Azimuthal anisotropy of heavy-flavor production with ALICE at the LHC

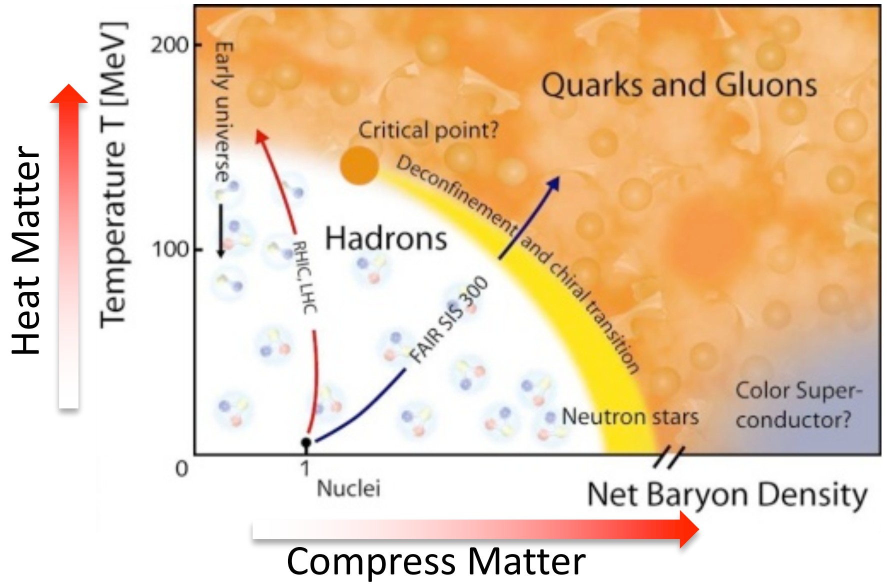
Grazia Luparello on behalf of the ALICE Collaboration

INFN – Sezione di Trieste

11^{th} International Workshop on Multiple Partonic Interactions at the LHC

Prague, 18- 22 November 2019

Creating hot and dense matter in the laboratory

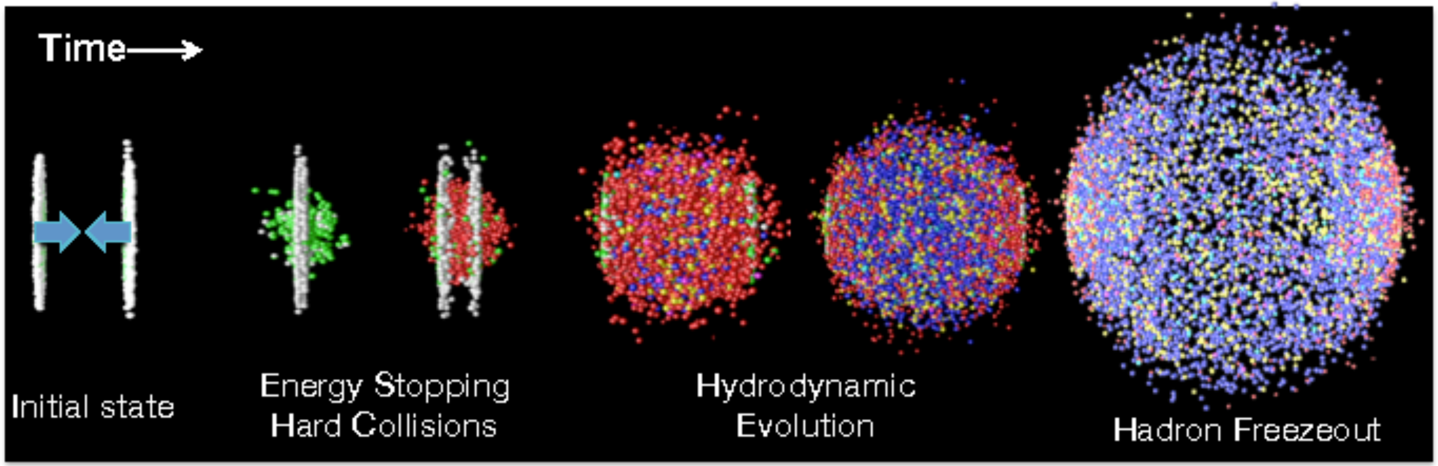


Collisions of relativistic heavy nuclei create the conditions for the phase transition from ordinary matter to a **strongly interacting, deconfined** medium:

Quark-Gluon Plasma (QGP)

- QGP evidence already at CERN-SPS and BNL-RHIC experiments
- At the LHC: precise characterization of QGP parameters
  (degree of freedom, transport properties,...)

Nuclear collision and QGP expansion



Pre-thermal processes
scattering of incoming quarks and gluons

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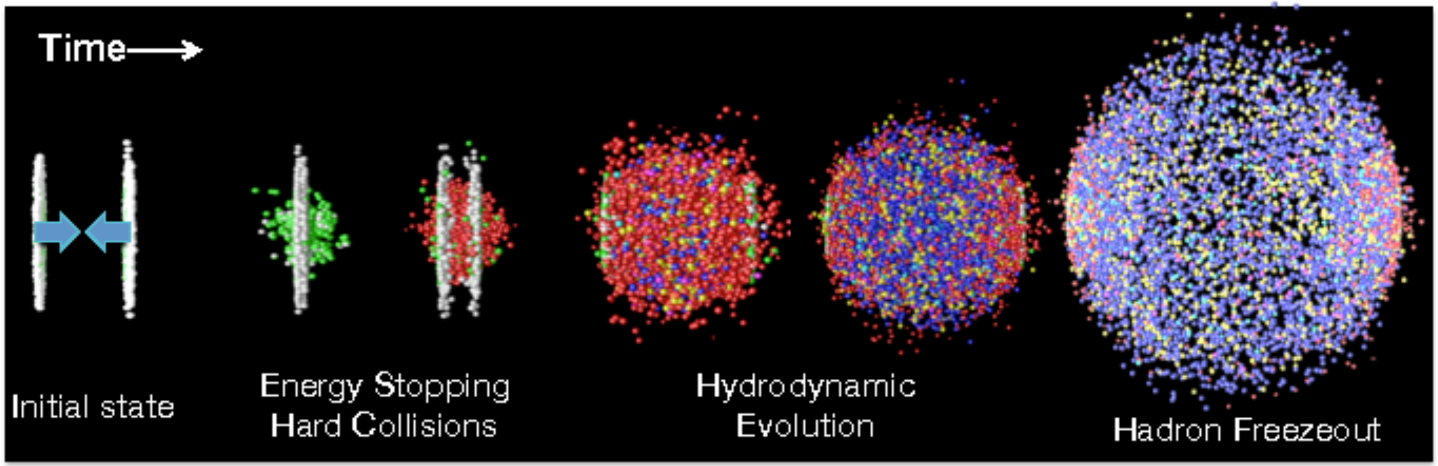

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Equilibrium is established (t~1 fm/c)

