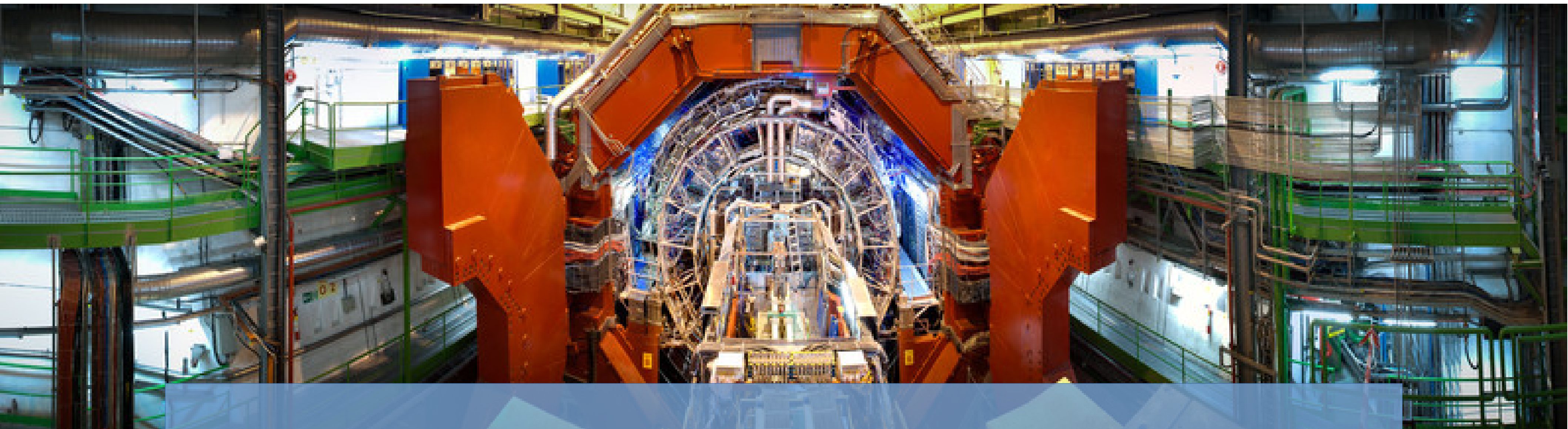
Utrecht University

QCD@LHC 2017
Debrecen
28th August - 1st September

ALICE



Charmed meson and baryon production in pp collisions with ALICE at the LHC

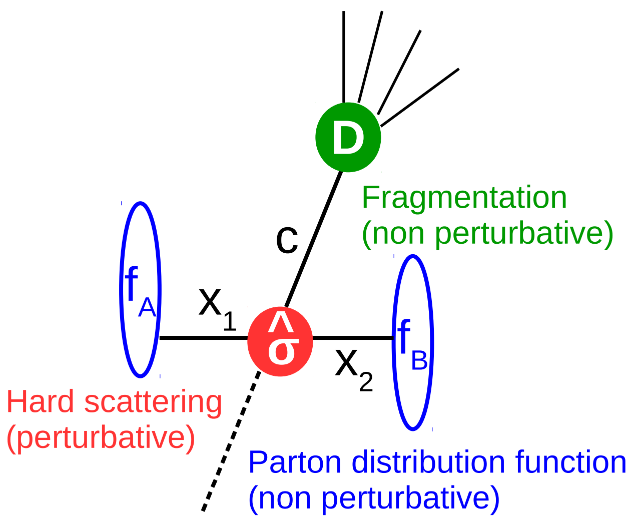
Luuk Vermunt, Utrecht University
for the ALICE Collaboration

Outline

- Physics motivation for charmed hadron studies.
- Charm particle reconstruction with the ALICE detector.
- Latest results in pp (charmed meson and baryon production).
  - D-meson production measurements at $\sqrt{s}$ = 5, 7, 8 and 13 TeV.
  - Λ_c^+ and Ξ_c^0 measurements at mid-rapidity at $\sqrt{s}$ = 7 TeV.
- Summary and outlook.

Heavy quarks (c, b) are mainly produced in initial hard scattering processes.

- Hard scale provided by large quark mass.
- Calculable with perturbative QCD.

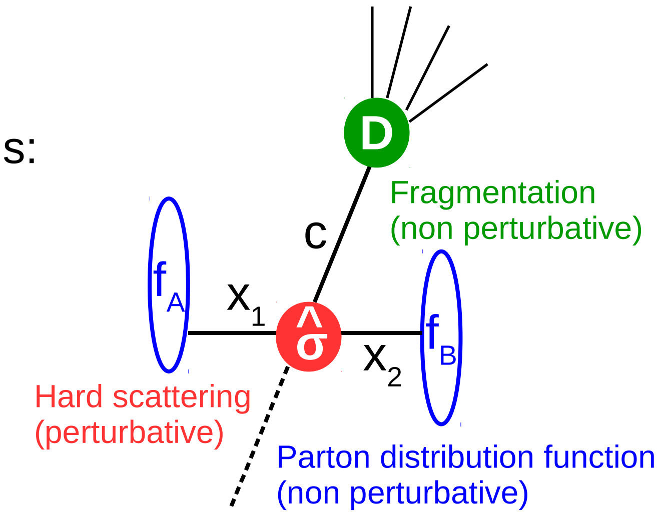


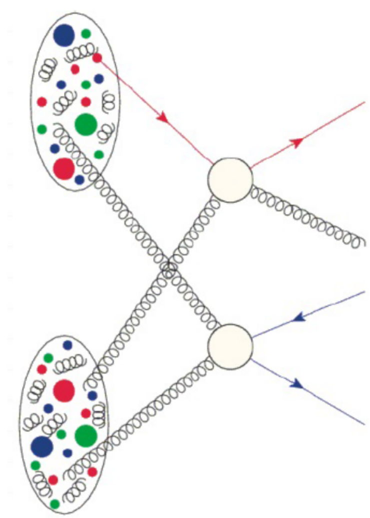
Heavy quarks (c, b) are mainly produced in initial hard scattering processes.

- Hard scale provided by large quark mass.
- Calculable with perturbative QCD.

Physics motivation for measuring charmed hadrons in pp collisions:

1. Production cross section down to $p_T \sim 0$.
   - Constraints for perturbative QCD models.
2. Production ratios of hadron species.
   - Fragmentation functions and hadronisation mechanisms.
3. Production ratios between various energies and rapidity regions.
   - Sensitive to gluon distribution function.
4. Production cross section as a function of particle multiplicity.
   - Role of Multiple-Parton Interactions (MPI).
5. Needed as reference for pA and AA collisions.
   - **See talk Robert Vertesi** (29/8/17, 12:00-12:30).





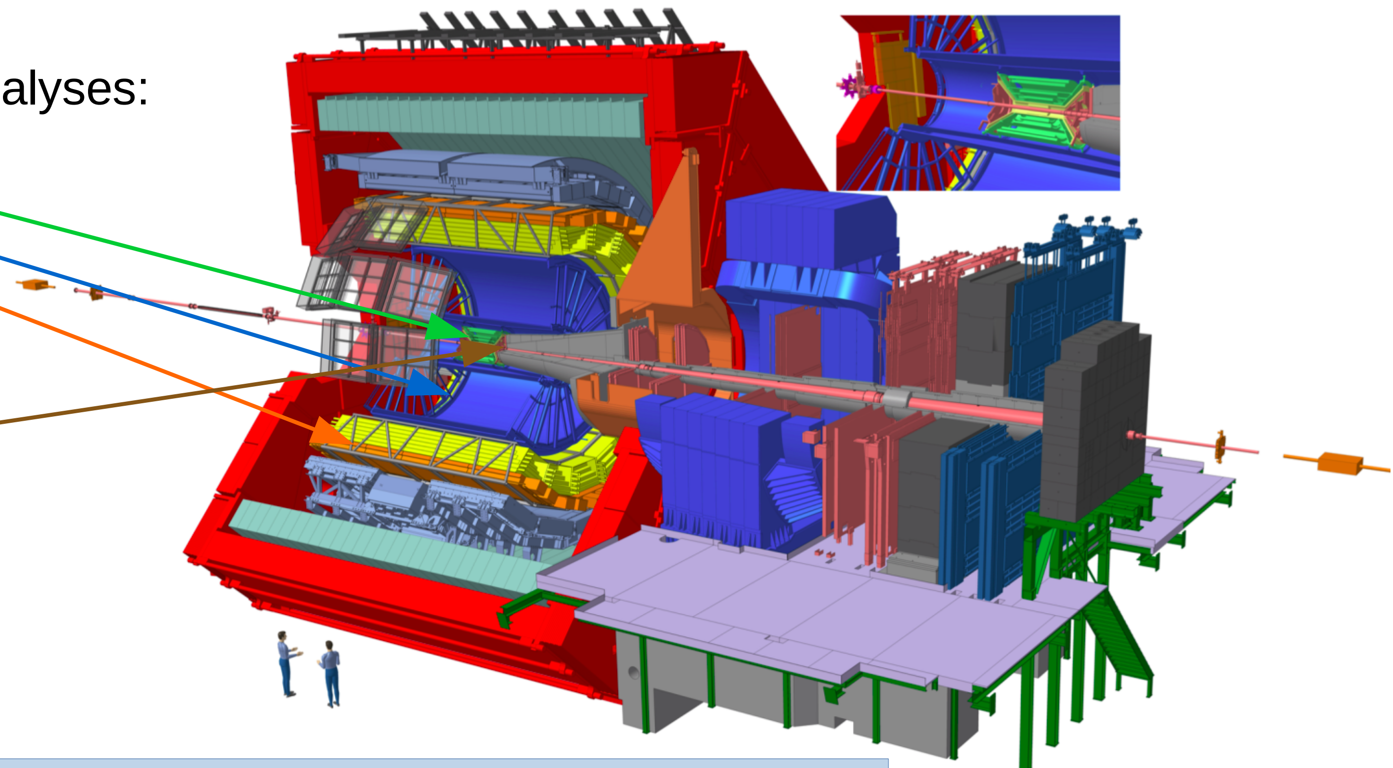
A Large **I**on **C**ollider **E**xperiment:

Optimised for track reconstruction from low to high p_T in high-particle-density environment with excellent particle identification capabilities.

Relevant detectors for these analyses:

Inner **T**racking **S**ystem
Time **P**rojection **C**hamber
Time **O**f **F**light detector
Vertexing, Tracking, PID
$|\eta| < 0.9$

V0
Trigger, Multiplicity
$2.8 < \eta < 5.1$
$-3.7 < \eta < -1.7$



Used data samples:

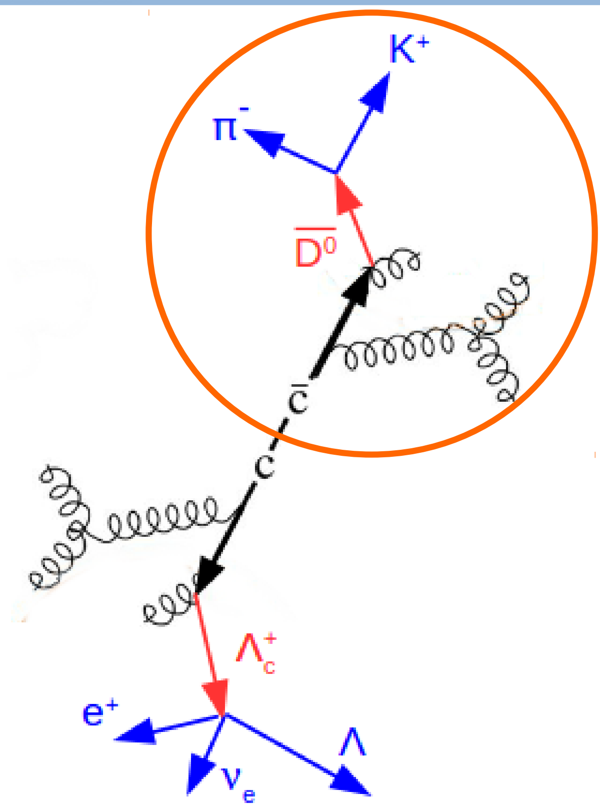
proton-proton collisions

Run-1:

- $\sqrt{s}$ = 2.76 TeV
  ~50M min. bias. events (L_{int}~0.9 nb^{-1})
- $\sqrt{s}$ = 7 TeV
  ~370M min. bias. events (L_{int}~6.0 nb^{-1})
- $\sqrt{s}$ = 8 TeV
  ~100M min. bias. events (L_{int}~1.8 nb^{-1})

Run-2:

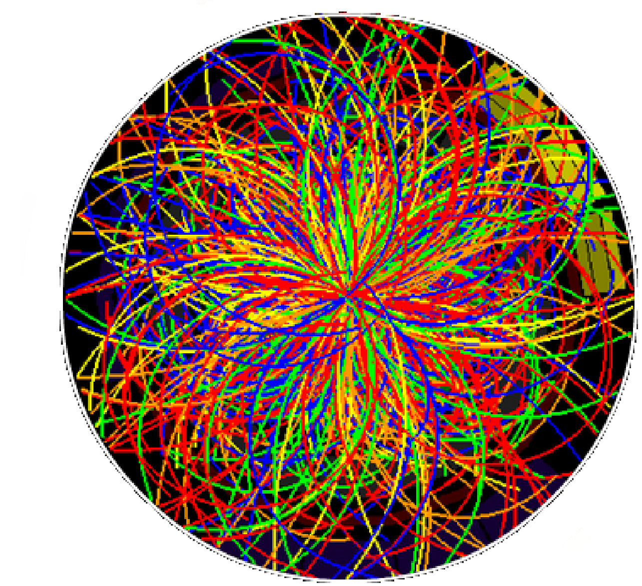
- $\sqrt{s}$ = 5.02 TeV:
  ~120M min. bias. events (L_{int}~2.3 nb^{-1})
- $\sqrt{s}$ = 13 TeV:
  ~190M min. bias. events (L_{int}~3.3 nb^{-1})



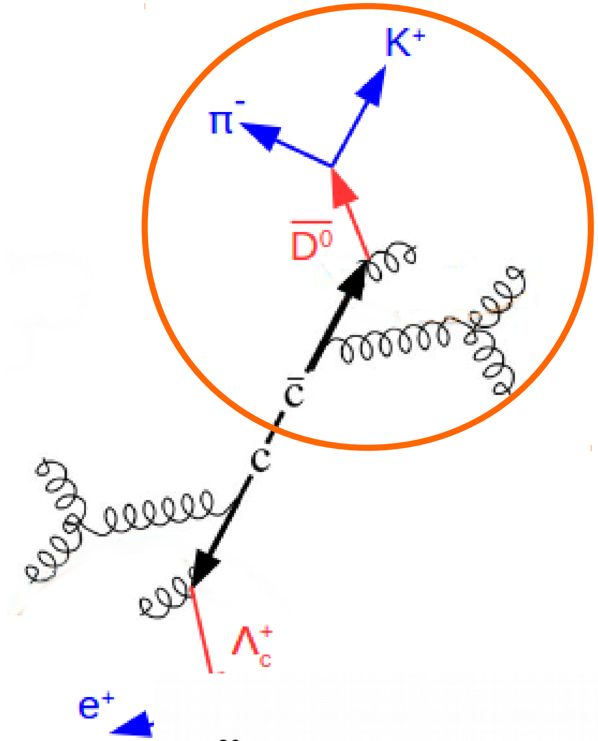
Analysis strategy:

- Combine track pairs/triplets with proper charge combinations.
- Reconstruct secondary vertex.
- Apply selection cuts to select decay-like topologies, exploiting decay-vertex displacement.
- Further background reduction using PID information via d*E*/dx (TPC) and time of flight (TOF) to identify pions, kaons and protons.

$D^0 \rightarrow K^- \pi^+$	(3.93 ± 0.04 %)	$c\tau \sim 123$ μm
$D^+ \rightarrow K^- \pi^+ \pi^+$	(9.46 ± 0.24 %)	$c\tau \sim 312$ μm
$D^{*+} \rightarrow D^0 \pi^+$	(67.7 ± 0.50 %)	$c\tau \sim 2$ fm
$D_s^+ \rightarrow \phi \pi^+$	(2.27 ± 0.08 %)	$c\tau \sim 150$ μm
$\Lambda_c^+ \rightarrow p K^- \pi^+$	(6.35 ± 0.33 %)	$c\tau \sim 60$ μm
$\Lambda_c^+ \rightarrow p K_S^0$	(1.58 ± 0.08 %)	$c\tau \sim 60$ μm



Particle reconstruction: Hadronic decays



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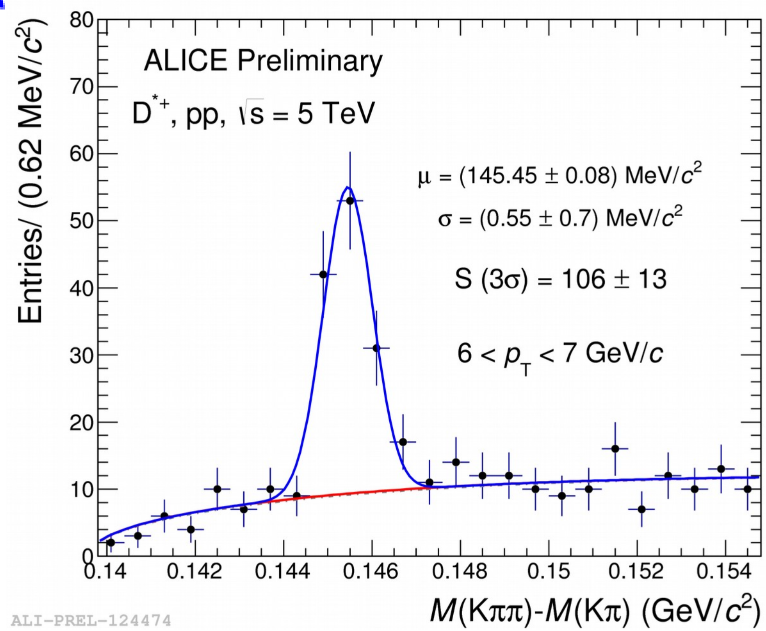
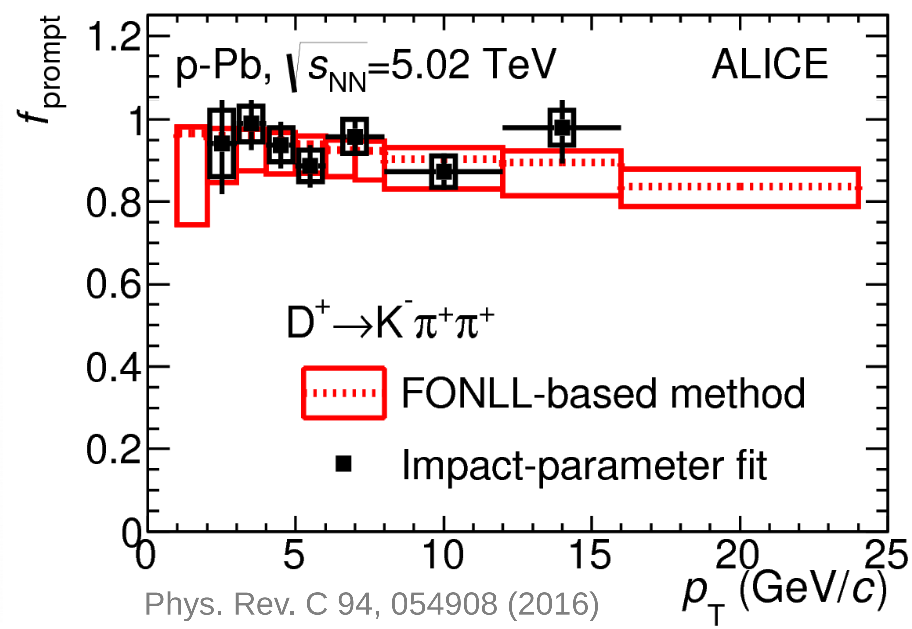
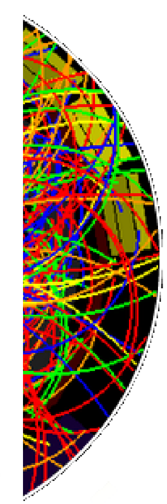
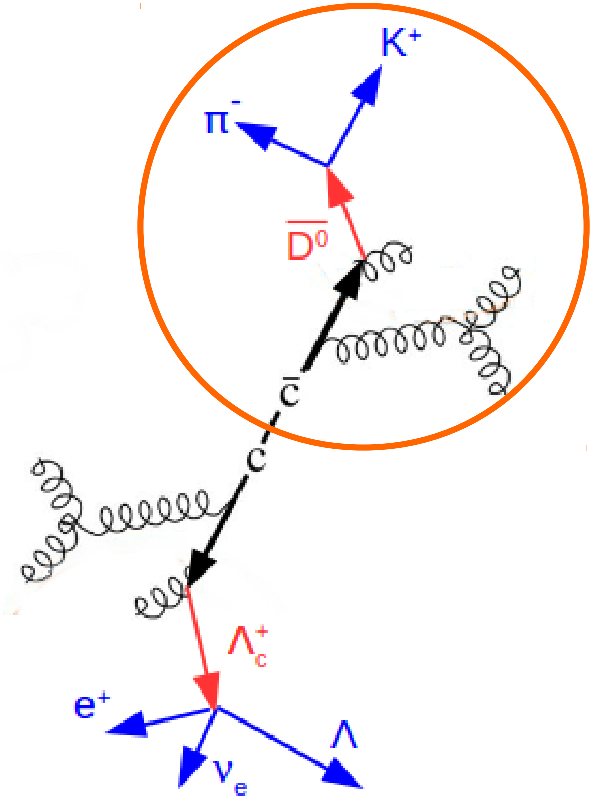
- Extract charm hadron signal via **invariant mass distributions**.
- Subtract **beauty feed-down**.





Phys. Rev. C 94, 054908 (2016)





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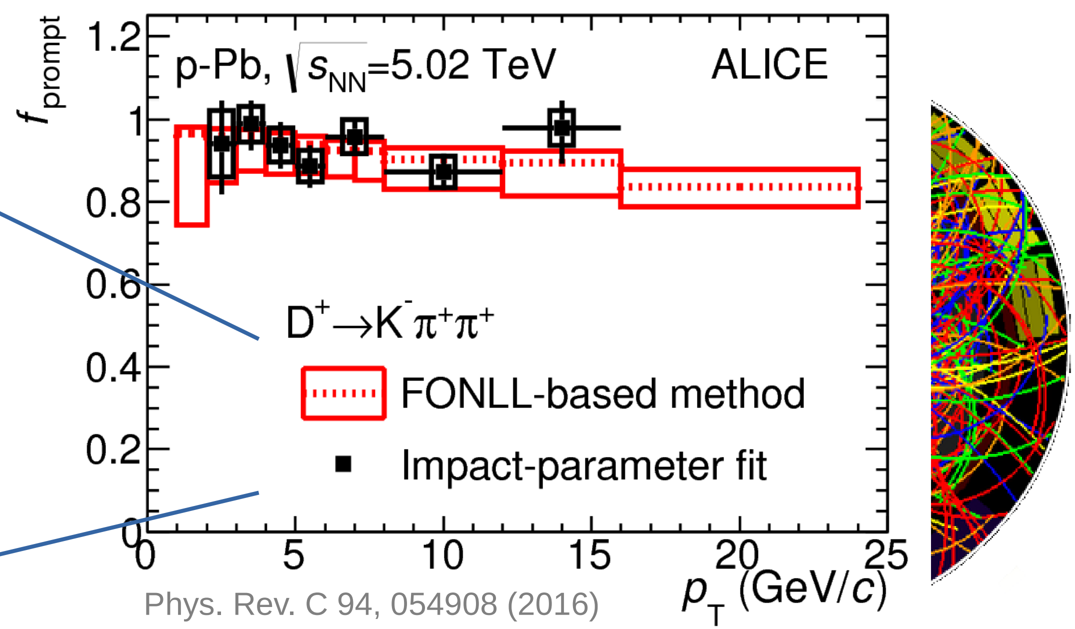
- Extract charm hadron signal via invariant mass distributions.
- Subtract **beauty feed-down**.

- Feed-down contribution estimated using FONLL predictions of D meson from beauty-hadron decay and prompt and feed-down D-meson reconstruction efficiencies.
- Method cross-checked with data-driven estimate from D-meson impact parameter fit.



