Universiteit Utrecht

ALICE

Measurement of D-meson nuclear modification factor and elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE at the LHC

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on behalf of the ALICE Collaboration

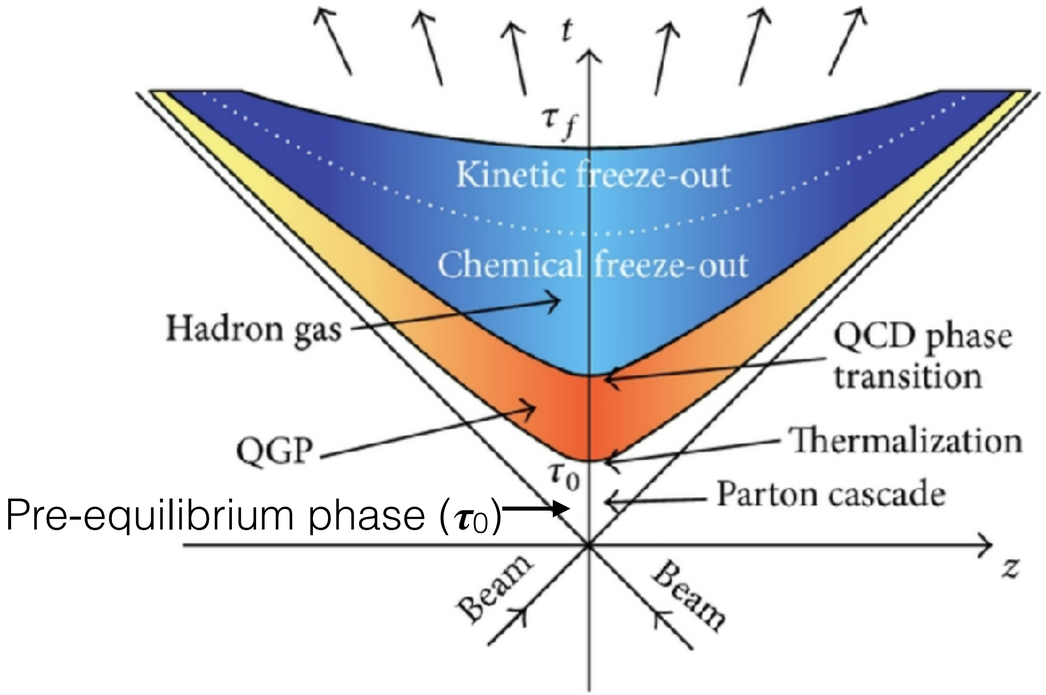
Outline

- Physics motivations
- The ALICE detector
- D-meson reconstruction in ALICE
- Results
  - D-meson nuclear modification factor as a function of p_T in 0-10%, 30-50% and 60-80% centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - D-meson azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Conclusions

Physics motivations: Heavy flavours in heavy-ion collisions

- ☑ Heavy flavours (HF) produced in the early stage of the collision, in hard parton scattering processes
- ☑ HF production:
  $\Delta t_{HF} < 1/(2m_{c,b}) \sim 0.1\ (0.01)$ fm/c for charm (beauty)
  Quark-Gluon Plasma formation time: ~ 0.3 fm/c at the LHC[1]
- ☑ HF experience the whole system evolution
- ☑ HF interact strongly with the constituents of the medium and lose part of their energy

→ **Effective probes of the Quark-Gluon Plasma**



Time evolution of the matter produced in heavy-ion collisions

[1] F. M. Liu, S. X. Liu, Phys. Rev. C 89, 034906 (2014)

Heavy-flavour observables in heavy-ion collisions

- Nuclear modification factor (R_{AA}):

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$\langle N_{coll} \rangle / \sigma_{inel}$

- Study the energy loss occurring via:
  - inelastic processes (gluon radiation) [1]
  - elastic scatterings (collisional processes) [2]
- Colour-charge and quark-mass dependence of energy loss [3]
- If hadronisation via coalescence of heavy quarks with quarks from the medium is an important mechanism of charm hadrons formation at low p_T

  -> D_s^+ production enhanced largely [4]

[1] Baier et al. Nucl. Phys. B 483 (1997) 291-320

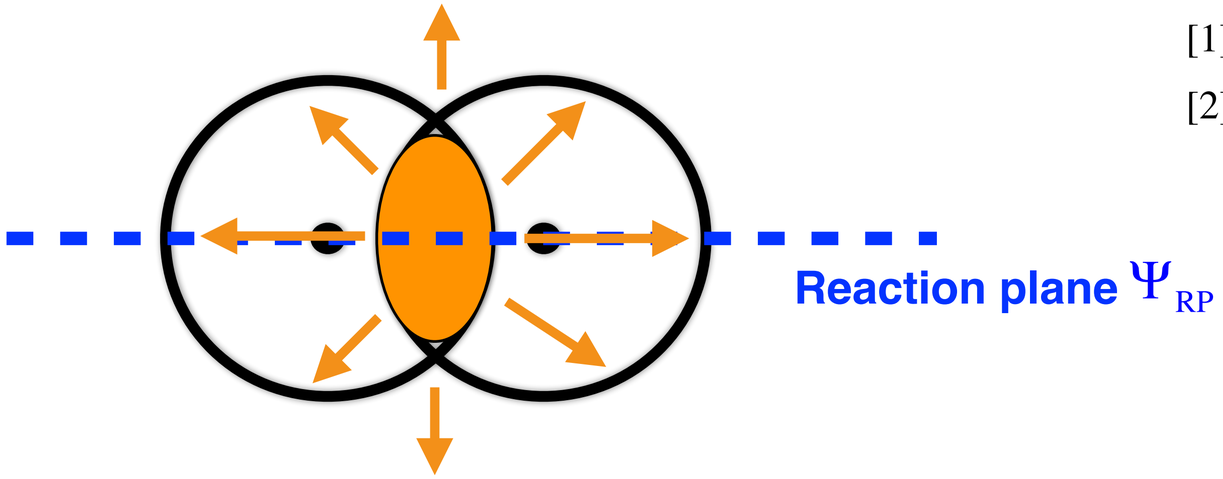
[2] E. Braaten, M. H. Thoma, Phys. Rev. D 44, no. 9, R2625 (1991)

[3] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B 519, 199 (2001)

[4] Kuznetsova, Rafelski, Eur. Phys. J. C 51 (2007) 113-133

Heavy-flavour observables in heavy-ion collisions

- Azimuthal anisotropy



[1] S. Batsouli, S. Kelly, M. Gyulassy, J. L. Nagle, Phys. Lett. B 557, 26 (2003)

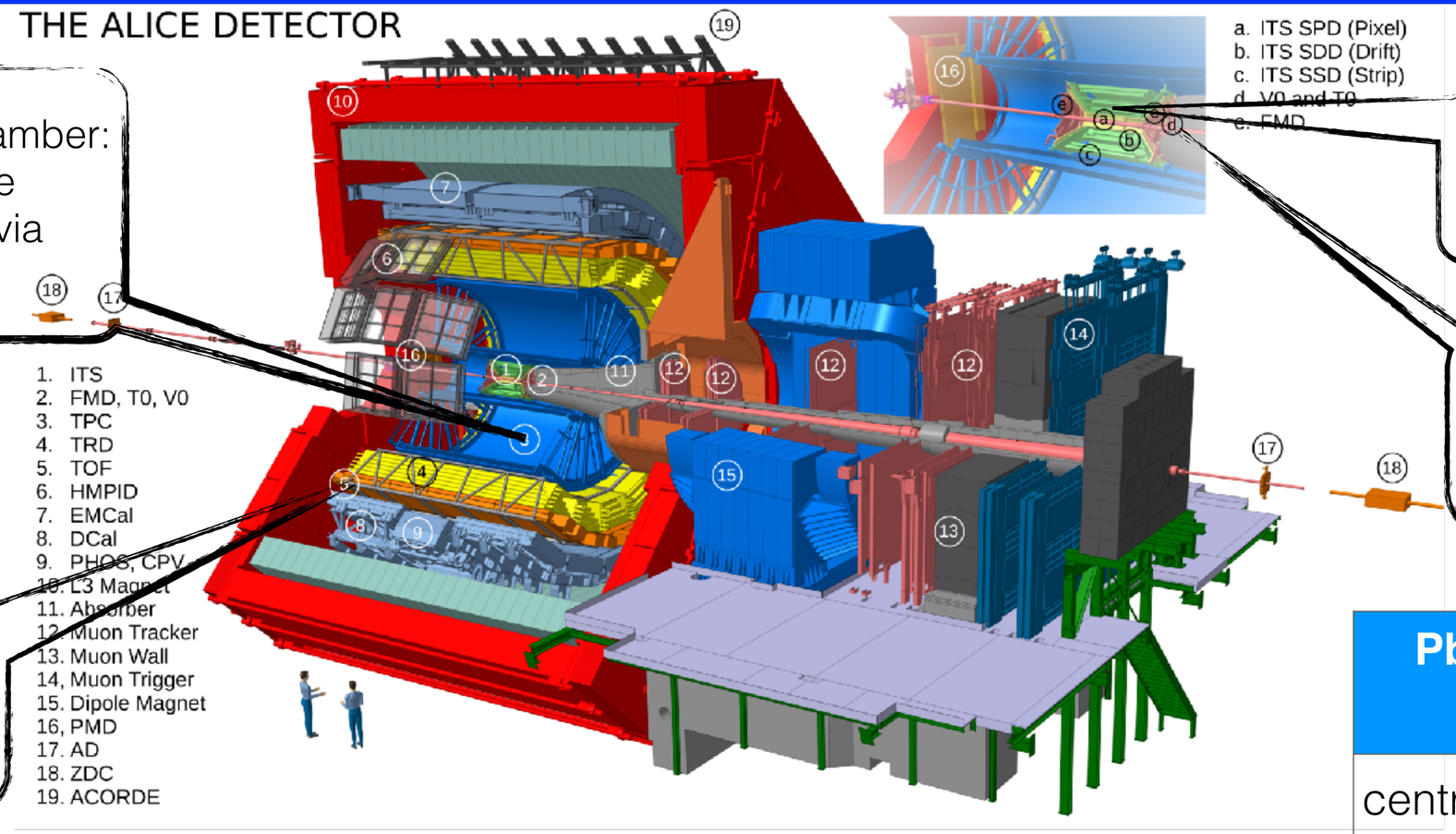
[2] M. Gyulassy, I. Vitev, X. N. Wang, Phys. Rev. Lett. 86, 2537 (2001)

