HEAVY QUARK DYNAMICS TOWARD THERMALIZATION: R_{AA} , v_1 , v_2 , v_3

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INFN Istituto Nazionale di Fisica Nucleare

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Utrecht 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 lQCD Diff. coeff.

- Initial state fluctuations within transport approach:
  - $v_n(p_T)$ of D mesons
  - v_n(heavy)-v_n(light) correlations

- Impact of ElectroMagnetic field on Heavy quarks dynamics: sizeable v_1 for charm quarks (anti-charms)

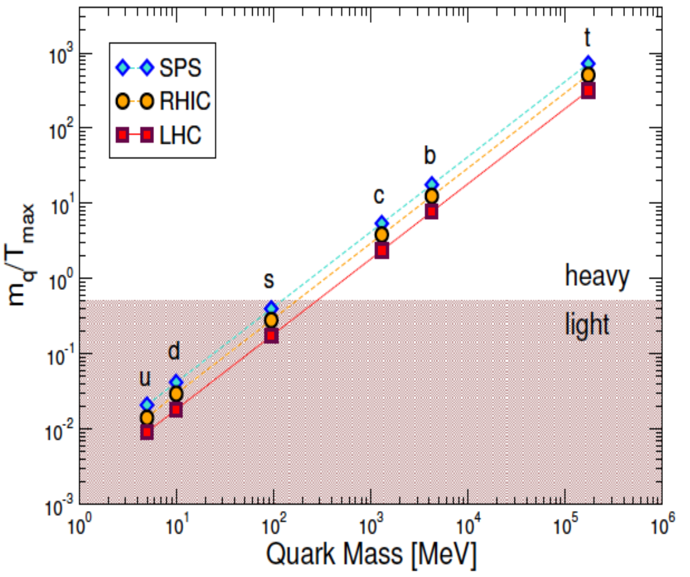
- Conclusions

Specific of Heavy Quarks

- $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD process (out of equilibrium)

- $m_{c,b} >> T_0$ no thermal production

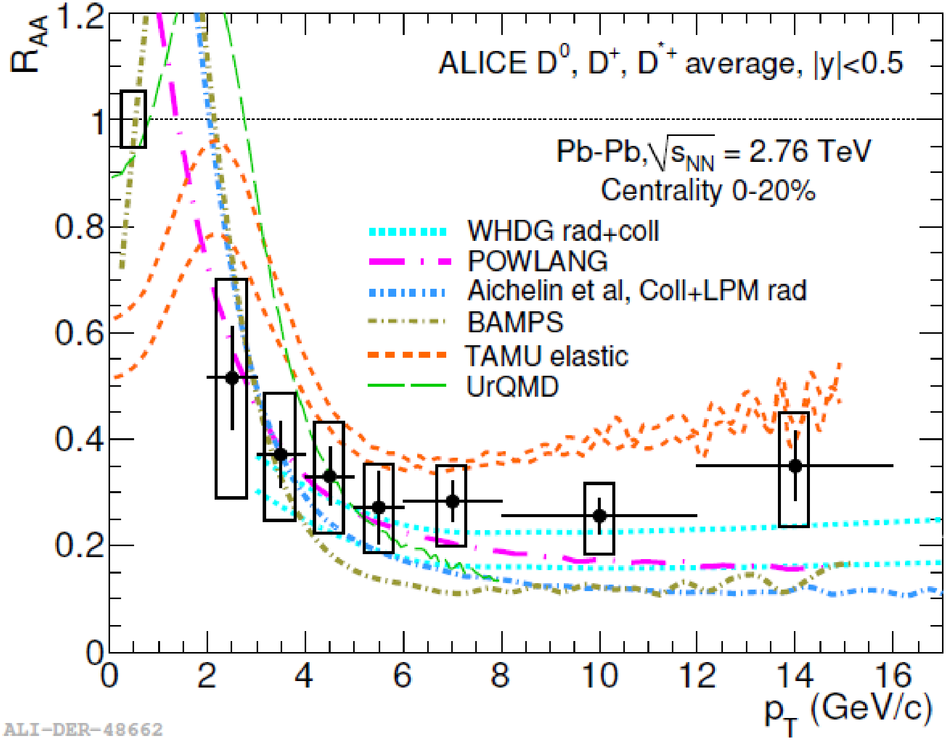
- $\tau_0 << \tau_{QGP}$ probes all the QGP life time



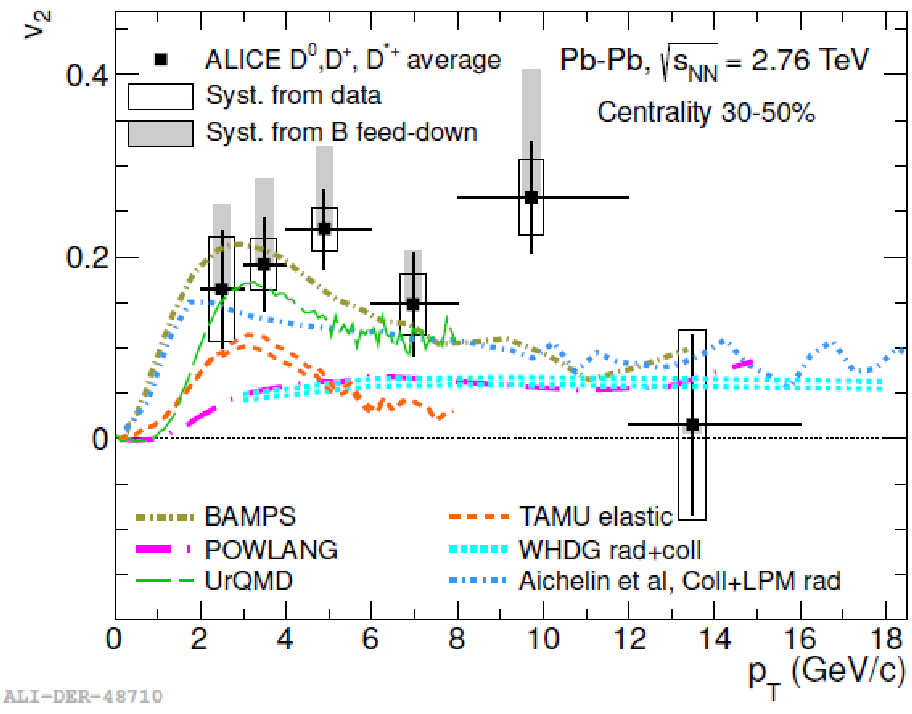
- $m >> T$, $q^2 << m^2$ → dynamics reduced to Brownian motion
(statement that can be challenged for charm quarks PRC**90**, 044901 (2014))

