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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

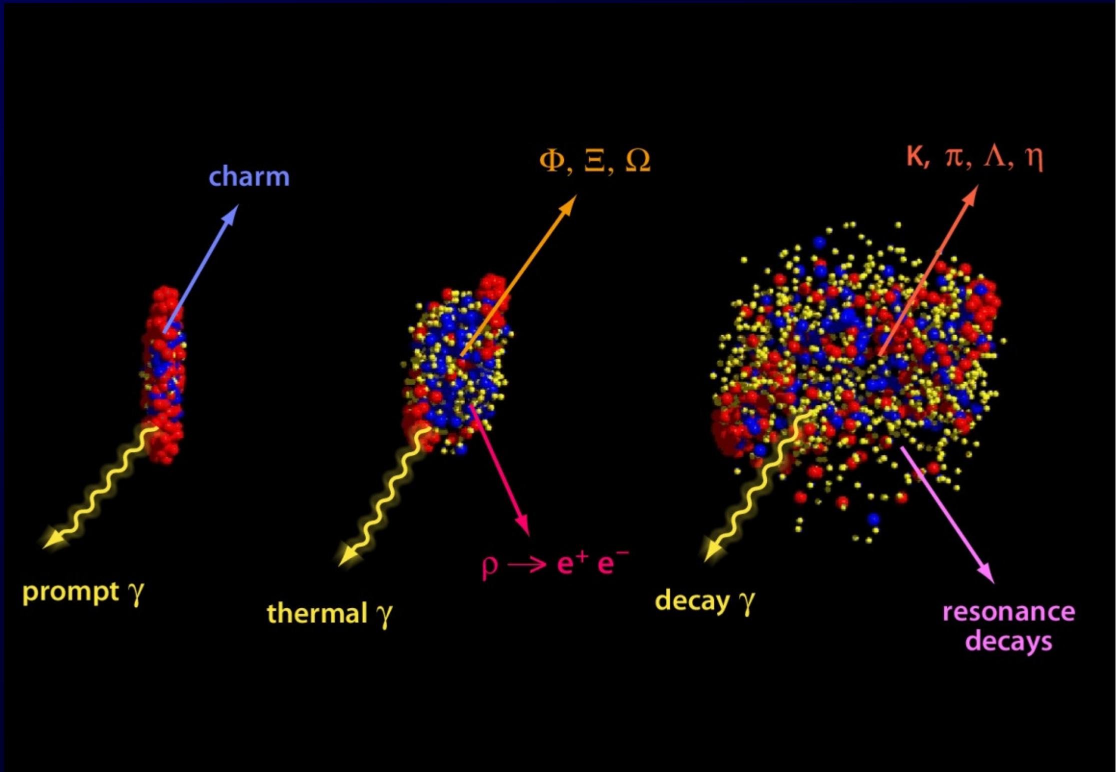
✓ provide undistorted information about their production channels

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

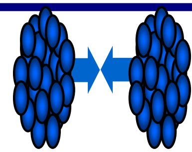
➔ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

Disadvantages:

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

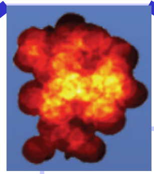


Dynamical models for HIC



Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodynamical equations for the fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous
(Romatschke, (2+1)D VISH2+1, (3+1)D MUSIC,…)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM, GiBUU, …)

Partonic cascades pQCD based
(Duke, BAMPS, …)

Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

! applicable for strongly interacting systems !

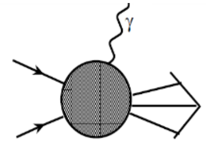
‚Hybrid' (Macro+Micro)
- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid'-UrQMD, EPOS, …)

Modeling of photon/dilepton emission

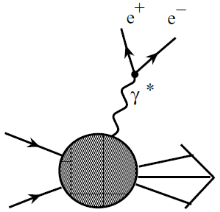
I. Emission rate from thermal field theory:

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 : $\Pi_{\mu\nu} \sim i\int d^4x\, e^{ipx} < [J_\mu(x), J_\nu(0)] >_T$

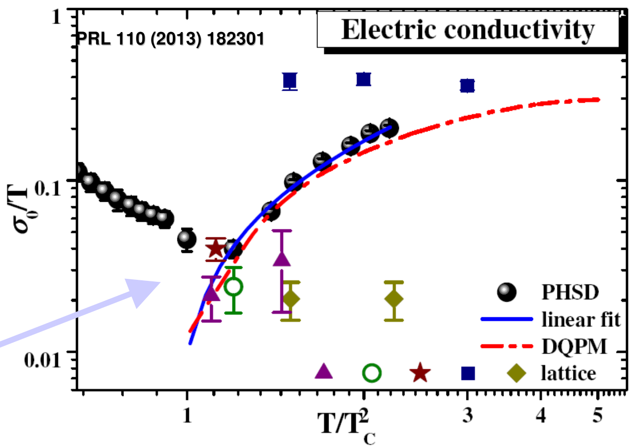
❑ **Hadron phase:** using **VDM**: $Im\Pi$ ~> ImD^ρ in-medium ρ-meson spectral function from many-body approach (cf. Rapp, Chanfrey, Wambach, NPA 617 (1997) 472)

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

➔ restoration of chiral symmetry (ρ-a_1):
ImD^ρ ~> chiral condensate (by Weinberg sum rules)
(cf. Hohler, Rapp, arXiv:1311.2921)

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

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



PHSD plot from Cassing et al., PRL 110 (2013) 182301;
cf. also NJL: Marty et al., PRC87 (2013) 3, 034912;
poster by R.Marty QM'14

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)

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

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

- *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:**

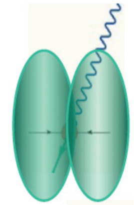
❑ very limited experimental information on mm, mB elementary reactions

❑ 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!

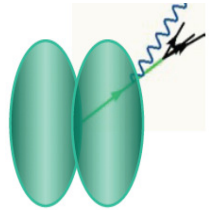
Production sources of photons in p+p and A+A

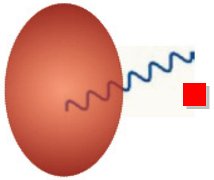
- **Decay photons** (in pp and AA):
  $m \rightarrow \gamma + X, \;\; m = \pi^0, \eta, \omega, \eta', a_1, \ldots$



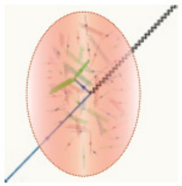
- **Direct photons:** (inclusive(=total) – decay) – measured experimentally

  - **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)

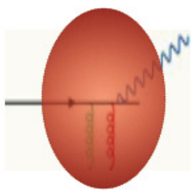




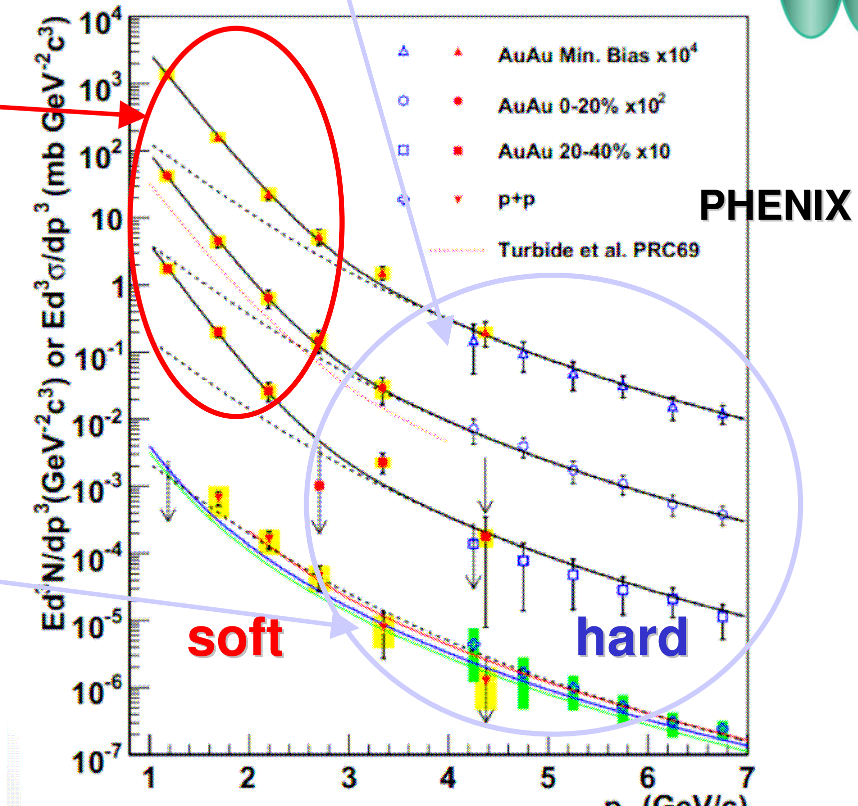
  - **thermal photons**:
    (low p_T, in AA)
    - QGP
    - Hadron gas



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



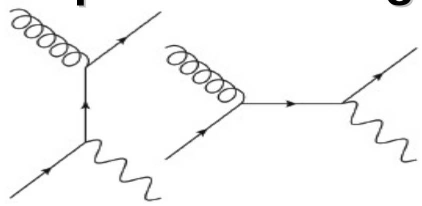
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

Thermal QGP:

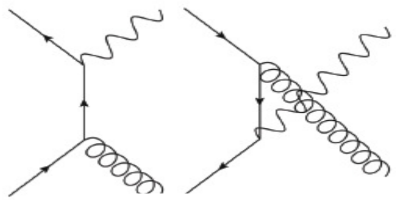
HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990), ...)

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:

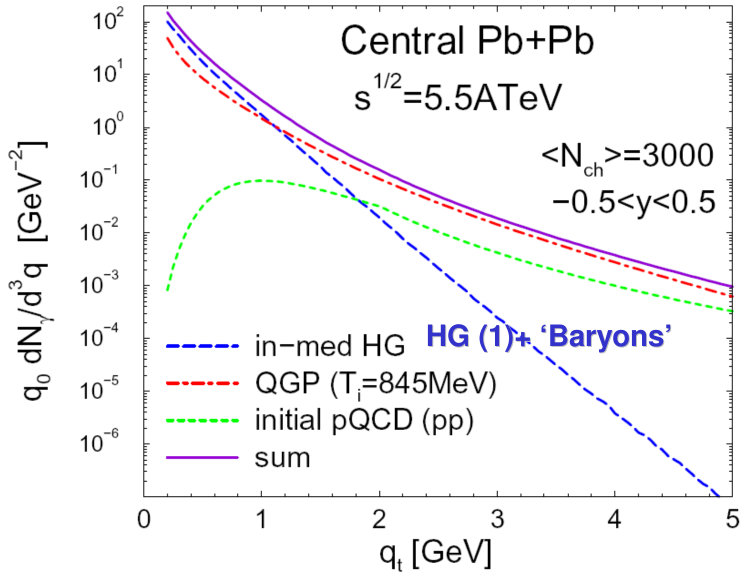
(1) secondary mesonic interactions:

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

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

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

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



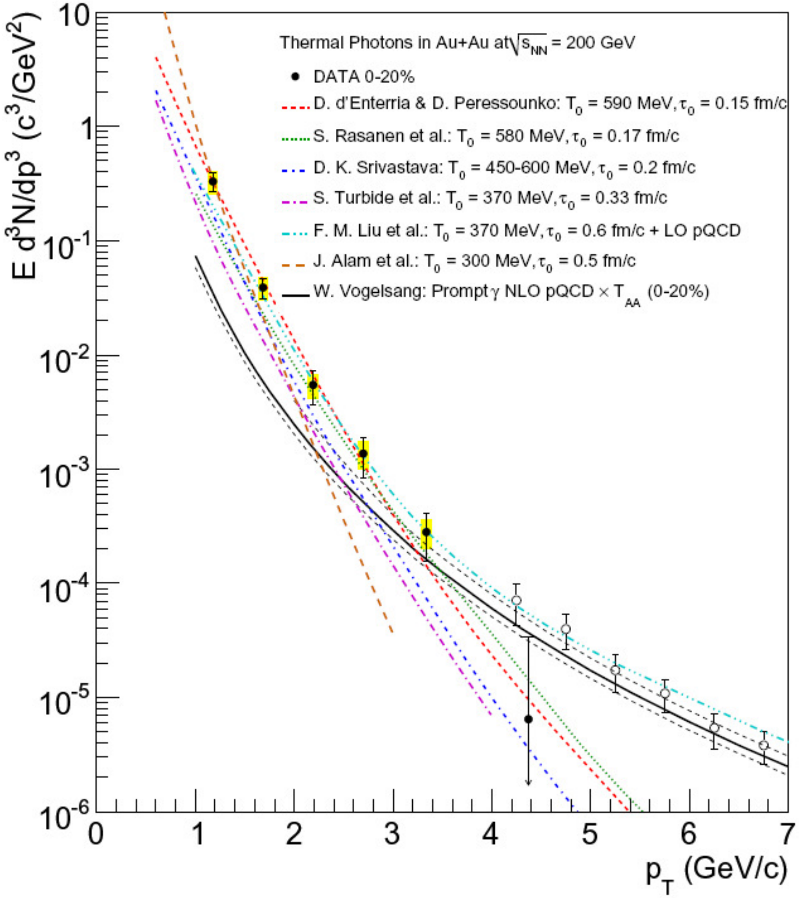
Models: chiral models, OBE, SPA ...
Kapusta, Gale, Haglin (91), Rapp (07), ...

