XXII International Baldin Seminar
on High Energy Physics Problems
*Relativistic Nuclear Physics &
Quantum Chromodynamics*
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Photons probe the QCD matter

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September 19, 2014

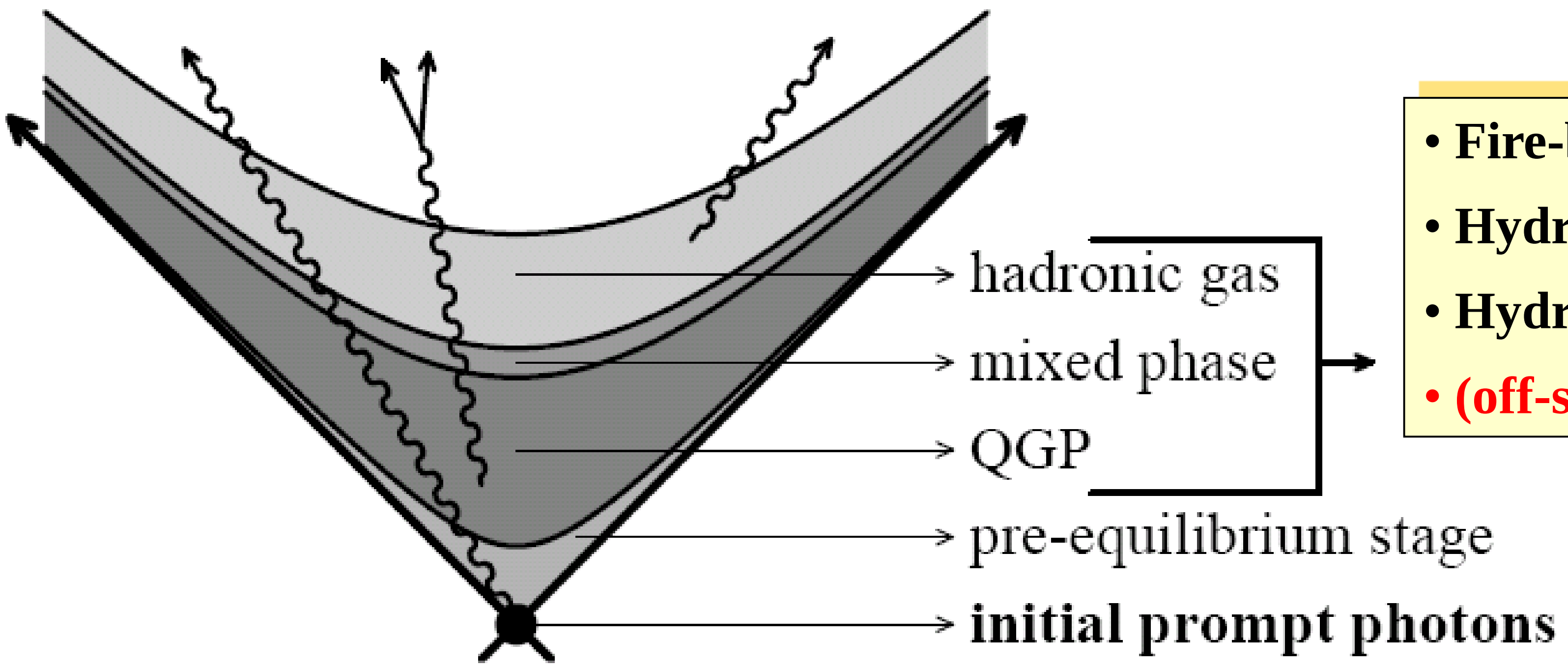
JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

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.

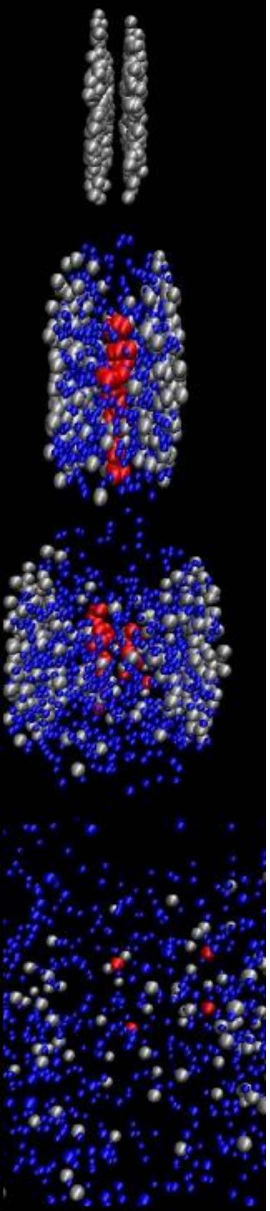
➔ Require models to describe the emission during the whole collision evolution



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

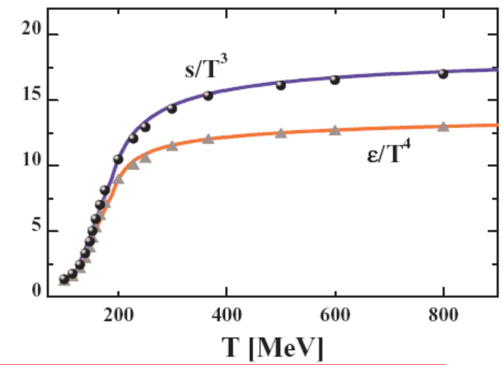
Graphics from the slides by D. Srivastava.

Parton-Hadron-String Dynamics



PHSD is a non-equilibrium relativistic off-shell transport model, microscopic description of the full heavy-ion collision evolution:

- **phase transition from hadrons to partons**
- **lQCD EoS**
- **explicit interaction between quarks and gluons**
- **dynamical hadronization**
- **off-shell hadronic collision dynamics in the later 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**

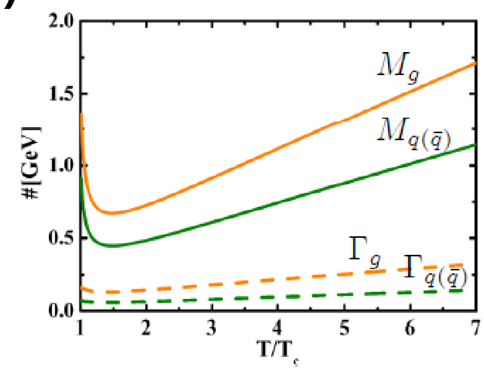
  - massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in self-generated mean-field potential

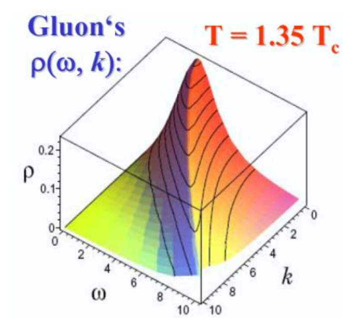
- **Spectral functions:**

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

$(i = q, \bar{q}, g)$

❑ **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 systems!)**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215, W. Cassing, EPJ ST 168 (2009) 3
W. Cassing, E.L. Bratkovskaya, Nucl.Phys. A831 (2009) 215; E.L.Bratkovskaya et al, NPA856 (2011) 162

Boltzmann equation -> off-shell transport

$$\left(\frac{\partial}{\partial t} + \vec{v}_1 \cdot \nabla_{\vec{r}} + \frac{\vec{K}}{m} \cdot \nabla_{\vec{v}_1}\right) f_1 = \int d\Omega \int d\vec{v}_2\, \sigma(\Omega)\, |\vec{v}_1 - \vec{v}_2| \left(f_1' f_2' - f_1 f_2\right)$$

GENERALIZATION

(First order gradient expansion of the Wigner-transformed Kadanoff-Baym equations)

drift term **Vlasov term** **backflow term** **collision term = ‚loss' term - ‚gain' term**

$$\diamond\{P^2 - M_0^2 - Re\Sigma_{XP}^{ret}\}\{S_{XP}^{<}\} - \diamond\{\Sigma_{XP}^{<}\}\{ReS_{XP}^{ret}\} = \frac{i}{2}\left[\Sigma_{XP}^{>} S_{XP}^{<} - \Sigma_{XP}^{<} S_{XP}^{>}\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation
! vanishes in the quasiparticle limit $A_{XP} = 2\pi\,\delta(p^2-M^2)$

Propagation of the Green's function $iS^{<}_{XP}=A_{XP} f_{XP}$, which carries information not only on the number of particles, but also on their properties, interactions and correlations

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma_{XP}^{ret})^2 + \Gamma_{XP}^2/4}$$

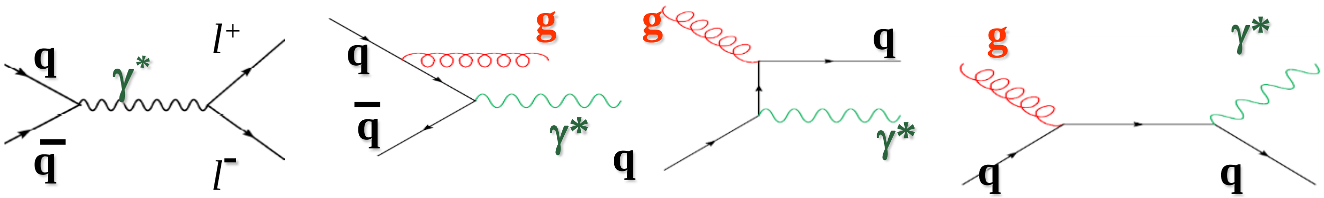
$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

Γ_{XP} – width of spectral function = reaction rate of a particle (at phase-space position XP)

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 4451

Dileptons sources

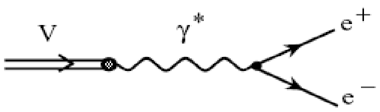
1) from the QGP via partonic (q,qbar, g) interactions:



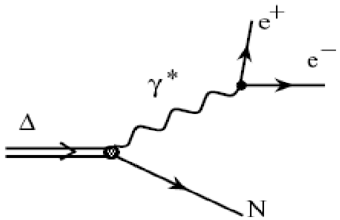
beyond pQCD: off-shell massive and broad q, g (used in PHSD):
O. Linnyk, JPG 38 (2011) 025105

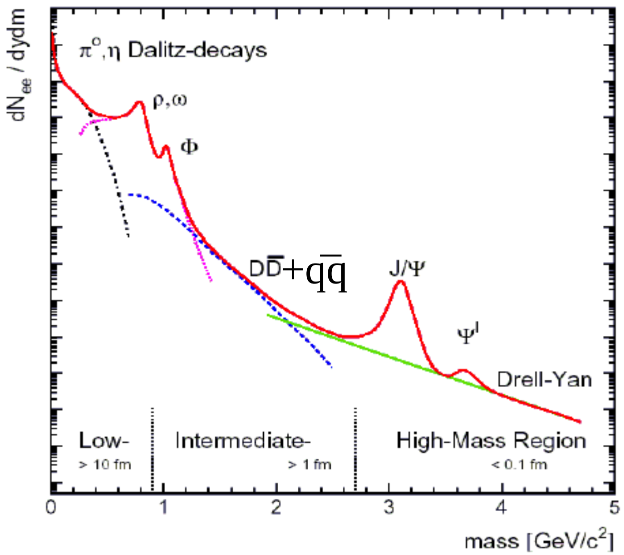
2) From hadronic sources:

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



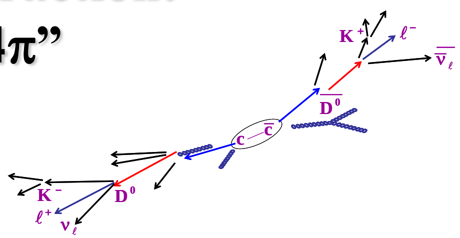
- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**



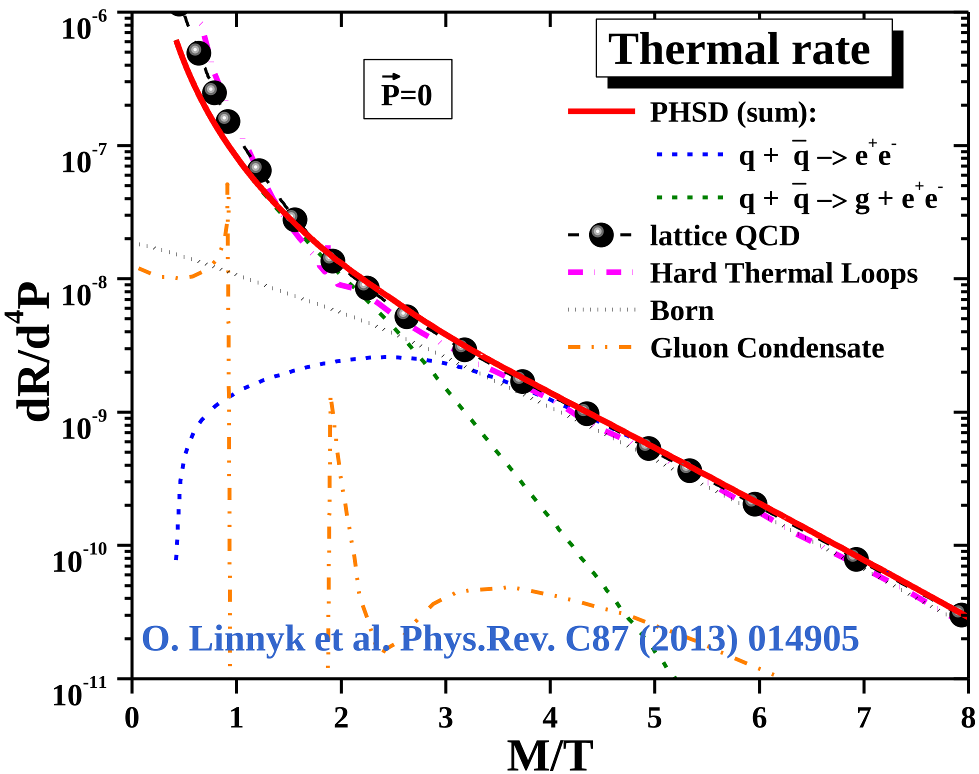


- **radiation from secondary meson interaction:**
$\pi + \pi$, $\pi + \rho$, $\pi + \omega$, $\rho + \rho$, $\pi + a1$ = “4π”

