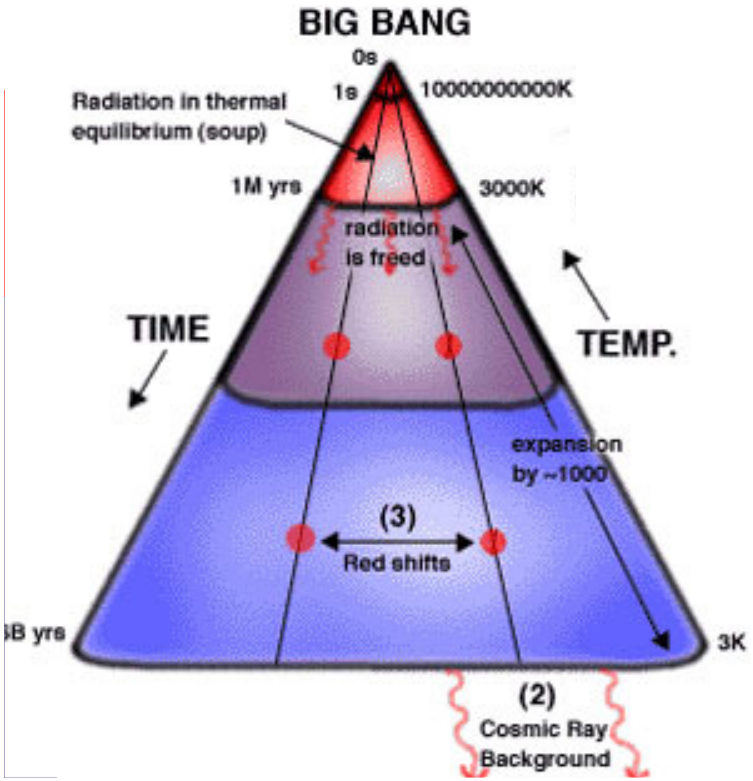
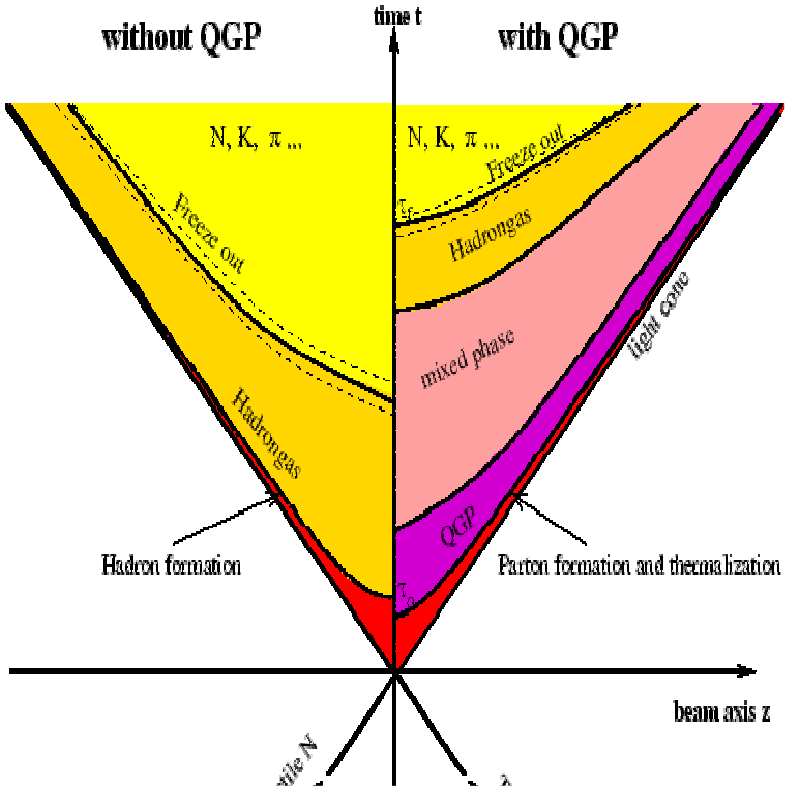
Photons and dileptons as probes of the hot and dense matter



Olena Linnyk

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

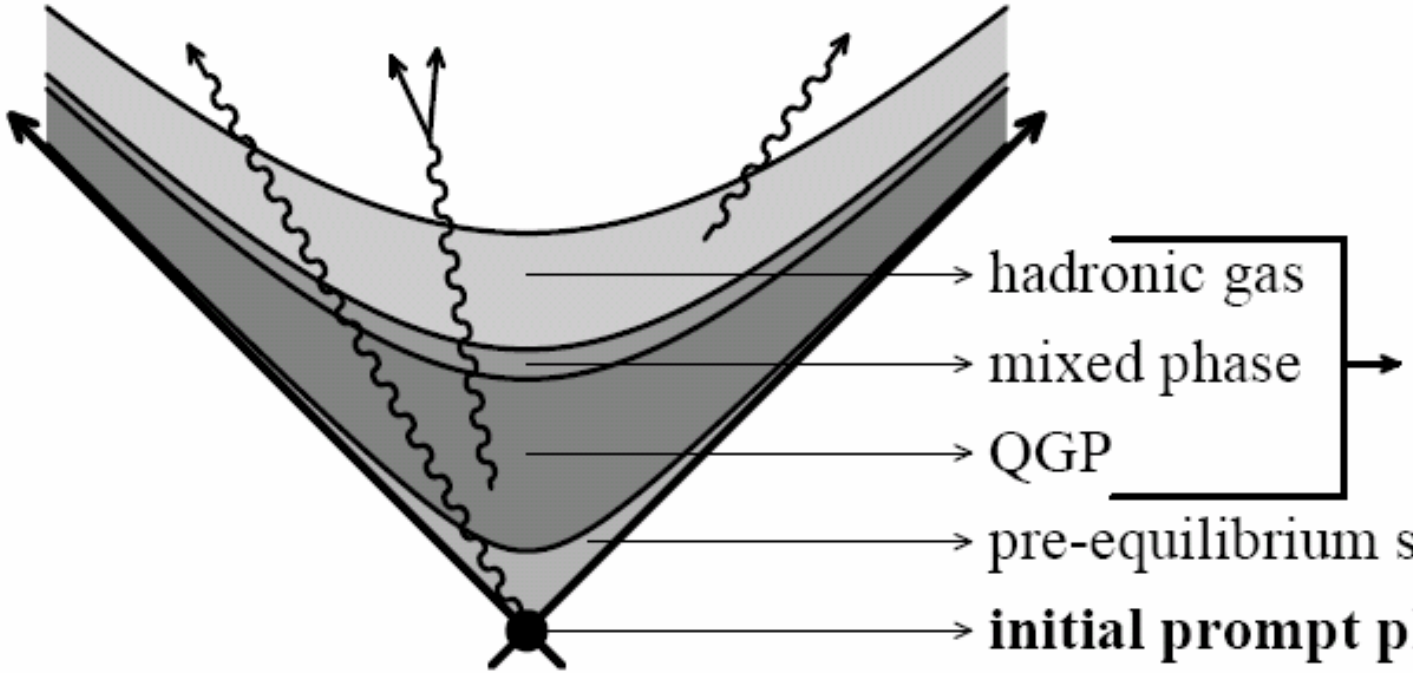


Photons as penetrating probes

E. L. Feinberg, Nuv. Cim. A 34 (1976) 391:
Direct photons; real or virtual are penetrating probes
for the bulk matter produced in hadronic collisions, as
- They do not interact strongly; - They have a large mean free path

Price: "Historians" of the heavy ion collision encode all sub-processes at all times.

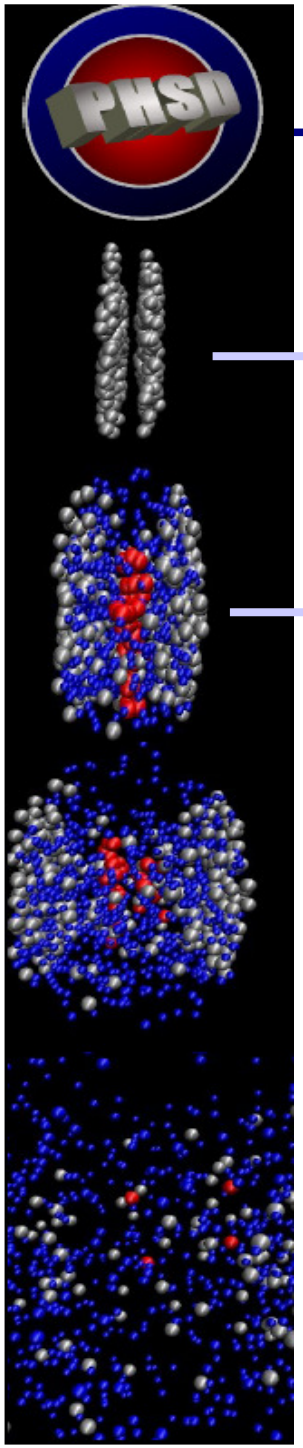
➔ **Require models to describe the emission during the whole collision evolution**



- **Fire-balls**
- **Hydrodynamics**
- **Hydro+Transport**
- **(off-shell) Transport**

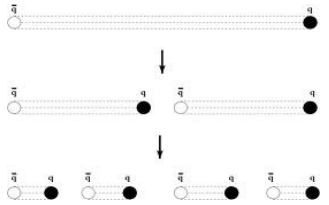
Graphics from the slides by D. Srivastava.

