Development of heavy-flavour flow-harmonics in high-energy nuclear collisions

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INFN

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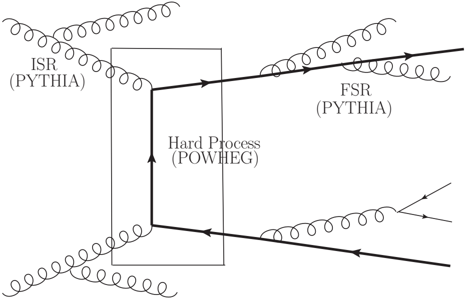
Outline

- The POWLANG transport setup (hard event + transport + in-medium hadronization)
- Event-by event fluctuations and development of HF azimuthal anisotropies (v_2 and v_3) in heavy-ion collisions
- Event-shape engineering and HF observables: preliminary studies

The POWLANG setup

- $Q\overline{Q}$ production;
- HQ transport;
- HQ hadronization.

HQ production: NLO calculation + Parton Shower



- A convenient automated tool to simulate the initial $Q\overline{Q}$ production (the POWHEG-BOX package) interfaces the output of a NLO event-generator for the hard process with a parton-shower describing the Initial and Final State Radiation and modeling other *non-perturbative processes* (intrinsic k_T, MPI, hadronizazion)
- This provides a *fully exclusive information on the final state*

Transport theory: the Boltzmann equation

Time evolution of HQ phase-space distribution $f_Q(t, \boldsymbol{x}, \boldsymbol{p})$[1]:

$$\frac{d}{dt} f_Q(t, \boldsymbol{x}, \boldsymbol{p}) = C[f_Q]$$

- Total derivative along particle trajectory

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \boldsymbol{v}\frac{\partial}{\partial \boldsymbol{x}} + \boldsymbol{F}\frac{\partial}{\partial \boldsymbol{p}}$$

  Neglecting $\boldsymbol{x}$-dependence and mean fields: $\partial_t f_Q(t, \boldsymbol{p}) = C[f_Q]$

- Collision integral:

$$C[f_Q] = \int d\boldsymbol{k} [\underbrace{w(\boldsymbol{p}+\boldsymbol{k}, \boldsymbol{k}) f_Q(\boldsymbol{p}+\boldsymbol{k})}_{\text{gain term}} - \underbrace{w(\boldsymbol{p}, \boldsymbol{k}) f_Q(\boldsymbol{p})}_{\text{loss term}}]$$

  $w(\boldsymbol{p}, \boldsymbol{k})$: HQ transition rate $\boldsymbol{p} \to \boldsymbol{p} - \boldsymbol{k}$

[1] Approach adopted by Catania, Nantes, Frankfurt, LBL... groups

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[2] (Landau)

$$C[f_Q] \approx \int d\boldsymbol{k} \left[k^i \frac{\partial}{\partial p^i} + \frac{1}{2} k^i k^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\boldsymbol{p}, \boldsymbol{k}) f_Q(t, \boldsymbol{p})]$$

[2] B. Svetitsky, PRD 37, 2484 (1988)

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The Boltzmann equation reduces to the *Fokker-Planck equation*

$$\frac{\partial}{\partial t} f_Q(t, \boldsymbol{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\boldsymbol{p}) f_Q(t, \boldsymbol{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\boldsymbol{p}) f_Q(t, \boldsymbol{p})] \right\}$$

where

$$A^i(\boldsymbol{p}) = \int d\boldsymbol{k}\, k^i w(\boldsymbol{p}, \boldsymbol{k}) \longrightarrow \underbrace{A^i(\boldsymbol{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\boldsymbol{p}) = \frac{1}{2} \int d\boldsymbol{k}\, k^i k^j w(\boldsymbol{p}, \boldsymbol{k}) \longrightarrow \underbrace{B^{ij}(\boldsymbol{p}) = (\delta^{ij} - \hat{p}^i \hat{p}^j) B_0(p) + \hat{p}^i \hat{p}^j B_1(p)}_{\text{momentum broadening}}$$

Problem reduced to the *evaluation of three transport coefficients*, directly derived from the scattering matrix

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The relativistic Langevin equation

The Fokker-Planck equation can be recast into a form suitable to follow the dynamics of each individual quark arising from the pQCD Monte Carlo simulation of the initial $Q\overline{Q}$ production: the Langevin equation

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}} ,$$

with the properties of the *white* ($\sim \delta_{tt'}$), *multiplicative* noise encoded in

$$\langle\xi^i(\boldsymbol{p}_t)\rangle = 0 \quad \langle\xi^i(\boldsymbol{p}_t)\xi^j(\boldsymbol{p}_{t'})\rangle = b^{ij}(\boldsymbol{p})\frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(\boldsymbol{p}) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