Various model at work

JHEP **1209** (2012) 112



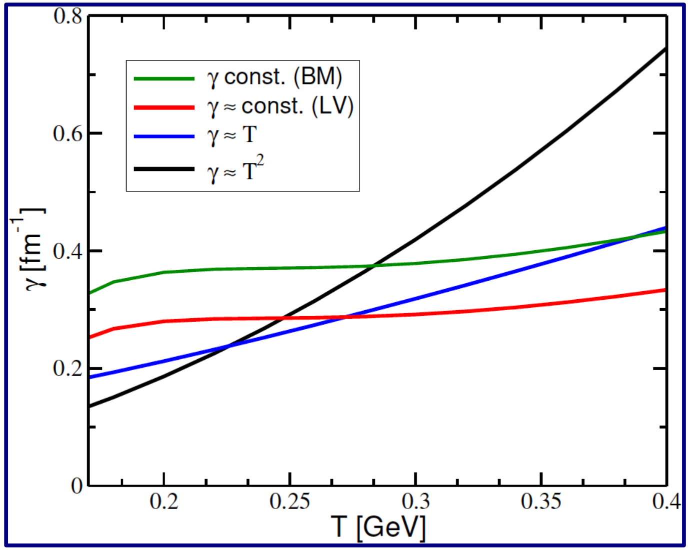
arXiv:1305.2707



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

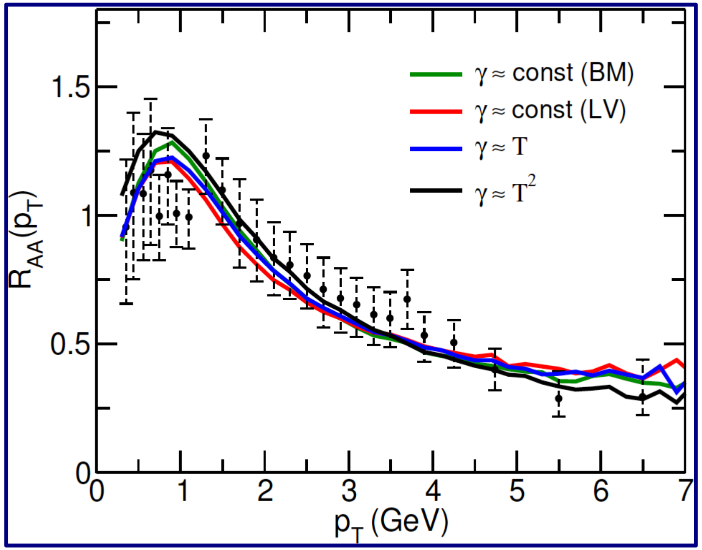
S.K. Das, F. Scardina, S. Plumari, V. Greco, PLB**747** (2015) 260.

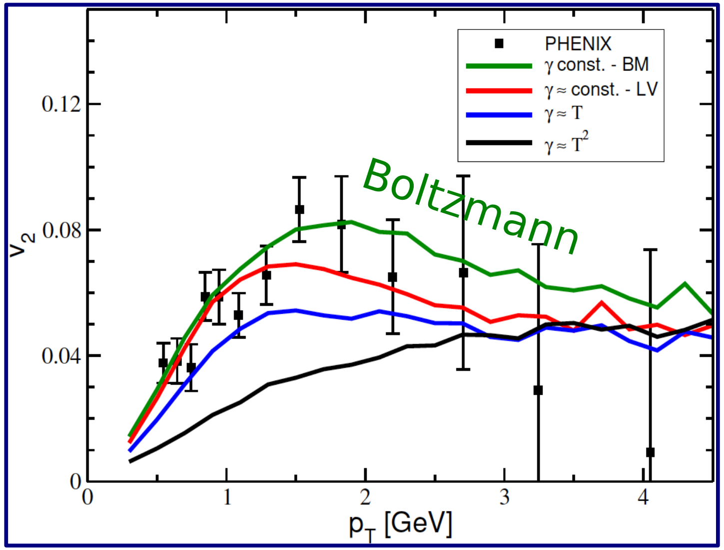


Looking at it beyond the specific modelings

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

Υ rescaled to fit R_{AA}





Boltzmann

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

free-streaming

field interaction
ε-3p≠0

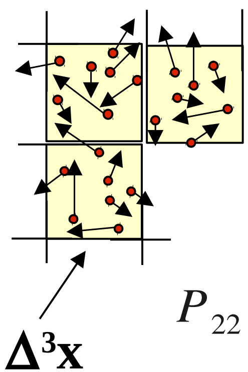
collisions
η≠0

- **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**

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

- **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



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

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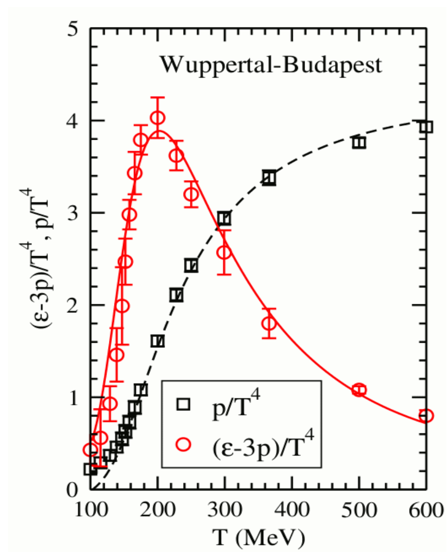
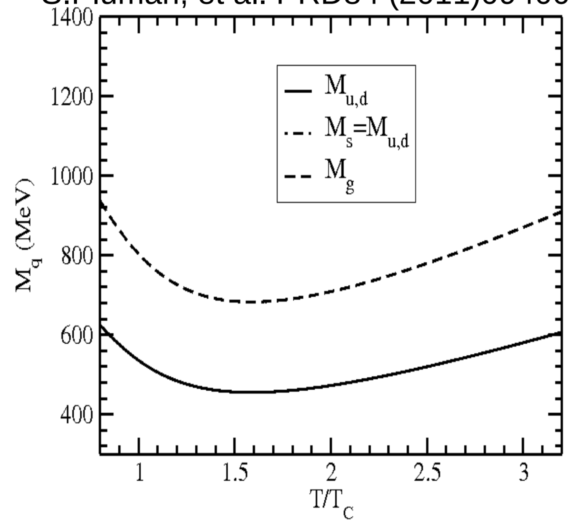
$$\begin{cases} p(T) = \displaystyle\sum_{i=g,q,\bar{q}} \frac{D_i}{(2\pi)^3} \int_0^{\infty} d^3k \frac{k^2}{3E_i(k)} f_i(k) - B(T) \\ \epsilon(T) = \displaystyle\sum_{i=g,q,\bar{q}} \frac{D_i}{(2\pi)^3} \int_0^{\infty} d^3k\, E_i(k) f_i(k) + B(T) \end{cases}$$

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

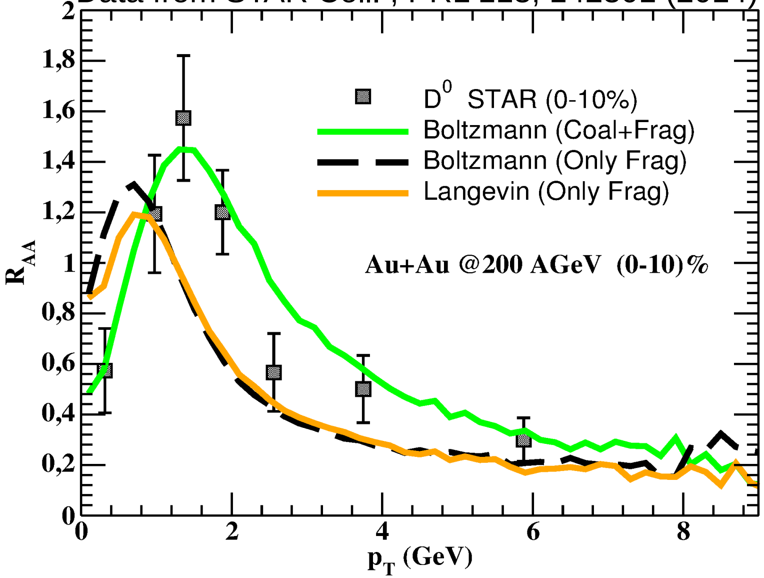


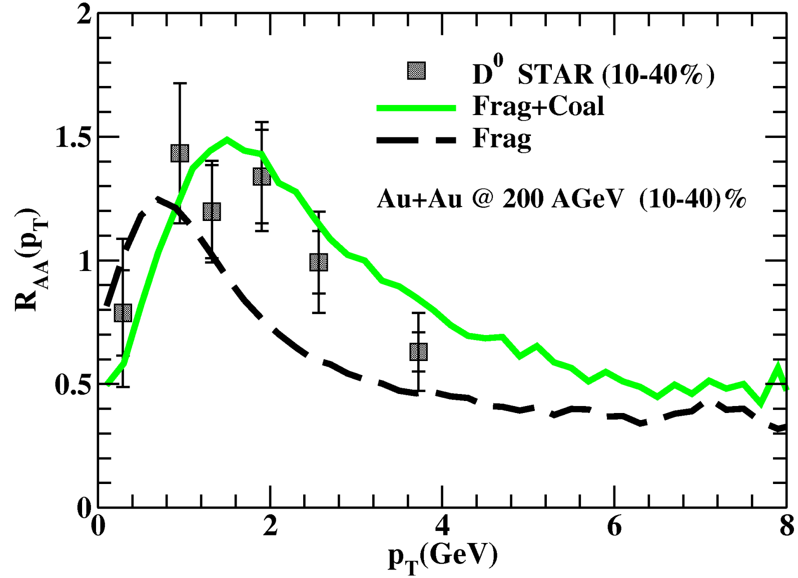
S.Plumari, et al. PRD84 (2011)094004.



