The 18th International Conference on
Strangeness in Quark Matter

SQM2019

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Collectivity and electromagnetic fields in proton-induced collisions

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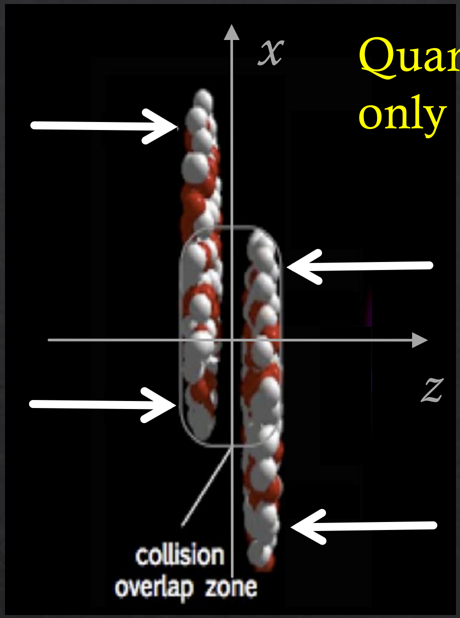
PHSD

Helmholtzzentrum für Schwerionenforschung GmbH

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

Alexander von Humboldt Stiftung/Foundation

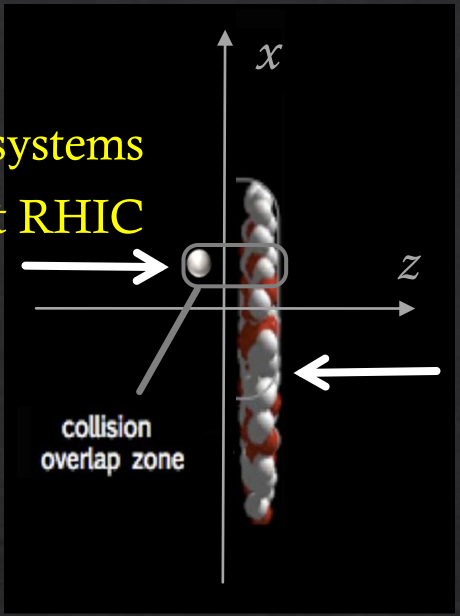


Quark Gluon Plasma (QGP) initially expected
only in high energy Heavy Ion Collisions (HICs)

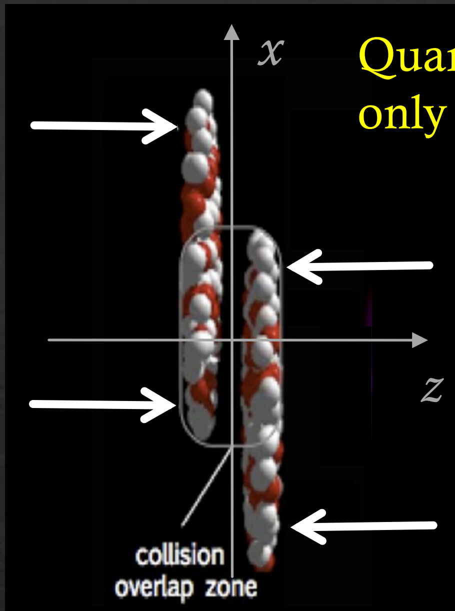
Signatures of collective flow found in small systems

p+Pb collisions at LHC, p/d/^{3}He+Au at RHIC

PHENIX Coll., Nature Phys. 15 (2019) 214



COLLECTIVITY IN SMALL SYSTEMS
AS SIGN OF QGP DROPLETS?



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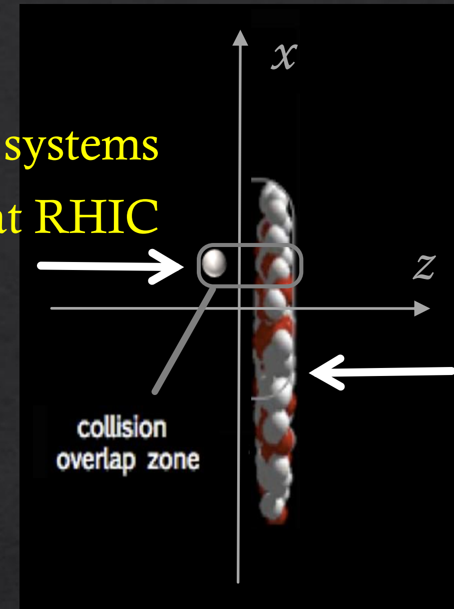
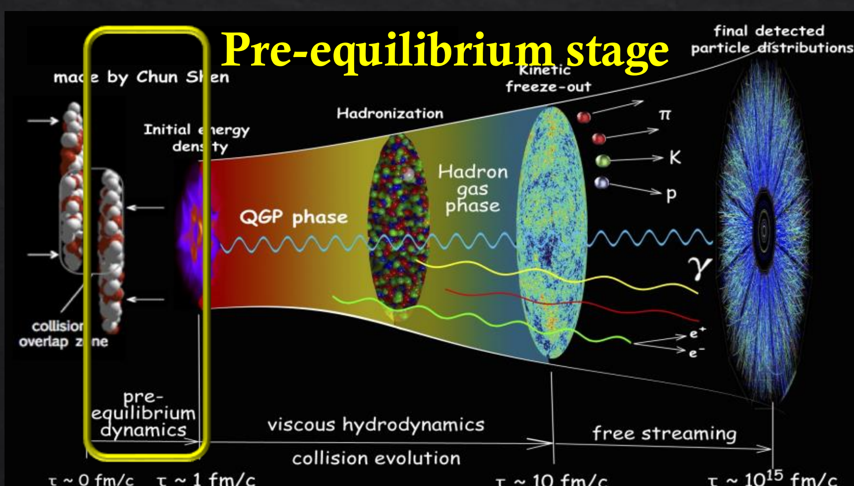


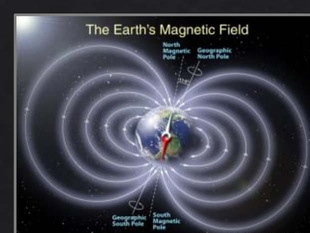
COLLECTIVITY IN SMALL SYSTEMS AS SIGN OF QGP DROPLETS?



Intense ElectroMagnetic Fields (EMF) in HICs

eB_y up to 5-50 m_π^2 ~ 10^{18}-10^{19} G

Kharzeev, McLerran and Warringa, NPA 803 (2008) 227
Skokov, Illarionov and Toneev, IJMPA 24 (2009) 5925



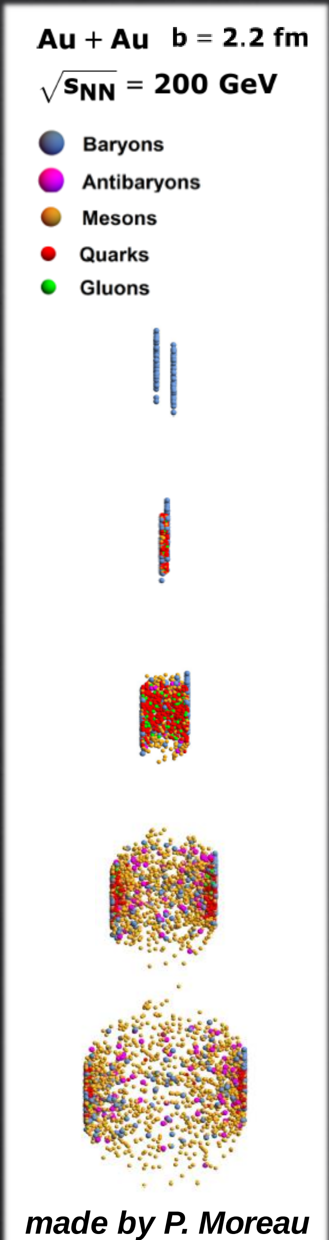
Earth
~ 1 G

laboratory
~ 10^6 G

magnetar
~ 10^{14}-10^{15} G

TRACES OF EMF VISIBLE IN PROTON-INDUCED COLLISIONS?

PHSD: Parton-Hadron-String Dynamics



A consistent non-equilibrium transport approach to describe large and small colliding systems

To study the phase transition from hadronic to partonic matter and QGP properties from a microscopic origin

- INITIAL A+A COLLISIONS: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons
- FORMATION OF QGP: if the energy density is above ε_C pre-hadrons dissolve in massive quarks and gluons + mean-field potential
- QGP STAGE: evolution based on off-shell transport eqs. derived by Kadanoff-Baym eqs. with the Dynamical Quasi-Particle Model (DQPM) defining parton spectral functions, i.e. masses and widths
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryon and mesons
- HADRONIC PHASE: evolution based on the off-shell transport equations with hadron-hadron interactions

Cassing and Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215
Cassing, EPJ ST 168 (2009) 3; NPA856 (2011) 162

PHSD + electromagnetic fields

PHSD includes the dynamical formation and evolution of the retarded electomagnetic field (EMF) and its influence on quasi-particle dynamics

$$\left\{\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{p_0} + \nabla_{\mathbf{p}} U\right)\nabla_{\mathbf{r}} + (-\nabla_{\mathbf{r}} U + e\mathbf{E} + e\mathbf{v} \times \mathbf{B})\nabla_{\mathbf{p}}\right\} f = C_{\mathrm{coll}}(f, f_1, \ldots, f_N)$$

Lorentz force

TRANSPORT EQUATIONS

consistent solution of particle and field evolution equations

charge distribution

electric current

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{E} = 4\pi\rho \qquad \nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

MAXWELL EQUATIONS

Voronyuk *et al.*, PRC 83 (2011) 054911
Toneev *et al.*, PRC 95 (2017) 034911

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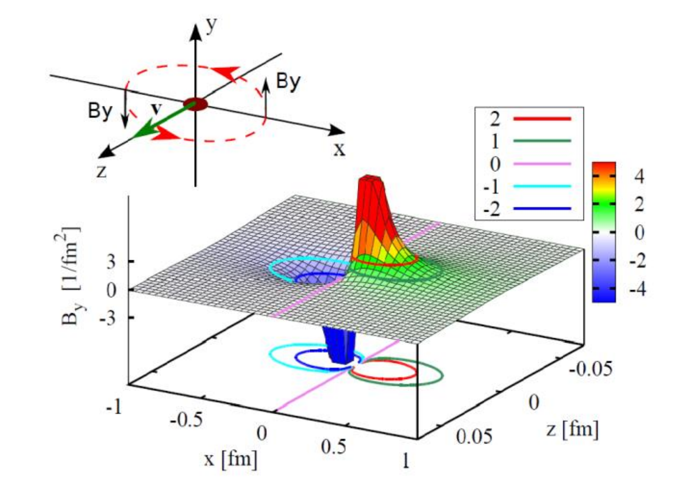
MAXWELL EQUATIONS

$$e\mathbf{E}(t,\mathbf{r}) = \alpha_{em}\frac{1-\beta^2}{\left[(\mathbf{R}\cdot\boldsymbol{\beta})^2 + R^2(1-\beta^2)\right]^{3/2}}\mathbf{R}$$

$$e\mathbf{B}(t,\mathbf{r}) = \boldsymbol{\beta}\times e\mathbf{E}(t,\mathbf{r})$$

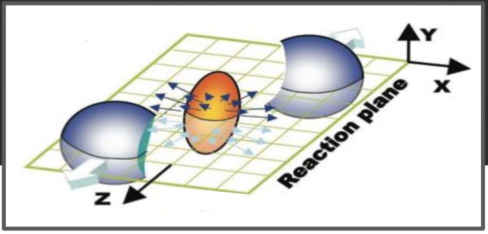
single freely moving charge



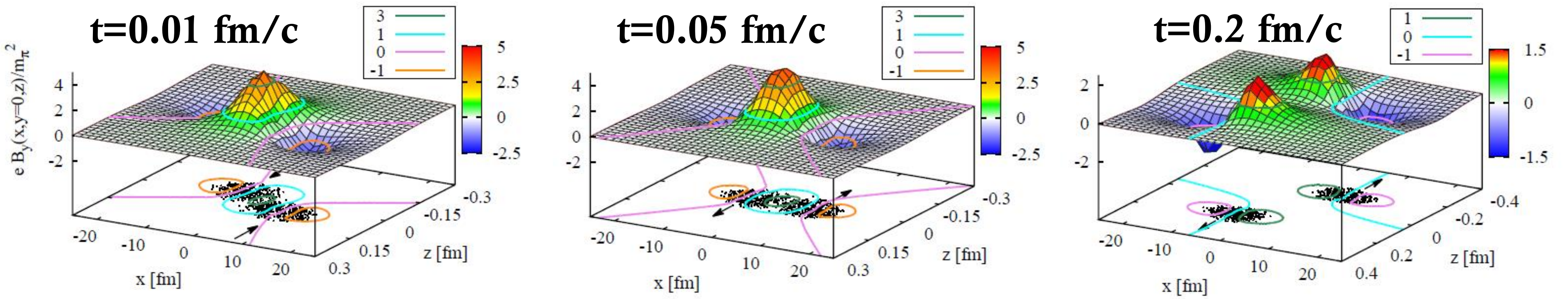
Voronyuk *et al.*, PRC 83 (2011) 054911
Toneev *et al.*, PRC 95 (2017) 034911

electromagnetic fields in HICs

in a nuclear collision the magnetic field is a superposition
of solenoidal fields from different moving charges



Au+Au @RHIC 200 GeV – b = 10 fm



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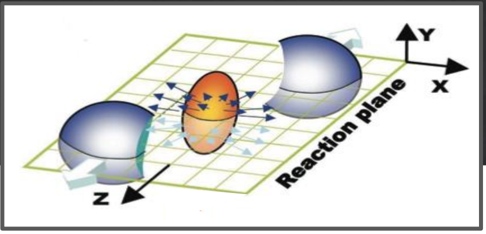

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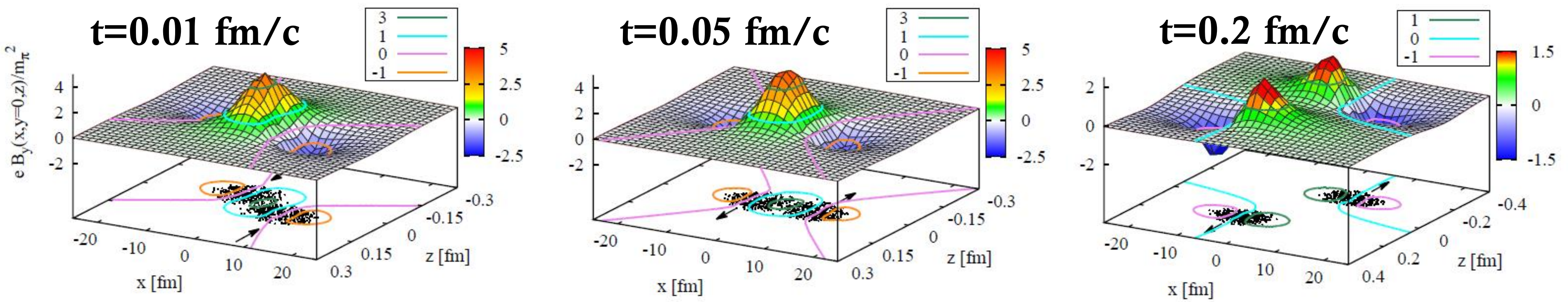
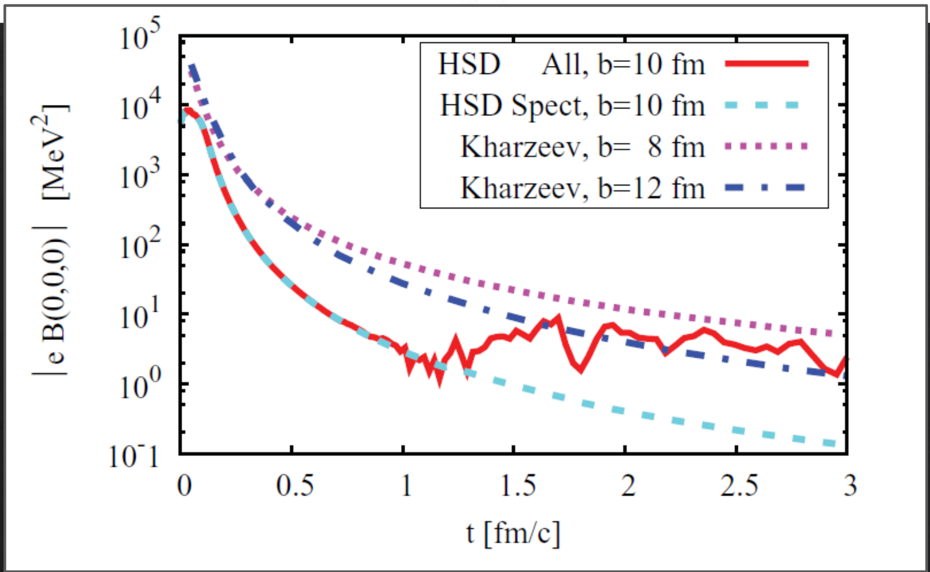


