EMMI Rapid Reaction Task Force

Direct-Photon Flow Puzzle

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

EMMI

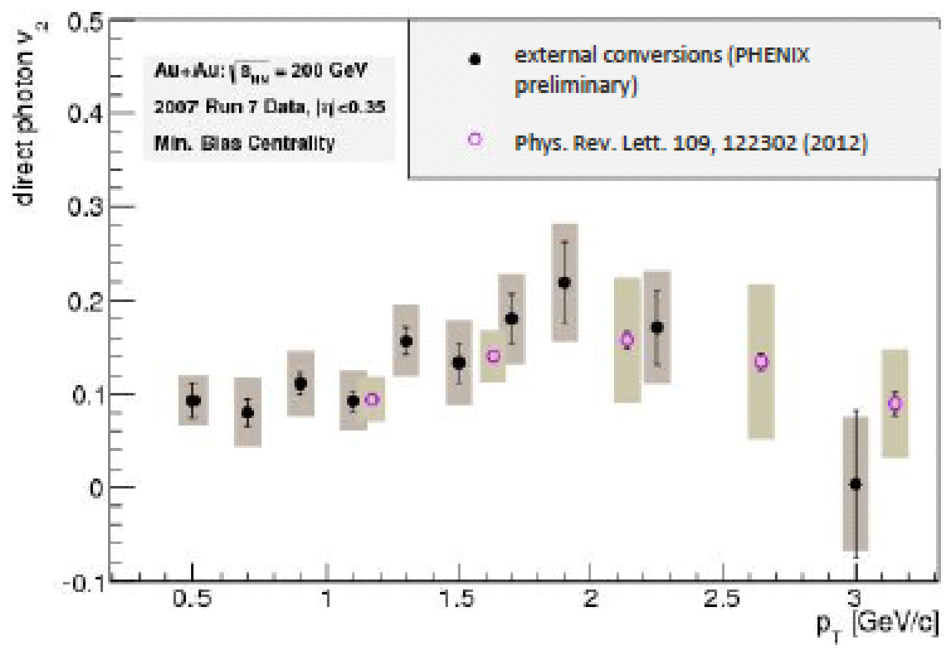
Photons from the parton-hadron transport approach

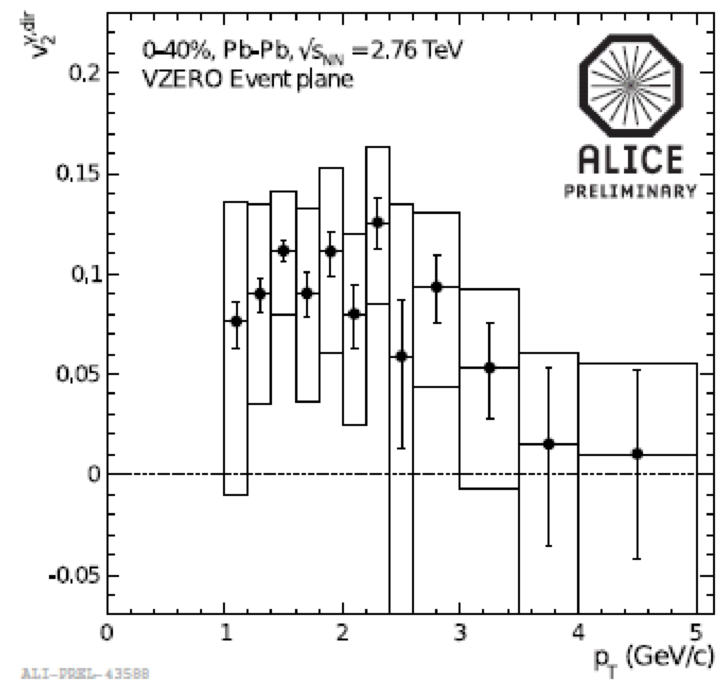
Olena Linnyk

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

PHSD

Direct photon v_2

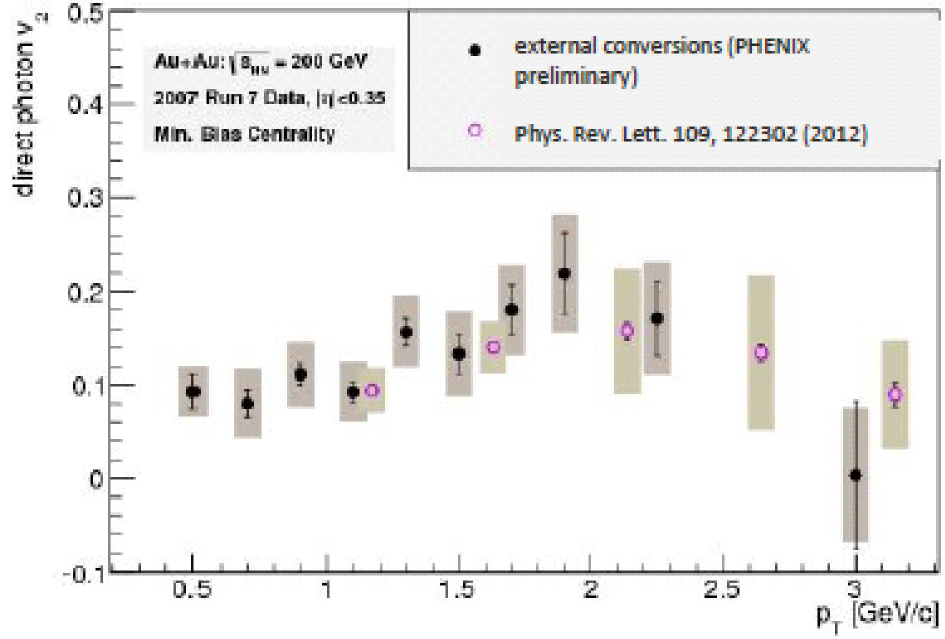


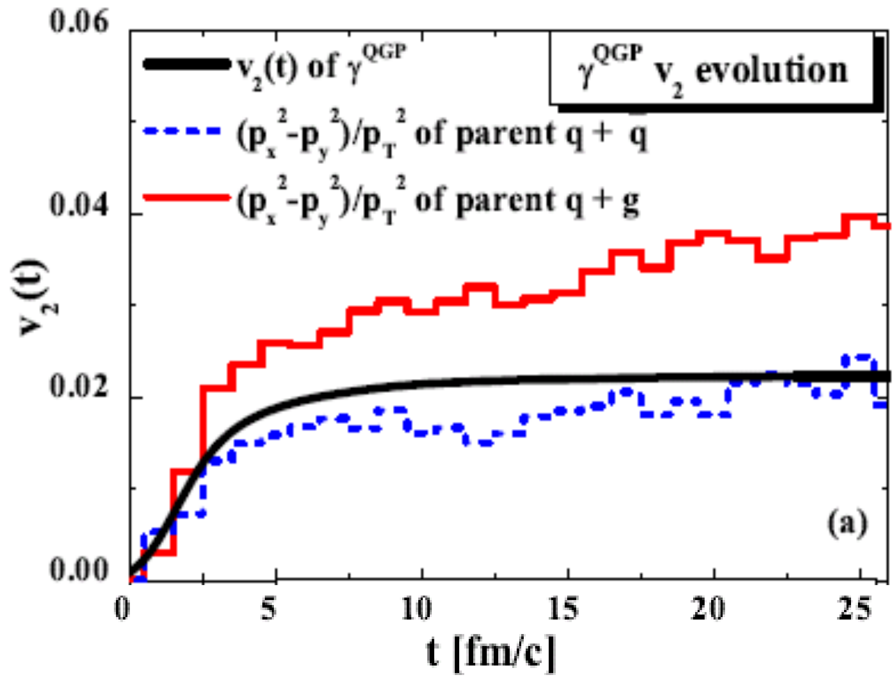


Opportunity for physics progress arose due to the recent measurements of direct photon spectra and elliptic flow by the ALICE and PHENIX Collaborations. Are the observed photons emitted in the initially produced quark-gluon plasma?

D. Lohner (for the ALICE Collaboration), arXiv:1212.3995 (2012)
M. Wilde (for the ALICE Collaboration), Nucl. Phys. A 904-905, 573c (2013)
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 109, 122302 (2012)
A. Adare et al. (PHENIX), Phys. Rev. C 81, 034911 (2010)
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 104, 132301 (2010)

Direct photon v_2



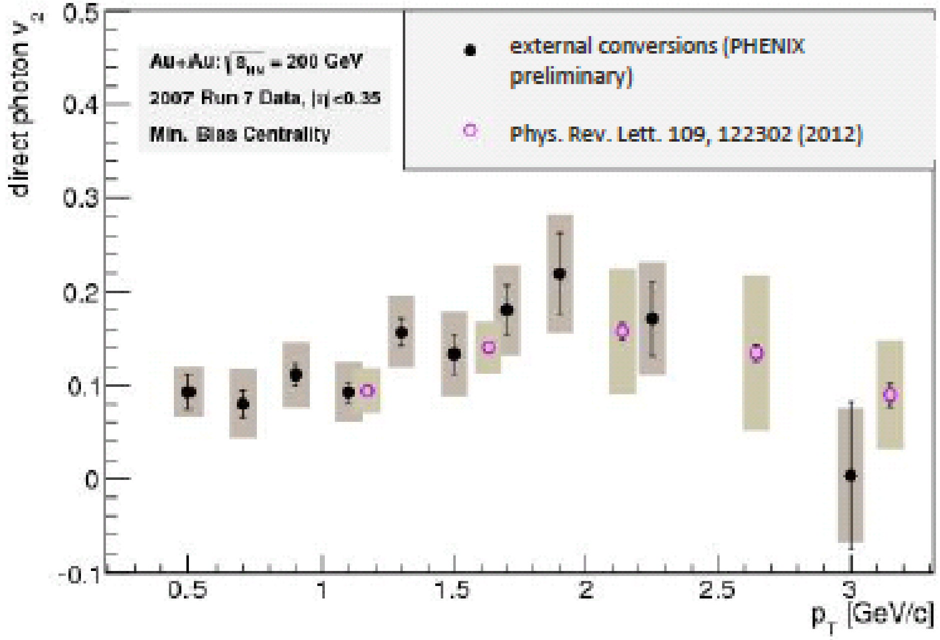


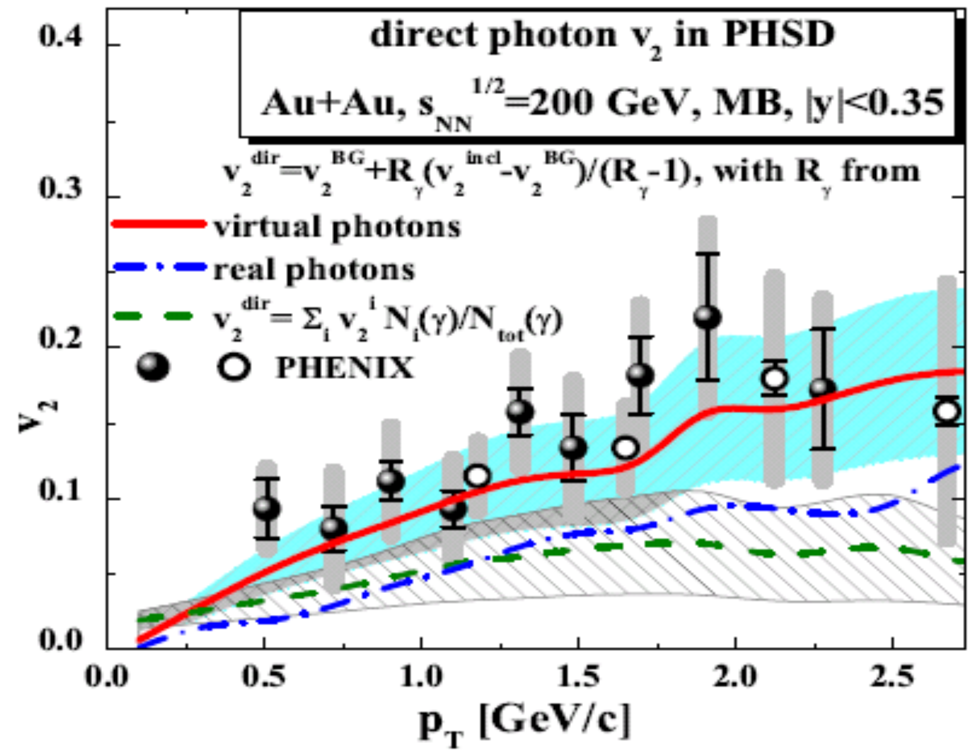
Strong elliptic flow of photons is surprising, if the origin is the QGP.

O. Linnyk et al. Phys.Rev. C88 (2013) 034904

R. Chatterjee, E. S. Frodermann, U.W. Heinz, and D. K. Srivastava, Phys.Rev.Lett. 96, 202302 (2006).
F.-M. Liu, T. Hirano, K.Werner, and Y. Zhu, Nucl.Phys. A830, 587C (2009).
M. Dion, C. Gale, S. Jeon, J.-F. Paquet, B. Schenke, et al., J.Phys. G38, 124138 (2011).
M. Dion, J.-F. Paquet, B. Schenke, C. Young, S. Jeon, et al., Phys.Rev. C84, 064901 (2011).
R. Chatterjee, H. Holopainen, I. Helenius, T. Renk, and K. J. Eskola (2013), arXiv: 1305.6443.
H. van Hees, C. Gale, and R. Rapp, Phys.Rev. C84, 054906 (2011).

Direct photon v_2





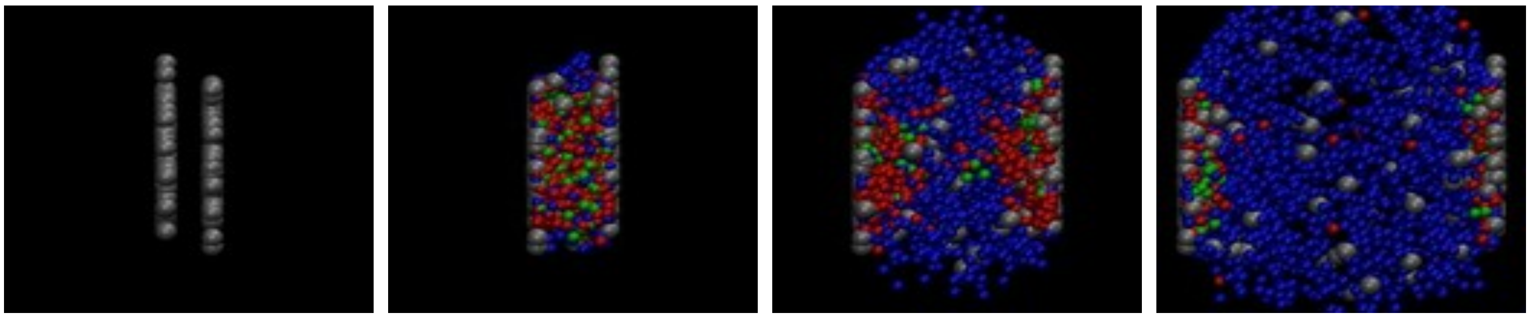
But the large elliptic flow v_2 of direct photons can be understood by taking into account multiple sources of their production throughout the collision evolution.

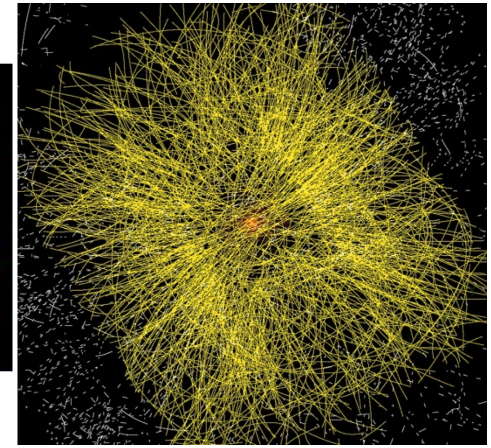
O. Linnyk et al. Phys.Rev. C88 (2013) 034904

Parton Hadron String Dynamics

Initial State

Hadronization





Au Au

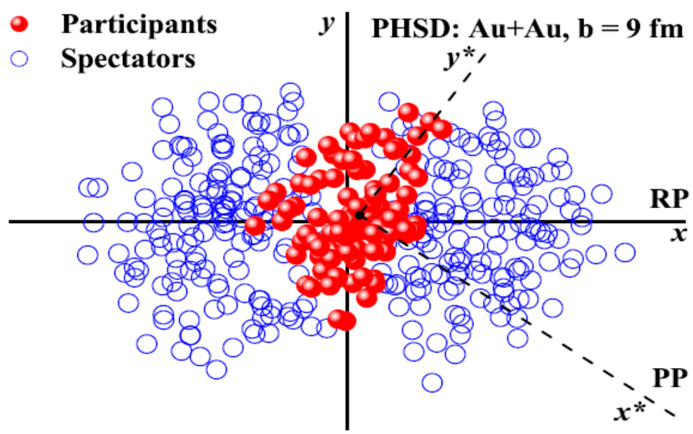
Equilibrium QGP?

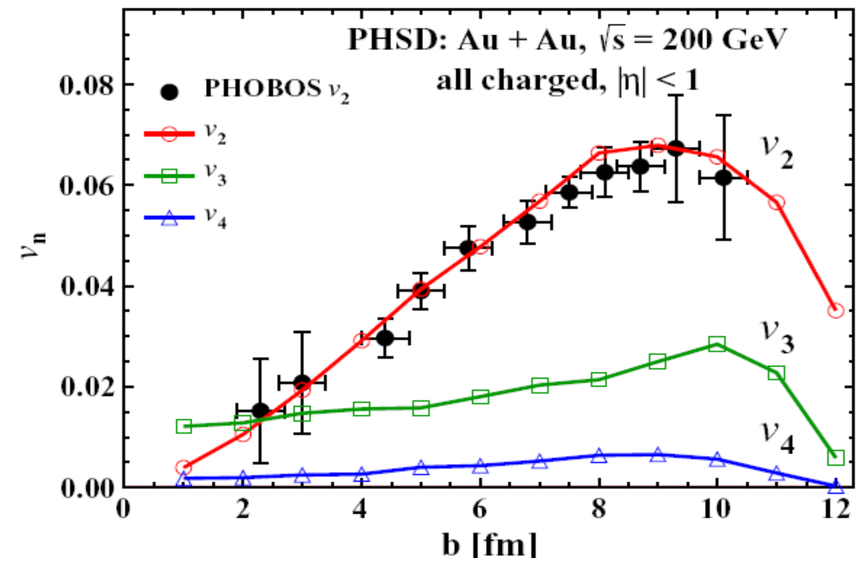
hadrons → quarks and gluons → hadrons

- **microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons**

→ PHSD

Example: Flow harmonics

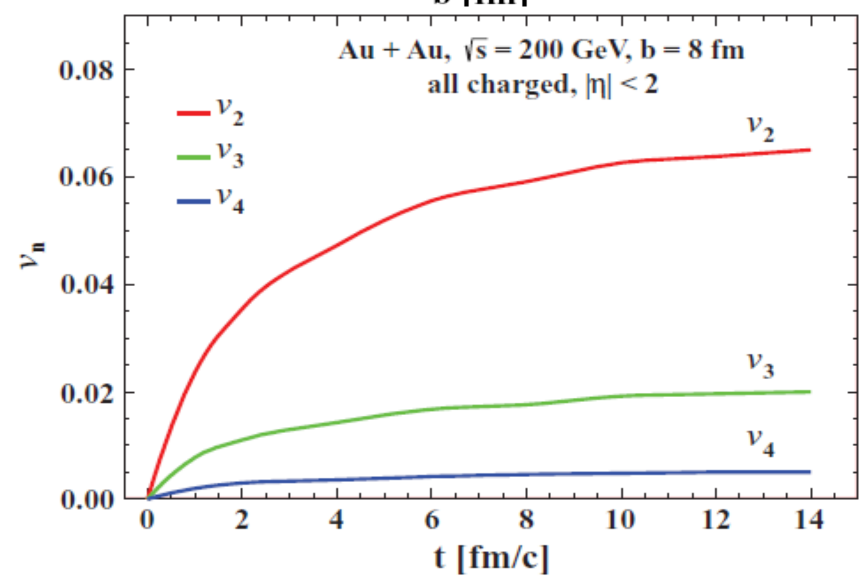




Fluctuating initial conditions!

v_2/ε = const, indicates near ideal hydrodynamic flow.

Eliptic flow gradually developes with time.

