Direct Flow of heavy mesons as unique probe of the initial E.M. fields in HICs

Gabriele Coci

INFN

In collaboration with:
V. Greco, S. Plumari, L. Oliva,
S. K. Das, V. Minissale

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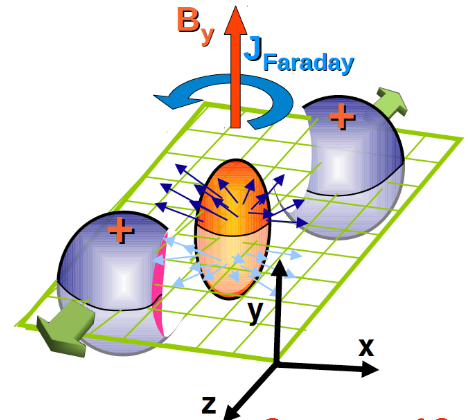
Electro-Magnetic field in HICs

Solve Maxwell Equations for point-like charges at fixed transverse coord. moving in +(-)z direction with velocity β.

$$\begin{cases} \nabla \cdot \vec{E} & = \delta(z' - \beta t)\delta(\vec{x}'_\perp - \vec{x}_\perp) \\ \nabla \cdot \vec{B} & = 0 \\ \nabla \times \vec{E} & = -\partial_t \vec{B} \\ \nabla \times \vec{B} & = (\partial_t + \sigma_{el})\vec{E} + e\vec{\beta}\delta(z' - \beta t)\delta(\vec{x}'_\perp - \vec{x}_\perp) \end{cases}$$

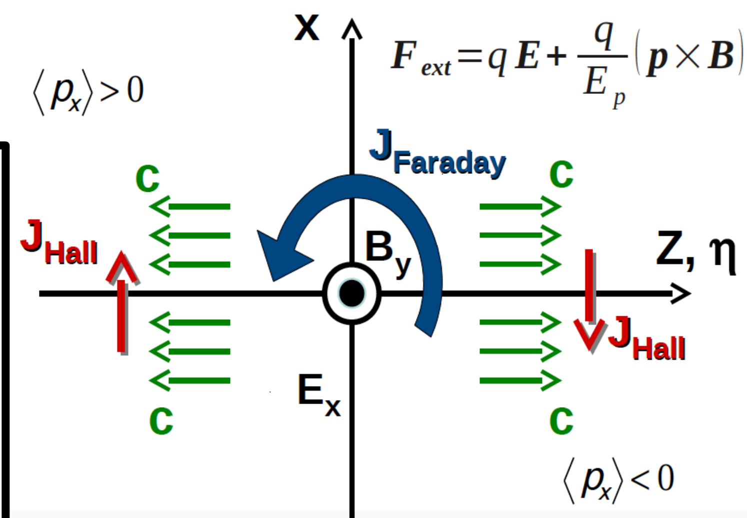
Convolute with nuclear transverse density of spectators then sum forward(+) and backward(-)

$$\begin{aligned} eB_{y,s} &= -Z \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{\rm in}(\phi')}^{x_{\rm out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \\ &\quad \times \left(eB_y^+(\tau, \eta, x_\perp, \pi - \phi) + eB_y^+(\tau, -\eta, x_\perp, \phi) \right) , \\ eE_{x,s} &= Z \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{\rm in}(\phi')}^{x_{\rm out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \\ &\quad \times \left(-eE_x^+(\tau, \eta, x_\perp, \pi - \phi) + eE_x^+(\tau, -\eta, x_\perp, \phi) \right) , \end{aligned}$$