MAGNETIC FIELD

- ❖ dominated by the y-component
- ❖ maximal strength reached during nuclear overlapping time
- ❖ only due to spectators up to $t \sim 1$ fm/c
- ❖ drops down by three orders of magnitude and become comparable with that from participants



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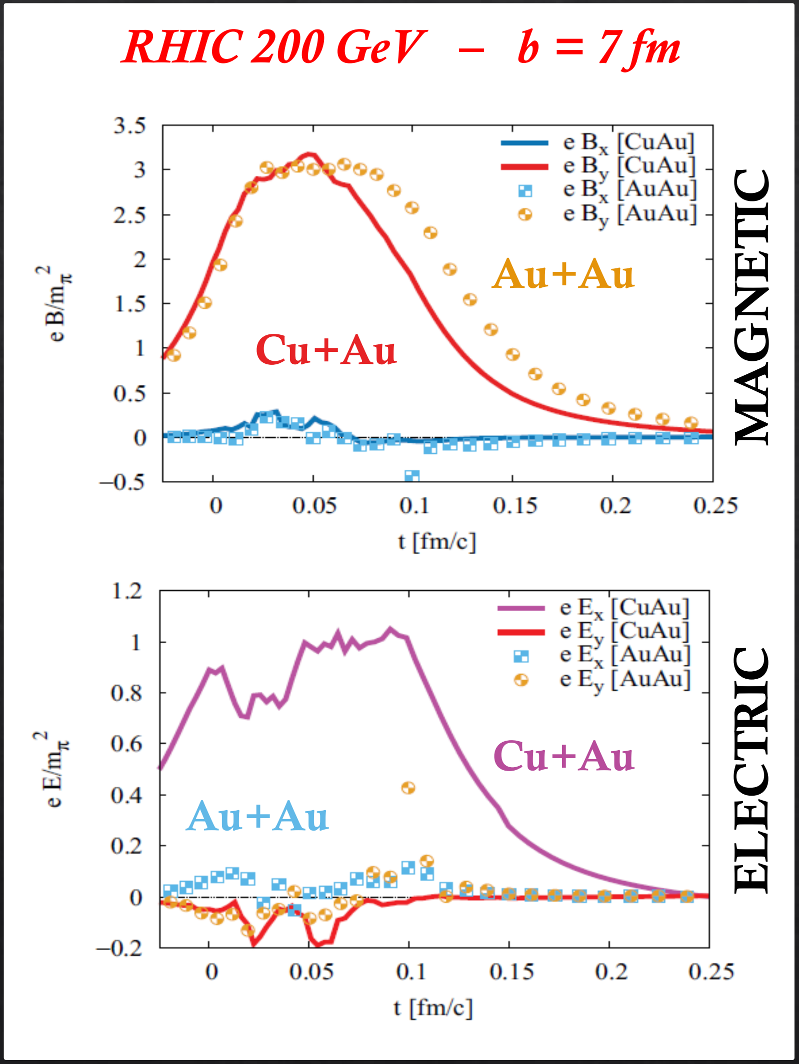
electromagnetic fields in HICs

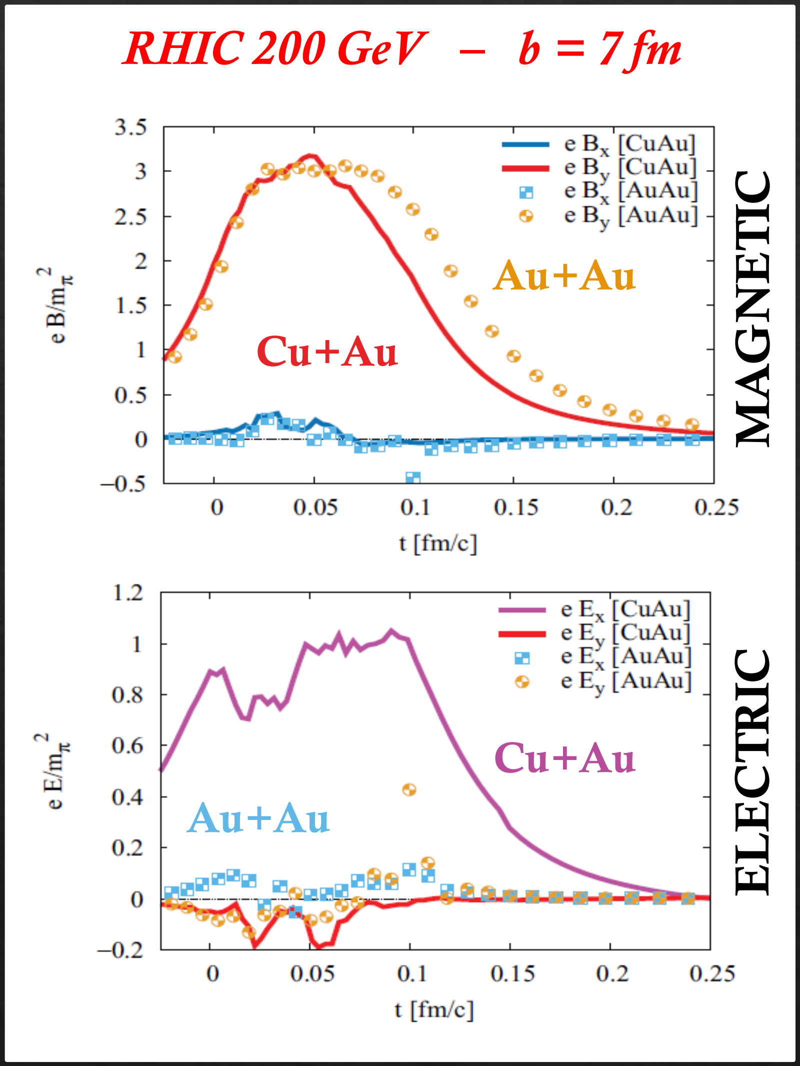


Voronyuk *et al*. (PHSD), PRC 90, 064903 (2014)

✓ SYMMETRIC SYSTEMS (e.g. Au+Au)
transverse momentum increments due to electric and magnetic fields compensate each other

✓ ASYMMETRIC SYSTEMS (e.g. Cu+Au)
an intense electric fields directed from the heavy nuclei to light one appears in the overlap region

electromagnetic fields in HICs



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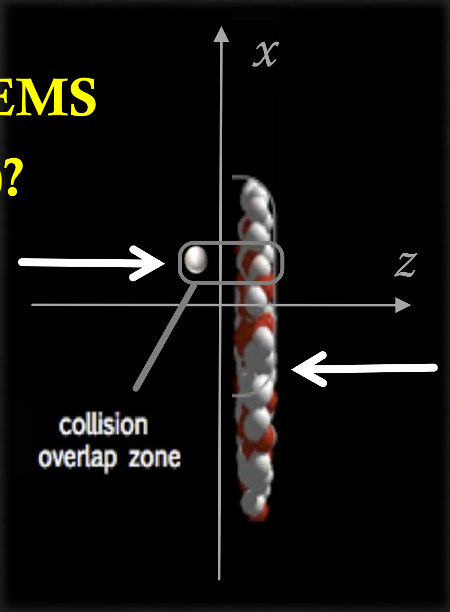
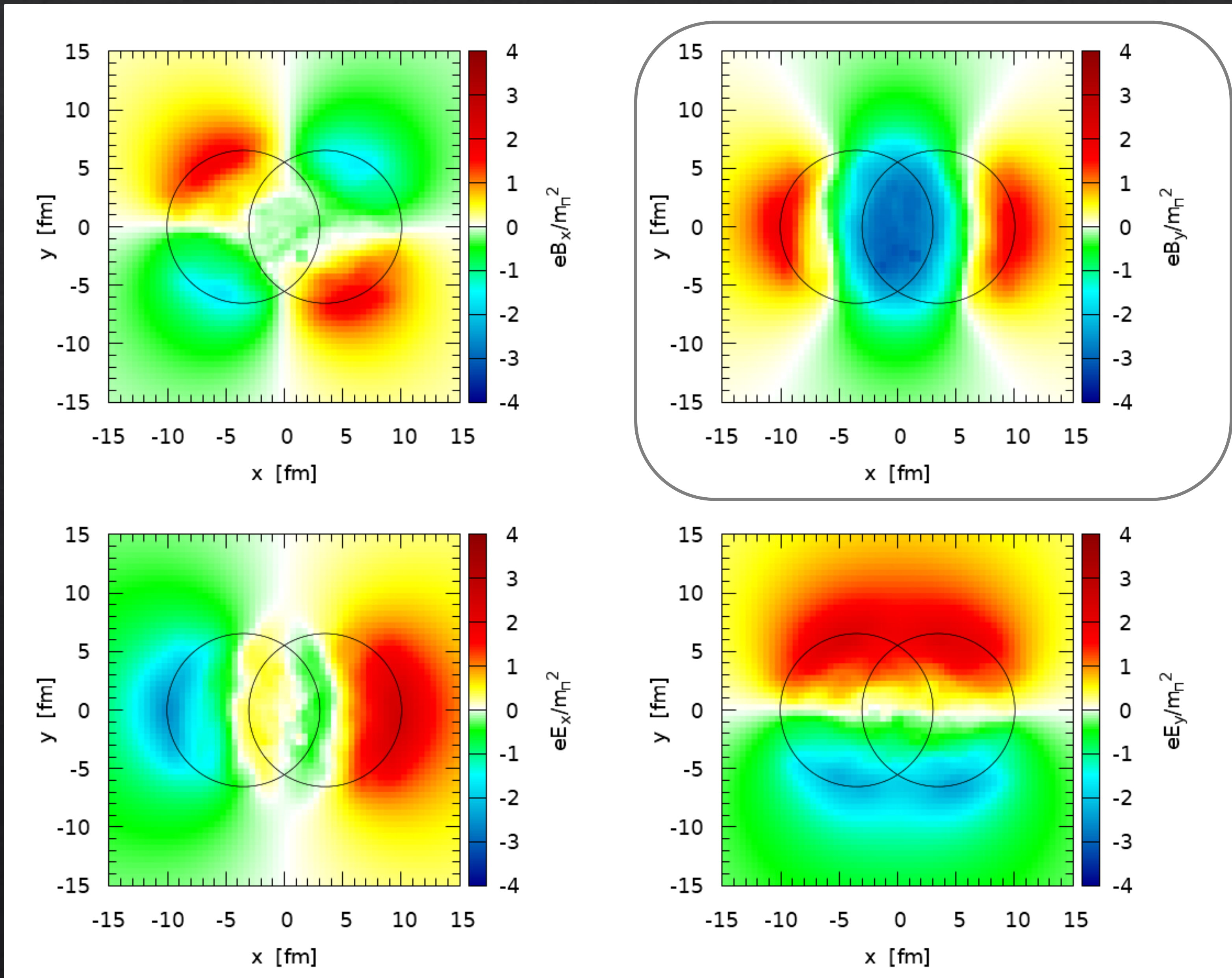
SMALL SYSTEMS (e.g. p+Au)?



