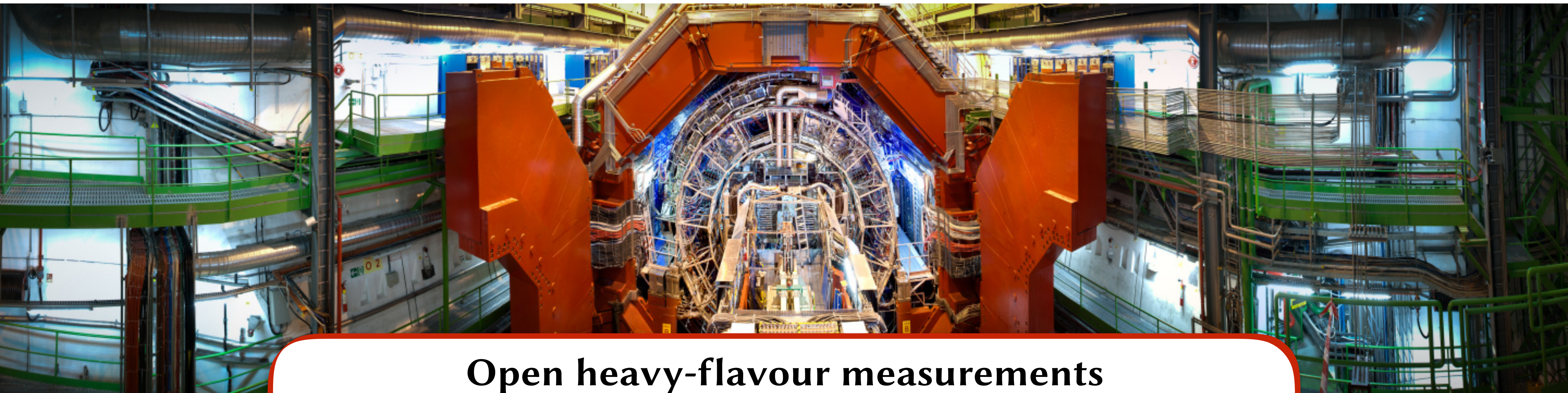


Open heavy-flavour measurements in proton-proton collisions with ALICE at the LHC

Julien Hamon[1], Andrea Rossi [2], for the ALICE Collaboration

1. University of Strasbourg

2. University of Padua

5 July 2018

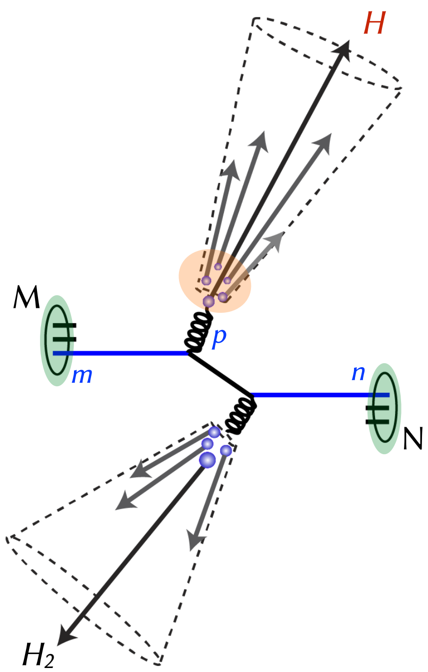
"Strong interactions and hadron physics"

Julien.Hamon@cern.ch

Heavy quarks in proton-proton collisions

Test for Quantum ChromoDynamics (QCD): perturbative processes ($m_{c,b} >> \Lambda_{QCD}$)

Charm ~ 1.3 GeV/c^2
Beauty ~ 4.2 GeV/c^2



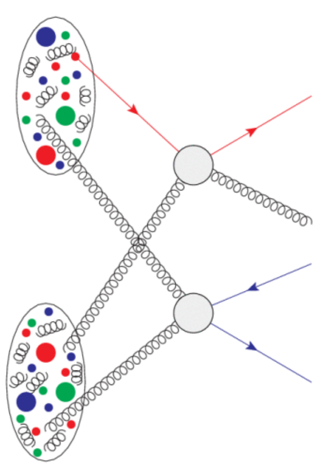
Factorisation theorem:

$$\sigma_{\mathrm{M+N}\to\mathrm{H+X}} = f_i^{\mathrm{M}}(x_m, Q^2)\, f_j^{\mathrm{N}}(x_n, Q^2) \otimes \sigma_{m,n\to p}(x_m, x_n, Q^2) \otimes D_{p\to H}(z_{H/p}, Q^2)$$

Parton distribution function (PDF) — Partonic hard scattering (pQCD) — Fragmentation function (FF)

FONLL: JHEP 10 (2012) 137 and references therein ***GM-VFNS:*** Eur. Phys. J. C72 (2012) 2082

- Production cross section of heavy-flavour hadrons down to p_{T} ~ 0 GeV/c
- Production ratios between various **energies** and **rapidity regions**
  → **gluon distribution functions** Cacciari et al.: Eur. Phys. J. C75 (2015) 610
- Production ratios of hadron **species** → **charm hadronisation**
  see also C. Bedda's talk (Friday)



Interplay between soft/hard processes:

- Production cross sections as a function of the **particle multiplicity of the collision**
- Role of **multi-parton interactions (MPI)**

Charm jets & fragmentation properties:

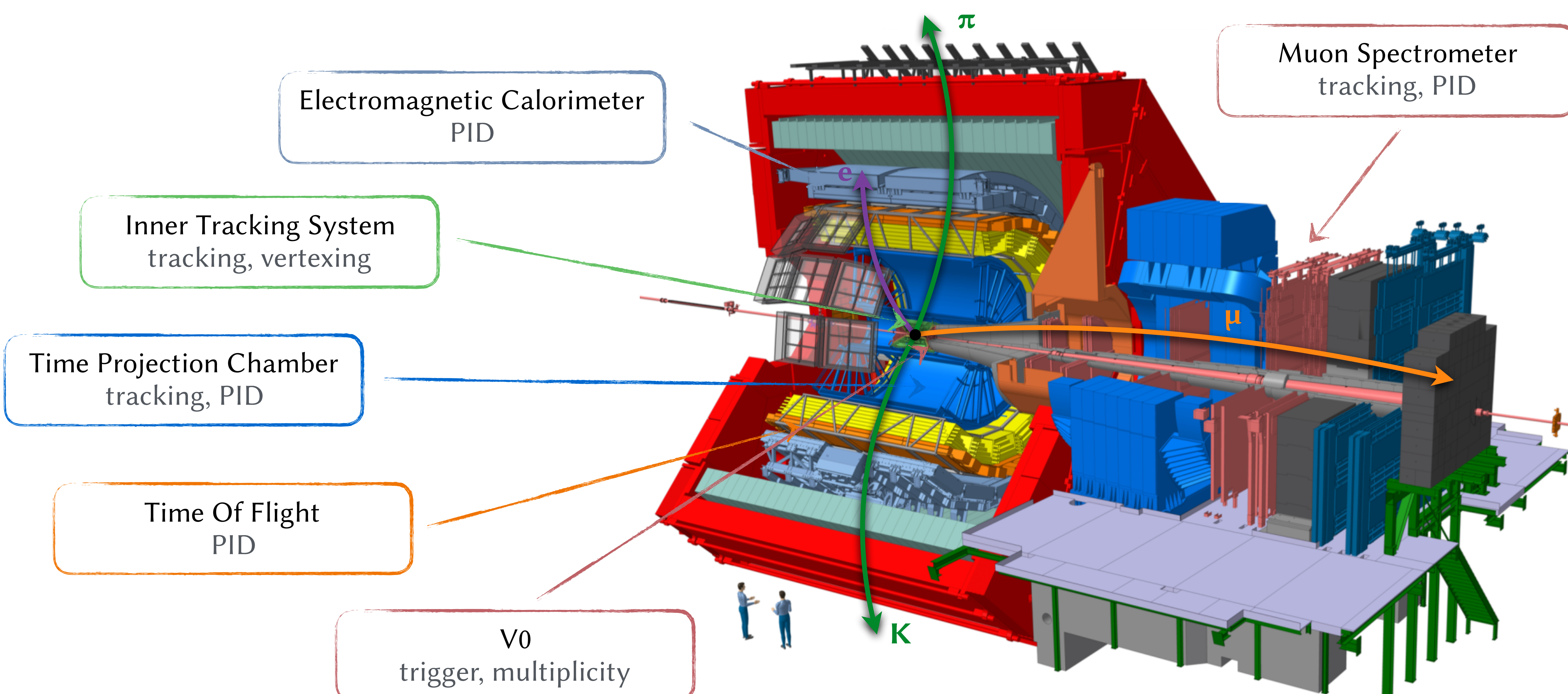
- D-meson-tagged **jets**
- D-meson azimuthal **correlations** with hadrons

A Large Ion Collider Experiment

$D^0\,(c\bar{u}) \longrightarrow K^-\pi^+$	1865 MeV/c^2	3.93 ± 0.04 %
$D^+\,(c\bar{d}) \longrightarrow K^-\pi^+\pi^+$	1869 MeV/c^2	9.46 ± 0.24 %
$D_s^+\,(c\bar{s}) \longrightarrow (\phi \longrightarrow K^+K^-)\pi^+$	1968 MeV/c^2	2.27 ± 0.08 %
$D^{*+}\,(c\bar{d}) \longrightarrow D^0\pi^+$	2010 MeV/c^2	67.7 ± 0.5 %
$\Lambda_c^+\,(cud) \longrightarrow pK^-\pi^+,\ pK_S^0$	2286 MeV/c^2	6.23 ± 0.33 %, 1.58 ± 0.08 %
$\Xi_c^0\,(cds) \longrightarrow e{+}\Xi^-\nu_e$	2470 MeV/c^2	—

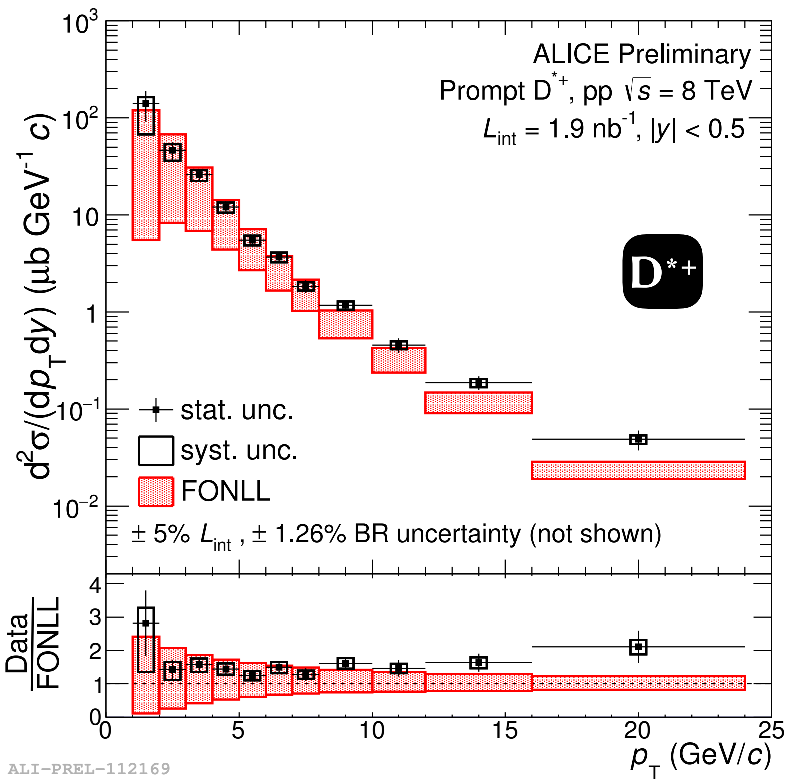
Open-charm hadrons studied in ALICE:

- Decay muons: D, Λ_c, B,... $\longrightarrow$ **μ** + X in $-4 < \eta < -2.5$
- Decay electrons: D, Λ_c, B,... $\longrightarrow$ **e** + X in $|\eta| < 0.9$
- Exclusive reconstruction of charmed hadron hadronic decays channels (**$\pi^\pm$**, **$K^\pm$**, **p**) in $|y| < 0.5$

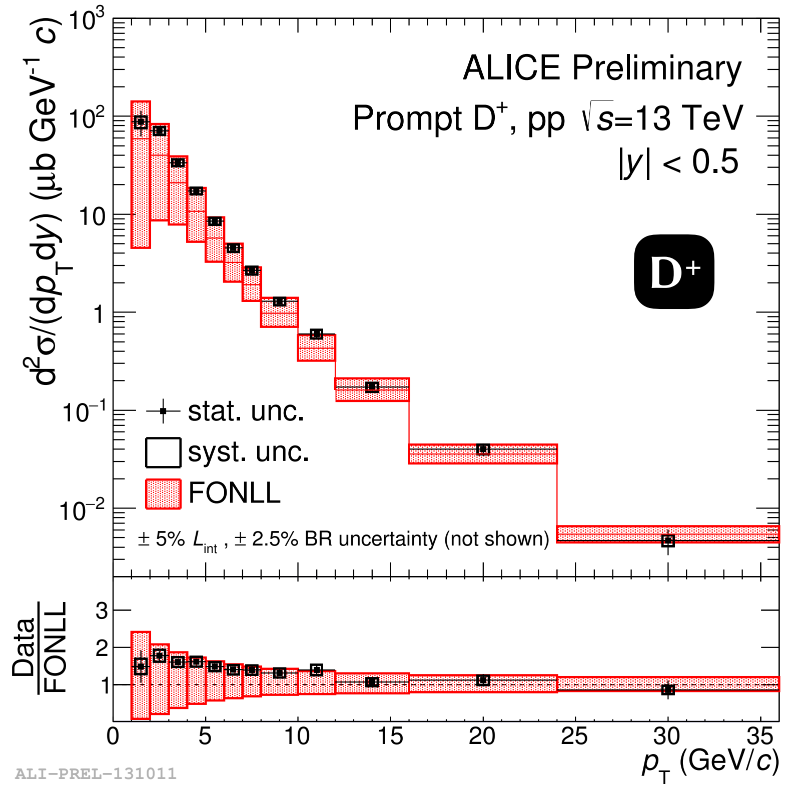


D-meson production cross section

$\sqrt{s}$ = 8 TeV



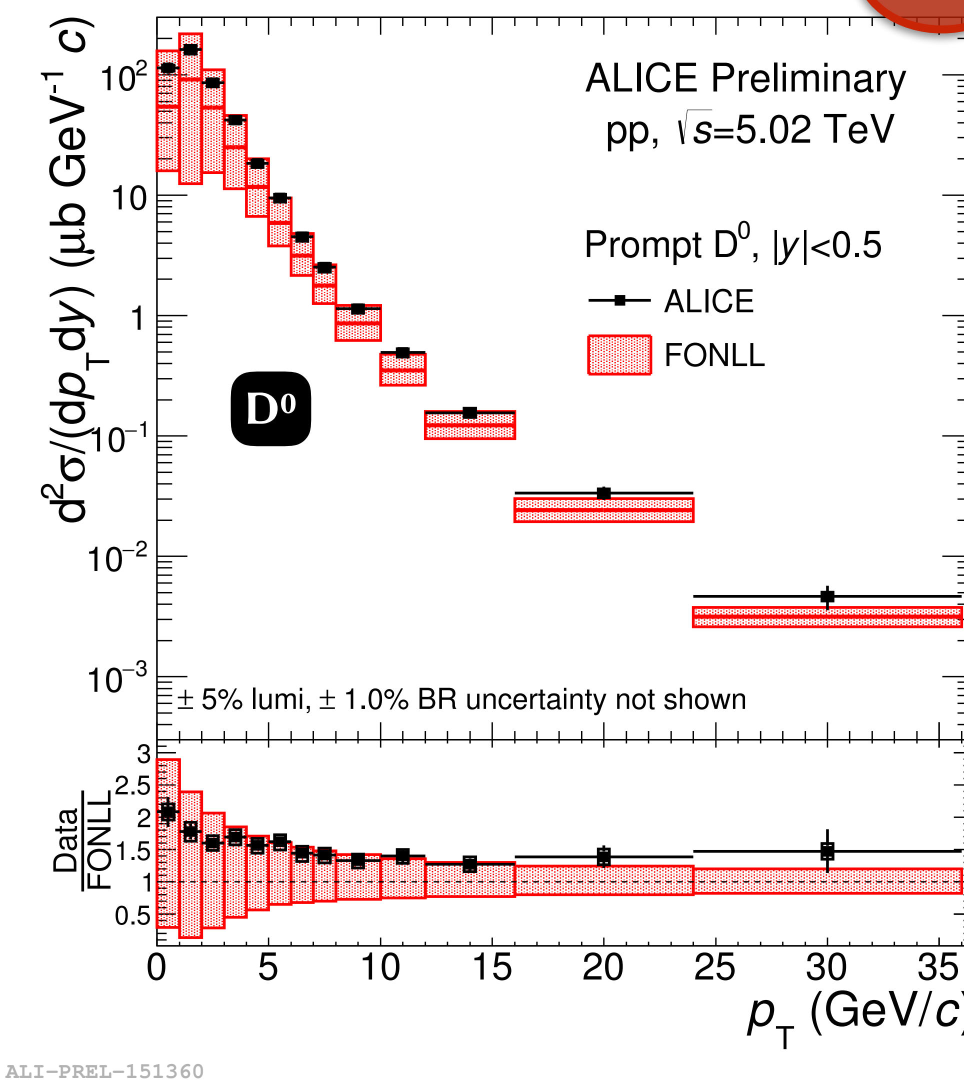
$\sqrt{s}$ = 13 TeV



$\sqrt{s}$ = 5.02 TeV

ALICE-PUBLIC-2018-006

New



pQCD models at LHC energies:

