FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR
Helmholtz International Center

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Electromagnetic probes of QGP

Elena Bratkovskaya

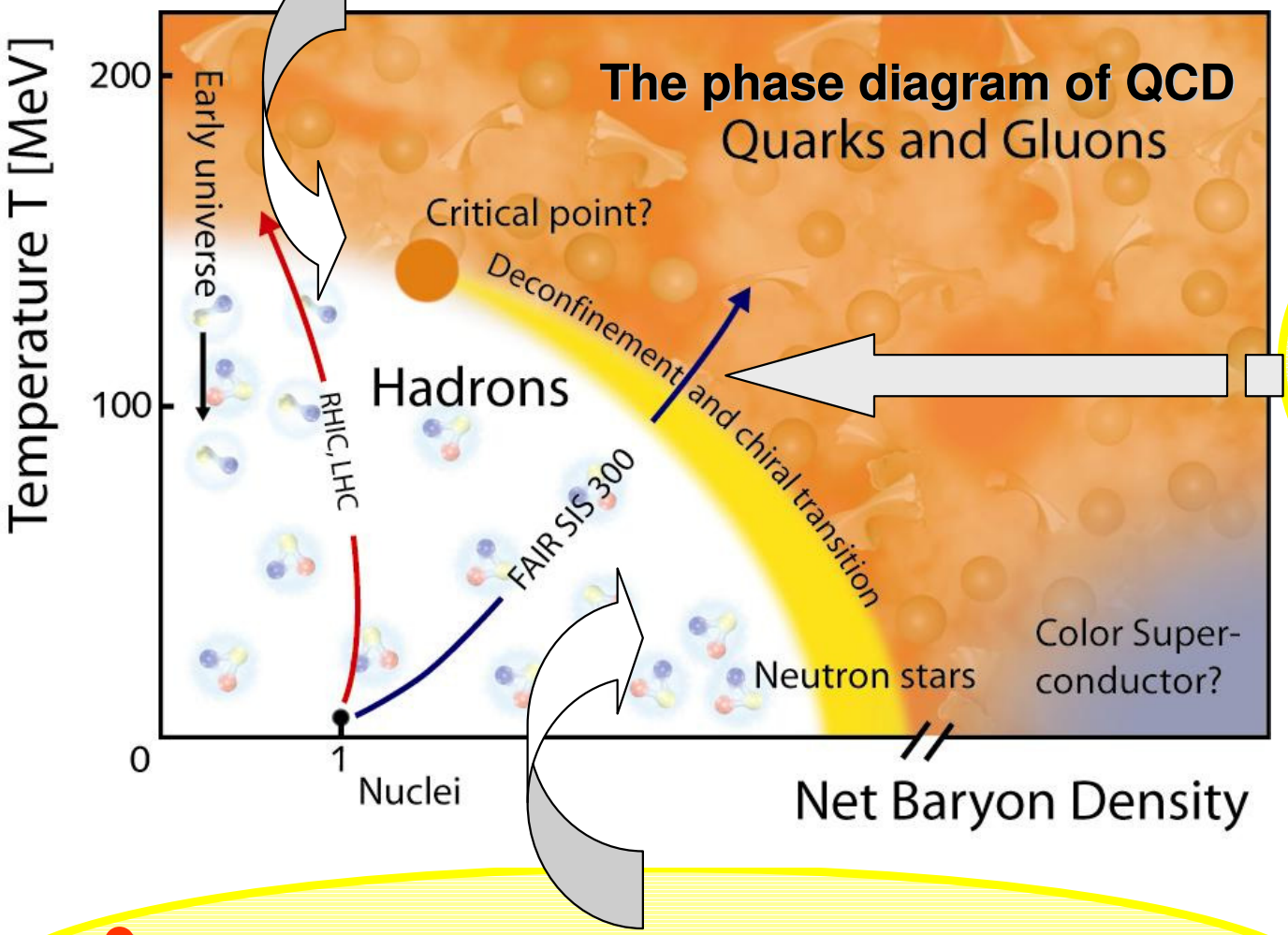
Institut für Theoretische Physik & FIAS, Uni. Frankfurt

The 30th Winter Workshop on Nuclear Dynamics

6-12 April 2014, Galveston, Texas, USA

Ultimate goals of heavy-ion research

- **Search for the critical point**

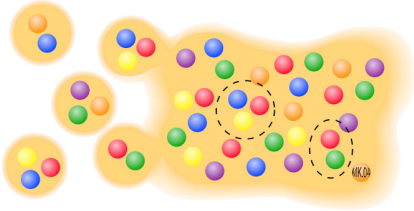


- **Study of the phase transition from hadronic to partonic matter (Quark Gluon Plasma)**

Dileptons

- **Study of the in-medium properties of hadrons at high baryon density and temperature**

From hadrons to partons



In order to study the dynamics of 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
- ❑ Non-equilibrium transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

⇒ **Parton-Hadron-String-Dynamics (PHSD)**

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

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

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 :**

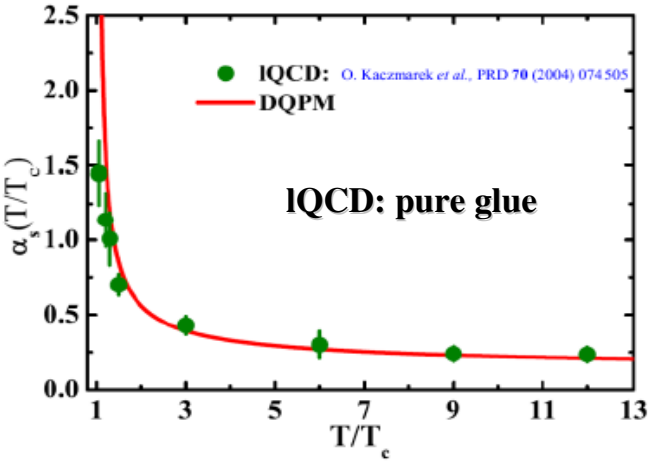
$$(i = q, \bar{q}, g) \qquad \rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^{\,2} - M_i^{\,2}(T)\right)^2 + 4\omega^2\Gamma_i^{\,2}(T)}$$

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

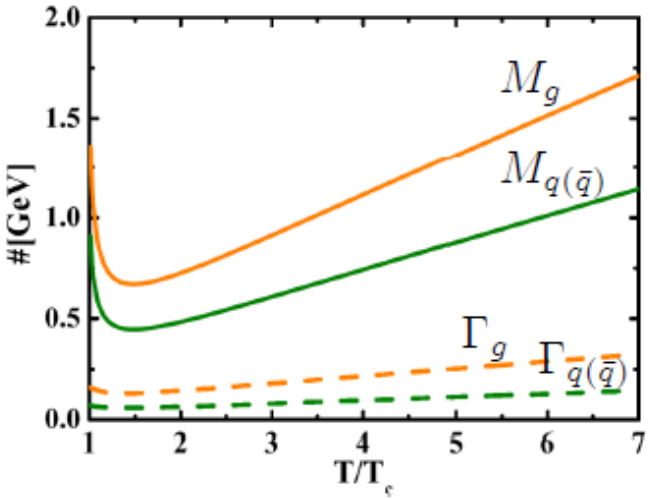
$$M_i(T) \propto \alpha_S(T) f_{HTL}(T), \qquad \Gamma_i(T) \propto \alpha_S(T) f_{HTL}(T)$$

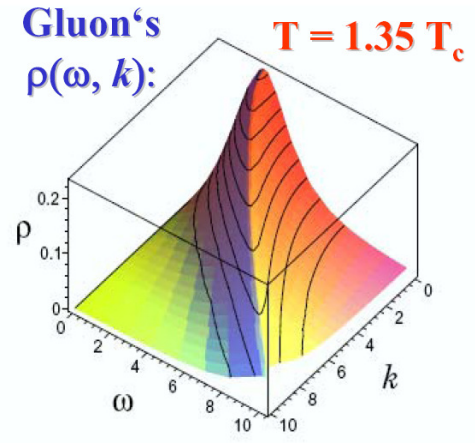
- **fit to lattice (lQCD) results (e.g. entropy density) with 3 parameters**

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



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

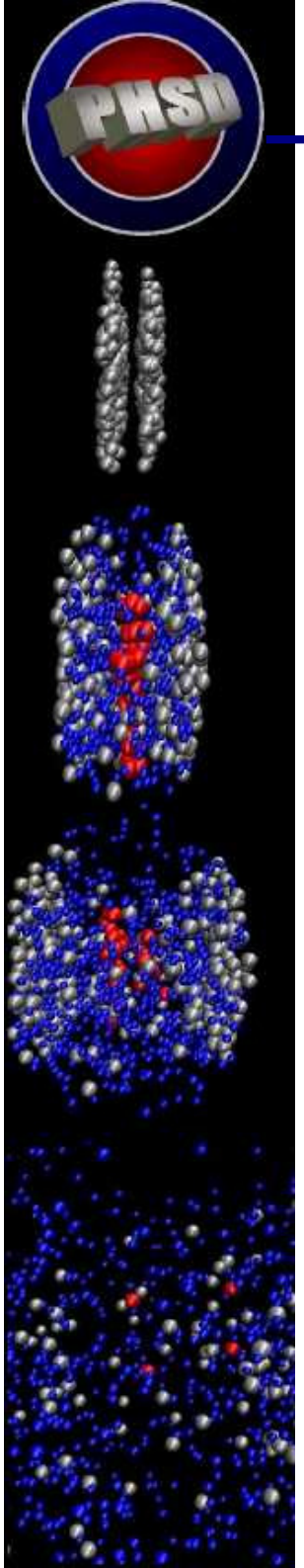




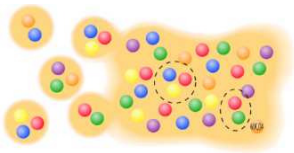
T_C=158 MeV
ε_C=0.5 GeV/fm^3

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

Parton Hadron String Dynamics

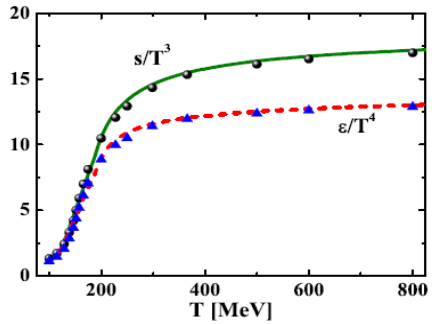


I. From hadrons to QGP:



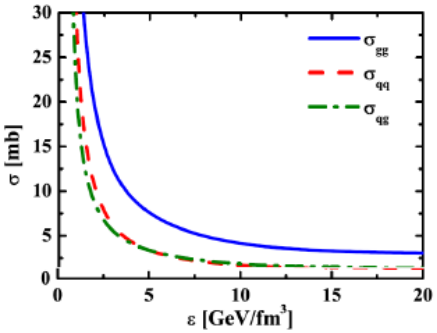
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- 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)



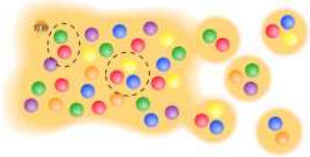
II. Partonic phase - QGP:

- 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

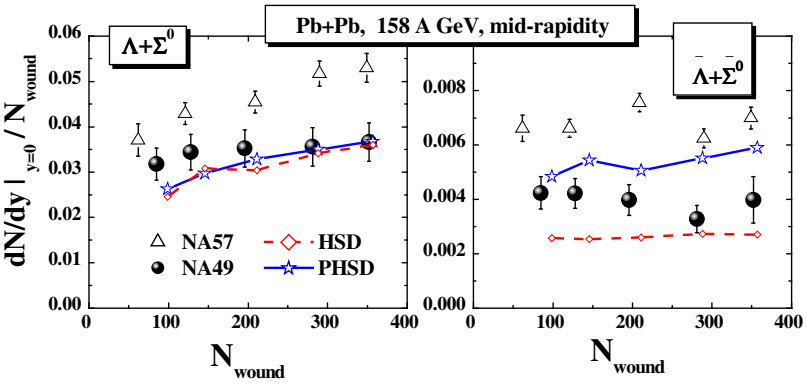
- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)

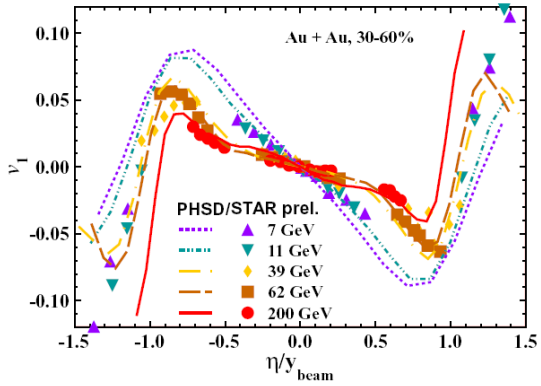


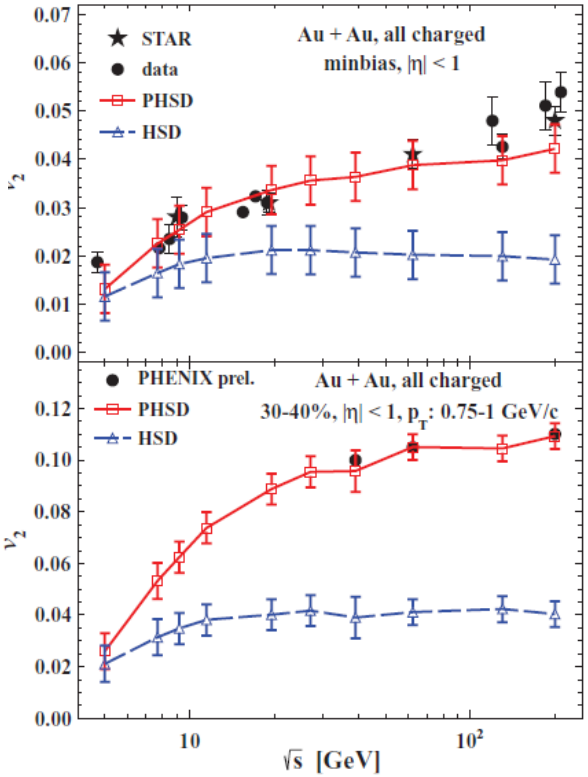
IV. Hadronic phase: hadron-string interactions – off-shell HSD

