INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
"The Strong Interaction:
From Quarks and Gluons to Nuclei and Stars"
Erice, Italy – September 16-24, 2018

Influence of the electromagnetic fields on hadronic observables in proton-induced collisions

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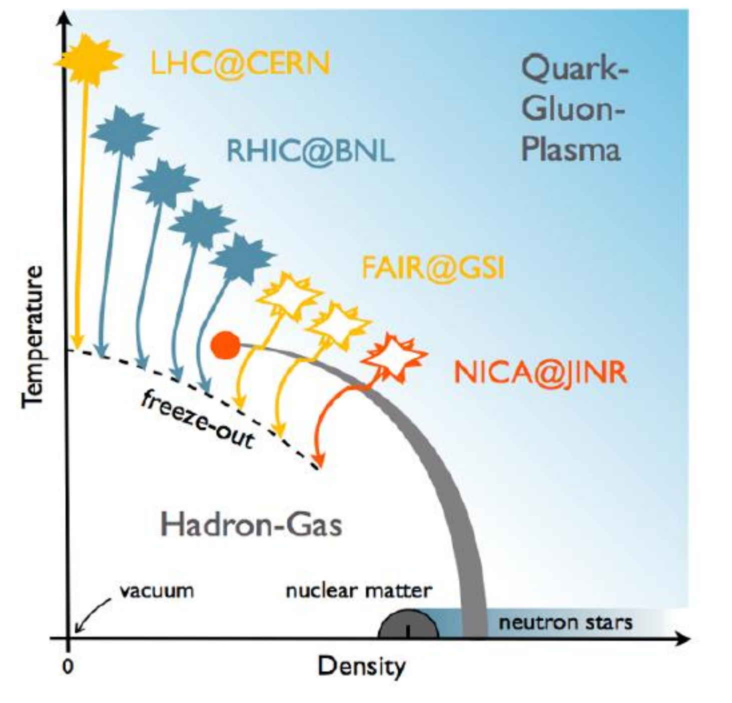
PHSD

GSI Helmholtzzentrum für Schwerionenforschung GmbH

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

QCD PHASE DIAGRAM

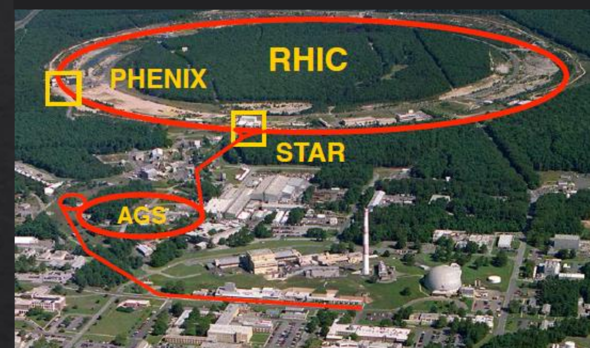


High energy heavy ion collisions

- ✓ allow to experimentally investigate the QCD phase diagram
- ✓ recreate the extreme condition of temperature and density required to form the **QUARK-GLUON PLASMA**

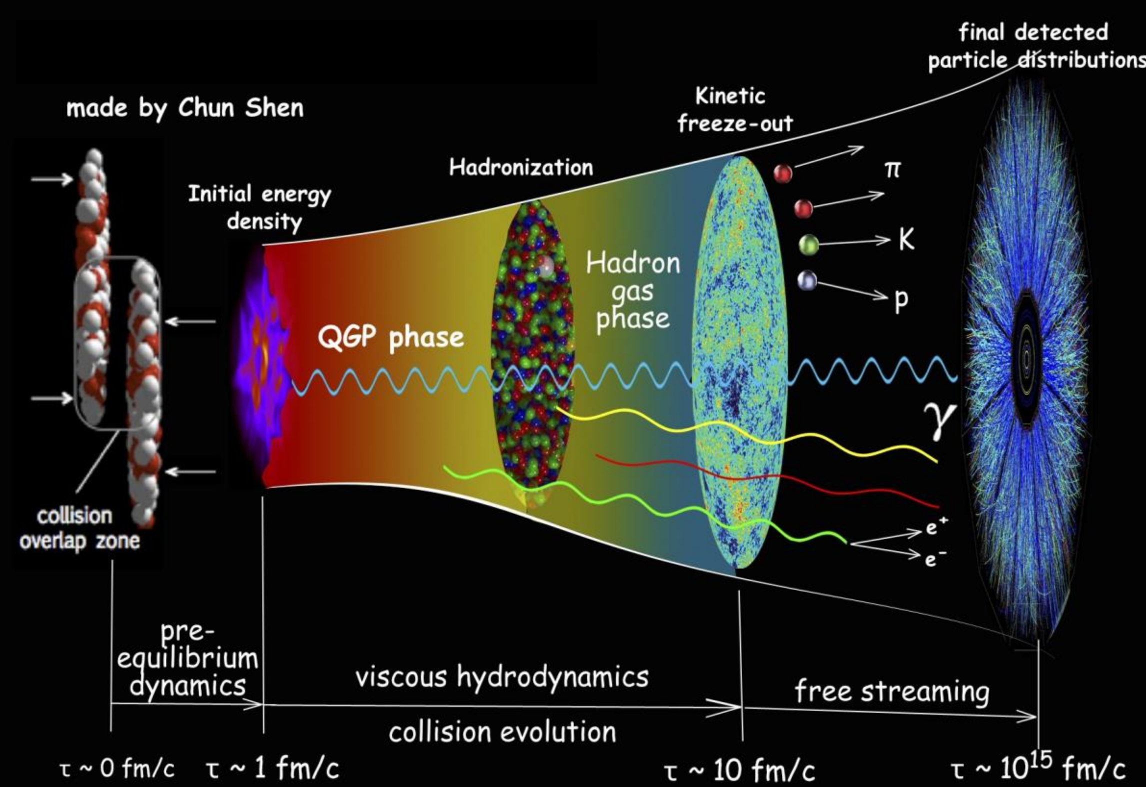
Large Hadron Collider (LHC)

Relativistic Heavy Ion Collider (RHIC)



Facility for Antiproton and Ion Research (FAIR)

Nuclotron-based Ion Collider fAcility (NICA)



EXPANDING FIREBALL

the evolution lasts about
t ~ 10-20 fm/c ~ 10^{-23} s

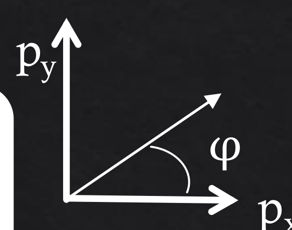
initial temperature is about
T ~ 300-600 MeV ~ 10^{12} K

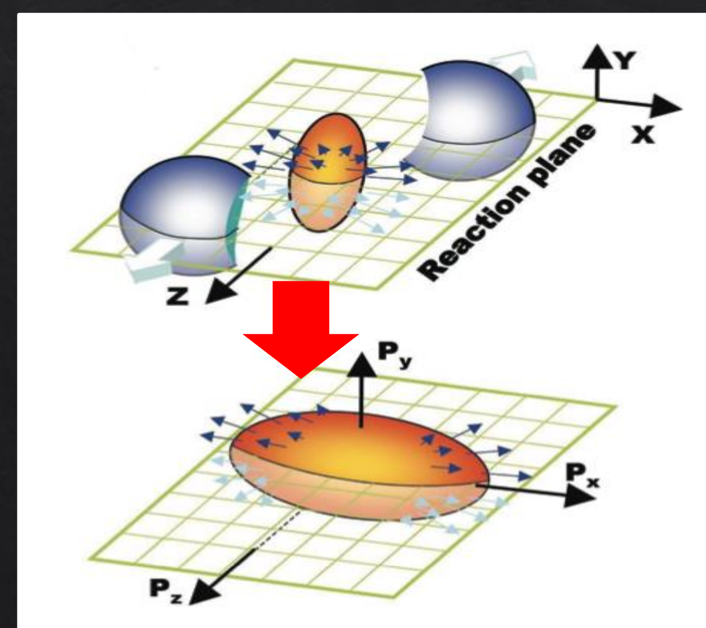
Quark-Gluon Plasma (QGP)

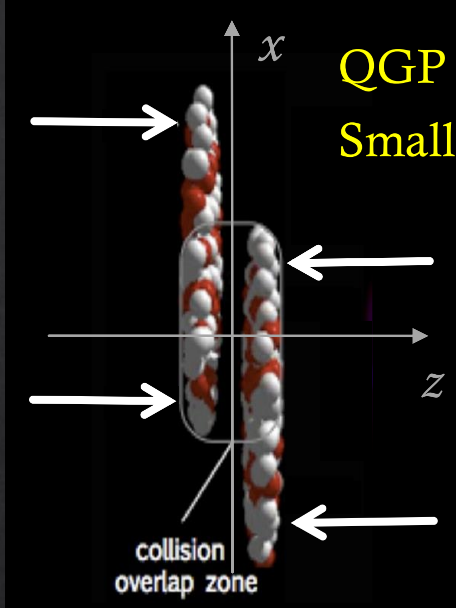
an "almost perfect fluid" with very low viscosity and the formation of collective flows

Anisotropic radial flow is described by the Fourier coefficients of the azimuthal particle distributions w.r.t. the reaction plane

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





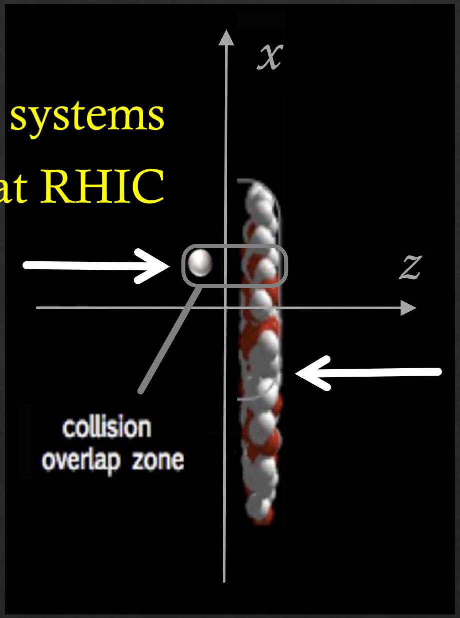


QGP initially expected only in high energy collisions of two heavy ions

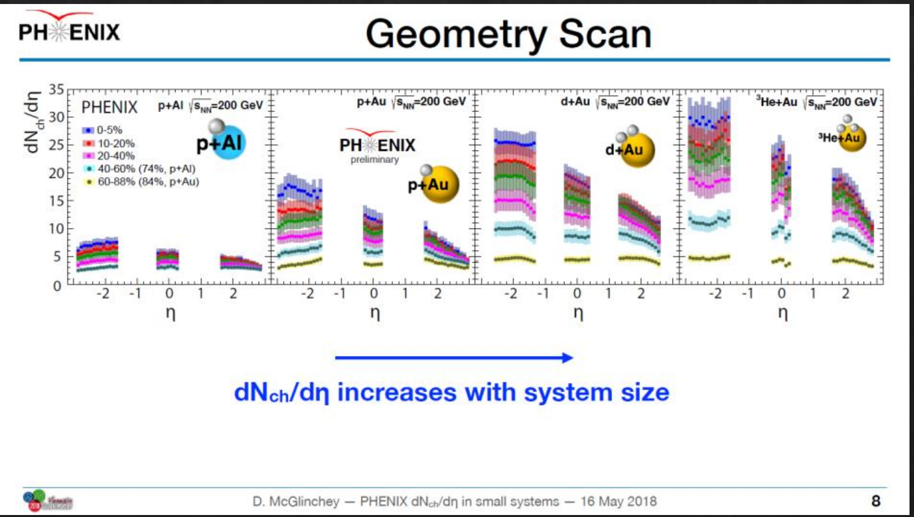
Small colliding systems initially regarded as control measurements

