Open heavy-flavour measurements in pp and p-Pb collisions with ALICE at the LHC

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On behalf of the ALICE collaboration

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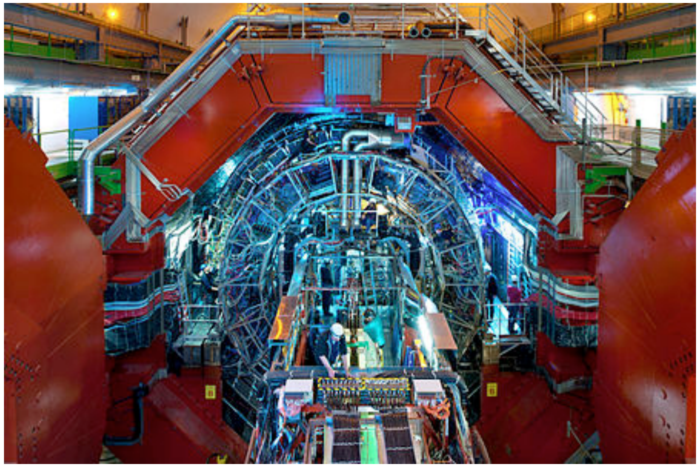
UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

ALICE
A JOURNEY OF DISCOVERY

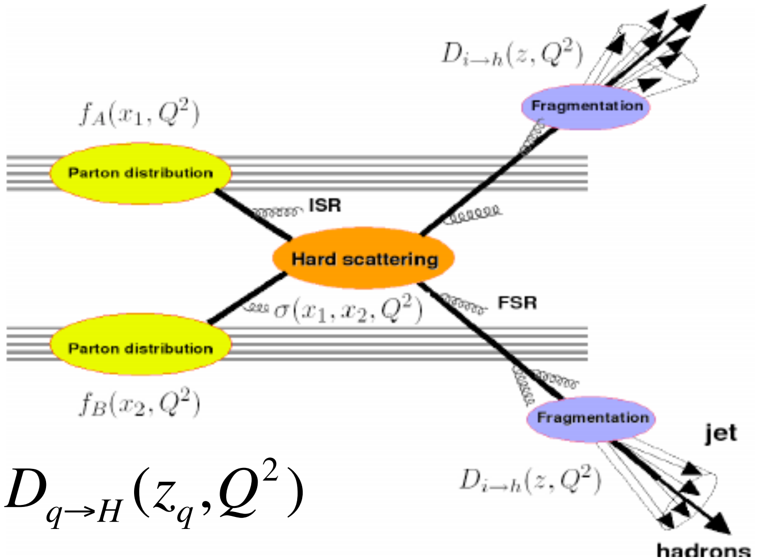
Outline

- Motivation and observables
- The ALICE detector and heavy-flavour reconstruction
- Results
- Summary and outlook



Heavy quark production at the LHC

- Heavy quarks (c,b) are produced in hard partonic scattering processes
  - Large Q^2, $m_{c,b} >> \Lambda_{QCD}$, production calculable perturbatively down to $p_T \sim 0$ GeV/c
- Hadron cross section calculated using factorisation approach:



$$\sigma_{hh\to H} = f_a(x_1,Q^2) \otimes f_b(x_2,Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q,Q^2)$$

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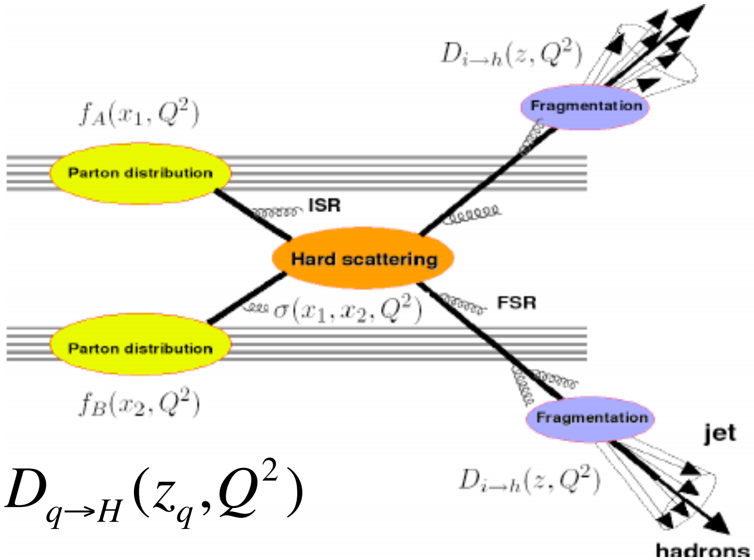

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- Heavy hadrons, and heavy-flavour decay electrons/muons measured in **pp collisions**:
  → test of perturbative QCD calculations
  → Reference for Pb-Pb, p-Pb measurements

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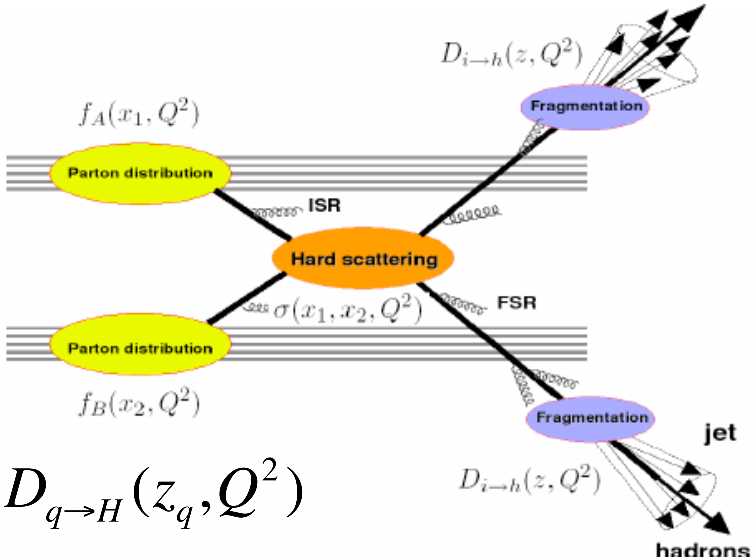

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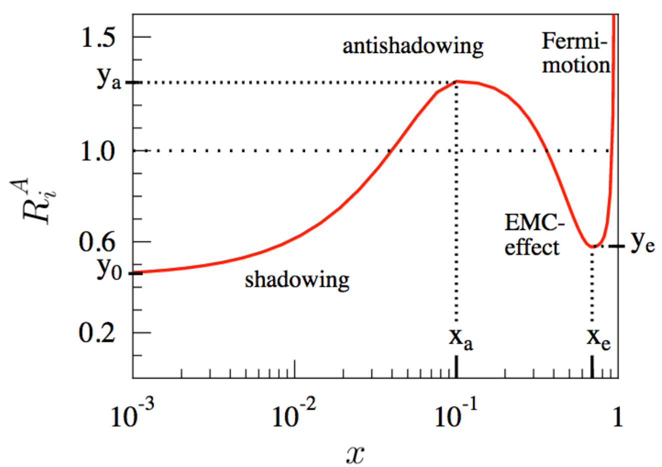
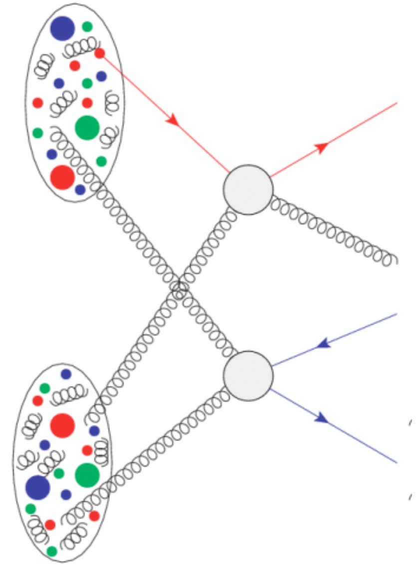
- Heavy hadrons, and heavy-flavour decay electrons/muons measured in **pp collisions**:
  - → test of perturbative QCD calculations
  - → Reference for Pb-Pb, p-Pb measurements
- In **p-Pb collisions**, heavy-flavour yield can be modified by various effects:
  - **Initial state effects:**
    - → Nuclear modification of the PDF
    - → k_T broadening
  - **Final state effects:**
    - → Energy loss in cold nuclear matter
    - → Collectivity in small systems?



More differential measurements

Heavy-flavour production as a function of multiplicity

- Correlating ‘hard’ and ‘soft’ parts of the collision helps with understanding interplay between hard and soft processes
  - ‘Underlying event’ of pp and p-Pb collisions more complex than simple 2→2 hard partonic scattering
    - Minijets from softer multi-parton interactions (MPI)
    - Initial and final-state radiation
    - Fragmentation of beam remnants
- Also allows study of possible centrality-dependent modification of p_T spectra in p-Pb w.r.t pp collisions



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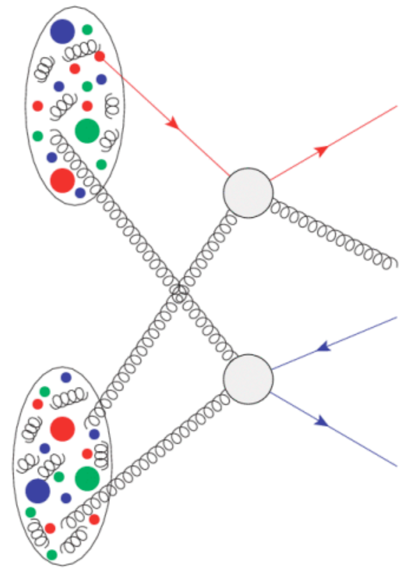
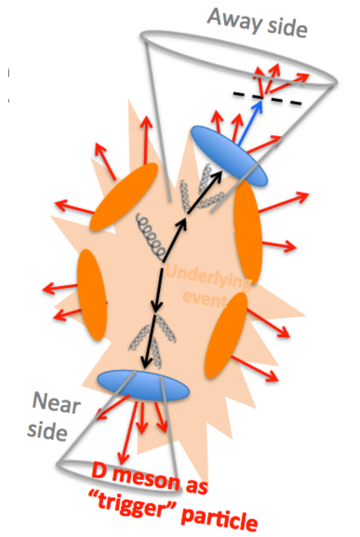
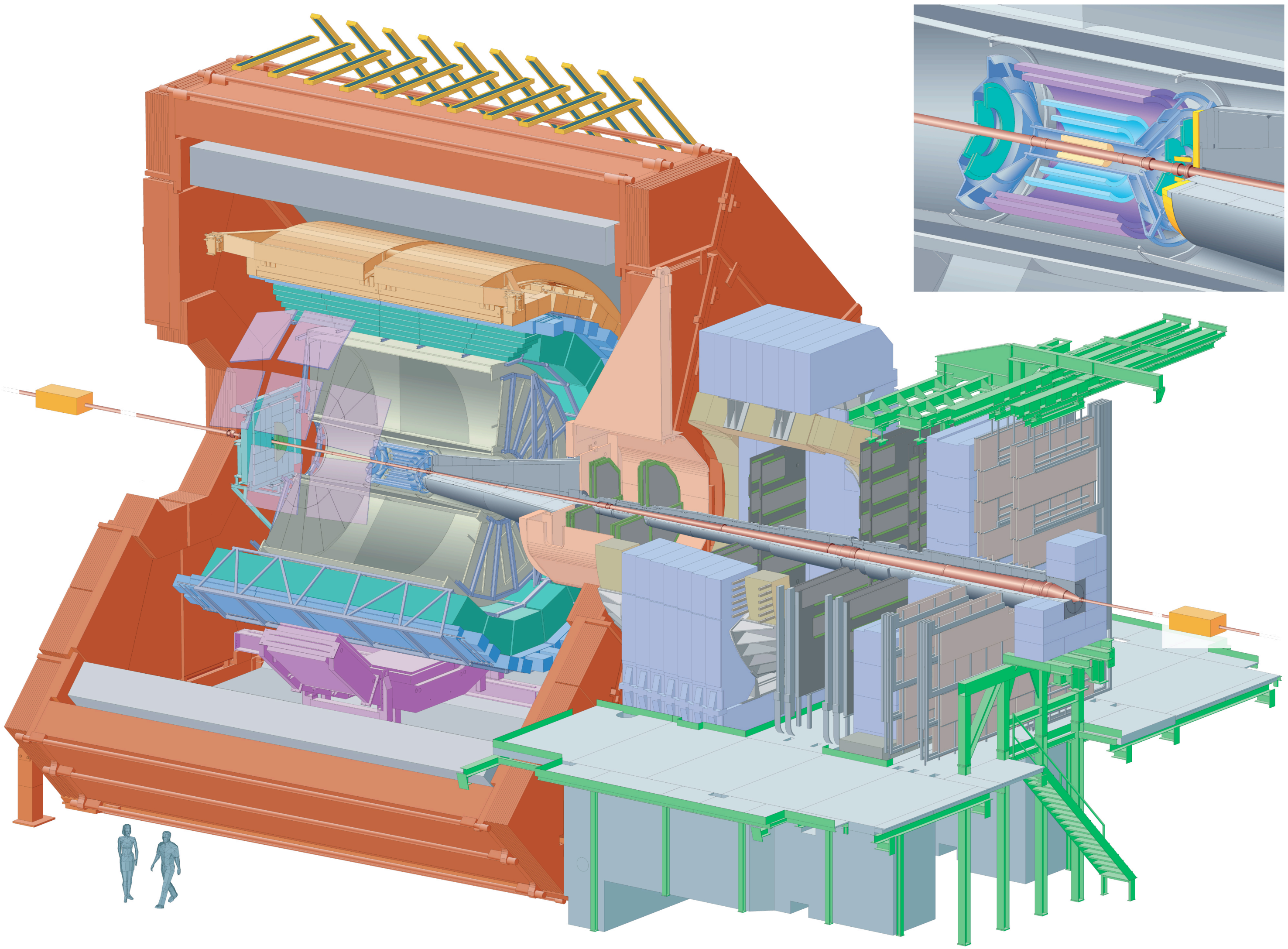


