Institut für
Theoretische Physik I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Evolution of electro-magnetic field in relativistic heavy-ion collisions from the HSD transport approach

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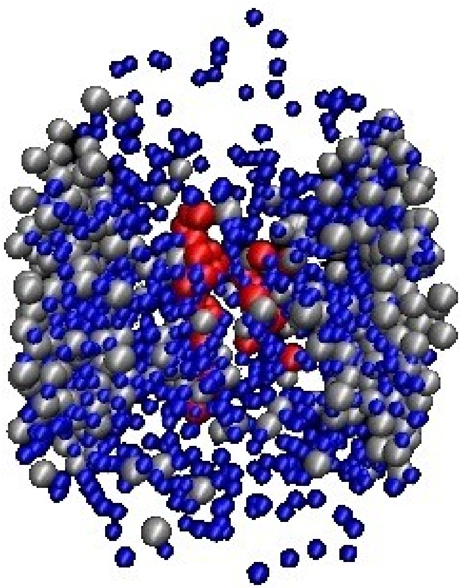


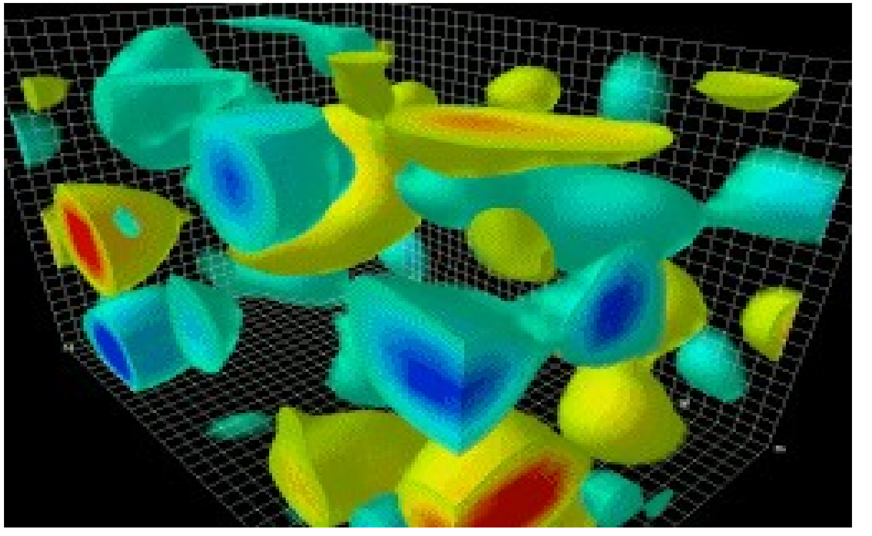
WPCF2011
Tokyo, Japan
23 September 2011

Parity violation in strong interactions

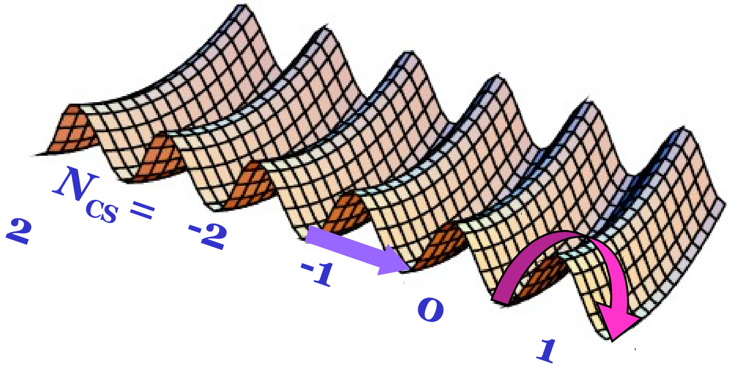
In QCD, chiral symmetry breaks due to a non-trivial topological effect; among the best evidence of this physics would be event-by-event strong parity violation.

The volume of the box is 2.4 by 2.4 by 3.6 fm.

The topological charge density of 4D gluon field configurations.
(Lattice-based animation by *Derek Leinweber*)



Energy of gluonic field is periodic in N_{CS} direction (~ a generalized coordinate)



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or crossing the barrier

Dynamics is a random walk between states with different topological charges.

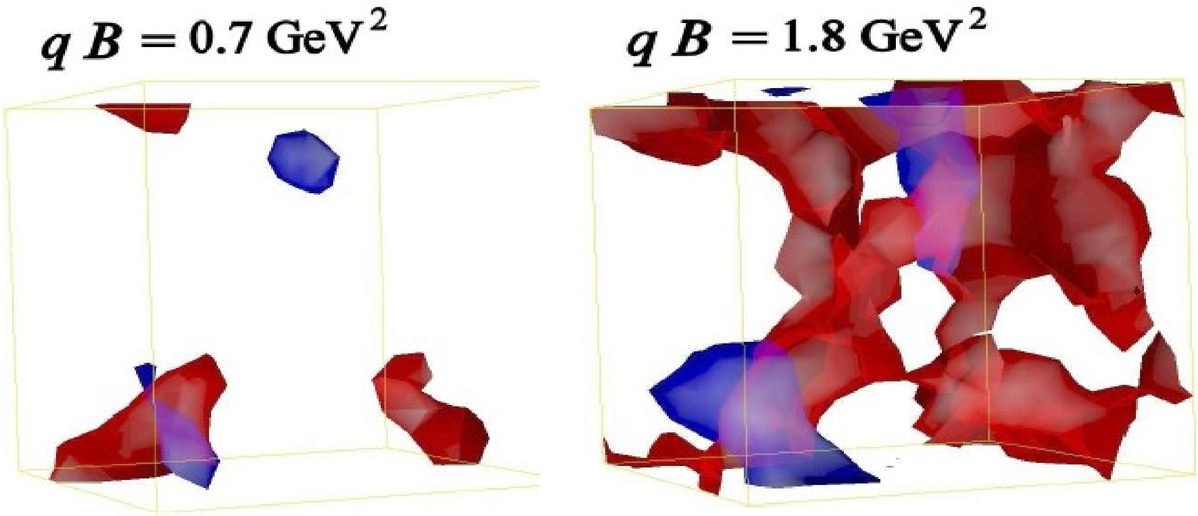
Charge separation: CP violation signal

Dynamics is a random walk between states with different topological charges. In this states a balance between left-handed and right-handed quarks is destroyed, $N_R - N_L = Q_T \rightarrow$ violation of P-, CP- symmetry.

Average total topological charge vanishes $\langle n_w \rangle = 0$ but its variance is equal to the total number of transitions $\langle n_w^2 \rangle = N_t$

Fluctuation of topological charges in the presence of magnetic field induces electric current which will separate different charges

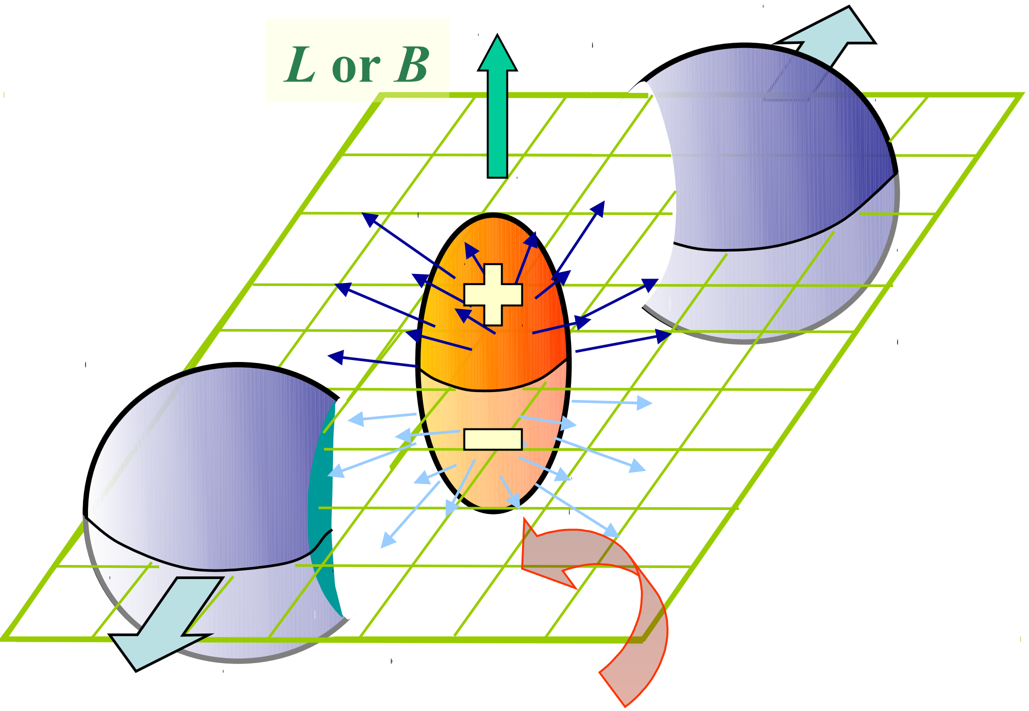
Lattice gauge theory



The excess of electric charge density due to the applied magnetic field. Red — positive charges, blue — negative charges.

