*Virtual RHIC & AGS*
*Annual Users' Meeting*

*Brookhaven National Laboratory*
*22nd October 2020*


# Electromagnetic field effects on large and small colliding systems

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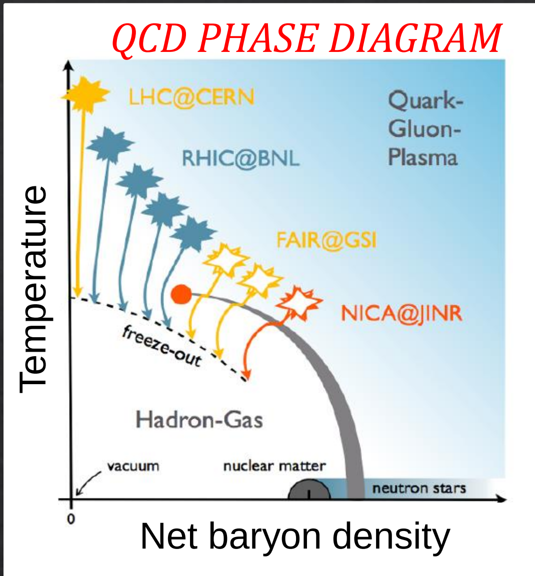
CRC-TR 211 Strong-interaction matter under extreme conditions




High-energy nuclear collisions recreate the extreme condition of temperature and density required to form the Quark-Gluon Plasma (QGP)

QGP initially expected only in Heavy-Ion Collisions (HICs)

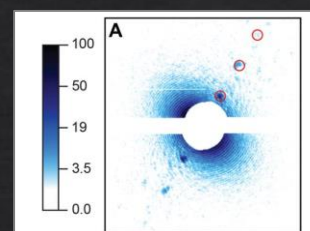
SIGNATURES OF COLLECTIVE FLOW IN SMALL SYSTEMS in high-multiplicity events of $p/d/^{3}He+Au$ at RHIC, p+p, p+Pb at LHC

## **STRONG FIELDS**: INTENSE VORTICITY AND ELECTROMAGNETIC FIELDS (EMF)

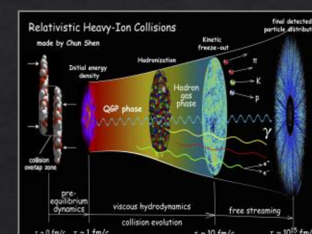
vorticity $\omega$

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

Jupiter's spot $\sim 10^{-4}\ s^{-1}$

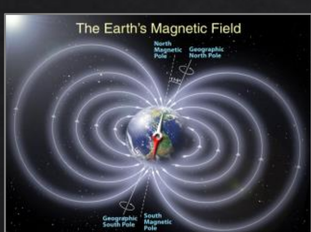



He nanodroplets $\sim 10^{7}\ s^{-1}$




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

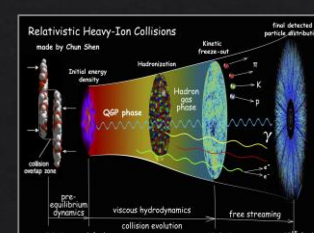
magnetic field $B$




Earth's field $\sim 1$ G

laboratory $\sim 10^{6}$ G

magnetars $\sim 10^{14}\text{–}10^{15}$ G




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

# Electromagnetic fields effects

Many interesting phenomena in high-energy nuclear collisions driven by the intense EMF

- chiral magnetic effect and related transport phenomena

  Kharzeev, McLerran and Warringa, Nucl. Phys. A 803, 227 (2008); Fukushima, Kharzeev and Warringa, Phys. Rev. D 78, 074033 (2008); Huang, Rept. Prog. Phys. 79, 076302 (2016); Kharzeev, Liao, Voloshin and Wang, Prog. Part. Nucl. Phys. 88, 1 (2016)

- polarization of hadrons

  Becattini, Karpenko, Lisa, Upsal and Voloshin, Phys. Rev. C 95, 054902 (2017); Han and Xu, Phys. Lett. B 786, 255 (2018); Sheng, Wang and Wang, Phys. Rev. D 102, 056013 (2020)

- early-time emission of photons and dileptons

  Fukushima and Mameda, Phys. Rev. D 86, 071501(R) (2012); Basar, Kharzeev and Skokov, Phys. Rev. Lett. 109, 202303 (2012); Basar, Kharzeev and Shuryak, Phys. Rev. C 90, 014905 (2014); Tuchin, Int. J. Mod. Phys. E 23, 1430001 (2014); Jia, Liu, Oliva, Huang, Fukushima and Ruggieri., in preparation

- Schwinger particle production

  Sheng, Fang, Wang, Rischke, Phys. Rev. D 99, 056004 (2019)

- CHARGE-DEPENDENT DIRECTED FLOW

  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014); Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014); Toneev, Voronyuk, Kolomeitsev and Cassing, Phys. Rev. C 95, 034911 (2017); Das, Plumari, Chatterjee, Alam, Scardina and Greco, Phys. Lett. B 768, 260 (2017); Gursoy, Kharzeev, Marcus, Rajagopal and Shen, Phys.Rev.C 98, 055201 (2018); Chatterjee and Bozek, Phys. Lett. B798, 134955 (2019); **Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020); Oliva, Plumari and Greco, 2009.11066**; Oliva, Eur. Phys. J. A 56, 255 (2020); Dubla, Gursoy and Snellings, 2009.09727

# Transport kinetic equations

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

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

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. $\longrightarrow$ Kadanoff-Baym eqs.

instead of particle distribution function ***f*** $\longrightarrow$ Green functions with complex self-energies

Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)

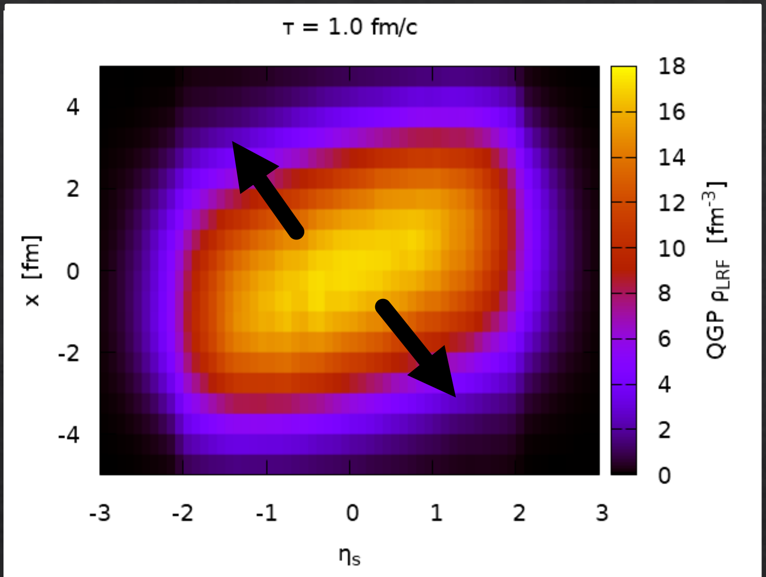
Bratkovskaya, et al., Nucl Phys. A 856, 162 (2011)

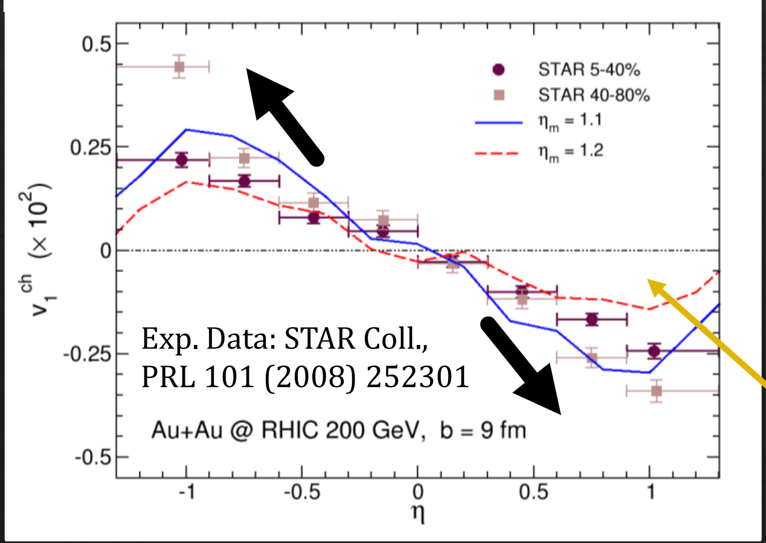
Xu and Greiner, Phys. Rev. C 79, 014904 (2009)

Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)

Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

# Vorticity and directed flow




Huge **orbital angular momentum (J ≈ $10^5$ - $10^6$ ħ)** of the colliding system

- dominated by the y component
- partly transferred to the plasma generating an asymmetry in local participant density from forward and backward going nuclei

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 $\eta$ dependence of the $v_1$ of bulk particles

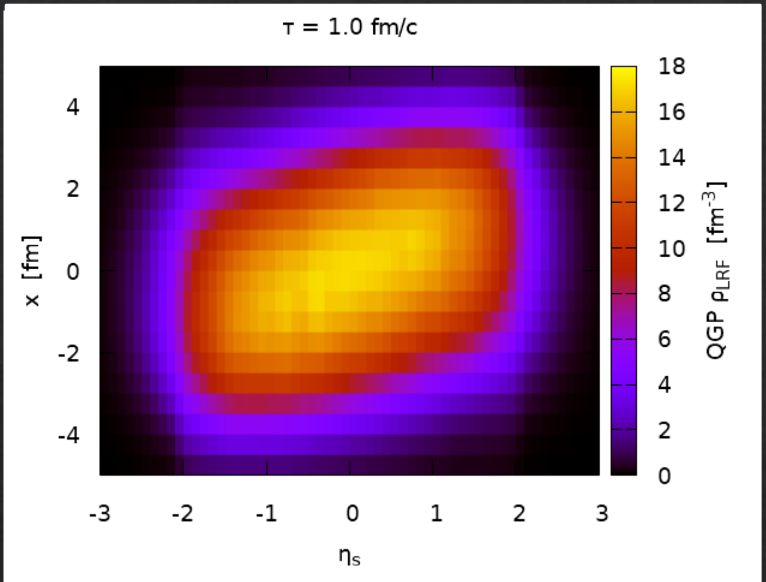
*$v_1$ is zero if the fireball is not tilted*

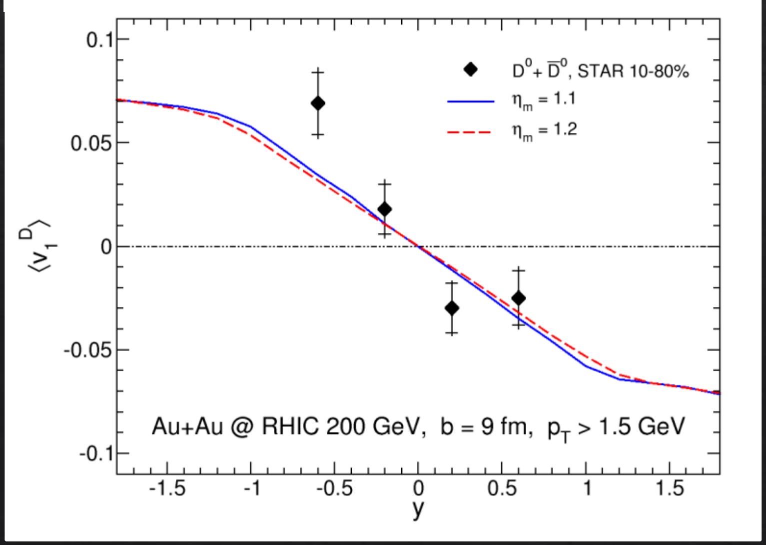
DIRECTED FLOW OF CHARGED PARTICLES



Oliva, Plumari and Greco, 2009.11066

# Vorticity and directed flow




DIRECTED FLOW OF NEUTRAL D MESONS

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

- $m_{c,b} \gg \Lambda_{QCD},\ m_{c,b} \gg T_{HICs}$

HQ produced in pQCD initial hard scatterings, 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

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)

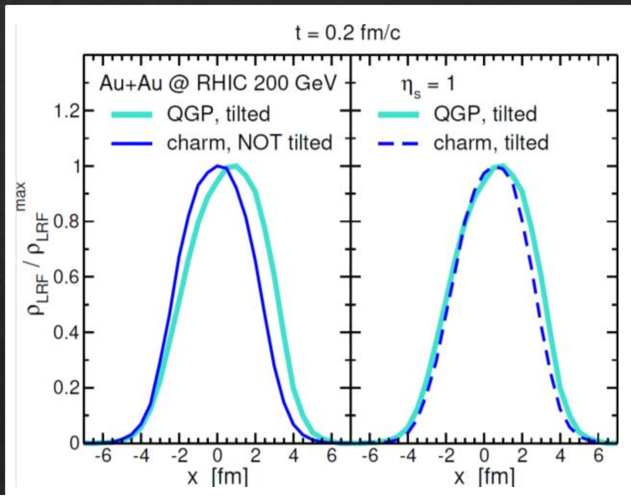
$$v_1\ (HQs) \gg v_1\ (QGP)$$

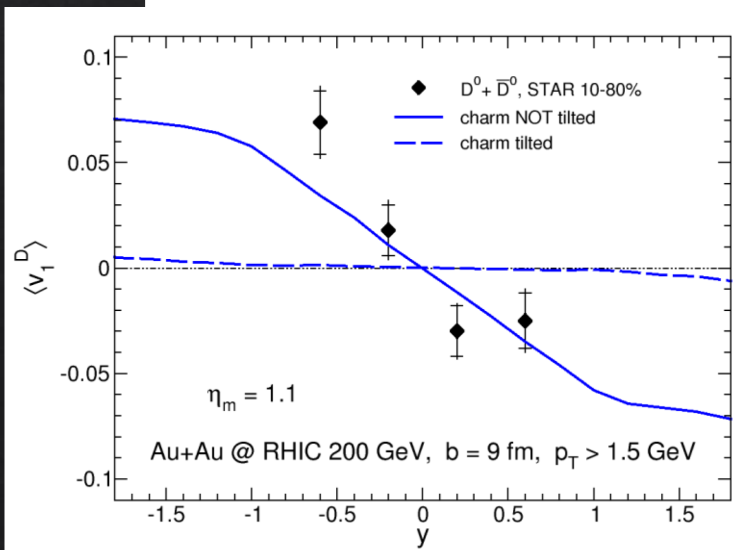
origin of the large directed flow of HQs different from the one of light particles


