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HEAVY-FLAVOR ANISOTROPIC FLOW AT RHIC AND LHC ENERGIES WITHIN A FULL TRANSPORT APPROACH

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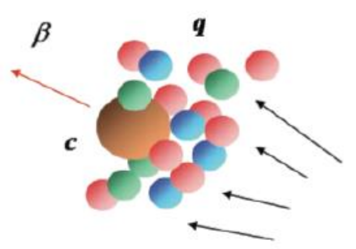
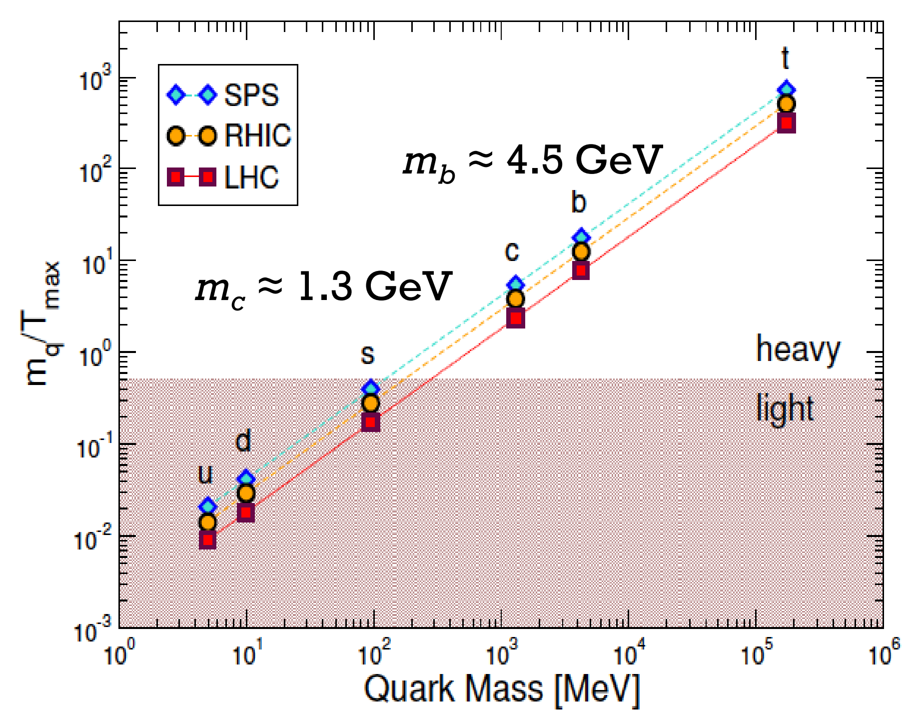
DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

HEAVY QUARKS (HQ) IN QGP: BASIC SCALES

few Heavy-Flavor (HF) quarks and antiquarks
CHARM and **BOTTOM**
produced in relativistic heavy-ion collisions





- $\mathbf{m_{HQ} \gg \Lambda_{QCD}}$ → HQ produced in pQCD initial hard scatterings
- $\mathbf{m_{HQ} \gg T_{HICs}}$ → negligible thermal production of HQs

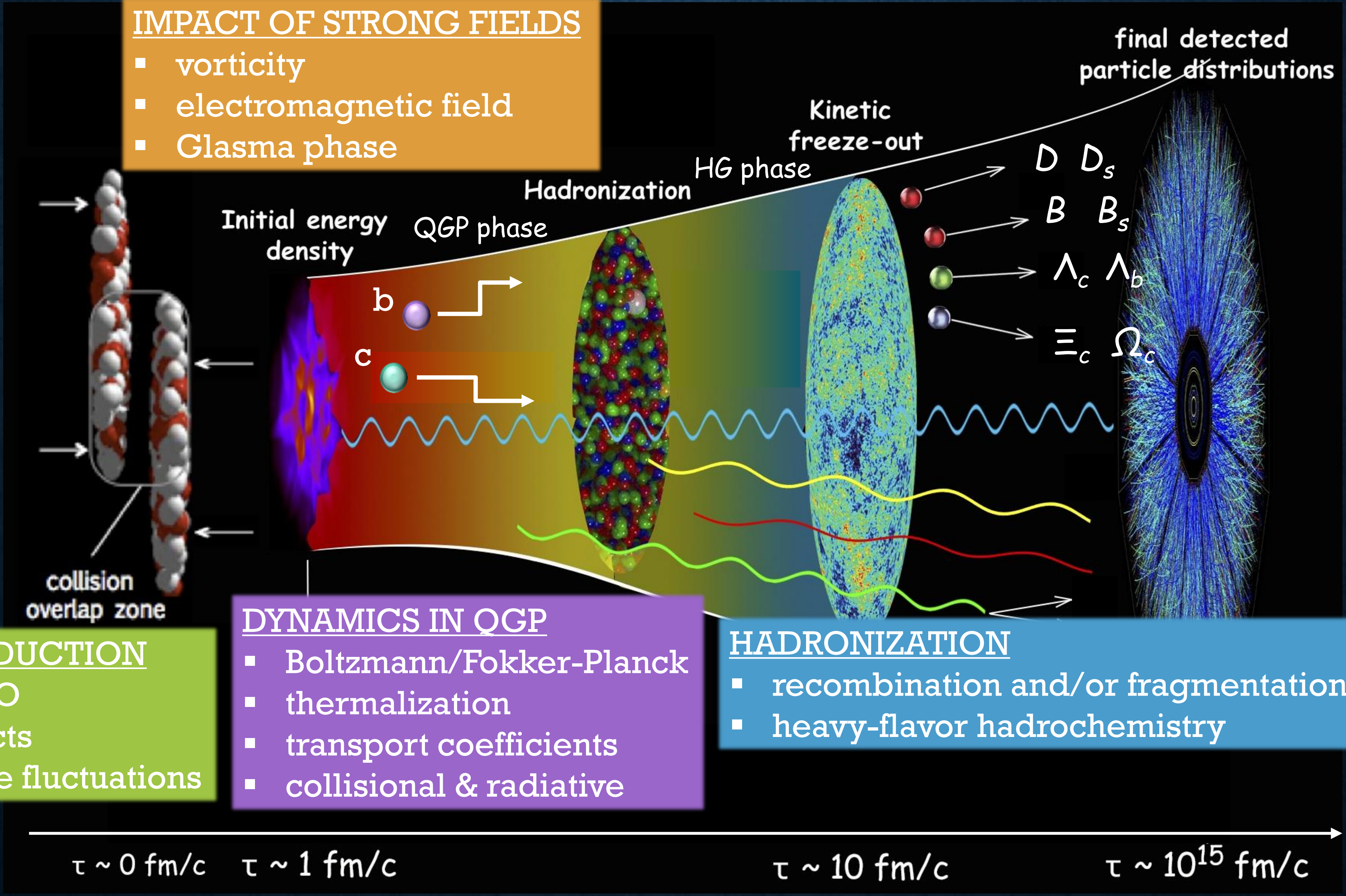
HQ production points symmetric in the forward-backward hemispheres

- $\tau_0^{HQ} < 0.08$ fm/c $\ll \tau_0^{QGP}$ → HQ production much earlier than QGP formation
- $\tau_{th}^{HQ} \approx \tau^{QGP} \approx$ 5-10 fm/c $\gg \tau_{th}^{QGP}$ → HQ thermalization time comparable to QGP life

HQ final states keep a better memory of both initial stage and QGP evolution

- $\mathbf{q < m_{HQ}, p_{HQ}; m_{HQ} \ll gT_{HICs}}$ (*b* or low momentum *c*) → Brownian motion of HQs in QGP

HEAVY FLAVORS IN RELATIVISTIC HICS



Modified from picture of Chun Shen (McGill University, Montreal QC, Canada)

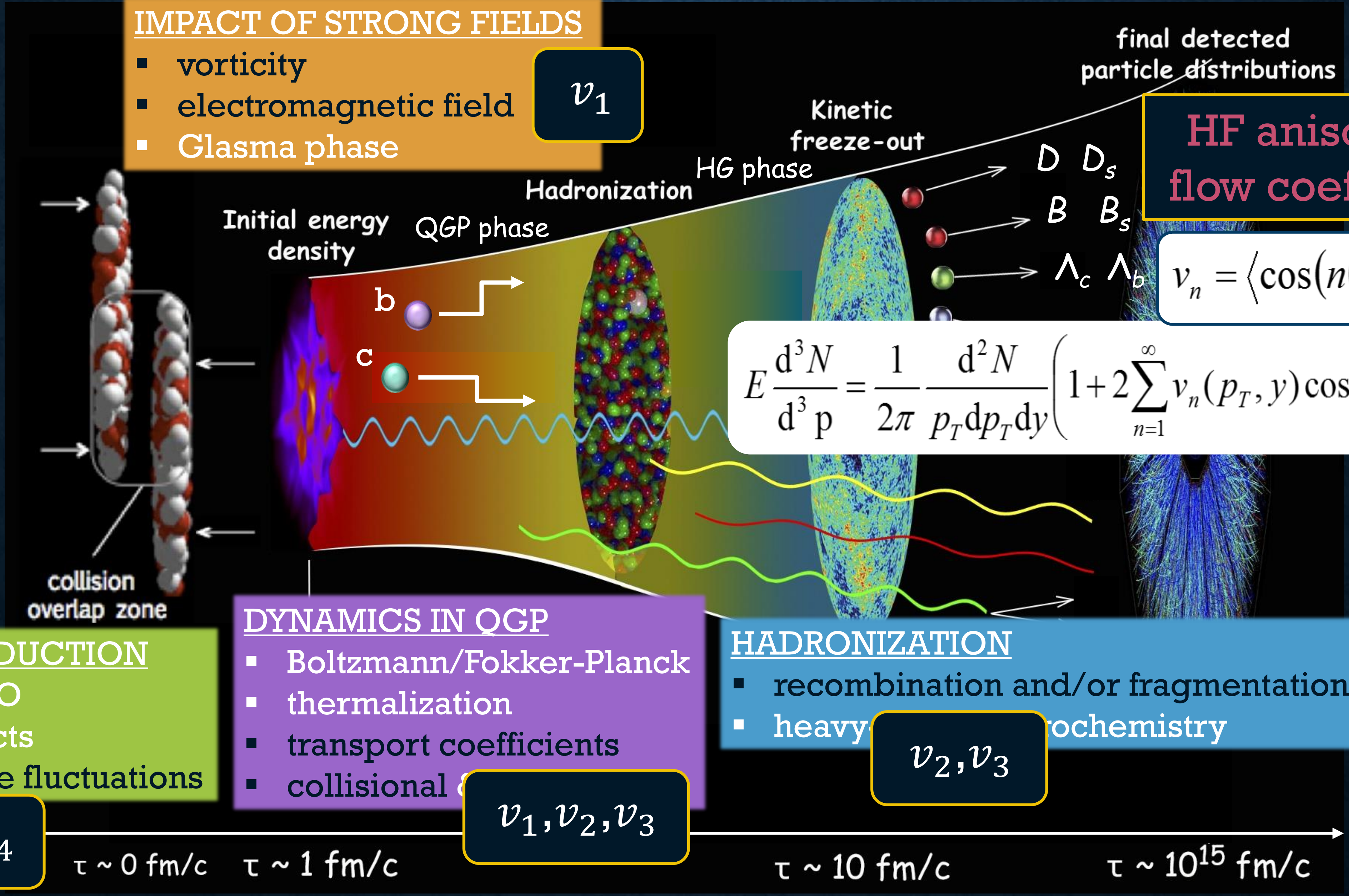
IMPACT OF STRONG FIELDS
- vorticity
- electromagnetic field
- Glasma phase

