Transport properties from Charm to Bottom: p_T suppression, anisotropic flow v_n and their correlations to the bulk dynamics

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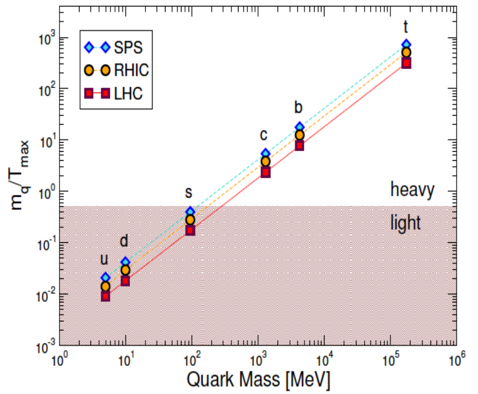
IN COLLABORATION WITH:
V. Minissale, G. Coci, L. Oliva,
S. K. Das, F. Scardina, V. Greco

Outline

- **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 Diffusion coefficient**
- **Initial state fluctuations within transport approach:**
  - **$v_n(p_T)$ of D mesons**
  - **v_n(heavy)-v_n(light) correlations**
- **Impact of initial ElectroMagnetic field and vorticity on Heavy quarks dynamics:**
  - **sizeable v_1 for charm quarks (anti-charms)**
- **Conclusions**

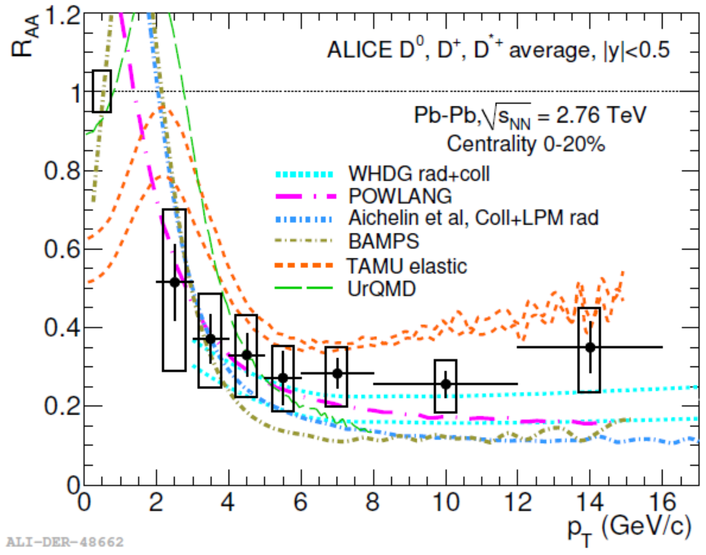
Specific of Heavy Quarks

- $m_{c,b} >> \Lambda_{QCD}$ 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))

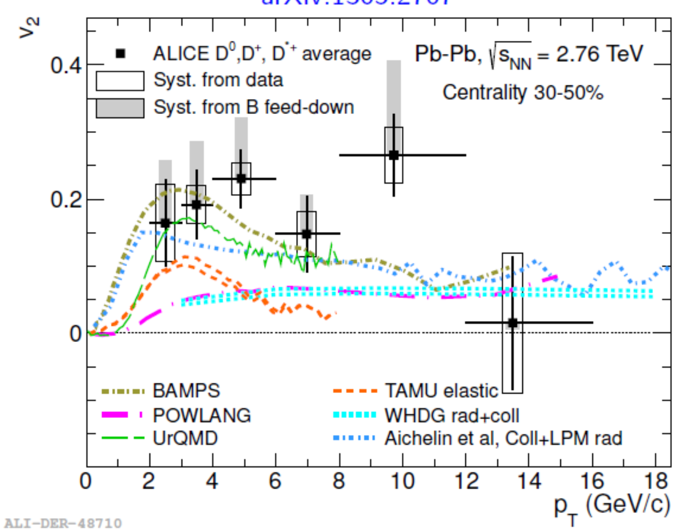


Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

JHEP **1209** (2012) 112



arXiv:1305.2707



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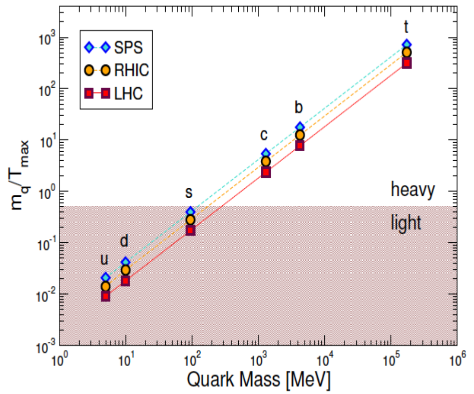
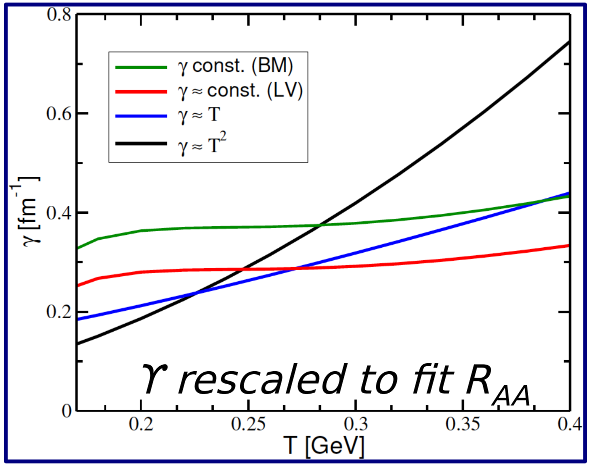
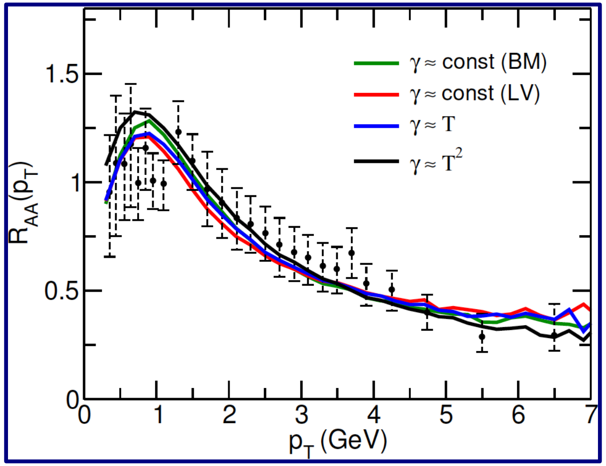
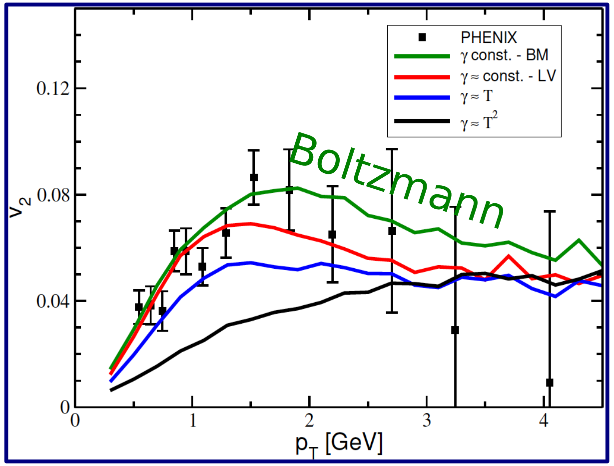


Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

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







Relativistic Boltzmann transport at finite η/s

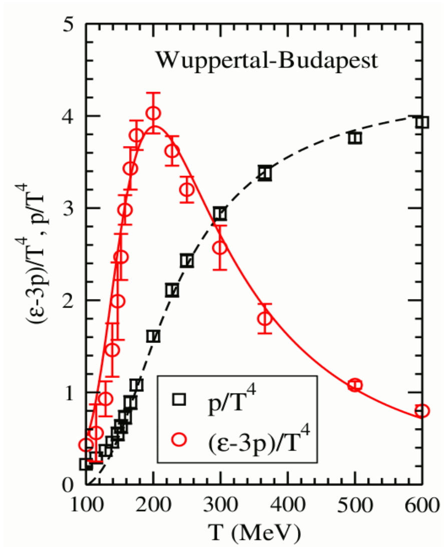
$$\underbrace{p^\mu \partial_\mu f(x,p)}_{\text{free-streaming}} + \underbrace{M(x)\partial_\mu^x M(x)\partial_p^\mu f(x,p)}_{\substack{\text{field interaction}\\ \varepsilon-3p\neq 0}} = \underbrace{C_{22}[f]}_{\substack{\text{collisions}\\ \eta\neq 0}}$$

- **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**

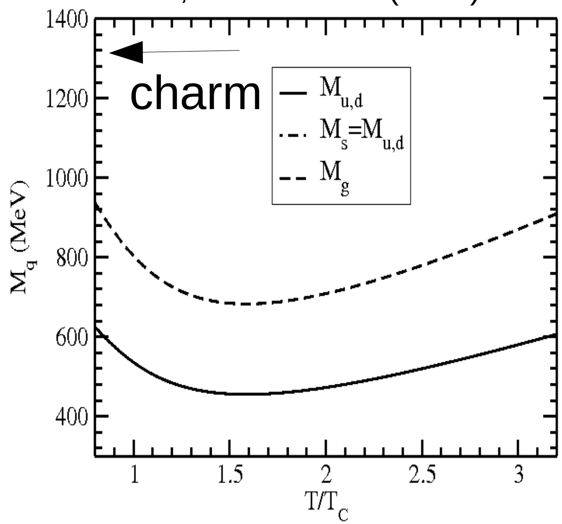
$$C_{22} = \int d^3k [\omega(p+k,k) f(p+k) - \omega(p,k) f(p)] \qquad \omega(p,k) = \int \frac{d^3q}{(2\pi)^3} f'(q) v_{rel} \sigma_{p,q\to p-k,q+k}$$

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

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.



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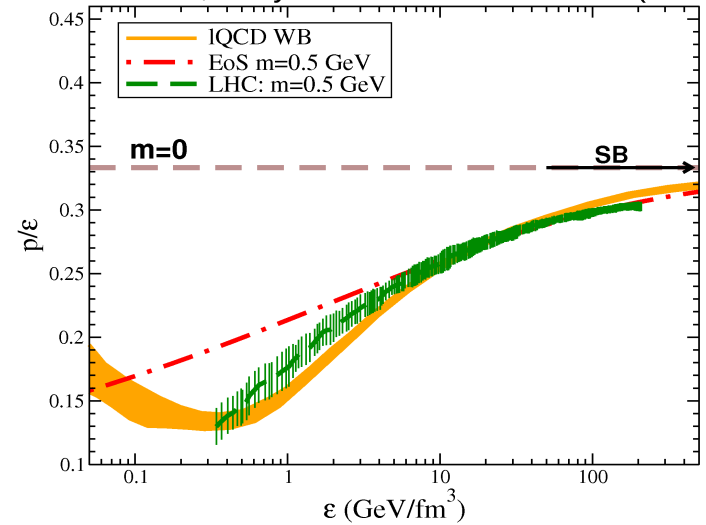
S. Plumari et al.,J.Phys.Conf.Ser. 981 012017 (2018).