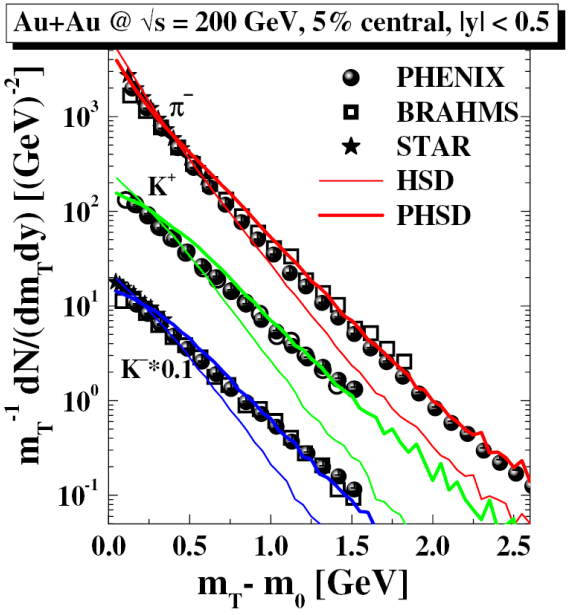
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

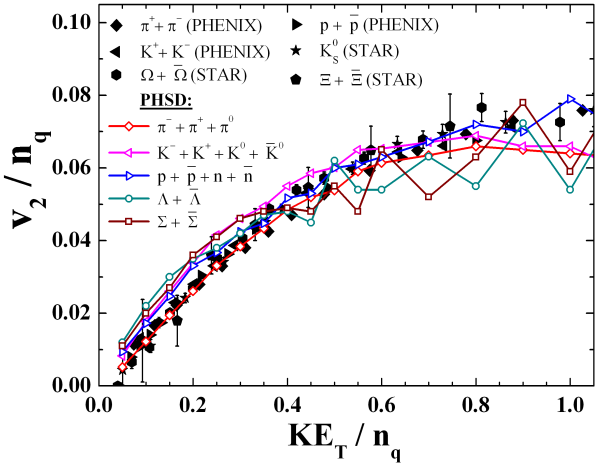
PHSD for HIC (highlights)

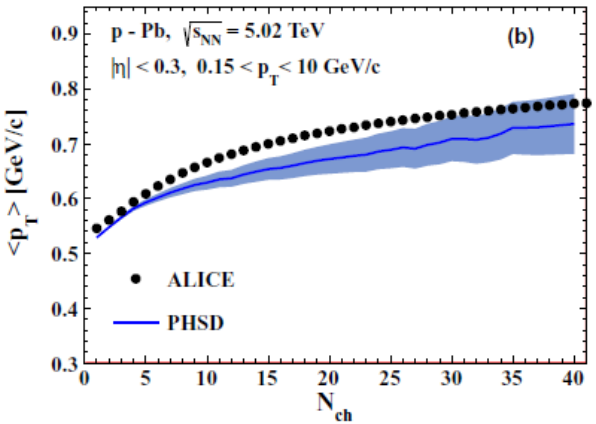


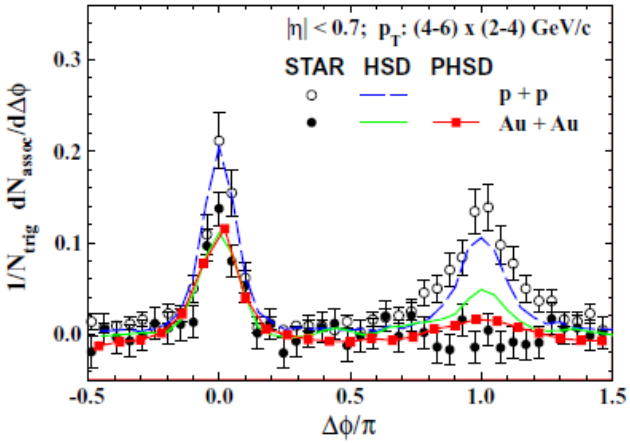








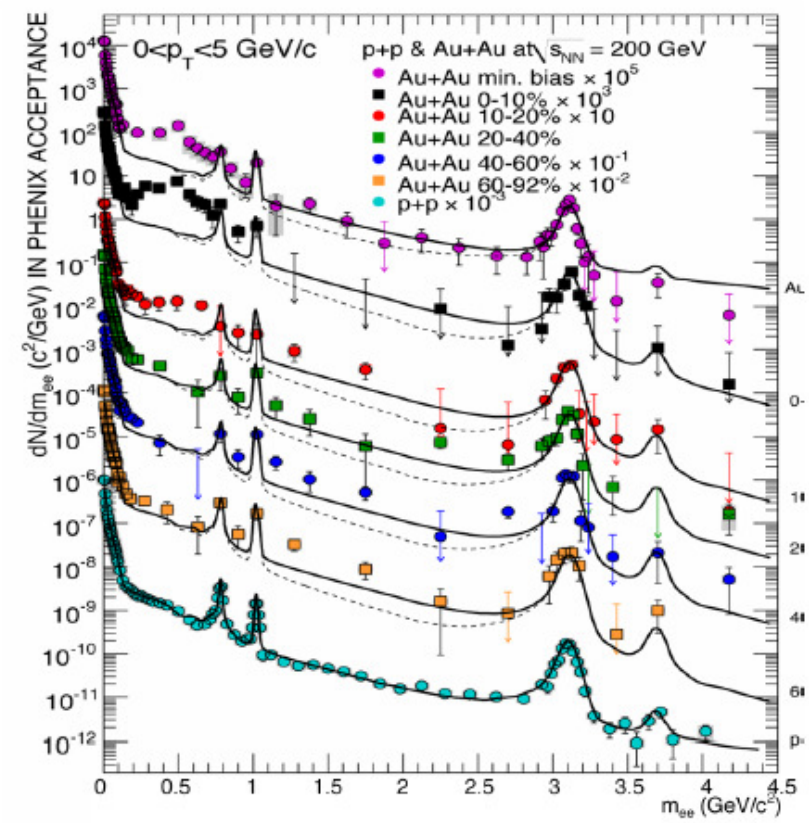


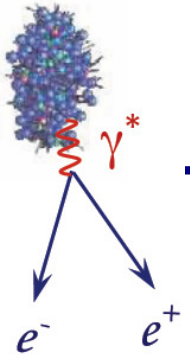


- **PHSD provides a consistent description of HIC dynamics**

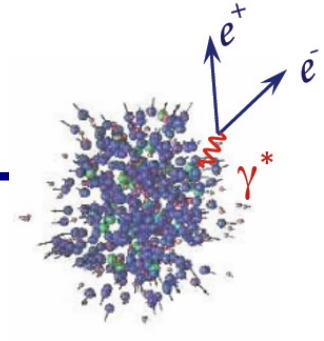
Dileptons: from SPS to LHC

I. PHENIX dilepton puzzle





Electromagnetic probes: dileptons and photons



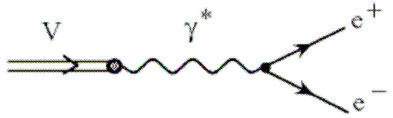
➢ **Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions**

Dilepton sources:

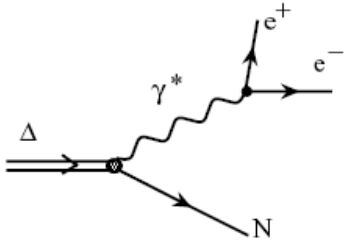
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

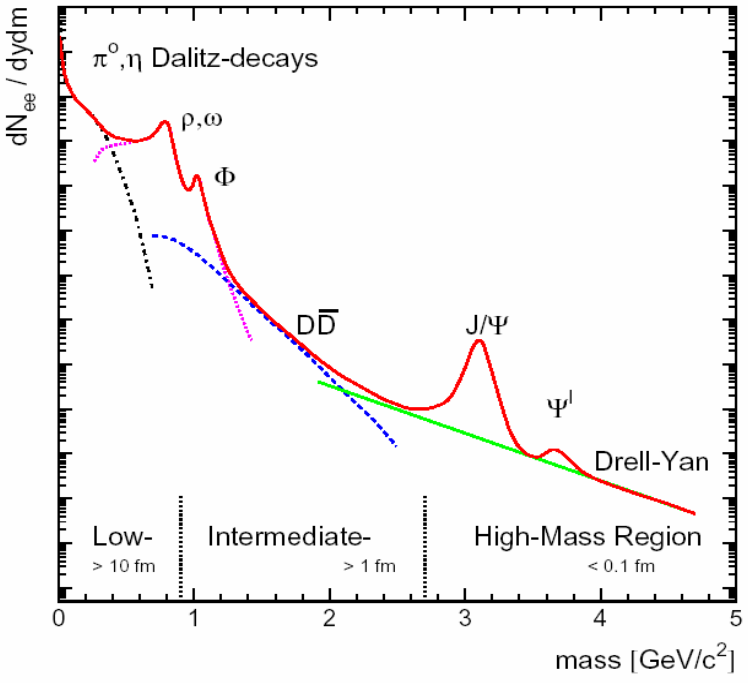
- **direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)**



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



- **correlated D+Dbar pairs**
- **radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π‘**

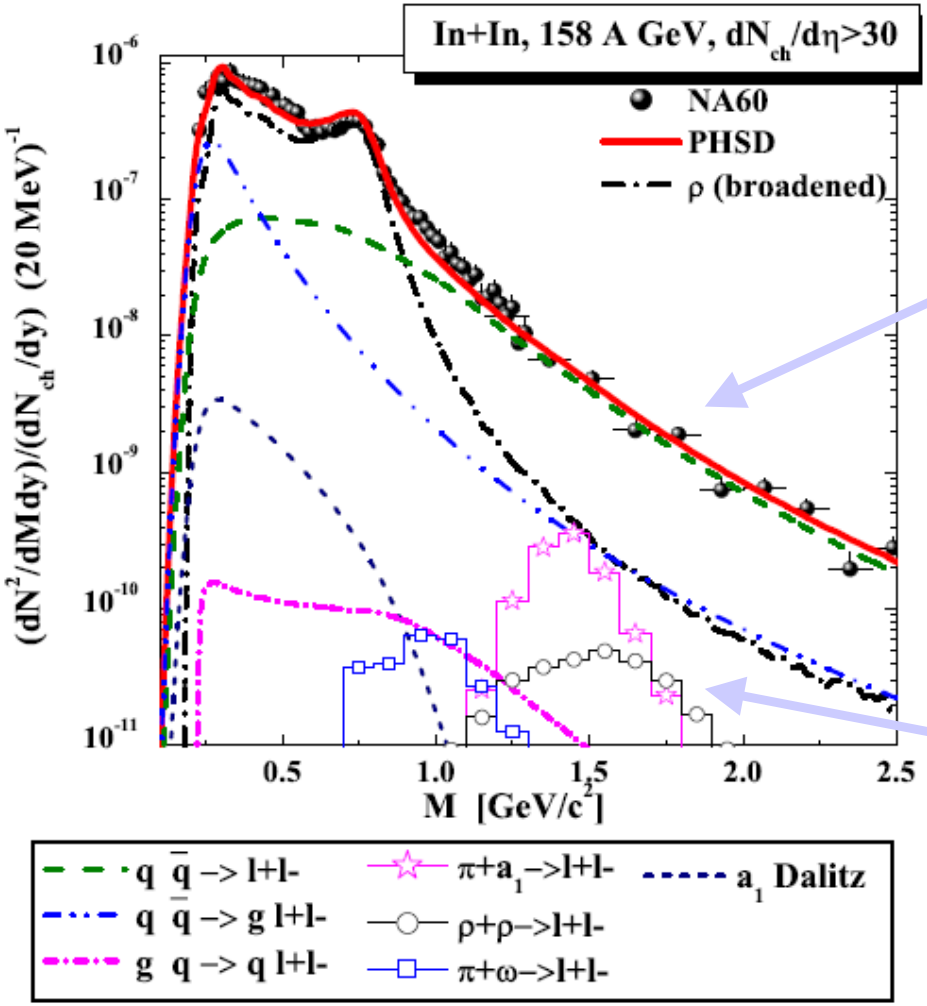


➔ **Dileptons are an ideal probe to study the properties of the hot and dense medium**