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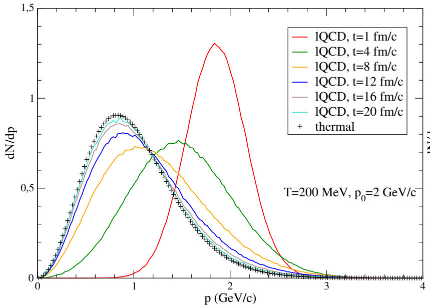
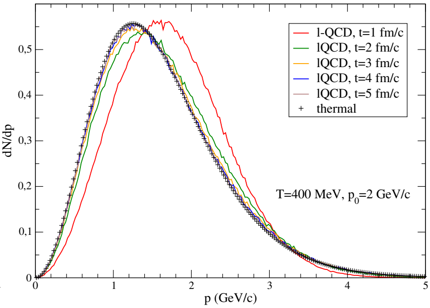
Transport coefficients related to the FP ones:

- *Momentum diffusion*: $\kappa_T(p) = 2B_0(p)$ and $\kappa_L(p) = 2B_1(p)$
- *Friction* term, in the *Ito pre-point discretization scheme*, fixed by the Einstein *fluctuation-dissipation* relation

$$\eta_D^{\text{Ito}}(p) = A(p) = \frac{B_1(p)}{TE_p} - \left[\frac{1}{p}\frac{\partial B_1(p)}{\partial p} + \frac{d-1}{p^2}(B_1(p) - B_0(p))\right]$$

A first check: thermalization in a static medium





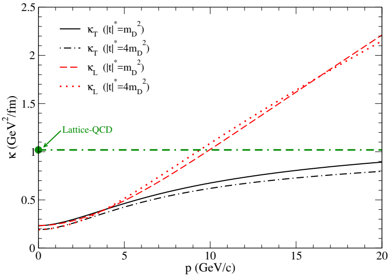
If the Einstein relation is imposed, for $t \gg 1/\eta_D$ HQ's approach kinetic equilibrium, with momenta described by a Maxwell-Jüttner distribution

$$f_{\rm MJ}(p) \equiv \frac{e^{-E_p/T}}{4\pi M^2 T\, K_2(M/T)}, \qquad \text{with} \int d^3p\, f_{\rm MJ}(p) = 1$$

The larger κ ($\kappa \sim T^3$), the faster the approach to thermalization.

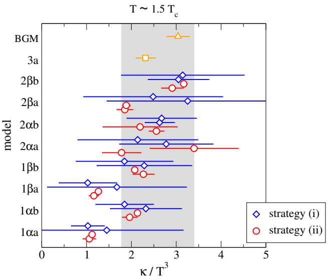
Transport coefficients: weak-coupling vs l-QCD

Weak-coupling (beauty shown)



Obtained accounting for $Qq \to Qq$ and $Qg \to Qg$ scattering, with resummation of medium effects for soft $(|t| < |t|^*)$ collisions (Hard Thermal Loop approximation)

Lattice QCD $(M = \infty)$



$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ}$$

given by *electric-field correlator*, available only for *imaginary times*

From quarks to hadrons

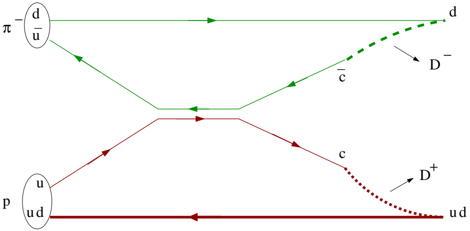
In the presence of a medium, rather then fragmenting like in the vacuum (e.g. $c \to cg \to c\overline{q}q$), HQ's can hadronize by recombining with light thermal partons from the medium.

