The QGP dynamics in relativistic heavy-ion collisions

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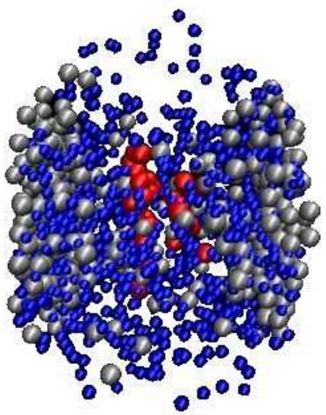
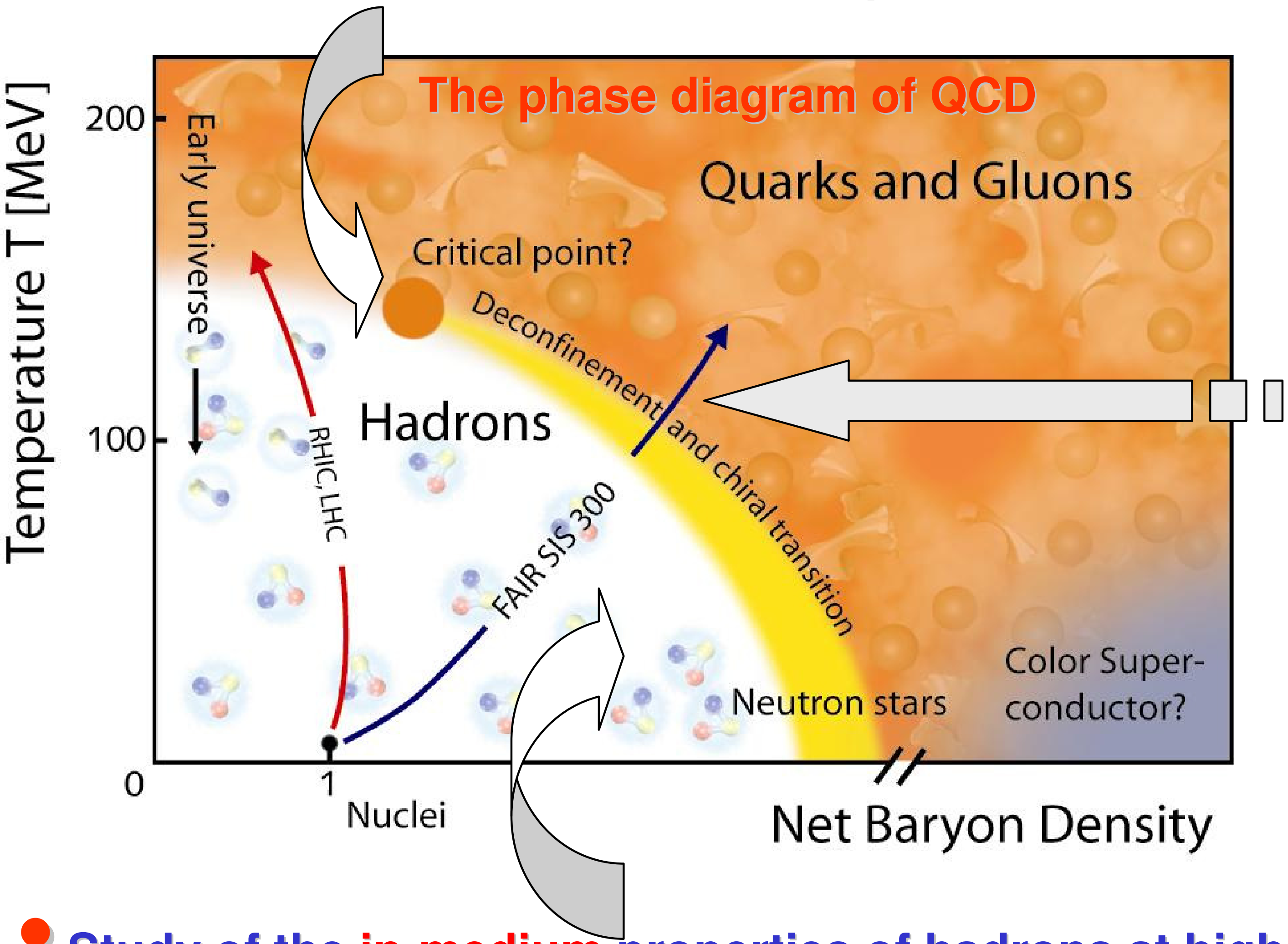


Kruger2014: The International Workshop on Discovery Physics at the LHC,

Protea Hotel Kruger Gate, South Africa
1-5 December 2014

The holy grail of heavy-ion physics:

- Search for the **critical point**



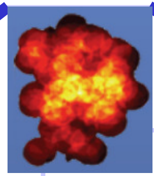
- Study of the **phase transition** from hadronic to partonic matter – **Quark-Gluon-Plasma**

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

Dynamical models for HIC

Macroscopic

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



ideal
(Jyväskylä,SHASTA, TAMU, …)

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

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

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

(‚hybrid'-UrQMD, EPOS, …)

Microscopic

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

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

Partonic cascades
pQCD based
(Duke, BAMPS, …)

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

(AMPT, HIJING)

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

(applicable for strongly interacting systems)

Semi-classical BUU equation

Ludwig Boltzmann

Boltzmann-Uehling-Uhlenbeck equation (non-relativistic formulation)
- propagation of particles in the **self-generated Hartree-Fock mean-field potential** *U(r,t)* with an on-shell **collision term:**

$$\frac{\partial}{\partial t} f(\vec{r},\vec{p},t) + \frac{\vec{p}}{m}\vec{\nabla}_{\vec{r}}\, f(\vec{r},\vec{p},t) - \vec{\nabla}_{\vec{r}} U(\vec{r},t)\, \vec{\nabla}_{\vec{p}} f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

collision term: elastic and inelastic reactions

$f(\vec{r},\vec{p},t)$ is the **single particle phase-space distribution function**
- probability to find the particle at position *r* with momentum *p* at time *t*

- self-generated **Hartree-Fock mean-field potential:**

$$U(\vec{r},t) = \frac{1}{(2\pi\hbar)^3} \sum_{\beta_{occ}} \int d^3r'\, d^3p\;\; V(\vec{r}-\vec{r}',t)\, f(\vec{r}',\vec{p},t) \; + \; (Fock\;\; term)$$

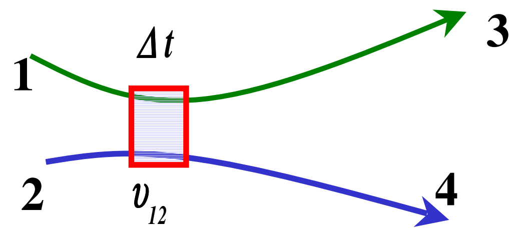
- **Collision term** for 1+2→3+4 (let‘s consider fermions) :

$$I_{coll} = \frac{4}{(2\pi)^3} \int d^3p_2\, d^3p_3 \int d\Omega\;\; |v_{12}|\, \delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot \frac{d\sigma}{d\Omega}(1+2\rightarrow 3+4)\cdot P$$

Probability including **Pauli blocking of fermions:**

$$P = f_3 f_4 (1-f_1)(1-f_2) \; - \; f_1 f_2 (1-f_3)(1-f_4)$$

Gain term: 3+4→1+2   **Loss term: 1+2→3+4**



Dynamical description of strongly interacting systems

- **Semi-classical on-shell BUU:** applies for small collisional width, i.e. for a weakly interacting systems of particles

How to describe strongly interacting systems?!

- **Quantum field theory →**

Kadanoff-Baym dynamics for resummed single-particle Green functions $S^<$

$$\hat{S}_{0x}^{-1} \, S_{xy}^{<} = \Sigma_{xz}^{ret} \odot S_{zy}^{<} + \Sigma_{xz}^{<} \odot S_{zy}^{adv}$$

(1962)

Integration over the intermediate spacetime

Green functions $S^<$ / self-energies Σ:

$$iS_{xy}^{<} = \eta \langle \{ \Phi^{+}(y) \Phi(x) \} \rangle$$

$$iS_{xy}^{>} = \langle \{ \Phi(y) \Phi^{+}(x) \} \rangle$$

$$iS_{xy}^{c} = \langle T^{c} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - causal$$

$$iS_{xy}^{a} = \langle T^{a} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - anticausal$$

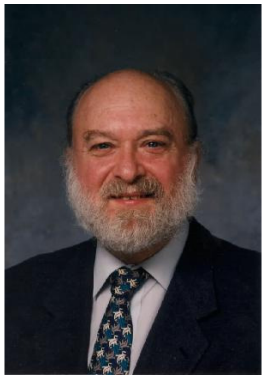
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

$$S_{xy}^{adv} = S_{xy}^{c} - S_{xy}^{>} = S_{xy}^{<} - S_{xy}^{a} \quad - advanced$$

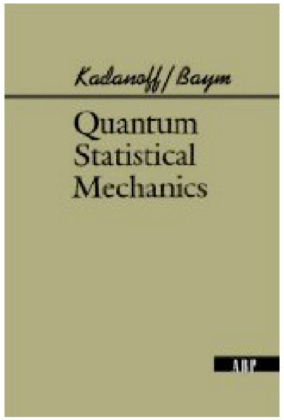
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

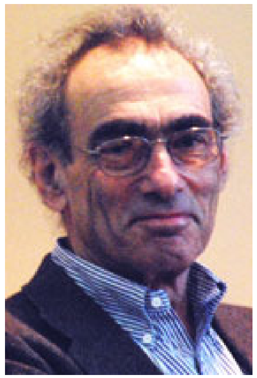
$$\eta = \pm 1 (bosons \, / \, fermions)$$

$$T^{a}(T^{c}) - (anti-)time-ordering \ operator$$



Leo Kadanoff





Gordon Baym

From Kadanoff-Baym equations to generalized transport equations

After the **first order gradient expansion of the Wigner transformed** Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations (GTE):

drift term — Vlasov term — backflow term — collision term = 'gain' - 'loss' 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 $A_{XP} \rightarrow \delta(p^2-M^2)$

- GTE: Propagation of the Green's function $iS^{<}_{XP}=A_{XP}N_{XP}$, which carries information not only on the **number of particles** (N_{XP}), but also on their **properties, interactions and correlations** (via A_{XP})

- **Spectral function:**

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

$\Gamma_{XP} = -Im\Sigma^{ret}_{XP} = 2p_0\Gamma$ – 'width' of spectral function
= **reaction rate** of particle (at space-time position X)

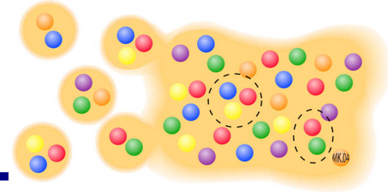
4-dimentional generalizaton of the Poisson-bracket:

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

- **Life time** $\tau = \frac{\hbar c}{\Gamma}$

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

From SIS to LHC: from hadrons to partons



The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from microscopic origin

➔ need a consistent non-equilibrium transport model

- ❑ with explicit parton-parton interactions (i.e. between quarks and gluons)
- ❑ explicit phase transition from hadronic to partonic degrees of freedom
- ❑ lQCD EoS for partonic phase (‚crossover' at μ_q=0)

❑ 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)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

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 with proper states in equilibrium

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

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles:
massive quarks and gluons (g, q, q_{bar})
with Lorentzian spectral functions :

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

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

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

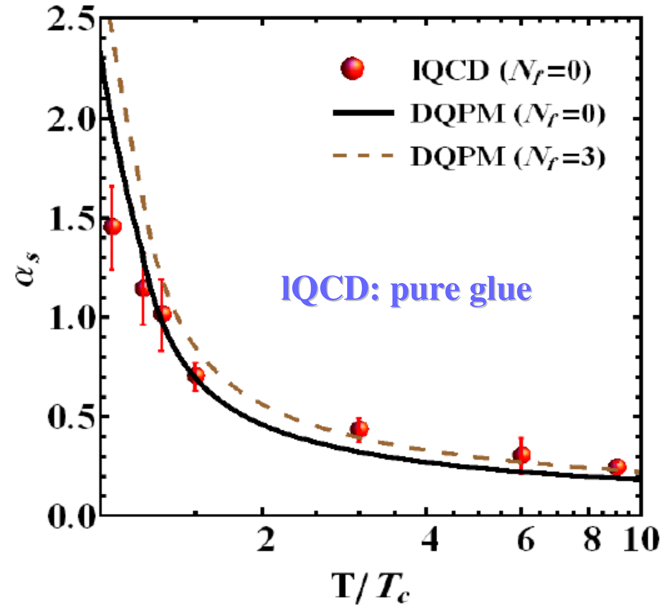
    $$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

    $N_c = 3$, $N_f = 3$

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

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



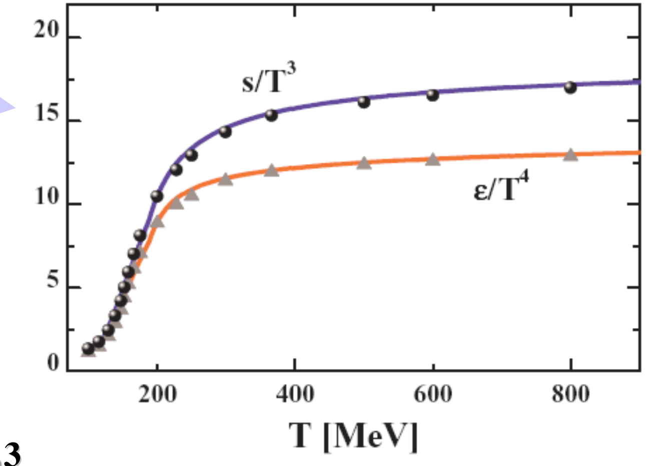
❑ **fit to lattice (lQCD) results (e.g. entropy density)**

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

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

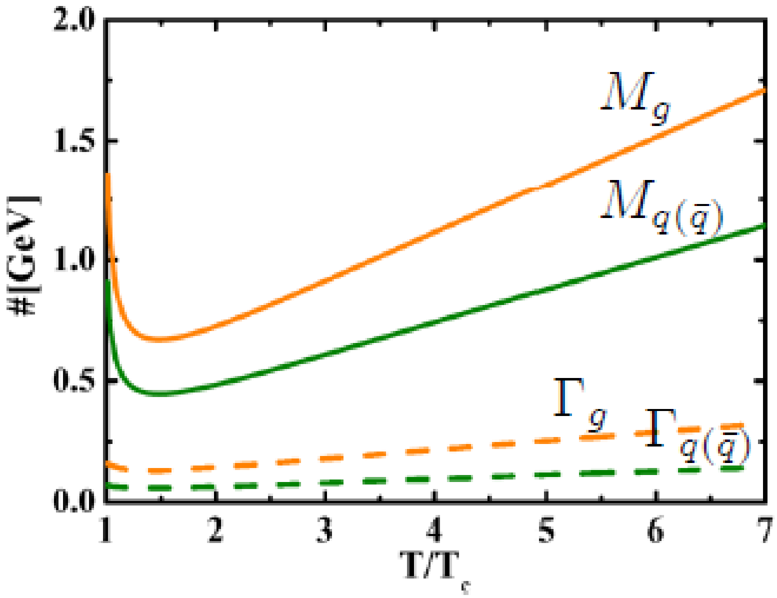
The Dynamical QuasiParticle Model (DQPM)

- fit to lattice (lQCD) results (e.g. entropy density)
  - BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073

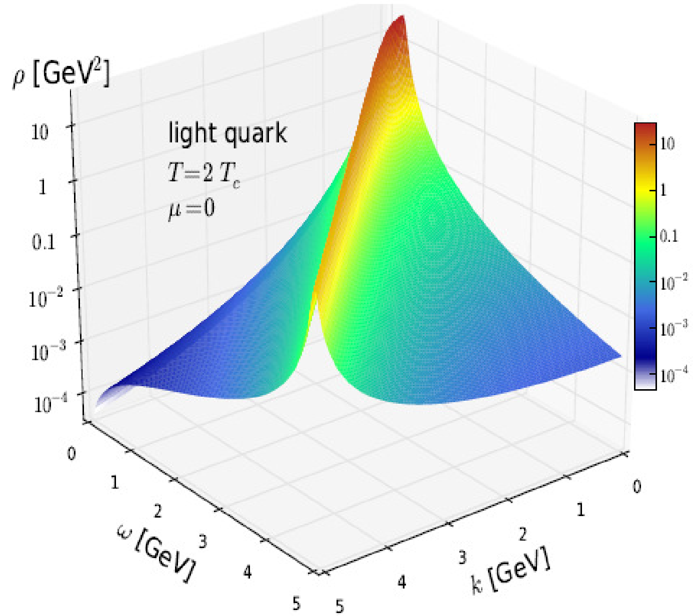


→ Quasiparticle properties:

- large width and mass for gluons and quarks



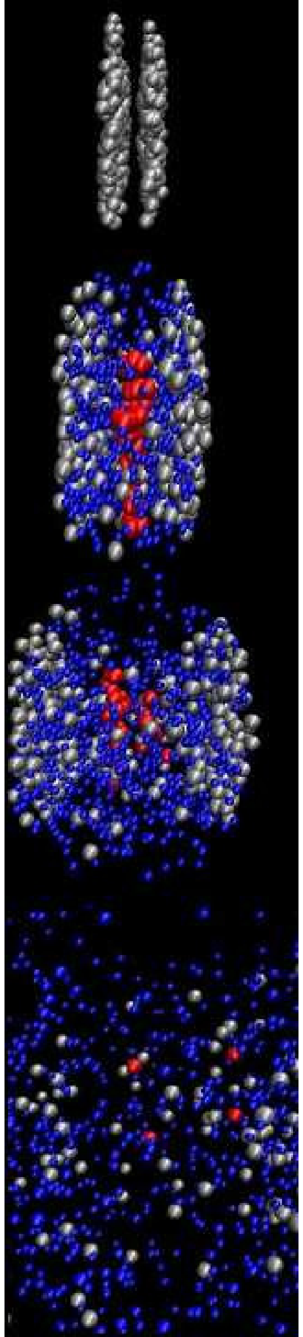
T_C=158 MeV
ε_C=0.5 GeV/fm^3



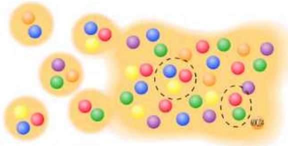
- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and qu
  as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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

Parton Hadron String Dynamics

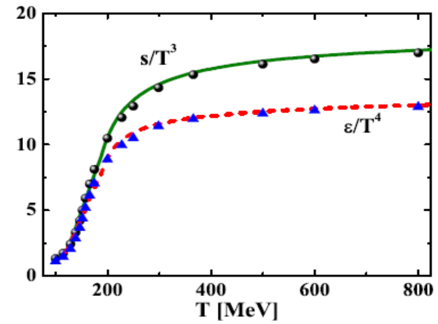


I. From hadrons to QGP:



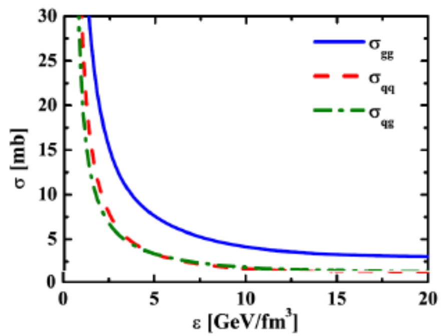
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- 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)



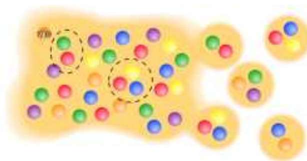
II. Partonic phase - QGP:

- 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

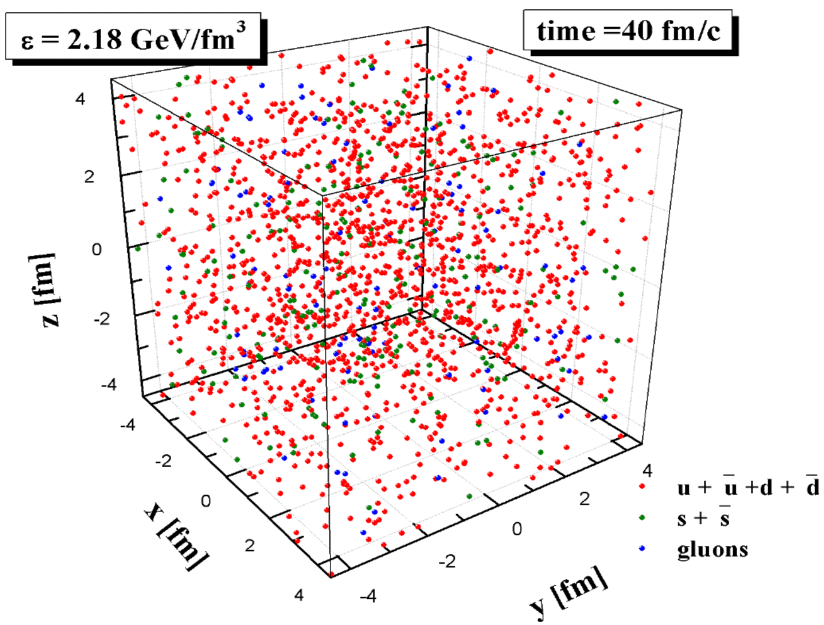
- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)



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.

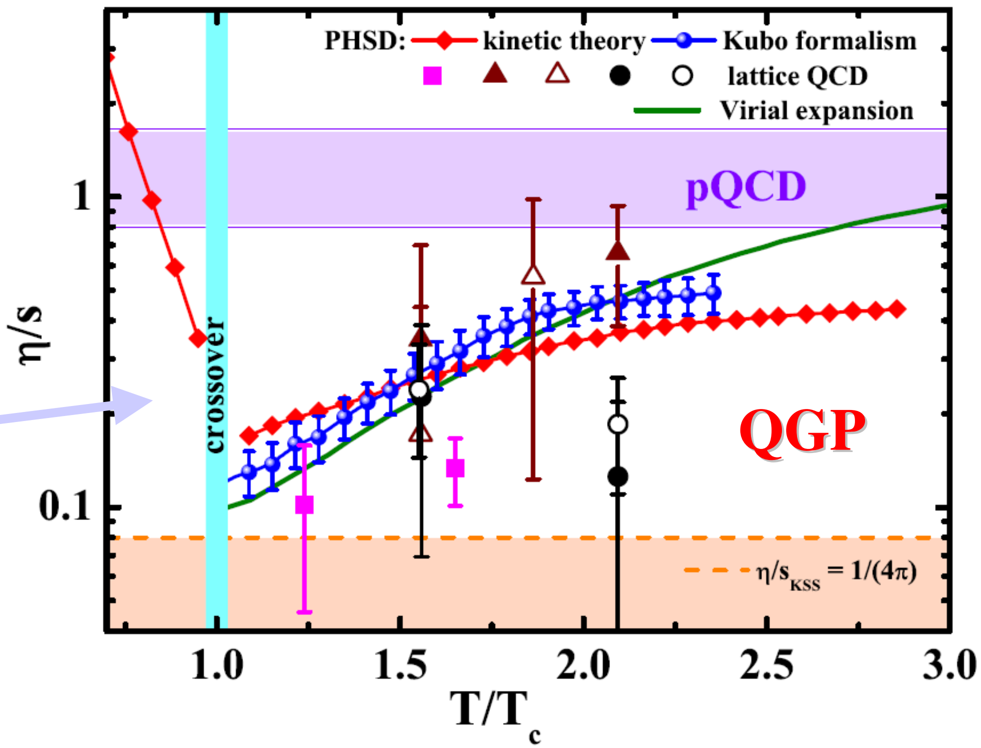
Properties of the QGP in equilibrium using PHSD



Properties of parton-hadron matter: 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 h/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



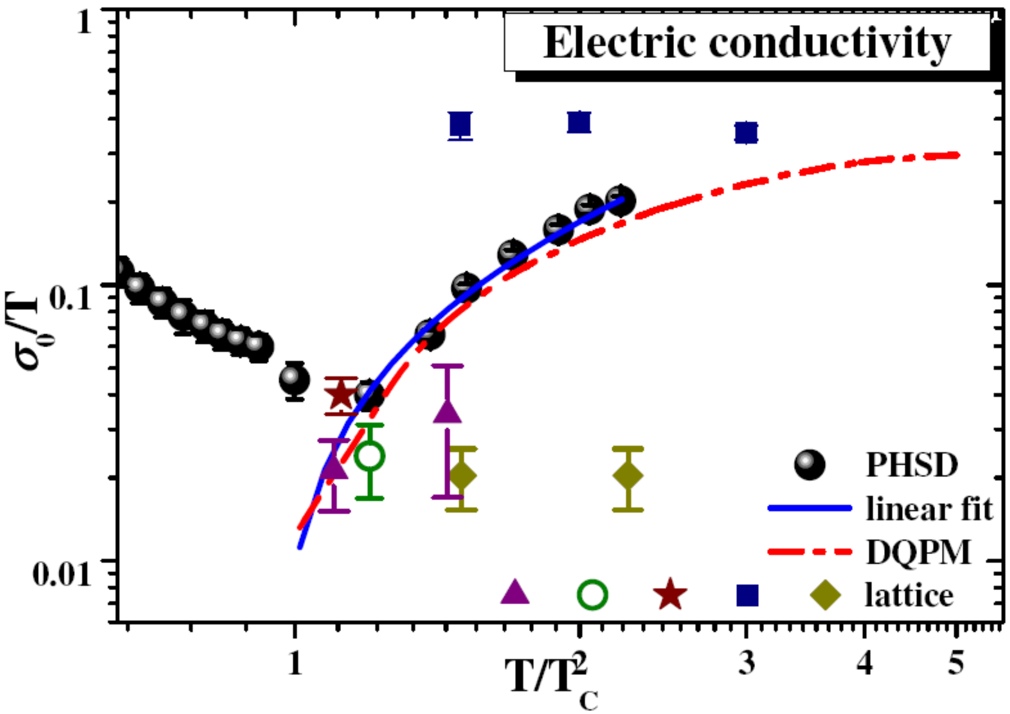
Virial expansion: S. Mattiello, W. Cassing, Eur. Phys. J. C 70, 243 (2010)

QGP in PHSD = strongly-interacting liquid

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

Properties of parton-hadron matter: electric conductivity

- The response of the strongly-interacting system in equilibrium to an **external electric field eE_z** defines the **electric conductivity σ_0**:



$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T},$$

$$j_z(t) = \frac{1}{V}\sum_j eq_j \frac{p_z^j(t)}{M_j(t)};$$

➔ the **QCD matter** even at T~ T_c is a **much better electric conductor than Cu or Ag** (at room temperature) by a factor of 500 !

❑ **Photon (dilepton) rates** at q_0→0 are related to electric conductivity σ_0

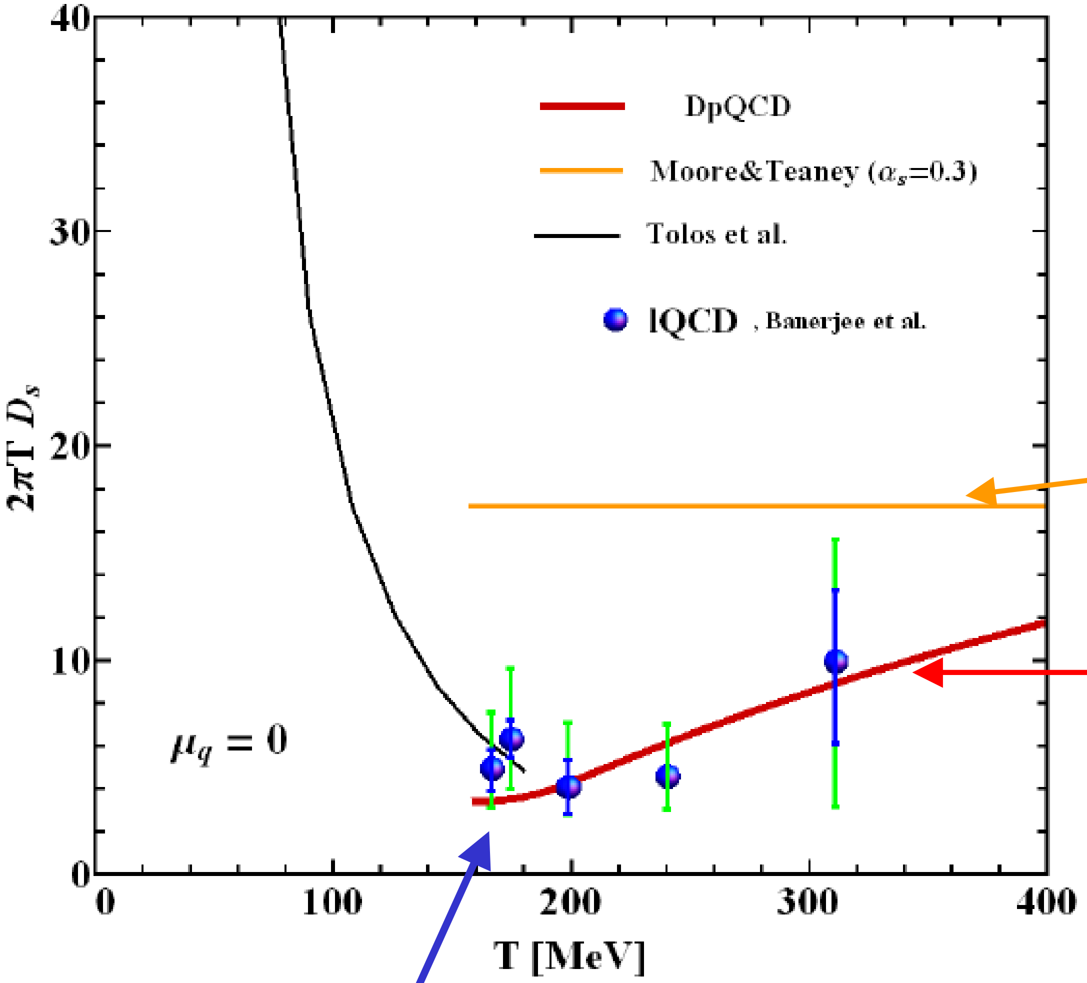
➔ Probe of **electric properties of the QGP**

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

W. Cassing et al., PRL 110(2013)182301

Charm spatial diffusion coefficient D_s in the hot medium

- D_s for heavy quarks as a function of T for $\mu_q=0$

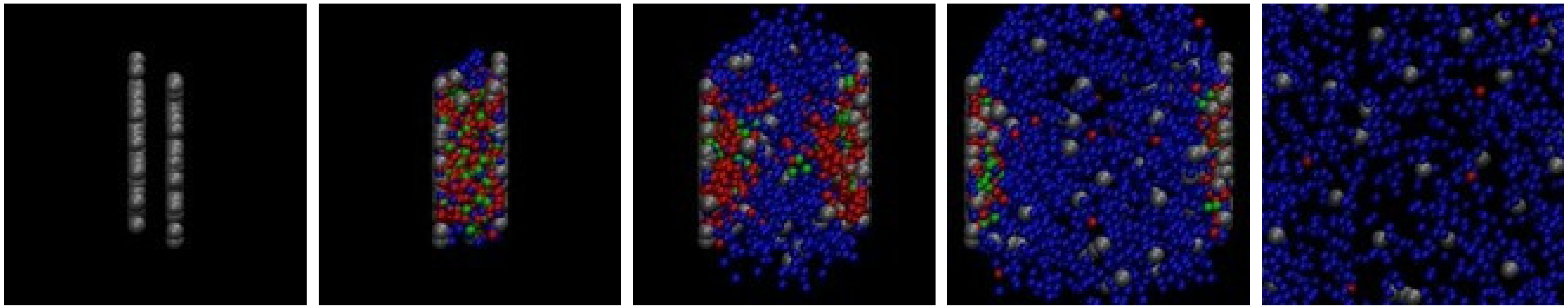


- T < T_c : hadronic D_s
  L. Tolos , J. M. Torres-Rincon, Phys. Rev. D 88, 074019 (2013)
- T > T_c : QGP D_s
  - pQCD - G. D. Moore, D. Teaney, Phys. Rev. C 71, 064904 (for α_s=0.3)
  - DQPM - H. Berrehrah et al, arXiv:1406.5322 [hep-ph]
  - lQCD - Banerjee et al., Phys. Rev. D 85, 014510 (2012).

