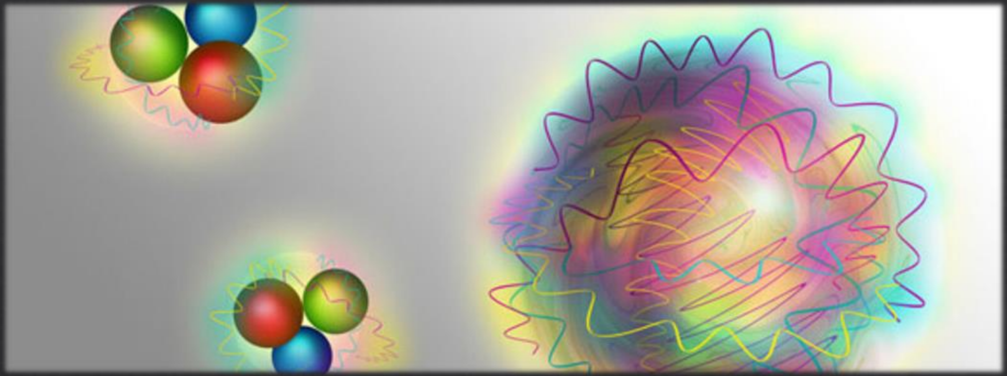
STRONG-2020

HEAVY-FLAVOR TRANSPORT IN QCD MATTER

ECT (online) – 29th April 2021*



Impact of the early-stage dynamics on heavy-flavor transport in ultrarelativistic heavy-ion collisions

Lucia Oliva

in collaboration with Vincenzo Greco, Salvatore Plumari, Yifeng Sun, Santosh K. Das, Jun-Hong Liu, Marco Ruggieri

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

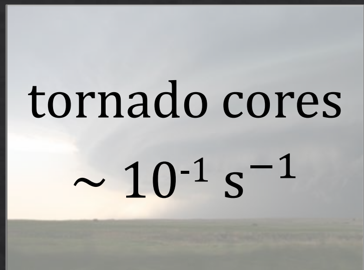
ITP Institute for Theoretical Physics

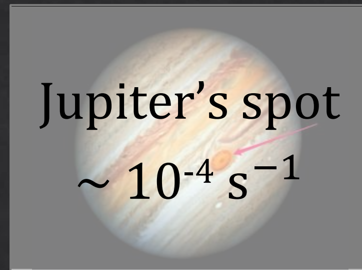
Alexander von Humboldt Stiftung/Foundation

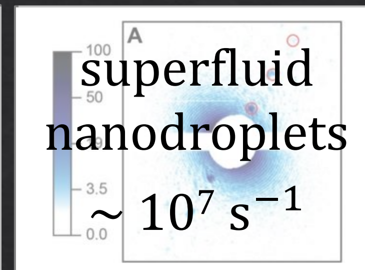
CRC-TR 211 Strong-interaction matter under extreme conditions

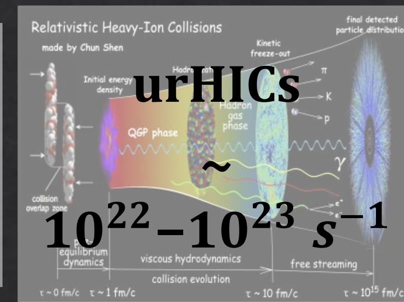
Intense fields and heavy flavor transport

✓ INTENSE **VORTICITY** FROM THE HUGE ANGULAR MOMENTUM



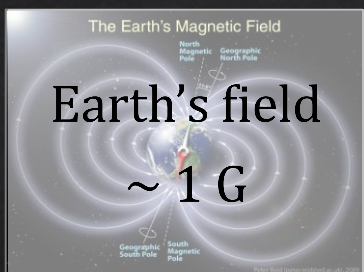


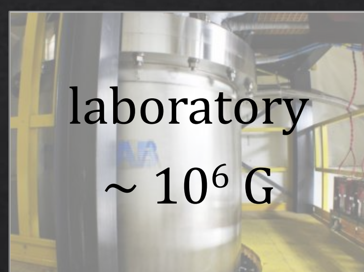


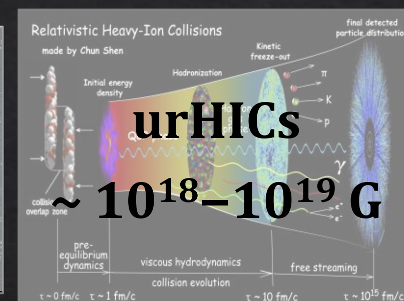


vorticity
ω

✓ INTENSE **ELECTROMAGNETIC FIELDS** (EMF)

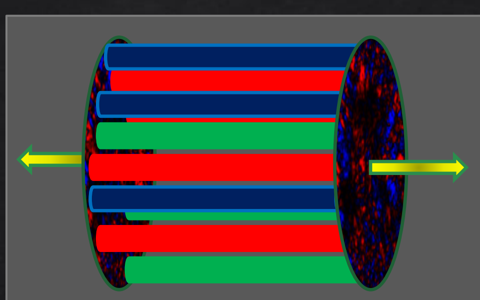






magnetic field
B

✓ INTENSE **COLOR FIELDS** IN THE EARLY STAGE OF URHICS



Among the many interesting effects these intense fields have an impact on transport coefficients and observables of heavy-flavor particles

Intense fields and heavy flavor transport

- ✓ INTENSE **VORTICITY** FROM THE HUGE ANGULAR MOMENTUM

  since 2017

  → heavy quark transport coefficients and D meson directed flow

  L. Oliva, S. Plumari and V. Greco, 2009.11066 (accepted in JHEP)

- ✓ INTENSE **ELECTROMAGNETIC FIELDS** (EMF)

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  → D meson directed flow

  S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina and V. Greco, PLB 768, 260 (2017)
  Y. Sun, S. Plumari and V. Greco, PLB 816, 136271 (2021)
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  → heavy quark transport coefficients and D meson R_{AA} and v_2

  Y. Sun, G. Coci, S. K. Das, S. Plumari, M. Ruggieri and V. Greco, PLB 798, 134933 (2019)
  J.-H. Liu, S. Plumari, S. K. Das, V. Greco and M. Ruggieri, PRC 102, 044902 (2020)
  J.-H. Liu, S. K. Das, V. Greco and M. Ruggieri, PRD 103, 034029 (2021)

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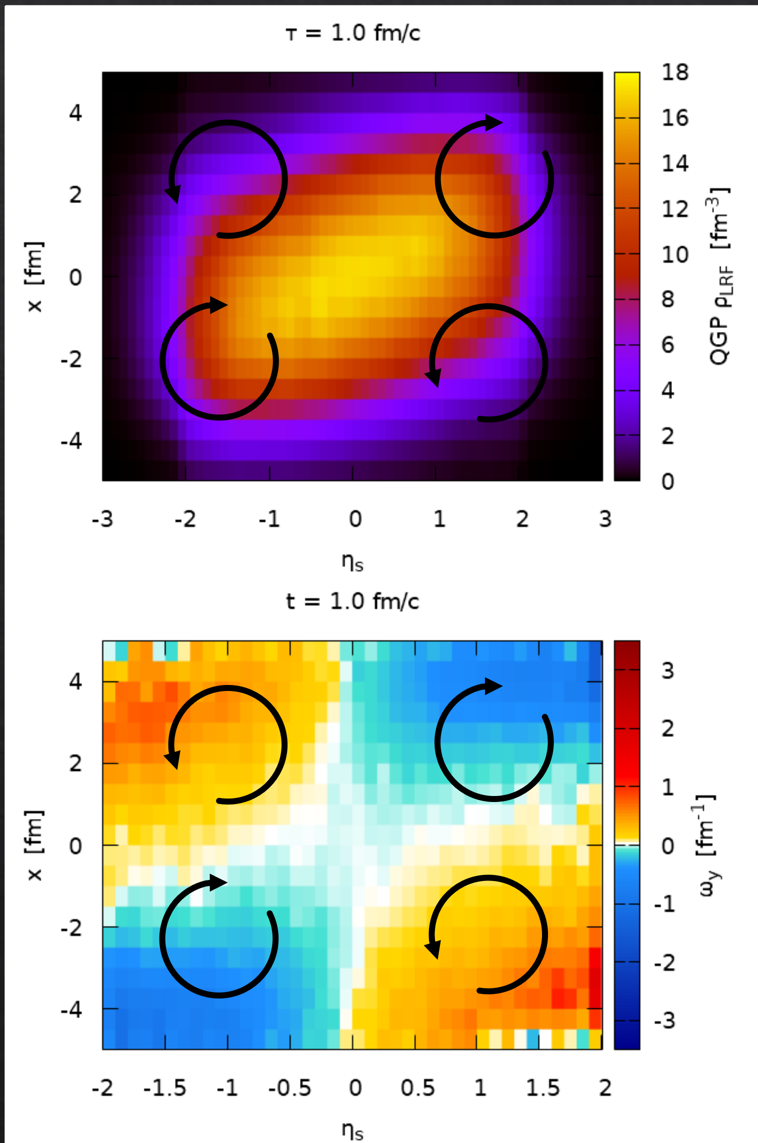
since 2018

