Electromagnetic and color fields in relativistic heavy-ion collisions

V.Voronyk (VBLHEP), G.Zinovjev (ITP,Kiev),
W.Cassing (Uni,Giessen), S.Molodtsov(BLTP,Dubna),
V.Toneev (BLTP,Dubna)

Dubna, October 19, 2015

Introduction

1. magnetic catalysis of chiral symmetry breaking [1996...]
2. inverse magnetic catalysis [2012-2014]
3. the possible ρ meson condensation in strong magnetic field at finite temperature and density [2010-2015]
4. properties of nuclear matter including quark-hadron phase transition (astrophysics)
5. anisotropic viscosity in hydrodynamical equations [2010-2014]
6. the enhanced anisotropic production of soft photons through "magneto-sonoluminescence"(the conversion of phonons into photons in an external magnetic field) [2010]
7. early stage phenomena in heavy ion collisions (like EM-field induced particle production) [2010]
8. dissociation of heavy flavor mesons [2011-2015]
9. chiral magnetic effect (CME) [2005-2008 ...]
10. chiral electric separate effect (CSE) [2013]
11. chiral magnetic waves (CMW) [2012]
12. chiral vorticity effect [2009-2011]
13. chiral vorticity waves [2015]

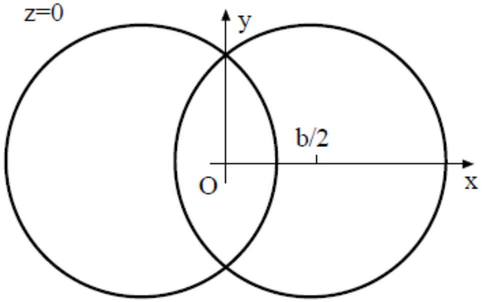
Electromagnetic fields can drive very interesting phenomena

A lot of these phenomena were treated in the approximation of a constant external field.

Field Dynamics ?

....

The first dynamical estimate of the magnetic field strength (Au-Au collisions, b=10 fm)



Lienard-Wiehert potential

$$e\vec{B}(t,\vec{x}_0) = \alpha_{\rm EM} \sum_n Z_n \frac{1-v_n^2}{\left(R_n - \vec{R}_n \vec{v}_n\right)^3} \left[\vec{v}_n \times \vec{R}_n\right],$$

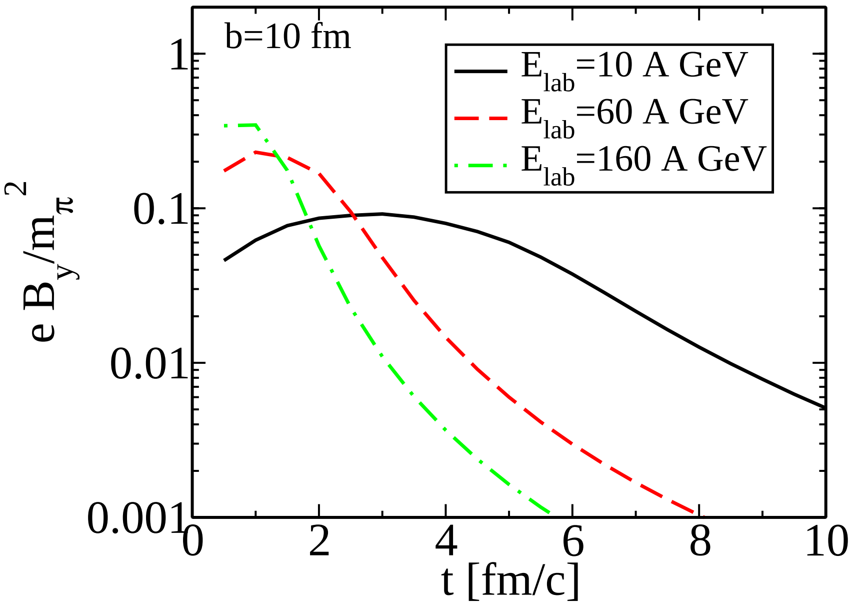
UrQMD

$$\vec{R}_n = \vec{x}_n - \vec{x}_0$$

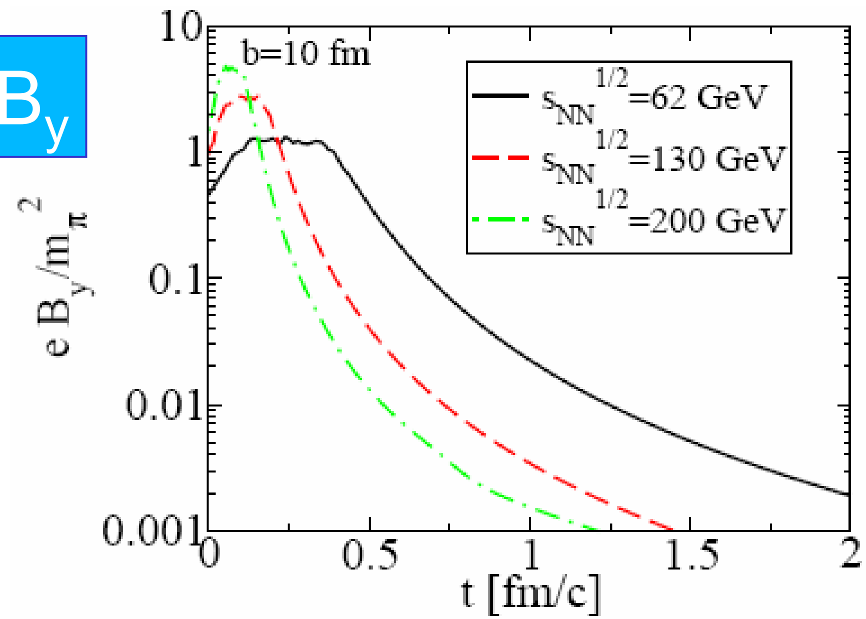
retardation condition

$$|\vec{x}_0 - \vec{x}_n(t')| + t' = t.$$

$$m_\pi^2 \approx 10^{18} \text{Gauss}$$



eB$_y$



V.Skokov, A.Illarionov, V.Toneev, Int. J. Mod. Phys. A24, 5925 (2009)

Citing >320

From SIS to LHC: from hadrons to partons

The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from a microscopic origin

➔ need a consistent non-equilibrium transport model

- ❑ with explicit parton-parton interactions (i.e. between quarks and gluons)
- ❑ explicit phase transition from hadronic to partonic degrees of freedom
- ❑ lQCD EoS for partonic phase (‚cross over' at μ_q=0)

❑ Transport theory for strongly interacting systems: 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)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

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 :

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

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

- **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:**

A. Peshier, PRD 70 (2004) 034016

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

$N_c = 3$, $N_f = 3$

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

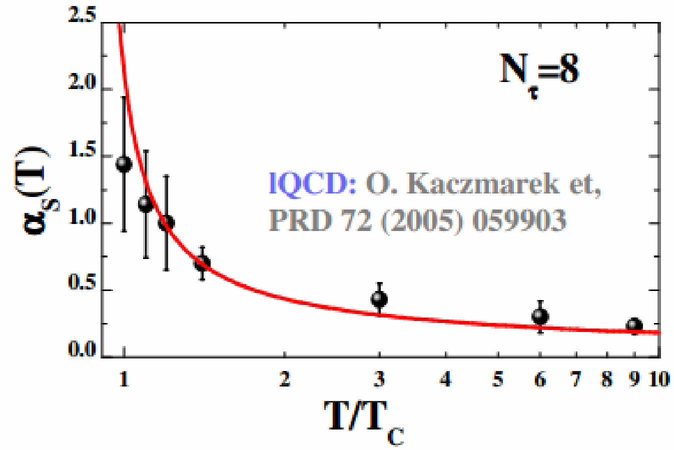
running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

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

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

with 3 parameters: $T_s/T_c = 0.46$; $c = 28.8$; $\lambda = 2.42$

➔ quasiparticle properties (mass, width)



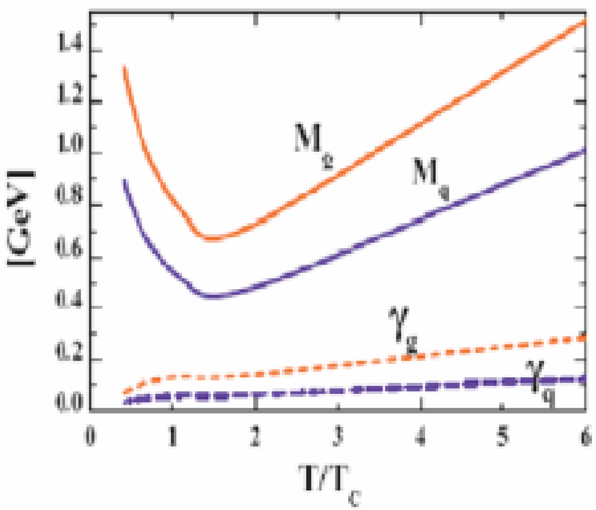
DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

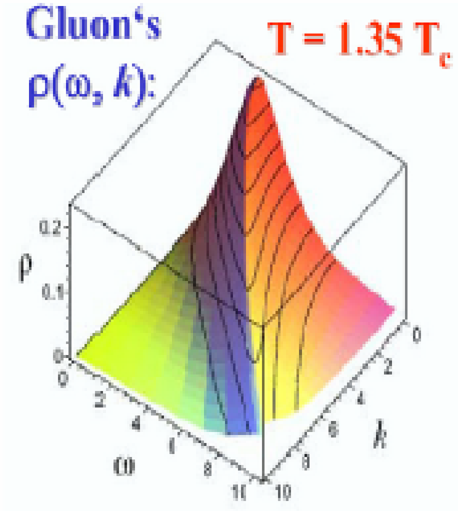
The Dynamical QuasiParticle Model (DQPM)

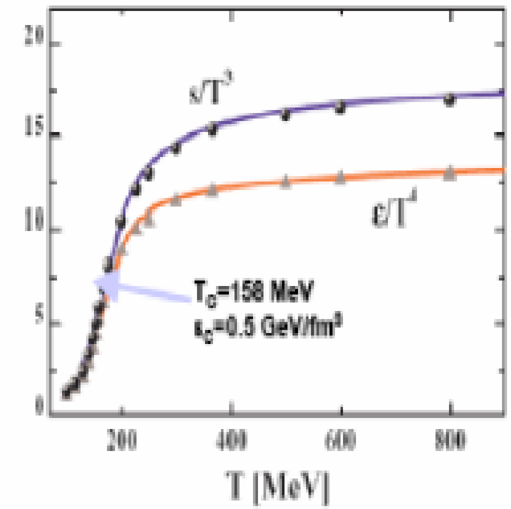
➔ **Quasiparticle properties:**

- large width and mass for gluons and quarks

➔ **Broad spectral function :**



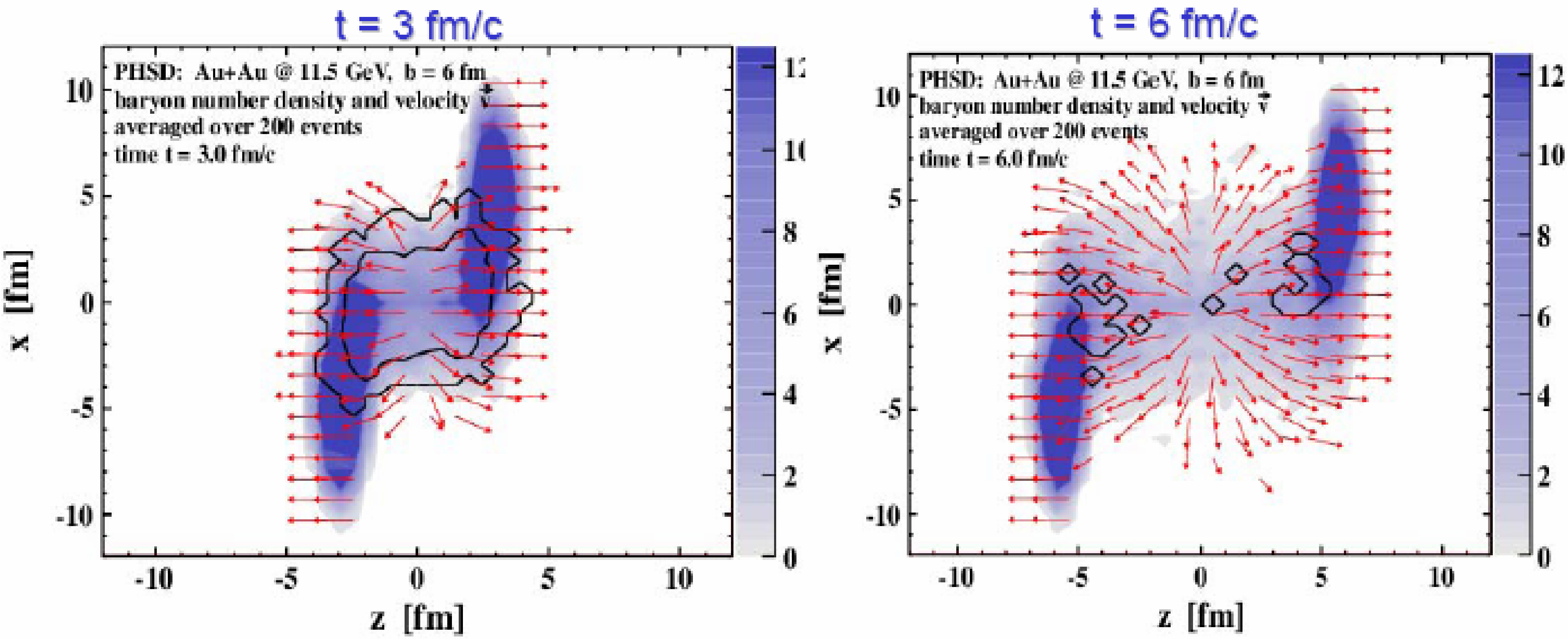




- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks !
  as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons ➔ PHSD (HSD)

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

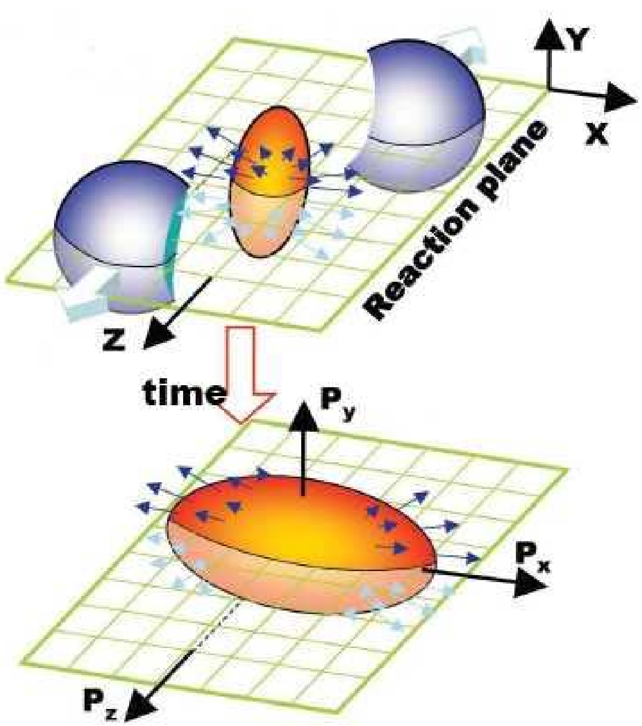
PHSD: snapshot in the reaction plane



- Color scale: baryon number density
- Black levels: parton density 0.6 and 0.01 fm^{-3}
- Red arrows: local velocity of baryon matter