Oliva, Plumari and Greco, 2009.11066

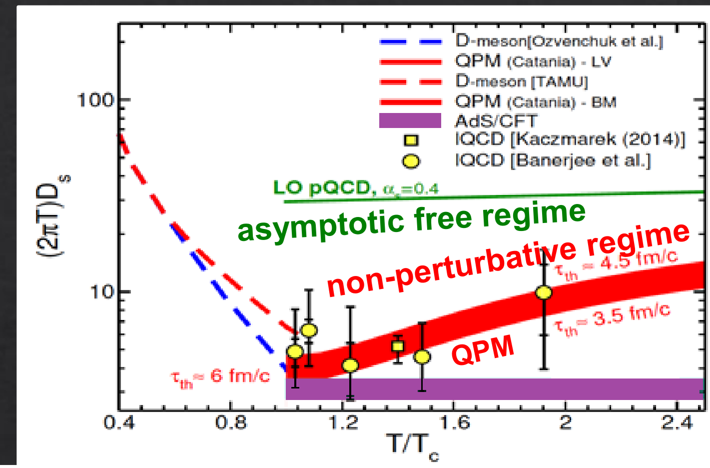
# Origin of D meson directed flow

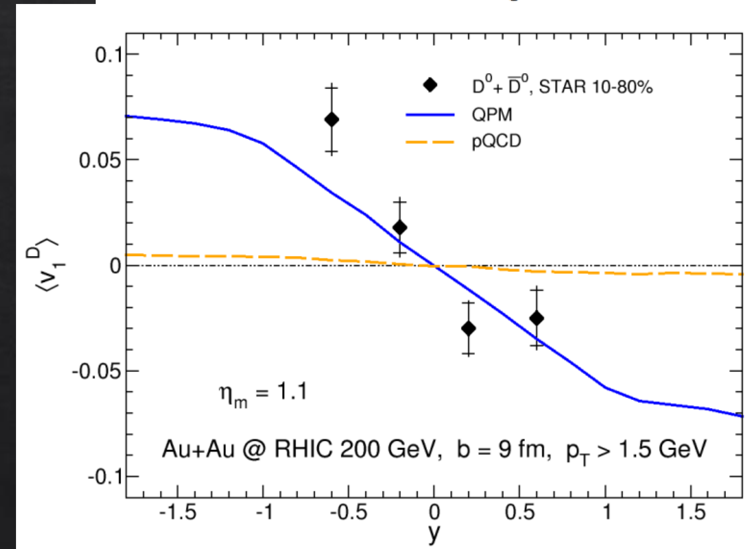
the longitudinal asymmetry between bulk and HQ initial profiles leads to a pressure push of the bulk on the HQs




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

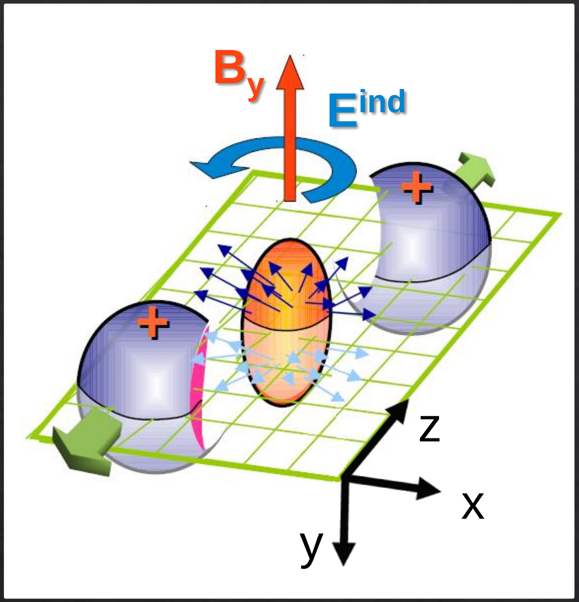



the transverse pressure gradient is effective because the HQ interaction in QGP is largely non-perturbative

Oliva, Plumari and Greco, 2009.11066

# Electromagnetic fields in HICs

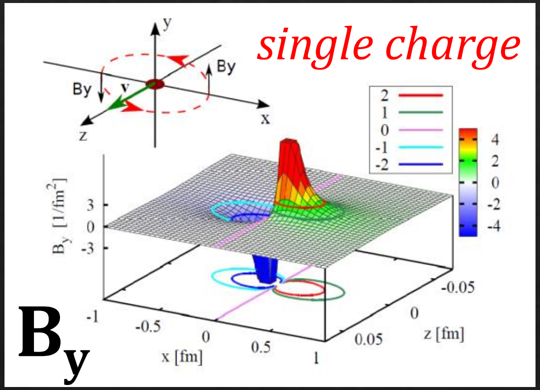



Huge **magnetic field** in the overlapping area of the collision

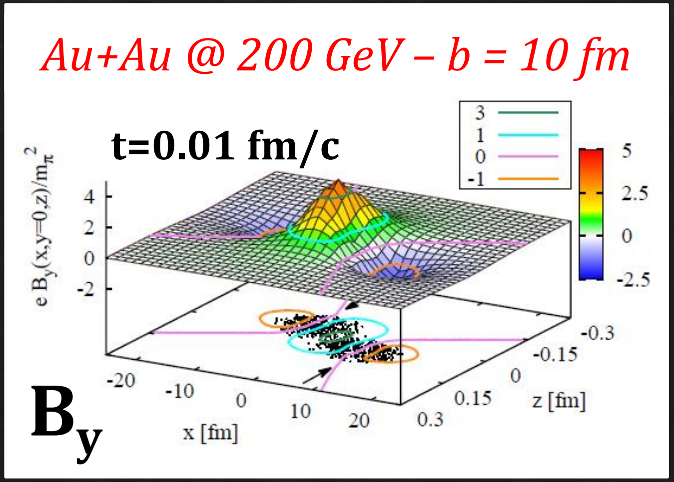
- in ultrarelatvistic HICs **$eB \approx$ 5-50 $m_\pi^2$** ~ **$10^{18}$-$10^{19}$ G**
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

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

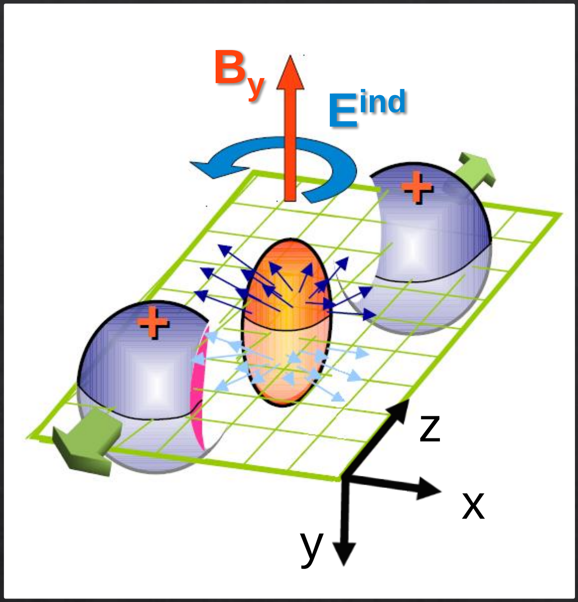
Voronyuk, Toneev, Cassing, Bratkovskaya, Konchakovski and Voloshin (HSD), Phys. Rev. C 83, 054911 (2011)

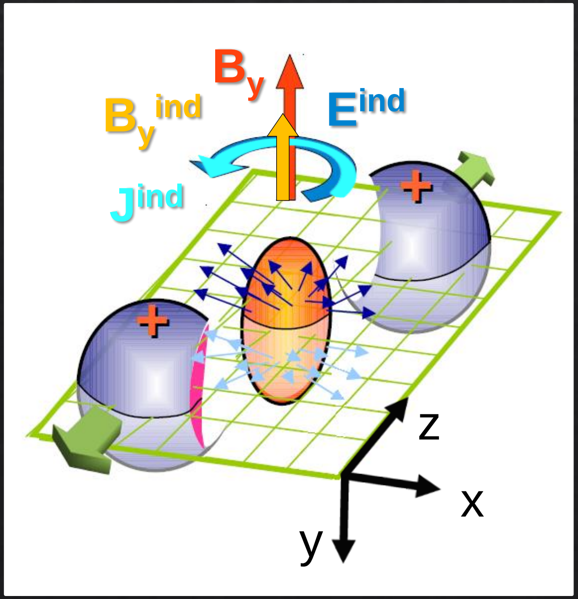



in a nuclear collision the EMF are a superposition of the fields produced by all moving charges



# Electromagnetic fields in HICs



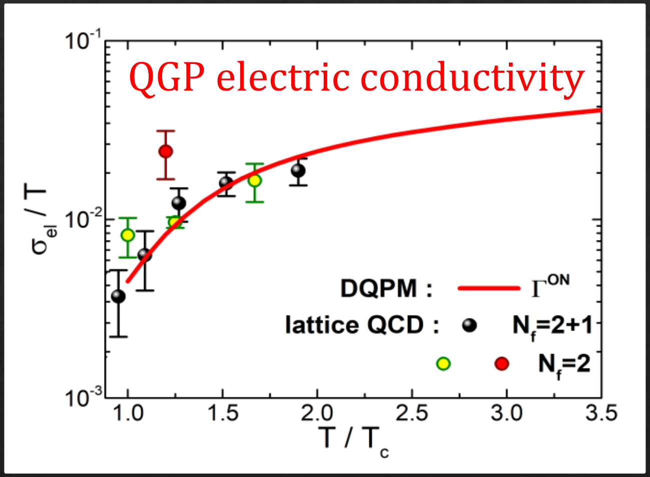

Huge **magnetic field** in the overlapping area of the collision

- in ultrarelatvistic HICs **$eB \approx 5\text{-}50\ m_\pi^2 \sim 10^{18}\text{-}10^{19}$ G**
- 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

# EMF: PHSD approach

Through Liénard-Wiechert potentials one gets the retarded EMF for a moving point-like charge

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

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

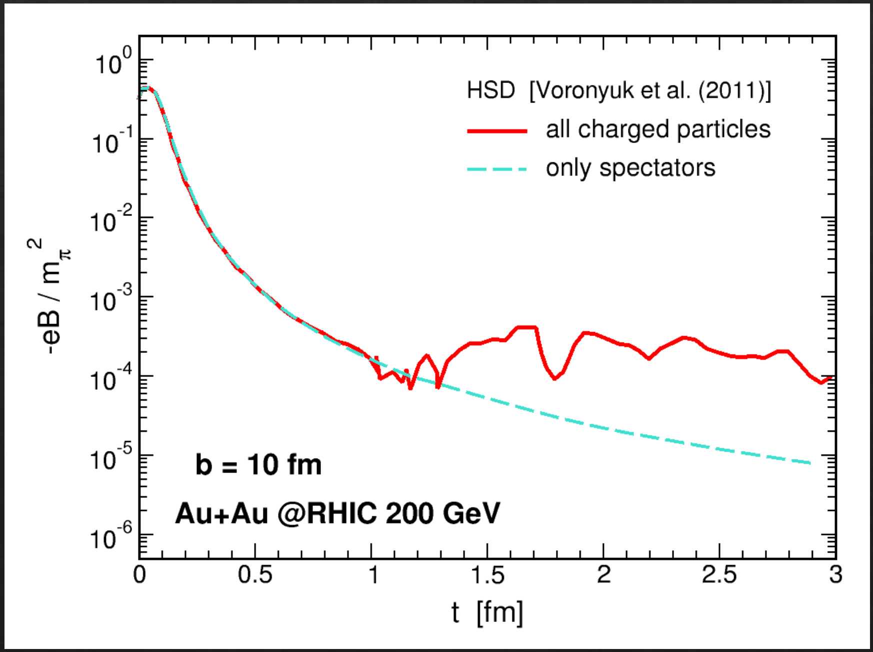
Coulomb    bremsstrahlung

**Neglecting the acceleration** one obtains the EMF generated by a charge in uniform motion

$$eE(r,t) = \sum_i \frac{\text{sgn}(q_i)\alpha_{em}\boldsymbol{R}_i(t)(1-\beta_i^2)}{\left\{[\boldsymbol{R}_i(t)\cdot\boldsymbol{\beta}_i]^2 + R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

$$eB(r,t) = \sum_i \frac{\text{sgn}(q_i)\alpha_{em}\boldsymbol{\beta}_i\times\boldsymbol{R}_i(t)(1-\beta_i^2)}{\left\{[\boldsymbol{R}_i(t)\cdot\boldsymbol{\beta}_i]^2 + R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

The EMF are obtained summing over all charges in the collisions: spectators and participants protons, newly produced particles (QGP)




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

# EMF: Catania approach

external charge and current produced by a point-like charge in longitudinal motion

$$\rho = \rho_{ext} \qquad \boldsymbol{J} = \boldsymbol{J}_{ext} + \boldsymbol{J}_{ind}$$

$$\rho_{ext} = e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x'}_\perp)$$

$$\boldsymbol{J}_{ext} = \hat{z}\beta e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x'}_\perp)$$

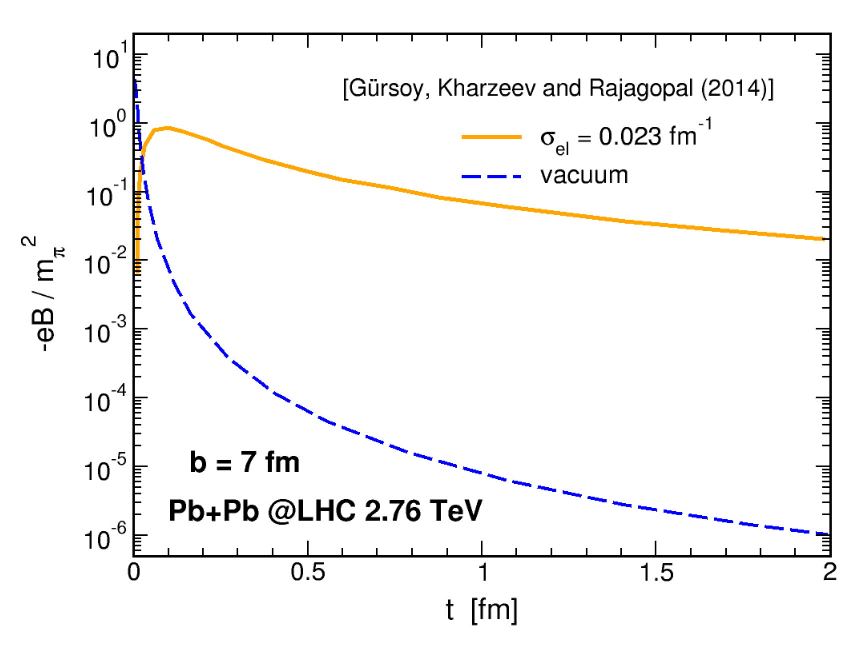
induced current from Ohm's law

$$\boldsymbol{J}_{ind} = \sigma_{el}\boldsymbol{E}$$

From Maxwell equations one obtains wave equations for the EMF that can be solved analytically considering a medium with **constant electric conductivity**

$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{B} = -\nabla \times \boldsymbol{J}_{ext}$$