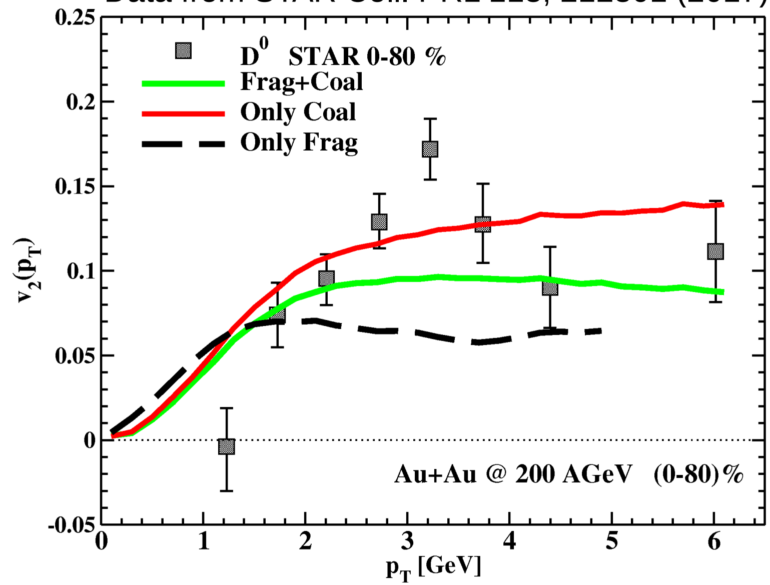
RHIC results: R_{AA} - v_2

Data from STAR Coll. , PRL 113, 142301 (2014)





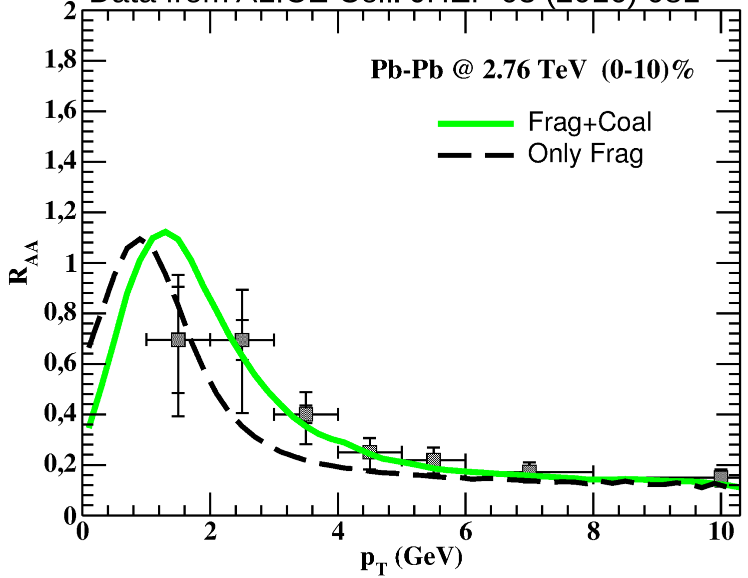
Data from STAR Coll. PRL 118, 212301 (2017)

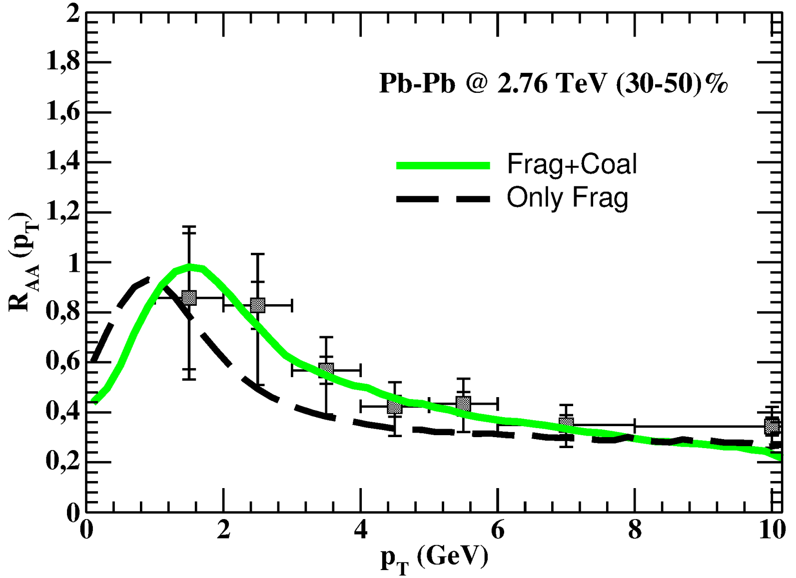


- In (0-10)% coalescence implies an increase of the R_{AA} for $p_T > 1$ GeV.
- The impact of coalescence decreases with p_T and fragmentation is dominant at high p_T.
- In (0-80)% the $v_2(p_T)$ due to only coalescence increase a factor 2 compared to the $v_2(p_T)$ charm.
- In (0-80)% coalescence+fragmentation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

