The QGP dynamics in relativistic heavy-ion collisions

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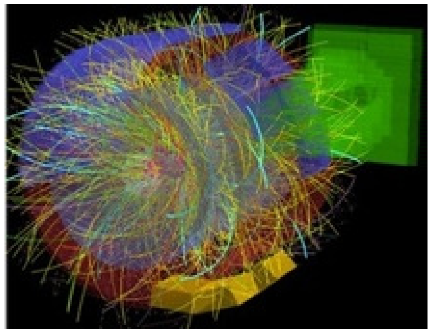
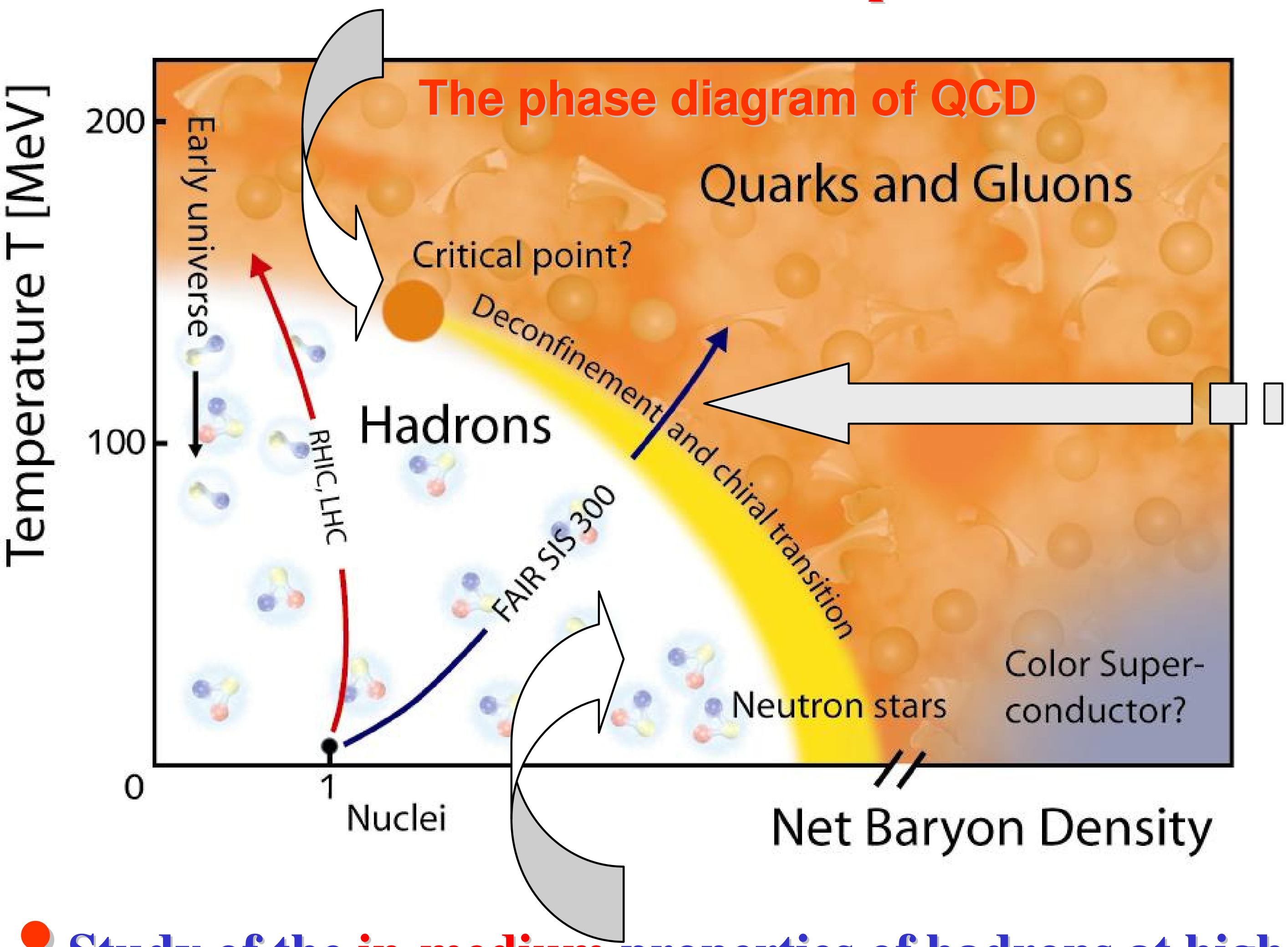


The holy grail:

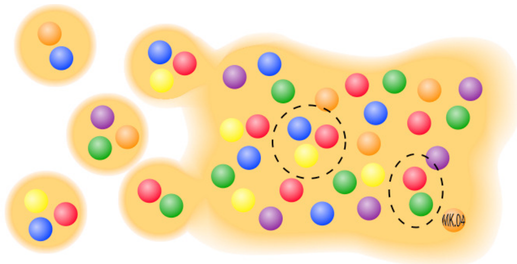
- Search for the critical point



- 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
- Study of the partonic medium beyond the phase boundary

From hadrons to partons



In order to study the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

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

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

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

The Dynamical QuasiParticle Model (DQPM)

Basic idea: **Interacting quasiparticles**

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

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

Fit from A. Peshier, PRD 70 (2004) 034016

- **quarks**

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

width: $\gamma_q(T) = \frac{N_c^2 - 1}{2N_c} \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$

- **gluons:**

$M^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{1}{2}N_f\right) T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$ $\qquad N_c = 3, N_f=3$

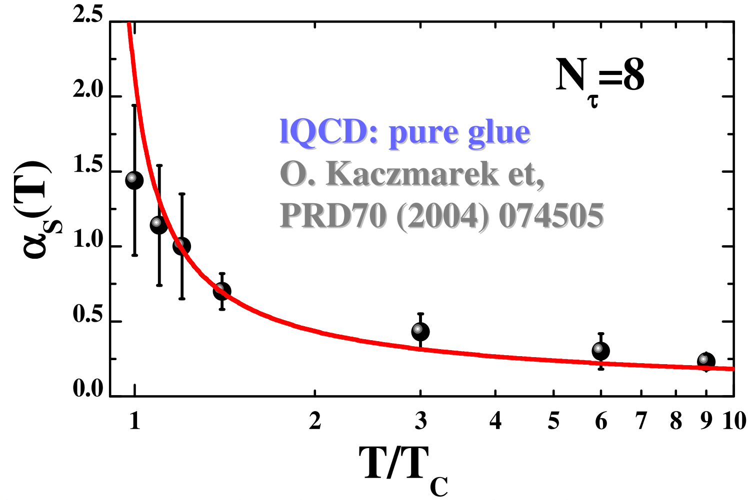
$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$

running coupling (pure glue): $\alpha_S(T) = g^2(T)/(4\pi)$

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

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)

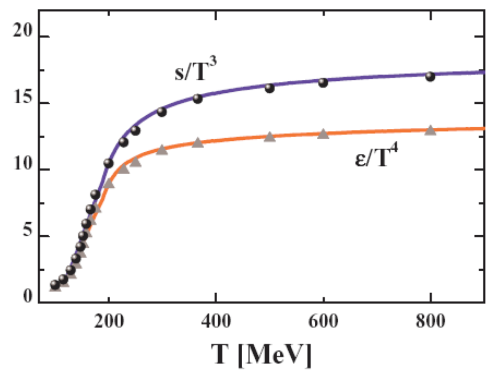
➢ **fit to lattice (lQCD) results** (e.g. entropy density)

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

The Dynamical QuasiParticle Model (DQPM)

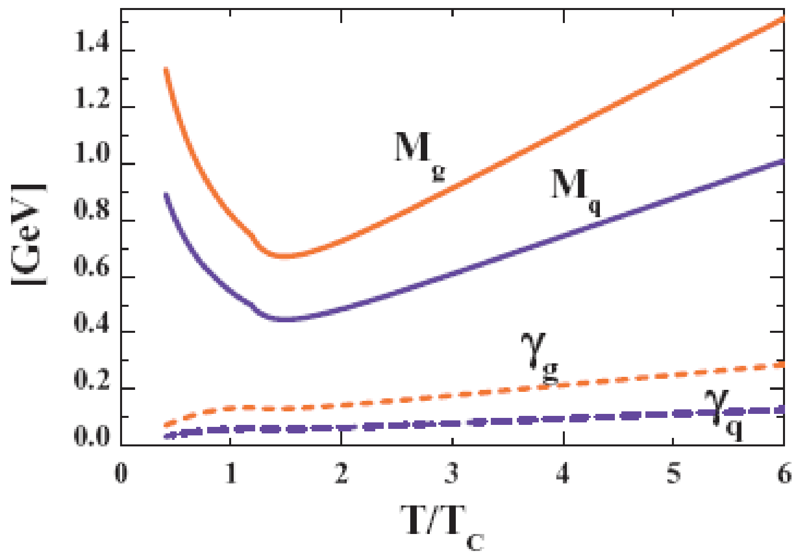
➢ fit to lattice (lQCD) results (e.g. entropy density)

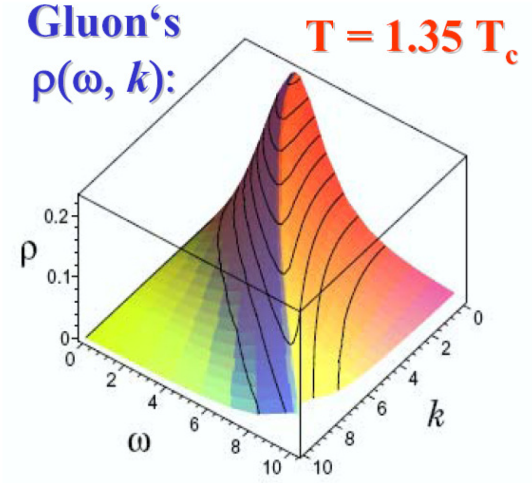
* fit to BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073



➔ Quasiparticle properties:

- large width and mass for gluons and quarks



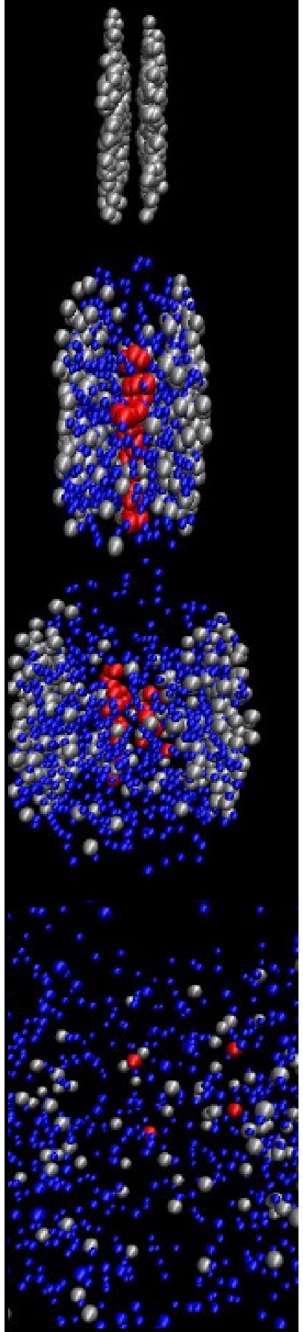


Plot from Peshier, PRD 70 (2004) 034016

- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks 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)

PHSD - basic concept



Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) - approximation to QCD

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

- ❑ **elastic and inelastic parton-parton interactions:**
using the effective cross sections from the DQPM
- ✓ **q + qbar (flavor neutral) <=> gluon (colored)**
- ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
- ✓ **q + qbar (color neutral) <=> hadron resonances**
- ❑ **self-generated mean-field potential for quarks and gluons !**

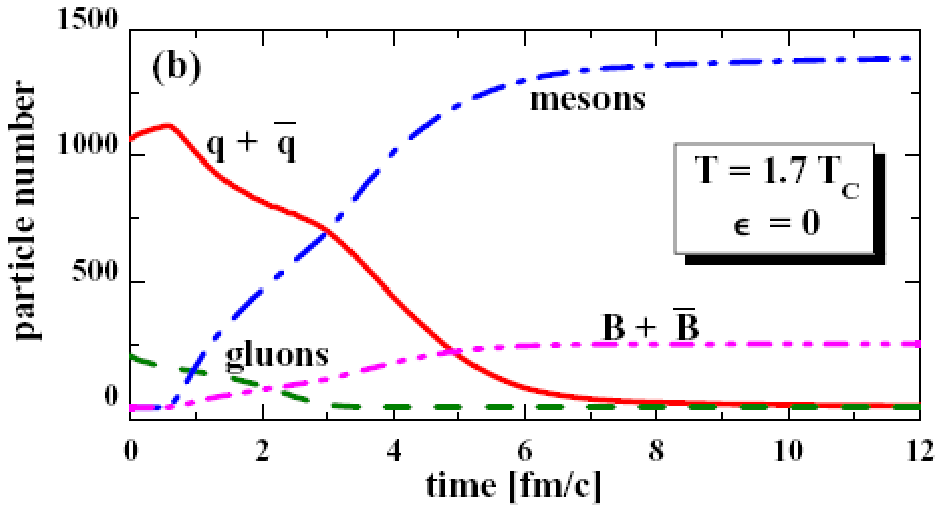
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states' for hadrons)

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

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

PHSD: hadronization of a partonic fireball

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at μ_q=0



Consequences:

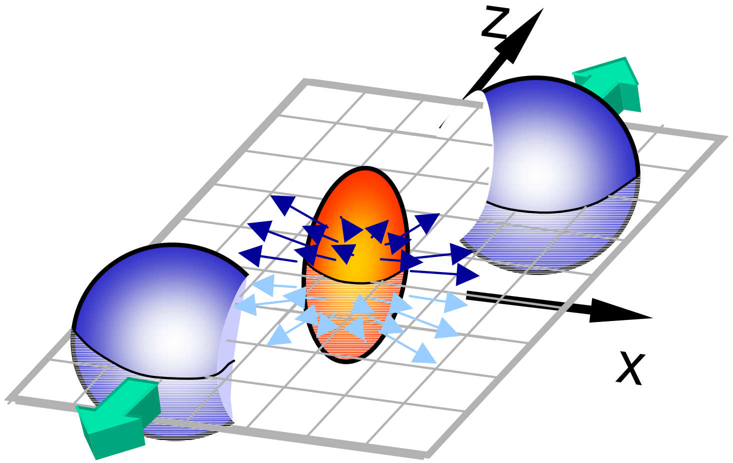
➢ Hadronization: q+q_{bar} or 3q or 3q_{bar} fuse to color neutral hadrons (or strings) which subsequently decay into hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!

