Workshop on Heavy Ion Physics and Compact Stars

Cuba (online) – 2nd December 2020

Hipstars

Exploring the mechanisms generating the directed flow in relativistic nuclear collisions

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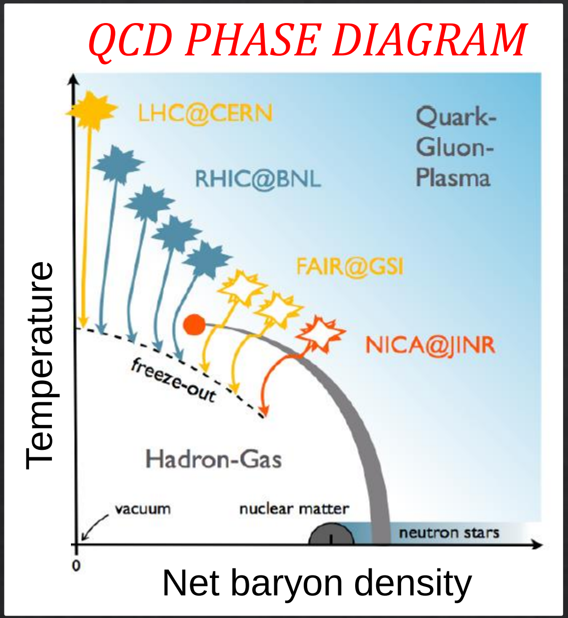
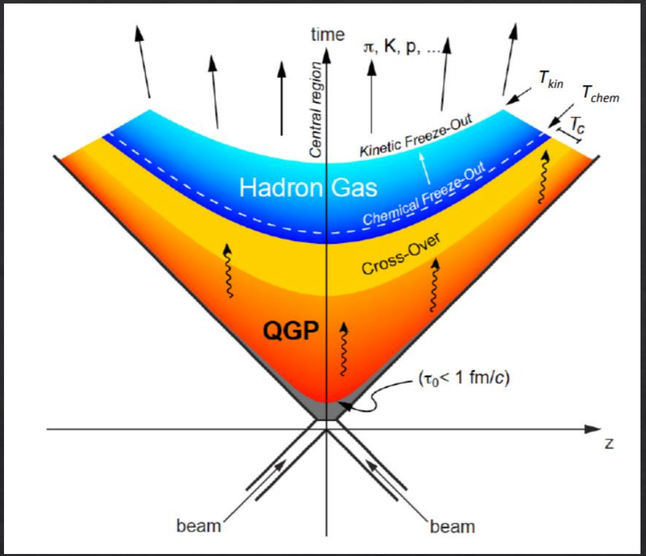
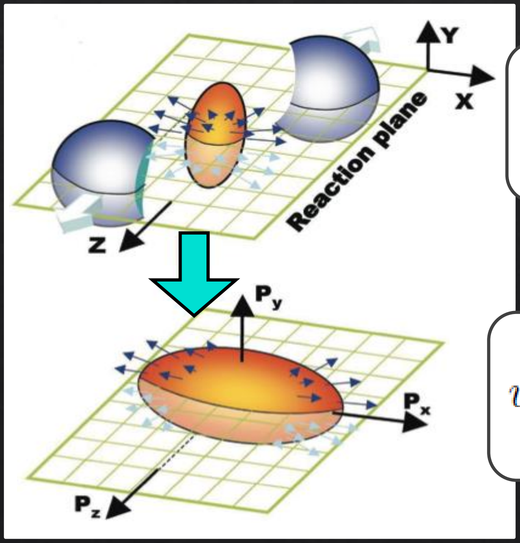
CRC-TR 211 Strong-interaction matter under extreme conditions

Heavy-ion collisions and quark-gluon plasma



Heavy-Ion Collisions (HICs)
at relativistic energy
recreate the extreme condition
of temperature and density
required to form the
Quark-Gluon Plasma (QGP)





eccentricity

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

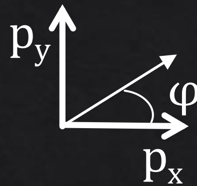
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

elliptic flow

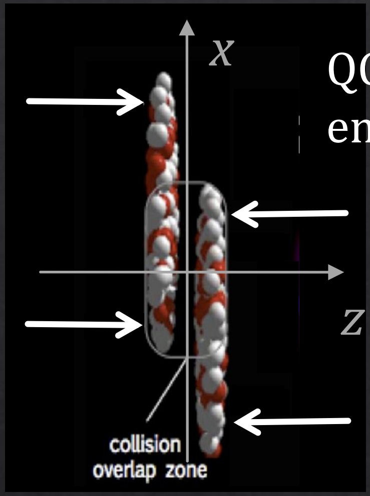
Anisotropic radial flow described by the Fourier coefficients of the azimuthal particle distributions w.r.t. the reaction plane

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

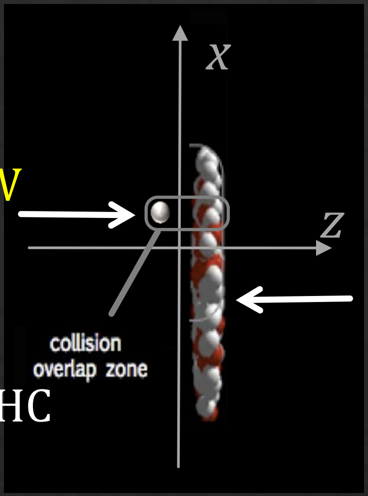
Quark-Gluon Plasma
hydrodynamical behaviour
with collective flows formation



Small colliding systems



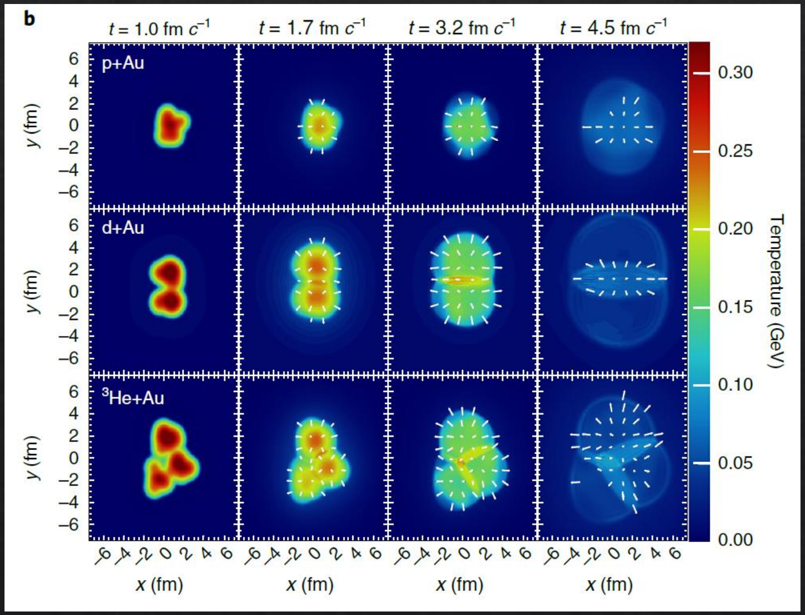
QGP initially expected only in high energy collisions of two heavy ions



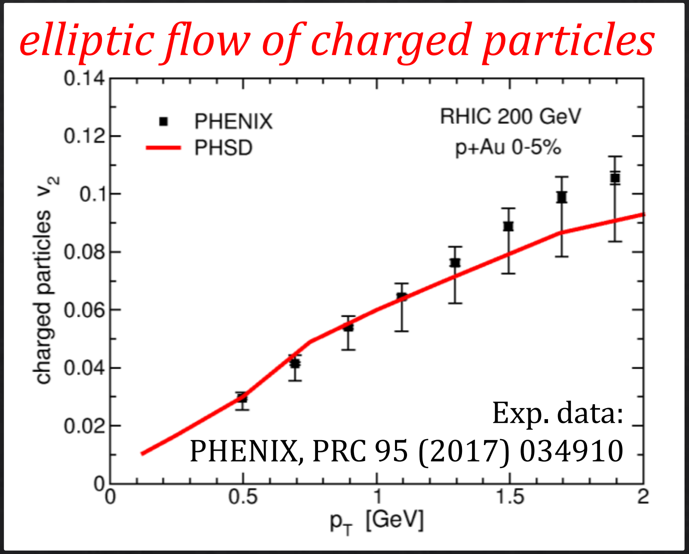
SIGNATURES OF COLLECTIVE FLOW FOUND IN SMALL SYSTEMS

in high-multiplicity events of

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



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



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

Strong fields in relativistic nuclear collisions

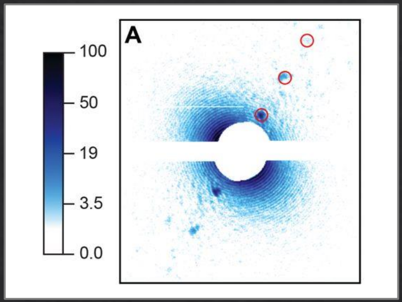
✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG VORTICITY

tornado cores

$\sim 10^{-1}\ s^{-1}$

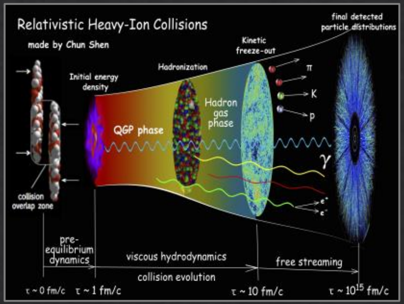
Jupiter's spot

$\sim 10^{-4}\ s^{-1}$



He nanodroplets

$\sim 10^{7}\ s^{-1}$



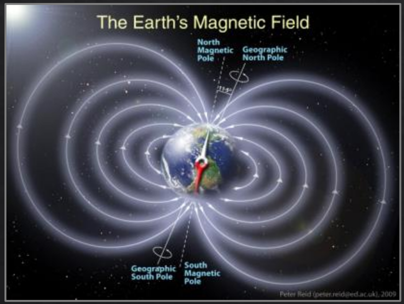
urHICs

$\boldsymbol{\sim 10^{22}\text{–}10^{23}\ s^{-1}}$

vorticity

ω

✓ INTENSE ELECTROMAGNETIC FIELDS (EMF)



Earth's field

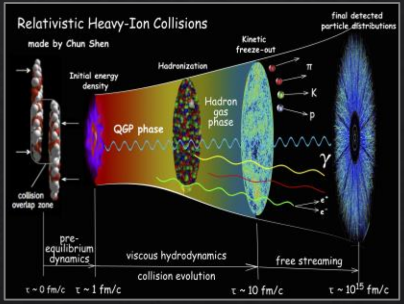
~ 1 G

laboratory

$\sim 10^{6}$ G

magnetars

$\sim 10^{14}\text{–}10^{15}$ G



urHICs

$\boldsymbol{\sim 10^{18}\text{–}10^{19}}$ **G**

magnetic field

B

Transport kinetic equations

Evolution of the fireball described at a microscopic level by the **transport equations**

$$\left(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial_\nu^p\right) f = \mathcal{C}[f]$$

RELATIVISTIC BOLZTMANN EQUATIONS

Free streaming

Field interaction

change of ***f*** due to interactions of the plasma with a field (*e.g.* color and **electromagnetic fields**)

collision integral

change of **f** due to collision processes responsible for deviations from ideal hydro ($\eta/s \neq 0$)

Generalization to off-shell dynamics

Parton-Hadron String Dynamics (PHSD)

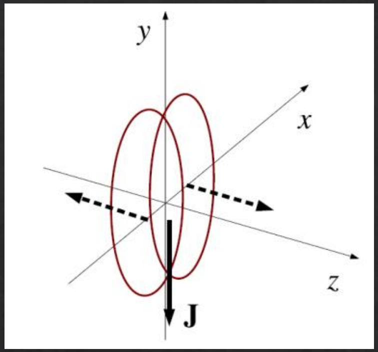
instead of Boltzmann eqs. ⟶ Kadanoff-Baym eqs.

instead of particle distribution function ***f*** ⟶ Green functions with complex self-energies

Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)
Bratkovskaya, et al., Nucl Phys. A 856, 162 (2011)

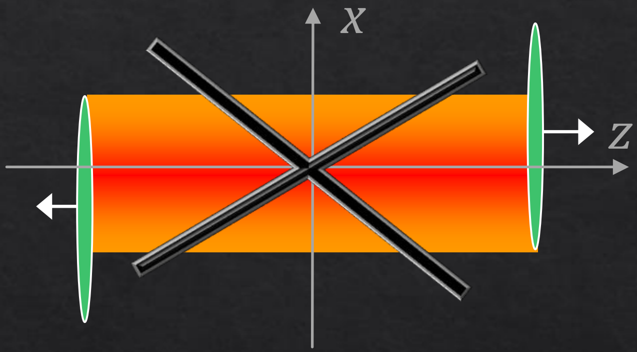
Xu and Greiner, Phys. Rev. C 79, 014904 (2009)
Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

