Directed flow in asymmetric HI collisions and the inverse Landau-Pomeranchuk-Migdal effect

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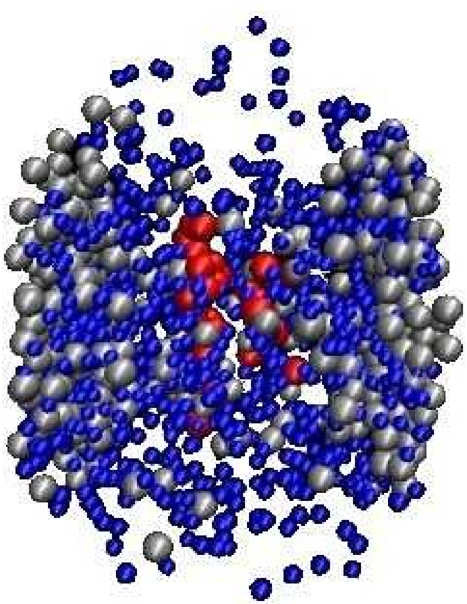
In collaboration with W. Cassing, E. Kolomeitsev and V. Toneev

THEORY of HADRONIC MATTER UNDER EXTREME CONDITIONS



Dubna
30 October-03 November 2016

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)

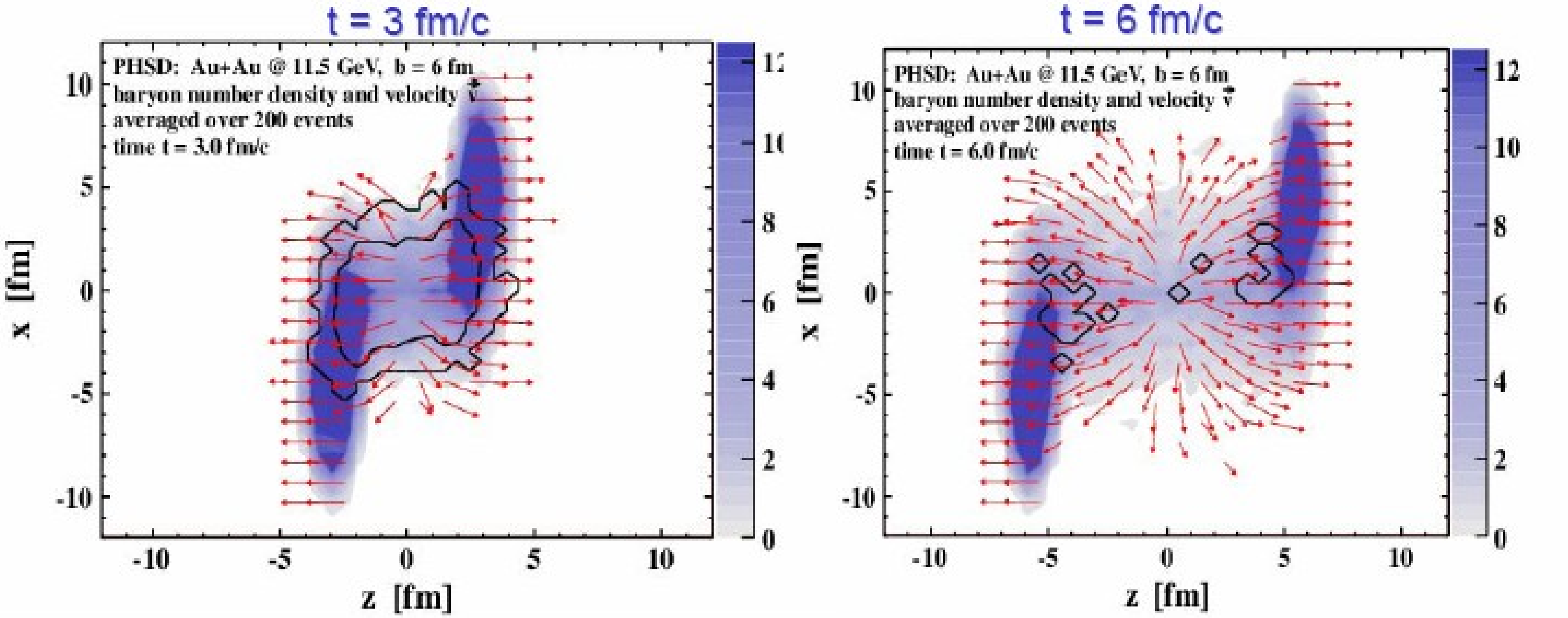
QGP phase described by

Dynamical QuasiParticle Model (DQPM)

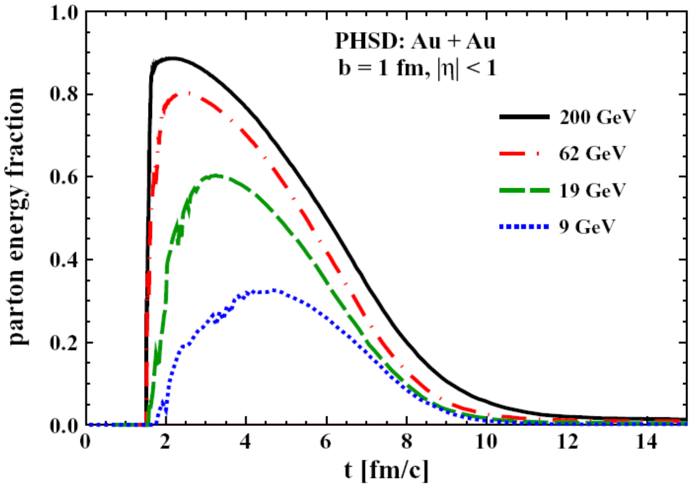
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

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

PHSD: snapshot in the reaction plane

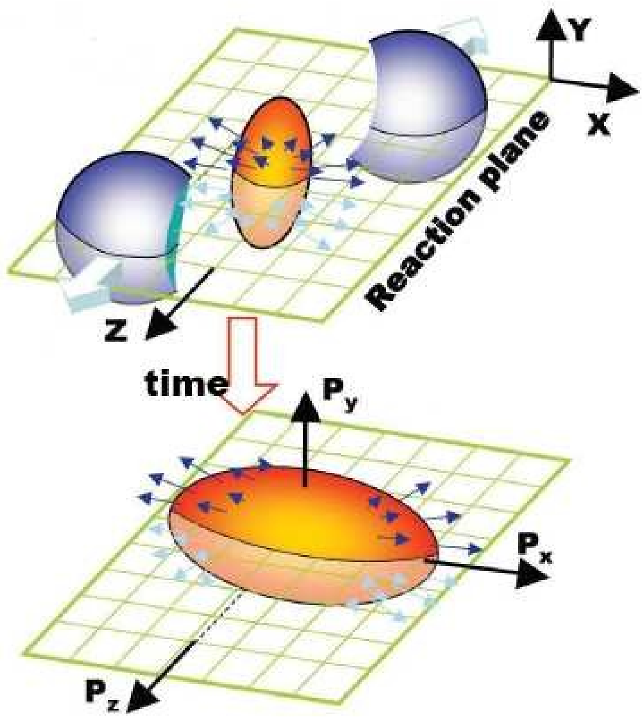


- Color scale: baryon number density
- Black levels: parton density 0.6 and 0.01 fm^{-3}
- Red arrows: local velocity of baryon matter



V. Konchakovsky

Excitation function of elliptic flow

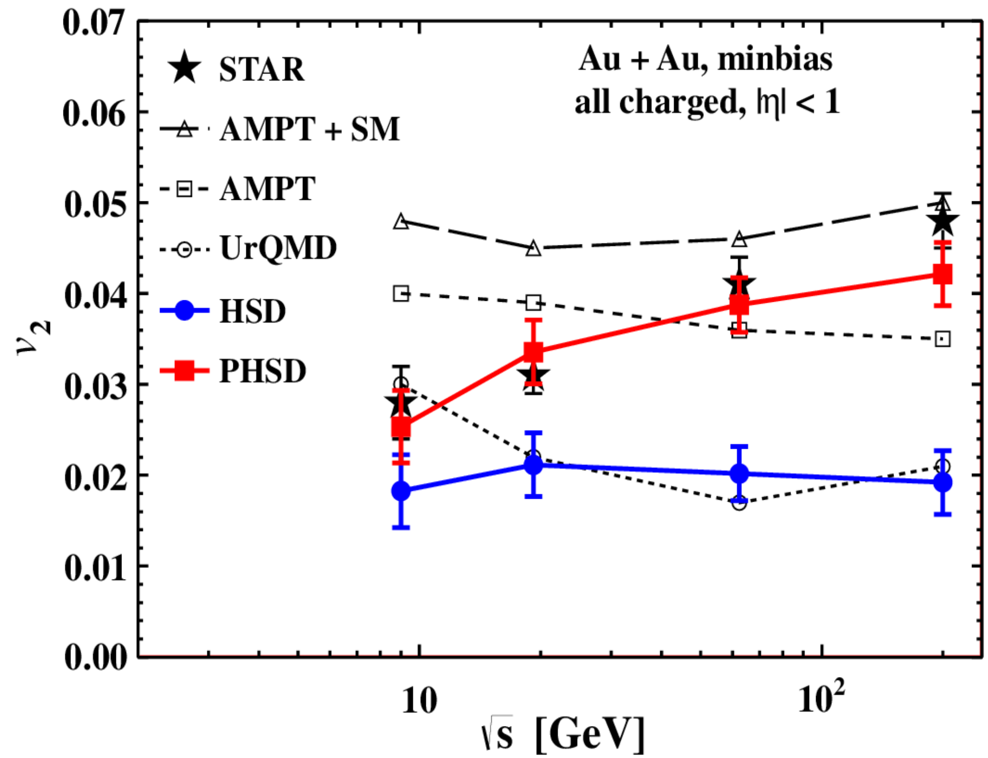


$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1} v_n \cos[n(\varphi - \psi_n)]\right)$$

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

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

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)