→ Continuous transition !

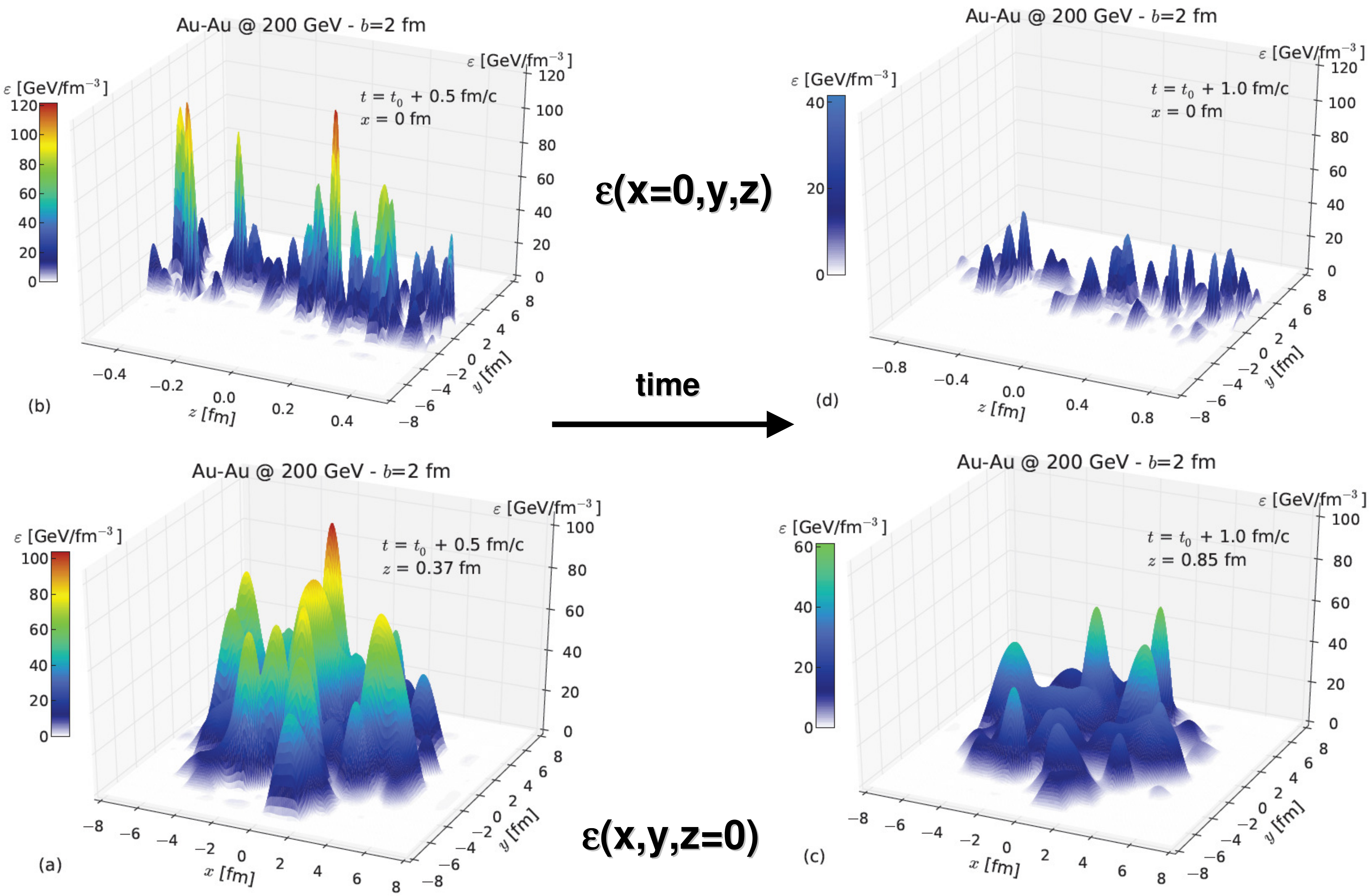
H. Berrehrah et al, PRC (2014), arXiv:1406.5322 [hep-ph]

‚Bulk' properties in Au+Au



Time evolution of energy density

PHSD: 1 event Au+Au, 200 GeV, b = 2 fm

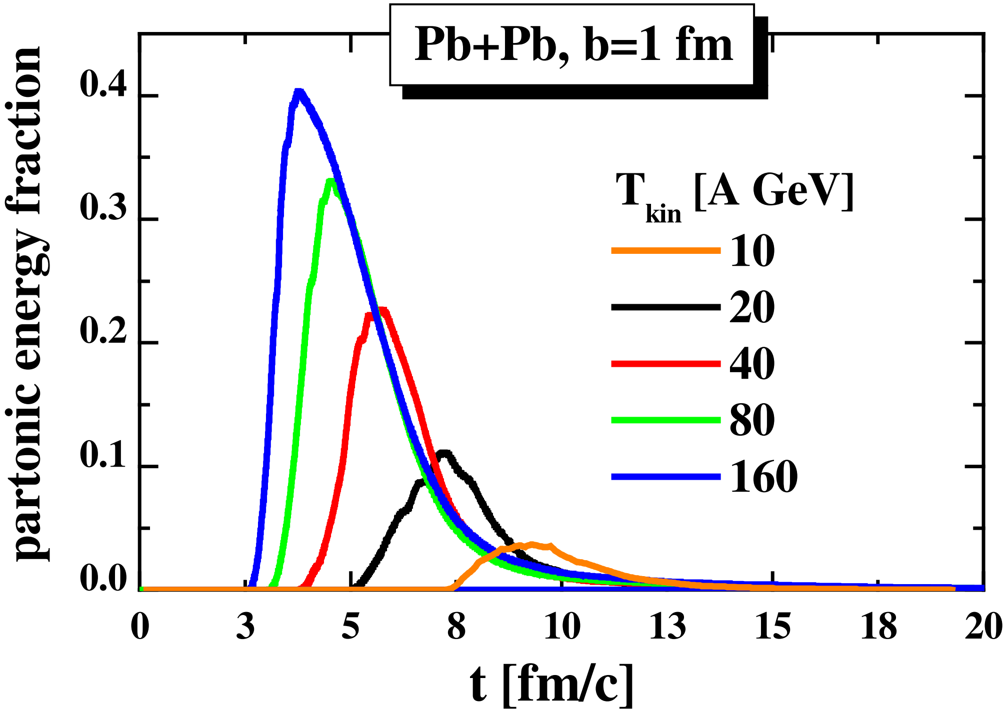


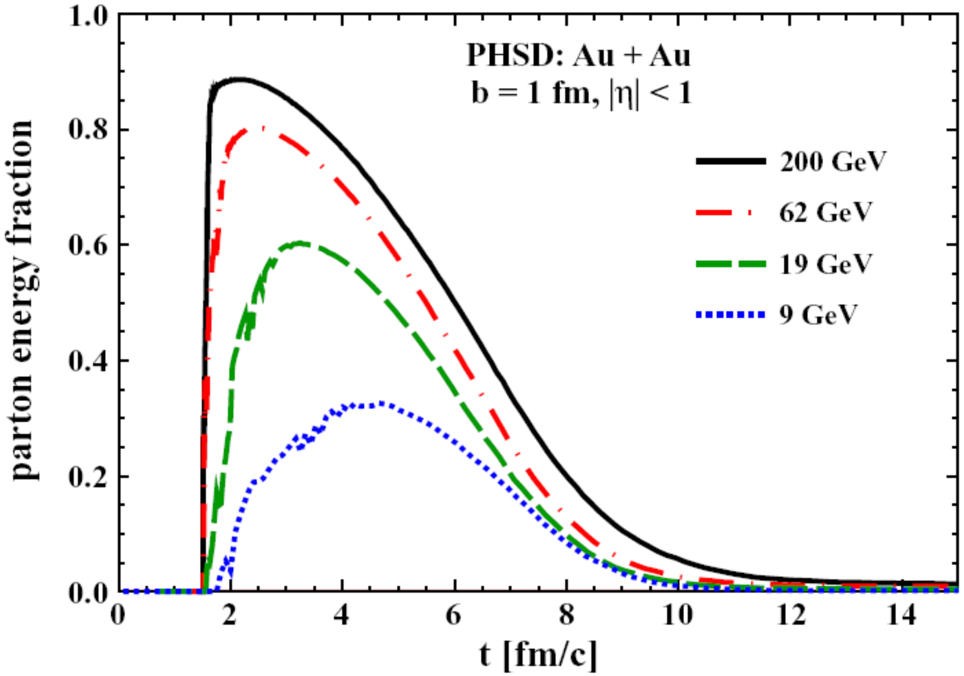
ΔV: Δx=Δy=1fm, Δz=1/γ fm

R. Marty et al, 2014

Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy





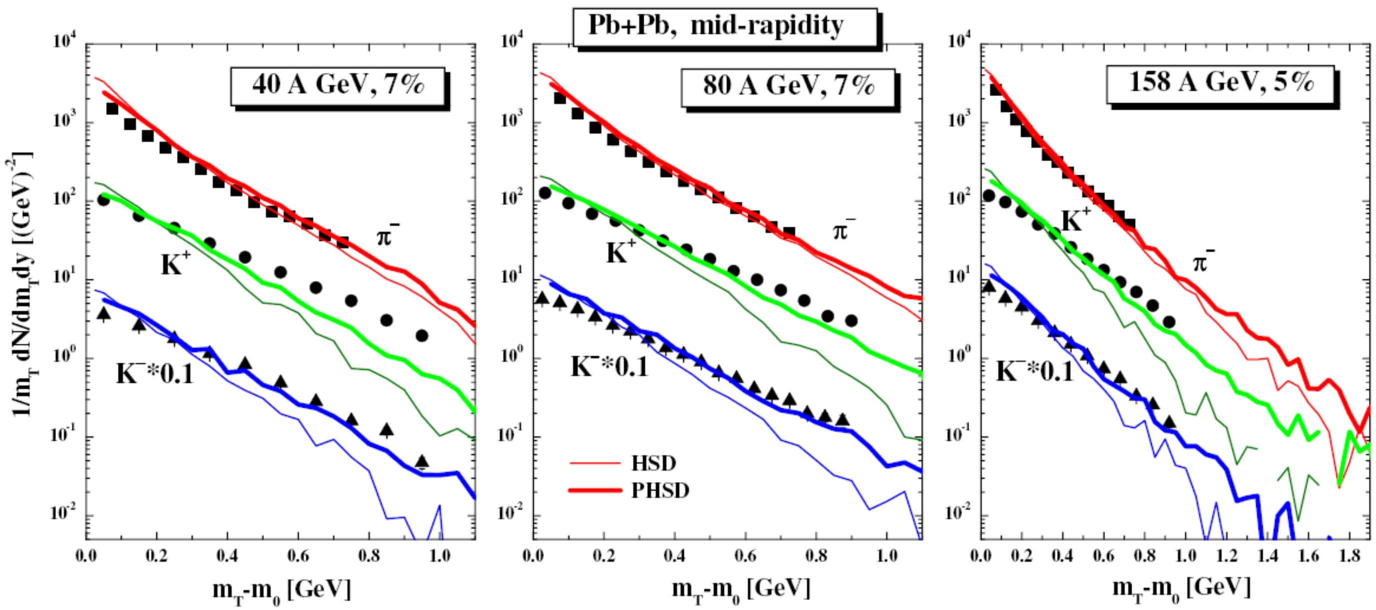
- Strong increase of partonic phase with energy from AGS to RHIC

- SPS: 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
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

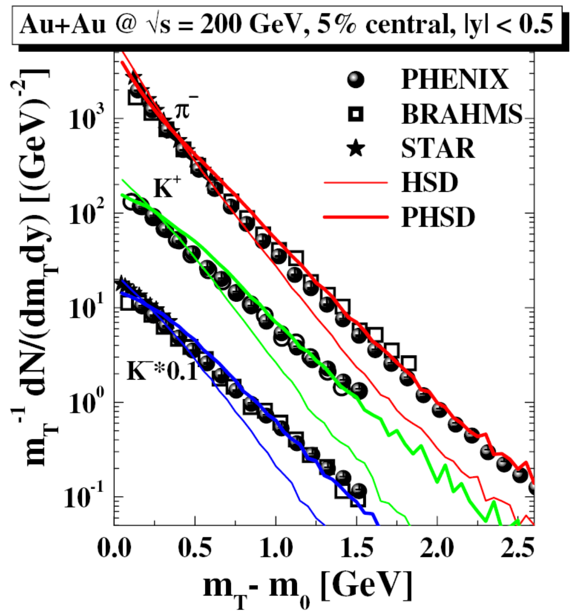
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies



Central Au+Au at RHIC

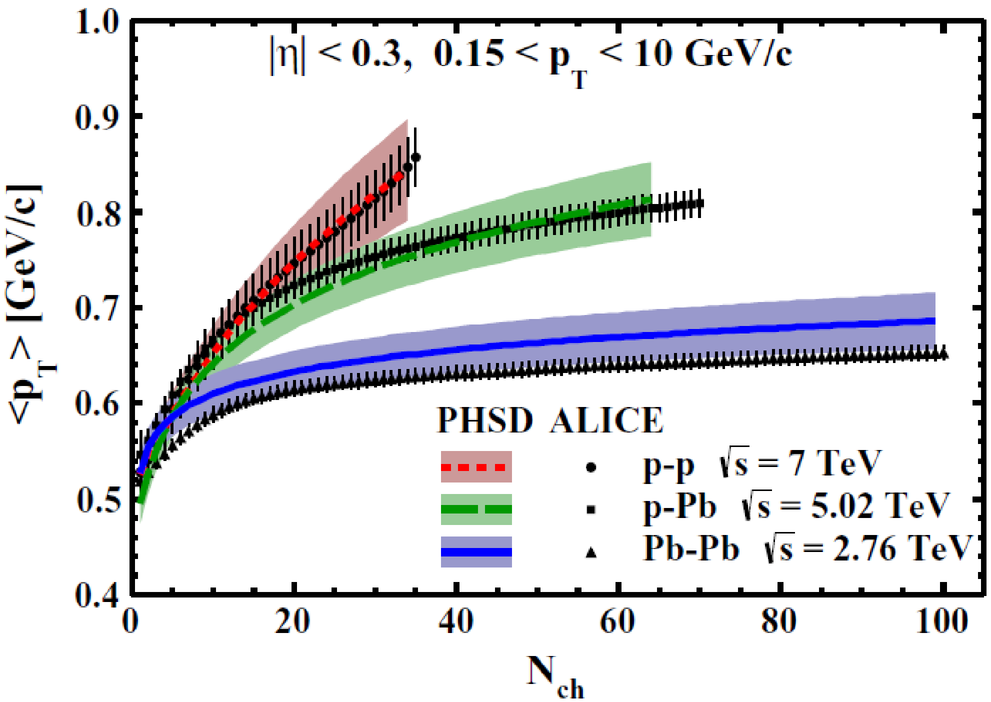


- PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

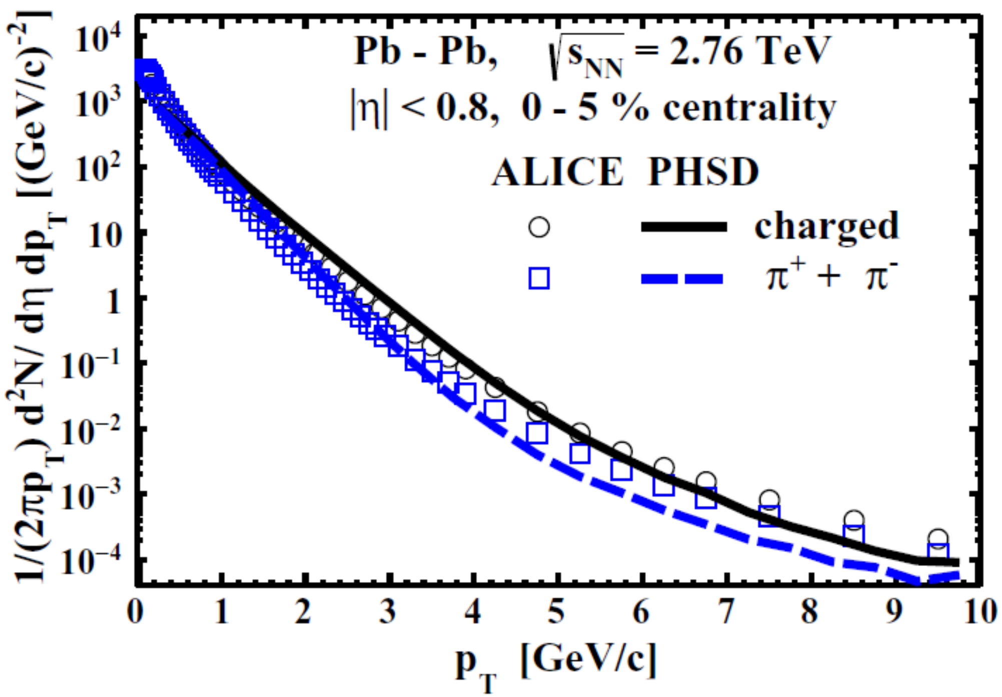
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

p_T spectra at LHC

Mean p_T of charged hadrons vs N_{ch}
p+p at $s^{1/2}$=7 TeV
p+Pb at $s^{1/2}$=5.02 TeV,
Pb+Pb at $s^{1/2}$=2.76 TeV