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$$p^{\mu}\partial_{\mu} f(x,p) + M(x)\partial^{x}_{\mu} M(x)\partial^{\mu}_{p} f(x,p) = C_{22}[f]$$

free-streaming — **field interaction** $\epsilon - 3p \neq 0$ — **collisions** $\eta \neq 0$

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Hadronization by coalescence plus fragmentation

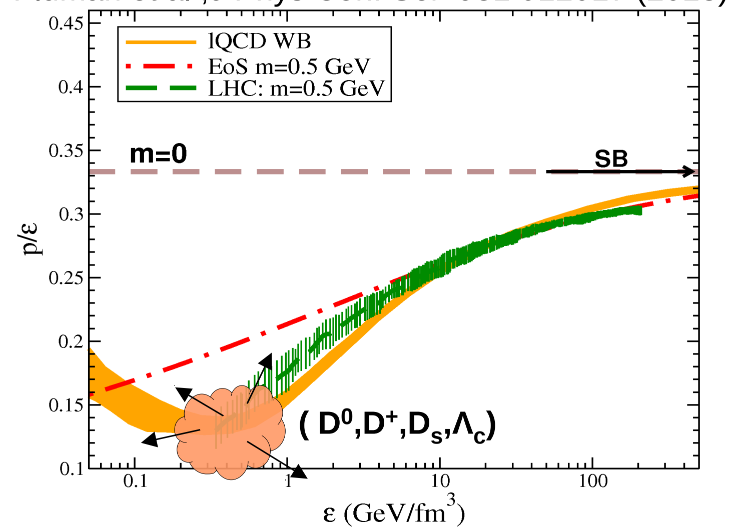
S. Plumari, V. Minissale, S.K. Das, G. Coci, V. Greco, EPJ **C78** (2018) no.4, 348

$$\begin{cases} \dfrac{dN_{Hadron}}{d^2p_T} = g_H \displaystyle\int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3p_i}{(2\pi)^3}\; f_q(x_i,p_i)\; f_W(x_1,\dots,x_n;p_1,\dots,p_n)\; \delta\left(p_T - \textstyle\sum_i p_{iT}\right) \\ \dfrac{dN_h}{d^2p_h} = \sum_f \displaystyle\int dz \frac{dN_f}{d^2p_f} D_{f\to h}(z) \end{cases}$$

Good description of spectra D^0, D^+, D_s.

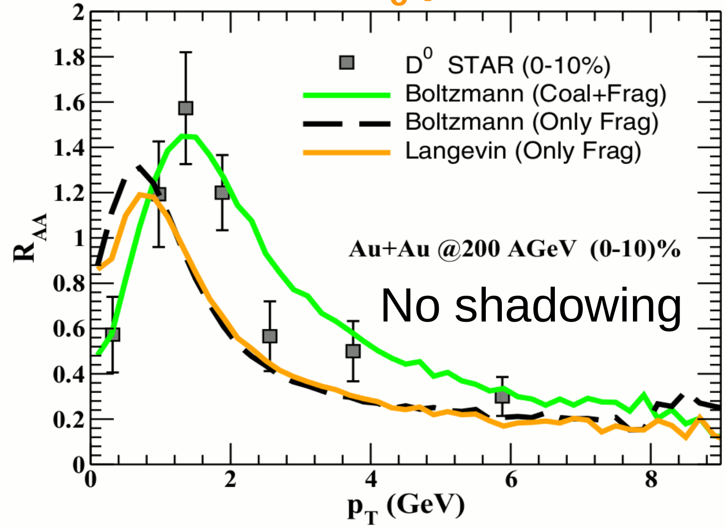
(see poster by V. Minissale THD13)

S. Plumari et al.,J.Phys.Conf.Ser. 981 012017 (2018).

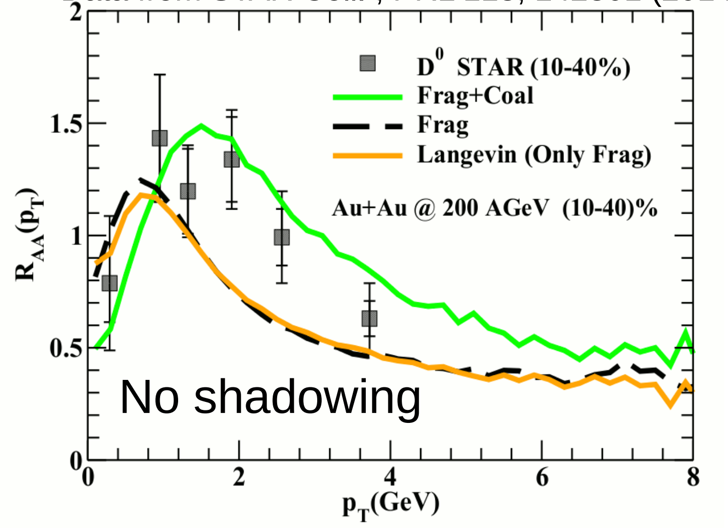


RHIC results: R_{AA} - v_2

Without Λ_c production

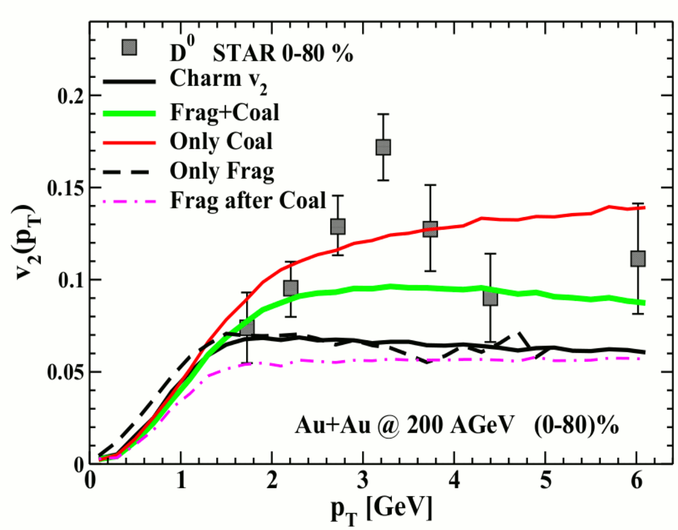


Data from STAR Coll. , PRL 113, 142301 (2014)



- 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.

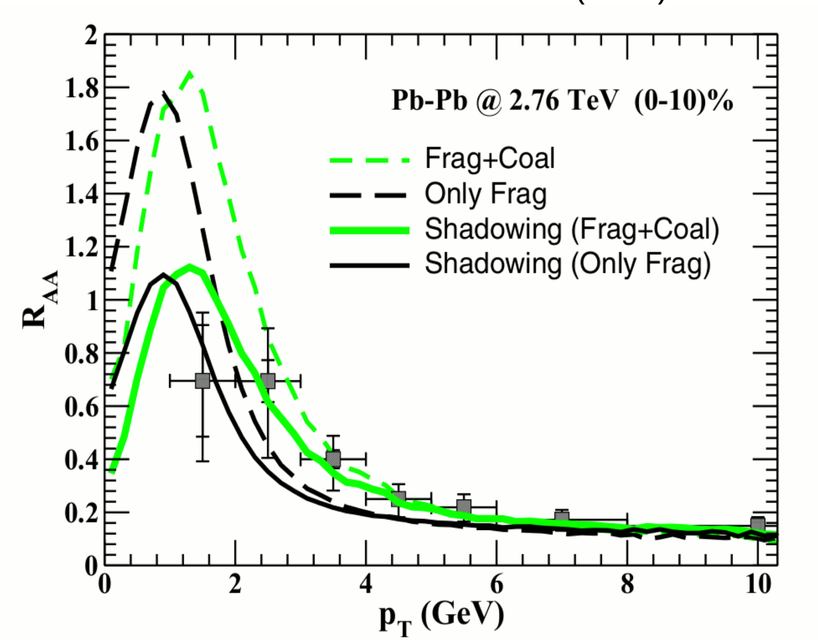
Data from STAR Coll. PRL 118, 212301 (2017)

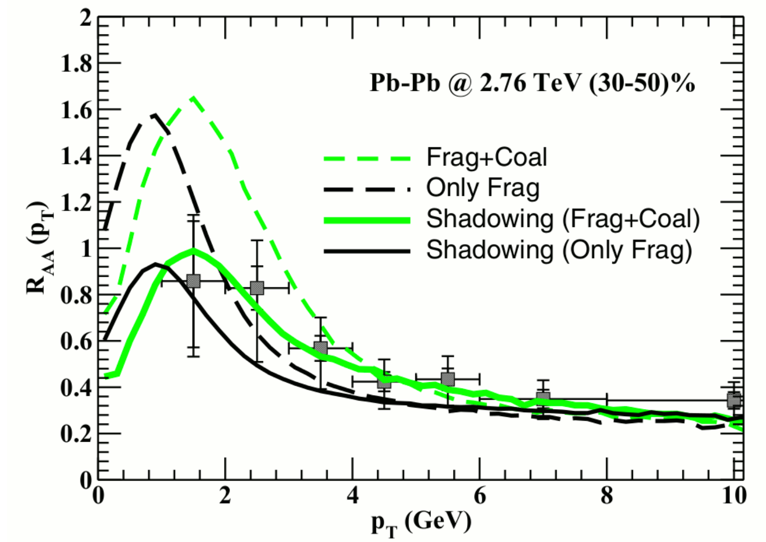


F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PR**C96** (2017) no.4, 044905.