P.V. Buividovich et al., PRD80 (2009) 054503

Charge separation in HIC



Non-zero angular momentum (or equivalently magnetic field) in heavy-ion collisions make it possible for P- and CP-odd domains to induce charge separation

D.Kharzeev, PLB 633 (2006) 260.

Electric dipole moment of QCD matter !

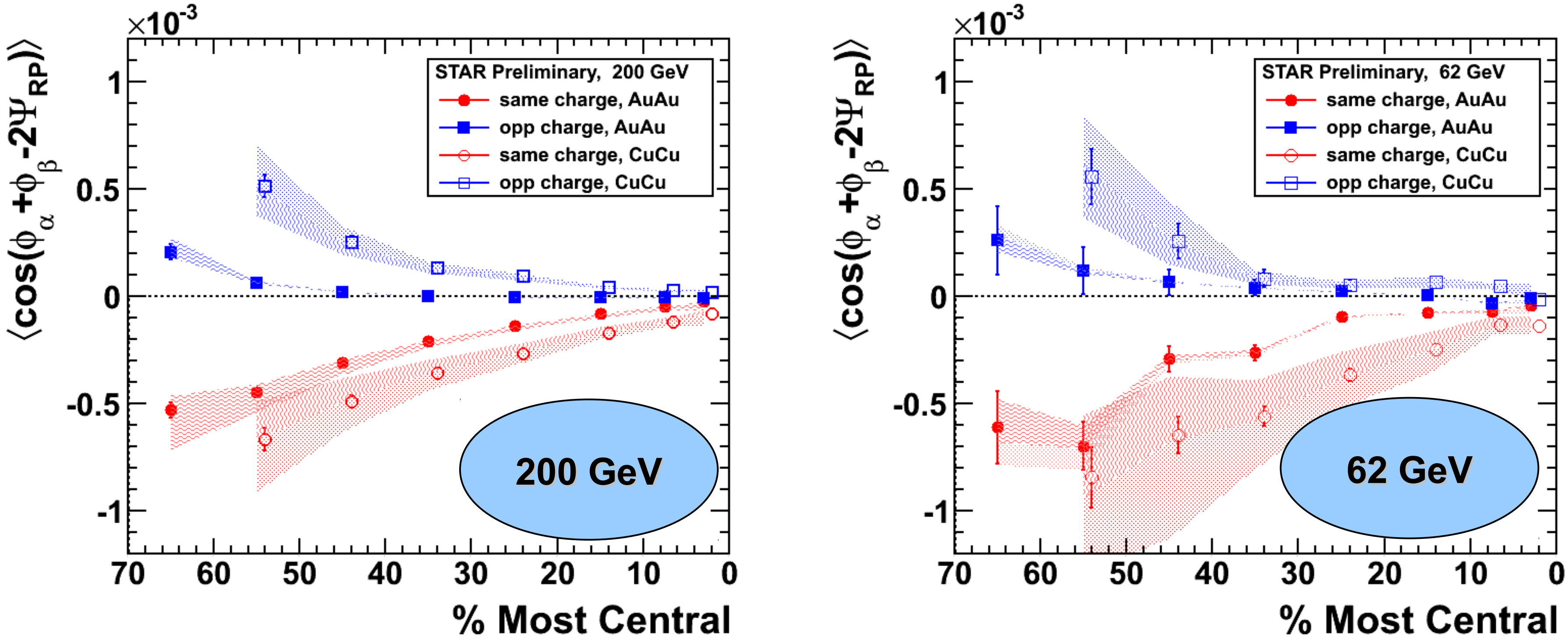
$\langle \cos(\varphi_a + \varphi_b - 2\psi_{RP}) \rangle$

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

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



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

Basic Concept of HSD Transport Approaches

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

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

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

Hadron-String-Dynamics
HSD

+

Retarded electromagnetic field

Transport model with electromagnetic field

The Boltzmann equation is the basis of QMD 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:

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

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

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

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

A general solution of the wave equations

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

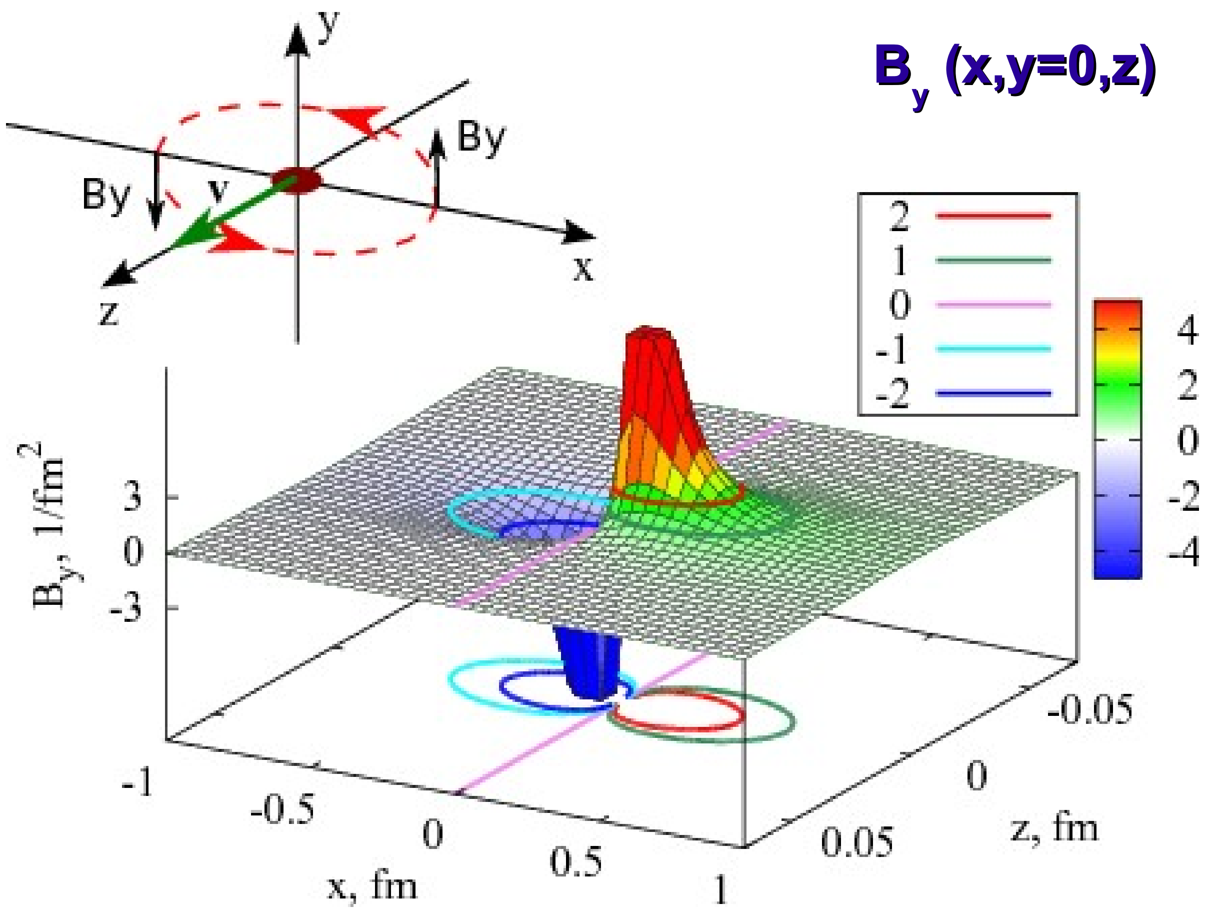
is as follows

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

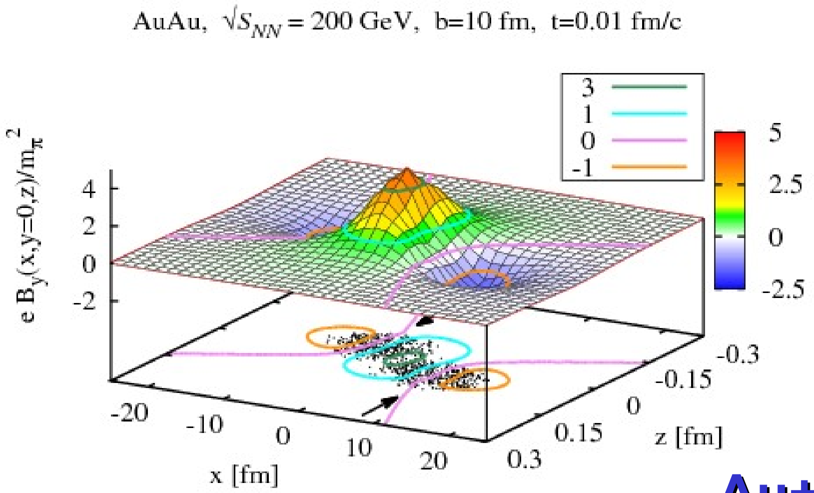
$$\Phi(\vec{r}, t) = \frac{1}{4\pi} \int \frac{\rho(\vec{r'}, t') \ \delta(t - t' - |\vec{r} - \vec{r'}|/c)}{|\vec{r} - \vec{r'}|} \, d^3r' dt'$$

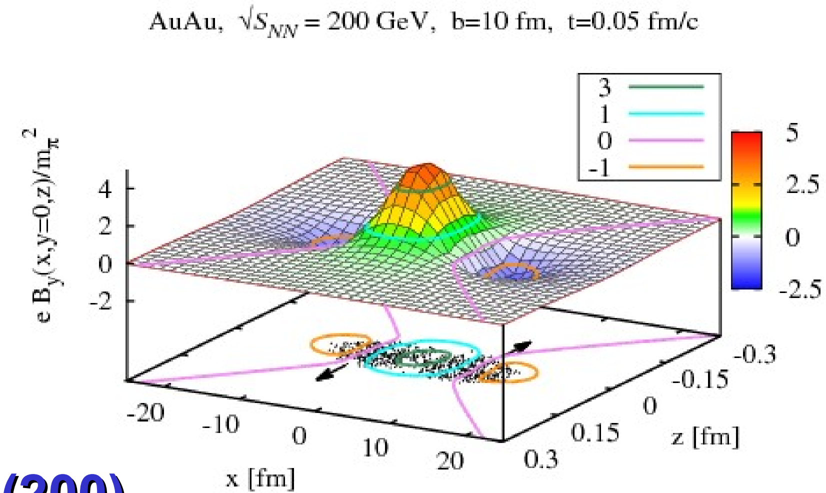
For point-like particles $\rho(\vec{r}, t) = e\ \delta(\vec{r} - \vec{r}(t));\quad \vec{j}(\vec{r}, t) = e\ \vec{v}(t)\ \delta(\vec{r} - \vec{r}(t))$ $\quad \vec{\nabla} \times \vec{A} \to LW eq.$