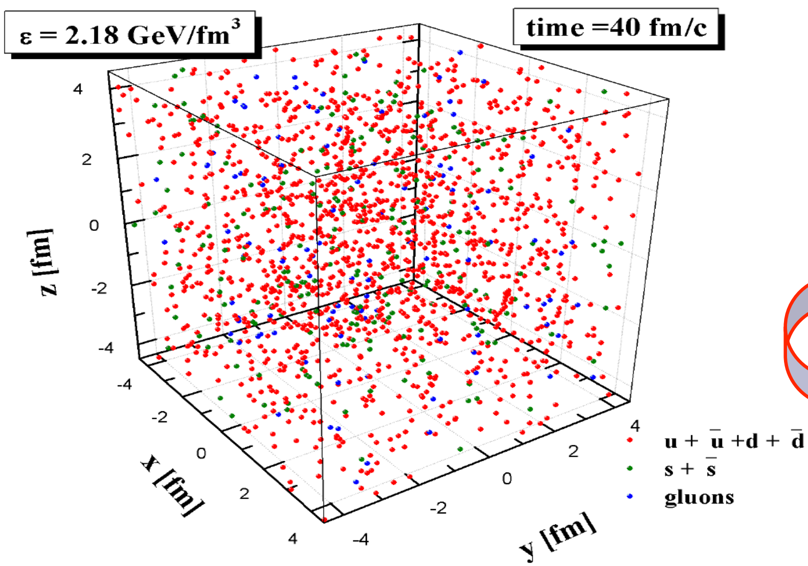


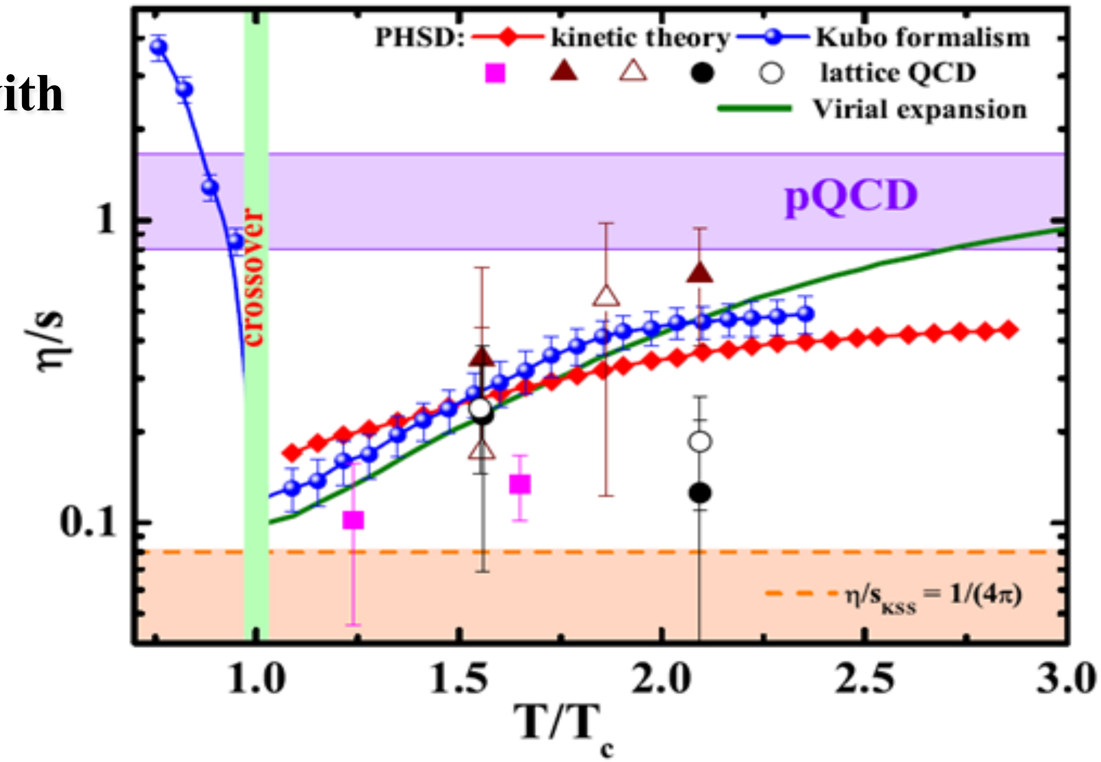
E. Bratkovskaya, et al, NPA856 (2011) 162, V. P. Konchakovski et al., PRC 85 (2012) 044922

Equilibrium QGP using PHSD

Initialize the system in a finite box with periodic boundary conditions with some energy density ε and chemical potential μ_q

Evolve the system in time until equilibrium is achieved



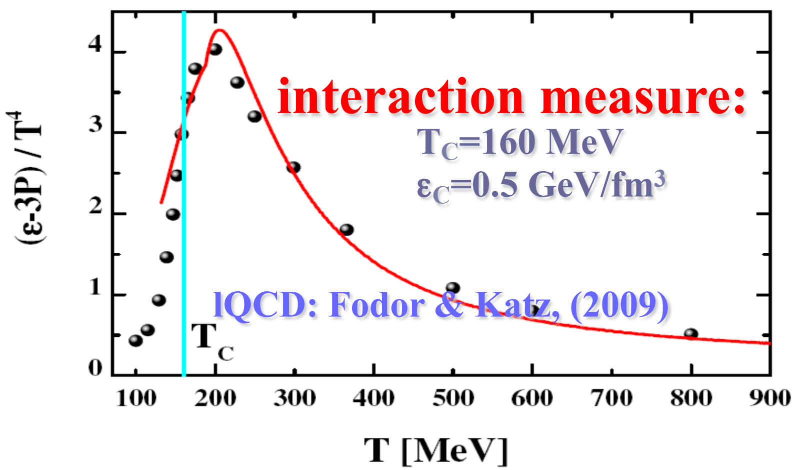


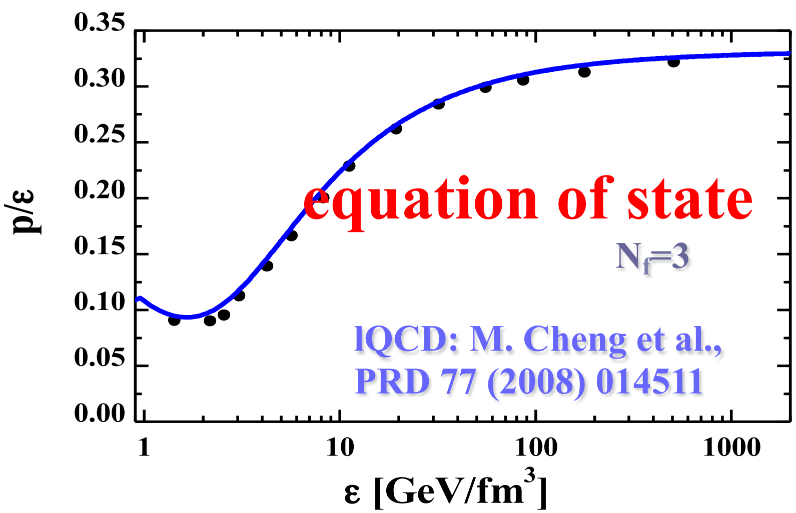
η/s using Kubo formalism and the relaxation time approximation (‚kinetic theory')

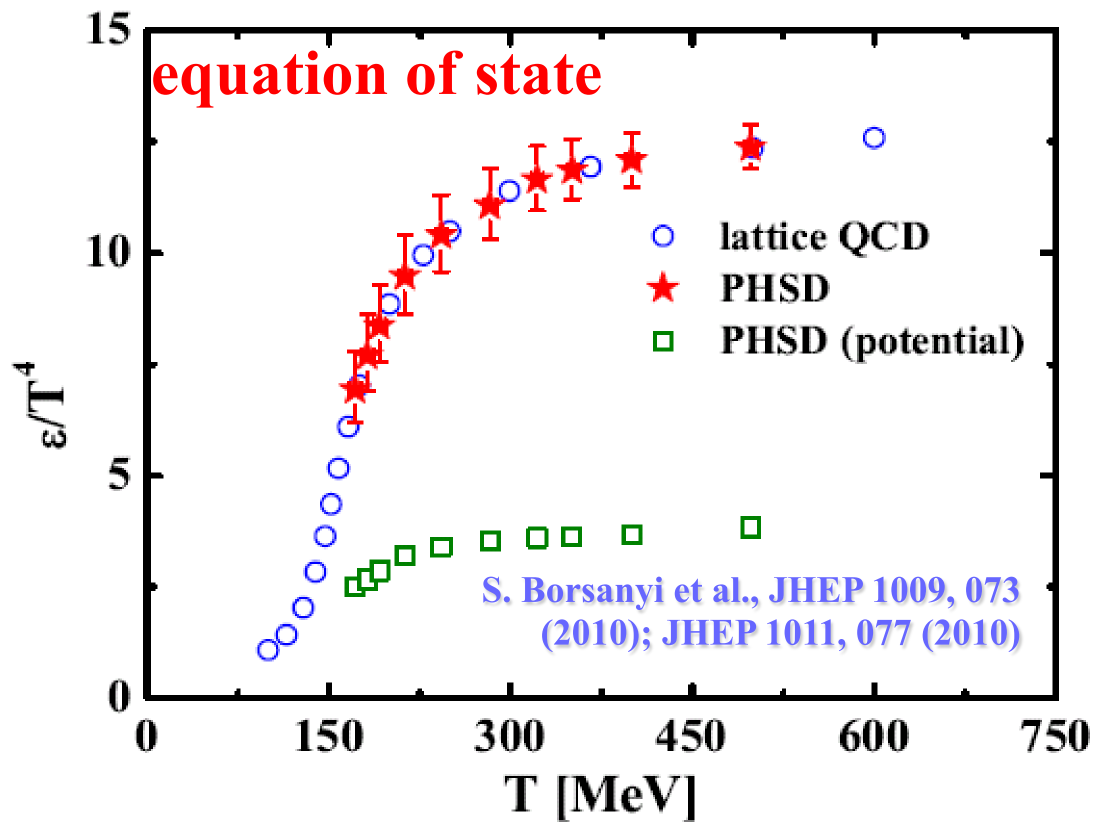
QGP in PHSD = strongly-interacting liquid

V. Ozvenchuk et al., PRC 87 (2013) 024901 V. Ozvenchuk et al., PRC 87 (2013) 064903

Lattice QCD <–> PHSD







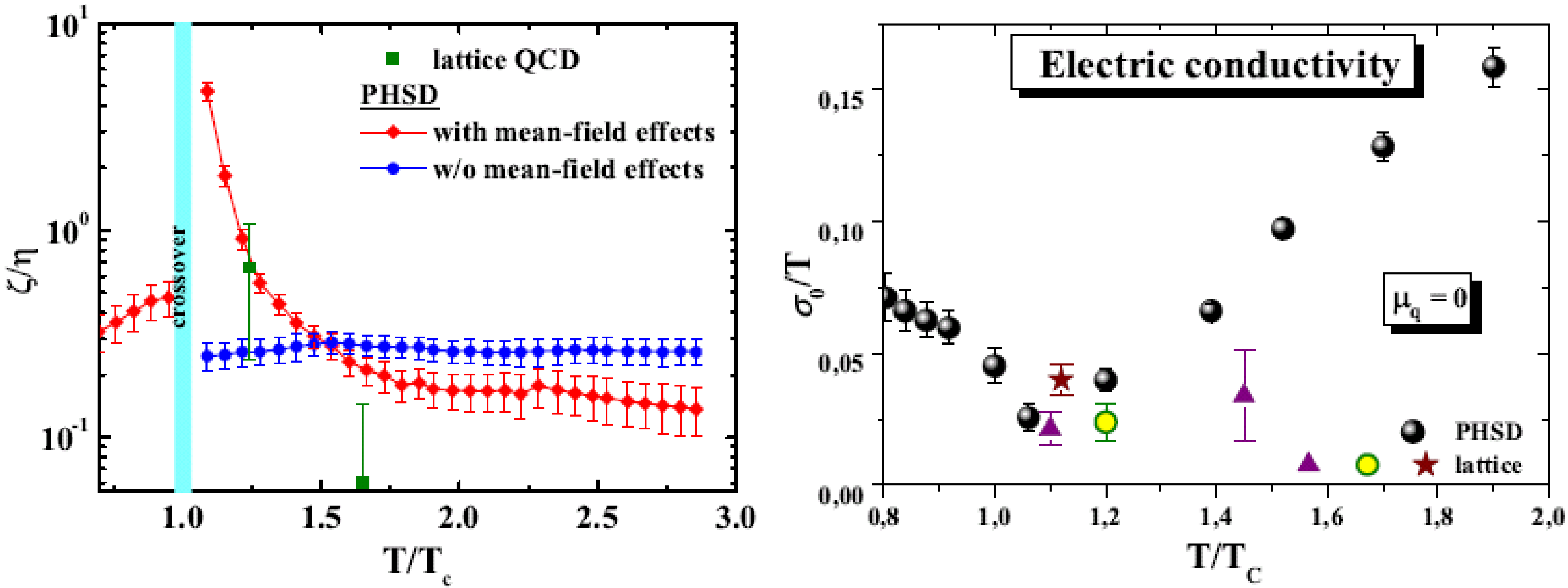
Quasiparticle properties:

- large width and mass for gluons and quarks

Lorentzian spectral function, HTL limit at high T

E.L.Bratkovskaya et al, NPA856 (2011) 162, V. Ozvenchuk et al, Phys.Rev. C87 (2013) 2, 024901

Bulk viscosity, electric conductivity



PHSD results: W. Cassing et al., PRL 110(2013)182301, T. Steinert, W. Cassing, arXiv:1312.3189

,

Lattice QCD results

Triangles: H.-T. Ding et al., Phys. Rev. D 83, 034504 (2011); O. Kaczmarek et al., PoS ConfinX, 185 (2012).

Star: P. V. Buividovich et al., Phys. Rev. Lett. 105, 132001 (2010).

Circle: B. B. Brandt, A. Francis, H. B. Meyer and H. Wittig, arXiv:1302.0675.

Squares: H.B.Meyer et al, Phys. Rev. D 76, 101701 (2007), Phys Rev. Lett. 100, 162001 (2008)

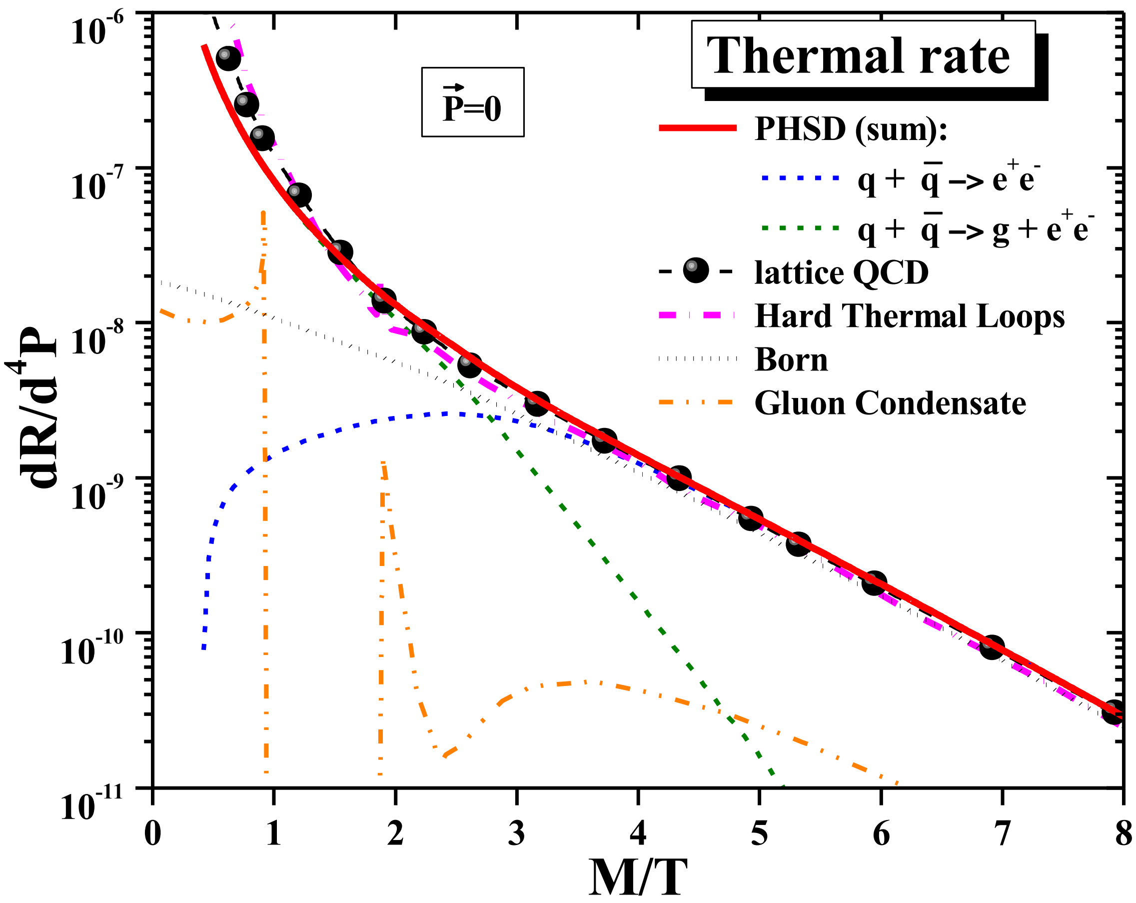
Thermal dilepton rates

Dileptons from dynamical off-shell quark and gluon interactions,
LO and NLO in the coupling

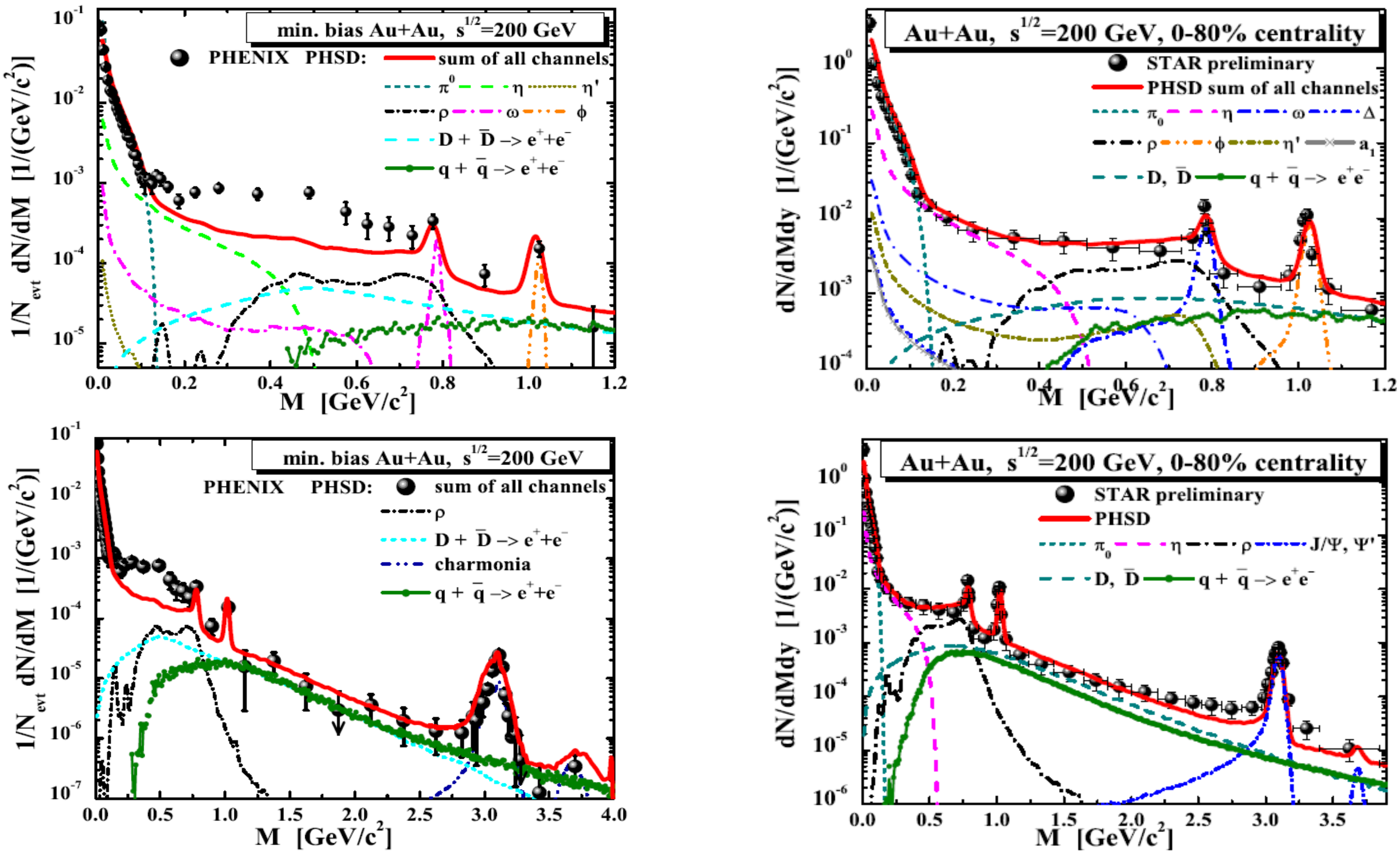
- Qualitative agreement of

  dynamical quasiparticels,
  lattice QCD,
  HTL

O. Linnyk et al. Phys.Rev. C87 (2013) 014905



RHIC dileptons: PHENIX and STAR



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

The scientific method

✓ Agreement with lattice QCD on equation of state and transport properties (including electro-magnetic spectral function)

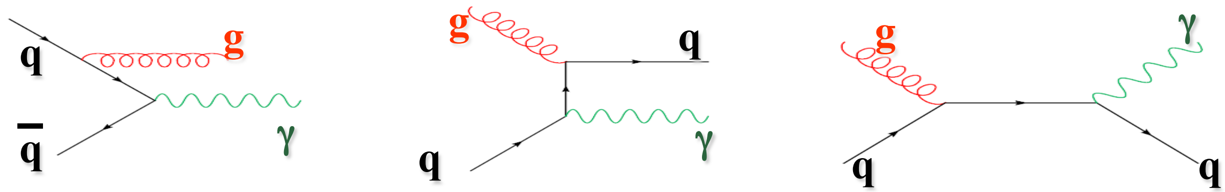
✓ Comparison to the data on dilepton production

✓ Photon production as a prediction

Photons from the hot and dense QCD medium

<u>Photon sources in PHSD</u>

1) From the QGP via partonic interactions:



2) From hadronic sources

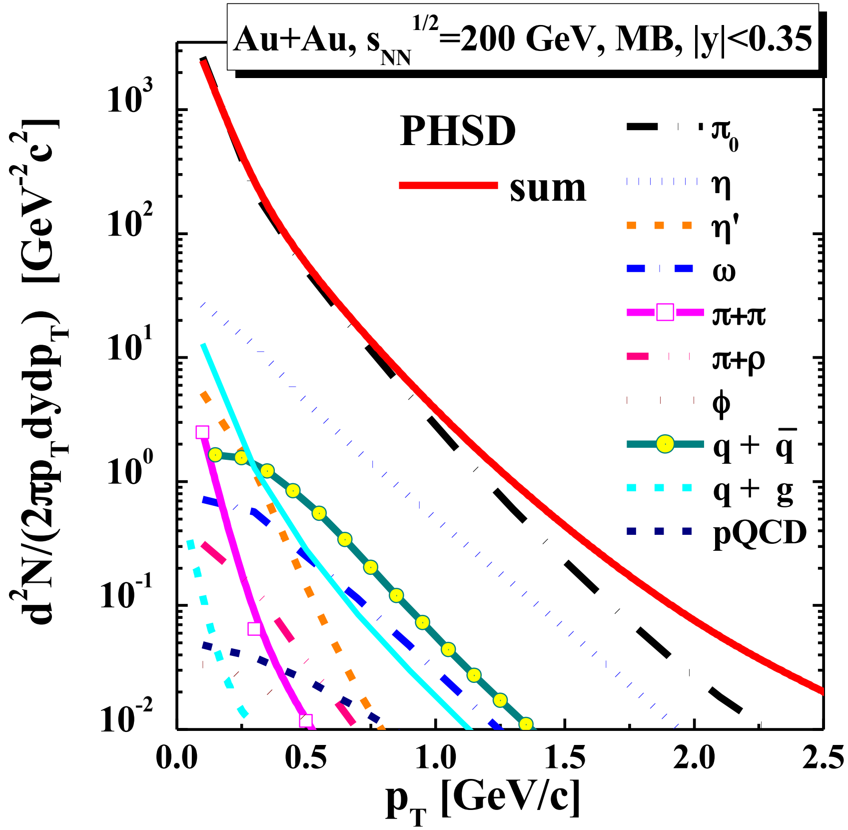
- **decays of mesons:** $\pi \rightarrow \gamma + \gamma,\ \eta \rightarrow \gamma + \gamma,\ \omega \rightarrow \pi + \gamma$
  $\eta' \rightarrow \rho + \gamma,\ \phi \rightarrow \eta + \gamma,\quad a_1 \rightarrow \pi + \gamma$

