Results on heavy-flavour production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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University of Trieste and INFN Trieste

Outline

- Physics motivations

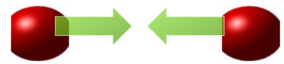
- Open heavy-flavour measurements with ALICE
  - Heavy-flavour decay electrons
  - D mesons
  - Heavy-flavour decay muons

  Heavy-flavour decay electrons and D mesons → Measurements in the central barrel (mid-rapidity region)

  Heavy-flavour decay muons → Measurement in the muon spectrometer (forward/backward rapidity)

- Main results:
  - **pp collisions @ $\sqrt{s}$ = 7 TeV**
  - **p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV**
  - **Pb-Pb collisions @ $\sqrt{s_{NN}}$= 2.76 TeV**

Motivations: why open heavy flavours?

- **HF in pp collisions:** 
    - Test of pQCD-based predictions for production cross sections
    - Study the effect of multi-parton interactions on the heavy-flavour sector
    - Reference for p-Pb and Pb-Pb measurements

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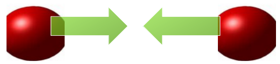
- **HF in pp collisions:** 
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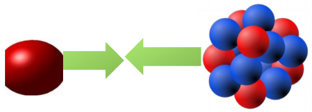
- **HF in p-Pb collisions:** 
  - Control experiment for Pb-Pb measurement
  - Address cold-nuclear-matter effects
    - Shadowing and gluon saturation K.J.Eskola et al., JHEP 0904(2009)65; H.Fuji & K.Watanabe, NPA 915(2013)1
    - Energy loss in cold nuclear matter I.Vitev at al., PRC 75(2007)064906
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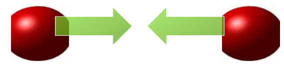
- **HF in pp collisions:** 
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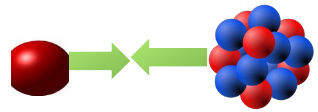
- **HF in p-Pb collisions:** 
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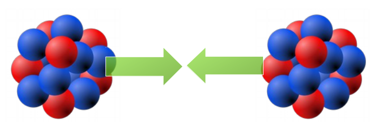
- **HF in Pb-Pb collisions:** 
  - Study of the interaction of heavy quarks with the medium

Because of their large mass, heavy-quarks are produced at the initial stage of the collisions in hard partonic scatterings $\tau_{form} \sim \frac{1}{2} m_Q \sim 0.02\text{-}0.1$ fm/c $<< \tau_{QGP}$

Flavour is conserved in strong interactions → They are transported through the full system evolution

Heavy-flavours in heavy-ion collisions

- Study HF interaction with the medium via:
  - **Parton energy loss**

    Depend on: colour charge, quark mass, path length and medium density

$\Delta E_{\mathrm{gluons}} > \Delta E_{\mathrm{light}} > \Delta E_{\mathrm{charm}} > \Delta E_{\mathrm{beauty}}$

$\Downarrow$

$R_{\mathrm{AA}}(\pi) < R_{\mathrm{AA}}(\mathrm{D}) < R_{\mathrm{AA}}(\mathrm{B})$

Caveats: different shapes of the p_{T} distributions of light and heavy flavours in pp collisions, different fragmentation functions, role of soft particle production for π at low p_{T}

Nuclear modification factor: $R_{AA} = \dfrac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$

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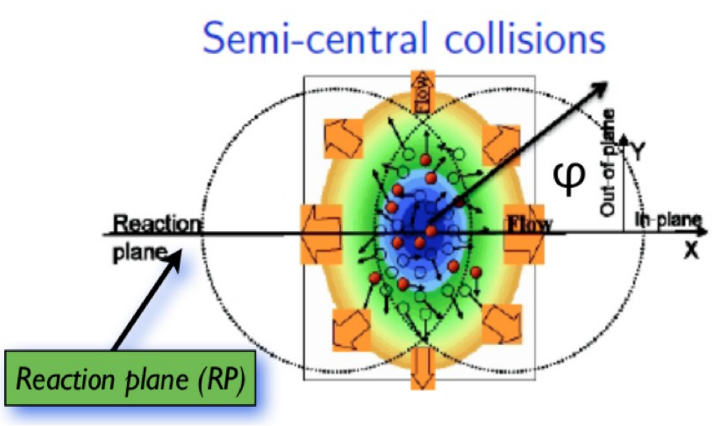
  - **Collectivity**



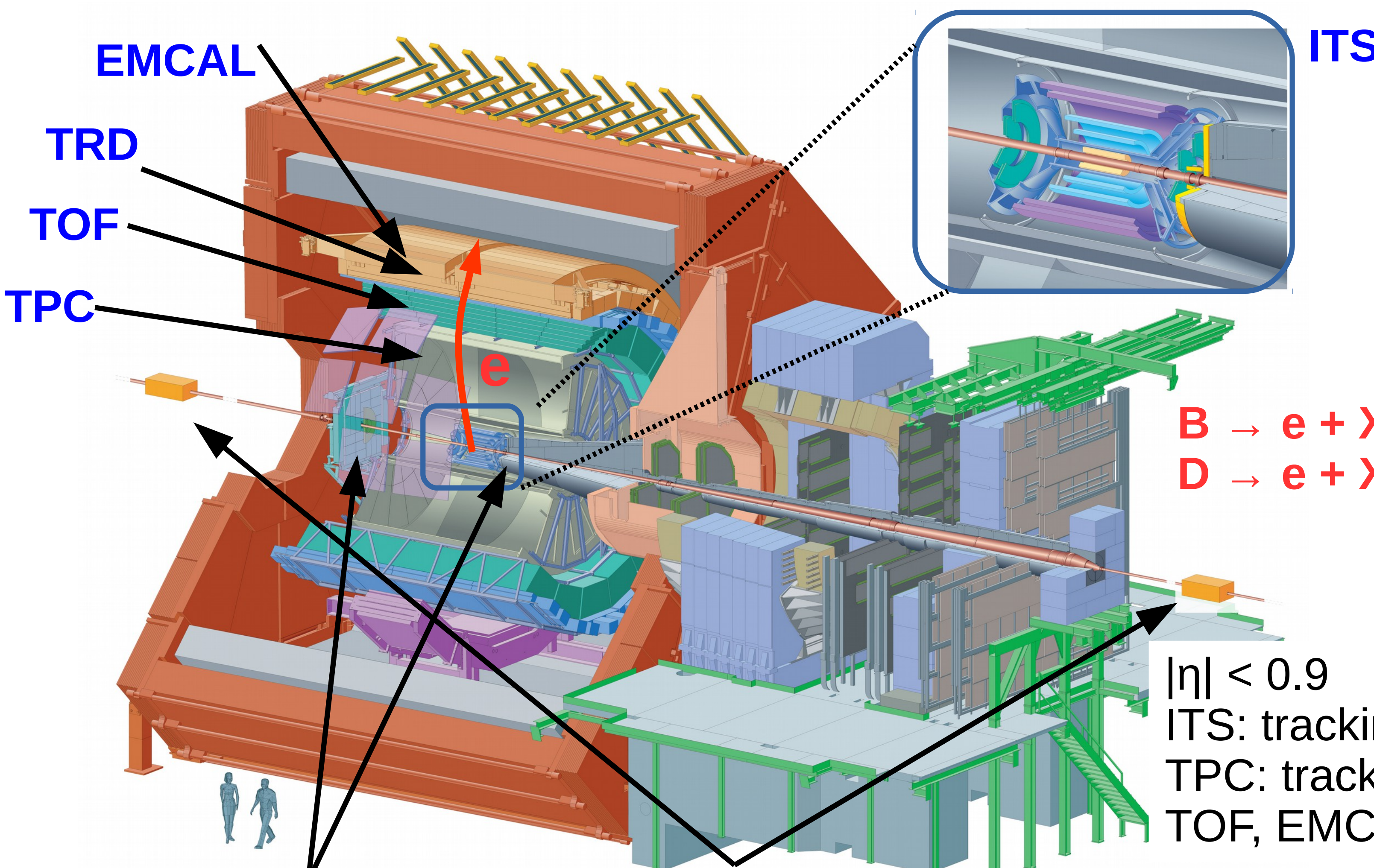
Initial spatial anisotropy → particle momentum anisotropy

Low p_T: degree of thermalization of heavy quarks in QGP

High p_T : path length dependence of energy loss

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2\cos[2(\varphi - \Psi_{RP})]} + \ldots)$$

Heavy-flavour decay electrons



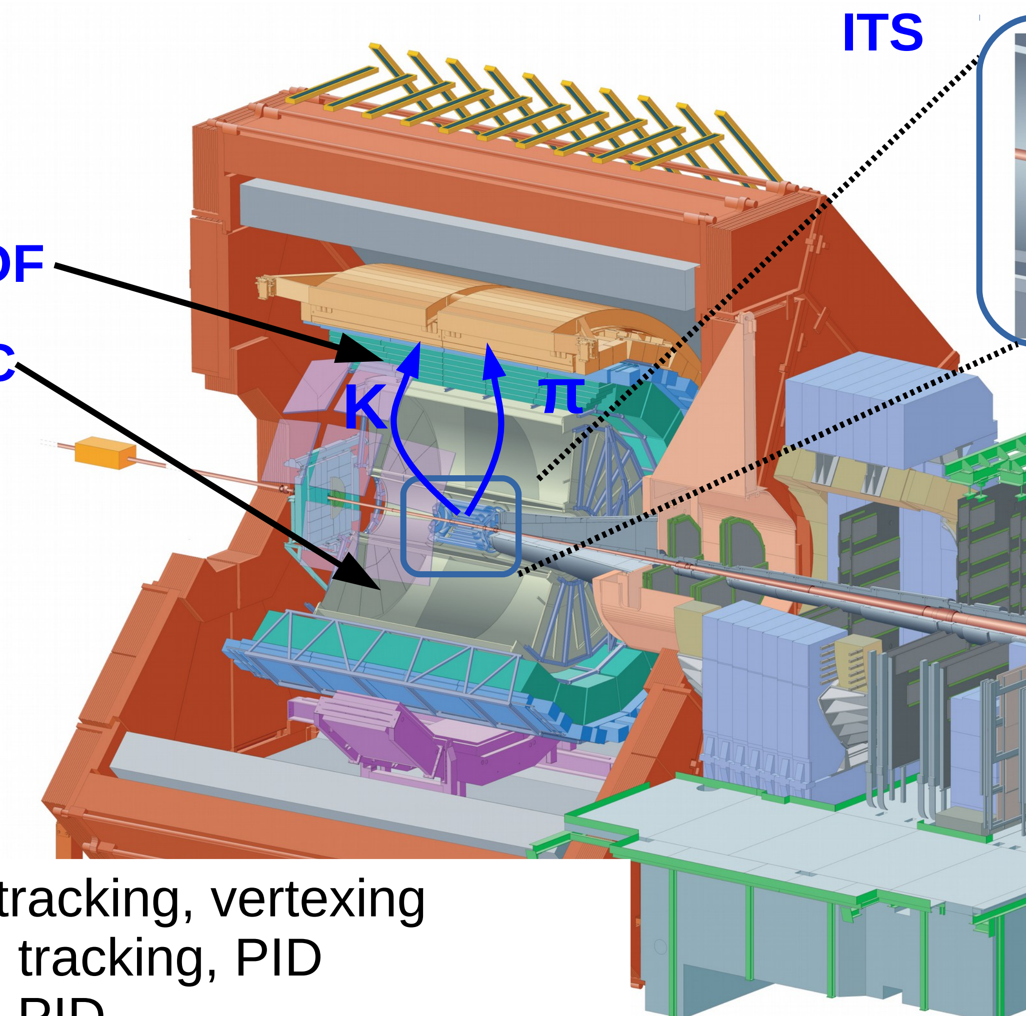
$B \rightarrow e + X$, B.R. ~ 11%
$D \rightarrow e + X$, B.R. ~ 10%

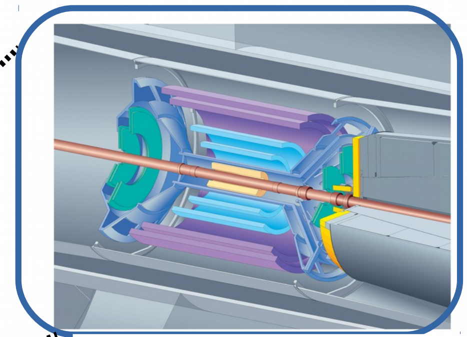
$|\eta| < 0.9$
ITS: tracking, vertexing, PID
TPC: tracking, PID
TOF, EMCAL, TRD: e-ID

VZERO*: trigger and centrality determination

ZDC*: event activity determination in p-Pb collisions
*common for all the channels

D mesons





Displaced decay vertices ($|\eta| < 0.8$):

$D^0 \rightarrow K^- \pi^+$, BR = 3.88 ± 0.05%

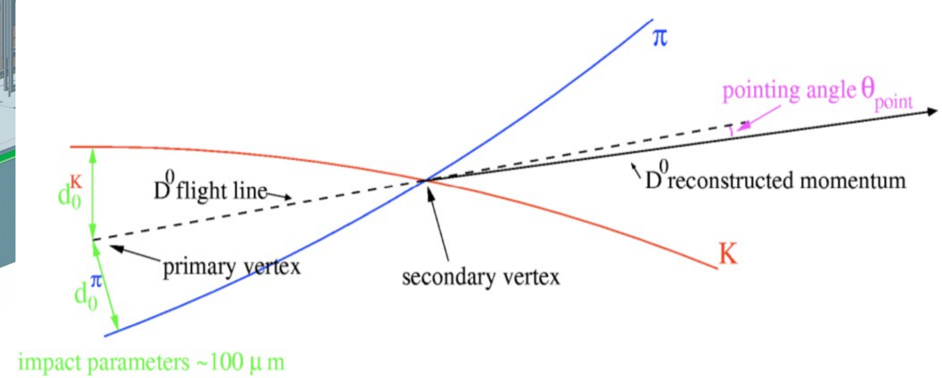
$D^+ \rightarrow K^- \pi^+\pi^+$, BR = 9.13 ± 0.19%

$D^{*+} \rightarrow D^0 \pi^+$, BR = 67.7 ± 0.5%

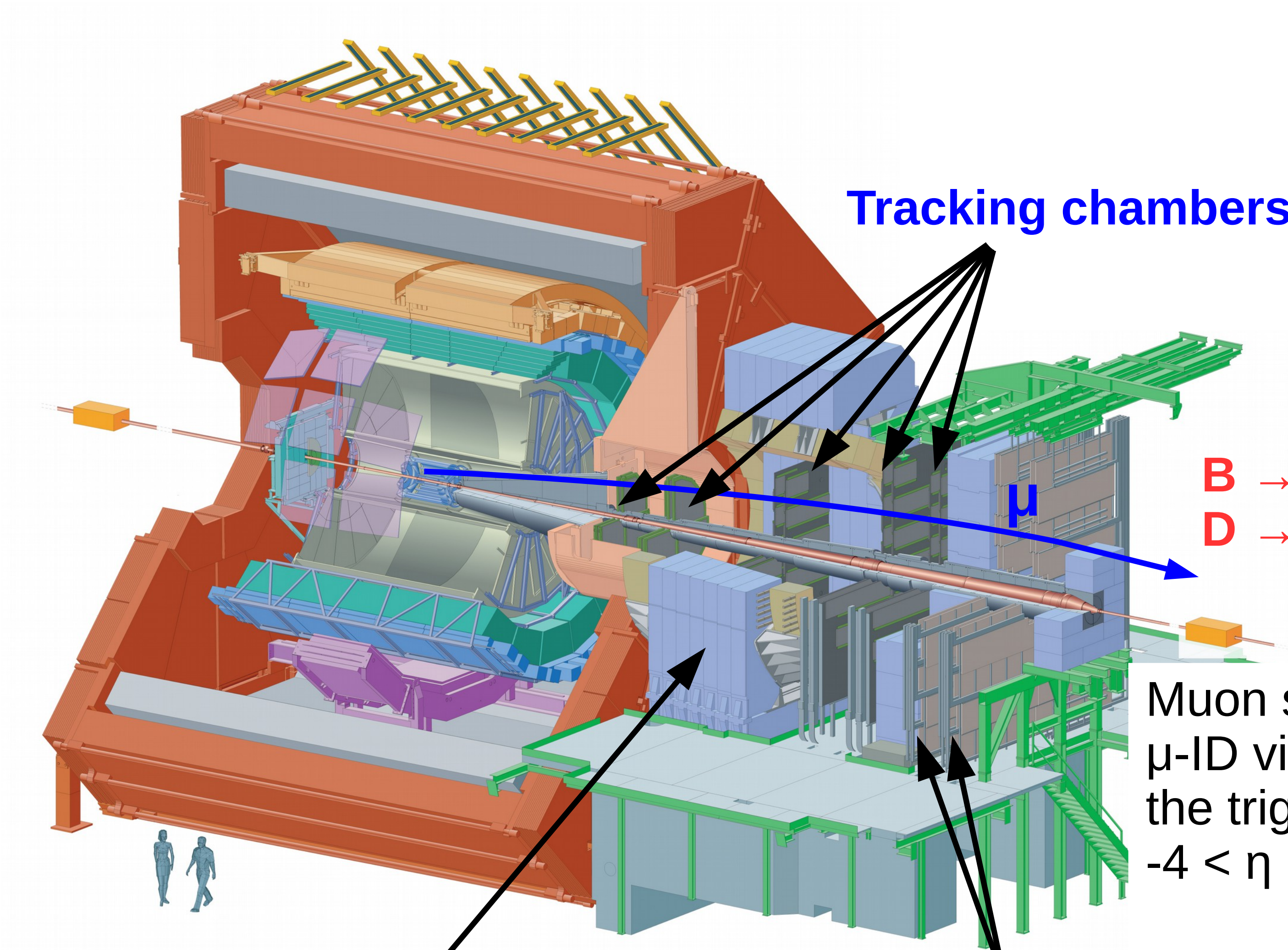
$D_s \rightarrow \phi\pi^+$

$\rightarrow K^-K^+\pi^+$, BR = 2.28 ± 0.12%

ITS: tracking, vertexing
TPC: tracking, PID
TOF: PID



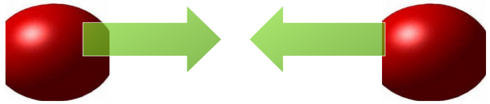
Heavy-flavour decay muons



$B \rightarrow \mu + X$, B.R. ~ 11%
$D \rightarrow \mu + X$, B.R. ~ 10%

Muon spectrometer:
μ-ID via tracks matched with the trigger system
$-4 < \eta < -2.5$