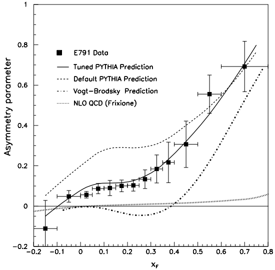
In-medium hadronization may affect the R_{AA} and v_2 of final D-mesons due to the *collective flow* of light quarks. We tried to estimate the effect through this model interfaced to our POWLANG transport code:

- At $T_{\rm dec}$ c-quarks coupled to light $\overline{q}$'s from a local *thermal distribution*, eventually *boosted* ($u^{\mu}_{\rm fluid} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons $(D + \pi + \dots)$

From quarks to hadrons

Breaking of factorized description of hadronization $d\sigma^h = d\sigma_f \otimes D_{f\to h}$ in terms of independent fragmentation functions already observed in hadronic collisions at Fermilab and at SPS





Second endpoint boosts the string along the direction of the beam-remnant (*beam-drag effect*), leading to an asymmetry in the rapidity distribution of D^+/D^- mesons

$$A = \frac{\sigma_{D^-} - \sigma_{D^+}}{\sigma_{D^-} + \sigma_{D^+}}$$

New results at 5.02 TeV: D-meson v_2 and v_3 in Pb-Pb

The study of higher flow-harmonics in AA collisions requires a modeling of initial-state event-by-event fluctuations. We perform a Glauber-MC sampling of the initial conditions, each one characterized by a *complex eccentricity*

$$s(\boldsymbol{x}) = \frac{K}{2\pi\sigma^2}\sum_{i=1}^{N_{\rm coll}} \exp\left[-\frac{(\boldsymbol{x}-\boldsymbol{x}_i)^2}{2\sigma^2}\right] \quad \longrightarrow \quad \epsilon_m e^{im\Psi_m} \equiv -\frac{\{r^2 e^{im\phi}\}}{\{r^2\}}$$

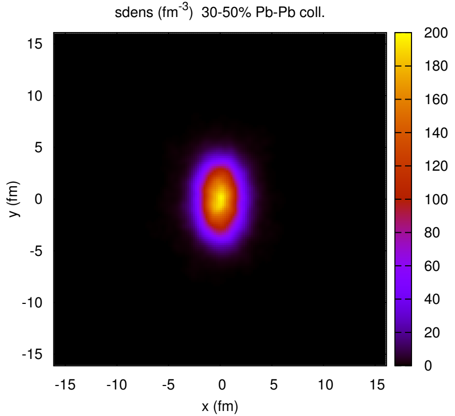
with orientation and modulus given by

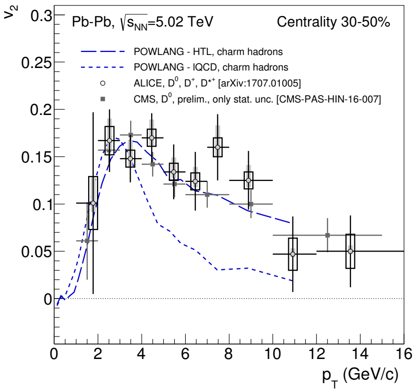
$$\Psi_m = \frac{1}{m}\,\mathrm{atan2}\left(-\{r^2\sin(m\phi)\}, -\{r^2\cos(m\phi)\}\right)$$

$$\epsilon_m = \frac{\sqrt{\{r_\perp^2\cos(m\phi)\}^2 + \{r_\perp^2\sin(m\phi)\}^2}}{\{r_\perp^2\}} = -\frac{\{r^2\cos[m(\phi-\Psi_m)]\}}{\{r^2\}}$$

Exploiting the fact that, on an event-by-event basis, for $m = 2, 3$ $v_m \sim \epsilon_m$ we consider an *average background* obtained summing all the events of a given centrality class, each one rotated by its *event-plane* angle ψ_m, depending on the harmonics one is considering.

New results at 5.02 TeV: *D*-meson v_2 and v_3 in Pb-Pb





Transport calculations carried out in JHEP 1802 (2018) 043, with hydro background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524)

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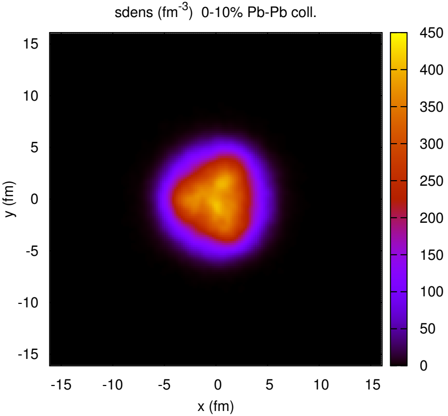