Signatures of collective flow found in small systems

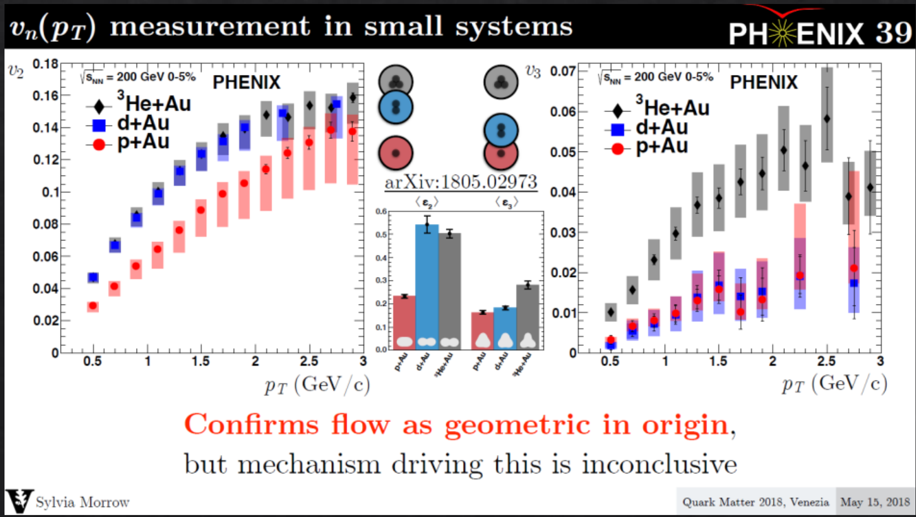
p+Pb collisions at LHC, p/d/^{3}He+Au at RHIC



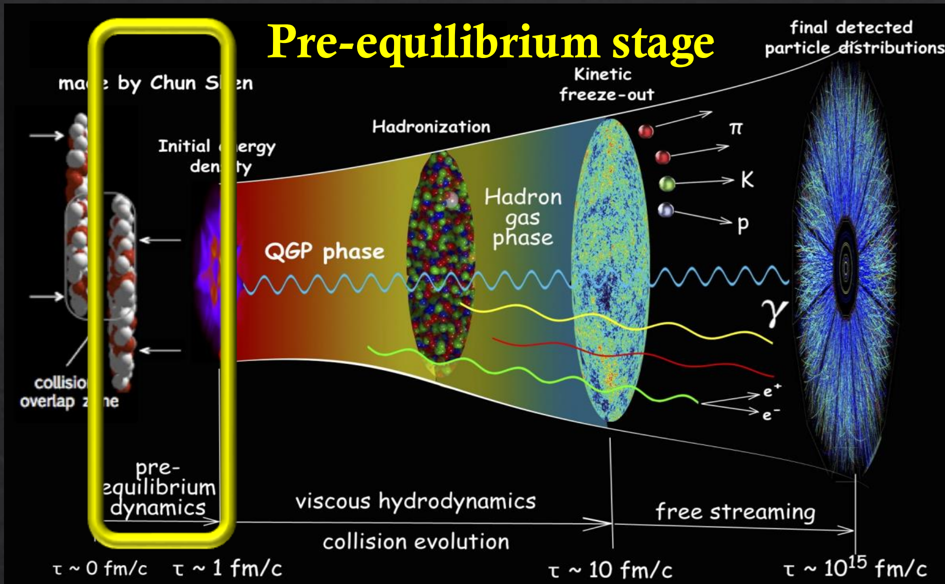
COLLECTIVITY IN SMALL SYSTEMS AS SIGN OF QGP DROPLETS?



PHENIX Collaboration, 1807.11928



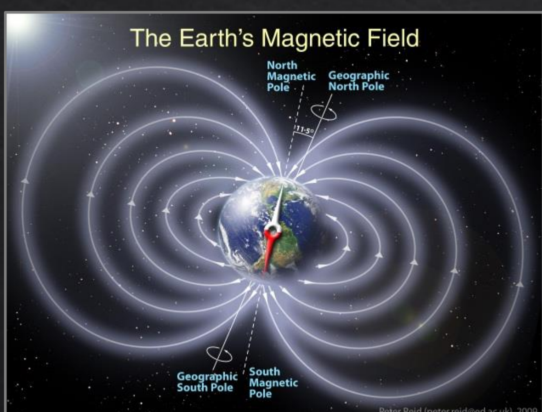
PHENIX Collaboration, 1805.02973



Intense magnetic field

$$eB_y \sim 5\text{-}50\ m_\pi^2 \sim 10^{18}\text{-}10^{19}\ \text{G}$$

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



Earth's magnetic field

~ 1 G

laboratory

~ 10^6 G

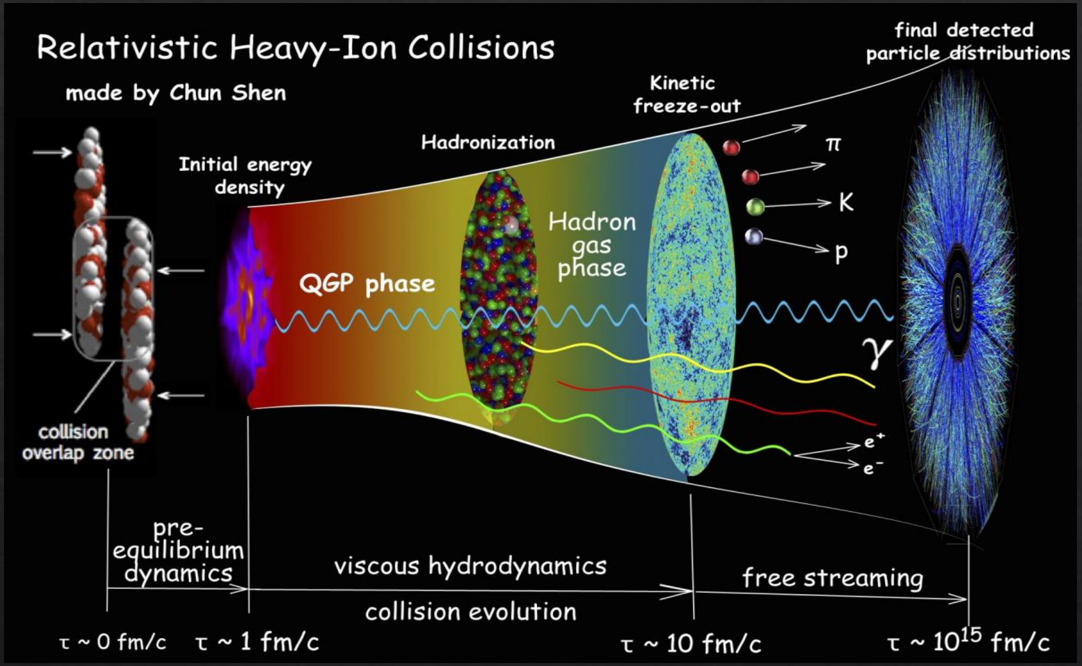
magnetar

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

PHSD: Parton-Hadron-String Dynamics

A consistent non-equilibrium transport approach to study heavy ion collisions (HICs) on a miscoscopic level

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



more details by Wolfgang Cassing

GOAL

study the phase transition from hadronic to partonic matter and the properties of the quark gluon plasma from a microscopic origin

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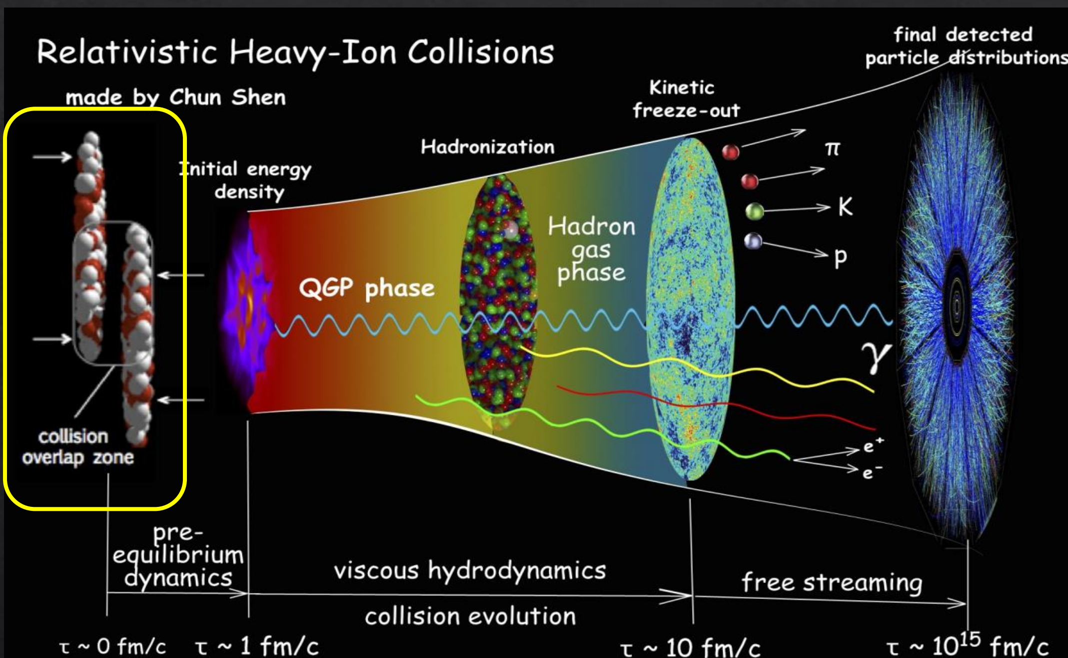
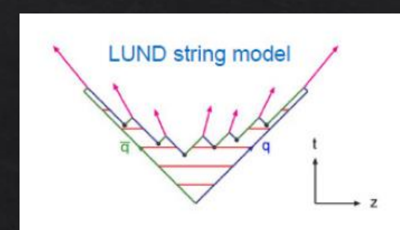


- string formation in primary nucleon-nucleon collisions
- string decay to pre-hadrons (baryons and mesons)



INITIAL A+A COLLISIONS
nucleon-nucleon collisions between the two incoming nuclei lead to the formation of strings that decay to pre-hadrons