LHC results: R_{AA} - v_2

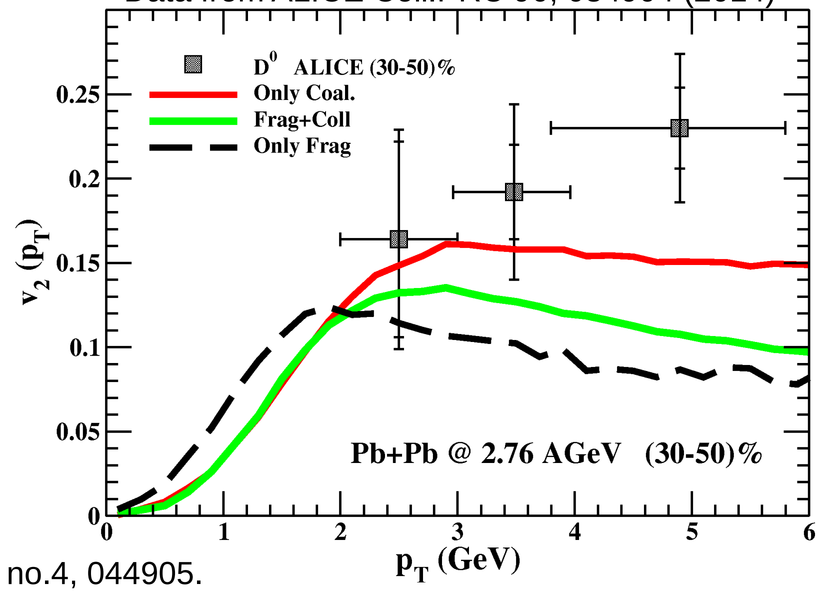
Data from ALICE Coll. JHEP 03 (2016) 081





- 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 $v_2(p_T)$.

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

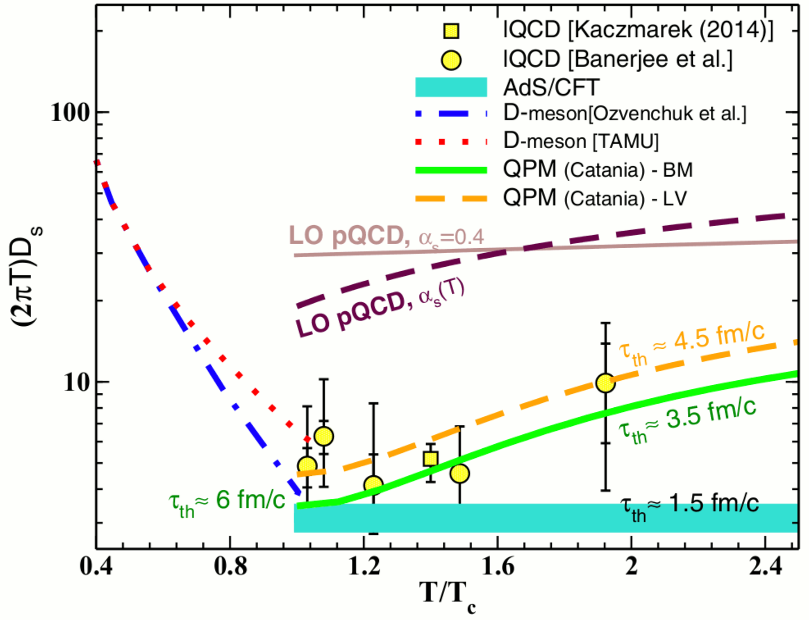


F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PR**C96** (2017) no.4, 044905.

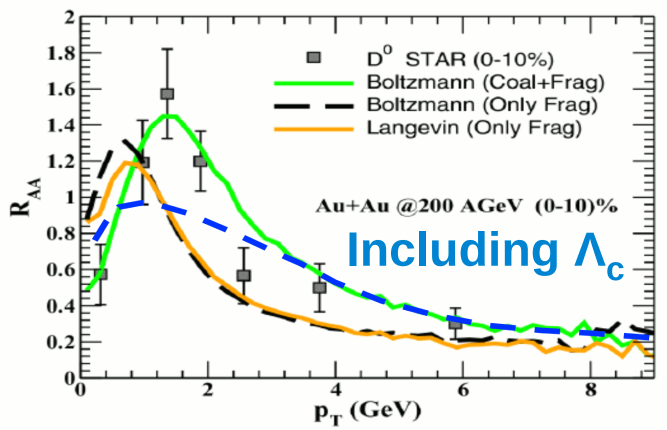
Comparison to lQCD Diff. coef.

F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PR**C96** (2017) no.4, 044905.

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



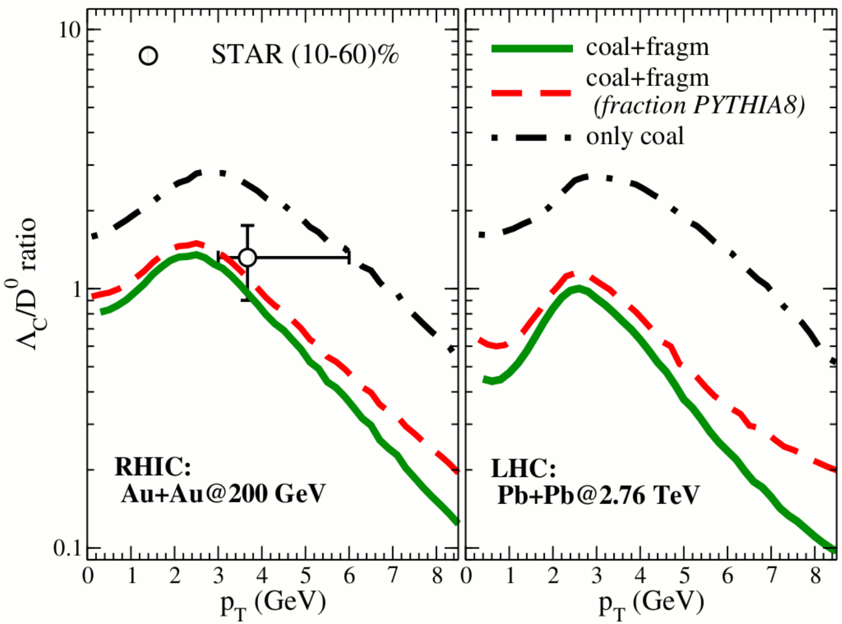
Data from STAR Coll. , PRL 113, 142301 (2014)



With the same coalescence plus fragmentation model we describe the Λ_c/D^0

S. Plumari, V. Minissale, S.K. Das, G. Coci, V. Greco, EPJ **C78** (2018) no.4, 348

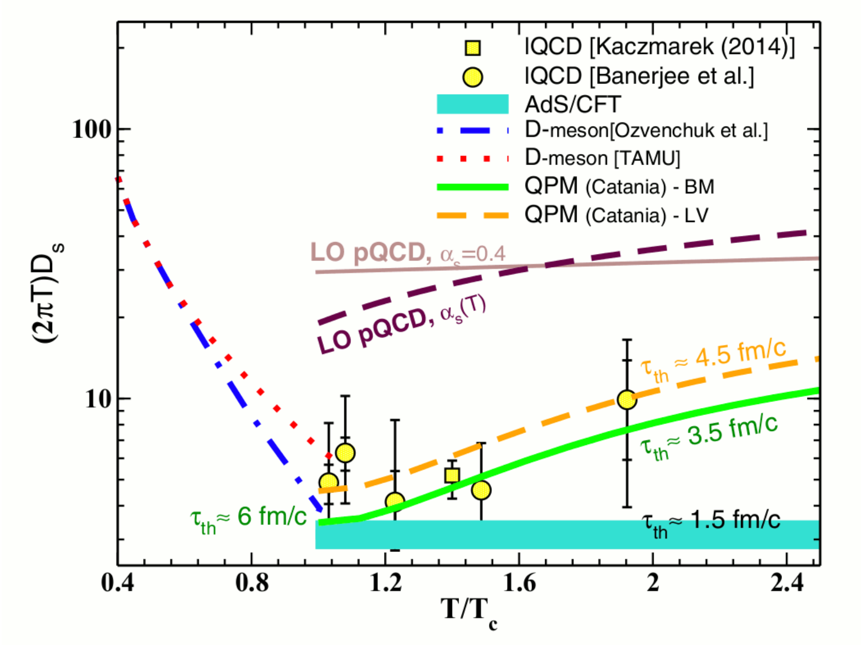
(for details see poster by V. Minissale THD13)

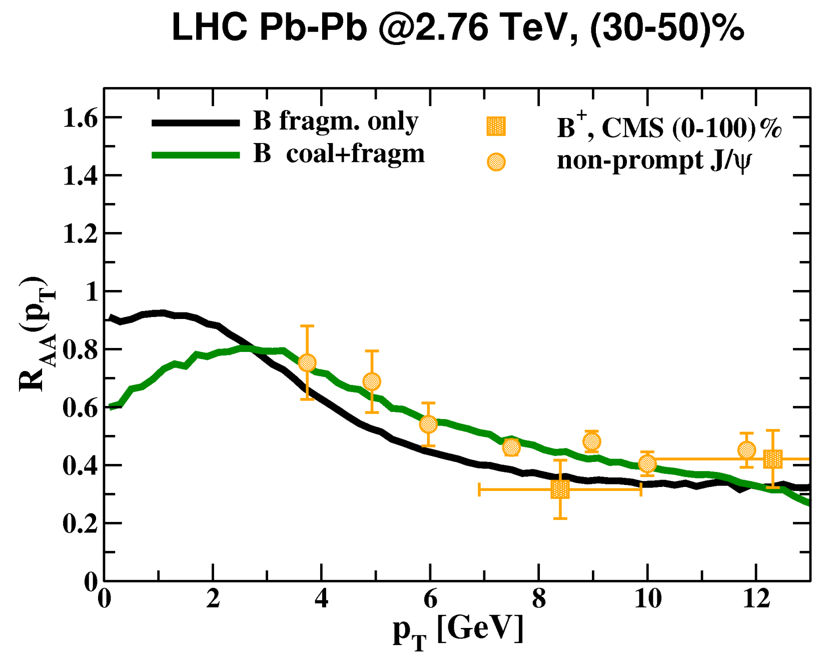


Data taken from STAR coll. Nucl.Phys. **A967** (2017) 620

Comparison to lQCD Diff. coef.

F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PR**C96** (2017) no.4, 044905.





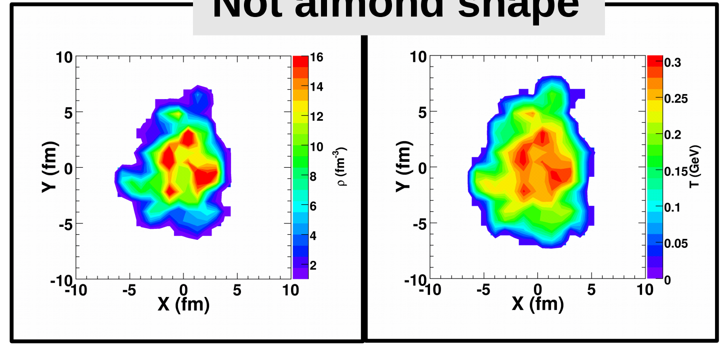
Extended to study B quarks *(preliminary)*:
Within current uncertainties B and D can be explained with the same underlying model which imply also a very similar D_S

Data taken from CMS Coll. T.W. Wang, Nucl.Part.Phys.Proc. 289-290 (2017) 229.
X. Dong, Nucl.Phys. A967 (2017) 192.

