The 31st Winter Workshop on Nuclear Dynamics
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Keystone, Colorado, USA

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

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on behalf of the ALICE Collaboration

Outline

- Open Heavy Flavours (HF): physics motivations
- HF measurements with ALICE
- D-meson production
  - Analysis strategy
  - Main results in
    - pp collisions @ 7 TeV
    - p-Pb collisions @ 5.02 TeV
    - Pb-Pb collisions @ 2.76 TeV
- Conclusions and perspectives

Why heavy flavours?

In pp collisions

- Reference for p-Pb and Pb-Pb collisions
- Test of perturbative QCD (pQCD) calculations at the highest collision energies

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  - Modification of Parton Distribution Functions, gluon saturation at low x
  - Energy loss in the initial and final stage of the collisions
  - k_T broadening

K.J.Eskola et al., JHEP 0904(2009)65
I.Vitev at al., PRC 75(2007)064906

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ALICE

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In Pb-Pb collisions

Powerful probes to study the Quark Gluon Plasma in heavy-ion collisions:

- Large mass ($m_c \approx 1.5$ GeV/c, $m_b \approx 5$ GeV/c) in high virtuality processes ($Q > 2m_{c|b}$)
  → **produced in the early stages of the collisions**

- Flavour is conserved in strong interactions
  → **Heavy quarks experience the whole evolution of the medium, interacting with its constituents**

ALICE

Open HF in A-A collisions: Observables

Parton energy loss

- ΔE depends on the parton color charge and mass, in-medium energy density, path length
- Investigated through the **Nuclear Modificaton Factor**

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_{charm} > \Delta E_{beauty}$ → $R^{\pi}_{AA}(p_T) < R^{D}_{AA}(p_T) < R^{B}_{AA}(p_T)$?

PLB 519 (2001) 199, PLB 649 (2007)139

ALICE

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PLB 519 (2001) 199, PLB 649 (2007)139

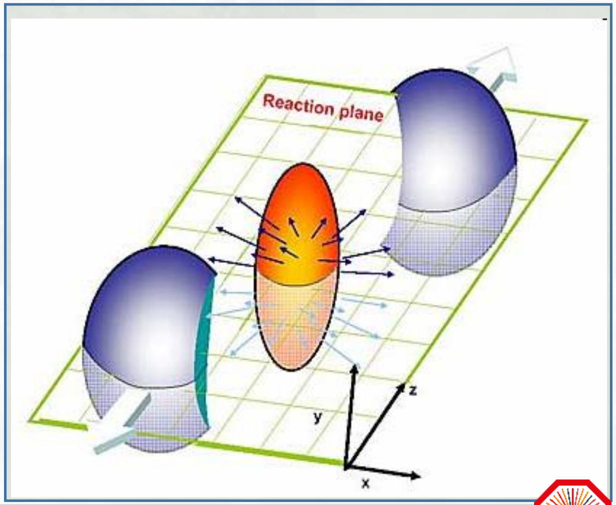
Azimuthal anisotropy

- Initial spatial anisotropy → azimuthally anisotropic momentum distribution
- non-central collisions

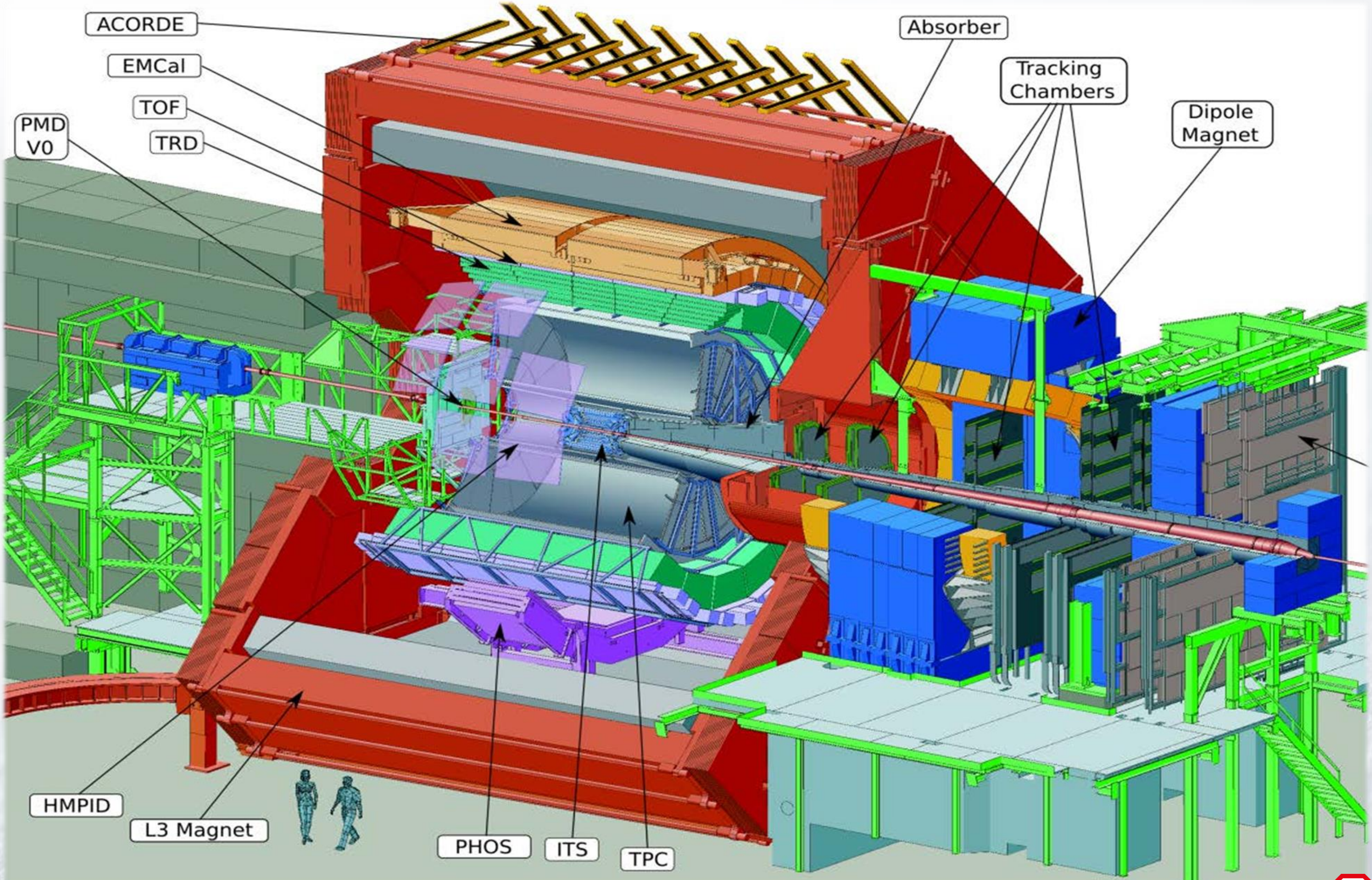
→ anisotropy dominated by **elliptic flow** v_2

  - **low p_T**: v_2 sensitive to collective expansion
  - **high p_T**: v_2 sensitive to path-length dependence of in-medium parton energy loss

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



HF measurements with ALICE



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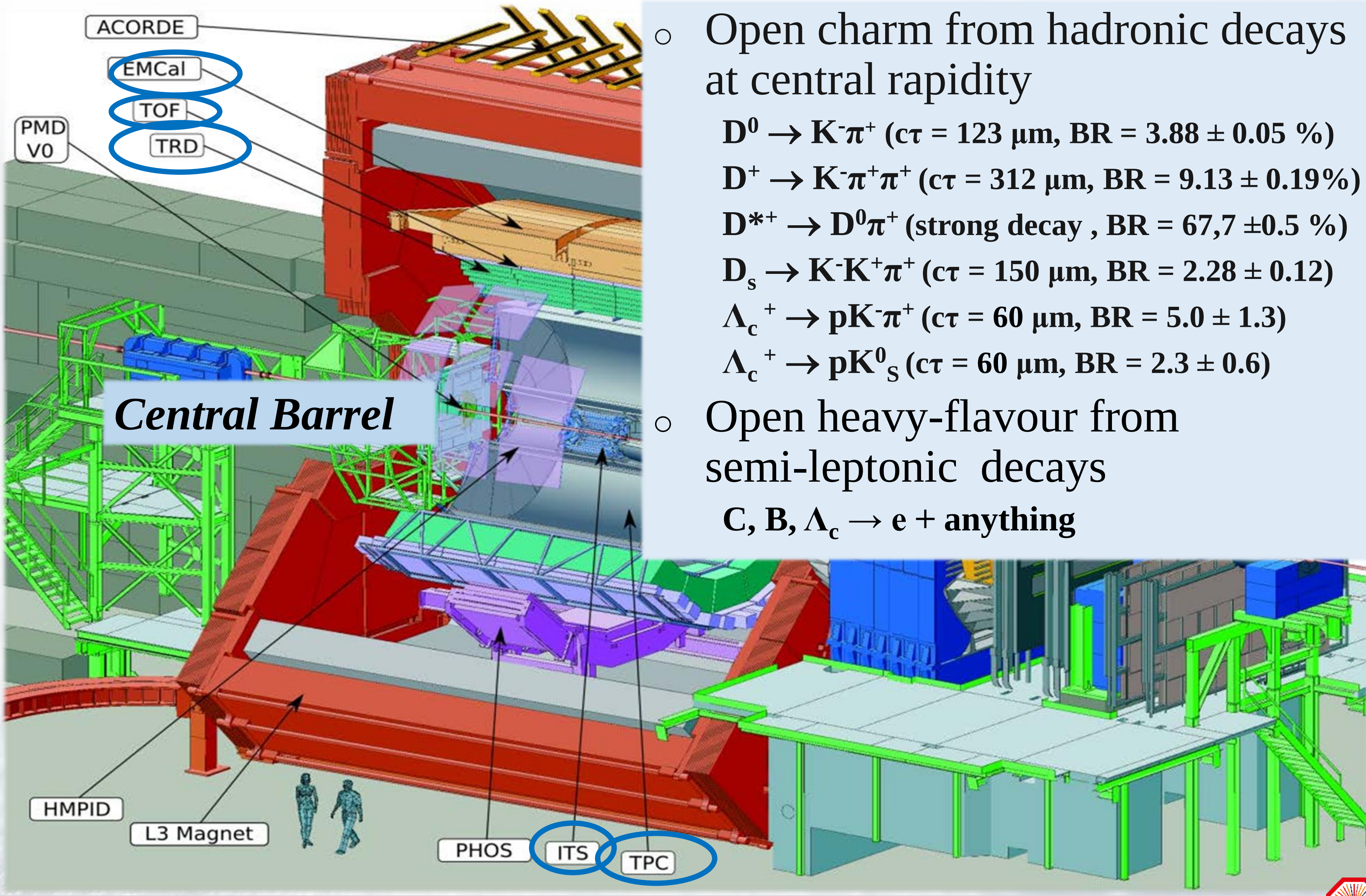
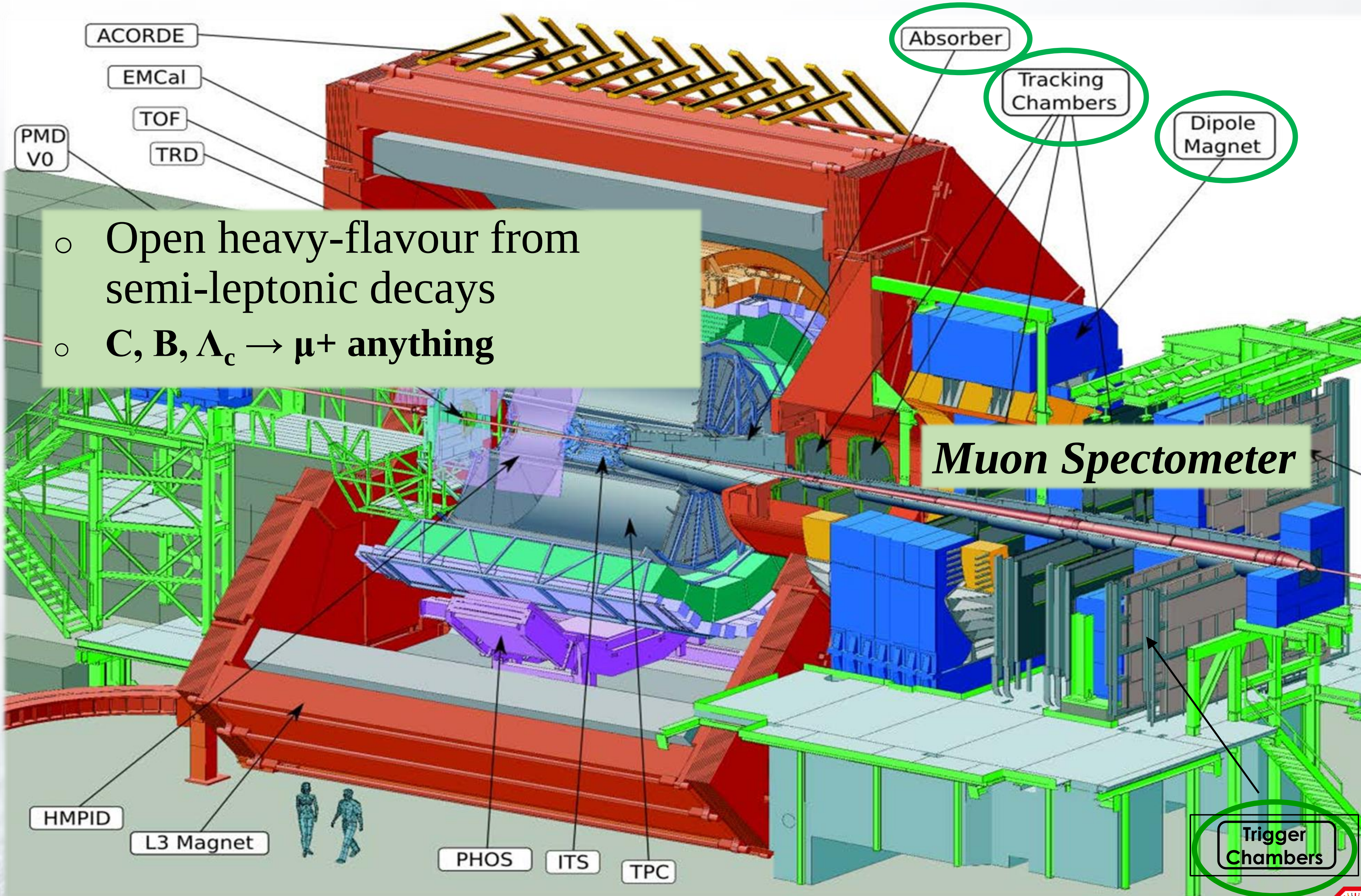