INITIAL PRODUCTION
- pQCD-NLO
- CNM effects
- initial-state fluctuations

DYNAMICS IN QGP
- Boltzmann/Fokker-Planck
- thermalization
- transport coefficients
- collisional & radiative

HADRONIZATION
- recombination and/or fragmentation
- heavy-flavor hadrochemistry

HEAVY FLAVORS IN RELATIVISTIC HICS



Modified from picture of Chun Shen (McGill University, Montreal QC, Canada)

IMPACT OF STRONG FIELDS
- vorticity
- electromagnetic field
- Glasma phase

v_1

HF anisotropic flow coefficients

$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos(n(\phi - \Psi_r))\right)$$

INITIAL PRODUCTION
- pQCD-NLO
- CNM effects
- initial-state fluctuations

v_2, v_3, v_4

DYNAMICS IN QGP
- Boltzmann/Fokker-Planck
- thermalization
- transport coefficients
- collisional

v_1, v_2, v_3

HADRONIZATION
- recombination and/or fragmentation
- heavy rochemistry

v_2, v_3

FULL BOLTZMANN TRANSPORT APPROACH

BULK EVOLUTION

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

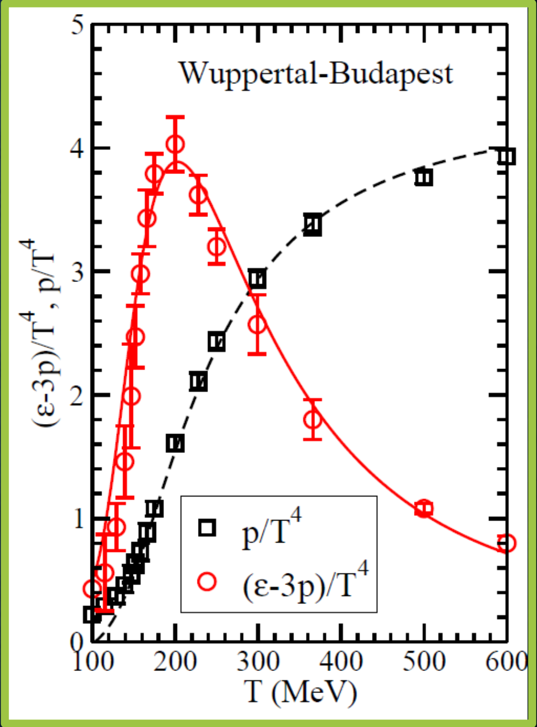
$$p^\mu \partial_\mu f_g(x,p) + m(x)\partial^x_\mu m(x)\partial^\mu_p f_g(x,p) = C[f_q, f_g]$$

Free-streaming

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

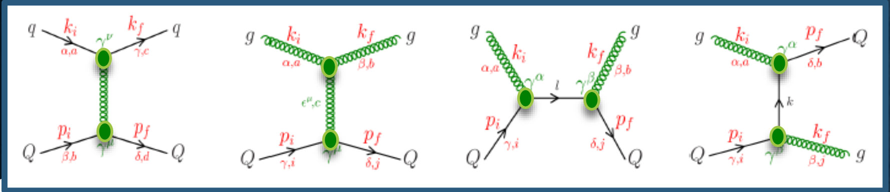
collision kernel gauged to some $\eta/s \neq 0$
M. Ruggieri et al., Phys. Rev. C 89, 054914 (2014)

Boltzmann transport equivalent to viscous hydro at $\eta/s \approx 0.1$



HQ EVOLUTION

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



$$\mathcal{C}[f_Q] = \frac{1}{2E_1}\int \frac{d^3p_2}{2E_2(2\pi)^3}\int \frac{d^3p'_1}{2E_{1'}(2\pi)^3} \times [f_Q(p'_1)f_{q,g}(p'_2) - f_Q(p_1)f_{q,g}(p_2)] \times |\mathcal{M}_{(q,g)+Q}(p_1p_2 \to p'_1p'_2)|^2 \times (2\pi)^4\delta^4(p_1+p_2-p'_1-p'_2)$$

Scardina et al., Phys. Rev. C 96, 044905 (2017)

Non perturbative dynamics:
$\mathcal{M}$ scattering matrices (q,g → Q)
evaluated by Quasi-Particle Model
fit to **lQCD thermodynamics**
S. Plumari et al., Phys. Rev. D 84, 094004 (2011)

$$m_g^2(T) = \frac{2N_c}{N_c^2-1}g^2(T)T^2 \qquad g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

$$m_q^2(T) = \frac{1}{N_c}g^2(T)T^2$$

extension of the QPM
(e.g., momentum dependence)

talk of M. L. SAMBATARO

FULL BOLTZMANN TRANSPORT APPROACH

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 $\varepsilon - 3p \neq 0$ | collision kernel gauged to some $\eta/s \neq 0$

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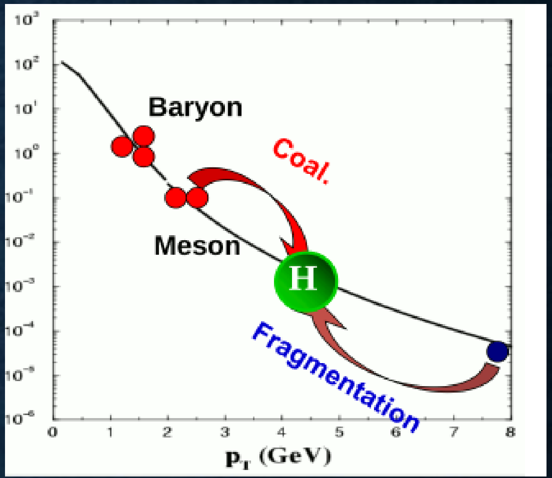


HQ EVOLUTION

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

Hybrid hadronization scheme for heavy quarks

COALESCENCE + FRAGMENTATION

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

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

F. Scardina et al., Phys. Rev. C 96, 044905 (2017)
S. Plumari, V. Minissale et al., Eur. Phys. J. C 78, 348 (2018)

Remarkable impact of coalescence for the description of experimental data (e.g., R_{AA}, v_2, v_3 for D mesons, charmed baryon/meson enhancement in pp)

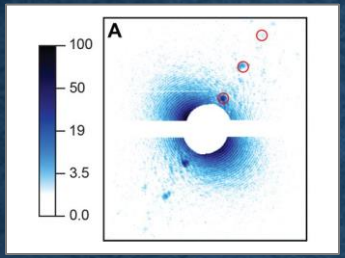
talk of V. MINISSALE

INTENSE FIELDS AND HEAVY FLAVOR TRANSPORT

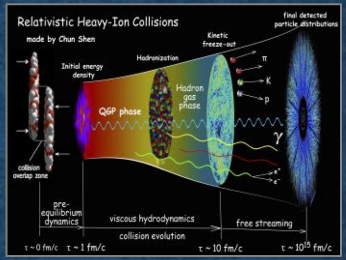
✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**


tornado cores
~ $10^{-1}\ s^{-1}$


Jupiter's spot
~ $10^{-4}\ s^{-1}$



He nanodroplets
~ $10^{7}\ s^{-1}$



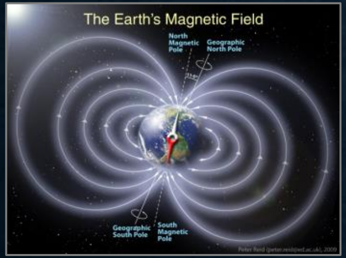
urHICs
~ 10^{22}–$10^{23}\ s^{-1}$

vorticity ω

since 2017

impact on HQ transport coefficients and D meson directed flow

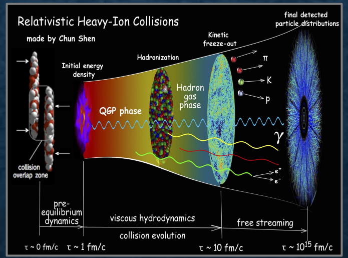
✓ INTENSE **ELECTROMAGNETIC FIELDS**



Earth's field
~ 1 G


laboratory
~ 10^{6} G


magnetars
~ 10^{14}–10^{15} G



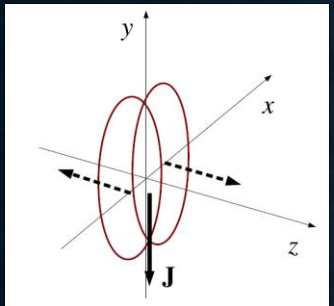
urHICs
~ 10^{18}–10^{19} G

magnetic field B

since 2016

impact on D meson directed flow

THE VORTICAL QUARK-GLUON PLASMA



Huge **orbital angular momentum** of the colliding system

- in ultra-relatvistic HICs **J ≈ 10^5 - 10^6 ħ**
- dominated by the y component perpendicular to the reaction plane
- partly transferred to the plasma

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

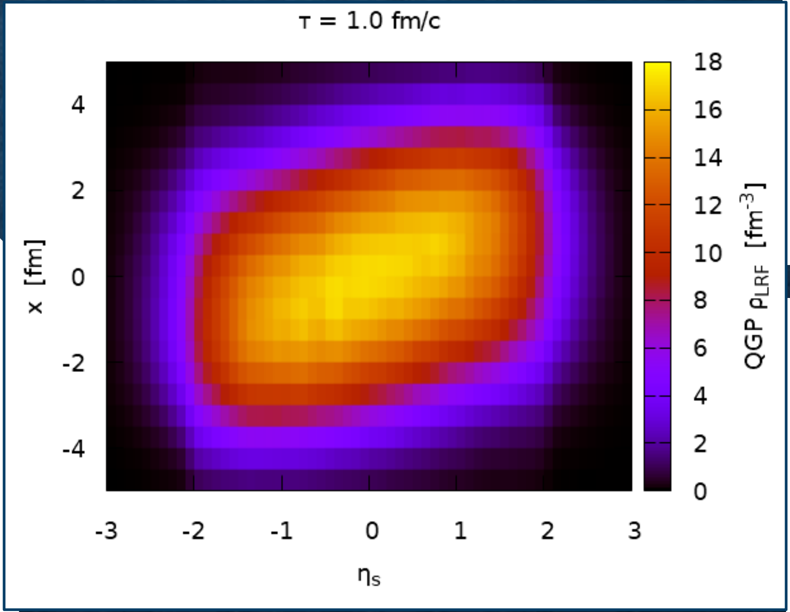
asymmetry in local participant density
from forward and backward going nuclei

