Charmed meson and baryon production with ALICE at the LHC

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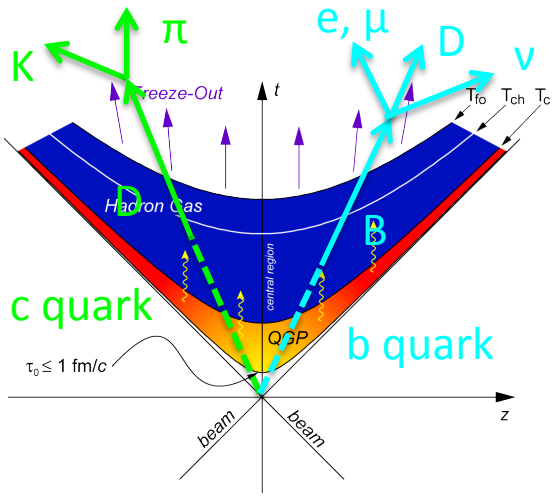
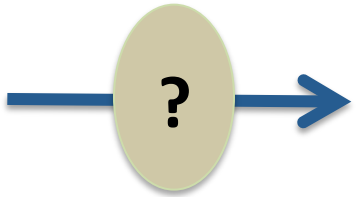
Heavy flavour in heavy-ion collisions

- Because of their large masses, charm ($m_c \approx 1.5$ GeV) and beauty ($m_b \approx 5$ GeV) are produced at the early stages of the collisions
  - hard scattering with large Q^2 → **production cross section calculable with perturbative QCD**

- $m_{c,b} >> \Lambda_{QCD}$ → heavy quarks are genuine hard probes **even at low p_T** (in contrast to jets)

- $\tau_{prod} \approx 1/(2m_Q) \approx 0.1$ fm/c << $\tau_{QGP} \approx 5 - 10$ fm/c at LHC
- they interact with the QCD high-density medium, but those interactions don't change their flavour
  - **destruction or creation in the medium is difficult**
  - **transported through the whole evolution of the system**



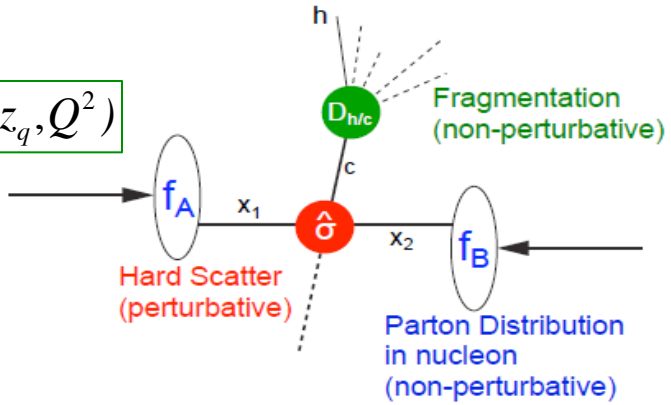


they behave as penetrating probes ("*direct*" info from the medium)

Heavy flavour in pp and p-Pb collisions

- **pp collisions**
  - precision test of pQCD-based predictions for production cross sections at the highest collision energies

$$\sigma_{hh\to Hx} = PDF(x_a,Q^2)PDF(x_b,Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q,Q^2)$$



  - reference for p-Pb and Pb-Pb measurements
  - relative production of baryon and meson ("baryon-to-meson" ratio) is particularly sensitive to the fragmentation mechanism

- **p-Pb collisions**
  - address initial-state (or cold-nuclear-matter) effects, such as
    - shadowing and gluon saturation (CGC)
    - energy loss in cold nuclear matter
    - k_T-broadening
  - reference for Pb-Pb measurements
  - address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions

K.J. Eskola et al, JHEP 0904 (2009) 65
H. Fuji, K. Watanabe, NPA 915 (2013) 1
I. Vitev et al, PRC 75 (2007) 064906
X.N. Wang, PRC 61 (2000) 064910

The ALICE experiment

High precision tracking, good vertexing capabilities and excellent particle identification

ITS: vertexing and tracking

EMCAL: ElectroMagnetic CALorimeter

TRD

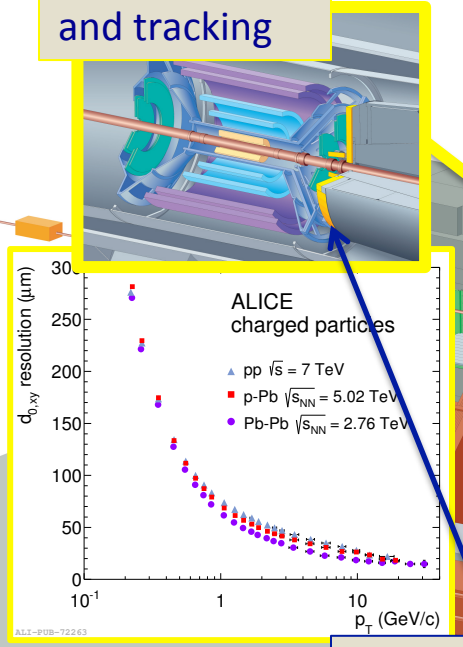
TOF: PID w/o Time of Flight

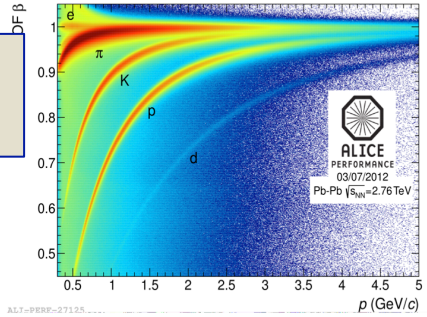
Forward Muon Spectrometer

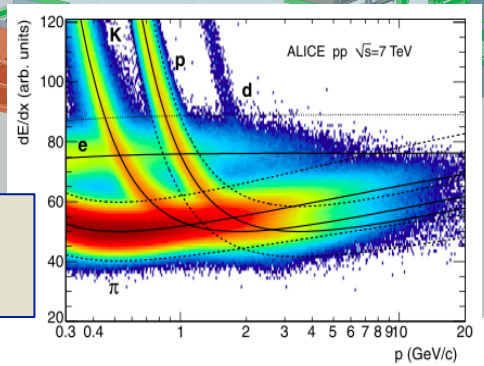
ZDC: event activity determination in p-Pb and Pb-Pb

V0: trigger and multiplicity

TPC: tracking and PID via dE/dx

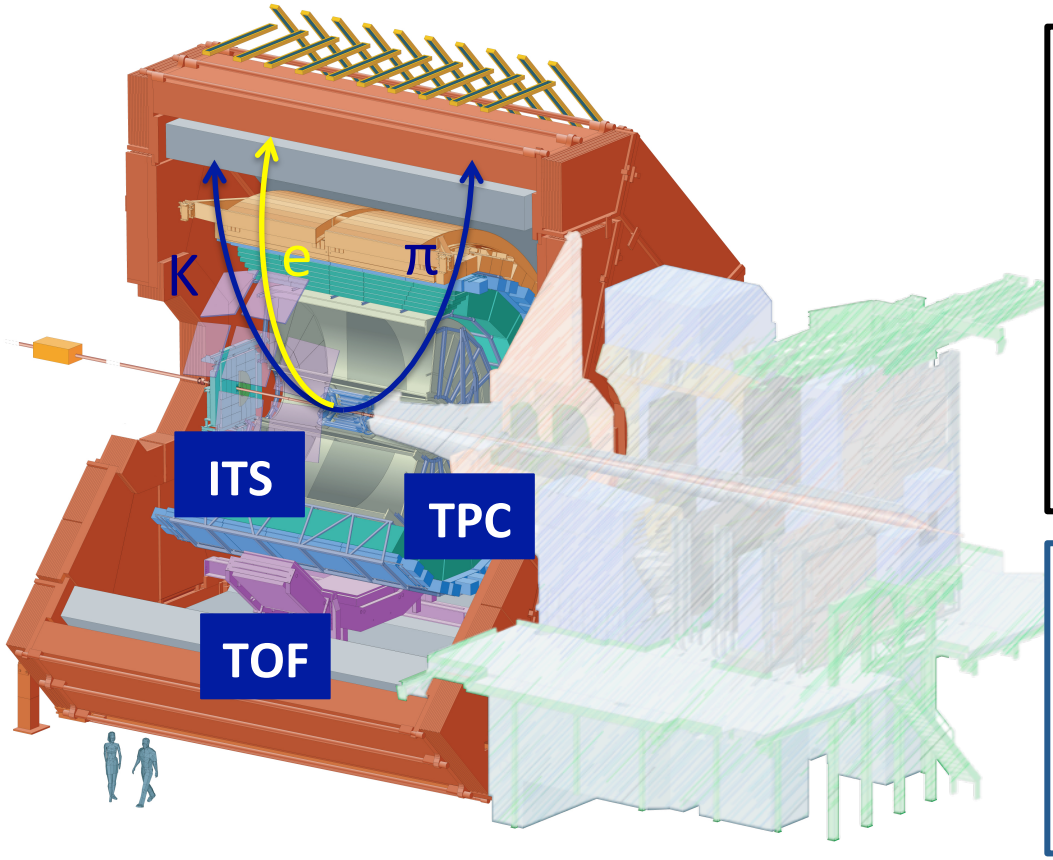






HF in the central barrel – D mesons and charmed baryons

$|y| < 0.5$



Fully reconstructed hadronic decays

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$
$\Lambda_c^+ \rightarrow p K^- \pi^+$
$\Lambda_c^+ \rightarrow p K_s^0$

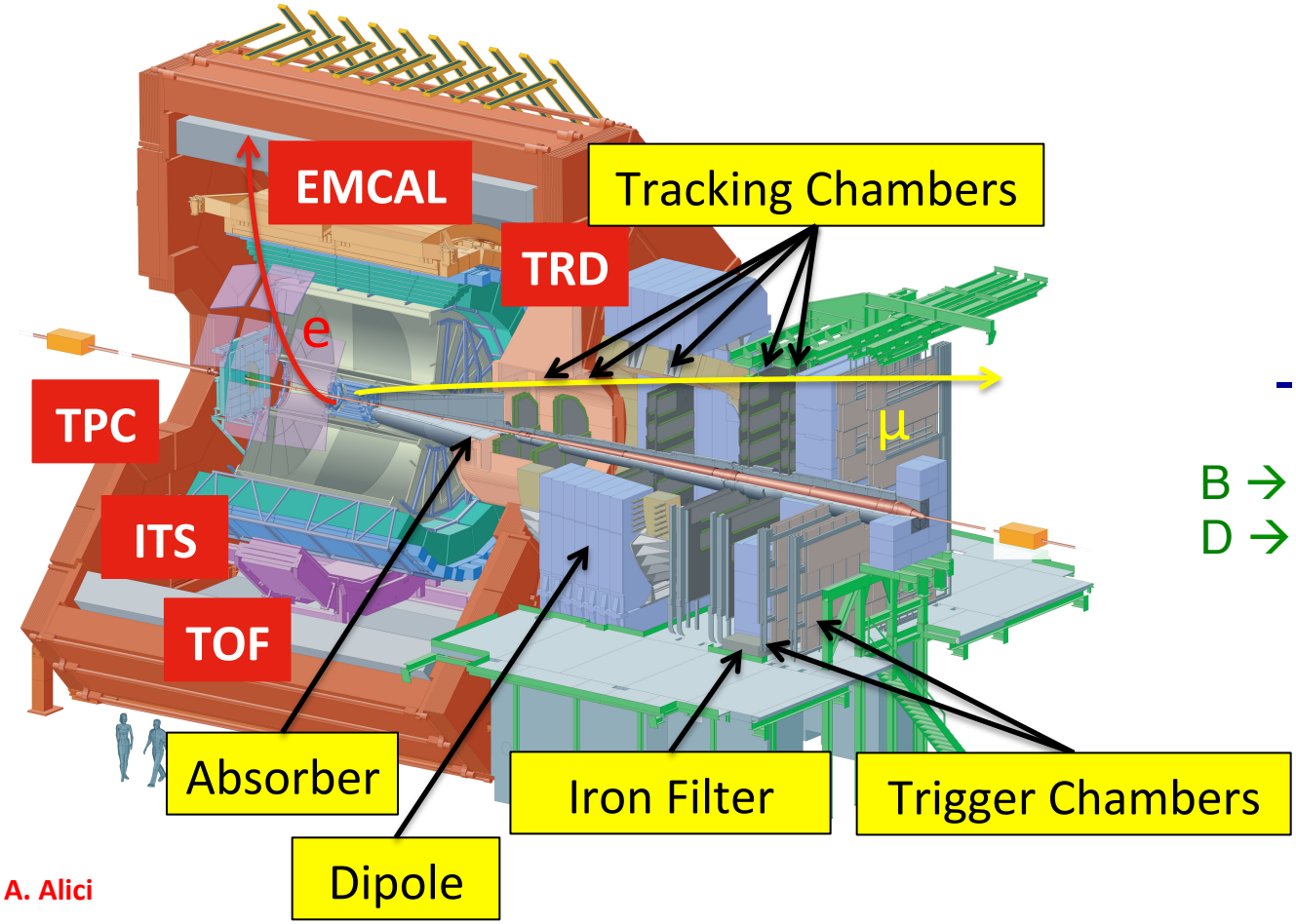
Partially reconstructed semi-leptonic decays

$\Lambda_c^+ \rightarrow e^+ \Lambda \nu_e$
$\Xi_c^0 \rightarrow e^+ \Xi^- \nu_e$

