# Event-multiplicity and event-shape dependence of open heavy-flavour production in pp collisions with ALICE at the LHC

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## HARD PROBES 2018
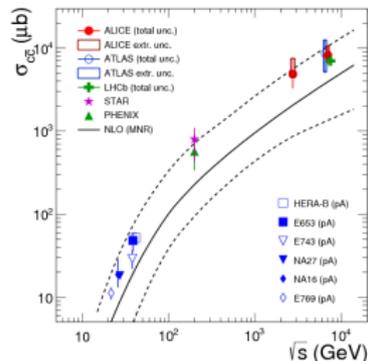**Aix-Les-Bains, France**

1-5 October, 2018

## Motivation



**Heavy-flavour studies in pp collisions :**

- **Important to test perturbative QCD calculations**

  ▷ Heavy quarks (charm, beauty) $\rightarrow$ produced at the early
    stages of the collision via hard scattering ( $m_{c,b} \gg \lambda_{QCD}$ )
    $$m_c \sim 1.3 \text{ GeV}/c^2 \qquad m_b \sim 4.2 \text{ GeV}/c^2$$
    $$\lambda_{QCD} \sim 200 \text{ MeV}$$

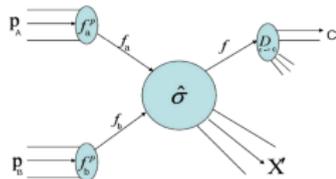  ▷ Production cross-section calculated down to $p_T \sim 0$
    using factorization theorem :

$$d\sigma_{AB \rightarrow C}^{hard} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma_{ab \rightarrow c}^{hard}(x_a, x_b, Q^2) \otimes D_{c \rightarrow C}(z, Q^2)$$

<span style="color:green">Parton Distribution Function (PDF)</span>　　<span style="color:red">Partonic hard scattering</span>　　<span style="color:purple">Fragmentation</span>
　　　　　　　　　　　　　　　　　　　<span style="color:red">cross-section</span>　　　　　<span style="color:purple">Function (FF)</span>



- **Provide a necessary reference for heavy-ion studies.**

  Heavy flavours in heavy-ion collisions :
  Effective probes for the hot and dense QCD matter (QGP) produced in the collisions

## Motivation

**Multiplicity dependent study of heavy-flavour production in pp collisions :**

- **Contradicts traditional wisdom.**

  **High multiplicity pp events** show properties similar to heavy-ion collisions e.g.

  - ▷ Ridge formation  (Phys. Lett. B 765 (2017) 193)
  - ▷ Strange baryon enhancement  (Nature Physics 13 (2017) 535-539)

  $\implies$ Collectivity in high-multiplicity pp events.

- **Gives insight into multiple-parton-interaction (MPI)  phenomena.**

  **MPI study at LHC :**

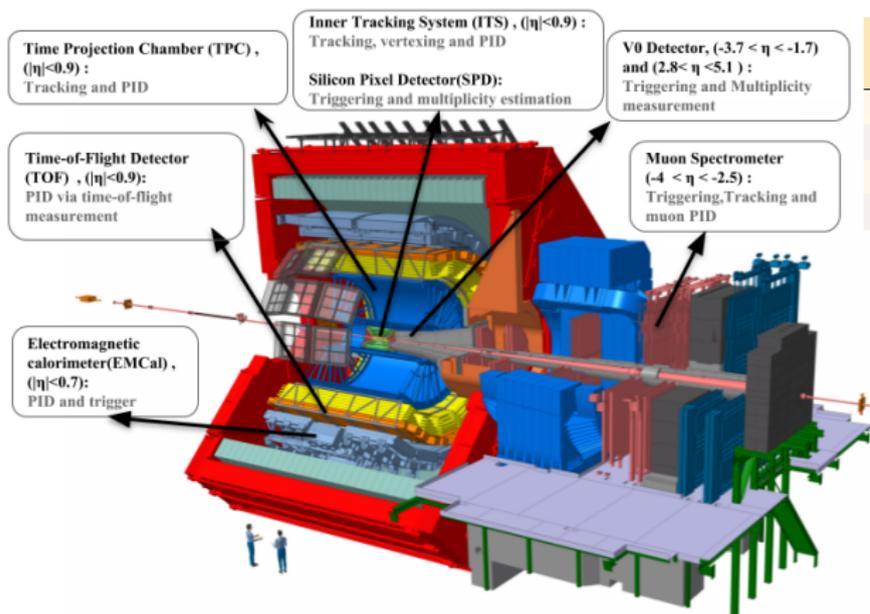  **CMS** : Study of jets and soft physics (Eur. Phys. J. C73(2013) 2674).
  MPIs have a substantial contribution at large multiplicity

