Heavy Flavour Dynamics in Heavy Ion Collisions: Anisotropic flows v_n and their Correlations to Bulk Dynamics and the Initial Field

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in collaboration with
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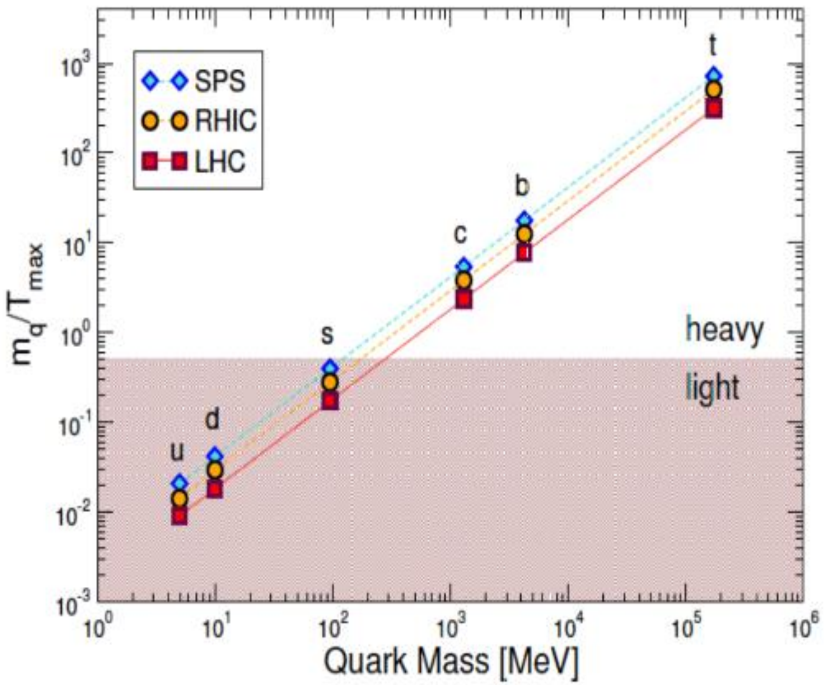
8-11 June 2021

Outline

- Introduction
- Heavy quarks dynamics in QGP within transport approach
- Initial state fluctuation → Event-Shape-Engineering
  - Anisotropic flows v_n and their correlations
- Impact of intense vorticity and initial ElectroMagnetic field on Heavy quarks dynamics:
  - sizeable v_1 for charm quarks (anti-charms)
- Conclusions

Basic scales of Heavy Quarks



- $m_{c,b} >> \Lambda_{QCD}$
  pQCD initial production
- $m_{c,b} >> T_{RHIC,LHC}$
  negligible thermal production
- $\tau_0 < 0{,}08$ fm/c $<< \tau_{QGP}$
- $\tau_{th} \approx \tau_{QGP} >> \tau_{g,q}$

They experience the full evolution of the QGP.

They carry more informations with respect to their light counterparts.

Relativistic Boltzmann eq. at finite η/s

Bulk evolution

$$p^\mu \partial_\mu f_q(x,p) + m(x)\partial_\mu^x m(x)\partial_p^\mu f_q(x,p) = C[f_q, f_g]$$

$$p^\mu \partial_\mu f_g(x,p) + m(x)\partial_\mu^x m(x)\partial_p^\mu f_g(x,p) = C[f_q, f_g]$$

Equivalent to viscous hydro η/s≈0.1

free-streaming

field interaction
ε-3p≠0

collision term
gauged to some η/s≠0

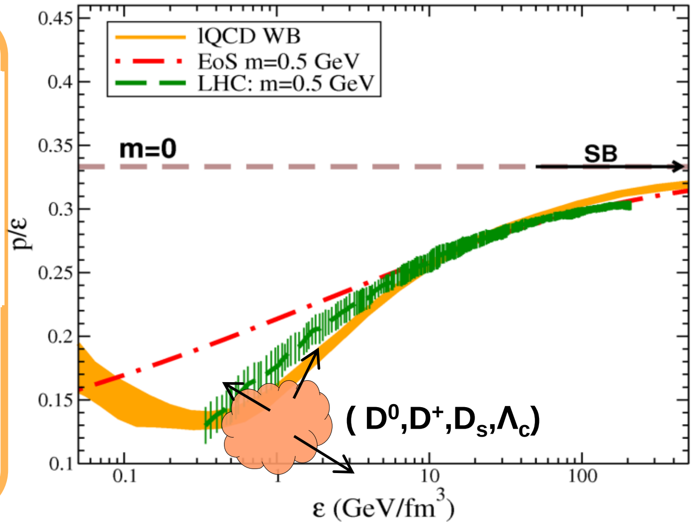
Heavy quark evolution

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

$$C[f] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}(f_1'f_2' - f_1 f_2) \times |\mathcal{M}_{12\to 1'2'}|(2\pi)^4\delta^{(4)}(p_1'+p_2'-p_1-p_2),$$

M scattering matrix by QPM model fit to
lQCD thermodynamics

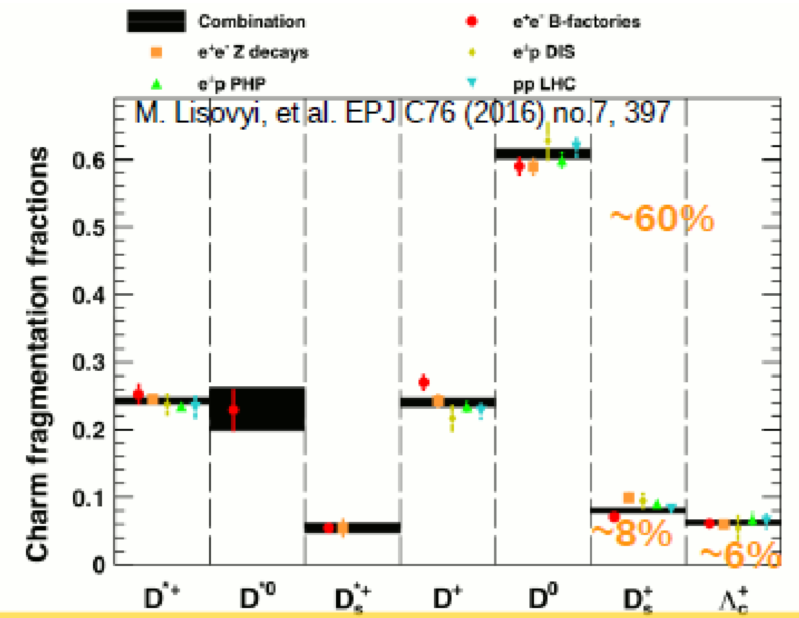
S. Plumari et al.,J.Phys.Conf.Ser. 981 012017 (2018).



Fragmentation

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

Fragmentation function



The distribution function is evaluated at the Fixed-Order plus Next-to-Leading-Log (FONLL)

M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001

We use the Peterson fragmentation function

C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas PRD **27** (1983) 105

$$D_{f \to h}(z) \propto \frac{1}{z\left[1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right]^2}$$

Recent update He-Rapp, PLB795(2019):
Increase ≈ 2 due to added Λ_c resonance not present in PDG, but predicted by RQM [assumed BR with Λ_c dominance]

*** Fragmentation functions**

$$\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-,\,pp} \simeq 0.1 \qquad \left(\frac{D_s^+}{D^0}\right)_{e^+e^-,\,pp} \simeq 0.13$$

*** Thermal models about 2 times larger**

A. Andronic et al., Phys. Lett. **B**571, 36 (2003)
I. Kuznetsova, J. Rafelski, EPJ C51, 113 (2007)

$$\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-,\,pp} \simeq 0.25 - 0.30$$

Heavy flavour Hadronization: Coalescence

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

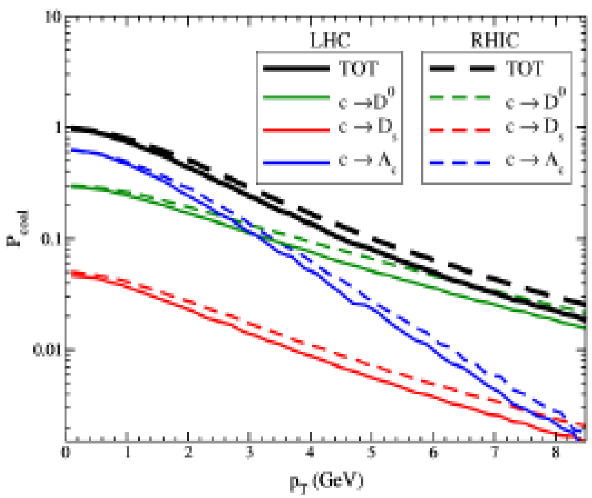
charm distribution function at mid-rapidity from parton simulations solving Boltzmann transport eq. that give good description of both R_{AA} and $v_2(p_T)$ from RHIC to LHC energies.

- *The width parameters σ in $f_W(\ldots)$ fixed by the root-mean-square charge radius as predicted by quark models*

C.-W. Hwang, EPJ C23, 585 (2002).
C. Albertus et al., NPA 740, 333 (2004)

$$\langle r^2 \rangle_{D^+} = 0.184\, fm^2 \quad \langle r^2 \rangle_{D_s^+} = 0.124\, fm^2 \quad \langle r^2 \rangle_{\Lambda_c^+} = 0.152\, fm^2$$

- Normalization in $f_W(\ldots)$ *fixed by requiring that $P_{coal}=1$ for $p=0$*

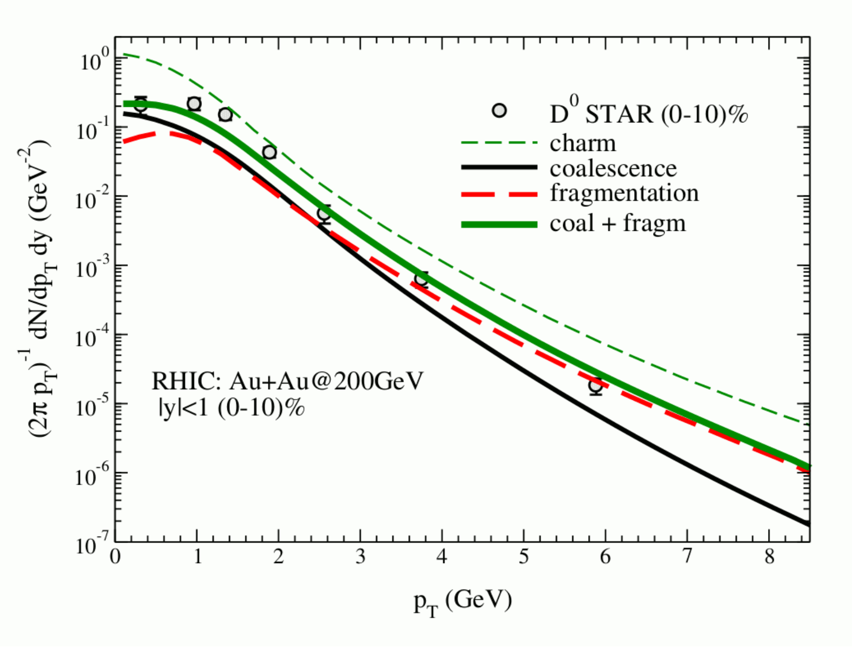


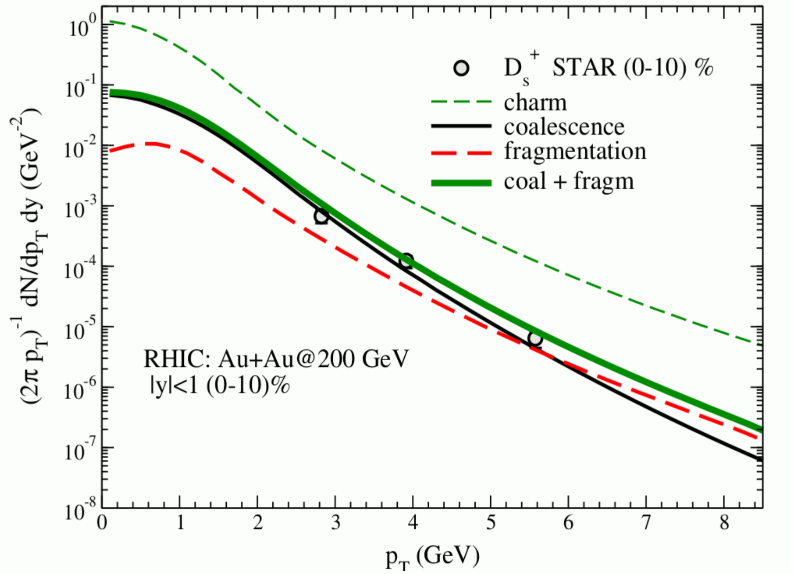
- *The charm not "coalesces" undergo fragmentation: charm number conserved at each p_T*
- *Is the same approach employed to predict Λ/K*