HF decays leptons

$|y| < 0.5$

B → e + X (B.R. ~ 11%)
D → e + X (B.R. ~ 10%)
large S/B from other electron sources, especially at high p_T



$-4 < \eta < -2.5$

B → μ + X (B.R. ~ 11%)
D → μ + X (B.R. ~ 10%)

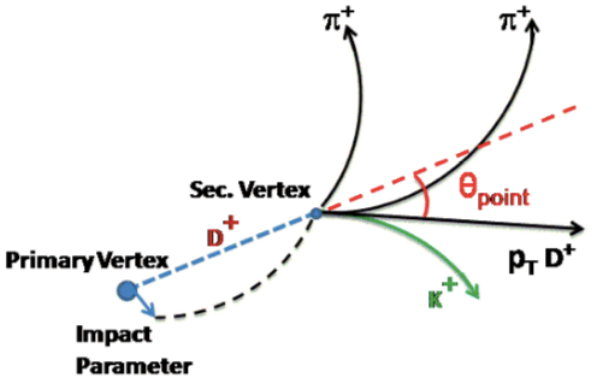
D meson hadronic decays

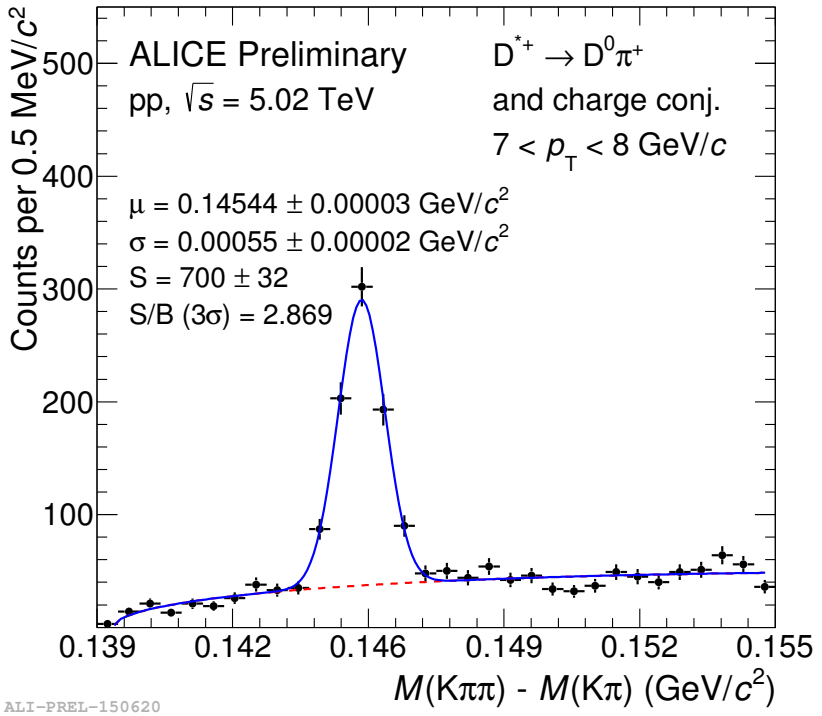
Reconstruction strategy

- **Invariant mass analysis** of fully reconstructed decay topologies displaced from the primary vertex

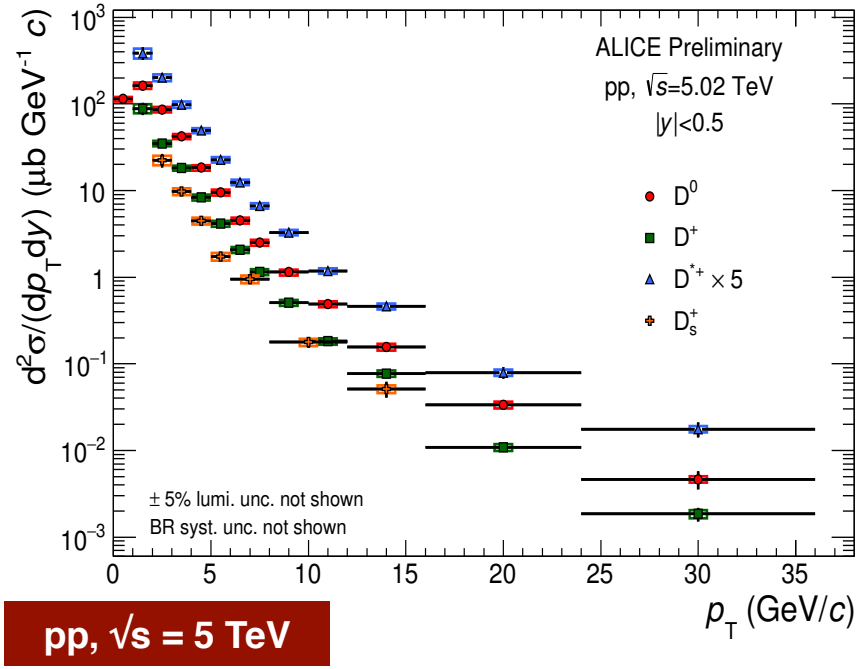
- **Combinatorial background** reduced using:
  - Geometrical selections on displaced decay-vertex topology
  - PID of decay products
  - For $D_s^+ \rightarrow \phi\,\pi^+ \rightarrow K^-K^+\pi^+$ cut on K^-K^+ invariant mass
  - For $D^0 \rightarrow K^-\pi^+$ in p_T <1 GeV/c, no selection on decay topology and combinatorial background shape estimated with track rotation, mixing event and like-sign

- **Feed-down from B-hadron** decays subtracted using pQCD (FONLL) predictions

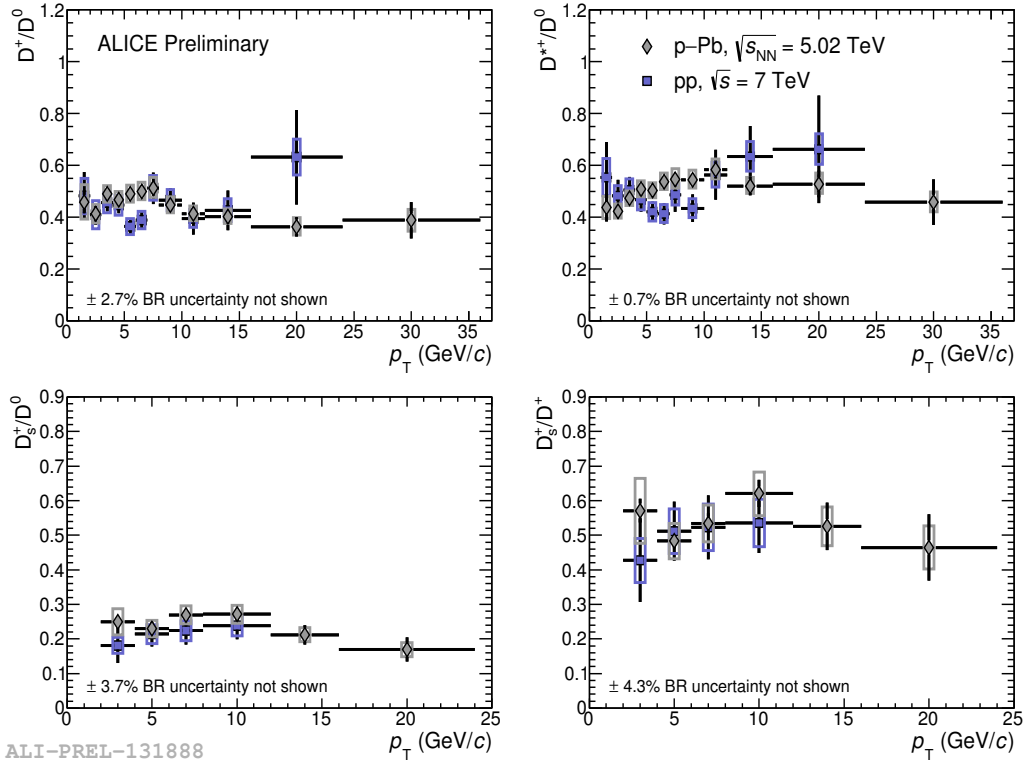




D-meson production cross sections



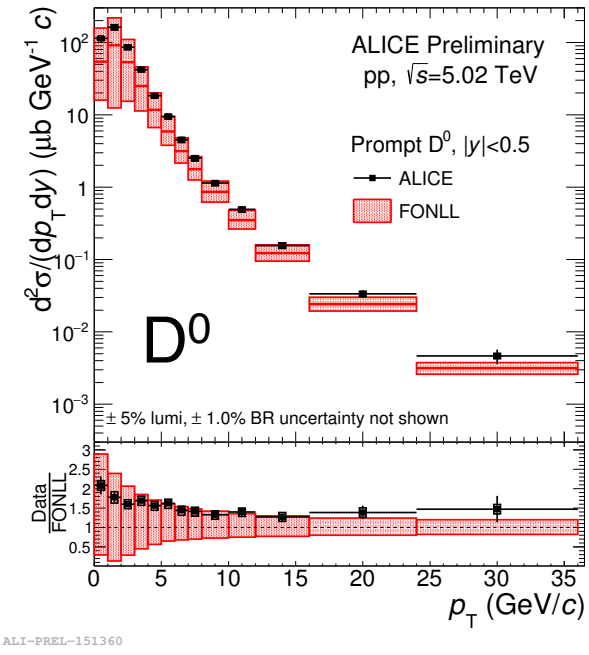
pp, √s = 5 TeV

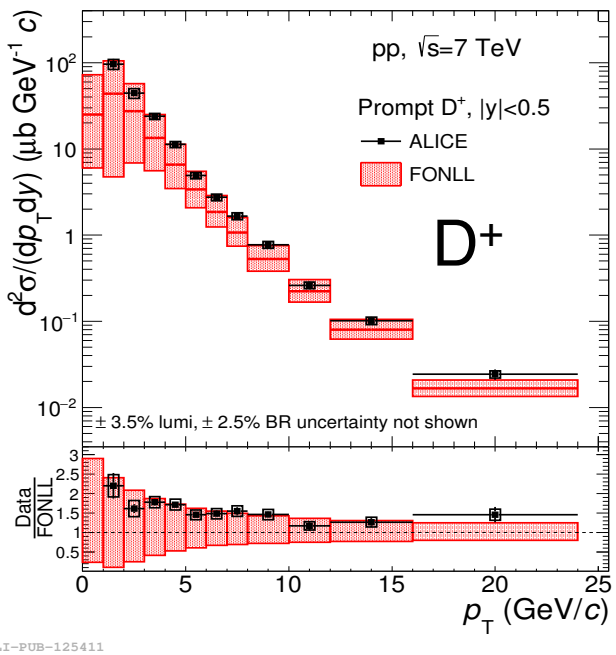


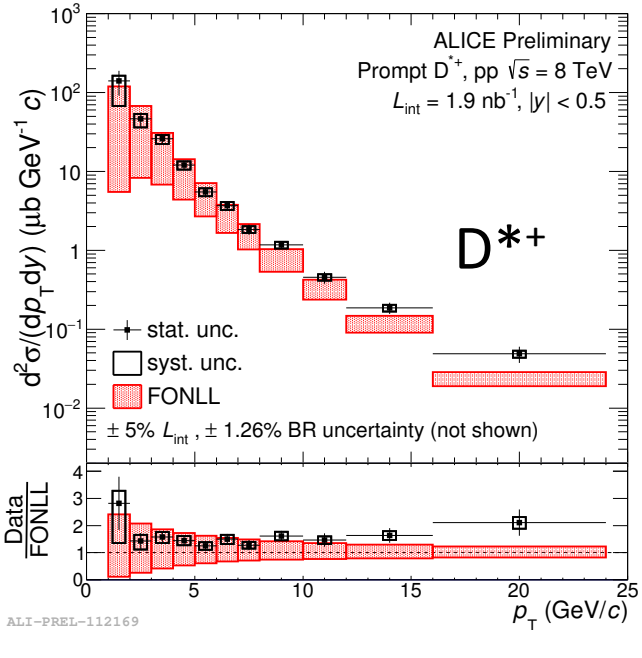
- D^0, D^+, D^{*+} and D_s^+ relative abundances are the same in pp (different centre-of-mass energies) and p-Pb

