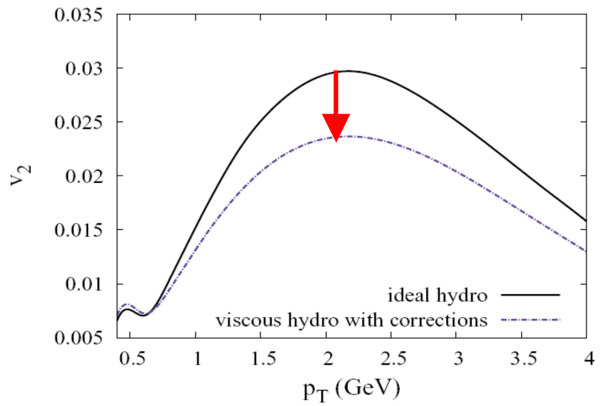
equilibrium contribution — first order viscous correction

❑ **(3+1)D MUSIC (McGill):**

M. Dion et al., PRC84 (2011) 064901

- viscous QGP and HG fluid
- Initial: ‚bumpy' ebe from IP-Glasma
- EoS: lQCD

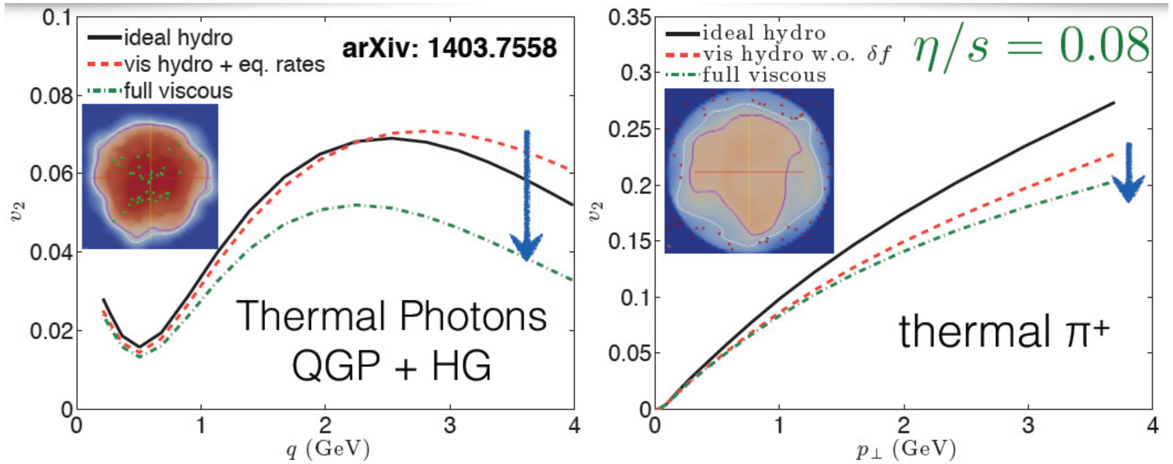




❑ **(2+1)D VISH2+1 (Ohio State) :**

C. Shen et al., arXiv:1308.2111, arXiv:1403.7558

- viscous QGP and HG fluid
- Initial: ‚bumpy' ebe from MC Glauber /KLN
- EoS: lQCD



➔ Effect of shear viscosity:

* small enhancement of the photon yield

* suppression of photon v_2

* effect on v_2 for photons is stronger than for hadrons

Important!

3. Influence of Glasma initial conditions with initial flow

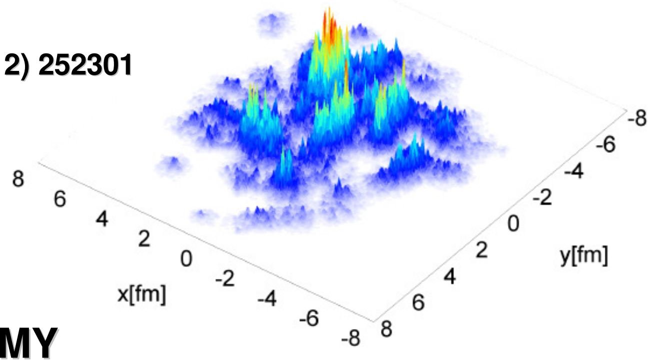
❑ (3+1)D MUSIC - 2014:

J-F. Paquet et al. (2014)

- viscous QGP and HG fluid ($\eta/s=0.22$)

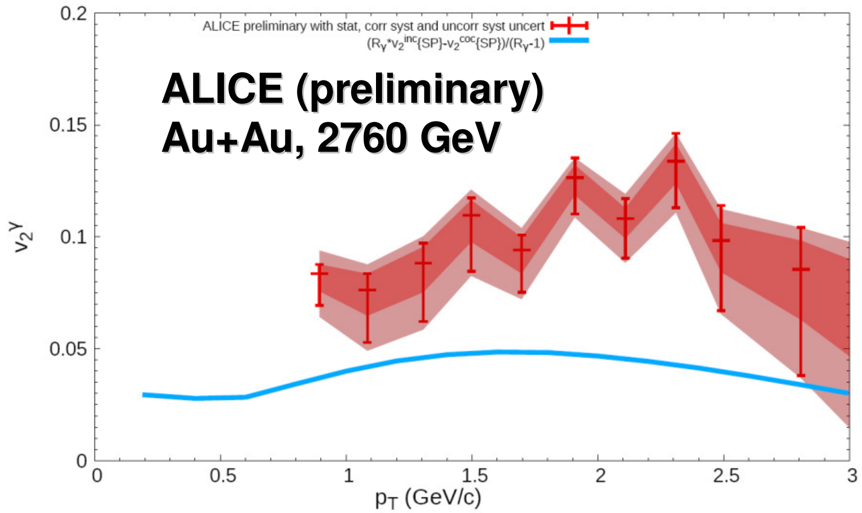
- Initial: 'bumpy' ebe from IP-Glasma ➔ generate initial flow due to fluctuations of IC

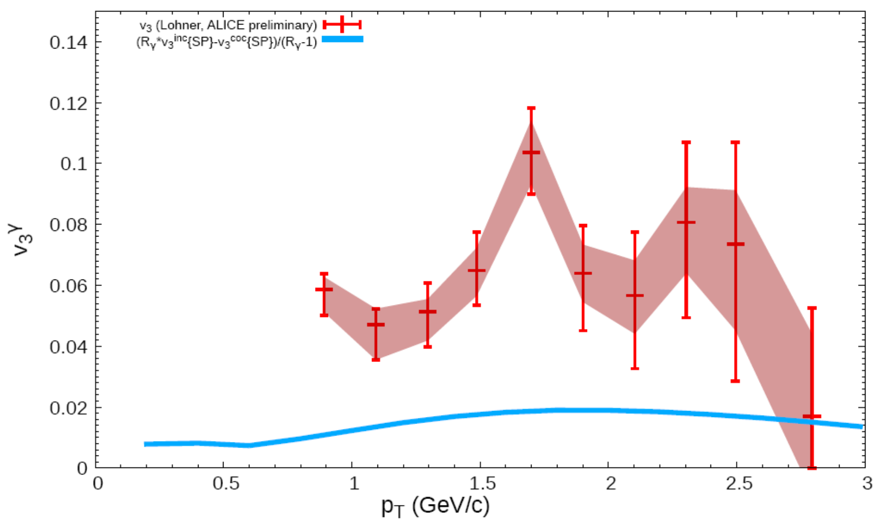
IP-Glasma:
Schenke et al., PRL108 (2012) 252301



- EoS: lQCD
- QGP photon rate: AMY
- HG photon rate: TGR for meson gas with viscous corrections + Rapp spectral function for ρ-mesons to account for the baryonic contributions

■ MUSIC with IC-Glasma describes hadronic flow v_n systematics at RHIC & LHC, however, missing v_2, v_3 of photons!





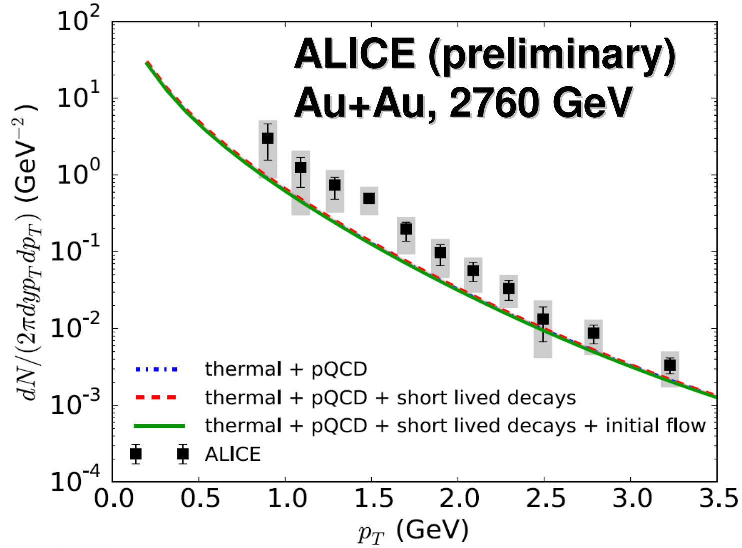
➔ 'Bumpy' ebe from IP-Glasma - small effect

4. Hydro with pre-equilibrium flow

- **‚Initial' flow:** rapid increase in bulk v_2 in fireball model
  van Hees, Gale, Rapp, PRC84 (2011) 054906

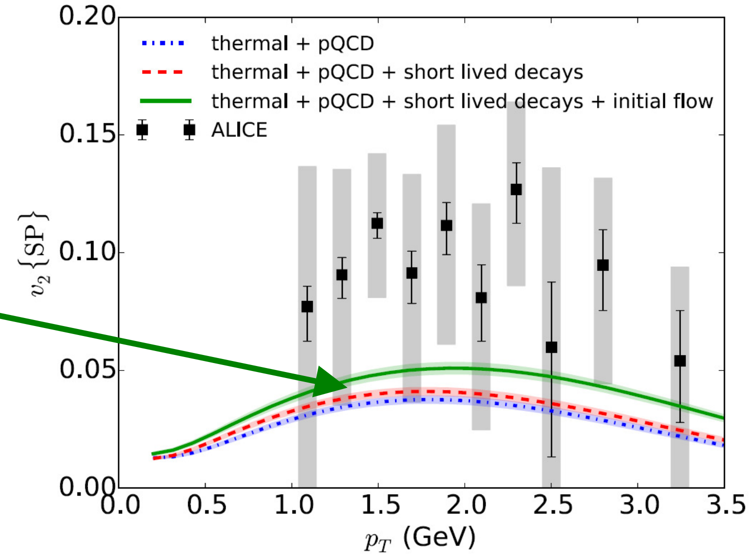
- **pre-equilibrium flow in (2+1)D VISH2+1 - 2014:**
C. Shen et al., arXiv:1308.2111, arXiv:1403.7558; Talk by C. Shen @ QM'2014

- viscous QGP and HG fluid (η/s=0.18)
- Initial: ‚bumpy' ebe from MC Glauber /KLN
- EoS: lQCD
- QGP photon rate: AMY
- HG photon rate: TGR for meson gas with viscous corrections



- Generation of pre-equilibrium flow:
using free-streaming model to evolve the partons right after the collisions to 0.6 fm/c
+ Landau matching to switch to viscous hydro

→ quick development of momentum anisotropy
with saturation near T_C



→ Pre-equilibrium flow:
- small effect on photon spectra
- slight increase of v_2

Warning: results can be considered as upper limit for the pre-equilibrium flow effect!