- **correlated semi-leptonic decays of D- and B-mesons**

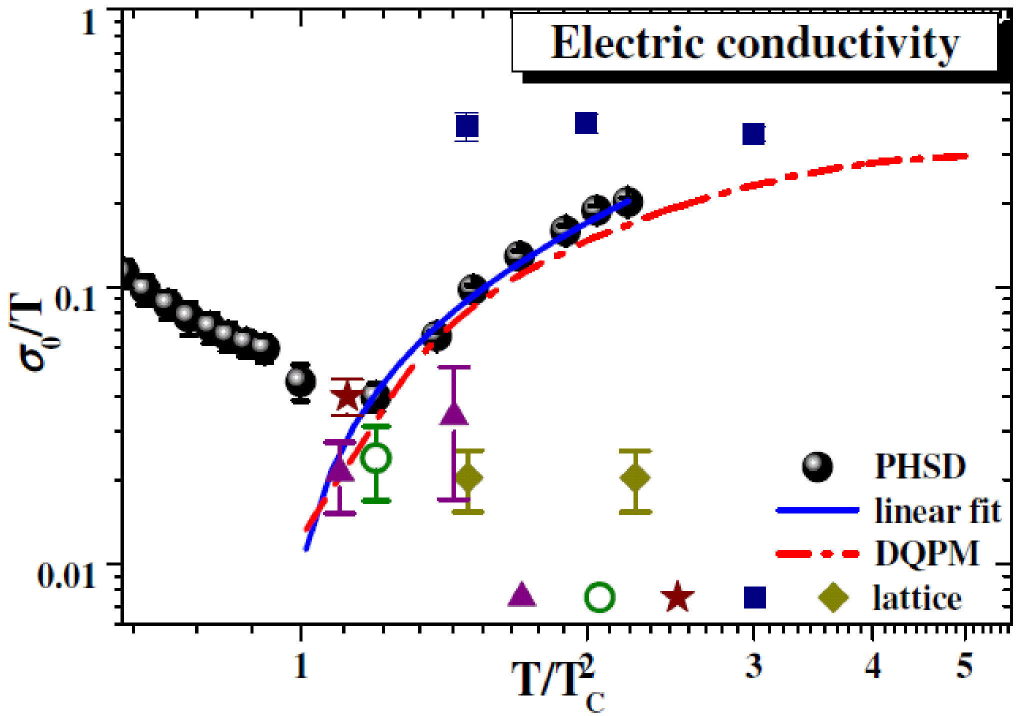


Photons and conductivity



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

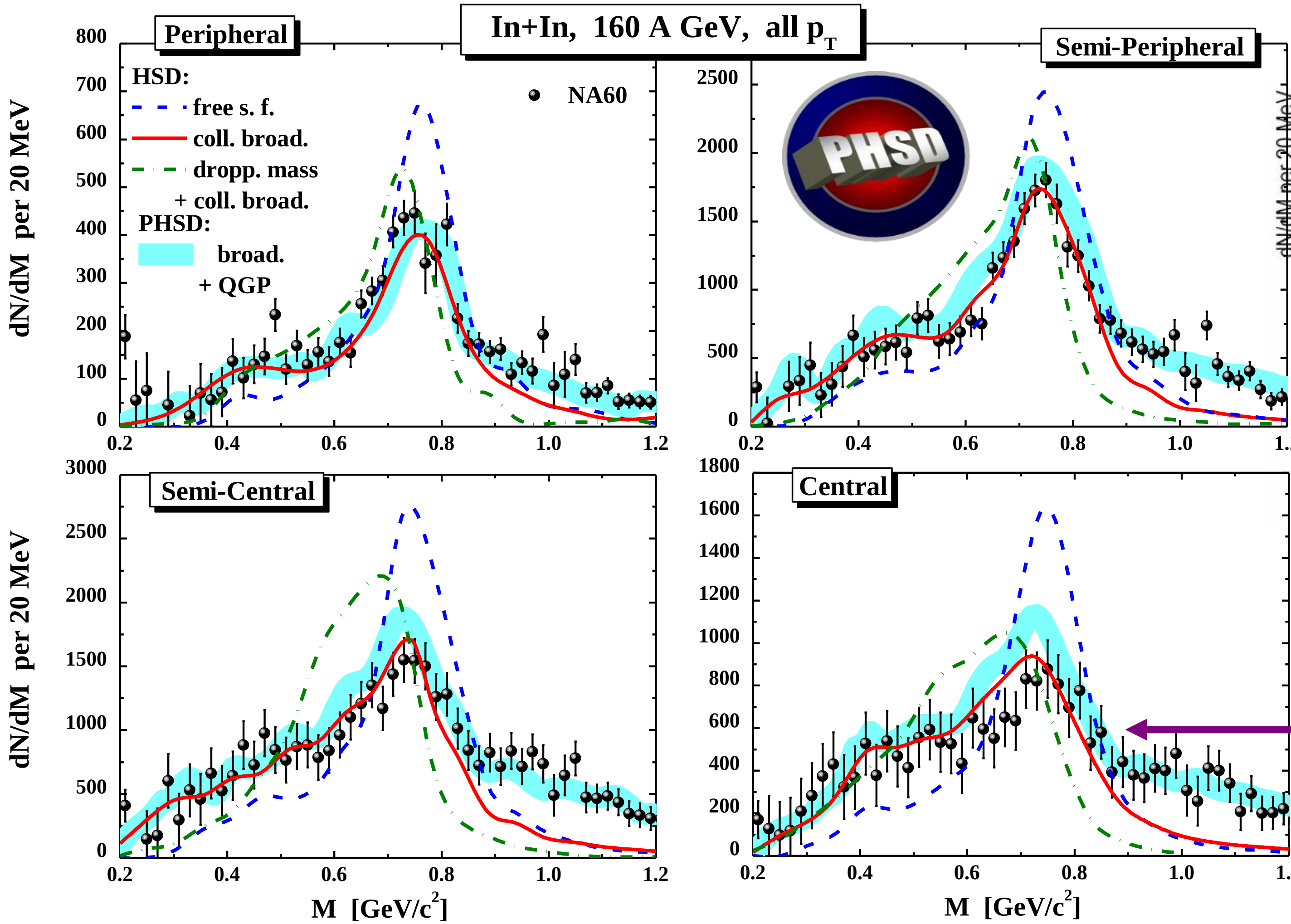
$$\frac{\sigma}{T} = \frac{C_{em}}{6}\lim_{\omega\to 0}\frac{\rho_{ii}(\omega,\vec{p}=0,T)}{\omega T}$$



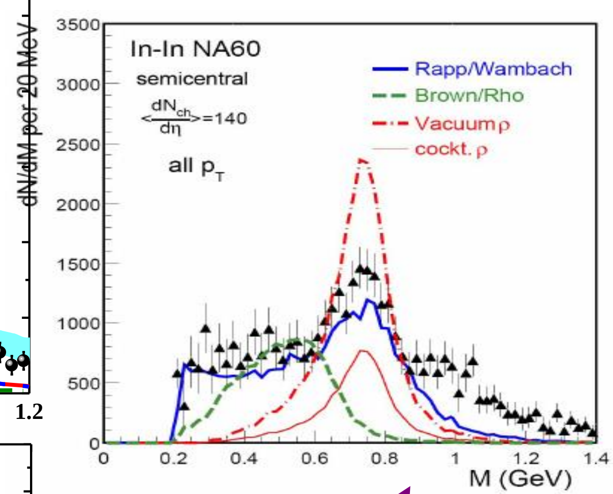
W. Cassing et al., Phys.Rev.Lett. 110 (2013) 182301

- 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

NA60: QGP shines already at SPS



fireball model



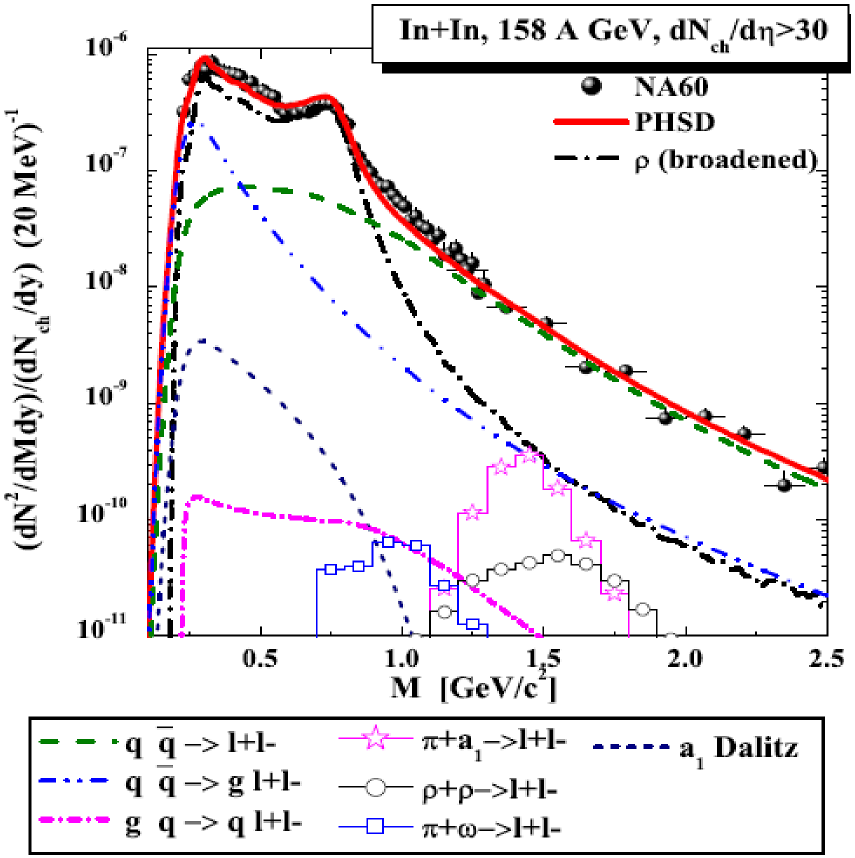
M>1 GeV
dominated by QGP

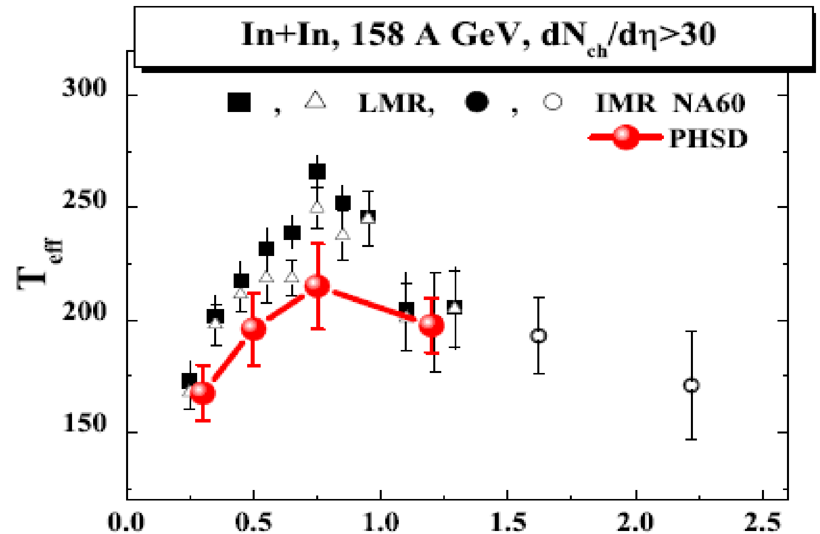
NA60 data at low M are well described by an in-medium scenario with collisional broadening

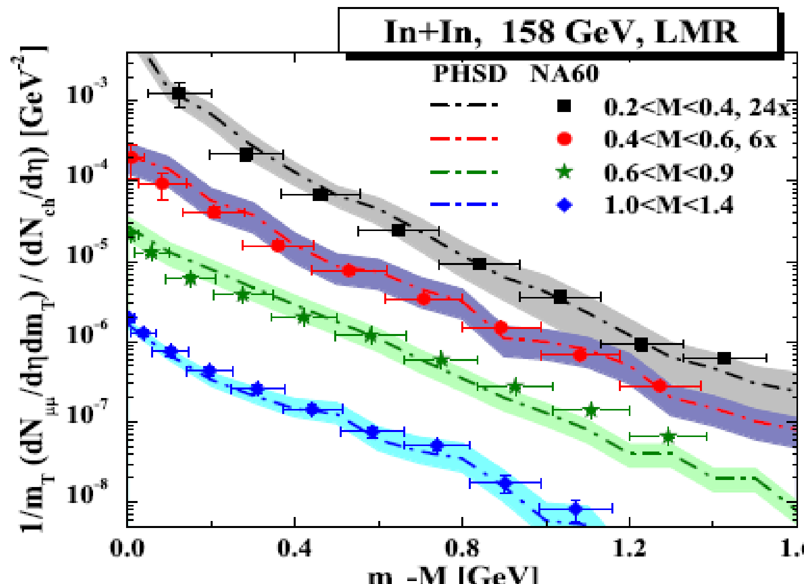
Dilepton spectra at low energies (CERES, HELIOS-3, DLS and HADES) show similar in-medium modification of vector mesons

E. Bratkovskaya, W. Cassing, O. Linnyk, PLB 670 (2009) 428

Dileptons at SPS: NA60





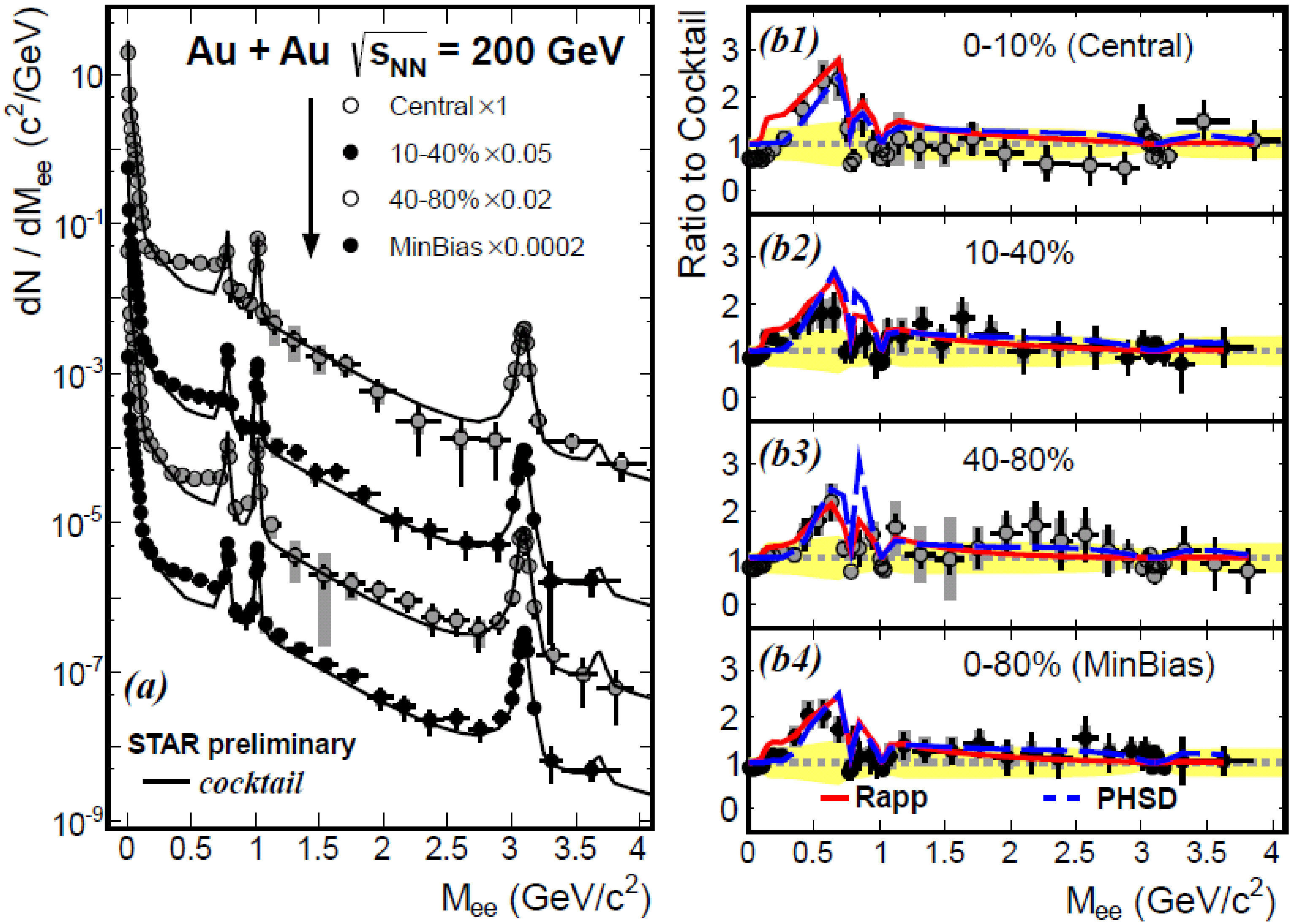


NA60 data at low M are well described by an in-medium scenario with collisional broadening

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

O. Linnyk, E. Bratkovskaya, V. Ozvenchuk, W. Cassing and C.M. Ko, PRC 84 (2011) 054917, O. Linnyk, J.Phys.G38 (2011) 025105, NA60 Collaboration, Eur. Phys. J. C 59 (2009) 607; CERN Courier 11/2009