The vortical quark-gluon plasma

Oliva, Plumari and Greco, JHEP (2021), 2009.11066



NONRELATIVISTIC VORTICITY

asymmetry in local participant density
from forward and backward going nuclei

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

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

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

inspired to initial conditions of hydro simulations
Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)

The huge angular momentum and the tilt of the fireball induce in the QGP an intense <u>VORTICITY</u>

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

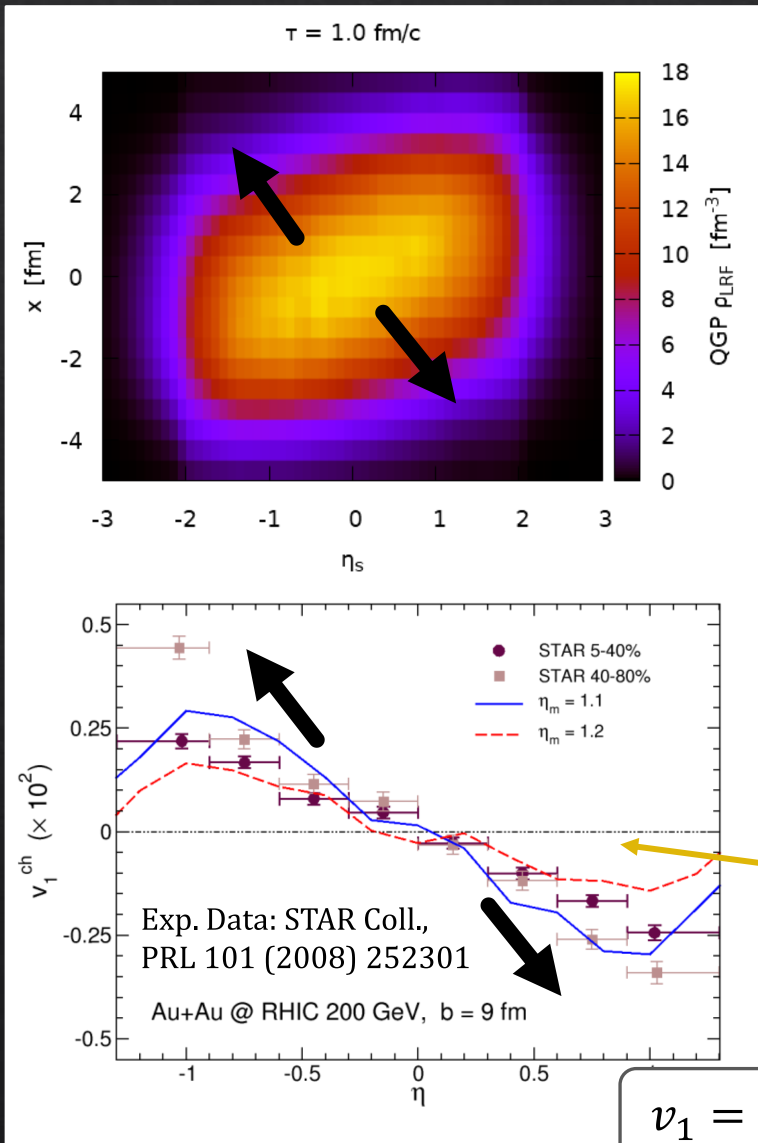
$$\omega_y \approx 3\ \mathrm{c/fm} \approx 10^{23}\ \mathrm{s}^{-1}$$

measure of the
local angular
velocity of the fluid

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)

Charged hadron directed flow

Oliva, Plumari and Greco, JHEP (2021), 2009.11066



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The huge angular momentum and the tilt of the fireball induce in the QGP a <u>DIRECTED FLOW</u>

$v_1 = 0$
if the fireball
is not tilted

collective sidewards
deflection of particles
along the x direction

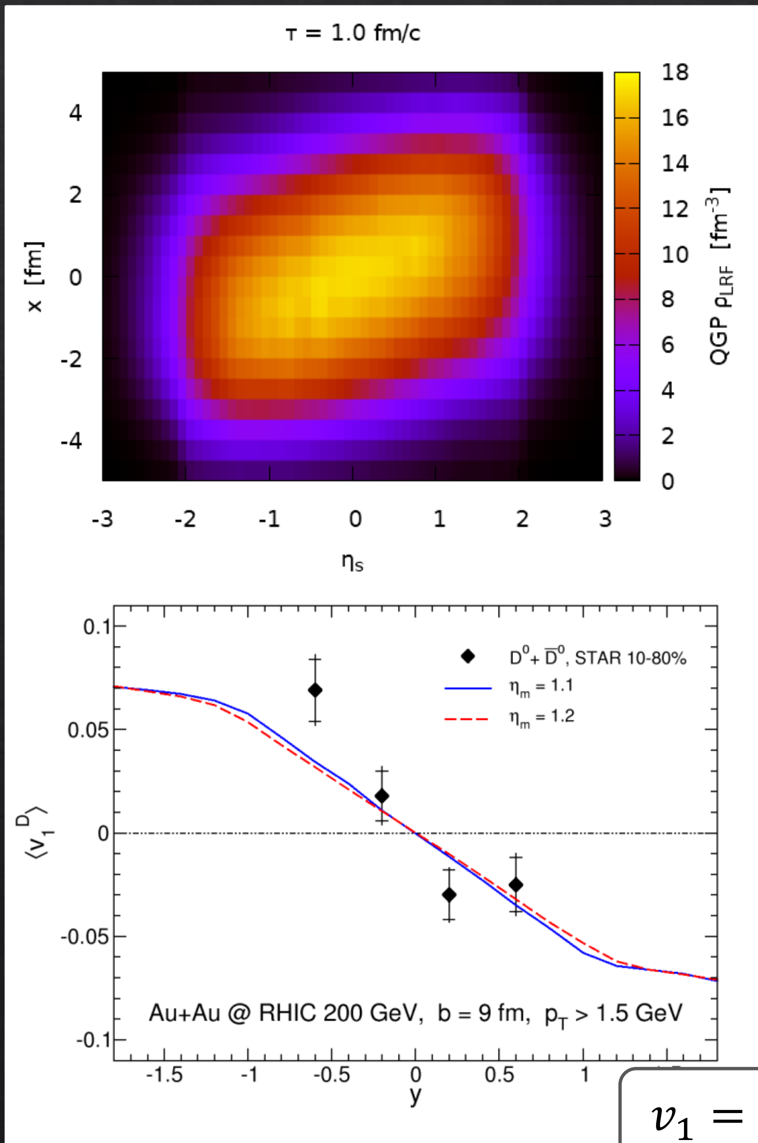
$$v_1 = \langle p_x / p_T \rangle$$

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

DIRECTED FLOW OF CHARGED PARTICLES

D meson directed flow

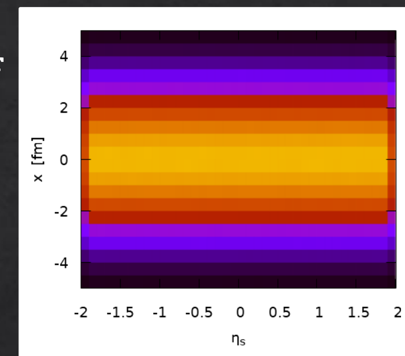
Oliva, Plumari and Greco, JHEP (2021), 2009.11066



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

Are HEAVY QUARKS affected by the initial tilt of the fireball and the directed flow of bulk medium?

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)

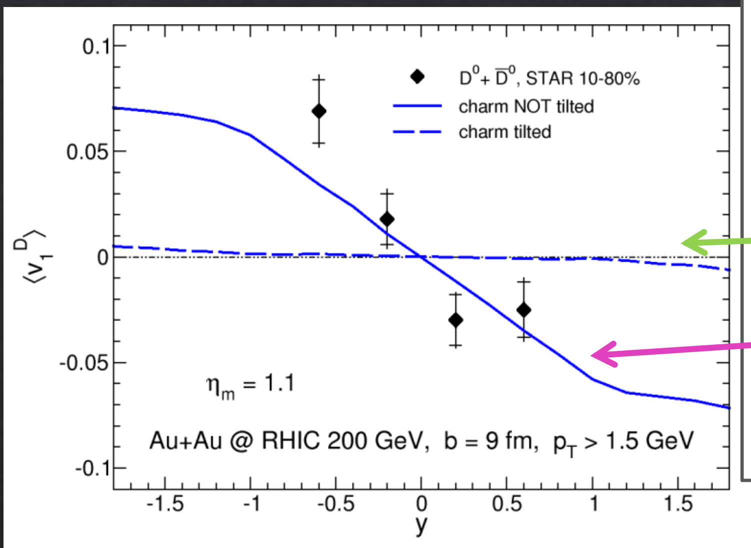
v_1 (HQs) ≫ v_1 (QGP)