D meson cross sections well described by pQCD-based models at all LHC energies

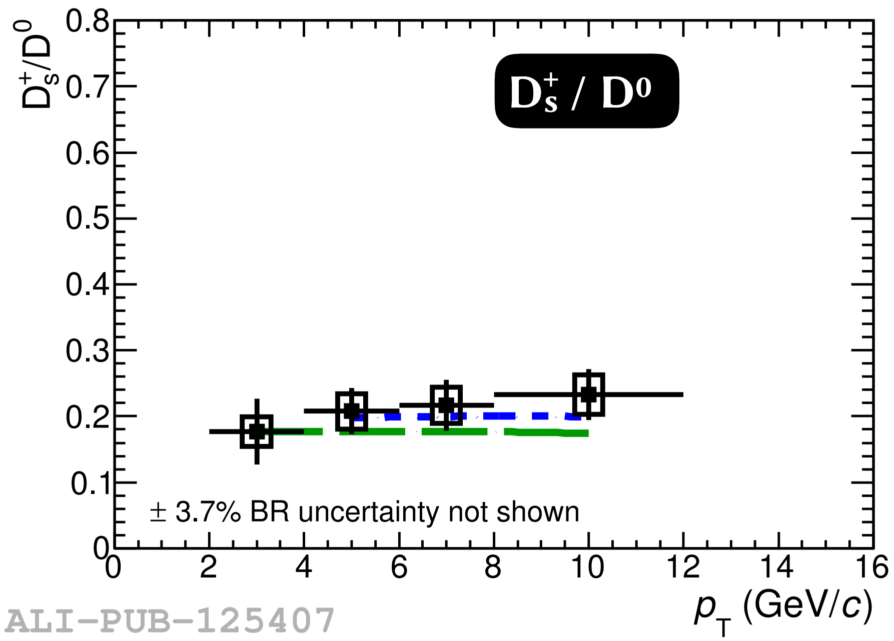
- ✔ pQCD calculations (FONLL) over a **wide p_T range** and down to **$p_T \sim 0$ GeV/c**
- ✔ Data uncertainties are smaller than uncertainties in pQCD calculations

D-meson production: different species

D-meson productions — *species*, *rapidity* and *energy* dependence — further constrain calculations

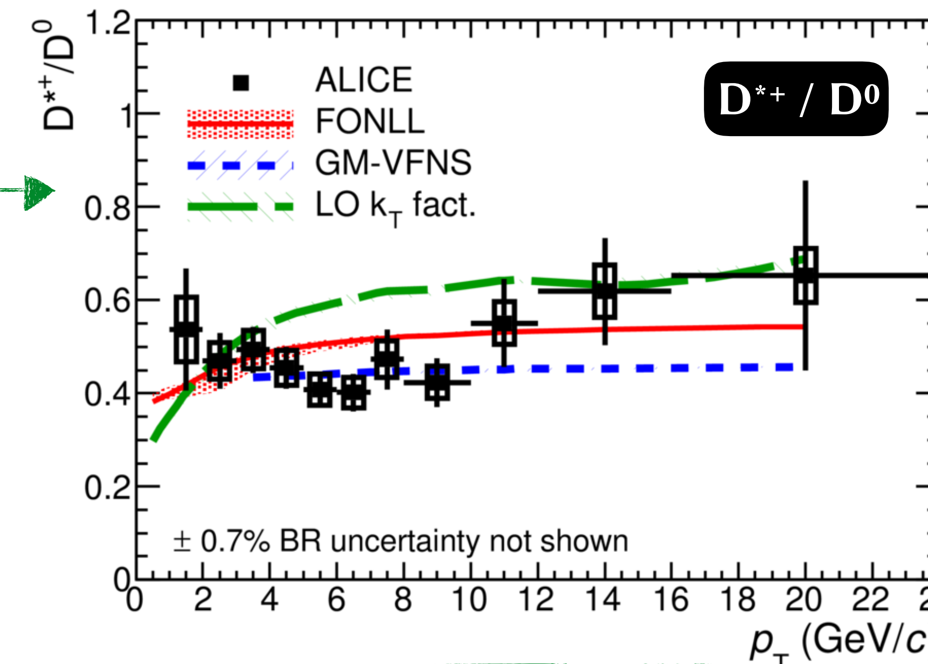
- ***D-meson species dependence:***

  → Mainly depend only on branching fractions and fragmentation functions



$\sqrt{s}$ = 7 TeV

Eur.Phys.J. C77 (2017) 8, 550



$\sqrt{s}$ = 13 TeV

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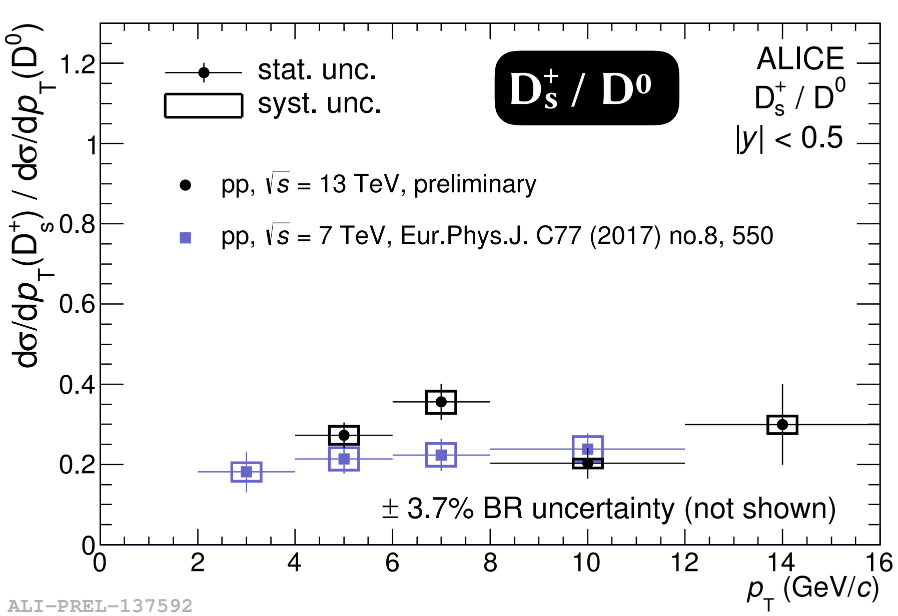
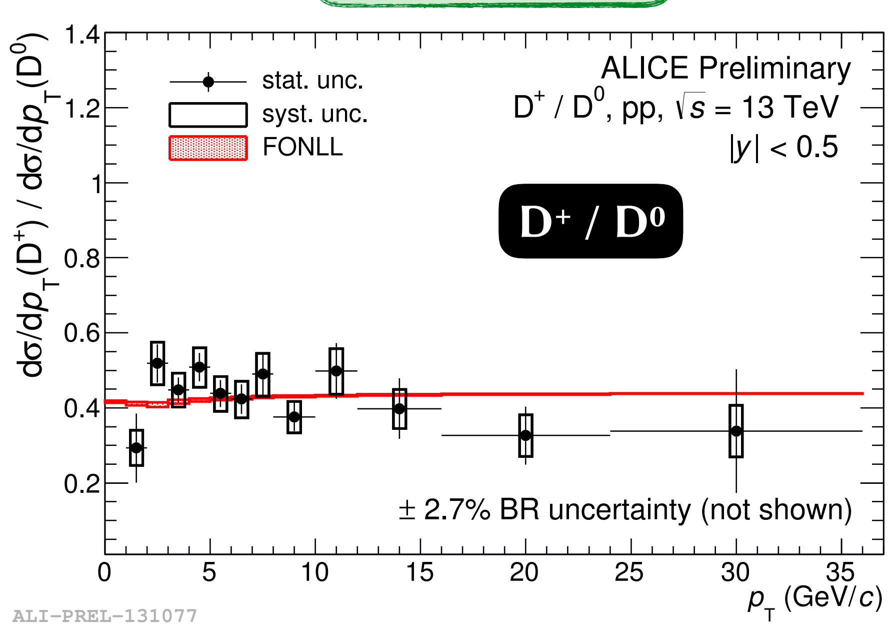
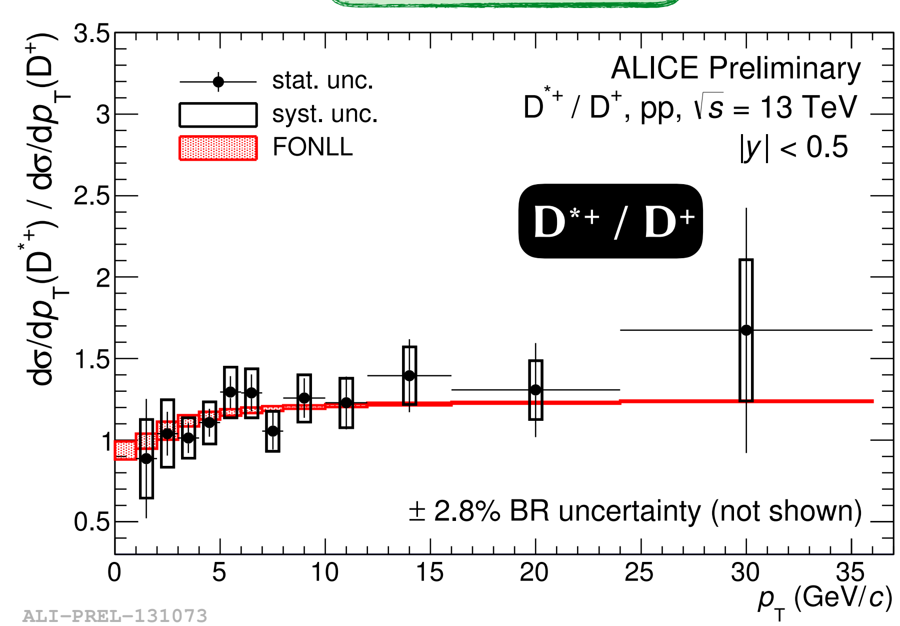






D-meson production: energy dependence

D-meson productions — *species*, *rapidity* and *energy* dependence — further constrain calculations

- ***D-meson species dependence:***

  → Mainly depend only on branching fractions and fragmentation functions

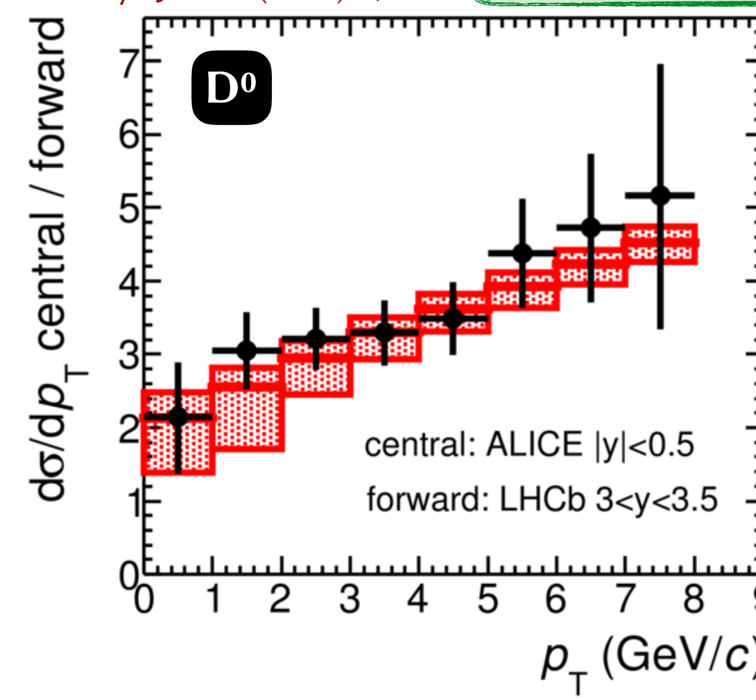
- ***D-meson energies and rapidity dependence:***

  → Double $\sqrt{s}$ and y ratio: independence of renormalisation/factorisation scales, branching ratios, ...

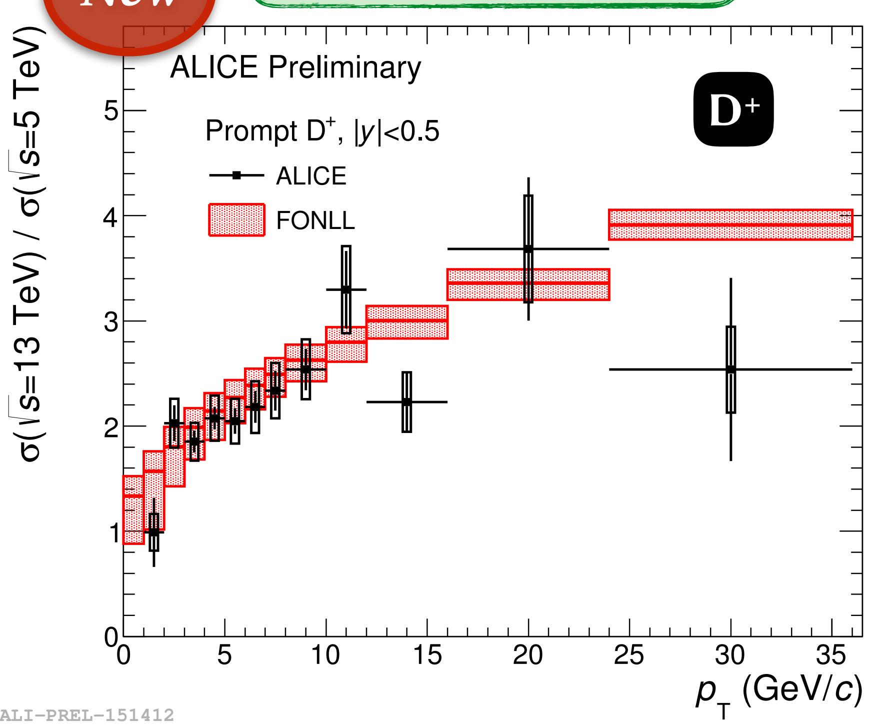
  → sensitivity to gluon PDF down to $x_B \sim 10^{-4}$ when $p_T(D) \sim 0$ GeV/c