Results in pp collisions @ $\sqrt{s}$ = 7 TeV



- Test of pQCD-based predictions for production cross sections
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pp @ √s = 7 TeV

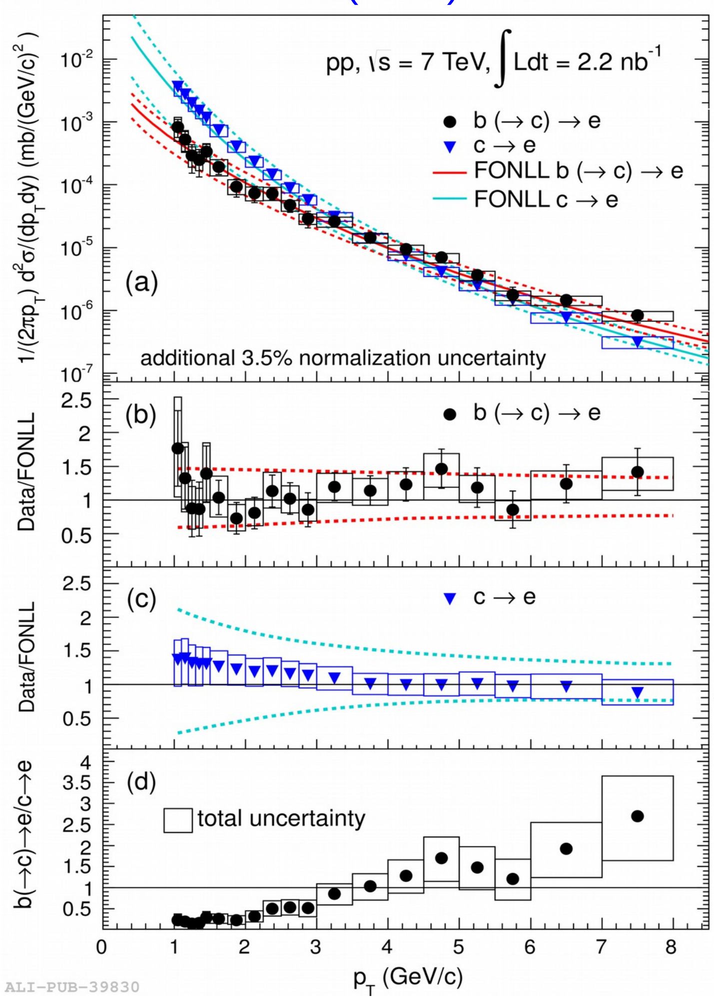
Open HF cross section at √s=7 TeV

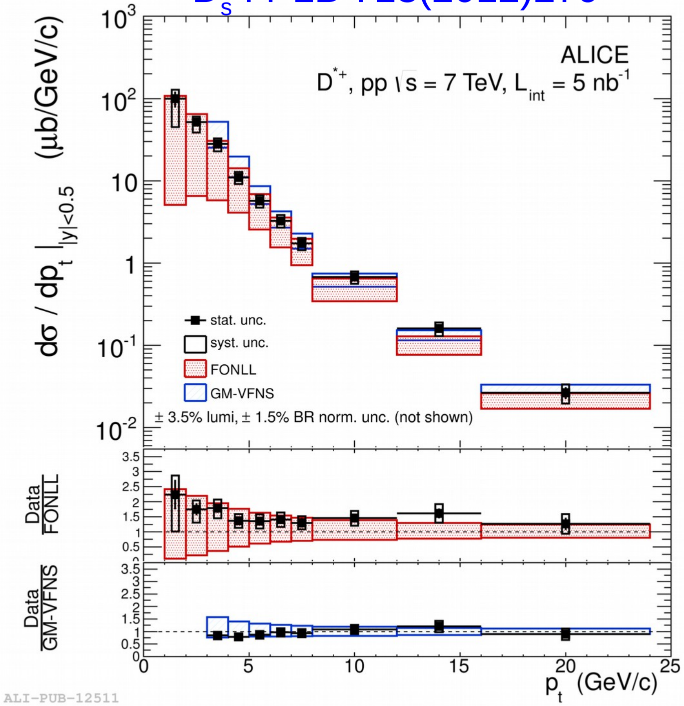
ALICE

- p_T-differential cross section in all channels

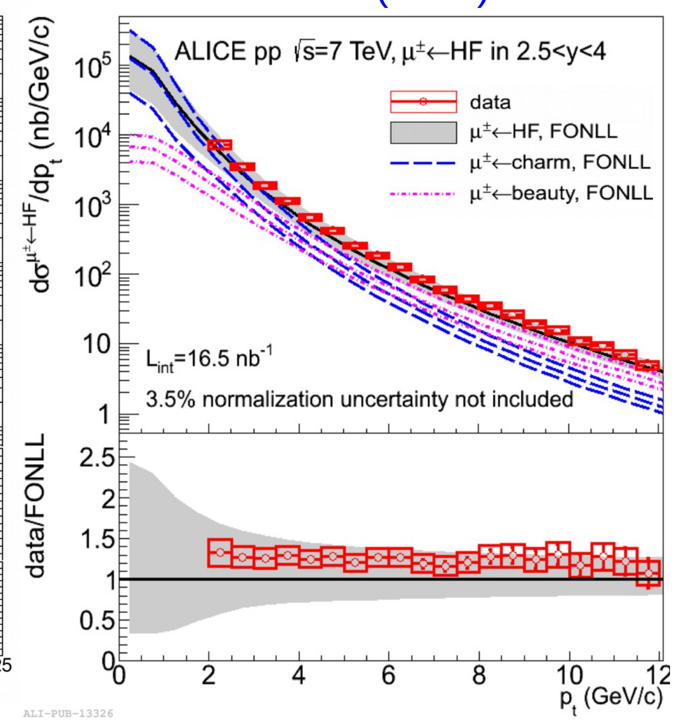
D mesons (e.g. D*+)
JHEP 1201(2012)128
D_s : PLB 718(2012)279

HF decay e
PLB 708(2012)2659





HF decay μ
PLB 708(2012)2659

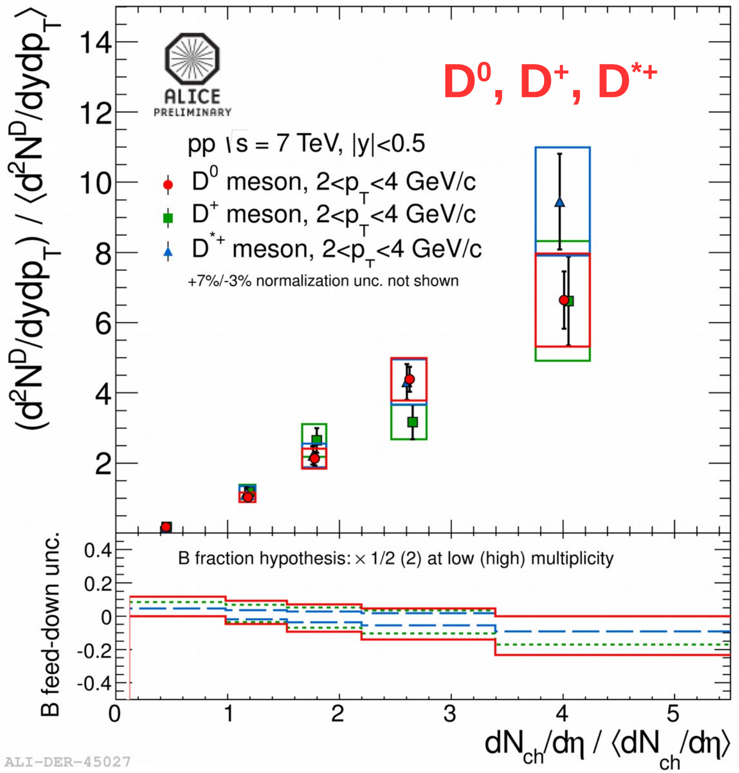


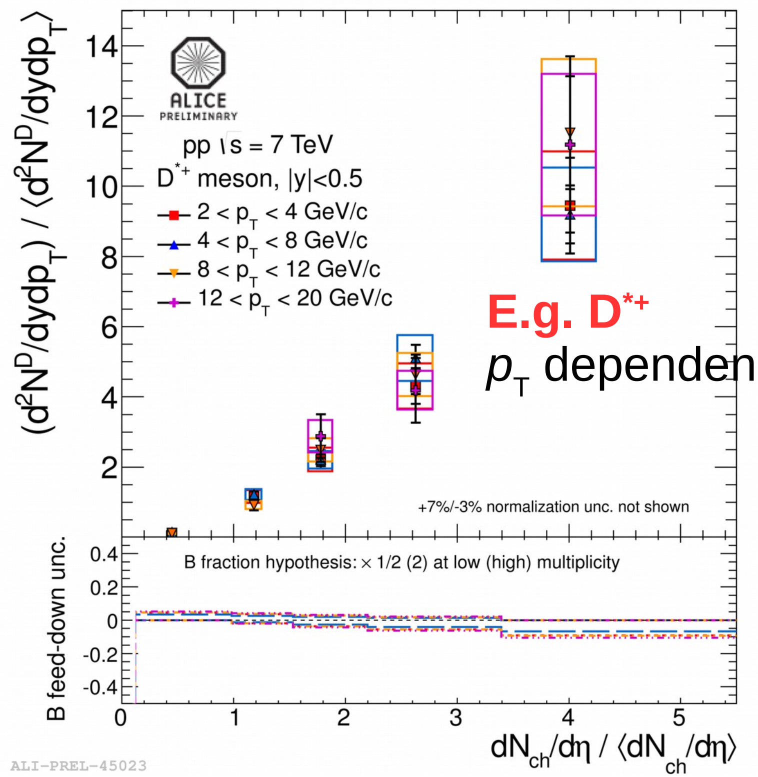
- pQCD-based calculations (FONLL, GM-VFNS, k_T-factorization) compatible with data
  FONLL: JHEP1210(2012)137; GM-–VFNS: Eur.Phys.JC72(2012); k_T factorization: Phys. Rev. D(2013)094022
- Similar situation at √s = 2.76 TeV
  JHEP 1207(2012)191; PRL 109(2012)112301; arXiv:1405.4117v1

pp @ $\sqrt{s}$ = 7 TeV

Multiplicity dependence of HF production

- Investigate the role of **Multi Parton Interactions** in heavy-flavour production
- Self-normalized D-meson yields vs. charged particle multiplicity



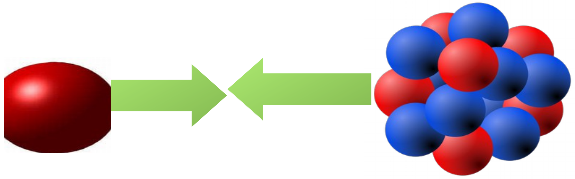


E.g. D*+
p_T dependence

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

- Self-normalized yields of all D-meson species increase with charged particle multiplicity without a significant p_T dependence (within uncertainties)
- Charm production connected with stronger hadronic activity and affected by MPI

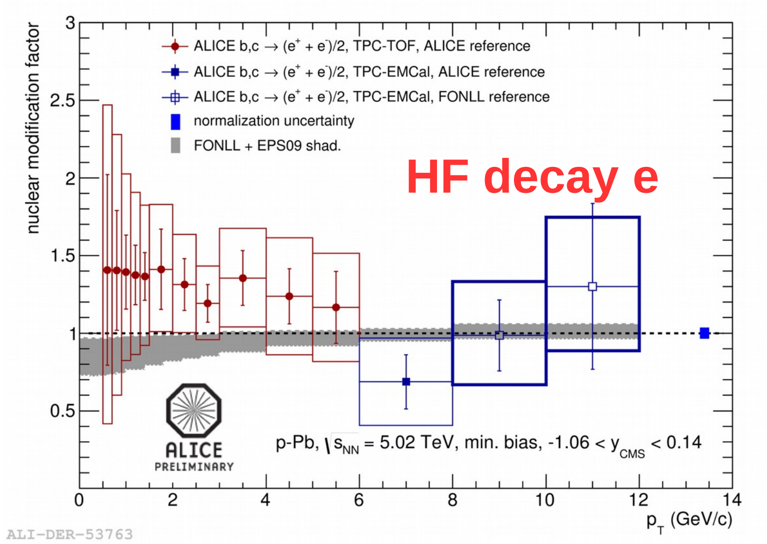
Results in p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV



- Control experiment for Pb-Pb measurement
- Address cold-nuclear-matter effects

HF decay e± nuclear modification factor

$$R_{pA} = \frac{d\sigma_{pA}/dp_T}{A \times d\sigma_{pp}/dp_T}$$



- R_{pPb} of **HF decay electrons (charm & beauty)** compatible with unity within uncertainties
- **Small cold nuclear matter effects in the measured p_T range**

  Good agreement with theoretical calculations
  - FONLL pQCD calculations with EPS09 PDF parameterizations of shadowing (JHEP 006(2001)0103; K.Eskola et al., JHEP 04 (2009) 065)

p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

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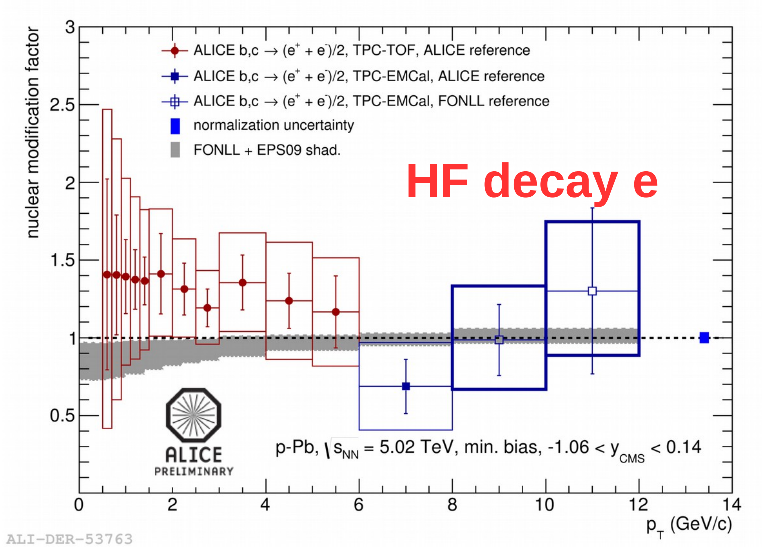
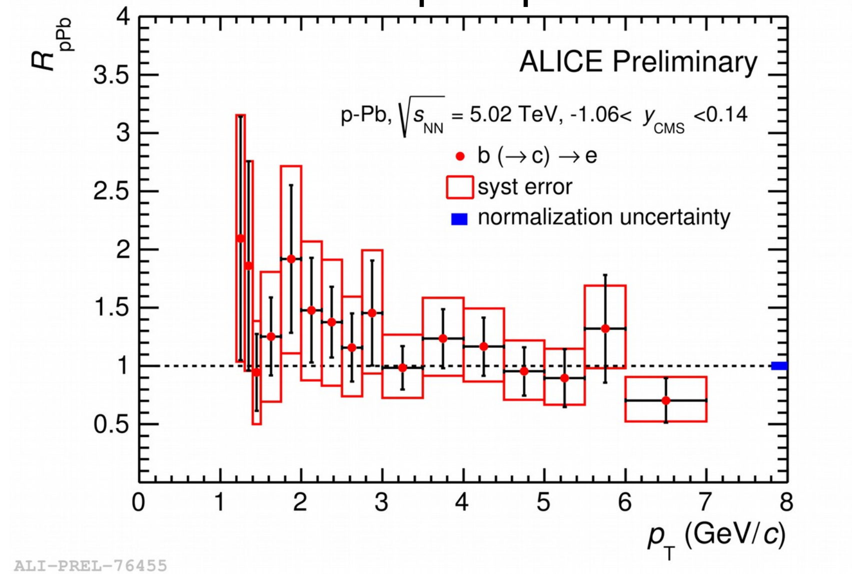


Beauty-hadron decay e

Analysis based on the study of the electron impact parameter distribution.