$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext}$$

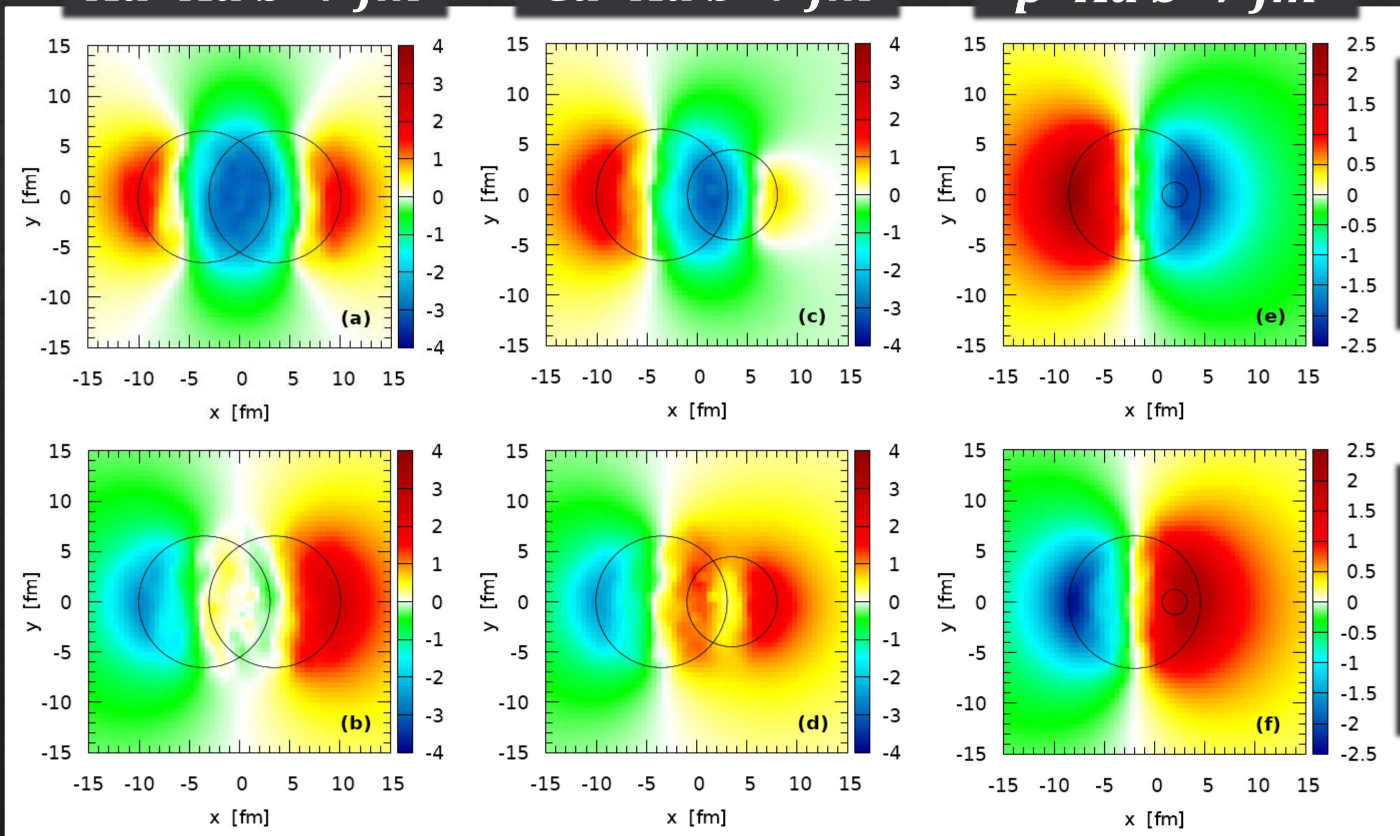



Fold the solution with the nuclear transverse density profile of the spectator nuclei and sum forward and backward contributions for obtaining the EMF produced in HICS

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

# EMF from large to small systems

***Au+Au b=7 fm*** ***Cu+Au b=7 fm*** ***p+Au b=7 fm***




$B_y/m_\pi^2$

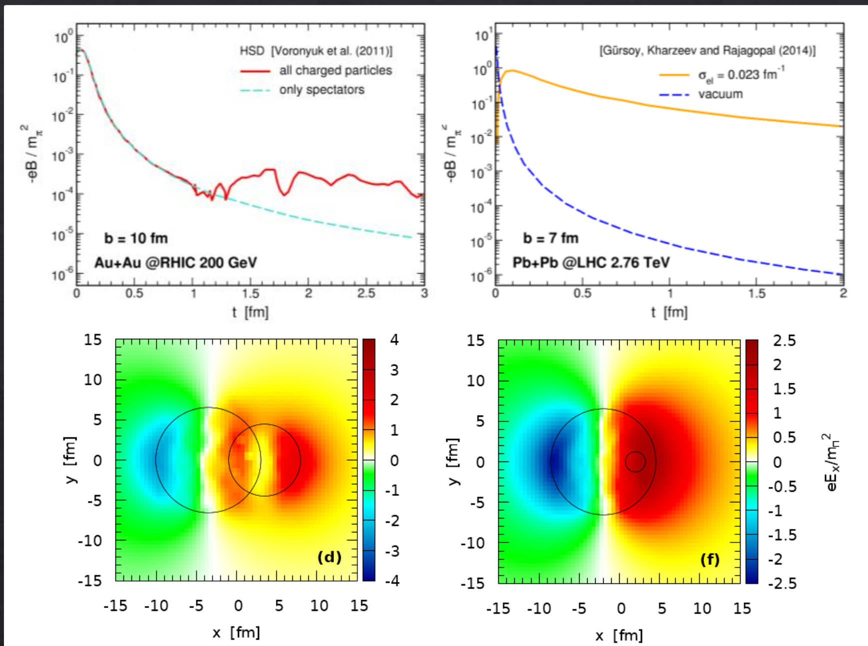
$E_x/m_\pi^2$

***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

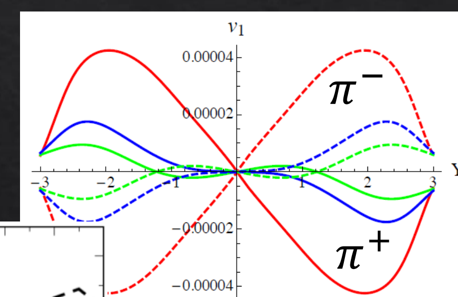



- maximal strength of $B_y$ during overlap
- in the early-stage $B_y$ due to spectators and dropping down some order of magnitude
- $B_y$ induces an intense electric field $E_x$
- in the later-stage $B_y$ decay slowed down by the QGP contribution
- intense initial $E_x$ in asymmetric systems

presence of charge in the early stage

QGP transport properties

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



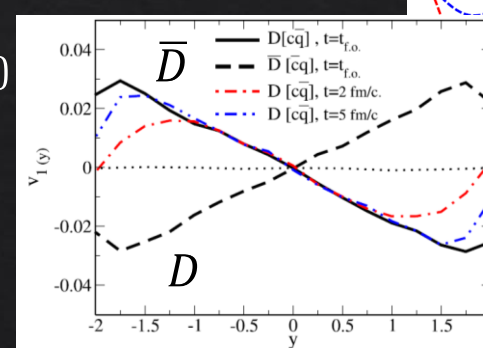

difference in the $v_1$ of light hadrons $O(10^{-4}$–$10^{-3})$

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

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

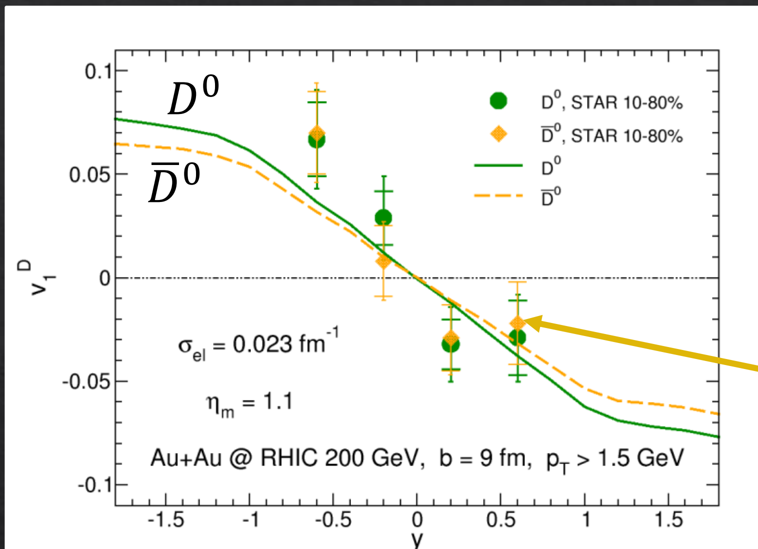
difference in the $v_1$ of heavy mesons $O(10^{-2})$

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

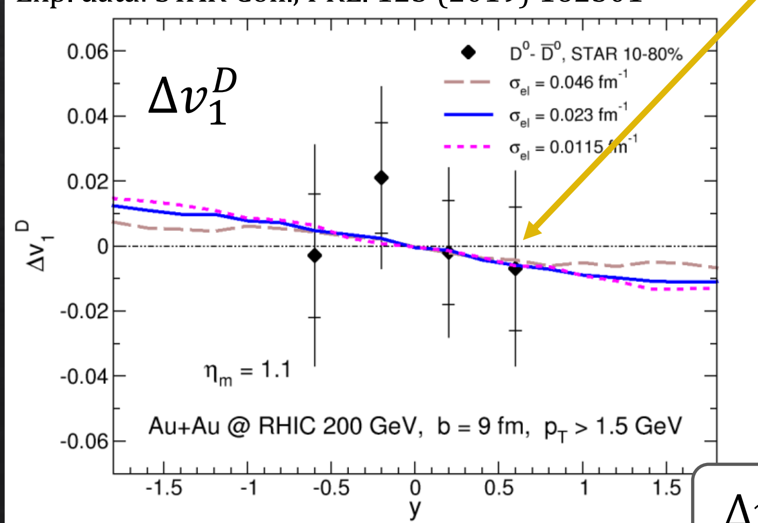



 *reviews*: Oliva, Eur. Phys. J. A 56, 255 (2020); Dubla, Gursoy and Snellings, 2009.09727 

# Directed flow in A+A




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



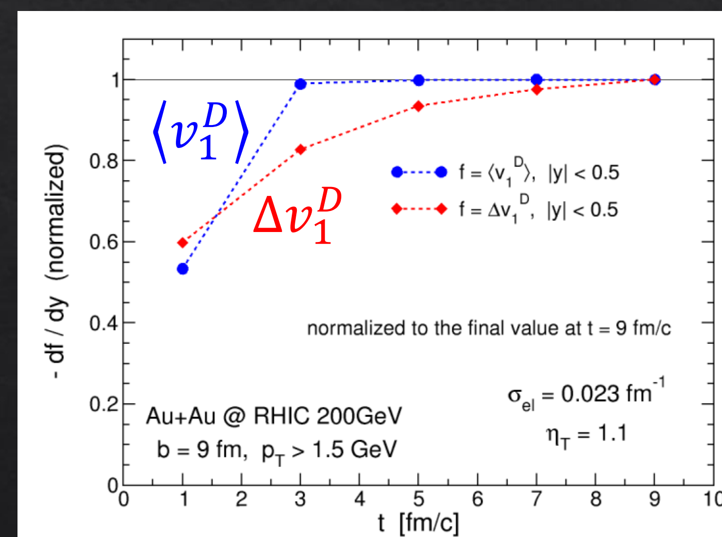

DIRECTED FLOW OF D MESONS

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 $\Delta v_1^{HQ}$ at top RHIC energy still consistent with zero due to the large exp. errors

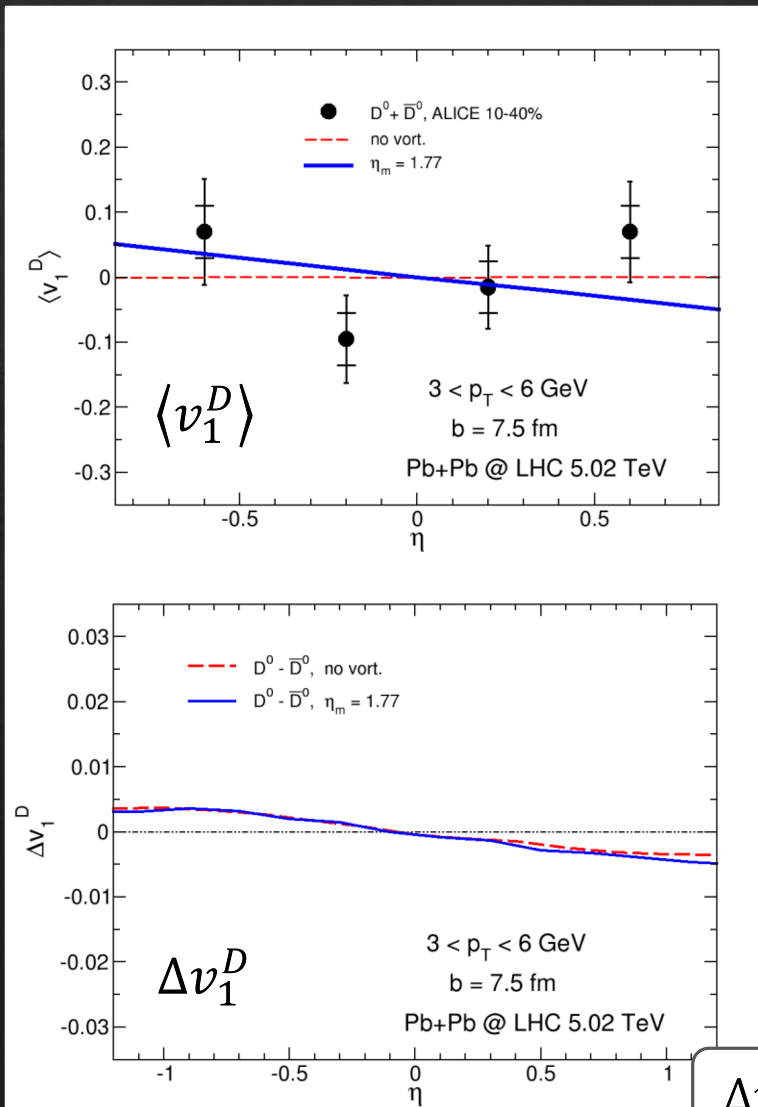



SLOPE TIME EVOLUTION

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

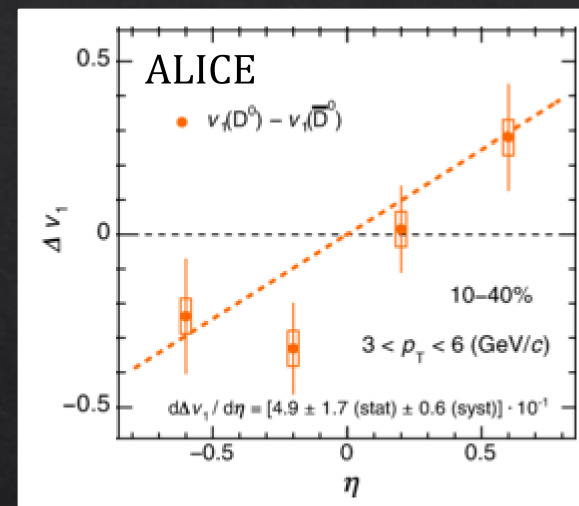
Oliva, Plumari and Greco, 2009.11066

# 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)



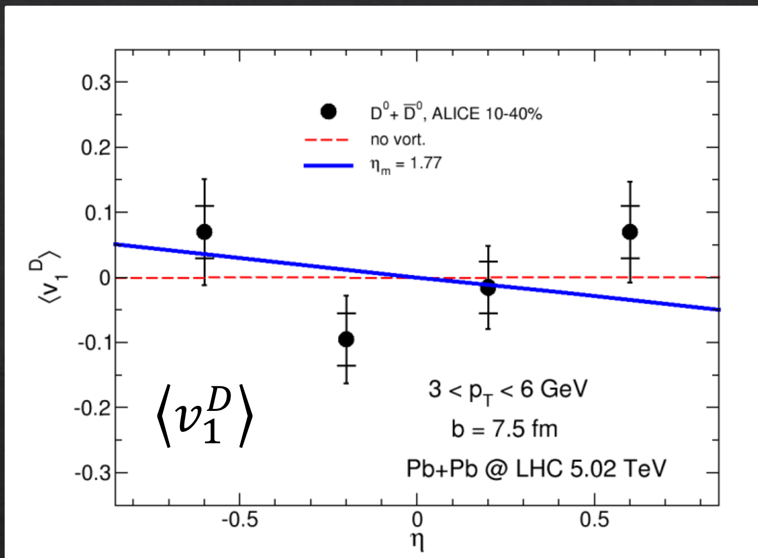

at LHC energy the current approaches cannot reproduce the ALICE data for the $v_1$ splitting