The vortical quark-gluon plasma

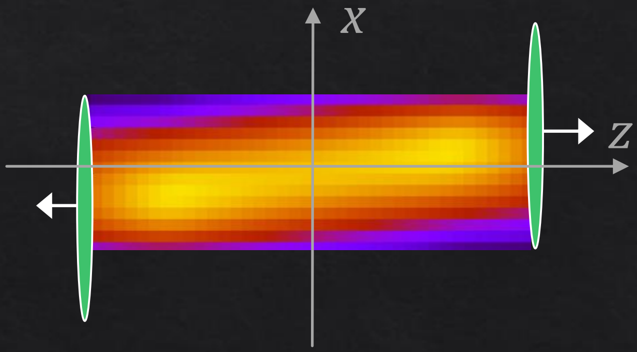


Huge **orbital angular momentum** of the colliding nuclear system

- in ultrarelatvistic HICs **$J \approx 10^5$ - 10^6 ħ**
- dominated by the y component perpendicular to the reaction plane
- partly trasferred to the plasma generating an asymmetry in local participant density from forward and backward going nuclei

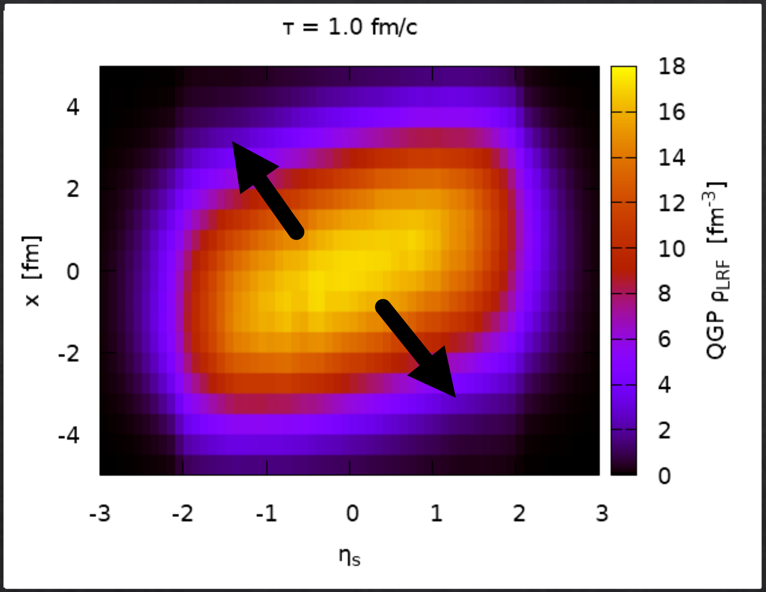


Not a symmetric energy distribution...



...but a TILTED FIREBALL on the reaction plane

Vorticity and directed flow



initial profile of QGP density
in the $x - \eta_s$ plane
(η_s: spacetime rapidity)

$$\rho(x_\perp, \eta_s) = \rho_0 \frac{W(x_\perp, \eta_s)}{W(0,0)} \exp\left[-\frac{(|\eta_s| - \eta_{s0})^2}{2\sigma_\eta^2} \theta(|\eta_s| - \eta_{s0}) \right]$$

$$W(x_\perp, \eta_s) = 2\left(N_A(x_\perp) f_-(\eta_s) + N_B(x_\perp) f_+(\eta_s)\right)$$

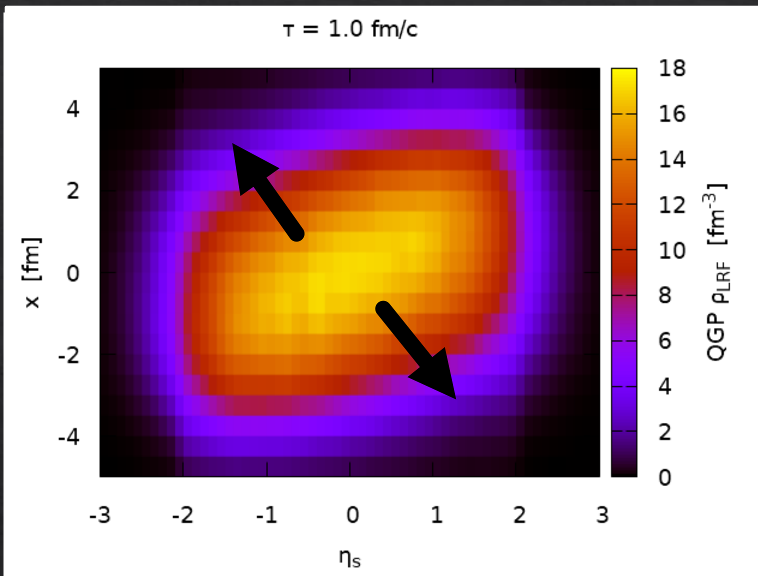
$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \frac{\eta_s + \eta_m}{2\eta_m} & -\eta_m \le \eta_s \le \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$

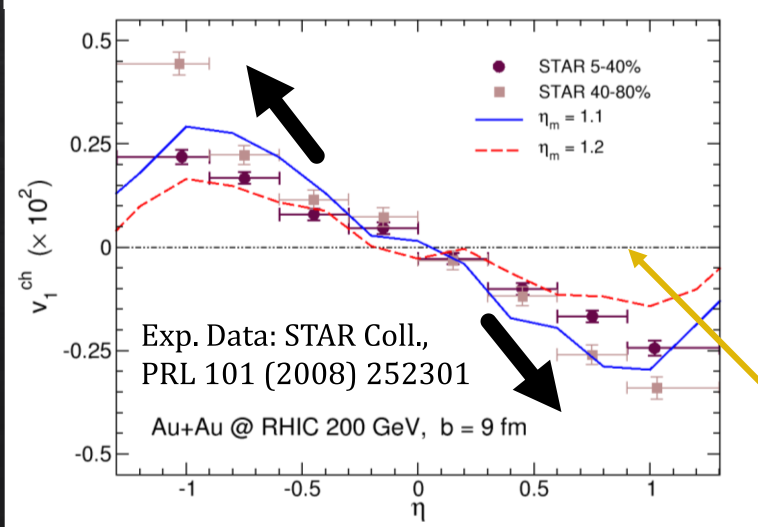
asymmetry in local participant density
from forward and backward going nuclei

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)

Oliva, Plumari and Greco, 2009.11066

Vorticity and directed flow





$$\rho(x_\perp,\eta_s) = \rho_0 \frac{W(x_\perp,\eta_s)}{W(0,0)} \exp\left[-\frac{(|\eta_s|-\eta_{s0})^2}{2\sigma_\eta^2}\theta(|\eta_s|-\eta_{s0})\right]$$

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The huge angular momentum and the tilt of the fireball induce in the QGP a DIRECTED FLOW

$$v_1 = \langle \cos\varphi \rangle = \langle p_x/p_T \rangle$$

collective sidewards deflection of particles along the x direction

The tilt of the fireball induce a negative slope in the η dependence of the v_1 of bulk particles

$v_1 = 0$ *if the fireball is not tilted*

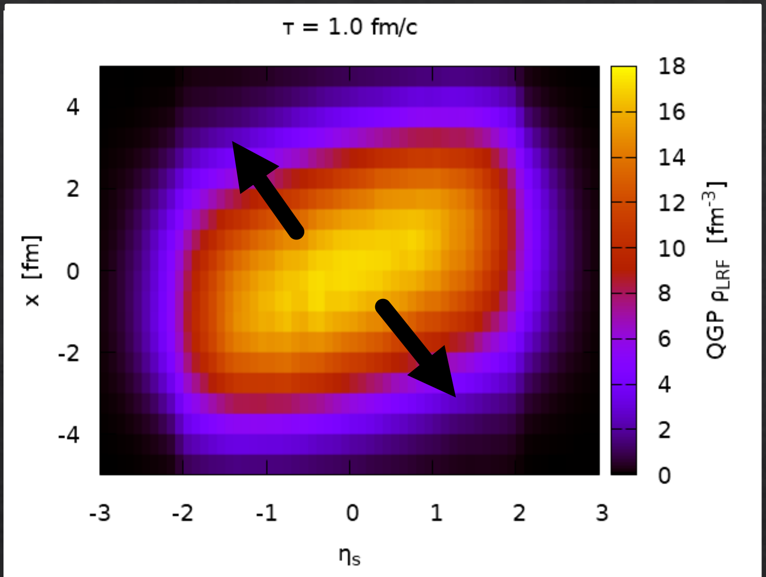
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

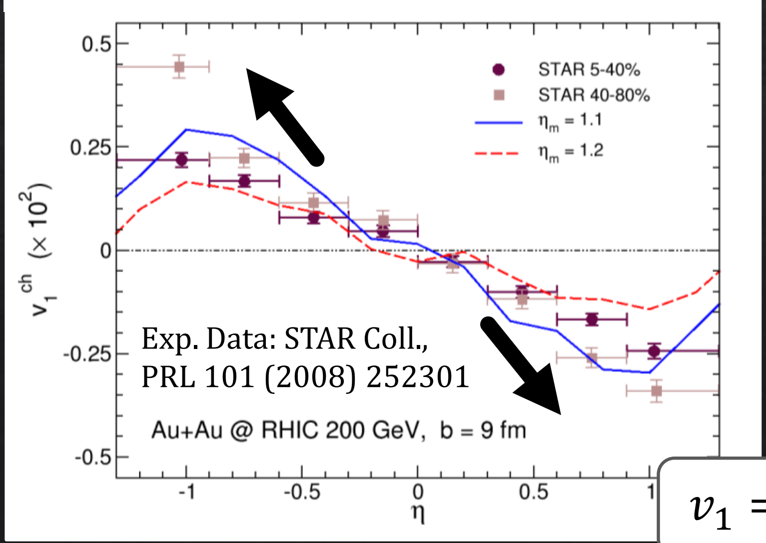
PSEUDORAPIDITY (θ: polar angle of particle momentum)

DIRECTED FLOW OF CHARGED PARTICLES

Oliva, Plumari and Greco, 2009.11066

Vorticity and directed flow





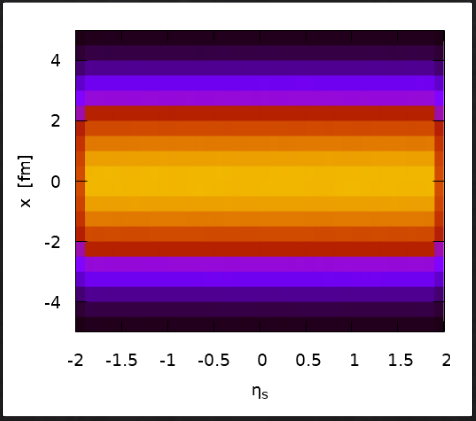
$v_1 = \langle p_x/p_T \rangle$

DIRECTED FLOW OF CHARGED PARTICLES

Are HEAVY QUARKS (HQs) affected by the initial tilt of the fireball and the v_1 of bulk medium?

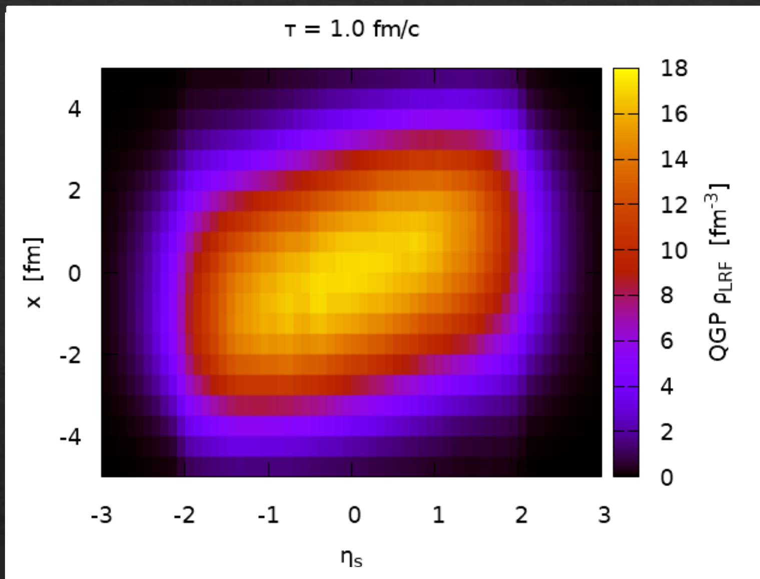
- **$m_{c,b} \gg \Lambda_{QCD}$**
  HQ produced in pQCD initial hard scatterings
- **$m_{c,b} \gg T_{HICs}$**
  negligible thermal production of HQ
- **$\tau_0^{HQ} < 0.1$ fm/c $\ll \tau_0^{QGP}$**
  HQ production much earlier than QGP formation
- **$\tau_{th}^{HQ} \approx \tau^{QGP} \approx$ 5-10 fm/c $\gg \tau_{th}^{QGP}$**
  HQ thermalization time comparable to QGP lifetime