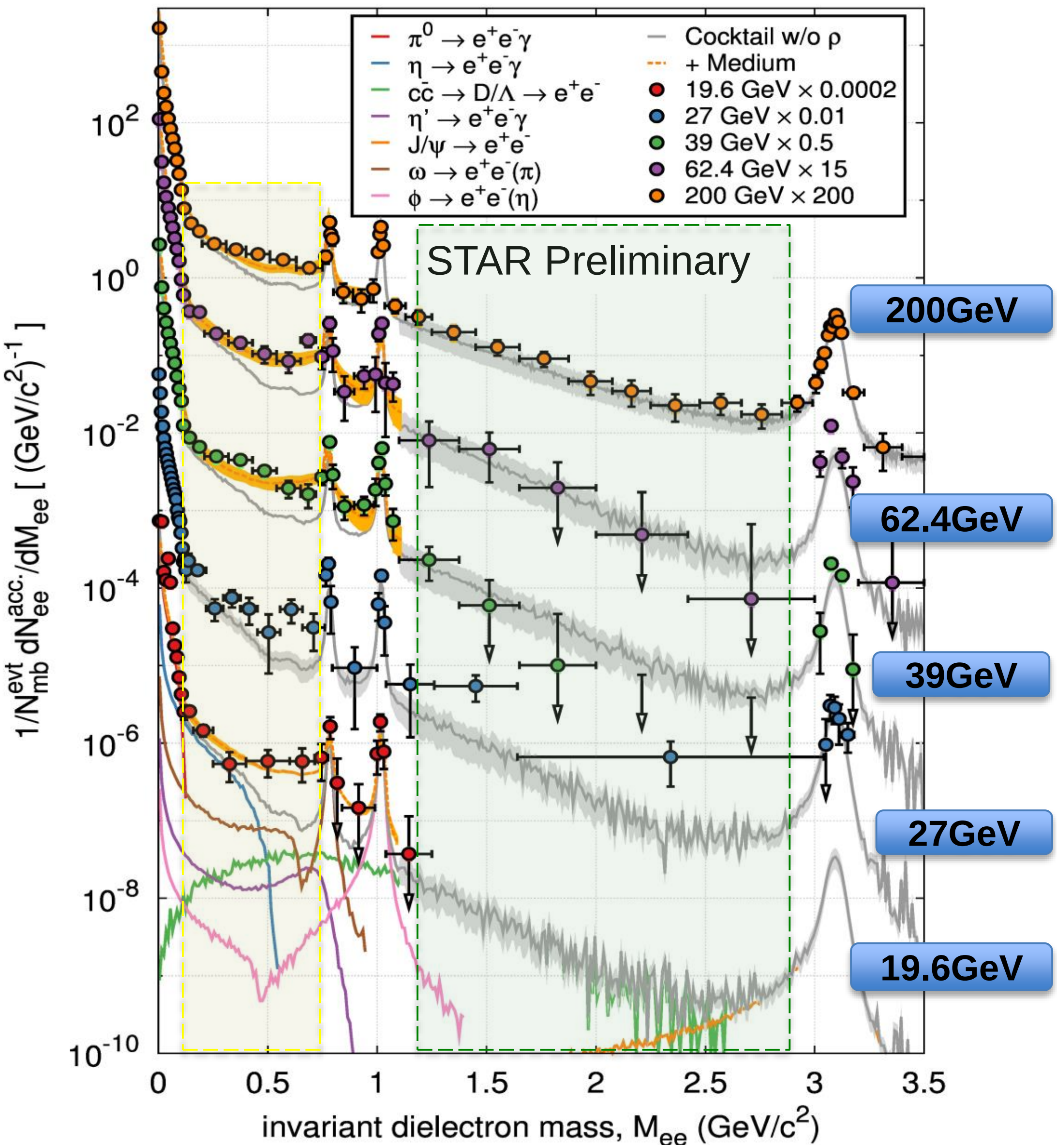
STAR: dilepton mass spectra



- Predictions confirmed by the extended data set at QM2014

O. Linnyk et al, PRC 85 (2012) 024910 , P. Huck (STAR Collaboration), proceedings of the QM 2014

Energy Dependence of Di-electrons



Bulk-penetrating probe:

1) **$M_{ee} \le 1GeV/c^2$:** In-medium broadened ρ, model results* are consistent with exp. data. At 200GeV, the enhancement is in the order of **1.77±0.11 ±0.24±0.33** within $0.3 < M_{ee} < 0.7 GeV/c^2$) (* driven by the baryon density in the medium)

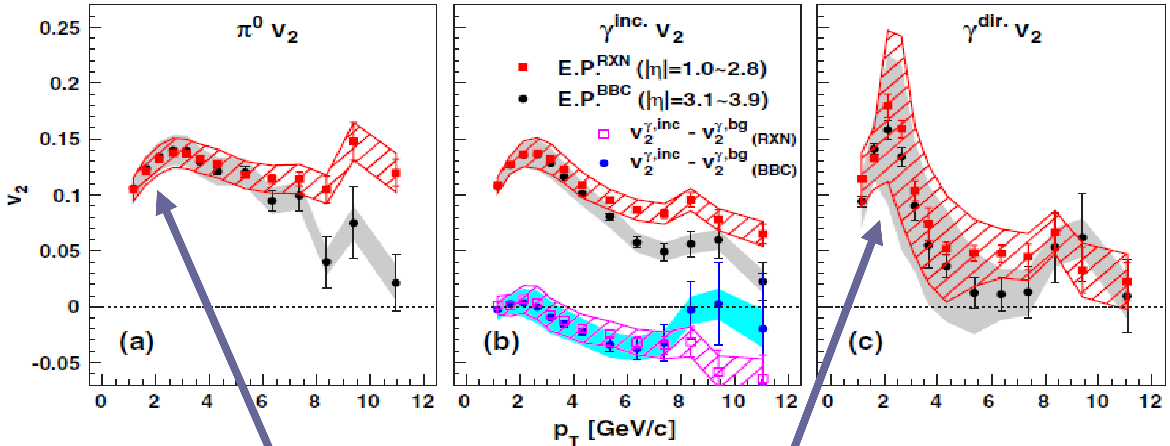
2) **$1 \le M_{ee} \le 3GeV/c^2$:** Thermal radiation: $\exp(-M_{ee}/T)$? HFT: Charm contributions.

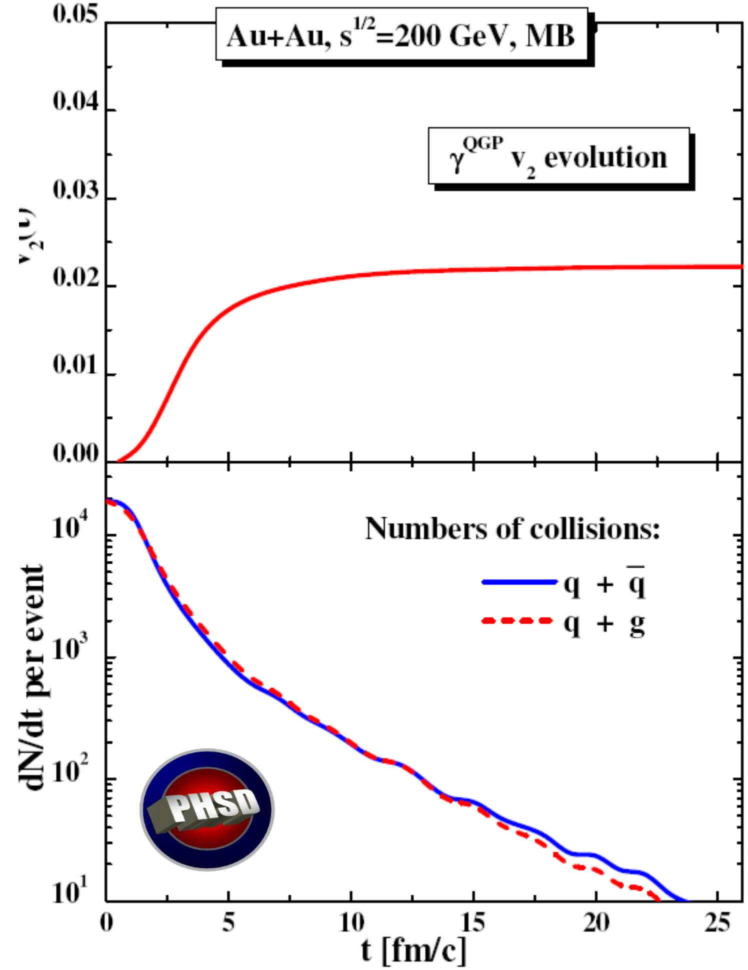
3) High statistics data are needed, **BES-II!**

- STAR: (200GeV data) sub. to PRL. 1312.7397
- R. Rapp: PoS CPOD13, 008(2013)
- O. Linnyk et al, PRC85, 024910(12)

Slide taken from Nu Xu

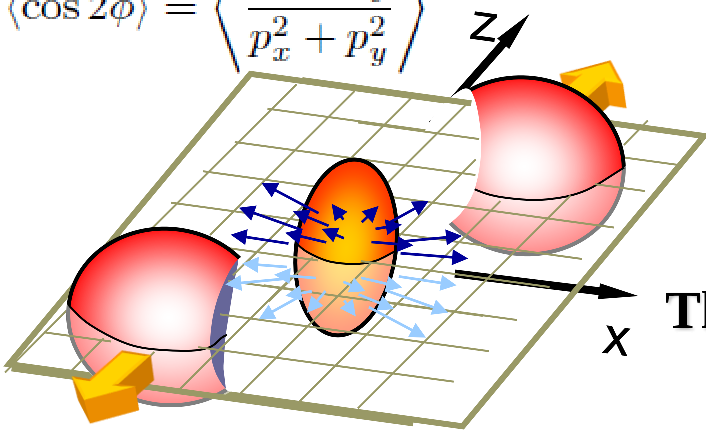
Photon v_2 puzzle





Strong elliptic flow of direct photons ($v_2(\gamma^{dir}) \sim v_2(\pi)$) seen by PHENIX is surprising,
Variety of models: $v_2(\gamma^{dir}) << v_2(\pi)$

$$v_2(\eta, p_T) = \langle \cos 2\phi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



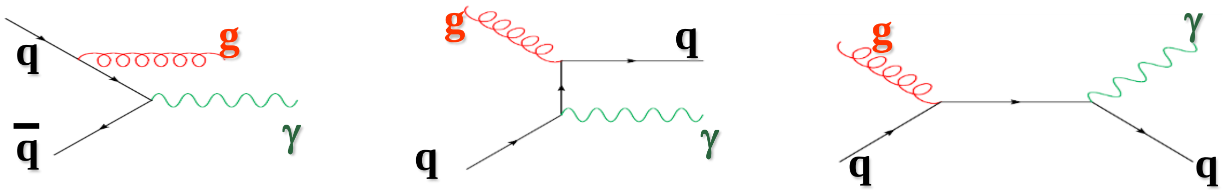
Thermal radiation occurs dominantly at early time,
when flow is not yet developed!

Phys. Rev. Lett. 109, 122302 (2012)

O. Linnyk et al., PRC 88 (2013) 034904

Photon sources

1) From the QGP via partonic interactions:



- pQCD LO 'AMY': Arnold, Moore, Yaffe, JHEP 12, 009 (2001)
- pQCD NLO: J. Ghiglieri et al (2014)
- HTL program: Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990)
- beyond pQCD: off-shell massive and broad q, g (used in PHSD): O. Linnyk, JPG 38 (2011) 025105

2) 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,**

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

Caution: uncertain!

using the soft photon approximation, with an average elastic cross section of 10 mb.

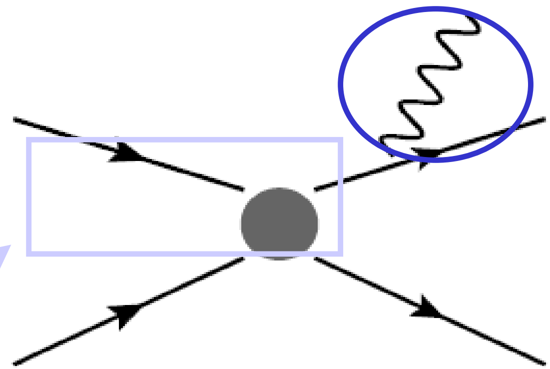
E. Bratkovskaya et al, Phys. Rev. C78, 034905 (2008), O. Linnyk et al. Phys.Rev. C88 (2013) 034904

Meson-meson Bremsstrahlung at SPS within SPA

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

Soft Photon Approximation:

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

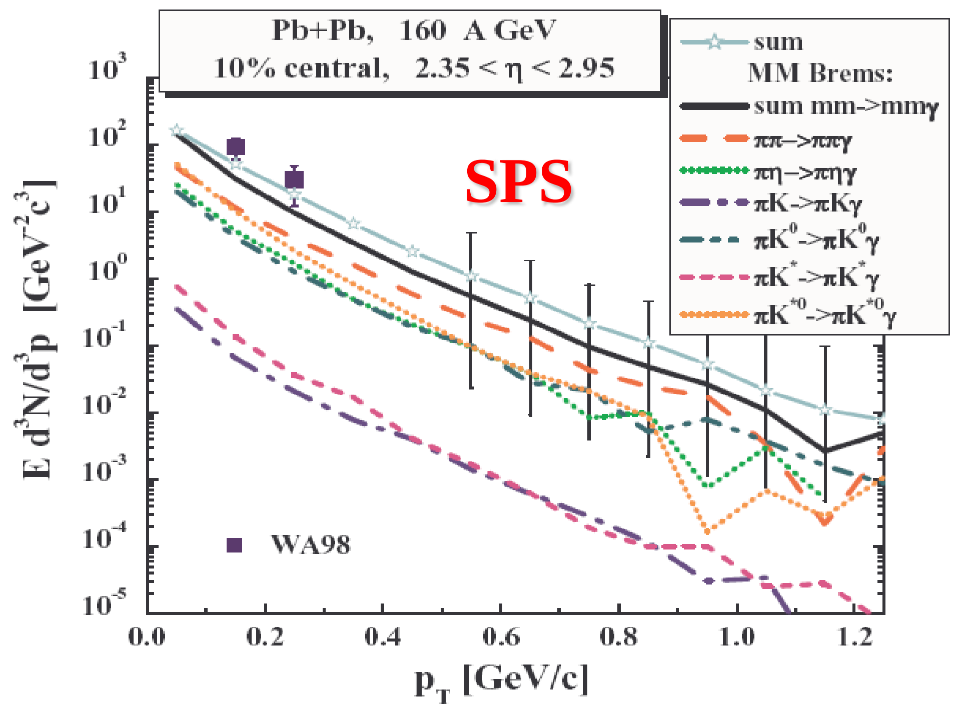


$$q_0 \frac{d^3\sigma^\gamma}{d^3 q} = \frac{\alpha}{4\pi}\frac{\bar{\sigma}(s)}{q_0^2}$$

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

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

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



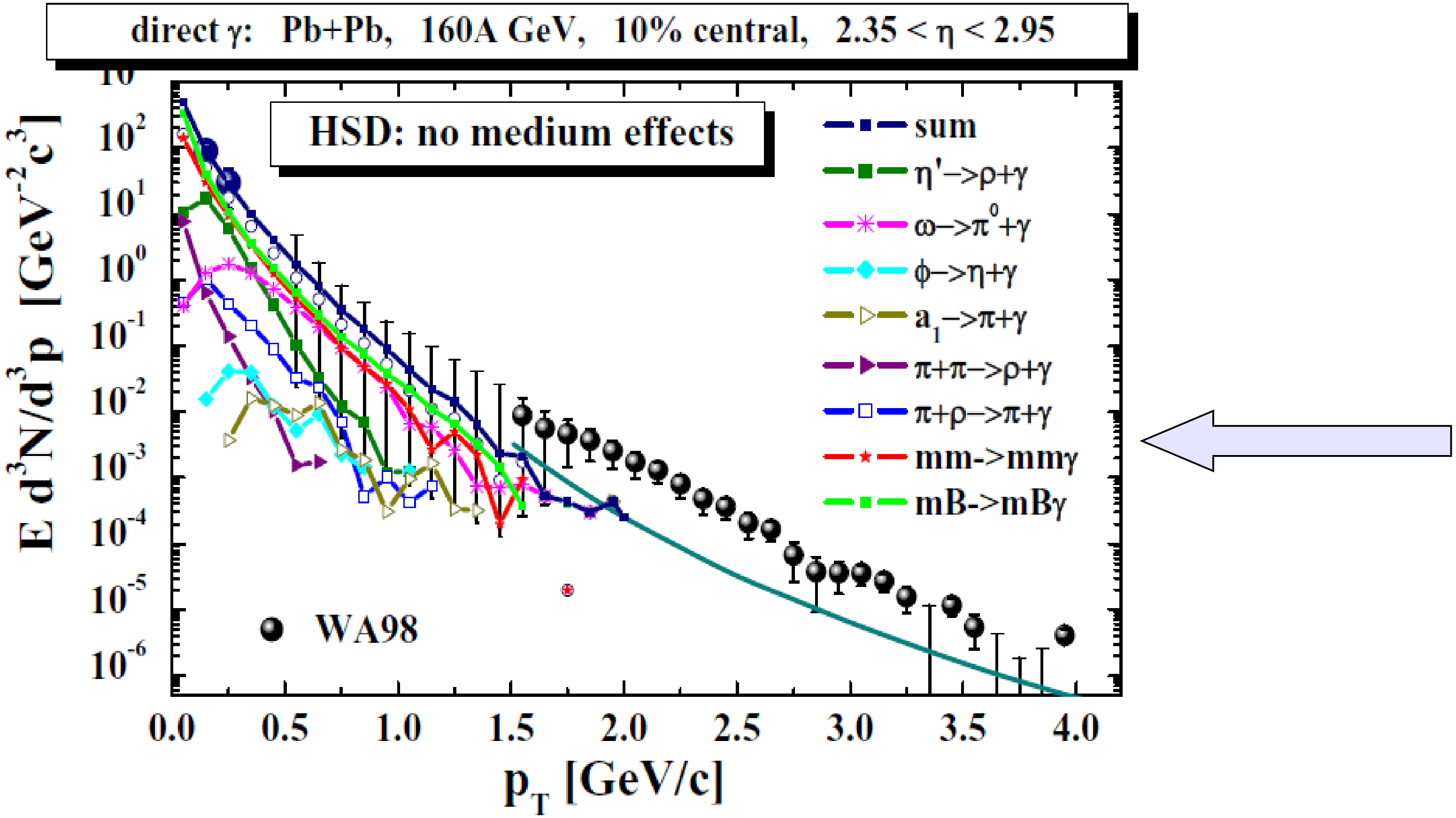
- ❑ Taken $\sigma(s)$ =10 mb for ALL m_1+m_2 channels !
- ❑ No isospin factors!

