XVIII Conference on
Theoretical Nuclear Physics
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Heavy quark as a probe of the initial electromagnetic fields and vorticity in relativistic HIC

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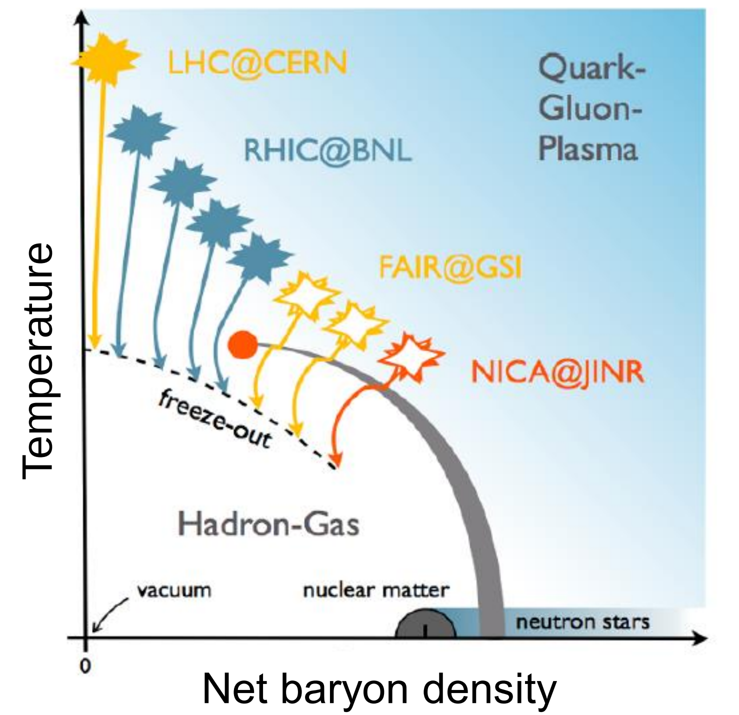
INFN Catania
Istituto Nazionale di Fisica Nucleare

Picture credit: https://www.etnafriends.it/img/notizie/eruzione_etna_20_04_13.jpg

QCD PHASE DIAGRAM



High energy heavy ion collisions

- ✓ allow to experimentally investigate the **QCD PHASE DIAGRAM**
- ✓ recreate the extreme condition of temperature and density required to form the **QUARK-GLUON PLASMA (QGP)**

Large Hadron Collider (LHC)

Pb+Pb 5.02 ATeV

Relativistic Heavy Ion Collider (RHIC)

Au+Au 200 AGeV

Facility for Antiproton and Ion Research (FAIR)

Au+Au 30 AGeV

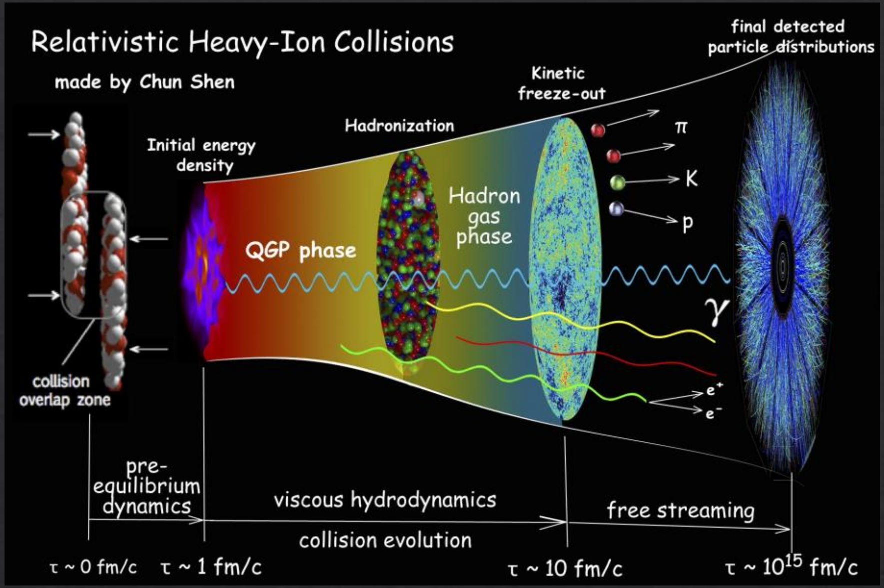
Au+Au 11 AGeV

UNDER CONSTRUCTION

Nuclotron-based Ion Collider fAcility (NICA)

EXPANDING FIREBALL

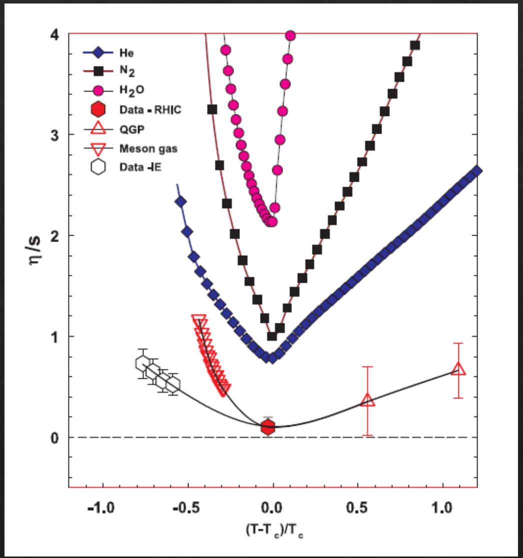
- $t \sim$ 10-20 fm/c $\sim 10^{-23}$-10^{-22} s
- $x \sim$ 10 fm $\sim 10^{-14}$ m
- $T_{in} \sim$ 300-600 MeV $\sim 10^{12}$ K

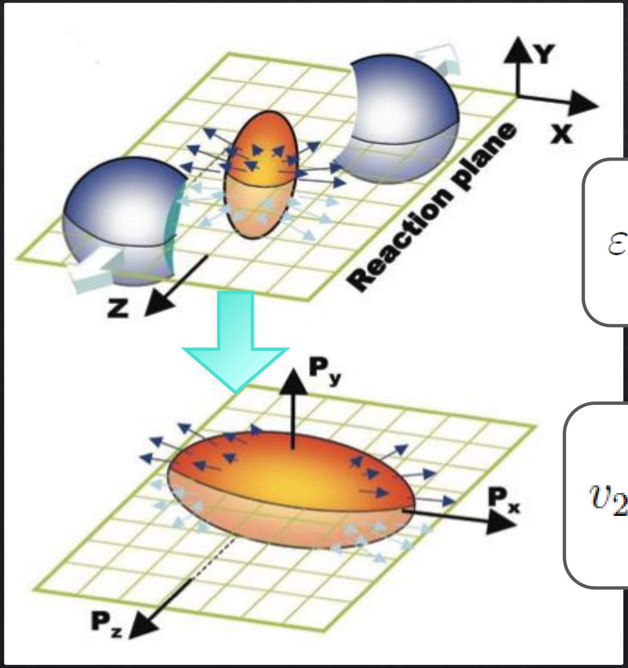


hydrodynamical behaviour of QGP with collective flows formation

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

Lacey and Taranenko, PoS CFRNC2006, 021 (2006)