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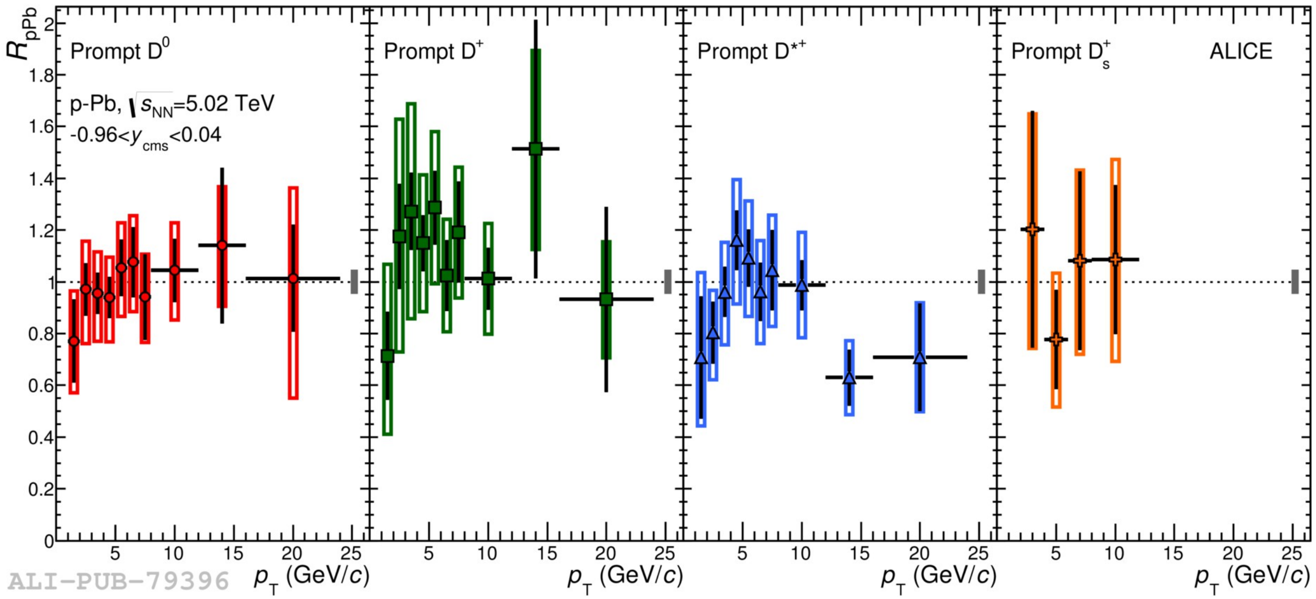
- R_{pPb} of **electrons from beauty-hadron decays** is also compatible with unity within uncertainties

D meson nuclear modification factor

$$R_{pA} = \frac{d\sigma_{pA}/dp_T}{A \times d\sigma_{pp}/dp_T}$$

arXiv:1405.3452



- R_{pPb} of **D mesons** compatible with unity within uncertainty
- **Small cold nuclear matter effects in the measured p_T range**

D meson nuclear modification factor

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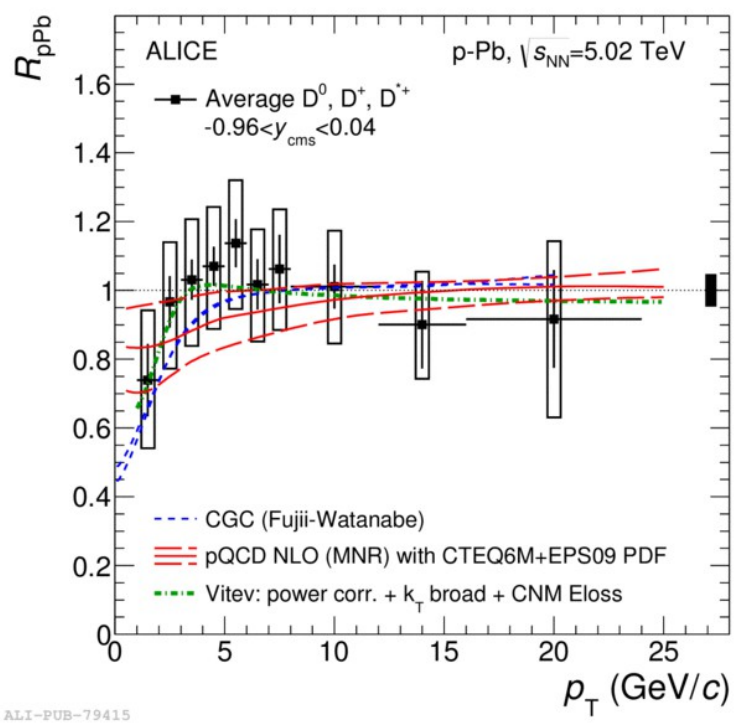
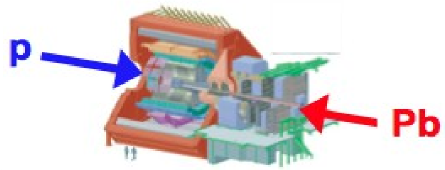


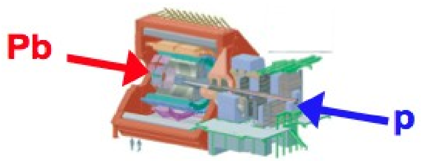
- R_{pPb} of **D mesons** compatible with unity within uncertainty
- **Small cold nuclear matter effects in the measured p_T range**
- Good agreement with theoretical calculations
  - Color Glass Condensate (CGC) calculations (H.Fujii,K.Watanabe arXiv: 1308.1258)
  - MNR pQCD calculations with EPS09 PDF parameterizations of shadowing (M.Mangano et al., Nucl.Phys.B 373(1992)295; K.Eskola et al., JHEP 04467(2009)065)
  - Energy loss in cold nuclear matter (Vitev: PRC 75(2007)064906)

p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

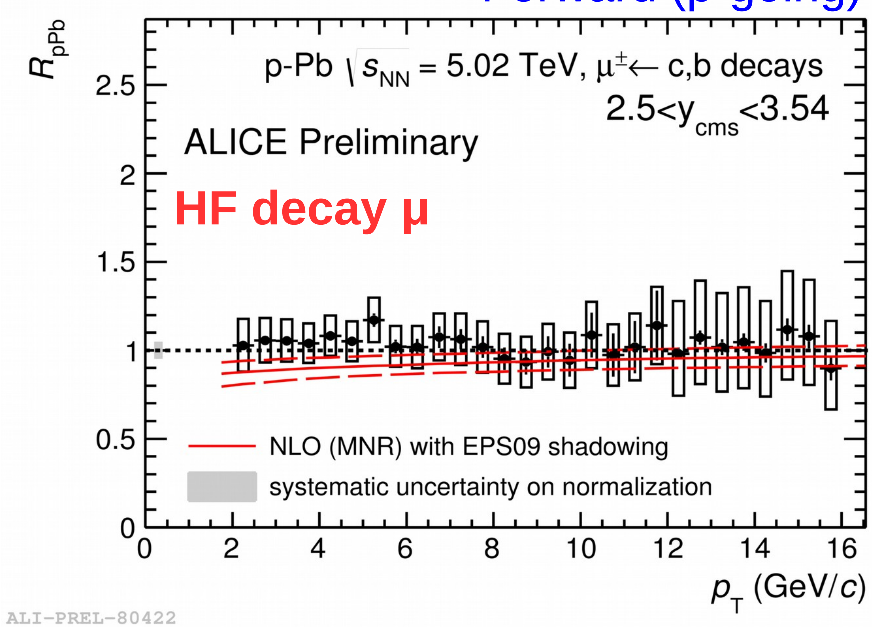
HF decay μ nuclear modification factor

$$R_{pA} = \frac{d\sigma_{pA}/dp_T}{A \times d\sigma_{pp}/dp_T}$$

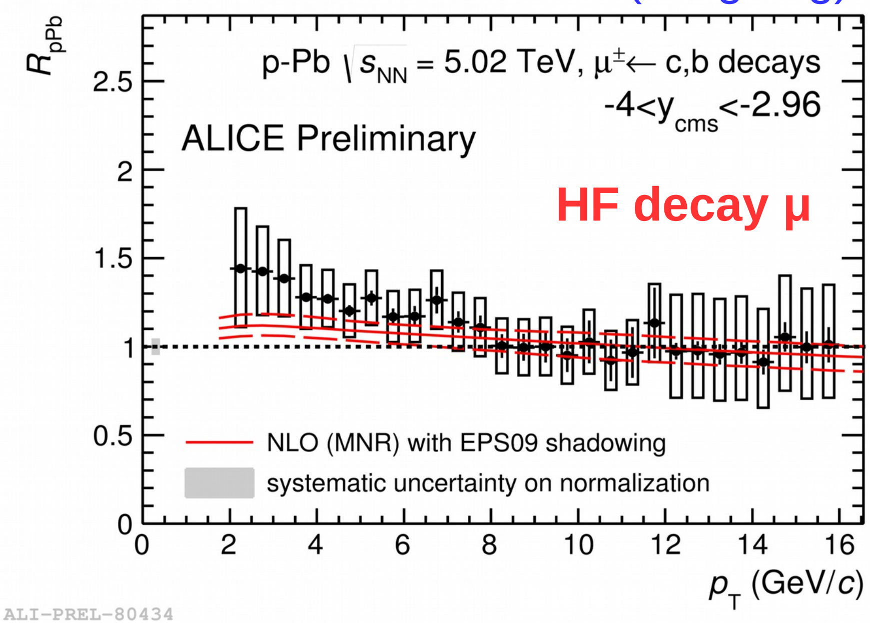




Forward (p-going)



Backward (Pb-going)

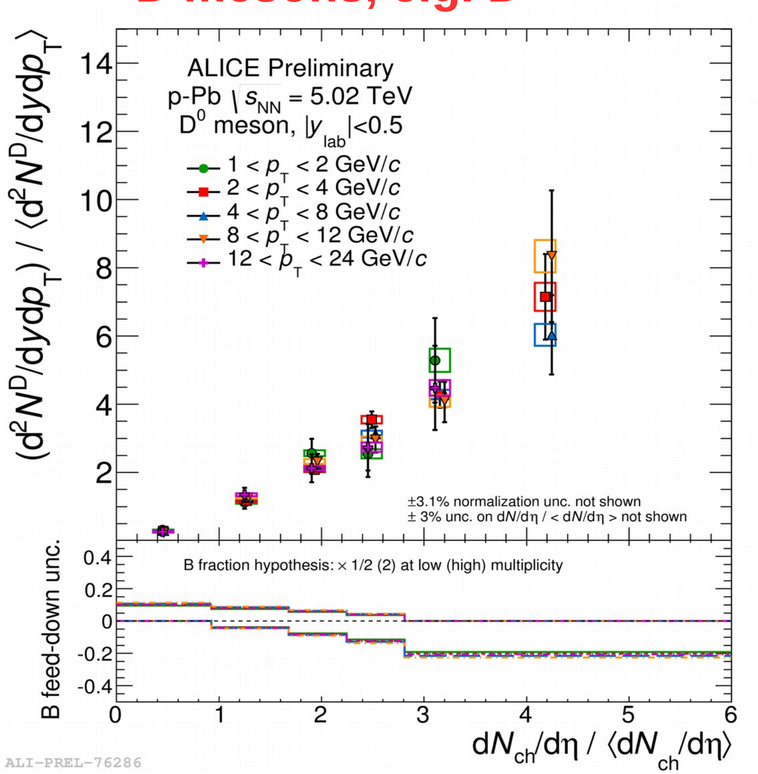


- R_{pPb} of **HF decay μ** consistent with unity at forward rapidity (p-going direction)
- R_{pPb} of **HF decay μ** slightly larger than unity in the range 2 < p_T < 4 GeV/c at backward rapidity (Pb-going direction)
- Described by MNR pQCD calculations with EPS09 PDF parameterizations of shadowing (M.Mangano et al., Nucl.Phys.B 373(1992)295; K.Eskola et al., JHEP 04467(2009)065)
- **Small cold nuclear matter effects in the measured p_T range**

p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

Multiplicity dependence of HF production

D mesons, e.g. D^0



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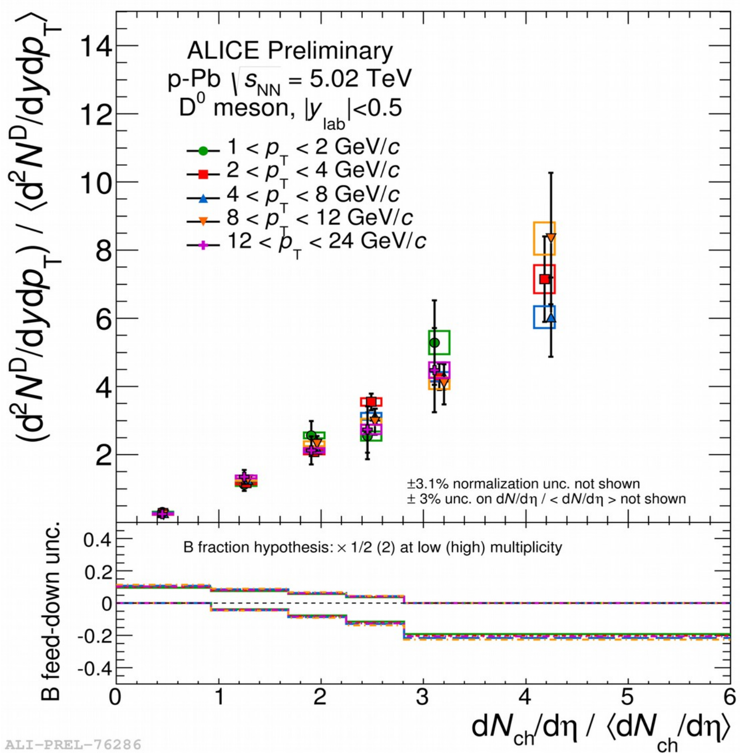

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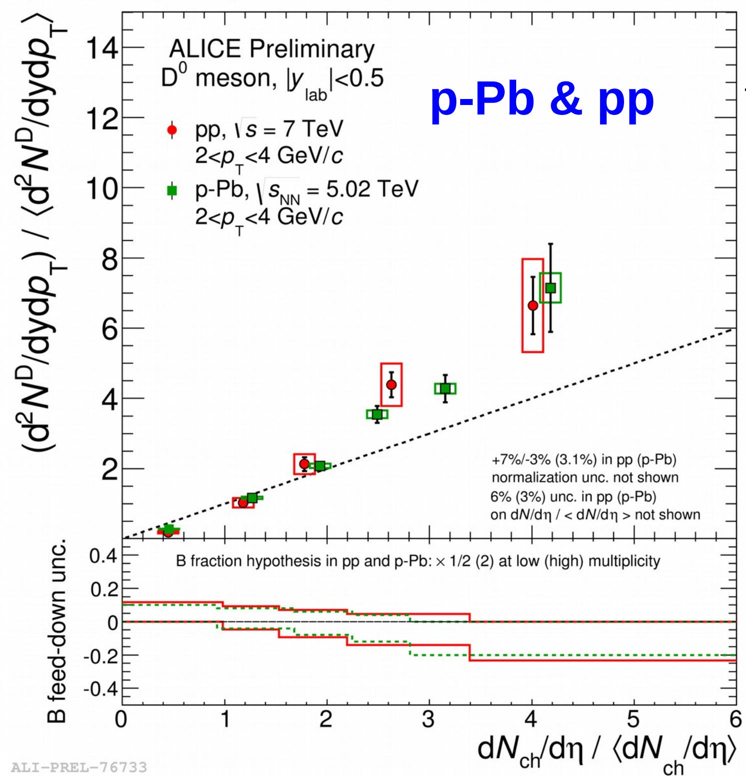

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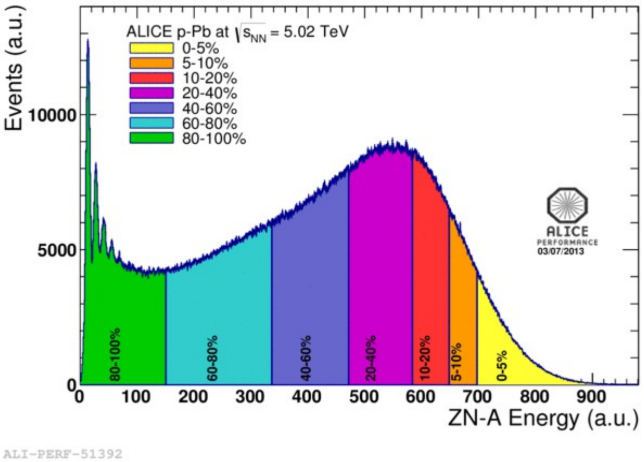
- D-meson self-normalized yields increase with charged particles multiplicity without a significant p_T dependence (within uncertainties)
- Similar trend observed in pp and p-Pb collisions
  - High-multiplicity pp collisions are mainly from MPIs, while high-multiplicity p-Pb collisions are also due to a larger number of binary nucleon-nucleon collisions

Multiplicity dependent nuclear modification factor

- Investigate a possible multiplicity dependent modification of the p_T spectra in p-Pb wrt pp collisions

$$Q^{mult}_{pPb}(p_T) = \frac{\left(dN^{mult}_{pPb}/dp_T\right)_i}{\langle N_{coll}\rangle_i \, dN_{pp}/dp_T}$$



- Event classes defined on the basis of the energy of the Pb-spectator neutrons deposited in the ZDC (ZN)
- $\langle N_{coll}\rangle$ in a ZN energy class obtained by scaling the minimum-bias value

$$\langle N_{coll}\rangle_i = \langle N_{coll}\rangle_{MB}\left(\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{MB}}\right)_{-1<\eta<0} - 1$$

Multiplicity dependent nuclear modification factor

ALICE

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$$Q_{pPb}^{mult}(p_T) = \frac{\left(dN_{pPb}^{mult}/dp_T\right)_i}{\langle N_{coll}\rangle_i \, dN_{pp}/dp_T}$$

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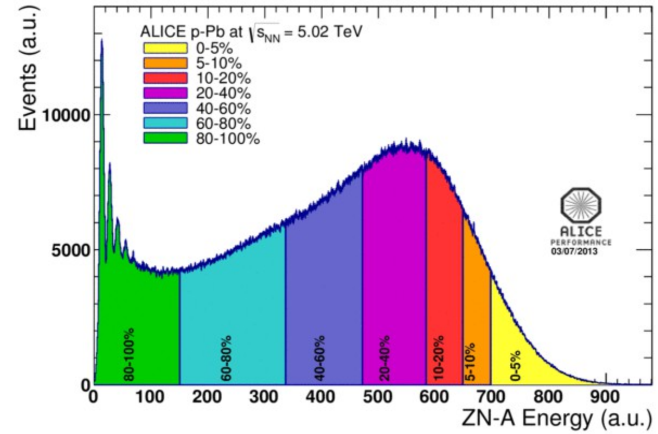
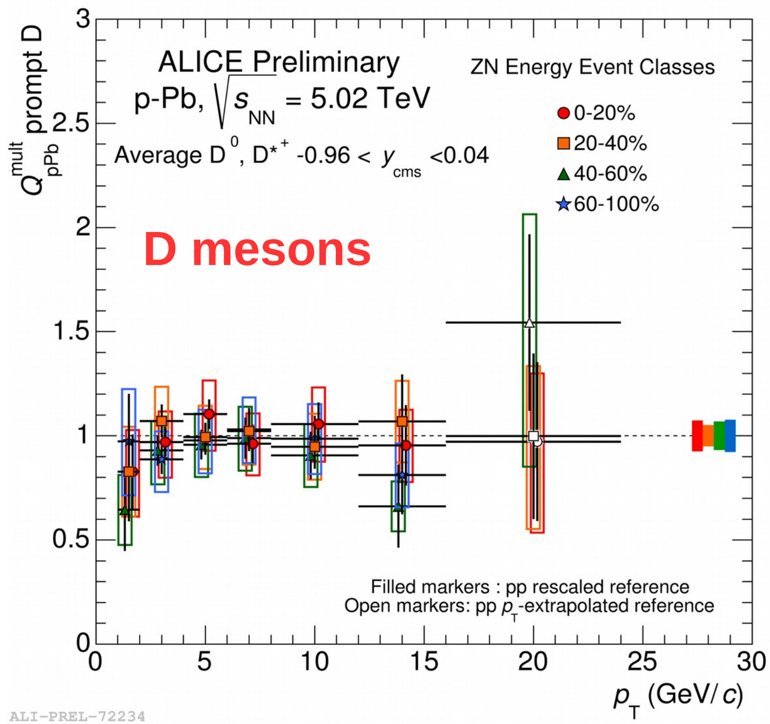