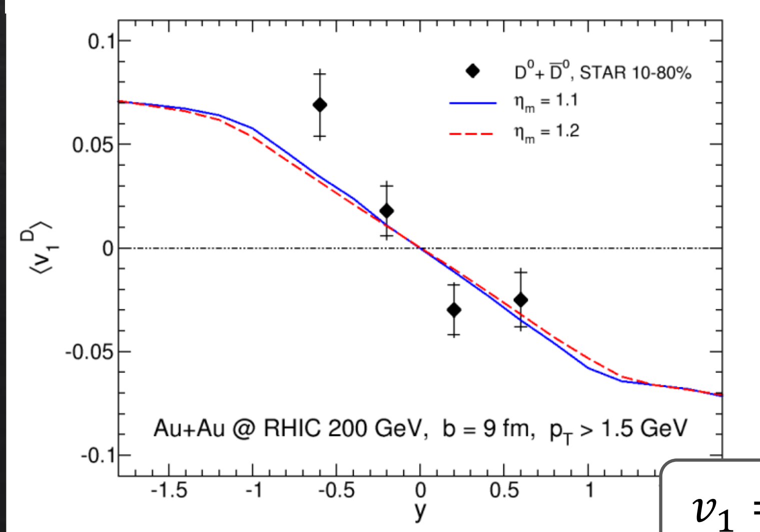
production points of HQs symmetric in the forward-backward hemispheres



 Oliva, Plumari and Greco, 2009.11066

Vorticity and directed flow





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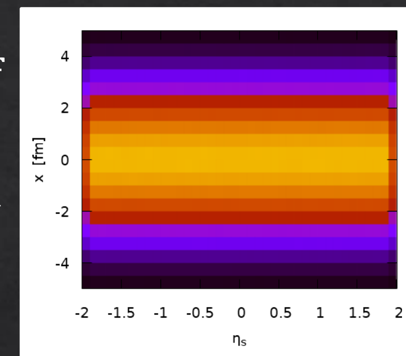


The directed flow of neutral *D* mesons is 20-30 times larger than that of light hadrons

Chatterjee and Bozek, Phys. Rev. Lett. 120, 192301 (2018)
STAR Collaboration, Phys. Rev. Lett. 123, 162301 (2019)

v_1 *(HQs)* $\gg$ v_1 *(QGP)*

origin of the large directed flow of HQs different from the one of light particles

$$v_1 = \langle p_x / p_T \rangle$$

$$y = \tanh^{-1} \frac{v_z}{c}$$

RAPIDITY
(v_z: longitudinal particle velocity)

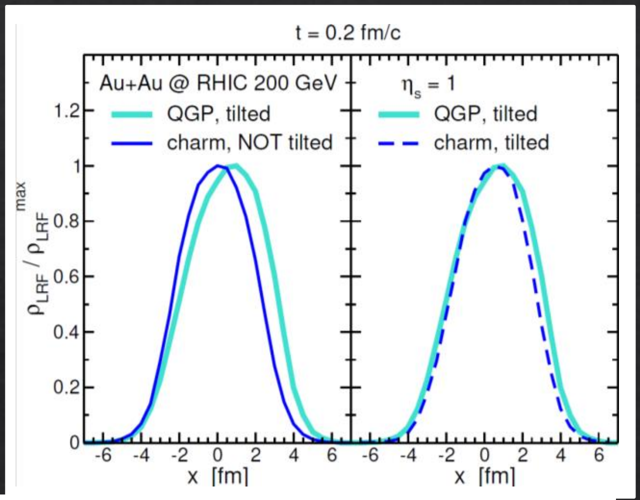
DIRECTED FLOW OF NEUTRAL D MESONS

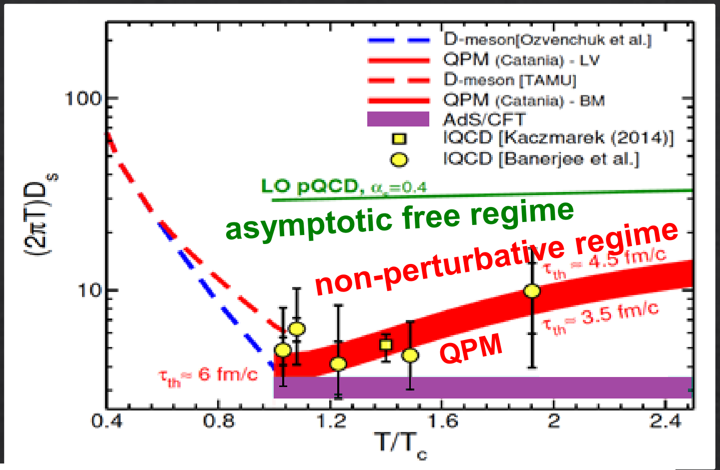
Oliva, Plumari and Greco, 2009.11066

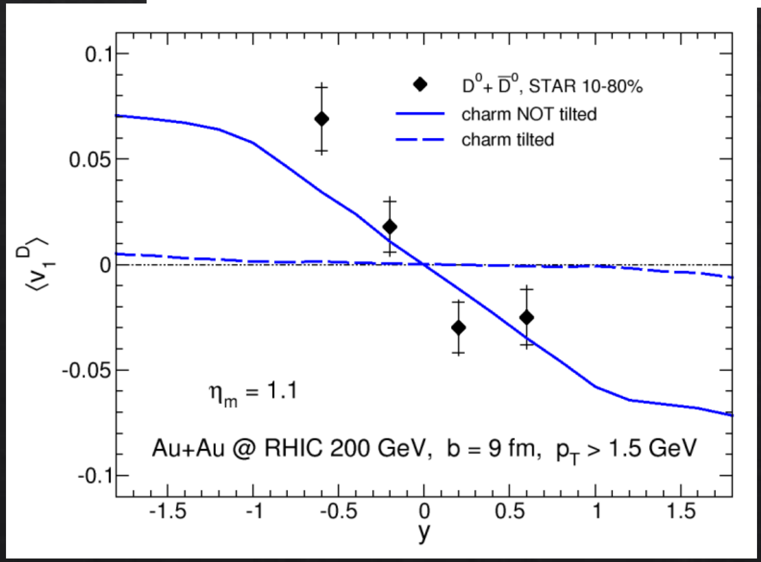
Origin of D meson directed flow

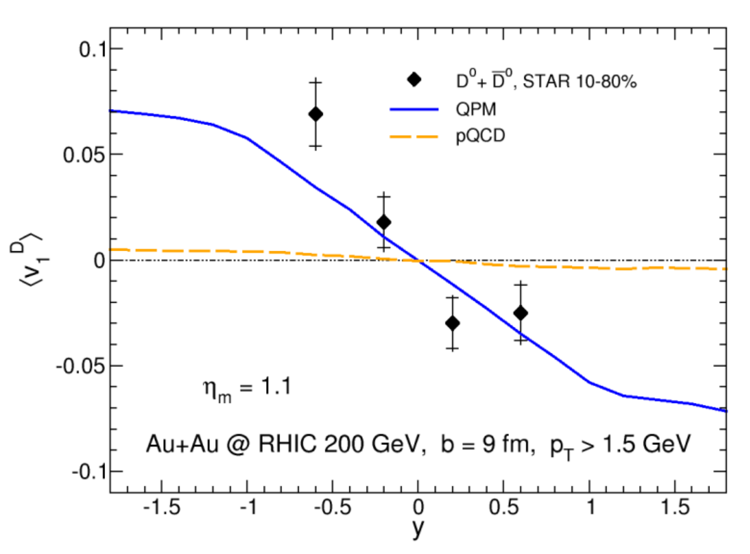
the longitudinal asymmetry between bulk and HQ initial profiles leads to a pressure push of the bulk on the HQs

Greco, Nucl. Phys. A 967, 200 (2017)





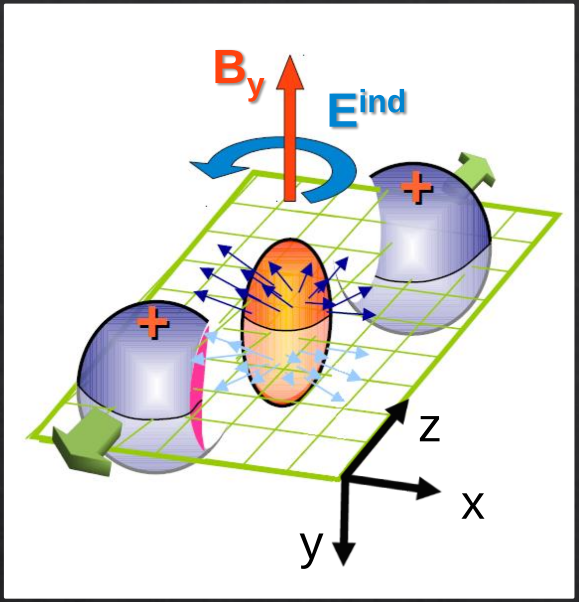




the transverse pressure gradient is effective because the HQ interaction in QGP is largely non-perturbative

Oliva, Plumari and Greco, 2009.11066

Electromagnetic fields in HICs

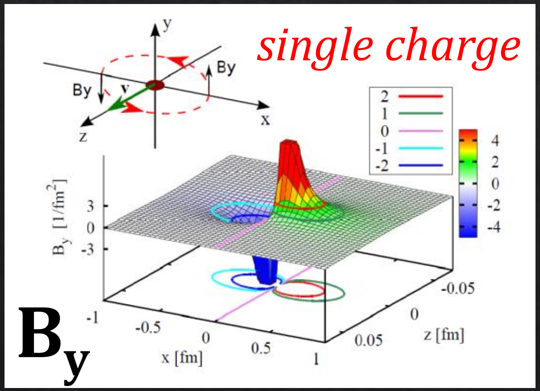


Huge **magnetic field** in the overlapping area of the collision

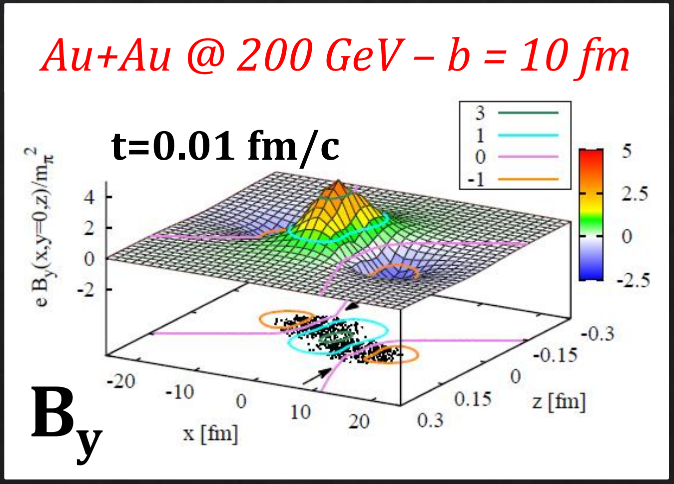
- in ultrarelatvistic HICs **eB ≈ 5-50 m_π^2 ~ 10^{18}-10^{19} G**
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

Kharzeev, McLerran and Warringa, Nucl. Phys. A 803, 227 (2008)
Skokov, Illarionov and Toneev, Int. J. Mod. Phys. A 24, 5925 (2009)

Voronyuk, Toneev, Cassing, Bratkovskaya, Konchakovski and Voloshin (HSD), Phys. Rev. C 83, 054911 (2011)



in a nuclear collision the EMF are a superposition of the fields produced by all moving charges



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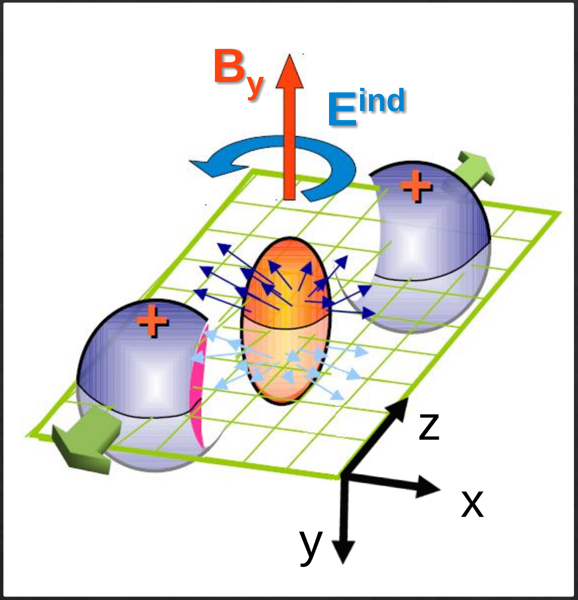

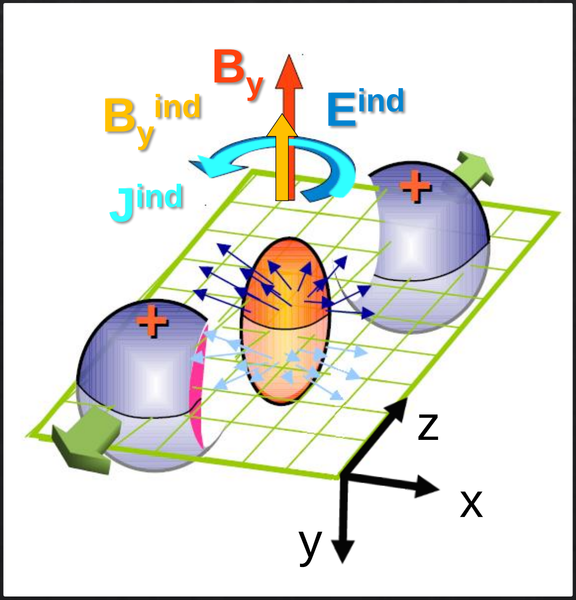

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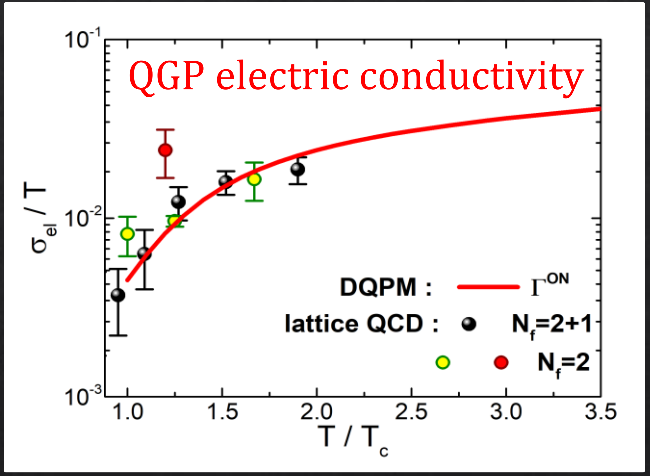
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