- Study whether heavy quarks participate in the collective expansion dynamics and thermalise in the medium via the 2nd harmonic coefficient **v_2 (Elliptic flow)**

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos\left(\phi - \Psi_{RP}\right) + 2v_2\cos 2\left(\phi - \Psi_{RP}\right) + \ldots\right)$$

- v_2 carries information on medium transport properties:
  - thermalisation of heavy quarks in QGP at low p_T [1]
  - path-length dependence of energy loss at high p_T [2]

ALICE detector



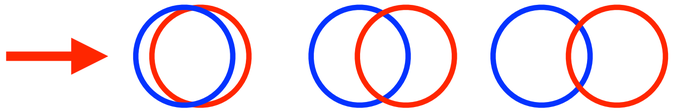
Time **P**rojection **C**hamber: tracking and **P**article **ID**entification (**PID**) via d*E*/d*x*

Inner **T**racking **S**ystem: tracking and vertexing

V0 detector: triggering, centrality and event-plane determination

Time **o**f **F**light detector: PID via time of flight

- Nuclei of lead atoms are large compared to protons
- As a result not all Pb-Pb collisions are the same in terms of the collision geometry
- Centrality is related directly to the initial overlap region of the colliding nuclei



Pb-Pb data sample 2015 at $\sqrt{s_{NN}}$ = 5.02 TeV	
centrality class (%)	N_{events}
0-10	10 M
30-50	20 M
60-80	20 M

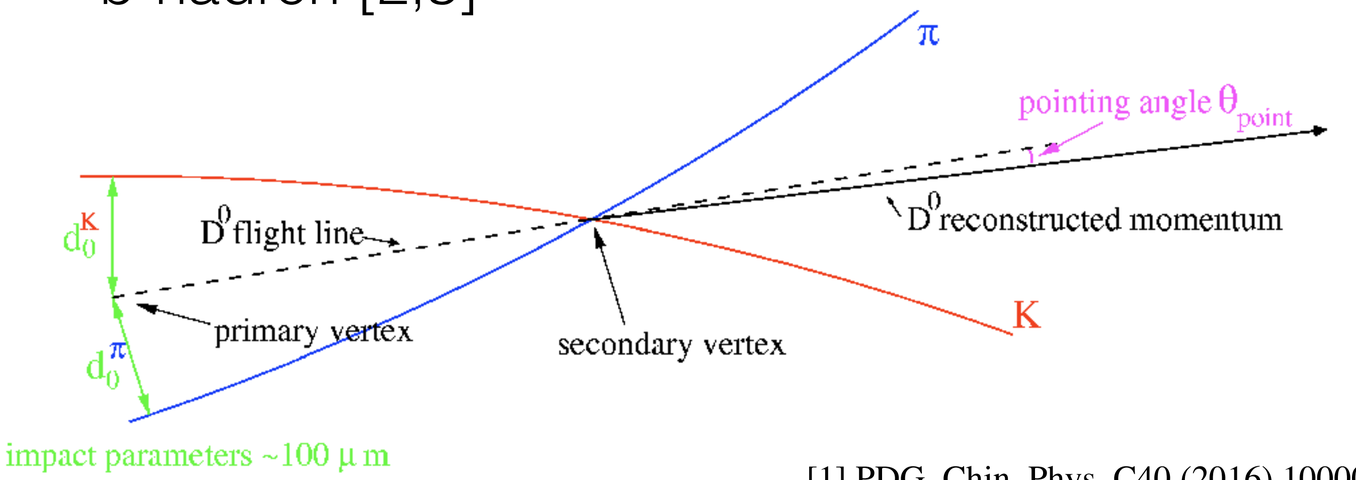
D-meson reconstruction in ALICE

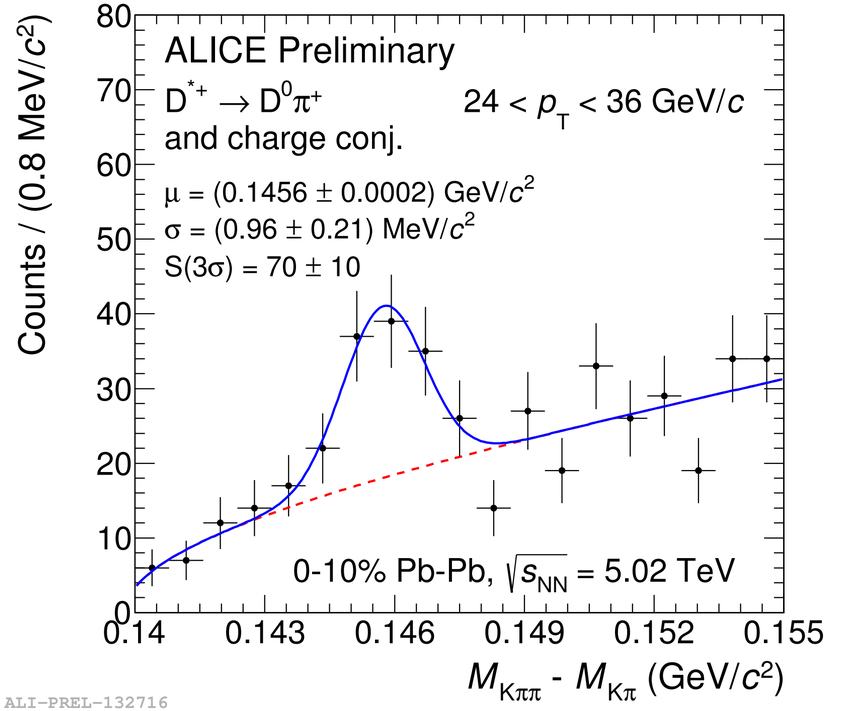
[1]

meson	M (GeV/c^2)	$c\tau$ (μm)	decay	BR (%)
D^0	1.865	123	$K^-\pi^+$	3.93
D^+	1.870	312	$K^-\pi^+\pi^+$	9.46
D^{*+}	2.010	Γ = 83.3	$D^0 (K^-\pi^+)\ \pi^+$	67.7 x 3.93
D^+_s	1.968	150	$\phi\ (K^-K^+)\ \pi+$	2.27

- Decay topology via secondary vertex reconstruction and particle identification to reduce combinatorial background

- Invariant mass analysis
- Using FONLL-based method to subtract feed-down from b-hadron [2,3]





[1] PDG, Chin. Phys. C40 (2016) 100001
[2] M. Cacciari, M. Greco, P. Nason, JHEP 9805, 007 (1998)
[3] ALICE Collaboration 10.1007/JHEP11(2015)205