Transport model with electromagnetic field

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

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

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

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

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

A general solution of the wave equations is as follows

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

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

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

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

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

For point-like particle

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

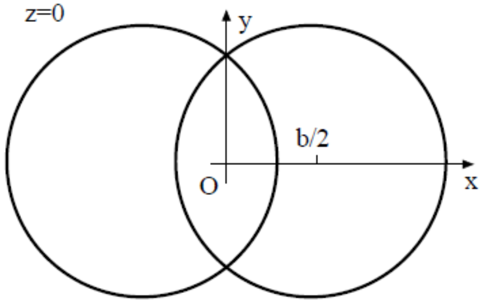
$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n(\mathbf{R}_n)\frac{1-v_n^2}{[R_n^2-(\mathbf{R}_n\times\mathbf{v}_n)^2]^{3/2}}\mathbf{v}_n\times\mathbf{R}_n$$

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

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 $eB_y \neq 0$

Beam energy dependence of eB_y



Lienard-Wiehert potential

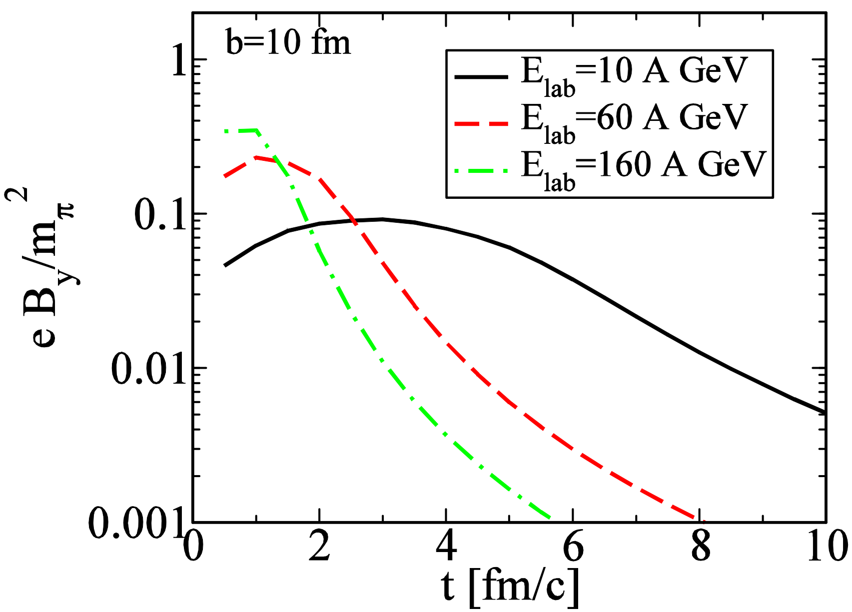
$$e\vec{B}(t,\vec{x}_0) = \alpha_{\rm EM} \sum_n Z_n \frac{1-v_n^2}{\left(R_n - \vec{R}_n \vec{v}_n\right)^3} \left[\vec{v}_n \times \vec{R}_n\right],$$

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

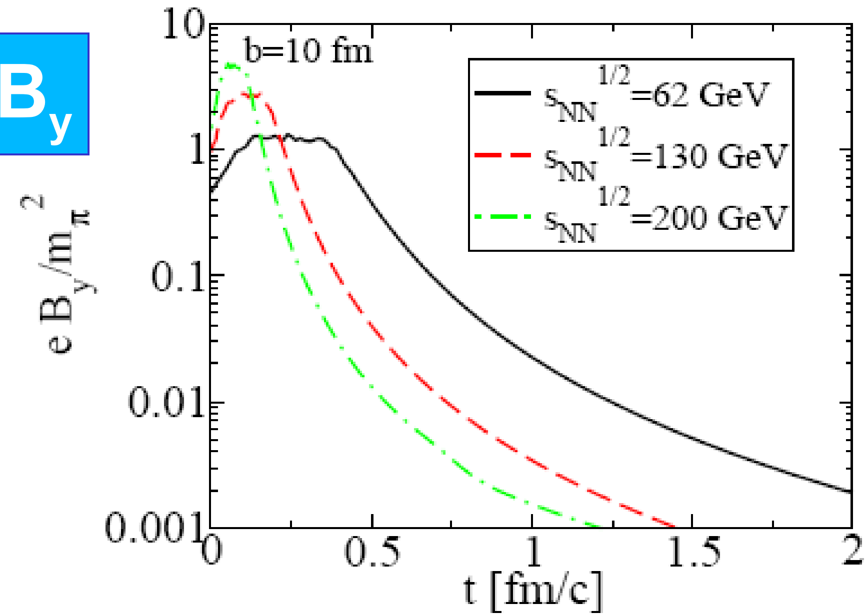
retardation condition

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

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



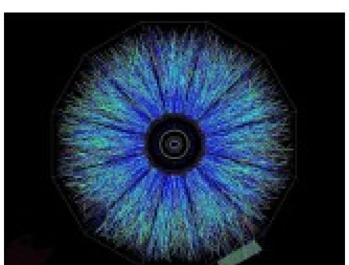
eB_y



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

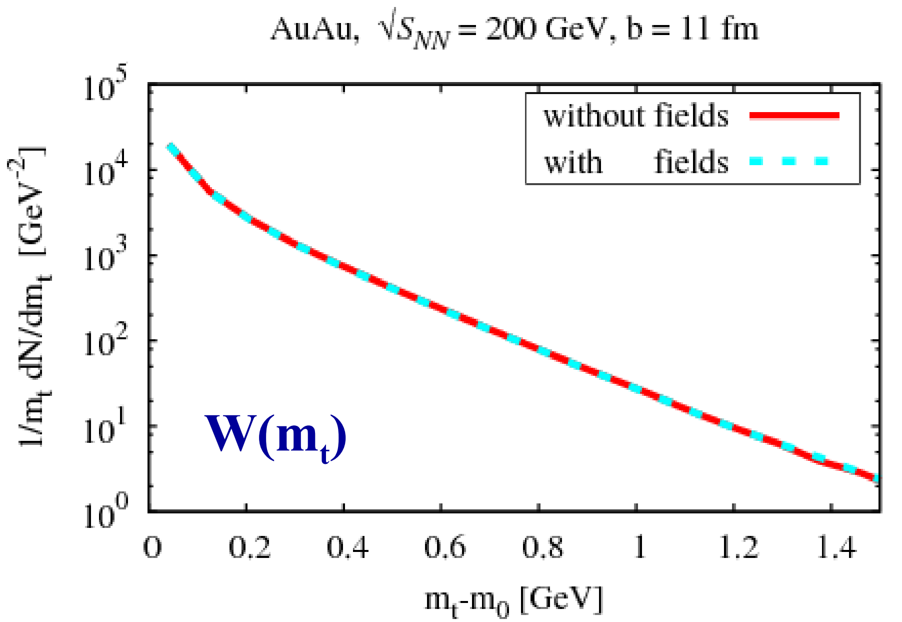


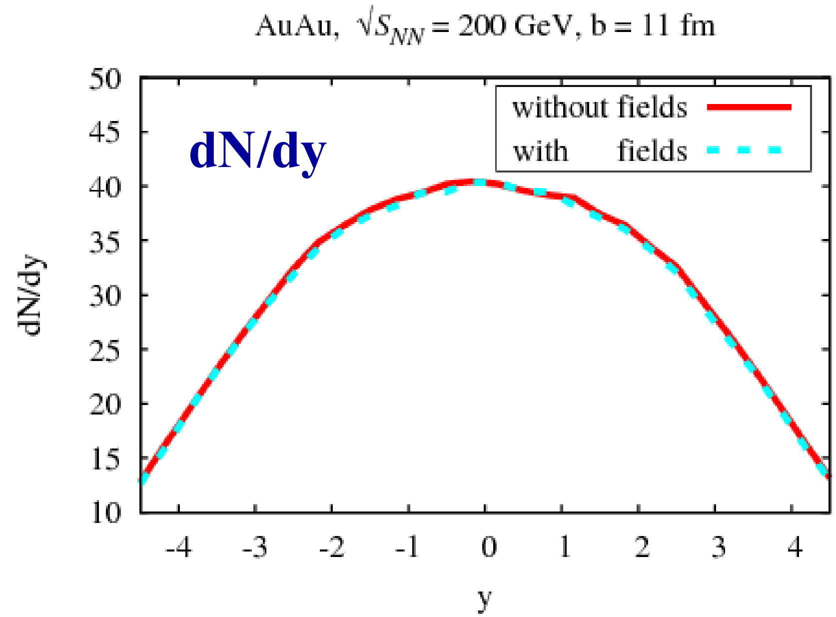
At BNL we beat them all!

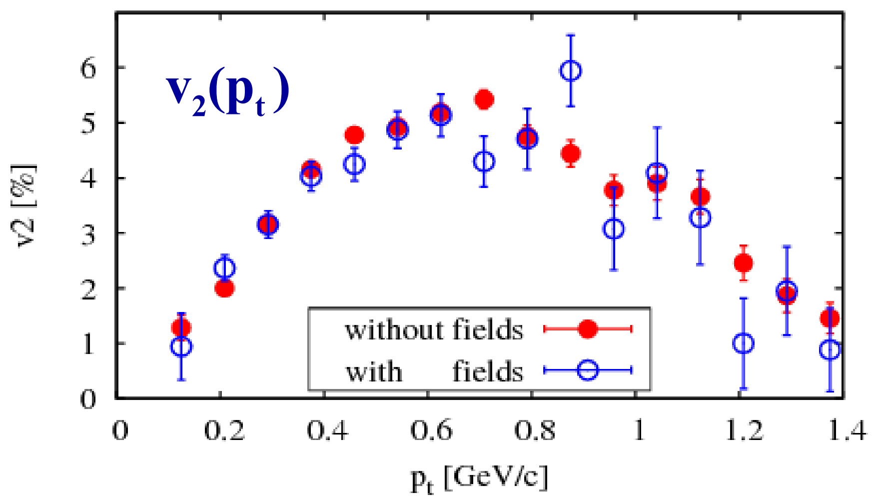
Off central Gold-Gold Collisions at 100 GeV per nucleon