eccentricity

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

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

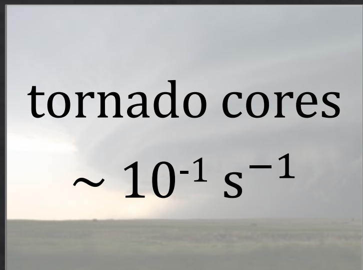
elliptic flow

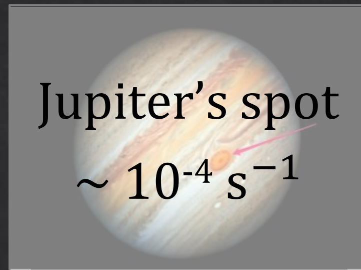
$$4\pi\eta/s \approx 1 - 2$$

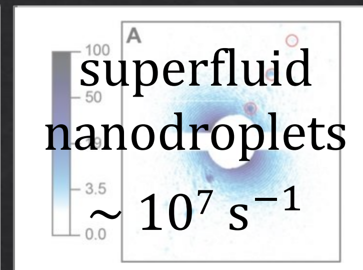
QGP flows like an almost perfect fluid with a very low η/s

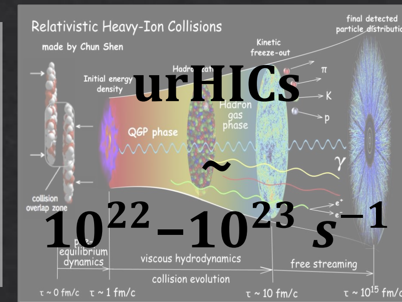
Intense fields and heavy flavor transport

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



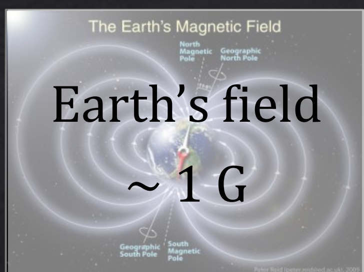


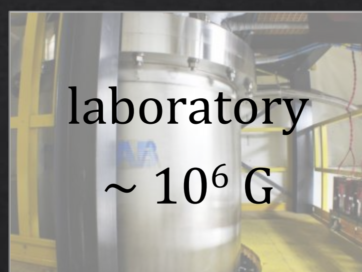


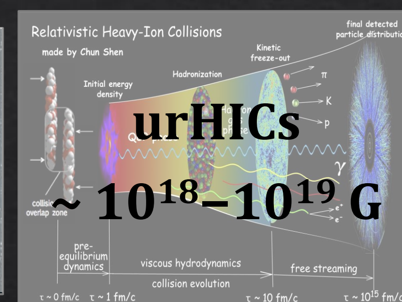


vorticity ω

✓ INTENSE **ELECTROMAGNETIC FIELDS** (EMF)

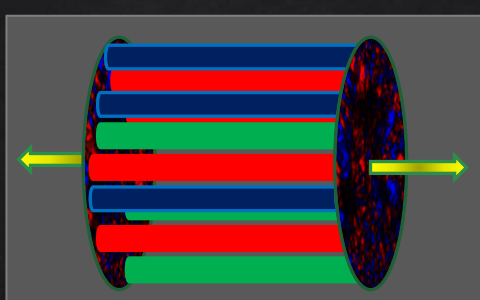






magnetic field B

✓ 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

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)

Boltzmann transport equivalent to viscous hydro at **$\eta/s \approx 0.1$**

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, JHEP 05, 034 (2021)

✓ INTENSE **ELECTROMAGNETIC FIELDS** (EMF)

since 2016

→ 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)

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

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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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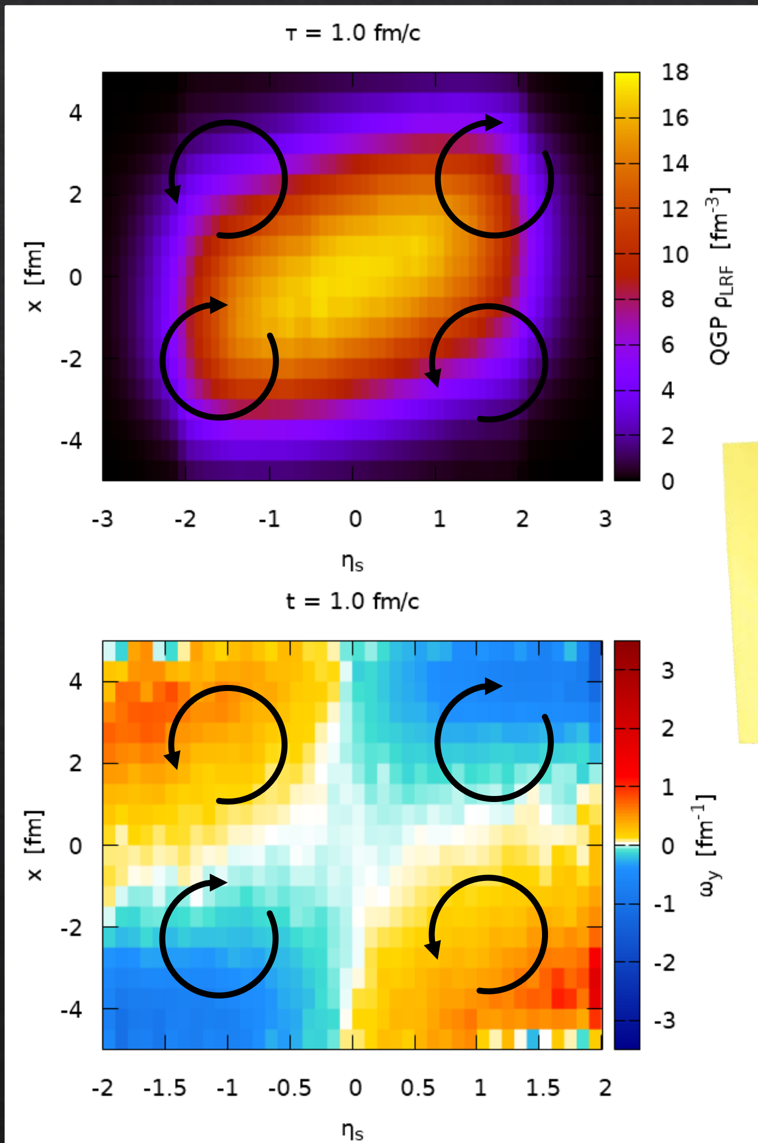
since 2018