$\sqrt{s}$ = 7 TeV

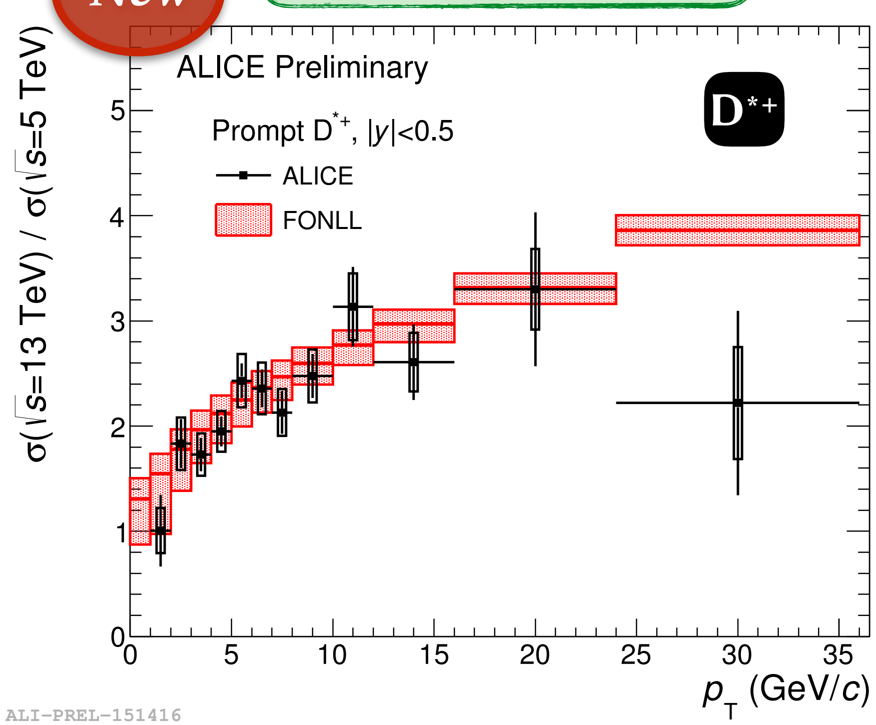
Eur.Phys.J. C77 (2017) 8, 550



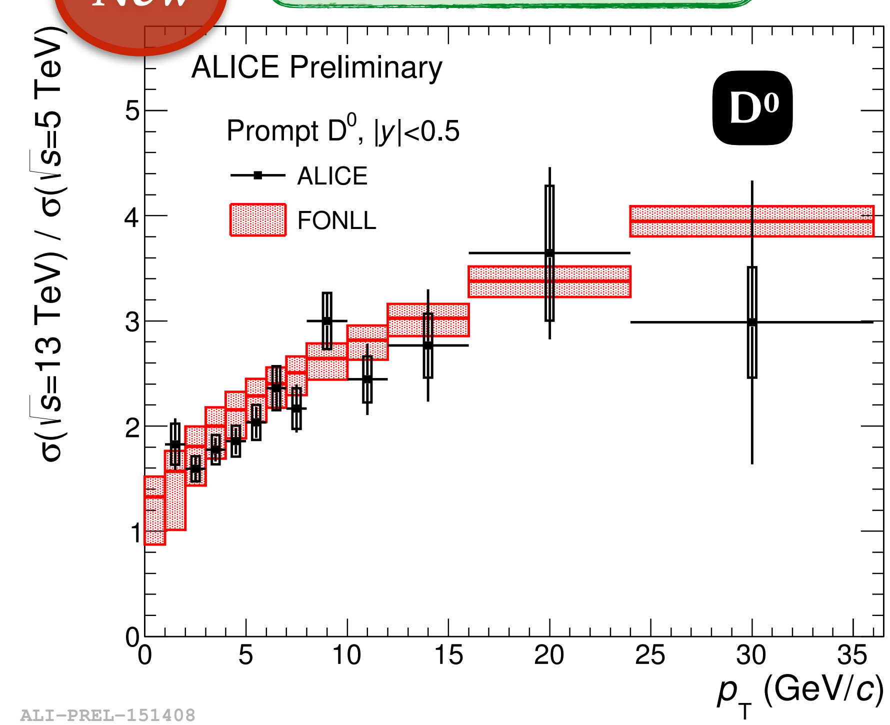
New — $\sqrt{s}$ = 13 / 5.02 TeV



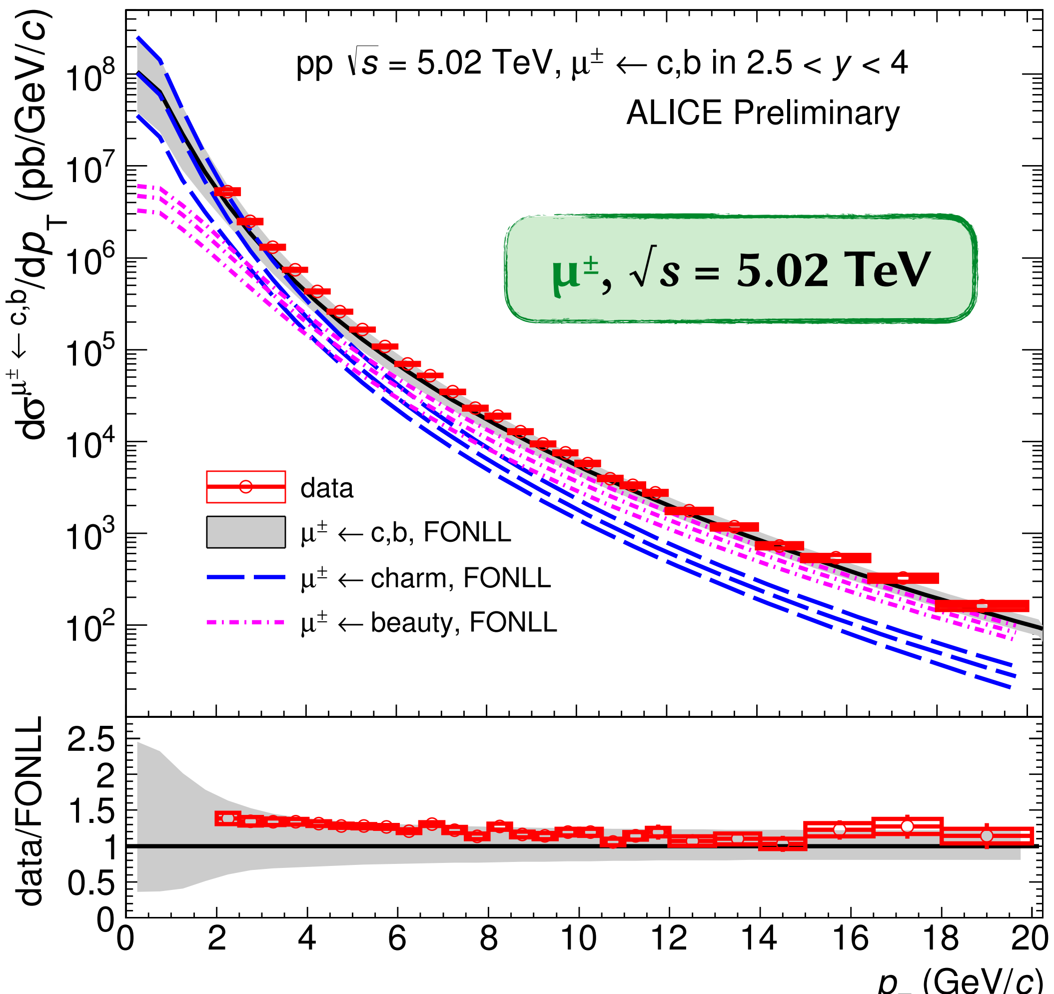
New — $\sqrt{s}$ = 13 / 5.02 TeV



New — $\sqrt{s}$ = 13 / 5.02 TeV



Heavy flavour semi-leptonic decays

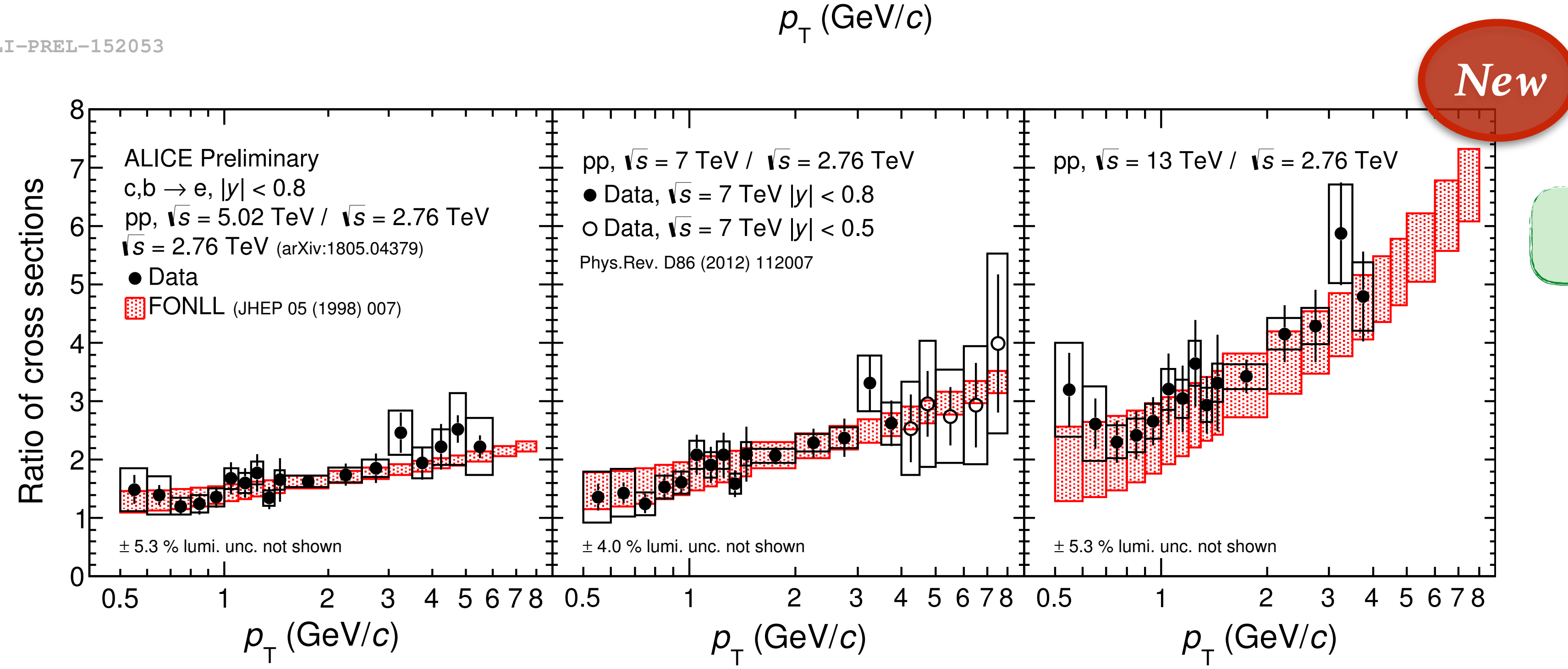


ALI-PREL-152053

Similar measurements are performed for semi-leptonic decays:

- $\mu \leftarrow$ **c, b** at forward rapidity ($2.5 < y < 4$)
- **e** $\leftarrow$ **c, b** at central rapidity ($|y| < 0.8$)

Insights into relative abundance of **charm** and **beauty quark** production



e$^{\pm}$, $\sqrt{s}$ **= (5.02, 7, 13) / 2.76 TeV**

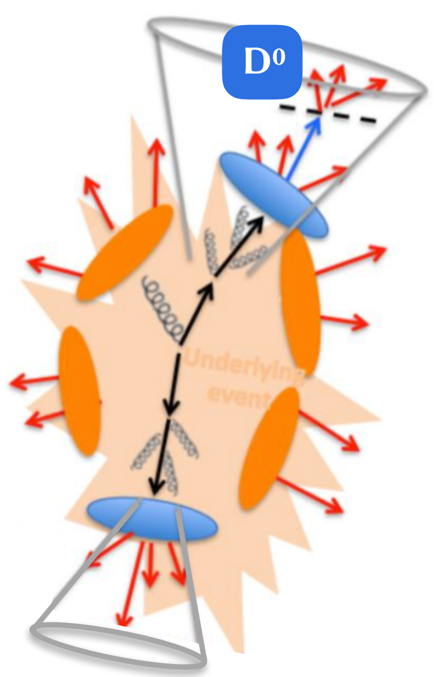
Down to p_{T} = 500 MeV/c

ALI-PREL-146830

$\sqrt{s}$ = 7 TeV

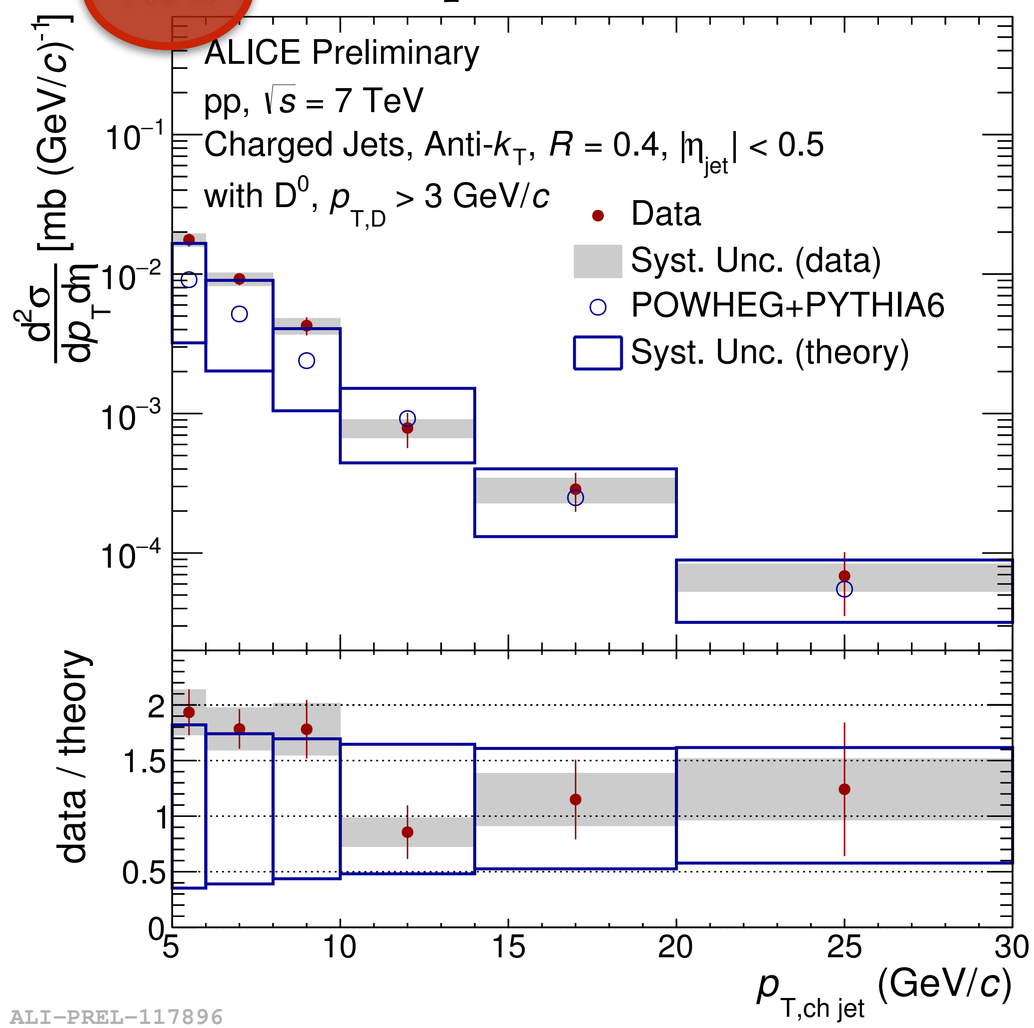
D^0-meson-tagged jet

Charm jet tagged by the presence of a D^0 meson among the jet constituents



New

D^0 p_T > 3 GeV/c



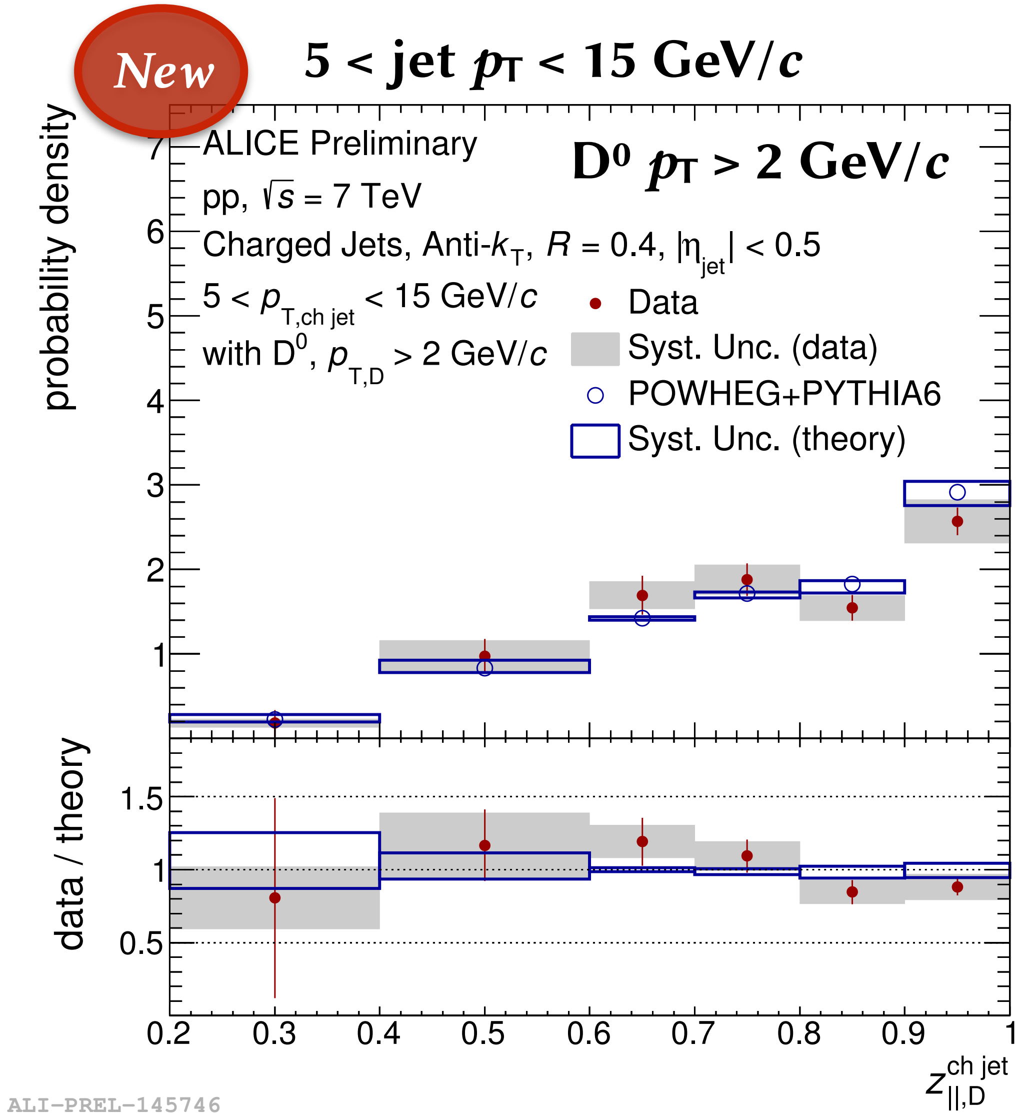
POWHEG: JHEP 0711 (2007) 070
PYTHIA6: JHEP 05 (2006) 026

Good agreement of data with POWHEG + PYTHIA6 predictions
(NLO generator) + (parton shower + hadronization)

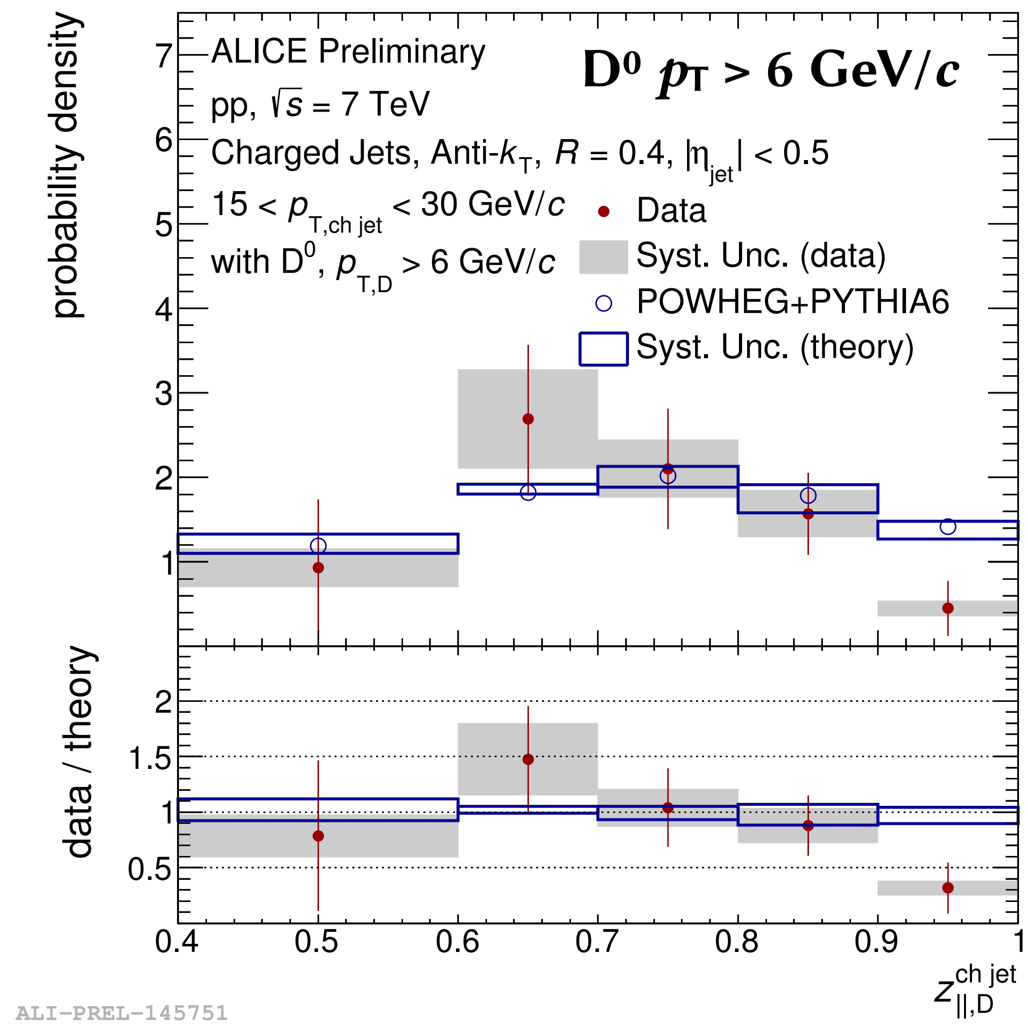
- Kinematics reach and precision can be **extended** with the $\sqrt{s}$ = 5.02 and 13 TeV datasets