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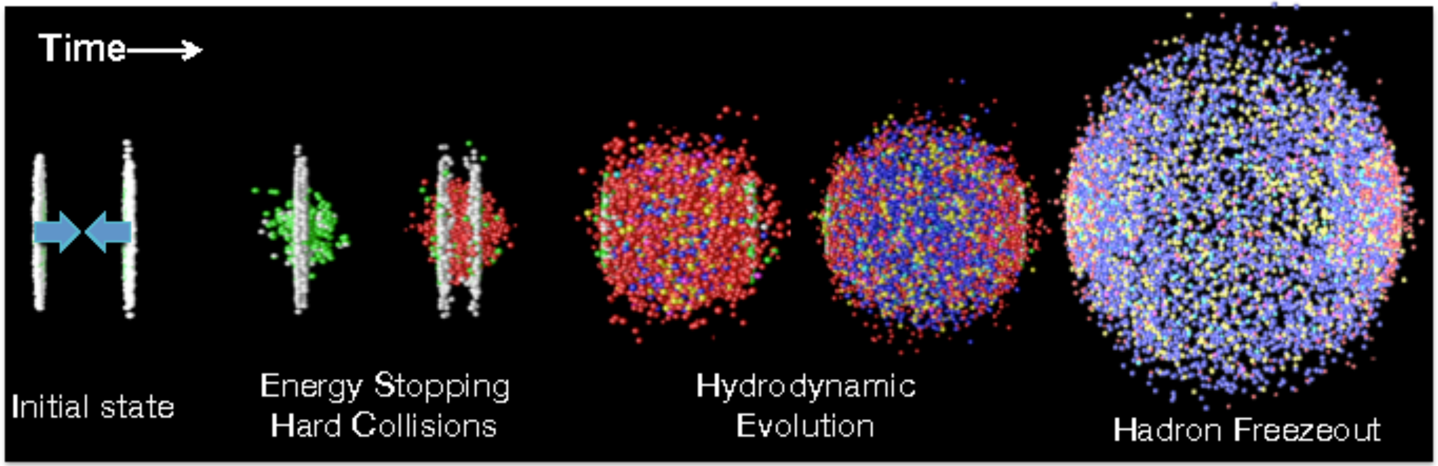

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Described by an almost perfect fluid dynamics

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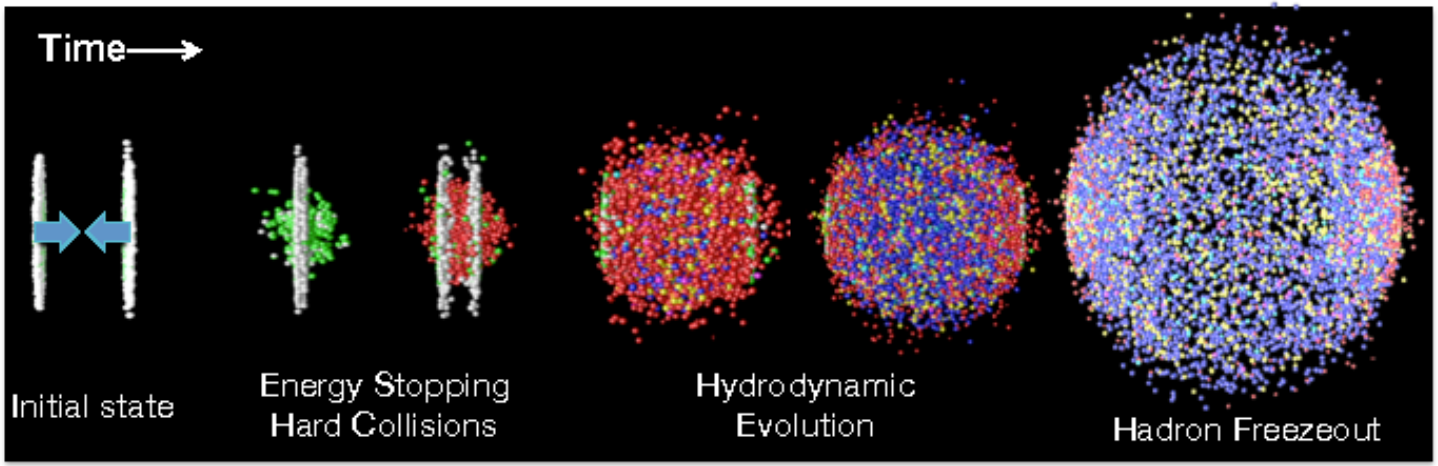

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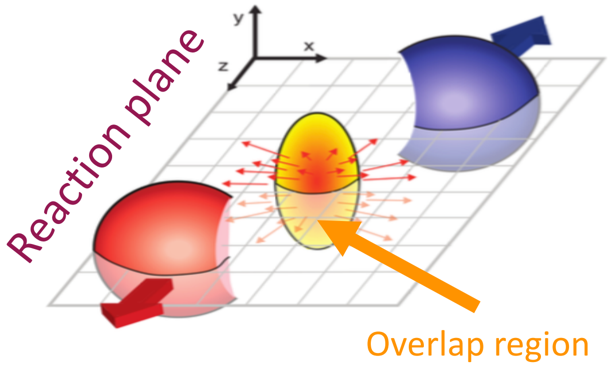
QGP expansion
(t~10 fm/c)
Described by an almost perfect fluid dynamics

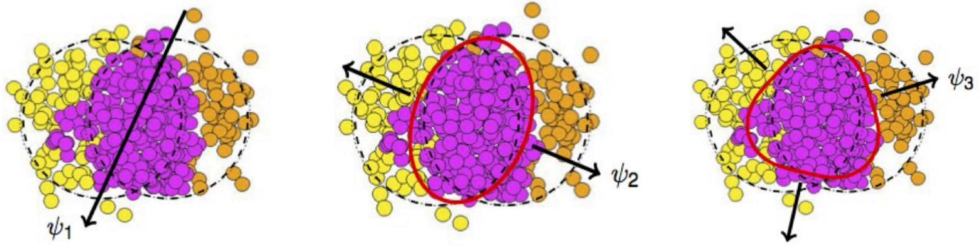
Hadronization, Chemical freeze-out
Inelastic interactions cease, particle abundances frozen

Kinetic freeze-out
Elastic interactions cease, particle dynamics (spectra) frozen

Anisotropic flow coefficients



- **Initial spatial anisotropy transferred into final anisotropy in momentum via collective interactions**
- Initial fluctuations in the nucleons position lead to higher moment deformations in the fireball, each with its own direction



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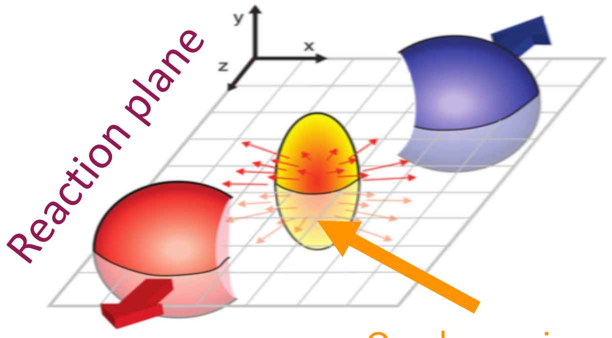

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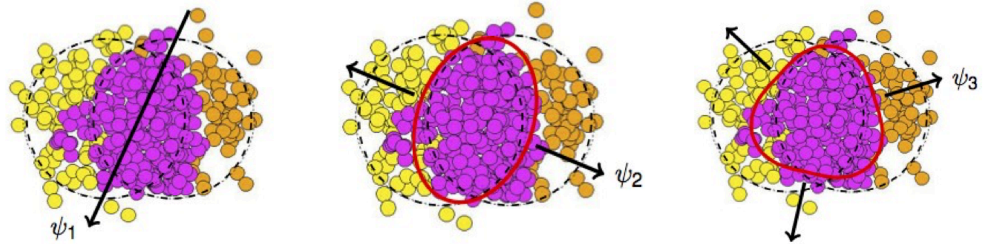


- Expressed via the **Fourier decomposition** of the azimuthal distribution of particle momenta

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

Flow coefficients

$$v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$$

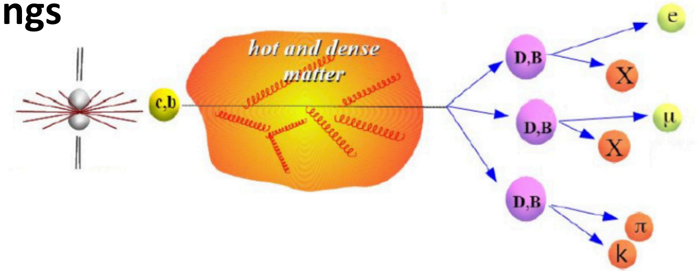
n^{th} symmetry plane

Why heavy-quark azimuthal anisotropies?