D meson-hadron correlations

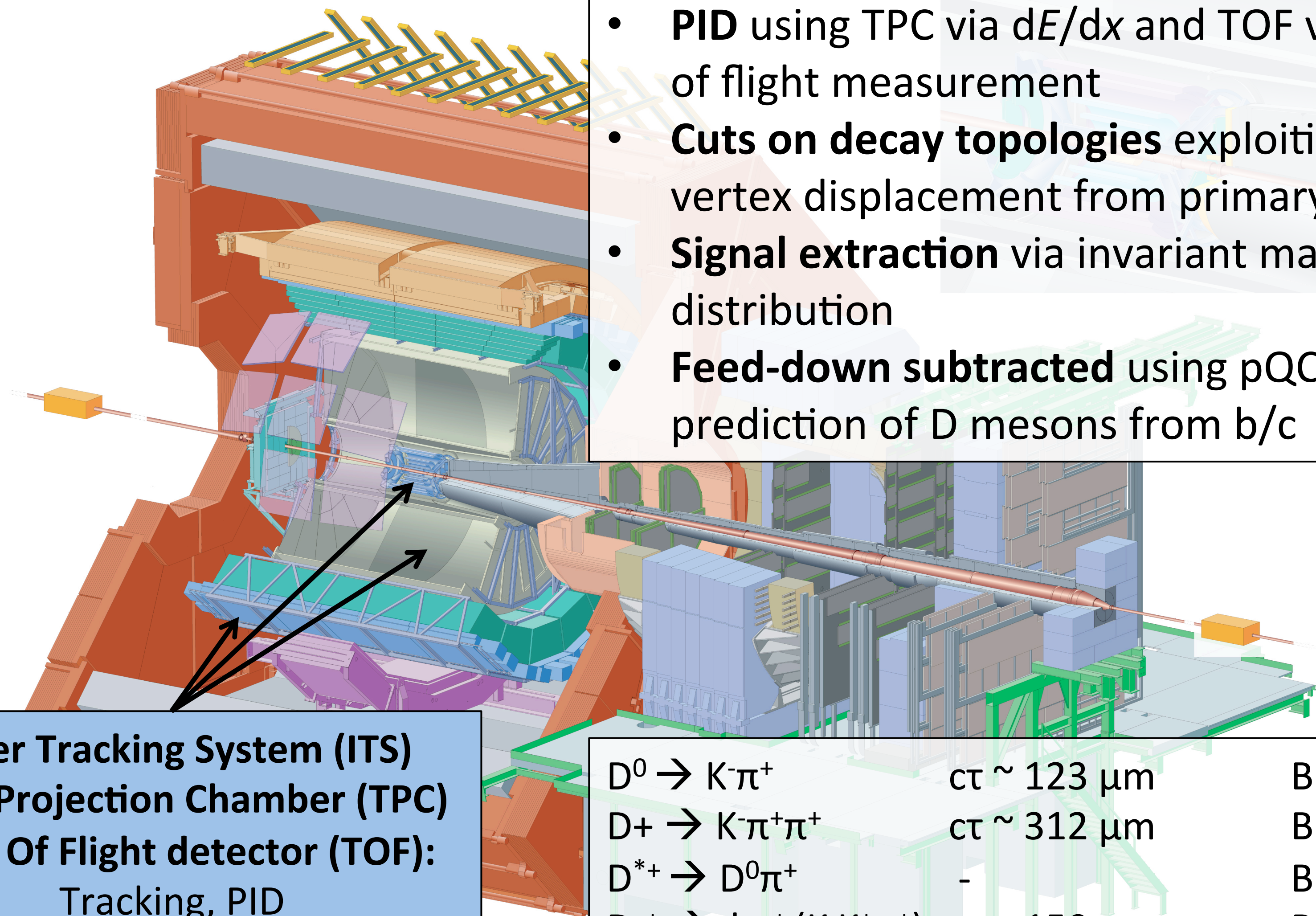
- Azimuthal correlations of D mesons and charged particles in pp and p-Pb collisions:
  - → Address charm jet/charm fragmentation properties
  - → Study possible collective effects in p-Pb/high multiplicity pp collisions
  - → Reference for future Pb-Pb measurements, providing further information on energy loss in the QGP



A Large Ion Collider Experiment



D mesons → hadrons



- **PID** using TPC via dE/dx and TOF via time of flight measurement
- **Cuts on decay topologies** exploiting decay vertex displacement from primary vertex
- **Signal extraction** via invariant mass distribution
- **Feed-down subtracted** using pQCD prediction of D mesons from b/c

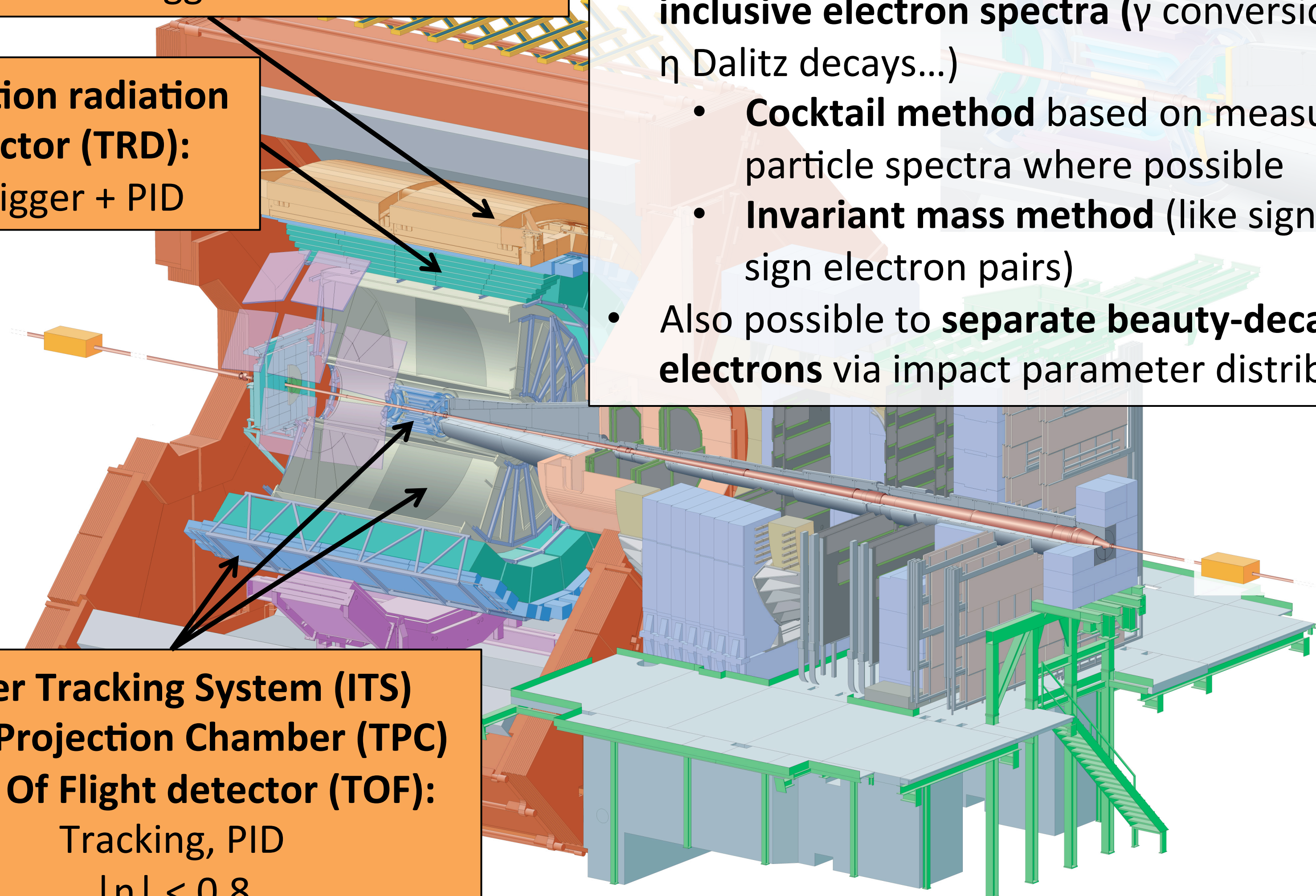
Inner Tracking System (ITS)
Time Projection Chamber (TPC)
Time Of Flight detector (TOF):
Tracking, PID
$|\eta| < 0.8$

$D^0 \rightarrow K^-\pi^+$	$c\tau \sim 123$ μm	BR ~ 3.88%
$D+ \rightarrow K^-\pi^+\pi^+$	$c\tau \sim 312$ μm	BR ~ 9.13%
$D^{*+} \rightarrow D^0\pi^+$	-	BR ~ 67.7%
$D_S^+ \rightarrow \phi\pi^+ (K^-K^+\pi^+)$	$c\tau \sim 150$ μm	BR ~ 2.28%

Heavy-flavour decay electrons

Electromagnetic calorimeter (EMCal):
$e^{\pm}$ trigger + PID

Transition radiation detector (TRD):
$e^{\pm}$ trigger + PID



- **Background contributions subtracted from inclusive electron spectra (**γ conversions, π and η Dalitz decays…)
  - **Cocktail method** based on measured particle spectra where possible
  - **Invariant mass method** (like sign – unlike sign electron pairs)
- Also possible to **separate beauty-decay electrons** via impact parameter distribution

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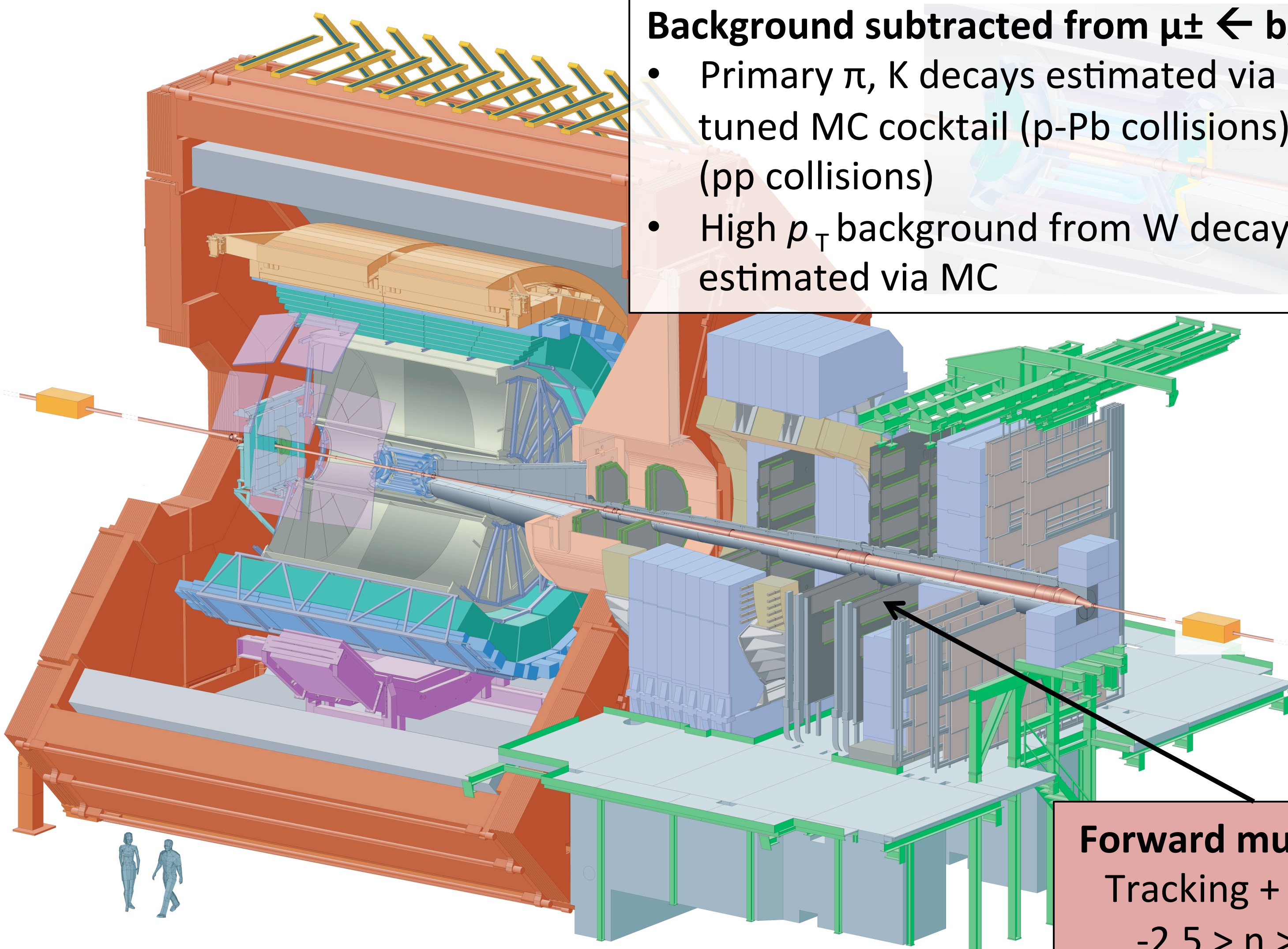
Heavy-flavour decay muons