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

Observable



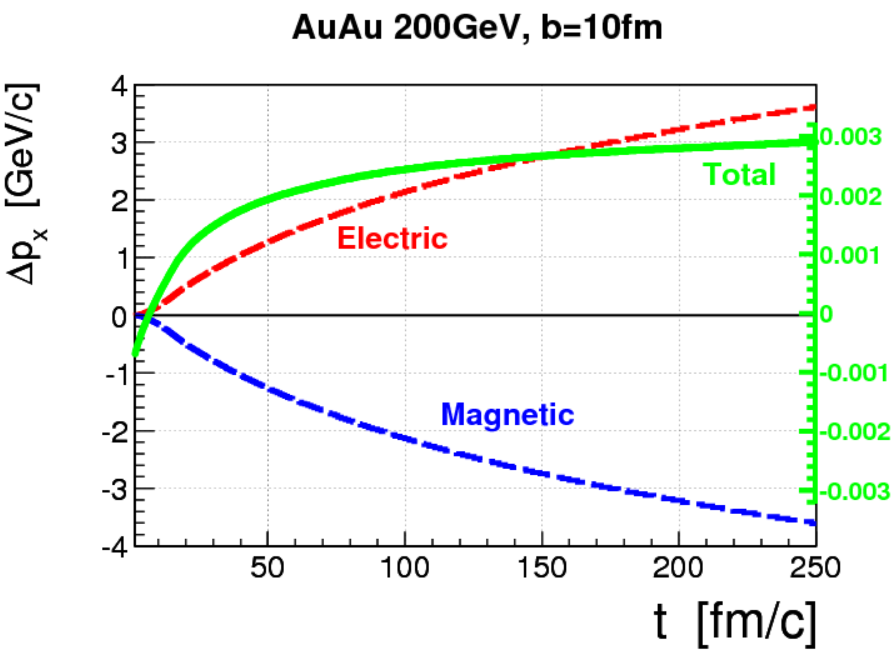


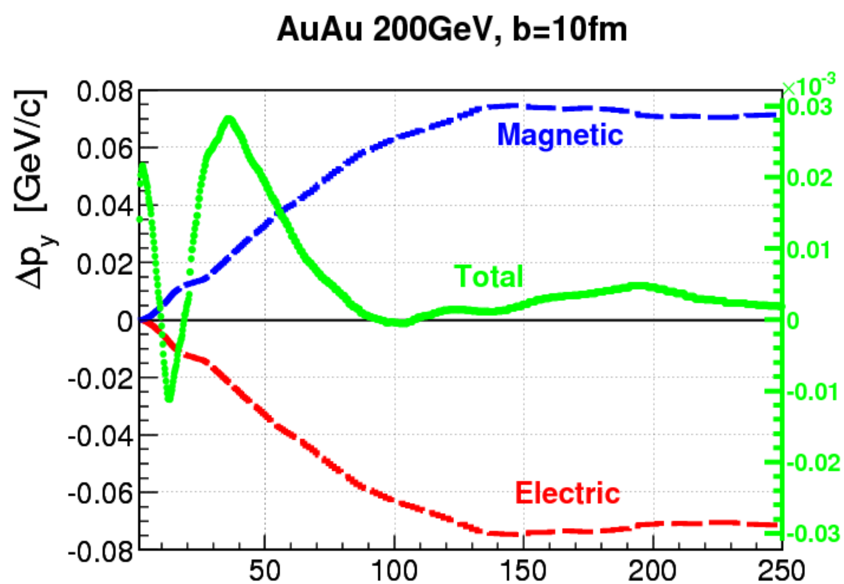


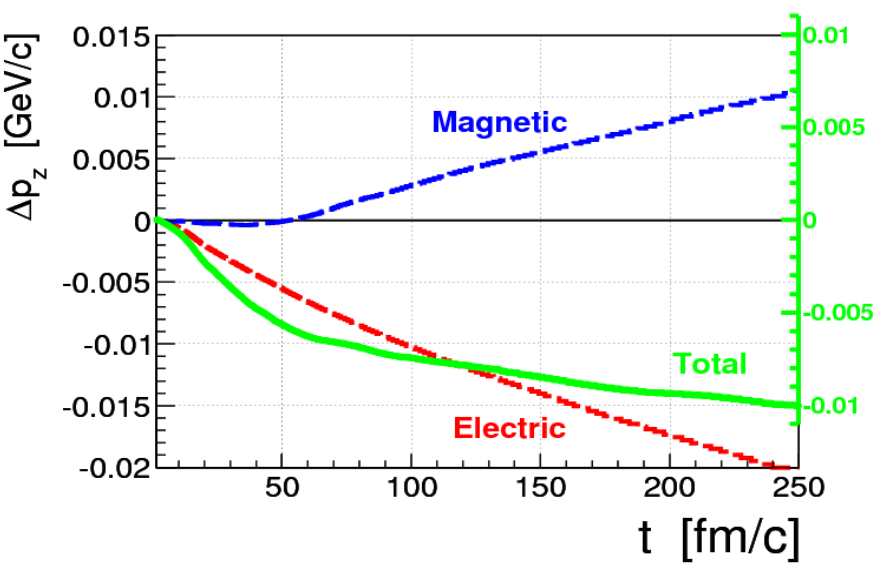
No electromagnetic field effects on global observables in symmetric nuclear collisions !

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

Compensation of electric and magnetic forces







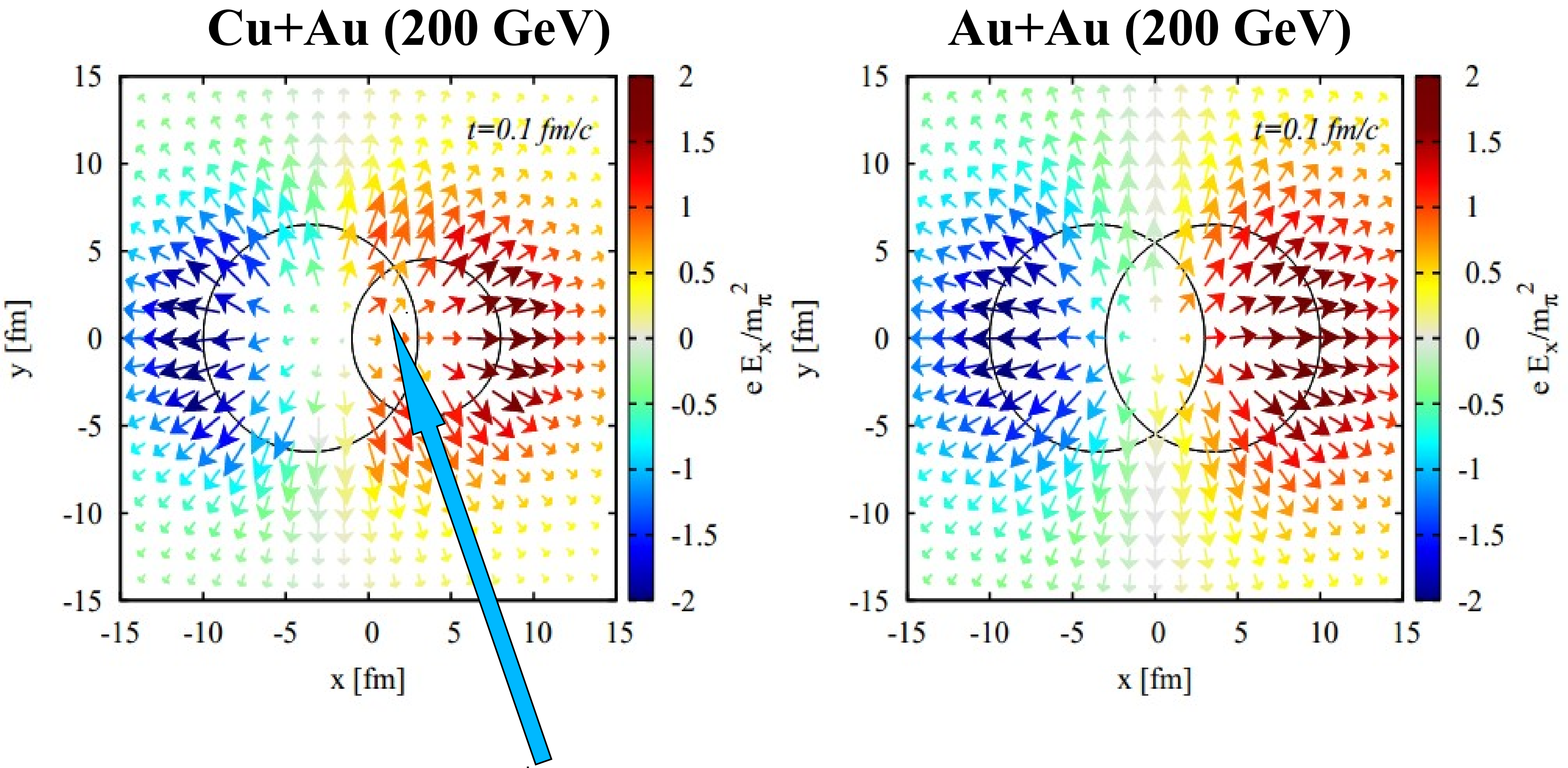
$$\dot{\vec{p}} \rightarrow e\vec{E} + e\vec{v} \times \vec{B}$$

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

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

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

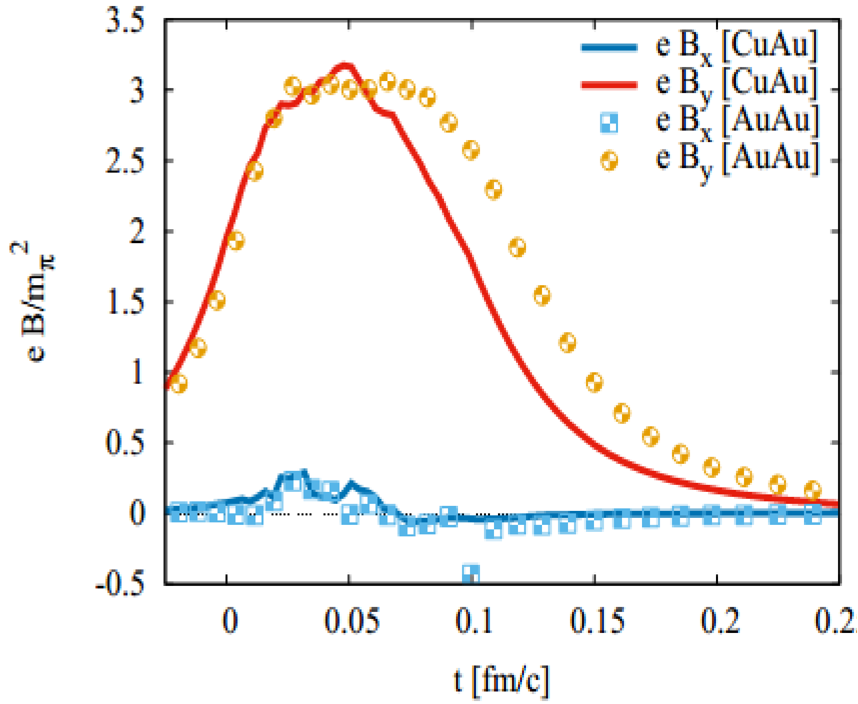
Electric field E_x in asymmetric collisions