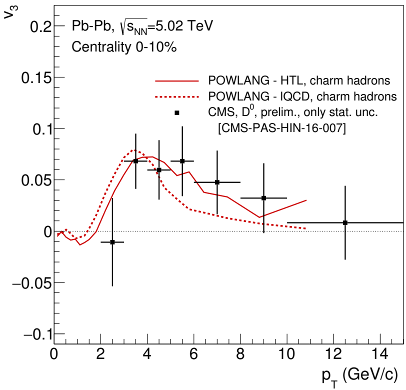

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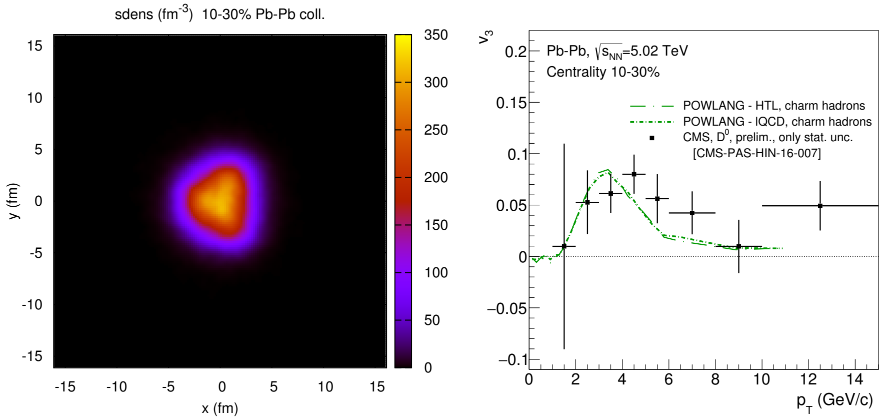

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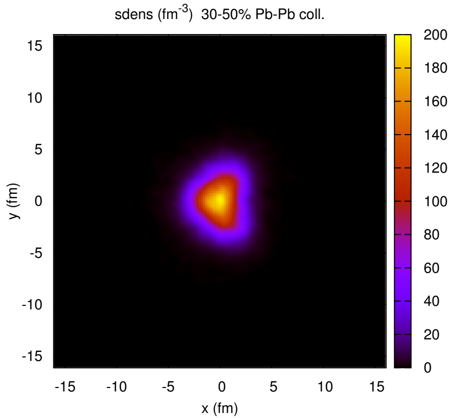

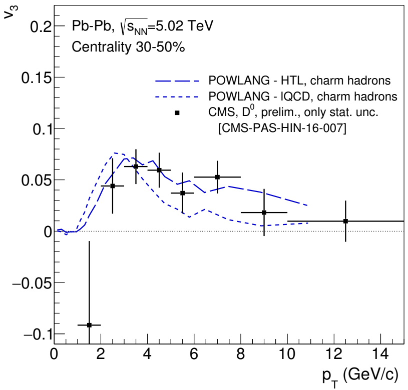

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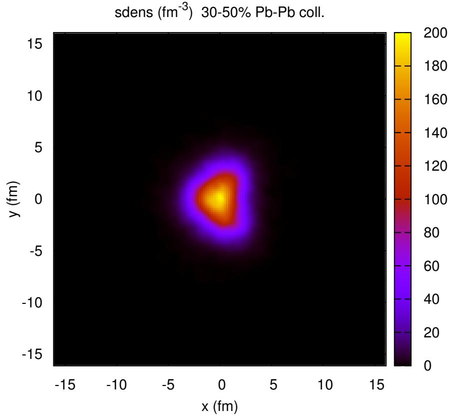

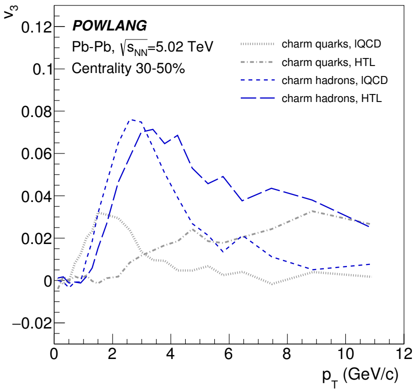

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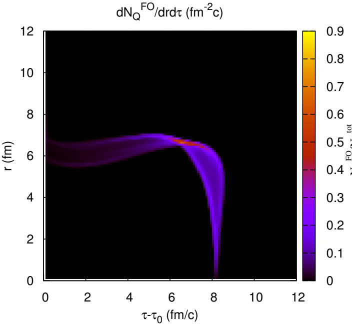
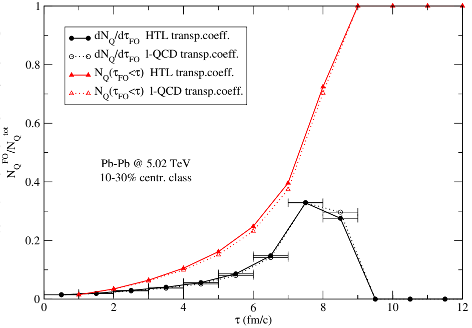
- CMS (and ALICE) data for D-meson $v_{2,3}$ satisfactory described;
- Recombination with light quarks provides a relevant contribution.