➢ Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!

➢ Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system

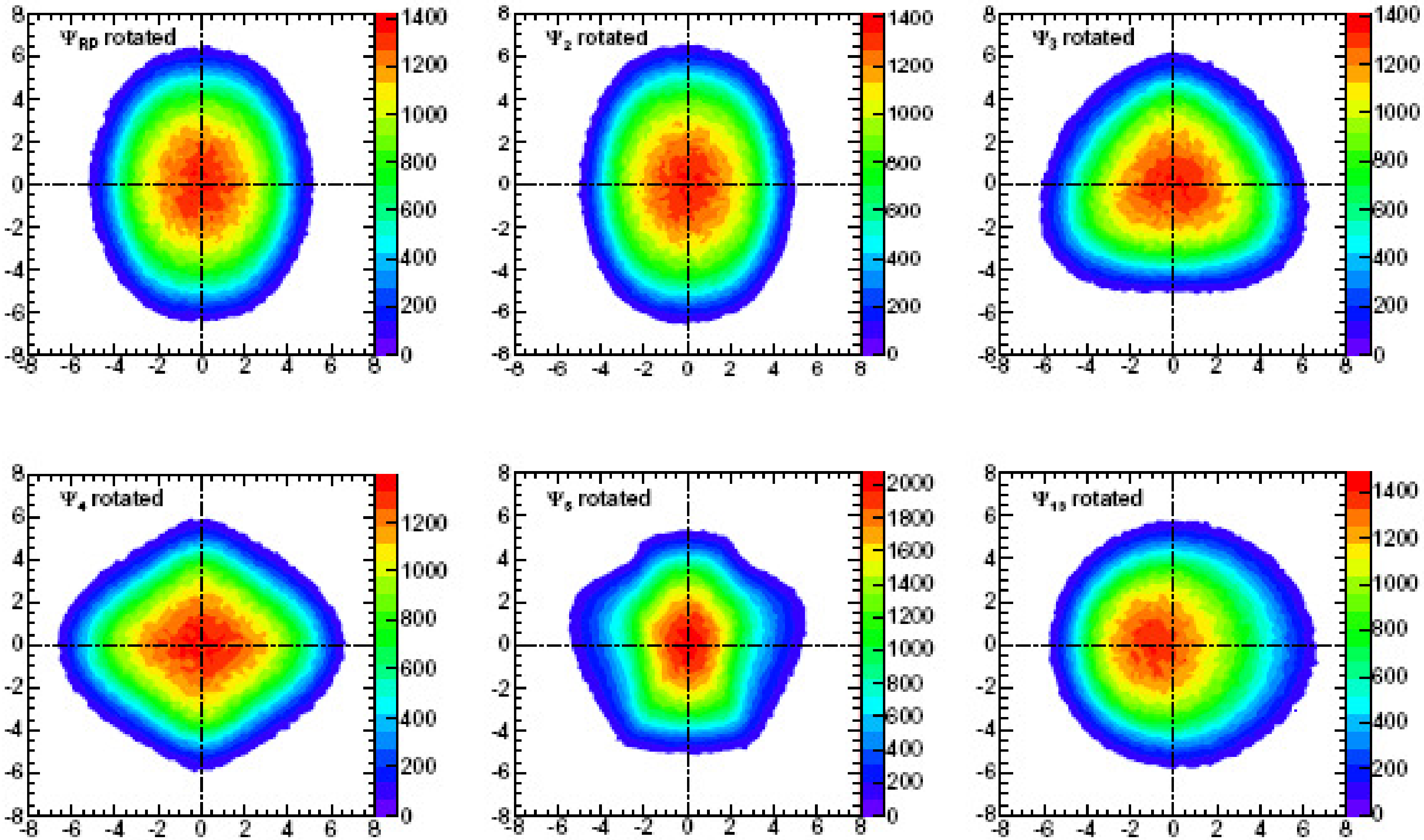
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

Collective flow: anisotropy coefficients (v_1, v_2, v_3, v_4) in A+A



Final angular distributions of hadrons

10k Au+Au collision events at b = 8 fm rotated to different event planes:

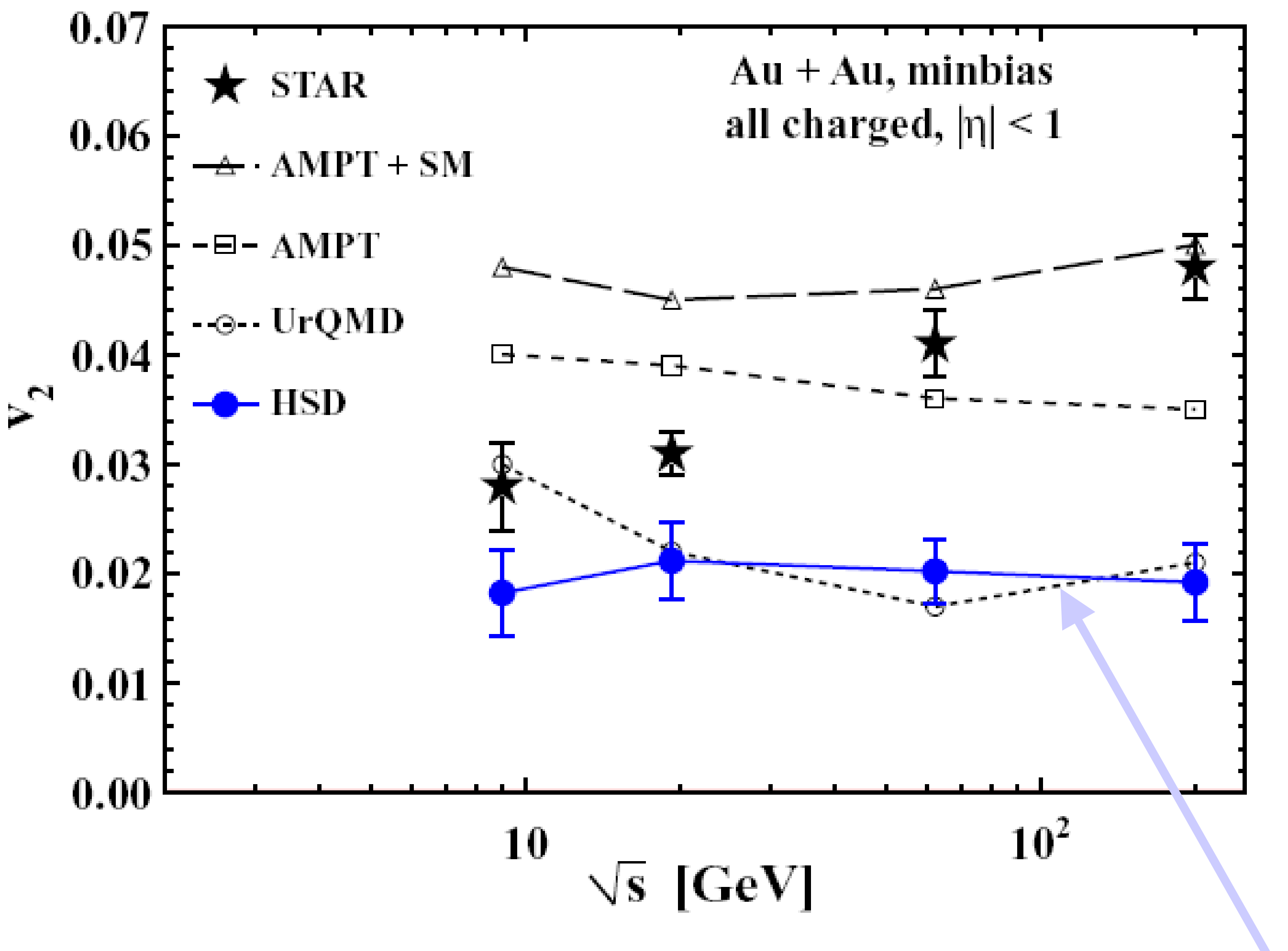


$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\psi - \Psi_n))\right)$$

show higher order harmonics v_n

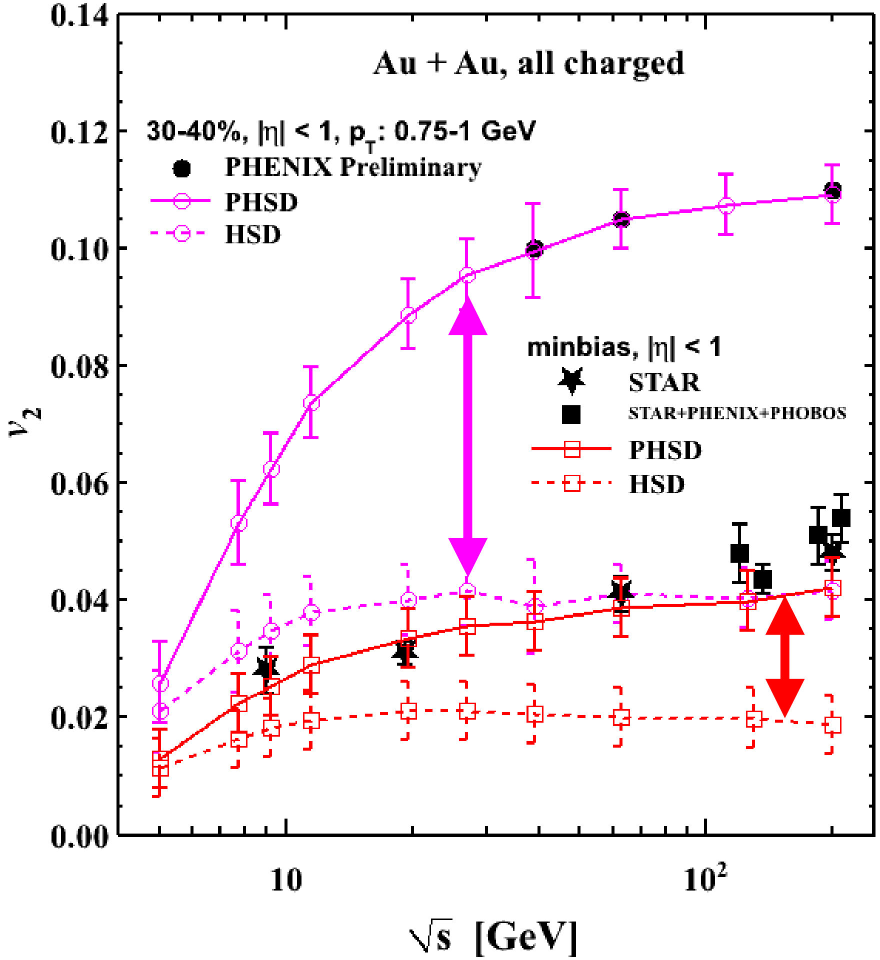
S. A. Voloshin, arXiv:1111.7241

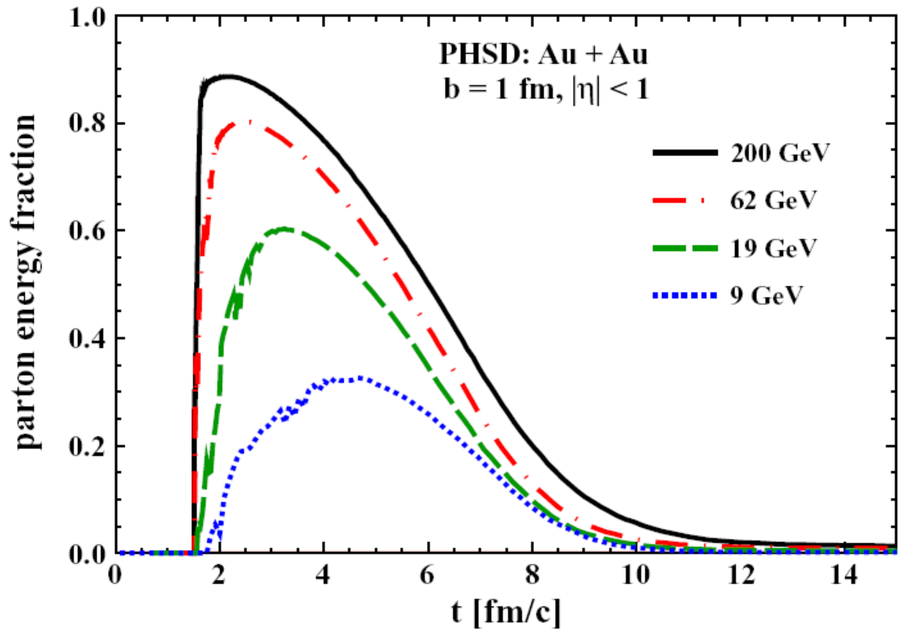
Excitation function of elliptic flow



Excitation function of elliptic flow is not described by hadron-string or purely partonic models !