V. Konchakovsky et al., PRC 90 (2014) 014903

Excitation function of elliptic flow

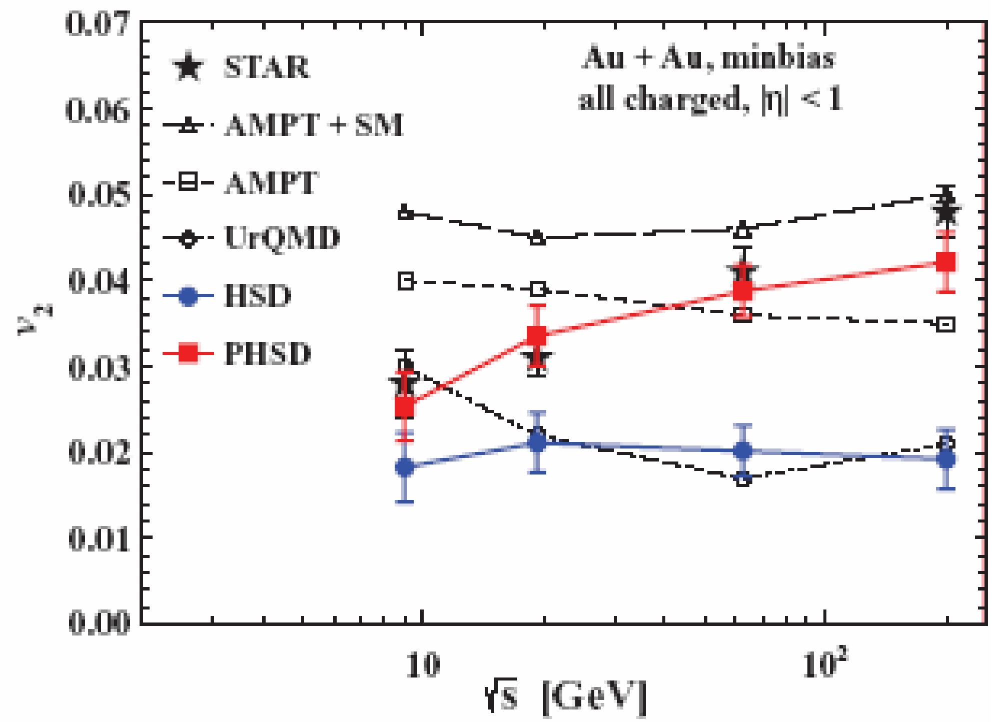


$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

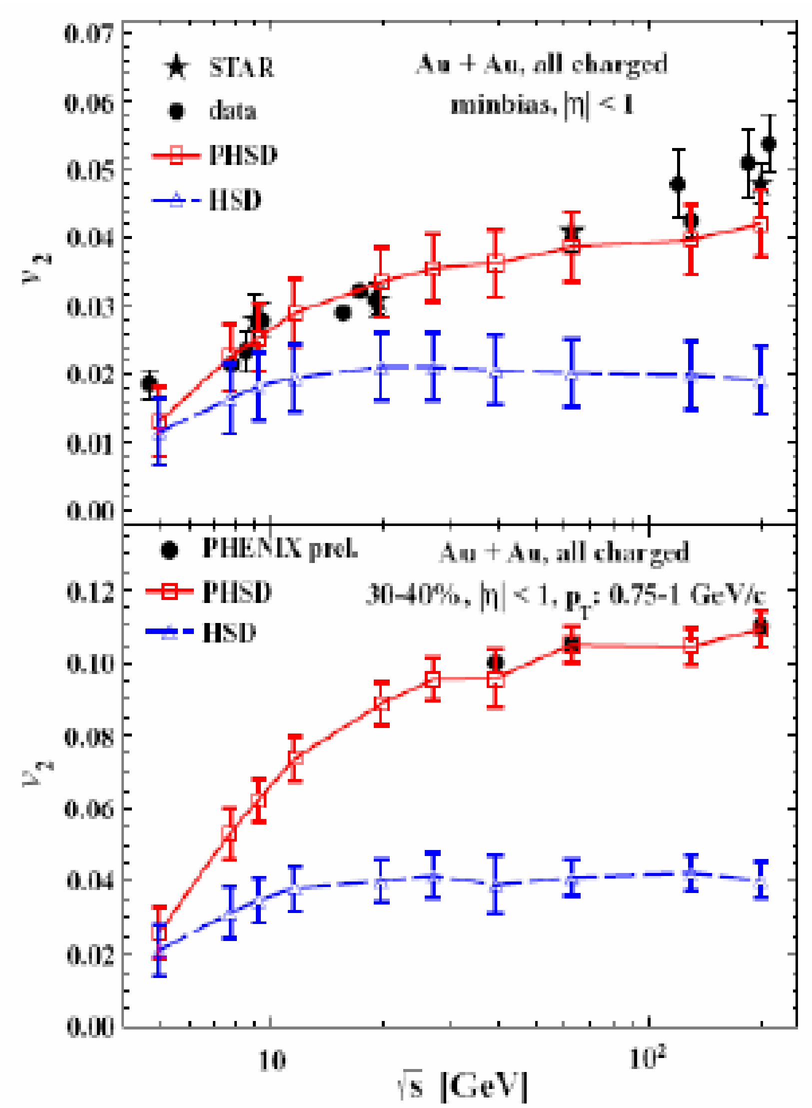
G.Odyniec, Acta Phys. Pol. B40, 1237 (2009)

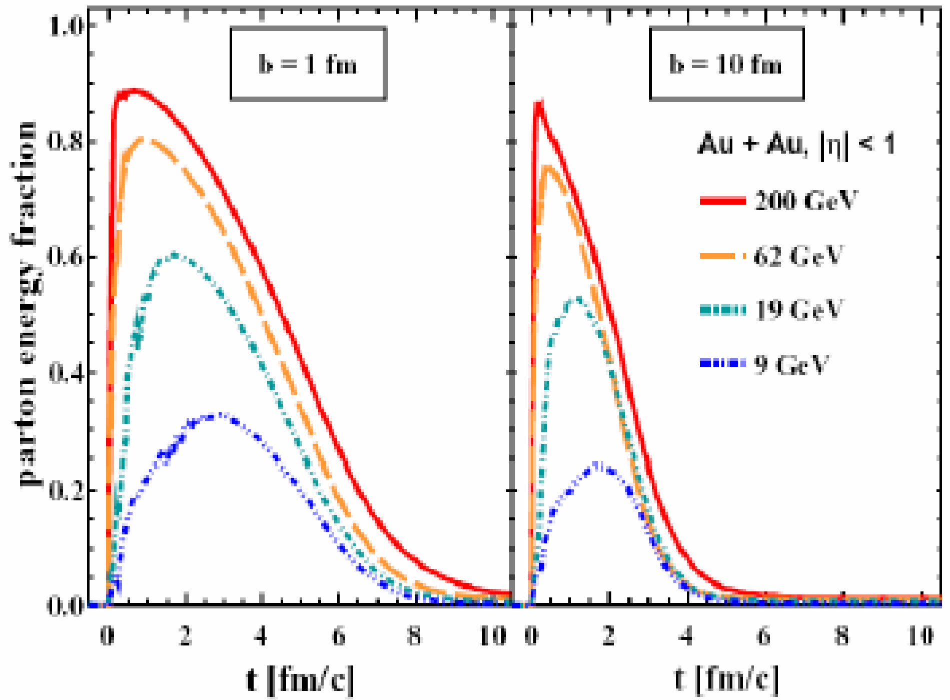


The growth of the elliptic flow is not reproduced by purely string-hadron and simplified partonic models

V. Konchakovski et al. PR C85, 011902 (2012) (R)

Elliptic flow from PHSD vs. STAR/PHENIX





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

V.Konchakovski et al. PR C85, 011902 (2012) (R)

Transport model with electromagnetic field

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

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

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

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

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

A general solution of the wave equations is as follows

$$div\ \mathbf{B} = 0 \qquad div\ \mathbf{E} = 4\pi\rho$$

$$rot\ \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad rot\ \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

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

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

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

For point-like particles $\rho(\vec{r},t) = e\ \delta(\vec{r}-\vec{r}(t));\quad \vec{j}(\vec{r},t) = e\ \vec{v}(t)\ \delta(\vec{r}-\vec{r}(t))$

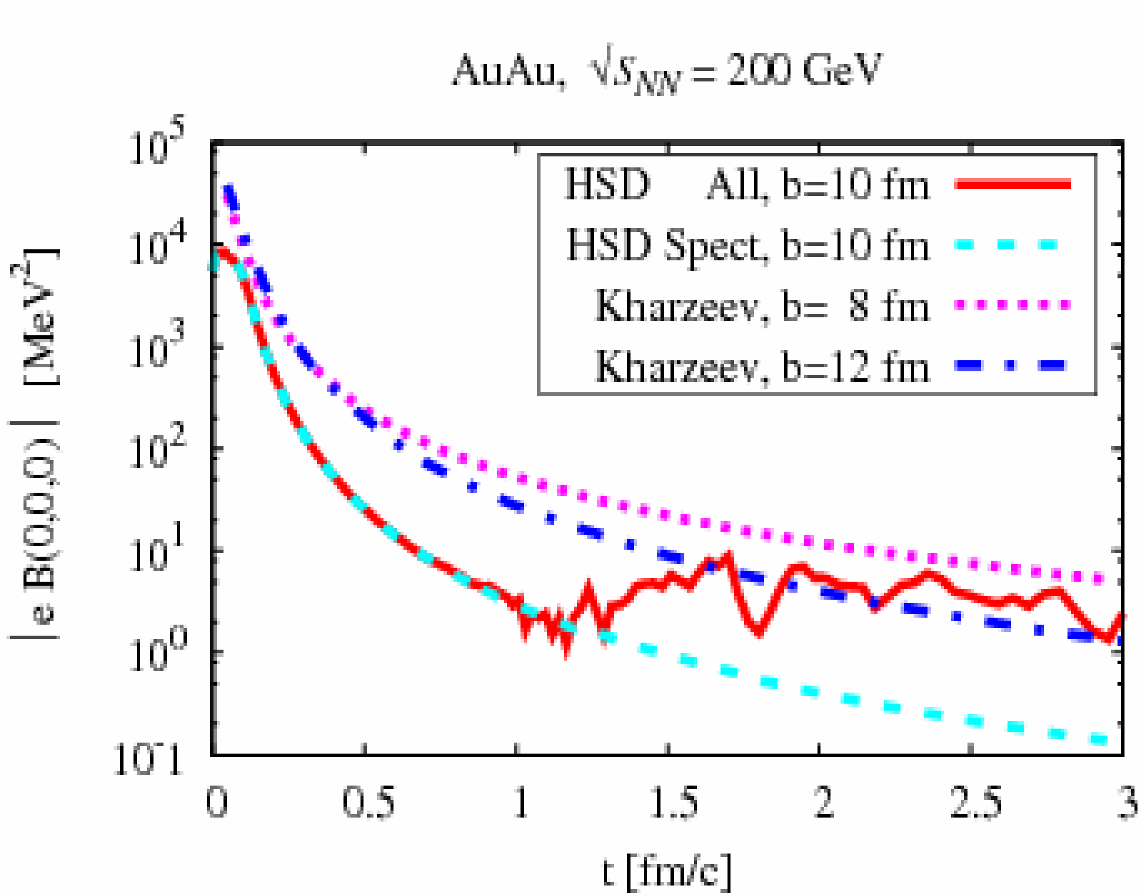
$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n(\mathbf{R}_n)\frac{1-v_n^2}{[R_n^2-(\mathbf{R}_n\times\mathbf{v}_n)^2]^{3/2}}\mathbf{v}_n\times\mathbf{R}_n$$

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n(\mathbf{R}_n)\frac{1-v_n^2}{[R_n^2-(\mathbf{R}_n\times\mathbf{v}_n)^2]^{3/2}}\mathbf{R}_n,$$

Liénard-Wiechert potential

b$\rightarrow 0$	$e\mathbf{B}, e\mathbf{E} \rightarrow 0$
v$\rightarrow 0$	$e\mathbf{B} \rightarrow 0,\ e\mathbf{E} \neq 0$
high energy	$e\mathbf{B}$ transverse
symmetry	only $eB_y \neq 0$

Time dependence of eB_y



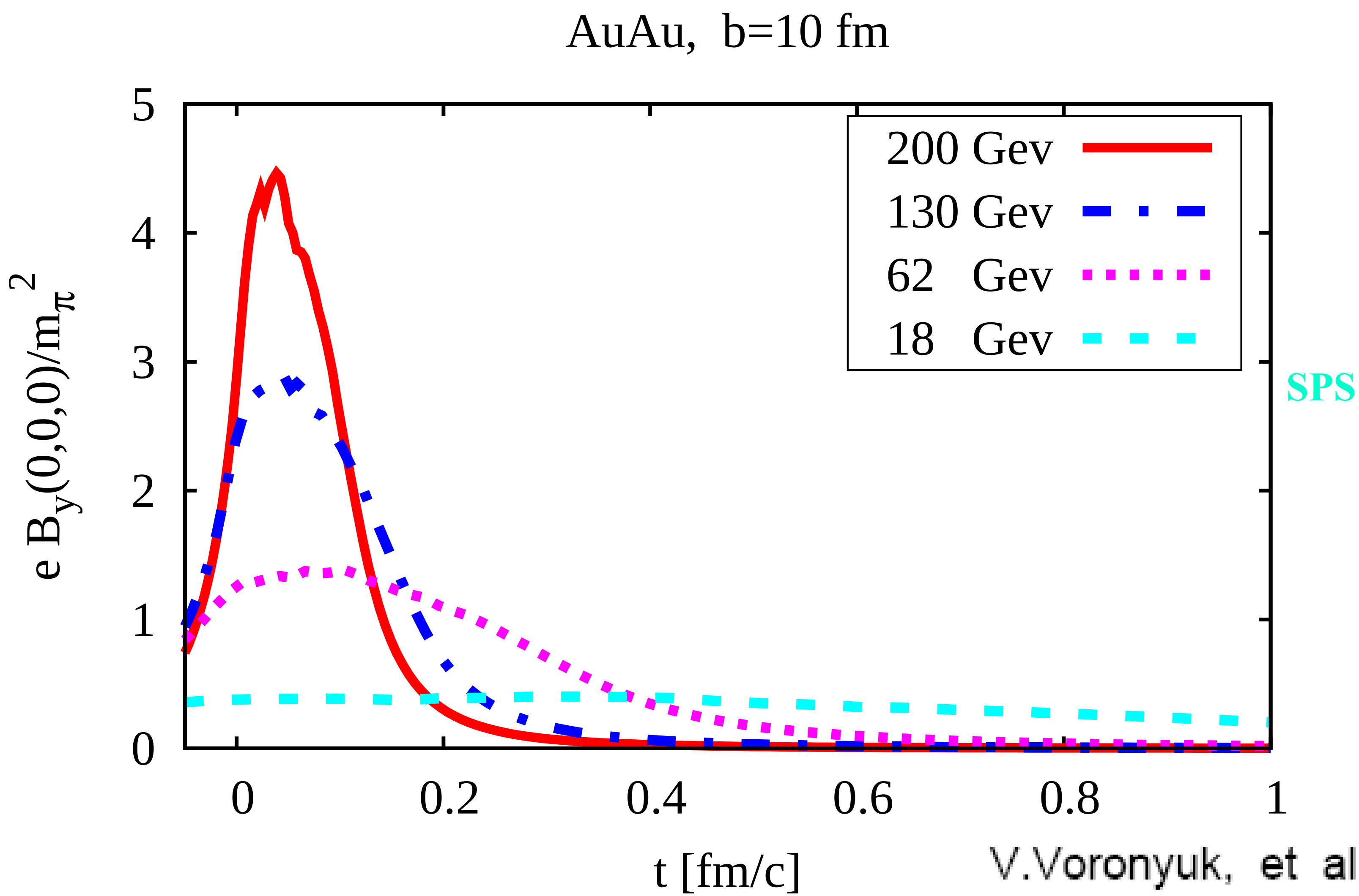
D.E. Kharzeev et al., Nucl. Phys. **A803**, 227 (2008)

Collision of two infinitely thin layers (pancake-like)

V.Voronyuk, V.Toneev et al., PR **C84**, 035202 (2011)

- **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.**

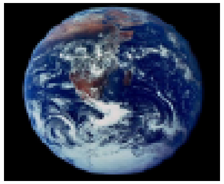
Beam energy dependence of eB_y



V.Voronyuk, et al., PR **C84**, 035202 (2011)

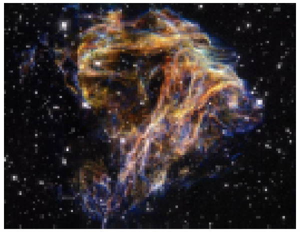
There is a non-vanishing field before nuclear touching moment

Comparison of magnetic fields



The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss

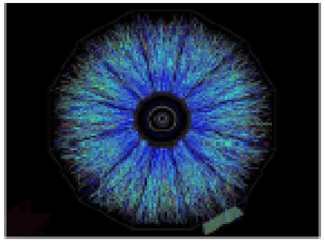
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss



Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html

several times 10^{18} G
Phys. Rev. C 89, 045805 (2014)



At BNL we beat them all!