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

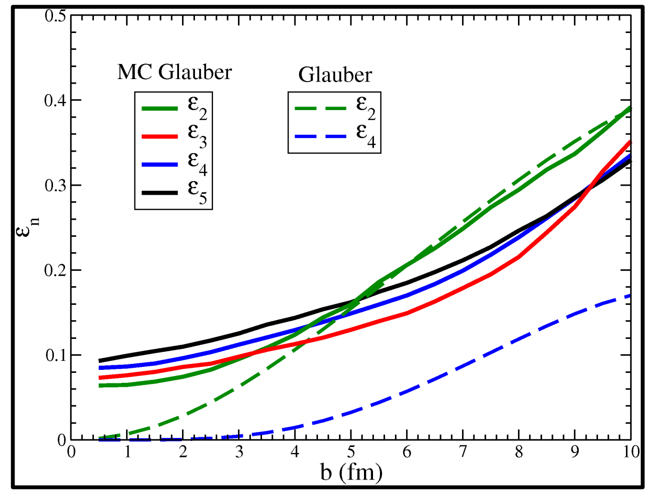
Not almond shape



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., Phys.Rev. C96 (2017) no.6, 064903.
A. Beraudo, A. De Pace, M. Monteno, M. Nardi, F. Prino, JHEP 1802 (2018) 043.



We implement Monte Carlo Glauber initial conditions

Characterization of the initial profile in terms of Fourier coefficients
G-Y. Qin, H. Petersen, S.A. Bass, B. Muller, PRC82,064903 (2010).
H.Holopainen, H. Niemi, K.J. Eskola, PRC83, 034901 (2011).

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

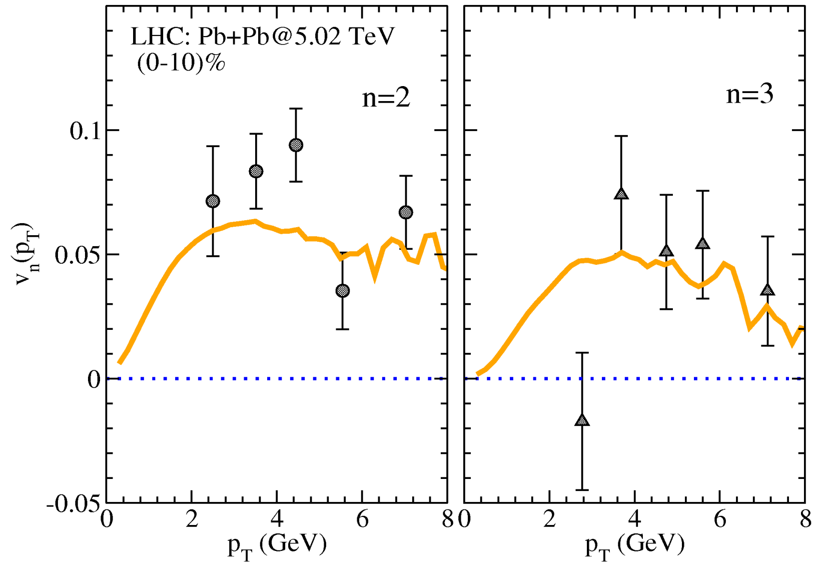
$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

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

Heavy Flavour dynamics: event-by-event transport approach

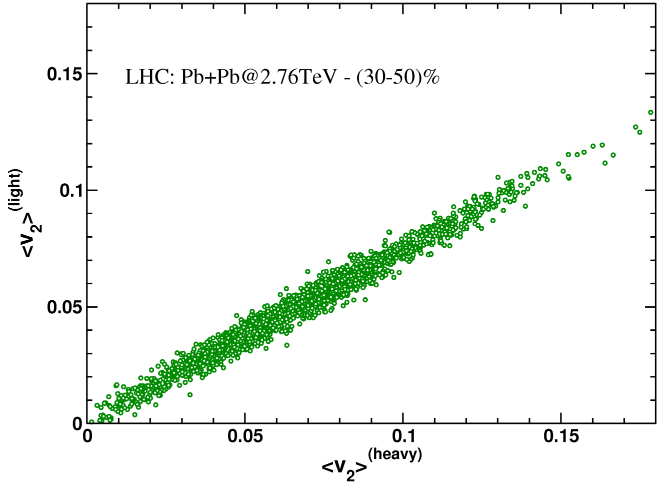
Data taken from CMS coll. arXiv: 1708.03497 [nucl-ex]
CMS-HIN-16-007, CERN-EP-2017-174

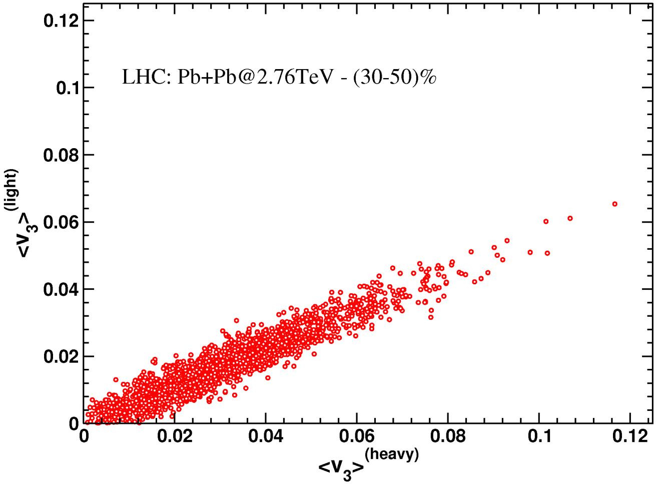
- Initial state fluctuations improve the description of $v_2(p_T)$ in more central collisions
- $v_3(p_T)$ same magnitude of exp. data



CORRELATIONS:

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



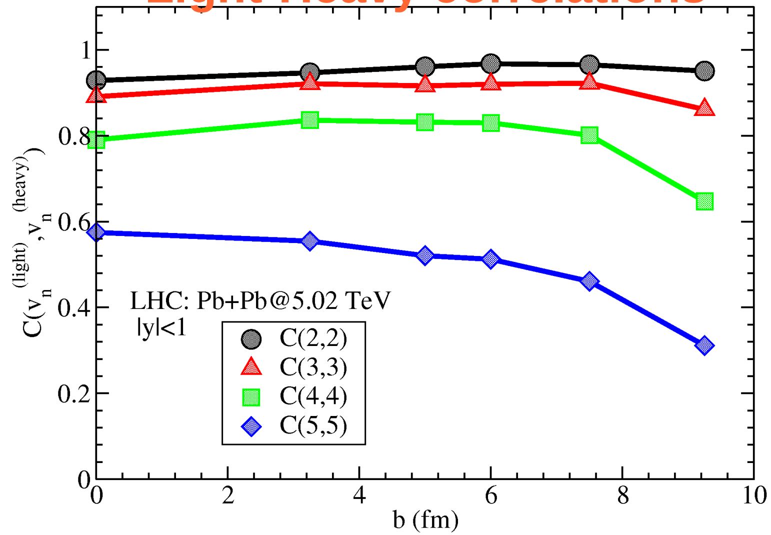


Heavy Flavour dynamics: event-by-event transport approach

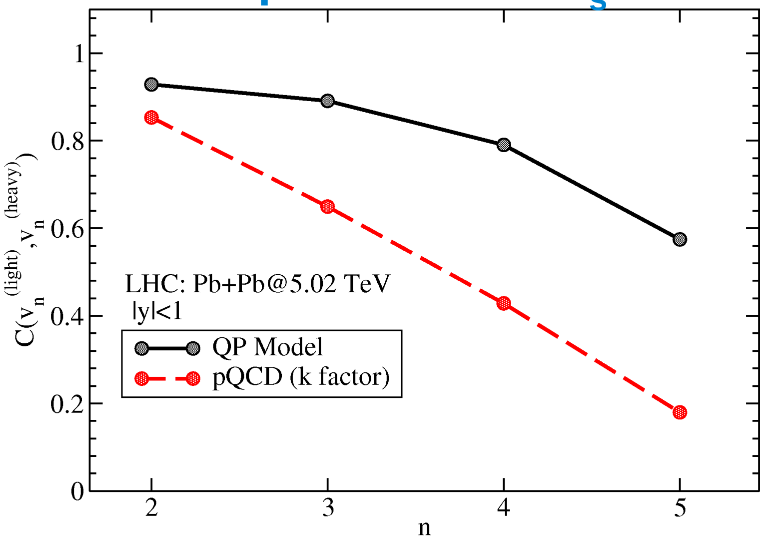
$$C\left(v_n^{light}, v_m^{heavy}\right) = \left\langle \frac{\left(v_n^{light} - \langle v_n^{light}\rangle\right)\left(v_m^{heavy} - \langle v_m^{heavy}\rangle\right)}{\sigma_{v_n^{light}}\,\sigma_{v_m^{heavy}}} \right\rangle$$

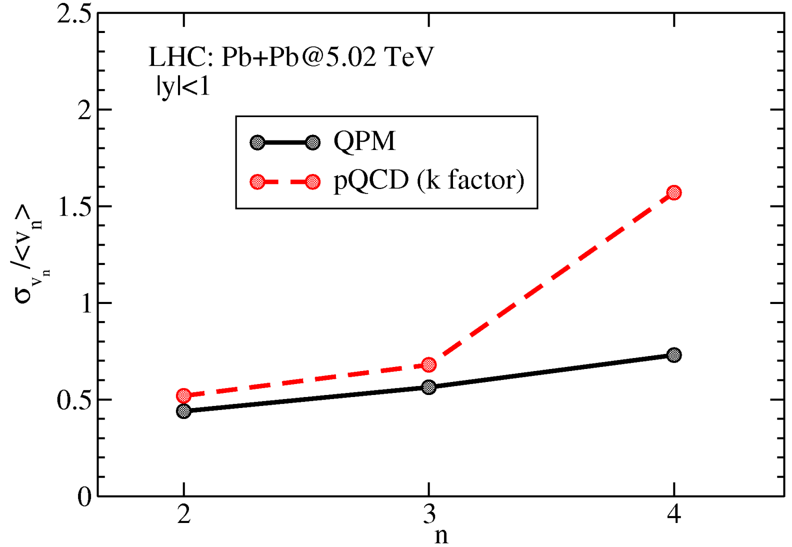
- v_2 and v_3 of light flavor linearly correlated to the corresponding v_2 and v_3 of heavy flavor with C~0.95
- We observe not strong dependence with b
- v_4 and v_5 weakly correlated