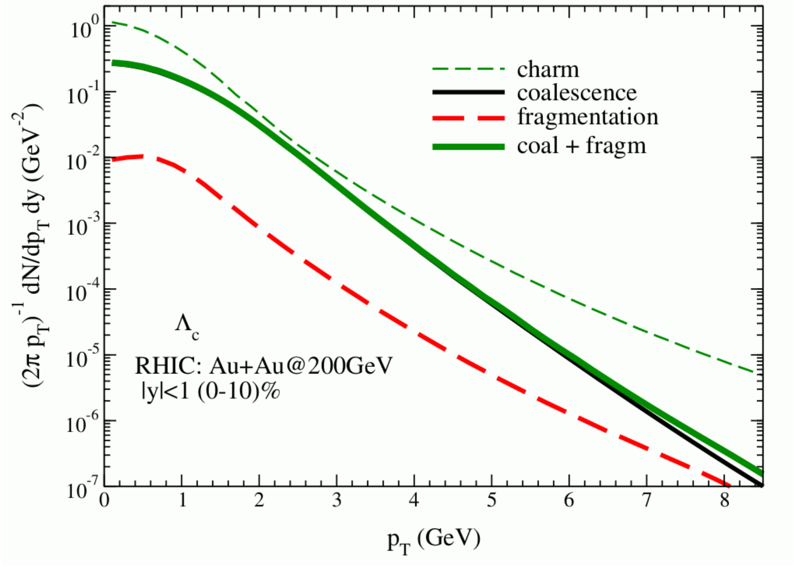
RHIC: results

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

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







S. Plumari, et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

RHIC: Baryon/meson

S. Plumari, et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

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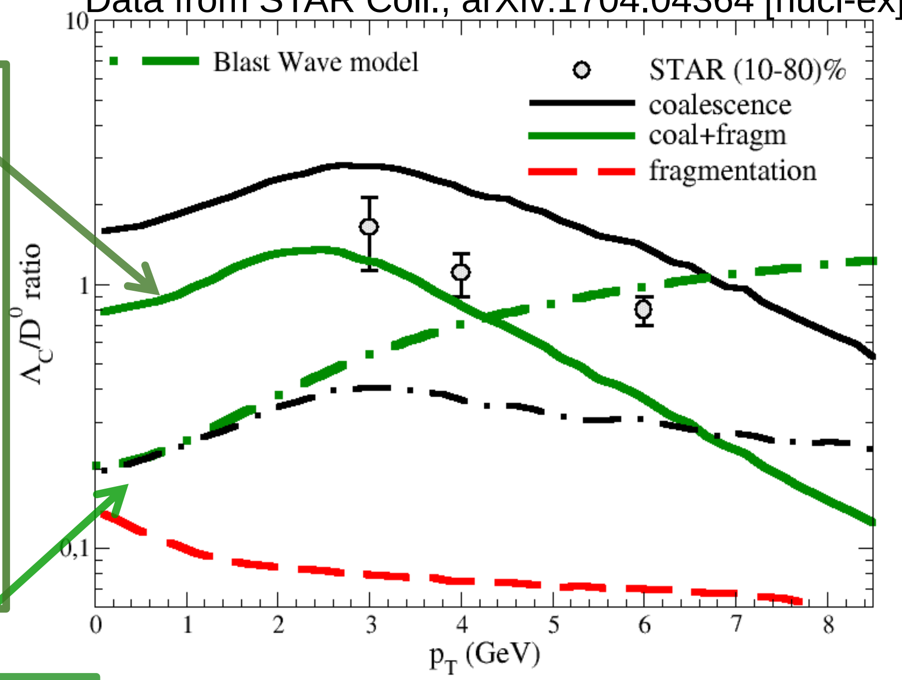

Coalescence

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 $p_T << m$

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

$$\mu_2 = \frac{m_3(m_1+m_2)}{m_1+m_2+m_3}$$ Is the reduced mass of the baryon

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 $p_T << m$

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

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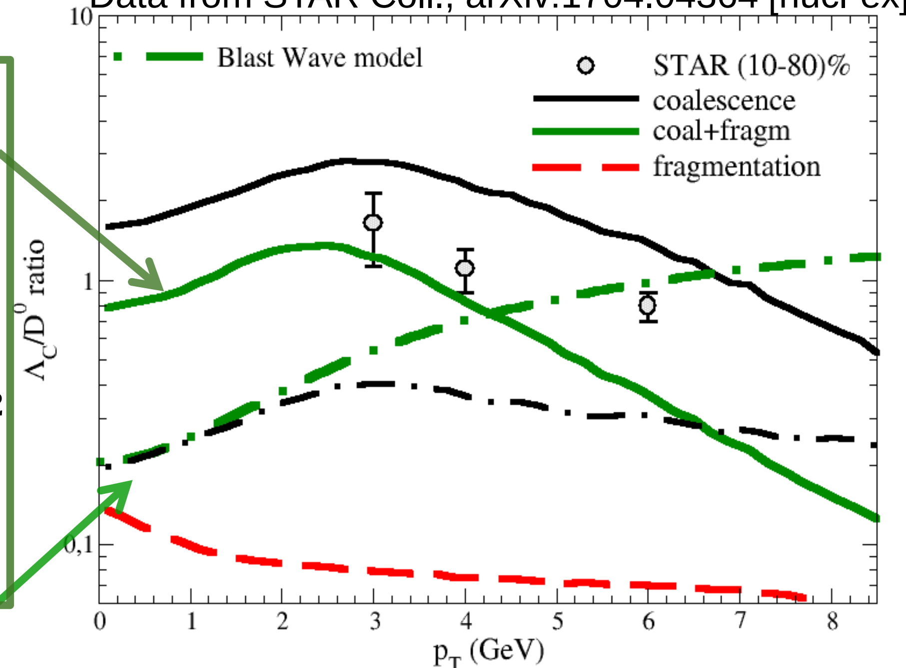

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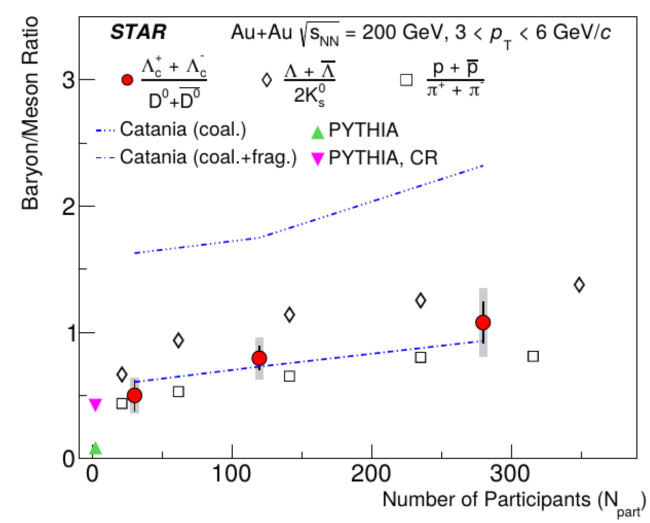
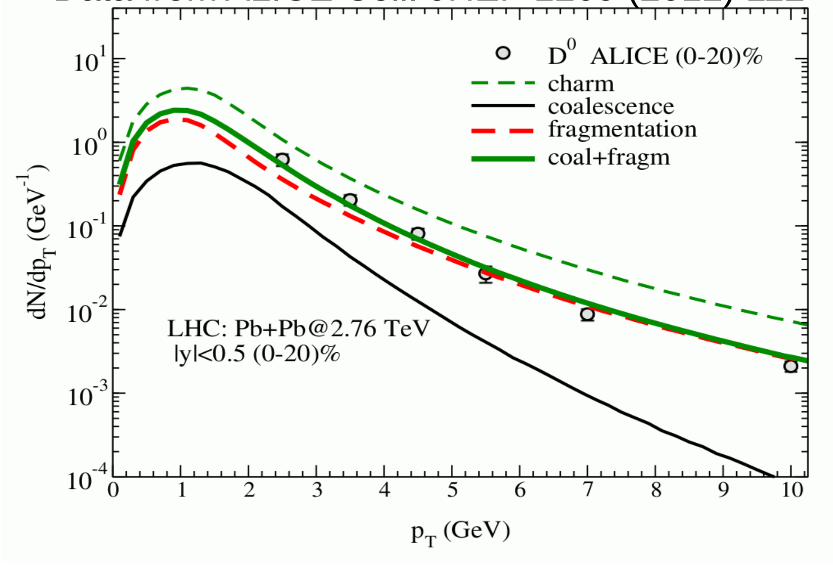
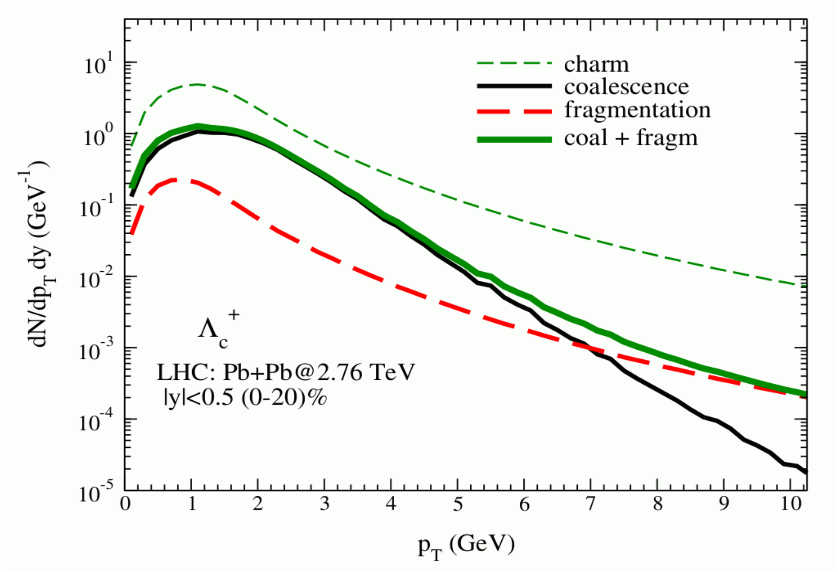


LHC: results

Data from ALICE Coll. JHEP 1209 (2012) 112

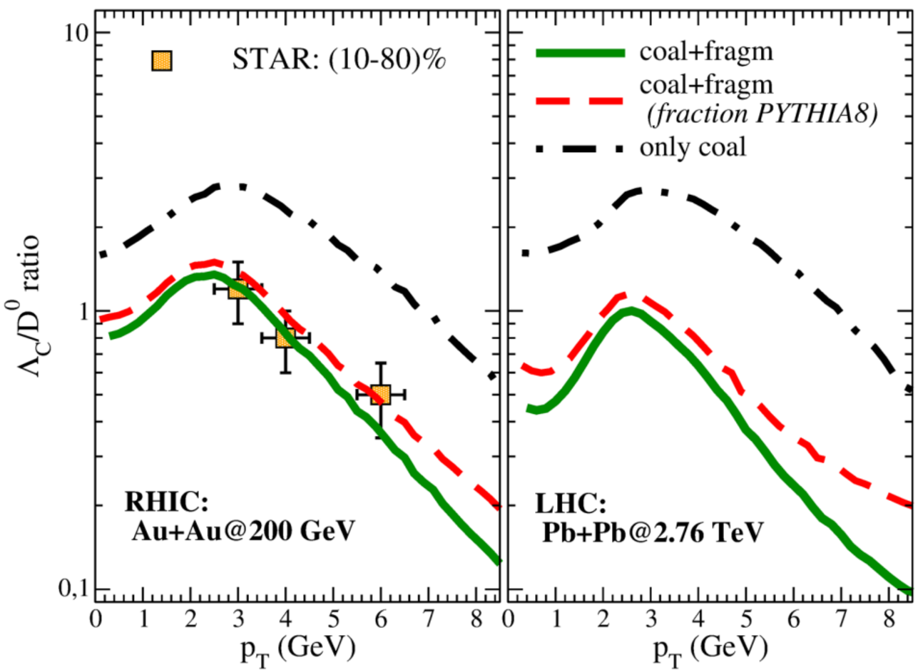




wave function widths σ_p of baryon and mesons

kept the same at RHIC and LHC!