Magnetic field for a single moving charge

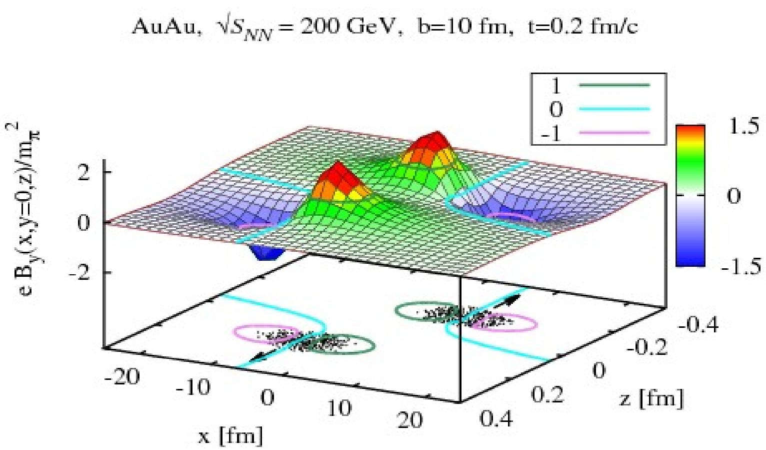


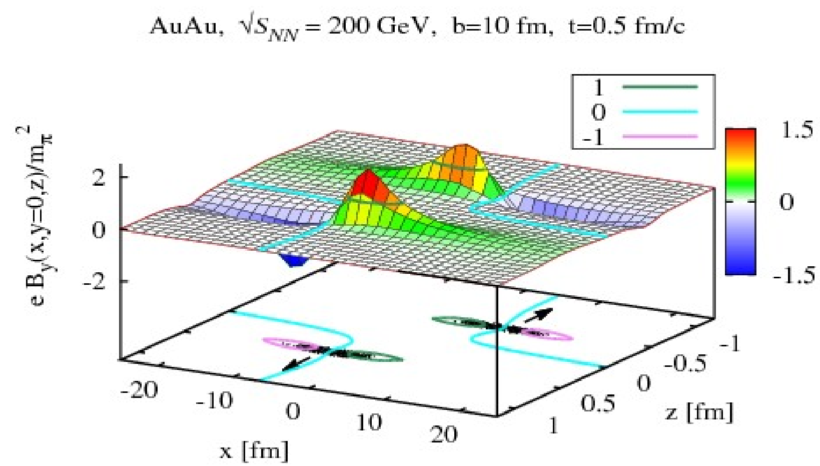
Magnetic field evolution





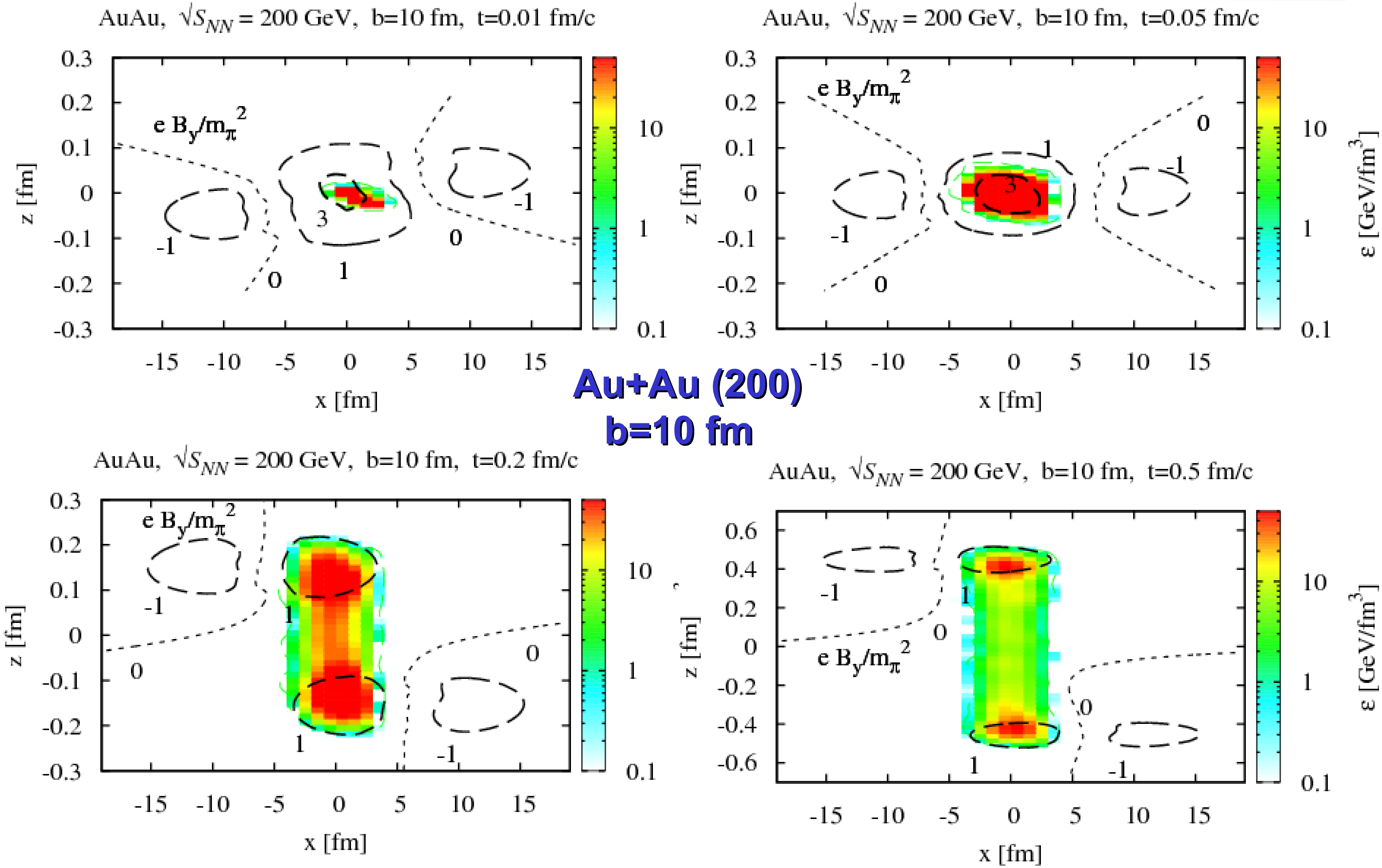
Au+Au (200)
b=10 fm





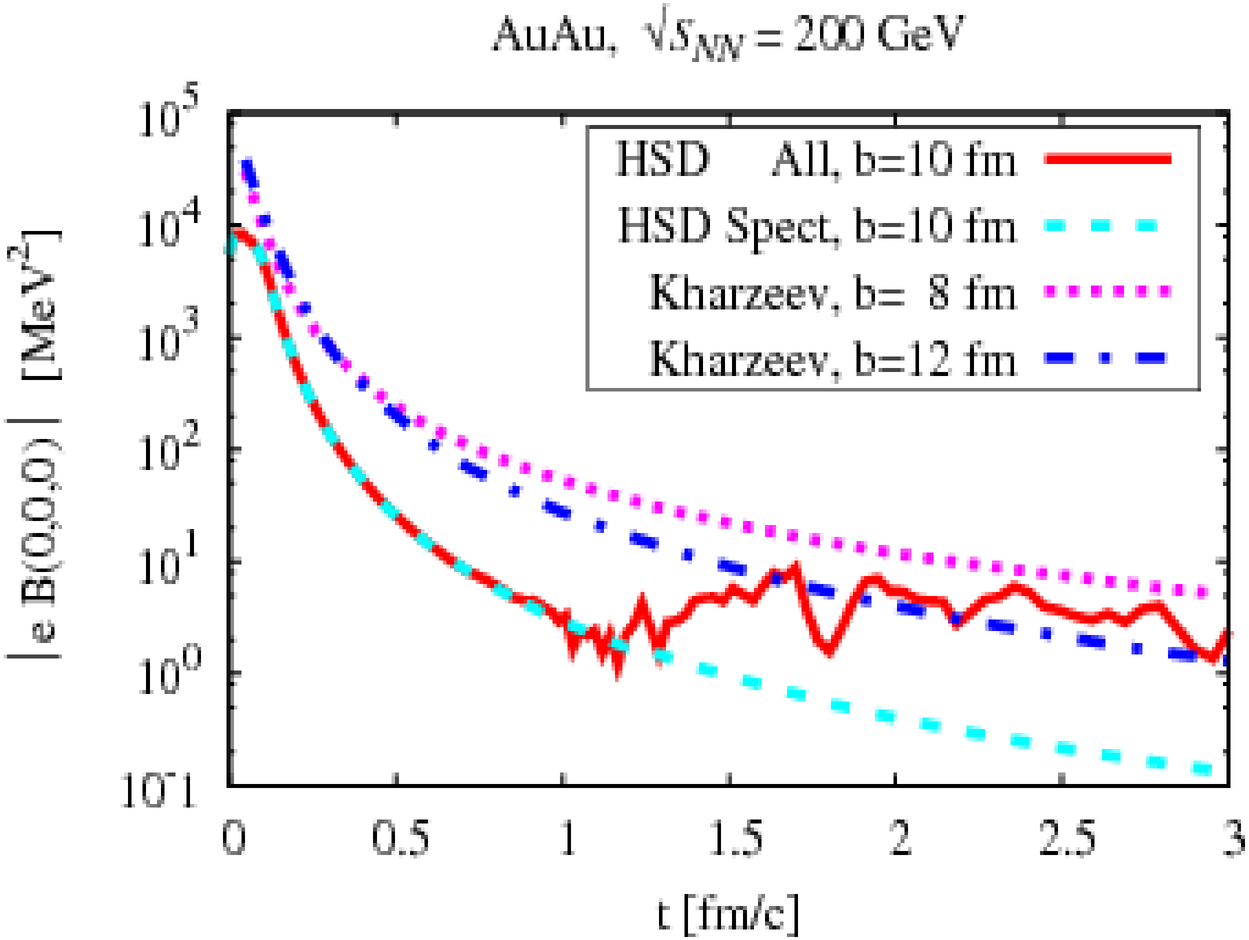
V.Voronyuk, et al., Phys.Rev. C83 (2011) 054911

Magnetic field and energy density correlation



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

Time dependence of eB_y



D.E. Kharzeev et al., Nucl. Phys. A803, 227 (2008)

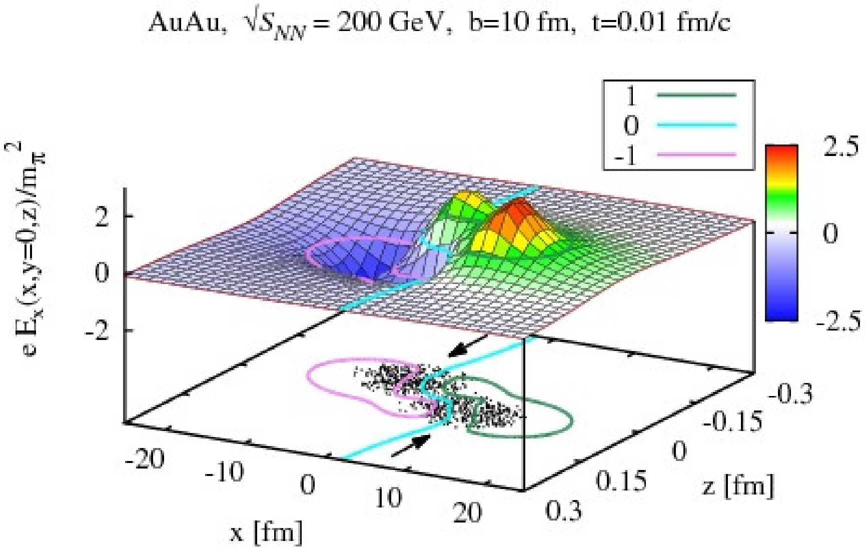
Collision of two infinitely thin layers (pancake-like)