- Open charm from hadronic decays at central rapidity
  - $D^0 \rightarrow K^-\pi^+$ (cτ = 123 μm, BR = 3.88 ± 0.05 %)
  - $D^+ \rightarrow K^-\pi^+\pi^+$ (cτ = 312 μm, BR = 9.13 ± 0.19%)
  - $D^{*+} \rightarrow D^0\pi^+$ (strong decay , BR = 67,7 ±0.5 %)
  - $D_s \rightarrow K^-K^+\pi^+$ (cτ = 150 μm, BR = 2.28 ± 0.12)
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ (cτ = 60 μm, BR = 5.0 ± 1.3)
  - $\Lambda_c^+ \rightarrow pK^0_S$ (cτ = 60 μm, BR = 2.3 ± 0.6)
- Open heavy-flavour from semi-leptonic decays
  - C, B, $\Lambda_c \rightarrow$ e + anything

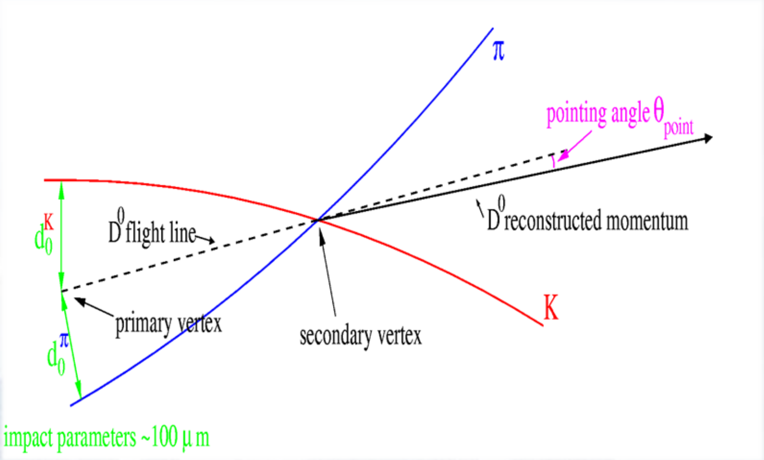
HF measurements with ALICE

- Open heavy-flavour from semi-leptonic decays
- **C, B, Λ_c → μ+ anything**



D-meson reconstruction in ALICE

- Reconstruction of secondary vertex topologies, displaced from the primary vertex by few hundred μm

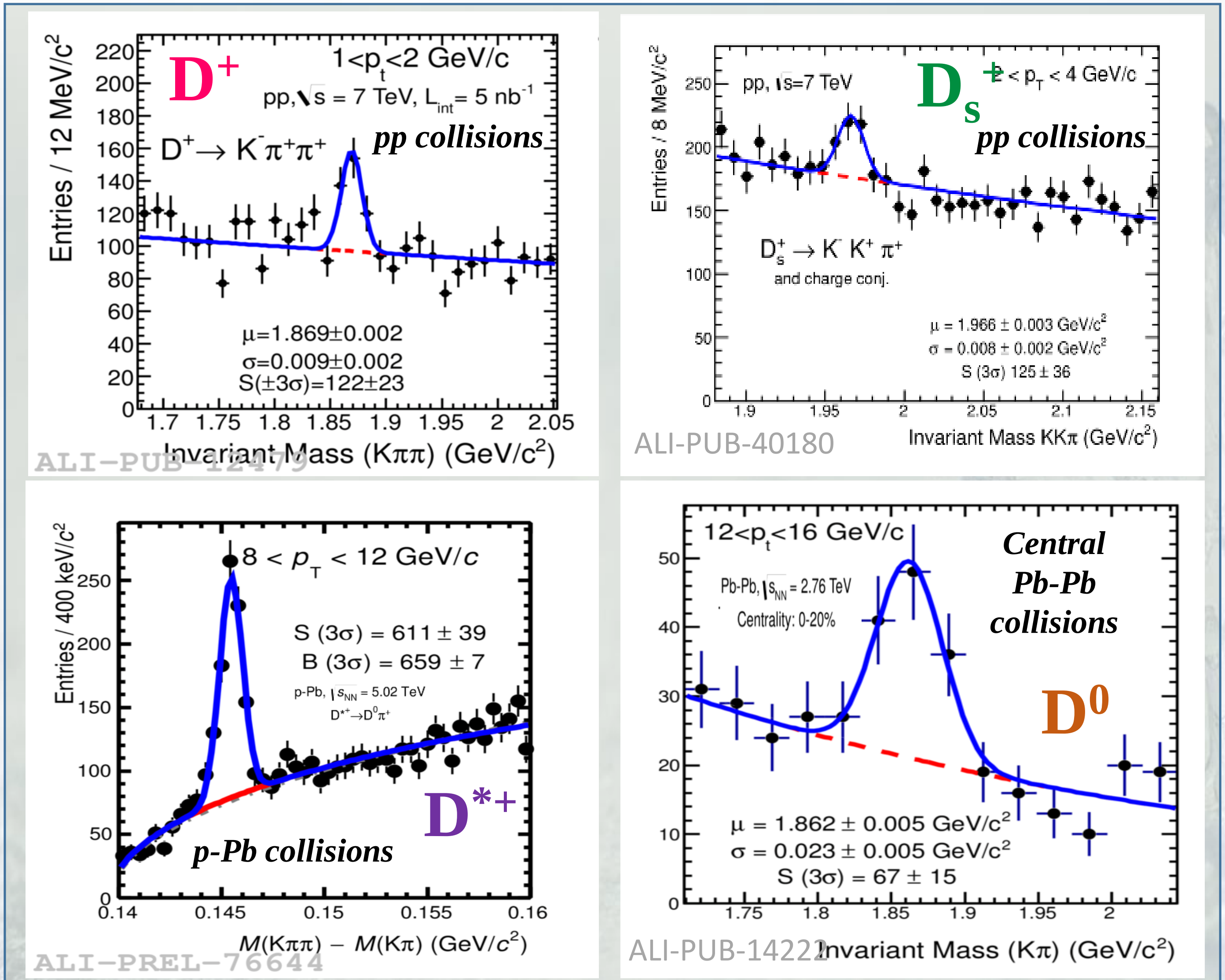


- D-meson candidates selected applying
  - **Kinematical cuts**: p_T, impact parameter of single tracks
  - **Topological selections**: cosine of pointing angle, distance between primary and secondary vertex, …

- **Particle identification** (using TOF and TPC information) in order to identify kaons and reduce the combinatorial background

D-meson reconstruction in ALICE

Raw yields extracted in different p_T intervals via a fit to the invariant mass distributions

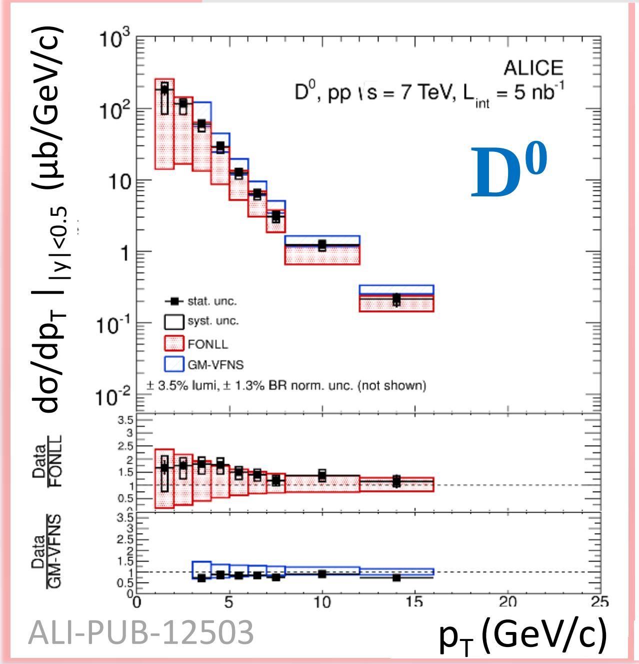


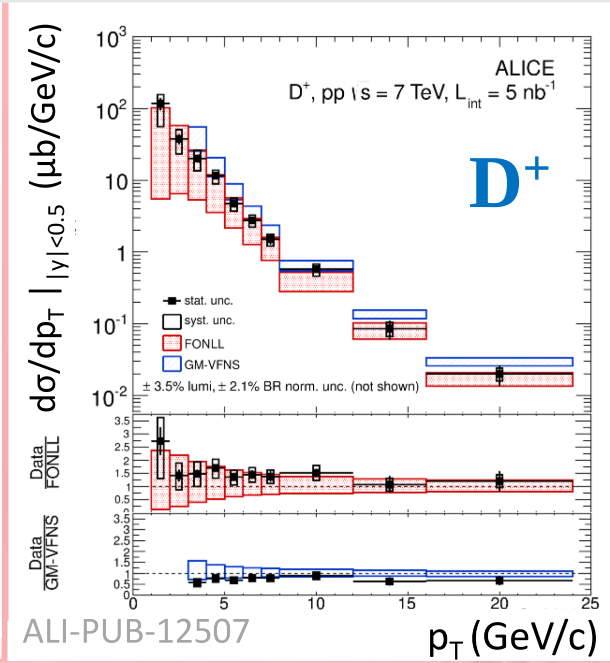
- pp collisions @ 7 TeV
  JHEP 1201 (2012) 128
  JHEP 1207 (2012) 191
  PLB 718 (2012) 279
- p-Pb collisions @ 5.02 TeV
  PRL 113, 232301
- Pb-Pb collisions @ 2.76 TeV
  JHEP 09 (2012) 112

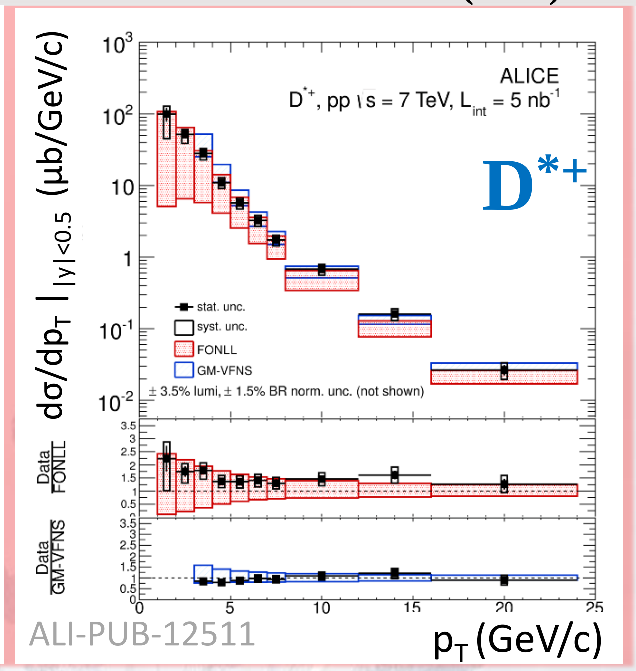

Results in pp collisions
@ 7 TeV

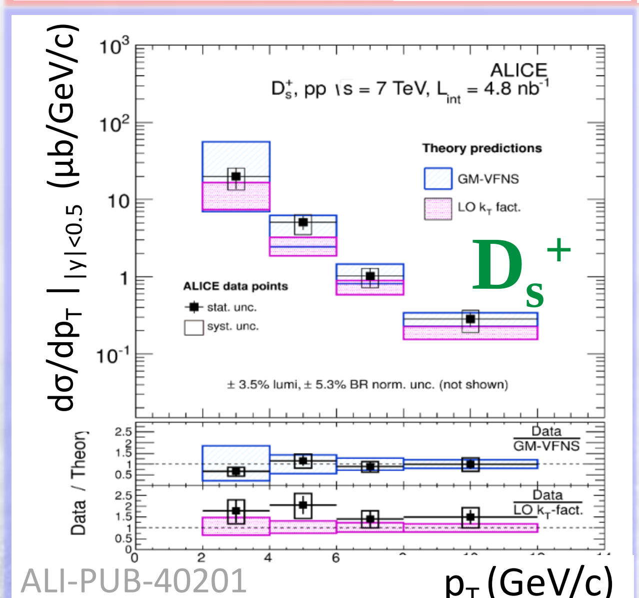
p_T-differential cross sections

JHEP 1201 (2012) 128









- p_T-differential cross section measured for
  - **D^0 in the range $1 < p_T < 16$ GeV/c**
  - **D^+ , D^{*+} in the range $1 < p_T < 24$ Gev/c**

JHEP 1201 (2012) 128

similar trend at $\sqrt{s}$ = 2.76 TeV

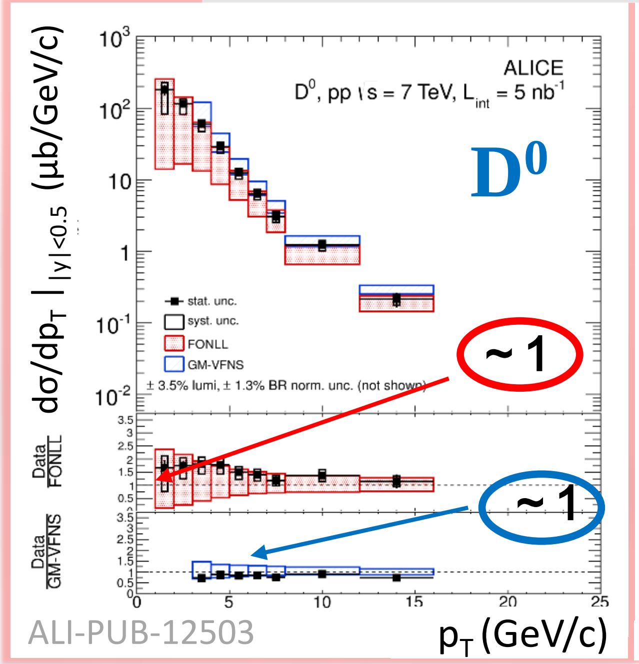
JHEP 1207 (2012) 191

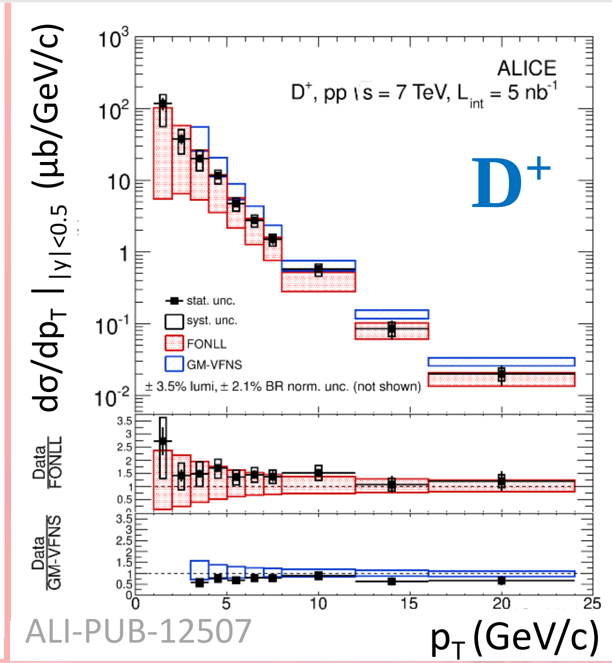
  - **D_s^+ in the range $2 < p_T < 12$ GeV/c**

