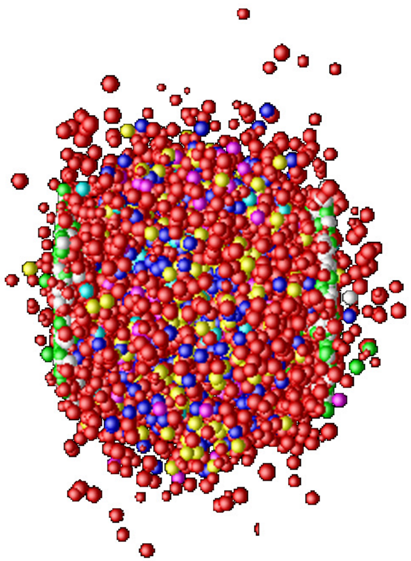
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Parton dynamics in heavy-ion collisions from FAIR to LHC



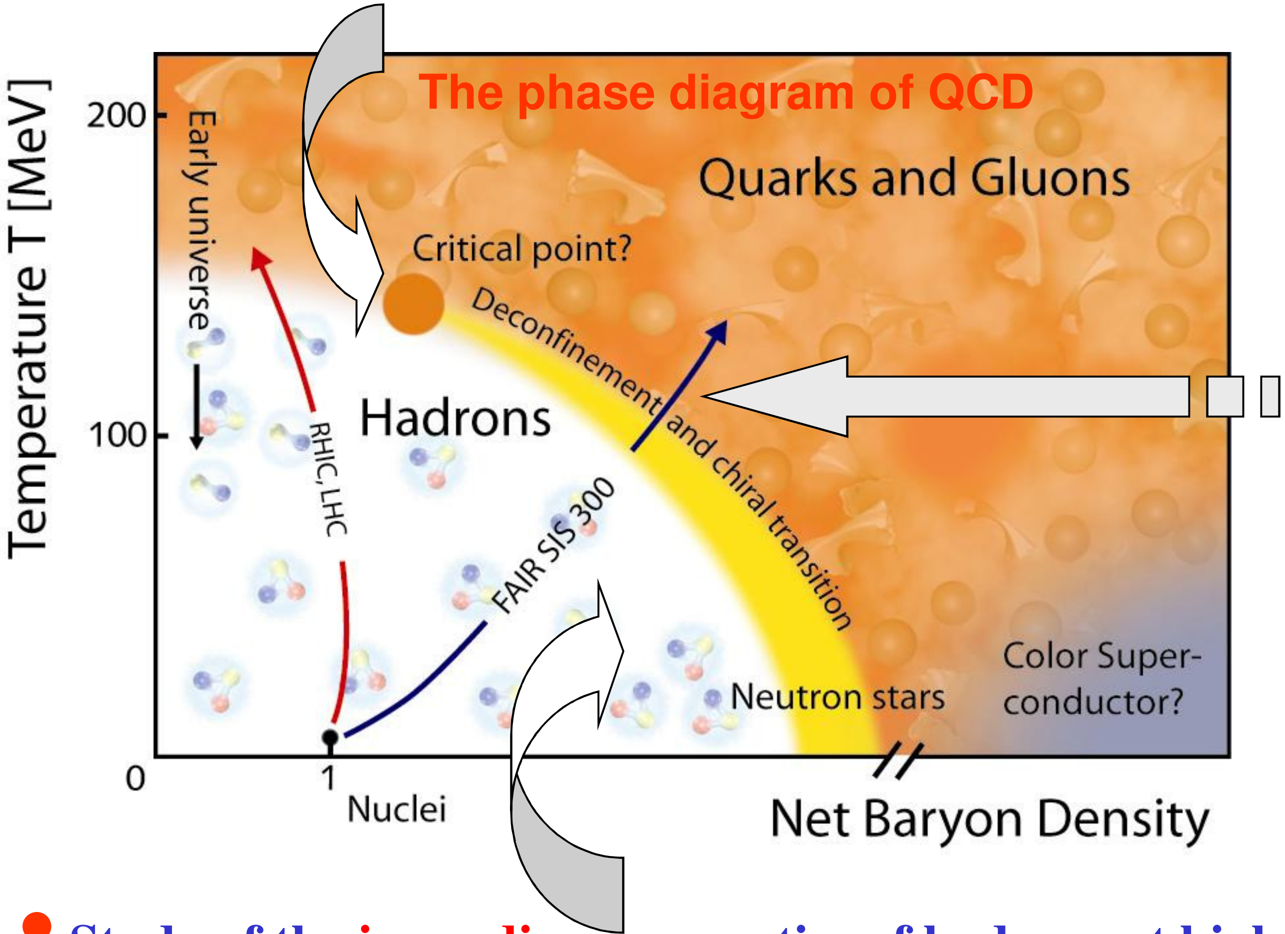
Wolfgang Cassing

Erice, 21.09.2012

PHSD

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**

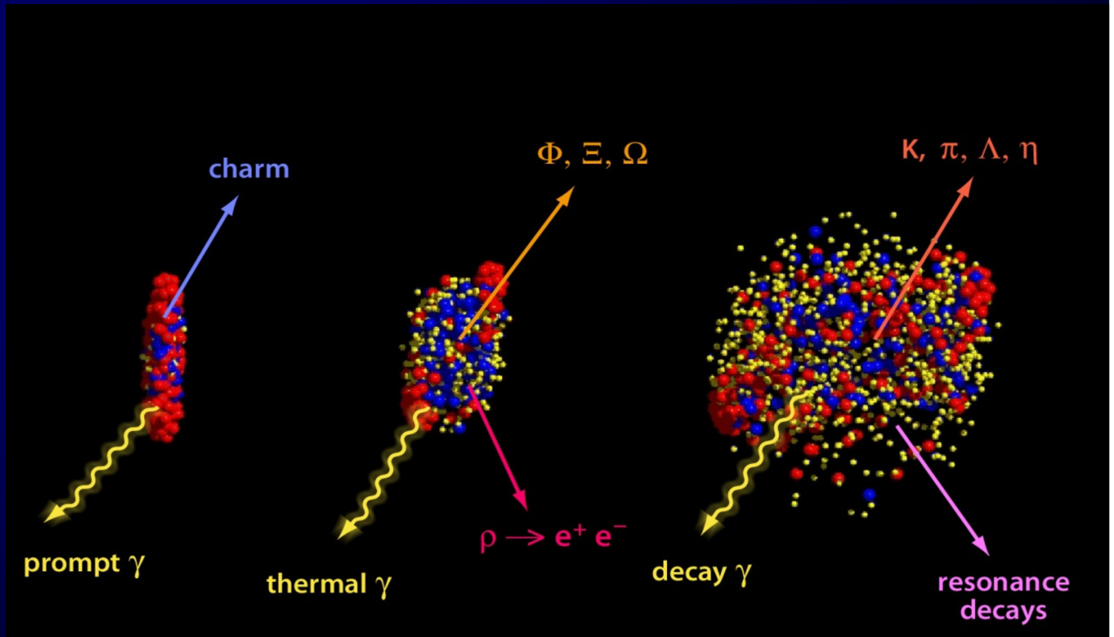
Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2, v_3, v_4)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- Chiral Magnetic Effect ?

Experiment: measures final hadrons and leptons

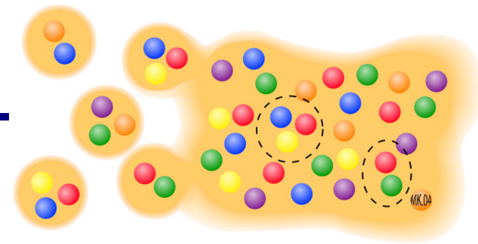
How to learn about physics from data?

Compare with theory!



Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions !

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 :**

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

$$E^2 = p^2 + M^2 - \gamma^2$$

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:**

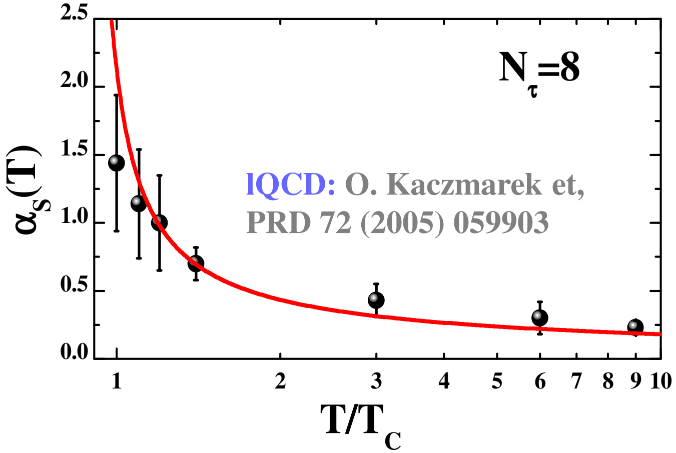
$$M^2(T) = \frac{g^2}{6} \left(\left(N_c + \frac{1}{2} N_f \right) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$$

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

$N_c = 3$, $N_f = 3$

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

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



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

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42

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

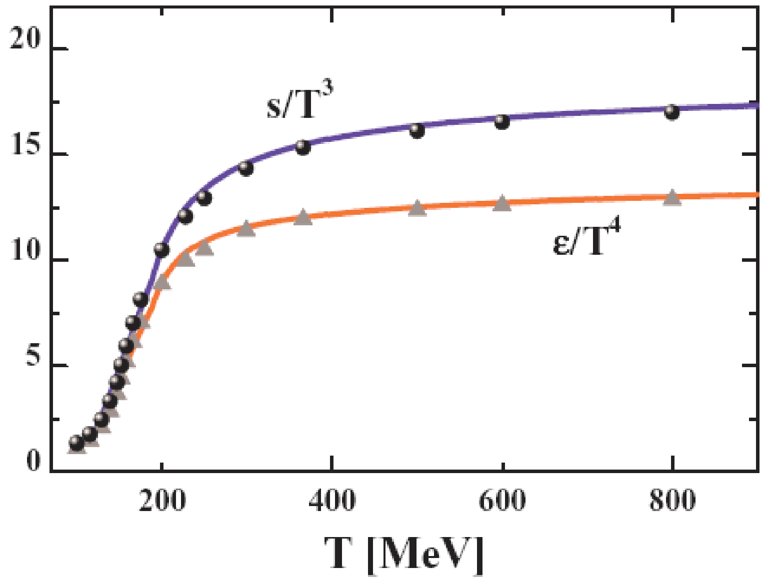
DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM thermodynamics (N_f=3) and lQCD

entropy $s = \frac{\partial P}{dT}$ → **pressure P**

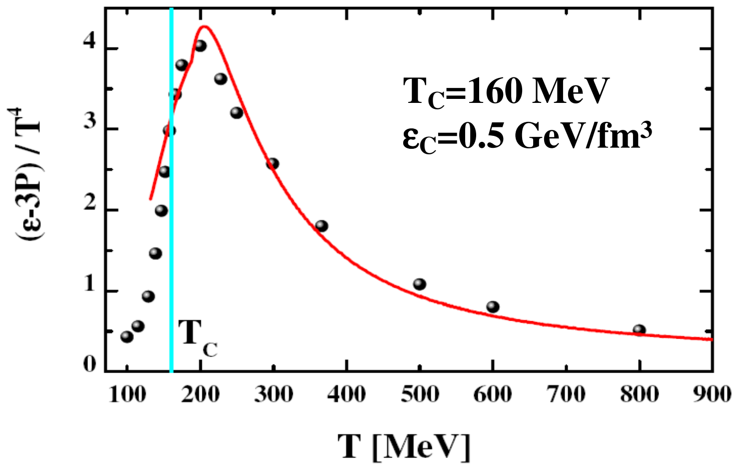
energy density: $\epsilon = Ts - P$

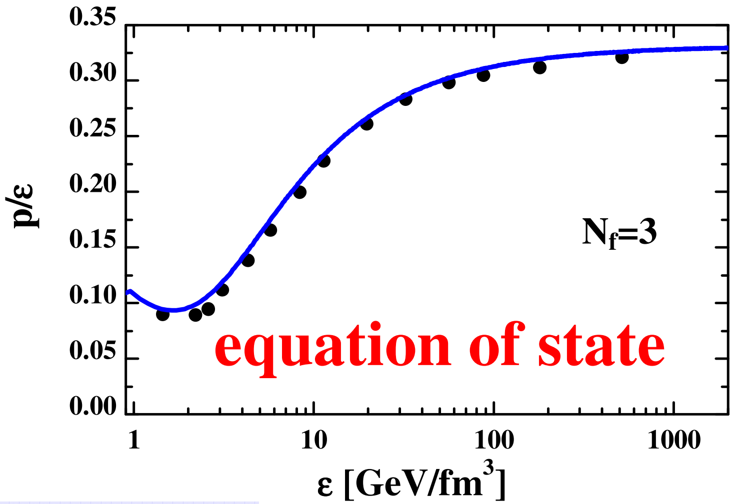
lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.