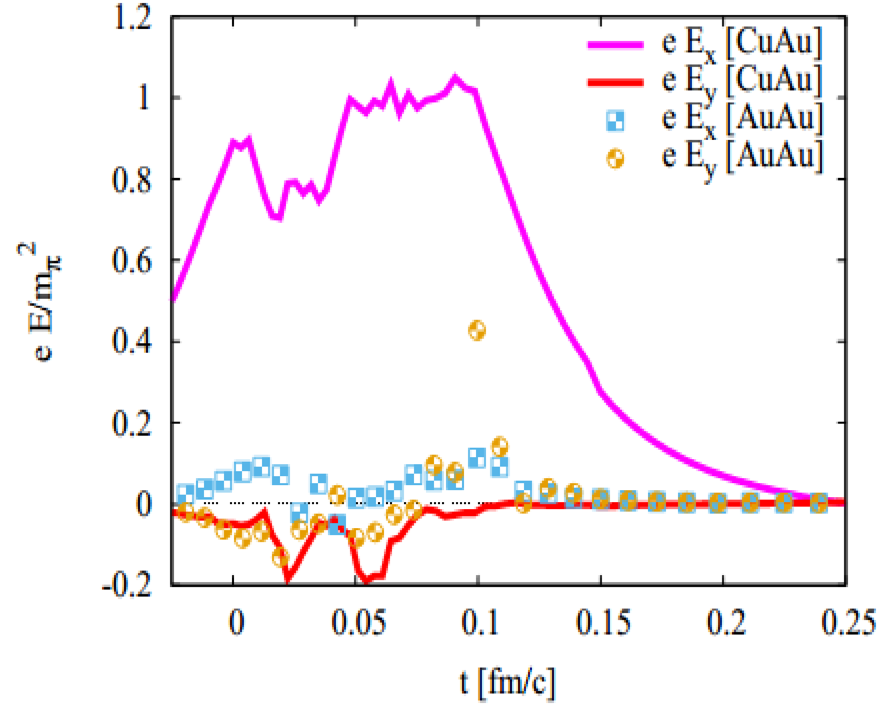


In the overlapping region of asymmetric peripheral collisions a finite electric current appears to be directed from the heavy nuclei to light one.

Fields in symmetric and asymetric systems

Au+Cu/Au ($\sqrt{s}$= 200 GeV)

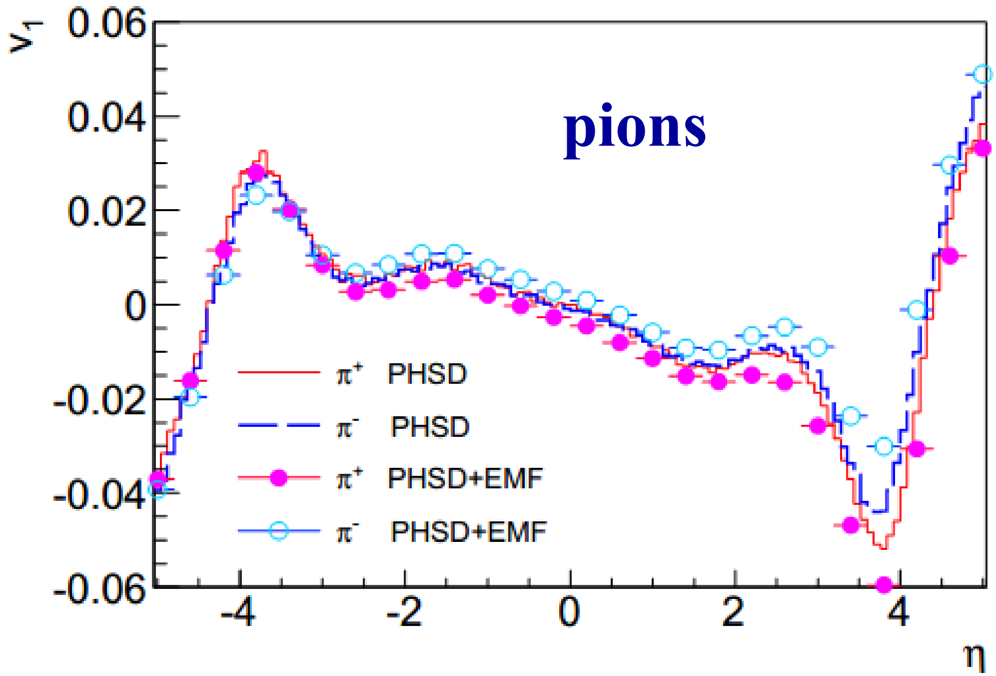




Time dependence of magnetic and electric fields in the center of overlapping region: creation of the non-compensated electric field E_x in asymmetric Cu+Au collisions and almost vanishing E_x, E_y components in the symmetric case.

Charge-dependent v_1 distributions in PHSD

Cu+Au ($\sqrt{s}$= 200 GeV)

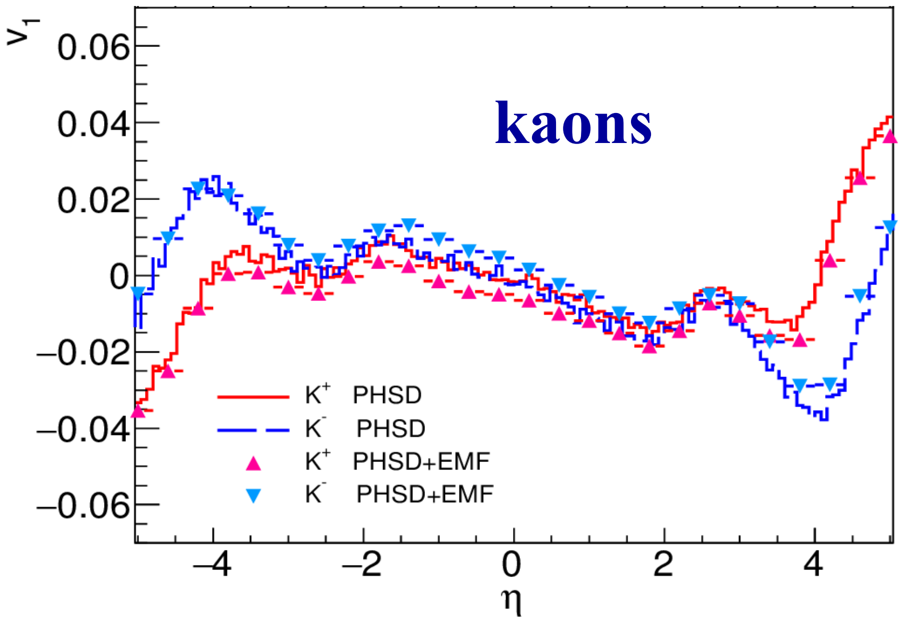


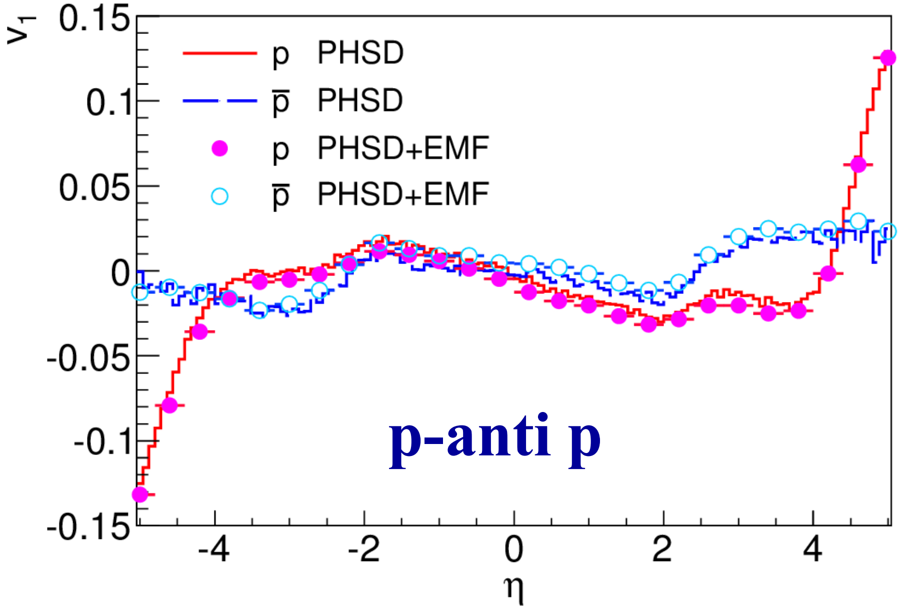
$$v_1(\eta) = \langle \cos(\phi - \phi_{RP}) \rangle = \left\langle p_x / \sqrt{p_x^2 + p_y^2} \right\rangle$$

$N_{ev} = 10^6$

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

η- distributions of v_1 at RHIC





Cu+Au (200 GeV)

Kaon pseudorapidity spectra look like that for pions but not as for protons-antiprotons

