Transport properties of Heavy Quarks and their correlations to the bulk dynamics and the initial Electromagnetic field

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V. Minissale, G. Coci, L. Oliva, S. K. Das, V. Greco

Outline

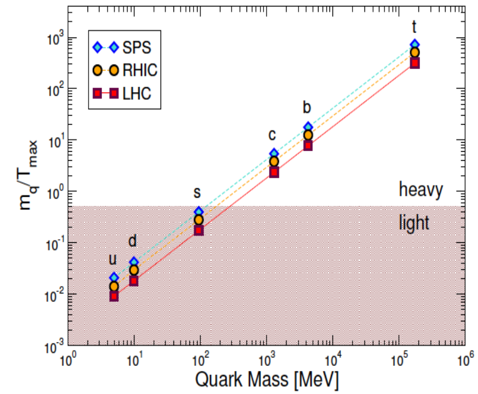
- Heavy quarks dynamics in QGP within transport approach
  - Determination of space Diffusion coefficient
    Boltzmann and Langevin

- New observables: v_n(light)- v_n(heavy) correlations, σ_{vn}/v_n

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

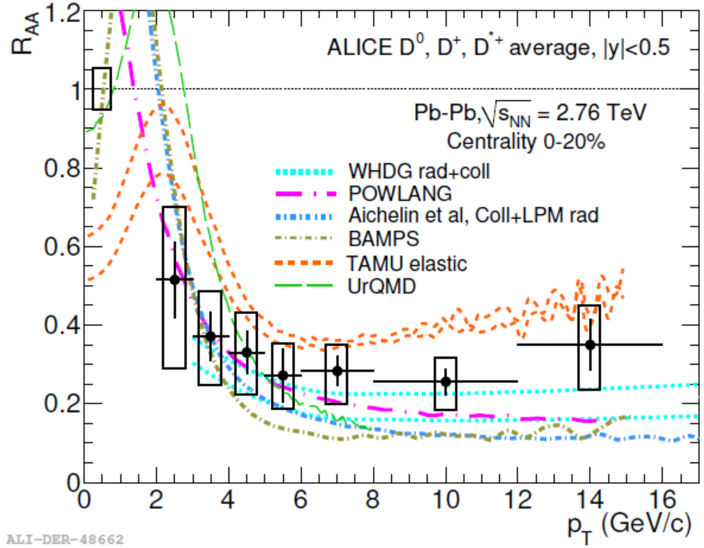
Specific of Heavy Quarks

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

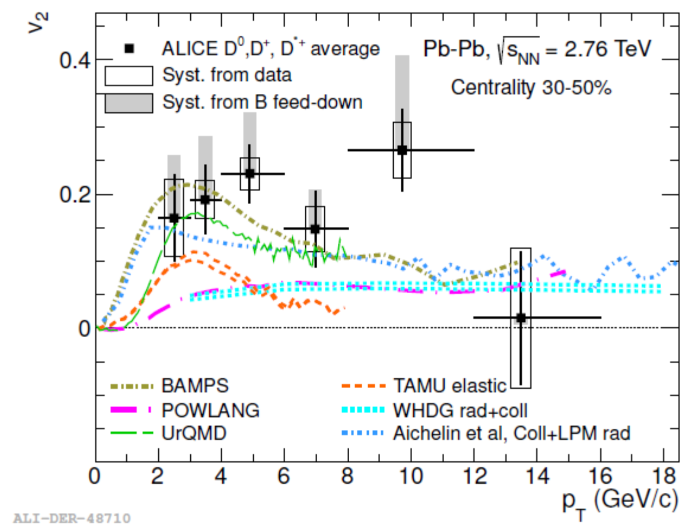


Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

JHEP **1209** (2012) 112



arXiv:1305.2707



Relativistic Boltzmann eq. at finite η/s

Bulk evolution

$$p^{\mu}\partial_{\mu}f_q(x,p)+m(x)\partial^x_{\mu}m(x)\partial^{\mu}_p f_q(x,p)=C[f_q,f_g]$$

$$p^{\mu}\partial_{\mu}f_g(x,p)+m(x)\partial^x_{\mu}m(x)\partial^{\mu}_p f_g(x,p)=C[f_q,f_g]$$

free-streaming | field interaction ε-3p≠0 | collision term gauged to some η/s≠0

Equivalent to viscous hydro η/s≈0.1

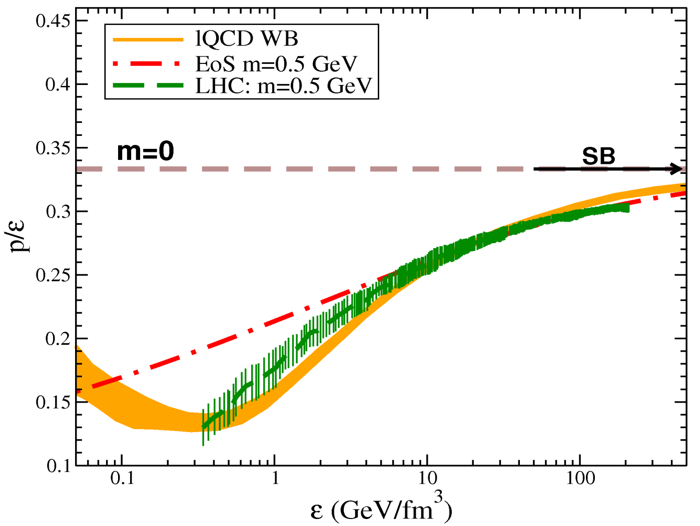
Heavy quark evolution

$$p^{\mu}\partial_{\mu}f_Q(x,p)=C[f_q,f_g,f_Q]$$

$$C[f_q,f_g,f_Q]=\frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p_1'}{2E_1'(2\pi)^3}$$
$$\times[f_Q(p_1')f_{q,g}(p_2')-f_Q(p_1)f_{q,g}(p_2)]$$
$$\times|M_{(q,g)\to Q}(p_1p_2\to p_1'p_2')|$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2')$$

M scattering matrix by QPM model fit to lQCD thermodynamics

S. Plumari EPJ **C79** (2019) no.1, 2



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free-streaming

field interaction
$\varepsilon-3p\neq 0$

collision term
gauged to some $\eta/s\neq 0$

Equivalent to viscous hydro $\eta/s\approx 0.1$

Heavy quark evolution

$$p^{\mu}\partial_{\mu}f_Q(x,p)=C[f_q,f_g,f_Q]$$

Hadronization by coalescence plus fragmentation

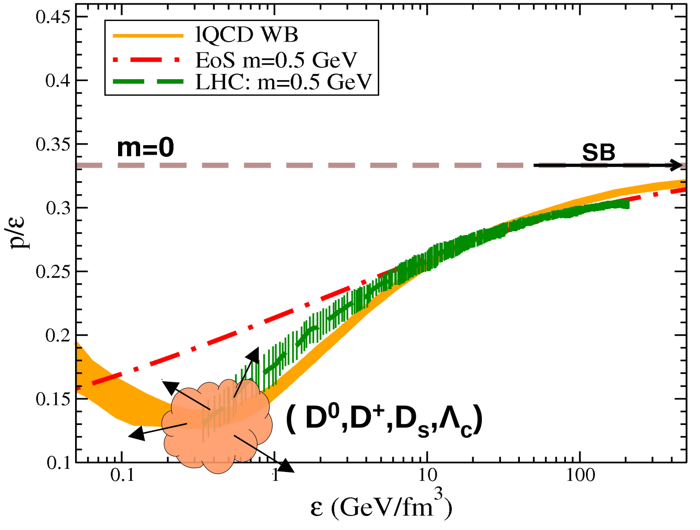
S. Plumari, V. Minissale, S.K. Das, G. Coci, V. Greco, EPJ **C78** (2018) no.4, 348

$$\frac{dN_{Hadron}}{d^2p_T}=g_H\int\prod_{i=1}^{n}p_i\cdot d\sigma_i\,\frac{d^3p_i}{(2\pi)^3}\;f_q(x_i,p_i)\;f_W(x_1,\dots,x_n;p_1,\dots,p_n)\;\delta\Big(p_T-\sum_i p_{iT}\Big)$$

$$\frac{dN_h}{d^2p_h}=\sum_f\int dz\,\frac{dN_f}{d^2p_f}D_{f\to h}(z)$$

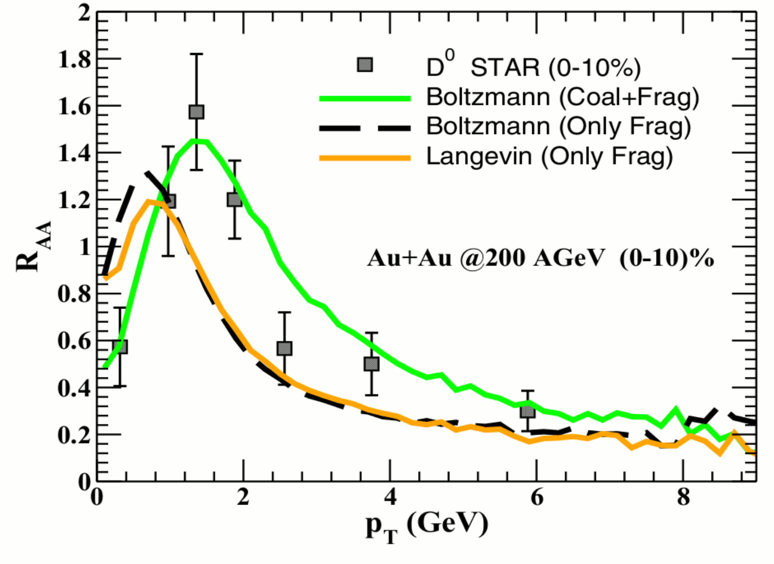
Good description of spectra D^0,D^+,D_s, Λ_c, B, Λ_b

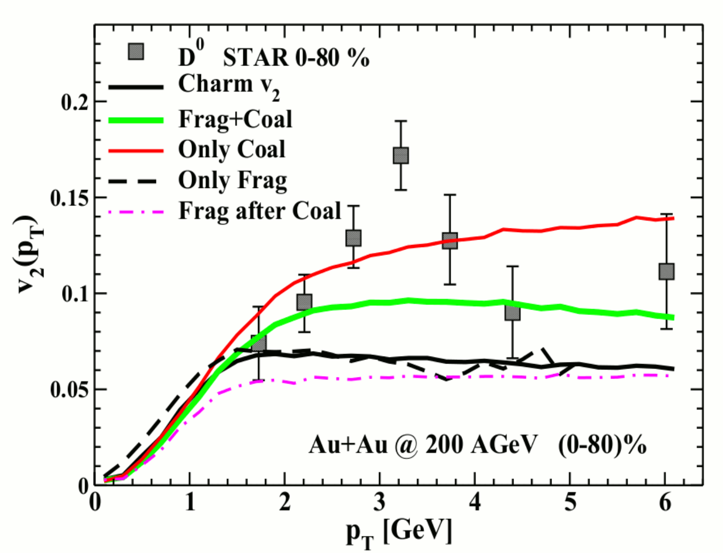
S. Plumari EPJ **C79** (2019) no.1, 2



RHIC results: R_{AA} - v_2

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





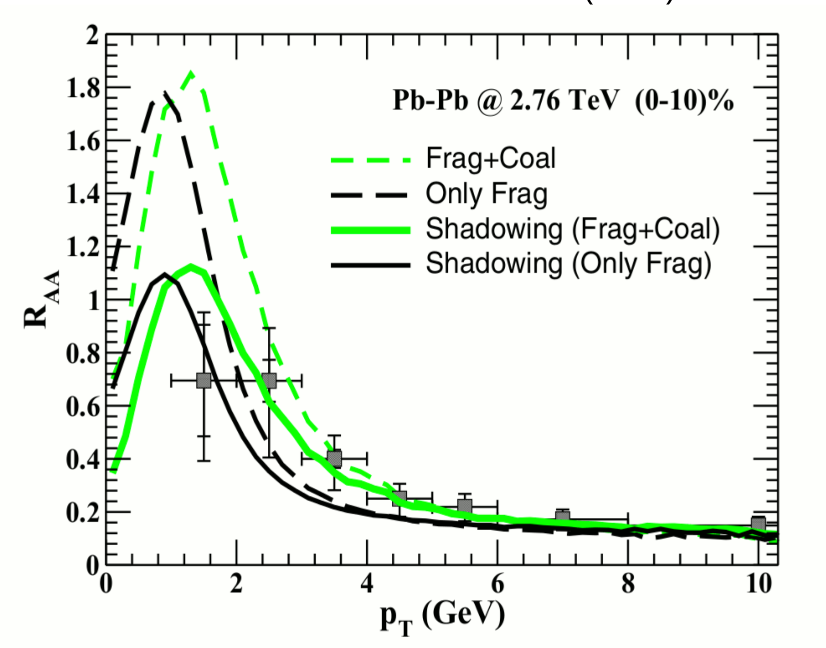
Data from STAR Coll. PRL 118, 212301 (2017)

- 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.