The vortical quark-gluon plasma

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



NONRELATIVISTIC VORTICITY

asymmetry in local participant density
from forward and backward going nuclei

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

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

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

SPACETIME RAPIDITY
$\eta_s=\tanh^{-1}\frac{z}{t}$

PROPER TIME
$\tau=\sqrt{t^2-z^2}$

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>

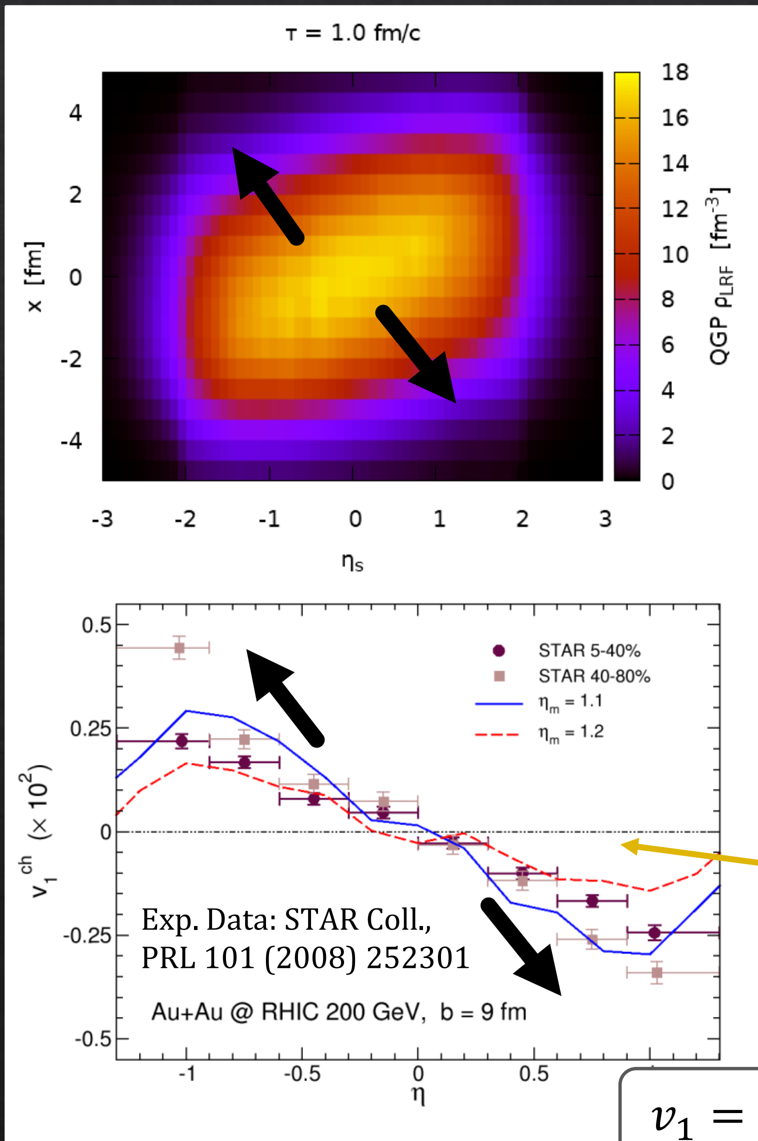
$\omega=\nabla\times v$ measure of the local angular velocity of the fluid

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

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 05, 034 (2021)



asymmetry in local participant density from forward and backward going nuclei

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

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

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

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

collective sidewards deflection of particles along the *x* direction

$v_1 = 0$ if the fireball is not tilted

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

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

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

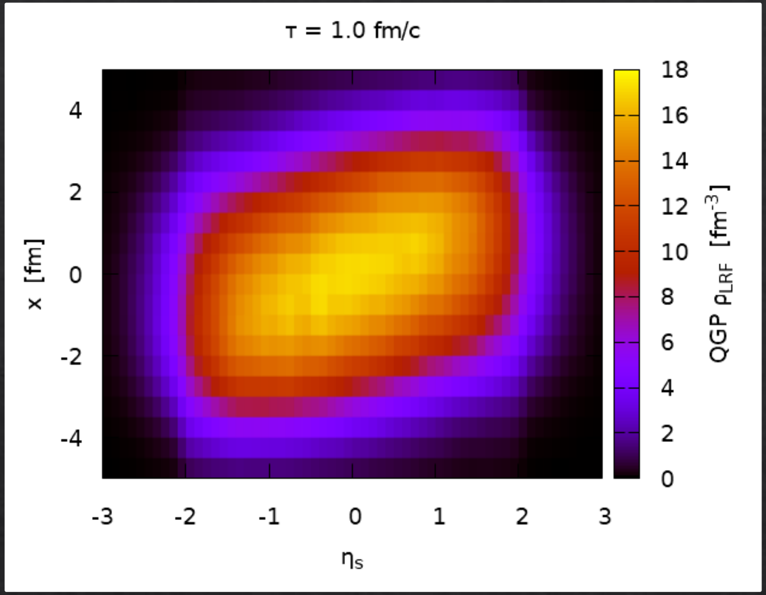
PSEUDORAPIDITY

(θ: polar angle of particle momentum)

DIRECTED FLOW OF CHARGED PARTICLES

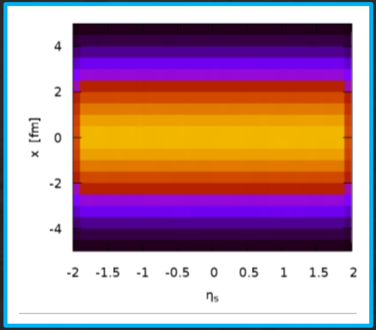
D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



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

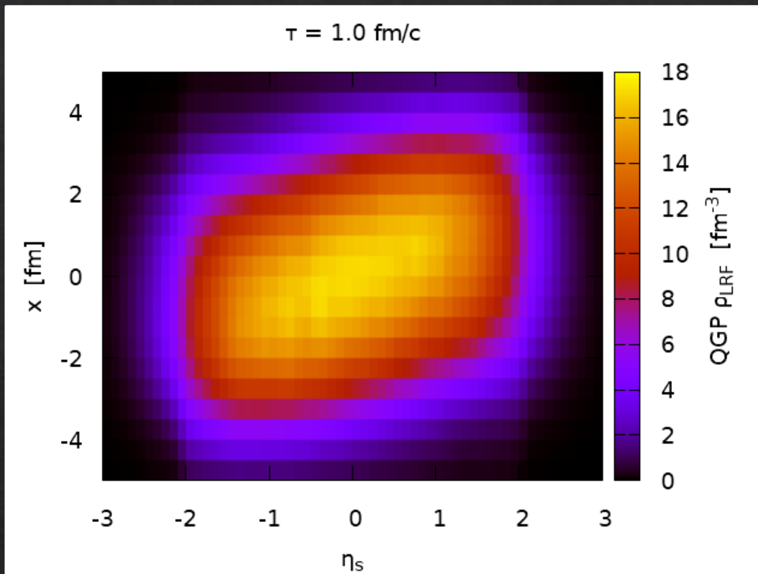
- **$m_{c,b} \gg \Lambda_{QCD}, T_{HICs}$**
  HQ produced in pQCD initial hard scatterings with production points symmetric in the forward-backward hemispheres