D-meson cross sections vs pQCD

EPJ C77 (2017) 550

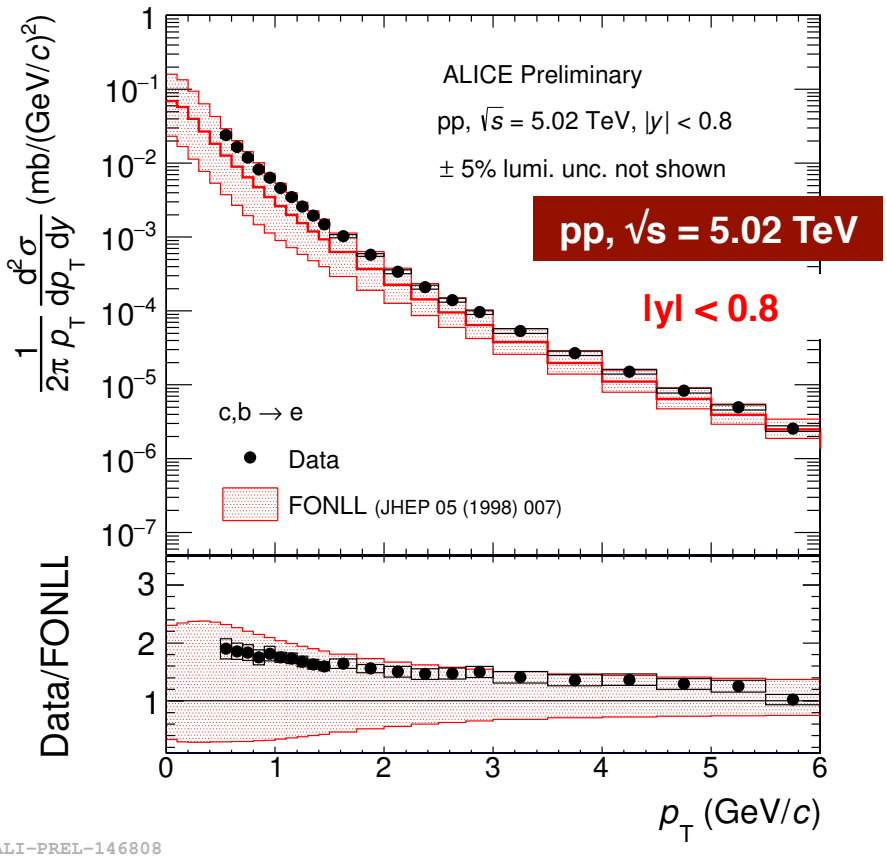




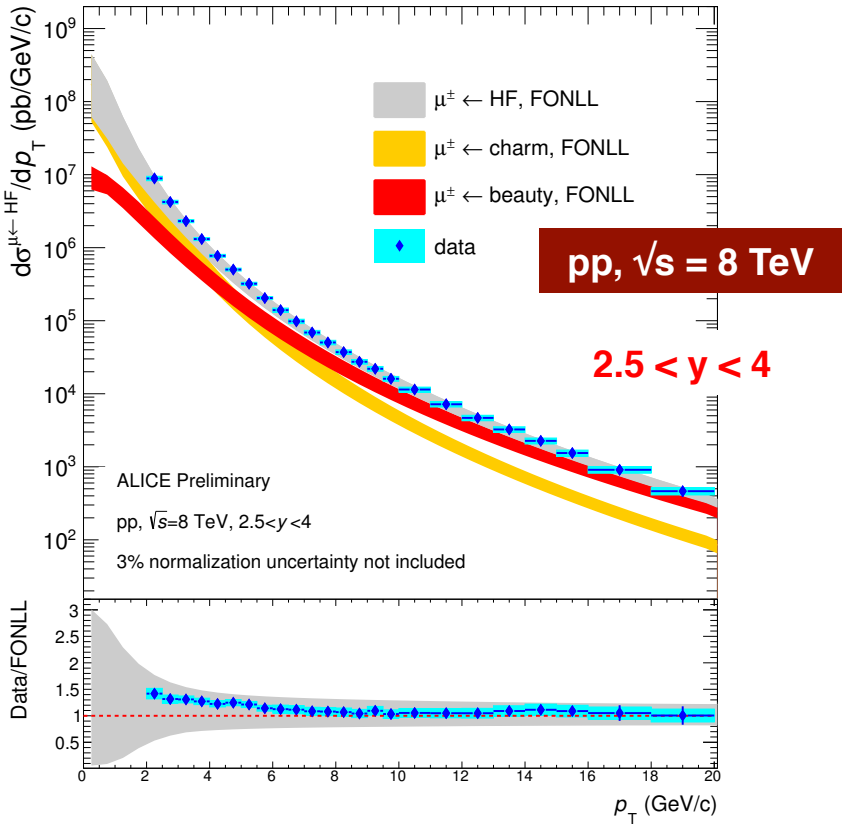


- D-meson cross sections vs p_T measured for several energies
- Excellent constraint for charm production cross section over a wide p_T interval
  - down to $p_T = 0$ for D^0 @ 7 TeV
- All measurements are described within uncertainties by pQCD calculations (FONLL, Fixed Order with Next to Leading Log resummation, Cacciari et al., LHEP 1210 (2012) 137)
  - **data uncertainties much lower than theoretical ones**

HF decay leptons vs pQCD



ALI-PREL-146808

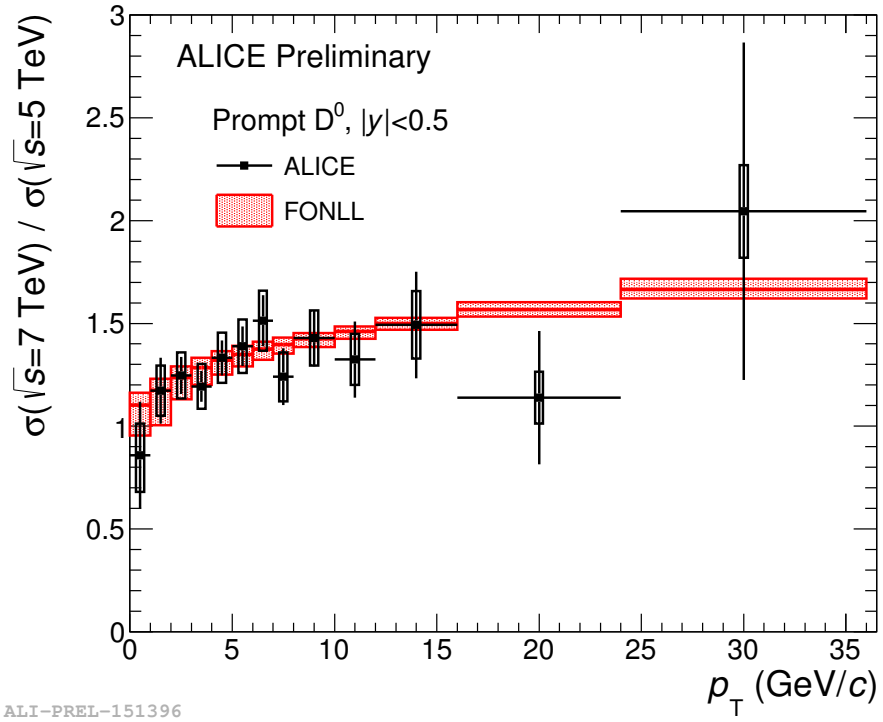


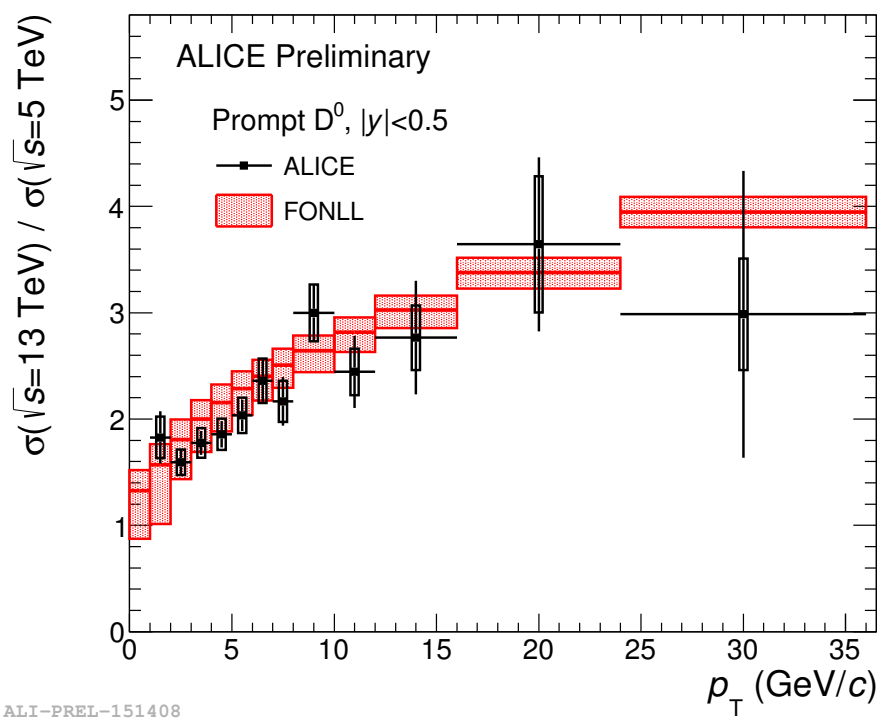
ALI-PREL-135644

- p_T-differential production cross section of HF decay leptons now measured for several centre-of-mass energies **down to very low p_T**
- measurements at mid (e ← HF) and forward (μ ← HF) rapidity
- data always on upper part of FONLL uncertainty band

D meson and PDFs

Ratios of cross sections at different centre-of-mass energies and rapidity can provide an additional test for pQCD calculations (theoretical uncertainties partly cancel out in the ratio)





fragmentation of charm quark to D mesons well described

D meson and PDFs

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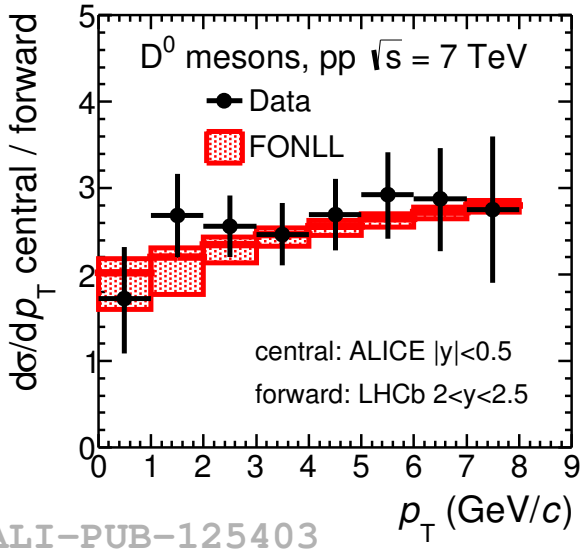
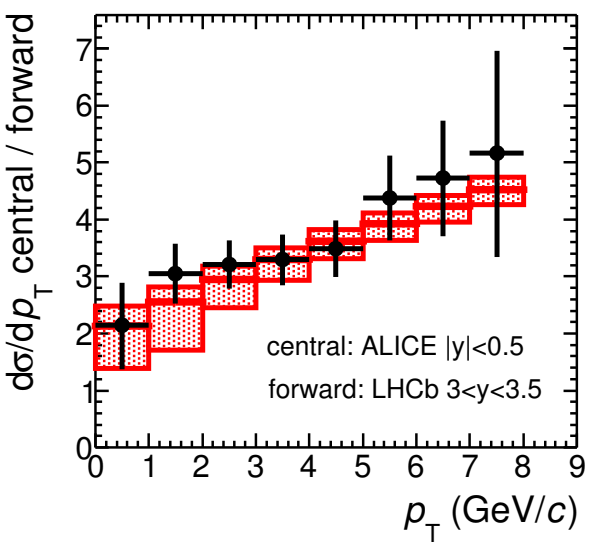
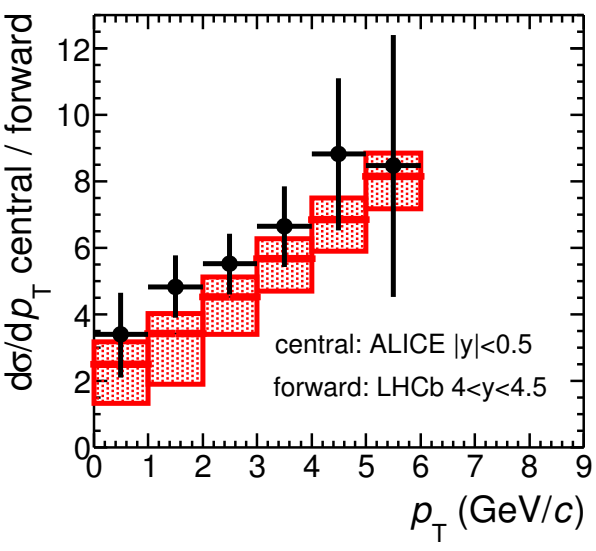