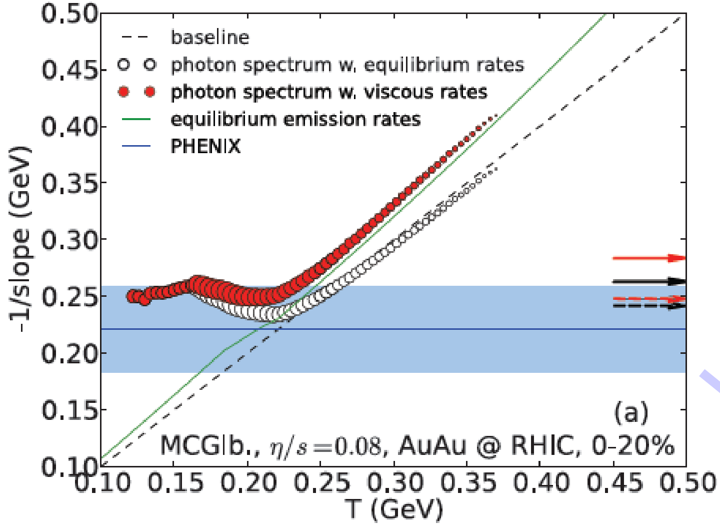
Are thermal photons a QGP thermometer?

C. Shen et al., PRC89 (2014) 044910; arXiv:1308.2440

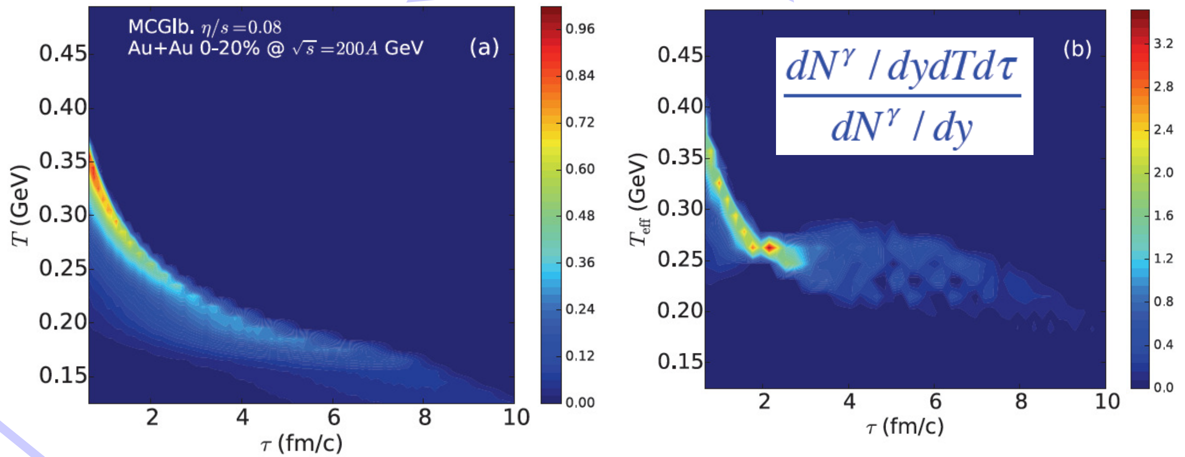
- (2+1)d viscous hydro VISH2+1 (Ohio)

▪ **Time evolution of the effective temperature**

▪ T_{eff}= -1/slope vs. local fluid cell temperature T



▪ Contour plots of differential photon yield vs. time and temperature T and T_{eff} :



Range of photon emission	Fraction of total photon yield	
	AuAu@RHIC 0–20% centr.	PbPb@LHC 0–40% centr.
T = 120–165 MeV	17%	15%
T = 165–250 MeV	62%	53%
T > 250 MeV	21%	32%
τ = 0.6–2.0 fm/c	28.5%	26%
τ > 2.0 fm/c	71.5%	74%

Exp. Data:

- RHIC: T_{eff}=221+19+19 MeV
- LHC: T_{eff}=304+51 MeV

- Measured Teff > ‚true' T $\quad T_{eff}=\sqrt{\frac{1+v}{1-v}}T$
- ‚blue shift' due to the radial flow!
- only ~1/3 at LHC and ~1/4 at RHIC of total photons come from hot QCD (T>250 MeV)

What else?!

- Further **improvements of hydro models** ?
  - Bulk viscosity
  - Modeling of initial pre-equlibrium effects
  - …

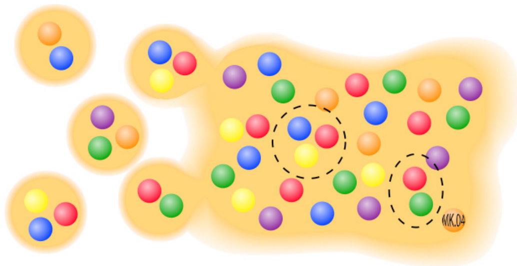
• Non-equilibrium dynamics ?

• Missing strength related to hadronic stage?

⇒ From hydro to non-equilibrium **microscopic transport models** :

use PHSD as a ‚laboratory' for that

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 (applicable for strongly interacting system!)

⇨ **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)

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

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 :**

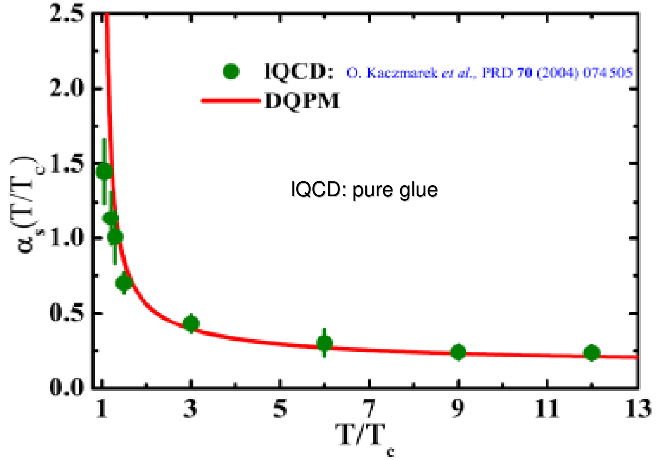
$$(i = q, \bar{q}, g) \qquad \rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**

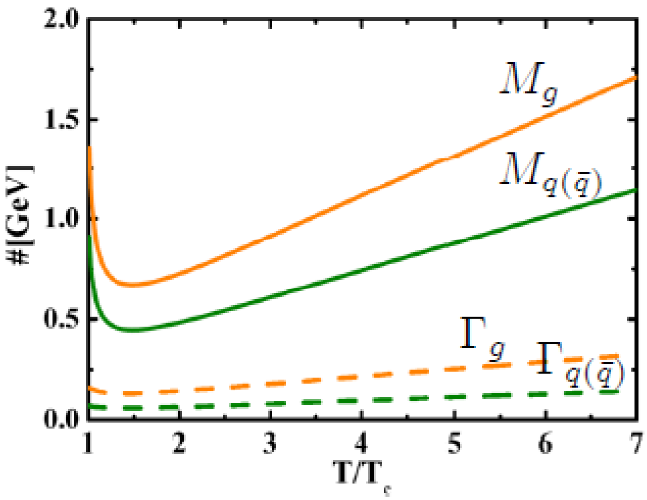
$$M_i(T) \propto \alpha_S(T) f_{HTL}(T), \qquad \Gamma_i(T) \propto \alpha_S(T) f_{HTL}(T)$$

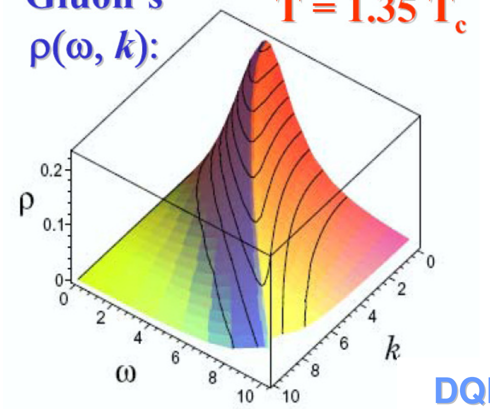
- **fit to lattice (lQCD) results (e.g. entropy density) with 3 parameters**

■ $\alpha_S(T)$ **- running coupling**



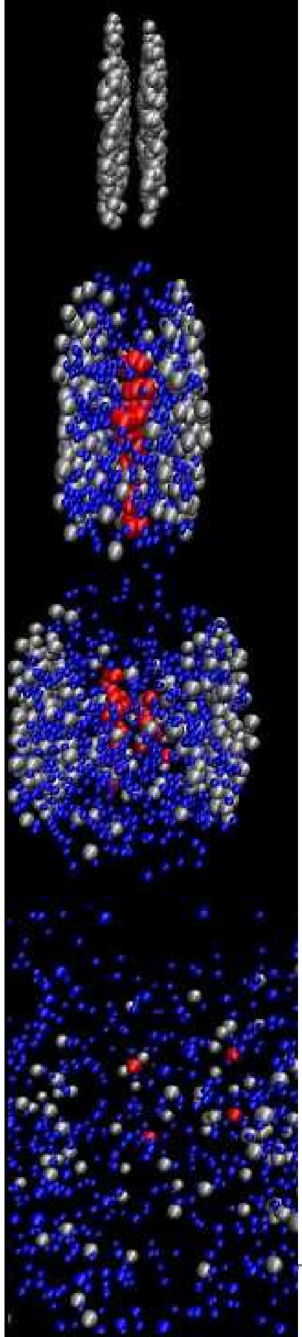
➔ **Quasi-particle properties:**
large width and mass for gluons and quarks





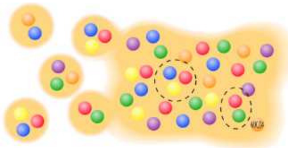
T_C=158 MeV
ε_C=0.5 GeV/fm^3

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



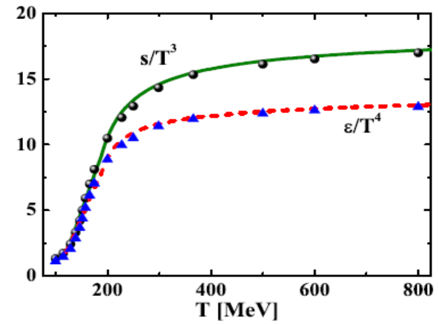
Parton Hadron String Dynamics

I. From hadrons to QGP:



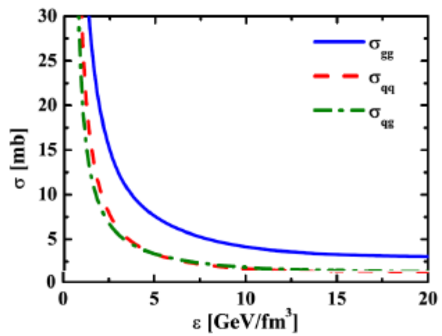
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- Initial A+A collisions:
  - string formation in primary NN collisions
  - strings decay to pre-hadrons (*B* - baryons, *m* – mesons)
- Formation of QGP stage by dissolution of pre-hadrons into massive colored quarks + mean-field energy based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$ + mean-field potential U_q at given ε – local energy density (related by lQCD EoS to T - temperature in the local cell)



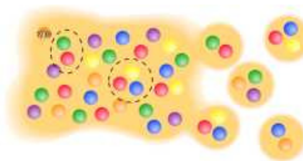
II. Partonic phase - QGP:

- quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM
- in self-generated mean-field potential for quarks and gluons U_q, U_g
- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM



III. Hadronization: based on DQPM

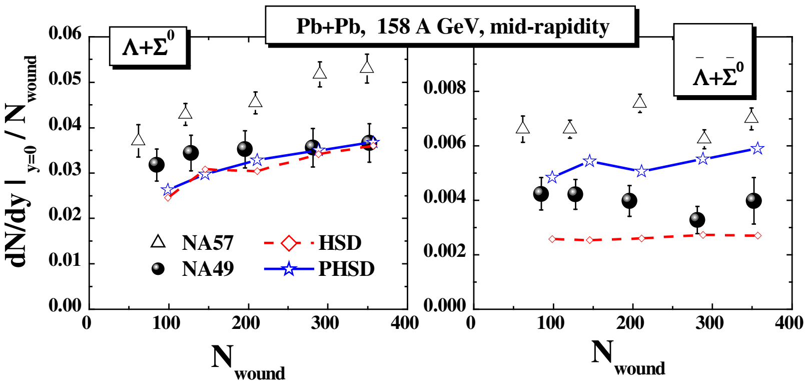
- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)