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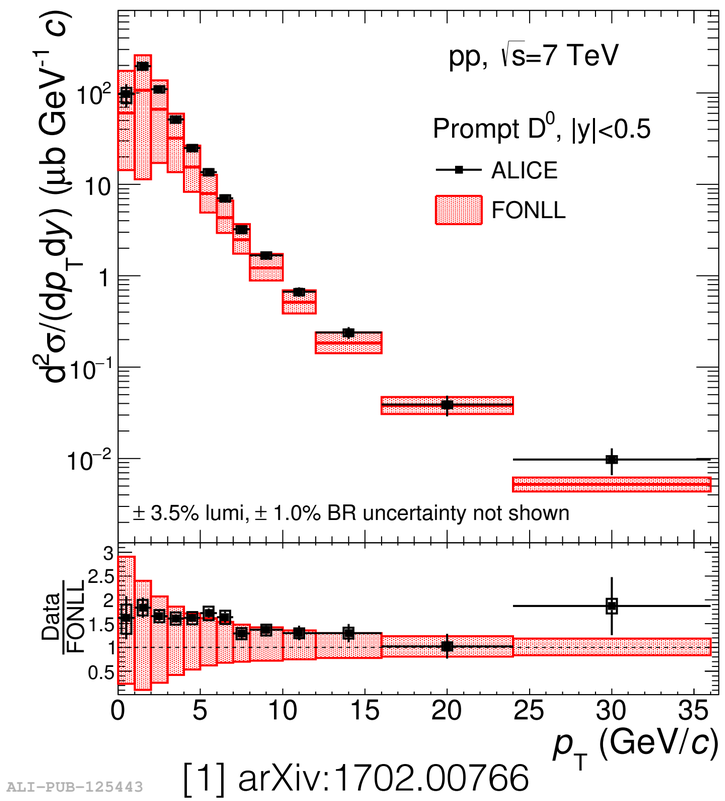
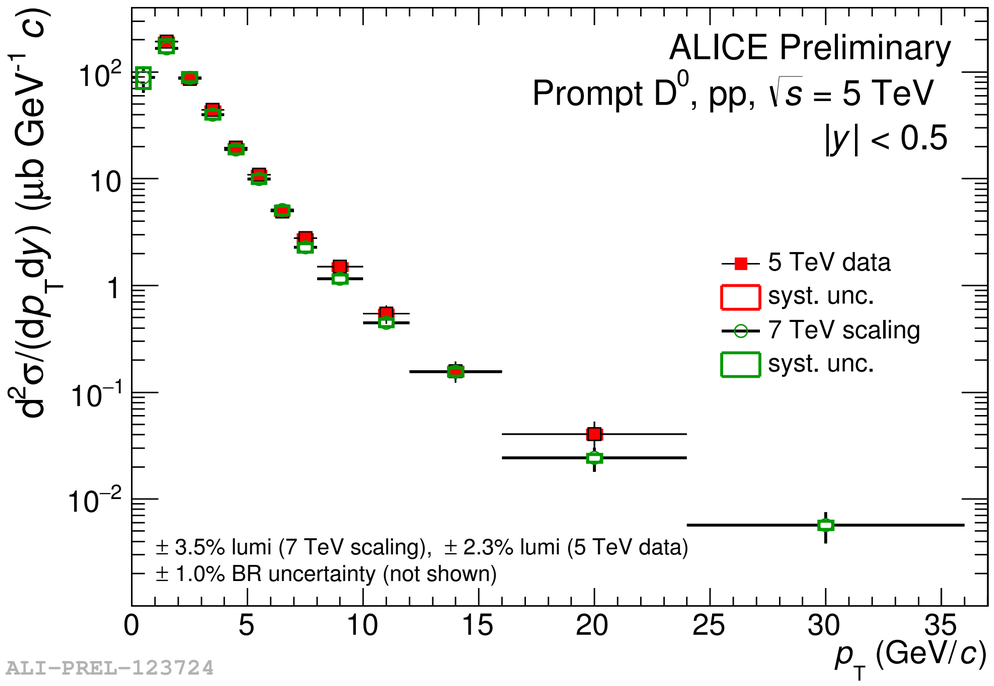
Towards R_{AA}: pp reference

D⁰ cross section in pp collisions at $\sqrt{s}$ = 7 TeV compared to FONLL



ALI-PUB-125443

[1] arXiv:1702.00766



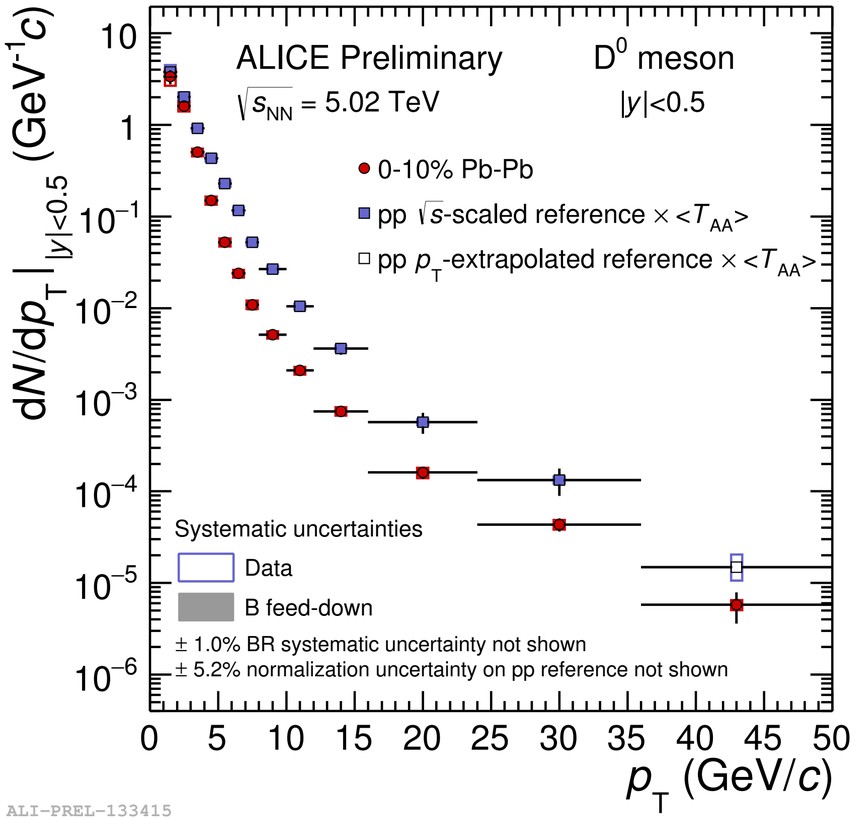
ALI-PREL-123724

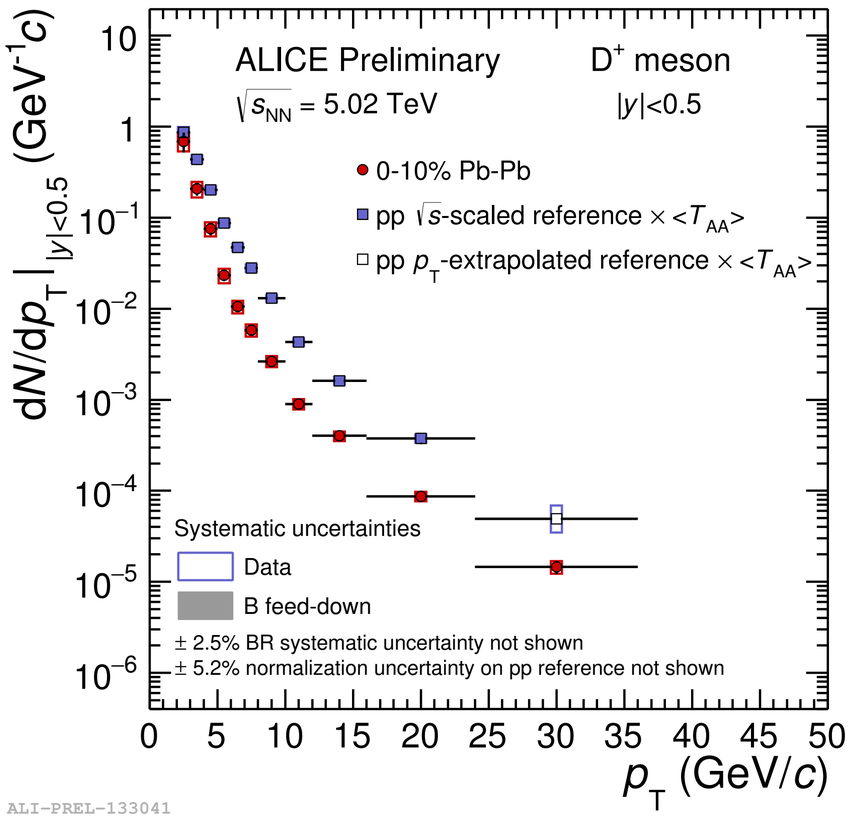
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

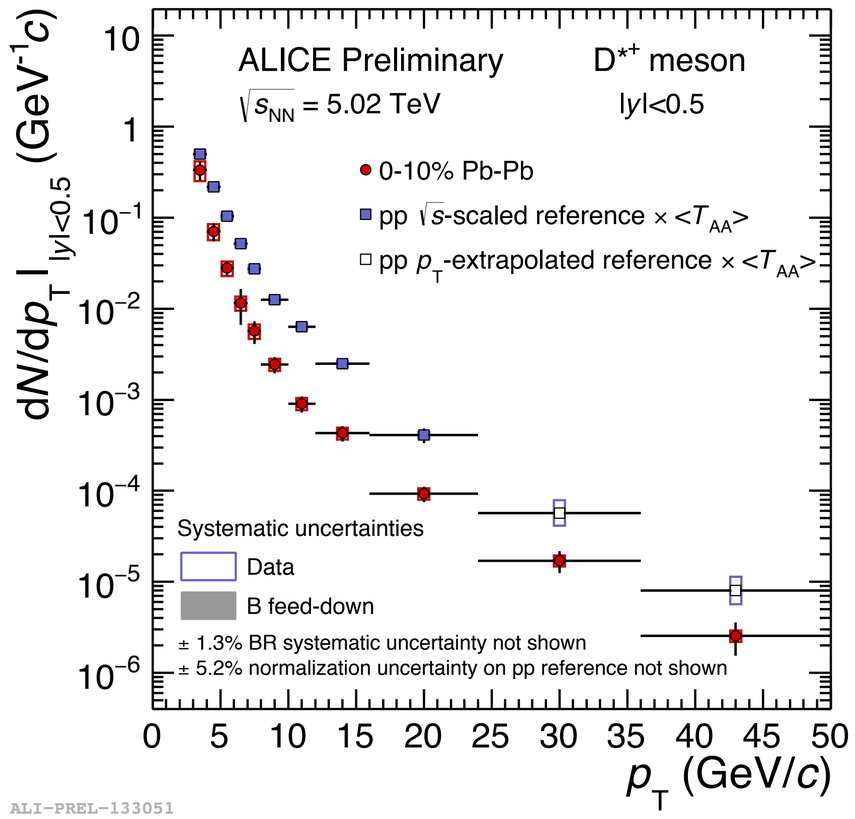
- ☑ Larger p_T coverage w.r.t. previous analysis
- ☑ Comparison of extrapolated pp reference from 7 TeV data (with FONLL prediction [1]) with 5.02 TeV (right plot)
- ☑ pp reference defined by scaling the 7 TeV measurement to 5.02 TeV
- ☑ FONLL calculations used for the scaling at 7 TeV [1]
- ☑ Reference extrapolated at high p_T (>36 GeV/c for D^0 and >24 GeV/c for D^+ and D^{*+}) by using the ratio data/theory