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

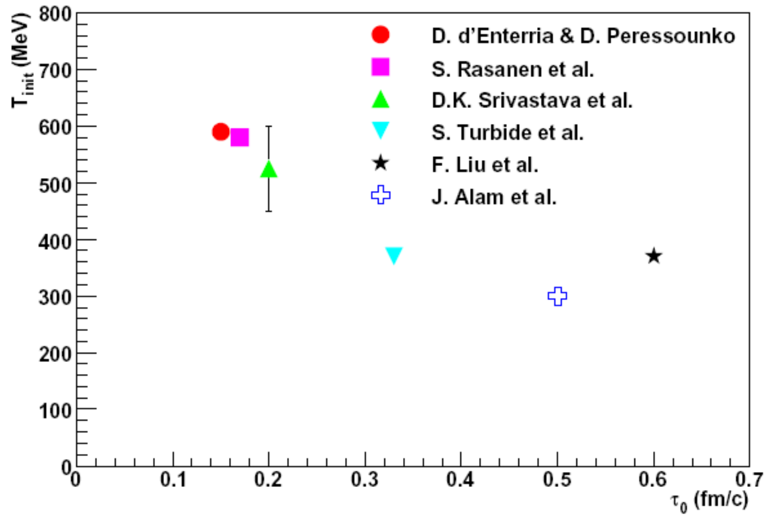
2010: Direct photon spectra for Au+Au at $s^{1/2}$=200 GeV

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

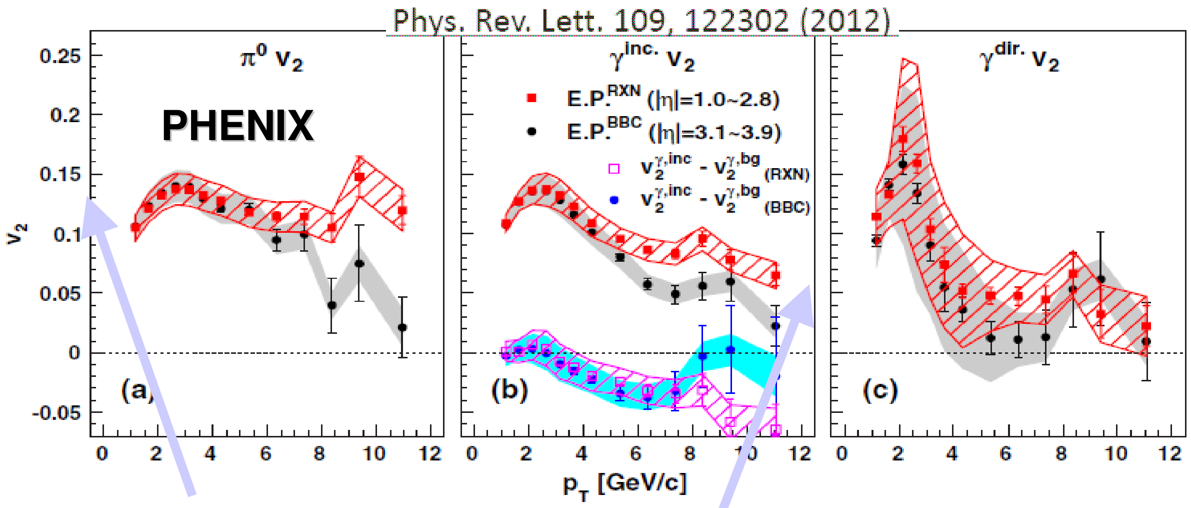


➔ Huge variations in T_{init} and τ_0!

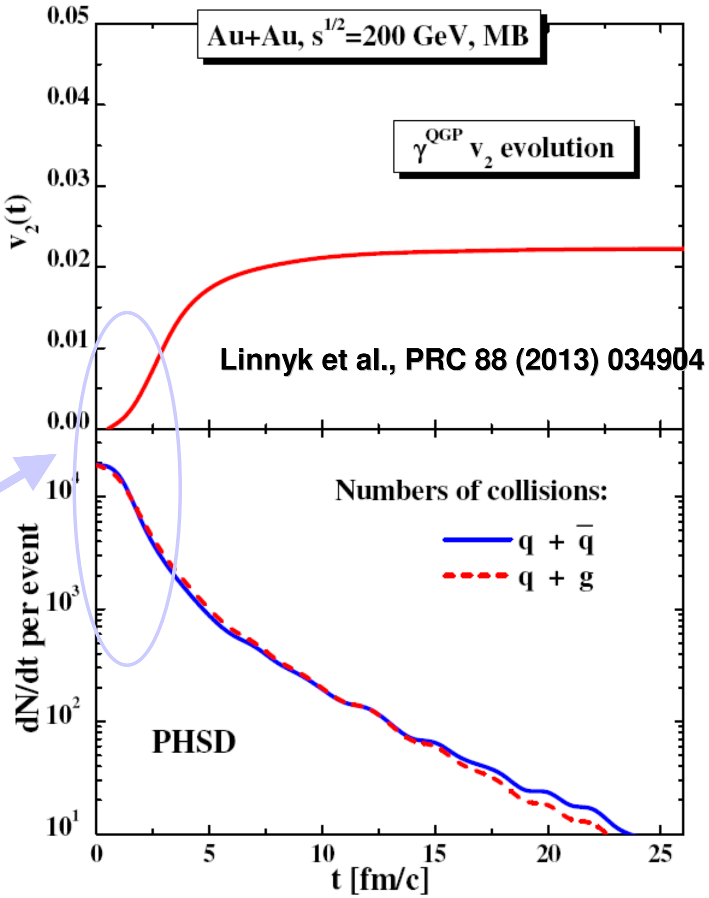
Warning: some model evolution was not fitted to the final hadron spectra!

❑ Photon spectra show sensitivity to the dynamical evolution!

PHENIX: Photon v_2 puzzle



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



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

v_2 = weighted average gives small $v_2(\gamma^{QGP})$ $\quad v_2 = \frac{\sum_i N^i \cdot v_2^i}{\sum_i N^i}$ → a large QGP contribution

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

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

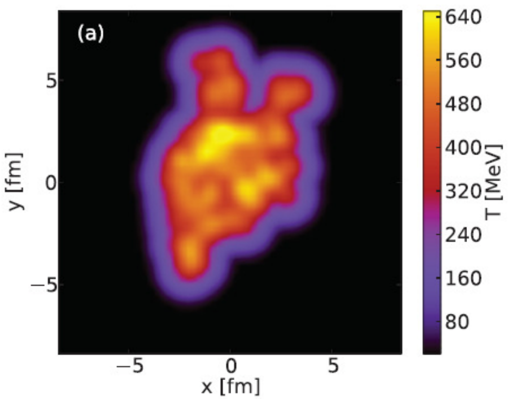
1. Hydro: Influence of e-b-e fluctuating initial conditions

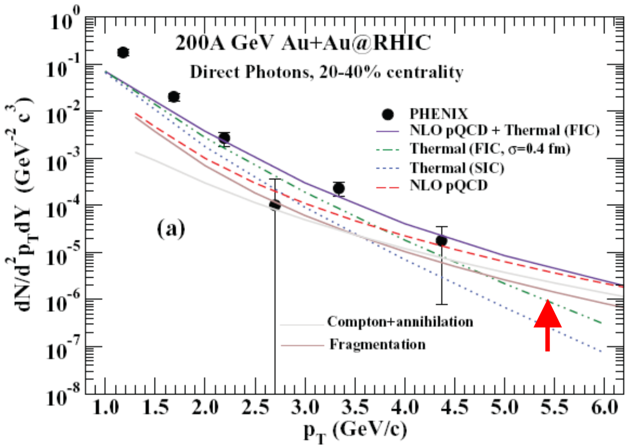
➔ **From smooth Glauber initial conditions**
to event-by-event hydro with fluctuating initial conditions

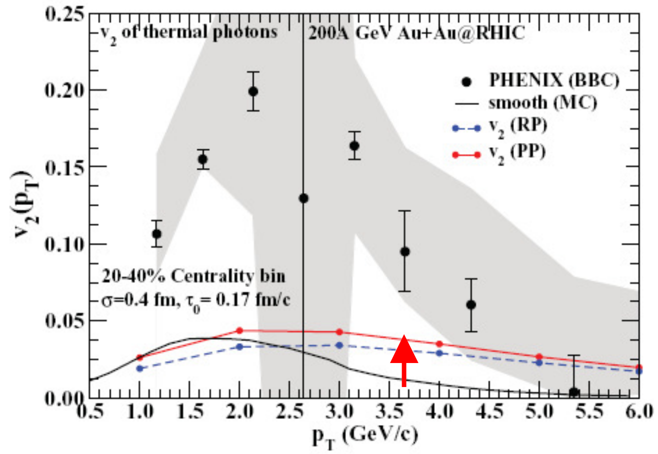
❑ **Jyväskylä ideal hydro**

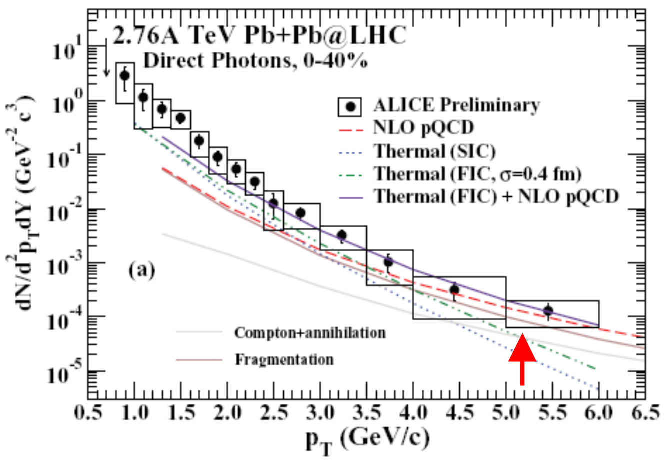
- Ideal QGP and HG fluid
- Initial: ‚bumpy' ebe MC Glauber
- EoS: lQCD

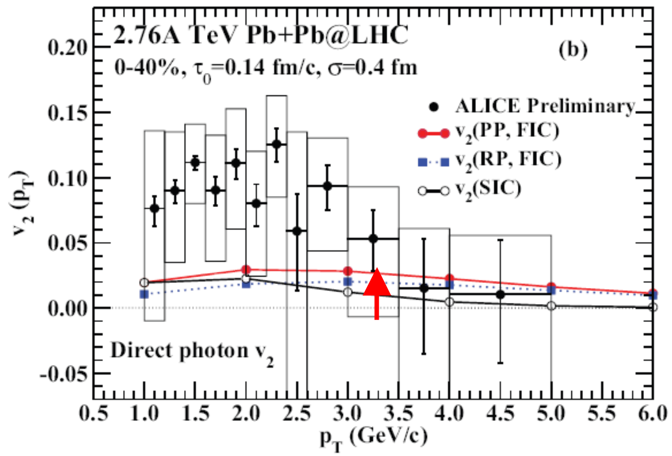
R. Chatterjee et al.,
PRC 88, 034901 (2013)











➔ **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?

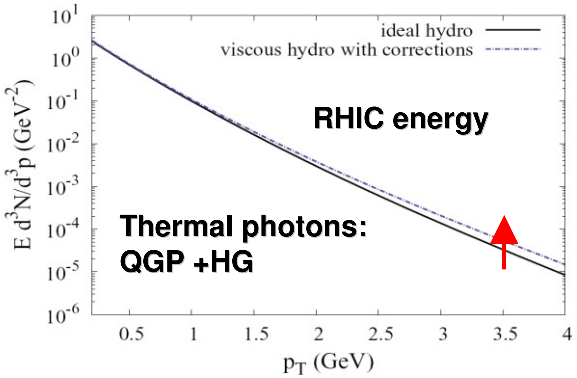
The thermal photon emission rates with viscous corrections:

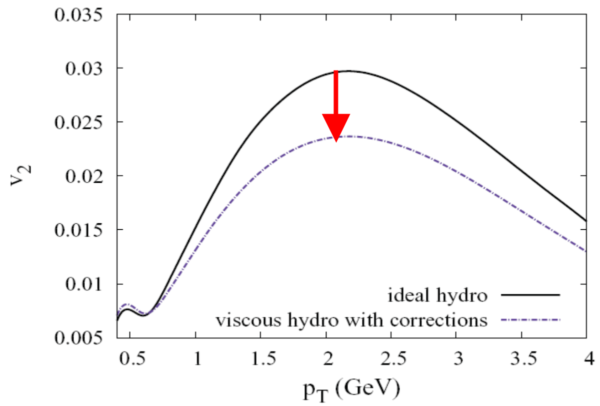
$$q\frac{dR}{d^3q}(q,T) = \Gamma_0(q,T) + \frac{\pi^{\mu\nu}}{2(e+P)}\Gamma_{\mu\nu}(q,T),$$

equilibrium contribution — **first order viscous correction**

❑ (3+1)D MUSIC (McGill):
M. Dion et al., PRC84 (2011) 064901

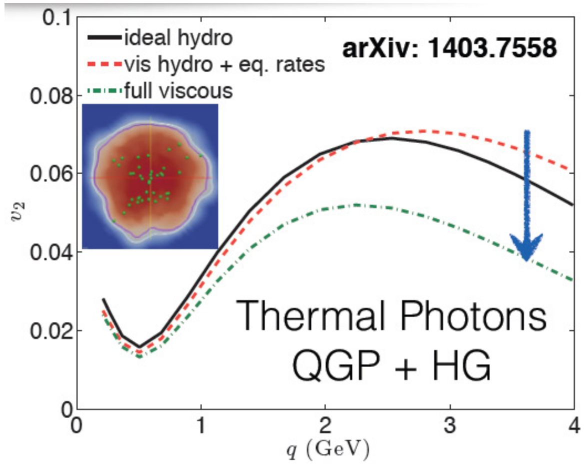
- **viscous QGP and HG fluid**
- **Initial: ‚bumpy' ebe from IP-Glasma**
- **EoS: lQCD**

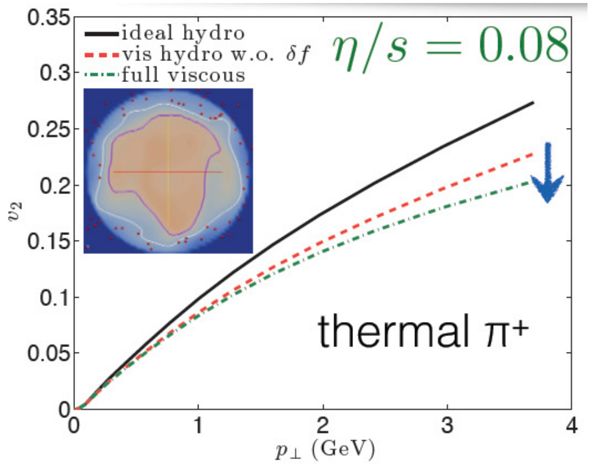




❑ (2+1)D VISH2+1 (Ohio State) :
C. Shen et al., arXiv:1308.2111, arXiv:1403.7558

- **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!