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

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

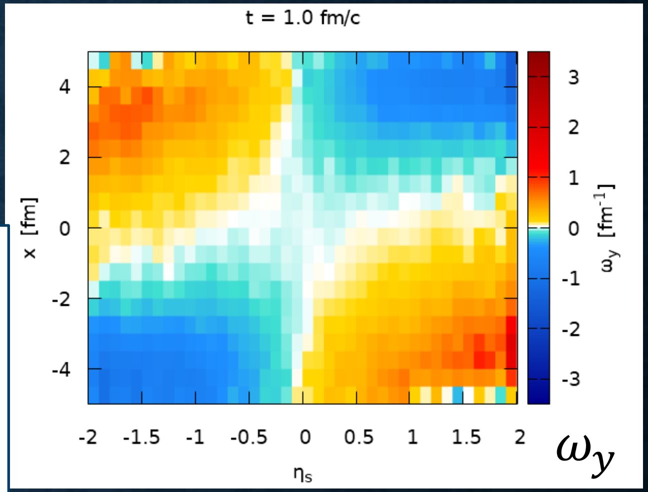
$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \frac{\eta_s+\eta_m}{2\eta_m} & -\eta_m \le \eta_s \le \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$

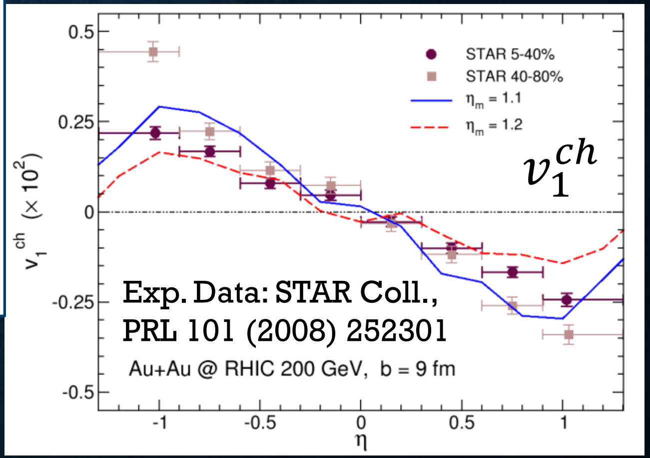
tilted initial conditions for the QGP evolution



TILTED FIREBALL
on the reaction plane

huge vorticity in agreement
with Λ polarization studies





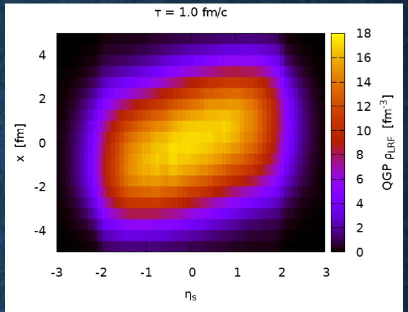
negative slope of
charged particle $v_1(\eta)$

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

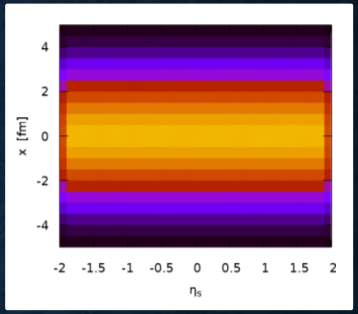
DIRECTED FLOW OF NEUTRAL *D* MESONS

Excellent qualitative prediction with LangevinV approach
$dv_1^D/dy \approx$ 0.02-0.04 (≈ 10-15 times larger than light charged)
S. Chatterjee and P. Bozek, Phys. Rev. Lett. 120, 192301 (2018)

tilted fireball



HQs production points



RHIC ENERGY

EXP: $dv_1^D/dy = -$ 0.080 ±0.017(stat)±0.016(syst)

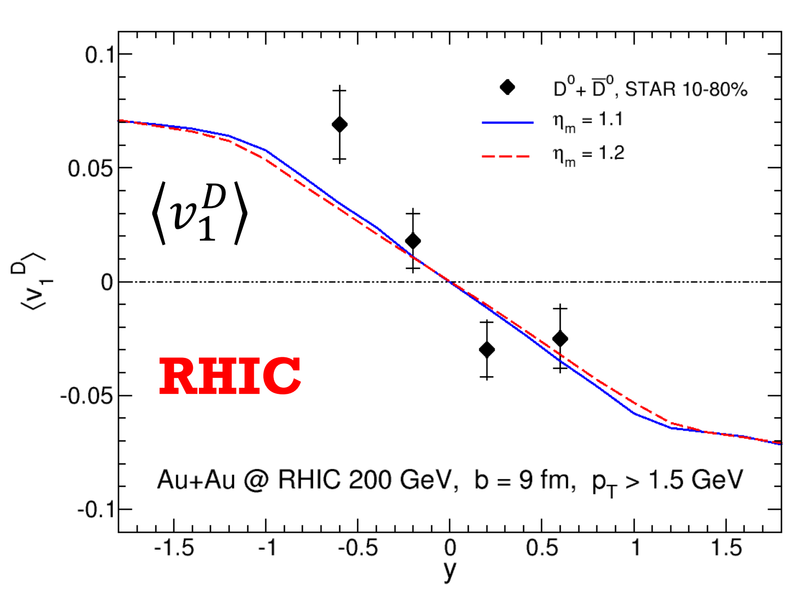
about 30 times larger than that of kaons

TH: $dv_1^D/dy = -$ 0.065 (25-30 times larger than ch.)

relativistic BM equations for both QGP and HQs

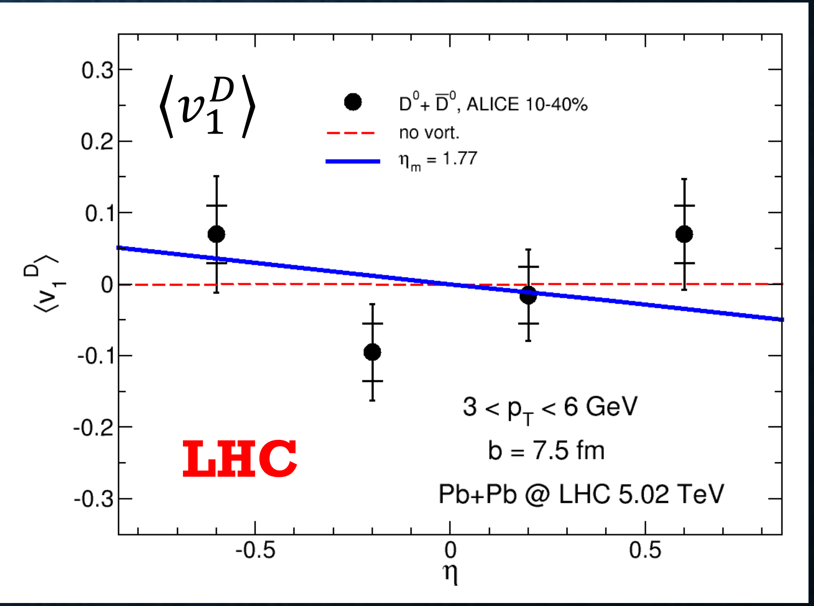
LHC ENERGY

the slope of $\langle v_1^D \rangle$ is ~ 50 times smaller than that at RHIC (in line with model predictions) and is consistent with 0



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

Exp. data: STAR Coll.,
Phys. Rev. Lett.. 123 (2019) 162301



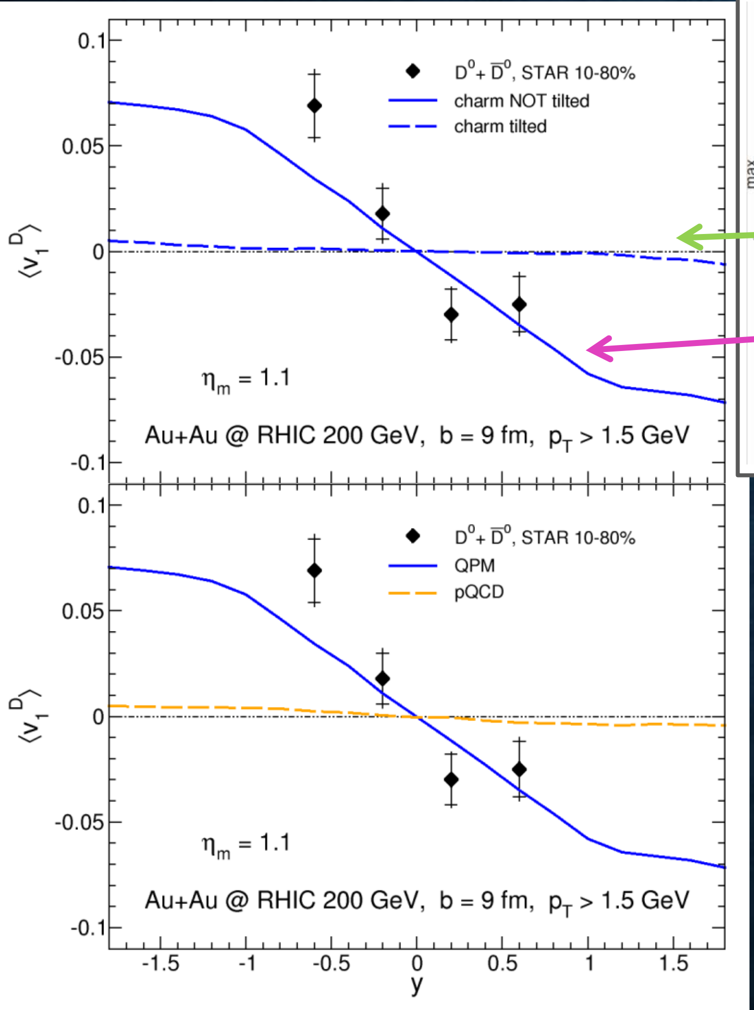
L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

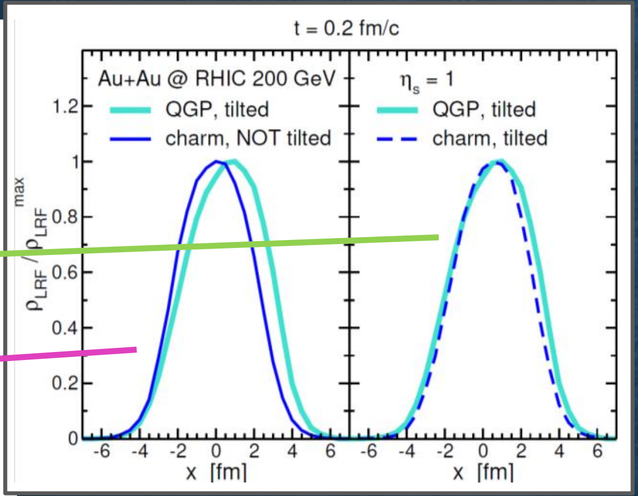
ORIGIN OF *D*-MESON DIRECTED FLOW

v_1 (HQs) $\gg$ v_1 (QGP)

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

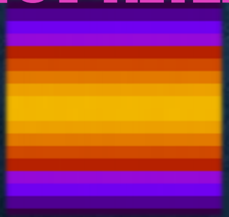
L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)



