

# OPEN HEAVY FLAVOR DYNAMICS IN HEAVY ION COLLISIONS: $R_{AA}$ , $v_1$ , $v_2$ , $v_3$

S. Plumari  
Università degli Studi di Catania  
INFN-



UNIVERSITÀ  
degli STUDI  
di CATANIA



IN COLLABORATION WITH:  
S. K. Das, F. Scardina, V. Minissale,  
G. Coci, L. Oliva, V. Greco



EPS Conference on High Energy Physics  
Venice, Italy 5-12 July 2017

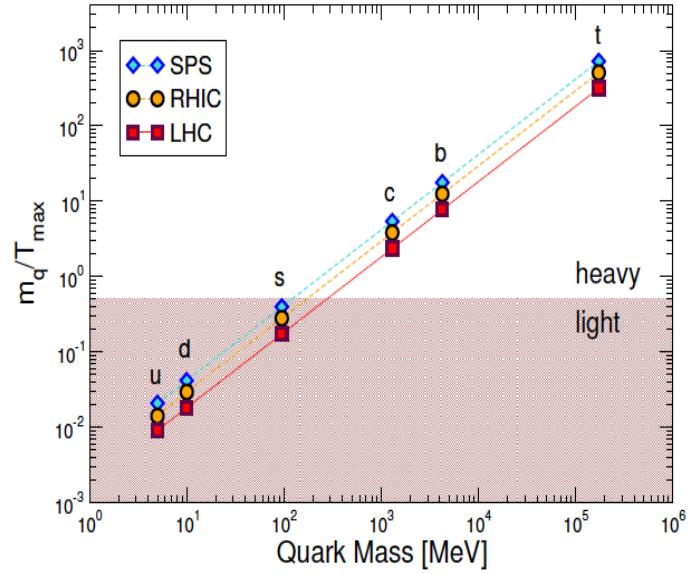


# Outline

- Introduction
- Heavy quarks dynamics in QGP within transport approach
  - The puzzling relation between  $R_{AA}$  and  $v_2(p_T)$  for Heavy Flavors
  - Comparison to IQCD Diff. coeff.
- Initial state fluctuations within transport approach:
  - $v_n(p_T)$  of D mesons
  - $v_n(\text{heavy}) - v_n(\text{light})$  correlations
- Impact of ElectroMagnetic field on Heavy quarks dynamics:  
sizeable  $v_1$  for charm quarks (anti-charms)
- Conclusions

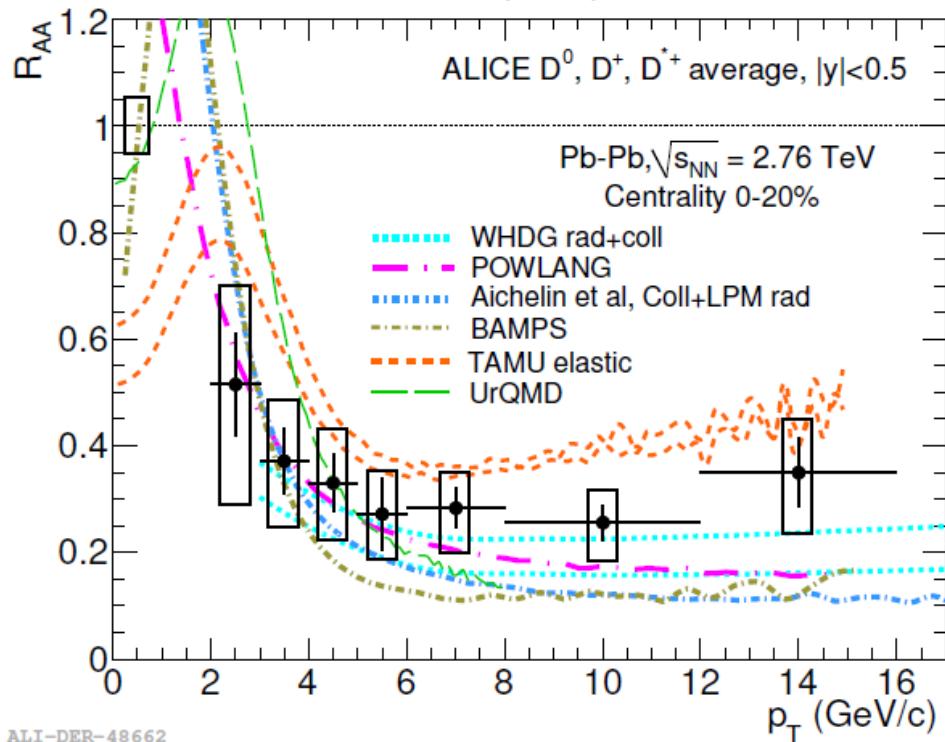
# Specific of Heavy Quarks

- $m_{c,b} \gg \Lambda_{\text{QCD}}$  produced by pQCD process (out of equilibrium)
- $m_{c,b} \gg T_0$  no thermal production
- $\tau_0 \ll \tau_{\text{QGP}}$  probes all the QGP life time
- $m \gg T, q^2 \ll m^2 \rightarrow \text{dynamics reduced to Brownian motion}$   
(statement that can be challenged for charm quarks PRC90, 044901 (2014))

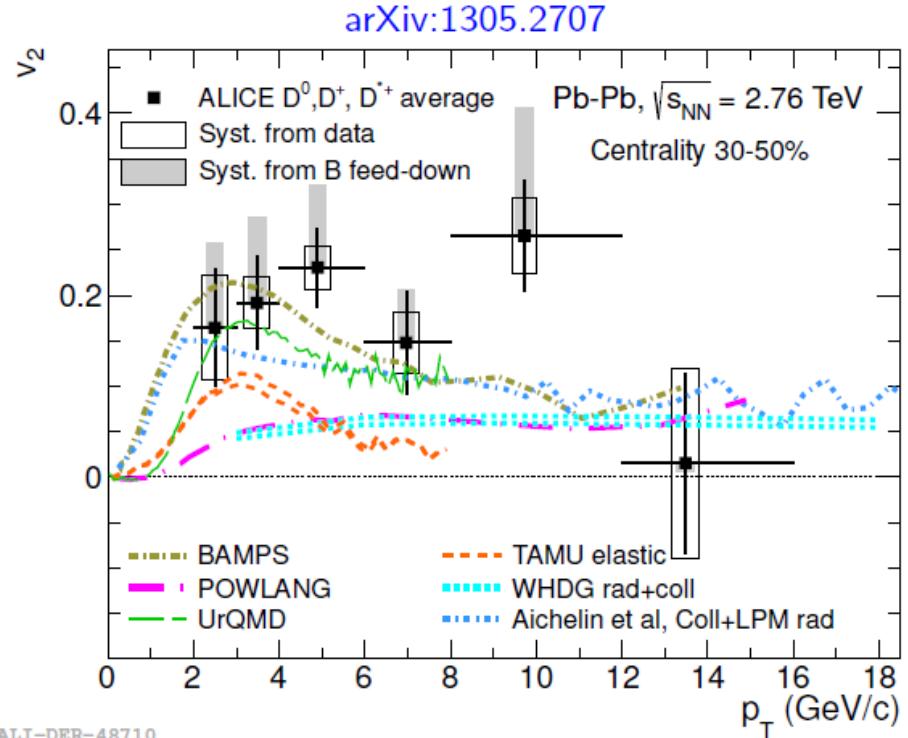


# Various model at work

JHEP 1209 (2012) 112



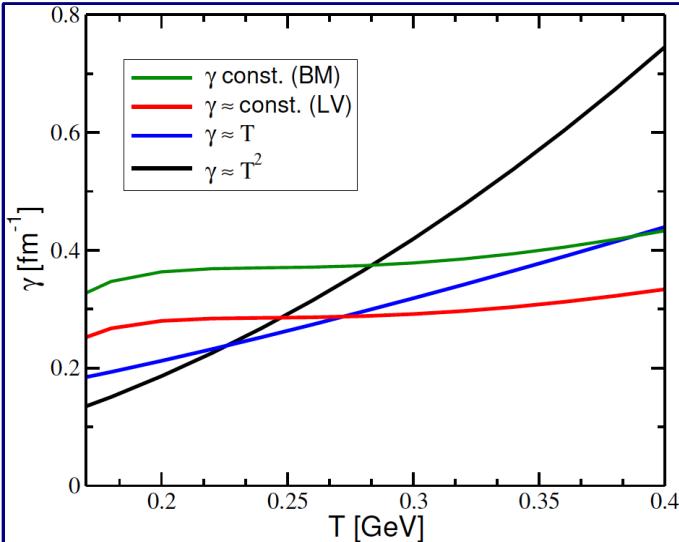
arXiv:1305.2707



Simultaneous description of  $R_{AA}$  and  $v_2$  is a tough challenge for all models