D-meson cross section compared with pp scaled reference

D^0, D^+, D^{*+} cross section in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in 0-10% centrality class

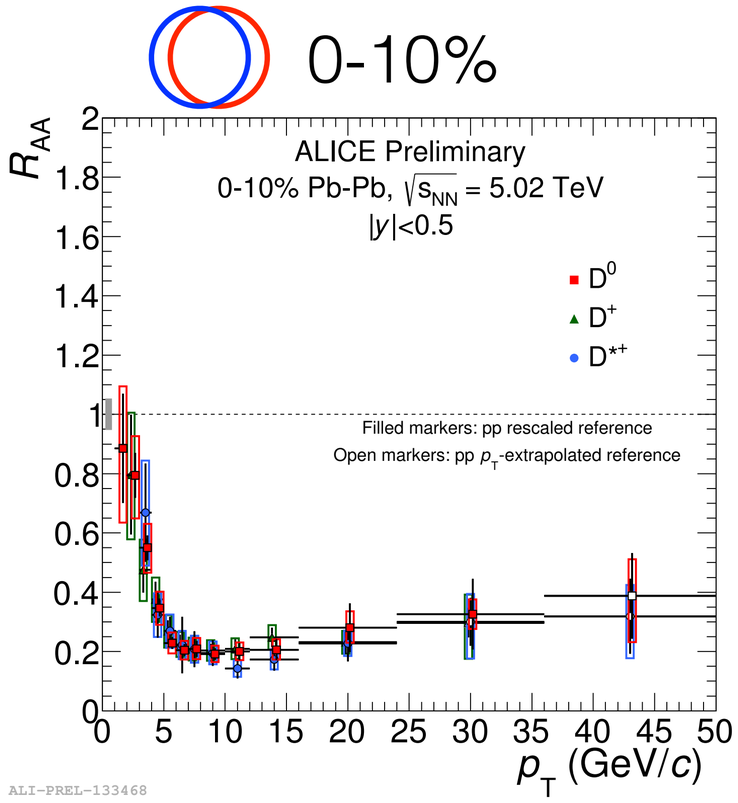


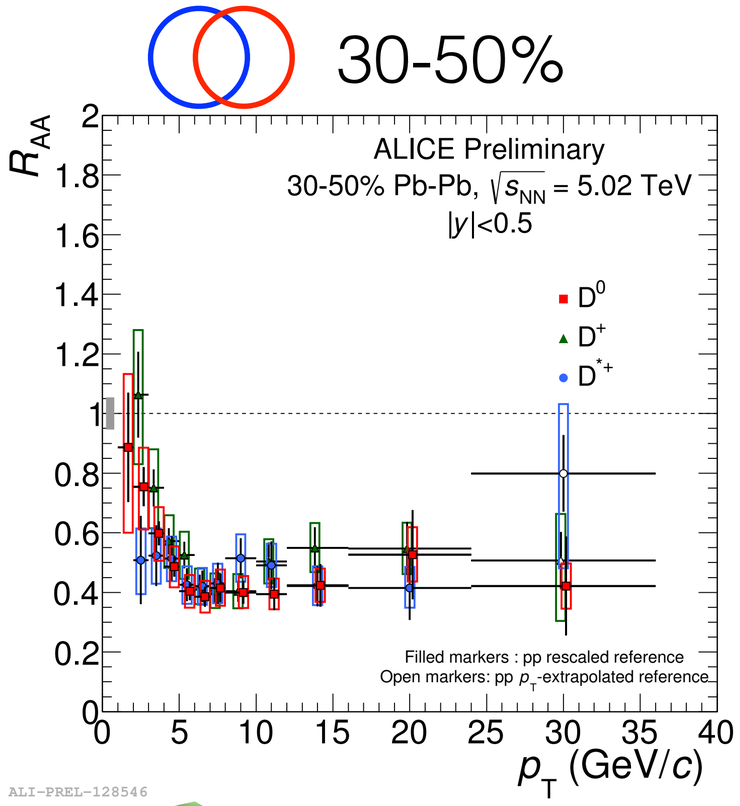


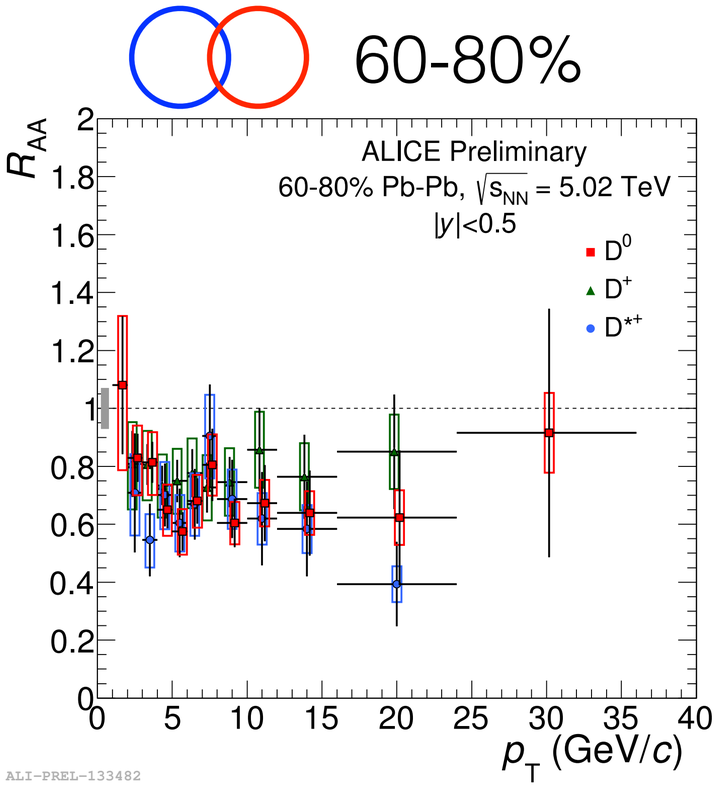


- ☑ pp data from 7 TeV scaled to 5.02 TeV and multiplied by $<T_{AA}>$
- ☑ Large suppression at high p_T

Results: D-meson R_{AA}







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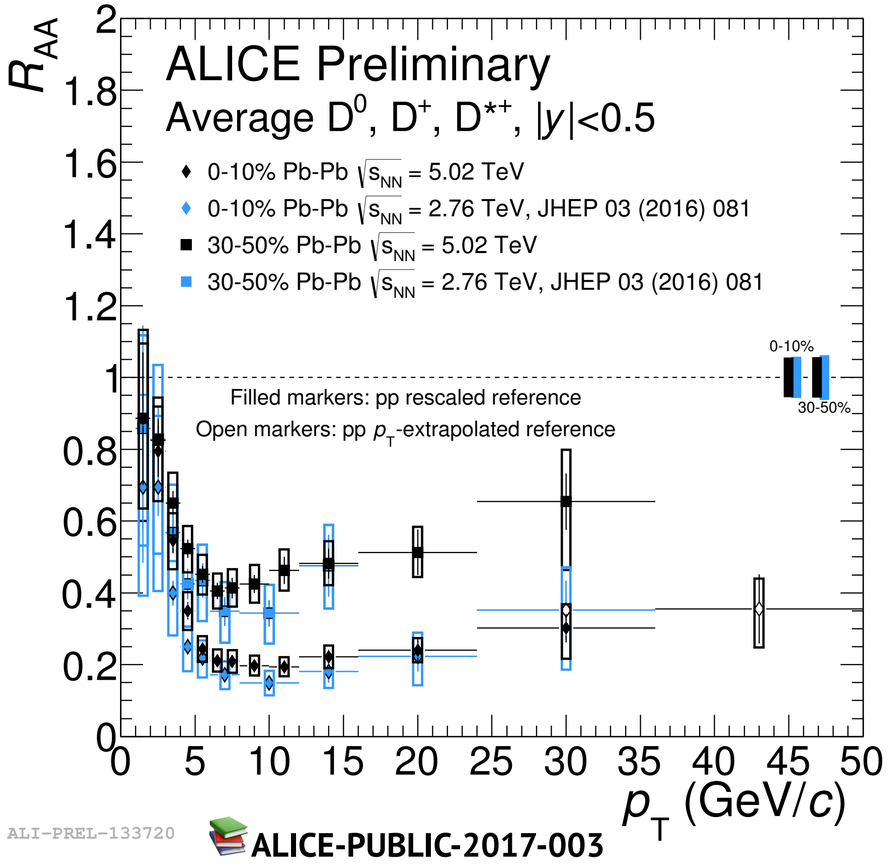
- ☑ D^0, D^+ and D^{*+} R_{AA} compatible within uncertainties
- ☑ R_{AA} peripheral events > R_{AA} central events → Increasing suppression from peripheral to central collisions