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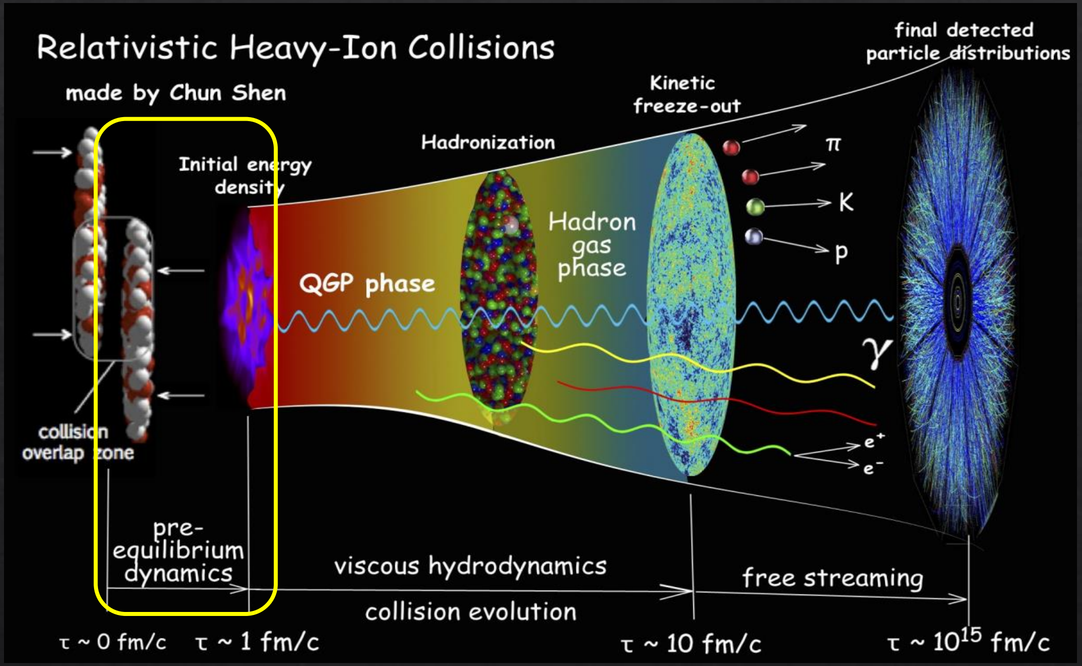
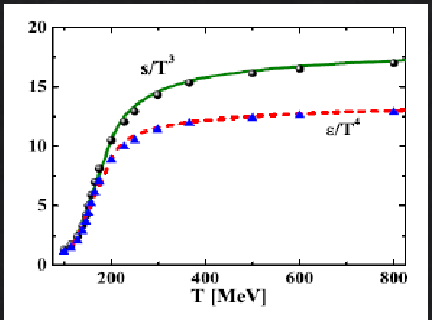


- the Dynamical Quasi-Particle Model (DQPM) defines parton spectral functions, i.e. masses $M_{q,g}(\varepsilon)$ and widths $\Gamma_{q,g}(\varepsilon)$
- mean-field potential U_q at given ε related by lQCD EoS to the local temperature



FORMATION OF QUARK-GLUON PLASMA
if the energy density is above the critical value
pre-hadrons dissolve in massive quarks and gluons

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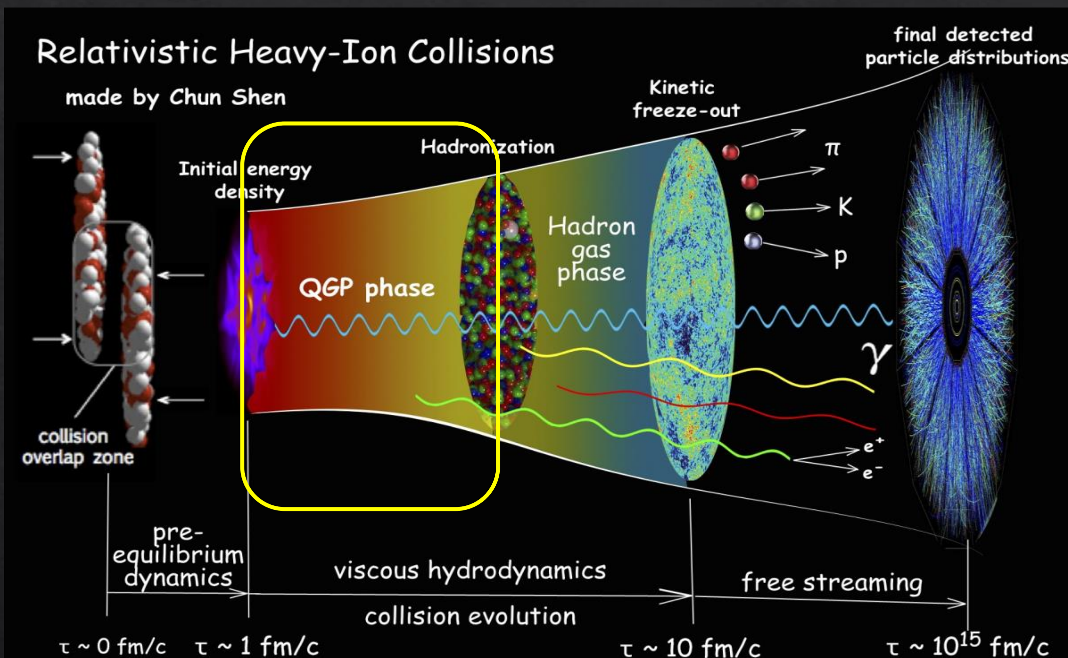
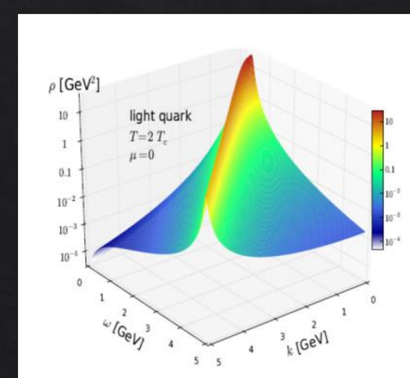


- quarks and gluons as 'dynamical quasiparticles' with off-shell spectral functions
- self-generated mean-field potential
- Equation of state from lattice QCD
- (quasi-)elastic and inelastic parton-parton interactions

PARTONIC STAGE
evolution based on off-shell transport equations and the Dynamical Quasi-Particle Model (DQPM)



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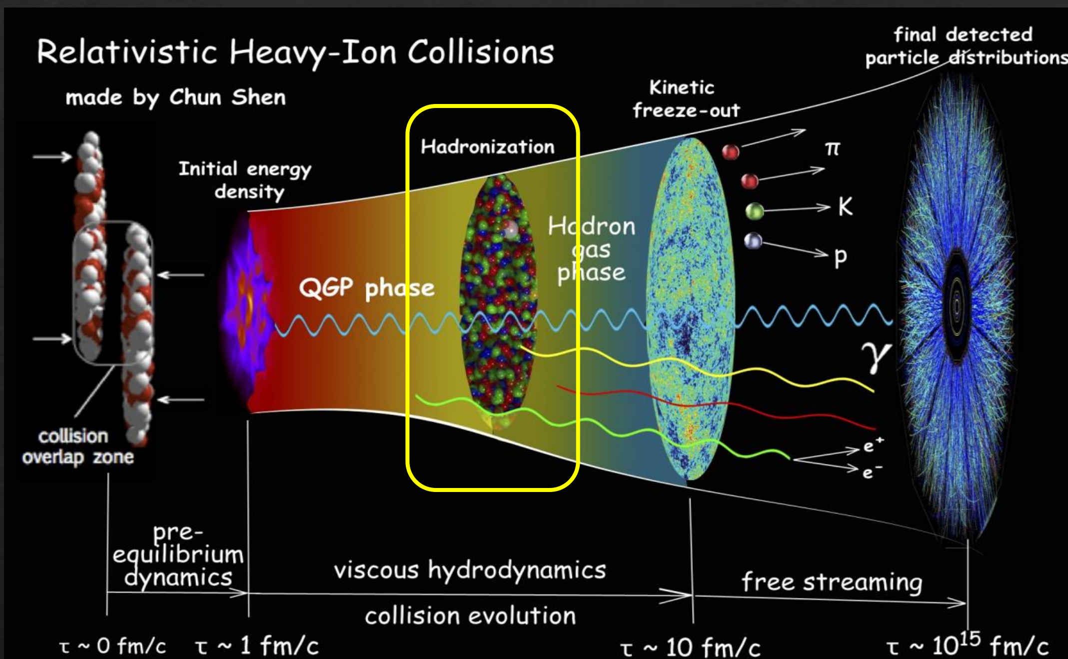
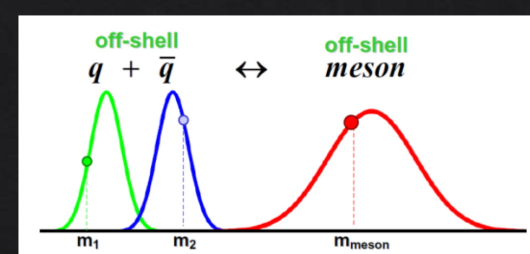


- massive off-shell quarks and antiquarks with broad spectral functions hadronize to off-shell mesons and baryons or strings
- local covariant off-shell transition rate for $q + \bar{q}$ fusion which lead to meson formation

HADRONIZATION
massive off-shell quarks with broad spectral functions hadronize to off-shell mesons and baryons



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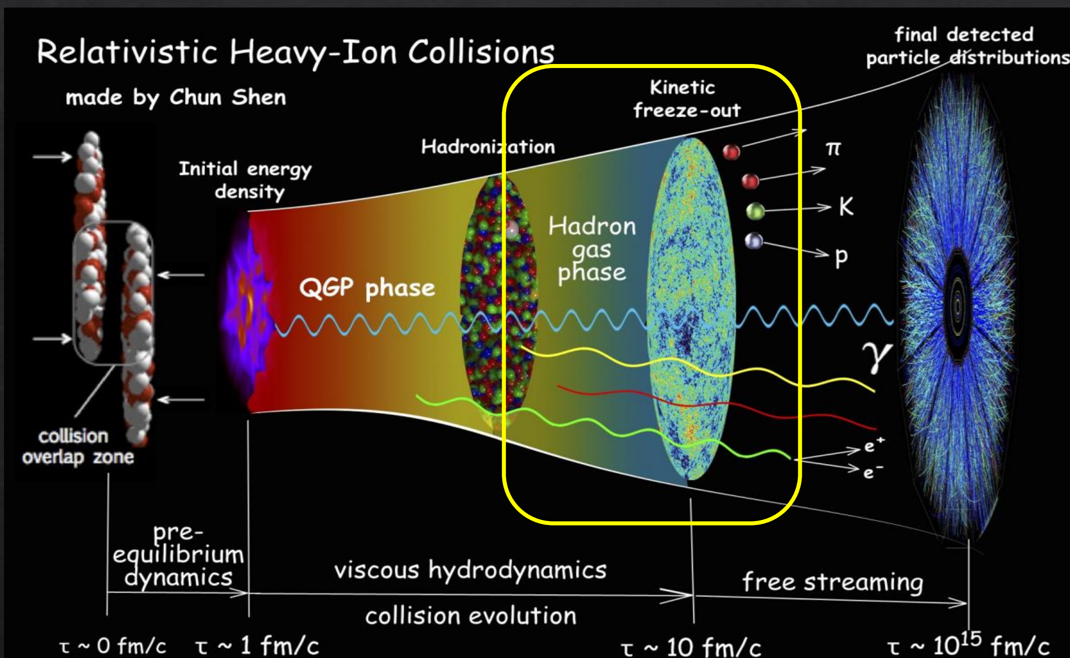
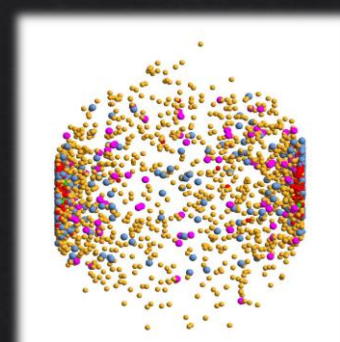


- off-shell propagation
- elastic and inelastic hadron-hadron interactions

HADRONIC PHASE
evolution based on off-shell transport equations with hadron-hadron interactions