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

DIRECTED FLOW OF D MESONS

Oliva, Plumari and Greco, 2009.11066

# Directed flow in A+A

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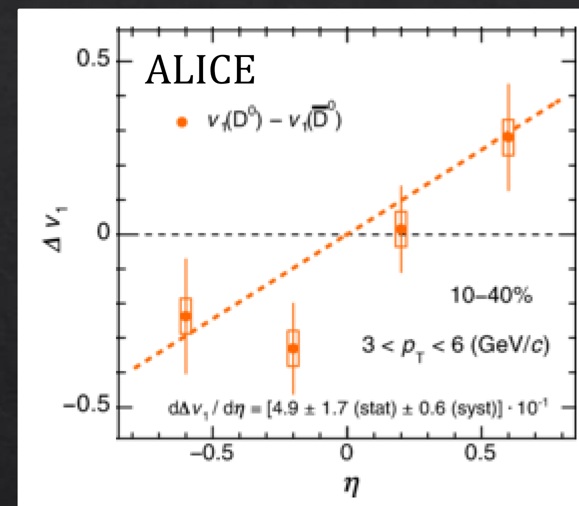
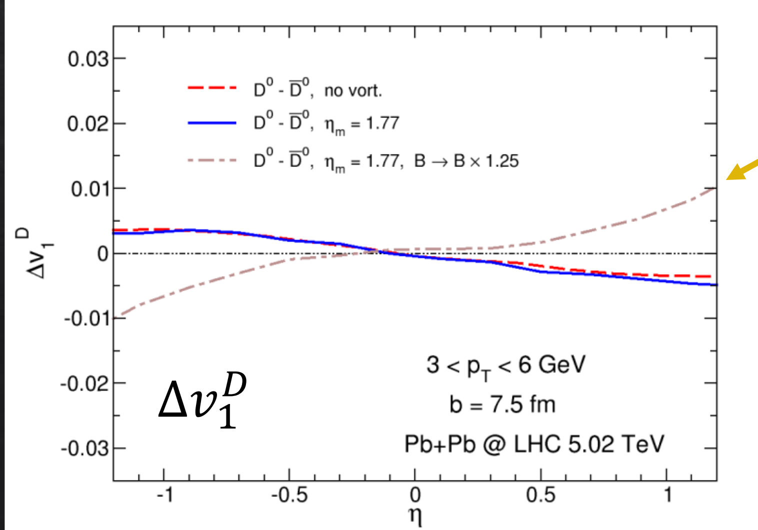
ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)




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

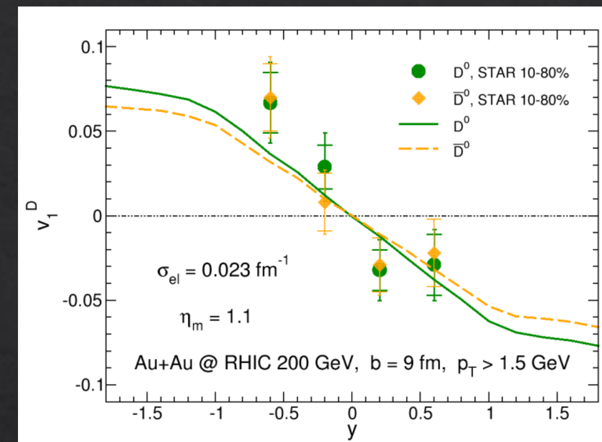
Oliva, Plumari and Greco, 2009.11066

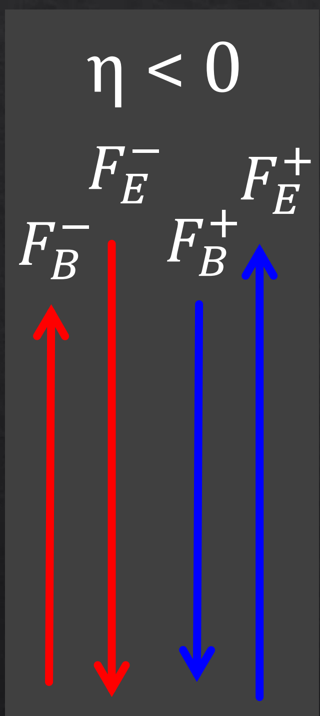
# EMF and directed flow in A+A

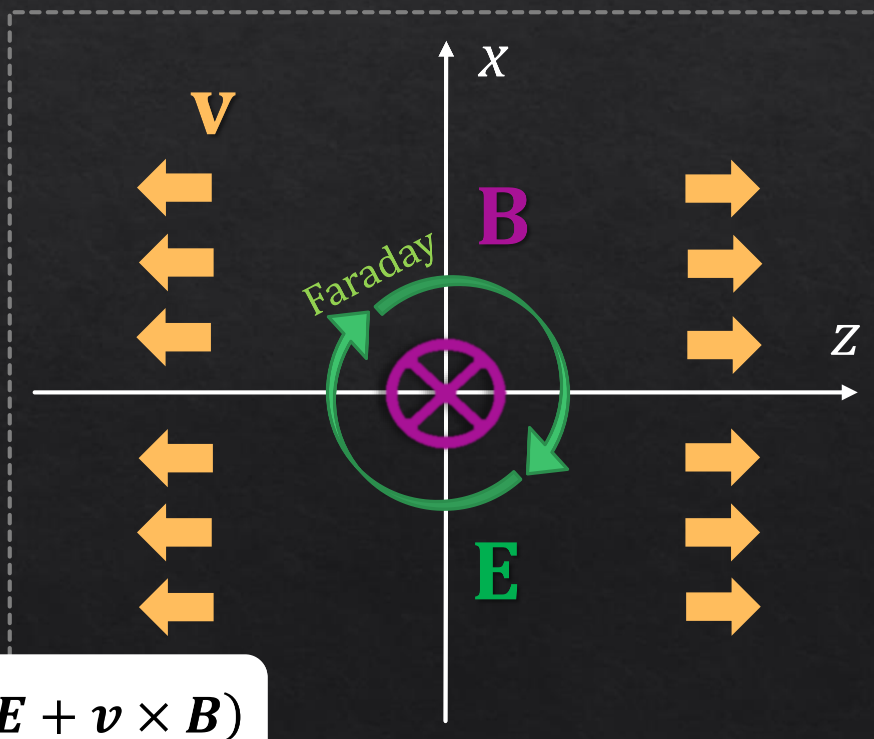
*rapidity dependence of the DIRECTED FLOW*

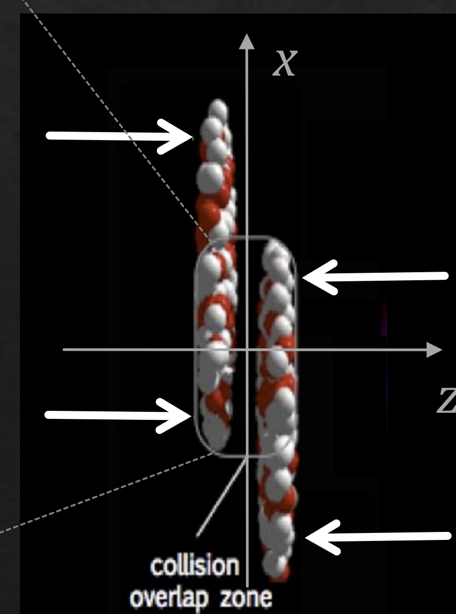
collective sidewards deflection of particles

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



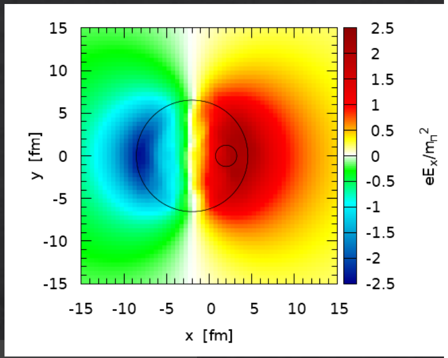



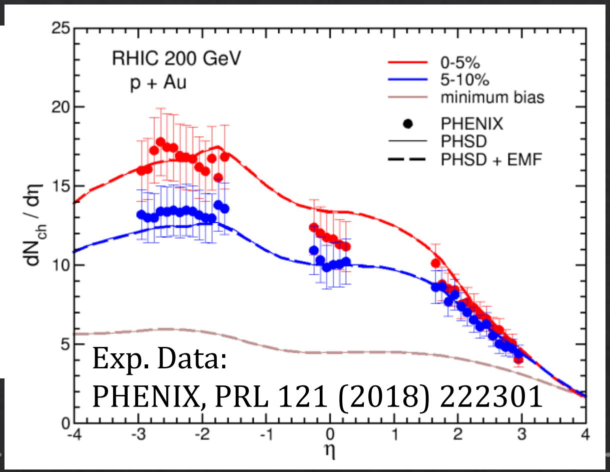




$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

# EMF and directed flow in p+A

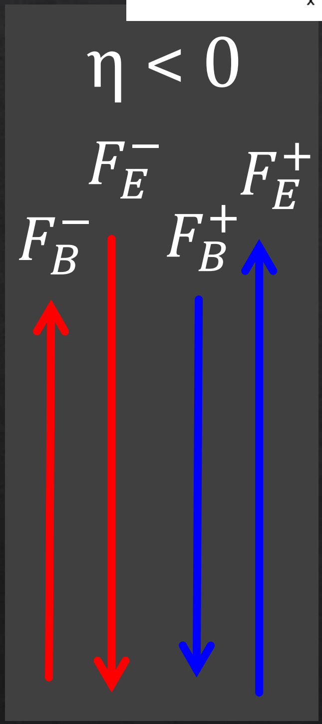


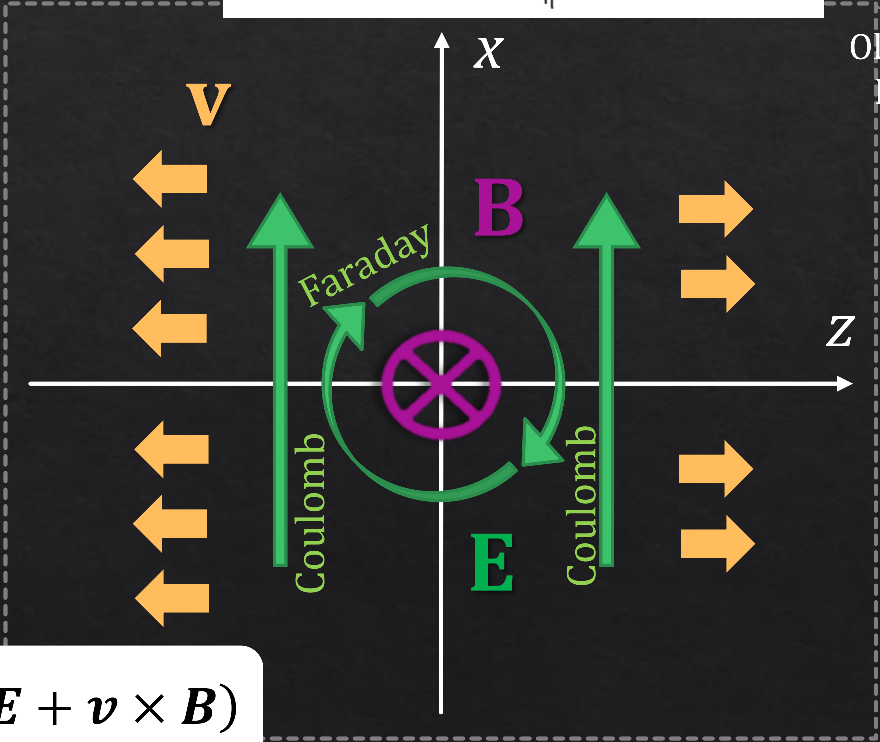



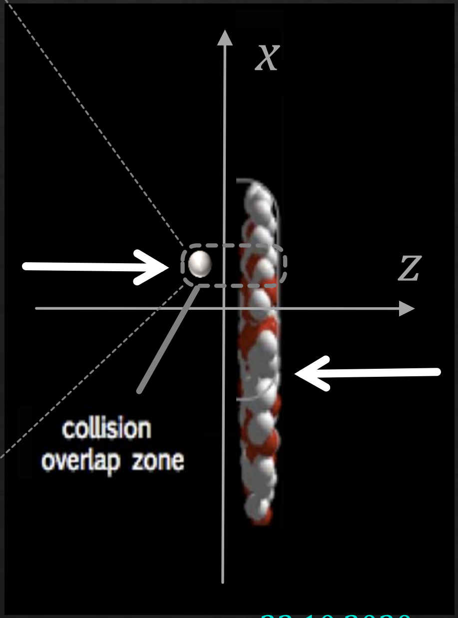

**Asymmetry in charged particle and electric field profiles in p+Au**

- 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)