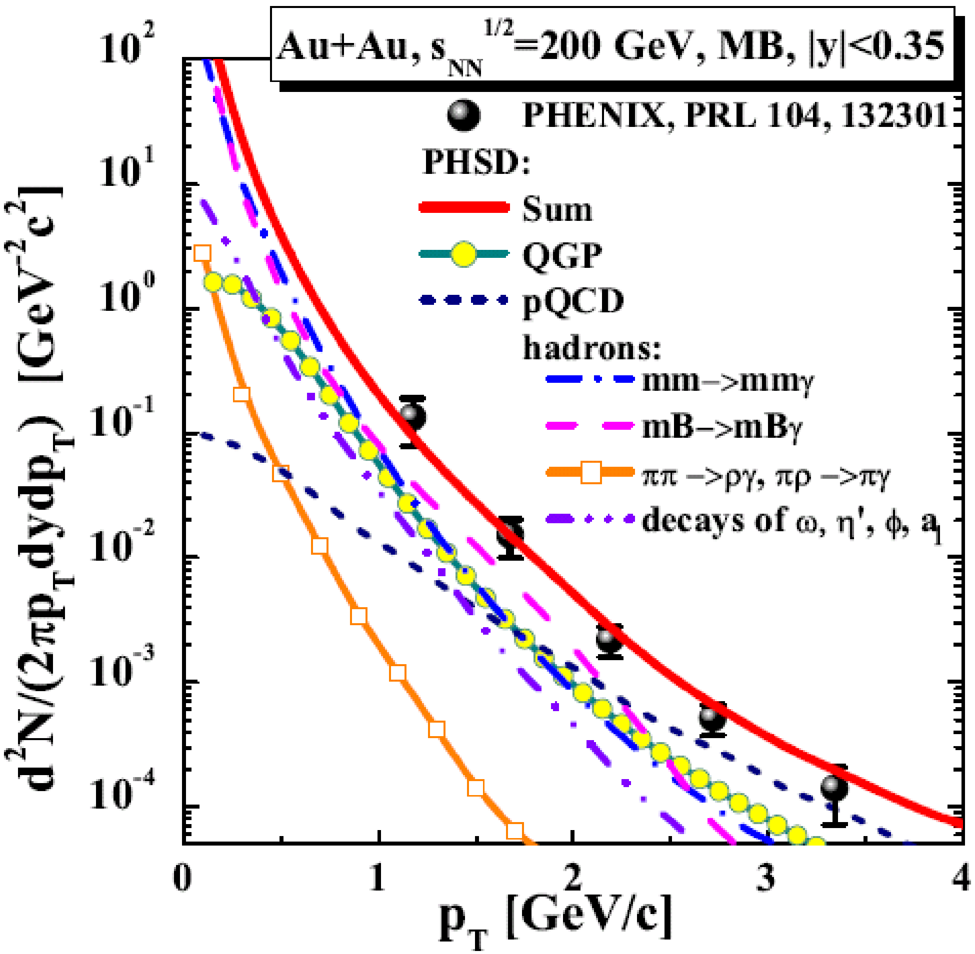
- **secondary meson interactions:** $\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma$
  using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

- **Meson-meson and meson-baryon bremsstrahlung**
  using soft photon approximation

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

Photon spectrum





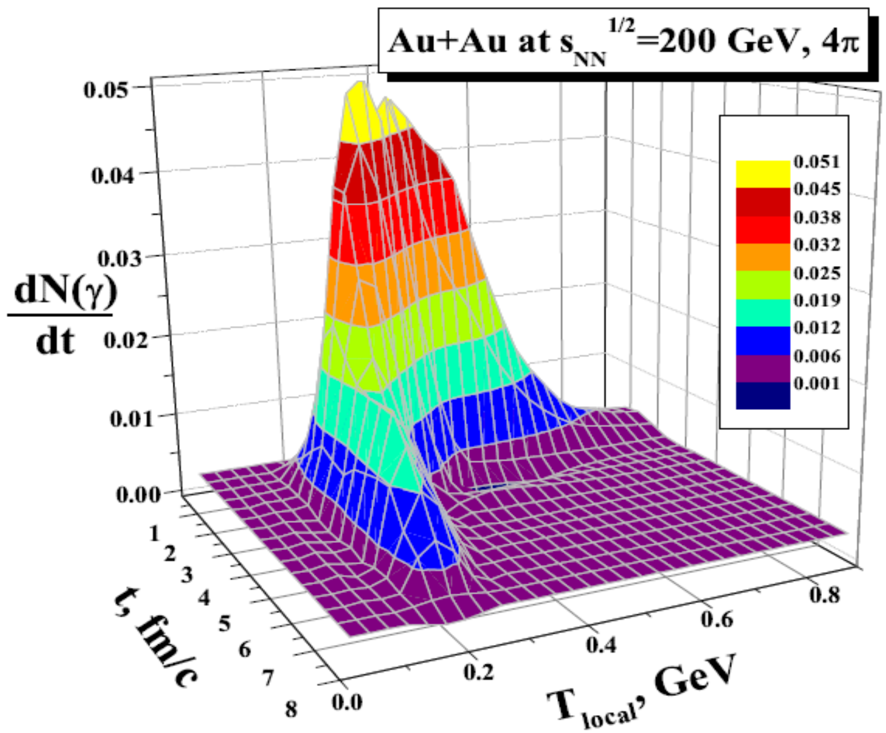
- **PHSD:** PHENIX data are well describe including mB bremsstrahlung

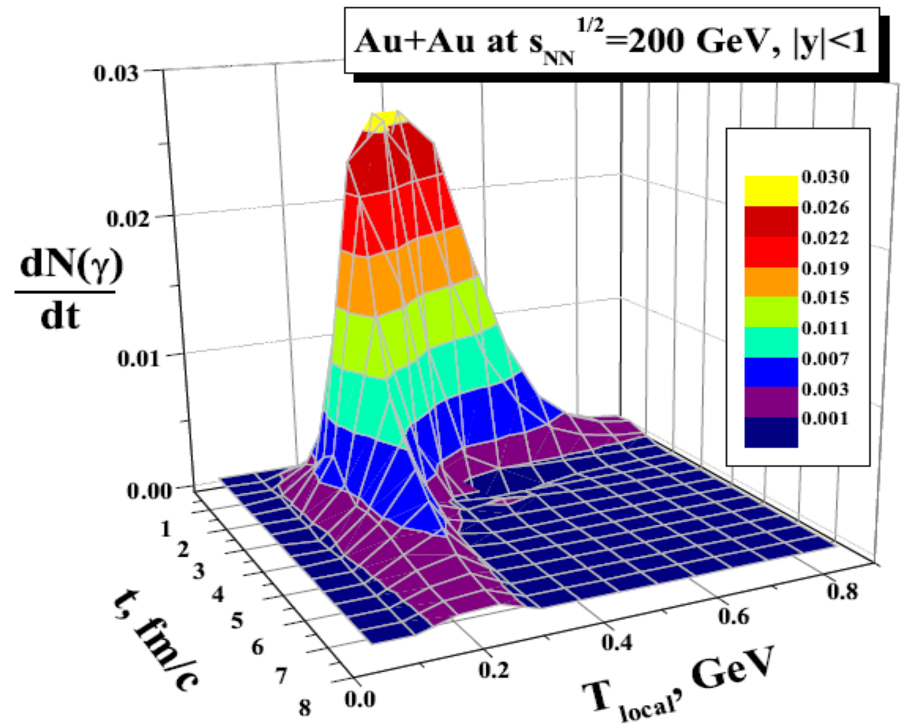
- QGP sources mandatory to explain the spectrum, but hadronic sources of ‘direct’ photons are considerable, too

O. Linnyk et al. Phys.Rev. C88 (2013) 034904

Time evolution of the photon production rate vs. T

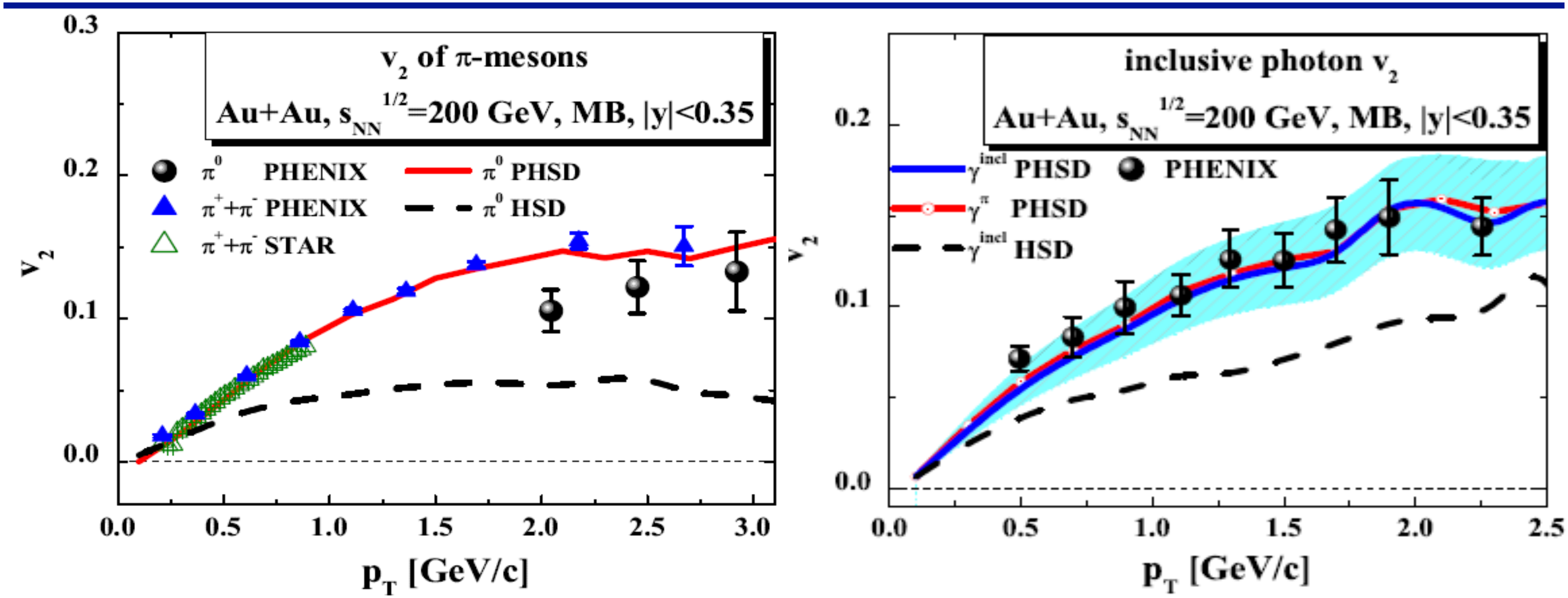
The photon production rate versus time and the local ’temperature’ at the production point in 4π and mid-rapidity Au+Au collisions:





O. Linnyk et al. Phys.Rev. C88 (2013) 034904

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

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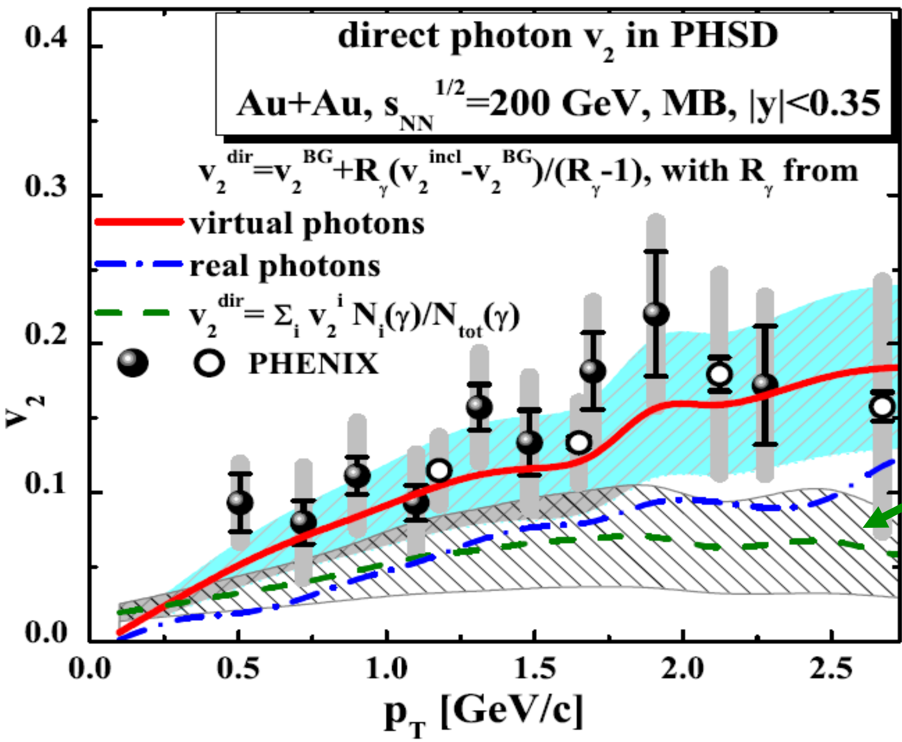
Elliptic flow from direct photons: method I

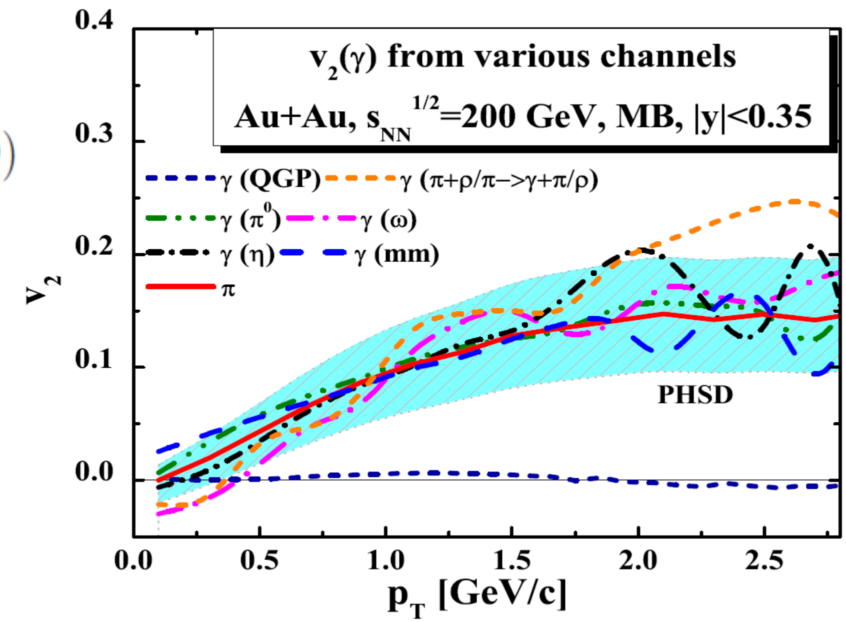
- ‚Weighted' method (theor. way):

direct photon v_2 (in PHSD) = sum of v_2 of the individual channels, using their contributions to the spectrum as the relative p_T -dependent weights $w_i(p_T)$:

$$v_2(\gamma^{dir}) = \sum_i v_2(\gamma^i) w_i(p_T) = \frac{\sum_i v_2(\gamma^i) N_i(p_T)}{\sum_i N_i(p_T)}$$

$$i = (q\bar{q} \to g\gamma, qg \to q\gamma, \pi\pi/\rho \to \rho/\pi\gamma, mm \to mm\gamma, \text{pQCD})$$





- 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

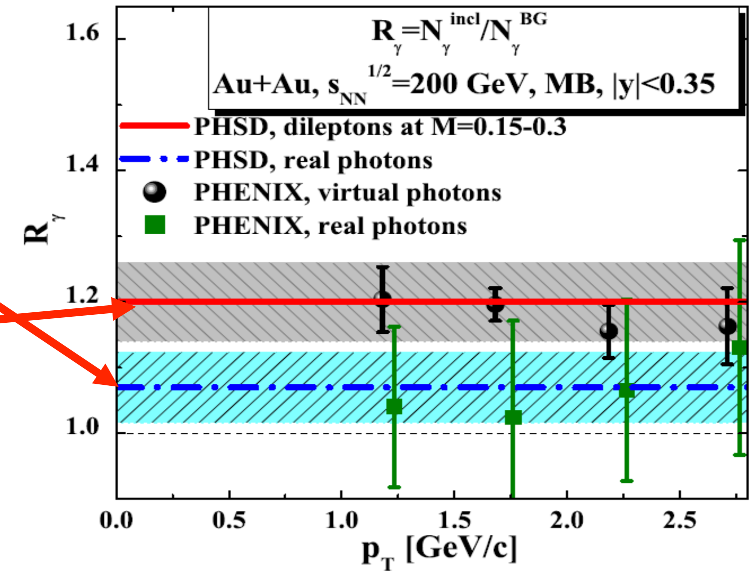
Elliptic flow from direct photons: method II

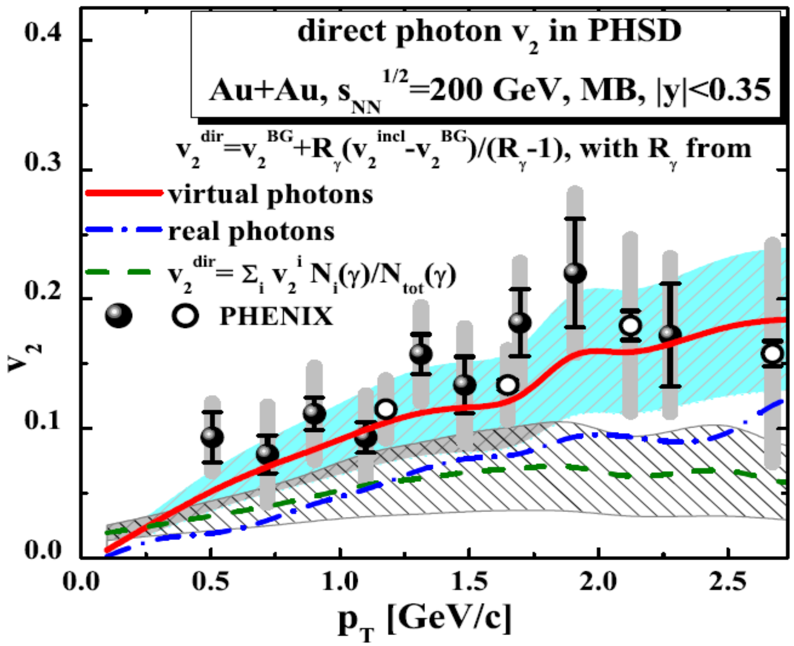
- ‚Background' subtraction method (exp. way):

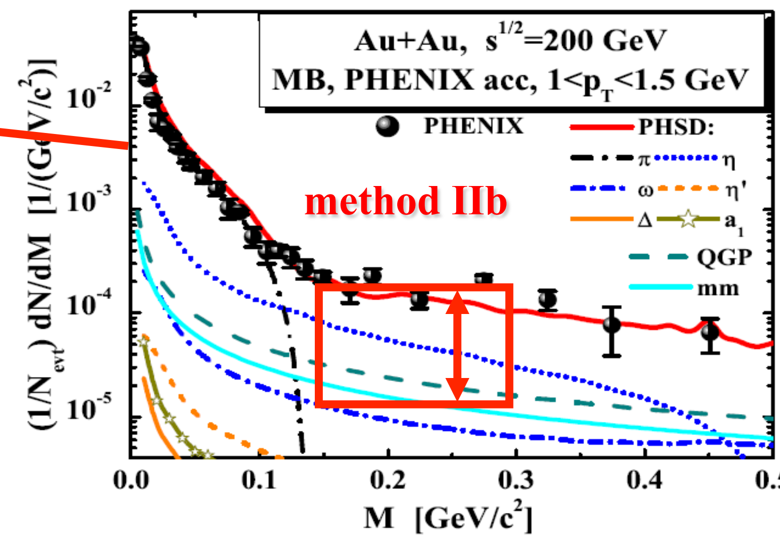
$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1}$$