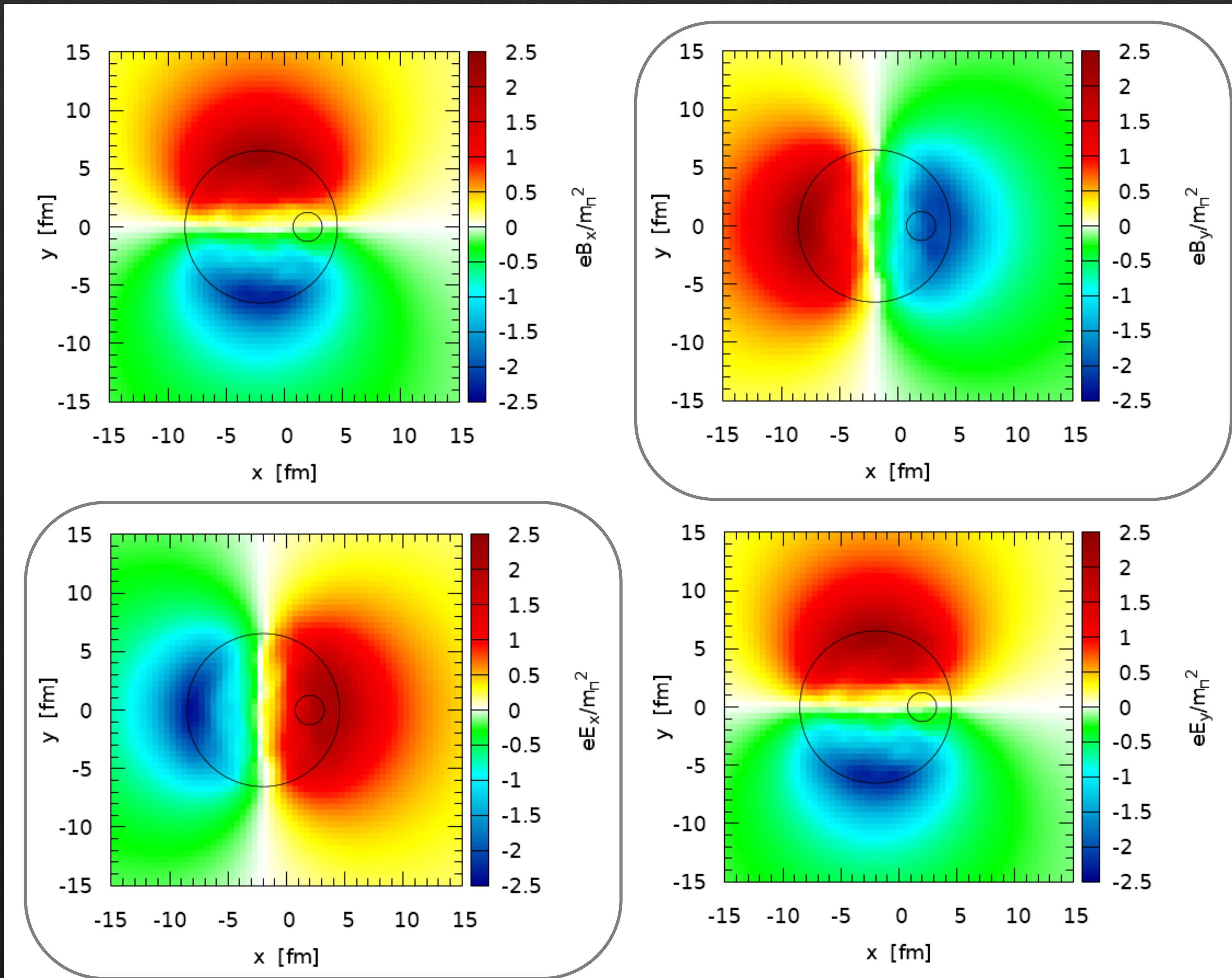
Au+Au collisions @RHIC 200GeV b=7 fm



MAGNETIC FIELD

ELECTRIC FIELD

p+Au collisions @RHIC 200GeV b=4 fm

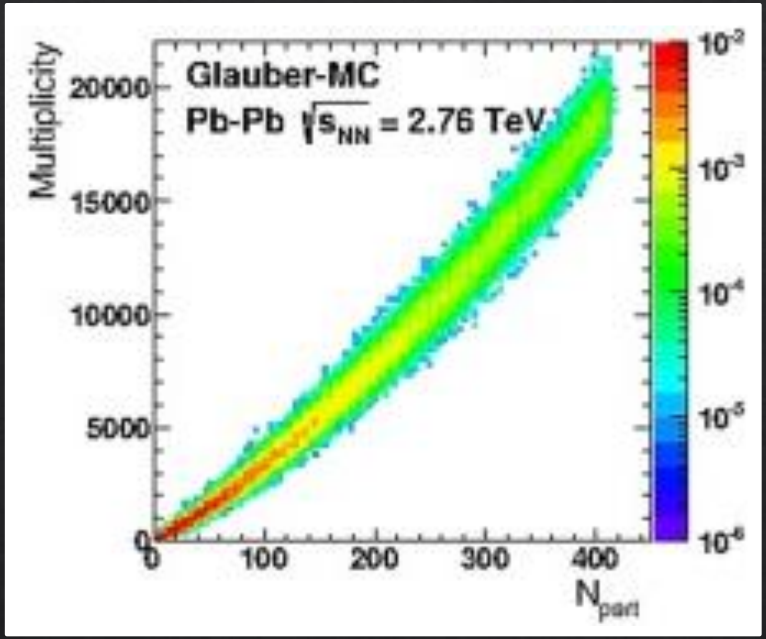


MAGNETIC FIELD

ELECTRIC FIELD

Centrality in small systems

In heavy ion collisions centrality characterizes the amount of overlap or size of the fireball in the collision region



ALICE, NPA 932 (2014) 399

Correlation between participant number and charged particle multiplicity at midrapidity

Centrality in small systems

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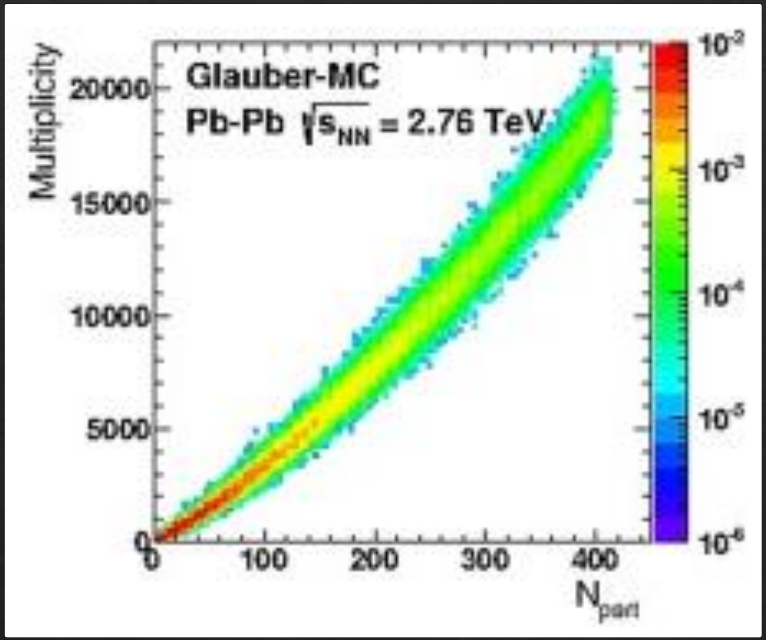
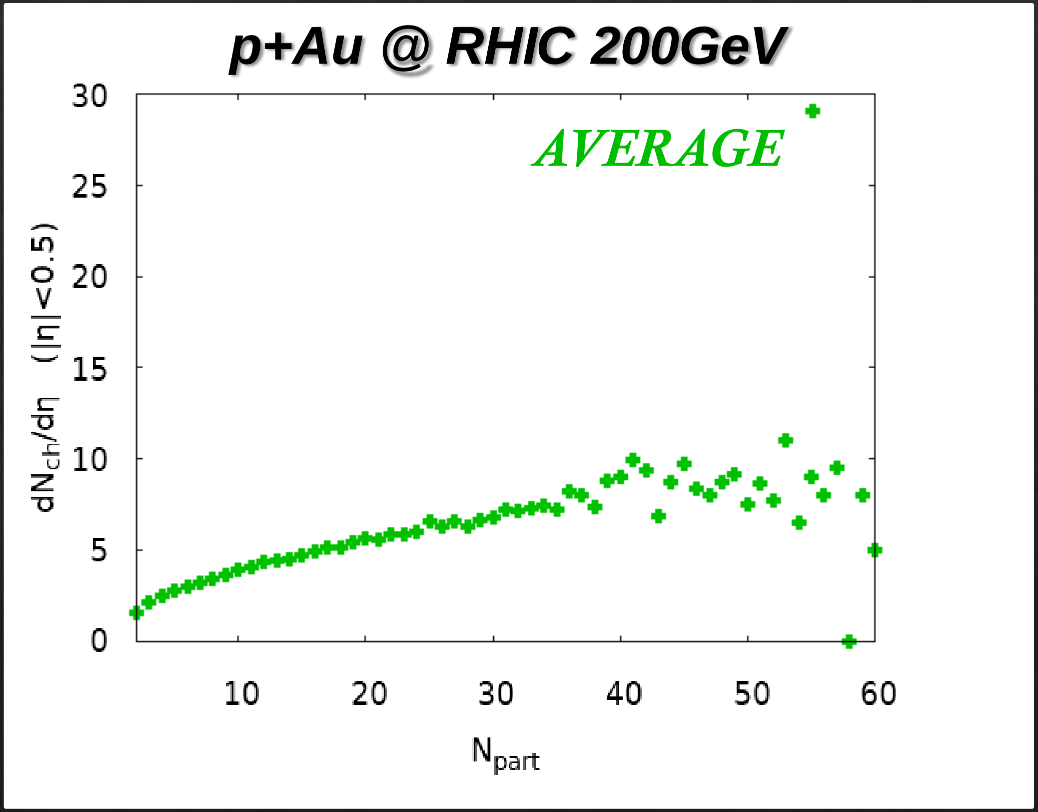


ALICE, NPA 932 (2014) 399



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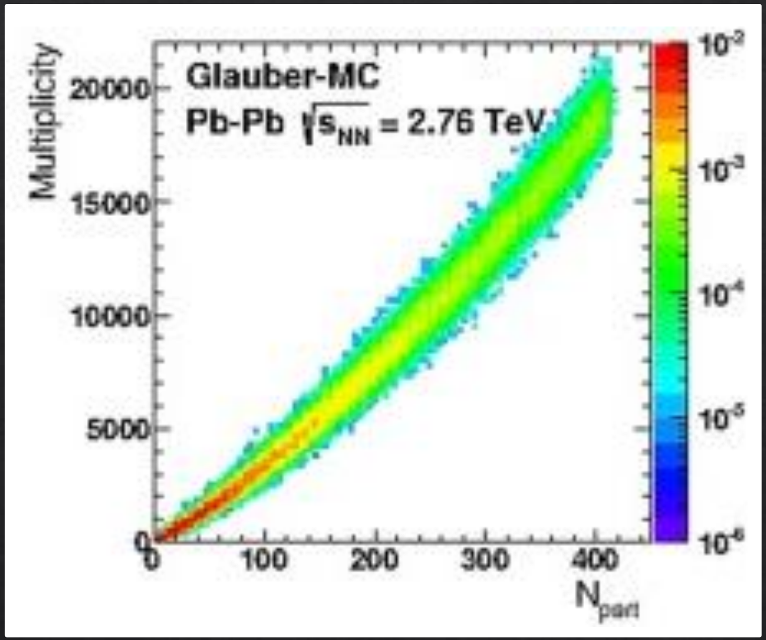

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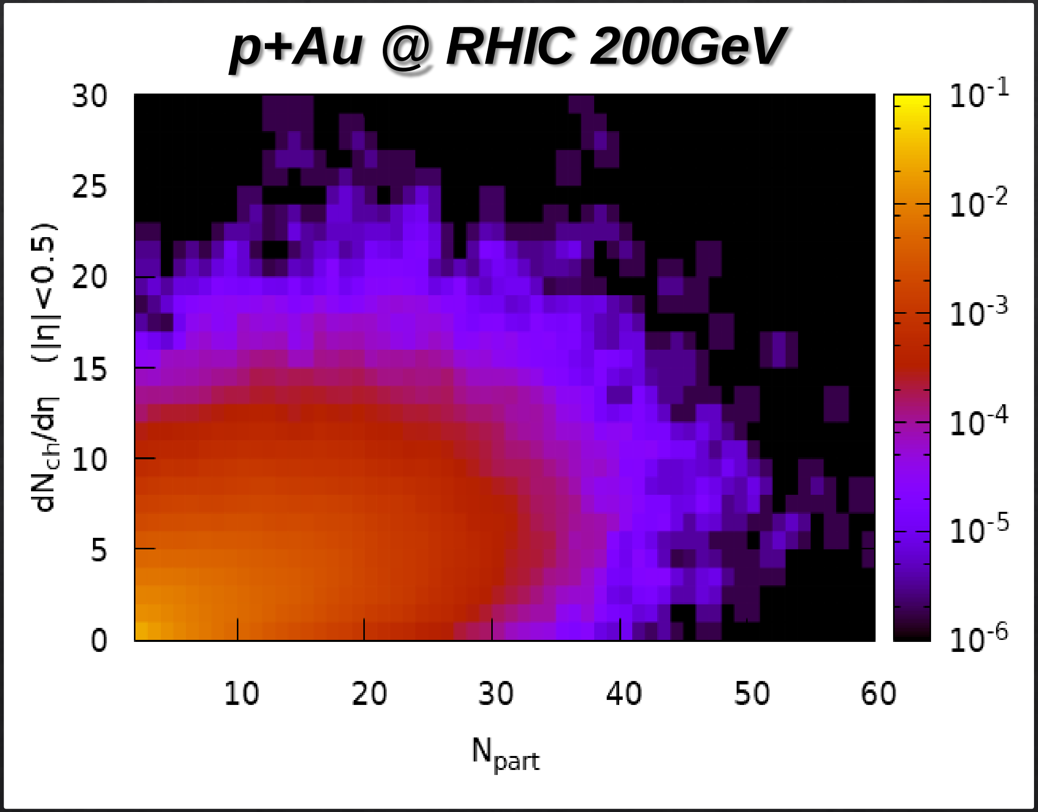
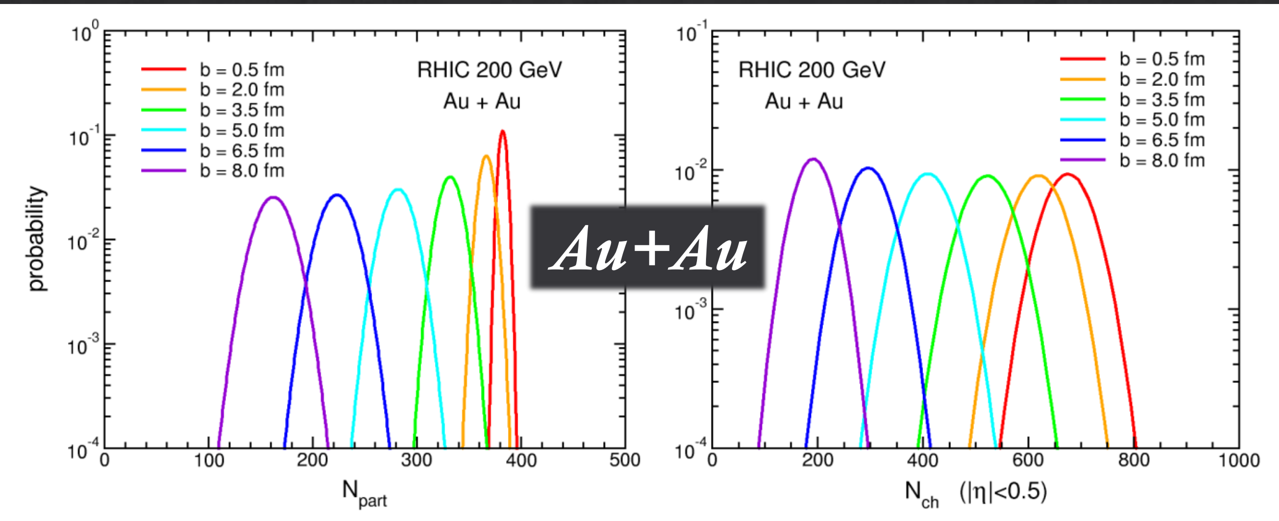


Correlation between participant number and charged particle multiplicity at midrapidity

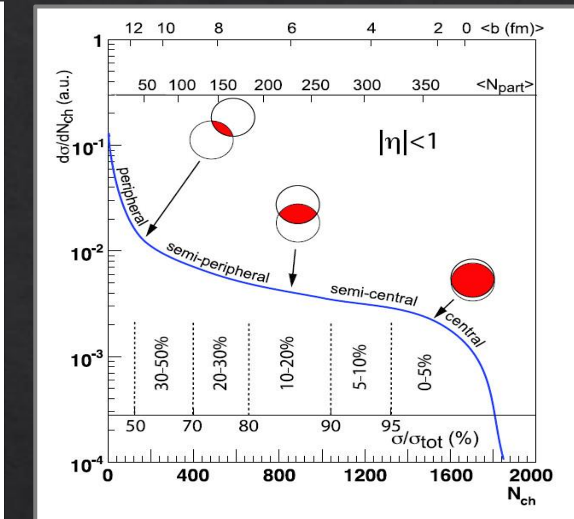
BUT

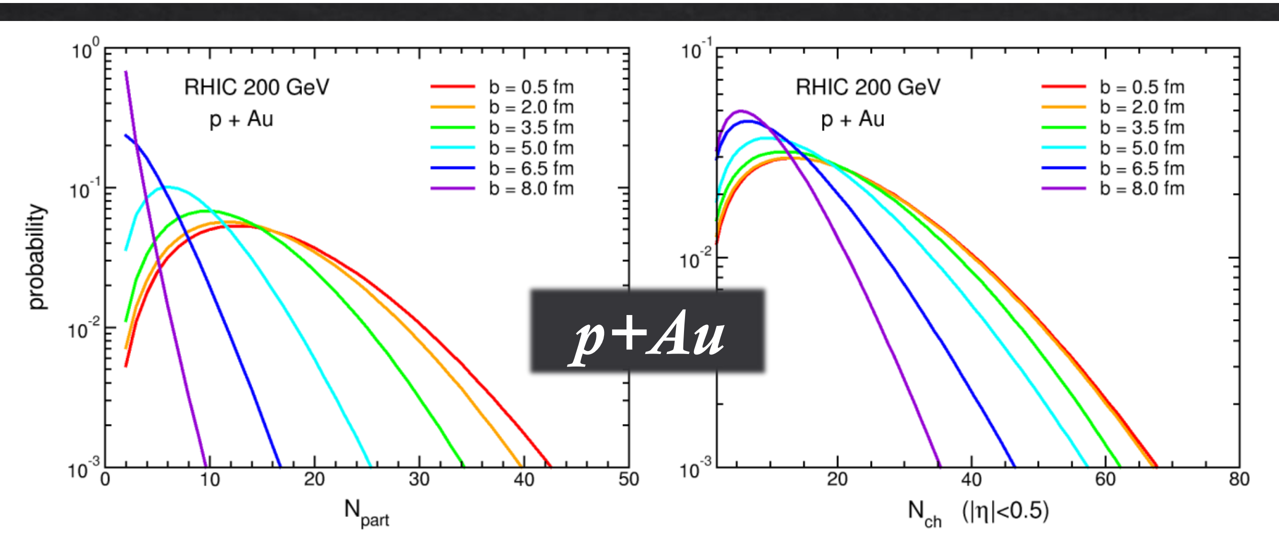
large dispersion in both quantities in p+A respect to A+A collisions