Off central Gold-Gold Collisions at 100 GeV per nucleon

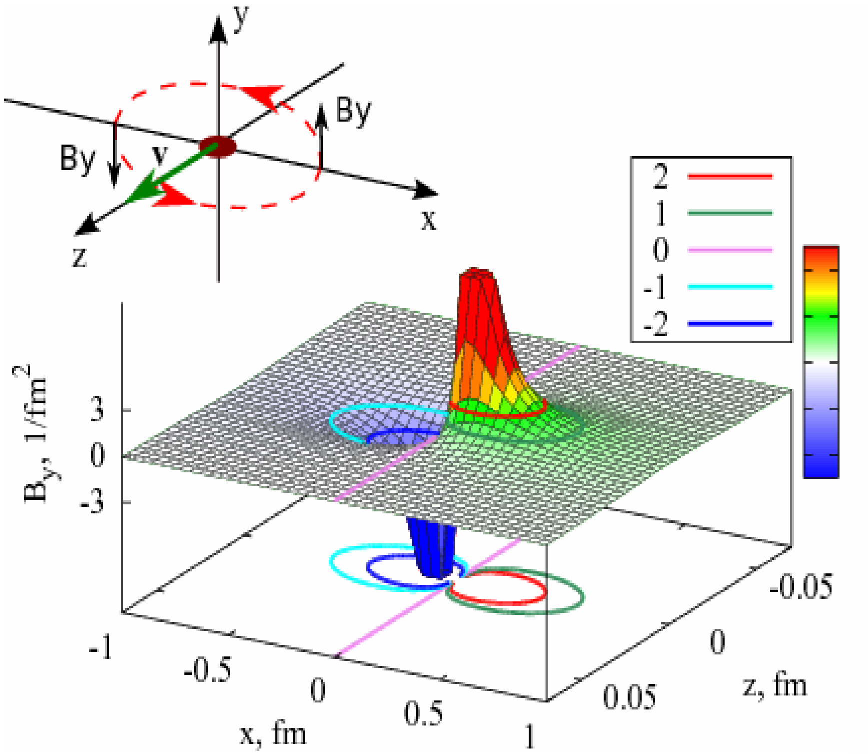
$$e\,B(\tau=0.2\,\text{fm}) \;=\; 10^3 \sim 10^4\ \text{MeV}^2 \sim 10^{17}\,\text{Gauss}$$

beam energy	peak value of $eB_y/(m_\pi^2)$
9 GeV (NICA)	~ 0.2
200 GeV (RHIC)	~ 4
2.76 TeV (LHC)	~ 10

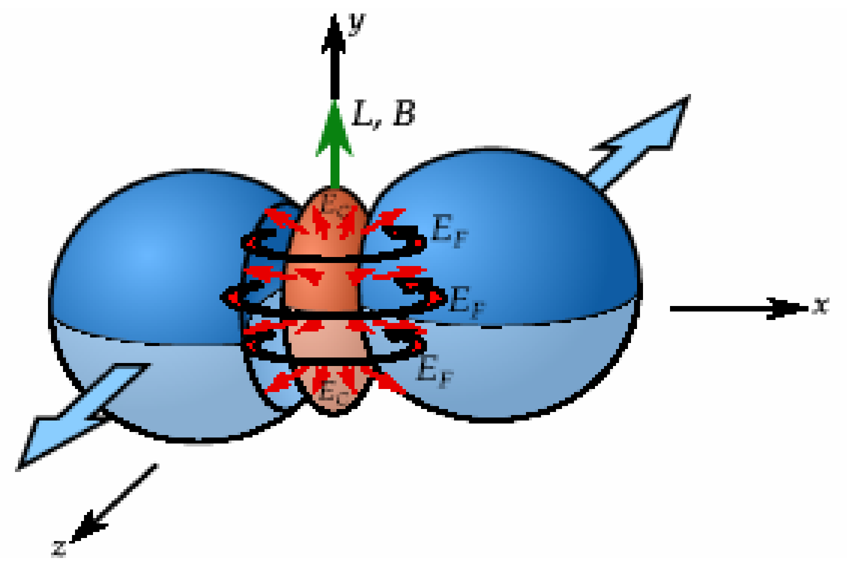
$$m_\pi^2 \approx 10^{18}\text{Gauss}$$

Magnetic field evolution

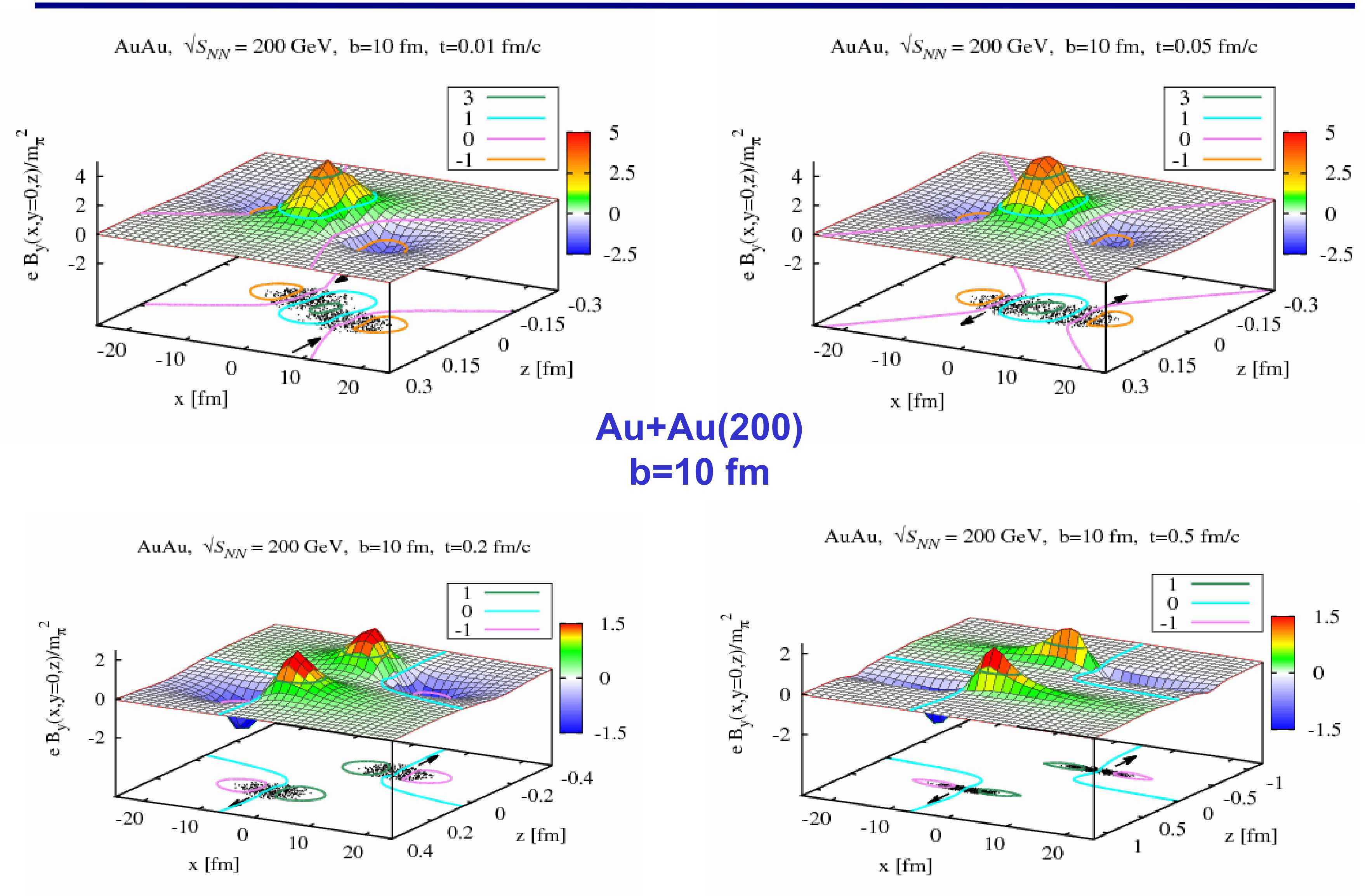
For a single moving charge
(HSD calculation result)



For two-nuclei collisions,
artist's view: arXiv:1109.5849



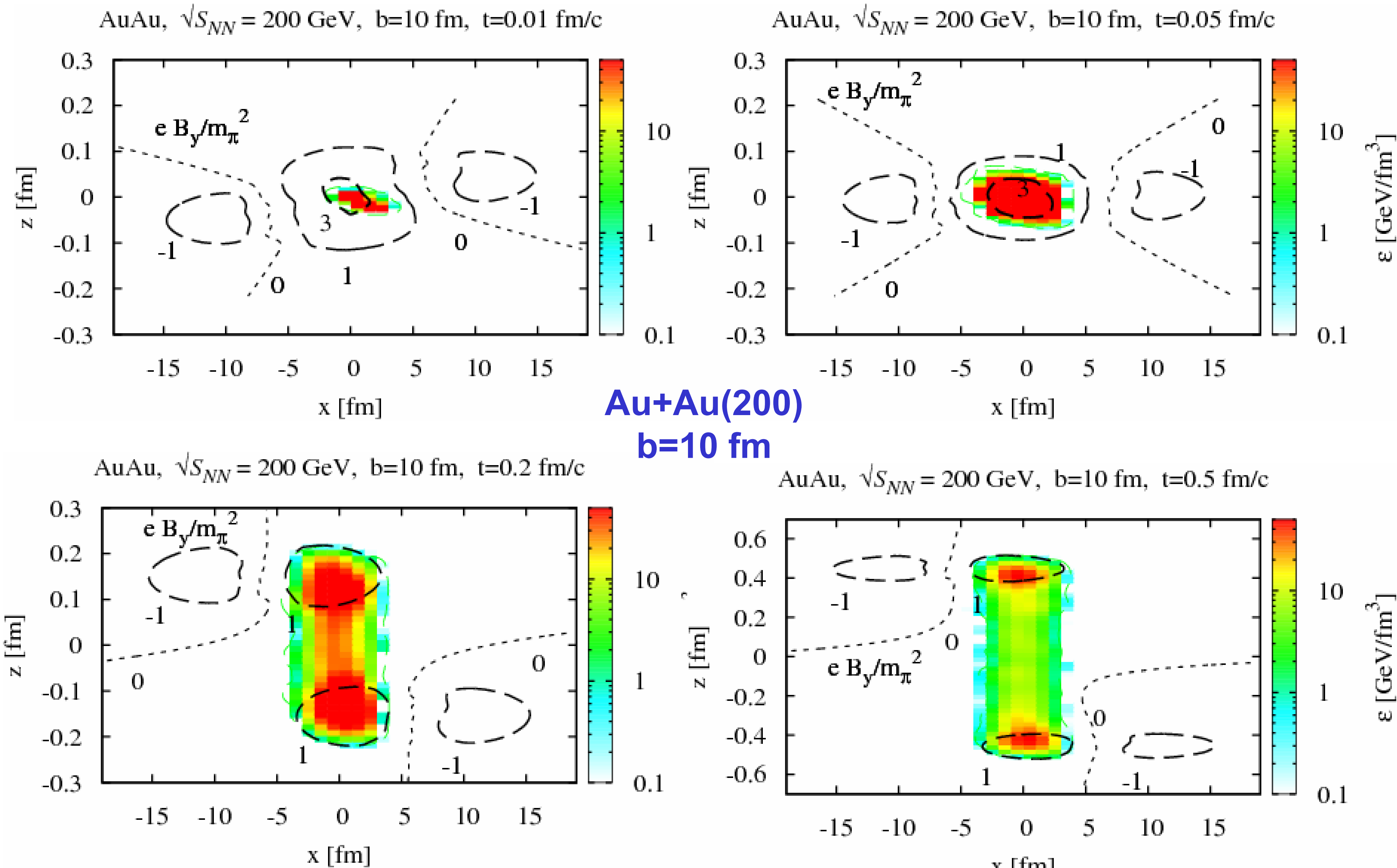
Time evolution of the magnetic field



Au+Au(200)
b=10 fm

V.Voronyuk, V.Toneev. et al., Phys. Rev. **C84**, 035202 (2011)

Magnetic field and energy density correlation

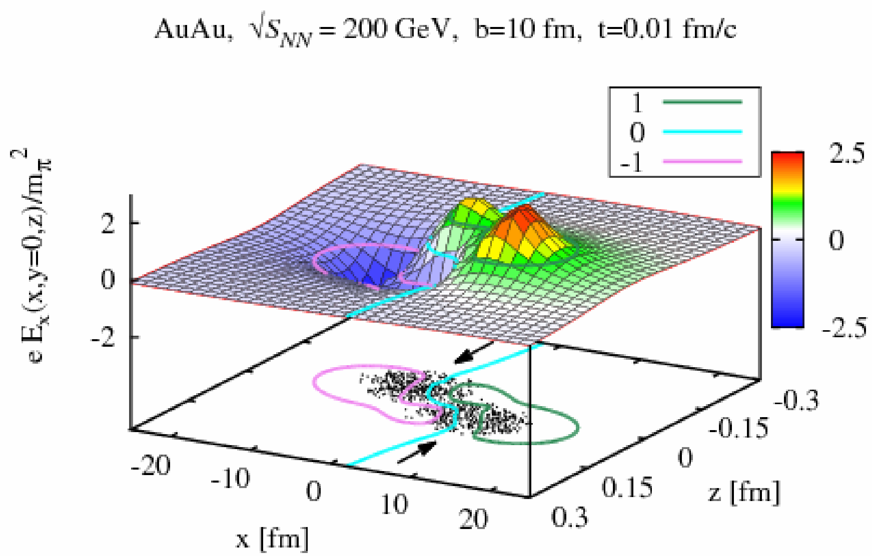


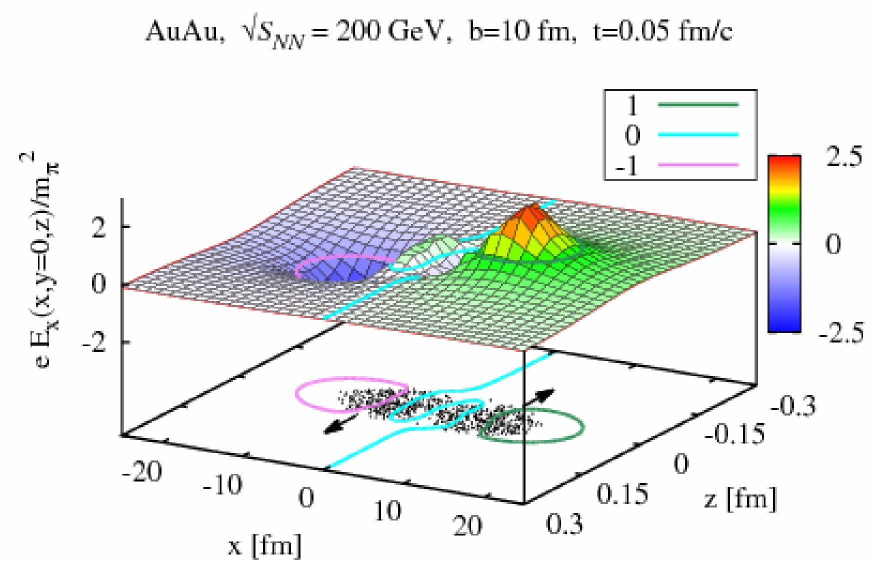
Au+Au(200)
b=10 fm

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

Electric field evolution

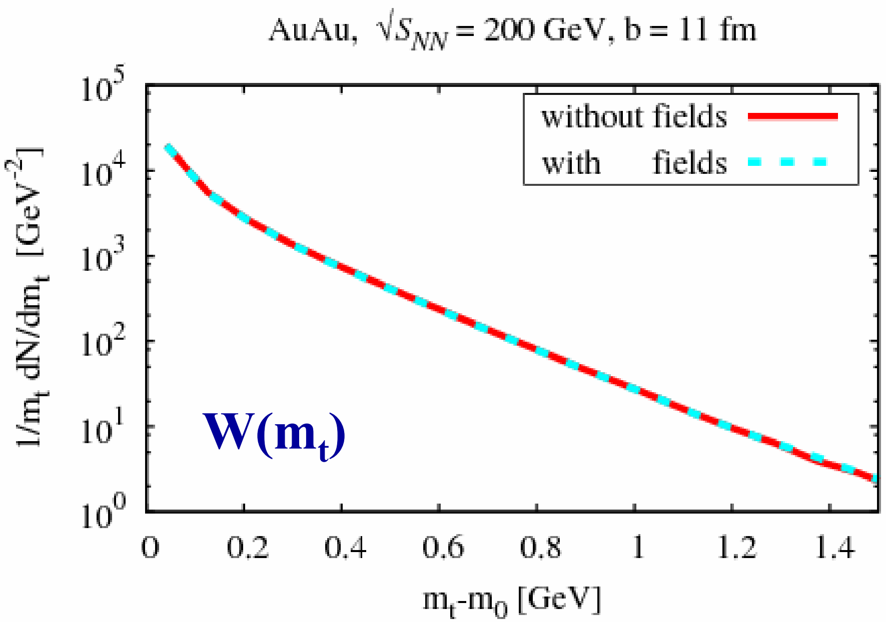
Electric field of a single moving charge has a "hedgehog" shape