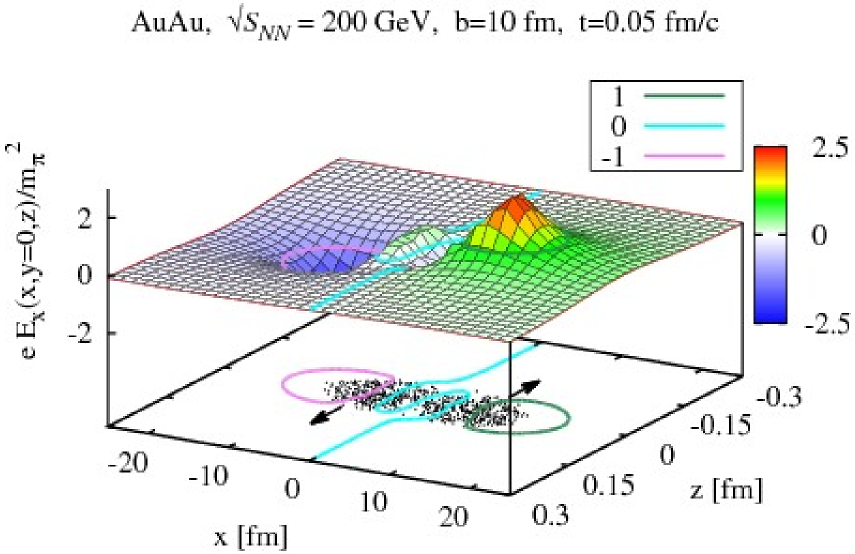
V.Voronyuk, et al., PRC83 (2011) 054911

- **Until t~1 fm/c the induced magnetic field is defined by spectators only.**
- **Maximal magnetic field is reached during nuclear overlapping time Δt~0.2 fm/c, then the field goes down exponentially.**

Electric field evolution

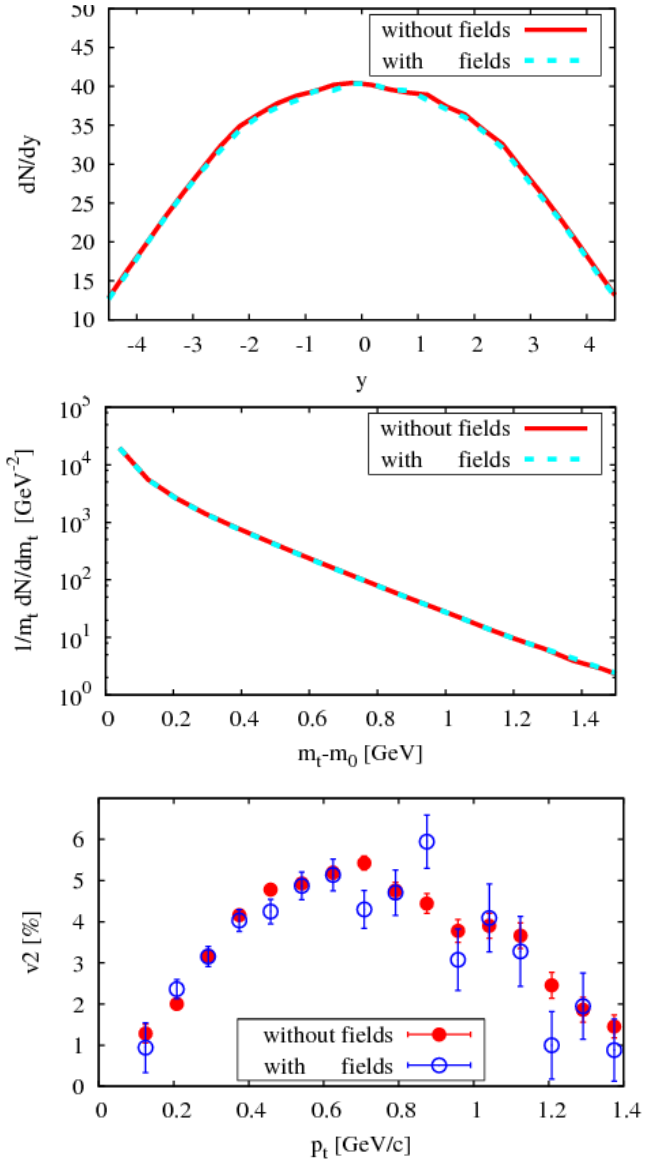
Electric field of a single moving charge has a "hedgehog" shape