Time development of azimuthal anisotropies





- Most of the HQ's decouple quite late ($\sim$ 50% after 8 fm/c);

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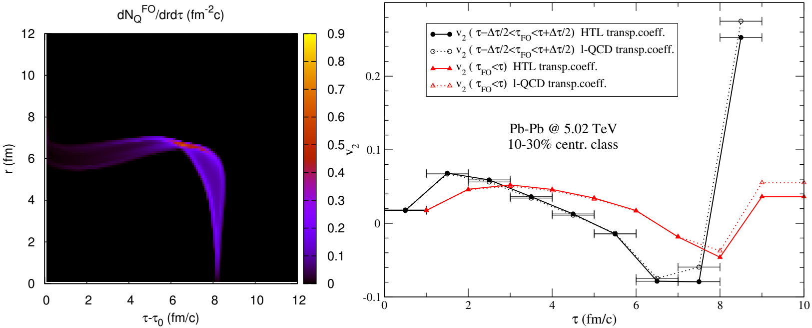

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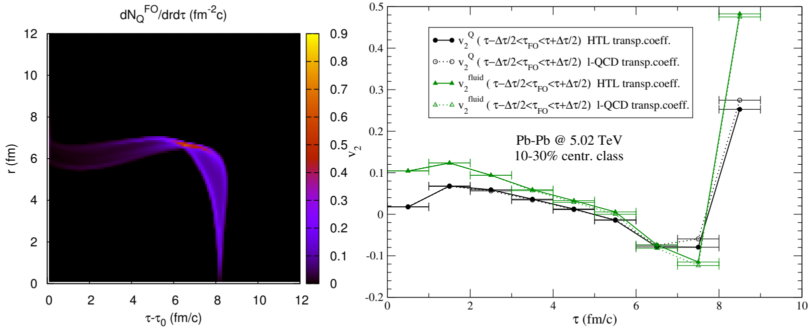

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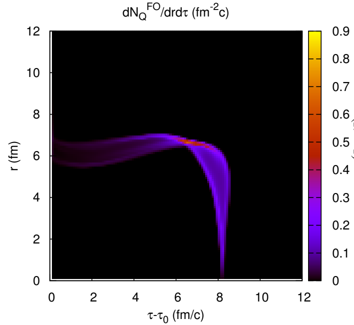

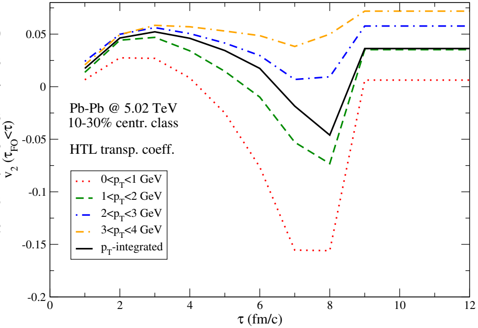

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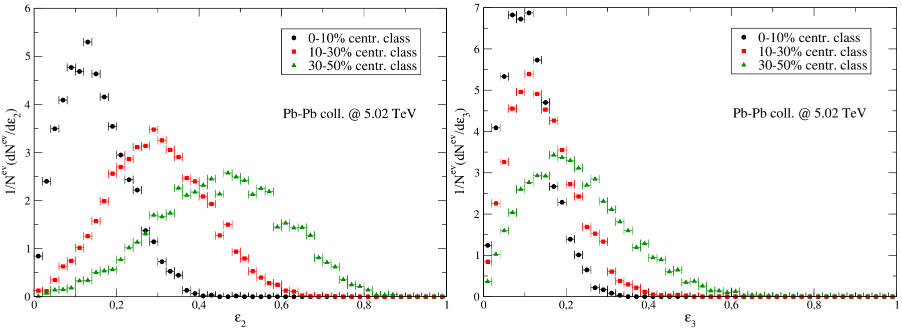
- supplementary information from p_T-differential analysis;

Eccentricity fluctuations



Events within the same *centrality class* can be characterized by very different eccentricities. Eccentricity distributions of different classes display a significant overlap, in particular for ϵ_3, which is less correlated with the impact parameter. It is interesting to study in each class the 0-20% high-ϵ_n and the 0-60% low-ϵ_n events. We want to extend this program, usually carried out for soft-hadrons (ALICE Coll. PRC 93 (2016), 034916), to HF particles.