Theoretical calculations indicates that QGP is a good electric conductor

Ohm's law

$$J = \sigma_{el} E$$



Soloveva, Moreau and Bratkovskaya, Phys. Rev. C 101, 045203 (2020)

Charged currents are induced in the QGP by the Faraday electric field that in turn generates a magnetic field pointing towards the initial one

Electromagnetic fields in HICs

In a kinetic framework the transport equations should be coupled to the Maxwell equations for describing the EMF produced in HICs and their effect on the medium

$$\left\{\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla_{\boldsymbol{r}} + q(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})\cdot\nabla_{\boldsymbol{p}}\right\} f = \mathcal{C}[f]$$

TRANSPORT EQUATIONS

Lorentz force

$$\nabla\cdot\boldsymbol{B} = 0 \qquad \nabla\times\boldsymbol{E} = -\frac{\partial\boldsymbol{B}}{\partial t} \qquad \nabla\cdot\boldsymbol{E} = \rho \qquad \nabla\times\boldsymbol{B} = \frac{\partial\boldsymbol{E}}{\partial t} + \boldsymbol{j}$$

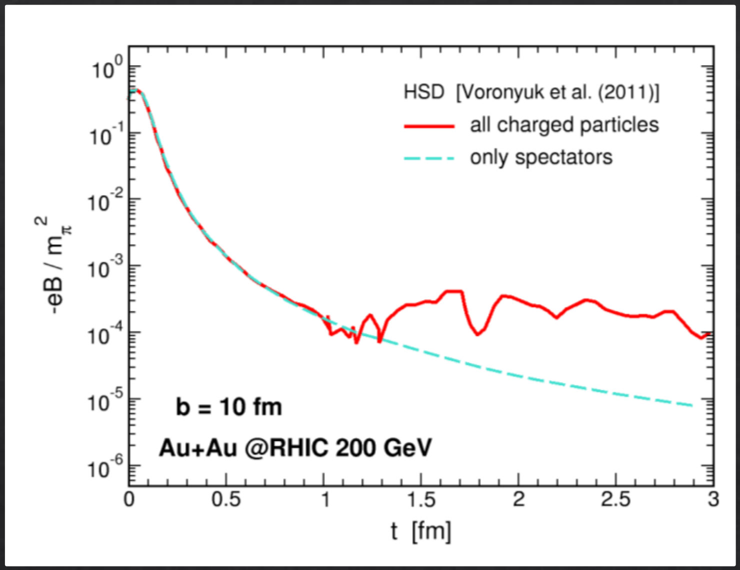
MAXWELL EQUATIONS

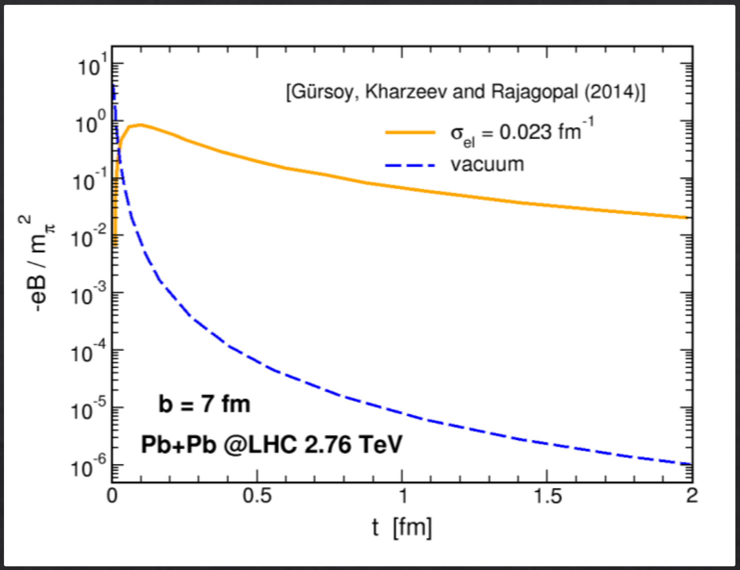
charge distribution **electric current**

For a complete description

- nontrivial electromagnetic response of the QGP (electromagnetic conductivity, chiral conductivity, …)
- consistent solution of evolution equations for the many-particle system and the EMF

Electromagnetic fields in HICs





Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)
Toneev *et al.* (PHSD), Phys. Rev. C 86, 064907 (2012)

Tuchin, Adv. High Energy Phys. 2013, 1 (2013)
Gursoy, Kharzeev, Rajagopal, Phys. Rev. C 89, 054905 (2014)

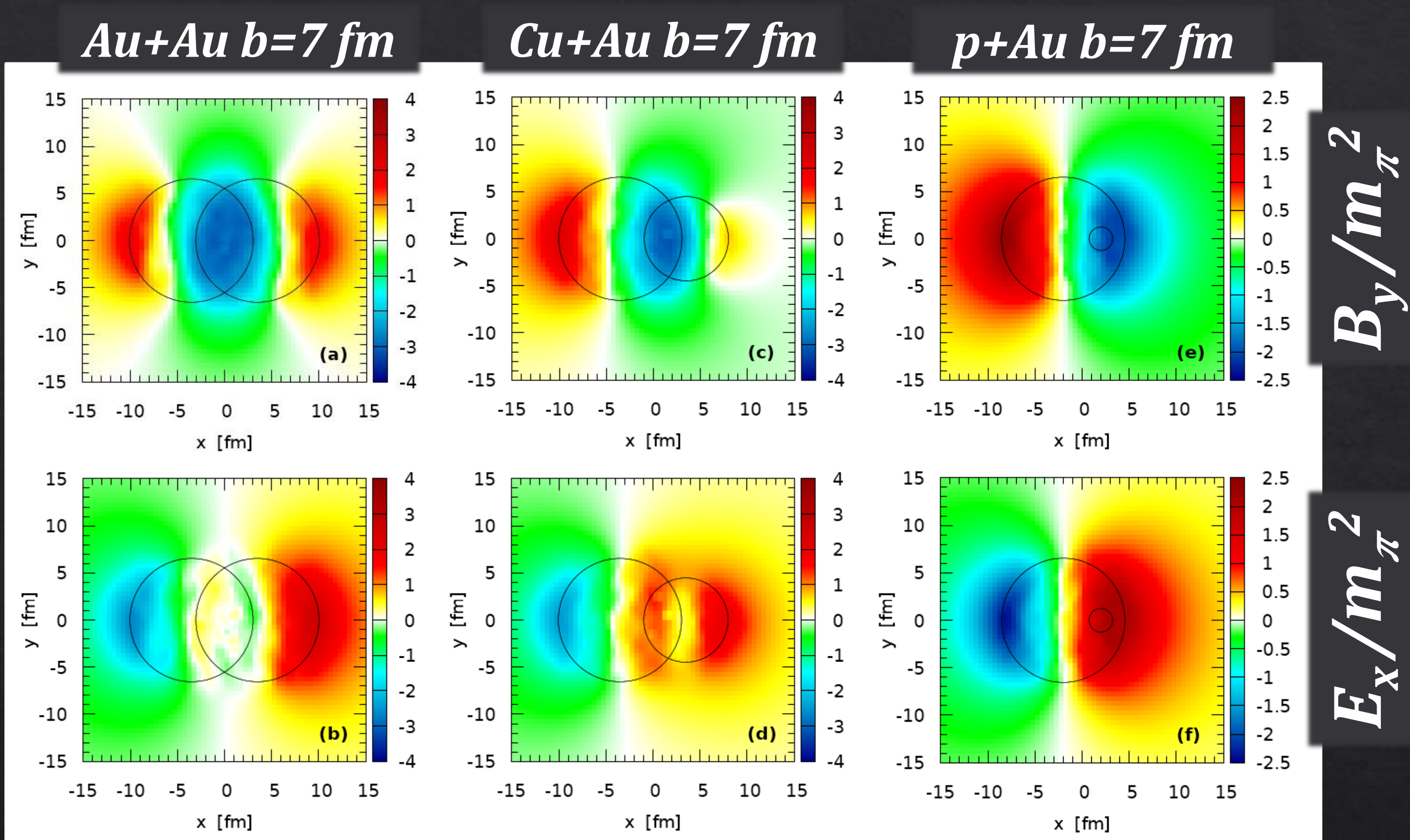
TIME EVOLUTION OF THE MAGNETIC FIELD

- maximal strength reached during nuclear overlapping time
- in the early-stage only due to spectators and dropping down by some orders of magnitude
- in the later-stage decay slowed down by the QGP contribution

presence of charge in the early stage

QGP transport properties

EMF from large to small systems

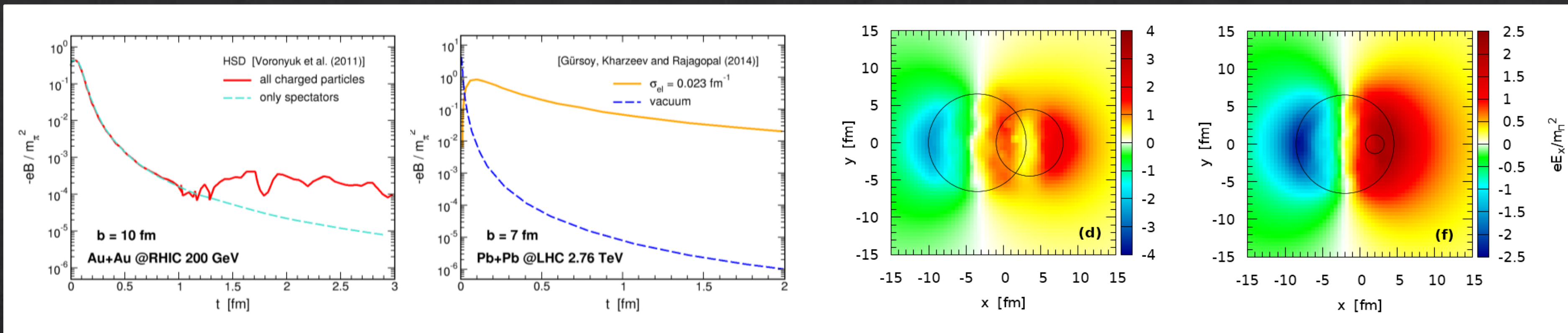


initial transvese profiles at RHIC 200 GeV

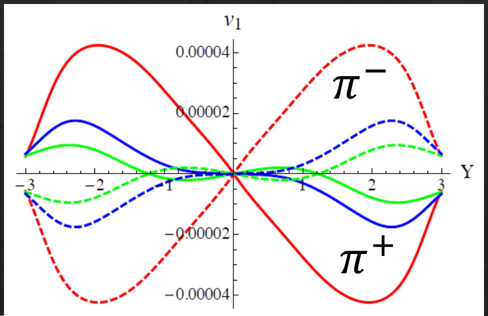
intense electric fields directed from the heavy nuclei to light one
in the overlap region of asymmetric colliding systems
due to the different number of protons in the two nuclei

Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014)
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Electromagnetic fields



The huge EMF induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge



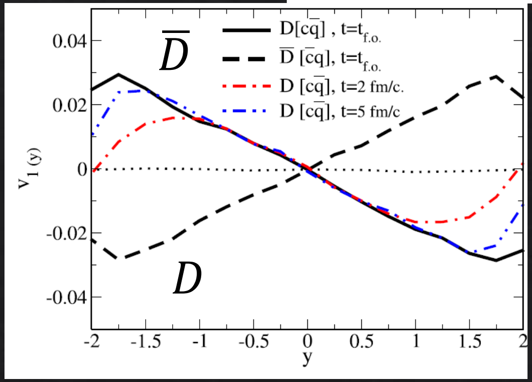
- difference in the v_1 of light hadrons $O(10^{-4}–10^{-3})$

  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014)

  Toneev, Voronyuk, Kolomeitsev and Cassing, Phys. Rev. C 95, 034911 (2017)