interaction measure:

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$



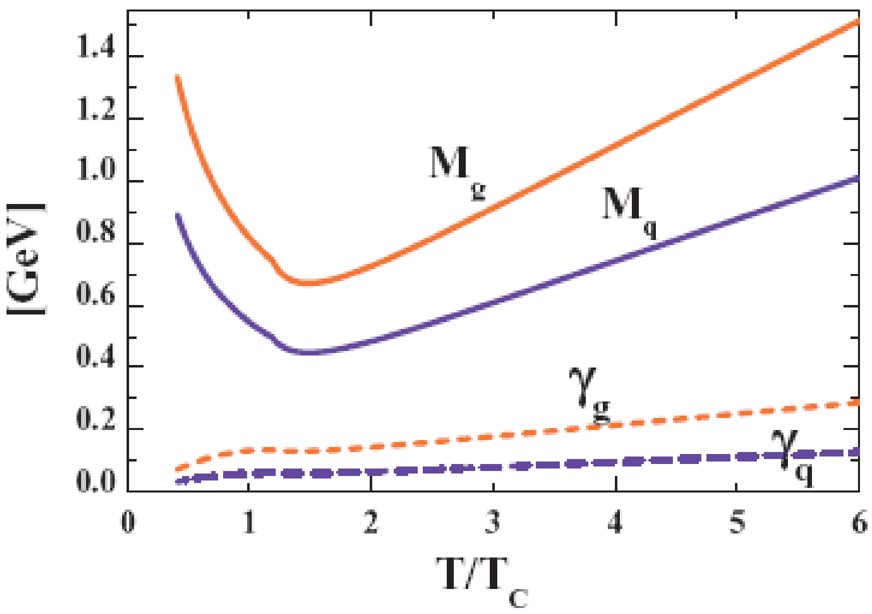


DQPM gives a good description of lQCD results !

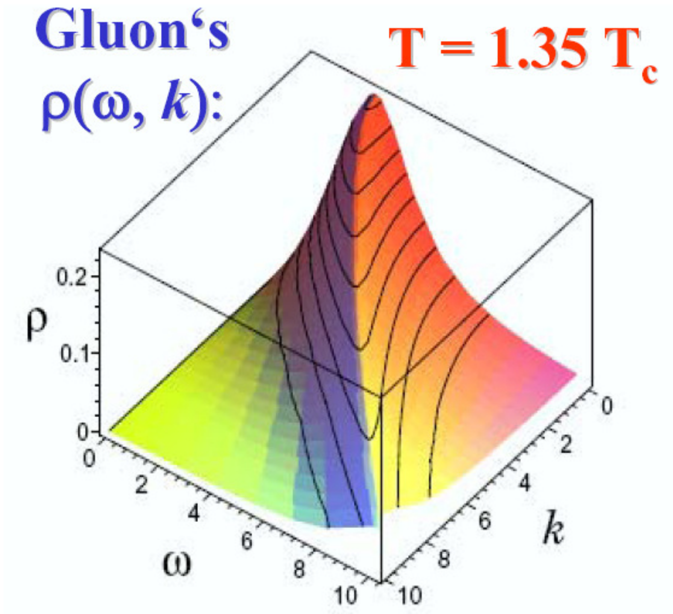
The Dynamical QuasiParticle Model (DQPM)

➔ **Quasiparticle properties:**

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



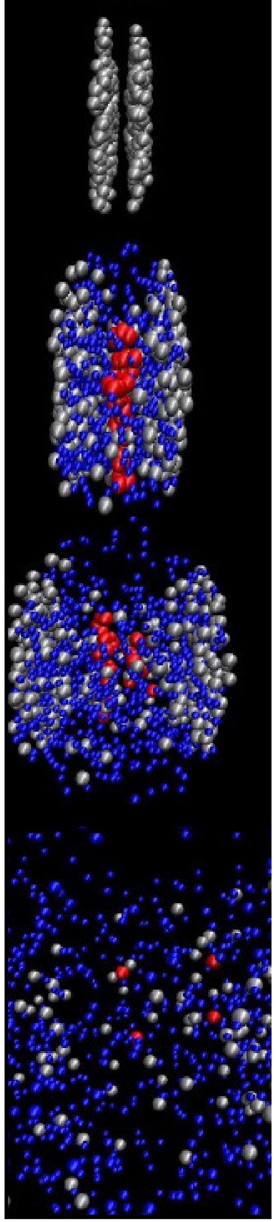
➔ **Broad spectral function :**



- **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 details

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

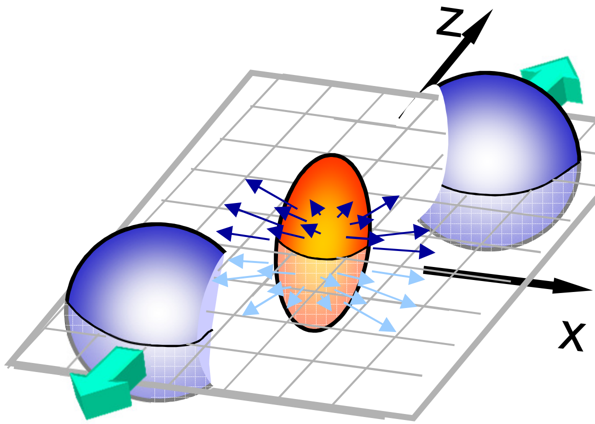
$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}}\ \delta^4(p - p_q - p_{\bar{q}})\ \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q\ \rho_q(p_q)\ \omega_{\bar{q}}\ \rho_{\bar{q}}(p_{\bar{q}})\ |v_{q\bar{q}}|^2\ W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q)\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

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

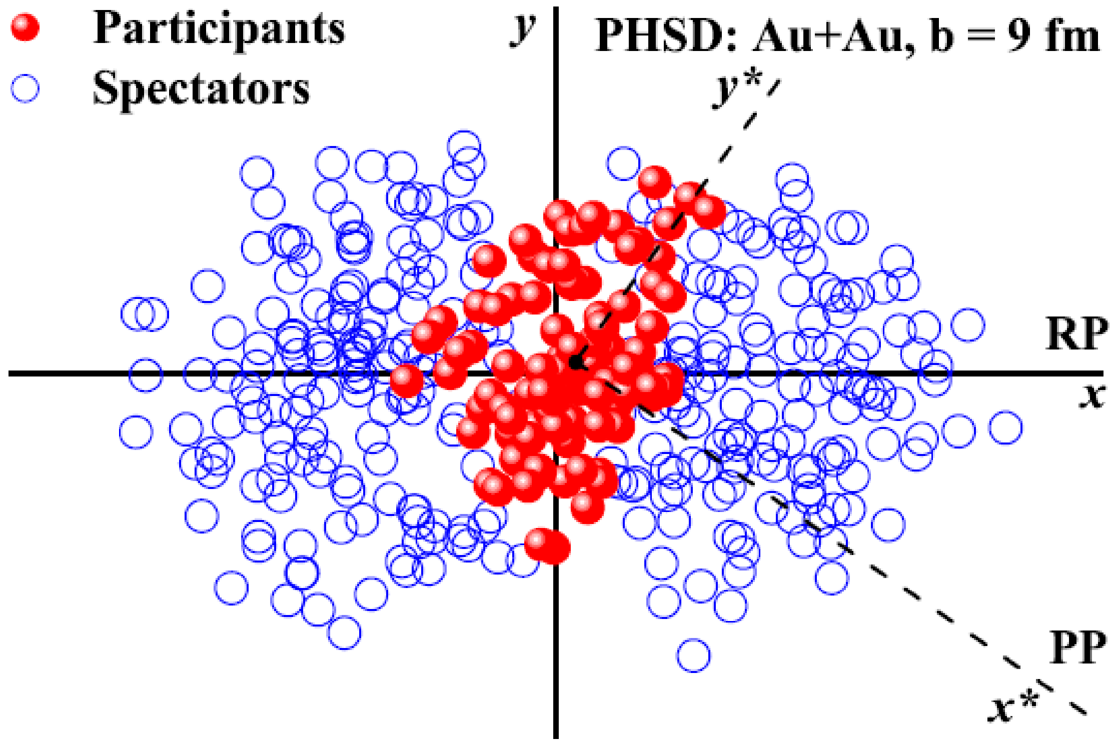
Cassing, Bratkovskaya, PRC 78 (2008) 034919; Cassing, EPJ ST 168 (2009) 3

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



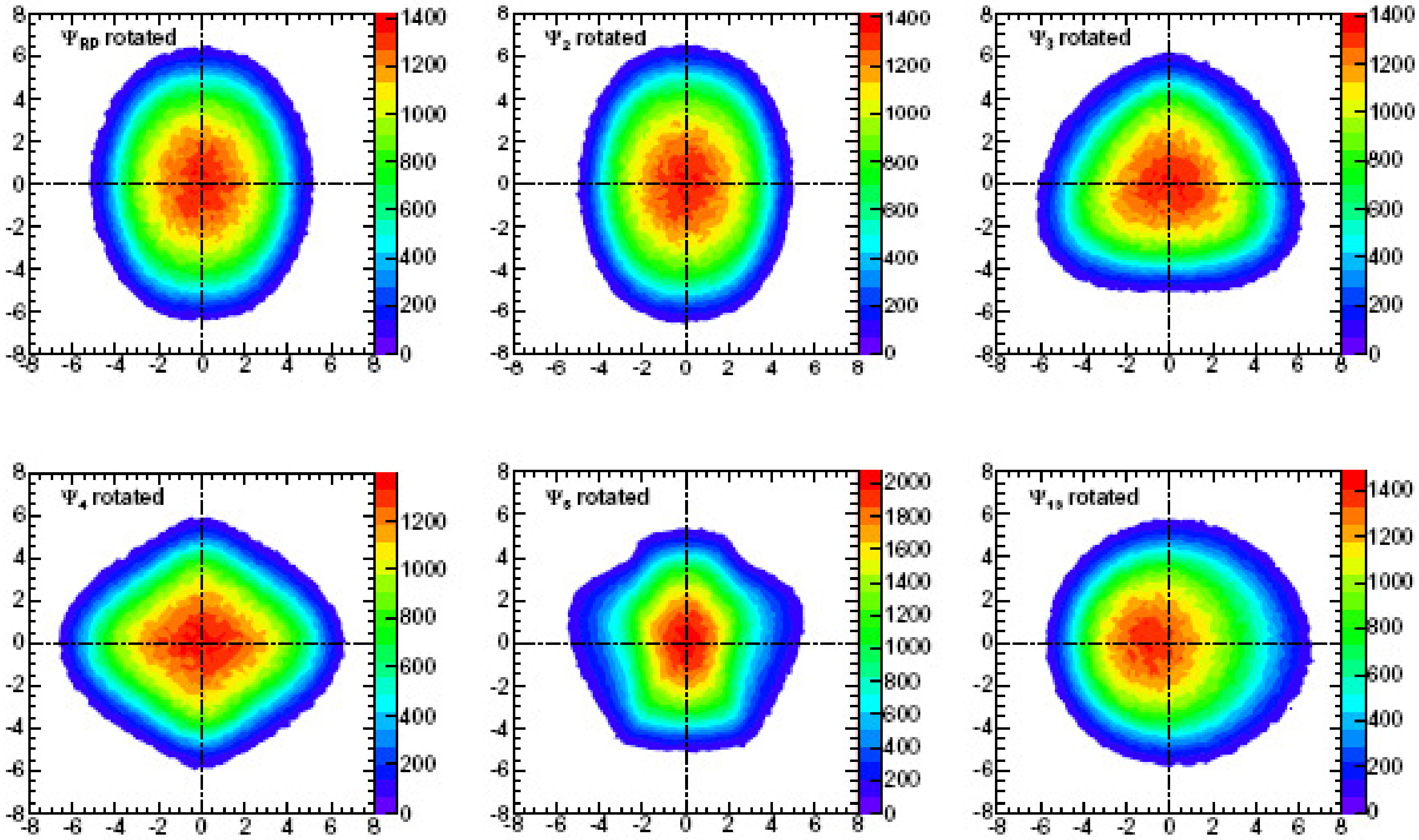
almond shaped interaction zone?