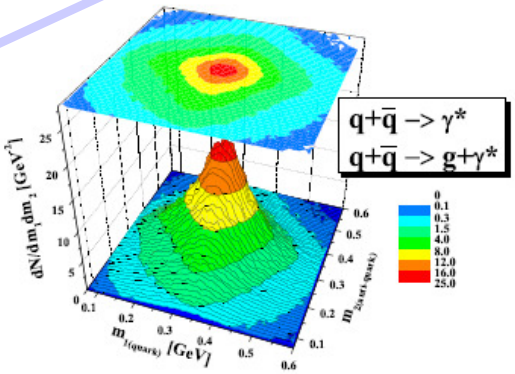
Dileptons at SPS: NA60

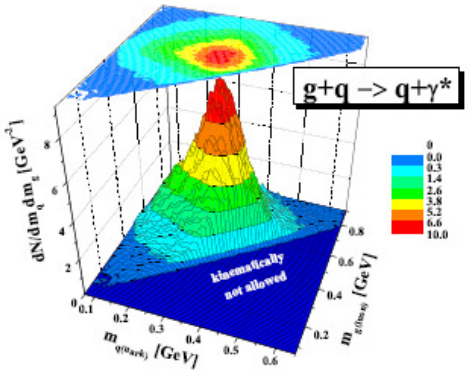
Acceptance corrected NA60 data

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



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

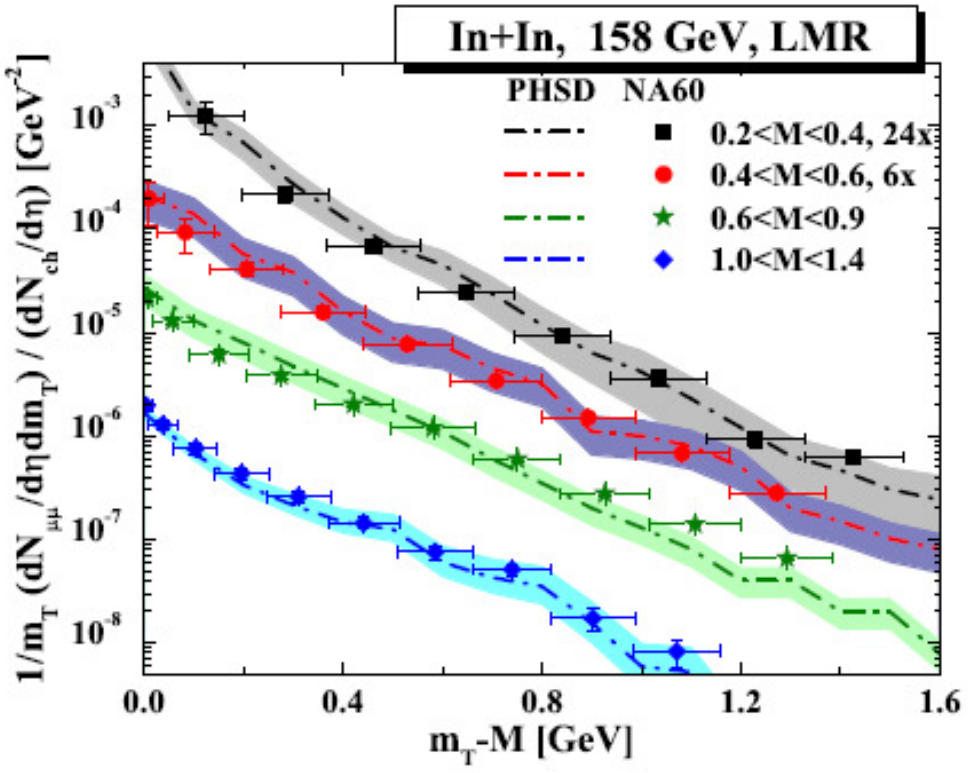




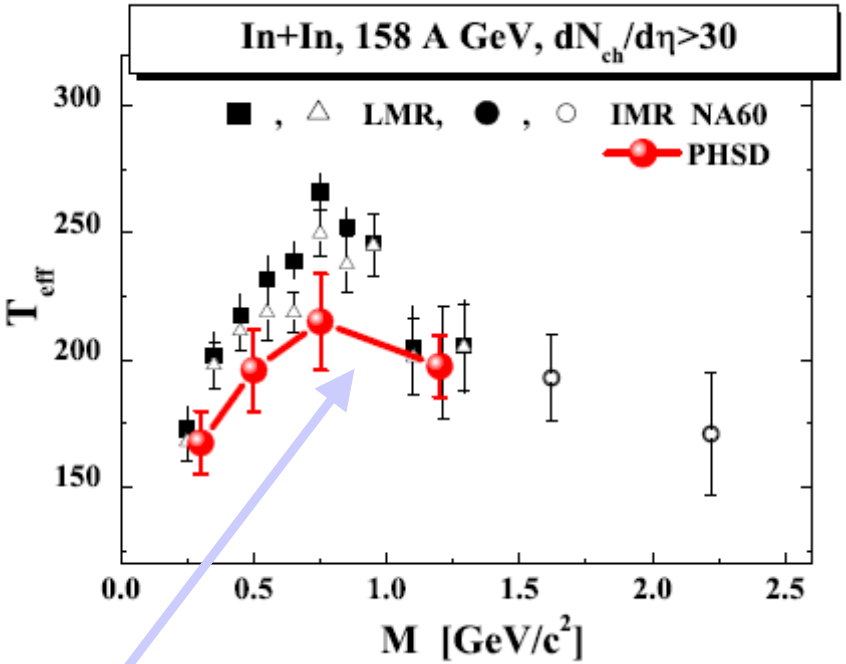
- Contributions of "4π" channels (radiation from multi-meson reactions) are small

* First discussion on "4π" : C. Song, C.M. Ko and C. Gale, PRD50 (1994) R1827

NA60: m_T spectra



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

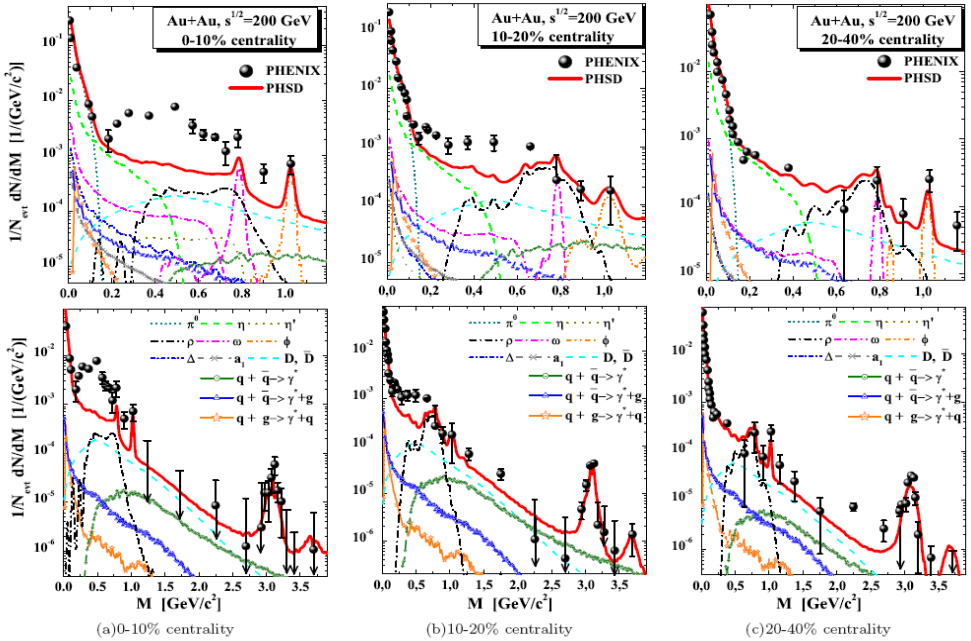


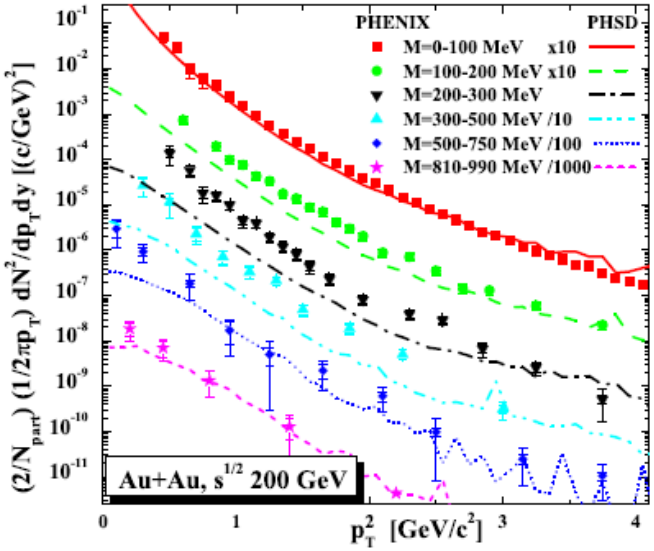
Conjecture:

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

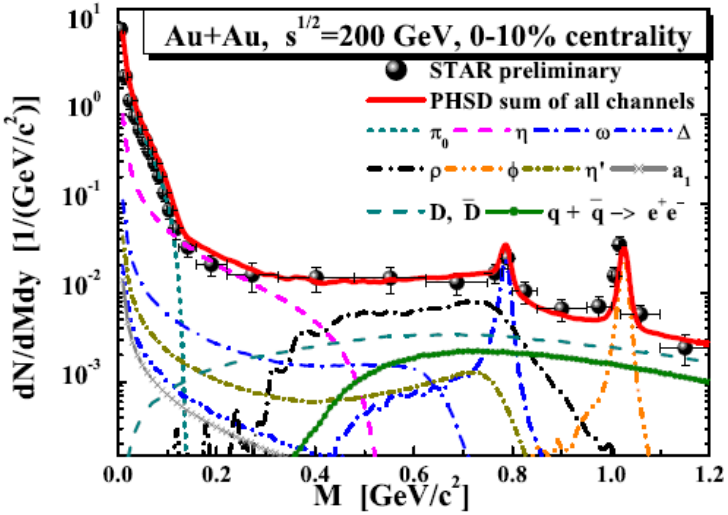
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

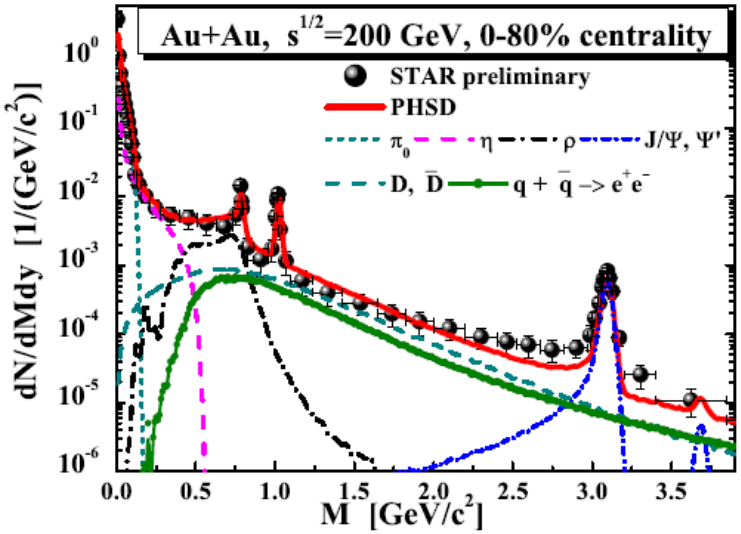
PHENIX vs. STAR dilepton spectra





- **PHENIX: Peripheral collisions (and pp) are well described, however, central fail!**