I. PHSD - basic concepts



I. From hadrons to QGP:

LUND string model



- **Initial A+A collisions – as in HSD:**
  - **string formation in primary NN collisions**
  - **string decay to pre-hadrons (*B* - baryons, *m* - mesons)**

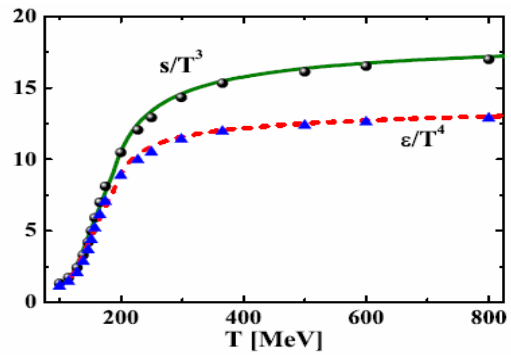
- **Formation of QGP stage by dissolution of pre-hadrons (all new produced secondary hadrons) into massive colored quarks + mean-field energy**

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

$$B \to qqq, \quad m \to q\bar{q} \qquad U_q$$

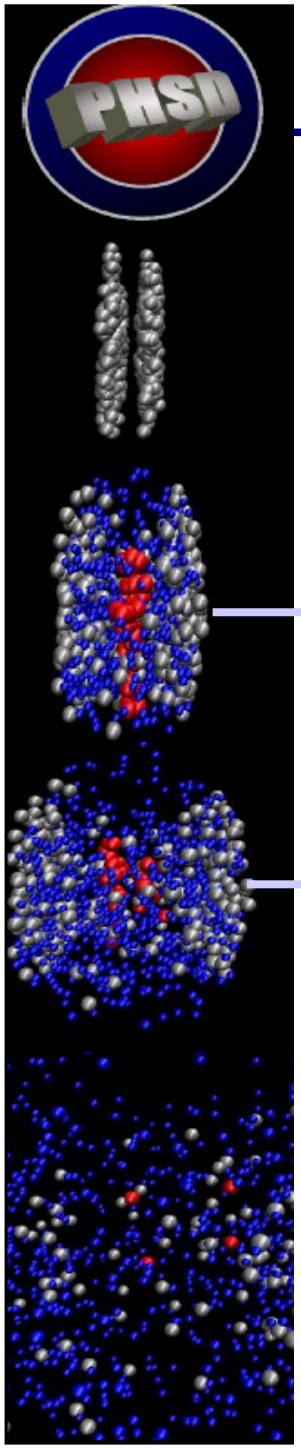
based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, i.e. masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$

+ mean-field potential U_q at given ε – local energy density



(ε related by lQCD EoS to *T* - temperature in the local cell)

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



II. PHSD - basic concepts

II. Partonic phase - QGP:

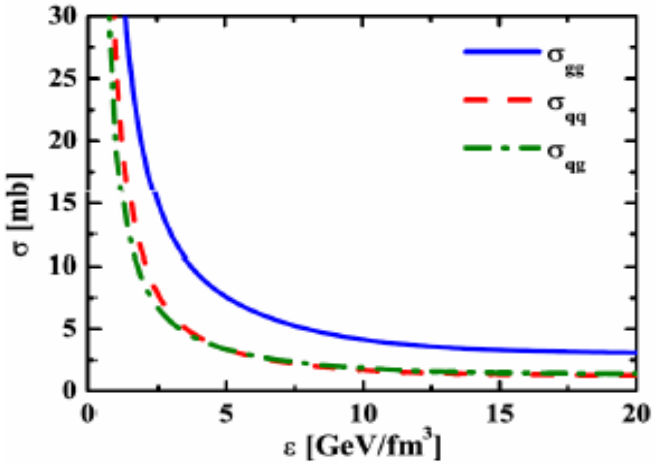
quarks and gluons (= ‚dynamical quasiparticles‘)
with off-shell spectral functions (width, mass) defined by the DQPM

- in self-generated mean-field potential for quarks and gluons U_q, U_g from the DQPM
- 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

- (quasi-) elastic collisions:

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

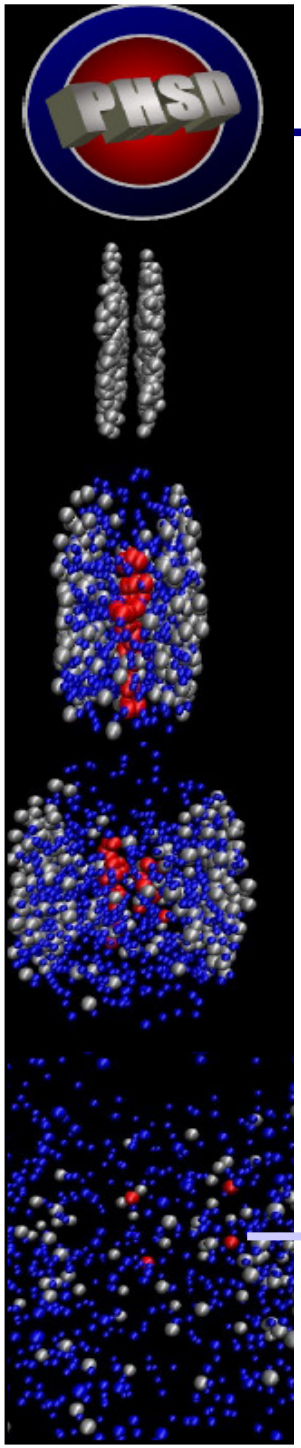


- inelastic collisions:
(Breight-Wigner cross sections)

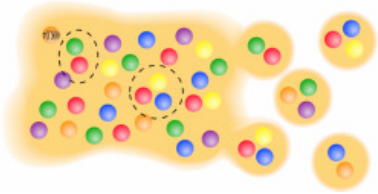
$$q+\bar{q} \to g \qquad g \to q+\bar{q}$$

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

suppressed (<1%) due to the large mass of gluons



III. PHSD - basic concepts



III. Hadronization:

❑ **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)

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

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

- **Local covariant off-shell transition rate for q+q$_{bar}$ fusion**

➔ **meson formation:**

$$Tr_j = \sum_j \int d^4x_j d^4p_j/(2\pi)^4$$

$$\frac{dN^{q+\bar{q}\to m}}{d^4x\ d^4p} = Tr_q Tr_{\bar{q}} \delta^4(p - p_q - p_{\bar{q}}) \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(flavor, color)$$

$$\cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2 \ W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$

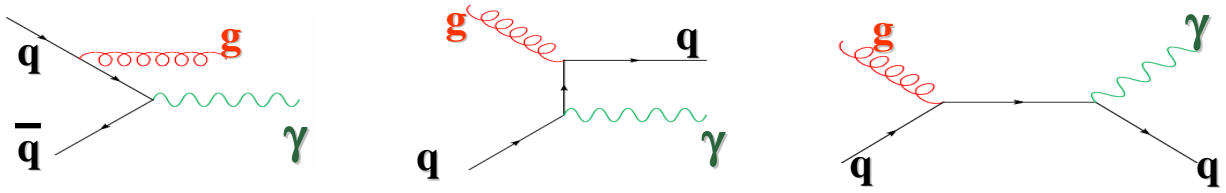
- $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- W_m is the phase-space distribution of the formed ‚pre-hadrons' (Gaussian in phase space)
- $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

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

Photons from the hot and dense medium

Photon sources in PHSD

1) From the QGP via partonic interactions:



2) From hadronic sources

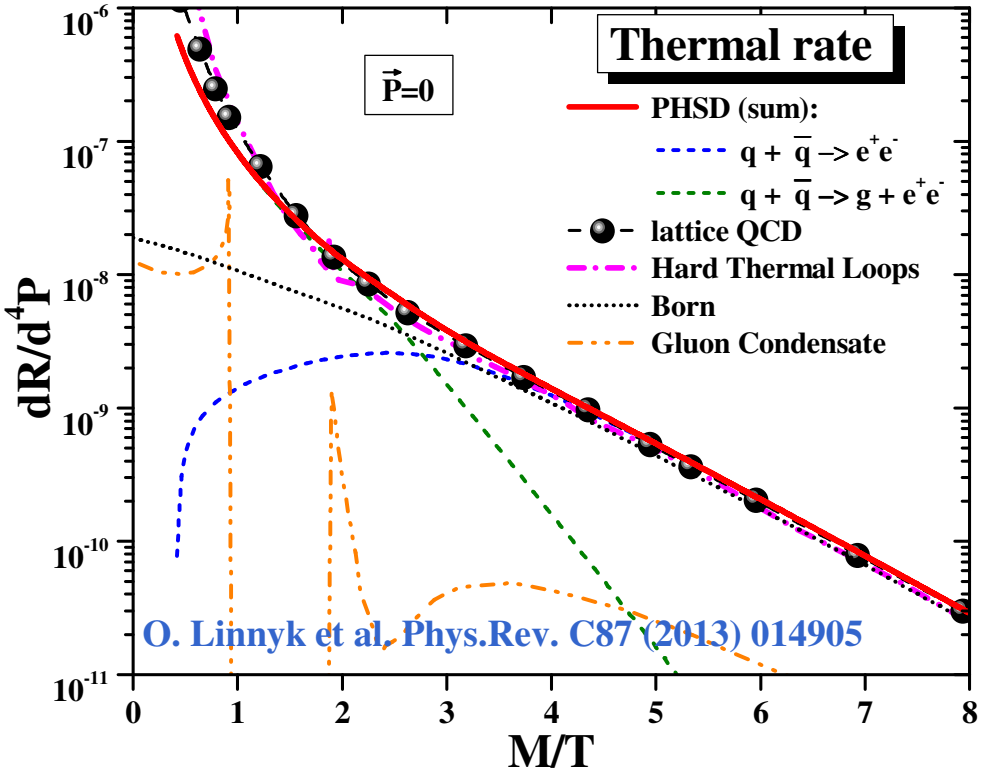
- **decays of mesons:** $\pi \to \gamma + \gamma,\ \eta \to \gamma + \gamma,\ \omega \to \pi + \gamma$
  $\eta' \to \rho + \gamma,\ \phi \to \eta + \gamma,\ a_1 \to \pi + \gamma$

- **secondary meson interactions:** $\pi + \pi \to \rho + \gamma,\ \rho + \pi \to \pi + \gamma$
  using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

- **Meson-meson and meson-baryon bremsstrahlung,**
  $m+m \to m+m+\gamma,\ \ m=\pi,\eta,\rho,\omega,K,K^*,\ldots$
  using the soft photon approximation, with an average elastic cross section of 10 mb.
  Caution: uncertain!

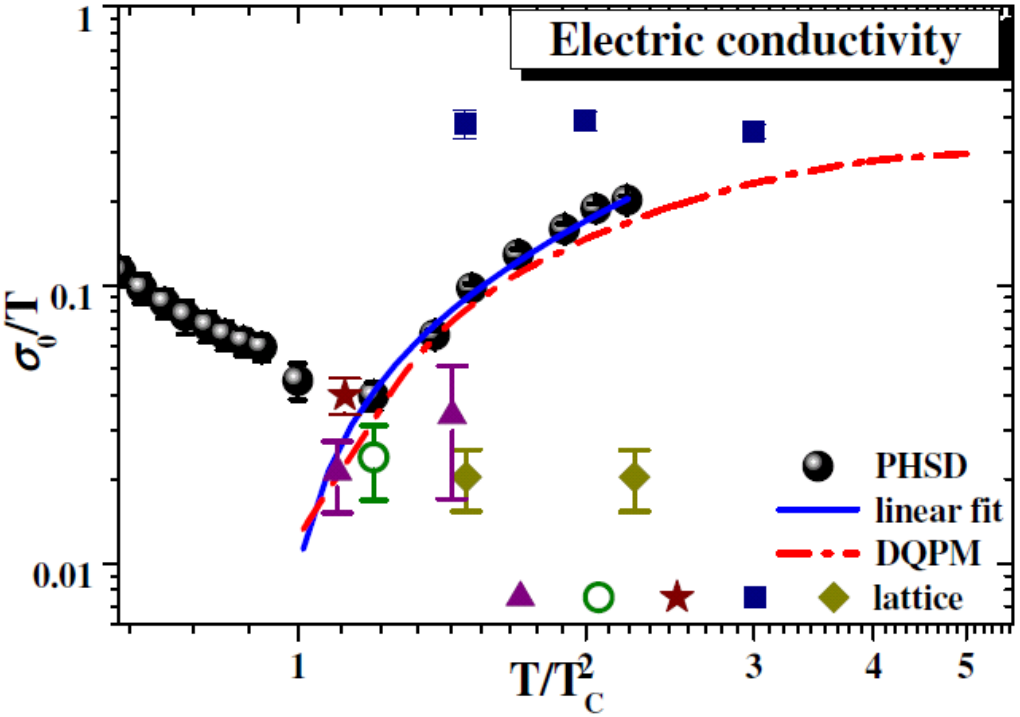
E. Bratkovskaya et al, Phys. Rev. C78, 034905 (2008), O. Linnyk et al. Phys.Rev. C88 (2013) 034904

Thermal rates and conductivity



$$\frac{dW}{d\omega d^3p} = \frac{5\alpha^2}{54\pi^3}\frac{1}{\omega^2(e^{\omega/T}-1)}\rho_V(\omega,\vec{p},T)$$

$$\frac{\sigma}{T} = \frac{C_{em}}{6}\lim_{\omega\to 0}\frac{\rho_{ii}(\omega,\vec{p}=0,T)}{\omega T}$$



- off-shell dynamical quasiparticle quark and gluon interaction
  Linnyk, J.Phys. G38 (2011) 025105
- lattice QCD
  Ding et al, PRD83 (2011) 034504
- Hard Thermal Loops
  Braaten, Pisarski, NP B337 (1990) 569

Photons from SPS to LHC:

direct photon flow puzzle

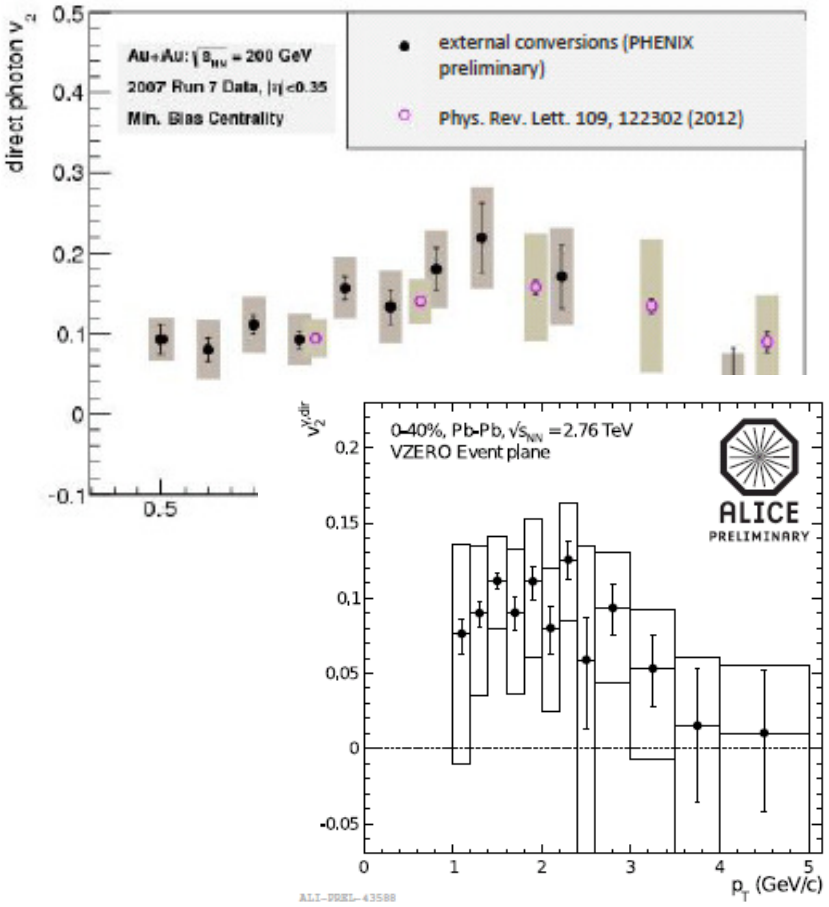


Figure 3. Direct-photon $v_2^{\gamma,\mathrm{dir}}$ in 0-40% Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [8].