$$R_\gamma = N^{incl}/N^{BG}$$

IIa) from real photons R_γ~1.05
IIb) from virtual photons R_γ~1.2



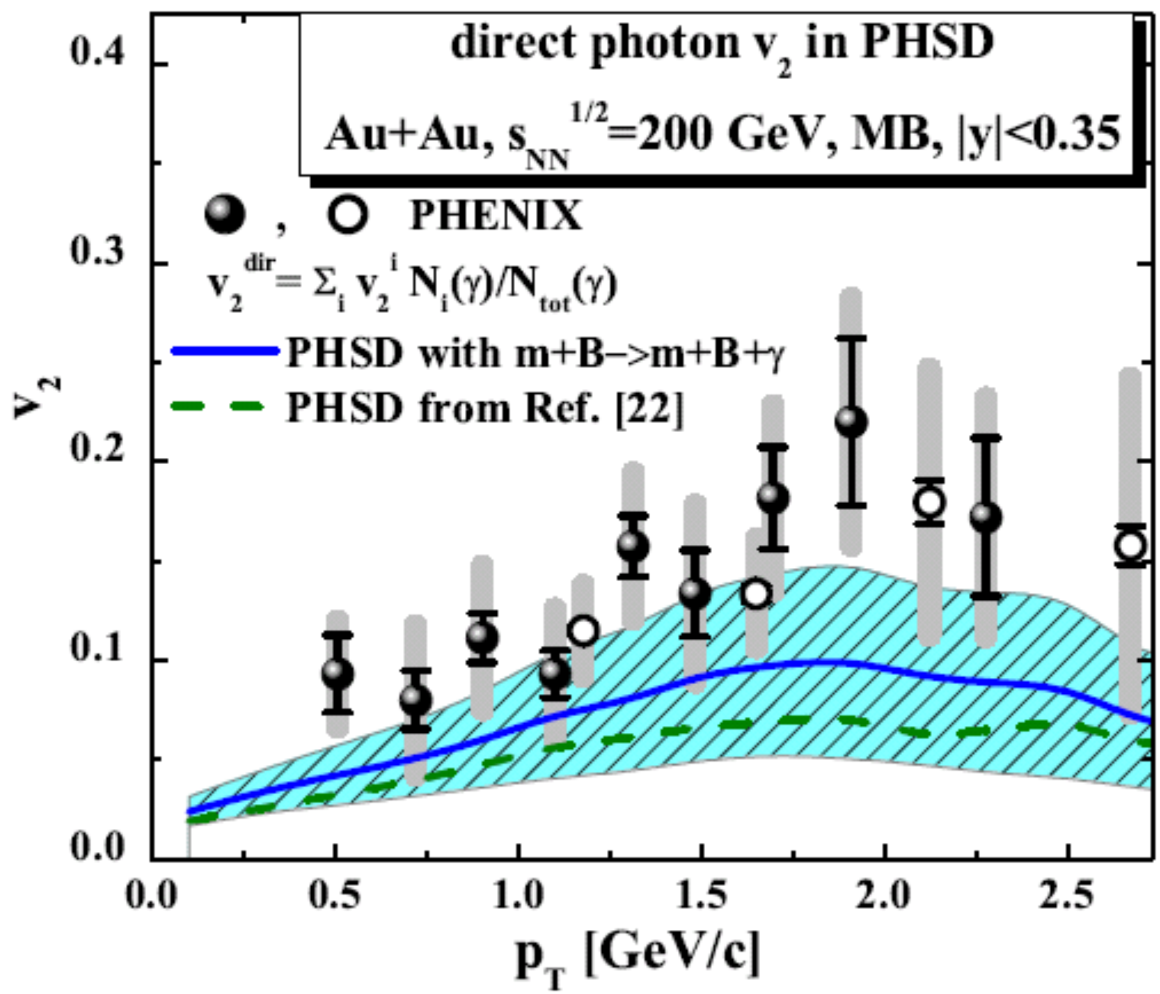




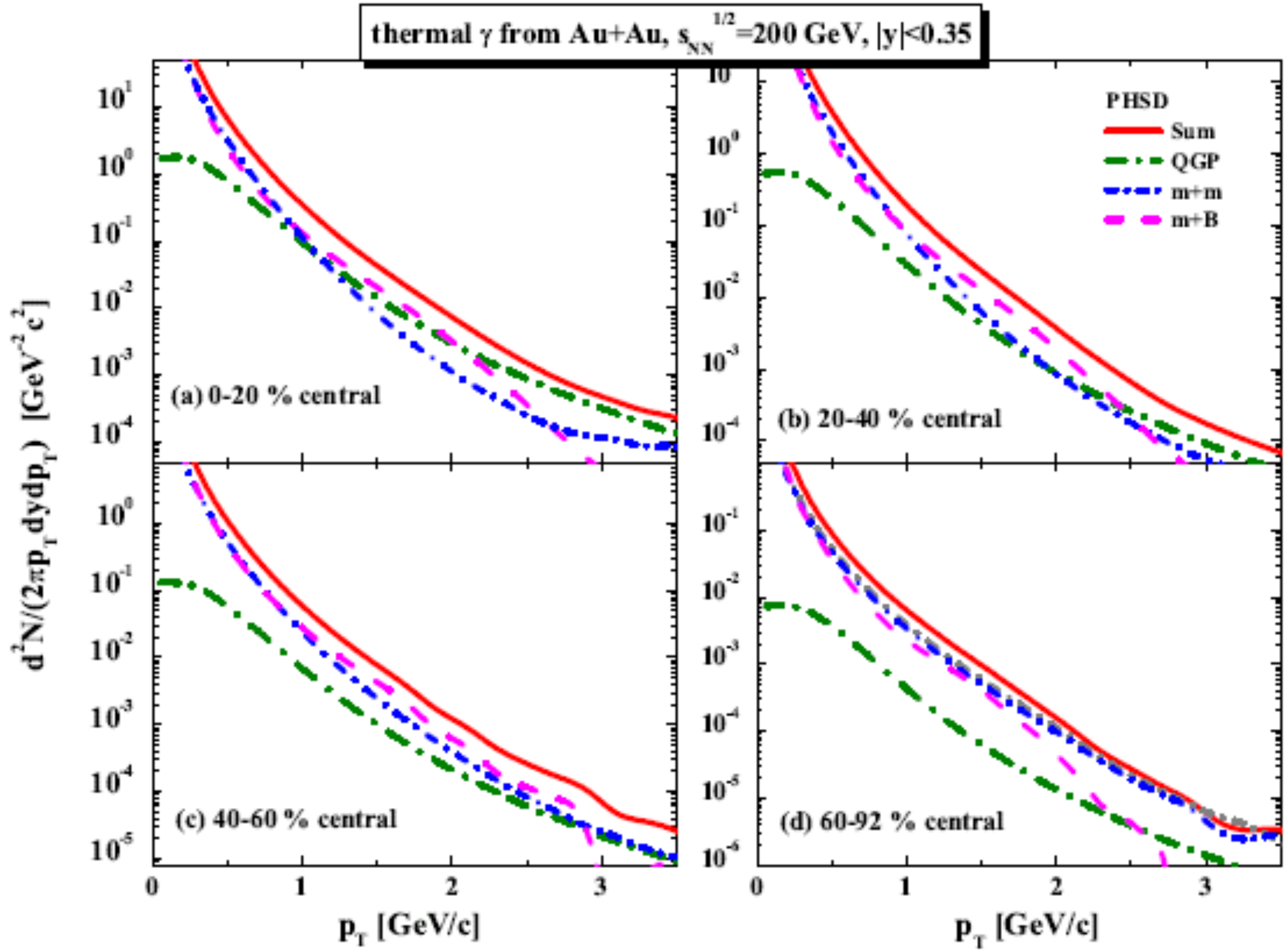
- v_2 of direct photons in PHSD - as evaluated by the ‚background' subtraction method IIb - is consistent with exp. data!

O. Linnyk et al. Phys.Rev. C88 (2013) 034904

Including baryonic channels



Centrality dependence of the thermal photon yield

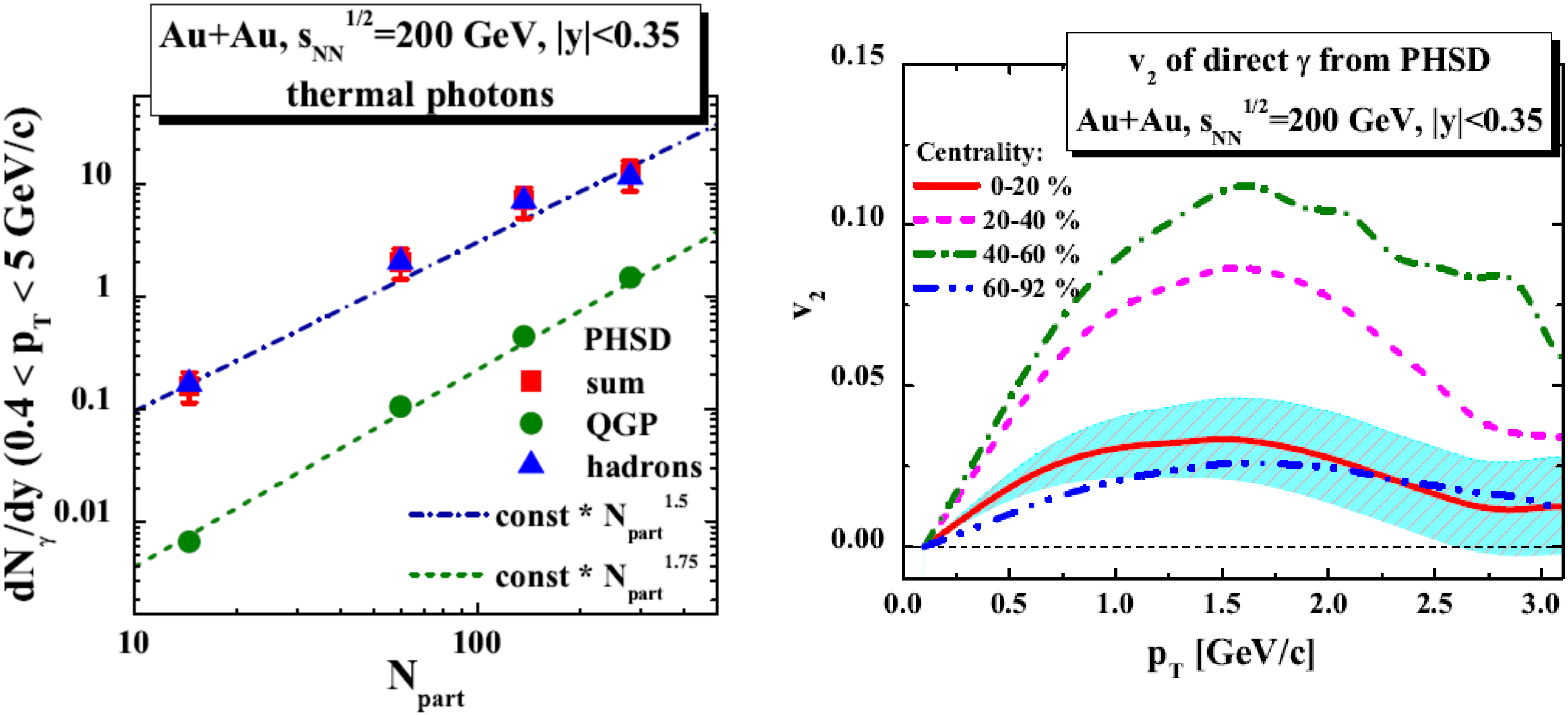


‘Thermal’ photon yield in different centrality bins. Even after the subtraction of the pQCD photons, the shape of the spectrum is not exponential.

Caution: LPM effect.

O. Linnyk et al. arXiv:1311.0279

Centrality dependence of the thermal photon yield



We observe scaling of the thermal photon yield with the number of participants in the power 1.5 and predict the centrality dependence of the direct photon eliptic flow.

O. Linnyk et al. arXiv:1311.0279

Conclusions

- **Direct photons - the photons produced in the QGP - contribute about 50% to the observed spectrum, but have small v_2**

- **Large measured direct photon v_2 – comparable to that of hadrons – is attributed mainly to the intermediate hadronic scattering channels**

- **The value of v_2 is sensitive to the hadronic 'background' subtraction method**

- **The QGP phase causes the strong elliptic flow of photons indirectly by enhancing the v_2 of final hadrons due to the partonic interactions in terms of explicit parton collisions and the mean-field potentials**

Thank you!

Wolfgang Cassing (Giessen U)
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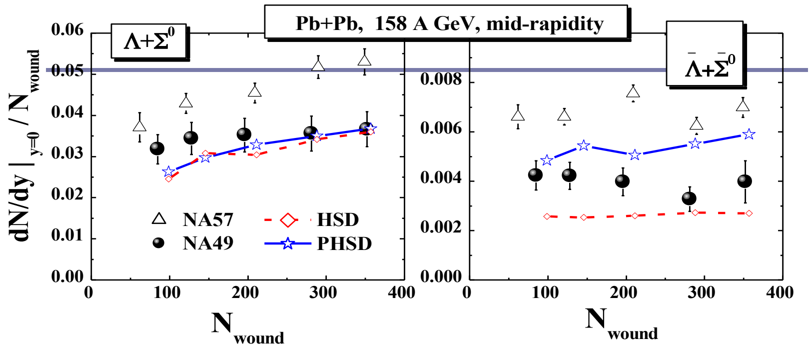
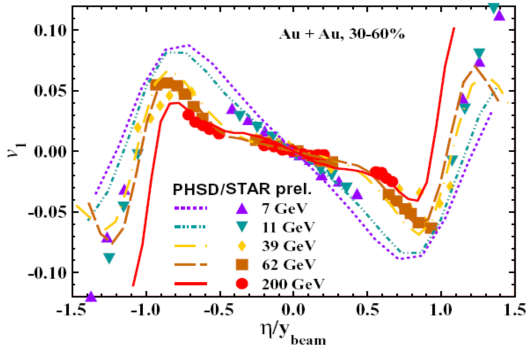
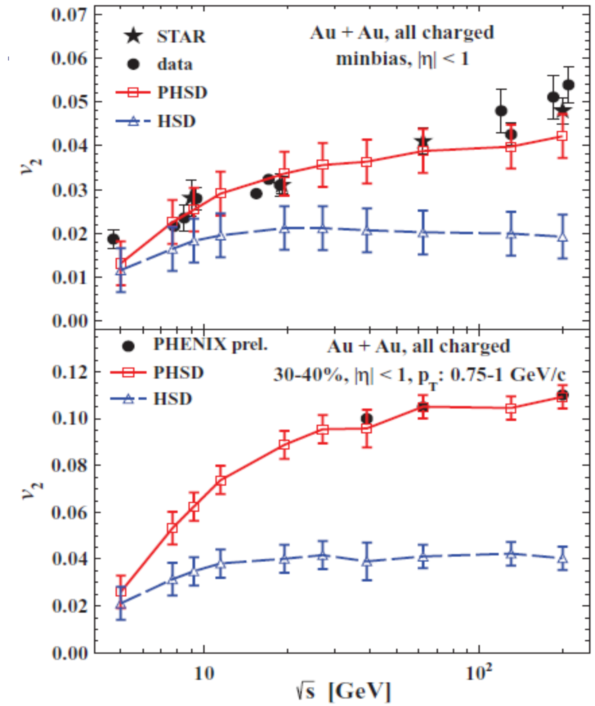
TEXAS A&M UNIVERSITY

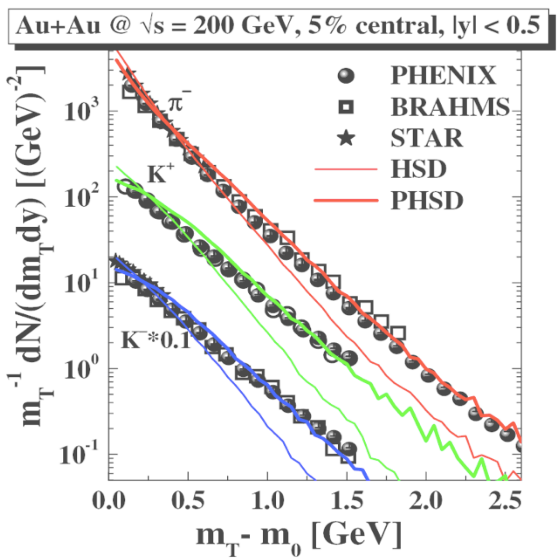
Backup

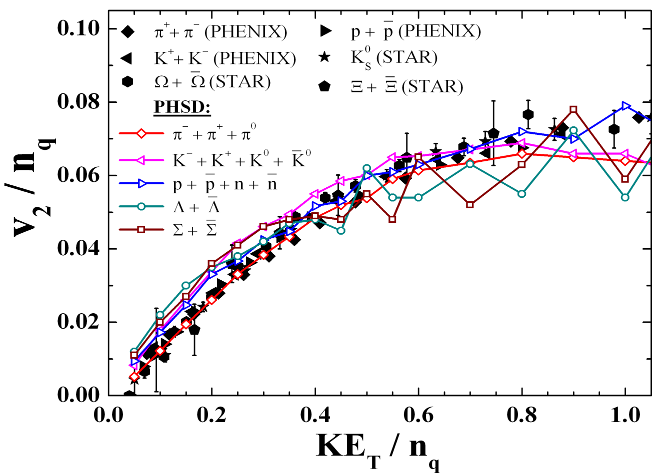
PHSD for HIC (highlights)

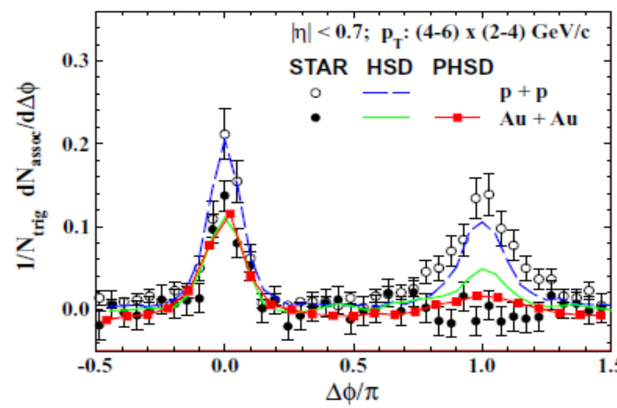






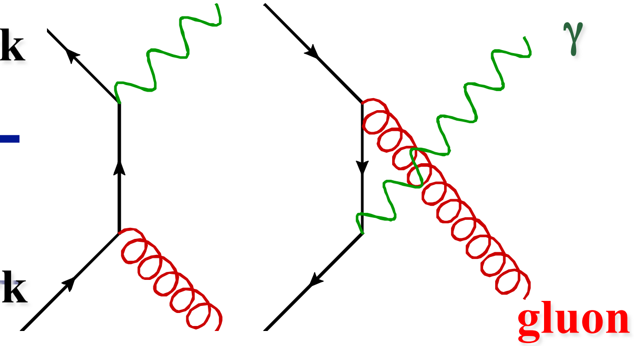






- PHSD provides a consistent description of HIC dynamics from AGS to RHIC energies

Off-shell q+qbar->g+γ



$$M = M_a + M_b$$

– $$d\sigma = \frac{\Sigma|\bar{M}_{i\to f}|^2 \varepsilon_1 \varepsilon_2 \Pi \frac{d^3 p_f}{(2\pi)^3}}{\sqrt{(p_1 p_2)^2 - m_1^2 m_2^2}} (2\pi)^4 \delta(p_1 + p_2 - \Sigma p_f)$$

$$M_a = -e_q e g_s T^l_{ij} \frac{\epsilon_\nu(q)\epsilon_{\sigma l}(k)}{p_3^2 - m_3^2} \times u_i(p_1, m_1) \left[\gamma^\nu(\hat{p}_3 + m_3)\gamma^\sigma\right] v_j(p_2, m_2)$$

$$M_b = -e_q e g_s T^l_{ij} \frac{\epsilon_{\sigma l}(k)\epsilon_\nu(q)}{\bar{p}_3{}^2 - m_3^2} \times u_i(p_1, m_1) \left[\gamma^\eta(\hat{\bar{p}}_3 + m_3)\gamma^\nu\right] v_j(p_2, m_2)$$

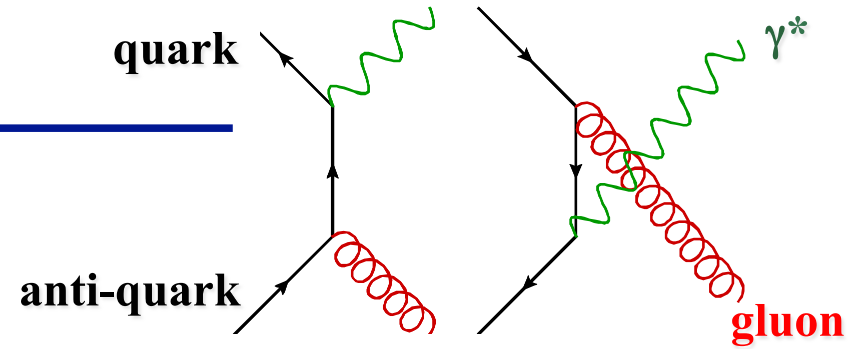
$$\sum |M|^2 = \sum M_a^* M_a + \sum M_b^* M_b + \sum M_a^* M_b + \sum M_b^* M_b,$$

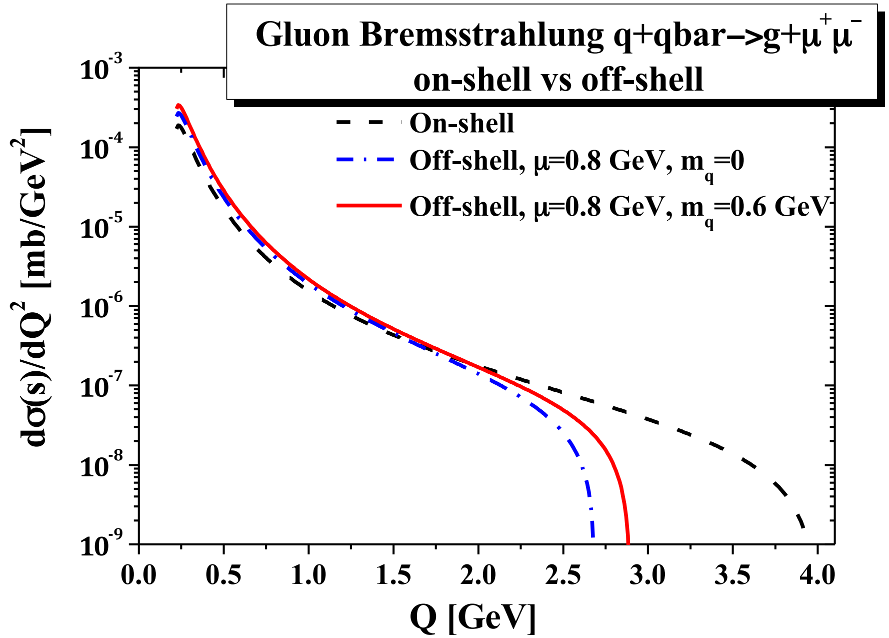
$$\begin{aligned}\sum |M_a|^2 = & -\frac{e_q^2 e^2 g_s^2 \mathrm{Tr}\{T^2\}}{(p_3^2 - m_3^2)^2} \Big[\mathrm{Tr}\left\{\gamma_\sigma(\hat{p_3} + m_3)\gamma_\nu(\hat{p_1} + m_1)\gamma^\nu(\hat{p_3} + m_3)\gamma^\sigma(\hat{p_2} - m_2)\right\} \\ & - \frac{1}{Q^2}\mathrm{Tr}\left\{\gamma_\sigma(\hat{p_3} + m_3)\hat{q}(\hat{p_1} + m_1)\hat{q}(\hat{p_3} + m_3)\gamma^\sigma(\hat{p_2} - m_2)\right\} \\ & - \frac{A}{k^2}\mathrm{Tr}\left\{\hat{k}(\hat{p_3} + m_3)\gamma_\nu(\hat{p_1} + m_1)\gamma^\nu(\hat{p_3} + m_3)\hat{k}(\hat{p_2} - m_2)\right\} \\ & + \frac{A}{k^2 Q^2}\mathrm{Tr}\left\{\hat{k}(\hat{p_3} + m_3)\hat{q}(\hat{p_1} + m_1)\hat{q}(\hat{p_3} + m_3)\hat{k}(\hat{p_2} - m_2)\right\}\Big]\end{aligned}$$

…etc. See details in

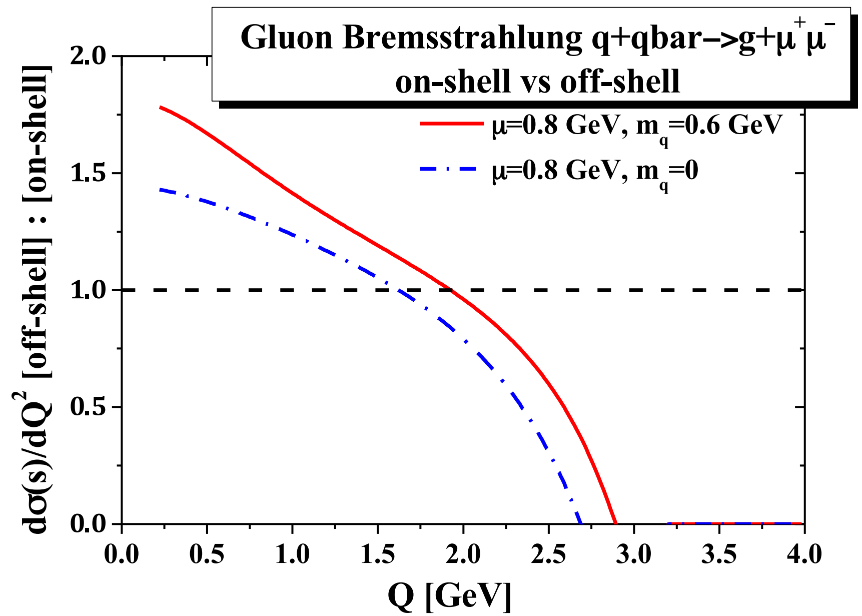
O. Linnyk, J.Phys. G38 (2011) 025105, arXiv:1004.2591

Off-shell NLO q+qbar





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



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

O. Linnyk, arXiv:1004.2591

HSD transport model

Based on:

Generalized transport equations on the basis of the off-shell Kadanoff-Baym equations for Greens functions $G^{<}_{h}(x,p)$ in phase-space representation (in the first order gradient expansion, beyond the quasiparticle approximation).