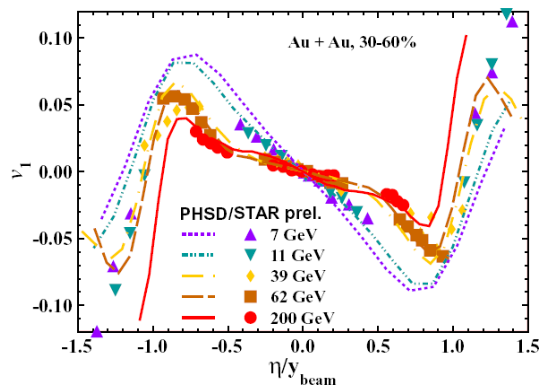


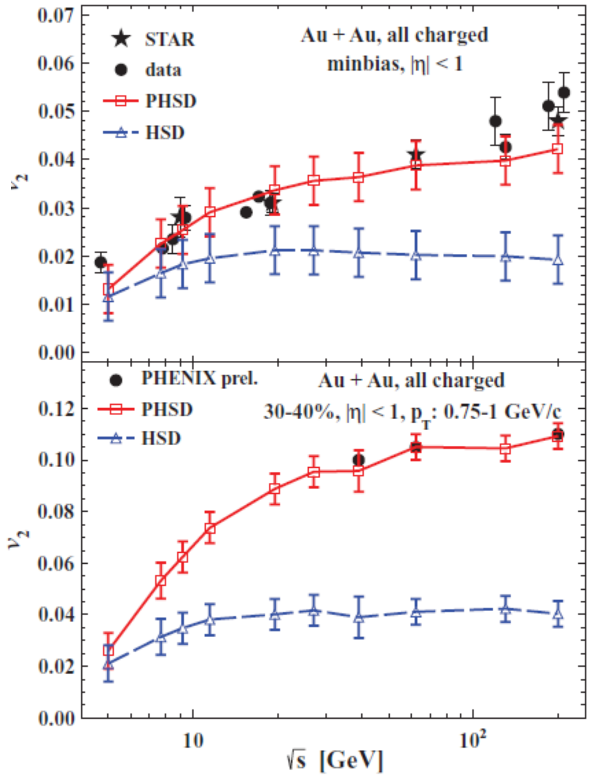
IV. Hadronic phase: hadron-string interactions – off-shell HSD

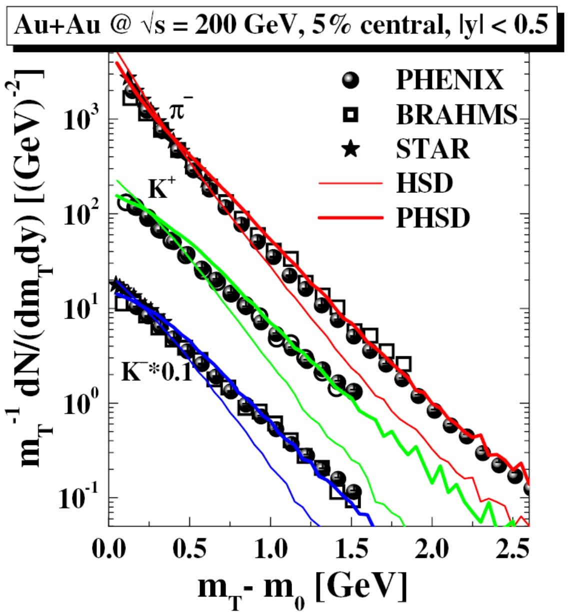
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

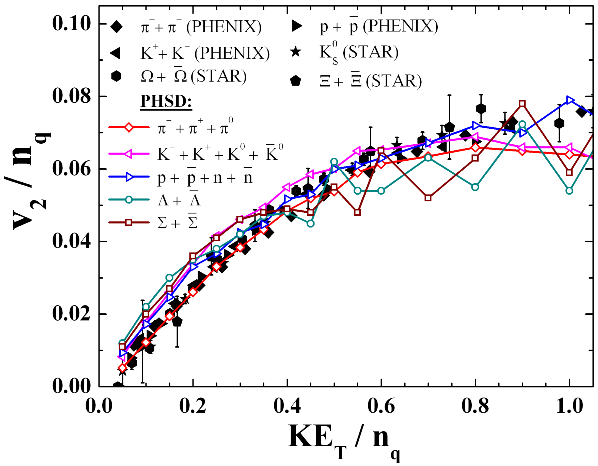
PHSD for HIC (highlights)

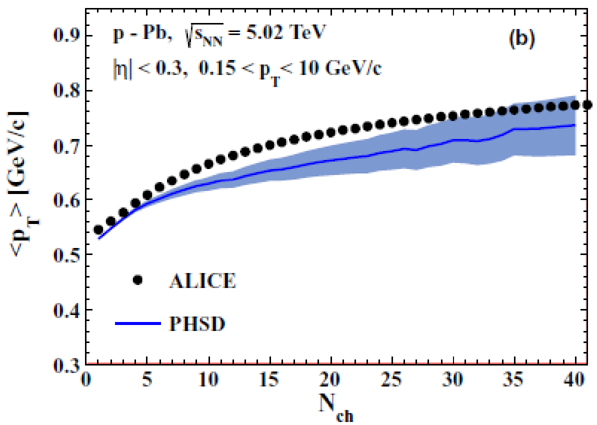


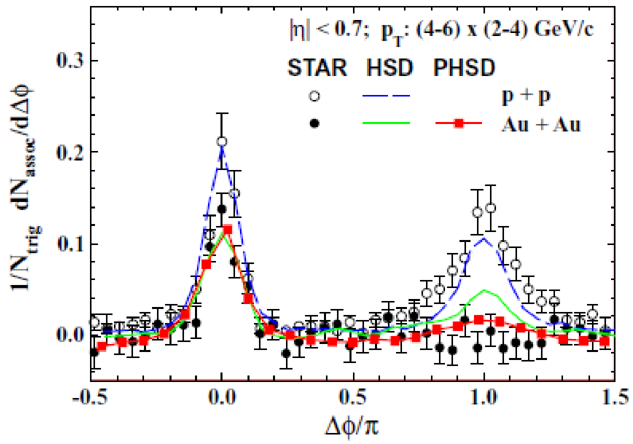










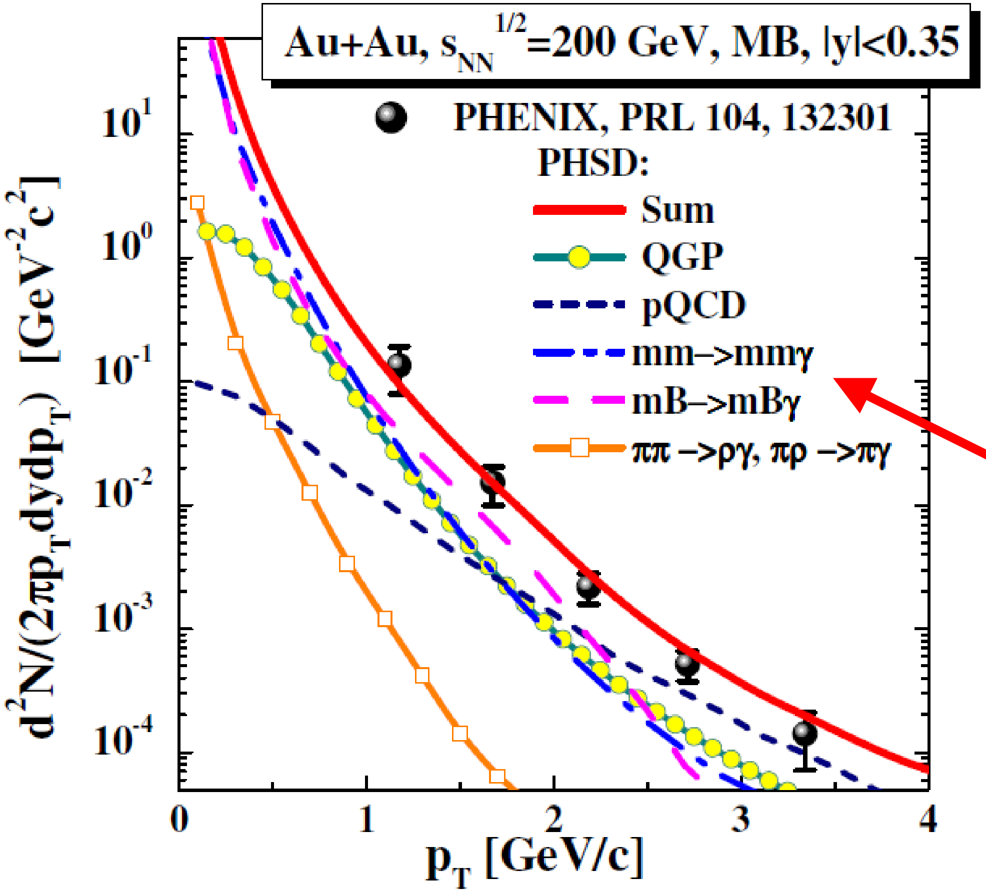


- **PHSD provides a consistent description of HIC**

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

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

- Direct photon spectrum (min. bias)



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

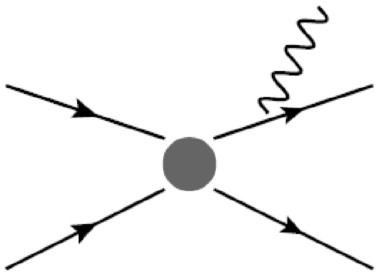
PHSD:

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

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

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

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



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

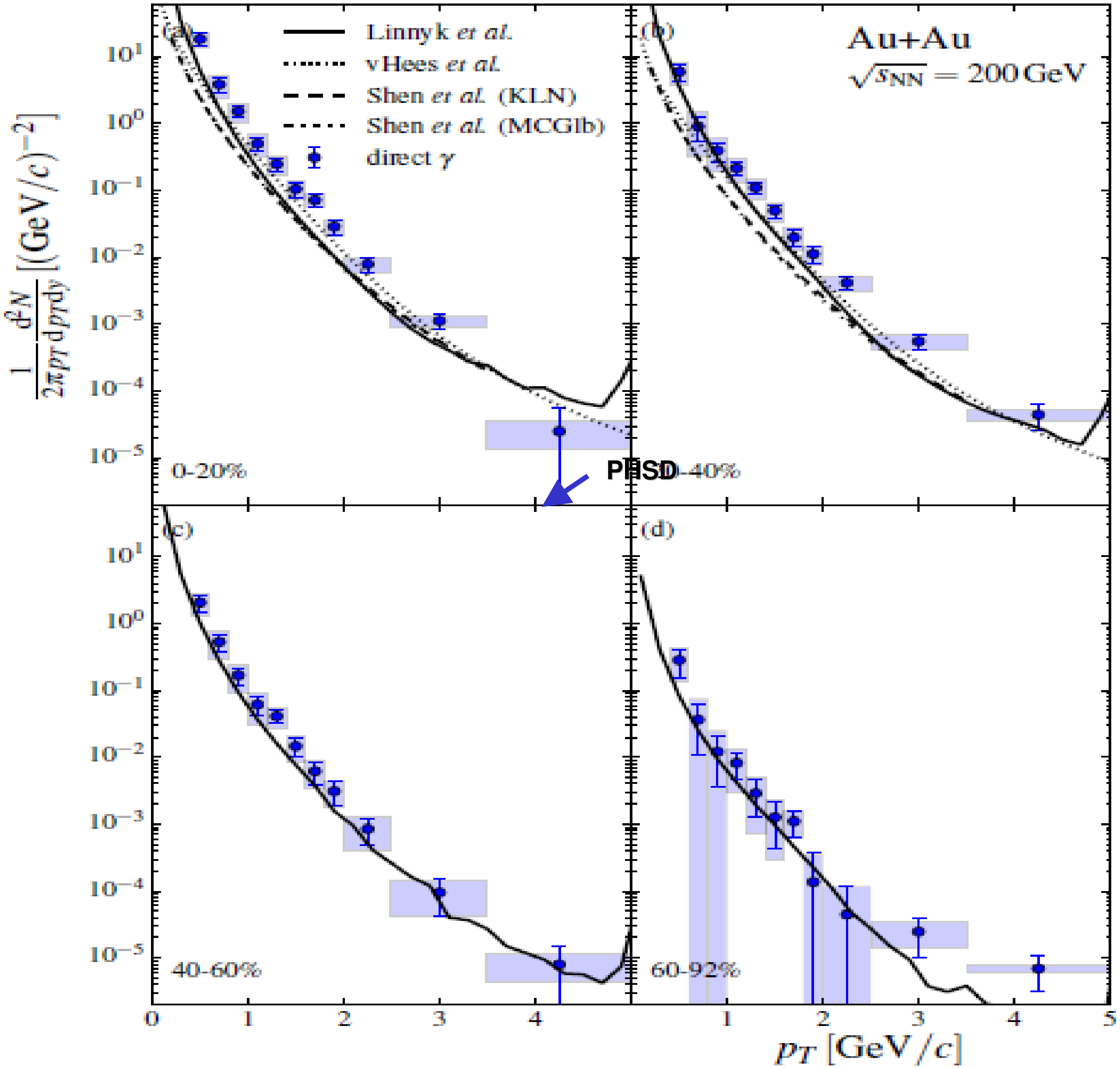
!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