➔ **Needs to be improved!**

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

Photon spectra at SPS

Updated HSD (2014) including meson-baryon bremsstrahlung



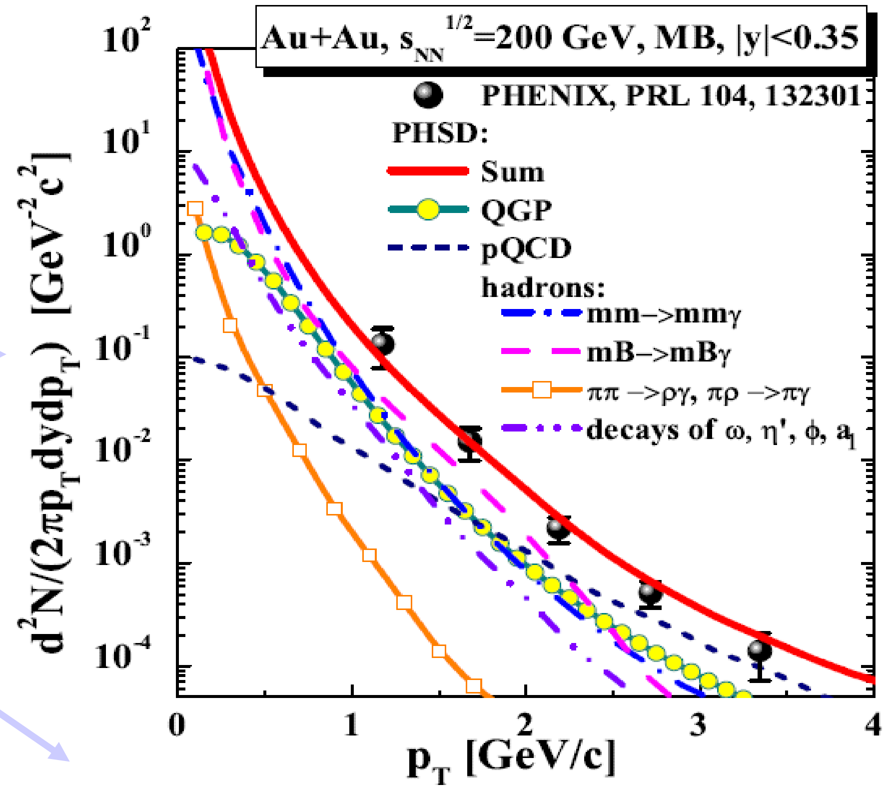
- **HSD: meson-meson and meson-baryon bremsstrahlung using SPA**

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

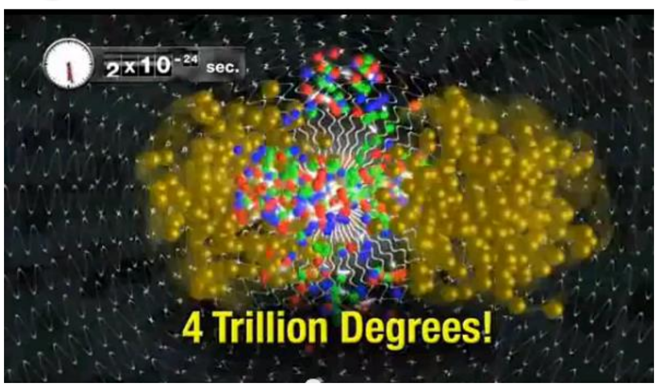
Photon spectra at RHIC

- π^0 and η subtracted the inclusive photon to obtain the direct photon spectrum

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



Guinness World Records: the highest man-made temperature



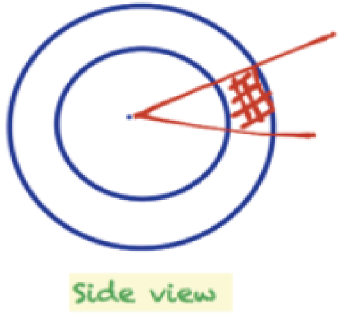
- The 'effective temperature' T_{eff}:

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

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

Are thermal photons a QGP thermometer?

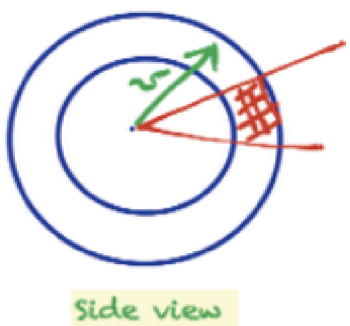
- **Static source:**



$$E\frac{d^3n}{d^3p} = E\,e^{-\beta E}$$

$\beta = 1/T$, T is a ‚true' temperature

- **Moving source:**



$$E\frac{d^3n}{d^3p} \approx E\,e^{-\beta\gamma E + \beta\gamma v E}$$

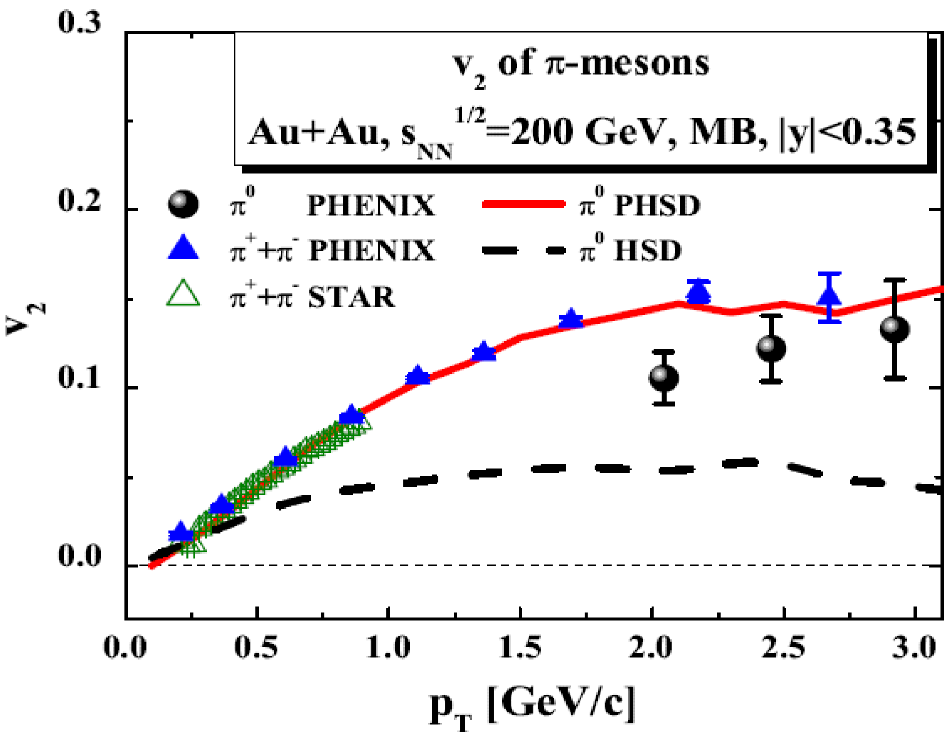
➔Doppler shift:

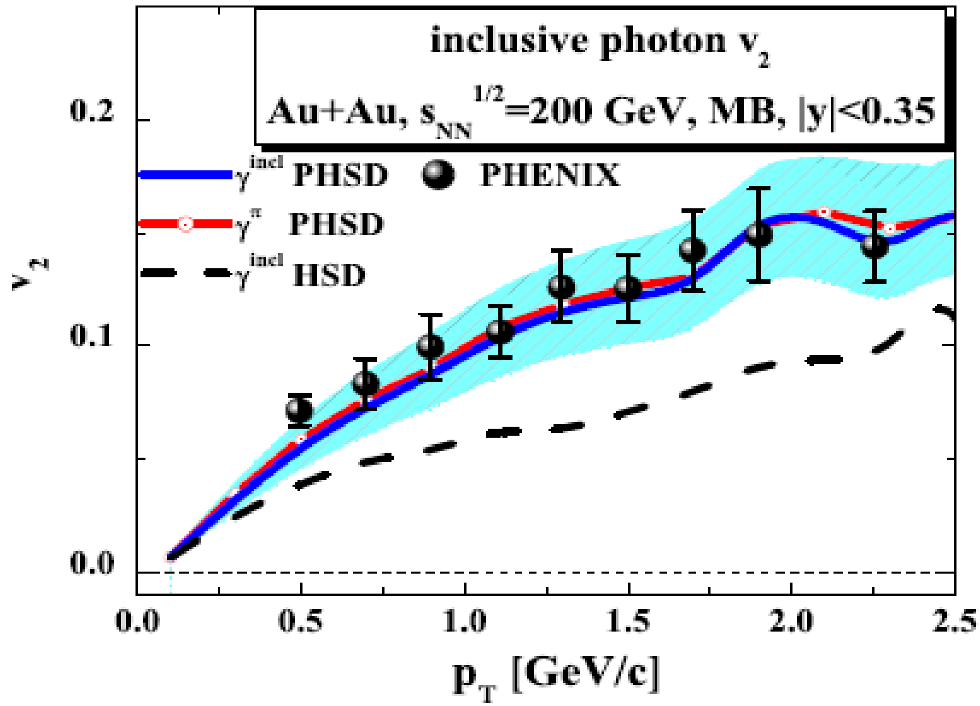
effective T_{eff} deduced from the slopes is NOT a ‚true' temperature

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

Pictures taken from Chares Gale

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

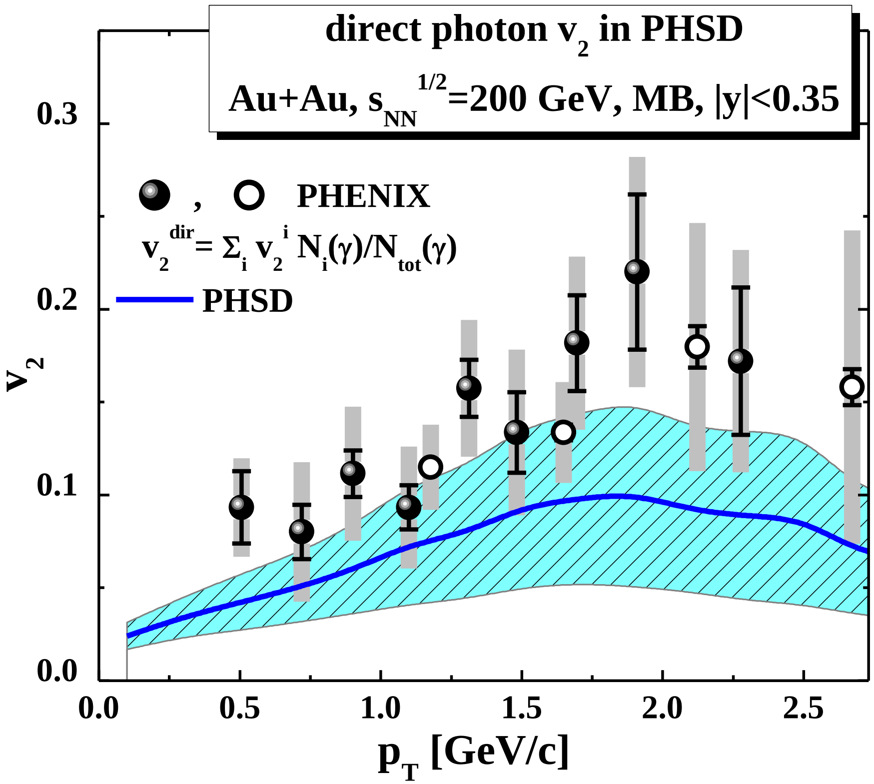
O. Linnyk et al., PRC 88 (2013) 034904; Phys.Rev. C88 (2013) 034904

Elliptic flow of direct photons at RHIC

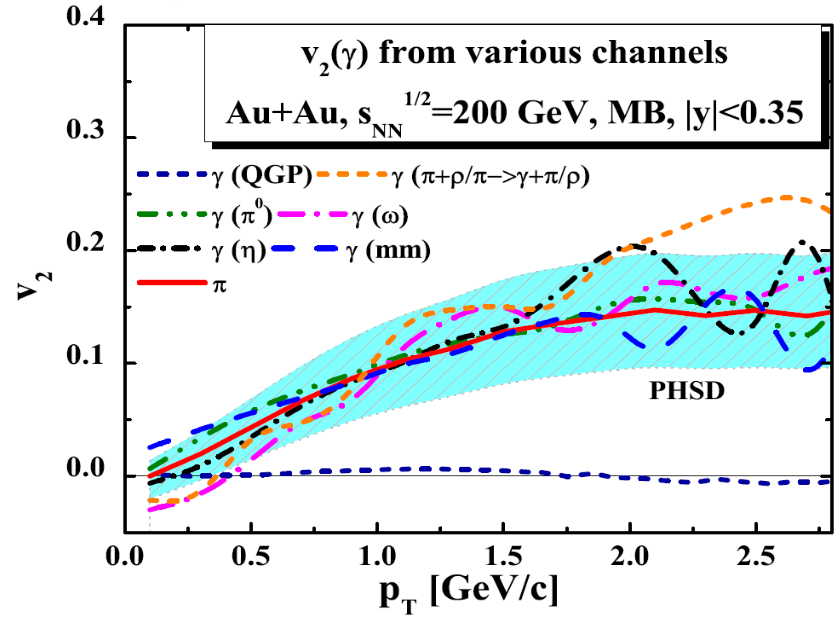
- Sum of v_2 of the individual channels, using their contribution to the spectra with the relative p_T-dependent weights $\omega_i(p_T)$:

$$\omega^i(p_T) = \frac{N^i(p_T)}{\sum_i N^i(p_T)}$$

$$v_2(p_T) = \frac{\sum_i N^i(p_T) \cdot v_2^i(p_T)}{\sum_i N^i(p_T)} = \sum_i \omega_i(p_T) \cdot v_2^i(p_T)$$



- v_2^i of the individual channels „i“

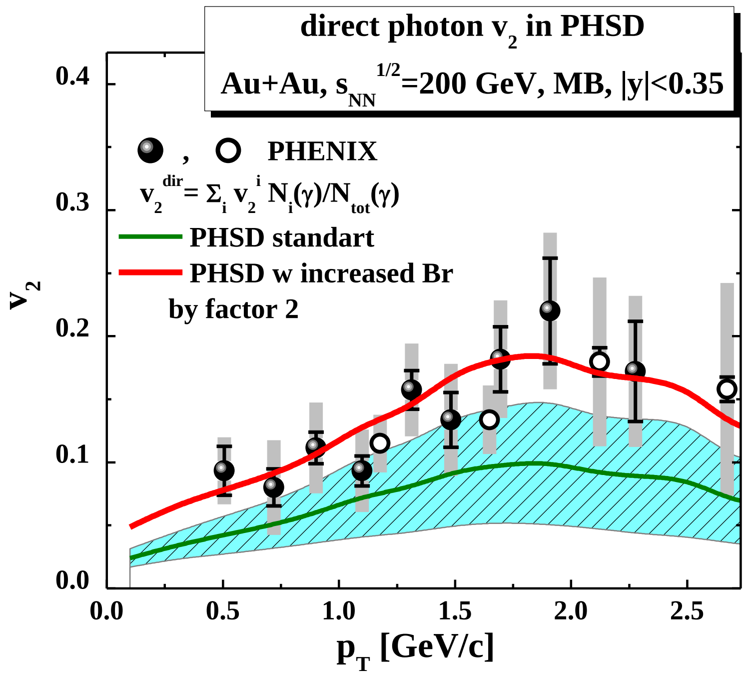


→ v_2 of direct photons in PHSD - as evaluated by the weighted average of direct photon channels – underestimates the exp. data

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?