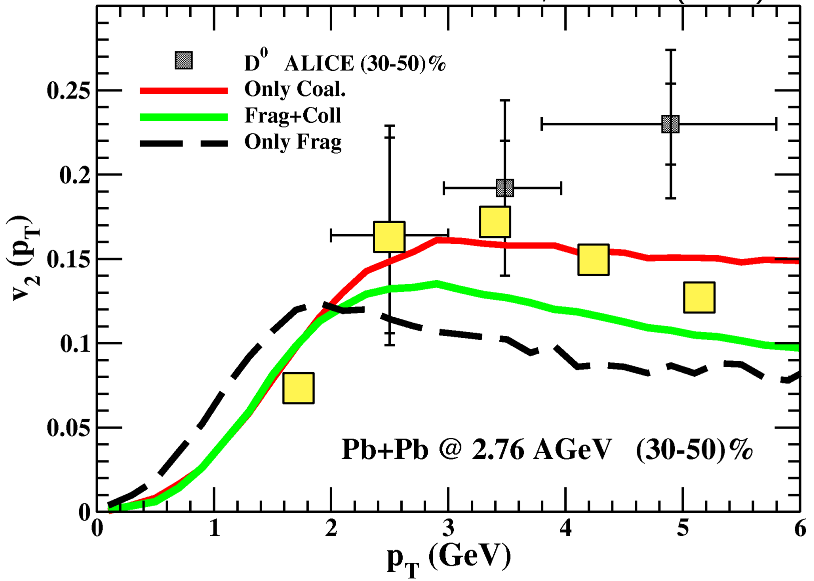
F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PR**C96** (2017) no.4, 044905.

LHC results: R_{AA} - v_2

Data from ALICE Coll. JHEP 03 (2016) 081



Data from CMS Coll. PRL **120** (2018) no.20, 202301
Data from ALICE Coll.PRC 90, 034904 (2014)

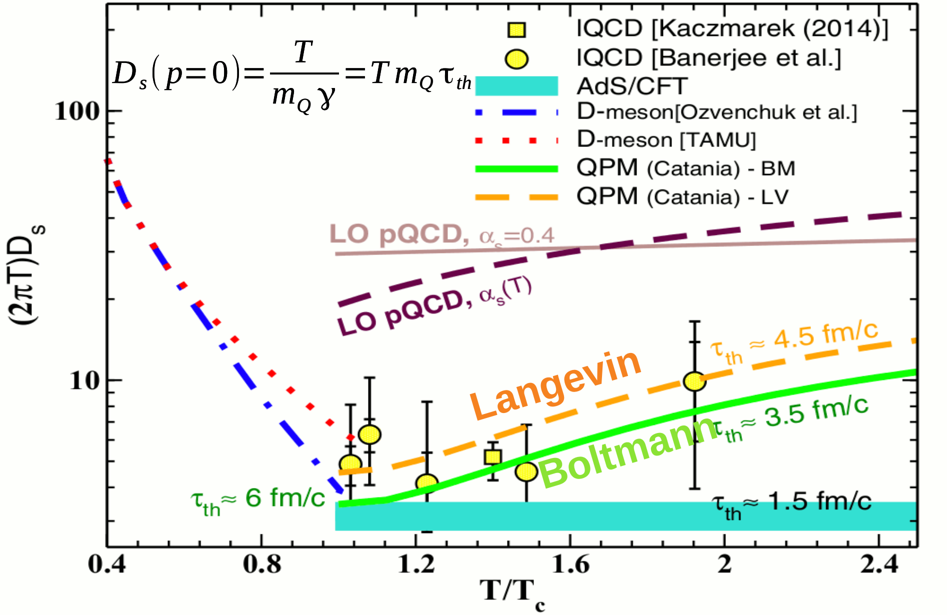


- Shadowing appear necessary EPS09, Eskola-Salgado JHEP(2009)
- At LHC the coalescence implies an increasing of the R_{AA} for p_T>1GeV similar to RHIC energies.
- Due to hadronization D meson $v_2(p_T)$ get an enhancement of about 20% respect to charm $v_2(p_T)$.

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.



- Not a model fit to lQCD data! but the result from $R_{AA}(p_T)$ & v_2 (p_T)

- 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

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

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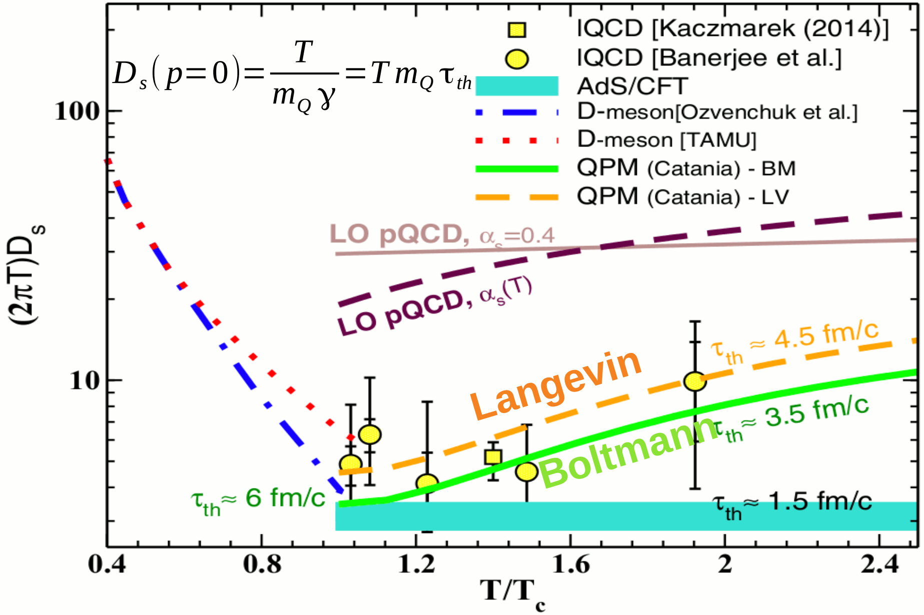

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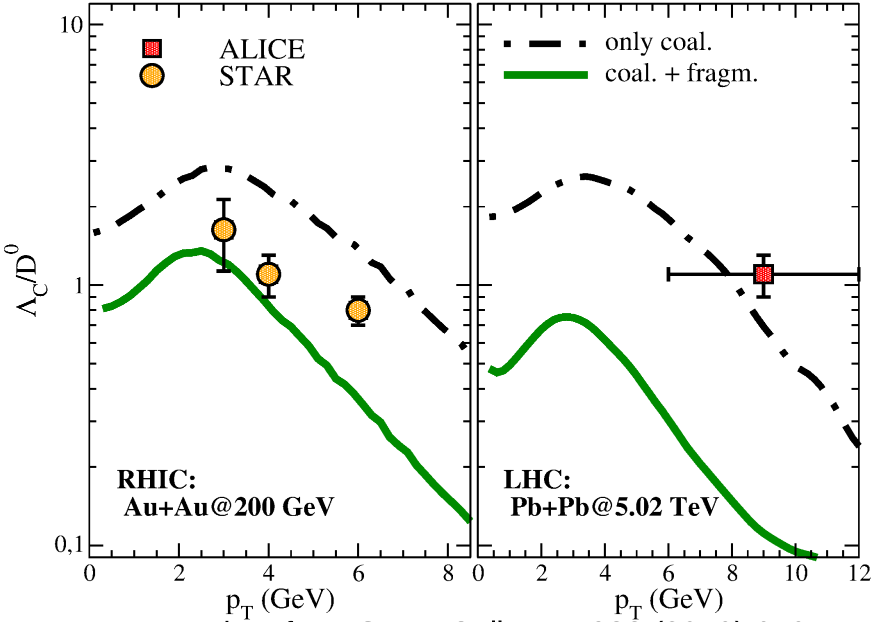
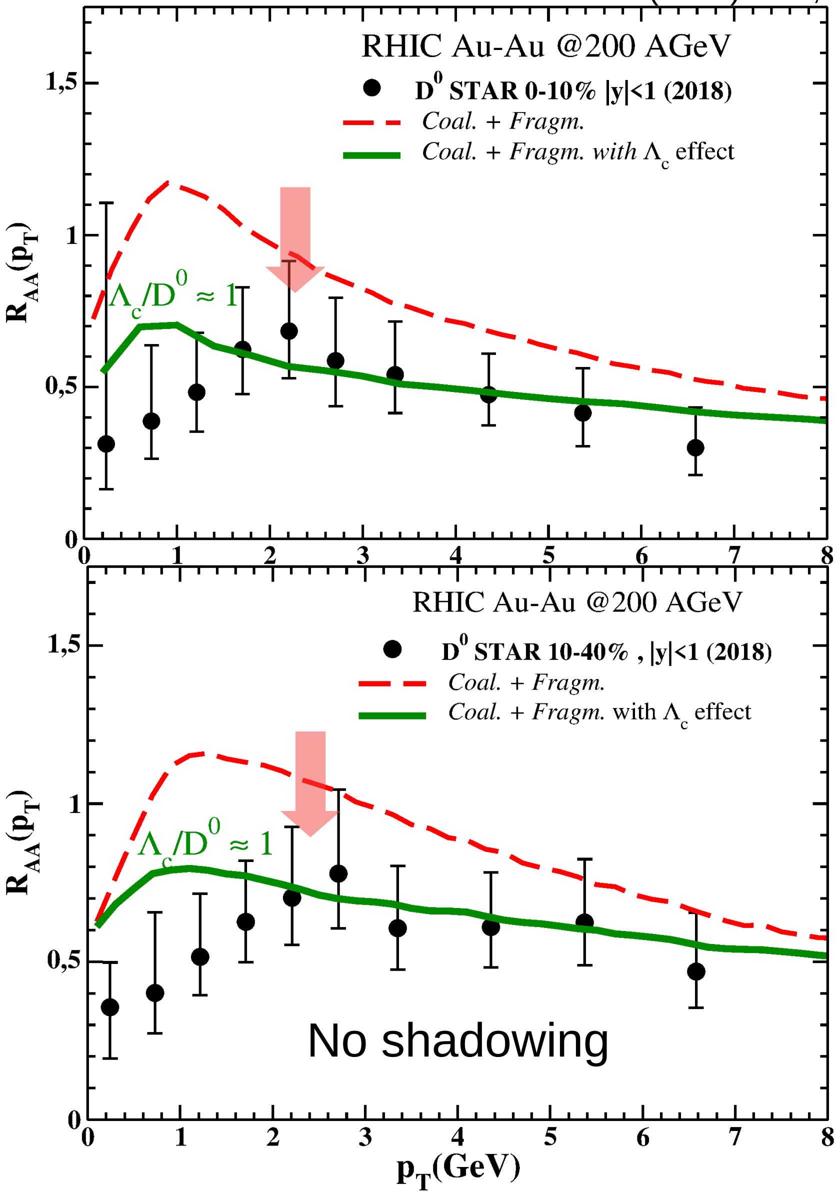


Data taken from STAR Coll. NP**A982** (2019) 659.