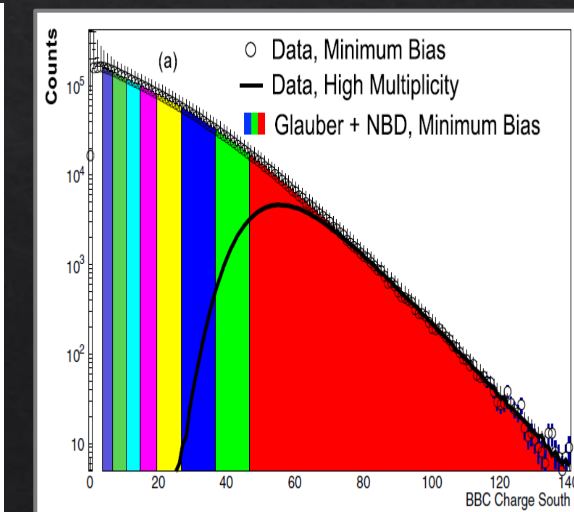
Centrality in small systems



Miller *et al.*, ARNPS 57 (2007) 205





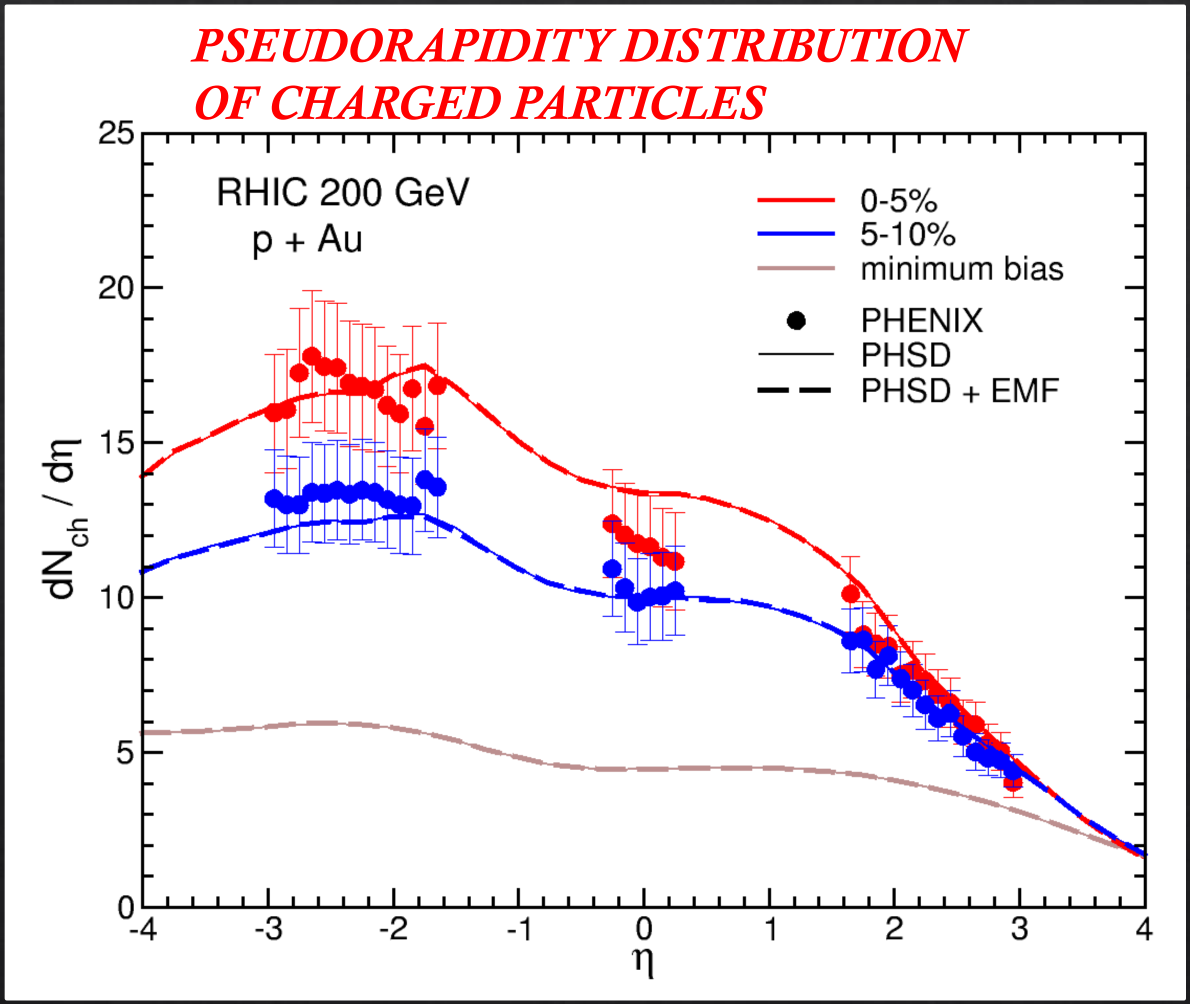


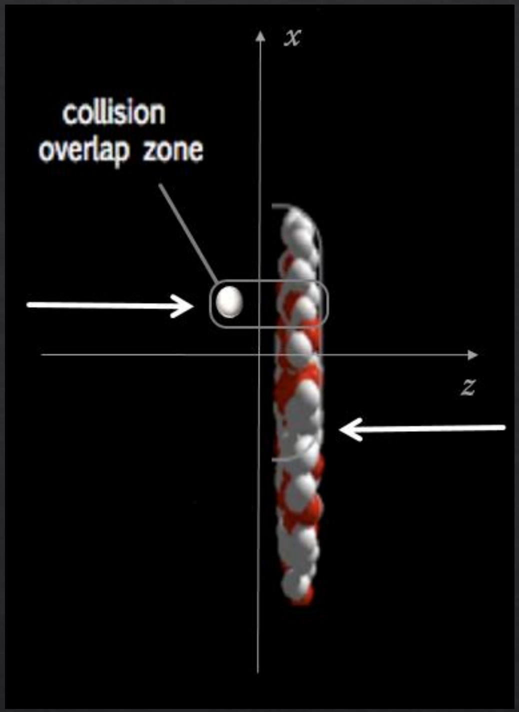
PHENIX, PRC 95 (2017) 034910

Multiplicity fluctuation in the final state mixes events from different impact parameters!

p+Au collisions @ RHIC 200 GeV

Exp. Data: PHENIX Collaboration, PRL 121 (2018) 222301



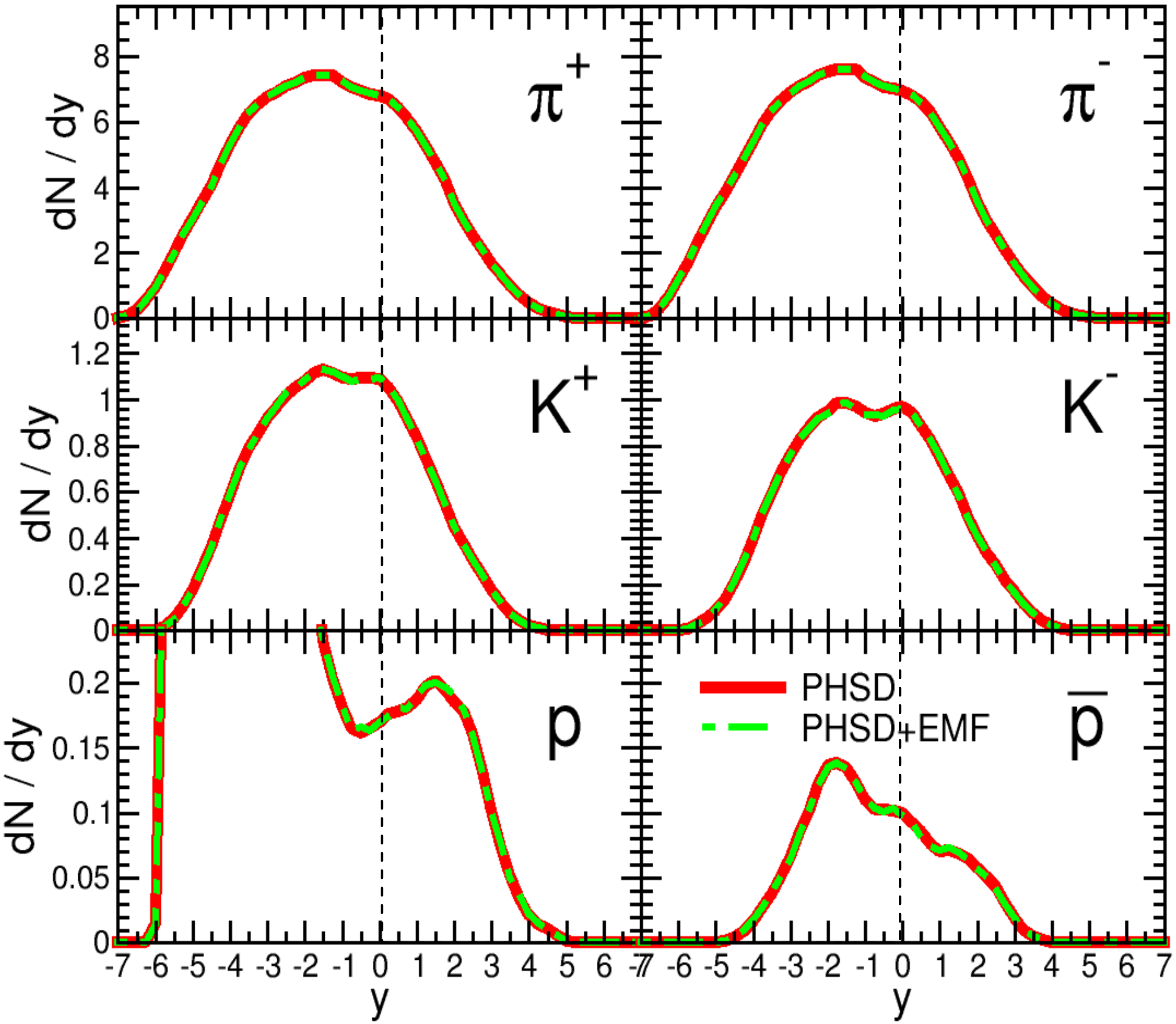


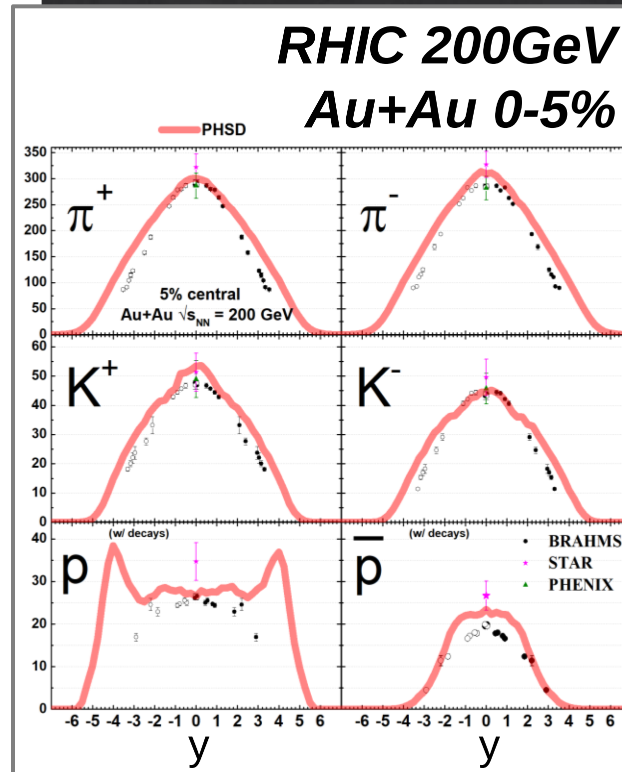
- enhanced particle production in the Au-going directions
- asymmetry increases with centrality of the collision

p+Au collisions @ RHIC 200 GeV

RAPIDITY DISTRIBUTION OF IDENTIFIED PARTICLES

RHIC 200GeV
p+Au 0-5%



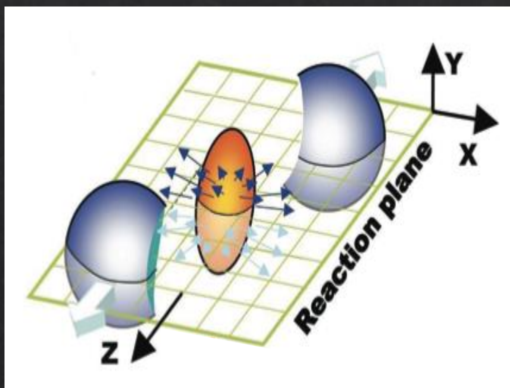


symmetric colliding system

Anisotropic radial flow

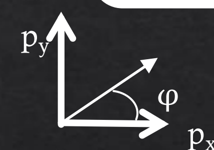
A DEEPER INSIGHT…INITIAL-STATE FLUCTUATIONS

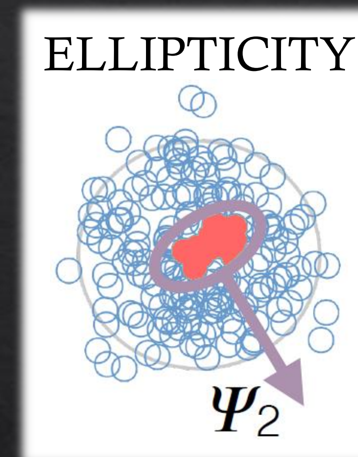
Not a simple **almond shape**
- ➢ odd harmonics = 0



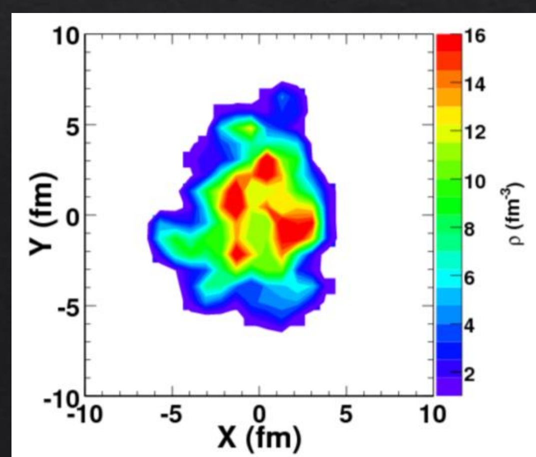
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty}v_n(p_T,y)\cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

$$v_n=\left\langle\cos\left(n\left(\phi-\Psi_r\right)\right)\right\rangle$$

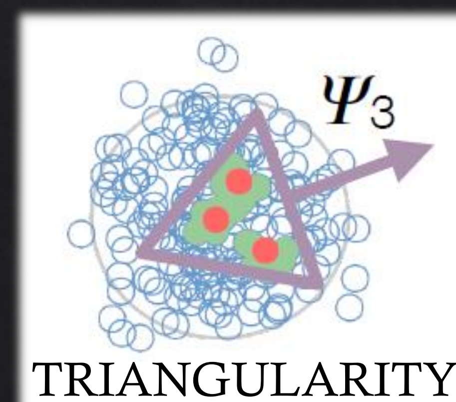




But a **"lumpy" profile due to fluctuations** of nucleon position in the overlap region
- ➢ odd harmonics ≠ 0