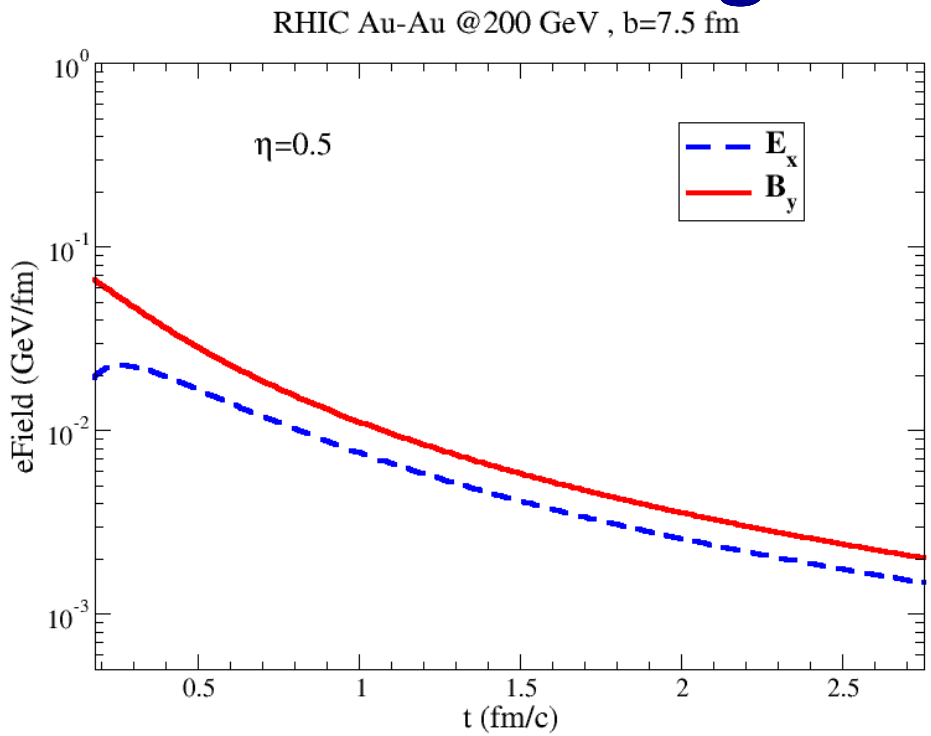


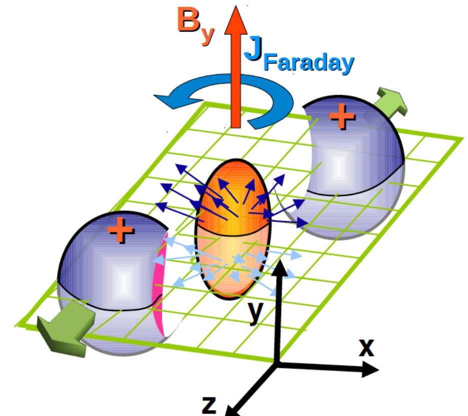
$B \approx (m_\pi)^2 \approx 10^{19}$ G

Tuchin PRC88, Adv. High En. Phys. 1 (2013)
Gürsoy, Kharzeev, Rajagopal PRC89 (2014)