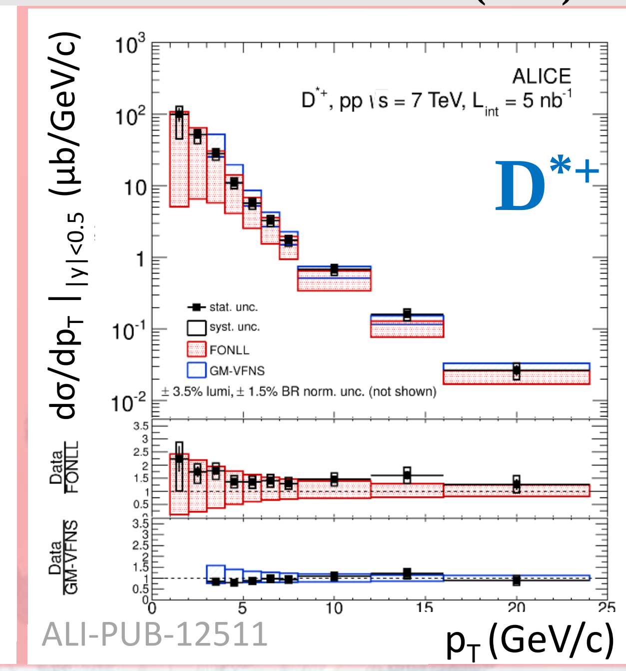
Phys.Lett. B718 (2012) 279-294

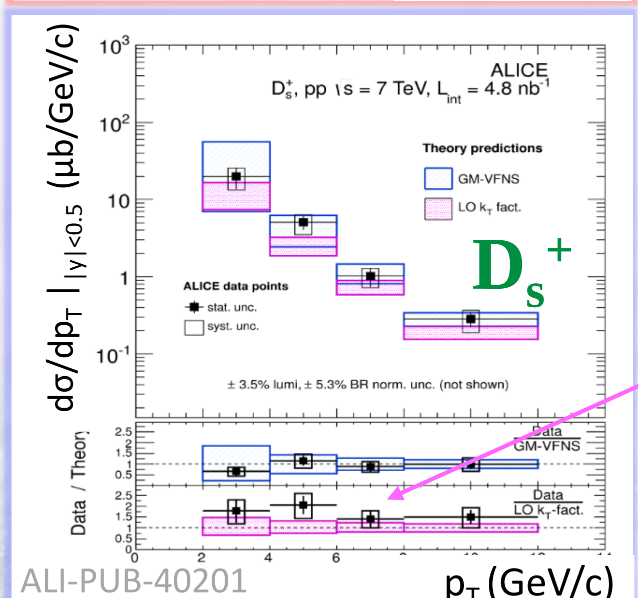
p_T-differential cross sections

JHEP 1201 (2012) 128







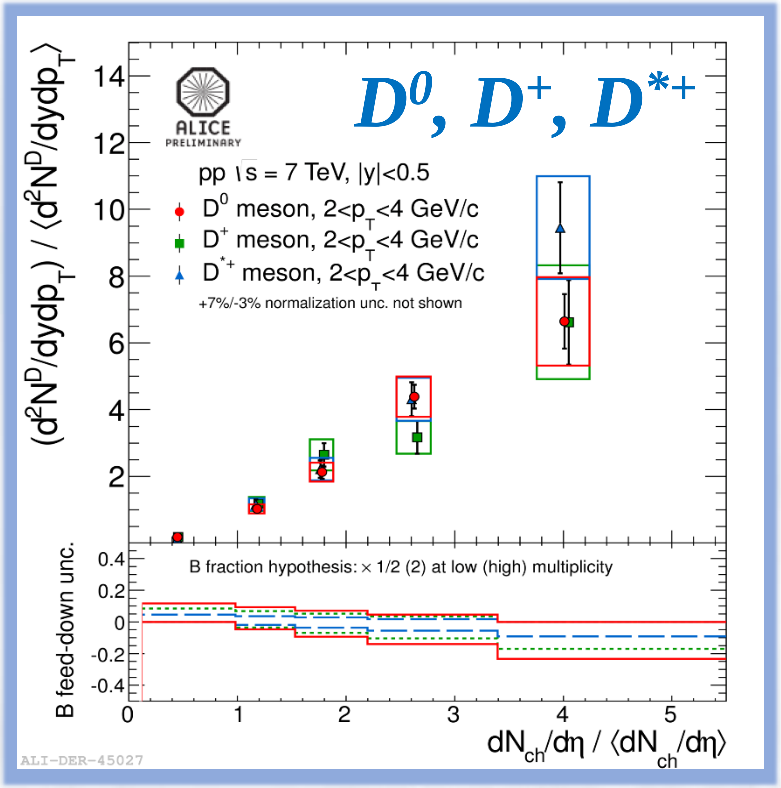


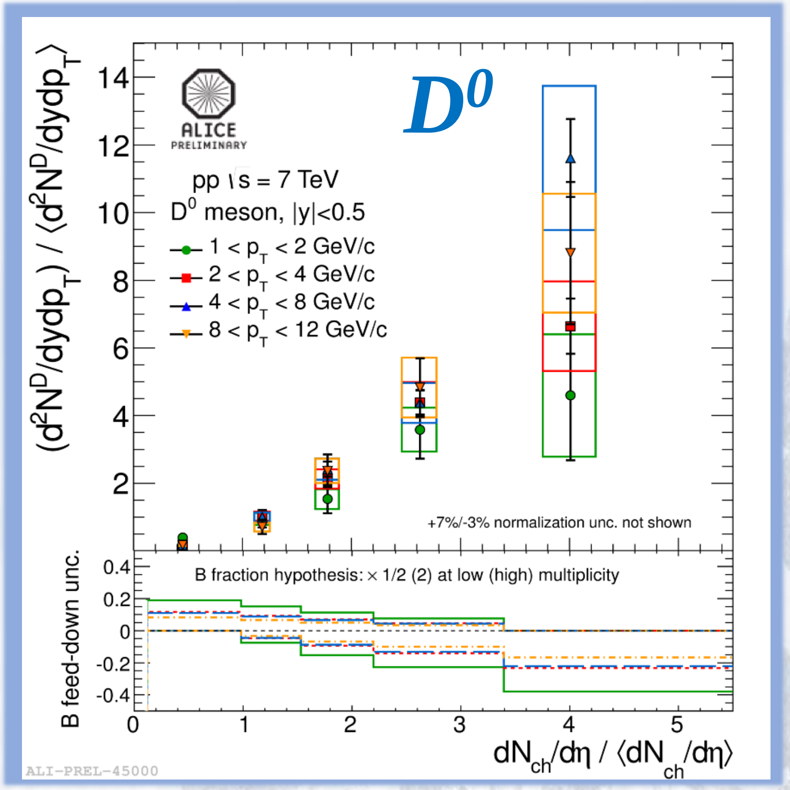
- p_T-differential cross sections reproduced within uncertainties by theoretical predictions based on pQCD:
  - FONLL CERN-PHTH/2011-227
  - GM-VFNS Eur.Phys.JC72(2012)
  - k_T-factorization approach arXiv:1208.6126 [hep-ph]

ALICE

Multiplicity dependence of open charm yields

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





- Results for D^0, D^+, D^{*+} in agreement within uncertainties

- Increasing trend of the D-meson yield as a function of charged-particle multiplicity
- no significant p_T dependence within uncertainties

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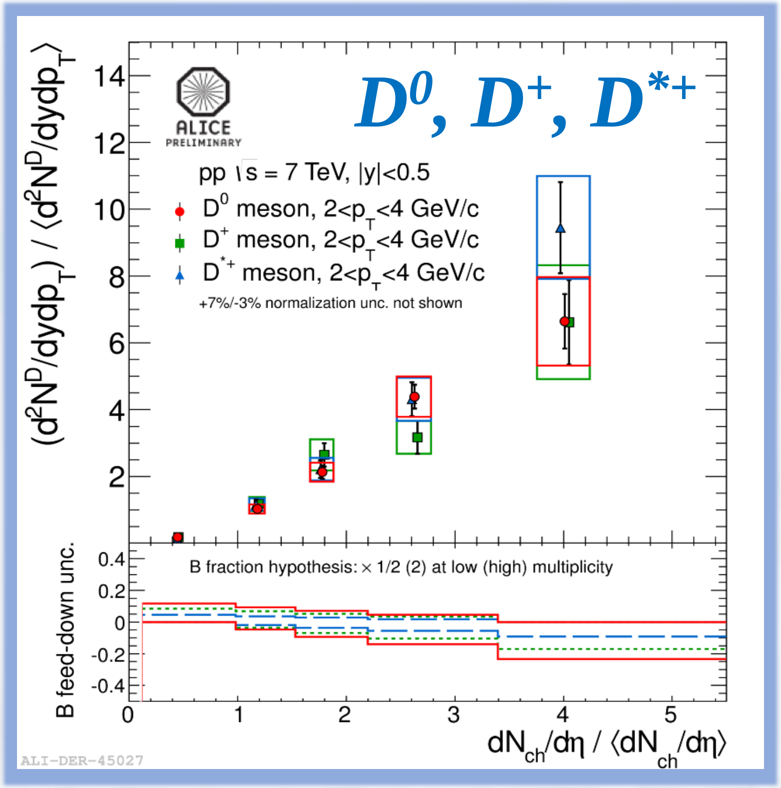

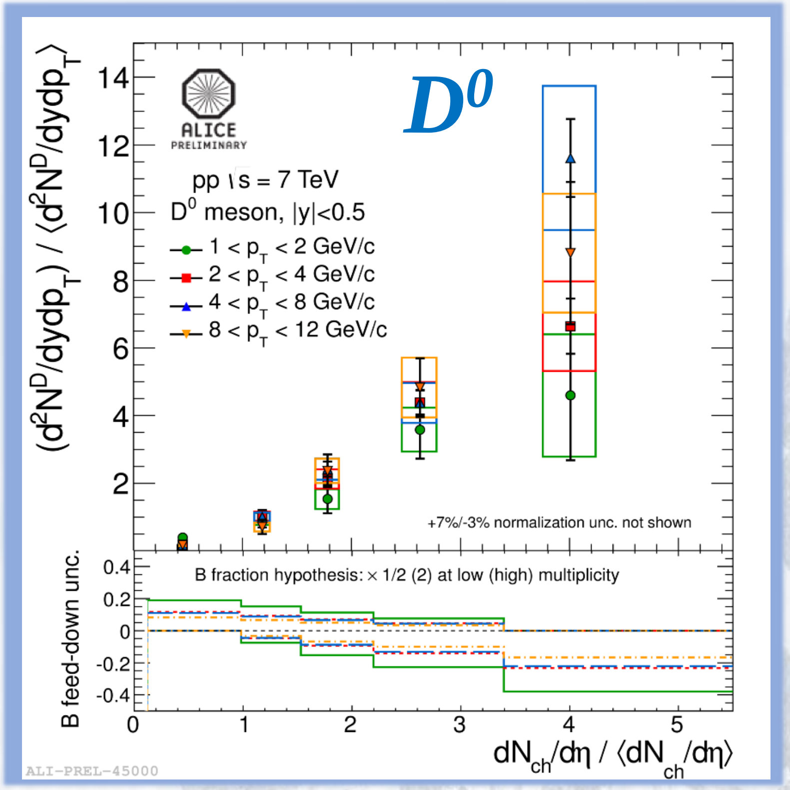

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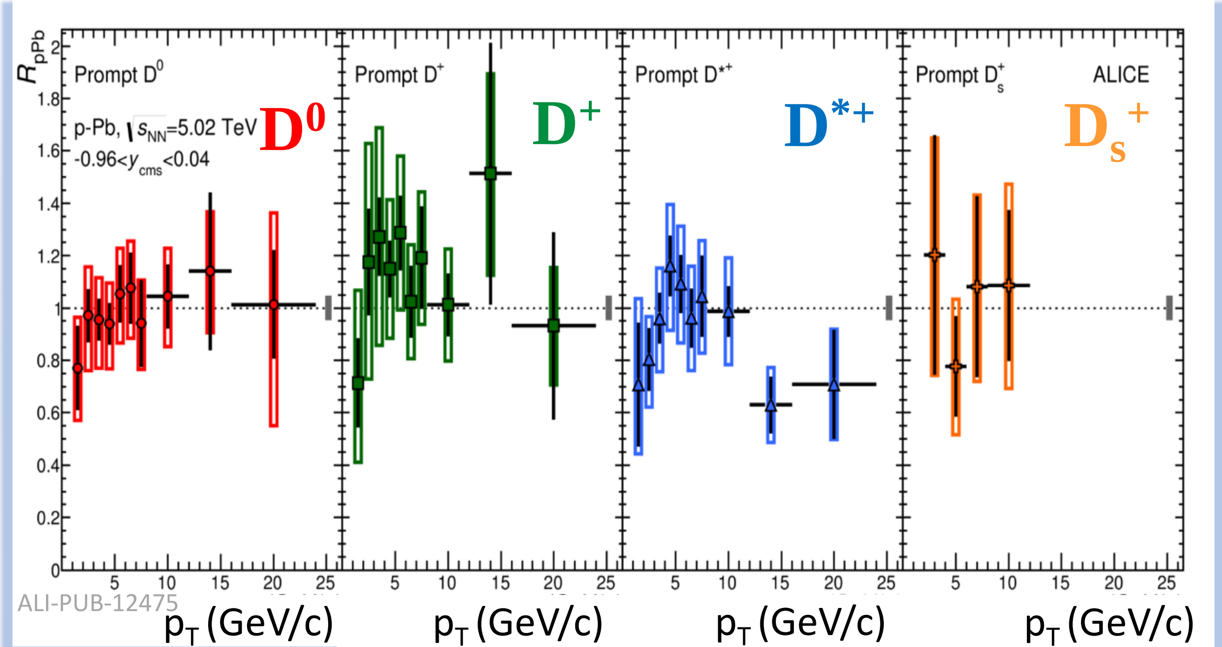
Heavy-flavour production could be affected by Multi Parton Interactions (MPIs)