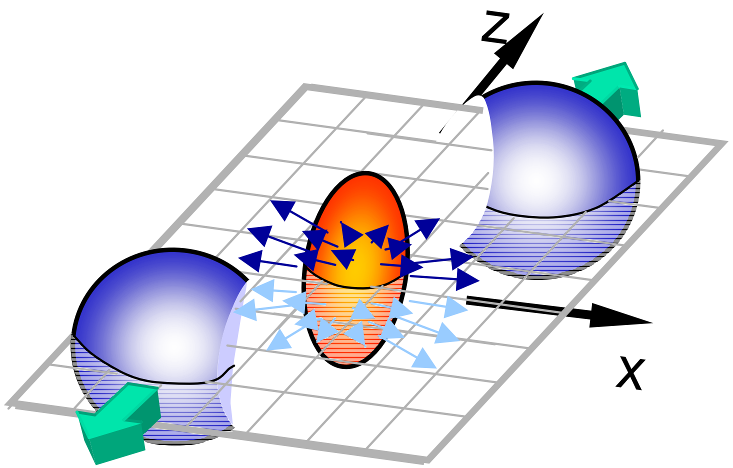
p_T spectra of charged hadrons and pions
central Pb+Pb at $s^{1/2}$=2.76 TeV



➔ **PHSD reproduces ALICE data**

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

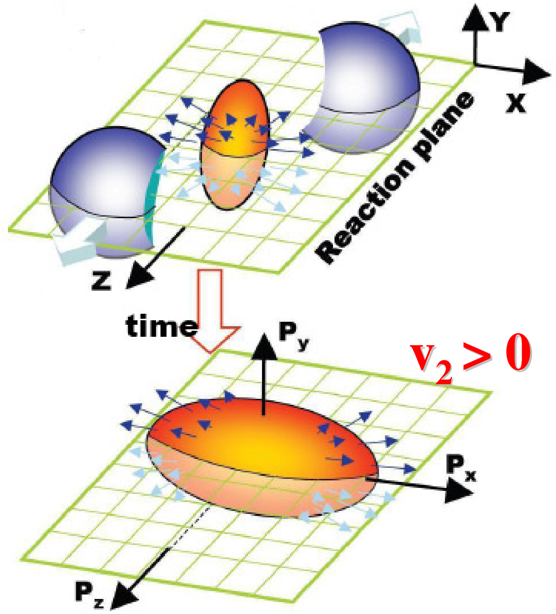
Collective flow, anisotropy coefficients (v_1, v_2, ...) in A+A



Anisotropy coefficients

Non central Au+Au collisions :

- interaction between constituents leads to a **pressure gradient** → **spatial asymmetry** is converted to an **asymmetry in momentum space** → **collective flow**



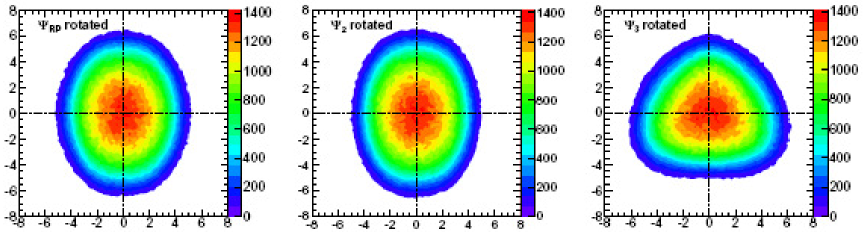
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

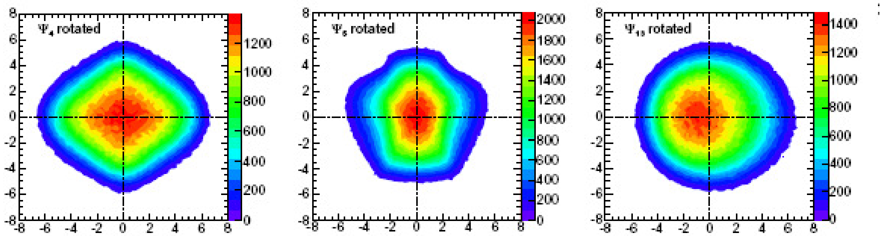
$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

v_1: directed flow

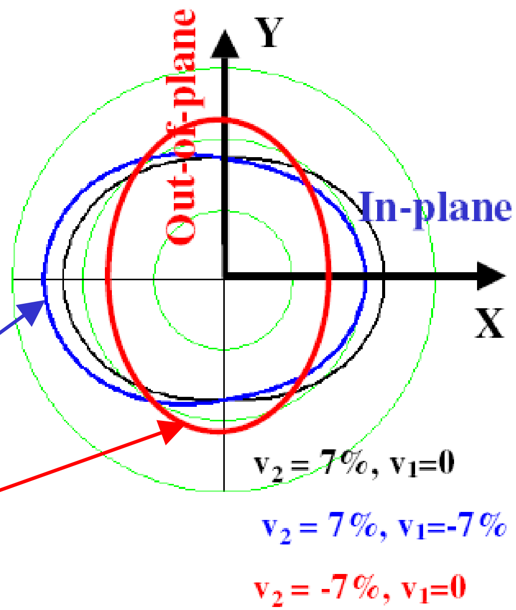
v_2: elliptic flow

v_3: triangular flow…..





from S. A. Voloshin, arXiv:1111.7241



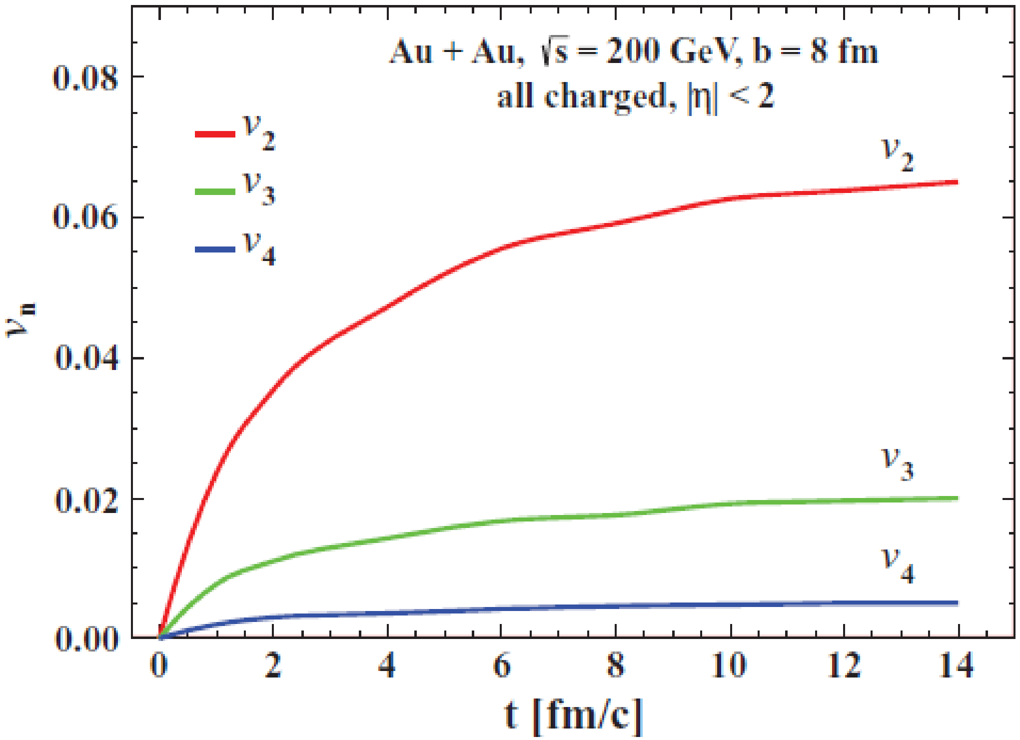
$v_2 > 0$ indicates in-plane emission of particles

$v_2 < 0$ corresponds to a squeeze-out perpendicular to the reaction plane (out-of-plane emission)

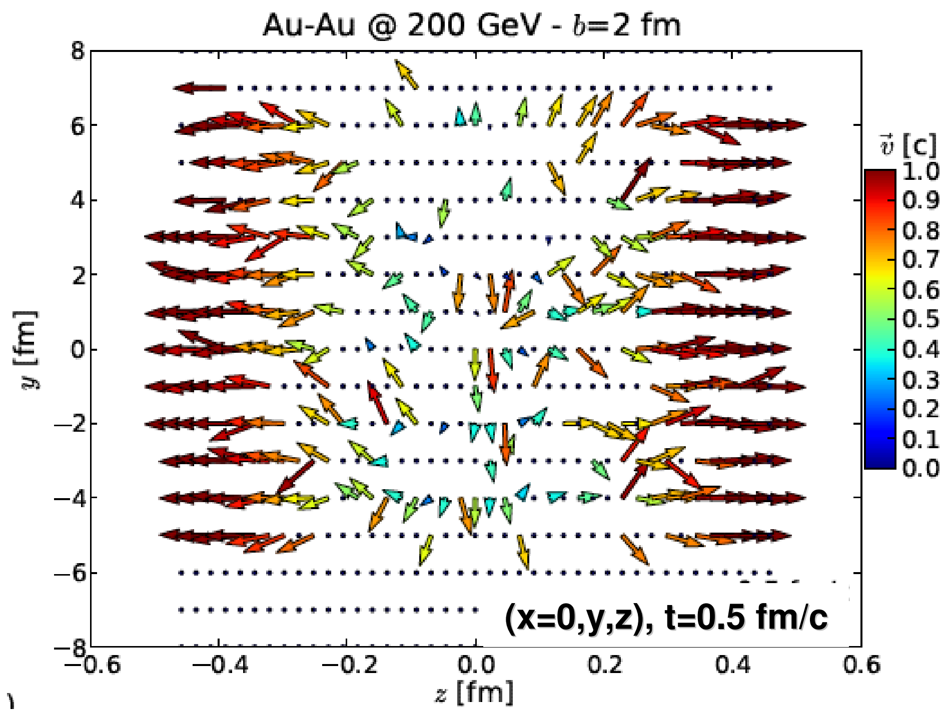
Development of azimuthal anisotropies in time

Au + Au collisions at $s^{1/2}$ = 200 GeV

- **Time evolution of v_n for b = 8 fm**



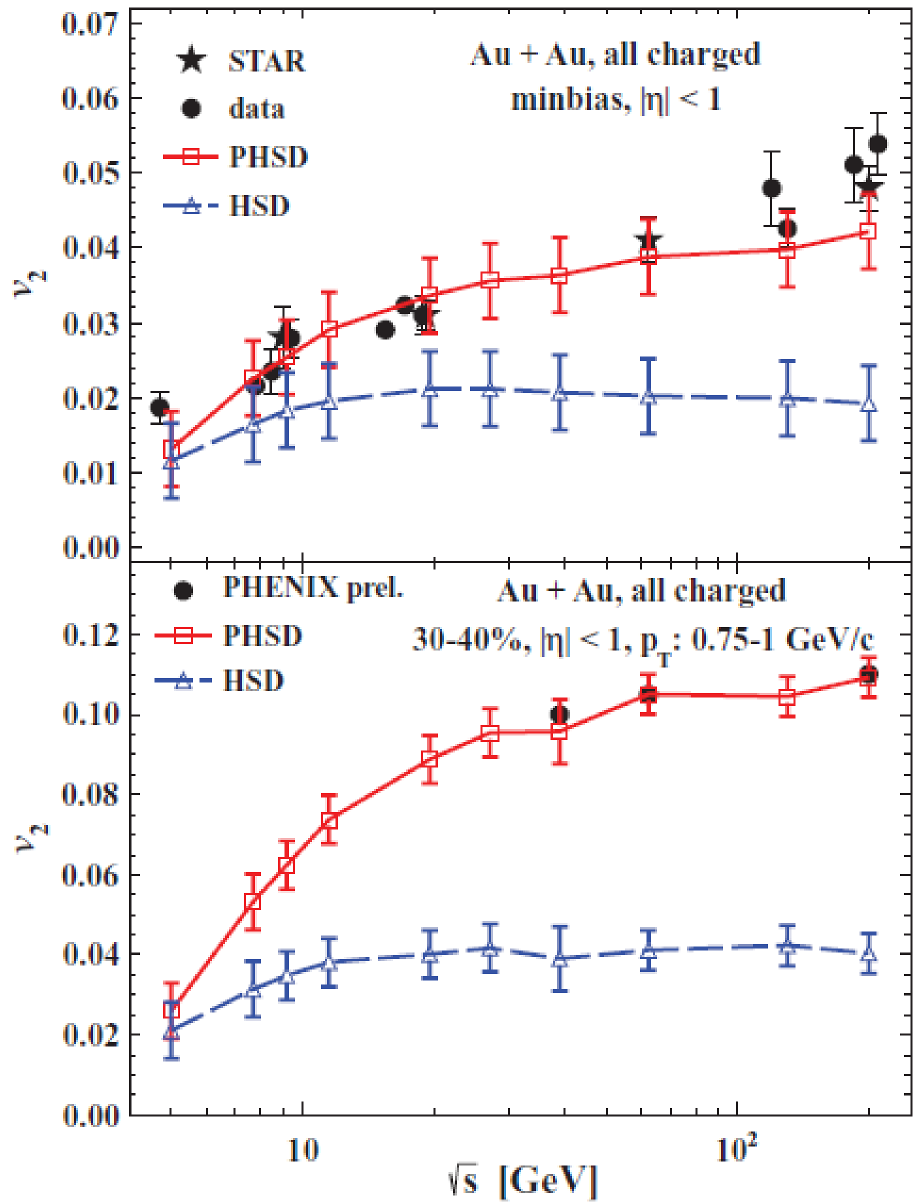
- **Flow velocity for b = 2 fm (x=0,y,z), t=0.5 fm/c**