Initial participants and spectators in event by event calculations



In each event the reaction plane is tilted in coordinate space and of irregular shape → higher order harmonics!

Final angular distributions of hadrons

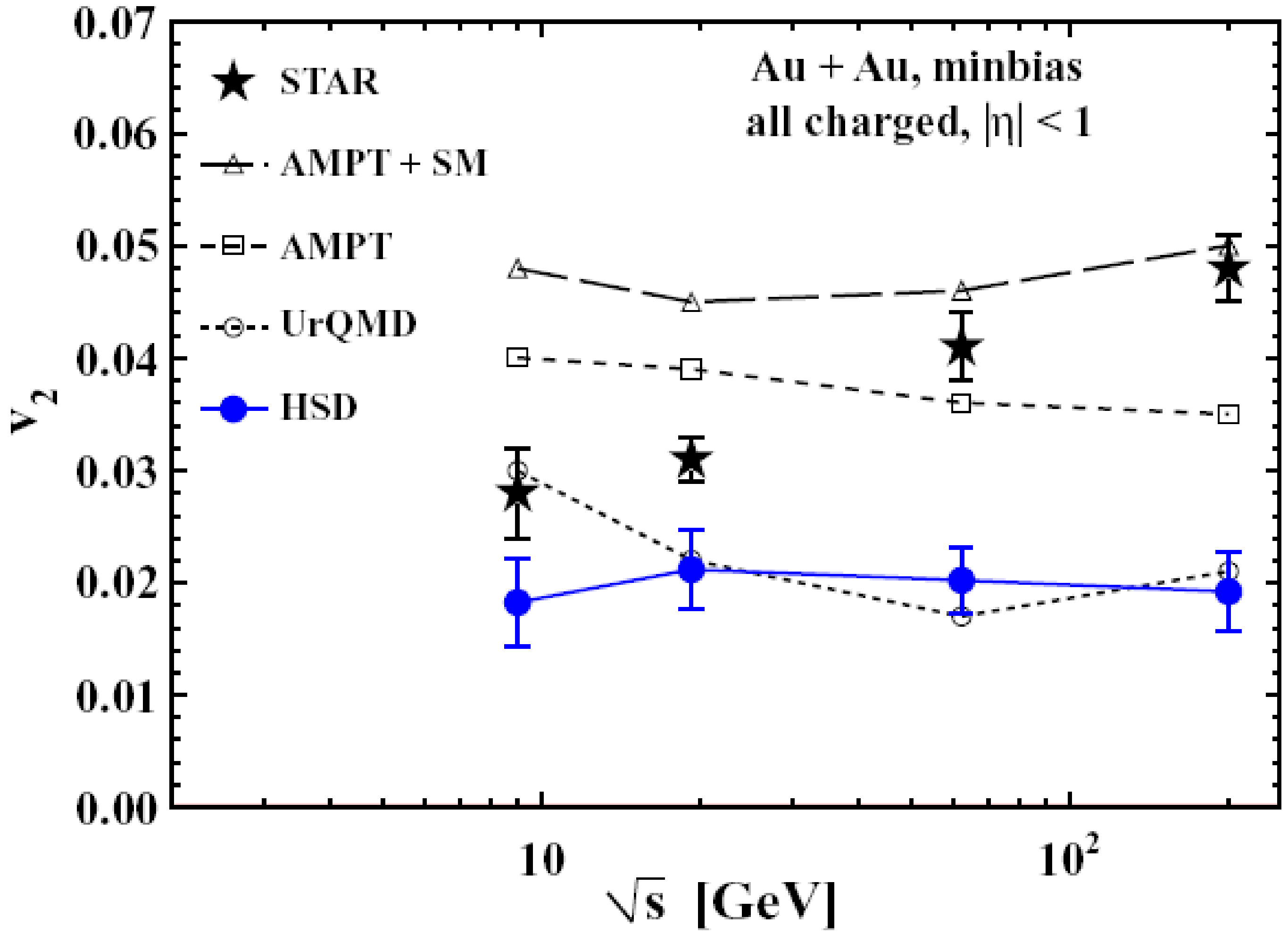


$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\psi - \Psi_n))\right)$$

S. A. Voloshin

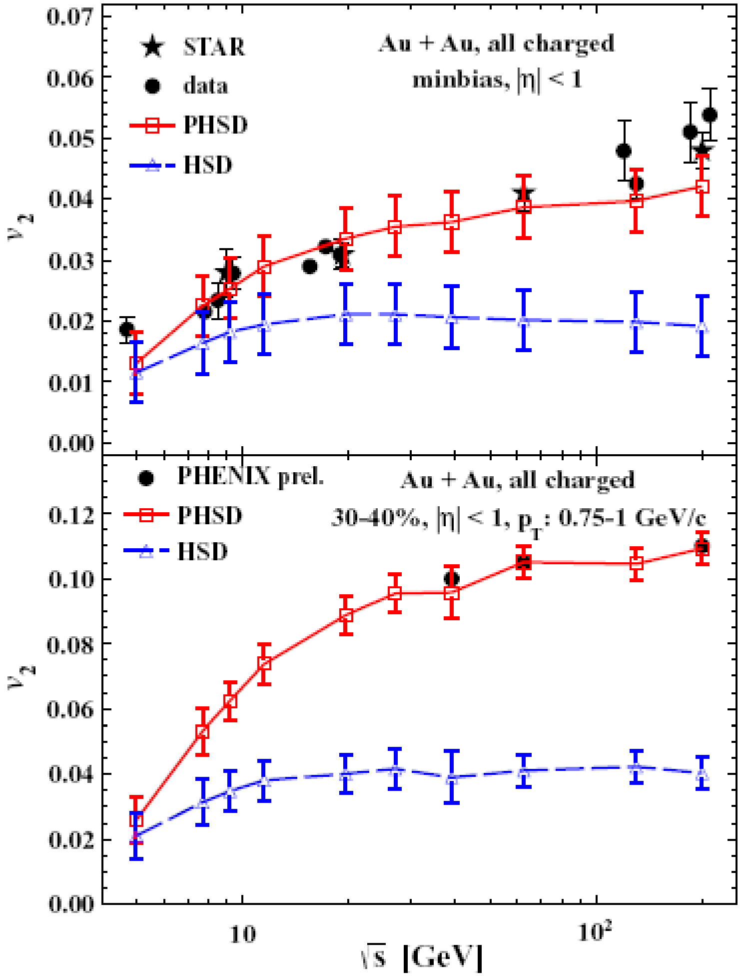
show higher order harmonics v_n

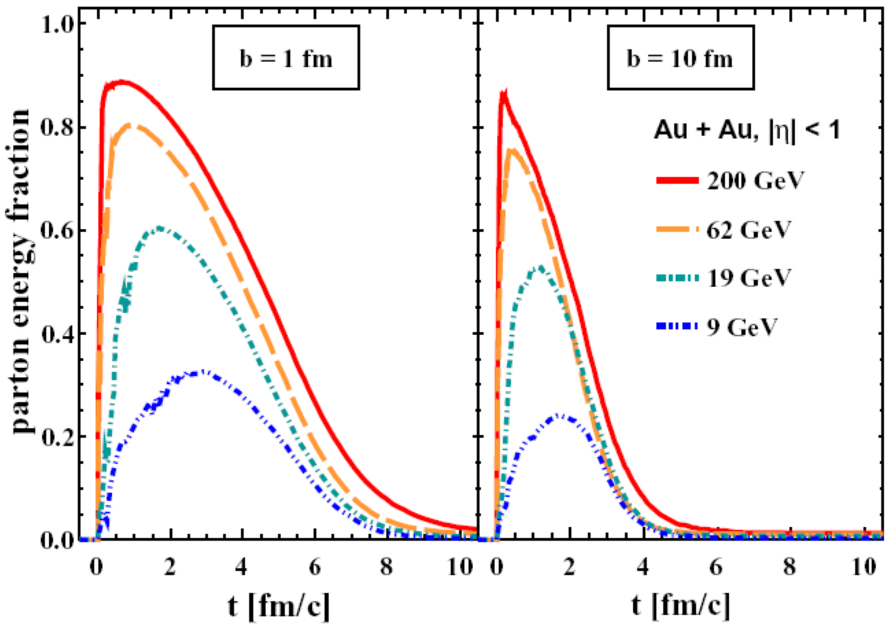
Excitation function of elliptic flow



is not described by hadron-string or purely partonic models !

Elliptic flow from PHSD versus STAR/PHENIX

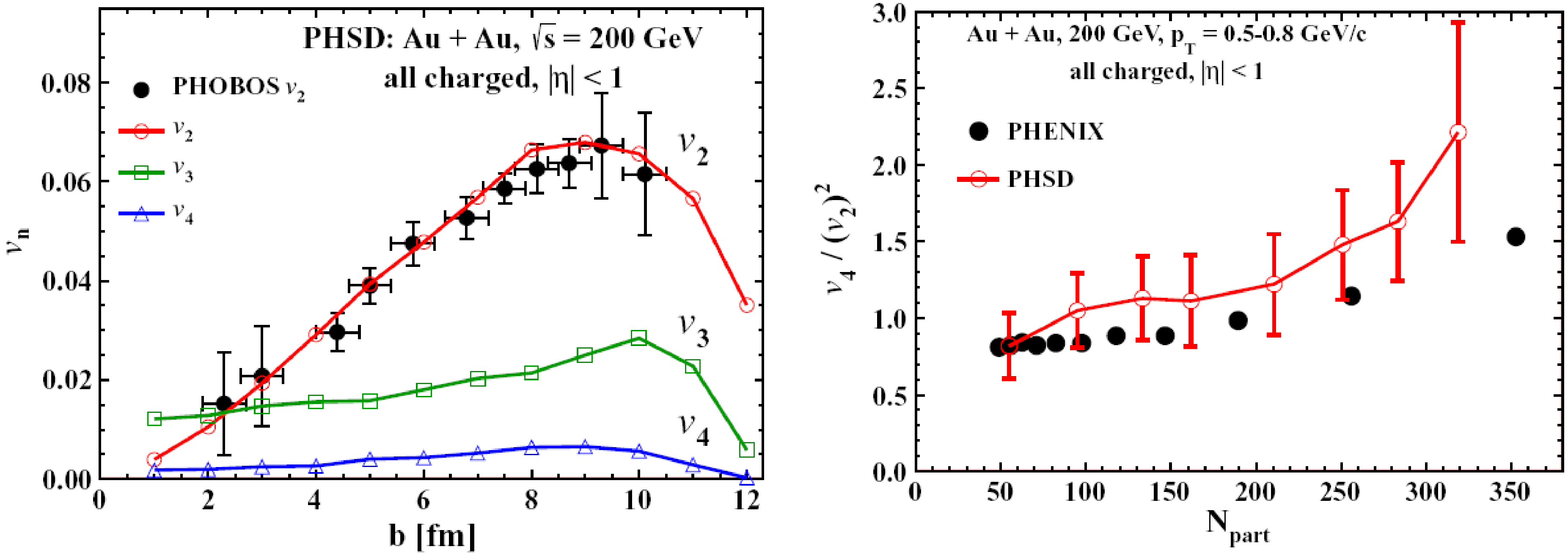




is reasonably described by PHSD due to an increasing fraction of partonic degrees-of-freedom !