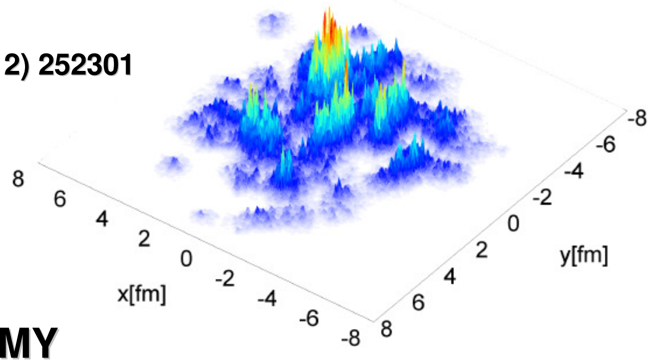
3. Influence of Glasma initial conditions with initial flow

❑ **(3+1)D MUSIC - 2014:**
J-F. Paquet et al. (2014)

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

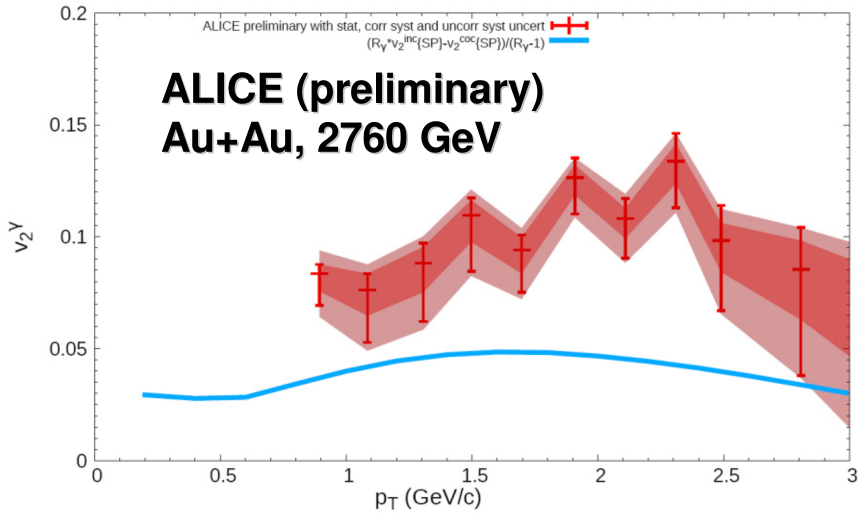
- **Initial: ‚bumpy' ebe from IP-Glasma ➔ generate initial flow due to fluctuations of IC**

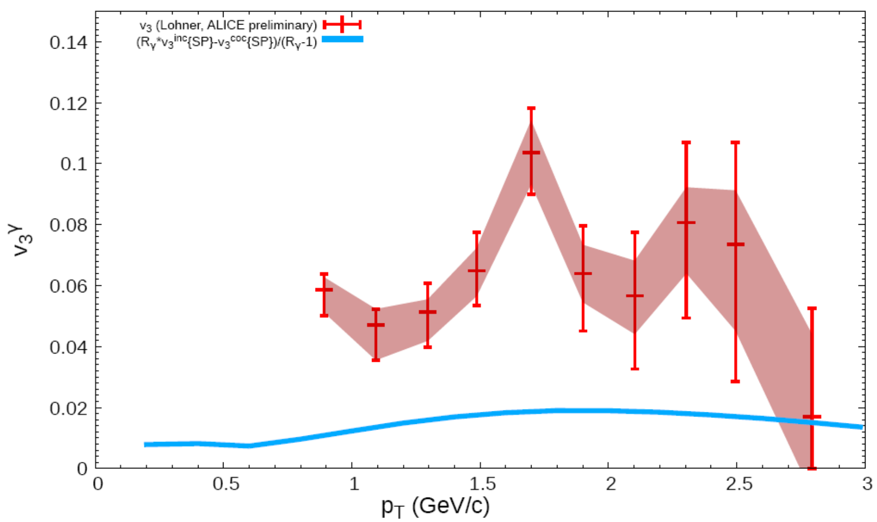
IP-Glasma:
Schenke et al., PRL108 (2012) 252301



- 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!**





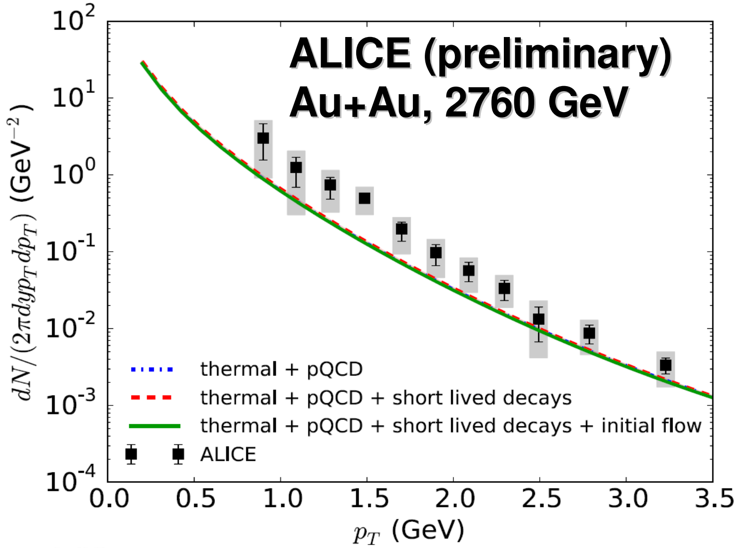
➔ ‚Bumpy' ebe from IP-Glasma - small effect

4. Hydro with pre-equilibrium flow

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

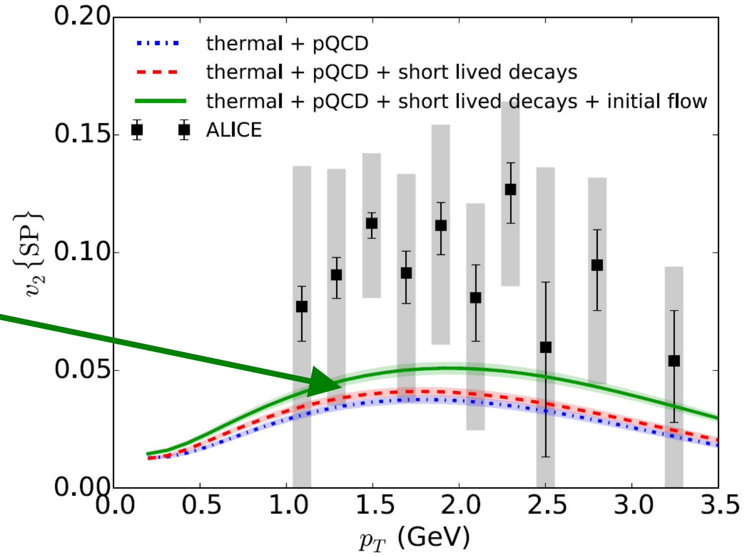
- **pre-equilibrium flow in (2+1)D VISH2+1 - 2014:**
  C. Shen et al., arXiv:1308.2111, arXiv:1403.7558; Talk by C. Shen @ QM'2014

  - 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!

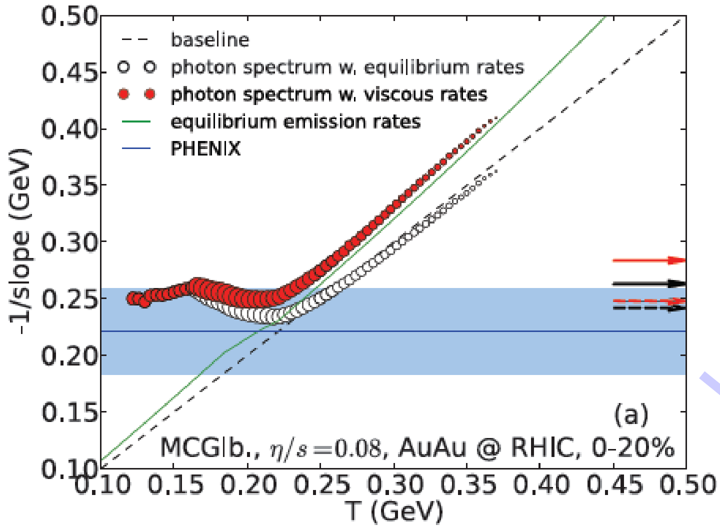
Are thermal photons a QGP thermometer?

❑ (2+1)d viscous hydro VISH2+1 (Ohio)

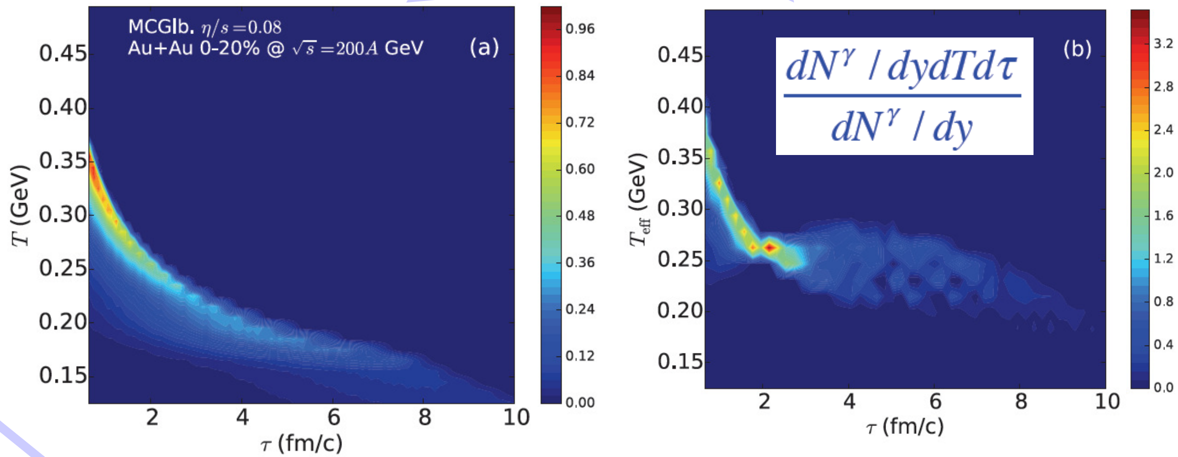
C. Shen et al., PRC89 (2014) 044910; arXiv:1308.2440

▪ 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

$$T_{eff} = \sqrt{\frac{1+v}{1-v}}T$$

❑ ‚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?!

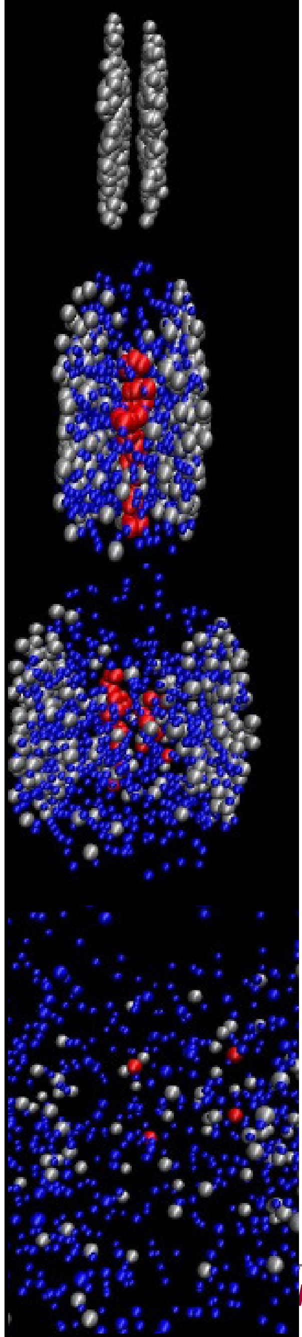
- Further **improvements of hydro models** ?
  - Bulk viscosity
  - Modeling of initial pre-equlibrium effects
  - …

- Non-equilibrium dynamics ?
- Missing strength related to hadronic stage?

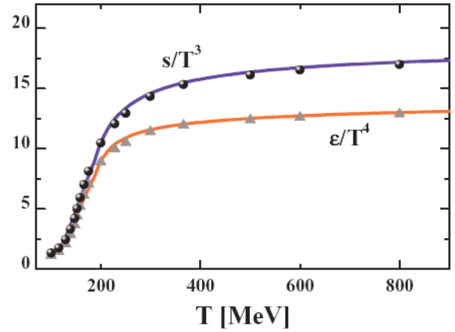
From hydro to non-equilibrium
microscopic transport models :

use PHSD as a ‚laboratory‘ for that

Parton-Hadron-String-Dynamics (PHSD)



PHSD is a non-equilibrium transport model which provides the microscopic description of the full collision evolution



Basic ideas:

- explicit phase transition from hadrons to partons
- lQCD EoS (cross over) for the partonic phase
- explicit parton-parton interactions - between quarks and gluons
- dynamical hadronization
- off-shell hadronic collision dynamics in the final reaction phase

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

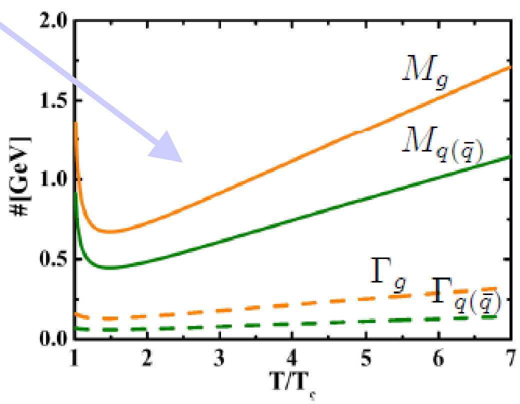
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

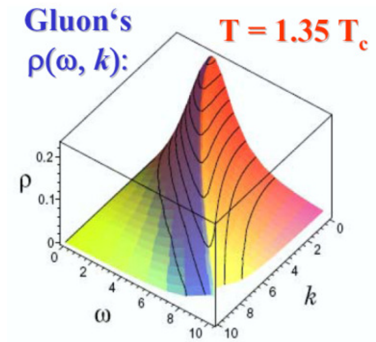
- strongly interacting quasi-particles

- massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in self-generated mean-field potential

- Spectral functions:

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



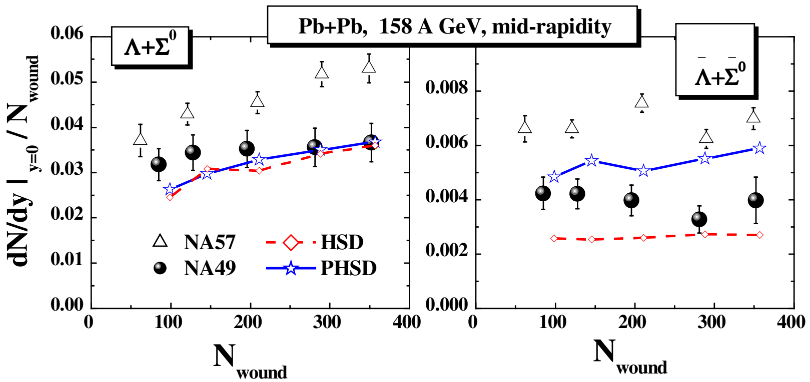


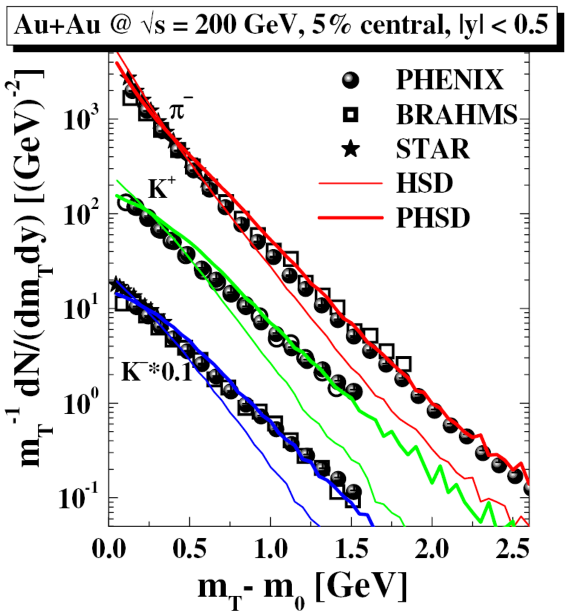
❑ DQPM matches well lattice QCD

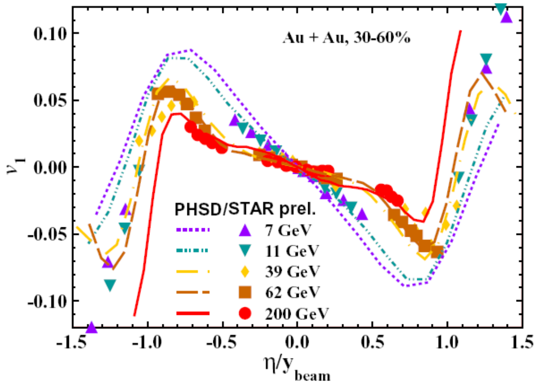
❑ Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting system!)