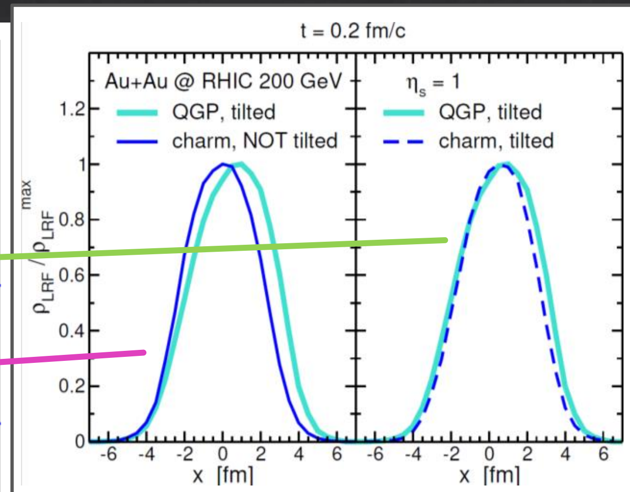
origin of the large directed flow of HQs different from the one of light particles

DIRECTED FLOW OF NEUTRAL D MESONS

Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP (2021), 2009.11066

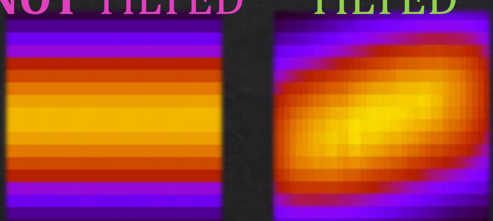




longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM **NOT** TILTED

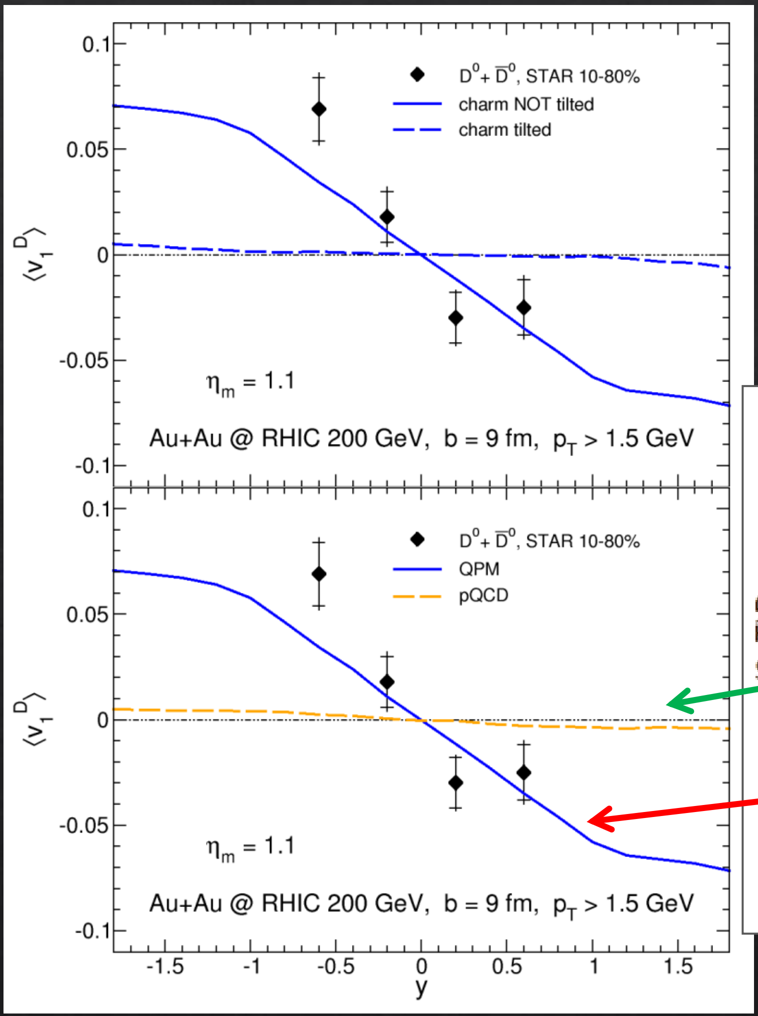
CHARM TILTED



QGP tilted in both cases

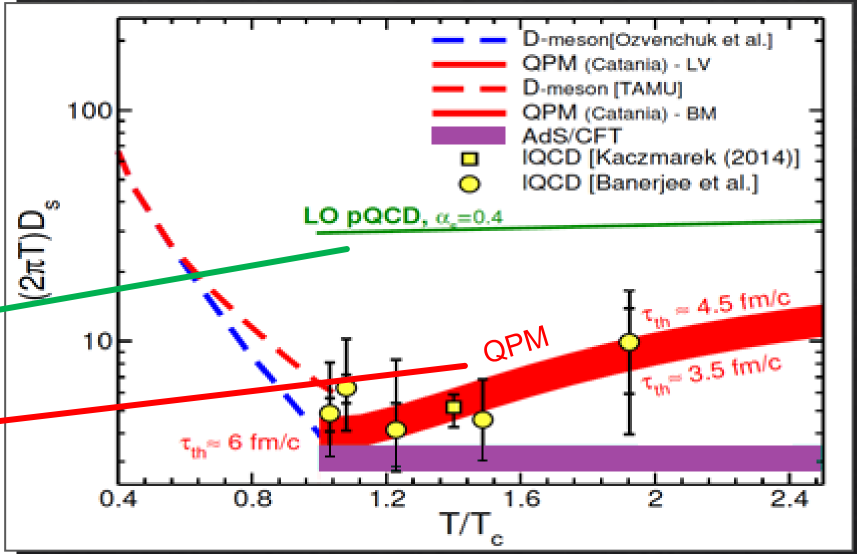
Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP (2021), 2009.11066



longitudinal asymmetry leads to pressure push of the bulk on the HQs

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



Greco, NPA 967, 200 (2017)

strict connection between the magnitude of the D-meson v_1 and the HQ diffusion coefficient

Similar conclusions with POWLANG approach

Beraudo, De Pace, Monteno, Nardi and Prino, 2102.08064

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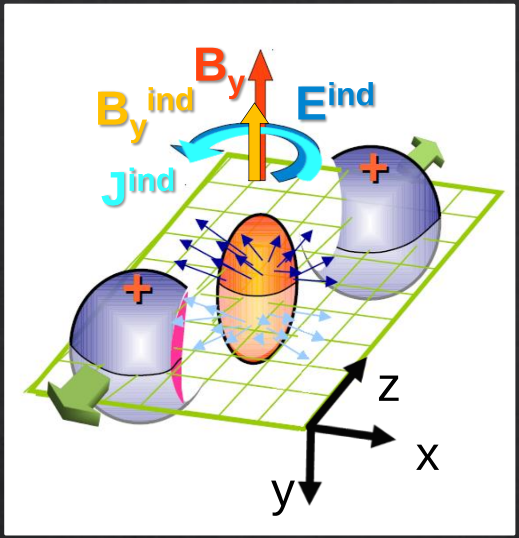
since 2018

Electromagnetic fields in HICs



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

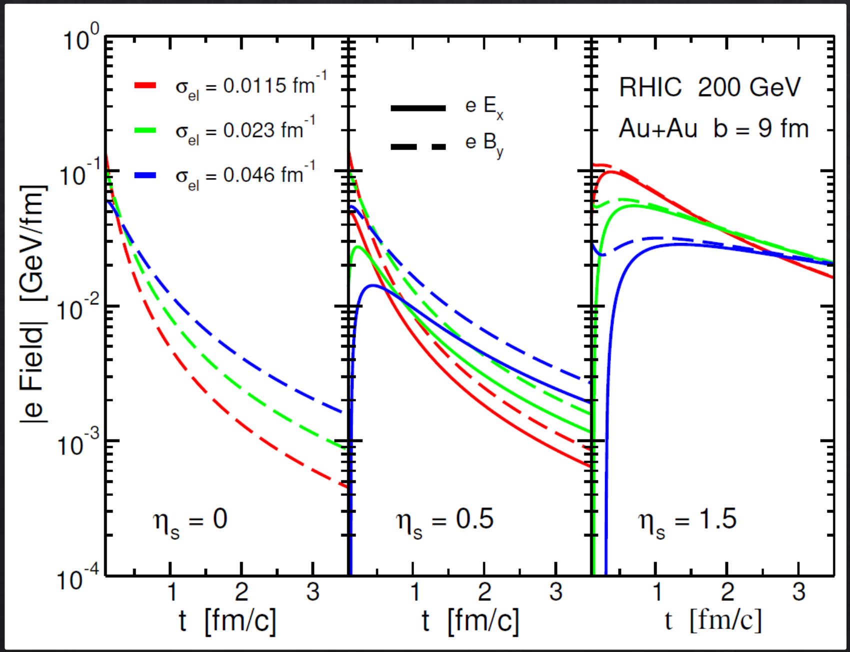
induced current from Ohm's law

$$J_{ind} = \sigma_{el} E$$

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

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

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



Oliva, Plumari and Greco, JHEP (2021), 2009.11066

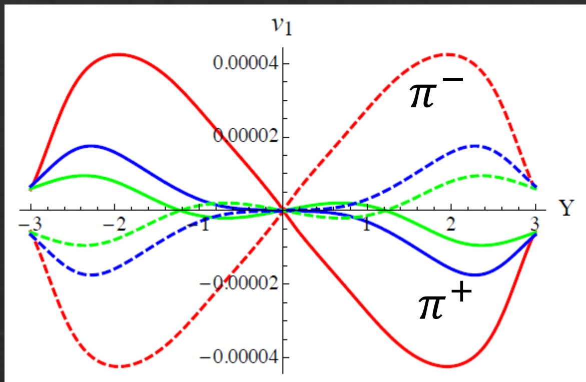
Maxwell equations for the EMF can be solved analytically considering a medium with **constant electric conductivity**