Electro-Magnetic field in HICs





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\end{aligned}
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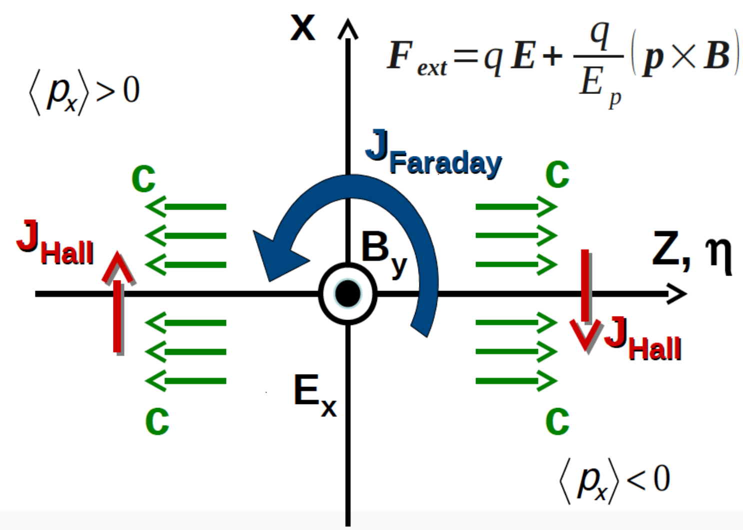
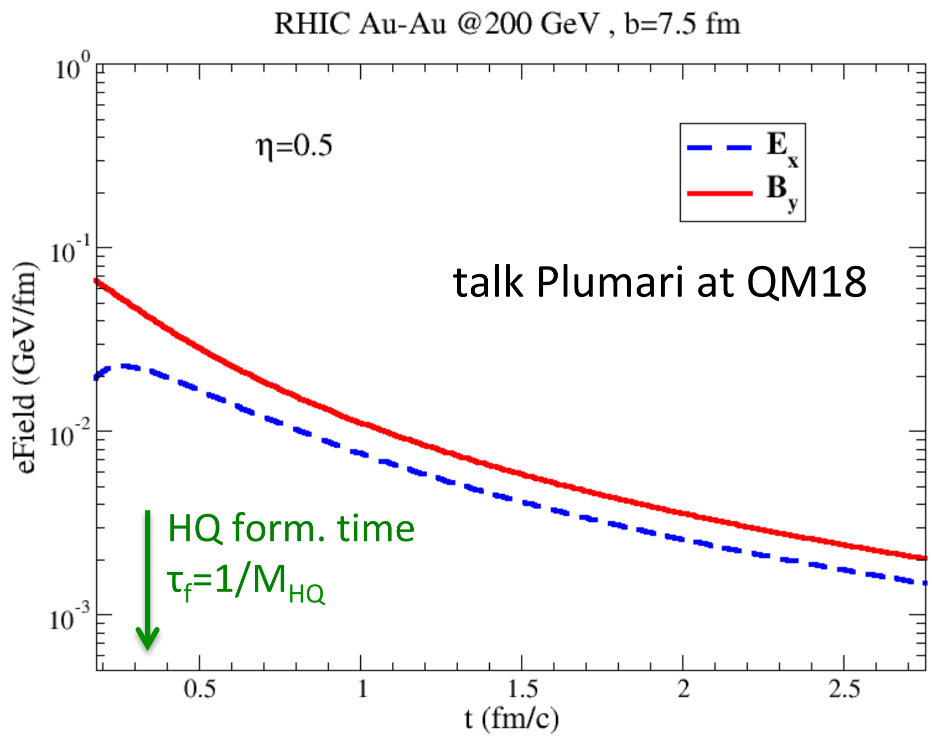
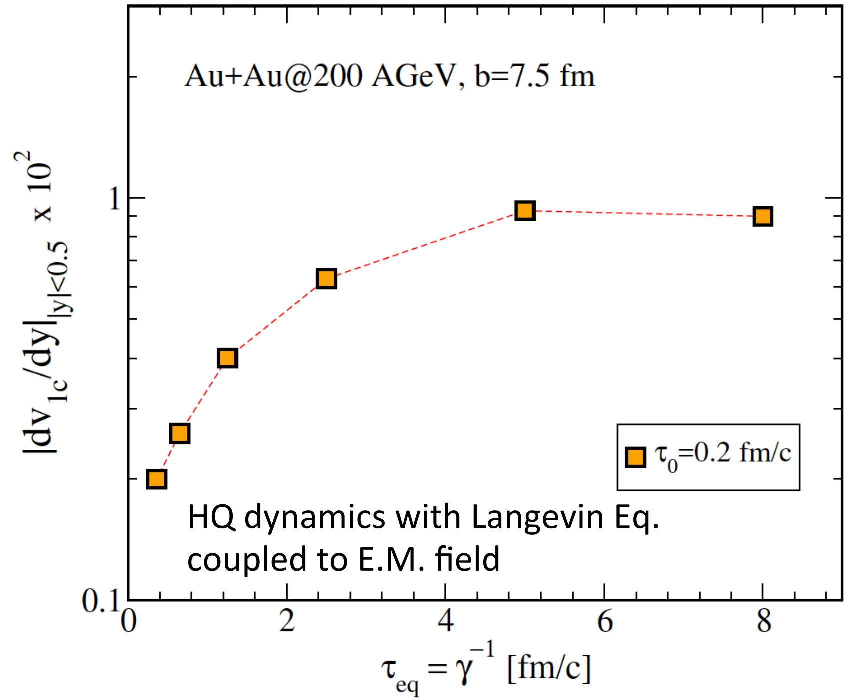


In light quark sector $v_1 \approx 10^{-3}$-10^{-4}… but HQs have the right features.

E.M. field & Heavy Quarks in HICs





[S.K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB768 (2017)]

Main properties of HQs in QGP:

- **$M_{HQ} >> \Lambda_{QCD}$** → HQ are produced in hard pQCD processes (decoupled from CME).
- **$M_{HQ} >> T$** → thermal production of HQ is negligible (out-of-equilibrium).
- **$\tau_{eq} \geq \tau_{QGP} >> \tau_f$** → probe the QGP evolution retaining the initial kick from E.M. field.

Boltzmann approach for HQ dynamics in QGP

$$\left[p_\mu \partial_x^\mu + \underbrace{qF_{\mu\nu}(x)}_{\text{Stress tensor }(\mathbf{E},\mathbf{B})} p^\nu \partial_p^\mu\right] f_{HQ} = \underbrace{C_{22}[f_{HQ}]}_{\text{Collision Integral} \approx \text{Dissipative}}$$

Stress tensor (**E**,**B**)