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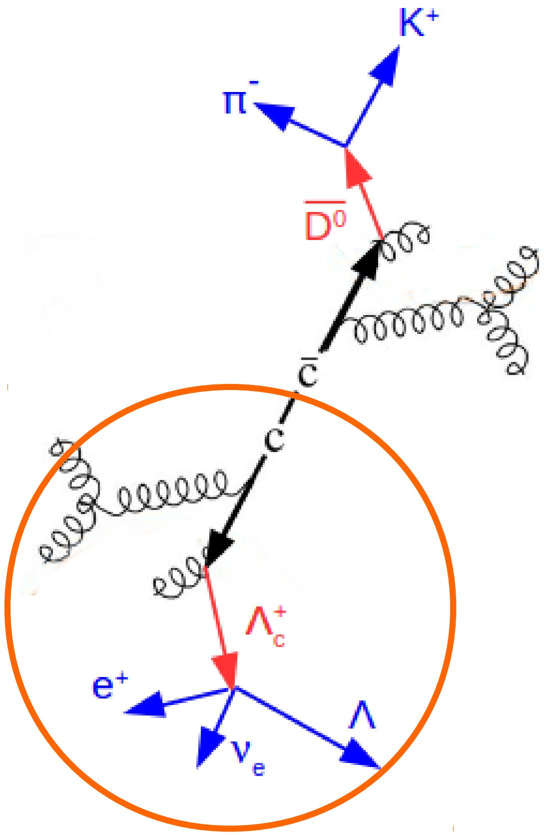
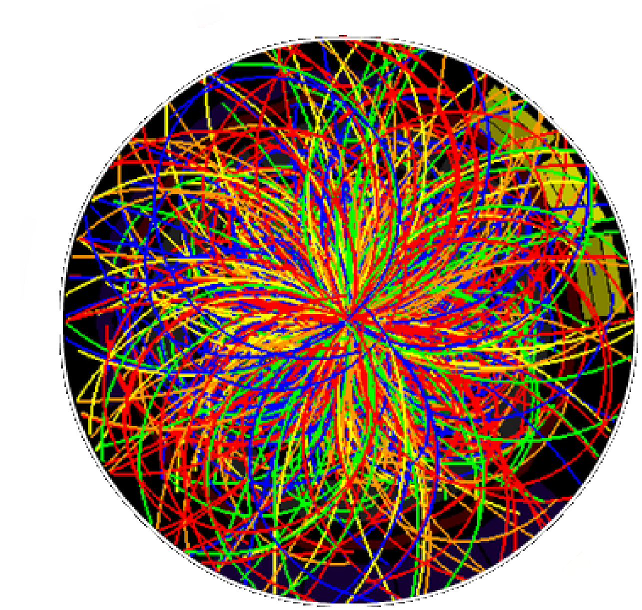
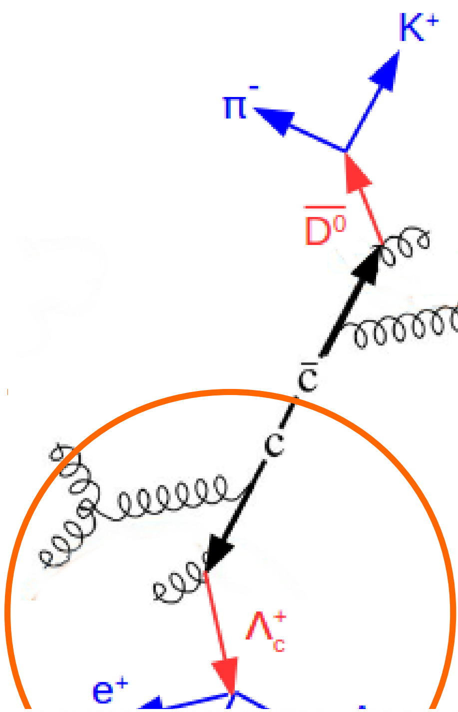


Analysis strategy:

- Combine an electron track originating close to primary vertex with a reconstructed Λ or $\Xi^\pm$ ($c\tau$ ~ 7.9 and 4.9 cm respectively).
- Apply selection cuts exploiting the decay vertex displacement of the Λ and $\Xi^\pm$ baryon to enhance the Λ and $\Xi^\pm$ signal purity.

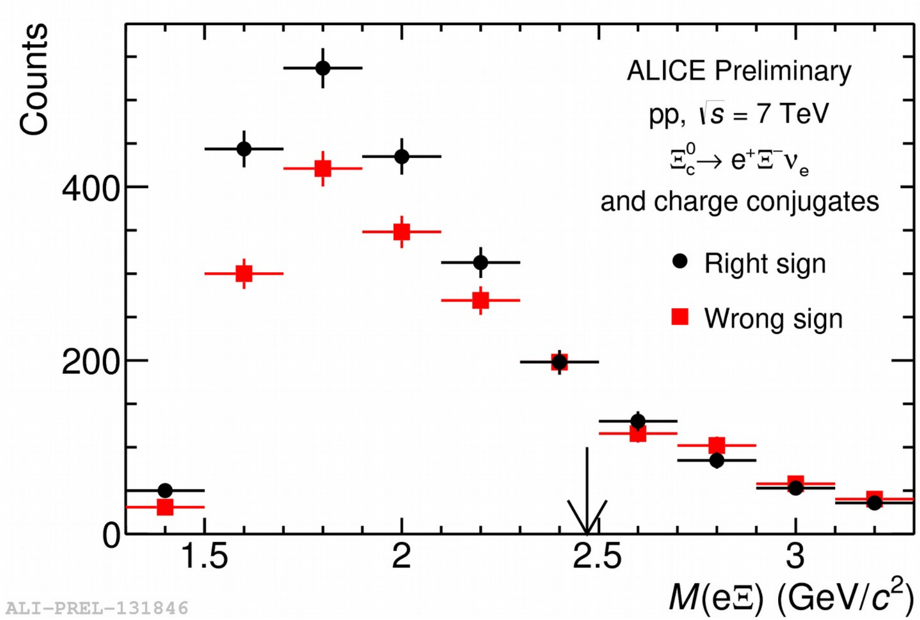
$\Lambda_c^+ \rightarrow e^+ \nu_e \Lambda$	(3.6 ± 0.4 %)	$c\tau$ ~ 60 μm
$\Xi_c^0 \rightarrow e^+ \nu_e \Xi^-$	BR unknown	$c\tau$ ~ 34 μm

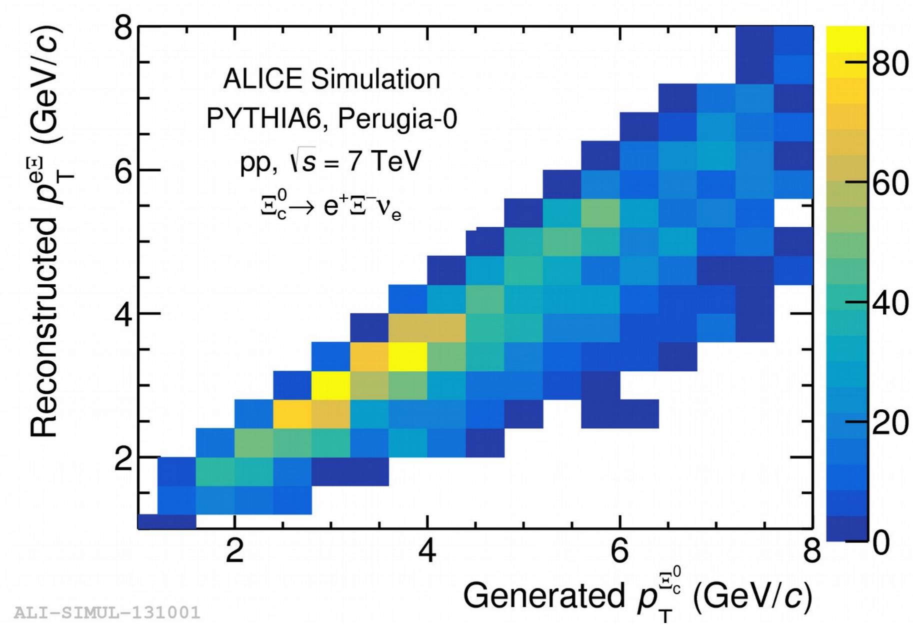


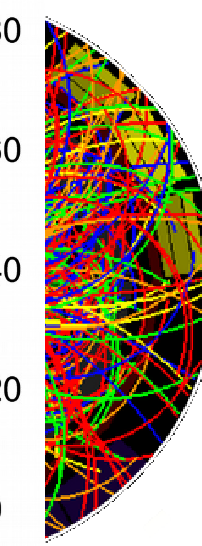


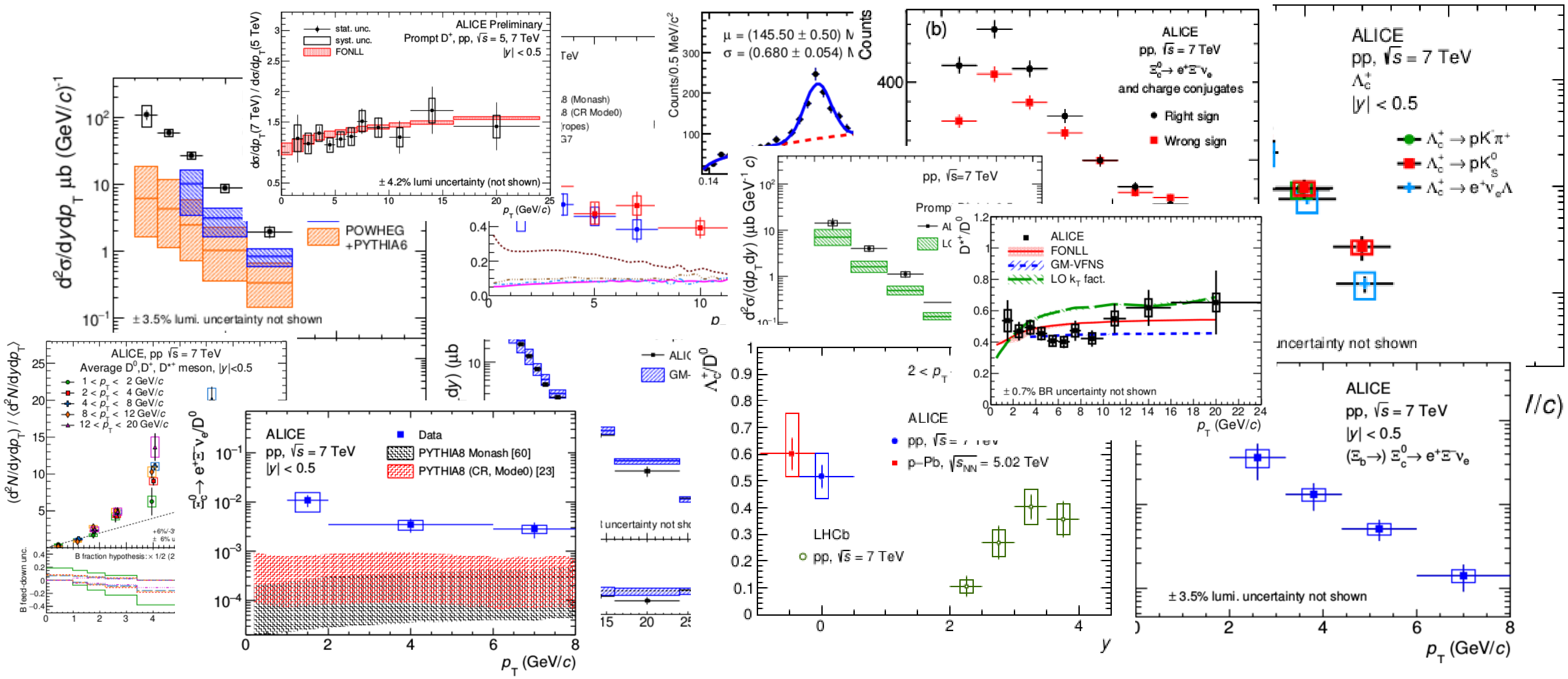
Analysis strategy:

- Combine an electron track originating close to primary vertex with a reconstructed Λ or Ξ± ($c\tau$ ~ 7.9 and 4.9 cm respectively).
- Apply selection cuts exploiting the decay vertex displacement of the Λ and Ξ± baryon to enhance the Λ and Ξ± signal purity.
- **Wrong sign** pairs $e^-\Lambda$ ($e^-\Xi^+$) subtracted from **right sign** spectra $e^+\Lambda$ ($e^+\Xi^-$).
- Correct for Λ_b^0 and Ξ_b^0 ($\Xi_c^{0,+}$) in wrong sign (right sign) spectra.
- Correct for missing momentum ν_e by **unfolding** $e^+\Lambda$ ($e^+\Xi^-$) p_T spectra.









ALICE Preliminary
Prompt D*, pp, √s = 5, 7 TeV
|y| < 0.5
stat. unc.
syst. unc.
FONLL
± 4.2% lumi uncertainty (not shown)
p_T (GeV/c)
POWHEG +PYTHIA6
± 3.5% lumi. uncertainty not shown
μ = (145.50 ± 0.50)
σ = (0.680 ± 0.054)
Counts/0.5 MeV/c²
Counts
(b)
ALICE
pp, √s = 7 TeV
and charge conjugates
Right sign
Wrong sign
pp, √s=7 TeV
ALICE
pp, √s = 7 TeV
|y| < 0.5
ALICE, pp √s = 7 TeV
Average D⁰,D⁺, D*⁺ meson, |y|<0.5
ALICE
pp, √s = 7 TeV
|y| < 0.5
Data
PYTHIA8 Monash [60]
PYTHIA8 (CR, Mode0) [23]
p_T (GeV/c)
ALICE
FONLL
GM-VFNS
LO k_T fact.
± 0.7% BR uncertainty not shown
ALICE
p–Pb, √s_NN = 5.02 TeV
LHCb
pp, √s = 7 TeV
y
ALICE
pp, √s = 7 TeV
|y| < 0.5
± 3.5% lumi. uncertainty not shown
p_T (GeV/c)

Results

D-meson cross sections

Production cross section of prompt D mesons:

$$\frac{\mathrm{d}^2\sigma^{\mathrm{D}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{1}{c_{\Delta y}\,\Delta p_{\mathrm{T}}}\frac{1}{\mathrm{BR}}\frac{\frac{1}{2}\, f_{\mathrm{prompt}} \cdot N^{\mathrm{D}+\overline{\mathrm{D}},\mathrm{raw}}\Big|_{|y|<y_{\mathrm{fid}}}}{(\mathrm{Acc}\times\varepsilon)_{\mathrm{prompt}}}\frac{1}{L_{\mathrm{int}}}$$

1) Number of reconstructed D mesons.
2) Efficiency and detector acceptance corrections.
3) Fraction of prompt D mesons.
4) Normalisation factors.