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

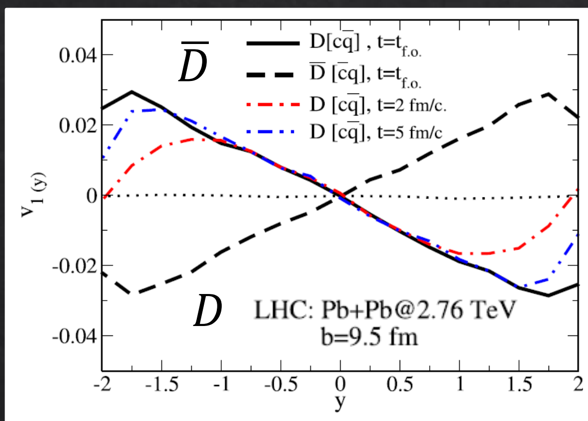
$$p^\mu \partial_\mu f(x,p) + q F^{\mu\nu}_{ext} p_\nu \partial^p_\mu f(x,p) = \mathcal{C}[f]$$

Boltzmann eq. with
EMF interaction term

EMF and directed flow splitting

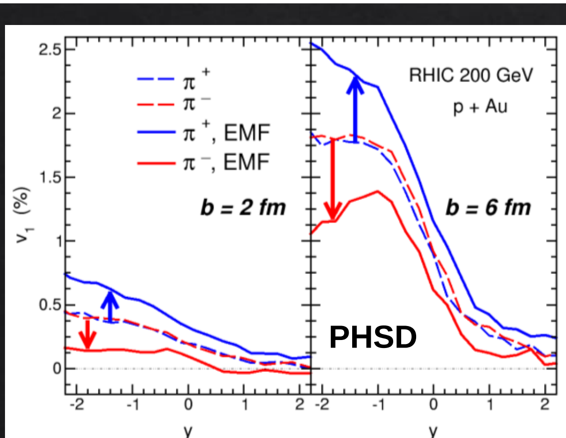


The huge EMF induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge



- difference in the v_1 of light hadrons in AA: $O(10^{-4}–10^{-3})$
  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 in AA: $O(10^{-2})$
  Das, Plumari, Chatterjee, Alam, Scardina and Greco,
  Phys. Lett. B 768, 260 (2017)
  Chatterjee and Bozek, Phys. Lett. B 798, 134955 (2019)



- difference in the v_1 of light mesons in pA: $O(10^{-2})$
  Oliva, Moreau, Voronyuk and Bratkovskaya,
  Phys. Rev. C 101, 014917 (2020)

reviews

Oliva, Eur. Phys. J. A 56, 255 (2020)

Dubla, Gursoy and Snellings,
Mod. Phys. Lett. A 35, 2050324 (2020)

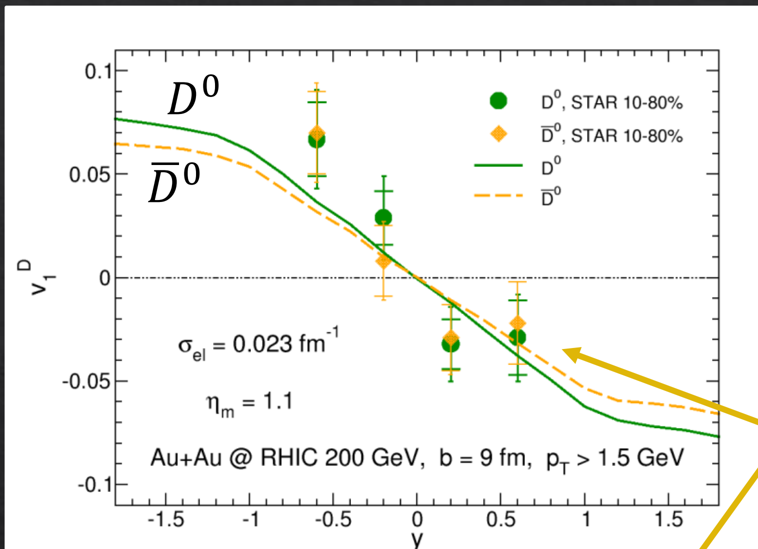
Directed flow in A+A at RHIC energy

Oliva, Plumari and Greco, JHEP (2021), 2009.11066

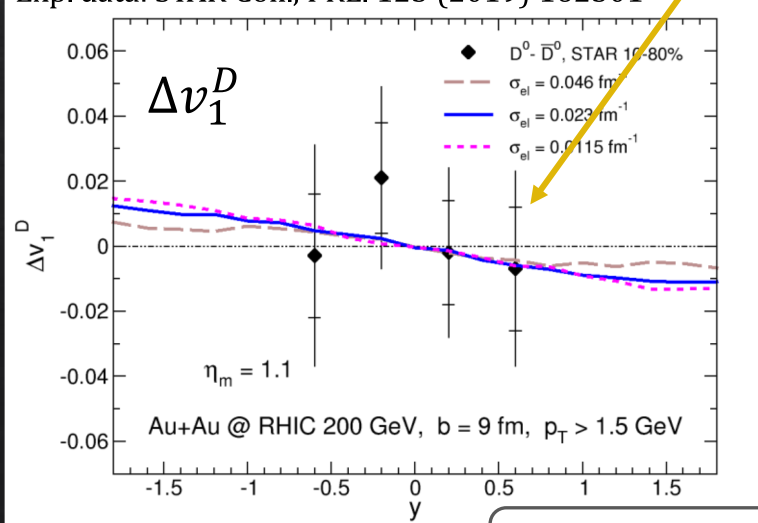
The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS

Δv_1 (HQ) $\gg$ Δv_1 (QGP)

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



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

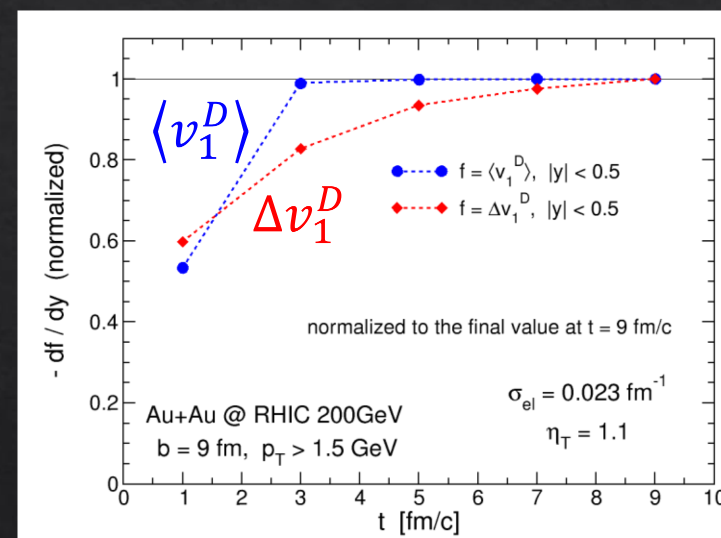


exp. Δv_1^D still consistent with zero due to the large errors

DIRECTED FLOW OF NEUTRAL D MESONS

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

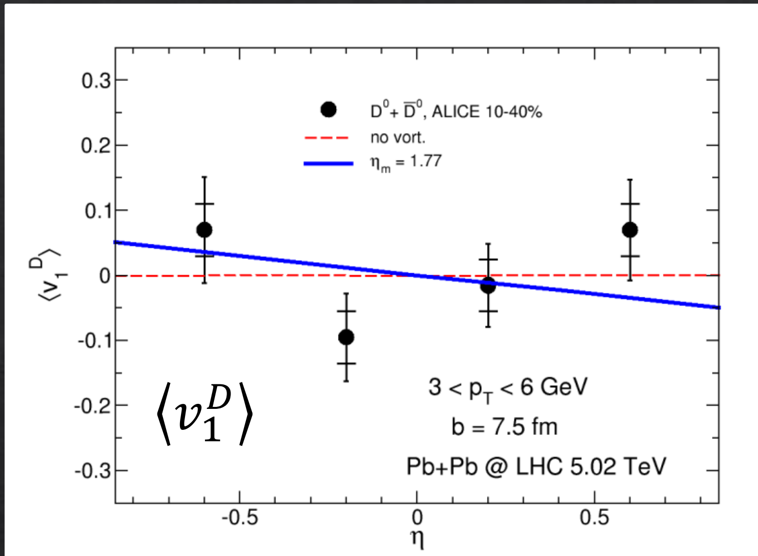
SLOPE TIME EVOLUTION

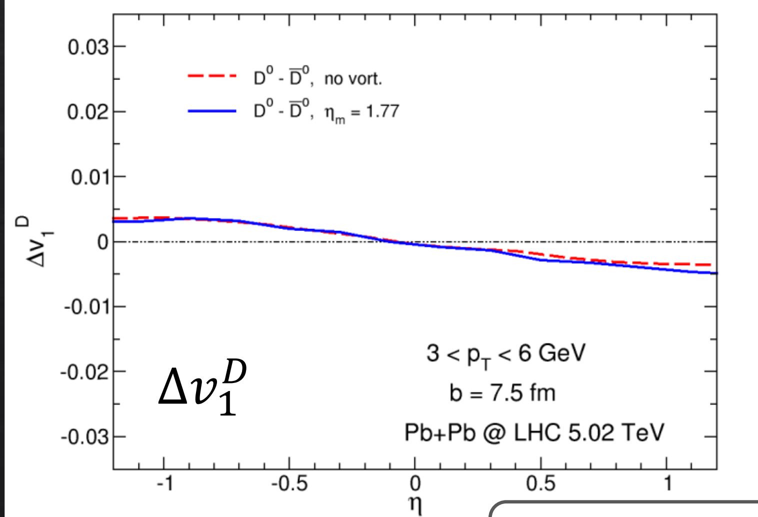


v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more $T \sim T_c$
$\rightarrow$ include v_1^D in Bayesian fits