STAR coll. arXiv:1910.14628

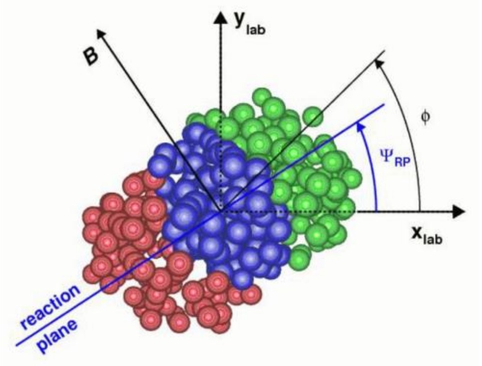


The Λ_c/D^0 ratio is smaller at LHC energies: fragmentation play a role at intermediate p_T

S. Plumari, et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

Extension to higher order anisotropic flows $v_n(p_T)$

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

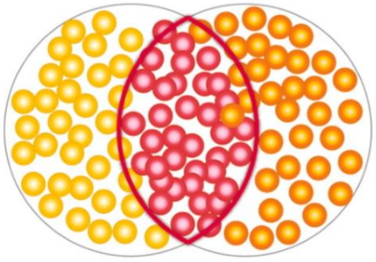


$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$ Elliptic flow

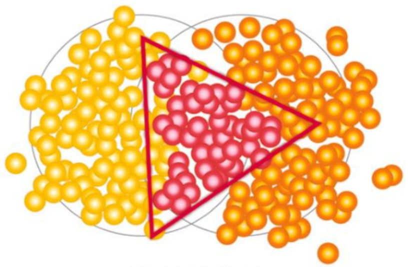
$$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$$ Triangular flow

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

$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$



Elliptic flow

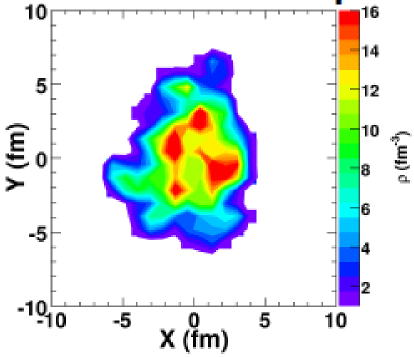


Triangular flow

Azimuthal anisotropies depend on

- the interaction and coupling of heavy quarks with the medium;
- the initial conditions of the system, i.e.geometry of the collision;

Not almond shape



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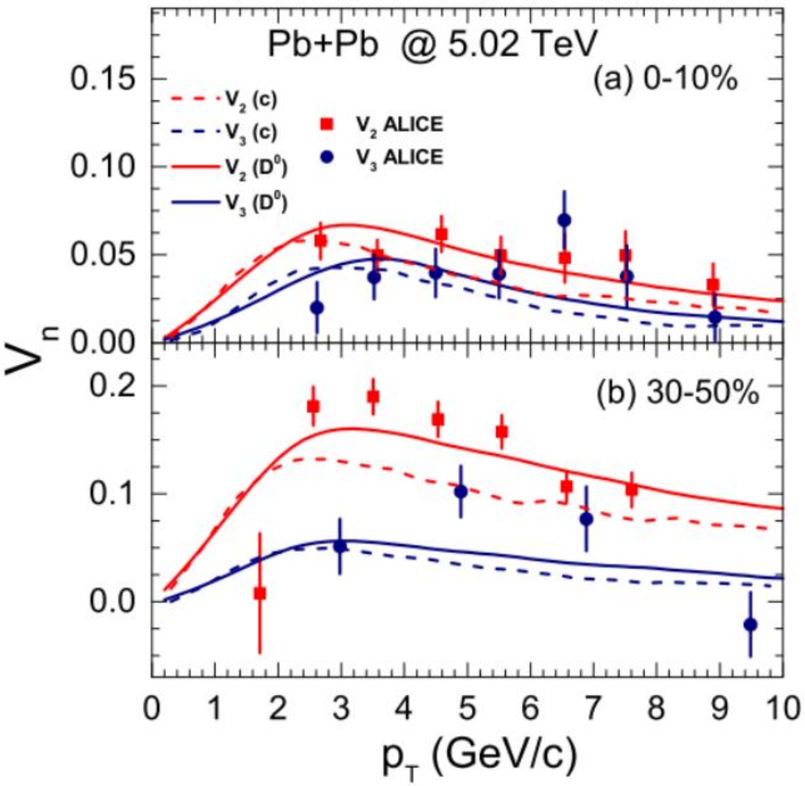
Y. Sun, M.L. Sambataro et al. in preparation



Data taken from ALICE collaboration: *Phys.Lett.B* 813 (2021) 136054

In the more peripheral collision (30-50 % centrality class) → larger v_2 and comparable v_3

- v_2 mainly from the geometry of overlapping region in larger centrality collision
- v_3 driven by the fluctuation of the triangularity of overlap region at all centrality

Extension to higher order anisotropic flows $v_n(p_T)$

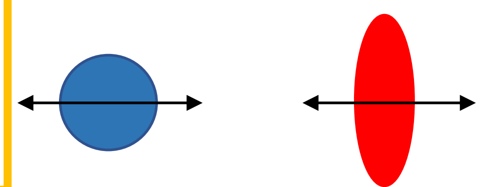
ESE tecnique and v_n correlations

Y. Sun, M.L. Sambataro et al. in preparation

Selection of events with the same centrality but different initial geometry on the basis of the magnitude of the second-order harmonic reduced flow vector q_2.

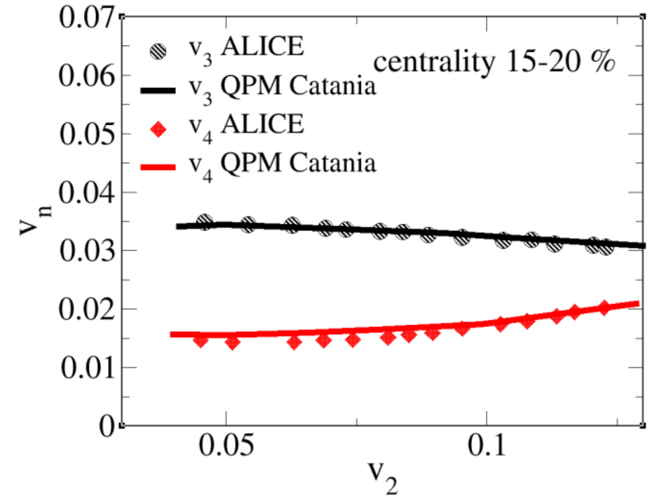
$$q_2 = |\vec{Q}_2|/\sqrt{M}$$

$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$

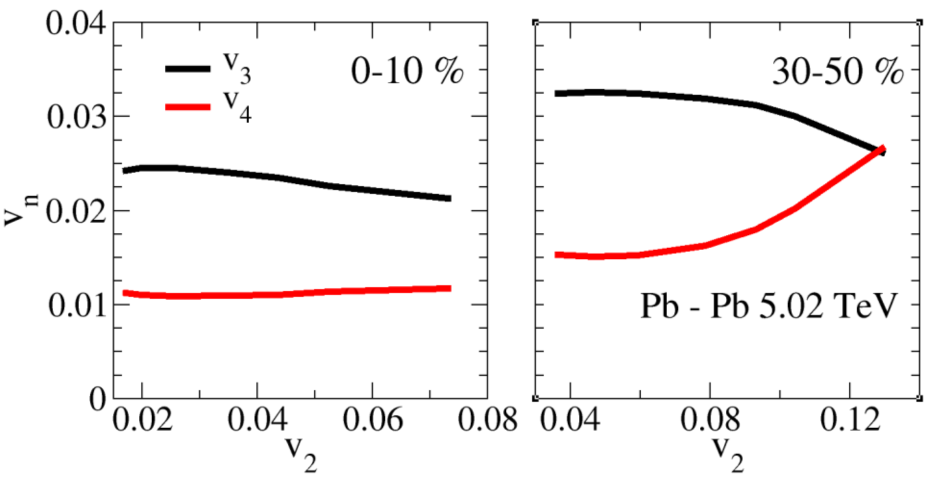


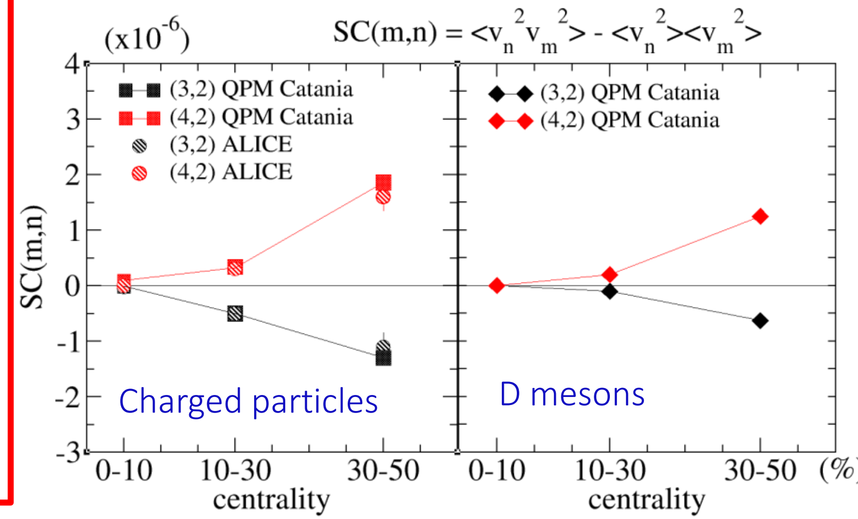
Large $q_2 \rightarrow$ large ε_2

Charged particles



Predictions for D mesons

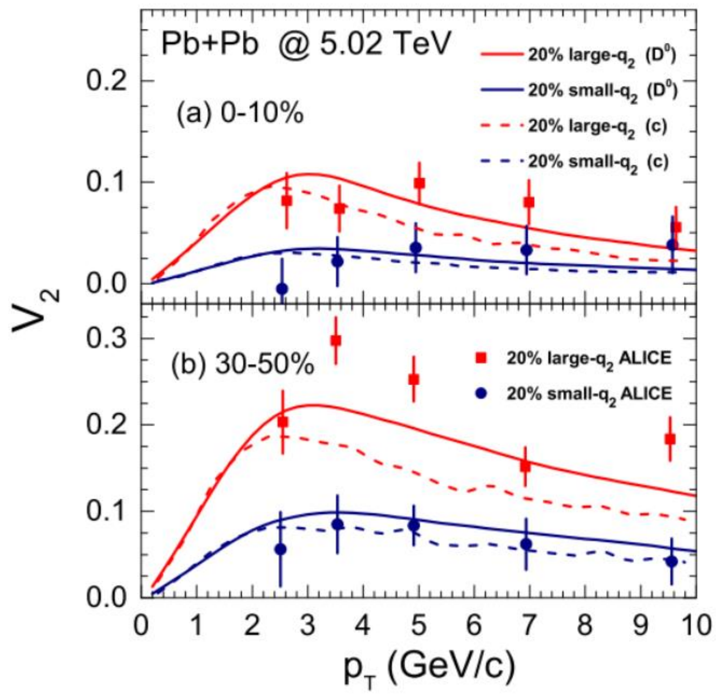




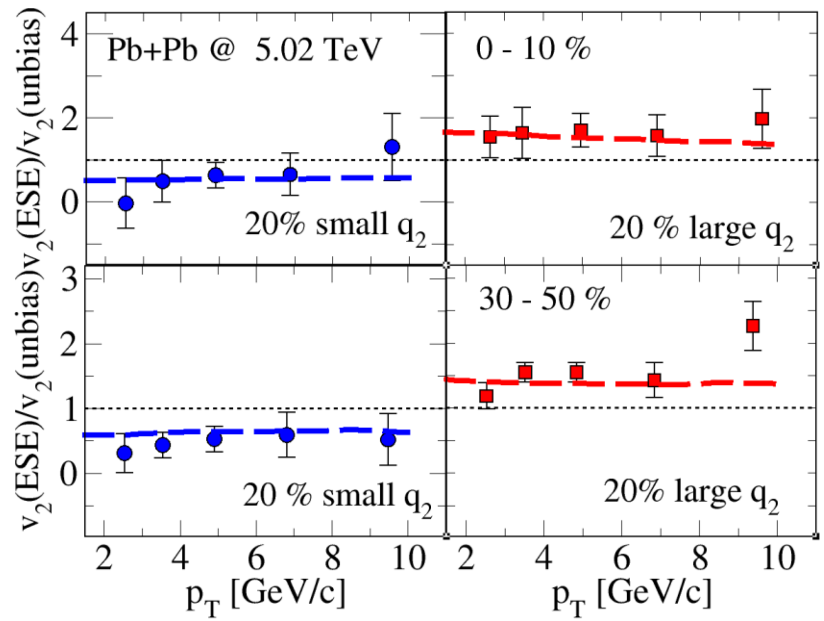
ESE: v_2 and spectra (20% small/large q_2)