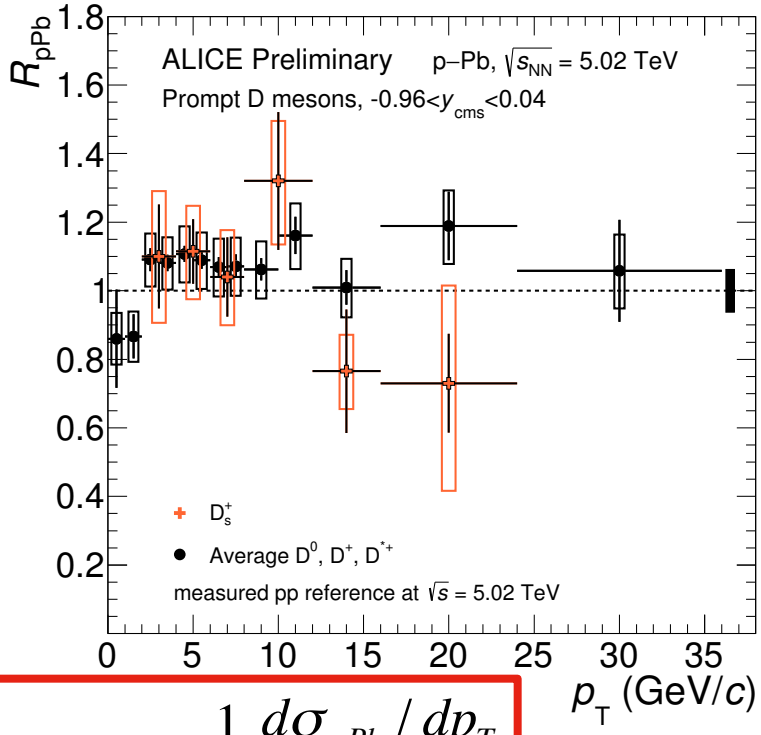
ALI-PUB-125403

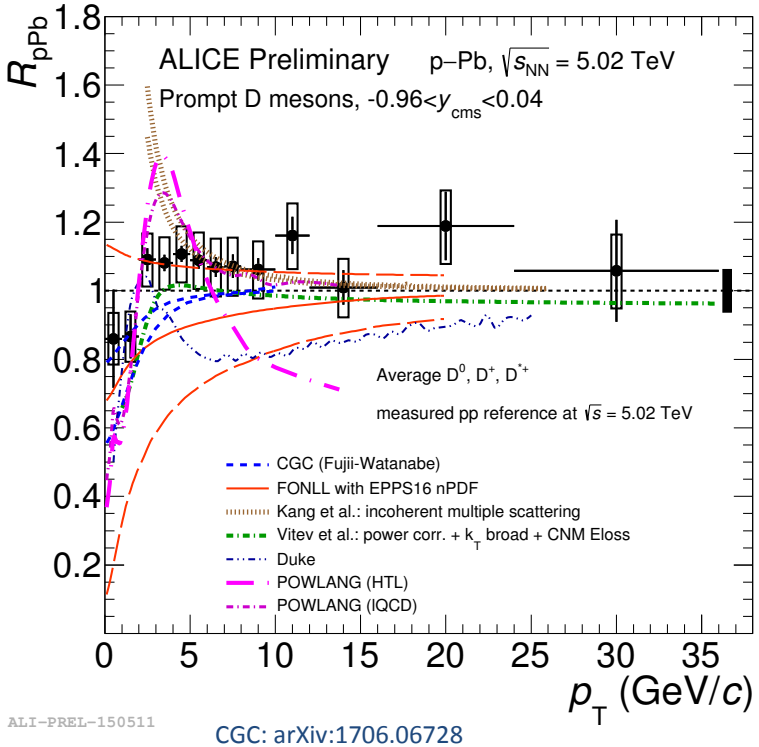
ALICE: EPJ C77 (2017) 550

LHCb: Nucl. Phys. B871 (2013) 1

fragmentation of charm quark to D mesons well described

D meson nuclear modification factor R_{pPb}





ALI-PREL-150511

$$R_{pPb}(p_T) = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

CGC: arXiv:1706.06728
FONLL (JHEP 1210 (2012) 137, arXiv:1205.6344) with EPPS16 nPDFs (Eur. Phys. J. C77 no. 3, (2017) 163, arXiv:1612.05741)
Vitev et al: Phys.Rev. C80 (2009) 054902, arXiv:0904.0032.
Kang et al.: Phys. Lett. B740 (2015) 23–29, arXiv:1409.2494.
Duke: Nucl. xPart. Phys. Proc. 276-278 (2016) 225–228, arXiv:1510.07520.
POWLANG JHEP 03 (2016) 123, arXiv:1512.05186.

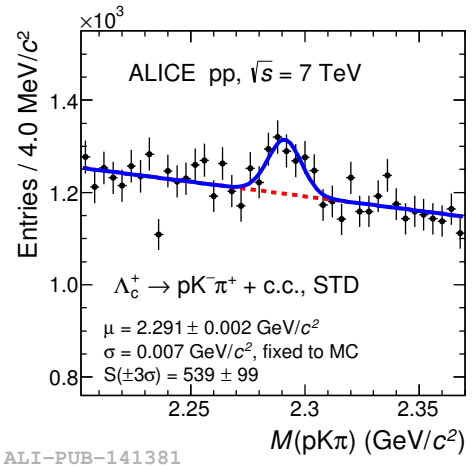
- D-meson R_{pPb} compatible with unity
- D_s R_{pPb} compatible with non-strange D mesons within uncertainties
- Data described by models including Cold Nuclear Matter effects, as well as effects deriving from the formation of QGP in p-Pb collisions

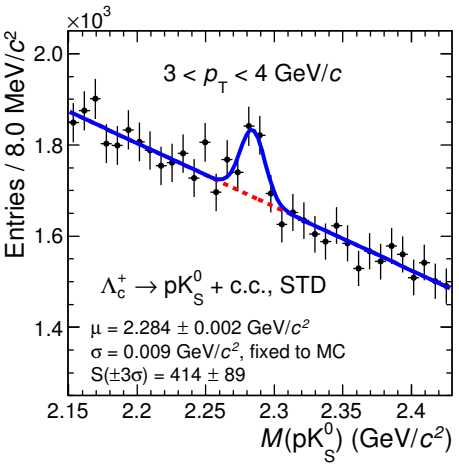
Open charm baryon reconstruction

JHEP 1804 (2018) 108

Reconstruction strategy (hadronic decays)

- **PID** using TPC via d*E*/d*x* and TOF via time-of-flight measurements (nσ cuts or Bayesian approach to identify particles)
- **Cuts on decay topologies** exploiting decay vertex displacement from primary vertex (for $\Lambda_c^+ \rightarrow p\,K^-\,\pi^+$ only, $c\tau = 90\mu m$)
- **Signal extraction** via invariant mass distribution in bins of transverse momentum p_T
- **B feed-down subtraction** using pQCD-based estimation of beauty baryon production





pp, √s = 7 TeV

Open charm baryon reconstruction

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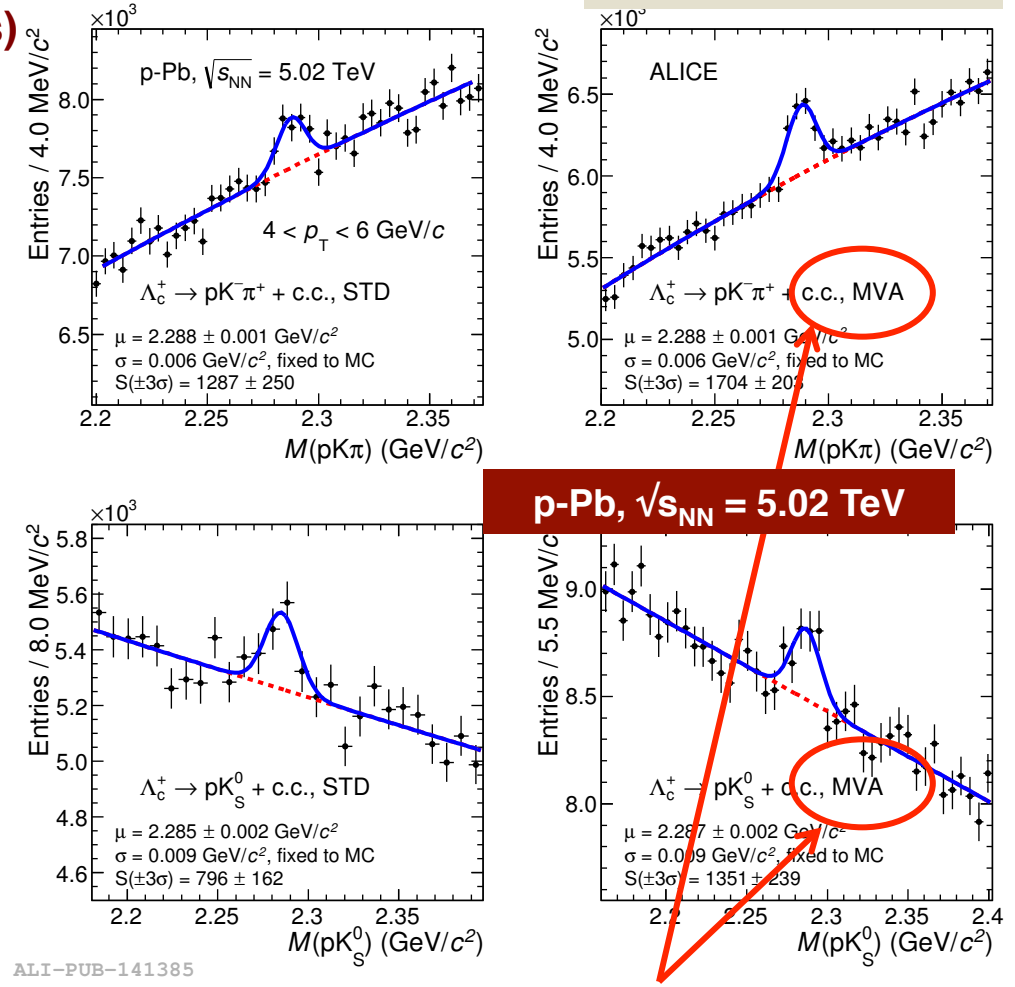


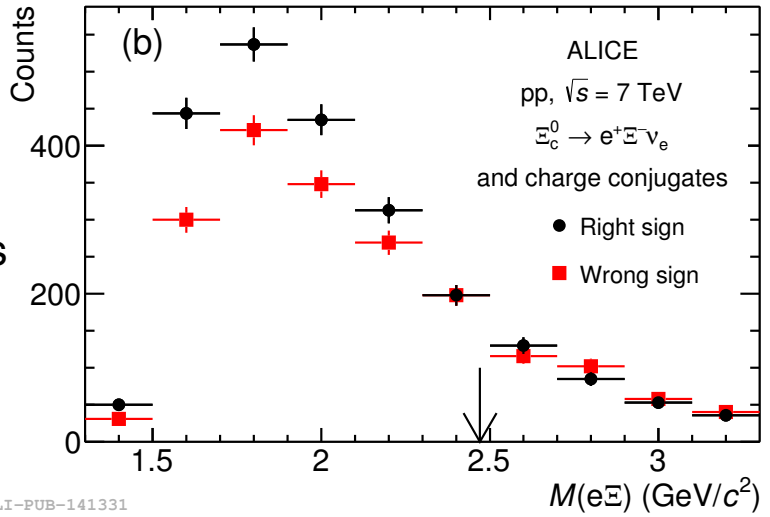
Multivariate Analysis technique

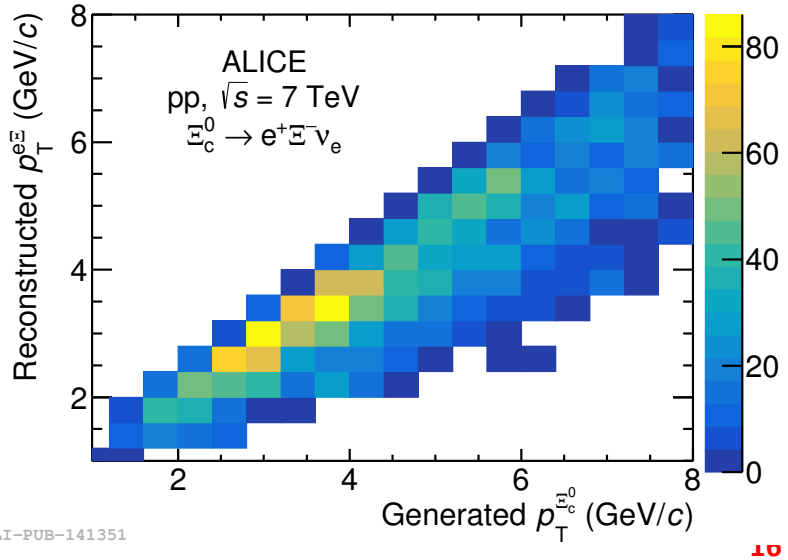
Open charm baryon reconstruction

PLB 781 (2018) 8

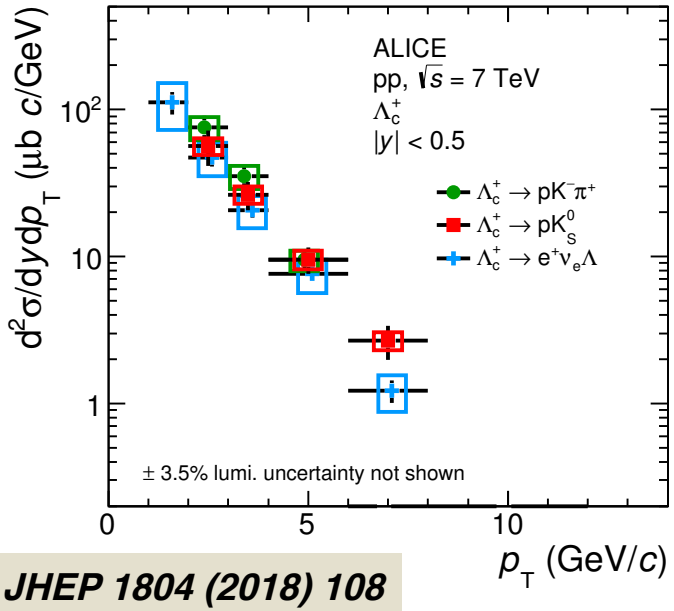
Reconstruction strategy (semileptonic decays)

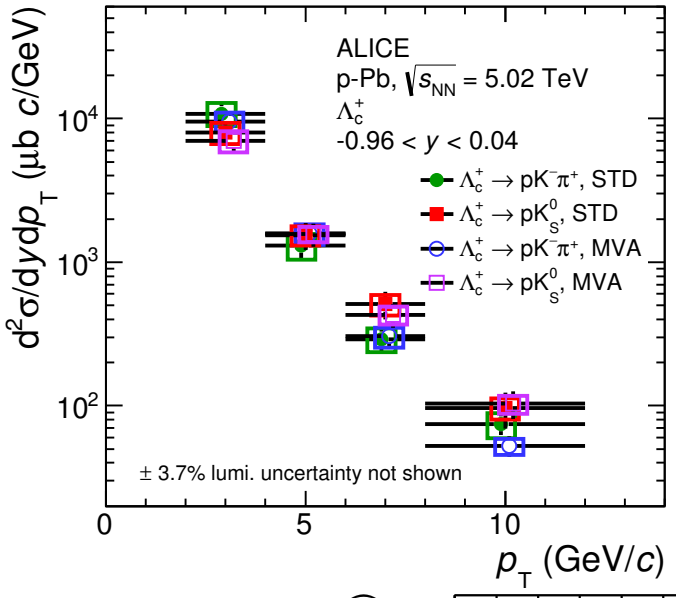
- Λ_c^+ and Ξ_c^0 candidates defined from $e^+\Lambda$ and $e^+\Xi^-$ right-sign pairs (and charge conjugates)
  - electron identification with TPC and TOF
  - "photonic" electrons removed with invariant mass technique (e^+e^- pairs)
- **Subtract background contribution** estimated from wrong-sign ($e^-\Lambda$ and $e^-\Xi^-$) pairs
- Correct for **missing neutrino momentum** via unfolding
- **B feed-down subtraction** using pQCD-based estimation of beauty baryon production (Λ_c^+ only)