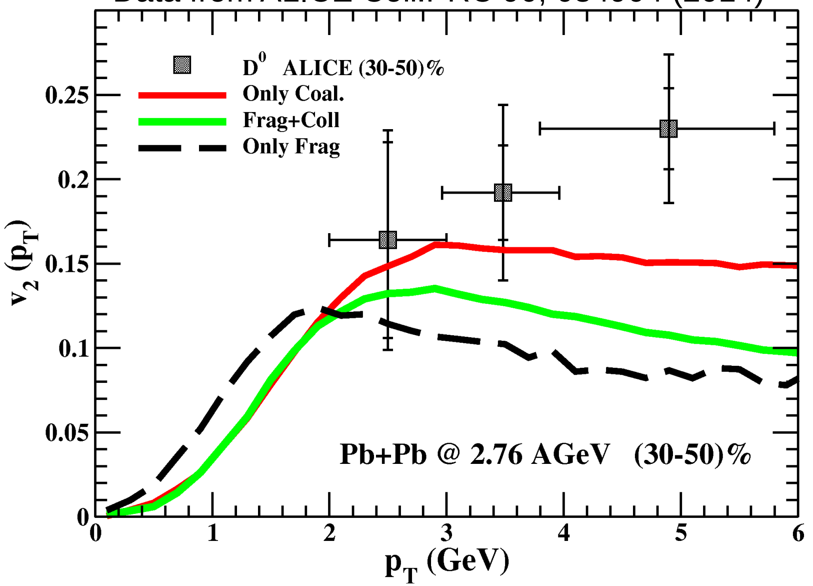
LHC results: R_{AA} - v_2

Data from ALICE Coll. JHEP 03 (2016) 081



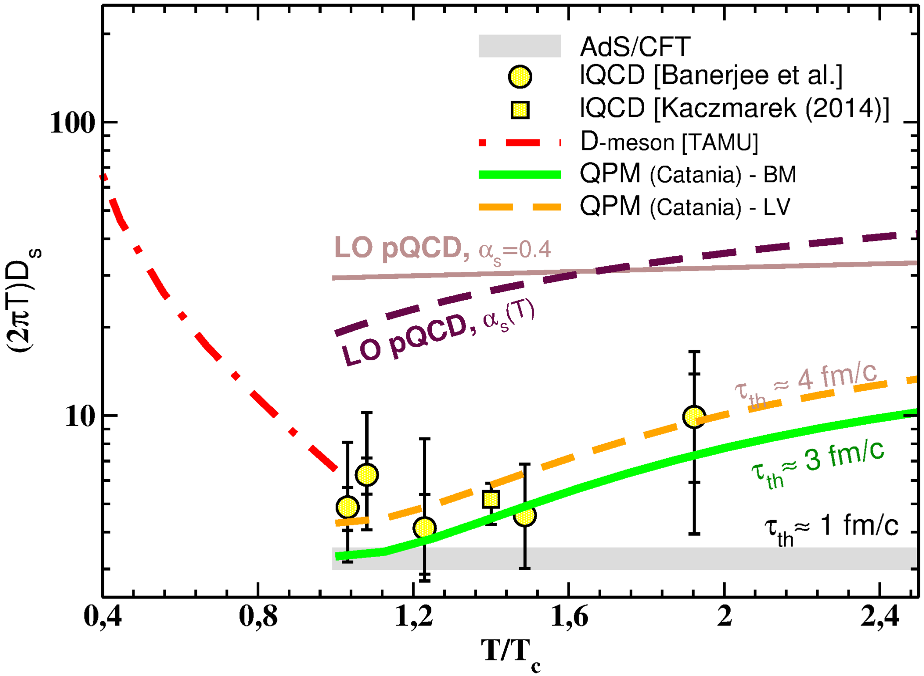


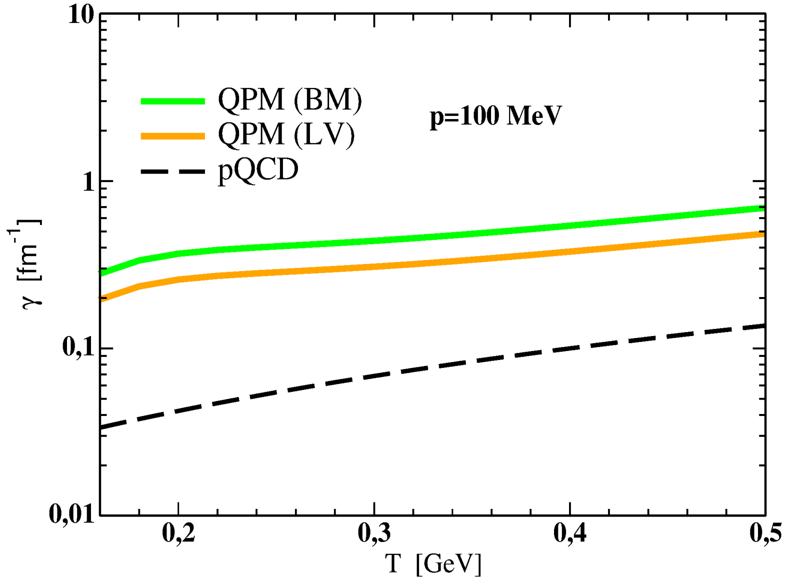
Data from ALICE Coll.PRC 90, 034904 (2014)



- At LHC the coalescence implies an increasing of the R_{AA} for p_T>1GeV 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 $v_2(p_T)$.

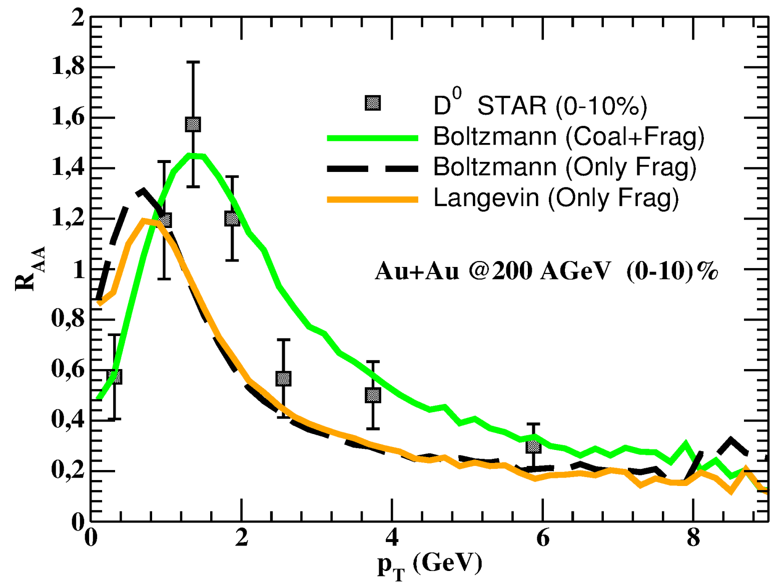
Comparison to lQCD Diff. coef.



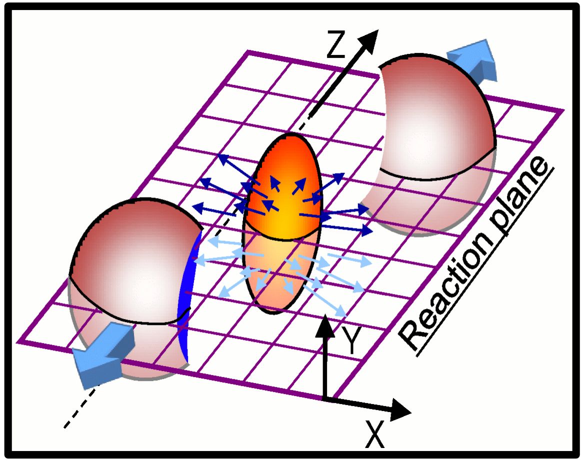


$$D_s(p=0)=\frac{T}{m_Q \gamma}=T\, m_Q \tau_{th}$$

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

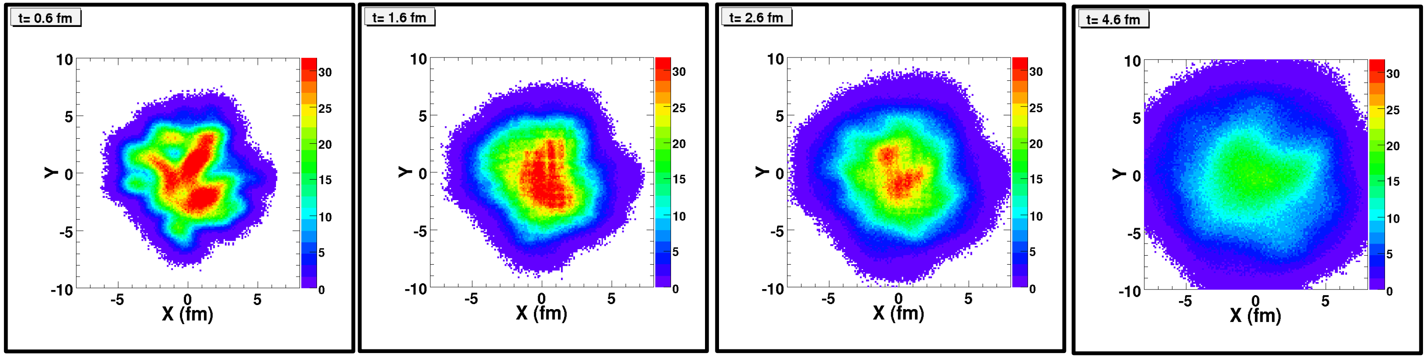


We have developed an event-by-event transport approach for the bulk:
S. Plumari, G.L. Guardo, F. Scardina, V. Greco PRC92 (2015) no.5, 054902