Numerical solution:

Monte Carlo simulations with a large number of test-particles

Degrees of freedom in HSD:

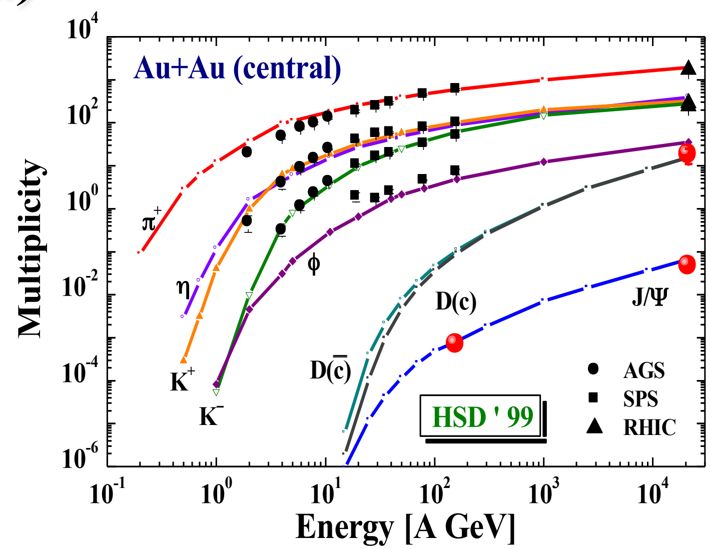
hadrons - baryons and mesons including excited states (resonances)

strings – excited color singlet states *(qq-q)* or *(q-qbar)*

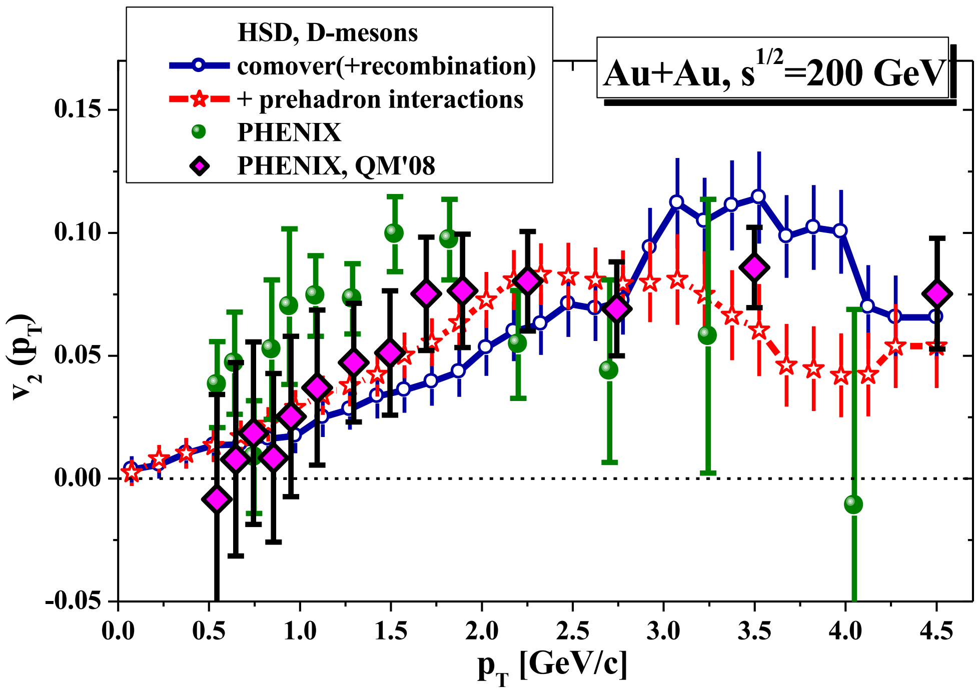
leading quarks *(q, qbar)* & diquarks *(q-q, qbar-qbar)*

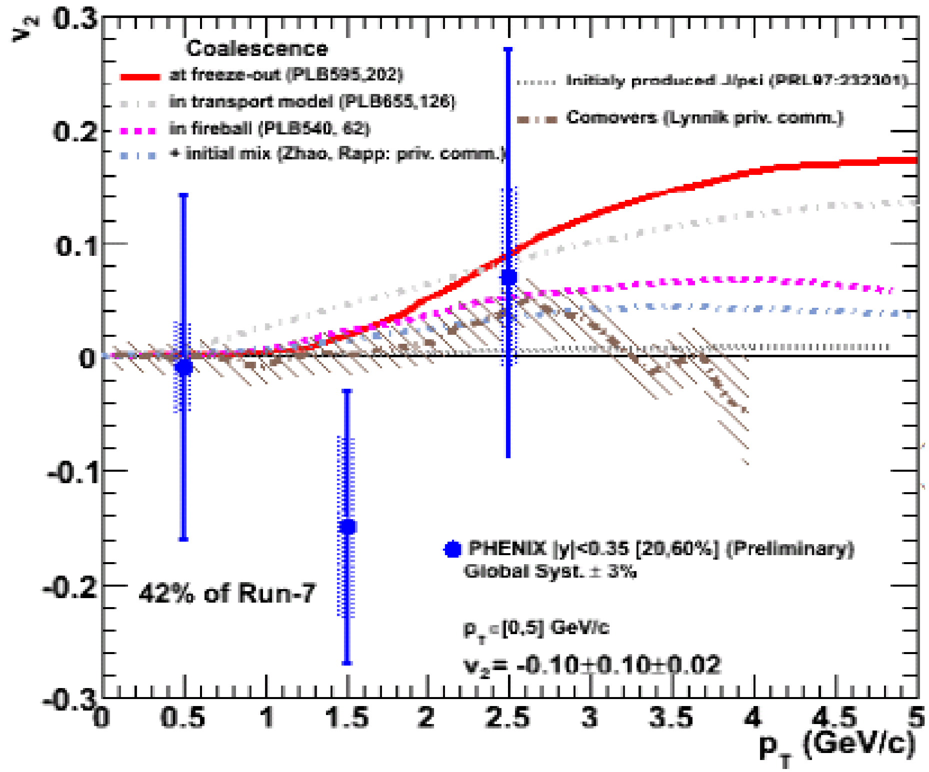
HSD – a microscopic model for heavy-ion reactions:

- very good description of particle production in pp, pA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (~20 TeV) energies



Elliptic flow of charm



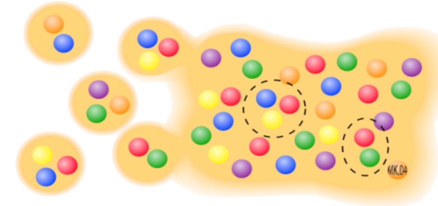


[R.Granier de Cassagnac J Phys G 35 (2008) 104023,
C.Silvestre J Phys G 35 (2008) 104136]

- The pre-hadronic scenario is ~consistent with the preliminary PHENIX data

[OL et al., NPA 807 (2008) 79]

Microscopic transport description of the partonic and hadronic phase



Problems:

- ❑ How to model a QGP phase in line with lQCD data?
- ❑ How to solve the hadronization problem?

Ways to go:

pQCD based models:

- QGP phase: pQCD cascade
- hadronization: quark coalescence

➔ BAMPS, AMPT, HIJING

‚Hybrid' models:

- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner
- hadron-string transport model

➔ Hybrid-UrQMD

- microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons

➔ PHSD

PHSD: hadronization

Based on DQPM; massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:

gluons → q + qbar   q + qbar → meson

q + q +q → baryon

Parton-parton recombination rate =

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}}\ \delta^4(p - p_q - p_{\bar{q}})\ \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q\ \rho_q(p_q)\ \omega_{\bar{q}}\ \rho_{\bar{q}}(p_{\bar{q}})\ |v_{q\bar{q}}|^2\ W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q)\ N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}})\ \delta(\text{flavor, color}). \quad (7)$$

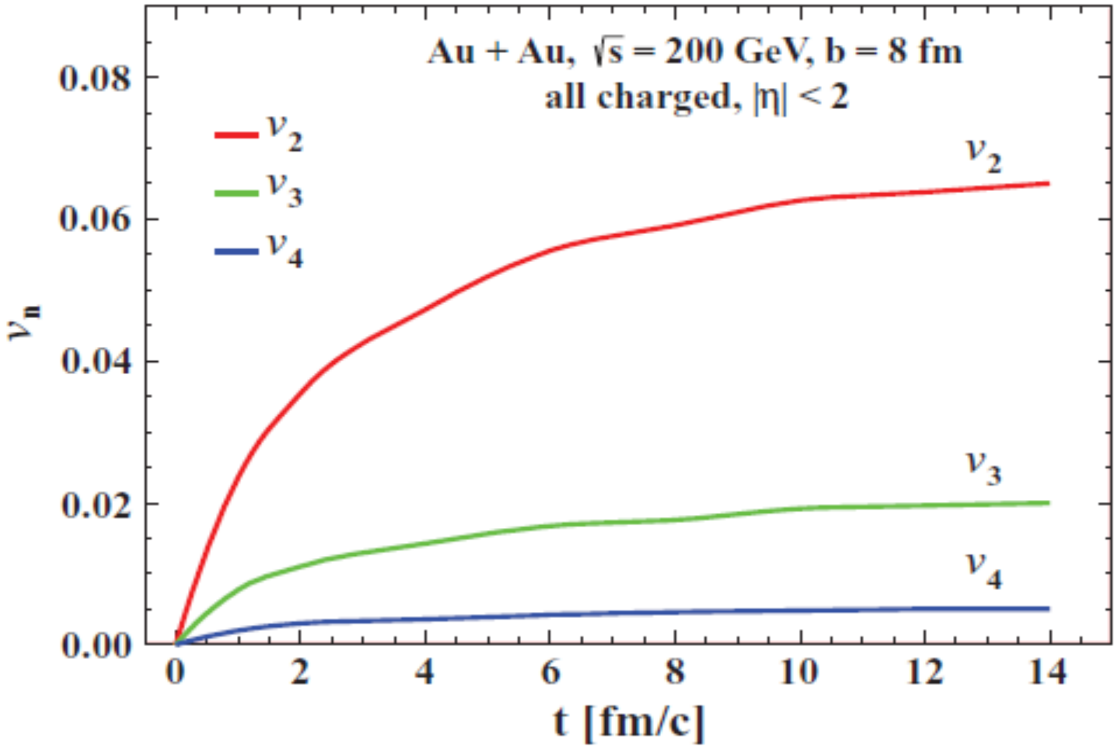
W_m - Gaussian in phase space with $\sqrt{< r^2 >} = 0.66$ fm

Hadronization happens when the effective interactions |v| become attractive, approx. for parton densities $1 < \rho_P < 2.2$ fm^{-3} <= from DQPM

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

Development of azimuthal anisotropies in time

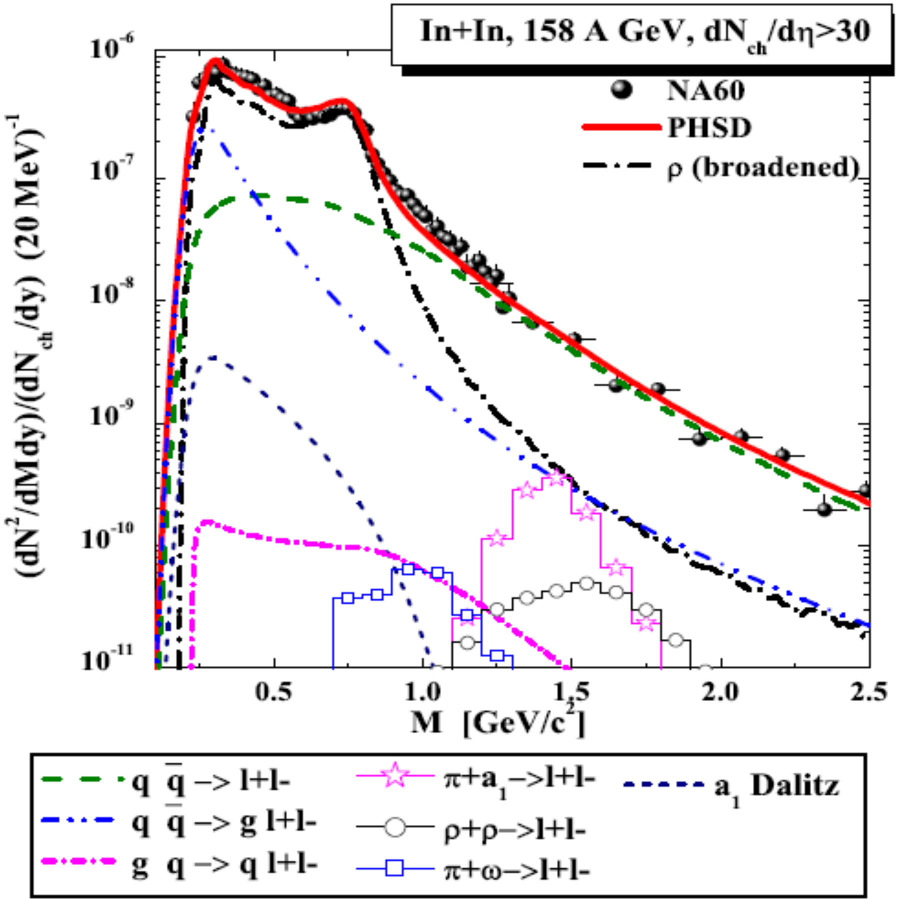
Time evolution of v_n for Au + Au collisions at $s^{1/2}$ = 200 GeV with impact parameter b = 8 fm.

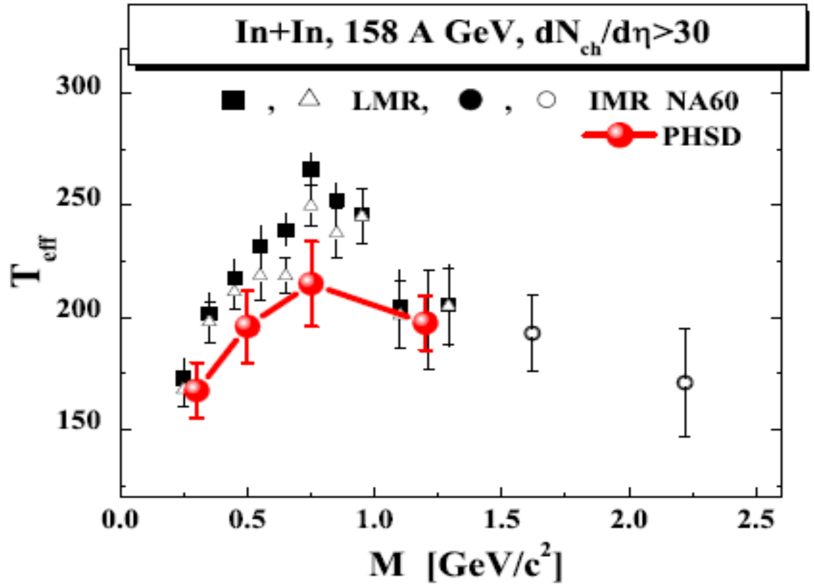


- **Flow coefficients reach their asymptotic values by the time of 6–8 fm/*c* after the beginning of the collision**

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Dileptons at SPS: NA60



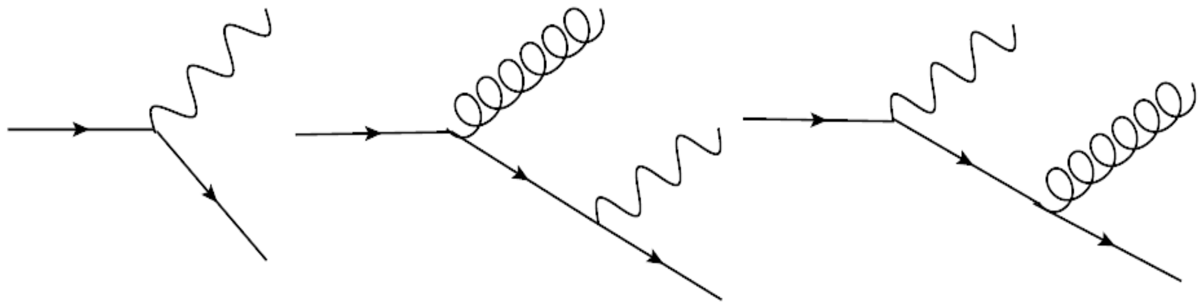


NA60 data at low M are well described by an in-medium scenario with collisional broadening

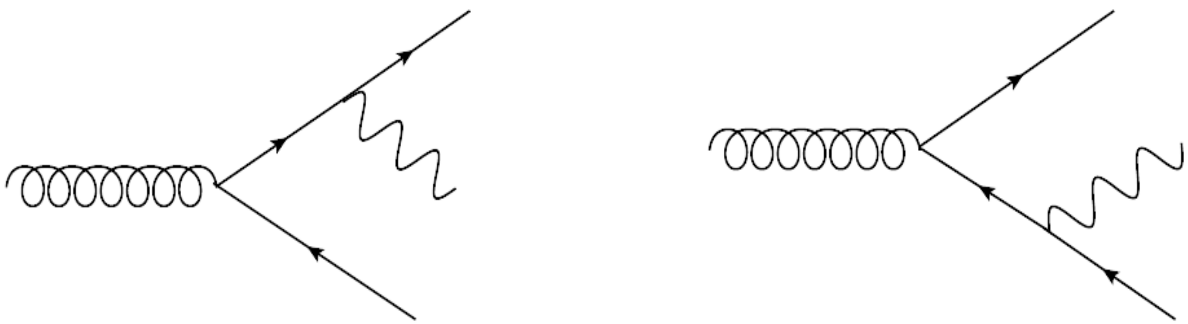
Mass region above 1 GeV is dominated by partonic radiation

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

Sub-leading diagrams



Virtual quark decay



Virtual gluon decay

O. Linnyk, arXiv:1004.2591

Electro-magnetic fields

PHSD - transport model with electromagnetic fields.

Generalized transport equations:

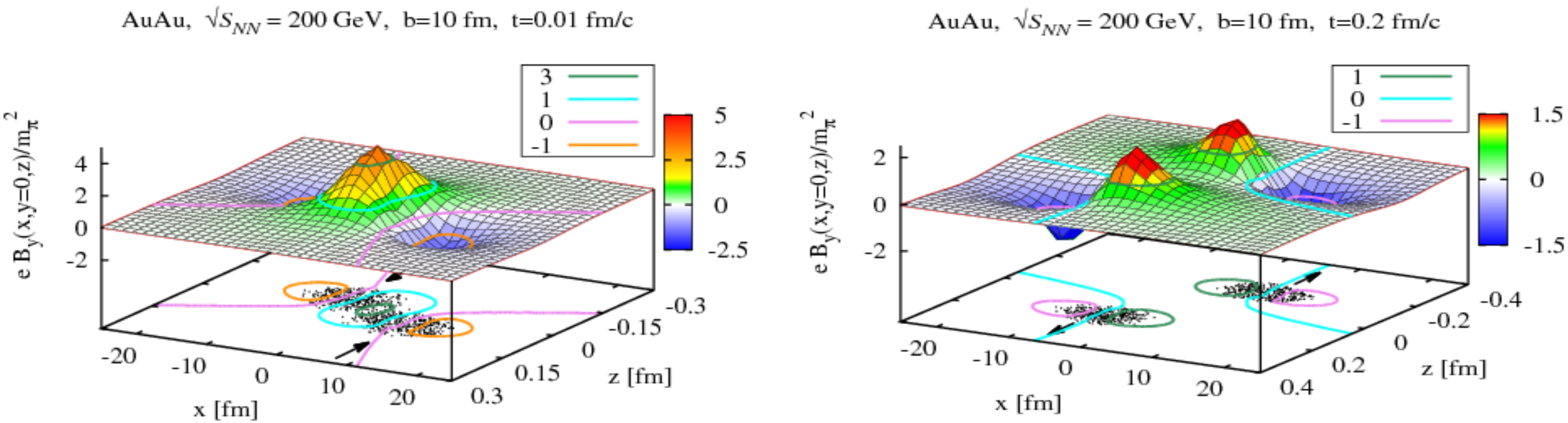
$$\dot{\vec{r}} \rightarrow \frac{\vec{p}}{p_0} + \vec{\nabla}_p U \ ,$$

$$\dot{\vec{p}} \rightarrow -\vec{\nabla}_r U + e\vec{E} + e\vec{v} \times \vec{B}$$

$$\vec{A}(\vec{r},t) = \frac{1}{4\pi} \int \frac{\vec{j}(\vec{r'},t')\ \delta(t-t'-|\vec{r}-\vec{r'}|/c)}{|\vec{r}-\vec{r'}|}\ d^3r'dt'$$