- **Heavy quarks are produced in partonic hard scatterings in the initial phases of the heavy-ion collision**

  production time of $c\bar{c}(b\bar{b})$ pair at rest :

  $\tau_{prod} = \hbar/2m_{c(b)} \simeq 0.1(0.02)$ fm/c < $\tau_{QGP} \simeq 0.1\text{-}1$ fm/c



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- Interact with medium constituents via elastic and inelastic processes
- **Reach (partial) thermalization**

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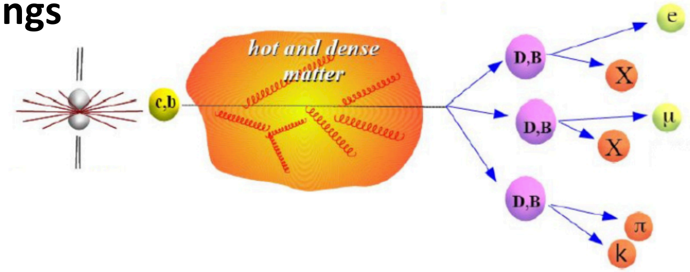

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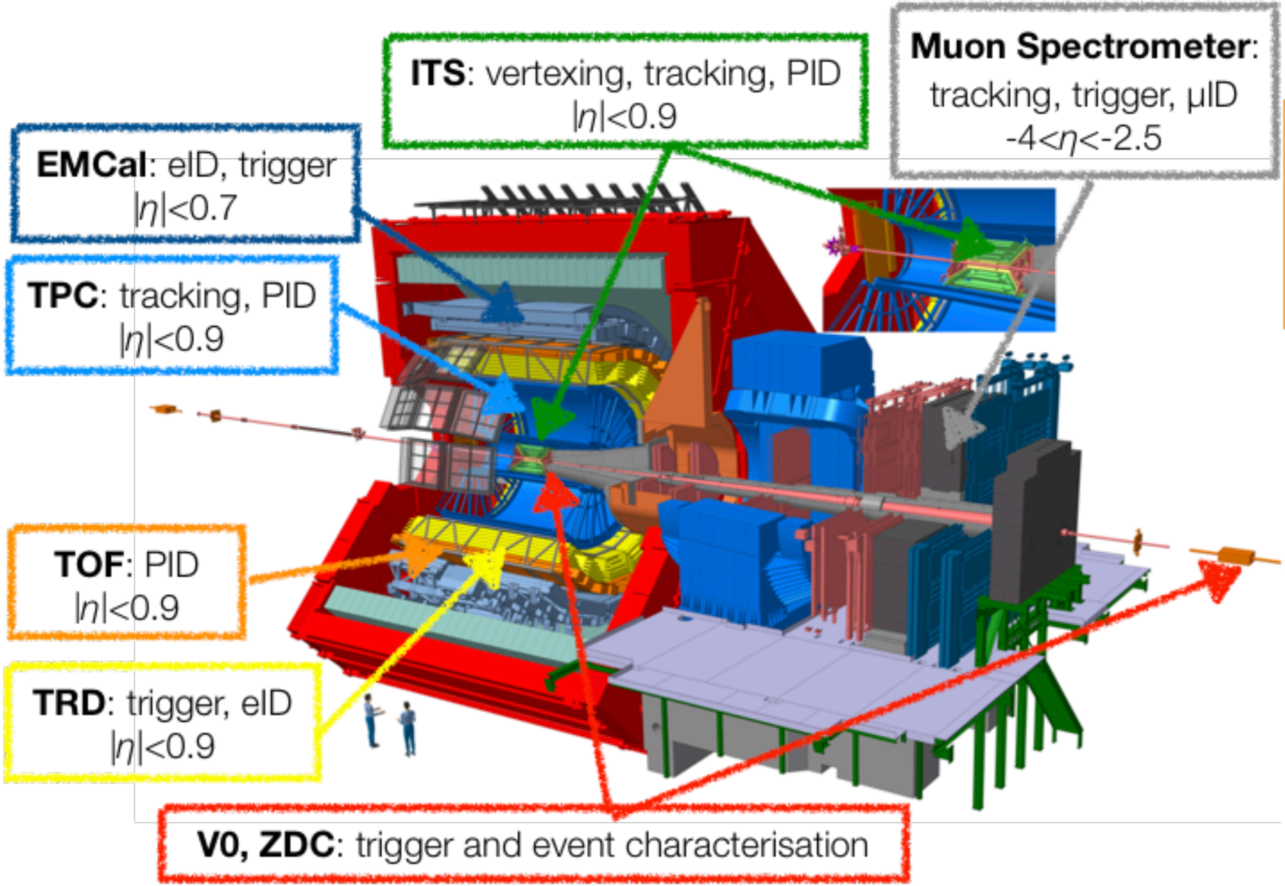
- **What can be tested?**
  - HQ participation in the collective expansion, **thermalization** in the medium (low p_T)
  - Path-length dependence of **in-medium energy loss** (high p_T)
  - **Modification of the hadronization mechanisms** in the medium
  - Magnetic fields produced in heavy-ion collisions

HF reconstruction in ALICE



Fully reconstructed D and Λ_c hadronic decays

$D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \Phi\, \pi^+ \rightarrow K^-K^+\pi^+$

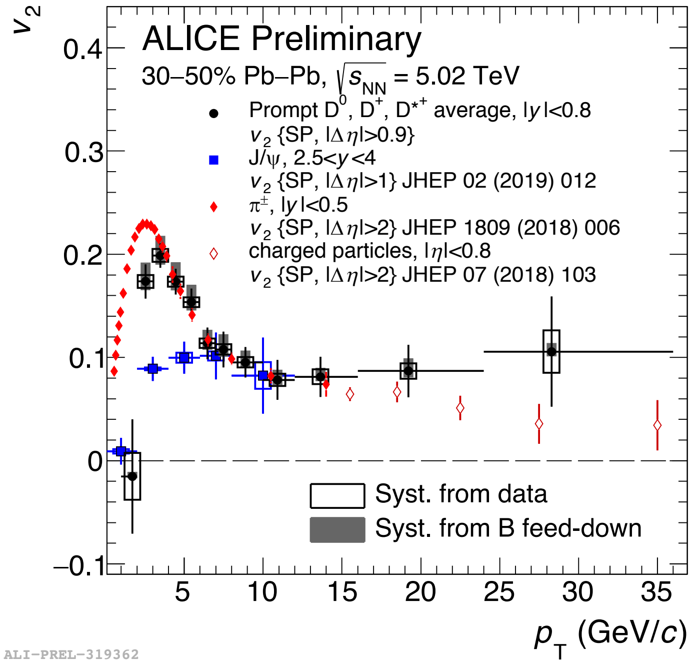
$\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow K_0^s\, p$