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)

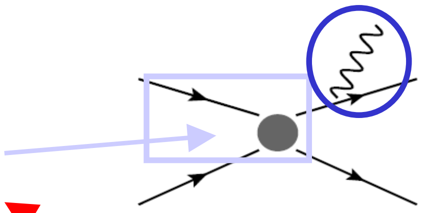
- **Soft Photon Approximation (SPA):**

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

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

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

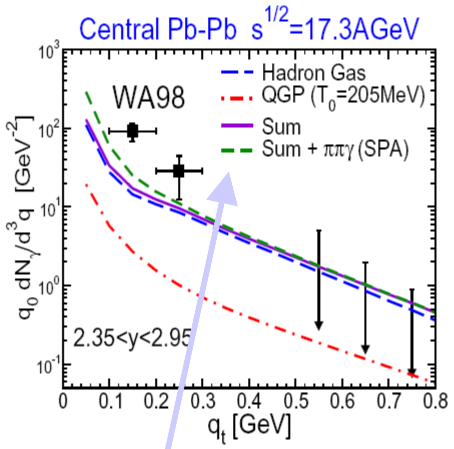
$$\bar{\sigma}(s) = \frac{s-(M_1+M_2)^2}{2M_1^2}\sigma(s),$$

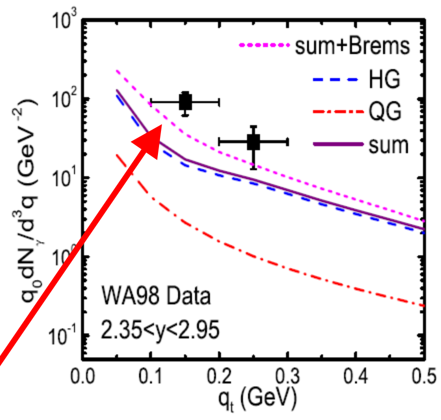


2) no experimental constraint on m+m and m+B differential elastic cross sections

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

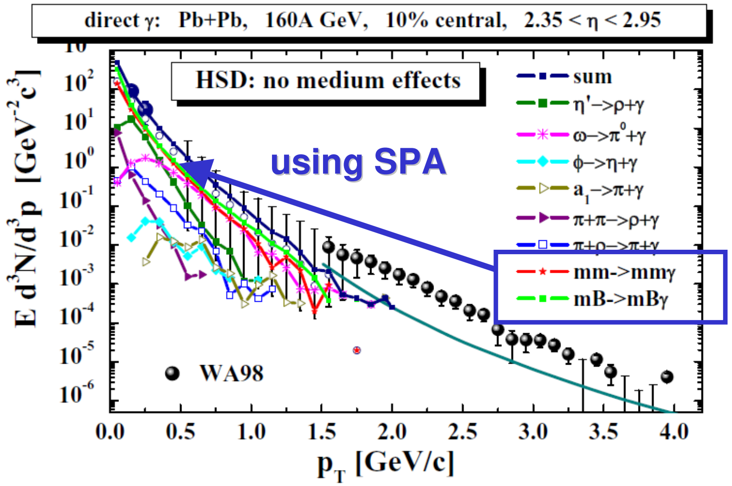
Firebal model: Liu, Rapp, Nucl. Phys. A 96 (2007) 101





- effective chiral model for $\pi\pi \rightarrow \pi\pi\gamma$, $\pi K \rightarrow \pi K\gamma$ bremsstrahlung gives larger contribution than SPA

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



➔ **mm and mB Bremsstrahlung seams to be an important source of soft photons!**
More work has to be done to have it under control!

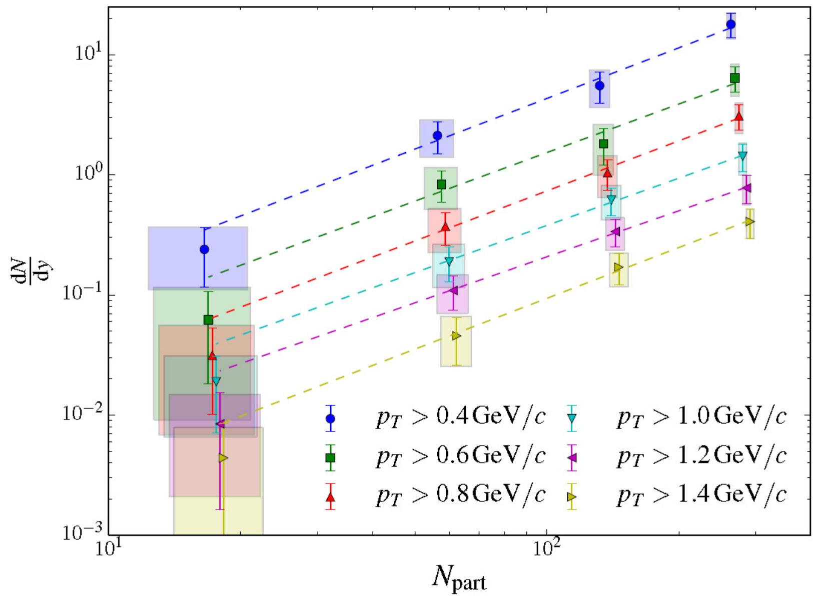
Centrality dependence of the ‚thermal' photon yield

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

PHENIX (arXiv:1405.3940):

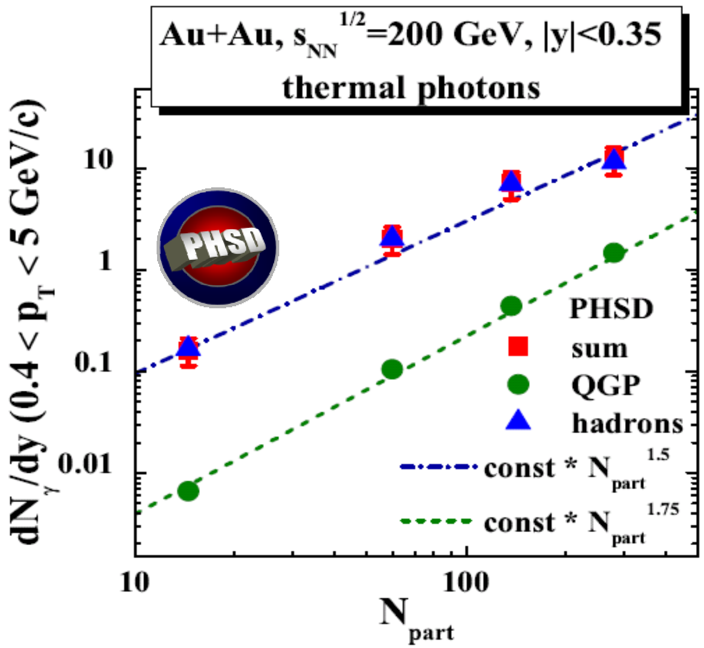
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

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



PHSD predictions:

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



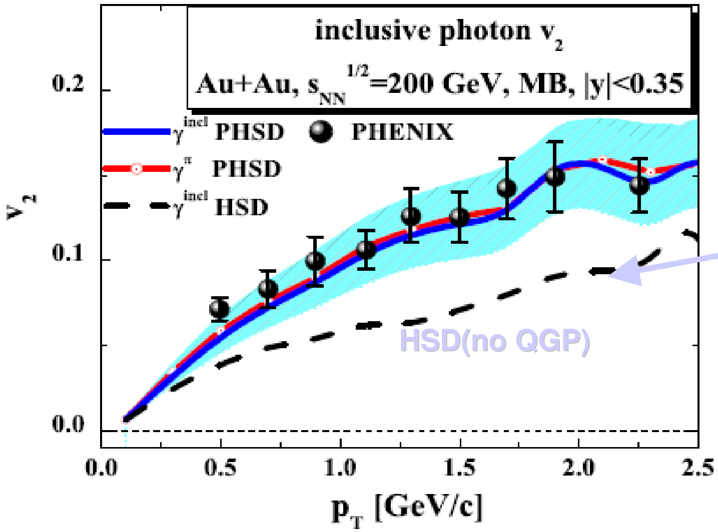
- ❑ PHSD: scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$
- ❑ similar results from viscous hydro:
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

➔ **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?**

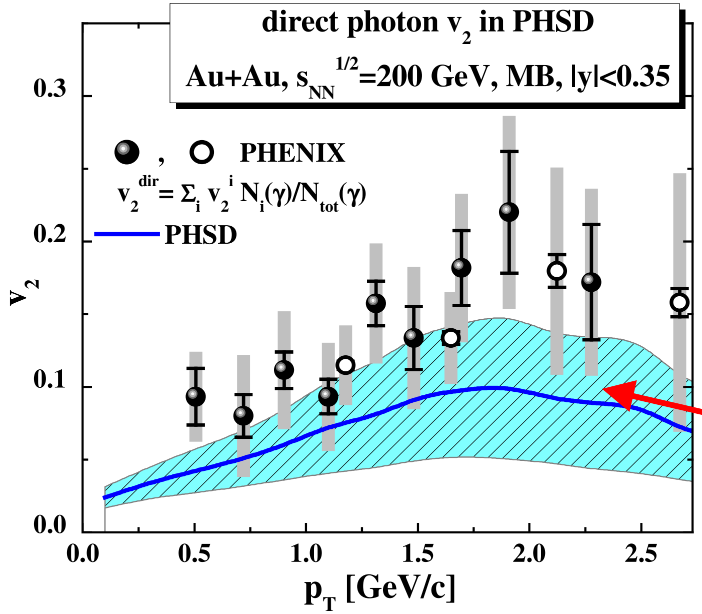
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



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):