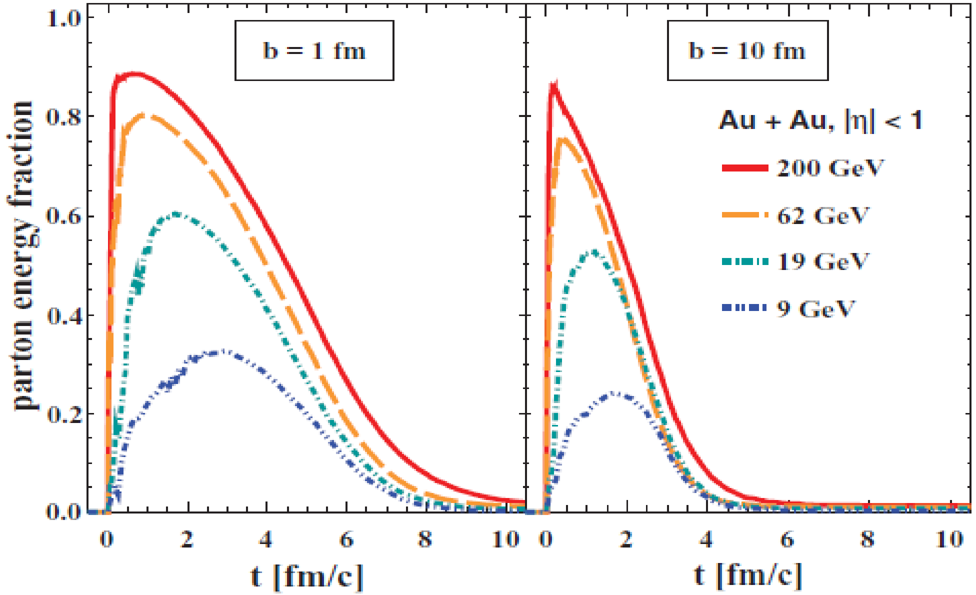


- **Flow coefficients reach their asymptotic values by the time of 6–8 fm/c after the beginning of the collision**

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

Elliptic flow v_2 vs. collision energy for Au+Au

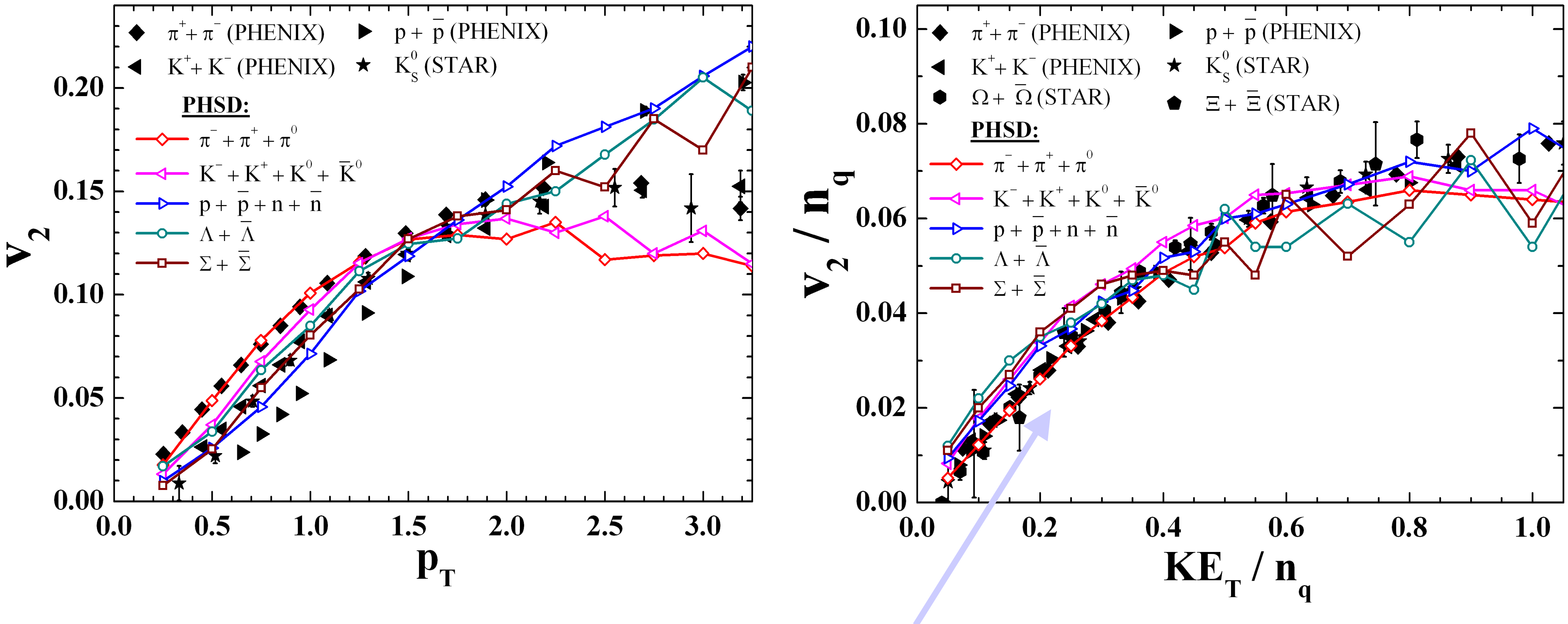




- **v_2 in PHSD is larger than in HSD** due to the **repulsive scalar mean-field potential $U_s(\rho)$** for partons
- **v_2 grows with bombarding energy** due to the **increase of the parton fraction**

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

Elliptic flow scaling at RHIC

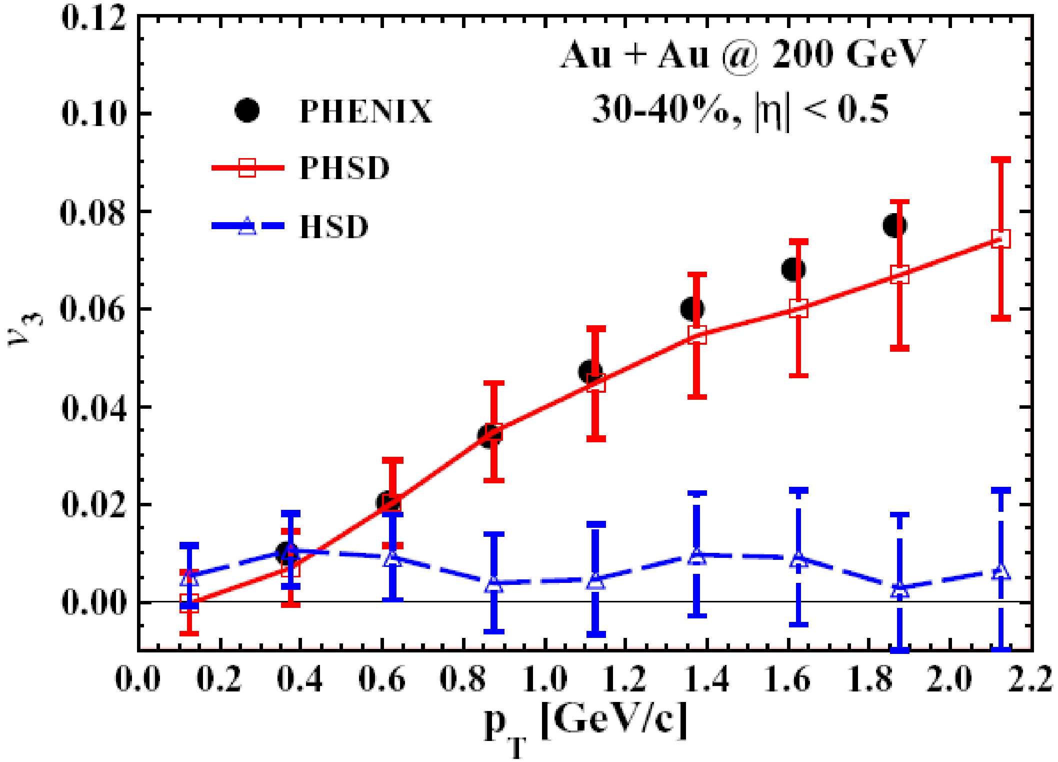


■ The mass splitting at low p_T is approximately reproduced in PHSD as well as the meson-baryon splitting for p_T > 2 GeV/c

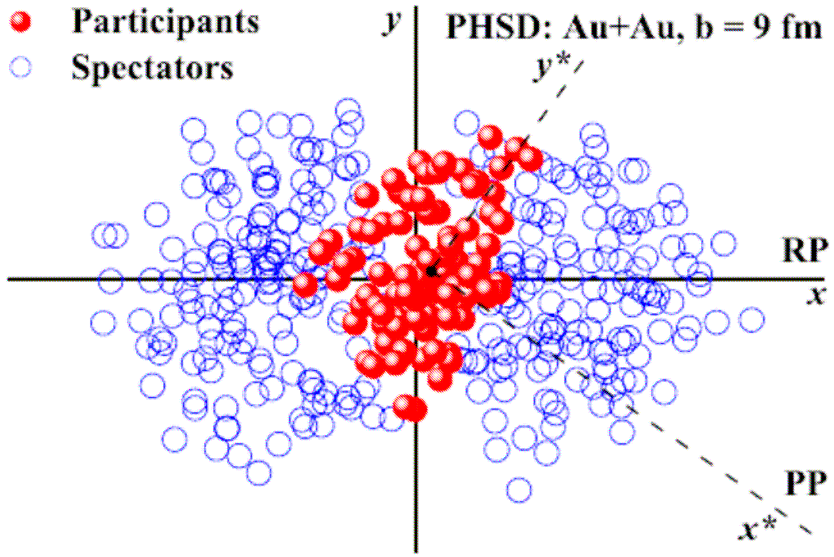
■ The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data

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

Transverse momentum dependence of triangular flow at RHIC



triangular flow

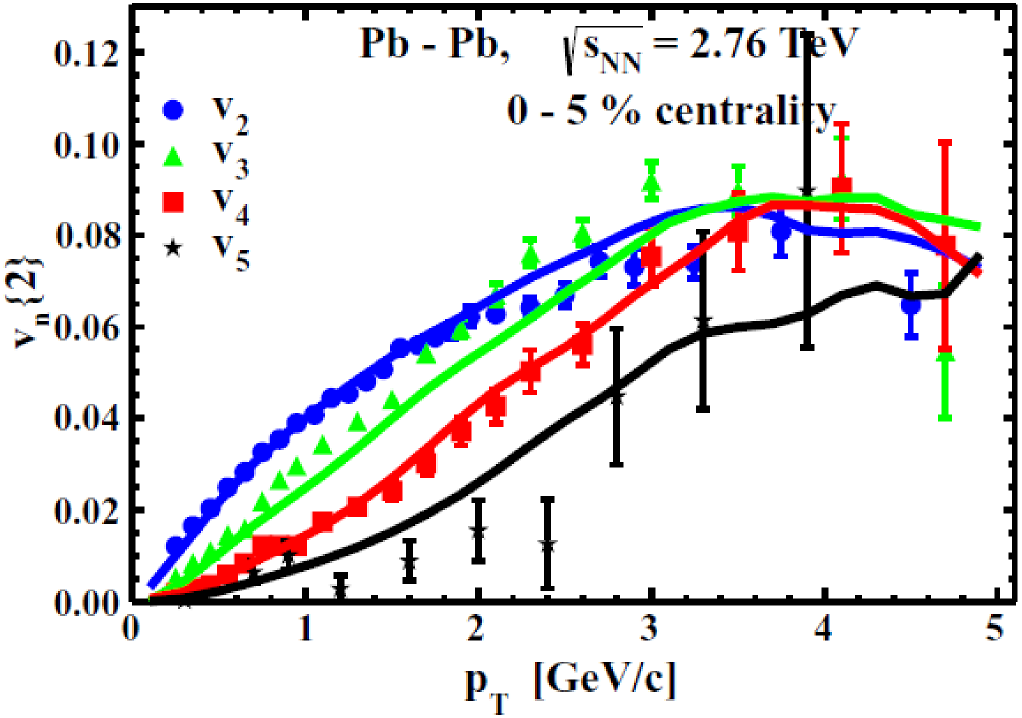


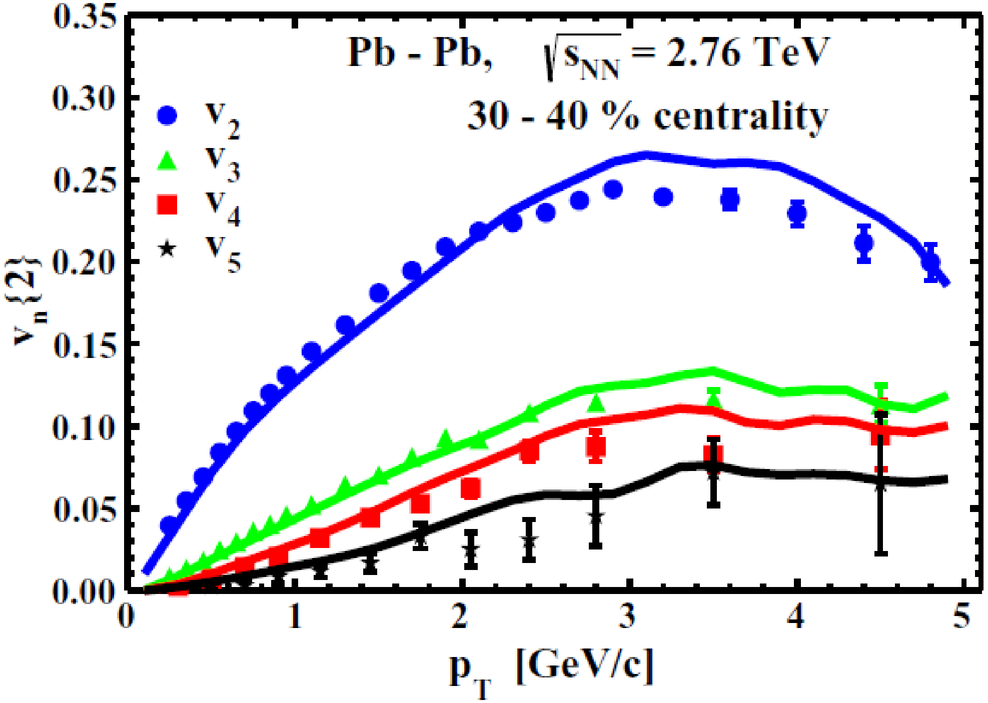
- **HSD (without QGP) shows a flat p_T distribution**
- **PHSD shows an increase of v_3 with p_T**

➔ v_3 : needs partonic degrees of freedom !

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

V_n (n=2,3,4,5) at LHC





symbols – ALICE

PRL 107 (2011) 032301

lines – PHSD

- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Messages from the study of spectra and collective flow

- PHSD gives harder m_T spectra than HSD (without QGP) at high energies – LHC, RHIC, SPS

- at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases

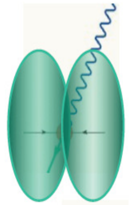
- Anisotropy coefficients v_n as a signal of the QGP:
  - quark number scaling of v_2 at ultrarelativistic energies – signal of deconfinement
  - growing of v_2 with energy – partonic interactions make a larger pressure than the hadronic interactions
  - v_n, n=3,.. – sesitive to QGP

Direct photons flow puzzle

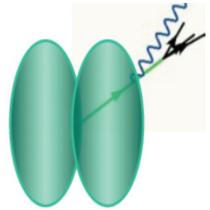
Production sources of photons in p+p and A+A

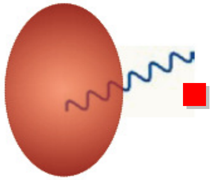
- **Decay photons** (in pp and AA):

$$m \rightarrow \gamma + X, \;\; m = \pi^0, \eta, \omega, \eta', a_1, \ldots$$

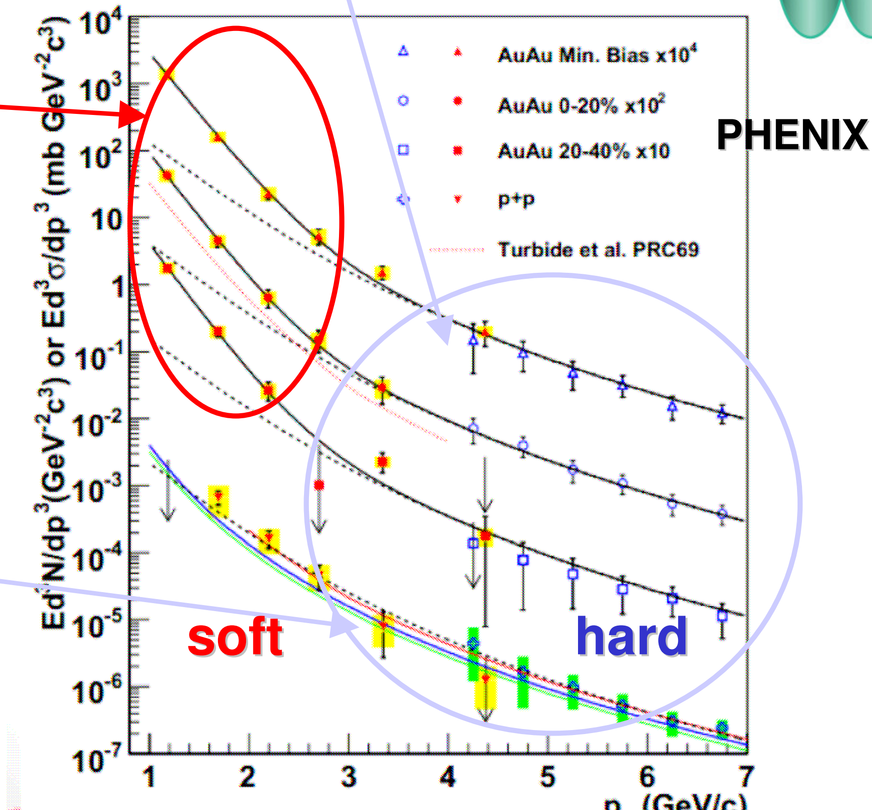


- **Direct photons:** (inclusive(=total) – decay) – measured experimentally
  - **hard photons**:
    (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung)
      (in AA can be modified by parton energy loss in medium)