Semi-leptonic decays

D, B $\rightarrow \mu^\pm X$

D, B, $\Lambda_c^+ \rightarrow e^\pm X$

D-meson v_2

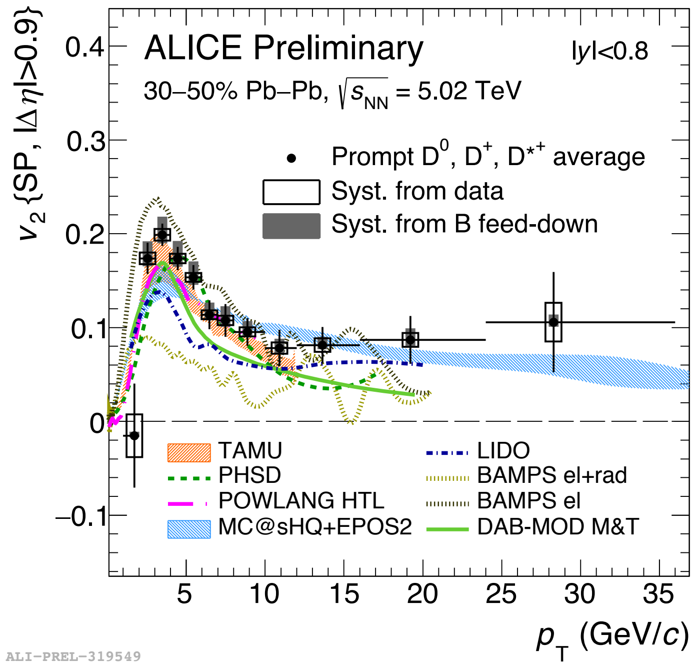


- **v_2 > 0 for non-strange D mesons** at p_T > 2 GeV/c in semi-central Pb-Pb collisions
- Indication of **v_2(D) < $v_2(\pi)$** at p_T < 4 GeV/c
- **v_2(D) > $v_2(J/\psi)$** at p_T < 6 GeV/c

Evidence of charm thermalization

Open-charm v_2 maybe enhanced from hadronization via coalescence of charm quarks with light quarks

D-meson v_2: comparison with models

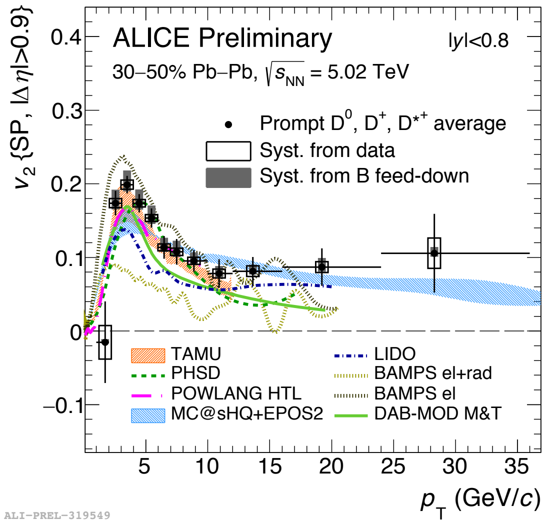


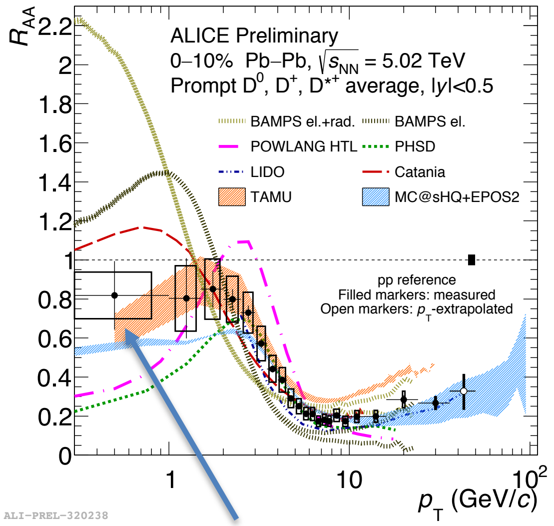
- **Comparison with theoretical calculations**
  - All models include a hydrodynamical model for the QGP expansion
  - TAMU, POWLANG, BAMPS-el include only collisional energy loss
  - All other models include also radiative energy loss
  - All models, but BAMPS and DAB-MOD, include hadronization via quark recombination together with fragmentation

TAMU: PLB 735 (2014) 445
PHSD: PRC 93 (2016) 034906
POWLANG: EPJC 75 (2015) 121
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LIDO: PRC 98 (2018) 064901
BAMPS: JPG 42, 115106 (2016)
DAB-MOD M&T: PRC 96 (2017) 064903

D-meson v_2: comparison with models

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





First measurement of charm down to p_T = 0 in Pb-Pb collisions

Important constraints to the models to predict simultaneously R_{AA} and flow of heavy-flavor hadrons

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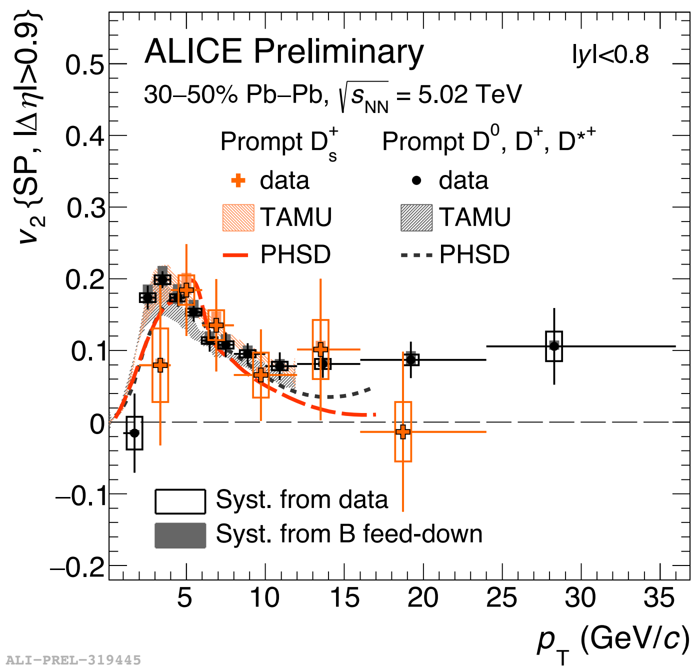
D_s^+-meson v_2



- $v_2(D_s^+) \approx v_2(D)$ within large uncertainties
- Hadronization via quark recombination included in both TAMU and PHSD models
- Good agreement between data and models

TAMU: PLB 735 (2014) 445
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Event-Shape Engineering (ESE)

- **Events classified on the basis of the eccentricity,** according to the magnitude of the **second harmonic reduced flow vector q_2**

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}, \quad Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \quad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

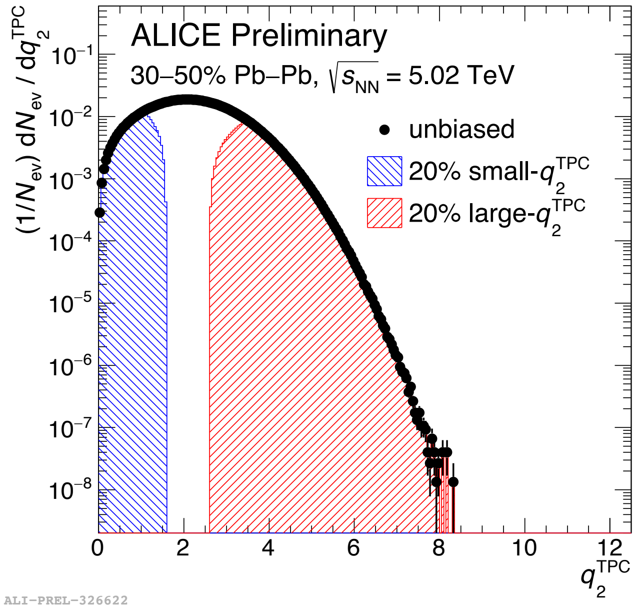
$$\langle q_2^2 \rangle \approx 1 + \langle M-1 \rangle \langle v_2^2 - \delta_2 \rangle$$

δ: non-flow effects

M: multiplicity v_2: flow strength

20% smallest q_2 — $\langle v_2 \rangle_{\mathrm{small}-q_2} < \langle v_2 \rangle_{\mathrm{unbiased}}$

20% largest q_2 — $\langle v_2 \rangle_{\mathrm{large}-q_2} > \langle v_2 \rangle_{\mathrm{unbiased}}$



- **Useful to study the interplay between the anisotropic flow of heavy quarks and that of the bulk**

