Dynamics of the QGP in relativistic heavy-ion collisions

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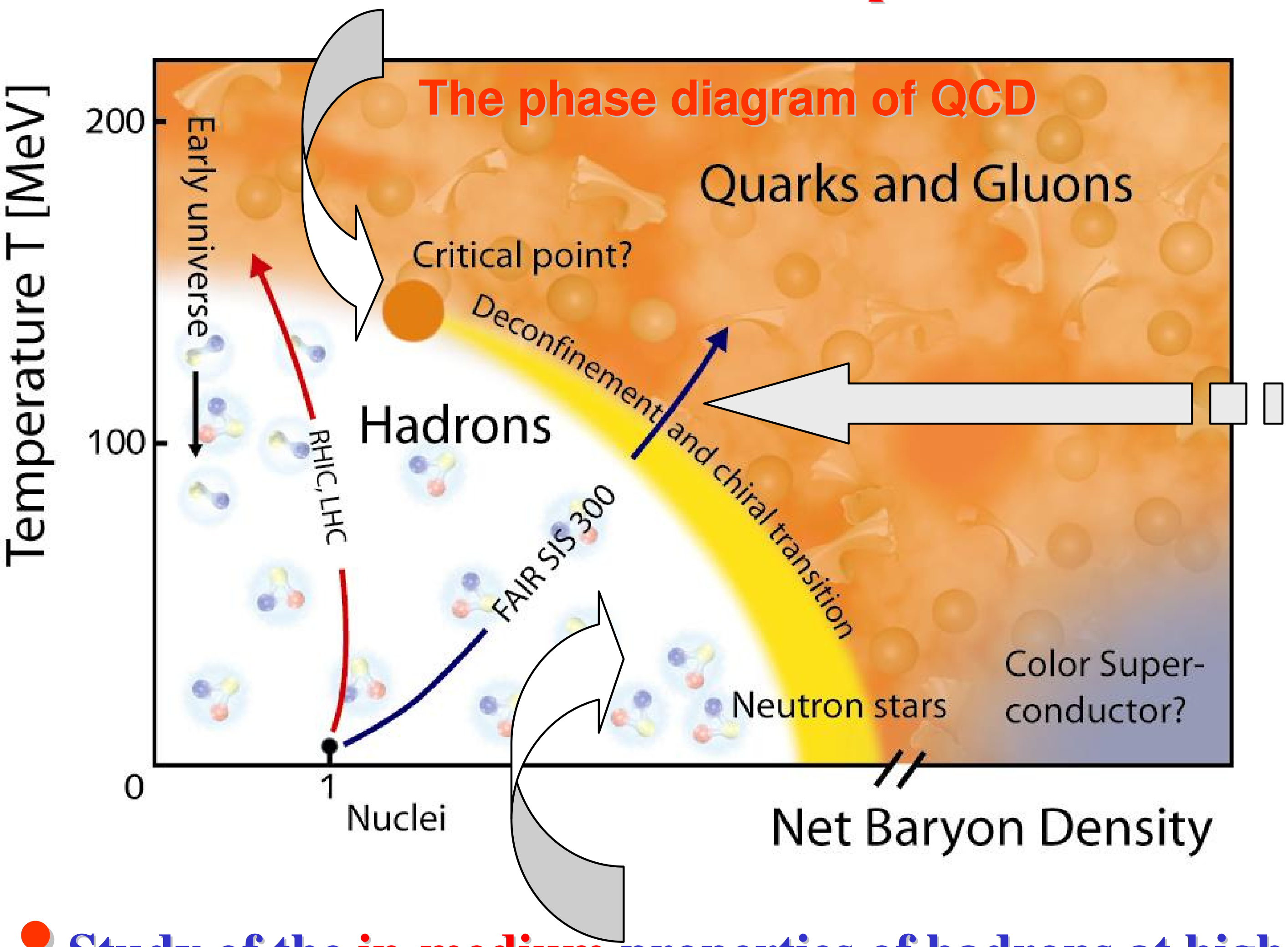
„Matter at highest baryon densities in the laboratory and in space“
Frankfurt-am-Main, Germany, 2-4 April 2012

The holy grail:

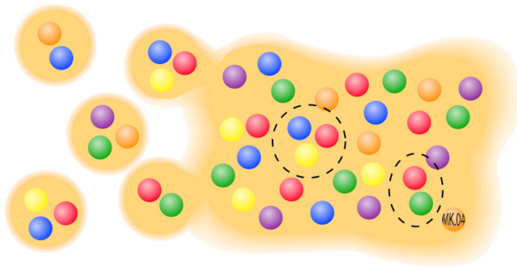
- Search for the **critical point**



- 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

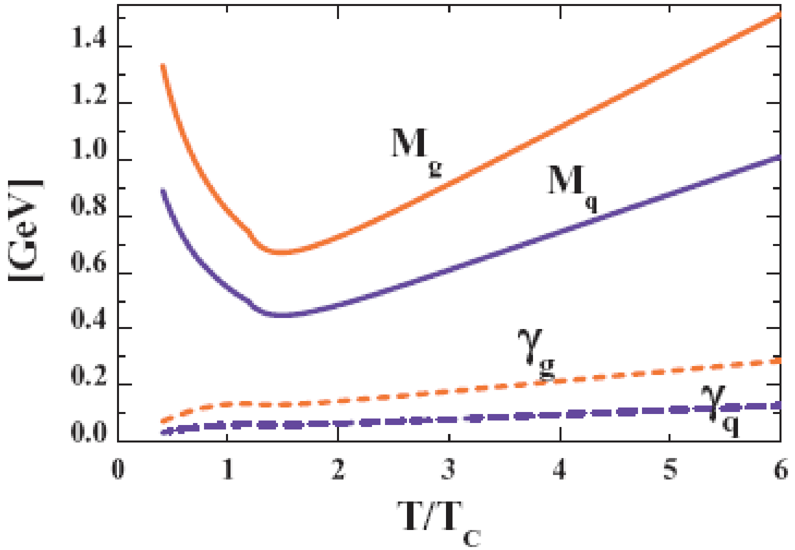
- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

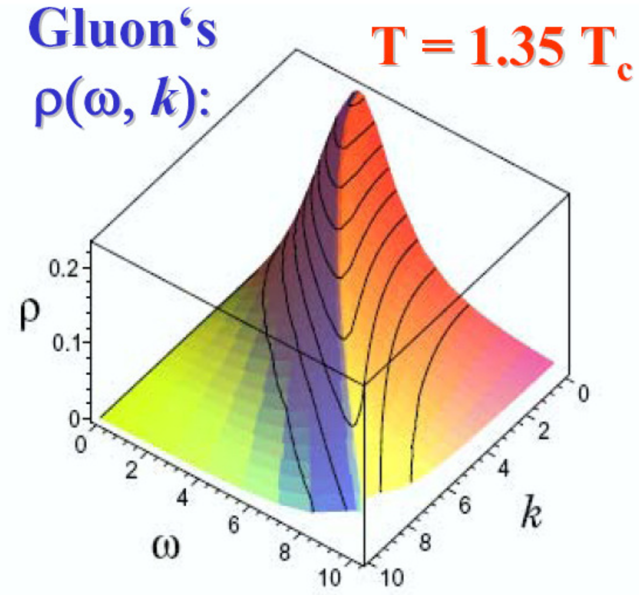
$$\rho(\omega) = \frac{\gamma}{E}\left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2}\right)$$

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

➔ Quasiparticle properties:

- large width and mass for gluons and quarks

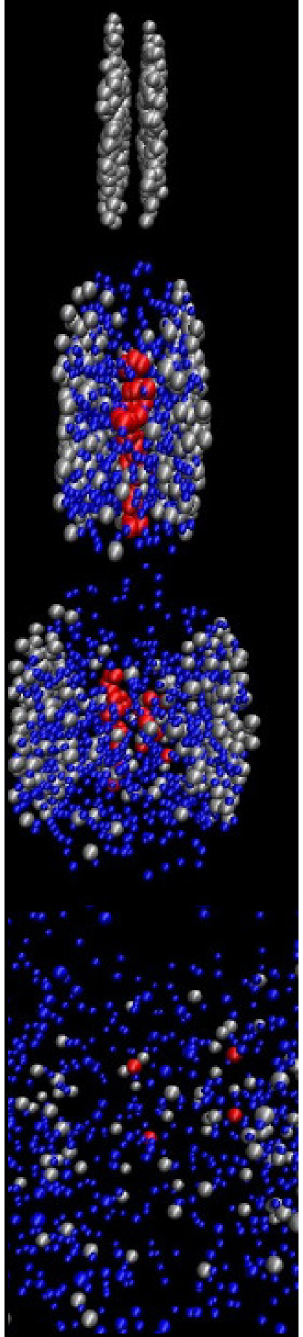




- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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 !**

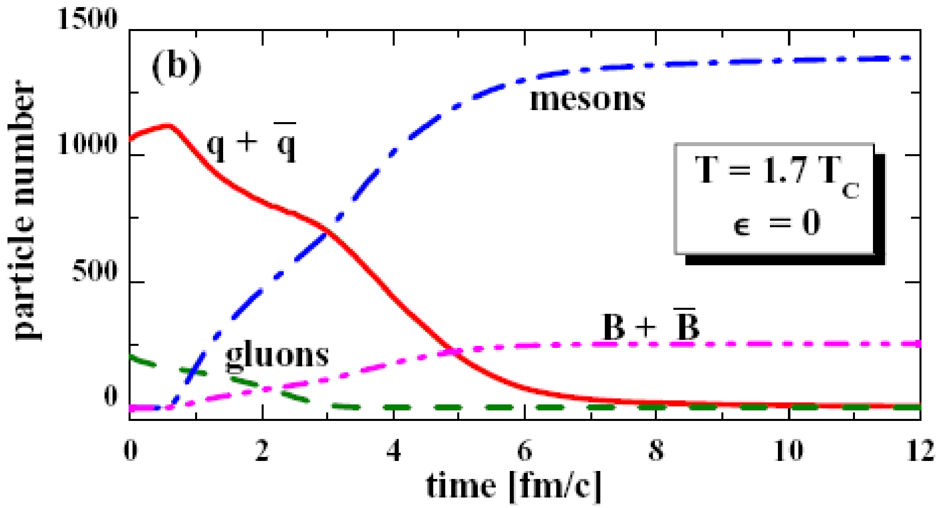
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states‘ for hadrons)

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!

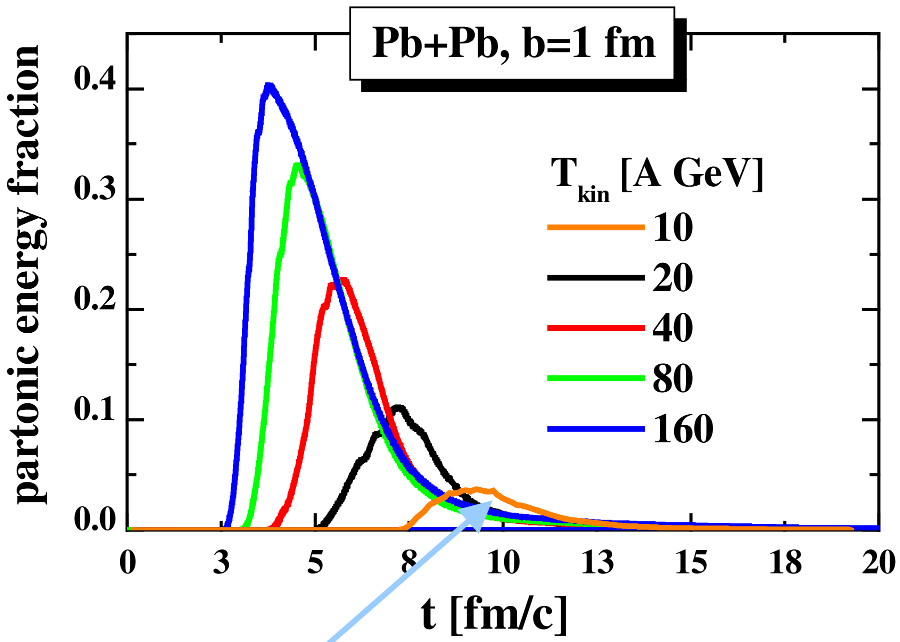
- **Off-shell parton transport** roughly leads a hydrodynamic evolution of the partonic system

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

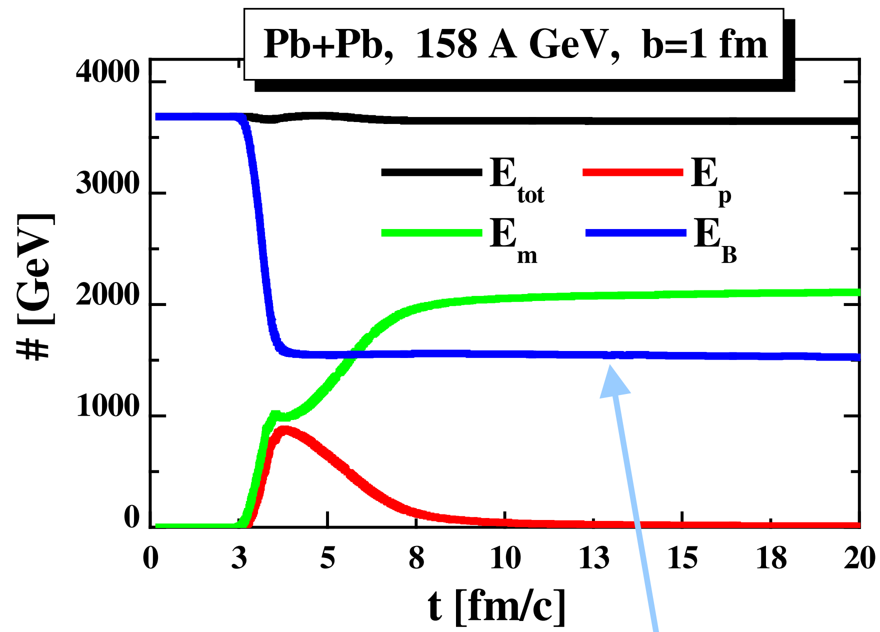
Bulk properties:
rapidity, m_T-distributions,
multi-strange particle enhancement in Au+Au

Application to nucleus-nucleus collisions

partonic energy fraction vs energy



energy balance



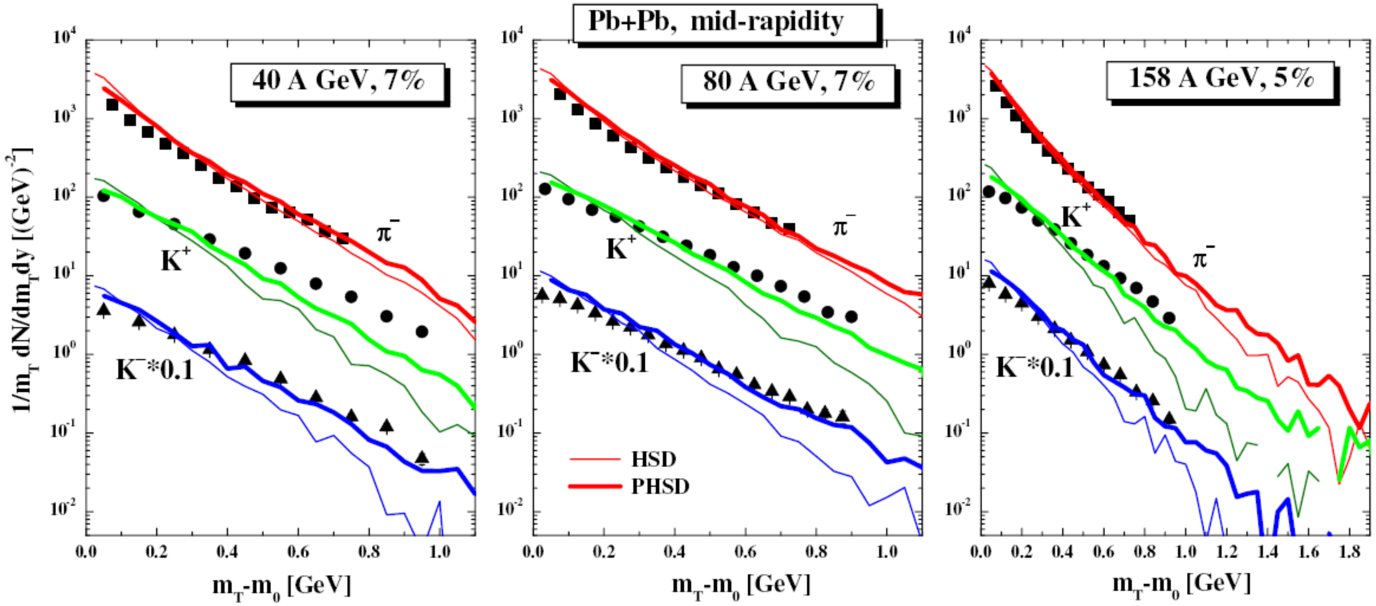
- Dramatic decrease of partonic phase with decreasing energy

- 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!