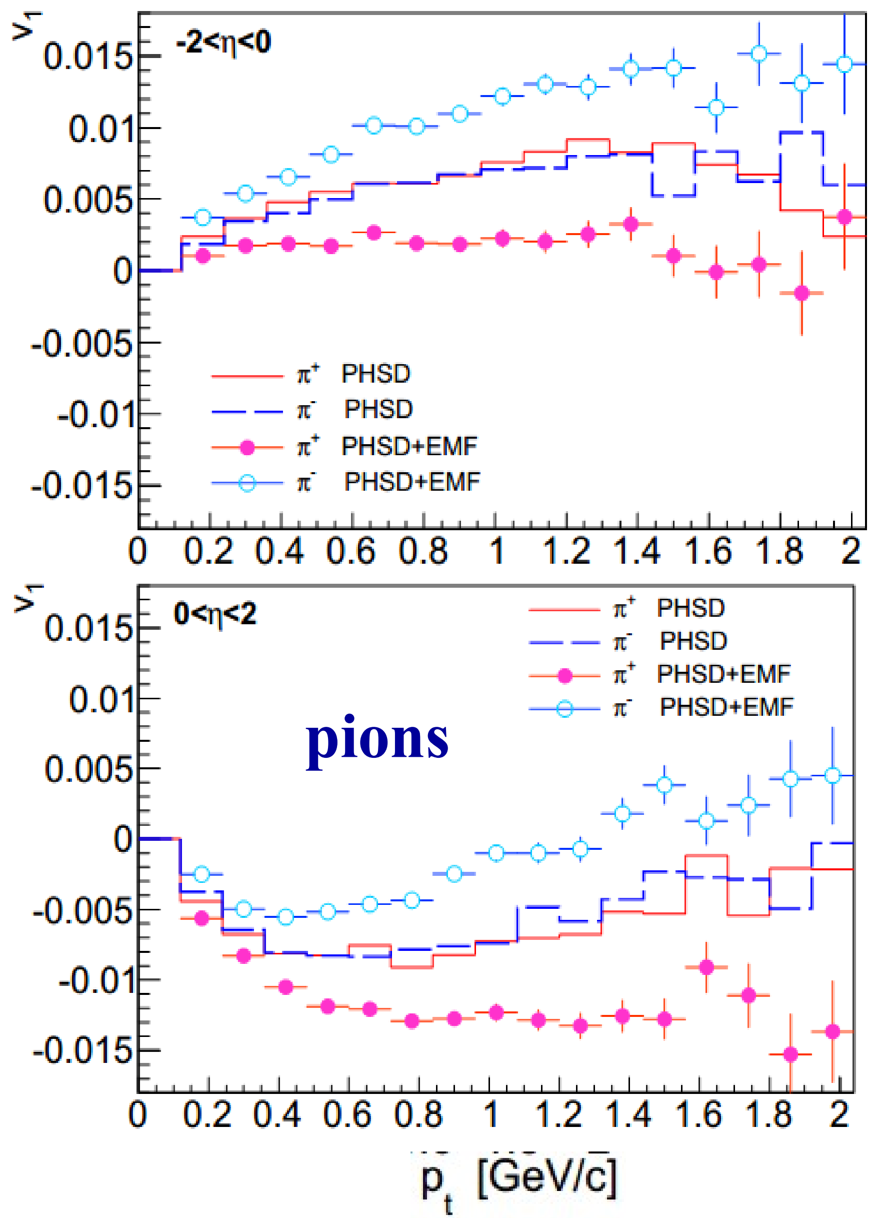
V.Voronyuk et al., Phys. Rev. C90, 064903 (2014)

p_t distributions of v_1 at RHIC

Cu+Au (√s=200 GeV)

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

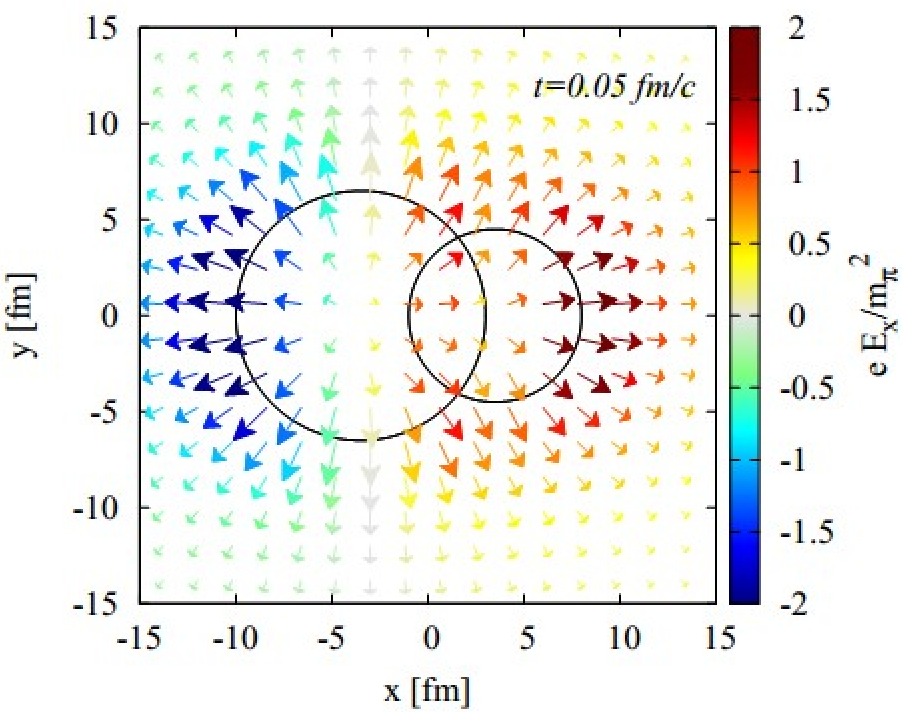
The difference between $v_1(p_T)$ for π^+ and π^- is prominent and getting larger with the p_T increase



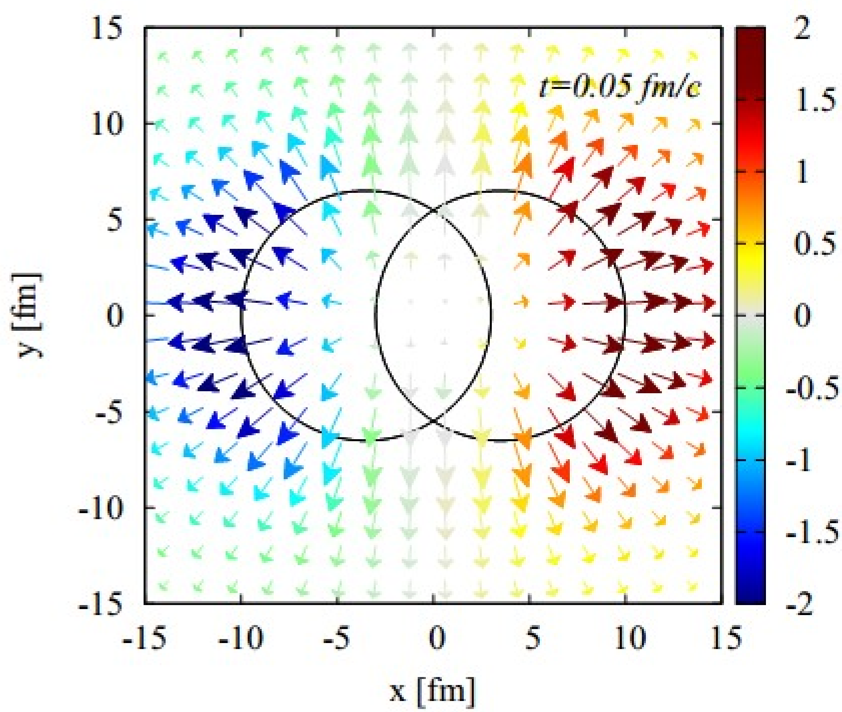
Distributions for the same hadron masses but opposite electric charges are splitted and this can be observed !

Charge-dependent v_1 distributions at NICA

Cu+Au ($\sqrt{s}$=9 GeV)



Au+Au ($\sqrt{s}$=9 GeV)

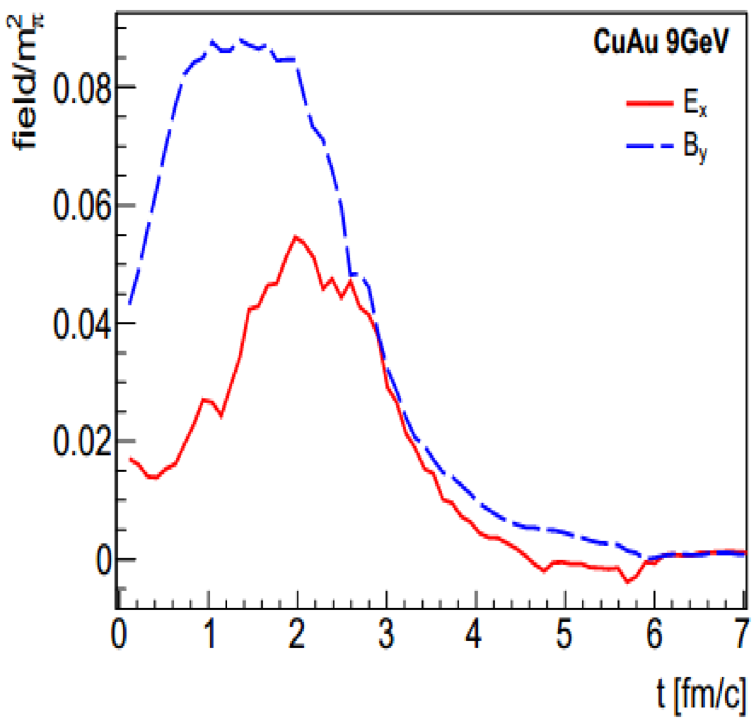


Electric field is directed from Cu to Au nucleus

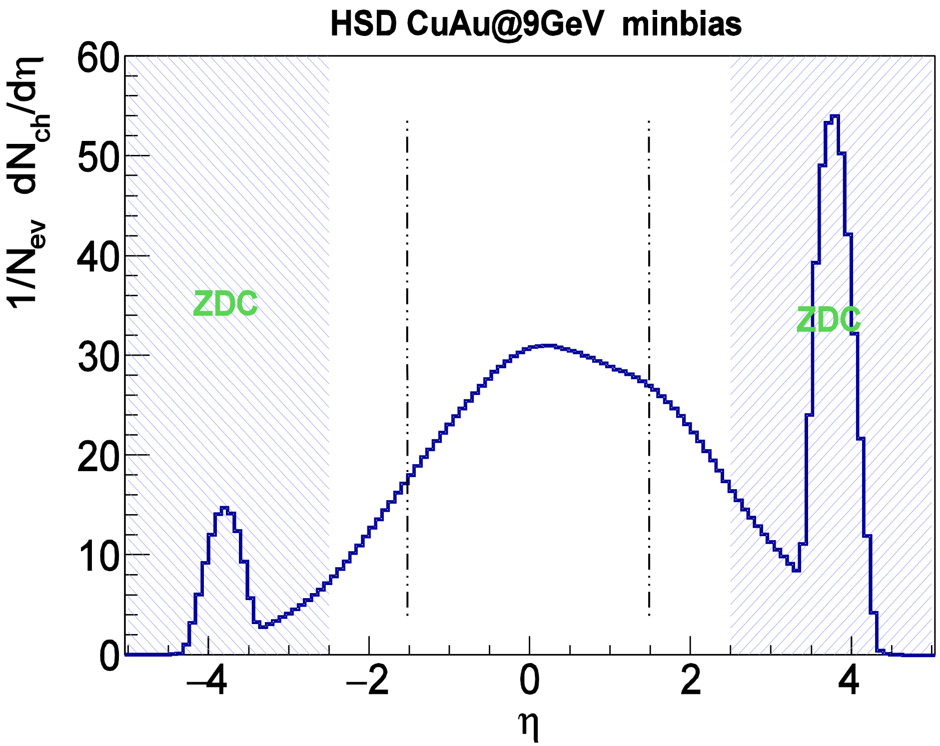
No field in the overlapping region of Au+Au collisions