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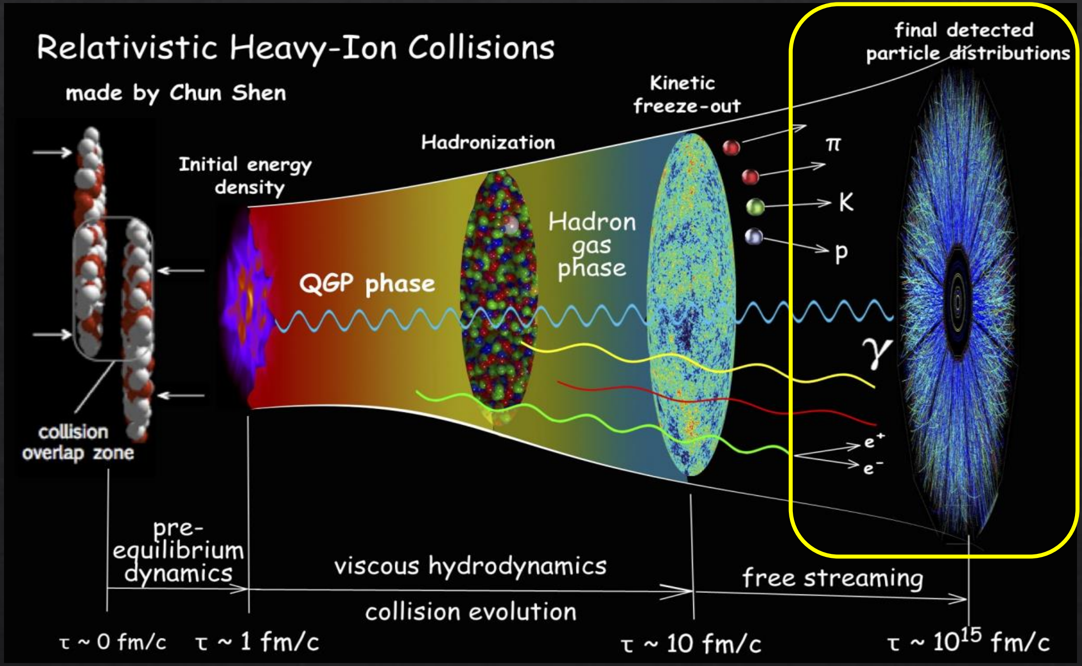


FINAL OBSERVABLES

good description of bulk observables (rapidity and transverse momentum distributions, flow coeficients, …) for A+A collisions from SPS to LHC energies

PHSD + electromagnetic fields

PHSD has been extended including the dynamical formation and evolution of the retarded electomagnetic field (EMF) and its influence on the quasi-particle (QP) dynamics

Voronyuk *et al.*, PRC 83 (2011) 054911
Toneev *et al.*, PRC 85 (2012) 034910; PRC 86 (2012) 064907; PRC 95 (2017) 034911

TRANSPORT EQUATION

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

Lorentz force

MAXWELL EQUATIONS

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

charge distribution

electric current

consistent solution of particle and field evolution equations

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

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

elastic Coulomb scatterings

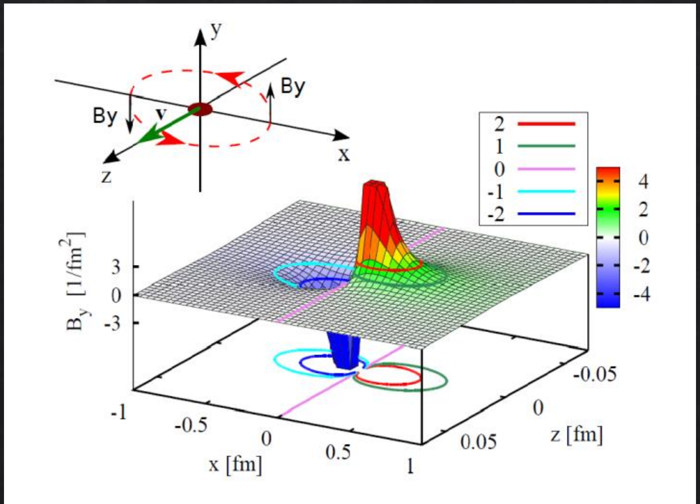
inelastic bremsstrahlung processes

Neglecting the acceleration

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

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

magnetic field created by a single freely moving charge

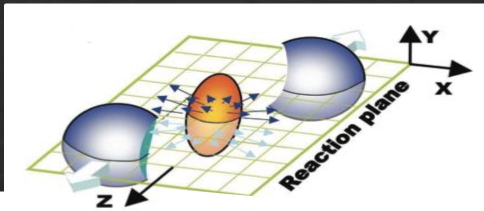


Voronyuk *et al.*, PRC 83 (2011) 054911

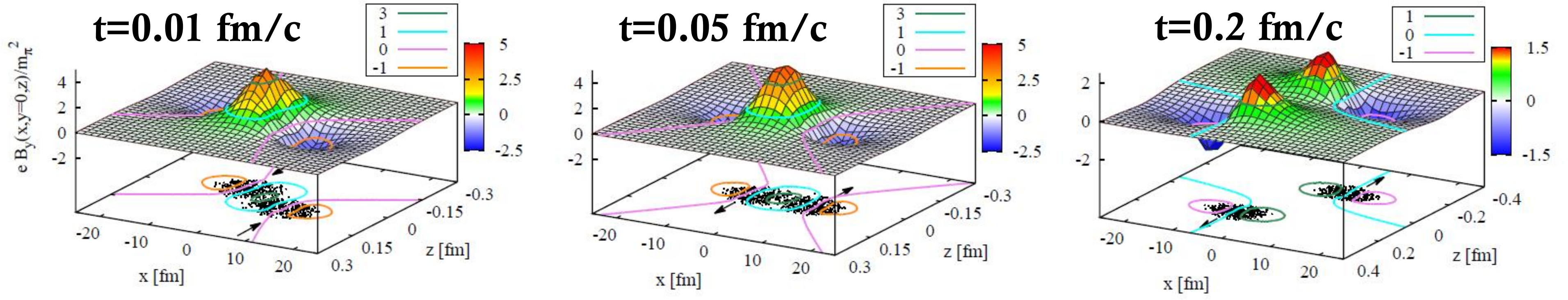
EM fields in nuclear collisions

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

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



Au+Au @RHIC 200 GeV – b = 10 fm



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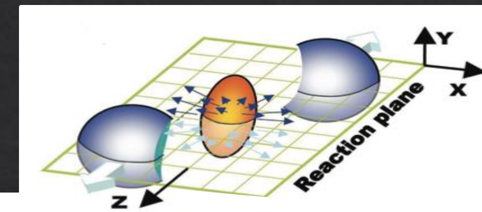

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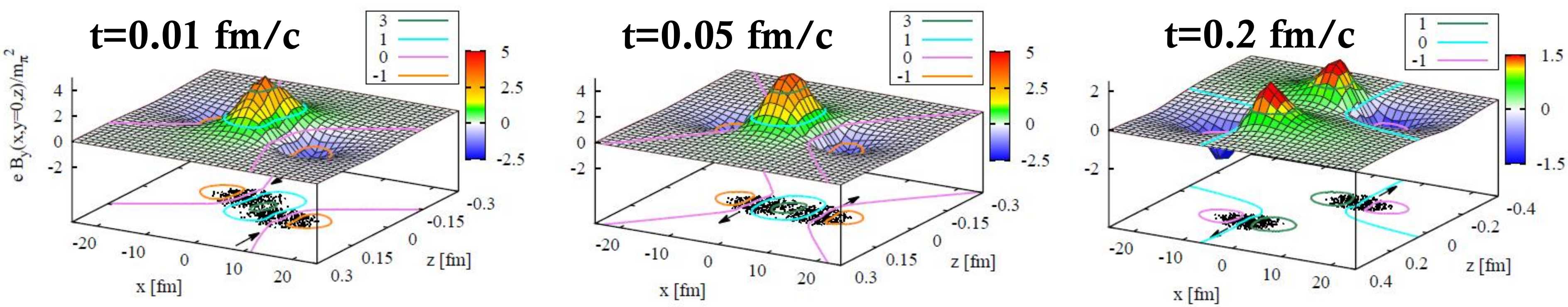
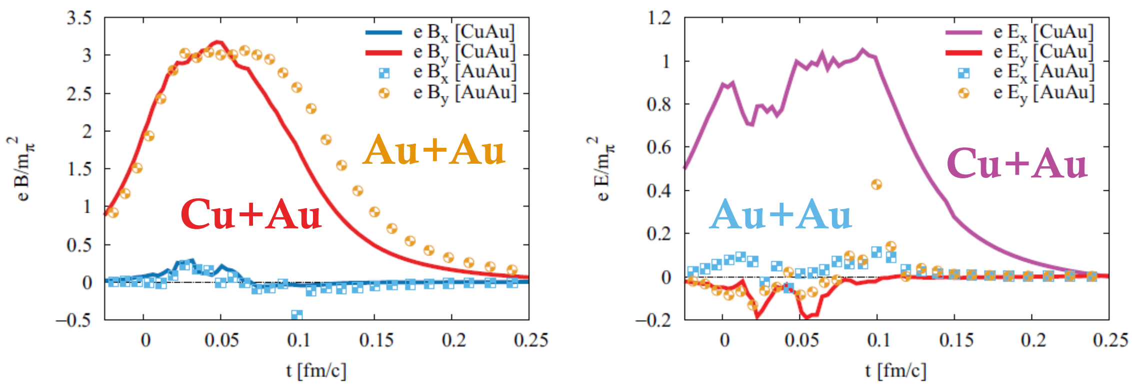


RHIC 200 GeV – b = 7 fm



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

- SYMMETRIC SYSTEMS (Au+Au, Pb+Pb)

  partial compensation of electric and magnetic forces

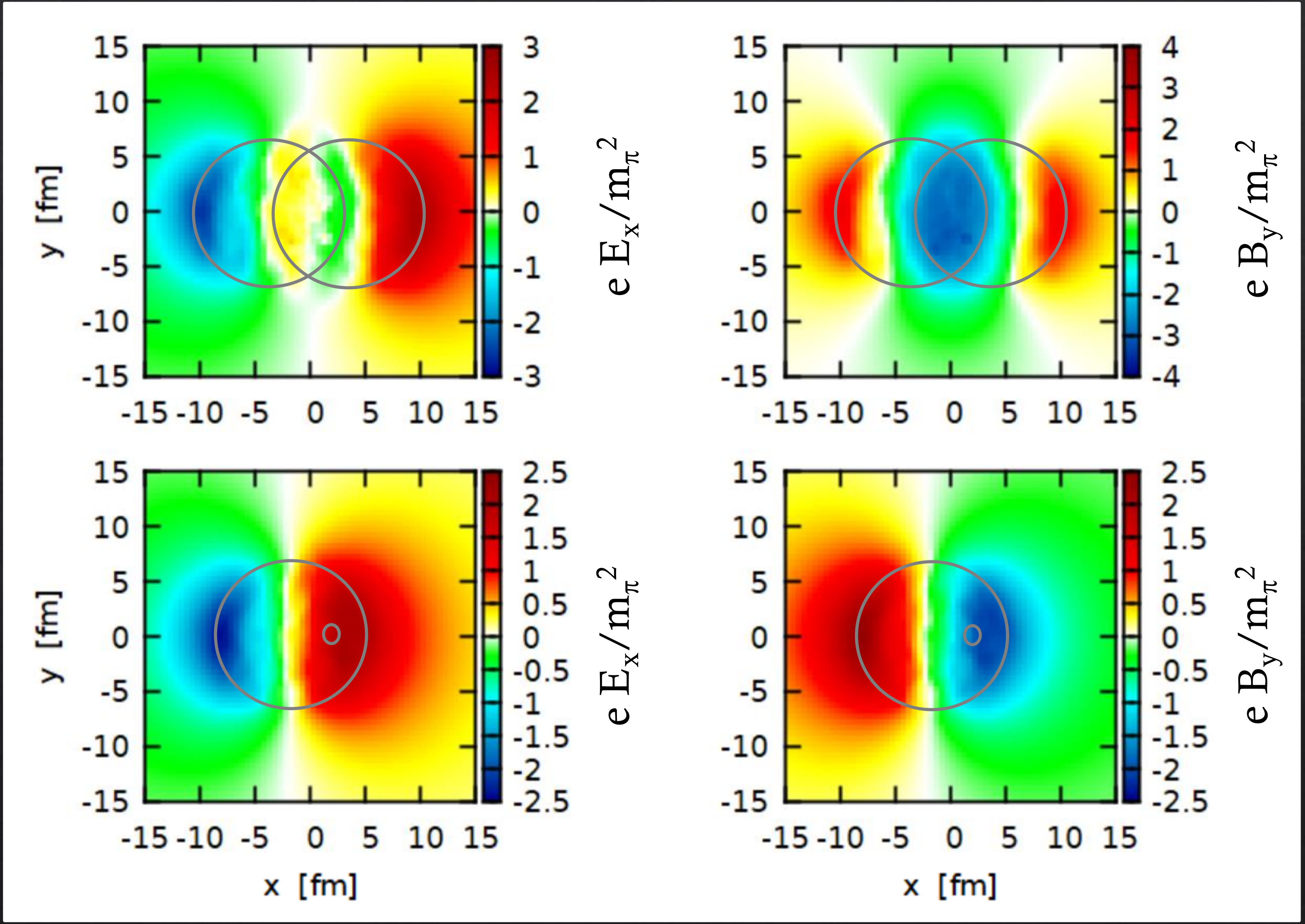
- ASYMMETRIC SYSTEMS (e.g. Cu+Au)