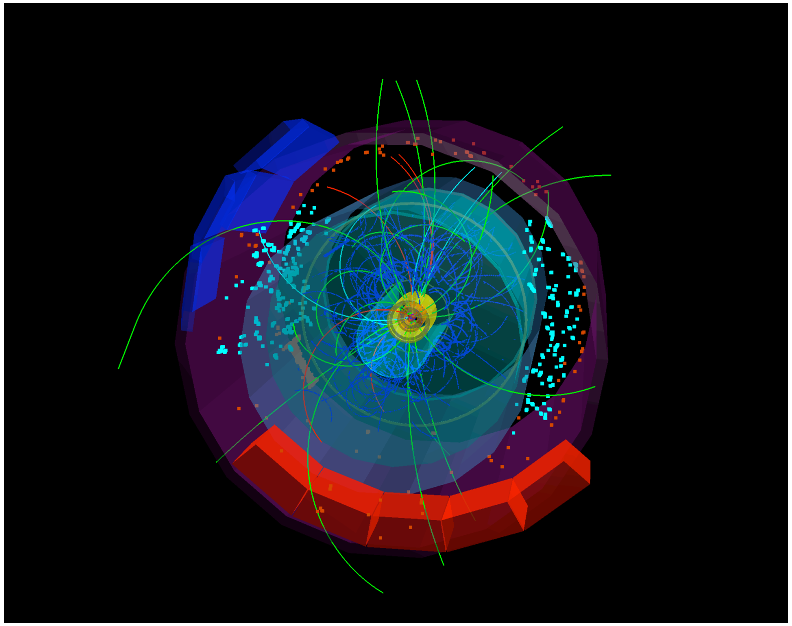


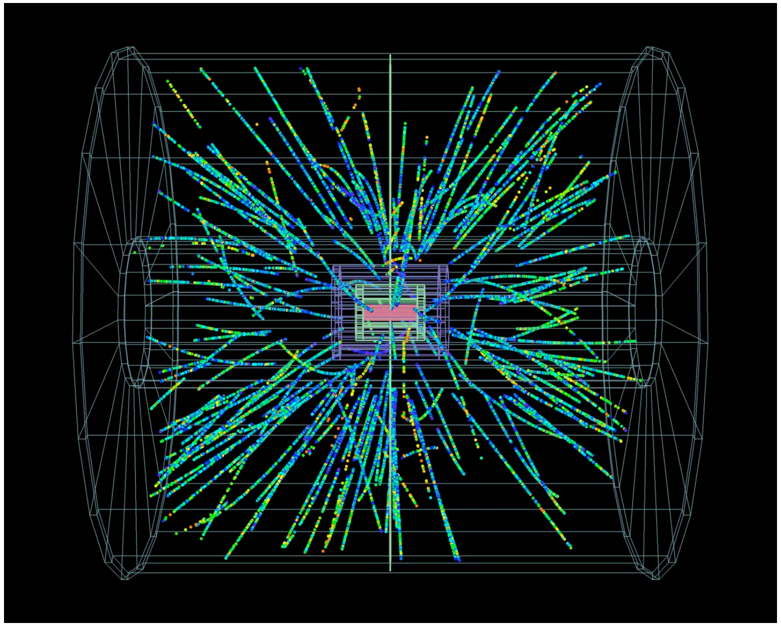
Background subtracted from μ± ← b, c :

- Primary π, K decays estimated via data – tuned MC cocktail (p-Pb collisions) or MC (pp collisions)
- High p_T background from W decays estimated via MC

Forward muon arm:
Tracking + trigger
$-2.5 > \eta > -4.0$

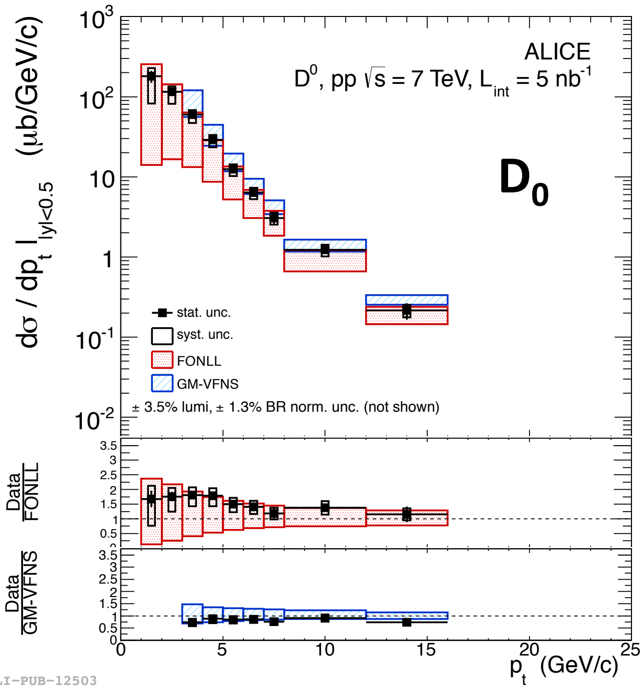
Results



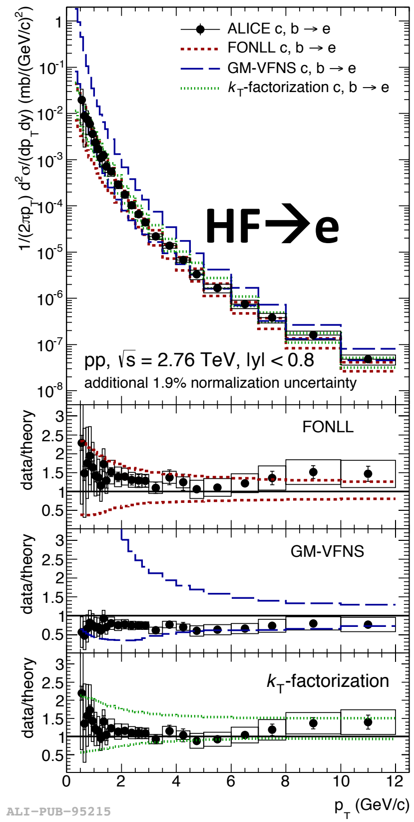


p_T-differential cross sections

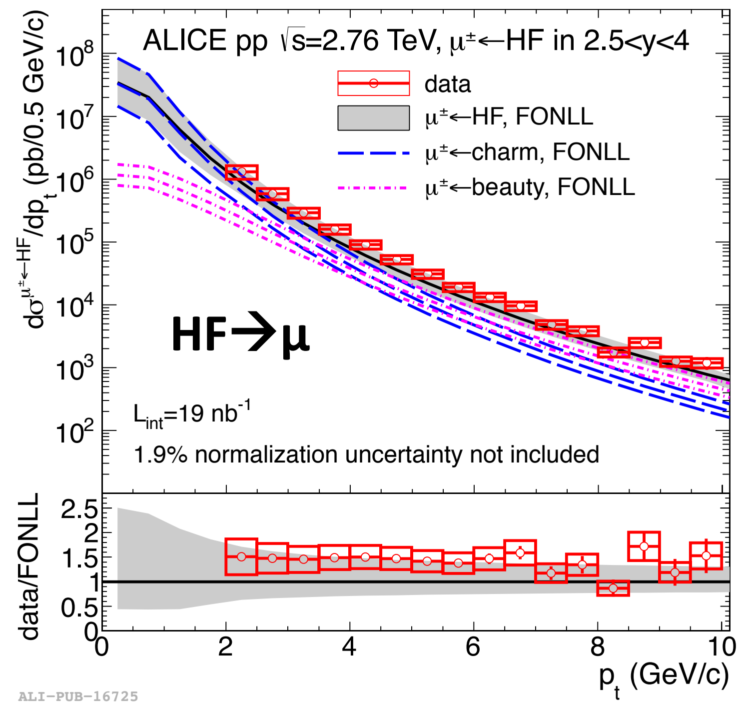
Examples… JHEP01(2012)128



Phys. Rev. D 91 (2015) 012001



Phys. Rev. Lett. 109, 112301 (2012)



- p_T-differential cross section measured for D^0, D^+, D^*, D_s, heavy-flavour decay muons, heavy-flavour decay electrons + beauty-decay electrons at $\sqrt{s}$ = 7 TeV, $\sqrt{s}$ = 2.76 TeV
- Described by pQCD calculations within uncertainties

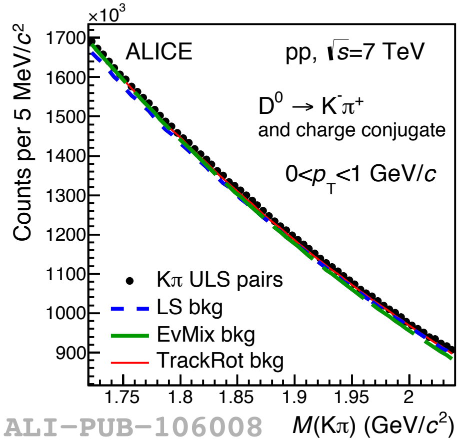
FONLL: JHEP9805(1998) 007; JHEP0103(2001) 006; JHEP1210(2012) 137; CERN-PH-TH/2011-227; JHEP05, 007 (1998)

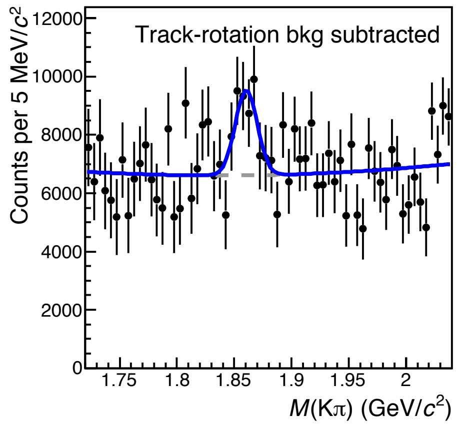
GM-VFNS:Phys. Rev. Lett.96(2006) 012001; Eur. Phys. J. C72 (2012) 2082; Nucl. Phys. B872 no. 2, (2013) 253-264; Nucl. Phys. B876 no. 1, (2013) 334-337; Phys.Rev.D71 (2005) 014018; Eur. Phys. J.C41 (2005) 199–212,

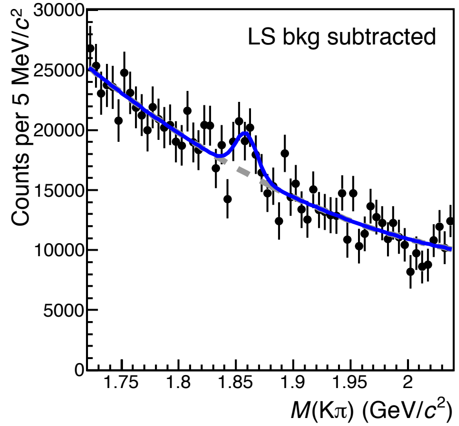
k_T factorisation Phys. Rev.D87 (2013) 094022