V. P. Konchakovski et al., PRC 85 (2012) 044922

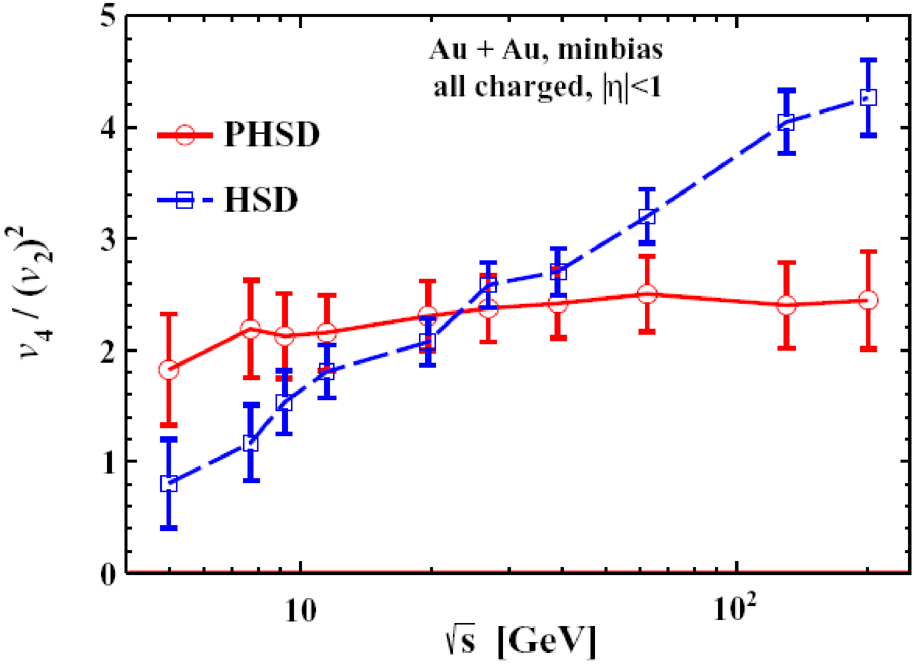
Flow coefficients versus centrality

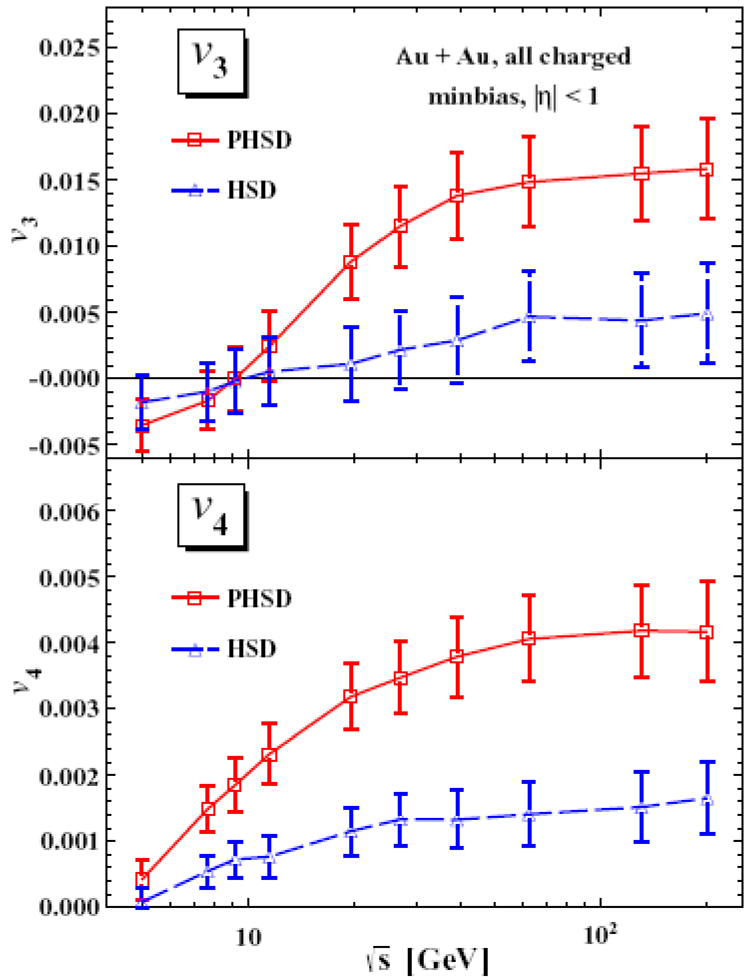


increase of v_2 with impact parameter but rather flat v_3 and v_4

V. P. Konchakovski et al., PRC 85 (2012) 044922

More excitation functions





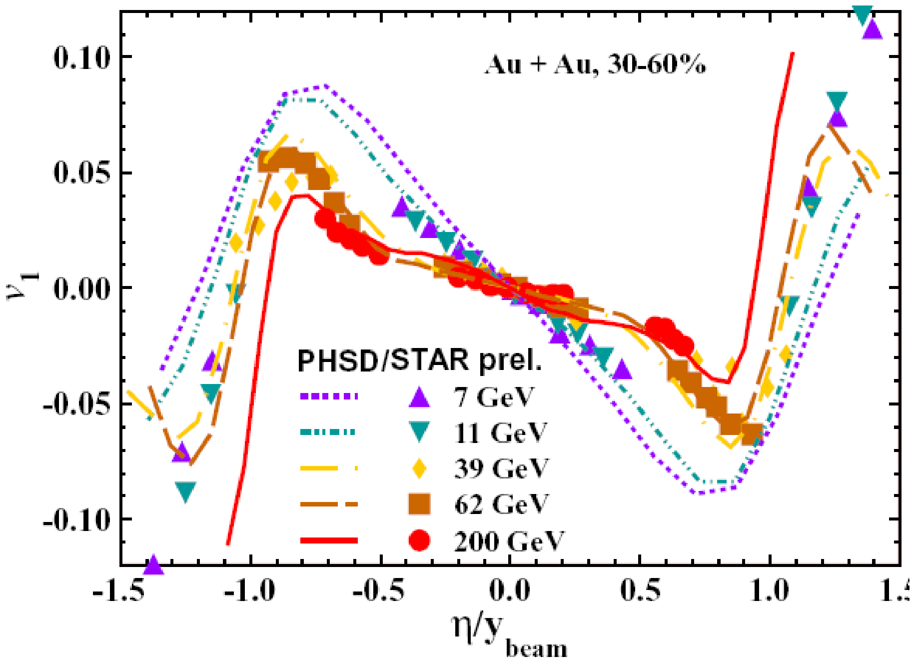
Very low v_3 and v_4 at FAIR energies

Almost constant $v_4/(v_2)^2$ for PHSD

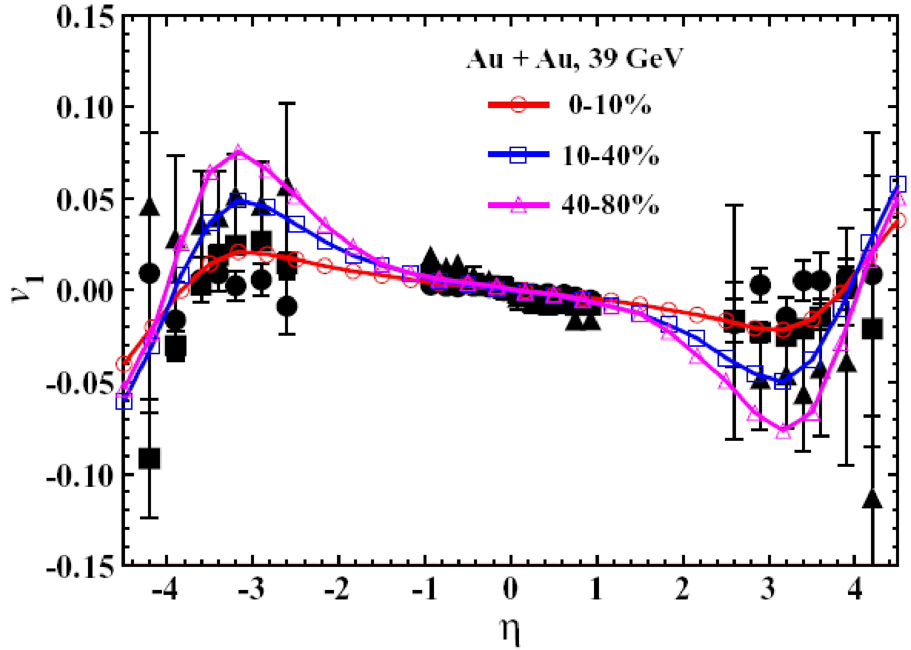
V. P. Konchakovski et al., PRC 85 (2012) 044922

In-plane flow v_1

versus beam energy



versus centrality

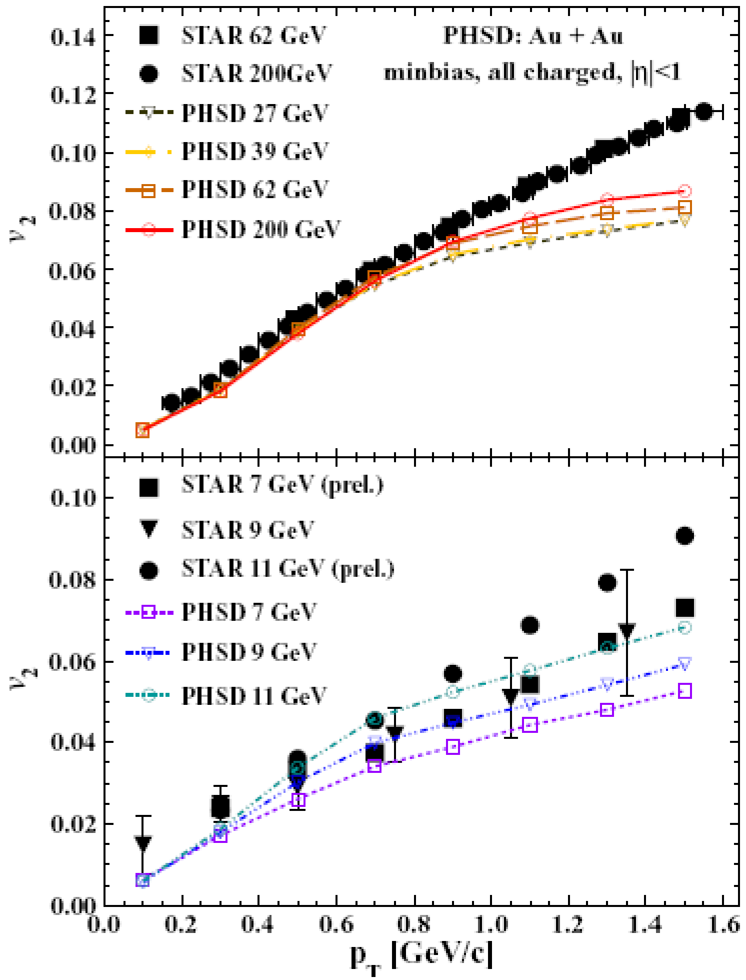


- **PHSD: v_1 vs. pseudo-rapidity follows an approximate scaling for high invariant energies $s^{1/2}$=39, 62, 200 GeV - in line with experimental data – whereas at low energies the scaling is violated!**