Y. Sun, M.L. Sambataro et al. in preparation

$q_2$selected $v_2(p_T)$



$q_2$selected $v_2(p_T)$ ratio



Data taken from ALICE collaboration: *Phys.Lett.B* 813 (2021) 136054

- v_2 (large- q_2 /small- q_2) $\gtrsim v_2$ (unbiased) of about 50% in both 0-10% and 30-50% centrality
- The standard approach for R_{AA} and v_2 works for ESE observables

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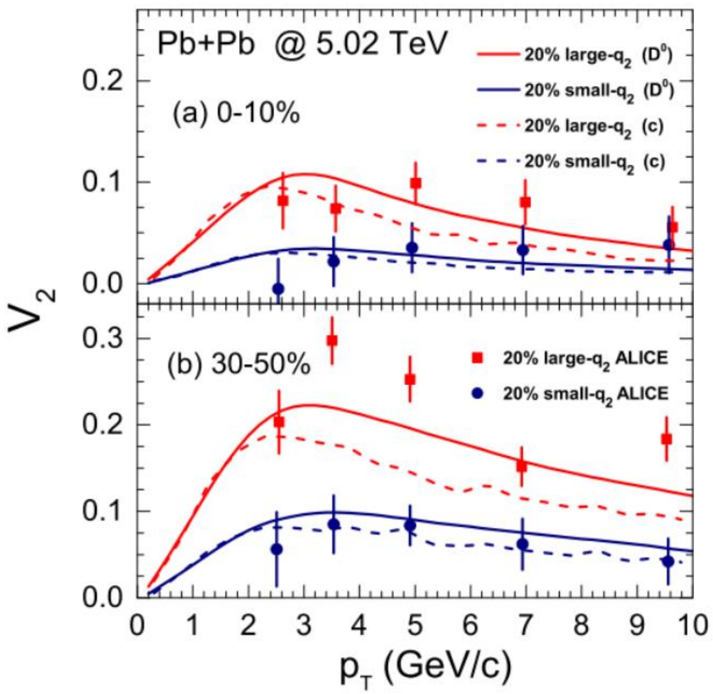

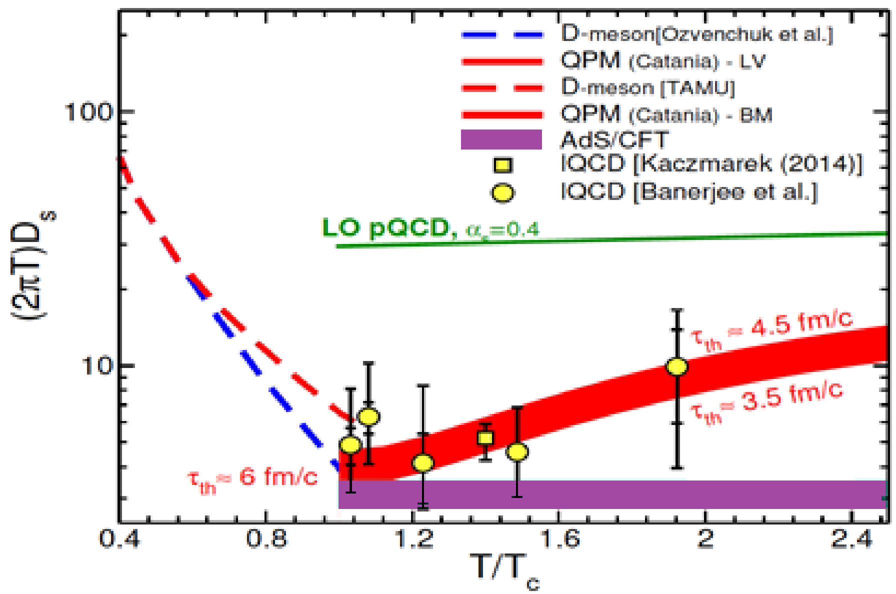

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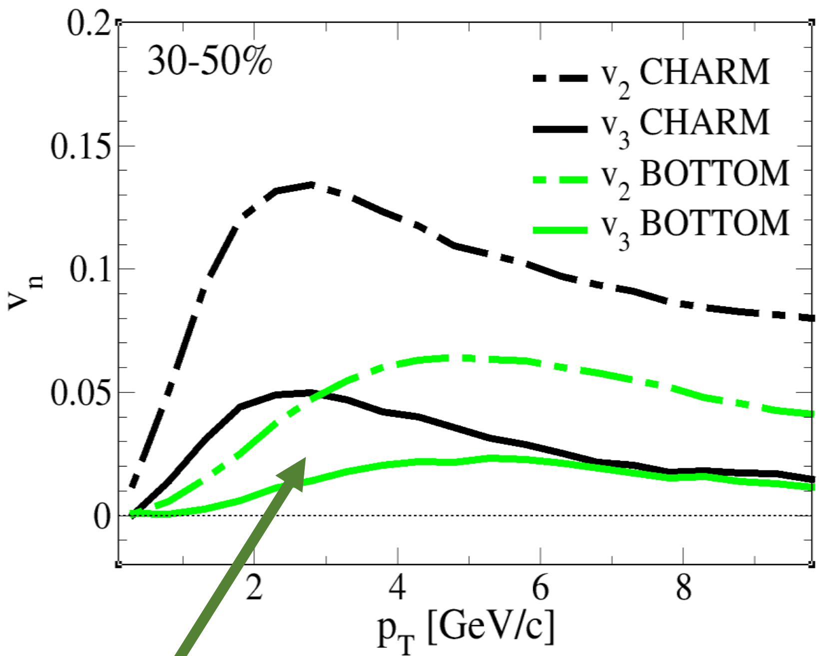
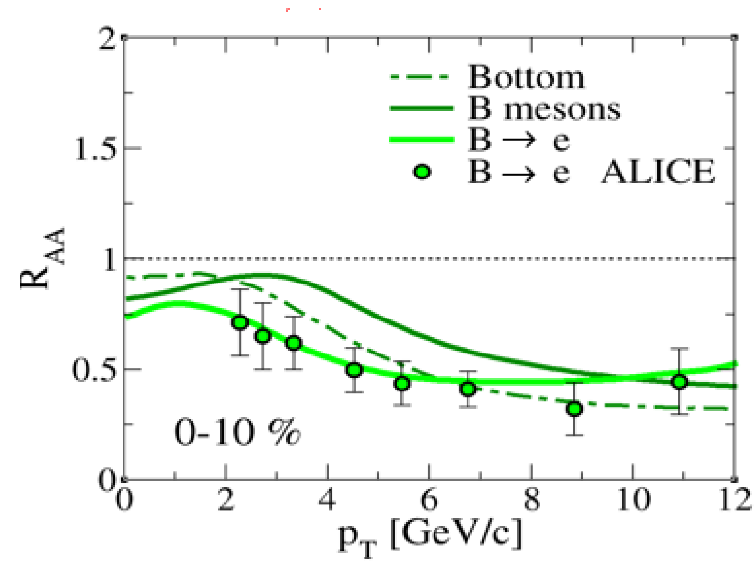
Extension to bottom dynamics: R_{AA} and v_n

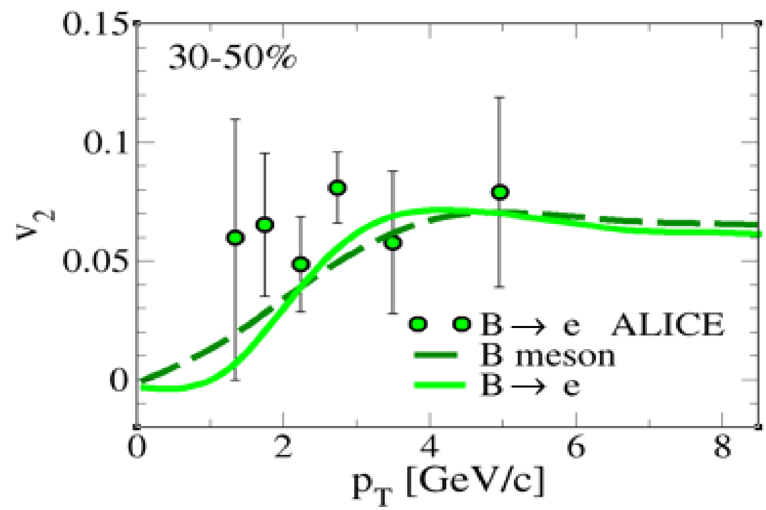
Prediction for B meson, electrons from semileptonic B meson decay within a coal + fragm model

Pb + Pb 5,02 TeV





Non-zero v_2, v_3 for bottom quark



M.L. Sambataro, V. Minissale et al., in preparation

Data taken from Arnaldi HP(2020)

Intense fields and heavy flavor transport

✓ **INTENSE VORTICITY FROM THE HUGE ANGULAR MOMENTUM**

→ **heavy quark transport coefficients and D meson directed flow**

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

✓ **INTENSE ELECTROMAGNETIC FIELDS (EMF)**

→ **D meson directed flow**

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

Y. Sun, S. Plumari and V. Greco, PLB 816, 136271 (2021)

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

Y. Sun, V. Greco and S. Plumari, arXiv:2104.03742 [nucl-th].

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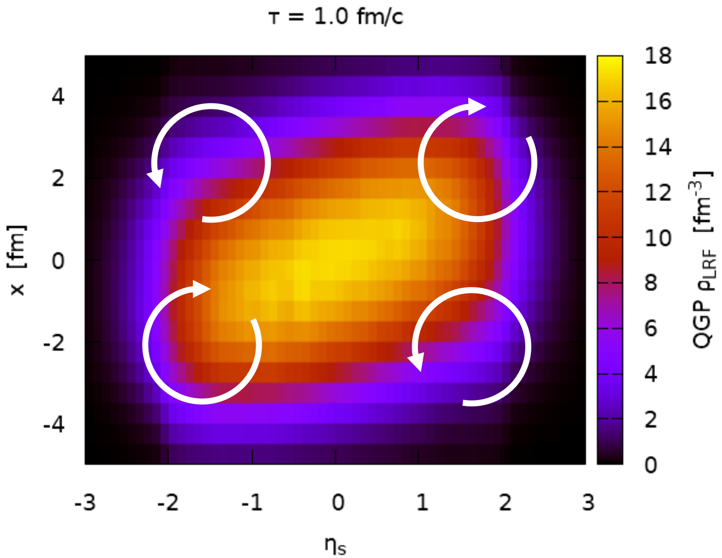
The vortical quark-gluon plasma