- difference in the v_1 of heavy mesons $O(10^{-2})$

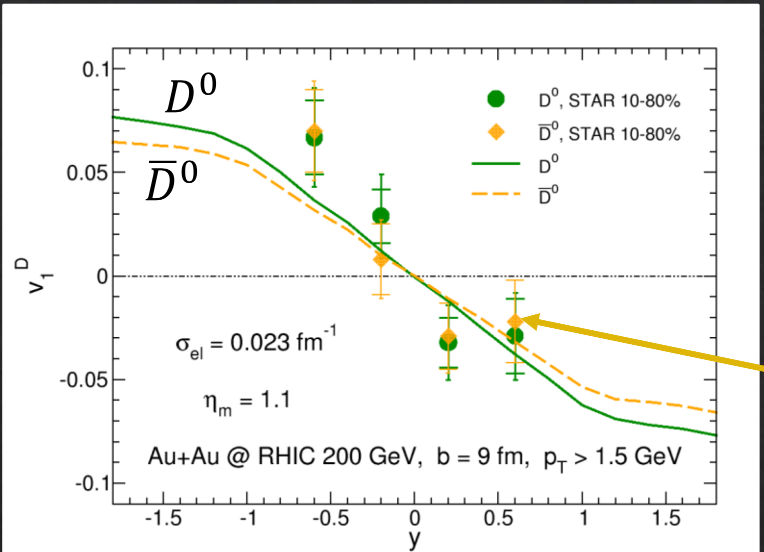
  Das, Plumari, Chatterjee, Alam, Scardina and Greco, Phys. Lett. B 768, 260 (2017)



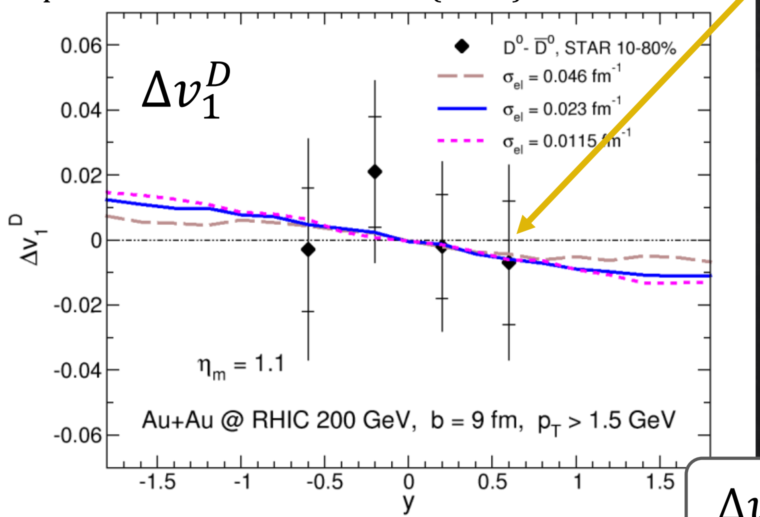
Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings, 2009.09727

reviews

Directed flow in A+A



Exp. data: STAR Coll., PRL. 123 (2019) 162301



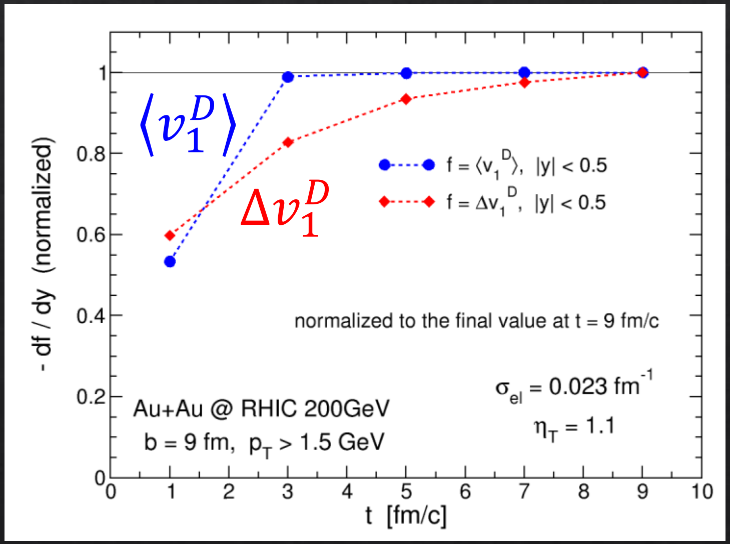
DIRECTED FLOW OF D MESONS

The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS

$$\Delta v_1\,(HQ) \gg \Delta v_1\,(QGP)$$

charm quarks are more sensitive to the EMF due to the early production

but Δv_1^{HQ} at top RHIC energy still consistent with zero due to the large exp. errors

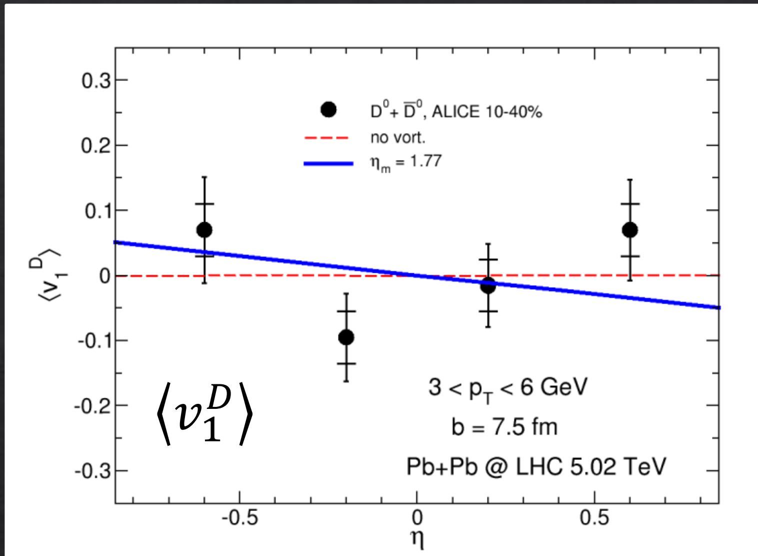


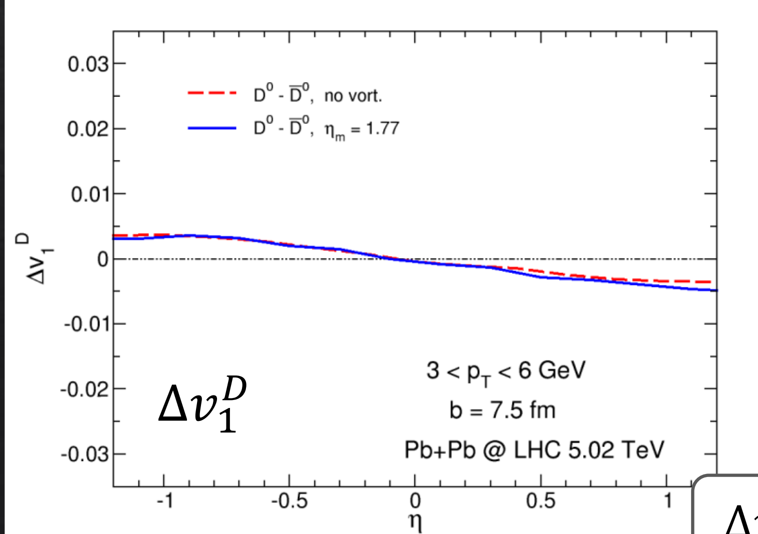
SLOPE TIME EVOLUTION

$$\Delta v_1^D = v_1(D^0) - v_1(\overline{D}^0)$$

Oliva, Plumari and Greco, 2009.11066

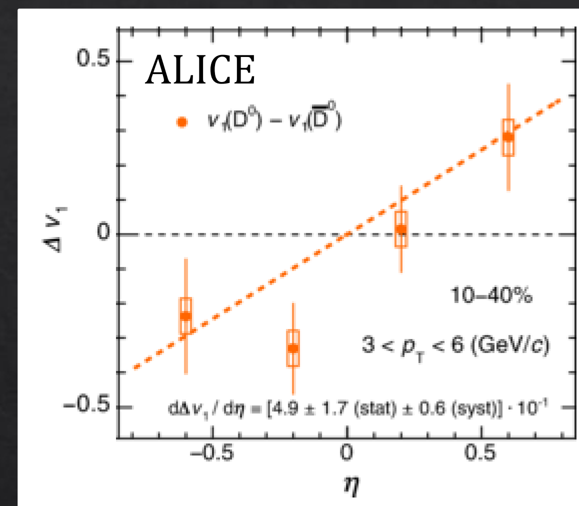
Directed flow in A+A





the slope of the combined v_1 of D^0 and $\bar{D}^0$ indicated by ALICE data is smaller than the one observed at RHIC and is consistent with zero

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



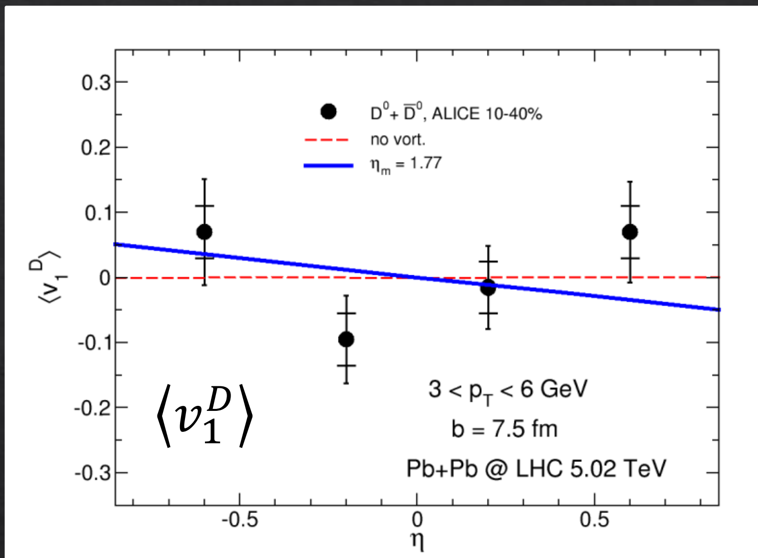
at LHC energy the current approaches cannot reproduce the ALICE data for the v_1 splitting

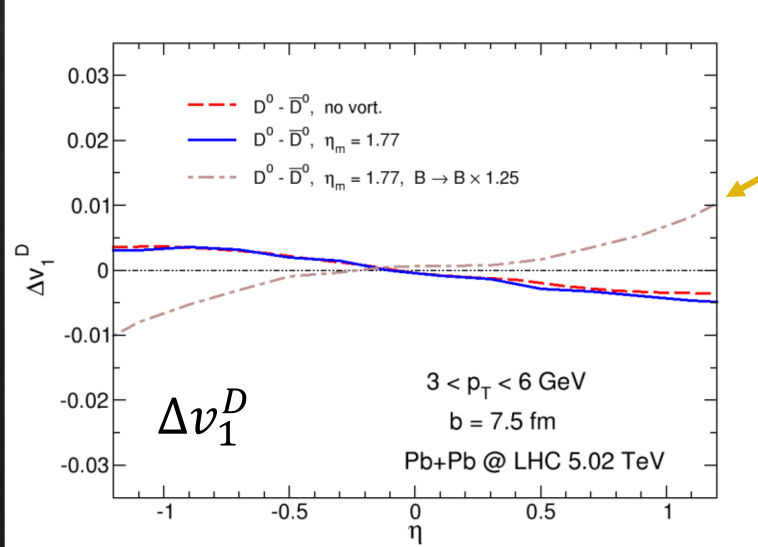
$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

DIRECTED FLOW OF D MESONS

Oliva, Plumari and Greco, 2009.11066

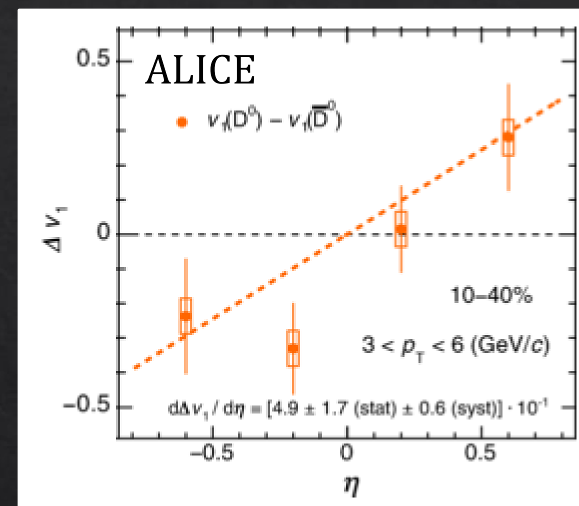
Directed flow in A+A





the slope of the combined v_1 of D^0 and $\bar{D}^0$ indicated by ALICE data is smaller than the one observed at RHIC and is consistent with zero

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



positive slope rising by hand the value of the magnetic field

if the splitting of neutral D mesons is of electromagnetic origin it is a proof of the formation of the QGP

