Institut für
Theoretische Physik I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Azimuthal flow and chiral magnetic effect in nucleus-nucleus collisions

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Basic Concept of HSD

HSD – Hadron-String-Dynamics transport approach

Ehehalt, Cassing, Nucl.Phys. A602 (1996) 449; Cassing, Bratkovskaya, Phys. Rep.308 (1999) 65.

- **the phase-space density f_i follows the transport equations**

$$\left(\frac{\partial}{\partial t}+\left(\nabla_{\vec{p}}H\right)\nabla_{\vec{r}}-\left(\nabla_{\vec{r}}H\right)\nabla_{\vec{p}}\right)f_i\left(\vec{r},\vec{p},t\right)=I_{coll}\left(f_1,f_2,\ldots,f_M\right)$$

with collision terms I_{coll} describing:

- **elastic and inelastic hadronic reactions:**

  baryon-baryon, meson-baryon, meson-meson

- **formation and decay of baryonic and mesonic resonances**
- **string formation and decay**

  (for inclusive particle production: BB -> X , mB -> X, X =many particles)

- **implementation of detailed balance on the level of 1<->2 and 2<->2 reactions (+ 2<->n multi-particle reactions in HSD !)**
- **no explicit phase transition from hadronic to partonic degrees of freedom**

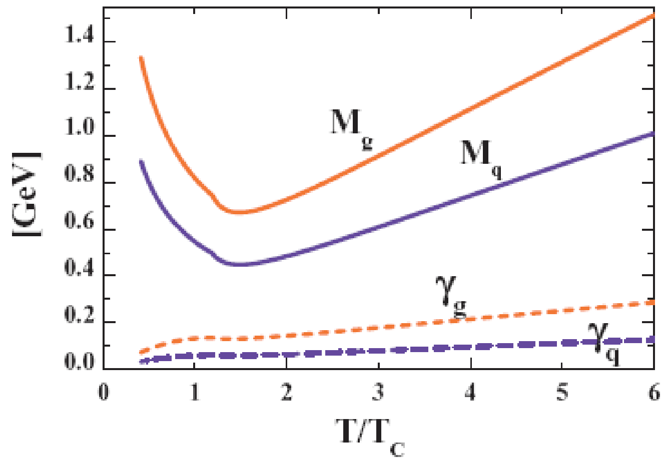
The Dynamical QuasiParticle Model (DQPM)

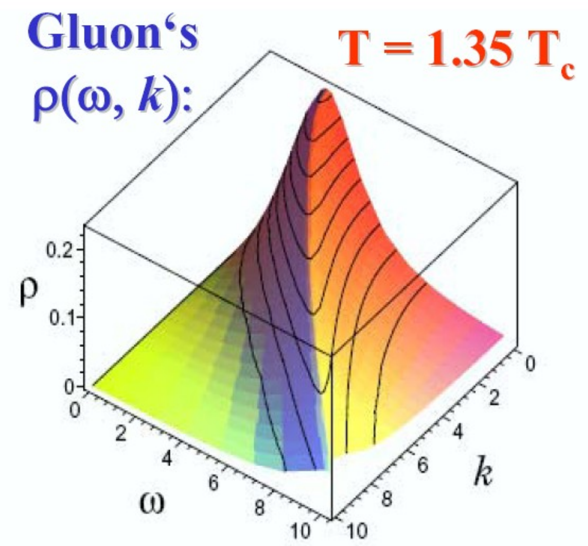
Interacting quasiparticles massive quarks and gluons (g, q, $\bar{q}$)
with spectral functions

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

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

Quasiparticle properties:
large width and mass for gluons and quarks



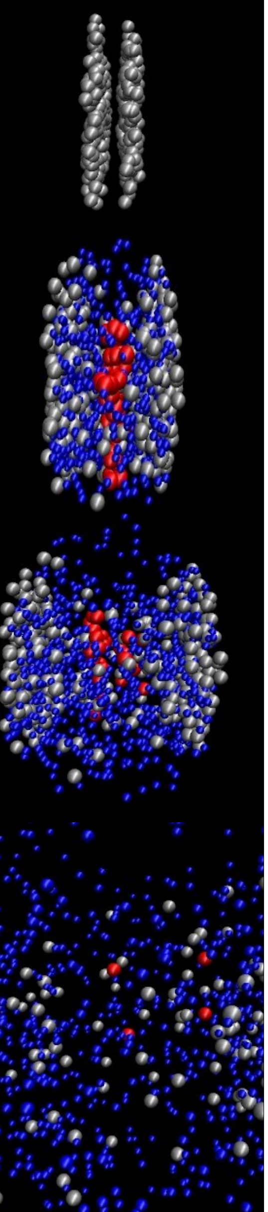


- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons => PHSD**

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

Yesterday talks by Olena Linnyk
Vitalii Ozvenchuk

Parton-Hadron String Dynamics (PHSD)



- **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**

DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365; NPA 795 (2007) 70.

- **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 + $\bar{q}$ (flavor neutral) <=> gluon (colored)
  - ✔ gluon + gluon <=> gluon (possible due to large spectral width)
  - ✔ q + $\bar{q}$ (color neutral) <=> hadron resonances

- **Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:**
  - ✔ gluons => q + $\bar{q}$
  - ✔ q + $\bar{q}$ => meson (or string)
  - ✔ q + q + q => baryon (or string)

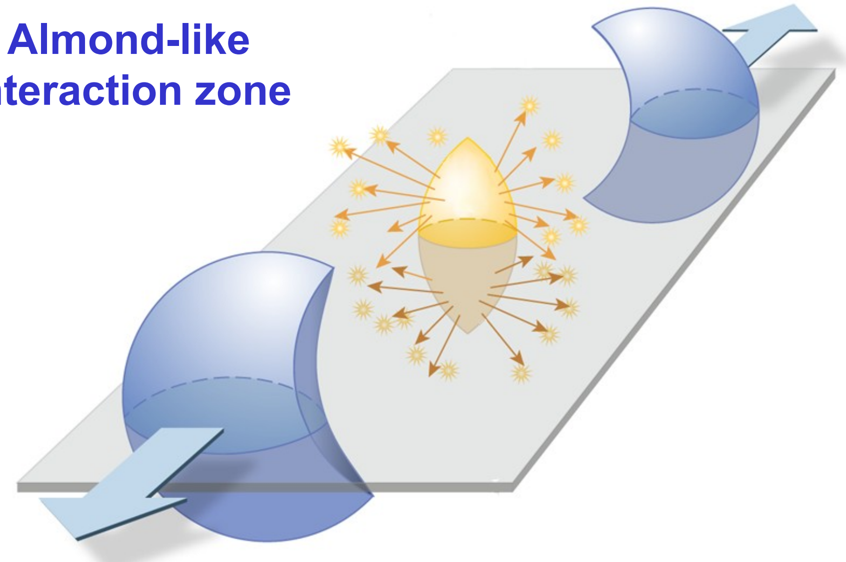
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3.