# Impact of T dep. interaction on $R_{AA}$ - $v_2$

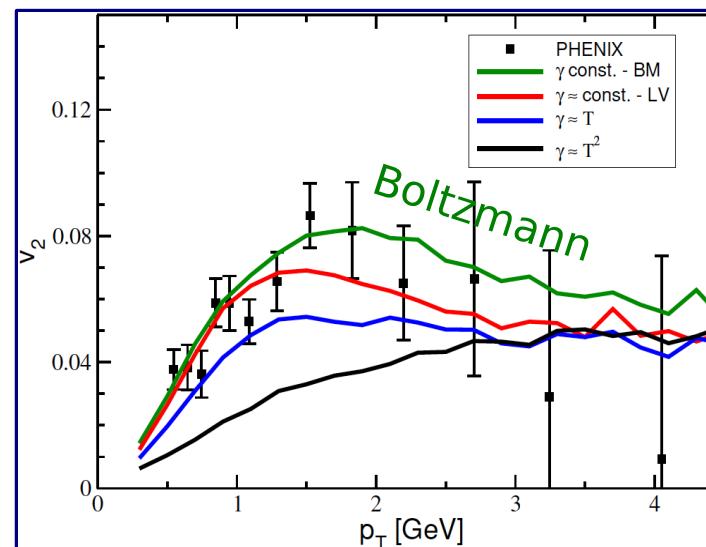
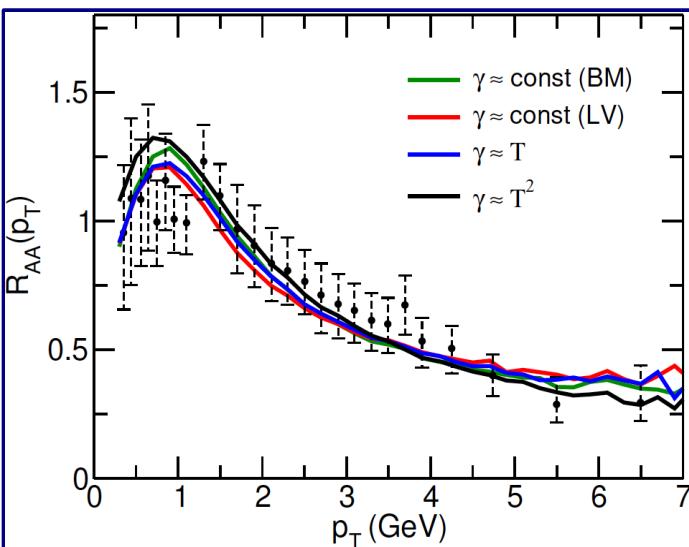
S.K. Das, F. Scardina, S. Plumari, V. Greco, PLB747 (2015) 260.



**Looking at it beyond the specific modelings**

- $\Upsilon \approx T^2$  [Ads/CFT, pQCD as=const]
- $\Upsilon \approx T$  [pQCD strong as running]
- $\Upsilon \approx \text{const.}$  [QPM]

$\gamma$  rescaled to fit  $R_{AA}$



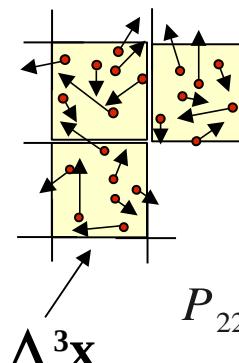
# Boltzmann

$$\underbrace{p^\mu \partial_\mu f(x, p)}_{\text{free-streaming}} + \underbrace{M(X) \partial_\mu M(X) \partial_p^\mu f(X, p)}_{\text{field interaction } \varepsilon - 3p \neq 0} = \underbrace{C_{22}}_{\text{collisions } \eta \neq 0}$$

- Describes the evolution of the one body distribution function  $f(x, p)$
- It is valid to study the evolution of both bulk and Heavy quarks
- Possible to include  $f(x, p)$  out of equilibrium

$$C_{22} = \int d^3 k [\omega(p+k, k) f(p+k) - \omega(p, k) f(p)] \quad \omega(p, k) = \int \frac{d^3 q}{(2\pi)^3} f'(q) v_{rel} \sigma_{p, q \rightarrow p-k, q+k}$$

- Numerically the Boltzmann eq. solved by standard test particle method to sample  $f(x, p)$ .
  - Numerical implementation of the collision integral by stochastic algorithm.
- Z. Xu, C. Greiner PRC 71 (2005) 064901



$$P_{22} = \frac{\Delta N_{coll}^{2 \rightarrow 2}}{\Delta N_1 \Delta N_2} = v_{rel} \sigma_{22} \frac{\Delta t}{\Delta^3 x}$$

# Boltzmann

$$p^\mu \partial_\mu f(x, p) + M(X) \partial_\mu M(X) \partial_p^\mu f(X, p) = C_{22}$$

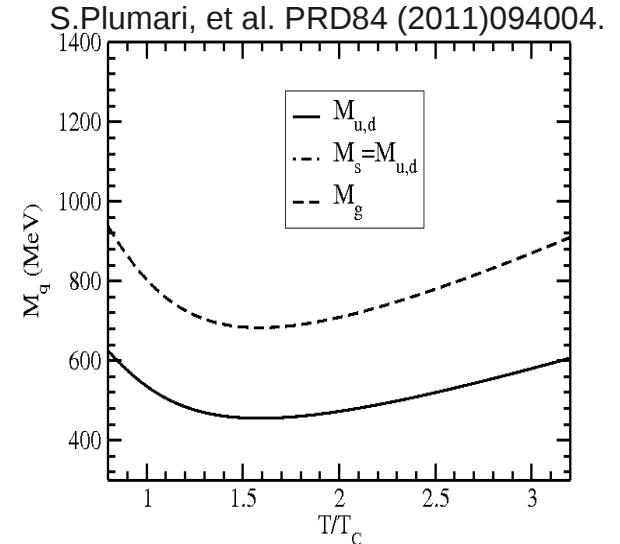
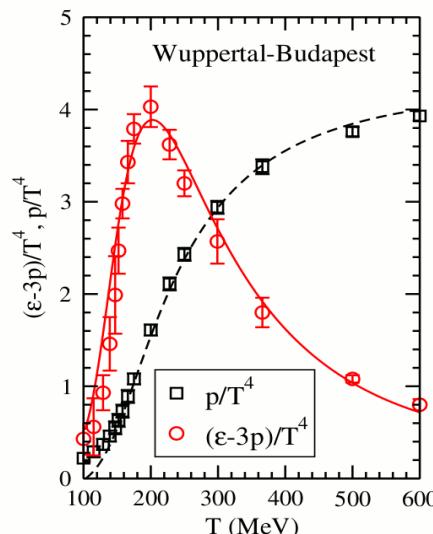
free-streaming      field interaction  
 $\varepsilon - 3p \neq 0$       collisions  
 $\eta \neq 0$