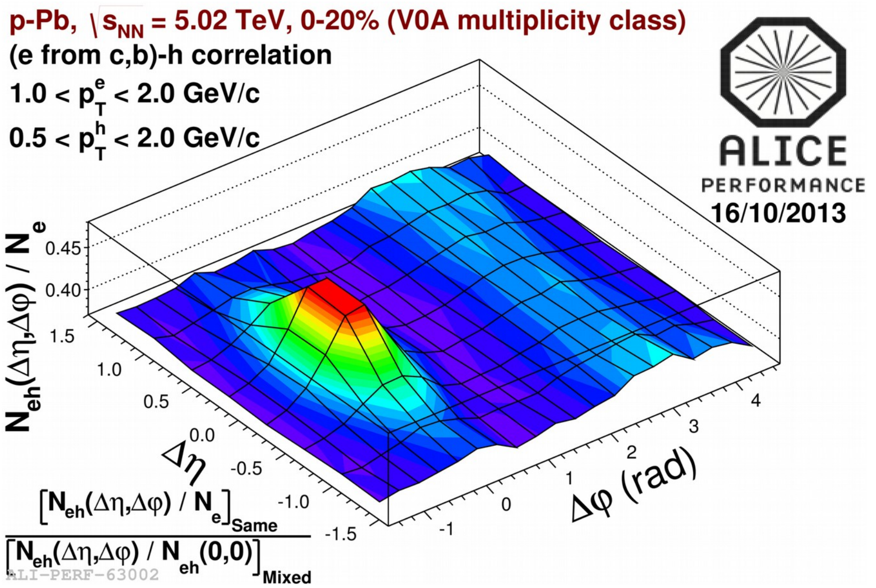


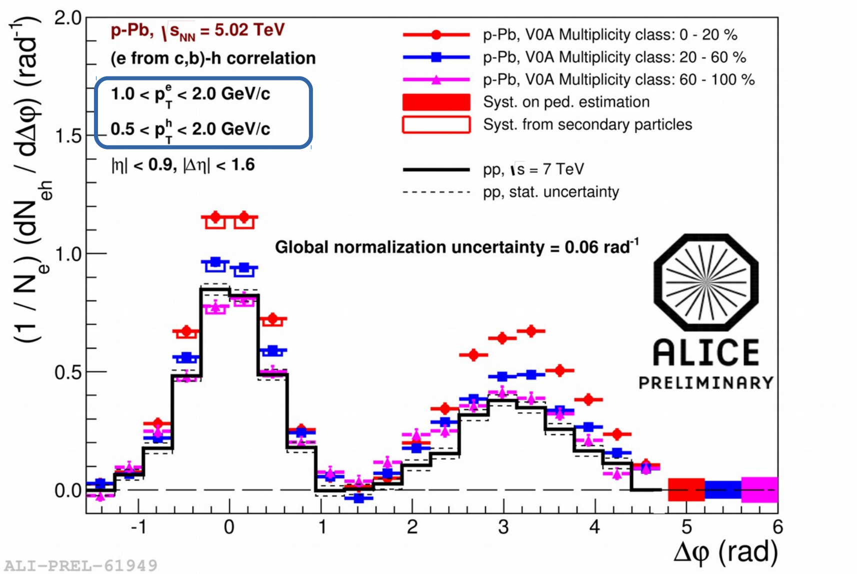
- **Q_{pPb} does not show a multiplicity dependence of the D-meson production in p-Pb relative to pp collisions**
- Similar for charged hadrons

Heavy-flavour e - h correlations

- Study of the angular correlation between an electron from heavy-flavour hadron decay (*trigger particle*) and a charged hadron (*associated particle*)
- Search for “double-ridge” structure as observed in the light-flavour sector

Phys. Lett. B 719 (2013)

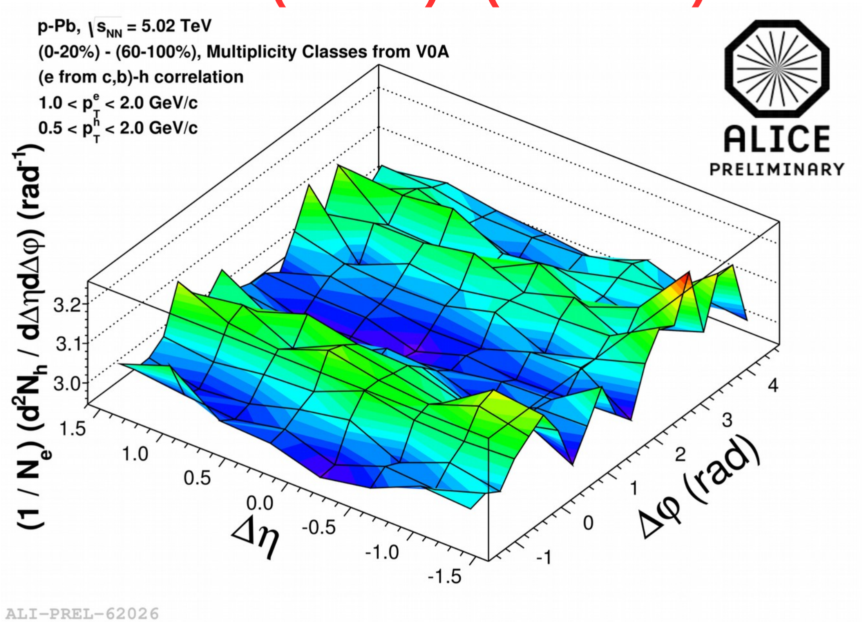


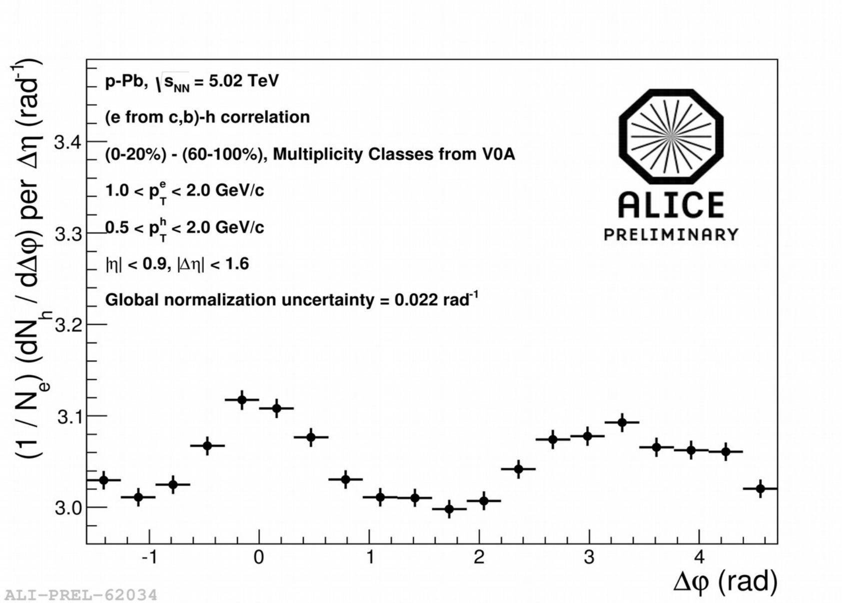


- Low-p_T trigger particle (1< p_T^e < 2 GeV/c): enhancement in the near and away side peaks for the highest multiplicity events (0-20%)
- Intermediate-p_T trigger particle (2< p_T^e < 6 GeV/c): correlation distributions in all multiplicity classes compatible with each other and with those measured in pp collisions at $\sqrt{s}$ = 7 TeV

Heavy-flavour e - h correlations

(0-20%) - (60-100%)

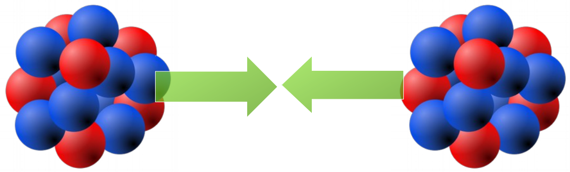




- Difference of highest multiplicity event class (0-20%) and lowest multiplicity event class (60-100%) to remove correlations due to jets
- **Double-ridge structure emerges also for HF decay e- h correlations**
- Do the responsible mechanisms (CGC, hydrodynamics) affect both light and heavy flavours?

  CGC: Bozek et al., PLB (2013) 1557; Hydro: Dusling et al., PRD87 (2013) 094034

Results in Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV

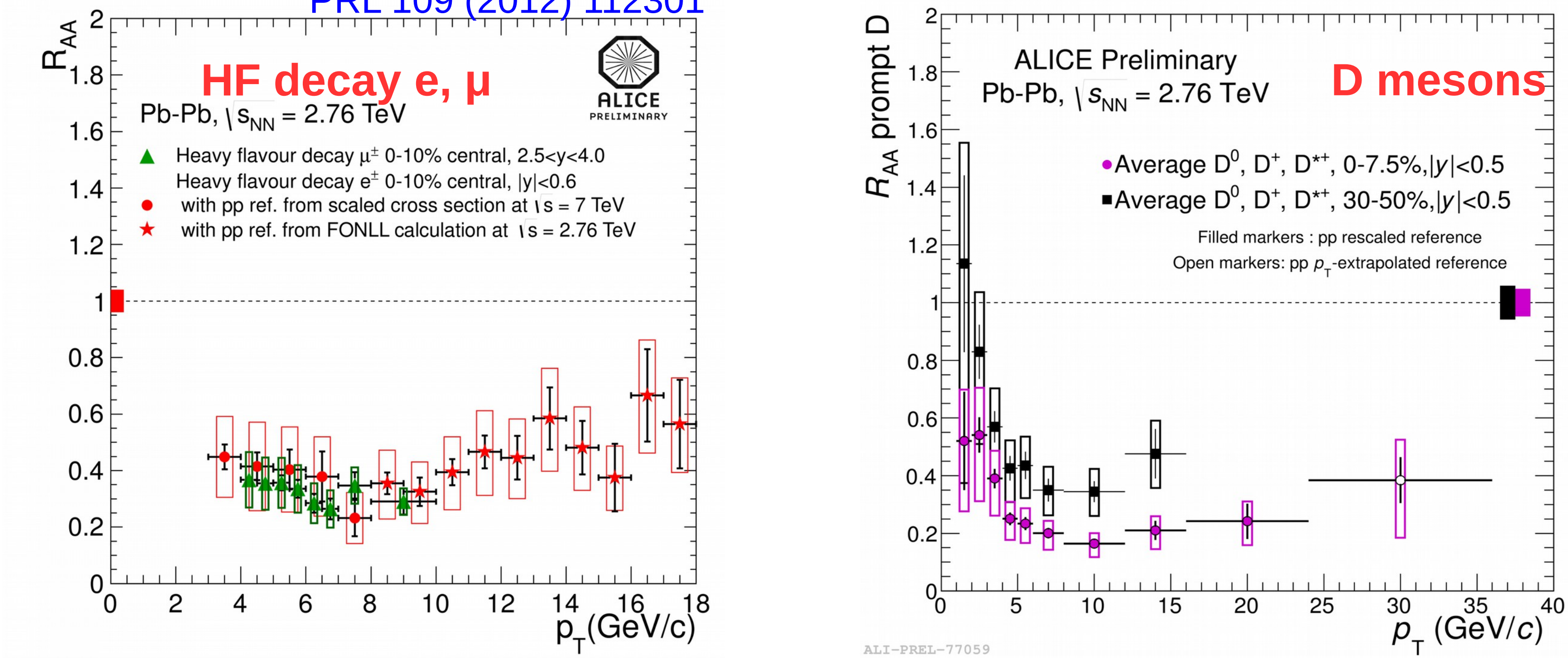


- Study of the interaction of heavy quarks with the medium

Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV

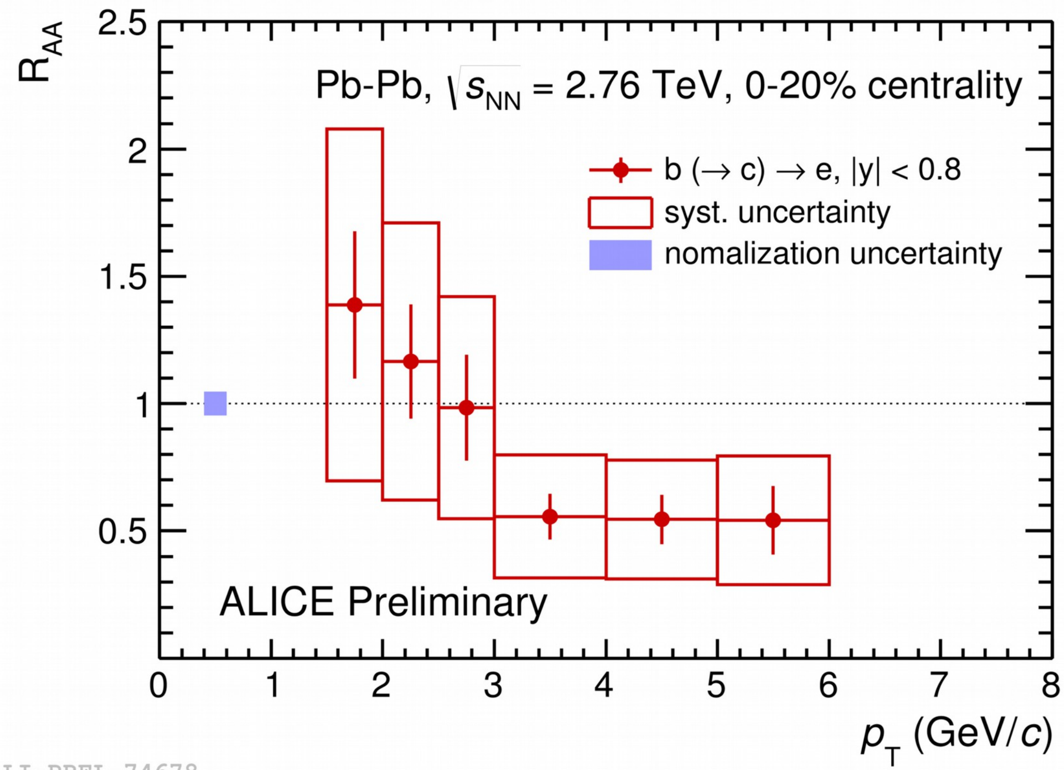
HF nuclear modification factor R_{AA}

PRL 109 (2012) 112301



- **Heavy-flavour production is suppressed at high p_T in the most central Pb-Pb collisions with respect to the binary scaled pp collisions**
- **R_{pA}~ 1 → the suppression is a final state effect due to hot and dense medium**
  - Similar HF decay e (|y|<0.6) and HF decay μ (2.5<y<4.0) R_{AA} in 0-10%
  - Also compatible with D-meson R_{AA} (|y|<0.5) in 0-7.5% considering the semileptonic decay kinematics ($p_{T,}^{e}$ ~ 0.5 p_T^B at high p_T)
- **Open heavy-flavour production is affected by partonic energy loss in the most central Pb-Pb collisions**

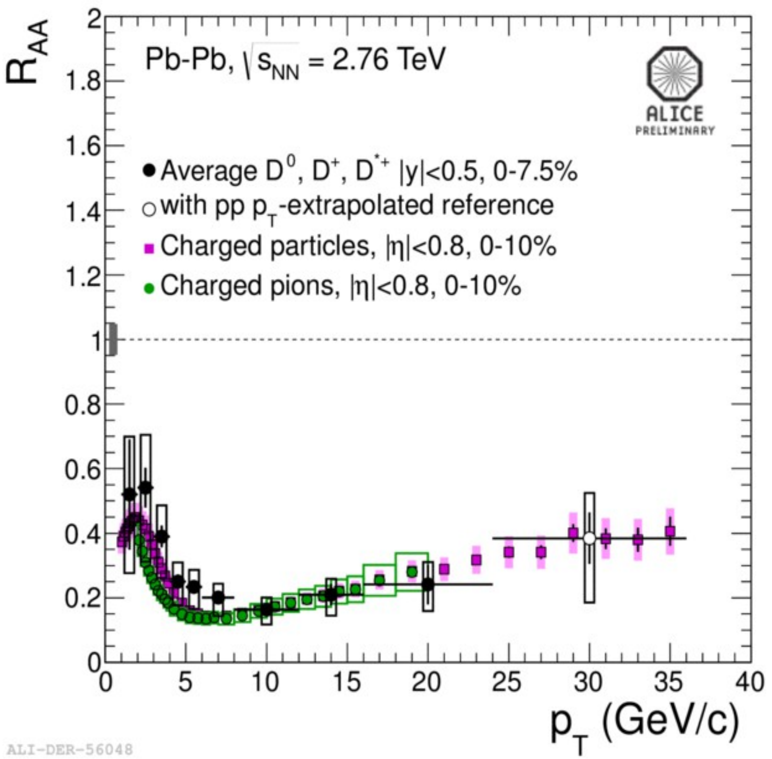
R_{AA} of electrons from beauty-hadron decays