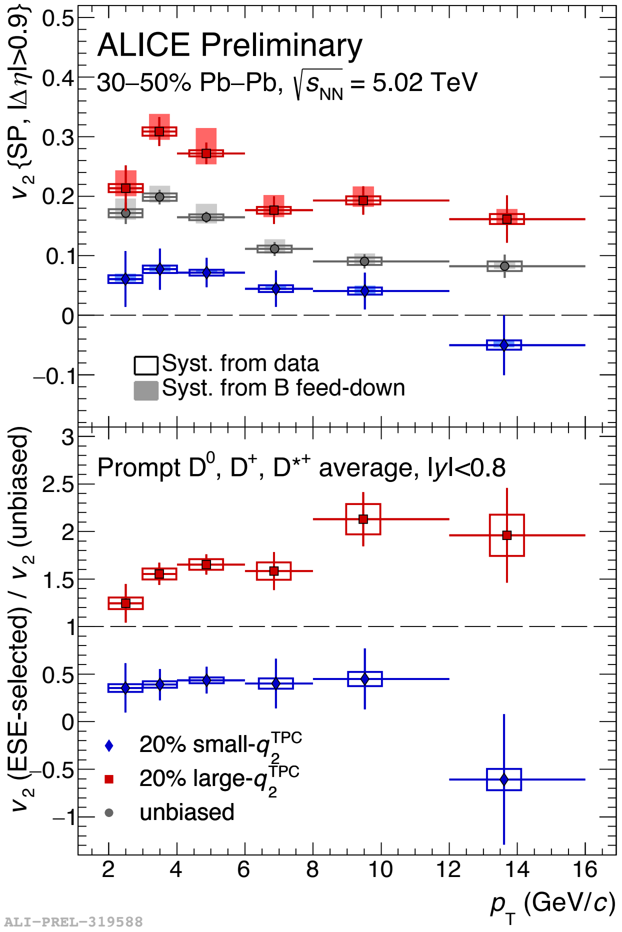
Event-Shape Engineering (ESE)

- **Events classified on the basis of the eccentricity,** according to the magnitude of the **second harmonic reduced flow vector q_2**

- **Clear separation between v_2 measured in events with small/large q_2**
  - v_2(large q_2) > v_2(unbiased)
  - v_2(small q_2) < v_2(unbiased)

  (Effect could be slightly enlarged by non-flow correlations)

D mesons sensitive to the light-hadron bulk collectivity



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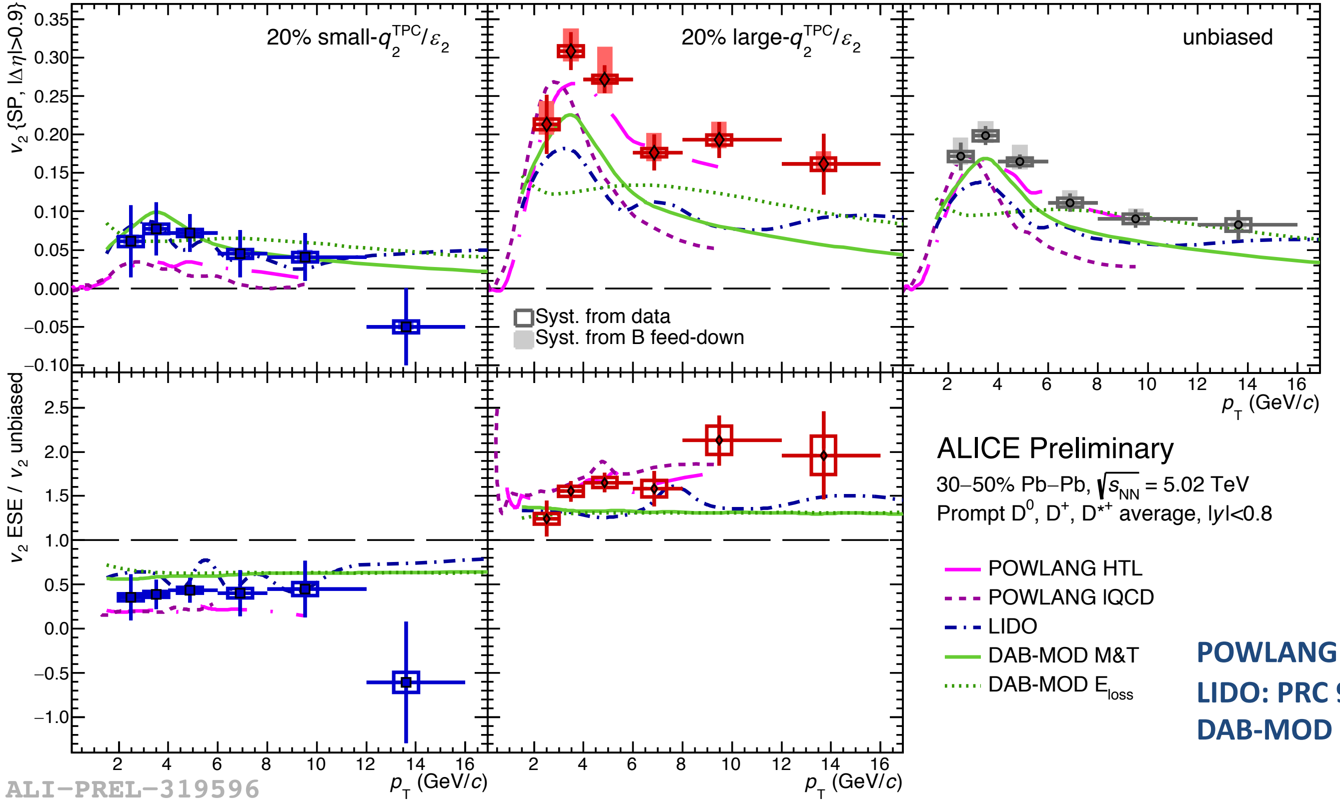

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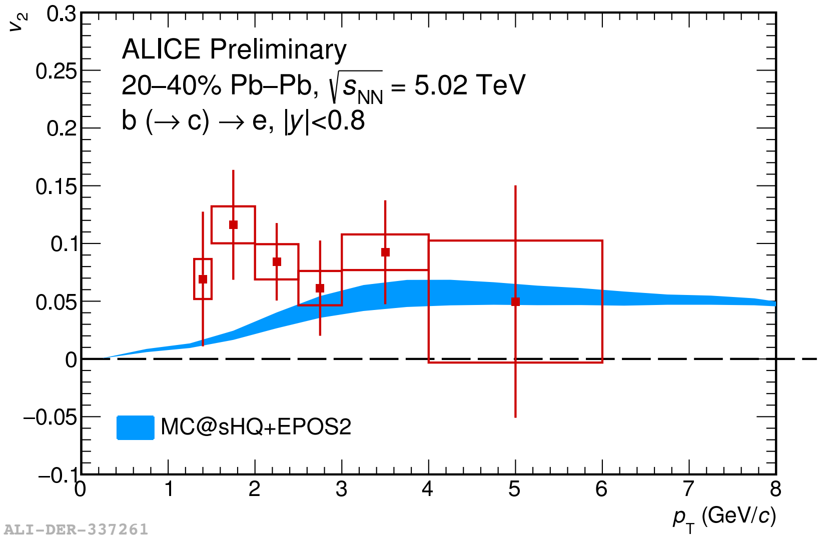
Transport models describe the q_2 dependence of elliptic flow