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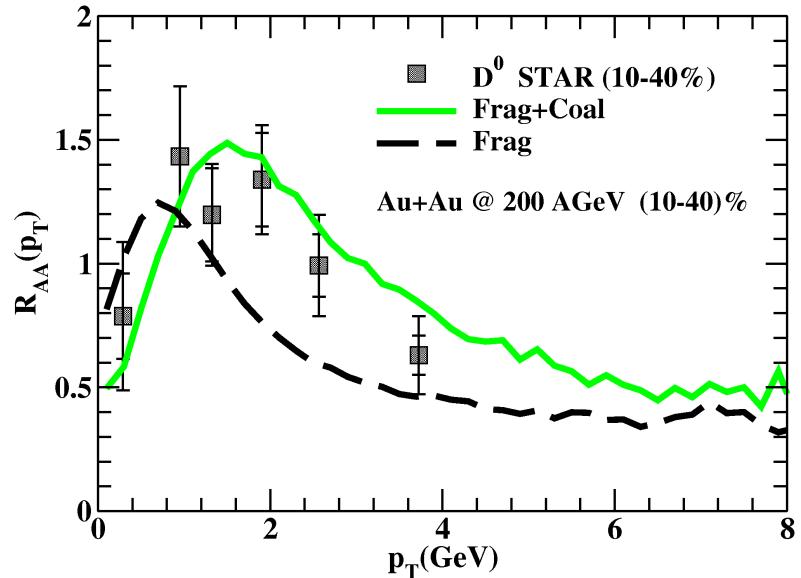
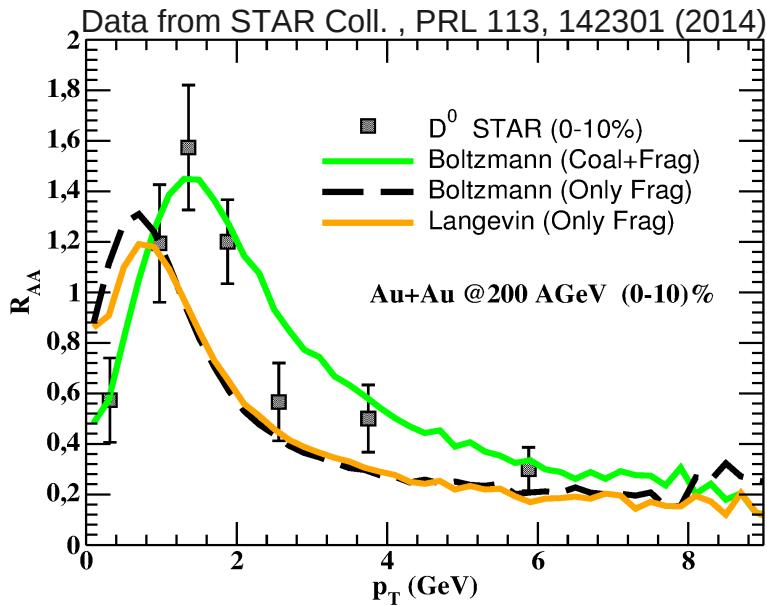
$$C_{22} = \int d^3k [\omega(p+k, k)f(p+k) - \omega(p, k)f(p)] \quad \omega(p, k) = \int \frac{d^3q}{(2\pi)^3} f'(q)v_{rel}\sigma_{p, q \rightarrow p-k, q+k}$$

$$\left\{ \begin{array}{l} p(T) = \sum_{i=g, q, \bar{q}} \frac{D_i}{(2\pi)^3} \int_0^\infty d^3k \frac{k^2}{3E_i(k)} f_i(k) - B(T) \\ \epsilon(T) = \sum_{i=g, q, \bar{q}} \frac{D_i}{(2\pi)^3} \int_0^\infty d^3k E_i(k) f_i(k) + B(T) \end{array} \right.$$

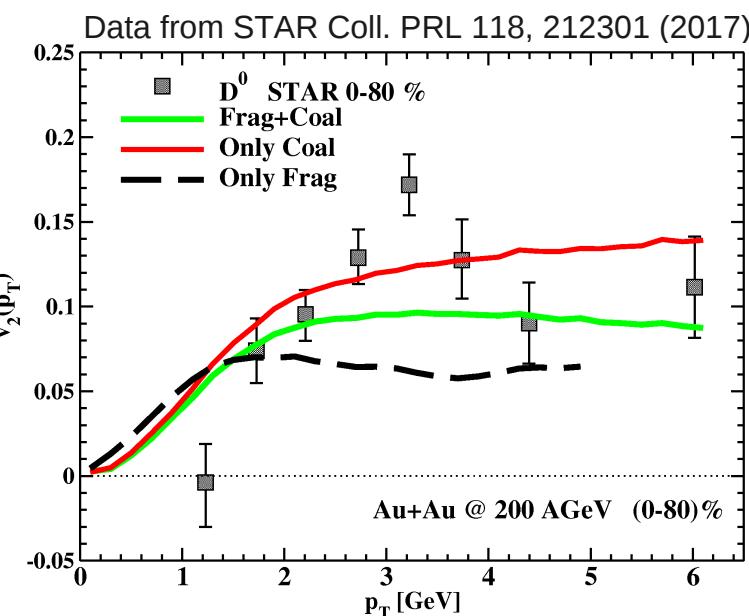
$M(T)$  and  $B(T)$  are fitted to reproduce lQCD data on  $\varepsilon$ .  
 Data taken from S. Borsanyi et al., JHEP 11 (2010) 077



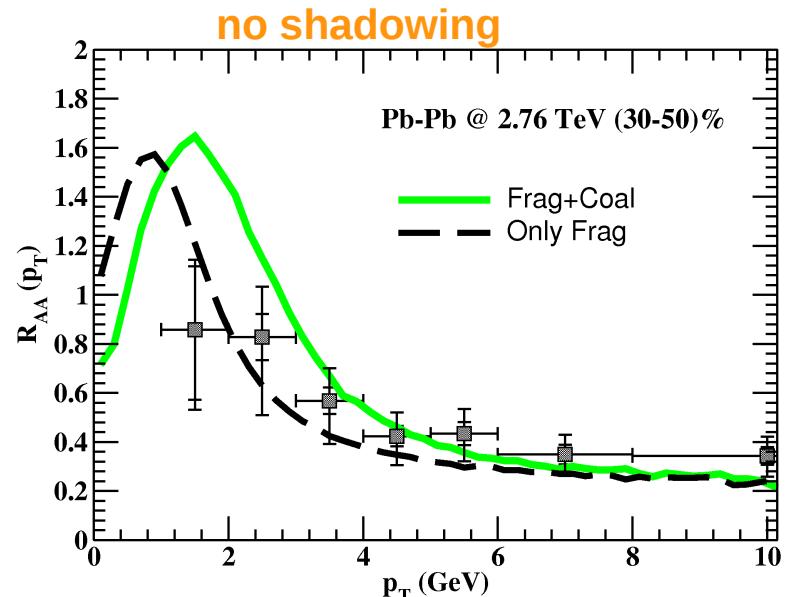
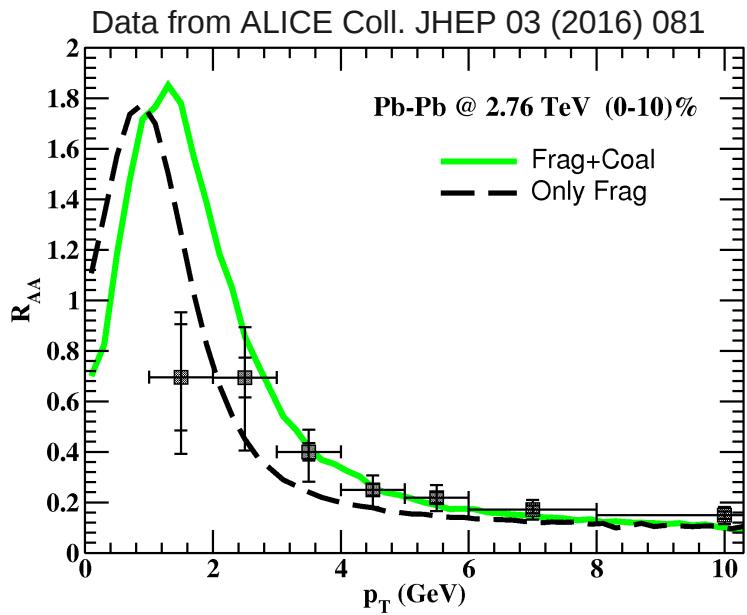
# RHIC results: $R_{AA}$ - $v_2$