  **ALICE** : Analysis of minijet production (JHEP 09 (2013) 049)
  MPI increases at higher multiplicities

- **Understand the interplay of hard and soft processes**
  - $\rightarrow$ to search possible connections between small and extended interacting systems.

# Open heavy flavours with the ALICE detector



Time Projection Chamber (TPC) , (|η|<0.9) :
Tracking and PID

Inner Tracking System (ITS) , (|η|<0.9) :
Tracking, vertexing and PID

Silicon Pixel Detector(SPD):
Triggering and multiplicity estimation

V0 Detector, (-3.7 < η < -1.7) and (2.8< η <5.1 ) :
Triggering and Multiplicity measurement

Time-of-Flight Detector (TOF) , (|η|<0.9):
PID via time-of-flight measurement

Muon Spectrometer (-4 < η <-2.5):
Triggering, Tracking and muon PID

Electromagnetic calorimeter(EMCal) , (|η|<0.7):
PID and trigger

| $\sqrt{s}$ (TeV) | Year | #MB Trig. | $\int Ldt$ (nb$^{-1}$) |
|---|---|---|---|
| 5.02 | 2017 | 990M | 19 |
| 7 | 2010 | 370M | 6.0 |
| 8 | 2012 | 100M | 1.8 |
| 13 | 2016 | 190M | 3.3 |

**Open heavy flavours studied in ALICE through :**

- **Hadronic Decay Channels** :

  Heavy-flavour hadron decays into hadrons, e.g.,

  $D^0 \rightarrow K^-\pi^+$   **BR** $\sim$ **3.89%**

  $D^+ \rightarrow K^-\pi^+\pi^+$   **BR** $\sim$ **8.98%**

  $D^{*+} \rightarrow D^0\pi^+$   **BR** $\sim$ **67.7%**

  $D_s^+ \rightarrow K^-K^+\pi^+$   **BR** $\sim$ **5.45%**

  Studied in mid-rapidity ($|\eta| < 0.9$)

  (M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018))

- **Semi-leptonic Decay Channels** :

  Heavy-flavour hadron decays into a  lepton + neutrino + hadron(s) through weak interaction, e.g.

  $B, D \rightarrow e + X$         Studied in mid-rapidity ($|\eta| < 0.9$)

  $B, D \rightarrow \mu + X$         Studied in forward-rapidity (-4 < $\eta$ <-2.5)

  (For both e and $\mu$ : **BR** $\sim$ **10%**)

## Open heavy flavours with the ALICE detector

- **D-meson reconstruction (Hadronic decay channels)** :
  - Particle identification using TPC and TOF
  - Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex
  - Feed down from B-hadron decays subtracted using pQCD (FONLL) predictions to extract results for prompt D mesons
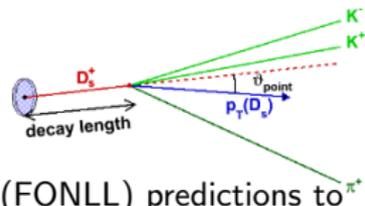
- **Electrons from semi-leptonic decay channels** :
  - Electron Identification
    Low and intermediate $p_T$ : TPC and TOF
    Intermediate and high $p_T$ : TPC and EMCAL
  - Background ( $\pi^0$ and $\eta$ Dalitz decays, $\gamma$ conversions) subtracted with $e^+e^-$ invariant mass analysis
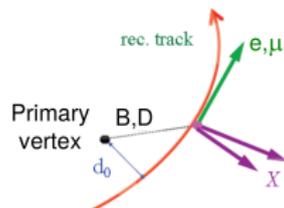
- **Muons from semi-leptonic decay channels** :
  - Muon selection using muon spectrometer($-4.0 < \eta < -2.5$)
  - Background from primary $\pi$, K decay subtracted $\rightarrow$ via simulation tuned on central barrel data
  - Background from $W/Z/\gamma^*$ subtracted $\rightarrow$ with templates obtained from simulation
  - Background from $J/\psi$ subtracted