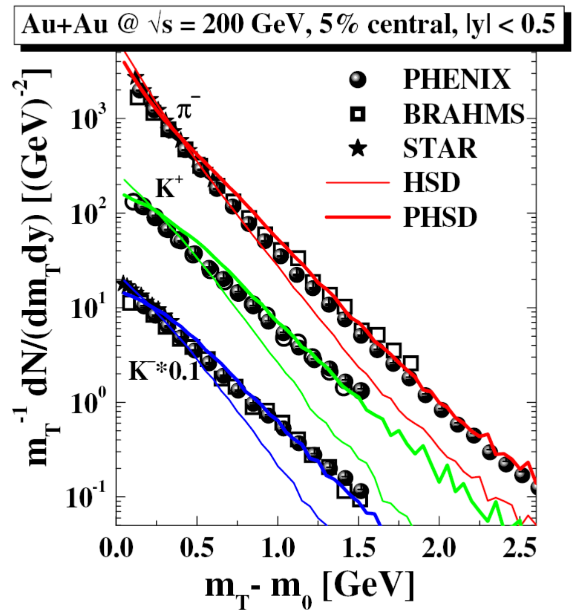
Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies



Central Au+Au at RHIC



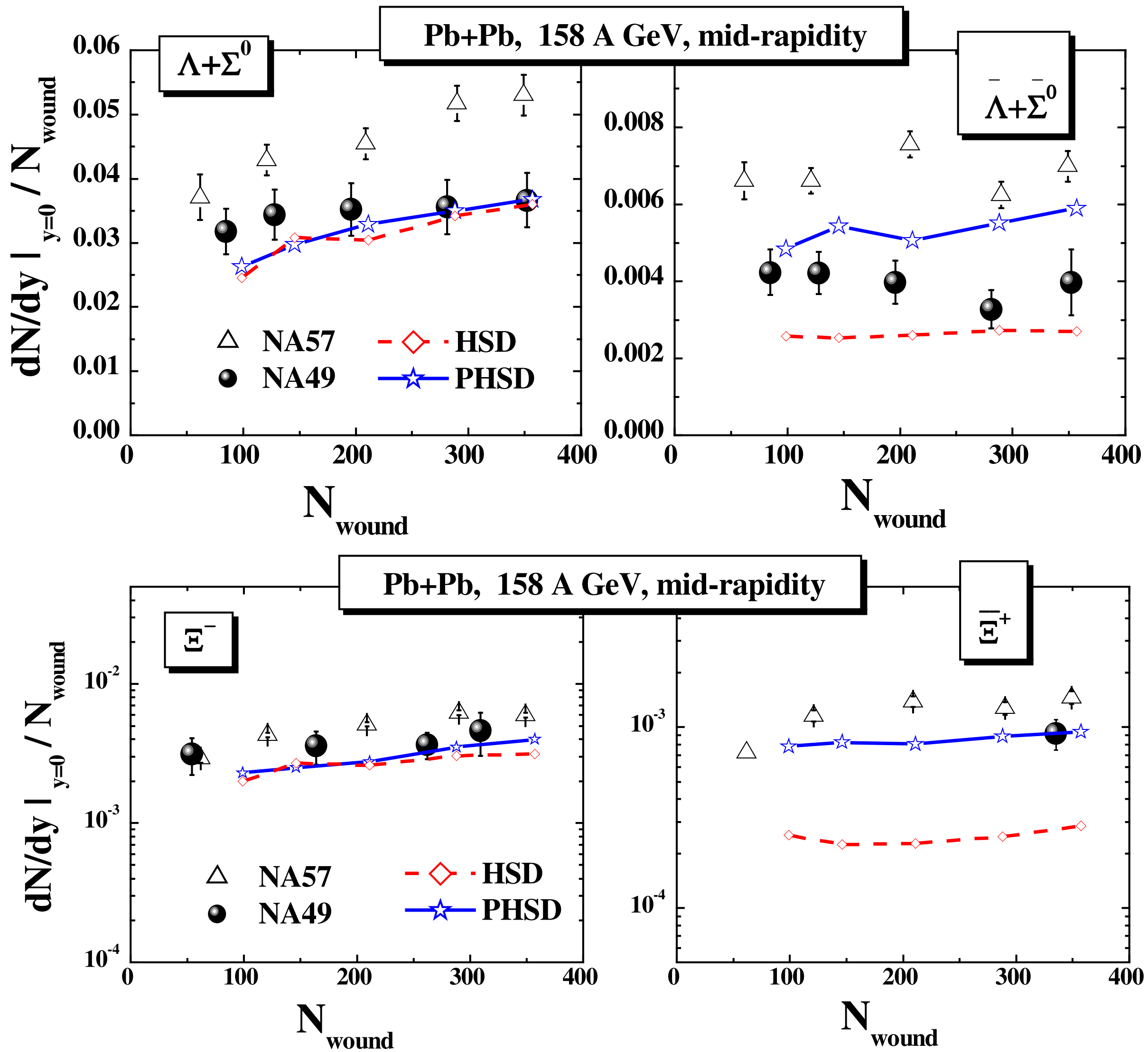
- PHSD gives harder m_T spectra and works better than HSD at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

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

Centrality dependence of (multi-)strange (anti-)baryons

strange baryons $\Lambda+\Sigma^0$

strange antibaryons $\bar{\Lambda}+\bar{\Sigma}^0$



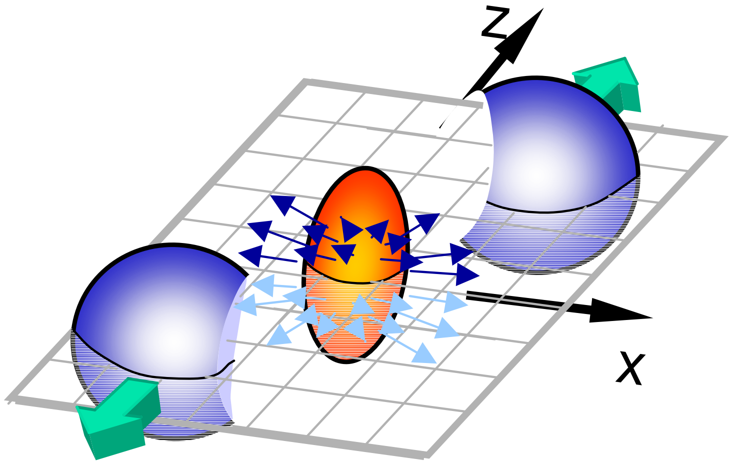
multi-strange baryon Ξ^-

multi-strange antibaryon $\bar{\Xi}^+$

➔ enhanced production of (multi-) strange antibaryons in PHSD relative to HSD

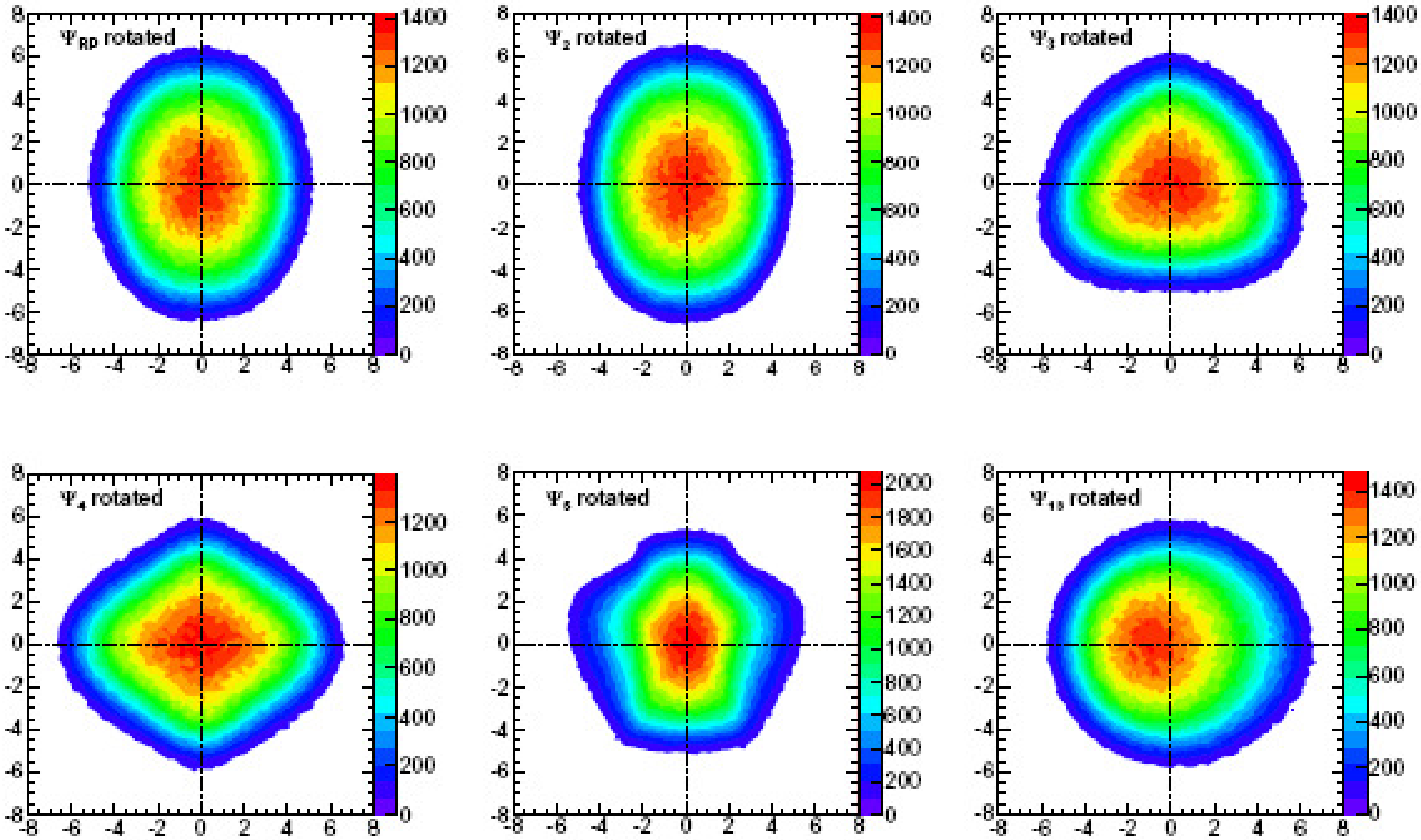
Cassing & Bratkovskaya, NPA 831 (2009) 215

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:

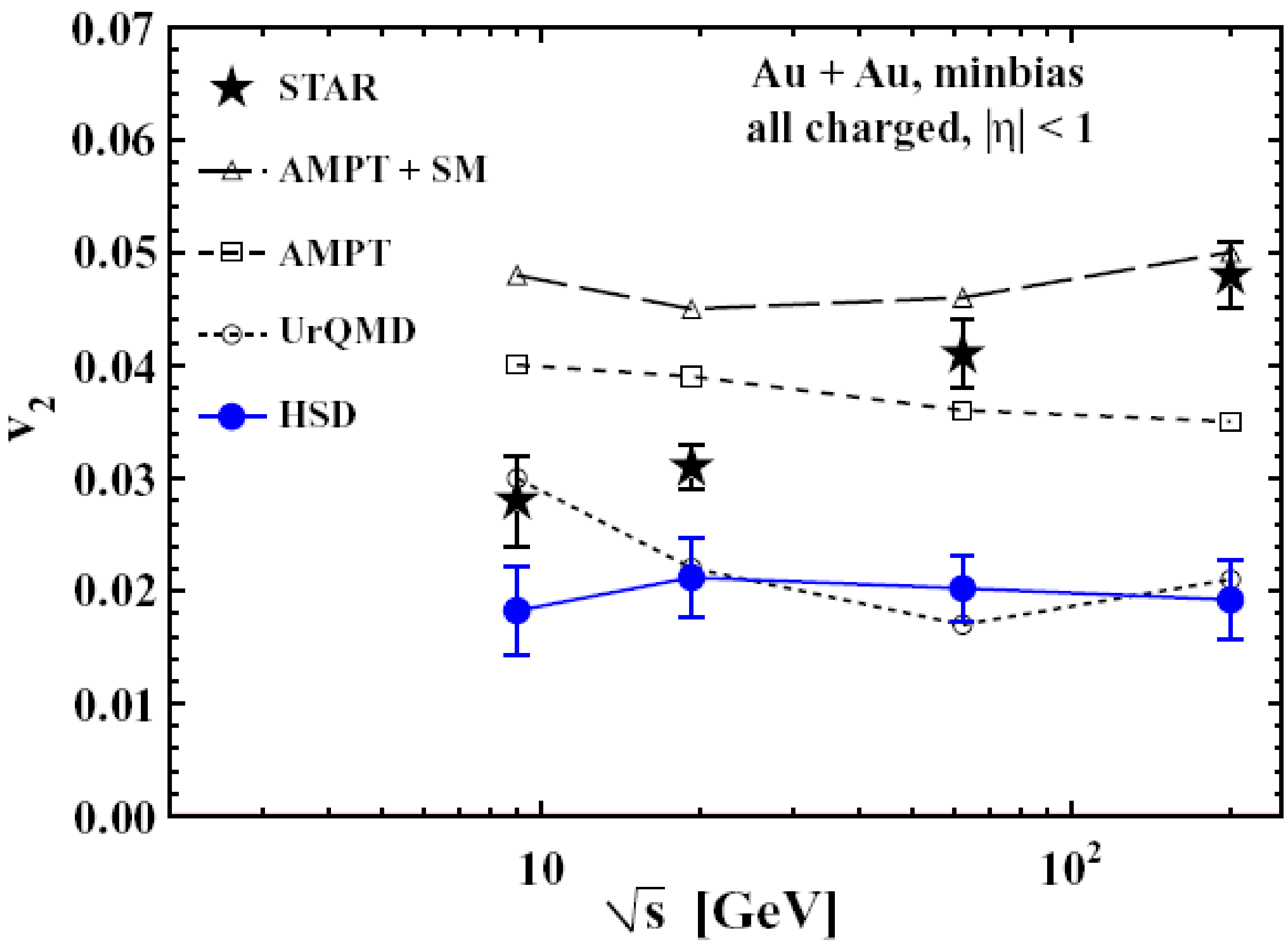


$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\psi - \Psi_n))\right)$$

show higher order harmonics v_n

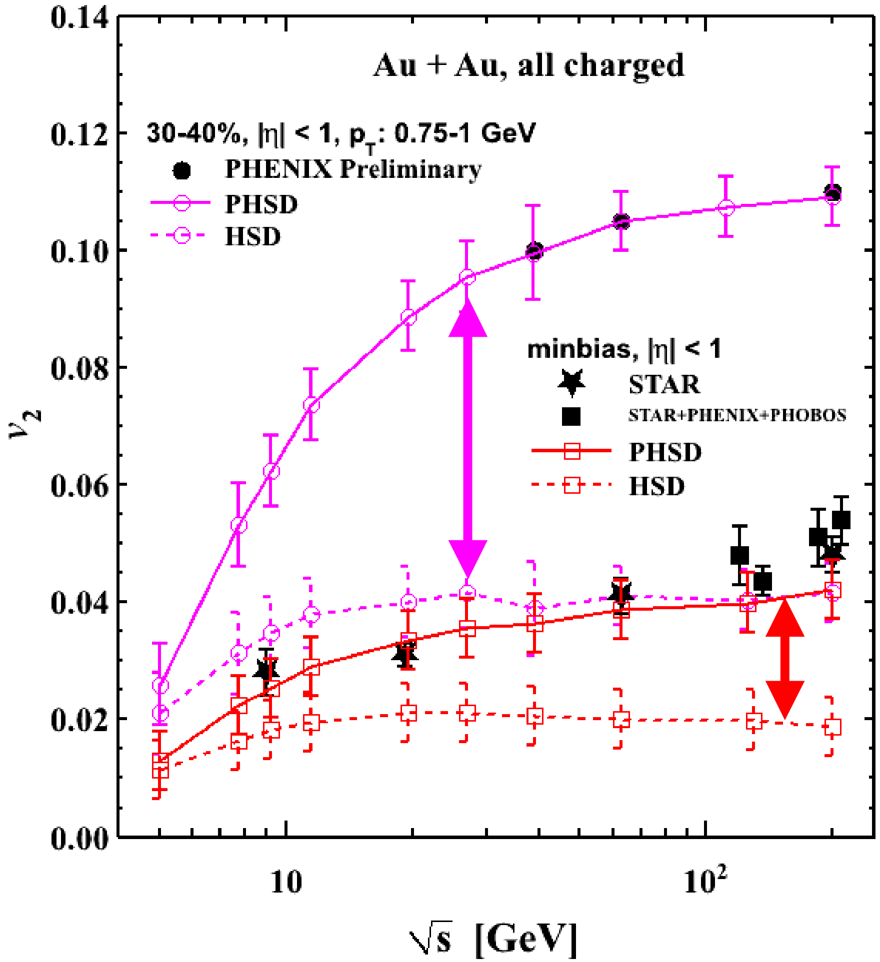
S. A. Voloshin, arXiv:1111.7241

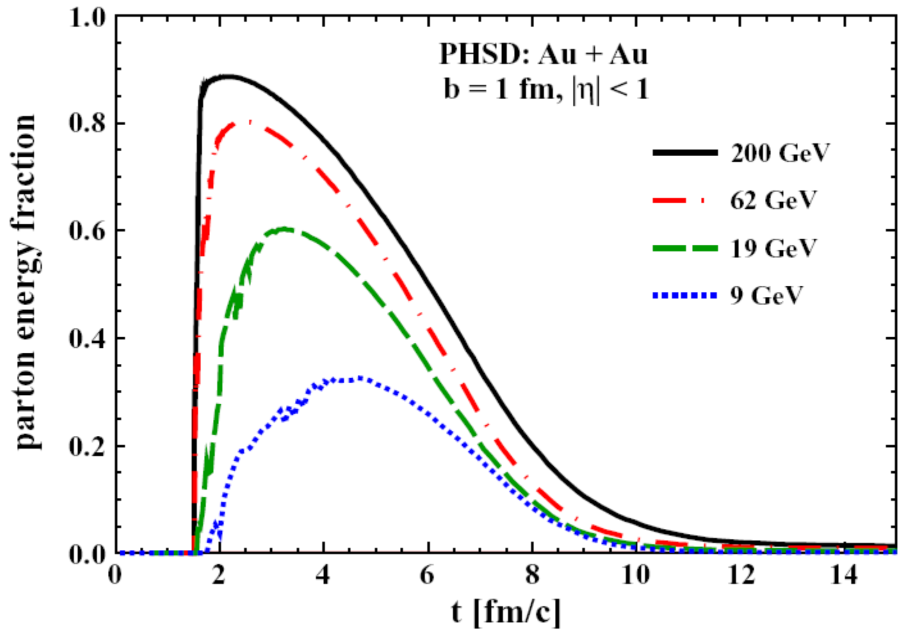
Excitation function of elliptic flow



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

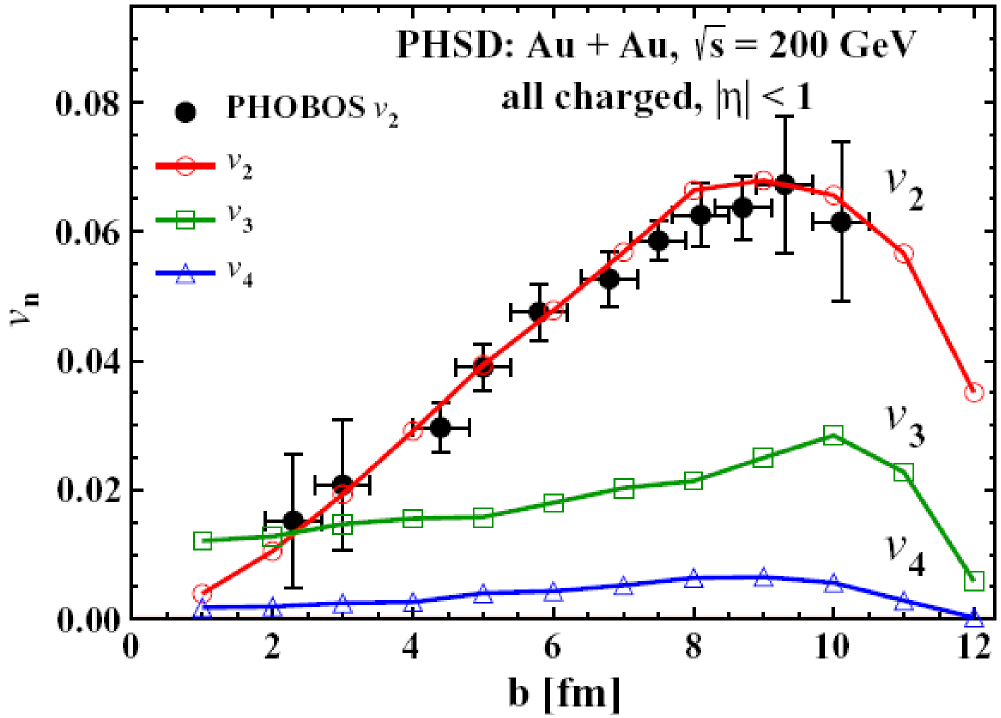


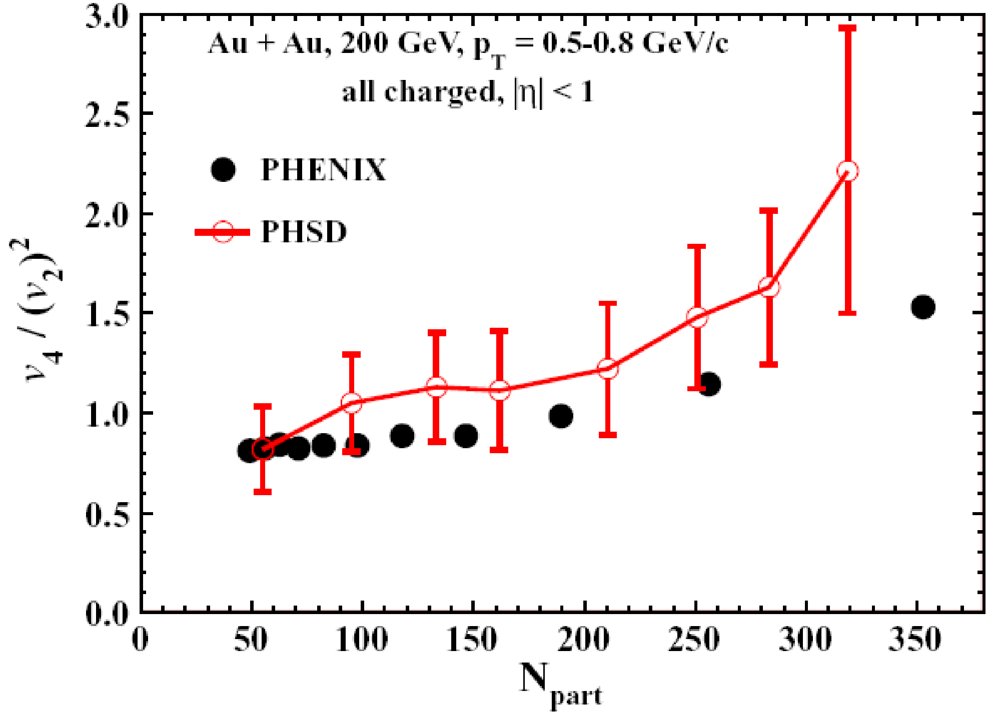


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

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

Flow coefficients versus centrality

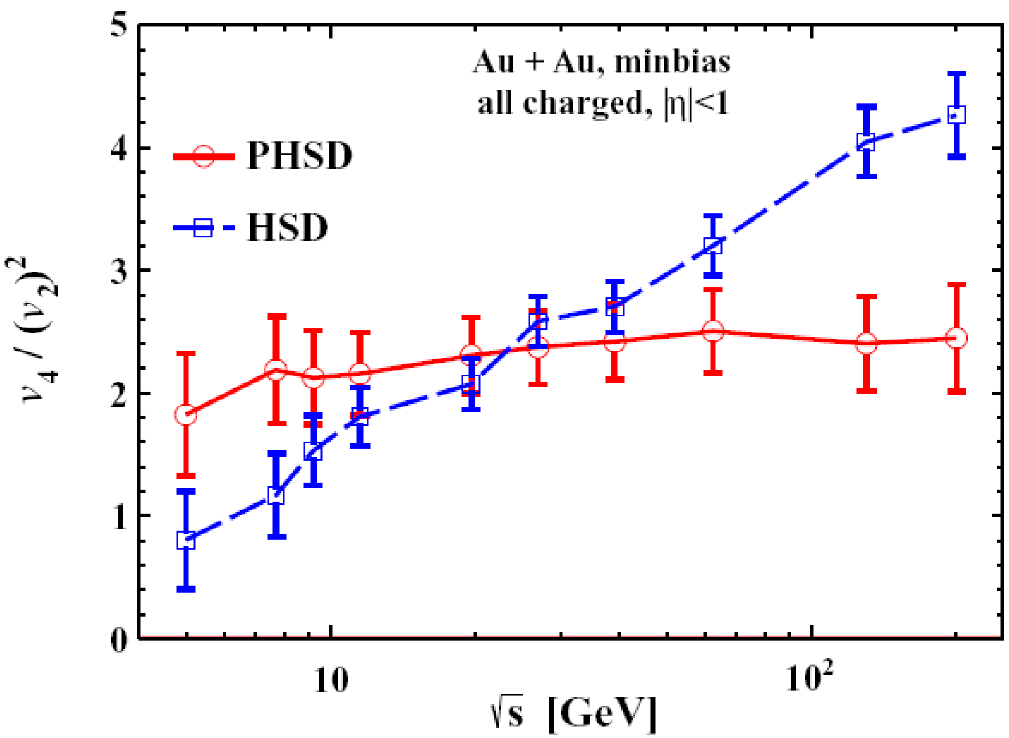


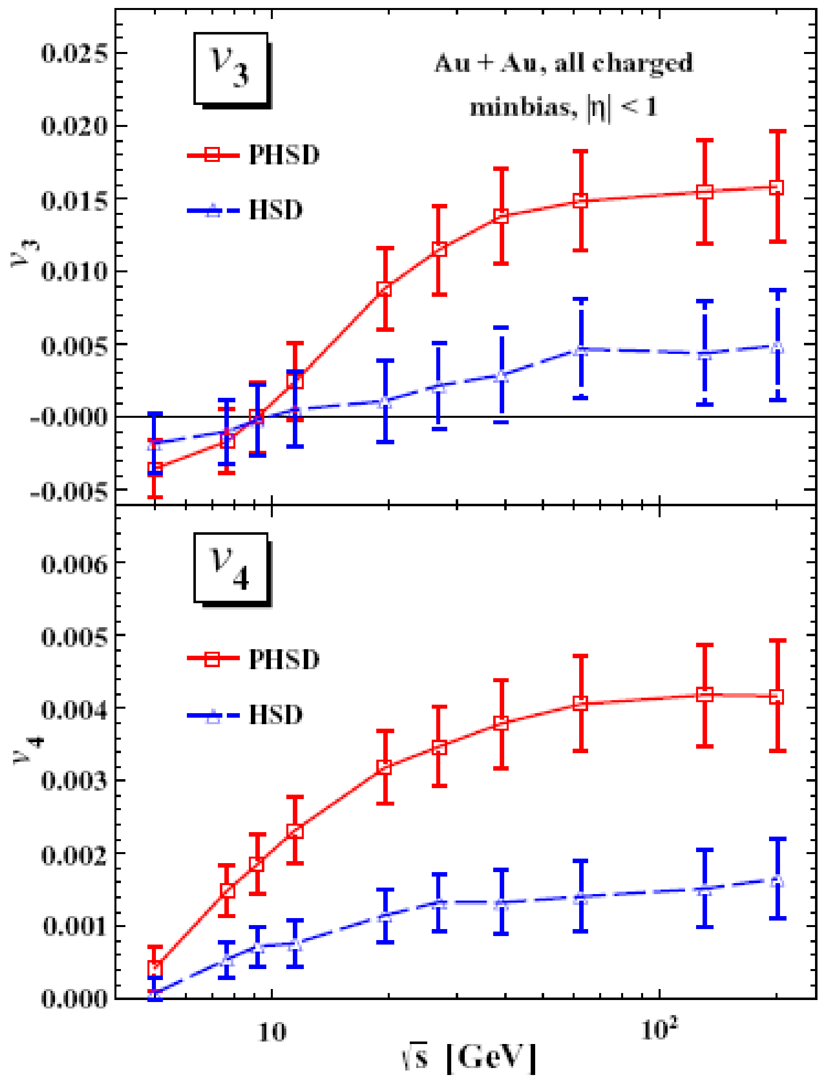


- increase of v_2 with impact parameter but flat v_3 and v_4

V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

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

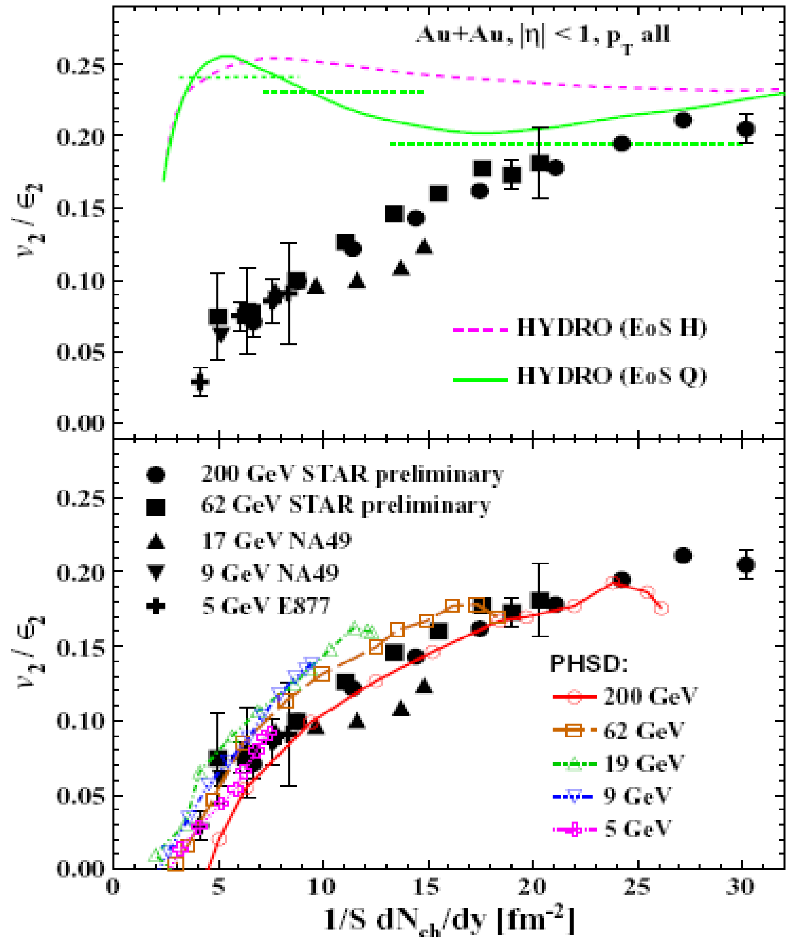


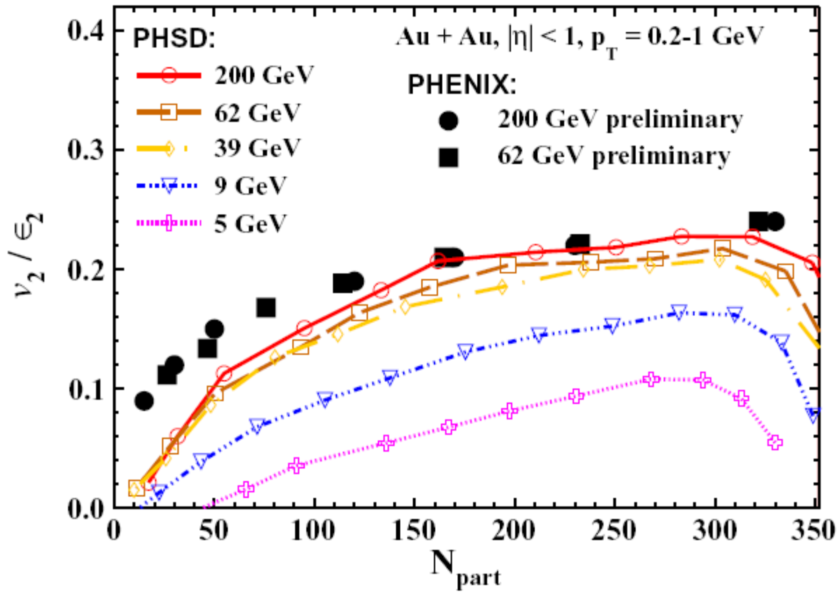