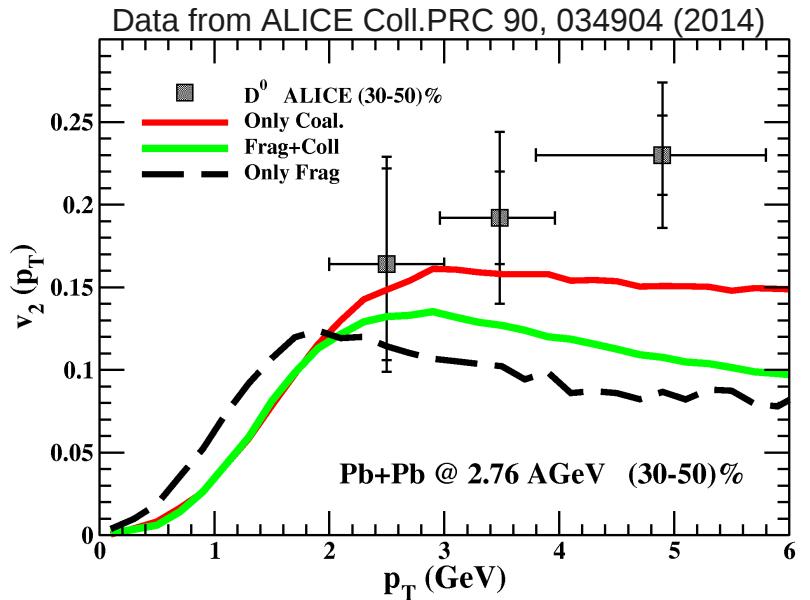
- In (0-10)% coalescence implies an increase of the  $R_{AA}$  for  $p_T > 1$  GeV.
- The impact of coalescence decreases with  $p_T$  and fragmentation is dominant at high  $p_T$ .
- In (0-80)% the  $v_2(p_T)$  due to only coalescence increase a factor 2 compared to the  $v_2(p_T)$  charm.
- In (0-80)% coalescence+fragmentation give a good description of exp. data.



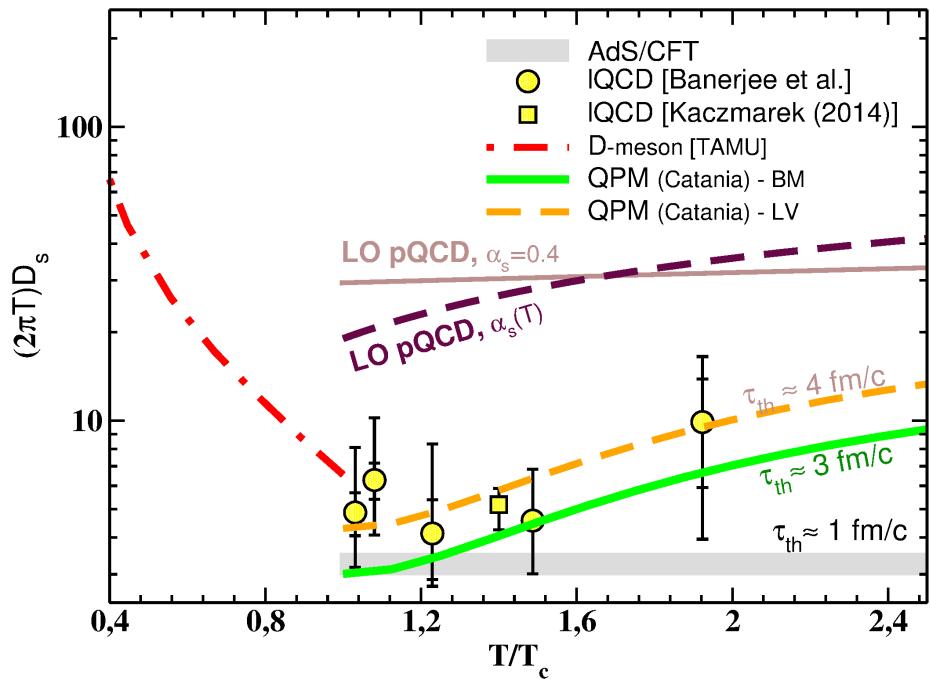
# LHC results: $R_{AA}$ - $v_2$



- At LHC the coalescence implies an increasing of the  $R_{AA}$  for  $p_T > 1$  GeV similar to RHIC energies.
- At LHC the effect of coalescence is less significant than RHIC energy.
- Due to hadronization D meson  $v_2(p_T)$  get an enhancement of about 20% respect to charm  $v_2(p_T)$ .