# D-meson production cross section
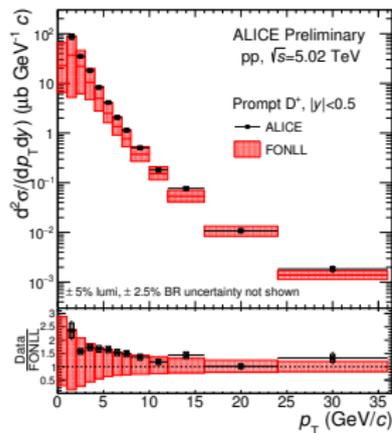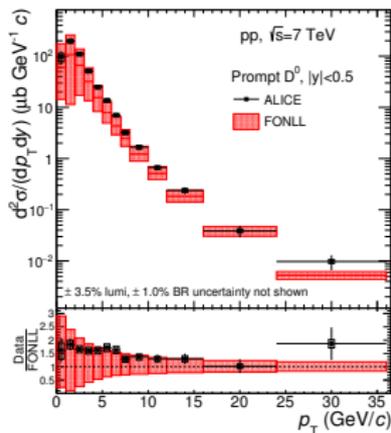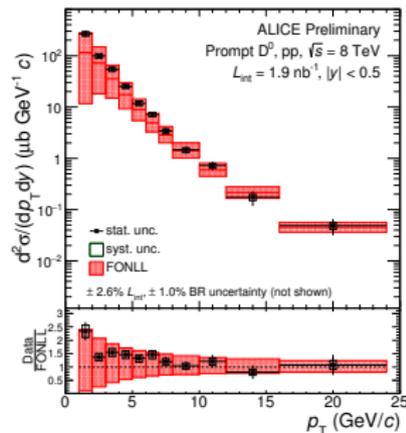


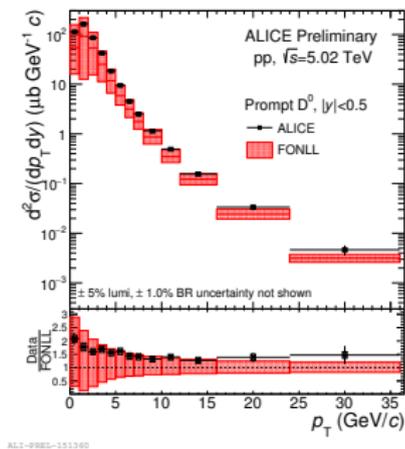**D-meson cross section at 4 different collision energies :**
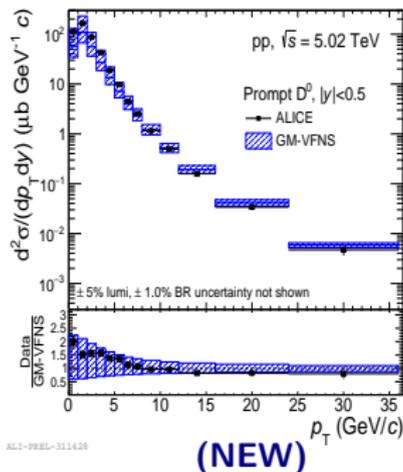**( 5.02 TeV, 7 TeV, 8 TeV, 13 TeV )**

- The **D-meson** cross section at LHC energies is **described well** by pQCD model (**FONLL**) over a wide $p_T$ range
- **Data** tend to **sit** on the **upper edge** of the theory uncertainty band

# D-meson production cross section vs. pQCD Calculations
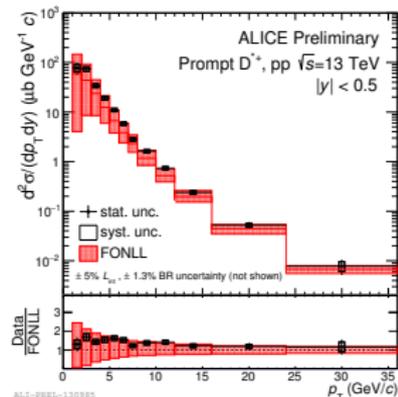


**$D^0$ cross section in pp at $\sqrt{s} = 5$ TeV**

**Precise measured pp reference (down to $p_T = 0$ for $D^0$)!**

– FONLL (Fixed Order with Next-to-Leading Log resummation) : Data lies within uncertainty, central value of predictions lies **below** the data (JHEP 10 (2012) 137)