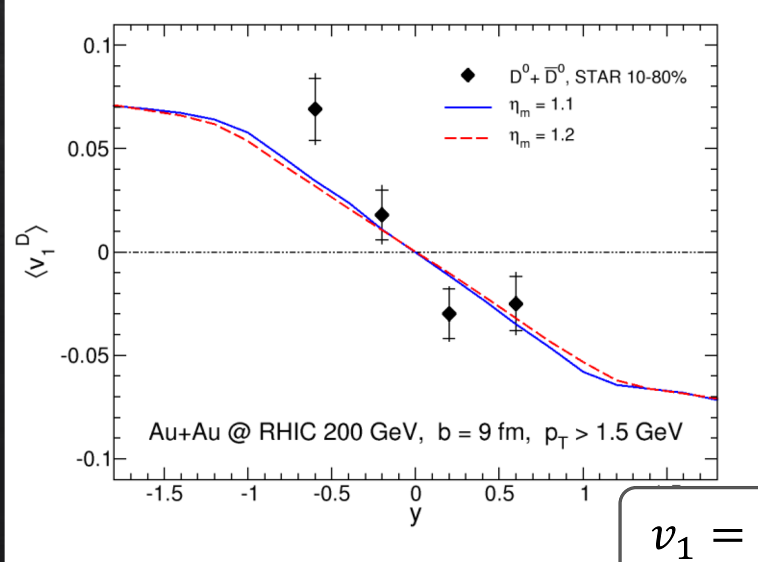


- **$\tau_0^{HQ} < 0.1$ fm/c $\ll \tau_0^{QGP}$**
  $\tau_{th}^{HQ} \approx \tau^{QGP} \gg \tau_{th}^{QGP}$
  HQ witness all fireball evolution keeping a better memory

D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)





$v_1 = \langle p_x / p_T \rangle$

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

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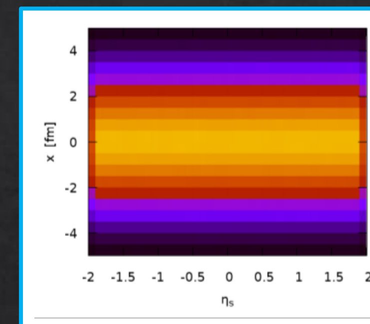


- $\boldsymbol{\tau_0^{HQ} < 0.1\ \mathrm{fm/c} \ll \tau_0^{QGP}}$

  $\boldsymbol{\tau_{th}^{HQ} \approx \tau^{QGP} \gg \tau_{th}^{QGP}}$

HQ witness all fireball evolution keeping a better memory

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

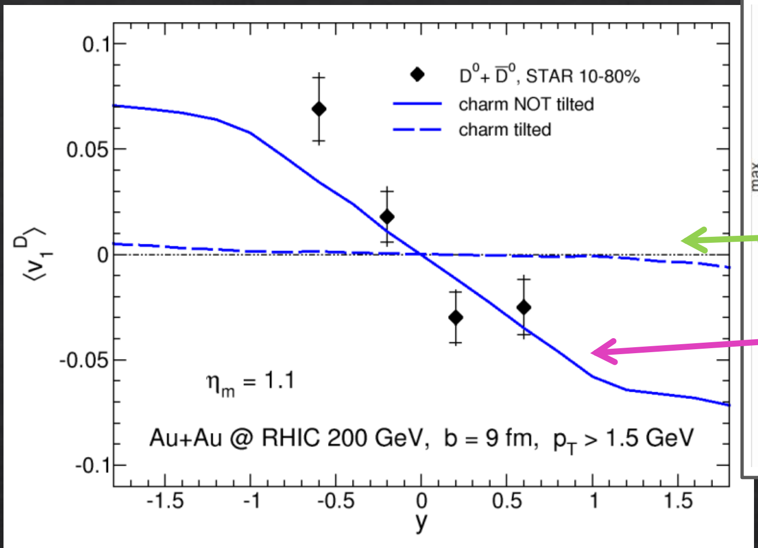
$y = \tanh^{-1} \frac{v_z}{c}$

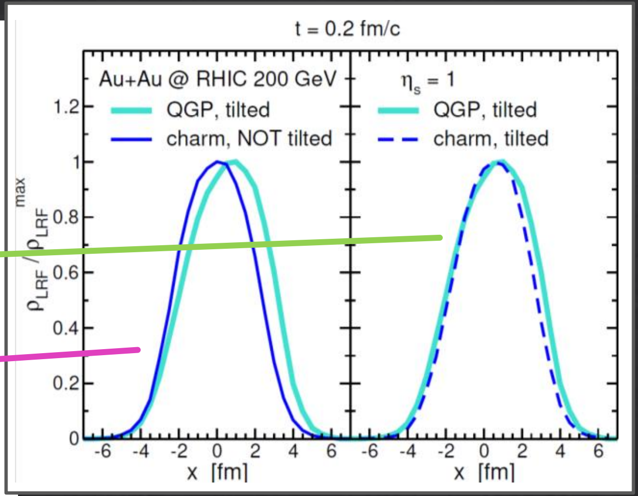
RAPIDITY relativistic analog of velocity (v_z: longitudinal particle velocity)