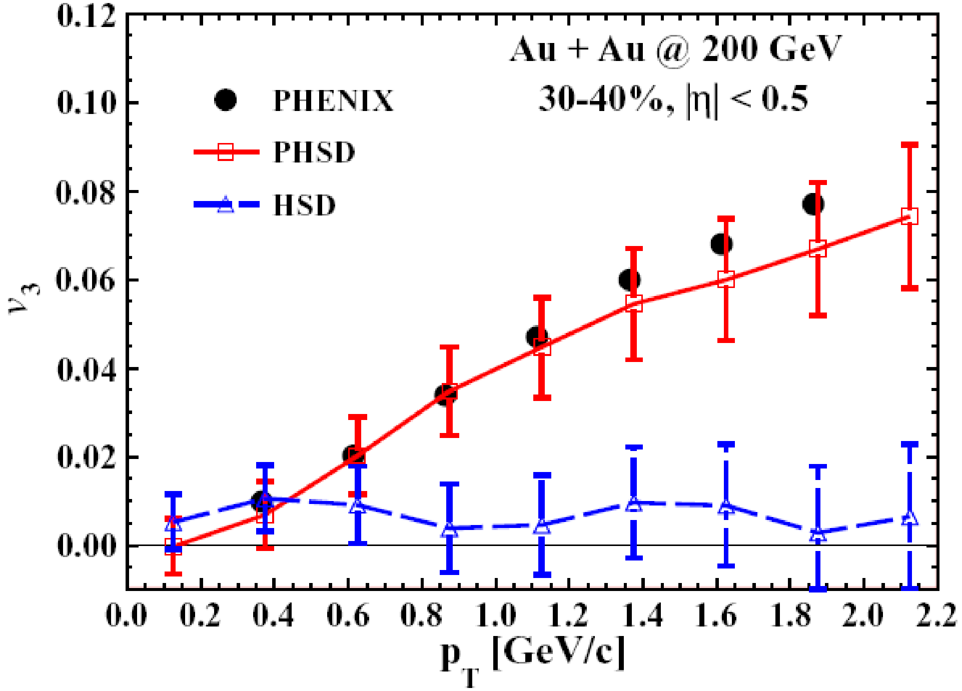
V. P. Konchakovski et al., PRC 85 (2012) 044922

Transverse momentum dependence

elliptic flow



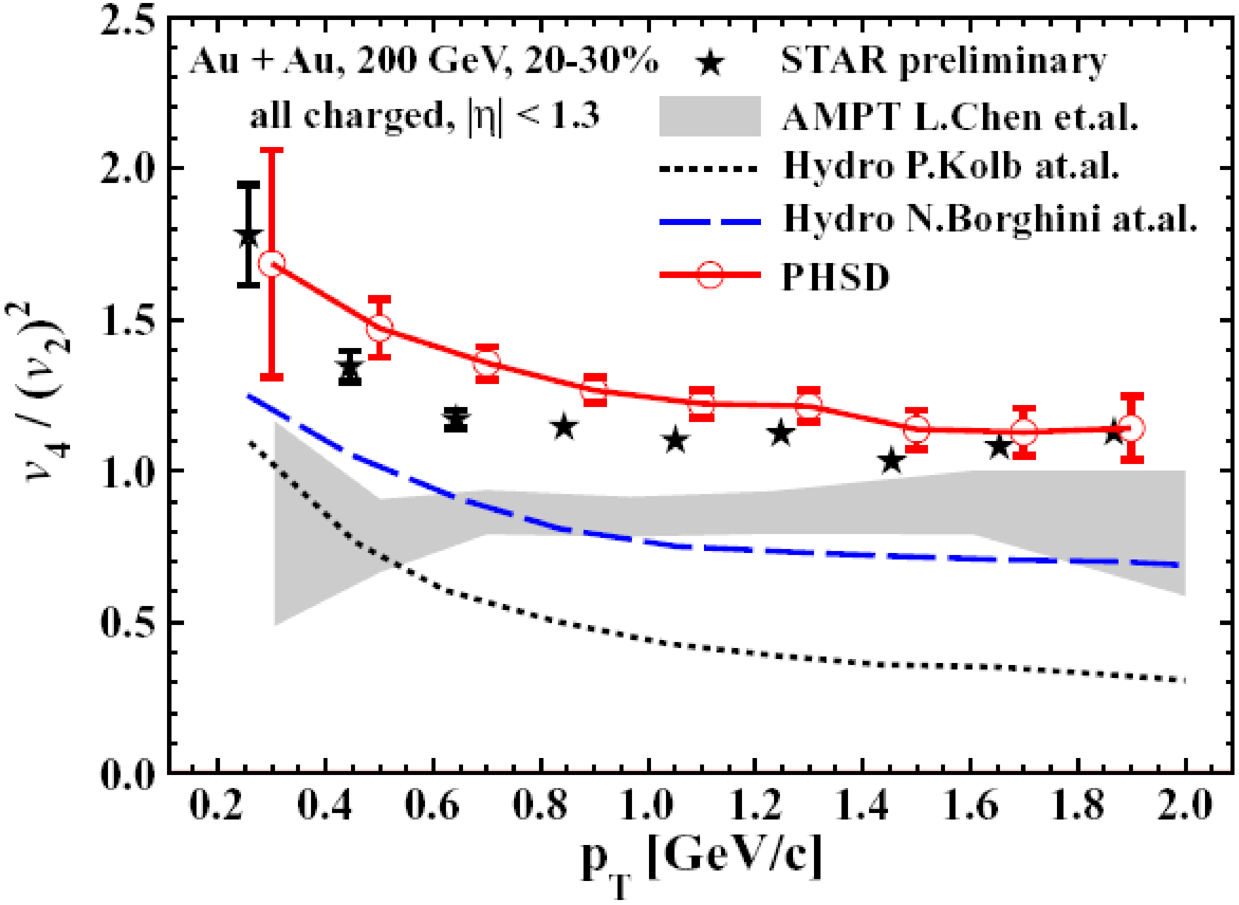
triangular flow



needs partonic degrees-of-freedom !

V. P. Konchakovski et al., PRC 85 (2012) 044922

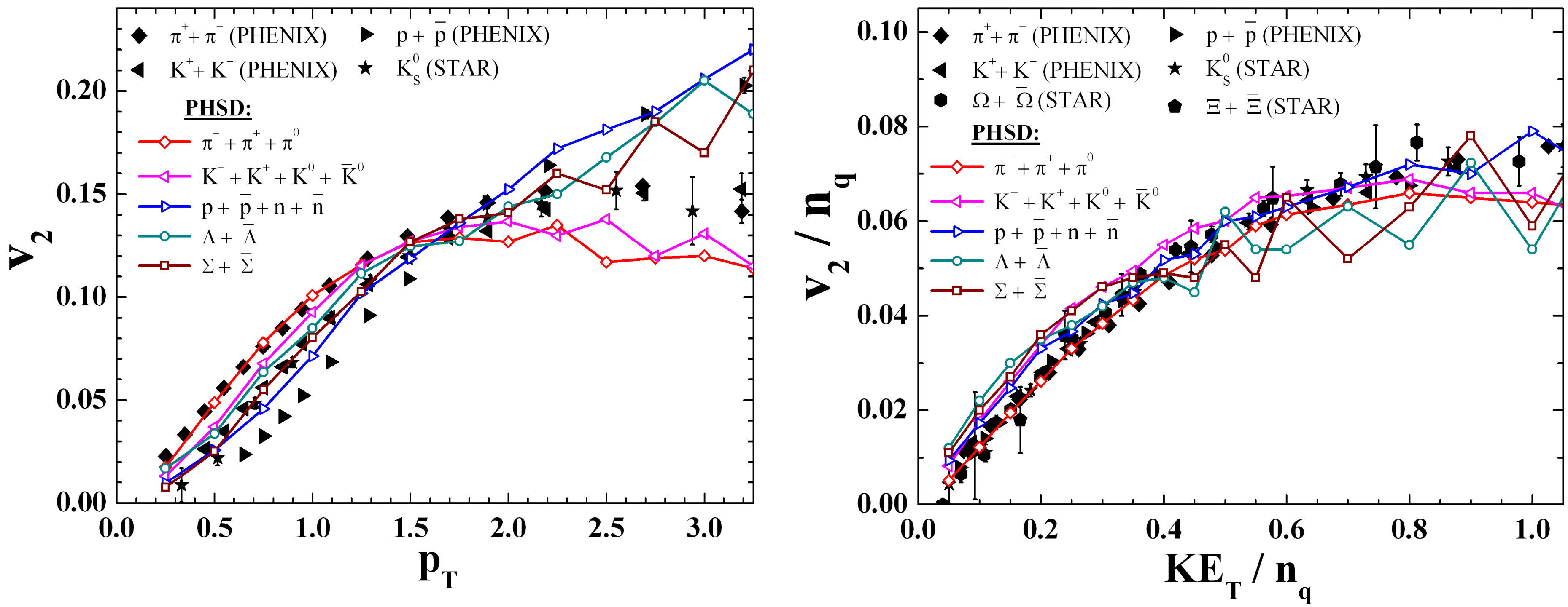
Ratio $v_4/(v_2)^2$ vs. p_T



is very sensitive to the microscopic dynamics !

V. P. Konchakovski et al., PRC 85 (2012) 044922

Elliptic flow scaling at RHIC

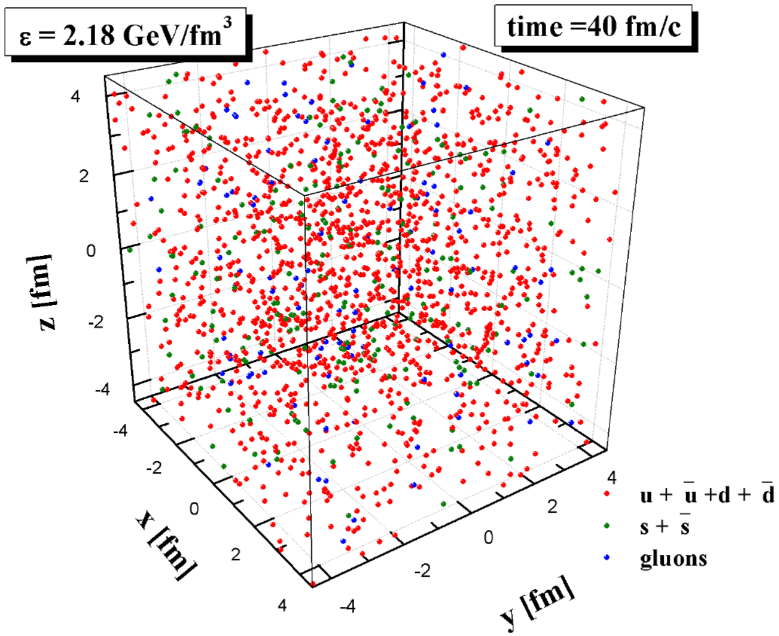


- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

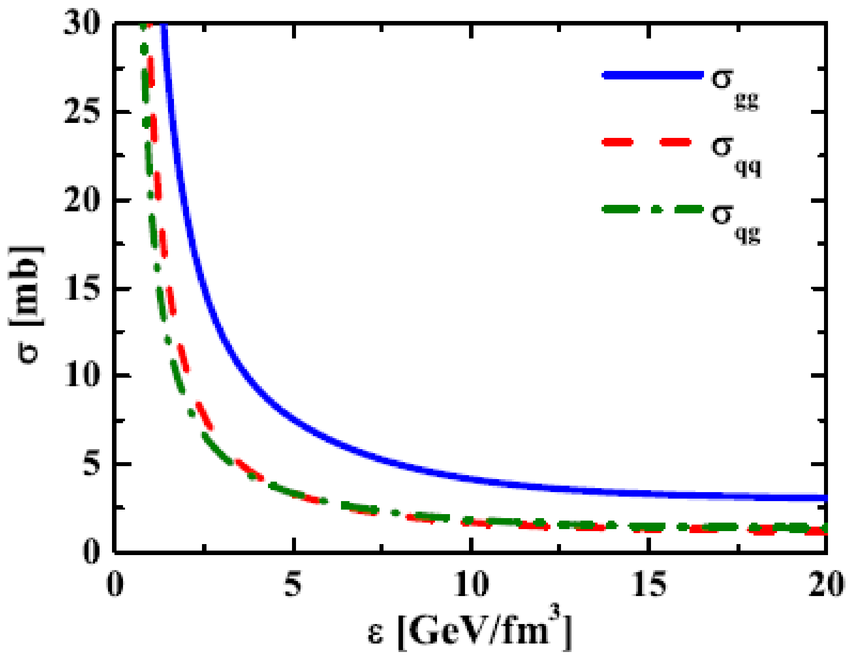
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Shear viscosity from PHSD in a box