– GM-VFNS (General-Mass Variable Flavour Number Scheme) : Data lies within uncertainty (JHEP 12 (2017) 021, arXiv:1703.04754)

**Cross section ratios at :**

$\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 5.02 TeV
for D$^+$-mesons

$\sqrt{s}$ = 13 TeV and $\sqrt{s}$ = 5.02 TeV
for D$^0$-mesons
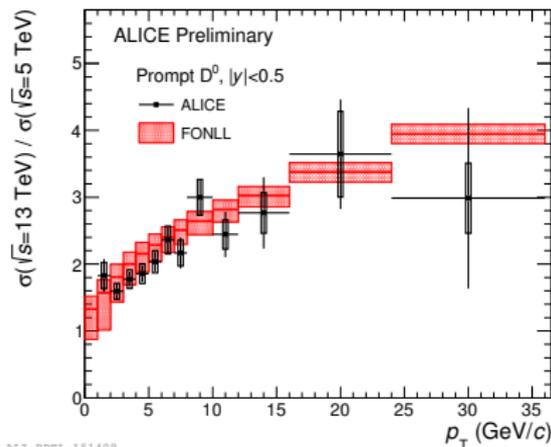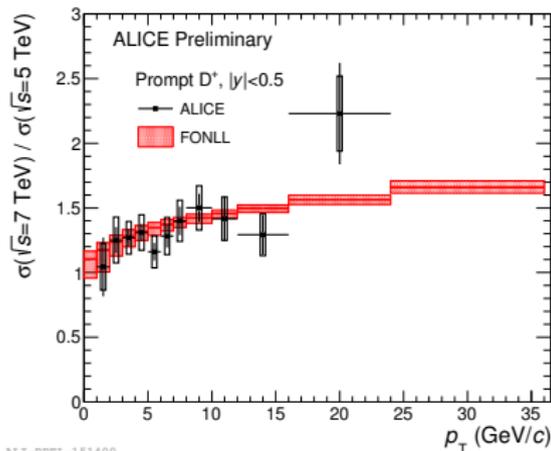


– Additional test for pQCD calculations

– The results are compared to FONLL calculations, which describe consistently the
slightly increasing trend as a function of $p_T$ observed in the data.

# D-meson cross section : Rapidity dependence

$D^0$-meson central-to-forward ratios are shown as a function of $p_T$ for $|y| < 0.5$ at mid rapidity and three different $y$ intervals at forward rapidity: $2 < y < 2.5$ , $3 < y < 3.5$ , $4 < y < 4.5$

(ALICE Collaboration, Eur. Phys. J. C77 (2017) 550)
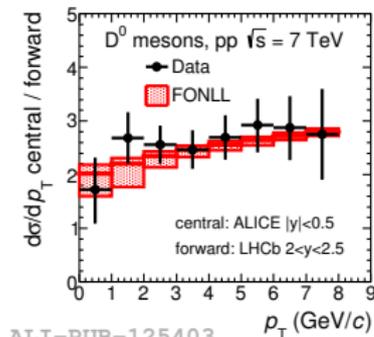


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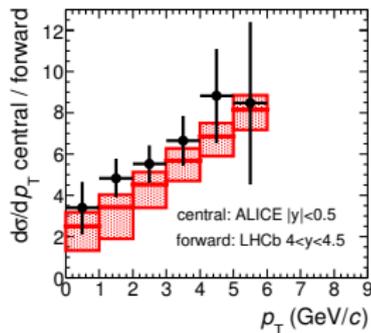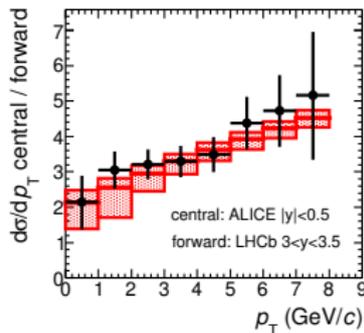
(LHCb Collaboration, Nucl. Phys. B871 (2013), 1-20)