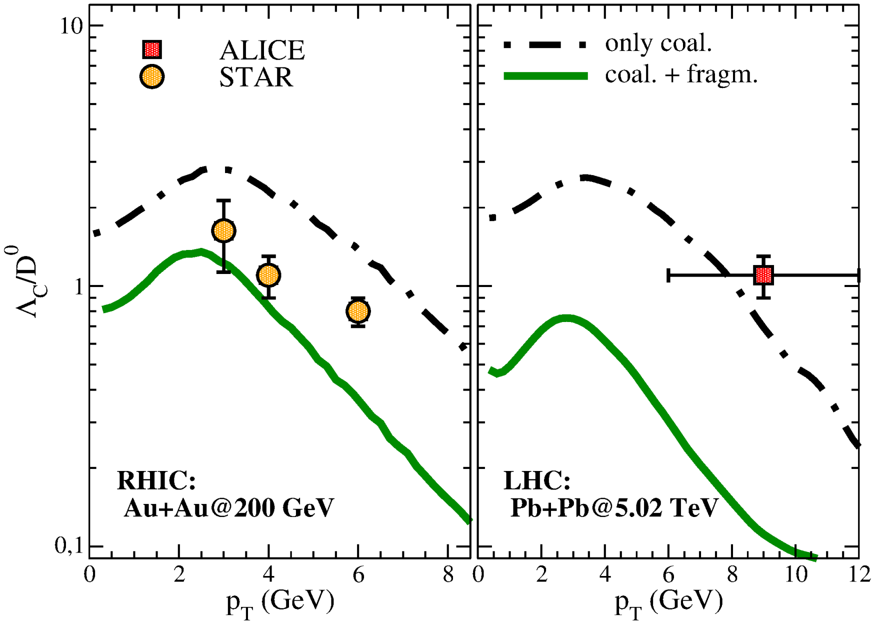
ALICE Coll. PL**B793** (2019) 212.

Comparison to lQCD Diff. coef.

Data taken from STAR Collaboration PR**C99** (2019) no.3, 034908



- This open a new paradigma in studying HF in the low p_T region
- The impact will be even larger for B meson where $\Lambda_b/B \approx 4$
- 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



Data taken from STAR Coll. NP**A982** (2019) 659.

ALICE Coll. PL**B793** (2019) 212.

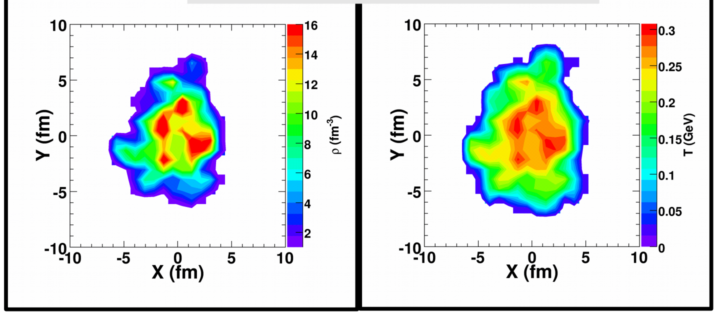
New observables are coming:
v_3, v_4, v_n(light)- v_n(heavy) correlations...

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
S. Plumari EPJ **C79** (2019) no.1, 2

Not almond shape

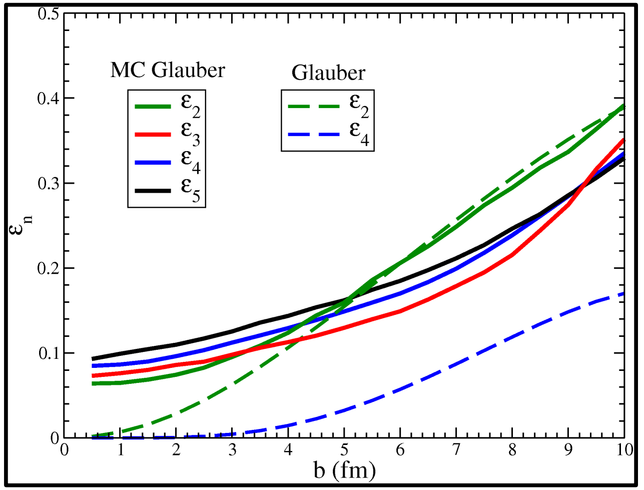


Extented to study:

- 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).

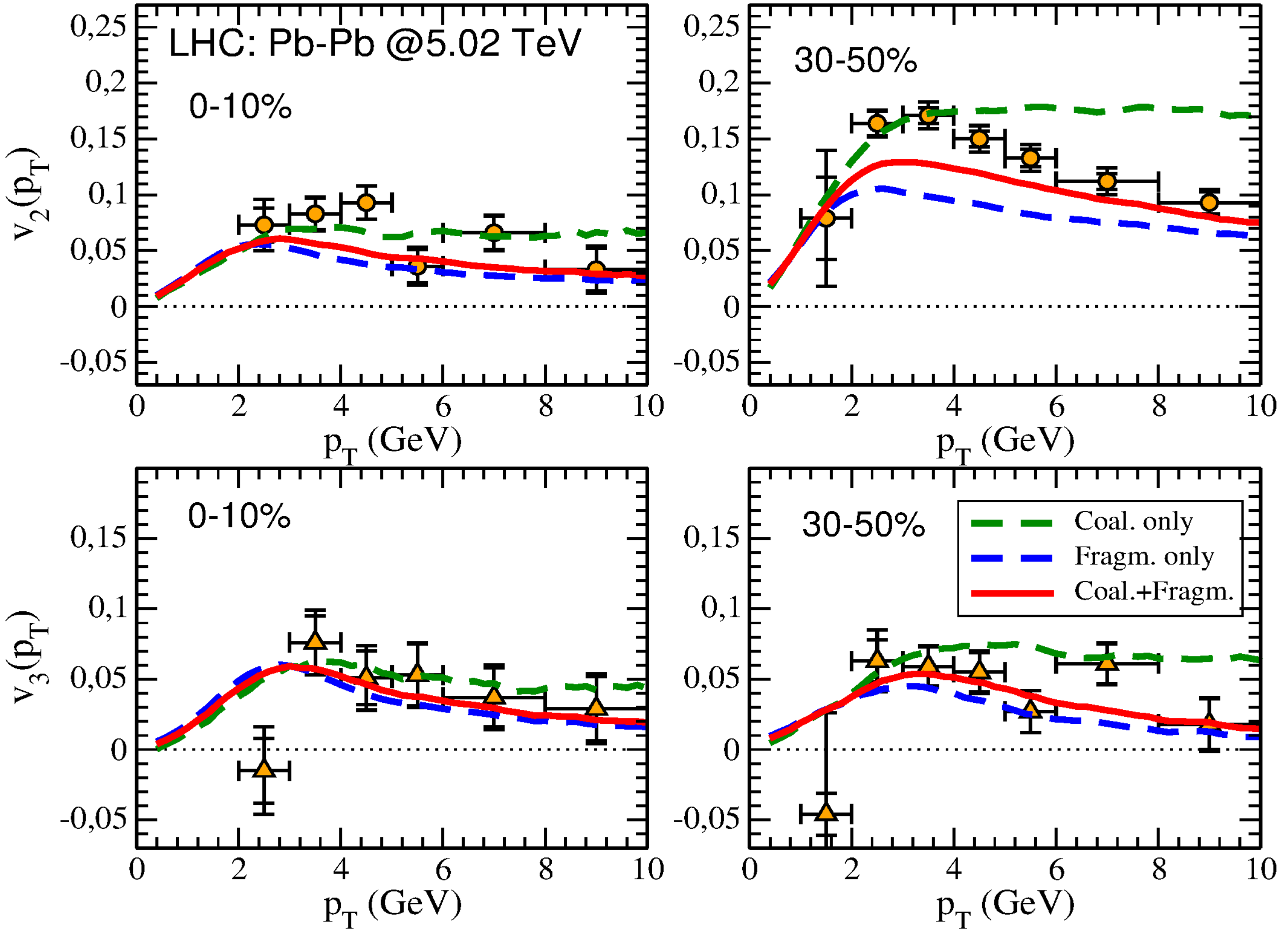
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)]\rangle}{\langle r_\perp^n \rangle}$$

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

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

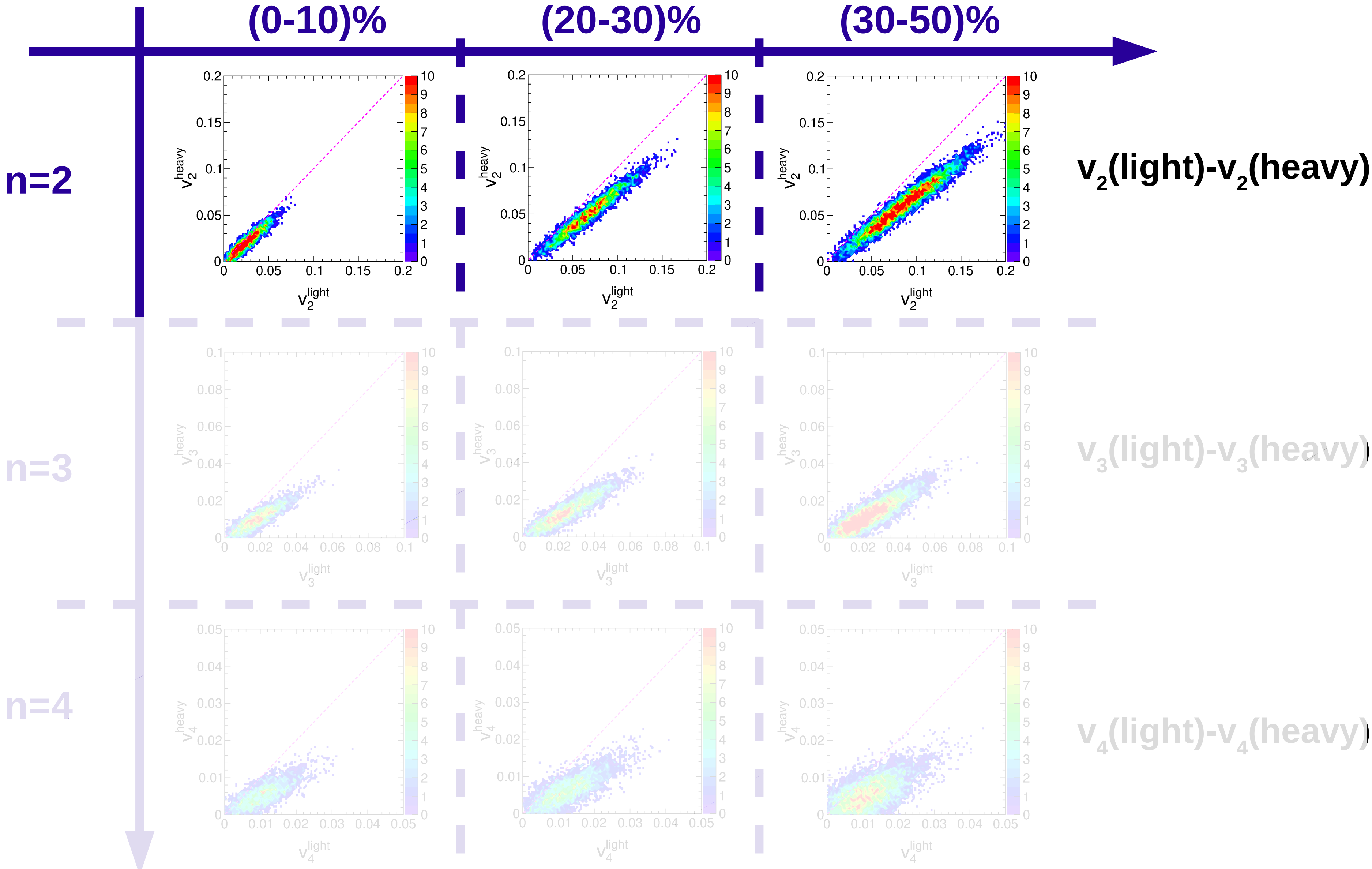
Heavy Flavour dynamics: event-by-event transport approach