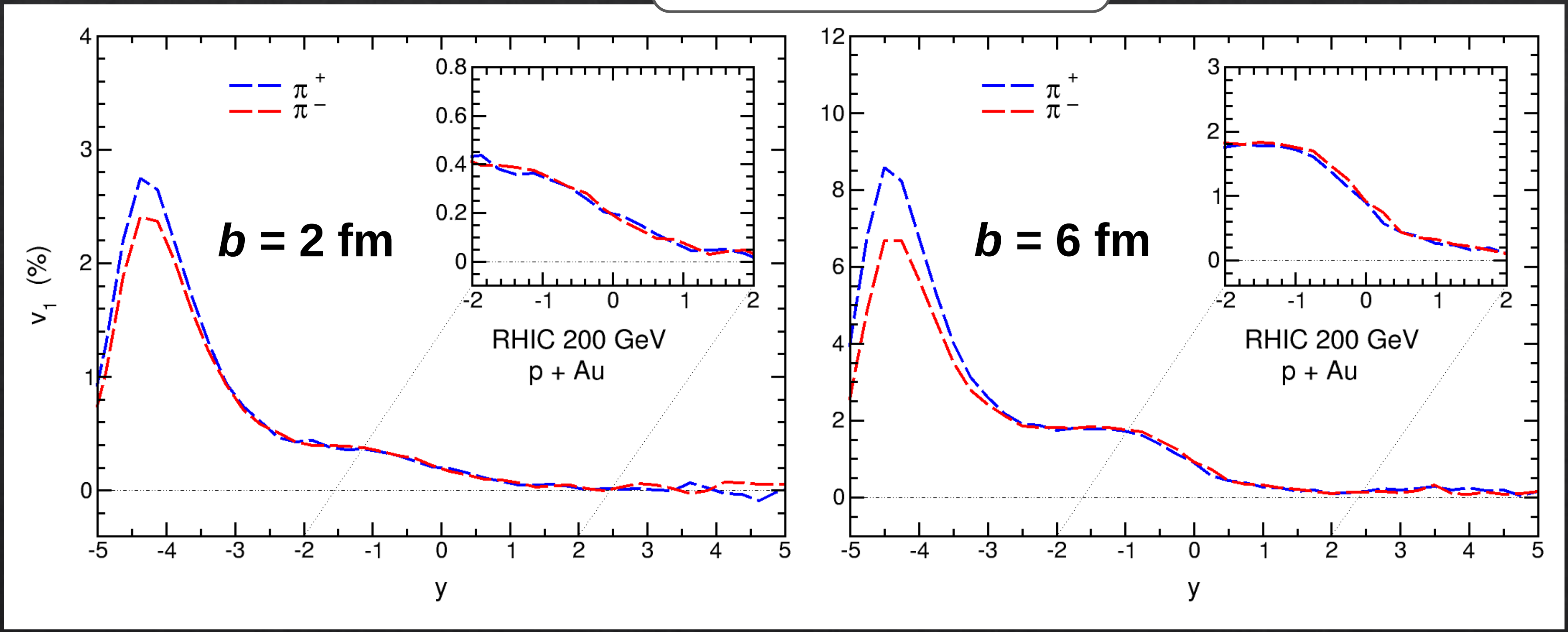




$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

# 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)

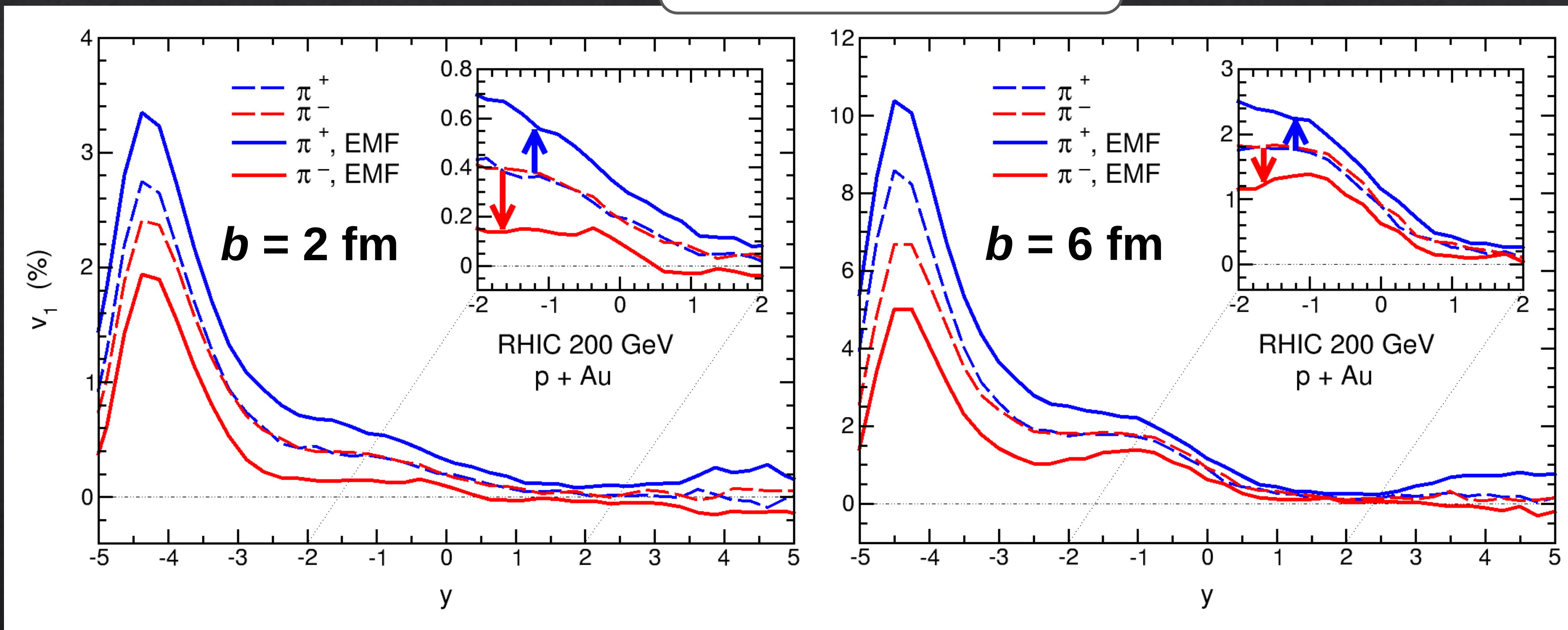
**SPLITTING of light mesons**

**INDUCED BY THE ELECTROMAGNETIC FIELD?**

# Directed flow in p+A

***rapidity dependence of the***
***DIRECTED FLOW OF PIONS***

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



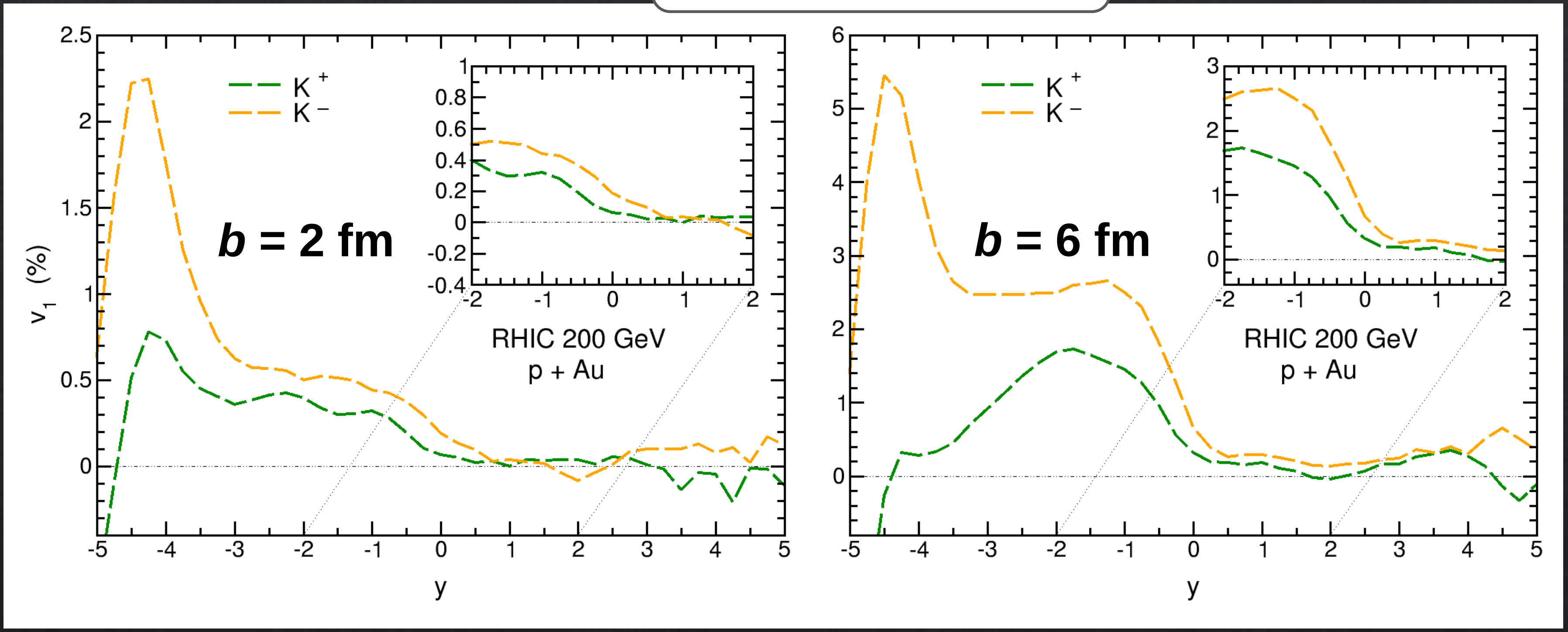

Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)


Splitting of $\pi^+$ and $\pi^-$ induced by the electromagnetic field

# Directed flow in p+A

***rapidity dependence of the***
***DIRECTED FLOW OF KAONS***

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

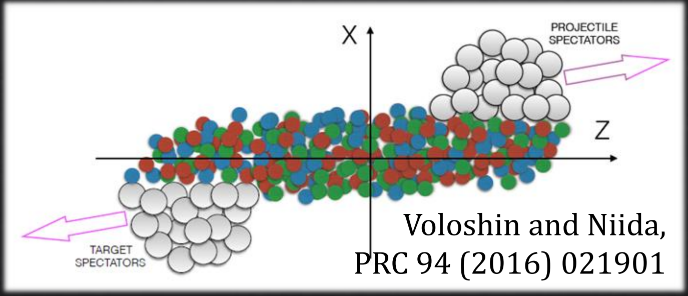



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

**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

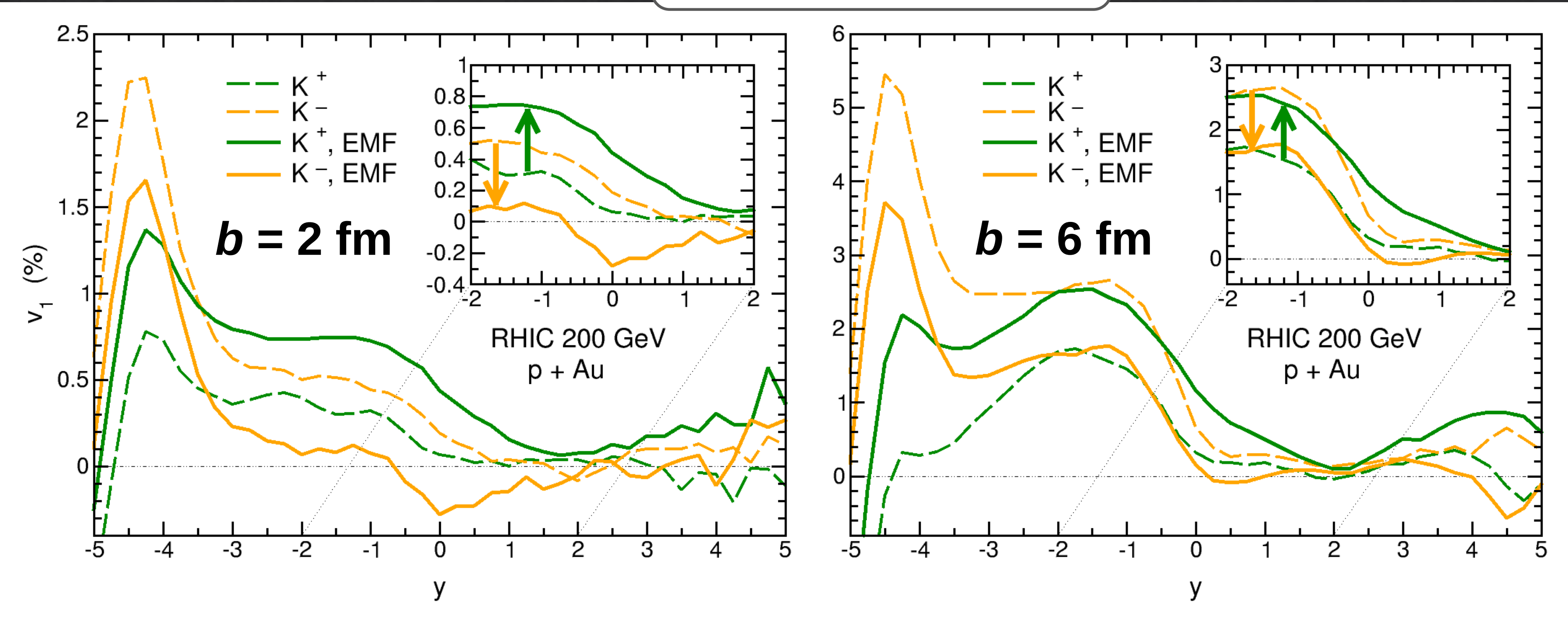



Voloshin and Niida, PRC 94 (2016) 021901

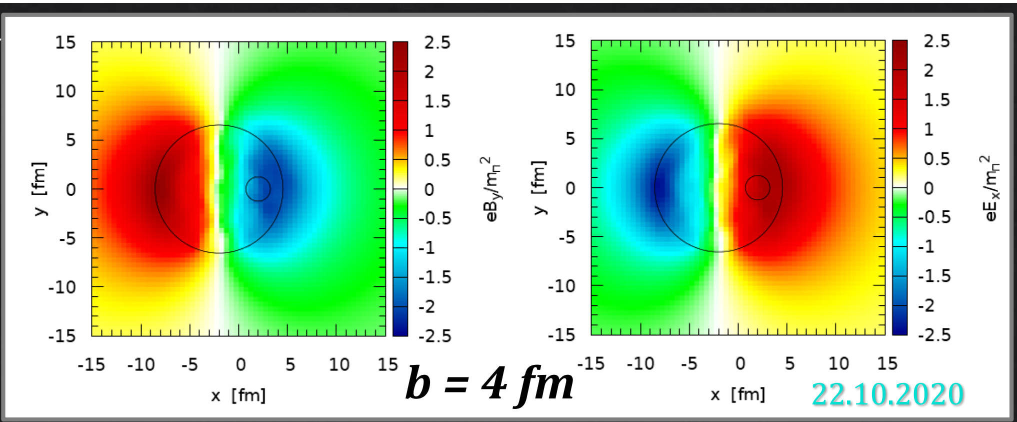
# Directed flow in p+A

***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

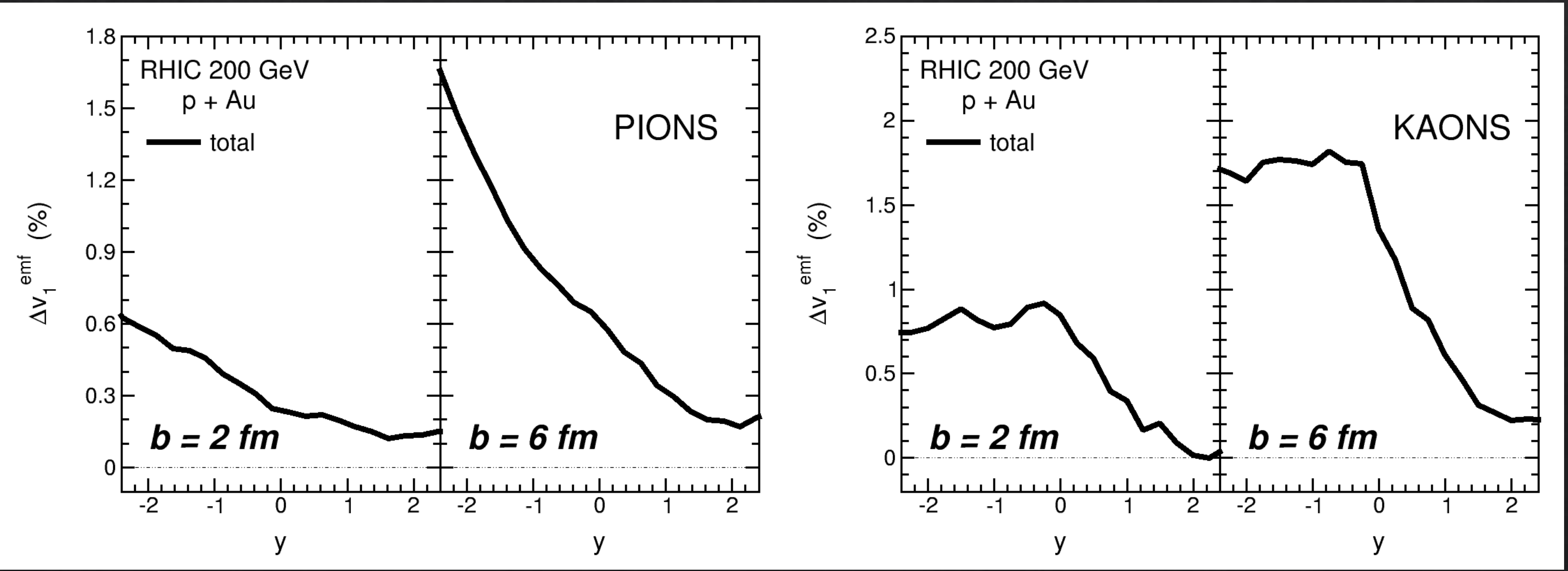
***ELECTROMAGNETICALLY-INDUCED SPLITTING in the directed flow of hadrons with same mass and opposite charge***