DIRECTED FLOW OF NEUTRAL D MESONS

Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

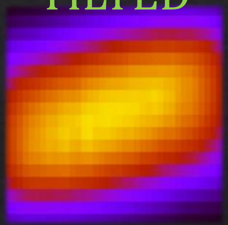




longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM **NOT** TILTED

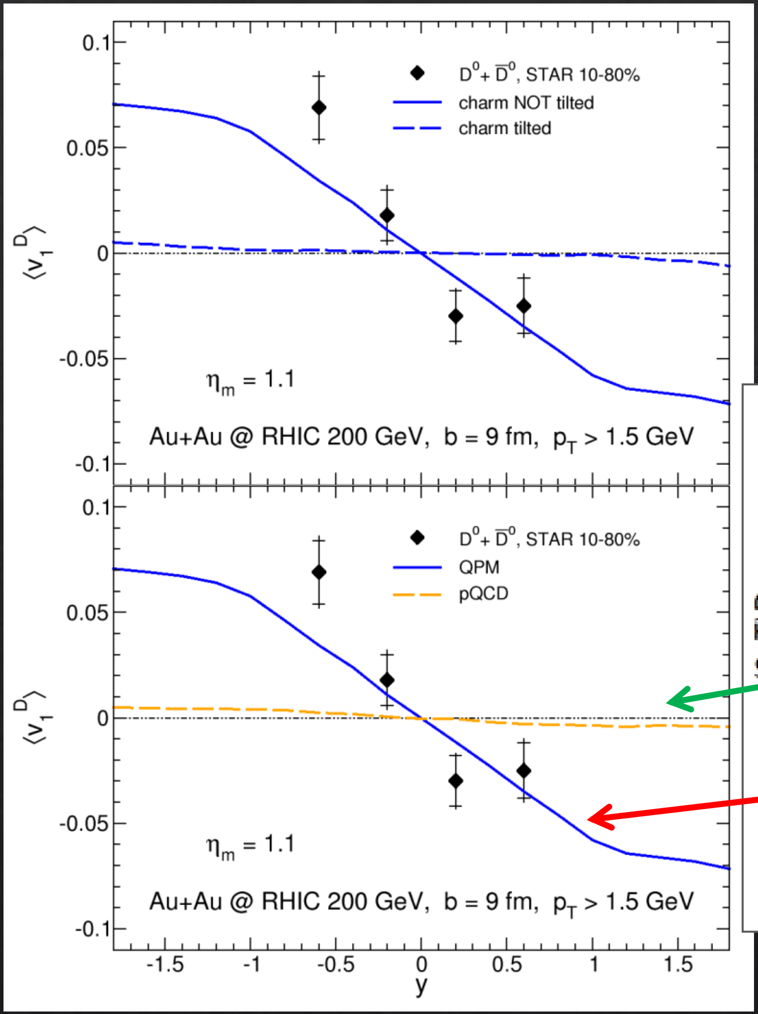
CHARM TILTED



QGP tilted in both cases

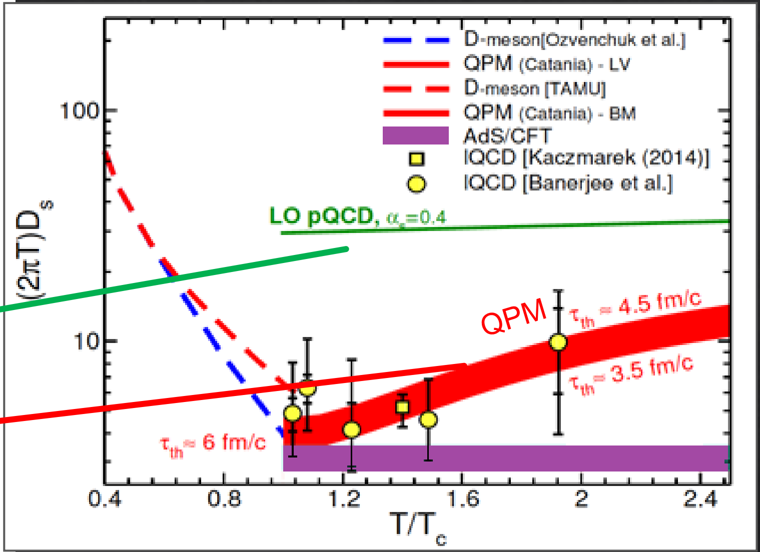
Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



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)

D_s : SPATIAL DIFFUSION COEFFICIENT

a small value characterizes strong coupling

Similar conclusions with POWLANG approach

Beraudo, De Pace, Monteno, Nardi and Prino, JHEP 05, 279 (2021)

$$2\pi T D_s \approx 3-6$$

QGP diffuses charm quarks like an almost perfect fluid with a very low $2\pi TD_s$

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L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

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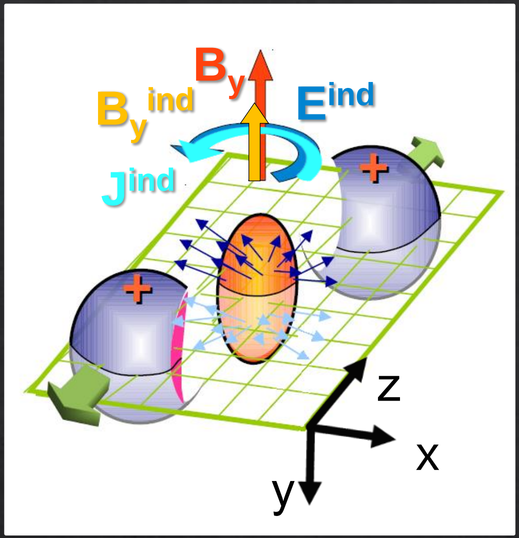
since 2018

Electromagnetic fields in HICs



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

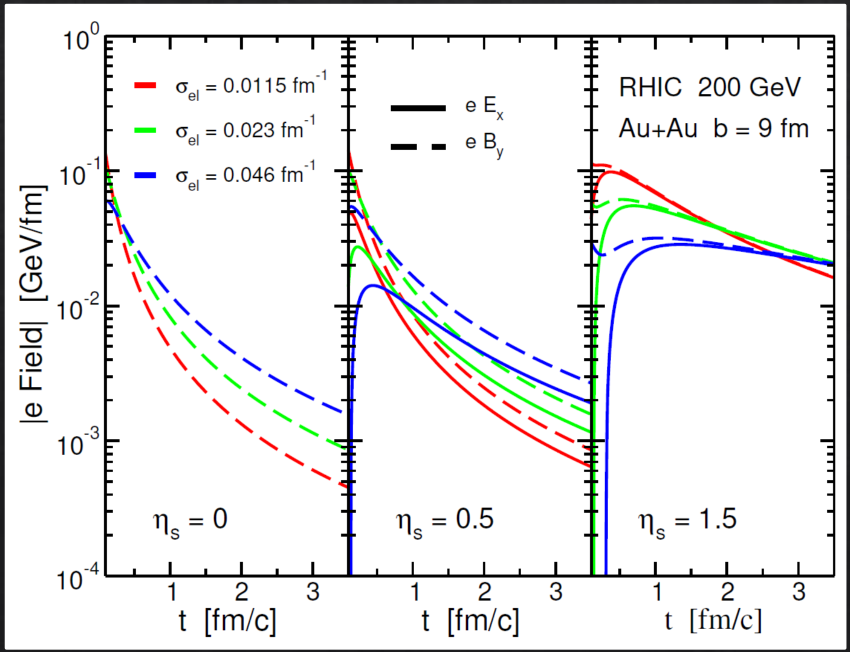
induced current from Ohm's law

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

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

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

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



Oliva, Plumari and Greco, JHEP 05, 034 (2021)

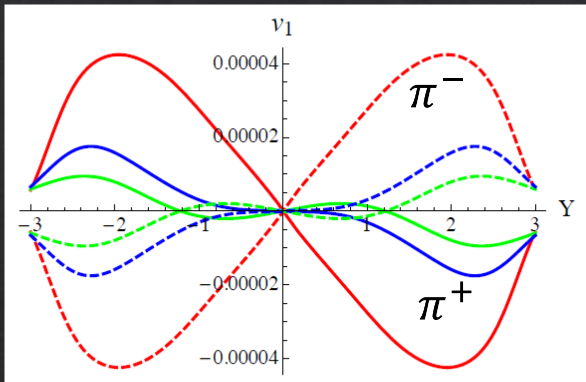
Maxwell equations for the EMF can be solved analytically considering a medium with **constant electric conductivity**

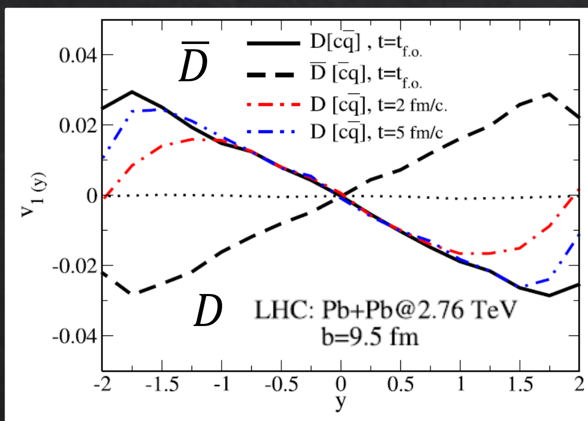
Tuchin, Adv. High Energy Phys. 2013, 1 (2013)
Gursoy, Kharzeev, Rajagopal, Phys. Rev. C 89, 054905 (2014)