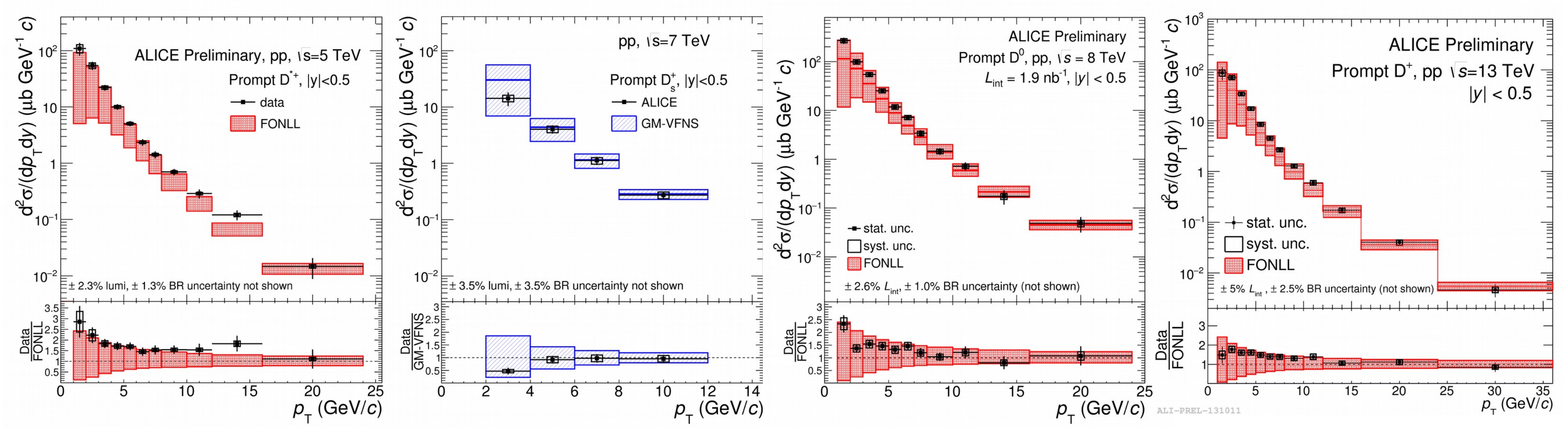
Production cross section of prompt D mesons:

$$\frac{d^2\sigma^{D}}{dp_{T}dy} = \frac{1}{c_{\Delta y}} \frac{1}{\Delta p_{T}\,BR} \frac{\frac{1}{2} f_{prompt} \cdot N^{D+\overline{D},raw}\Big|_{|y|<y_{fid}}}{(Acc\times\varepsilon)_{prompt}} \frac{1}{L_{int}}$$

1) Number of reconstructed D mesons.
2) Efficiency and detector acceptance corrections.
3) Fraction of prompt D mesons.
4) Normalisation factors.

- p_T-differential cross section of D mesons described within uncertainties by pQCD calculations (FONLL and GM-VFNS) at √s = 5, 7, 8, 13 TeV.

D^{*+} 5 TeV — **D_s^+ 7 TeV** — **D^0 8 TeV** — **D^+ 13 TeV**



FONLL: JHEP 05 (1998) 007 GM-VFNS: Eur. Phys. J. C41 (2005), Eur. Phys. J. C72 (2012) 2082

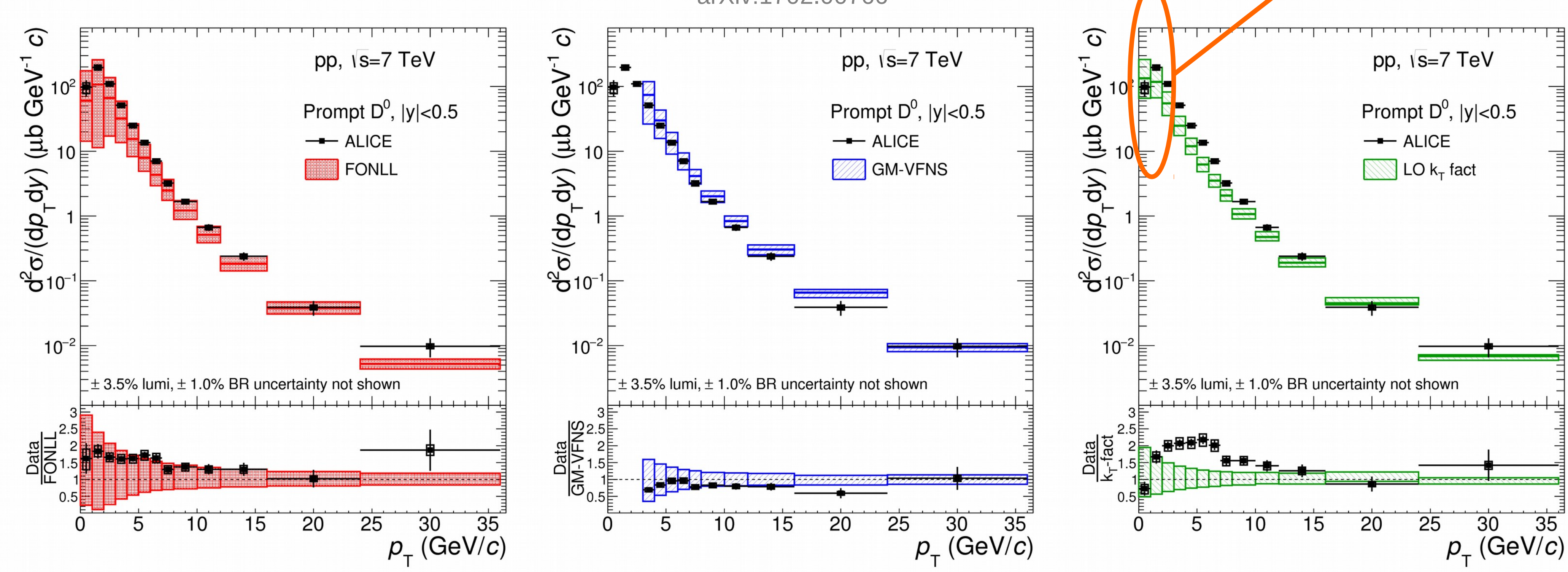
D-meson cross sections

- Analysis of pp data at $\sqrt{s}$ = 7 TeV (collected in 2010).
  - p_T coverage down to zero for the D^0 meson.

➔ Data described within uncertainties by FONLL and GM-VFNS. LO k_T factorisation calculations underestimate cross section at intermediate p_T.

Data point in $0 < p_T < 1$ GeV/c is obtained from analysis without decay vertex reconstruction.

arXiv:1702.00766



FONLL: JHEP 10 (2012) 137; GM-VFNS: Eur. Phys. J. C41 (2005), Eur. Phys. J. C72 (2012) 2082 kT: Phys. Rev. D87 no. 9 (2013)

Cross section ratios

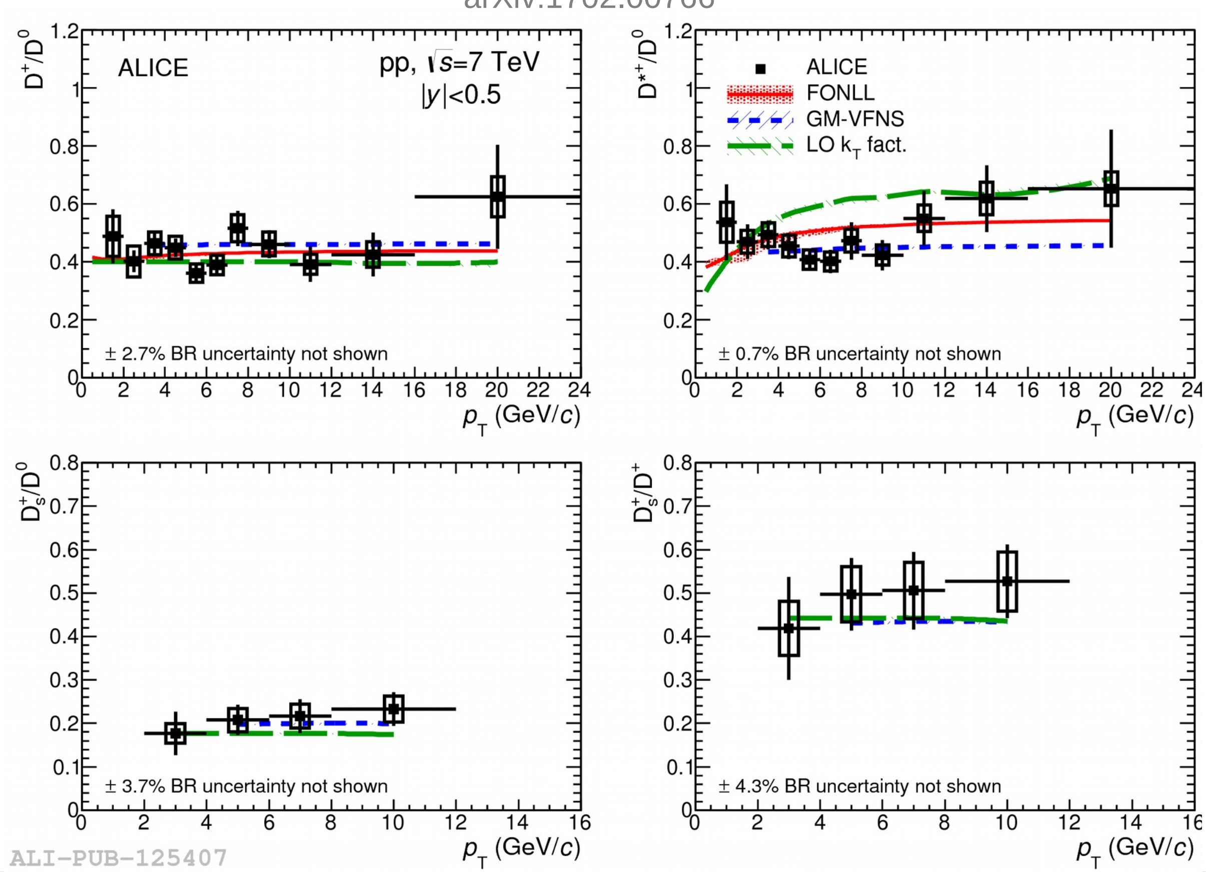
D-meson cross section ratios help to further constrain pQCD calculations.

- **Species**, *rapidity* and *energy* ratios.
- Several systematic uncertainties of pQCD models cancel.

➔ D-meson species ratios well described by models.

- Sensitive to fragmentation functions.
- No significant p_T dependence observed.

arXiv:1702.00766



FONLL:
JHEP 10 (2012) 137
JHEP 05 (1998) 007
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- *Species*, **rapidity** and **energy** ratios.
- Several systematic uncertainties of pQCD models cancel.

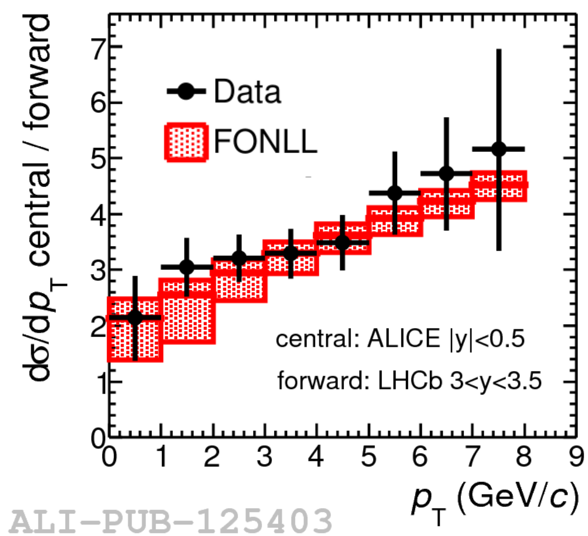
➔ D-meson species ratios well described by models.