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



asymmetry in local participant density from forward and backward going nuclei

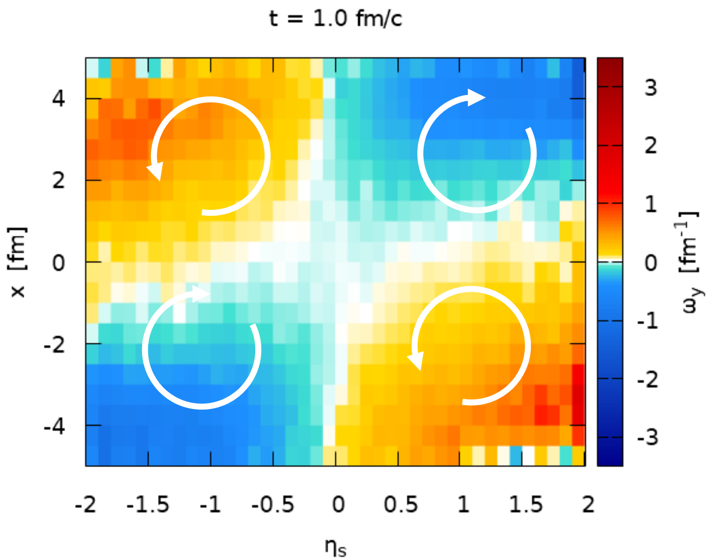
$$\rho(x_\perp,\eta_s)=\rho_0\frac{W(x_\perp,\eta_s)}{W(0,0)}\exp\left[-\frac{(|\eta_s|-\eta_{s0})^2}{2\sigma_\eta^2}\theta(|\eta_s|-\eta_{s0})\right]$$

$$W(x_\perp,\eta_s)=2\left(N_A(x_\perp)f_-(\eta_s)+N_B(x_\perp)f_+(\eta_s)\right)$$

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

inspired to initial conditions of hydro simulations

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)



The huge angular momentum and the tilt of the fireball induce in the QGP an intense <u>VORTICITY</u>

$$\omega=\nabla\times v$$

measure of the local angular velocity of the fluid

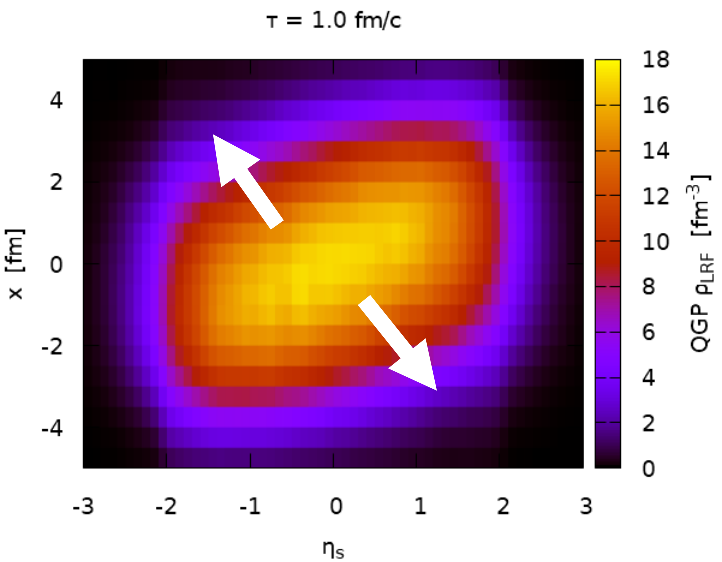
$$\omega_y\approx 3\ \text{c/fm}\approx 10^{23}\ \text{s}^{-1}$$

NONRELATIVISTIC VORTICITY

Csernai, Magas and Wang, Phys. Rev. C 87, 034906 (2013)
Deng and Huang, Phys. Rev . C 93, 064907 (2016)
Jiang, Lin and Liao, Phys. Rev. C 94, 044910 (2016)

Charged Directed flow v_1

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



asymmetry in local participant density from forward and backward going nuclei

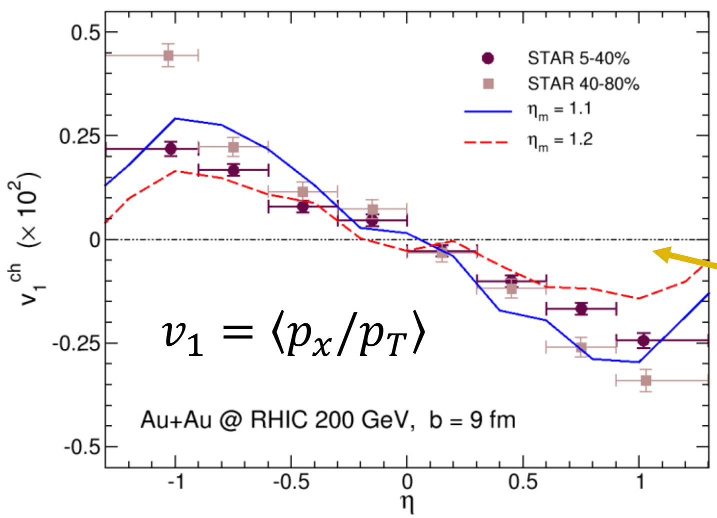
$$\rho(x_\perp, \eta_s) = \rho_0 \frac{W(x_\perp, \eta_s)}{W(0,0)} \exp\left[-\frac{(|\eta_s| - \eta_{s0})^2}{2\sigma_\eta^2}\theta(|\eta_s| - \eta_{s0})\right]$$

$$W(x_\perp, \eta_s) = 2\left(N_A(x_\perp) f_-(\eta_s) + N_B(x_\perp) f_+(\eta_s)\right)$$

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

inspired to initial conditions of hydro simulations

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)



DIRECTED FLOW OF CHARGED PARTICLES

The huge angular momentum and the tilt of the fireball induce in the QGP a <u>DIRECTED FLOW</u>

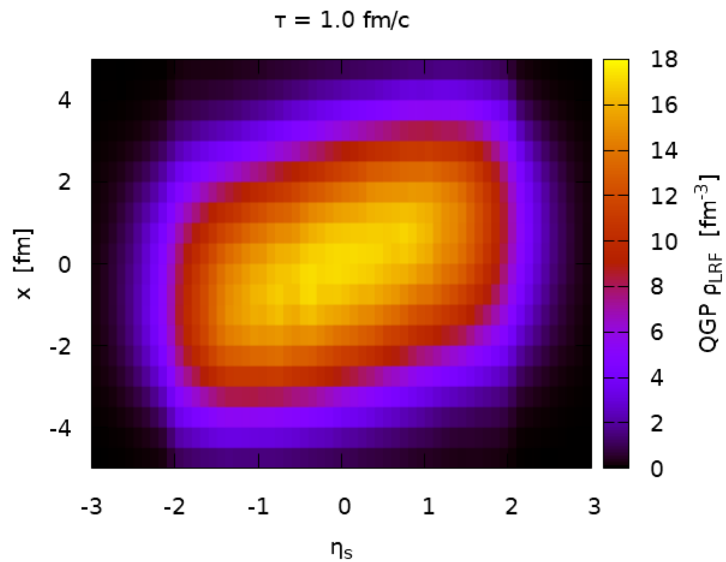
v_1 = 0 if the fireball is not tilted

collective sidewards deflection of particles along the *x* direction

The tilt of the fireball induce a negative slope in the η dependence of the v_1 of bulk particles

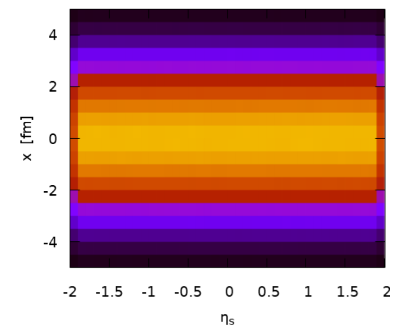
D meson directed flow

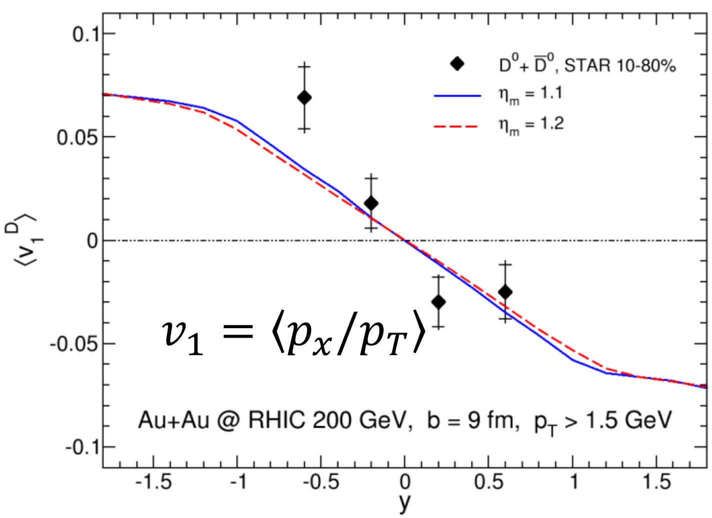
Oliva, Plumari and Greco, JHEP 05, 034 (2021)



Are HEAVY QUARKS affected by the initial tilt of the fireball and the directed flow of bulk medium?

production points of HQs symmetric in the forward-backward hemispheres





The directed flow of neutral *D* mesons is 20-30 times larger than that of light hadrons

Chatterjee and Bozek, Phys. Rev. Lett. 120, 192301 (2018)
STAR Collaboration, Phys. Rev. Lett. 123, 162301 (2019)

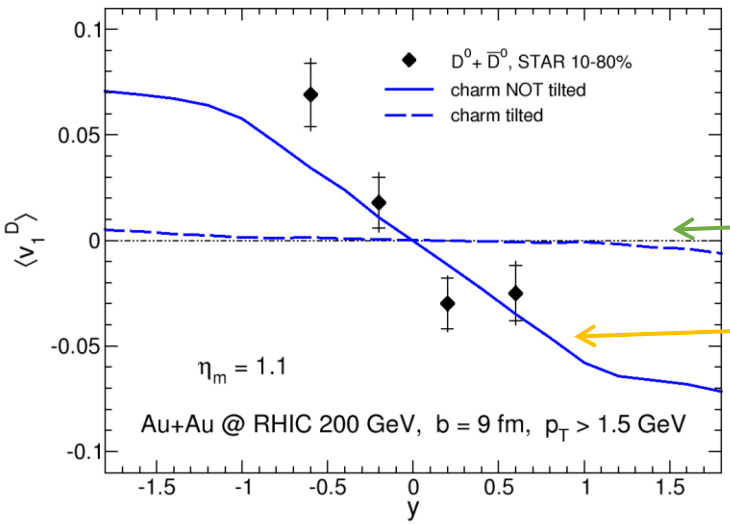
v_1 (HQs) >> v_1 (QGP)

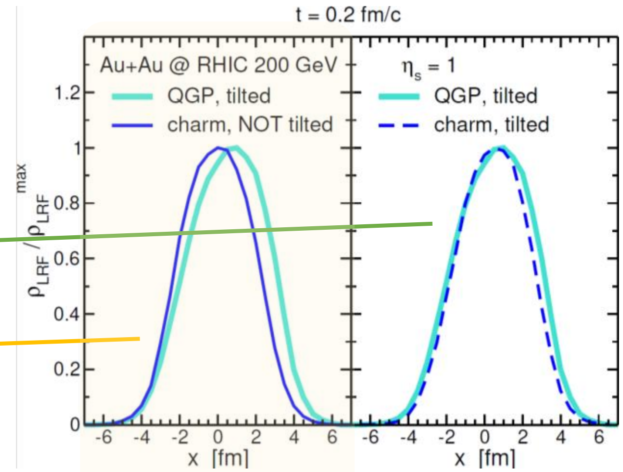
origin of the large directed flow of HQs different from the one of light particles

