Charmed baryon production in pp collisions with ALICE

Jaime Norman for the ALICE collaboration
LPSC Grenoble

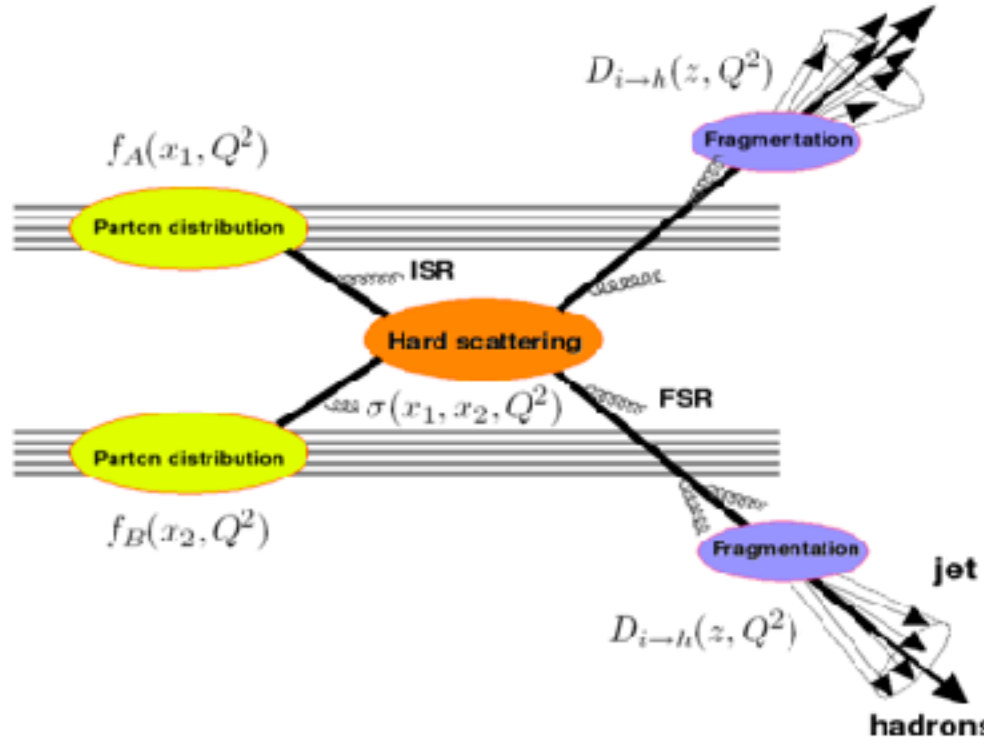
Workshop on singly and doubly charmed baryons, LPNHE Paris
26th June 2018

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

ALICE

Open heavy-flavour production in pp collisions

- Heavy quarks (charm and beauty) are produced in hard partonic scattering processes
  - $m_{c,b} >> \Lambda_{QCD} \rightarrow \alpha_s(m_q^2) \propto \ln^{-1}(m_q^2/\Lambda_{QCD}^2) << 1$
  - m_Q sets hard scale - perturbative QCD applicable