Data taken from CMS Collaboration PRL **120** (2018) no.20, 202301

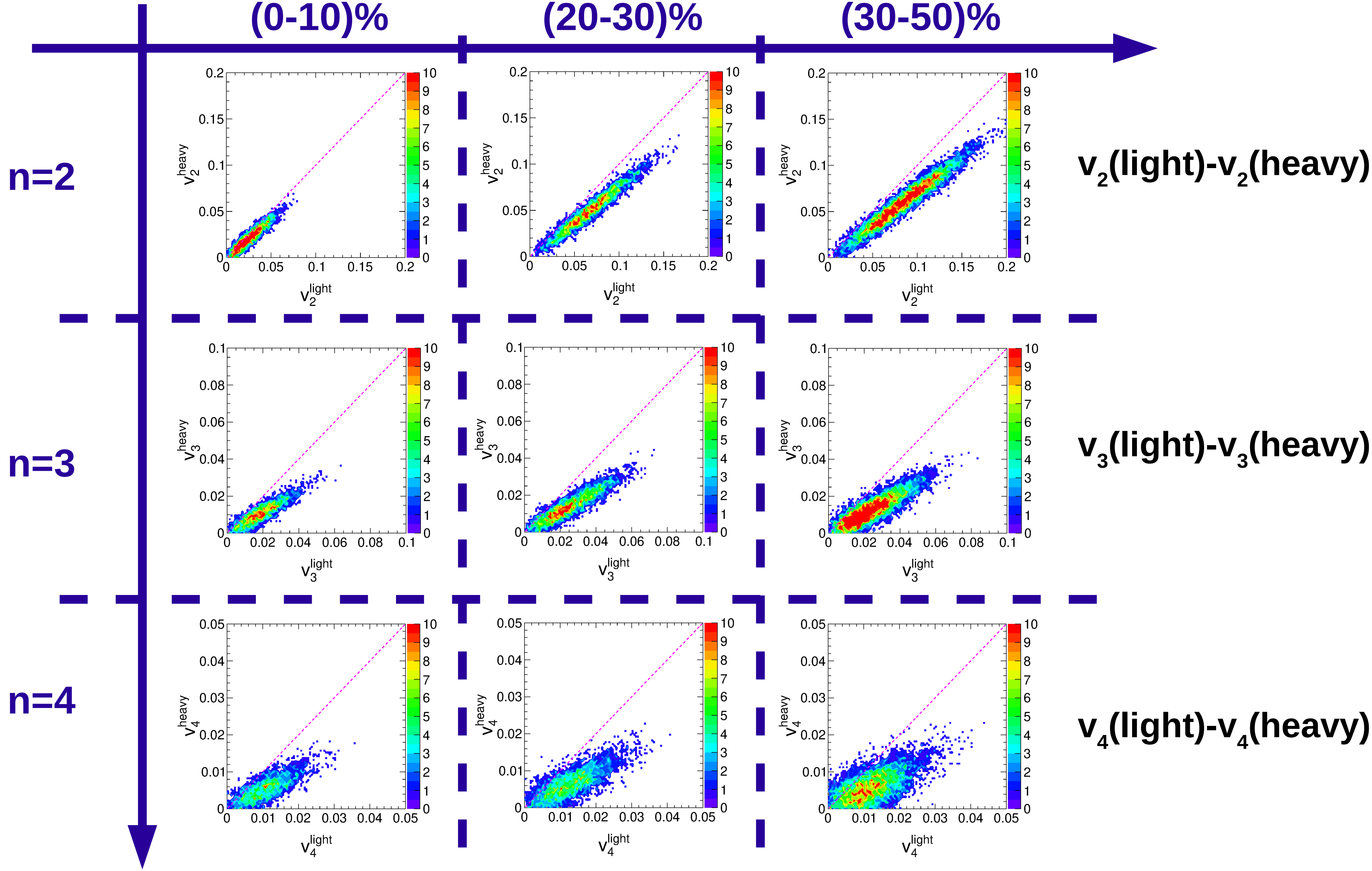


- Initial state fluctuations improve the description of $v_2(p_T)$ in more central collisions.
- within current uncertainty satisfying prediction for $v_3(p_T)$ within coal.+fragm.
- It is possible to study event-by-event light-heavy correlation...

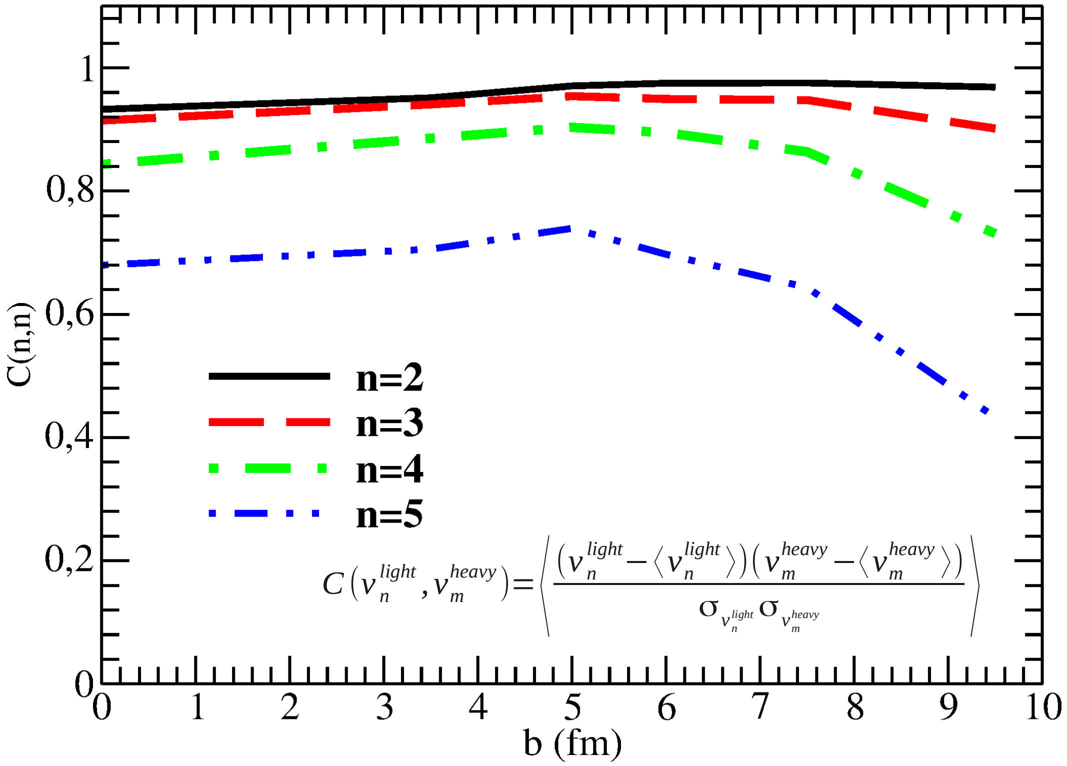
Initial state fluctuation: $v_n^{(light)}$ vs $v_n^{(heavy)}$