Light-Heavy correlations



Impact of T dependence of D_s on correlation



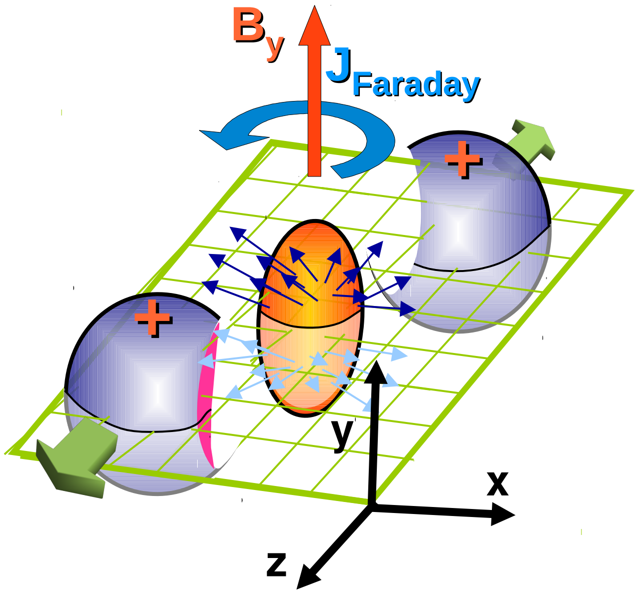


Going to Magnetic vortical HQ dynamics

- **Intense magnetic field B:**

  created on Earth ≈ 10^7 Gauss
  in Neutron Star ≈ 10^{13} Gauss
  in uRHIC ≈ 10^{19} Gauss ≈ 10 m_π^2

  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.



- ***Are HQ affected by the initial EM field produced in a HIC?*** *(see poster by G. Coci)*

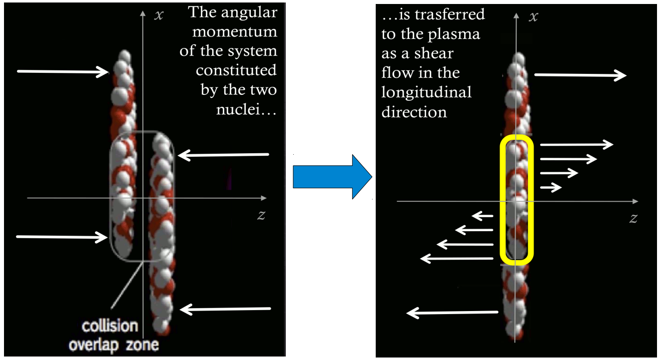
  Solving the relativistic Langevin eq. With Lorentz force a sizeable v_1 for charm (anti-charm) quarks is produced

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

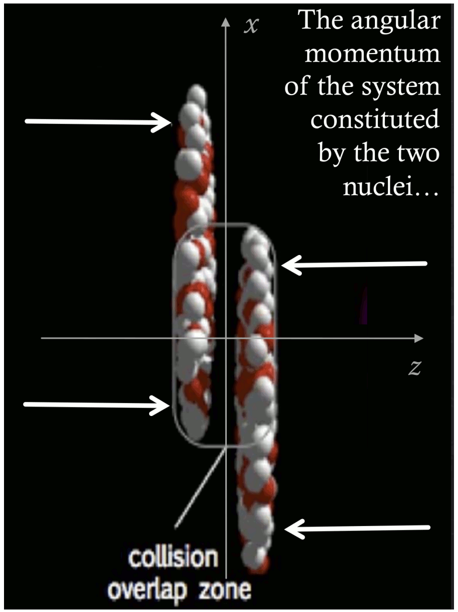
- **Vorticity due to the large orbital angular momentum in uRHIC J ≈ 10^5 - 10^7 ħ**

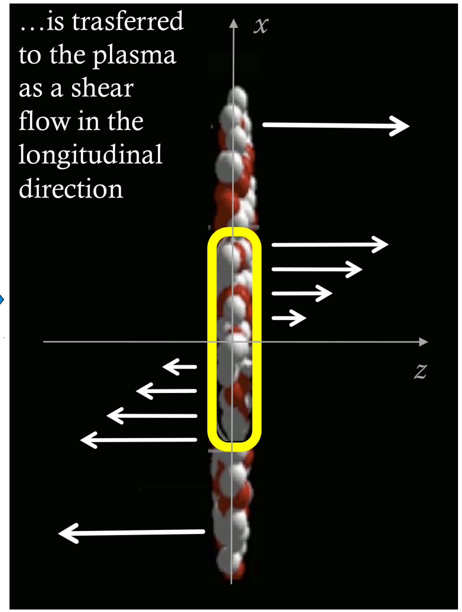
  Becattini, Piccinini e Rizzo, PRC 77, 024906 (2008)
  Csernai, Magas and Wang - Phys. Rev. C 87 (2013) 034906
  Becattini et al, EPJ C 75, 406 (2015)
  Deng and Huang, PRC 93, 064907 (2016)
  Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

- ***Are HQ affected by the initial vorticity of the QGP?***

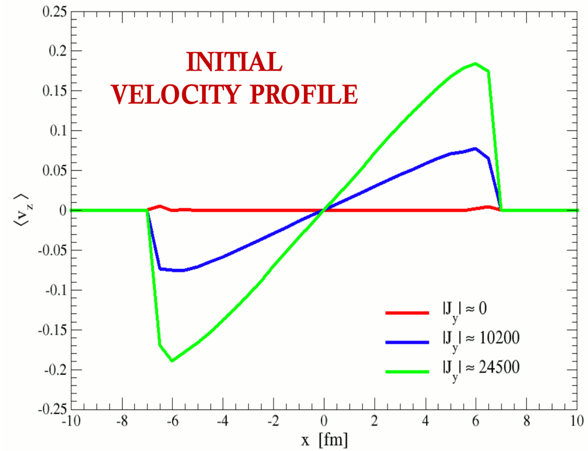


Vorticity in Heavy Ion Collisions

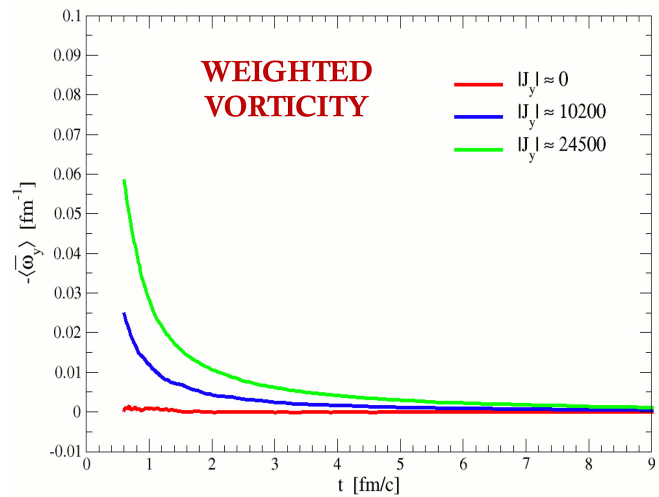




Velocity profile similar to Deng and Huang, PRC93, 064907 (2016)



Vorticity field decreases during temporal evolution in agreement with Jiang, Lin, Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)



Becattini, Piccinini e Rizzo, PRC 77, 024906 (2008)
Csernai, Magas and Wang - Phys. Rev. C 87 (2013) 034906
Becattini et al, EPJ C 75, 406 (2015)
Deng and Huang, PRC 93, 064907 (2016)
Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

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 $\boldsymbol{\beta}$.

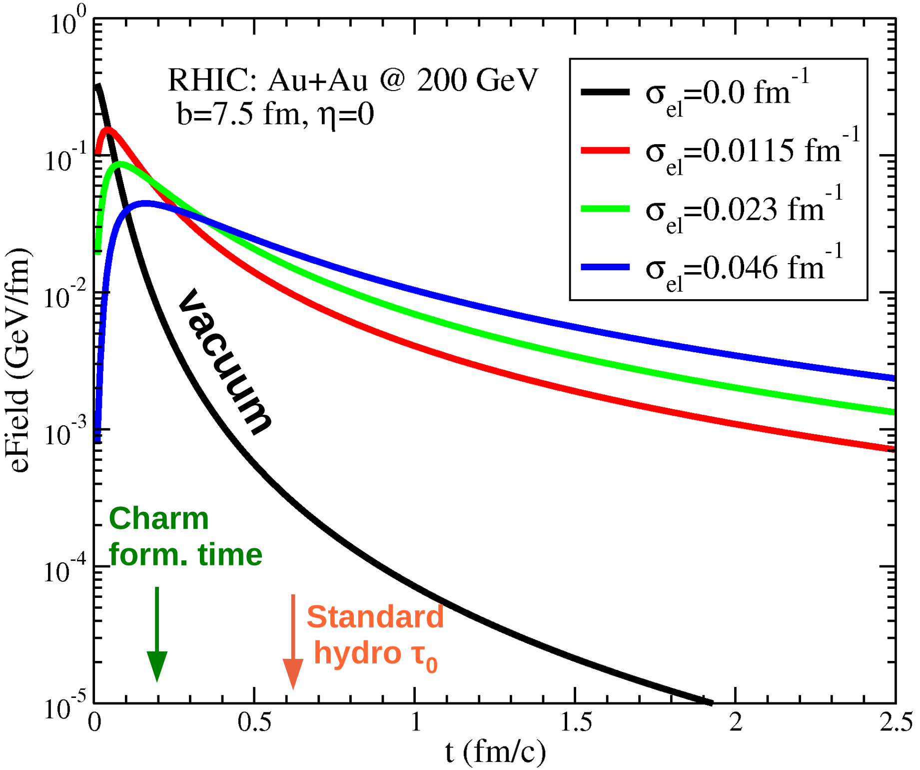
$$\begin{cases} \nabla \cdot \boldsymbol{E} = e\,\delta(z-\beta t)\,\delta(\boldsymbol{x}-\boldsymbol{x}_T) \\ \nabla \cdot \boldsymbol{B} = 0 \qquad \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{B} = \dfrac{\partial \boldsymbol{E}}{\partial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

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

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

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

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

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 (-)