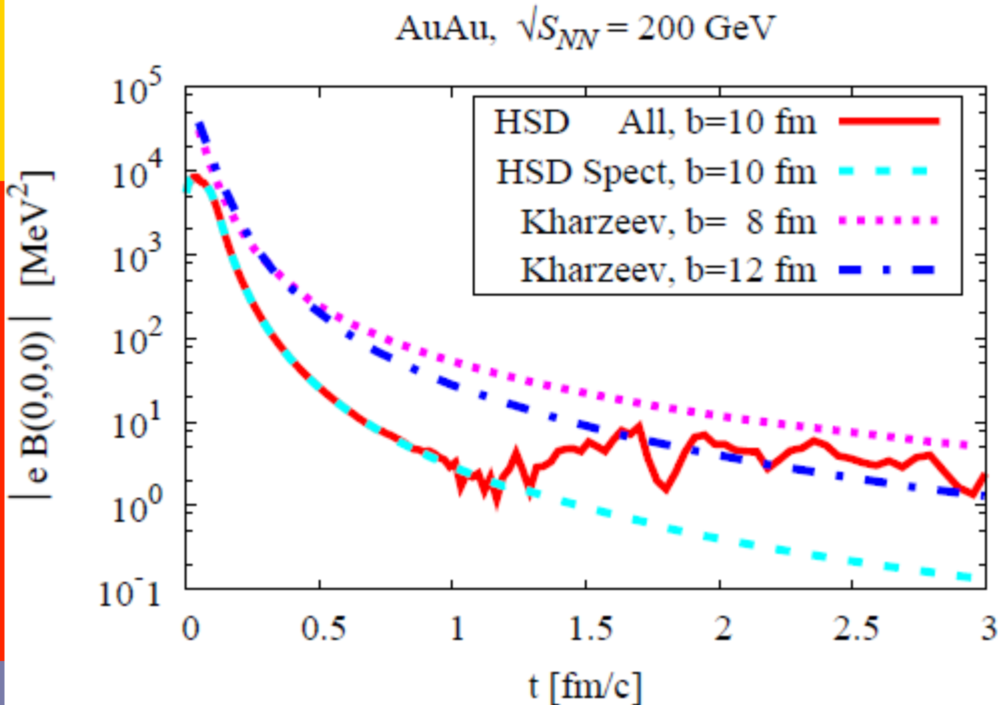
$$\Phi(\vec{r},t) = \frac{1}{4\pi} \int \frac{\rho(\vec{r'},t')\ \delta(t-t'-|\vec{r}-\vec{r'}|/c)}{|\vec{r}-\vec{r'}|}\ d^3r'dt'$$

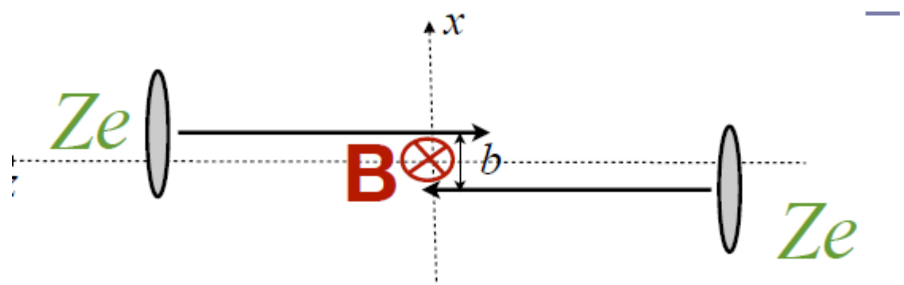
Magnetic field evolution in HSD/PHSD :



V. Voronyuk et al., Phys.Rev. C83 (2011) 054911

Electro-magnetic fields in HIC





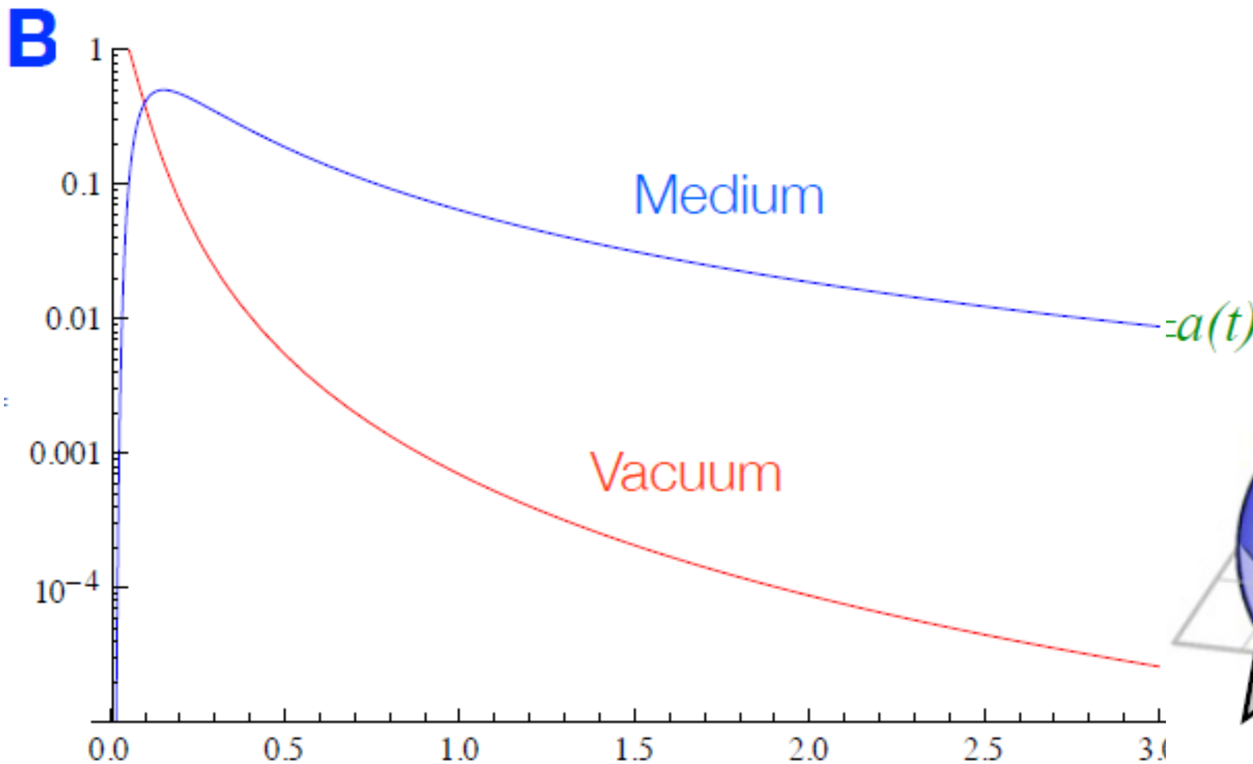
$$B \sim Ze\frac{b}{R^3}\gamma$$

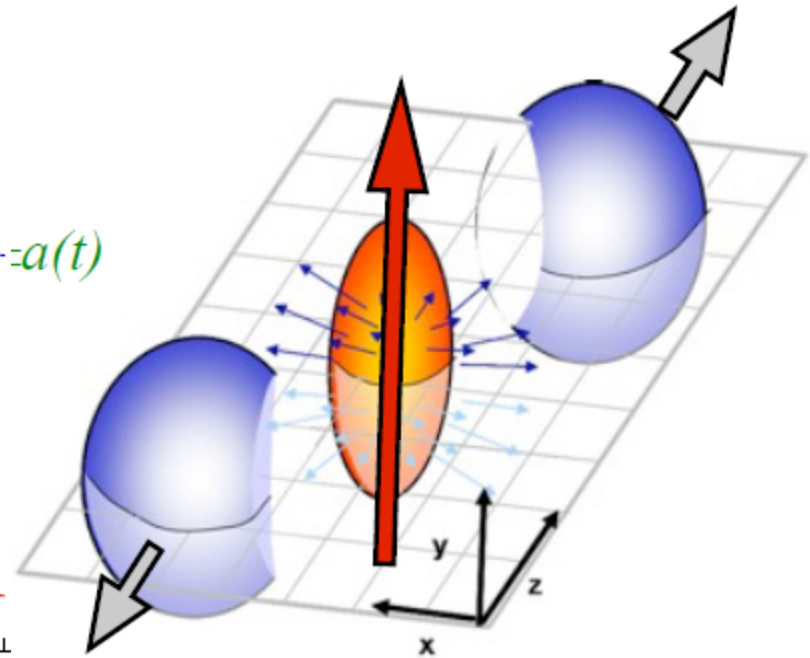
For $Z=79$, $b=7\ fm$, $\gamma=100$ we get $eB = (200\ MeV)^2 \approx m_\pi^2$

V. Voronyuk et al Phys.Rev. C83 (2011) 054911

UrQMD based calculation: Skokov, Illarionov, Toneev (2009)

Magnetic field in matter





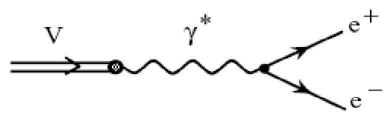
Dileptons - an ideal probe to study the properties of the hot and dense medium

Dilepton sources:

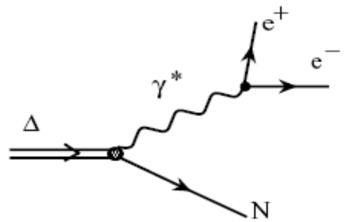
1) from the QGP via partonic (q,qbar, g) interactions:

2) from hadronic sources:

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



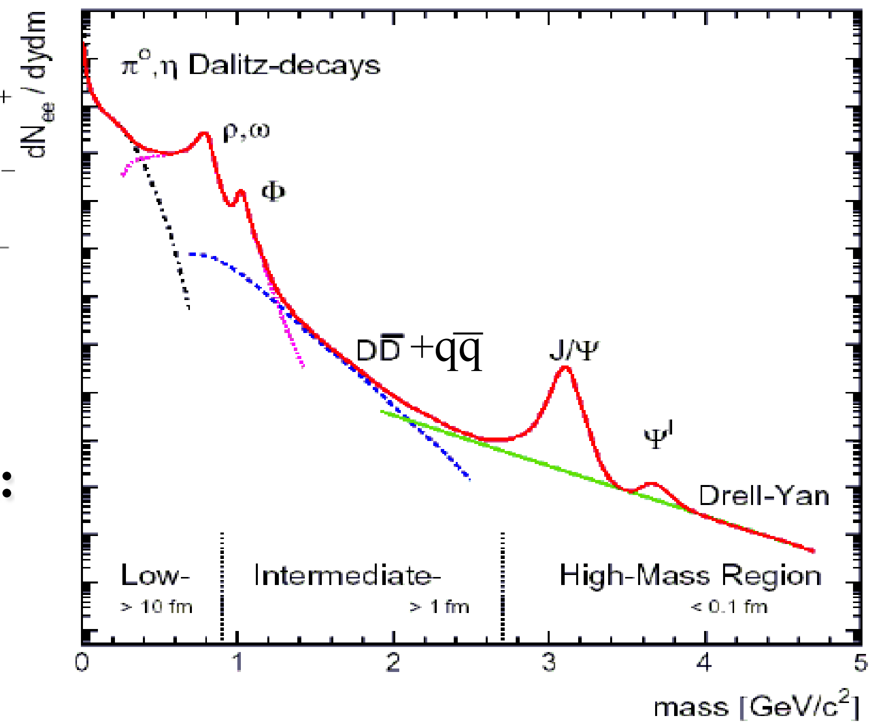
- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**



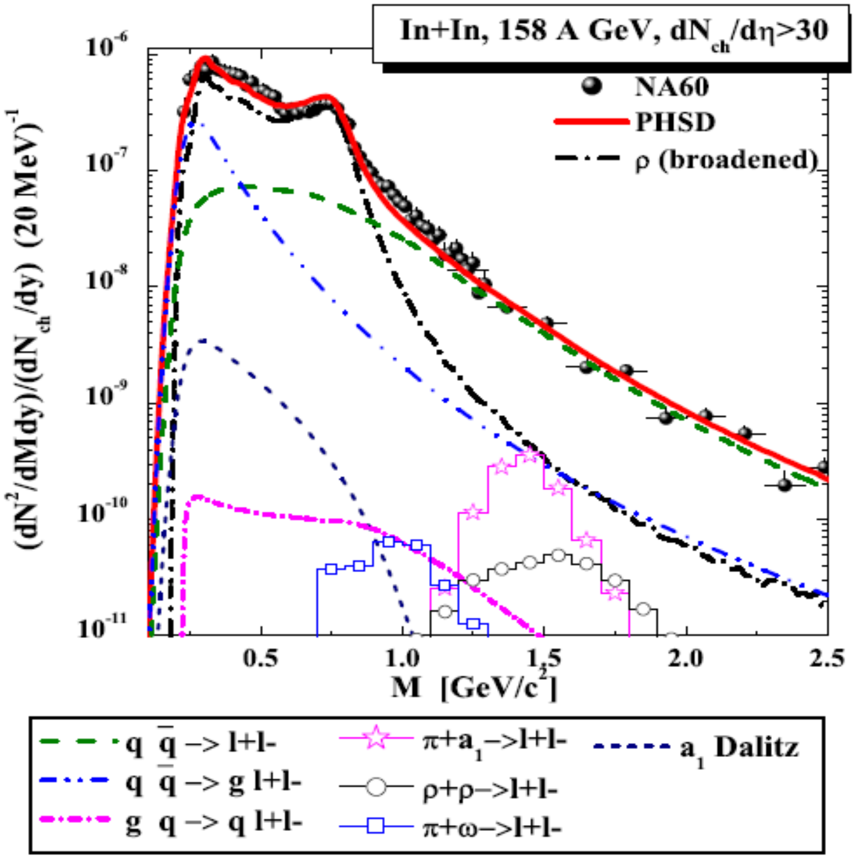
- **radiation from secondary meson interaction:**

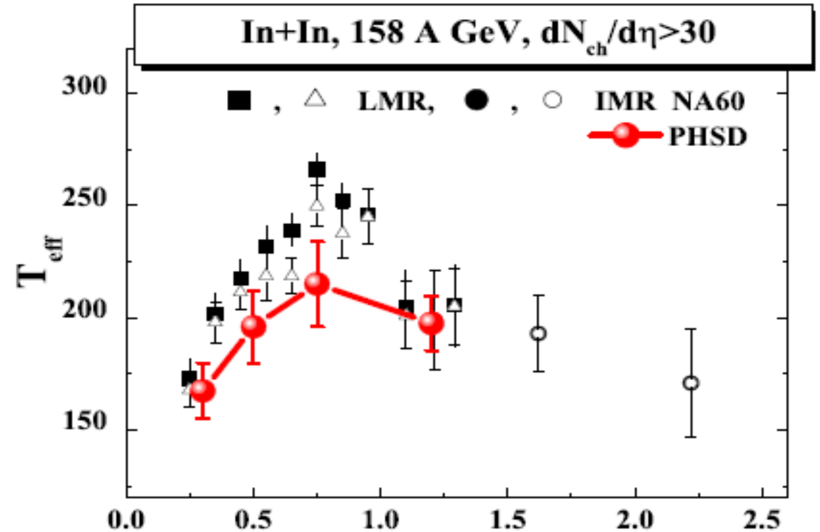
π + π, π + ρ, π + ω, ρ + ρ, π + a1

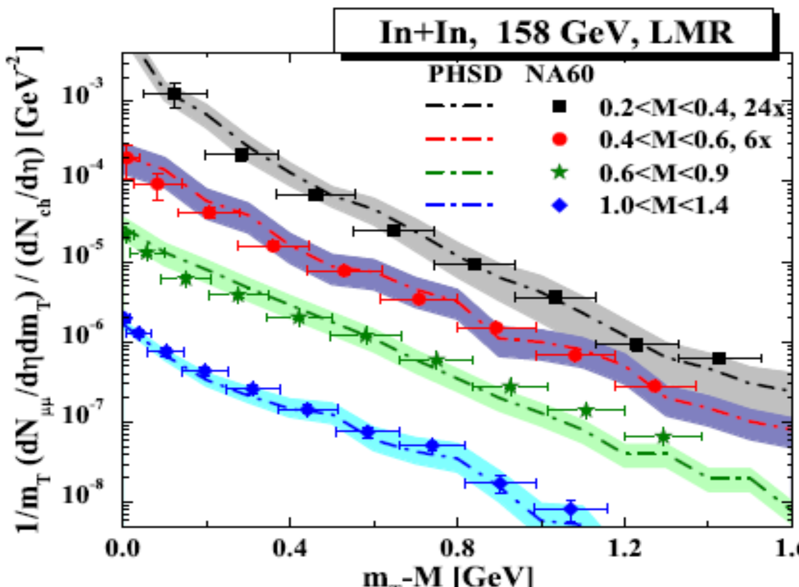
- **correlated semi-leptonic decays of D- and B-mesons**



Dileptons at SPS: NA60





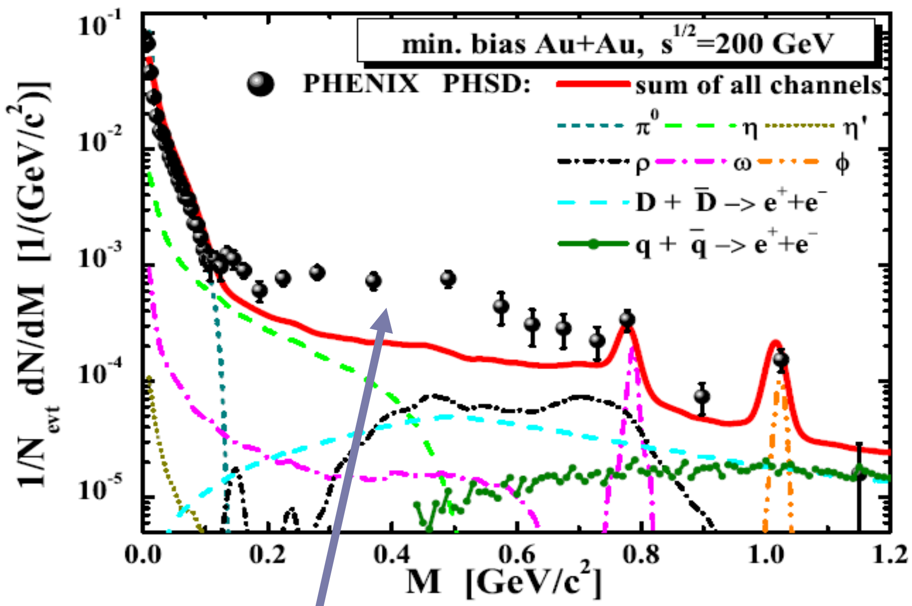


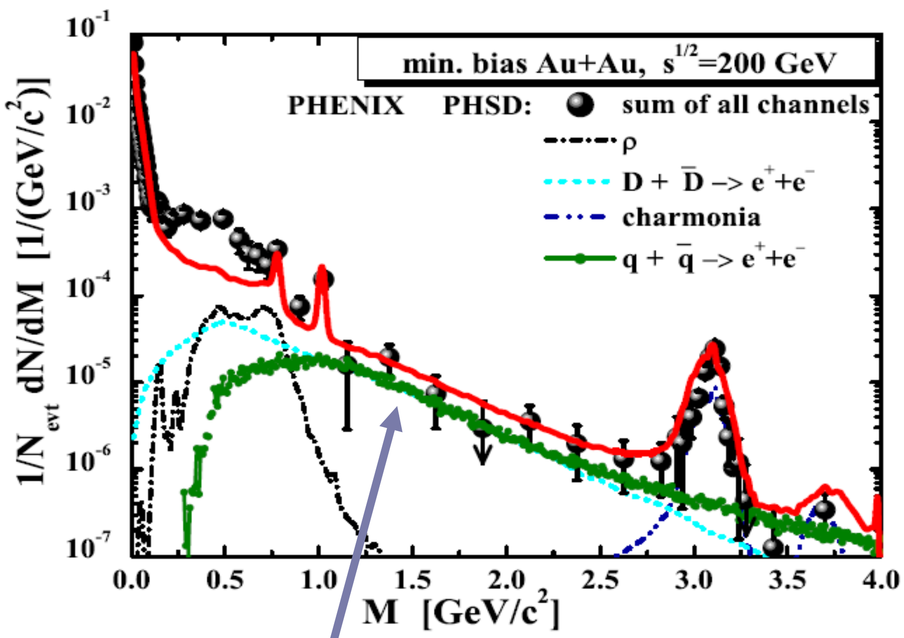
NA60 data at low M are well described by an in-medium scenario with collisional broadening