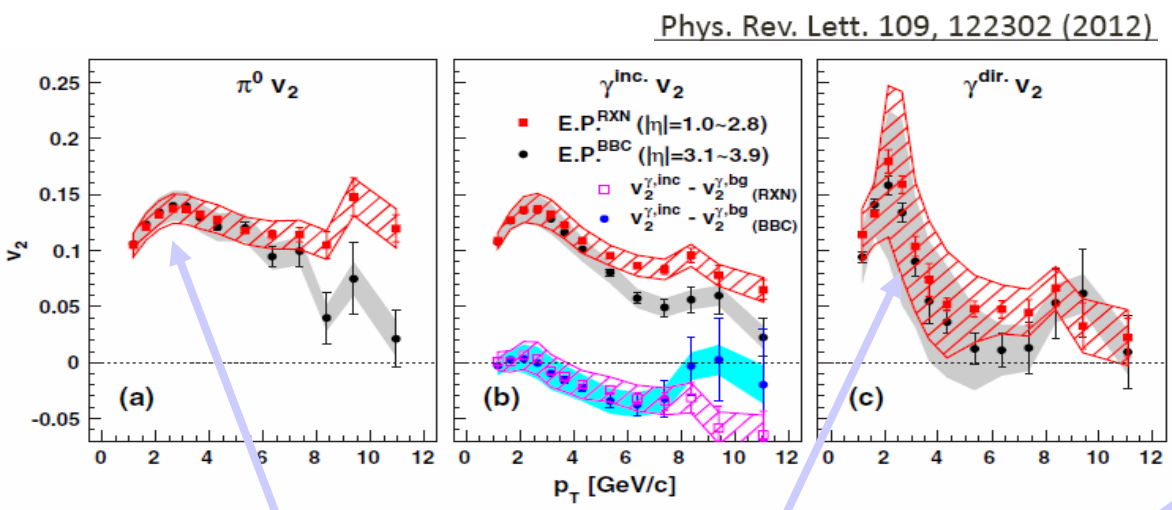
?

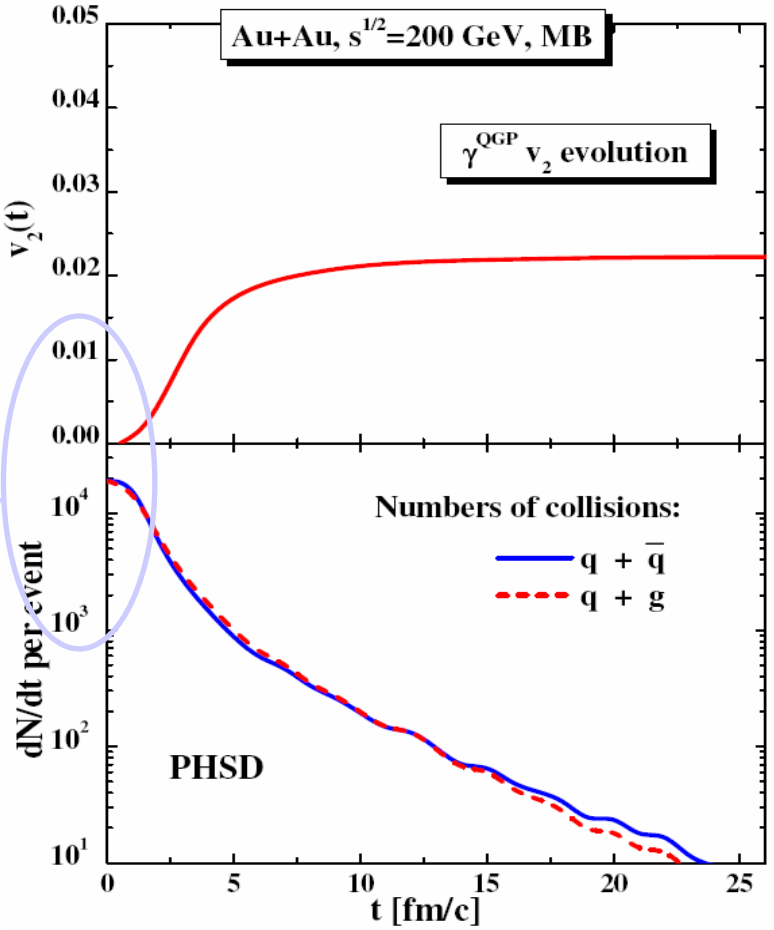
EMMI Rapid Reaction Task Force

Direct-Photon Flow Puzzle

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

Photon v_2 puzzle





Strong elliptic flow of photons ($v_2(\gamma^{dir})\sim v_2(\pi)$) seen by PHENIX is surprising, if the origin would be the QGP !

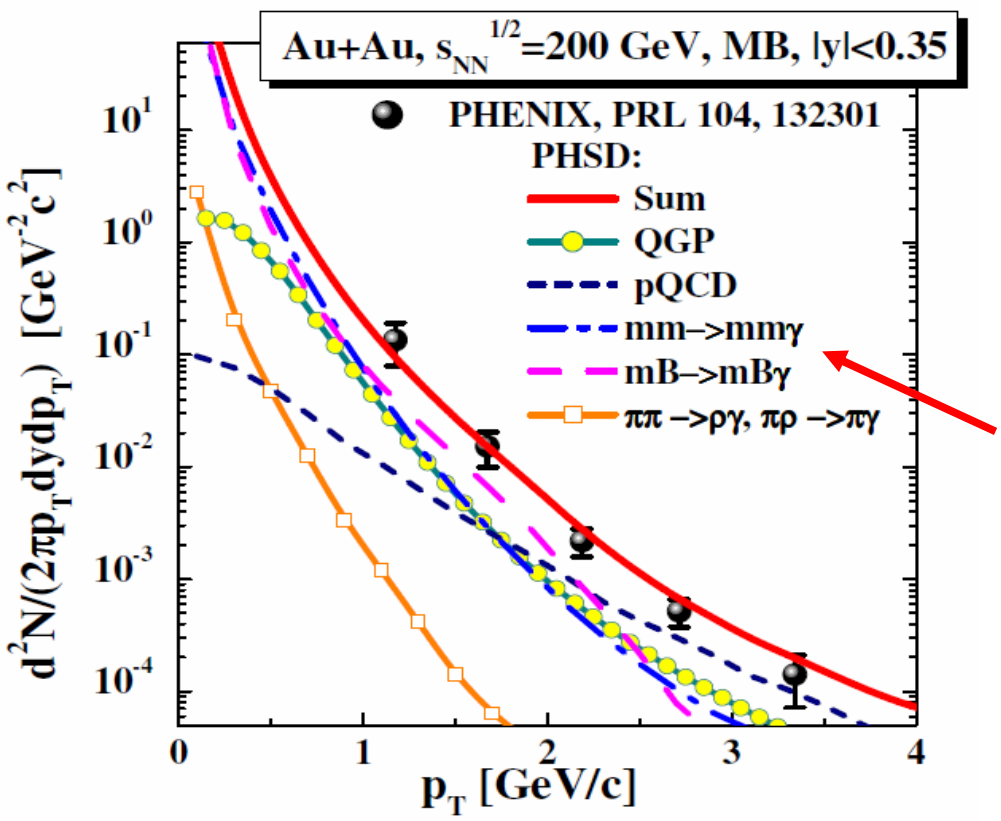
Variety of models: $v_2(\gamma^{dir}) << v_2(\pi)$

QGP radiation occurs at early time when flow is not yet developed!

Olena Linnyk et al., PRC 88 (2013) 034904; Phys. Rev. C88 (2013) 034904

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

- **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**

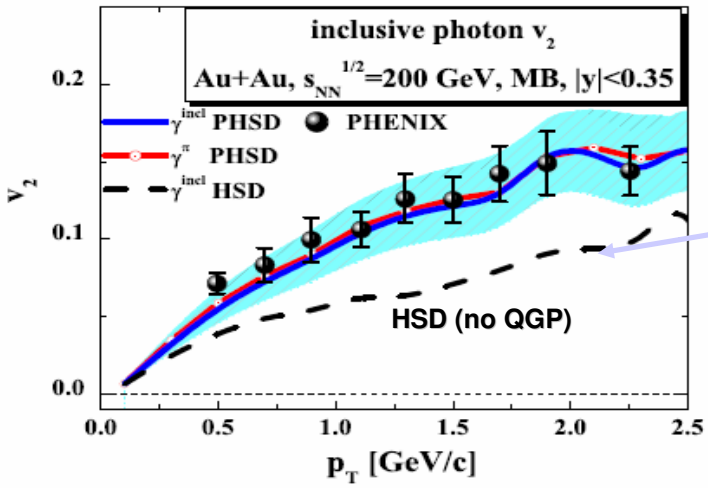
! sizeable contribution from hadronic sources – meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

mm and mB bremsstrahlung channels can not be subtracted experimentally

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

Are the direct photons a barometer of the QGP?