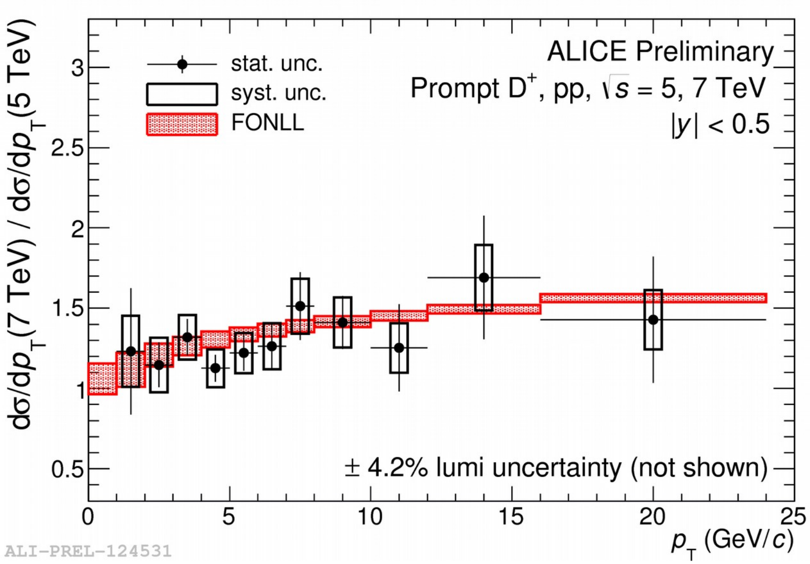
- Sensitive to fragmentation functions.
- No significant p_T dependence observed.

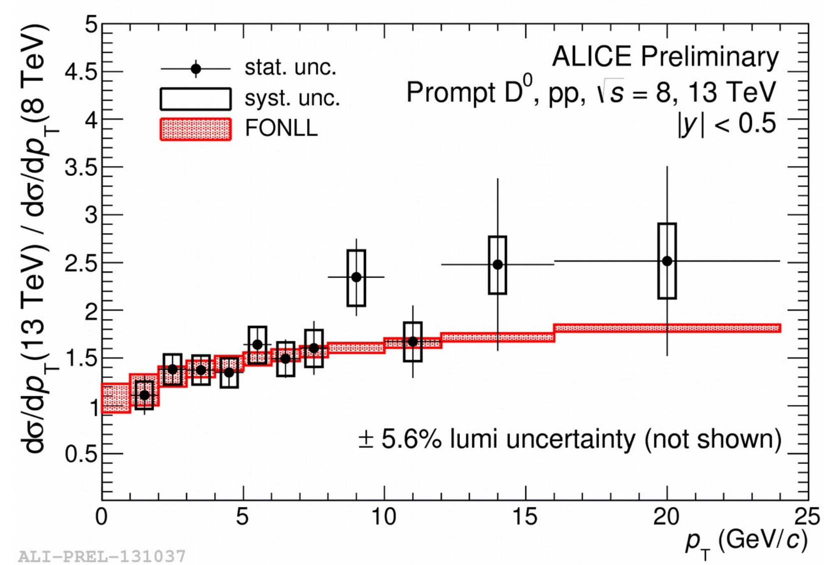
➔ D-meson rapidity and energy ratios compatible with FONLL.

- Sensitive to gluon PDF at small Bjorken-x.

arXiv:1702.00766

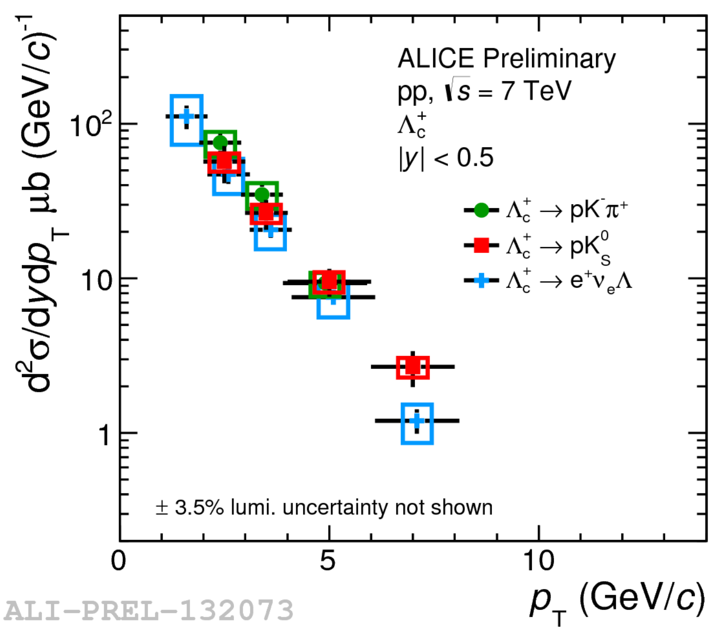


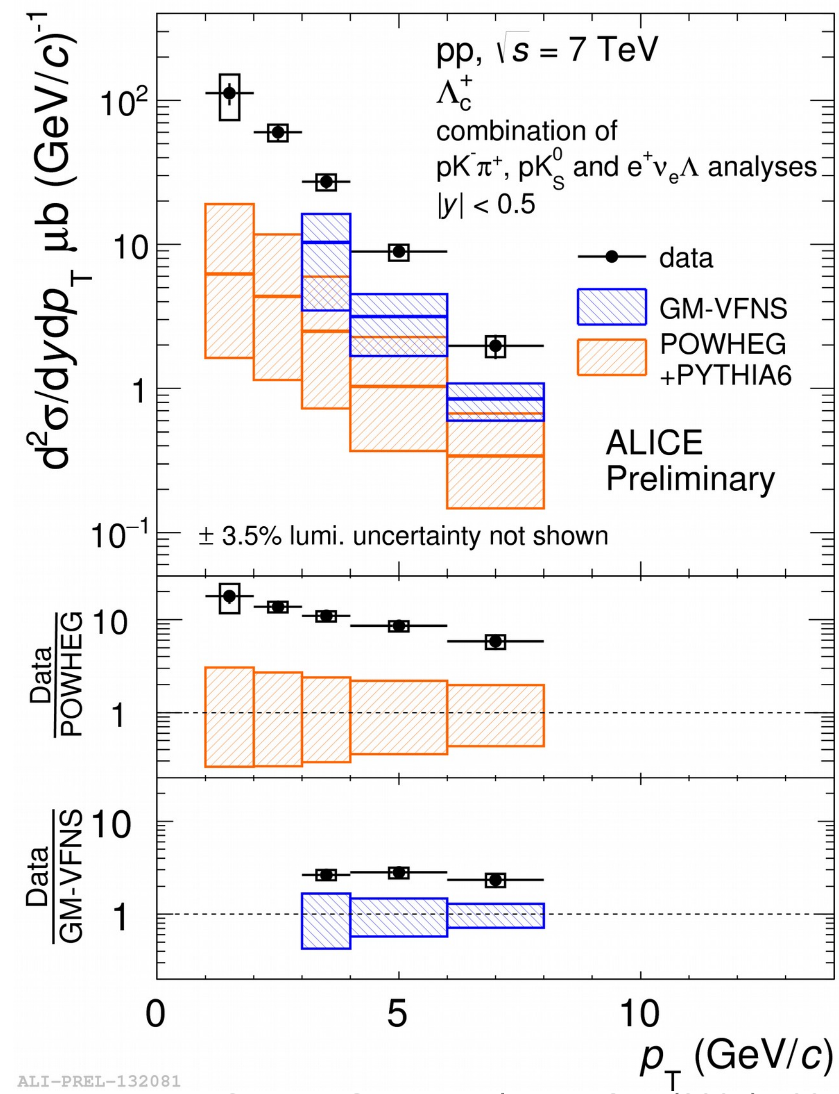




FONLL: JHEP 05 (1998) 007

Λ_c^+-baryon cross section





GM-VFNS: Eur. Phys. J. C41 (2005) 199–212
Eur. Phys. J. C72 (2012) 2082
POWHEG: JHEP 09 (2007) 126

Λ_c^+ cross section is measured in three decay channels.

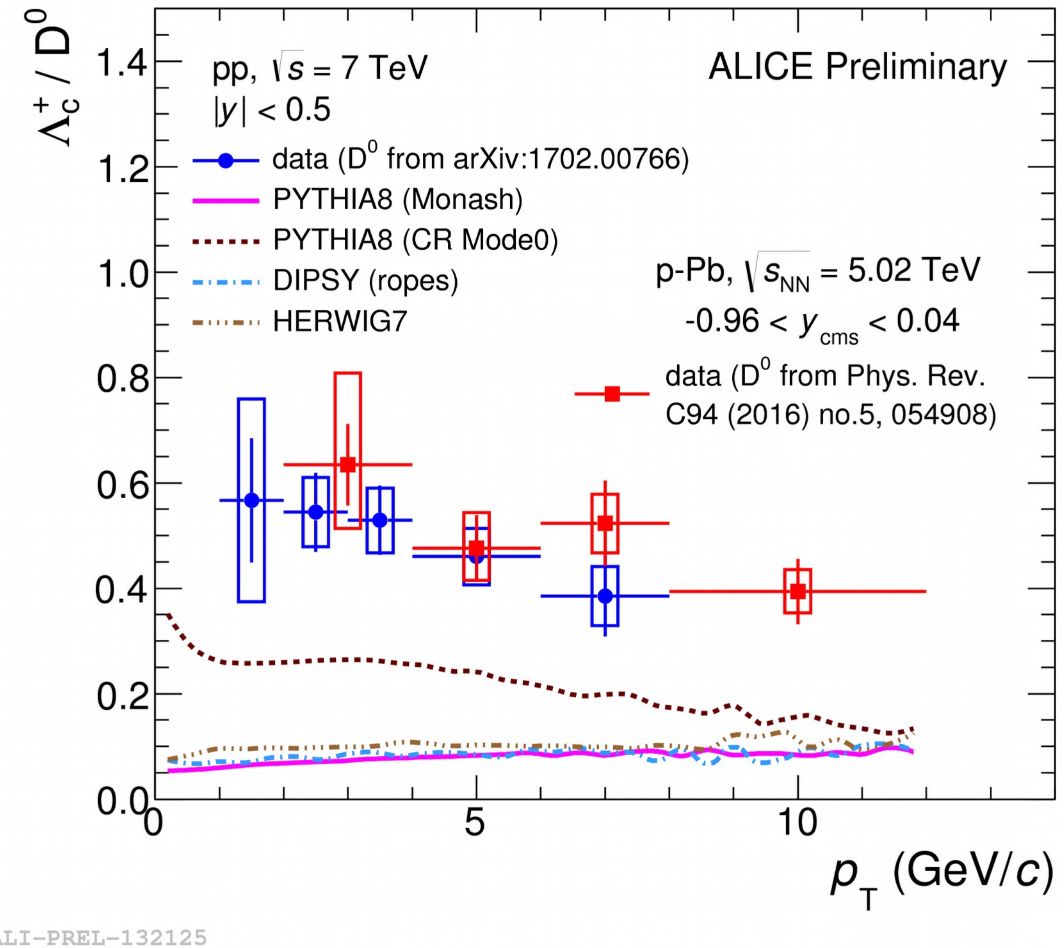
- **First** Λ_c^+ production measurements at mid-rapidity at the LHC.
- Compatible within uncertainties (1.7σ deviation in p_T bin 6 – 8 GeV/c).
- Averaged to one final cross section.

Cross section underestimated by theory.

- ~2 (~20) times higher than GM-VFNS (POWHEG+PYTHIA6).
- GM-VFNS compatible with Λ_c^+ measurement by LHCb at 2 < y < 4.5 [1].

[1] Nucl.Phys. B871 (2013) 1-20

Λ_c^+ / D^0 baryon-to-meson ratio



Sensitive to implementation of hadronisation:

PYTHIA8

- String formation model.
- **Monash** (standard) and **Mode0** tune (beyond leading-colour approximation).

DIPSY

- Colour rope model.
- Expected to increase baryon-to-meson ratio.

HERWIG7

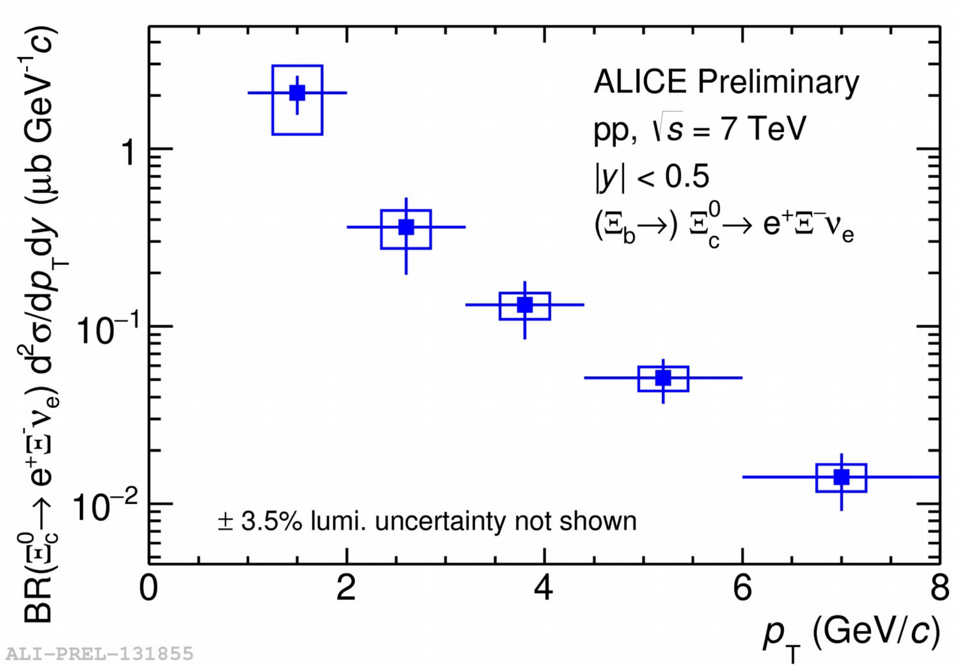
- Cluster hadronisation mechanism.