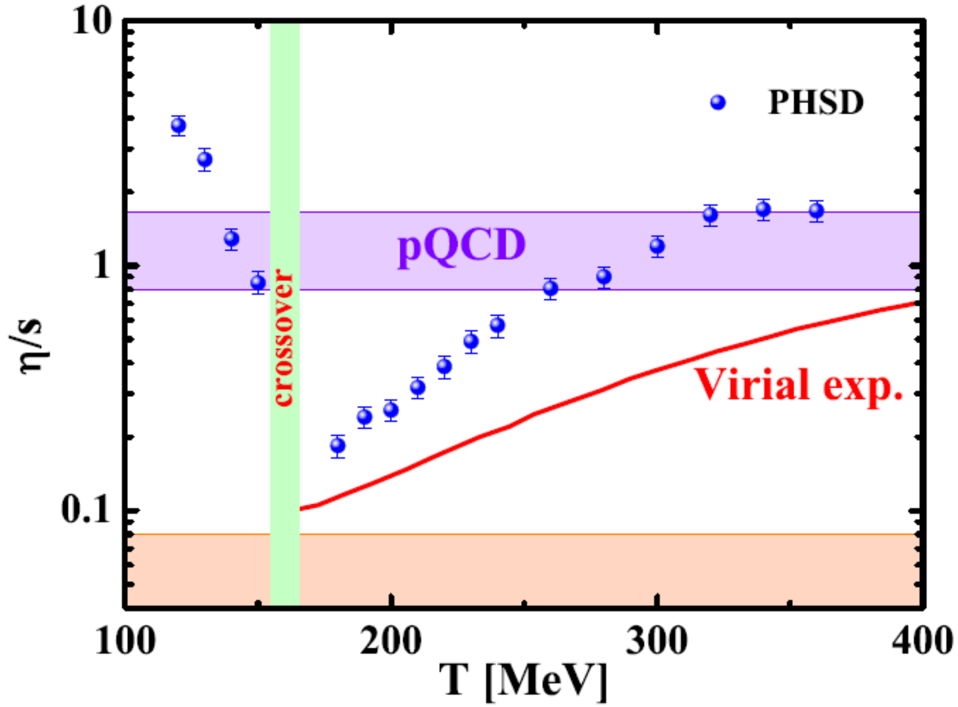
$$\eta = \frac{1}{T} \int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle_{\text{equil}}$$



Transport coefficients



Cross sections in PHSD



Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state

- 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
  - near-side ridge …

⇒ evidence for strong partonic interactions in the early phase of relativistic heavy-ion reactions from FAIR to LHC energies

⇒ initial fluctuations generate odd flow components!

⇒Shear viscosity to entropy density has a minimum close to Tc.

⇒Collective flow is also generated by the scalar partonic mean-field!

PHSD group

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- Che-Ming Ko

JINR, Dubna:
- Vadim Voronyuk
- Viatcheslav Toneev

Kiev Univ.:
- Mark Gorenstein

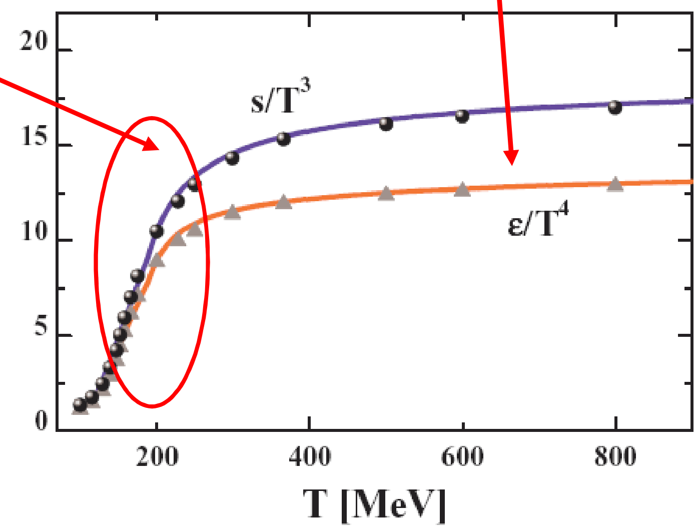
Barcelona Univ.
- Laura Tolos, Angel Ramos

Outlook - Perspectives

What is the stage of matter close to T_c at finite quark chemical potential:

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

Lattice EQS ➔ ‚crossover‘ , $T > T_c$



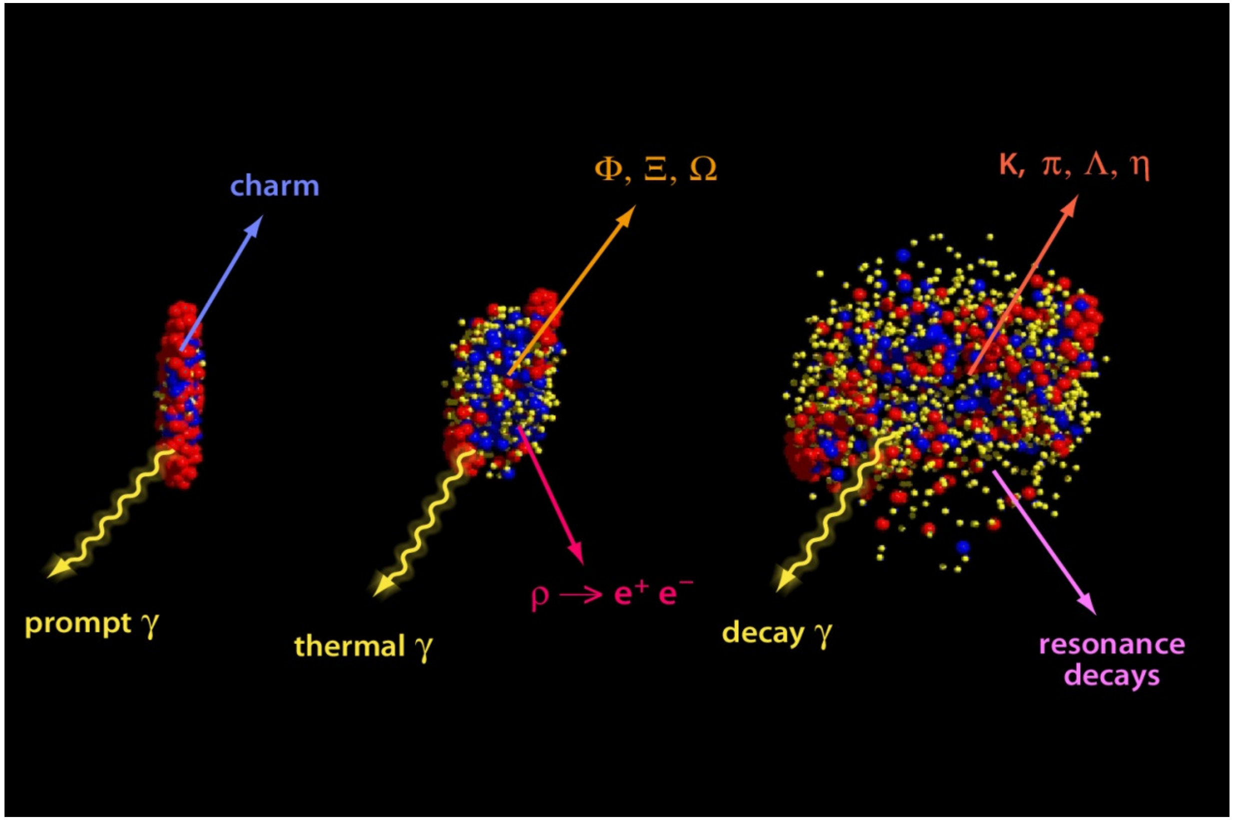
Open problems:

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

A possible solution (?) :

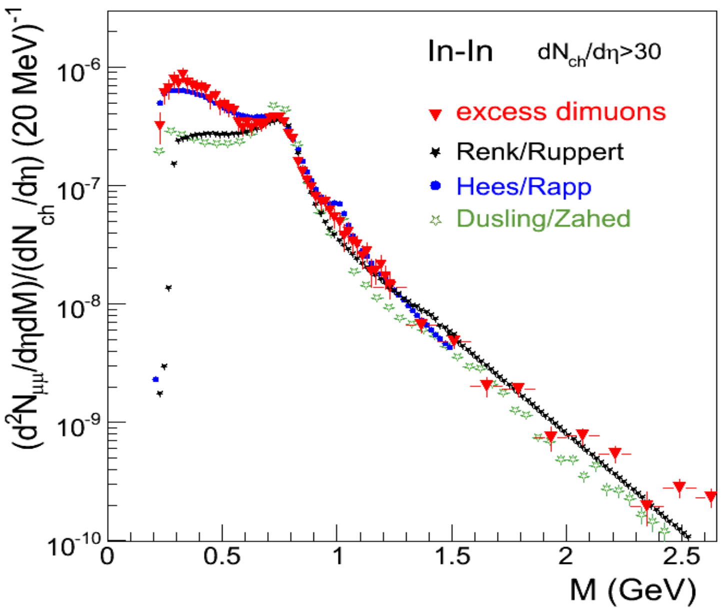
➢ **‚mixed‘ phase description within molecular dynamics?**

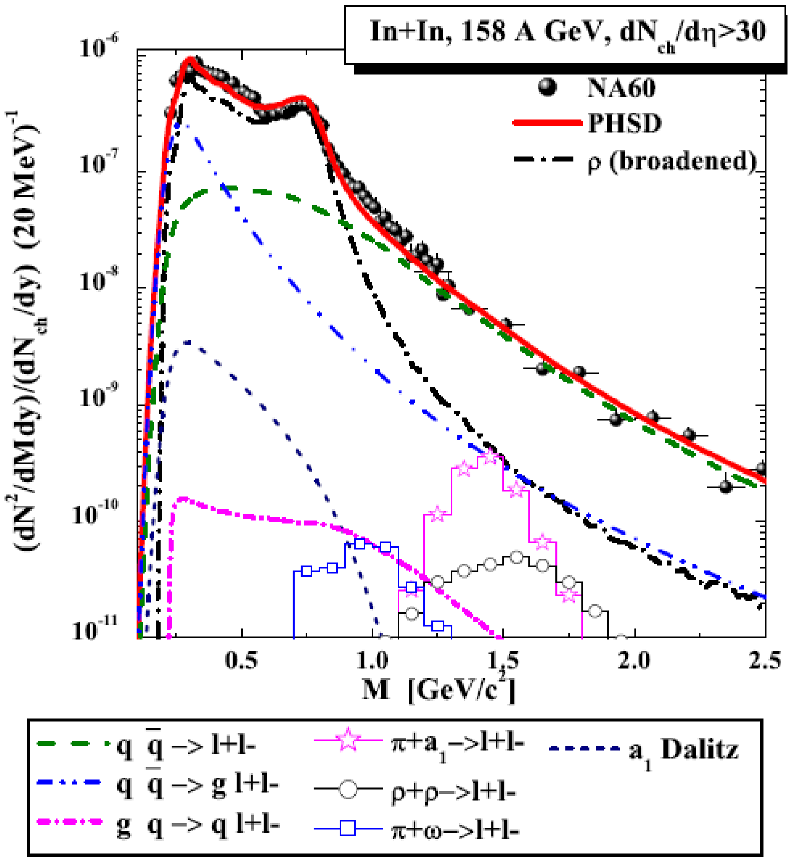
Dileptons



are produced throughout all reaction phases!