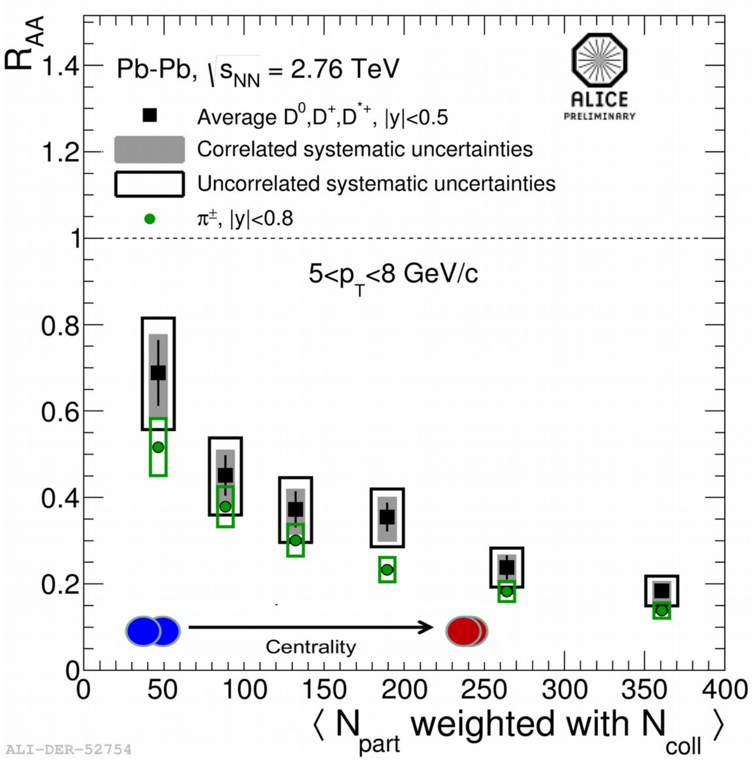


- R_{AA} of electrons from beauty hadron decays in 0-20% central Pb-Pb collisions
- Analysis based on the study of the electron impact parameter distribution
- First measurement indicates R_{AA} < 1 for p_T > 3 GeV/c
- **Hint for a suppression of beauty decay electrons with p_T > 3 GeV/c in central Pb-Pb collisions**

R_{AA} mass hierarchy: comparison with π

Expected: $\Delta E_{gluons} > \Delta E_{light} > \Delta E_{charm} > \Delta E_{beauty} \rightarrow \boxed{R_{AA}(\pi) < R_{AA}(D)} < R_{AA}(B)$



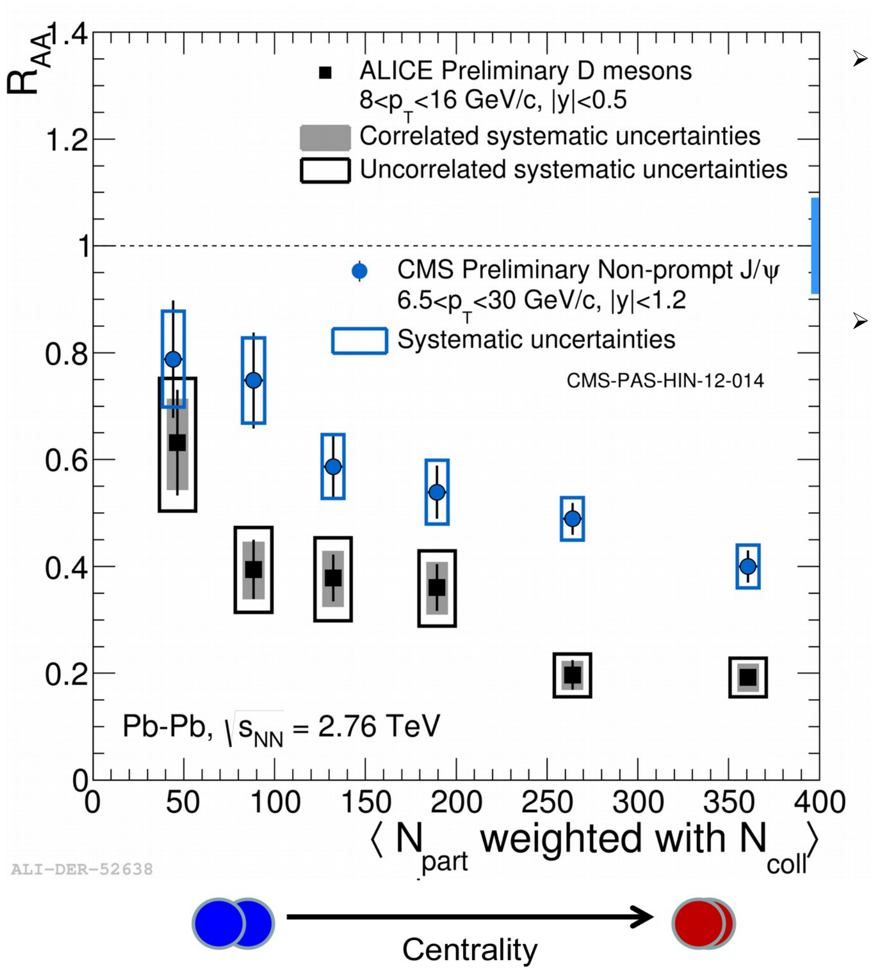


- **D-meson and π R_{AA} compatible within uncertainties**
- **Measurement not yet conclusive**
- In agreement with models including $\Delta E_{gluons} > \Delta E_{light} > \Delta E_{charm}$
  - Different shapes of the parton p_T distributions
  - Different fragmentation functions
  - Soft production mechanism for low-p_T π

M.Djordjevic, arXiv:1307.4098
Wicks, Horowitz, Djordjevic, Nucl. Phys. A 872 (2011) 265

Comparison with non-prompt J/ψ

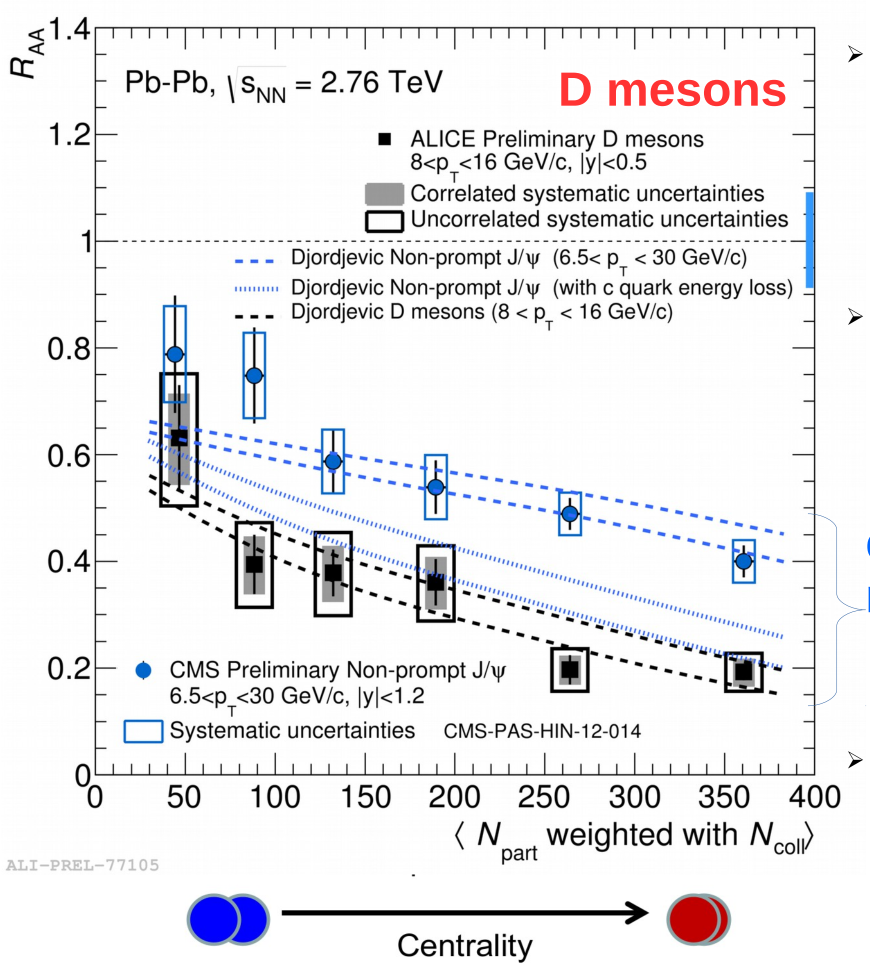
Expected: $\Delta E_{gluons} > \Delta E_{light} > \Delta E_{charm} > \Delta E_{beauty} \rightarrow R_{AA}(\pi) < \boxed{R_{AA}(D) < R_{AA}(B)}$



- ALICE prompt D-meson R_{AA} compared with non-prompt J/ψ from CMS in a similar kinematic range (<p_T> ~10 GeV/c, slightly different rapidity)
- **Indication of R_{AA}(D) < R_{AA}(J/ψ ← B) in central Pb-Pb collisions**

Comparison with non-prompt J/ψ

Expected: $\Delta E_{gluons} > \Delta E_{light} > \Delta E_{charm} > \Delta E_{beauty} \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$



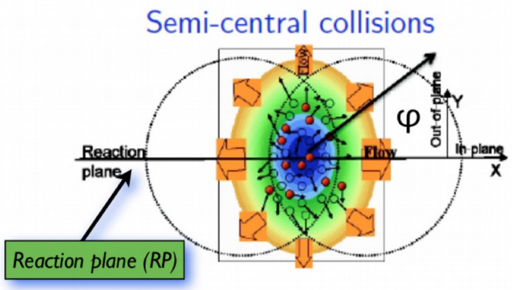
- ALICE prompt D-meson R_{AA} compared with non-prompt J/ψ from CMS in a similar kinematic range (<p_T> ~10 GeV/c, slightly different rapidity)
- **Indication of R_{AA}(D) < R_{AA}(J/ψ ← B) in central Pb-Pb collisions**

consequence of mass difference in pQCD based model calculation (Djordjevic, arXiv:1307.4098)

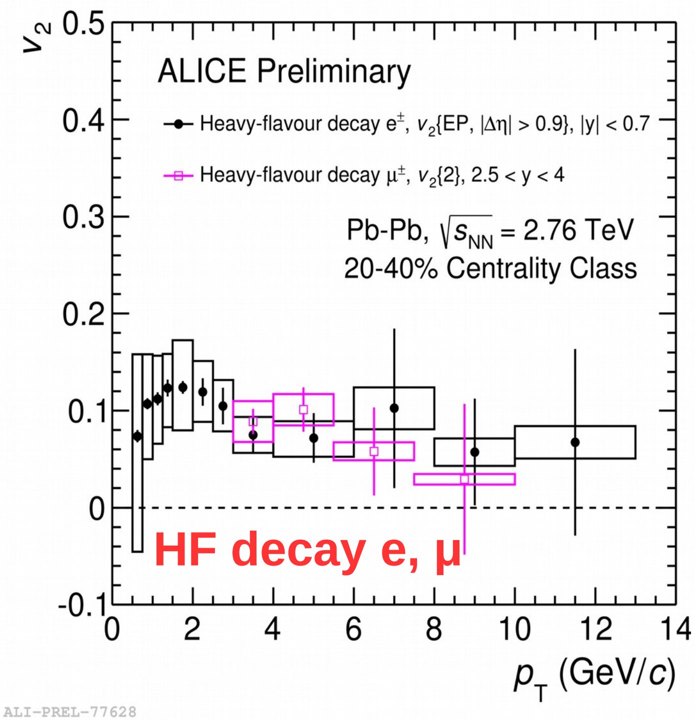
- **pQCD models including mass-dependent radiative and collisional energy loss predict a difference between the D-meson and non-prompt J/ψ similar to that observed**
- Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.)

BAMPS: J.Phys.G38(2011)124152,
WHDG: J.Phys.G38(2011)124114,
Vitev et al., Phys.Rev.C80(2009)054902

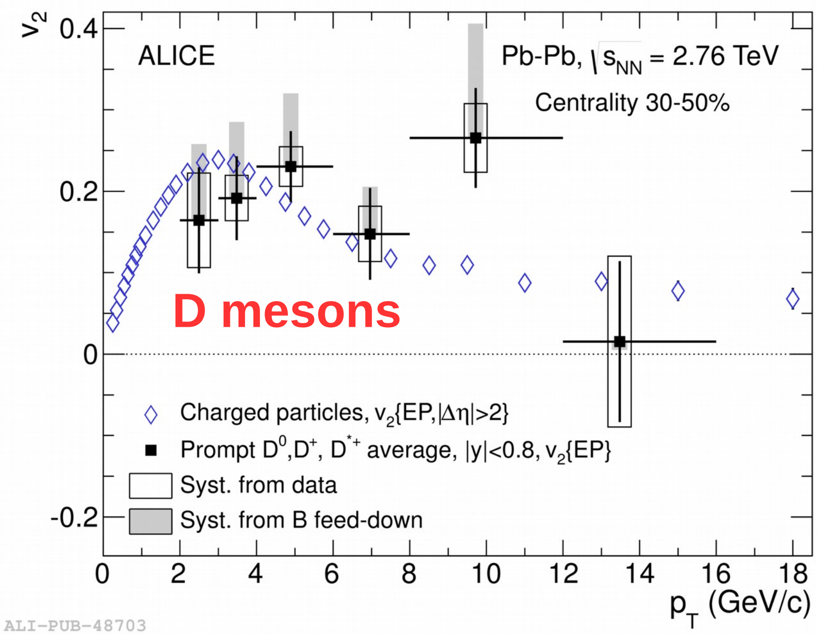
Azimuthal anisotropy



$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2\cos[2(\varphi - \Psi_{RP})]} + \ldots)$$



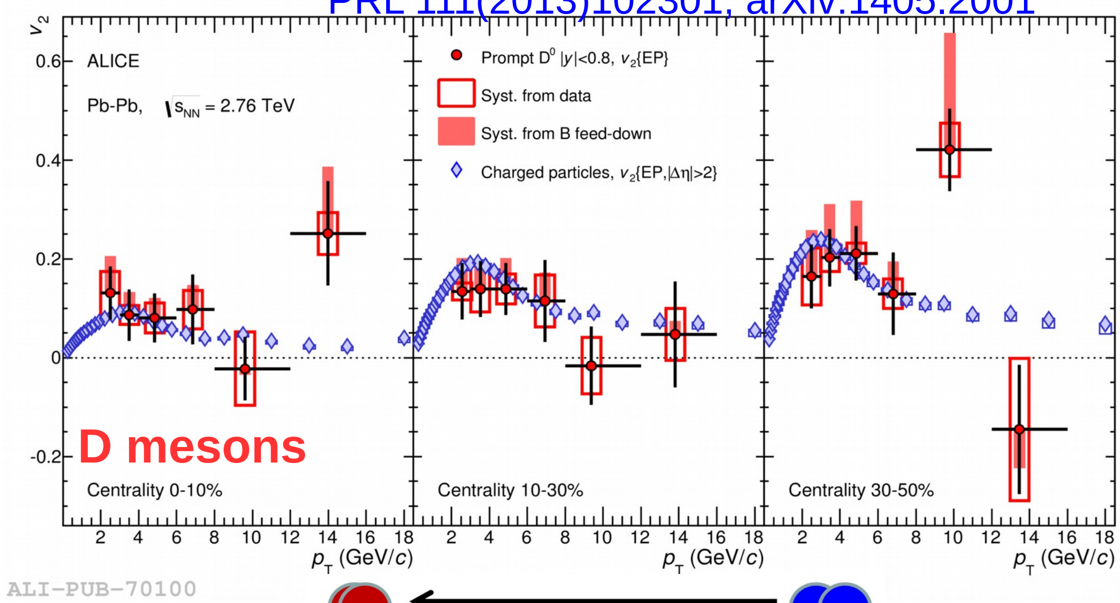
PRL 111(2013)102301, arXiv:1405.2001



- **Positive open heavy-flavour v_2 in Pb-Pb semi-central collisions**
  - HF decay electrons, >3σ effect for $2 < p_T < 3$ GeV/c
  - Similar v_2 values for HF decay μ and HF decay e in different rapidity regions
  - D mesons, 5.7σ effect for $2 < p_T < 6$ GeV/c
  - Open heavy-flavour v_2 is similar to that of charged particles

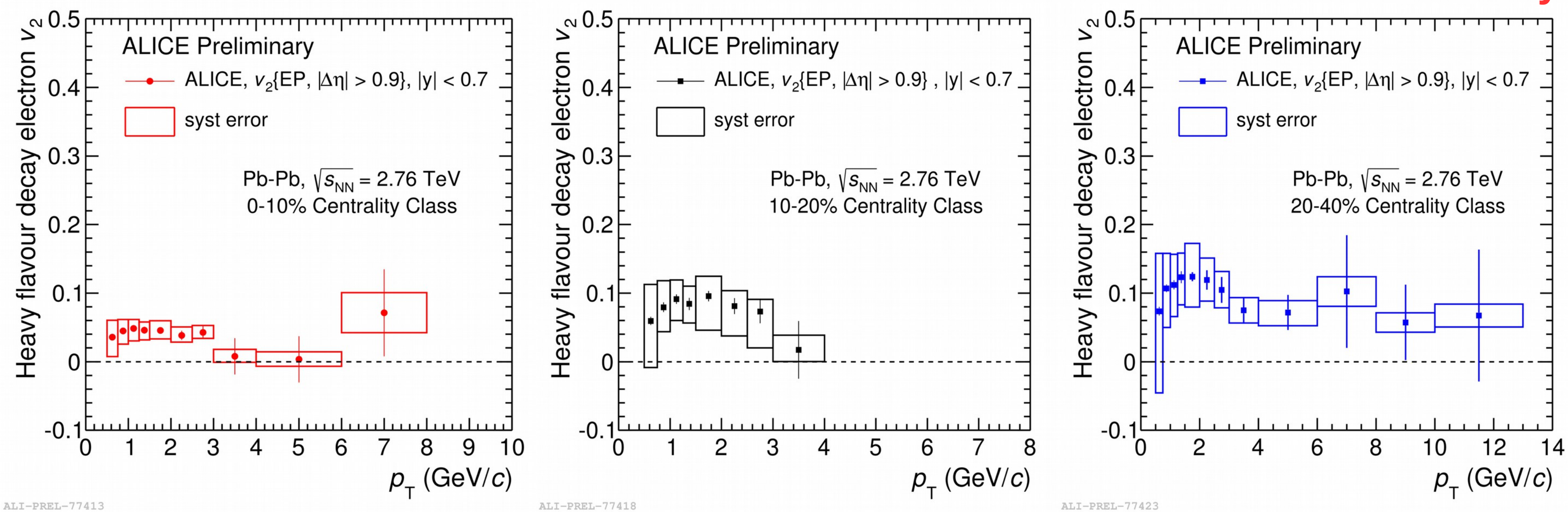
Azimuthal anisotropy: centrality dependence