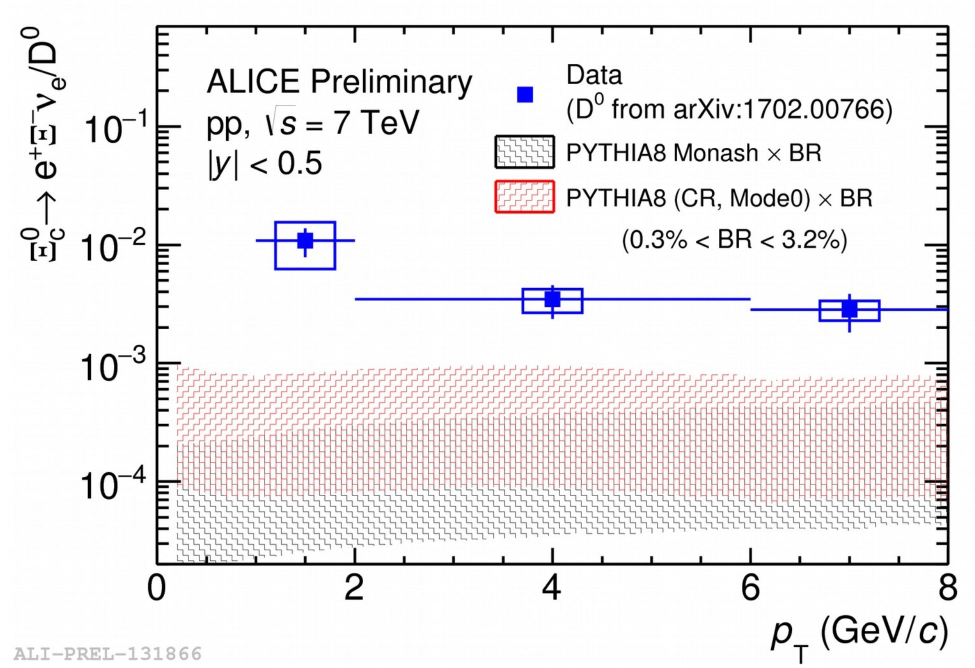
➔ All theoretical predictions underestimate Λ_c^+ / D^0 ratio.

- PYTHIA8 with colour-reconnection closest to data.
- Ratios in pp and p-Pb collisions compatible with each other.

PYTHIA8 Monash:	Eur. Phys. J. C74 (2014) 3024
PYTHIA8 (CR, Mode0):	JHEP 08 (2015) 003
DIPSY:	Phys. Rev. D 92 094010 (2015)
HERWIG7:	Eur. Phys. J. C58 (2008) 639–707

Ξ_c^0 cross section and Ξ_c^0 / D^0 ratio





- **First measurement** of Ξ_c^0 baryon at LHC.
  - Cross section multiplied by branching ratio (theoretical expectation: 0.3 – 3.2% [1]).
  - Feed-down contribution not subtracted.

- Ξ_c^0 / D^0 ratio significantly underestimated by both PYTHIA 8 tunes.

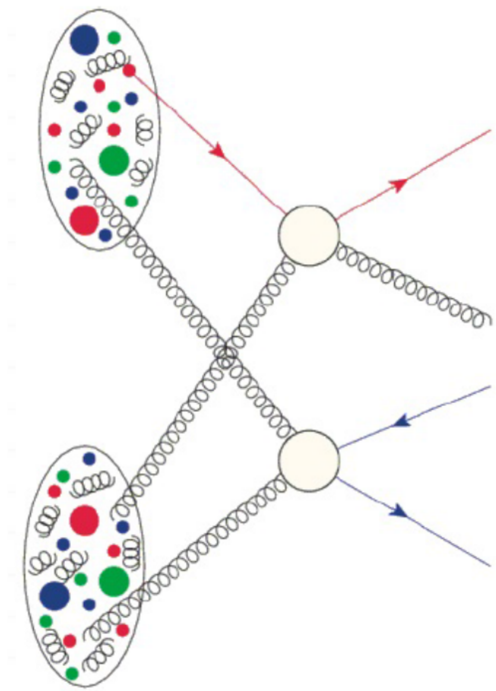
[1] Phys. Rev. D40 (1989) 2955, Phys. Rev. D43 (1991) 2939, Phys. Rev. D53 (1996) 1457
PYTHIA8 Monash: Eur. Phys. J. C74 (2014) 3024
PYTHIA8 (CR, Mode0): JHEP 08 (2015) 003

Multiple-parton interactions on hard scale?

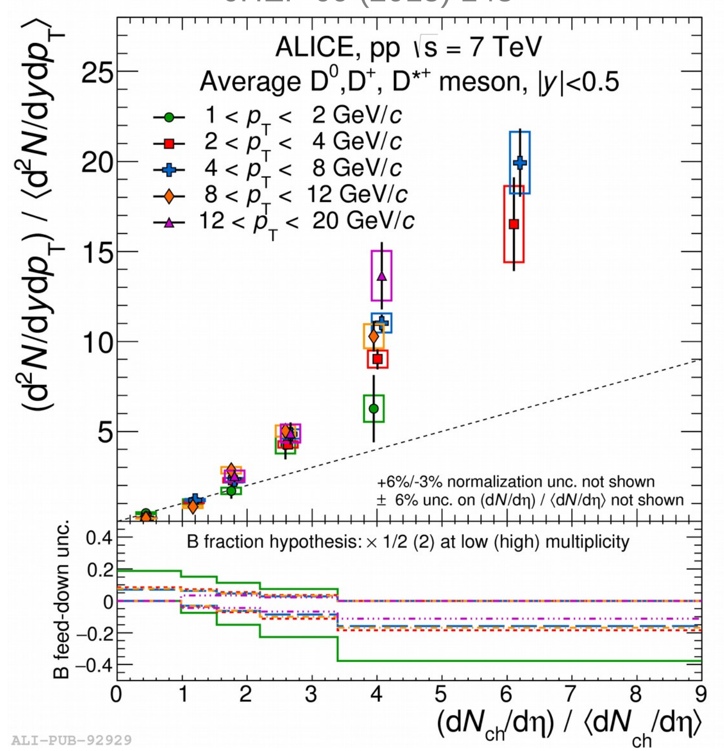
- D-meson yield may be correlated to the event charged-particle multiplicity.

➡ Steeper-than-linear increase of D^0, D^+ and D^{*+} yields versus multiplicity.

- Similar trend for prompt and non-prompt J/Ψ.
- Multi-parton interactions and/or additional hadronic activity?



JHEP 09 (2015) 148



JHEP 09 (2015) 148

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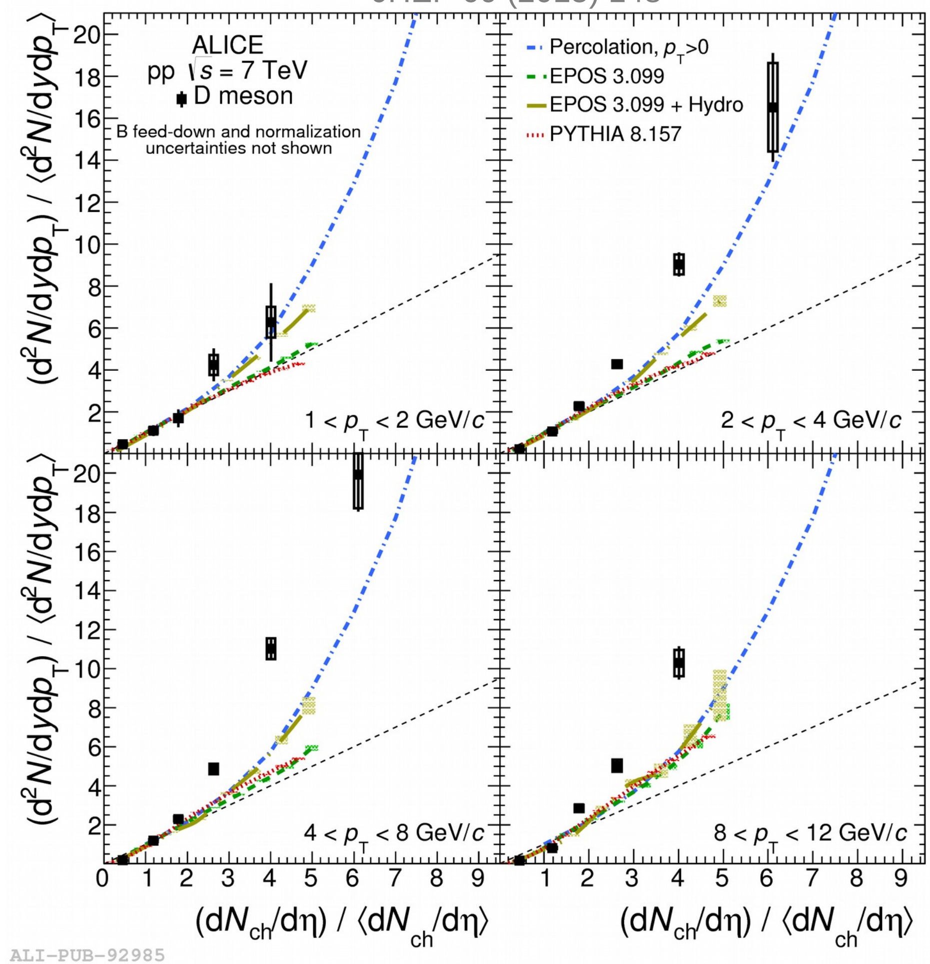
➔ Steeper-than-linear increase of D^0, D^+ and D^{*+} yields versus multiplicity.

- Similar trend for prompt and non-prompt J/Ψ.
- Multi-parton interactions and/or additional hadronic activity?

➔ Models including MPI predict steeper-than-linear increase.

- Reproduce the data at low multiplicity while deviate at high multiplicity.



Phys.Rept. 350 (2001) 93–289, Phys.Rev. C89 (2014) 064903

Percolation

- Colour sources with finite spatial extension (similar scenario as MPI).
- Steeper-than-linear increase.

EPOS 3.099 + *Hydro*

- Parton based Gribov-Regge formalism.
- N_{MPI} directly related to multiplicity.
- Steeper-than-linear for hydro.

Pythia 8.157

- Soft QCD with colour reconnection.
- MPI implemented in combination with initial- and final-state radiation.
- Almost linear increase.

Phys.Rev. C86 (2012) 034903, arXiv:1501.03381

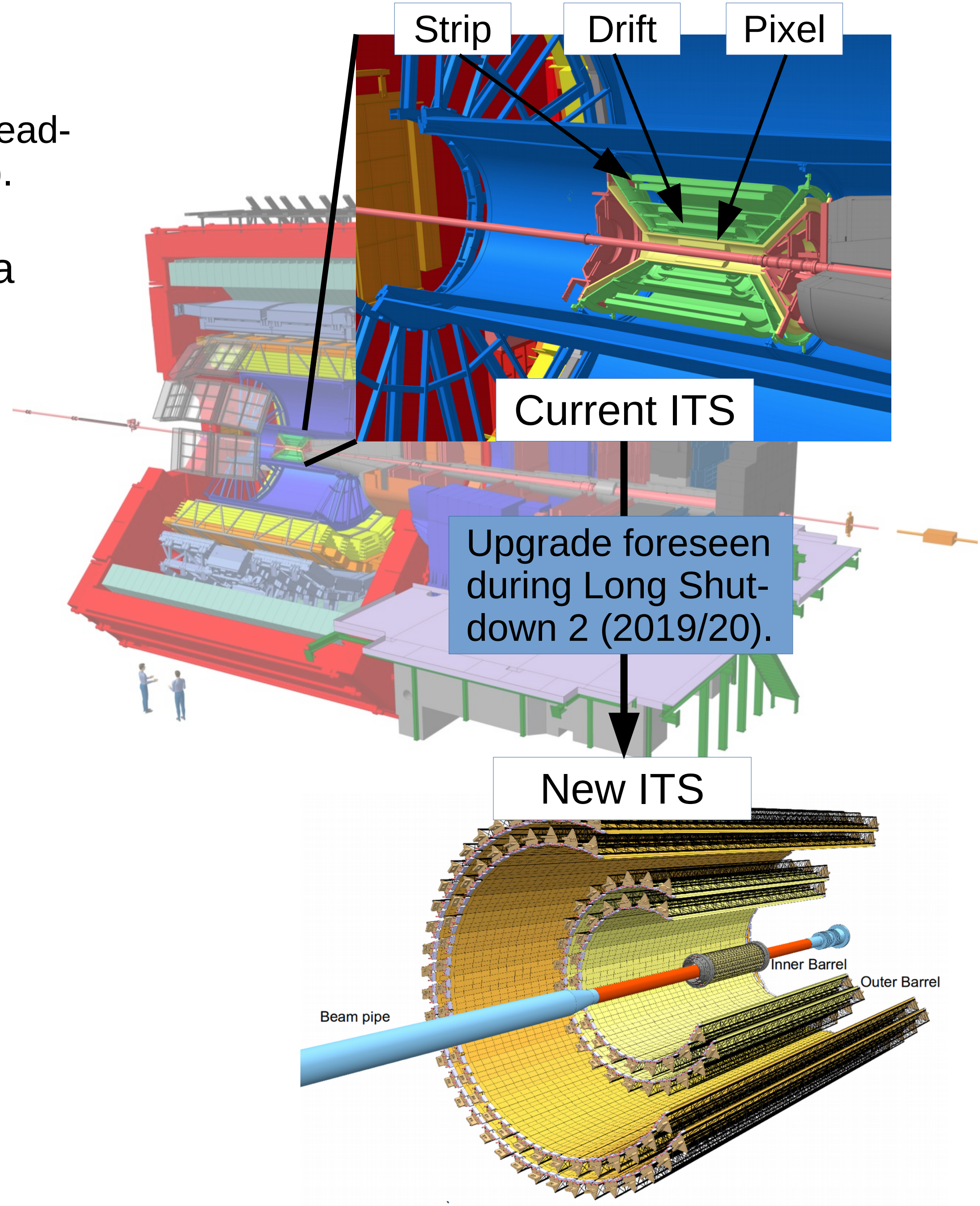
Comput. Phys. Commun. 178 (2008) 852–867

Coming soon: ALICE upgrade

Major upgrade ALICE foreseen:

- **New ITS**, new Muon Forward Tracker, TPC, read-out electronics, trigger and Online/Offline (O^2).