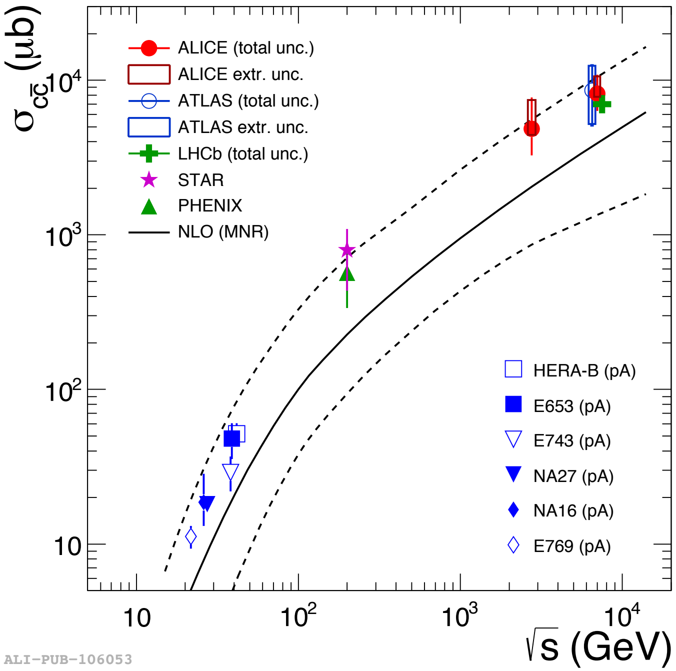
Low p_T D^0-meson cross section

Phys. Rev. C 94 (2016) 054908







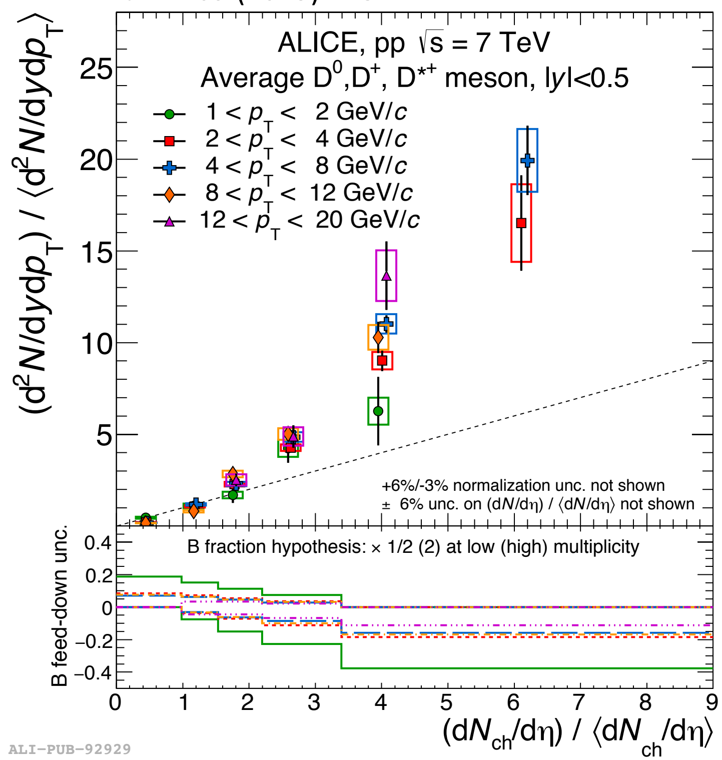


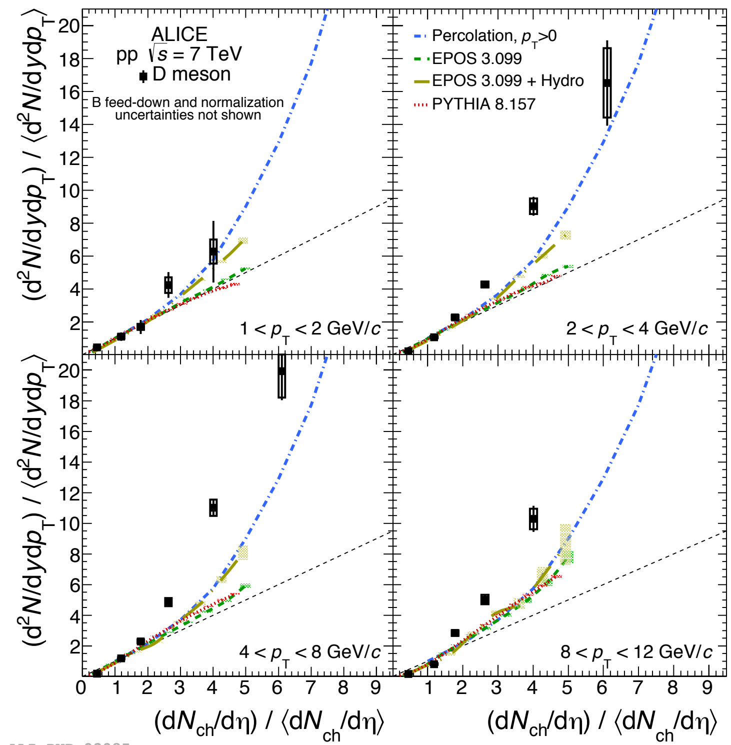
- Analysis with PID and detailed study of background (**no** topological selection) allows for D^0 measurement down to $p_T = 0$ GeV/c
- Allows for **factor ~ 2** reduction of systematic uncertainty on overall charm cross section at $\sqrt{s}$ = 7 TeV

D-meson yield vs dN_{ch}/dη

pp collisions:

JHEP 09 (2015) 148





Self-normalised yield as a function of dN_{ch}/dη in pp collisions:

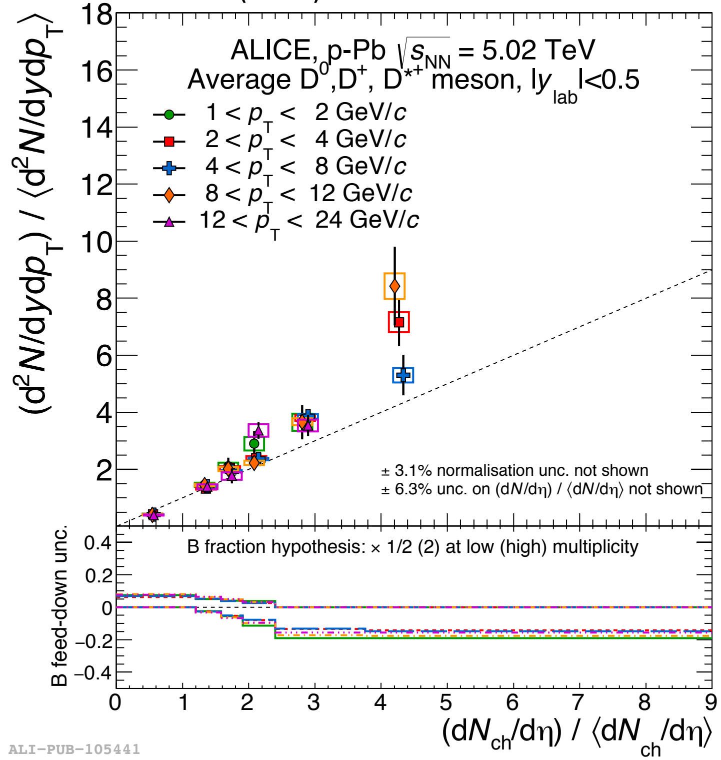
- **Increases steeper than linearly**
- **No p_T dependence**
- Models including MPIs + hydrodynamical effects can qualitatively reproduce the observed trend

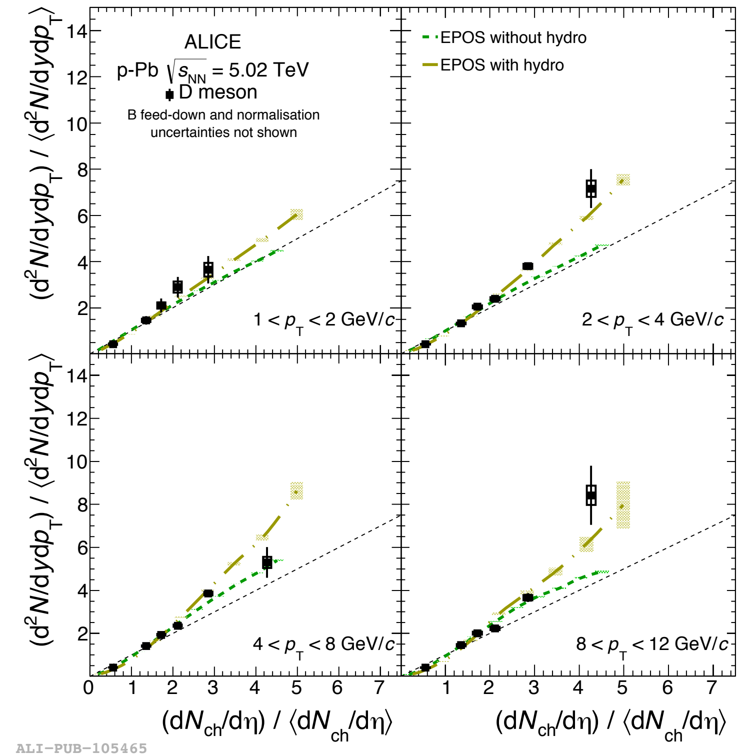
Percolation: arXiv:1501.03381, EPOS3: Phys.Rept. 350 (2001) 93–289; Phys.Rev.C89 (2014) 064903, PYTHIA: Comput.Phys.Commun. 178 (2008) 852–867

D-meson yield vs dN_{ch}/dη

p-Pb collisions:

JHEP 8 (2016) 1-44





Self-normalised yield as a function of dN_{ch}/dη in p-Pb collisions:

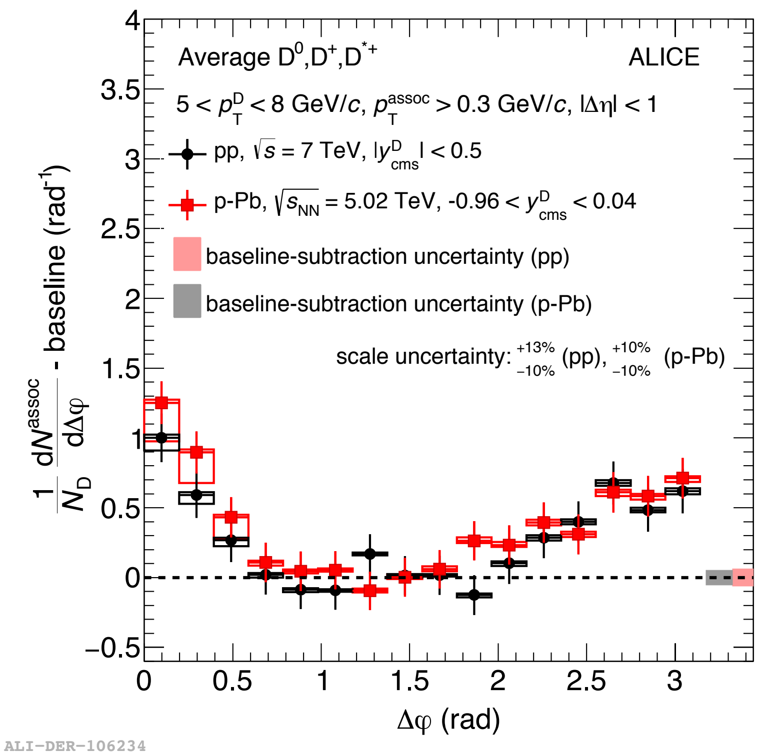
- **Increases steeper than linearly**
- **No p_T dependence**
- Reproduced by model including hydrodynamic flow

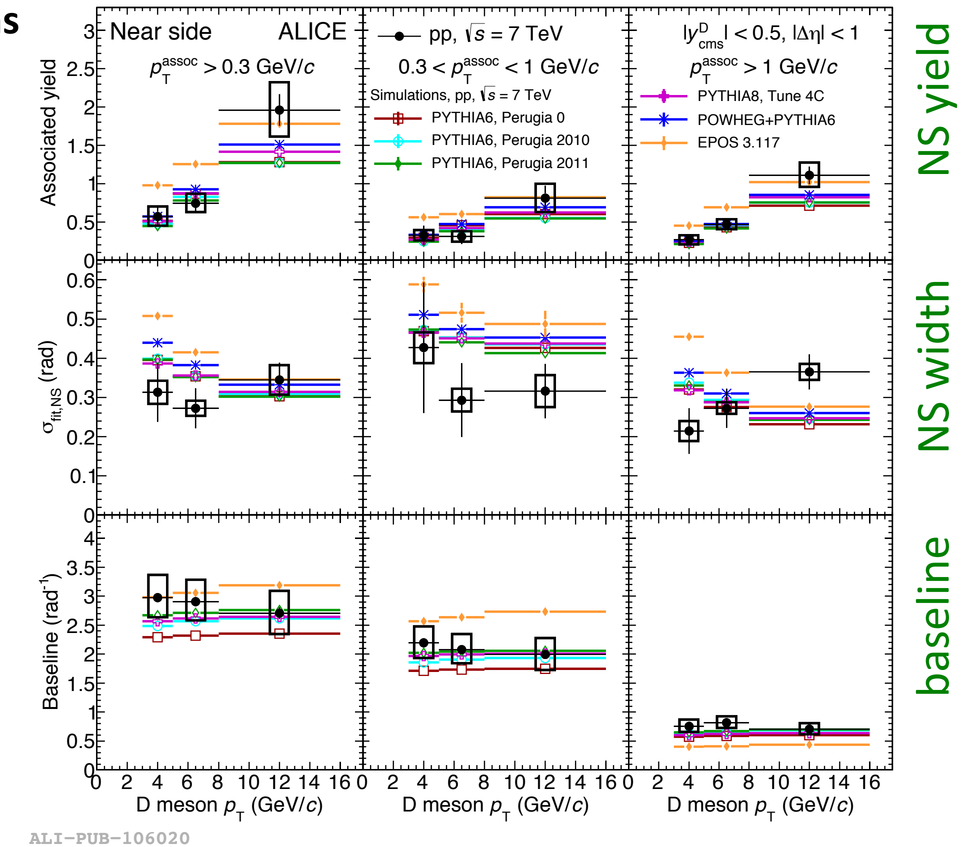
EPOS3: Phys.Rept. 350 (2001) 93–289;
Phys.Rev.C89 (2014) 064903

Azimuthal correlations

arXiv:1605.06963

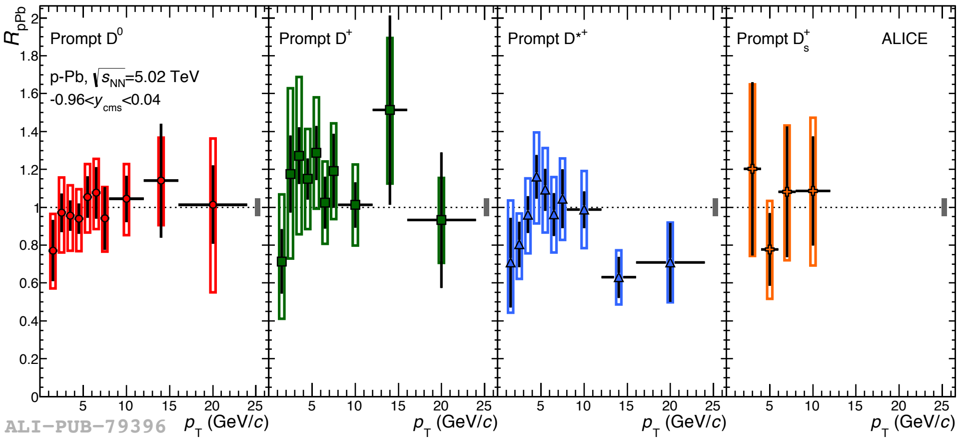
Analysis done in **3(2) p_T^D** intervals in **pp(p-Pb) collisions**
3 p_T^{assoc} intervals