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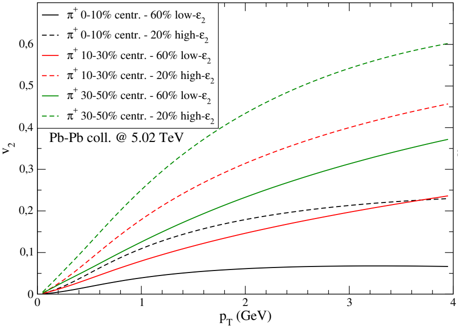

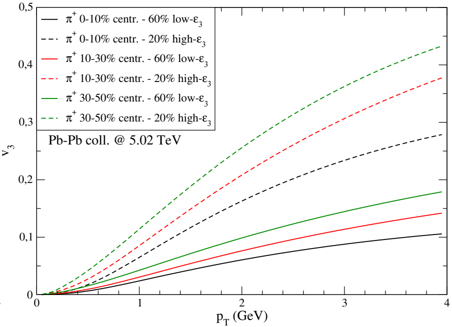

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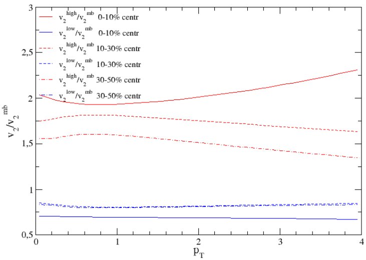

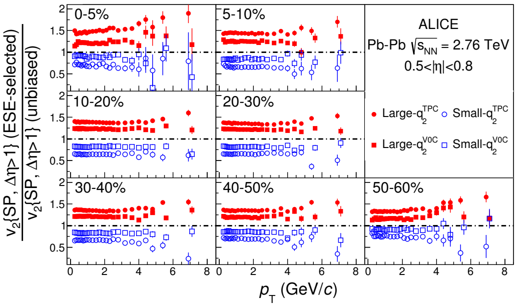

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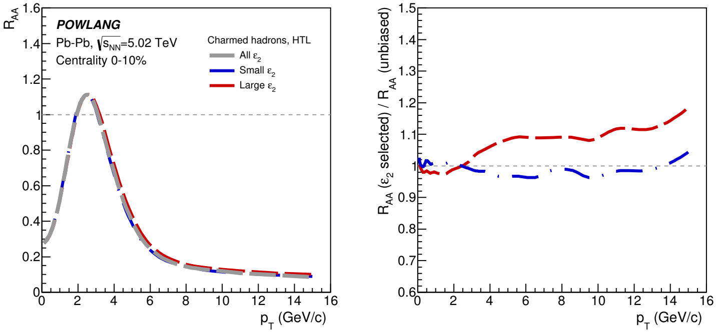
ESE and HF observables: nuclear modification factor



The nuclear modification factor of charmed hadrons, within a given centrality class, displays only a *mild dependence on the initial eccentricity*. This holds for both choices of transport coefficients.

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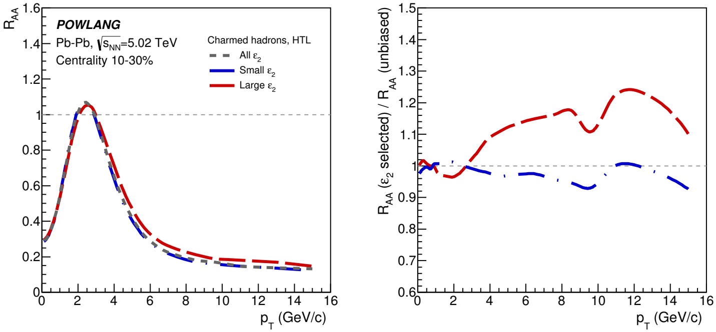

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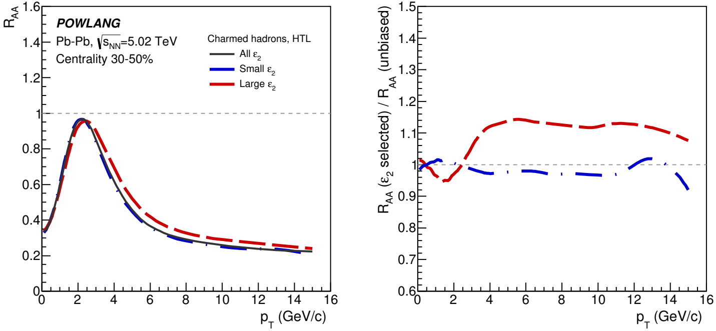