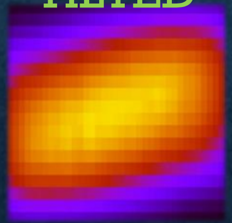


longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM **NOT** TILTED



CHARM TILTED



QGP tilted in both cases

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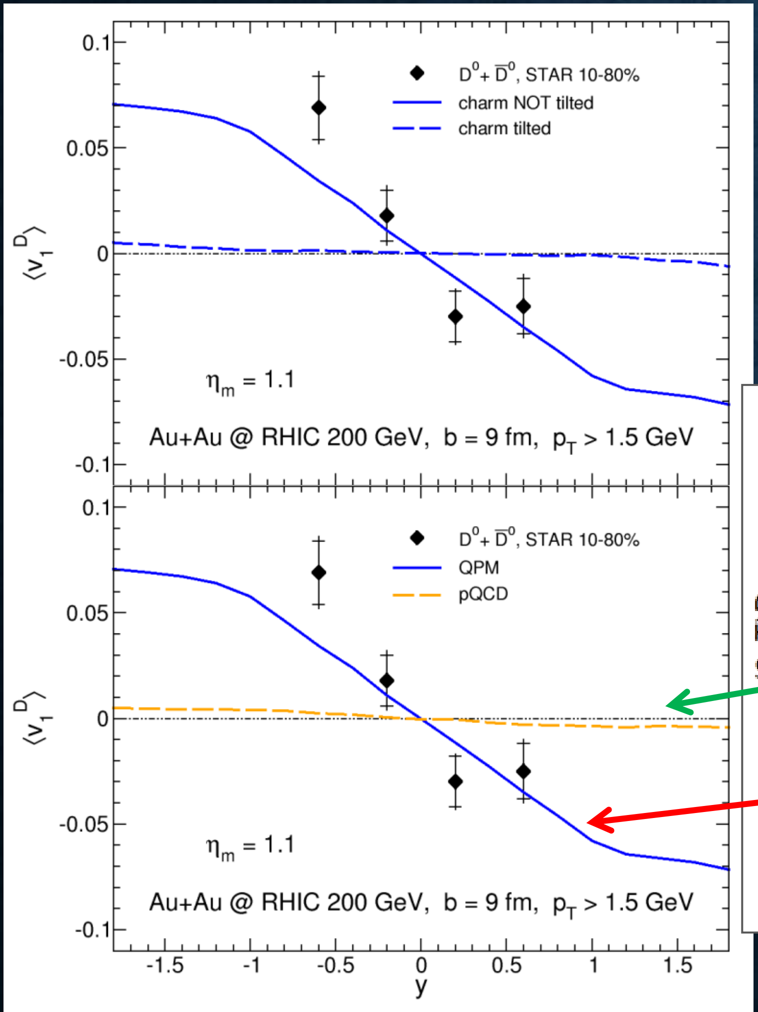
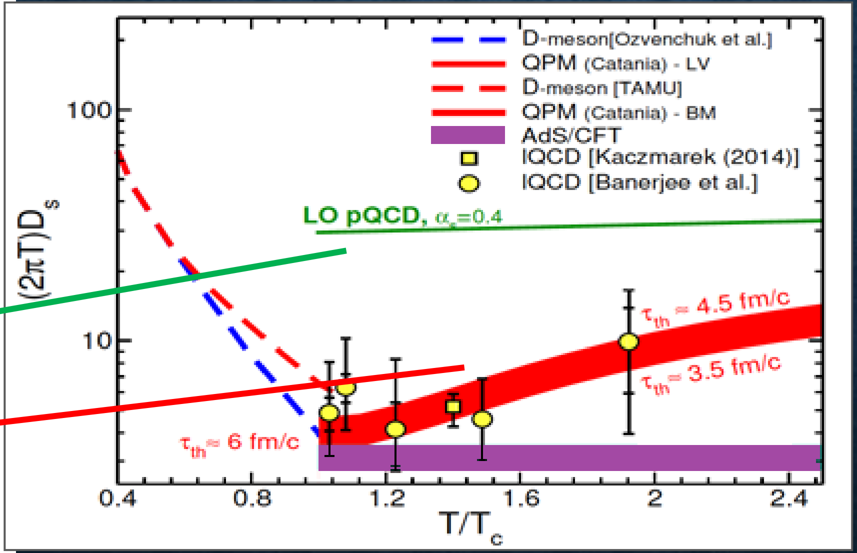
L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)



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

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



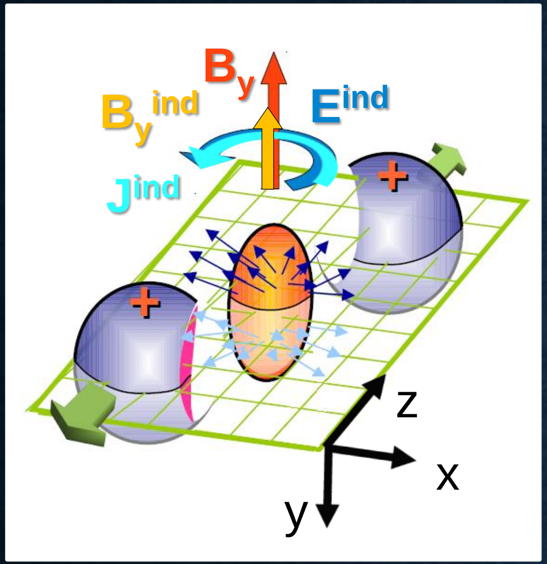
V. Greco, Nucl. Phys. A 967, 200 (2017)

Similar conclusions with POWLANG approach

A. Beraudo et al., JHEP 05, 279 (2021)

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

ELECTROMAGNETIC (EM) FIELDS IN HICS



Huge **magnetic field** in the overlap area up to **eB ≈ 5-50 m_π^2**

- mainly produced by spectators protons
- dominated by the y component
- intense electric field generated by Faraday induction
- charged currents induced in the conducting QGP generates a magnetic field pointing towards the initial one

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

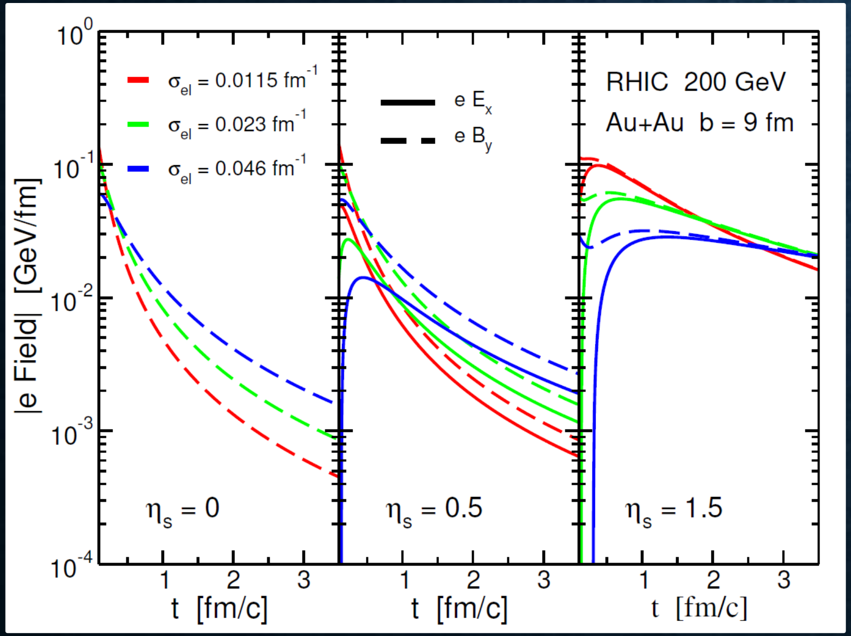
$$\rho = \rho_{ext} \qquad J = J_{ext} + J_{ind}$$