Initial state fluctuation: $v_n^{(light)}$ vs $v_n^{(heavy)}$

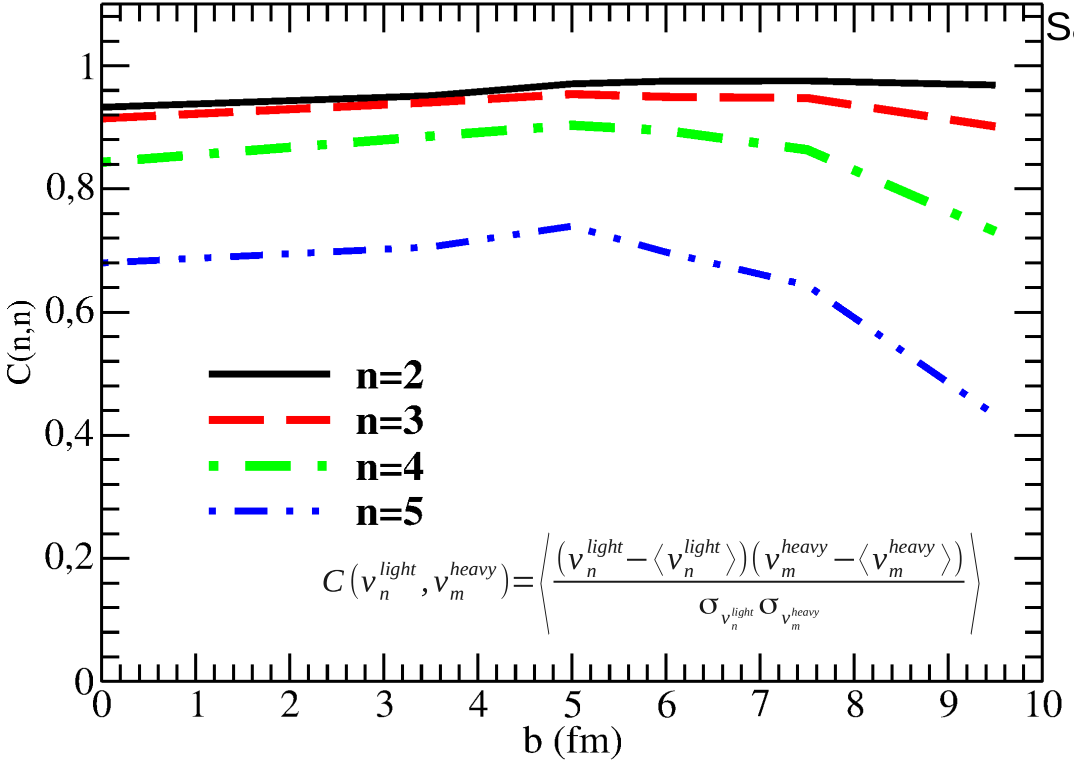


Initial state fluctuation: $v_n^{(light)}$ vs $v_n^{(heavy)}$

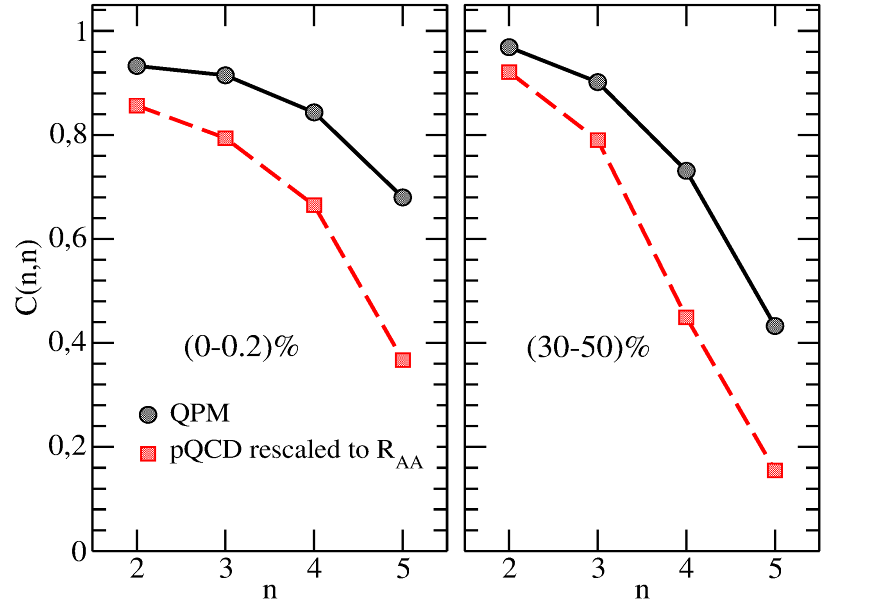


- v_2(light) and v_3(light) linearly correlated to the corresponding v_2(heavy) and v_3(heavy) respectively.
- C(2,2)>C(4,4)>C(5,5) for all centralities.
- v_4(light) and v_4(heavy) weak correlated.
- For central collisions v_n are strongly correlated: v_n(light)$\propto$ v_n(heavy) for n=2,3,4.

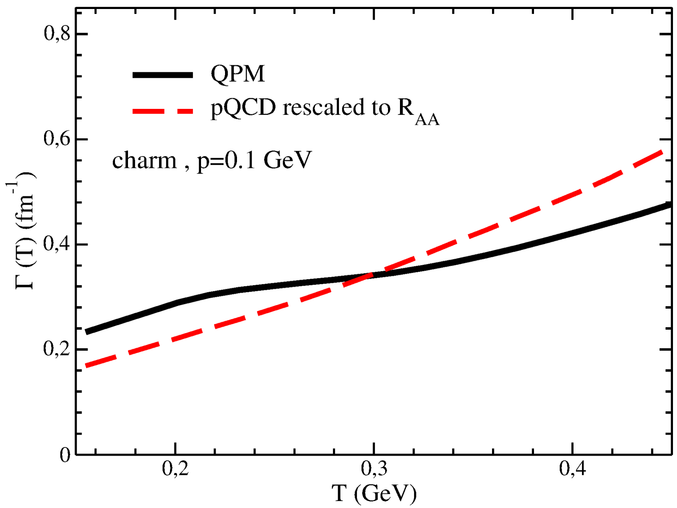
Initial state fluctuation: $v_n^{(light)}$ vs $v_n^{(heavy)}$



Same $R_{AA}(p_T)$ for both QPM and pQCD rescaled to R_{AA}



- For Ultra-Central collisions with QPM not only large C(2,2) but $\langle v_2(light)\rangle \approx \langle v_2(heavy)\rangle$
- Strong sensitivity of C(n,n) on T dependence of transport coefficients.



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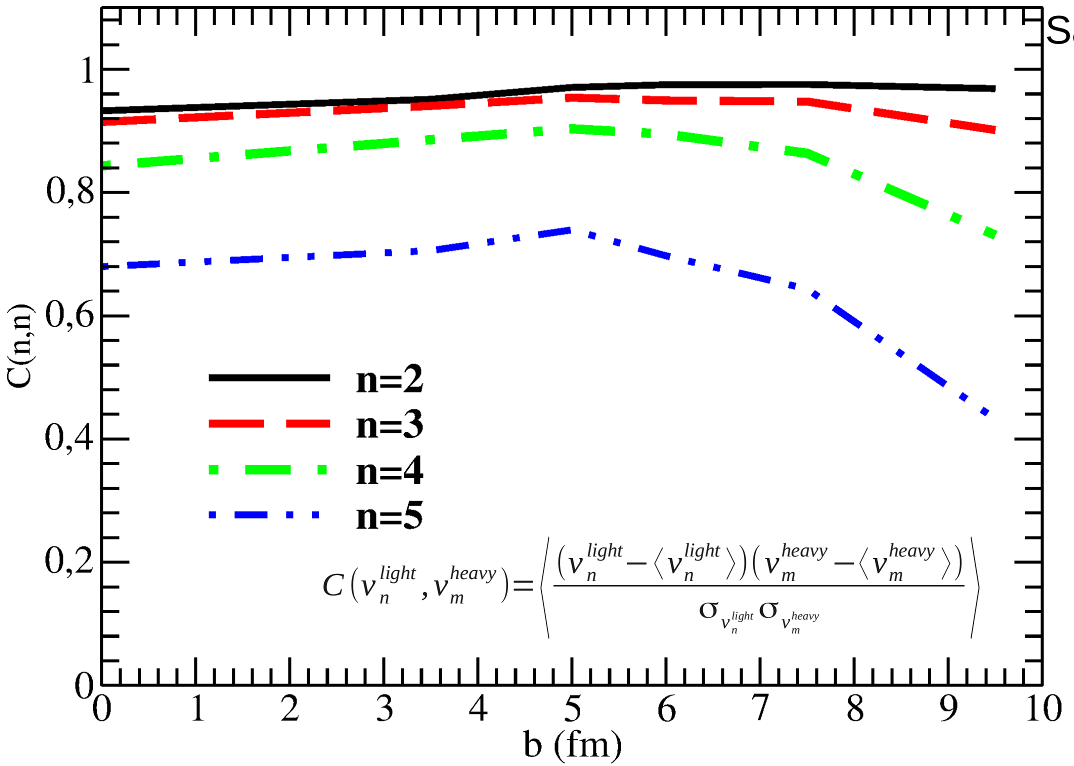

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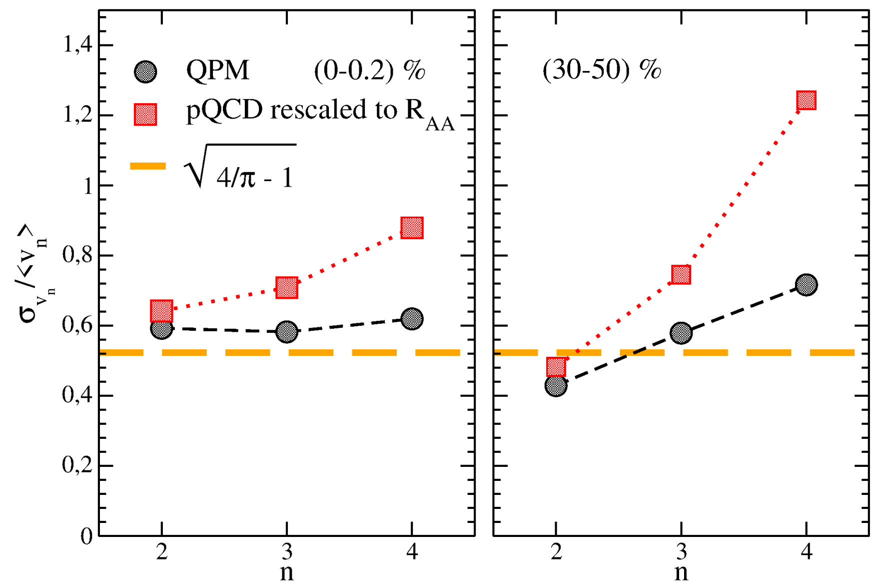
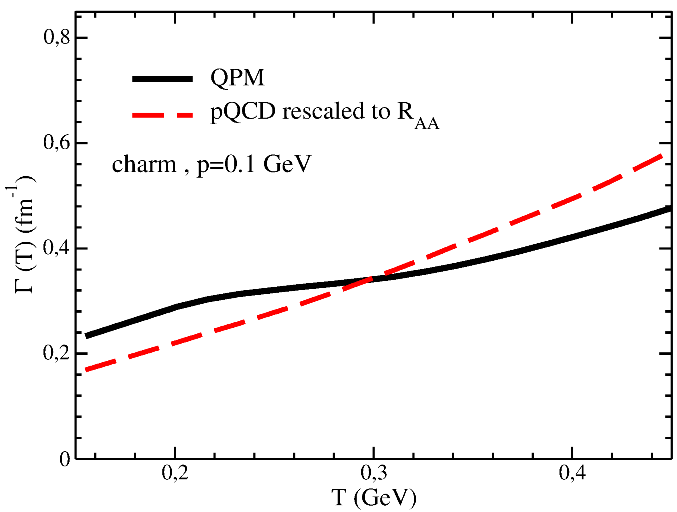




- For Ultra-Central collisions with QPM not only large C(2,2) but v_2(light)=v_2(heavy)
- Strong sensitivity of C(n,n) on T dependence of transport coefficients.
- σ_{vn}/v_n quite different from light ones

Heavy Flavour dynamics: sources of v_1 for charm quarks

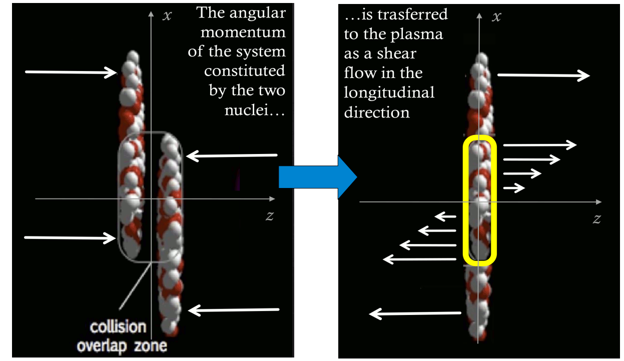
- **Vorticity due to the large orbital angular momentum in uRHIC $J \approx 10^5 - 10^6\ \hbar$**

  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?***

    Solving the relativistic Langevin eq. with tilted initial distribution in the reaction plane produce a v_1 of D meson several times larger than that of charged particle.