DIRECTED FLOW OF NEUTRAL D MESONS

Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

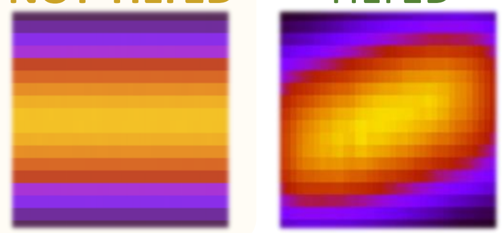




longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM NOT TILTED

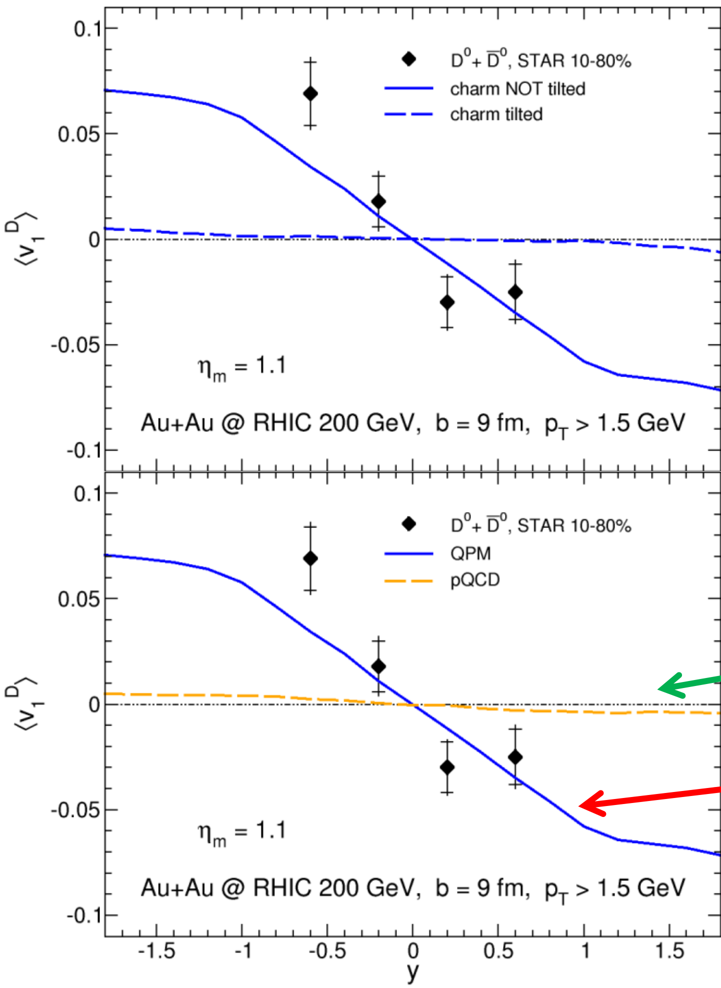
CHARM TILTED



QGP tilted in both cases

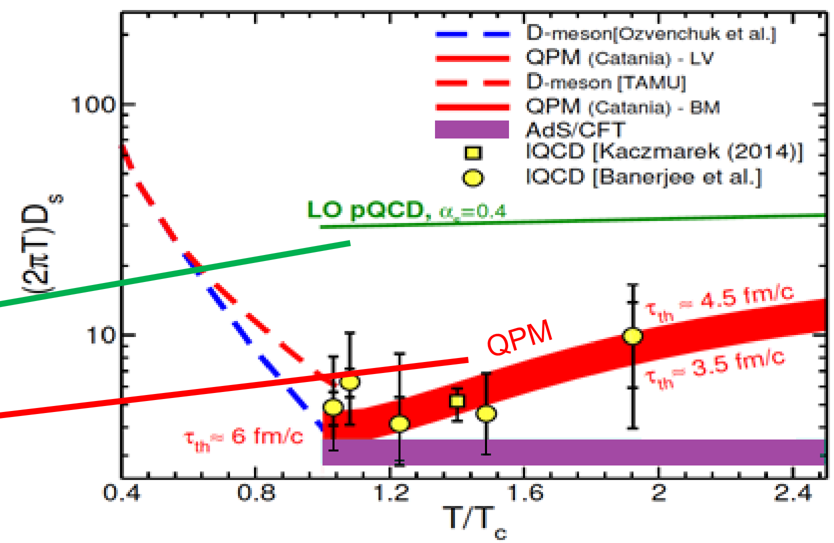
Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



longitudinal asymmetry leads to pressure push of the bulk on the HQs

effective because the HQ interaction in QGP is largely non-perturbative



Greco, NPA 967, 200 (2017)

strict connection between the magnitude of the D-meson v_1 and the HQ diffusion coefficient

Similar conclusions with POWLANG approach

Beraudo, De Pace, Monteno, Nardi and Prino, 2102.08064

Intense fields and heavy flavor transport

✓ INTENSE VORTICITY FROM THE HUGE ANGULAR MOMENTUM

→ heavy quark transport coefficients and D meson directed flow

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

✓ INTENSE ELECTROMAGNETIC FIELDS (EMF)

→ D meson directed flow

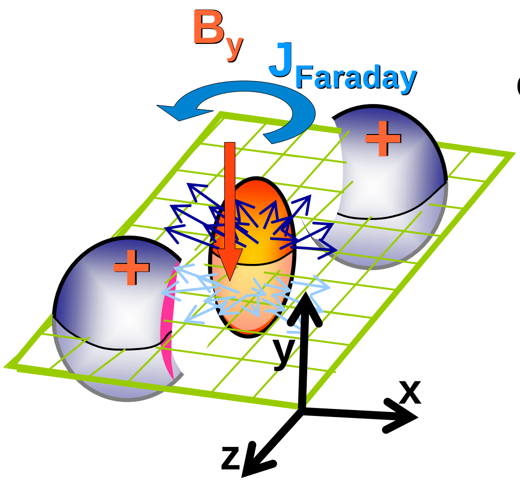
S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina and V. Greco, PLB 768, 260 (2017)

Y. Sun, S. Plumari and V. Greco, PLB 816, 136271 (2021)

L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

Y. Sun, V. Greco and S. Plumari, arXiv:2104.03742 [nucl-th].

Electromagnetic fields in HICs



external charge and current produced by a point-like charge in longitudinal motion

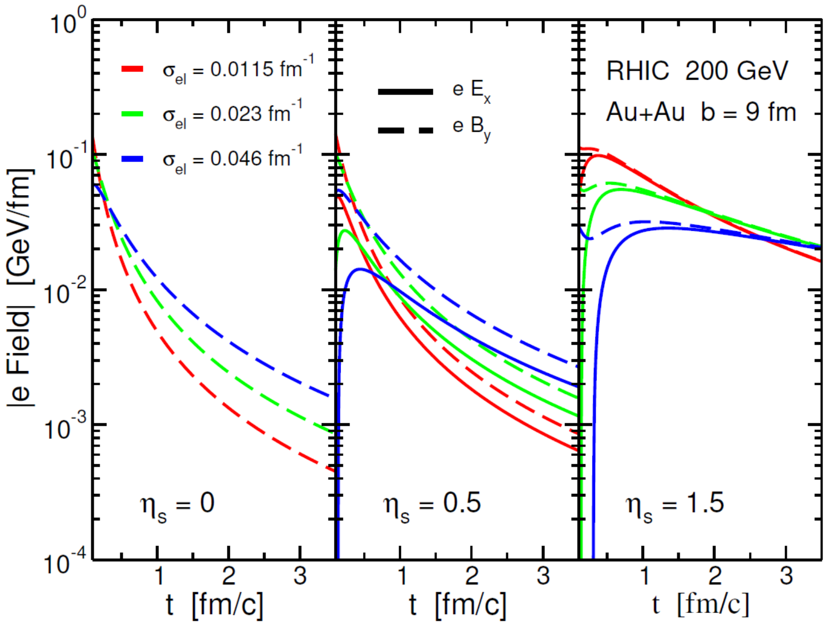
induced current from Ohm's law

$$\boldsymbol{J}_{ind} = \sigma_{el}\boldsymbol{E}$$

$$\rho = \rho_{ext} \qquad \boldsymbol{J} = \boldsymbol{J}_{ext} + \boldsymbol{J}_{ind}$$

$$\rho_{ext} = e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x}'_\perp)$$

$$\boldsymbol{J}_{ext} = \hat{z}\beta e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x}'_\perp)$$



Oliva, Plumari and Greco, JHEP 05, 034 (2021)

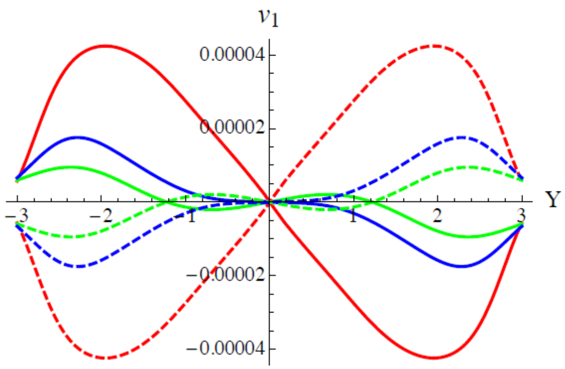
Maxwell equations for the EMF can be solved analytically considering a medium with **constant electric conductivity**

Tuchin, Adv. High Energy Phys. 2013, 1 (2013)
Gursoy, Kharzeev, Rajagopal, Phys. Rev. C 89, 054905 (2014)

We solve the Boltzmann eq. with EMF interaction term

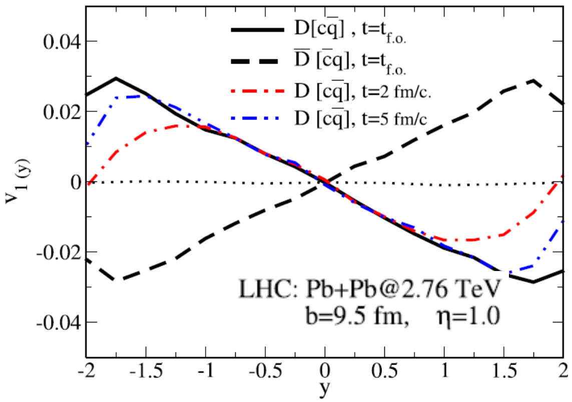
$$p^\mu \partial_\mu f(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f(x,p) = \mathcal{C}[f]$$

EMF and directed flow splitting



The huge EMF induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

- difference in the v_1 of light hadrons in AA: $O(10^{-4}–10^{-3})$
  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014)
  Toneev, Voronyuk, Kolomeitsev and Cassing,
  Phys. Rev. C 95, 034911 (2017)



- difference in the v_1 of heavy mesons in AA: $O(10^{-2})$
  Das, Plumari, Chatterjee, Alam, Scardina and Greco,
  Phys. Lett. B 768, 260 (2017)
  Chatterjee and Bozek, Phys. Lett. B 798, 134955 (2019)

reviews

Oliva, Eur. Phys. J. A 56, 255 (2020)