Beauty-quark v_2

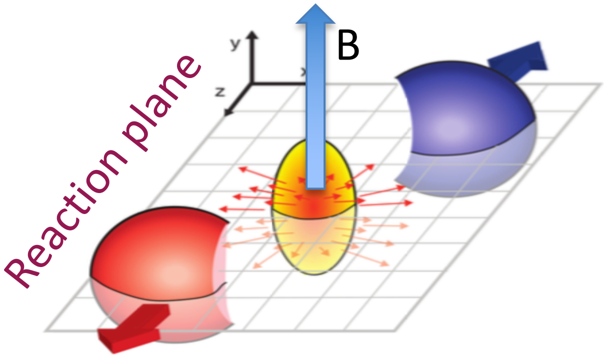


ALI-DER-337261

- **Non-zero v_2 for e^- from beauty-hadron decays** measured in semi-central Pb-Pb collisions
- **Significance of ~3.5σ** for $1.3 < p_T < 4$ GeV/c
- Model describes the data well at high p_T

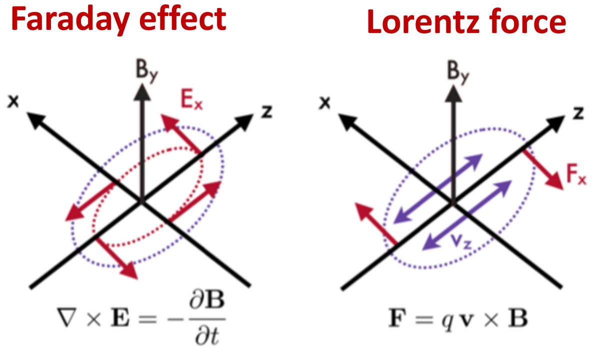
Hint of beauty-quark participation in collective behavior of the medium

D-meson v_1



- **Strong magnetic field (~10^{18} G)** generated by the movement of spectator protons

  (quickly decreases (~1 fm/*c*) as the spectators fly away
- **Charge-dependent v_1** due to two competing effects:
  - **Lorentz force vs. Faraday effect**



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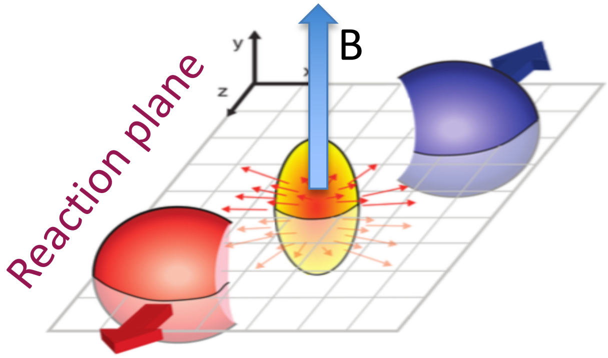
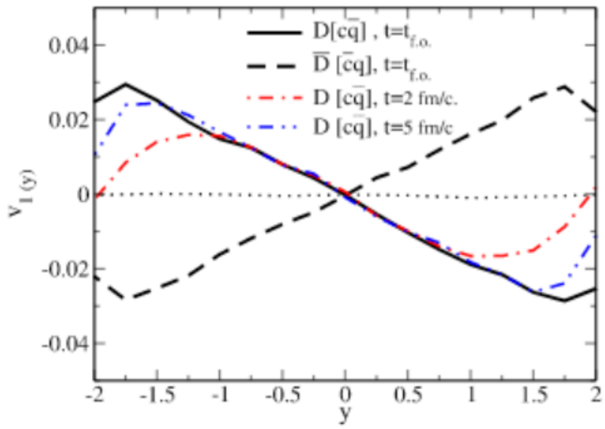


- **Charm quarks are ideal probes** of the properties of this **magnetic field B**
  - **produced when the B is maximum**
  - kinetic relaxation time of charm similar to the QGP lifetime
- Theory predictions: **larger directed flow** of charm quarks compared to light quarks



PLB 768 (2017) 260-264

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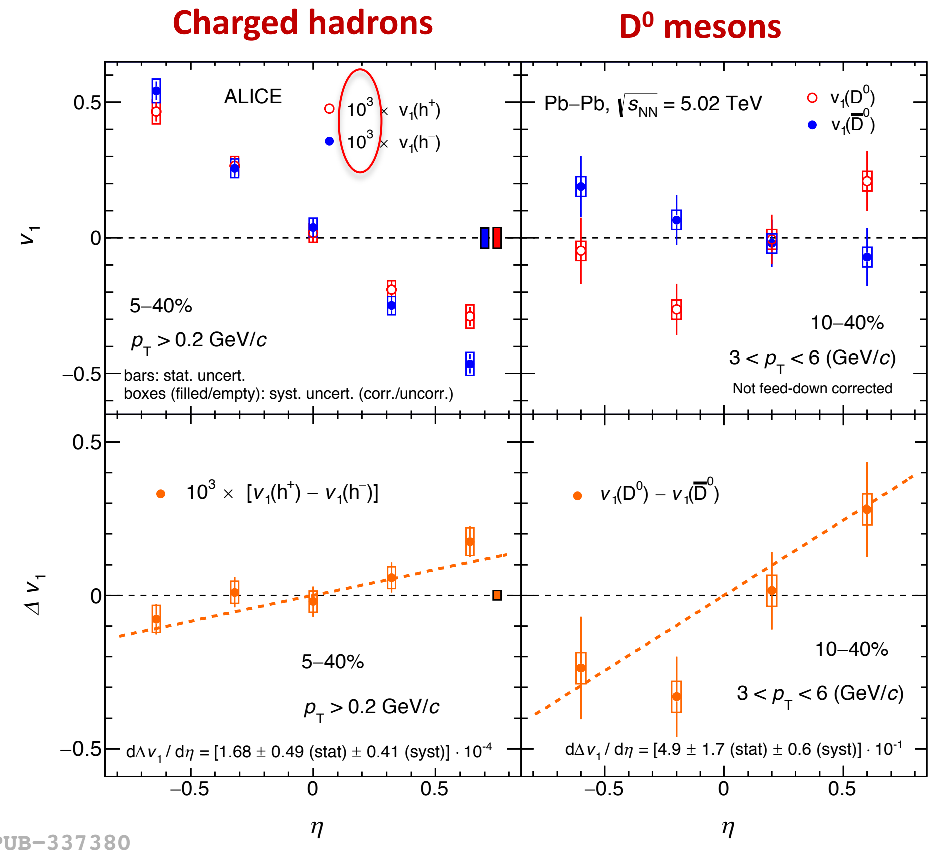


arXiv:1910.14406

ALI−PUB−337380

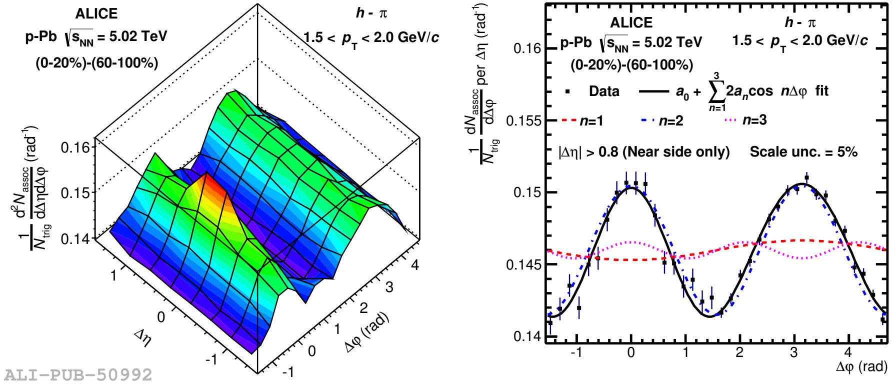
- Slope:
  - h = [1.68 ± 0.49 (stat.) ± 0.41 (syst.)]*10^{-4}
  - D^0: [4.9 ± 1.7 (stat.) ± 0.6 (syst.)]*10^{-1}

  Larger than 0 with a 2.7σ significance

Provide insights into the effects of the strong magnetic fields created in non-central heavy-ion collisions