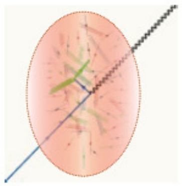




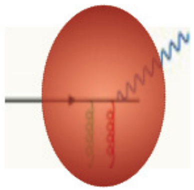
  - **thermal photons**: (low p_T, in AA)
    - QGP
    - Hadron gas



Phys. Rev. C 81, 034911 (2010)



  - **jet-γ-conversion** in plasma
    (large p_T, in AA)



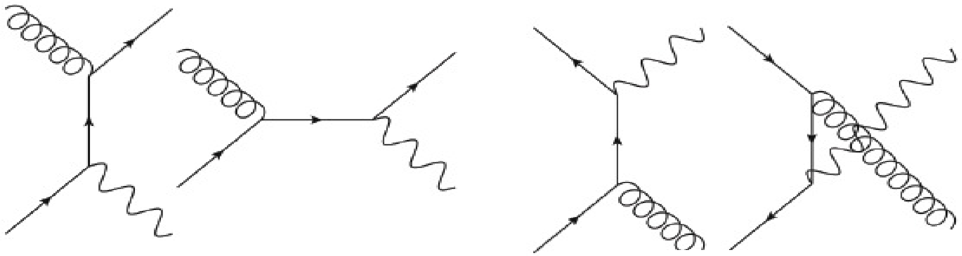
  - **jet-medium photons**
    (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP} \rightarrow \gamma+q$,
    $q_{hard}+\bar{q}_{QGP} \rightarrow \gamma+q$

Production sources of thermal photons

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

Thermal QGP:

Compton scattering　　　　q-qbar annihilation



+ soft ...

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

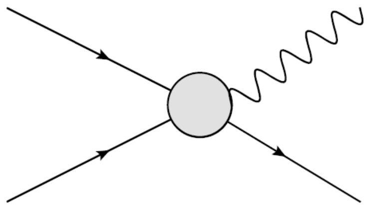
- in PHSD - rates beyond pQCD: off-shell massive q, g

O. Linnyk, JPG 38 (2011) 025105

Hadronic sources:

(1) secondary mesonic interactions:

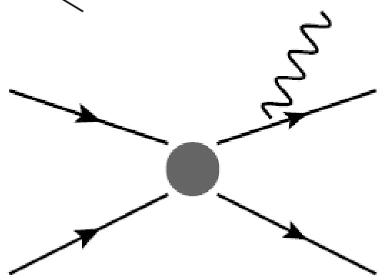
$\pi+\pi \rightarrow \rho+\gamma,\;\; \rho+\pi \rightarrow \pi+\gamma,\;\; \pi+K \rightarrow \rho+\gamma, \ldots$



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

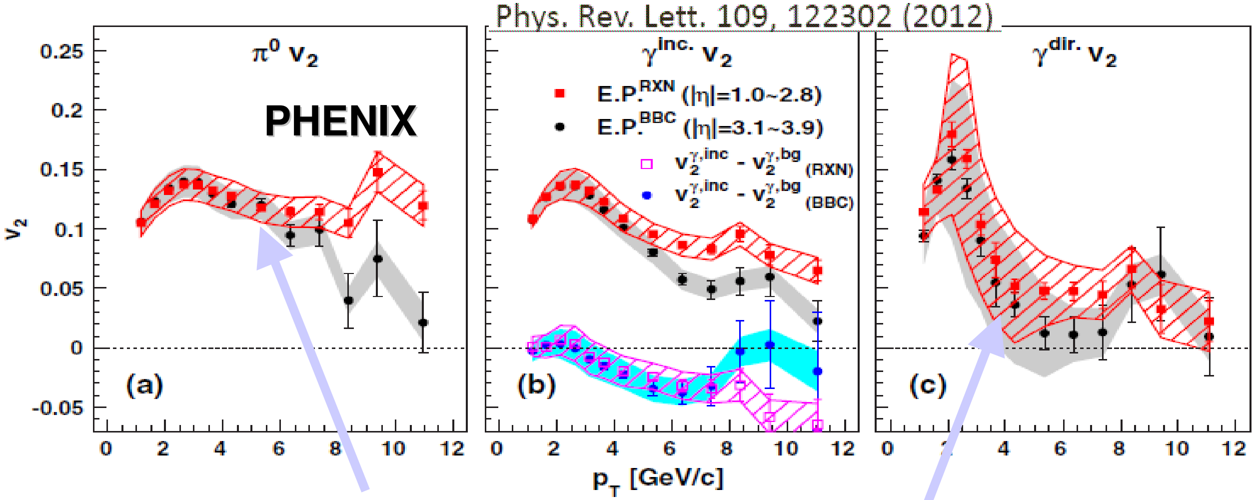
$m+m \rightarrow m+m+\gamma, \quad m+B \rightarrow m+B+\gamma,$

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

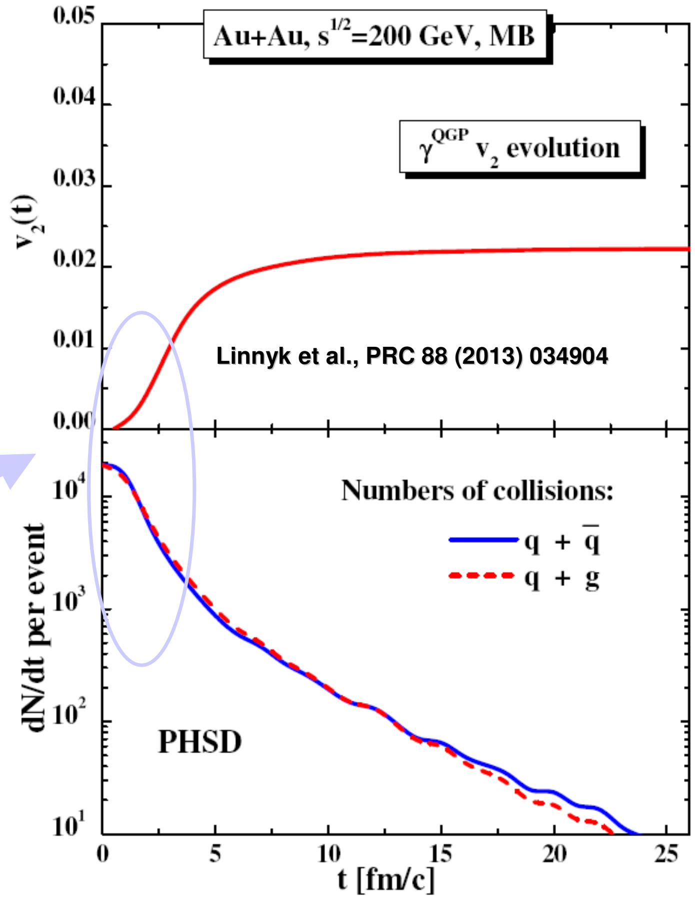


Models: chiral models, OBE, SPA ...

PHENIX: Photon v_2 puzzle



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



!

- **PHENIX (also now ALICE):**
  strong elliptic flow of photons $v_2(\gamma^{dir}) \sim v_2(\pi)$
- **Result from a variety of models:** $v_2(\gamma^{dir}) << v_2(\pi)$
- **Problem:** QGP radiation occurs at **early times** when elliptic flow is not yet developed → expected $v_2(\gamma^{QGP}) \to 0$
- v_2 = weighted average $v_2 = \frac{\sum_I N^I \cdot v_2^I}{\sum_I N^I}$ → **a large QGP contribution gives small** $v_2(\gamma^{QGP})$

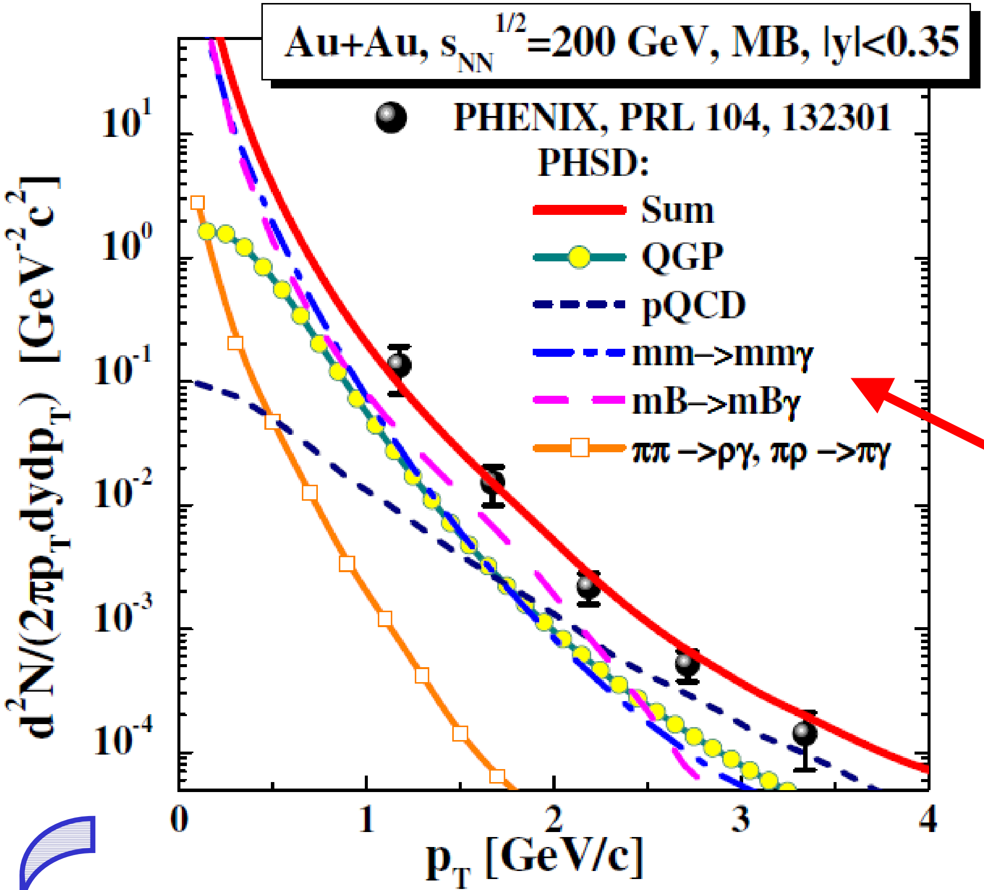
- **NEW** (QM'2014): **PHENIX, ALICE experiments** - **large photon v_3 !**

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

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

- Direct photon spectrum (min. bias)

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



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

PHSD:

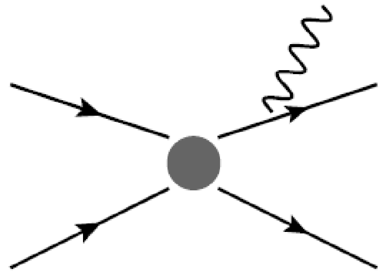
- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

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

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

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

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



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

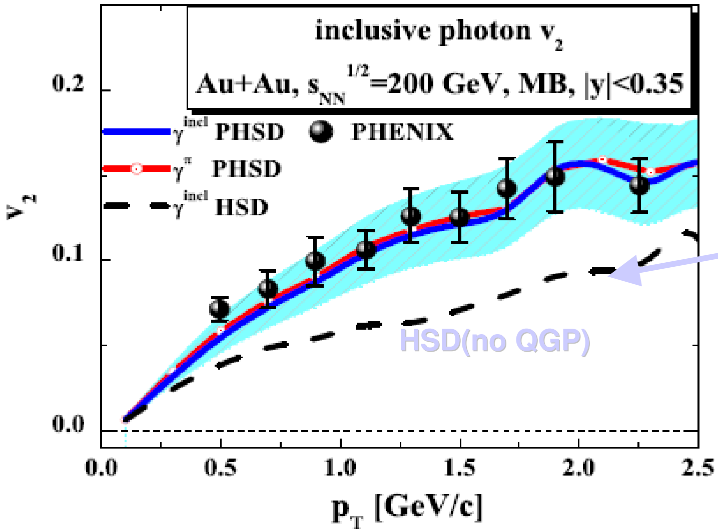
Measured Teff > ‚true' T ➔ ‚blue shift' due to the radial flow!

Cf. Hydro: Shen et al., PRC89 (2014) 044910

Are the direct photons a barometer of the QGP?

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

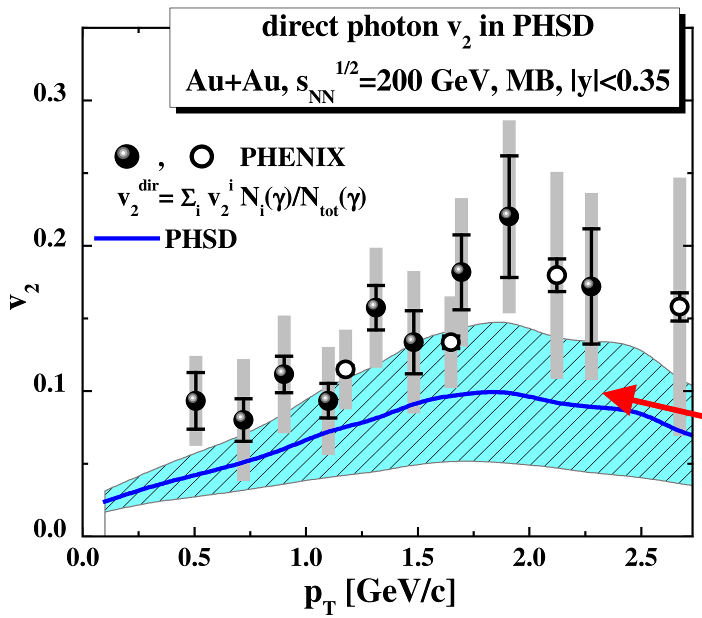
❑ Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources?**



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - **inclusive photons** mainly come from π^0 decays

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

➔ The **QGP causes the strong elliptic flow of photons indirectly,** by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

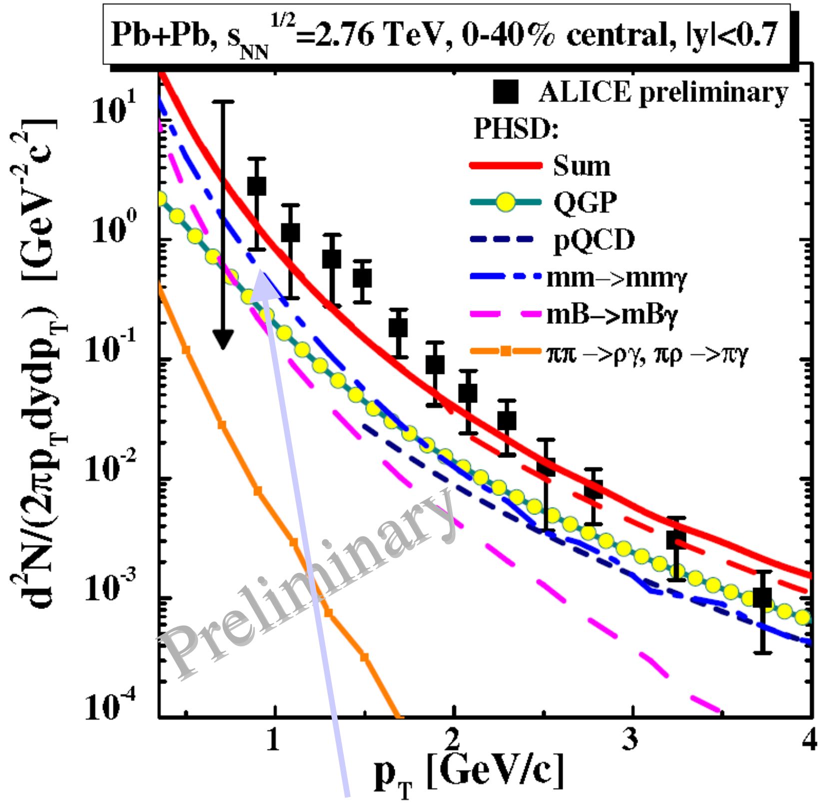
2) $v_2(\gamma^{dir})$ of **direct photons** in PHSD underestimates the PHENIX data :