- Data at **different energies** at mid-rapidity useful to **set constraints on gluon PDF**, especially if **combined with forward rapidity data** (Cacciari, Matteo et al. Eur.Phys.J. C75 (2015) no.12, 610)
- Measurements at $\sqrt{s} = 5.02$ and 13 TeV ongoing

Ratios of the $p_{\mathrm{T}}$ -differential cross sections of $D^0$, $D^{*+}$, $D^+$, $D_s^+$-mesons at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV



ALI-PREL-150559
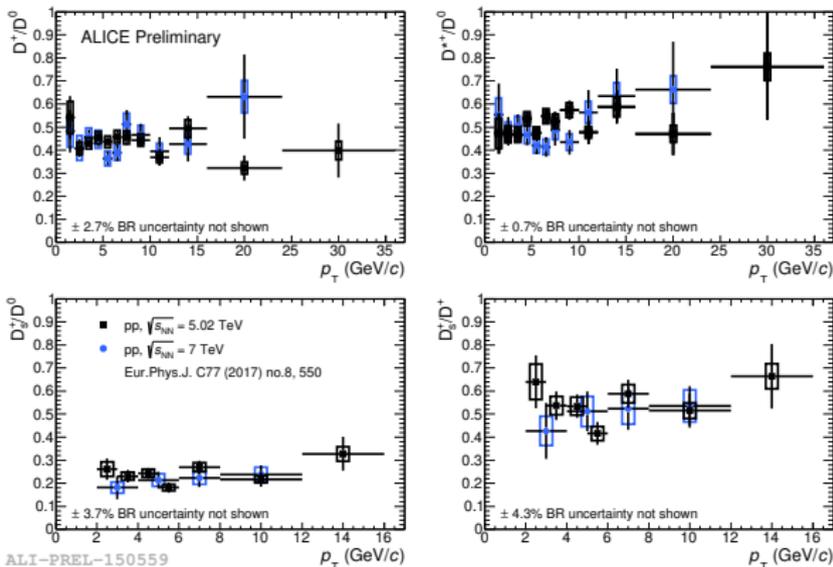
– **No significant $p_{\mathrm{T}}$ dependence** within the experimental uncertainties

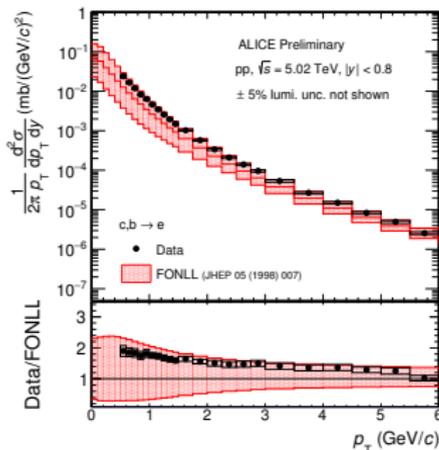▷ Small difference between the fragmentation functions of the different species

# Heavy-flavour semi-leptonic decays

Heavy-flavour hadron decay muon (forward rapidity, $2.5 < y < 4$) and electron (mid rapidity, $|y| < 0.8$) cross section at $\sqrt{s} = 5.02$ TeV:

**c,b $\rightarrow \mu$ , $2.5 < y < 4$**
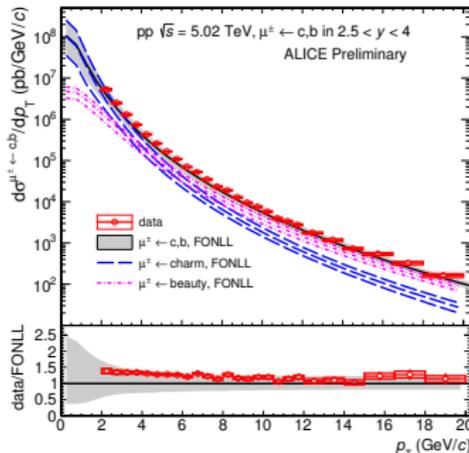
**c,b $\rightarrow$ e , $|y| < 0.8$**



- **Data lies on the upper edge** of the theoretical (**FONLL**) uncertainty band for both electrons and muons
- Insight about **relative abundance of beauty** and **charm quarks** from the muon cross section
  - ▷ At low $p_T$ charm decay is dominant
  - ▷ Beauty is the main component for $p_T > \sim 5$ GeV/$c$