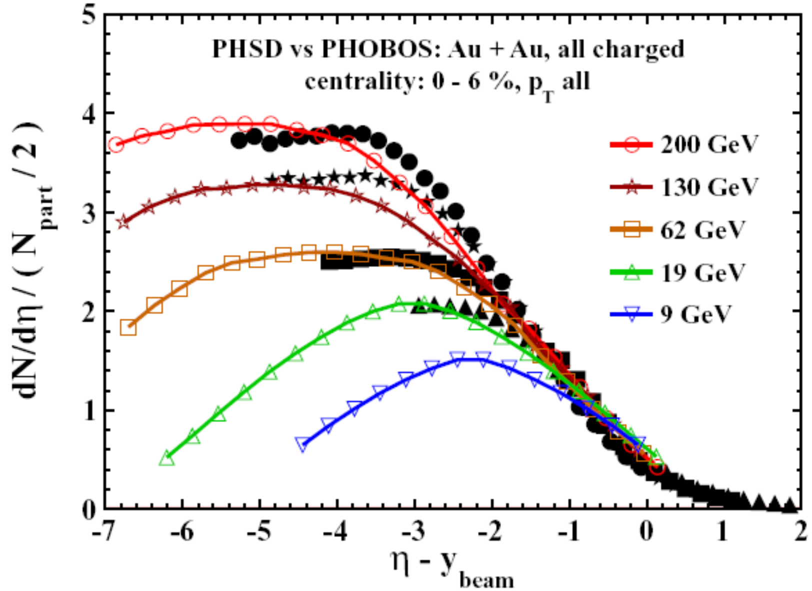
- v_3, v_4 from PHSD are systematically larger than those from HSD
- very low v_3 and v_4 at FAIR/NICA energies
- almost constant $v_4/(v_2)^2$ for PHSD

V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

Scaling properties





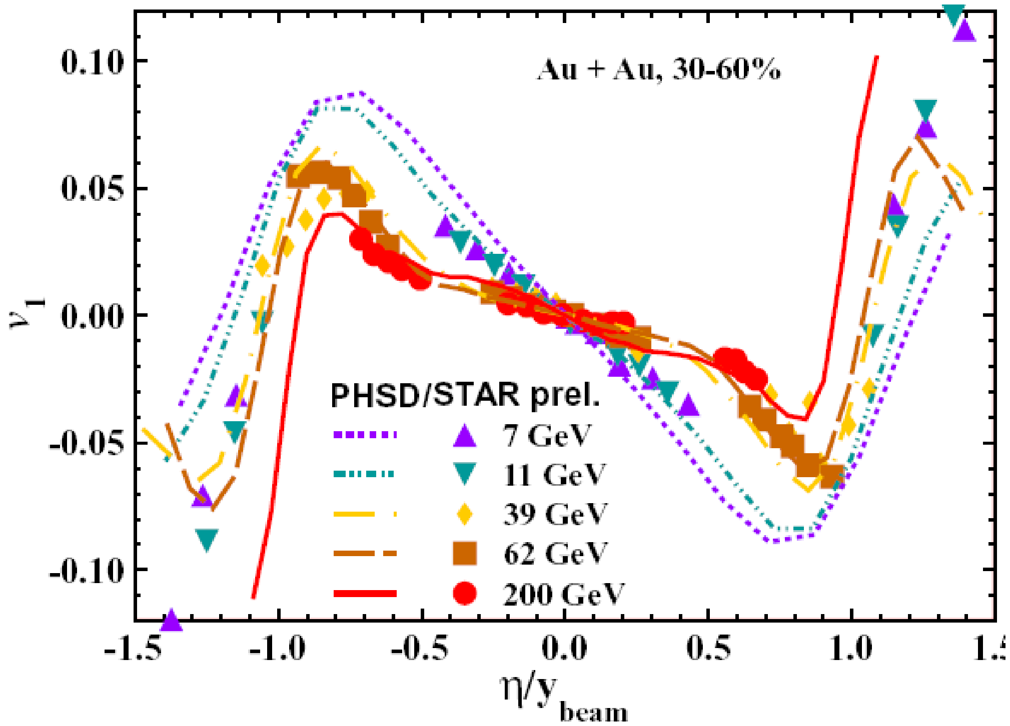


- **PHSD: v_2/ε vs. centrality follows an approximate scaling with energy in line with experimental data**

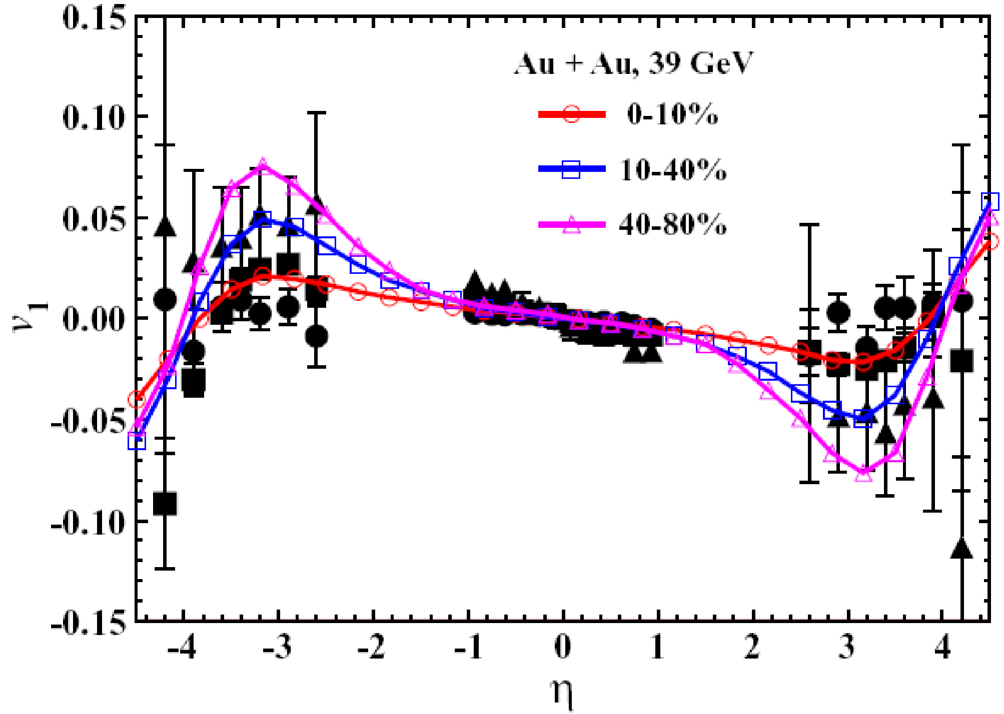
V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

In-plane flow v_1

versus beam energy



versus centrality

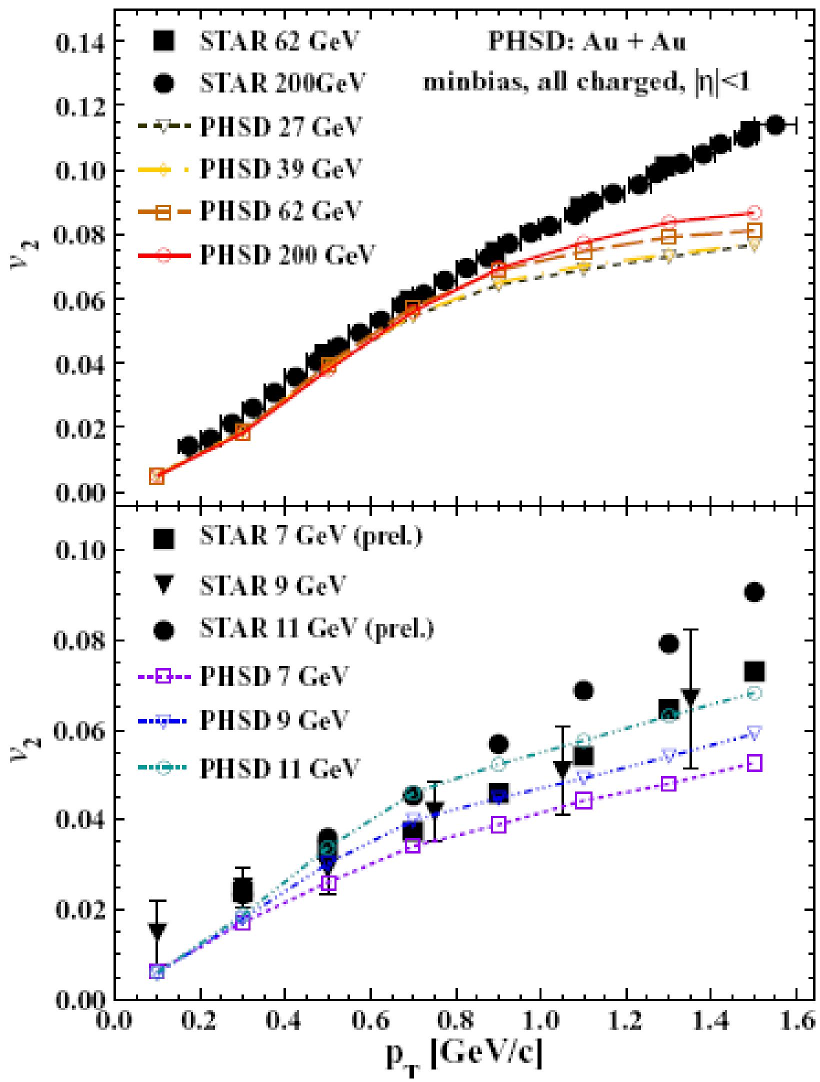


- PHSD: v_1 vs. pseudo-rapidity follows an approximate scaling for high invariant energies $s^{1/2}$=39, 62, 200 GeV - in line with experimental data – whereas at low energies the scaling is violated!

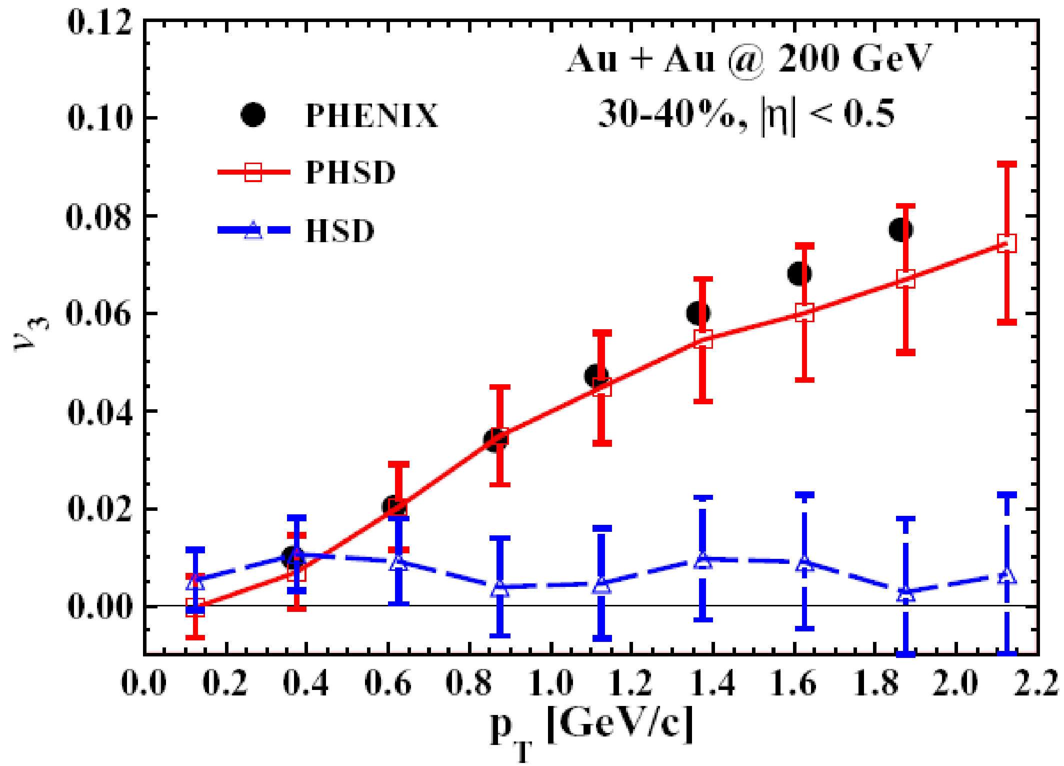
V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