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

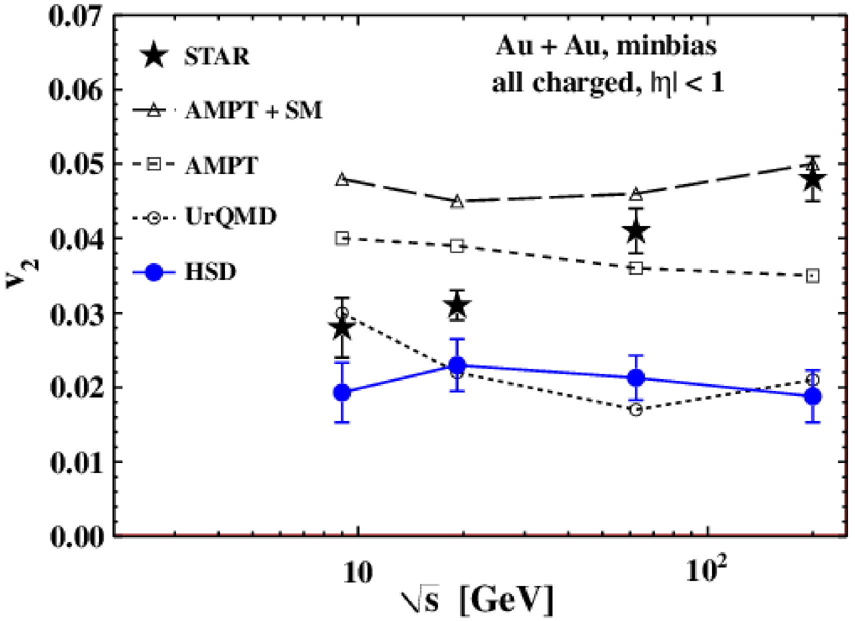

PHSD: Au+Au @ 21300 AGeV, b = 1 fm
t = 0.3 fm/c
Section View
baryon
meson
quark
gluon
PHSD
Konchakovski

Flow harmonics: motivation

Almond-like interaction zone



M.Nasim et al., PRC82, 054908 (2010)



pressure gradient

=> spatial asymmetry is converted to an asymmetry in momentum space

=> collective flow

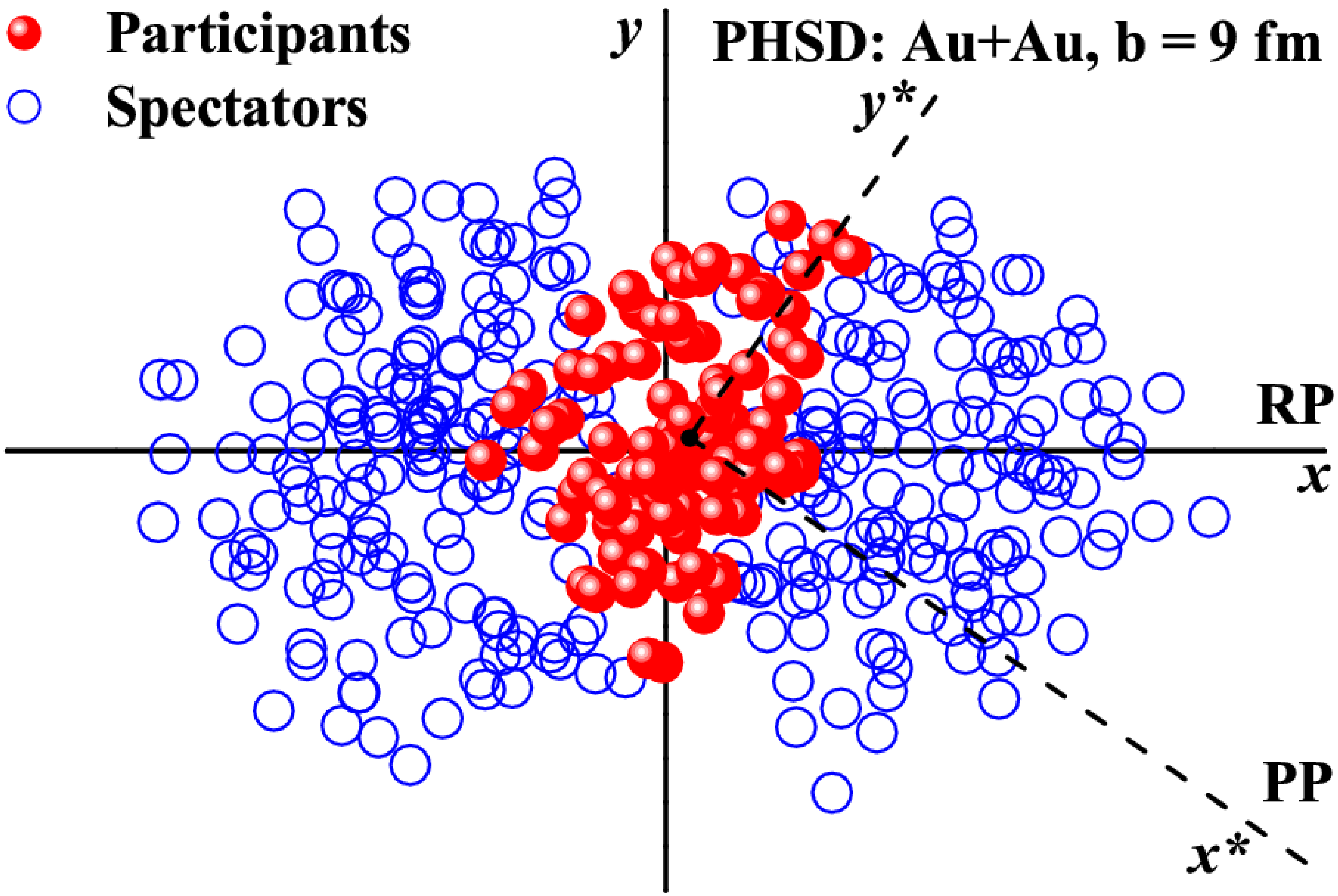
$$\frac{dN}{dy p_T dp_T d\phi} = \frac{dN}{dy p_T dp_T} \frac{1}{2\pi} \left(1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right)$$

$$v_1 = < \frac{p_x}{p_T} >$$ Direct flow

$$v_2 = < \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} >$$ Elliptic flow

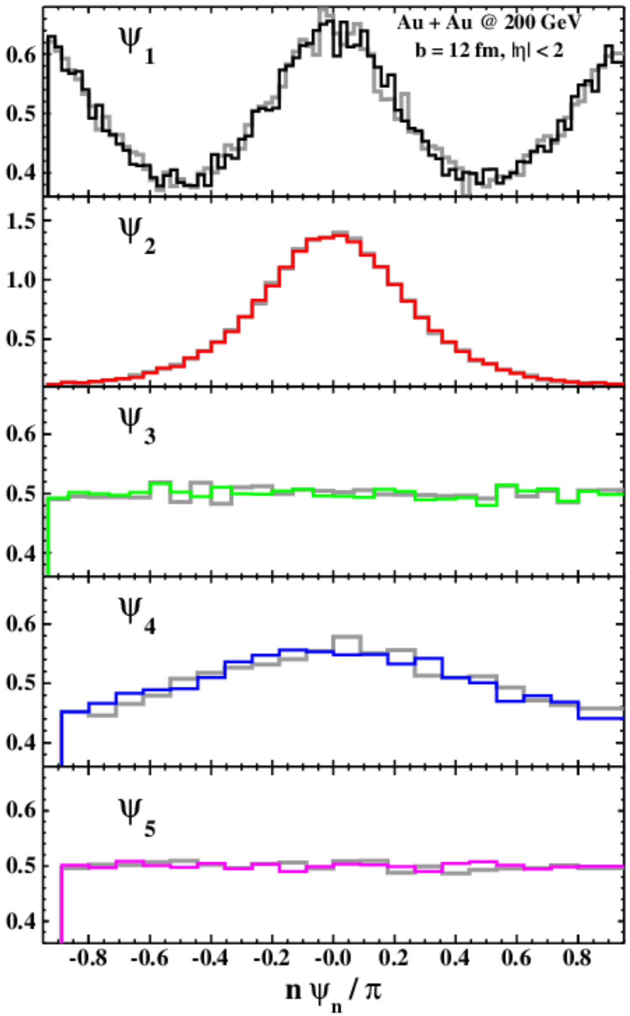
Neither hadronic nor partonic models can explain the energy dependence of v_2!