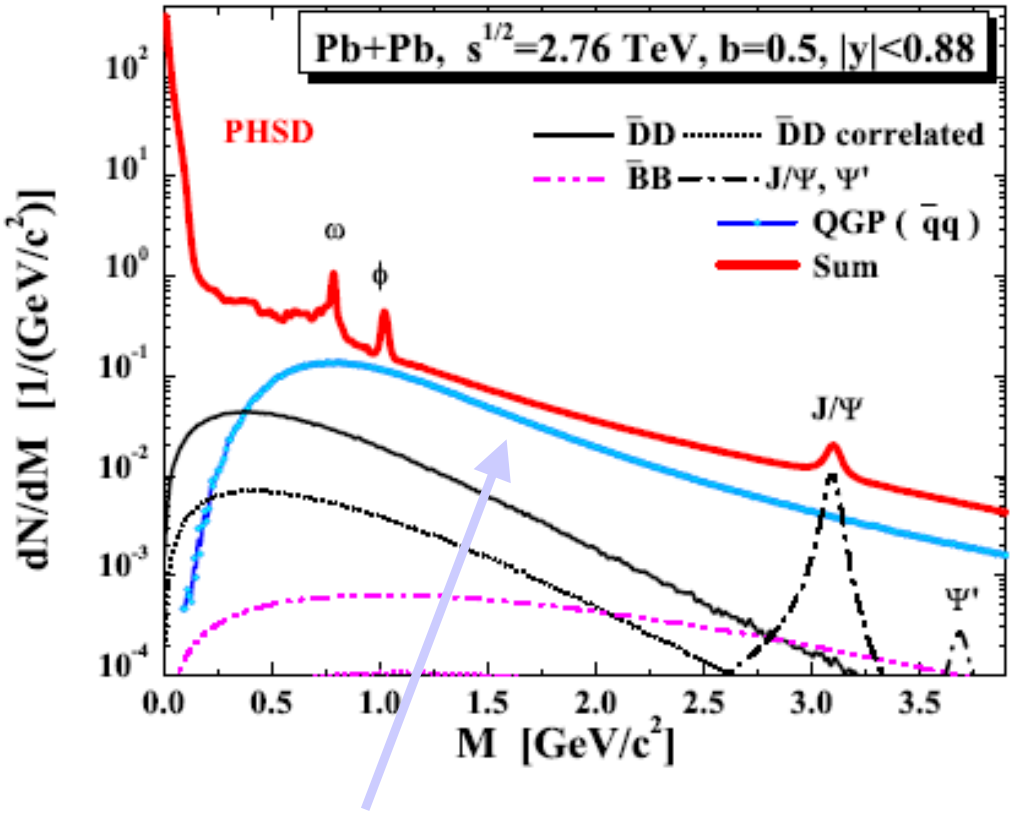


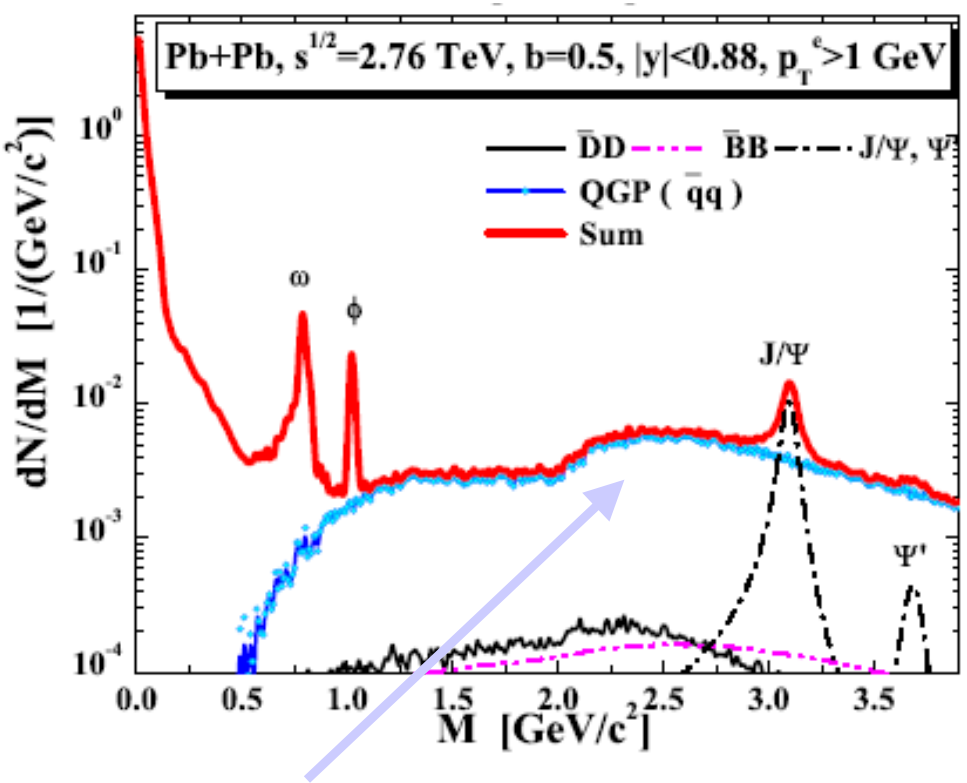


- **STAR data are well described!**

O. Linnyk et al., PRC 85 (2012) 024910

LHC: mass spectra with exp. cuts





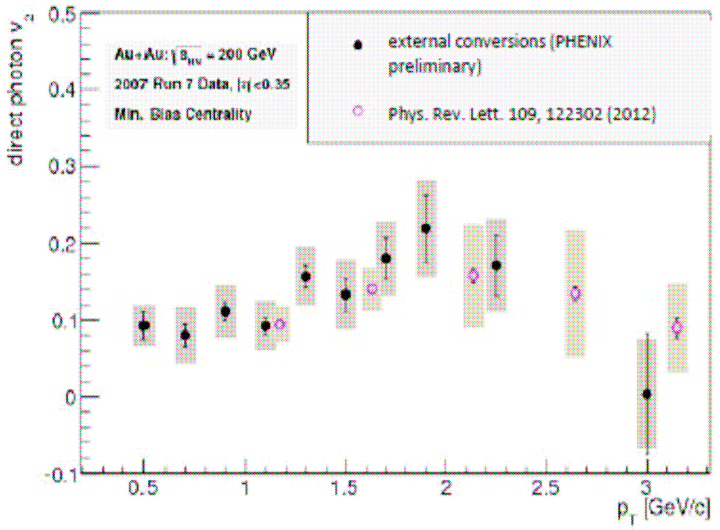
- QGP(qbar-q) dominates at M>1.2 GeV !
- p_T cut enhances the signal of QGP(qbar-q)

D-, B-mesons: from Pol-Bernard Gossiaux and Jörg Aichelin
J/Ψ, Ψ': from C.M. Ko and T. Song

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

Photons from SPS to LHC

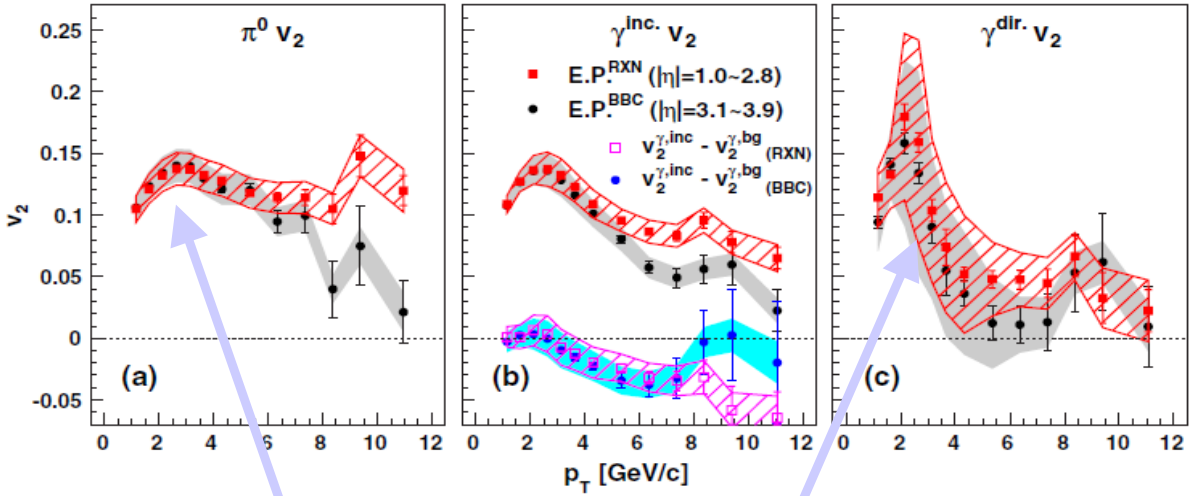
II. Direct photon flow puzzle

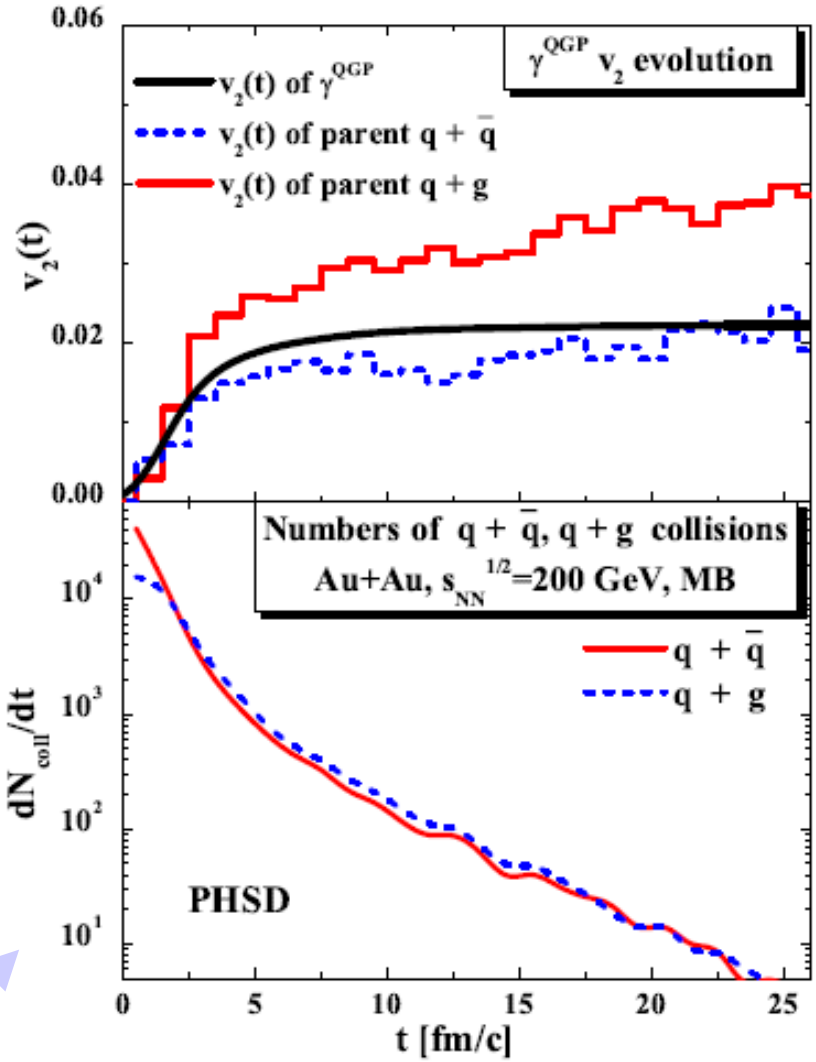


?

EMMI Rapid Reaction Task Force ‚Direct Photon Flow Puzzle‘,
24-28 February 2014, GSI Darmstadt

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!

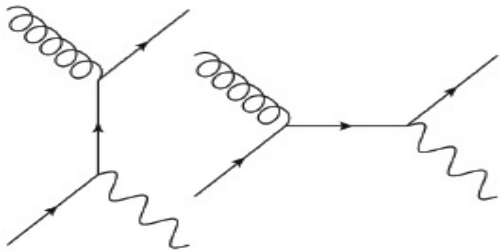
Olena Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Photons from the hot and dense medium

Photon sources:

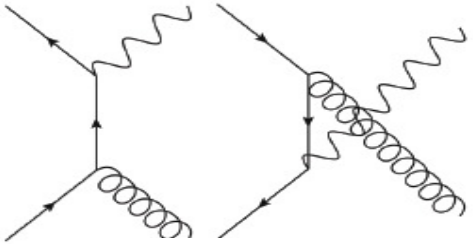
- **from the QGP via partonic interactions:**

Compton scattering



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

q-qbar annihilation



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

- **from hadronic sources:**

- **decays of mesons:**

$$\pi \rightarrow \gamma + \gamma,\ \eta \rightarrow \gamma + \gamma,\ \omega \rightarrow \pi + \gamma$$
$$\eta' \rightarrow \rho + \gamma,\ \phi \rightarrow \eta + \gamma,\ \ a_1 \rightarrow \pi + \gamma$$

- **secondary meson interactions:** $\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma$

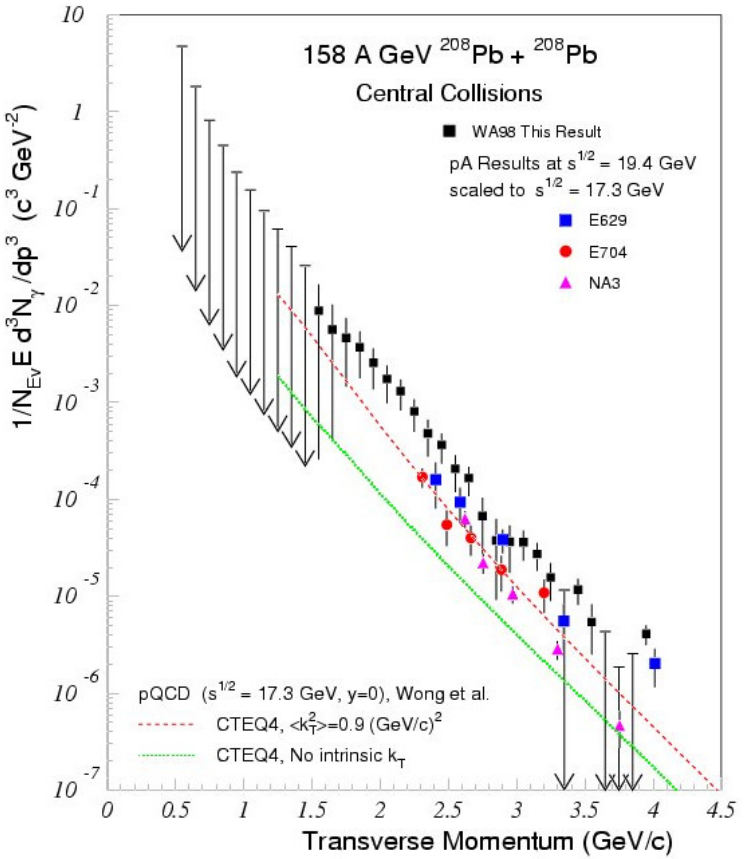
using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

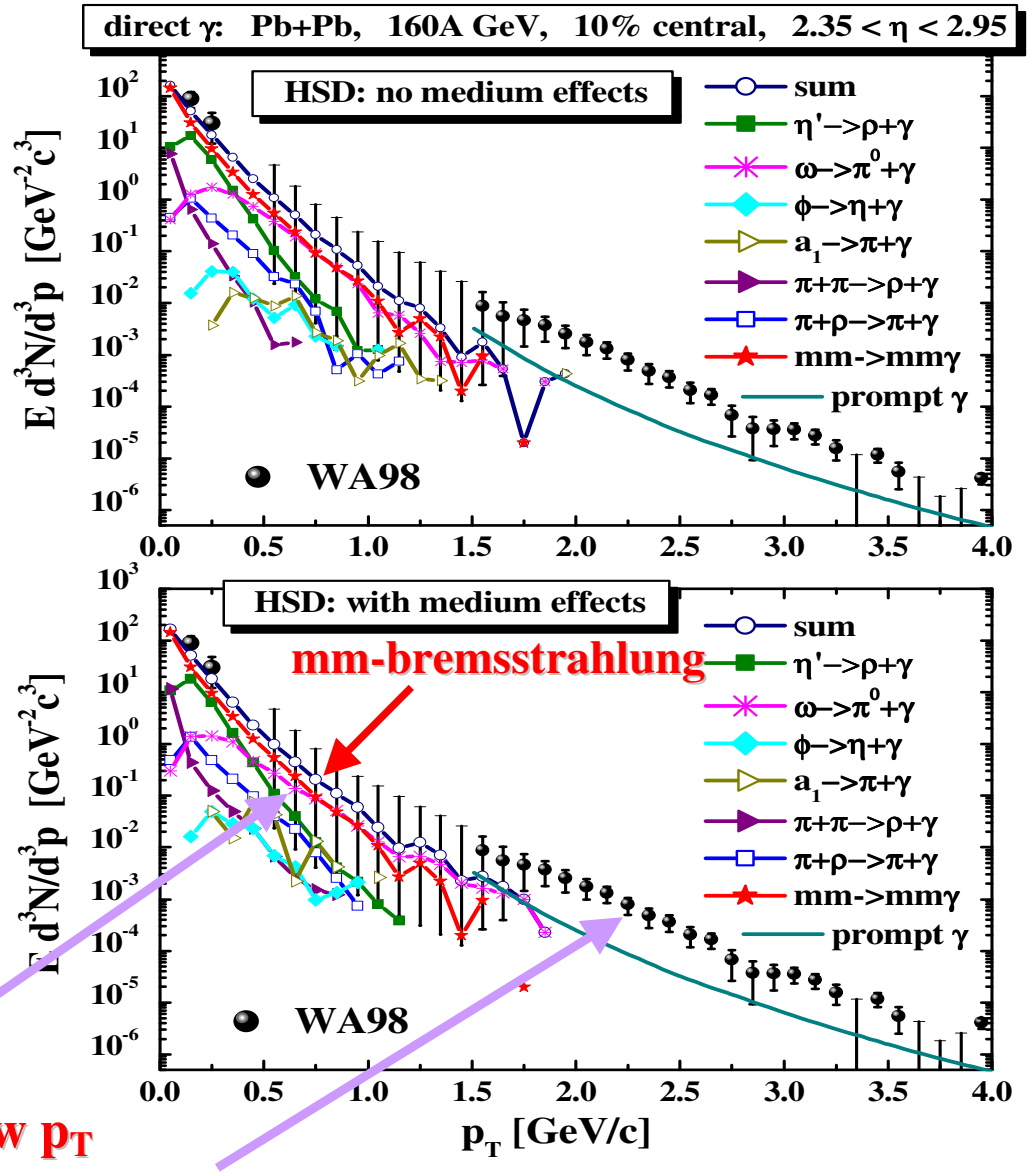
- **meson-meson and meson-baryon bremsstrahlung:**