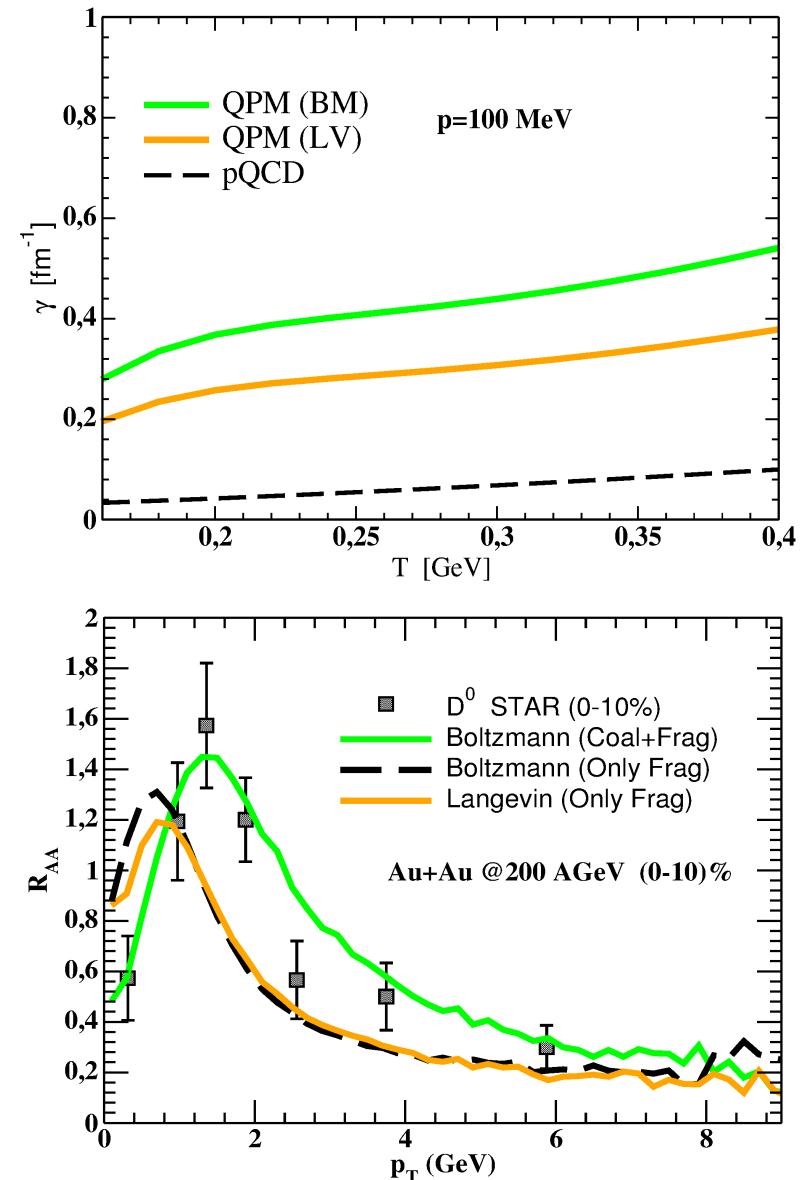


# Comparison to IQCD Diff. coef.

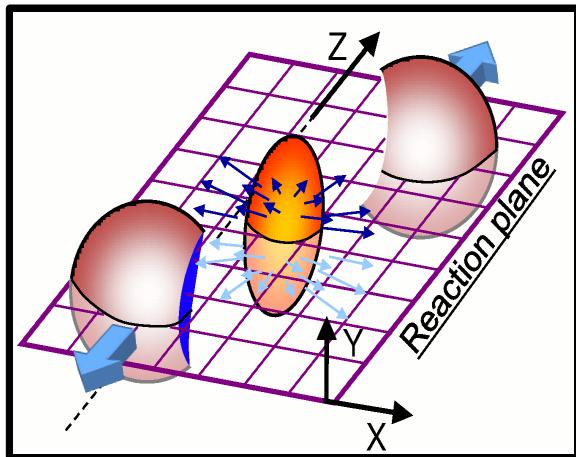


$$D_s(p=0) = \frac{T}{m_Q \gamma} = T m_Q \tau_{th}$$

we need a smaller drag coefficient in Langevin (LV) dynamics to describe the same  $R_{AA}$  about 30% of reduction compared to Boltzmann (BM)



# Heavy Flavour dynamics: event-by-event transport approach



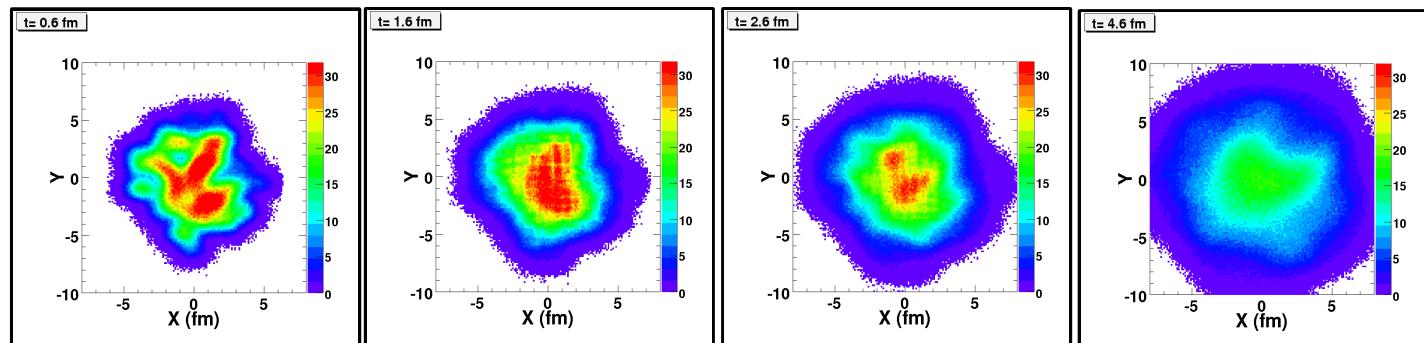
We have developed an event-by-event transport approach for the bulk:  
S. Plumari, G.L. Guardo, F. Scardina, V. Greco PRC92 (2015) no.5, 054902

## Extented to study:

- Heavy quark  $v_n(p_T)$
- Heavy quark-bulk correlations

## Some recent calculations using event-by-event viscous hydro

M. Nahrgang, J. Aichelin, S. Bass,  
P. B. Gossiaux, K. Werner PRC91 (2015) no.1, 014904.  
C. A. G. Prado et al., arXiv:1611.02965 [nucl-th].



# Heavy Flavour dynamics: event-by-event transport approach

We implement Monte Carlo Glauber initial conditions

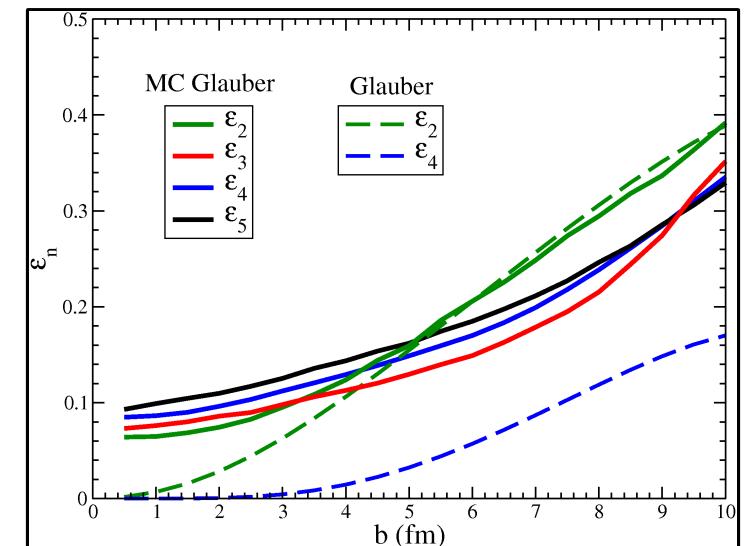
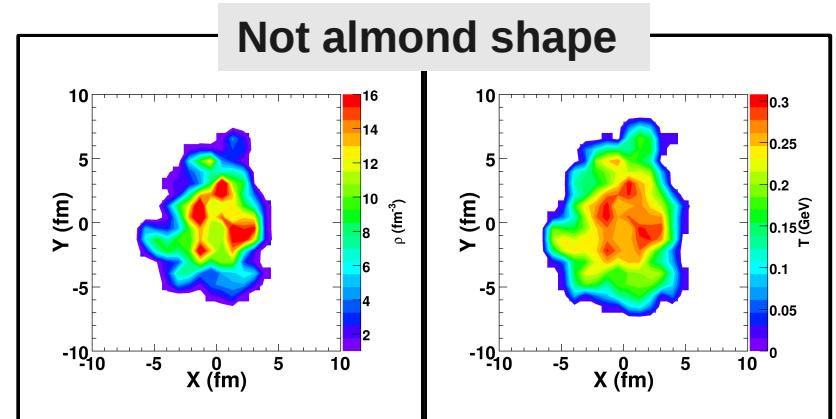
Characterization of the initial profile in terms  
of Fourier coefficients



$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\phi - \Phi_n)] \rangle}{\langle r_\perp^n \rangle} \quad \Phi_n = \frac{1}{n} \arctan \frac{\langle r_\perp^n \sin(n\phi) \rangle}{\langle r_\perp^n \cos(n\phi) \rangle}$$

G-Y. Qin, H. Petersen, S.A. Bass, B. Muller, PRC82, 064903 (2010).  
H. Holopainen, H. Niemi, K.J. Eskola, PRC83, 034901 (2011).