D^0-meson-tagged jet

5 < jet p_T < 15 GeV/c



15 < jet p_T < 30 GeV/c



POWHEG: JHEP 0711 (2007) 070
PYTHIA6: JHEP 05 (2006) 026

$$z_{||,\mathrm{D}}^{\mathrm{ch\ jet}} = \frac{\vec{p}_{\mathrm{ch\ jets}} \cdot \vec{p}_{\mathrm{D}}}{\vec{p}_{\mathrm{ch\ jets}} \cdot \vec{p}_{\mathrm{ch\ jets}}}$$

Charged jet momentum fraction carried by the D^0 meson

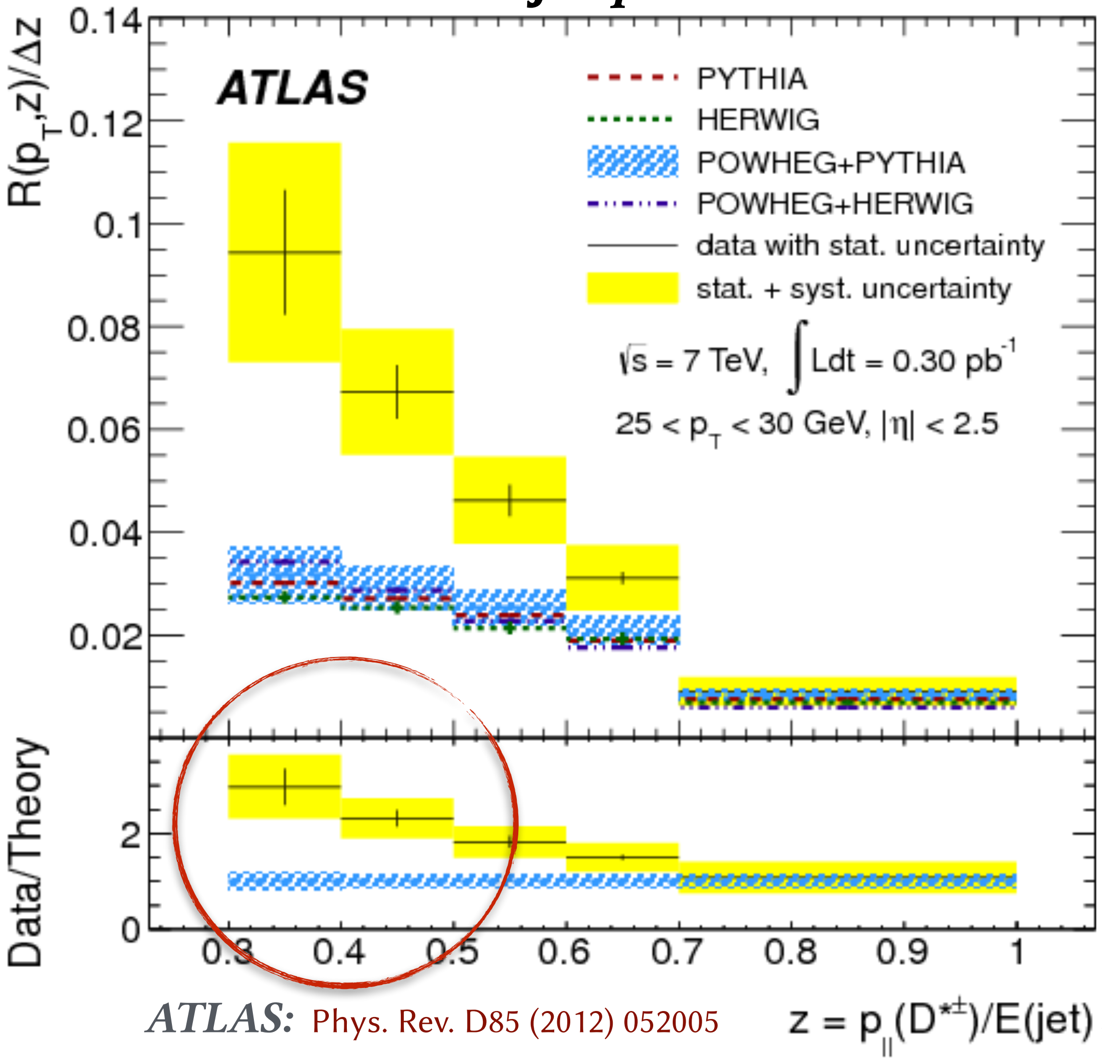
Good agreement of data with POWHEG + PYTHIA6 predictions
(NLO generator) + (parton shower + hadronization)

- Kinematics reach and precision can be **extended** with the $\sqrt{s}$ = 5.02 and 13 TeV datasets

$\sqrt{s}$ = 7 TeV

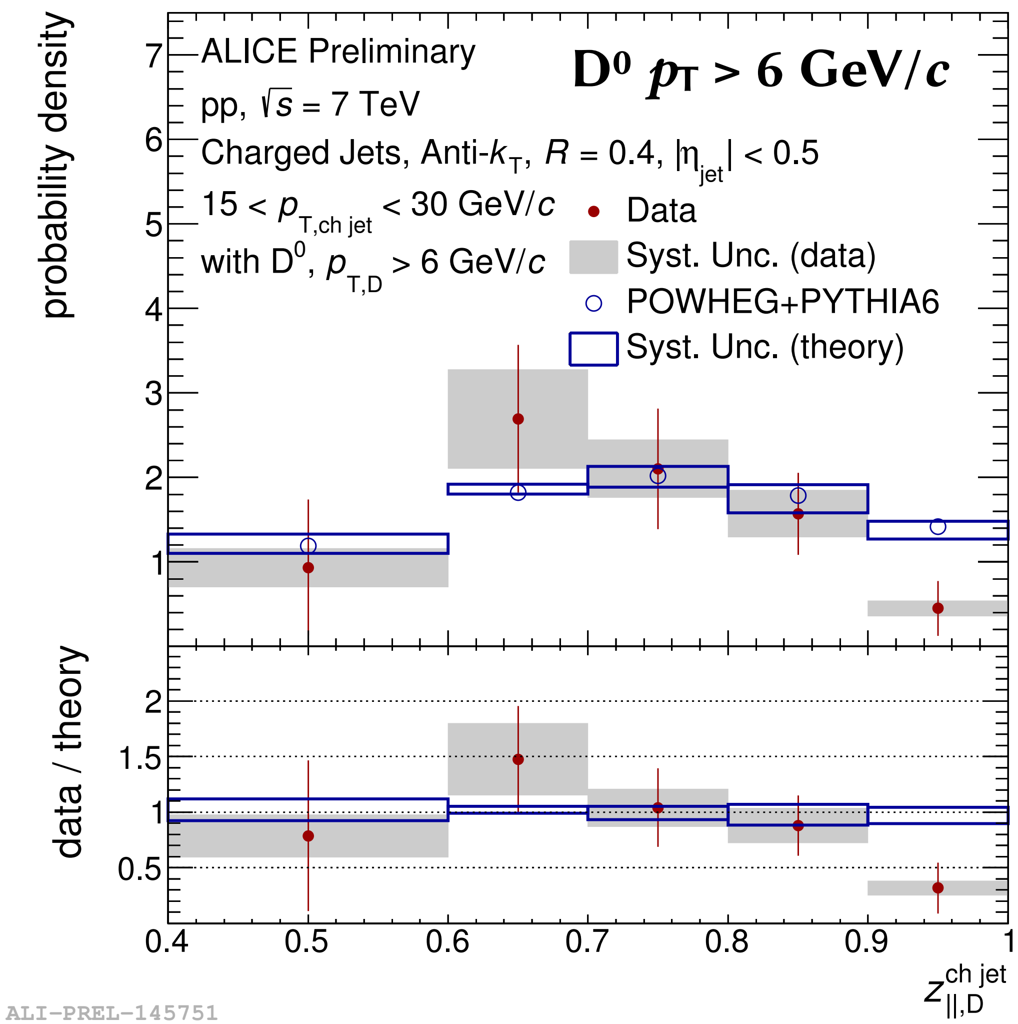
D⁰-meson-tagged jet

25 < D*+ jet p_T < 30 GeV/c



ATLAS: Phys. Rev. D85 (2012) 052005

15 < jet p_T < 30 GeV/c



POWHEG: JHEP 0711 (2007) 070

PYTHIA6: JHEP 05 (2006) 026

$$z_{||,\mathrm{D}}^{\mathrm{ch\ jet}} = \frac{\vec{p}_{\mathrm{ch\ jets}} \cdot \vec{p}_{\mathrm{D}}}{\vec{p}_{\mathrm{ch\ jets}} \cdot \vec{p}_{\mathrm{ch\ jets}}}$$

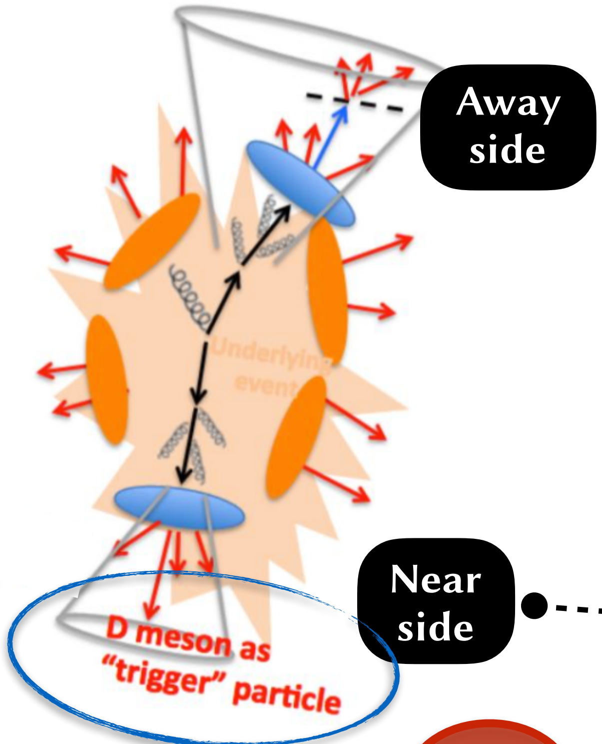
Charged jet momentum fraction carried by the D⁰ meson

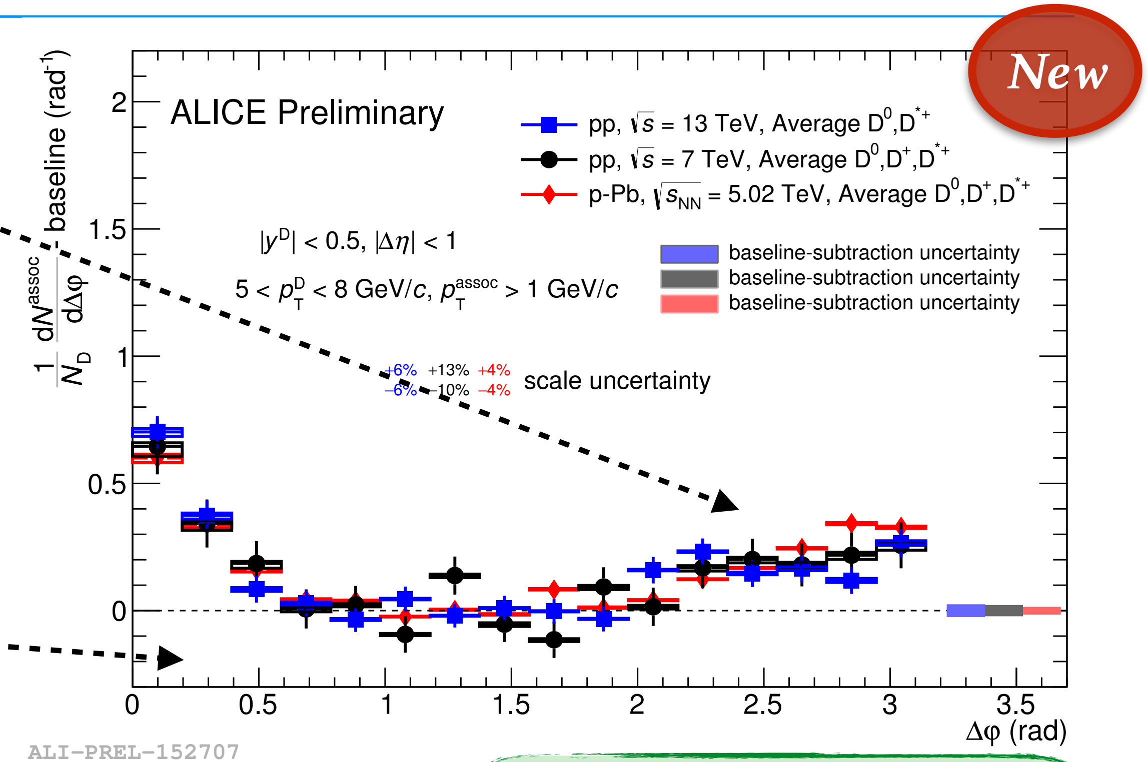
Good agreement of data with POWHEG + PYTHIA6 predictions

(NLO generator) + (parton shower + hadronization)

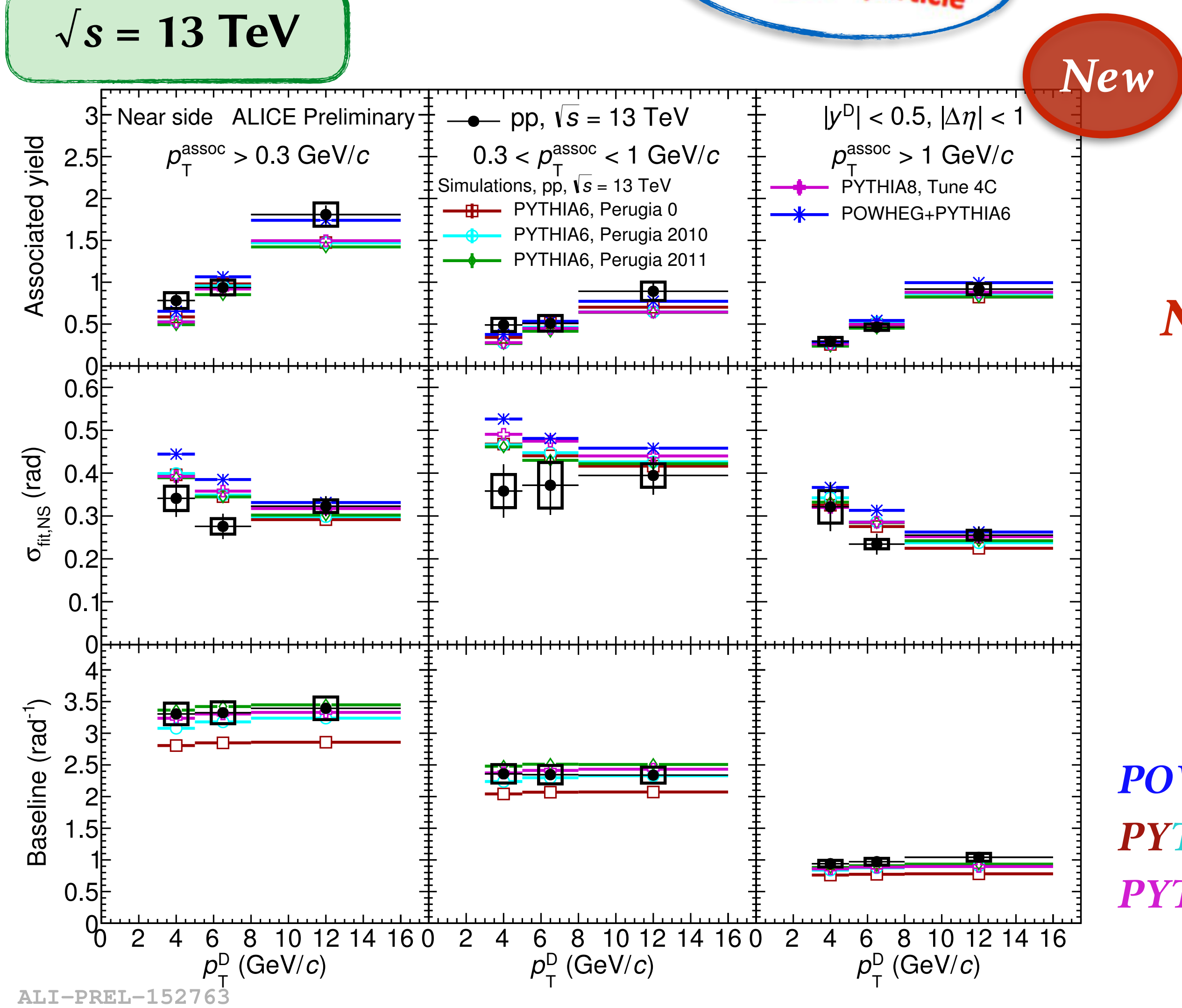
- Kinematics reach and precision can be **extended** with the $\sqrt{s}$ = 5.02 and 13 TeV datasets

Azimuthal correlations of D mesons with charged particles





$\sqrt{s}$ = 13 TeV



pp, $\sqrt{s}$ = 13 TeV
pp, $\sqrt{s}$ = 7 TeV
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Near side observables:

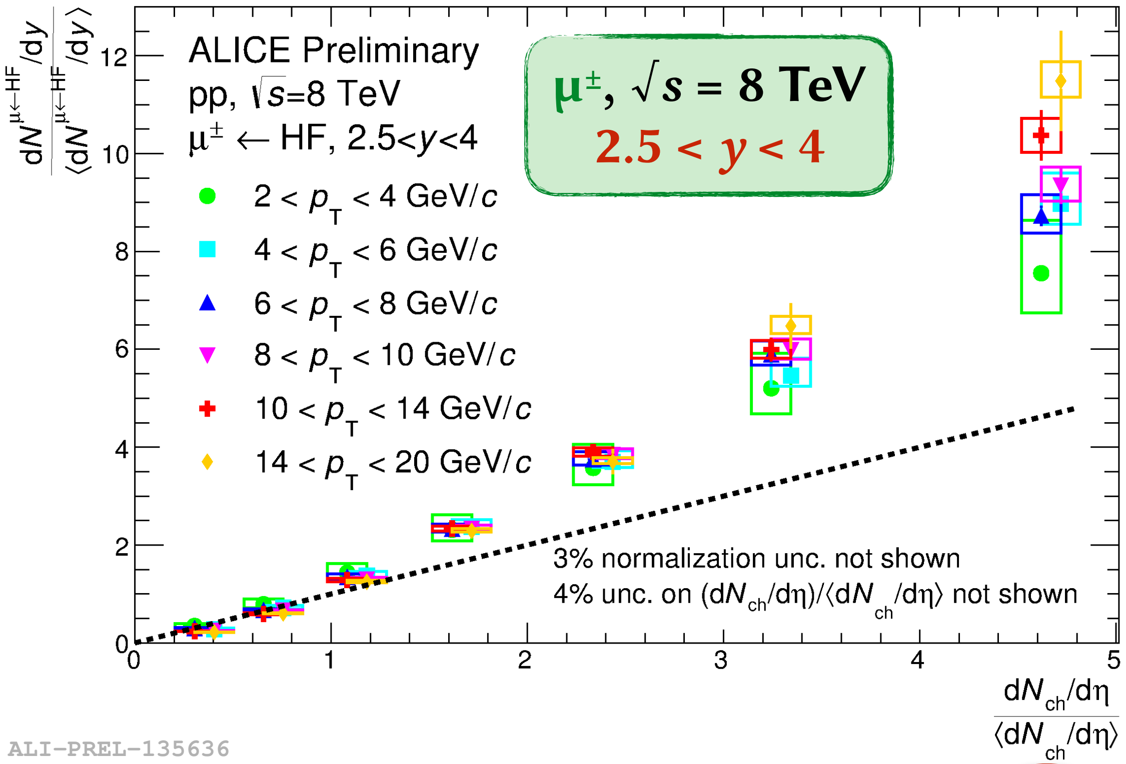
- Yields and width extracted **from fit**

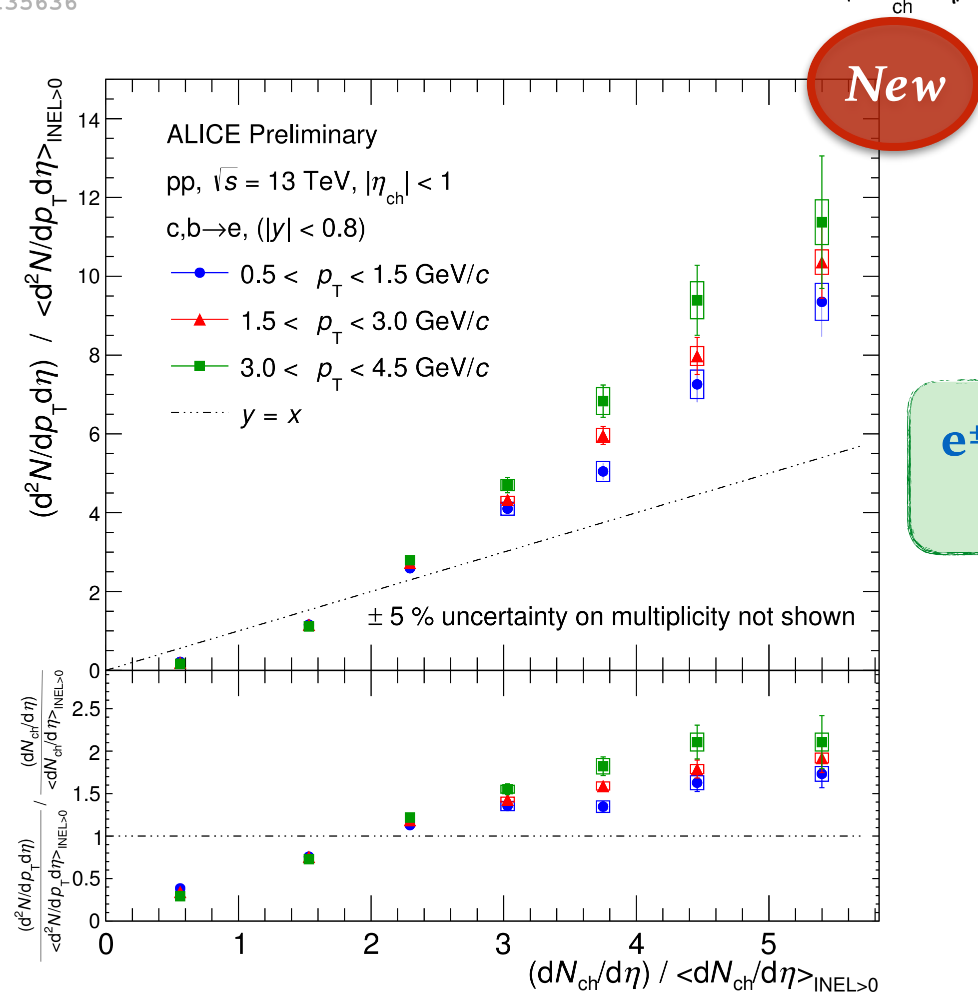
$$f(\Delta\varphi) = c + \frac{Y_{NS}}{\sqrt{2\pi}\sigma_{NS}} e^{\frac{(\Delta\varphi - \mu_{NS})^2}{2\sigma_{NS}^2}} + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}} e^{\frac{(\Delta\varphi - \mu_{AS})^2}{2\sigma_{AS}^2}}$$

- Models describe the data within uncertainties

POWHEG: JHEP 0711 (2007) 070
PYTHIA6: JHEP 05 (2006) 026
PYTHIA8: Comput. Phys. Commun. 191 (2015) 159

Heavy flavour versus charged-particle multiplicity





Self-normalised yield of **heavy flavour** versus **multiplicity**:

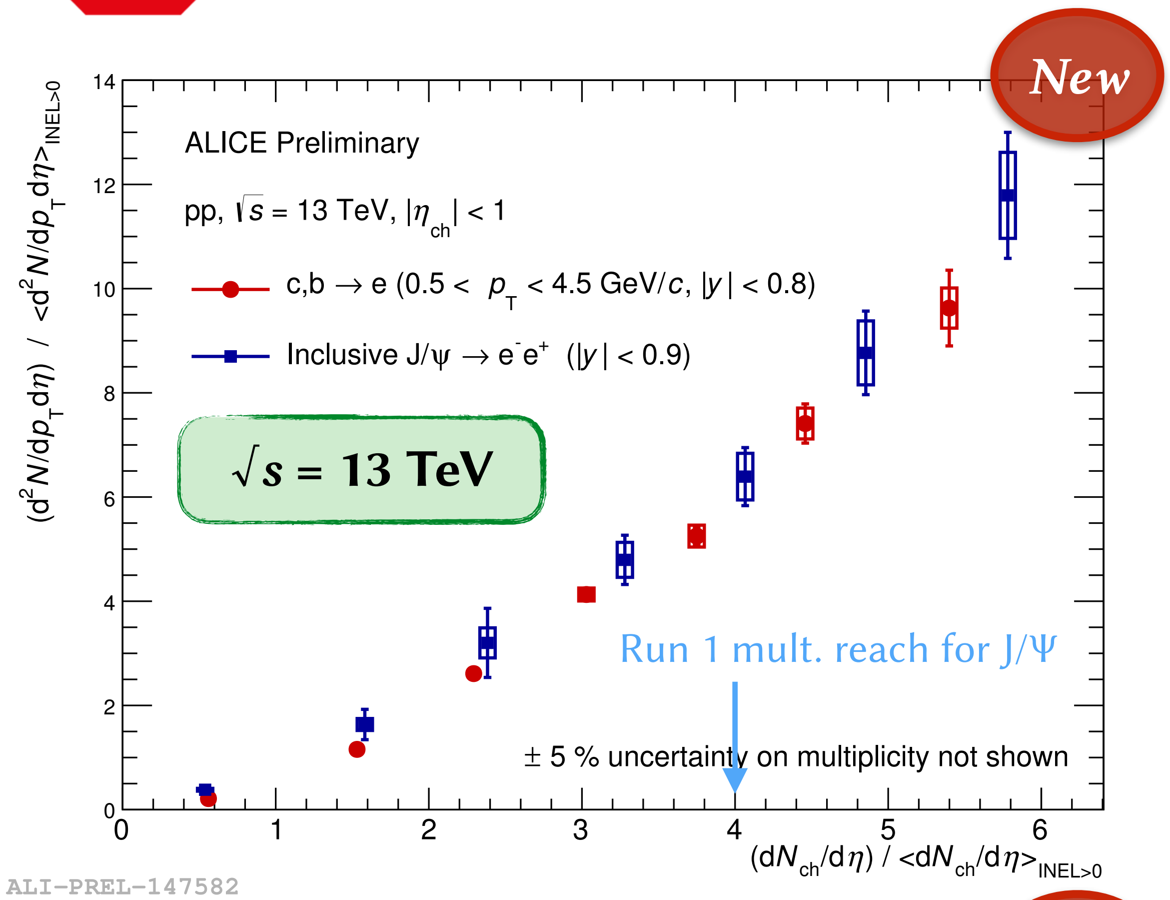
- **μ ← c, b** at forward rapidity ($2.5 < y < 4$)
- **e ← c, b** at central rapidity ($|y| < 0.8$)

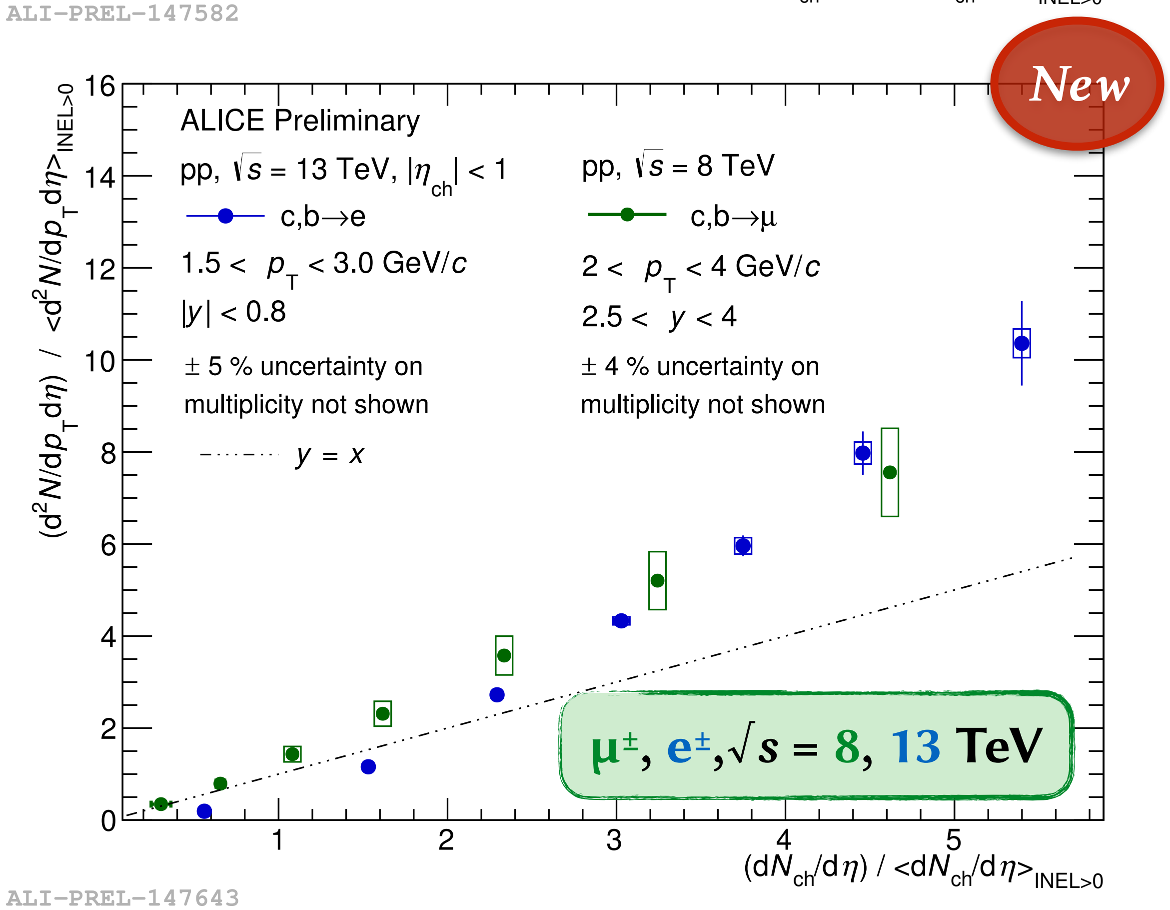
e±, √s = 13 TeV
|y| < 0.8

Faster than linear increasing trend with **multiplicity**:

- Hint of steeper increase for **higher p_T** intervals

Heavy flavour versus charged-particle multiplicity





Self-normalised yield of **heavy flavour** versus **multiplicity**:

- **μ ← c, b** at forward rapidity (2.5 < y < 4)
- **e ← c, b** at central rapidity ($|y|$ < 0.8)

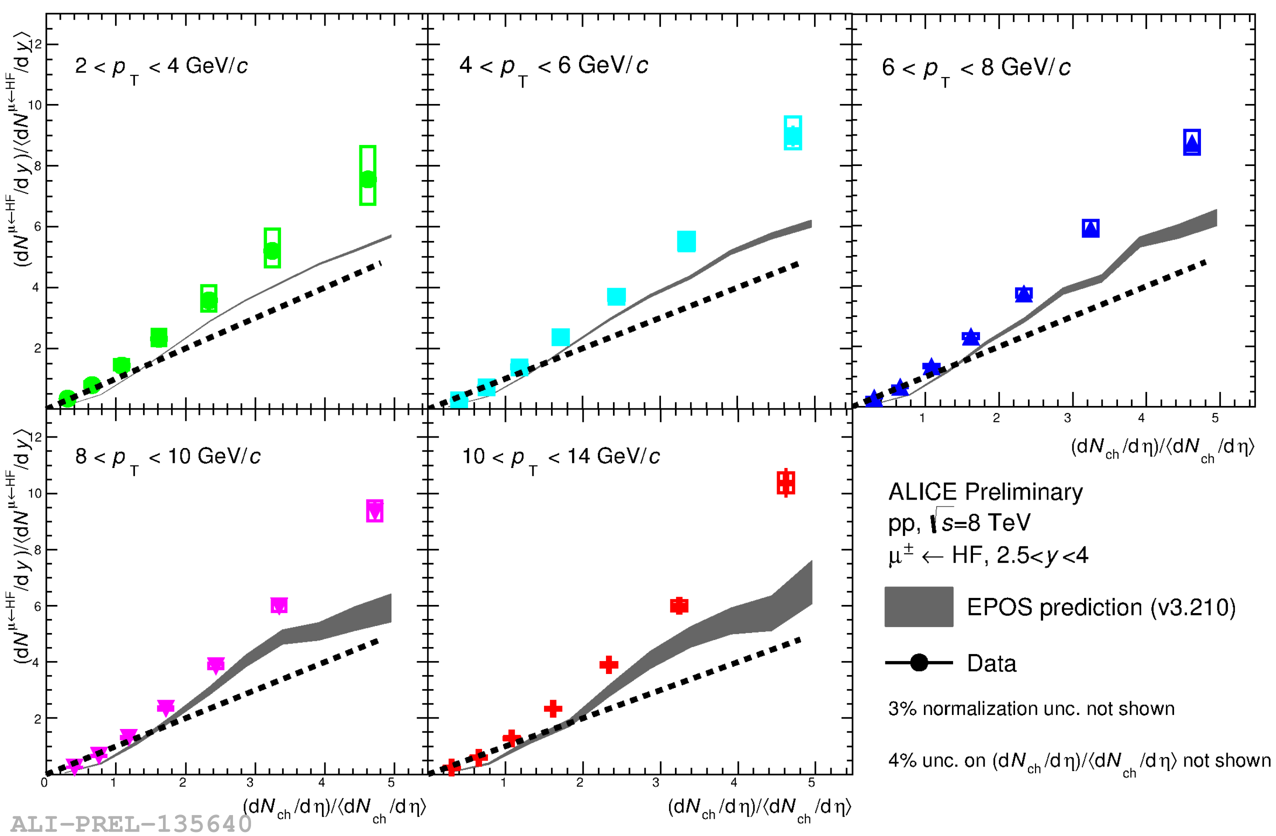
Faster than linear increasing trend with **multiplicity**:

- Hint of steeper increase for **higher p_T** intervals
- Similar results for **e ← c, b** and (inclusive) **J/Ψ ← c, b**
- Different trend of **μ ← c, b** (forward *y*, $\sqrt{s}$ = 8 TeV) with respect to **e ← c, b** (central *y*, $\sqrt{s}$ = 13 TeV) at low multiplicity