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

using the soft-photon approximation

Direct photons at SPS: WA98



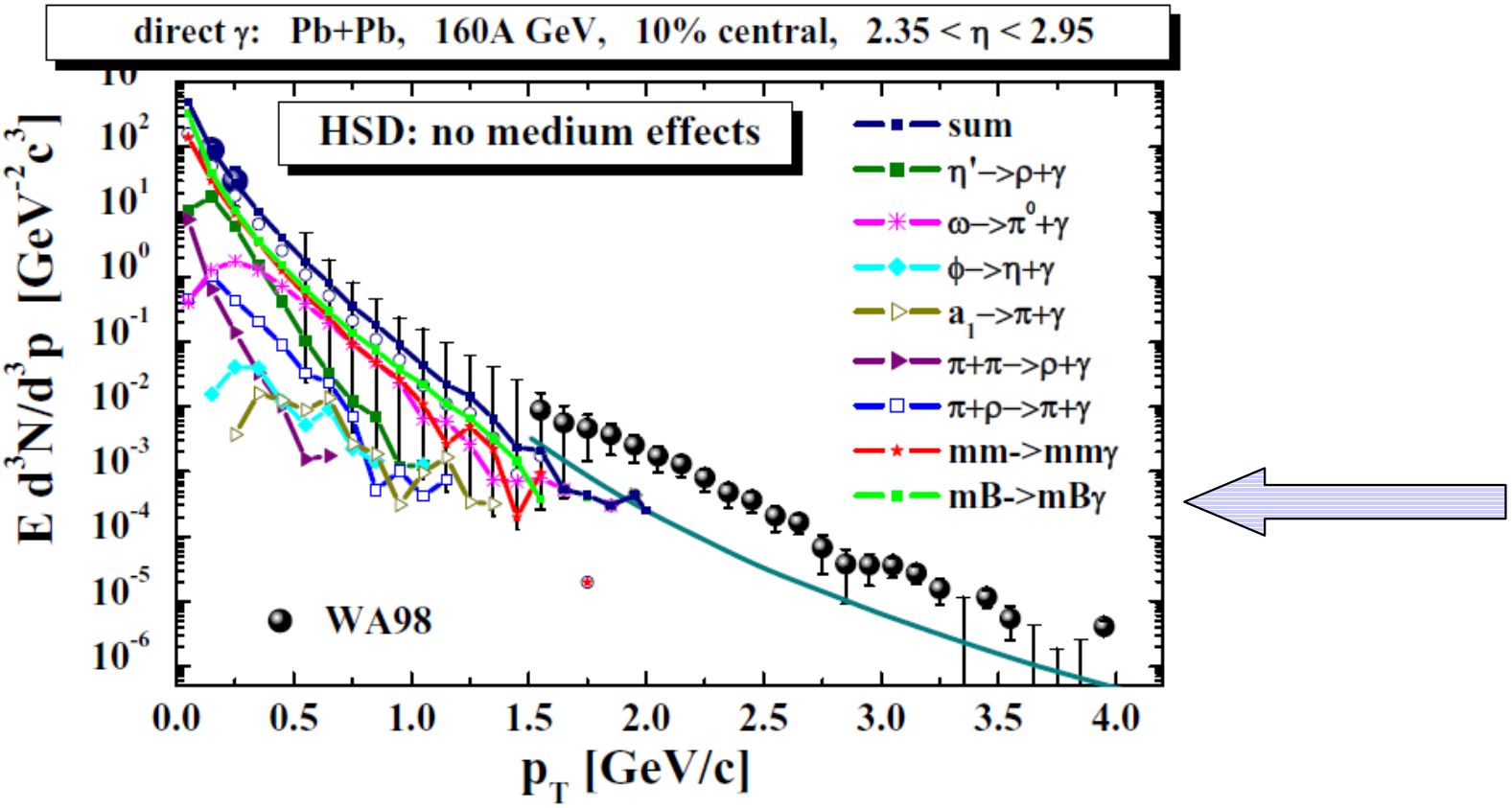


- **Hadronic sources dominate at low p_T**
- **High p_T: dominated by thermal photons from QGP**

E. B., 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**

- **Bremsstrahlung rates are uncertain !!!**

Meson-meson Bremsstrahlung at SPS within SPA

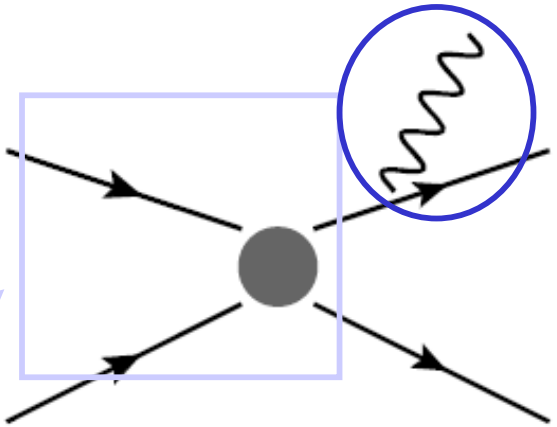
C. Gale, J. Kapusta, Phys. Rev. C 35 (1987) 2107

Soft Photon Approximation:

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

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

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

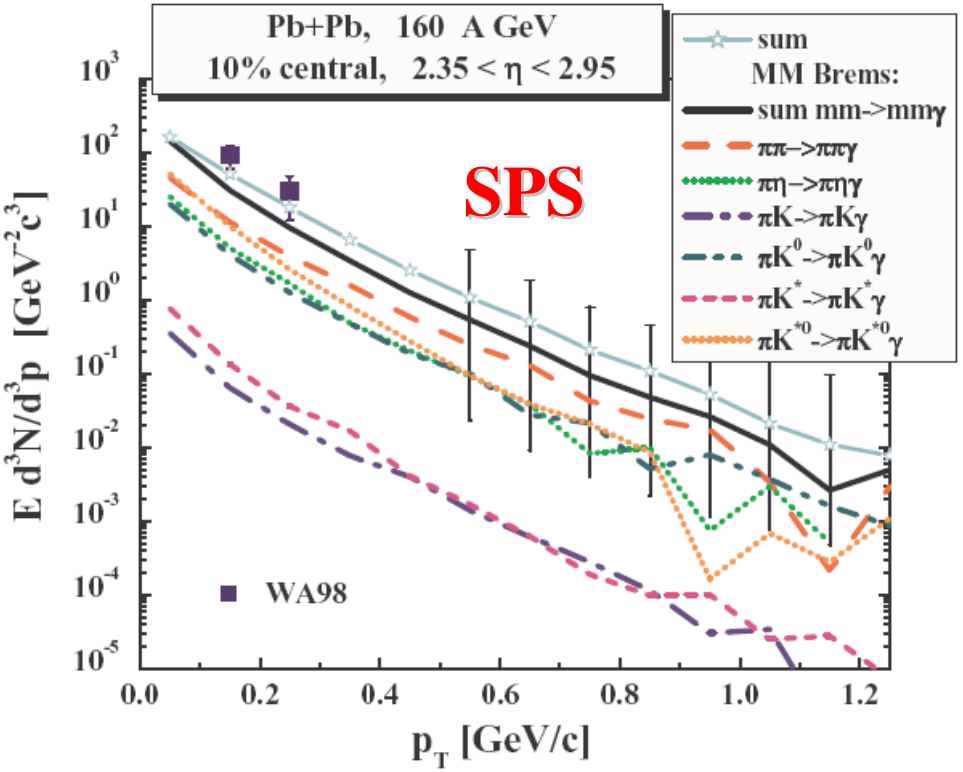


$\sigma(s)$ – elastic meson-meson cross section

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

- Taken $\sigma(s)$ =10 mb for ALL m_1+m_2 channels !
- No isospin factors!

➔ Needs to be improved!



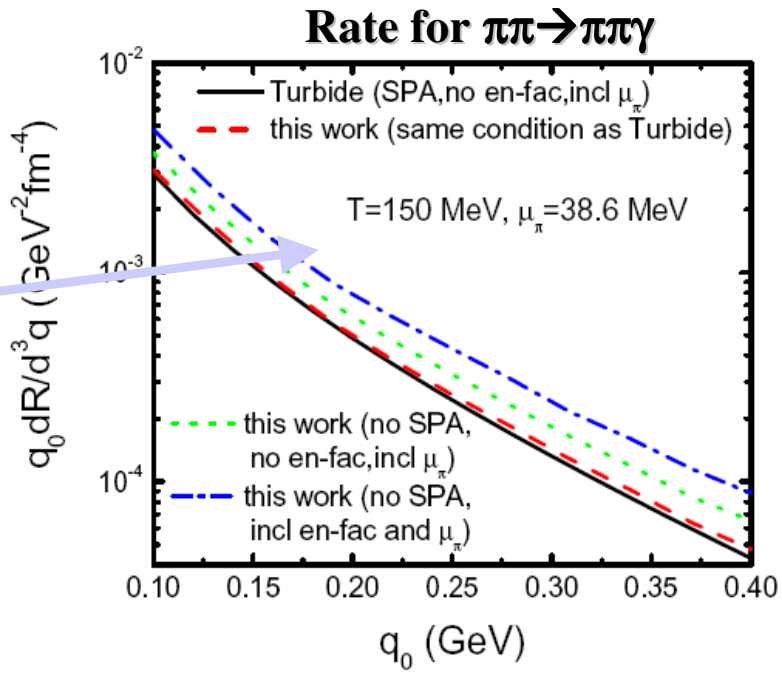
E. B., S.M. Kiselev, and G.B. Sharkov, PR C78 (2008) 034905

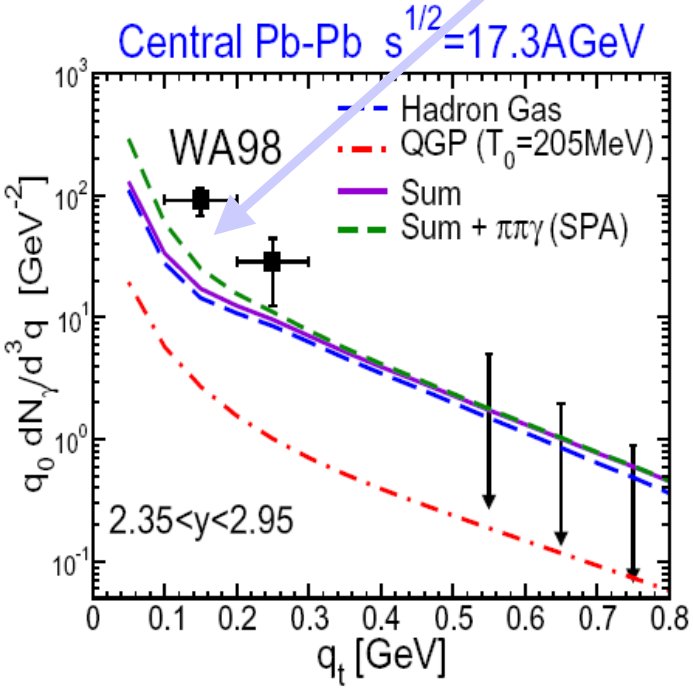
mm bremsstrahlung beyond SPA

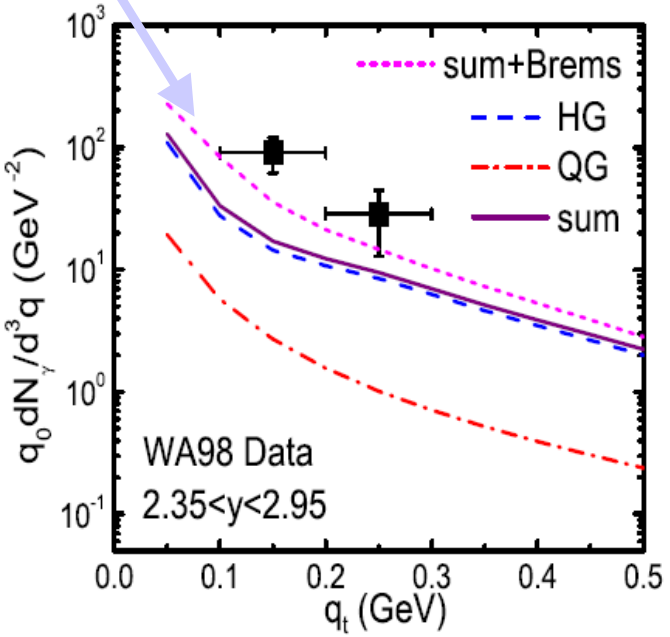
W. Liu and R. Rapp, Nucl. Phys. A 96 (2007) 101