$v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield ➔ lowering flow

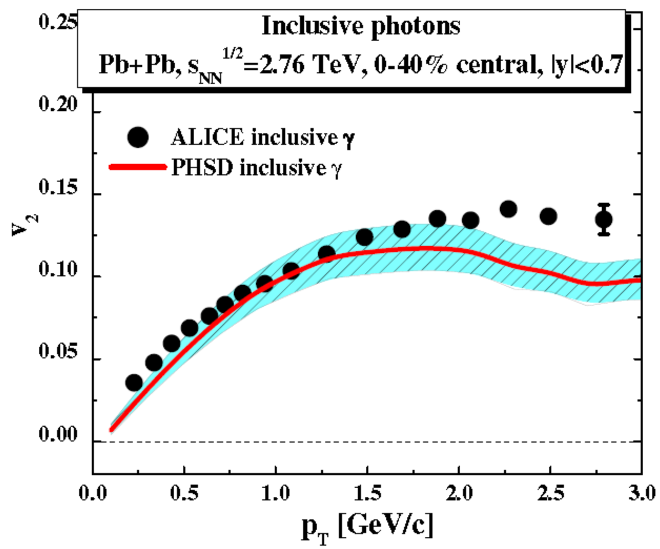
➔**PHSD:** $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung !**

Photons from PHSD at LHC

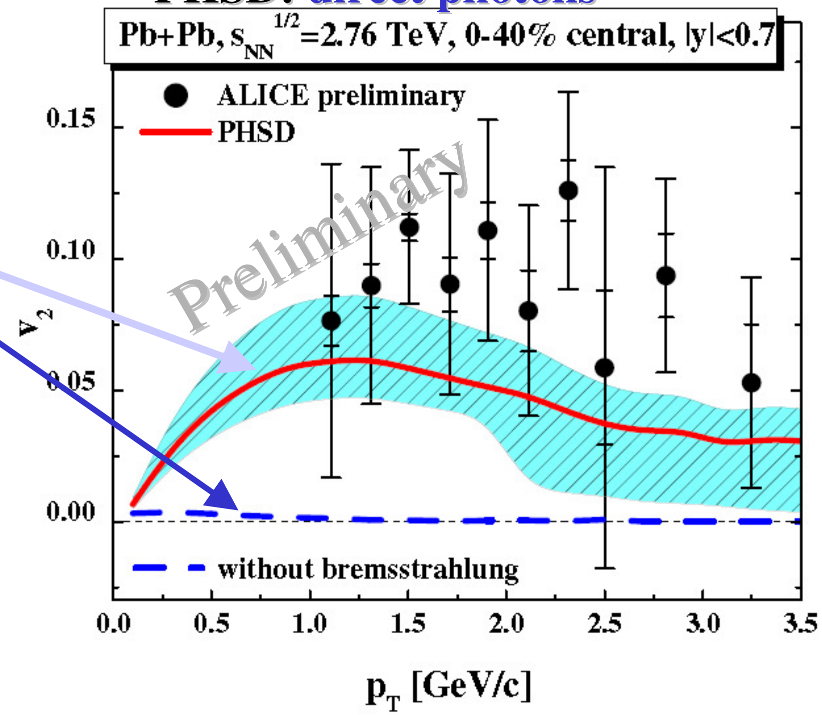
PHSD- preliminary: Olena Linnyk



PHSD: v_2 of inclusive photons



PHSD: direct photons



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

→ LHC (similar to RHIC): hadronic photons dominate spectra and v_2

Messages from the photon study

- sizeable contribution from hadronic sources - at RHIC and LHC hadronic photons dominate spectra and v_2

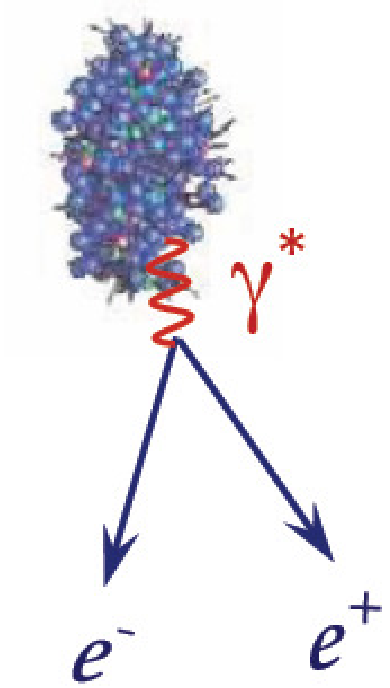
- meson-meson (mm) and meson-Baryon (mB) bremsstrahlung are important sources of direct photons

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

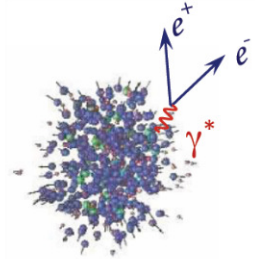
- The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions

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

Dileptons



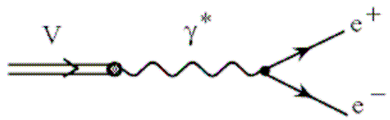
Dilepton sources



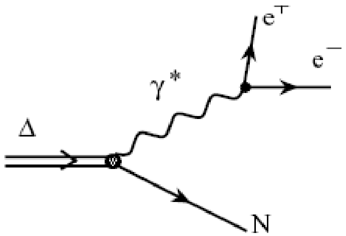
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

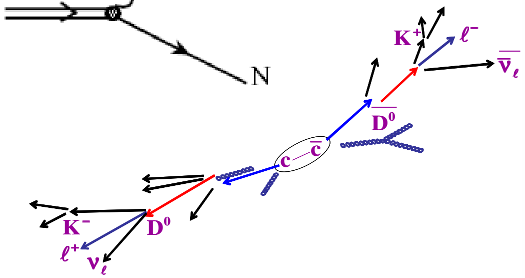
- **direct decay of vector mesons (ρ,ω,φ,J/Ψ,Ψ')**

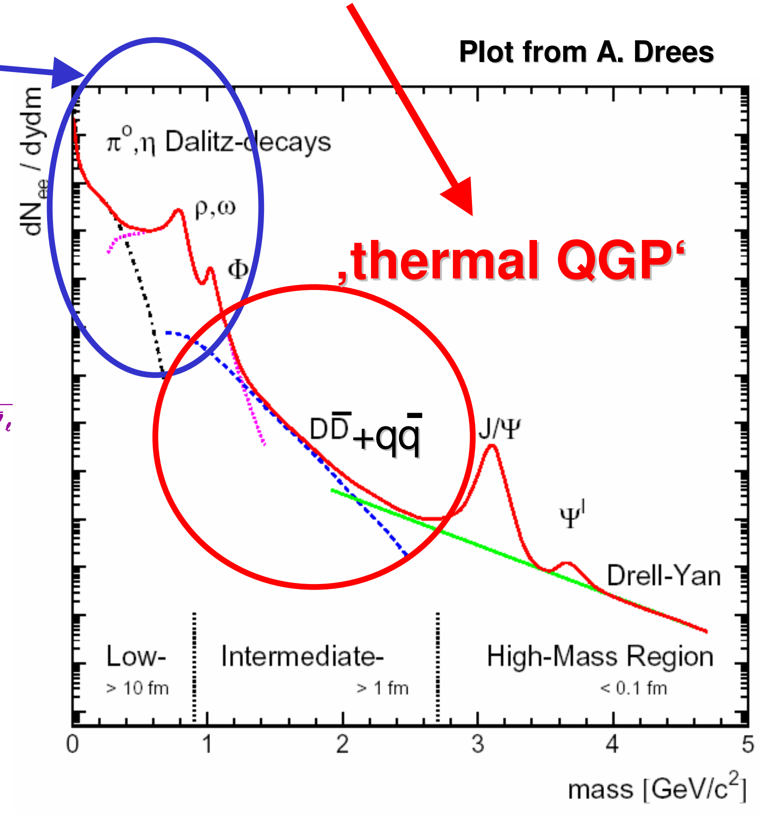


- **Dalitz decay of mesons and baryons (π^0,η, Δ,...)**



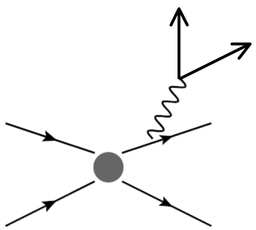
- **correlated D+Dbar pairs**





- **radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - '4π'**

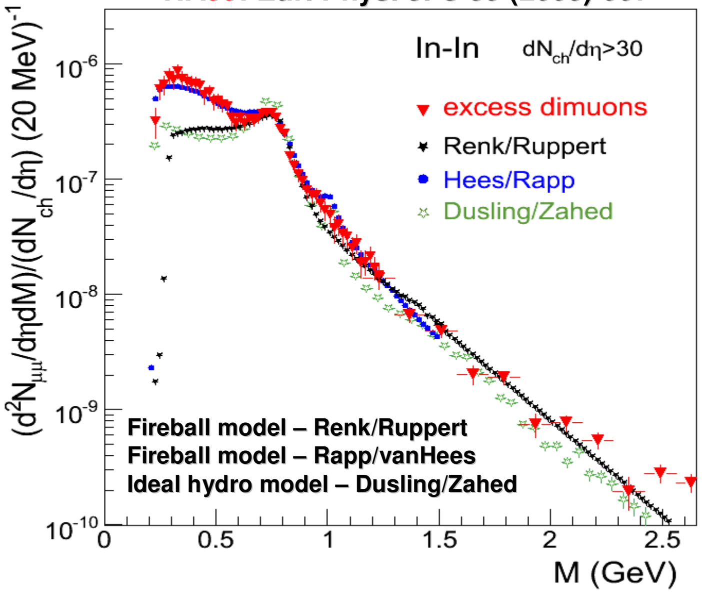
- **hadronic bremsstrahlung**



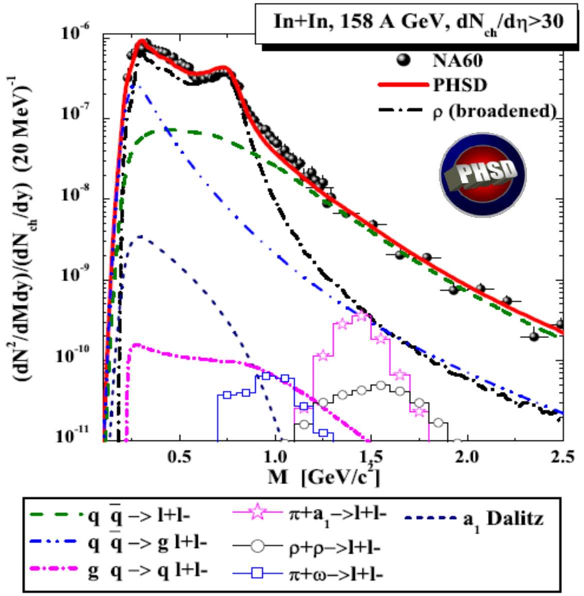
Lessons from SPS: NA60

❑ Dilepton invariant mass spectra:

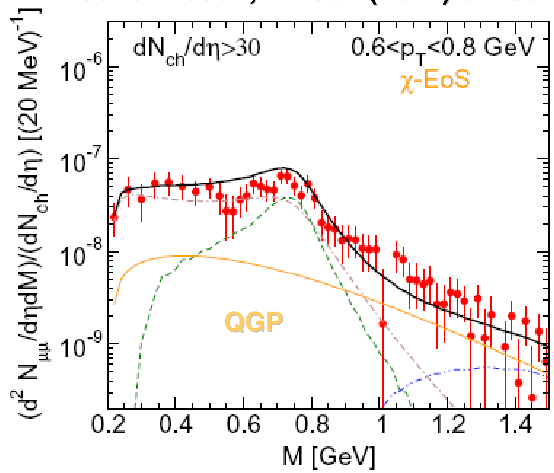
NA60: Eur. Phys. J. C 59 (2009) 607



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

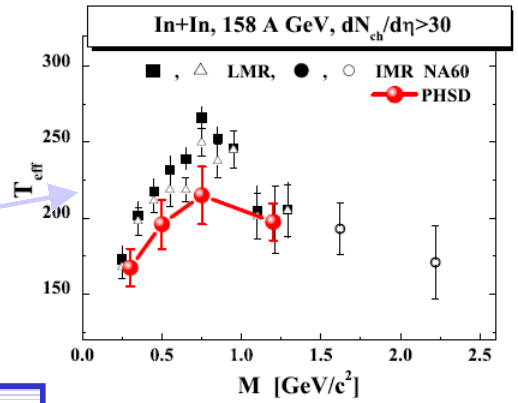


Hybrid-UrQMD:
Santini et al., PRC84 (2011) 014901



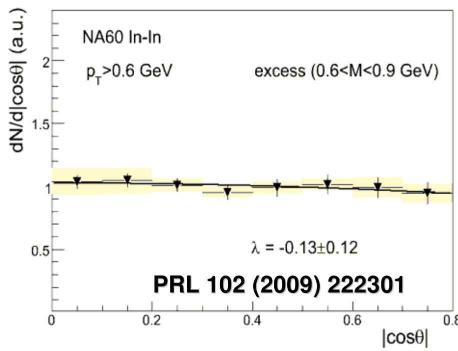
❑ Inverse slope parameter T_{eff}:

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

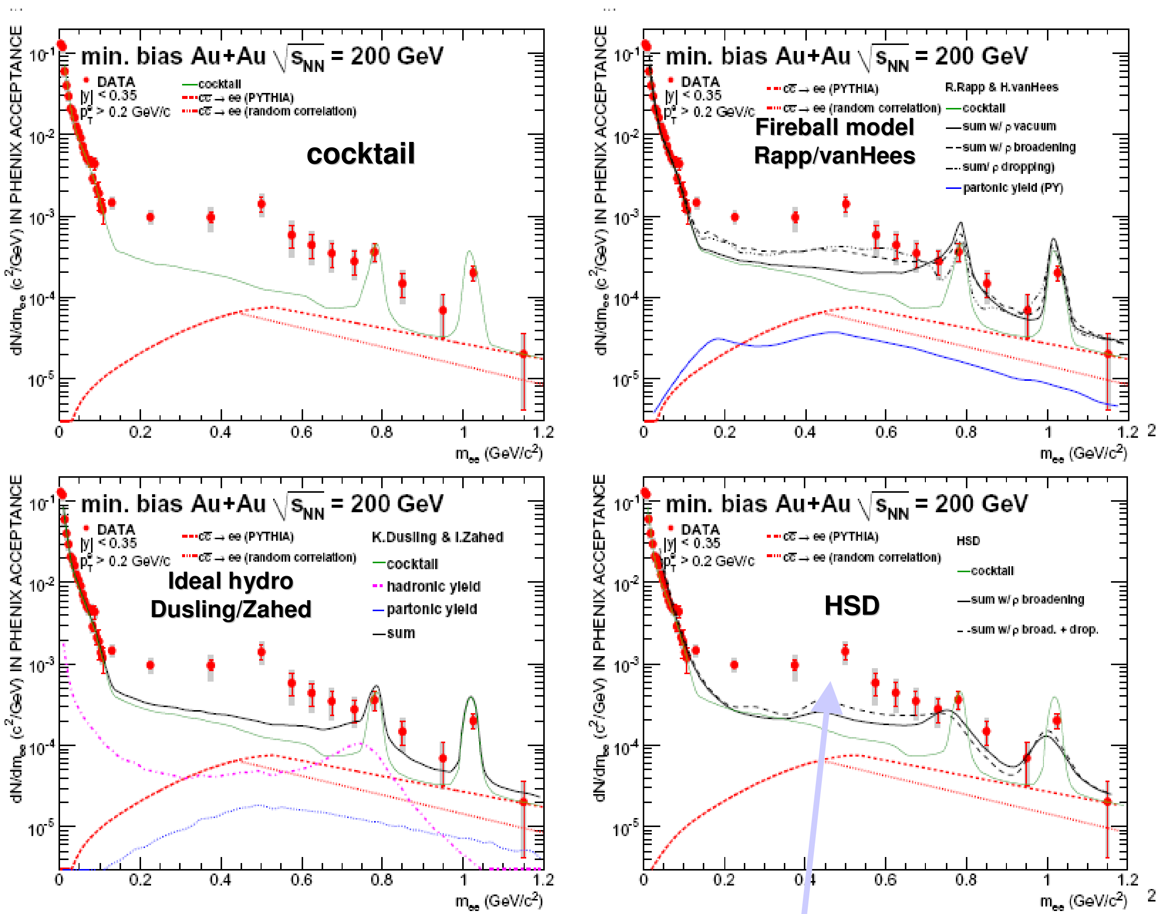


Message from SPS: (based on NA60 and CERES data)