DIRECTED FLOW OF D MESONS

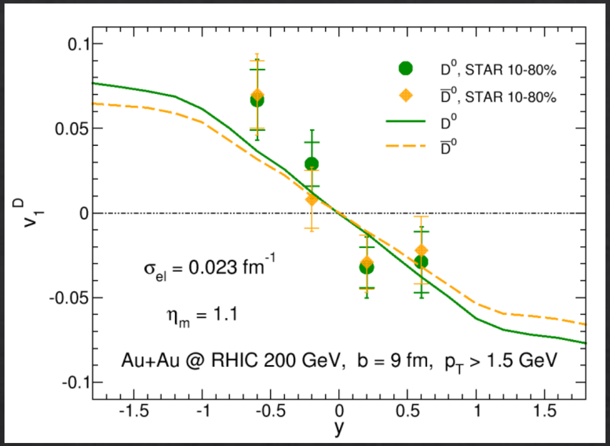
Oliva, Plumari and Greco, 2009.11066

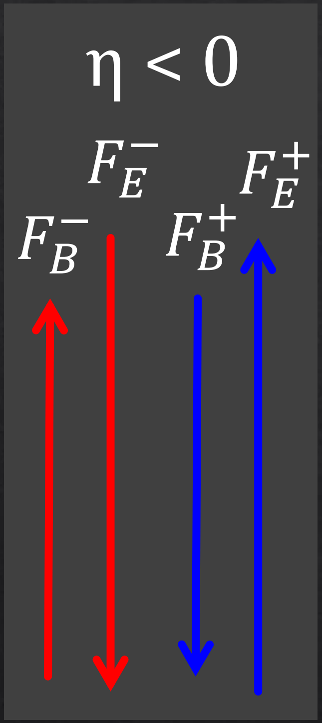
EMF and directed flow in A+A

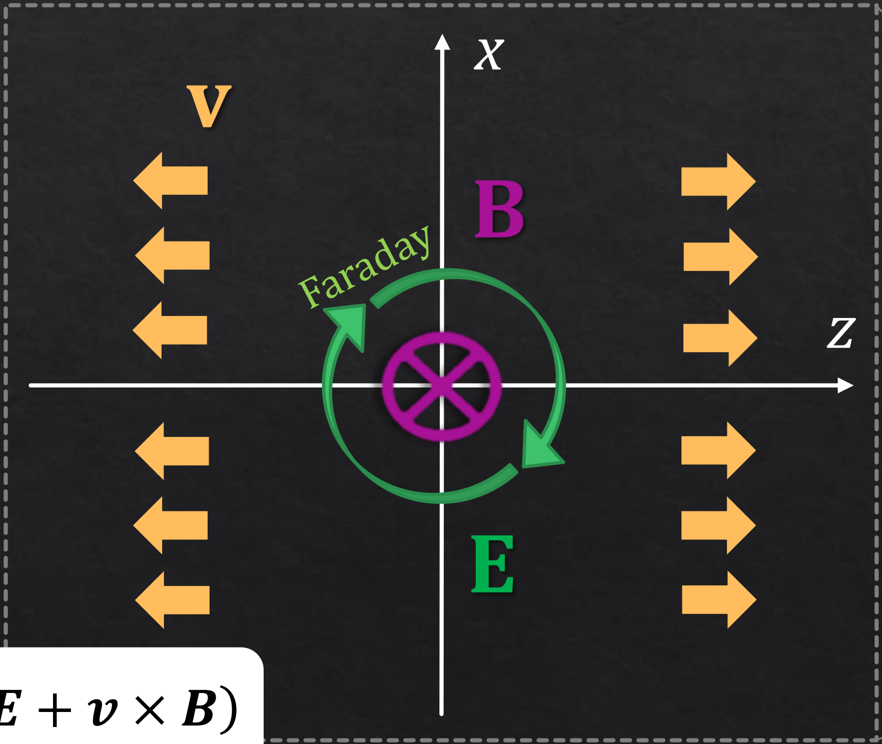
rapidity dependence of the
DIRECTED FLOW

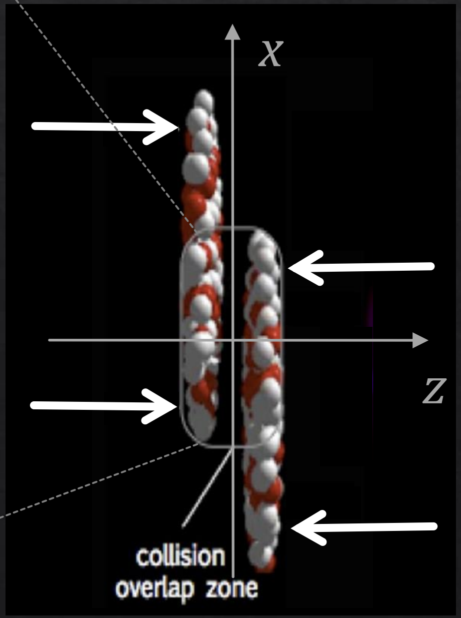
collective sidewards deflection of particles

$$v_1 = \langle \cos\varphi \rangle = \langle p_x / p_T \rangle$$



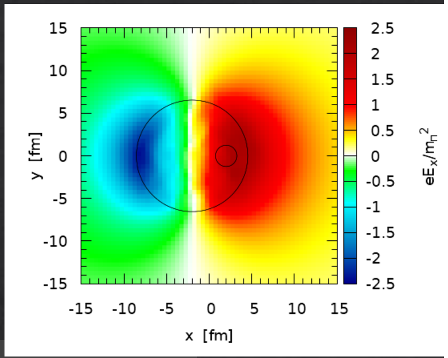


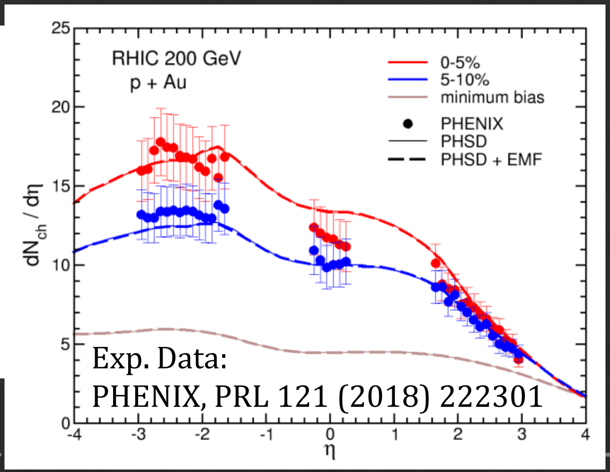




$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

EMF and directed flow in p+A

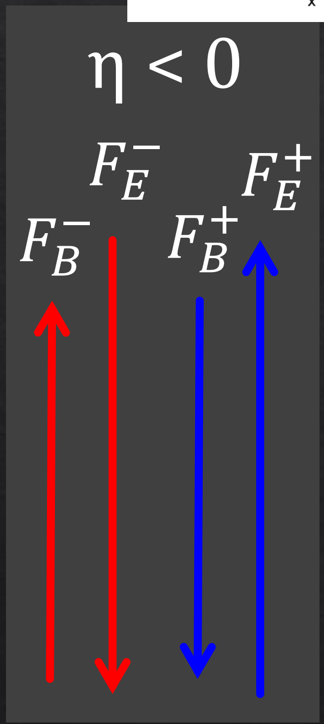


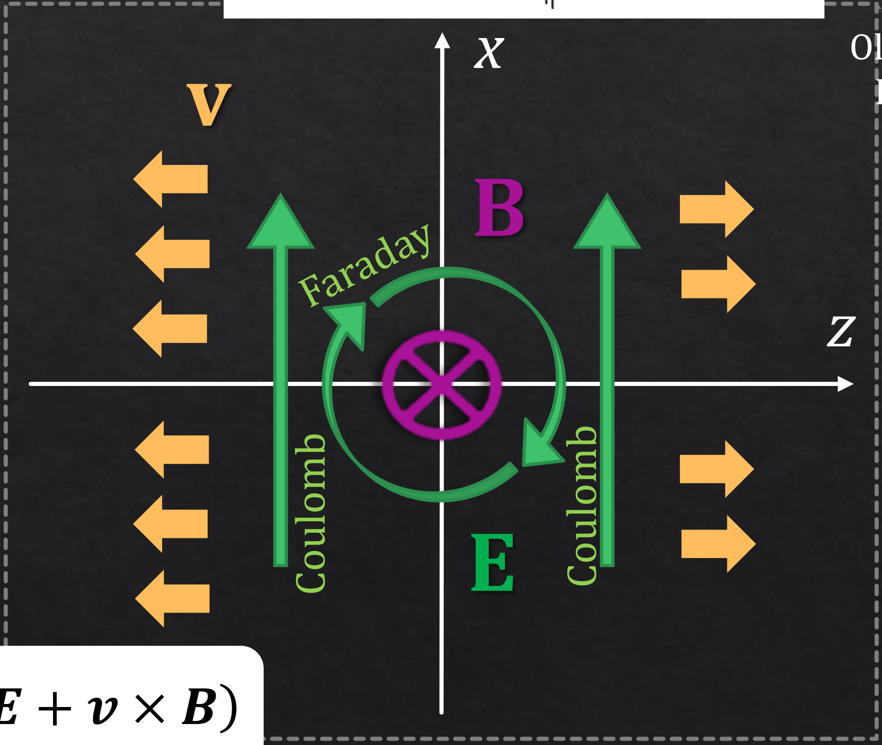


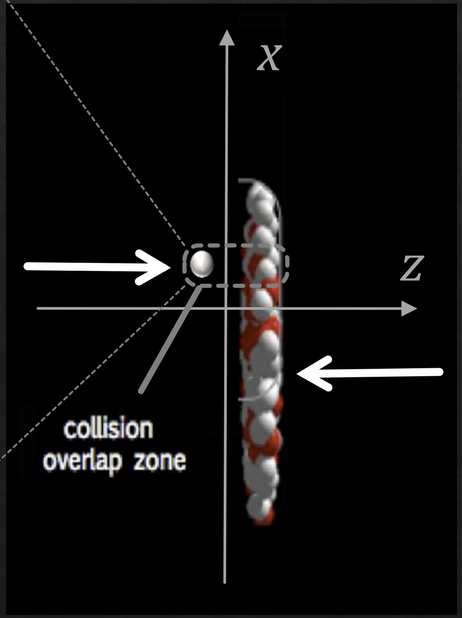
Asymmetry in charged particle and electric field profiles in p+Au

- enhanced particle production in the Au-going direction
- electric field directed from the heavy ion to the proton

Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)