Results in p-Pb collisions @ 5.02 TeV

Nuclear Modification Factor

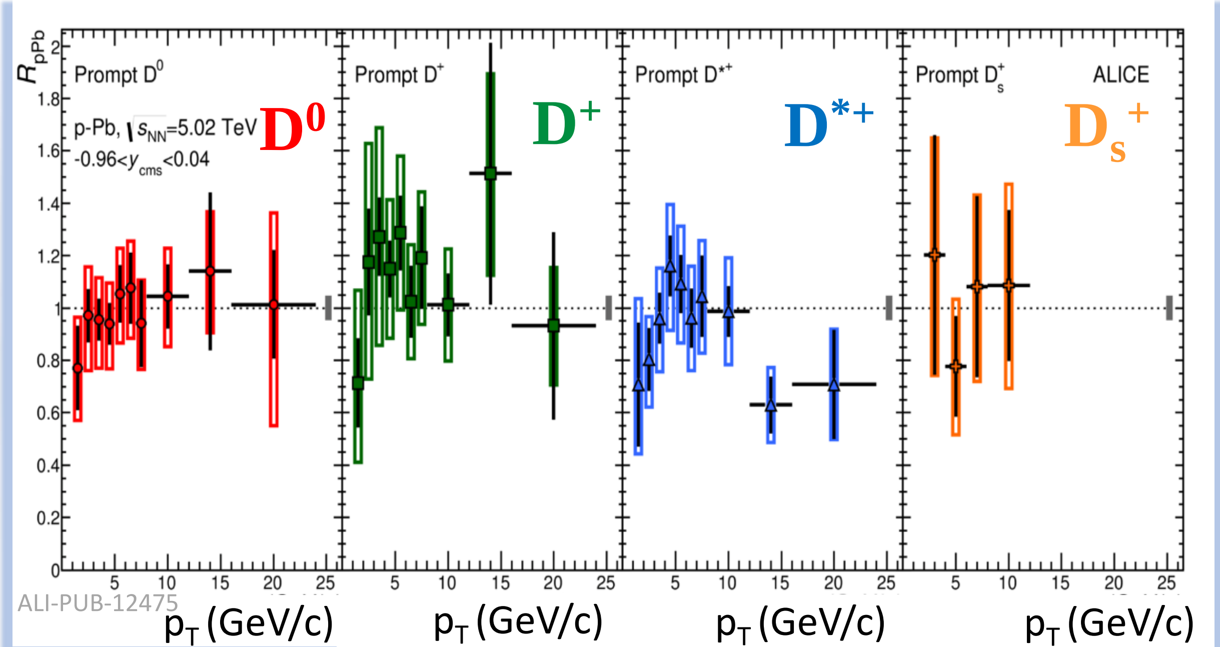


Phys.Rev.Lett. 113 (2014) 23, 232301

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

- No significant difference between the R_{pPb} of the four D-meson species
- R_{pPb} compatible with unity in $1 < p_T < 24$ GeV/c within the uncertainties

Nuclear Modification Factor



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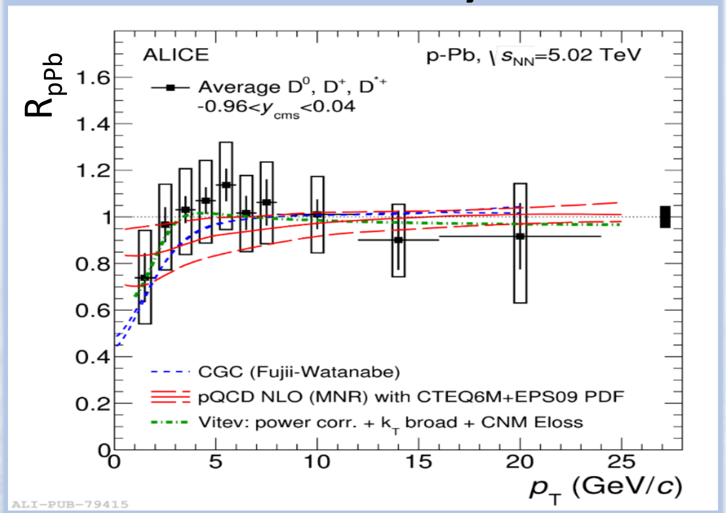
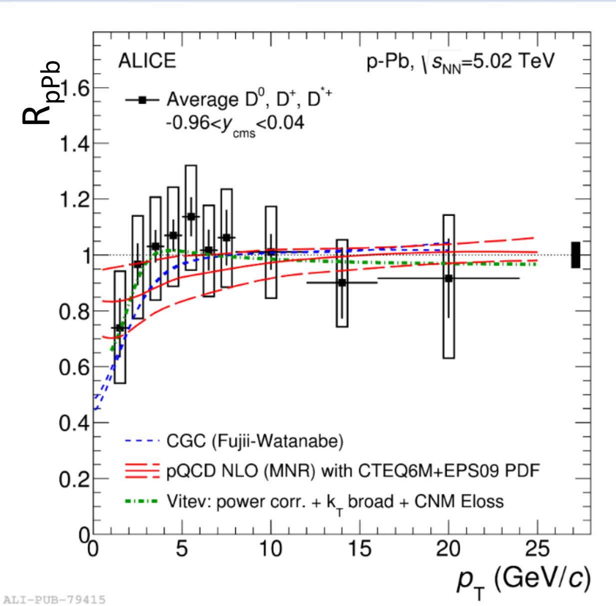


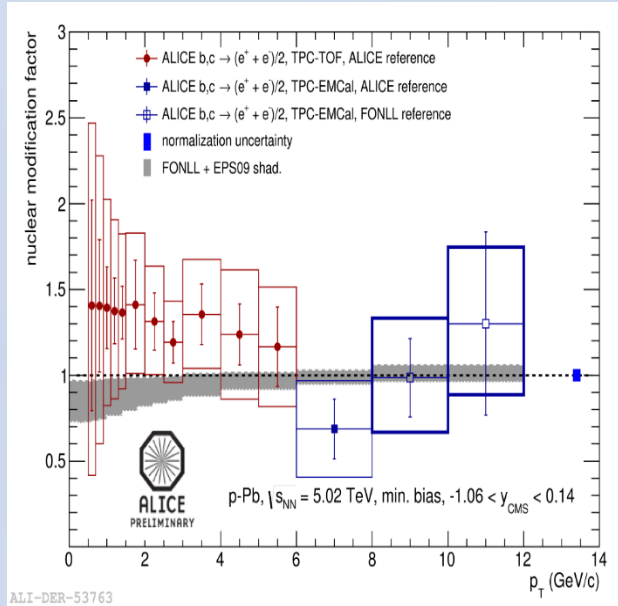
- Results described within uncertainties by theoretical calculations that include **initial-state effects:**
  - NLO pQCD with EPS09 Nucl. Phys. B 373 (1992) 295
  - Color Glass Condensate arXiv:1308.1258
  - Energy loss, nPDFs, k_T-broadening JHEP 09 (2012) 112 Phys. Rev. C 80 (2009) 054902

Nuclear Modification Factor

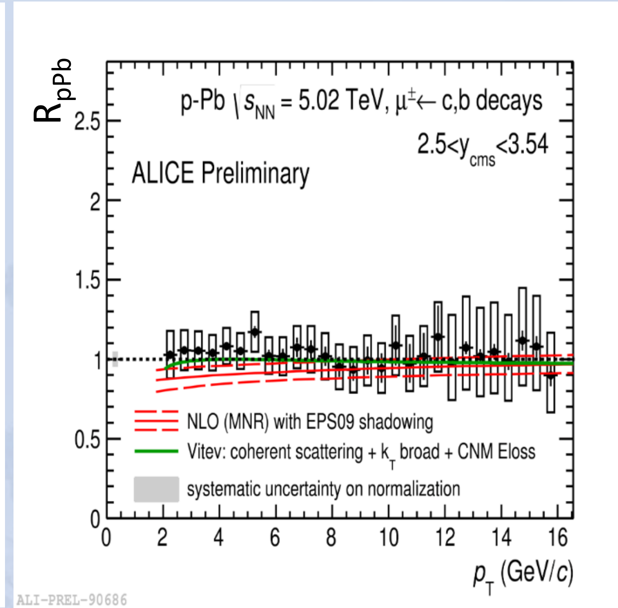
D meson



HF decay e



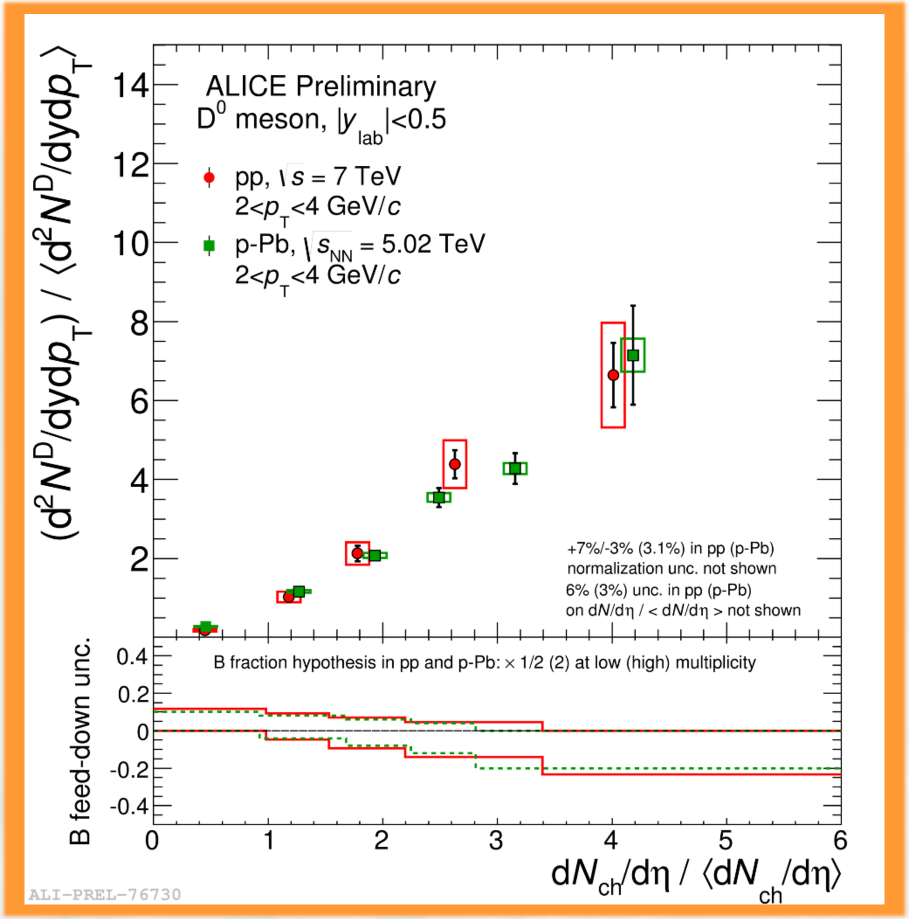
HF decay μ



Phys.Rev.Lett. 113 (2014) 23, 232301

- Similar trend for D mesons, electrons and muons from heavy-flavour decays
- Good agreement with theoretical calculations that include **initial-state effects**

Multiplicity dependence of open charm yields



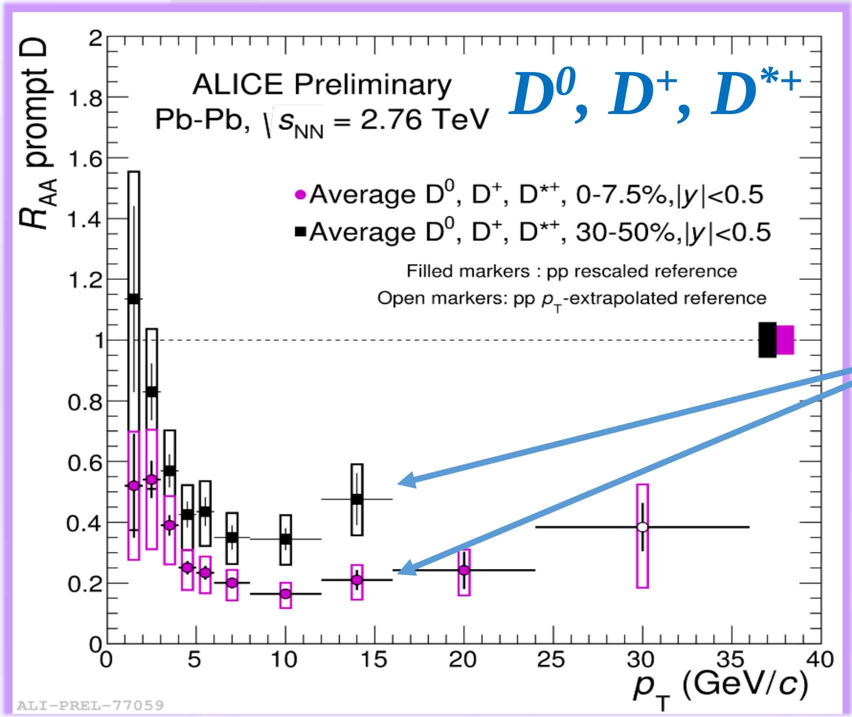
$$\frac{d^2N/dydp_T}{< d^2N/dydp_T >} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

- D-meson self-normalized yields increase with charged-particle multiplicity
- no significant p_T dependence within uncertainties
- Similar trend observed in pp and p-Pb collisions

➢ **MPIs contribute to high-multiplicity events in pp collisions**
➢ **The larger number of binary nucleon-nucleon collisions is expected to also contribute to high-multiplicity events in p-Pb collisions**

Results in Pb-Pb collisions @ 2.76 TeV

Nuclear Modification Factor

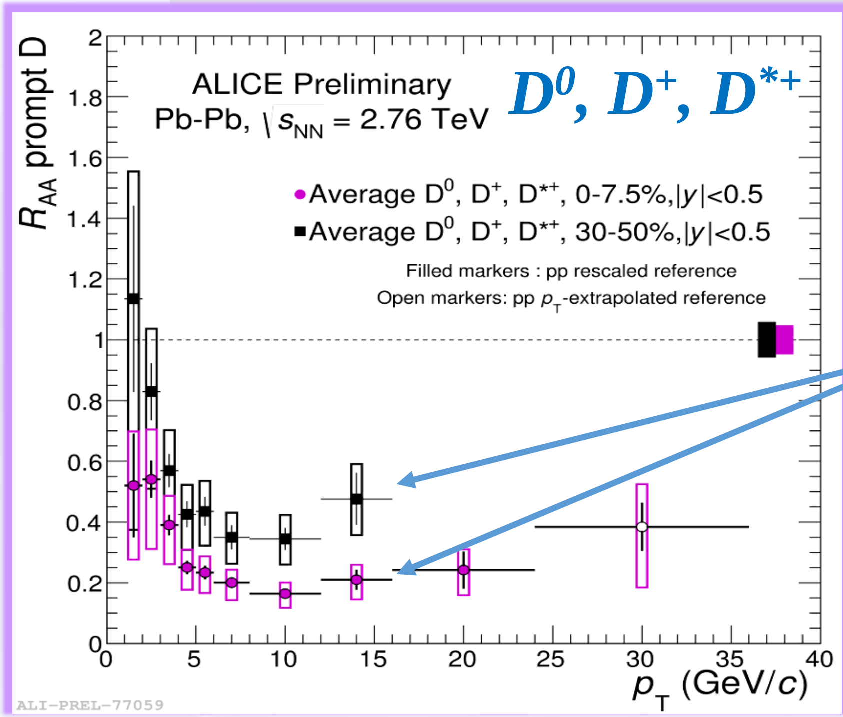


$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

at high p_T

- suppression in most central collisions
- less suppression in peripheral collisions!