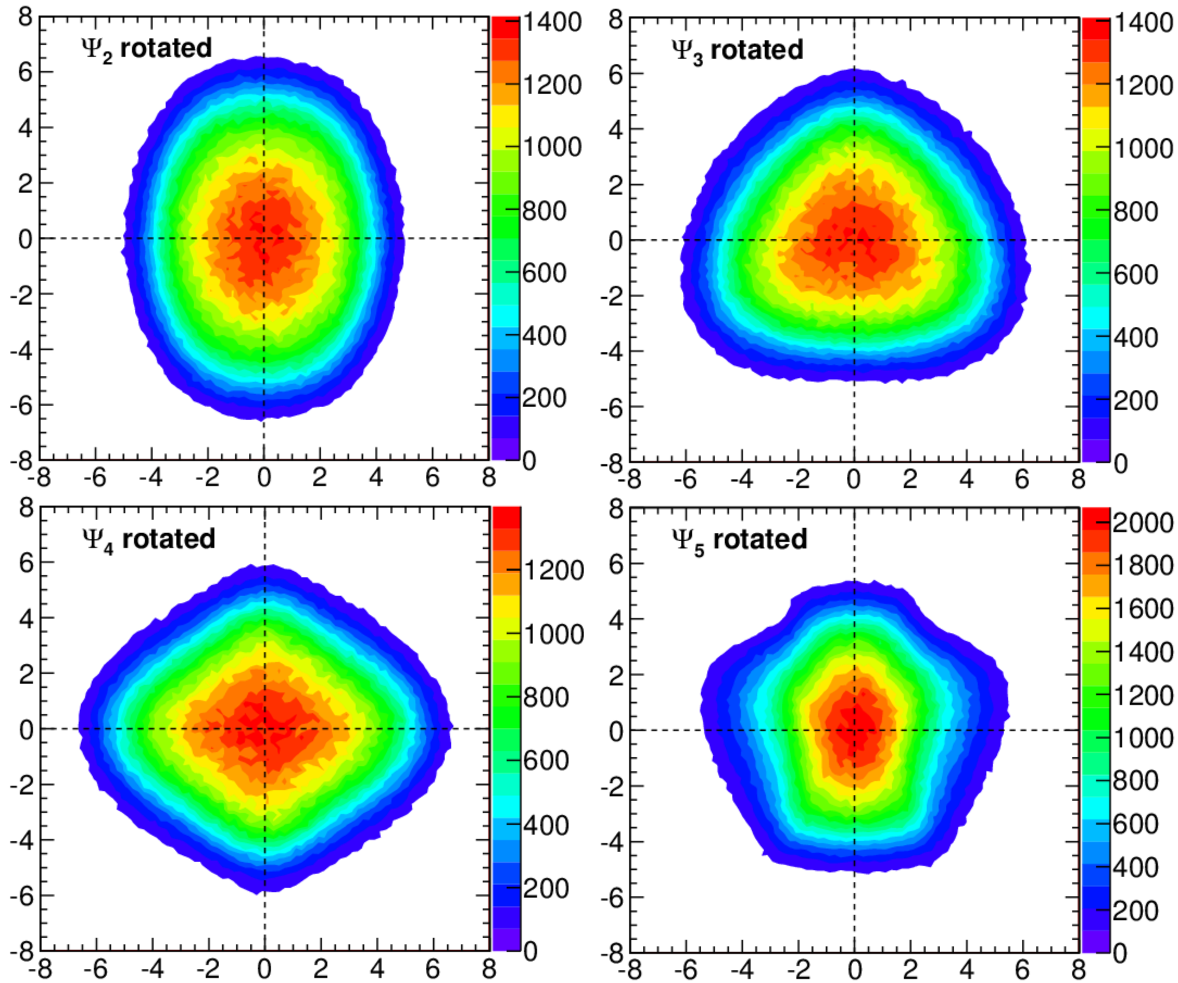
Initial spatial distribution in a single event



In a single event the Participant Plane (PP) is tilted relative to the Reaction Plane (RP).
Higher order harmonics may be formed, too!

Final angular distribution in p-space



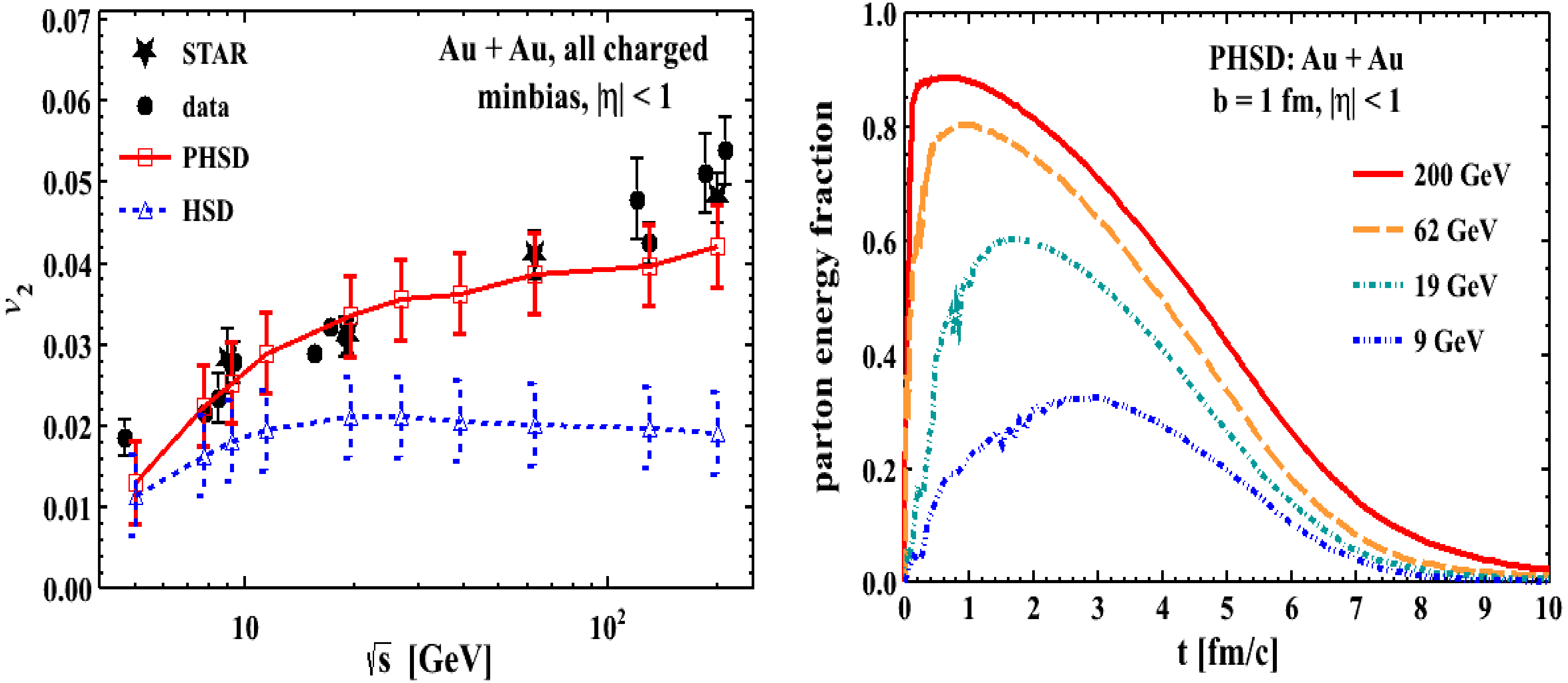


Event plane distributions:
even – peaked,
odd – flat.

Au+Au collisions
rotated to different event planes.