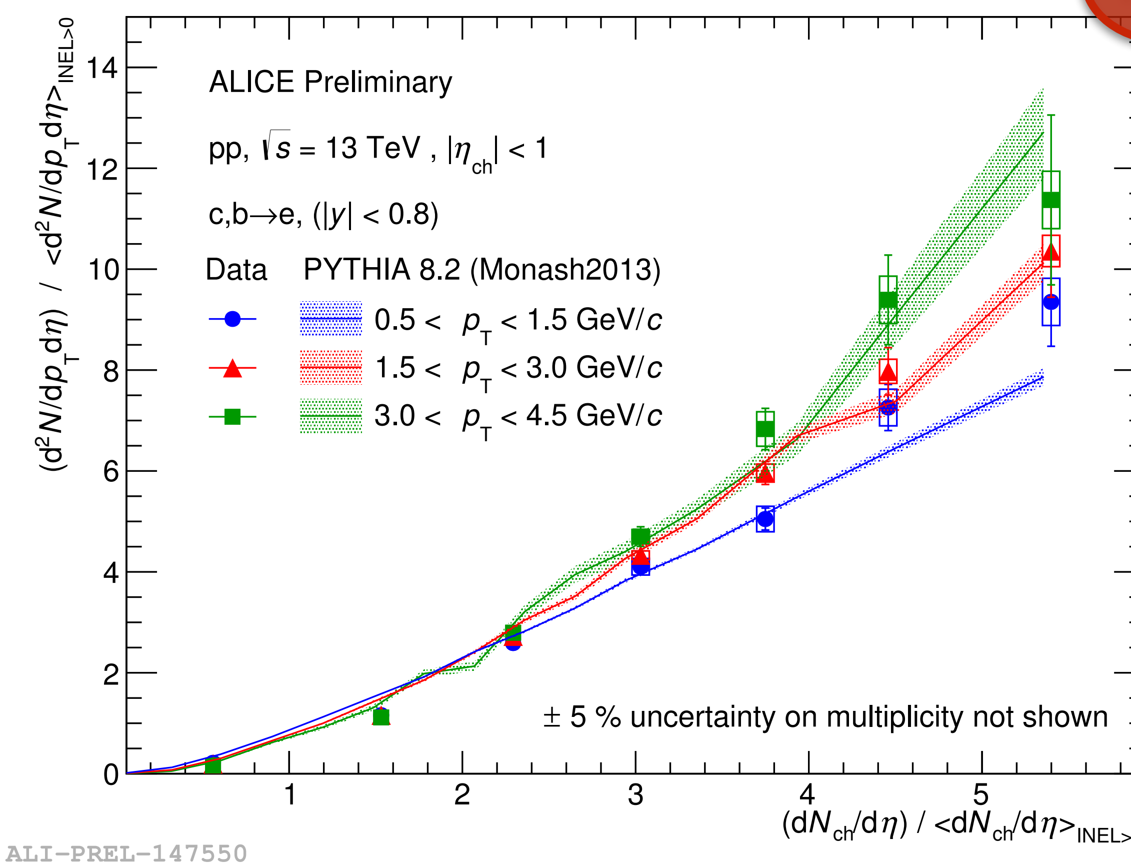
→ *Possibly smaller* **jet bias** *and* **autocorrelation effects** *for the* **μ ← c, b** *measurement at* ***forward y***

Heavy flavour versus charged-particle multiplicity

$\mu^{\pm}$, $\sqrt{s}$ = 8 TeV



$e^{\pm}$, $\sqrt{s}$ = 13 TeV *New*



Data compared to EPOS 3.210 (including hydrodynamics) and PYTHIA8

- Fair agreement of **EPOS 3** at low multiplicities, deviation at high multiplicities
- **PYTHIA8** qualitatively reproduces the data at all multiplicities

PYTHIA8: Comput. Phys. Commun. 191 (2015) 159
EPOS3.210: Phys. Rev. C 89 (2014) 064903

Conclusion and prospects

Open heavy flavours (HF) in proton-proton collisions:

- Efficient tool to investigate the interplay between **hard** and **soft** QCD processes

- Various measurements at several LHC energies: $\sqrt{s}$ = 2.76, 5, 7, 8, 13 TeV

Measurement	D mesons	e	μ
p_T-differential production cross sections	■	■	■
Production ratios amongst energies	■	■	■
Production ratios amongst HF hadron species	■		
HF inside charged jets	■		
HF-hadron azimuthal correlations	■		
Production versus charged-particle multiplicity	■	■	■

■ **D mesons (+ Λ_c^+) in $|y| < 0.5$**
■ **e ← c, b in $|y| < 0.8$**
■ **μ ← c, b in $2.5 < y < 4$**

Prospects:

- Run 2: additional datasets need to be analysed ⟶ better precision and more differential measurements

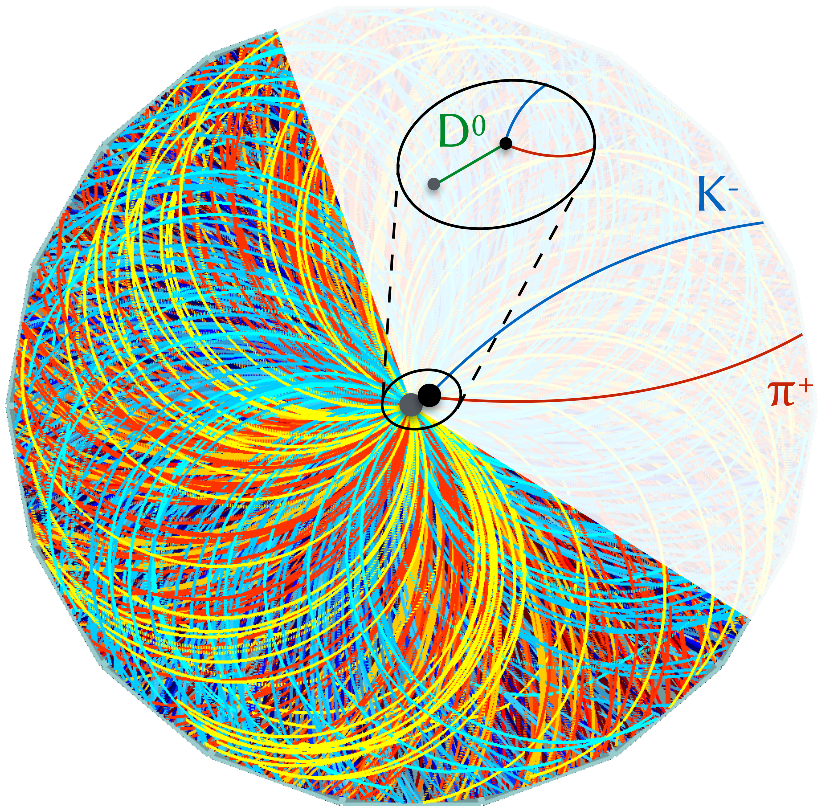
- Run 3: ALICE Upgrades will further improve the heavy-flavour hadron reconstruction

- Charmed baryons: heavy flavour measurements recently extended to Λ_c^+ and Ξ_c^+

Surprises with charm baryons ⟶ *C. Bedda's talk (Friday)*

Extra slides

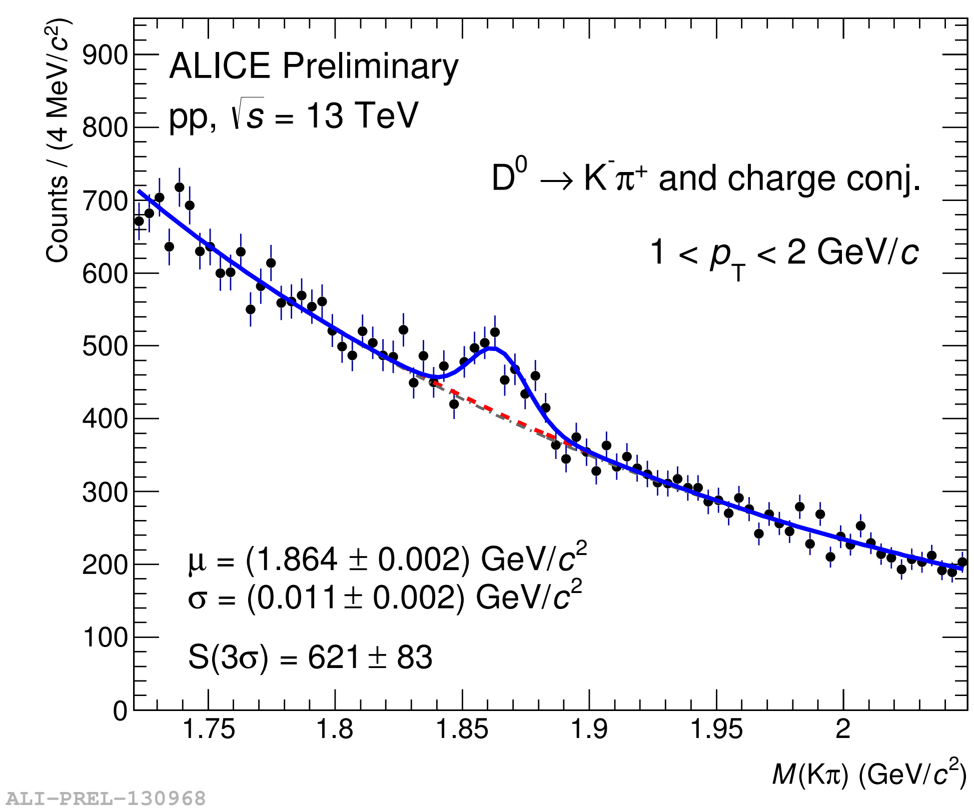
D-meson hadronic full reconstruction



✔	D^0 ($c\bar{u}$) ⟶ $K^-\pi^+$ (3.93 ± 0.04 %)	1864.8 MeV/c^2	$c\tau$ ~ 123 μm
✔	D^+ ($c\bar{d}$) ⟶ $K^-\pi^+\pi^+$ (9.46 ± 0.24 %)	1869.6 MeV/c^2	$c\tau$ ~ 312 μm
✔	D_s^+ ($c\bar{s}$) ⟶ (ϕ⟶ K^+K^-)π^+ (2.27 ± 0.08 %)	1968.3 MeV/c^2	$c\tau$ ~ 150 μm
✔	D^{*+} ($c\bar{d}$) ⟶ $D^0\pi^+$ (67.7 ± 0.5 %)	2010.3 MeV/c^2	$c\tau$ ~ 2 fm

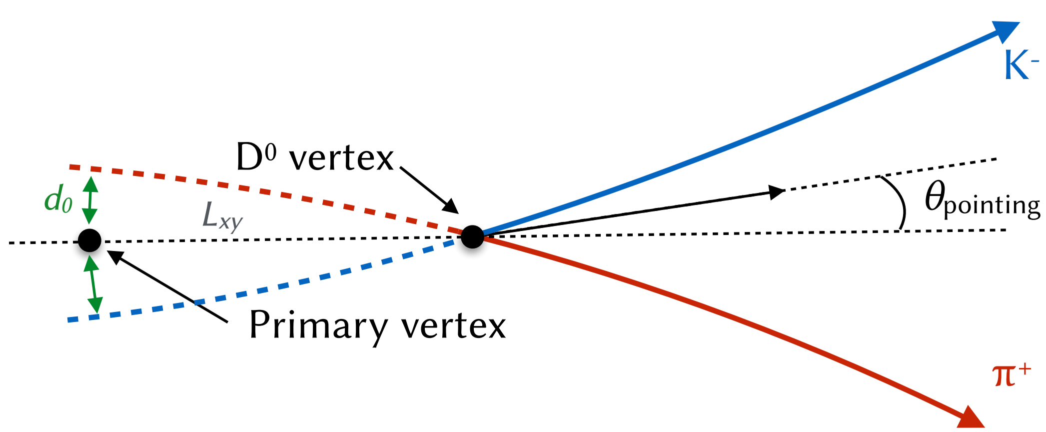
Analysis strategy:

- combination of track pairs/triplets with proper charge combinations and PID information
- secondary vertex reconstruction
- exploit the D-meson vertex displacement by applying kinematic and geometrical selections



Typical topological selections: *to be optimised per p_T interval*

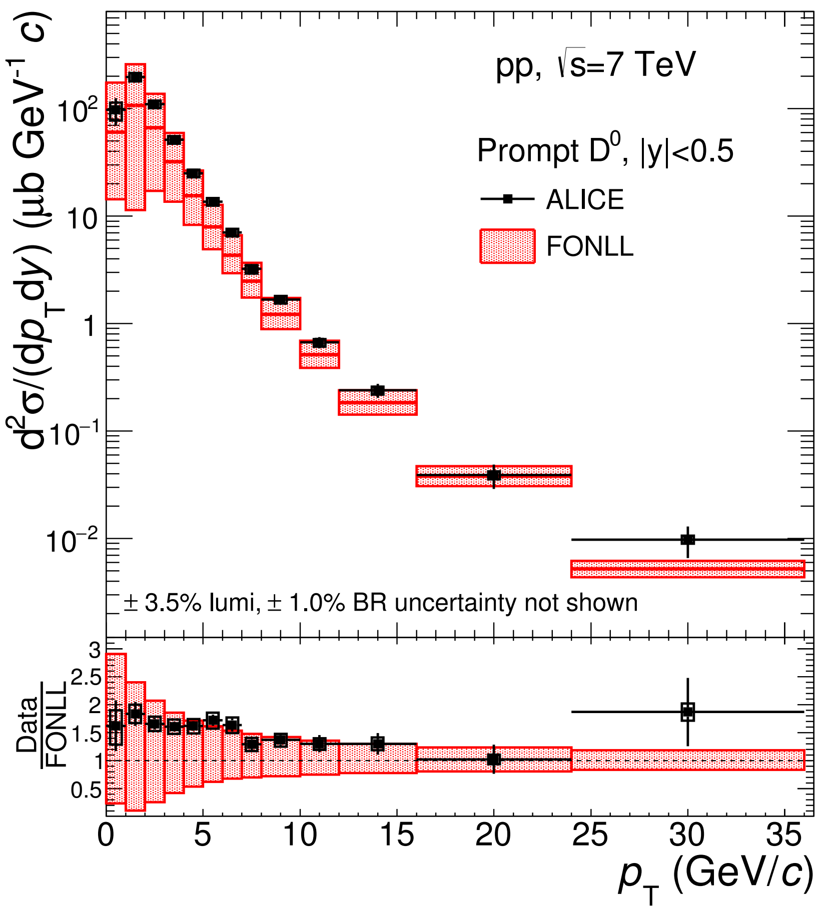
- D-meson decay length: L_{xy}
- D-meson pointing angle: $\cos(\theta_{pointing})$
- Impact parameter of daughters: d_0
- …