Charge-dependent v_1 distributions at NICA

Cu+Au (9 GeV)



Field evolution in the center of overlapping region



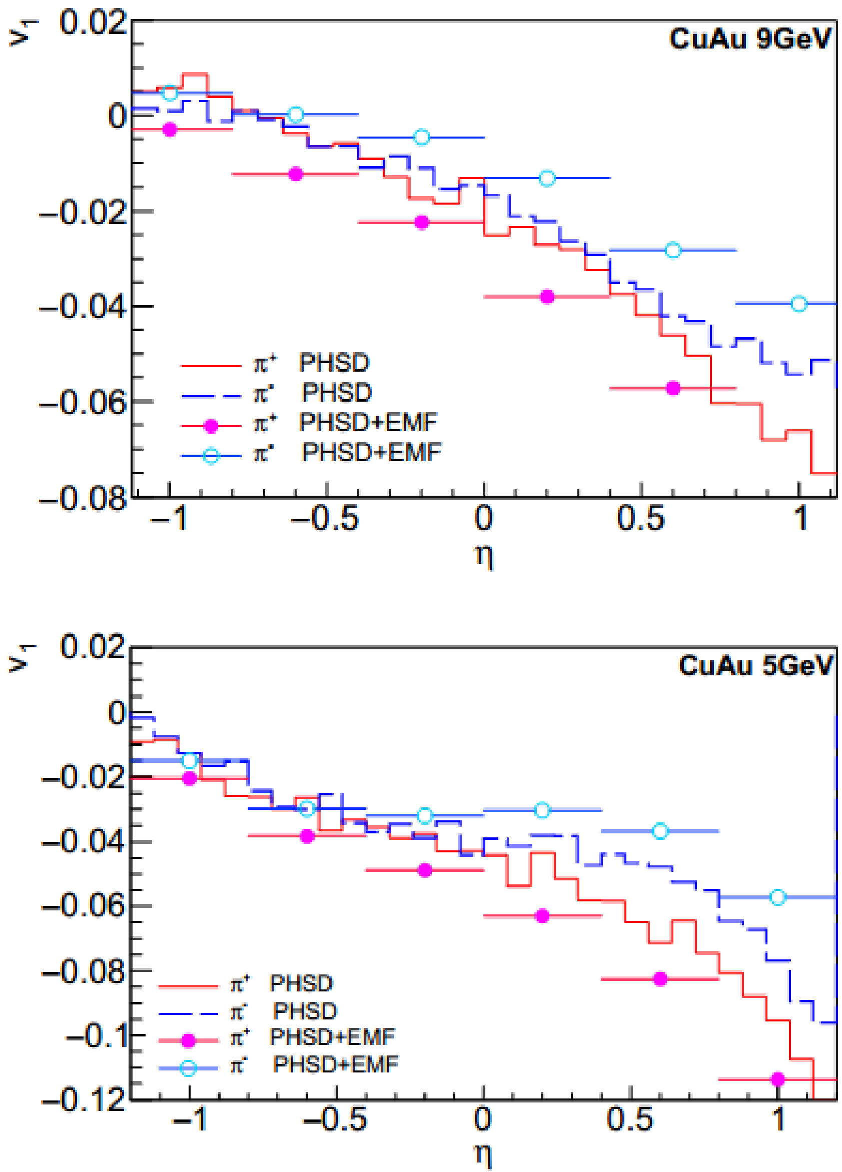
TPC: η<1.2 p_T>0.15 GeV/c

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

Charge-dependent v_1 distributions at NICA

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

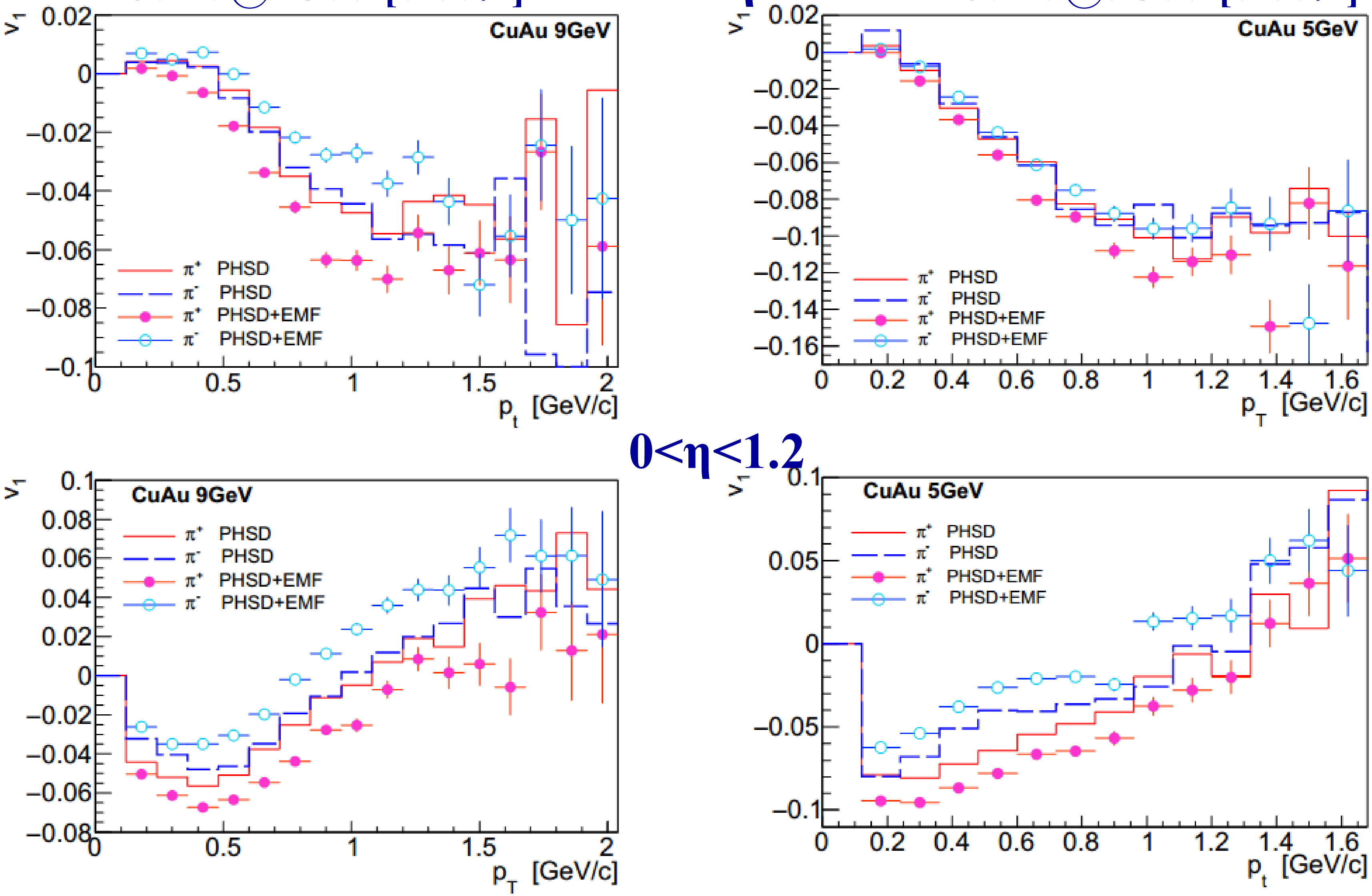
TPC: η<1.2 p_T>0.15 GeV/c



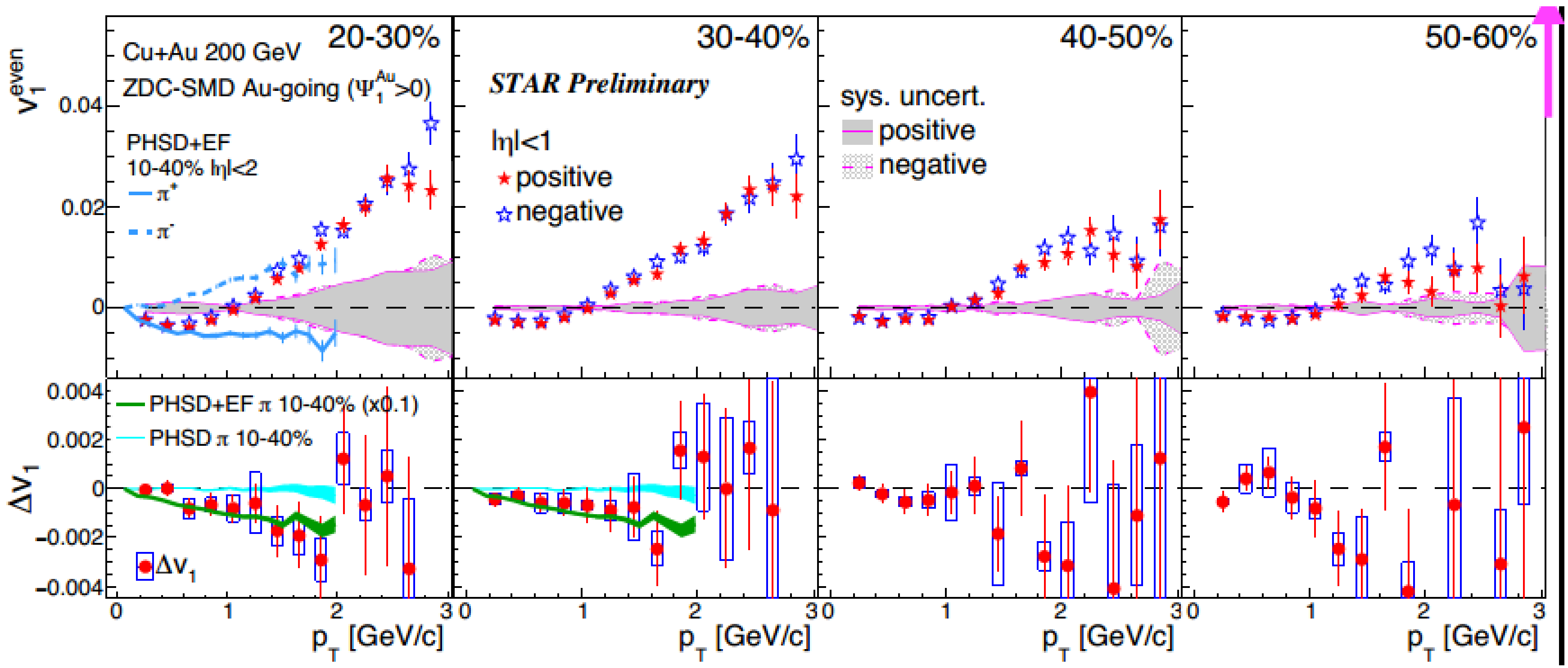
V.Toneev, O.Rogachevsky, V.Voronyk, Contribution to NICA WP (EPJA, 2015)

Charge-dependent p_T distributions at NICA

CuAu@9GeV [0-80%] $-1.2<\eta<0$ CuAu@5GeV [0-80%]



Comparison to STAR data (QM2015-T.Niida)



$\Delta v_1 = v_1(h^+) - v_1(h^-)$, and v_1~1%, Δv_1<0.2%

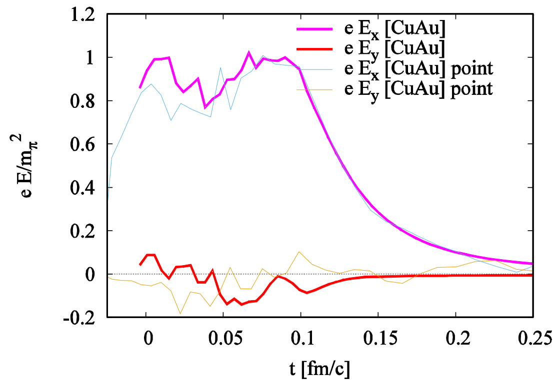