- 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

PHENIX: dileptons from QGP



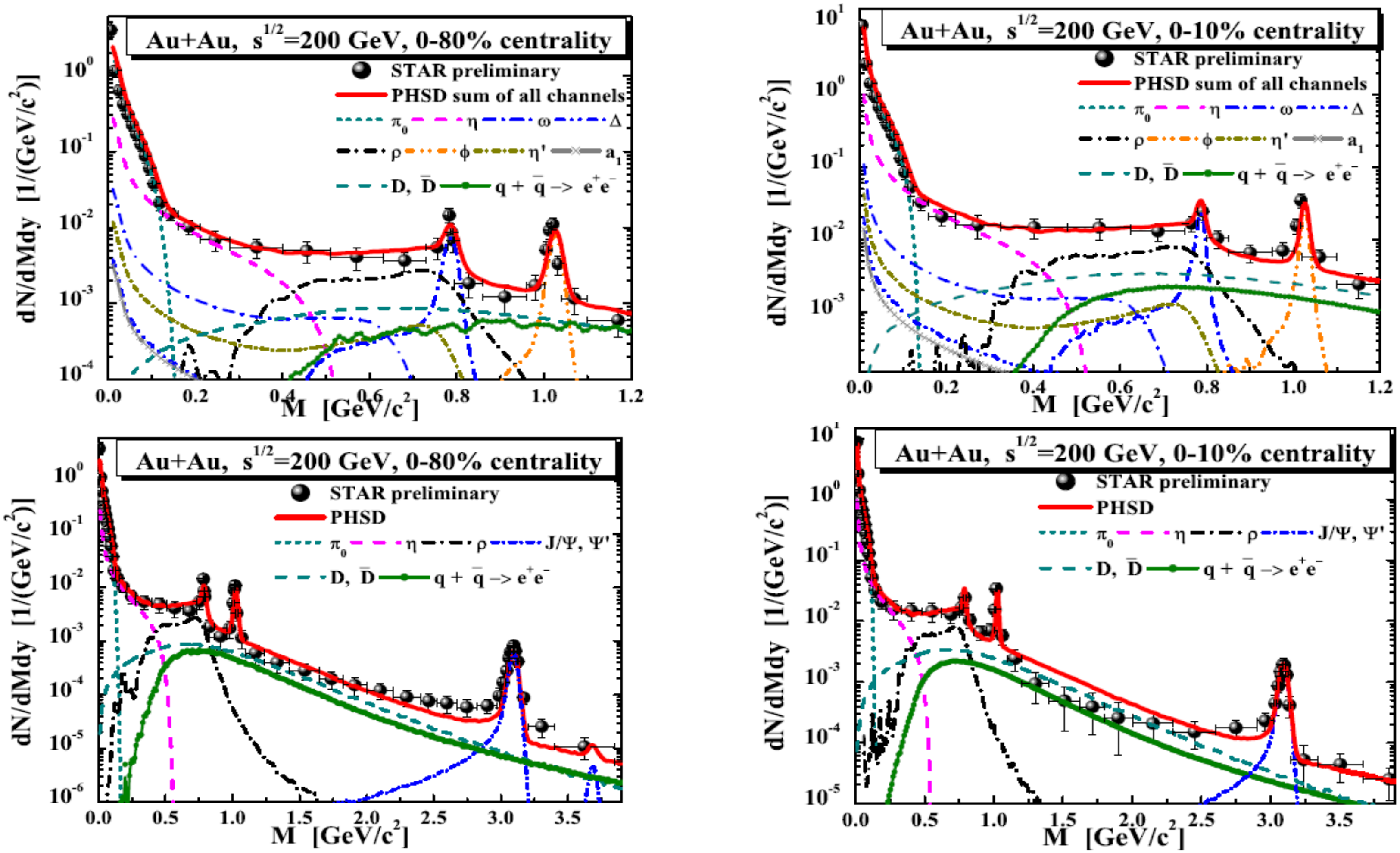


- The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD

- 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

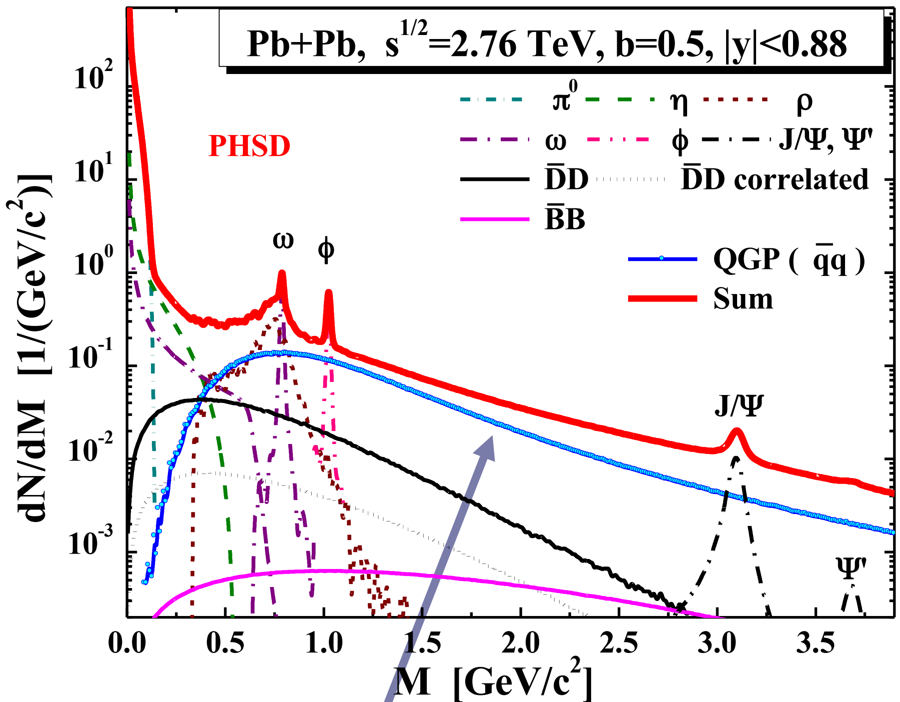
STAR: dilepton mass spectra

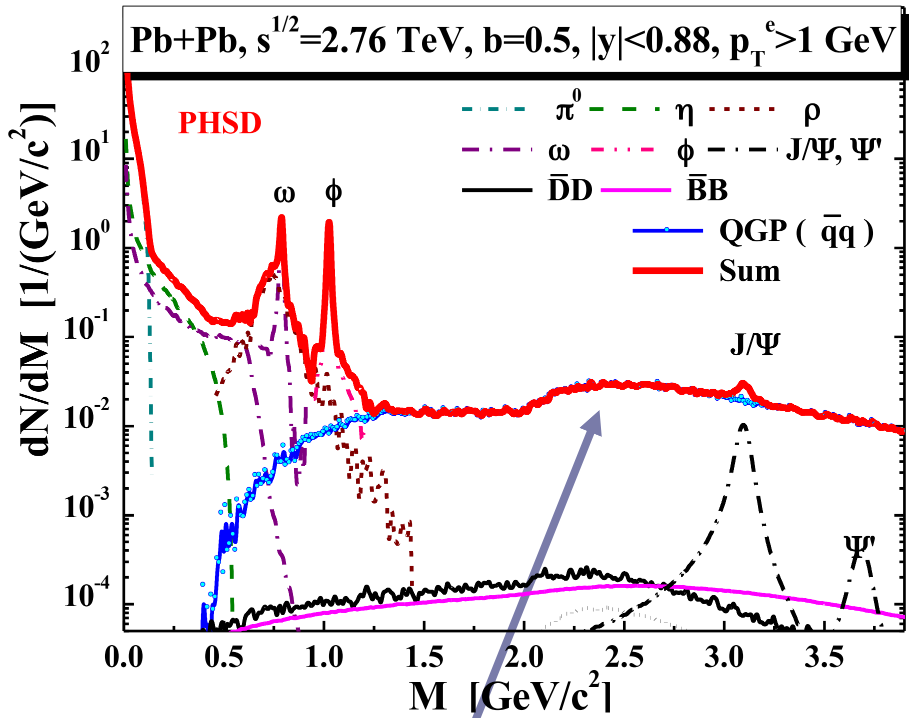


- STAR data are well described by the PHSD predictions
- Confirmed by the extended data set at QM2012

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

Predictions for LHC





QGP(qbar-q) dominates at M>1.2 GeV

p_T cut enhances the signal of QGP(qbar-q)

D-, B-mesons energy loss from Pol-Bernard Gossiaux and Jörg Aichelin

JPsi and Psi' nuclear modification from Che-Ming Ko and Taesoo Song

O. Linnyk et al. Phys.Rev. C87 (2013) 014905

Parton-Hadron-String Dynamics (PHSD)

Description of heavy-ion collisions as well as p+p, p+A, d+A, π+A reactions.

Features:

- ✓ **Unified description of collisions at all energies from AGS to LHC.**
- ✓ **Non-equilibrium approach: applicable to far from equilibrium configurations as explosion-like heavy-ion collisions as well as to equilibrated matter („in the box“).**
- ✓ **Dynamics: mean fields (hadronic and partonic), scattering (elastic, inelastic, 2<−>2, 2<−>n), resonance decays, retarded electro-magnetic fields.**
- ✓ **Phase transition (cross over) according to the lattice QCD equation of state, hadronic and partonic degrees of freedom, spacial co-existance, dynamical hadronisation.**
- ✓ **Off-shell transport: takes into account 2-particle correlations beyond the one-particle distributions.**

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**

$$\diamond \{ P^2 - M_0^2 - Re\Sigma^{ret}_{XP} \} \{ S^{<}_{XP} \} - \diamond \{ \Sigma^{<}_{XP} \} \{ Re S^{ret}_{XP} \} = \frac{i}{2} [\Sigma^{>}_{XP} S^{<}_{XP} - \Sigma^{<}_{XP} S^{>}_{XP}]$$

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

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

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

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

Off-shell equations of motion

Employ **testparticle Ansatz** **for the real valued quantity** $i\, S^{<}_{XP}$ **-**

$$F_{XP} = A_{XP} N_{XP} = i\, S^{<}_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

General testparticle off-shell equations of motion:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_{i} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

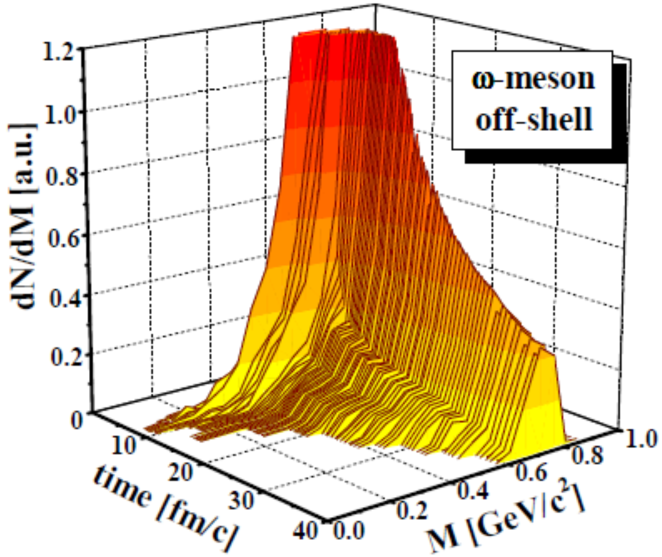
with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

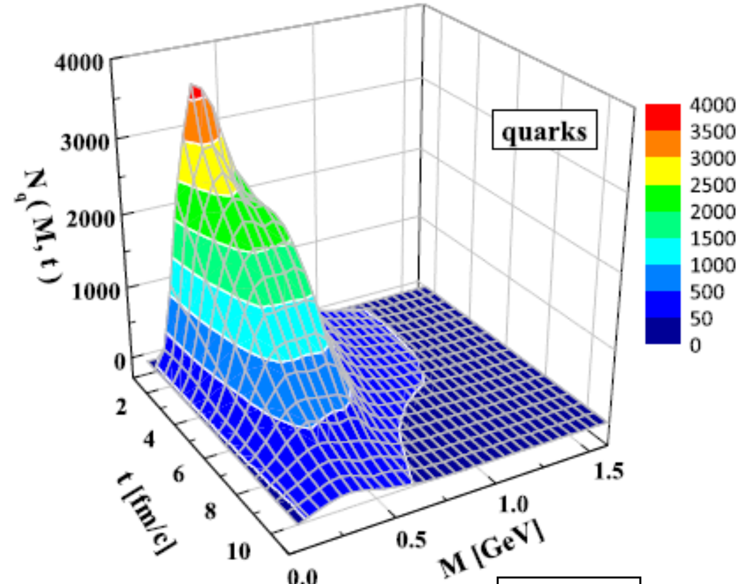
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

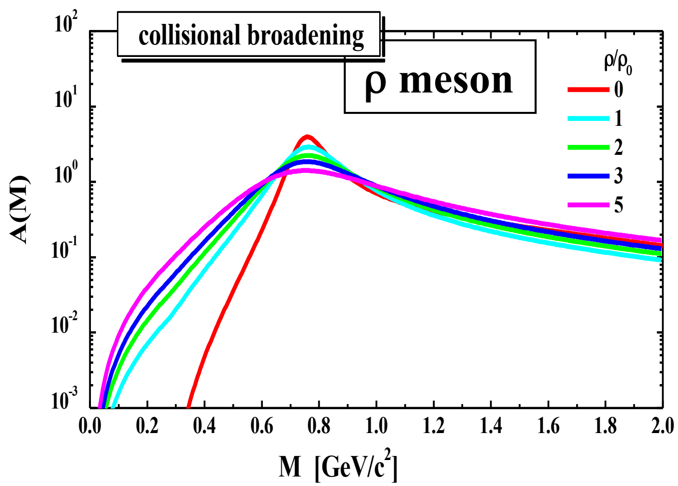
W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

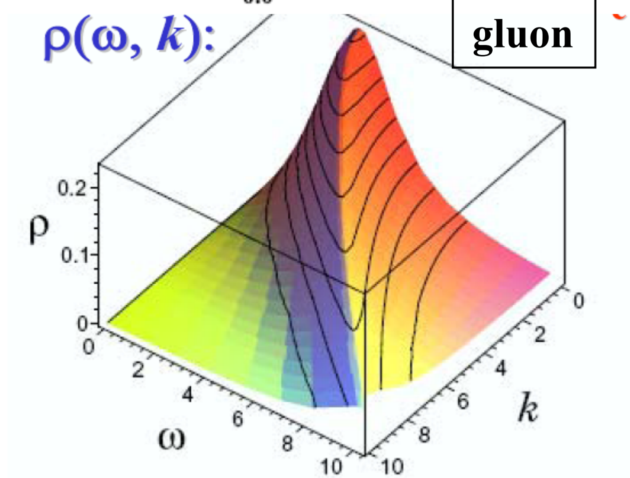
Off-shell propagation

The off-shell spectral function becomes on-shell in the vacuum dynamically!









E.L. Bratkovskaya, W. Cassing, V. P. Konchakovski, O. Linnyk, NPA856(2011) 162; E.L. Bratkovskaya, W. Cassing, NPA 807 (2008) 214;

Interacting quasiparticles

Entropy density of interacting bosons and fermions (G. Baym 1998): **(2PI)**

$$s^{dqp} = -d_g \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_B}{\partial T} \left(\mathrm{Im} \ln(-\Delta^{-1}) + \mathrm{Im}\Pi \, \mathrm{Re}\Delta \right)$$ **gluons**

$$-d_q \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_F((\omega-\mu)/T)}{\partial T} \left(\mathrm{Im} \ln(-S_q^{-1}) + \mathrm{Im}\Sigma_q \, \mathrm{Re}S_q \right),$$ **quarks**

$$-d_{\bar{q}} \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_F((\omega+\mu)/T)}{\partial T} \left(\mathrm{Im} \ln(-S_{\bar{q}}^{-1}) + \mathrm{Im}\Sigma_{\bar{q}} \, \mathrm{Re}S_{\bar{q}} \right),$$ **antiquarks**

with $d_g = 16$ for 8 transverse gluons and $d_q = 18$ for quarks with 3 colors, 3 flavors and 2 spin projections

Bose distribution function: $n_B(\omega/T) = \left(exp(\omega/T) - 1\right)^{-1}$

Fermi distribution function: $n_F((\omega-\mu_q)/T) = \left(exp((\omega-\mu_q)/T) + 1\right)^{-1}$

Simple approximations → DQPM:

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:** $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

(scalar)

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles

- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

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

- **quarks**

mass: $$M^2_{q(\bar{q})}(T) = \frac{N_c^2-1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

width: $$\Gamma_{q(\bar{q})}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

- **gluons:**

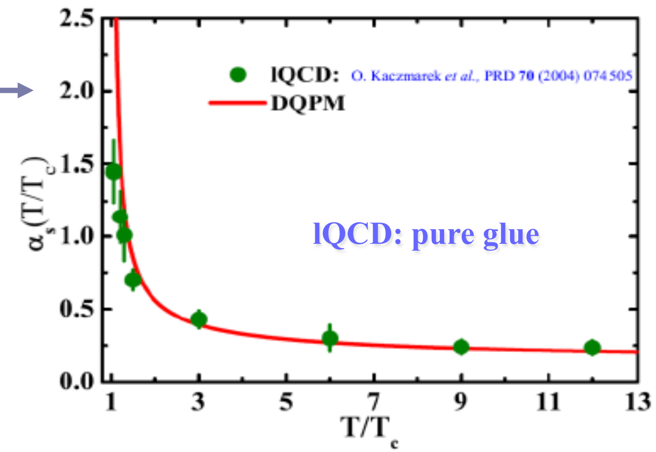
$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

$N_c = 3$, $N_f = 3$

- **running coupling (pure glue):**

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



❑ **fit to lattice (lQCD) results** (e.g. entropy density)

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42 (for pure glue N_f=0)

➔ **quasiparticle properties** (mass, width)

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

PHSD: Hadronization details

Local covariant off-shell transition rate for q+qbar fusion
=> meson formation

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}}\ \delta^4(p - p_q - p_{\bar{q}})\ \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q\ \rho_q(p_q)\ \omega_{\bar{q}}\ \rho_{\bar{q}}(p_{\bar{q}})\ |v_{q\bar{q}}|^2\ W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q)\ N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}})\ \delta(\text{flavor, color}).$$

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

- ***$N_j(x,p)$*** **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)** $\sqrt{< r^2 >} = 0.66$ fm
- $v_{q\bar{q}}$ **is the effective quark-antiquark interaction from the DQPM**

Cassing, Bratkovskaya, PRC 78 (2008) 034919; Cassing, EPJ ST 168 (2009) 3

Bulk viscosity (mean-field effects)

- bulk viscosity in relaxation time approximation with mean-field effects:

Chakraborty, Kapusta, Phys. Rev.C 83, 014906 (2011).

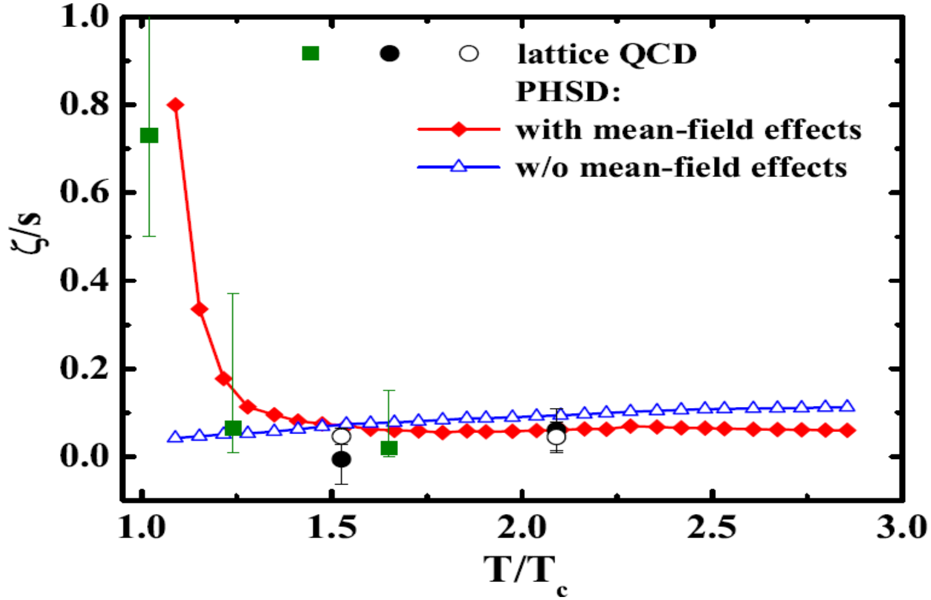
$$\zeta = \frac{1}{TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\Big[\Big(\frac{1}{3}-v_s^2\Big)|\mathbf{p}|^2 - v_s^2\Big(m_i^2 - T^2\frac{dm_i^2}{dT^2}\Big)\Big]^2$$

use DQPM results for masses for μ_q=0:

$$m_q^2 = \frac{1}{3}g^2T^2, \qquad m_g^2 = \frac{3}{4}g^2T^2$$

PHSD using the relaxation time approximation:

- significant rise in the vicinity of critical temperature
- in line with the ratio from lQCD calculations

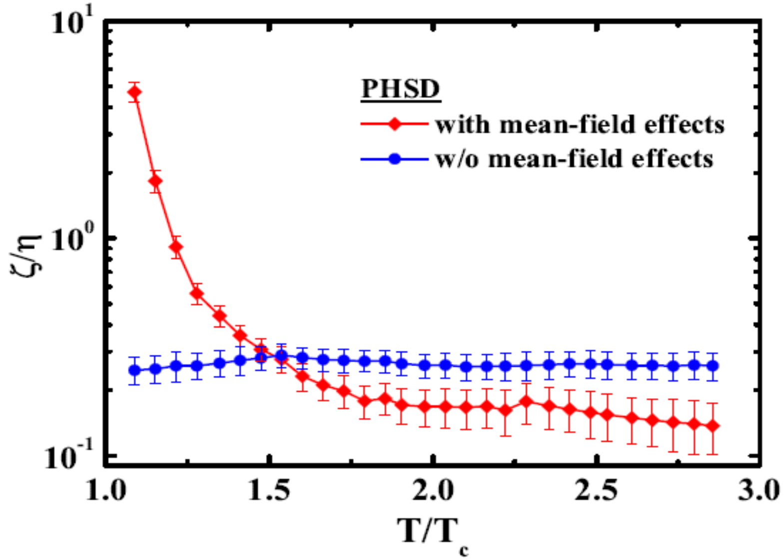


lQCD: Meyer, Phys. Rev. Lett. 100, 162001 (2008); Sakai,Nakamura, Pos LAT2007, 221 (2007).