Results: D-meson R_{AA}

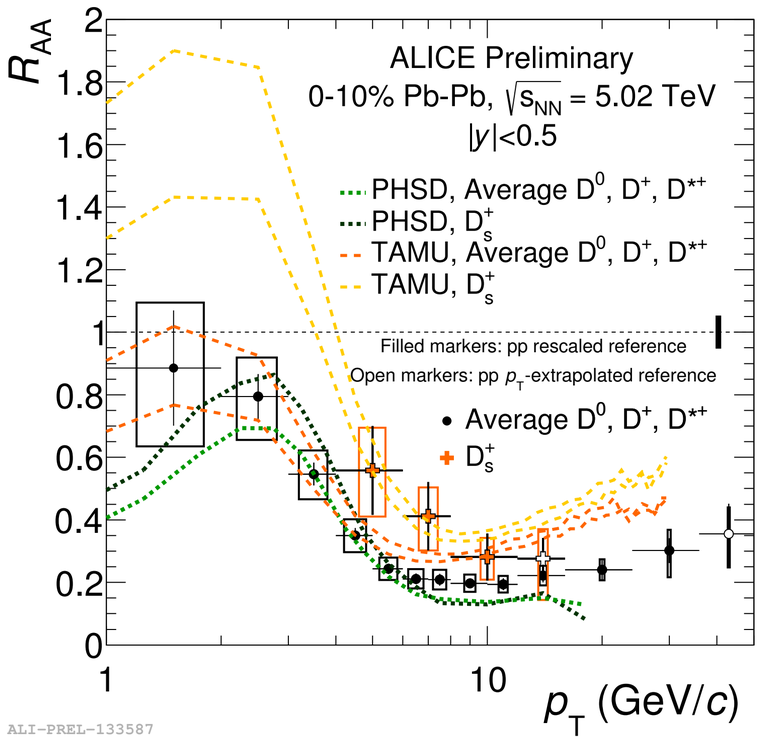


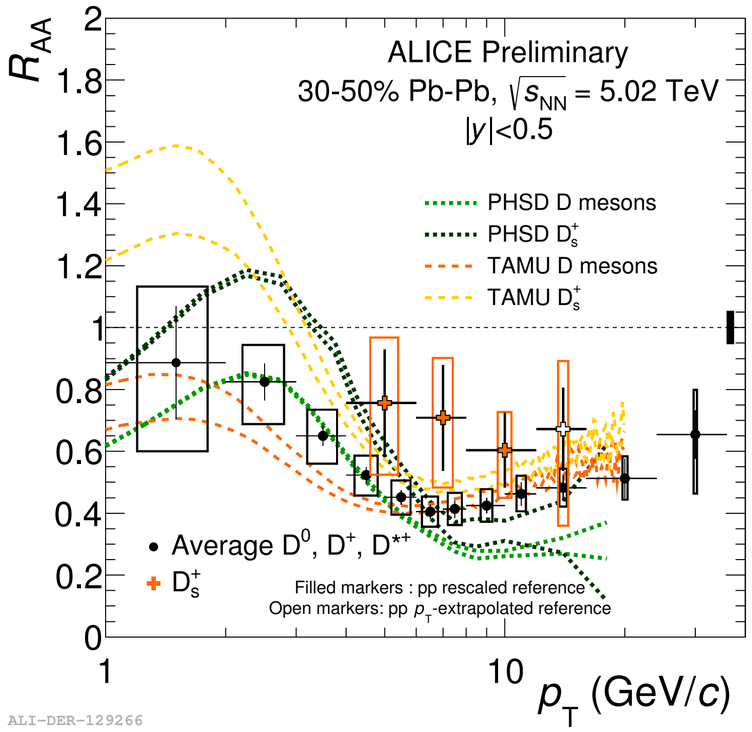
Run1: 2.76 TeV

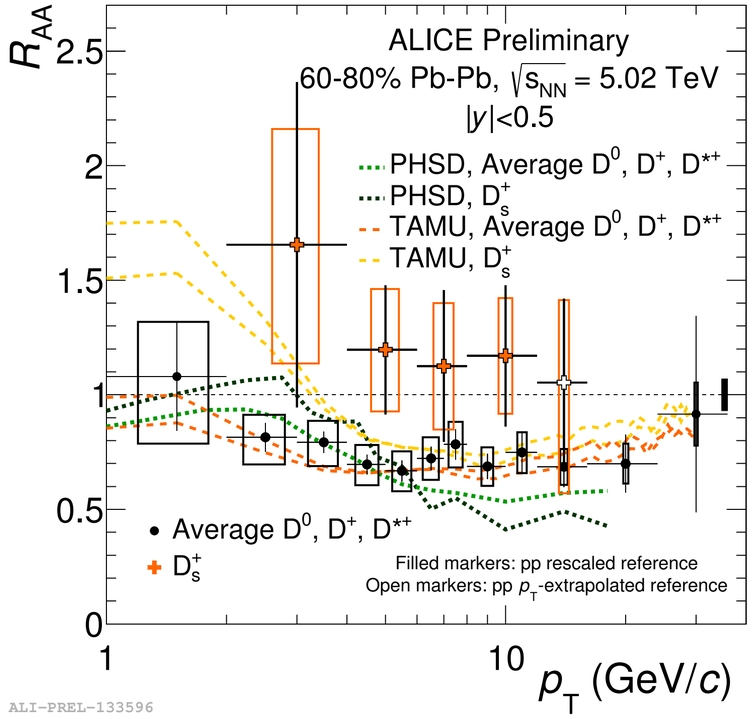
Run 2: 5.02 TeV

- ☑ Increasing suppression from peripheral to central events
- ☑ D-meson R_{AA} compatible between Run 2 and Run1 data
- ☑ Improved measurement (precision and p_T reach) of D-meson R_{AA} using Run 2 data with respect to Run1 data

Results: Strange and non-strange D-meson R_{AA}







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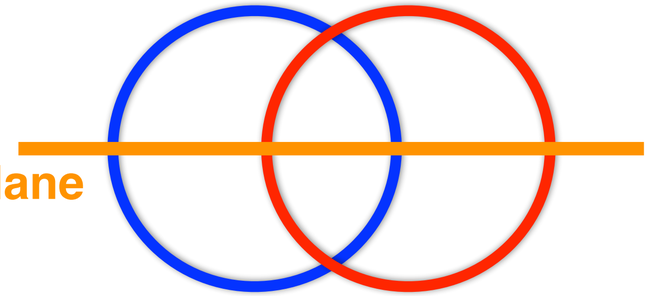
TAMU: Phys. Lett. B 735, 445-450 (2014)

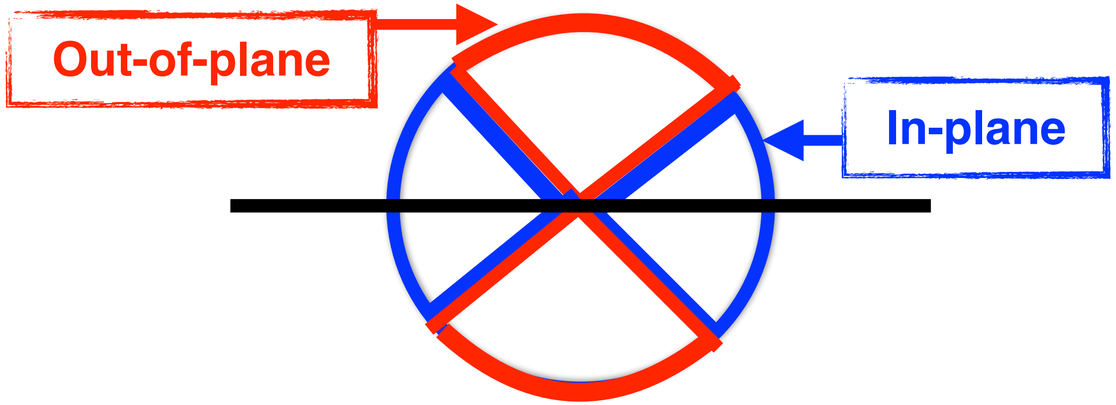
PHSD: Phys. Rev. C 92, 014910 (2015)

- ☑ Hint of higher D_s^+-meson R_{AA} relative to non-strange D-meson in all centralities
- ☑ Expected by models including D_s^+ formation via coalescence of charm quarks with strange quarks, abundant in the QGP medium