Elliptic flow v_2 vs. collision energy for Au+Au

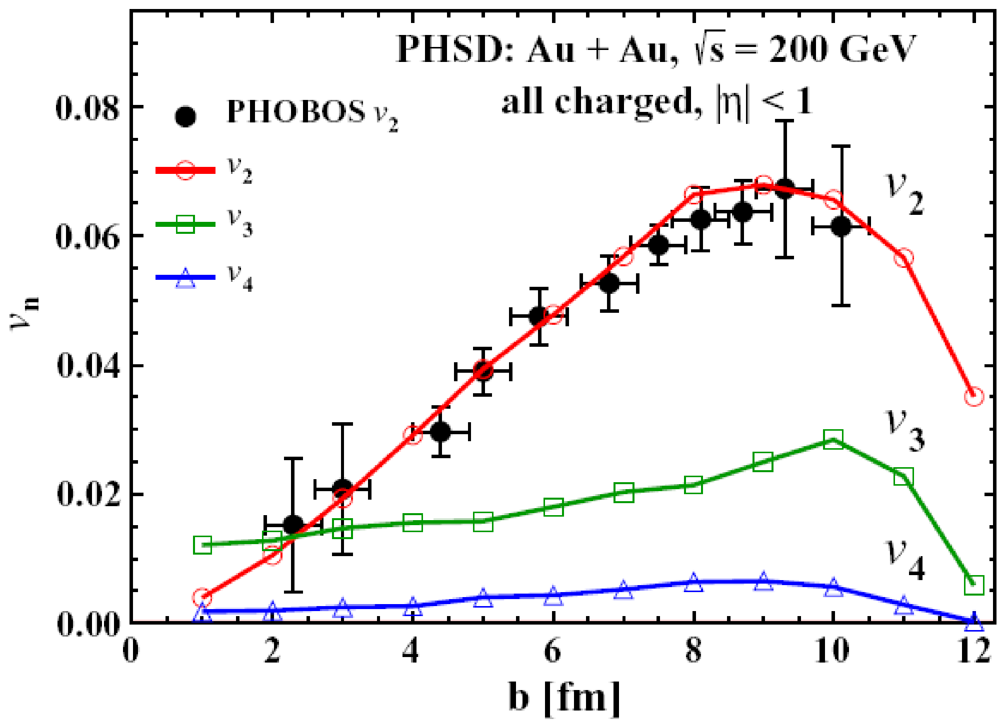


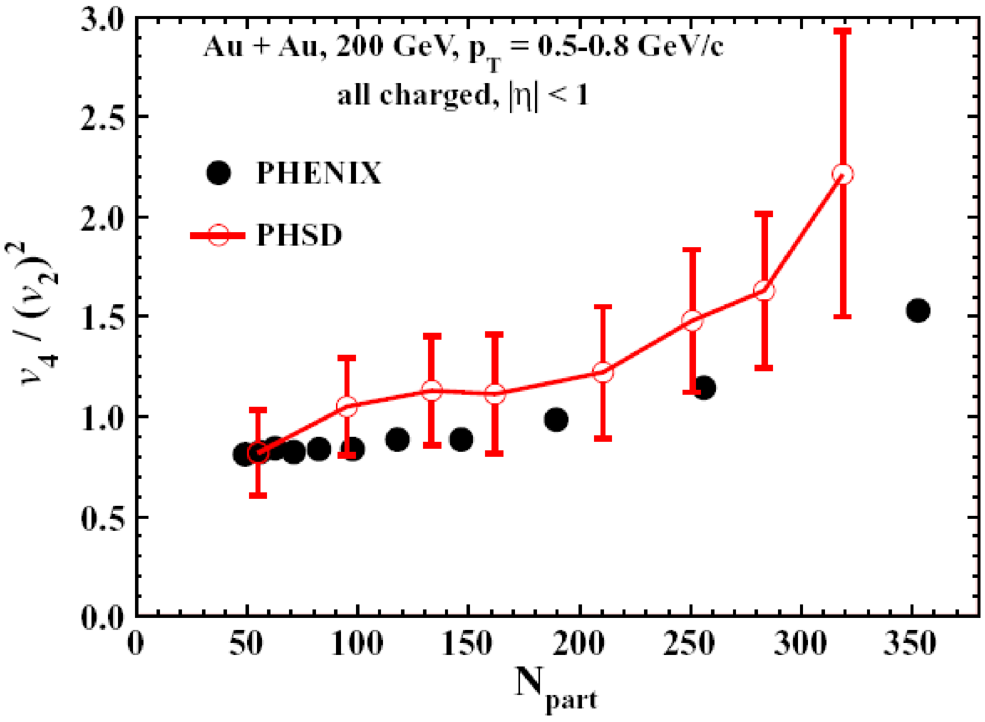


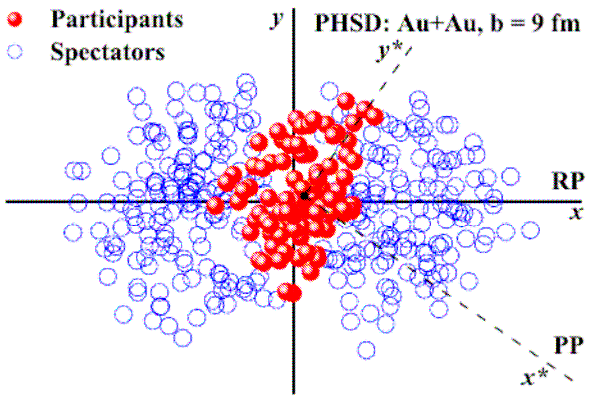
- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

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

Flow coefficients versus centrality at RHIC



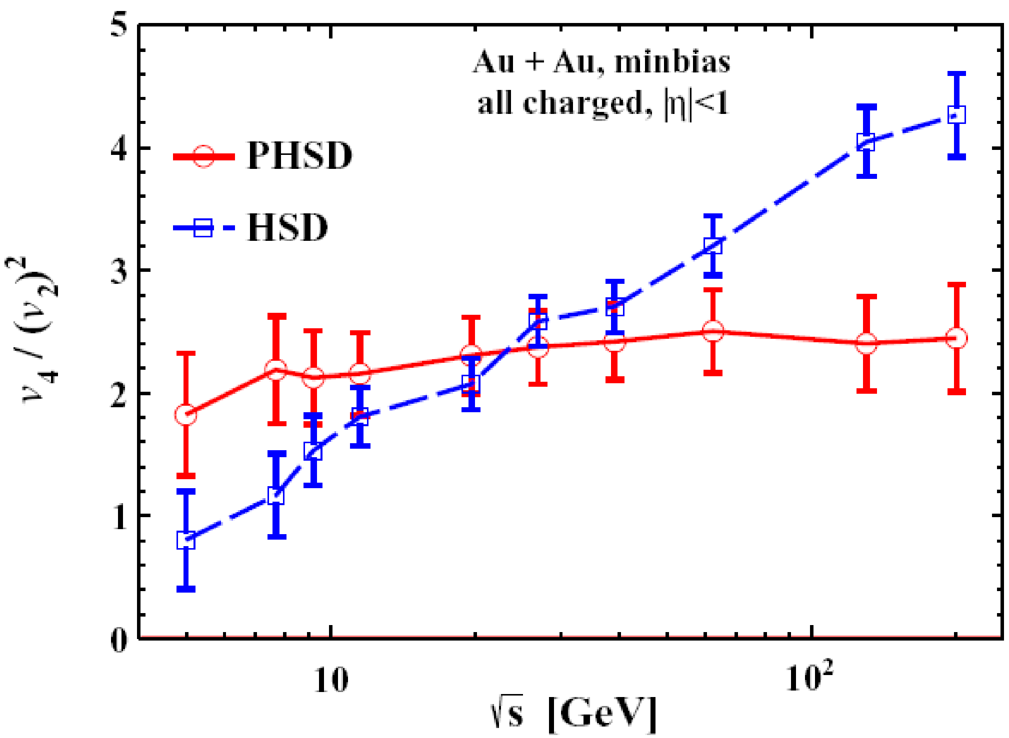


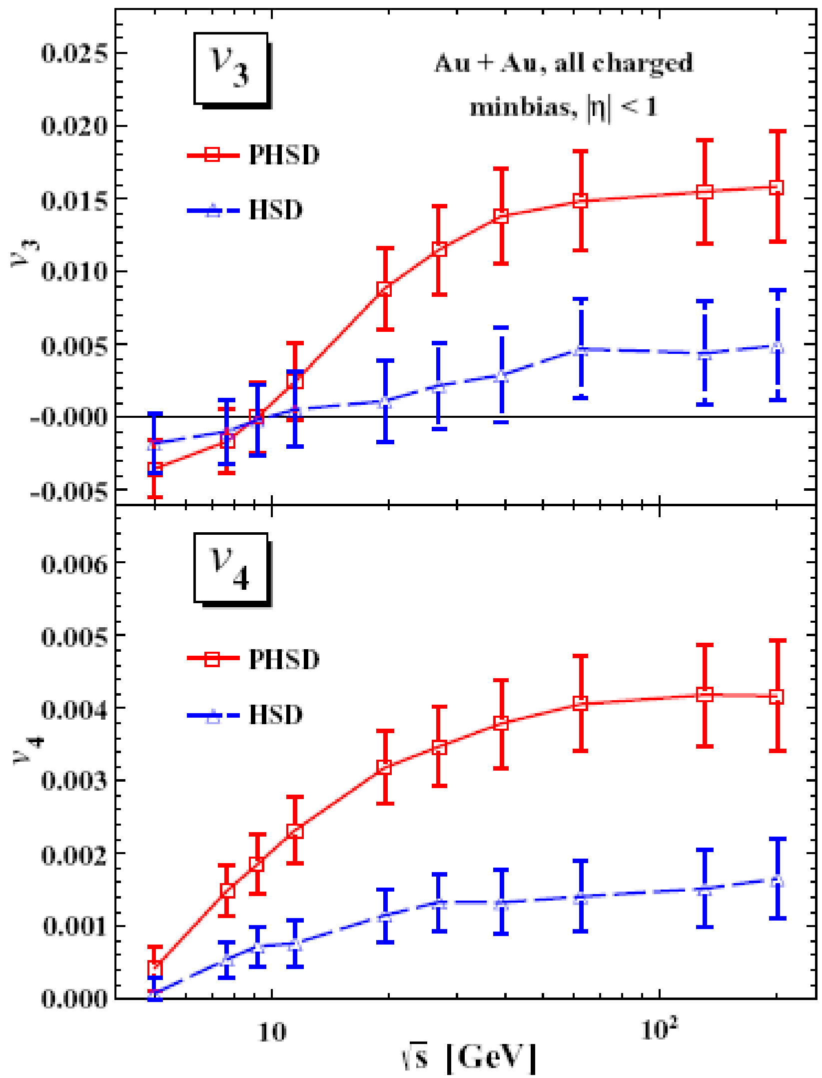


- increase of v_2 with impact parameter but flat v_3 and v_4

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

$v_4/(v_2)^2$, v_3, v_4 excitation functions at RHIC

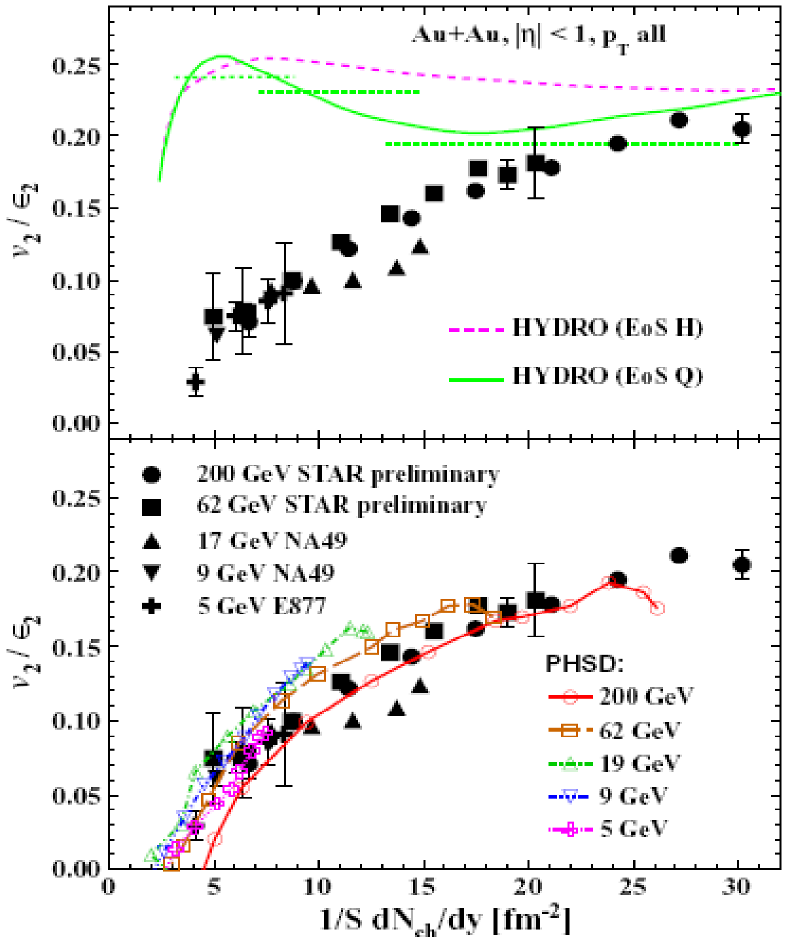


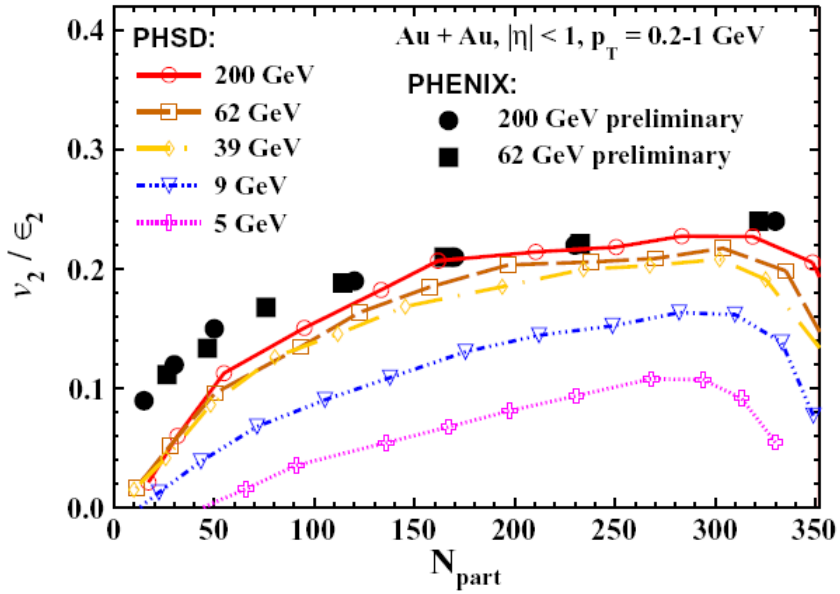


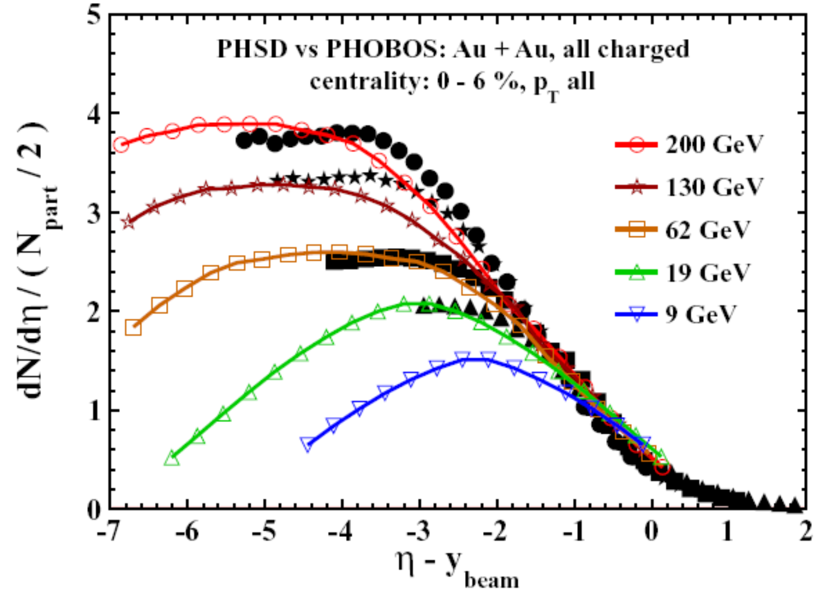
- v_3, v_4 from PHSD are systematically larger than those from HSD
- very low v_3 and v_4 at FAIR/NICA energies
- almost constant $v_4/(v_2)^2$ for PHSD