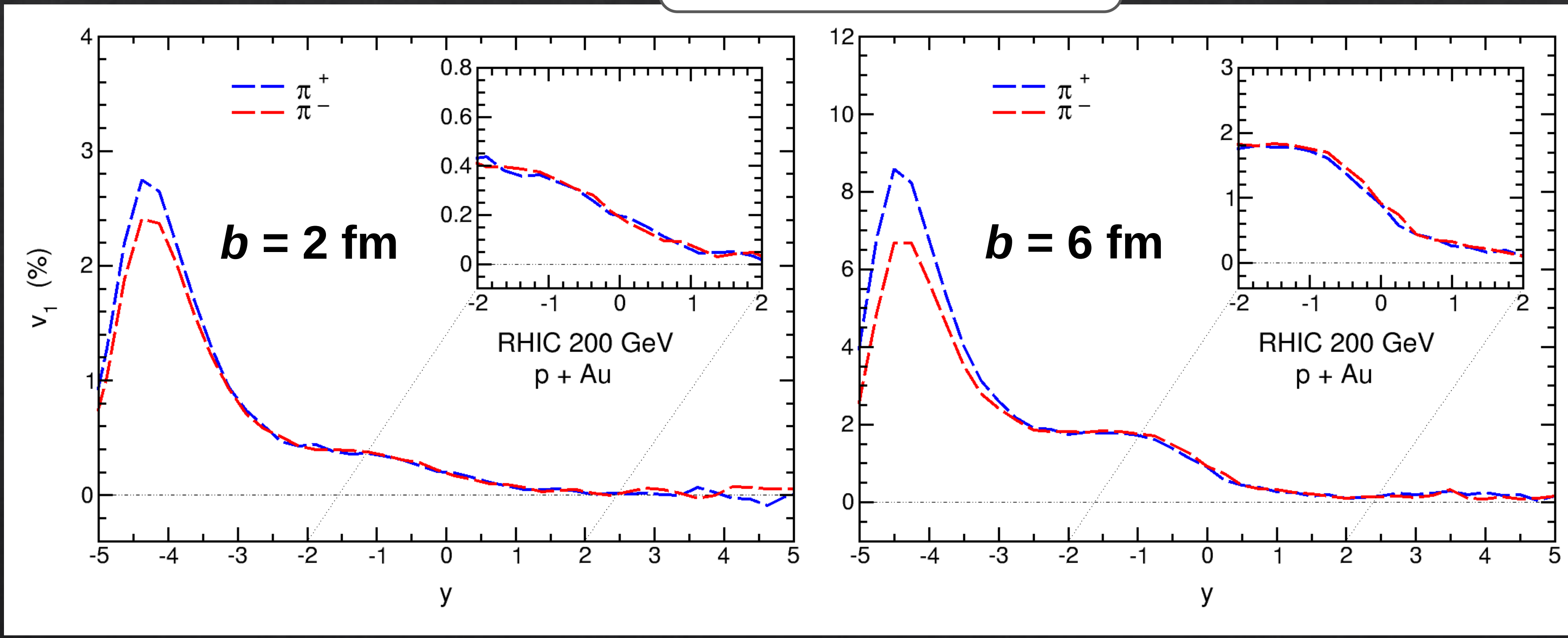


$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF PIONS

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



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

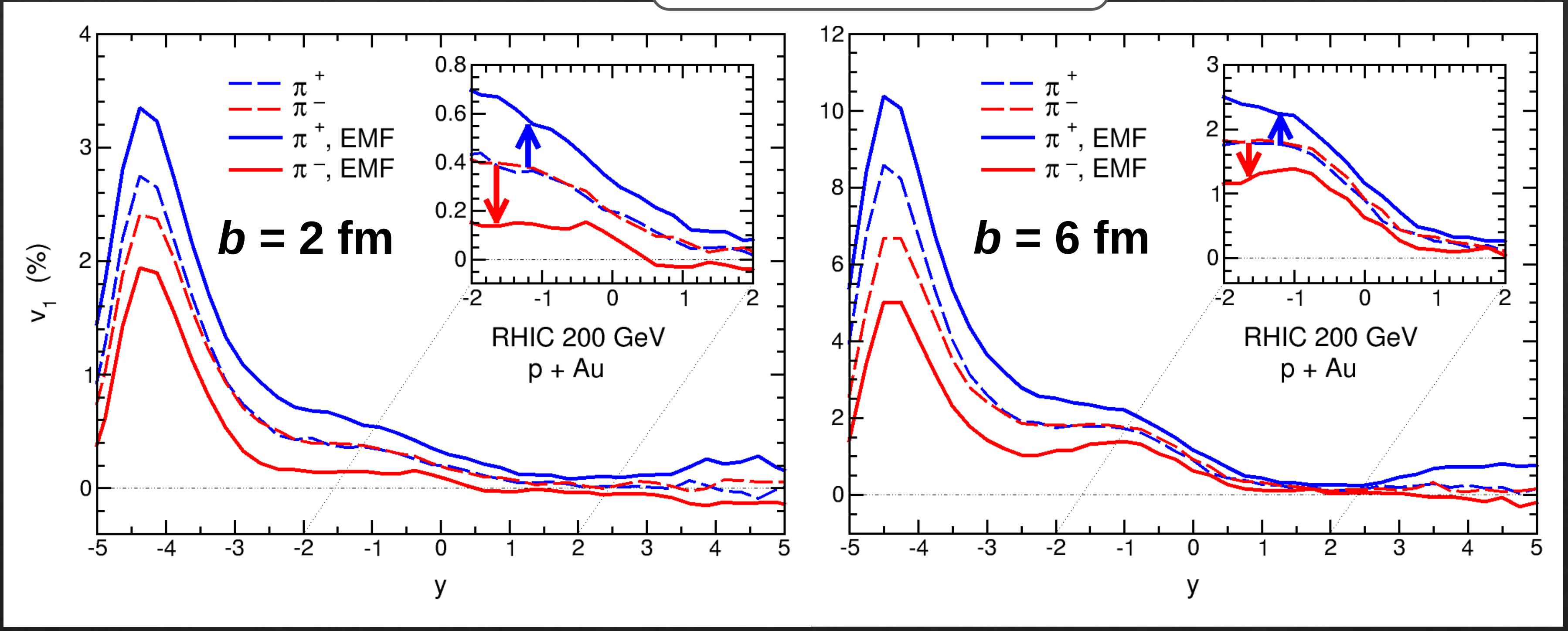
SPLITTING of light mesons

INDUCED BY THE ELECTROMAGNETIC FIELD?

Directed flow in p+A

rapidity dependence of the DIRECTED FLOW OF PIONS

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



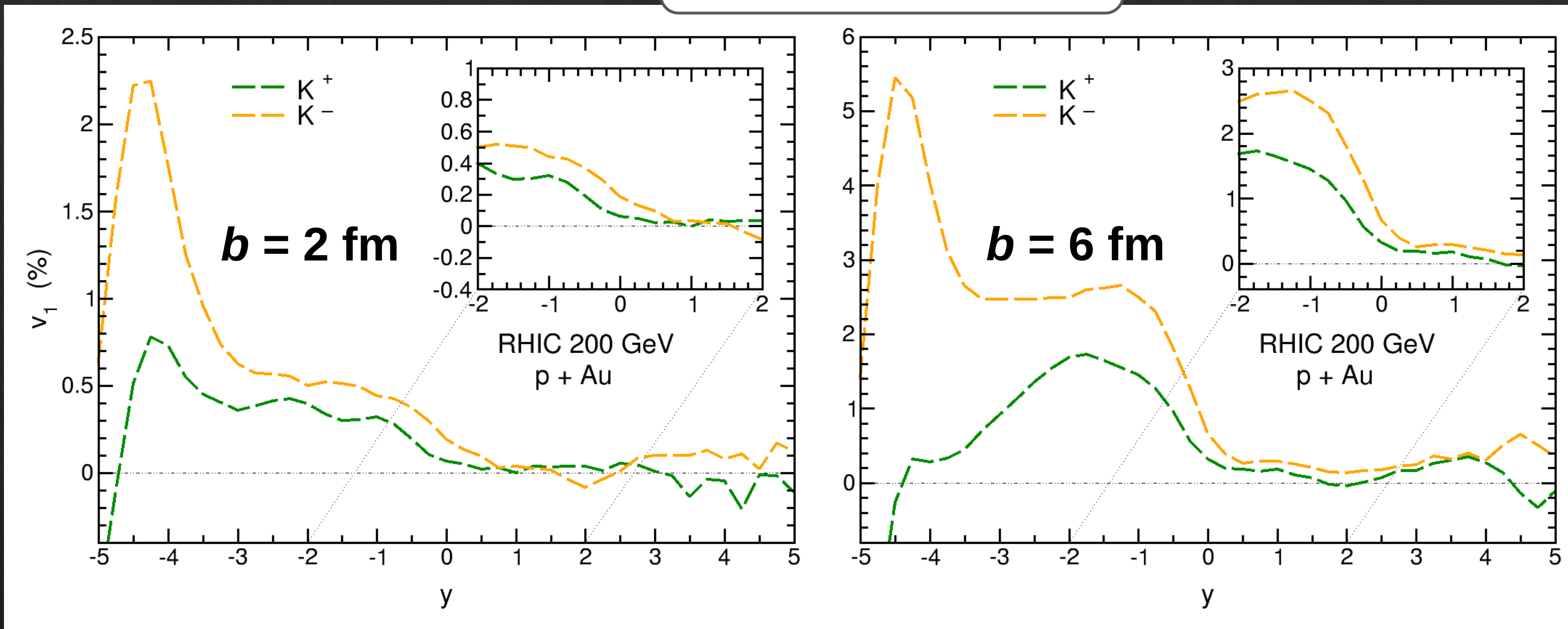
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Splitting of π^+ and π^- induced by the electromagnetic field

Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF KAONS

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

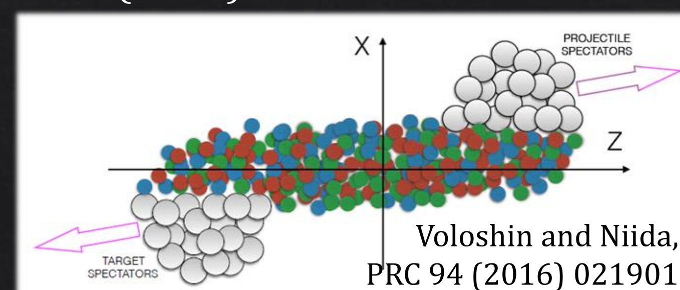


Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

different v_1 also in simulations without EMF

more contributions to K^+ $(\bar{s}u)$ with respect to K^- $(s\bar{u})$ from quarks of the initial colliding nuclei

STAR Coll., PRL 120 (2018) 062301

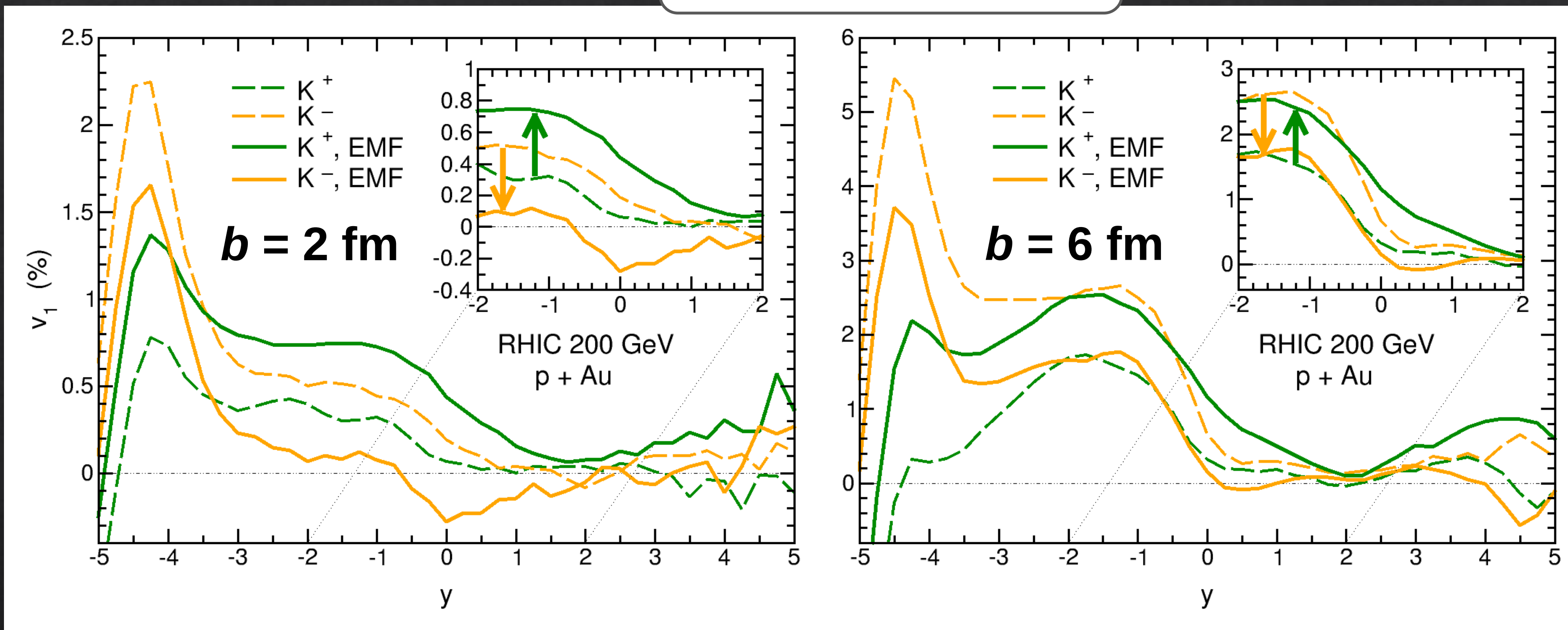


Voloshin and Niida, PRC 94 (2016) 021901

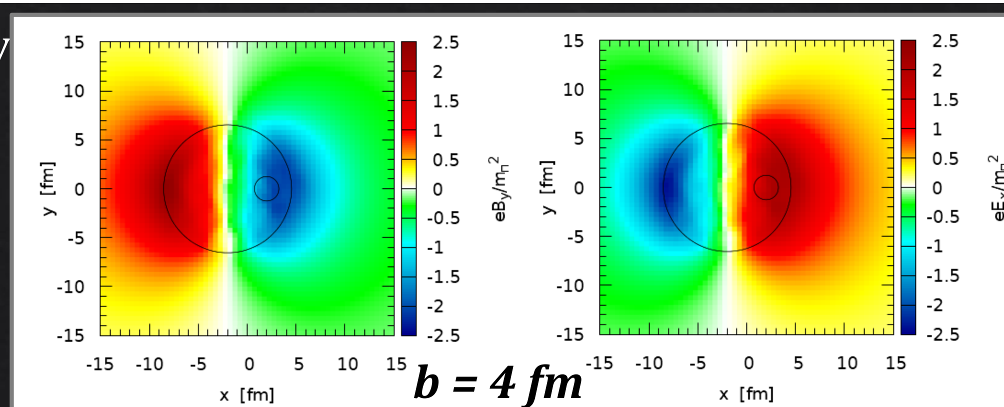
Directed flow in p+A

rapidity dependence of the DIRECTED FLOW OF KAONS

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



Oliva, Moreau, Voronyuk and Bratkovskaya



Splitting of K^+ and K^- induced by the electromagnetic field

Directed flow in p+A

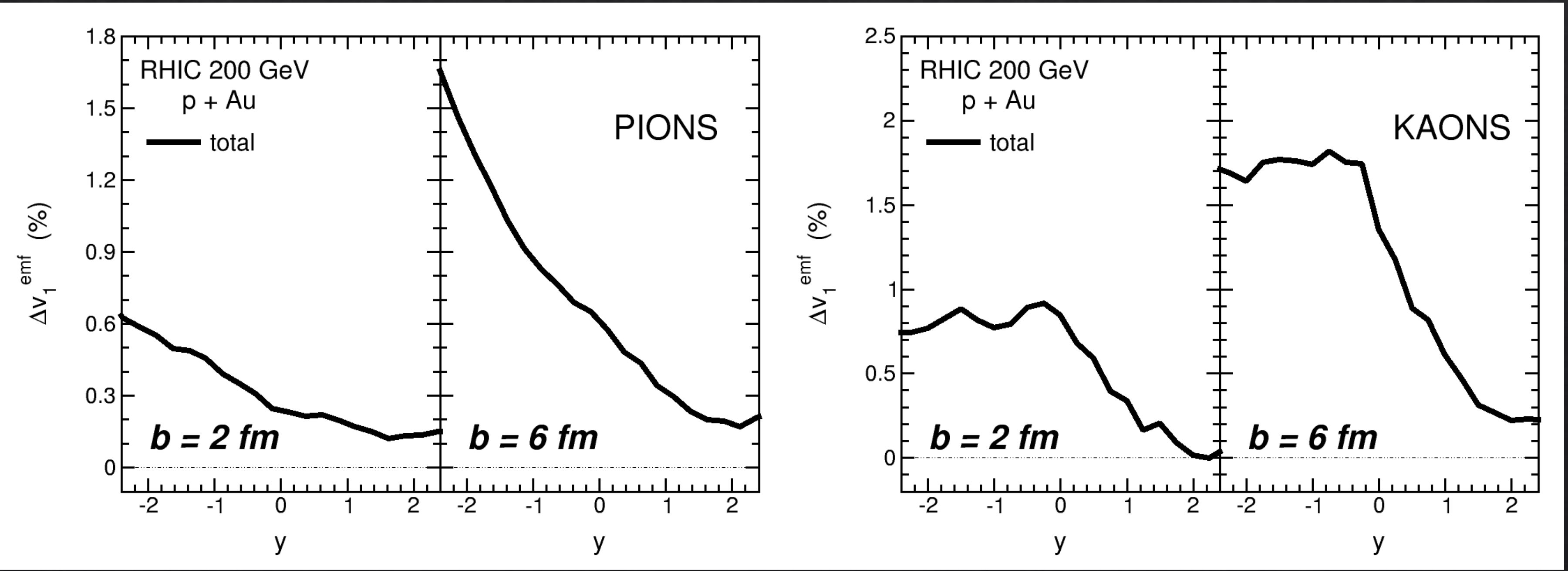
ELECTROMAGNETICALLY-INDUCED SPLITTING in the directed flow of hadrons with same mass and opposite charge