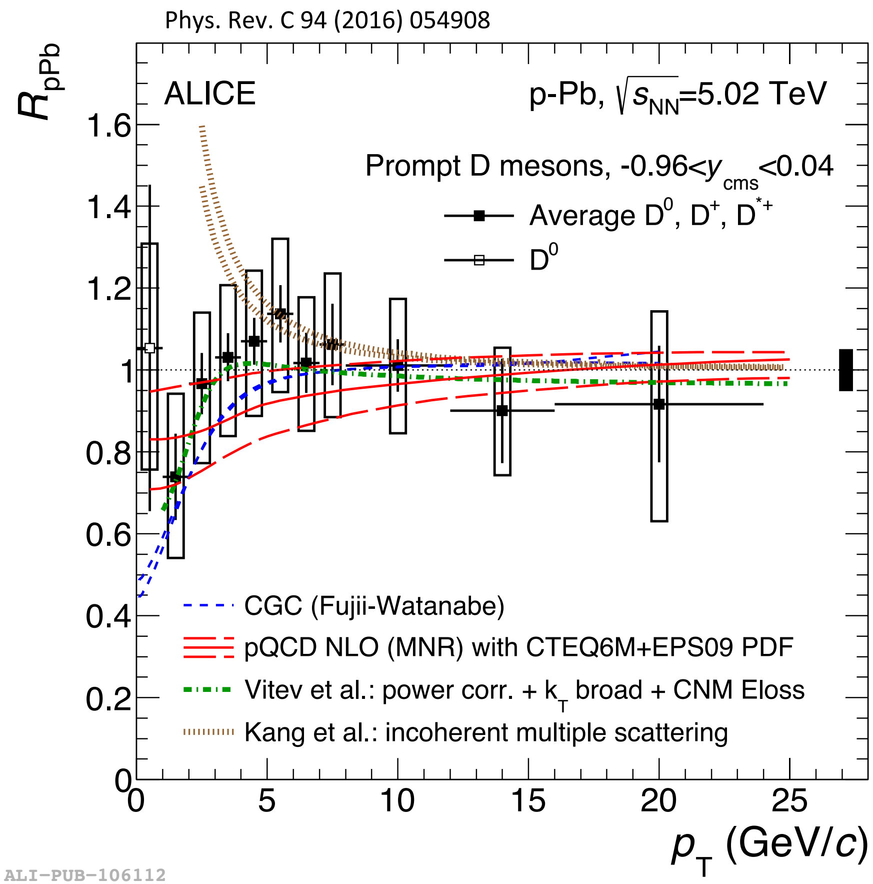


- D-meson and charged particles azimuthal correlation ($\Delta\phi$) distribution in pp and p-Pb collisions **compatible within uncertainties**
- Baseline subtracted $\Delta\phi$ distribution, and associated yield, with of near-side peak and baseline in agreement with PYTHIA 6, PYTHIA 8, POWHEG +PYTHIA

D-meson R_{pPb}



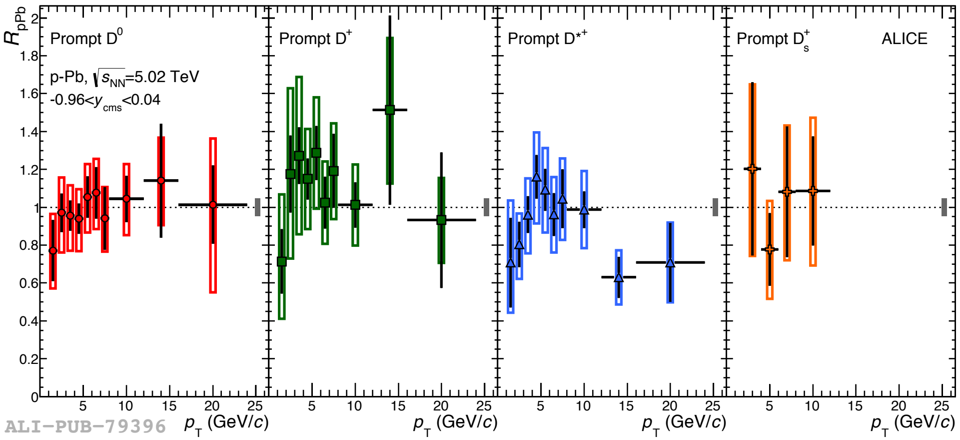
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



- D-meson R_{pPb} mostly **consistent with unity** for all D-meson species

- Compatible with models which include **initial-state effects + CNM energy loss**

- **pQCD NLO (MNR)**: Nucl. Phys. B 373 (1992) 295, JHEP 04 (2009) 065, JHEP 0310 (2003) 046, **CGC:** arXiv:1308.1258, **Vitev:** Phys. Rev. C 80 (2009) 054902



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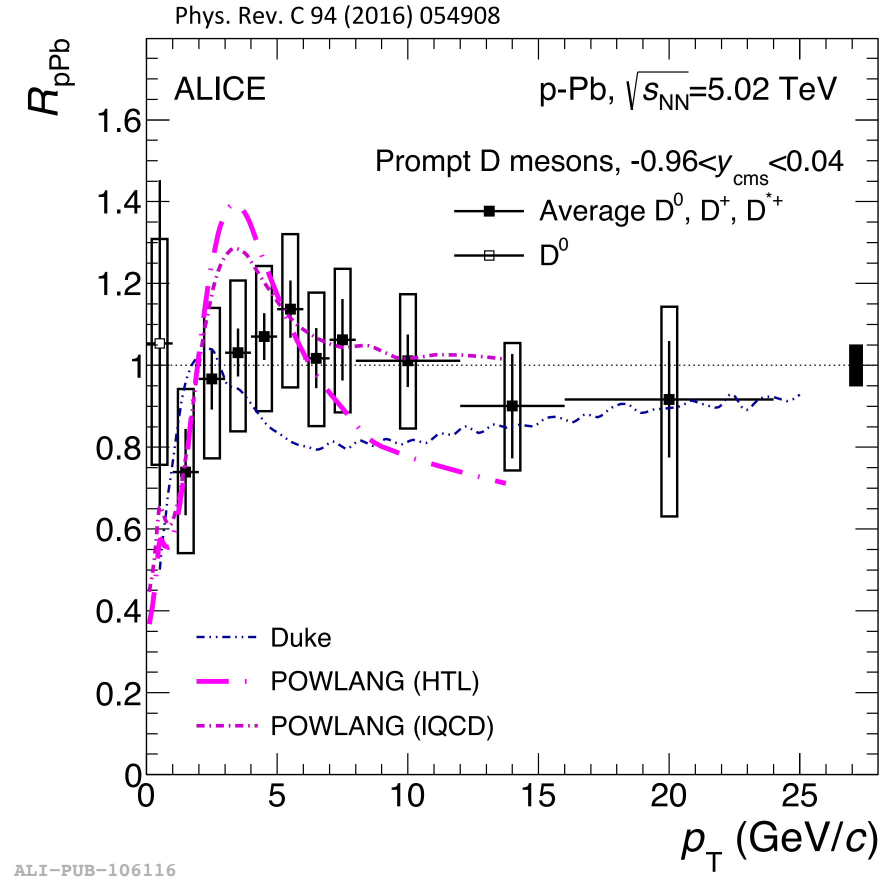

- D-meson R_{pPb} mostly **consistent with unity** for all D-meson species
- Compatible with models which include **initial-state effects + CNM energy loss**
- Compatible with models including **medium effects (small QGP)**

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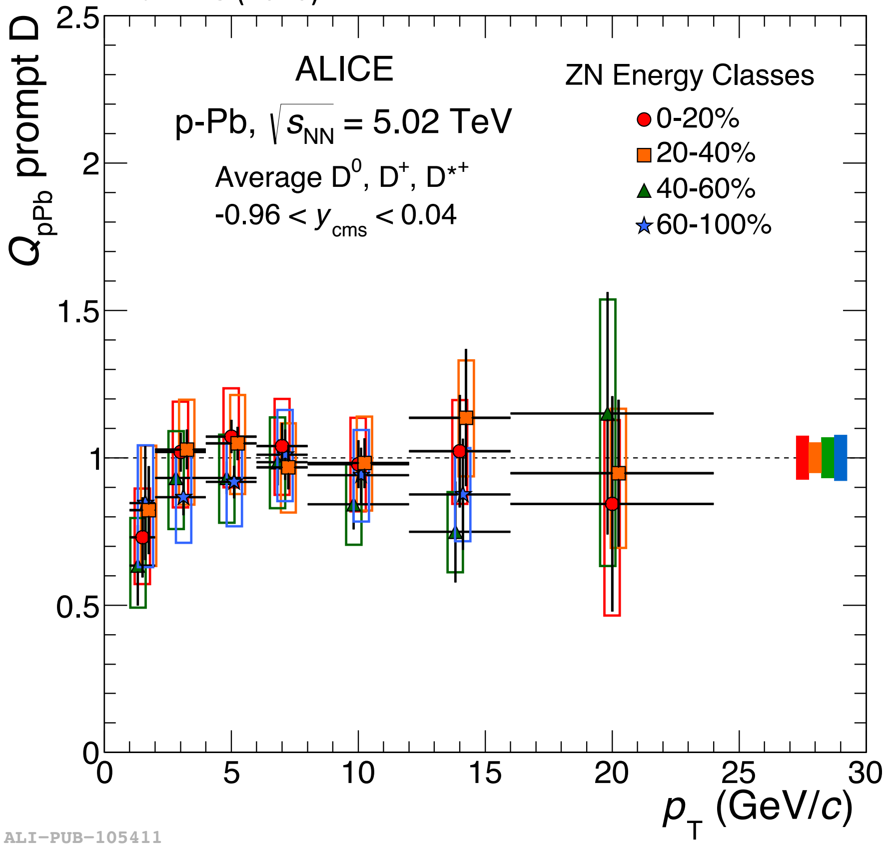
D-meson Q_{pPb}

JHEP 8 (2016) 1-44



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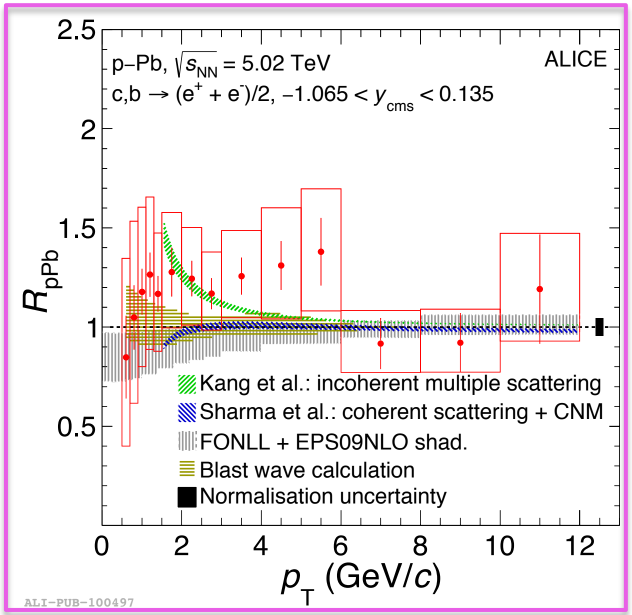
$$Q^{mult}_{pPb}(p_T) = \frac{1}{\langle T^{mult}_{pPb} \rangle} \frac{dN_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

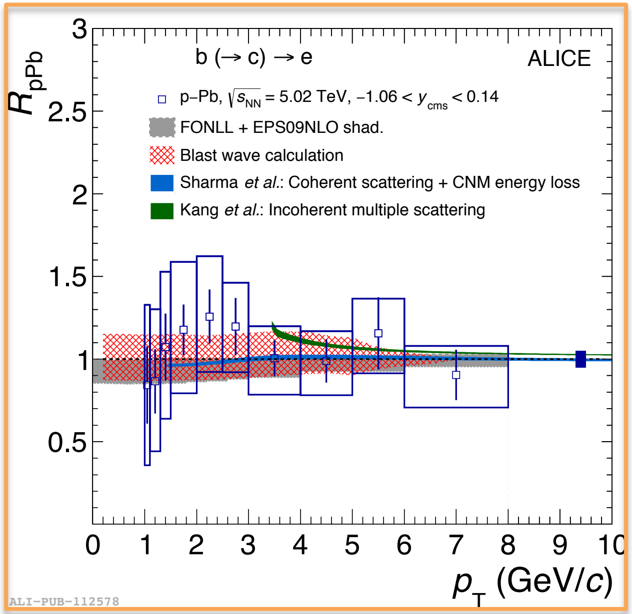
- Q_{pPb} equivalent to R_{pPb} measured in different multiplicity (centrality) intervals
- Centrality determined using Zero-Degree Neutron Calorimeter (ZN)

→ **No centrality dependence seen in the D-meson Q_{pPb}**

Heavy-flavour decay lepton R_{pPb}

Phys. Lett. B 754 (2016) 81-93





- R_{pPb} of inclusive heavy-flavour decay electrons and electrons from beauty-hadron decays **consistent with unity**
  - Compatible with models that include initial-state + cold nuclear matter effects