  electric field strongly asymmetric inside the overlap region

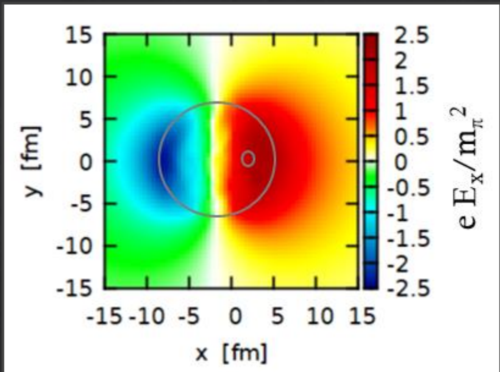
EM fields in proton-induced collisions

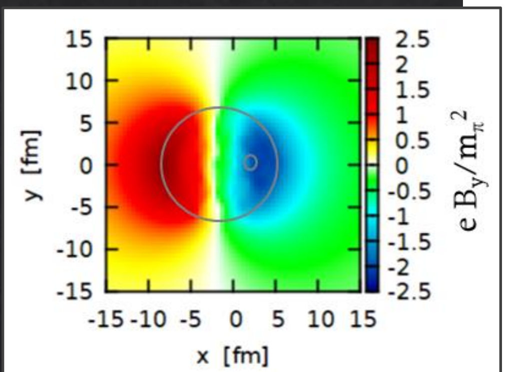
Au+Au collisions @RHIC 200GeV b=7 fm

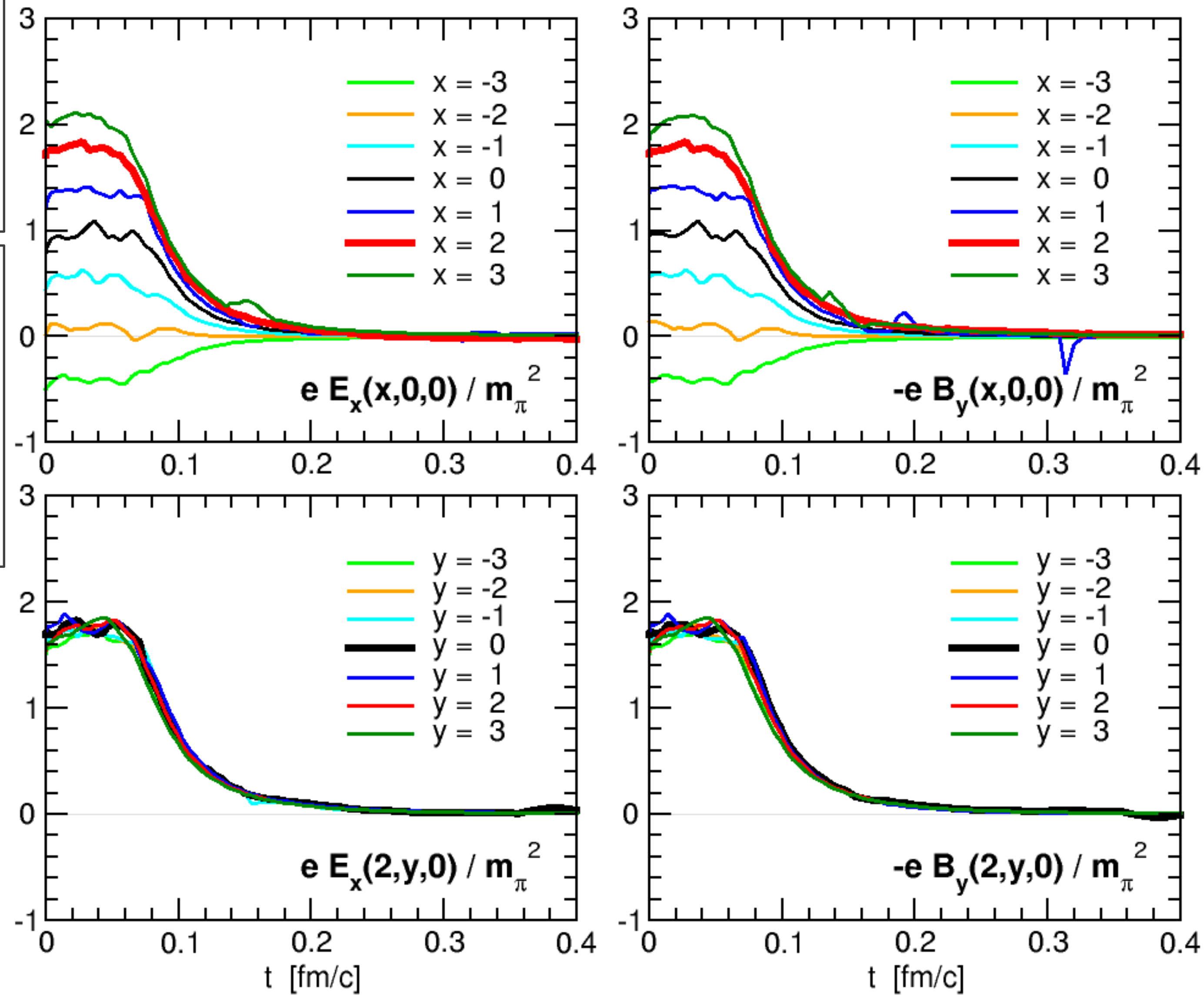
p+Au collisions @RHIC 200GeV b=4 fm



EM fields in proton-induced collisions







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

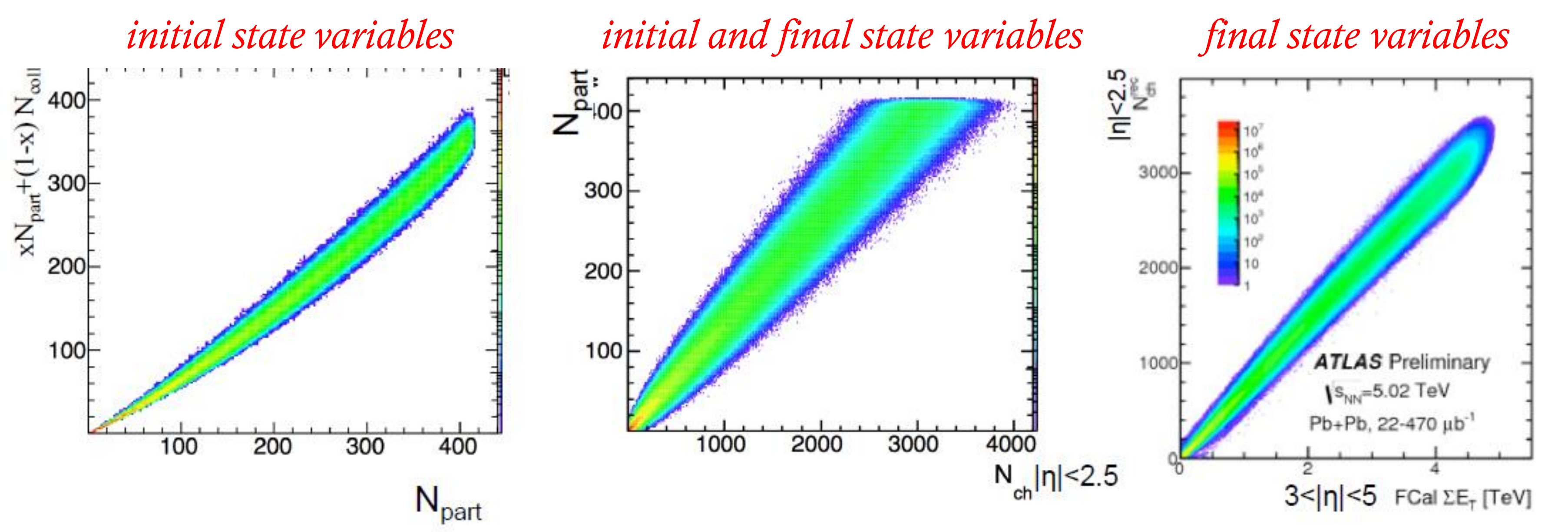
Centrality in heavy ion collisions

Centrality characterizes the amount of overlap or size of the fireball in the collision region

e.g. (MC-)Glauber model

INITIAL STATE QUANTITIES ⟷ FINAL STATE OBSERVABLES

b, N_{part}, $\{N_{part}, N_{coll}\}$, N_{qp} — N_{ch}, E_T, $N_{neutron}$



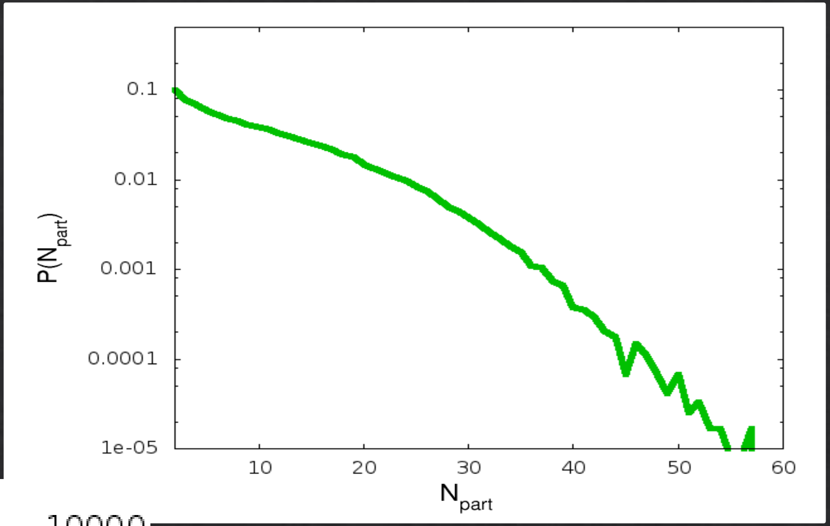
from talk of Jiangyong Jia at MIAPP (2018)