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

Scaling properties





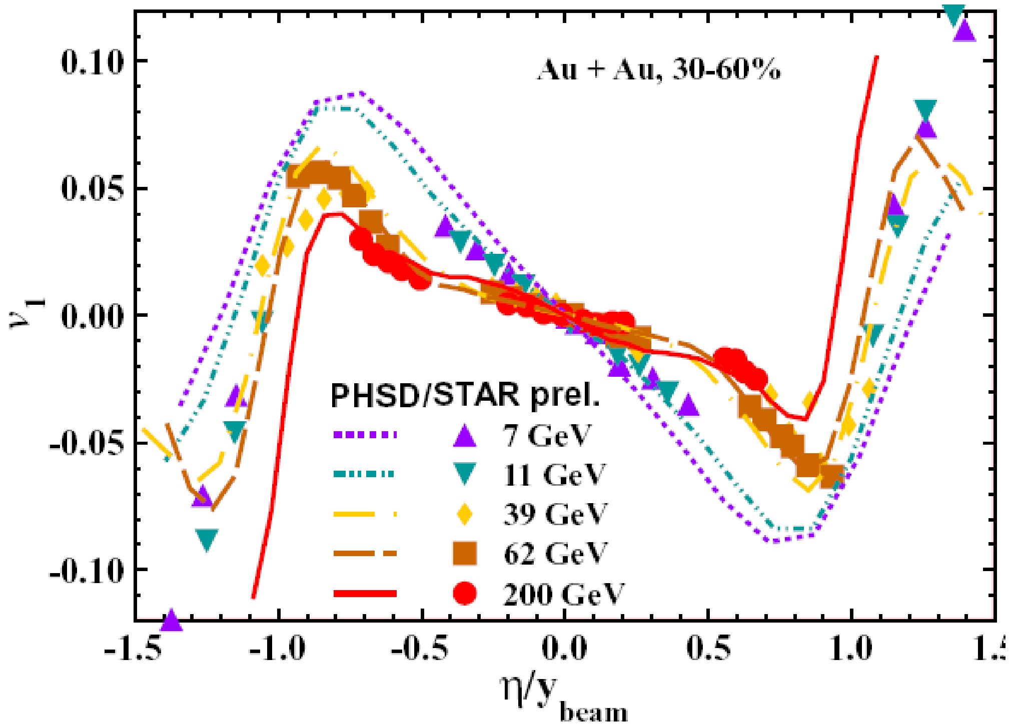


- **PHSD: v_2/ε vs. centrality follows an approximate scaling with energy in line with experimental data**

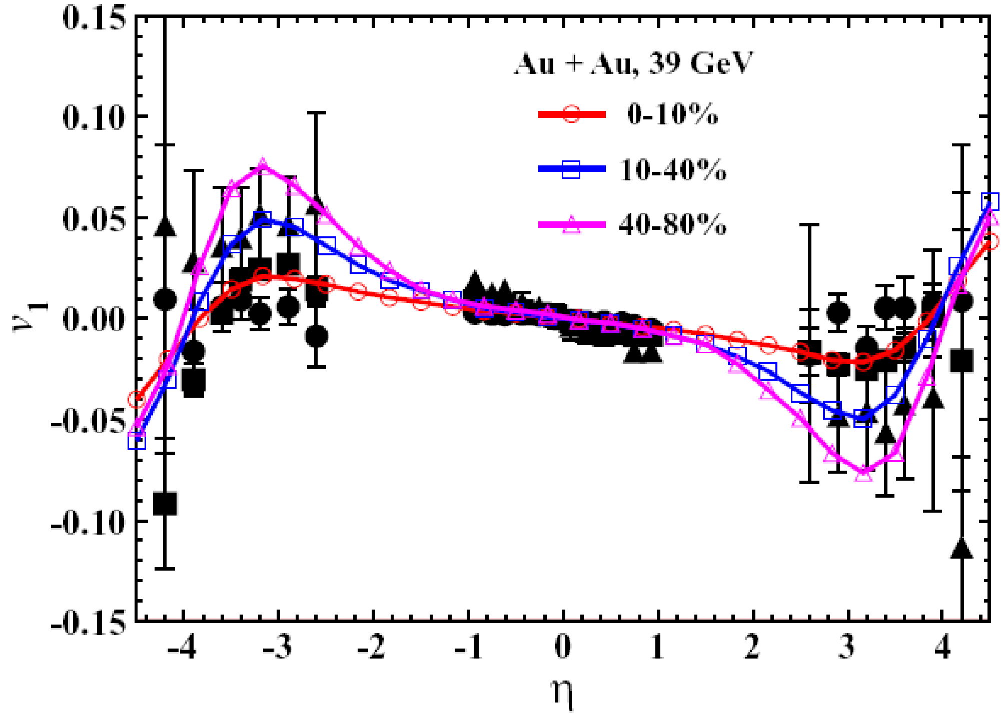
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

In-plane flow v_1 at RHIC

versus beam energy



versus centrality

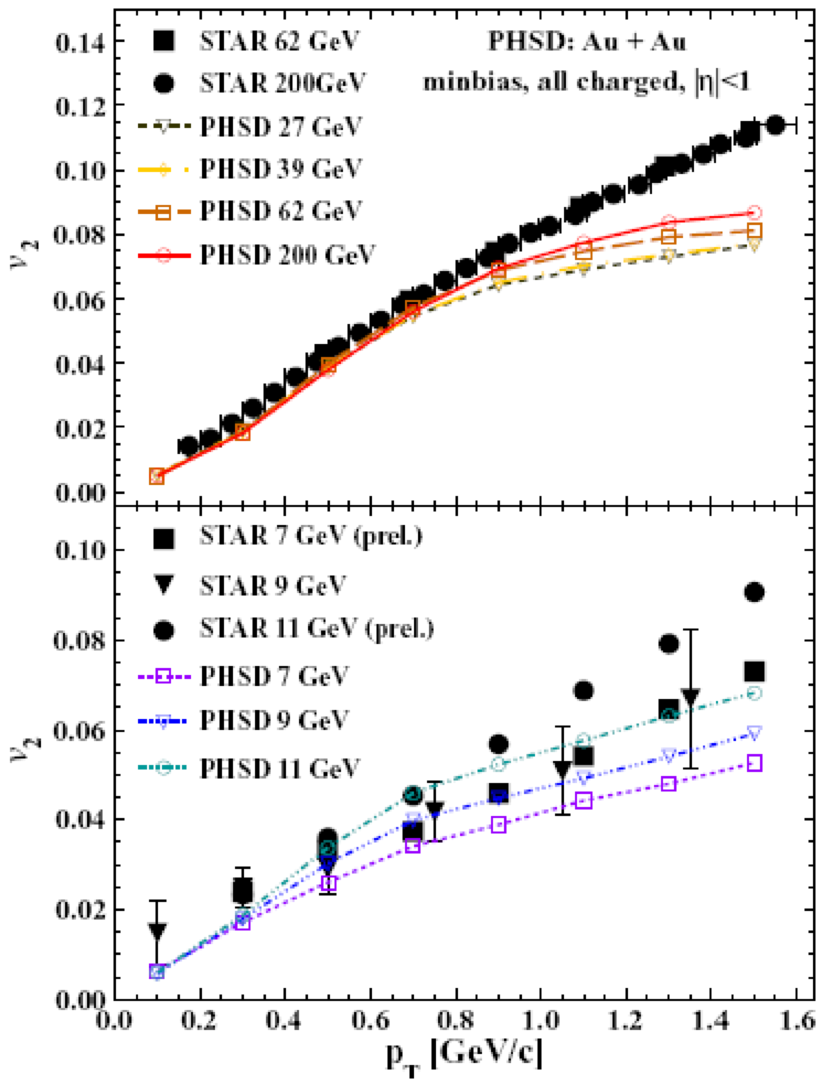


- **PHSD: v_1 vs. pseudo-rapidity follows an approximate scaling for high invariant energies $s^{1/2}$=39, 62, 200 GeV - in line with experimental data – whereas at low energies the scaling is violated!**

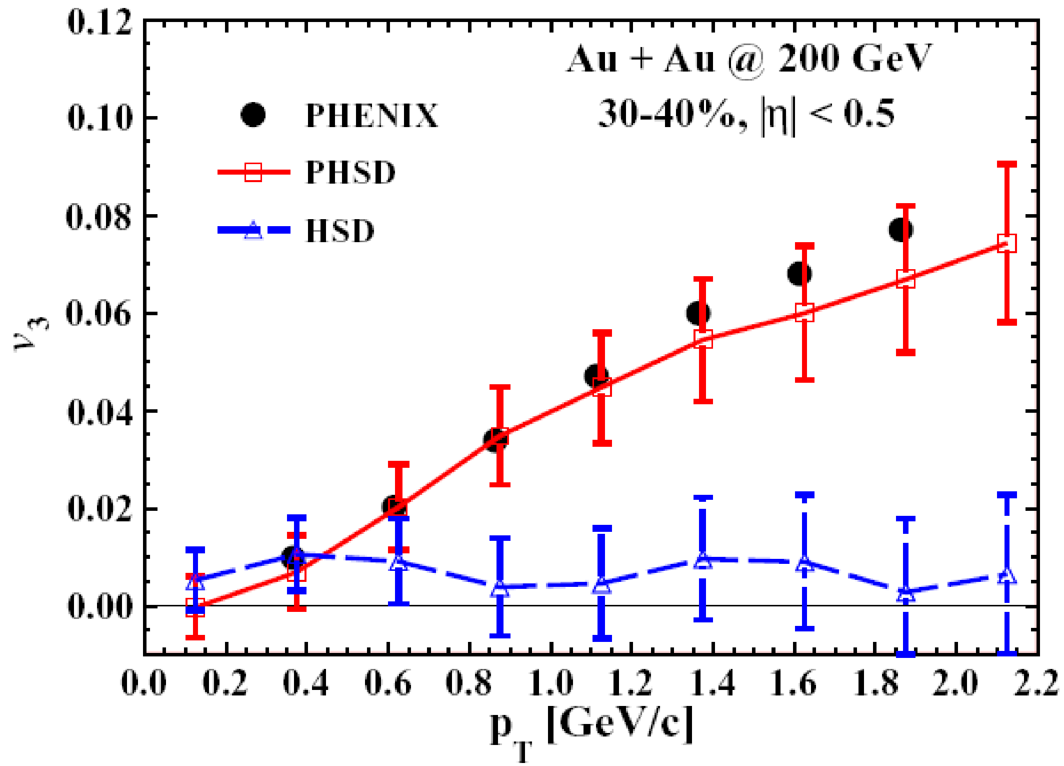
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