    S. Chatterjee, P. Bożek PRL 120 (2018) no.19, 192301



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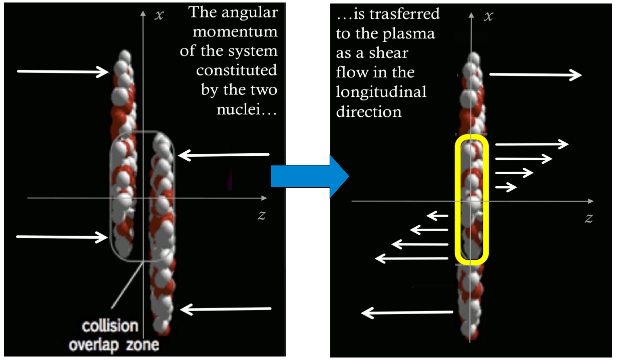


- **Intense magnetic field B:**

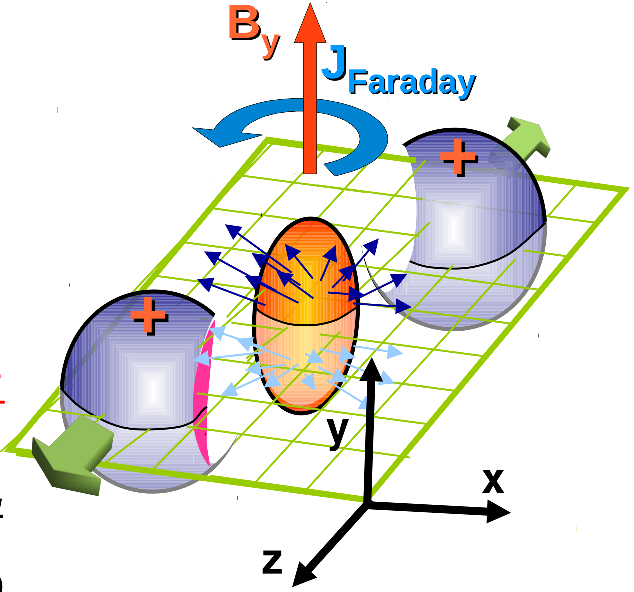
  created on Earth ≈ 10^7 Gauss
  in Neutron Star ≈ 10^{13} Gauss
  in uRHIC ≈ 10^{19} Gauss ≈ $10\ m_\pi^2$

  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?***

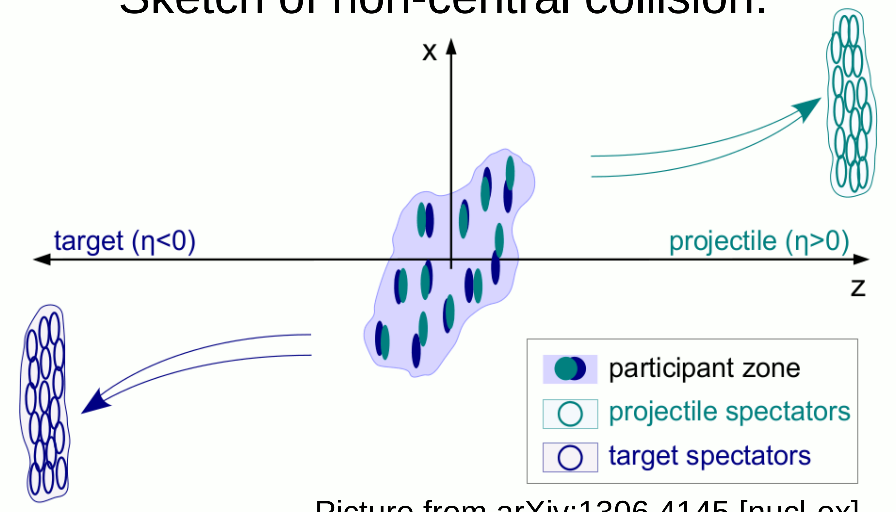
    Solving the relativistic Langevin eq. with Lorentz force a sizeable v_1 for charm (anti-charm) quarks is produced.

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

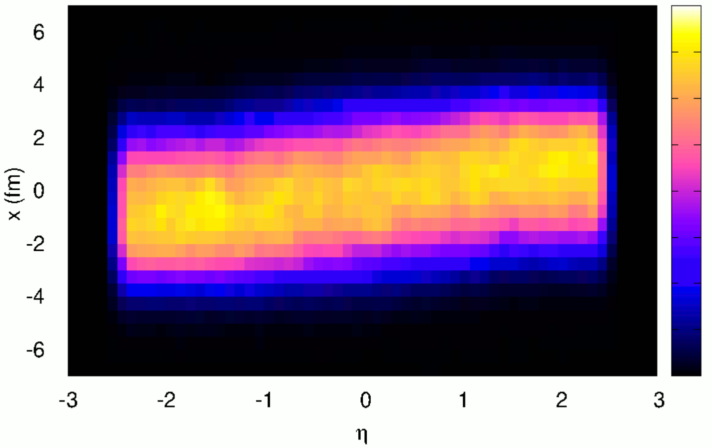


Vorticity in Heavy Ion Collisions

Sketch of non-central collision.



Picture from arXiv:1306.4145 [nucl-ex]



time evolution of vorticity field in agreement with Jiang, Lin, Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

Asymmetry in local participant density from forward backward going nuclei ➔ tilt of the fireball in the reaction plane
P. Bozek, I. Wyskiel PRC81 (2010) 054902

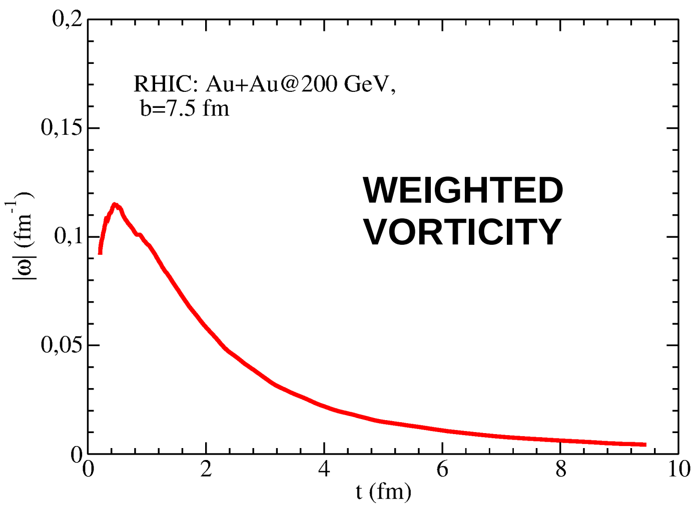
$$s(r_T,\eta)\propto\{\alpha N_{coll}+(1-\alpha)[N^{+}_{part}f_{+}(\eta)+N^{-}_{part}f_{-}(\eta)]\}f(\eta)$$

with

$$f(\eta)=\exp\left[-\theta(|\eta|-\eta^0)\frac{(|\eta|-\eta^0)^2}{2\sigma^2}\right]$$

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

and $f_{-}(\eta)=f_{+}(-\eta)$



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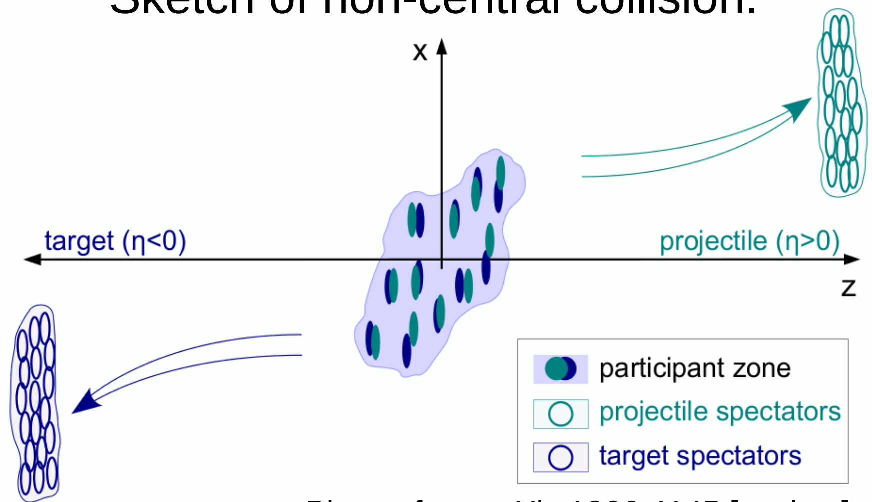

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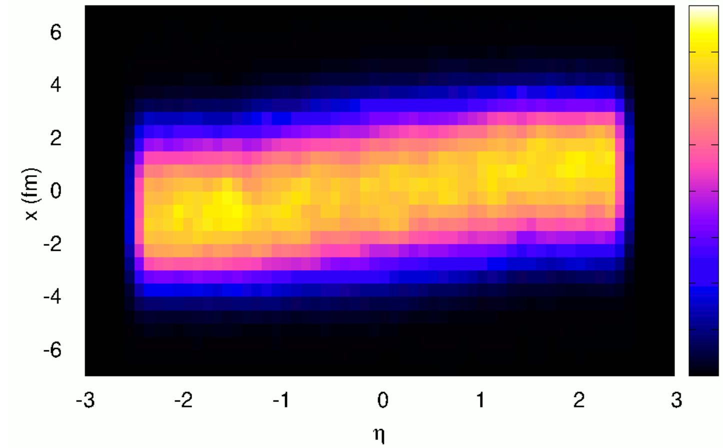

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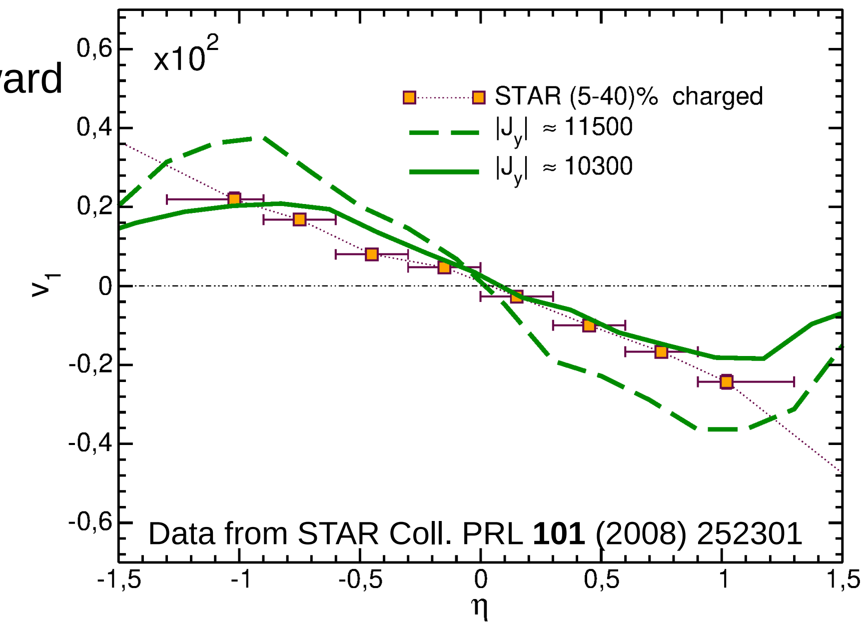
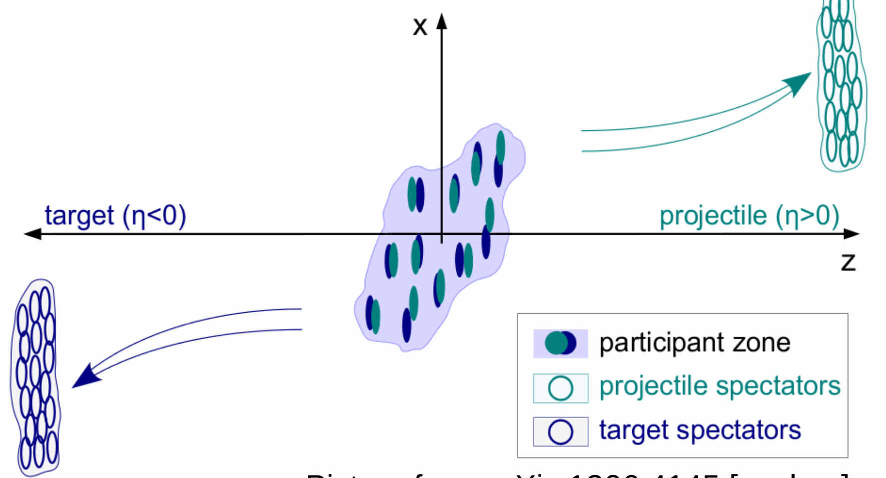
$$f_{+}(\eta)=\begin{cases}0 & \eta<-\eta_T\\ \dfrac{\eta_T+\eta}{2\eta_T} & -\eta_T<\eta<\eta_T\\ 1 & \eta>\eta_T\end{cases}$$