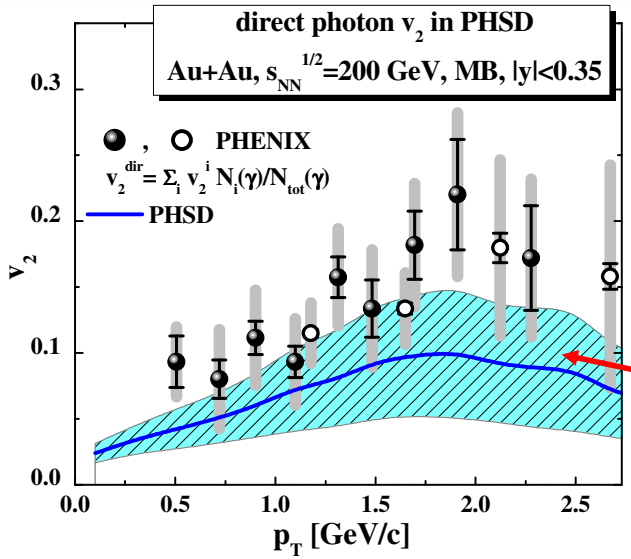
❑ Do we see the QGP pressure in $v_2(\gamma)$ if the photon productions is dominated by hadronic sources?



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 !

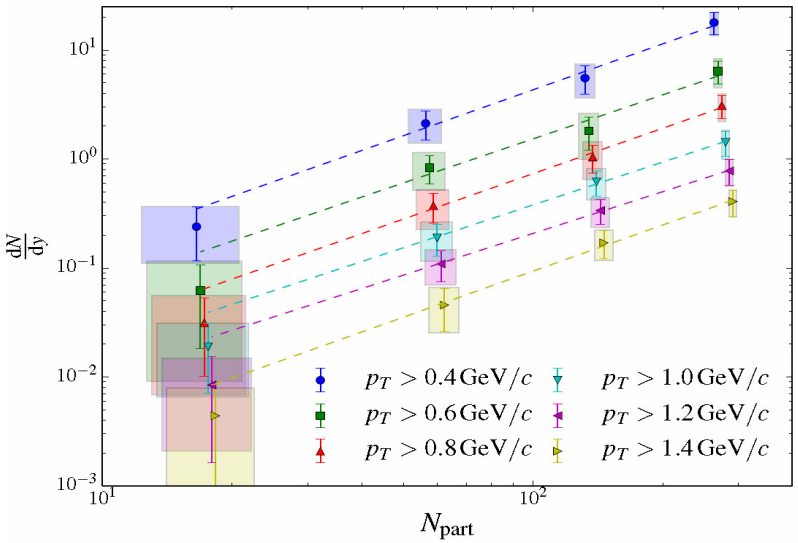
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908

Centrality dependence of the thermal photon yield

PHENIX (arXiv:1405.3940):

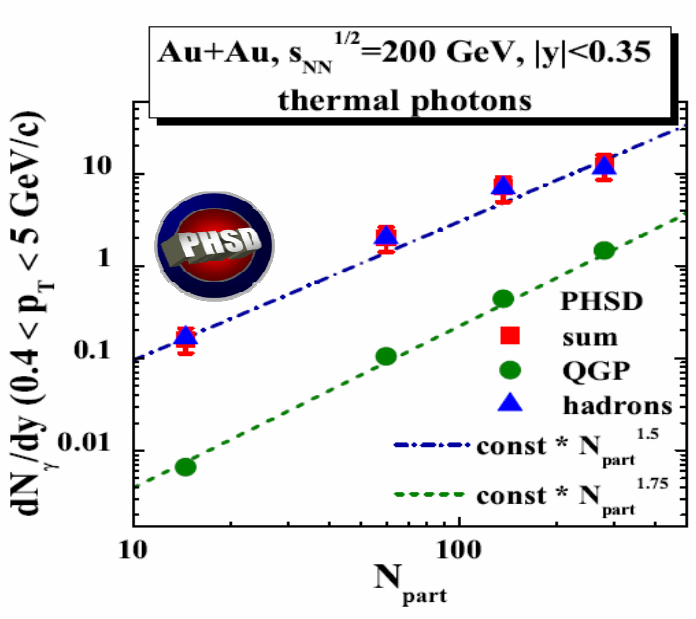
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{a}$ with $a \sim 1.48 \pm 0.08$

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



PHSD predictions:

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



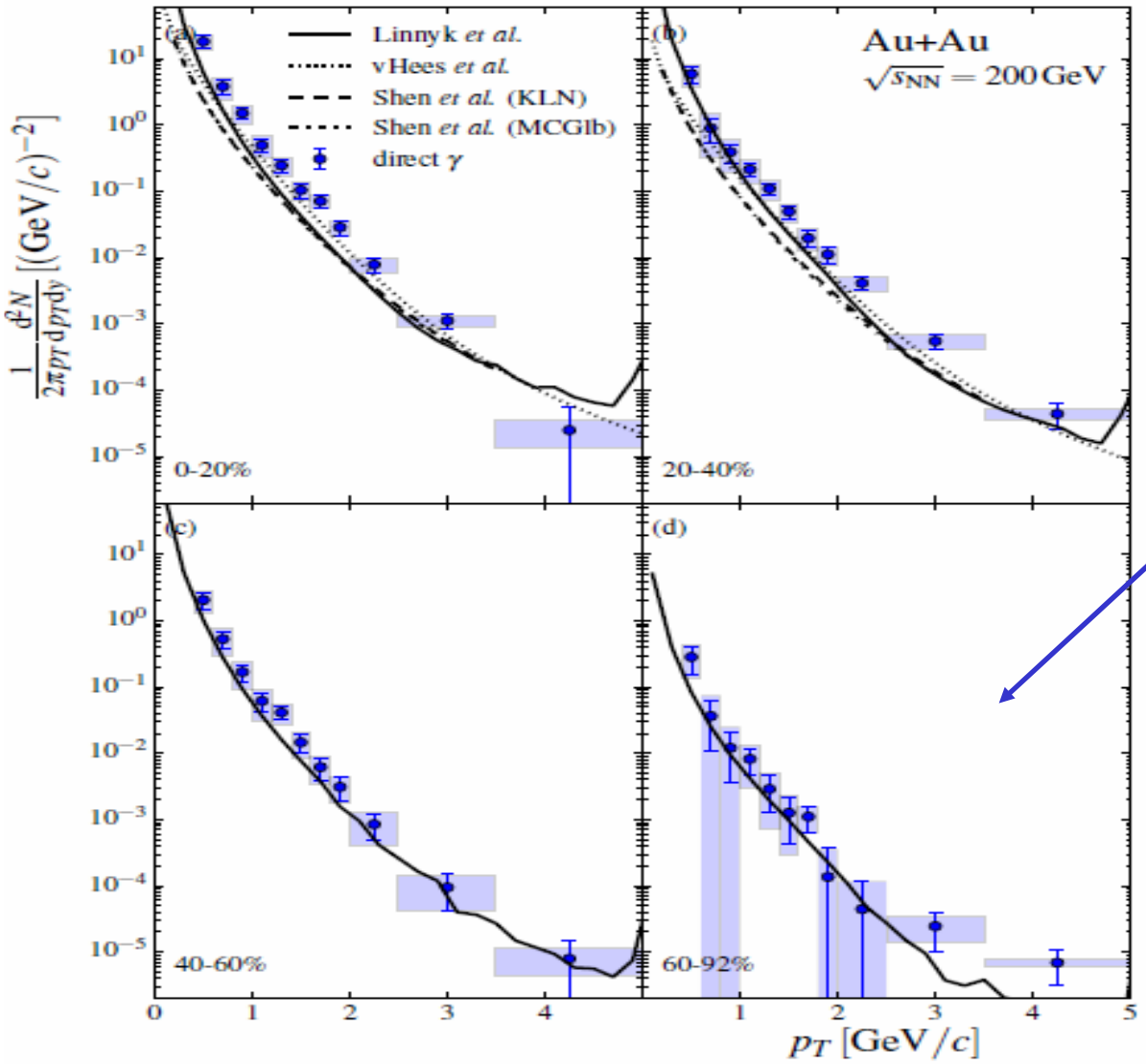
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