Kang et al.: PLB 740 (2015) 23 ; Sharma et al.:Phys. Rev. C80 (2009) 054902;FONLL M. Cacciari et al., JHEP 9805 (1998) 007; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065;

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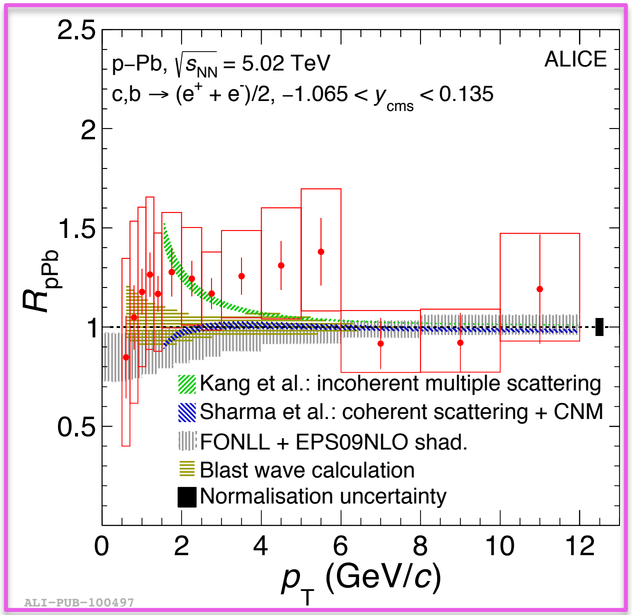

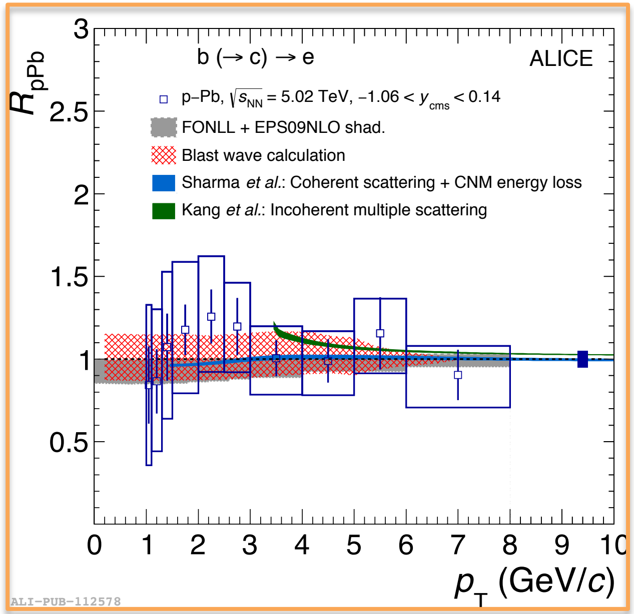

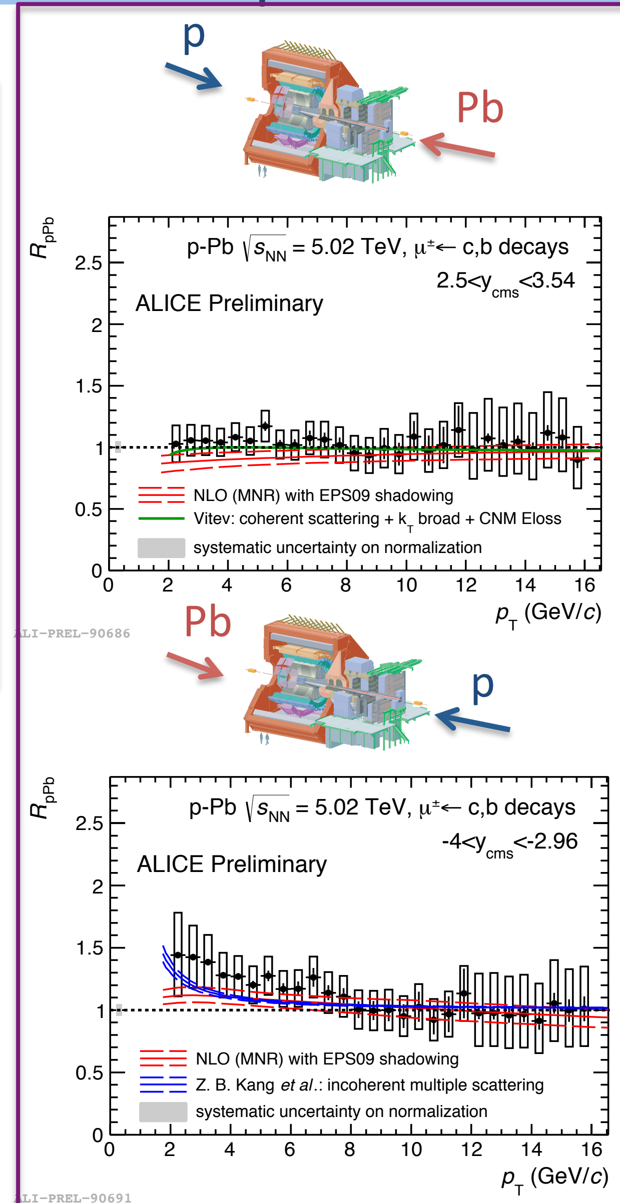

- R_{pPb} of inclusive heavy-flavour decay electrons and electrons from beauty-hadron decays **consistent with unity**
  - Compatible with models that include initial-state + cold nuclear matter effects
- R_{pPb} of heavy-flavour decay muons described by calculations including initial-state +cold nuclear matter effects

Kang et al.: PLB 740 (2015) 23 ; Sharma et al.:Phys. Rev. C80 (2009) 054902;FONLL M. Cacciari et al., JHEP 9805 (1998) 007; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065;

pQCD NLO (MNR): Nucl.Phys. B 373 (1992) 295; EPS09: JHEP 04 (2009) 065 ;Z. B. Kang et al.: PLB 740 (2015) 23 ; I. Vitev: PRC 75 (2007) 064906

Summary and outlook

- **Lots of interesting results from LHC Run 1 data in pp and p-Pb collisions**
  - High-precision charm + beauty production cross sections measured
  - Multiplicity dependent yield of heavy-flavour particles measured to probe production mechanisms, **faster than linear increase** in yield as function of multiplicity
  - First D-hadron azimuthal correlation measurement in pp and p-Pb collisions **consistent with event generators**
  - R_{pPb} and Q_{pPb} **consistent with unity** and **models including cold matter effects**
    - **No centrality dependence** in D-meson Q_{pPb}

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- **Much more to look forward to for Run 2 and beyond...**
  - Successful 2016 **p-Pb** run allowed for **~6x minimum bias statistics at $\sqrt{s_{NN}}$ = 5.02 TeV**, plus **large sample at $\sqrt{s_{NN}}$ = 8.16 TeV**

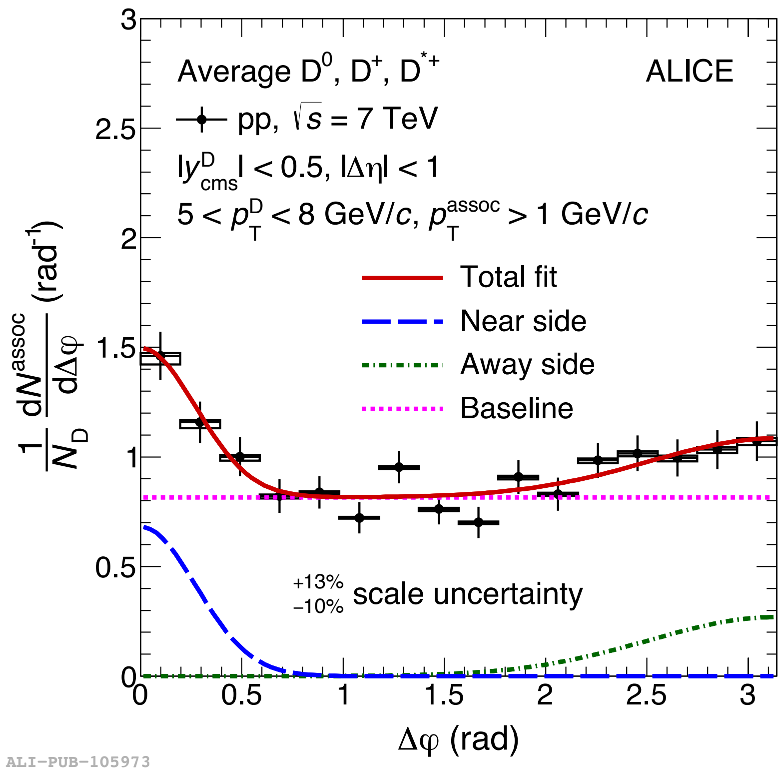
    → Can reduce statistical uncertainty of all measurements

    → How do measurements scale with $\sqrt{s_{NN}}$?
  - Large sample of **high-multiplicity triggered pp data at $\sqrt{s}$ = 13 TeV** will allow to improve high-multiplicity measurements
  - Upgrade program for Run 3 (2021) includes full ITS upgrade, Muon Forward Tracker (MFT), continuous TPC readout for precision/statistical improvement...

Stay tuned for many more exciting results

Backup

Correlations

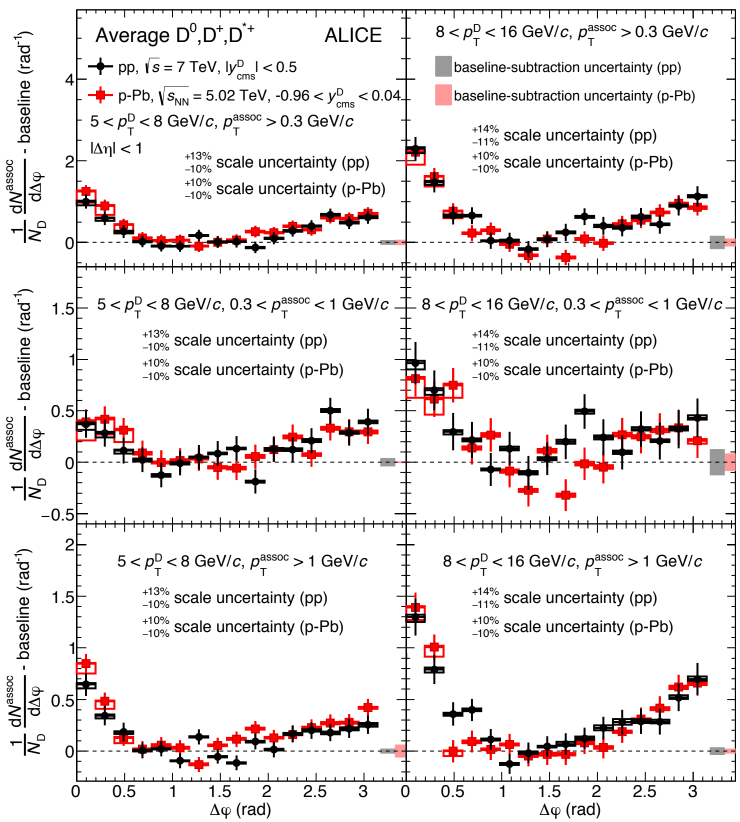


$$f(\Delta\varphi) = b + \frac{A_{NS}}{\sqrt{2\pi}\sigma_{fit,NS}} e^{-\frac{(\Delta\varphi)^2}{2\sigma^2_{fit,NS}}} + \frac{A_{AS}}{\sqrt{2\pi}\sigma_{fit,AS}} e^{-\frac{(\Delta\varphi-\pi)^2}{2\sigma^2_{fit,AS}}}$$

baseline — Near side peak — Away side peak

- Fit function described properties of azimuthal correlations
  - 2 Gaussian terms describing near and away side peaks
  - Constant term describing the baseline
- Integrals of gaussian terms A_{NS} ,A_{AS} – associated particle yields
- $\sigma_{fit,NS}$, $\sigma_{fit,AS}$ quantify widths of the correlation peaks.
- b represents physical minimum of the $\Delta\phi$ distribution

Correlations



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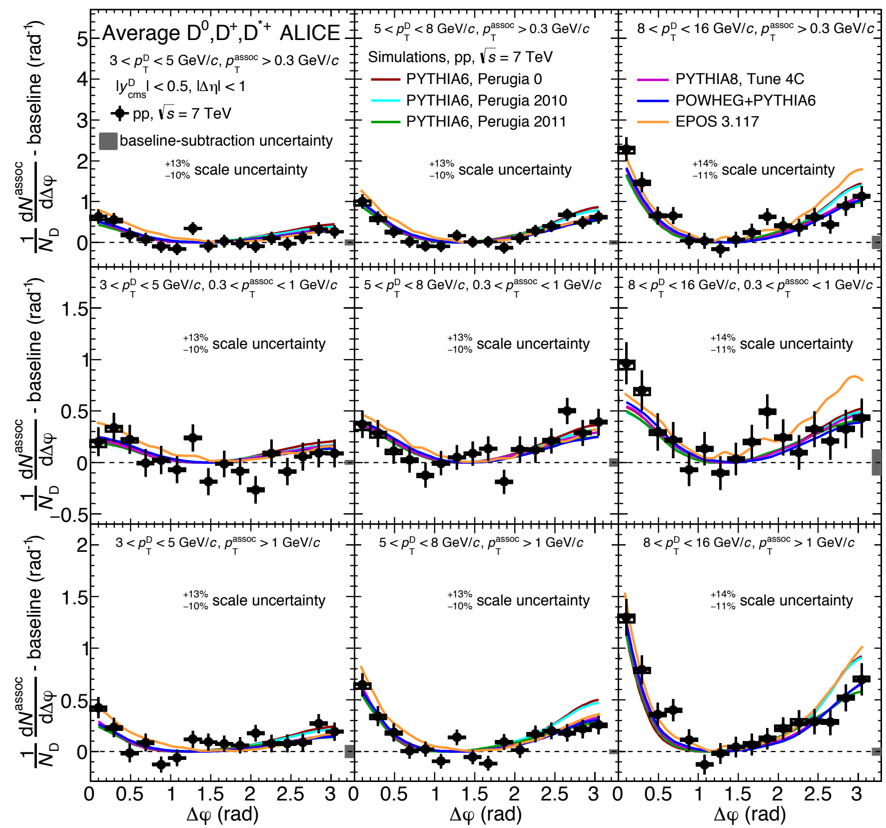