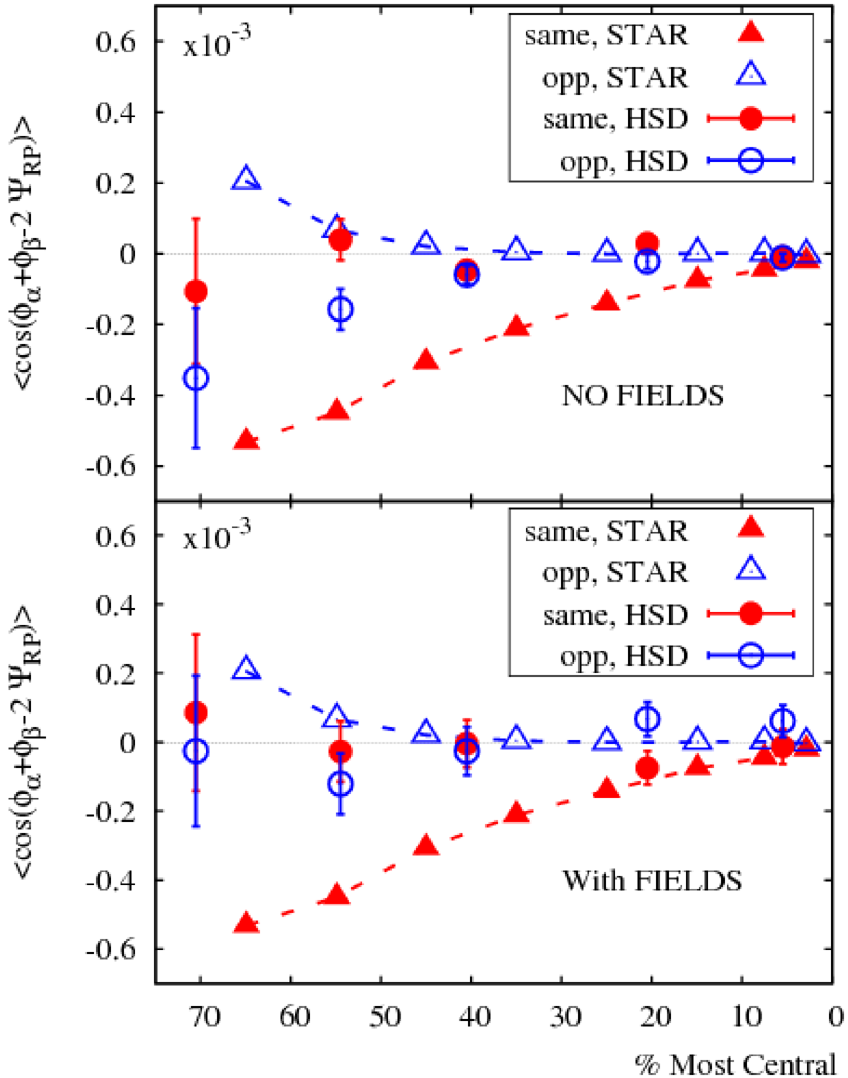




V.Voronyuk, et al., Phys.Rev. C83 (2011) 054911

Observables

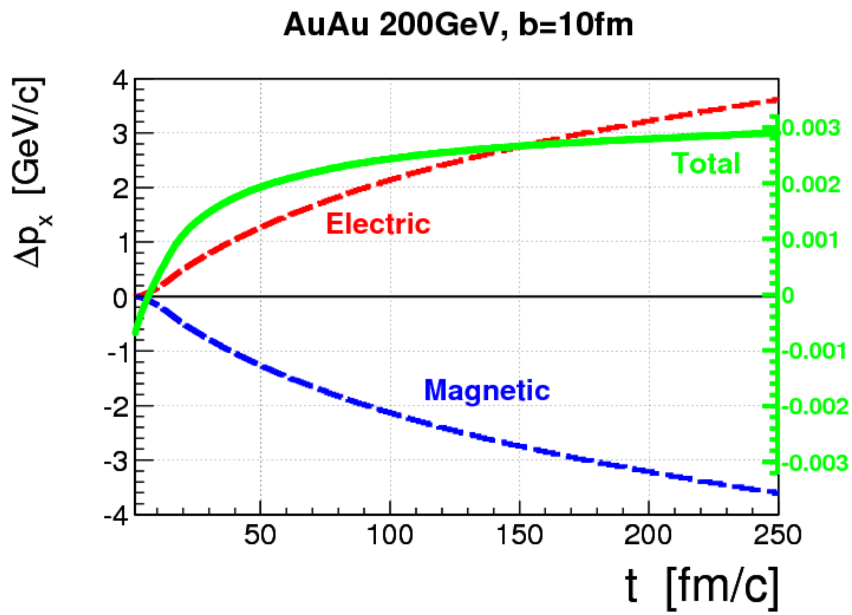


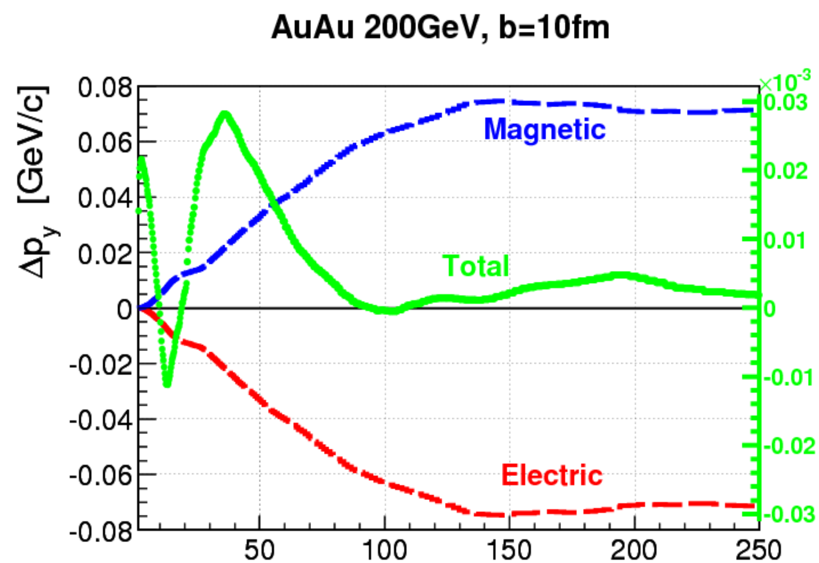


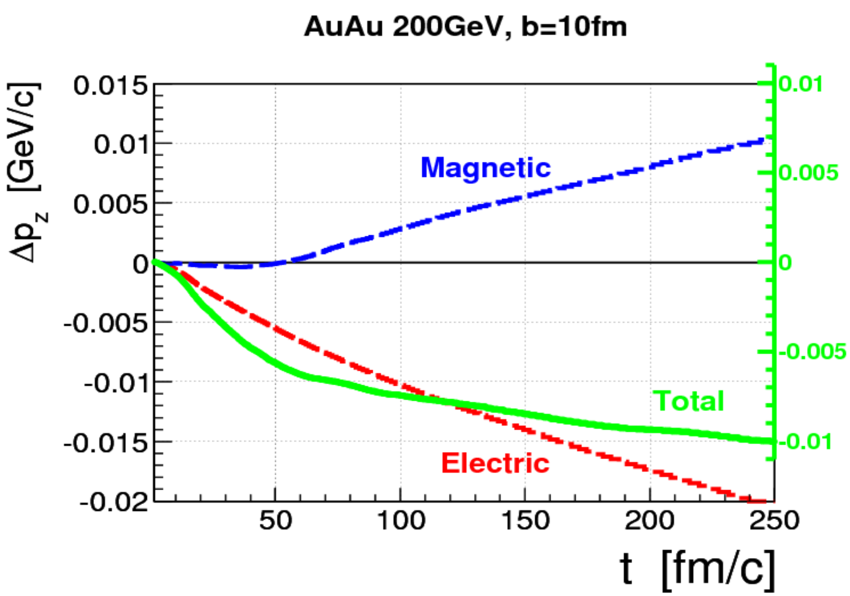
V.Voronyuk, et al., Phys.Rev. C83 (2011) 054911

No electromagnetic field effects on observables !

Average momentum increment





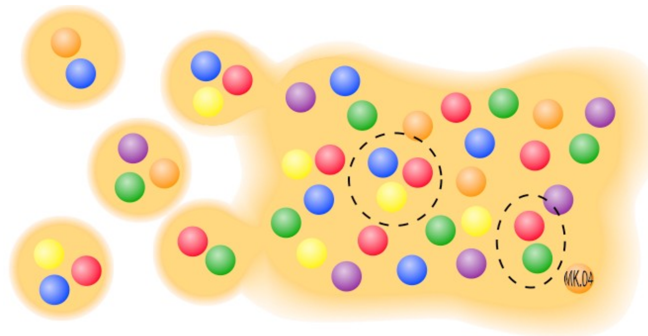


$$\dot{\vec{p}} \to e\vec{E} + e\vec{v} \times \vec{B}$$

$$\Delta\vec{p} = \sum_i \langle\, \delta\vec{p}\,\rangle_i \qquad for \;\; p_z > 0$$

Transverse momentum increments Δp due to electric and magnetic fields compensate each other !

Transport description of the partonic and hadronic phase

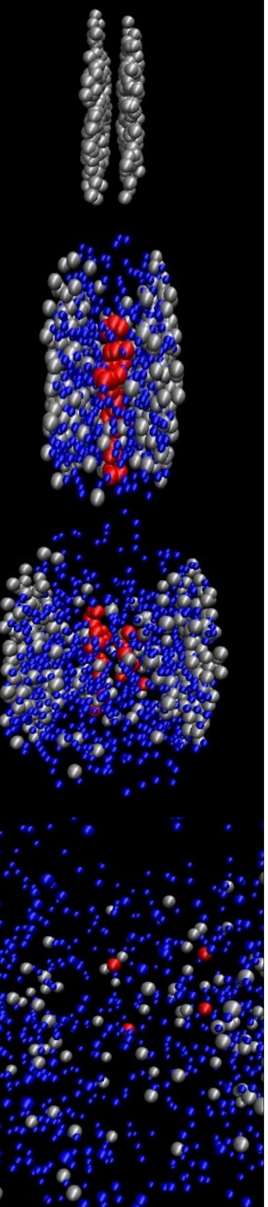


Parton-Hadron-String-Dynamics

PHSD

PHSD - basic concepts

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



- **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)

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

Summary

- 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

- Direct inclusion of quarks and gluons in evolution is needed => PHSD model, wich provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state

- Experiments on the CME planned at RHIC by the low-energy scan program are of great interest since they hopefully will allow to infer the critical magnetic field eB_{crit} governing the spontaneous local CP violation

ありがとう

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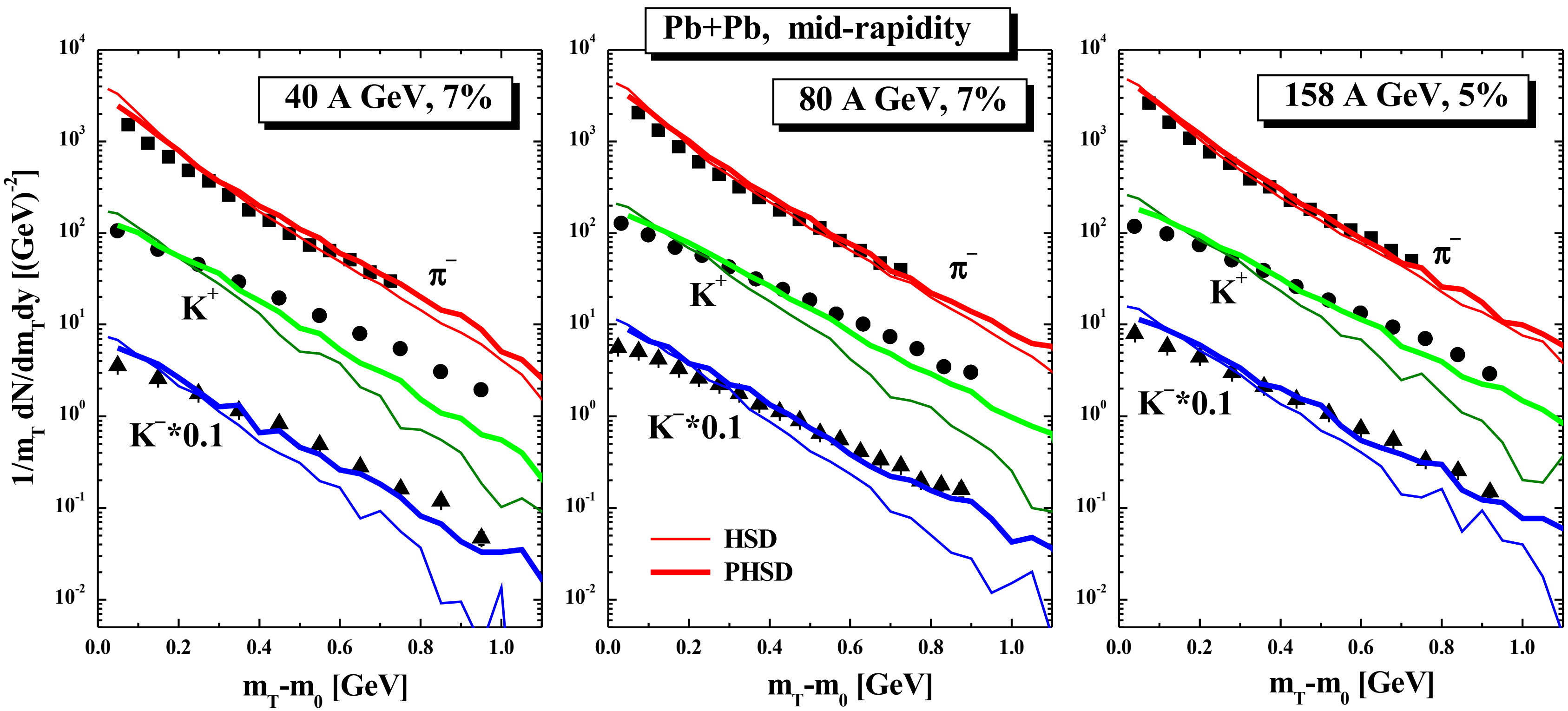
Transverse mass spectra at SPS energies