and $f_{-}(\eta)=f_{+}(-\eta)$

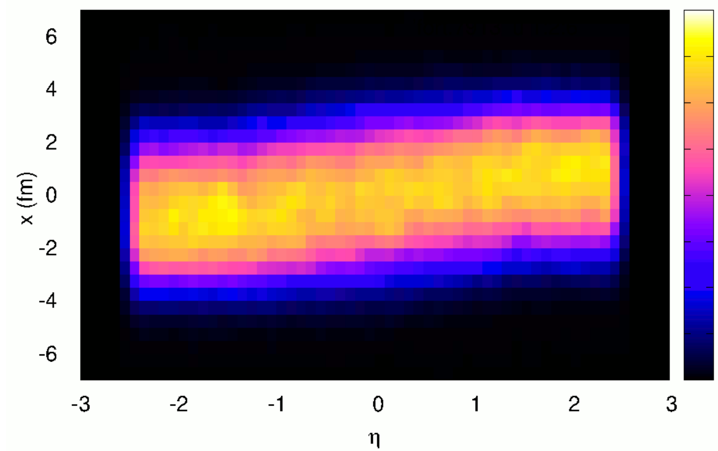


Vorticity in Heavy Ion Collisions

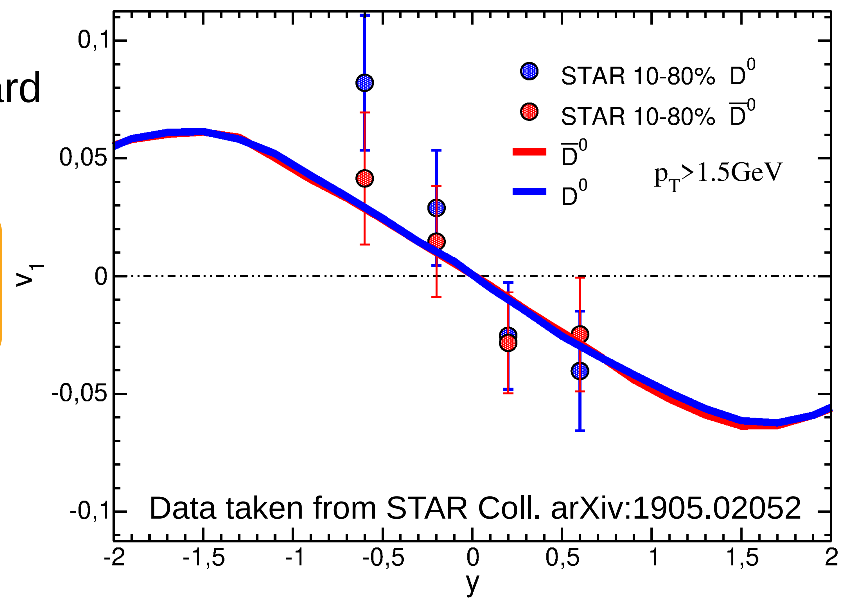
Sketch of non-central collision.



Picture from arXiv:1306.4145 [nucl-ex]



Large D meson v_1: order of magnitude larger than that of charged particle



Asymmetry in local participant density from forward backward going nuclei → tilt of the fireball in the reaction plane

Heavy quarks from hard processes → forward backward symmetric → Large v_1

$$v_1(HQ) > v_1(Bulk)$$

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 **β**.

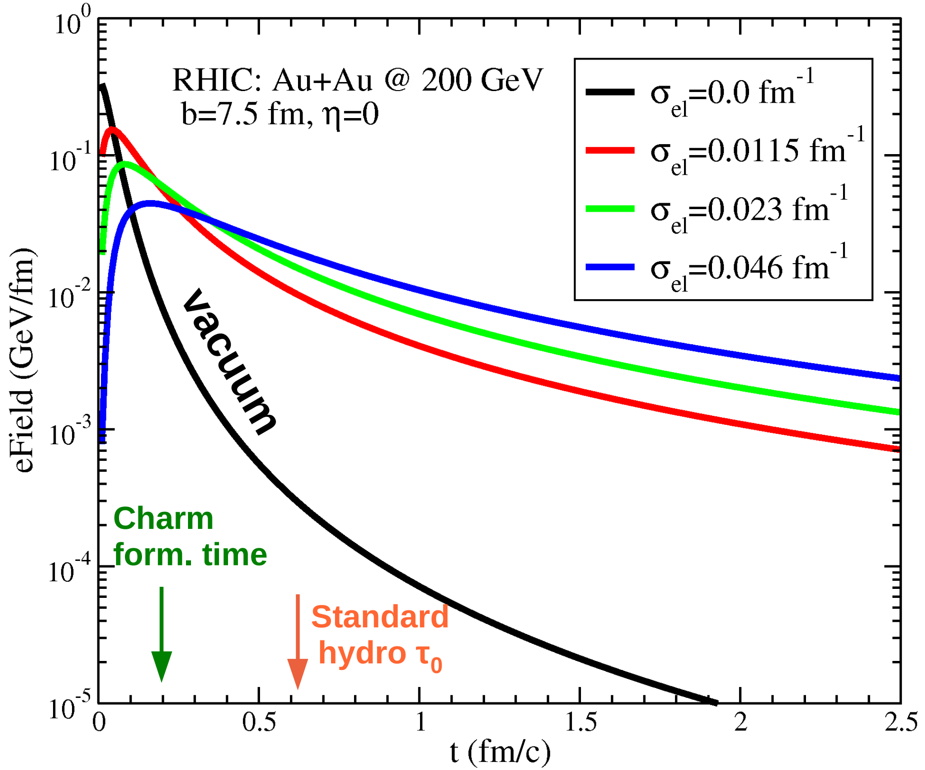
$$\begin{cases} \nabla \cdot \boldsymbol{E} = e\,\delta(z-\beta t)\,\delta(\boldsymbol{x}-\boldsymbol{x}_T) \\ \nabla \cdot \boldsymbol{B} = 0 \qquad \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{B} = \dfrac{\partial \boldsymbol{E}}{\partial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

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:

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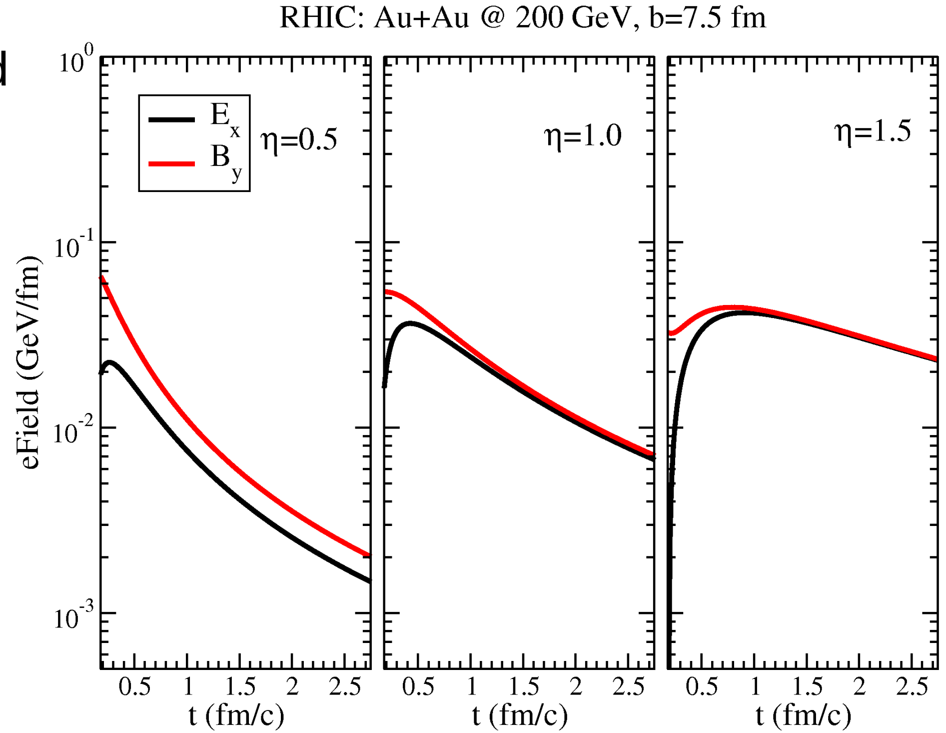

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Direct Flow v_1 of charm quarks

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

$$p^{\mu}\partial_{\mu}f_{q}(x,p)+m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_{q}(x,p)+qF^{\mu\nu}_{ext}p_{\mu}\partial_{\mu}f_{q}(x,p)=C[f_{q},f_{g}]$$

$$p^{\mu}\partial_{\mu}f_{g}(x,p)+m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_{g}(x,p)=C[f_{q},f_{g}]$$

Heavy quark evolution

$$p^{\mu}\partial_{\mu}f_{Q}(x,p)+qF^{\mu\nu}_{ext}p_{\mu}\partial_{\mu}f_{Q}(x,p)=C[f_{q},f_{g},f_{Q}]$$

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

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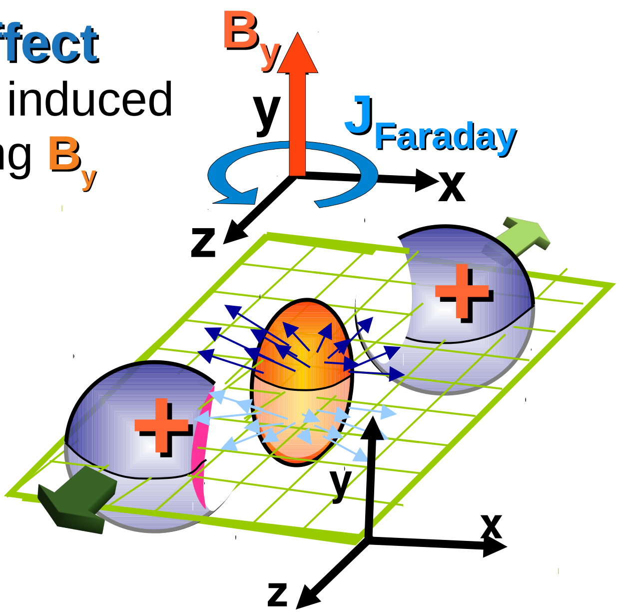
The direct flow v_1 originates from two competing effects:

Faraday effect

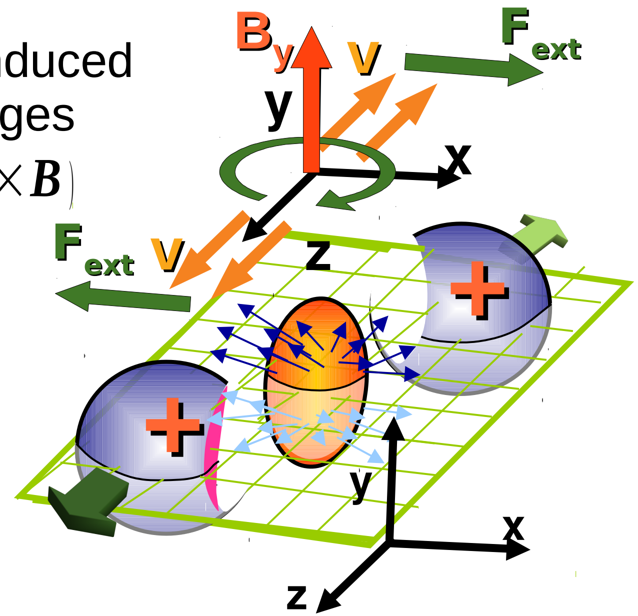
Electric field induced by decreasing B_y