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

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

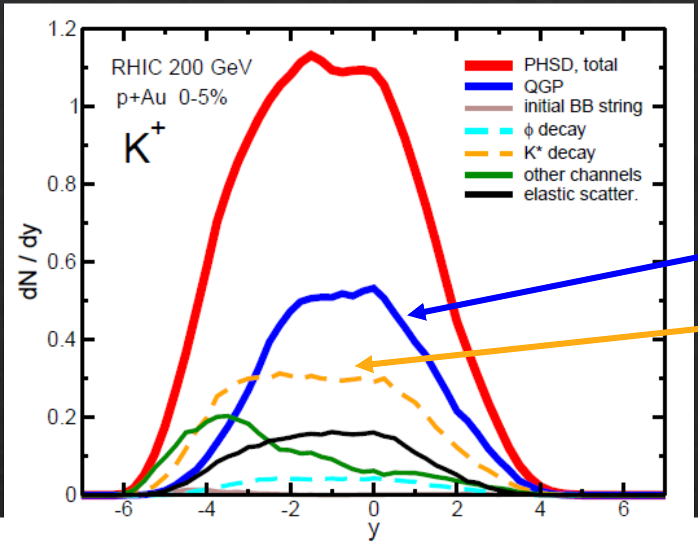
$$\Delta v_1 \equiv v_1^+ - v_1^-$$

- 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

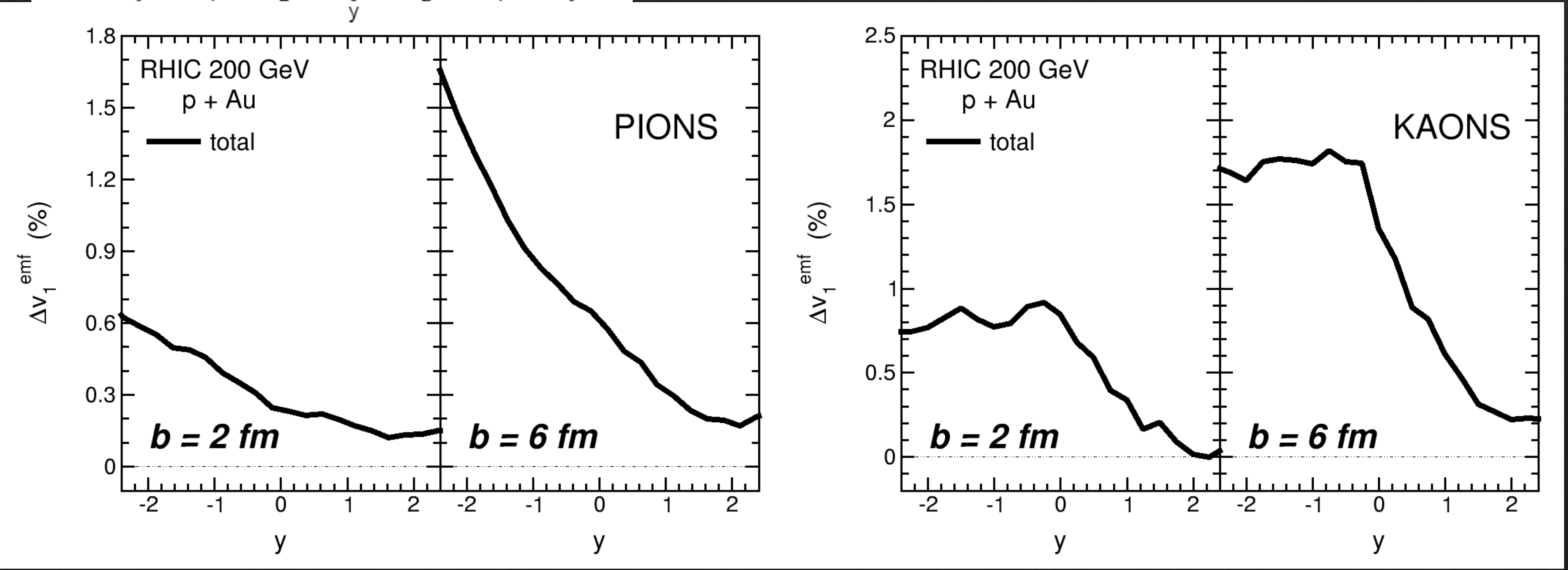



large amount of hadrons escapes from the medium just after hadronization without further rescattering

directly from QGP hadronization

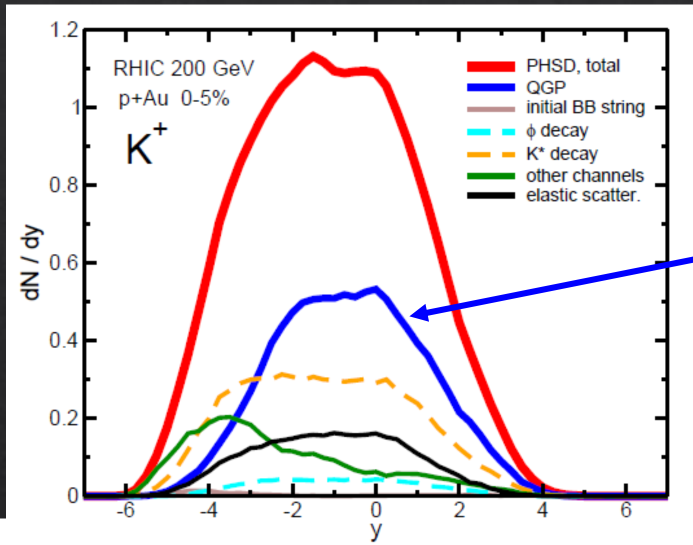
from K* decay

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)

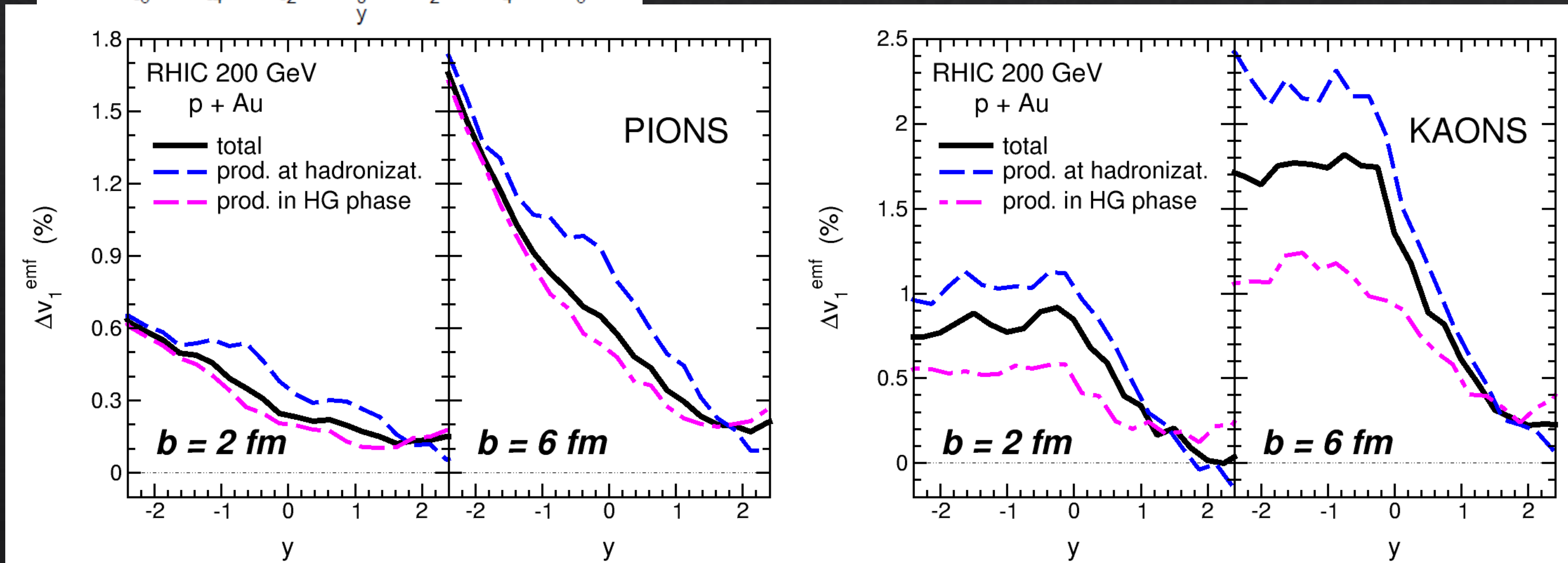
# Directed flow in p+A




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

directly from QGP hadronization

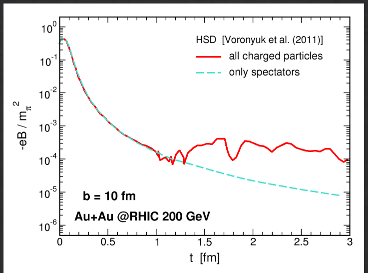
$v_1$ splitting mainly generated at partonic level (especially for kaons)



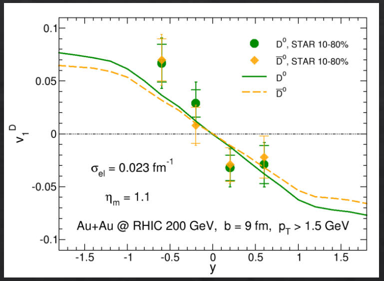

Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

# CONCLUSIONS

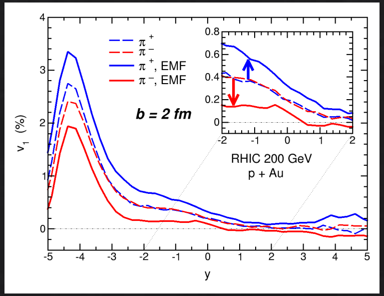
**STRONG FIELDS** in ultra-relativistic nuclear collisions:
large vorticity induced by the huge angular momentum
and **intense electromagnetic fields** (EMF)




- ✓ **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**

Elena Bratkovskaya (Frankfurt Uni, GSI Darmstadt)

Vincenzo Greco (Catania Uni, INFN-LNS)

Pierre Moreau (Duke Uni)

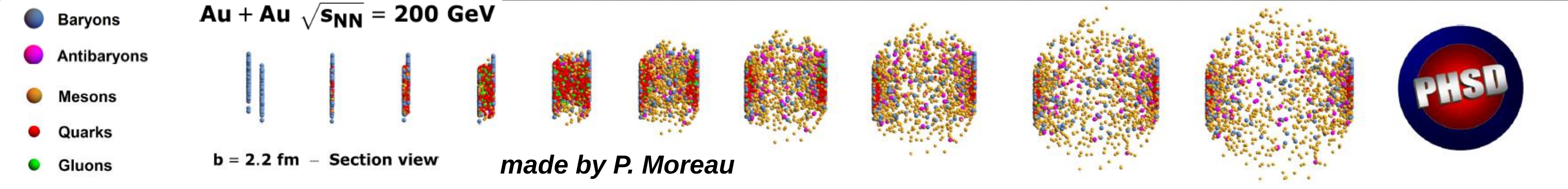
Salvatore Plumari (Catania Uni, INFN-LNS)

Vadim Voronyuk (JINR Dubna)

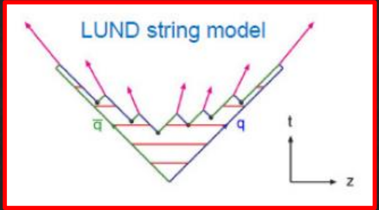
# PHSD: Parton-Hadron-String Dynamics

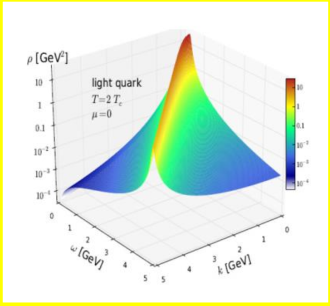
**non-equilibrium off-shell transport approach** to describe HICs and small systems

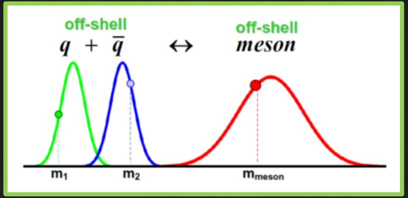
to study the phase transition from hadronic to partonic matter
and QGP properties from a microscopic origin




- INITIAL A+A COLLISIONS: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons
- FORMATION OF QGP: if energy density $\varepsilon > \varepsilon_C$ pre-hadrons dissolve in massive quarks and gluons + mean-field potential
- PARTONIC STAGE: evolution based on off-shell transport equations with the DQPM defining parton spectral functions
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryons and mesons
- HADRONIC PHASE: evolution based on the off-shell transport equations with hadron-hadron interactions




Cassing and Bratkovskaya, Phys. Rev. C 78, 034919 (2008); Nucl. Phys. A 831, 215 (2009)

# Generalized Transport Equations (GTE)

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one obtain GTE which describes the dynamics of broad strongly interacting quantum states