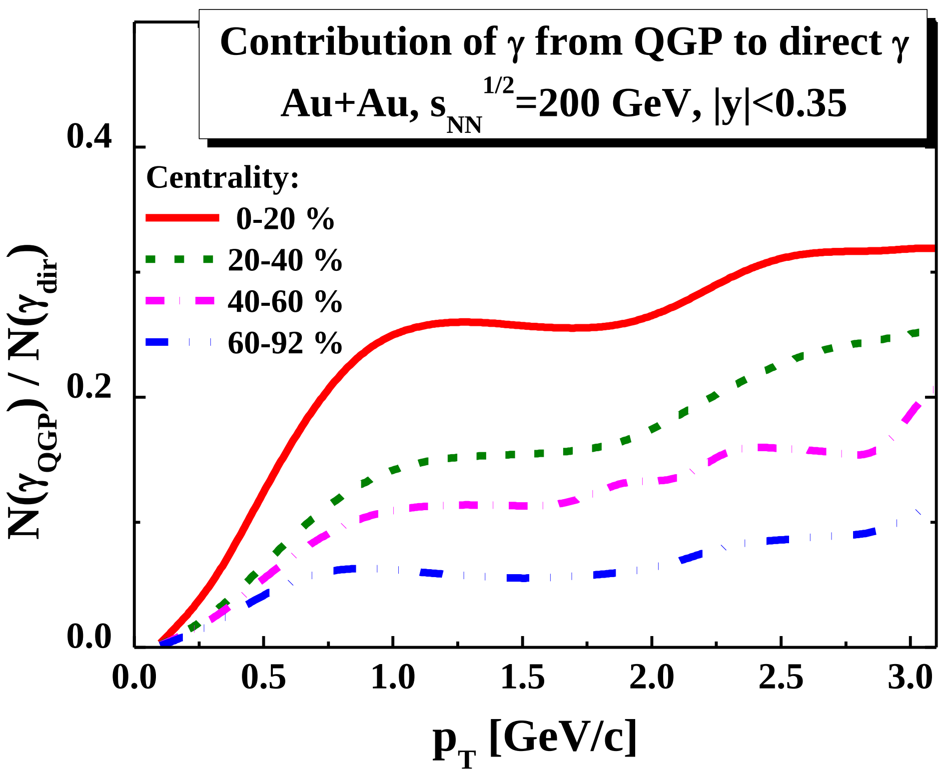
(due to the uncertainties in SPA and mm and mB elastic cross sections)

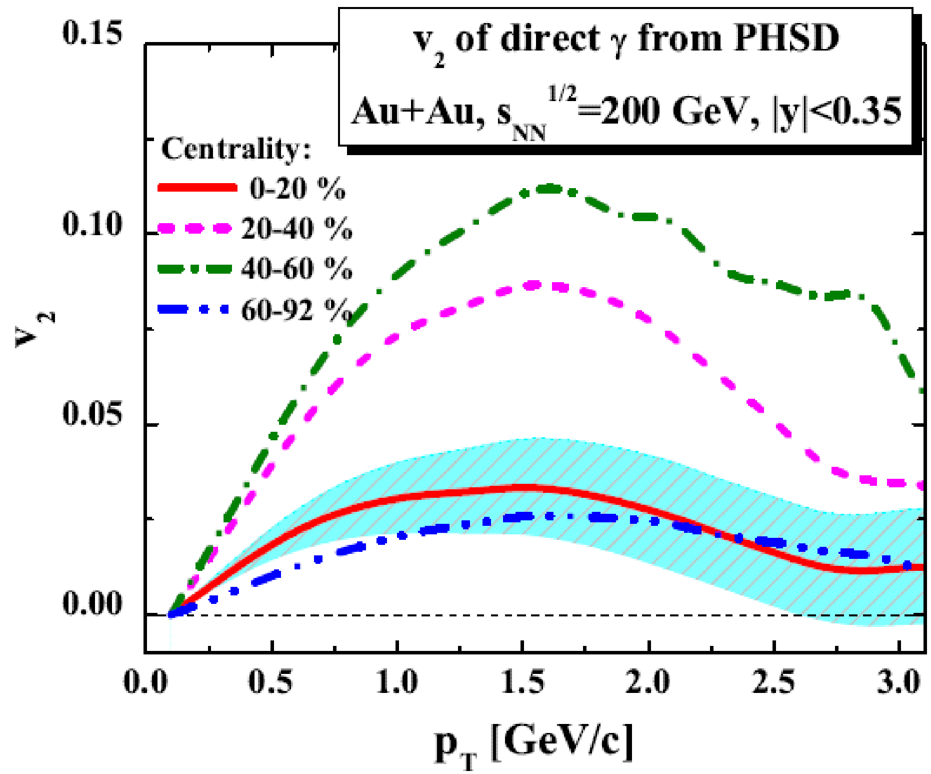
Other ideas:

- **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 ‚thermal' γ v_2

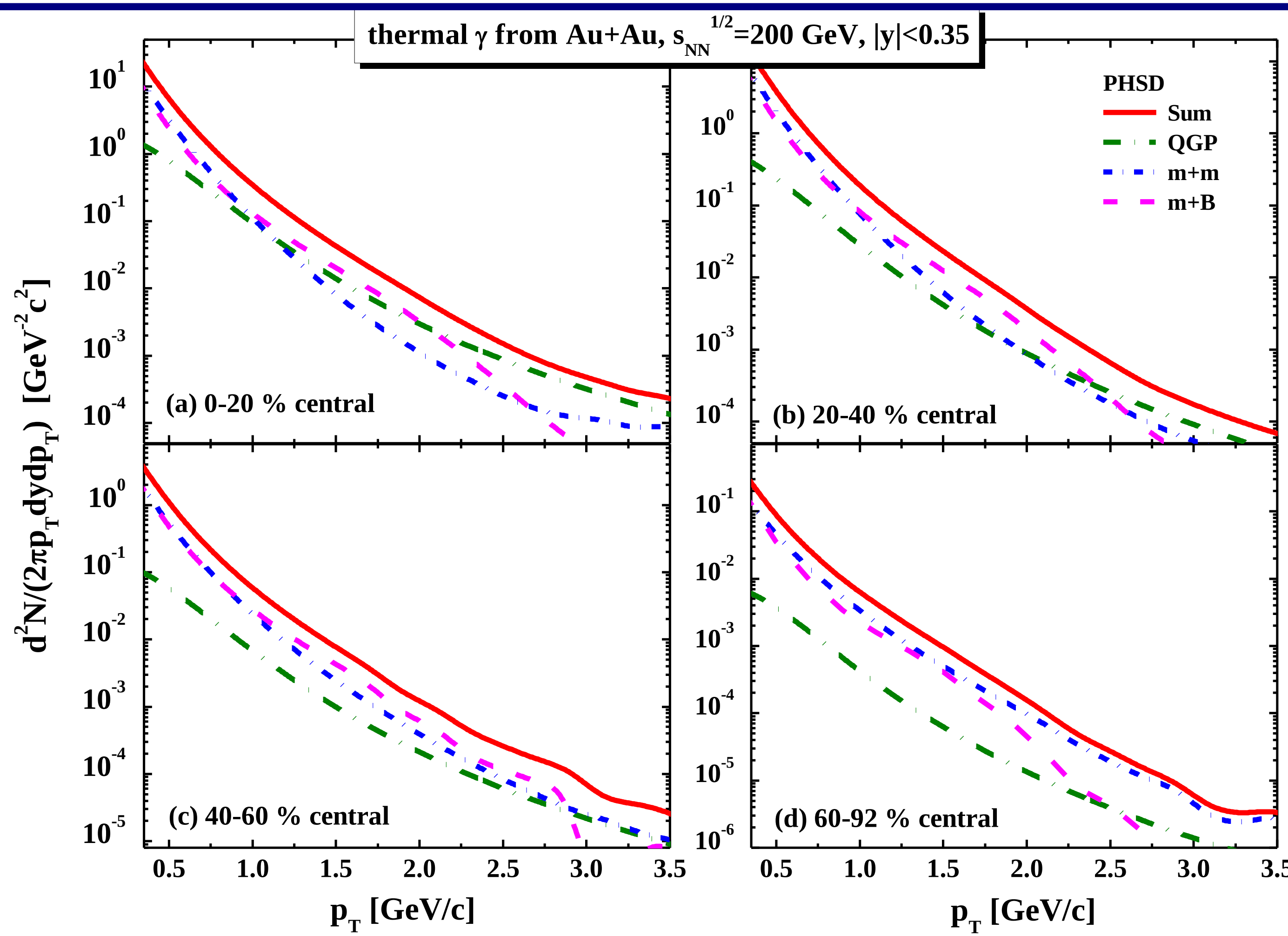




- The contribution of the QGP photons decreases substantially for more peripheral collisions and the photon elliptic flow increases accordingly.

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

Centrality dependence of the thermal γ yield



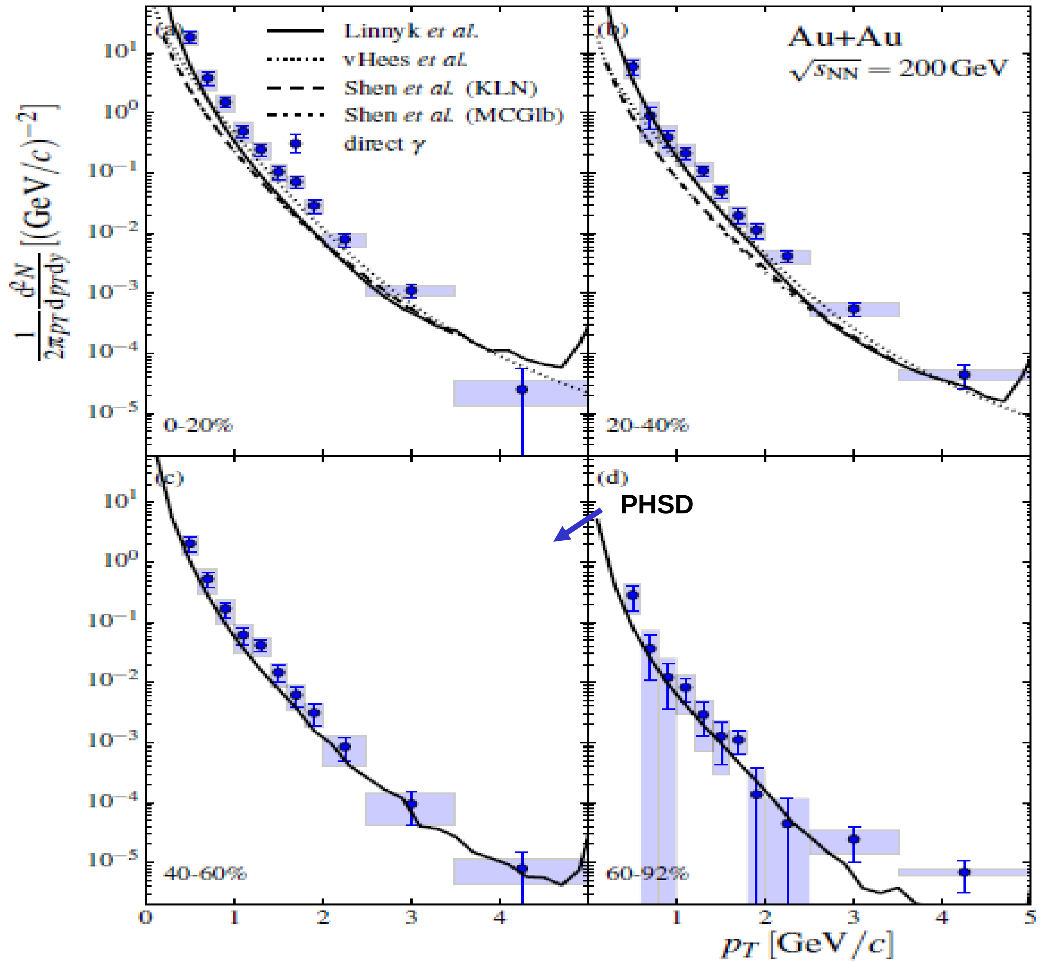
'Thermal' photon yield in different centrality bins.

The most peripheral collisions are defined by the bremsstrahlung.

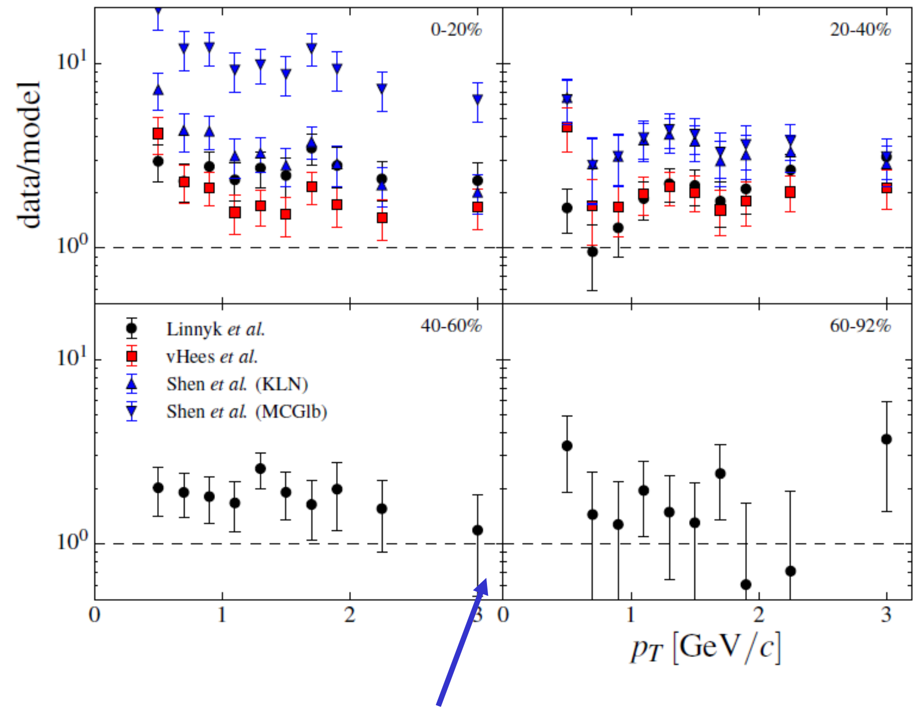
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

Centrality dependence of the direct photon yield

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 constrained by the peripheral collisions**