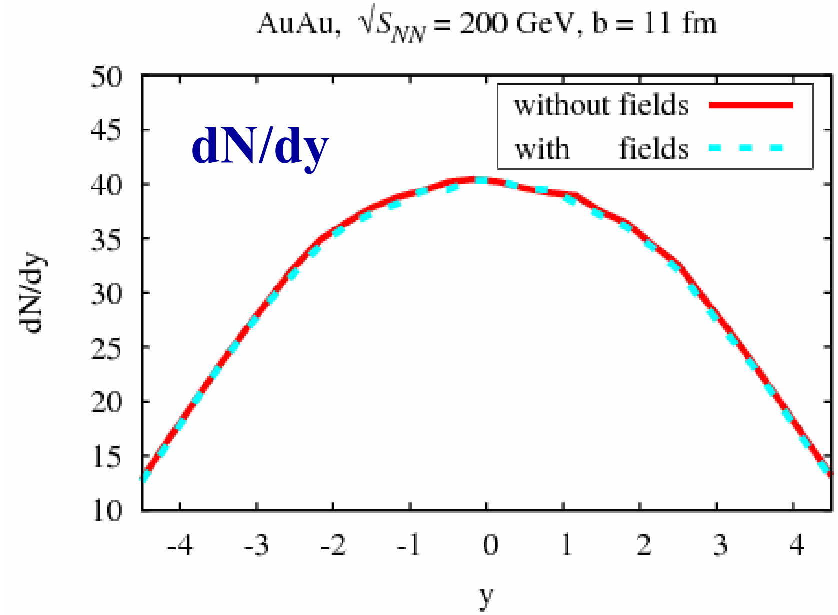


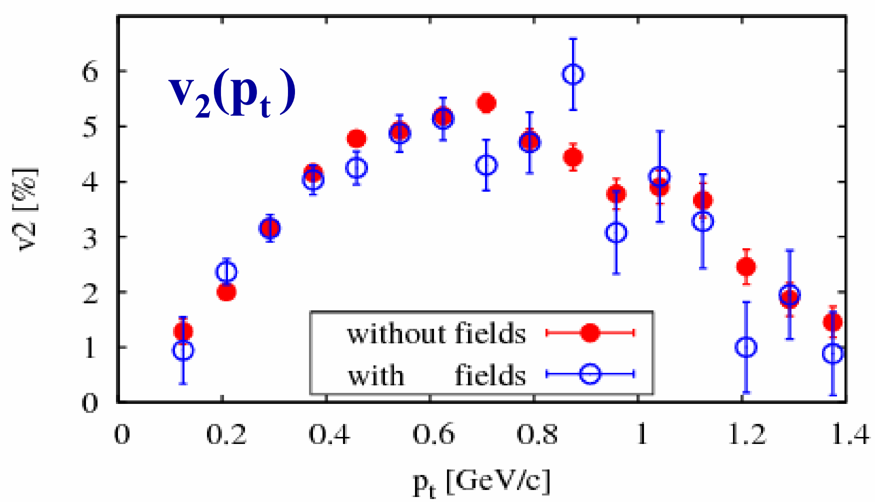


V.Voronyuk, V.Toneev. et al., Phys. Rev. **C84**, 035202 (2011)

Observable





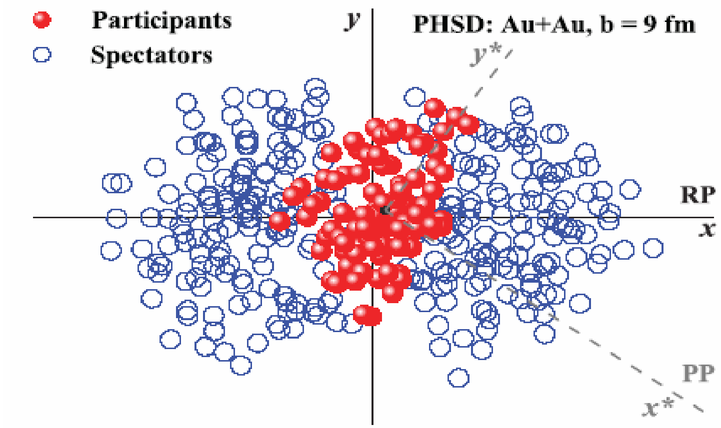


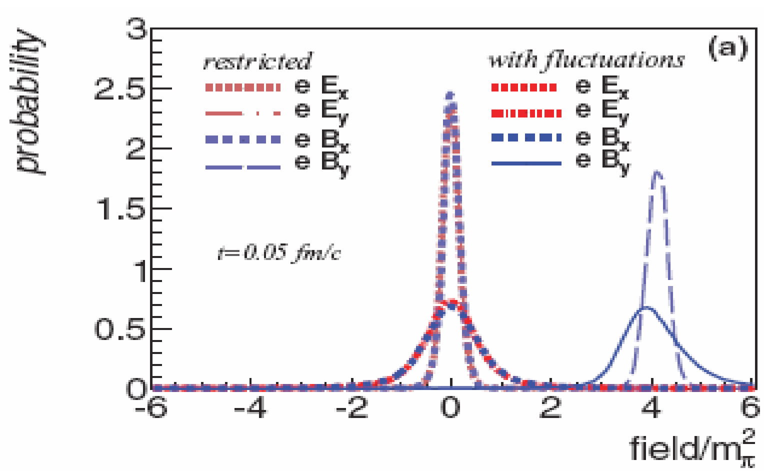
No electromagnetic field effects on global observables in symmetric nuclear collisions !

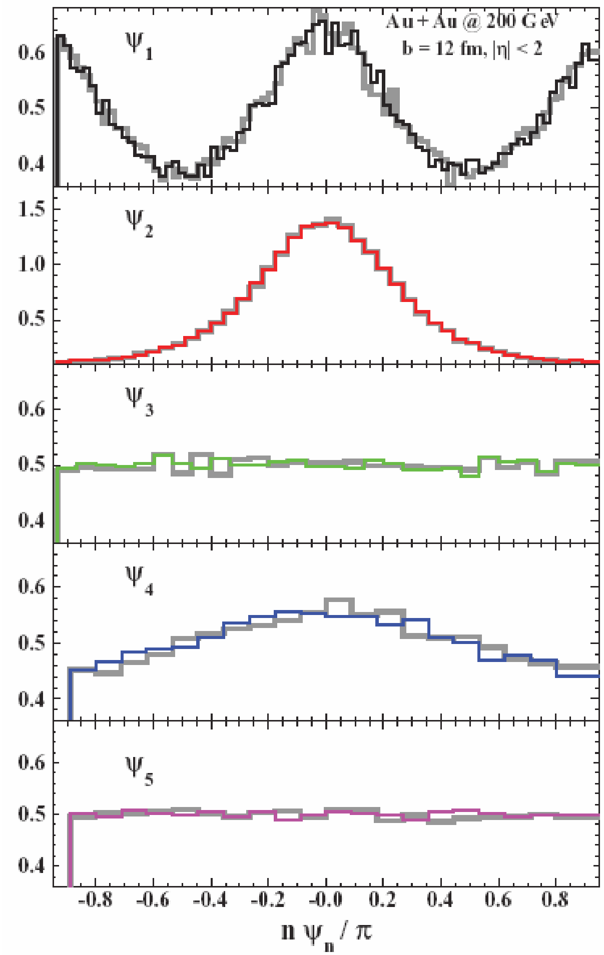
V.Voronyuk, V.Toneev et al., Phys. Rev. **C84**, 035202 (2011)

Fluctuations in the early state of HIC

V.Toneev et al., PR **C65**, 034910 (2012)



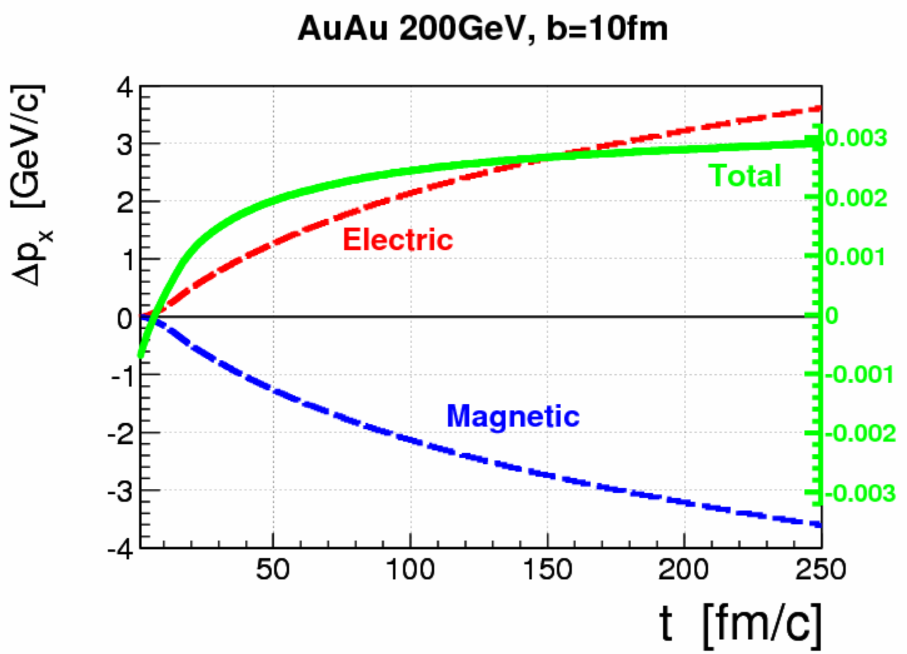


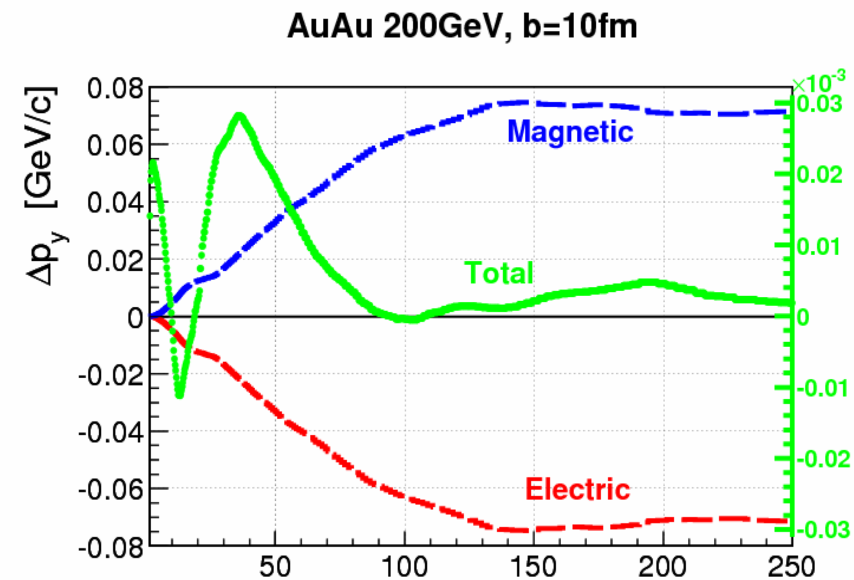


Fluctuation of nucleon positions in the initial state changes EM distribution and is important for definition of the reaction plane but EM field does not influence v_n

gray – without EM field

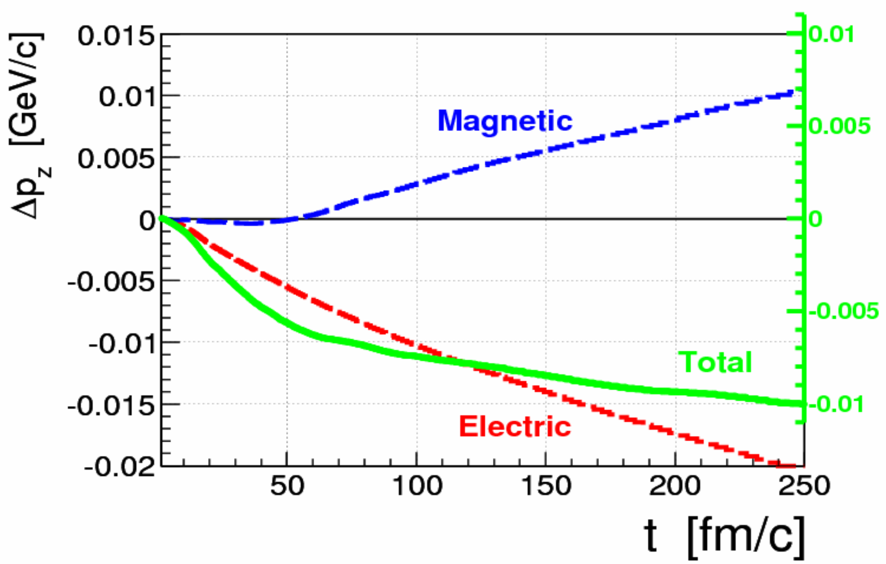
Compensation of electric and magnetic forces





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

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



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

$$eE = -e\frac{\partial A}{\partial t} \sim -e\frac{\partial A}{\partial x}\frac{dx}{dt} \sim -eBv$$

CME: a possible CP violation signal

A remarkable property of gauge theories is the existance of nontrivial topological configurations of gauge fields. Gauge field transitions with changing the topological charge involve configurations which may violate P and CP invariance of strong interactions.

$$Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

Fermions can interact with a gauge field configurations, transforming left- into right-handed quarks and vice-versa via the axial chiral anomaly and thus resulting in generated asymmetry between left- and right-handed fermions. In this states a balance between left-handed and right-handed chiral quarks is destroyed.

$$(N_L - N_R)_{t=\infty} = 2N_f Q_w$$

In the presence of inbalanced chirality a magnetic field induces a chiral electric current along the the magnetic field **(CME)**.