PRL 111(2013)102301, arXiv:1405.2001

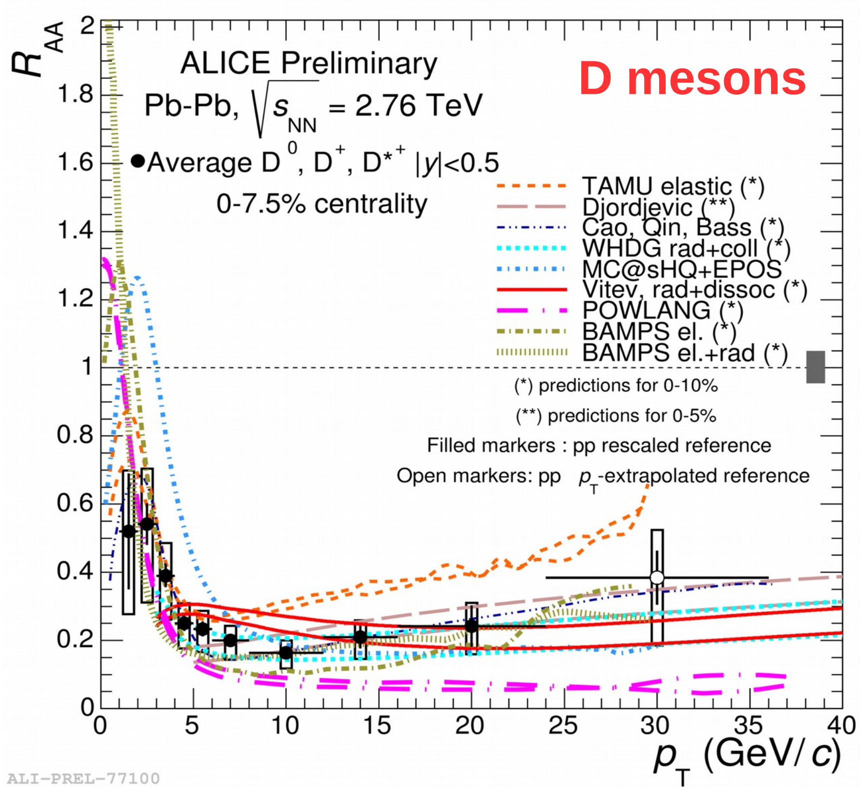


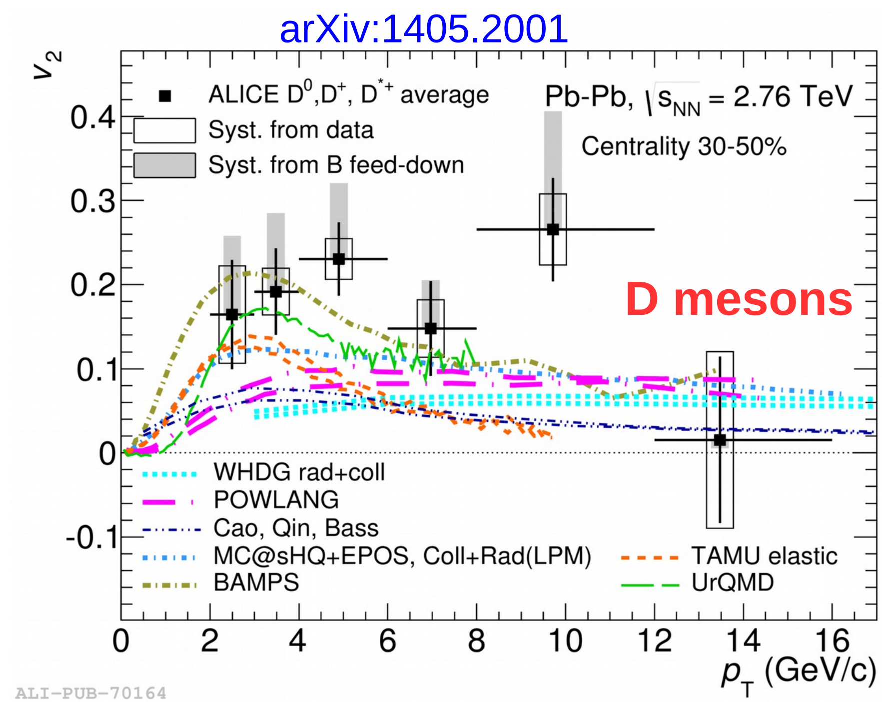
- Hints of centrality dependence: v_2 increases from central to semi-central collisions
- Similar to charged hadrons

HF decay e



Comparisons with models





- Results from different observables (p_T spectra, R_{AA}, azimuthal anisotropy) compared to theory can constrain the energy loss models
- The simultaneous description of open heavy-flavour R_{AA} and v_2 is challenging

TAMU elastic: arXiv:1401.3817; Djordjevic: arXiv:1307.4098; Cao, Qin, Bass: PRC 88 (2013) 044907; WHDG rad+coll: Nucl. Phys. A 872 (2011) 265; MC@sHQ+EPOS: PRC 89 (2014) 014905; Vitev, rad+dissoc: PRC 80 (2009) 054902; POWLANG: JPG 38 (2011) 124144; BAMPS: PLB 717 (2012) 430

Conclusions

pp collisions

- Open heavy-flavour production is well described by pQCD calculations
- D-meson yields increase with charged-particle multiplicity: the pp trend suggests that MPI affect hard momentum scale relevant for heavy-flavour production

p-Pb collisions

- Indication of small cold nuclear matter effects (R_{pPb}~ 1 in the measured p_{T} range at mid and forward rapidity and at $p_{\mathrm{T}} > 4$ GeV/c at backward rapidity)
- Data described within uncertainties by different models including initial-state effects
- No multiplicity dependent modification of the p_{T} distribution of D mesons in p-Pb collisions with respect to the binary scaled pp collisions is observed
- Double-ridge structure observed in HF e- h correlations. Same origin as for light flavours?

Pb-Pb collisions

- Heavy-flavour production is suppressed at high p_{T} in the most central Pb-Pb collisions with respect to the binary scaled pp collisions
- The suppression is due to final-state effects due to parton energy loss in the medium
- Consistent with expected mass ordering
- $v_2 > 0$ suggests that charm quarks participate in the system collective motion

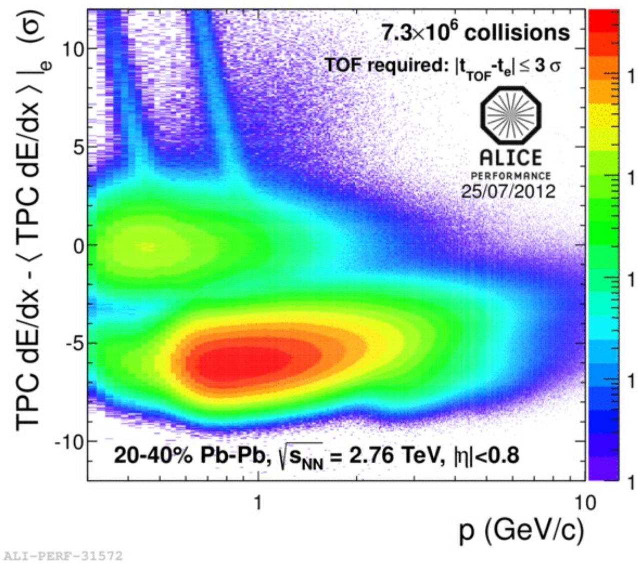
Further progresses require more statistics

- Higher statistics at higher energies expected for Run 2 (beyond 2015)
- ALICE Upgrade (2018): faster readout and improved tracking and vertexing resolution. High precision measurements of R_{AA} and v_2 for several HF species and HF baryons will become accessible in Pb-Pb collisions

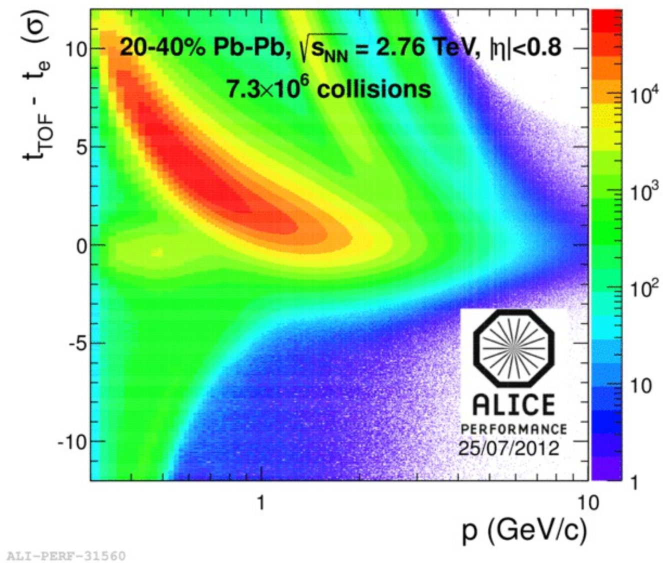
Back up slides

Electron identification

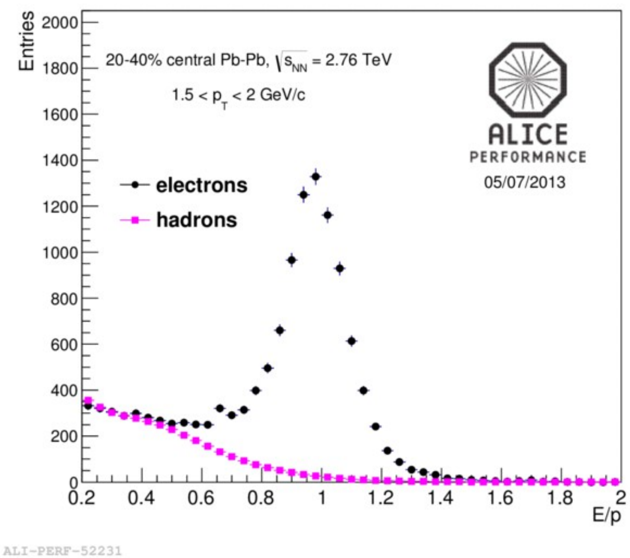
TPC



TOF



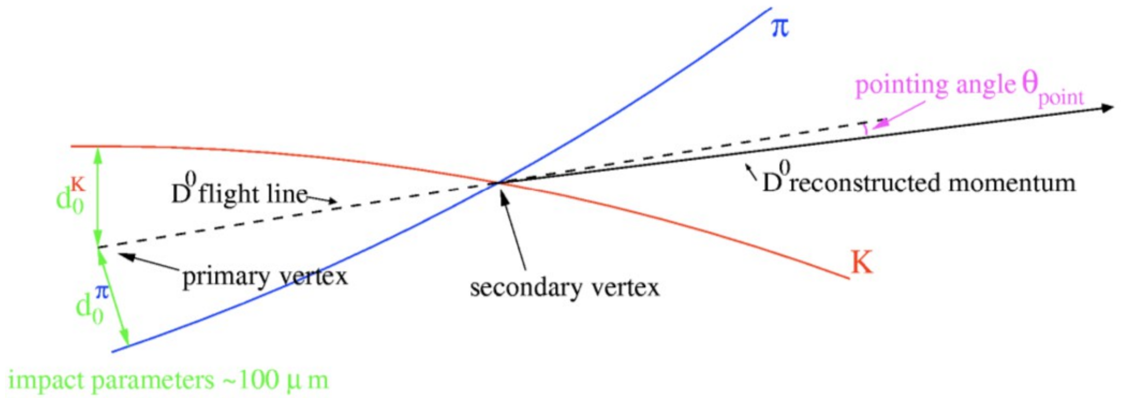
EMCAL

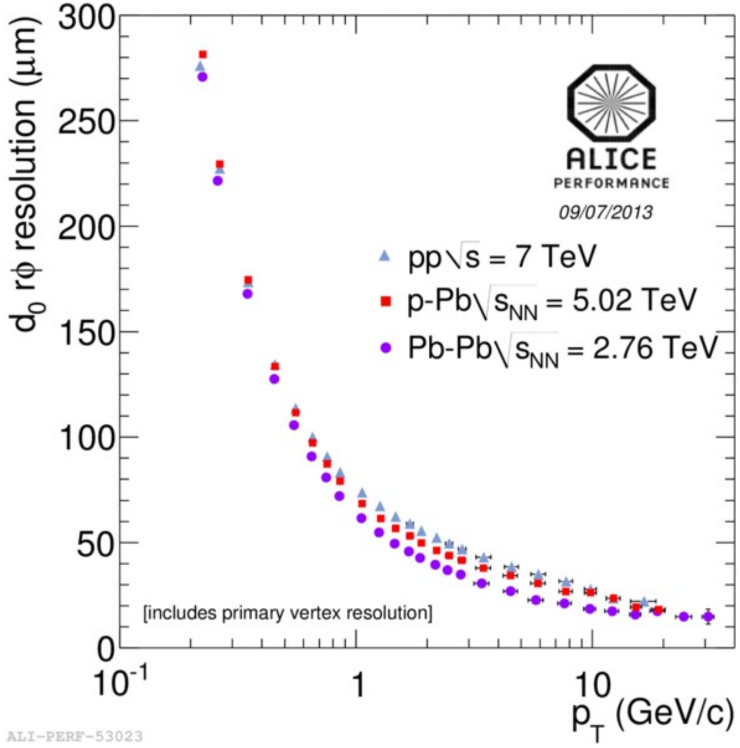


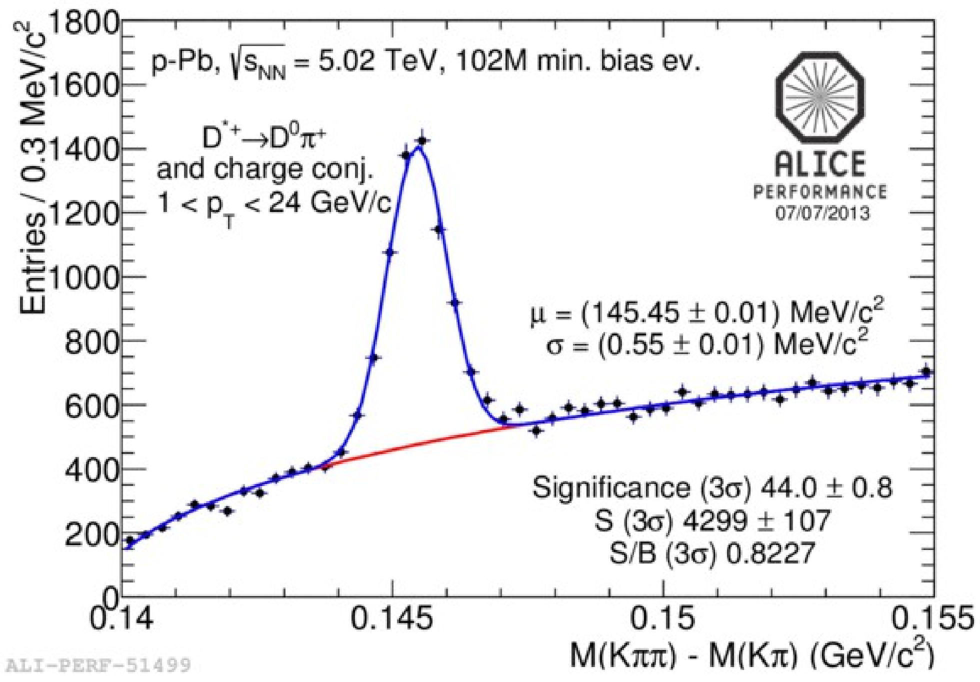
- Identification with TPC, TOF and EMCAL
- Background subtraction methods
  - MC cocktail of relevant background sources: Photon conversions, Dalitz decay of π^0 and η and light mesons, non-photonic sources
  - e^+e^- invariant mass method: Dalitz decay and photon conversion measured via invariant mass selection and subtracted statistically

D meson reconstruction

- Invariant mass analysis based on **displaced secondary vertices,** selected with **topological cuts and PID in TPC and TOF**







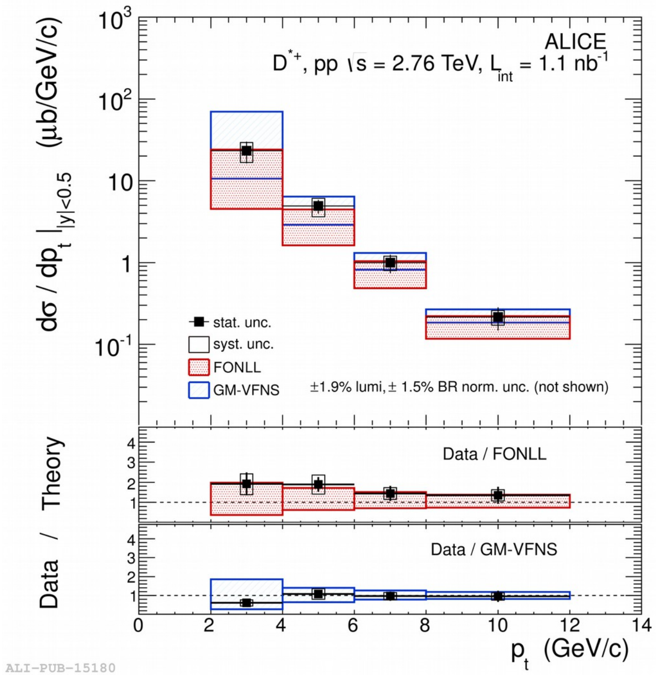
Muon reconstruction

- Muons defined as matched tracks with tracklet in the trigger chambers
- Cut p vs. DCA $\rightarrow$ reject tracks from beam-gas interactions
- Subtraction of background from primary $\pi^{\pm}$ and $K^{\pm}$ decays.