S. Voloshin, arXiv: 1111.7241

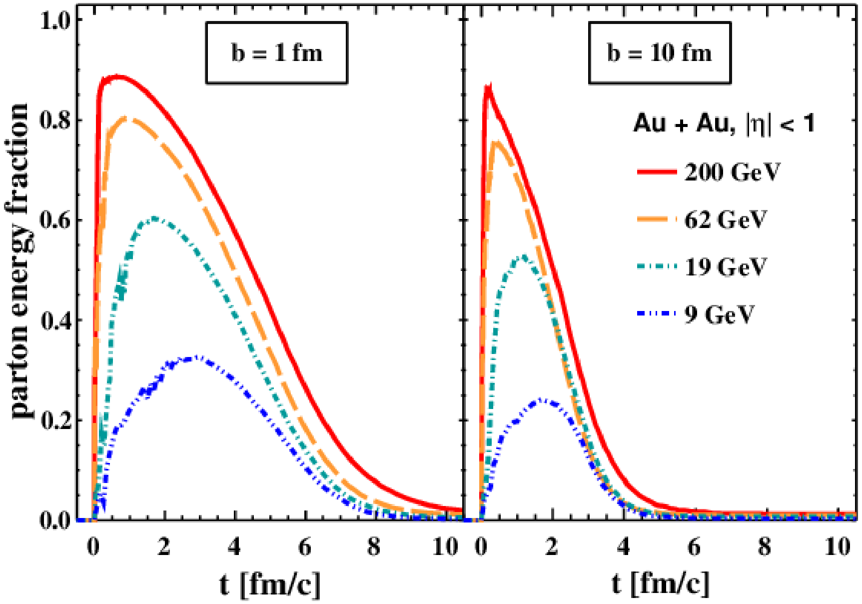
Energy dependence of v_2 from PHSD

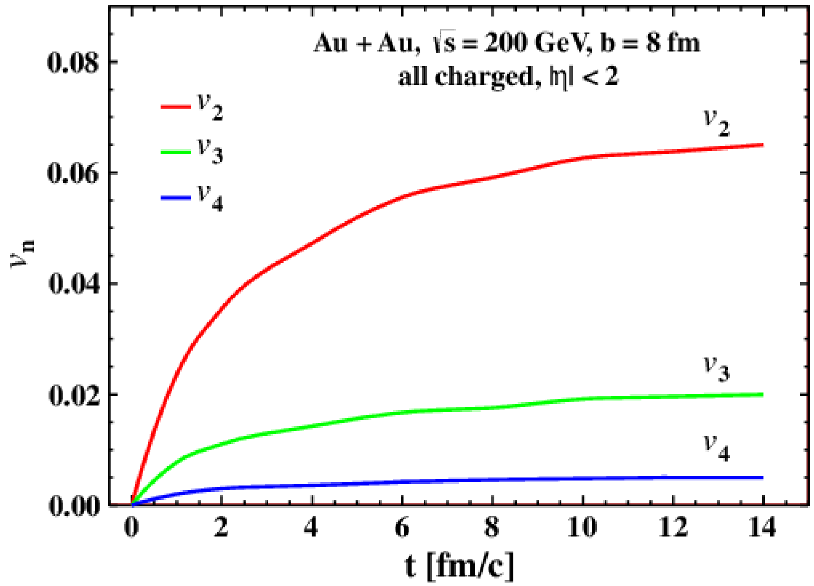


Increase of elliptic flow v_2 with collision energy is reasonably discribed by PHSD due to an increasing fraction of partonic degrees of freedom.

Phys. Rev. C85, 011902 (2012)

Formation of flow

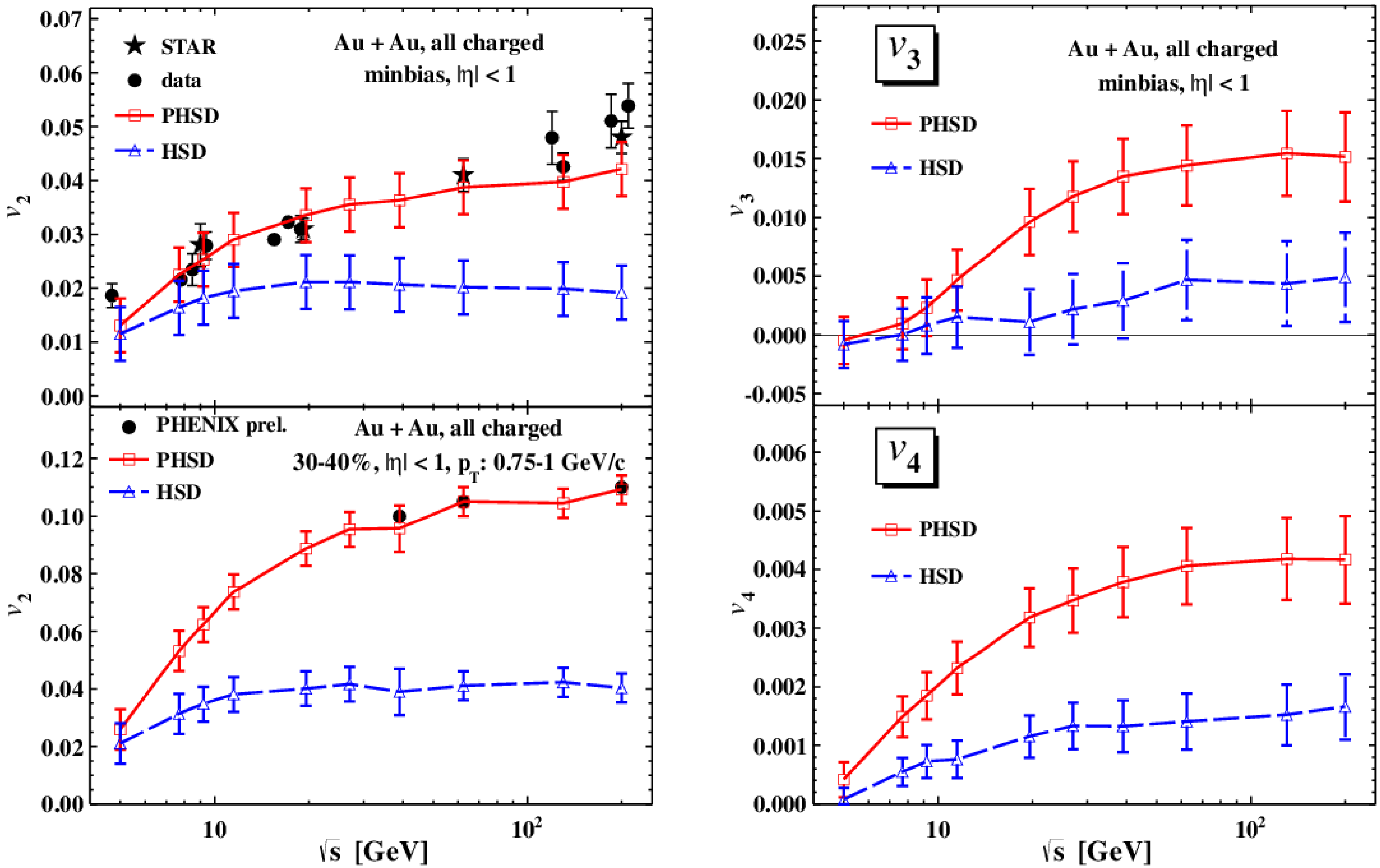




- Relative number of partons does not depend much on centrality.
- In peripheral collisions the duration of the partonic phase is short.
- Collective flow is formed mainly during the partonic phase.