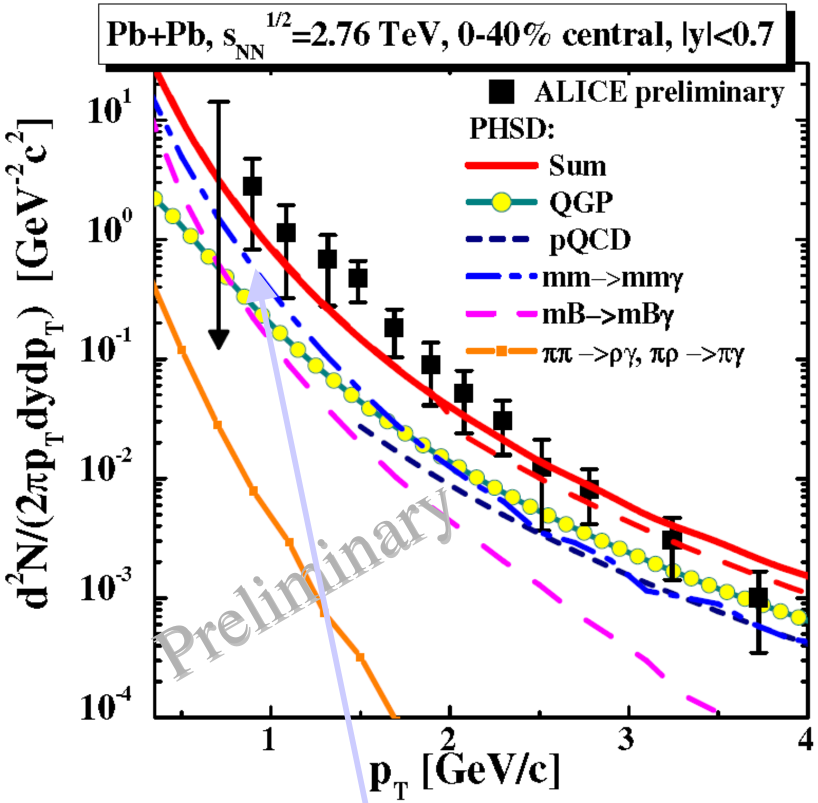
2) $v_2(\gamma^{dir})$ of direct photons in PHSD underestimates the PHENIX data :

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

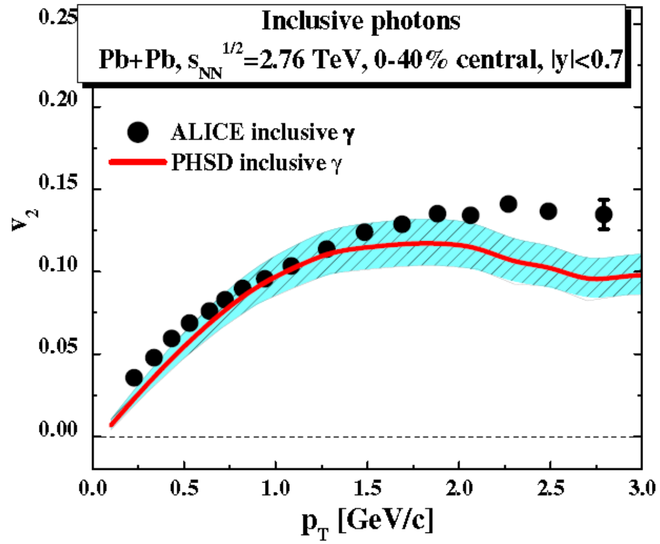
➔PHSD: $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung !**

Photons from PHSD at LHC

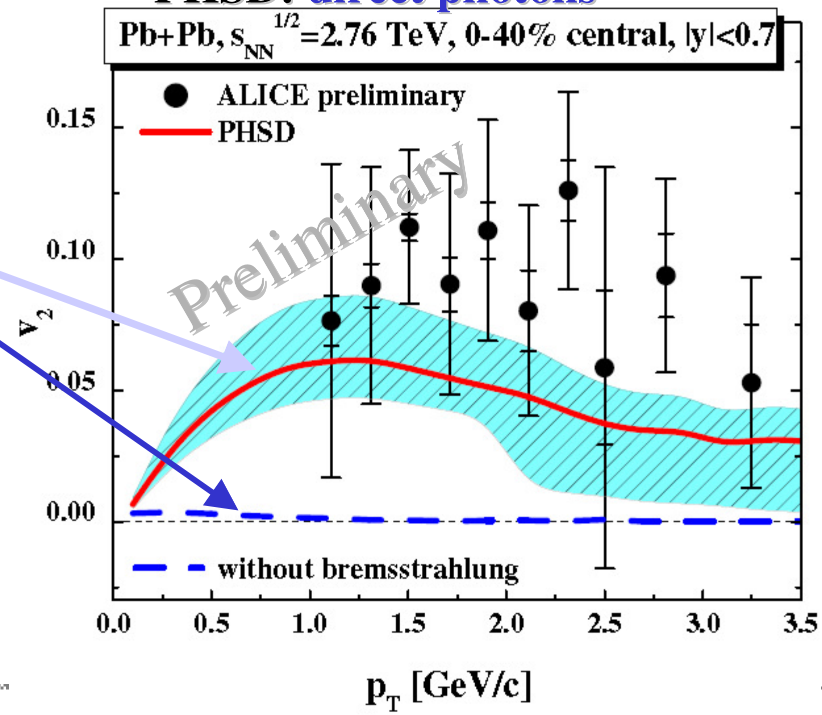
PHSD- preliminary: Olena Linnyk



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)

- non-perturbative effects?

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

- ???

?

… shining in the darkness

Some messages from the 'photon adventure':

- Can thermal QGP accelerate photons enough?!

- The role of hadronic sources (like bremsstrahlung) were underestimated?

- The importance of initial phases of the reaction:
  Large photon v_2 requires the development of pre-equilibrium / initial flow ?!

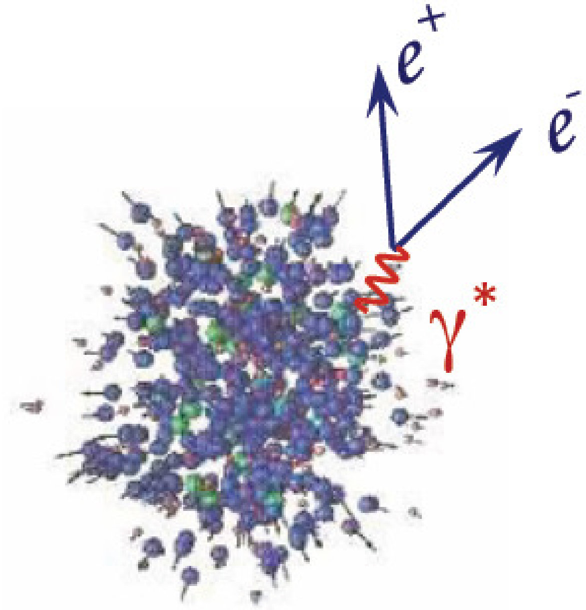
- New sources of photon emission? Why not seen in dileptons?!

- The photons provide a critical test for the theoretical models:
  models constructed to reproduce the ‚hadronic world' fail to explain the photon experimental data!

➔ Additional impuls for the development of dynamical models:
e.g. from ideal to ebe viscous hydro, EoS, realistic non-equilibrium dynamics …

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

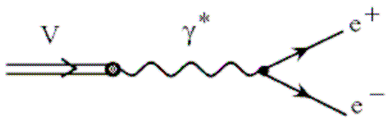
Dileptons: from SPS to LHC



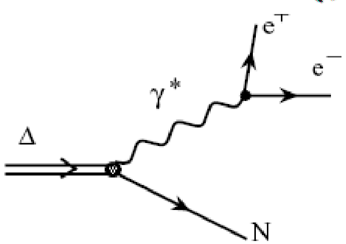
Dilepton sources

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

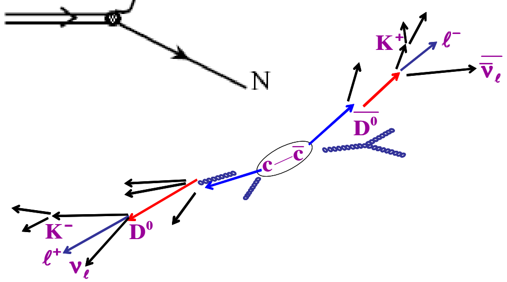
- **from hadronic sources:**



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

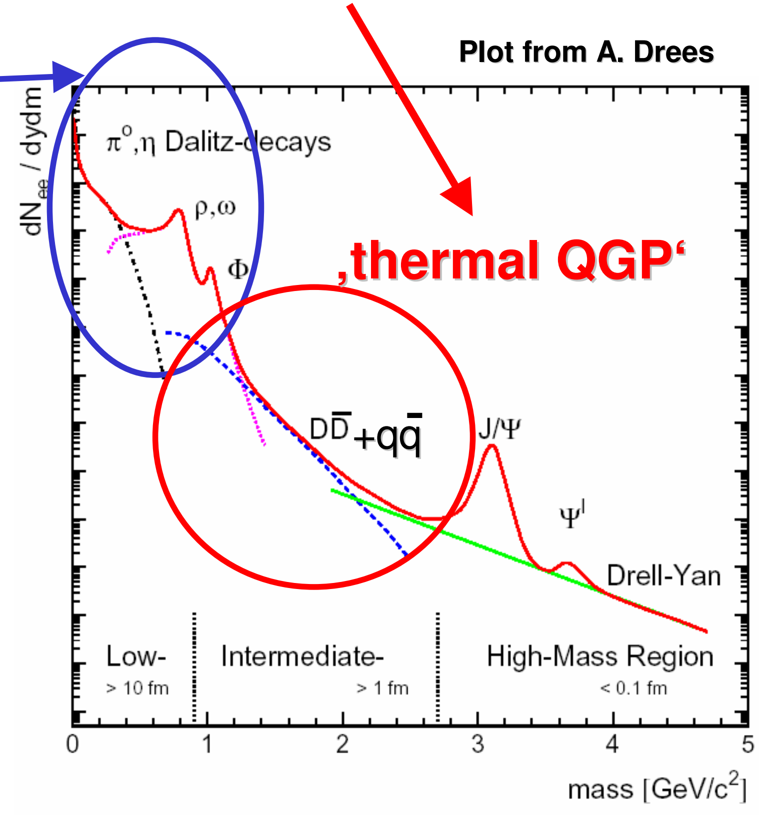


- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**

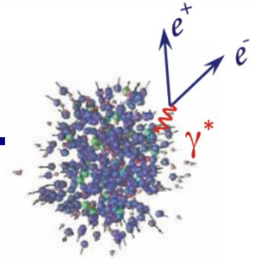


- **correlated D+Dbar pairs**

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

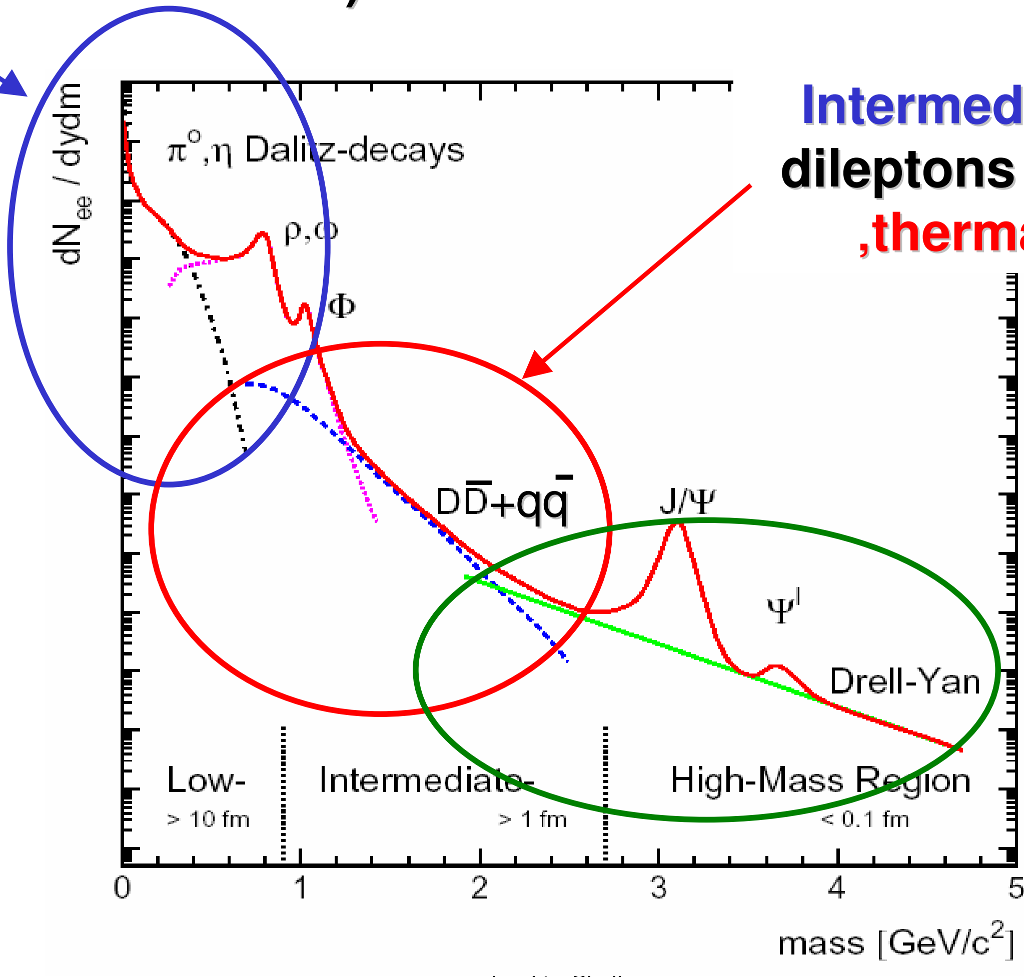


Physics with dilepton



Low mass dileptons
-probe of hadronic in-medium effects
(late time emission)