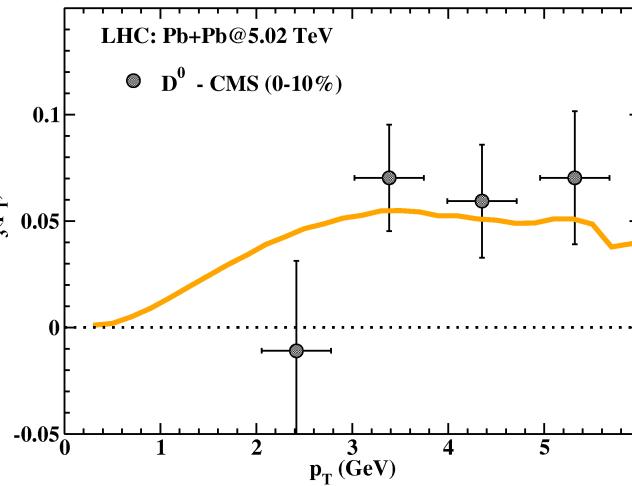
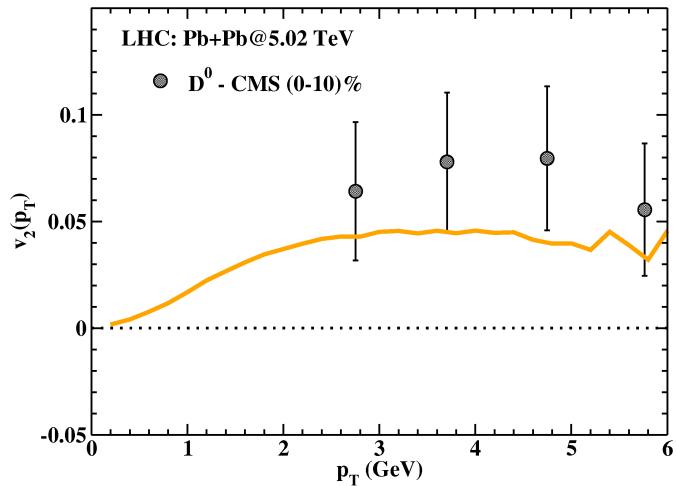
$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} \left[ 1 + \sum_n 2 v_n(p_T) \cos[n(\phi - \psi_n)] \right]$$



# PRELIMINARY

# Heavy Flavour dynamics: event-by-event transport approach

Data taken from CMS coll. talk by J. Sun QM2017

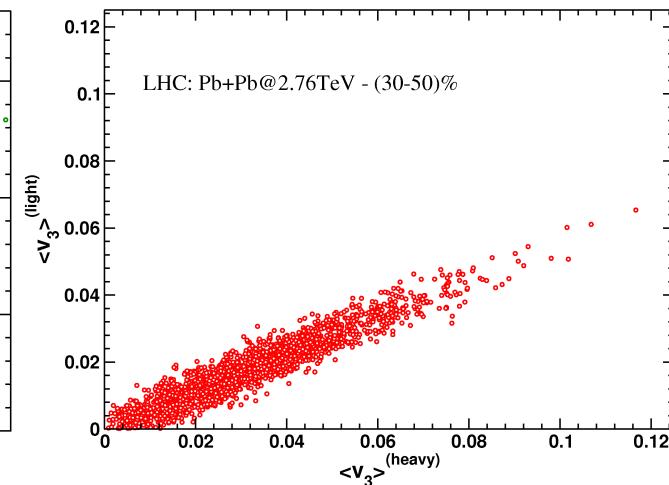
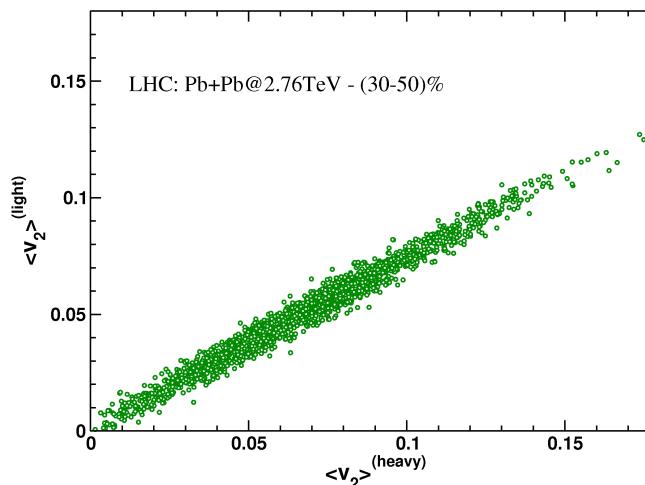


- Initial state fluctuations improve the description of  $v_2(p_T)$  in more central collisions
- $v_3(p_T)$  same magnitude of exp. data

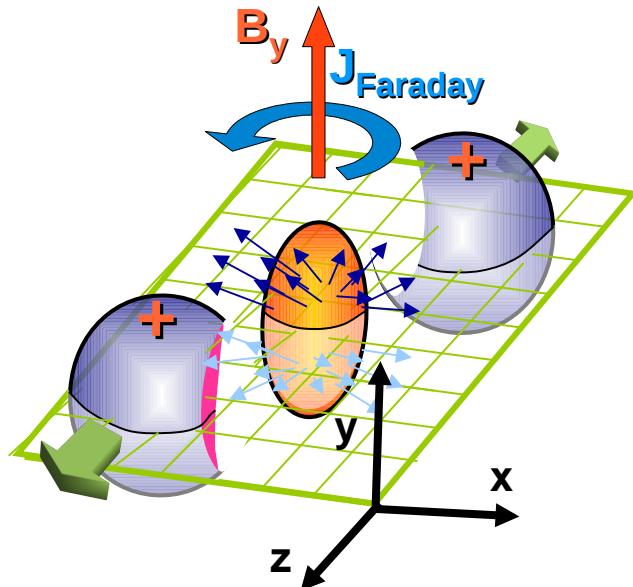
**NO Coal. Incl.**

## CORRELATIONS:

- Strong linear correlation between  $v_2^{(\text{light})}$  and  $v_2^{(\text{heavy})}$
- Weaker linear correlation between  $v_3^{(\text{light})}$  and  $v_3^{(\text{heavy})}$



# Impact of large Electromagnetic field on the Charm dynamics



- A. Bzdak, V. Skokov, PLB **710** (2012) 171-174  
K. Tuchin, PRC **88**, 024911 (2013).  
K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).  
K. Hattori, X.-G. Huang Nucl.Sci.Tech. 28 (2017) no.2, 26.

## B field strength:

- created on Earth  $\approx 10^7$  Gauss
- Neutron Star  $\approx 10^{13}$  Gauss
- uRHIC  $\approx 10^{19}$  Gauss  $\approx 10 m_\pi^{-2}$

## Impacts on:

- Quarkonia states
- Radiative  $E_{\text{loss}}$
- Electromagnetic radiation
- HQ transport coefficient  $D_T \gg D_{\parallel}$

- We solve the relativistic Langevin equation in an expanding QGP background with Lorentz force.
- Initial conditions constrained by experimental data on the  $R_{AA}(p_T)$  and  $v_2$  of D meson

# Electromagnetic field: time evolution

Solve the Maxwell eq.s by starting with a point-like charge at the  $\mathbf{x}_T$  in the transverse plane and moving in the  $+z$  direction with velocity  $\beta$ .

$$\left\{ \begin{array}{l} \nabla \cdot \mathbf{E} = e \delta(z - \beta t) \delta(\mathbf{x} - \mathbf{x}_T) \\ \nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \sigma_{el} \mathbf{E} + e \beta \delta(z - \beta t) \delta(\mathbf{x} - \mathbf{x}_T) \end{array} \right.$$