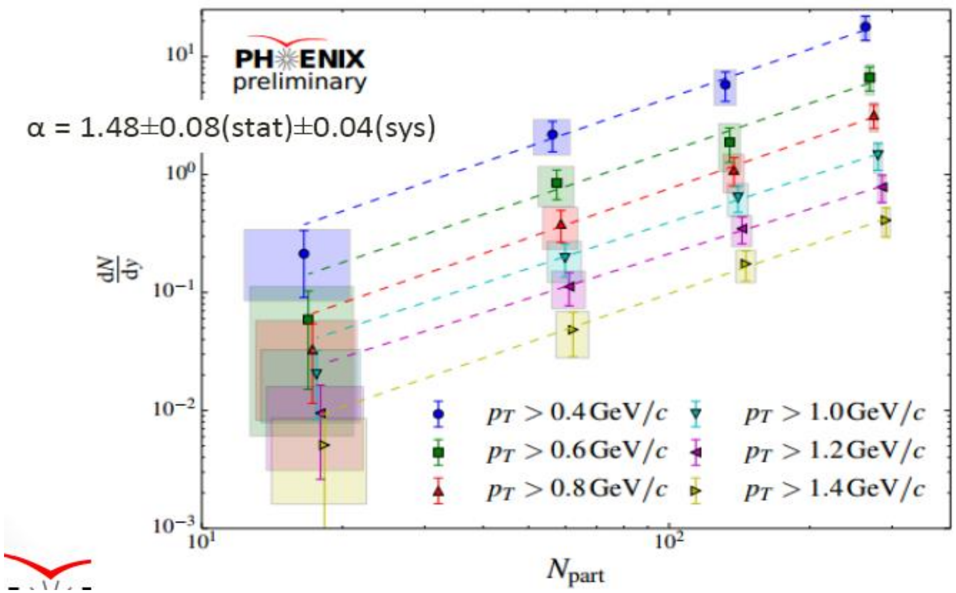
Warning: **large uncertainties in the Bremsstrahlung channels in the present PHSD results !**

Scaling of the thermal γ yield

PHENIX:
scaling of thermal photon yield vs centrality:

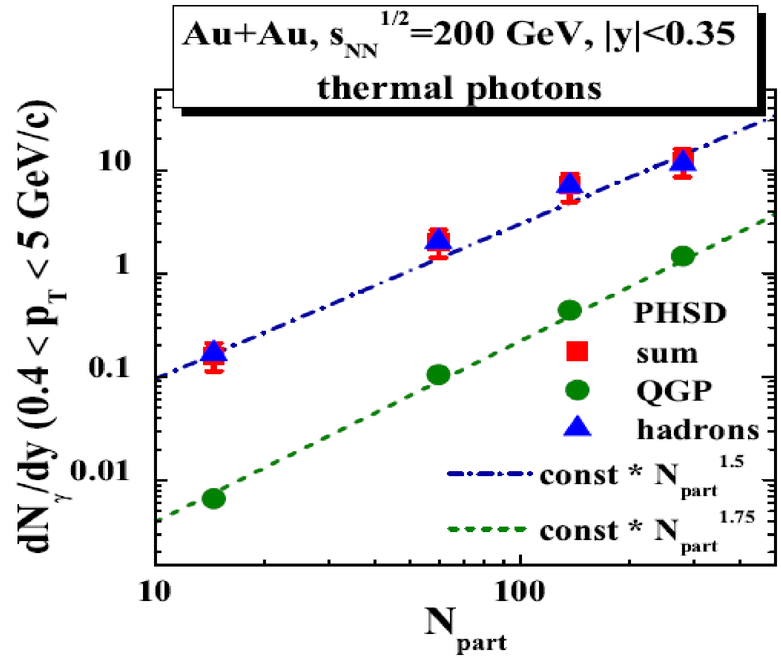
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

('Thermal' photon yield = direct photons - pQGP - hadronic decays)



PHSD predictions:

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



- **PHSD: scaling of the direct photon yield with the number of participants to the power 1.5**
- **similar results from (2+1)d viscous hydro (Ohio): HG ~1.46, QGP ~2**

➔ **indication for a hadronic origin ?!**

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

Summary

- **The in-medium modification of vector mesons (collisional broadening) is observed in the low-mass dilepton spectra, at SPS and RHIC. The QGP radiation dominates the spectra at M>1.2 GeV.**

- **The photons produced in the QGP contribute up to 50% to the observed spectrum, but have small v_2. The measured large direct photon elliptic flow v_2 is attributed to hadronic scattering channels m+m–>m+m+γ and m+B–>m+B+γ. The QGP phase causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of hadrons due to the partonic interaction in the early stage.**

- **The yield of photons from the hadronic channels scales as $N_{part}^{1.5}$ (as seen by PHENIX), that from the partonic channels scales as $N_{part}^{1.75}$.**

- **Outlook: realistic treatment of the photon bremsstrahlung in meson+meson and meson+baryon interaction.**

Thank you!

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Alessia Palmese (Giessen U)
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Collaboration

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN
Subatech
UAB Universitat Autònoma de Barcelona
HIC for FAIR
TEXAS A&M UNIVERSITY

Happy 3rd birthday!

Backup

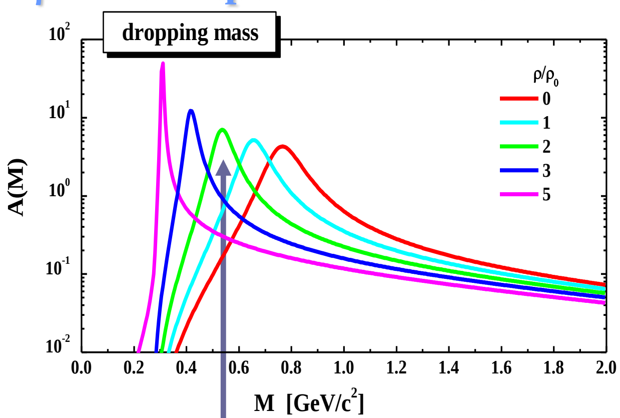
Modelling of in-medium spectral functions for vector mesons

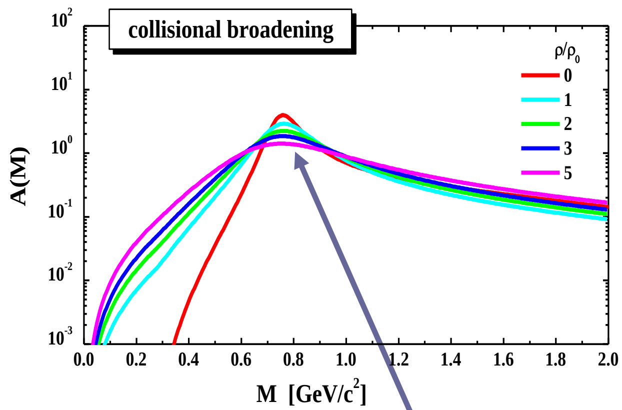
In-medium scenarios:

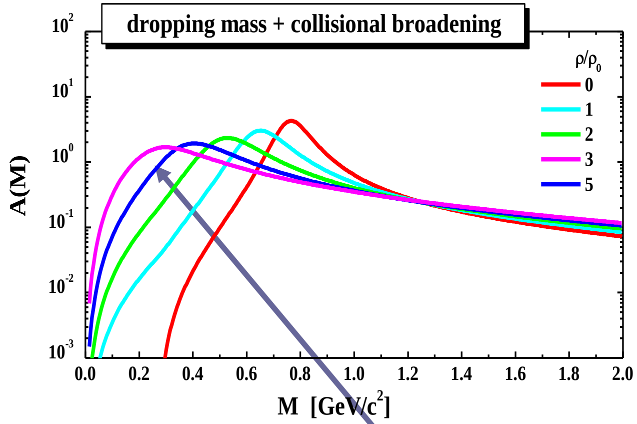
dropping mass	collisional broadening	dropping mass + coll. broad.
$m^*=m_0(1-\alpha\ \rho/\rho_0)$	$\Gamma(M,\rho)=\Gamma_{vac}(M)+\Gamma_{CB}(M,\rho)$	m^* & $\Gamma_{CB}(M,\rho)$

Collisional width $\Gamma_{CB}(M,\rho) = \gamma\ \rho < \upsilon\ \sigma_{VN}^{tot}>$

ρ–meson spectral function:



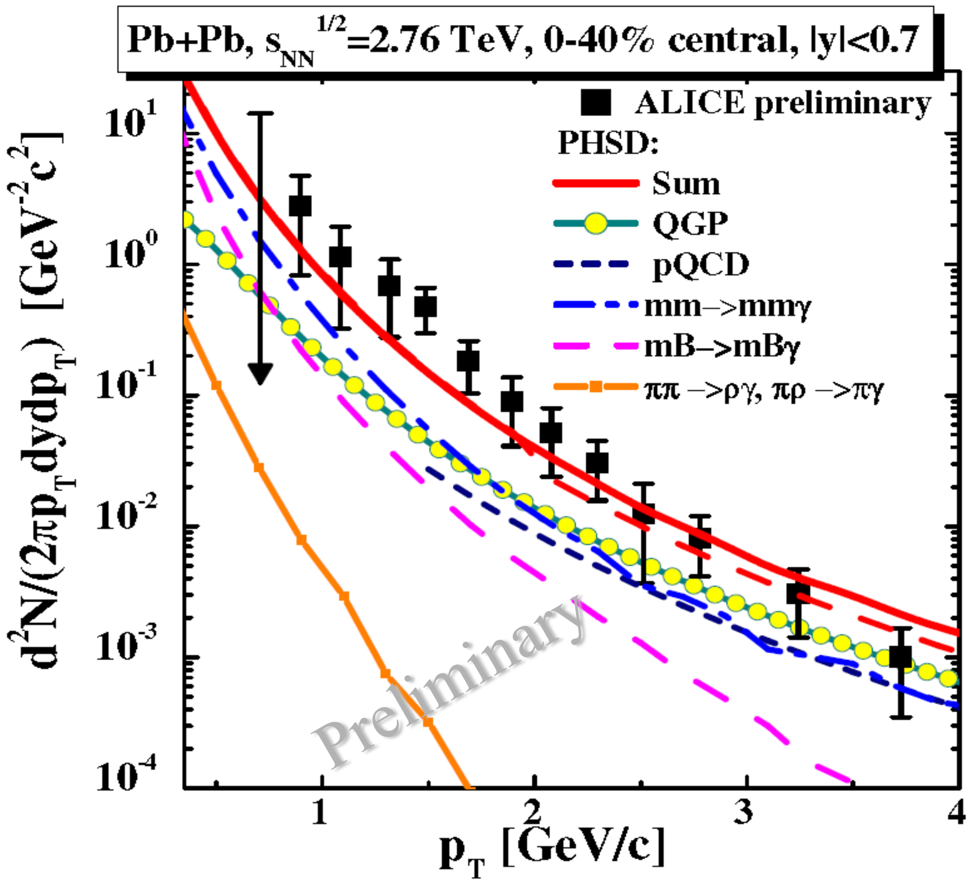


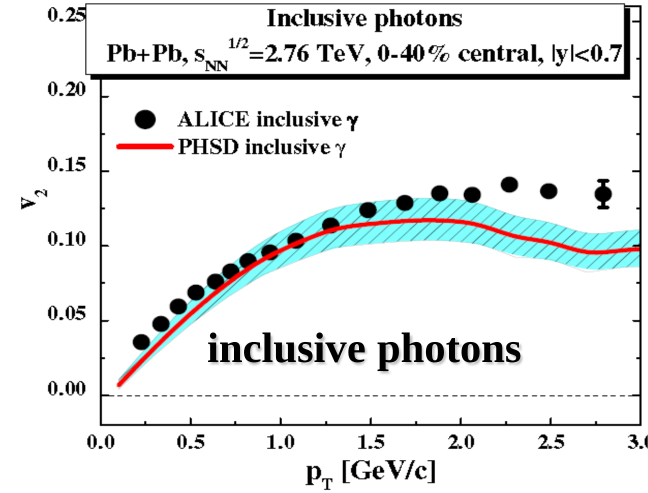


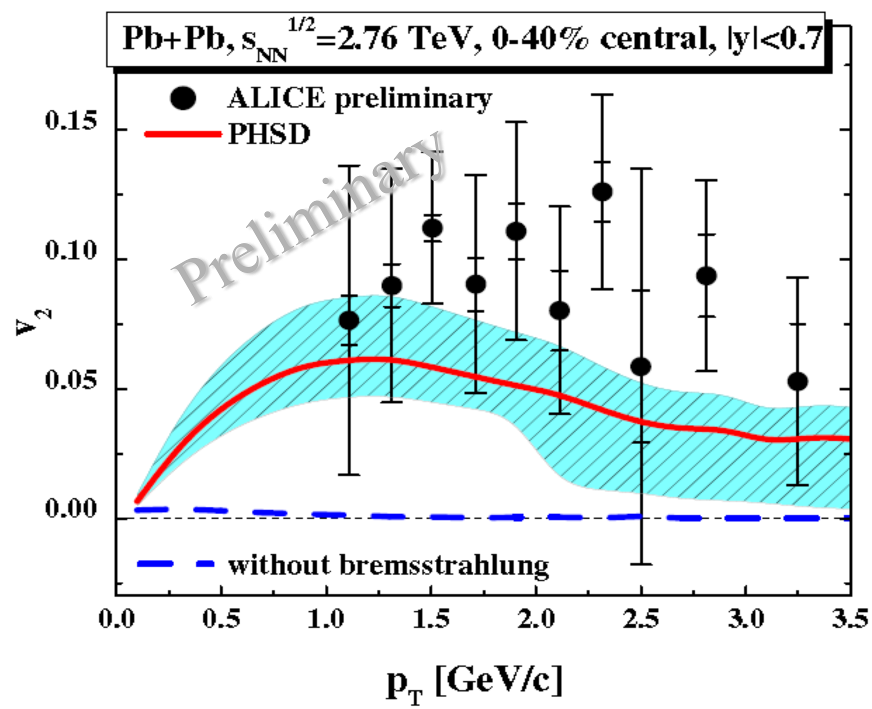
Consequences when increasing the baryon density ρ:

dropping mass	collisional broadening	dropping mass + coll. broad.
➢ pole position m_0 : shift to low M	➢ pole position m_0 : unchanged	➢ pole position m_0 : shift to low M
➢ spectral function : narrowing	➢ spectral function : broadening	➢ spectral function : broadening

PHSD results for Pb+Pb at 2.76 TeV: photons

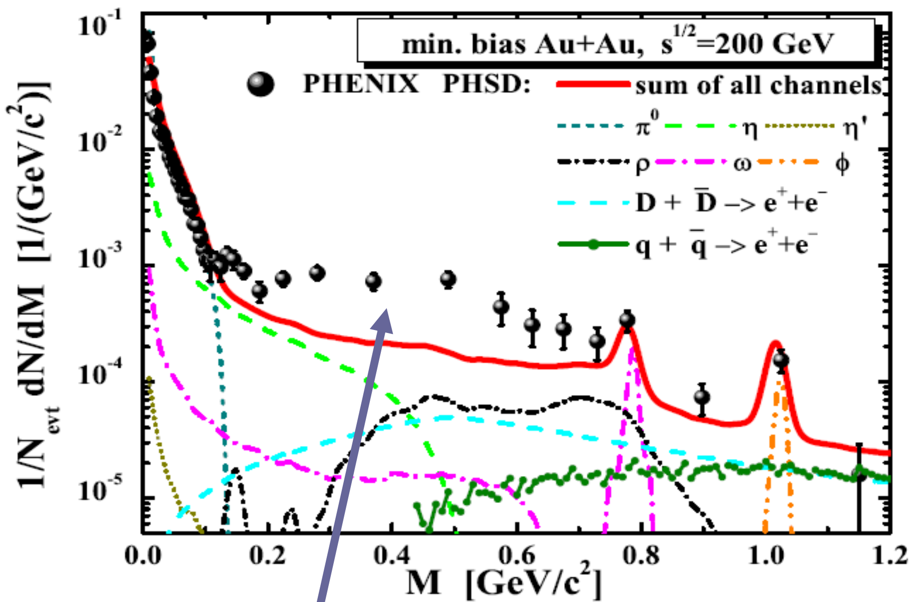


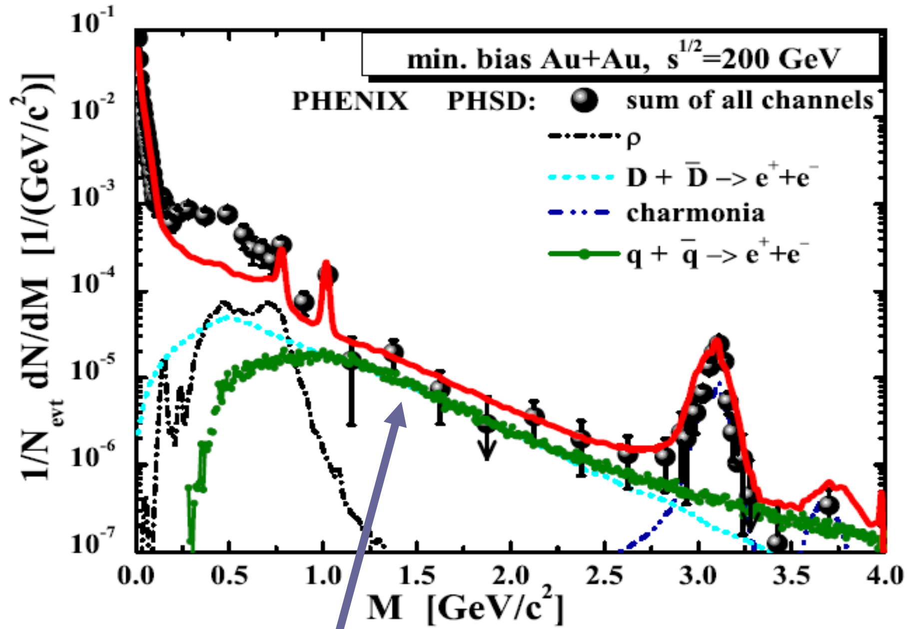




- Is the considerable elliptic flow of direct photons at the LHC of **hadronic origin ?!**
- The photon elliptic flow at LHC is lower than at RHIC due to a larger/longer relative QGP contribution.