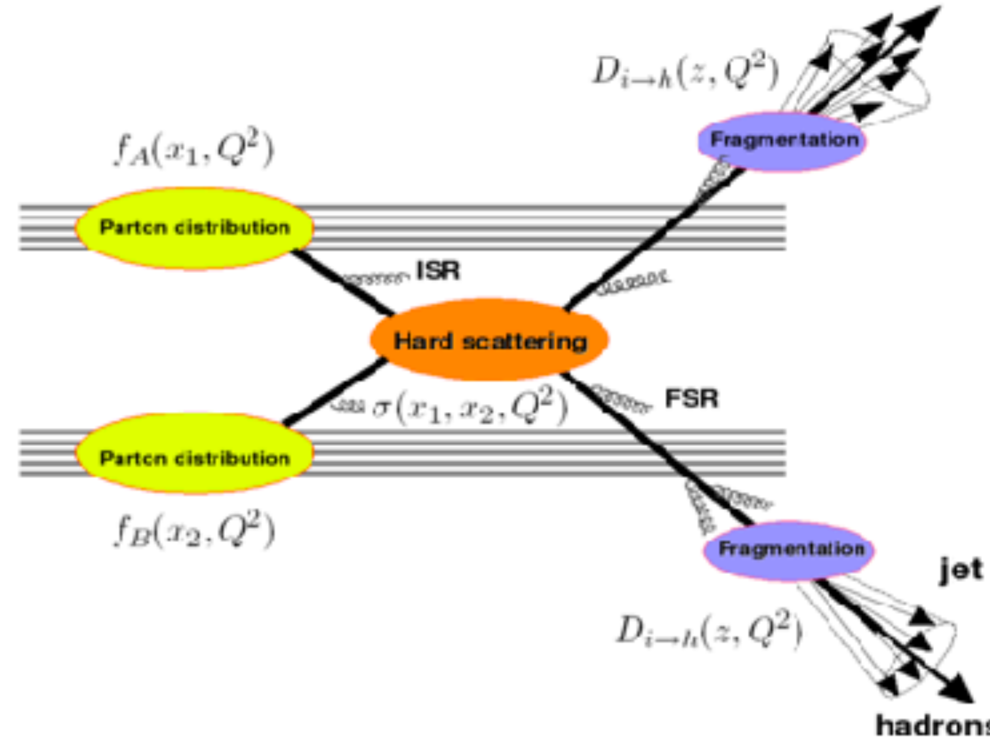


"Factorisation":

$$d\sigma^{hard}_{AB\rightarrow h} = f_{b/B}(x_1, Q^2) \otimes f_{a/A}(x_2, Q^2) \otimes d\sigma^{hard}_{ab\rightarrow c}(x_1, x_2, Q^2) \otimes D_{c\rightarrow h}(z, Q^2)$$

Open heavy-flavour production in pp collisions

- Heavy quarks (charm and beauty) are produced in hard partonic scattering processes
  - $m_{c,b} >> \Lambda_{QCD} \rightarrow \alpha_s(m_q^2) \propto \ln^{-1}(m_q^2/\Lambda_{QCD}^2) << 1$
  - m_Q sets hard scale - perturbative QCD applicable



"Factorisation":

$$d\sigma^{hard}_{AB\rightarrow h} = f_{b/B}(x_1,Q^2) \otimes f_{a/A}(x_2,Q^2) \otimes d\sigma^{hard}_{ab\rightarrow c}(x_1,x_2,Q^2) \otimes D_{c\rightarrow h}(z,Q^2)$$

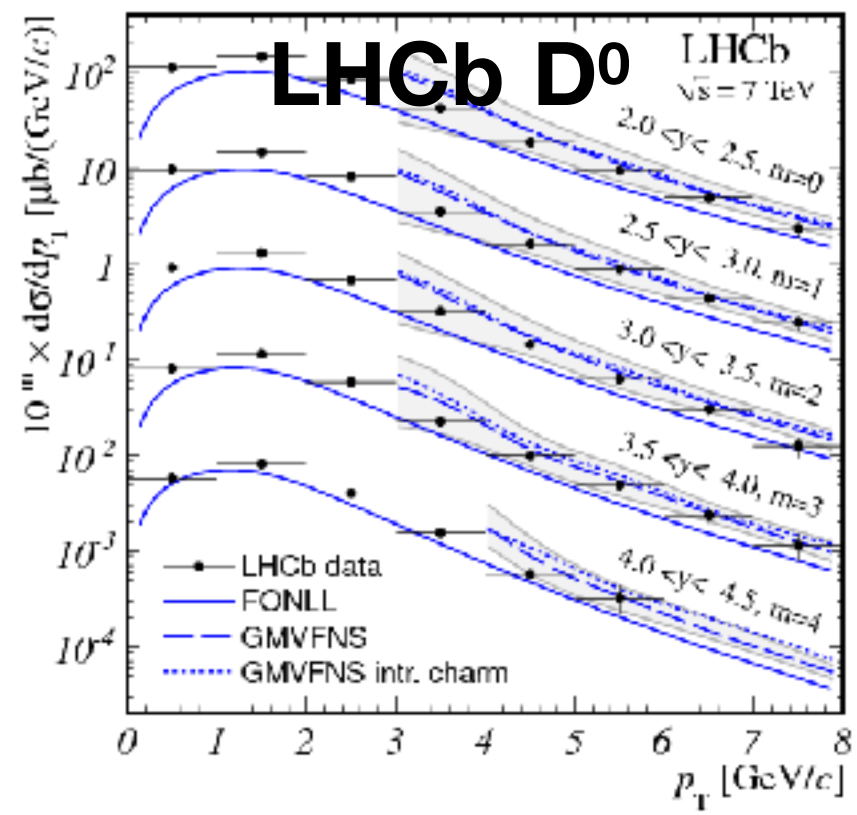
- Open heavy-flavour production measurements in pp collisions:
  - **Important test of pQCD-based calculations**
  - **Sensitive to fragmentation functions** determined from e^+e^- collisions
  - Sensitivity to **low-*x* gluon PDF** ($p_T \rightarrow 0$)