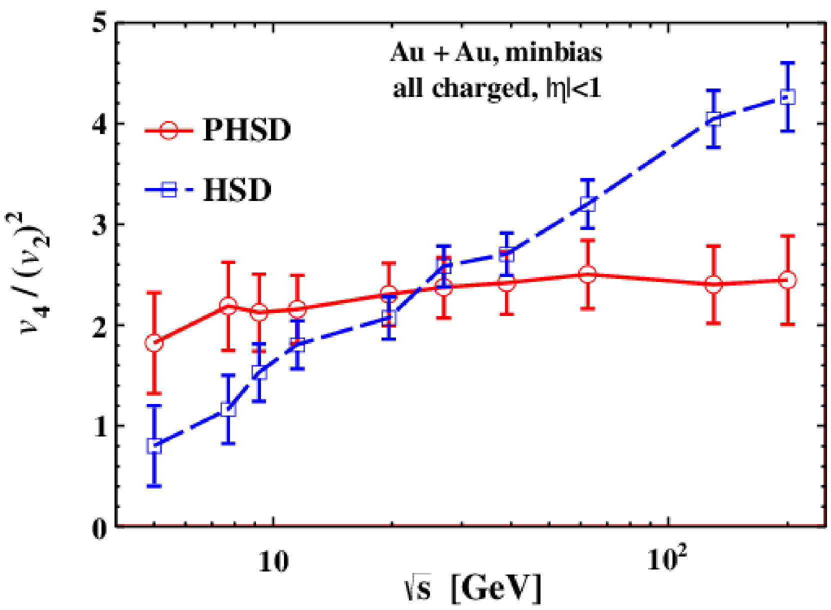
Phys. Rev. C85, 044922 (2012)

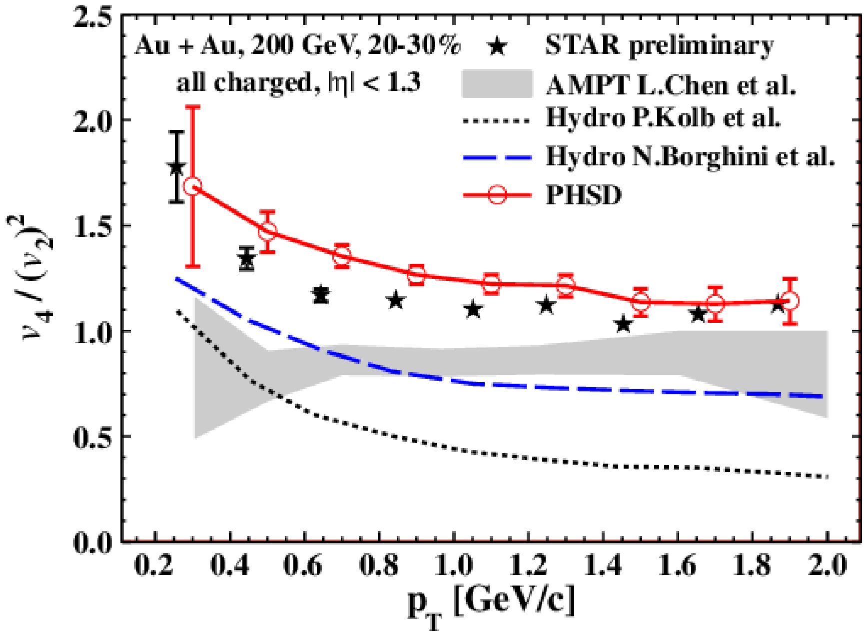
More exitation functions



Phys. Rev. C85, 044922 (2012)

Ratio v_4 / v_2^2



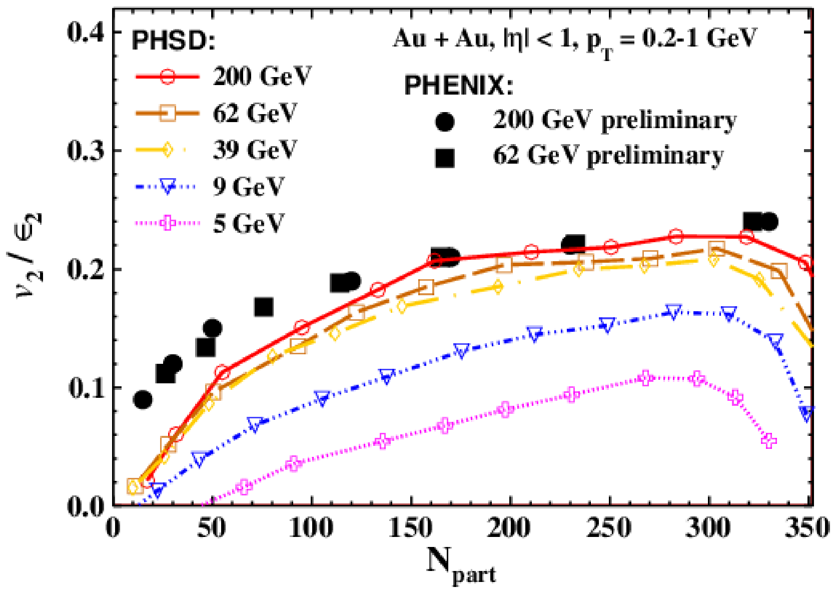


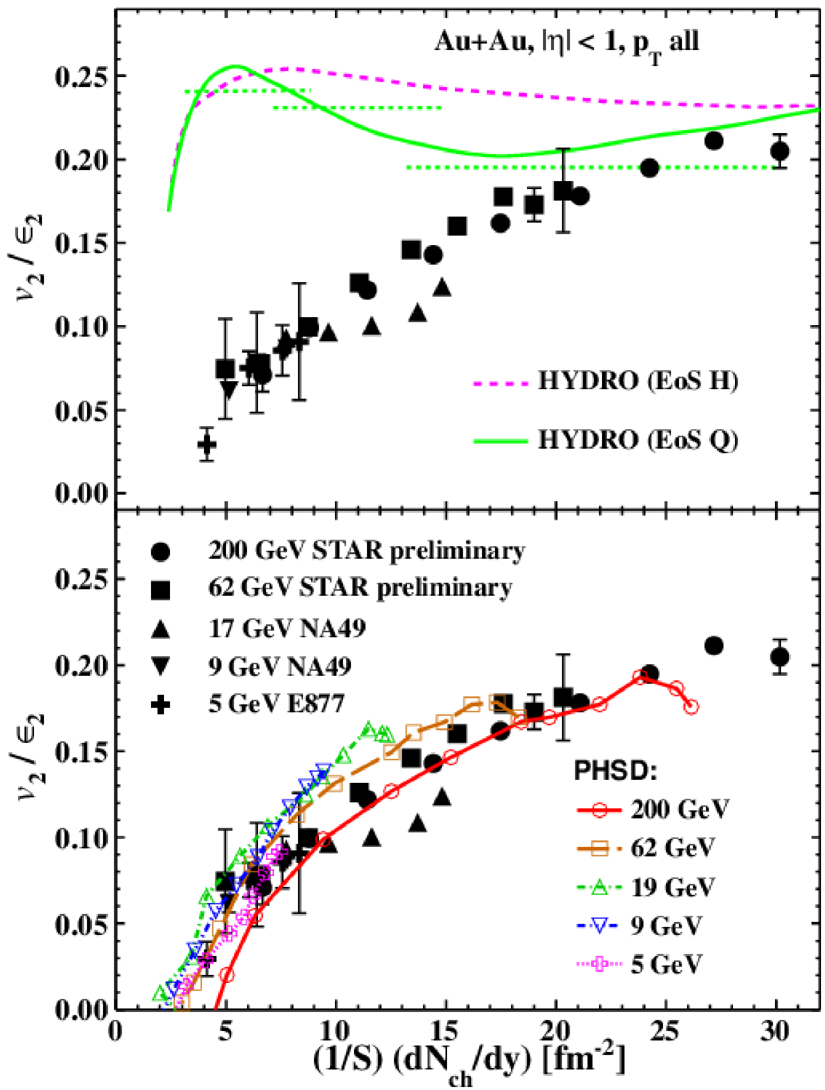
$v_4 / (v_2)^2$ is almost constant vs energy for PHSD

Not compatible with ideal hydrodynamics and very sensitive to the microscopic dynamics

Phys. Rev. C85, 044922 (2012)