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

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

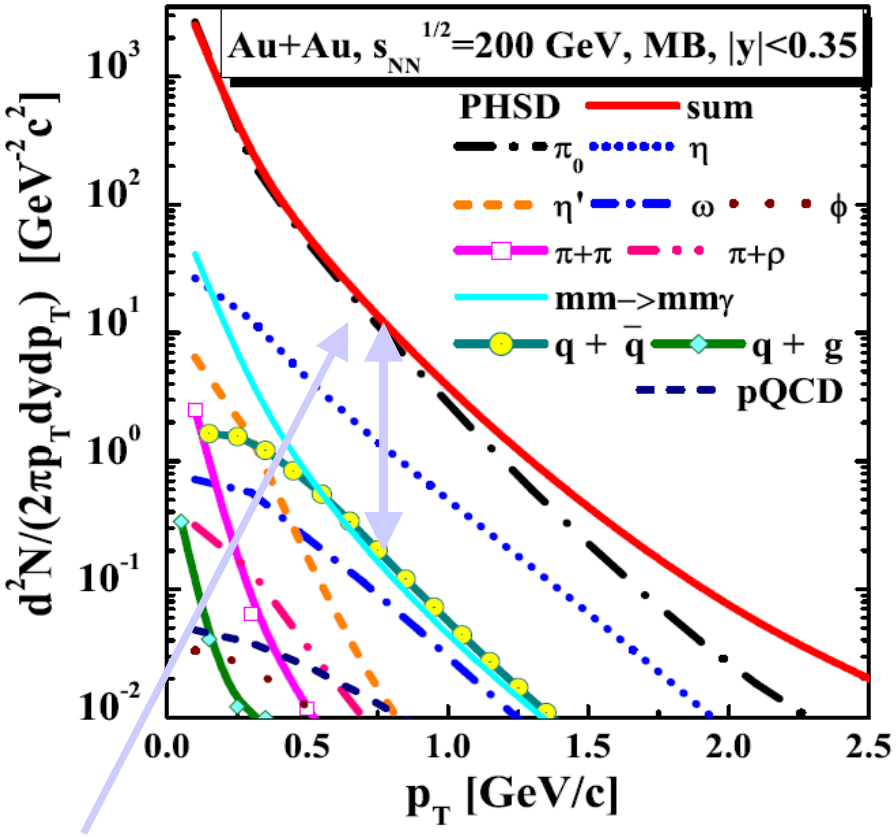




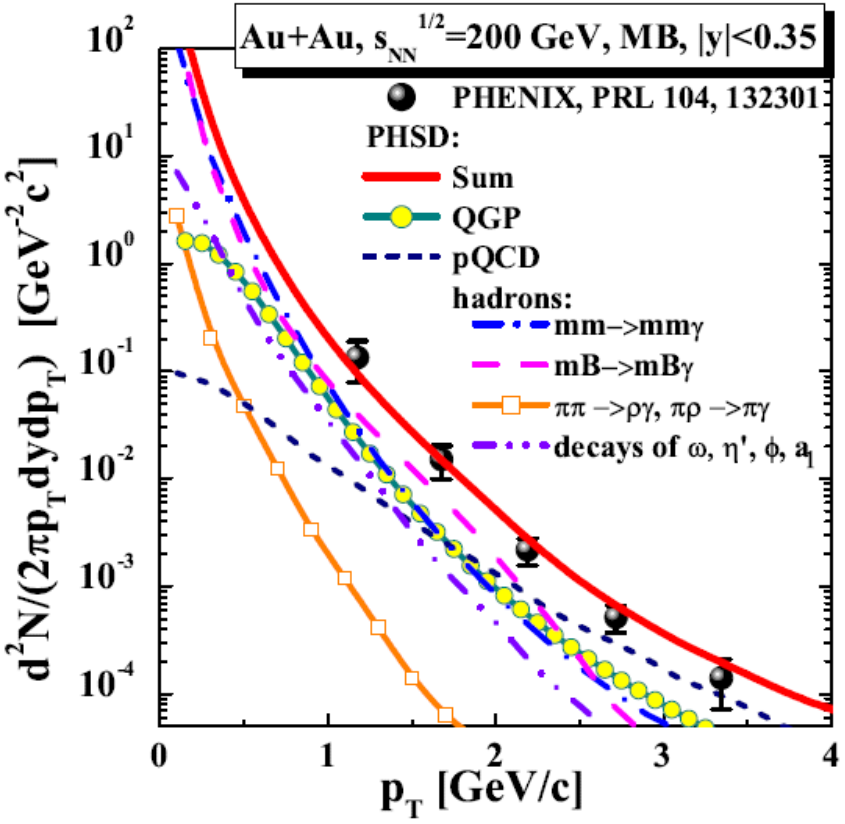


Photon spectra at RHIC

- Inclusive photon spectrum



- π^0 and η subtracted photon spectrum



- π^0 and η decays dominate the low p_T spectra

- QGP sources mandatory to explain the spectrum (~50%), but hadronic sources are considerable, too !

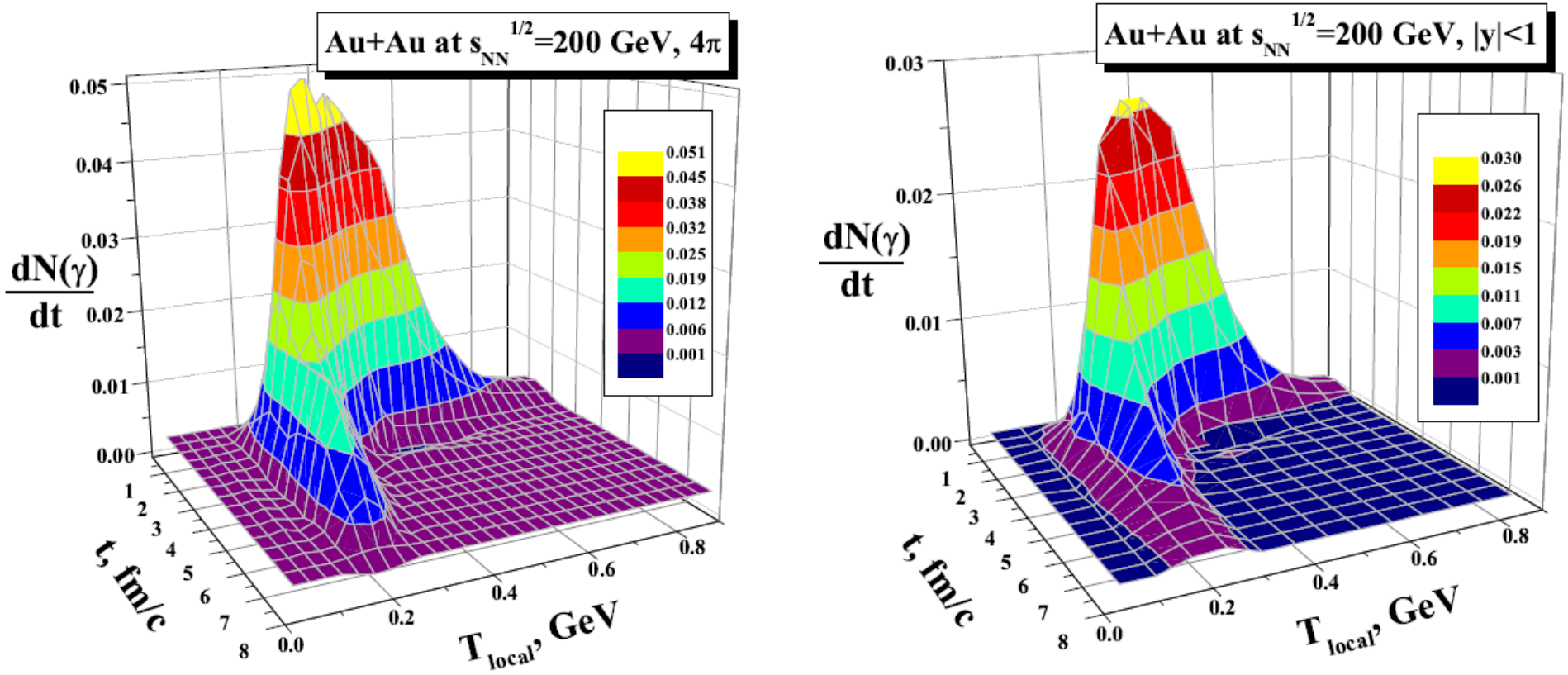
- The 'effective temperature' T_{eff}:

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

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Time evolution of the photon production rate vs. T

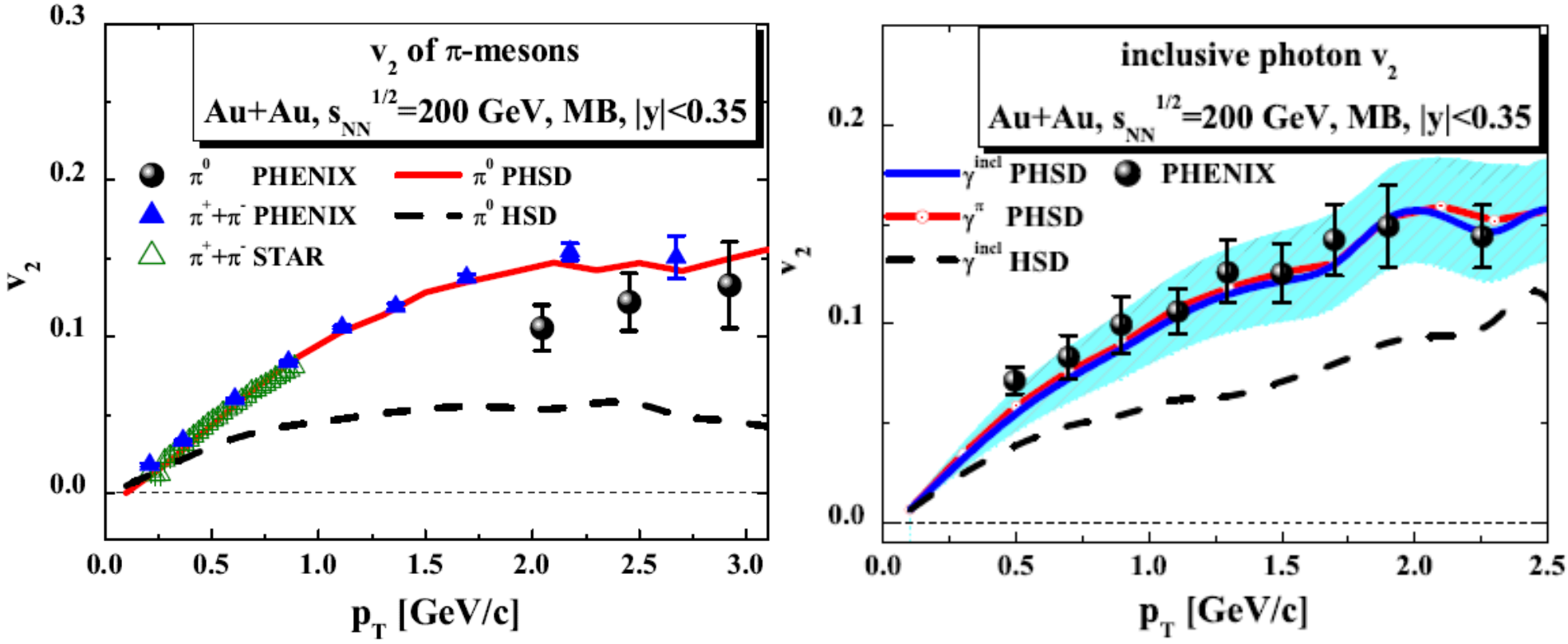
- **The photon production rate versus time and the local 'temperature' at the production point in 4π and mid-rapidity Au+Au collisions:**



- **Broad distribution of 'temperatures' ➔ no universal 'temperature' can be assigned to the whole volume of the QGP - even in the mid-rapidity region !**

Olena Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Inclusive photon elliptic flow