**drift term** **Vlasov term** **backflow term** **collision term = ‚gain' - ‚loss' term**

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \boxed{\diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\}} = \frac{i}{2}\left[\Sigma^>_{XP}S^<_{XP} - \Sigma^<_{XP}S^>_{XP}\right]$$

$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

off-shell behavior

GTE govern the propagation of the Green functions $i\,S^<_{XP} = A_{XP}\,N_{XP}$

particle spectral function

number of particles

Dressed propagators ($S_q$, $\Delta_g$)

$$S = (P^2 - \Sigma^2)^{-1}$$

with complex self-energies ($\Sigma_q$, $\Pi_g$):

$$\Sigma = m^2 - i2\gamma\omega$$

- ❖ the real part describes a dynamically generated mass ($m_q$, $m_g$)
- ❖ the imaginary part describes the interaction width ($\gamma_q$, $\gamma_g$)

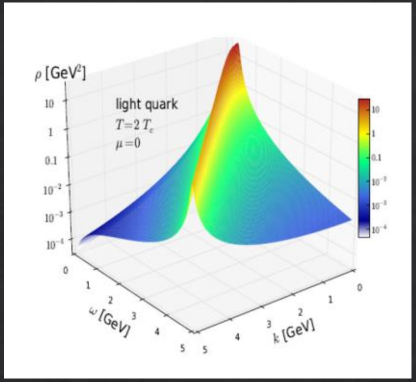
Cassing and Juchem, Nucl. Phys. A 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

# Dynamical QuasiParticel Model (DQPM)

The DQPM describes QGP in terms of interacting quasiparticle: massive quarks and gluons with Lorentzian spectral functions

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

$$\tilde{E}_j = p^2 + m^2 - \gamma^2$$



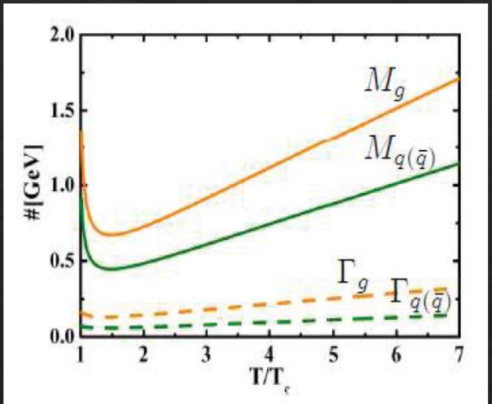

GLUONS QUARKS

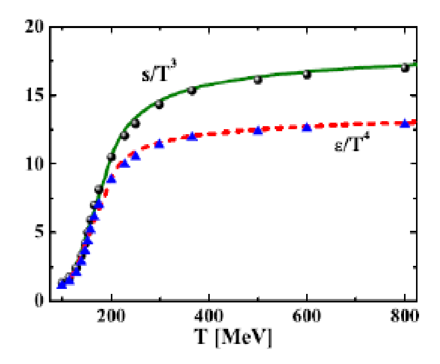
MASSES

$$m_g^2 = \frac{g^2}{6}\left(N_c + \frac{1}{2}N_f\right)T^2, \qquad m_q^2 = g^2\frac{N_c^2-1}{8N_c}T^2$$

WIDTHS

$$\gamma_g = \frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right), \quad \gamma_q = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$




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

RUNNING COUPLING

parameters from fit of lattice QCD thermodynamics

Peshier, Phys. Rev. D 70, 034016 (2004)
Peshier and Cassing, Phys. Rev. Lett. 94, 172301 (2005)
Cassing, Nucl. Phys. A 791, 365 (2007);
Nucl. Phys. A 795, 70 (2007)

PHSD extended to include chemical potential dependence of scattering cross sections

Moreau, Soloveva, LO, Song, Cassing and Bratkovskaya, Phys. Rev. C 100, 014911 (2019)

# Catania transport approach

The temporal evolution of the QGP fireball and the heavy quarks (HQ) in relativistic HICs is described by solving the **relativistic Boltzmann transport equation** for the parton distribution function **f(x,p)**

**QGP**

$$p^\mu \partial_\mu f_g(x,p) = \mathcal{C}[f_g, f_q]$$

$$p^\mu \partial_\mu f_q(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_q(x,p) = \mathcal{C}[f_g, f_q]$$

**HEAVY QUARKS**

$$p^\mu \partial_\mu f_{HQ}(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_{HQ}(x,p) = \mathcal{C}[f_g, f_q, f_{HQ}]$$

RELATIVISTIC BOLZTMANN EQUATIONS

***Field interaction***

change of ***f*** due to interactions of the partonic plasma with the external electromagnetic field

**Collision integral**

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

$$\mathcal{C}[f] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}(f'_1 f'_2 - f_1 f_2) \times |\mathcal{M}_{12\to 1'2'}| (2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2),$$

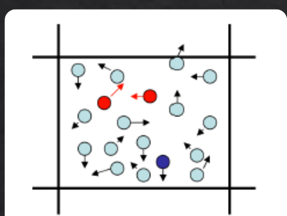
Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

# Catania transport approach

The temporal evolution of the fireball produced in relativistic HICs is described by solving the **relativistic Boltzmann equation** for the parton distribution function **f(x,p)**

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

***collision integral***
**$\eta/s \neq 0$**



$\Delta x$

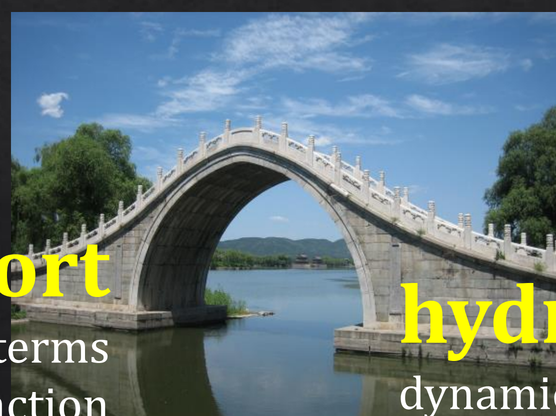
- TEST PARTICLES METHOD
  to map the phase space
- STOCHASTIC METHOD
  to simulate collisions

Instead of starting from cross sections we simulate a fluid at **fixed $\eta/s$**

CHAPMAN-ENSKOG EQUATION

$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho} \frac{1}{\sigma}$$

Plumari, Puglisi, Scardina and Greco, Phys. Rev. C 86 (2012) 054902



**transport**
microscopic description in terms of parton distribution function

**hydro**
dynamical evolution governed by macroscopic quantities

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 ($J \approx 10^5$ - $10^6\ \hbar$)** of the colliding system

- dominated by the y component perpendicular to the reaction plane
- partly trasferred to the plasma

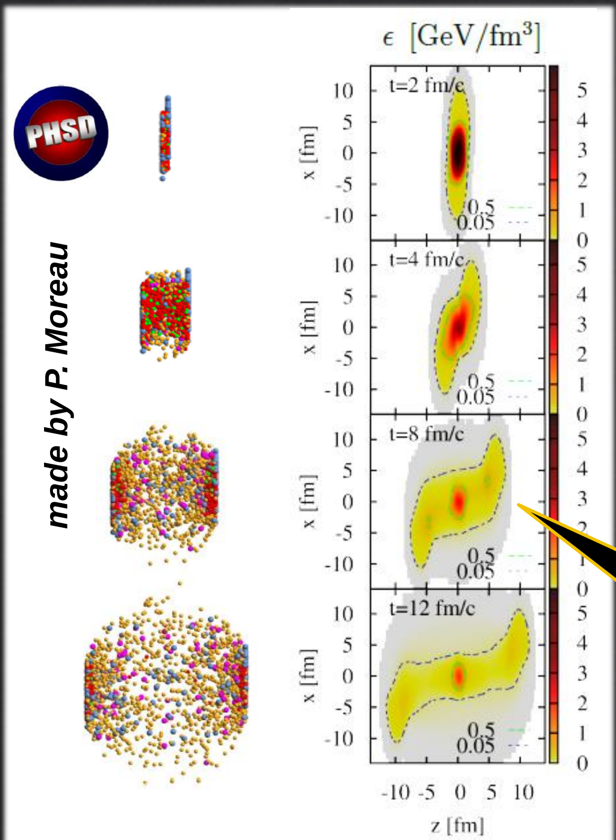
asymmetry in local participant density from forward and backward going nuclei

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

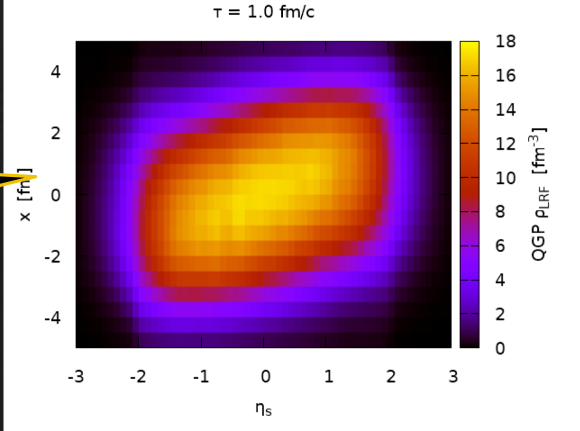
$$W(x_\perp,\eta_s) = 2\left(N_A(x_\perp)f_-(\eta_s) + N_B(x_\perp)f_+(\eta_s)\right)$$

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

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)
Oliva, Plumari and Greco, 2009.11066



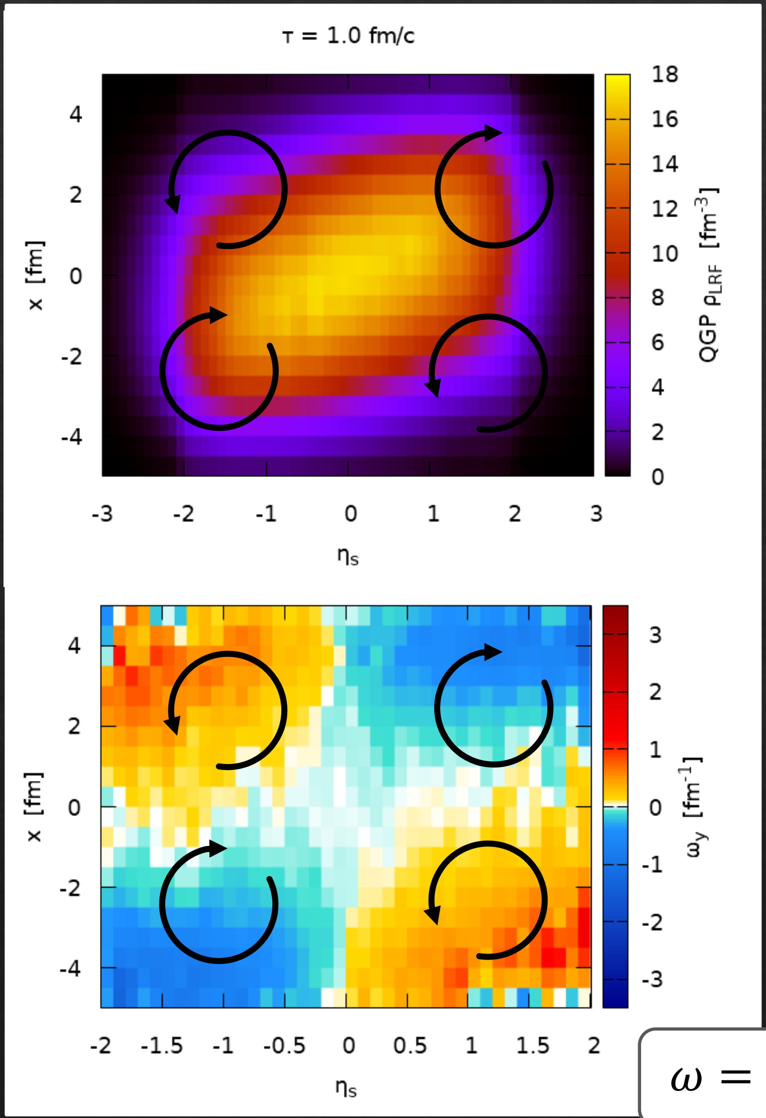

tilted fireball on the reaction plane




Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)
Kolomeitsev, Toneev and Voronyuk, Phys. Rev. C 97, 064902 (2018)

# The vortical quark-gluon plasma

Oliva, Plumari and Greco, 2009.11066

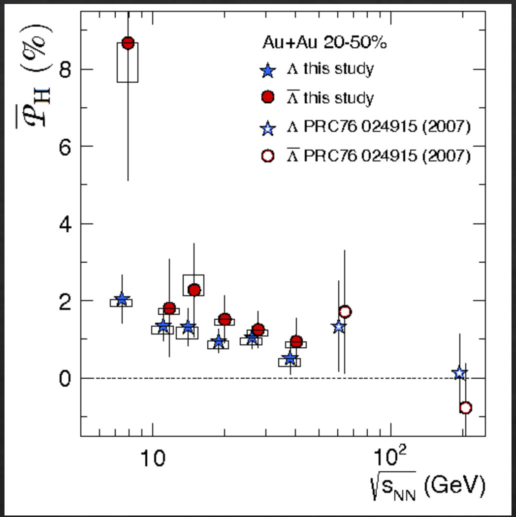



The huge angular momentum and the tilt of the fireball induce in the QGP an intense VORTICITY

The vorticity $\boldsymbol{\omega}$ is a measure of the local angular velocity of the fluid


Vorticity induce polarization of $\Lambda$ hyperons

STAR Collaboration, Nature 548, 62 (2017)
Becattini and Lisa, arXiv:2003.03640




**QGP as the most vortical fluid**
with the largest ω ever observed in nature

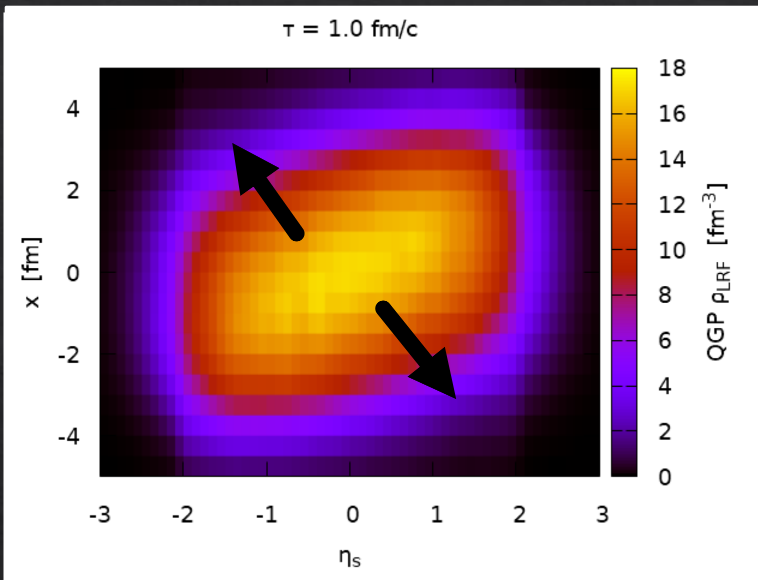
$$\omega \approx 3\ \mathrm{c/fm} \approx 10^{23}\ \mathrm{s}^{-1}$$