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

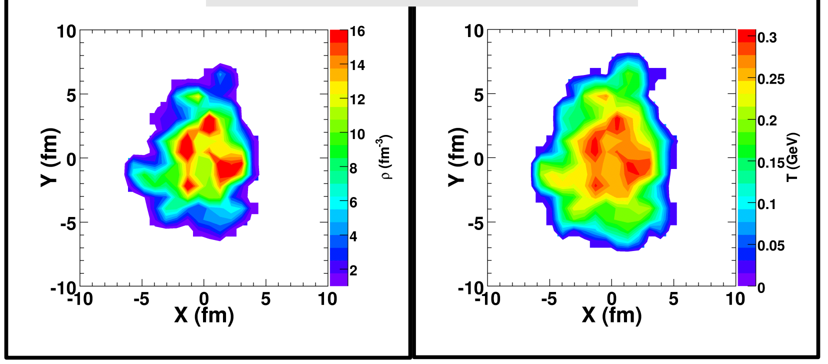
Characterization of the initial profile in terms of Fourier coefficients

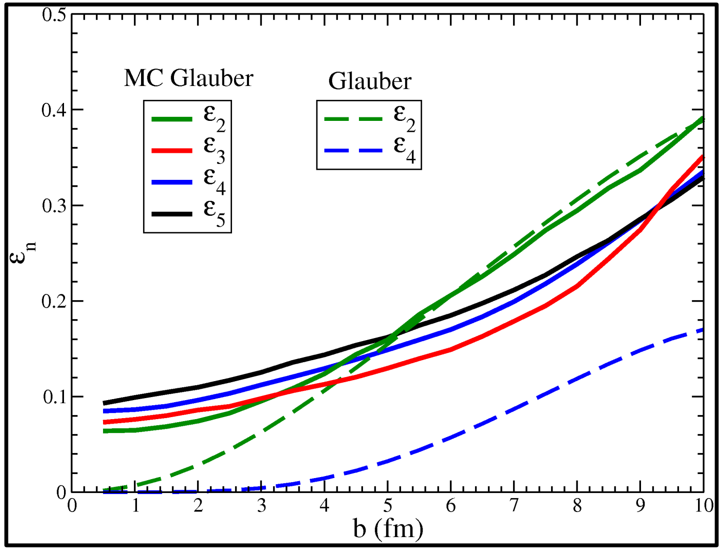
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)] \rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n} \arctan \frac{\langle r_\perp^n \sin(n\varphi) \rangle}{\langle r_\perp^n \cos(n\varphi) \rangle}$$

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

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

Not almond shape

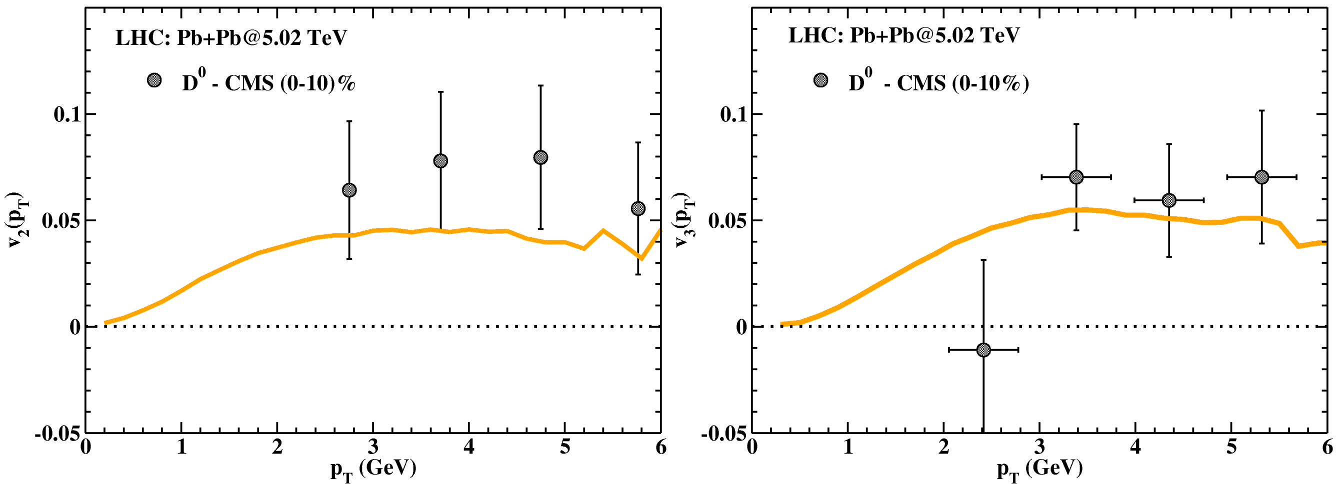




PRELIMINARY

Heavy Flavour dynamics: event-by-event transport approach

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

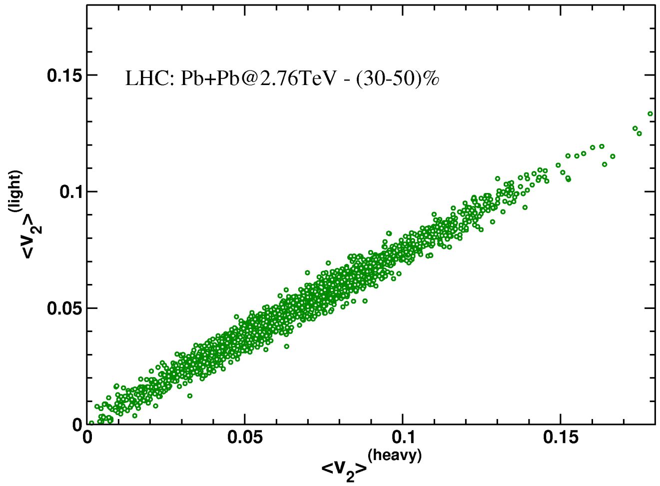


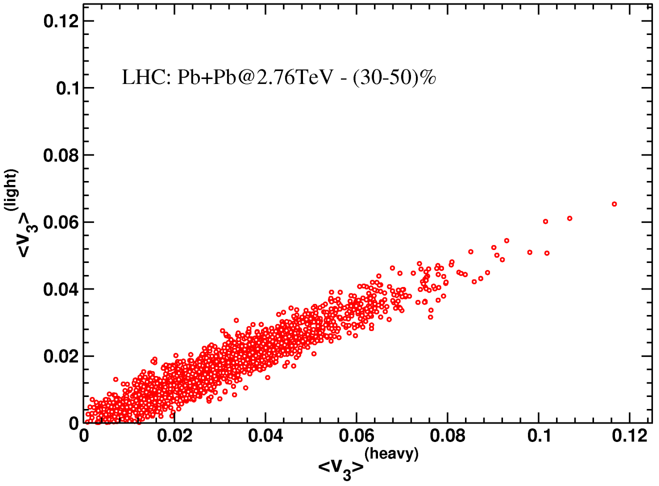
- Initial state fluctuations improve the description of $v_2(p_T)$ in more central collisions
- $v_3(p_T)$ same magnitude of exp. data

NO Coal. Incl.