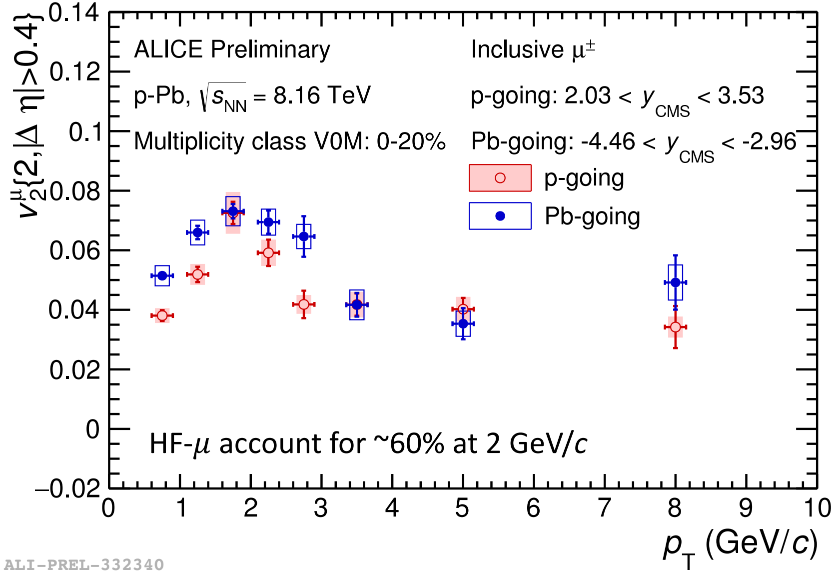
What about collectivity in p–Pb collisions?

PLB 719 (2013) 29-41



- **Long-range flow-like angular correlations observed in p–Pb collisions**
  - Small-size QGP in p–Pb collisions?
  - Initial conditions effect?
  - QCD effects to be taken into account?

v_2 of muons from HF decays in p–Pb collisions



- **$v_2(\mu) > 0$** in p–Pb collisions at 8.16 TeV with **significance > 5σ for 0.5 < p_T < 6 GeV/c**
- Tendency for smaller v_2 at low p_T in p-going direction

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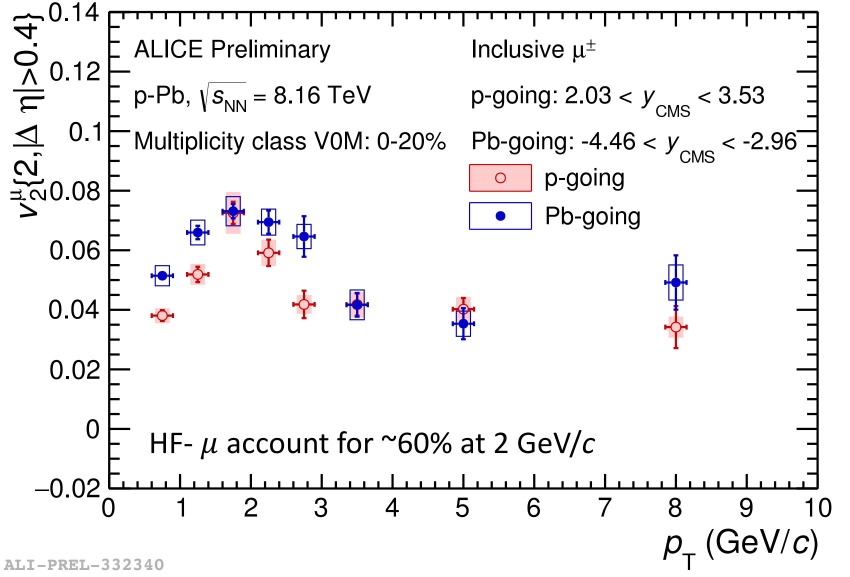

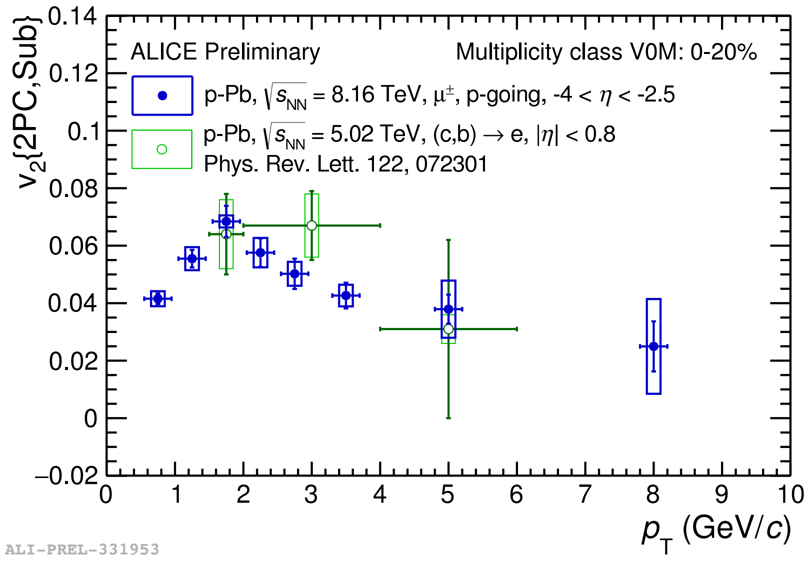

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- **Compatible** v_2 of muons at forward rapidity and v_2 of e^- from HF-hadron decays at mid-rapidity in p–Pb collisions at 5.02 TeV

Conclusions

In Pb–Pb collisions:

- **D-meson $v_2 > 0$:** participation of charm quarks in the collective expansion of the system
- **ESE measurement:** confirmation of a correlation between the anisotropic flow of charm quarks and bulk matter
- **Precision measurements start to constrain QGP parameters in models**

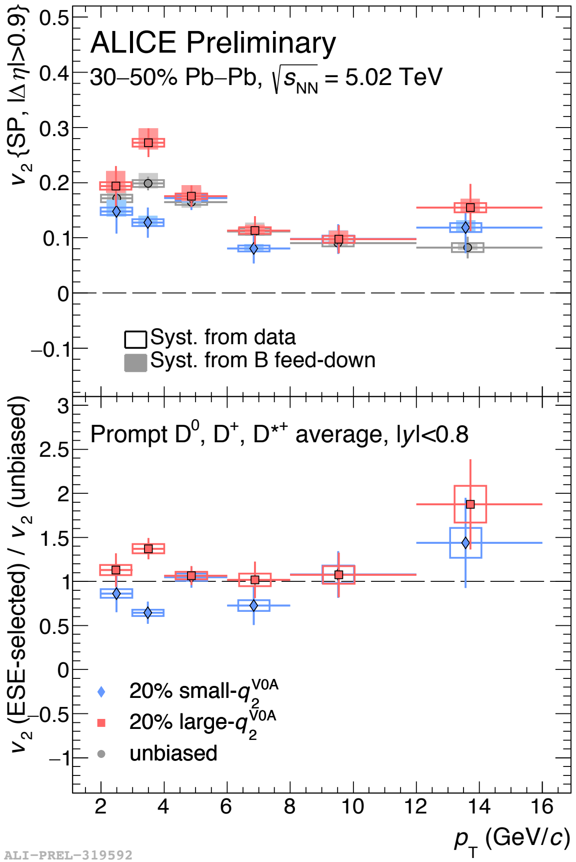
- **Direct flow measurement:** positive slope of $d\Delta v_1/d\eta$ for D^0 and $\overline{D}^0$
- **v_2 of e^- from beauty hadron decays > 0:** participation of charm quarks in the collective expansion

In p–Pb collisions:

- Positive v_2 of leptons from decays of open heavy-flavor hadrons in high multiplicity p–Pb collisions: Collective effects? Initial or final state cold nuclear matter effects?