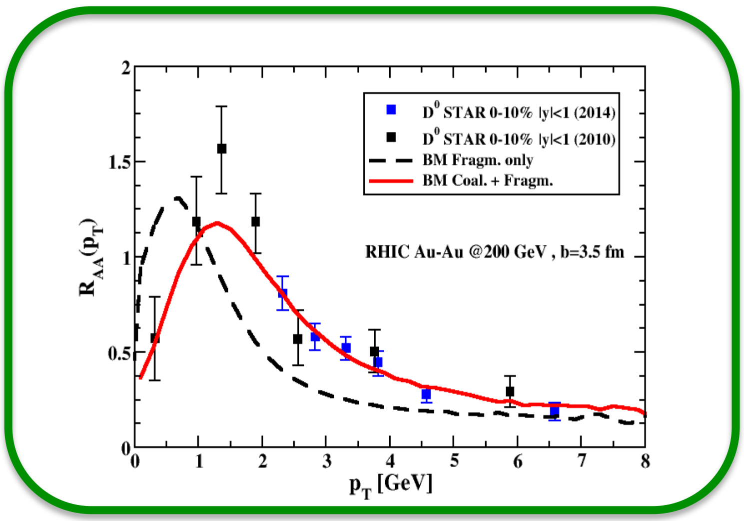
Collision Integral
≈ Dissipative

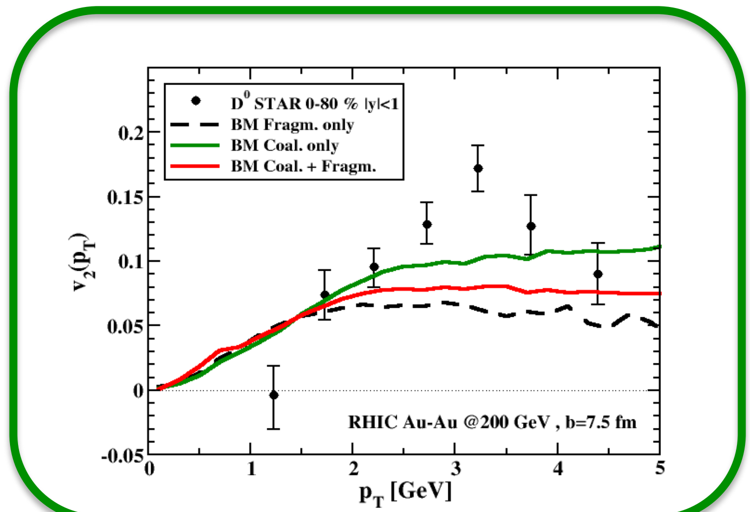
BM Eq. solved numerically
+
Hadronization:
fragm. & coalescence

[Scardina, Das, Minissale, Plumari and Greco, PRC 96 (2017)]

[Plumari, Minissale, Das, Coci and Greco, EPJ C 78 (2018)]
[poster Minissale at QM18]

Good description of $\boldsymbol{R_{AA}(p_T)}$ and $\boldsymbol{v_2(p_T)}$ simultaneously





Boltzmann approach for HQ dynamics in QGP

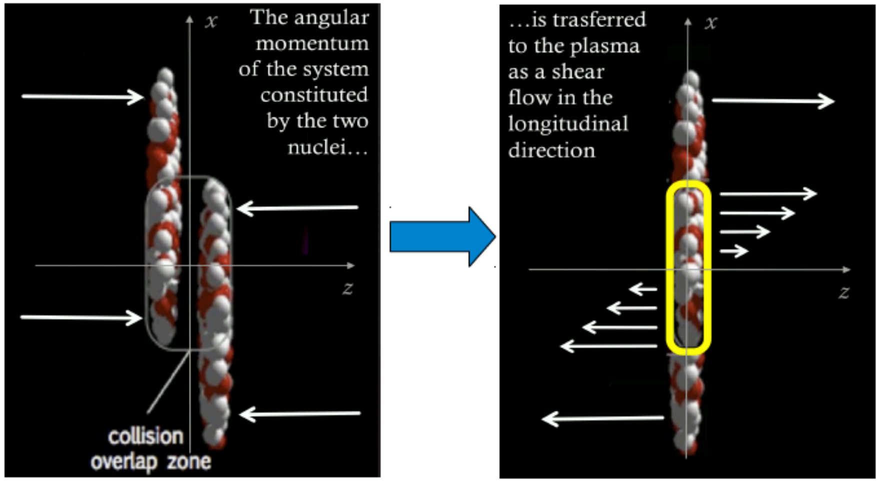
$$\left[p_\mu \partial_x^\mu + \underbrace{qF_{\mu\nu}(x)}_{\text{Maxwell tens. }(\mathbf{E},\mathbf{B})} p^\nu \partial_p^\mu\right] f_{HQ} = \underbrace{C_{22}[f_{HQ}]}_{\text{Collision Integral} \approx \text{Dissipative}}$$