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

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

$$J_{ind} = \sigma_{el} E$$

induced current from Ohm's law



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

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

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

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

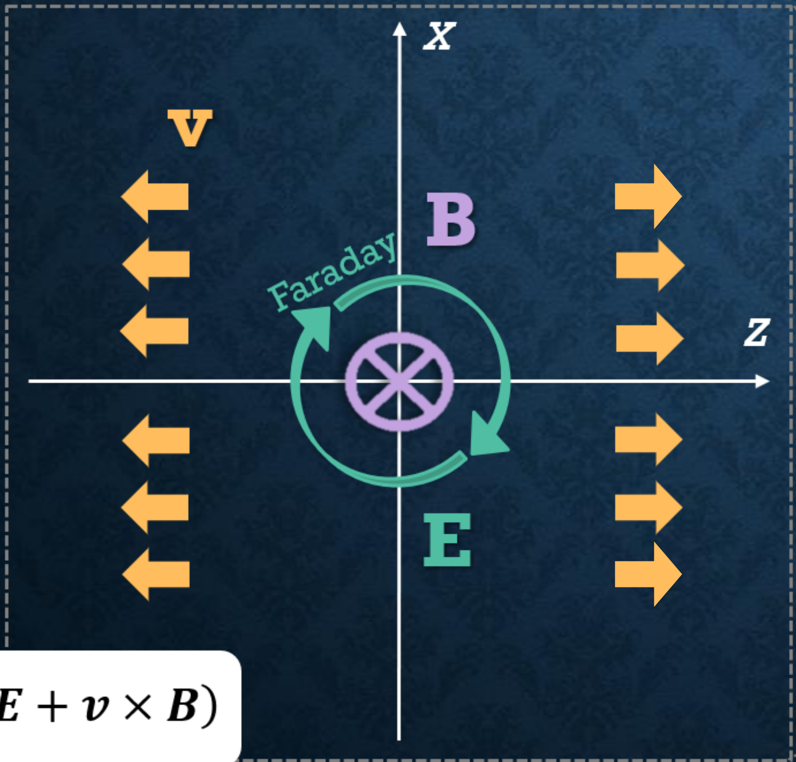
BM eq. with EM interaction term

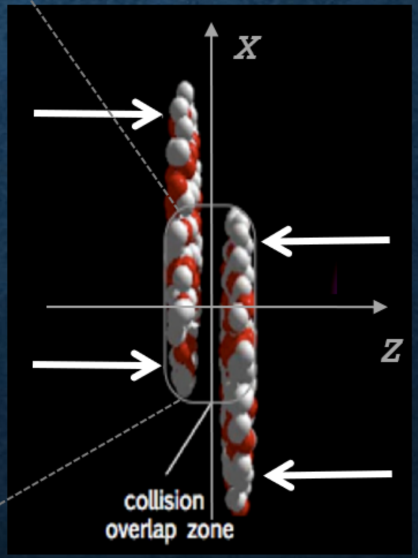
EMF AND DIRECTED FLOW

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

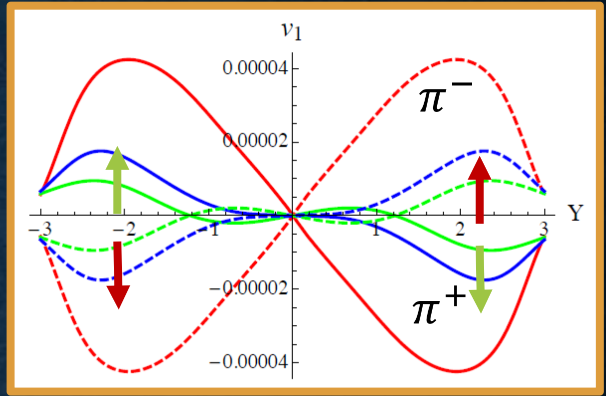
$$\Delta v_1 = v_1^+ - v_1^-$$

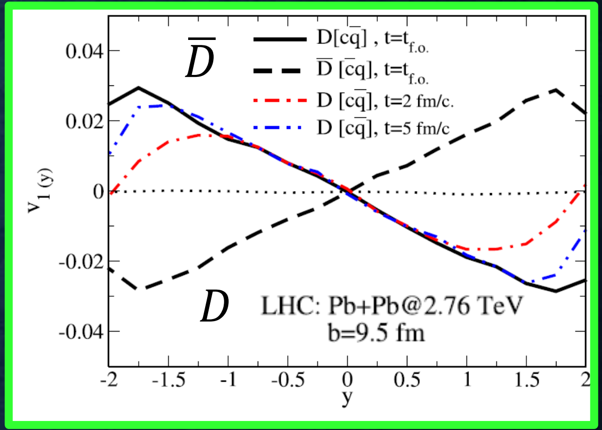
- Δv_1 of light hadrons in AA: $O(10^{-4}$–$10^{-3})$
  U. Gursoy et al., Phys. Rev. C 89, 054905 (2014)
- Δv_1 of heavy mesons in AA: $O(10^{-2})$
  S.K. Das et al., Phys. Lett. B 768, 260 (2017)
- Δv_1 of light mesons in pA: $O(10^{-2})$
  L. Oliva et al., Phys. Rev. C 101, 014917 (2020)

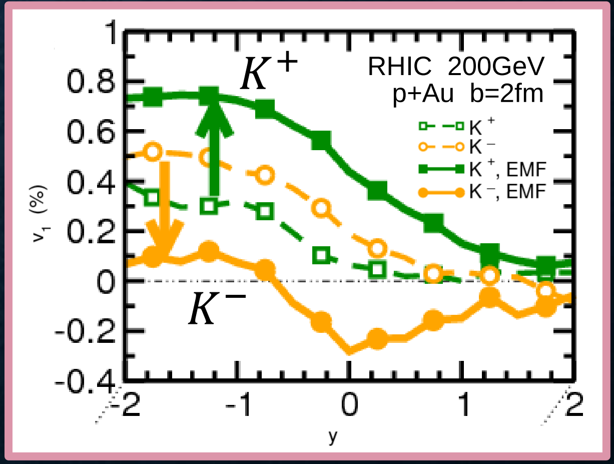




$$F_{Lorentz} = q(E + v \times B)$$





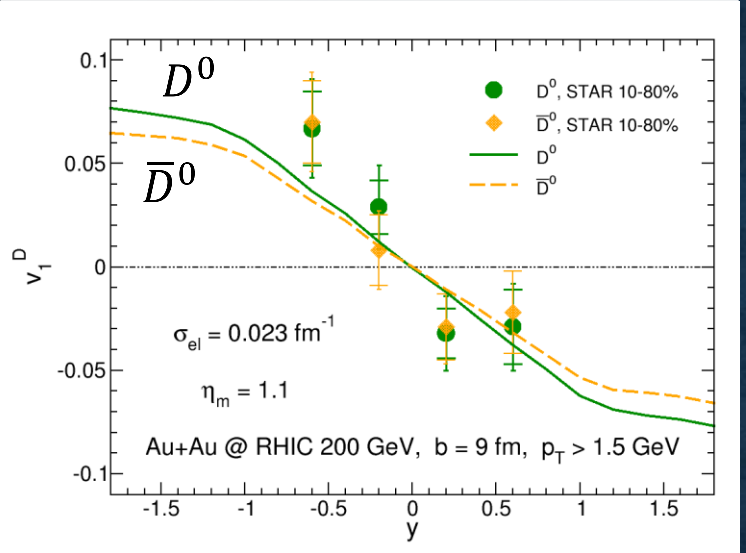


reviews

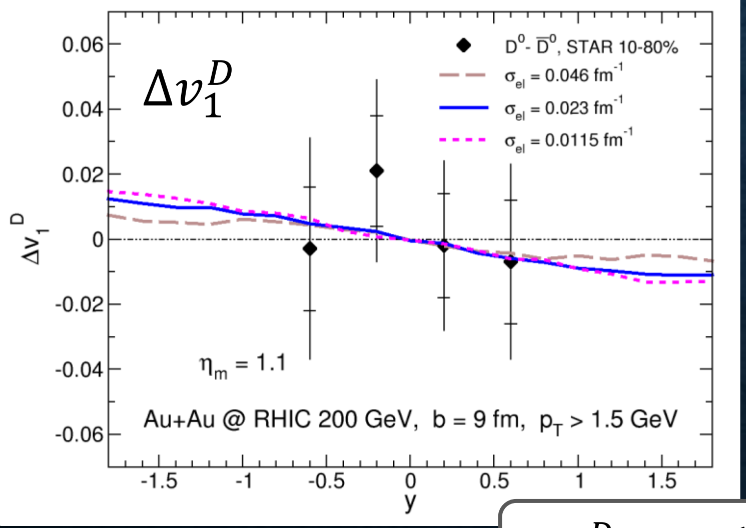
L. Oliva, Eur. Phys. J. A 56, 255 (2020)
A. Dubla, U. Gursoy and R. Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

DIRECTED FLOW IN A+A AT RHIC ENERGY

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



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



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

DIRECTED FLOW OF NEUTRAL *D* MESONS

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

RHIC ENERGY

$d(\Delta v_1)/dy|_{exp} = -0.011 \pm 0.024(stat) \pm 0.016(syst)$

$d(\Delta v_1)/dy|_{th} = -0.01$

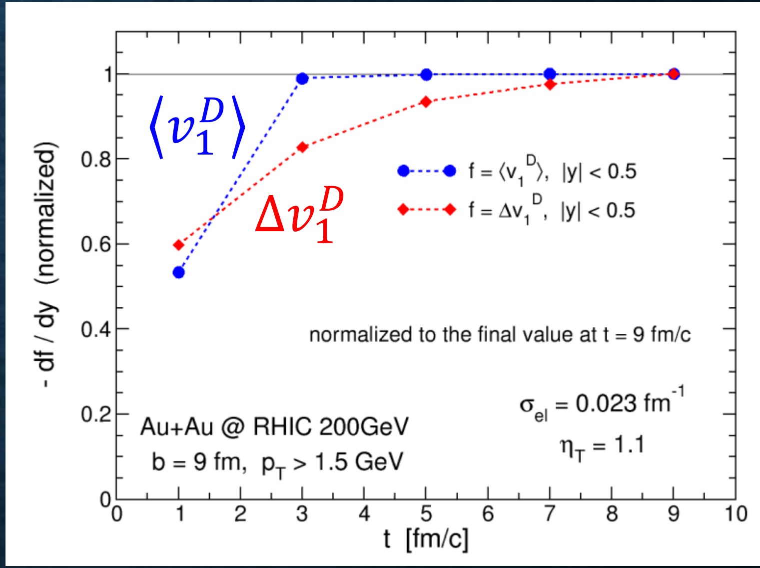
≈ 10 times larger than charged
in agreement with
S.K. Das et al., Phys. Lett. B 768, 260 (2017)

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

Δv_1 (HQ) ≫ Δv_1 (QGP)

charm quarks are more sensitive to the EM fields due to the early production

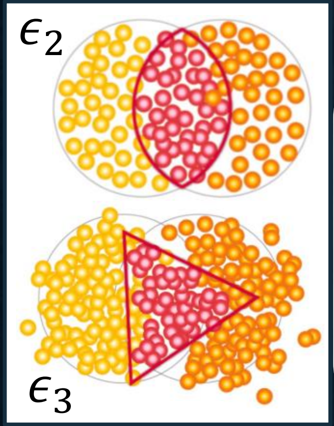
SLOPE TIME EVOLUTION



v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more T~T_c
→ include v_1^D in Bayesian fits

EVENT-BY-EVENT FLUCTUATIONS

Event-by-event fluctuations in the initial nucleon positions



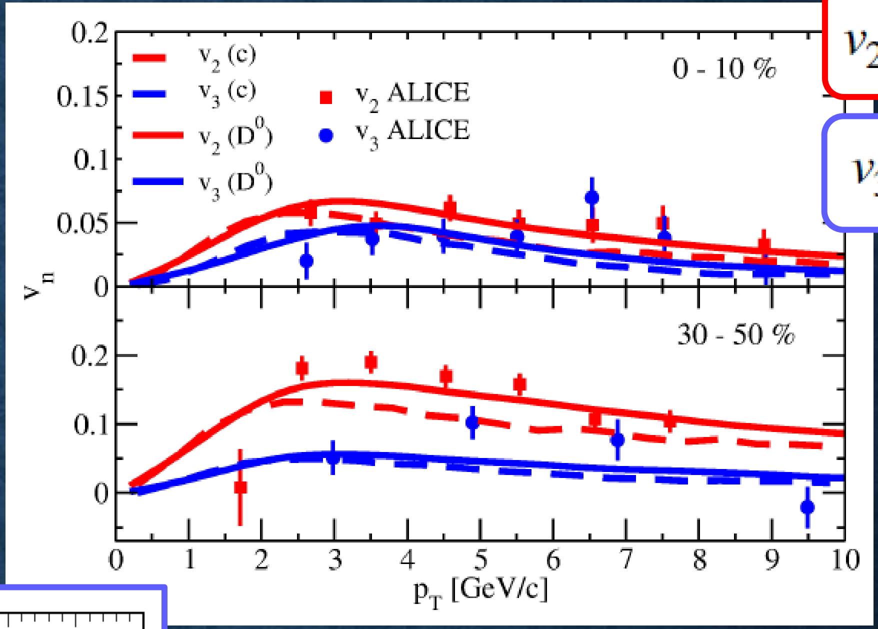
*n*th-order spatial eccentricities

$$\epsilon_n = \frac{r_\perp^n \cos[n(\phi - \Psi_n)]}{r_\perp^n}$$

$$\Psi_n = \frac{1}{n} \arctan \frac{r_\perp^n \sin(n\phi)}{r_\perp^n \cos(n\phi)}$$