Fold them with the nuclear transverse density profile of the spectator nuclei and sum forward (+) and backward (-)

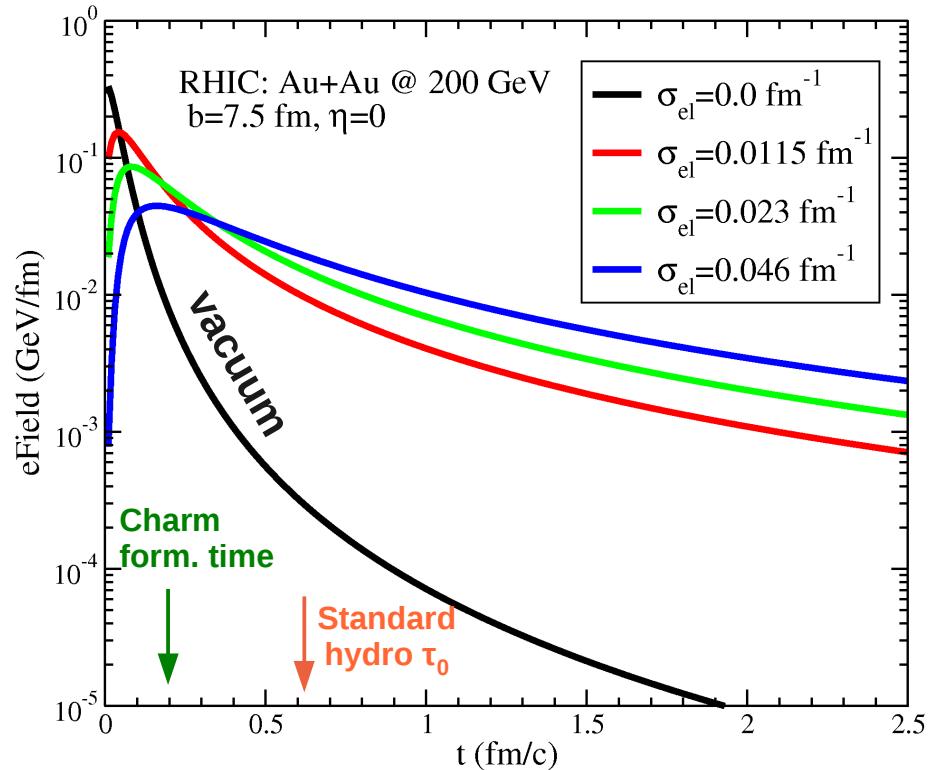
$$\begin{aligned} eB_{y,s} &= -Z \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{in}(\phi')}^{x_{out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \\ &\quad \times (eB_y^+(\tau, \eta, x_\perp, \pi - \phi) + eB_y^+(\tau, -\eta, x_\perp, \phi)) , \\ eE_{x,s} &= Z \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}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

like in:

K. Tuchin, PRC 88, 024911 (2013).

K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).

U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).



S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB768 (2017) 260-264.

## Assumptions:

- Electric conductivity  $\sigma_{el}$  const. in time
- Modification in the bulk due to currents is negligible
- No event-by-event fluctuations

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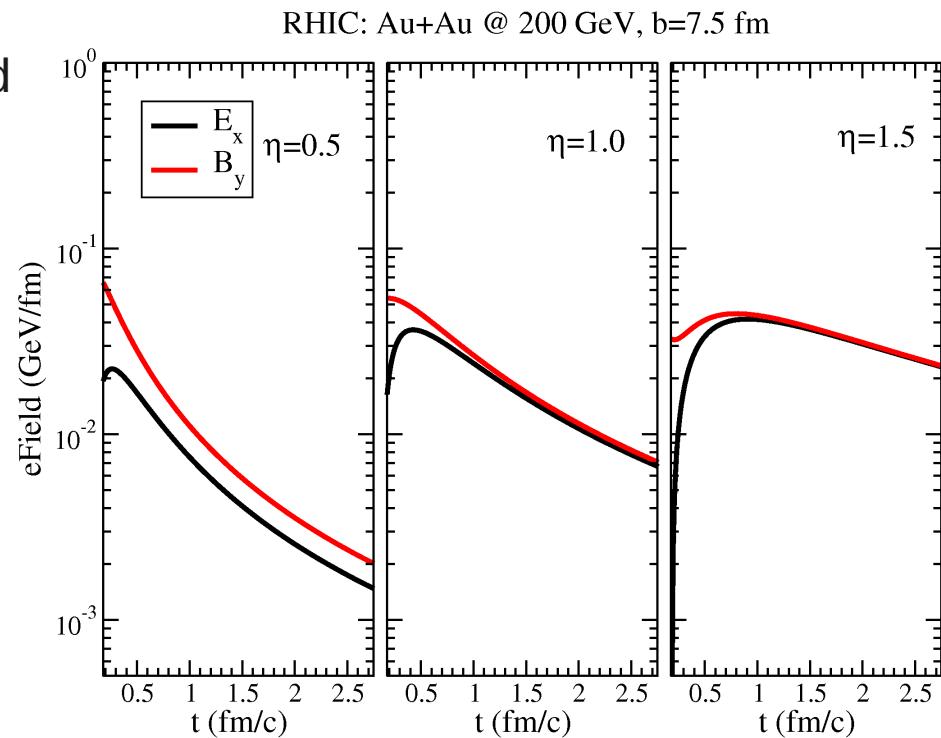
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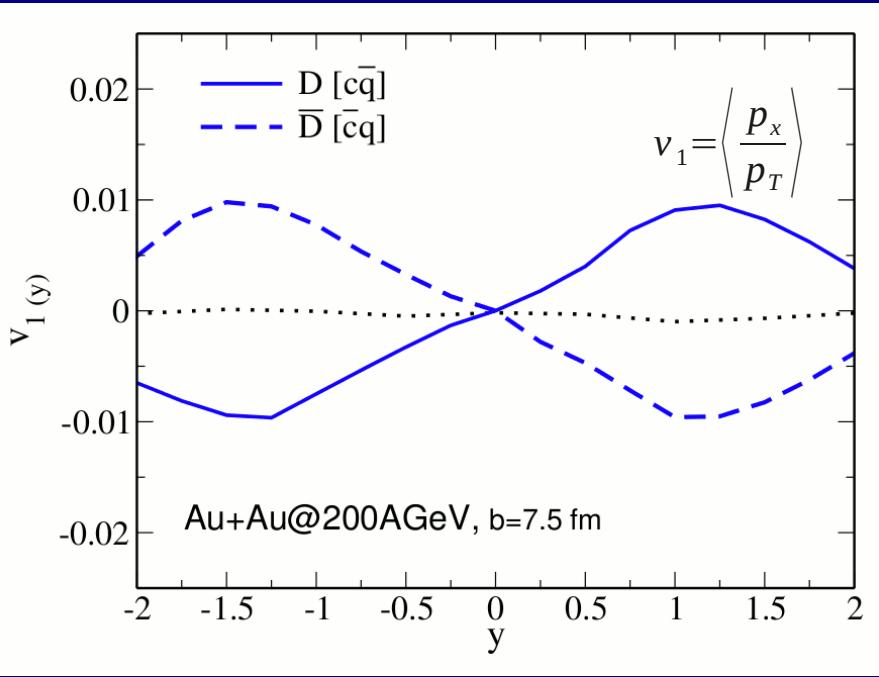


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# Direct Flow $v_1$ of charm quarks