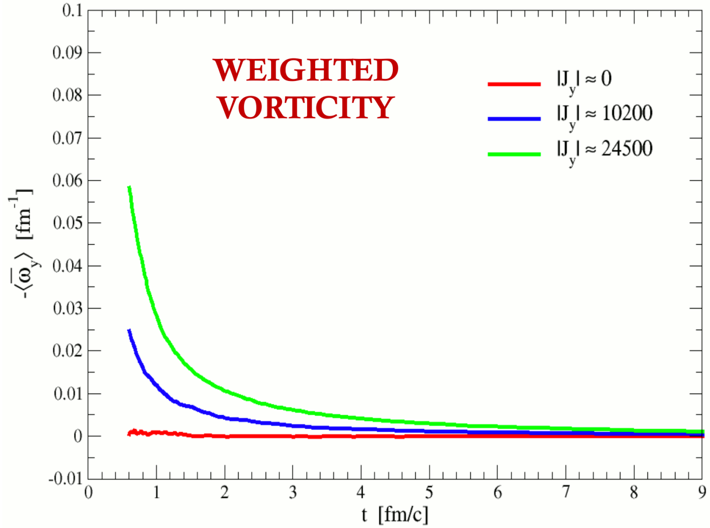
Maxwell tens. (**E**,**B**)

Collision Integral
≈ Dissipative

[Scardina, Das, Minissale, Plumari and Greco, PRC 96 (2017)]
[Plumari, Minissale, Das, Coci and Greco, EPJ C 78 (2018)]