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

Centrality dependence of the direct photon yield

from talk by S. Mizuno at QM'2014

PHENIX data - arXiv:1405.3940



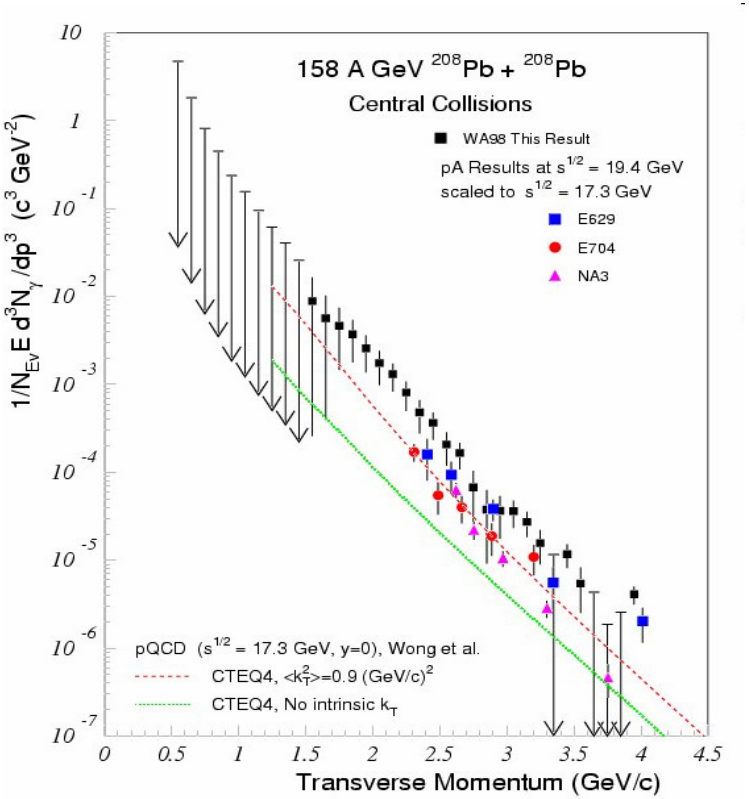
PHSD predictions:
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

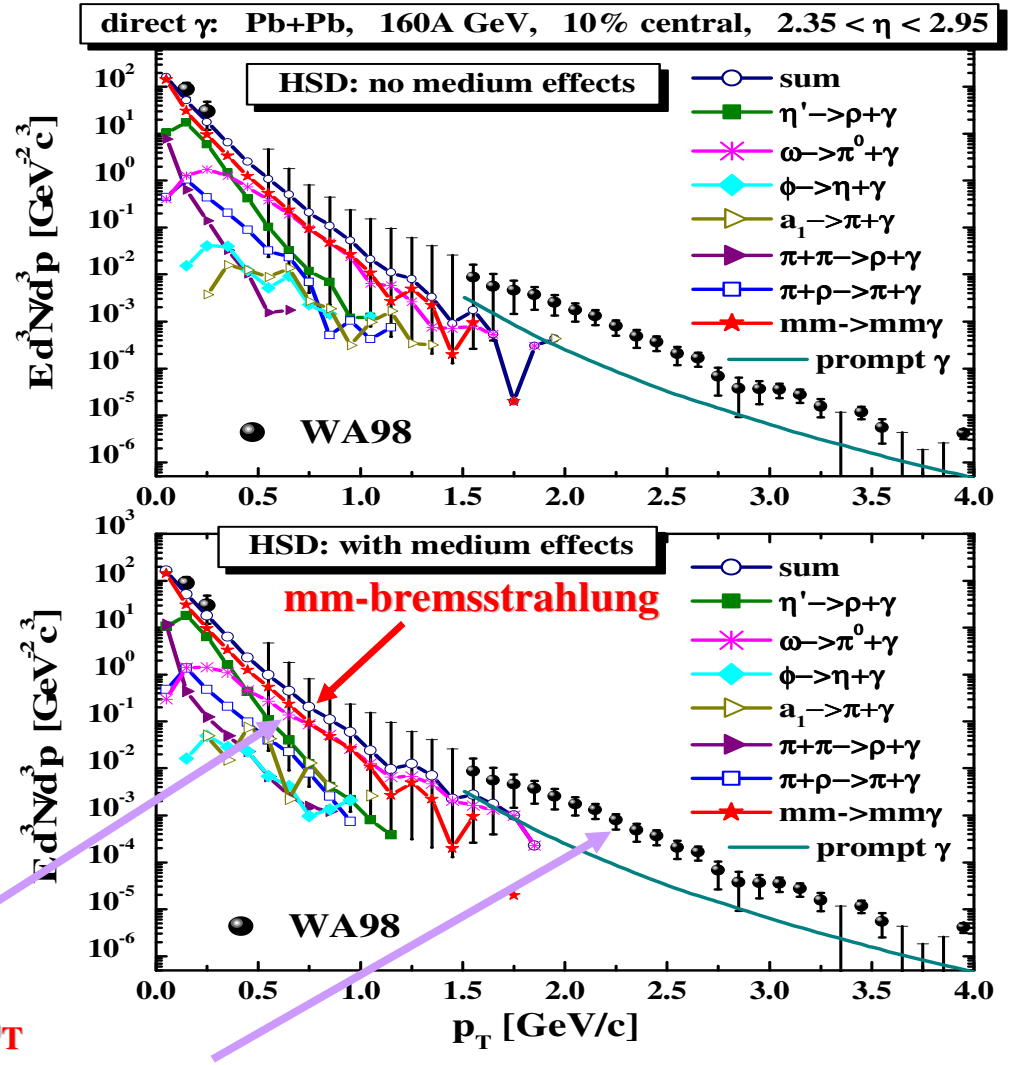
❑ PHSD approximately reproduces the centrality dependence