Transverse momentum dependence at RHIC

elliptic flow



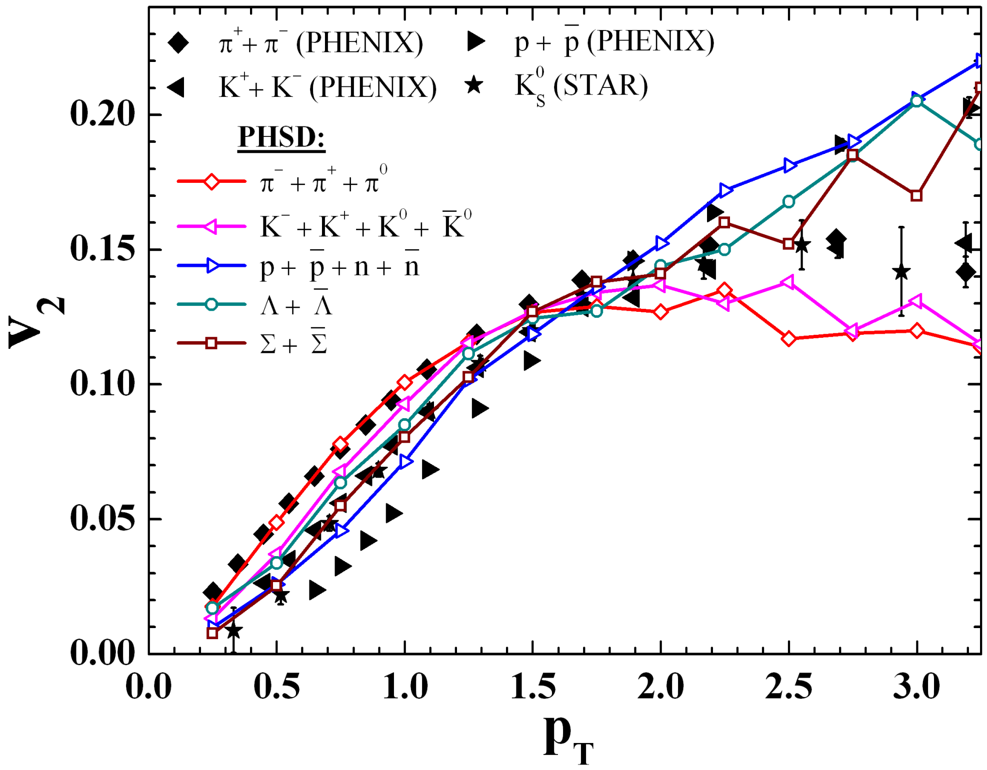
triangular flow

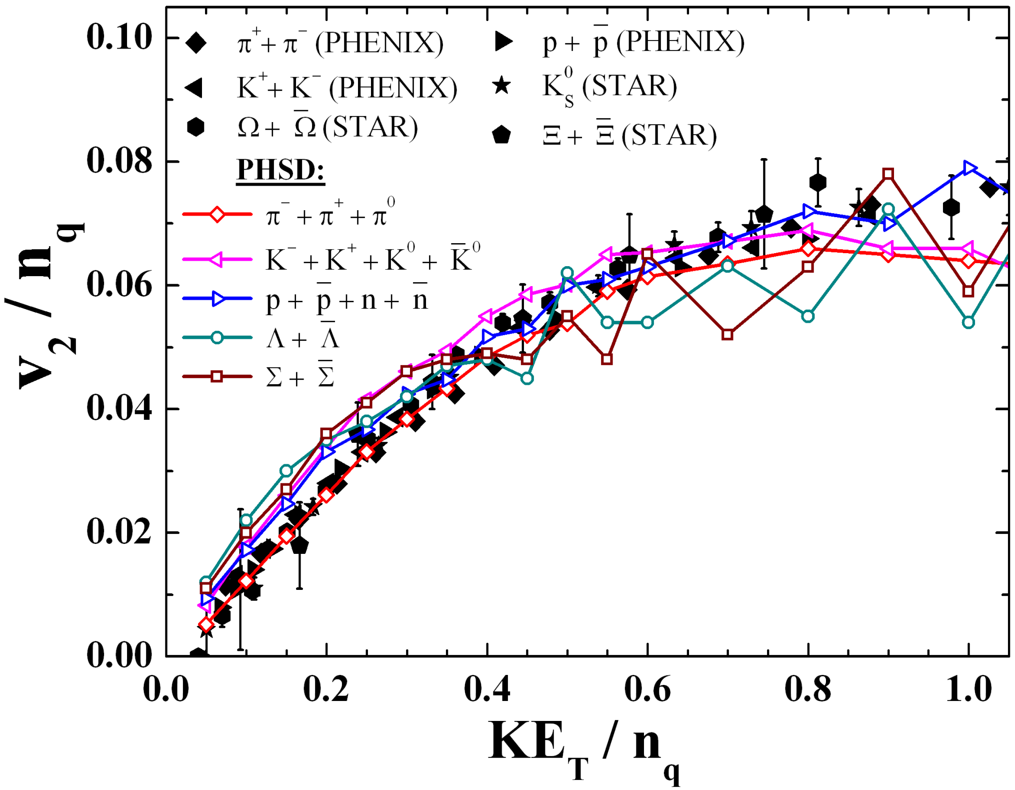


- v_2 vs. p_T follows an approximate scaling for high invariant energies $s^{1/2}$=27, 39, 62, 200 GeV
- v_3 : needs partonic degrees-of-freedom !

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

Elliptic flow scaling at RHIC

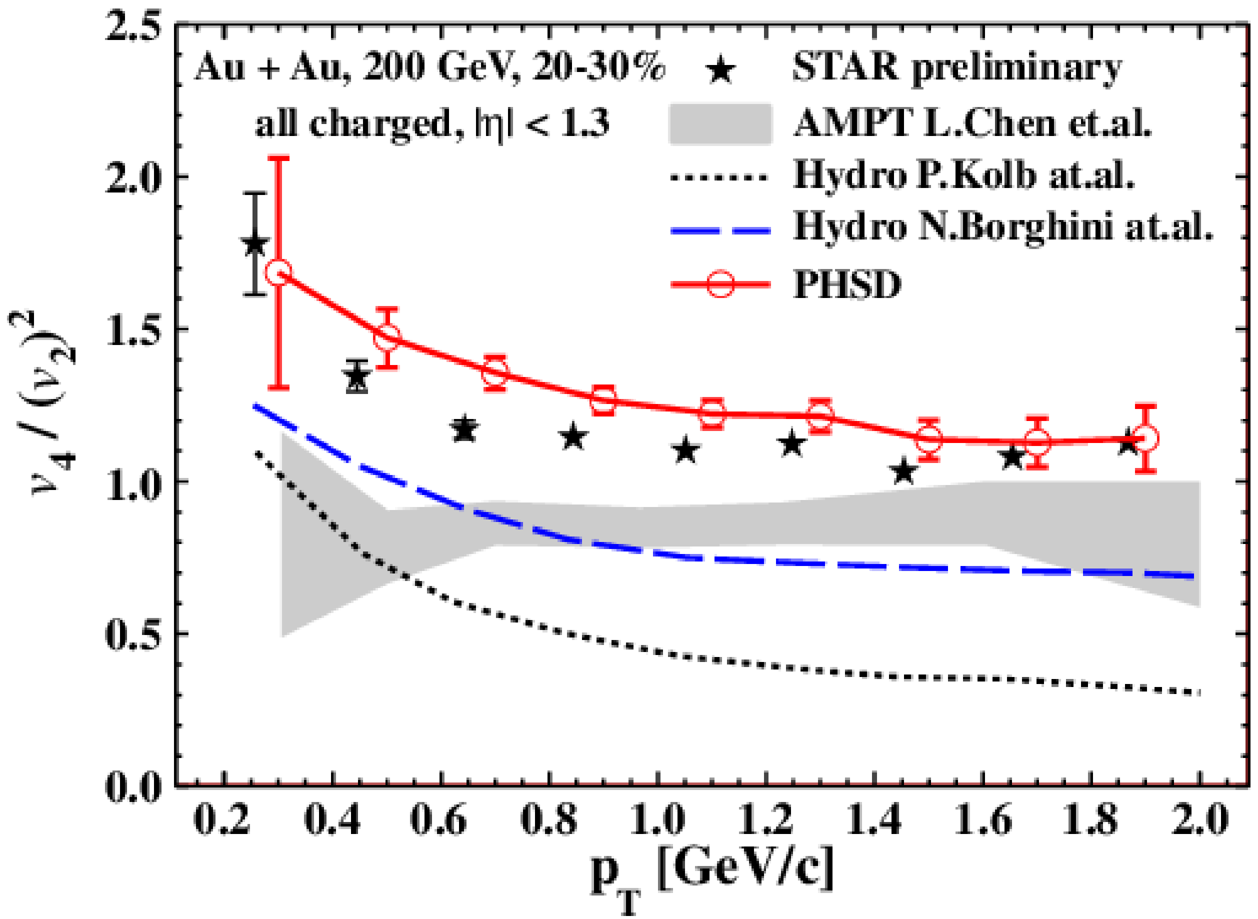




- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

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

Ratio $v_4/(v_2)^2$ vs. p_T at RHIC

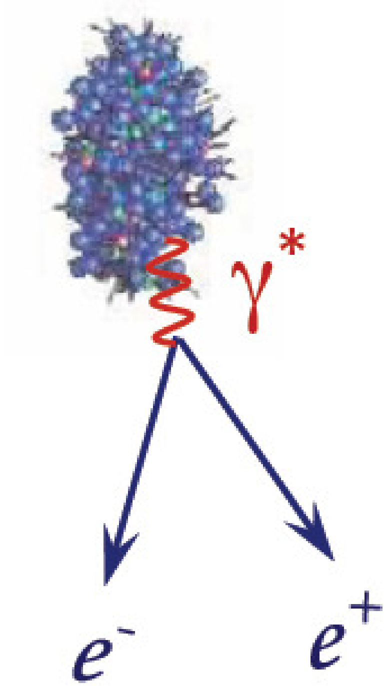


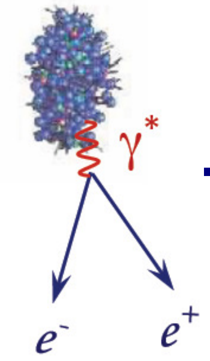
The ratio $v_4/(v_2)^2$:

- is very sensitive to the microscopic dynamics
- PHSD: ratio grows at low p_T - in line with exp. data

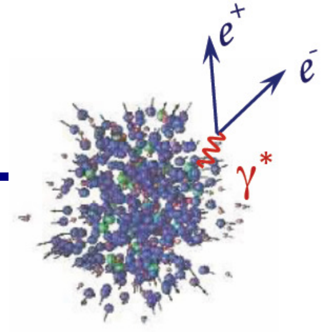
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

Dileptons





Electromagnetic probes: dileptons and photons



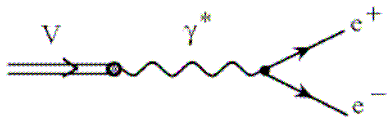
➢ Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions

Dilepton sources:

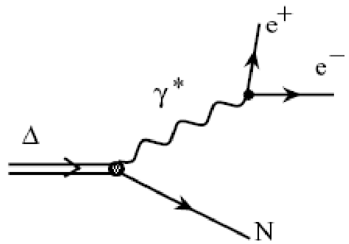
▪ from the QGP via partonic (q,qbar, g) interactions:

▪ from hadronic sources:

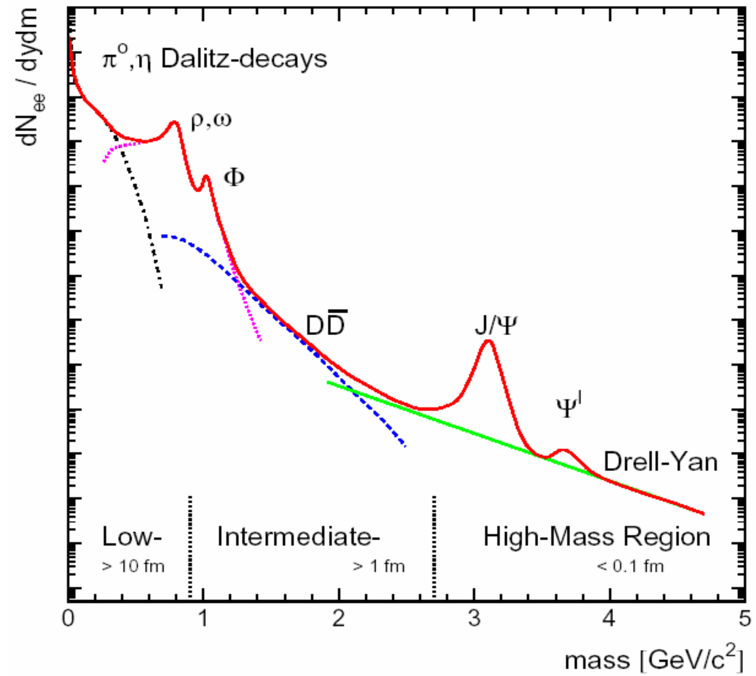
- direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ')



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



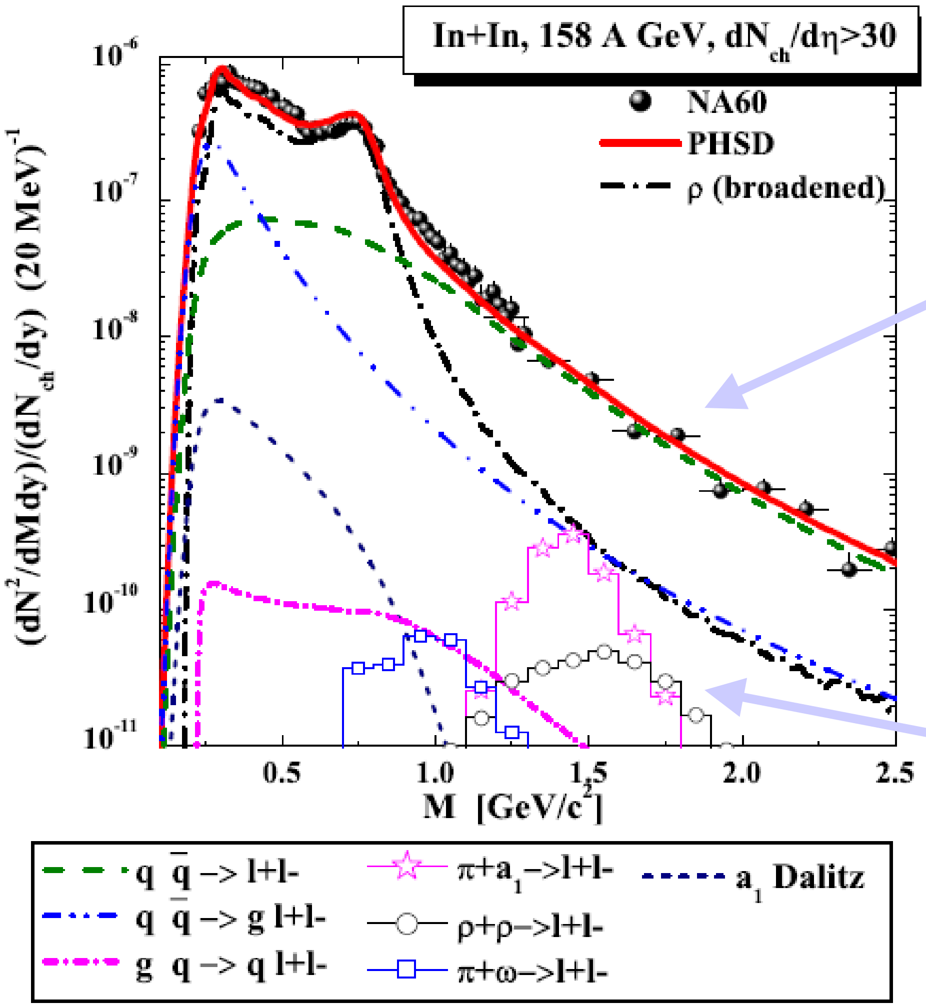
- correlated D+Dbar pairs
- radiation from multi-meson reactions (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - ‚4π'



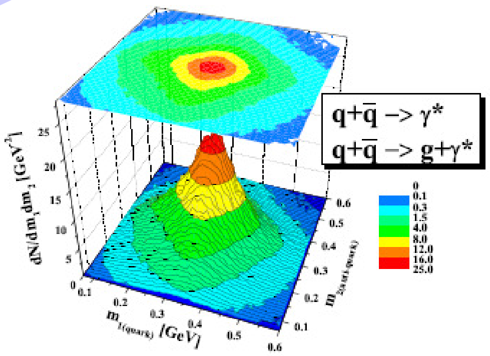
➔ Dileptons are an ideal probe to study the properties of the hot and dense medium