Scaling properties





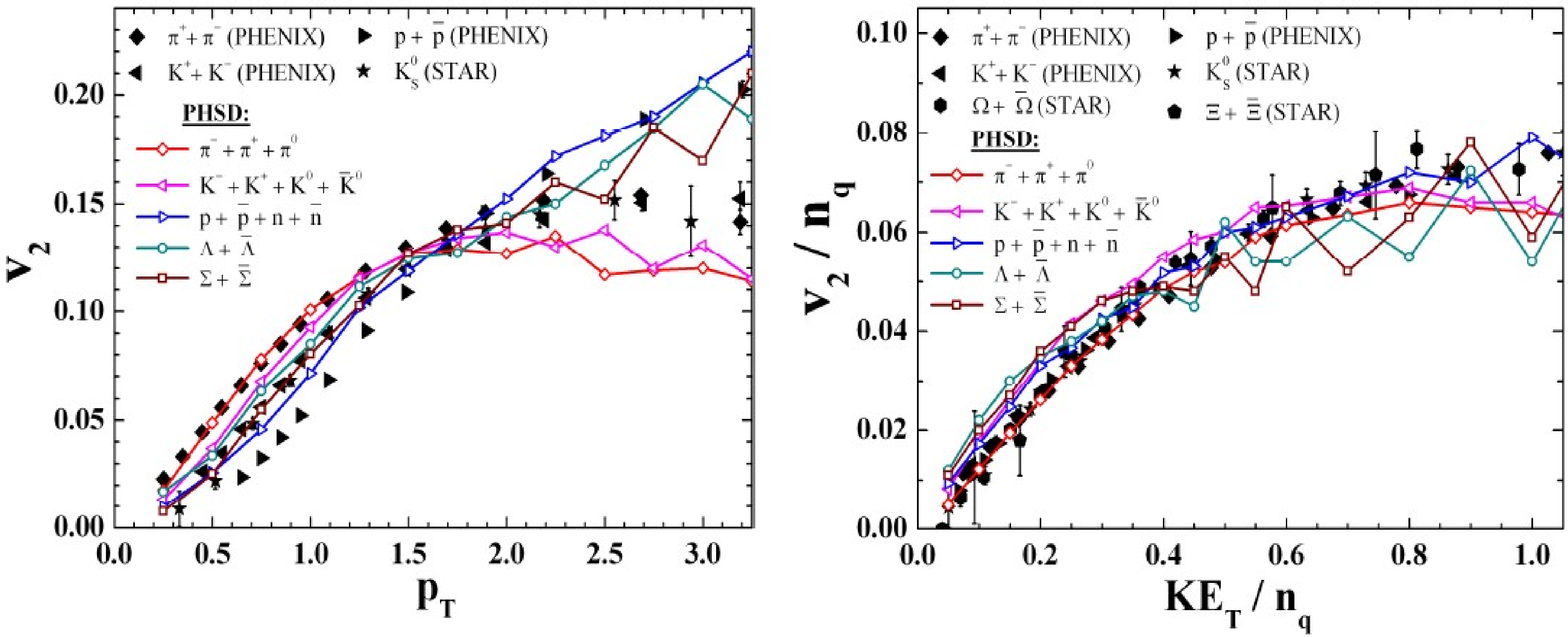
Initial assymetry:

$$\text{eccentricity } \epsilon_2 = \langle y^2 - x^2 \rangle / \langle x^2 + y^2 \rangle$$

“universal” scaling approximately works in PHSD but fails in hydrodynamics

Phys. Rev. C85, 044922 (2012)

Quark number scaling

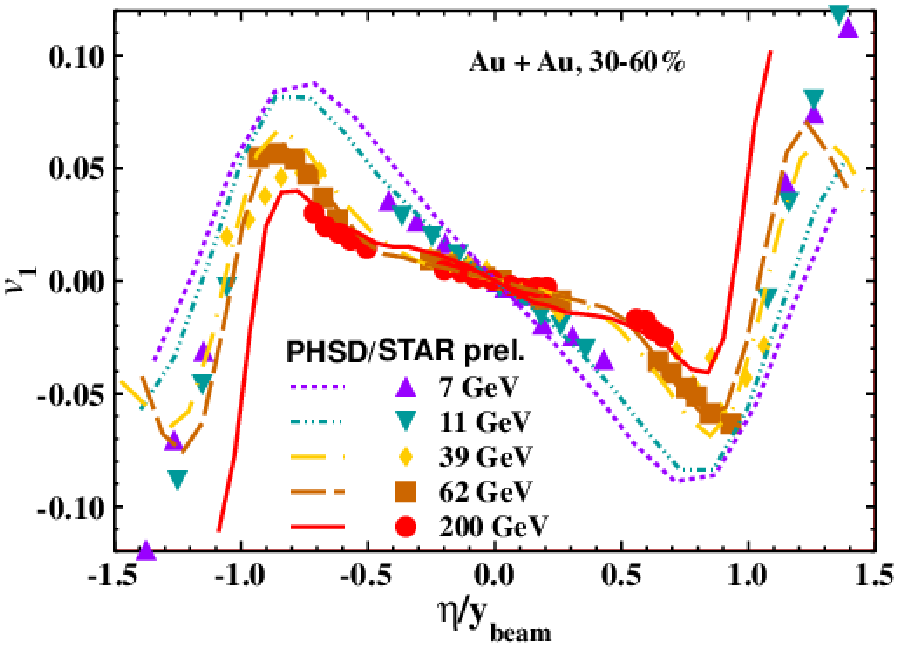


- The mass splitting at low p_T is approximately reproduced as well as the baryon-meson splitting for p_T > 2 GeV/c
- The scaling of v_2 with the number of constituent quarks is roughly in line with the data

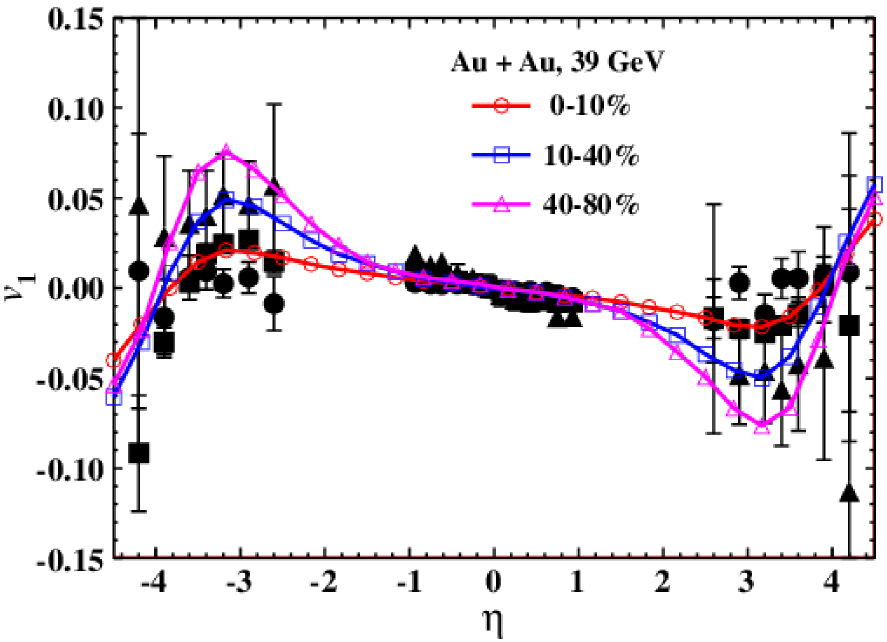
E. Bratkovskaya, W. Cassing, VK, O. Linnyk, Nucl. Phys. A856, 162 (2011)

Direct flow v_1

energy dependence



centrality dependence



PHSD: v1 vs. pseudo-rapidity follows an approximate scaling for higher energies – in line with experimental data – whereas at low energies the scaling is violated!