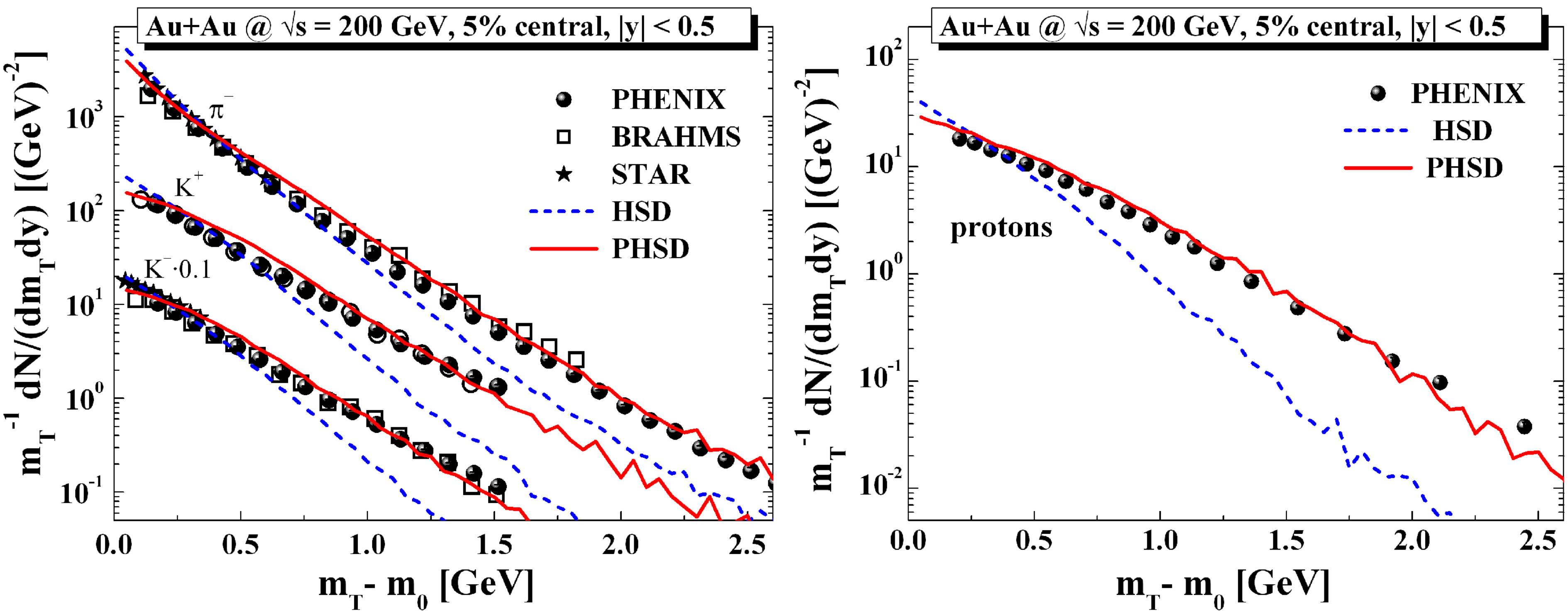
Central Pb + Pb at SPS energies



- **PHSD gives harder spectra and works better than HSD at SPS (and top FAIR) energies**
- **At low SPS (and low FAIR) energies the effect of the partonic phase is less pronounced in rapidity distributions and m_T spectra**

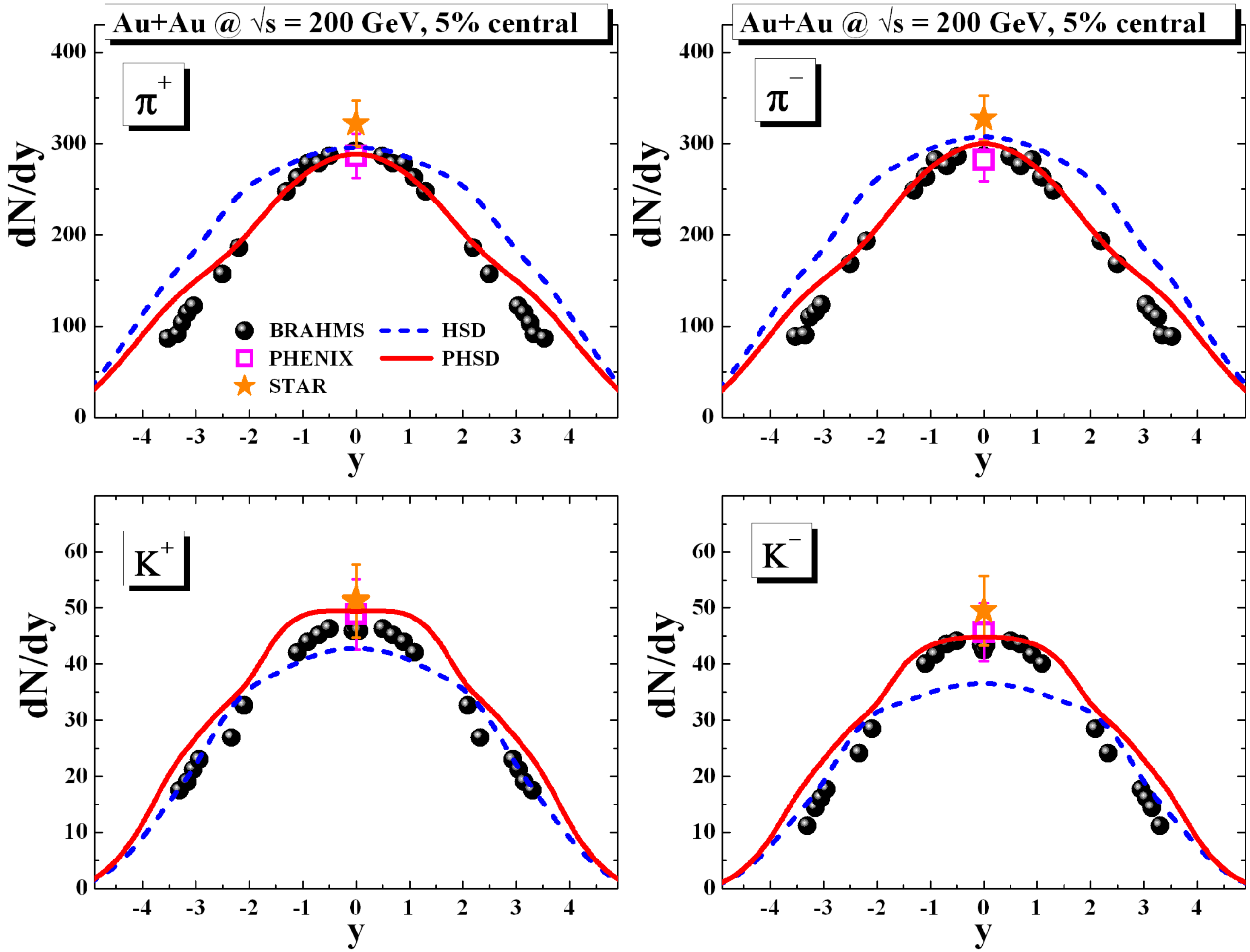
Cassing & Bratkovskaya, NPA 831 (2009) 215

Transverse mass spectra at RHIC energies



PHSD improves significantly with respect to HSD (and the data) !