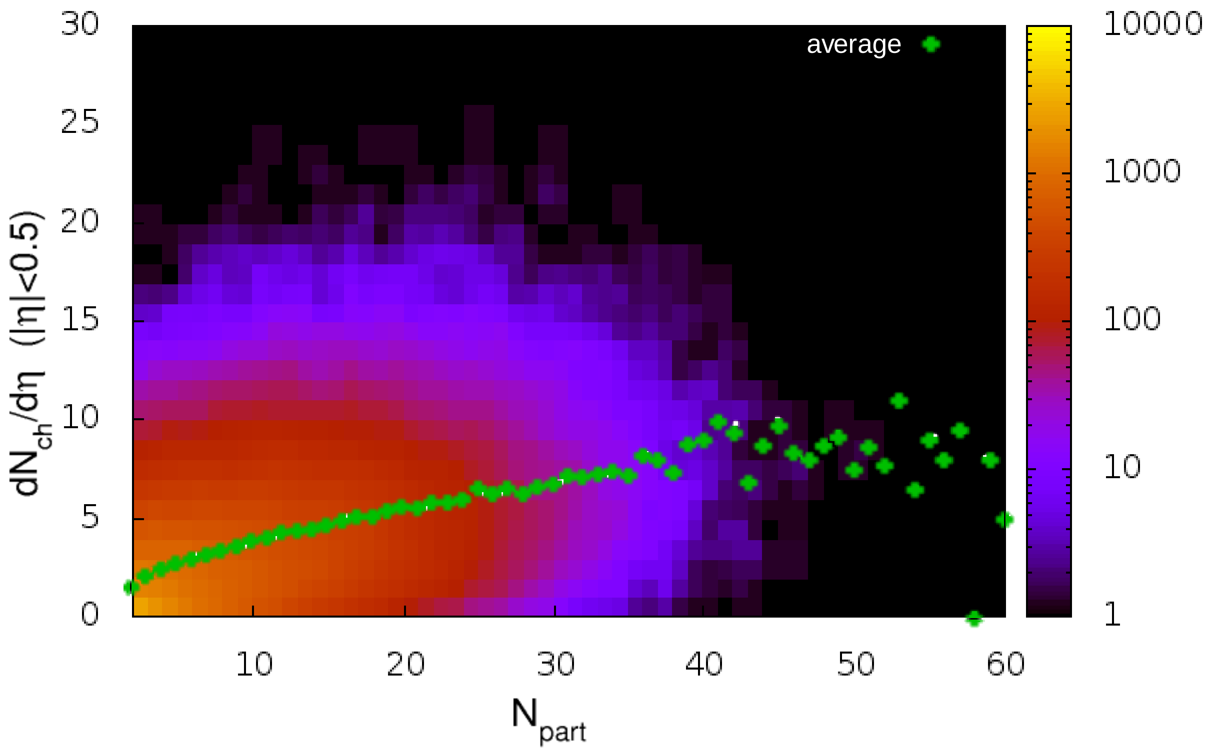
CENTRALITY FLUCTUATION

- ❖ main uncertainty for many measurements
- ❖ large in peripheral collisions or small collision systems

p+Au collisions @ RHIC 200 GeV

PROBABILITY DISTRIBUTION IN THE NUMBER OF PARTICIPANTS AND CHARGED HADRON MULTIPLICITY AT MIDRAPIDITY



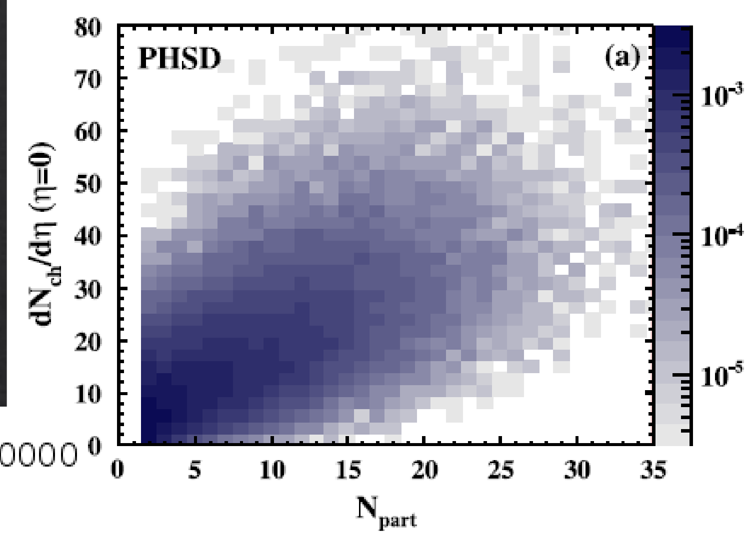


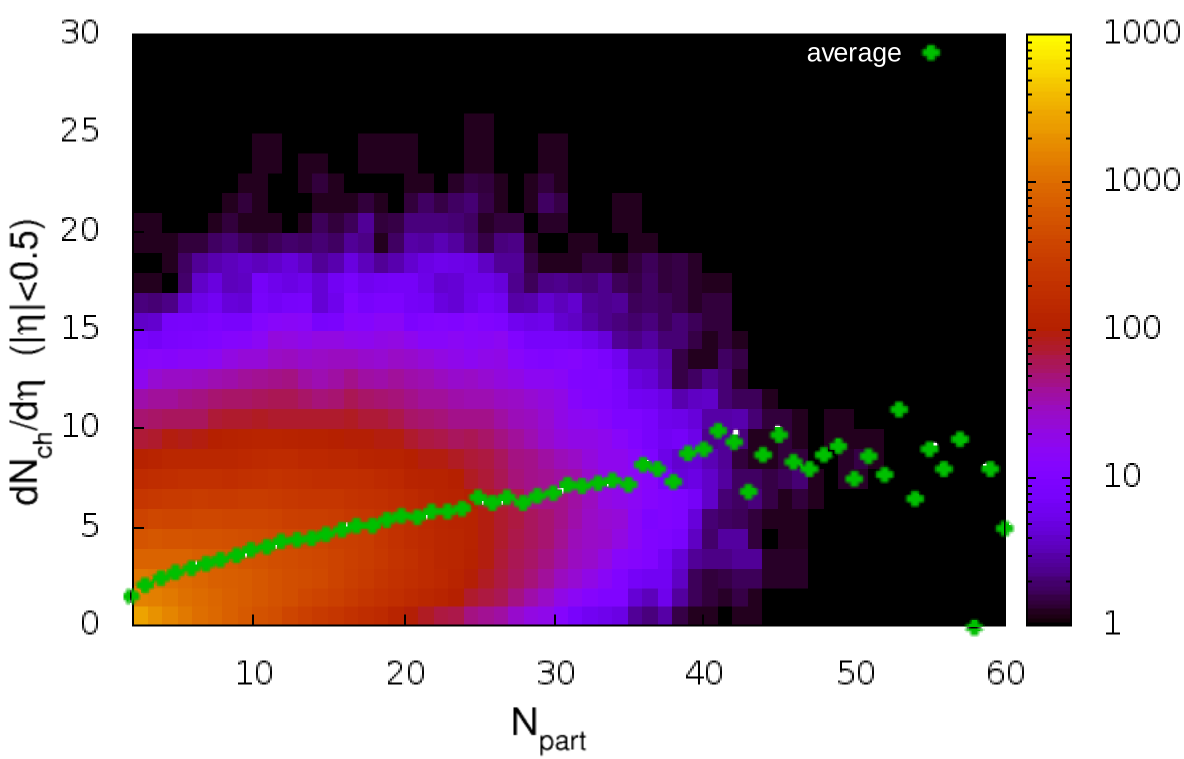
- correlation between $N_{ch}(|\eta|<0.5)$ and N_{part}
- large dispersion respect to AA collisions

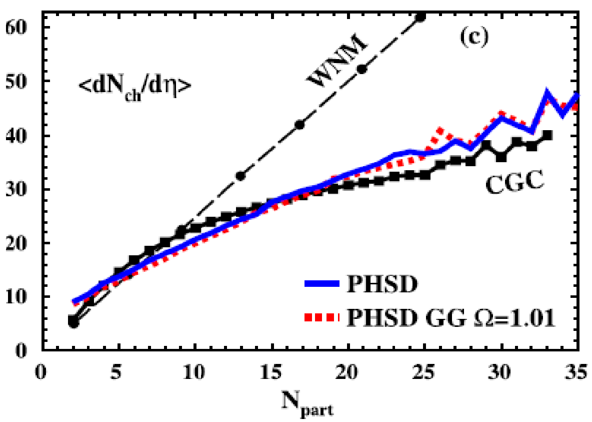
p+Au collisions @ RHIC 200 GeV

PROBABILITY DISTRIBUTION IN THE NUMBER OF PARTICIPANTS AND CHARGED HADRON MULTIPLICITY AT MIDRAPIDITY

p+Pb collisions @ LHC 5.02 TeV



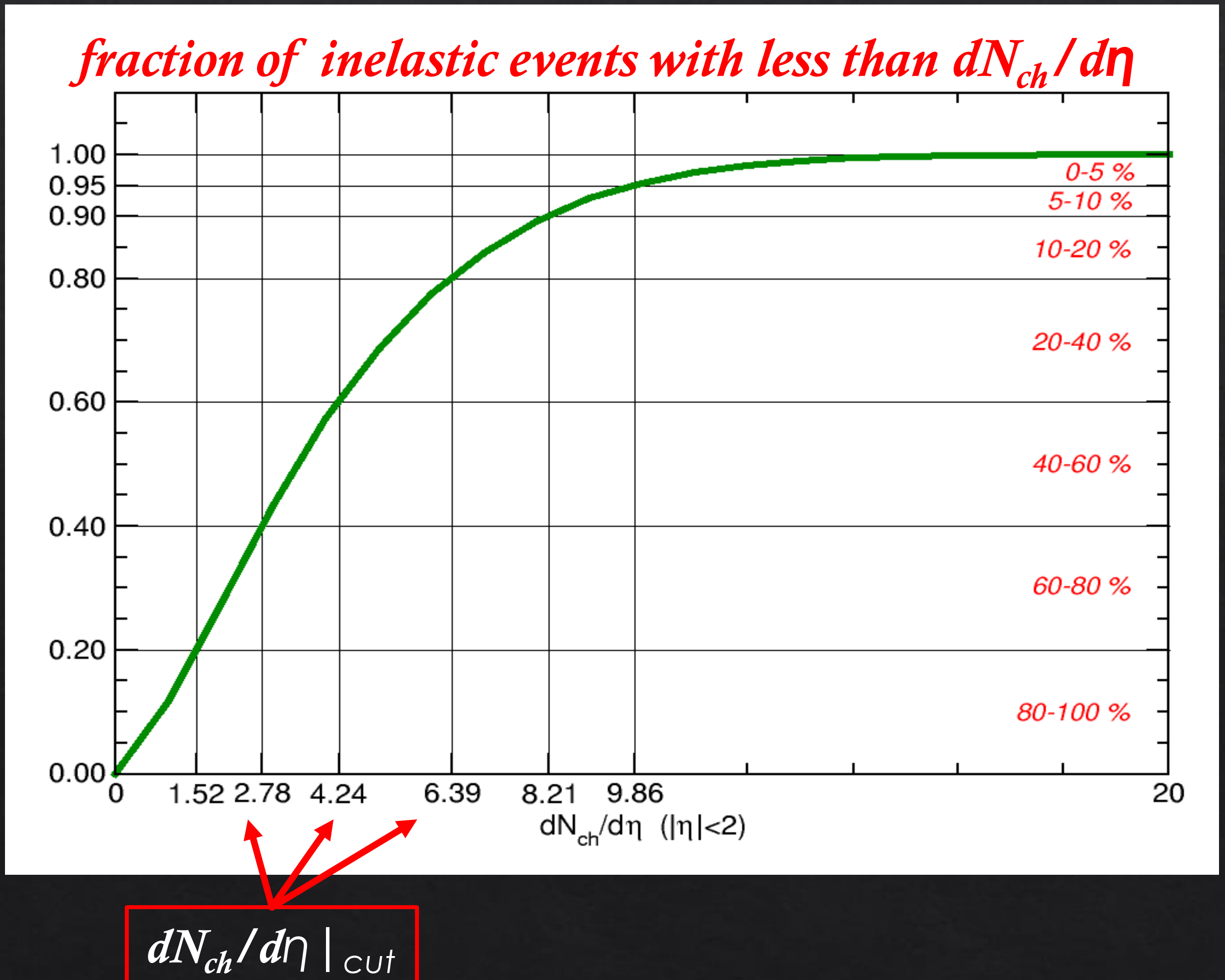




Konchakovski, Cassing and Toneev
JPG 41, 105004 (2014)