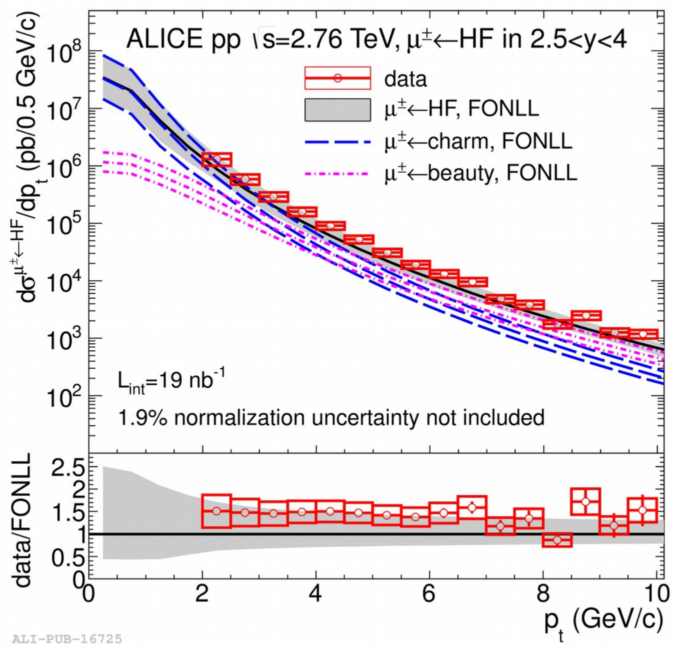
HF cross section at √s=2.76 TeV

- p_T-differential cross section in all channels

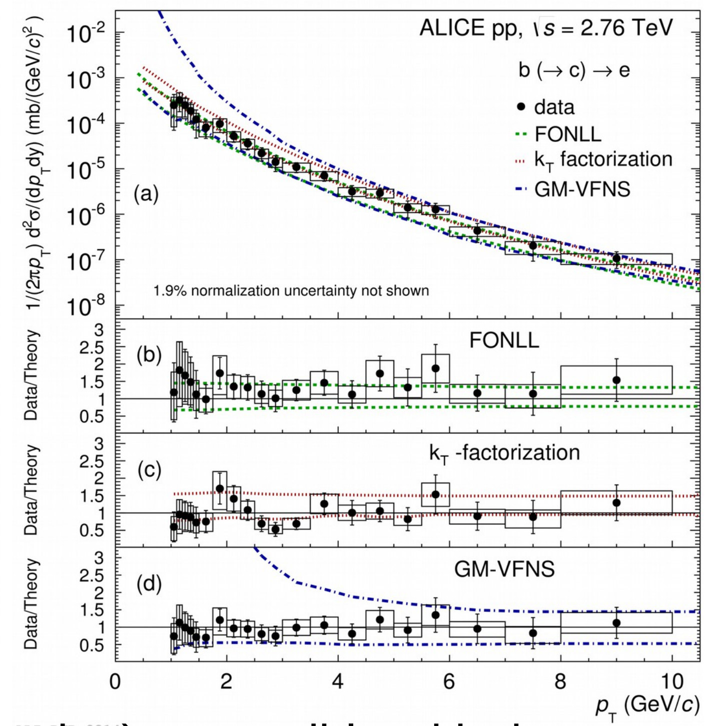
D mesons (e.g. D^{*+})
JHEP 1207(2012)191



HF decay μ
PRL 109(2012)112301



HF decay e
ArXiv:1405.4117v1



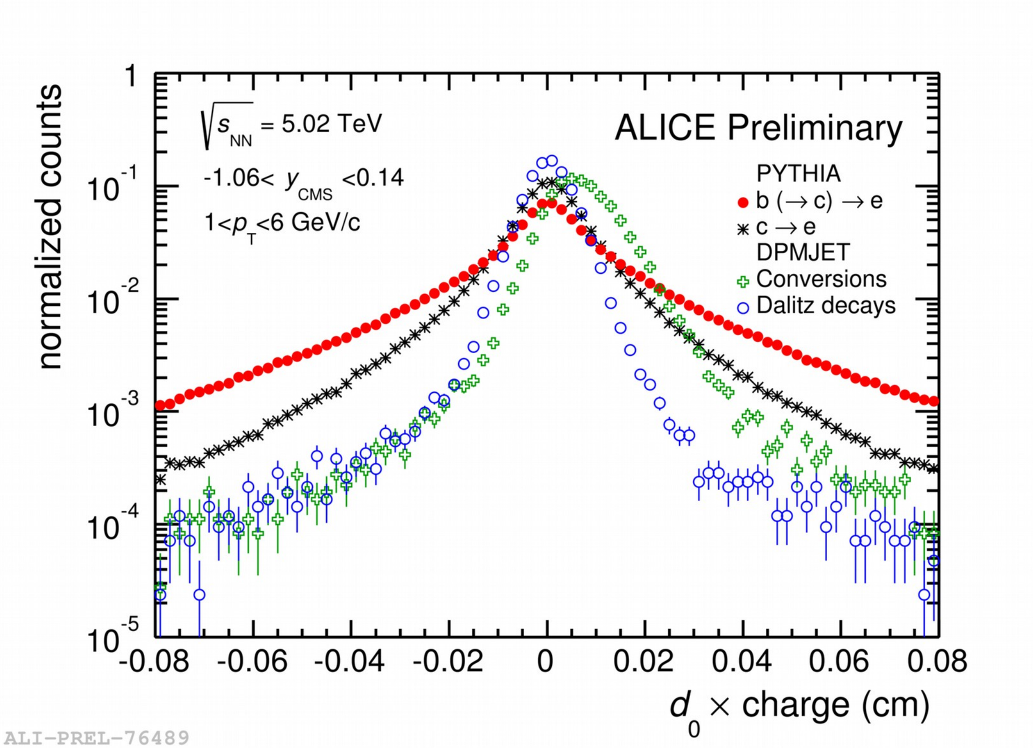
- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
- HF decay μ cross section used as reference for Pb-Pb at the same energy
- For other channels a √s extrapolations based on pQCD calculations is used

R.Averbeck et al.,arXiv:1107.3243

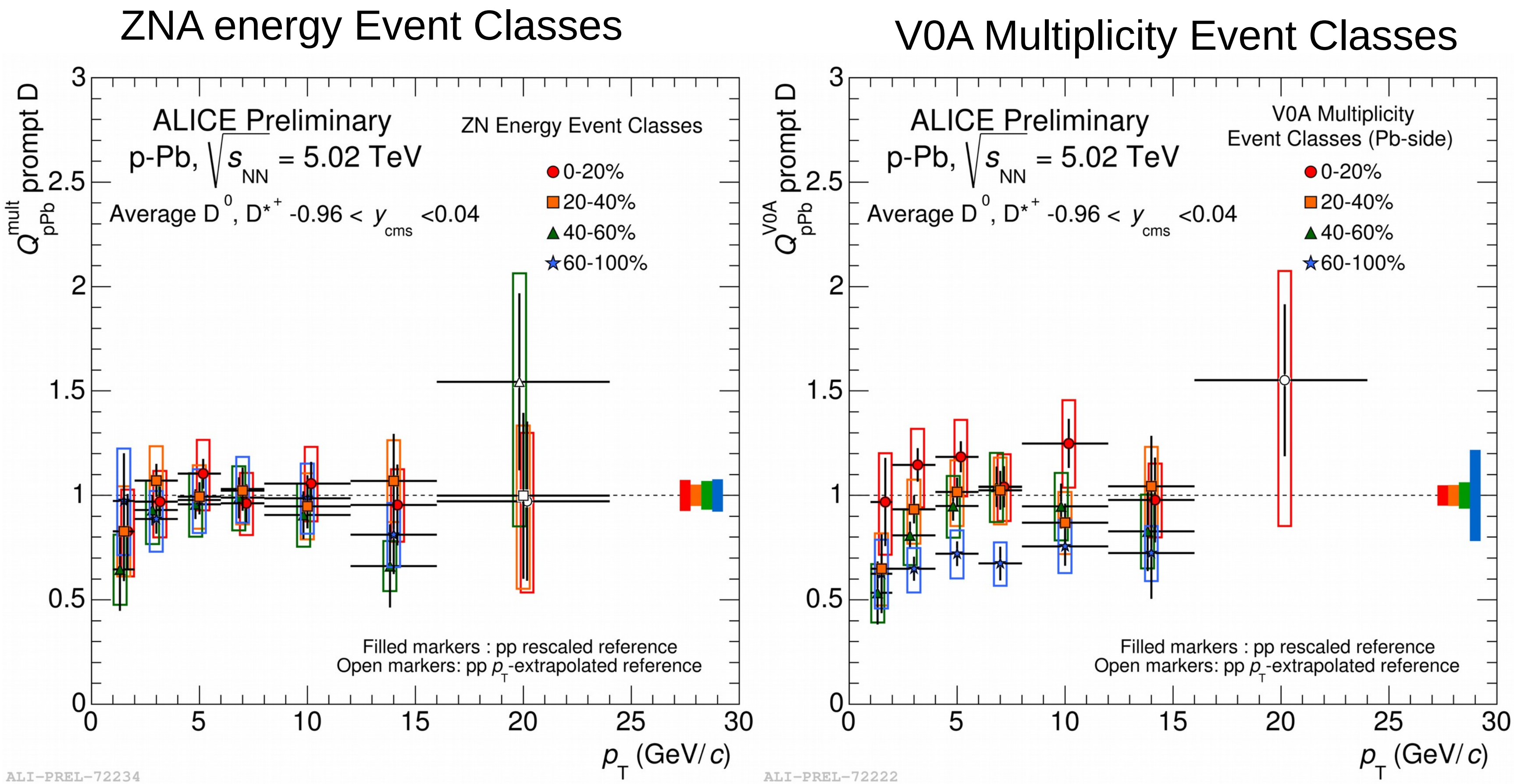
FONLL:JHEP1210(2012)137; GM-–VFNS: Eur.Phys.JC72(2012); k_T factorization: arXiv:1301.3033

Beauty hadron decay electrons

- Exploit long lifetime of beauty hadrons ($c\tau \sim 500\ \mu m$)
  - Electrons from beauty hadrons displaced from the primary vertex -> wide impact parameter, d_0 distribution
    - Impact parameter cut to select beauty decay electrons
    - Remaining background subtracted via simulations based on measured π and D-meson cross sections

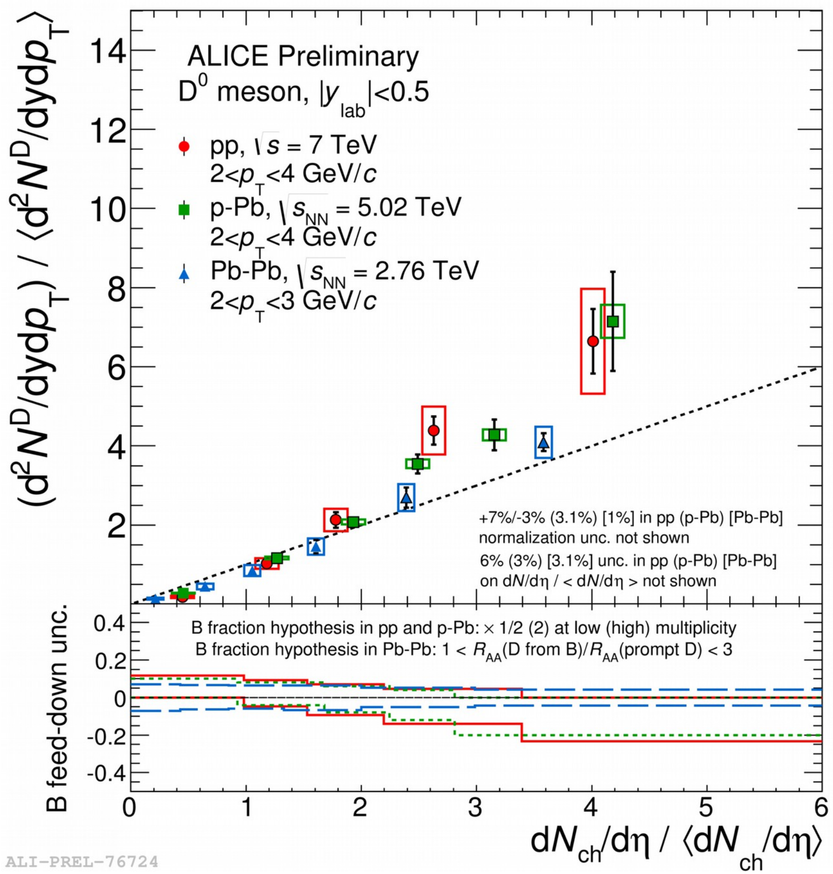


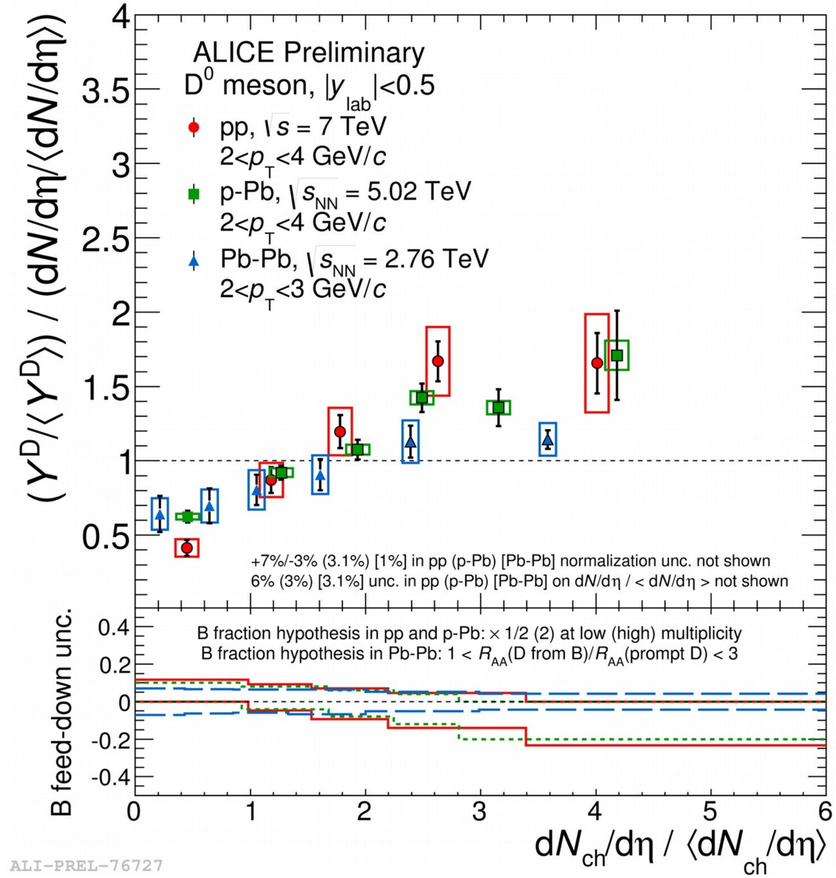
Q_{pPb} in multiplicity classes in p-Pb collisions



Residual bias when using the VZERO detector
to define the multiplicity classes

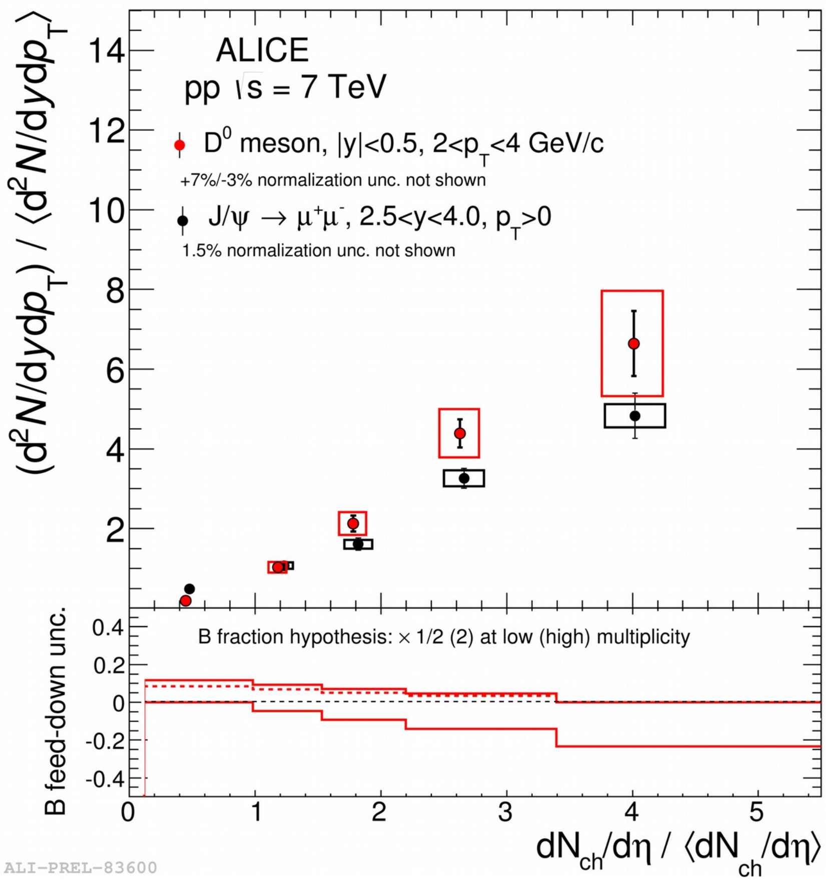
Multiplicity dependence: comparison with Pb-Pb