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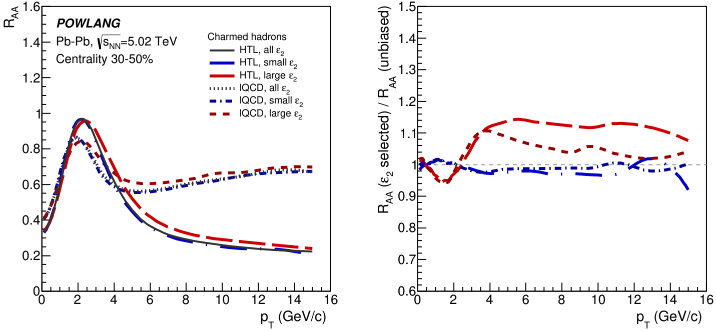

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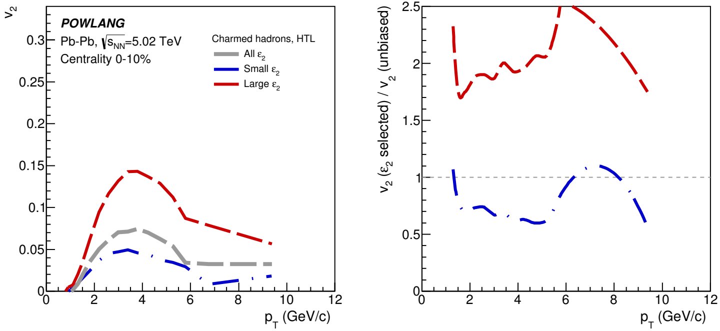

Charmed hadron v_2 is strongly affected by eccentricity fluctuations within a given centrality class. The size of the effect looks independent from the choice of the transport coefficients.

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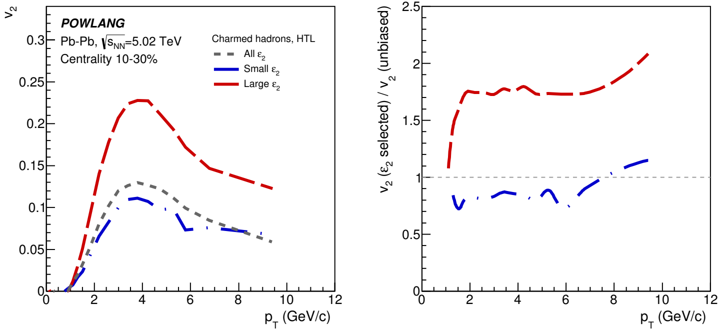

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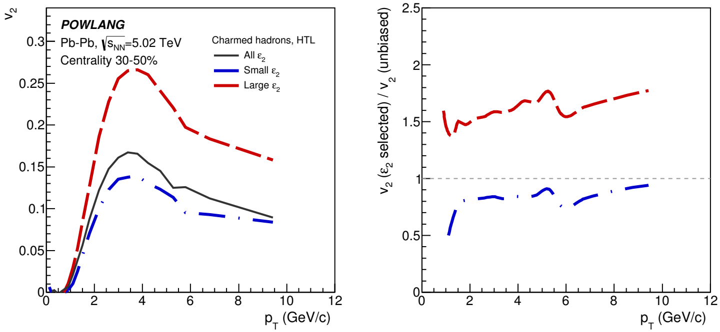

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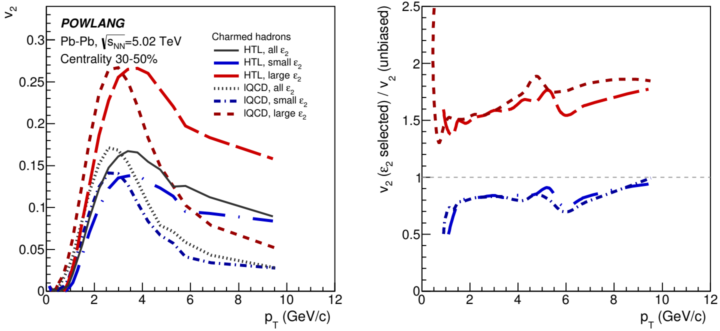