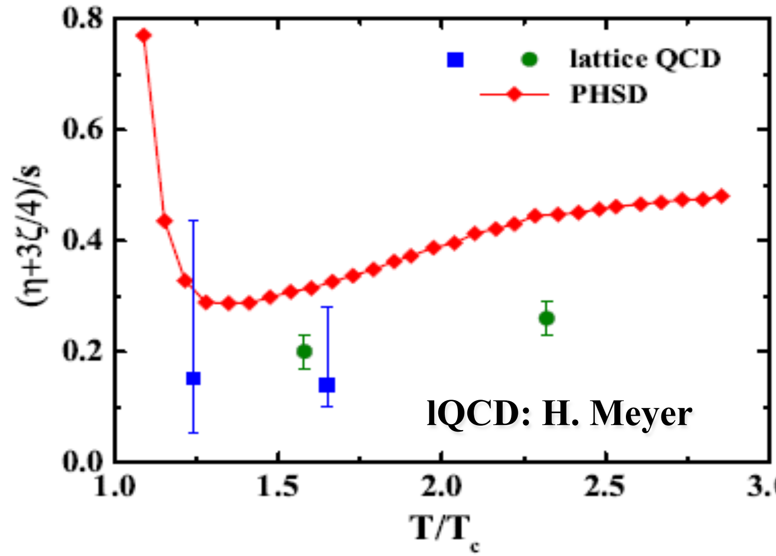
V. Ozvenchuk et al., arXiv:1212.5393

Bulk to shear viscosity ratio and specific sound

Bulk to shear viscosity ratio ζ/η as a function of temperature T



Specific sound channel (η+3ζ/4)/s as a function of temperature T



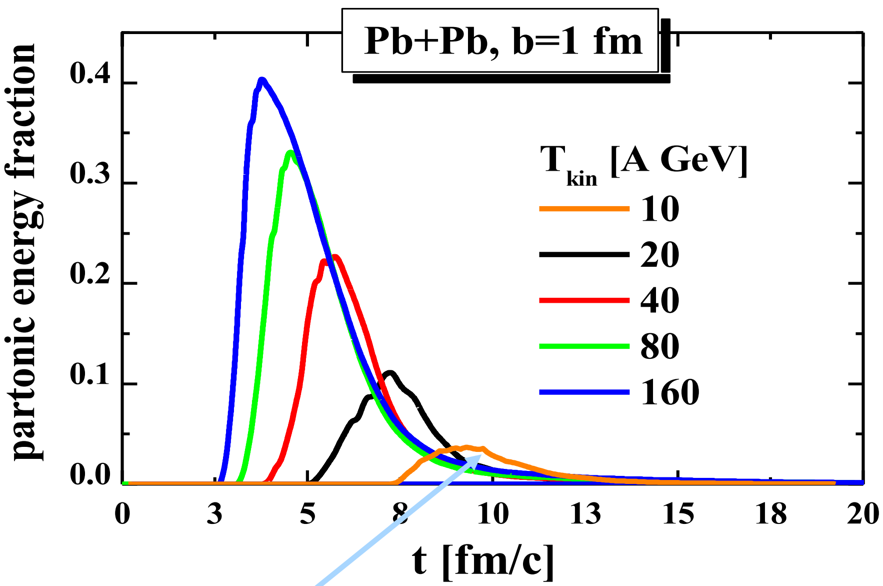
- ζ/η **without** mean-field effects → almost temperature **independent** behavior
  ζ/η **with** mean-field effects → **strong increase** close to the **critical** temperature

- **(η+3ζ/4)/s:** both the shear and bulk viscosities contribute to the **damping of sound waves in the medium** and provide a further constraint on the viscosities

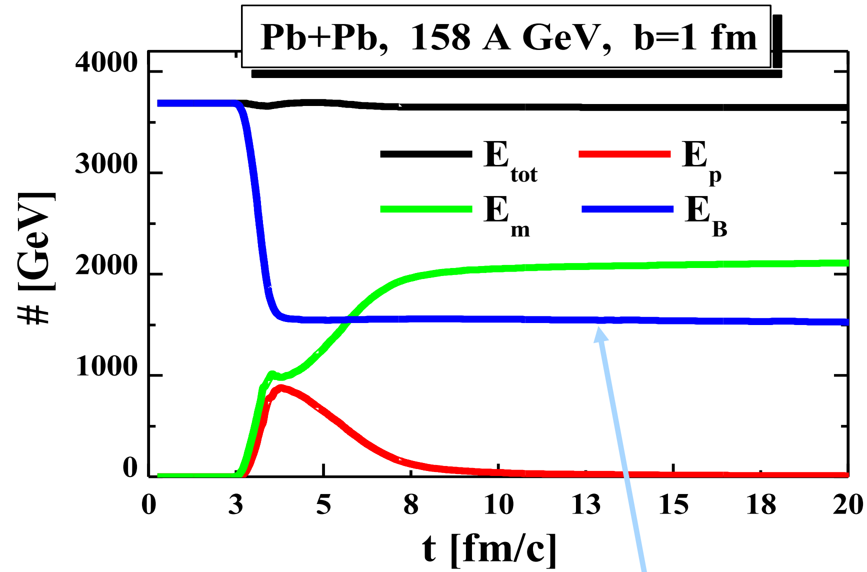
V. Ozvenchuk et al., arXiv:1212.5393

Application to nucleus-nucleus collisions

partonic energy fraction vs energy



energy balance



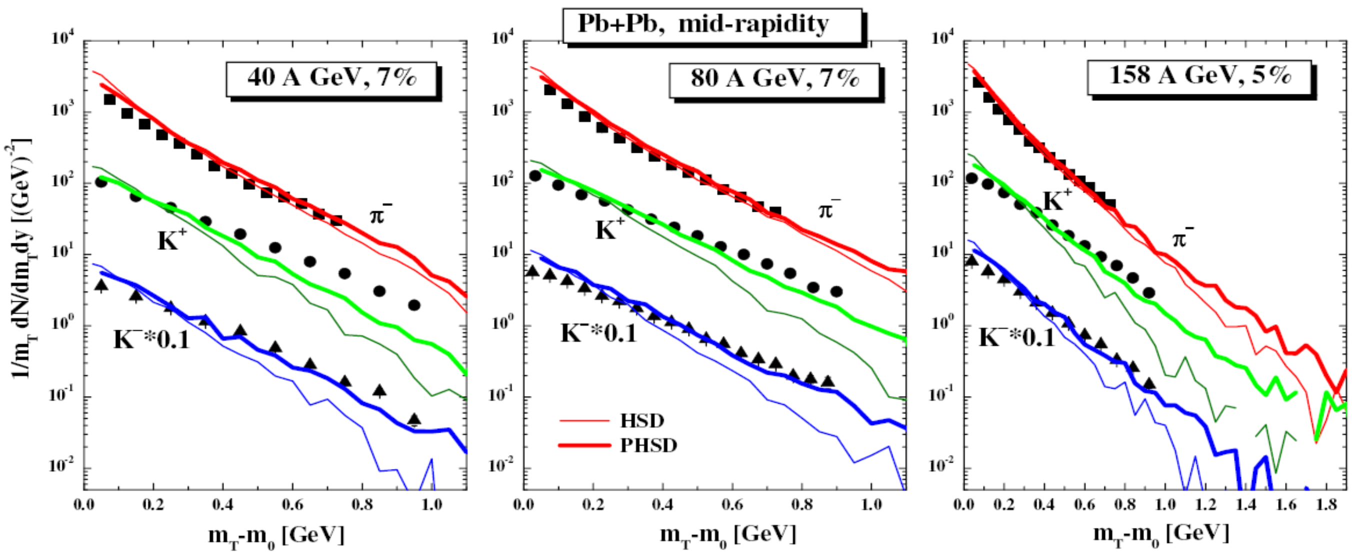
- Dramatic decrease of partonic phase with decreasing energy

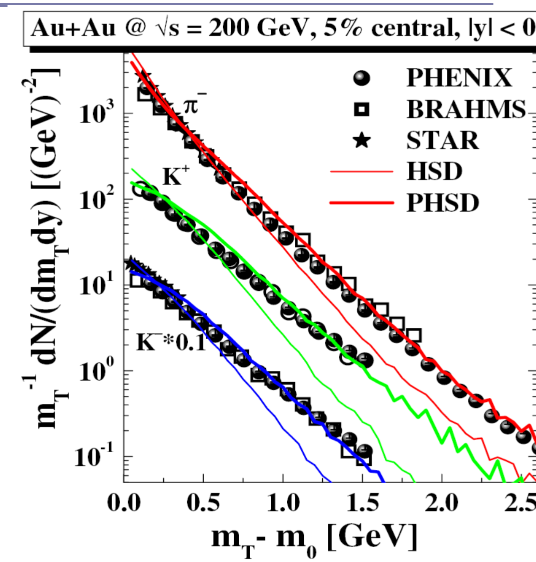
- Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons!
(hadronic corona effect, cf. talk by J. Aichelin)

Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies | **Central Au+Au at RHIC**

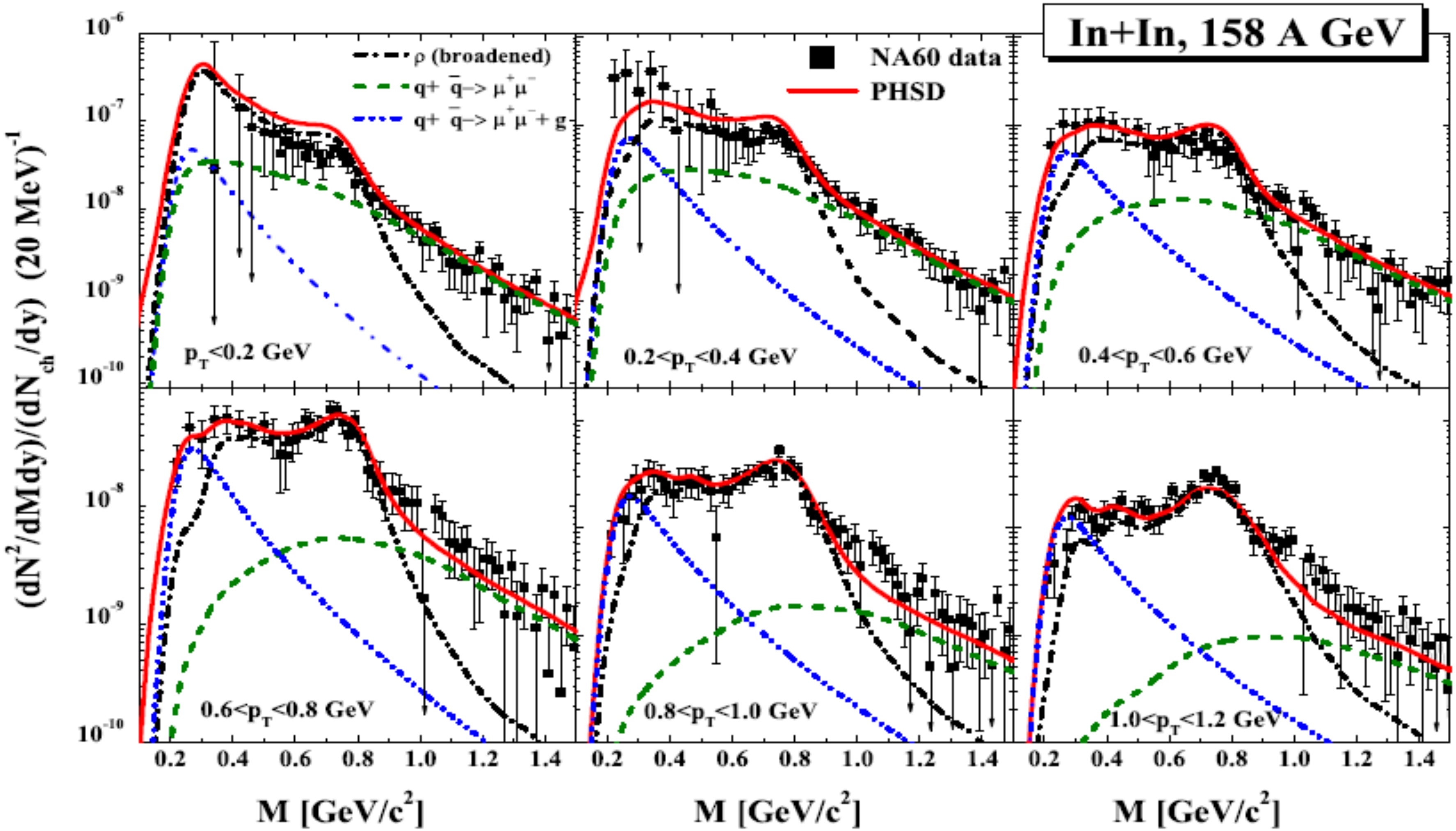




- PHSD gives harder m_T spectra and works better than HSD at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

NA60: differential spectrum



Parton dominance at M>1 GeV and rho broadening confirmed by the differencial data

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

Shear viscosity (Kubo formalism)

- **Kubo formula for the shear viscosity:**

Kubo, J. Phys. Soc. Japan 12, 570 (1957); Rep. Prog. Phys. 29, 255 (1966).

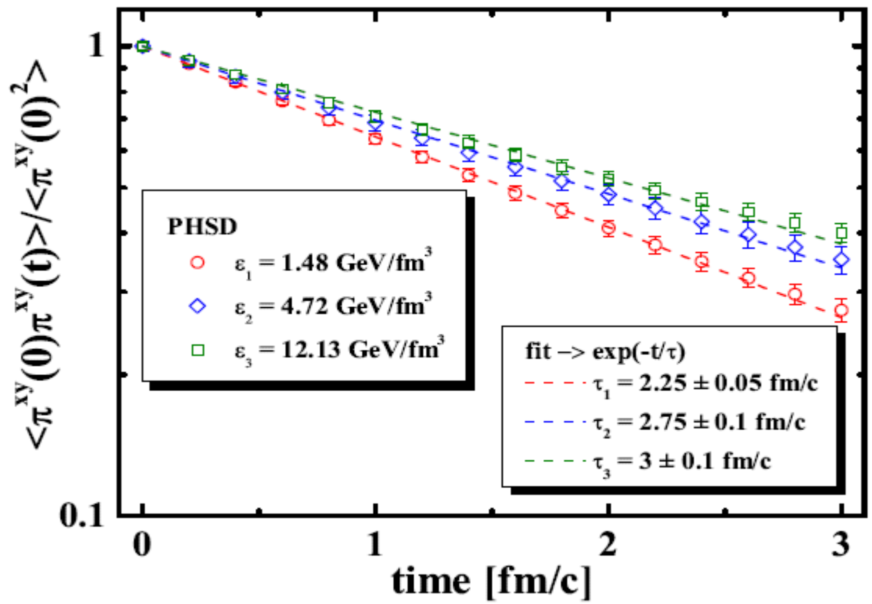
$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle$$

- **shear component of the energy momentum tensor**

$$\pi^{xy}(\mathbf{r},t) = \int \frac{d^3p}{(2\pi)^3}\frac{p^x p^y}{E} f(\mathbf{r},\mathbf{p},t) \qquad E = \sqrt{\mathbf{p}^2 + U_s^2}$$

- **test-particles ansatz** ➔

$$\pi^{xy}(t) = \frac{1}{V}\sum_{i=1}^{N}\frac{p_i^x p_i^y}{E_i}$$



PHSD: V. Ozvenchuk et al., arXiv: 1203.4734

- **correlation functions are empirically found to decay exponentially in time:**

$$\langle \pi^{xy}(0)\pi^{xy}(t)\rangle = \langle \pi^{xy}(0)\pi^{xy}(0)\rangle\, e^{-t/\tau} \Rightarrow$$

Green-Kubo formula:

$$\eta = \frac{V}{T}\langle \pi^{xy}(0)^2\rangle \tau$$

Bulk viscosity (mean-field effects)

- **starting hypothesis:** the collision integral can be approximated by

$$C[f] = -\frac{f - f^{eq}}{\tau}$$

τ - relaxation time

- **shear and bulk viscosities assume the following expressions:**

$$\eta = \frac{1}{15T} \sum_a \int \frac{d^3p}{(2\pi)^3} \frac{|\mathbf{p}|^4}{E_a^2} \tau_a(E_a) f_a^{eq}(E_a/T)$$

$$a = q, \bar{q}, g$$

$$\zeta = \frac{1}{9T} \sum_a \int \frac{d^3p}{(2\pi)^3} \frac{\tau_a(E_a)}{E_a^2} [(1-3v_s^2)E_a^2 - m_a^2]\, f_a^{eq}(E_a/T)$$

speed of sound:

$$v_s = v_s(T)$$

Hosoya, Kajantie, Nucl. Phys. B 250, 666 (1985); Gavin, Nucl. Phys. A 435, 826 (1985);
Chakraborty,K apusta, Phys. Rev.C 83, 014906 (2011).

- **In PHSD:** $\tau_a = \Gamma_a^{-1}$

- **in numerical simulations for the test-particle ansatz:**

$$\eta = \frac{1}{15TV} \sum_{i=1}^{N} \frac{|\mathbf{p}_i|^4}{E_i^2} \Gamma_i^{-1},$$

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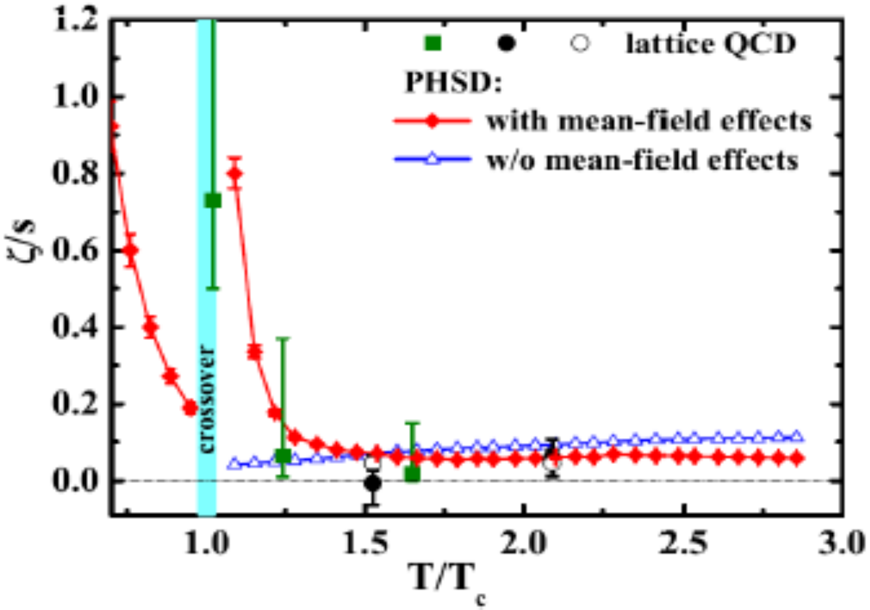
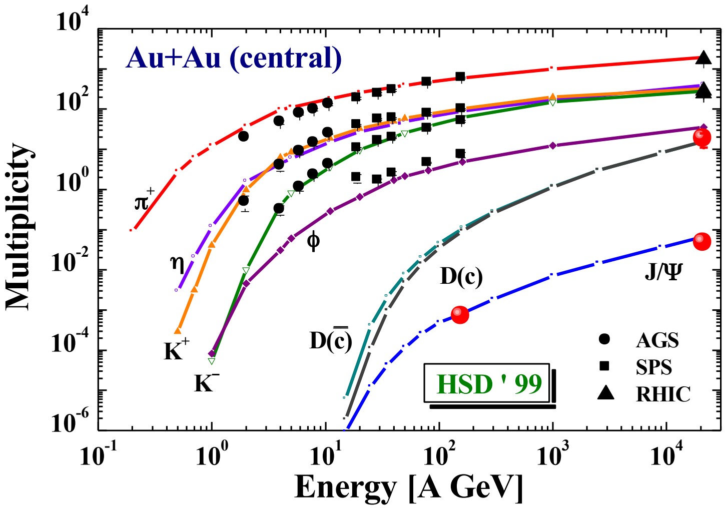
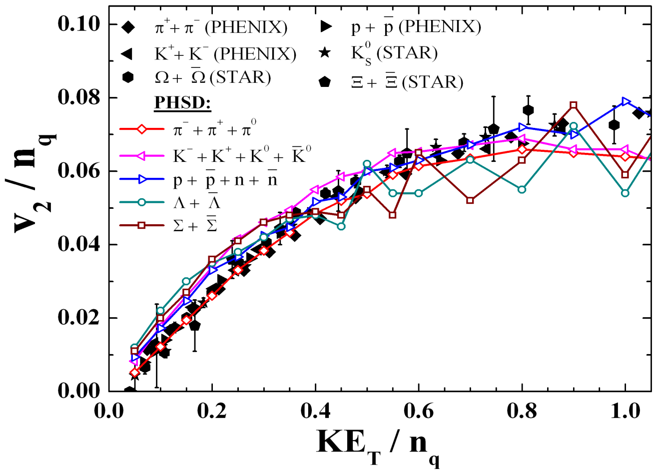


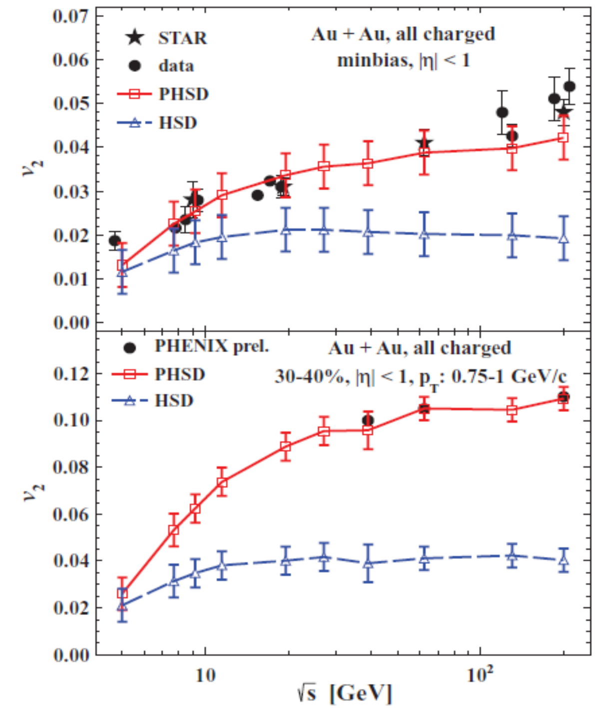
lQCD: Meyer, Phys. Rev. Lett. 100, 162001 (2008);
Sakai,Nakamura, Pos LAT2007, 221 (2007).

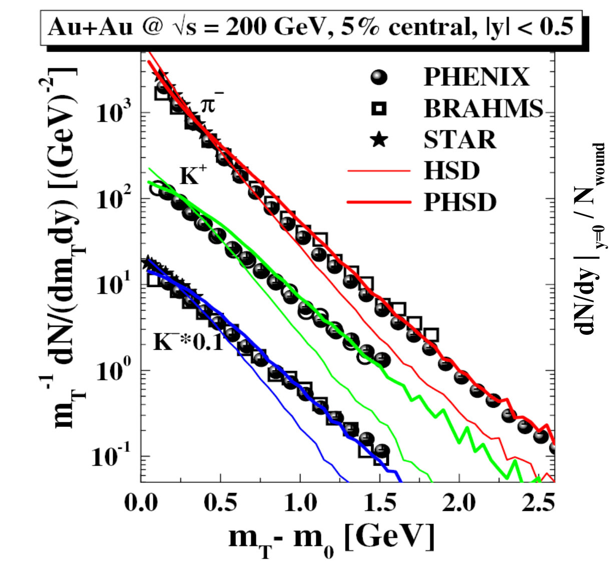
V. Ozvenchuk et al., PRC 87 (2013) 064903

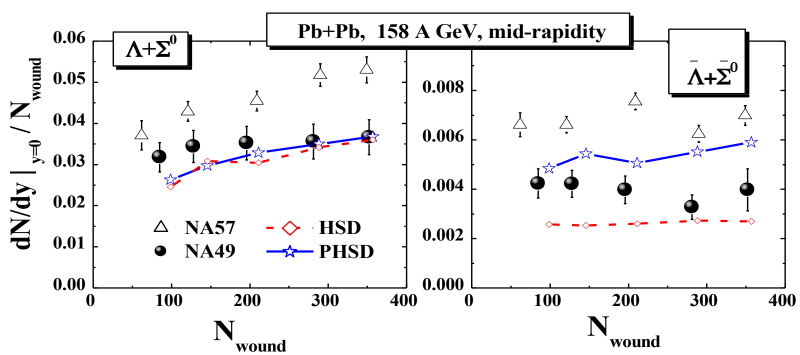
PHSD for HIC (highlights)

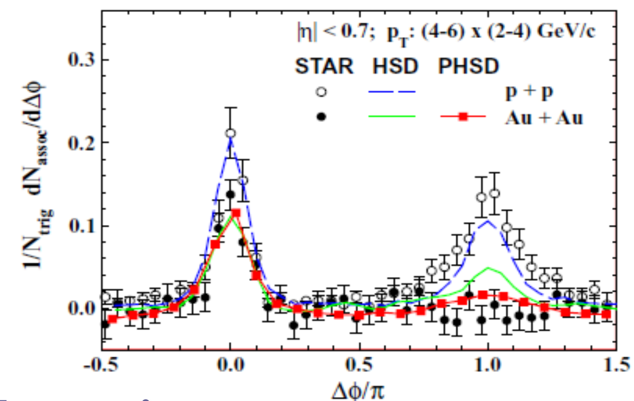












PHSD provides a consistent description of HIC dynamics