# Heavy-flavour dependence on event multiplicity

**Self-normalized yield of heavy-flavour decay muons ($\sqrt{s} = 8$ TeV, forward rapidity) and electrons ($\sqrt{s} = 13$ TeV, mid rapidity) versus multiplicity:**

pp , $\sqrt{s} = 8$ TeV
c,b $\rightarrow \mu$ , $2.5 < y < 4$

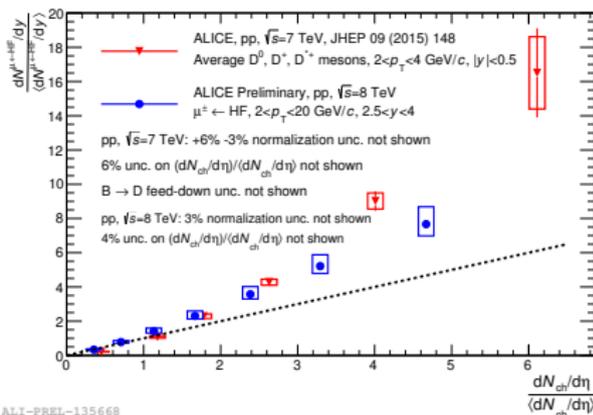pp , $\sqrt{s} = 13$ TeV
c,b $\rightarrow$ e , $|y| < 0.8$
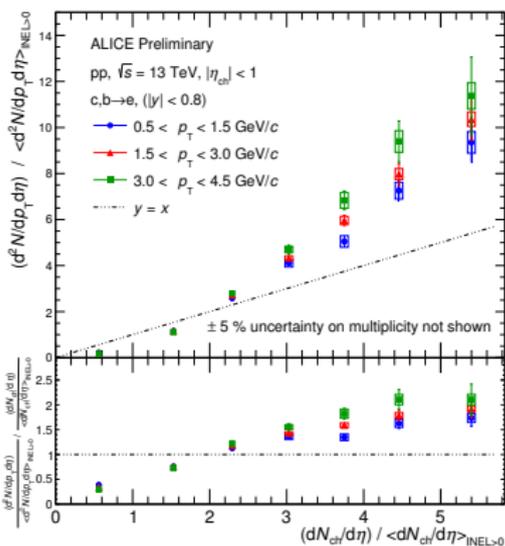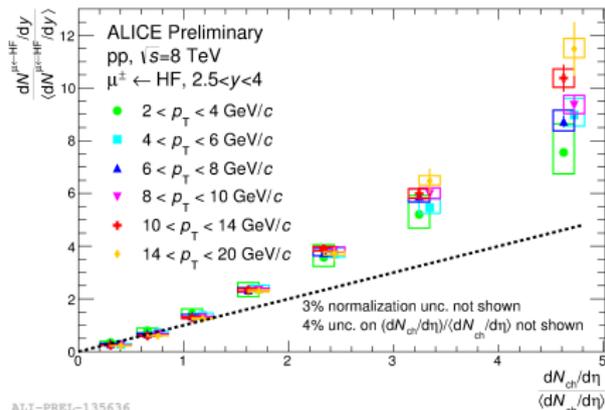


**Multiplicity measurement for both e and $\mu$ using SPD tracklets at mid rapidity ($|\eta| < 1$)**

- The self-normalized yields show a **faster than linearly increasing** trend
- **Higher $p_T$ ranges** show tendency for **steeper increase**

# Heavy-flavour dependence on event multiplicity

**Comparison of self-normalized yield at forward (c,b → μ ) and mid rapidity (c,b → e, D-mesons)**
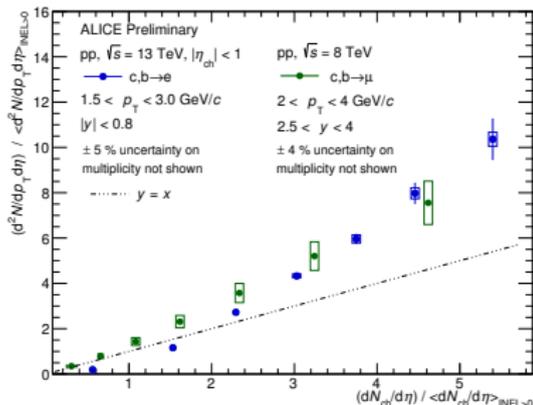