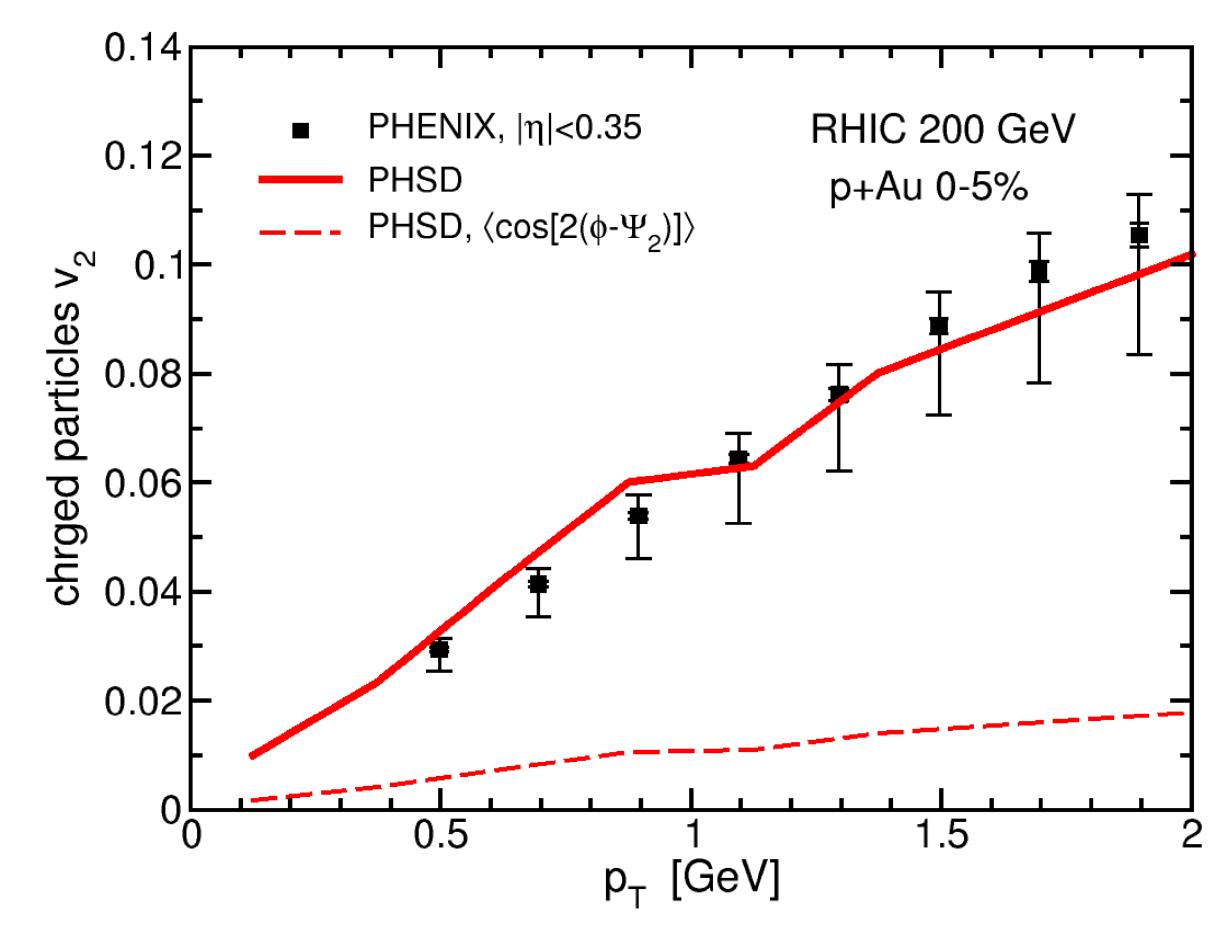
Plumari et al., PRC 92 (2015) 054902



p+Au collisions @ RHIC 200 GeV

ELLIPTIC FLOW OF CHARGED PARTICLES

$$v_2(p_T) = \frac{\langle\cos[2(\varphi(p_T) - \Psi_2)]\rangle}{Res(\Psi_2)}$$



Event-plane angle in $-3 < \eta < -1$:
$Res(\Psi_2^{PHSD}) = 0.175$
$Res(\Psi_2^{PHENIX}) = 0.171$

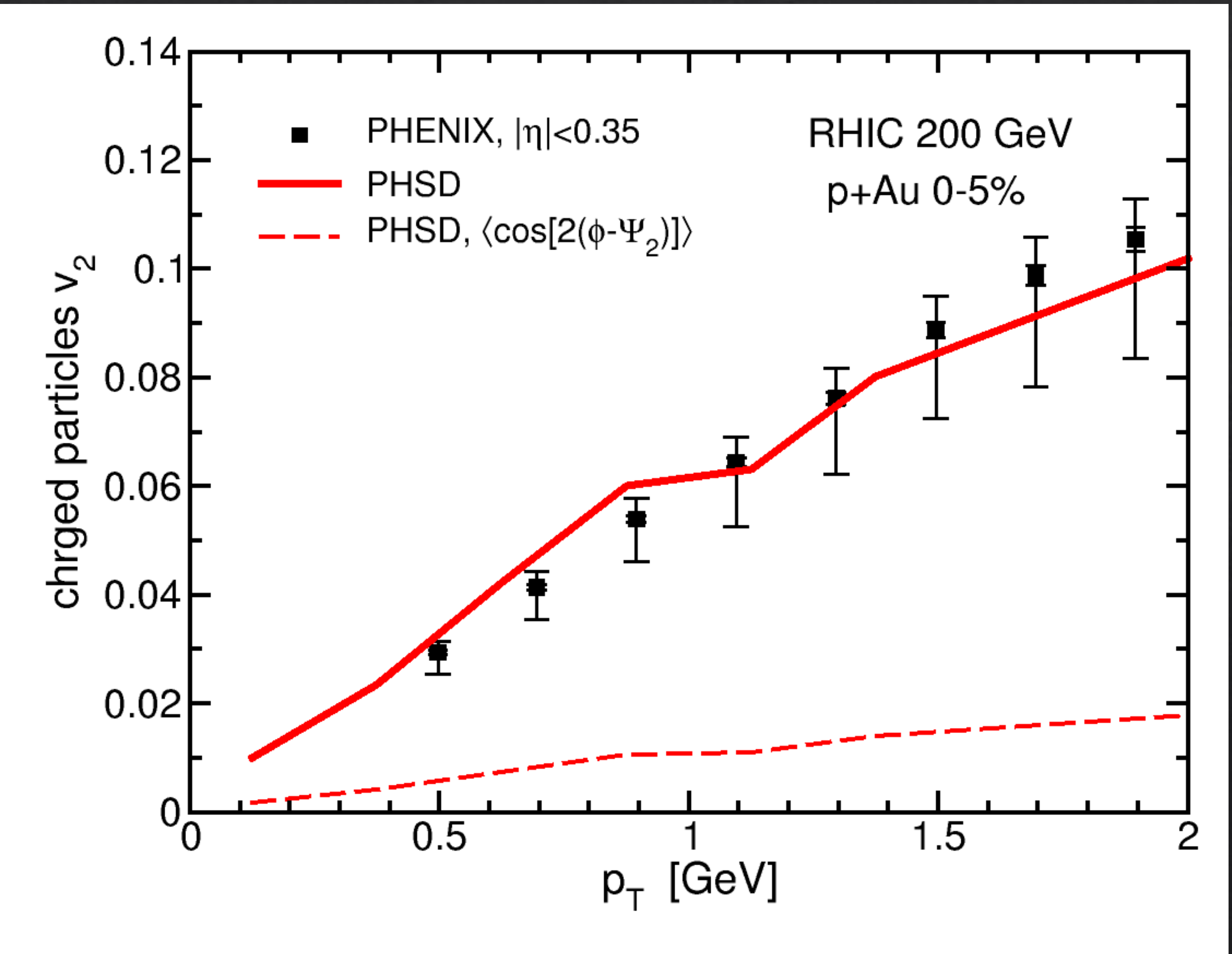
- magnitude correlated with the determination of the reaction plane
- comparable to that found in collisions between heavy nuclei
- indicate the formation of short-lived droplets of quark-gluon plasma

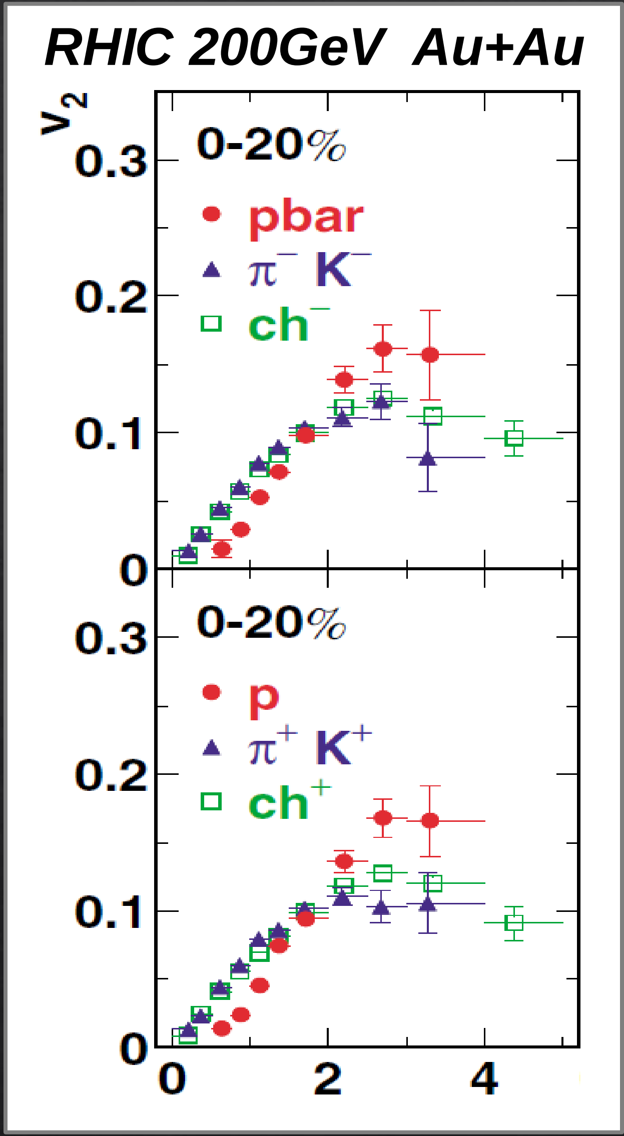
Exp. data: Aidala et al. (PHENIX Collaboration), PRC 95 (2017) 034910