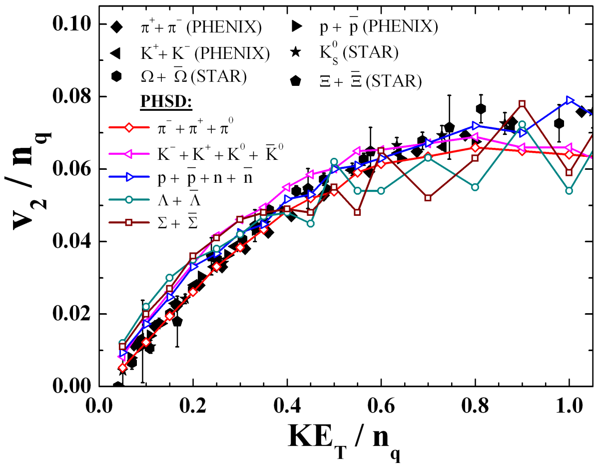
W. Cassing, E. B., PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

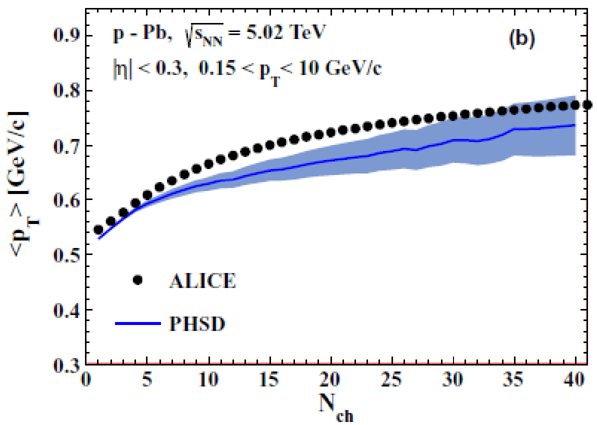
PHSD for HIC (highlights)

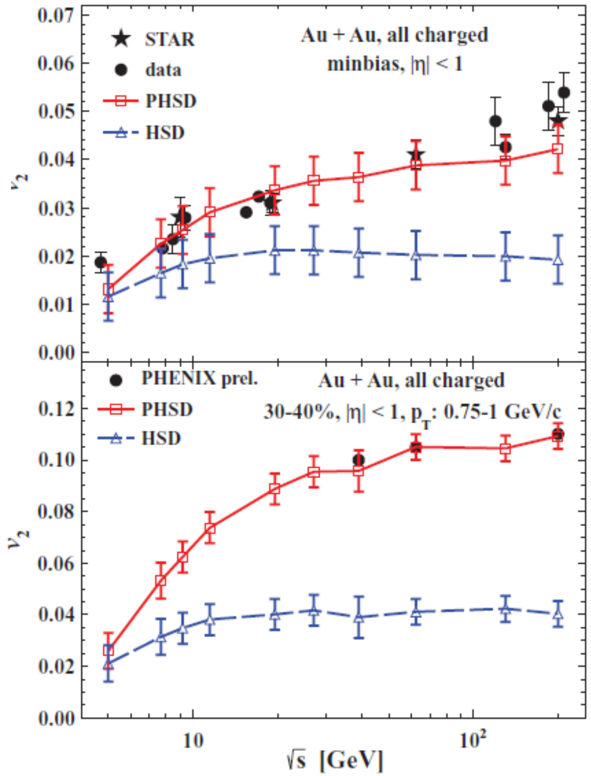


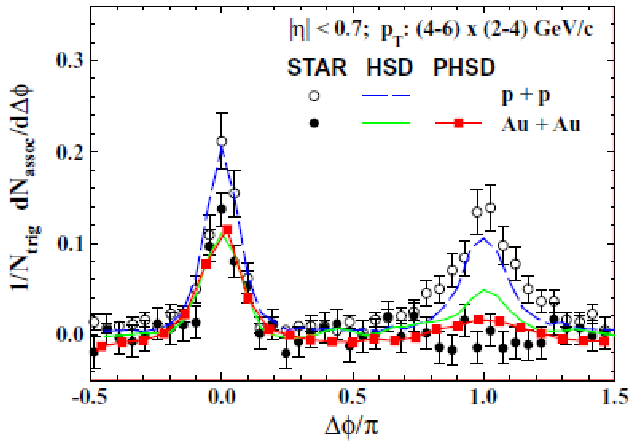










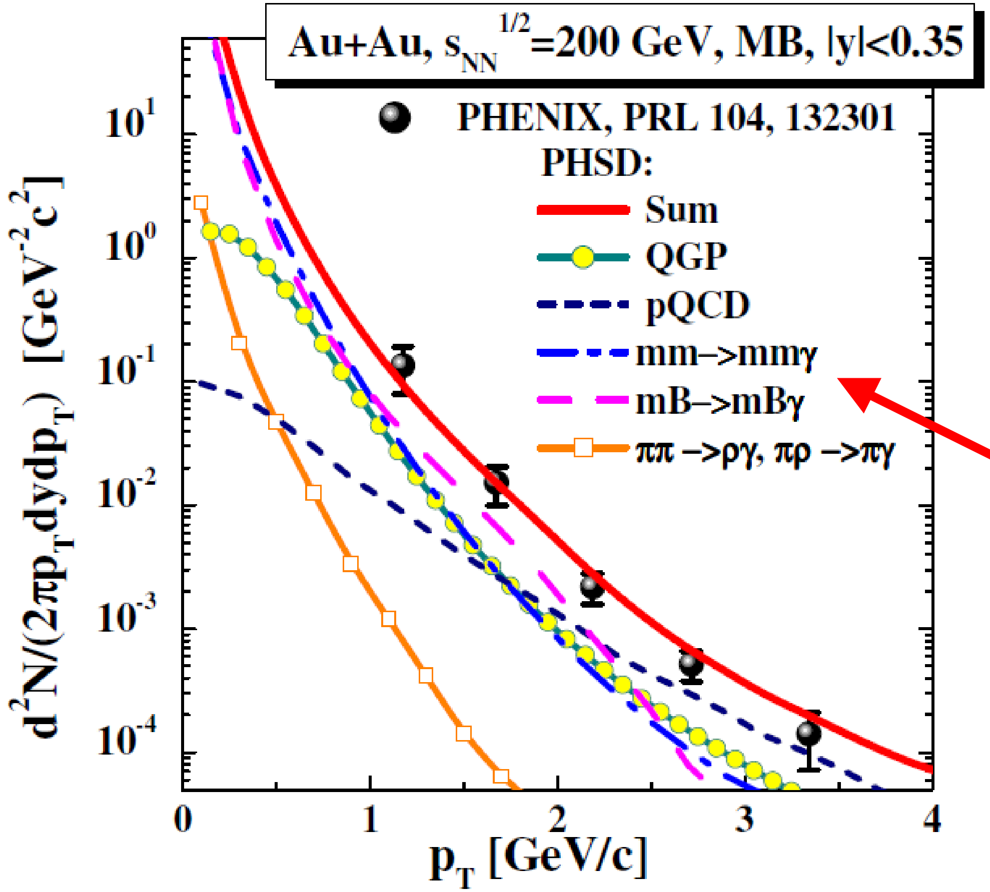


- **PHSD provides a consistent description of HIC**

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	$233 \pm 14 \pm 19$

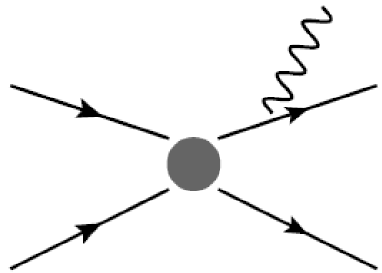
PHSD:

- **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**

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

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



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

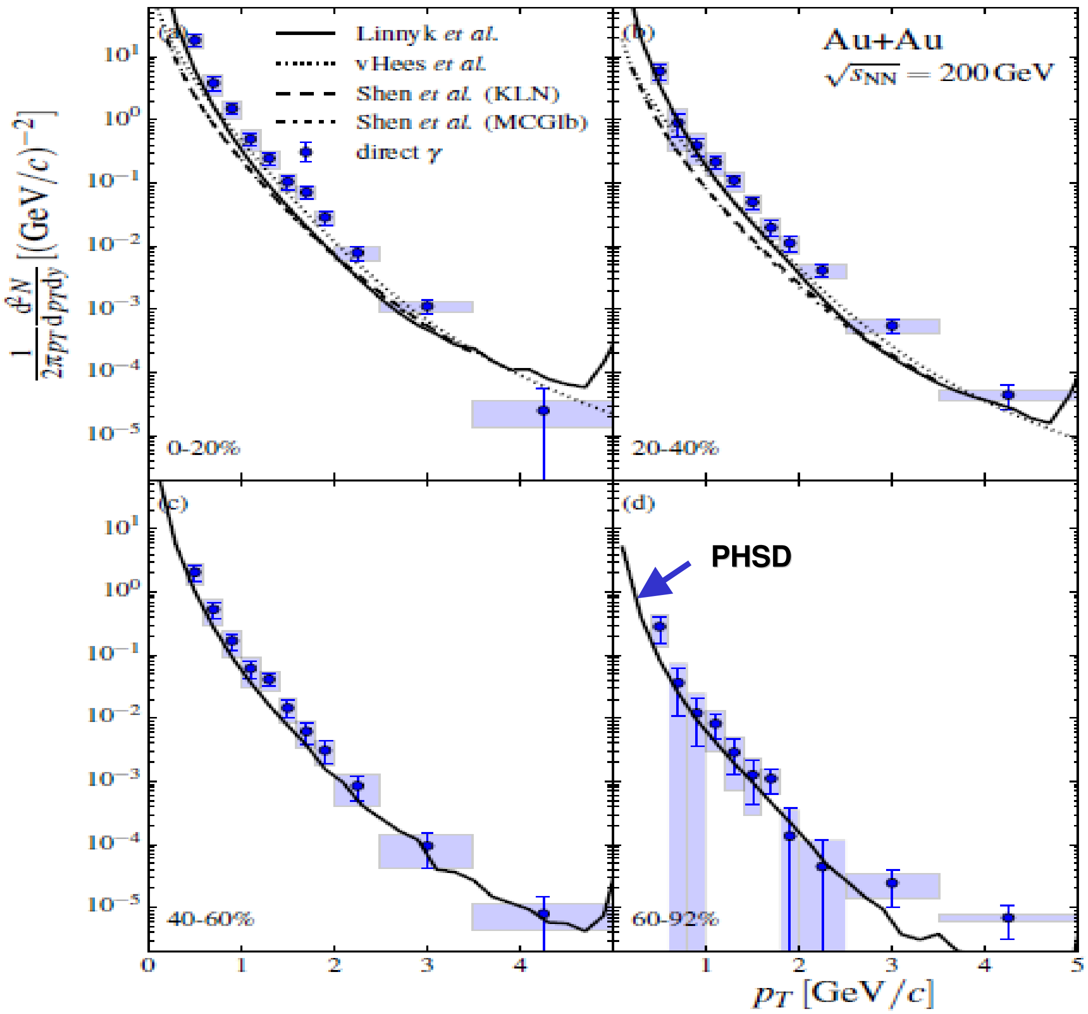
!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

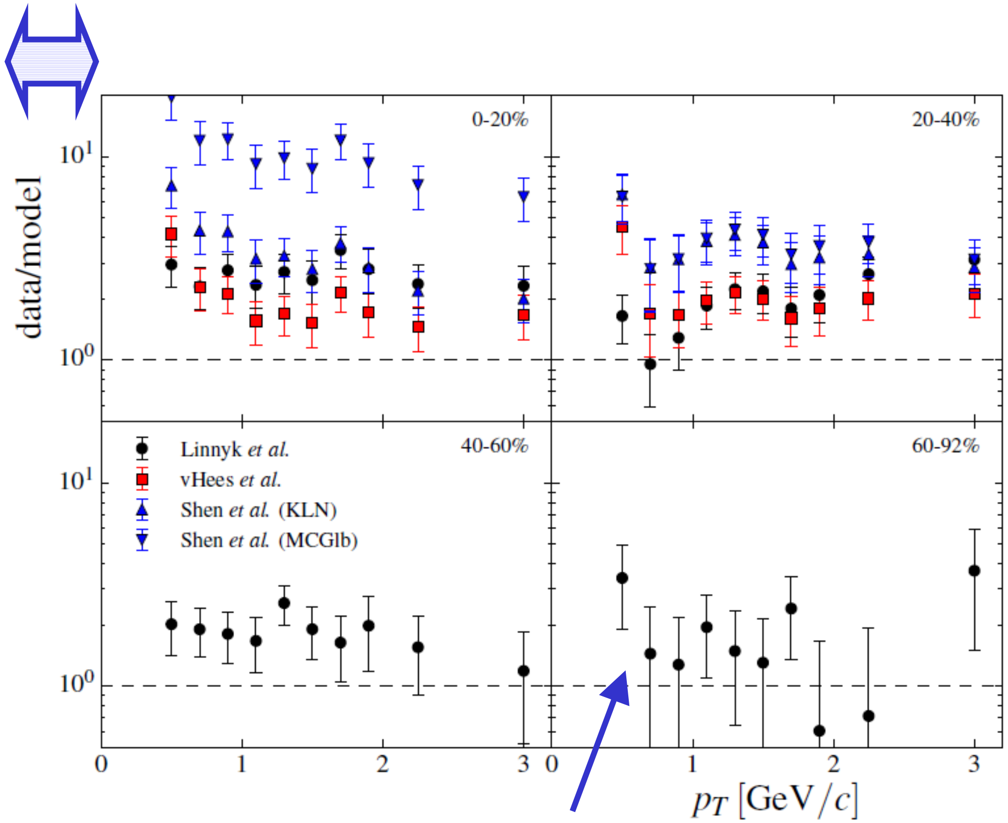
Photon p_T spectra at RHIC for different centralities