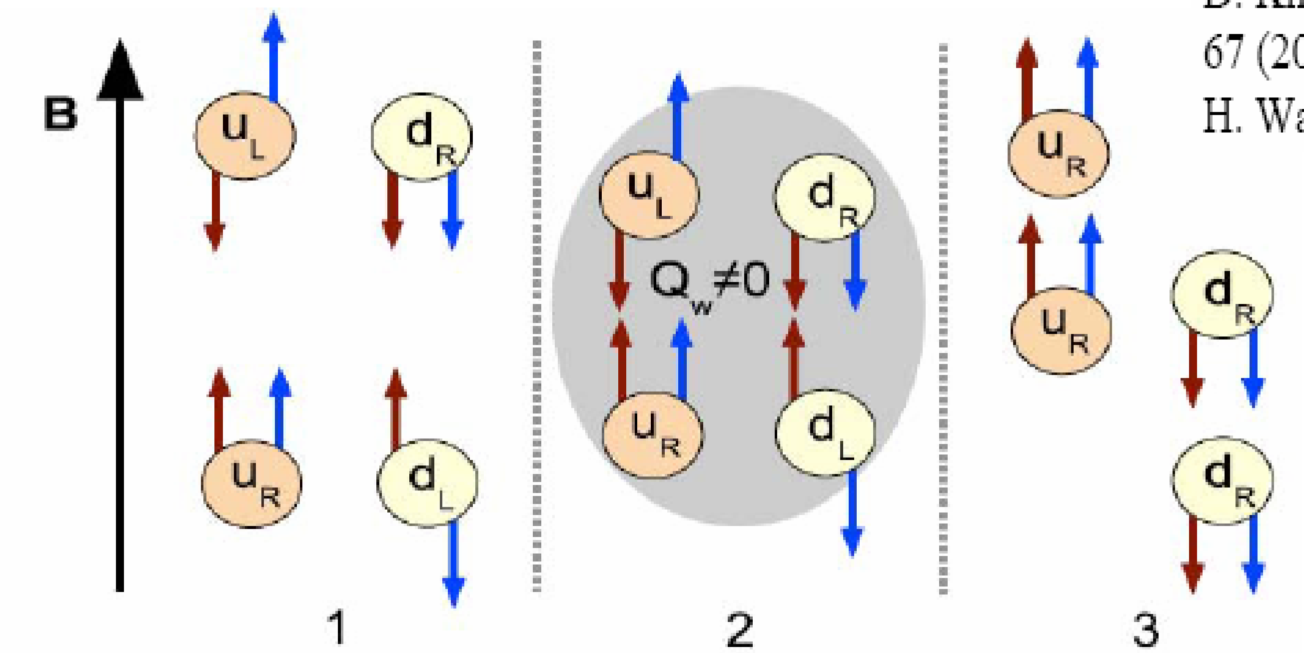
D.Kharzeev et al., NP **A803,** 227 (2008);

Ann.Phys**. 325,** 205 (2010); PR **D78,** 074033 (2008)

$$\mathbf{j} = N_c \sum_f \frac{q_f^2 \mu_5}{2\pi^2}\mathbf{B}$$

Chiral magnetic effect in pictures

D. Kharzeev, PL **B633**, 260 (2006); D. Kharzeev. A. Zhitnitsky, NP **A797**, 67 (2007); D. Kharzeev., L. McLerran, H. Warringa, NP **A803**, 227 (2008).

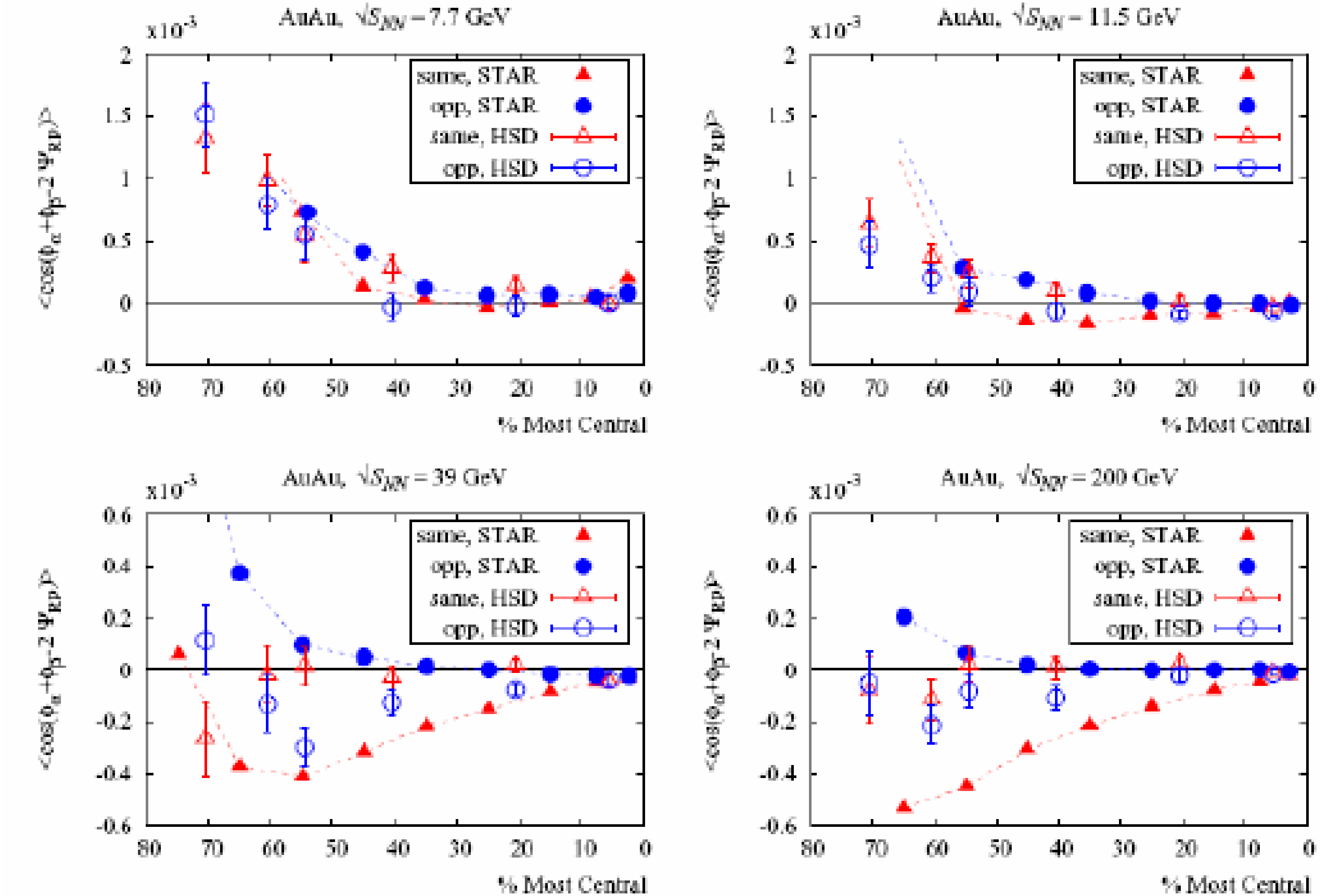


Red arrow - momentum; blue arrow - spin;
In the absence of topological charge no asymmetry between left and right (fig.1) ;the fluctuation of topological charge (fig.2) in the presence of magnetic field induces electric current (fig.3)

Background for BES experiments on CME

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

V.Toneev et al., PR **C85**, 034910 (2012)
STAR Coll., J.Phys. **G38**, 124166 (2012)



Angular correlation is of hadronic origin **up to** $\sqrt{s}$=11 GeV !

In-plane and out-of-plane corr. (worrings)

Measure the difference between **in-plane** and **out-of-plane** correlations:

STAR, PR **C81**, 054908 (2010)

$$\boxed{\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle} = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle =$$

Voloshin PRC70:057901 (2004)

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)}] - [\langle a_\alpha a_\beta \rangle + Bg^{(out)}]$$

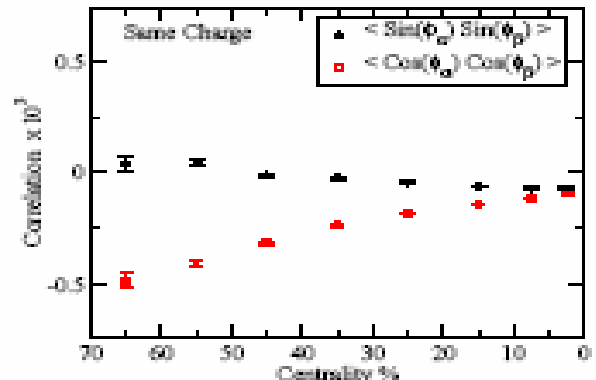
$$\Delta\phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP}$$

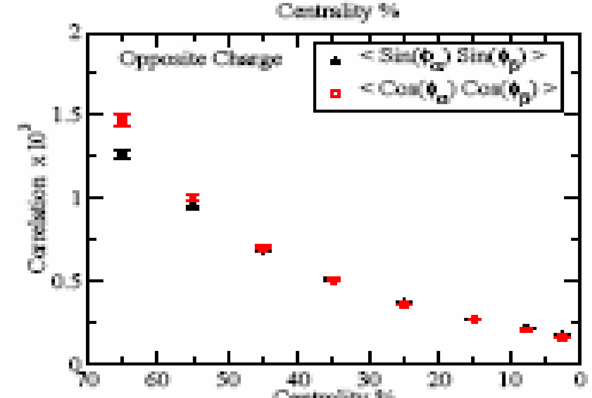
- For same sign pairs:

$$\langle \sin(\phi_\alpha)\sin(\phi_\beta) \rangle_{same} \simeq 0,$$
$$\langle \cos(\phi_\alpha)\cos(\phi_\beta) \rangle_{same} < 0.$$

- For opposite sign pairs

$$\langle \sin(\phi_\alpha)\sin(\phi_\beta) \rangle_{opposite} \simeq \langle \cos(\phi_\alpha)\cos(\phi_\beta) \rangle_{opposite} > 0.$$

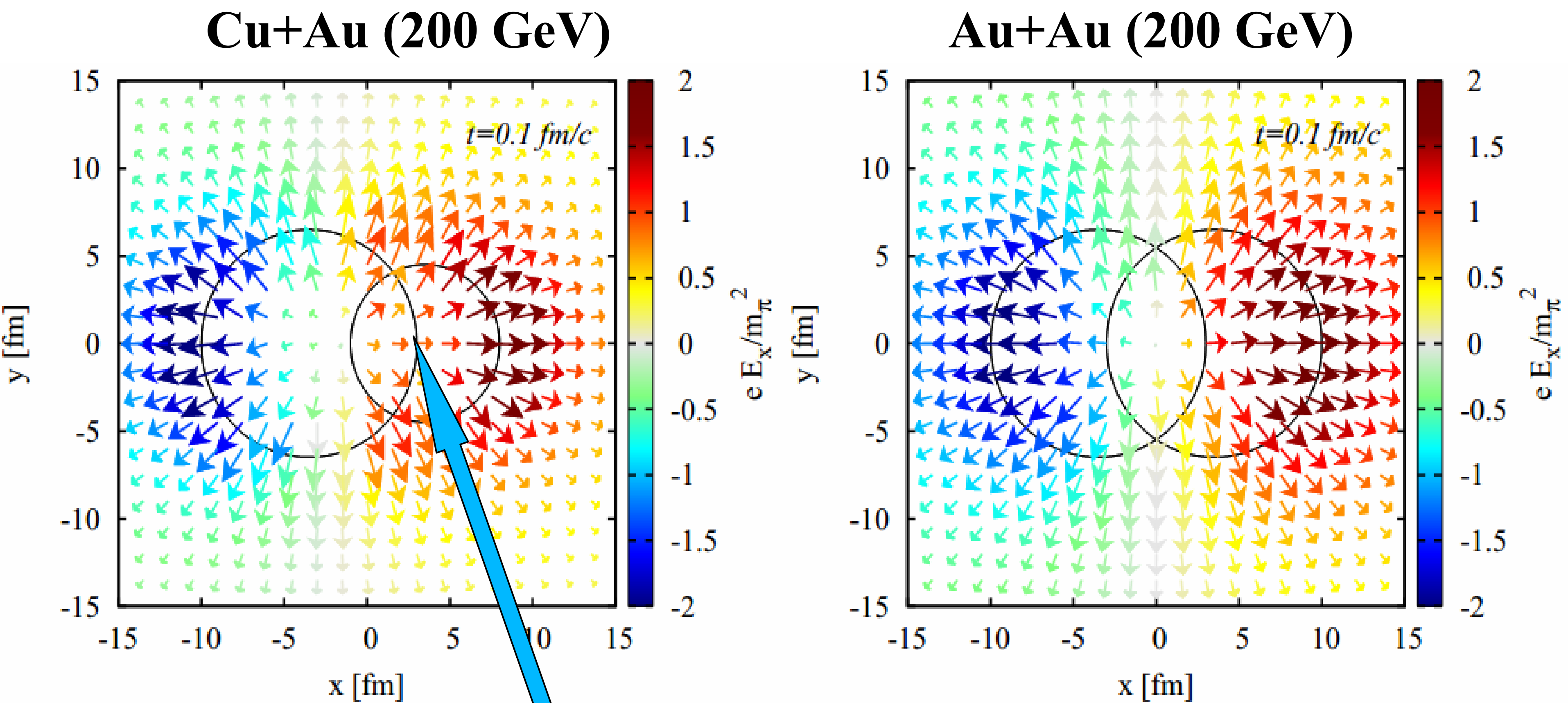




The observed correlations are in-plane, contrary to CME expectations ?!

(A.Bzdak, V.Koch, J.Liao, PR **C81**,031901)

Electric field E_x in the transverse plane

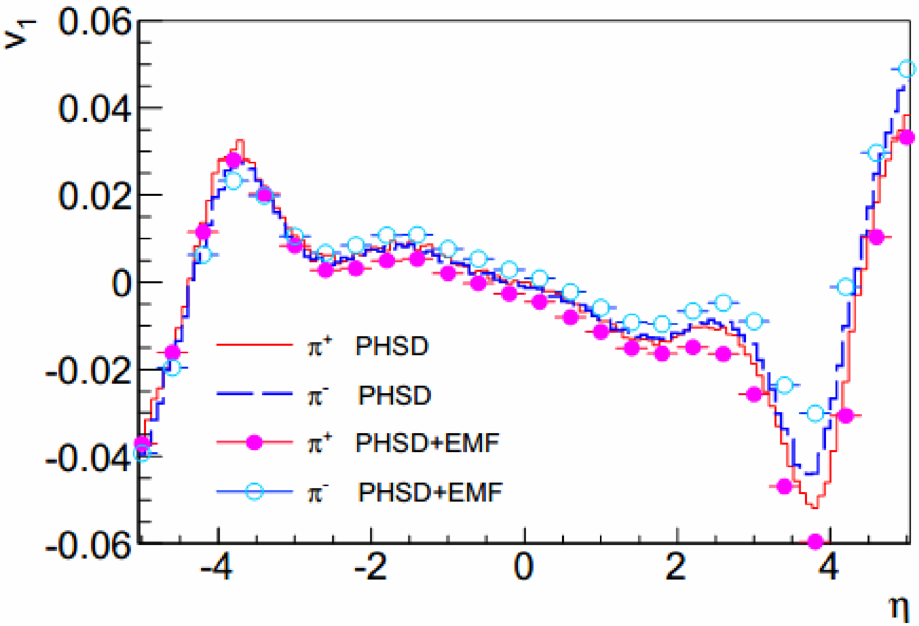


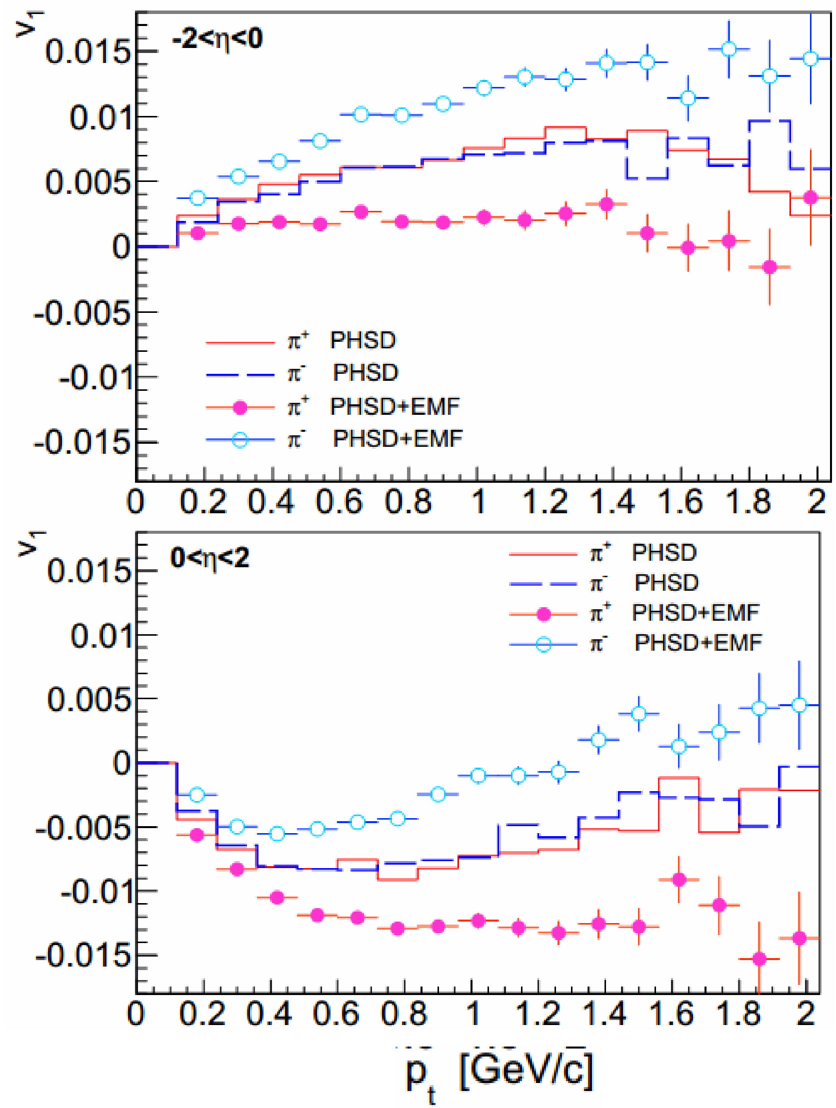
In the overlapping region of asymmetric peripheral collisions a finite electric current appears to be directed from the heavy nuclei to light one.