Λ_c and Ξ_c production cross sections





Agreement among the results from different decay channels

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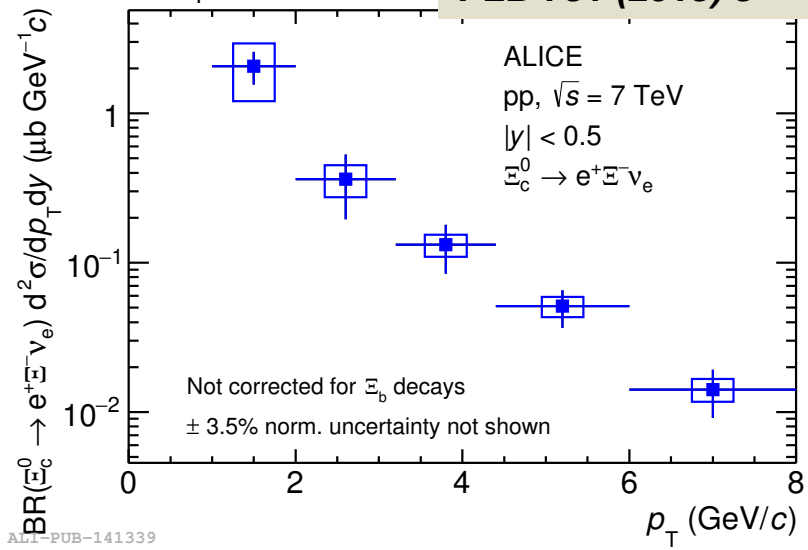
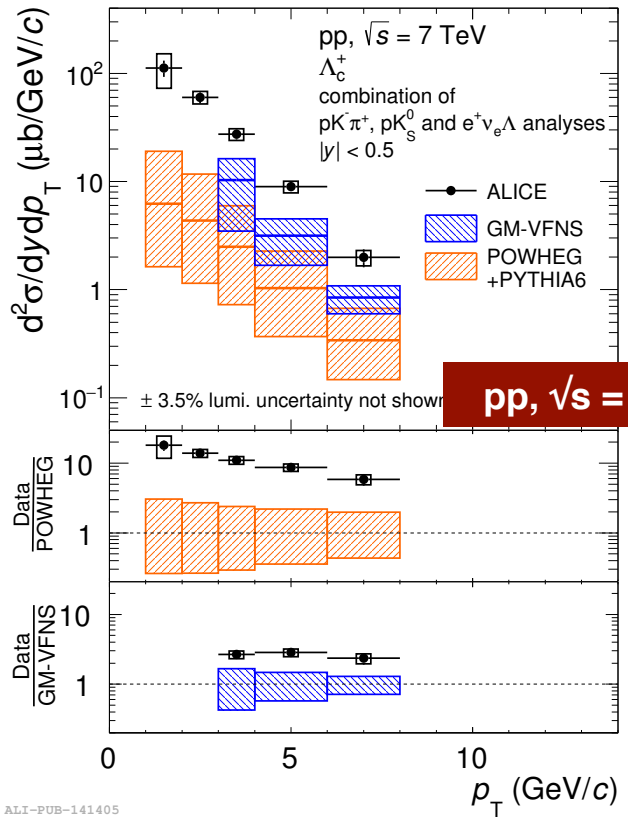
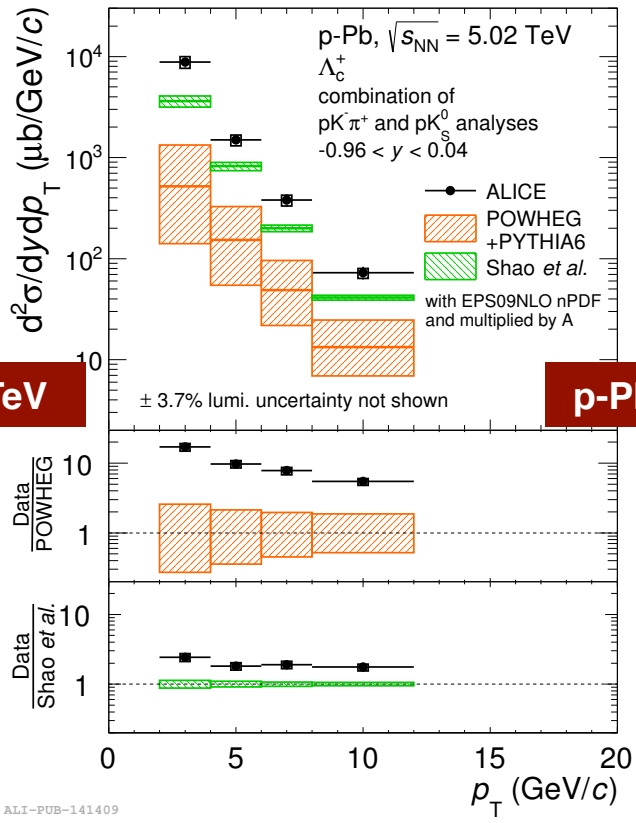
First Ξ_c^0 production measured at the LHC
(BR unknown)
Not feed-down corrected (includes $\Xi_b \to \Xi_c X \to e^+ \Xi^- \nu_e$)



Λ_c production cross sections vs pQCD



pp, $\sqrt{s}$ = 7 TeV



p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

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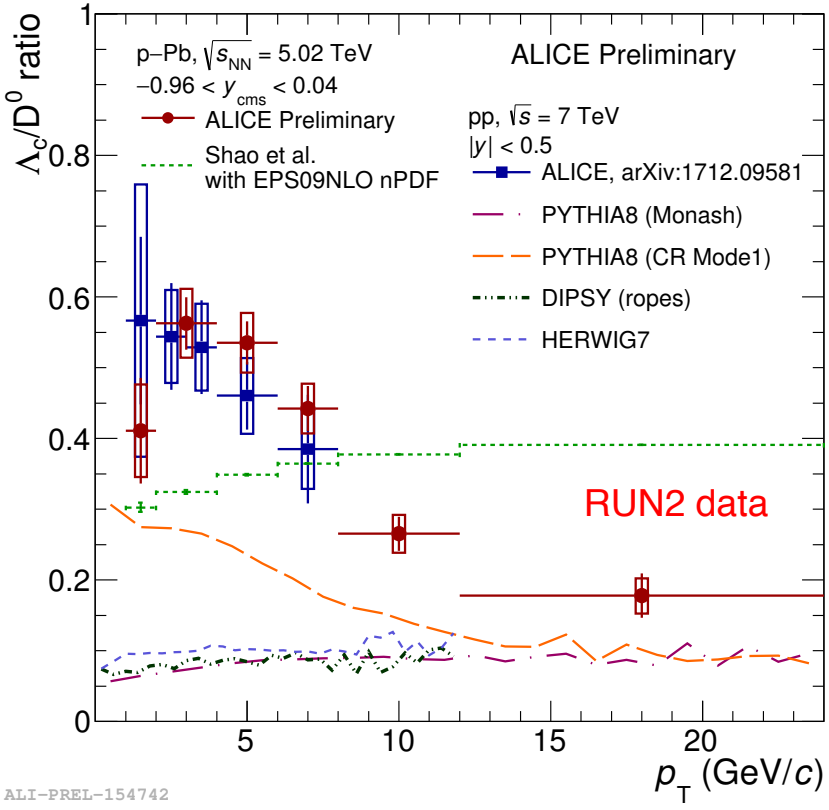
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 72 (2012) 2082
Shao et al: Eur. Phys. J. C 77 (2017)
POWHEG: S. Frixione et al.: JHEP 09 (2007) 126

- Λ_c p_T-differential cross section significantly underestimated by models
  - in GM-VNFS and POWEG the non perturbative fragmention fractions f(c→Λ_c) estimated from e^+e^- collisions data
  - Shao et al. data-driven model based on pp LHCb data + nPDF

fragmentation to heavy-flavour baryons is not well understood

Λ_c/D^0 baryon-to-meson ratio



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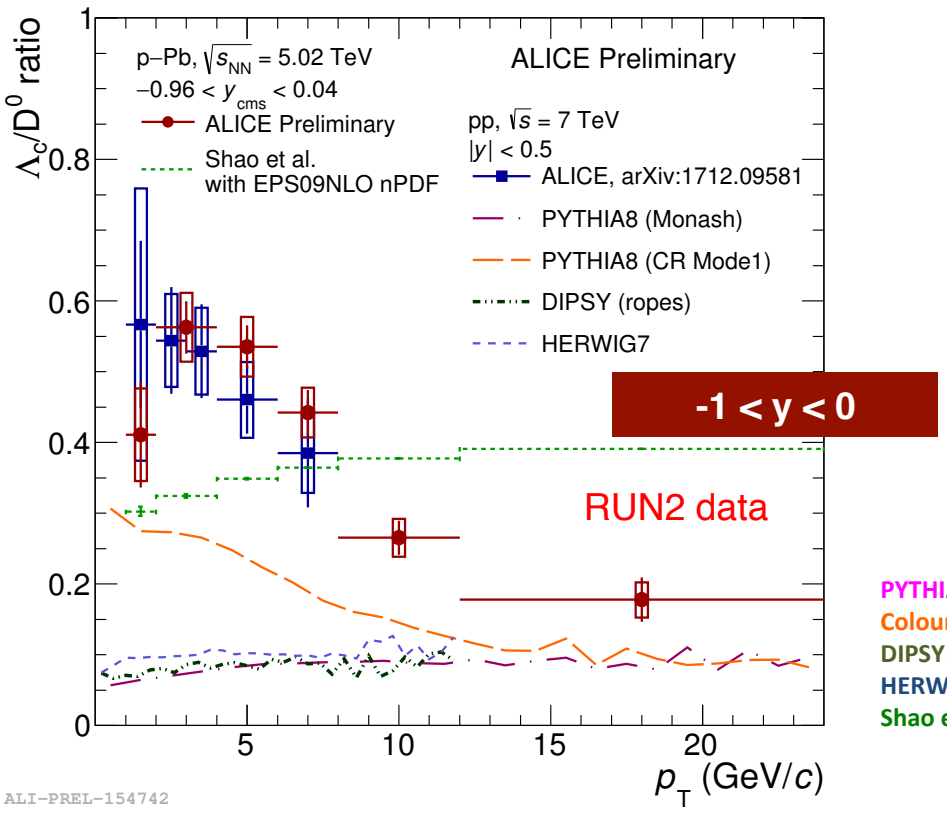
	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320

PYTHIA8 Monash: P. Skands et al., Eur. Phys. J. C (2014) 74:3024
Colour reconnection (CR): J. R. Christiansen and P. Skands, JHEP 08 (2015) 003
DIPSY: JHEP 08 (2011) 103
HERWIG7: Eur. Phys. J. C58 (2008) 639-707
Shao et al: Eur. Phys. J. C 77 (2017)