Phys. Rev. C85, 044922 (2012)

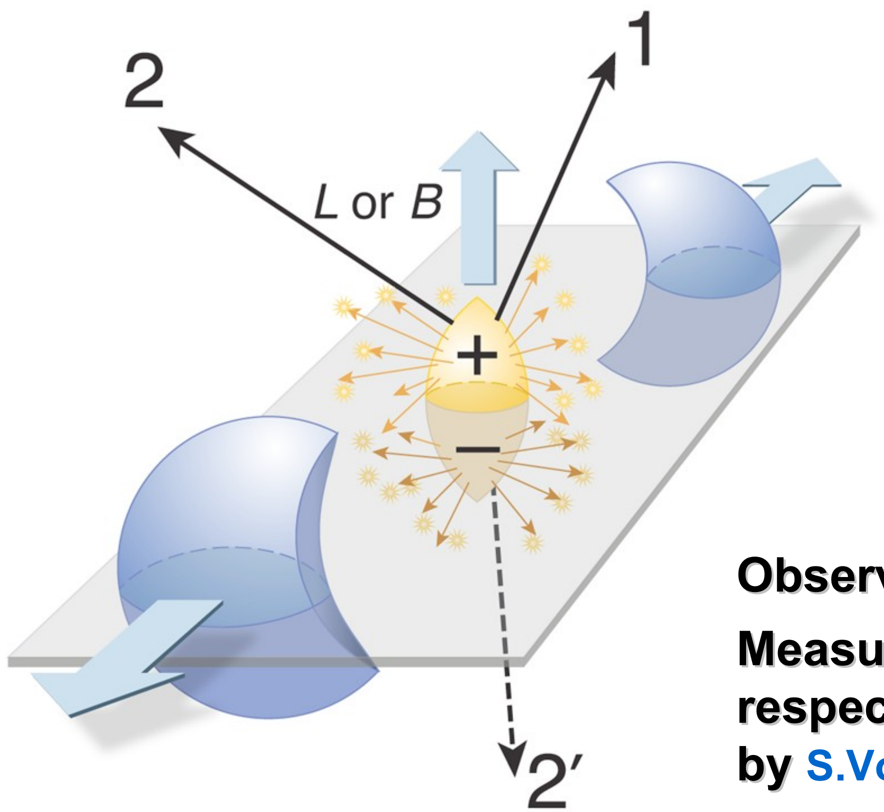
CME: Charge separation in HIC

Nontrivial topological configurations exist in the QCD vacuum.

Transition between these states leads to a local P and CP symmetry violation.

The fluctuation of topological charges in the presence of magnetic field induces an electric current which will separate different charges.

illustration: Carin Cain



D.Kharzeev, PLB 633 (2006) 260.

In heavy-ion collision a strong magnetic field is produced mainly from charged spectators

Is the observed charge separation a signature of spontaneous chiral symmetry breaking?

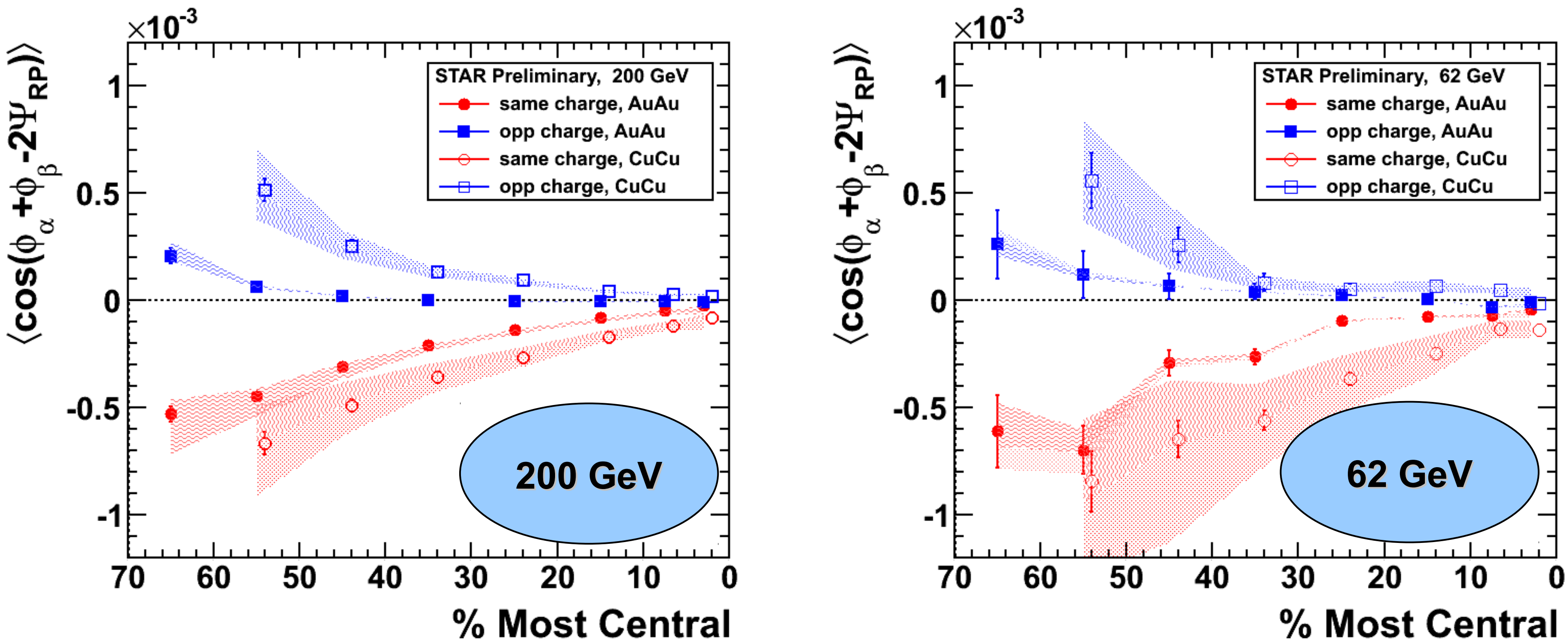
Observable: $\langle\cos(\varphi_a+\varphi_b-2\psi_{RP})\rangle$

Measuring the charge separation with respect to the reaction plane was proposed by S.Voloshin, Phys. Rev. C 70 (2004) 057901.

Charge separation in RHIC experiments

STAR Collaboration, PRL 103 (2009) 251601

$<\cos(\varphi_a+\varphi_b-2\psi_{RP})>$



Combination of intense B and deconfinement is needed for a spontaneous parity violation signal

Hadron-String-Dynamics
HSD

+

Retarded electromagnetic field

Transport model with electromagnetic field

The Boltzmann equation is the basis of BUU like models:

$$\{\frac{\partial}{\partial t} + \dot{\vec{r}} \cdot \vec{\nabla}_r + \dot{\vec{p}} \cdot \vec{\nabla}_p\}\ f(\vec{r},\vec{p},t) = I_{coll}(f, f_1, ...f_N)$$

Generalized on-shell transport equations in the presence of electromagnetic fields can be obtained formally by the substitution:

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

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

$$\{\frac{\partial}{\partial t} + \left(\frac{\vec{p}}{p_0} + \vec{\nabla}_{\vec{p}}\, U\right)\vec{\nabla}_{\vec{r}} - \left(\vec{\nabla}_{\vec{r}}\, U - e\vec{E} - e\vec{v} \times \vec{B}\right)\vec{\nabla}_{\vec{p}}\ \}\ f(\vec{r},\vec{p},t) = I_{coll}(f, f_1, ...f_N)$$

$$U \sim Re(\Sigma^{ret})/2p_0$$

A general solution of the wave equations

$$\left\{\begin{array}{l} \vec{B} = \vec{\nabla} \times \vec{A} \\ \vec{E} = -\vec{\nabla}\Phi - \frac{\partial \vec{A}}{\partial t} \end{array}\right.$$