p+Au collisions @ RHIC 200 GeV

PHENIX, PRL 91 (2003) 182301

ELLIPTIC FLOW OF CHARGED PARTICLES





Exp. data: Aidala et al. (PHENIX Collaboration), PRC 95 (2017) 034910

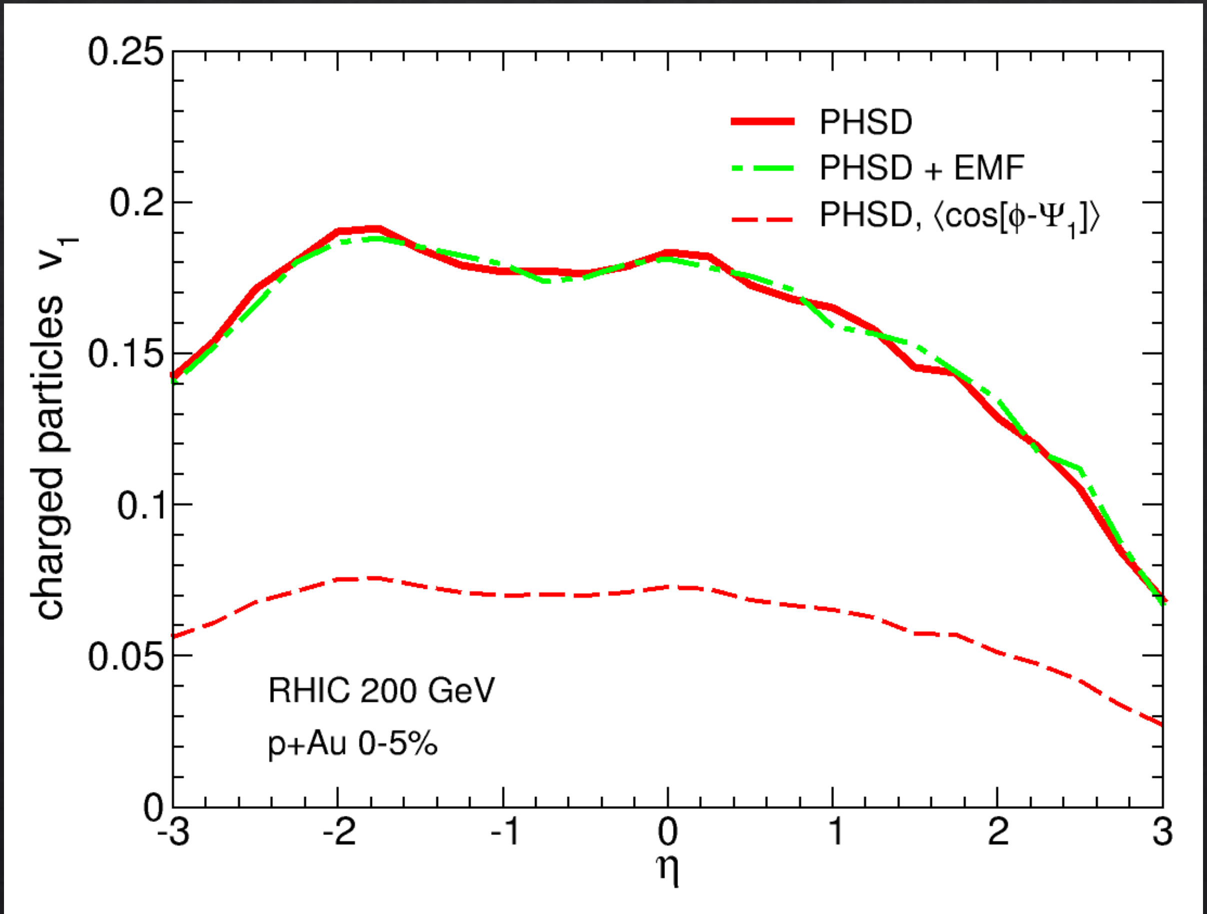
p+Au collisions @ RHIC 200 GeV

PRELIMINARY

pseudorapidity dependence of the DIRECTED FLOW OF CHARGED PARTICLES

$$v_1(\eta) = \frac{\langle \cos[\varphi(\eta) - \Psi_1] \rangle}{Res(\Psi_1)}$$

Event-plane angle in $-4 < \eta < -3$: $Res\left(\Psi_1^{PHSD}\right) = 0.397$

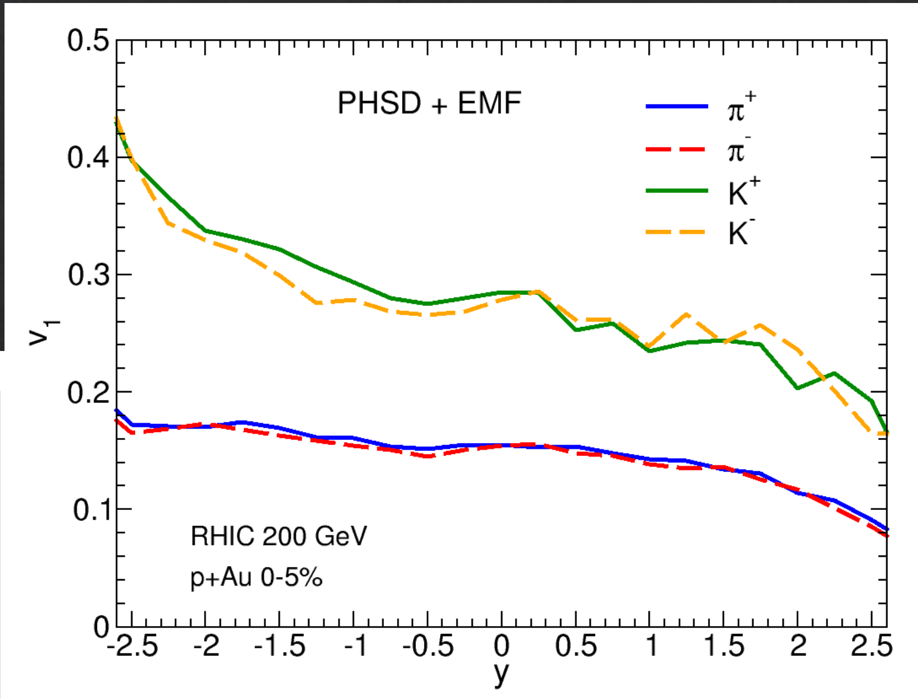


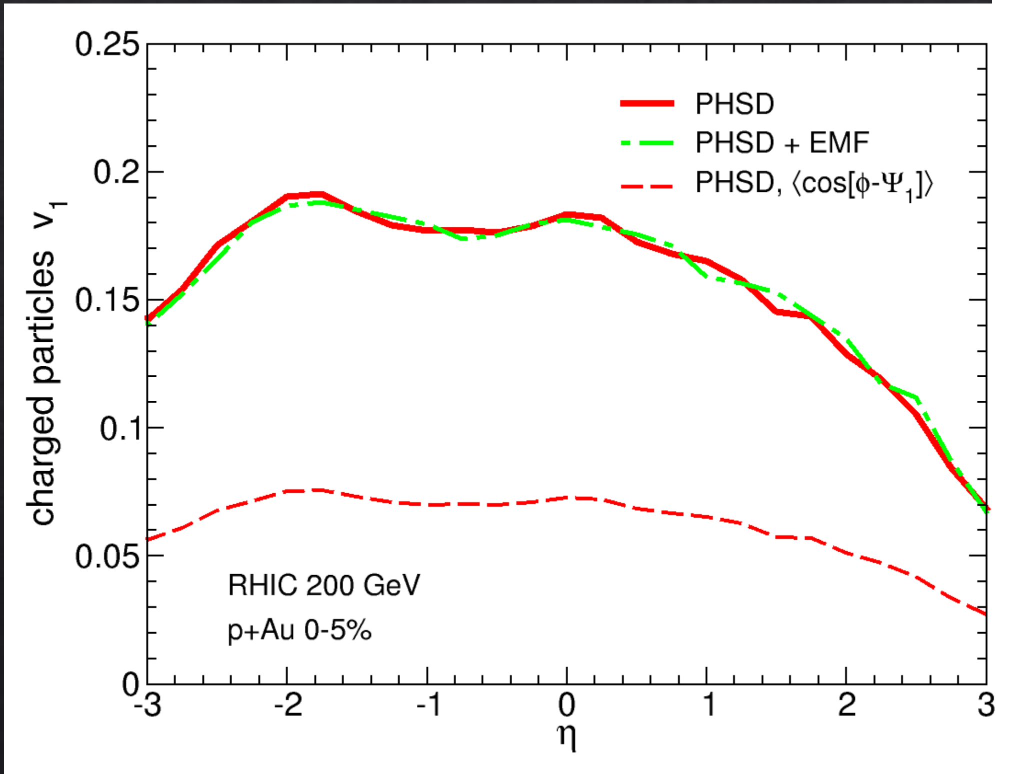
- magnitude correlated with the determination of the reaction plane
- dominated by initial-state fluctuations

p+Au collisions @ RHIC 200 GeV

PRELIMINARY

pseudorapidity dependence of the
DIRECTED FLOW OF
IDENTIFIED PARTICLES





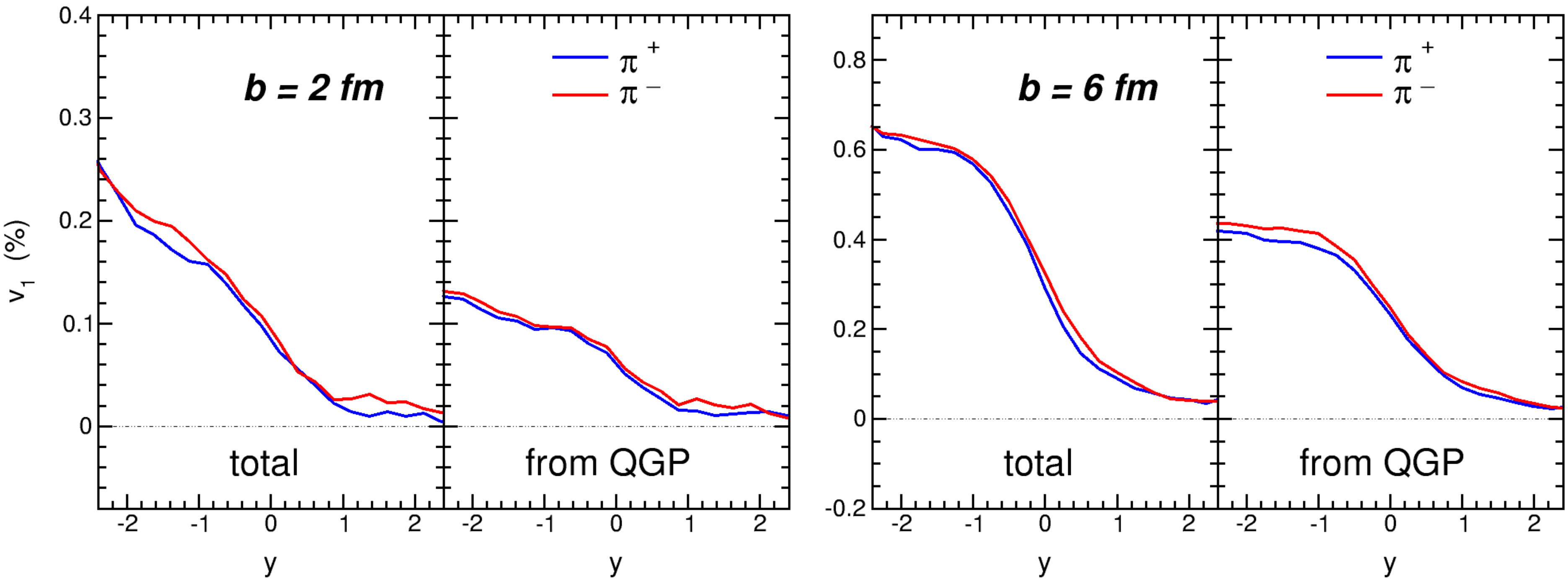
- splitting of positively and negatively charged particles induced by the electromagnetic field?
- NO visible splitting in $v_1(y)$ in 0-5% most central collisions

p+Au collisions @ RHIC 200 GeV

rapidity dependence of the
DIRECTED FLOW OF PIONS

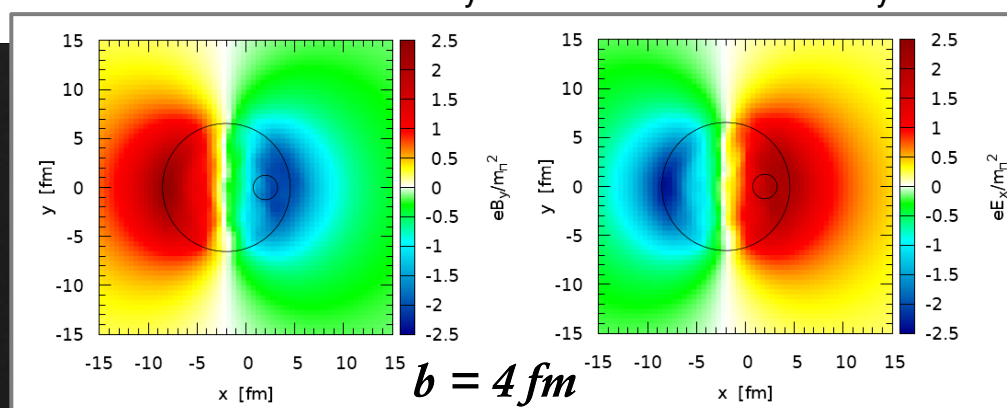
PRELIMINARY

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



Splitting of π^+ and π^- induced by electric and magnetic field

increasing magnitude with impact parameter



p+Au collisions @ RHIC 200 GeV

rapidity dependence of the
DIRECTED FLOW OF PIONS

PRELIMINARY

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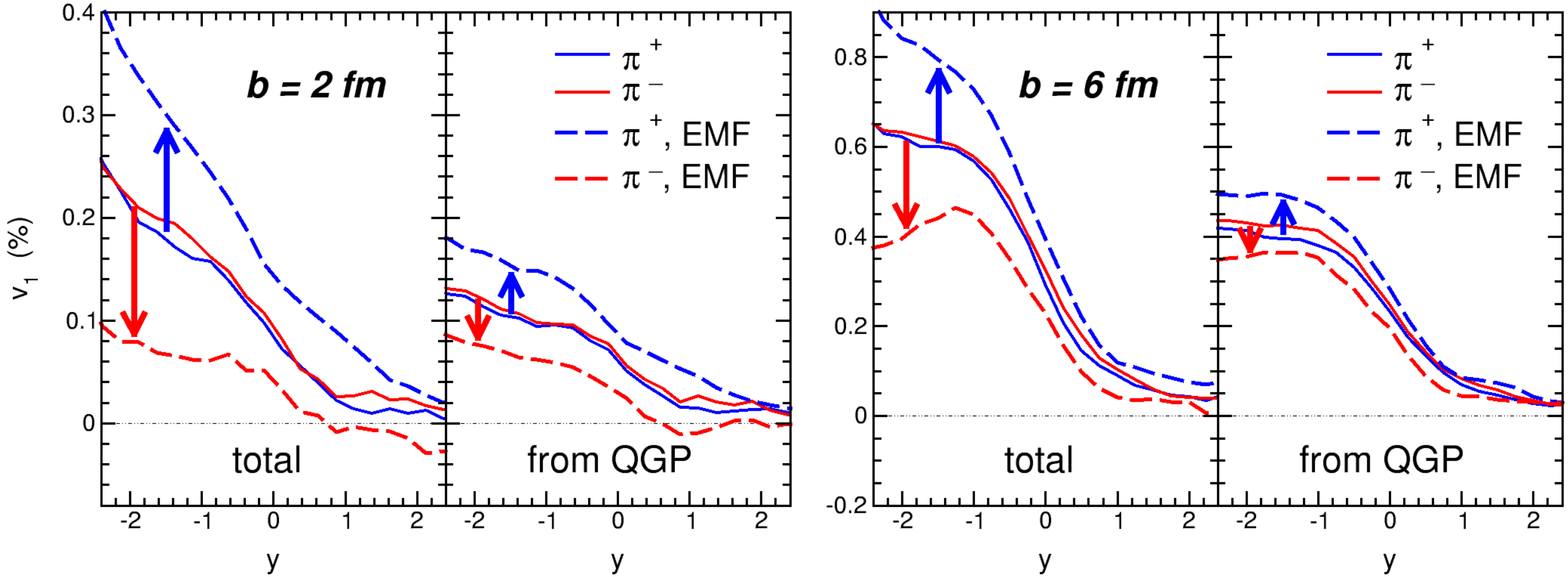

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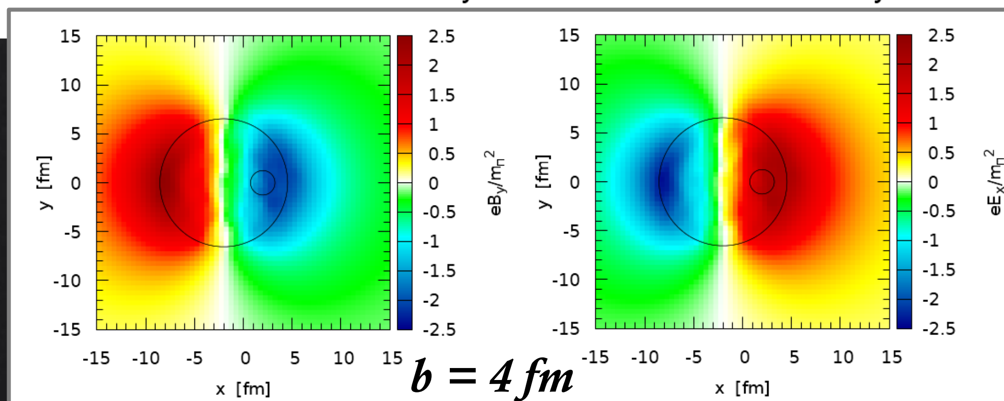
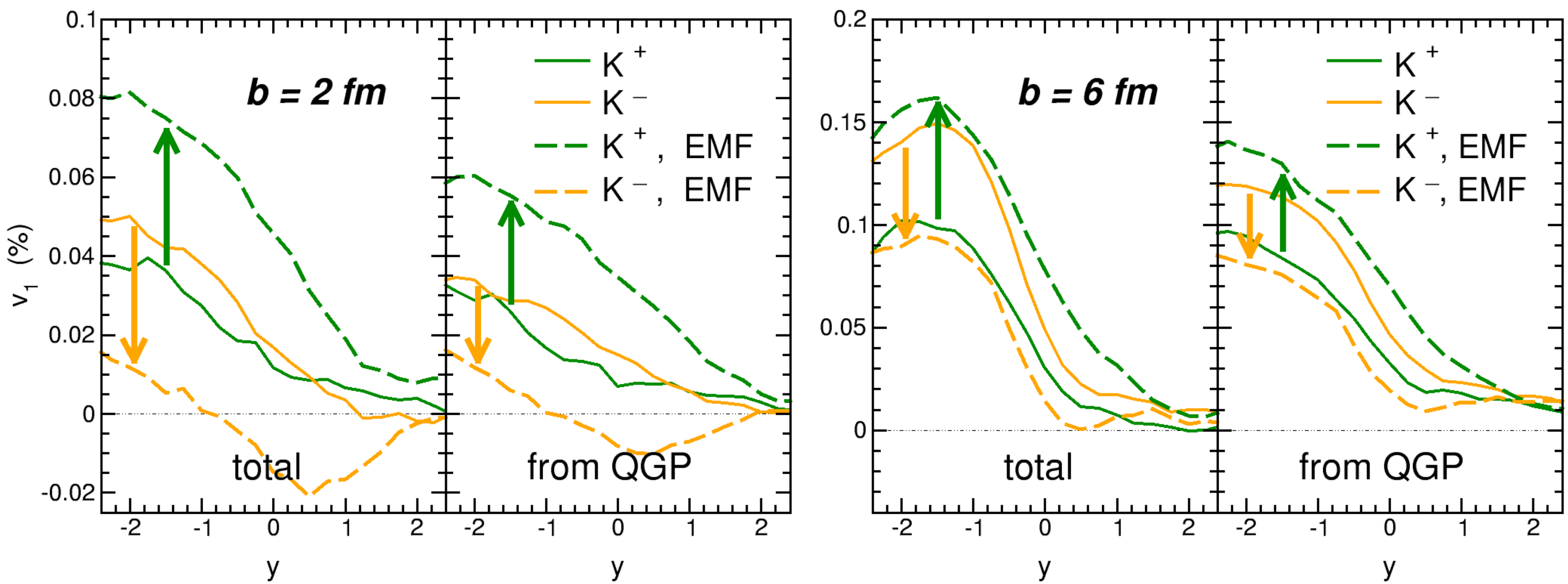