❑ mm and mB bremsstrahlung is dominant at peripheral collisions

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

Direct photons at SPS: WA98



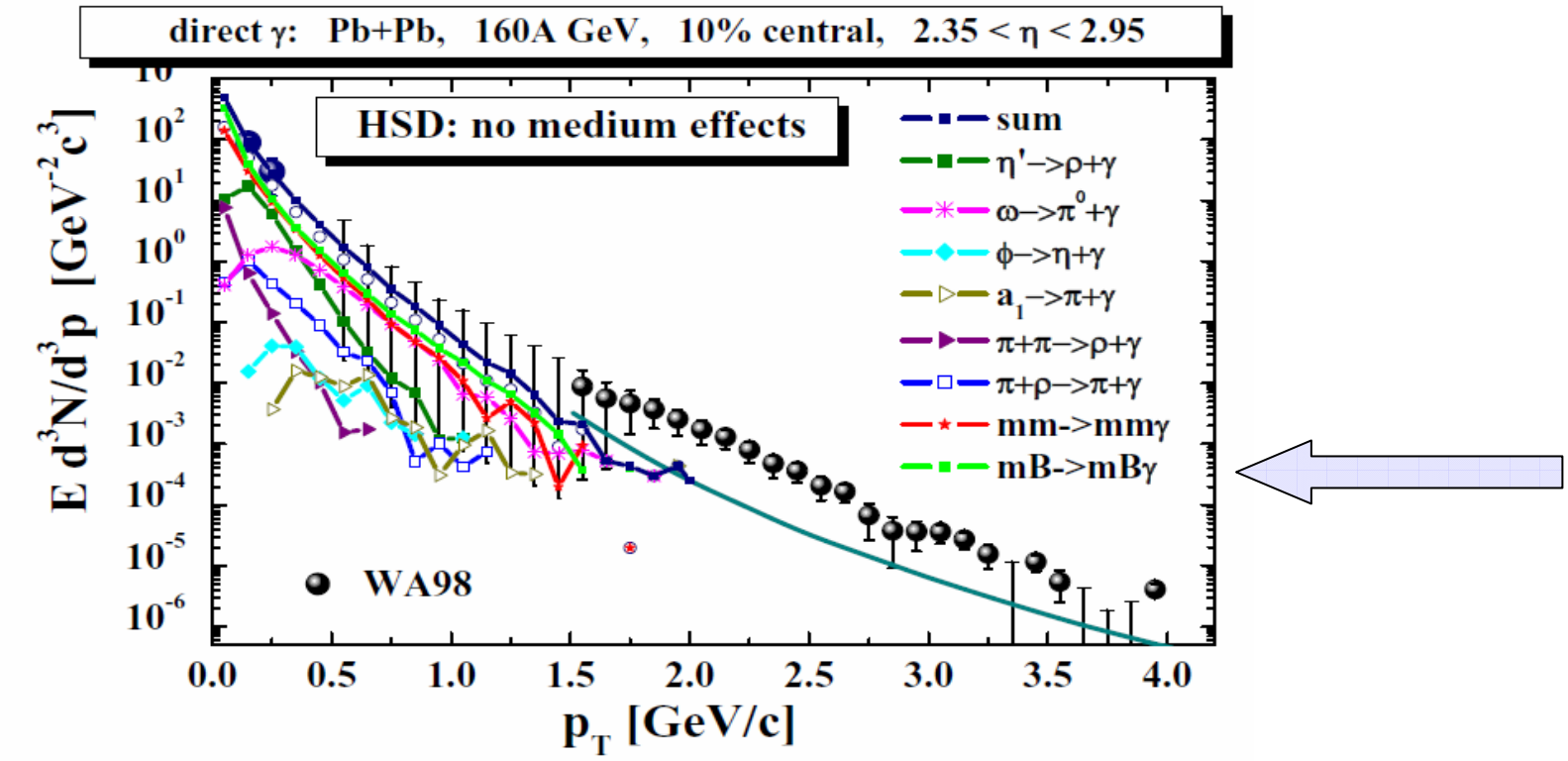


- **Hadronic sources dominate at low p_T**
- **High p_T: dominated by thermal photons from QGP**

E. Bratkovskaya, S.M. Kiselev, and G.B. Sharkov, PR C78 (2008) 034905

Photon spectra at SPS

Updated HSD (2014) including meson-baryon bremsstrahlung



- **HSD: meson-meson and meson-baryon bremsstrahlung using SPA**

- **<u>But bremsstrahlung rates are uncertain</u>**

Meson-meson Bremsstrahlung at SPS within SPA

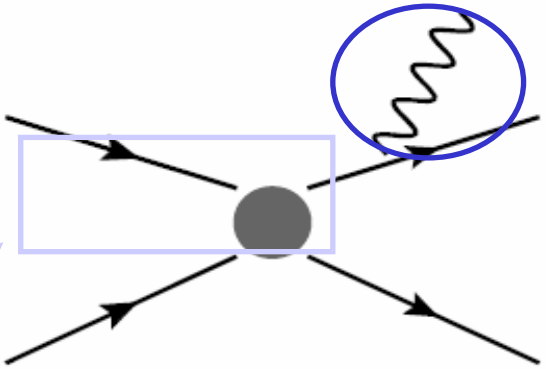
C. Gale, J. Kapusta, Phys. Rev. C 35 (1987) 2107

Soft Photon Approximation:

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

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

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

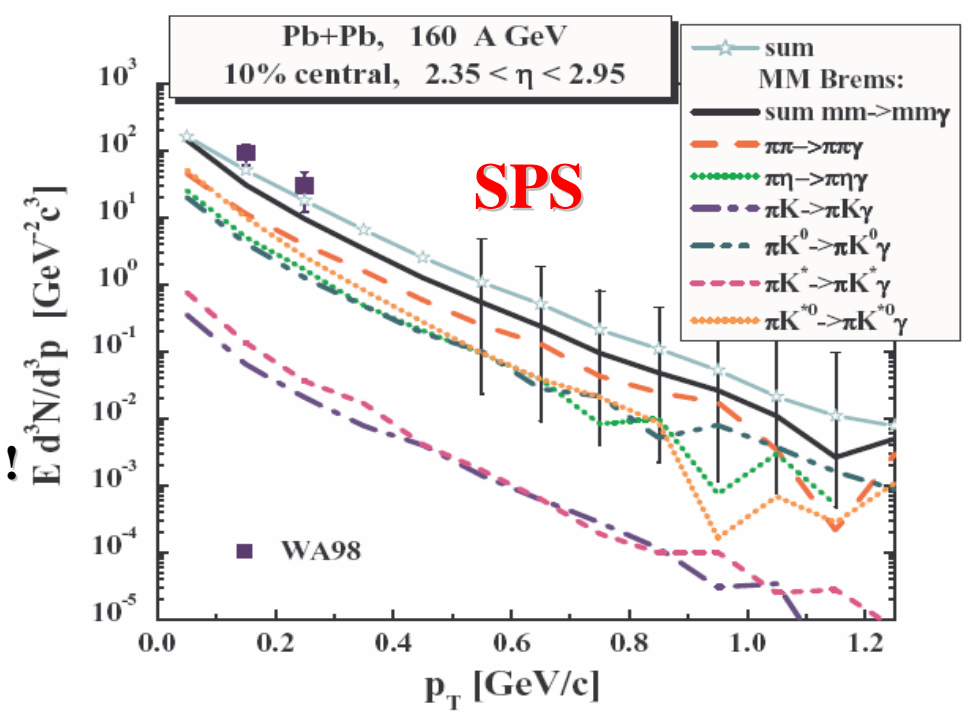


σ(s) – elastic meson-meson cross section

$m_1+m_2 \rightarrow m_1+m_2$ **-???**

- **Taken σ(s) =10 mb for ALL m_1+m_2 channels !**
- **No isospin factors!**

➔ **Needs to be improved!**



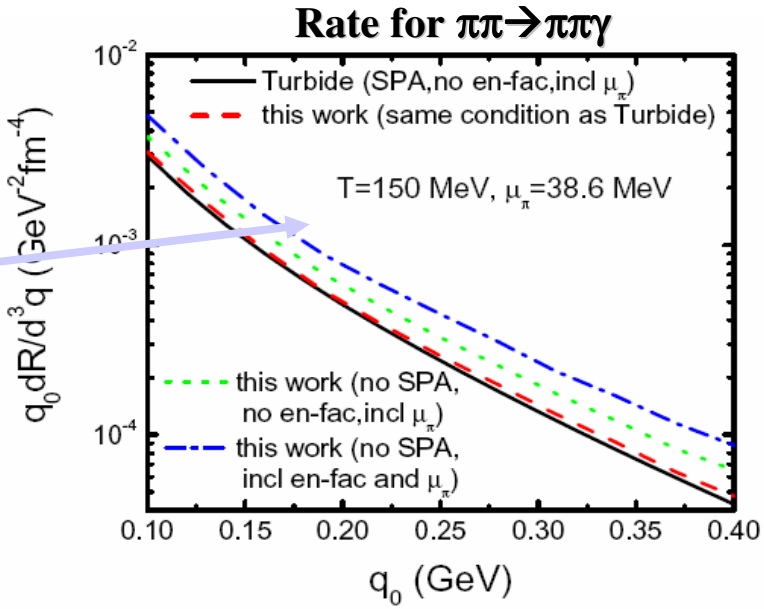
E. Bratkovskaya., S.M. Kiselev, and G.B. Sharkov, PR C78 (2008) 034905