- Δv_1 looks to be negative in p_T<2 GeV/c,
- similar p_T dependence to PHSD model (PRC90.064903), but **smaller by a factor of 10**

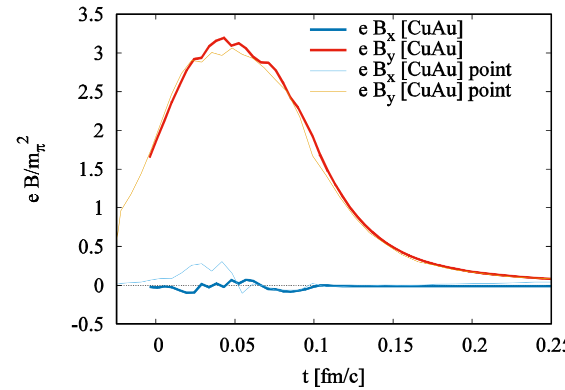
Finite Δv_1 indicates the **existence of E-field**

v_1 splitting -- an electric field puzzle ?

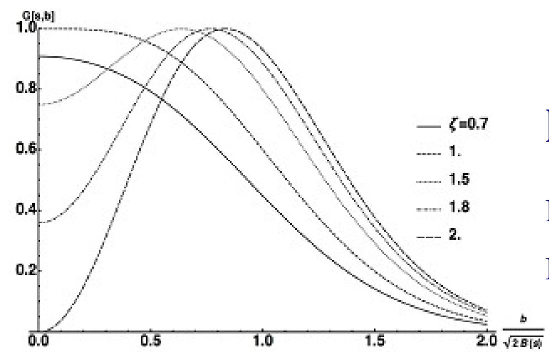
Cu+Au(200) b=7fm (1,0,0)

Coulom singularity. Point-like and ball-like charges (PHSD) ?





Transition to the hollowed toroid-like proton shape (analysis of elastic pp scattering) ?



pp

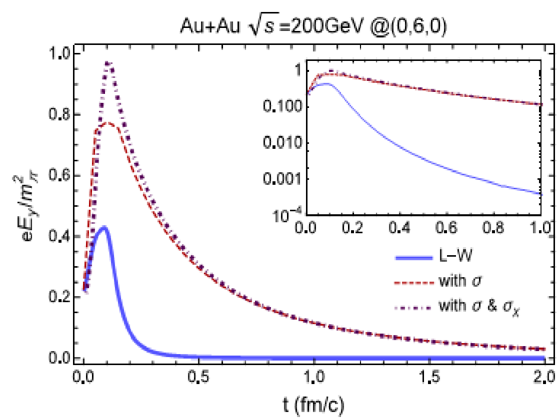
ISR

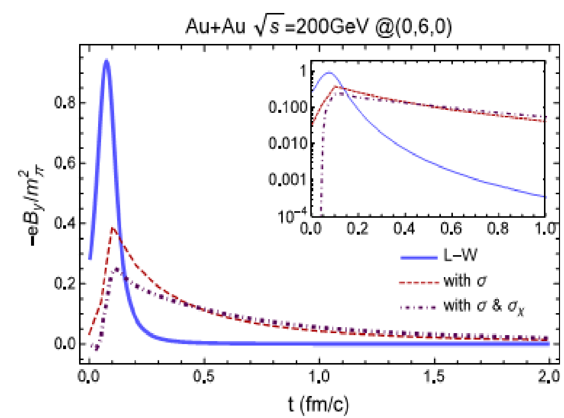
LHC

black disc

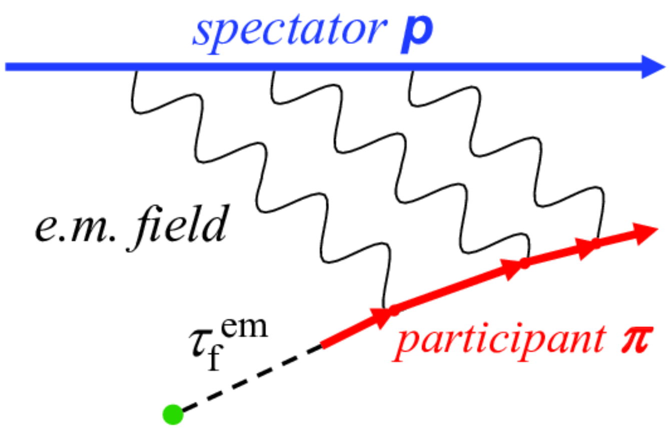
I.M. Dremin, arXiv:1605.08216

Electric σ and chiral σ_χ magnetic conductivity ? (arXiv:1602.02223)