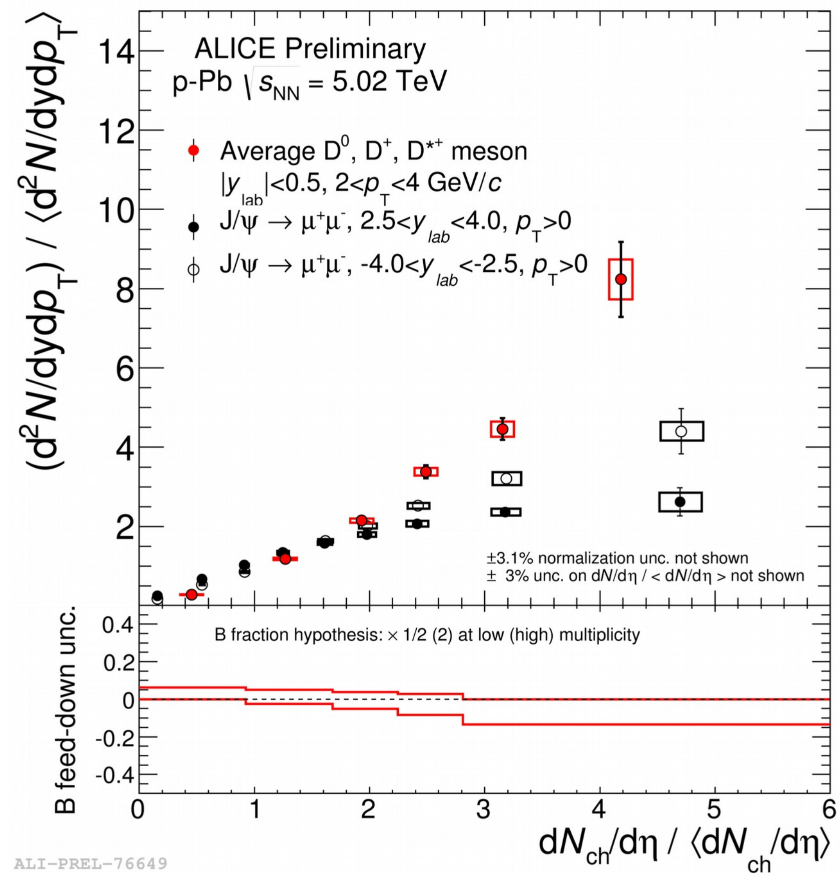




- Trend reflects evolution of N_{coll} and R_{AA} with centrality
- Caveat: comparing pp with Pb-Pb collisions: highest multiplicity bin corresponds to 10% of the total cross section in Pb-Pb but only 1% in pp collisions

Multiplicity dependence: comparison with J/psi

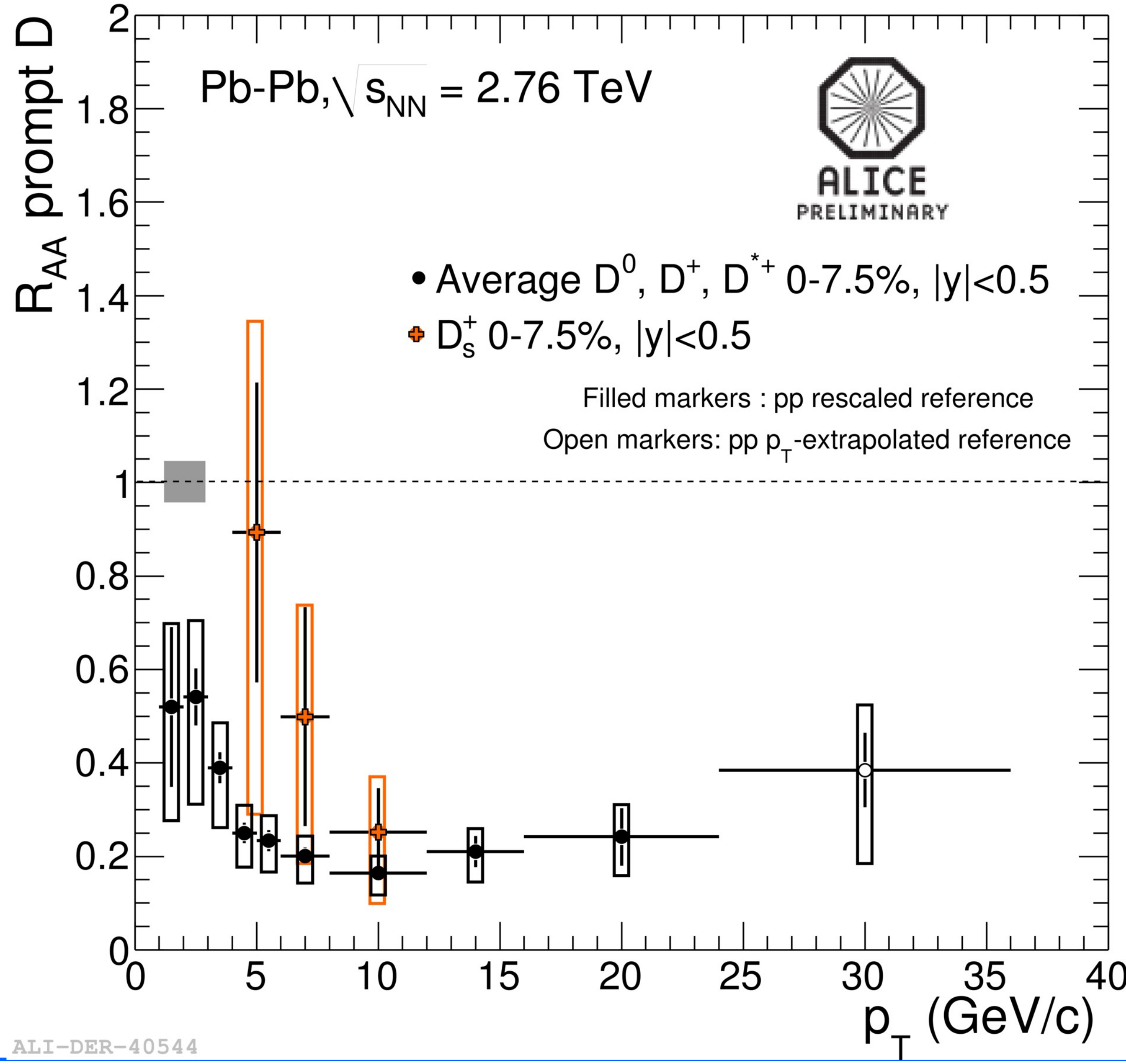




Similar increase of the relative J/ψ (inclusive) and D-meson (prompt) yields with the relative charged-particle multiplicity in pp collisions, whereas in p-Pb collisions D-meson relative yields increase faster than the J/ψ ones.

- Caveat: different rapidity and p_T intervals in these measurements.
- High-multiplicity pp collisions are mainly from MPIs, while high-multiplicity p-Pb collisions are also due to a larger number of binary collisions.

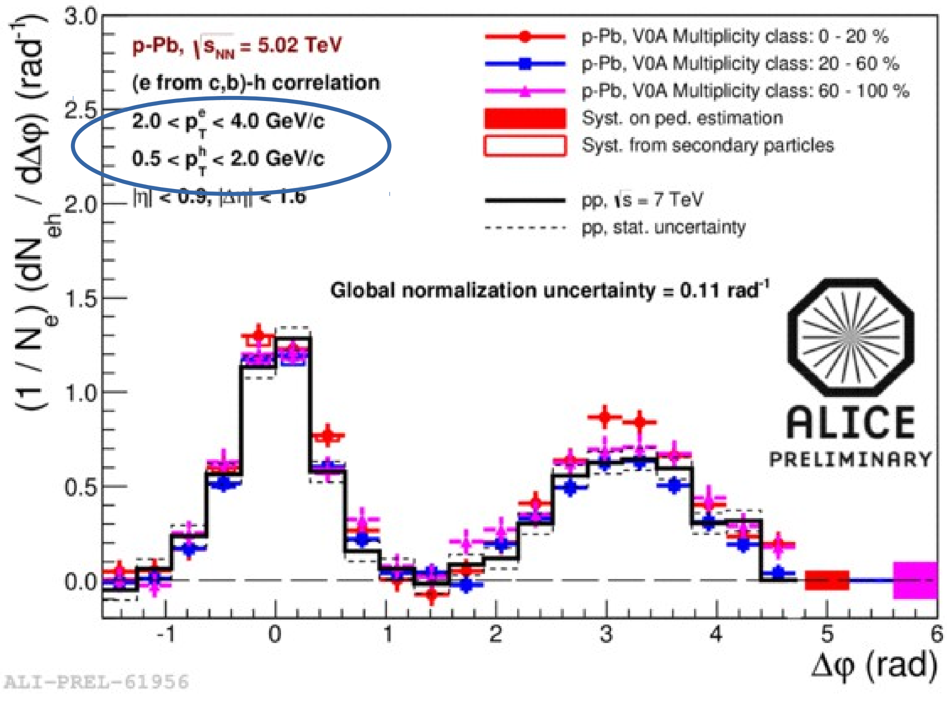
D_s R_{AA}

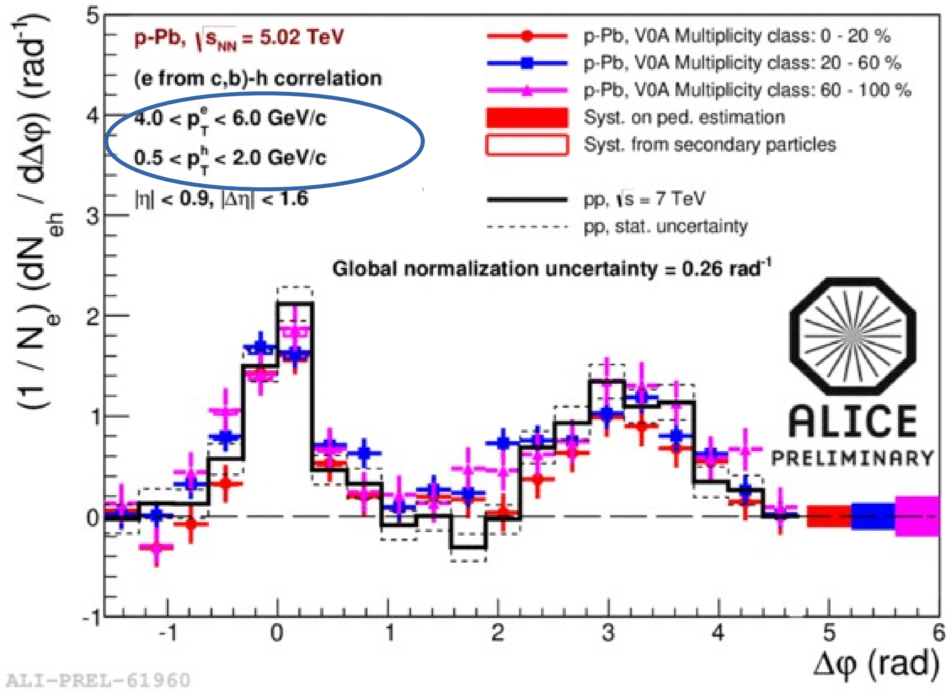


Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE
PRELIMINARY
Average D^0, D^+, D^{*+} 0-7.5%, |y|<0.5
D_s^+ 0-7.5%, |y|<0.5
Filled markers : pp rescaled reference
Open markers: pp p_T-extrapolated reference
R_{AA} prompt D
p_T (GeV/c)
ALI-DER-40544

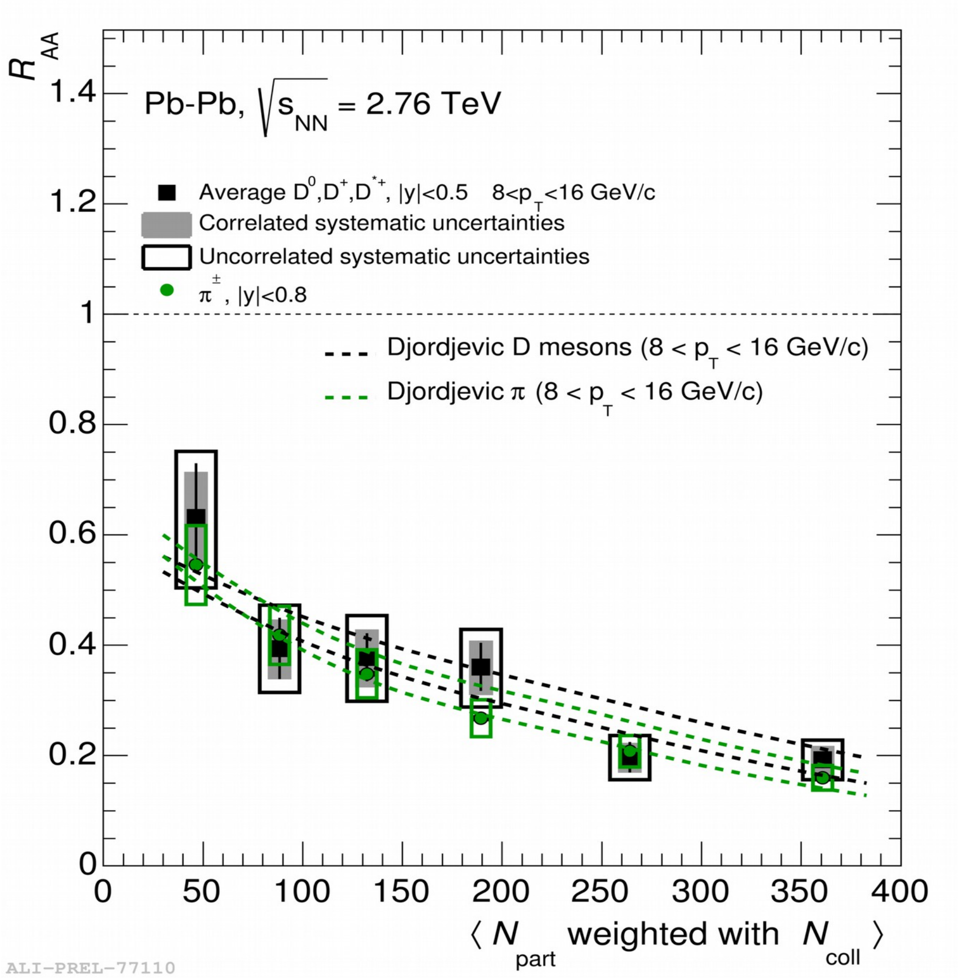
Heavy-flavour e - h correlations

- Intermediate p_T trigger particle

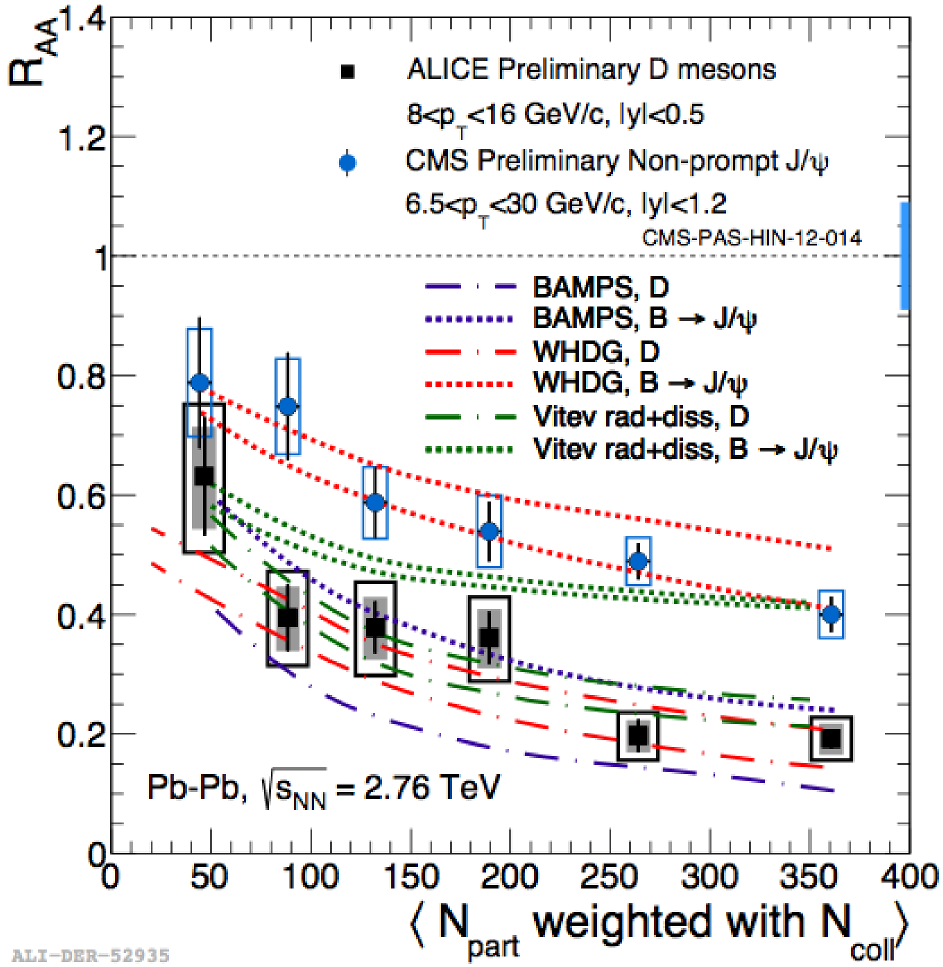




D meson R_{AA} compared with π (and models)



D meson R_{AA} compared with non-prompt J/ψ



- ✓ BAMPS: collisional energy loss in an expanding medium.
- ✓ WHDG: collisional and radiative energy loss in an anisotropic medium.
- ✓ Vitev et al.: radiative energy loss + D meson in-medium formation and dissociation.

BAMPS: JPG 38 (2011)124152
WHDG: Nucl. Phys. A 784 (2007) 426
Vitev et al.: PRC 80 (2009) 054902