- Improve low p_T tracking, vertexing and data rate performances.
  - 6 → 7 layers (closer to interaction point).
  - Reduce material budget and pixel size.
  - Improve read-out electronics.



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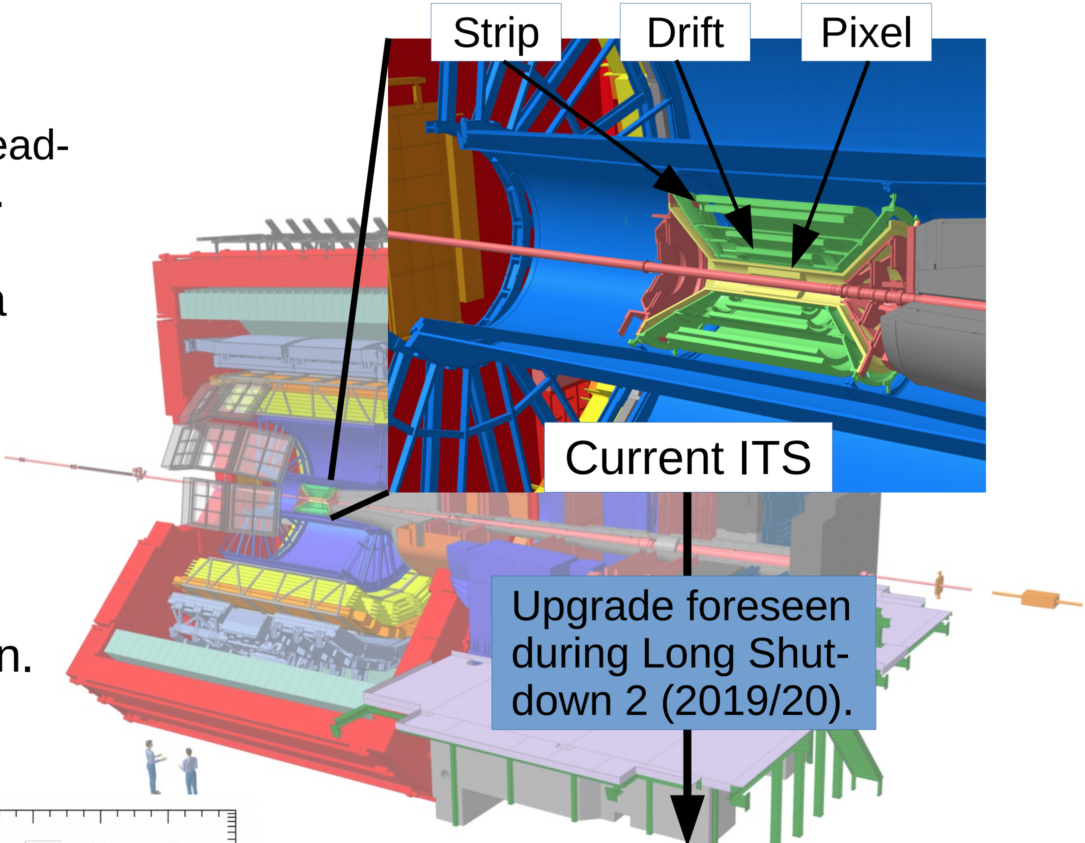
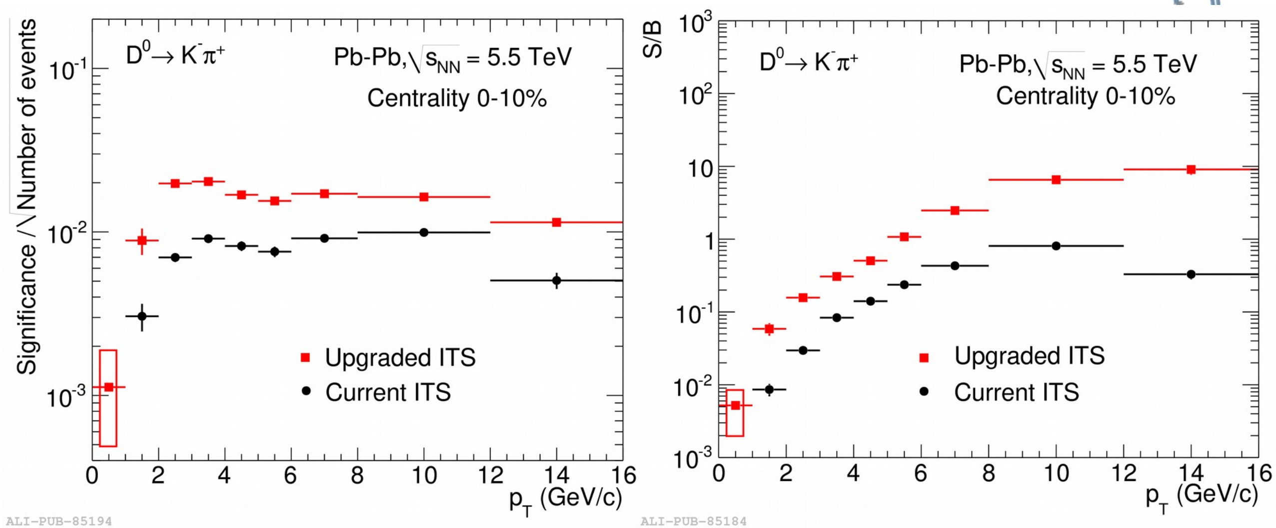
➔ Improve low p_T tracking, vertexing and data rate performances.

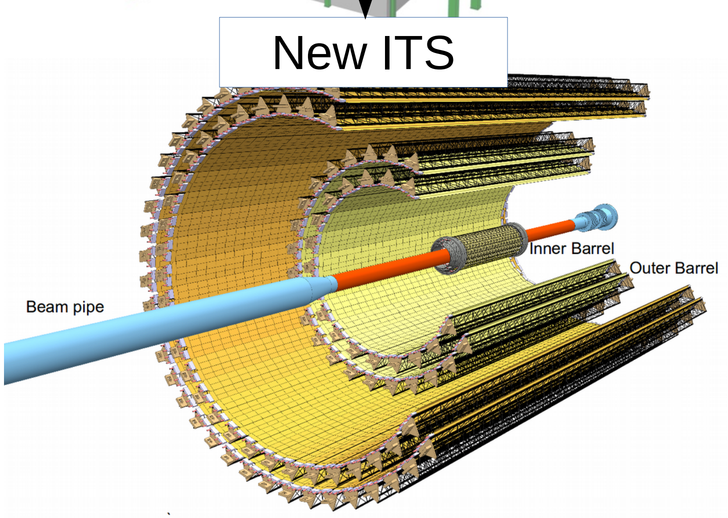
- 6 → 7 layers (closer to interaction point).
- Reduce material budget and pixel size.
- Improve read-out electronics.

➔ Improve heavy-flavour background rejection.

- A factor 4-5 for D^0 mesons with p_T > 2 GeV/c.







Summary and outlook

D mesons in proton-proton collisions:

- p_T-differential cross sections at √s = 5,7,8 and 13 TeV are **compatible with pQCD predictions**.
- **Provide constraints** to models with precise differential cross section measurements and ratios amongst charmed hadrons, energies and rapidities.

Charmed baryons in proton-proton collisions:

- **First** Λ_c^+ and Ξ_c^0 production measurements at mid-rapidity.
- Production cross section **underestimated by models**.
- Λ_c^+ / D^0 and Ξ_c^0 / D^0 ratios **higher than MC predictions**.

Charm production versus event charged-particle multiplicity:

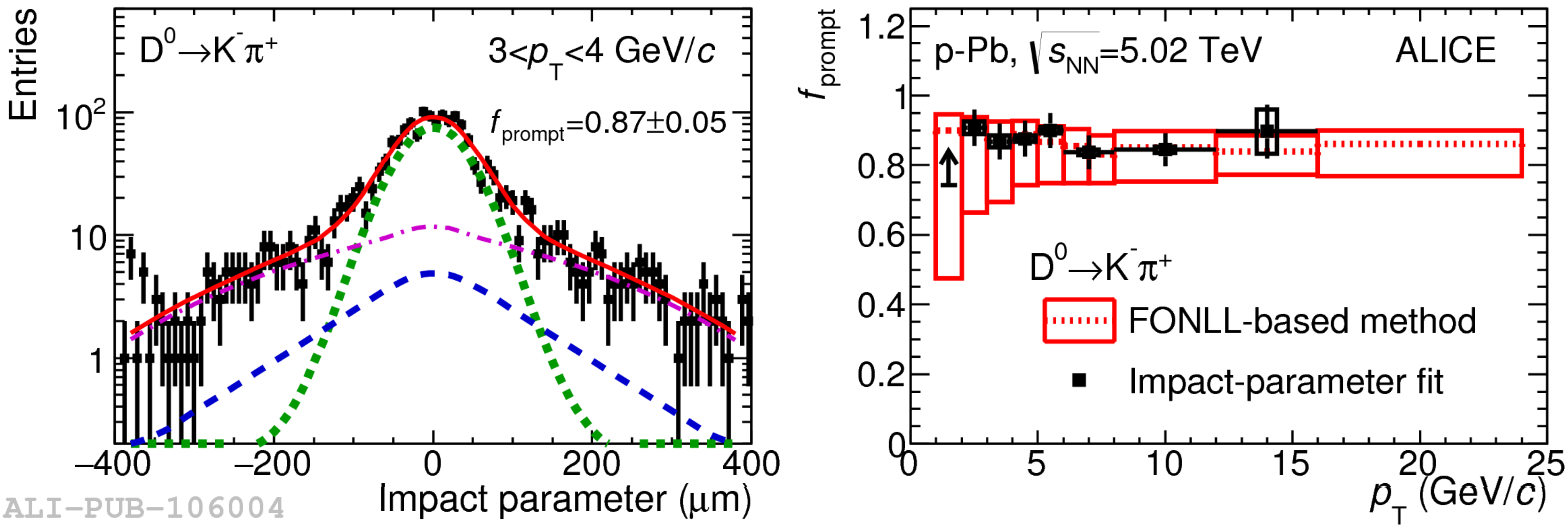
- D-meson yield increases **steeper-than-linear** with multiplicity.
- Suggests that **multiple-parton interactions** and/or additional hadronic activity play an important role at high multiplicity.

Prospects:

- *LHC Run 2*: Additional measurements in pp collisions at √s = 5 and 13 TeV with more statistics.
- *LHC Run 3*: Improvement of factor 10-100 on statistics and better vertexing with the new ITS.
    - Precision measurements on charm sector and direct access to beauty sector.