- **Different trend** of self-normalized yield for **mid rapidity** (c,b → e, D-mesons) and **forward rapidity** (c,b → μ )
- Possibly due to **autocorrelation effects** and **jet bias**
  - ▷ Due to **overlap in the rapidity** regions of **multiplicity estimator** (mid rapidity) and **HF yield** (c,b → e , D-mesons at mid rapidity)

**Comparison of self-normalized heavy-flavour yield with model expectations**
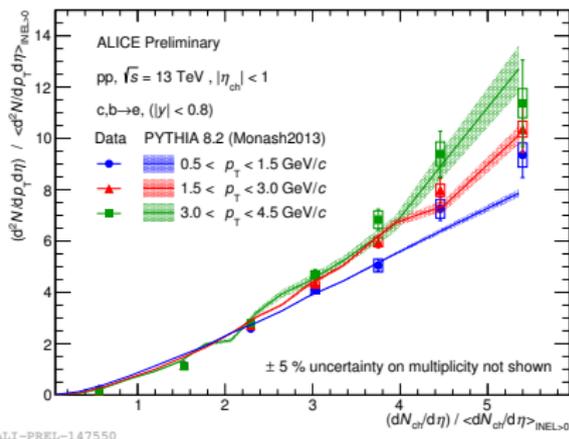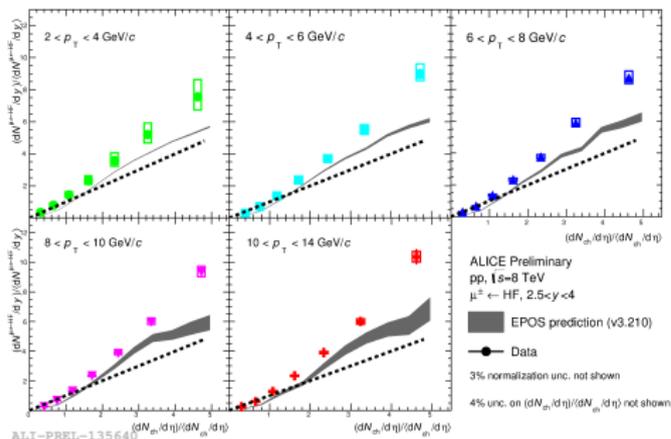


- **c,b → μ data** compared to **EPOS3.210 (including hydrodynamics)** prediction (Phys. Rev. C 89 (2014) 064903)

  ▷ EPOS3.210 underestimates data at higher multiplicities for all $p_T$ ranges

- **c,b → e data** compared to **PYTHIA8.2 (MPI based model)** prediction (Comput. Phys. Commun. 191 (2015) 159)

  ▷ PYTHIA8.2 predictions fairly match with the data

# $D^0$-meson production vs. Sphericity

$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left( \frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$

$$S_0 = \begin{cases} 0 \text{ "jetty" limit (hard events)} \\ 1 \text{ "isotropic" limit (soft events)} \end{cases}$$
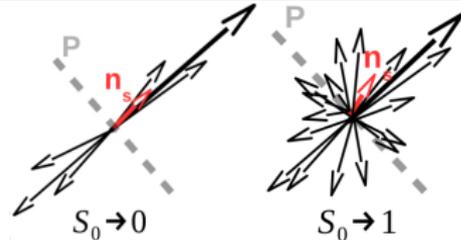