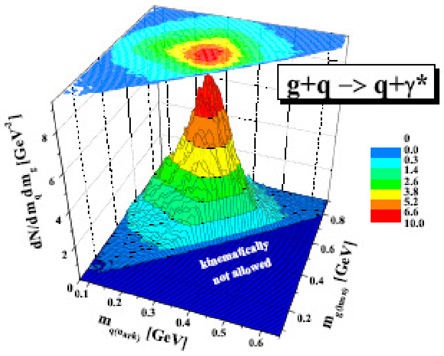
Dileptons at SPS: NA60

Acceptance corrected NA60 data



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

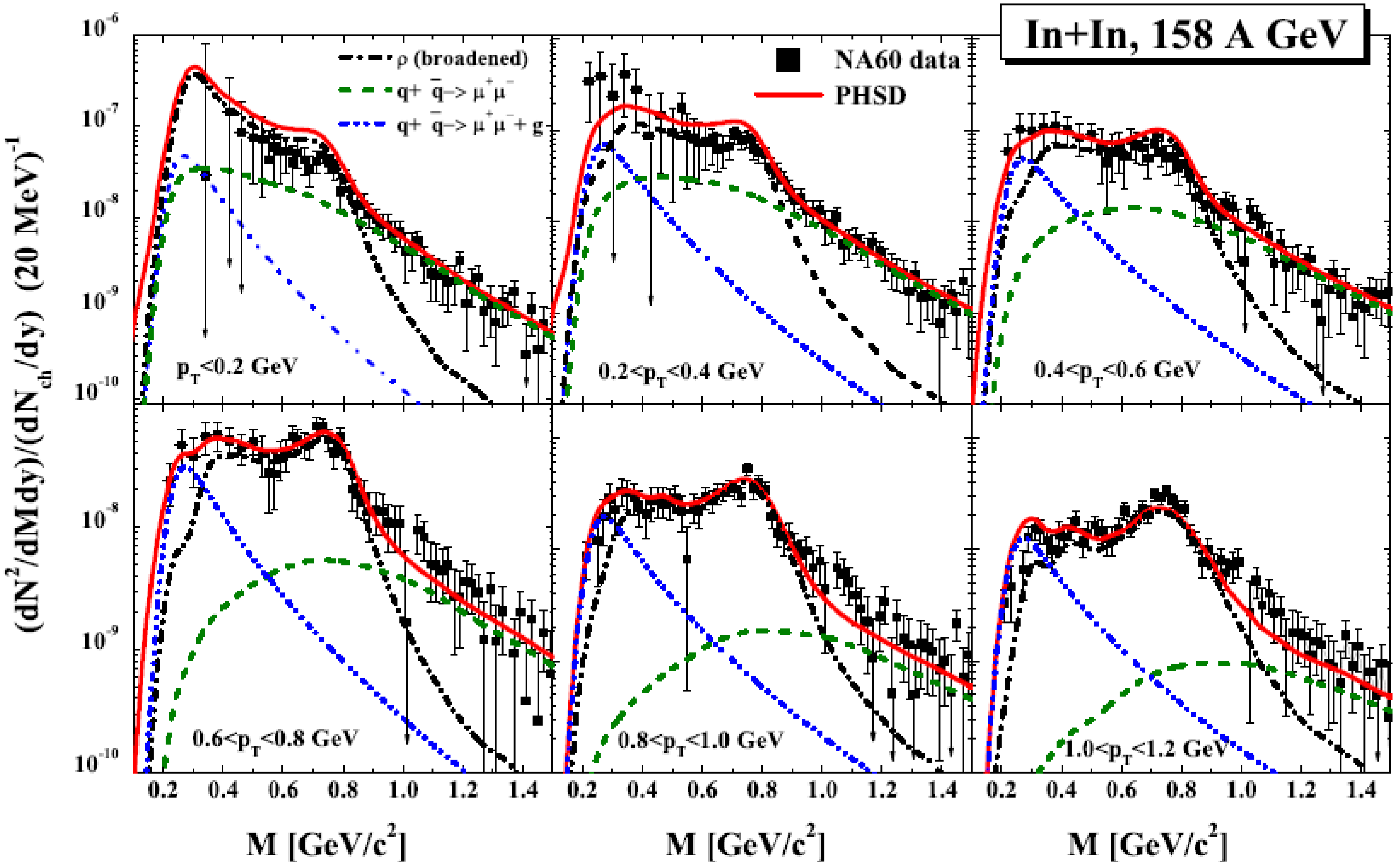




- Contributions of "4π" channels (radiation from multi-meson reactions) are small

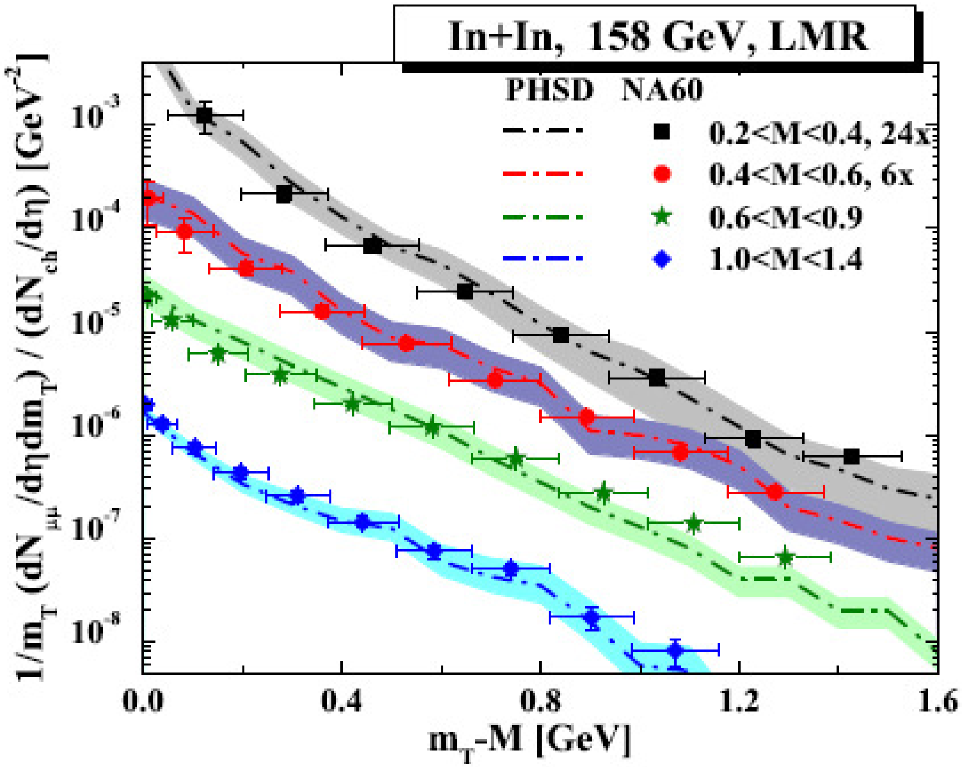
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

Dileptons at SPS: NA60

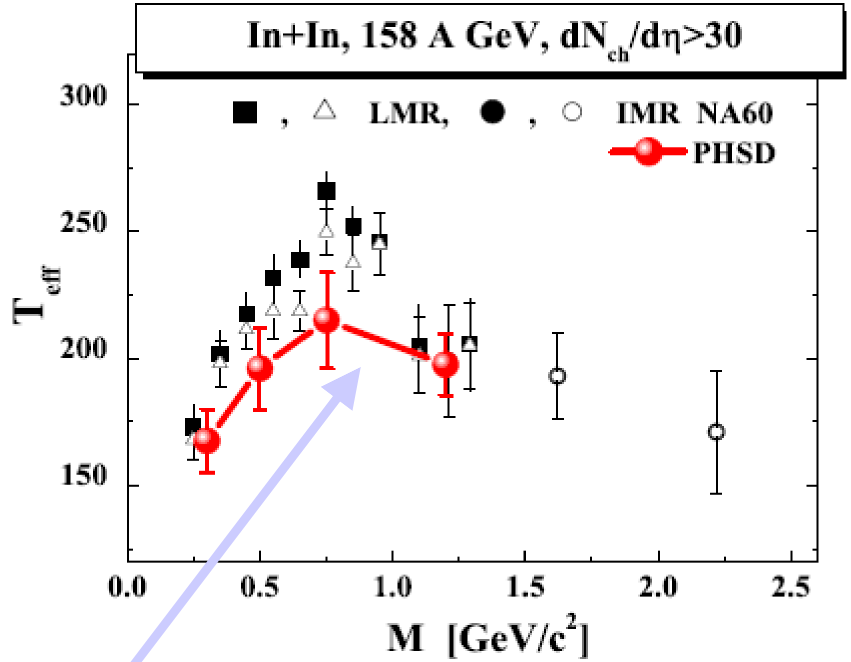


O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60: m_T spectra



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

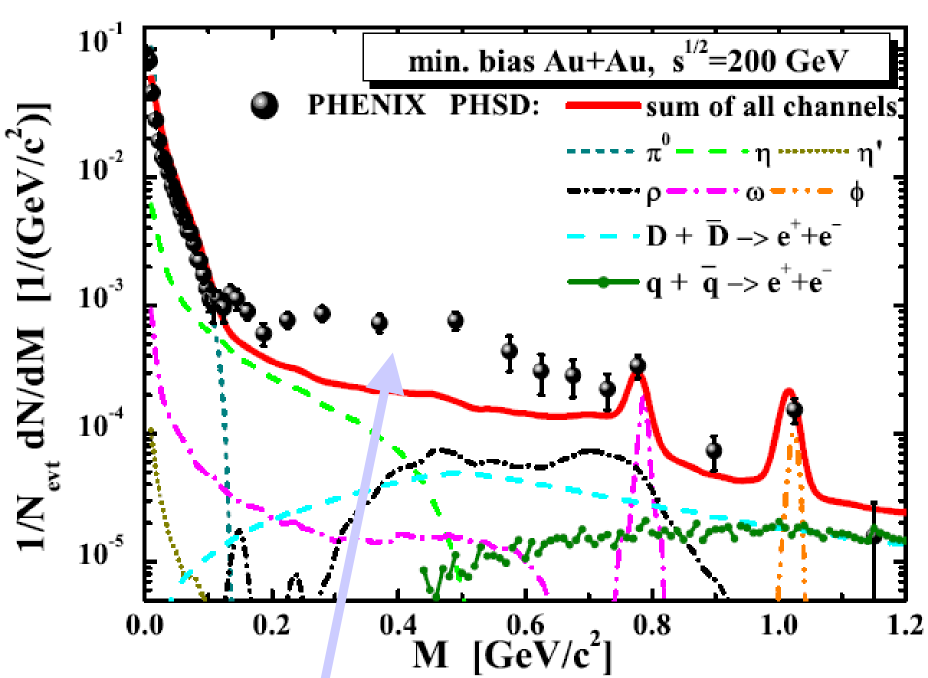


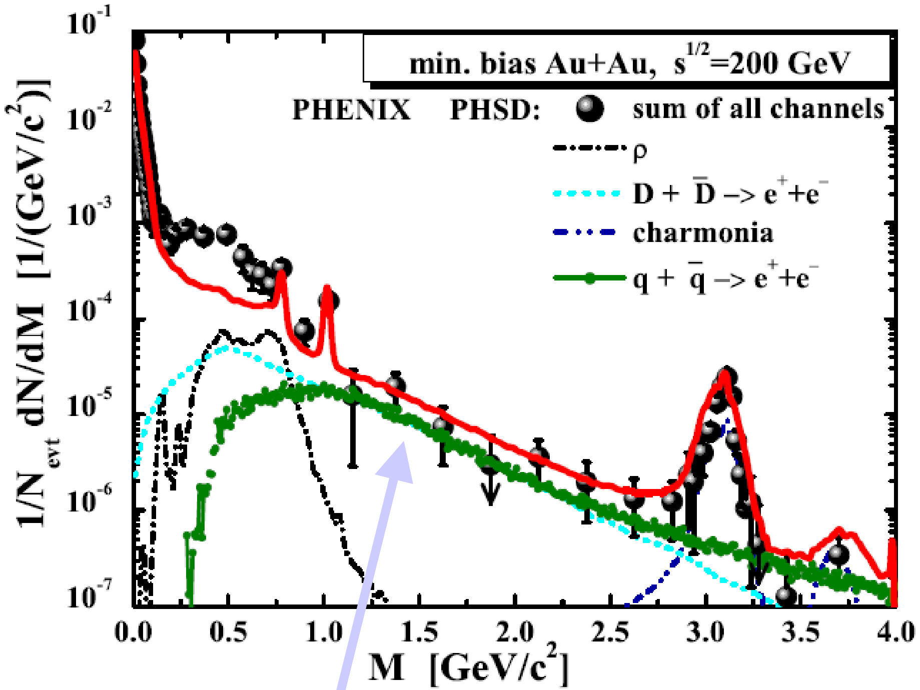
Conjecture:

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

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

PHENIX: dileptons from partonic channels

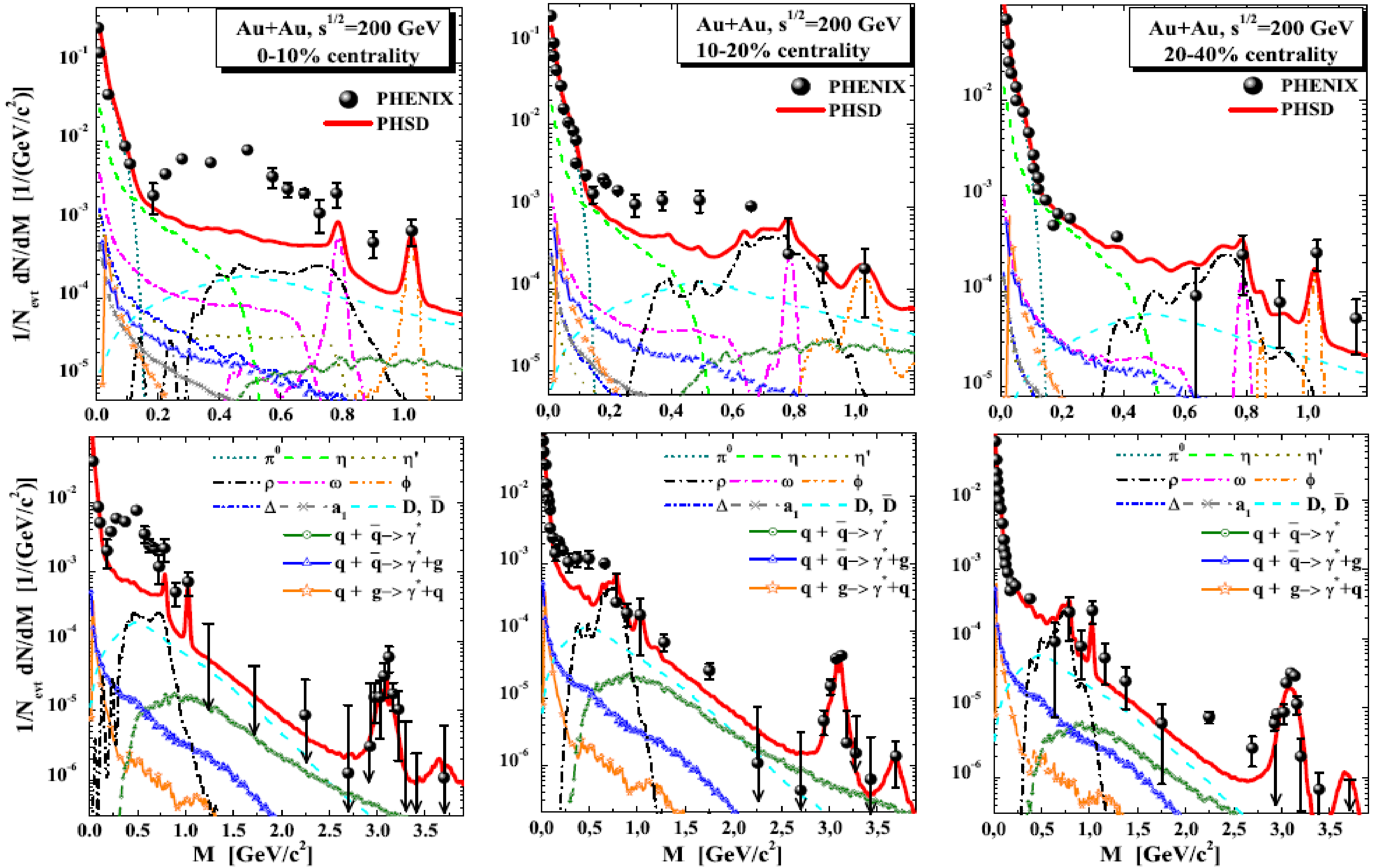




- The **excess** over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD
- The **partonic channels** fill up the discrepancy between the hadronic contributions and the data for M>1 GeV