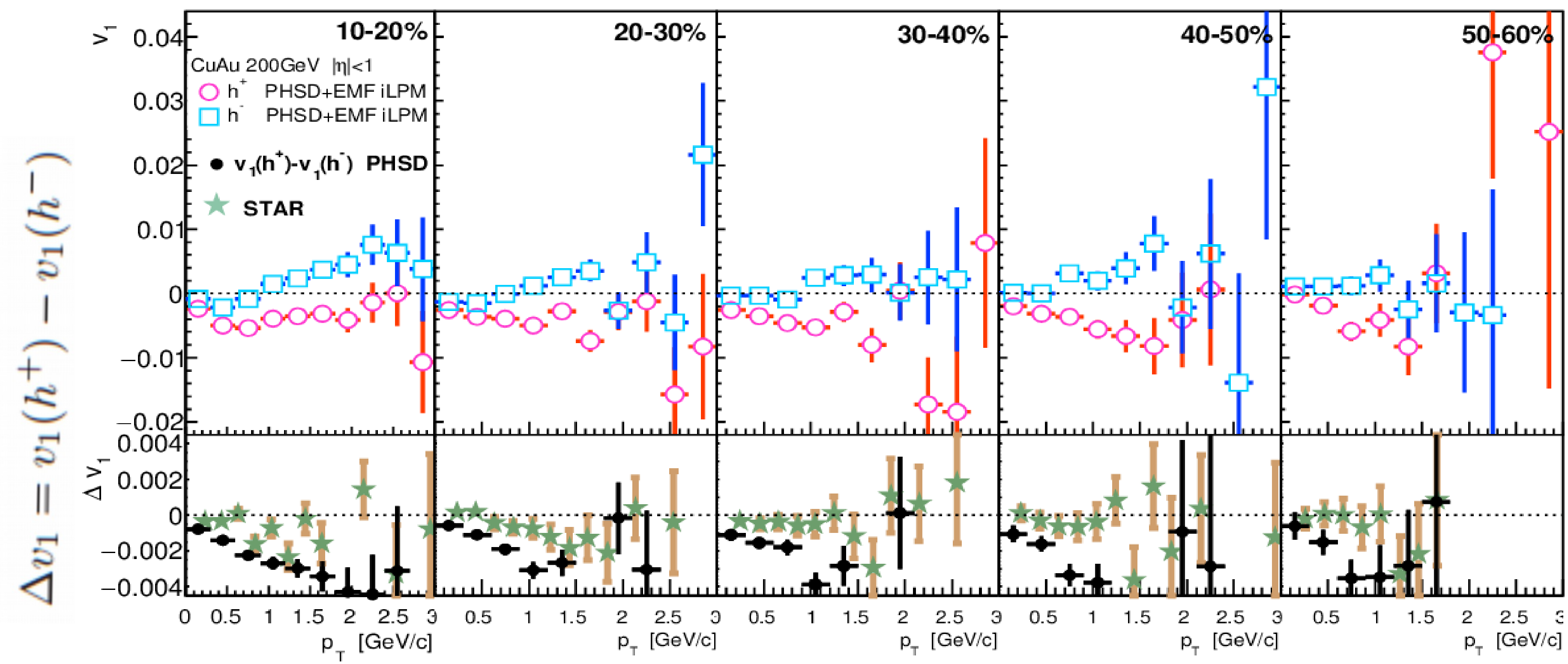


Inverse Landau-Pomeranchuk-Migdal effect

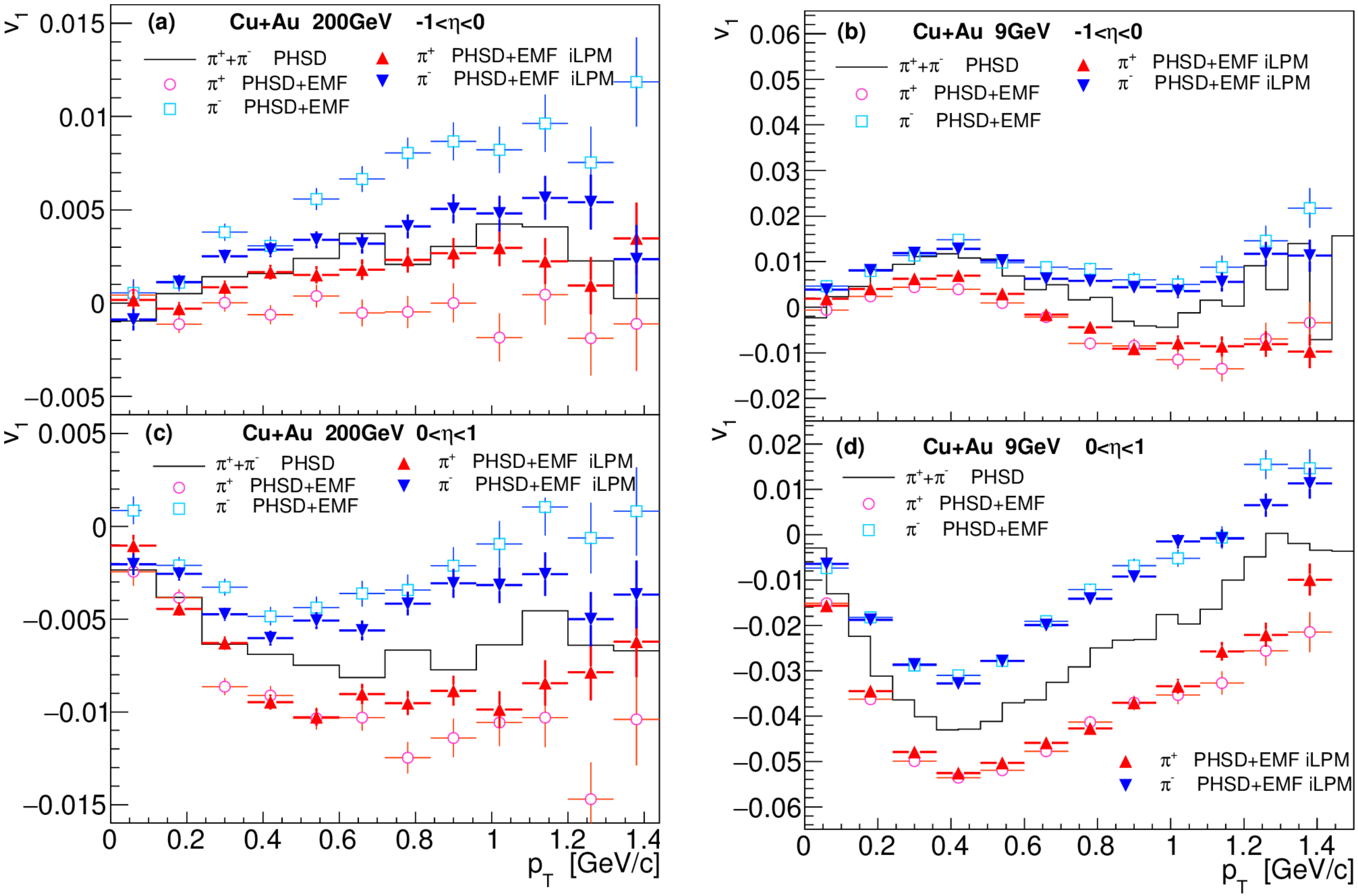


$\tau_f^{em} = (1/10)\ \tau_f \qquad \tau_f = \tau_0 E/m_t$

Electric charge does not feel the EM field only during very short time τ_f^{em}



Inverse Landau-Pomeranchuk-Migdal effect



For NICA the magnitude of flow is much higher + iLPM effect is suppressed.

Conclusions

- The microscopic PHSD approach is generalized to include the creation of electromagnetic (EM) field in heavy-ion collisions, its propagation and influence on the quasiparticle transport. Temporal and spacial distributions of EM fields are investigated.
- It turned out that that global characteristics are practically insensitive to EM effects for collisions of symmetric nuclei. The solution of this puzzle has been found: It is not due too a short interaction time but follows from the compensation effect between electric and magnetic components of the Lorentz force.
- It has been found that for asymmetric colliding systems - like Cu+Au - the directed flow is sensitive to the inclusion of the EM fields resulting in charge-dependent distributions. Observation of charge-dependent splitting of the $v_1(\eta, p_t)$ would evidence on the creation of strong EM fields in HIC.
- PHSD model results compared with the first STAR data at 200 GeV over-estimate the measured directed flow splitting Δv_1 by the factor of about 10. The inverse Landau-Pomeranchuk-Migdal effect which suppresses the influence of the created electric field on the charge motion during a rather short initial part of the particle formation time allows one to reconcile the model results with the experiment.
- New experiments at lower energies (the lowest RHIC and NICA energies) are very needed.

Thank you for your attention

The Dynamical QuasiParticle Model (DQPM)

Basic idea: **Interacting quasiparticles**

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

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

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

- **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

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

$N_c = 3$, $N_f = 3$

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

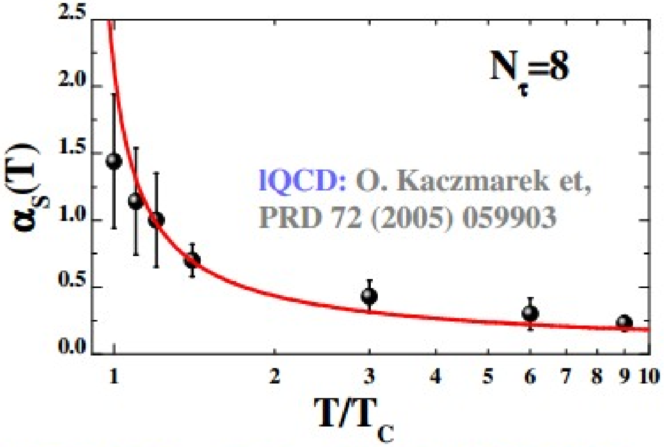
running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

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

➢ **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)

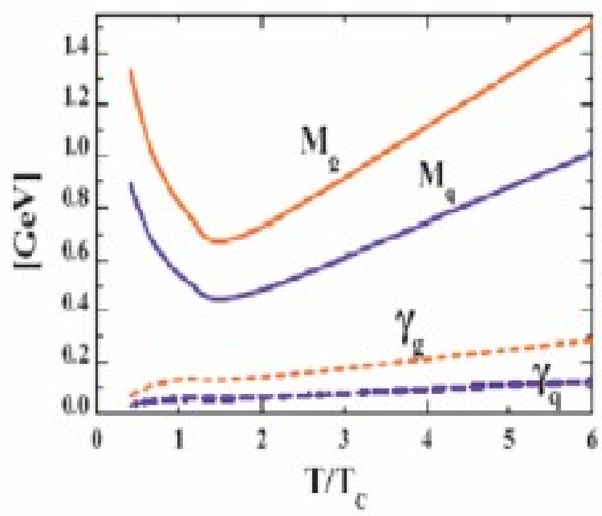


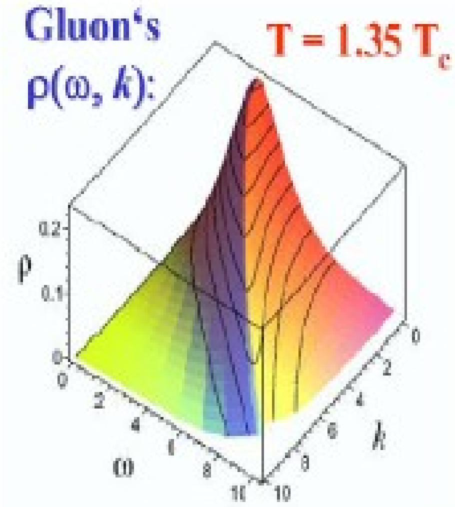
DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

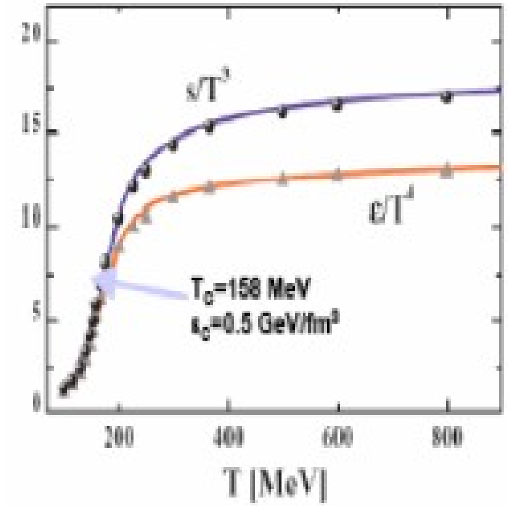
The Dynamical QuasiParticle Model (DQPM)

→ **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)