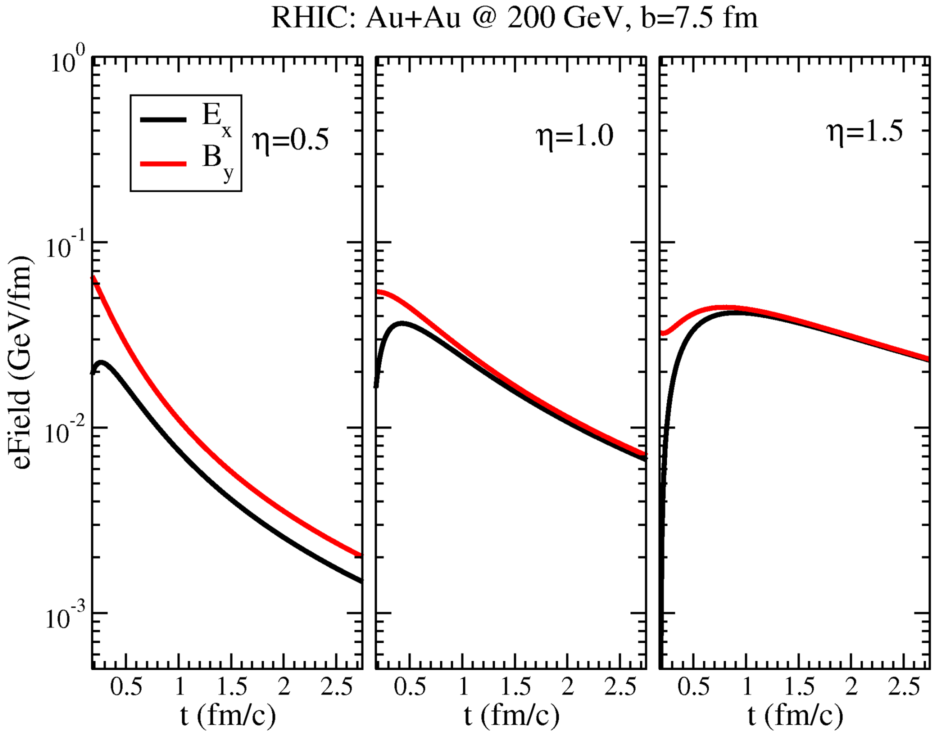
$$\begin{aligned} eB_{y,s} &= -Z\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{\rm in}(\phi')}^{x_{\rm out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \\ &\quad \times \left(eB_y^+(\tau,\eta,x_\perp,\pi-\phi)+eB_y^+(\tau,-\eta,x_\perp,\phi)\right)\,, \\ eE_{x,s} &= Z\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}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

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:

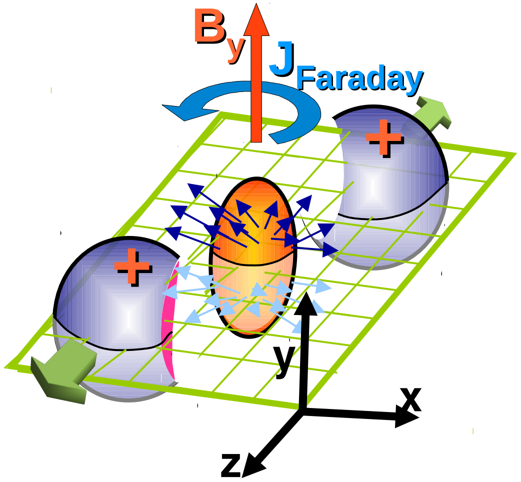
- Electric conductivity σ_{el} const. in time
- Modification in the bulk due to currents is negligible
- No event-by-event fluctuations

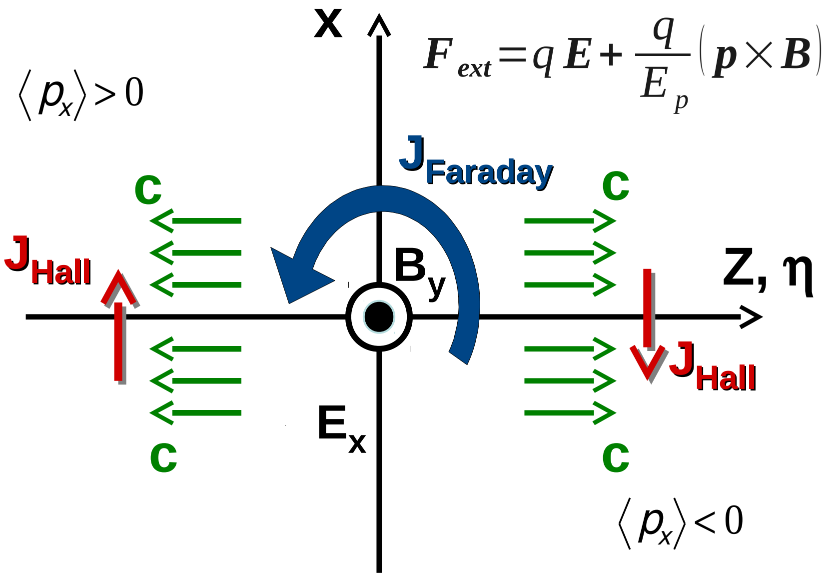
Direct Flow v_1 of charm quarks

- **We solve the relativistic Boltzmann eq coupled with the external EM field.**

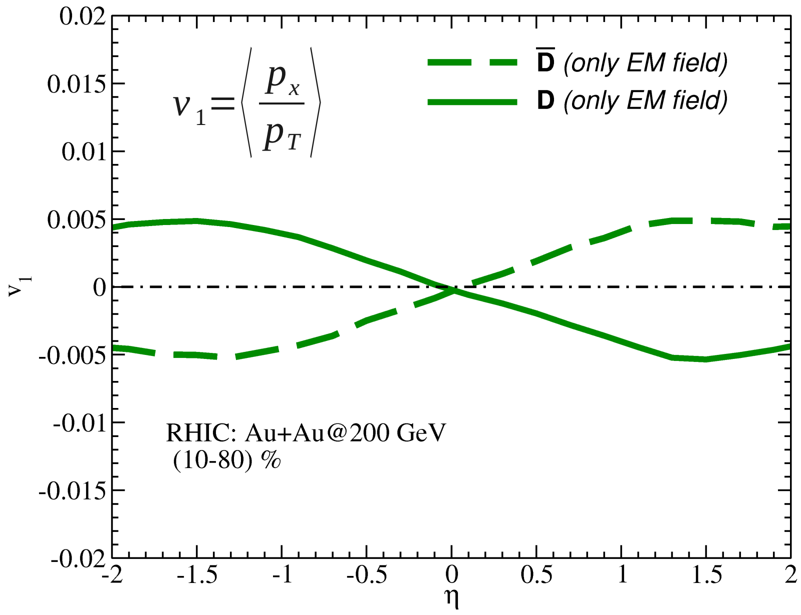
$$p^{\mu}\partial_{\mu}^{x} f(x,p) + F^{\mu\nu}\partial_{\nu}^{p} f(x,p) = C_{22}[f]$$

- **Charm diffusion constrained by experimental data on the $R_{AA}(p_T)$ and v_2 of D meson**





Direct Flow v_1 of charm quarks

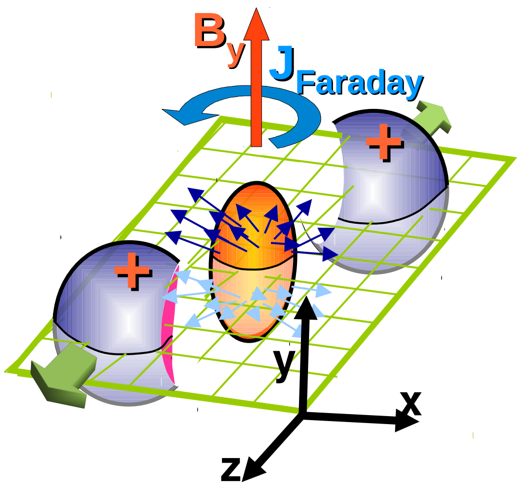


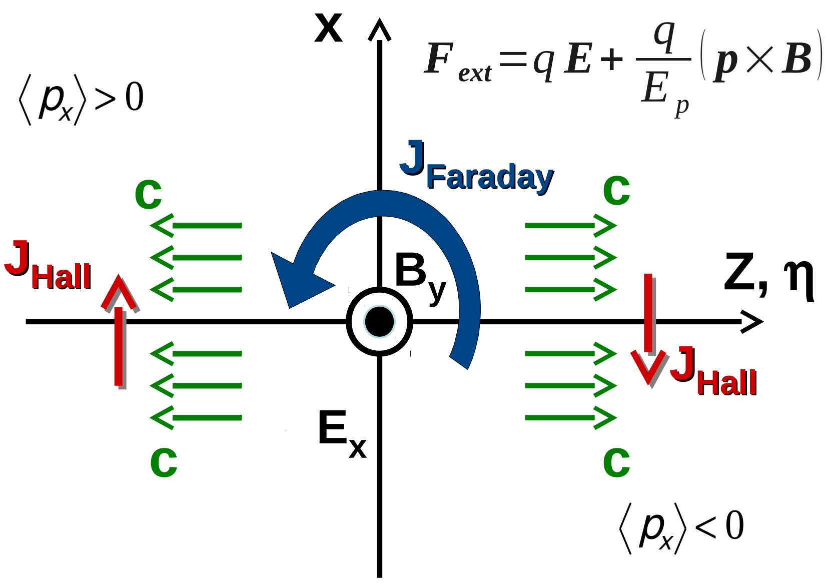
For light quarks was predicted $v_1 \approx 10^{-3}$ -10^{-4}

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

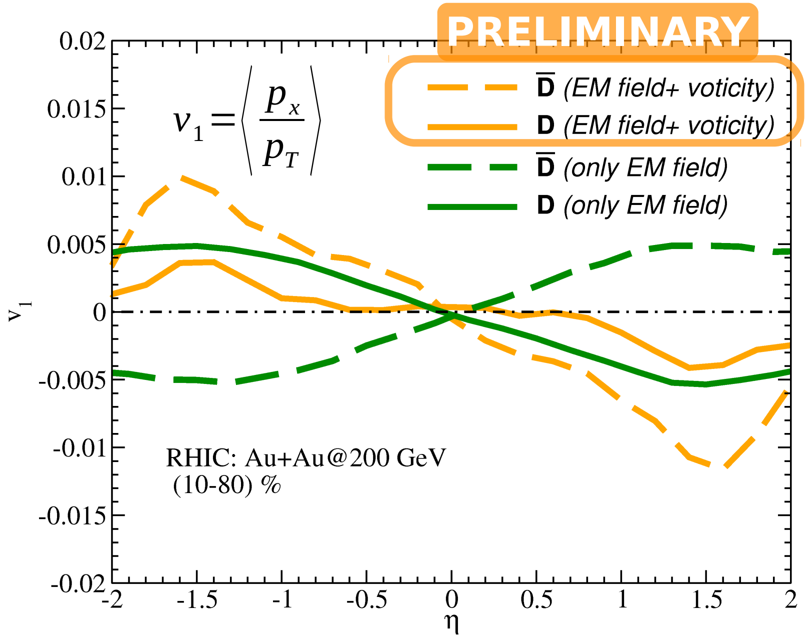
For charm quarks due to early production we find a sizeable v_1 with the same E-B evolution