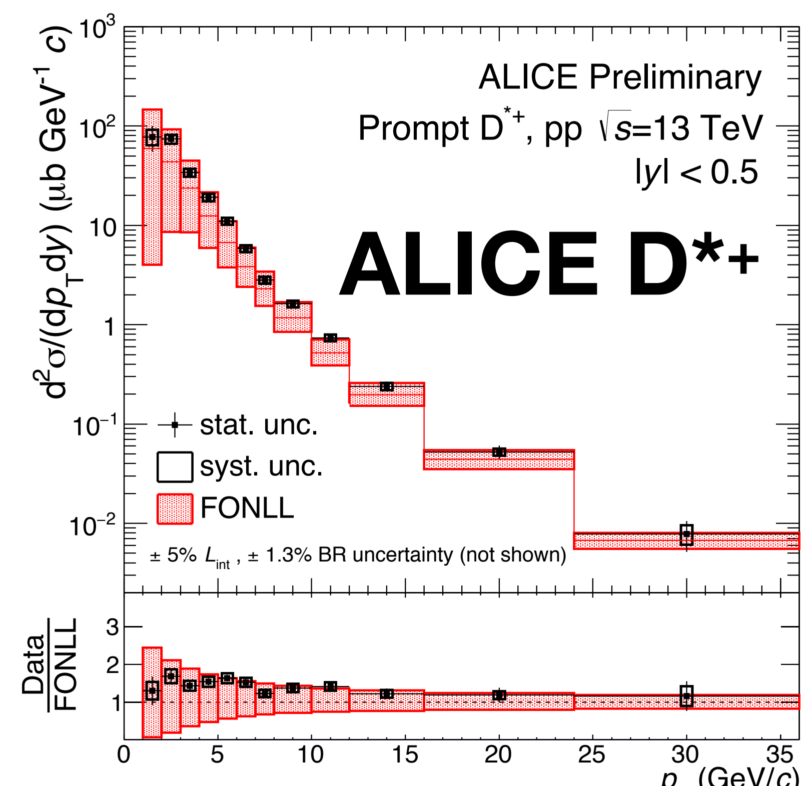
Charm production at the LHC

Charmed-hadron production - test of pQCD

- Heavy-flavour production **extensively studied** in hadron collisions
- Cross sections of D mesons at the LHC **in agreement with pQCD predictions** at central and forward rapidity
- Similar observations made at different collision energies
- Beauty-meson production also described well by theory

LHCb: Nucl. Phys.B871 (2013) 1–20





FONLL: M. Cacciari et al. JHEP 05 (1998), JHEP 10 (2012)
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082