PHENIX: dileptons from QGP





- The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD

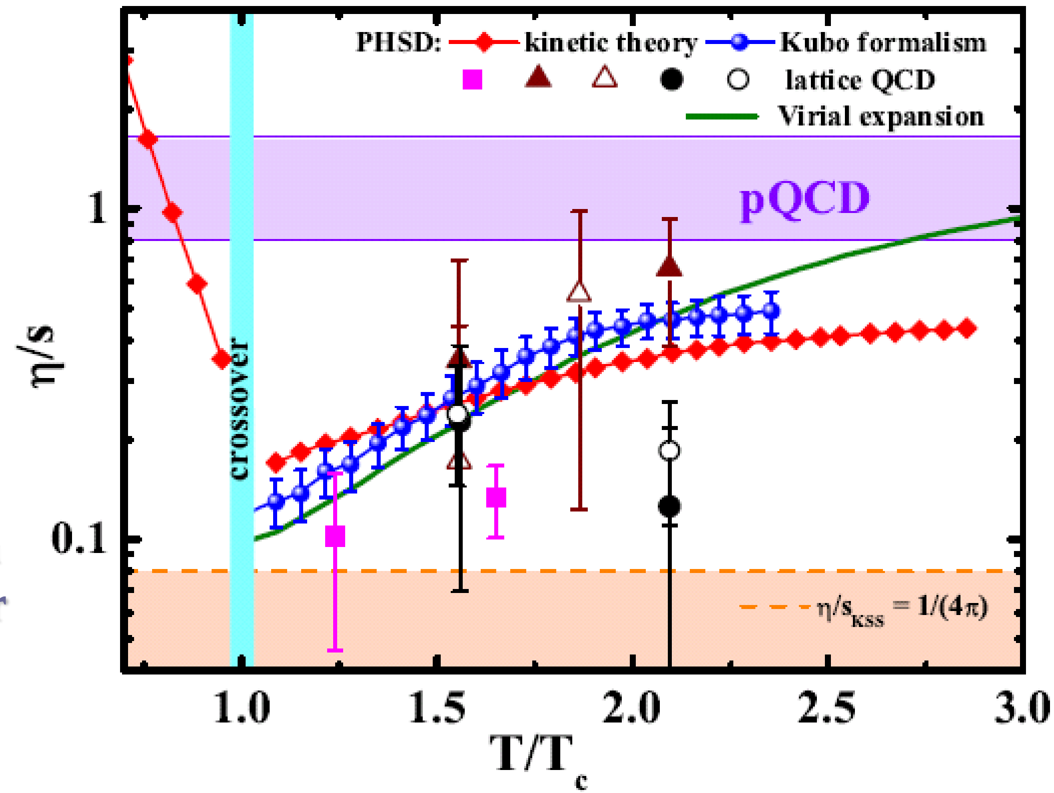
- The partonic channels fill up the discrepancy between the hadronic contributions and the data for M>1 GeV

O. Linnyk, W. Cassing, J. Manninen, E.Bratkovskaya and C.M. Ko, PRC 85 (2012) 024910

Shear viscosity

η/s using **Kubo formalism** and the **relaxation time approximation** (‚kinetic theory‘)

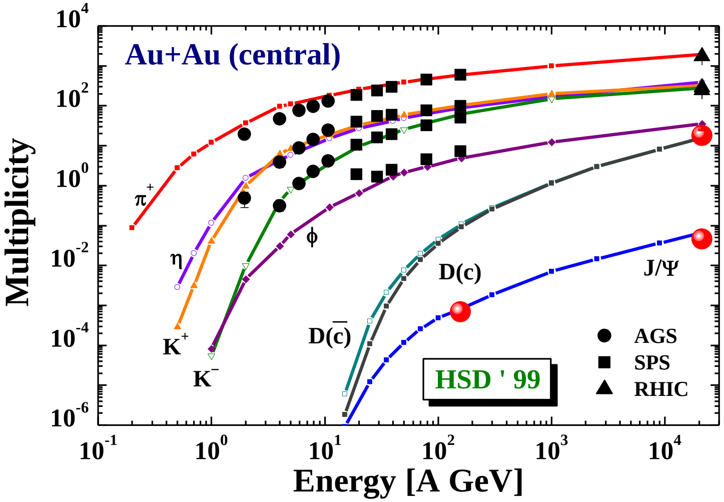
- ❑ **$T=T_C$: η/s shows a minimum (~0.1) close to the critical temperature**
- ❑ **$T>T_C$: QGP - pQCD limit at higher temperatures**
- ❑ **$T<T_C$: fast increase of the ratio η/s for hadronic matter ➔**
  - lower interaction rate of hadronic system
  - smaller number of degrees of freedom (or entropy density) for hadronic matter compared to the QGP

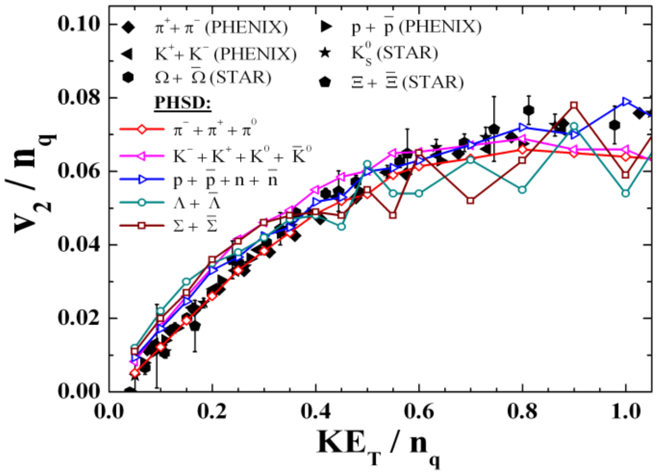


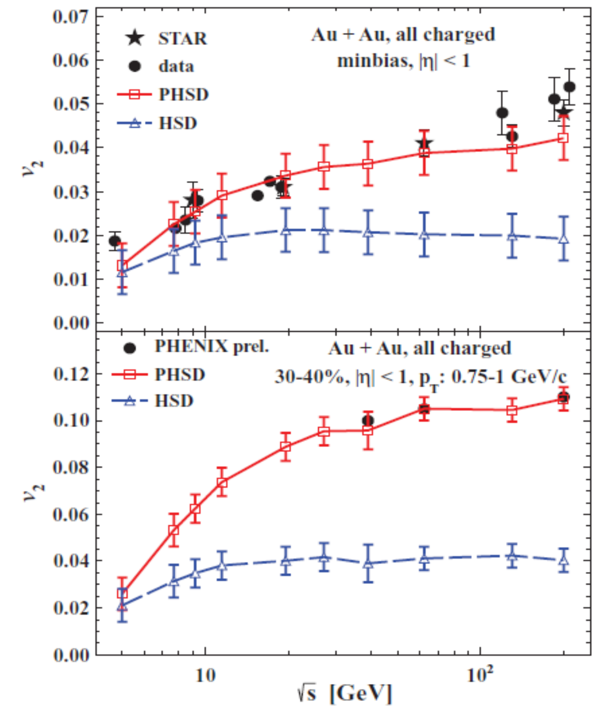
QGP in PHSD = strongly-interacting liquid

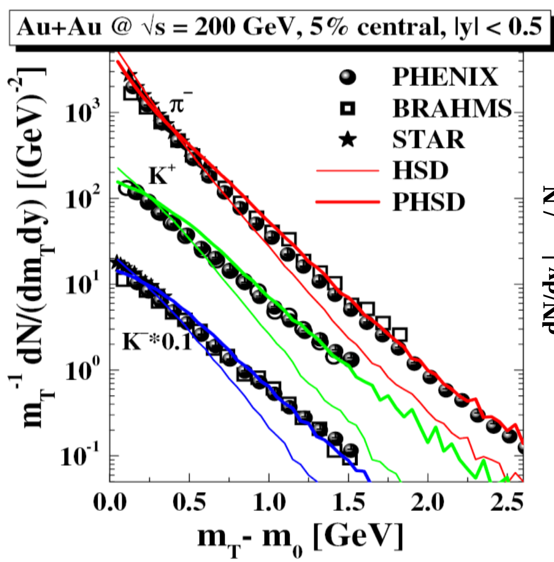
V. Ozvenchuk et al., PRC 87 (2013) 024901; V. Ozvenchuk et al., arXiv:1212.5393 (accepted to PRC)

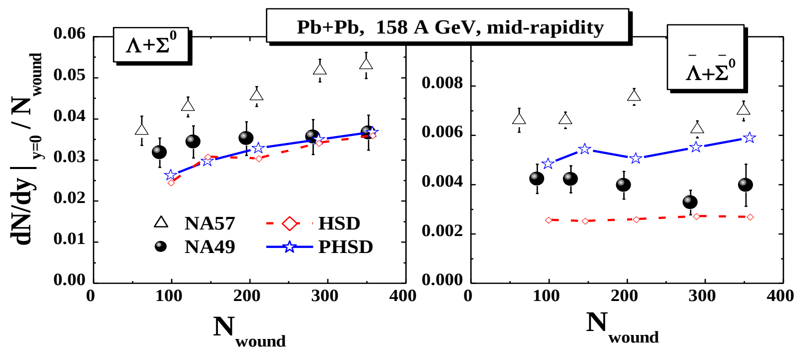
PHSD for HIC (highlights)