Nuclear Modification Factor



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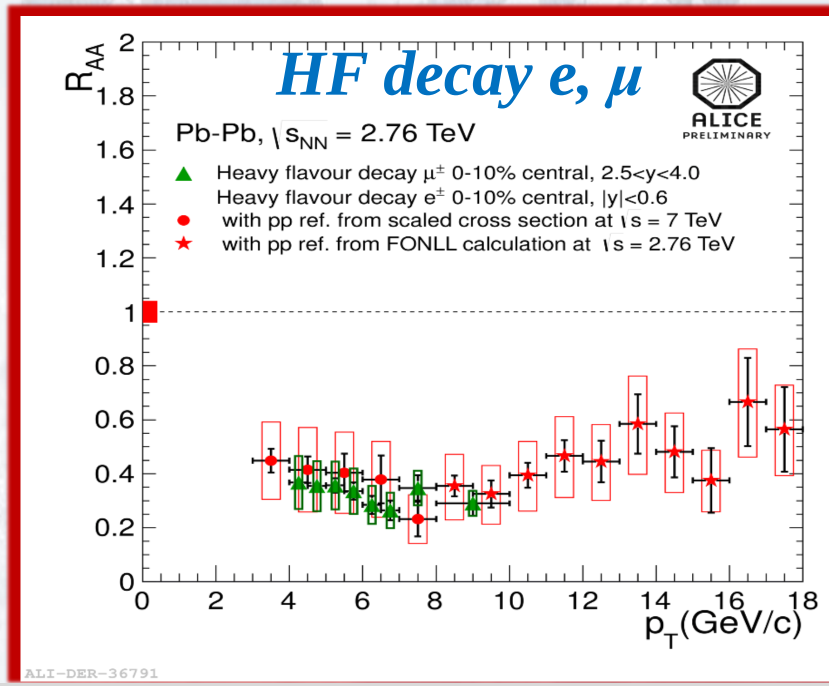
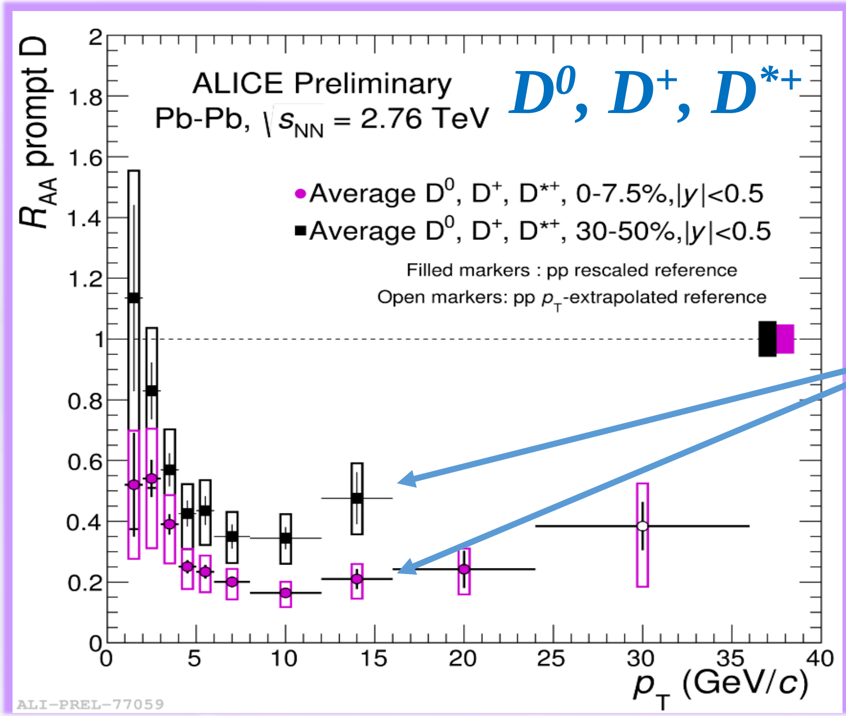


- Trend similar to that observed for
  - HF decay electrons (|y|<0.6)
  - HF decay muons (2.5<y<4.0)

Nuclear Modification Factor



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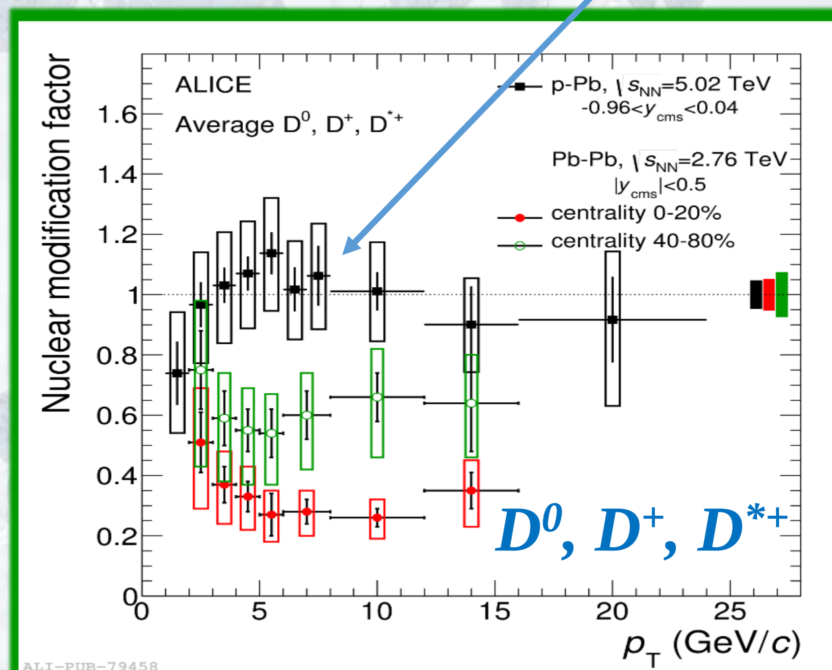
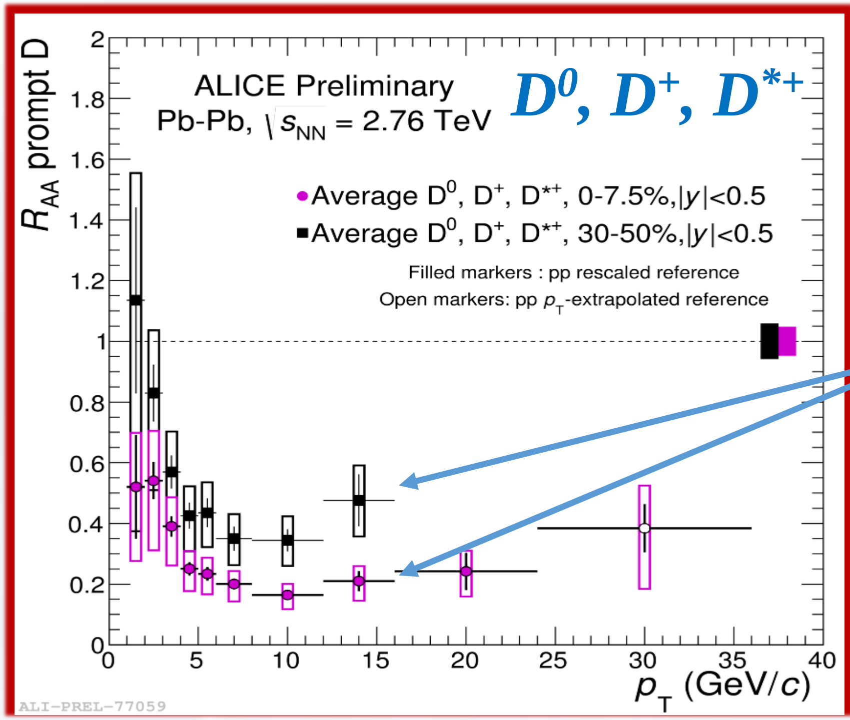
R_{pPb} ~ 1



- No indication for cold nuclear matter effects within uncertainties for $p_T \geq 2$ GeV/c

Nuclear Modification Factor



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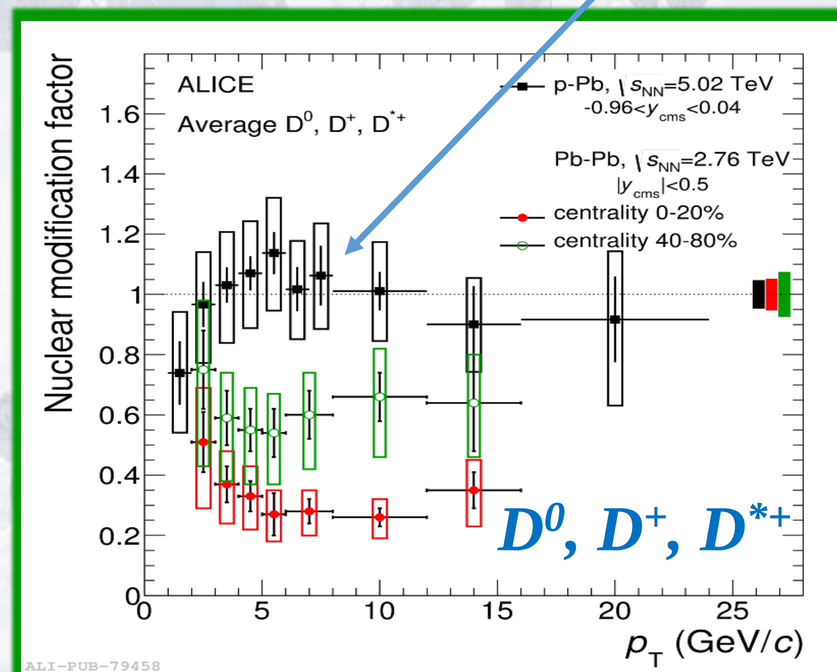

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JHEP 09 (2012) 112

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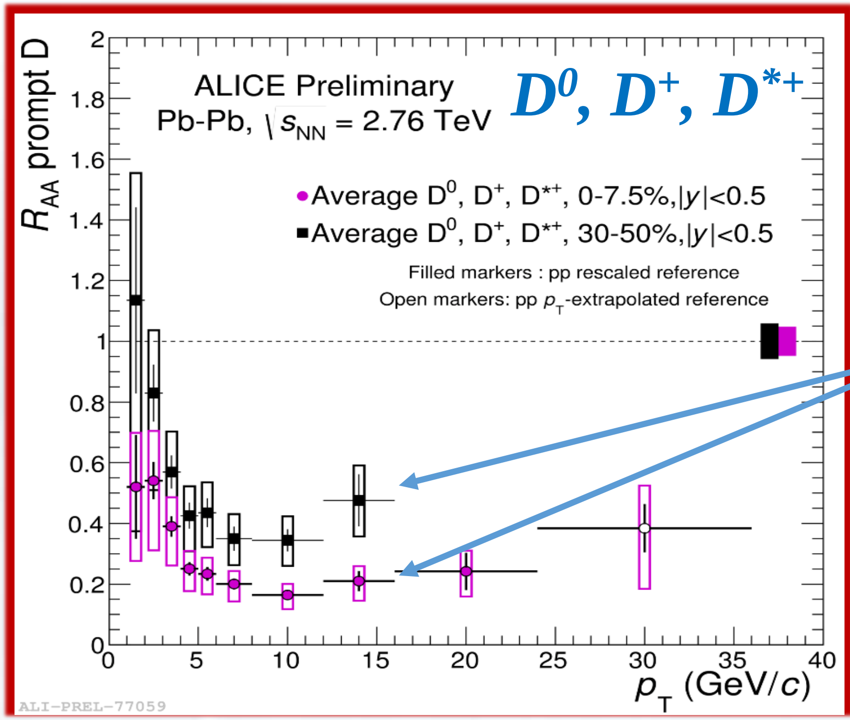

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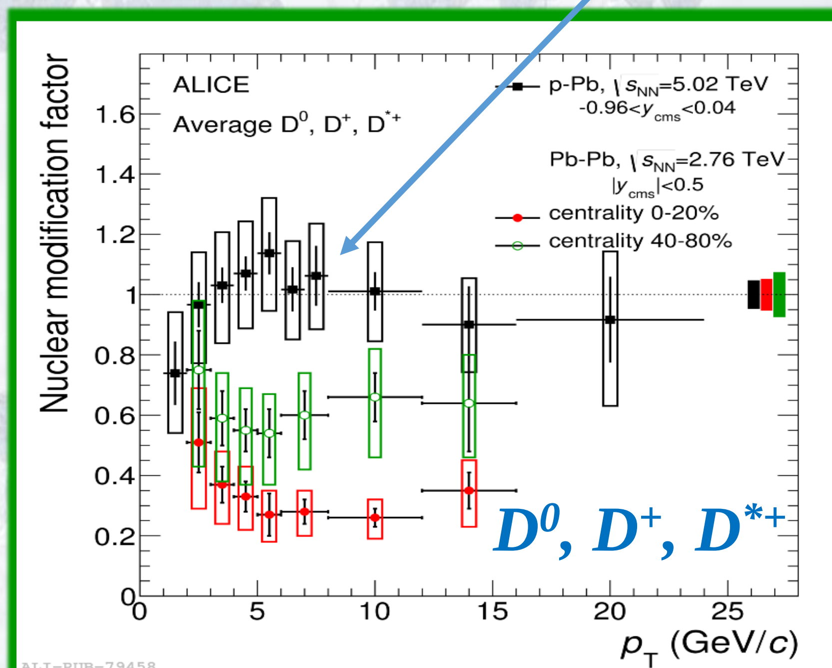
$R_{pPb} \sim 1$