Charm quark fragmentation

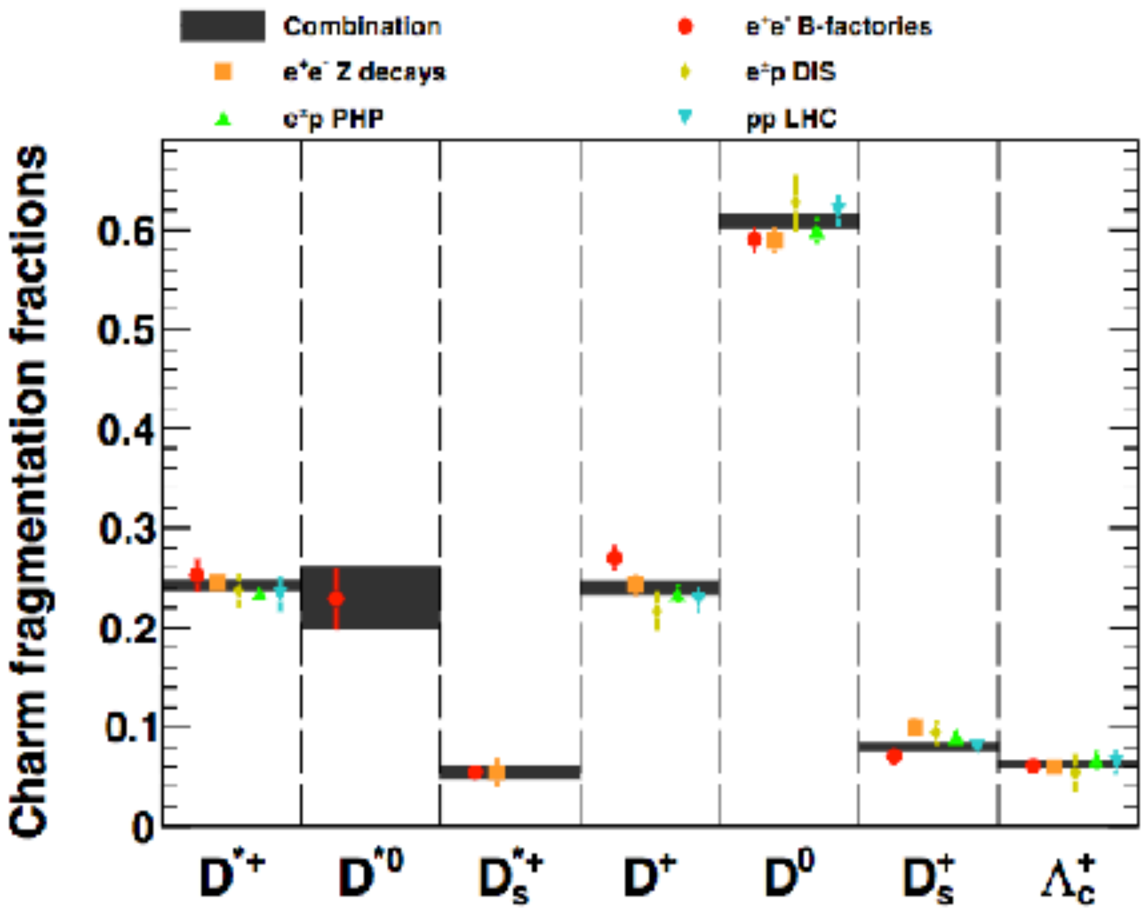
Charmed-hadron ratios - sensitive to fragmentation process

- fragmentation fractions **expected to be universal** (*fragmentation universality*)

  → same in different systems, energies, etc

- Measurements in different collision systems (ee, ep, pp) and energies support this picture