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



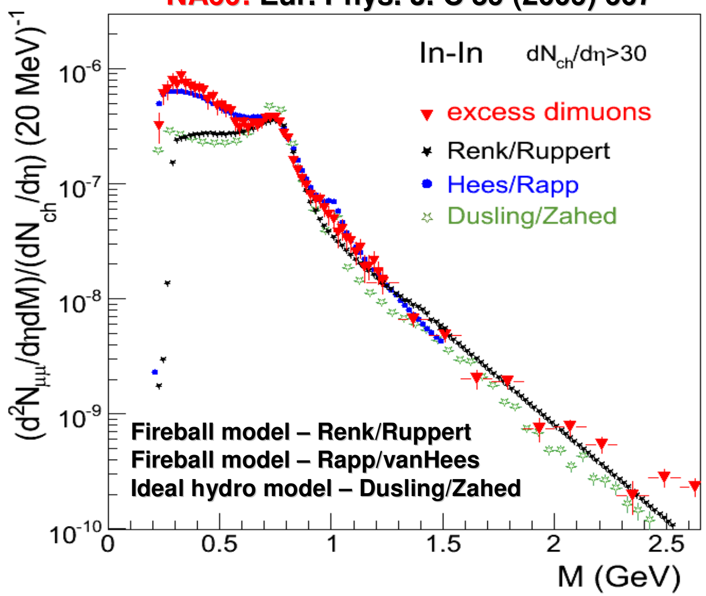
Intermediate mass dileptons – probe of ‚thermal QGP‘

High-mass dileptons – probe of pQGP and hard probes
(early time emission)

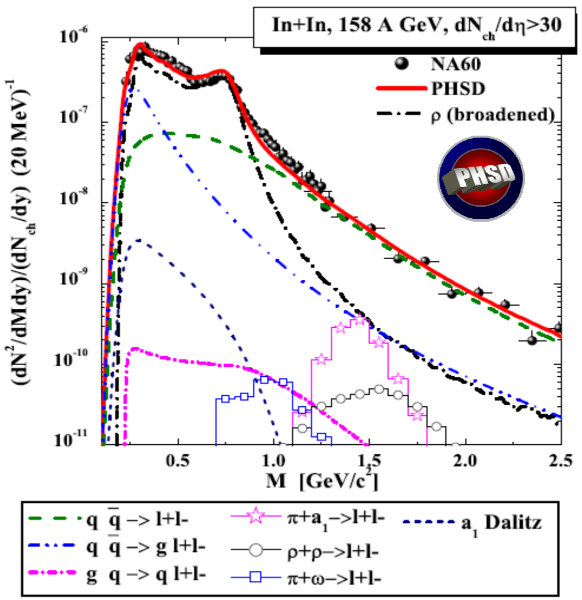
Lessons from SPS: NA60

Dilepton invariant mass spectra:

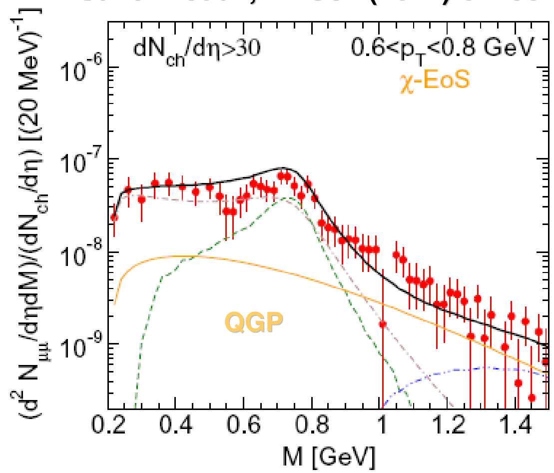
NA60: Eur. Phys. J. C 59 (2009) 607



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

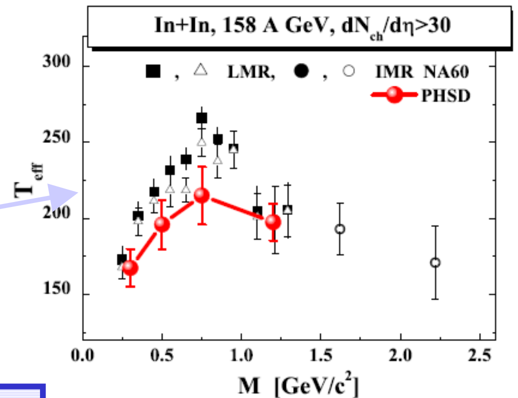


Hybrid-UrQMD:
Santini et al., PRC84 (2011) 014901



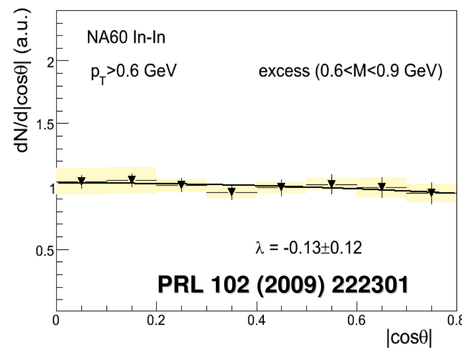
Inverse slope parameter T_{eff}:

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

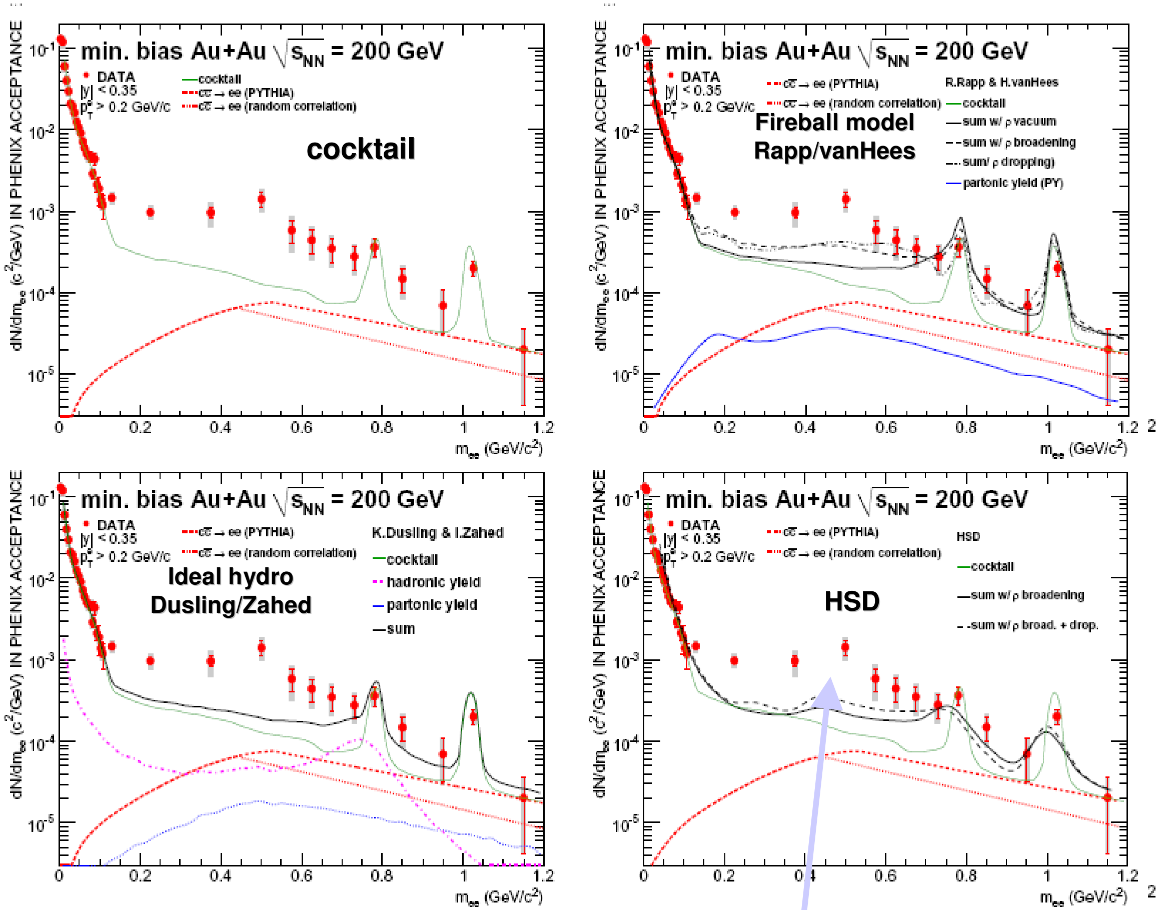


Message from SPS: (based on NA60 and CERES data)

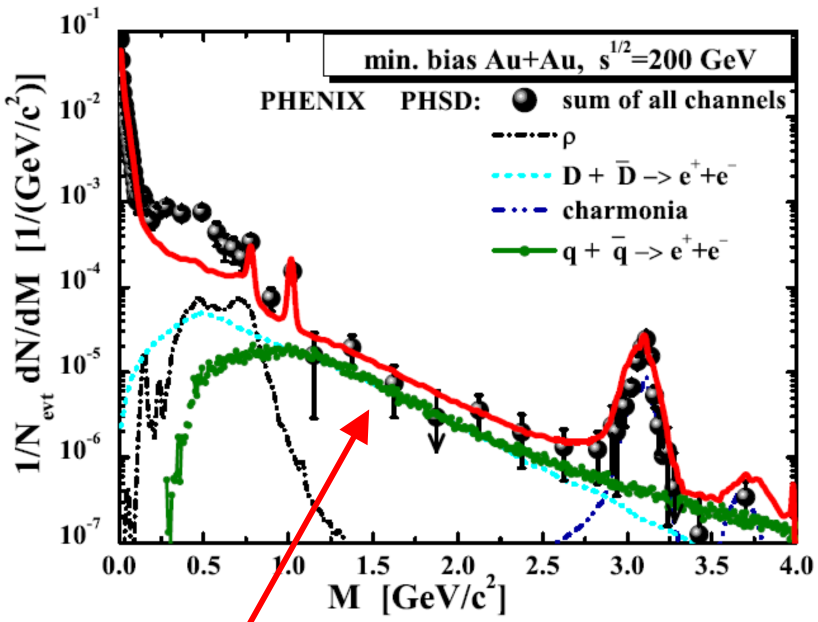
1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons



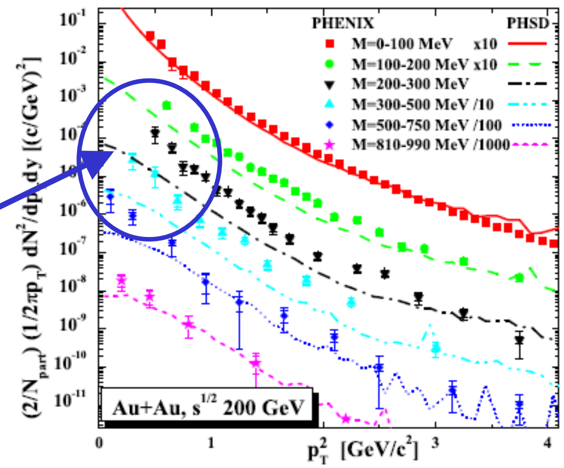
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