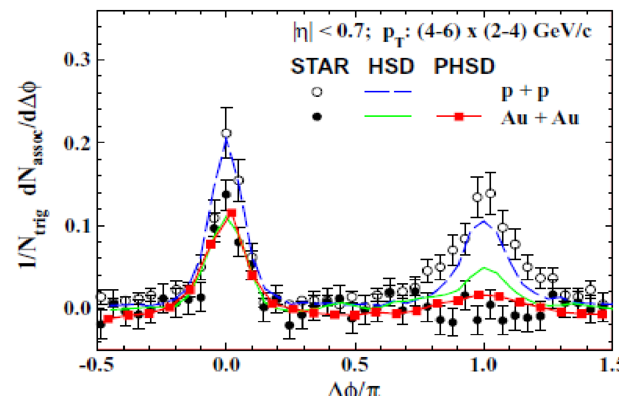






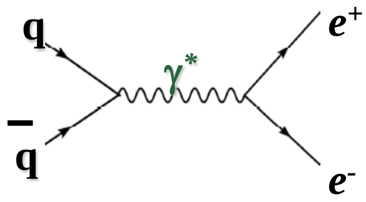


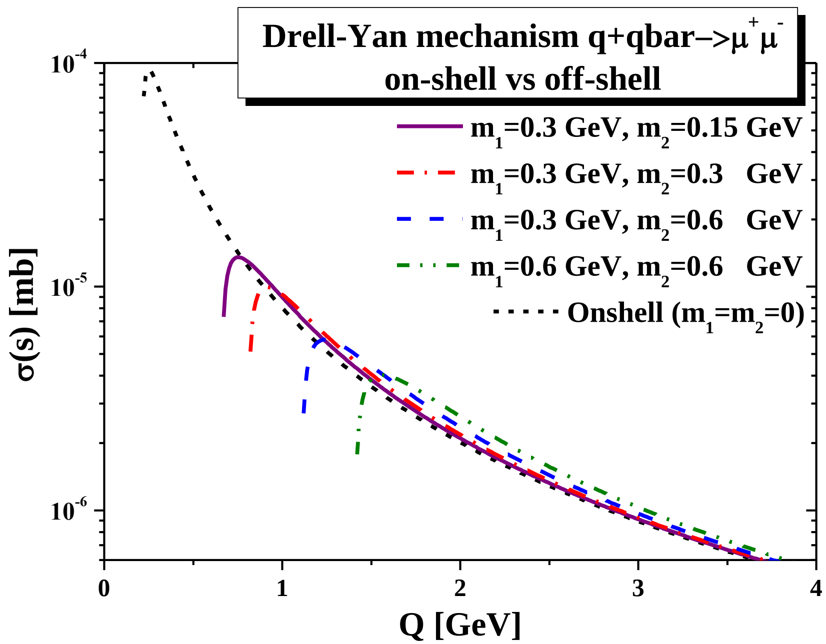


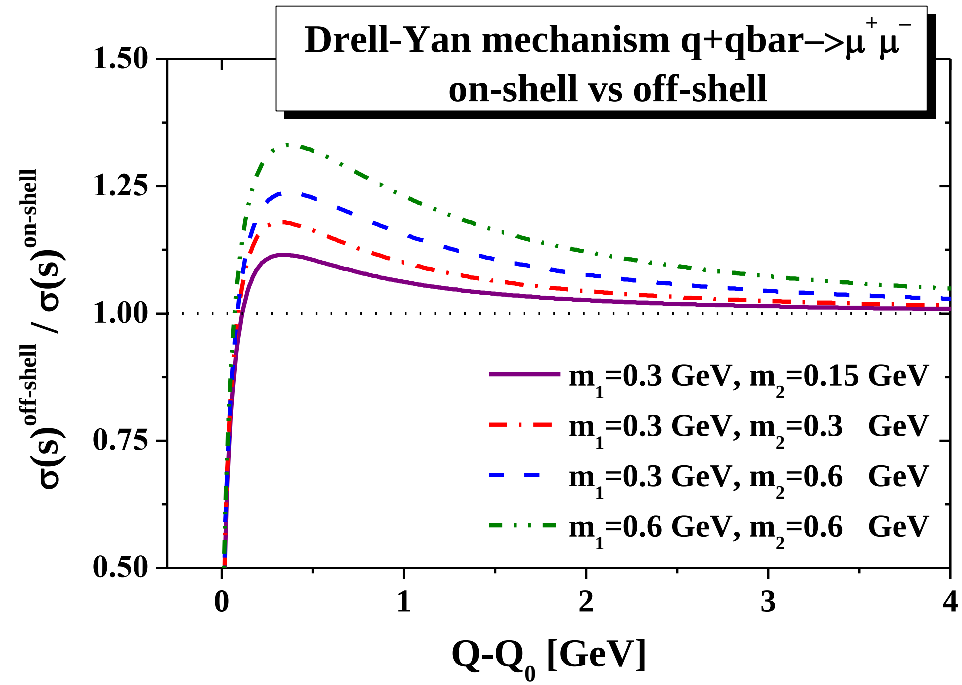


PHSD provides a consistent description of HIC dynamics

Off-shell LO q+qbar





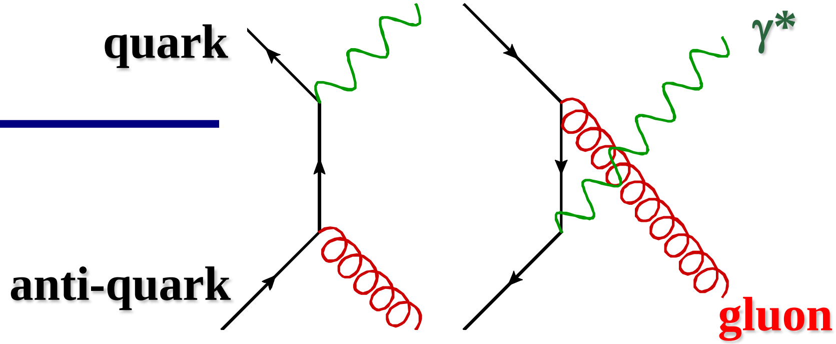


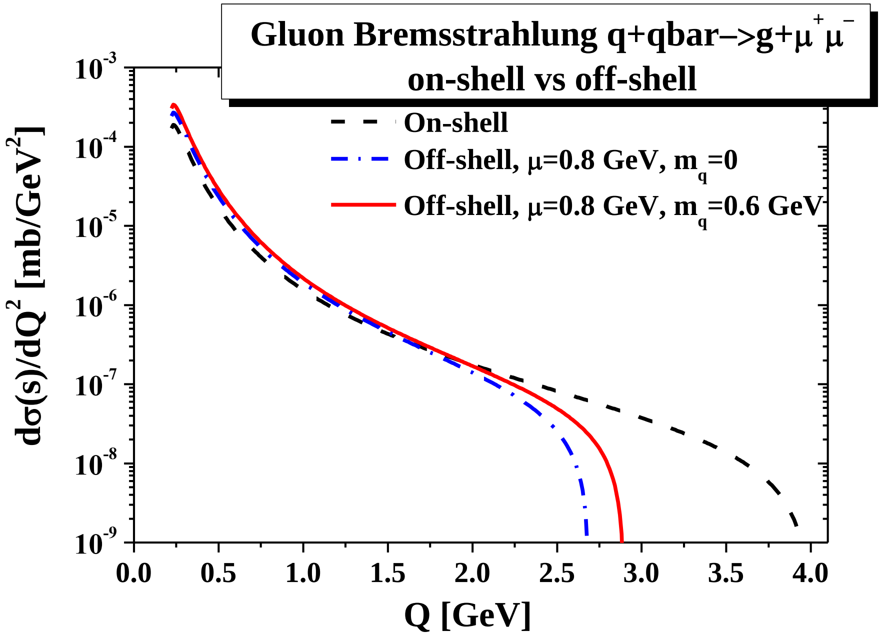
$$Q_0^2 \equiv s_0 = (m_1 + m_2 + 2m_{lept})^2 > 4m_{lept}^2$$

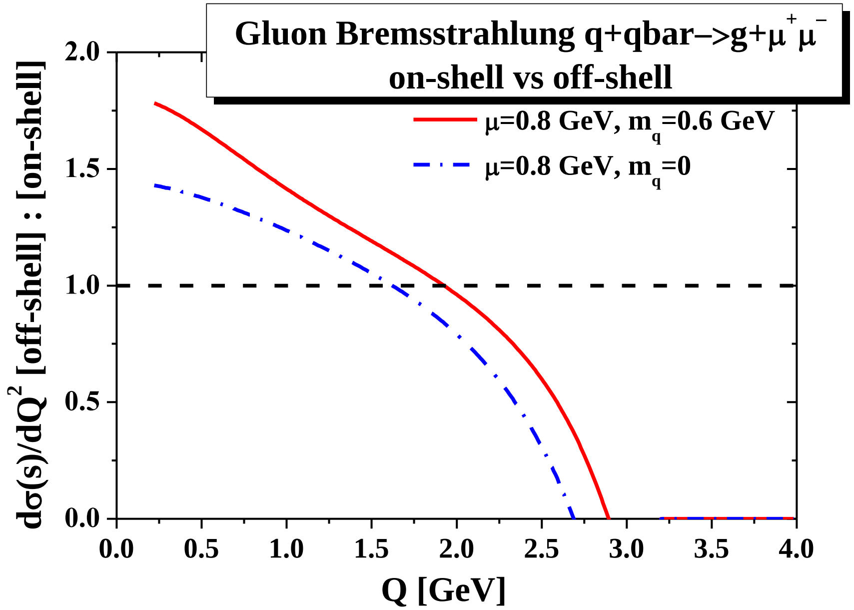
As large Q, the perturbative QCD result is recovered

O. Linnyk, arXiv:1004.2591

Off-shell NLO q+qbar





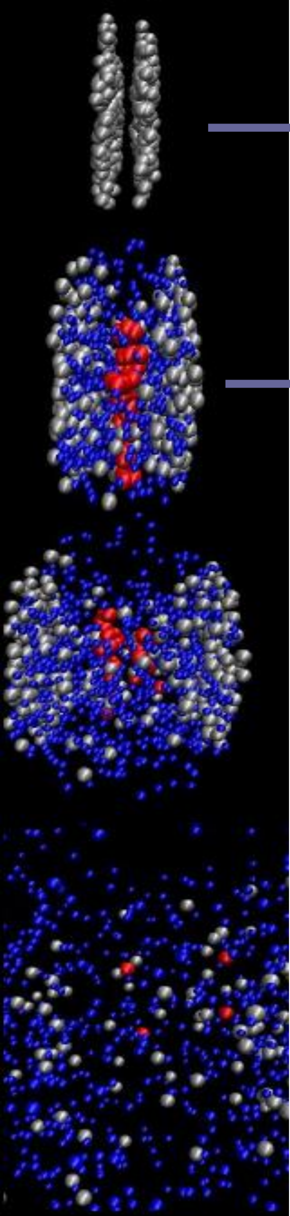


$$4m_{lept}^2 < Q^2 < (\sqrt{s} - \mu)^2$$

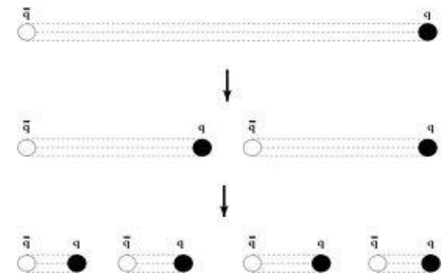
Note: In the limit of parton masses→0, the perturbative QCD result is recovered

O. Linnyk, arXiv:1004.2591

I. PHSD - basic concepts: from hadrons to QGP



- Initial N+N collisions:
  resonances and strings are produced
  and decay to pre-hadrons (LUND string model)



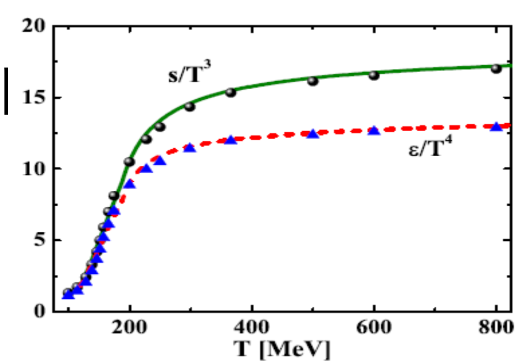
- Formation of QGP by dissolution of pre-hadrons
into massive colored quarks + mean-field energy

$$\text{Baryon} \rightarrow qqq, \quad \text{meson} \rightarrow q\bar{q} \qquad U_q$$

($\varepsilon > \varepsilon_{critical}$)

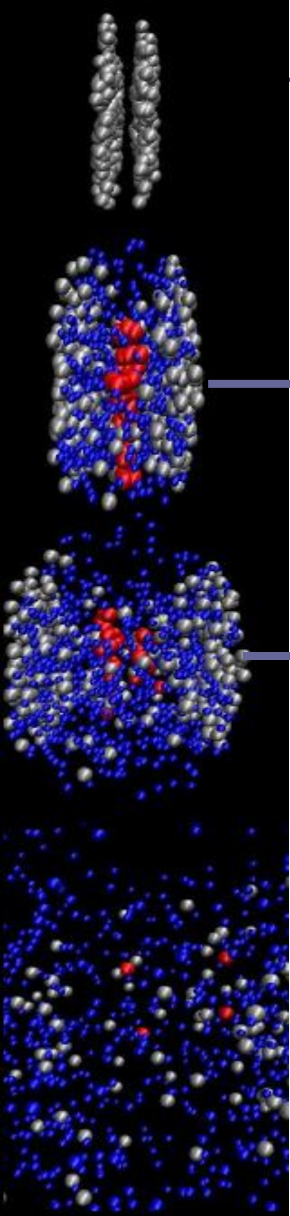
Dynamical Quasi-Particle Model (DQPM) defines quark spectral functions, i.e. masses $M_q(e)$ and widths $G_q(e)$, and mean-field potential U_q at given e – local energy density

(e related by lQCD EoS to T - tem al cell)



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

II. PHSD - basic concept



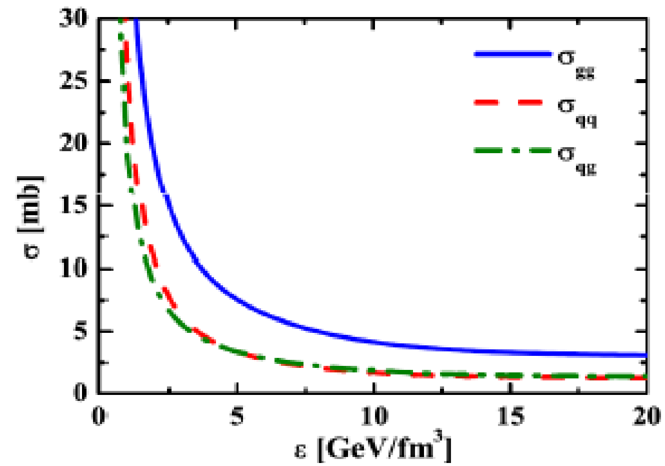
II. Partonic phase - QGP:

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:**

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



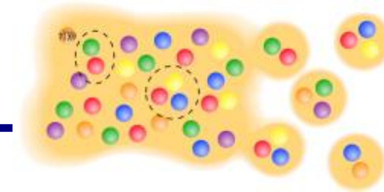
▪ **inelastic collisions:**
(Breight-Wigner cross sections)

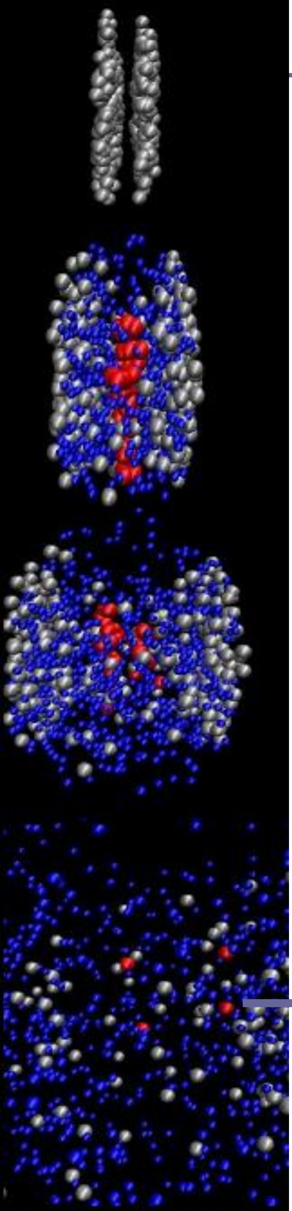
$$q+\bar{q} \to g$$
$$g \to q+\bar{q}$$

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

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

III. PHSD - basic concept





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)

$$g \to q + q\,, \qquad q + q \leftrightarrow meson\ ('string')$$
$$q + q + q \leftrightarrow baryon\ ('string')$$

- Local covariant off-shell transition rate for q+qbar fusion

➔ meson formation:

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

$$\frac{dN^{q+\bar{q}\to m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\, \delta^4(p - p_q - p_{\bar{q}})\, \delta^4\!\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(flavor, color)$$
$$\cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\, W_m\!\left(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}\right)$$

- $N_j(x,p)$ 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

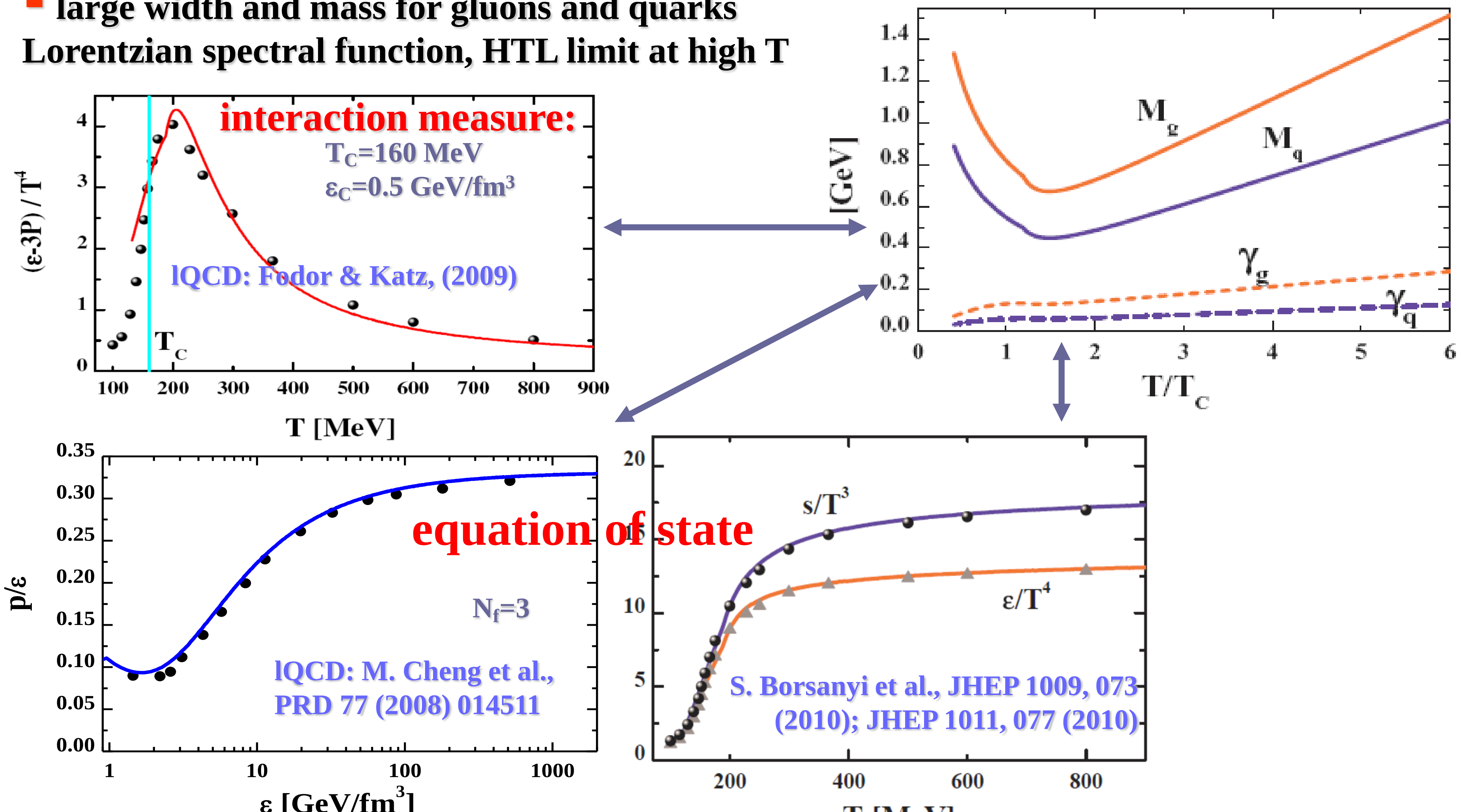
IV. Hadronic phase: hadron-string interactions – off-shell HSD

Lattice QCD –> The Dynamical QuasiParticle Model (DQPM)

Quasiparticle properties:

- **large width and mass for gluons and quarks**

Lorentzian spectral function, HTL limit at high T



E.L.Bratkovskaya, W. Cassing, V.P. Konchakovski, O. Linnyk, NPA856 (2011) 162