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

M. L. Sambataro et al., 2206.03160



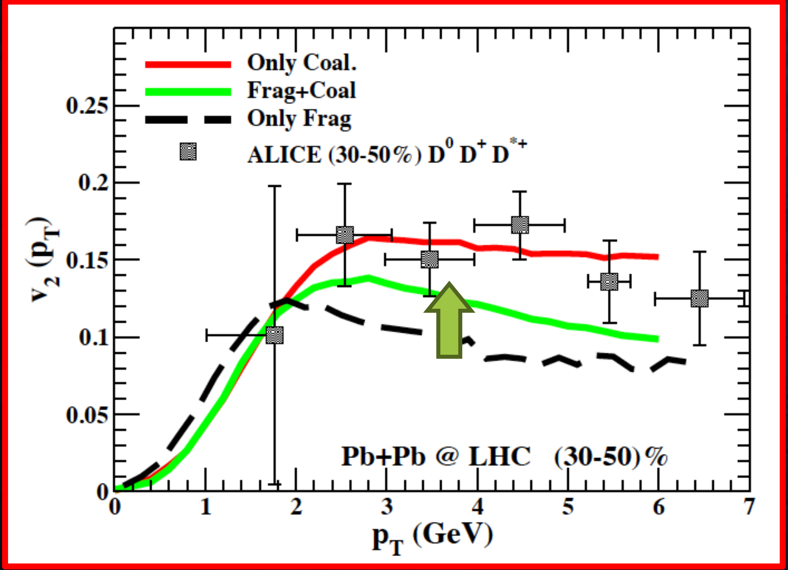
elliptic flow

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

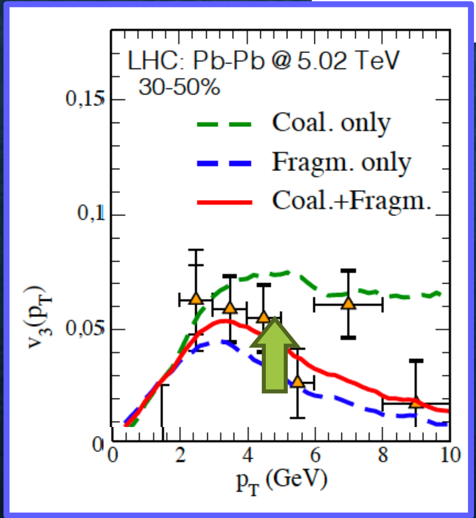
$$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$$

triangular flow

Exp. Data: ALICE Coll., Phys. Lett. B 813, 136054 (2021)



F. Scardina et al., Phys. Rev. C 96, 044905 (2017)



S. Plumari et al., Phys. Lett. B 805, 135460 (2020)

D-MESON v_2 AND v_3

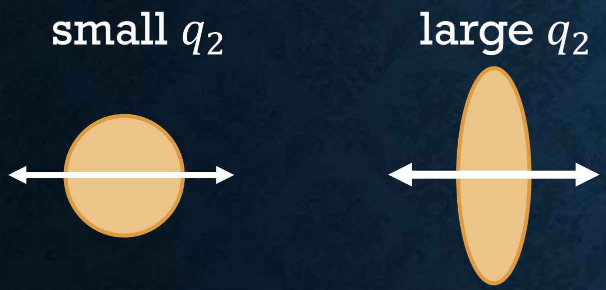
- v_2 larger in more peripheral collisions → mainly generated by the geometry of overlap region
- v_3 not much sensitive to the collision centrality → mainly driven by the fluctuations of the triangularity of overlap region
- coalescence increases v_2 and v_3 at p_T > 2 GeV

EVENT-SHAPE ENGINEERING (ESE)

ESE technique: selection of events with **same centrality** but **different average bulk flow** on the basis of the magnitude of the 2°-order harmonic reduced flow vector q_2

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

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



$v_2 \propto \epsilon_2$, $v_3 \propto \epsilon_3$ for small values of η/s

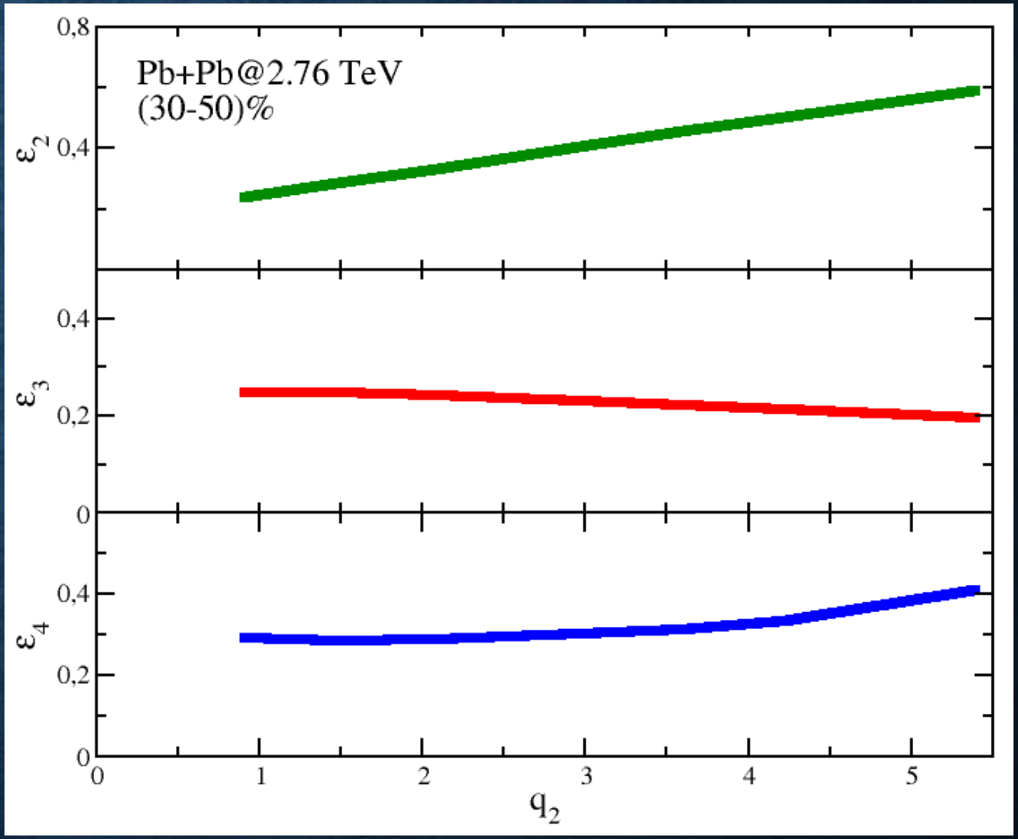
⇩

access to the **initial fireball geometry**

small/large q_2 → small/large ϵ_2

M. L. Sambataro et al., 2206.03160

SPATIAL ECCENTRICITIES



- ❑ Anti-correlation between ε_2 and ε_3
- ❑ Non-linear correlation between ε_2 and ε_4

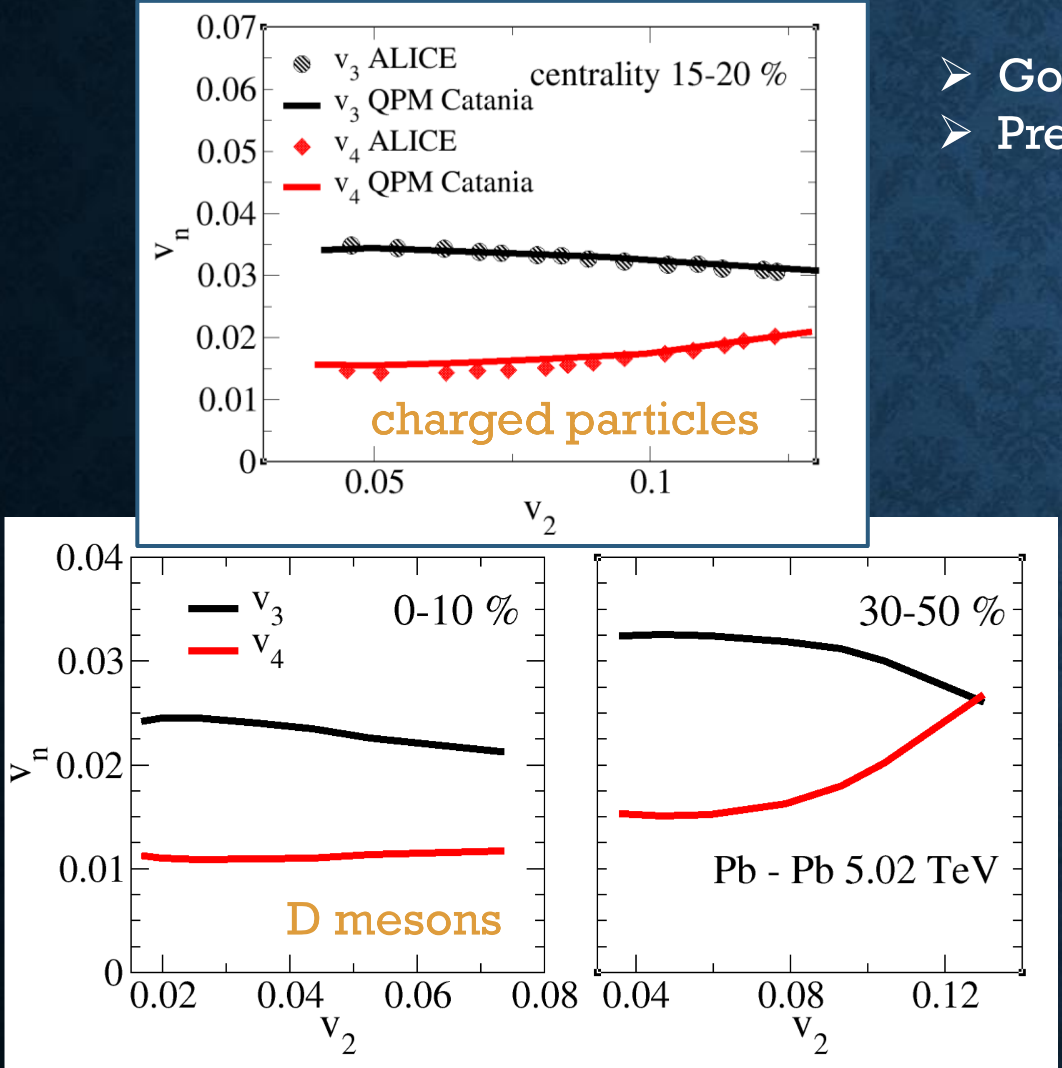
Increasing interest on studying observables with multi-differential methods based on event shape

- ➢ Transverse spherocity analysis in small systems

L. Oliva, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, 220404194

ESE: v_n-v_m CORRELATIONS

Exp. Data: S. Mohapatra, Nucl. Phys. A 956, 59 (2016)