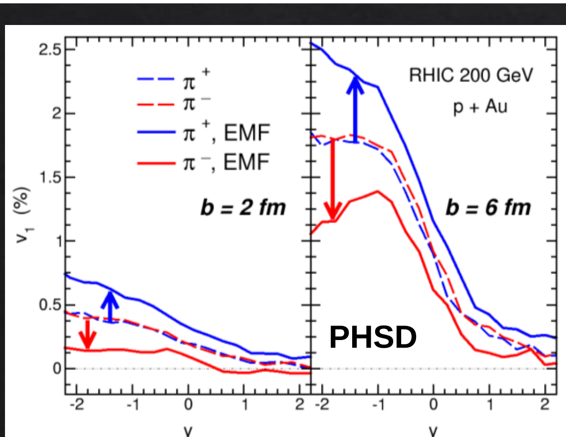
$$p^\mu \partial_\mu f(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f(x,p) = \mathcal{C}[f]$$

Boltzmann equation with EMF interaction term

EMF and directed flow splitting







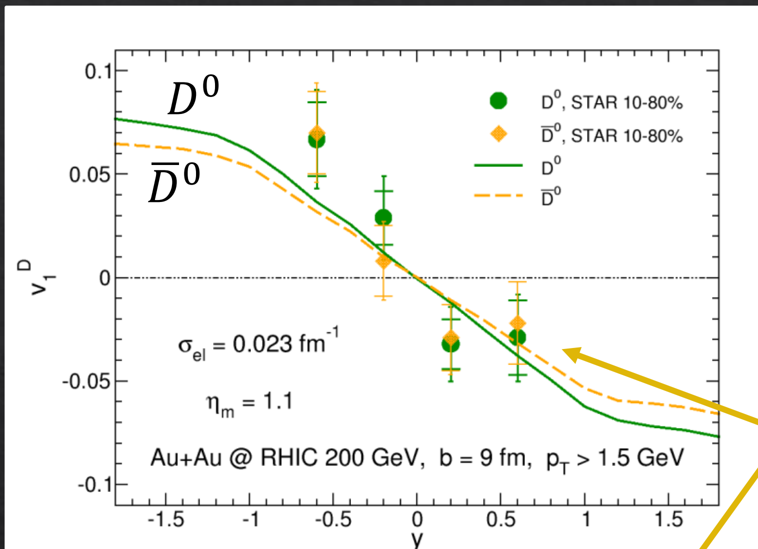
The huge EMF induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

- 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)

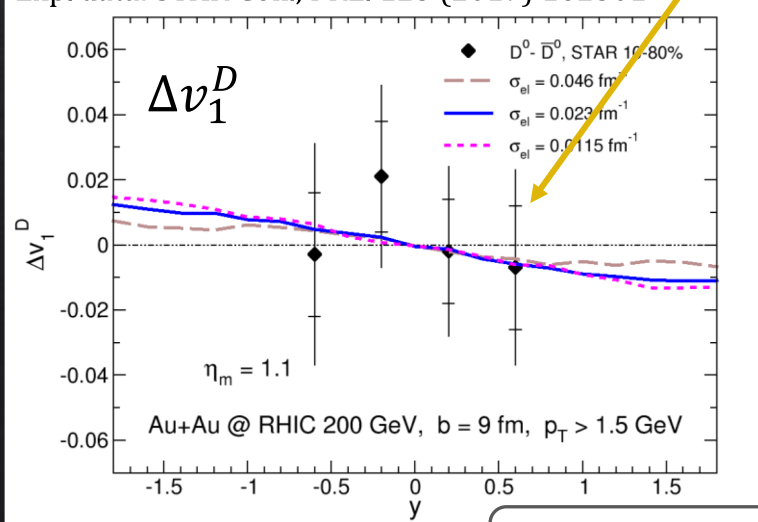
reviews
Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

Directed flow in A+A at RHIC energy

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



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



DIRECTED FLOW OF NEUTRAL D MESONS

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

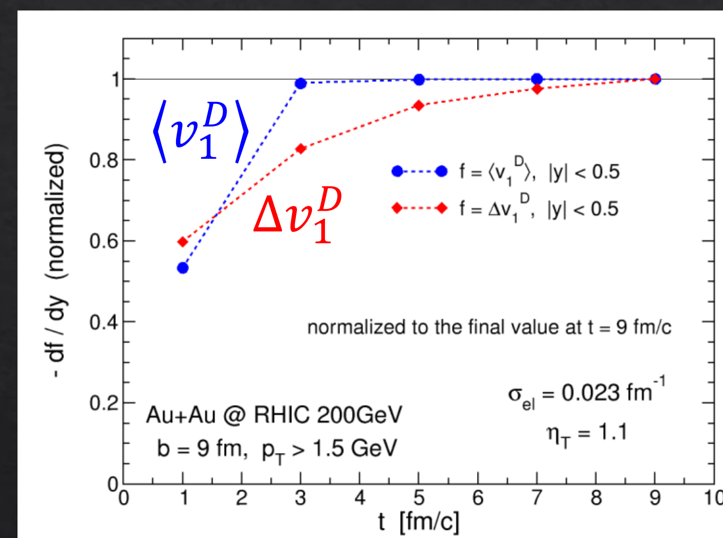
The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS

Δv_1 (HQ) $\gg$ Δv_1 (QGP)

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

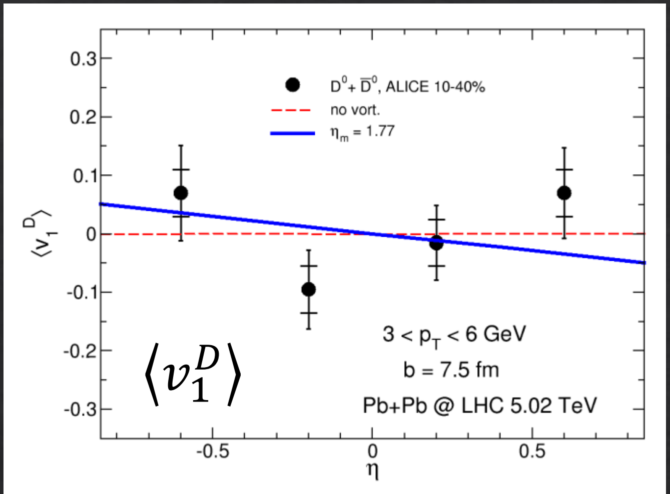
exp. Δv_1^D still consistent with zero due to the large errors

SLOPE TIME EVOLUTION



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

Directed flow in A+A at LHC energy



Oliva, Plumari and Greco, JHEP 05, 034 (2021)

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

ALICE exp. measurements:

- the slope of $\langle v_1^D \rangle$ is ~ 50 times smaller than that at RHIC and is consistent with zero
- the $\Delta v_1{}^D$ has opposite sign and magnitude ~ 40 times larger than model predictions

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

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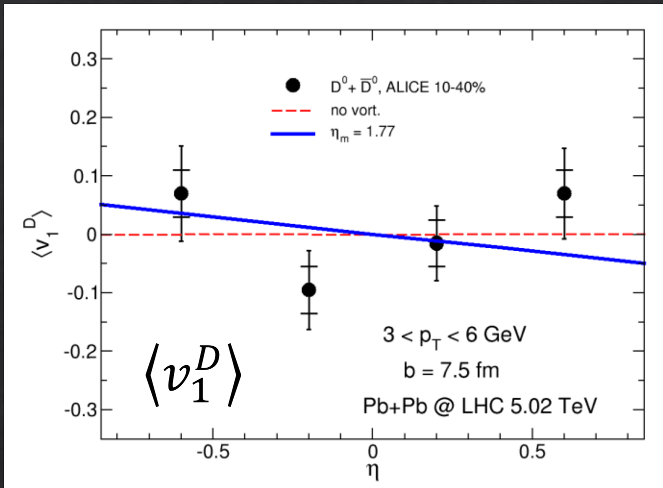

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)

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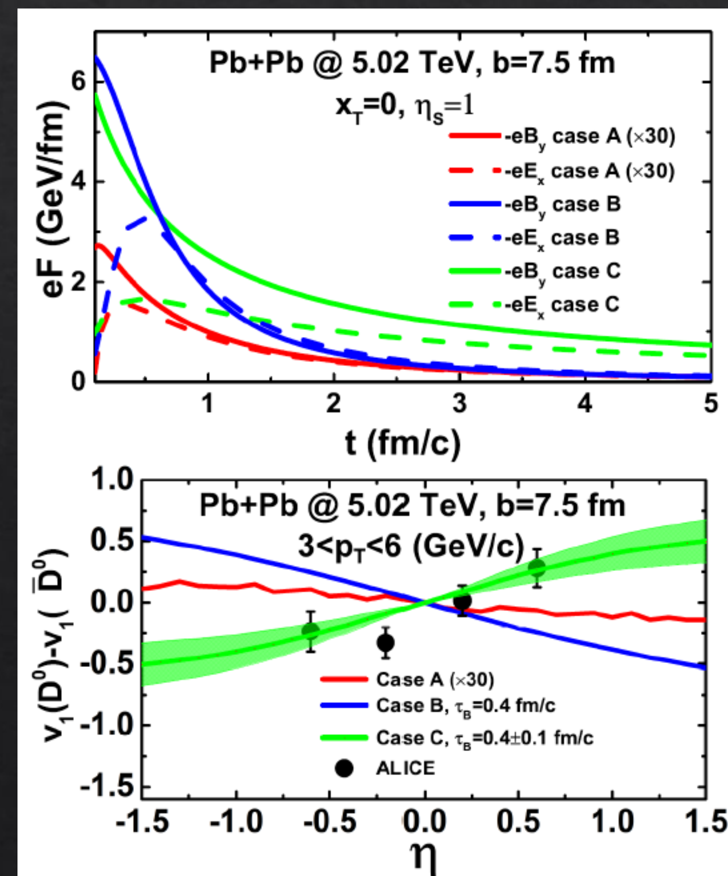
Sun, Plumari and Greco, Phys. Lett. B 816, 136271 (2021)



- ❖ 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

if the Δv_1 of neutral D mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

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, JHEP 05, 034 (2021)

✓ INTENSE **ELECTROMAGNETIC FIELDS** (EMF)

since 2016

→ 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)

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

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

since 2018

→ 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)

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)

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

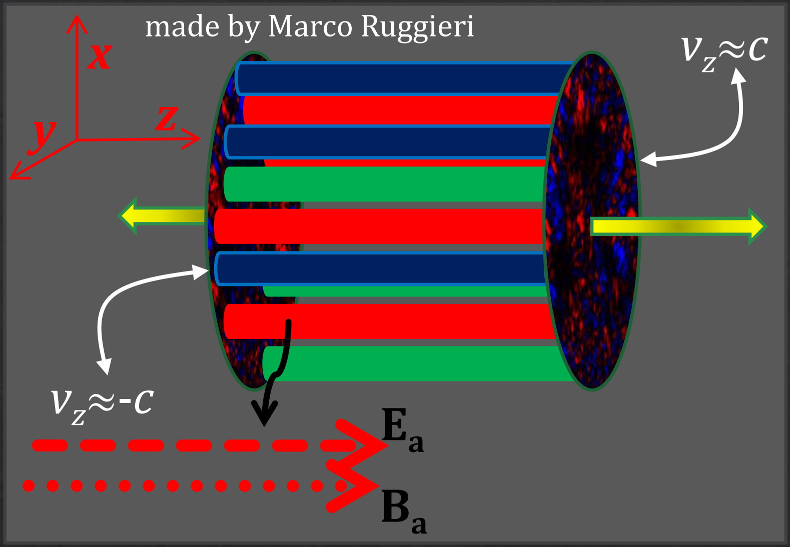
Classical Yang-Mills (CYM) equations for the dynamical evolution of glasma

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

solved in SU(2)

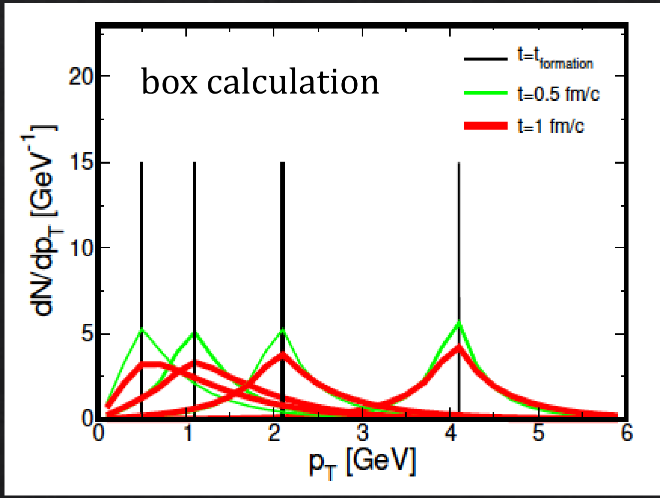
Wong equations for the dynamics of a heavy quark in the evolving glasma

$$\frac{dx_i}{dt} = \frac{p_i}{E}$$
$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu}p^\nu$$
$$E\frac{dQ_a}{dt} = -Q_c\varepsilon^{cba}A_b\cdot p$$