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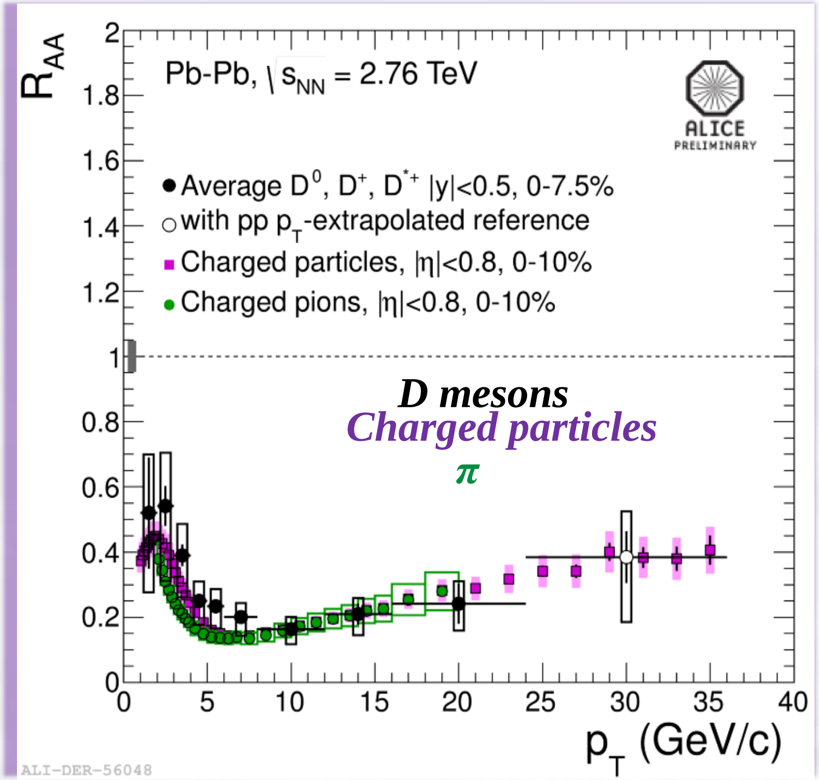
JHEP 09 (2012) 112

Suppression observed in Pb–Pb collisions due to strong final-state effects

Mass hierarchy: $R_{AA}(p_T)$ D vs π

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_{charm} > \Delta E_{beauty}$ → $R^{\pi}_{AA}(p_T) < R^{D}_{AA}(p_T)$?



- Average D-meson and π R_{AA} close to each other within uncertainties

Caveats:

- Different shape of parton momentum spectra
- Different fragmentation functions

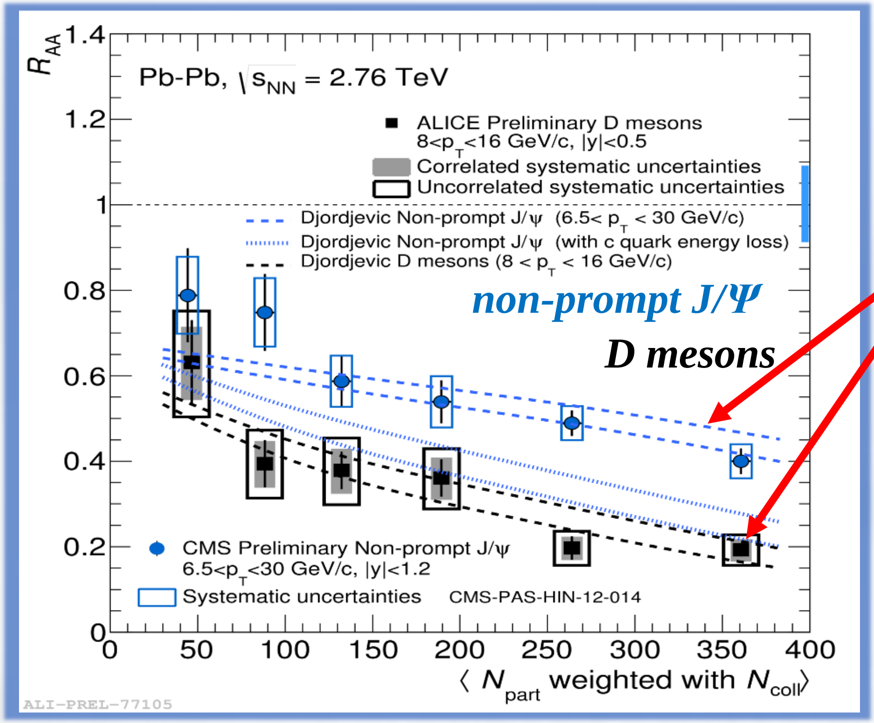
Djordjevic, PL B734(2014)286; Wicks et al., NP A872(2011)265

- Contribution of soft processes at low p_T

➢ Comparison not conclusive, more precise measurements of the transverse momentum dependence are required

Mass hierarchy: $R_{AA}(p_T)$ D vs B

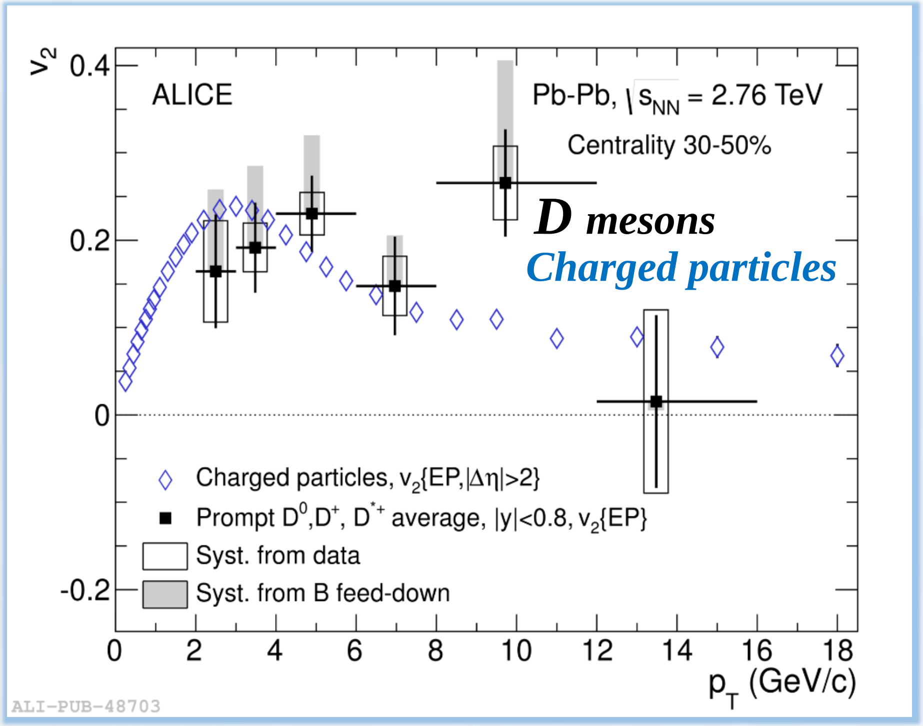
$\Delta E_g > \Delta E_{u,d,s} > \Delta E_{charm} > \Delta E_{beauty}$ → $R^{D}_{AA}(p_T) < R^{B}_{AA}(p_T)$?



- D-meson R_{AA} is lower than R_{AA} of J/ψ from B decays measured by CMS (similar p_T range but $|y|_{J/\psi} < 1.2$ $|y|_D < 0.5$)
  CMS-PAS-HIIN-12-014
  - ➢ consistent with the expectation from the predicted energy loss hierarchy

- Difference between D mesons and non-prompt J/Ψ due to the mass-dependent radiative and collisional energy loss, according to pQCD based model calculations **Djordjevic, PL B734 (2014) 286-289**
  - ➢ Good agreement between model predictions and experimental data

Elliptic flow v_2



PRL 111, 102301 (2013)

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

- Average v_2 of the three mesons larger than zero in $2 < p_T < 6$ GeV/c with a significance of 5.7 σ
- v_2 comparable in magnitude to that of inclusive charged particles (dominated by light flavour hadrons) in $2 < p_T < 6$ GeV/c

arXiv:1205.5761

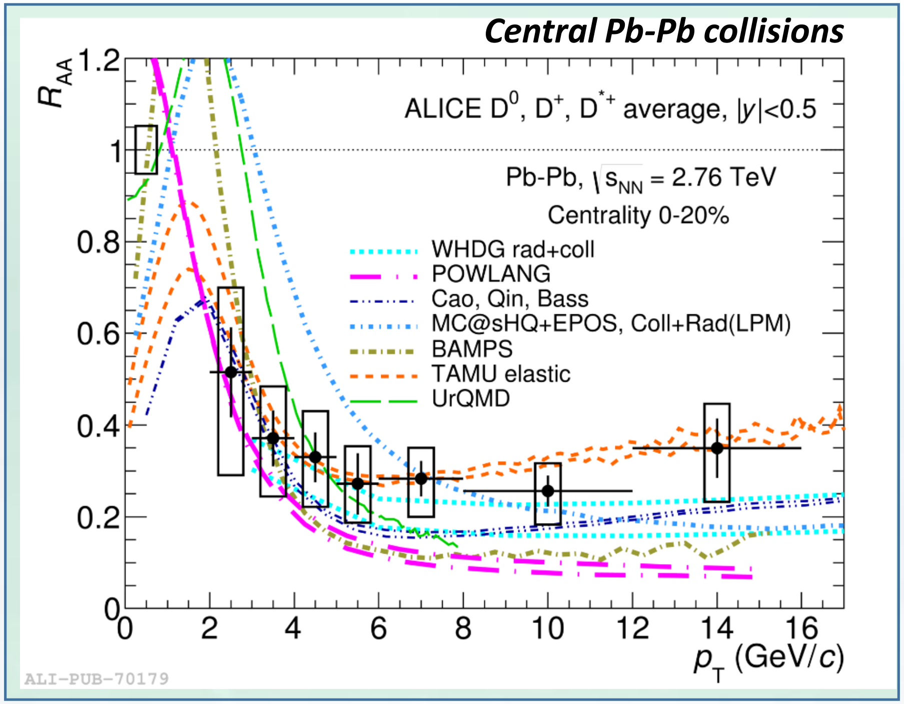
Low p_T charm quarks participate in the collective motion of the system

- A positive v_2 is also observed for $p_T > 6$ GeV/c

but a proper study of the path-length dependence of partonic energy loss via v_2 measurements needs more statistics

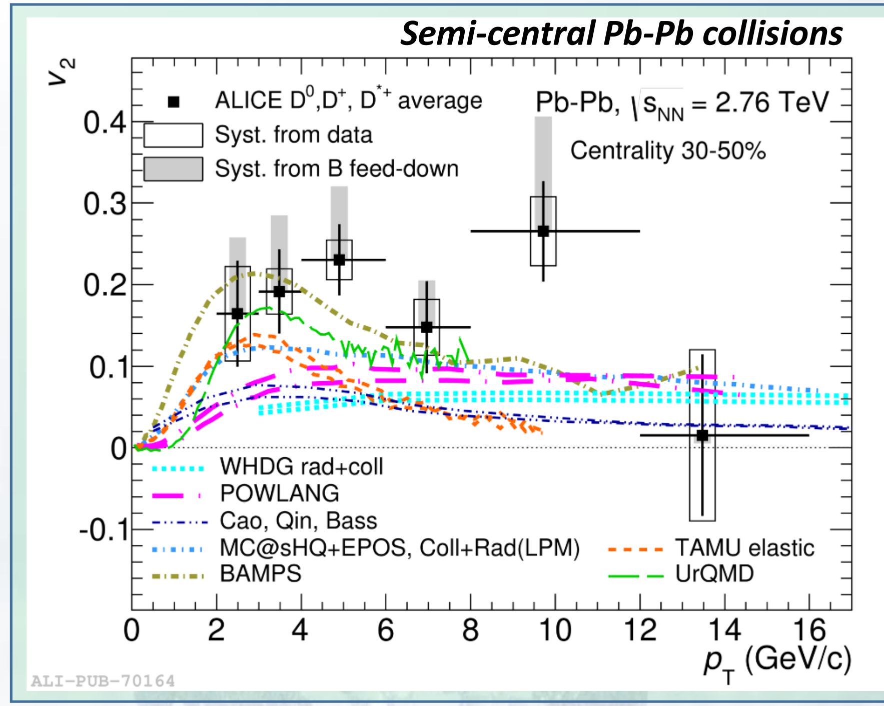
Comparison with models

D mesons



D mesons

PR C90(2014)034904



TAMU elastic: PL B735(2014)445; Cao, Qin, Bass: PR C88(2013)044907; WHDG rad+coll: NP A872(2011)265; MC@sHQ+EPOS: PR C89(2014)014905; Vitev, rad+dissoc: PR C80(2009)054902; POWLANG: JP G38(2011)124144; BAMPS: PL B717(2012)430

- Models that are best in describing R_{AA} tend to underestimate v_2 and the models that describe v_2 tend to overestimate the measured R_{AA} at high p_T

Simultaneous description of the large suppression of D mesons in central collisions and their anisotropy in non-central collisions is challenging

Conclusions

- Excellent performance of ALICE for heavy-flavour measurements

- D-meson production in pp collisions:
  - well described by pQCD calculations within uncertainties
  - multiplicity trend of p_T-differential yields can be interpreted in terms of MPIs

- D-meson production in p-Pb collisions:
  - Small modification with respect to pp collisions, well described by models including cold nuclear matter effects

- D-meson production in Pb-Pb collisions:
  - Strong suppression at high p_T in the most central collisions, due to the parton energy loss in the medium
  - v_2 in $2 \leq p_T \leq 6$ GeV suggests that low p_T charm quarks participate in collective motion of the system

Perspectives

More data are required to sharpen conclusions and provide new results

- With RUN II (More statistics available and increased beam energy)
  - Improve D^0, D^+, D^{*+} measurements precision, going to lower and higher p_T
  - Perform measurements for rare charmed hadrons D_s^+, Λ_c^+

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- With ALICE Experiment Upgrade (2018)
  - Unique HF measurements will be available