Charge-dependent v_1 distributions at RHIC

Cu+Au (200 GeV)

$$v_1(\eta) = \langle \cos(\phi - \phi_{RP}) \rangle = \left\langle p_x / \sqrt{p_x^2 + p_y^2} \right\rangle$$

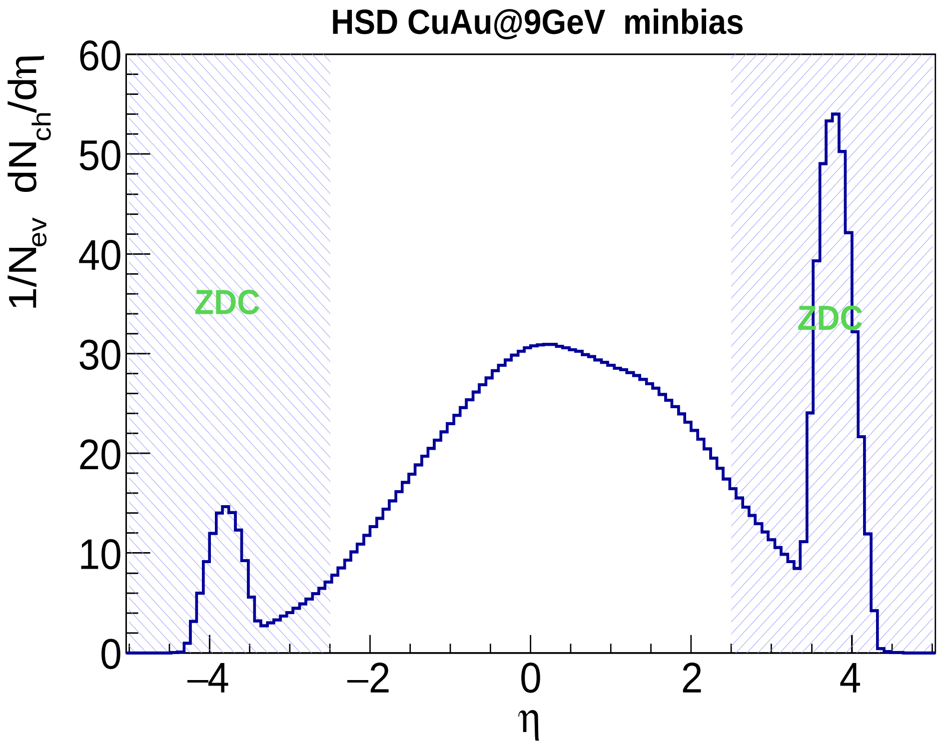


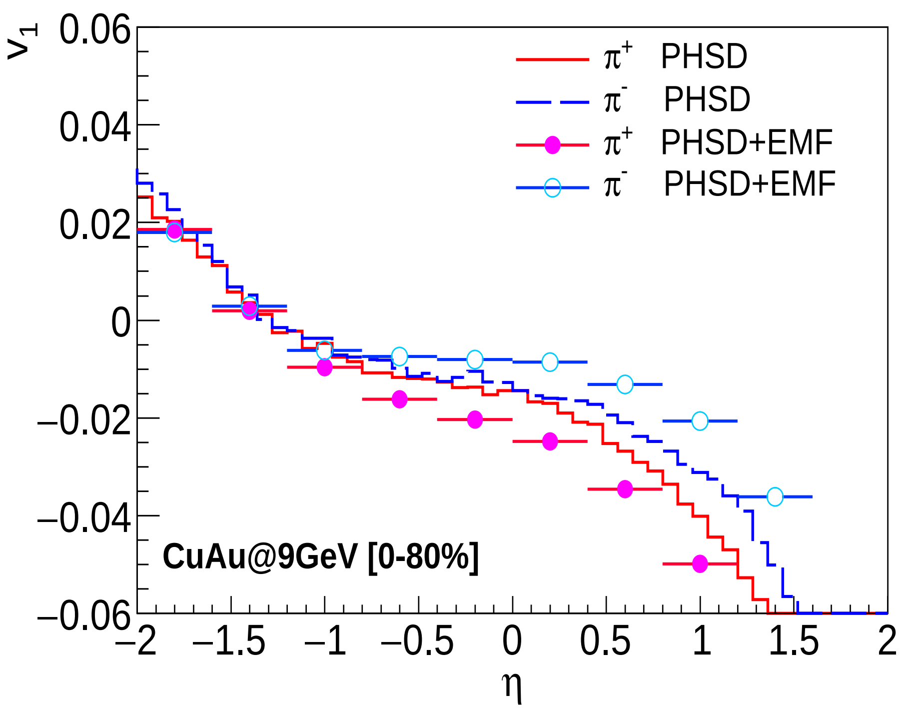


Distributions for the same hadron masses but opposite electric charges are splitted and this can be observed !

Charge-dependent v_1 distributions at NICA

Cu+Au (9 GeV)





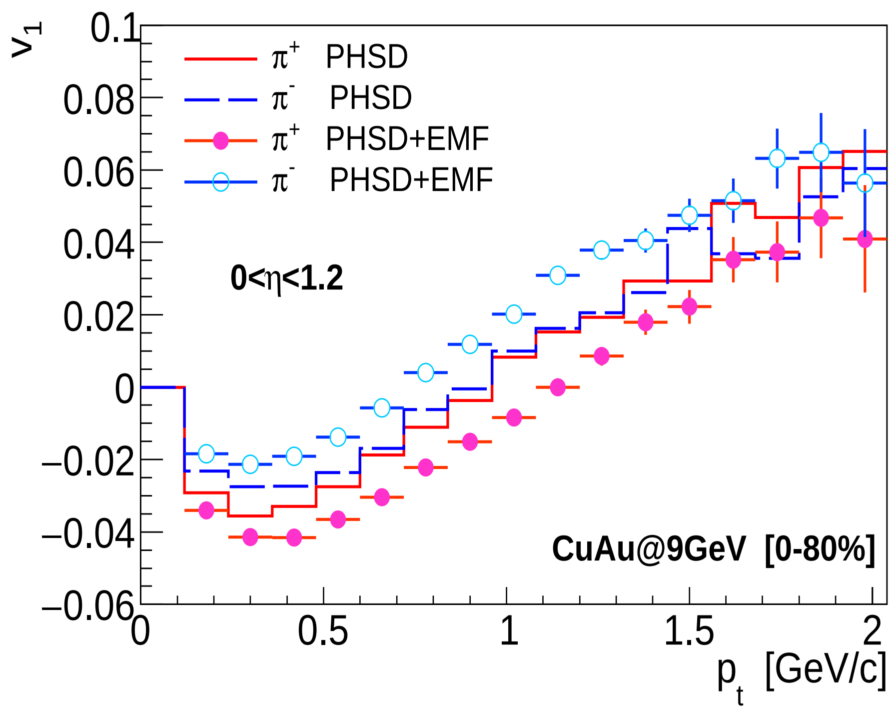
TPC: $\eta<1.2$ $p_T>0.15$ GeV/c

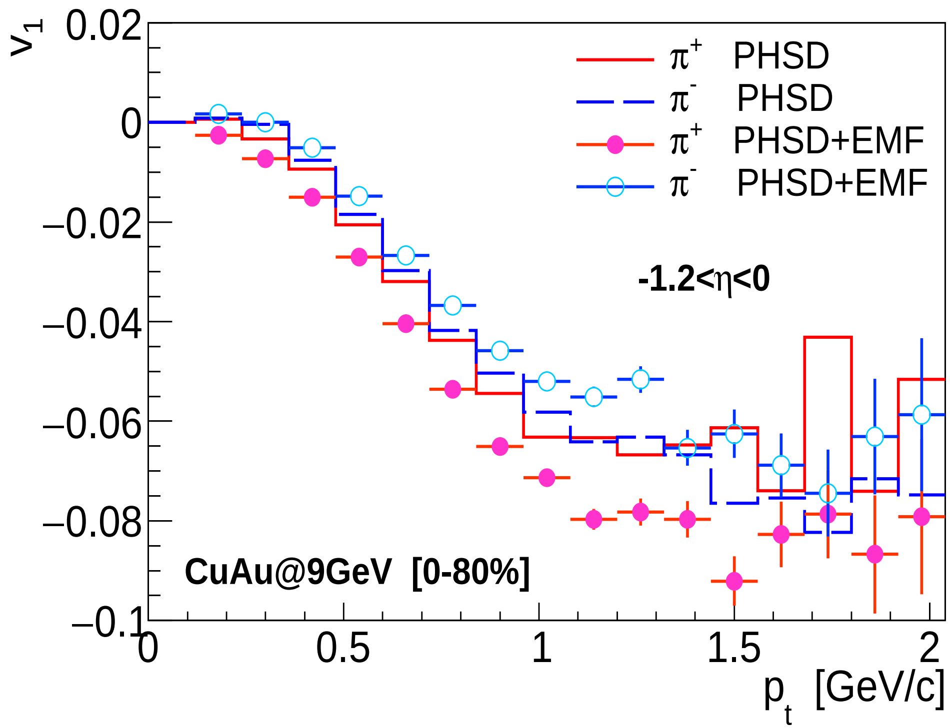
In the presence of the electromagnetic force the splitting of π^+ and π^- is clearly seen => Signal of strong electric strength is realized in heavy-ion collisions

V.Toneev, O.Rogachevsky, V.Voronyk, Contribution to NICA WP (EPJA, 2015)

Charge-dependent p_T distributions at NICA

The transverse momentum v_1 distributions of +/- pions are different in the Cu- and Au-sites. The shape of spectra differs in forward and backward semispheres





The difference between $v_1(p_T)$ for π^+ and π^- is prominent and getting larger with p_T increase

Non-Abelian fields

we consider SU(2) non-Abelian fields only.
In the classical approximation they are c-number functions to be solutions of the classical Yang-Mills equations

$$\mathcal{L} = -\frac{1}{4}\widetilde{G}^{\mu\nu}\widetilde{G}_{\mu\nu} - \widetilde{j}^{\mu}\widetilde{A}_{\mu}$$

Color vector $\widetilde{A}_\mu = (A^1_\mu, A^2_\mu, A^3_\mu)$ - a triplet of the Yang-Mills fields of different colors,
$\widetilde{j}^\mu$ - the current density of external color sources,
$\widetilde{G}_{\mu\nu} = \partial_\mu \widetilde{A}_\nu - \partial_\nu \widetilde{A}_\mu + g\widetilde{A}_\mu \times \widetilde{A}_\nu$ - the gluon field tensor,
$\widetilde{D^\mu f} = \partial^\mu \widetilde{f} + g\widetilde{A}^\mu \times \widetilde{f}$ - the covariant derivative.

The classical equations of motion $\widetilde{D^\mu G_{\mu\nu}} = \widetilde{j}_\nu$.

The compatibility conditions of this system $\widetilde{D^\mu j_\mu} = 0$.
It generally implies that the color vector charge is not conserved in a sense similar to electrodynamics.

A suitable solution of the Yang- Mills equations for a single particle with constant color charge $\widetilde{C}$ one may take the potentials of the form

$$\widetilde{\varphi} = \frac{1}{4\pi}\left[\frac{\widetilde{C}}{R - \boldsymbol{v}\boldsymbol{R}}\right]_{t'}, \quad \widetilde{\boldsymbol{A}} = \frac{1}{4\pi}\left[\frac{\widetilde{C}\,\boldsymbol{v}}{R - \boldsymbol{v}\boldsymbol{R}}\right]_{t'}$$

$$\boldsymbol{R} = \boldsymbol{r}_0 - \boldsymbol{r}(t')$$

Chromoelectric and chromomagnetic fields

As an approximate solution, we consider a superposition of the Liénard-Wiechert potentials in which the vector of the particle color charge can change in time and should be taken at the retarded time.

$$\widetilde{\varphi}(\boldsymbol{r},t) = \frac{1}{4\pi} \int \frac{\widetilde{\rho}(\boldsymbol{r}',t')\;\delta(t-t'-|\boldsymbol{r}-\boldsymbol{r}'|)}{|\boldsymbol{r}-\boldsymbol{r}'|}\; d^3r'dt' \;,$$

$$\widetilde{\boldsymbol{A}}(\boldsymbol{r},t) = \frac{1}{4\pi} \int \frac{\widetilde{\boldsymbol{j}}(\boldsymbol{r}',t')\;\delta(t-t'-|\boldsymbol{r}-\boldsymbol{r}'|)}{|\boldsymbol{r}-\boldsymbol{r}'|}\; d^3r'dt' \;.$$

Covariant four-current for a pointlike particle and the compatibility condition are

$$\widetilde{j}_\mu(\boldsymbol{r}',t') = (\widetilde{C}\;\delta(\boldsymbol{r}'-\boldsymbol{r}(t)), \widetilde{C}\;\boldsymbol{v}(t)\;\delta(\boldsymbol{r}'-\boldsymbol{r}(t)))\;,$$

$$\dot{\widetilde{C}} = g\;\left[\widetilde{\varphi}(t,\boldsymbol{r}) - \boldsymbol{v}\;\widetilde{\boldsymbol{A}}(t,\boldsymbol{r})\right] \times \widetilde{C}\;. \quad [\alpha_g = g^2/(4\pi) = 0.3]$$

Thus, taking proper derivatives the non-Abelian chromo-fields are $(\boldsymbol{n} = \boldsymbol{R}/|\boldsymbol{R}|)$

$$\widetilde{\boldsymbol{E}} \;=\; \frac{1}{4\pi}\left[\frac{\widetilde{C}}{R^2}\frac{(1-\boldsymbol{v}^2)(\boldsymbol{n}-\boldsymbol{v})}{(1-\boldsymbol{v}\boldsymbol{n})^3} + \frac{\widetilde{C}}{R}\frac{\boldsymbol{n}\times(\boldsymbol{n}-\boldsymbol{v})\times\dot{\boldsymbol{v}}}{(1-\boldsymbol{v}\boldsymbol{n})^3} + \frac{\widetilde{D}}{R}\frac{\boldsymbol{n}-\boldsymbol{v}}{(1-\boldsymbol{v}\boldsymbol{n})^2}\right]_{t'} \;; \quad \widetilde{D} = \frac{\partial\widetilde{C}}{\partial t'}$$

$$\widetilde{\boldsymbol{H}} \;=\; \frac{1}{4\pi}\left[-\frac{\widetilde{C}}{R^2}\frac{\boldsymbol{n}\times\boldsymbol{v}}{(1-\boldsymbol{v}\boldsymbol{n})^3}(1-\boldsymbol{v}^2+\dot{\boldsymbol{v}}\boldsymbol{R}) - \frac{\widetilde{C}}{R}\boldsymbol{n}\times\dot{\boldsymbol{v}} - \frac{\widetilde{D}}{R}\frac{\boldsymbol{n}\times\boldsymbol{v}}{(1-\boldsymbol{v}\boldsymbol{n})^2}\right]_{t'} = \boldsymbol{n}\times\widetilde{\boldsymbol{E}}\;.$$

Two point-like sources located at z=0 and 1

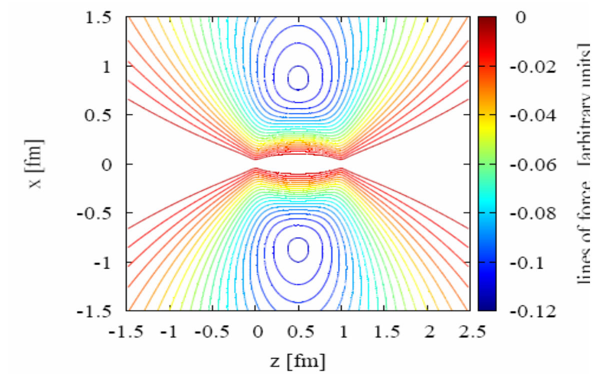
Assuming one particle carries a color charge $\tilde{P}$ and the other particle a charge $\tilde{Q}$, the consistency equations are simplified as

$$\dot{\tilde{P}} = g\,\tilde{\varphi}(t,\boldsymbol{x}_1)\times\tilde{P}\ ,\ \text{and}\ \dot{\tilde{Q}} = g\,\tilde{\varphi}(t,\boldsymbol{x}_2)\times\tilde{Q}\ ,$$

which result in charge modulus conservation $\dot{\tilde{P}}^2 = 0$ and $\dot{\tilde{Q}}^2 = 0$.