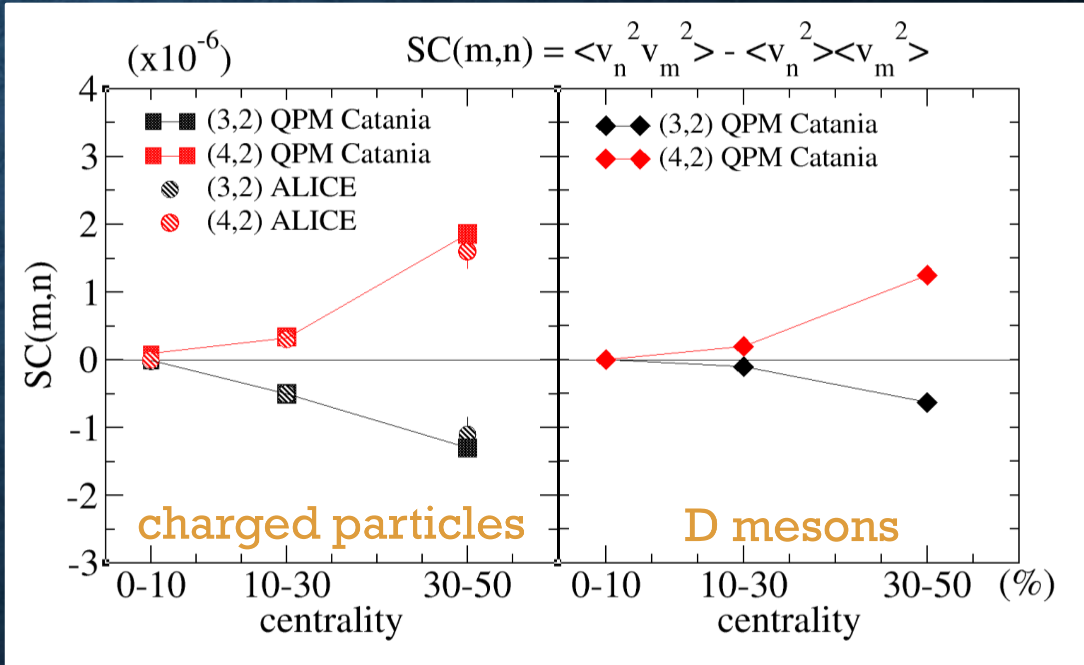


$v_n - v_m$ CORRELATIONS

Correlations between ϵ_n and ϵ_m in the initial geometry leads to correlations between v_n and v_m

- Good description of experimental data for charged particles
- Prediction of comparable *D*-meson correlations w.r.t. bulk

Exp. data: ALICE Coll., Phys. Lett. B 818, 136354 (2021)



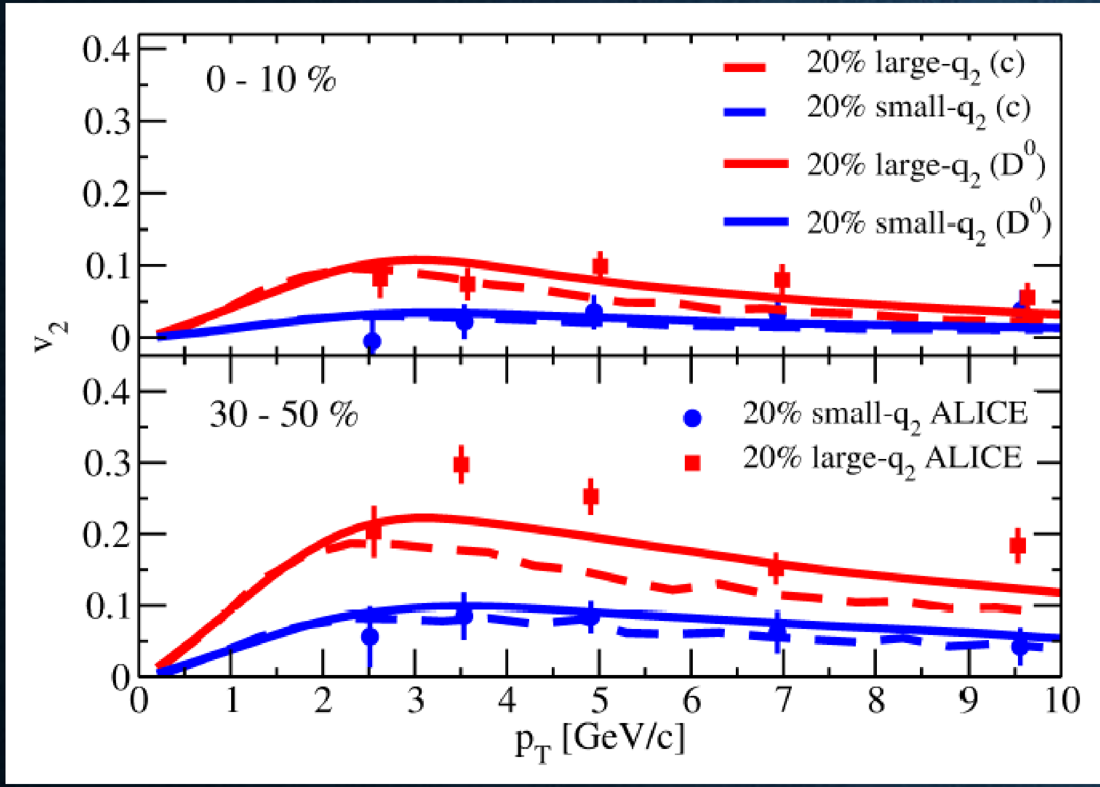
SYMMETRIC CUMULANT CORRELATOR

Same approach and $D_s(T)$ describing $R_{AA}(p_T)$ & $v_2(p_T)$

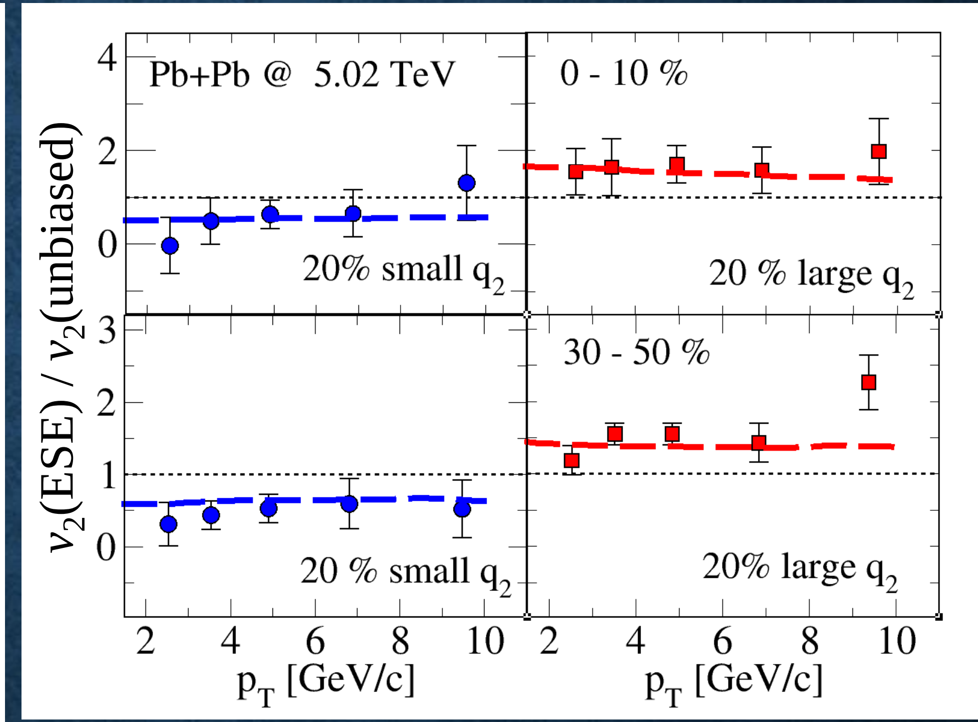
M. L. Sambataro et al., 2206.03160

ESE: q_2-SELECTED ELLIPTIC FLOW

Exp. Data: ALICE Collaboration, Phys. Lett. B 813, 136054 (2021)

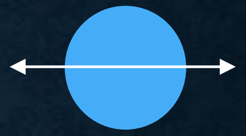


q_2-SELECTED D-MESON $v_2(p_T)$

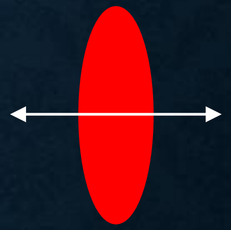


D-MESON $v_2(p_T)$ RATIO

20% small q_2



20% large q_2



v_2 (small q_2) $<$ v_2 (unbiased)

v_2 (large q_2) $>$ v_2 (unbiased)

about 50% difference between q_2-selected and unbiased events in both centrality class with no transverse momentum dependence

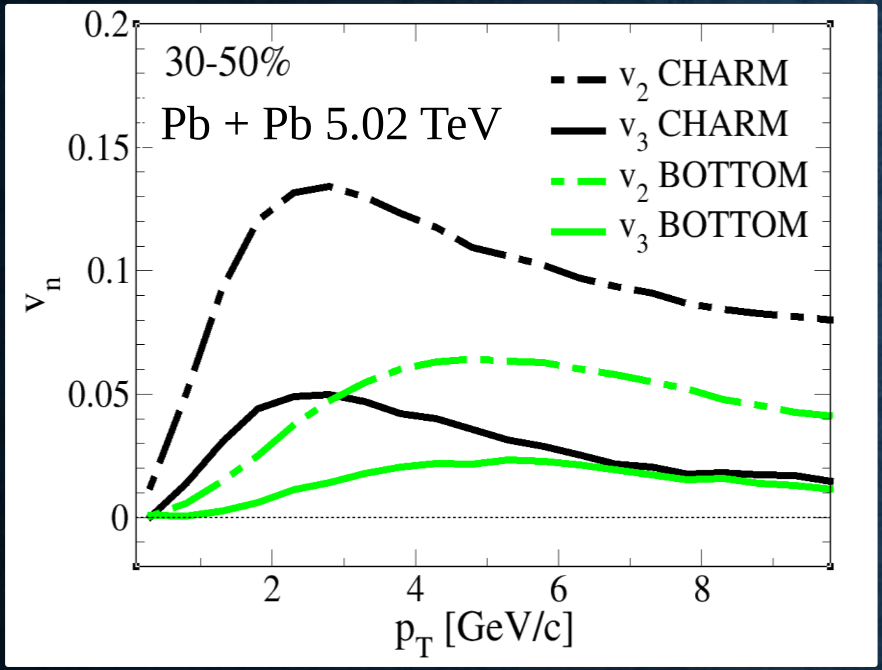
⇨ ESE selection related to a global property of the events

Same approach and $D_s(T)$ describing $R_{AA}(p_T)$ & $v_2(p_T)$

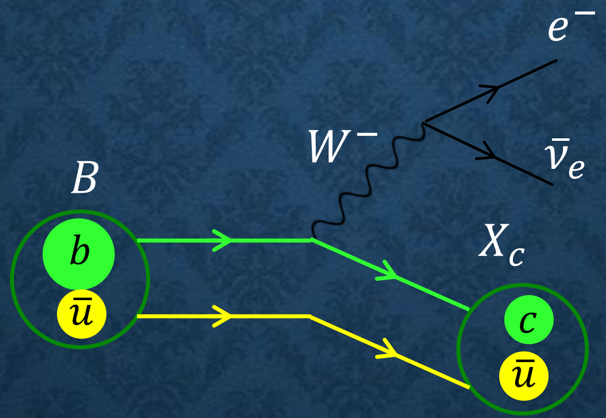
M. L. Sambataro et al., 2206.03160

EXTENSION TO BOTTOM DYNAMICS

CHARM vs BOTTOM FLOW COEFFICIENTS



substantial v_2 and v_3 of bottom quarks though smaller than that of charm but still