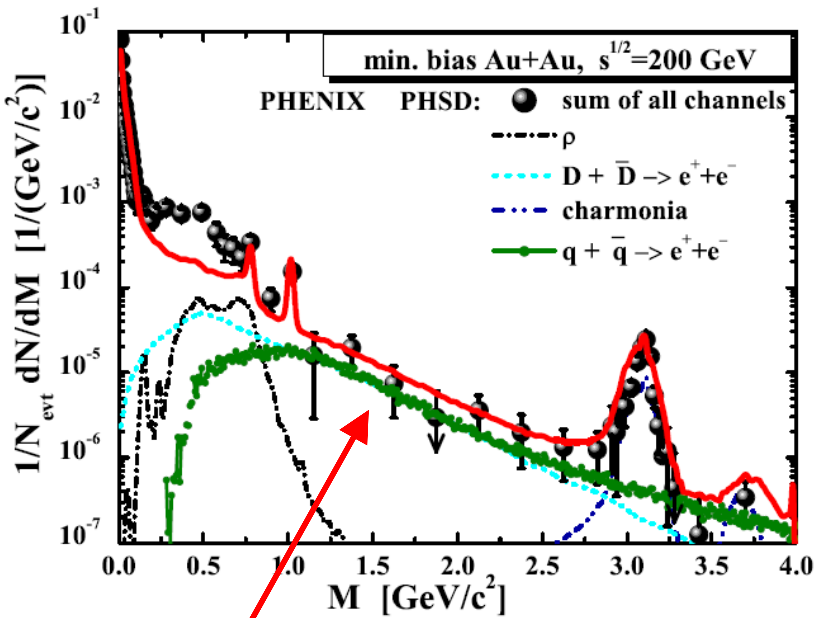
1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons



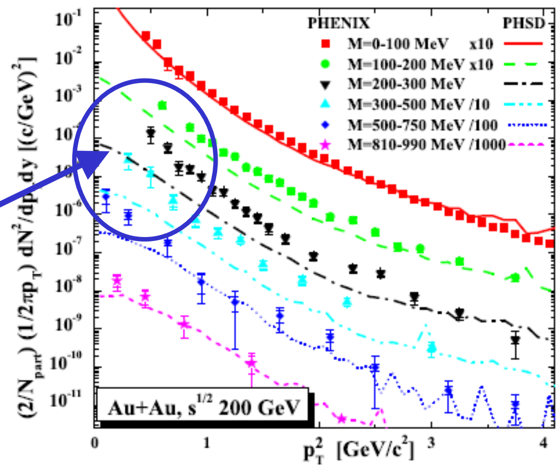
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



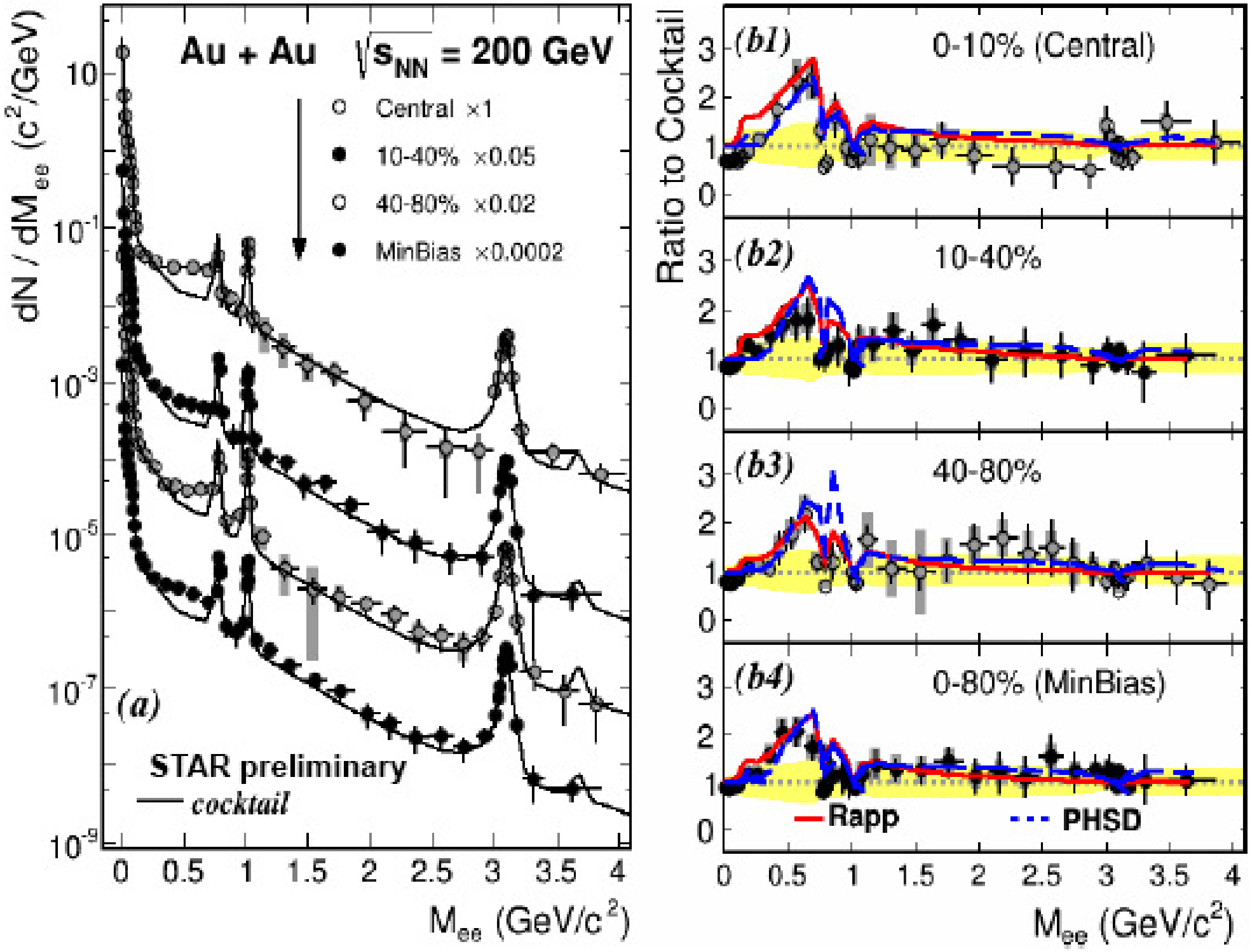
Message:

- **Models** provide a **good description of pp data** and **peripheral Au+Au** data, however, **fail in describing the excess for central collisions** even with **in-medium scenarios** for the vector meson spectral function
- The **'missing source'(?)** is located at **low p_T**
- **Intermediate mass spectra – dominant QGP contribution**

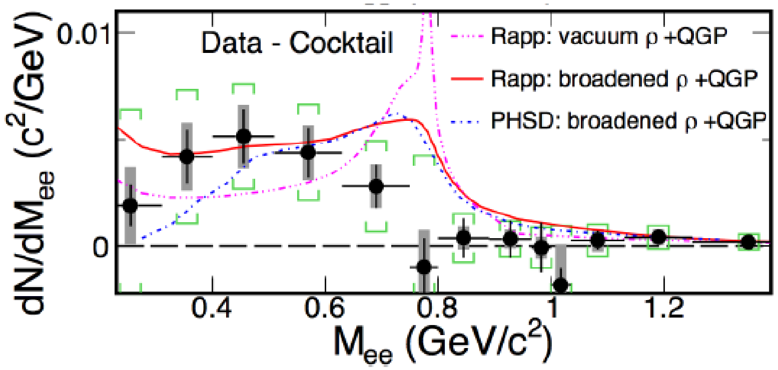
Dileptons at RHIC: STAR data vs model predictions

(STAR: arXiv:1407.6788)

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models (predictions):

- **Fireball model – R. Rapp**
- **PHSD**

Low masses:

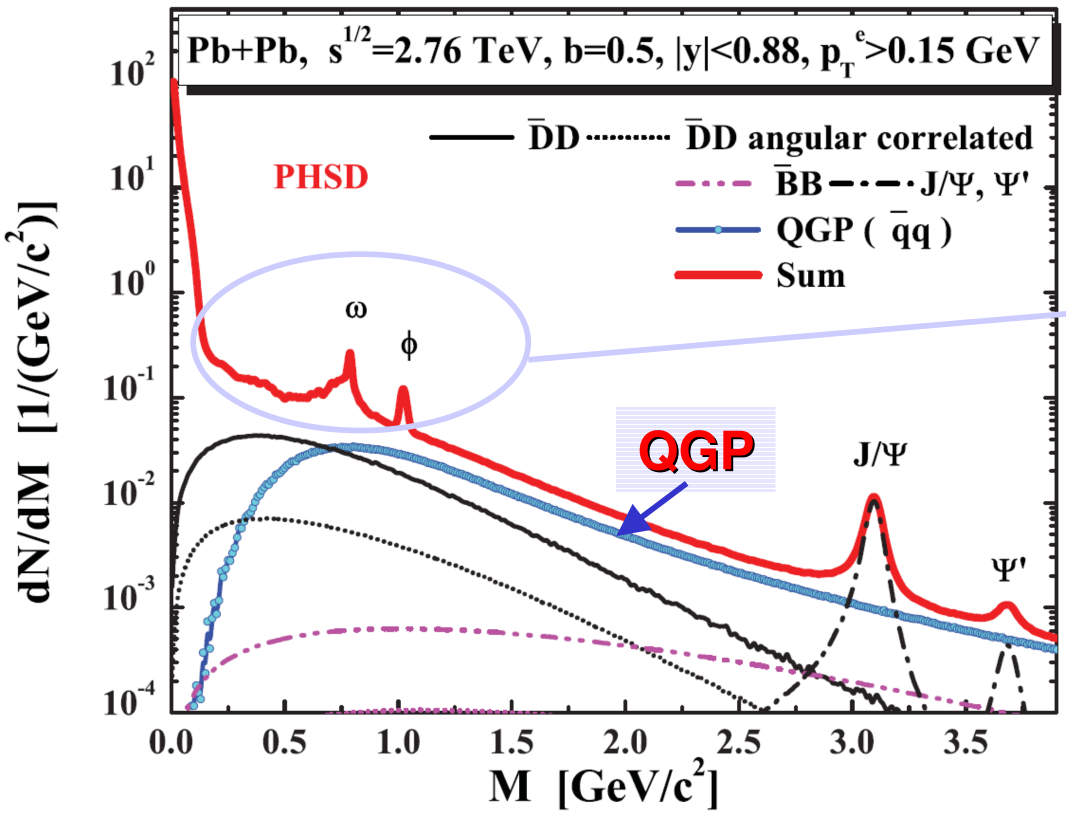
collisional broadening of ρ

Intermediate masses:

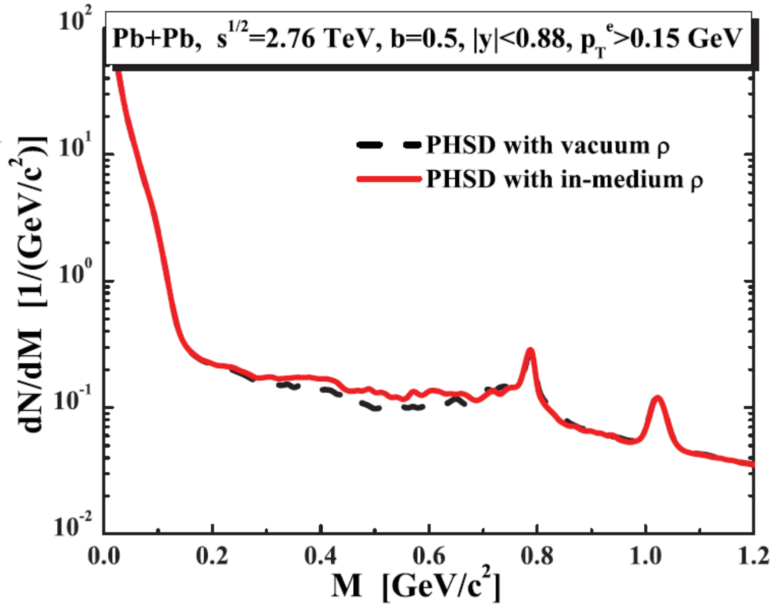
QGP dominant

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

Dileptons at LHC



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



Message:

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

Messages from dilepton data

- **Low dilepton masses:**

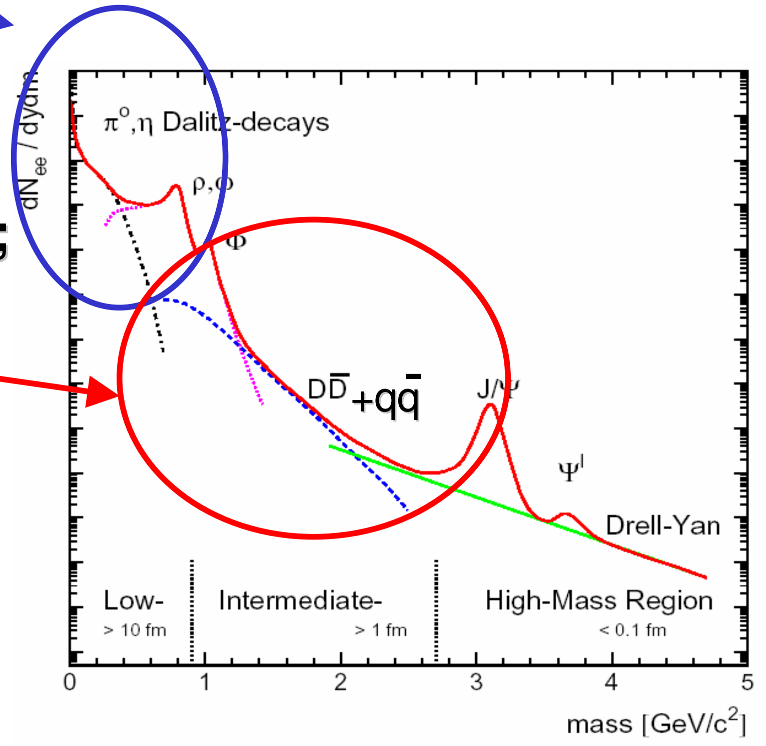
  - **Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally**

  - **In-medium effects can be observed at all energies from SIS to LHC**

- **Intermediate dilepton masses:**

  - **The QGP (qbar-q) dominates for M>1.2 GeV**

  - **Fraction of QGP grows with increasing energy; at the LHC it is dominant**



Outlook:
*** experimental energy scan**
*** experimental measurements of dilepton's higher flow harmonics v_n**

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Thank you !