Dileptons at SPS: NA60





Fireball model – Renk/Ruppert

Fireball model – Rapp/vanHees

Hydro model – Dusling/Zahed

Parton-Hadron-String-Dynamics microscopic transport model - PHSD

➔ good agreement with data in shape and absolute yield

- **Mass region above 1 GeV is dominated by partonic radiation**
- **Contributions of "4π" channels (radiation from multi-meson reactions) are small**

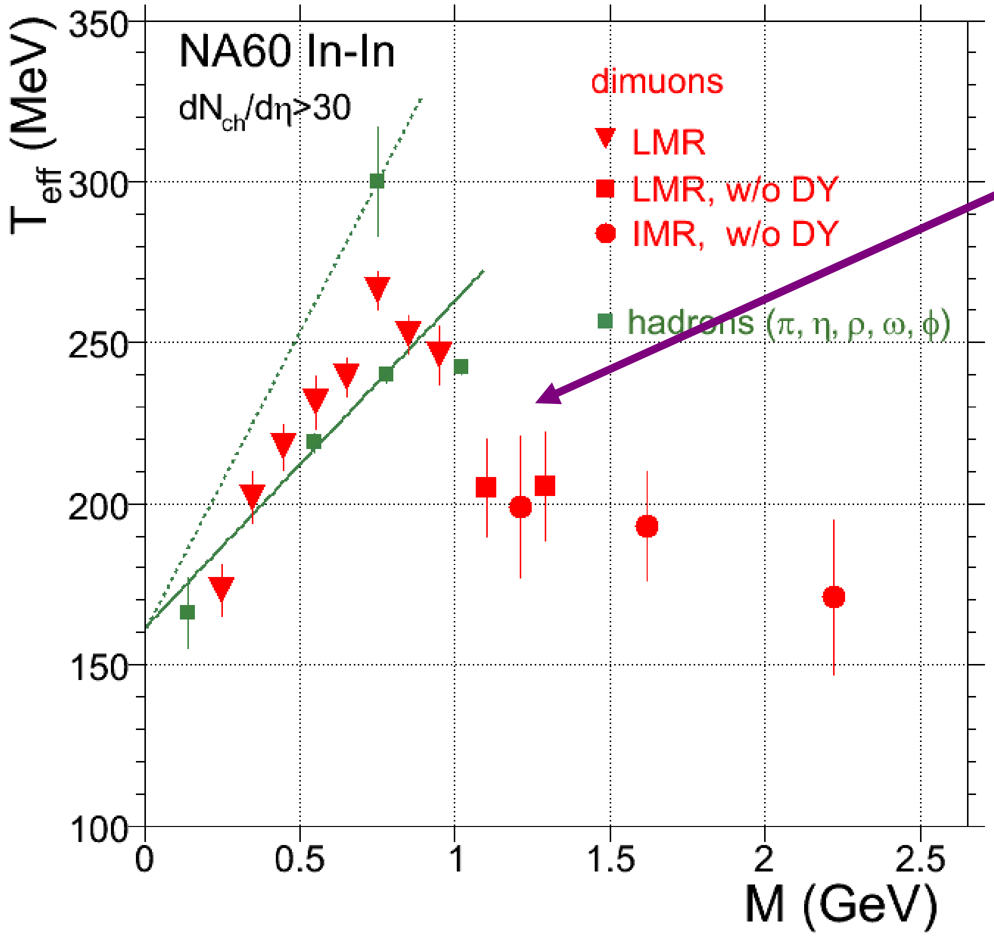
O. Linnyk, E. Bratkovskaya, V. Ozvenchuk, W. Cassing and C.M. Ko, PRC 84 (2011) 054917

NA60 Collaboration, Eur. Phys. J. C 59 (2009) 607; CERN Courier 11/2009

The rise and fall of radial flow of thermal dimuons

▪*NA60: Phys. Rev. Lett. 100 (2008) 022302*

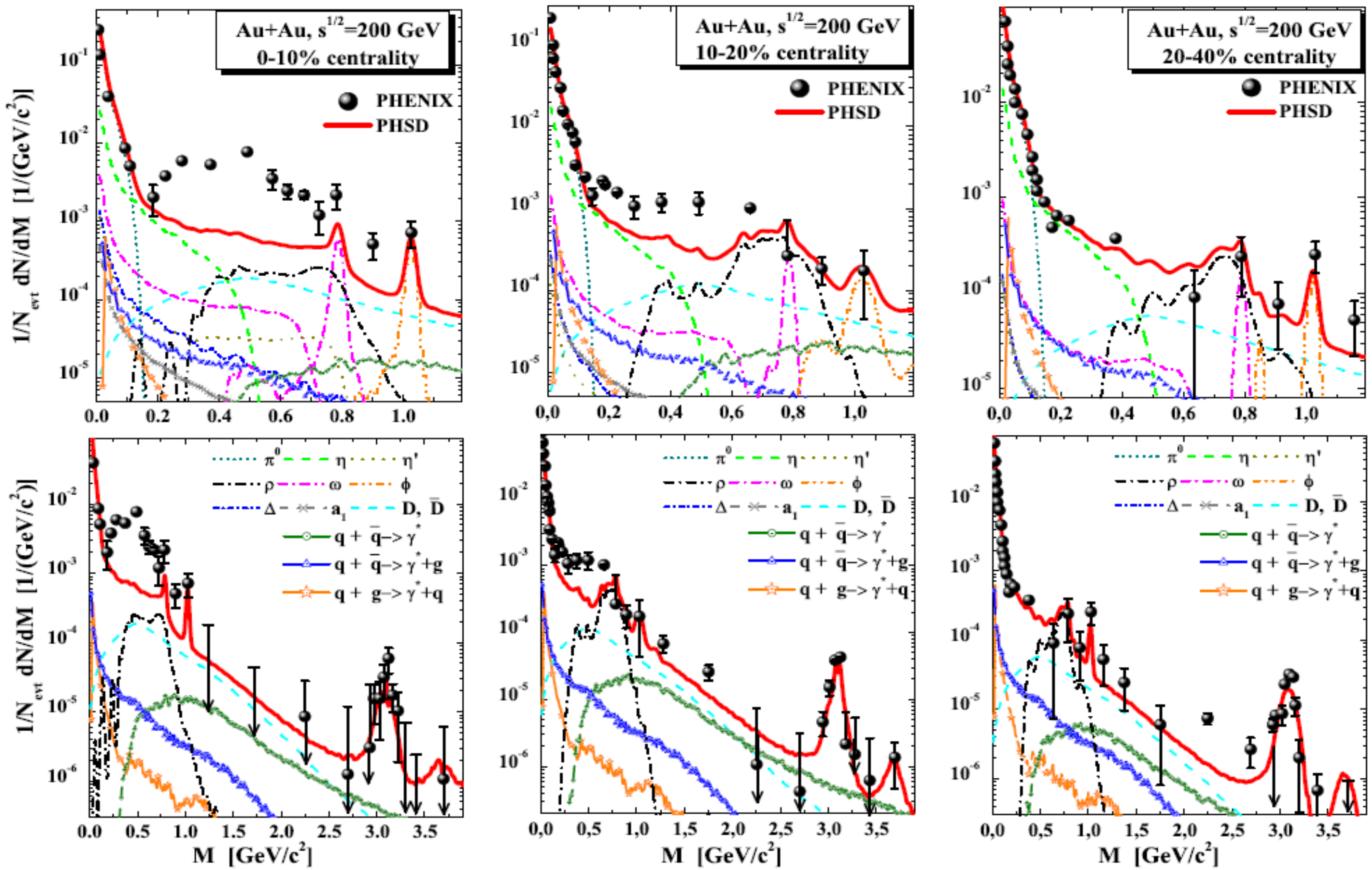
▪ S. Damjanovic, Trento 2010:



- **Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for M>1 GeV:**
  - **Rise consistent with radial flow of a hadronic source (here $\pi^+\pi^- \to \rho \to \mu^+\mu^-$), taking the freeze-out 〉 as the reference (from a separate analysis of the ρ peak and the continuum)**
  - **The drop of T_{eff} signals a sudden transition to a low-flow source, i.e. a source of partonic origin (here $q\bar{q} \to \mu^+\mu^-$)**

▪**NA60: Dileptons for M >1 GeV are of dominantly partonic origin !**

PHENIX: mass spectra

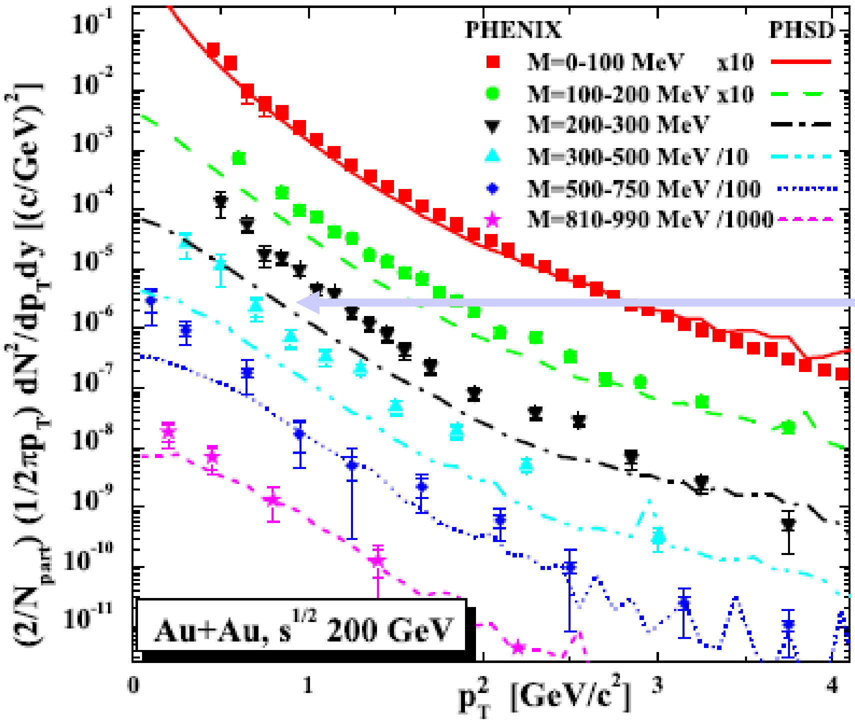


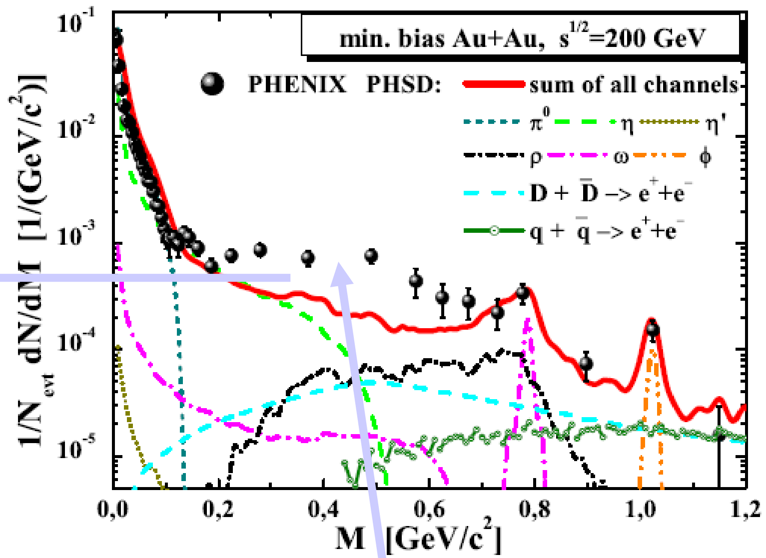
(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