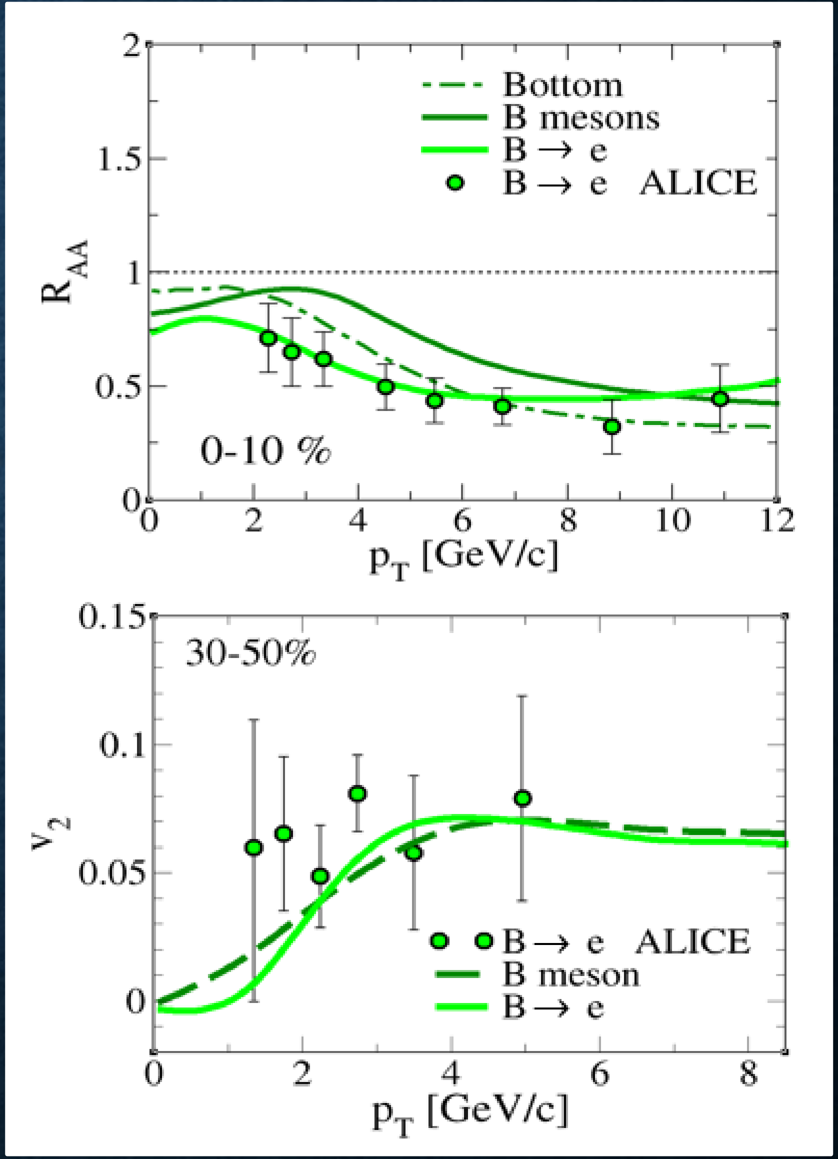


- Good description of R_{AA} and v_2 of electrons from semileptonic B decay
- Prediction of R_{AA} and v_2 for B meson

indication for a strong coupling of bottom quarks with collectively expanding bulk

M.L. Sambataro et al., in preparation

NUCLEAR MODIFICATION FACTOR

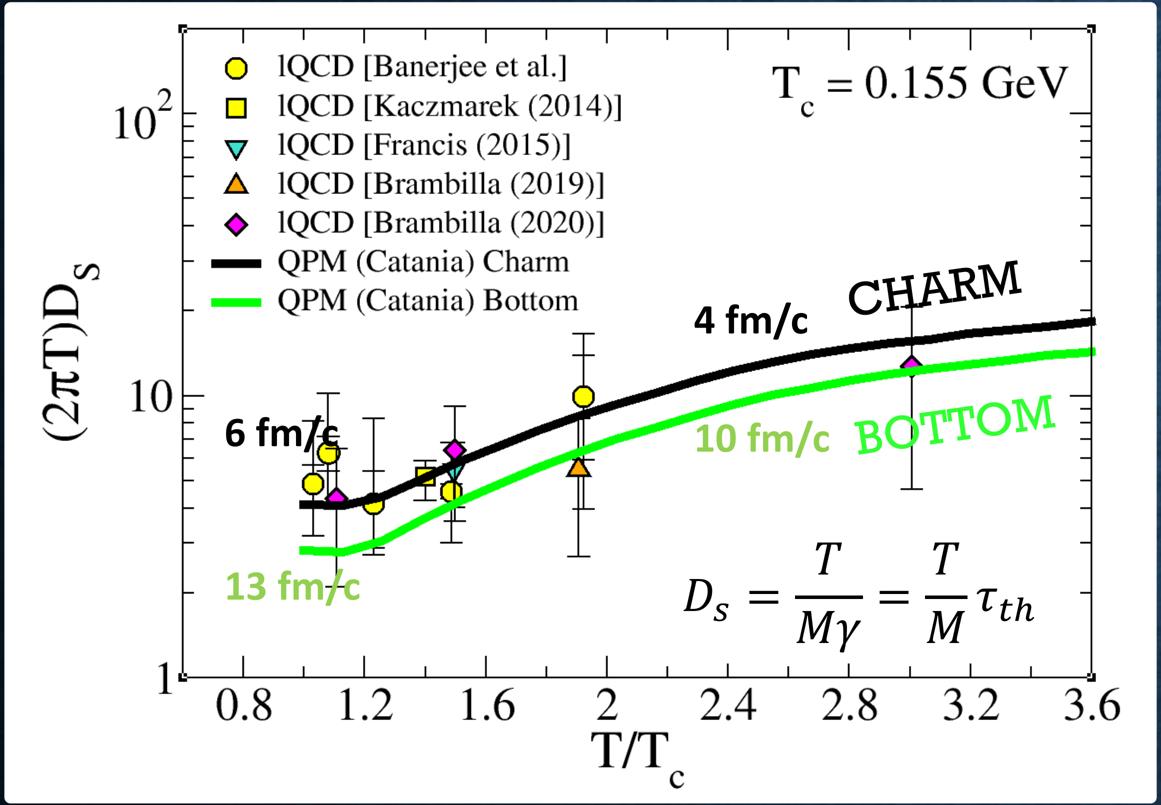


ELLIPTIC FLOW

Exp. data from talk of R. Arnaldi at HP2020

BOTTOM SPATIAL DIFFUSION COEFFICIENT

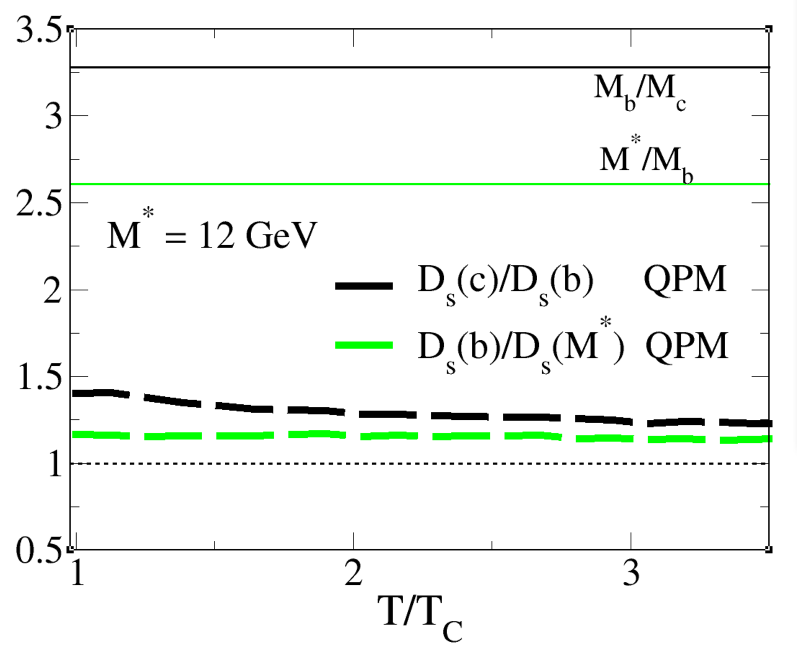
Results from $R_{AA}(p_T)$ and $v_2\ (p_T)$ of B mesons



CHARM vs BOTTOM SPATIAL DIFFUSION COEFFICIENT

- ❑ D_s is ideally M independent (M → ∞) since from kinetic theory: $\tau_{th}^{b}/\tau_{th}^{c} \approx \gamma_c/\,\gamma_b \approx M_b/M_c$
- ❑ D_s is a measure of thermalization time:

$$\tau_{th} \simeq 1.3\ M\,\frac{2\pi T D_s}{(T/T_c)^2}\ \text{fm}/c$$

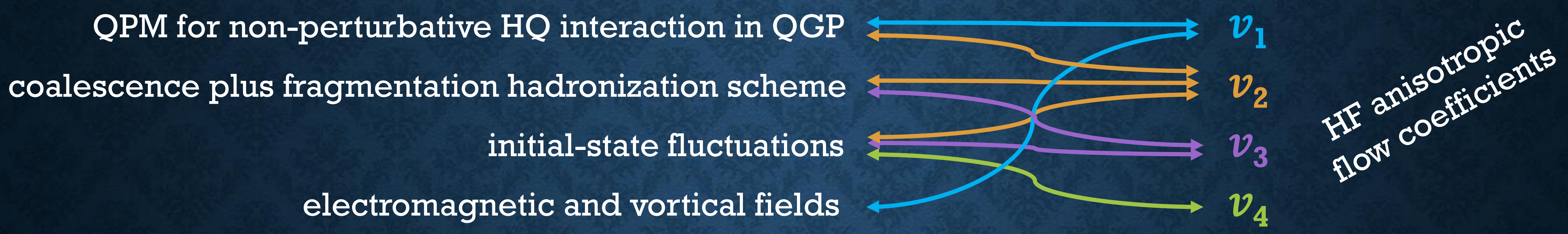


- ➢ In QPM approach D_s(c) is 30-40% larger than D_s(b)
- ➢ Bottom quarks expected to be fully thermalized @ FCC

M.L. Sambataro et al., in preparation

CONCLUSIONS

Full Boltzmann transport approaches for the description of HQ dynamics in relativistic heavy-ion collisions



- ✓ The D^0-meson v_1 gives information on the transport properties of the hot QCD matter: magnitude associated with the HQ diffusion coefficient and splitting connected to the QGP electric conductivity
- ✓ For D mesons v_1 is more sensitive to the early QGP evolution when T is higher, while v_2 probes more $T \sim T_c$. Inclusion in Bayesian fit and for $D_s(T)$ estimate?
- ✓ 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 coefficients
- ✓ Prediction for significant v_n–v_m correlation of D mesons, comparable to that of bulk particles
- ✓ Indication for a strong coupling of bottom quarks with the collectively expanding bulk

Thank you for your attention!