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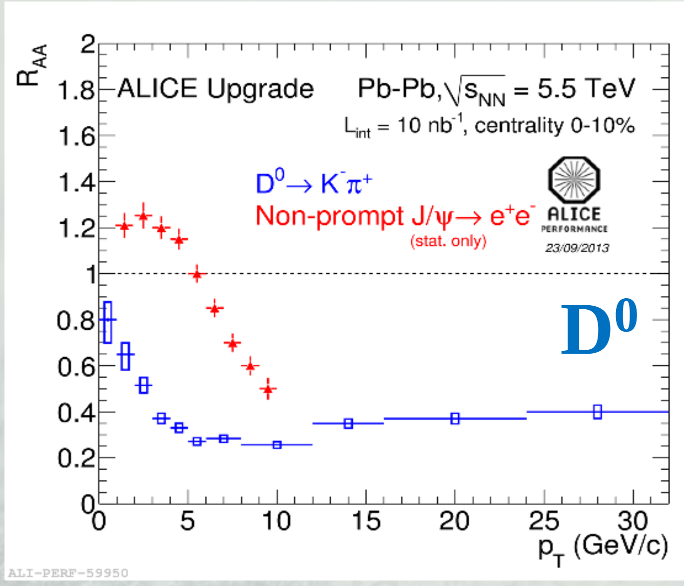
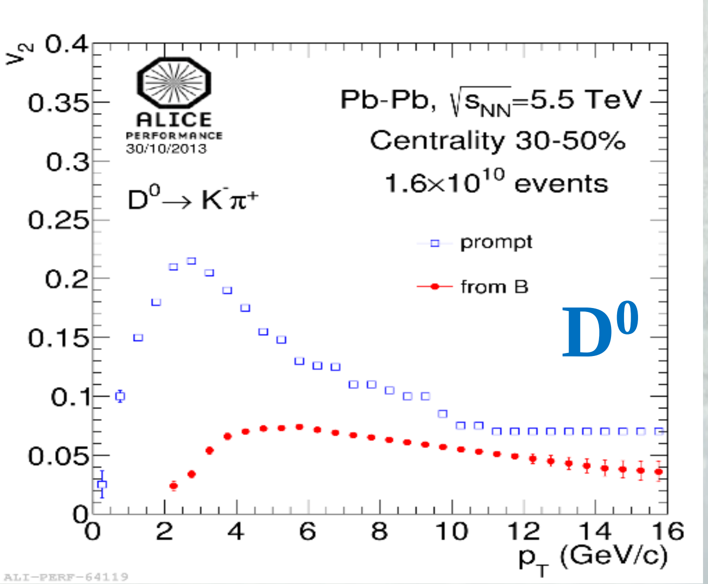
ALICE, CERN-LHCC-2013-024



ALICE, CERN-LHCC-2013-024



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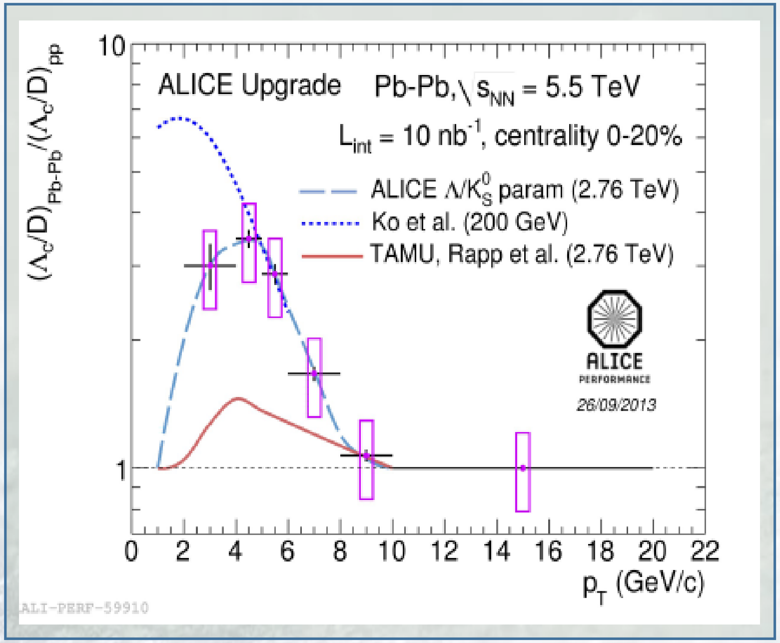


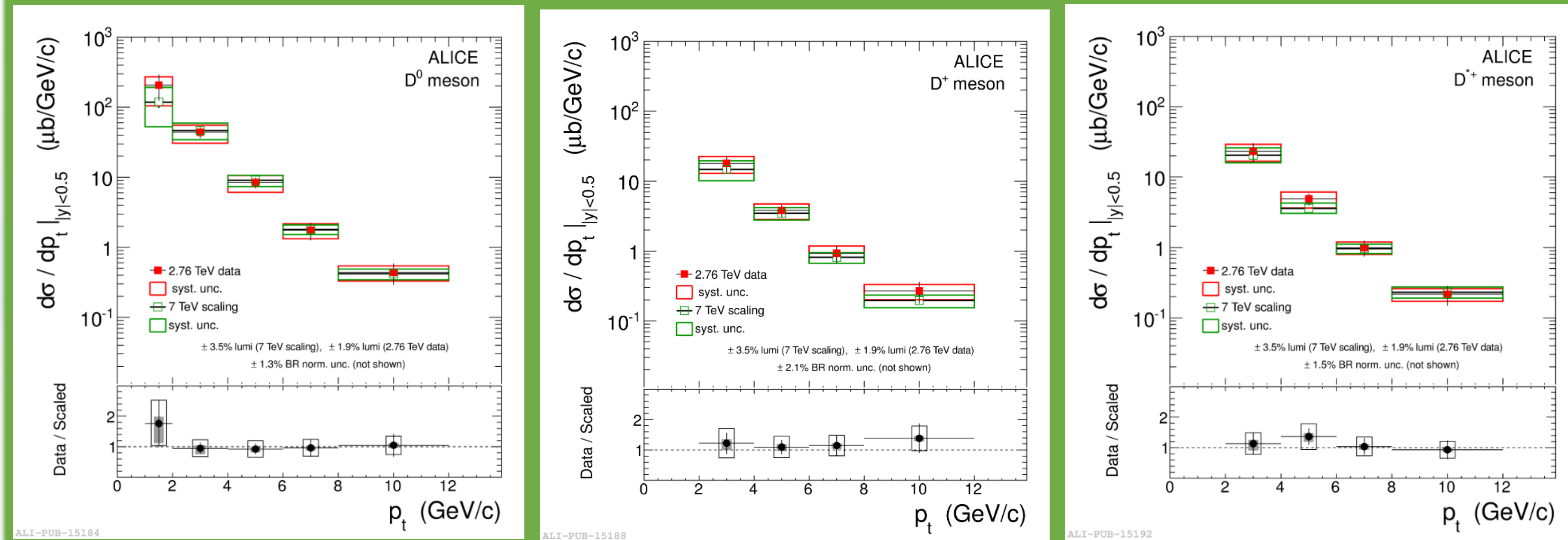
Λ_c measurements for the first time in Pb-Pb collisions at the LHC

M. He et al., arXiv:1204.4442[nucl-th] Y.Oh et al. Phys. Rev. C79, 044905(2009)

Thanks for your attention

Back up

Cross section in pp collisions @ 2.76 TeV



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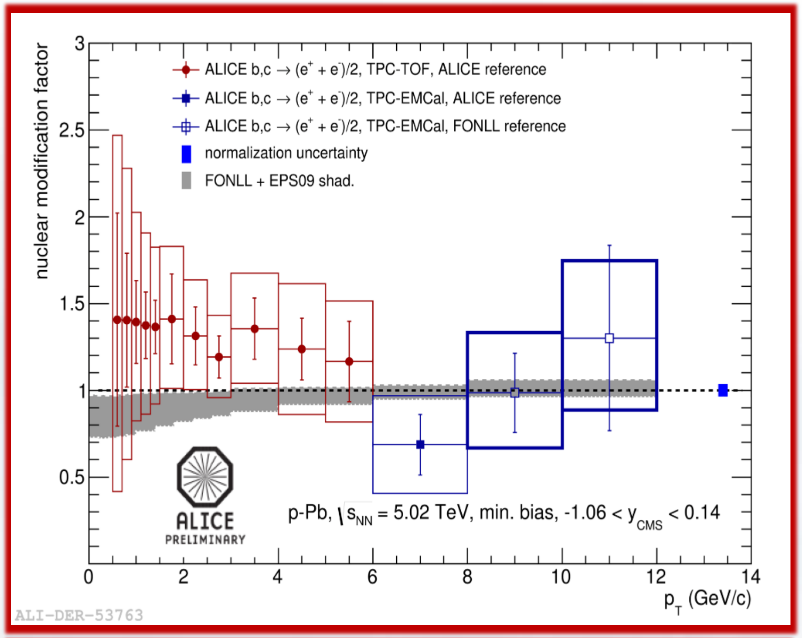
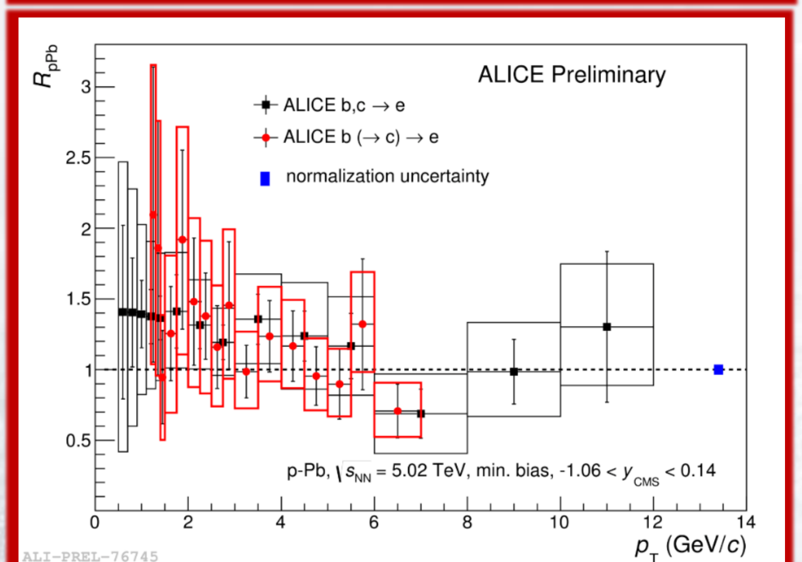
- p_T differential cross section measured for
  - D^0 in the range $1 < p_T < 12$ GeV/c
  - D^+ , D^{*+} in the range $2 < p_T < 12$ Gev/c

Heavy flavour decay electron R_{pPb}





HF decay e

$$R_{pA} = \frac{d\sigma_{pA}/dp_{\mathrm{T}}}{A \times d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

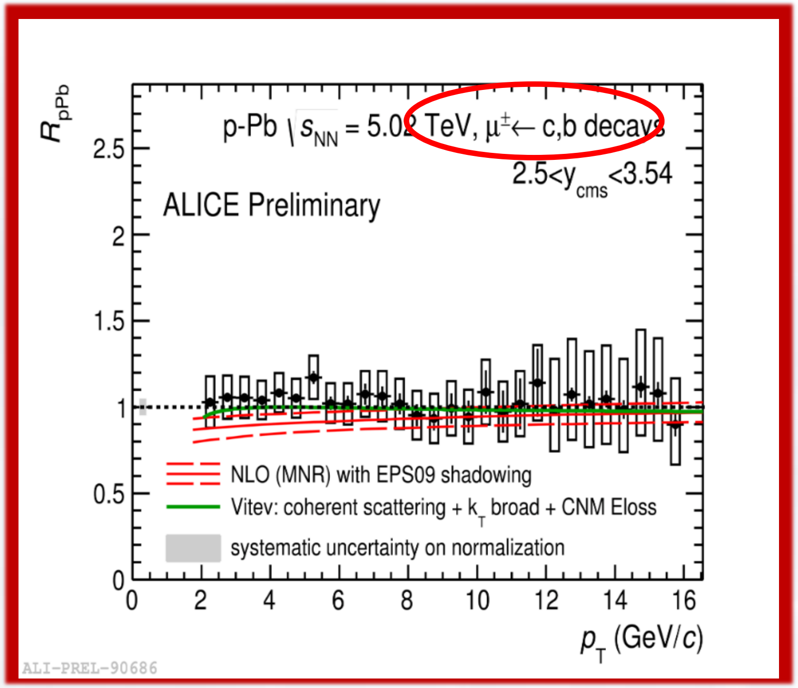
- HF decay e^+/e^- R_{pPb} consistent with unity within uncertainties
- Good agreement with theoretical FONLL pQCD calculations with EPS09 PDF parameterizations of shadowing

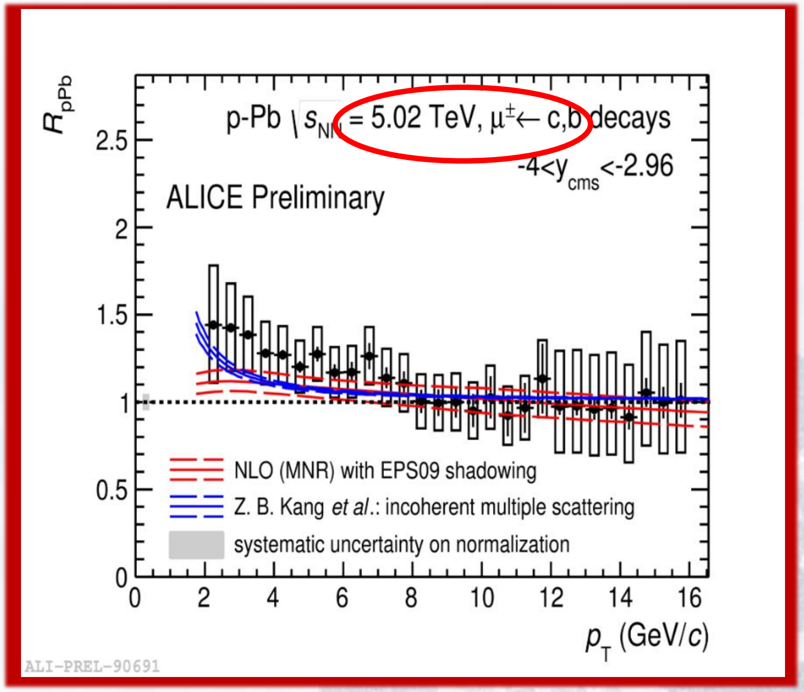
Beauty-hadron decay e

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

Heavy flavour decay muon R_{pPb}

FORWARD rapidity ***HF decay μ*** **BACKWARD rapidity** $R_{pA} = \frac{d\sigma_{pA}/dp_T}{A \times d\sigma_{pp}/dp_T}$