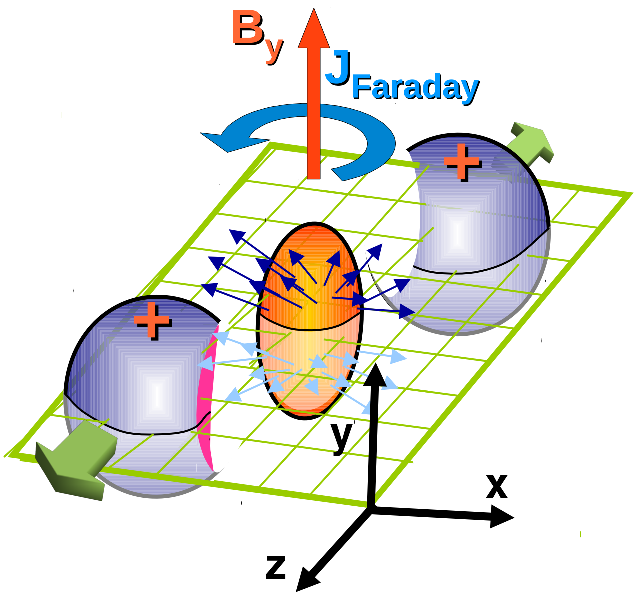
CORRELATIONS:

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





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 ≈ 10^7 Gauss**
- **Neutron Star ≈ 10^{13} Gauss**
- **uRHIC ≈ 10^{19} Gauss ≈ 10 m_π^2**

Impacts on:

- **Quarkonia states**
- **Radiative E_{loss}**
- **Electromagnetic radiation**
- **HQ transport coefficient $D_T >> D_{||}$**

- **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 $\boldsymbol{\beta}$.

$$\begin{cases} \nabla \cdot \boldsymbol{E} = e\,\delta(z-\beta t)\,\delta(\boldsymbol{x}-\boldsymbol{x}_T) \\ \nabla \cdot \boldsymbol{B} = 0 \qquad \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{B} = \dfrac{\partial \boldsymbol{E}}{\partial t} + \sigma_{el}\boldsymbol{E} + e\boldsymbol{\beta}\,\delta(z-\beta t)\,\delta(\boldsymbol{x}-\boldsymbol{x}_T) \end{cases}$$

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

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

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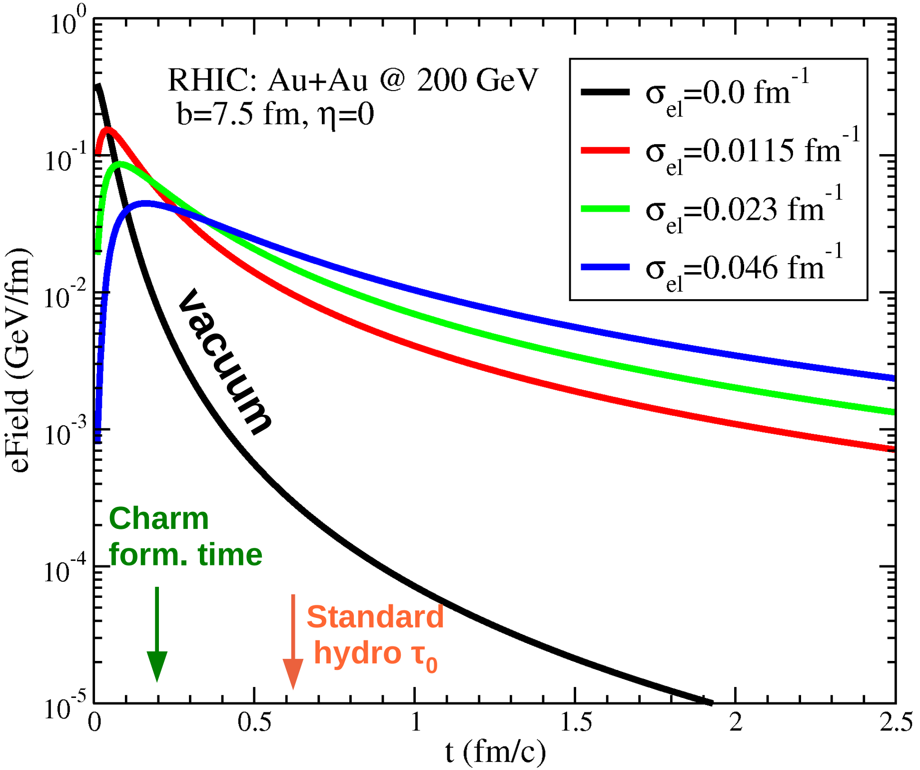
like in:

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, PLB**768** (2017) 260-264.

Assumptions:

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

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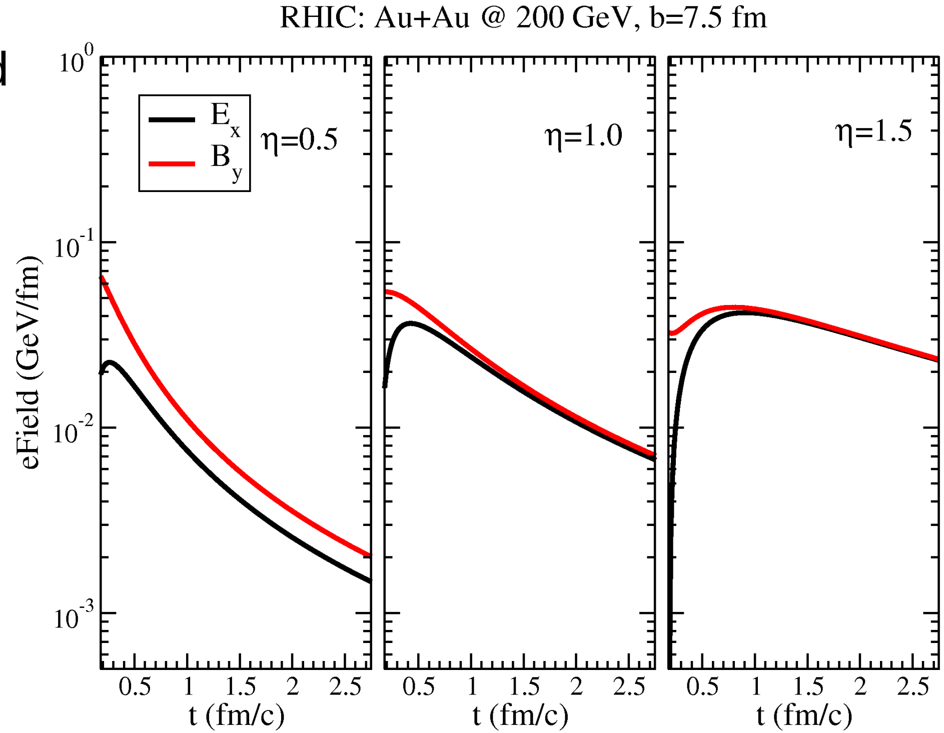

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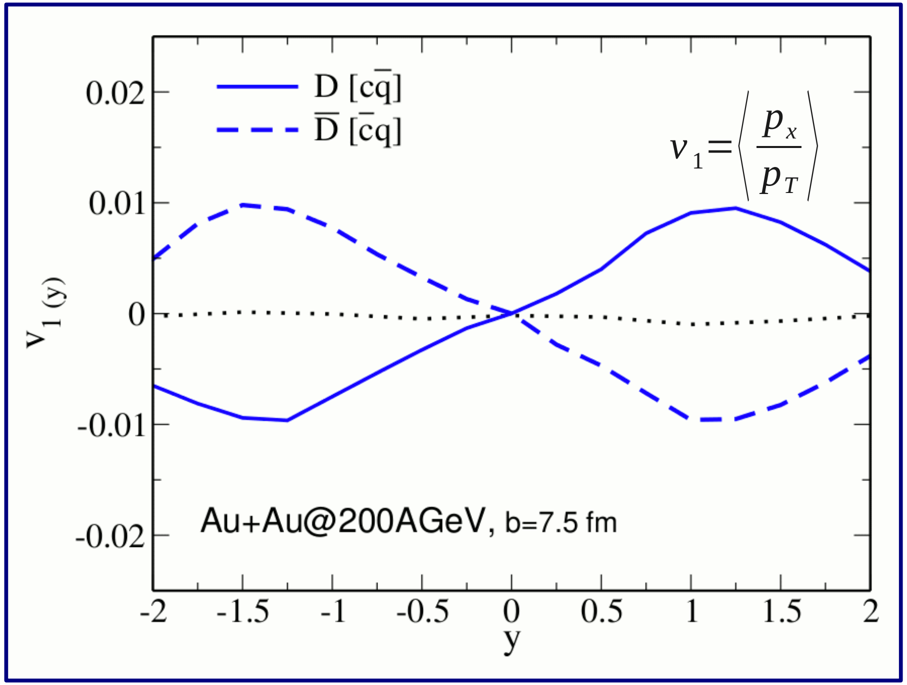
Direct Flow v_1 of charm quarks