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

PHENIX: mass spectra

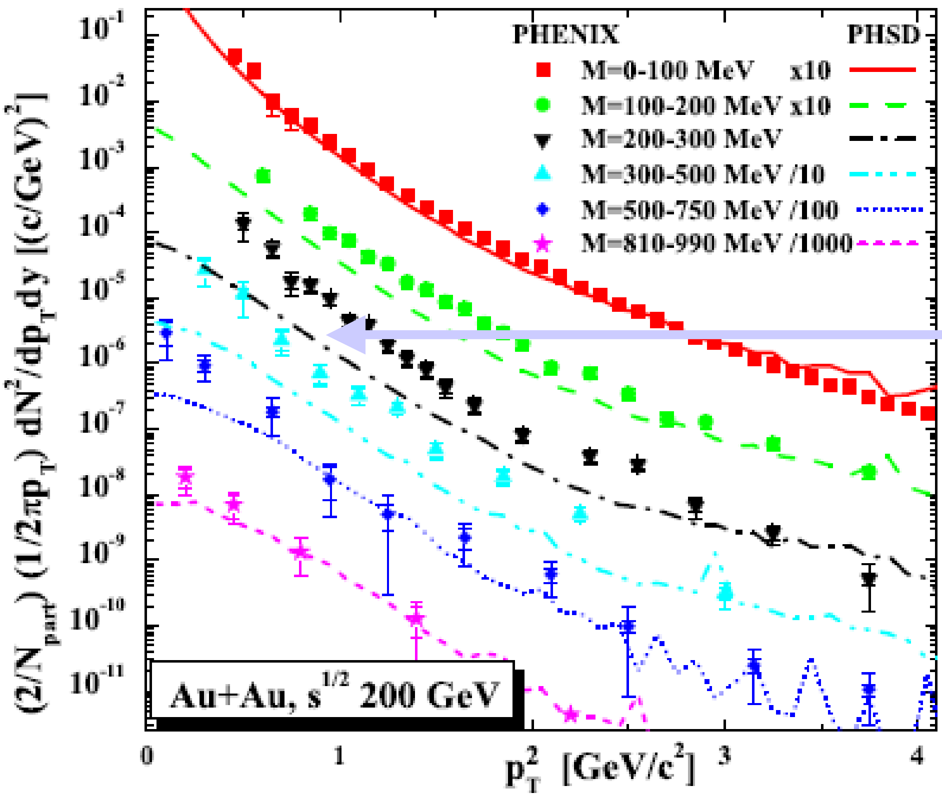


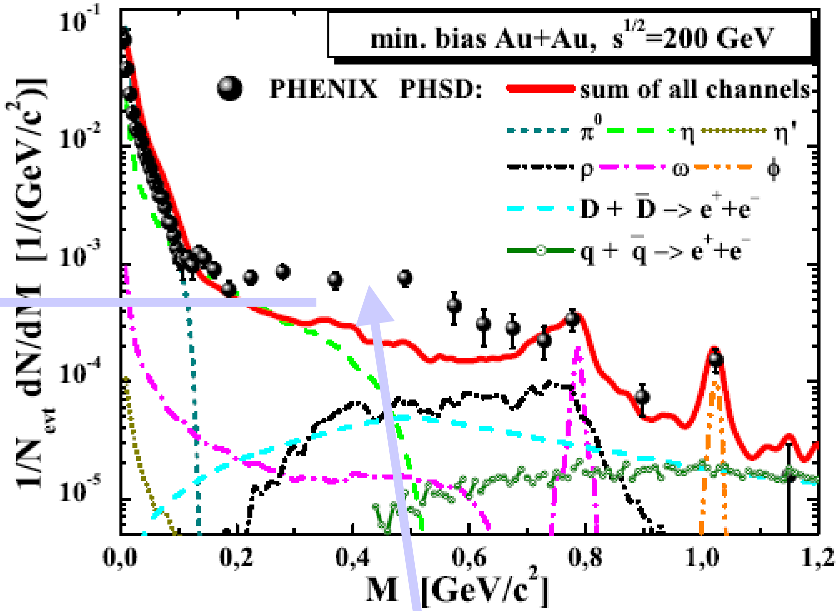
(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

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

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

PHENIX: p_T spectra

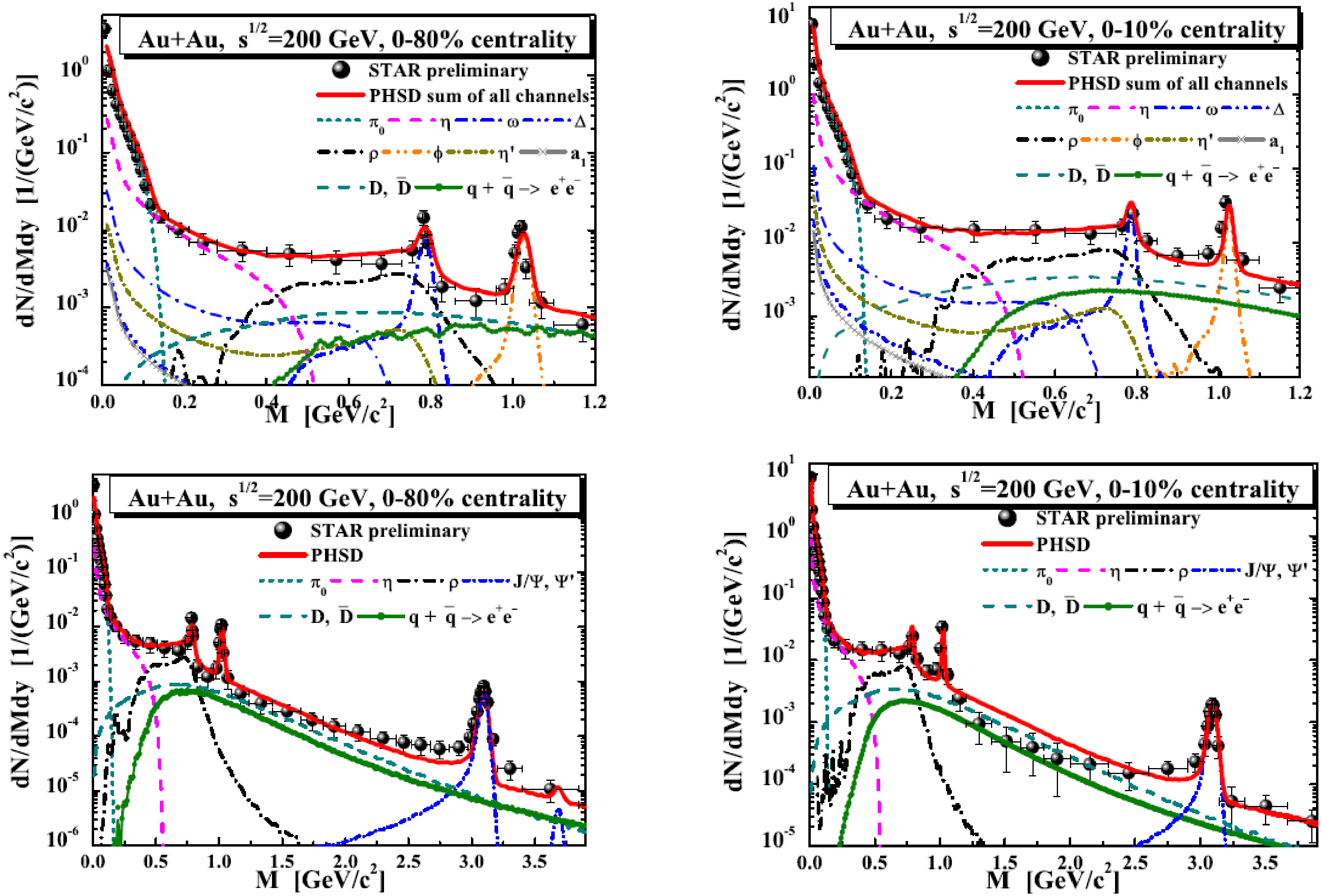




- The lowest and highest mass bins are described very well
- Underestimation of p_T data for 100<M<750 MeV bins consistent with dN/dM
- The 'missing source'(?) is located at low p_T !