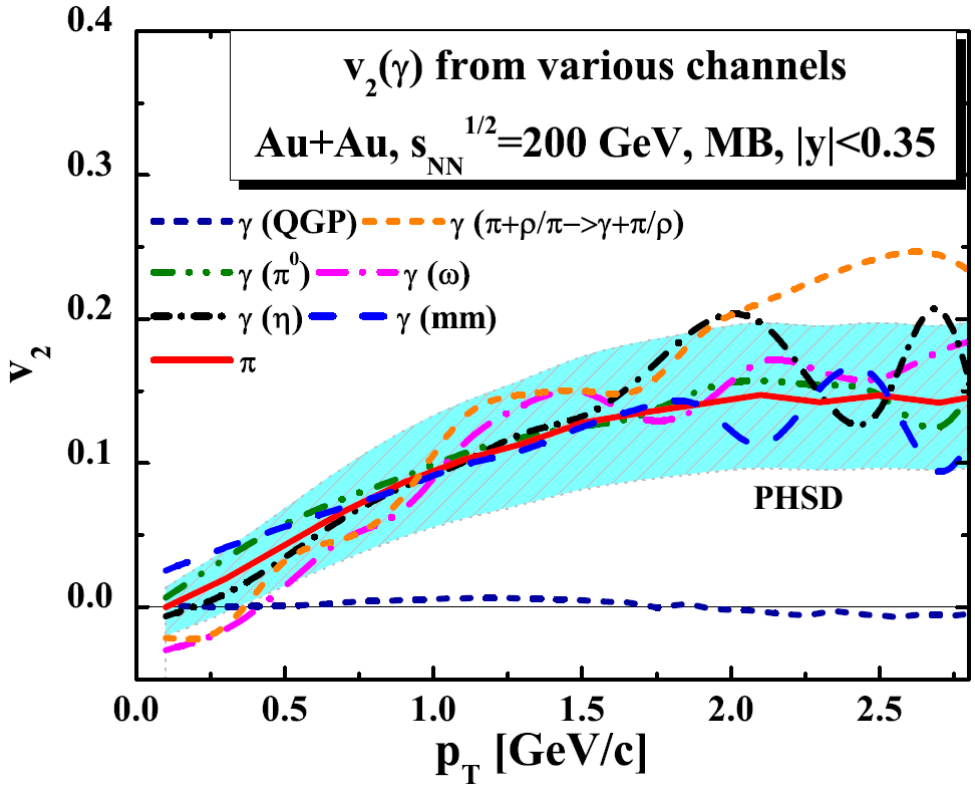


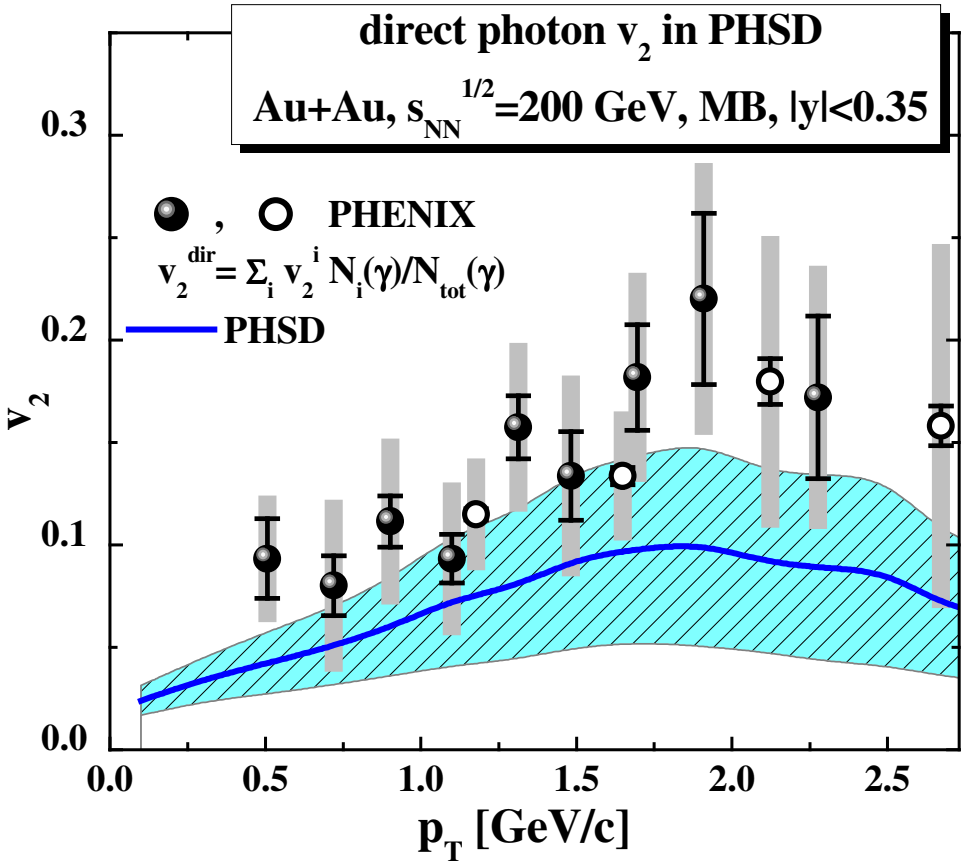
- **Pion elliptic flow is reproduced in PHSD and underestimated in HSD (i.e. without partonic interactions)**
- **➔ large inclusive photon v_2 - comparable to that of hadrons - is reproduced in PHSD, too, because the inclusive photons are dominated by the photons from pion decay**

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Elliptic flow of direct photons

❑ Sum of v_2 of the individual channels, using their contribution to the spectra with the relative p_T -dependent weights $w_i(p_T)$:



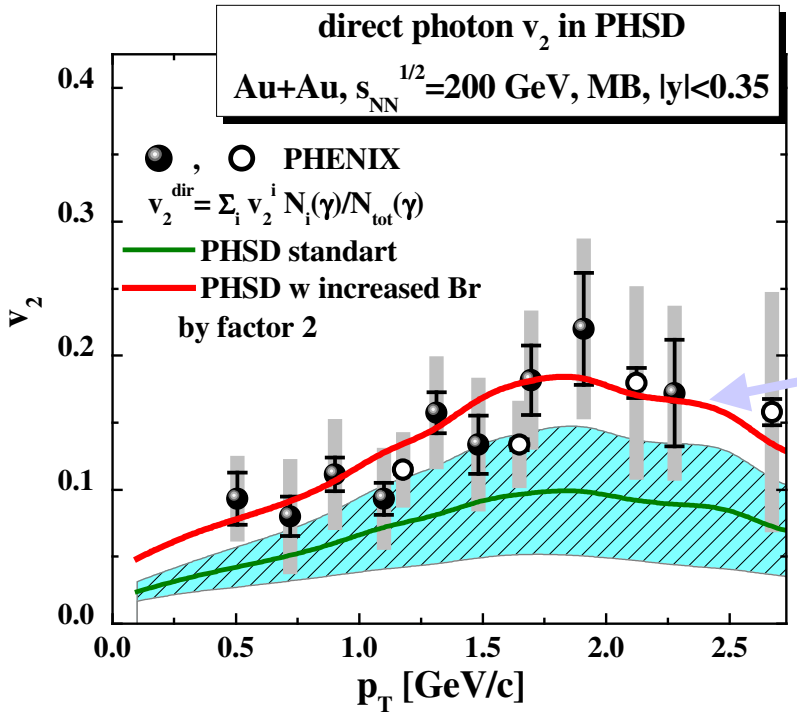


➔ v_2 of direct photons in PHSD - as evaluated by the weighted average of direct photon channels – underestimates the exp. data

O. Linnyk et al. Phys.Rev. C88 (2013) 034904; Phys. Rev. C 89 (2014) 034908

Towards the solution of the v_2 puzzle

- **Is bremsstrahlung a solution?**



Bremsstrahlung increased by a factor 2

(might be due to the uncertainties in SPA and mm mB elastic cross sections)

Other ideas:

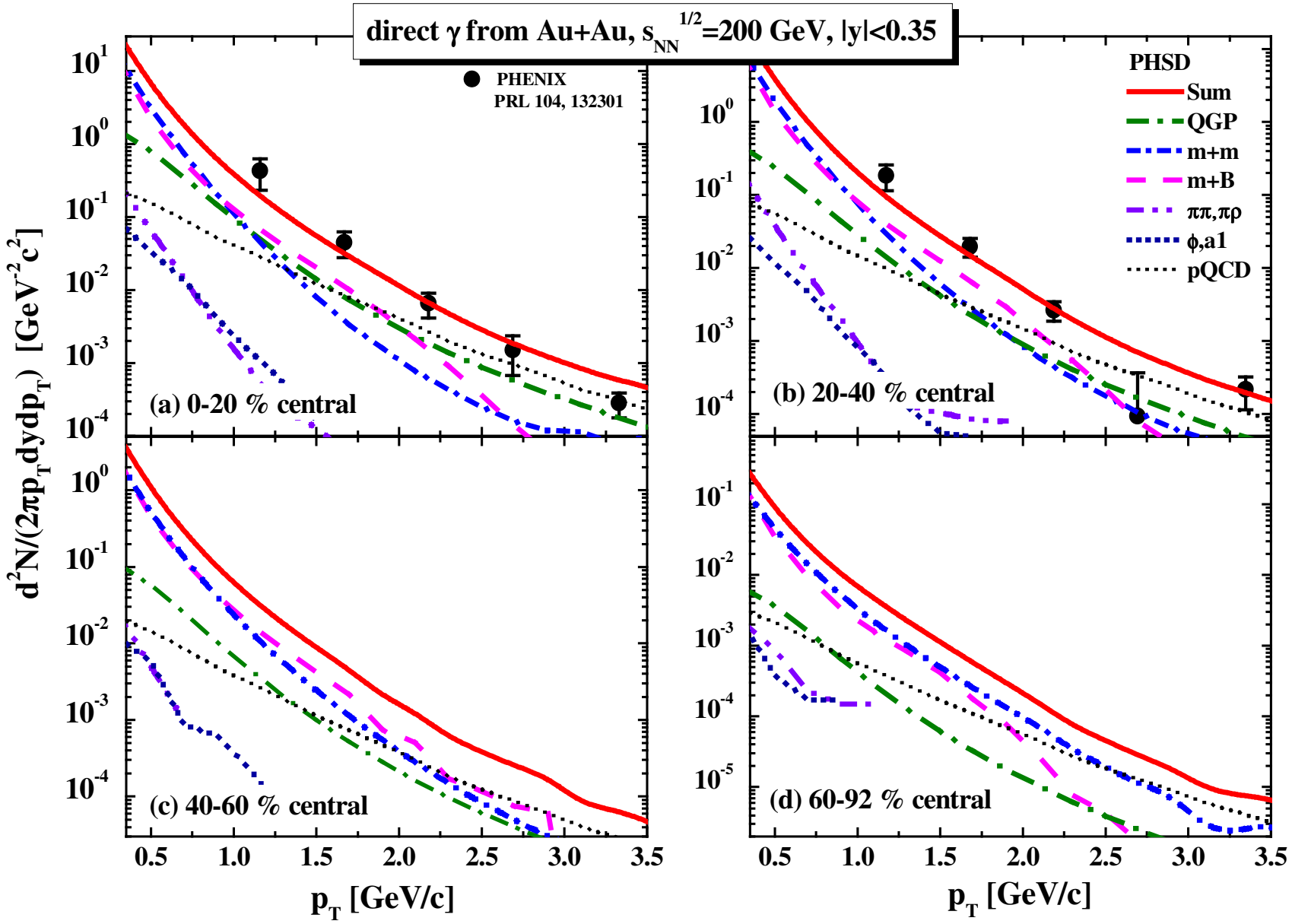
- **Early-time magnetic field effects ?**

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

- **Glasma effects ?** (L. McLerran)
- **Primodial flow ?** (R. Rapp, H. van Hees)
- **???**

➢ **More experimental information is needed ➔ new PHENIX data on centrality dependence**

Centrality dependence of the direct photon yield



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

Centrality dependence of the ‚thermal' photon yield

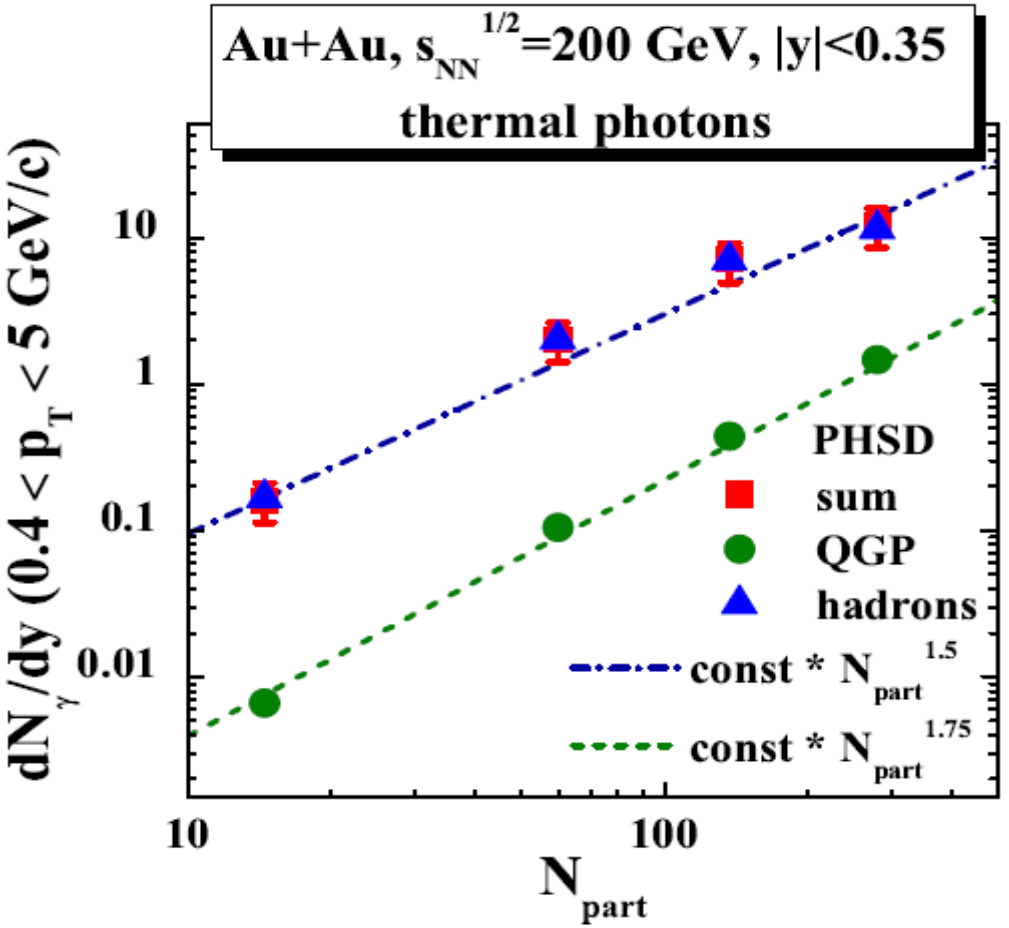
- **'Thermal' photon yield = direct photons - pQGP - hadronic decays - secondary meson interactions**