Results: D-meson elliptic flow in Pb-Pb collisions

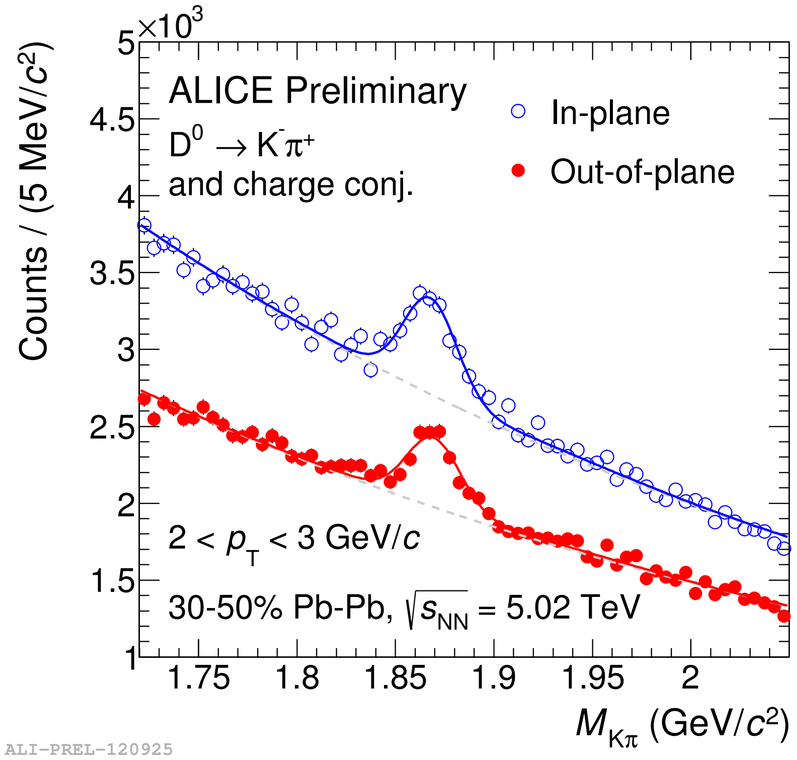


- ☑ Event-plane: estimator of the Reaction plane
- ☑ Event plane measured using V0 detector:
  $-3.7 < \eta < -1.7$ U $2.8 < \eta < 5.1$



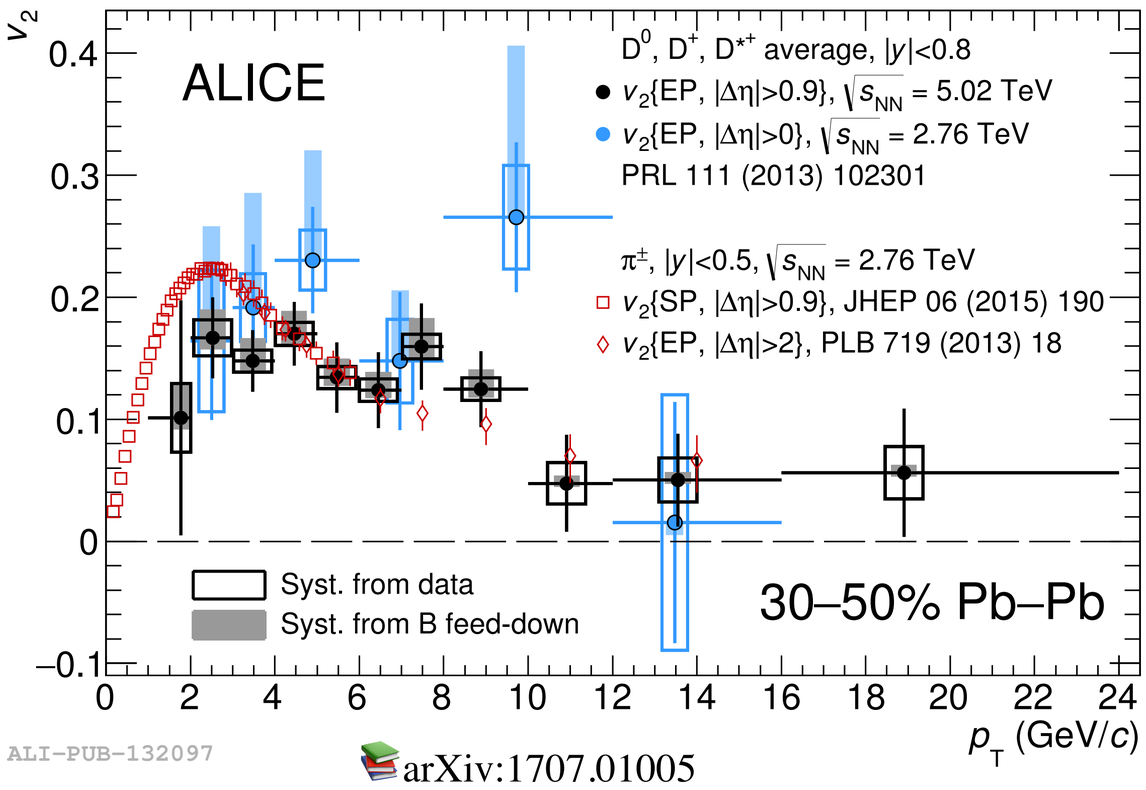
$$v_2\{\mathrm{EP}\} = \frac{1}{R_2}\frac{4}{\pi}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

R_2 is the event-plane resolution

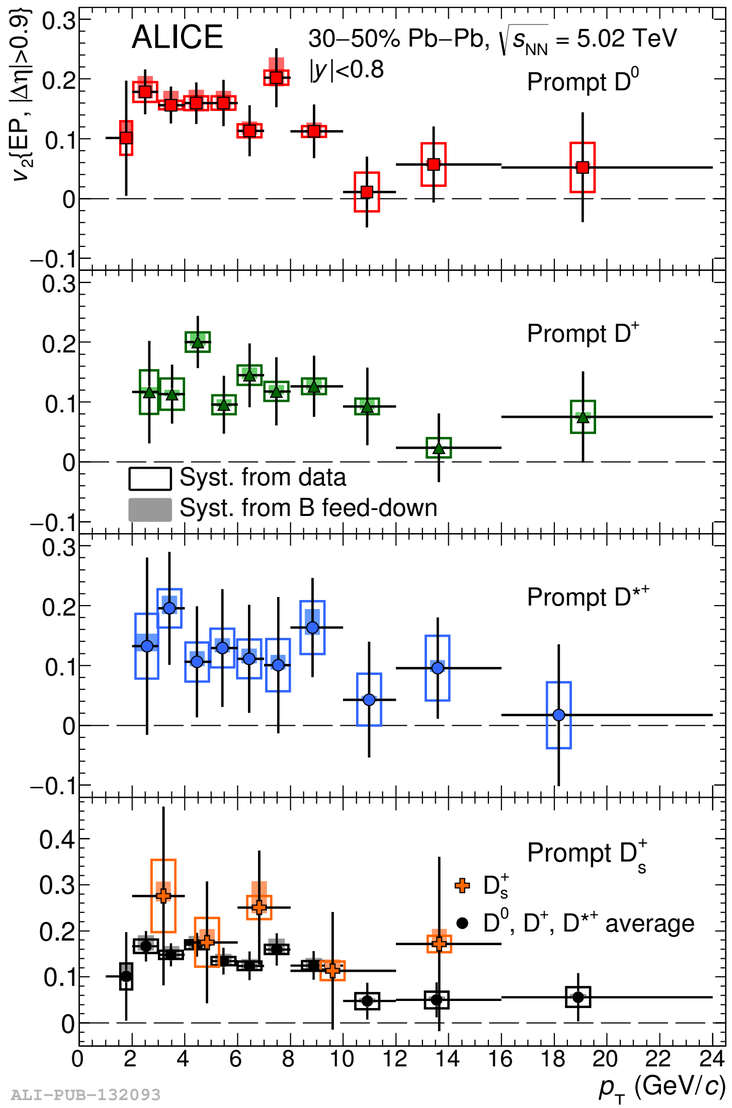


- ☑ Initial spatial azimuthal anisotropy -> anisotropic pressure gradients -> azimuthal anisotropy of the momenta distribution of the final particles
- ☑ Fourier decomposition of particle azimuthal distribution -> v_2, elliptic flow = 2nd order harmonic coefficient