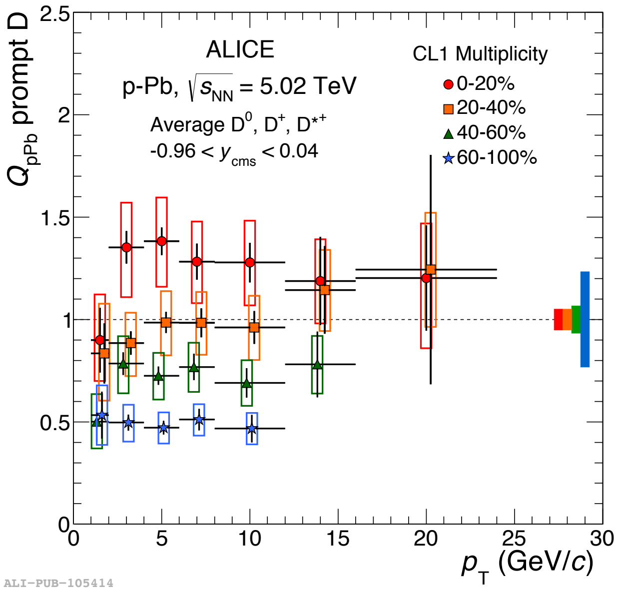
ALI-PUB-106084

Baseline subtracted Δϕ distribution, and associated yield, with of near-side peak and baseline in agreement with PYTHIA 6, PYTHIA 8, POWHEG+PYTHIA

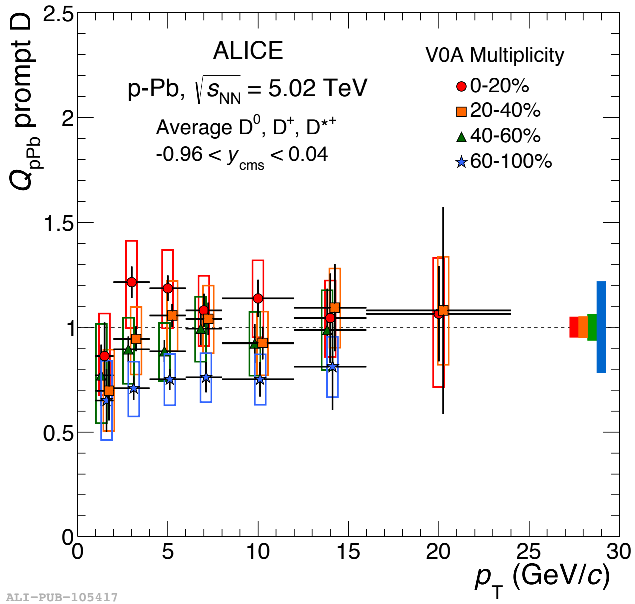
D-meson Q_{pPb}

Increasing η-gap between D-mesons/ multiplicity estimator

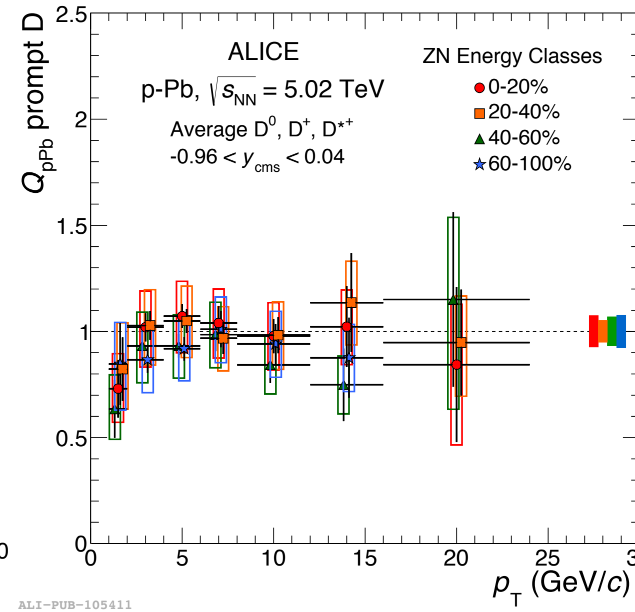
SPD: |η|<2.0 and|η|<1.4



−3.7<η<−1.7 **(V0C)** and 2.8<η<5.1 **(V0A)**

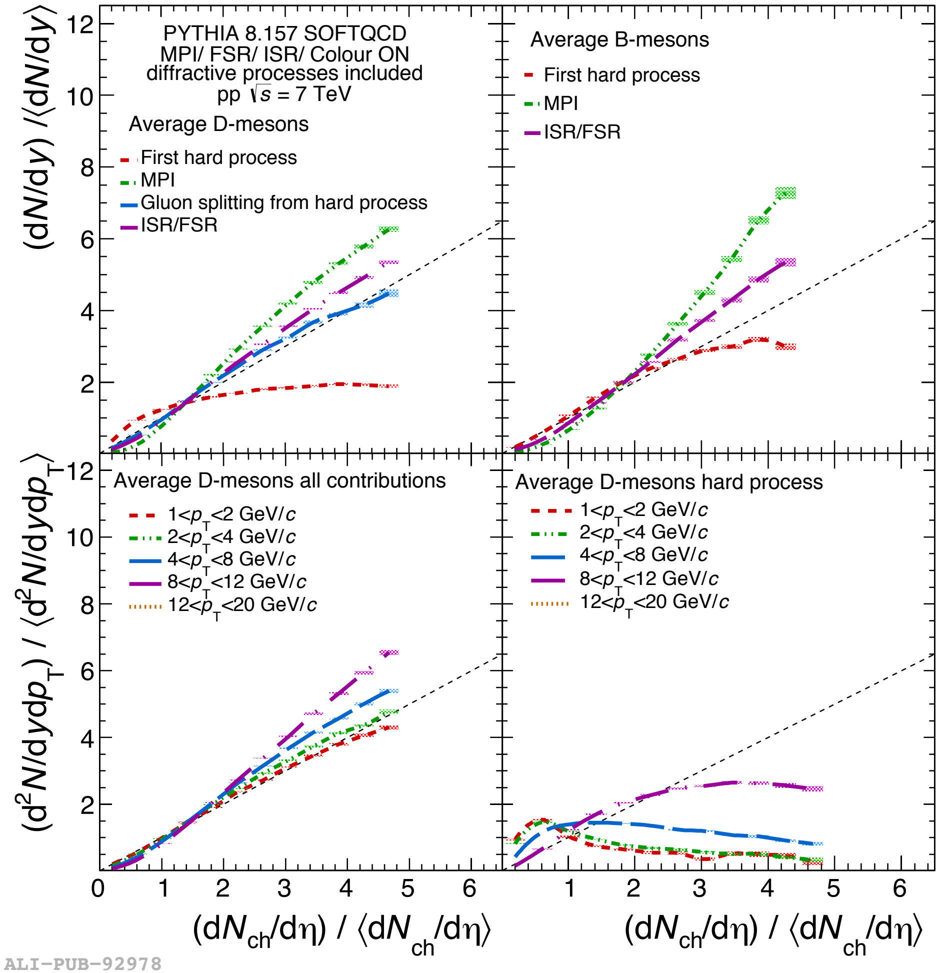


ZDC



- Analysis repeated with different multiplicity estimators including SPD, V0 and ZDC

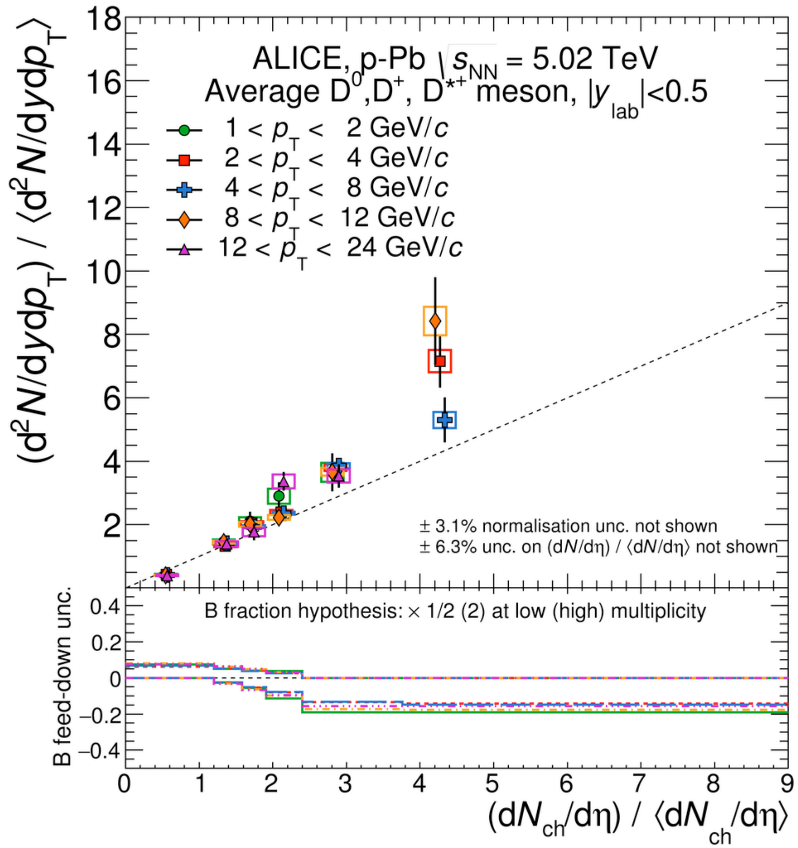
D-meson yield vs dN_{ch}/dη in PYTHIA



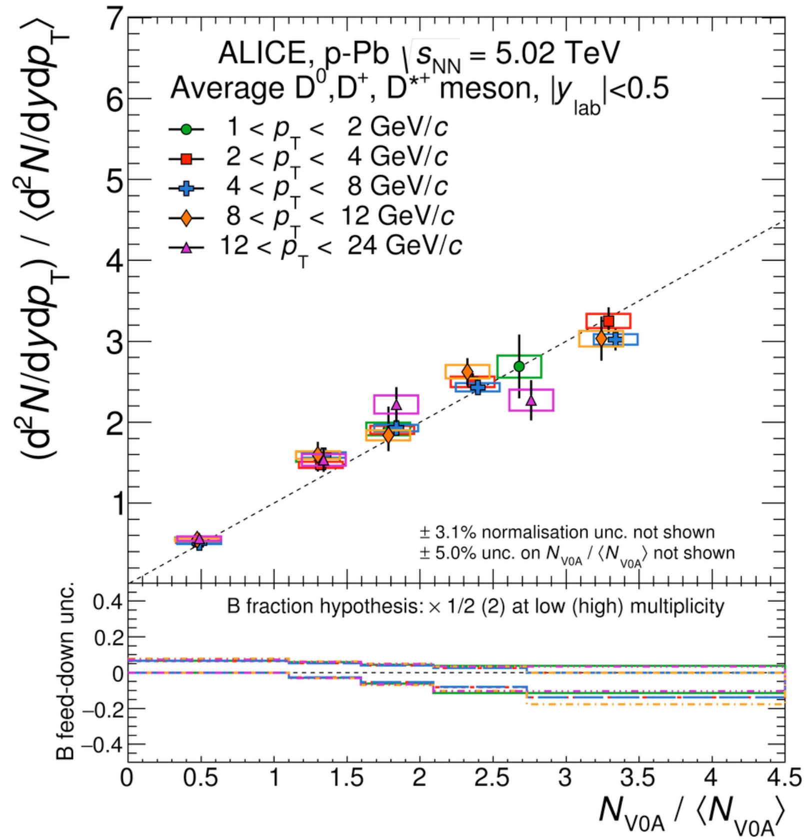
- PYTHIA 8 includes updated description of MPIs, ISR/FSR
- Yield vs multiplicity in PYTHIA can give insight into how each process contributes