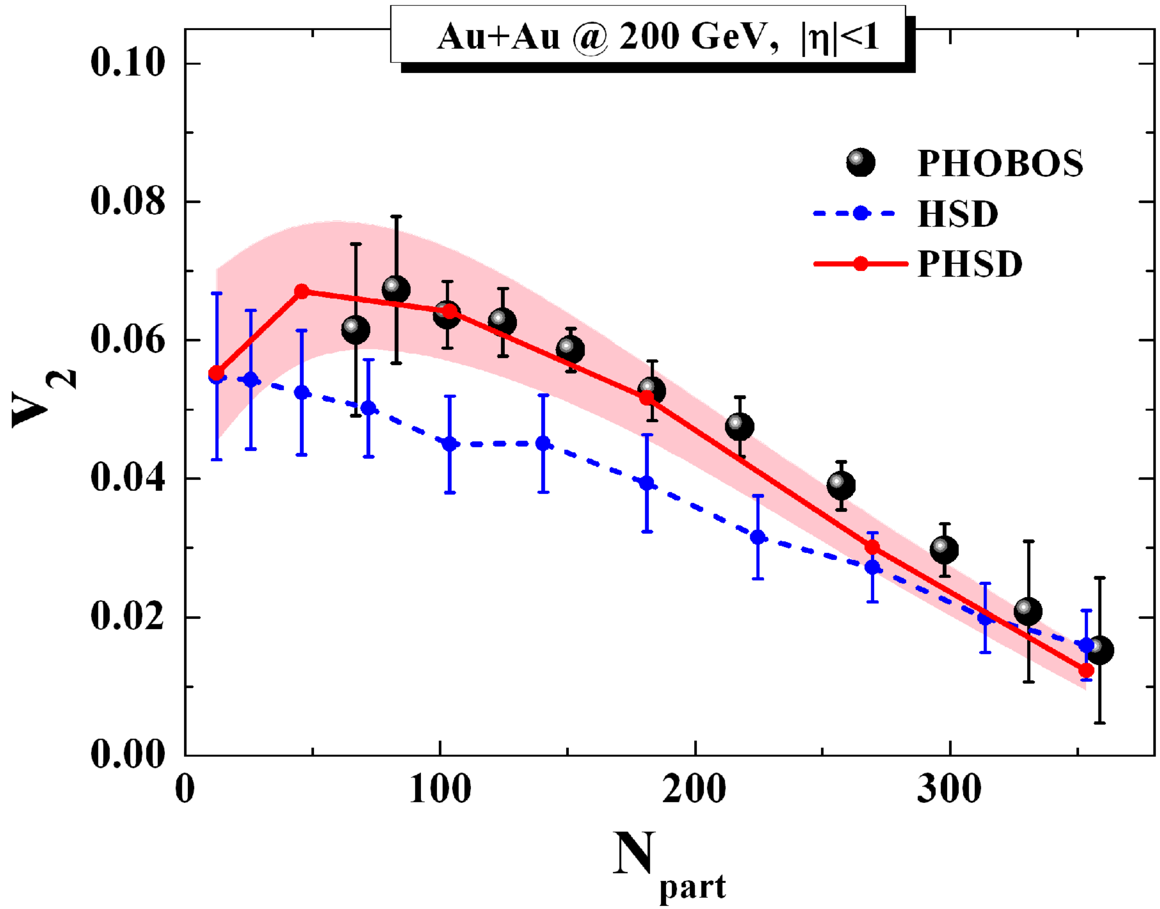
Rapidity distributions at RHIC energies



Look quite reasonable in comparison to data from STAR, PHENIX and BRAHMS

Elliptic flow vs. centrality

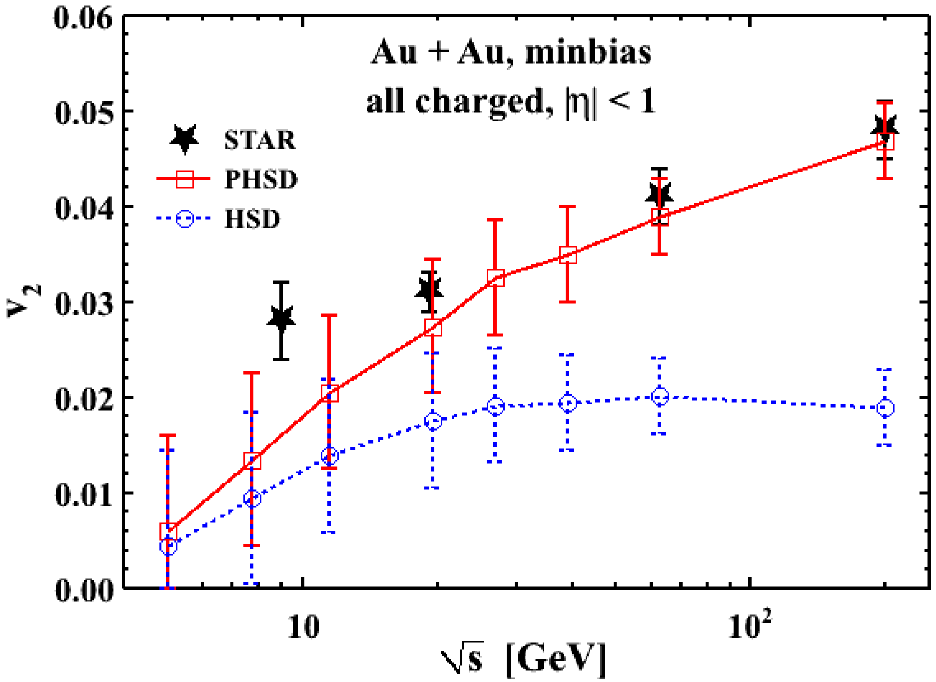
Au + Au collisions at $\sqrt{s}$ = 200 GeV



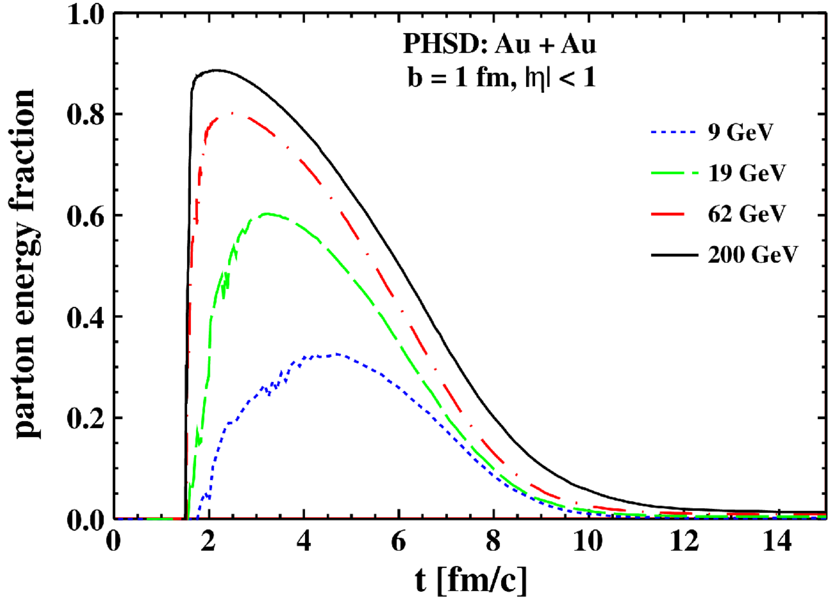
PHSD improves relative to HSD (in line with the data from PHOBOS)

Elliptic flow vs. collision energy

Elliptic flow v_2 at midrapidity



Parton energy fraction at midrapidity



Increase of parton fraction with energy leads to increasing v2