p+Au collisions @ RHIC 200 GeV

rapidity dependence of the
DIRECTED FLOW OF KAONS

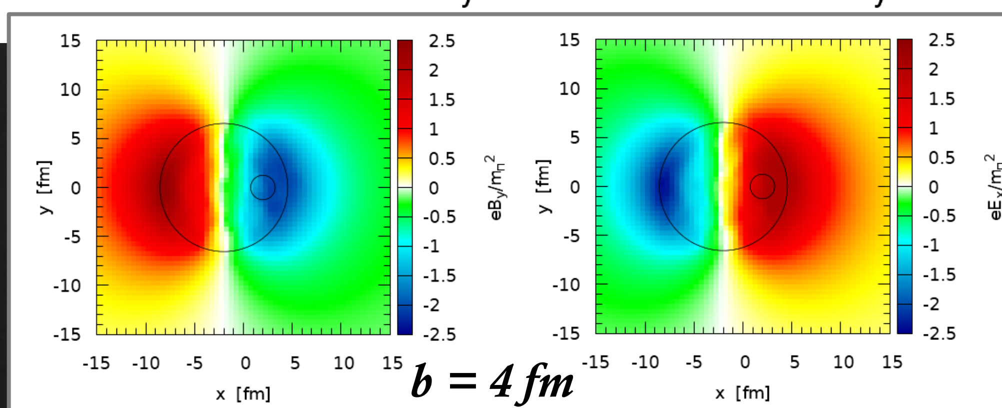
PRELIMINARY

$v_1(y) = \langle \cos[\varphi(y)] \rangle$



Splitting of K⁺ and K⁻ induced by electric and magnetic field

increasing magnitude with impact parameter



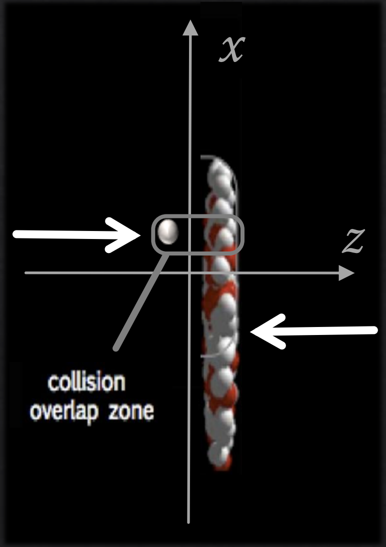
CONCLUDING….

The Parton-Hadron-String-Dynamics (PHSD) describes the entire dynamical evolution of heavy ion collisions within one single theoretical framework

PHSD includes in a consistent way the intense electromagnetic fields produced in the very early stage of the collision

Study of p+Au collisions at top RHIC energy:

- ✓ the electric field is strongly asymmetric inside the overlap region
- ✓ asymmetry of charged-particle rapidity distributions increasing with centrality
- ✓ collectivity as signal of quark-gluon plasma formation
- ✓ effect of electromagnetic fields in directed flow of mesons: splitting between positively and negatively charged particle

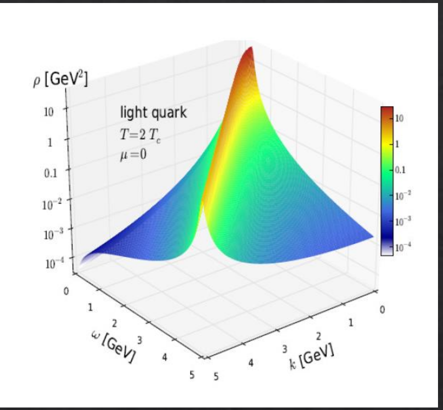


Thank you
for your attention!

DQPM: Dynamical QuasiParticle Model

The QGP phase is described in terms of interacting quasiparticle: massive quarks and gluons (g, q, $\bar{q}$) with Lorentzian spectral functions

$$\rho_j(\omega, \mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega - \tilde{E}_j)^2 + \gamma_j^2} - \frac{1}{(\omega + \tilde{E}_j)^2 + \gamma_j^2}\right) \equiv \frac{4\omega\gamma_j}{\left(\omega^2 - \mathbf{p}^2 - M_j^2\right)^2 + 4\gamma_j^2\omega^2}$$



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:

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

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

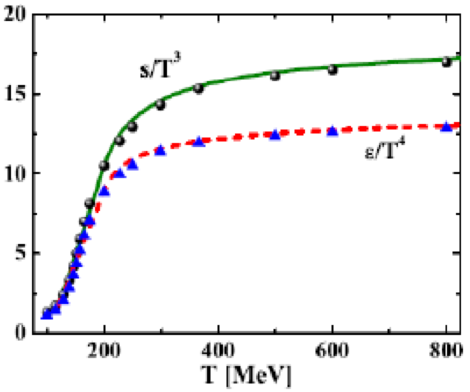
$N_c = 3$, $N_f = 3$

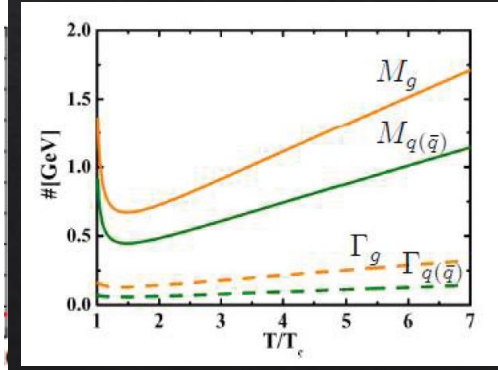
running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

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

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

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





Peshier, PRD 70 (2004) 034016
Peshier and Cassing, PRL 94 (2005) 172301
Cassing, NPA 791 (2007) 365; NPA 793 (2007)

retarded electromagnetic fields

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}$$

General solution of the wave equation for the electromagnetic potentials

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

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

$$\mathbf{r}' \equiv \mathbf{r}(t')$$

$$t' = t - \frac{\mathbf{r}-\mathbf{r}'}{c}$$

Liénard-Wiechert potentials for a moving point-like charge

$$\Phi(\mathbf{r},t) = \frac{e}{4\pi}\left[\frac{1}{R(1-\mathbf{n}\cdot\boldsymbol{\beta})}\right]_{\mathrm{ret}} \qquad \mathbf{A}(\mathbf{r},t) = \frac{e}{4\pi}\left[\frac{\boldsymbol{\beta}}{R(1-\mathbf{n}\cdot\boldsymbol{\beta})}\right]_{\mathrm{ret}}$$

ret: evaluated at the times t'

$$\mathbf{R} = \mathbf{r} - \mathbf{r}'$$

$$\mathbf{n} = \frac{\mathbf{R}}{R}$$

$$\boldsymbol{\beta} = \frac{\mathbf{v}}{c}$$

Voronyuk *et al.*, PRC 83 (2011) 054911

retarded electromagnetic fields

Retarded electric and magnetic fields for a moving point-like charge

$$\mathbf{E}(\mathbf{r},t) = \frac{e}{4\pi}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3\gamma^2R^2} + \frac{\mathbf{n}\times\left((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3 cR}\right]_{\mathrm{ret}} \qquad \mathbf{B}(\mathbf{r},t) = [\mathbf{n}\times\mathbf{E}(\mathbf{r},t)]_{\mathrm{ret}}$$

elastic Coulomb scatterings | **inelastic bremsstrahlung processes**

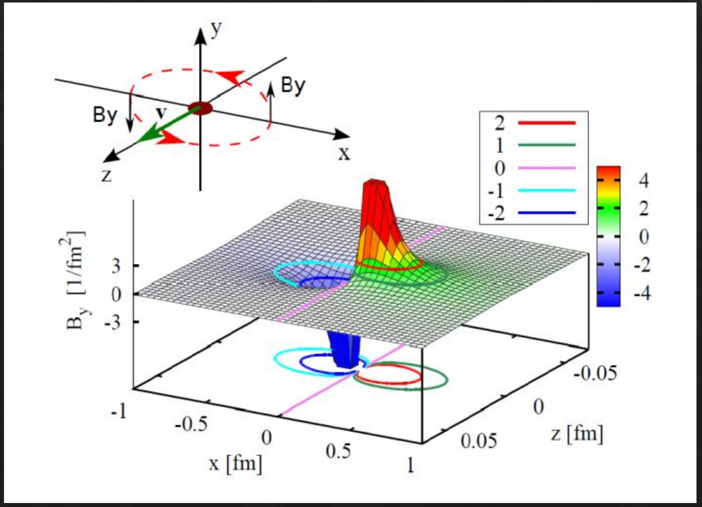
$$\mathbf{R} = \mathbf{r}-\mathbf{r}' \qquad \mathbf{n} = \frac{\mathbf{R}}{R} \qquad \boldsymbol{\beta} = \frac{\mathbf{v}}{c}$$

Neglecting the acceleration

$$e\mathbf{E}(t,\mathbf{r}) = \alpha_{em}\frac{1-\beta^2}{\left[(\mathbf{R}\cdot\boldsymbol{\beta})^2 + R^2(1-\beta^2)\right]^{3/2}}\mathbf{R}$$

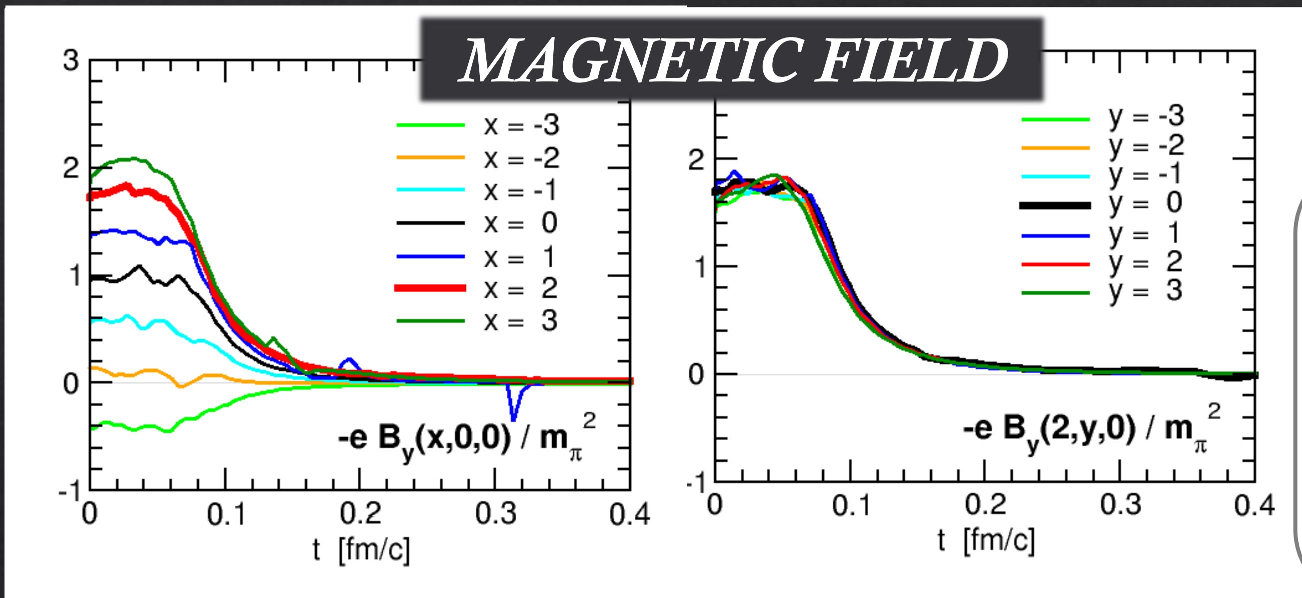
$$e\mathbf{B}(t,\mathbf{r}) = \alpha_{em}\frac{1-\beta^2}{\left[(\mathbf{R}\cdot\boldsymbol{\beta})^2 + R^2(1-\beta^2)\right]^{3/2}}\boldsymbol{\beta}\times\mathbf{R}$$