Dubla, Gursoy and Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

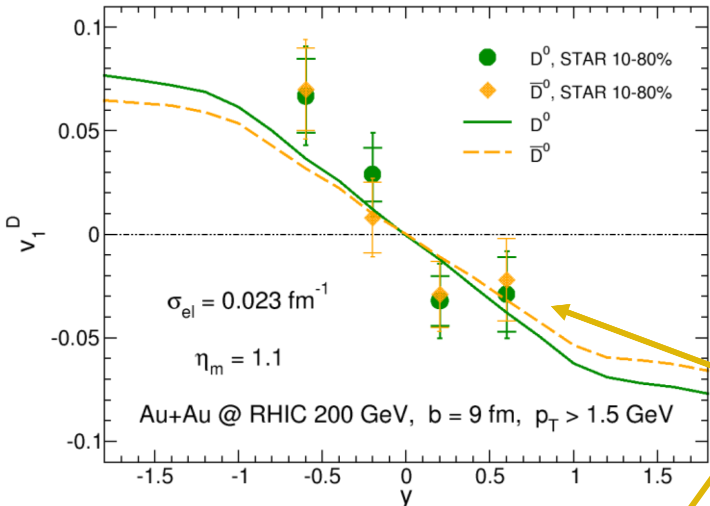
Directed flow in A+A at RHIC energy

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS

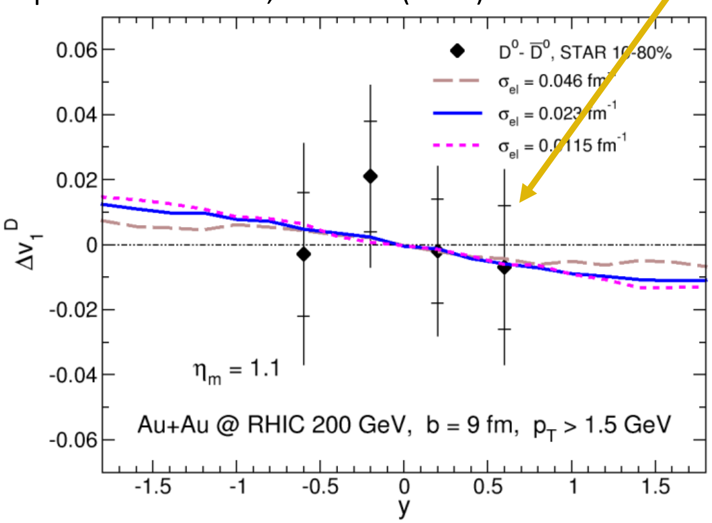
v_1 (HQ) - v_1 (QGP)

charm quarks are more sensitive to the EMF due to the early production

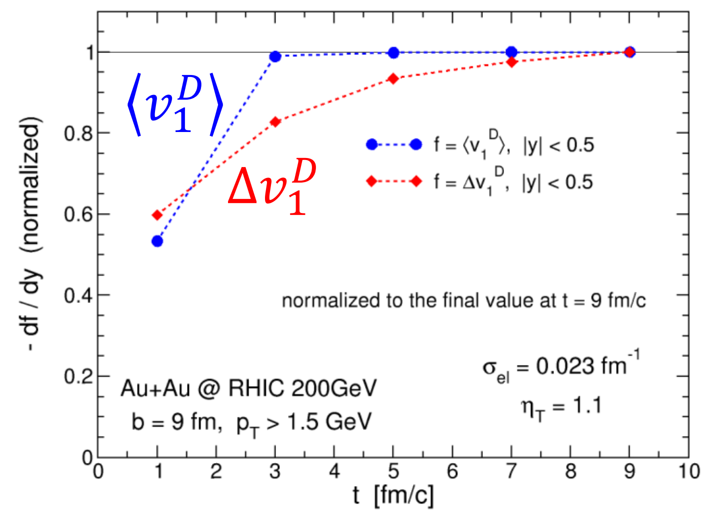


exp. Δv_1^D still consistent with zero due to the large errors

Exp. data: STAR Coll., PRL. 123 (2019) 162301



SLOPE TIME EVOLUTION



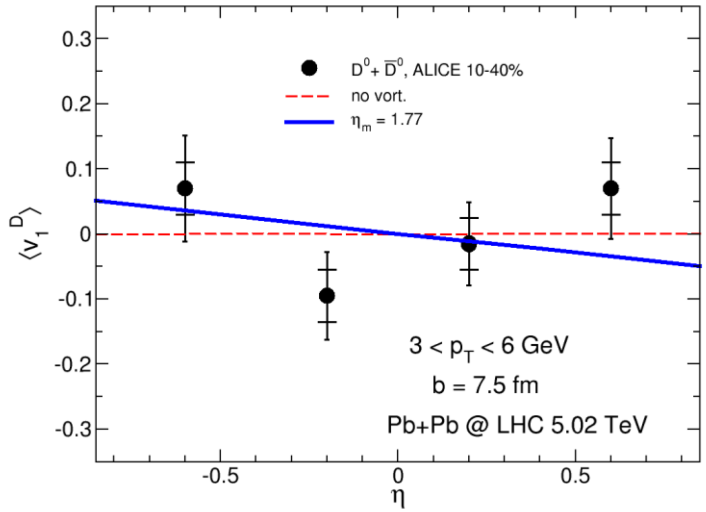
DIRECTED FLOW OF NEUTRAL D MESONS

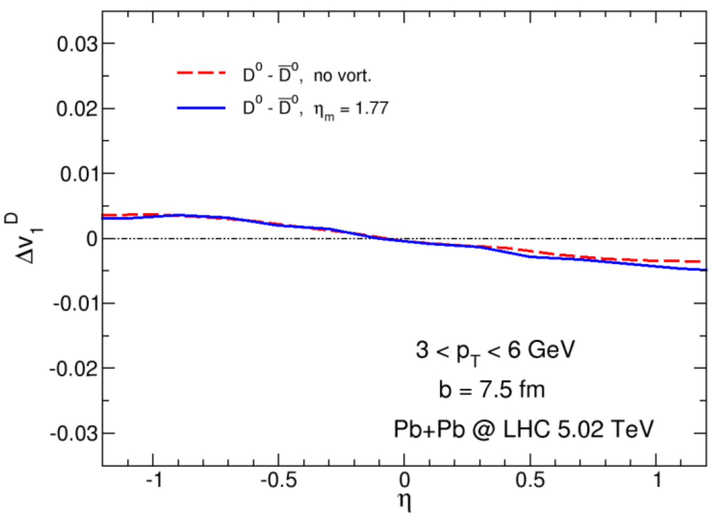
$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more $T \sim T_c$
$\rightarrow$ include v_1^D in Bayesian fits

Directed flow in A+A at LHC energy

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



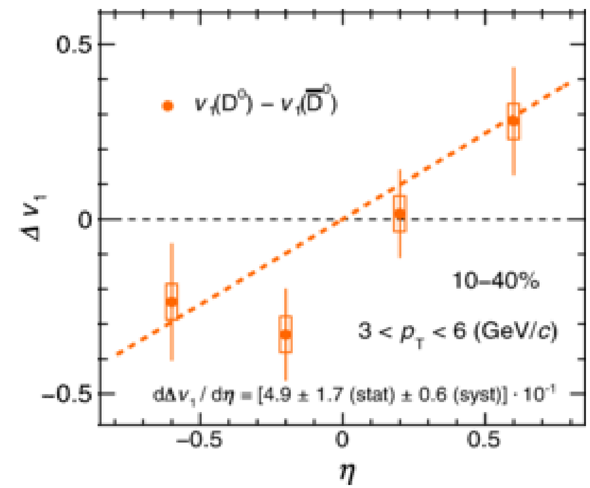


DIRECTED FLOW OF NEUTRAL D MESONS

$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

the slope of the combined v_1 of D^0 and $\bar{D}^0$ indicated by ALICE data is smaller than the one observed at RHIC and is consistent with zero

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



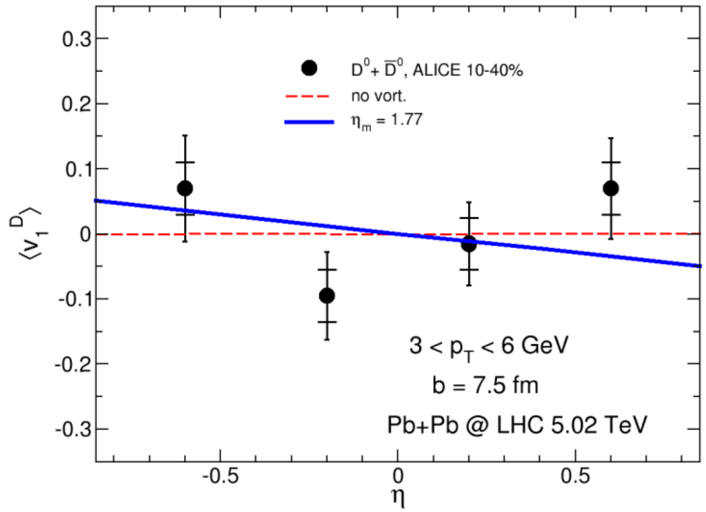
$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

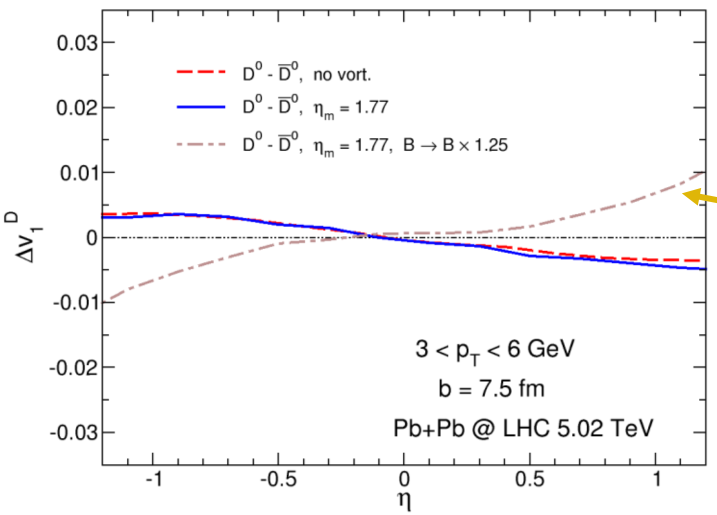
the Δv_1 of D^0 and $\bar{D}^0$ measured by ALICE has opposite sign and magnitude ~50 times larger

if the v_1 splitting of neutral *D* mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

Directed flow in A+A at LHC energy

Oliva, Plumari and Greco, JHEP 05, 034 (2021)





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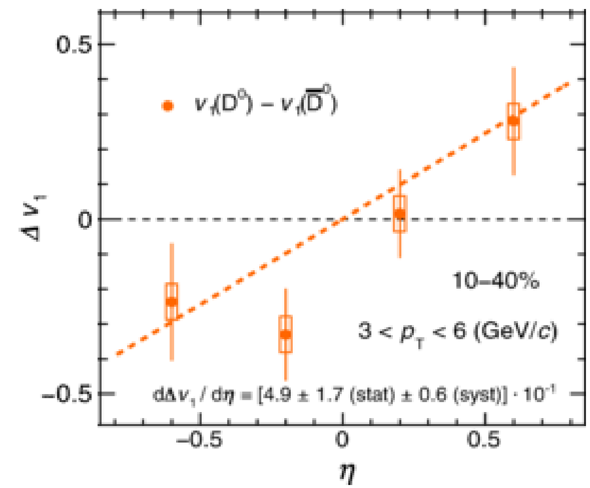
ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

positive slope rising by hand the value of the magnetic field

if the v_1 splitting of neutral *D* mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

DIRECTED FLOW OF NEUTRAL D MESONS

$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

Conclusions

Spatial diffusion coefficient $D_S(T)$ that reproduces D meson $R_{AA}$and v_2 gives correct predictions for v_3 and q_2 selected anisotropic flow/spectra.

Prediction for significant $v_n - v_m$ correlation of hard particles, similar correlation between v_n of soft and hard particles.

New perspectives: B meson v_3 and impact of $\Lambda_B/\ B^0$ on B meson R_{AA}.

STRONG FIELDS IN ULTRARELATIVISTIC COLLISIONS

- intense **vorticity** induced by the huge angular momentum
- intense **electromagnetic fields**

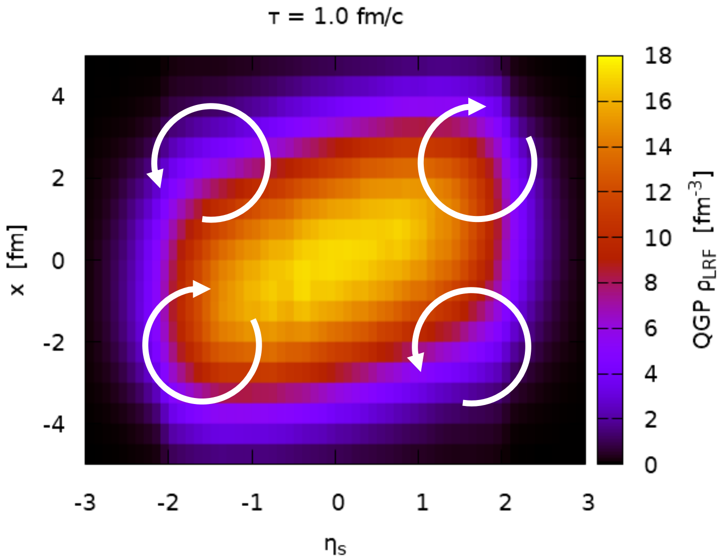
Among the many interesting effects these intense fields have an impact on transport coefficients and observables of heavy-flavor particles.