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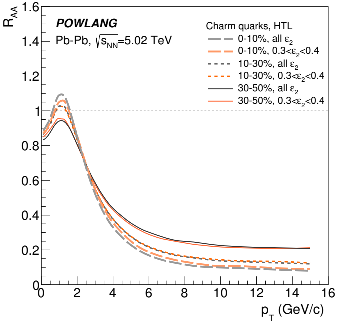
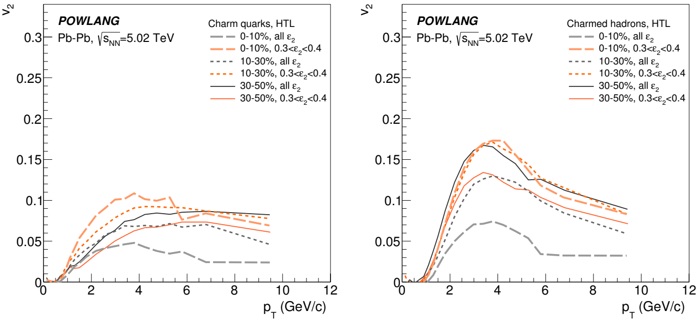
Selecting events at fixed eccentricity



One can adopt a different strategy and select events of a given eccentricity (e.g. $0.3 < \epsilon_2 < 0.4$) in the different centrality classes.

- the $R_{\rm AA}$ depends only on the centrality and not on ϵ_2

Selecting events at fixed eccentricity



One can adopt a different strategy and select events of a given eccentricity (e.g. $0.3 < \epsilon_2 < 0.4$) in the different centrality classes.

- the $R_{\rm AA}$ depends only on the centrality and not on ϵ_2
- the HF *hadron* v_2 looks similar (at low-p_T) for events with the same ϵ_2 belonging to different centrality classes. The scaling does not hold for quarks (drag depends on medium density!). Hadronization plays an important role.

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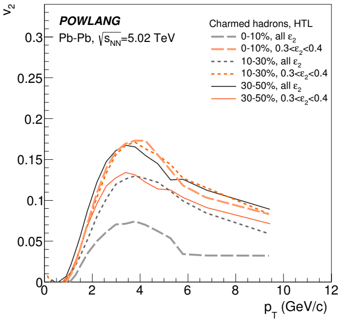

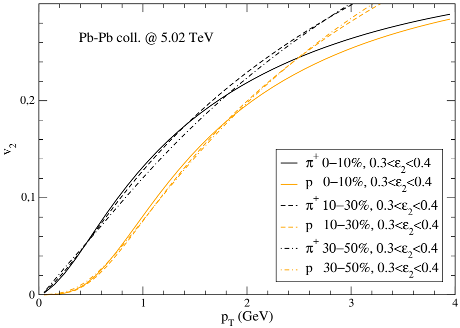

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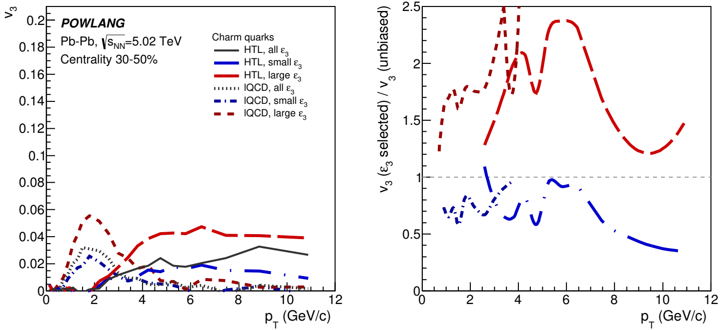
ESE and HF observables: elliptic flow



First results obtained also for the triangular flow

- Dependence of the HQ v_3 on the transport coefficients;
- Strong dependence on ϵ_3 fluctuations;
- HF v_3 increased by in-medium hadronization (recombination)

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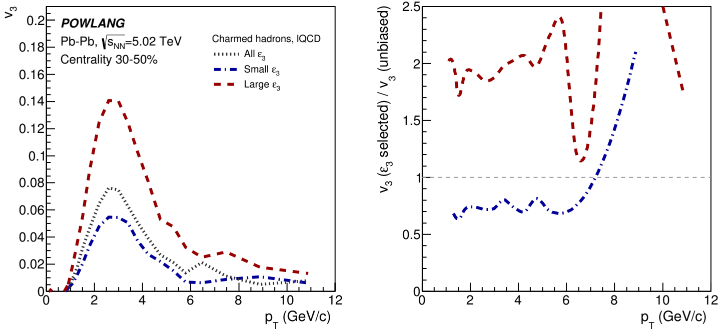

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Conclusions

- With initial conditions accounting for event-by-event fluctuations it is possible to provide a consistent description of even and odd harmonics of HF azimuthal anisotropies (v_2 and v_3);
- The way is open to perform the study of HF observables within an Event-Shape-Engineering analysis: the potential to extract information on the initial conditions and on the transport coefficients of the medium has to be explored;
- More results going to become available soon.