magnetic field created by a single freely moving charge

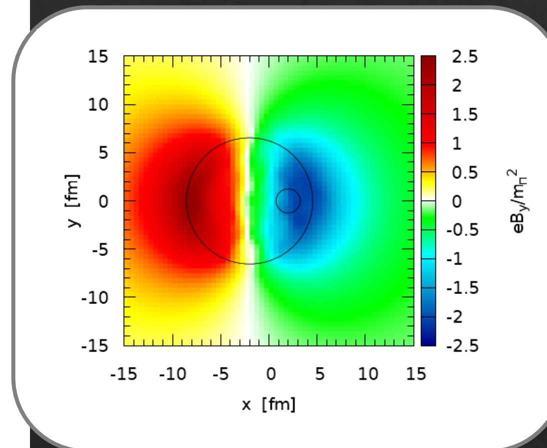


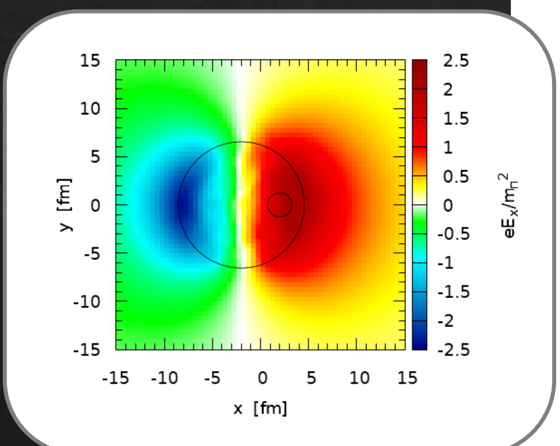
Voronyuk *et al.*, PRC 83 (2011) 054911

p+Au collisions @RHIC 200GeV b=4 fm

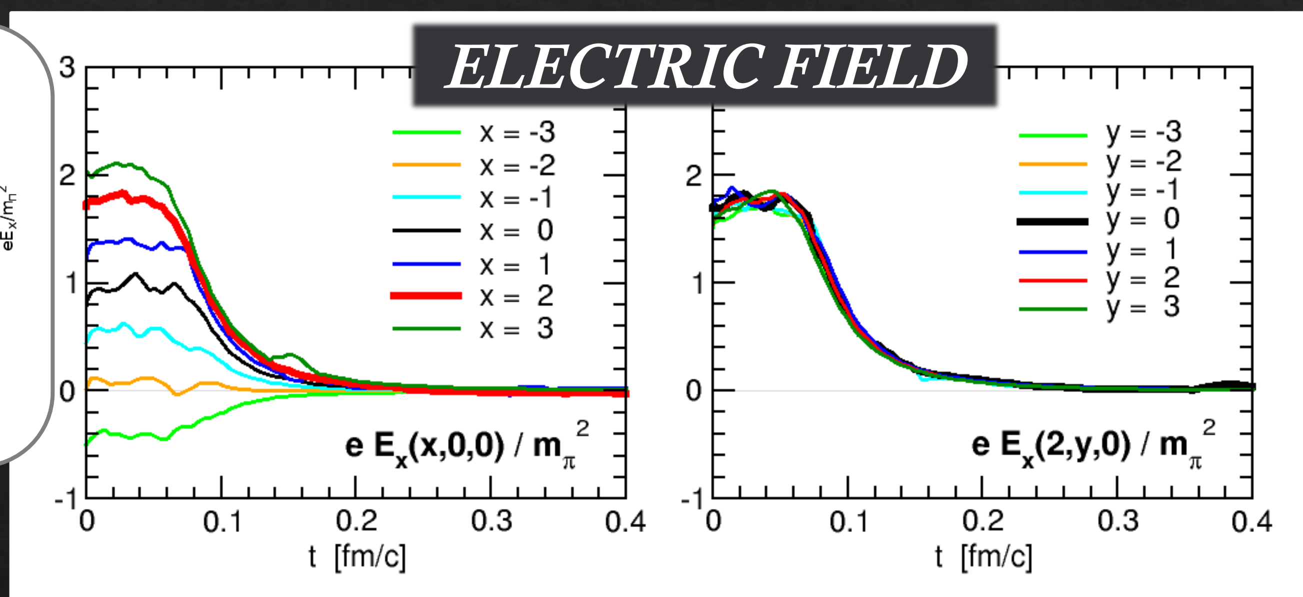


B_y



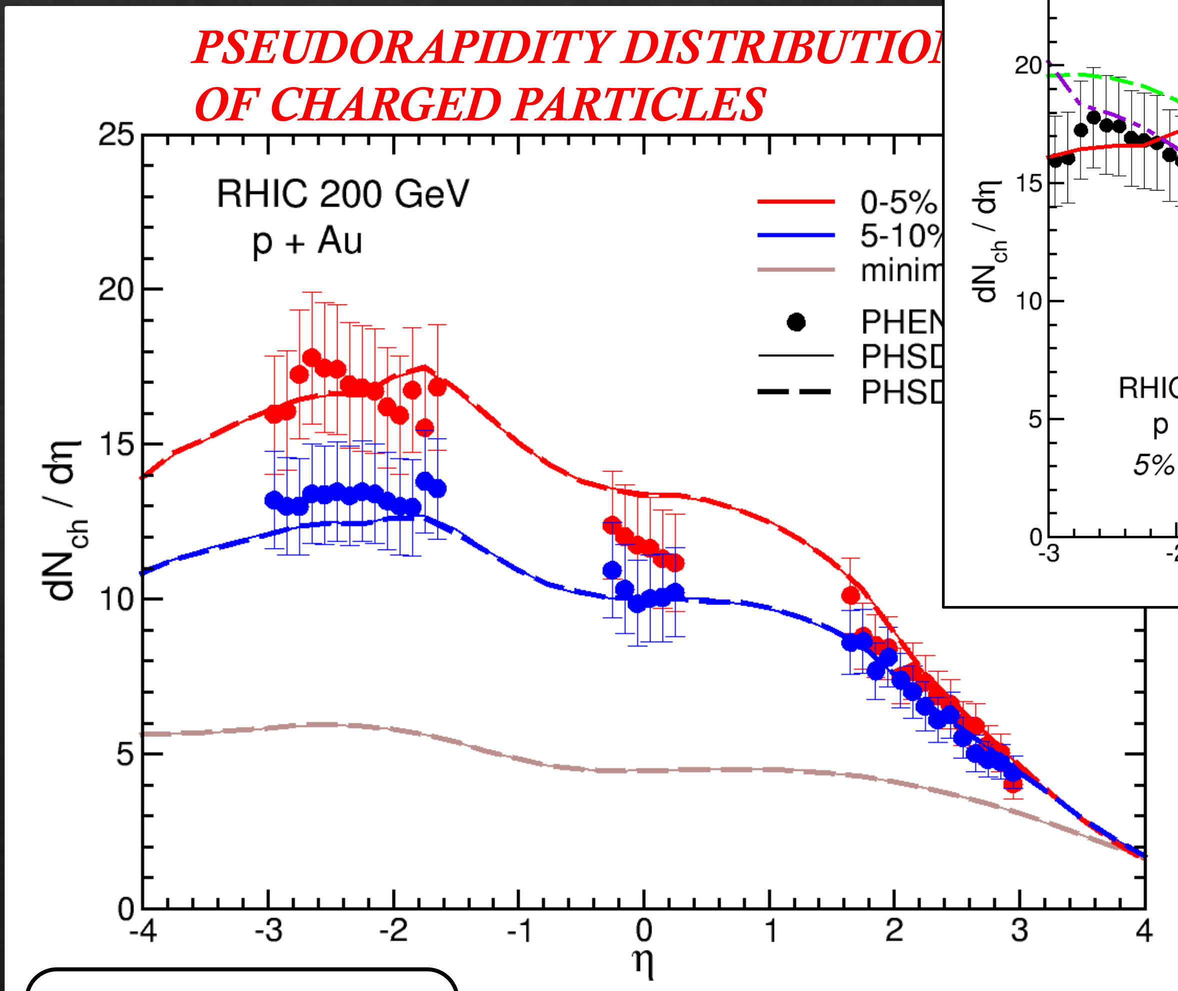


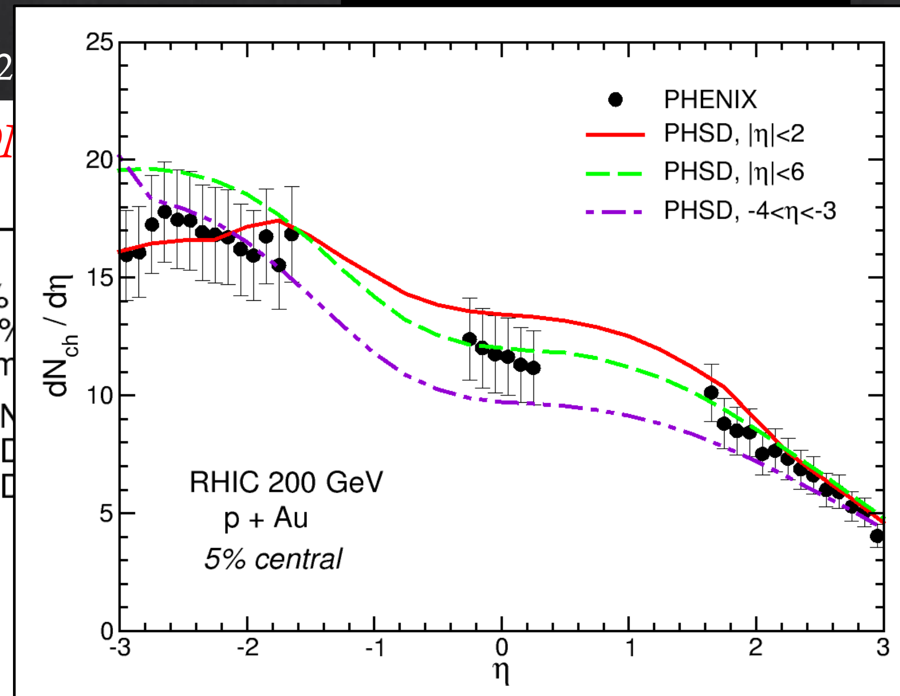
E_x



p+Au collisions @ RHIC 200 GeV

Exp. Data: PHENIX Collaboration, PRL 121 (2018) 222





$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

- enhanced particle production in the Au-going directions
- asymmetry increases with centrality of the collision

Anisotropic radial flow

A DEEPER INSIGHT…FINITE EVENT MULTIPLICITY

azimuthal particle distributions
w.r.t. the reaction plane

$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2 v_n(p_T) \cos[n(\varphi - \Psi_n)]$$

n-th order
flow harmonics

$$v_n = \frac{\langle \cos[n(\varphi - \Psi_n)] \rangle}{Res(\Psi_n)}$$

event-plane angle resolution
(three-subevent method)

n-th order
event-plane angle

$$\Psi_n = \frac{1}{n} \mathrm{atan2}(Q_n^y, Q_n^x)$$

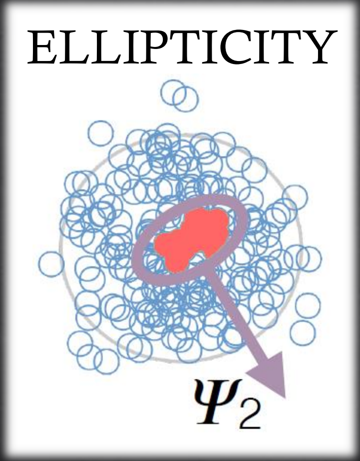
$$Q_n^x = \sum_i \cos[n\varphi_i]$$

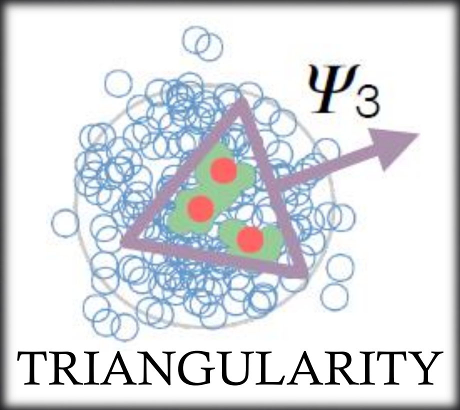
$$Q_n^y = \sum_i \sin[n\varphi_i]$$

Since the finite number of particles produces limited resolution in the determination of Ψ_n, the v_n must be corrected up to what they would be relative to the real reaction plane

Poskanzer and Voloshin, PRC 58 (1998) 1671

Important especially for small colliding system, e.g. p+A



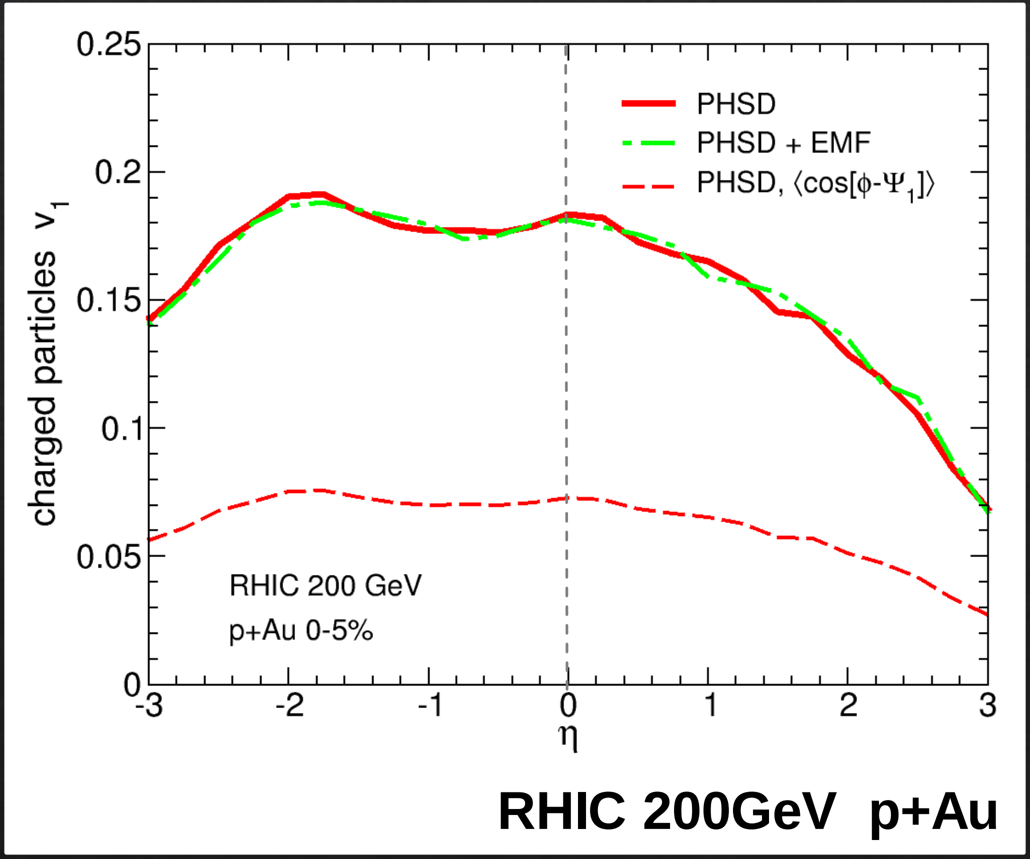


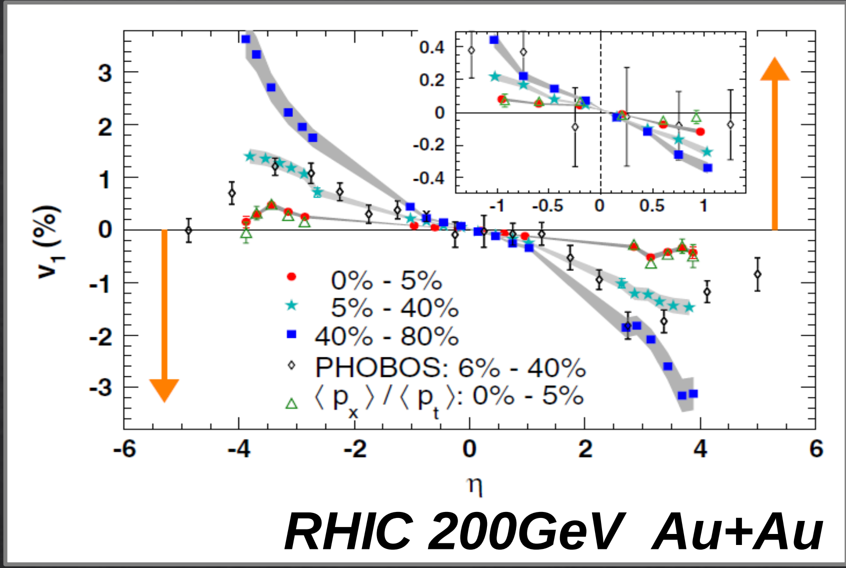
p+Au collisions @ RHIC 200 GeV

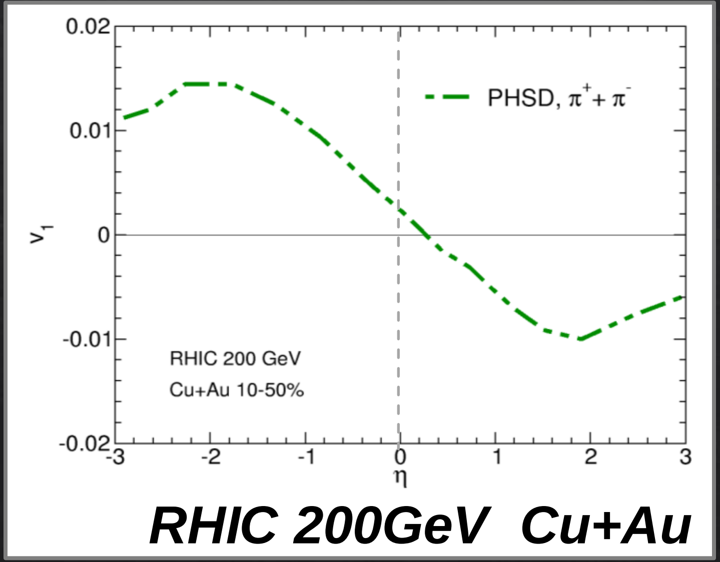
PRELIMINARY

STAR Collaboration, PRL 101 (2008) 252301

pseudorapidity dependence of the
DIRECTED FLOW OF
CHARGED PARTICLES







Voronyuk *et al.*, PRC 90 (2014) 064903
Toneev *et al.*, PRC 95 (2017) 034911