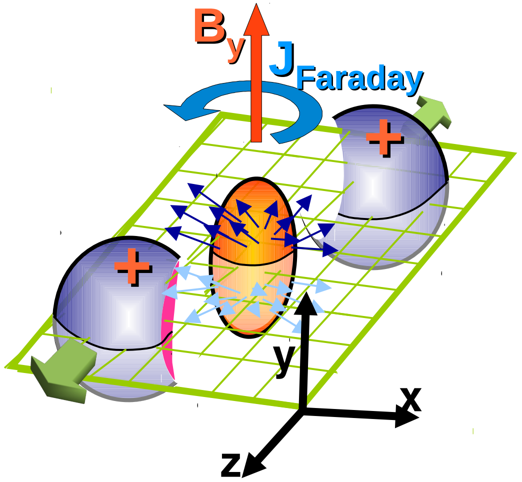


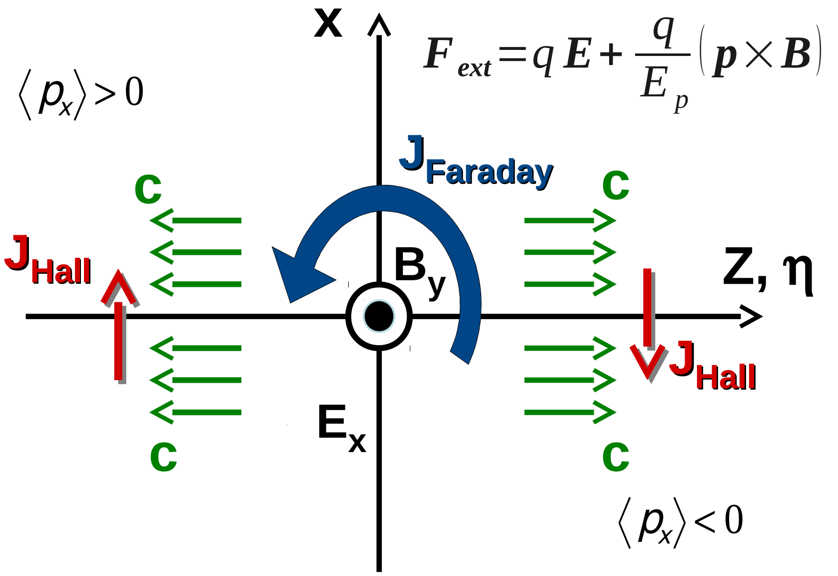
For light quarks was predicted $v_1 \approx 10^{-3}$ -10^{-4}

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

S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB**768** (2017) 260-264.





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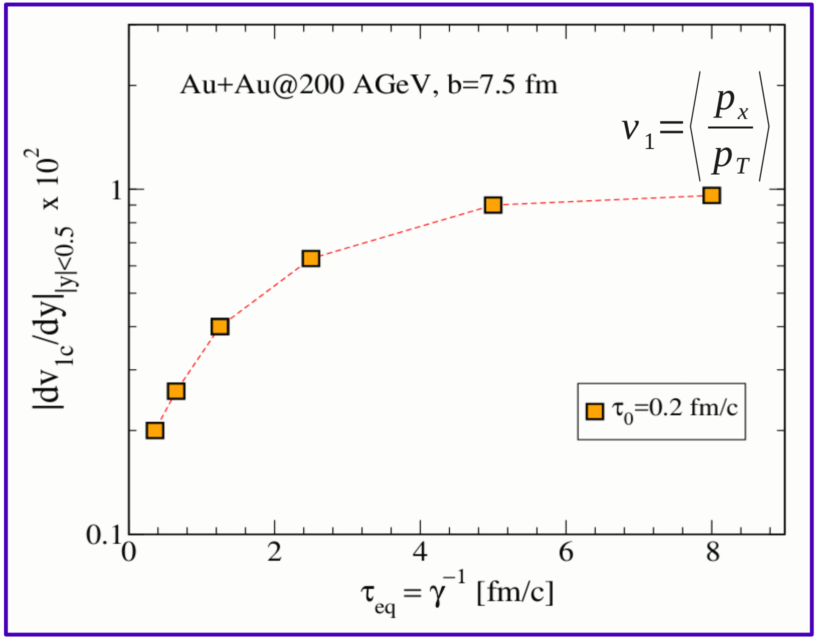
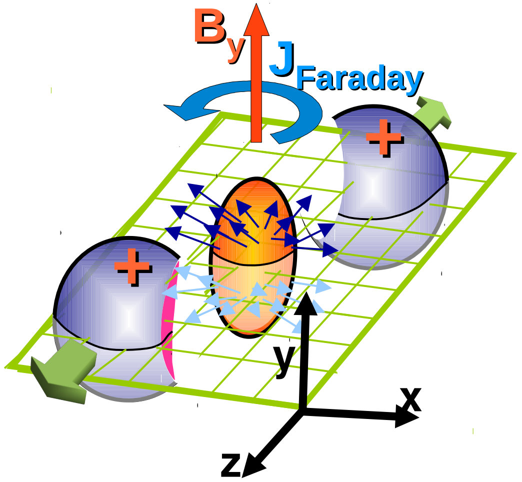


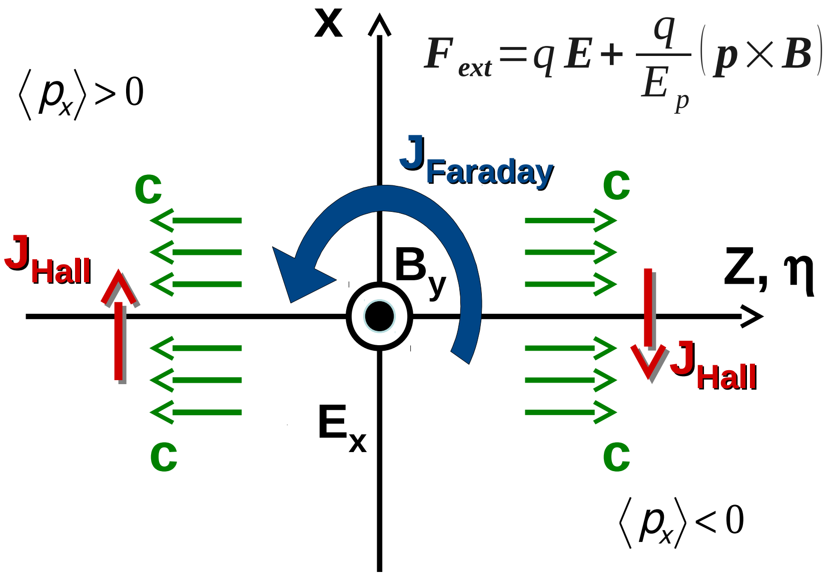
For light quarks was predicted $v_1 \approx 10^{-3}$ -10^{-4}

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

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

S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB**768** (2017) 260-264.