Hadronic channels scale as

$\sim N_{part}^{1.5}$

Partonic channels scale as

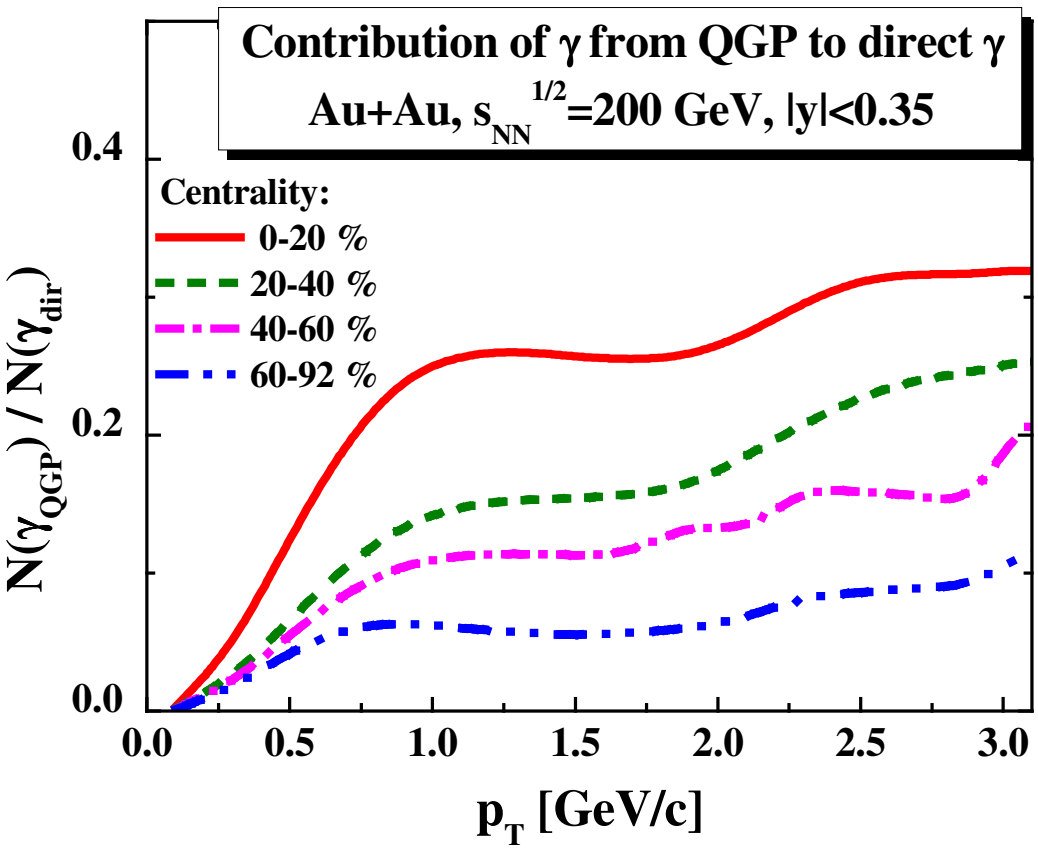
$\sim N_{part}^{1.75}$

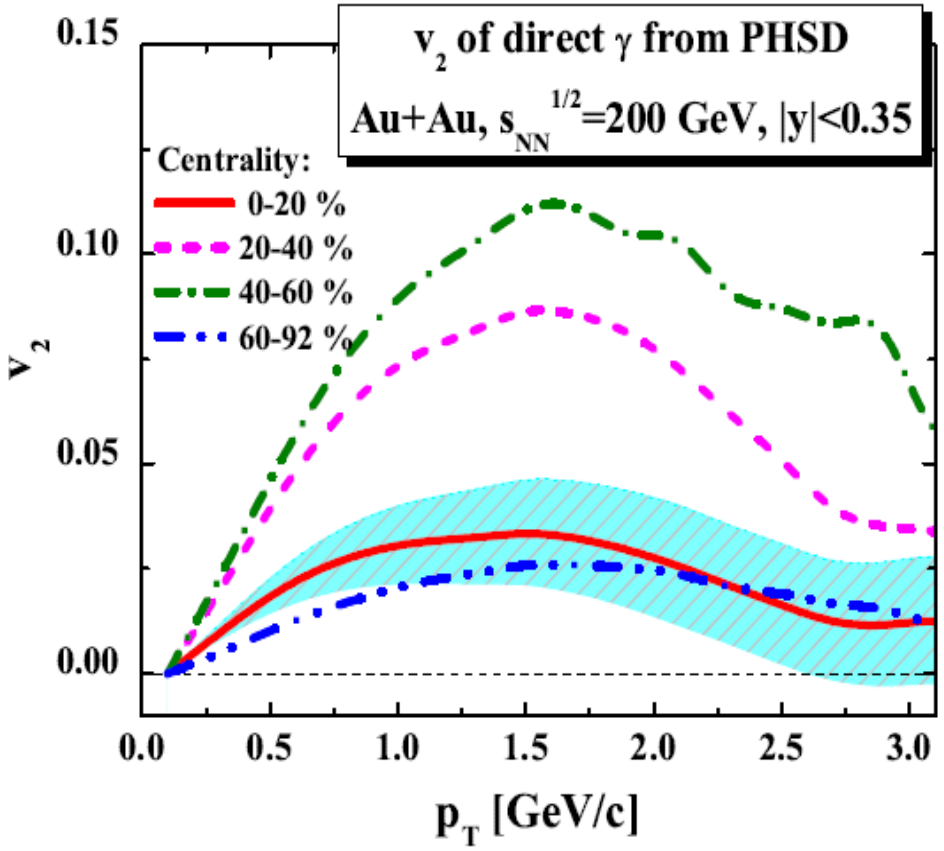


➔ **PHSD: scaling of the direct photon yield with the number of participants to the power 1.5**

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

Centrality dependence of the ‚thermal' photon v_2

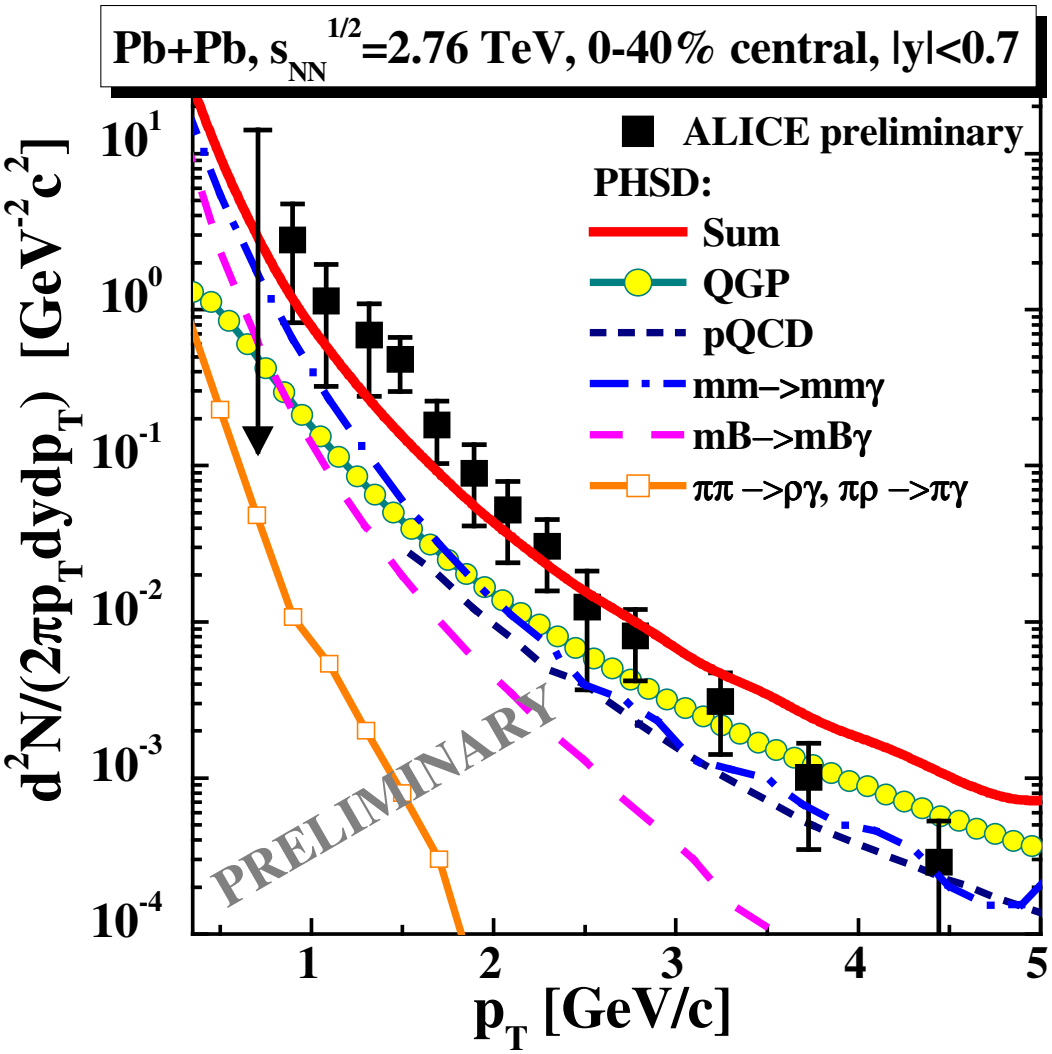


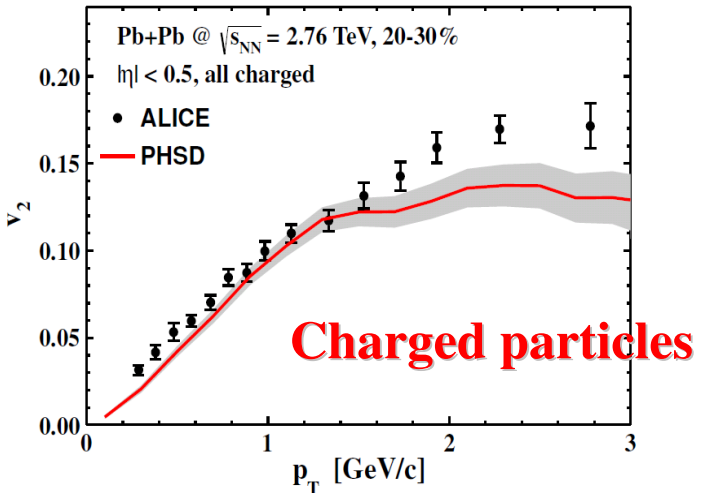


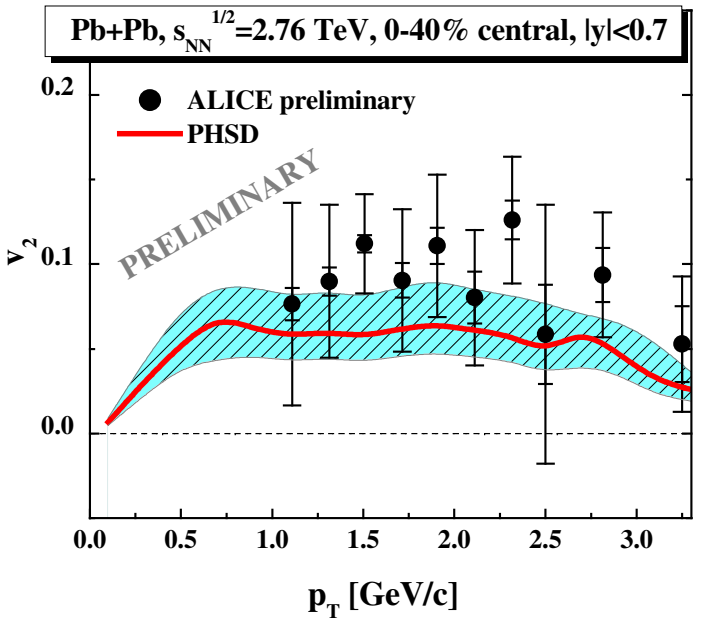
- The contribution of the QGP photons decreases substantially for more peripheral collisions and the photon elliptic flow increases accordingly.

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

Preliminary PHSD results for Pb+Pb at 2.76 TeV







❑ **Considerable elliptic flow of direct photons at the LHC reflects the importance of hadronic scattering channels. However, the photon elliptic flow is lower than at RHIC due to a larger/longer relative QGP contribution.**

Summary

I. Dilepton spectra - according to the PHSD predictions - show sizeable changes due to the different in-medium scenarios (as collisional broadening and dropping mass) which can be observed experimentally

- **In-medium effects can be observed at all energies from SIS to LHC**
- **At SPS, RHIC and LHC the QGP (qbar-q) dominates at M>1.2 GeV**

II. Direct photons - the photons produced in the QGP contribute about 50% to the observed spectrum, but have small v2

- **Large direct photon v_2 – comparable to that of hadrons – is attributed to the intermediate hadronic bremsstrahlung and hadronic scattering channels not subtracted from the data**
- **The QGP phase causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interaction in terms of explicit parton collisions and the mean-field potentials**

PHSD group

FIAS & Frankfurt University
Elena Bratkovskaya
Rudy Marty
Hamza Berrehrah
Daniel Cabrera
Taesoo Song
Andrej Ilner

Giessen University
Wolfgang Cassing
Olena Linnyk
Volodya Konchakovski
Thorsten Steinert
Alessia Palmese

External Collaborations

SUBATECH, Nantes University:
Jörg Aichelin
Christoph Hartnack
Pol-Bernard Gossiaux
Vitalii Ozvenchuk

Texas A&M University:
Che-Ming Ko

JINR, Dubna:
Viacheslav Toneev
Vadim Voronyuk

BITP, Kiev University:
Mark Gorenstein

Barcelona University:
Laura Tolos
Angel Ramos

Thank you!