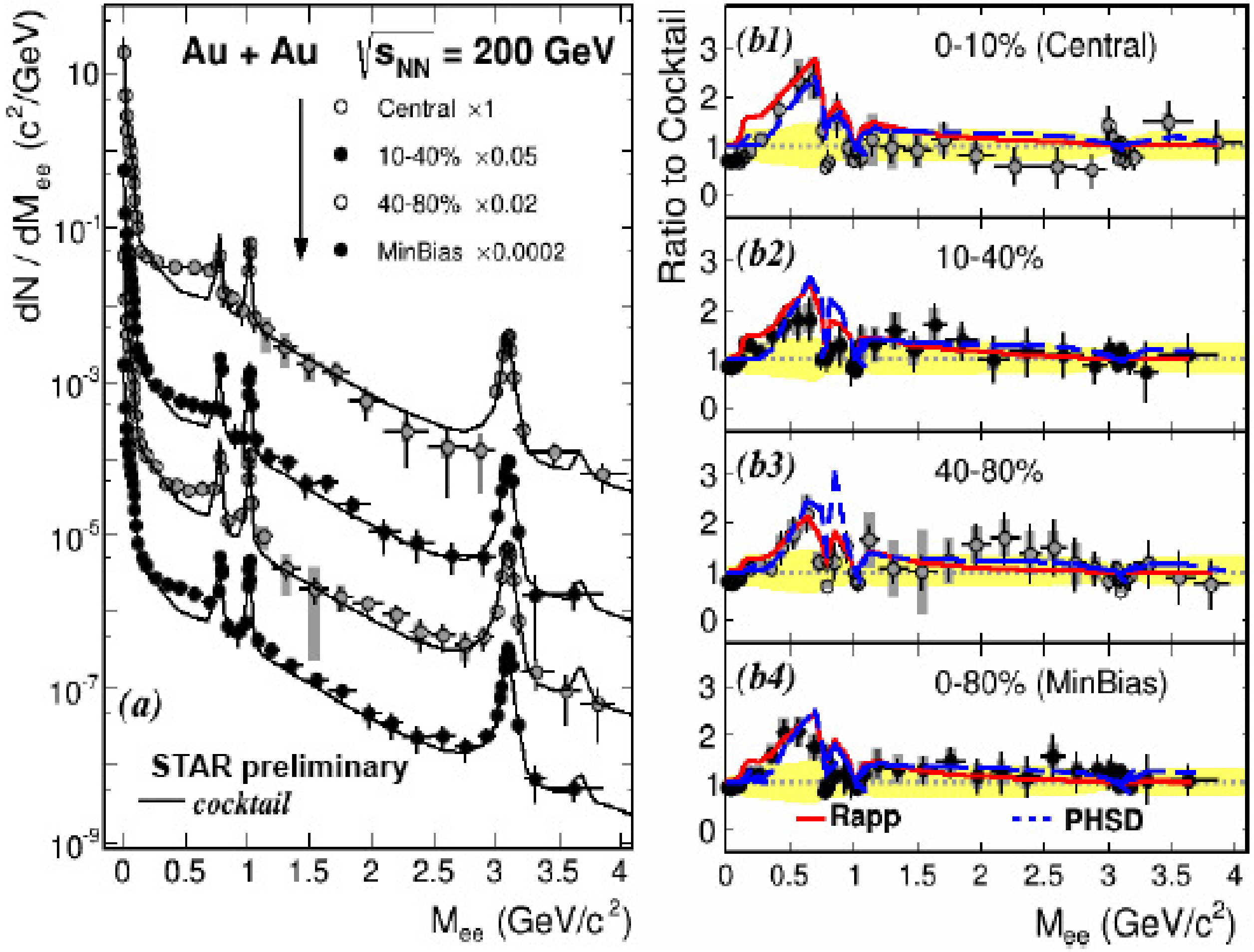
Message:

- **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**

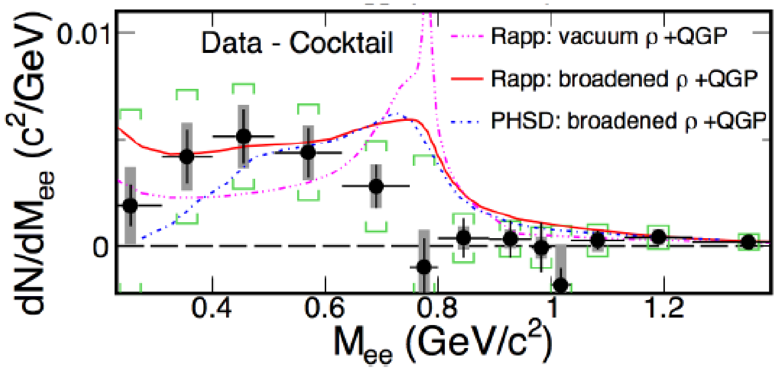
Dileptons at RHIC: STAR data vs model predictions

(Talk by P. Huck at QM‘2014)

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models:

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

Low masses:

collisional broadening of ρ

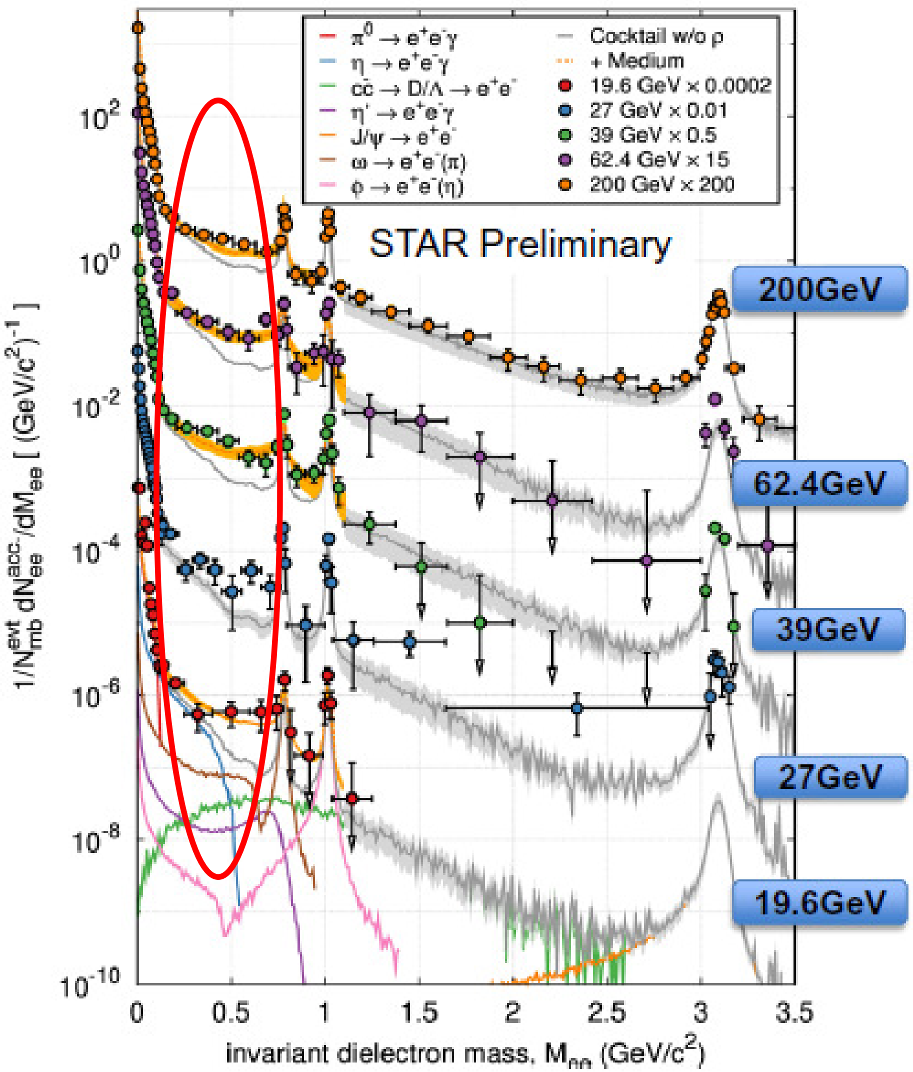
Intermediate masses:

QGP dominant

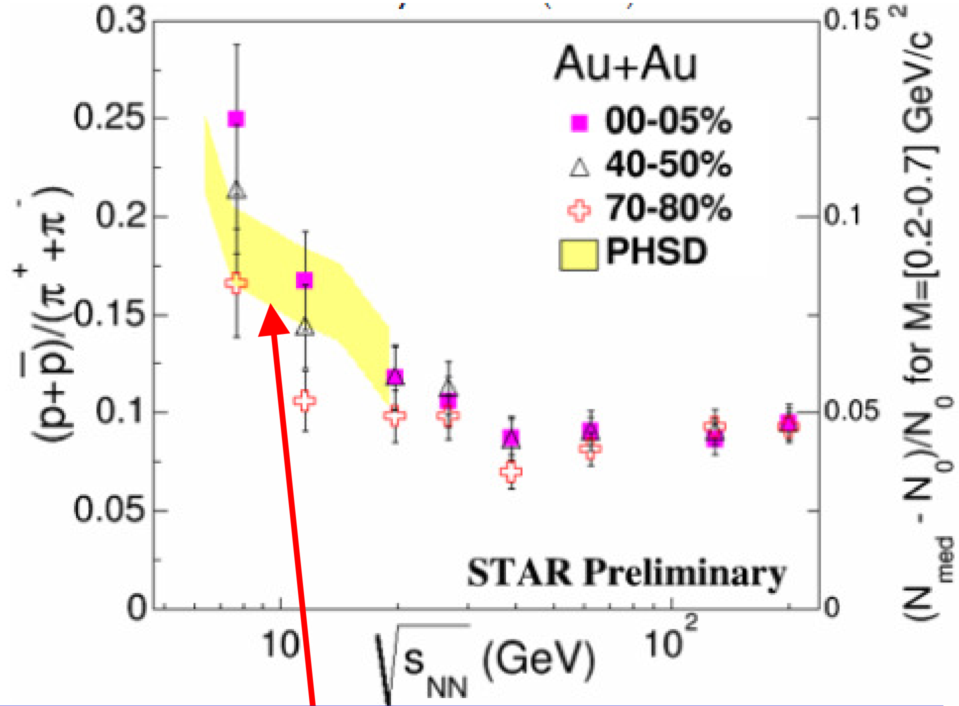
Message: **STAR data** are described by models within a **collisional broadening** scenario for the vector meson spectral function + **QGP**

Dileptons from RHIC BES: STAR

(Talk by Nu Xu at QM'2014)