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





Direct Flow v_1 of charm quarks



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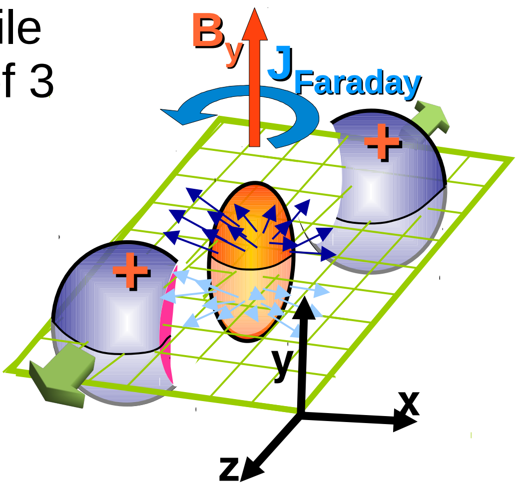
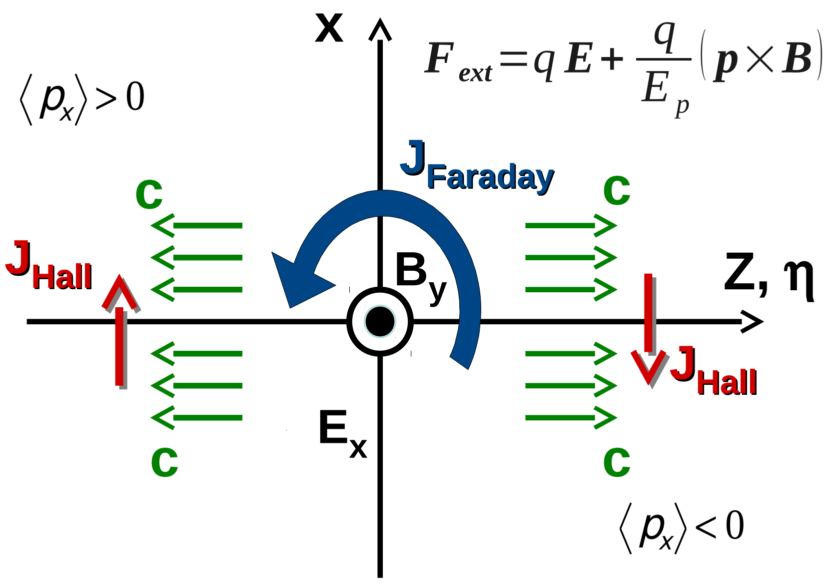
S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB768 (2017) 260-264.

For charm quarks we assume the same vorticity of the bulk
***(for details see poster by G. Coci* OHF07)**

With Becattini's profile we expect a factor of 3 larger v_1





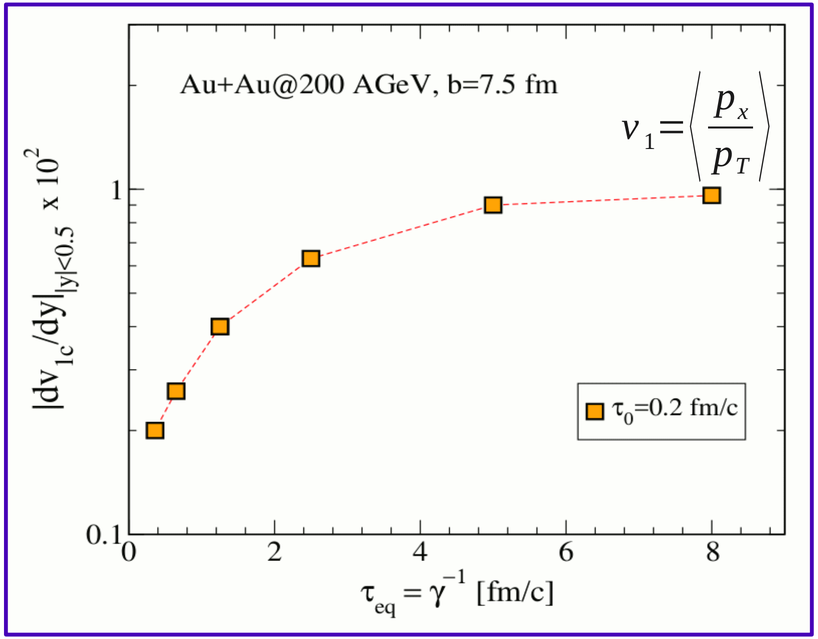
Conclusions

- **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 with $(2\pi T)D_s \sim T$**
  - **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**
  - **Novel 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)**

- **Heavy quarks v1 larger w.r.t. light quarks thanks to 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 <u>initial vorticity</u> and initial E-M field

Direct Flow v_1 of charm quarks



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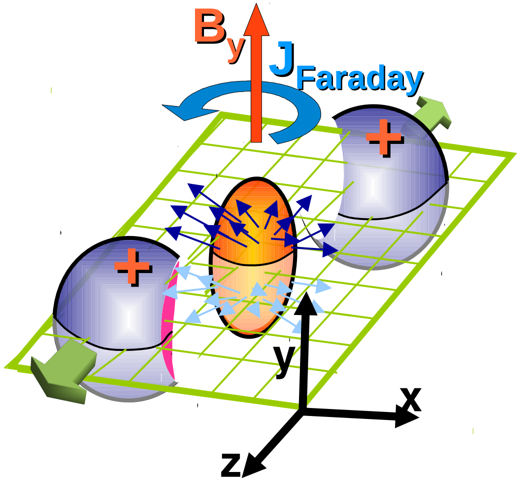
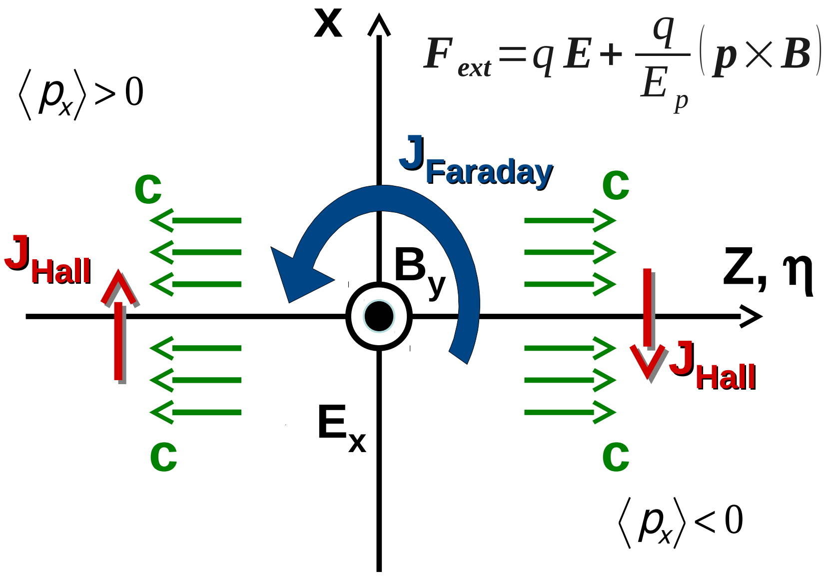
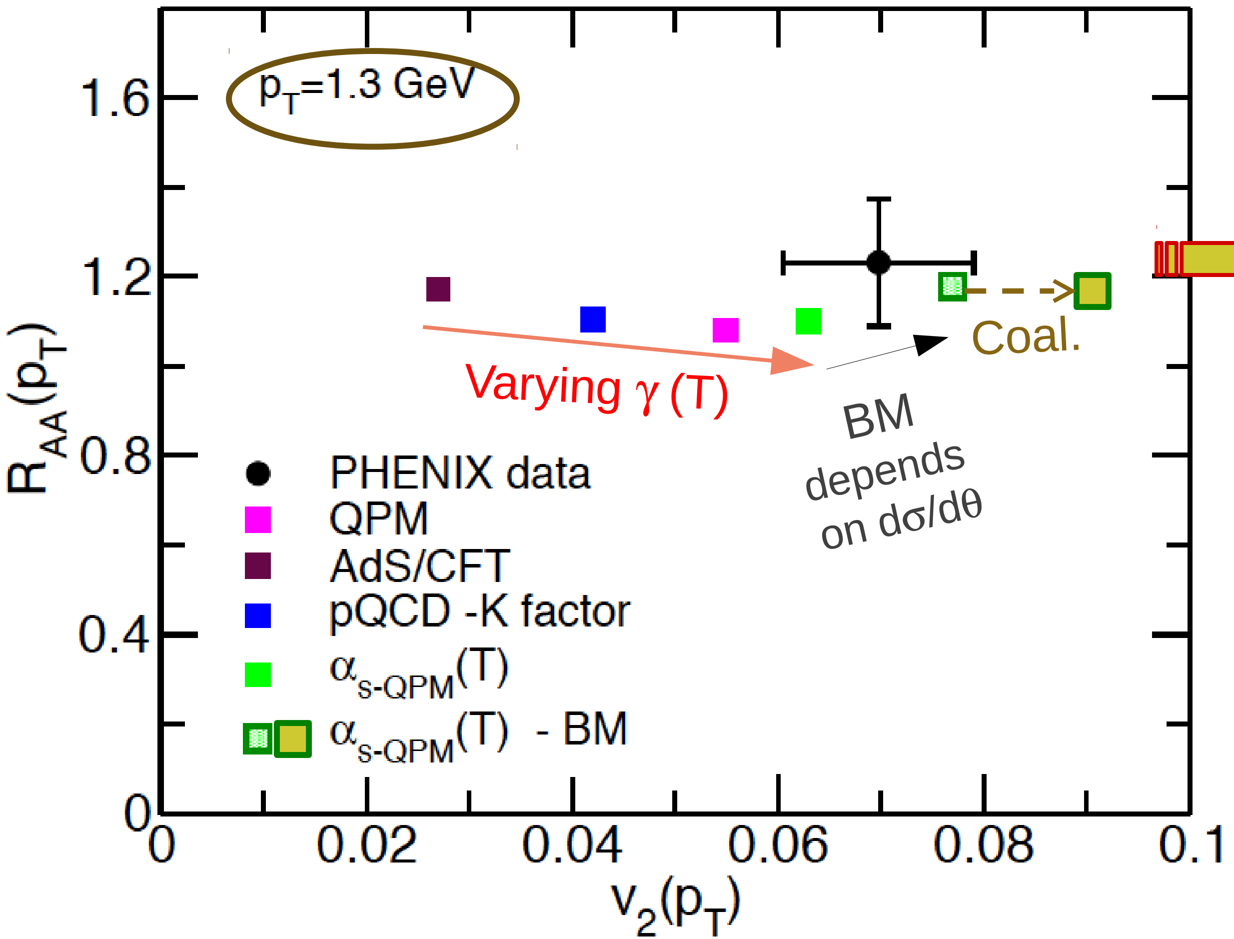