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)

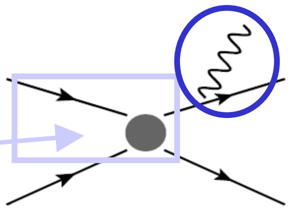
- **Soft Photon Approximation (SPA):**

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

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

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

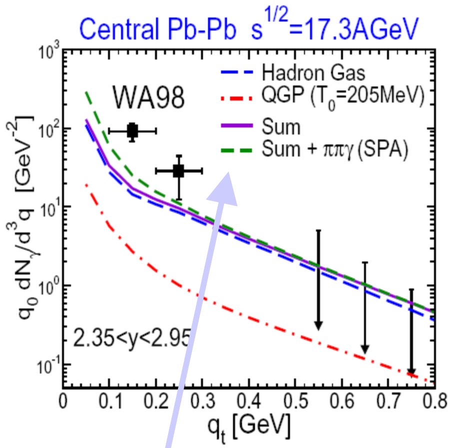
$$\bar{\sigma}(s) = \frac{s-(M_1+M_2)^2}{2M_1^2}\sigma(s),$$

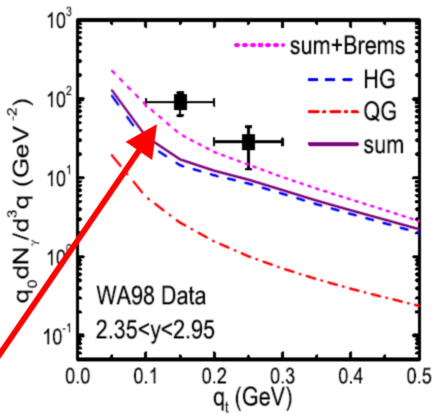


2) no experimental constraint on m+m and m+B differential elastic cross sections

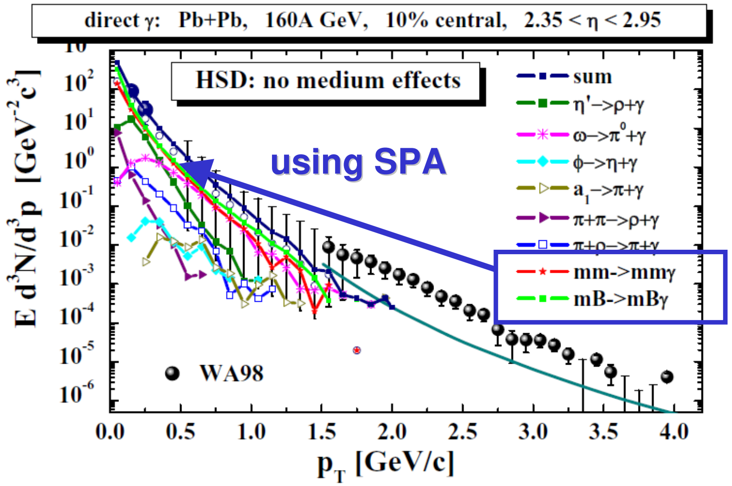
- **Bremsstrahlung: seen at SPS - WA98**

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





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



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

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

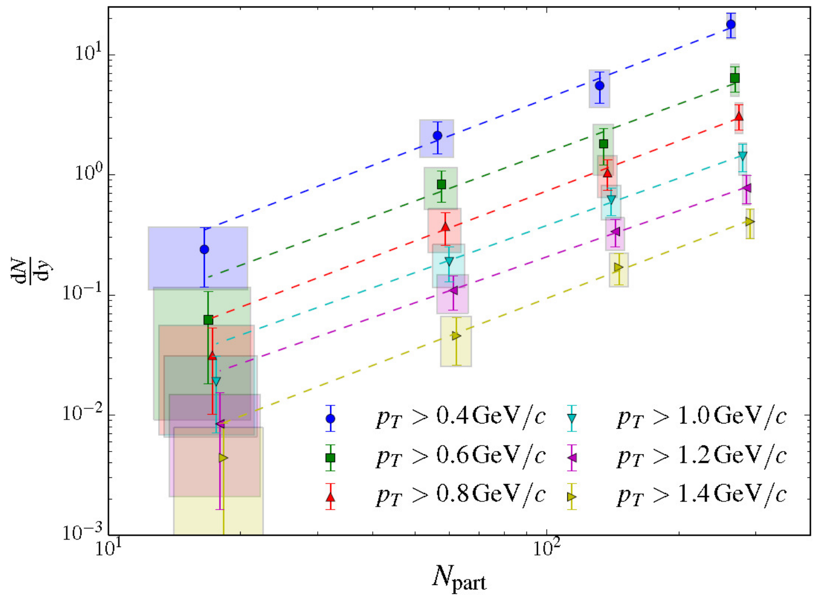
Centrality dependence of the ‚thermal' photon yield

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

PHENIX (arXiv:1405.3940):

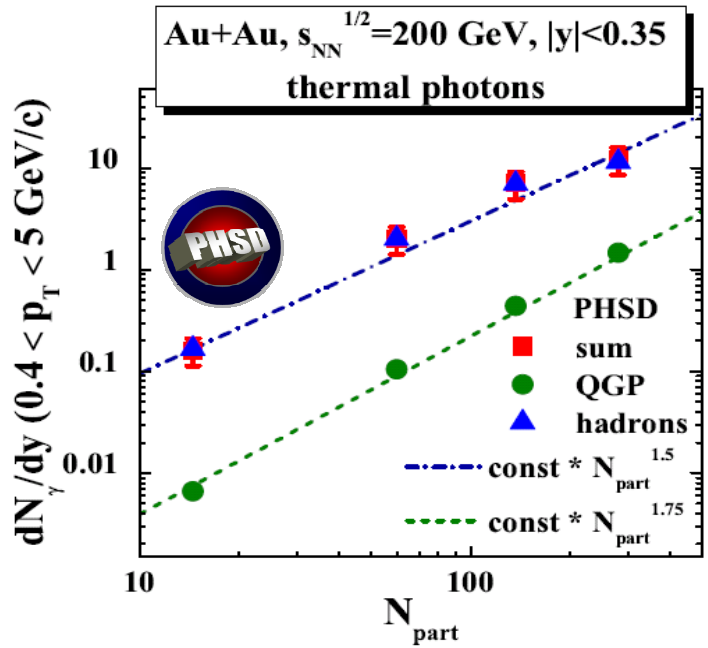
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

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



PHSD predictions:

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



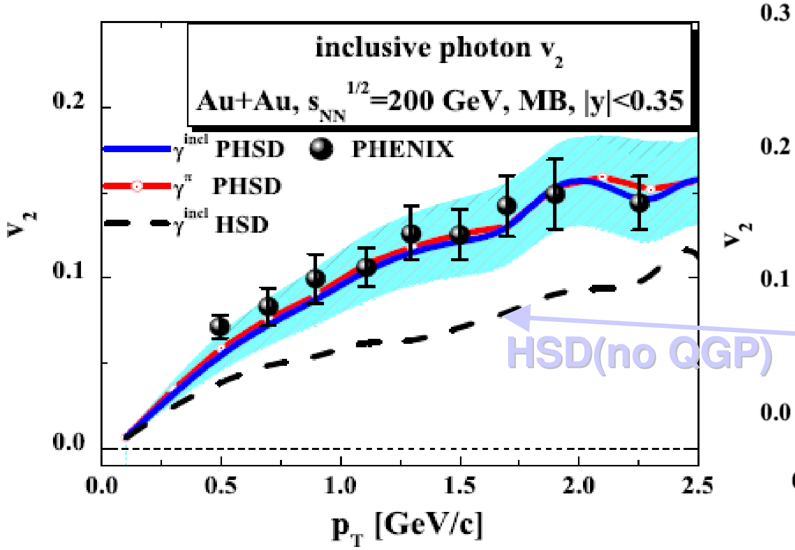
- ❑ PHSD: scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$
- ❑ similar results from viscous hydro:
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

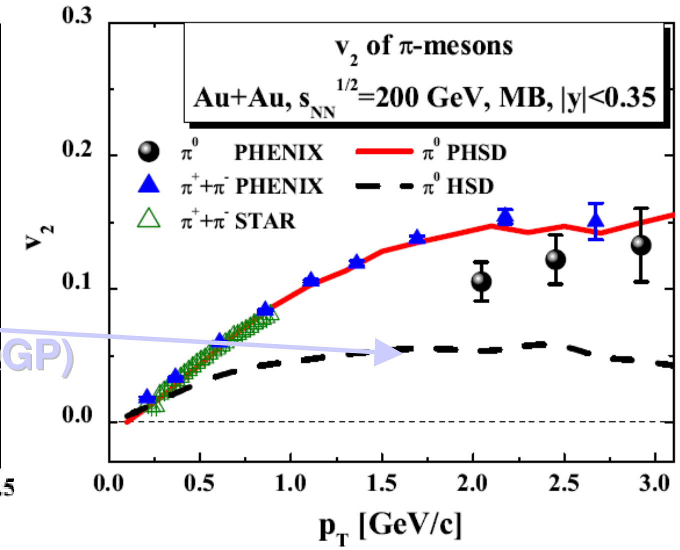
➔ **What do we learn?**
Indications for a dominant hadronic origin of thermal photon production?!

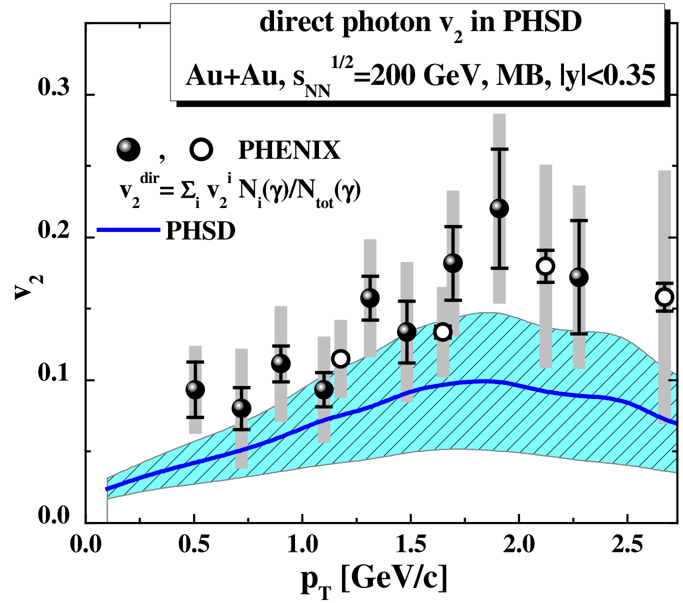
Are the direct photons a barometer of the QGP?

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

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

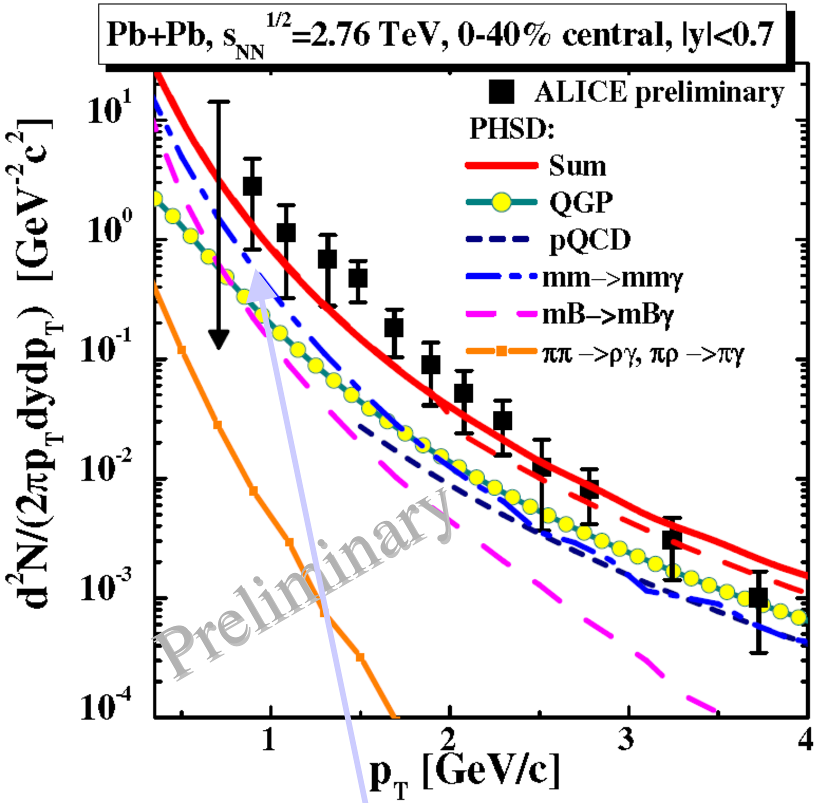
- model without QGP (HSD) underestimates **v_2 of hadrons** and inclusive photons by a factor of 2 wheras the model with QGP (PHSD) is consistent with exp. data

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

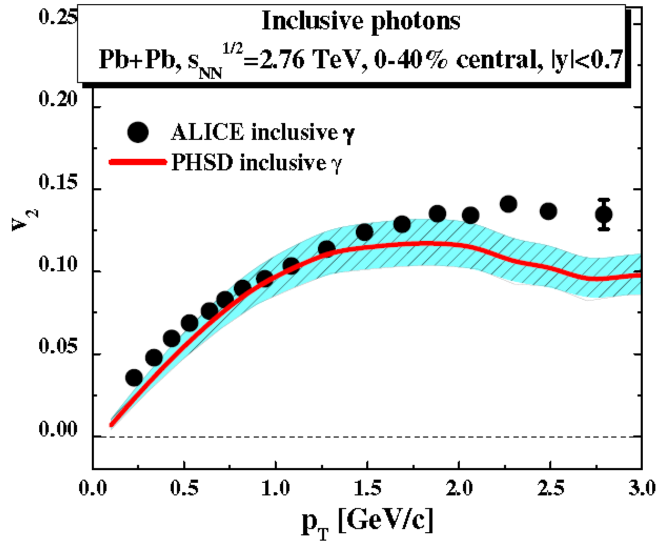
> ➔ The **QGP causes the strong elliptic flow of photons indirectly,** by enhancing the v_2 of final hadrons due to the partonic interactions
>
> ➔ **PHSD:** $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung ?!**