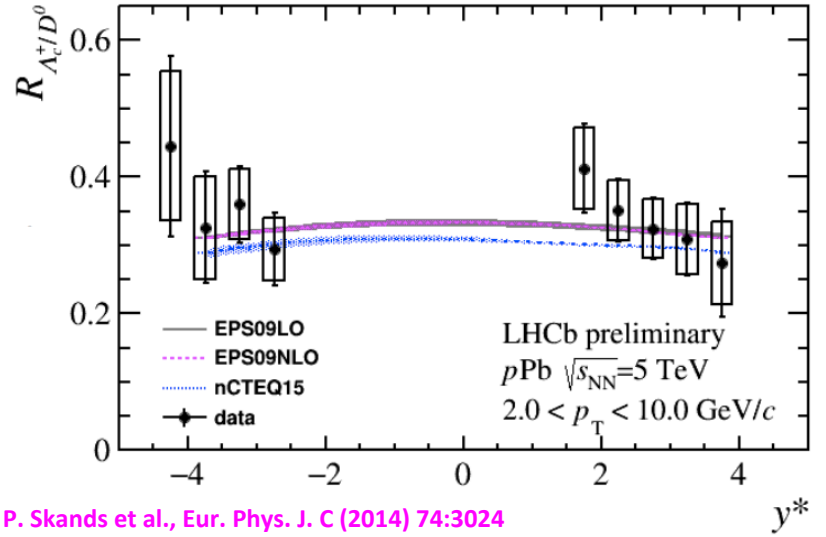
- Λ_c/D^0 ratios in pp and p-Pb collisions are compatible within uncertainties
- Λ_c/D^0 ratio in pp and p-Pb collisions higher than previous measurements in ee and ep collisions at lower centre-of-mass energy

hint of a **violation of the universality of the fragmentation functions**

Λ_c/D^0 baryon-to-meson ratio



LHCb-PAPER-2018-021 in preparation



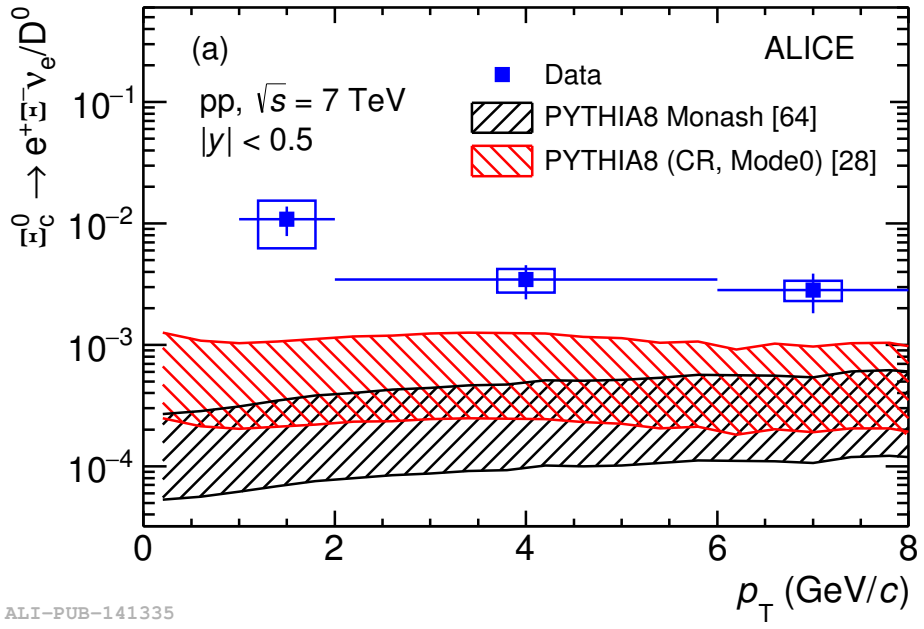
PYTHIA8 Monash: P. Skands et al., Eur. Phys. J. C (2014) 74:3024
Colour reconnection (CR): J. R. Christiansen and P. Skands, JHEP 08 (2015) 003
DIPSY: JHEP 08 (2011) 103
HERWIG7: Eur. Phys. J. C58 (2008) 639-707
Shao et al: Eur. Phys. J. C 77 (2017)

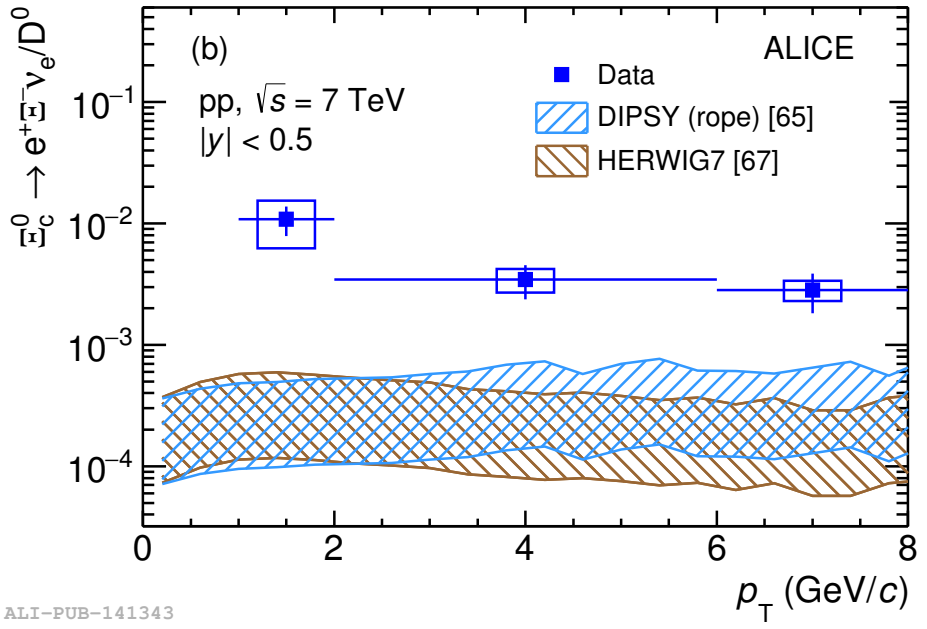
- Λ_c/D^0 ratios in pp and p-Pb collisions are compatible within uncertainties
- Λ_c/D^0 ratio in pp and p-Pb collisions higher than previous measurements in ee and ep collisions at lower centre-of-mass energy

hint of a **violation of the universality of the fragmentation functions**

Ξ_c/D^0 baryon-to-meson ratio

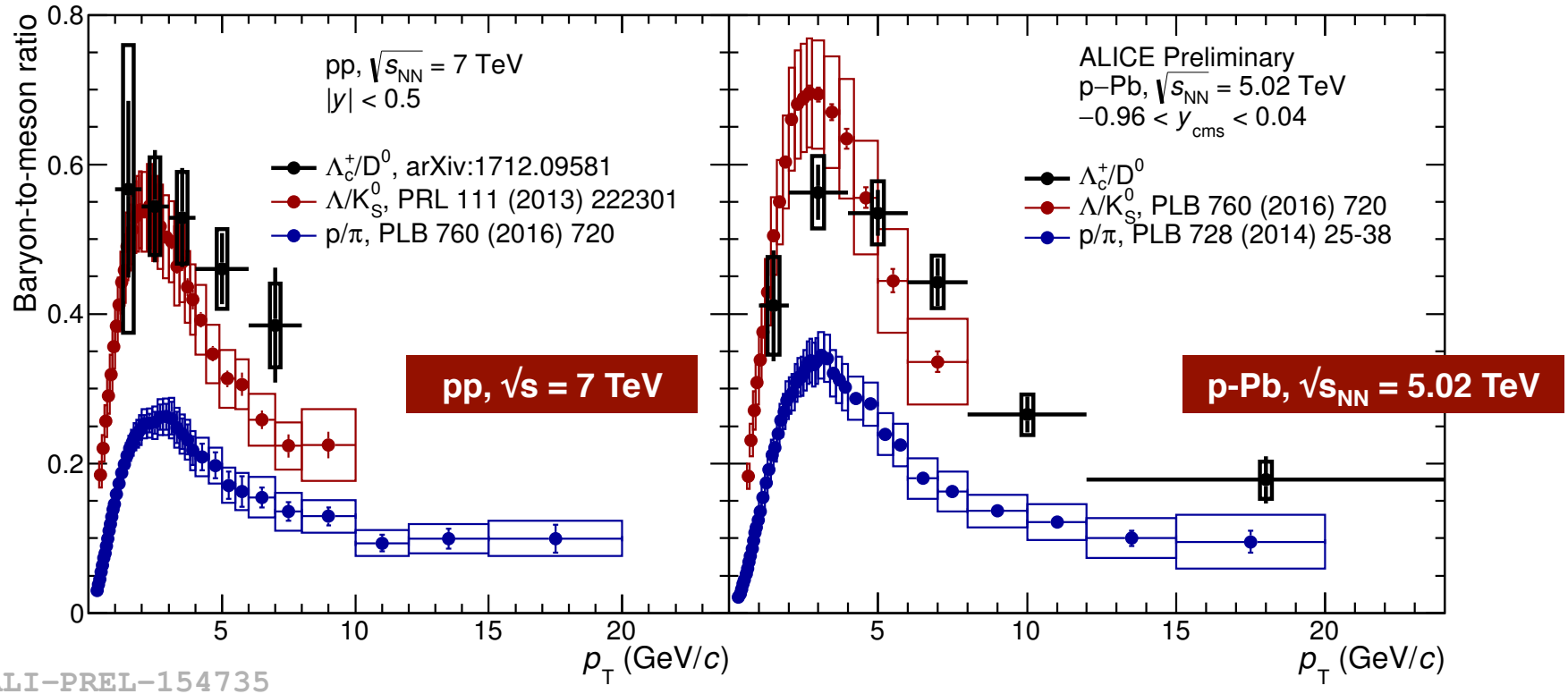
PLB 781 (2018) 8





- Ξ_c/D^0 ratio larger than model predictions
  - PYTHIA8 with enhanced colour reconnection closer to data
  - bands on models due to unknown BR($\Xi_c^0 \rightarrow e^+ \Xi^- \nu_e$), theory predictions: 0.3% – 3.2%

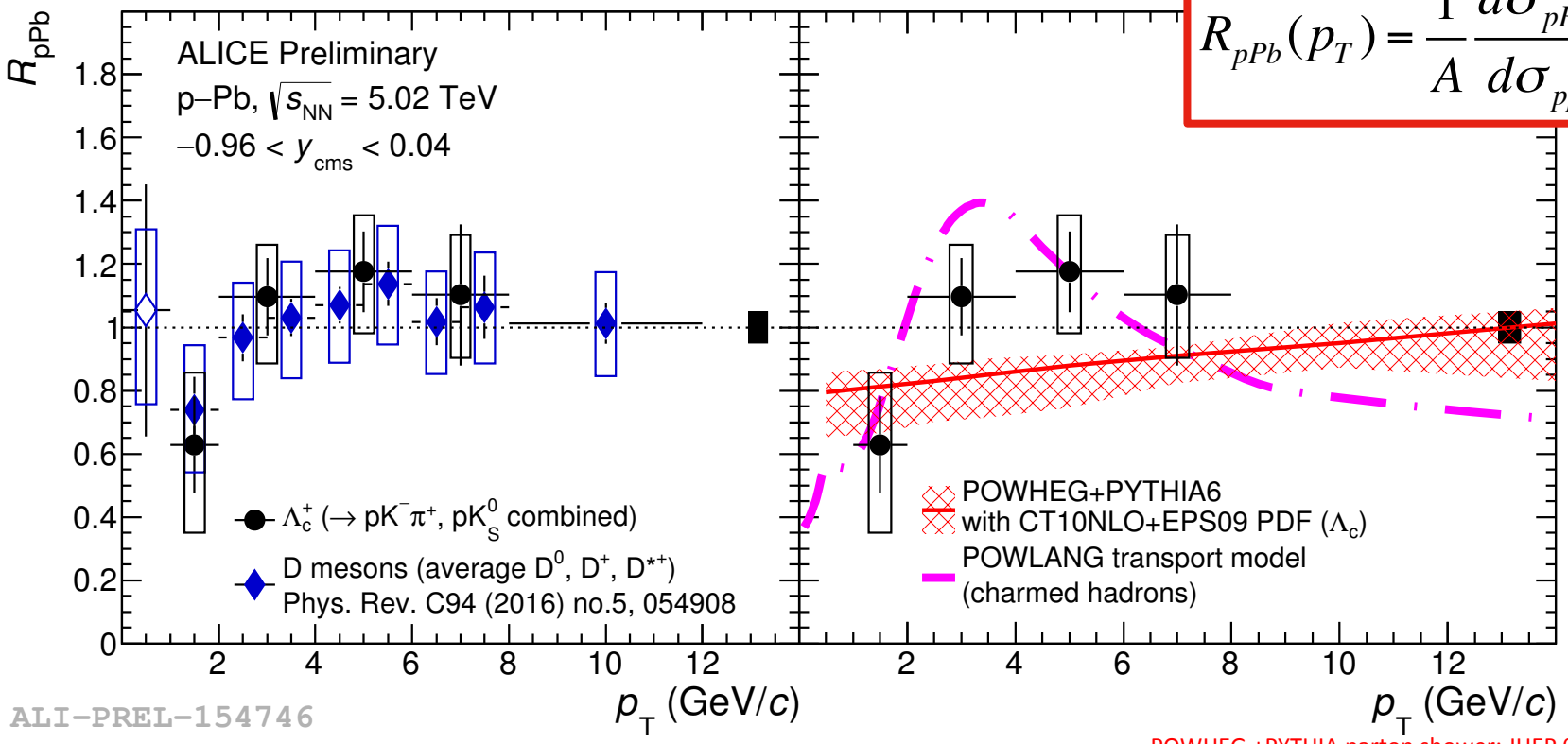
Λ_c/D^0 baryon-to-meson ratio



- Similar trend with p_T as baryon-to-meson ratio in the light-flavour sector

Λ_c nuclear modification factor R_{pPb}

$$R_{pPb}(p_T) = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$



POWHEG +PYTHIA parton shower: JHEP 0709:126,2007
POWLANG: JHEP03(2016)123

Λc R_{pPb} is consistent with unity as D-meson R_{pPb} and with model predictions within uncertainties:

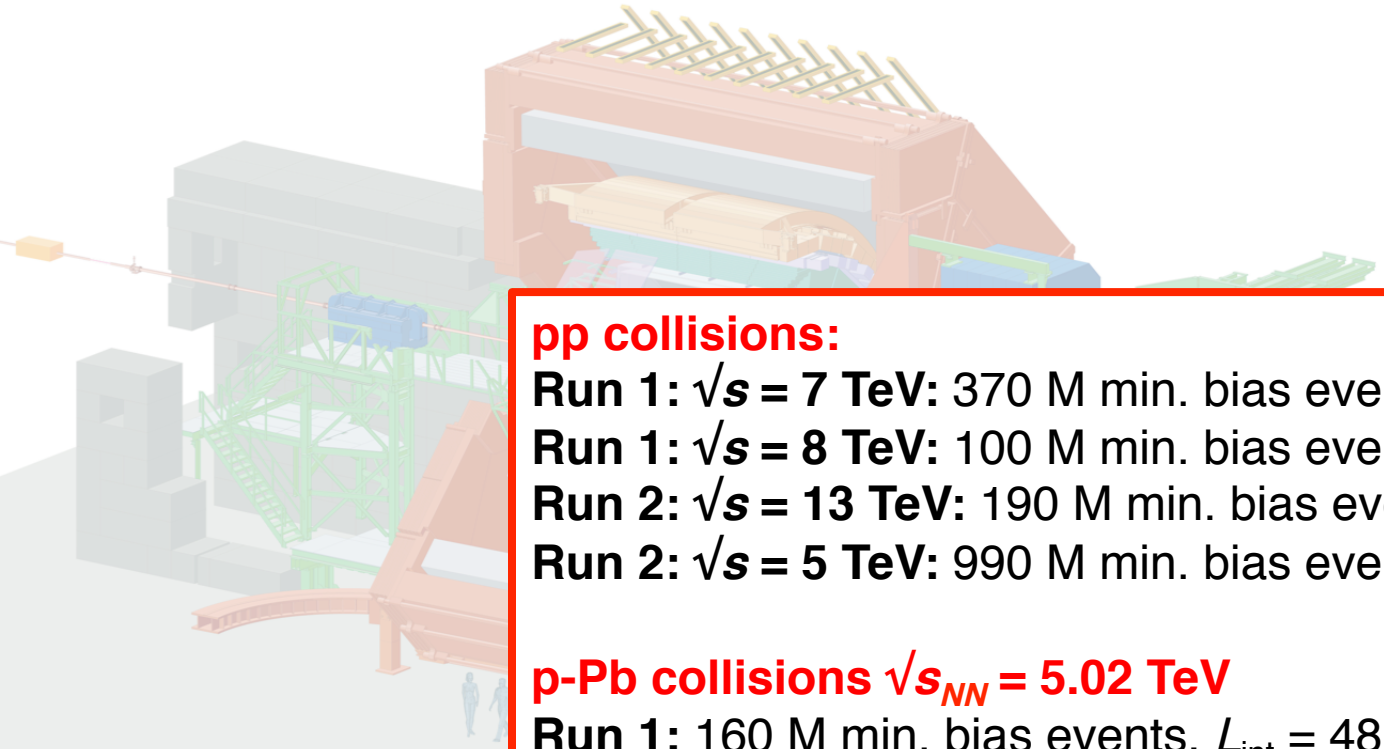
- POWHEG+PYTHIA6 with CT10NLO+EPS09 PDF: Cold Nuclear Matter effects
- POWLANG with "small-size" QGP formation: hot medium effects, collisional energy loss

Conclusions

- D-meson production in pp collisions at the LHC is described within uncertainties by pQCD calculations down to $p_T = 0$ at all energies
- D-meson particle ratios compatible between pp and p-Pb collisions and well reproduced by pQCD calculations
- Charmed baryon production in pp and p-Pb collisions underestimated by models and event generators
- First Ξ_c^0 production measurement at the LHC
- Baryon-to-meson ratio:
  - Λ_c/D^0 and Ξ_c^0/D^0 higher than MC predictions
  - Λ_c/D^0 higher than previous measurements in ee and ep collisions
  - **violation of fragmentation universality?**

BACKUP

Data samples



pp collisions:

Run 1: $\sqrt{s}$ **= 7 TeV:** 370 M min. bias events, L_{int} = 6.0 nb^{-1}

Run 1: $\sqrt{s}$ **= 8 TeV:** 100 M min. bias events, L_{int} = 1.8 nb^{-1}

Run 2: $\sqrt{s}$ **= 13 TeV:** 190 M min. bias events, L_{int} = 3.3 nb^{-1}

Run 2: $\sqrt{s}$ **= 5 TeV:** 990 M min. bias events, L_{int} = 19 nb^{-1}

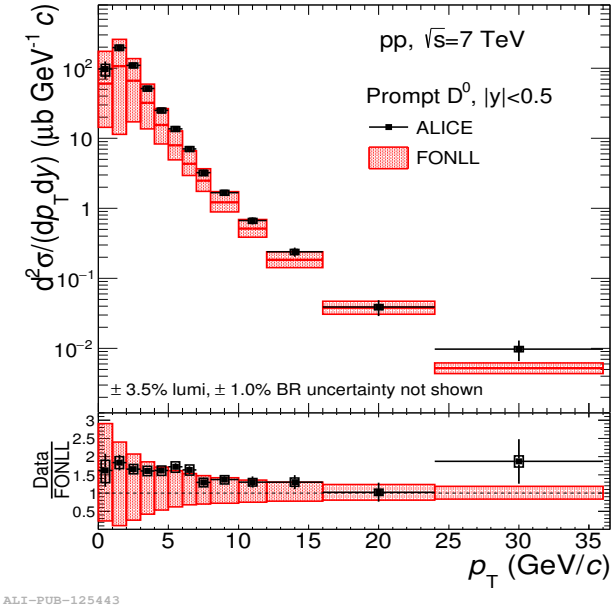
p-Pb collisions $\sqrt{s_{NN}}$ **= 5.02 TeV**

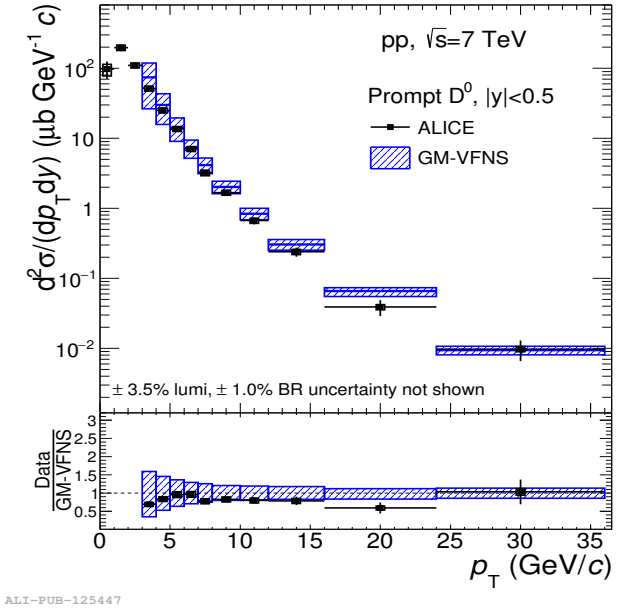
Run 1: 160 M min. bias events, L_{int} = 48.6 μb^{-1}

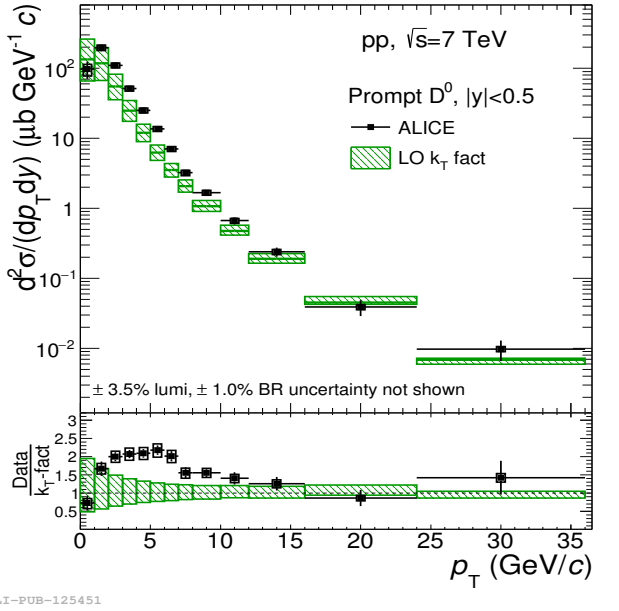
Run 2: 600 M min. bias events, L_{int} = 292 μb^{-1}

D-meson cross sections vs pQCD

EPJ C77 (2017) 550







FONLL: JHEP 1210 (2012) 37

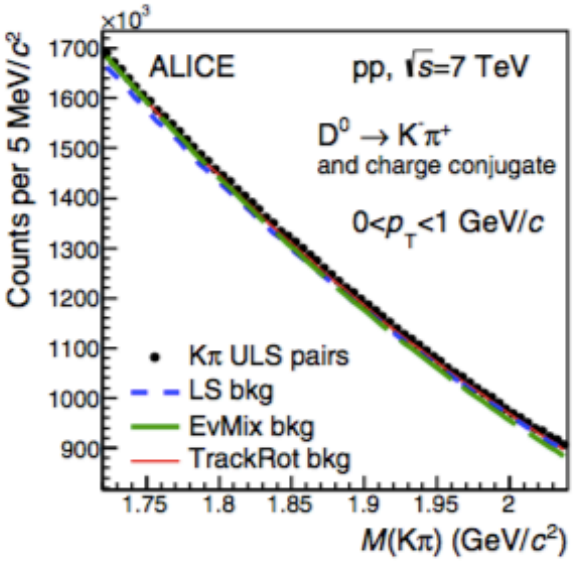
GM-VFNS: EPJ C72 (2012) 2082

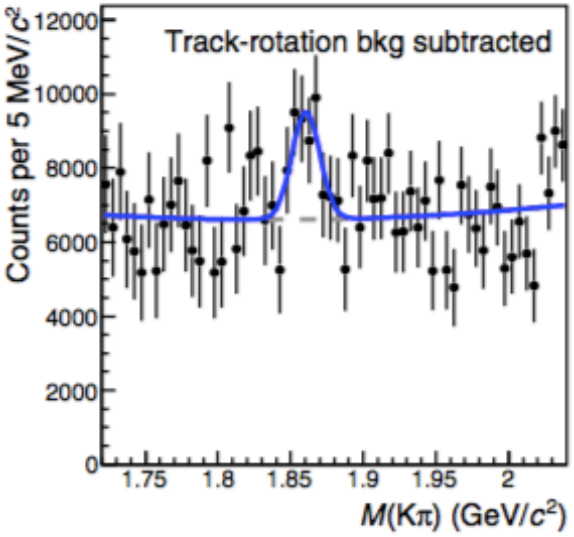
LO k_T factorization: Phys. Rev. D87 (2013) 094022

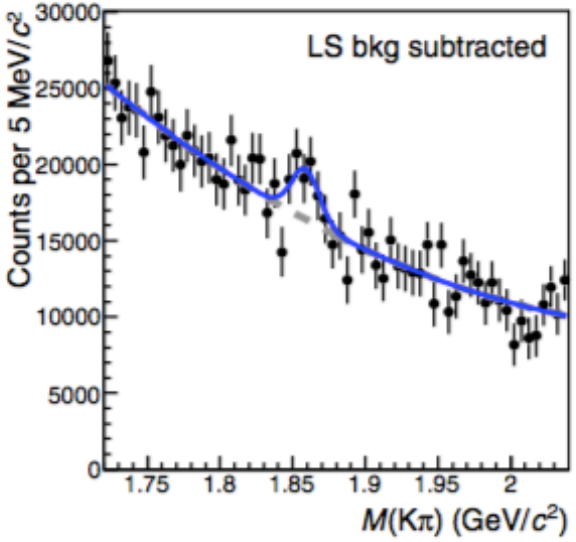
D^0 cross sections @ 7 TeV compared to pQCD calculations:

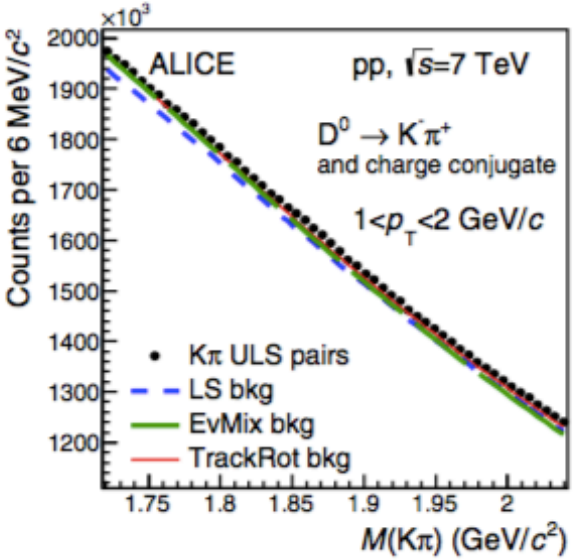
- FONLL: describes data within uncertainties, central value below data
- GM-VFNS: describes data within uncertainties, central value above data
- k_T-factorization: underestimate data in $2 < p_T < 10$ GeV/c

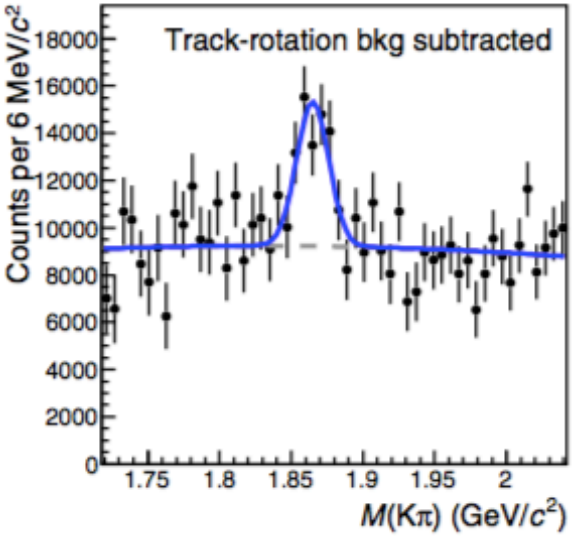
Bkg shape estimation D^0 $p_T < 1$ GeV/c