Results: D-meson v_2 in mid-central Pb-Pb collisions



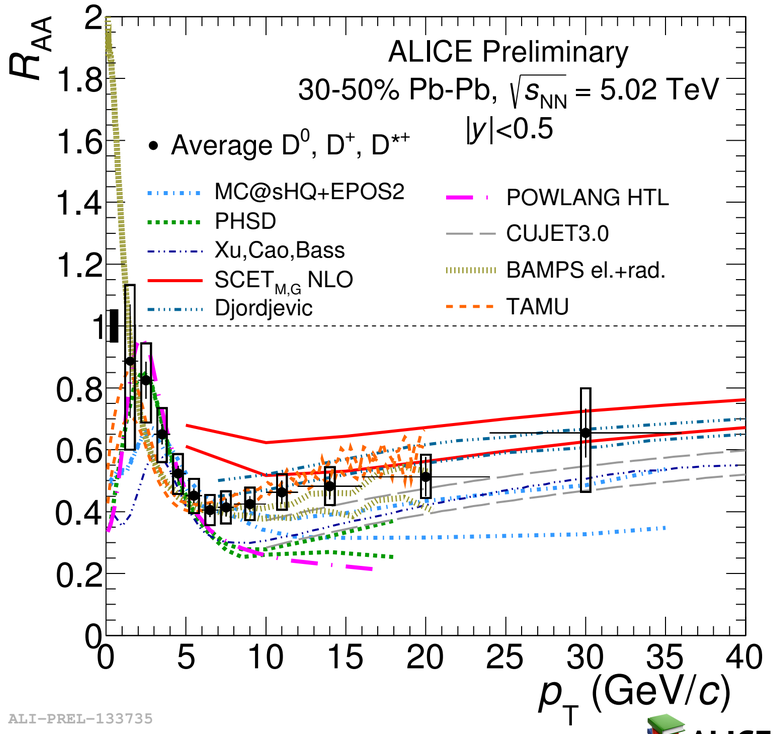
arXiv:1707.01005

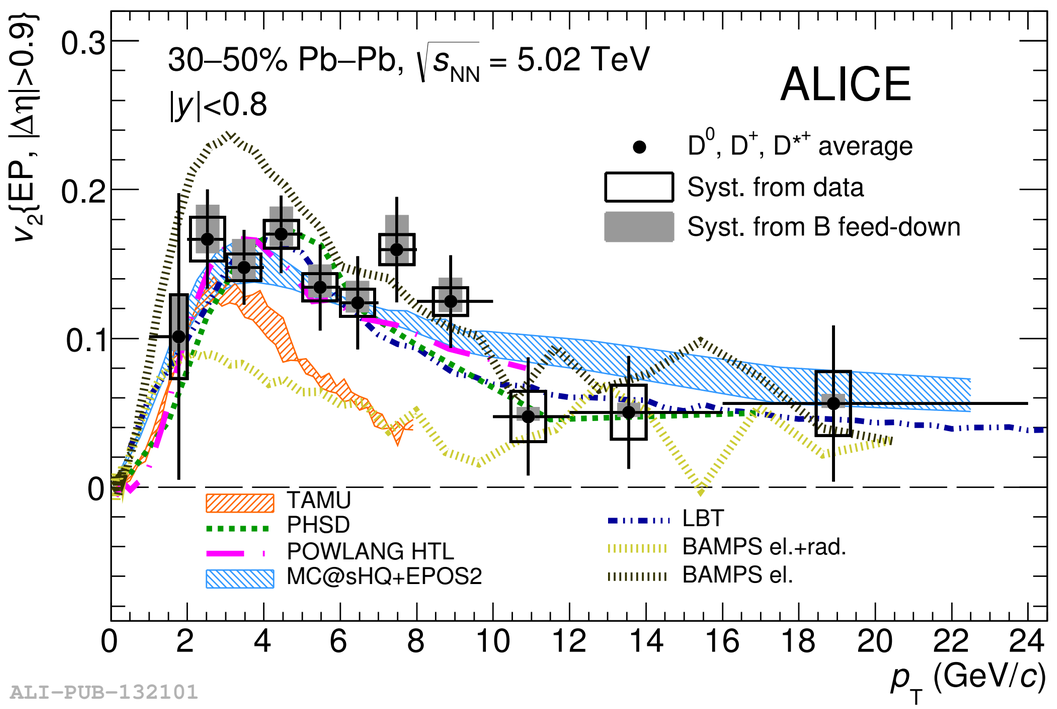


arXiv:1707.01005

- Non-zero D-meson v_2 for $2 < p_T < 10$ GeV/c
- D_s^+-meson v_2 compatible with all D-meson v_2
- D-meson v_2 compatible at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
- Participation of charm quarks in the collective expansion of the system
- Similar results between D-meson v_2 and $\pi^{\pm}$ v_2

Results: D-meson R_{AA} and v_2 compared to model predictions





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- Improved precision with Run 2 data
  -> provide important constraints to the models

HF transport models

- TAMU: PLB 735, 445-450 (2014)
- PHSD: PRC 92, 014910 (2015)
- POWLANG: EPJC 75, 121 (2015)
- LBT: arXiv:1703.00822
- BAMPS: JPG 42, 115106 (2015)
- Xu,Cao,Bass: PRC 88, 044907 (2013)

pQCD energy loss based models

- Djordevic: PRC 92, 024918 (2015)
- SCET: JHEP 03, 146 (2017)
- MC@sHQ+EPOS: PRC 89, 014905 (2014)
- CUJET: JHEP 02, 169 (2016)

Event shape engineering for the D-meson v_2

- The second-harmonic reduced flow vector q_2 can be used to quantify the eccentricity (average v_2) of the events

$$q_2 = \frac{|Q_2|}{\sqrt{M}}, \qquad M : \text{multiplicity}$$

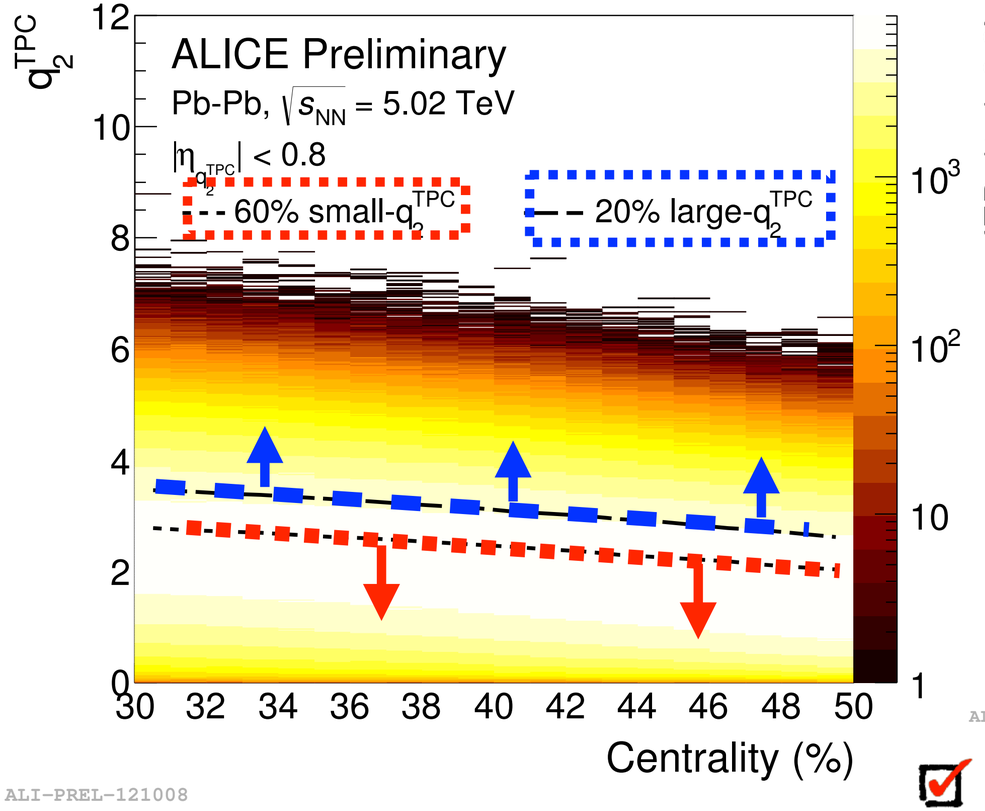
$$|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$$

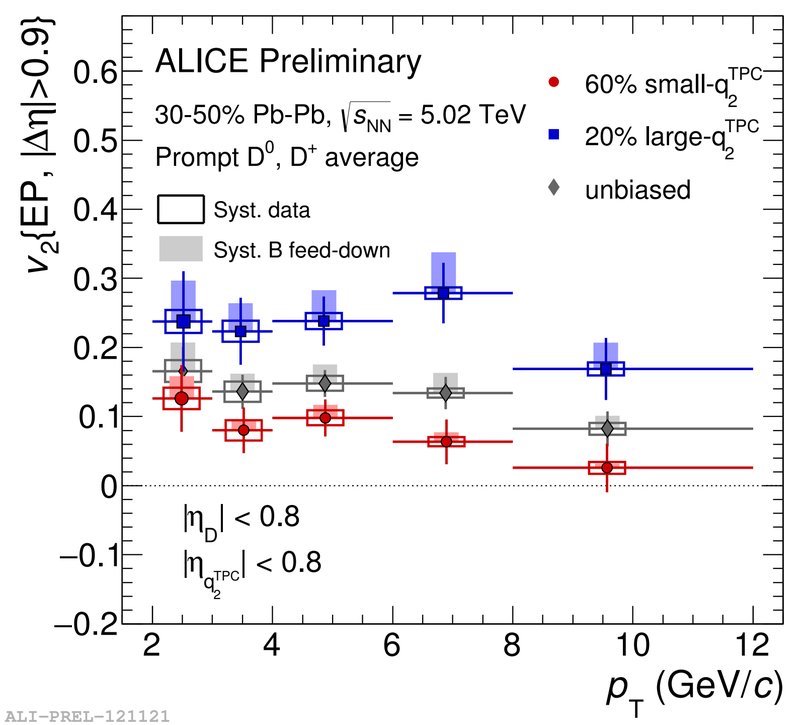
$$Q_{2,x}^2 = \sum_{i=1}^{M} \cos\ 2\varphi_i \ , Q_{2,y}^2 = \sum_{i=1}^{M} \sin\ 2\varphi_i$$