Photons from PHSD at LHC

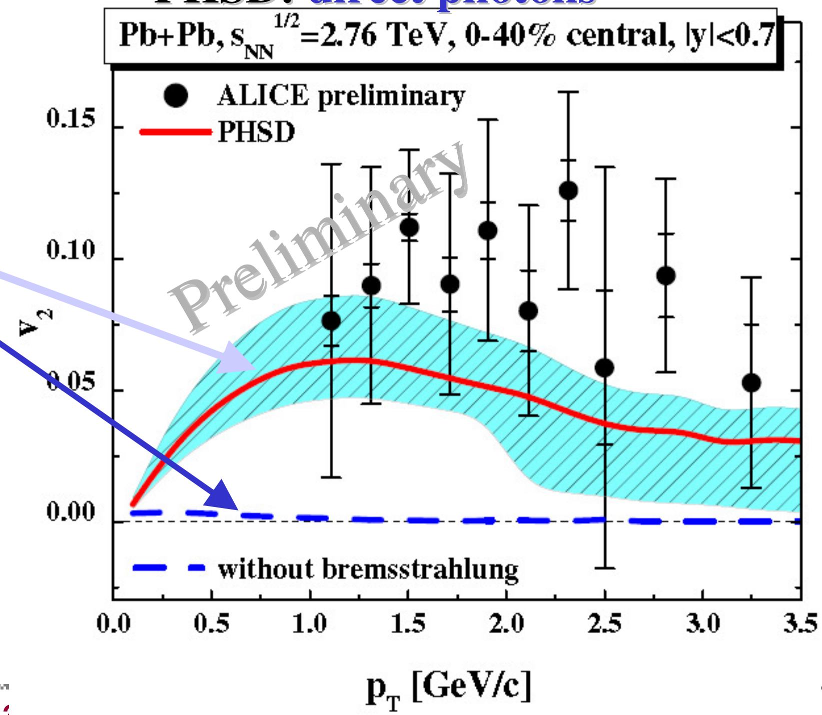
PHSD- preliminary: Olena Linnyk



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 - „Electromagnetic probes: 2-2" (Monday)

- non-perturbative effects?

semi-QGP - cf. talk by S. Lin - „Electromagnetic probes: 2-2" (Monday)

- ???

… shining in the darkness

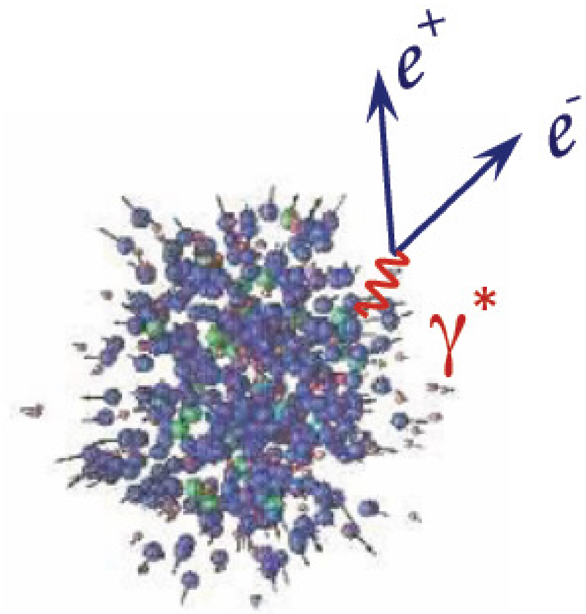
Some messages from the ‘photon adventure’:

- **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!

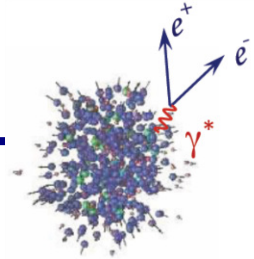
➔ **Additional impuls for the development of dynamical models:**
e.g. from ideal to ebe viscous hydro, EoS, realistic non-equilibrium dynamics …

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

Dileptons: from SPS to LHC



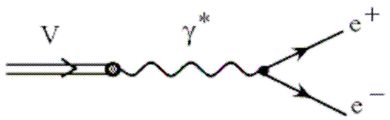
Dilepton sources



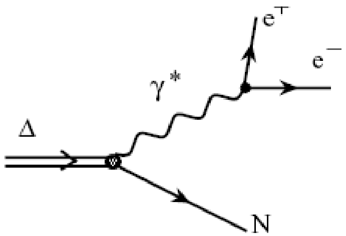
from the QGP via partonic (q,qbar, g) interactions:

from hadronic sources:

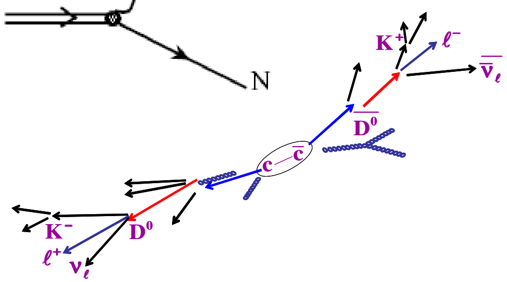
- **direct decay** of vector mesons (ρ,ω,φ,J/Ψ,Ψ')



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

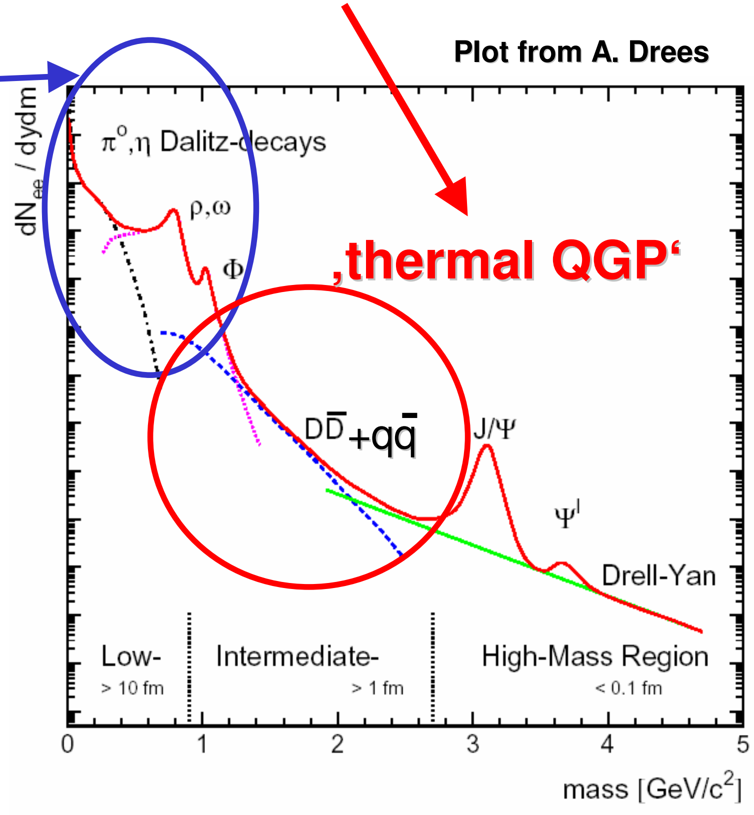


- **correlated D+Dbar pairs**

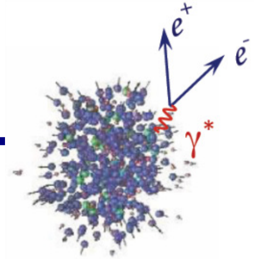


- radiation from **multi-meson reactions** (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - '4π'

Plot from A. Drees

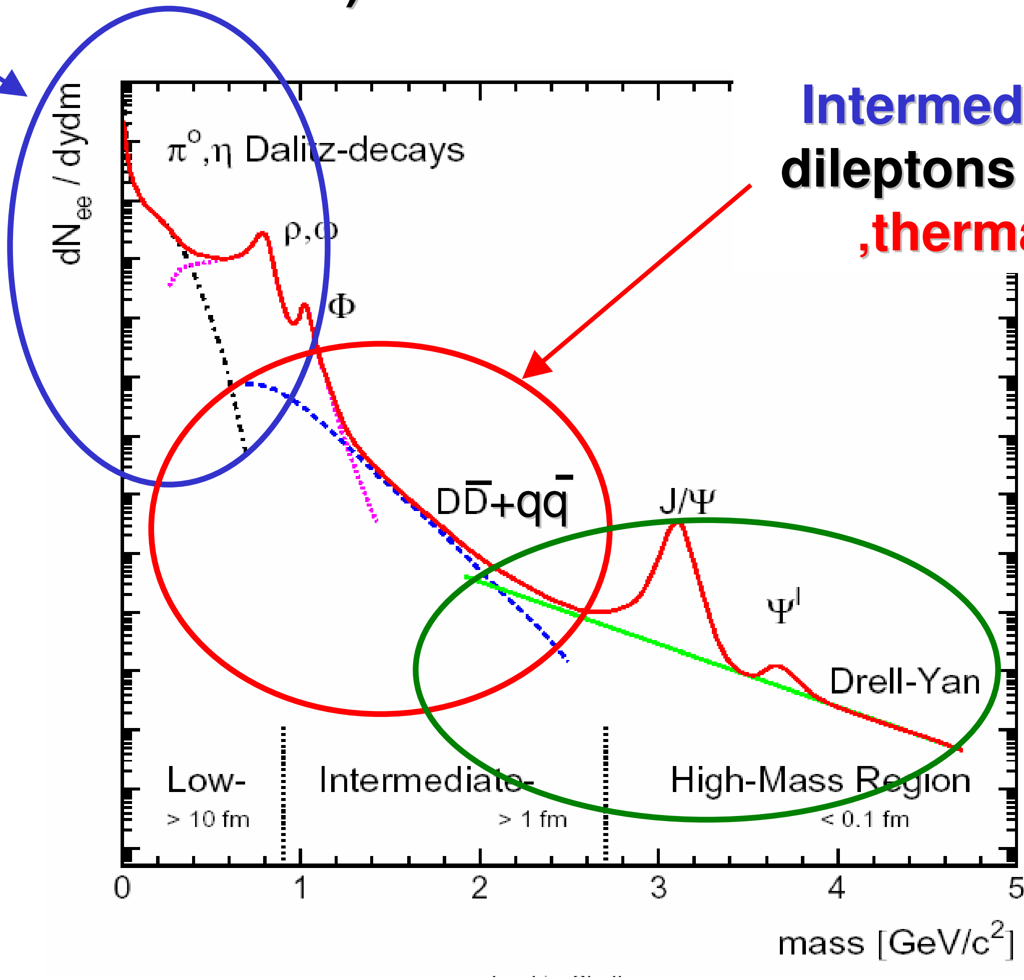


Physics with dilepton



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



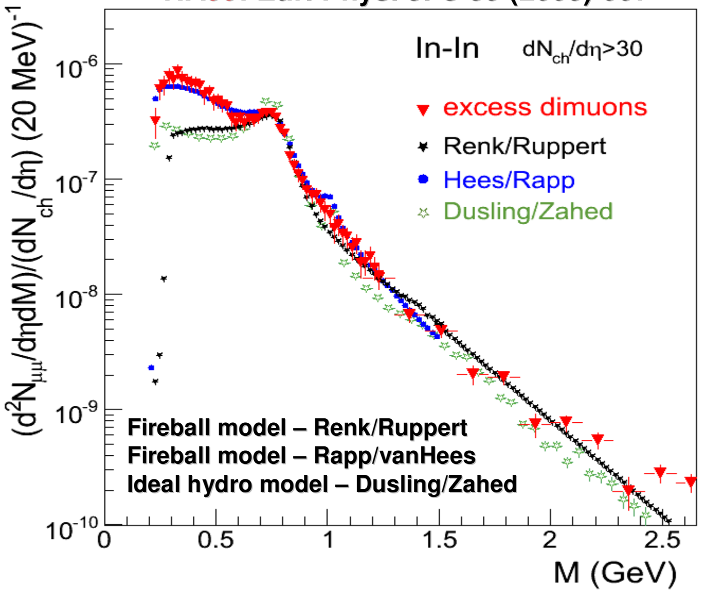
Intermediate mass dileptons – probe of ‚thermal QGP‘

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

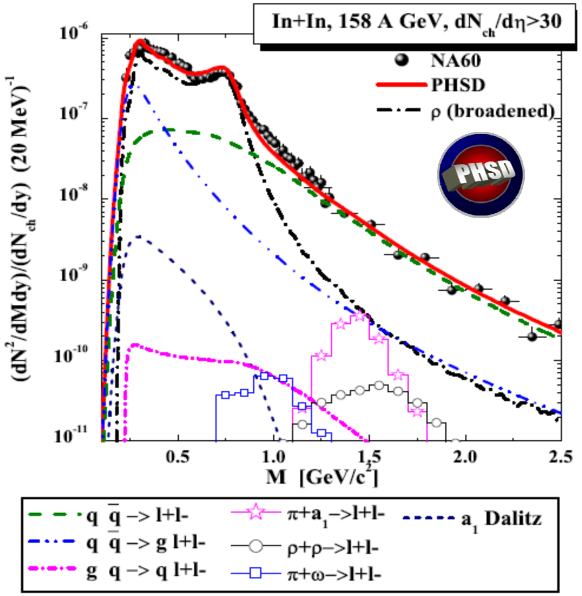
Lessons from SPS: NA60

❑ Dilepton invariant mass spectra:

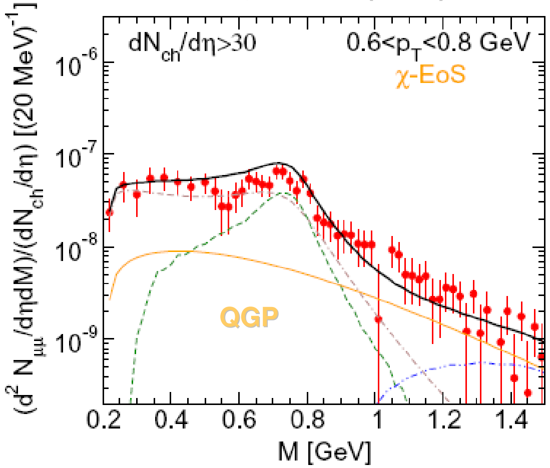
NA60: Eur. Phys. J. C 59 (2009) 607

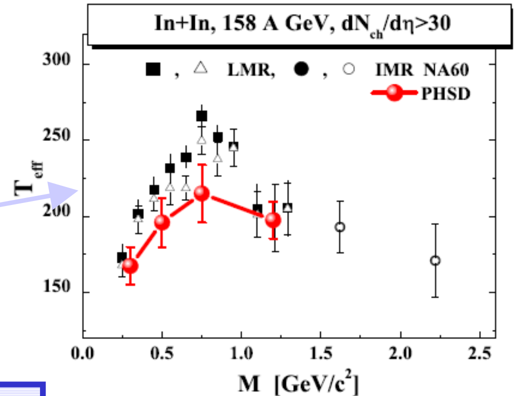


PHSD:
Linnyk et al, PRC 84 (2011) 054917



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



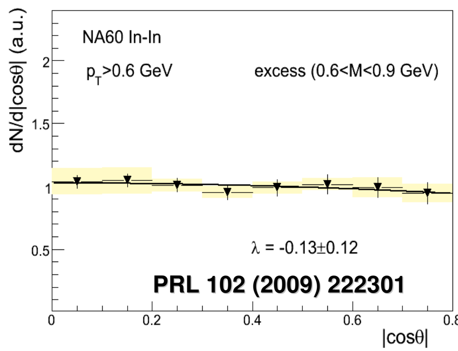


❑ Inverse slope parameter T_{eff}:

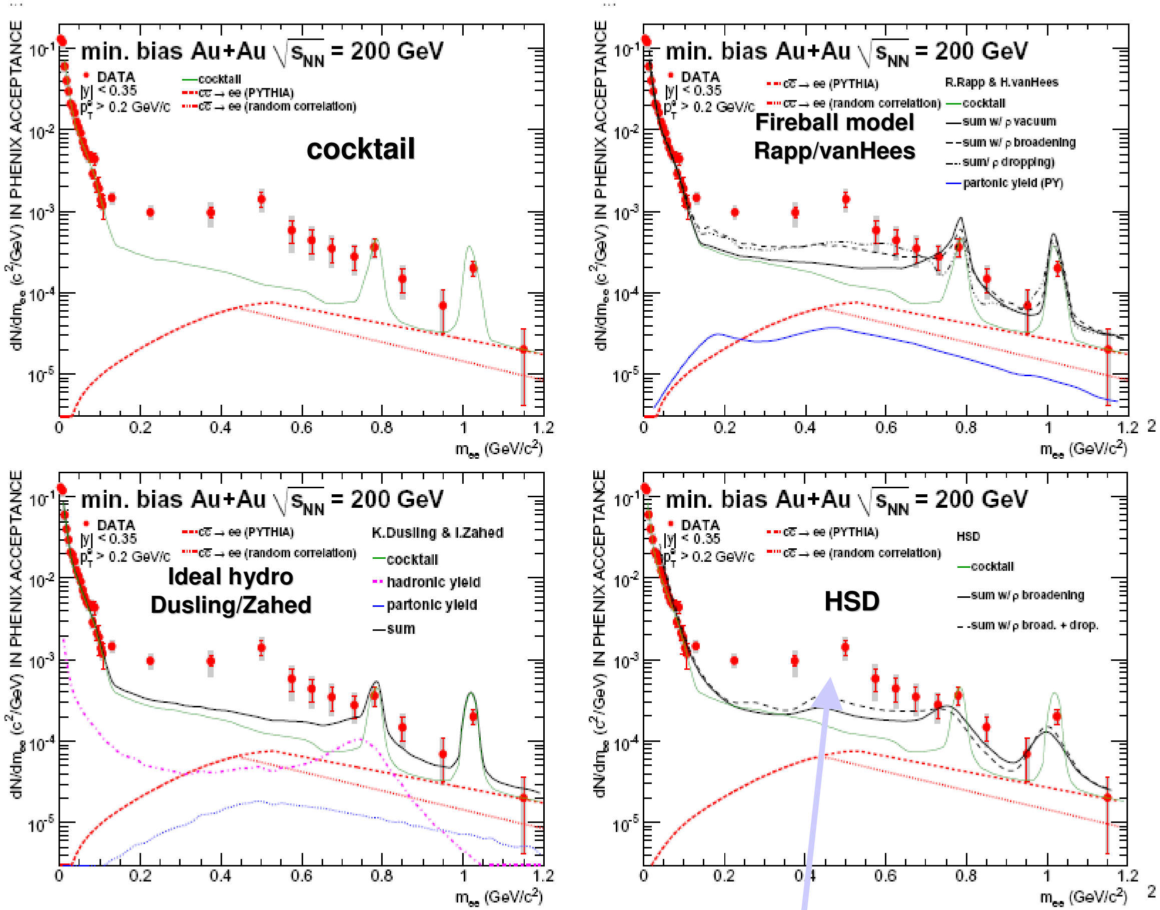
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed

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

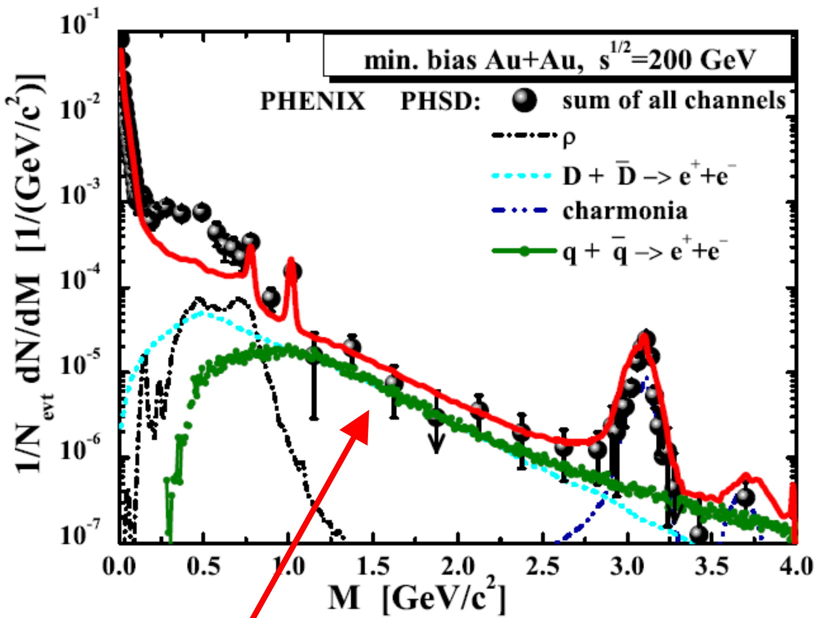
1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons



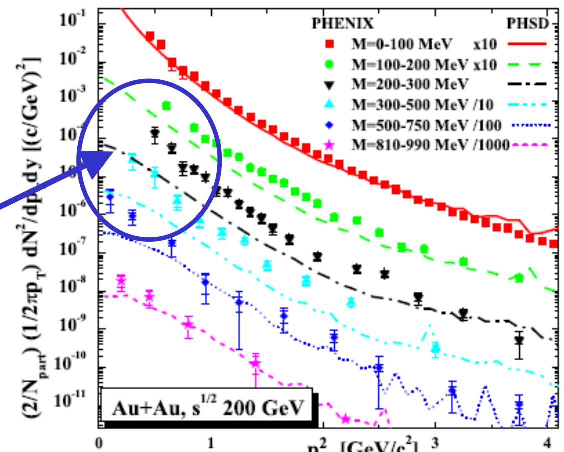
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



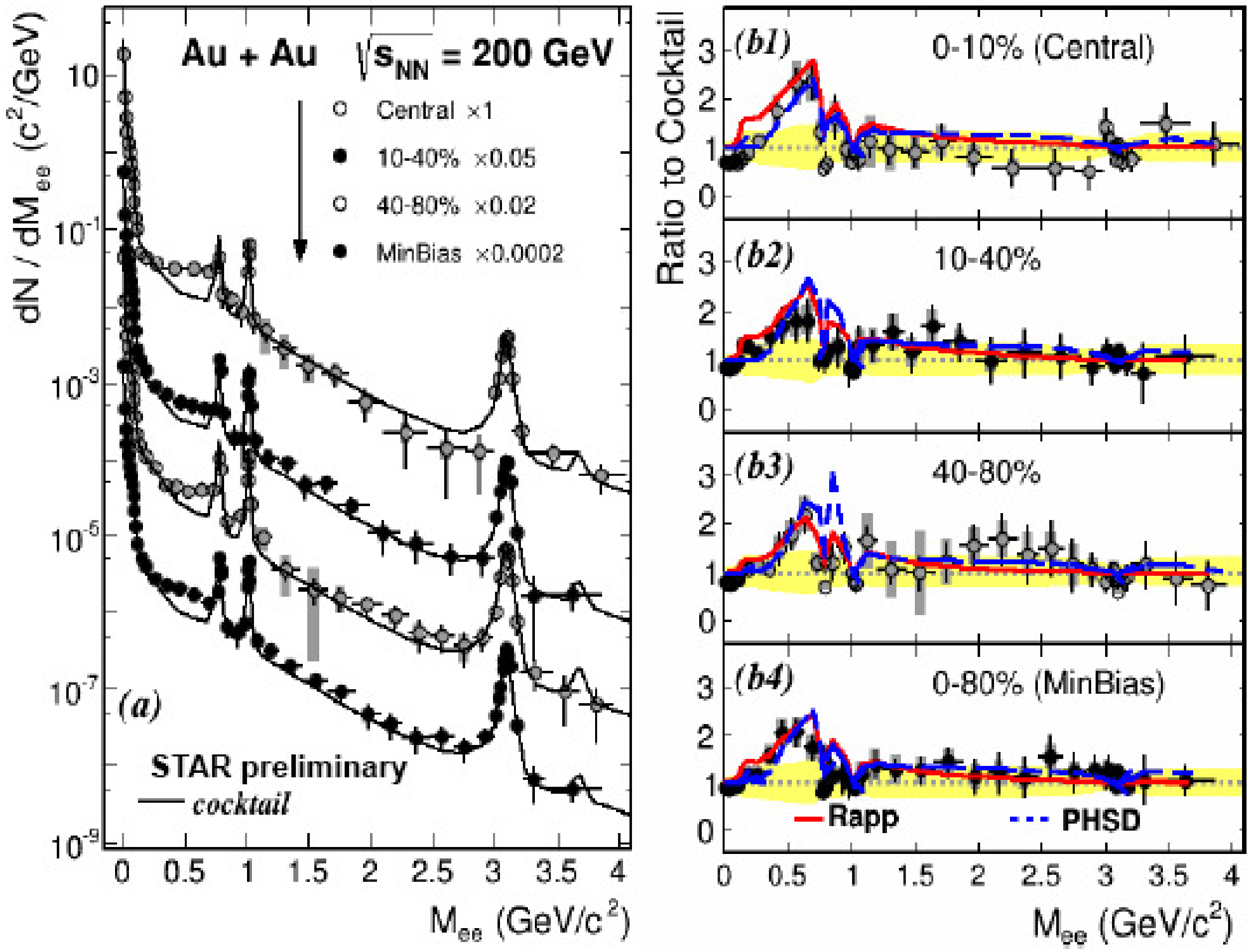
Message:

- **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**

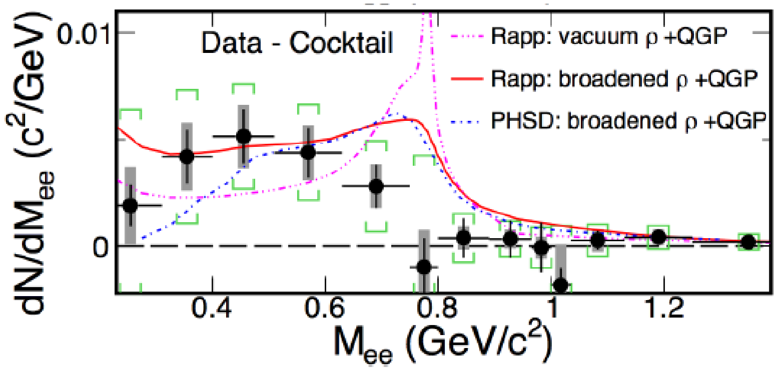
Dileptons at RHIC: STAR data vs model predictions

(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

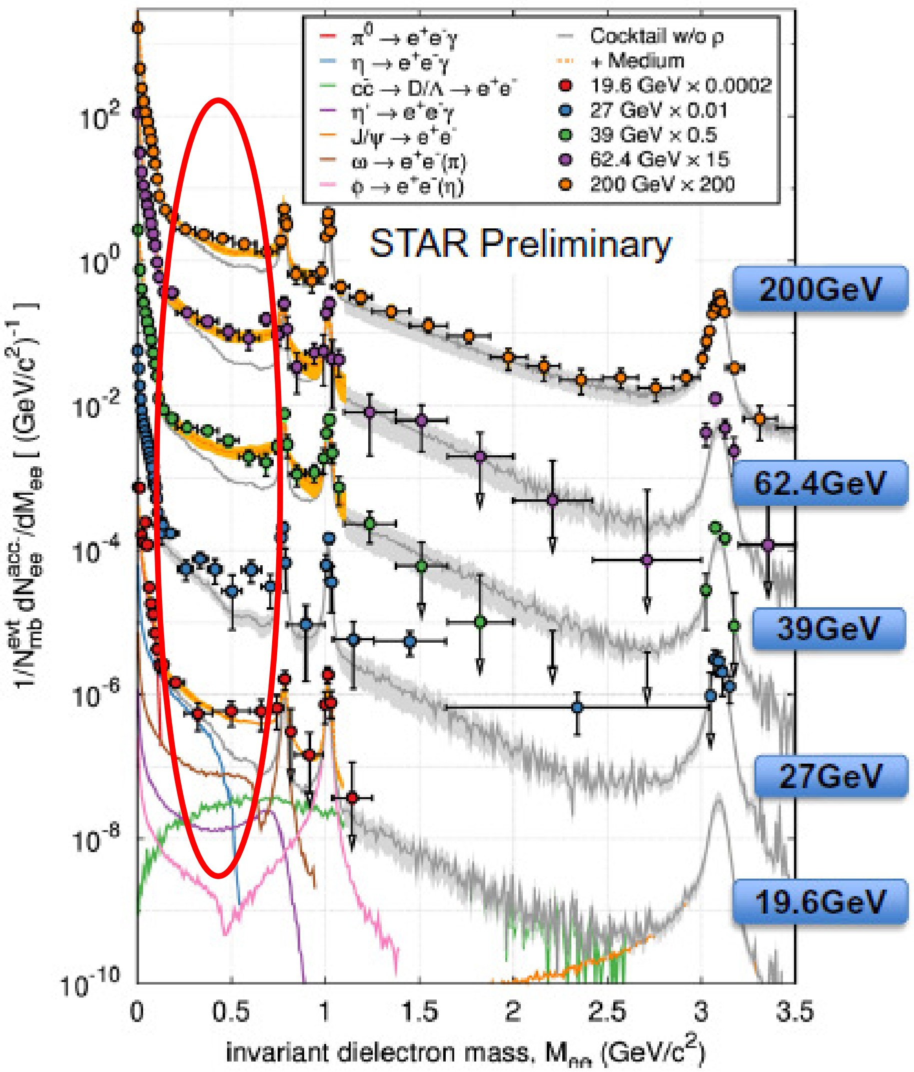
Intermediate masses:

QGP dominant

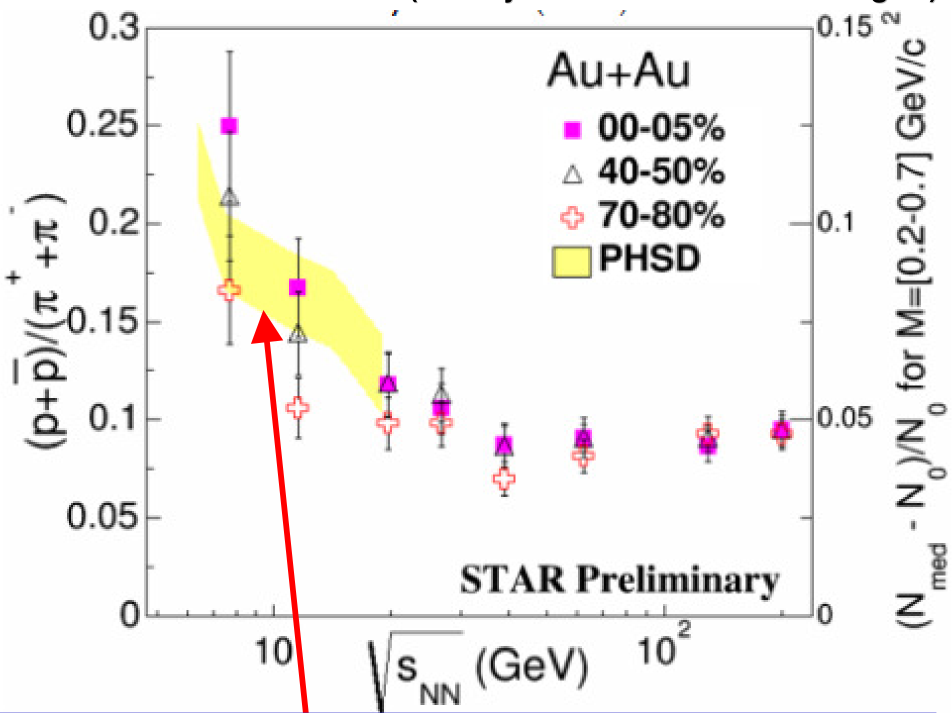
Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

Dileptons from RHIC BES: STAR

(Talk by Nu Xu at QM'2014)



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

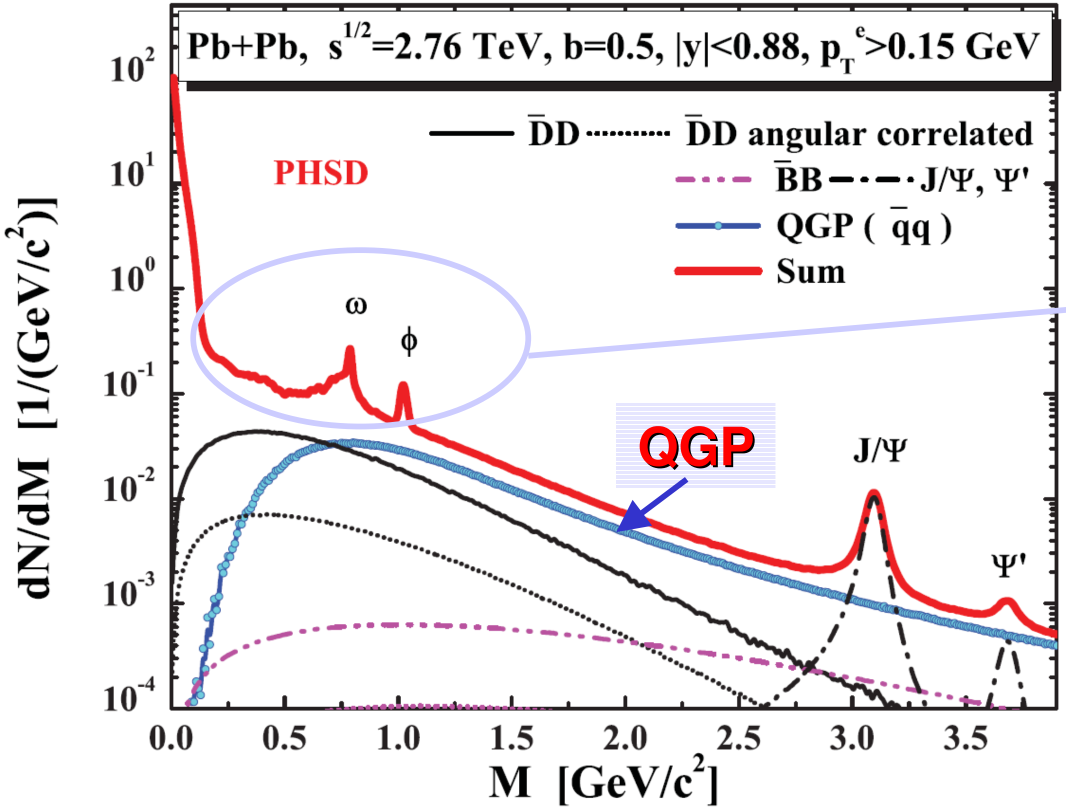


Message:

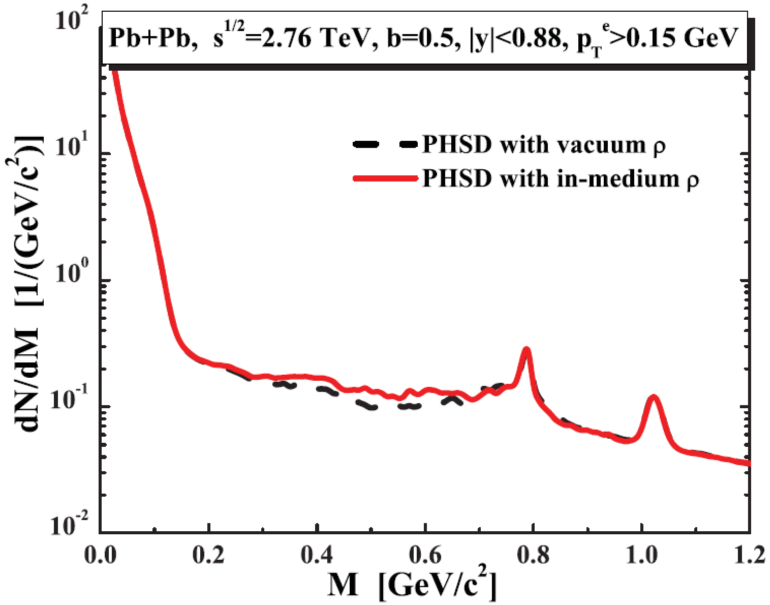
- **BES-STAR data** show a **constant low mass excess** (scaled with N(π^0)) within the measured energy range
- PHSD model: **excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon density phase

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

Dileptons at LHC



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



Message:

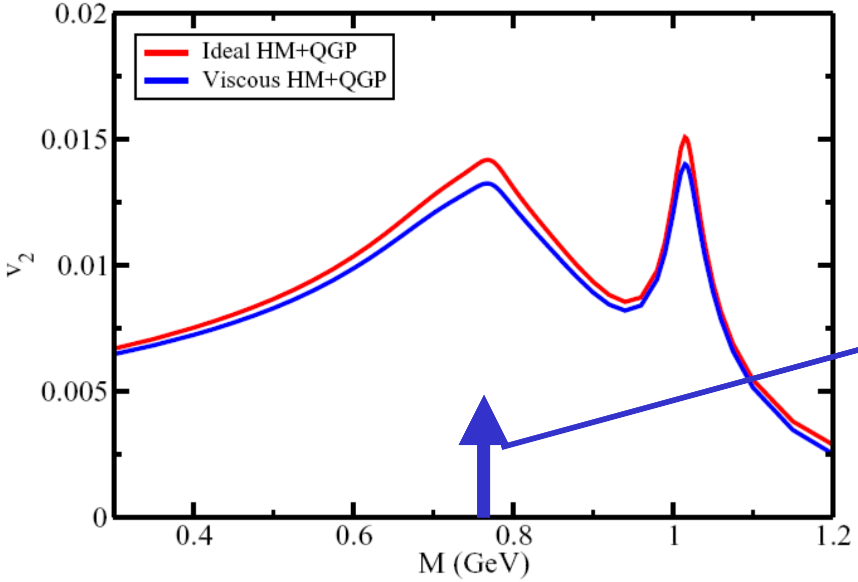
- low masses - **hadronic sources: in-medium effects for ρ** mesons are small
- intermediate masses: **QGP + D/Dbar**
  - charm 'background' is smaller than thermal QGP yield
  - **QGP(qbar-q) dominates at M>1.2 GeV ➔ clean signal of QGP at LHC!**

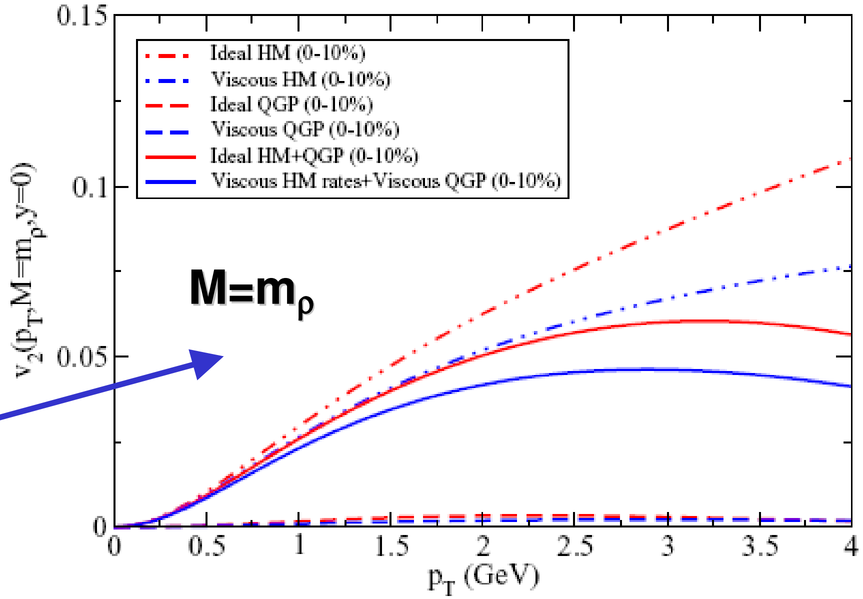
Perspectives with dileptons: v_n

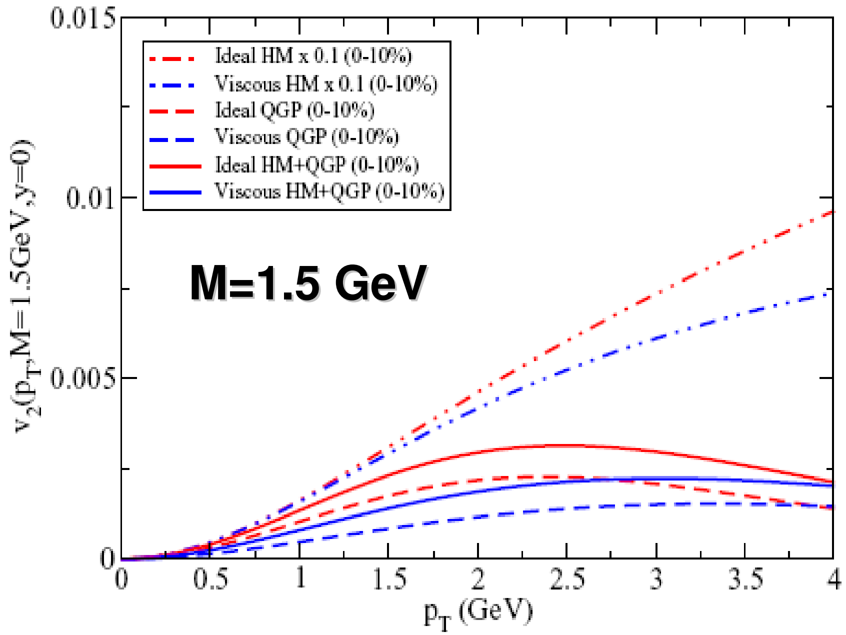
Talk by Vujanovic, QM'2014

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:**

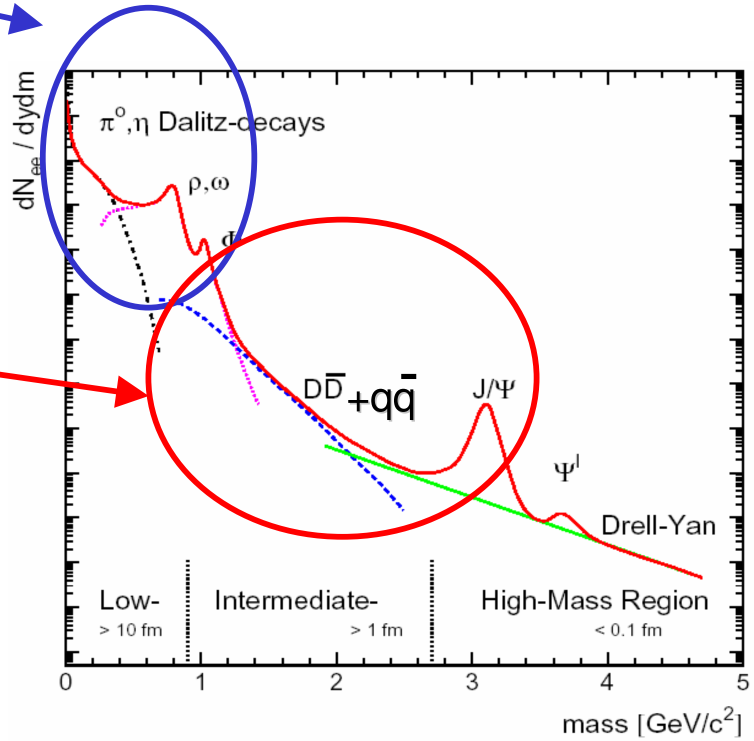
- **Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally**

- **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

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Thank you!

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