Directed flow in A+A at LHC energy

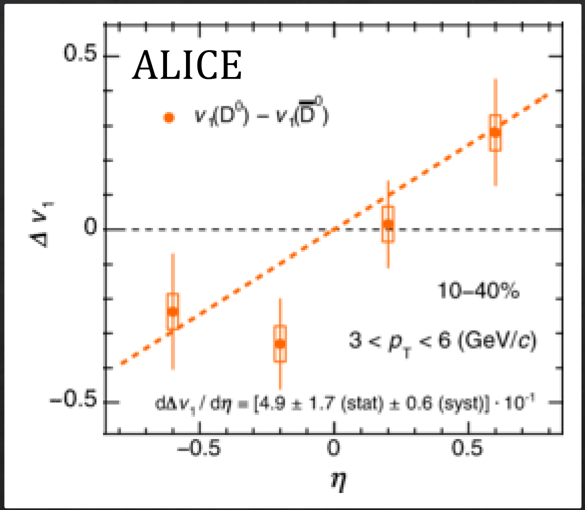
Oliva, Plumari and Greco, JHEP (2021), 2009.11066





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)



$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

the Δv_1 of D^0 and $\bar{D}^0$ measured by ALICE has opposite sign and magnitude ~50 times larger

if the v_1 splitting of neutral D mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

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

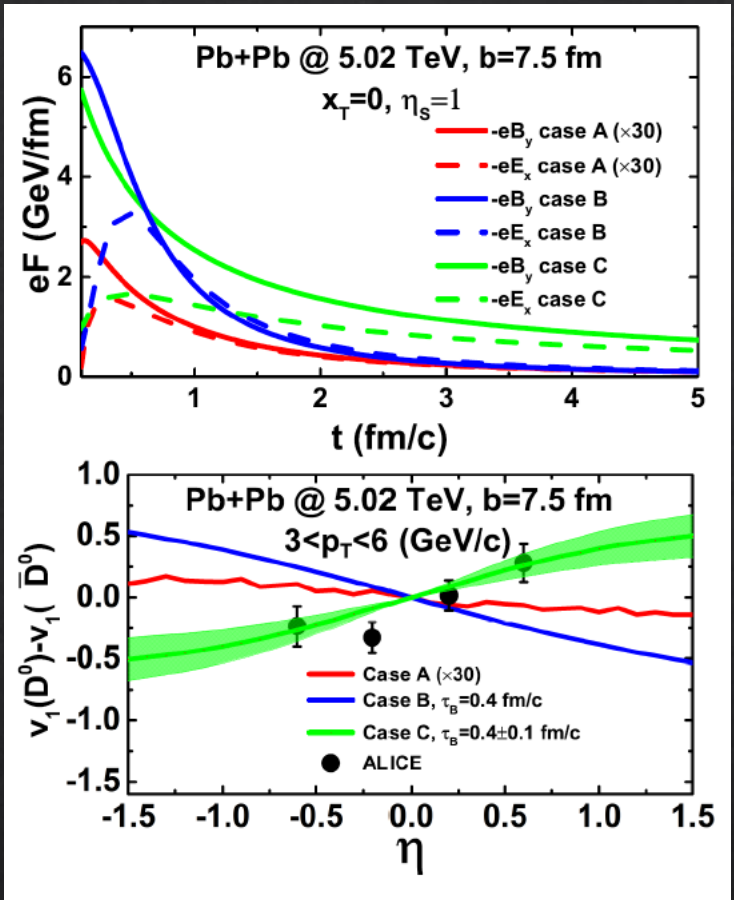
DIRECTED FLOW OF NEUTRAL D MESONS

Directed flow of charm and leptons

Sun, Plumari and Greco, Phys. Lett. B 816, 136271 (2021)

- ❖ Analytic solution of EMF with constant σ_{el} case A
- ❖ Magnetic field parametrization between in-vacuum and in-medium decay: $B(\tau) = B_0/[1 + (\tau/\tau_B)^n]$
  case B n=2 case C n=1
  Electric field from Faraday law

case C reproduces the ALICE data for the Δv_1 $(D^0,\bar{D}^0)$ but it is really a slow time decay of B



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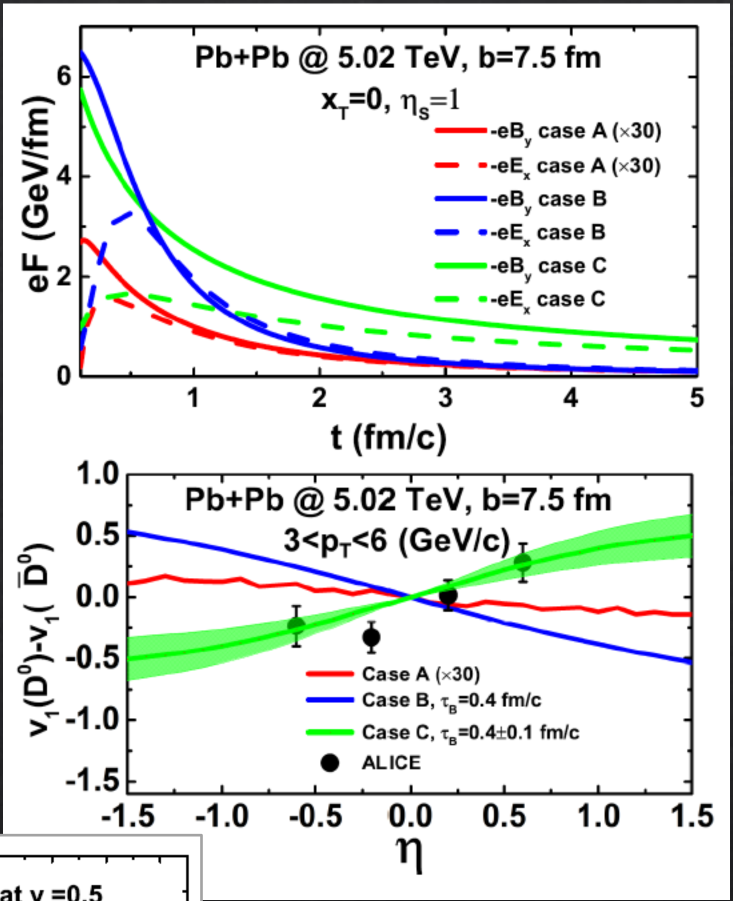
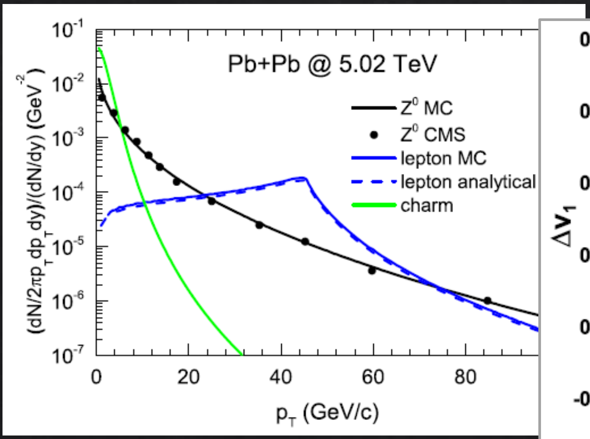
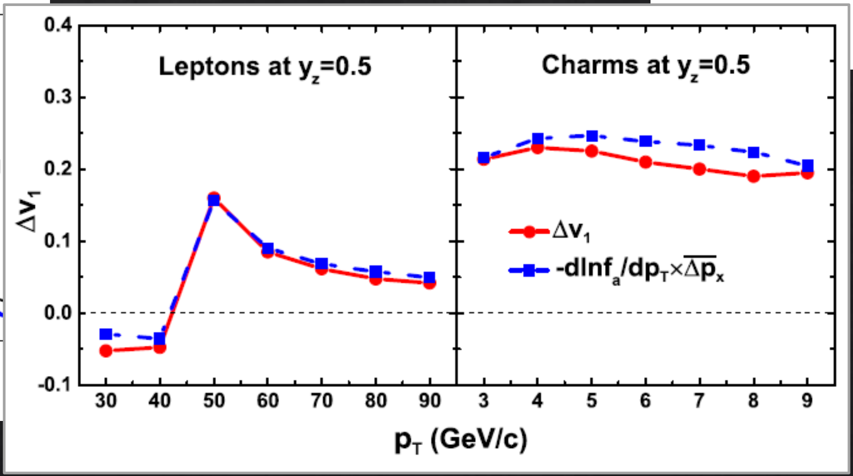


Probing the EMF with leptons from Z^0 decay

- charged leptons interact only electromagnetically
- $\tau_{decay}(Z^0) \approx \tau_{form}(c) \approx 0.08$ fm$/c$

$$v_1(p_T, y) \approx \frac{\overline{\Delta p}_x(p_T, y)}{2} \frac{-\partial \ln f_a}{\partial p_T}$$





Δv_1 of leptons from Z^0 decay can help to clarify the electromagnetic origin of Δv_1 of neutral D mesons

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J.-H. Liu, S. K. Das, V. Greco and M. Ruggieri, PRD 103, 034029 (2021)

Heavy quarks in the glasma

What happens for 0<t<0.3 fm/c?
Has the very early stage left some imprints on heavy flavor transport?