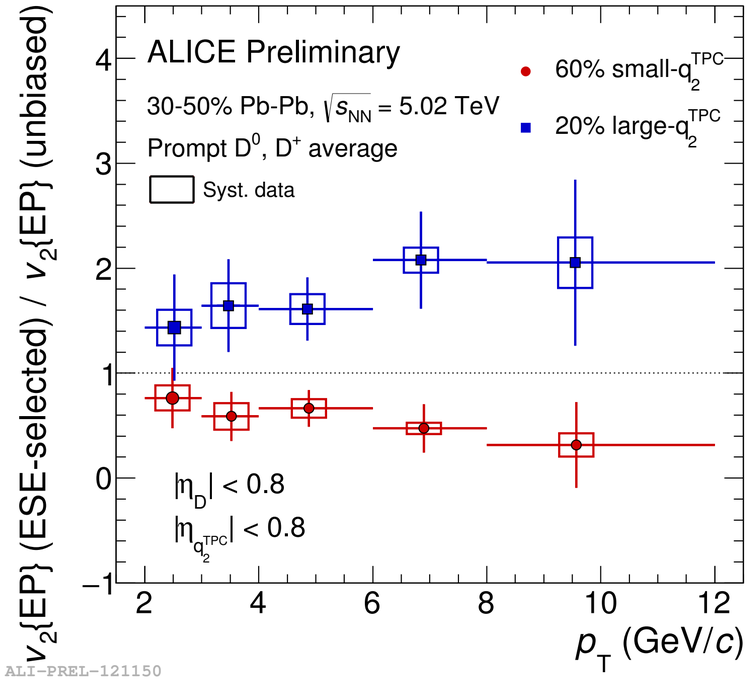
- Measuring the D-meson v_2 for different q_2 values gives the opportunity to study the coupling of c quark to the bulk of light quarks

$$\left\langle q_2^2 \right\rangle \simeq 1 + \left\langle (M-1) \right\rangle \left\langle \left(v_2^2 + \delta_2 \right) \right\rangle$$ **non-flow effect**

Event shape engineering for the D-meson v_2







- Events divided into 2 groups:
  - 60% events with **small q_2**
  - 20% events with **large q_2**

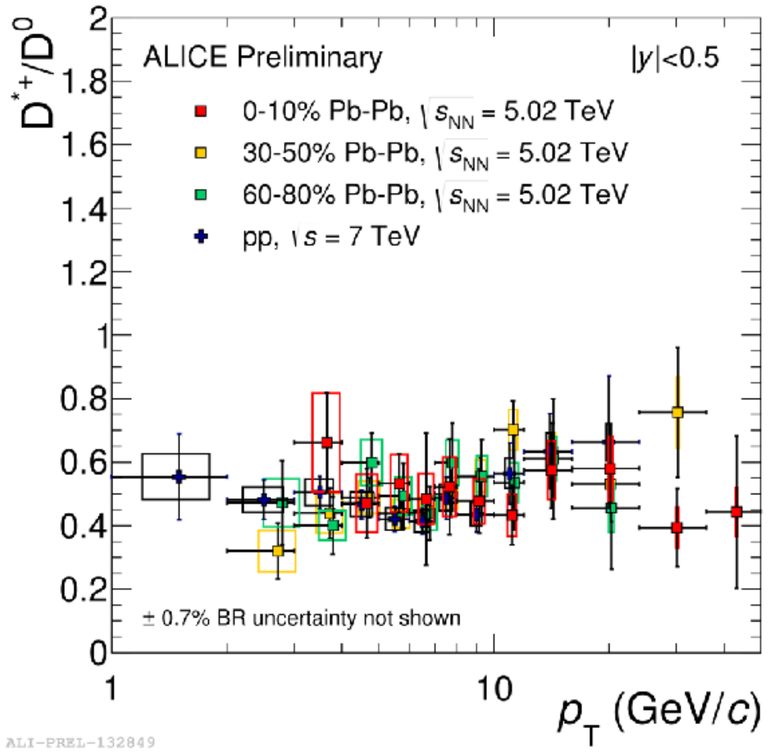
- D-meson v_2 related to q_2:
  v_2 with **large q_2** > v_2 with **small q_2**
- Autocorrelations and non-flow correlations between q_2 and D-meson v_2
- The sensitivity of charm quarks to the light quarks collectivity and event-by-event fluctuations in the initial state

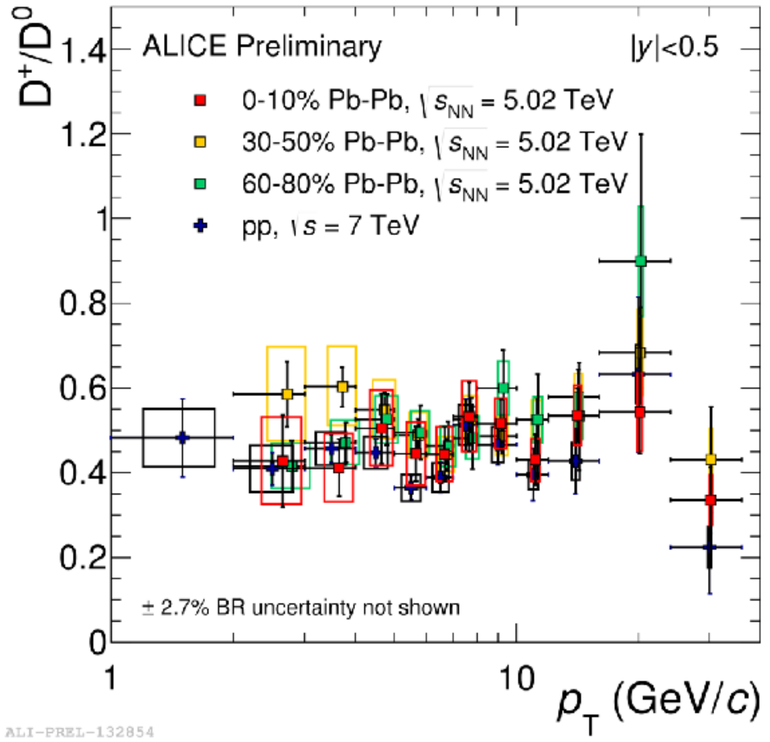
Conclusions

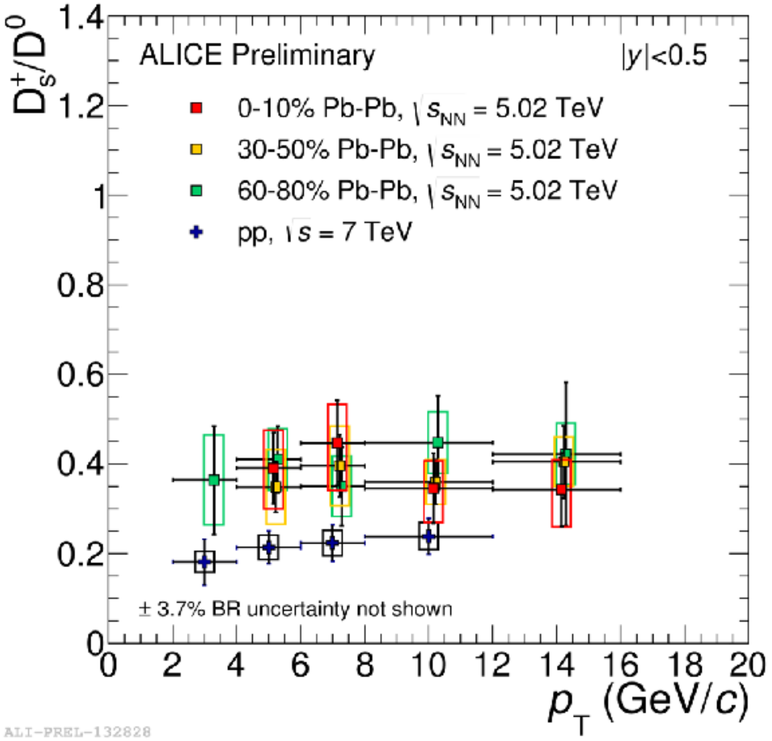
- **New measurements** for non-strange D-meson and strange D-meson nuclear modification factor in Pb-Pb collisions at 5.02 TeV for central, mid-central and peripheral events
  -> increasing suppression from peripheral to central collisions
- Hint of D_s^+ -yield enhancement w.r.t. non-strange D-meson: from hadronisation via coalescence?
- Significant D-meson flow observed from low to high p_T
  -> charm quarks sensitive to collective expansion of the systems
- **First measurement** of the D_s^+ v_2 in mid-central Pb-Pb collisions at 5.02 TeV
  -> strong coupling of charm quarks with the medium
- D-meson R_{AA} and v_2 measurements provide together important constraints to models
- **First measurement** of event shape engineering for D-meson elliptic flow
  -> sensitivity of D-meson to the light-quark collectivity and event-by-event fluctuations in the initial state

BACK UP

Results: D-meson ratios







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- ☑ Hint of D_s^+ abundance compare to other D mesons in Pb-Pb with respect to pp collisions
  - → strangeness enhancement?
- ☑ Similar results for D^{*+}/D^0 and D^+/D^0 in pp and Pb-Pb collisions