Back up slides

Event-Shape Engineering



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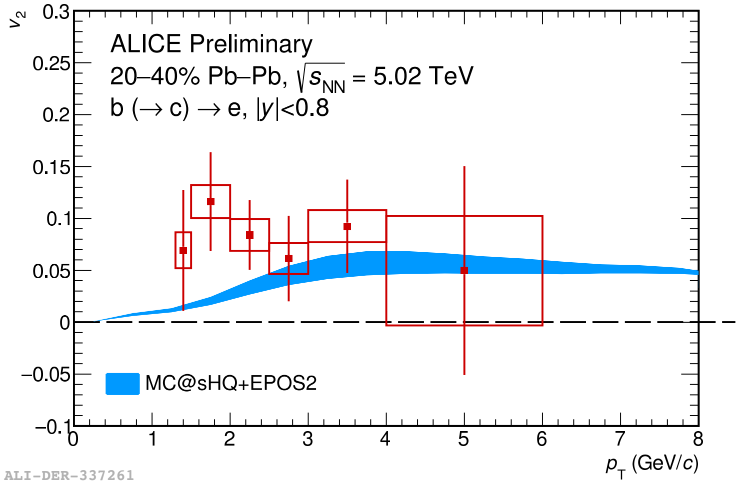
$$\langle q_2^2 \rangle \approx 1 + \langle M-1 \rangle \langle v_2^2 - \delta_2 \rangle$$

δ: non-flow effects

M: multiplicity v_2: flow strength

- q_2 calculated with V0A
- Reduced eccentricity discriminating power
- Hint of separation also with q_2^{V0A}

Beauty-quark v_2



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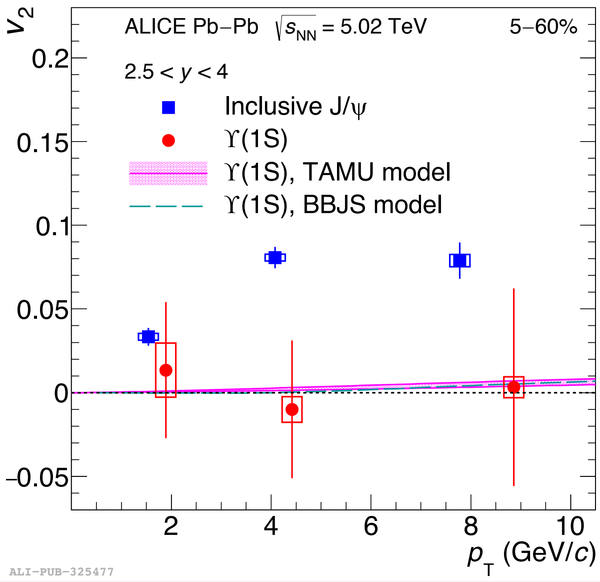
  - **Significance of ~3.5σ** for 1.3 < p_T < 4 GeV/c
  - Model describes the data well at high p_T

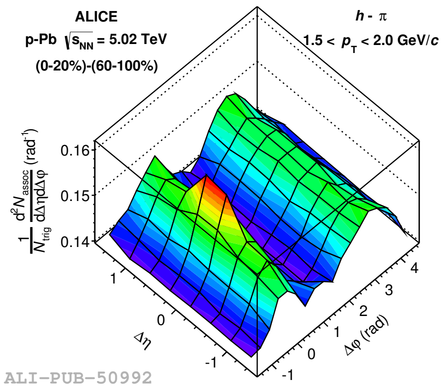
- Bottomonia (bb bound state) v_2~0
  - Impact of path-length dependent energy loss and coalescence?

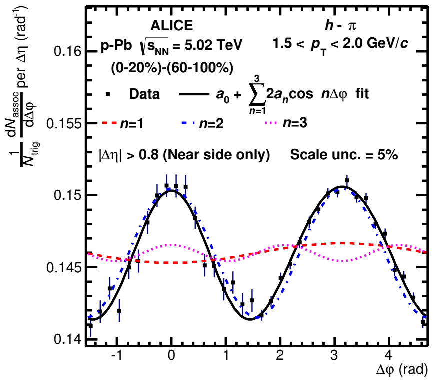


PRL 123, 192301

What about collectivity in p–Pb collisions?

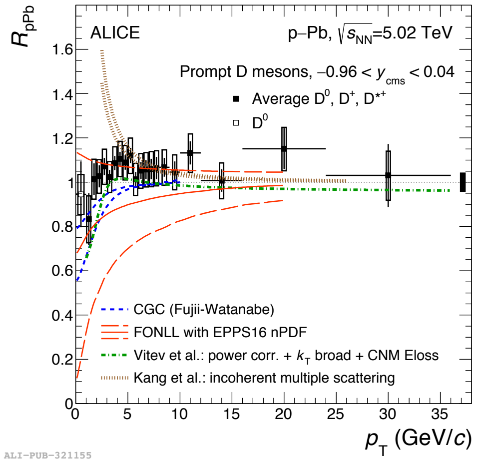
PLB 719 (2013) 29-41





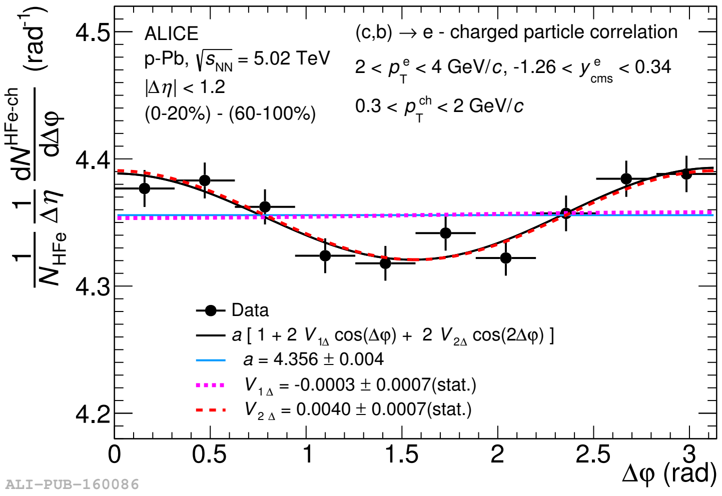
- **Long-range flow-like angular correlations observed in p–Pb collisions**
  - Small-size QGP in p–Pb collisions?
  - Initial conditions effect?
  - QCD effects to be taken into account?

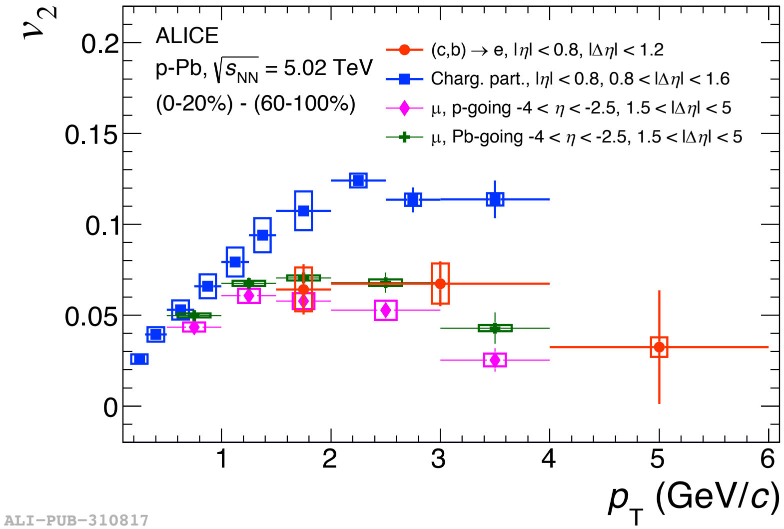
- No modification of production yield in p–Pb collisions wrt pp collisions
- Indication of possible difference in the production cross section in central vs peripheral events



arXiv:1906.03425

e⁻ from HF decays in p–Pb collisions





PRL 122 (2019) 072301

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