Implement VORTICITY from initial angular momentum conservation

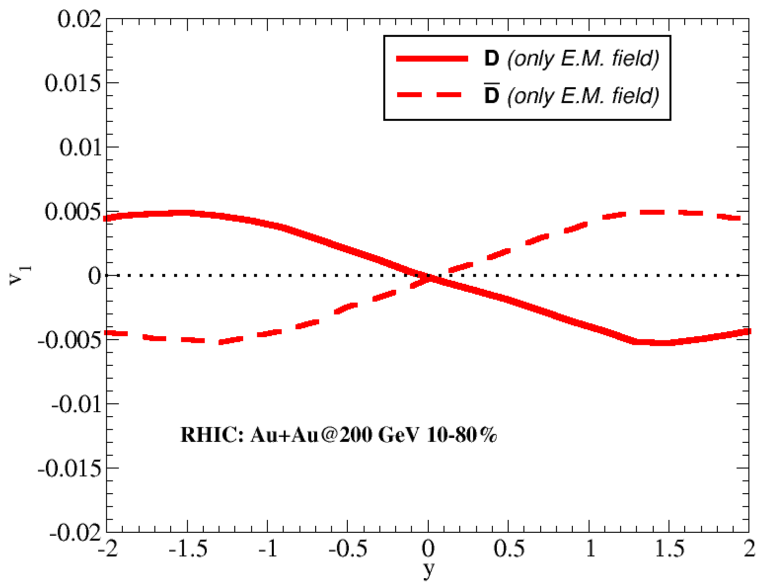


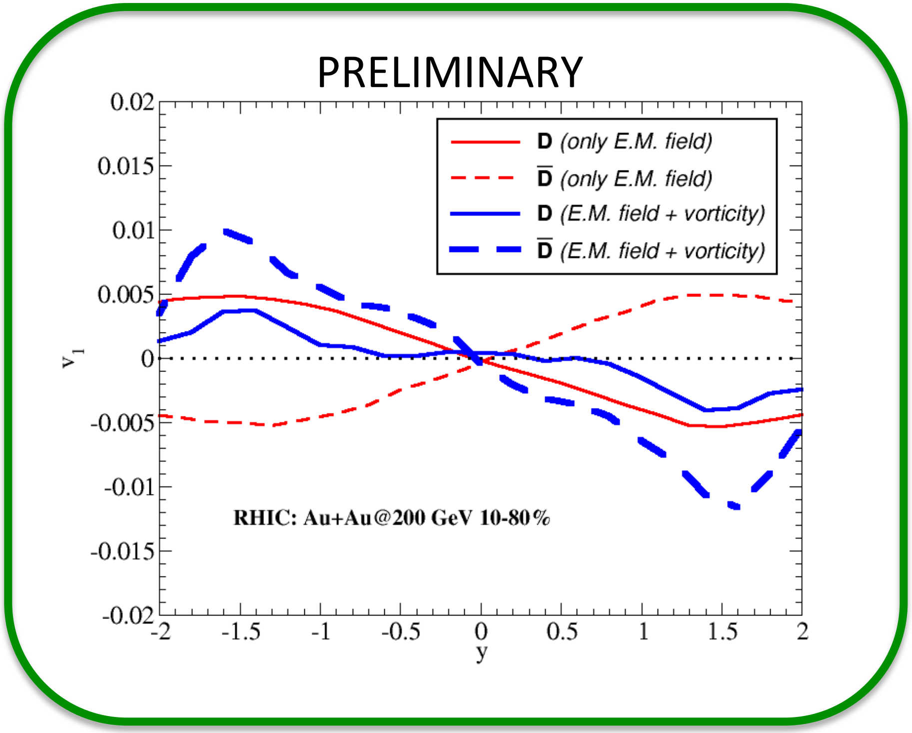


In agreement with other models:
[Deng and Huang PRC93 (2016)]
[Jiang, Lin, Liao, PRC 94 (2016); PRC 95 (2017)]

RESULTS:

Smaller formation time and longer thermalization allow HQs to gain larger v_1 compared to light quarks.





talk Plumari at QM18

CONCLUSIONS:

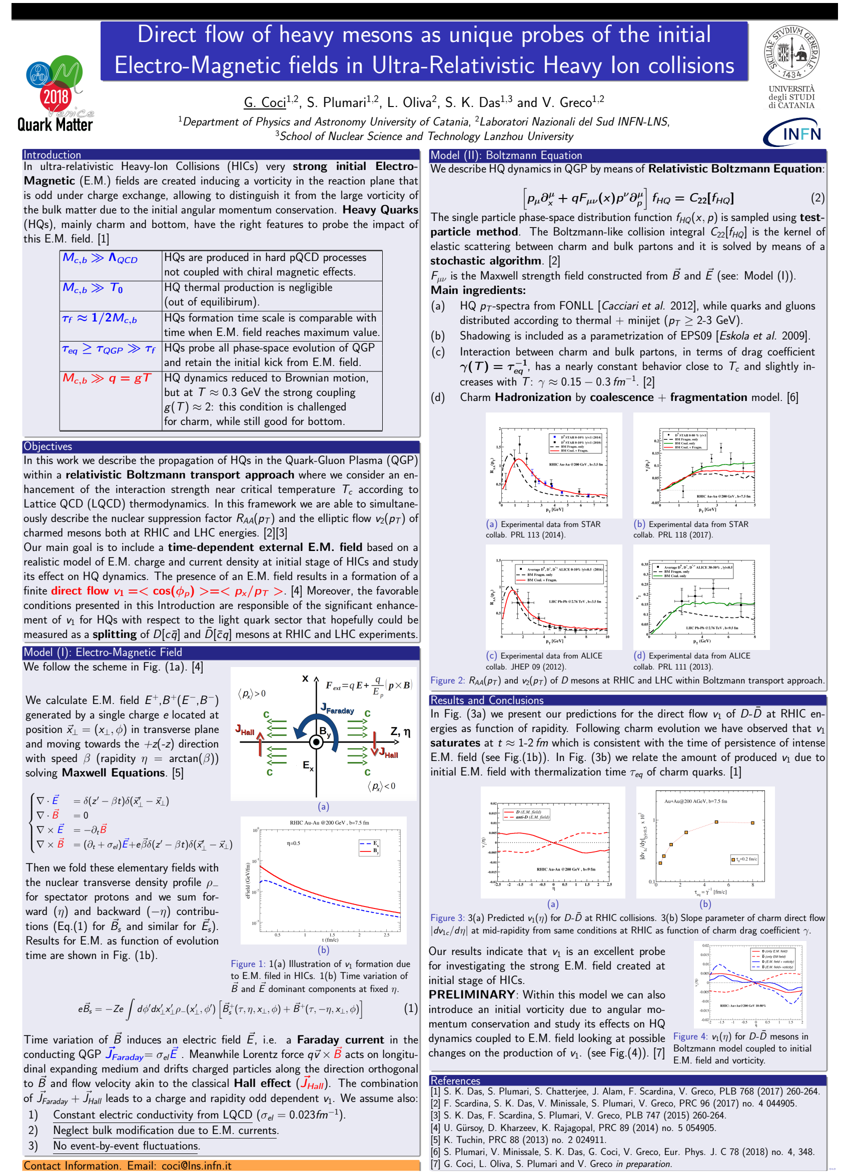
✧ V_1 is a powerful probe of the strong E.M. field created at initial stage of HICs.