- **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

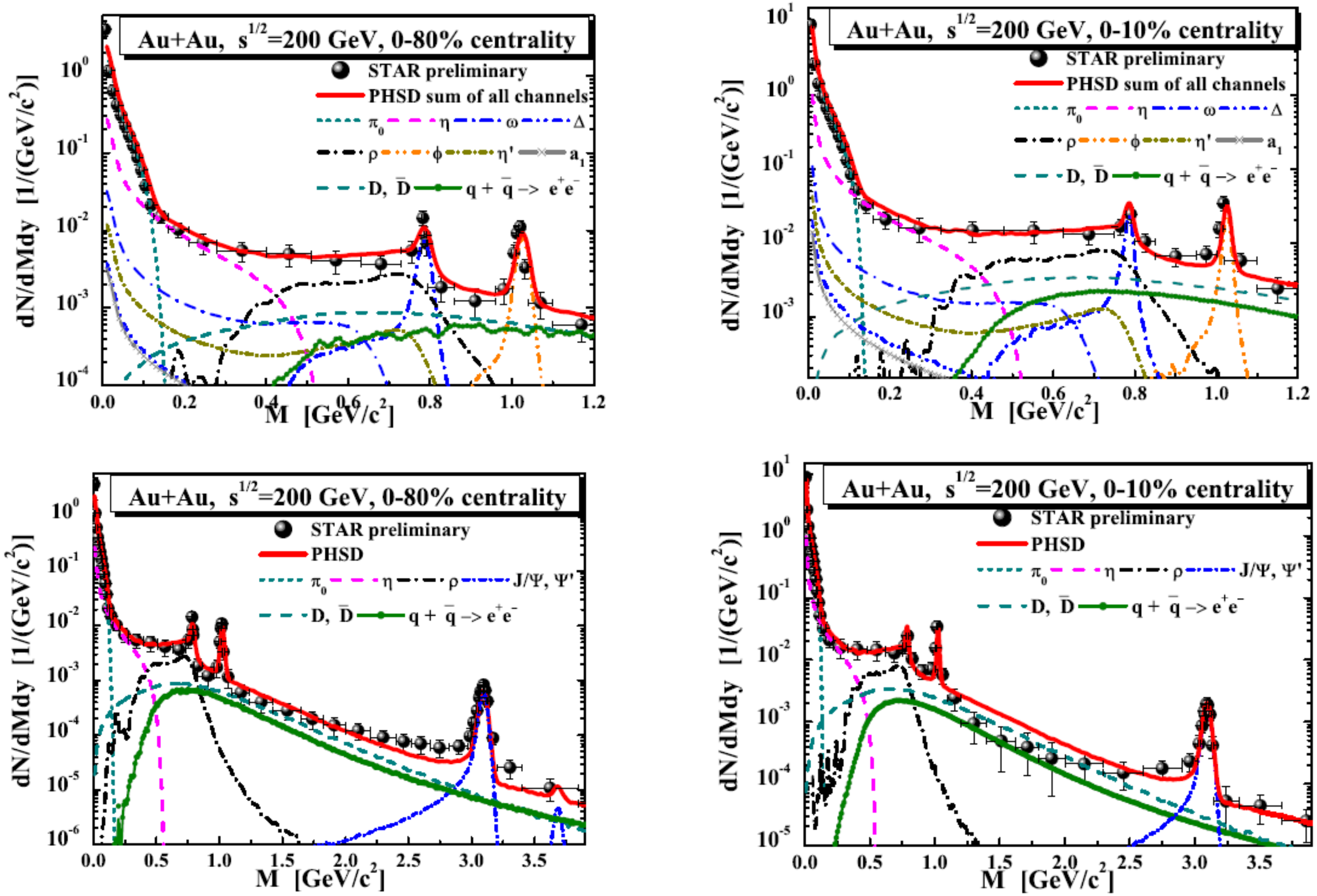




- The lowest and highest mass bins are described very well
- Underestimation of p_T data for 100<M<750 MeV bins consistent with dN/dM
- The ‘missing source’(?) is located at low p_T !

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

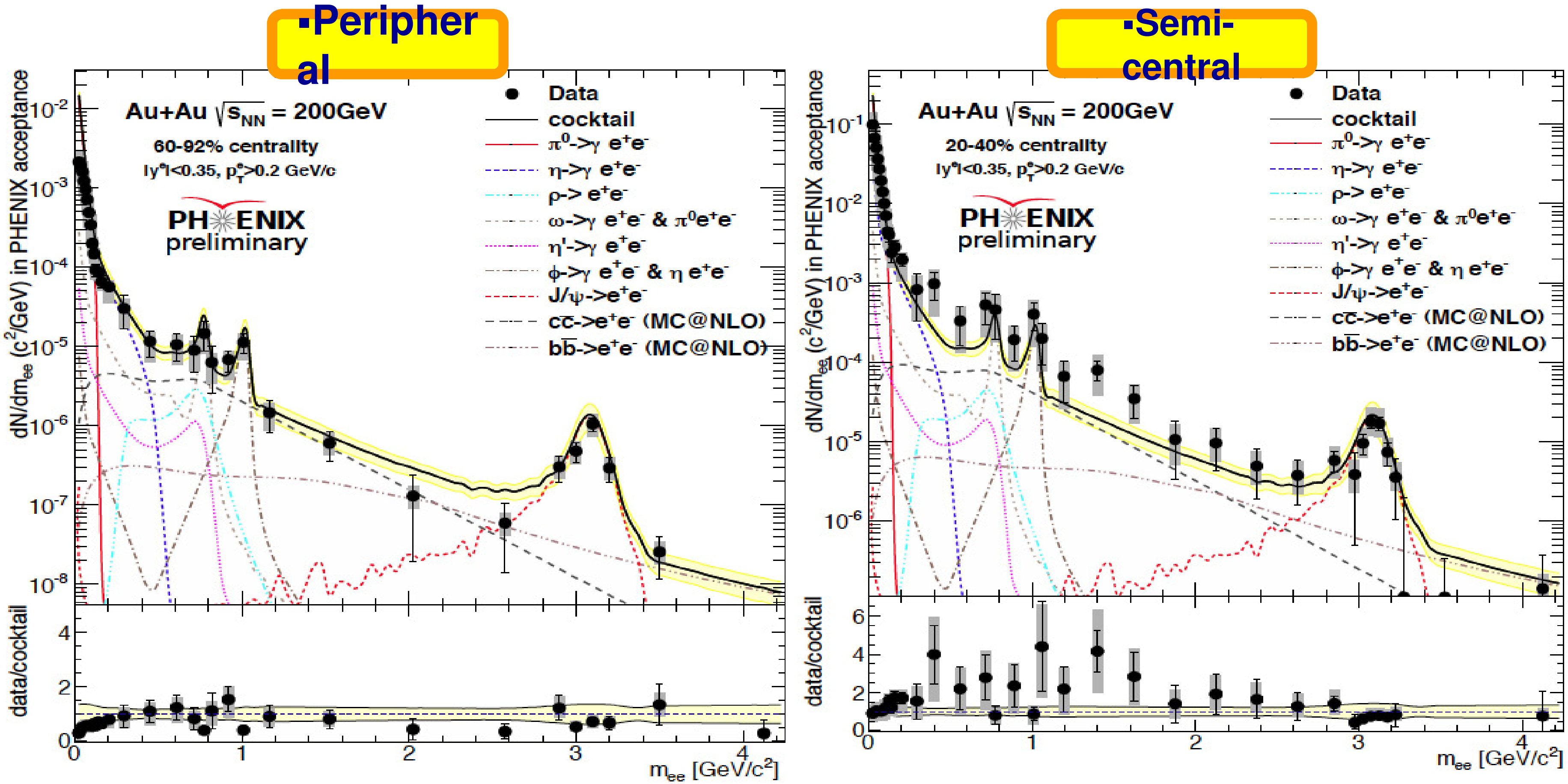
STAR: dilepton mass spectra



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

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

PHENIX: mass spectra with HBD

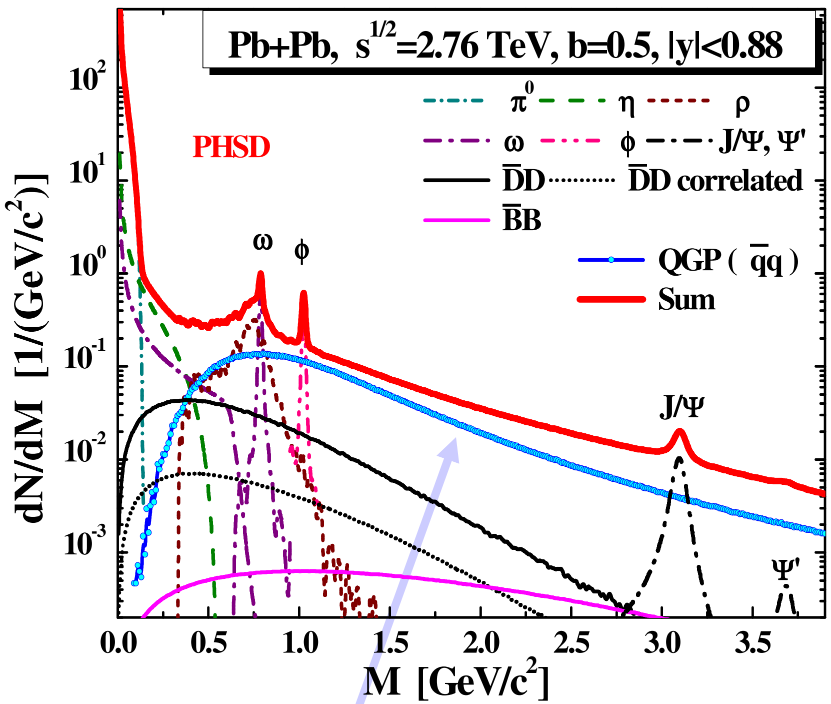


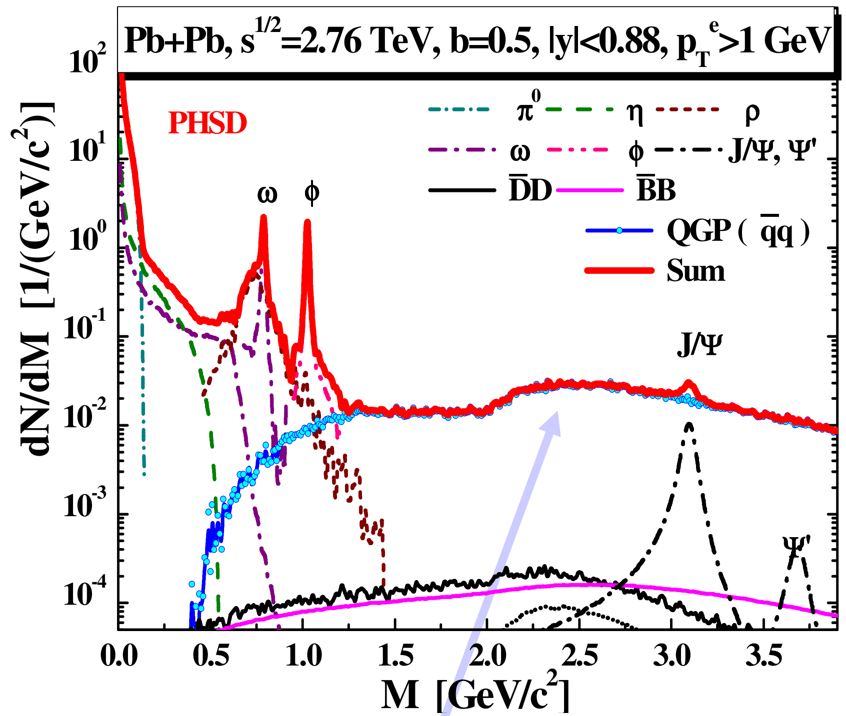
▪Preliminary PHENIX data with Hadron-Blind Detector (HBD) presented at QM 2012

▪Room for the QGP yield at M>1 GeV and for the in-medium modification of rho at low mass

I. Tserruya for PHENIX Collaboration, Quark Matter 2012

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. arXiv:1208.1279 (2012)