McLerran-Venugopalan (MV) model for the initial conditions of the classical gluon field

McLerran and Venugopalan, Phys. Rev. D 49, 2233 (1994); Phys. Rev. D 49, 3352 (1994); Phys. Rev. D 50, 2225 (1994)

$$\langle \rho_A^a(x_T)\rho_A^b(y_T)\rangle = (g^2\mu_A)^2\delta^{ab}\delta^{(2)}(x_T - y_T)$$

Classical Yang-Mills (CYM) equations for the dynamical evolution of glasma

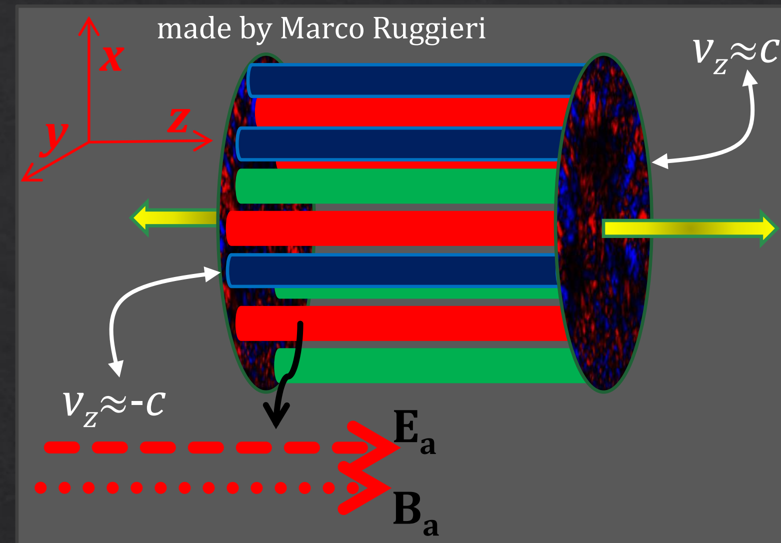
$$\begin{aligned} E^i &= \tau\partial_\tau A_i, & \partial_\tau E^i &= \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji}, \\ E^\eta &= \frac{1}{\tau}\partial_\tau A_\eta, & \partial_\tau E^\eta &= \frac{1}{\tau}D_j F_{j\eta}. \end{aligned}$$

solved in SU(2)

Wong equations for the dynamics of a heavy quark in the evolving glasma

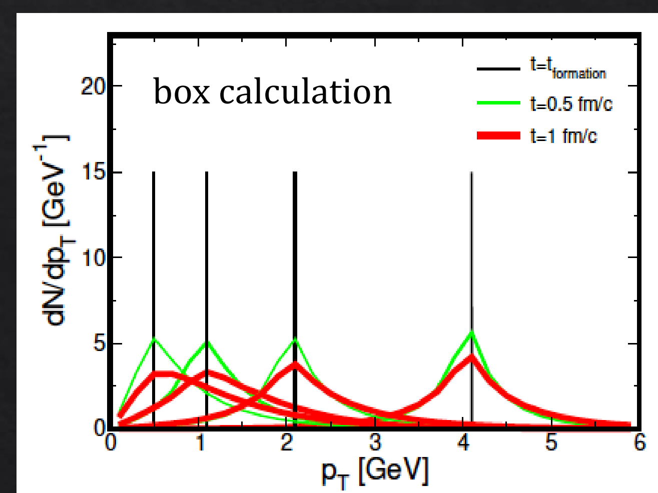
$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E\frac{dQ_a}{dt} = -Q_c\varepsilon^{cba}A_b\cdot p$$

$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu}p^\nu$$



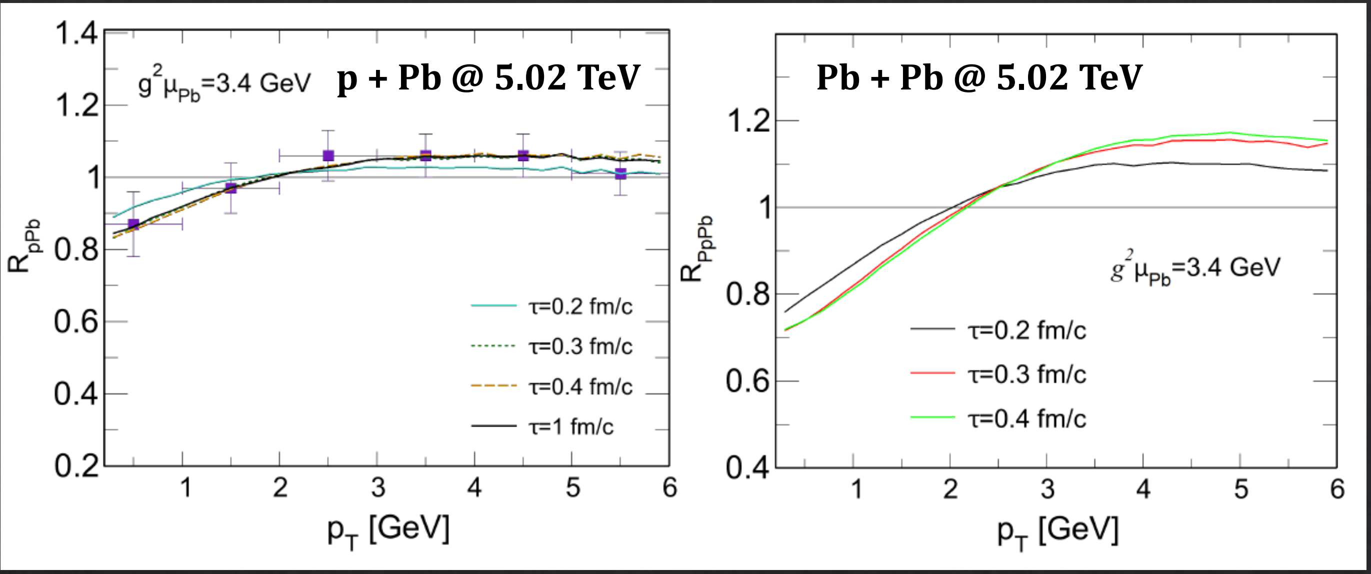
interaction with the initial glasma induce strong diffusion of charm quarks

Mrowczynski, Eur. Phys. J. A 54, 43 (2018)
Ruggieri and Das, Phys. Rev. D 98, 094024 (2018)



Heavy quarks in the glasma

Liu, Plumari, Das, Greco and Ruggieri, Phys. Rev. C 102, 044902 (2020)

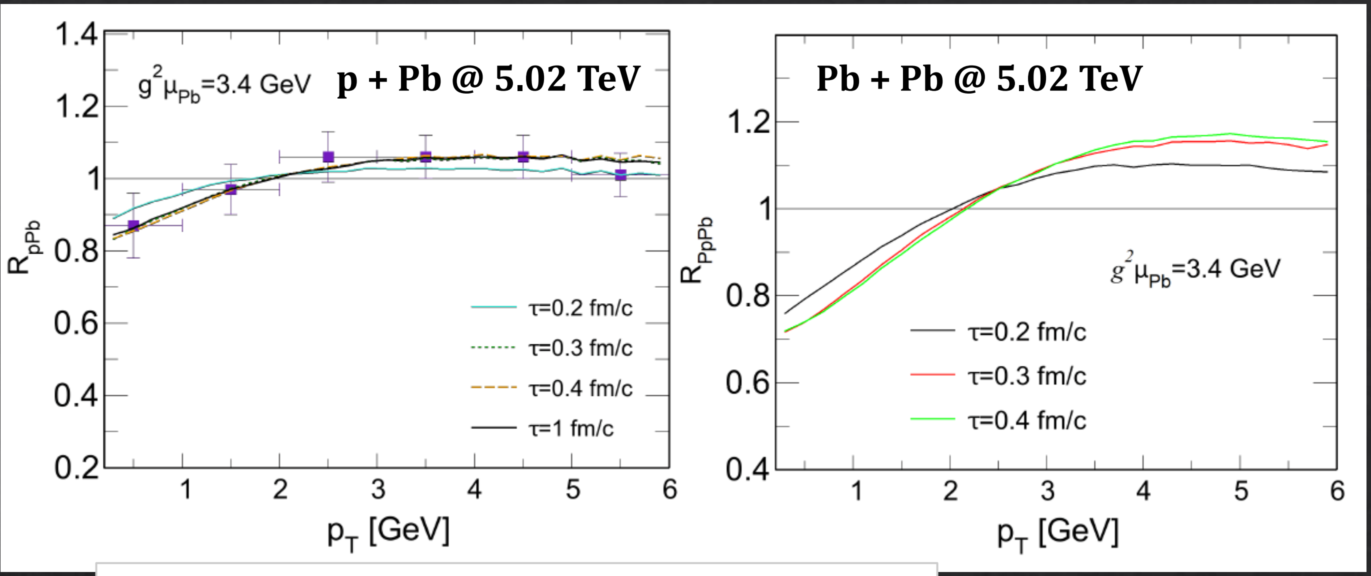


Strong and fast diffusion of HQs in the glasma

The dominance of diffusion-like dynamics leads to an **enhancement of R_{AA} at high p_T**