Transverse momentum dependence

elliptic flow



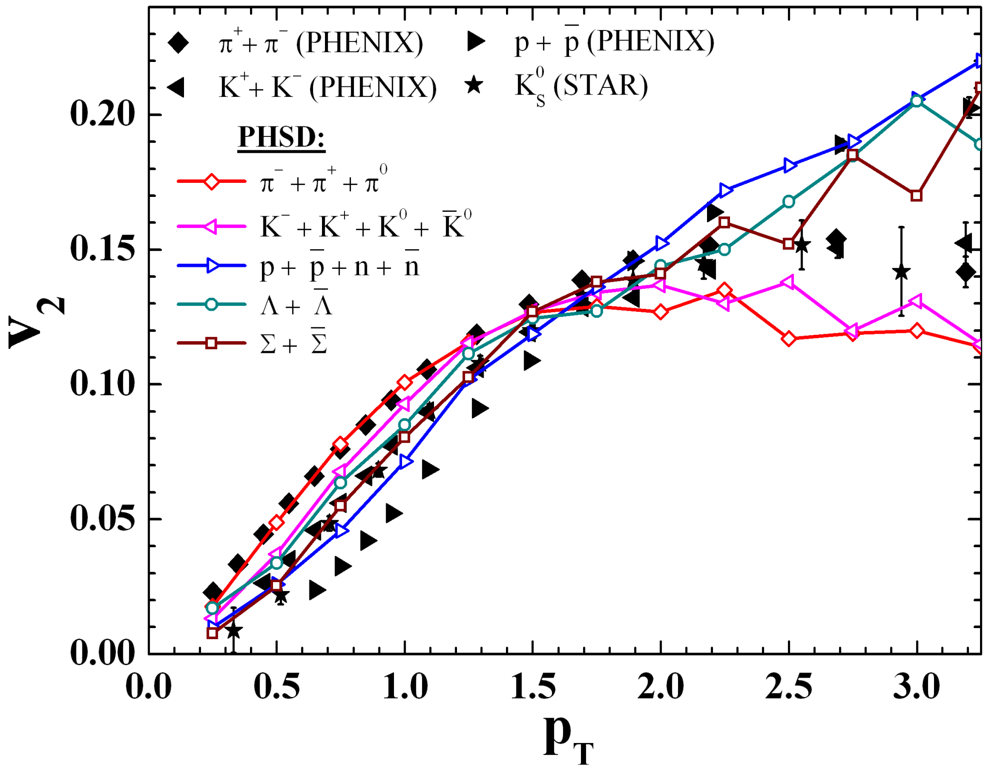
triangular flow

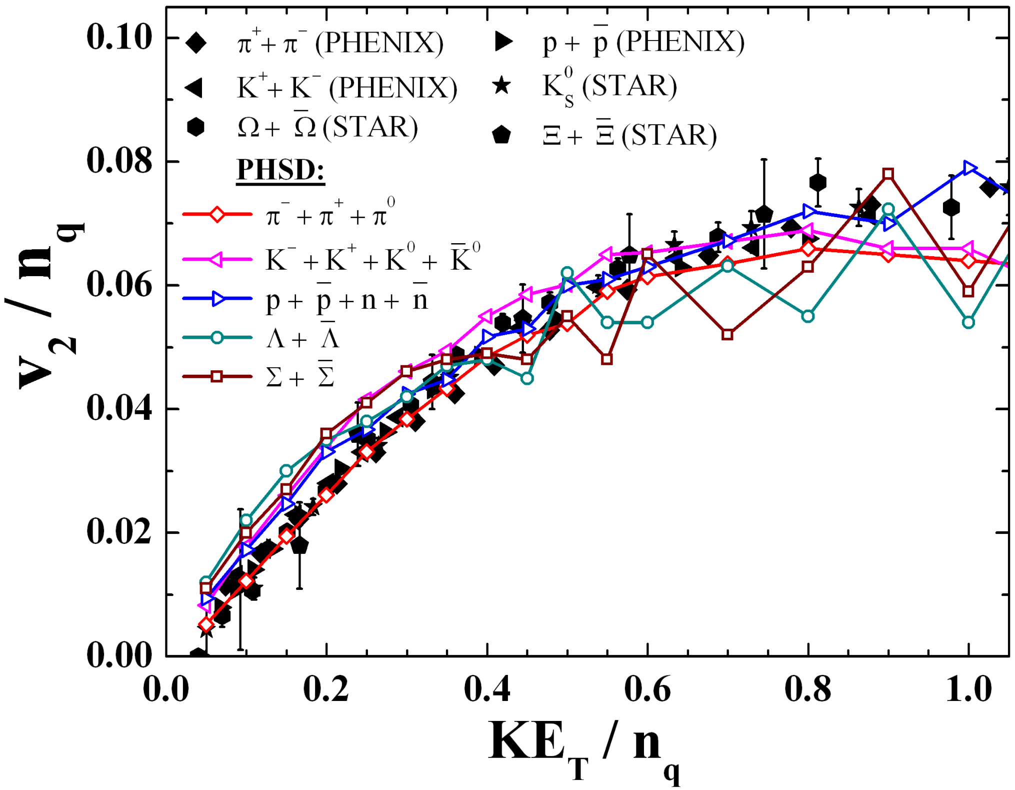


- v_2 vs. p_T follows an approximate scaling for high invariant energies $s^{1/2}$=27, 39, 62, 200 GeV
- v_3 : needs partonic degrees-of-freedom !

V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

Elliptic flow scaling at RHIC

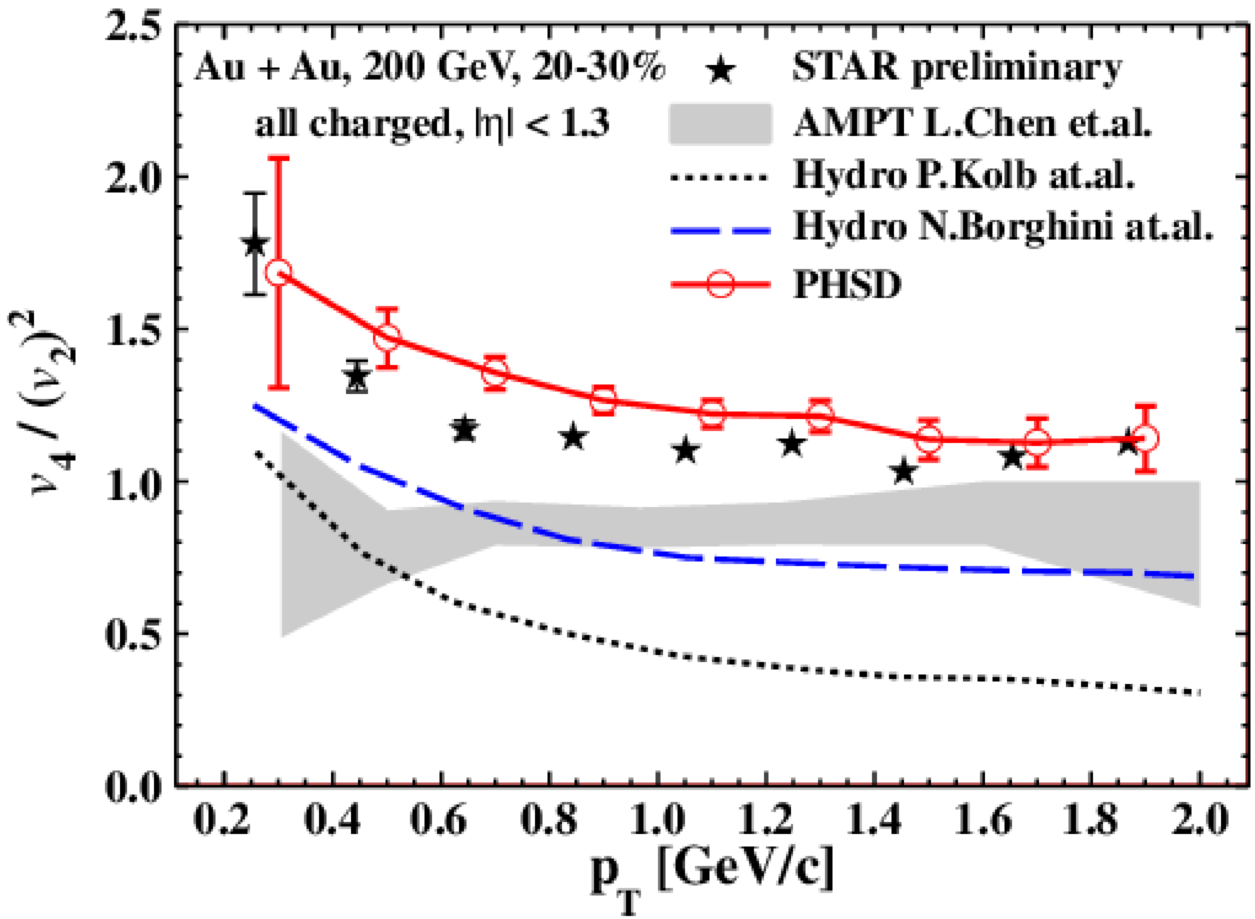




- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

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

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

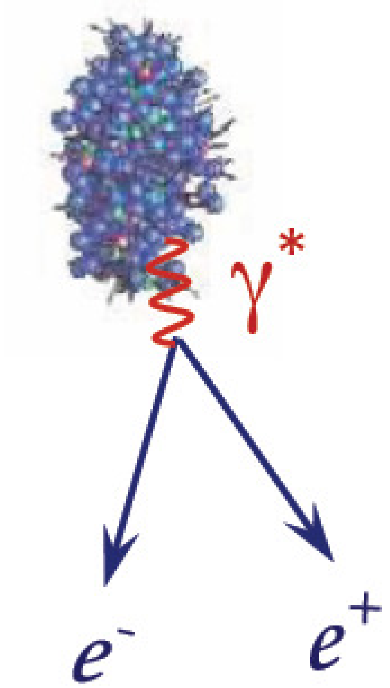


The ratio $v_4/(v_2)^2$:

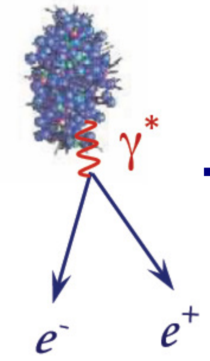
- is very sensitive to the microscopic dynamics
- PHSD: ratio grows at low p_T - in line with exp. data

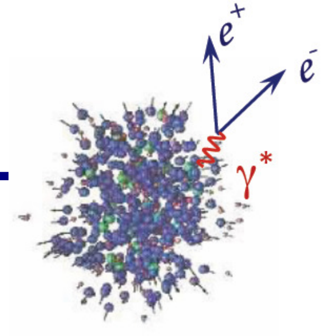
V. P. Konchakovski et al., PRC (2012), arXiv:1201.3320

Dileptons



Electromagnetic probes: dileptons and photons





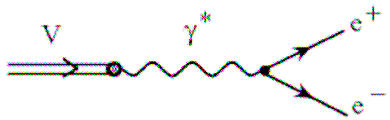
➢ Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions

Dilepton sources:

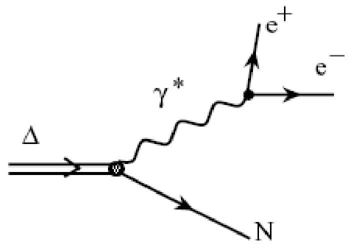
- from the QGP via partonic (q,qbar, g) interactions:

- from hadronic sources:

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

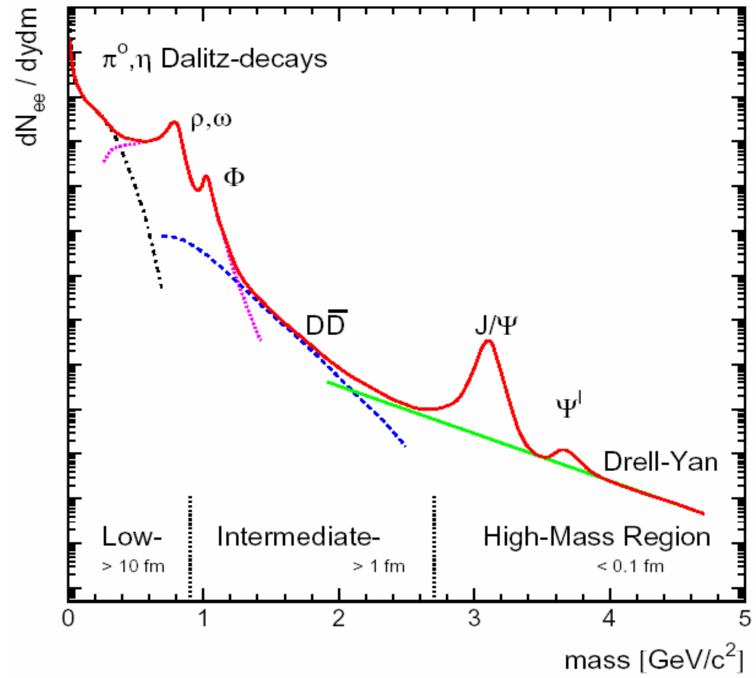


•Dalitz decay of mesons and baryons (π^0,η, Δ,…)



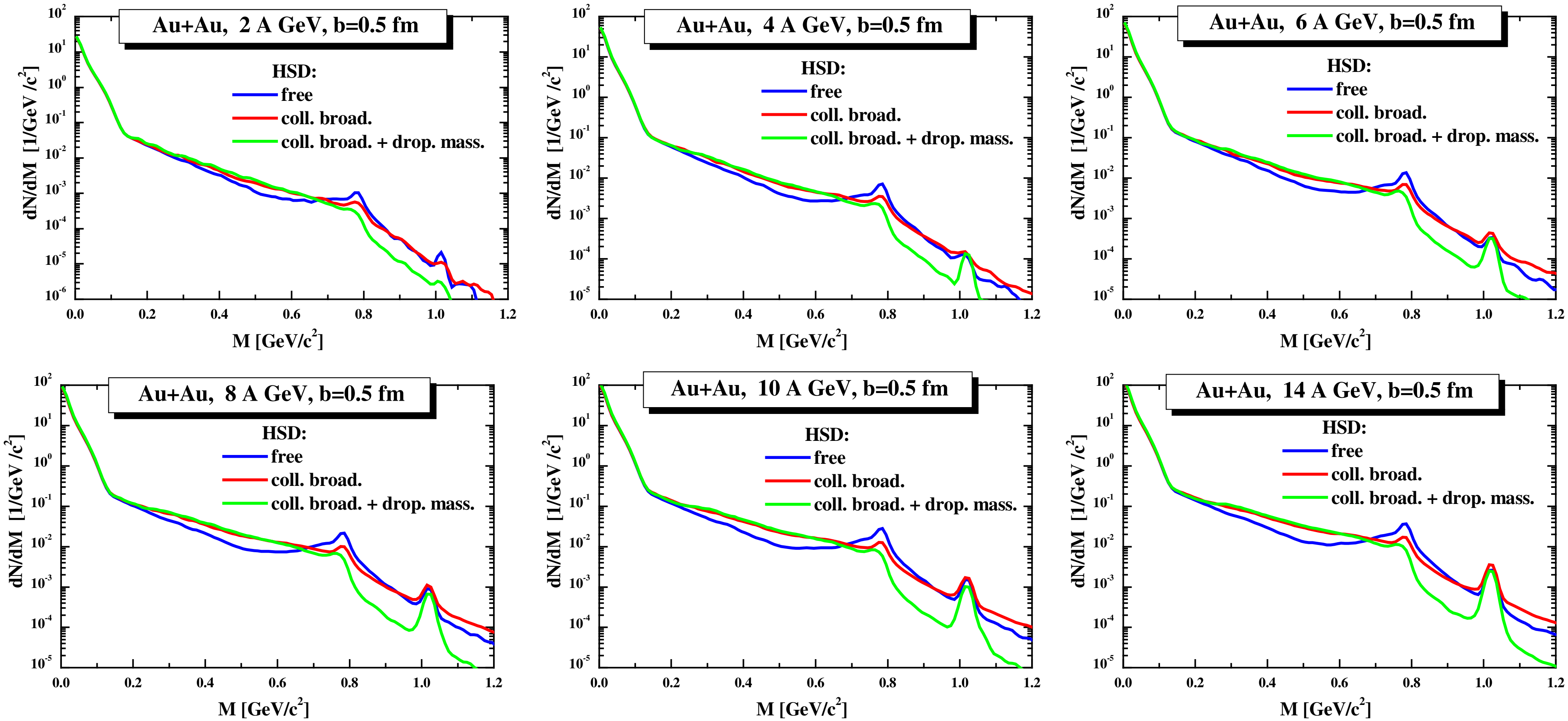
•correlated D+Dbar pairs

•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 from SIS to FAIR/NICA

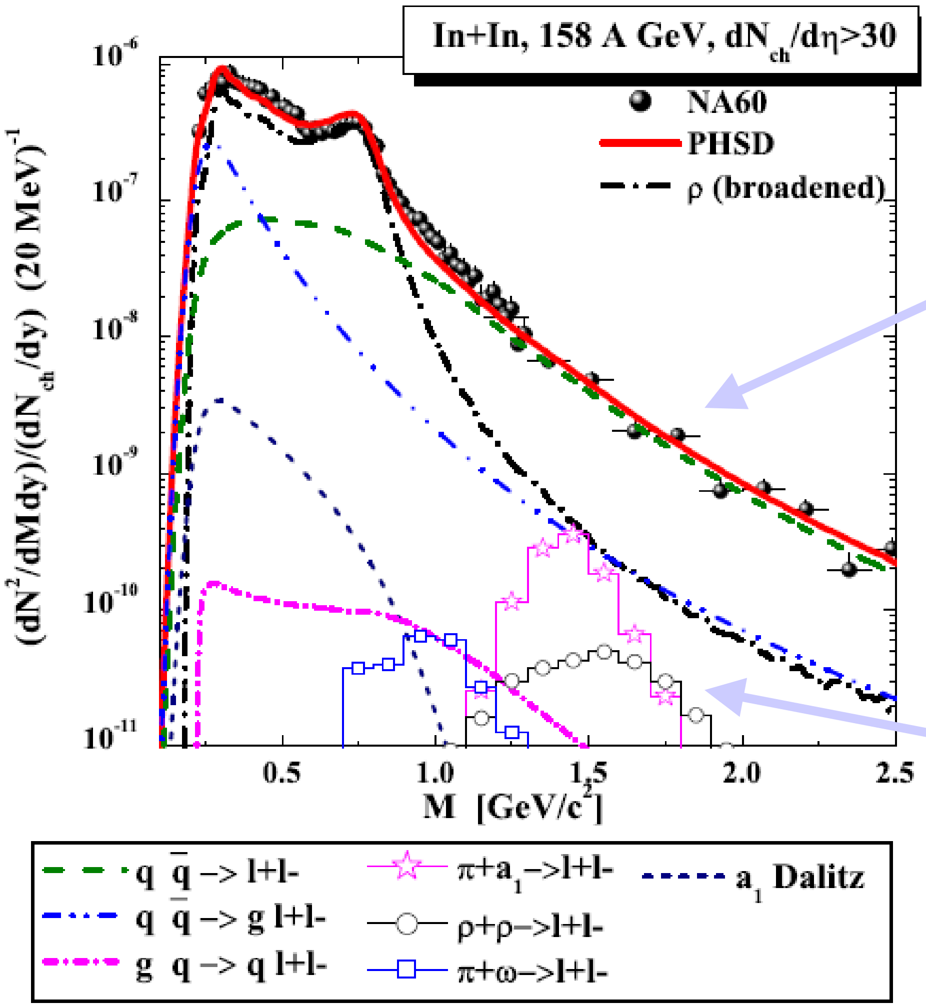


Dileptons : ‚free‘ vs. ‚in-medium‘ scenarios (collisional broadening , collisional broadening +dropping mass) for vector mesons (ρ,ω,ϕ)