p+Au collisions @ RHIC 200 GeV

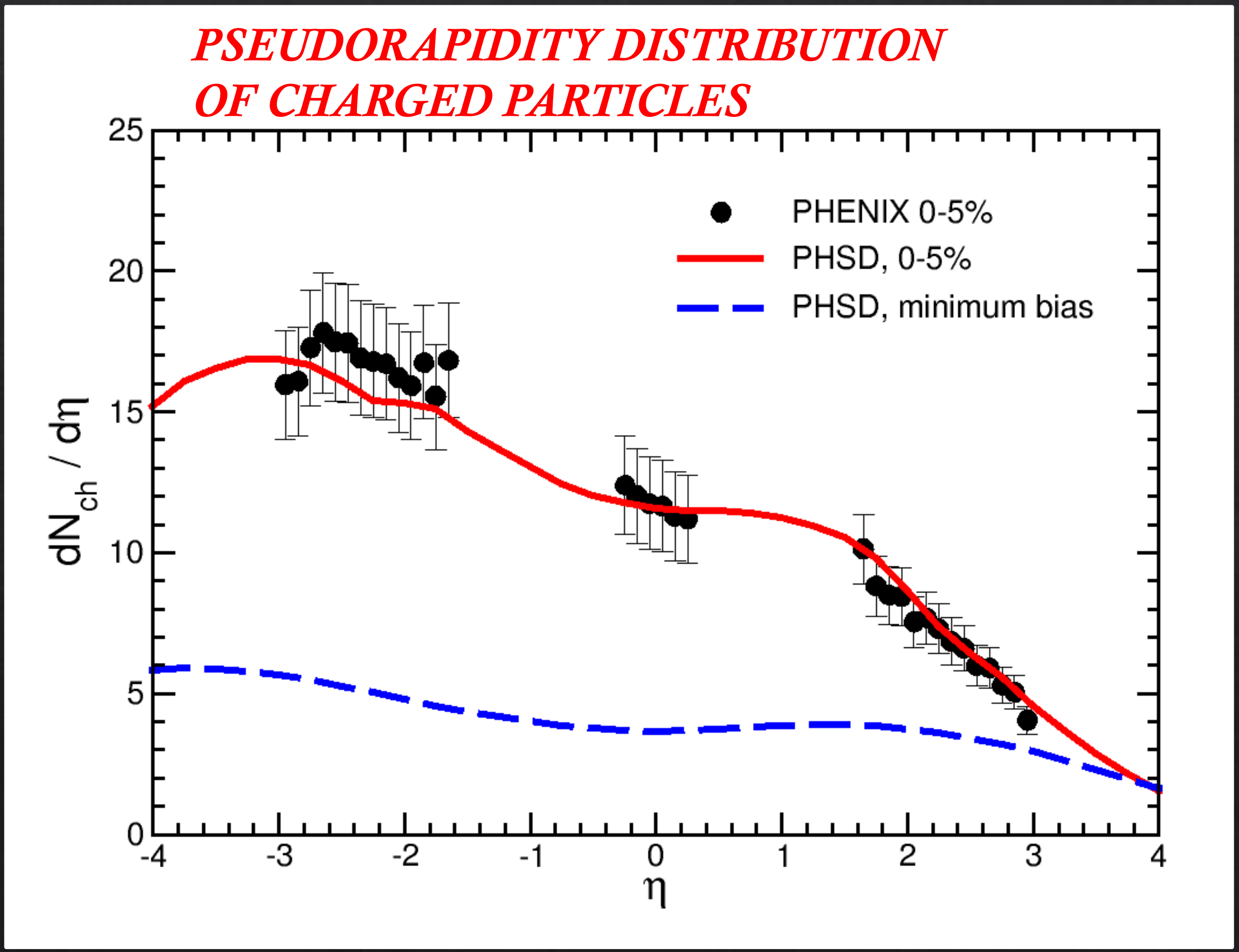
CENTRALITY SELECTION
FROM MINIMUM BIAS EVENTS

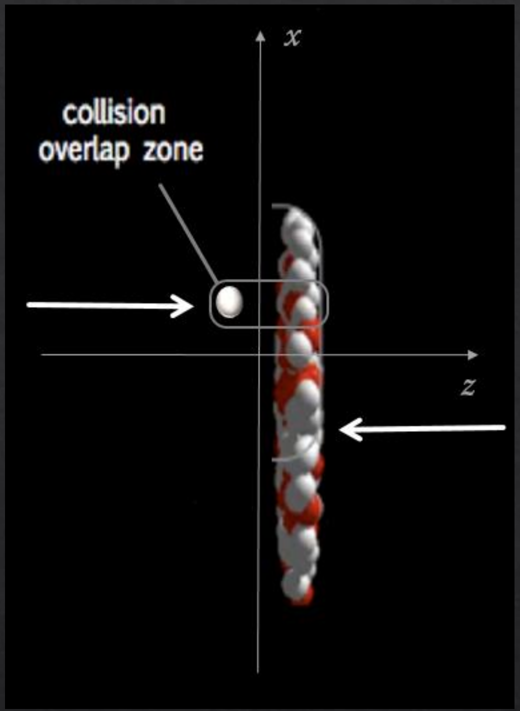


$\lvert\eta\rvert<2$	$<dN_{ch}/d\eta>$
0-5%	11.9
5-10%	8.9
10-20%	7.2
20-40%	5.1
40-60%	3.5
60-80%	2.2
80-100%	0.7

p+Au collisions @ RHIC 200 GeV

$$\eta = \frac{1}{2} \log \frac{1+\cos\theta}{1-\cos\theta}$$

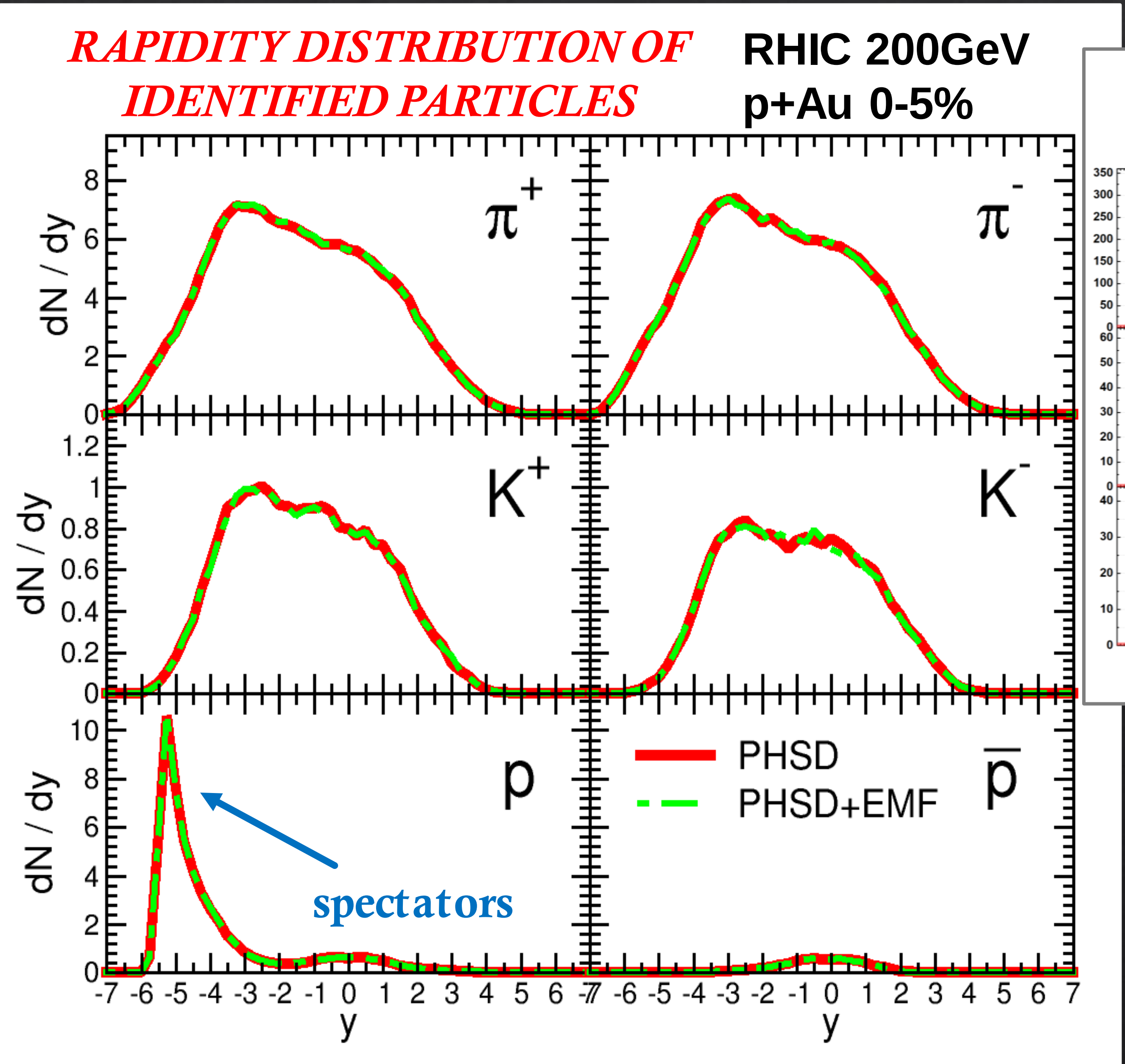


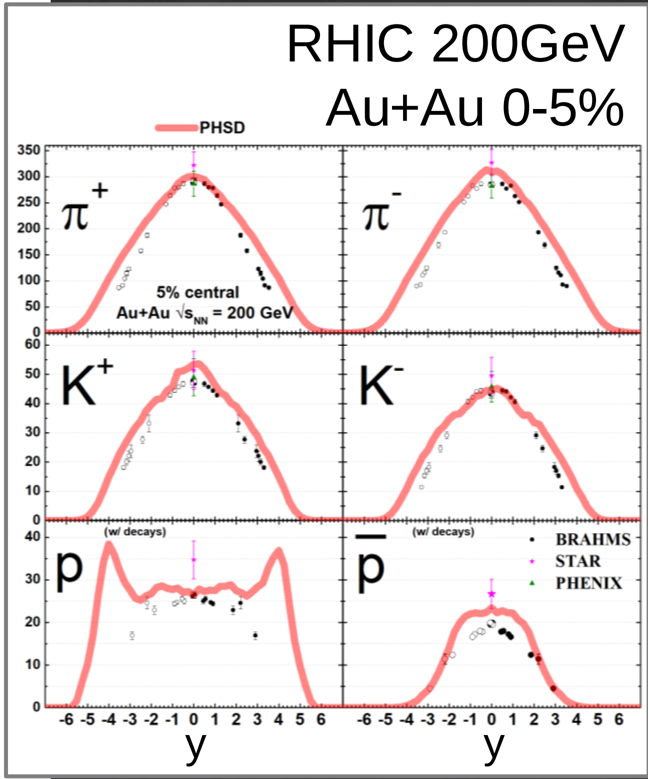


- enhanced particle production in the Au-going directions
- asymmetry increases with centrality of the collision