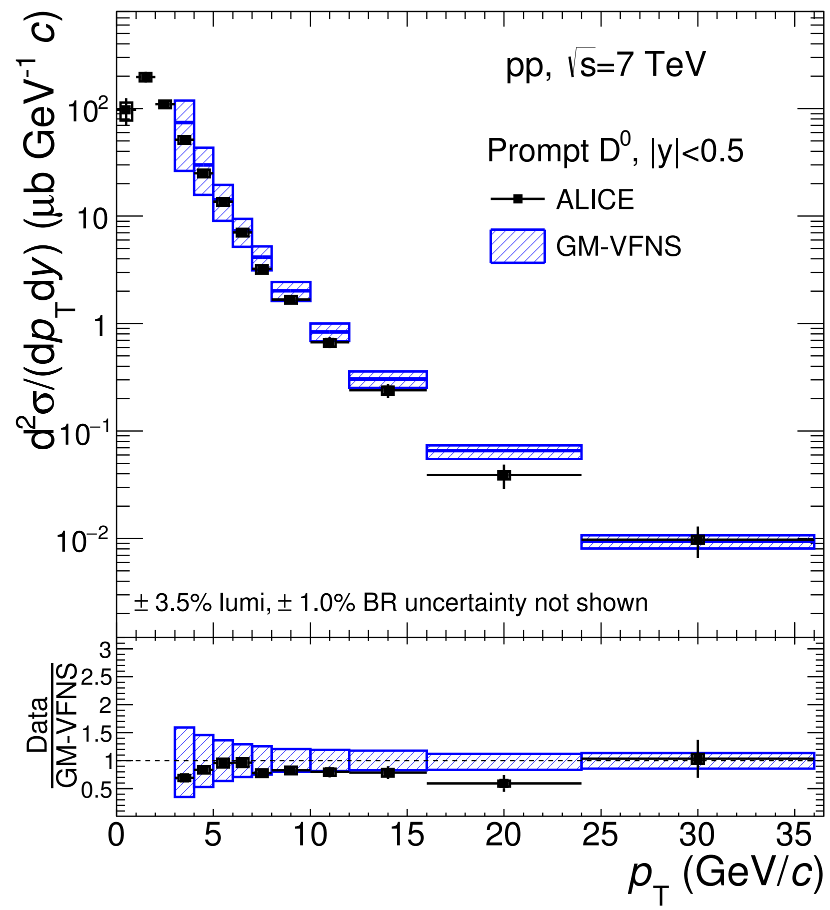


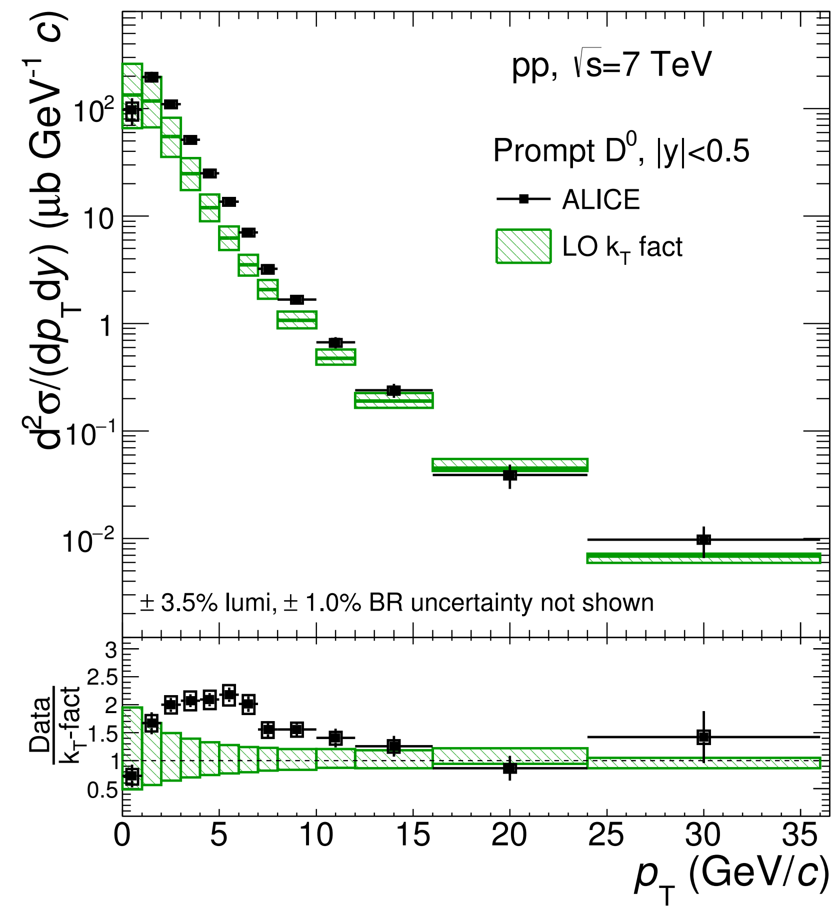
Eur.Phys.J. C77 (2017) 8, 550

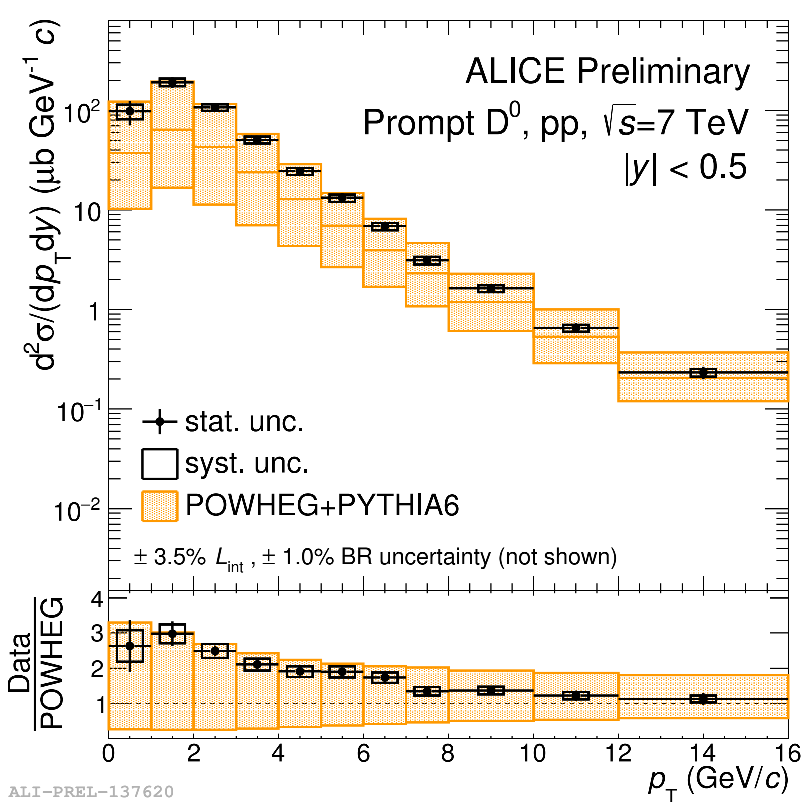
$\sqrt{s}$ = 7 TeV

D-meson production cross section





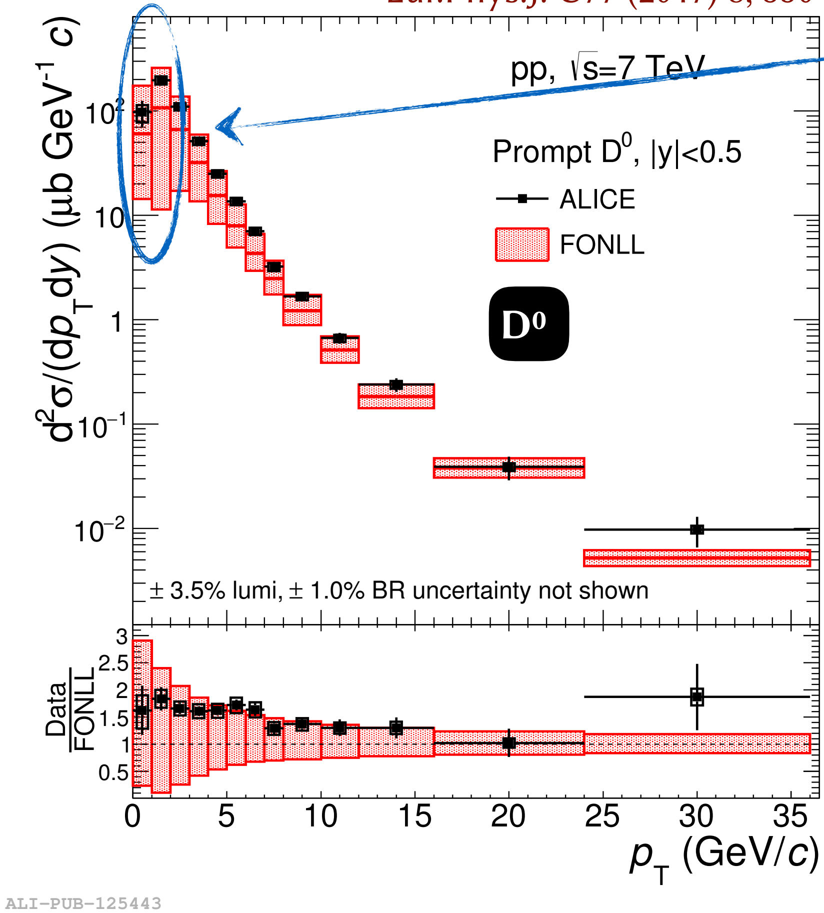




- **Fixed-Order-Next-to-Leading-Log (FONLL):** JHEP 10 (2012) 137 and references therein
- **General Mass Variable Flavour Number Scheme (GM-VFNS):** Eur. Phys. J. C72 (2012) 2082
- **k_T factorisation:** Phys. Rev. D87 (2013) 094022
- ***POWHEG + PYTHIA6*:** JHEP 0711 (2007) 070 **+** JHEP 05 (2006) 026

Measurements down to low p_T

Eur.Phys.J. C77 (2017) 8, 550



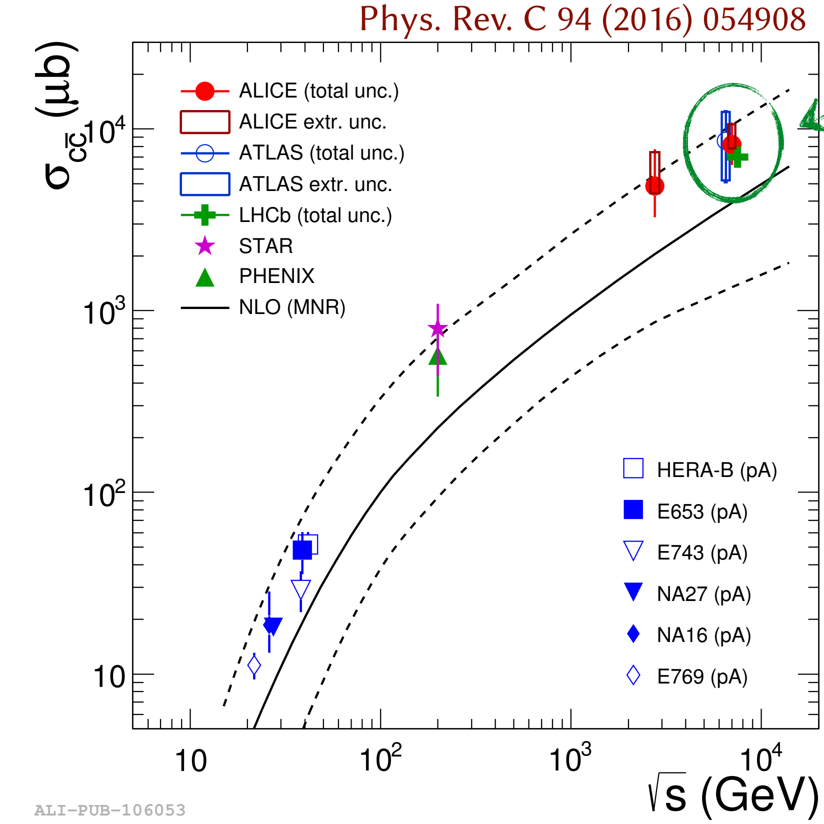
Different analysis method allows us to measure D^0 *down to $p_T = 0$*

- no selection on secondary vertex, only combinatorics
- estimation + subtraction of the background (event mixing, rotational, ...)

pQCD calculations (FONLL) are compatible within uncertainties with the data for all D-meson species.

FONLL: JHEP 10 (2012) 137

Phys. Rev. C 94 (2016) 054908



Total charm cross-section estimated by extrapolating D^0 measurement to full solid angle

Data in agreement with QCD predictions at NLO, within large uncertainties, over a wide $\sqrt{s}$ range

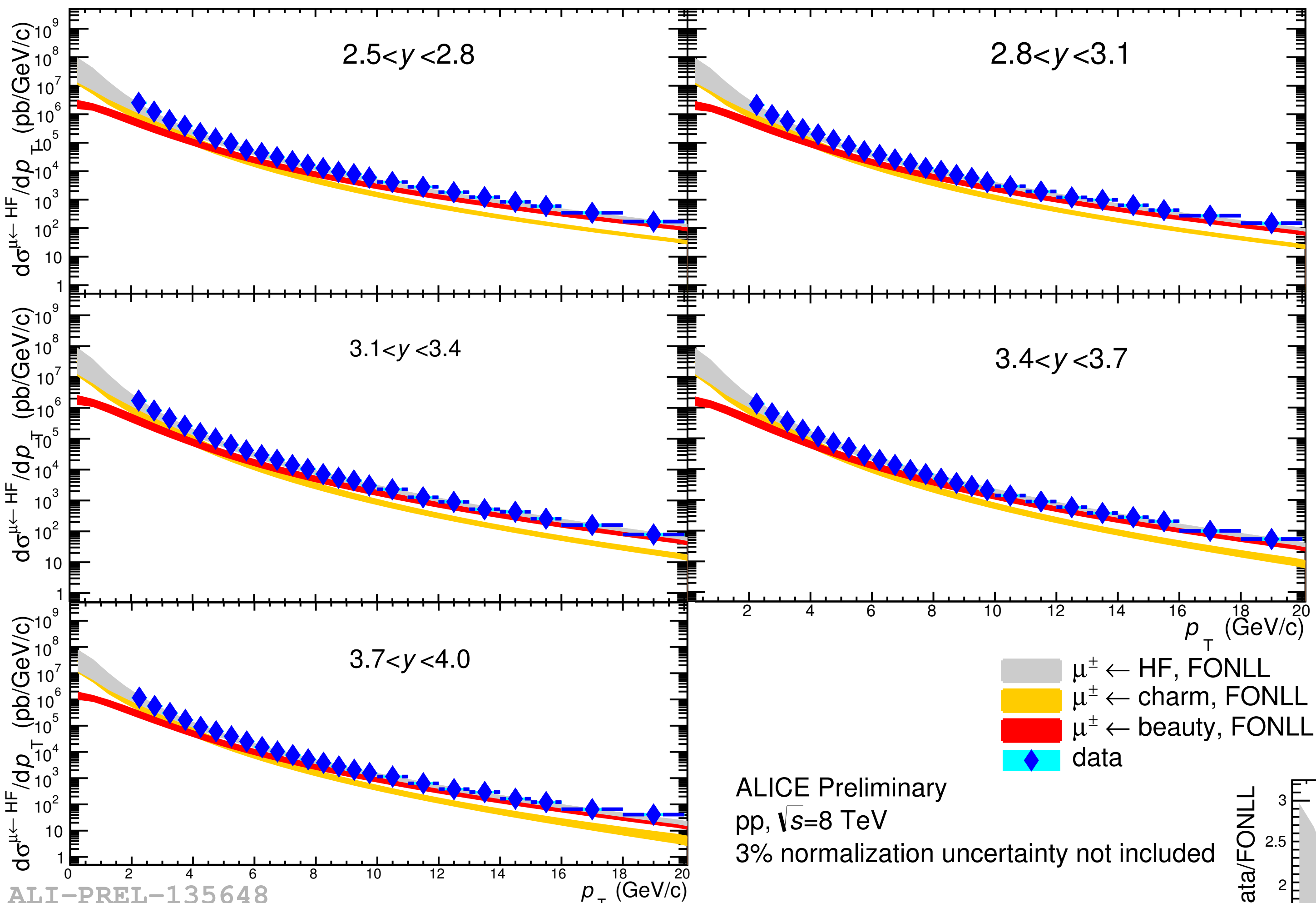
NLO MNR: Nucl. Phys. B373 (1992) 295-345

+ $c\bar{c}$ cross section is a basic ingredient for studying charmonium (re)generation in Pb-Pb collisions

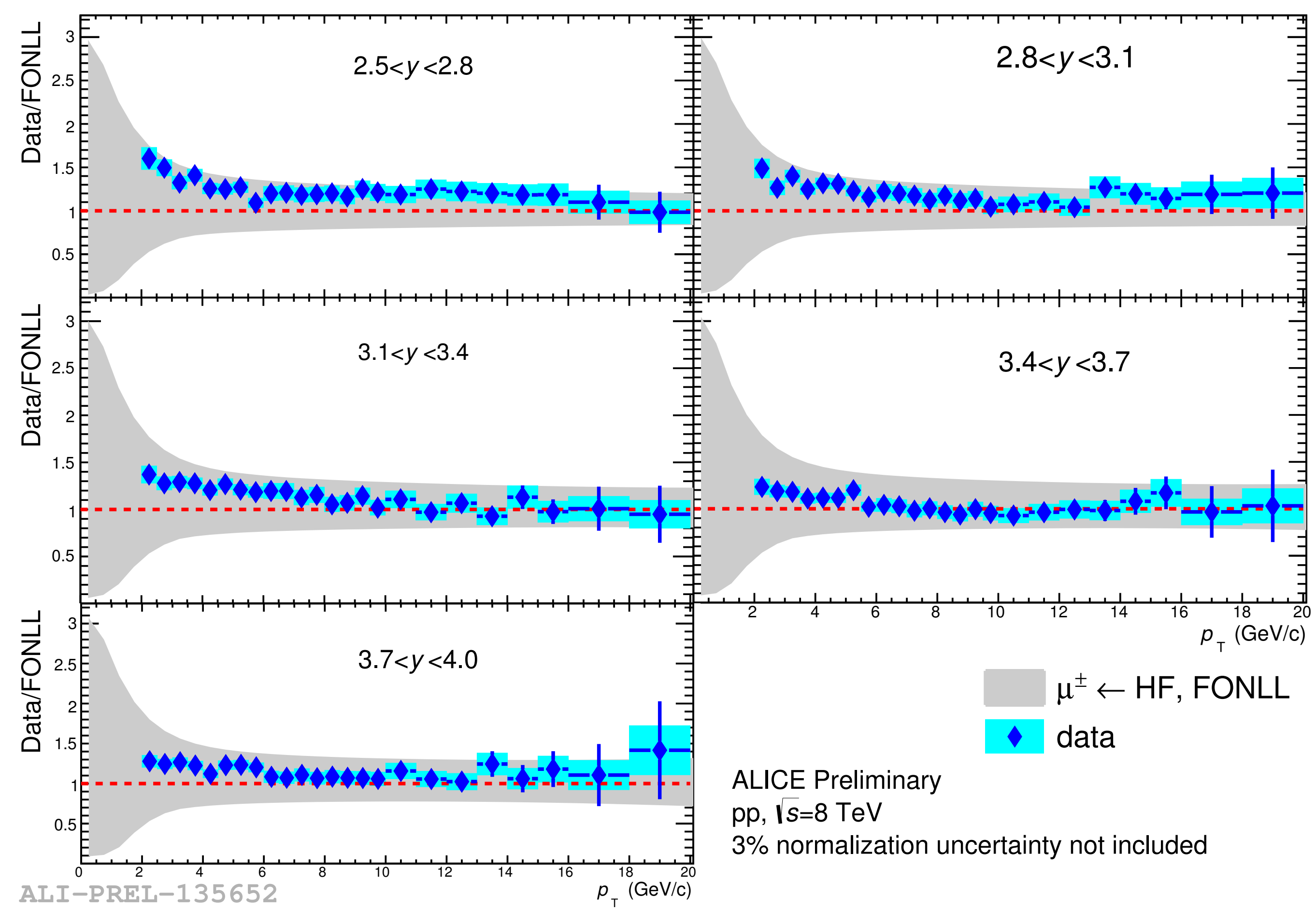
Heavy flavour muon decays

$\mu^{\pm}$, $\sqrt{s}$ = 8 TeV

- $\mu \leftarrow$ **c, b** at forward rapidity (2.5 < y < 4) divided into several rapidity intervals