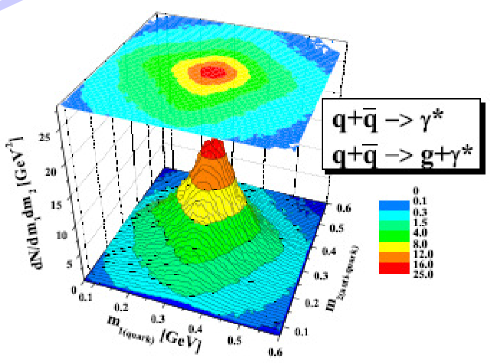
➔enhancement of dilepton yield for 0.2<M<0.7 GeV and
➔reduction at $M \sim m_{\rho/\omega}$ for all energies from SIS to FAIR/NICA!

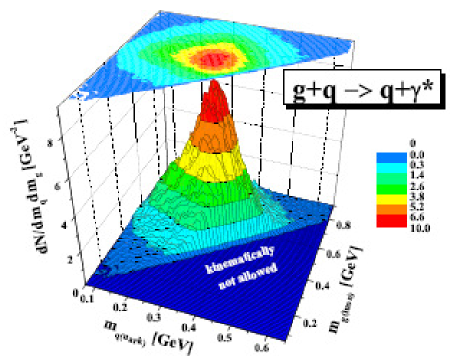
Dileptons at SPS: NA60

Acceptance corrected NA60 data



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

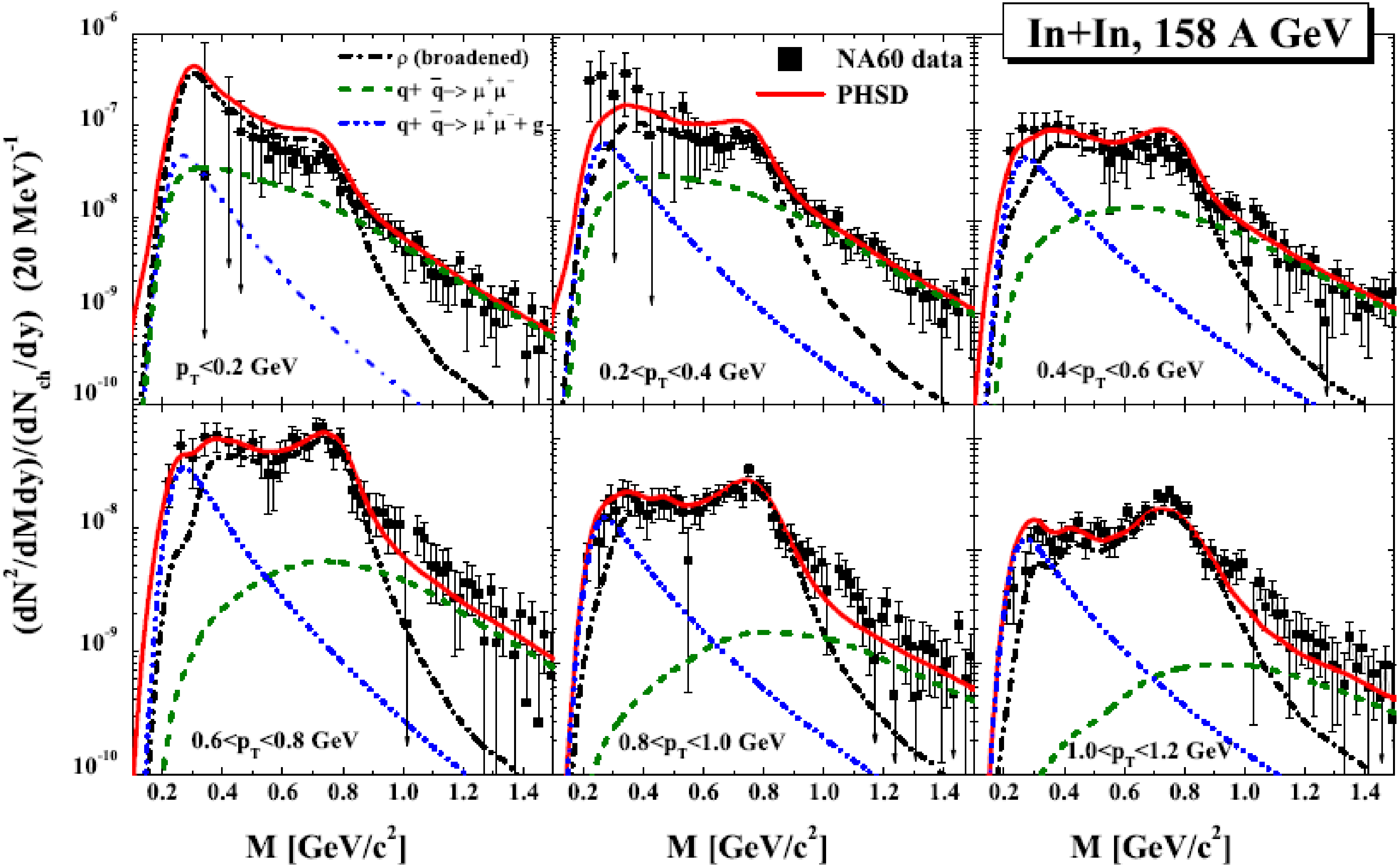




- Contributions of "4π" channels (radiation from multi-meson reactions) are small

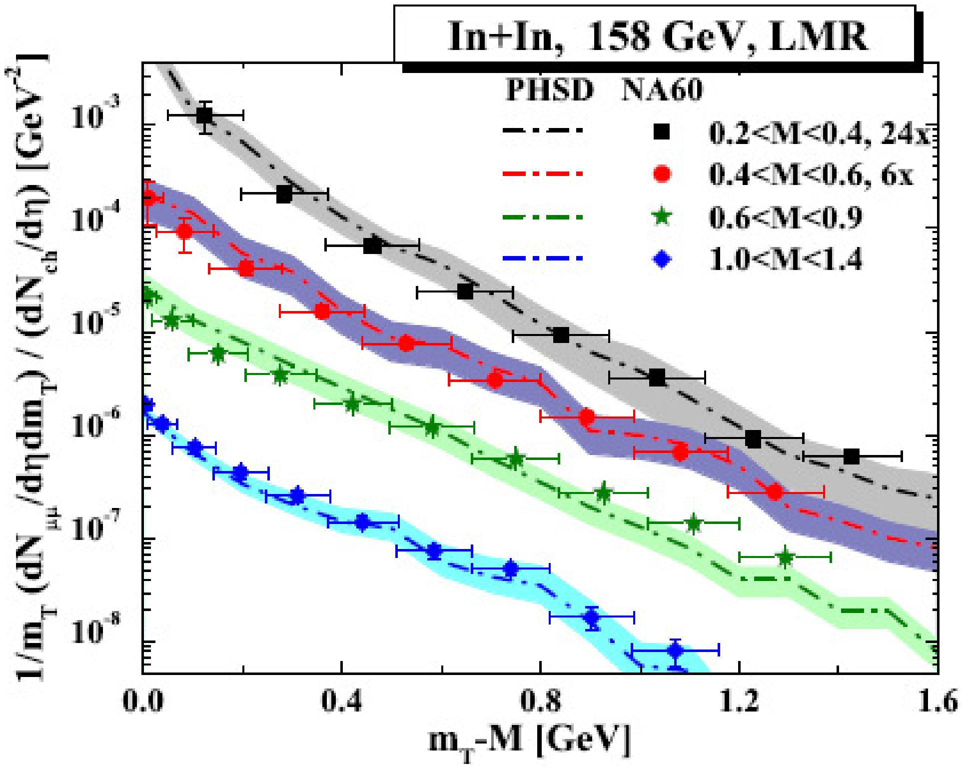
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

Dileptons at SPS: NA60

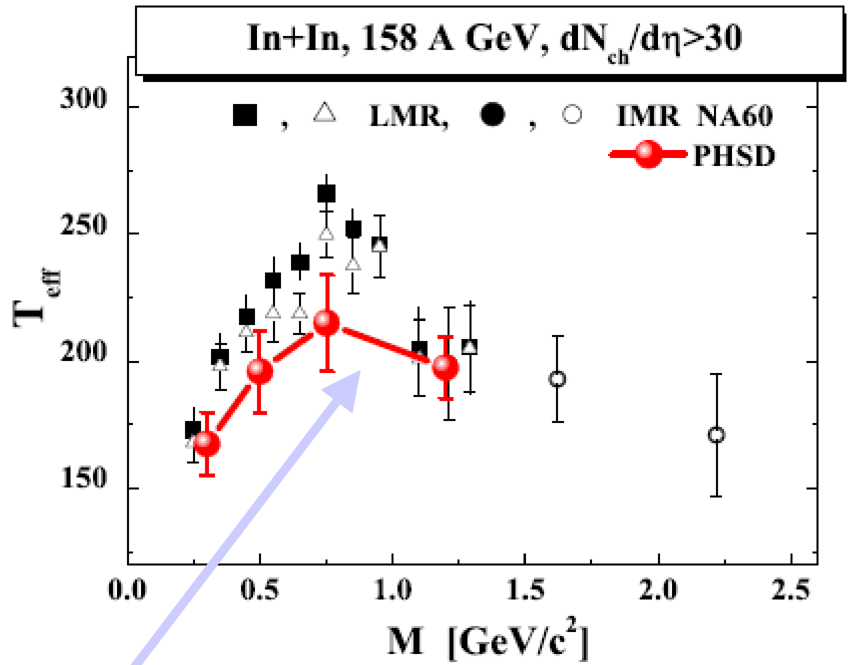


O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60: m_T spectra



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

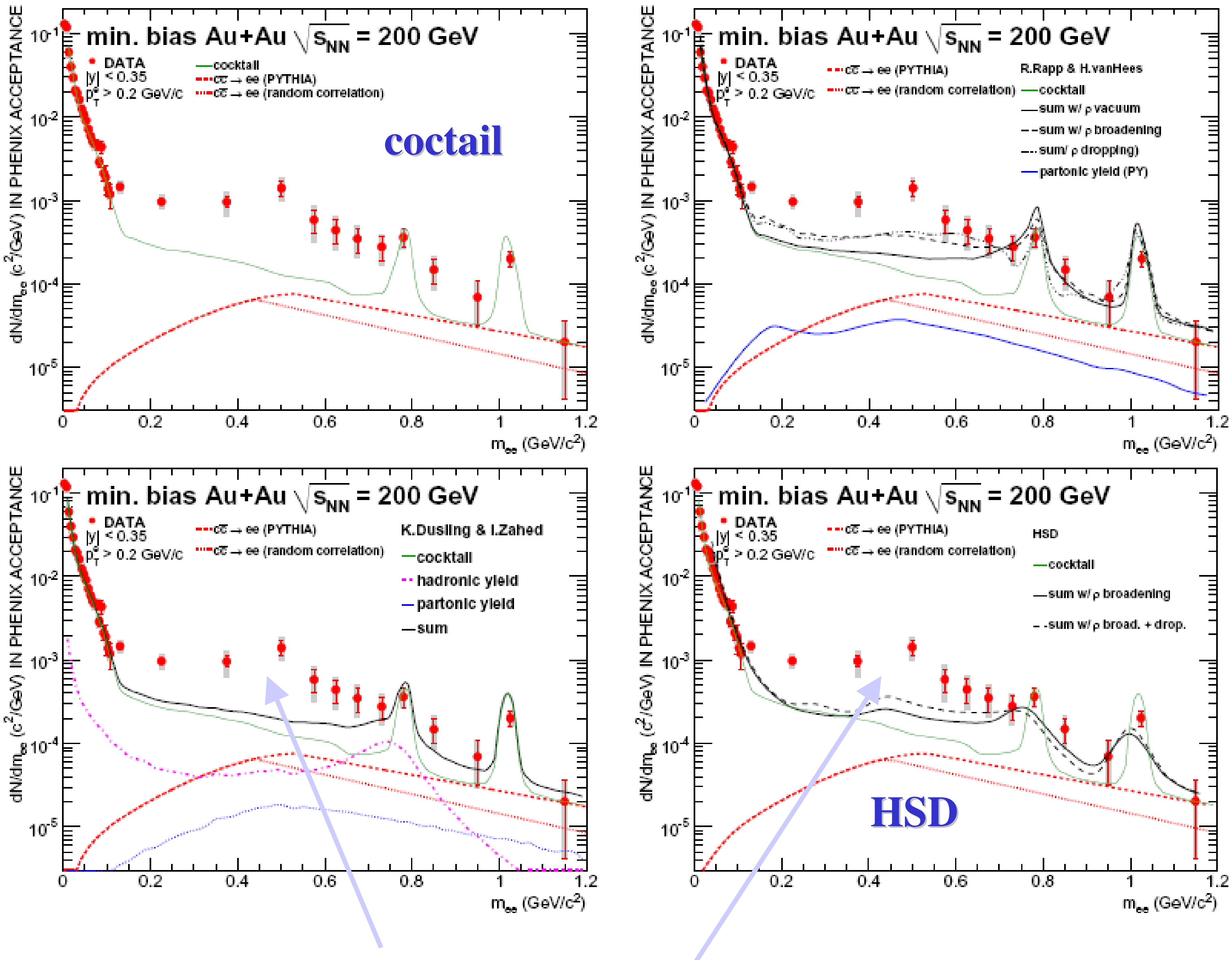


Conjecture:

▪ 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

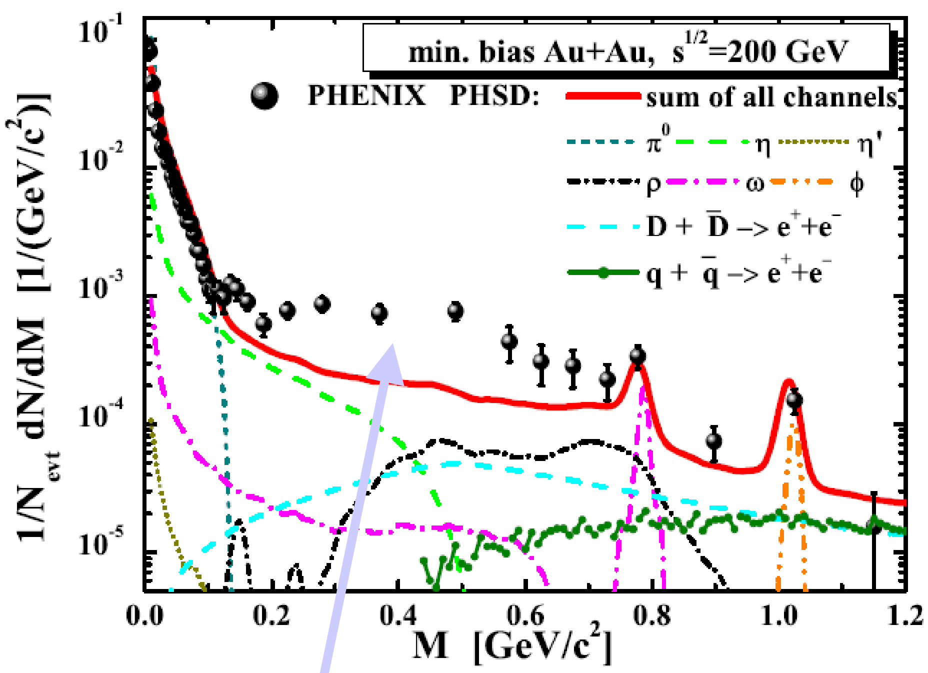
Dileptons at RHIC: data vs. theor. models

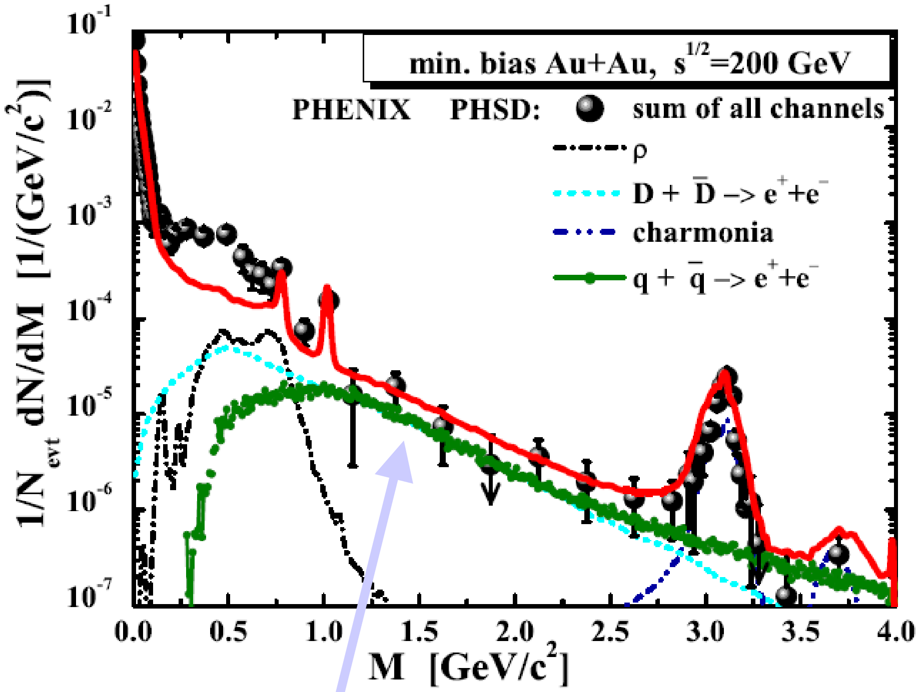


PHENIX: Au+Au

➔ **PHENIX dilepton puzzle ?!**

PHENIX: dileptons from partonic channels



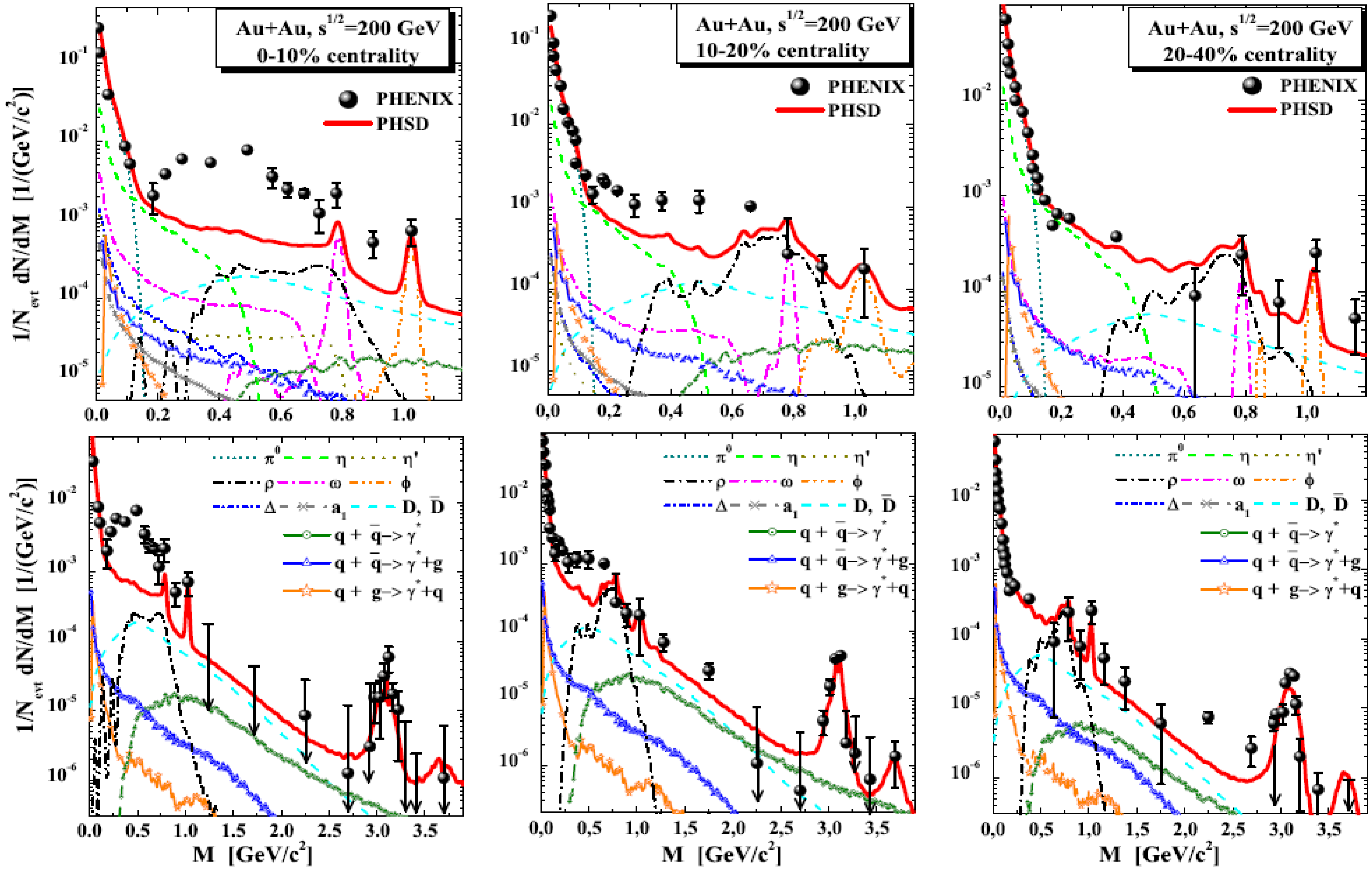


- The **excess** over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD

- 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

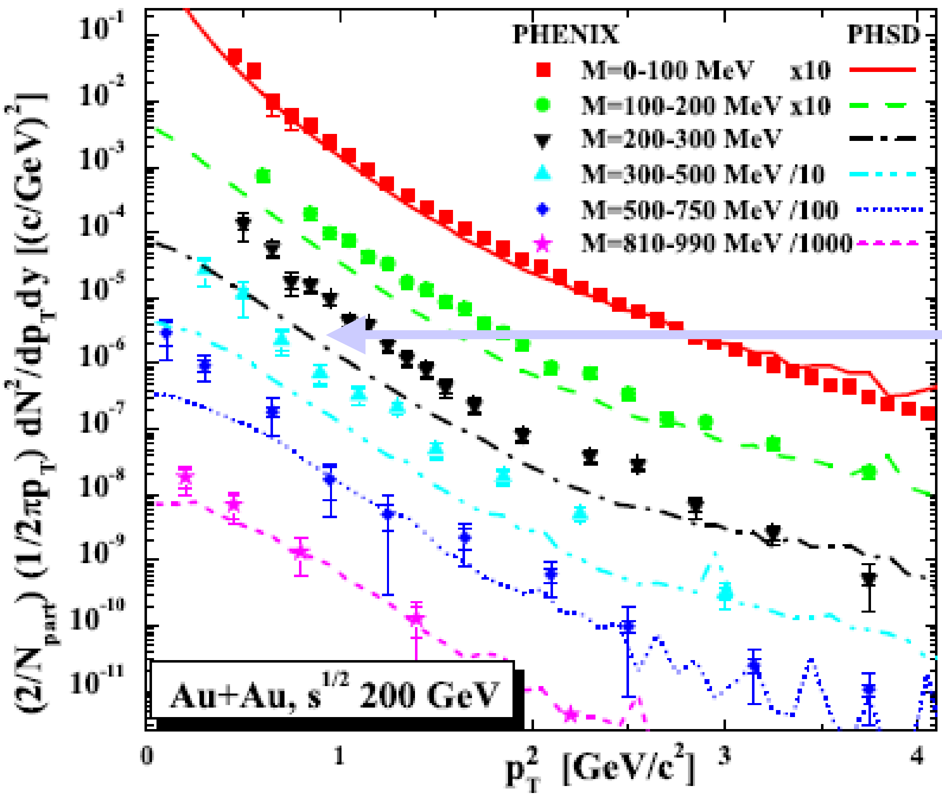


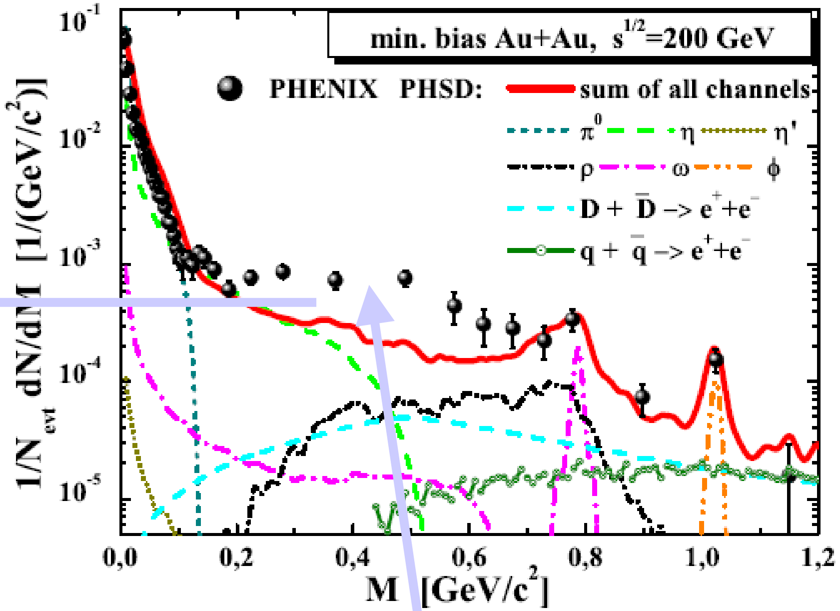
(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

- **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

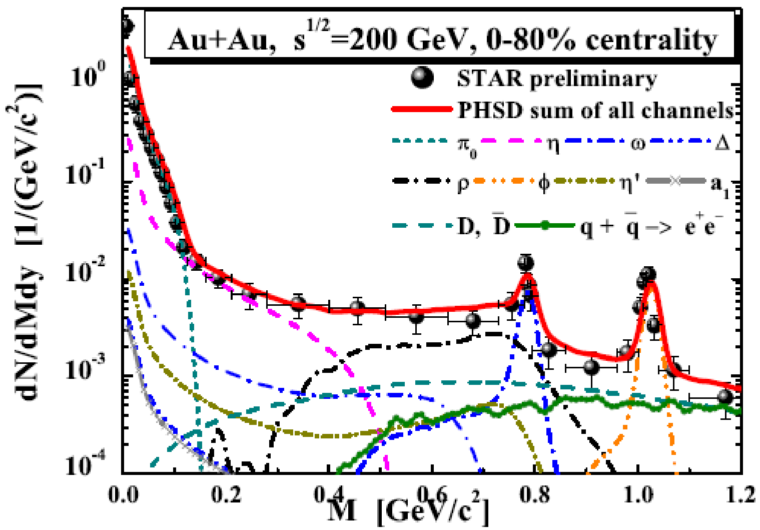


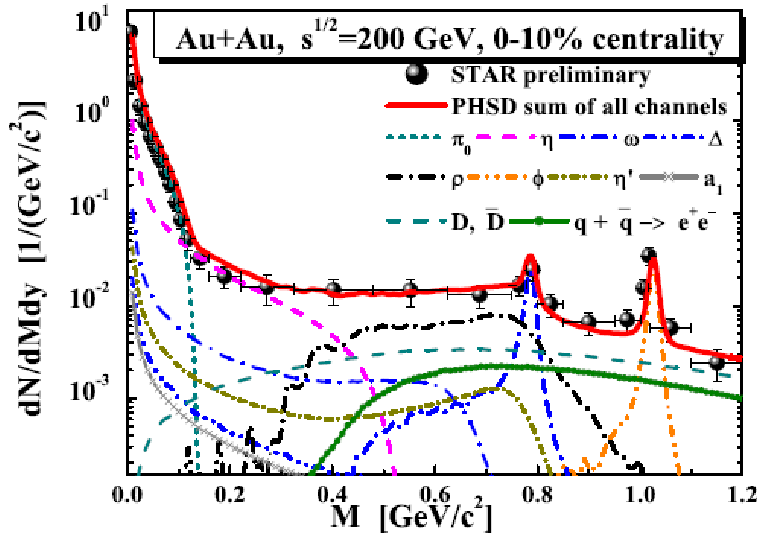


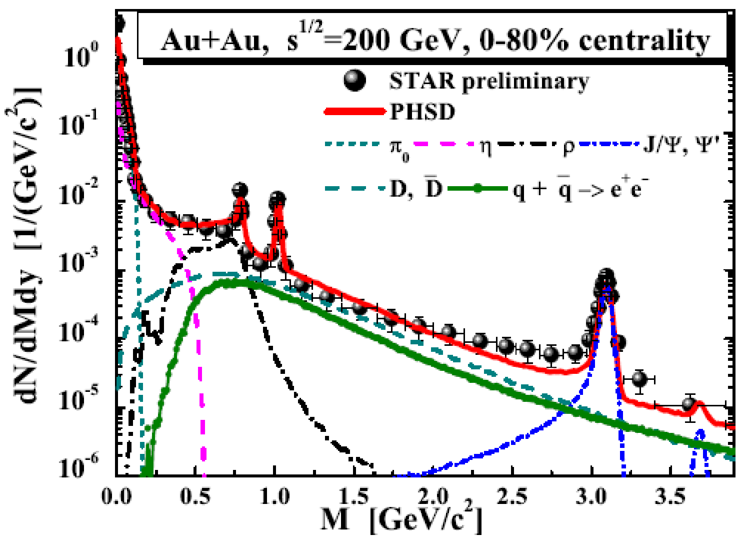
- The lowest and highest mass bins are described very well
- Underestimation of p_T data for 100<M<750 MeV bins consistent with dN/dM
- The 'missing source'(?) is located at low p_T !