Back-up

Phys. Rev. C 94, 054908 (2016)



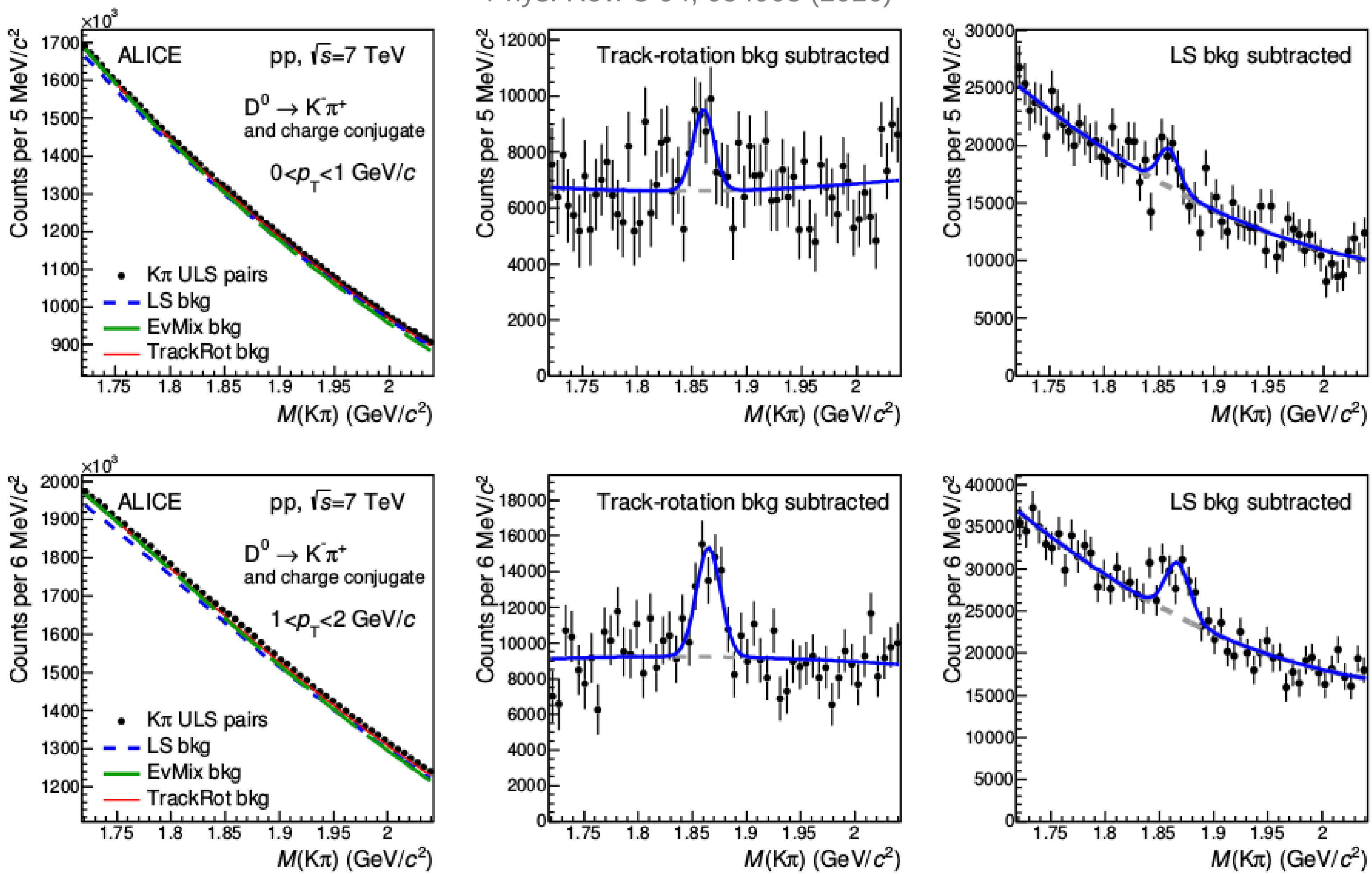
- Feed-down for D mesons and Λ_c baryon determined using theory-based method using theoretical prediction of charmed hadrons from beauty.
  - Λ_c measurements uses input from measured Λ_b cross section for systematic uncertainties.

- Up to now, D mesons in p-Pb collisions checked using data-driven method.
  - Unbinned log-likelihood fit to impact parameter distribution with different distributions for prompt and feed-down D mesons.

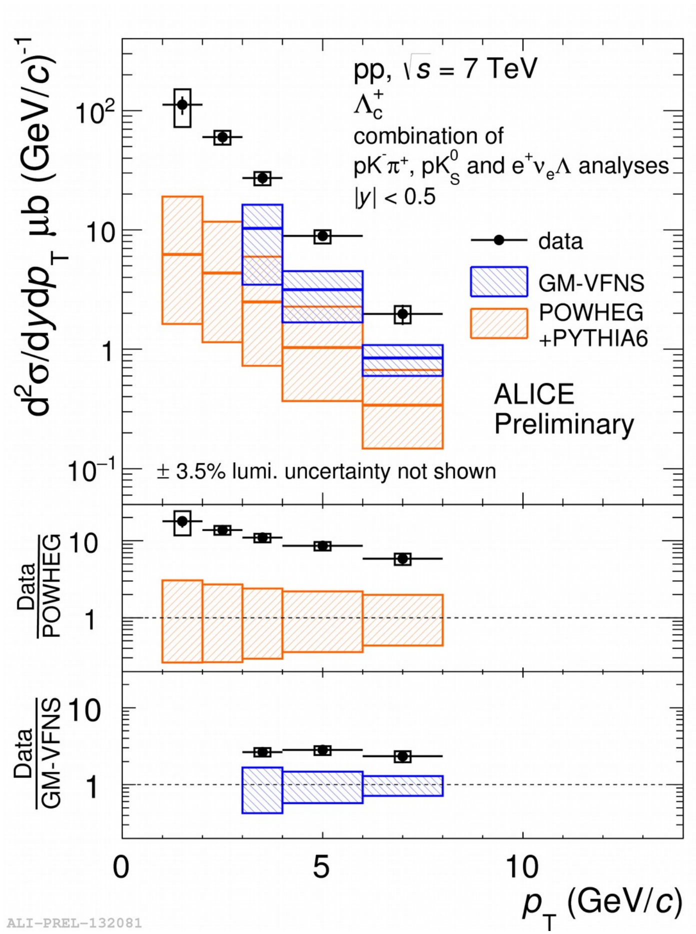
D^0 cross section down to zero p_T

- Different analysis method allows us to measure D^0 down to $p_T = 0$.
  - No secondary vertex reconstruction, no topological selection.
  - Background subtraction by event mixing, like-sign distribution, track rotation or fit of sidebands.

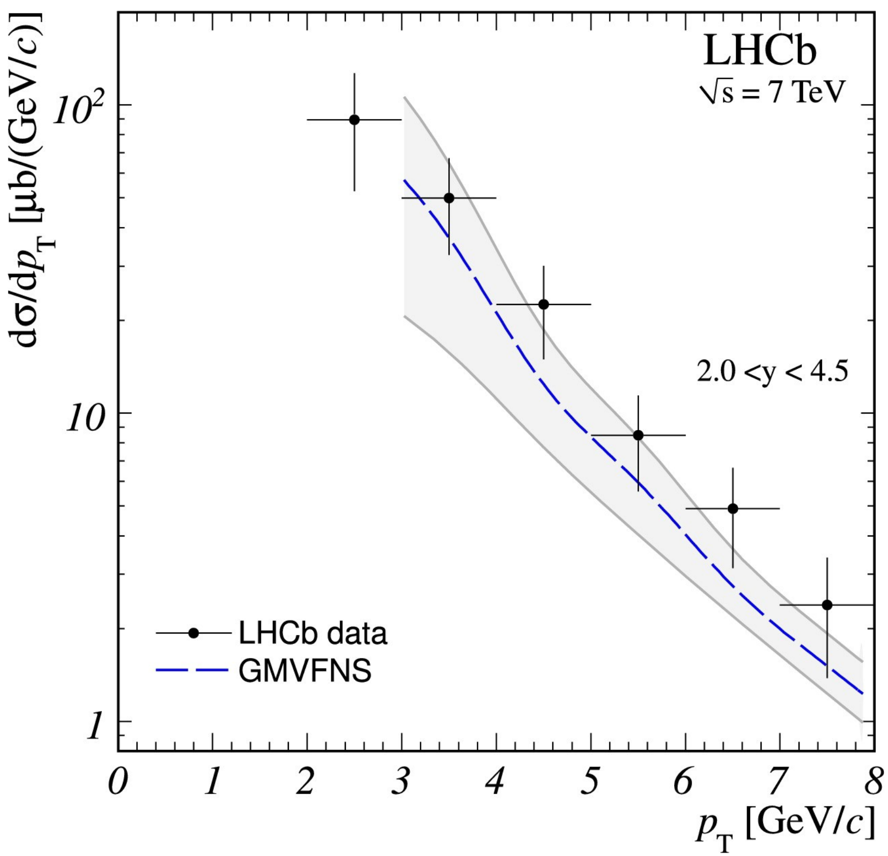
Phys. Rev. C 94, 054908 (2016)



Λ_c^+ measurement in LHCb



Nucl.Phys. B871 (2013) 1-20

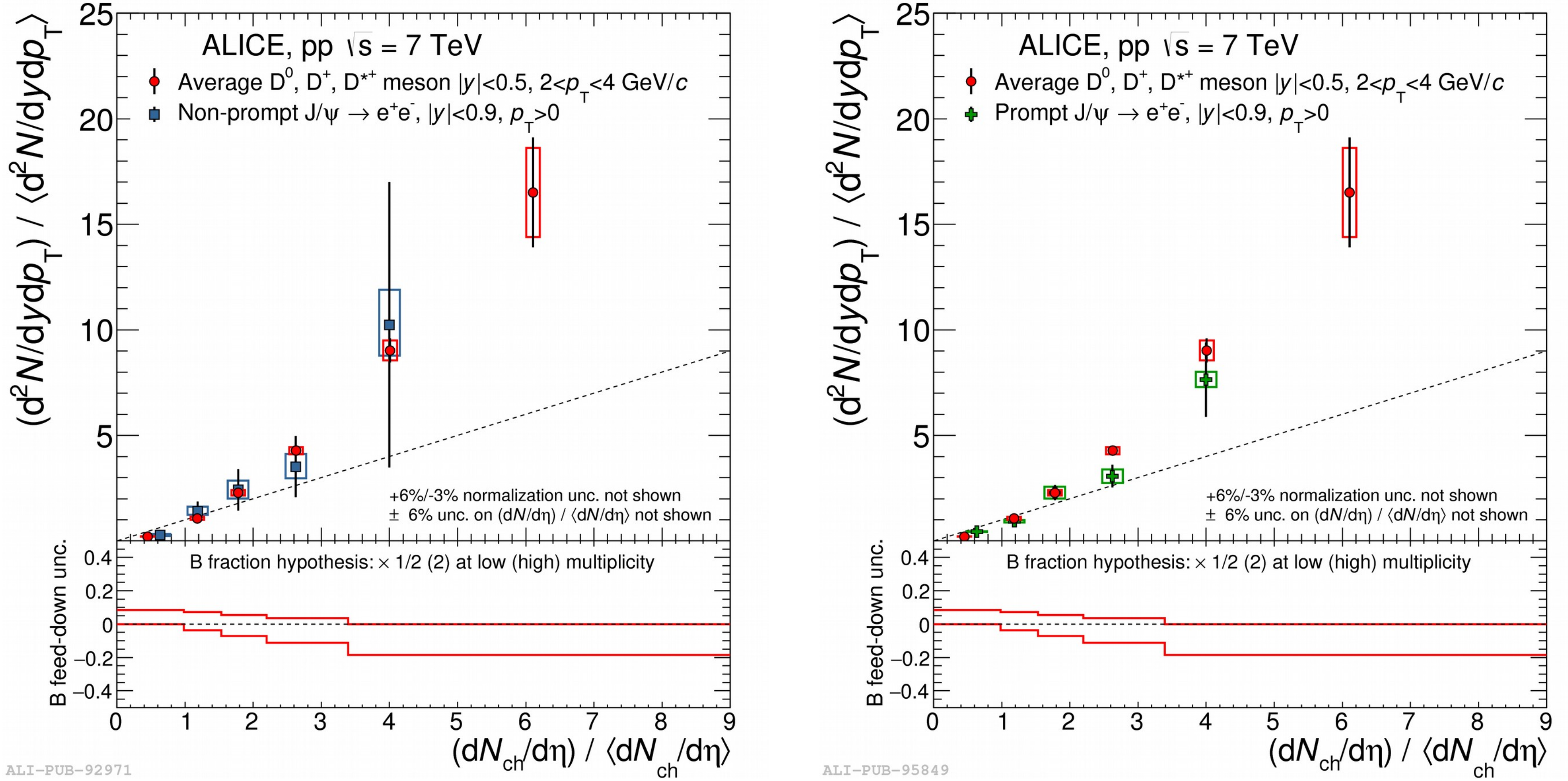


- Differential cross sections for Λ_c^+ baryon production compared to GM-VFNS for ALICE ($|y| < 0.5$) and LHCb ($2.0 < y < 4.5$).
  - Suggests a rapidity dependence.

GM-VFNS: Eur. Phys. J. C41 (2005) 199–212
Eur. Phys. J. C72 (2012) 2082
POWHEG: JHEP 09 (2007) 126

J/Ψ yields versus multiplicity

JHEP 09 (2015) 148



- Production of **D mesons** increases steeper-than-linear with multiplicity.
- Same trend for **non-prompt (B→)J/Ψ** as well as **prompt J/Ψ** yields.
  - *Caveat:* Different η and p_T regions.