Different multiplicity estimators

SPD: |η|<2.0 and |η|<1.4



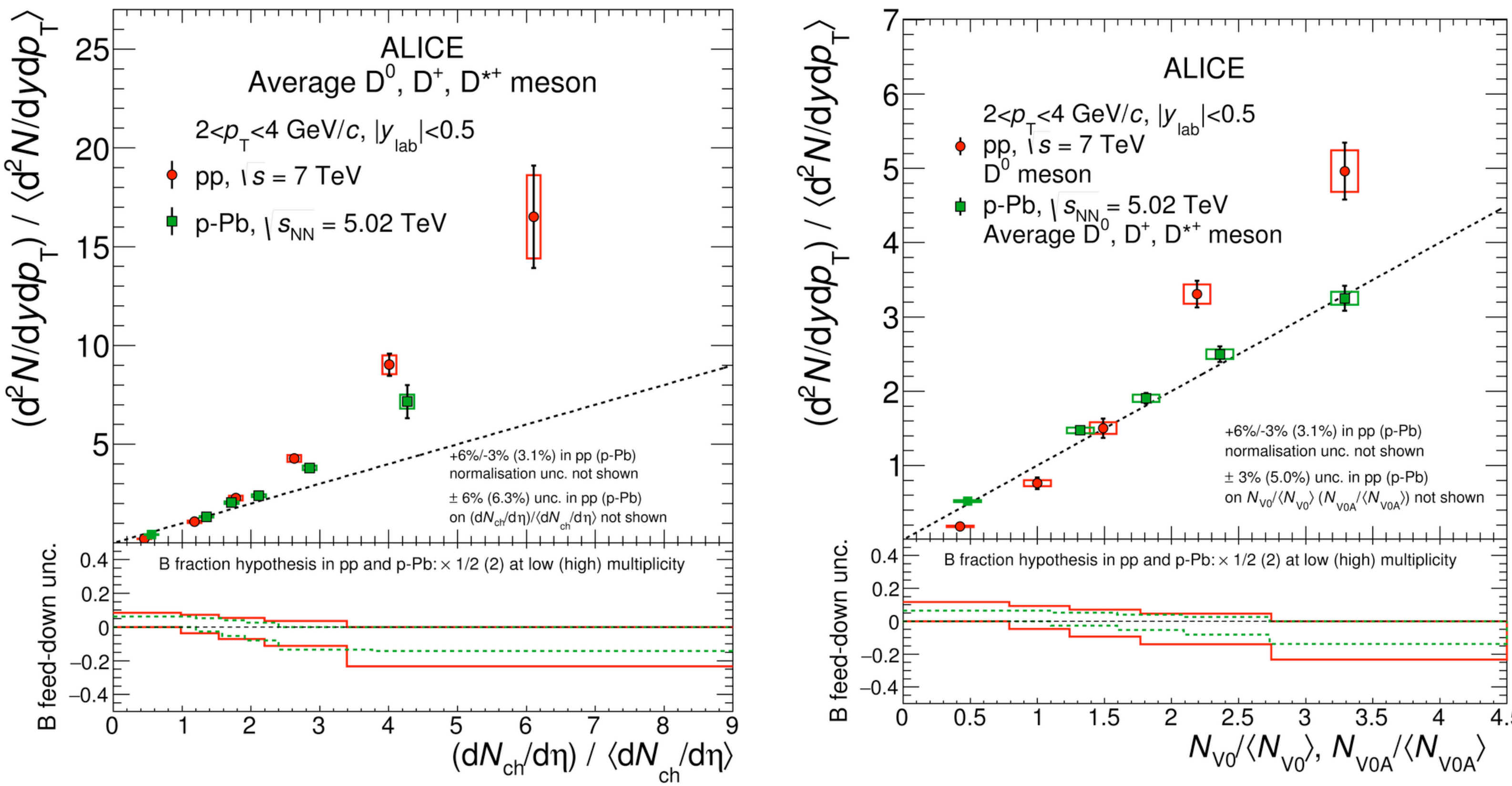
2.8<η<5.1 **(V0A)** (Pb going direction)



- Faster than linear increase in yield as function of multiplicity using SPD multiplicity estimator
- ~Linear increase in yield as function of multiplicity using V0A multiplicity estimator
  → Different scaling of charged particle multiplicity with number of participant nucleons

→ Phys.Rev. C91 (2015) no.6, 064905

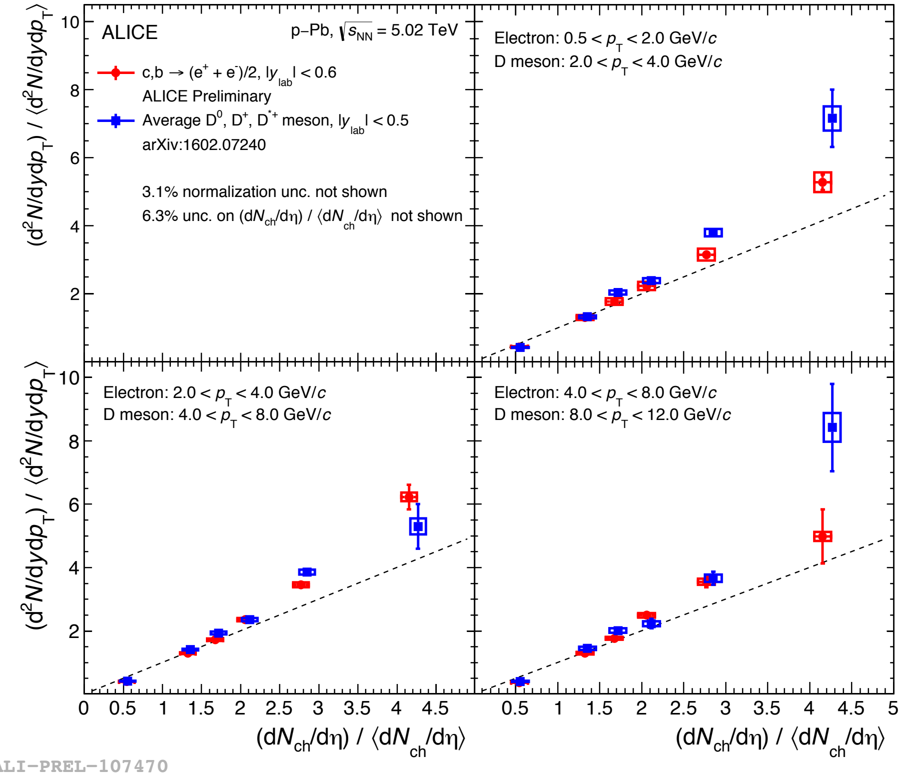
D-meson yield in pp and p-Pb collisions

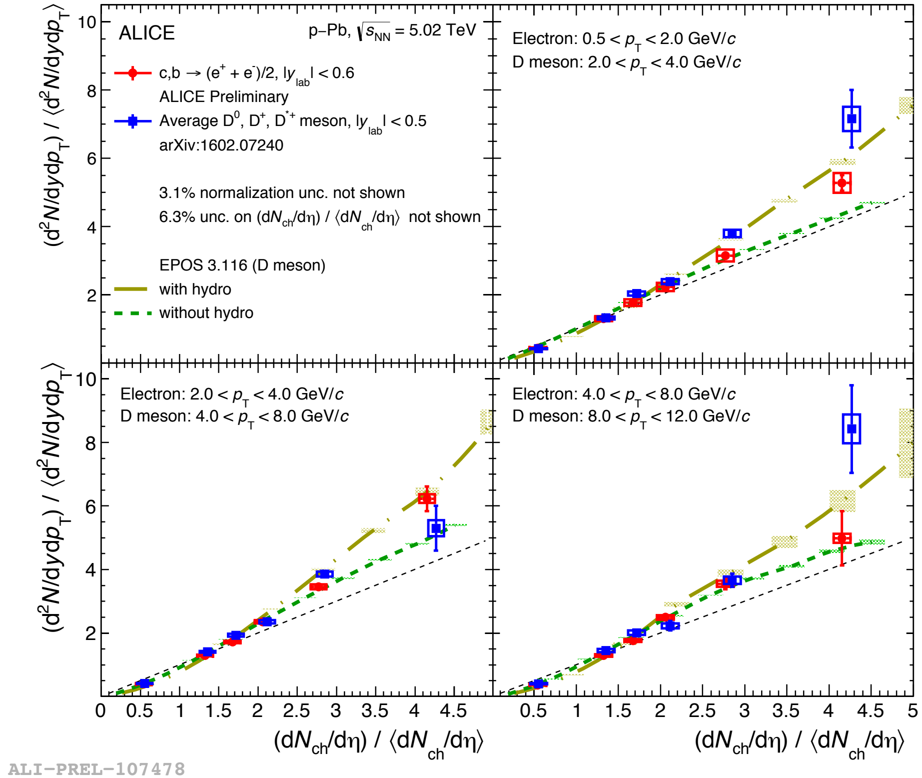


- Similar increase for D-meson yields as function of multiplity in pp and p-Pb collisions
- Curve gets less steep for p-Pb with larger η gap
  - → pp collisions – MPIs
  - → p-Pb collisions – multiple (softer) nucleon-nucleon collisions

Heavy-flavour electron yield vs dN_{ch}/dη

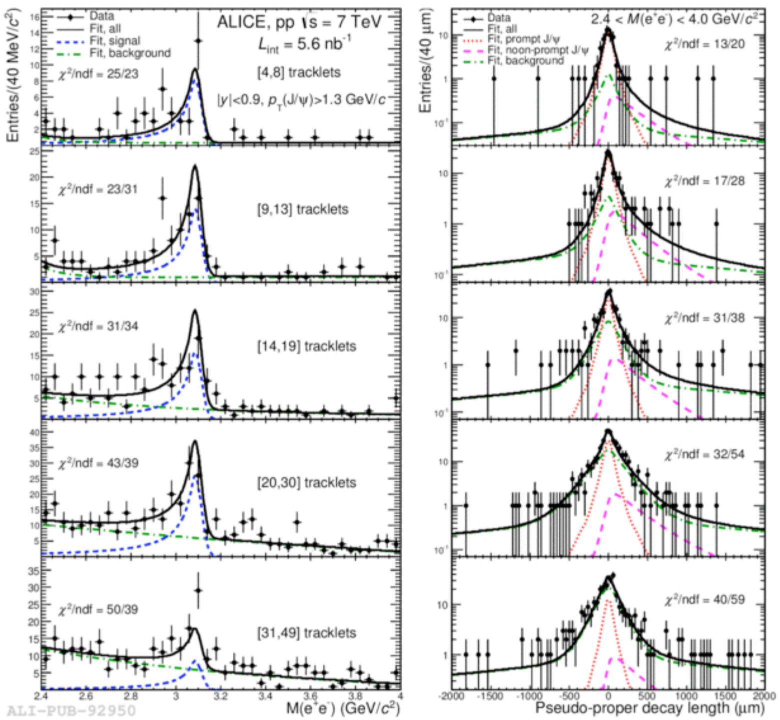
JHEP 1608 (2016) 078

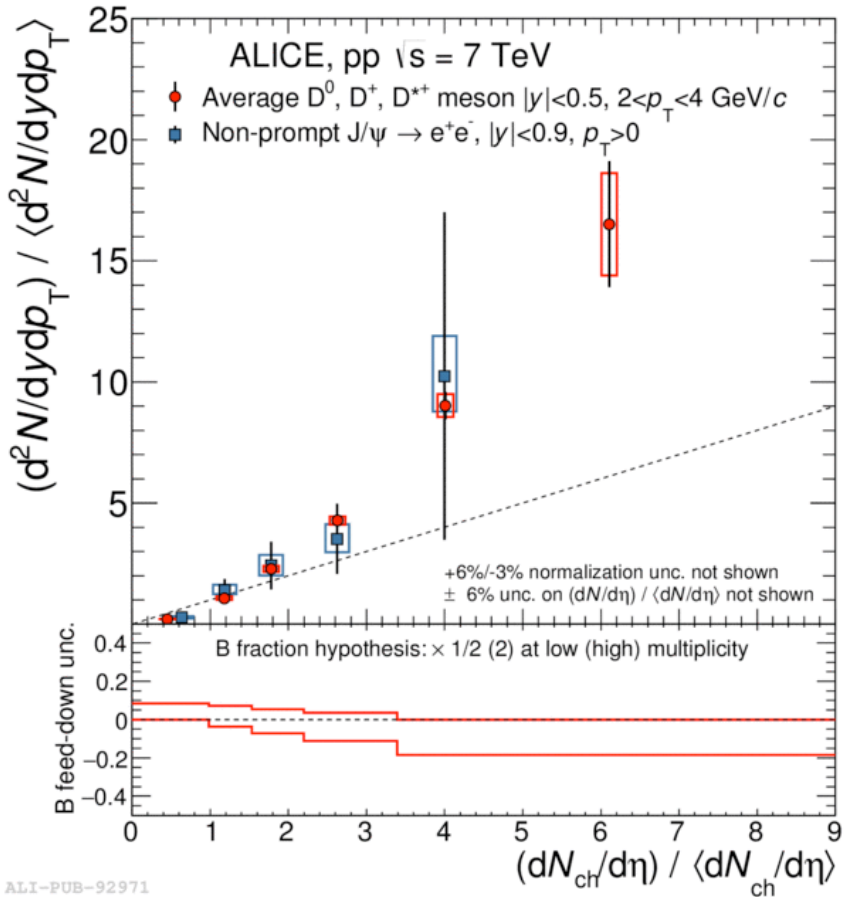




- Qualitatively similar faster than linear increase for heavy-flavour electron yield as a function of multiplicity
- Described by EPOS, better agreement with hydrodynamical evolution

Non-prompt J/ψ yield vs $dN_{ch}/d\eta$





- Non-prompt J/ψ yield determined from simultanious fit to invariant mass of e^+e^- pairs and pseudo-proper decay length (inclusive j/psi here?)

- **Similar increase of yield** as function of multiplicity to D-mesons
  →Most likely related to the $c\bar{c}$ and $b\bar{b}$ production processes, and is not significantly influenced by hadronisation