Summary on the build-up of v2 at ≈ fixed RAA



Drag

$\gamma(T) \approx$ cost

Space- diffusion

$D_s \approx T$

$\gamma(T)$ for HQ more impact than $\eta/s(T)$ for bulk QGP.:

- factor 2.5 vs 20%

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

Heavy flavour: Resonance decay

In our calculations we take into account main hadronic channels, including the ground states and the first excited states for D and Λ_c

MESONS

- $\mathbf{D^+}$ *(I=1/2,J=0)*
- $\mathbf{D^0}$ *(I=1/2,J=0)*
- $\mathbf{D_s^+}$ *(I=0,J=0)*

Resonances

- $\mathbf{D^{*+}}$ *(I=1/2,J=1)* → $\mathbf{D^0\,\pi^+}$ *B.R. 68%*
  → $\mathbf{D^+\,X}$ *B.R. 32%*
- $\mathbf{D^{*0}}$ *(I=1/2,J=1)* → $\mathbf{D^0\,\pi^0}$ *B.R. 62%*
  → $\mathbf{D^0\,\gamma}$ *B.R. 38%*
- $\mathbf{D_s^{*+}}$ *(I=0,J=1)* → $\mathbf{D_s^+\,X}$ *B.R. 100%*
- $\mathbf{D_{s0}^{*+}}$ *(I=0,J=0)* → $\mathbf{D_s^+\,X}$ *B.R. 100%*

Statistical factor

$$\frac{\left[(2J+1)(2I+1)\right]_{H*}}{\left[(2J+1)(2I+1)\right]_{H}}\left(\frac{m_{H*}}{m_H}\right)^{3/2} e^{-(E_{H*}-E_H)/T}$$

BARYONS

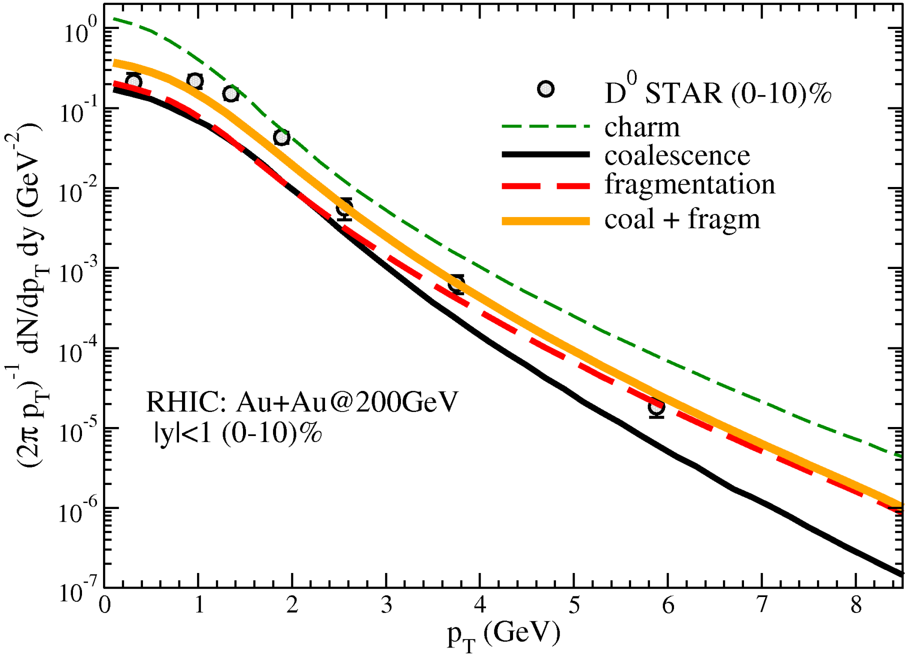
- $\mathbf{\Lambda_c^+}$ *(I=0, J=1/2)*

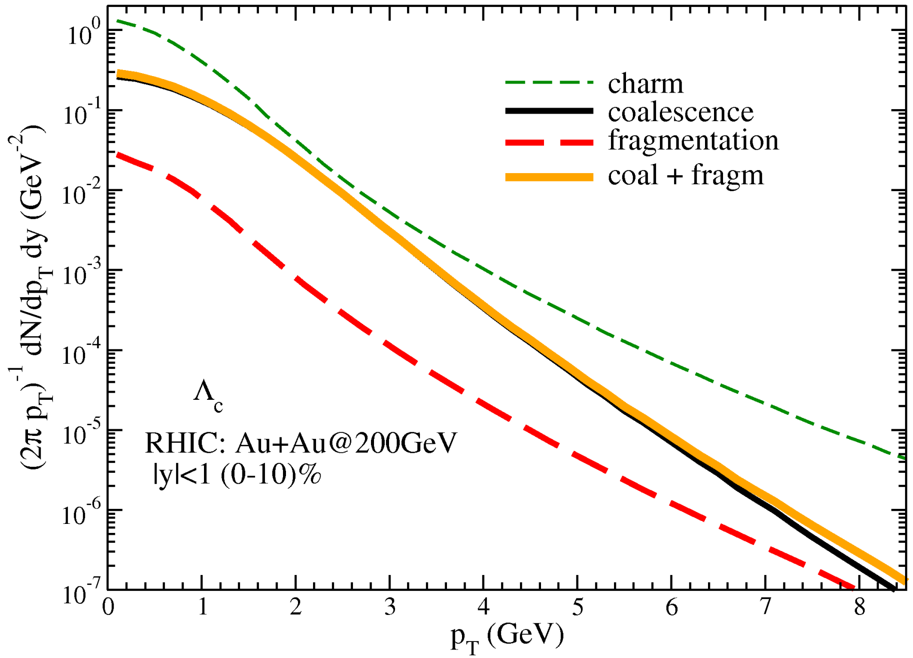
Resonances

- $\mathbf{\Lambda_c^+(2595)}$ *(I=0,J=1/2)* → $\mathbf{\Lambda_c^+}$ *B.R. 100%*
- $\mathbf{\Lambda_c^+(2625)}$ *(I=0,J=3/2)* → $\mathbf{\Lambda_c^+}$ *B.R. 100%*
- $\mathbf{\Sigma_c^+(2455)}$ *(I=1,J=1/2)* → $\mathbf{\Lambda_c^+\pi}$ *B.R. 100%*
- $\mathbf{\Sigma_c^+(2520)}$ *(I=1,J=3/2)* → $\mathbf{\Lambda_c^+\pi}$ *B.R. 100%*

RHIC: results

Data from STAR Coll. PRL **113** (2014) no.14, 142301





RHIC: Baryon/meson

Coalescence

Following: L.W.Chen, C.M. Ko, W. Liu, M. Nielsen, PRC 76, 014906 (2007). K.-J. Sun, L.-W. Chen, PRC 95, 044905 (2017).

For hypersurface of proper time τ and non relativistic limit:

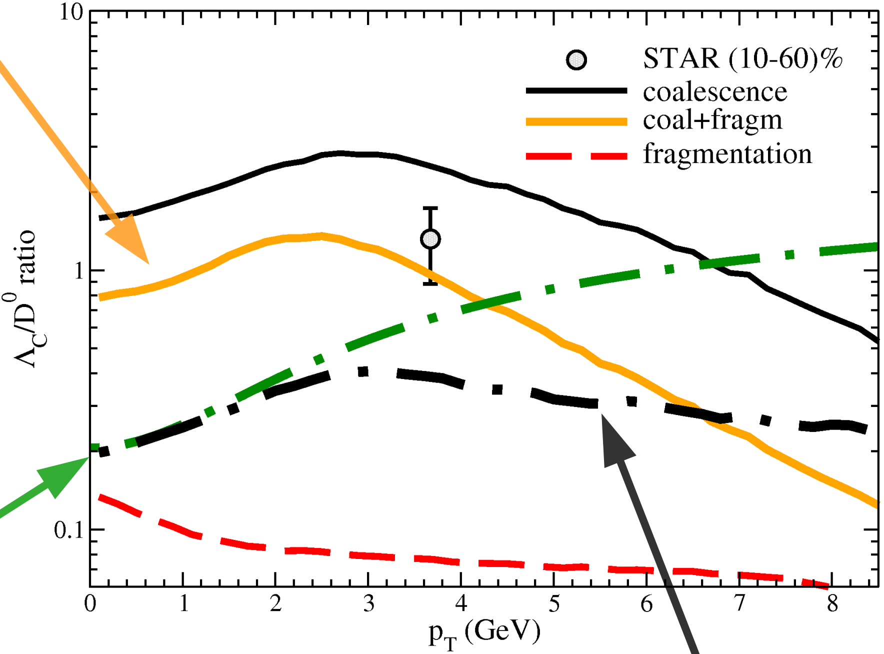
for $p_T << m$

$$\frac{\Lambda_c^+}{D^0} \propto \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right) e^{-(m^\Lambda - m^D)/T_C} \quad \tau\mu_2$$

$$\mu_2 = \frac{m_3(m_1+m_2)}{m_1+m_2+m_3}$$

Is the reduced mass of the baryon

Data from STAR Coll., arXiv:1704.04364 [nucl-ex].



Blast Wave model:

$$\frac{\Lambda_c^+}{D^0} = \frac{g_\Lambda}{g_D}\frac{m_T^\Lambda}{m_T^D}\frac{K_1(m_T^\Lambda/T_C)}{K_1(m_T^D/T_C)}$$

for $p_T << m$

$$\approx \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right)^{1/2} e^{-(m^\Lambda - m^D)/T_C} \approx 0.17$$

Coal+fragm with wave function width σ_p of D^0 and Λ_c changed to have Λ_c/D^0=thermal ratio at $p_T \rightarrow 0$