$$\Delta v_1{}^{emf} \equiv \Delta v_1{}^{(PHSD+EMF)} - \Delta v_1{}^{(PHSD)}$$

$$\Delta v_1 \equiv v_1^+ - v_1^-$$

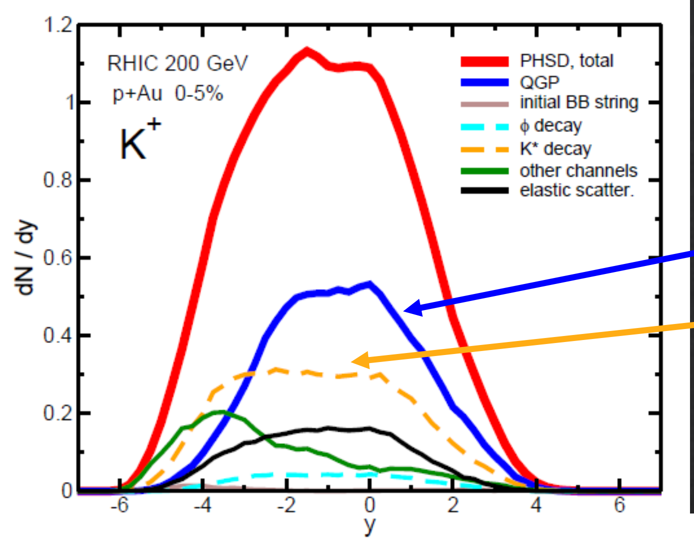
$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- magnitude increasing with impact parameter
- larger splitting for kaons than for pions



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Directed flow in p+A

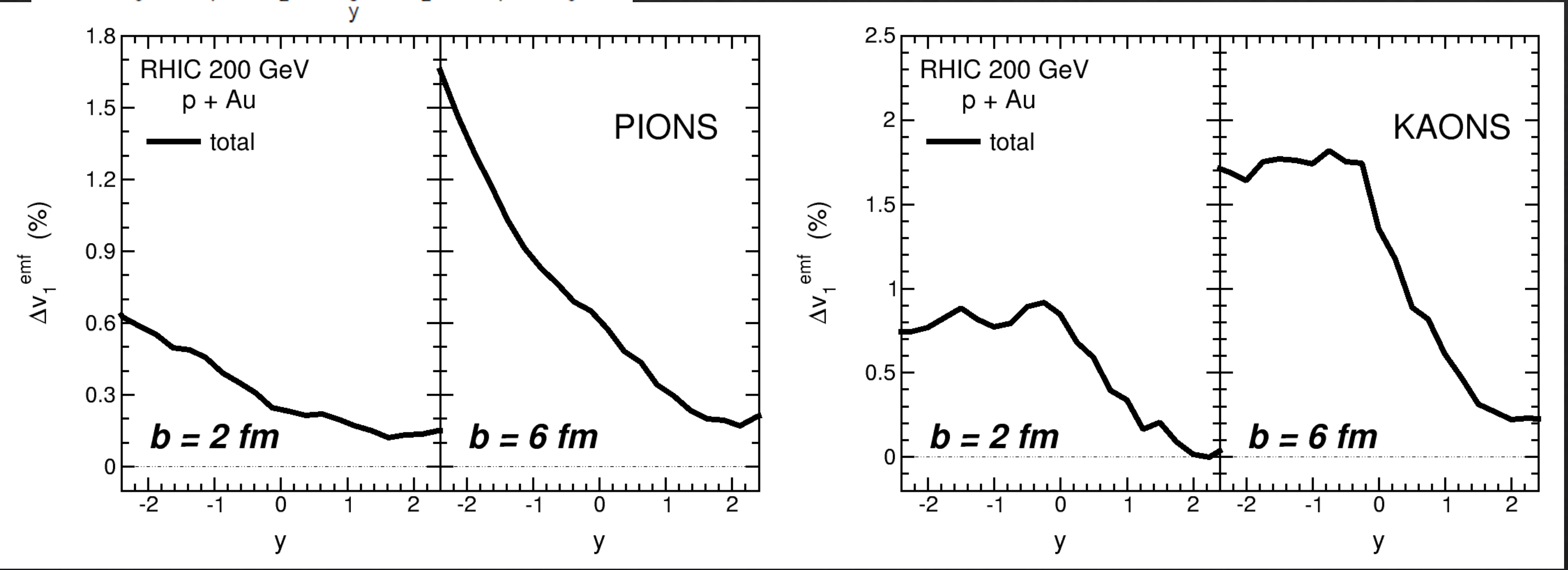


large amount of hadrons escapes from the medium just after hadronization without further rescattering

directly from QGP hadronization

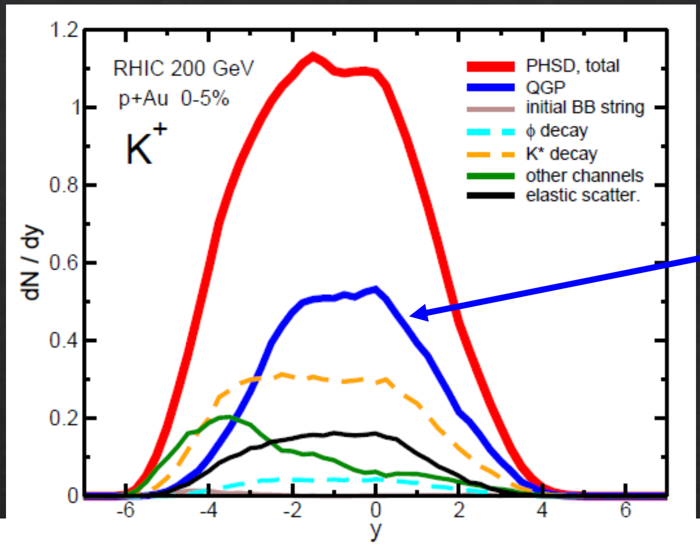
from K* decay

in A+A kaons created by K* decay are about twice those generated directly from QGP



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

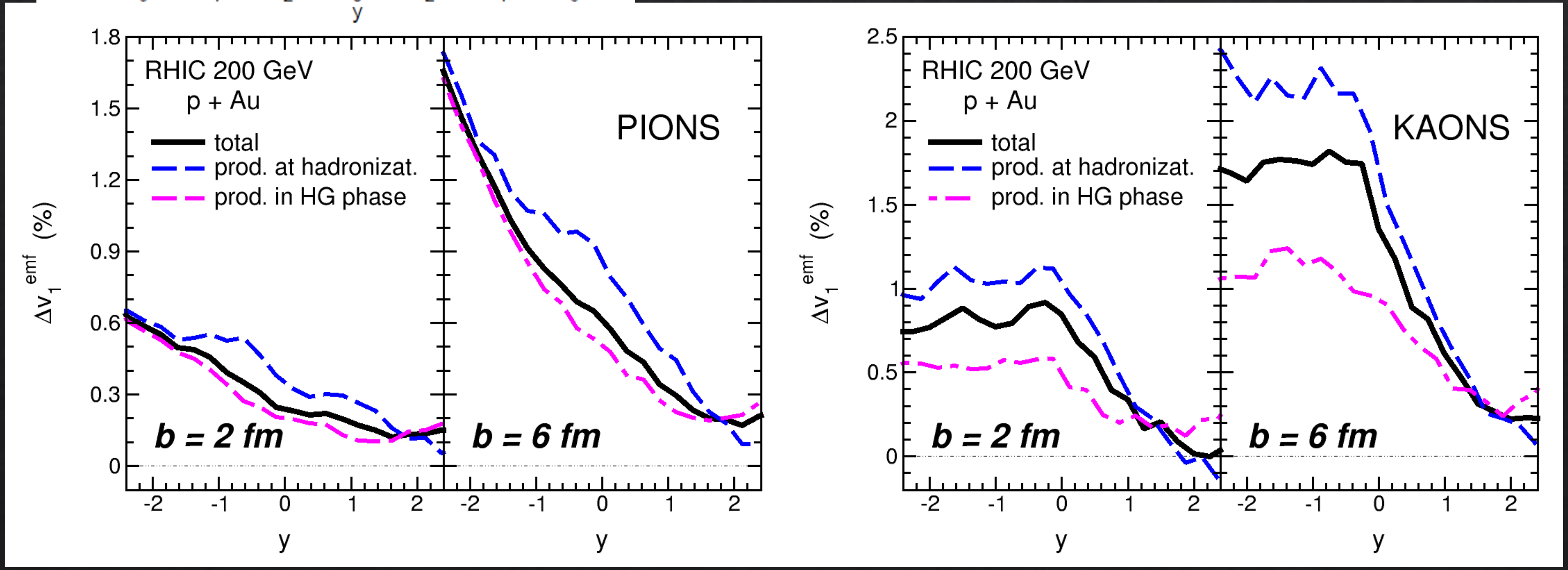
Directed flow in p+A



large amount of hadrons escapes from the medium just after hadronization without further rescattering

directly from QGP hadronization

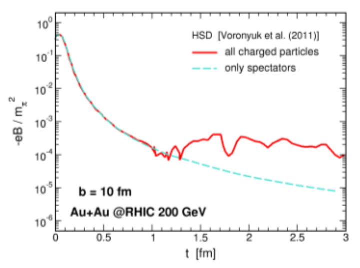
v_1 splitting mainly generated at partonic level (especially for kaons)



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

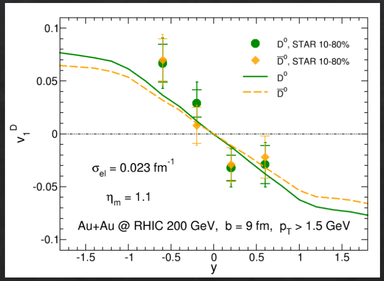
CONCLUSIONS

Strong fields in ultra-relativistic nuclear collisions:
large **vorticity** induced by the huge angular momentum
and **intense electromagnetic fields** (EMF)



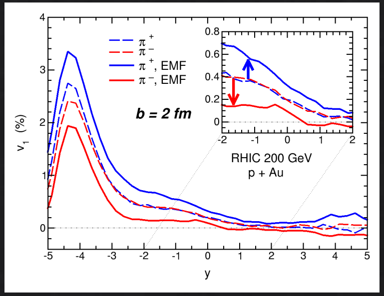
- ✓ **Relativistic transport theory** allows to describe the whole evolution of heavy-ion reactions and small colliding systems, including both vorticity and EMF

- ✓ The **directed flow v_1** of light and heavy mesons can shed light on
  - strength and time evolution of vorticity and EMF
  - presence of charges in the pre-equilibrium stage
  - transport properties of QGP (such as electric conductivity)



- ✓ **Heavy quarks** are a sensitive probe to the initial vorticity and EMF
  - the very large v_1 for D mesons is due to the longitudinal asymmetry between bulk matter and charm quarks and the large non-perturbative interaction of heavy quarks in QGP
  - the splitting of neutral D mesons is order of magnitudes larger than that of light hadrons and represents a further probe of deconfinement

- ✓ **Small systems** are an unexpected laboratory for studying the QGP properties and the impact of the EMF and vorticity
  the combined asymmetry of charged particle and electric field profiles inside the overlap area leads to a sizeable electromagnetically-induced splitting of pions and kaons, mainly generated in the deconfined phase



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Thank you for your attention!

Many thanks to my collaborators

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Salvatore Plumari (Catania Uni, INFN-LNS)

Vadim Voronyuk (JINR Dubna)