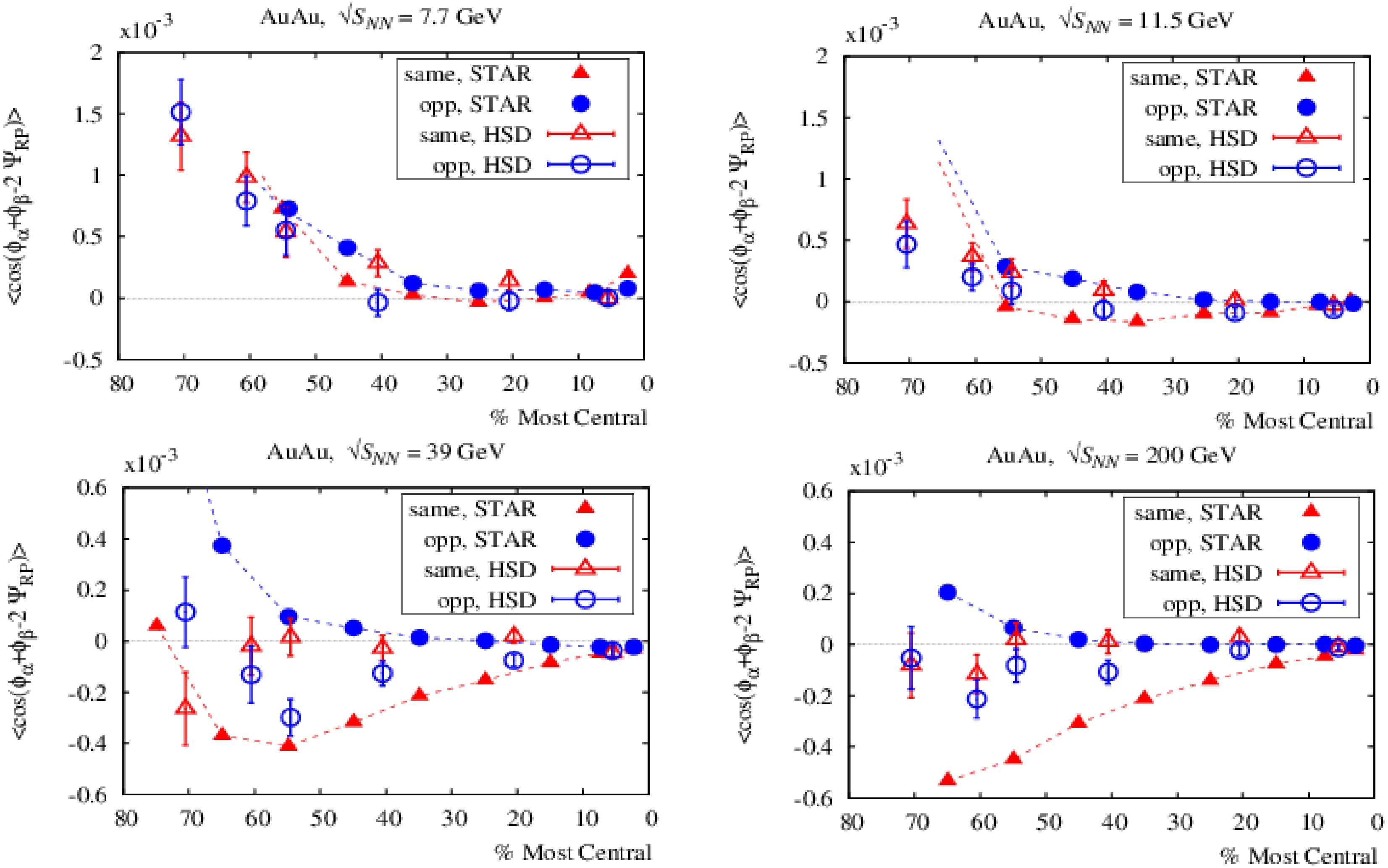
is as follows

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

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

For point-like particles $\rho(\vec{r},t) = e\ \delta(\vec{r} - \vec{r}(t));\quad \vec{j}(\vec{r},t) = e\ \vec{v}(t)\ \delta(\vec{r} - \vec{r}(t))$ $\quad \vec{\nabla} \times \vec{A} \rightarrow LW eq.$

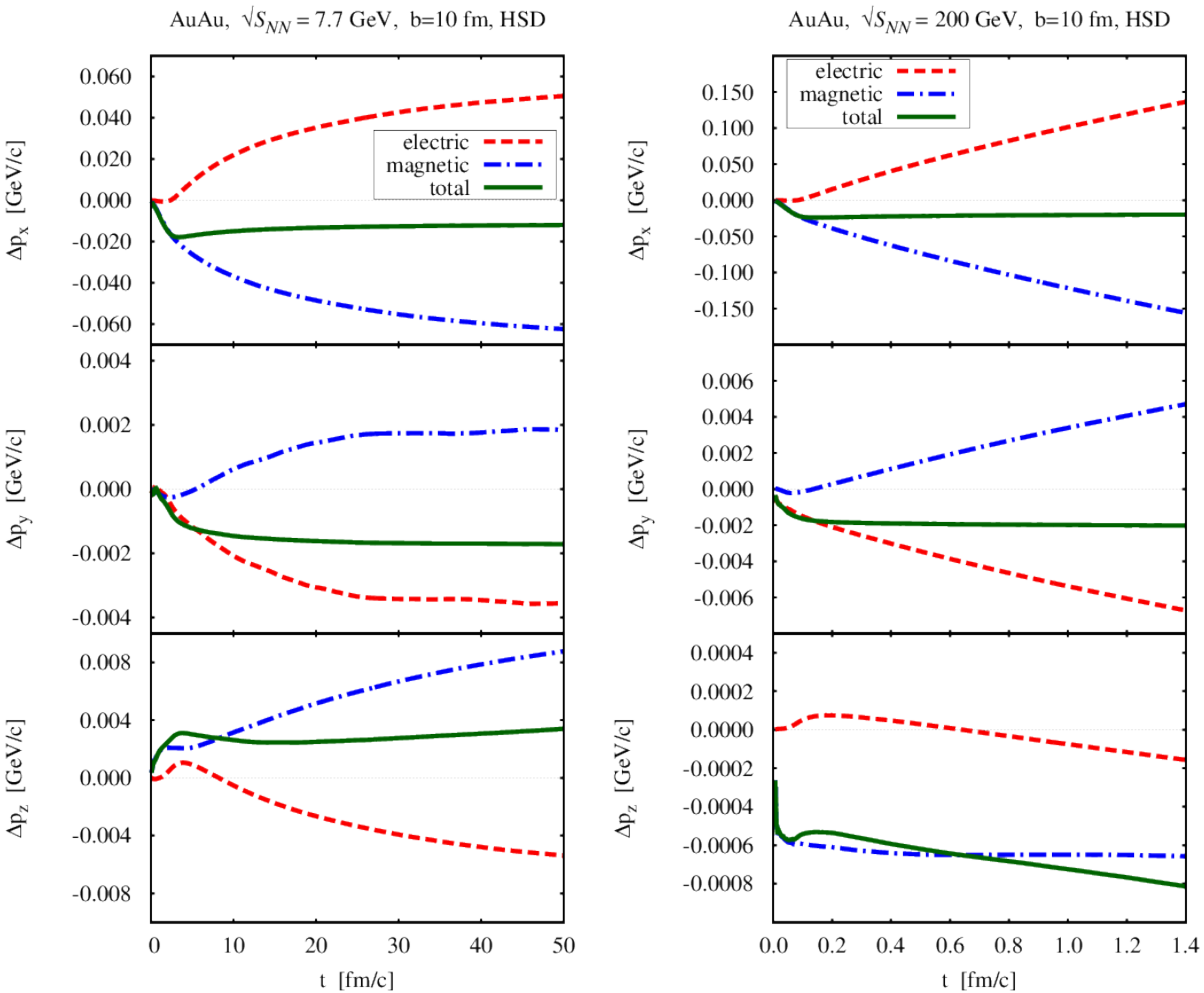
Angular correlations



are well described by hadronic sources up to 11 GeV

V.D. Toneev et al., Phys.Rev. C85, 034910 (2012)

Compensation of magnetic and electric forces



V.D. Toneev et al., Phys.Rev. C85, 034910 (2012)

Summary

- PHSD model with direct inclusion of quarks and gluons provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state.

- A study of the elliptic flow v_2 (as well as v_3 and v_4) from $\sqrt{s}$ = 7.7 GeV to 200 GeV has been made in the PHSD on an event-by-event basis. Partonic degrees of freedom gives a rise in the elliptic flow with energy observed experimentally

- Quark number scaling is described by PHSD

- The HSD transport model with retarded electromagnetic fields has been developed. Actual calculations show no noticeable influence of the created electromagnetic fields on observables. This happens due to a compensating effect between electric and magnetic fields

Thanks

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