Adare et al. (PHENIX Collaboration), 1807.11928

p+Au collisions @ RHIC 200 GeV





symmetric colliding system

p+Au collisions @ RHIC 200 GeV

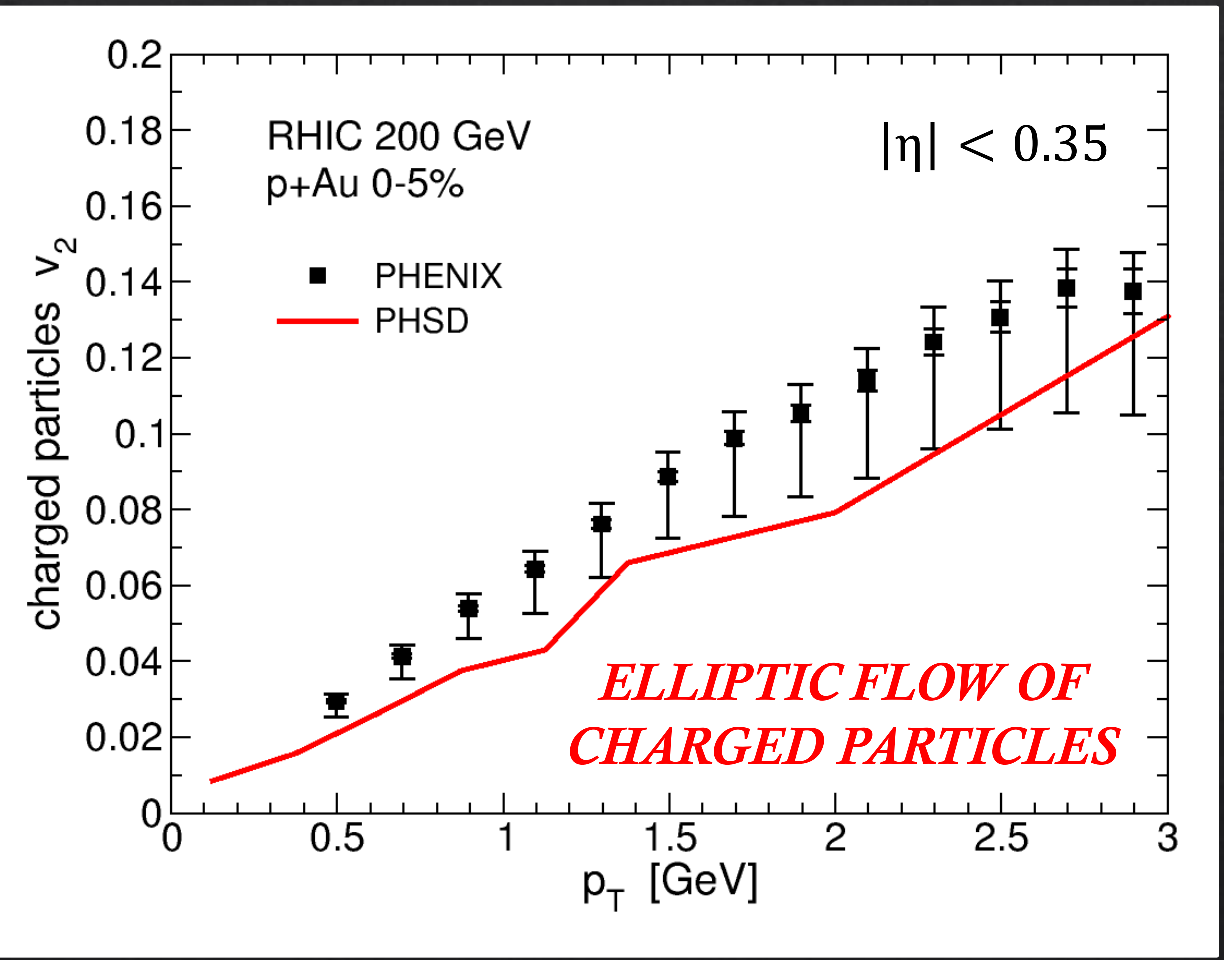
PRELIMINARY

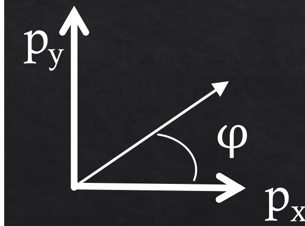
$$v_2(p_T) = \langle \cos 2[\varphi_i(p_T)] - \Psi_2 \rangle$$

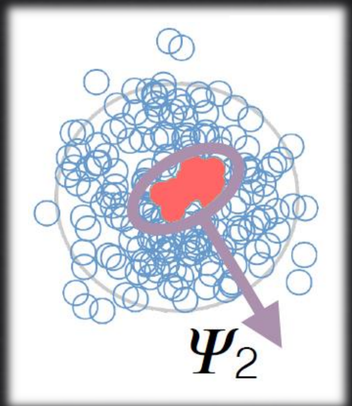
$$\Psi_2 = \mathrm{atan2}(Q_2^y, Q_2^x)$$

$$Q_2^x = \sum_i w_i \cos[2\varphi_i]$$

$$Q_2^y = \sum_i w_i \sin[2\varphi_i]$$







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

p+Au collisions @ RHIC 200 GeV

PRELIMINARY

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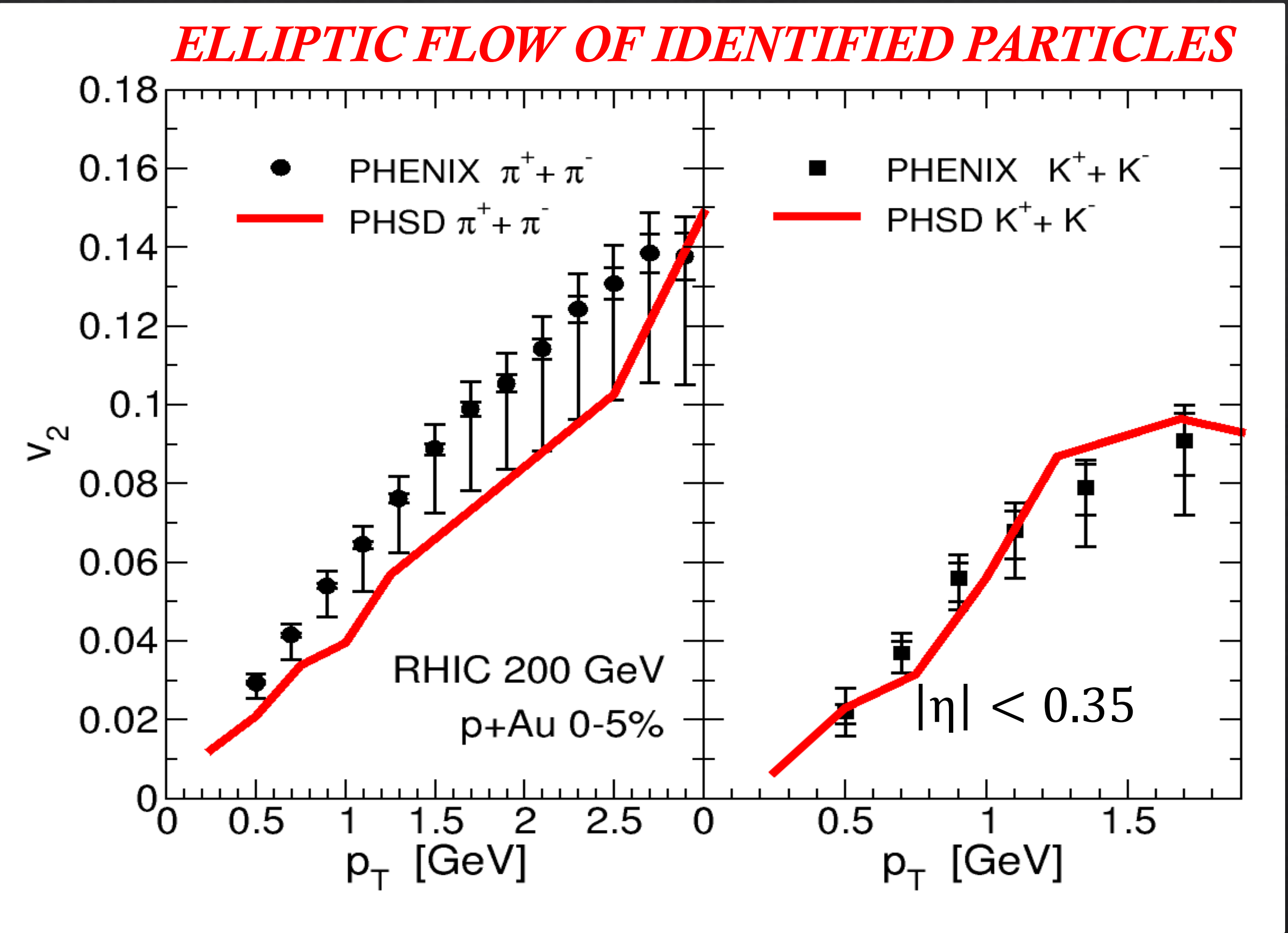
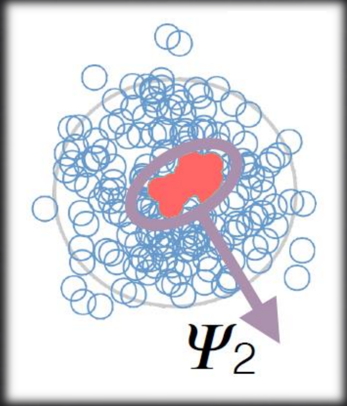
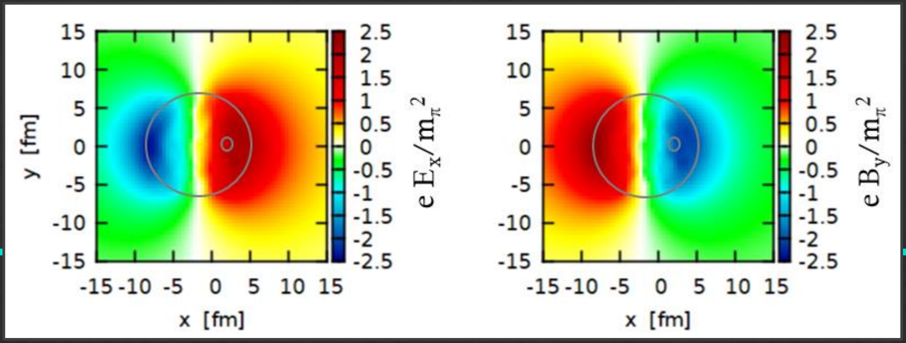




Experimental data: Adare et al. (PHENIX Collaboration), PRC 97 (2018) 064904



CONCLUDING….

- The Parton-Hadron-String-Dynamics (PHSD) describes the entire dynamical evolution of heavy ion collisions within one single theoretical framework
- PHSD has been extended to include in a consistent way the intense electromagnetic fields produced in the very early stage of the collision
- Preliminary 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

…LOOKING FORWARD

- Evolution dynamics and properties of the matter created in small and asymmetric systems (e.g. p+Au, d+Au, ^{3}He+Au @ RHIC, p+Pb @ LHC)
- Influence of the intense electric field created in asymmetric collisions on the formation of the quark-gluon plasma

Thank you
for your attention!