Heavy quarks in the glasma

Liu, Plumari, Das, Greco and Ruggieri, Phys. Rev. C 102, 044902 (2020)



Strong and fast diffusion of HQs in the glasma

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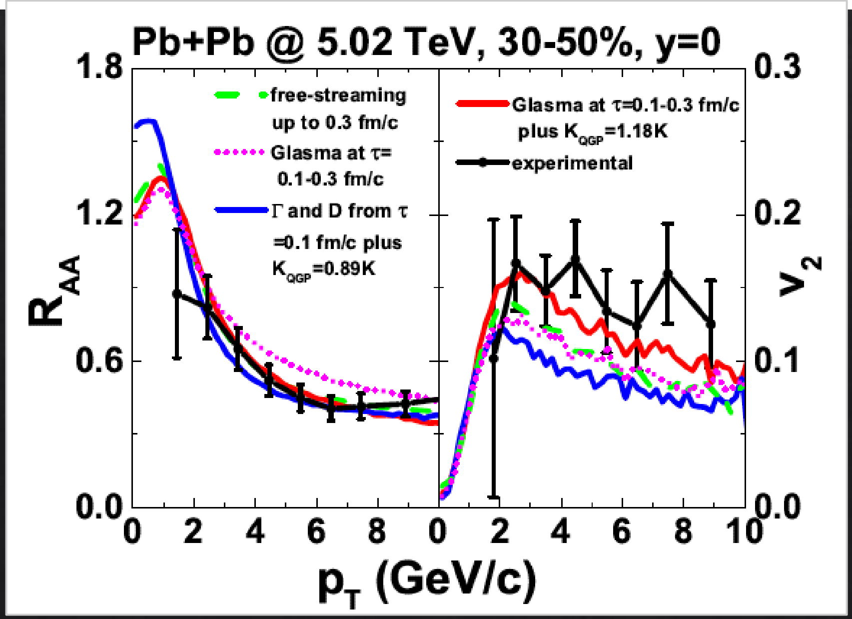


HQ spectrum in the glasma phase as initialization of HQs in the QGP for studying the impact on D-meson observables in AA collisions

The inclusion of the glasma phase leads to a **gain in $v_2(p_T)$:** larger interaction in QGP stage to have the same $R_{AA}(p_T)$

Sun, Coci, Das, Plumari, Ruggieri and Greco, Phys. Lett. B 798, 134933 (2019)

CONCLUSIONS

STRONG FIELDS IN ULTRARELATIVISTIC COLLISIONS

- intense **vorticity** induced by the huge angular momentum
- intense **electromagnetic fields**
- intense **color fields** in the very early stage

Among the many interesting effects these intense fields have an impact on transport coefficients and observables of heavy-flavor particles.

- ✓ The very large v_1 for D mesons can be generated only if there is a longitudinal asymmetry between the bulk matter and the charm quarks and if the latter have a large non-perturbative interaction in the QGP medium.
- ✓ The v_1 splitting of neutral D mesons is well described at RHIC energy but still a challenge at LHC. If confirmed to be of electromagnetic origin it is a proof of QGP formation. The $\Delta v_1(l^+, l^-)$ from Z^0 decay can help to clarify it.
- ✓ Heavy-flavor particles can play a role in spotting the glasma dynamics and linking pA and AA collisions.

Thank you for your attention!

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

Collision integral

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

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

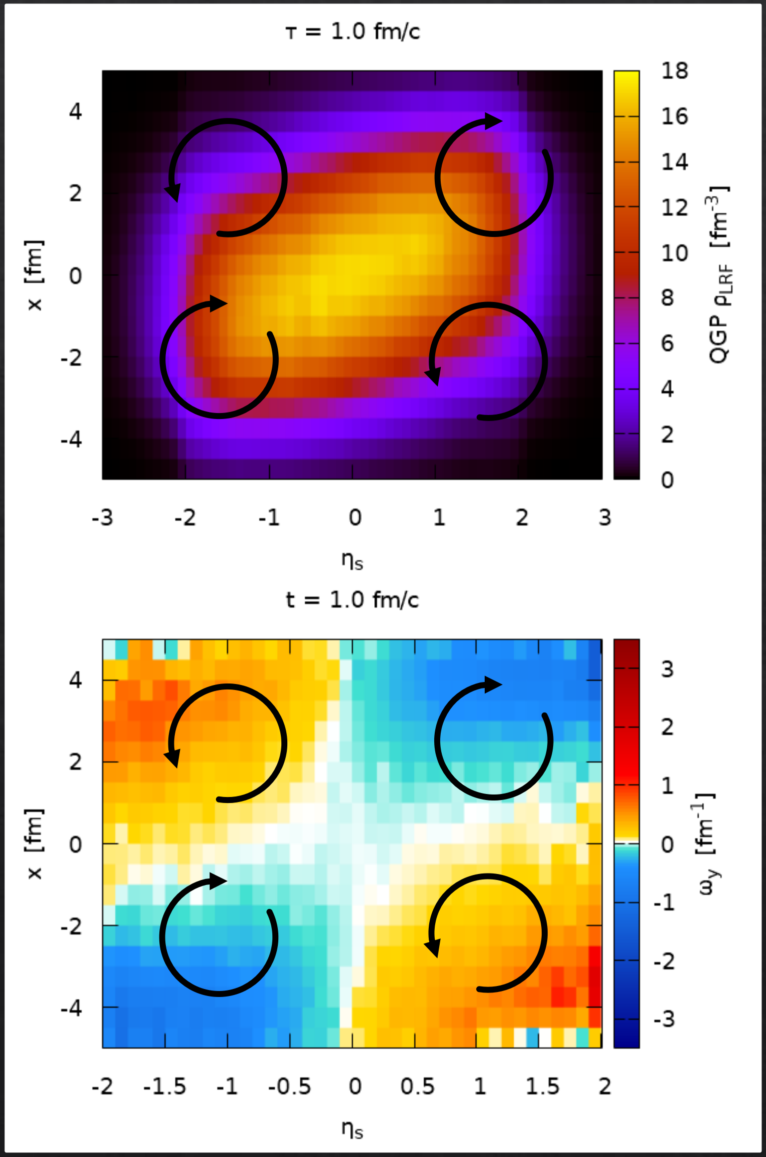
Field interaction

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

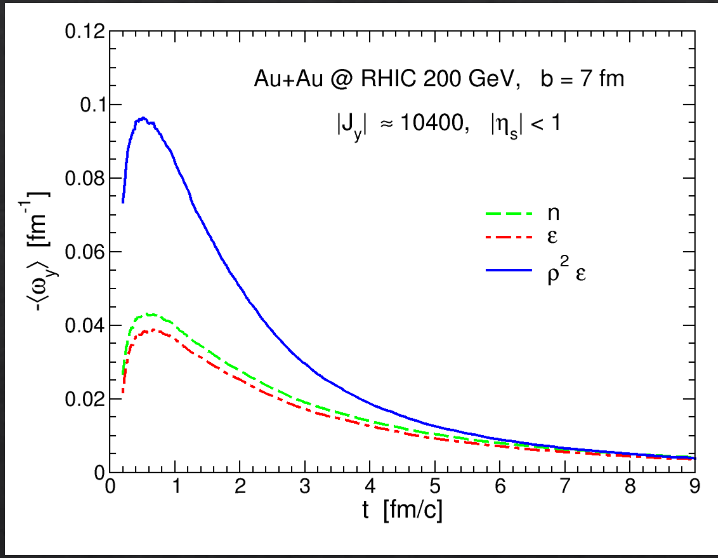
Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

The vortical quark-gluon plasma

Oliva, Plumari and Greco, JHEP (2021), 2009.11066



NONRELATIVISTIC VORTICITY



$$\langle\omega_y\rangle(\boldsymbol{x},t) = \frac{\int d^3x\, w(\boldsymbol{x},t)\omega_y(\boldsymbol{x},t)}{\int d^3x\, w(\boldsymbol{x},t)}$$