- **Higher rate** of **high-$p_T$** D meson in **low-sphericity events**, expected from jet contribution to event sphericity
- **Similar rate** of low $p_T$ D mesons at **different sphericity**
- The trend of $D^0$ production remains **same** for **two different multiplicity** regions
- Data trend **reproduced by PYTHIA** in both multiplicity intervals
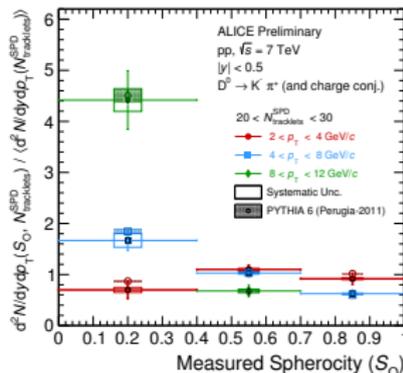
## Summary
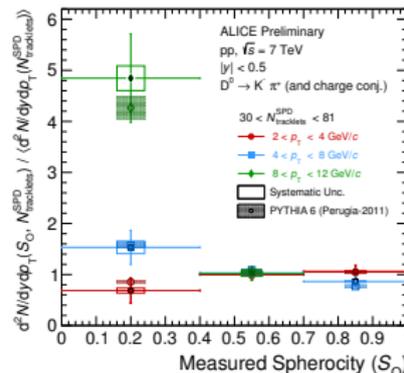
- **D-meson** production **in pp** at several collision energies
  - Compared with **pQCD calculation** (FONLL, GM-VFNS)
  - **Described well** within uncertainty of pQCD (FONLL) predictions at all $\sqrt{s}$
  - Useful to set constraints on gluon PDF (work on going)

- **HF** production **vs. multiplicity** in **pp** at several collision energies
  - **Faster than linear increasing** trend w.r.t charged-particle multiplicity.
  - **Higher** $p_{\mathrm{T}}$ ranges show a tendency of **steeper increase**
  - **Different trend** for mid rapidity electrons and forward rapidity muons
    - $\rightarrow$ possibly due to autocorrelation effects and jet bias
  - Compared with model expectation – **PYTHIA 8.2** and **EPOS3.2**

- **$D^0$-meson** production **vs. spherocity** and **multiplicity**
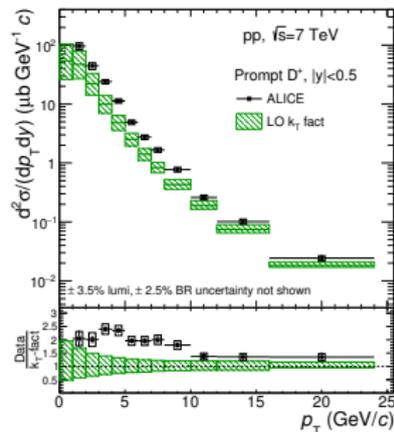  - Gives further **insight** into **HF-production mechanisms**

**Back-up :**

# D-meson production cross section vs. pQCD Calculations
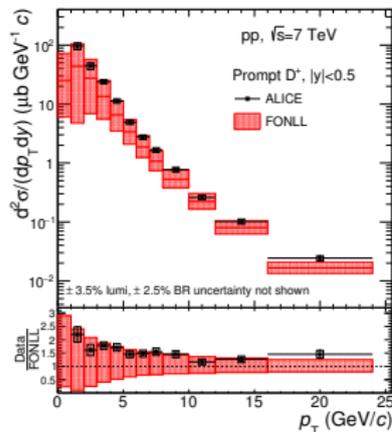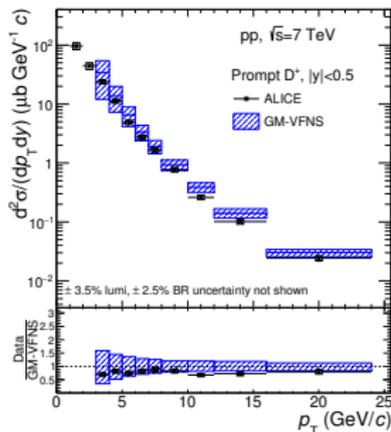


(Eur. Phys. J. C77 (2017) 550)

**D$^+$ cross section at $\sqrt{s} = 7$ TeV compared to perturbative QCD calculations :**

- FONLL (Fixed Order with Next-to-Leading Log resummation) : Data lies within uncertainty, central value of predictions lies **below** the data (JHEP 10 (2012) 137)

- GM-VFNS (General-Mass Variable Flavour Number Scheme) : Data lies within uncertainty, central value of predictions lies **above** the data (Eur. Phys. J. C72 (2012) 2082)

- $k_T$-factorization : Prediction **underestimates data** within $2 < p_T < 10$ GeV/$c$ (PRD 87 (2013) 094022)