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

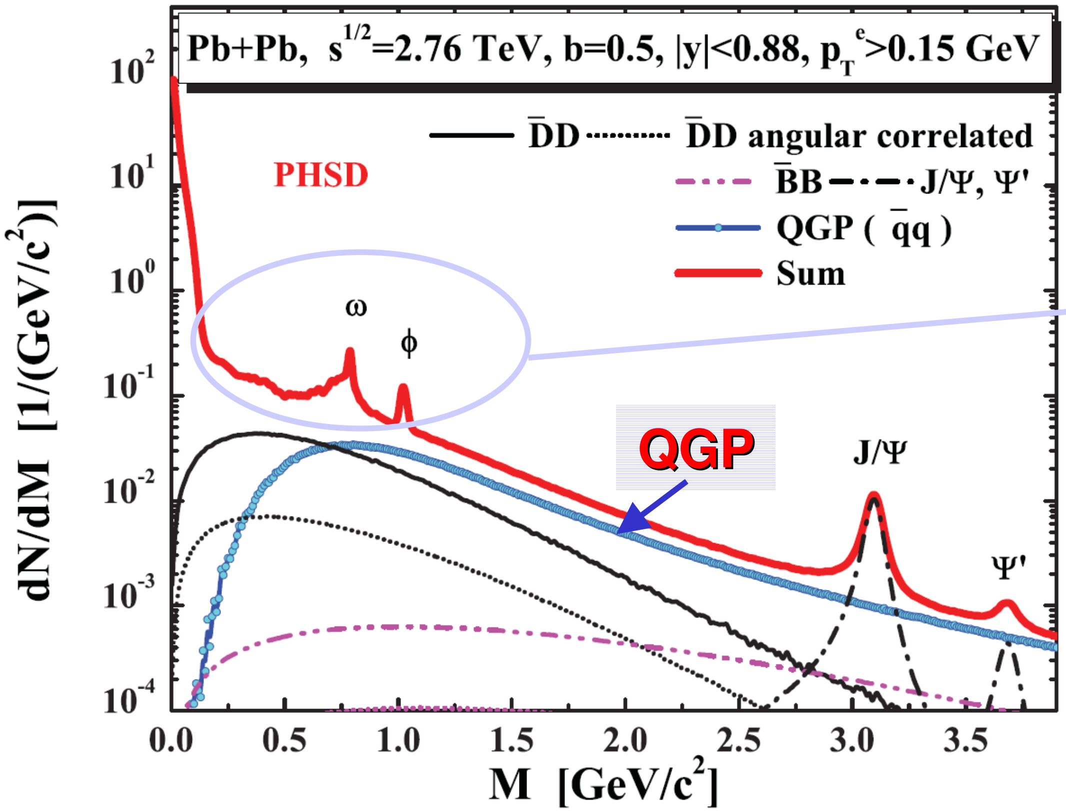


Message:

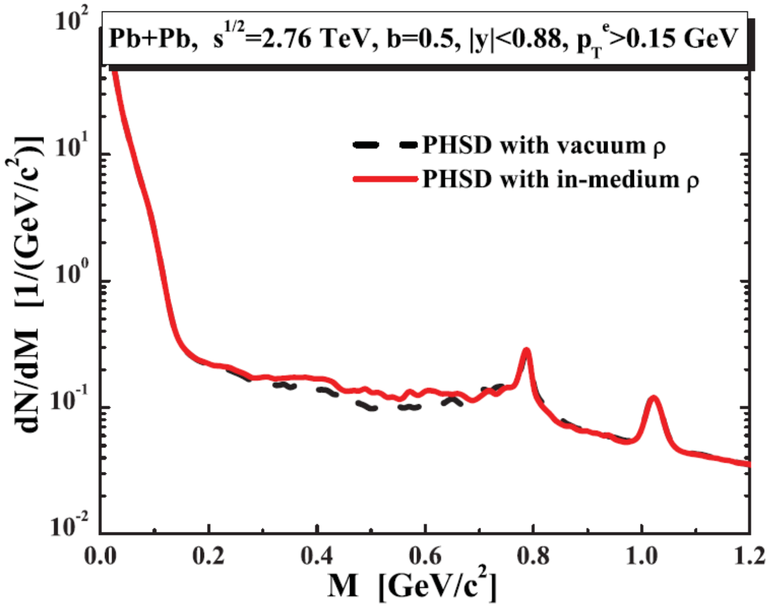
- **BES-STAR data** show a **constant low mass excess** (scaled with $N(\pi^0)$) within the measured energy range
- PHSD model: **excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon density phase

➔ 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



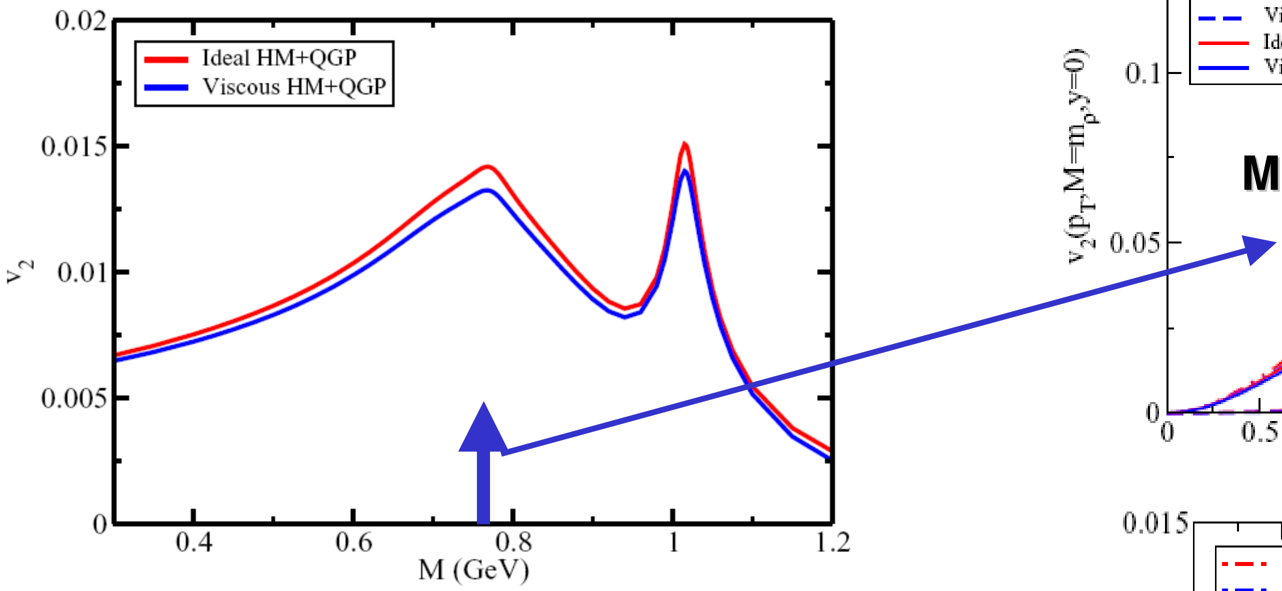
Message:

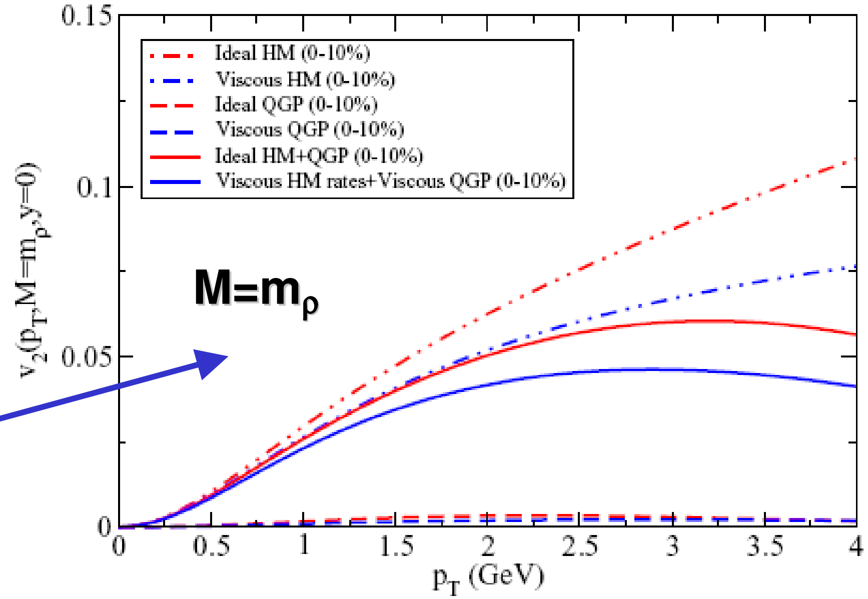
- low masses - hadronic sources: in-medium effects for ρ mesons are small
- intermediate masses: QGP + D/Dbar
  - charm 'background' is smaller than thermal QGP yield
  - QGP(qbar-q) dominates at M>1.2 GeV → clean signal of QGP at LHC!

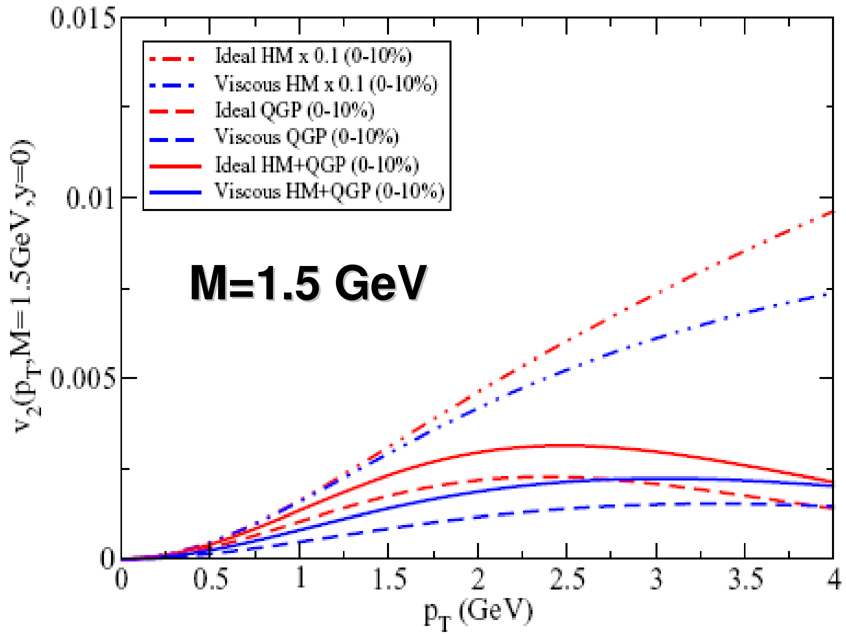
Perspectives with dileptons: v_n

Vujanovic, Young, Schenke, Rapp, Jeon, Gale, PRC 89 (2014) 034904

(3+1)d MUSIC: Au+Au, RHIC, 10% central







v_2 (similar for v_3):

- sensitive to the EoS and η/s
- sensitive to the sources

Dileptons: advantages compared to photons – extra degree of freedom M allows to disentangle the sources!

Messages from dilepton data

- **Low dilepton masses:**

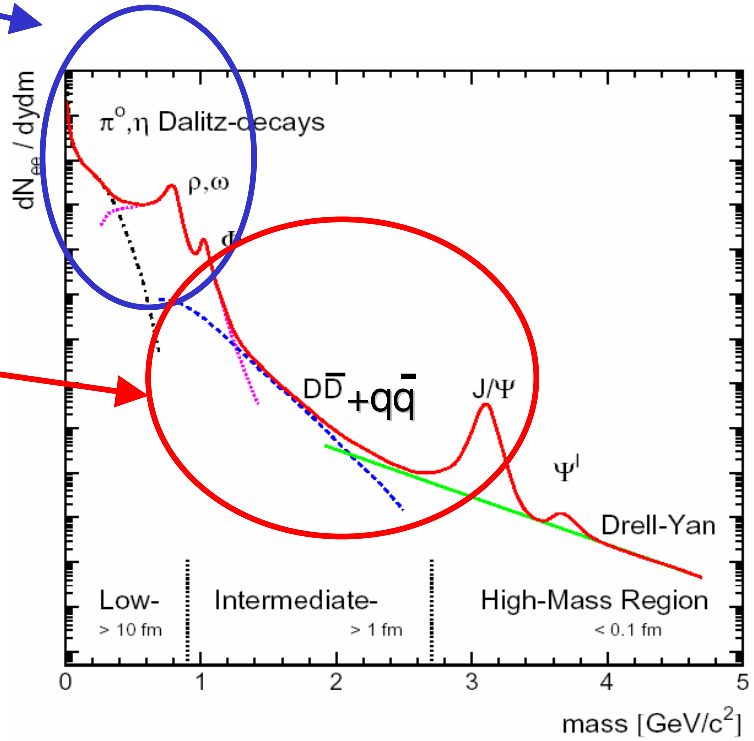
- Dilepton spectra show **sizeable changes due to the in-medium effects – modification of the properties of vector mesons** (as collisional broadening) - which are observed experimentally

- **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