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

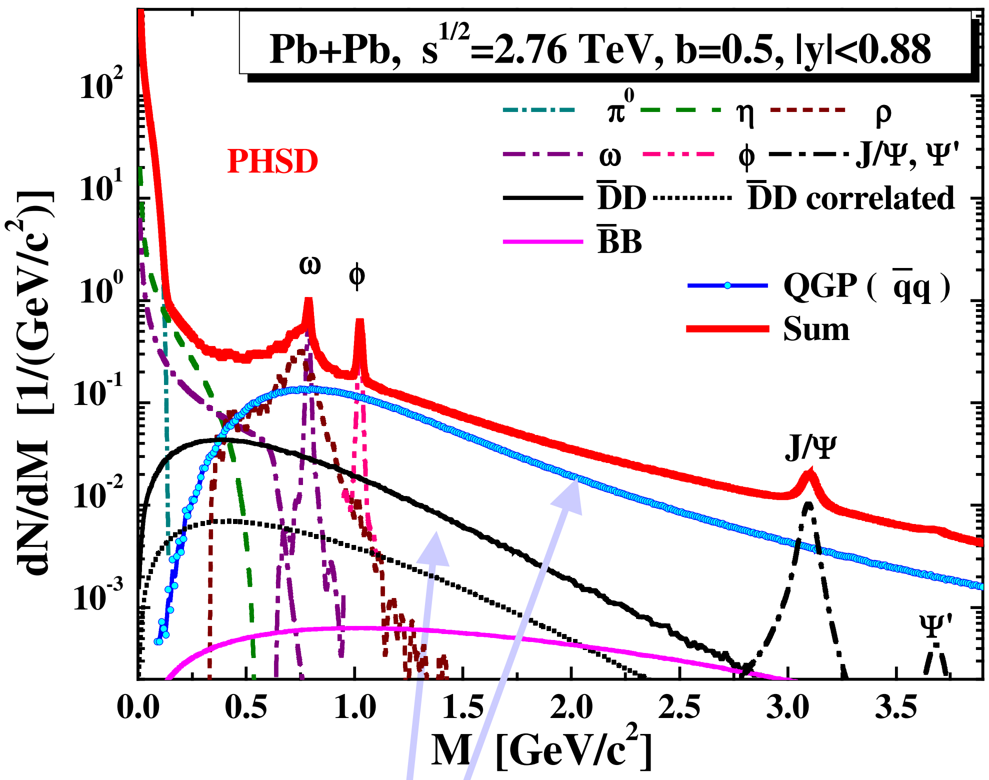
STAR: mass spectra

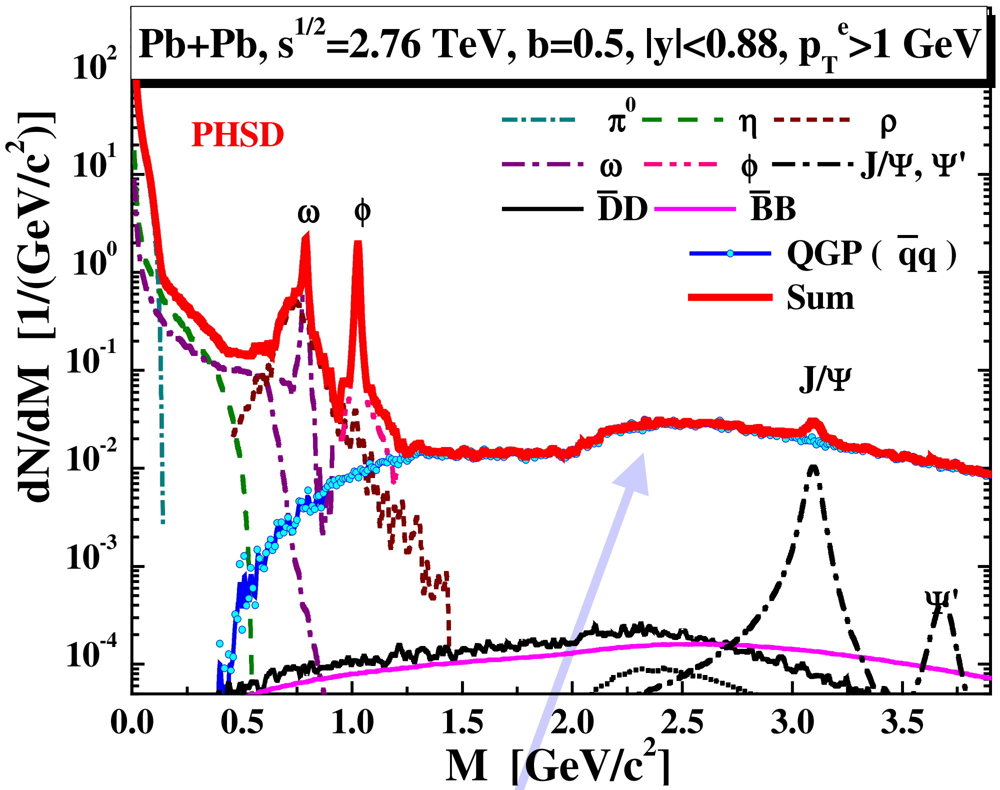


- **STAR data are well described!**

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

Predictions for LHC





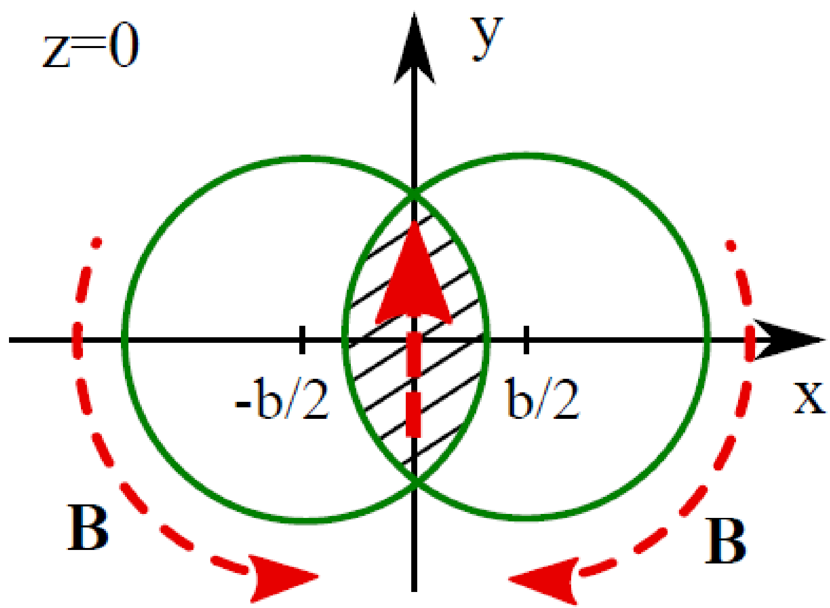
QGP(qbar-q) dominates at M>1.2 GeV

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

- D-, B-mesons energy loss from Pol-Bernard Gossiaux and Jörg Aichelin
- J/Ψ and Ψ' nuclear modification from Che-Ming Ko and Taesoo Song

O. Linnyk, W. Cassing, J. Manninen, E. L. B., P. B. Gossiaux, J. Aichelin, T. Song, C. M. Ko , arXiv:1208.1279

Chiral magnetic effect and evolution of the electromagnetic field in relativistic heavy-ion collisions



PHSD - transport model with electromagnetic fields

Generalized transport equations in the presence of electromagnetic fields :

$$\dot{\vec{r}} \rightarrow \frac{\vec{p}}{p_0} + \vec{\nabla}_p U \ , \qquad U \sim Re(\Sigma^{ret})/2p_0$$

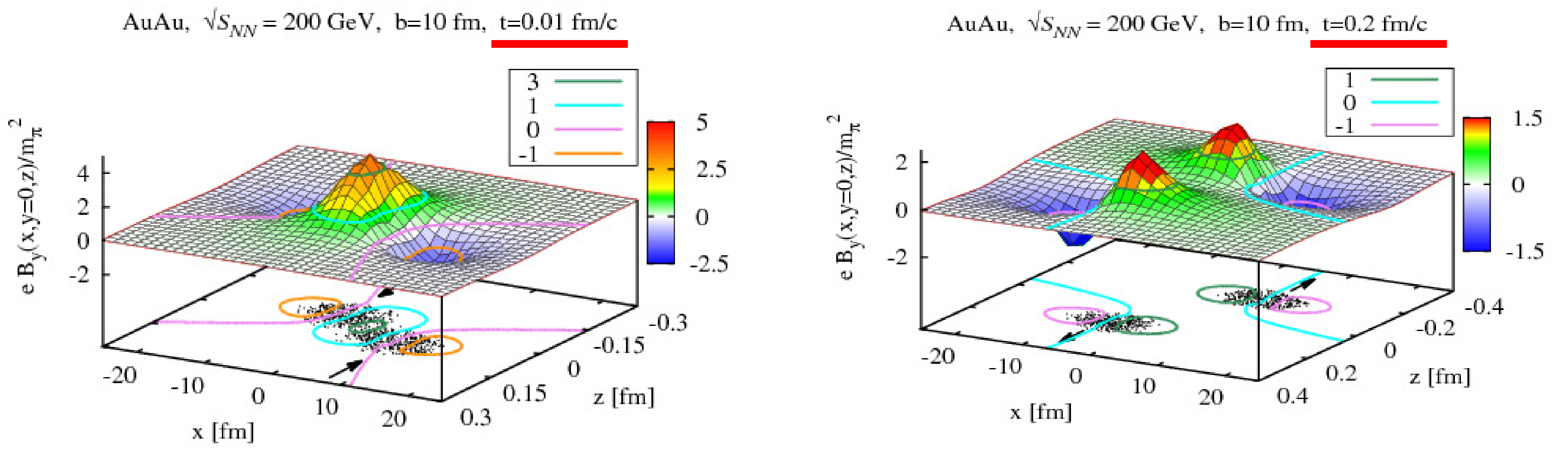
$$\dot{\vec{p}} \rightarrow -\vec{\nabla}_r U + e\vec{E} + e\vec{v} \times \vec{B}$$

$$\begin{cases} \vec{B} = \vec{\nabla} \times \vec{A} \\ \vec{E} = -\vec{\nabla}\Phi - \frac{\partial \vec{A}}{\partial t} \end{cases}$$

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

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

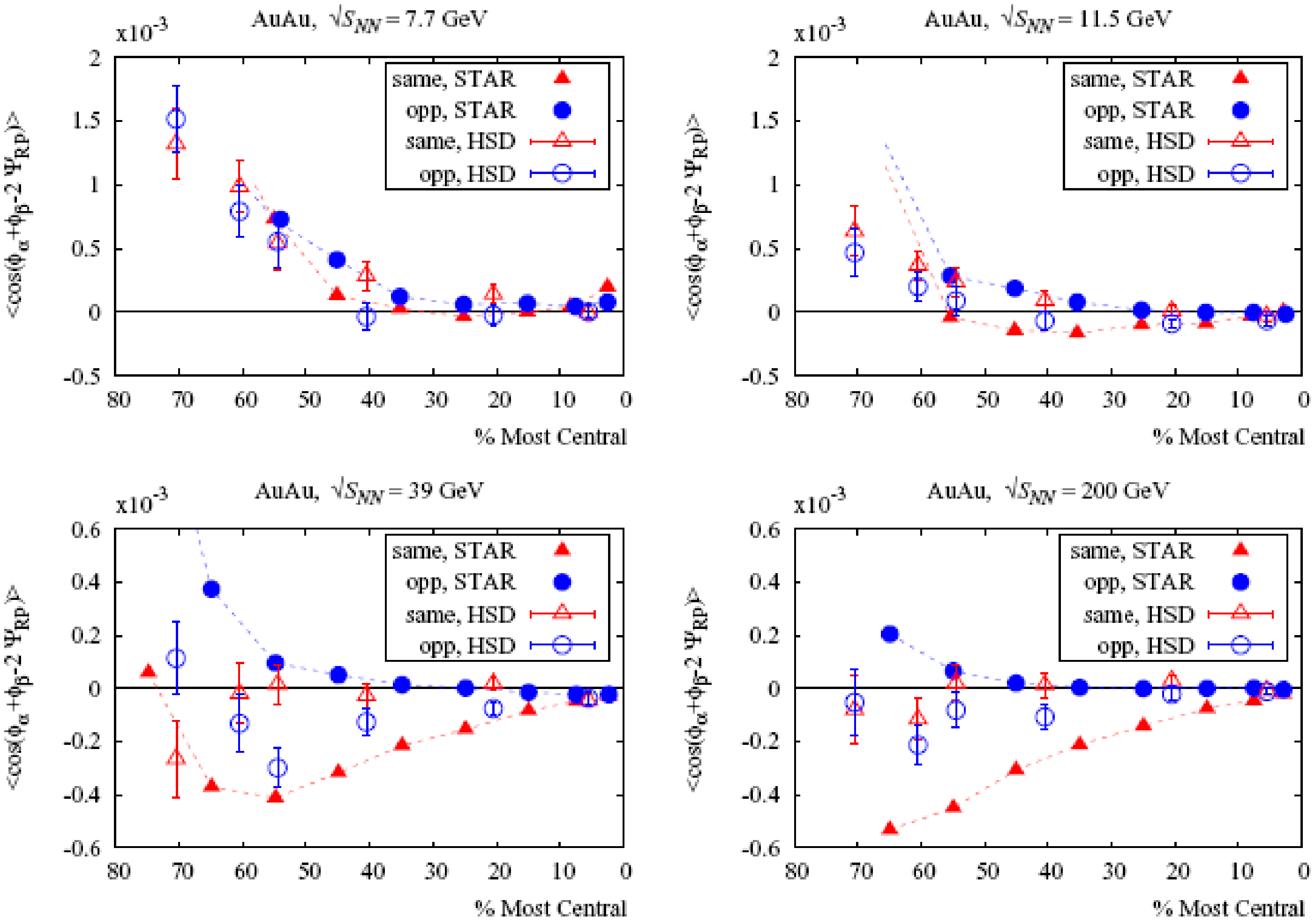
- **Magnetic field evolution in HSD/PHSD :**



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

Angular correlation wrt. reaction plane

$$\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle$$



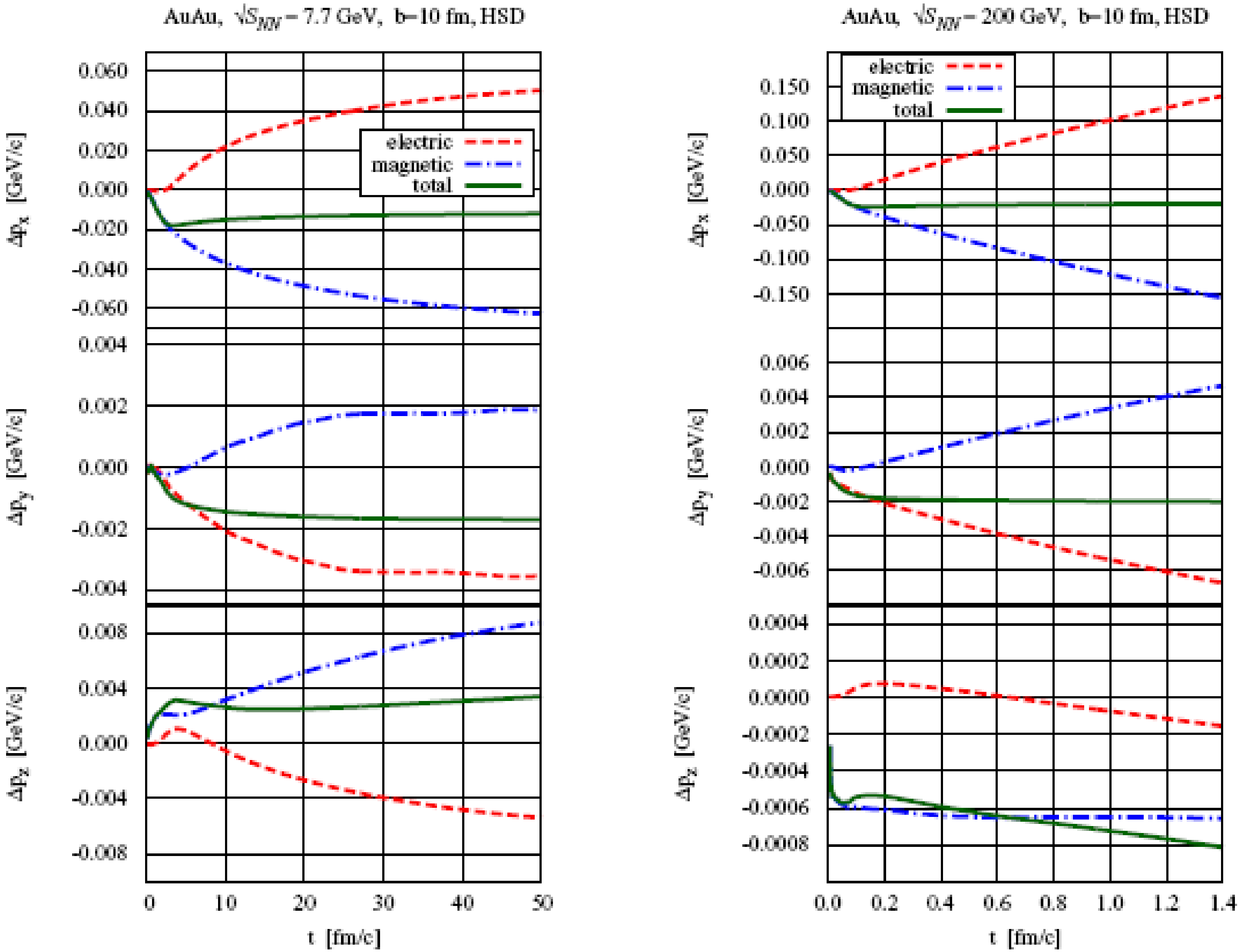
Angular correlation is of hadronic origin up to sqrt(s) = 11 GeV !

V. D. Toneev et al., PRC 85 (2012) 044922 , arXiv:1112.2595

Compensation of magnetic and electric forces

Forces

$\dot{\vec{p}} \rightarrow e\vec{E} + e\vec{v} \times \vec{B}$



There are not only strong magnetic forces but also strong electric forces which compensate each other!

V. D. Toneev et al., PRC 85 (2012) 044922 , arXiv:1112.2595

Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state (from the BMW collaboration)

- PHSD versus experimental observables:
  - enhancement of meson m_T slopes (at top SPS and RHIC)
  - strange antibaryon enhancement (at SPS)
  - partonic emission of high mass dileptons at SPS and RHIC
  - enhancement of collective flow v_2 with increasing energy
  - quark number scaling of v_2 (at RHIC)
  - jet suppression
  - …

⇒ evidence for strong nonhadronic interactions in the early phase of relativistic heavy-ion reactions

⇒ formation of the sQGP

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