[Das, Plumari, Chatterjee, Alam, Scardina and Greco, PLB768 (2017)]

✧ V_1 is very sensitive to the combined effect of vorticity + E.M. field.

→ THEORY: dynamics, modelling EXPERIMENTS: v_1 at RHIC and LHC

Thank you!



Direct flow of heavy mesons as unique probes of the initial Electro-Magnetic fields in Ultra-Relativistic Heavy Ion collisions

G. Coci[1,2], S. Plumari[1,2], L. Oliva[2], S. K. Das[1,3] and V. Greco[1,2]

[1]Department of Physics and Astronomy University of Catania, [2]Laboratori Nazionali del Sud INFN-LNS, [3]School of Nuclear Science and Technology Lanzhou University

Introduction

In ultra-relativistic Heavy-Ion Collisions (HICs) very **strong initial Electro-Magnetic** (E.M.) fields are created inducing a vorticity in the reaction plane that is odd under charge exchange, allowing to distinguish it from the large vorticity of the bulk matter due to the initial angular momentum conservation. **Heavy Quarks** (HQs), mainly charm and bottom, have the right features to probe the impact of this E.M. field. [1]

$M_{c,b} \gg \Lambda_{QCD}$	HQs are produced in hard pQCD processes not coupled with chiral magnetic effects.
$M_{c,b} \gg T_0$	HQ thermal production is negligible (out of equilibirum).
$\tau_f \approx 1/2M_{c,b}$	HQs formation time scale is comparable with time when E.M. field reaches maximum value.
$\tau_{eq} \geq \tau_{QGP} \gg \tau_f$	HQs probe all phase-space evolution of QGP and retain the initial kick from E.M. field.
$M_{c,b} \gg q = gT$	HQ dynamics reduced to Brownian motion, but at $T \approx 0.3$ GeV the strong coupling $g(T) \approx 2$: this condition is challenged for charm, while still good for bottom.

Objectives

In this work we describe the propagation of HQs in the Quark-Gluon Plasma (QGP) within a **relativistic Boltzmann transport approach** where we consider an enhancement of the interaction strength near critical temperature T_c according to Lattice QCD (LQCD) thermodynamics. In this framework we are able to simultaneously describe the nuclear suppression factor $R_{AA}(p_T)$ and the elliptic flow $v_2(p_T)$ of charmed mesons both at RHIC and LHC energies. [2][3]

Our main goal is to include a **time-dependent external E.M. field** based on a realistic model of E.M. charge and current density at initial stage of HICs and study its effect on HQ dynamics. The presence of an E.M. field results in a formation of a finite **direct flow $v_1 =< \cos(\phi_p) >=< p_x/p_T >$**. [4] Moreover, the favorable conditions presented in this Introduction are responsible of the significant enhancement of v_1 for HQs with respect to the light quark sector that hopefully could be measured as a **splitting** of $D[c\bar{q}]$ and $\bar{D}[\bar{c}q]$ mesons at RHIC and LHC experiments.

Model (I): Electro-Magnetic Field

We follow the scheme in Fig. (1a). [4]

We calculate E.M. field $E^+,B^+(E^-,B^-)$ generated by a single charge e located at position $\vec{x}_\perp = (x_\perp, \phi)$ in transverse plane and moving towards the $+z(-z)$ direction with speed β (rapidity $\eta = \arctan(\beta)$) solving **Maxwell Equations**. [5]

$$\begin{cases} \nabla \cdot \vec{E} &= \delta(z' - \beta t)\delta(\vec{x}'_\perp - \vec{x}_\perp) \\ \nabla \cdot \vec{B} &= 0 \\ \nabla \times \vec{E} &= -\partial_t \vec{B} \\ \nabla \times \vec{B} &= (\partial_t + \sigma_{el})\vec{E} + e\vec{\beta}\delta(z' - \beta t)\delta(\vec{x}'_\perp - \vec{x}_\perp) \end{cases}$$

Then we fold these elementary fields with the nuclear transverse density profile ρ_- for spectator protons and we sum forward (η) and backward ($-\eta$) contributions (Eq.(1) for $\vec{B}_s$ and similar for $\vec{E}_s$). Results for E.M. as function of evolution time are shown in Fig. (1b).