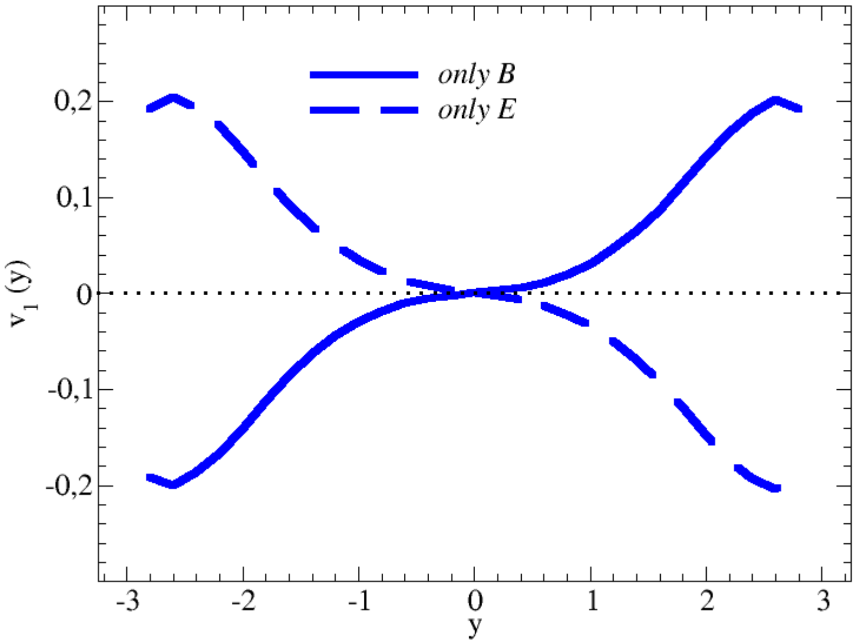
Hall effect

Lorentz force induced by moving charges

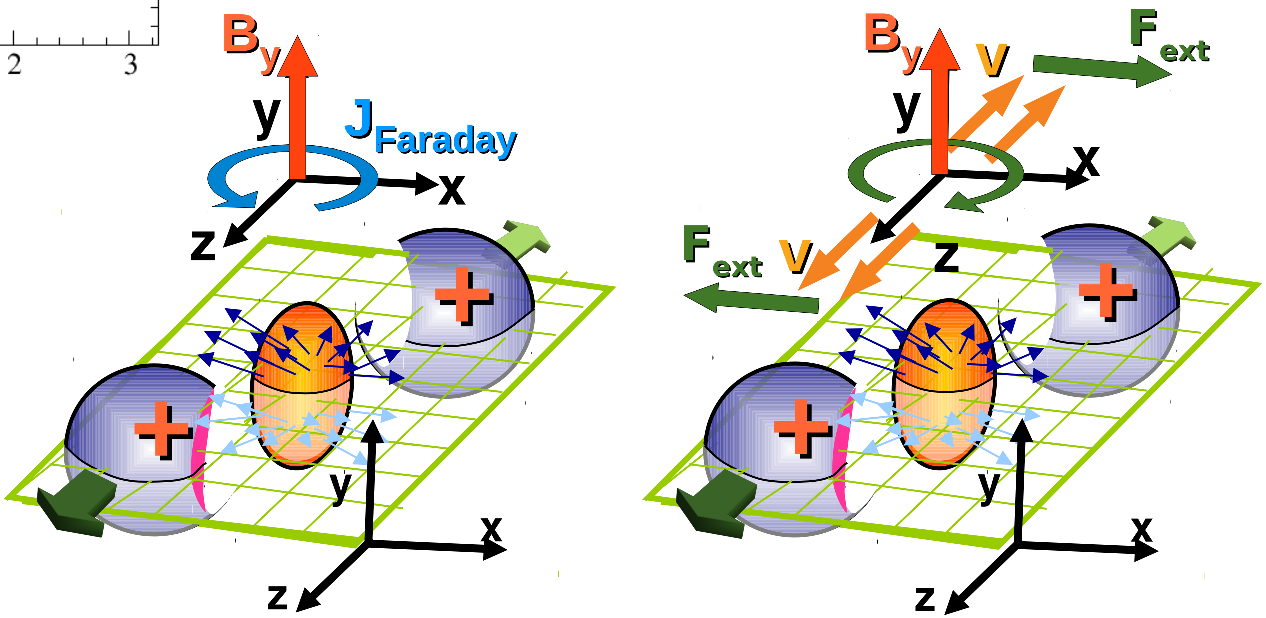
$$F_{ext}=qE+\frac{q}{E_p}(p\times B)$$



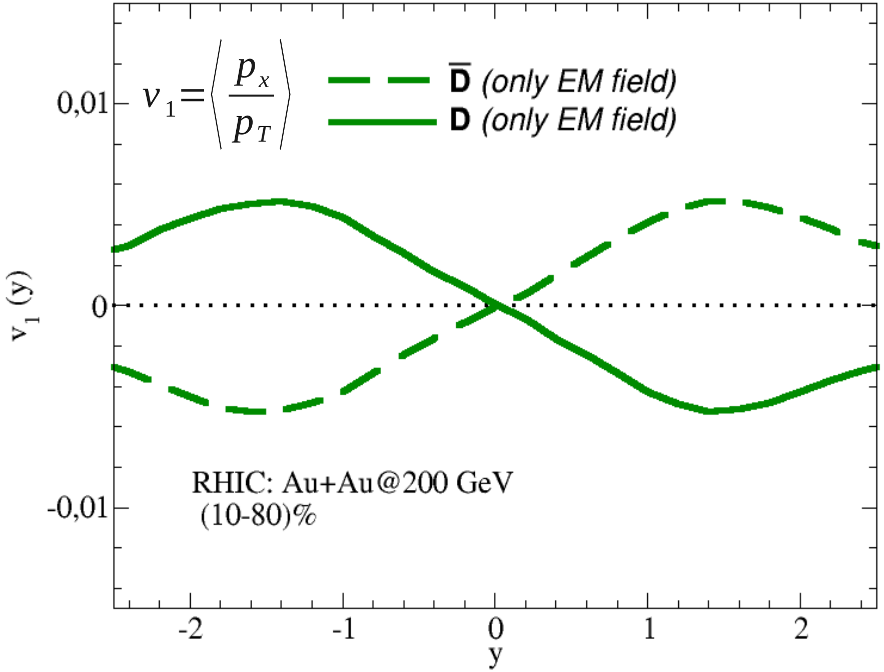
Balance between Magnetic and Electric fields



- Decreasing magnetic field B_y creates E_x that induces a current in opposite direction w.r.t. to the Magnetic Hall drift: delicate balance!
- Larger initial (t<1 fm/c) field important to determine a sizeable v_1 flow
  S.K. Das et al., PLB 768 (2017)



Direct Flow v_1 of charm quarks



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

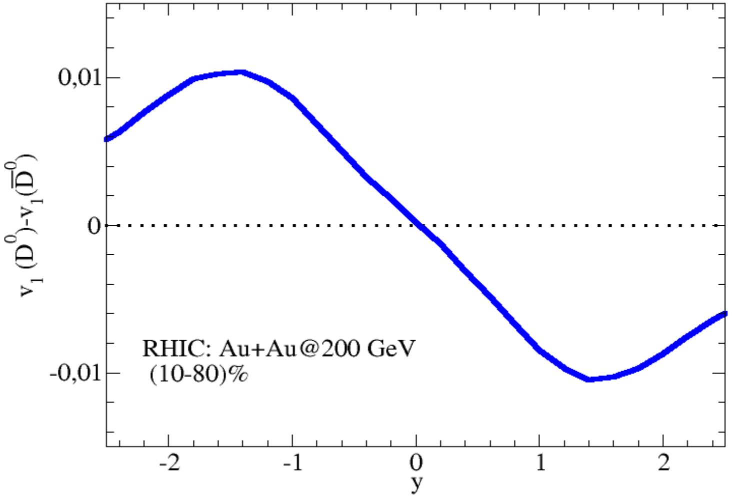
U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).

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

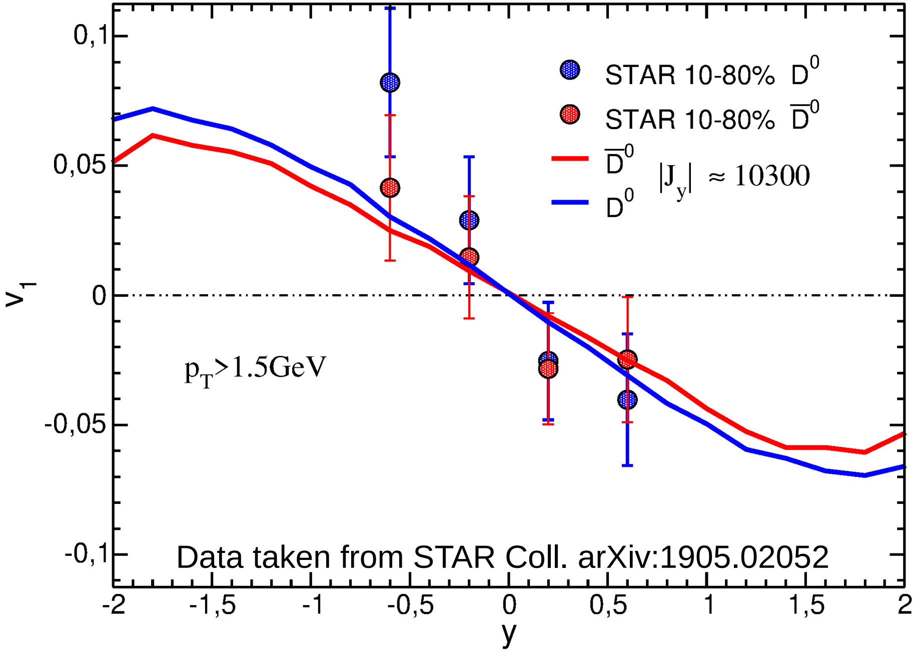
S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB768 (2017) 260-264.

HQ best probe for v_1 from e.m. field:

- $t_{form} \approx 0.1$ fm/c
- **$\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$**
- do not mix vorticity [Odd- parity]



Direct Flow v_1 of charm quarks



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Conclusions

- Good description of R_{AA} and $v_2(p_T)$ from RHIC to LHC with $(2\pi T)D_s \sim T$ within lQCD results. $(2\pi T)D_s \sim$ 3-4 around Tc

- Event-by-event transport approach: new observables
  - v_n(HQ)-v_n(QGP) correlation new sensitive observable
  - Strong correlation between v_2(QGP) and v_2(HF)
  - σ_{vn}/v_n much more sensitive to T dependence of D_s

- Heavy flavor directed flow as a probe of initial state physics:
  - Initial vorticity: Heavy flavor directed flow order of magnitude larger than the bulk directed flow explained by tilted initial condition.
  - The electromagnetic field and medium conductivity
  - Splitting of particle antiparticle v_1 of the order of 1% both at RHIC and LHC

- At LHC the current approach cannot reproduce the current ALICE exp. data: very exciting!! something new to understand about inial vorticy and EM field