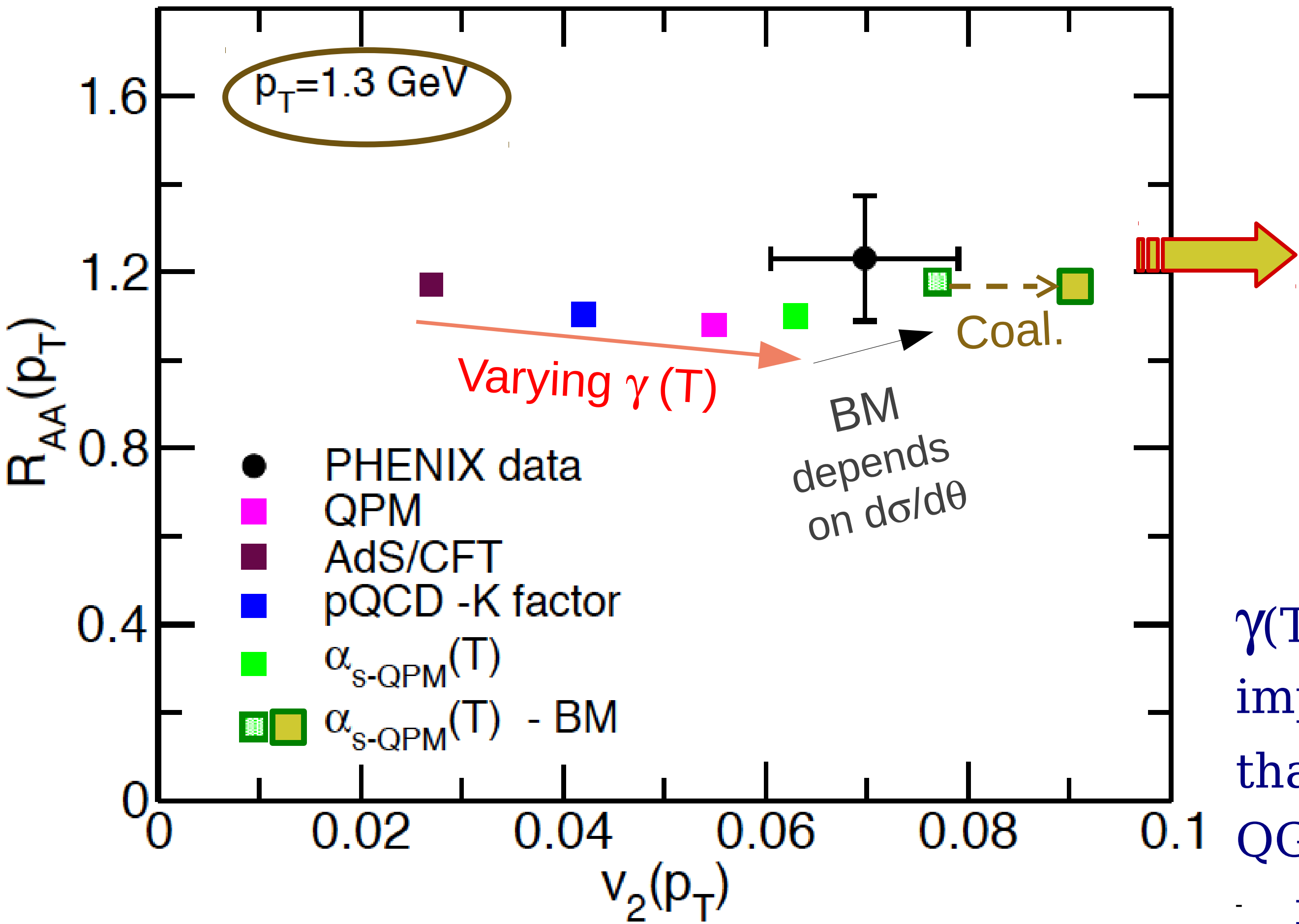




Conclusions

- 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%
- <u>Event-by-event transport approach</u>: new observables
  - Further constraints for transport coefficients from $v_2(p_T)$ and $v_3(p_T)$
  - Strong correlation between v_2(light) and v_2(heavy)
  - weaker correlation between v_3(light) and v_3(heavy)
- Electromagnetic field impact: heavy quarks larger w.r.t. light quarks consequence of early formation time ($\tau_0 \approx$ 0.1 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 v2 at ≈ fixed RAA



Drag

γ(T) ≈ cost

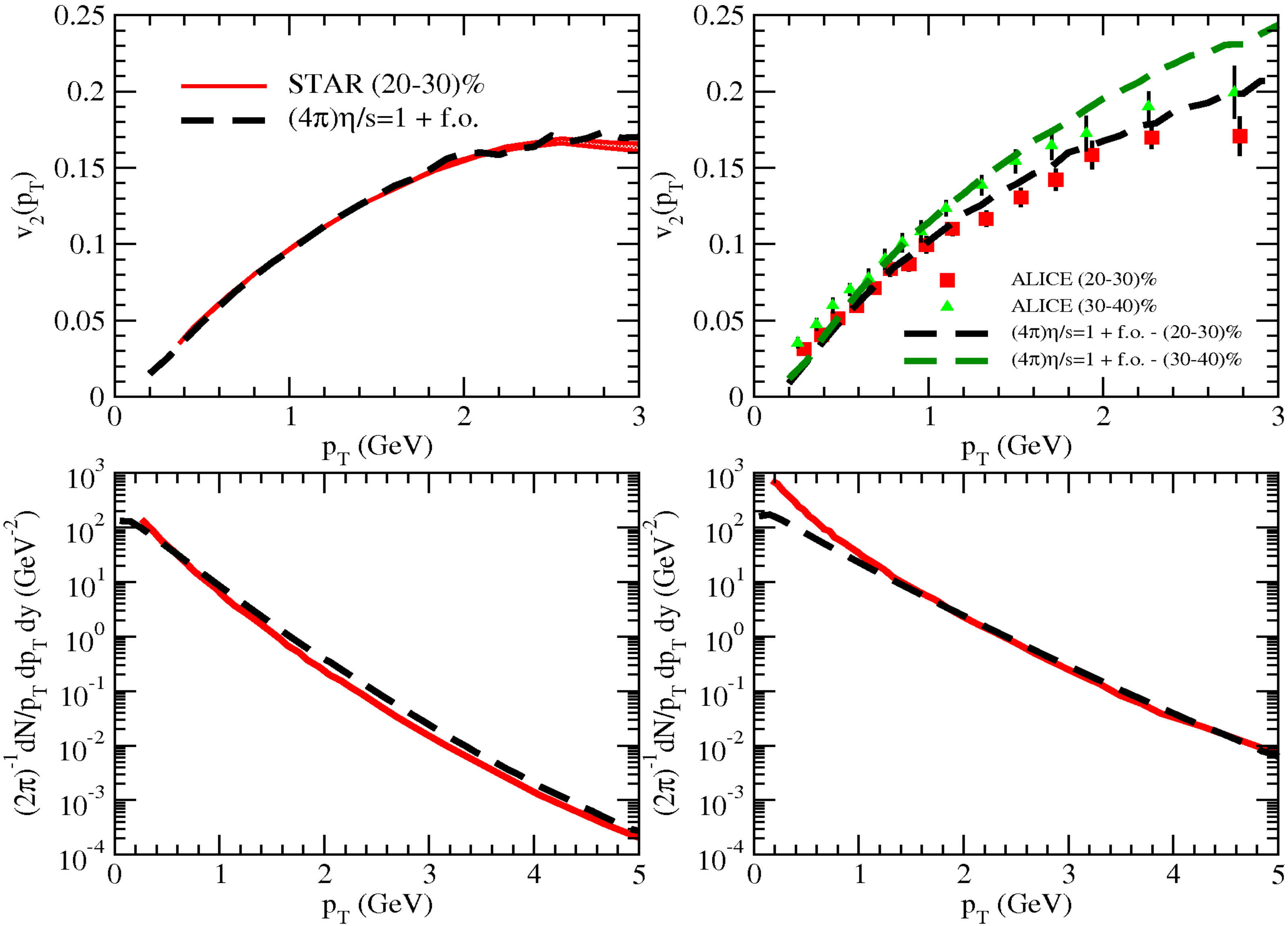
Space- diffusion

Ds≈ T

γ(T) for HQ more impact than η/s(T) for bulk QGP.:

- factor 2.5 vs 20%

$\tau_c \approx \tau_{QGP} >> \tau_{q,g}$



STAR (20-30)%
(4π)η/s=1 + f.o.
ALICE (20-30)%
ALICE (30-40)%
(4π)η/s=1 + f.o. - (20-30)%
(4π)η/s=1 + f.o. - (30-40)%
v2(pT)
pT (GeV)
(2π)-1dN/pT dpT dy (GeV-2)