Figure 1: 1(a) Illustration of v_1 formation due to E.M. filed in HICs. 1(b) Time variation of $\vec{B}$ and $\vec{E}$ dominant components at fixed η.

$$e\vec{B}_s = -Ze \int d\phi' dx'_\perp x'_\perp \rho_-(x'_\perp, \phi') \left[\vec{B}_s^+(\tau, \eta, x_\perp, \phi) + \vec{B}^+(\tau, -\eta, x_\perp, \phi)\right] \quad (1)$$

Time variation of $\vec{B}$ induces an electric field $\vec{E}$, i.e. a **Faraday current** in the conducting QGP $\vec{J}_{Faraday} = \sigma_{el}\vec{E}$. Meanwhile Lorentz force $q\vec{v} \times \vec{B}$ acts on longitudinal expanding medium and drifts charged particles along the direction orthogonal to $\vec{B}$ and flow velocity akin to the classical **Hall effect** ($\vec{J}_{Hall}$). The combination of $\vec{J}_{Faraday} + \vec{J}_{Hall}$ leads to a charge and rapidity odd dependent v_1. We assume also:

1) Constant electric conductivity from LQCD ($\sigma_{el} = 0.023 fm^{-1}$).
2) Neglect bulk modification due to E.M. currents.
3) No event-by-event fluctuations.

Contact Information. Email: coci@lns.infn.it

Model (II): Boltzmann Equation

We describe HQ dynamics in QGP by means of **Relativistic Boltzmann Equation**:

$$\left[p_\mu \partial_x^\mu + qF_{\mu\nu}(x)p^\nu \partial_p^\mu\right] f_{HQ} = C_{22}[f_{HQ}] \quad (2)$$

The single particle phase-space distribution function $f_{HQ}(x,p)$ is sampled using **test-particle method**. The Boltzmann-like collision integral $C_{22}[f_{HQ}]$ is the kernel of elastic scattering between charm and bulk partons and it is solved by means of a **stochastic algorithm**. [2]

$F_{\mu\nu}$ is the Maxwell strength field constructed from $\vec{B}$ and $\vec{E}$ (see: Model (I)).

Main ingredients:

(a) HQ p_T-spectra from FONLL [*Cacciari et al.* 2012], while quarks and gluons distributed according to thermal + minijet ($p_T \geq$ 2-3 GeV).
(b) Shadowing is included as a parametrization of EPS09 [*Eskola et al.* 2009].
(c) Interaction between charm and bulk partons, in terms of drag coefficient $\gamma(T) = \tau_{eq}^{-1}$, has a nearly constant behavior close to T_c and slightly increases with T: $\gamma \approx 0.15 - 0.3\, fm^{-1}$. [2]
(d) Charm **Hadronization** by **coalescence** + **fragmentation** model. [6]

(a) Experimental data from STAR collab. PRL 113 (2014).
(b) Experimental data from STAR collab. PRL 118 (2017).
(c) Experimental data from ALICE collab. JHEP 09 (2012).
(d) Experimental data from ALICE collab. PRL 111 (2013).

Figure 2: $R_{AA}(p_T)$ and $v_2(p_T)$ of D mesons at RHIC and LHC within Boltzmann transport approach.

Results and Conclusions

In Fig. (3a) we present our predictions for the direct flow v_1 of D-$\bar{D}$ at RHIC energies as function of rapidity. Following charm evolution we have observed that v_1 **saturates** at $t \approx$ 1-2 fm which is consistent with the time of persistence of intense E.M. field (see Fig.(1b)). In Fig. (3b) we relate the amount of produced v_1 due to initial E.M. field with thermalization time τ_{eq} of charm quarks. [1]

Figure 3: 3(a) Predicted $v_1(\eta)$ for D-$\bar{D}$ at RHIC collisions. 3(b) Slope parameter of charm direct flow $|dv_{1c}/d\eta|$ at mid-rapidity from same conditions at RHIC as function of charm drag coefficient γ.

Our results indicate that v_1 is an excellent probe for investigating the strong E.M. field created at initial stage of HICs.

PRELIMINARY: Within this model we can also introduce an initial vorticity due to angular momentum conservation and study its effects on HQ dynamics coupled to E.M. field looking at possible changes on the production of v_1. (see Fig.(4)). [7]

Figure 4: $v_1(\eta)$ for D-$\bar{D}$ mesons in Boltzmann model coupled to initial E.M. field and vorticity.

References

[1] S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB 768 (2017) 260-264.
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[4] U. Gürsoy, D. Kharzeev, K. Rajagopal, PRC 89 (2014) no. 5 054905.
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[6] S. Plumari, V. Minissale, S. K. Das, G. Coci, V. Greco, Eur. Phys. J. C 78 (2018) no. 4, 348.
[7] G. Coci, L. Oliva, S. Plumari and V. Greco *in preparation*.

Link to poster: https://indico.cern.ch/event/656452/contributions/2871147/