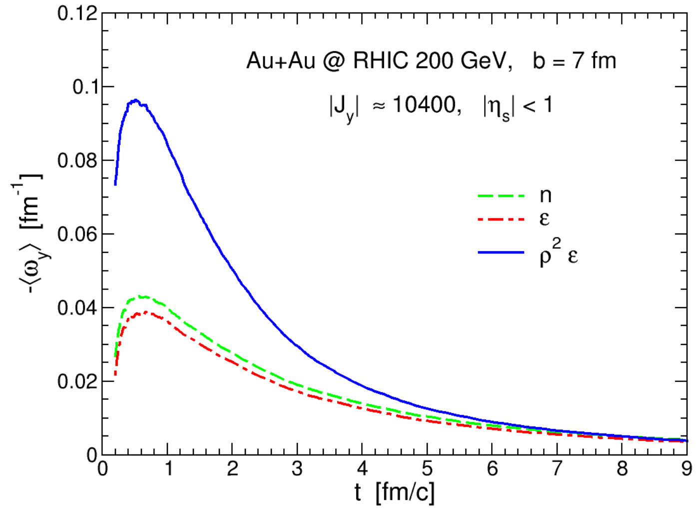
✓ The very large v_1 for *D* mesons can be generated only if there is a longitudinal asymmetry between the bulk matter and the charm quarks and if the latter have a large non-perturbative interaction in the QGP medium.

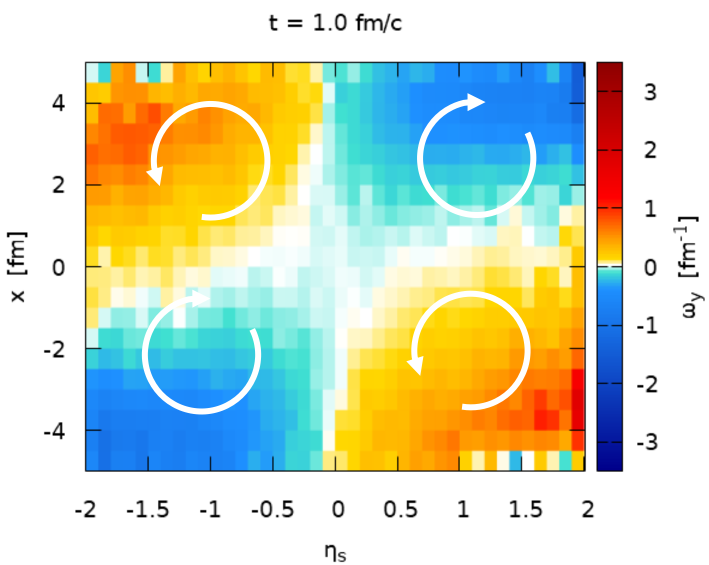
✓ The v_1 splitting of neutral *D* mesons is well described at RHIC energy but still a challenge at LHC

The vortical quark-gluon plasma

Oliva, Plumari and Greco, JHEP 05, 034 (2021)







$$\langle\omega_y\rangle(\boldsymbol{x},t) = \frac{\int d^3x\, w(\boldsymbol{x},t)\omega_y(\boldsymbol{x},t)}{\int d^3x\, w(\boldsymbol{x},t)}$$

$w(\boldsymbol{x},t)$ = weigthing function

$n(\boldsymbol{x},t), \varepsilon(\boldsymbol{x},t), \rho^2(\boldsymbol{x})\varepsilon(\boldsymbol{x},t)$

Csernai, Magas and Wang, Phys. Rev. C 87, 034906 (2013)
Deng and Huang, Phys. Rev . C 93, 064907 (2016)
Jiang, Lin and Liao, Phys. Rev. C 94, 044910 (2016)

Heavy flavour (charm): 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

Statistical factor

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

MESONS

D^+ *(I=1/2,J=0)*

D^0 *(I=1/2,J=0)*

D_s^+ *(I=0,J=0)*

Resonances

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

BARYONS

Λ_c^+ *(I=0, J=1/2)*

Resonances

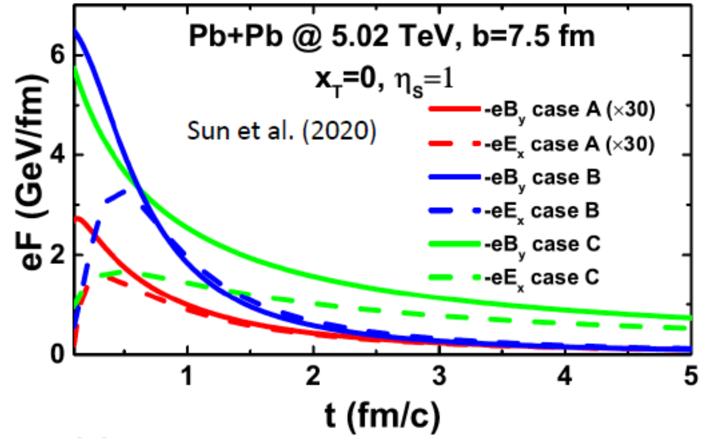
$\Lambda_c^+(2595)$ *(I=0,J=1/2)*	→	Λ_c^+	*B.R. 100%*
$\Lambda_c^+(2625)$ *(I=0,J=3/2)*	→	Λ_c^+	*B.R. 100%*
$\Sigma_c^+(2455)$ *(I=1,J=1/2)*	→	$\Lambda_c^+\pi$	*B.R. 100%*
$\Sigma_c^+(2520)$ *(I=1,J=3/2)*	→	$\Lambda_c^+\pi$	*B.R. 100%*

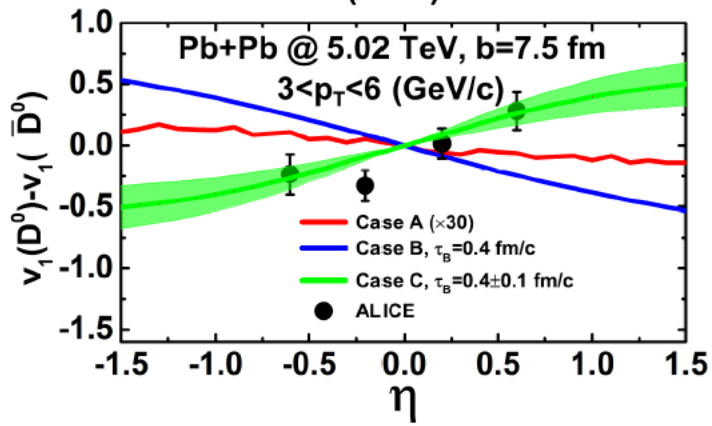
Directed flow of charm and leptons

Sun, Plumari and Greco, Phys. Lett. B 816, 136271 (2021)

- Analytic solution of EMF with constant σ_{el} case A
- Magnetic field parametrization between in-vacuum and in-medium decay: $B(\tau) = B_0/[1 + (\tau/\tau_B)^n]$
  case B n=2 case C n=1
  Electric field from Faraday law

case C reproduces the ALICE data for the $\Delta v_1\,(D^0,\bar{D}^0)$ but it is really a slow time decay of B





Directed flow of charm and leptons

Sun, Plumari and Greco, Phys. Lett. B 816, 136271 (2021)

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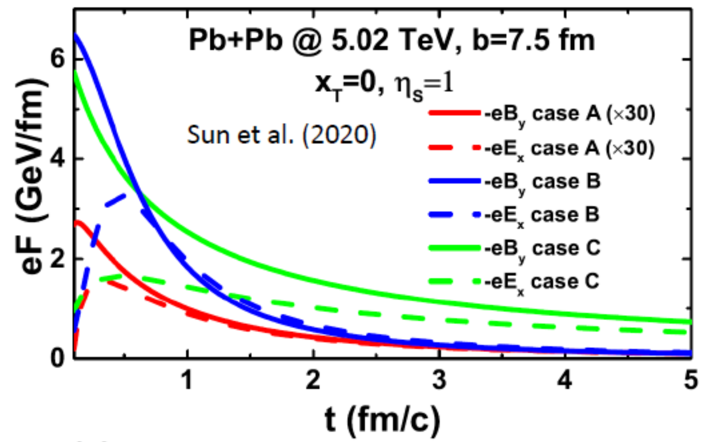
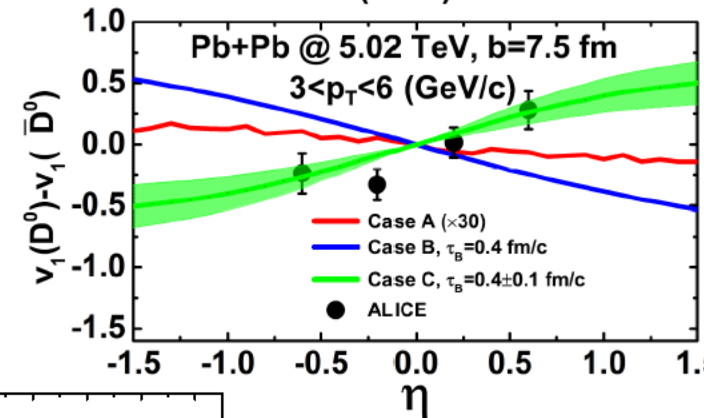


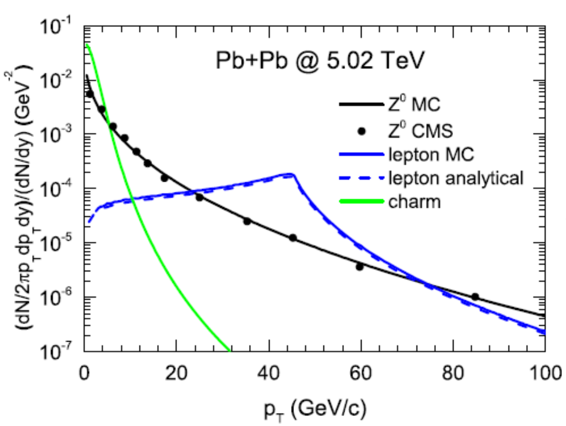
case C reproduces the ALICE data for the Δv_1 (D^0,$\overline{D}^0$) but it is really a slow time decay of B

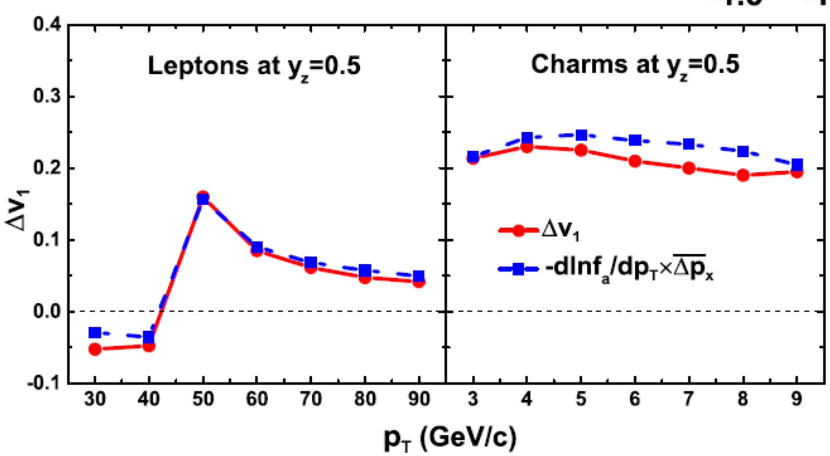


Probing the EMF with leptons from Z^0 decay

- charged leptons interact only electromagnetically
- $\tau_{decay}(Z^0) \approx \tau_{form}(c) \approx 0.08$ fm/c

$$v_1(p_T, y) \approx \frac{\overline{\Delta p_x}(p_T, y)}{2} \frac{-\partial \ln f_a}{\partial p_T}$$





Δv_1 of leptons from Z^0 decay can help to clarify the electromagnetic origin of Δv_1 of neutral D mesons