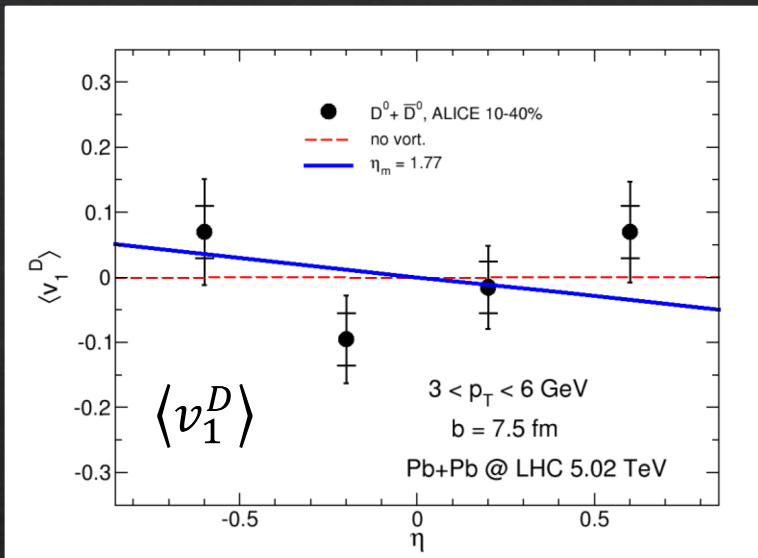
$w(\boldsymbol{x},t)$ = weigthing function

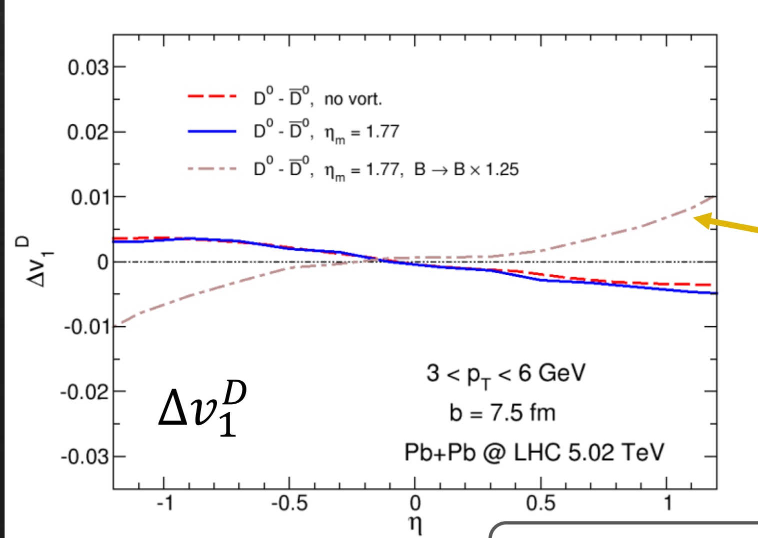
$n(\boldsymbol{x},t), \varepsilon(\boldsymbol{x},t), \rho^2(\boldsymbol{x})\varepsilon(\boldsymbol{x},t)$

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)

Directed flow in A+A at LHC energy

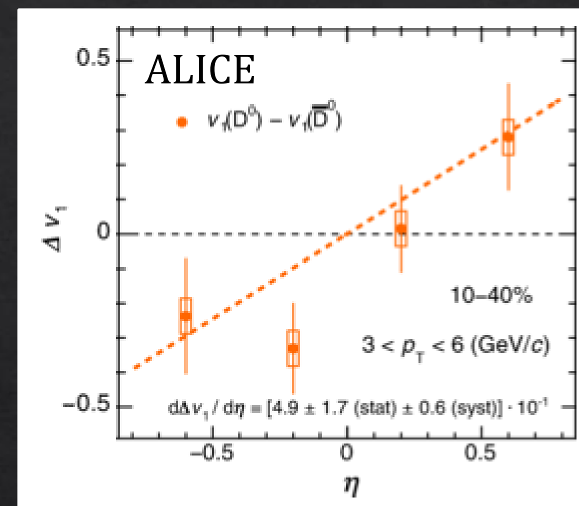
Oliva, Plumari and Greco, JHEP (2021), 2009.11066





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)



$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

positive slope rising by hand the value of the magnetic field

if the v_1 splitting of neutral D mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

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

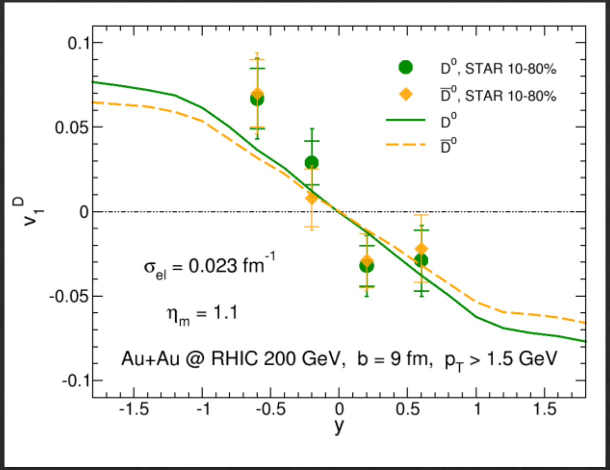
DIRECTED FLOW OF NEUTRAL D MESONS

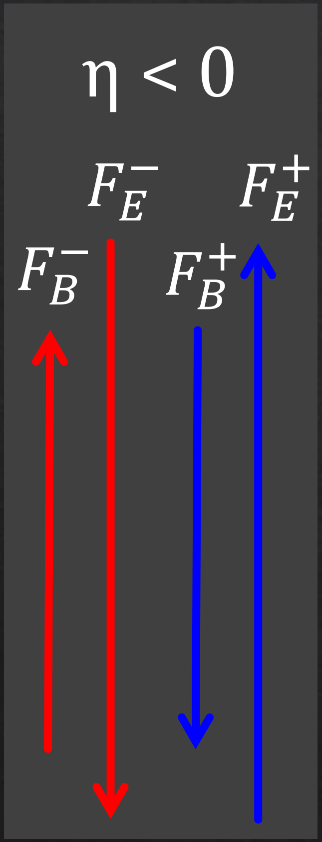
EMF and directed flow in A+A

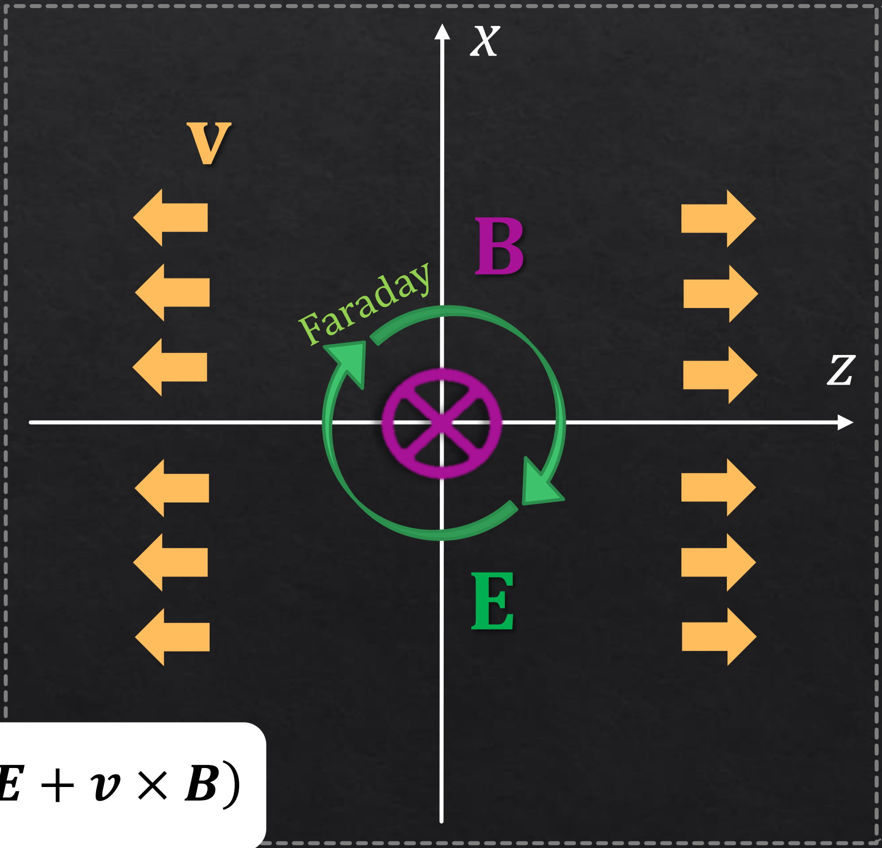
rapidity dependence of the DIRECTED FLOW

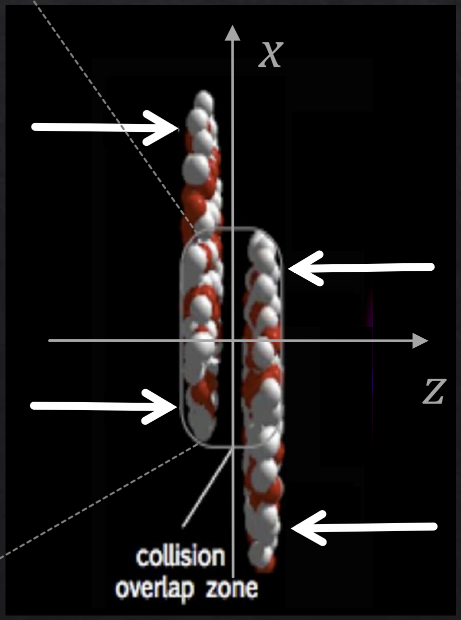
collective sidewards deflection of particles

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









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