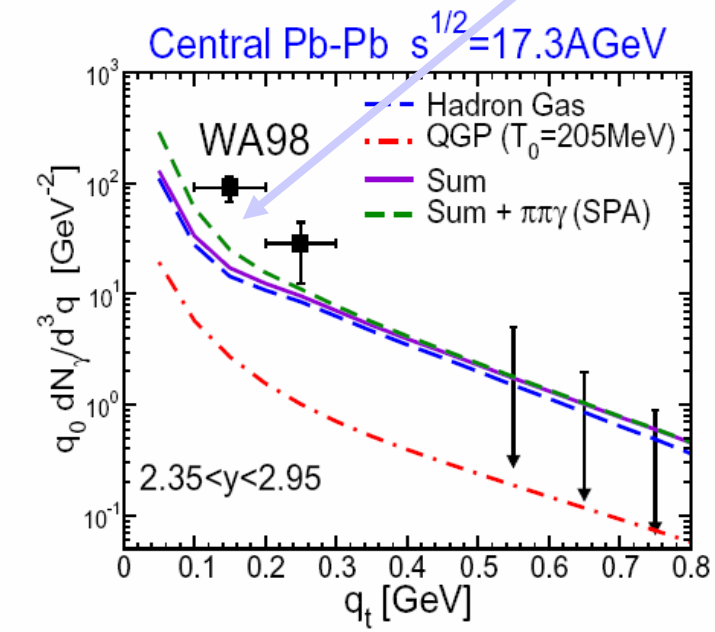
mm bremsstrahlung beyond SPA

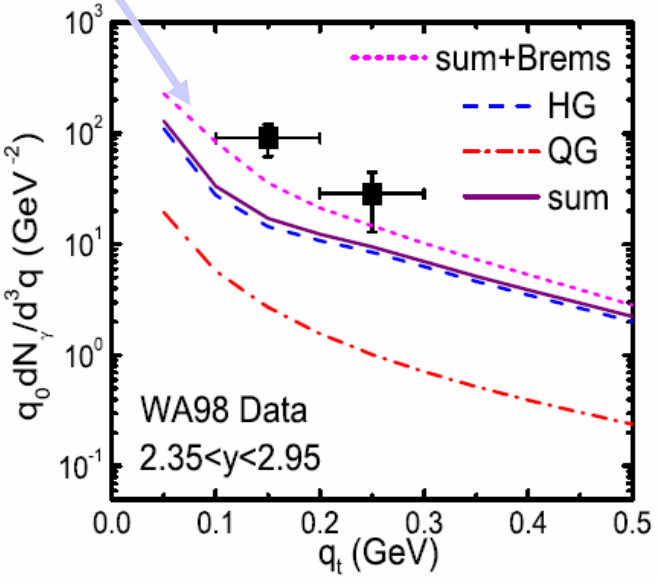
W. Liu and R. Rapp, Nucl. Phys. A 96 (2007) 101

- **$\pi\pi \rightarrow \pi\pi\gamma$, $\pi K \rightarrow \pi K\gamma$ bremsstrahlung:**

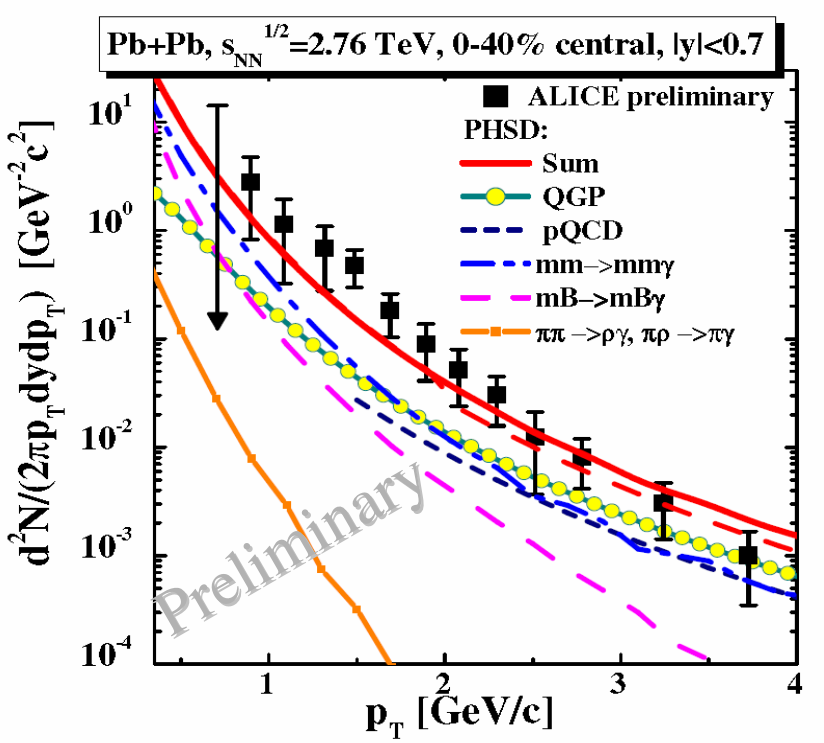
the photon yield within an effective chiral hadronic model including electromagnetic interaction via $U_{em}(1)$ gauge is larger than using SPA !



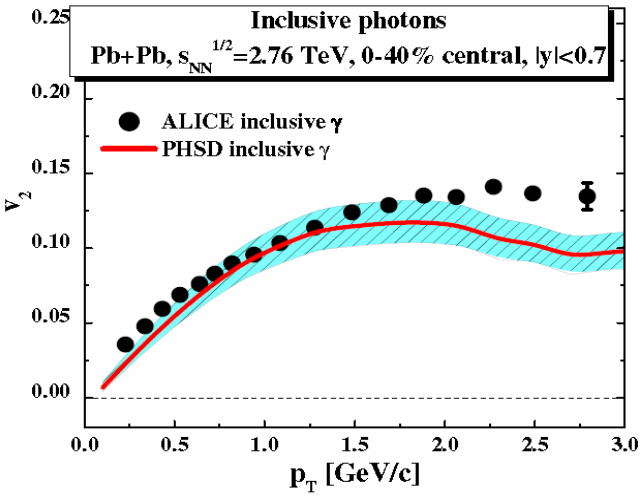




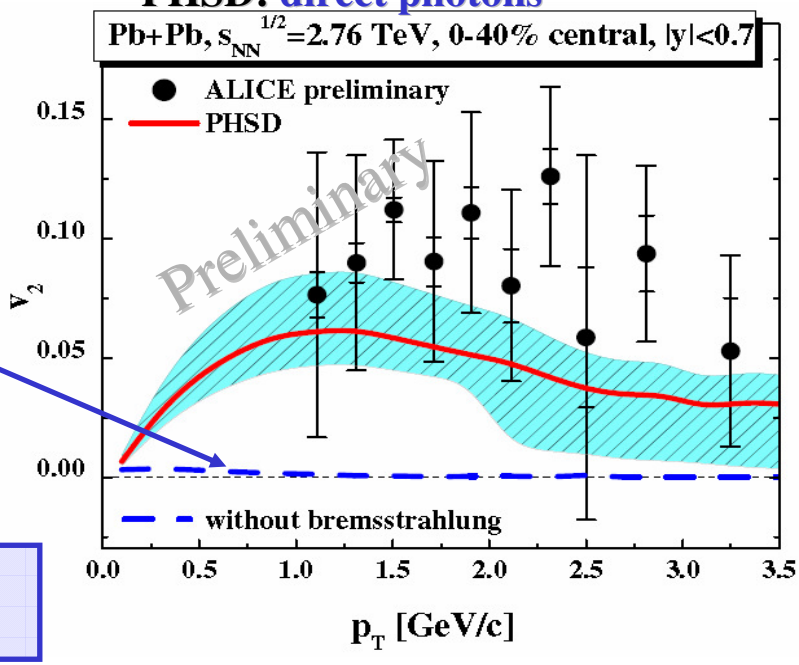
Photons from PHSD at LHC



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)

- Glasma effects ?

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

- Pseudo-Critical Enhancement of thermal photons near T_C ?

(H. van Hees, M. He, R. Rapp, arXiv:1404.2846)

- ???

Summary

- The photons produced in the QGP contribute up to 50% to the spectrum, but have small v2.
- The measured direct photon elliptic flow v2 – comparable to that of hadrons – is attributed mainly to intermediate hadronic scattering channels.
- Hadronic channels scale as Npart1.5 (as seen by PHENIX). Partonic channels scale as Npart1.75.
- More sound theoretical understanding of bremsstrahlung by mesons and baryons is needed.

Outlook

- Reducing the uncertainties in the bremsstrahlung rates (beyond SPA).
- Direct photon spectra at low p_T , incorporating the LPM effect microscopically.
- Combining the pieces: electric conductivity, photon production, dilepton production.
- Elliptic flow of dileptons vs mass: disentangling the QGP and hadronic contributions to the dilepton spectra.
- Dileptons at lower collision energies: Beam energy scan, FAIR.

Thank you!

HIC for FAIR

PHSD Team

Wolfgang Cassing (Giessen U)
Elena Bratkovskaya (FIAS & ITP Frankfurt U)
Volodya Konchakovski (Giessen U)
Thorsten Steinert (Giessen U)
Alessia Palmese (Giessen U)
Eduard Seifert (Giessen U)
Rudy Marty (FIAS, Frankfurt U)
Hamza Berrehrah (FIAS, Frankfurt U)
Daniel Cabrera (FIAS, Frankfurt U)
Taesoo Song (FIAS, Frankfurt U)
Andrei Ilner (FIAS, Frankfurt U)

Collaboration

Che-Ming Ko
Jörg Aichelin
Pol Bernard Gossiaux
Vitalii Ozvenchuk
Mark I. Gorenstein
Viacheslav D. Toneev
Vadym Voronyuk
Laura Tolos
Angel Ramos
Sergei Voloshin

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Subatech

UAB Universitat Autònoma de Barcelona

JINR

TEXAS A&M UNIVERSITY

Thank you!