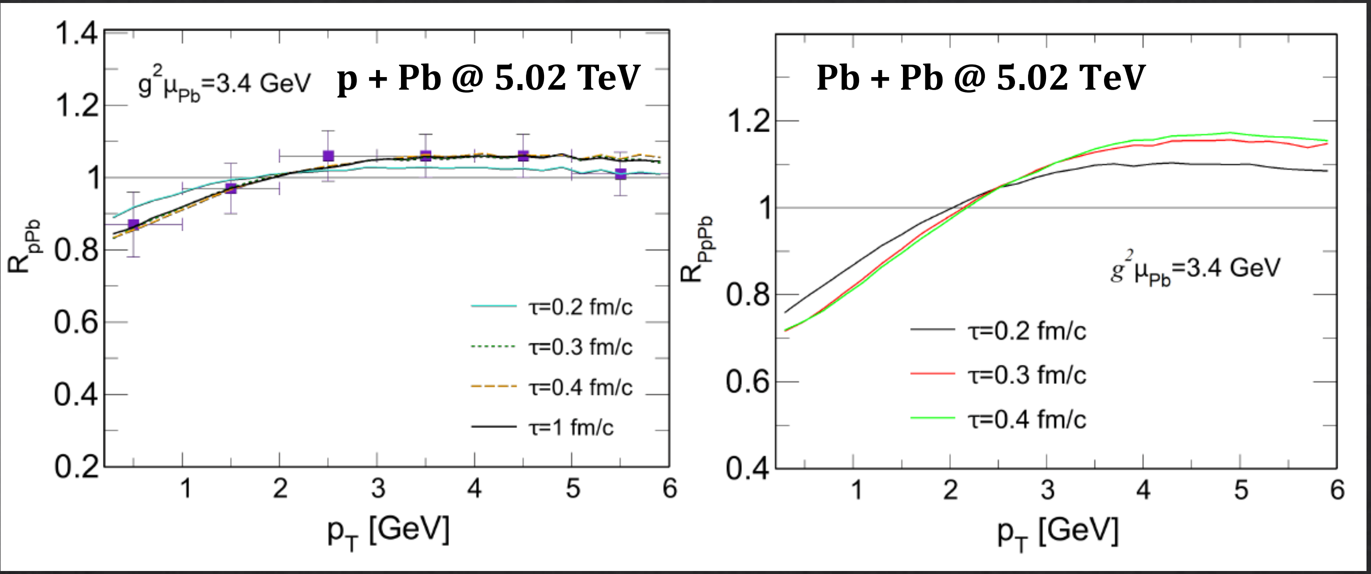
interaction with the initial glasma induce strong diffusion of charm quarks

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

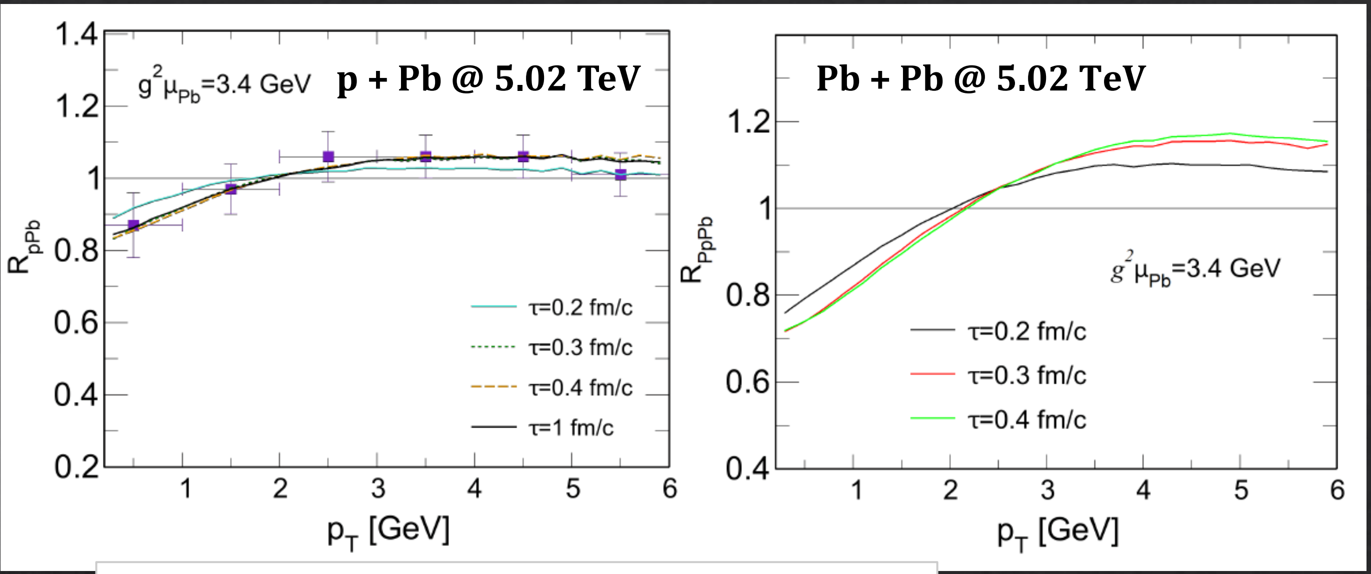
The dominance of diffusion-like dynamics leads to an **enhancement of R_{AA} at high p_T**

NUCLEAR MODIFICATION FACTOR

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{binary}^{AA} \times dN_{pp}/dp_T}$$

Heavy quarks in the glasma

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



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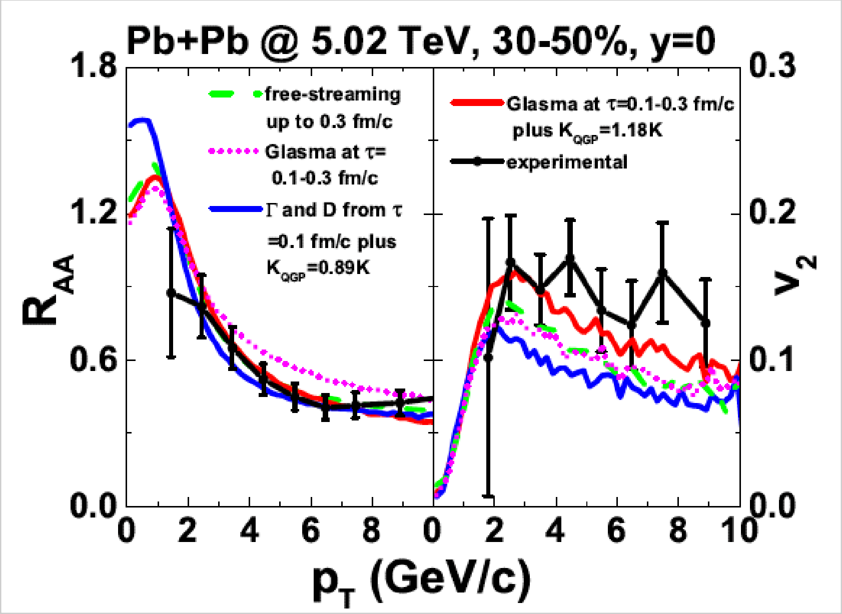

HQ spectrum in the glasma phase as initialization of HQs in the QGP for studying the impact on D-meson observables in AA collisions

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.
- ✓ Heavy-flavor particles can play a role in spotting the glasma dynamics and linking pA and AA collisions.

Thank you for your attention!