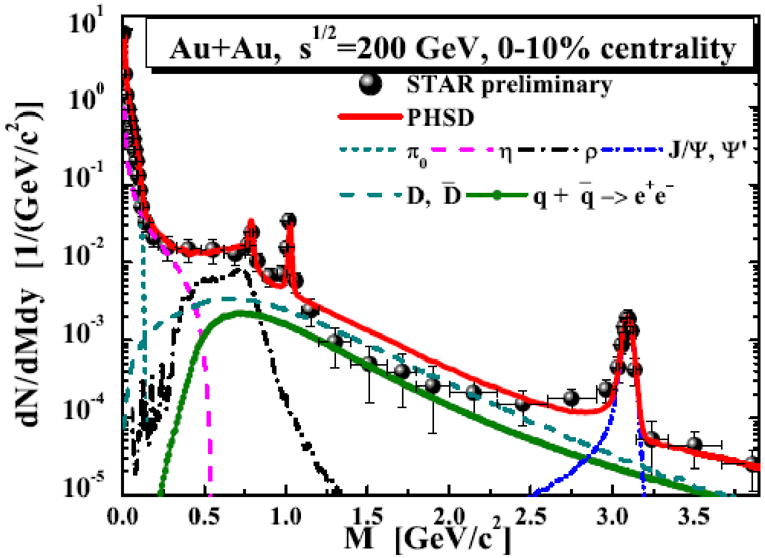
O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

STAR: mass spectra





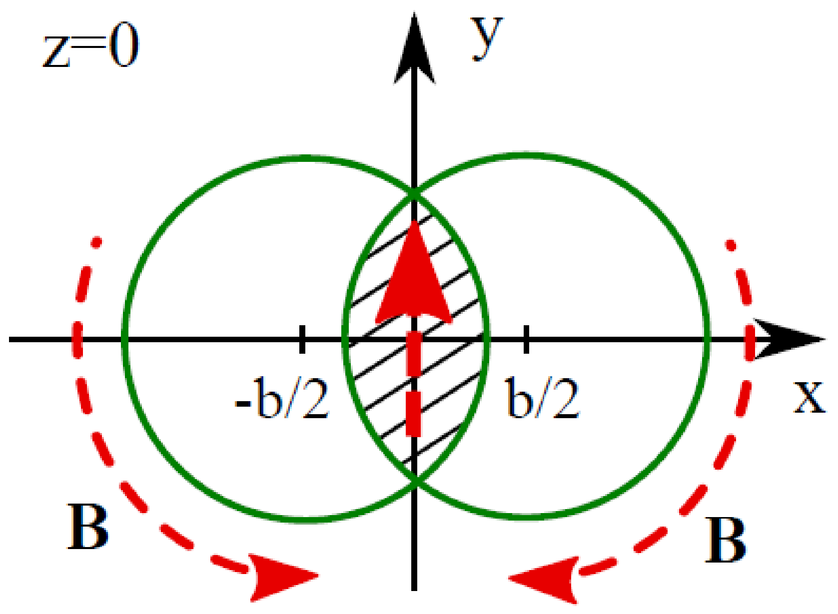




- **STAR data are well described!**

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

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 :

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

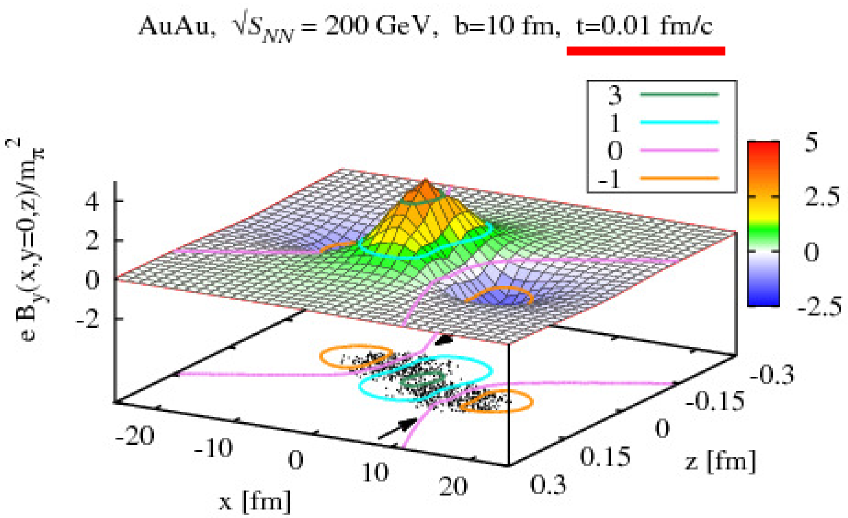
$$\dot{\vec{p}} \rightarrow -\vec{\nabla}_r U + e\vec{E} + e\vec{v} \times \vec{B}$$

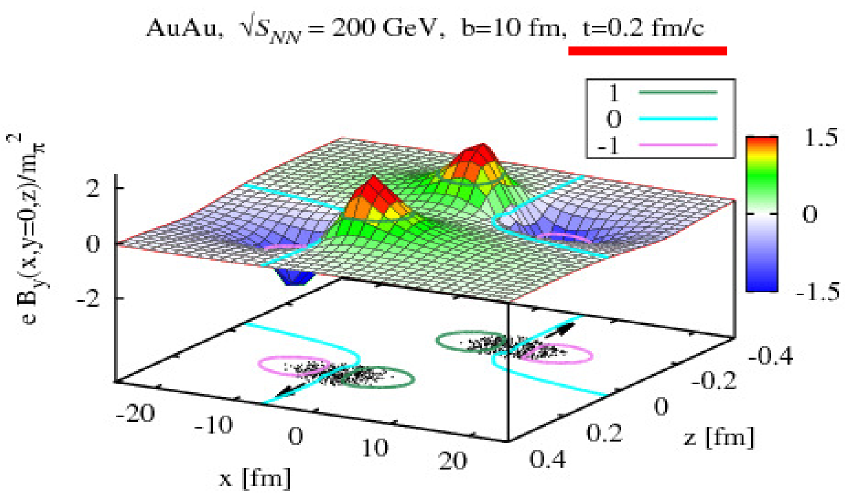
$$\begin{cases} \vec{B} = \vec{\nabla} \times \vec{A} \\ \vec{E} = -\vec{\nabla}\Phi - \dfrac{\partial \vec{A}}{\partial t} \end{cases}$$

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

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

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

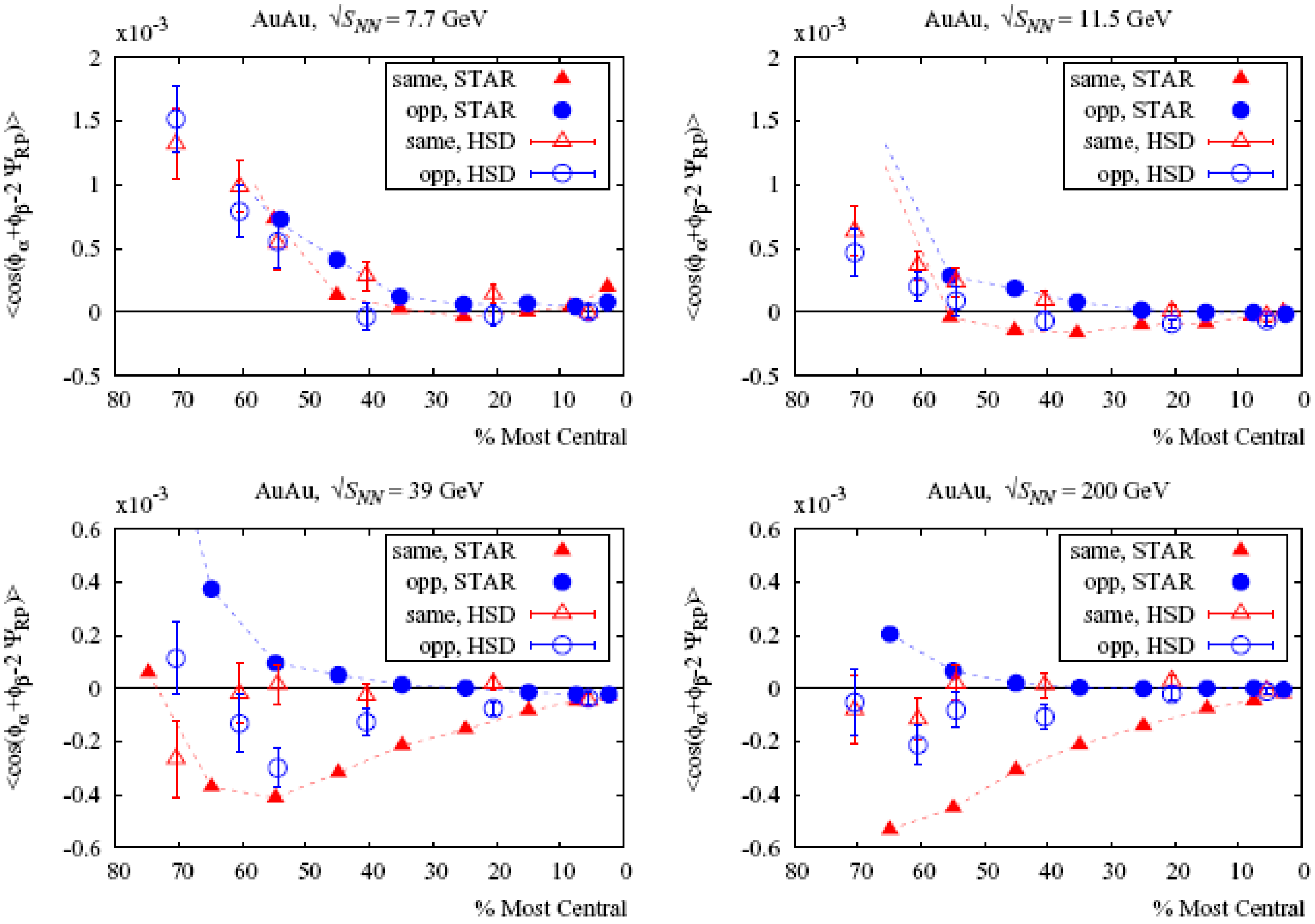




V. Voronyuk, et al., Phys.Rev. C83 (2011) 054911

Angular correlation wrt. reaction plane

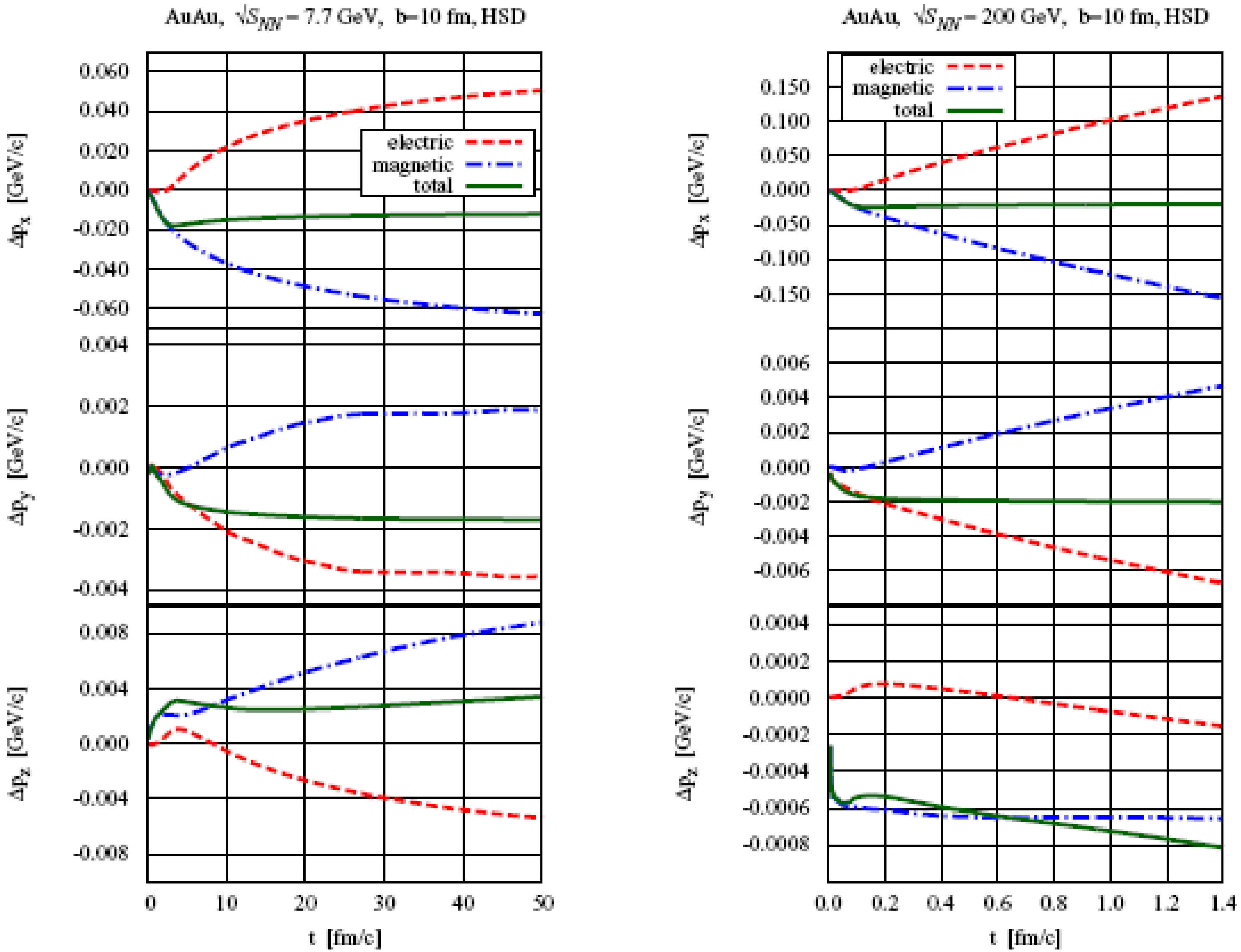
$$\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle$$



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

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

Compensation of magnetic and electric forces



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

V. D. Toneev et al., PRC 85 (2012), 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

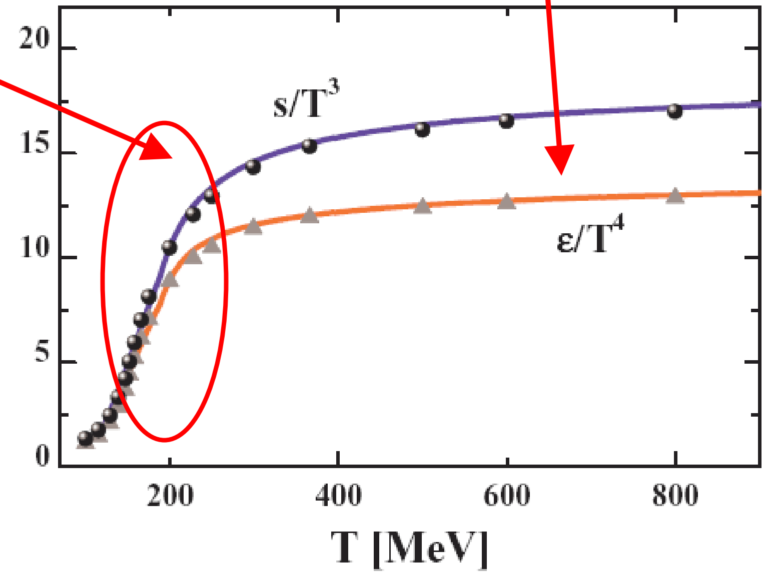
⇒ formation of the sQGP !

Outlook - Perspectives

What is the stage of matter close to T_c :

Lattice EQS ➔ ‚crossover' , $T > T_c$

- ❑ 1st order phase transition?
- ❑ ‚Mixed' phase = interaction of partonic and hadronic degrees of freedom?



Open problems:

- How to describe a first-order phase transition in transport models?
- How to describe parton-hadron interactions in a ‚mixed' phase?

A possible solution (?) :

➢ ‚mixed' phase description within molecular dynamics?

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- Sergei Voloshin