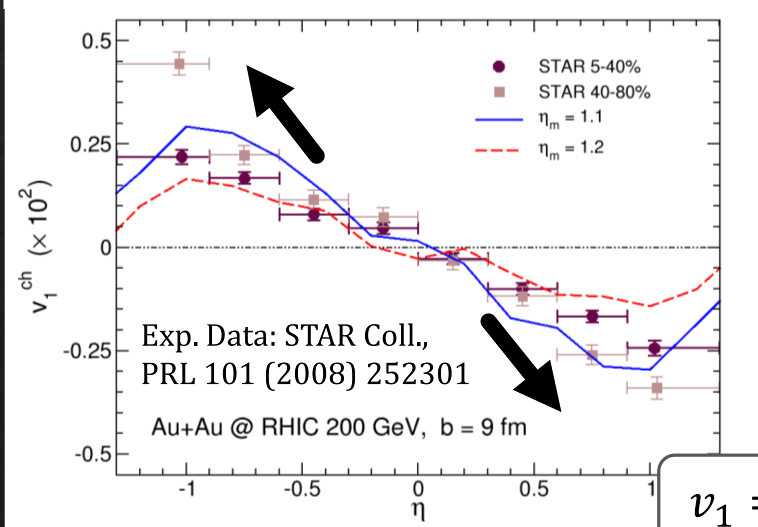
$$\omega = \nabla \times v$$

NONRELATIVISTIC VORTICITY

Csernai, Magas and Wang, Phys. Rev. C 87, 034906 (2013)
Deng and Huang, Phys. Rev . C 93, 064907 (2016)
Jiang, Lin and Liao, Phys. Rev. C 94, 044910 (2016)

# Vorticity and directed flow



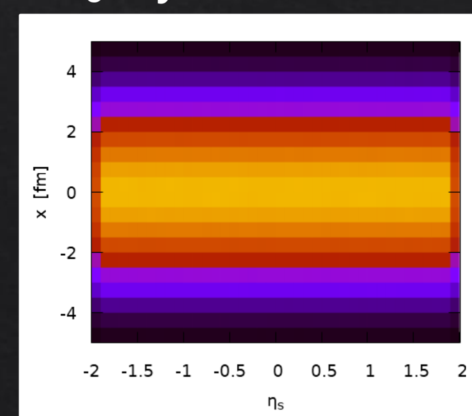

$$v_1 = \langle p_x / p_T \rangle$$

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**



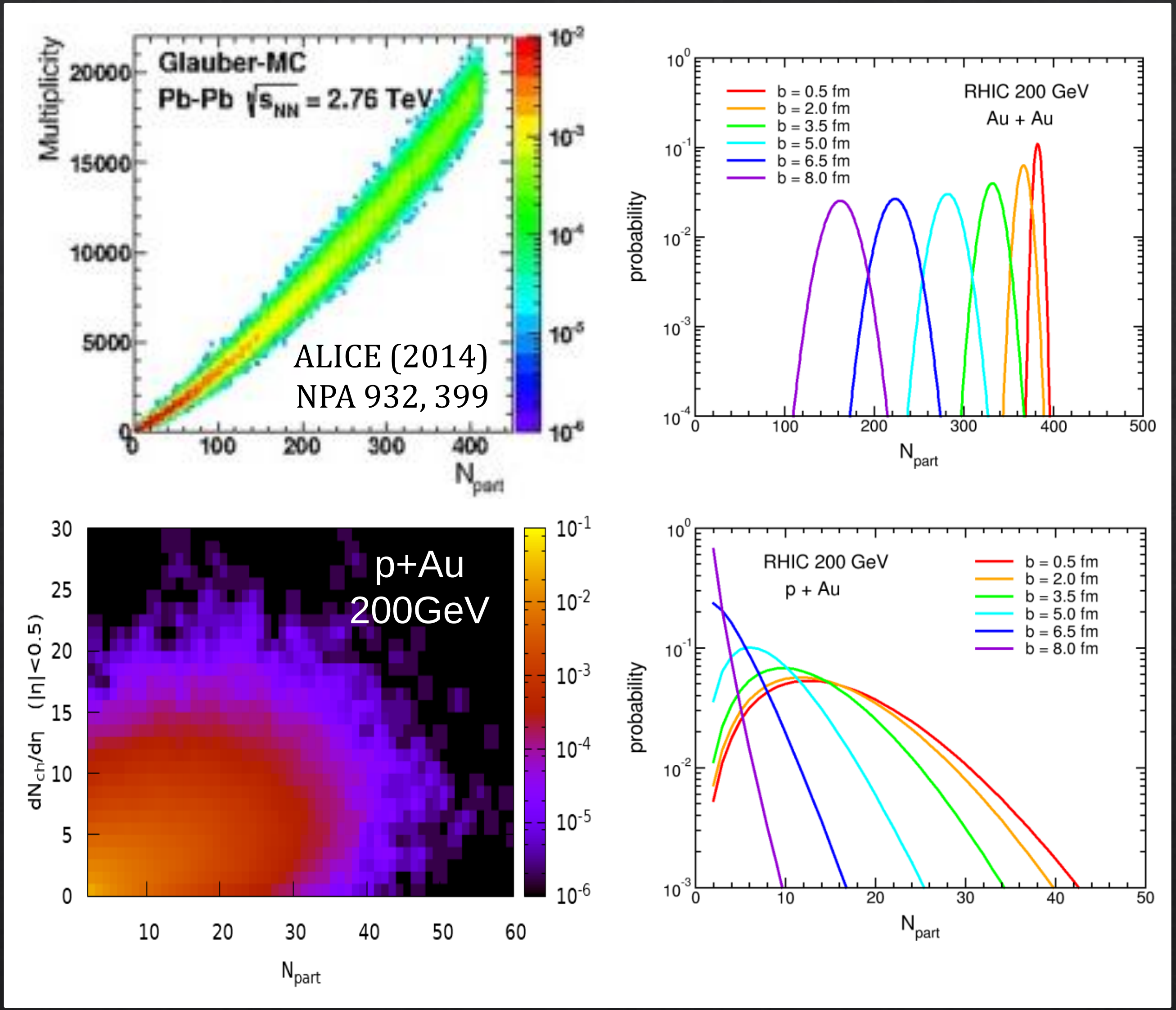
# Centrality determination : A+A vs p+A

***A+A***

centrality characterizes the amount of overlap in the interaction area

***p+A***

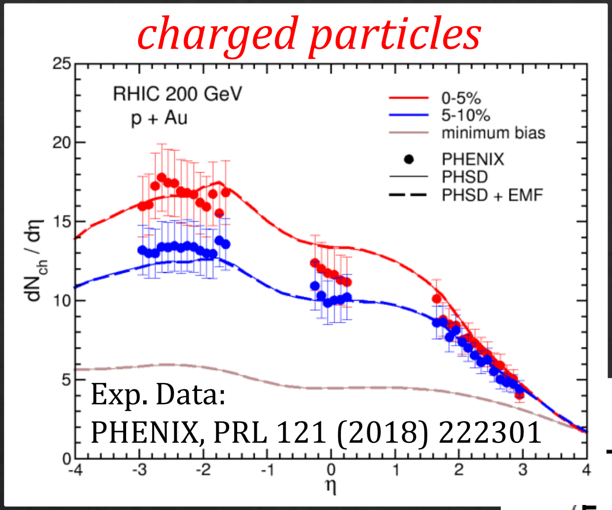
multiplicity fluctuation mixes events from different impact parameters




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

# p+Au: rapidity distributions

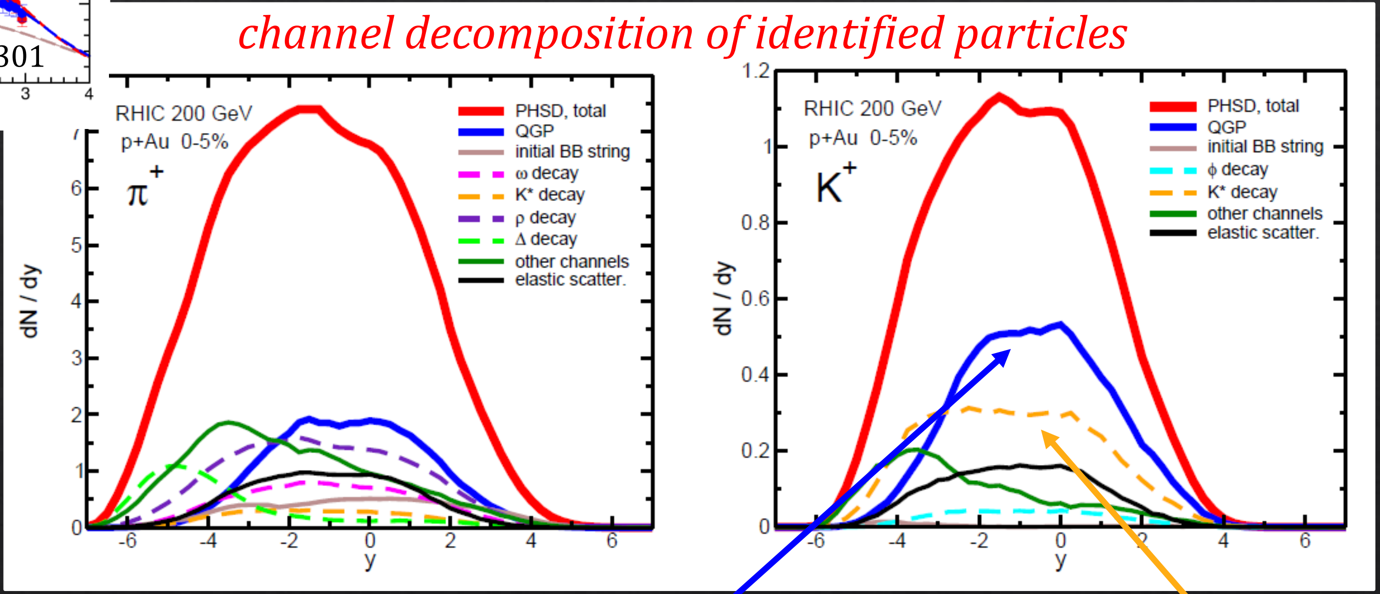
*charged particles*




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

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

*channel decomposition of identified particles*




- p+A: production of kaons directly from QGP hadronization larger than from K* decay
- 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)

# Anisotropic radial flow

**INITIAL-STATE FLUCTUATIONS AND 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)

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

n-th order
**event-plane angle**

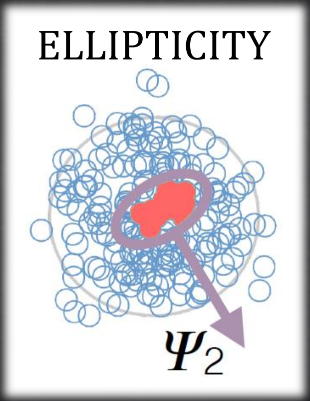
$$\Psi_n = \frac{1}{n} \mathrm{atan2}\left(Q_n^y, Q_n^x\right)$$

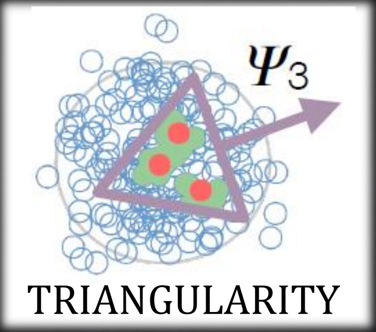
$$Q_n^x = \sum_i \cos[n\varphi_i]$$

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

Since the finite number of particles produces limited resolution in the determination of $\Psi_n$, 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

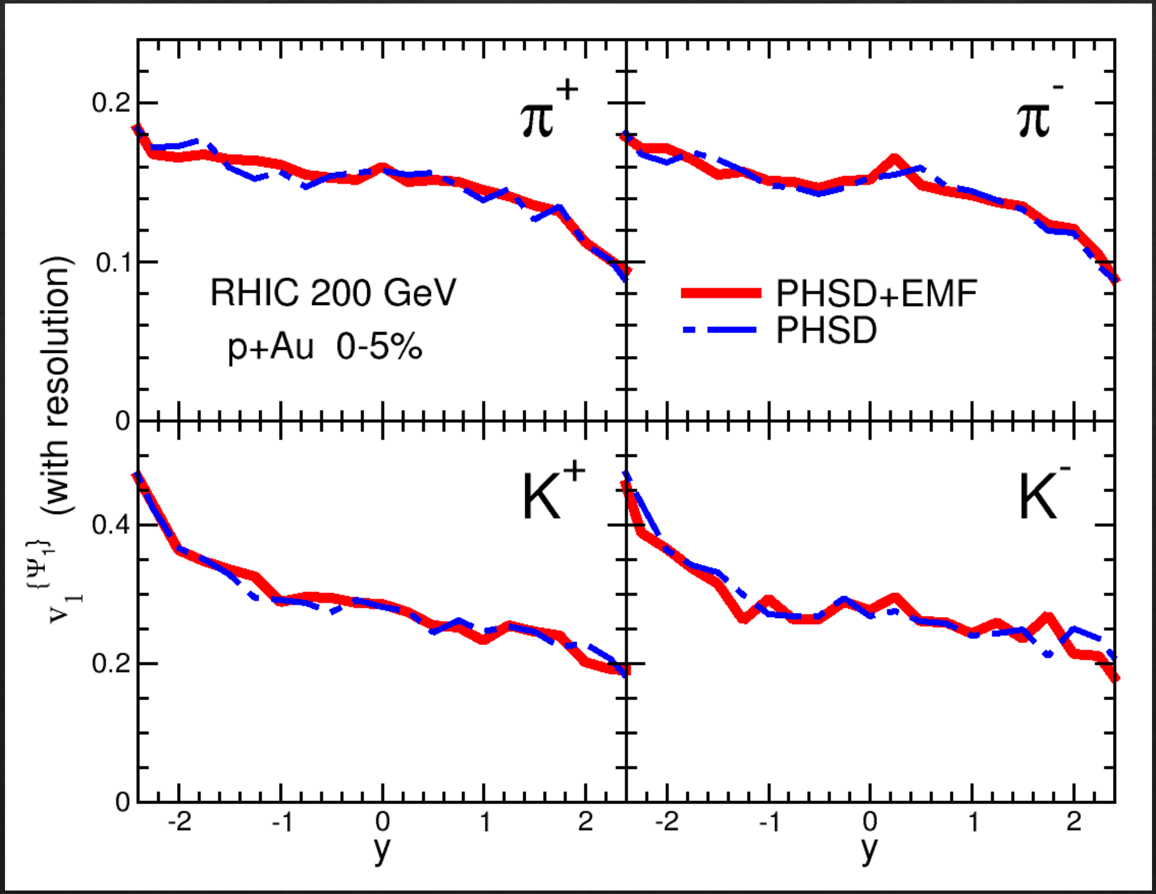


# p+Au: directed flow

***rapidity dependence of the DIRECTED FLOW OF IDENTIFIED PARTICLES***

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




**SPLITTING of positively and negatively charged particles INDUCED BY THE EMF?**

**5% central collisions**

no visible changes with and without electromagnetic fields

BUT clearly visible in simulations at fixed impact parameter…
…experimental challenge!

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