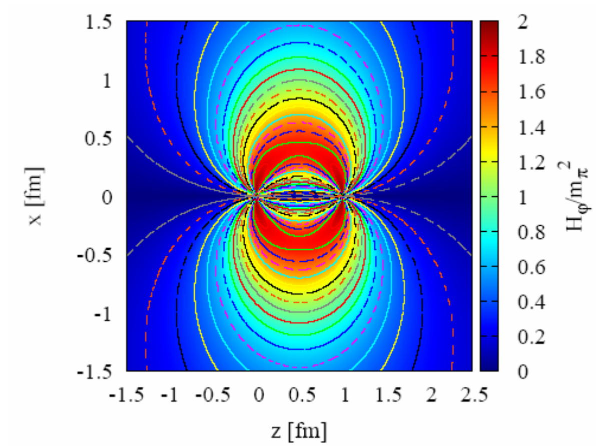
If the scalar potential $\tilde{\varphi}$ is spanned by the two color vectors defined above $\tilde{\varphi} = \varphi_1\,\tilde{P} + \varphi_2\,\tilde{Q}$, then the vector potential $\tilde{A}$ is spanned by the vector product of charges only $\tilde{\boldsymbol{A}} = \boldsymbol{a}\,\tilde{P}\times\tilde{Q}$. The last two equations fix the Coulomb gauge. So, we have equations for the potential components φ_1, φ_2 and the vector field $\boldsymbol{a}$

Results are obtained in a quark model with four-fermion interaction generated by strong stochastic gluon vacuum fields (instanton liquid).



Force lines of color field

looks very similar to the EM field picture



Isolines of the chromoelect. field

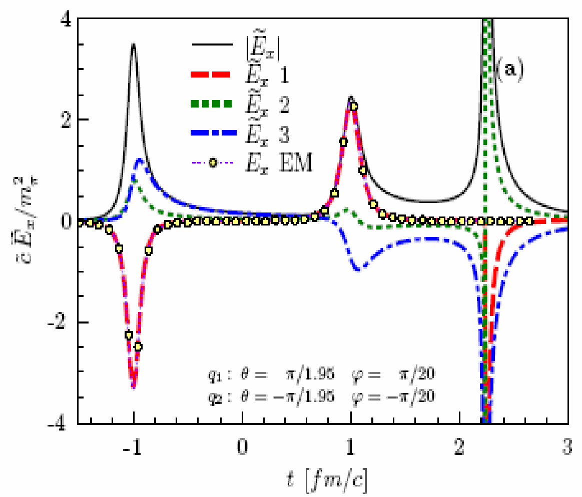
G.Zinovjev, C.Molodtsov, Phys.Atom.Nucl.**70**, 1136 (2006); Eur. Phys. J. **C75**, 141 (2015).

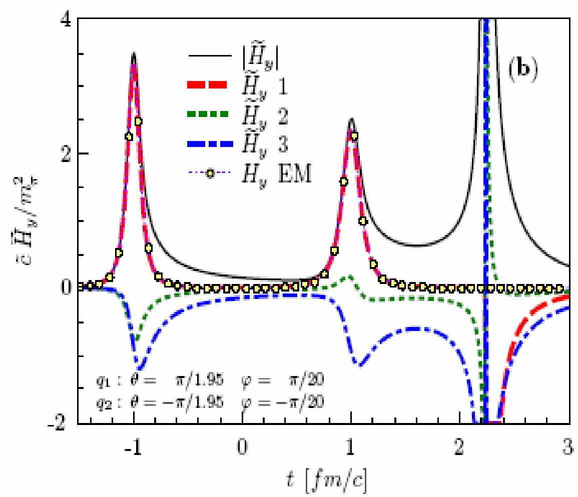
W.Cassing, V.Goloviznin, S.Molodtsov et al., Phys.Rev **C88**, 064909 (2013)

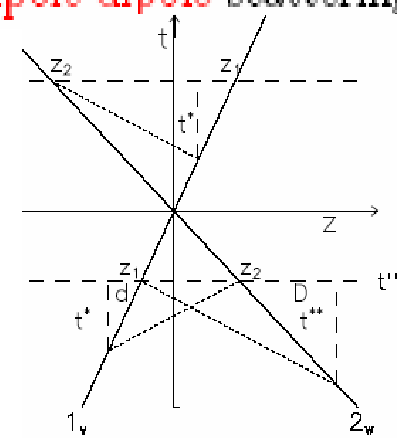
Simplest color configurations

Two color charges $\widetilde{P}$, $\widetilde{Q}$ moving along the z-axis towards each other with velocities $v_P = 1 - 2{\cdot}10^{-2}$ and $|w_Q| = 1 - 1{\cdot}10^{-2}$, respectively. The observation point is $x = 2$ fm, $z = 1$ fm, meeting point $\sqrt{5} \sim 2.24$. The initial angles in the color space are $\theta_P = \pi/1.95$, $\phi_P = \pi/20$ and $\theta_Q = -\pi/1.95$, $\phi_Q = -\pi/20$ => almost oppositely directed charges. The field created by by electric charge $\pm e$ is assumed of the same interaction strength as the color charges $(e^2/(4\pi) = g^2/(4\pi) = 0.3)$.

Particularities: Field picture depends on the initial color state;
The color charges are rotating infinitely fast near the meeting point, $\omega'' = \alpha_q/ln|t|$;
There is a new color glow effect (not observable for electromagnetic field)
These particularities inherent also to color charge-dipole and dipole-dipole scatterings







A charge enters the interaction area at $T = -d/(v+w)$;

$$t'_1 = \frac{1-w}{1+v}\,T, \quad t'_2 = \frac{1-v}{1+w}\,T$$

W.Cassing, et al., Phys.Rev **C88**, 064909 (2013)

PHSD with color fields

The PHSD transport model is generalized to account for creation of color fields

$$\left\{\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{p_0} + \nabla_{\mathbf{p}}\, U\right)\nabla_{\mathbf{r}} \; + \left(-\nabla_{\mathbf{r}}\, U + \widetilde{C}\ \widetilde{\mathbf{E}} + \widetilde{C}\ \{\mathbf{v}\times\widetilde{\mathbf{B}}\}\right)\nabla_{\mathbf{p}}\ \right\} f = C_{coll}(f, f_1, ...f_{N-1})\ .$$

The quasiparticle propagation in the color field is calculated according to the Wong force

$$\frac{d\mathbf{p}}{dt} = \widetilde{C}\ \widetilde{\mathbf{E}} + \widetilde{C}\ \{\mathbf{v}\times\widetilde{\mathbf{B}}\}\ .$$

We assume that quarks between collisions move with a constant velocity and the change in the color charge is neglected, but the collective interaction resulting from the Debye screening is taken into consideration by using the chromo fields. Thus

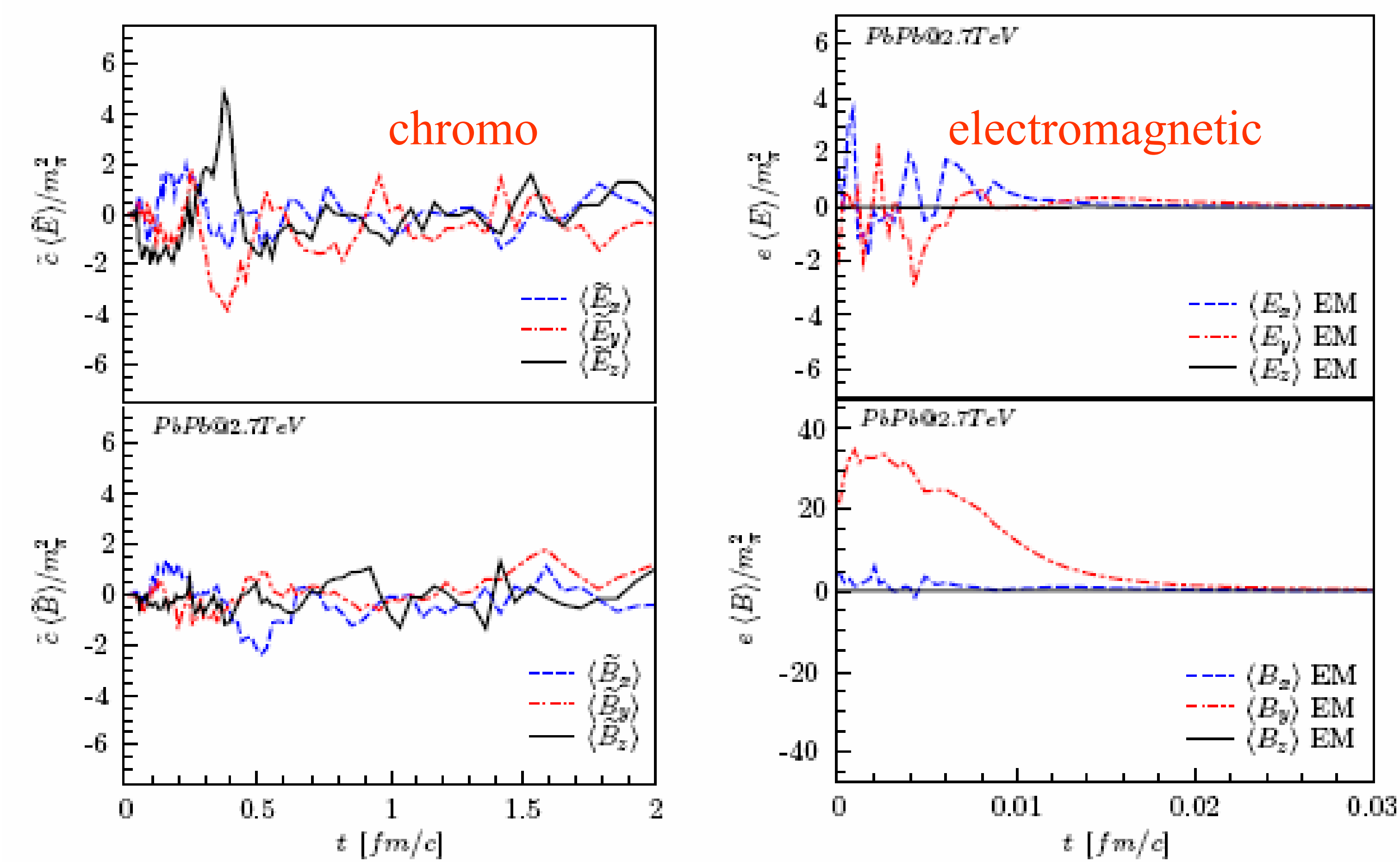
$$\widetilde{\boldsymbol{E}} = \frac{\widetilde{C}}{4\pi}\,\frac{e^{-MX}(1+MX)(1-v^2)}{R^2(1-\boldsymbol{vn})^3}\,(\boldsymbol{n}-\boldsymbol{v}), \qquad \widetilde{\boldsymbol{H}} = \boldsymbol{v}\times\widetilde{\boldsymbol{E}}\ ,$$

with $X = |\boldsymbol{X}| = \gamma R\ |1-(\boldsymbol{vn})|$. For moderate temperatures $T \lesssim$300 MeV the chromo fields practically are not suppressed by the Debye factor and their values are close to those for the point-like source.

V.Voronyuk, G.Zinovjev et al., Yad. Fys. **78**, 338 (2015)

Color field fluctuations in heavy ion collisions

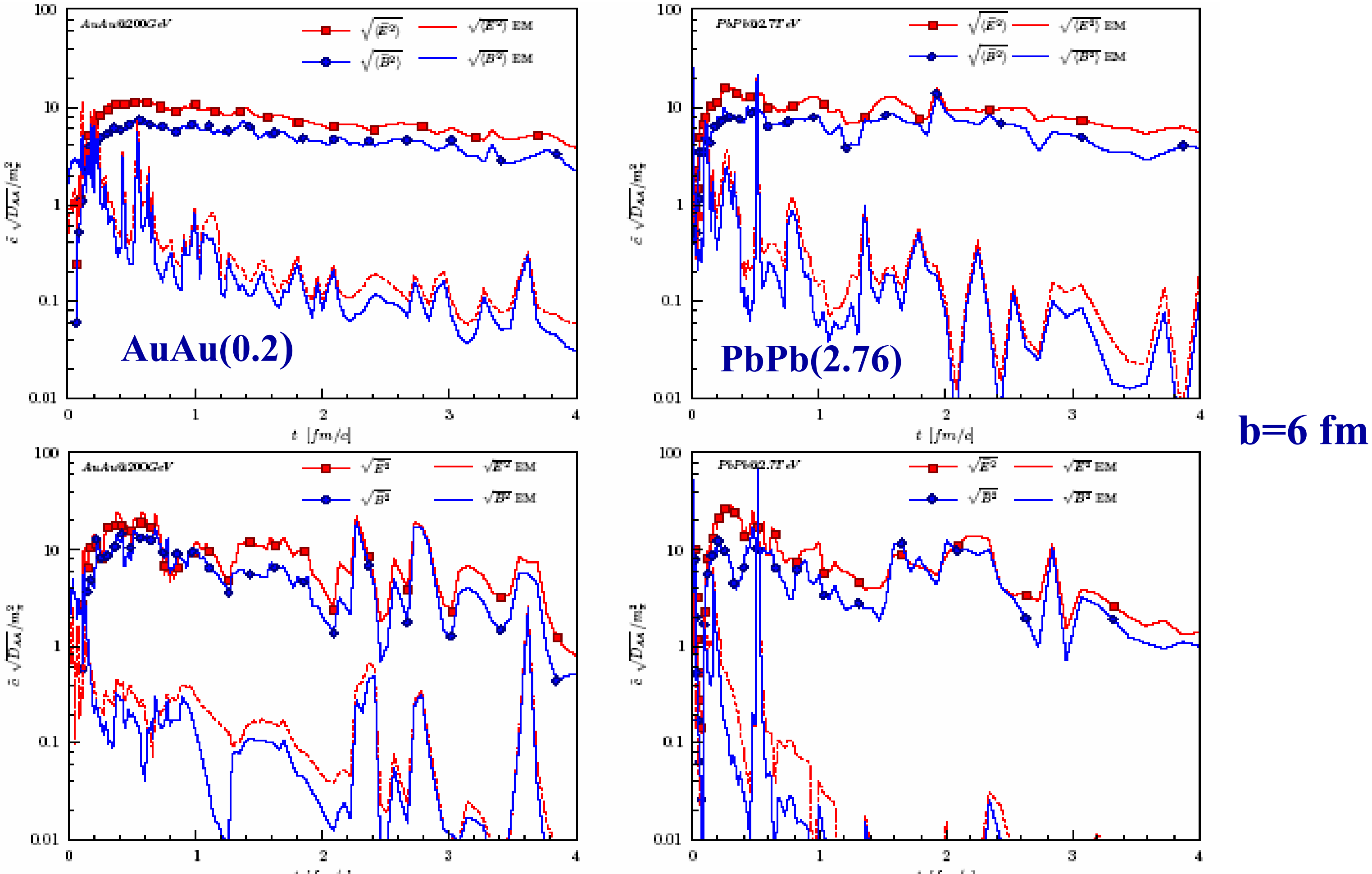
Pb+Pb (2.76 TeV), b=6 fm; N_{ev}=10



The strength of the chromoelectric and chromagnetic fields strongly fluctuates and exhibits a stochastic behavior of the event-by-event calculation results.