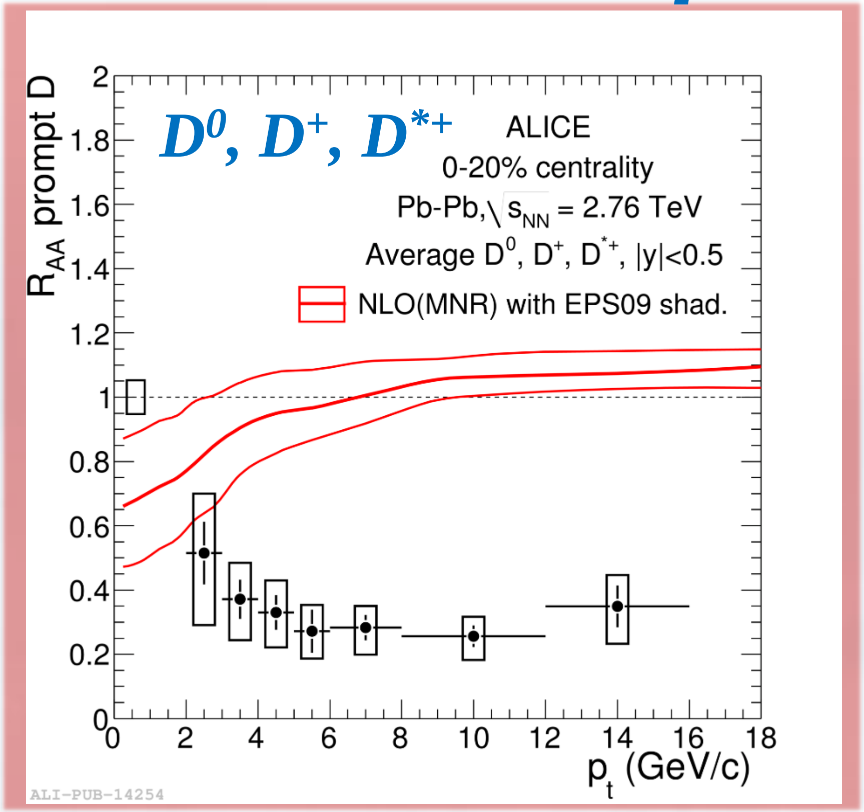




- R_{pPb} of HF decay μ consistent with unity at forward rapidity (p-going direction)
- R_{pPb} slightly larger than unity in the range $2 < p < 4$ GeV/c at backward rapidity (Pb-going direction)

described by MNR pQCD calculations with EPS09 PDF parameterizations of shadowing

Nuclear Modification Factor $R_{AA}(p_T)$



Average R_{AA} of D mesons in the 0–20% centrality class compared to the expectation from NLO pQCD with nuclear shadowing

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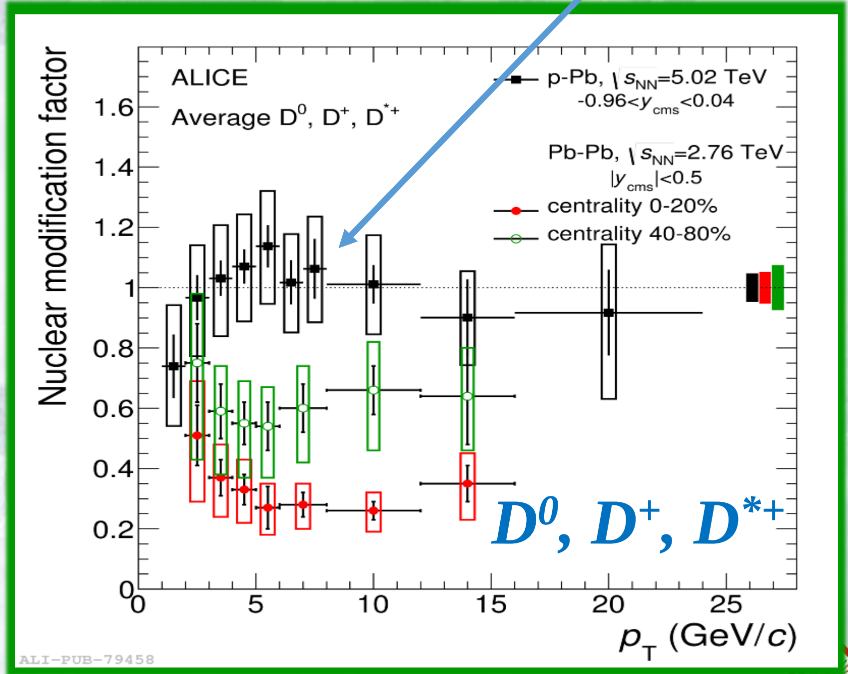
- EPS09 nuclear PDF parametrization predicts small initial state effects for Pb–Pb collisions

R_{pPb} ~ 1



- Cold nuclear matter effects smaller than uncertainties for $p_T \geq 3$ GeV/c

Suppression observed in Pb–Pb collisions due to strong final-state effects

ALICE Experiment Upgrade

- New Silicon Trackers
  - new beam pipe with smaller diameter
  - new, high-resolution, low material Inner Tracking System (ITS)

Improve impact parameter resolution
Improve tracking efficiency and p_T resolution at low p_T

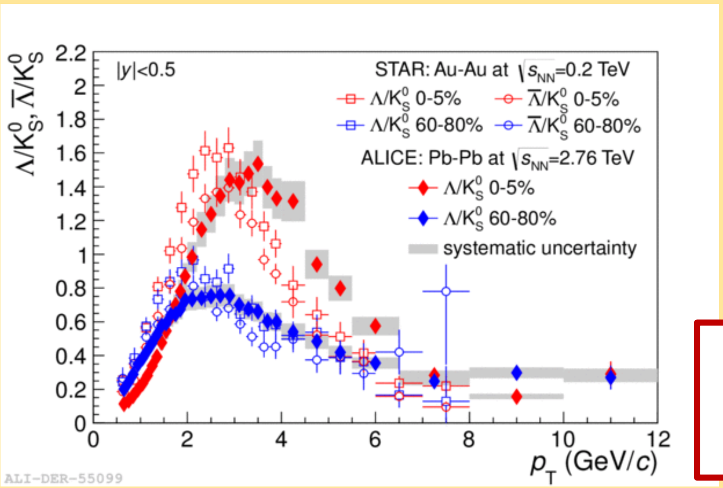
  - new Muon Forward Tracker (MFT) to add vertexing capabilities to the current Muon Spectrometer

- Detector readout and online systems upgrade
  - MWPCs with micropattern gaseous detectors, new read-out electronic
  - Transition Radiation Detector (TRD), Time Of Flight detector (TOF), and Muon Spectrometer - upgrade of the read-out electronics
  - Forward trigger detectors upgrade
  - Online systems and offline reconstruction and analysis framework upgrade (O2)

Physics motivations: Λ_c in Pb-Pb collisions

- Charm is a very sensitive probe of the high-density color deconfined state, the Quark Gluon Plasma (QGP).
- The measurement of Λ_c^+ could give an insight into the hadronization mechanisms:

Excess of baryons with respect to mesons, measured with STAR at RHIC and ALICE at the LHC in the **light** sector, suggests **hadronization** via coalescence of constituent quarks

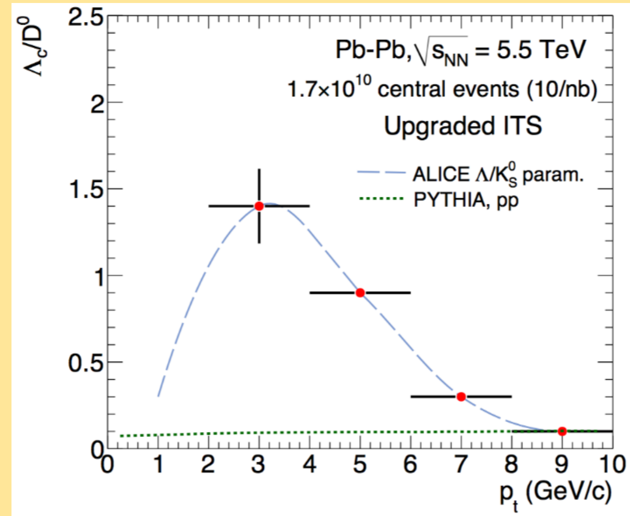


Phys. Rev. Lett. 111, 222301 (2013)

What about charm sector?

Caveat: role of **radial flow**

Expected performance with ITS upgrade (Monte Carlo studies)

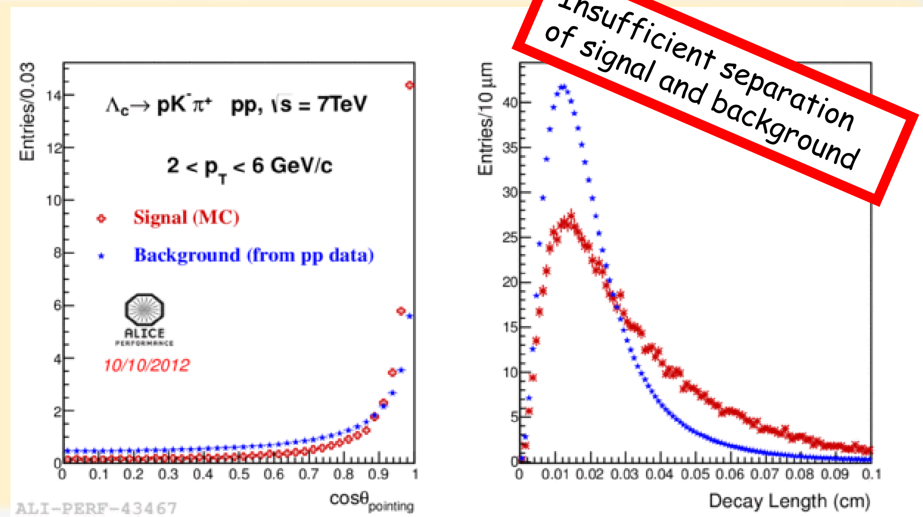


ALICE,CERN-LHCC-2013-024

The measurement of the Λ_c yield relative to D mesons in Pb-Pb collisions would address the baryon over meson ratio in the heavy-quark sector

$\Lambda_c^+ \rightarrow pK^-\pi^+$ in pp and p-Pb collisions

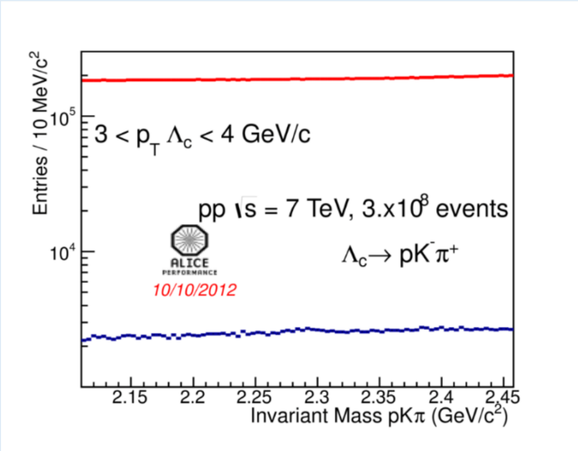
❖ **Analysis based on the reconstruction of displaced decay vertices**
- Reduce the combinatorial background via topological selection and identification of the decay particles



Insufficient separation of signal and background

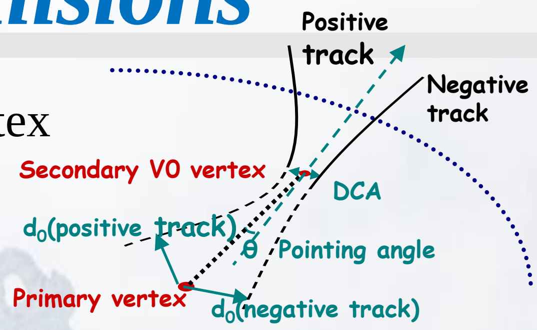
❖ LOOSE TOPOLOGICAL CUTS
- **ct**(Λ_c^+) is only 60 µm, small compared to resolution on the vertex position provided by the current ITS

❖ Particle Identification (PID), to identify p, K, π, essential for this analysis
- Bayesian approach to combine response of TPC and TOF
- Maximum probability criterion to identify tracks uniquely



Background reduced by a factor 100 applying PID!

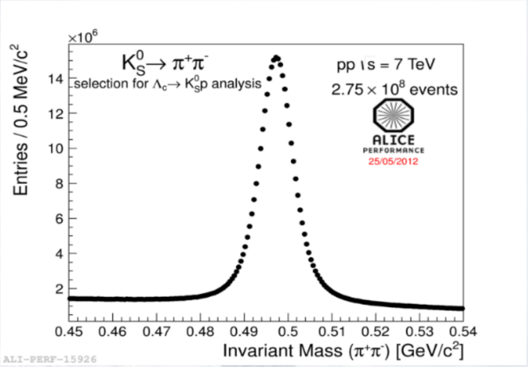
$\Lambda_c^+ \rightarrow pK^0_S$ *in pp and p-Pb collisions*



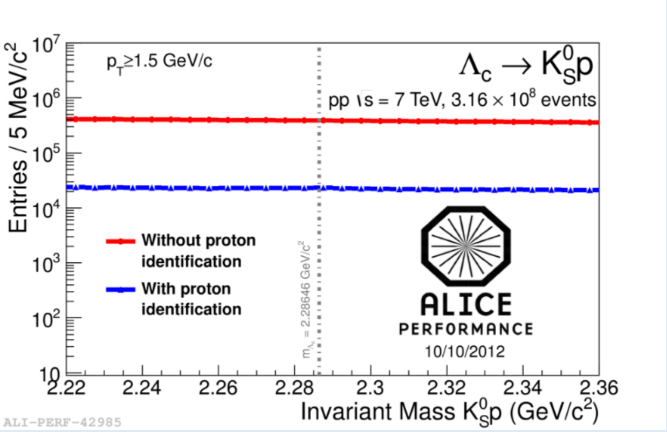
- K^0_S reconstructed from pairs of opposite-sign tracks forming a vertex displaced from the interaction vertex
  - Tracks selected according to topological cuts

- A third track identified as a proton is attached to the K^0_S to form the Λ_c^+ candidate

A clear K^0_S signal in $m_{inv}(\pi^+,\pi^-)$ limits the combinatorial background, despite of low B.R.



- Particle Identification (PID), to identify p, essential for this analysis
  - Detector used: TOF and TPC
  - Approach: number of sigma cuts



Background is suppressed by a factor **20** using PID!