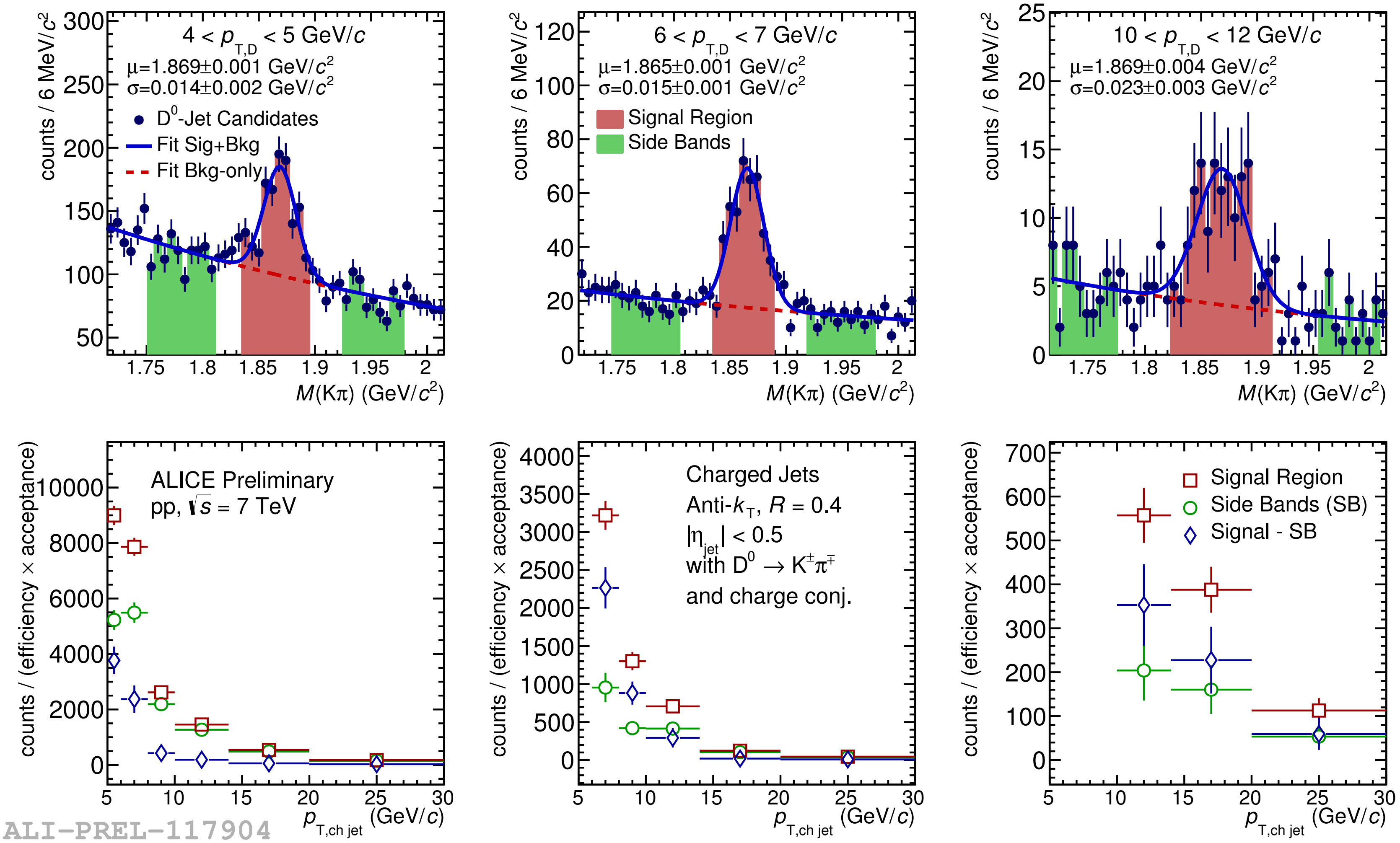


Insights into relative abundance of **charm** and **beauty quark** production



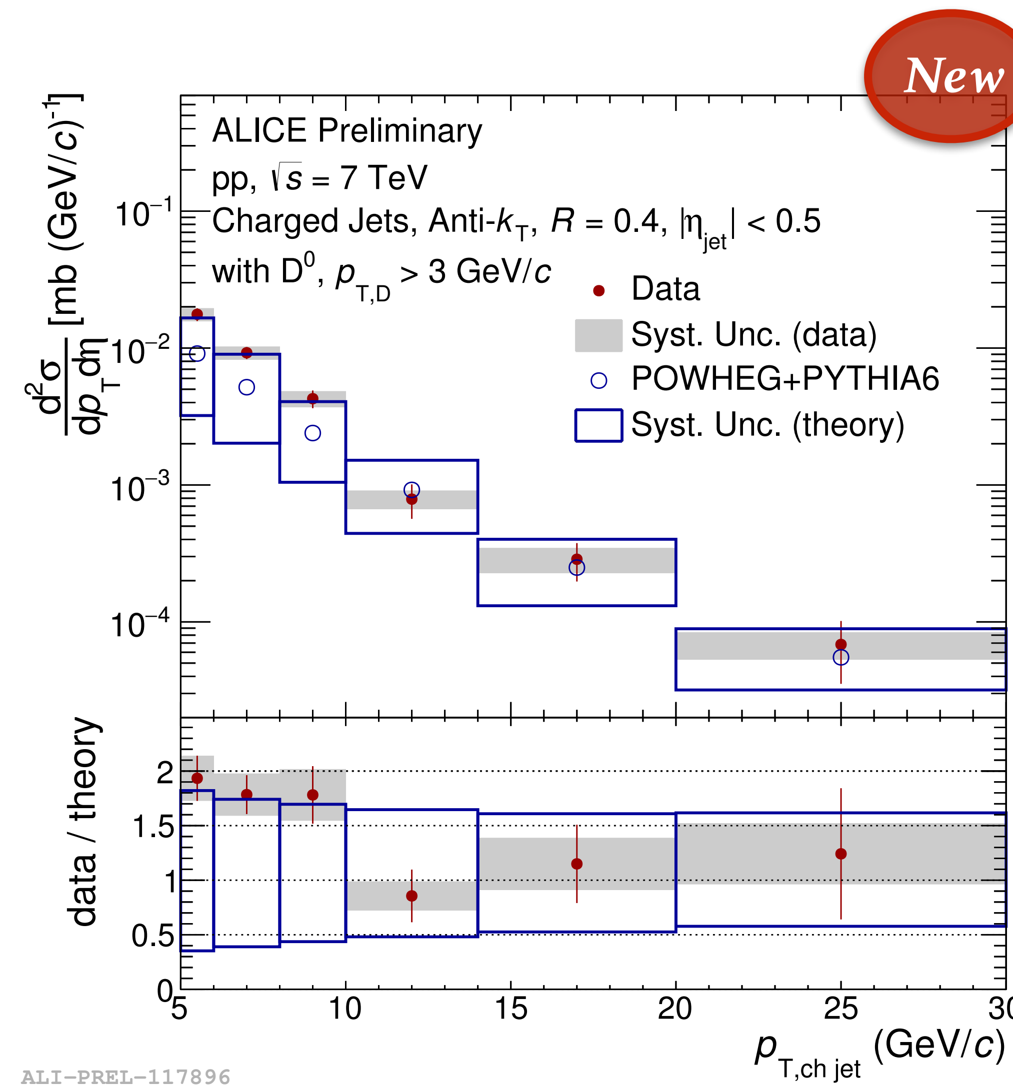
- **FONLL:** JHEP 10 (2012) 137 and references therein

$\sqrt{s}$ = 7 TeV — D⁰-meson-tagged jet



4 < D⁰ p_T < 5 GeV/c **6 < D⁰ p_T < 7 GeV/c** **10 < D⁰ p_T < 12 GeV/c**

- D-jet raw spectrum extracted from invariant mass analysis
- Correction for D-jet efficiency and beauty feed-down
- Corrected jet-p_T spectra unfolded for detector effects



$\sqrt{s}$ = 7 TeV

D meson yields vs. multiplicity

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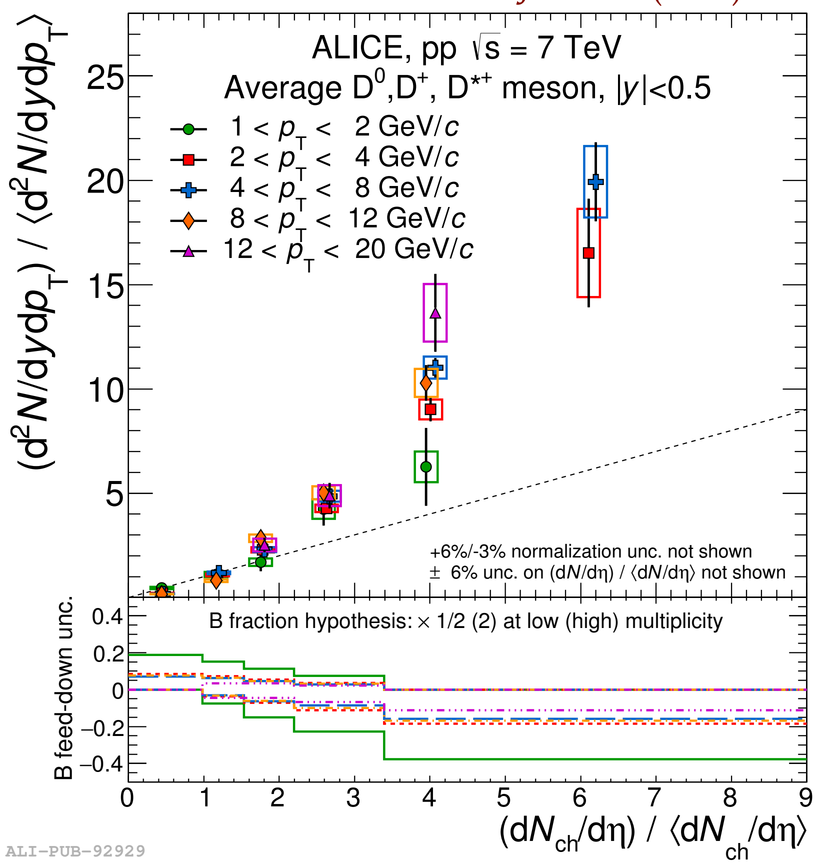
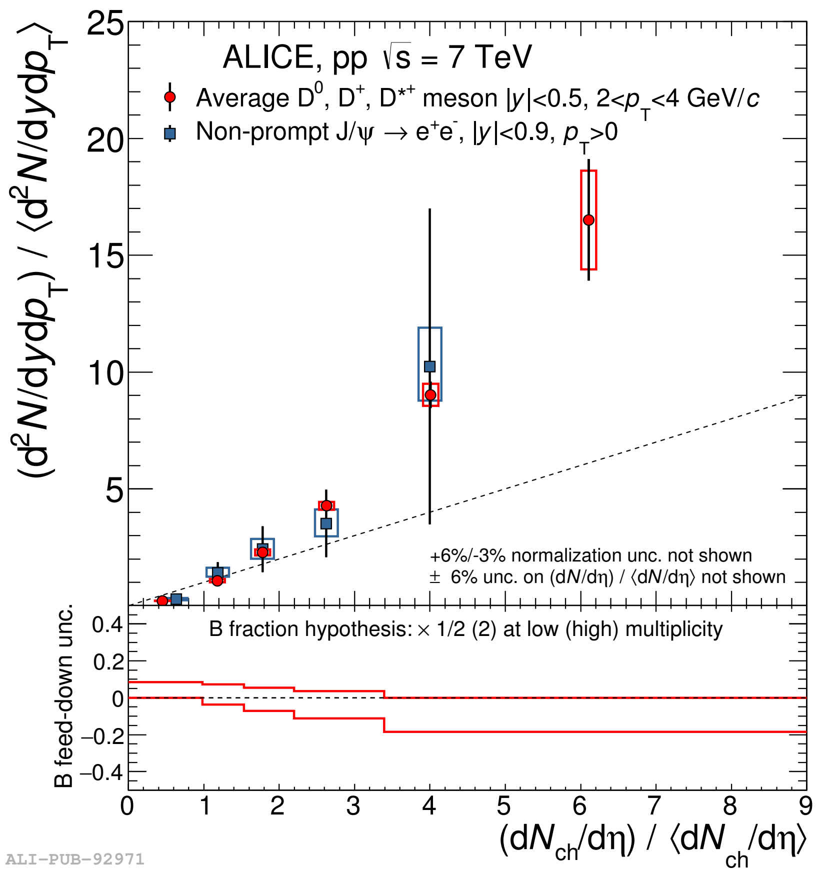


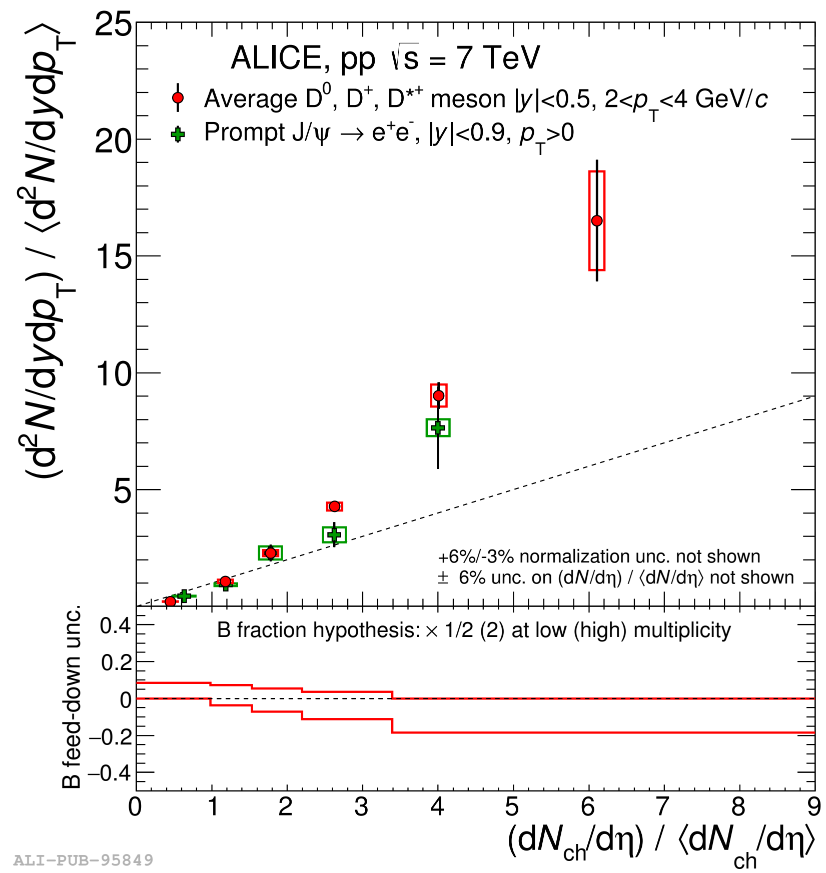
- Production of **D mesons** increases steeper than linear with multiplicity
- Similar trend for **non-prompt (B⟶) J/Ψ** yields
- Similar trend for **prompt J/Ψ** yields

Caveat: different η and p_T regions

Interpretation:

- No strong ***flavour*** dependence
- Enhancement may be related to ***cc and bb production processes***, potentially not strongly influenced by hadronisation





D meson yields vs. multiplicity

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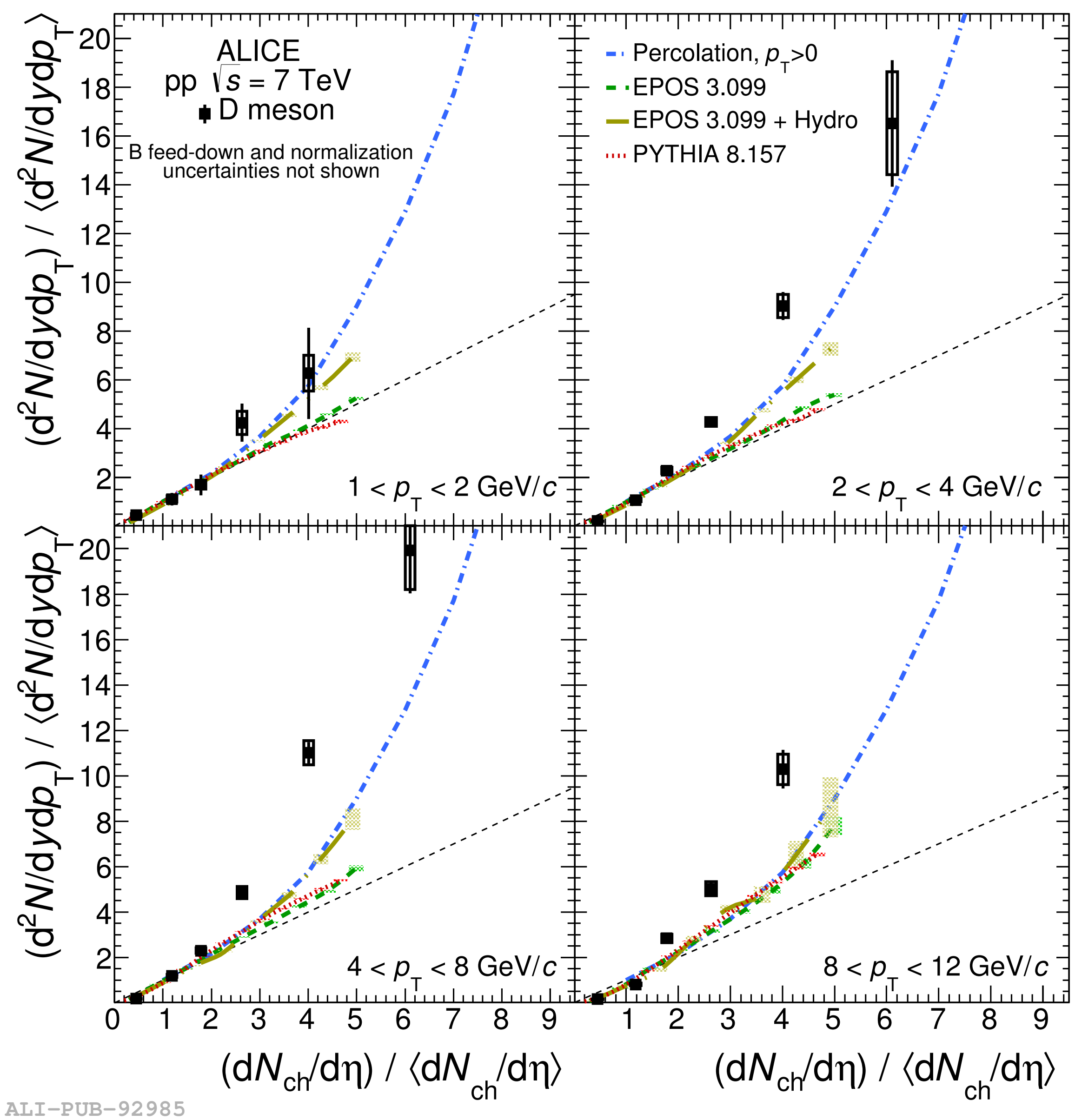

Percolation model:

- Color sources with finite spatial extension (~mimic MPI)
- Steeper-than-linear increase

EPOS 3.099 + Hydrodynamic evolution:

- Gribov-Regge formalism
- MPI linked to multiplicity: $N_{\text{hard process}} \propto N_{\text{MPI}} \propto N_{\text{multiplicity}}$
- Steeper-than-linear increase with hydrodynamic

PYTHIA8:

- Soft QCD with colour reconnections
- Initial and final state radiations
- MPI
- Almost linear increase