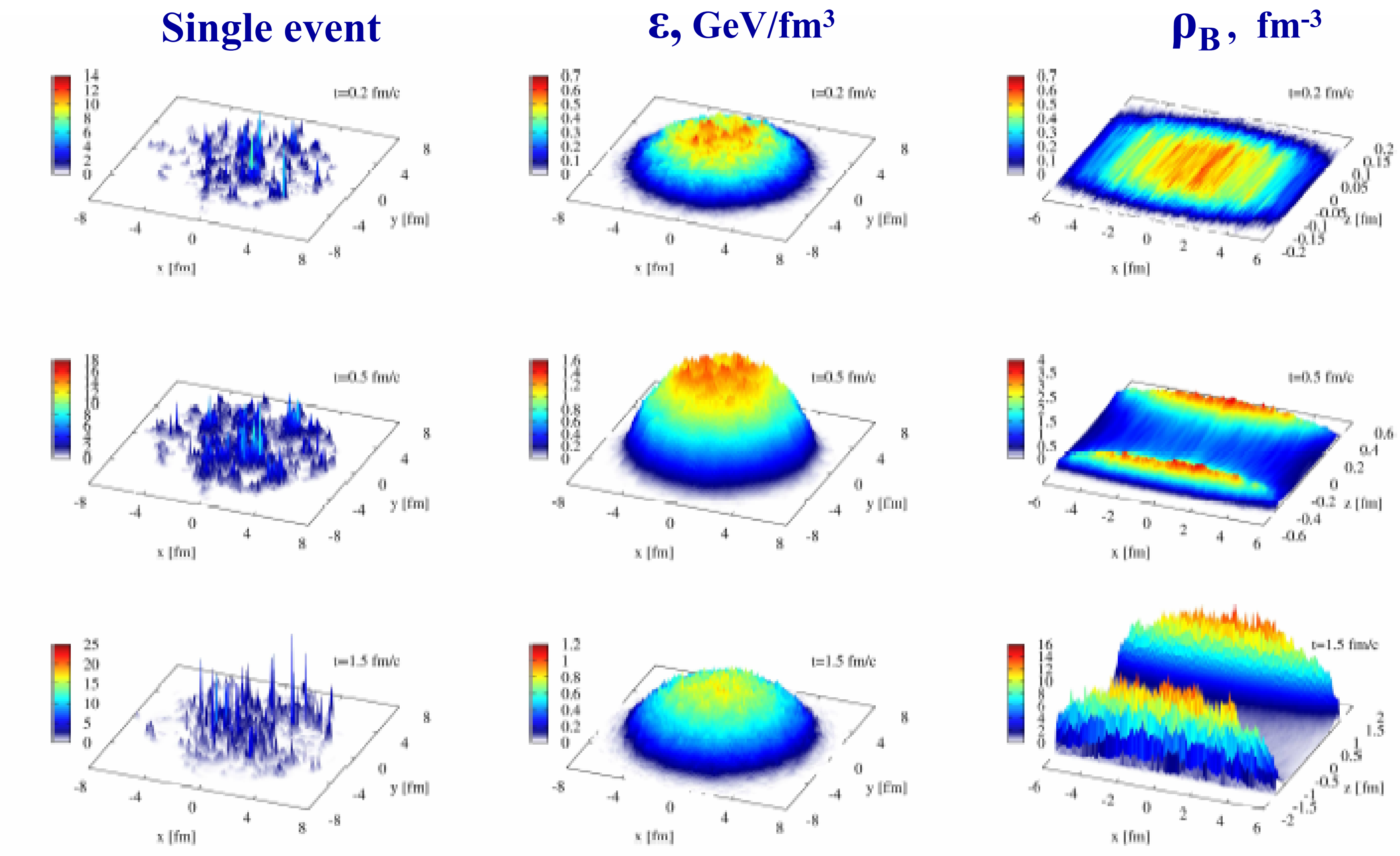
Abelian and and non-Abelian dispersion

Dispersion of the color field strength $D^E_{AA} = \langle \widetilde{E}^2 \rangle - \langle \widetilde{E} \rangle^2$. If the space components are approximately equal to each other then, $\sqrt{D^E_{AA}} \approx \langle\langle|\widetilde{E}|\rangle\rangle\langle N_s\rangle$.



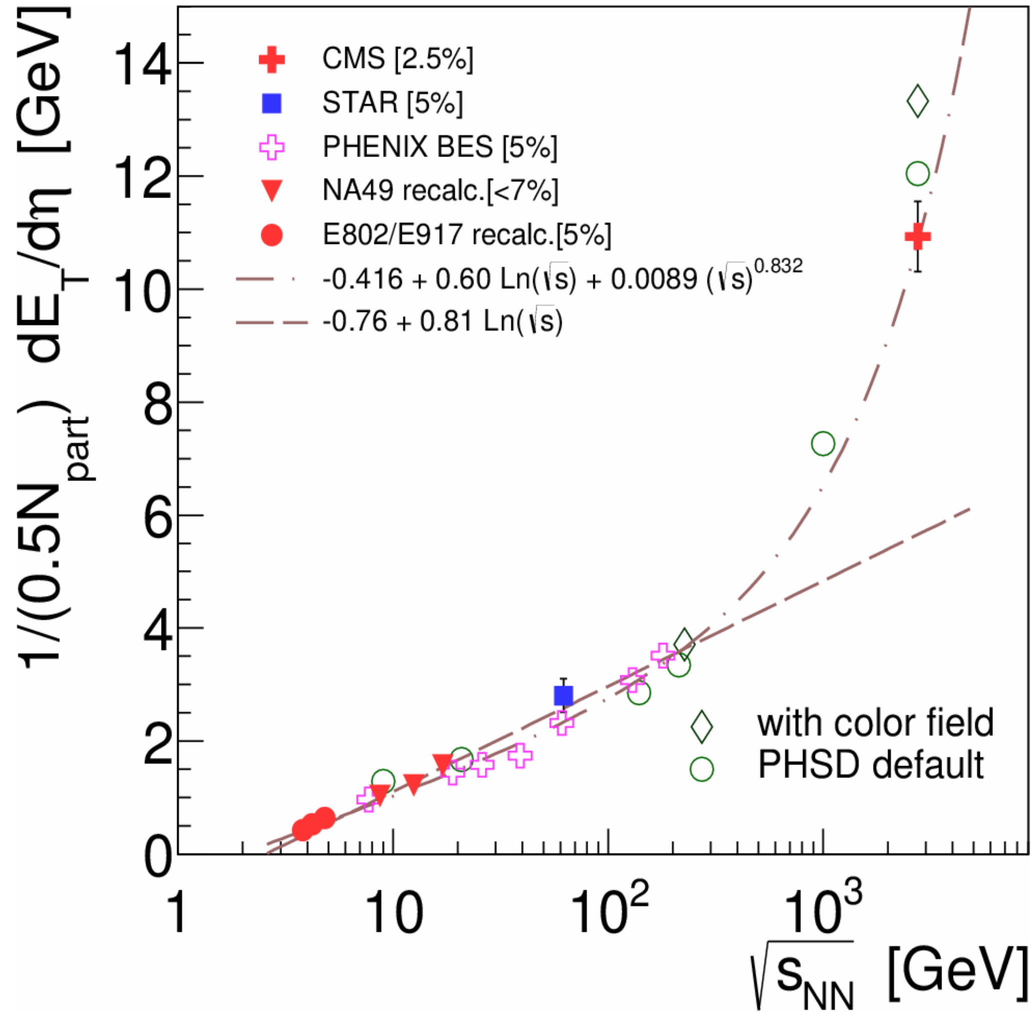
V.Voronyuk, G.Zinovjev et al., Yad. Fys. **78**, 338 (2015)

Space-time evolution of parton density

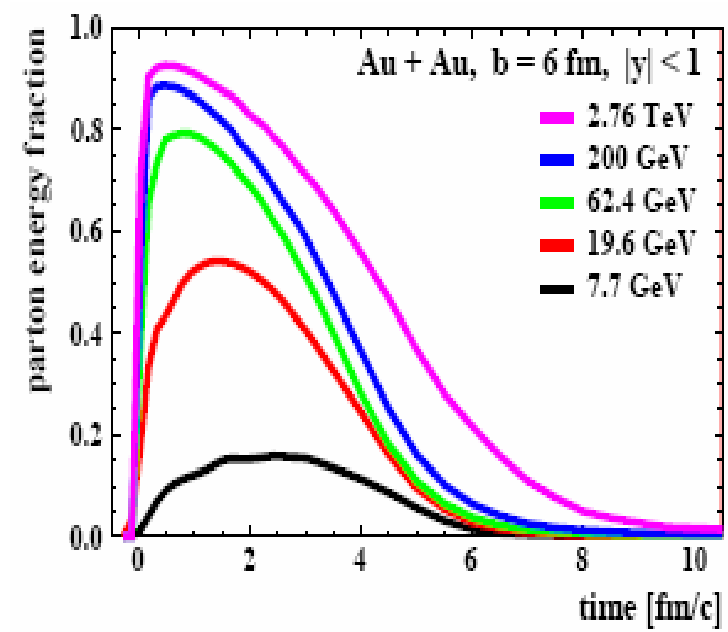


Au+Au(0.2 TeV), b=0.5 fm

Comparison with heavy-ion experiment



R.Sahoo et al., arXiv:1408.5773



The rise is due to the quark-quark interaction rather than chromo effect

Chromo effect is not seen in global characteristics below the RHIC energy and effect is minor at higher one. Further work is needed.

Main results

⋆ The microscopic PHSD transport approach is generalized to include the creation of the electromagnetic field in heavy-ion collisions, its propagation and influence on the quasiparticle transport. It is demonstrated that the EM strength reached in HIC is highest among all processes in nature. Temporal and spatial distributions of EM fields are investigated.

⋆ It is turned out that global HIC characteristics are practically insensitive to the EM effects. An account of EM field fluctuations does not change this fact. The solution of this puzzle has been found: It is not due to the short interaction time but follows from a compensation effect between electric and magnetic components of the Lorentz force.

⋆ As a particular effect, observables for the Chiral Magnetic Effect was investigated with background treated in the PHSD model with EM field. The STAR data at $\sqrt{s_{NN}}$ ==7.7 and 11.2 GeV were successfully described. It says that there is no CME at these low (NICA ?!) energies. Discrepancy at higher energies points out that other sources (including a possible CME) may contribute at higher energy.

⋆ It has been found that for asymmetric systems -- like Cu-Au collisions – the directed flow is sensitive to inclusion of the electromagnetic field resulting in charge-dependent distributions. Observation of charge-dependent splitting would evidence the creation of strong electromagnetic fields in HIC. Predictions for the NICA energy are presented.

⋆ The Yang-Mills theory is analyzed in the SU(2) classical approximation. The calculated chromomagnetic and chromoelectric fields for two color charges at rest exhibit structure very close to that for the electromagnetic field.

Main results, cont'd

⋆ As a prelude to the kinetic approach, the ultrarelativistic scattering of two simplest colored configurations (charge-charge, charge-dipole, dipole-dipole) moving along a straight line towards each other is treated in the classical approximation. The time evolution of chromomagnetnic and chromoelectric field strength is studied in non-Abelian and Abelian cases. Quantum rotation of color charge vector in the non-Abelian case results in a maximum in field strength at the the moment of passing of two color charges through each other (color charge glow effect). This effect was not observed earlier and is absent in the Abelian case.

⋆ The PHSD kinetic approach is generalized to include the creation of chromo field in relativistic HIC. The field of a point-like charge propagating along the trajectory $v(\mathrm{r}(t))$ is described by the (retarded) Liénard-Wiechert potential and its influence on the quasiparticle transport. The color field strength wildly fluctuates almost vanishing in average, while in the EM case the dominating B_y component, coming from the regular motion of spectators, is rather smooth. Dispersions of chromomagnetic and chromoelectric field strength are very large, slowly changing in time and exceeding those in the EM case roughly as $\alpha_g/\alpha_{em} \sim 40$. Temporal and spatial distributions of chromo fields are investigated.

⋆ Due to fluctuation the nature of chromo field, its influence on global obsrvables in ultrarelativistic (above the top RHIC energy) collisions is quite minor. In contrast to expectation, the sharp $\sqrt{s_{NN}}$ growth of average multiplicity and average transverse energy at the mid-rapidity observed in the LHC experiments is mainly explained by an increase in quark-quark interaction energy (similarly to the rise of v_2 in the RHIC energy range). Correction from the color fields is small. Further analysis including various observables is needed.

List of presented publications

1. V. Skokov, A. Illarionov and V. Toneev, Estimate of the magnetic field strength in heavy-ion collisions, International Journal of Modern Physics A24, 5925-5932 (2009). [320]

2. V.D. Toneev and V. Voronyuk, Beam-energy and system-size dependence of the CME, Письма в ЭЧАЯ, 8, 103-111 (2011). [18]

3. V. Voronyuk, V.D Toneev, W. Cassing, E.L. Bratkovskaya, V.P. Konchakovski, and S.A. Voloshin, Electromagnetic field evolution in relativistic heavy-ion collisions, Phys. Rev. C83, 054911 (2011) (17 pages). [100]

4. V. D. Toneev and V. Voronyuk, Chiral Magnetic Effect and evolution of electromagnetic field, Acta Phys. Pol. Suppl. B5, 887-896 (2012). [1]

5. V. P. Konchakovski, E. L. Bratkovskaya, W. Cassing, V. D. Toneev, S. A. Voloshin and V. Voronyuk, Azimuthal anisotropies for Au+Au collisions in the parton-hadron transient energy range, Phys. Rev. C85, 044922 (2012) (15 pages). [30]

6. V. D. Toneev, V. Voronyuk, E. L. Bratkovskaya, W. Cassing, V. P. Konchakovski and S. A. Voloshin, Theoretical analysis of a possible observation of the chiral magnetic effect in Au+Au collisions within the RHIC beam energy scan program, Phys. Rev. C85, 034910 (2012) (6 pages). [16]

7. V.D. Toneev, V.P. Konchakovski, V. Voronyuk, E.L. Bratkovskaya and W. Cassing, Event-by-event background in estimates of the chiral magnetic effect, Phys. Rev. C86, 064907 (2012), (20 pages).[5]

List of presented publications, cont'd

8. W. Cassing, V.D. Toneev, C.A. Voloshin and V. Voronyuk, Charge-dependent directed flow in asymmetric nuclear collisions, Phys. Rev. C90, 064903 (2014) (8 pages).[5]

9. V. Toneev, O. Rogachevsky and V. Voronyuk, Evidence for creation of strong electromagnetic fields in relativistic heavy-ion collisions, contribution to the NICA White Paper (Eur. Phys. J. A52 2015 (in print), 2 pages).

10. Molodtsov and Zinovjev, Quantum liquids resulting from quark systems with four-quark interaction, Eur. Phys. Journ. C75, 141(2015) (21 pages).

11. Г.М. Зиновьев и С.В. Молодцов, Об экранировании цветового поля инстантонной жидкостью, Яд. Физ. 70, 1172-1181 (2007).[3]

12. W. Cassing, V.V. Goloviznin, S.V. Molodtsov, A.M. Snigirev, V. Voronyuk, V.D. Toneev and G.M. Zinovjev, Non-Abelian color fields from relativistic color charge configuration in the classical limit, Phys. Rev. C88, 064909 (2013), (20 pages).[1]

13. В. Воронюк, В.В. Головизнин, Г.М. Зиновьев, В. Кассинг, С.В. Молодцов, А.М. Снигирев и В.Д. Тонеев, Классические глюонные поля и коллективная динамика систем цветовых зарядов, Яд. Физ. 78, №3-4, 338-363 (2015).