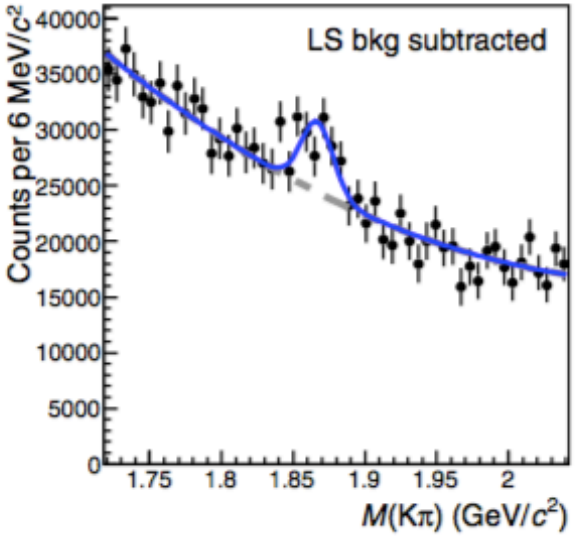




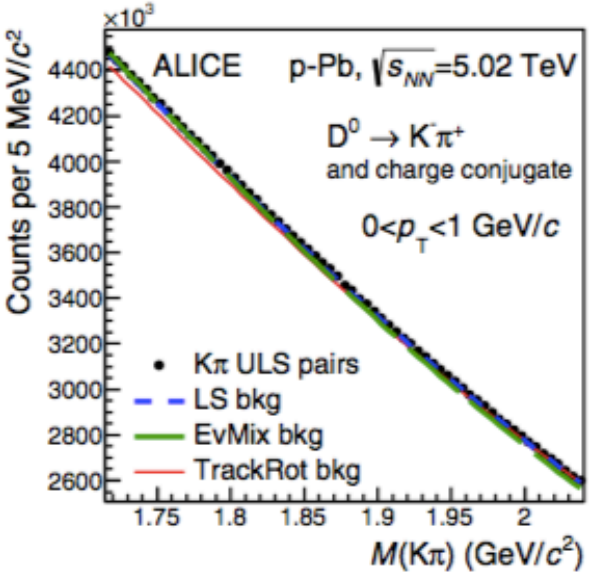


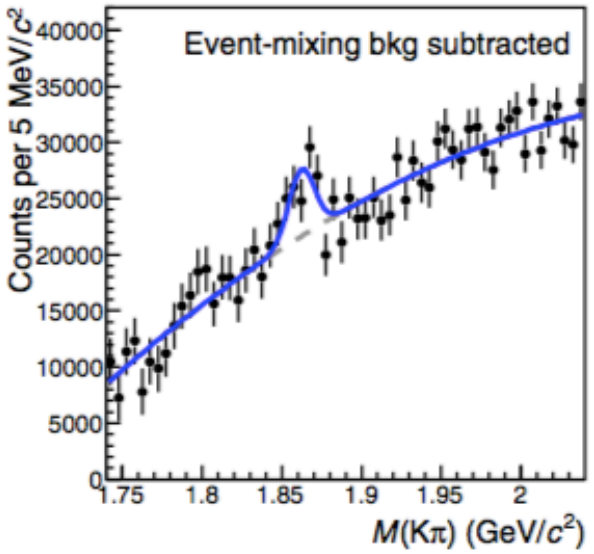


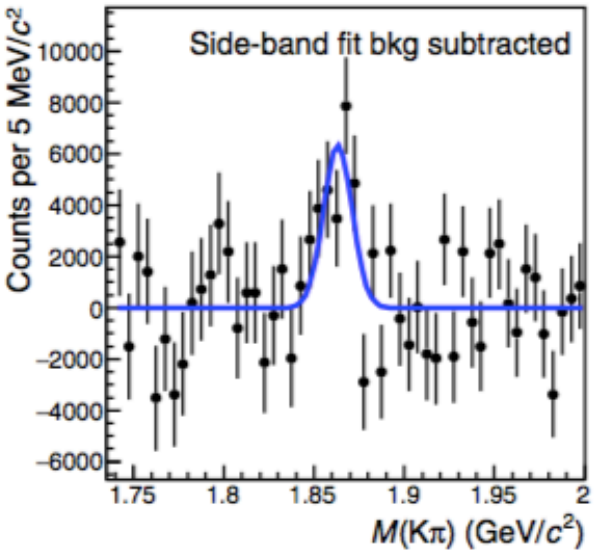


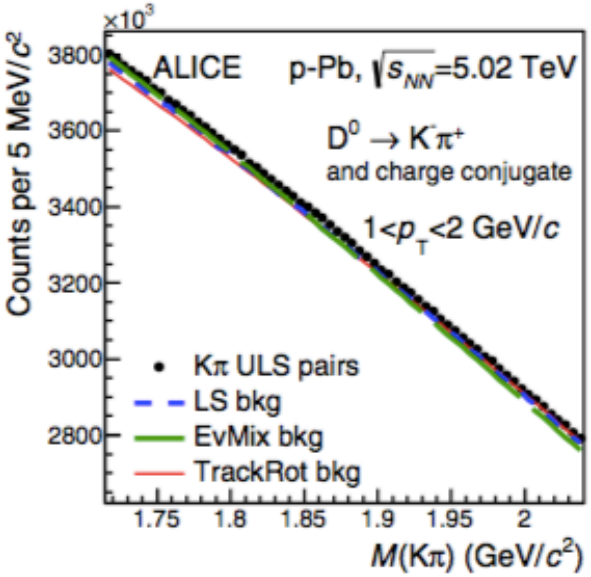


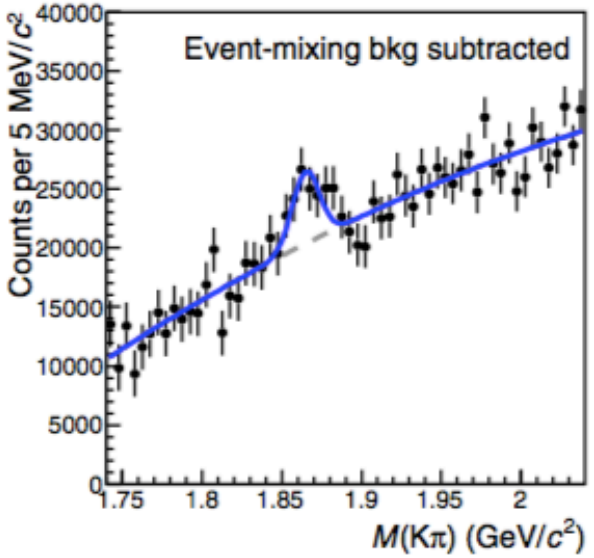
Bkg shape estimation D^0 $p_T < 1$ GeV/c

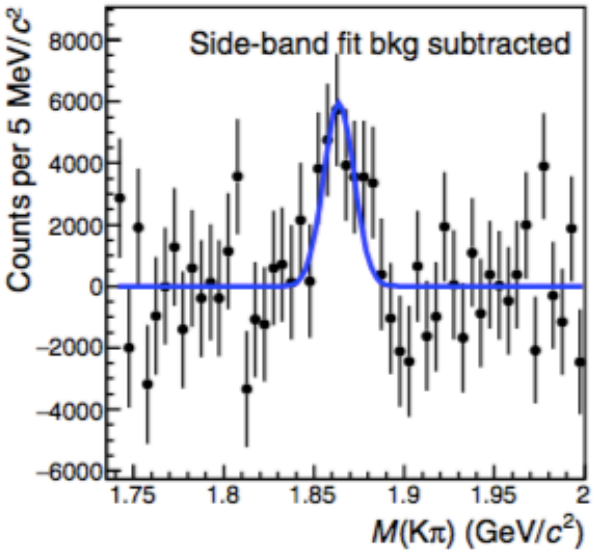












Feed-down from B-hadron

The f_{prompt} fraction was calculated using the B production cross sections from FONLL calculations [6,41], the $\mathrm{B} \rightarrow \mathrm{D} + X$ decay kinematics from the EvtGen package [42] and the efficiencies for feed-down D mesons reported in Fig. 2:

$$f_{\mathrm{prompt}} = 1 - \frac{N_{\mathrm{raw}}^{\mathrm{D\ feed\text{-}down}}}{N_{\mathrm{raw}}^{\mathrm{D}}} = 1 - \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right)_{\mathrm{feed\text{-}down}}^{\mathrm{FONLL}} \cdot \frac{(\mathrm{Acc} \times \varepsilon)_{\mathrm{feed\text{-}down}} \cdot c_{\Delta y} \Delta p_{\mathrm{T}} \cdot \mathrm{BR} \cdot L_{\mathrm{int}}}{N^{\mathrm{D}+\overline{\mathrm{D}},\mathrm{raw}}/2}, \quad (2)$$

Colour reconnection

The new CR model in PYTHIA is applied just prior to the hadronization. It takes the leading-colour ($N_c \to \infty$) strings and transform them to a different colour configuration based on three principles: firstly the SU(3) colour rules from QCD determine if two strings are colour compatible (e.g. there is only a 1/9 probability that the top configuration of fig. 1 can transform to the left configuration purely from colour considerations). Secondly a simplistic space-time picture to check causal contact between the strings. Finally the λ measure (which is a string-length measure) to decide whether a possible reconnection is actually favoured. Since the model relies purely on

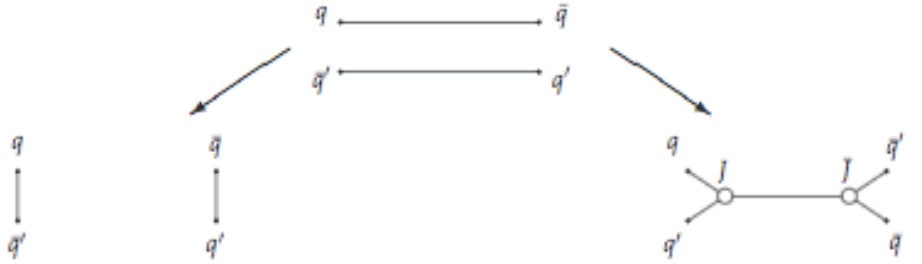


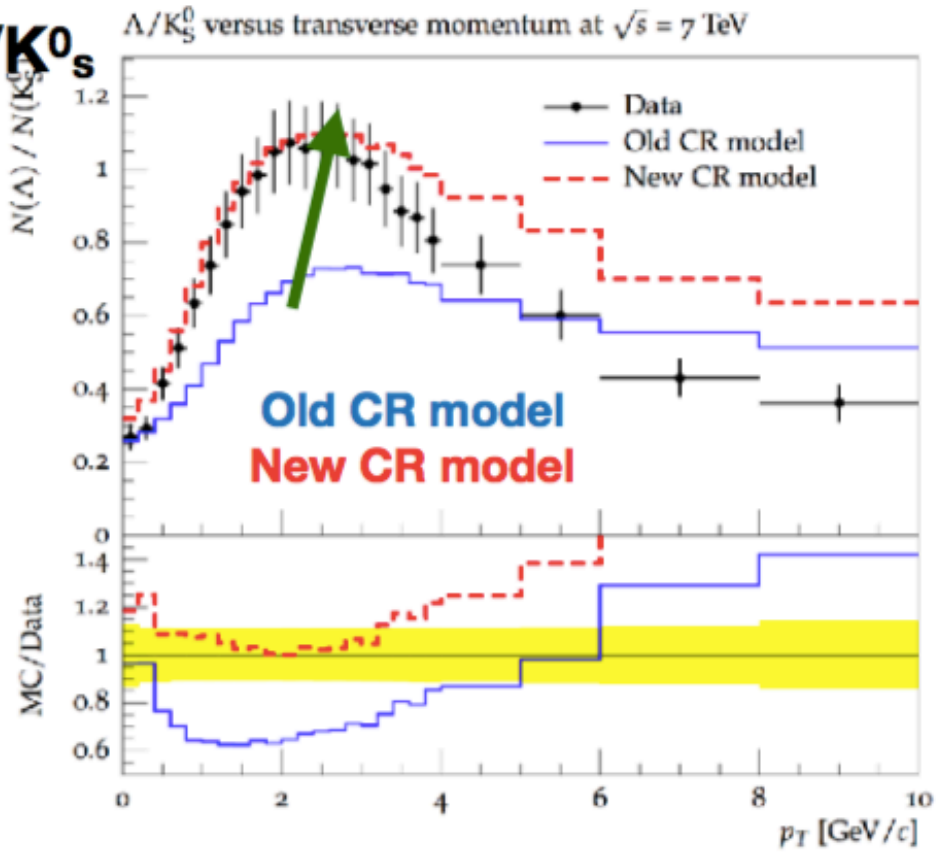
Figure 1: Sketch of how two $q\bar{q}$ dipoles (top) can be reconnected to different colour topologies (left and right). The right connection gives rise to a double junction, which in turn will produce baryons. Notice that the placement of the pairs differs in the junction figure.

the outgoing partons, it is applicable to any type of collision. The main extension compared to the other CR models in PYTHIA is the introduction of reconnections that form junction structures (fig. 1). From a pure colour consideration the probability to form a junction topology is three times larger than an ordinary reconnection. The junction will introduce additional strings, however, and it is therefore often disfavoured due to a larger λ measure. Given the close connection between junctions and baryons, the new model predicts a baryon enhancement. It was shown to be able to simultaneously describe the Λ production for both LEP and LHC experiments, which neither of the earlier PYTHIA tunes have been able to do.

Data samples

Can hadronisation be modified?

Λ/K^0_S



- **Multi-parton interactions**, coherence effects at LHC energies may affect hadronisation
- e.g. within PYTHIA, **enhanced colour reconnection** modes gives better agreement with measured Λ/K^0_S ratio
  - String formation beyond the leading-colour approximation, specific tuning of the colour reconnection parameters
  - String junctions provide new source of baryon production
- Gives physical, microscopic picture of hadronisation

Interesting to extend these studies to heavy-flavour sector → Λ_c^+/D^0