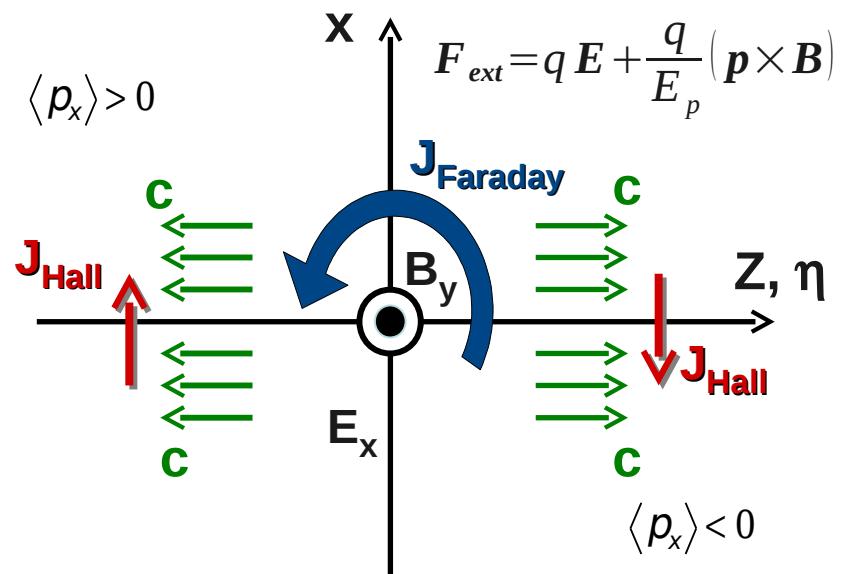
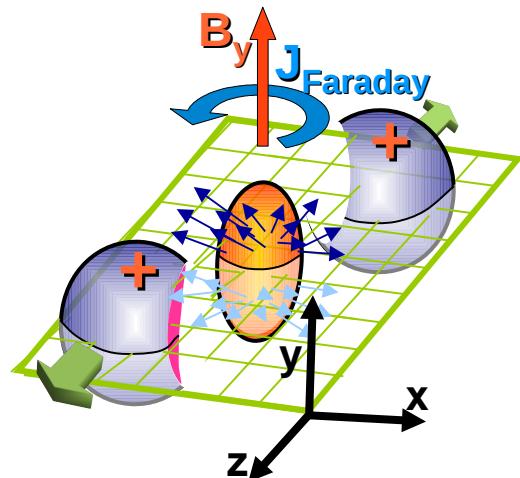


For light quarks was predicted  $v_1 \approx 10^{-3}$  -  $10^{-4}$

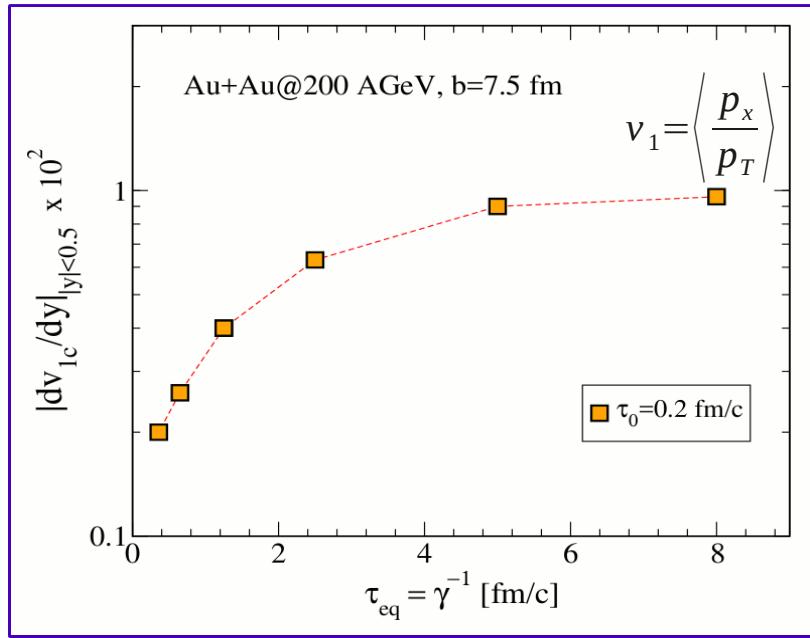
U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).

For charm quarks due to early form. time we find a sizeable  $v_1$  with the same E-B evolution

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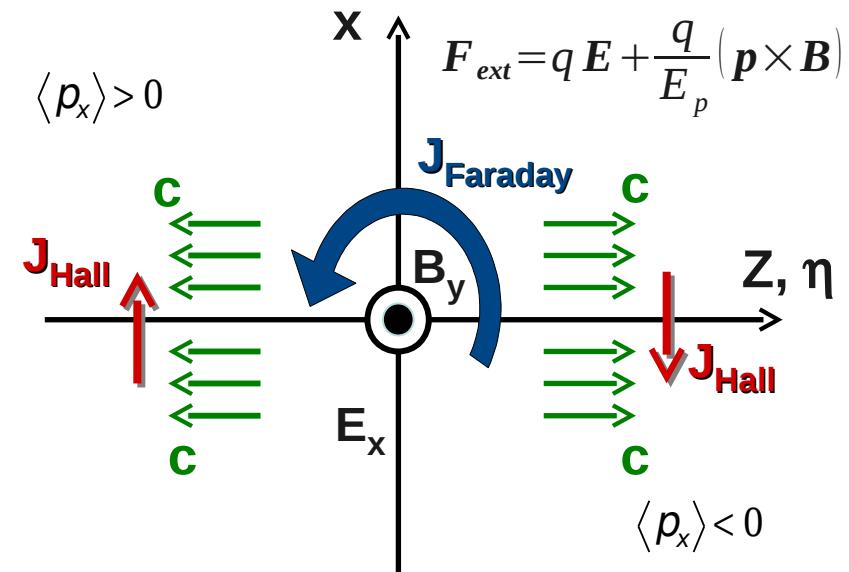
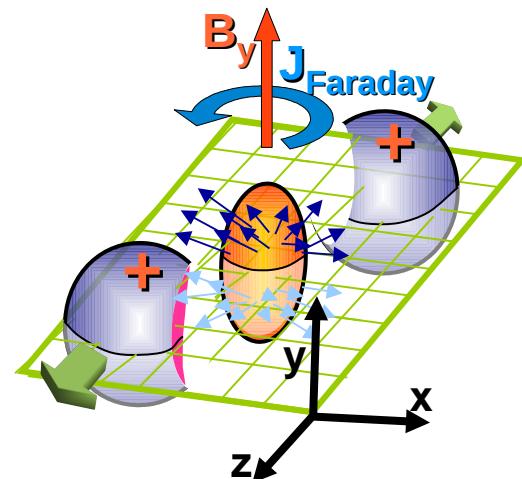


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U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).

For charm quarks due to early production we find a sizeable  $v_1$  with the same E-B evolution

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# Conclusions

- Simultaneous predict of both  $R_{AA}$  and  $v_2$ :  
needs T dep. of Ds + coal. + BM dynamics
  - Good description of  $R_{AA}$  and  $v_2(p_T)$  from RHIC to LHC
  - At RHIC hadronization by coal.+fragm. increases  $v_2(p_T)$  of about 30%
  - At LHC energies the effect is smaller of about 20%
- Event-by-event transport approach: new observables
  - Further constraints for transport coefficients from  $v_2(p_T)$  and  $v_3(p_T)$
  - Strong correlation between  $v_2(\text{light})$  and  $v_2(\text{heavy})$
  - weaker correlation between  $v_3(\text{light})$  and  $v_3(\text{heavy})$
- Electromagnetic field impact: heavy quarks larger w.r.t. light quarks  
consequence of early formation time ( $\tau_0 \approx 0.1 \text{ fm/c}$ ) and larger kinetic equilibration time  
Large charm  $v_1(p_T)$  permits to access to the initial E-M field

# Summary on the build-up of $v_2$ at $\approx$ fixed RAA