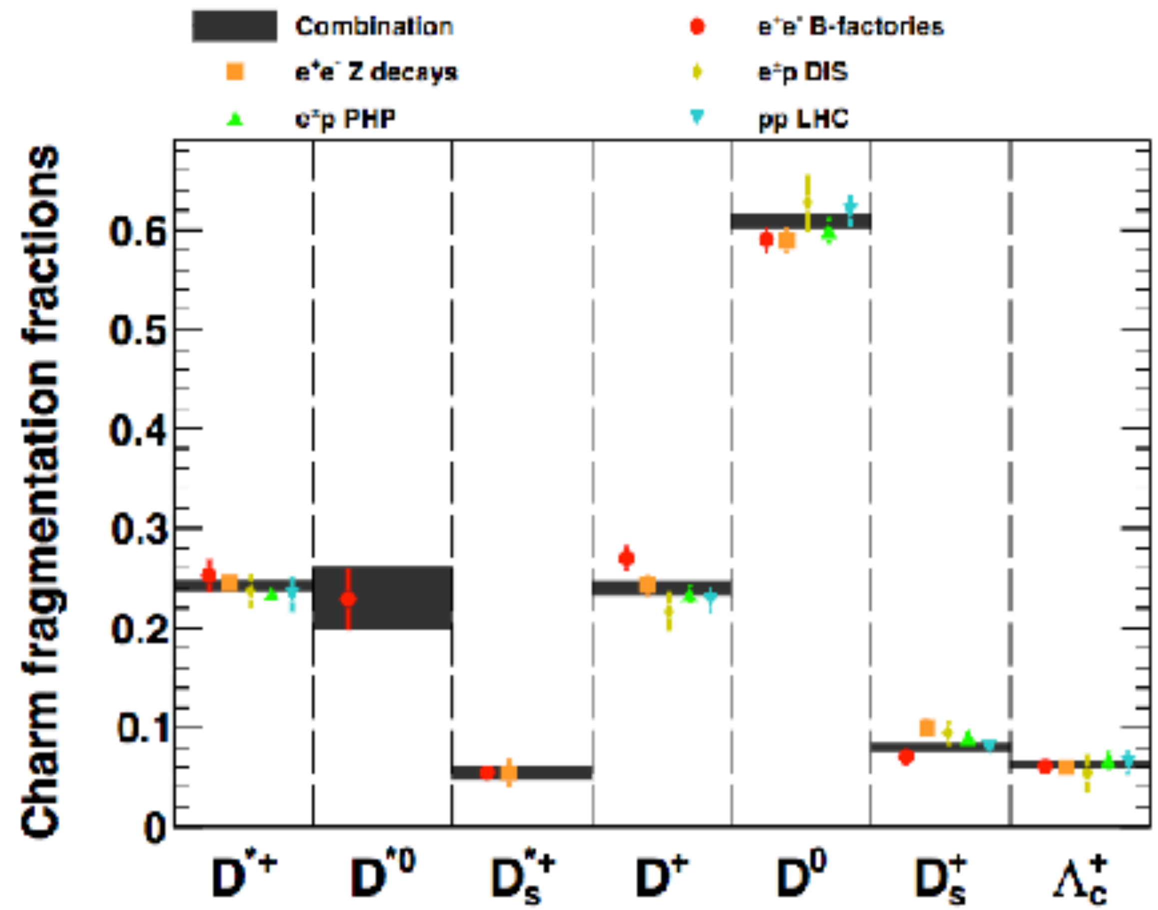
EPJ C 76 (2016) no.7, 397



Charm quark fragmentation

Charmed-hadron ratios - sensitive to fragmentation process

EPJ C 76 (2016) no.7, 397



- fragmentation fractions **expected to be universal** (*fragmentation universality*)
  - → same in different systems, energies, etc
- Measurements in different collision systems (ee, ep, pp) and energies support this picture

Baryon production measurements

- Very few charmed-baryon production measurements in hadron colliders
  - Λ_C production measured by LHCb at $\sqrt{s}$ = 7 TeV
  - Higher-mass charmed baryon production measurements (e.g. Ξ_c^0) only exist in e^+e^- collisions

LHCb: Nucl. Phys.B871 (2013) 1–20

- Indication in beauty sector that **beauty-baryon** production **depends on collision system**

CDF: Phys.Rev.D77:072003,2008
LHCb: Phys. Rev. D85 , 032008 (2012)

- Predictions of baryon production including string formation beyond leading colour approximation anticipates *larger* baryon/meson ratios

C. Bierlich, J.R. Christiansen, Phys. Rev. D 92 (2015) 094010
J.R. Christiansen, P.Z. Skands JHEP 08 (2015) 003

Charmed baryon production with ALICE

Λ_c^+ production in pp collisions at $\sqrt{s}$ = 7 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

JHEP 1804 (2018) 108

First measurement of Ξ_c^0 production in pp collisions at $\sqrt{s}$ = 7 TeV

Phys.Lett. B781 (2018) 8-19

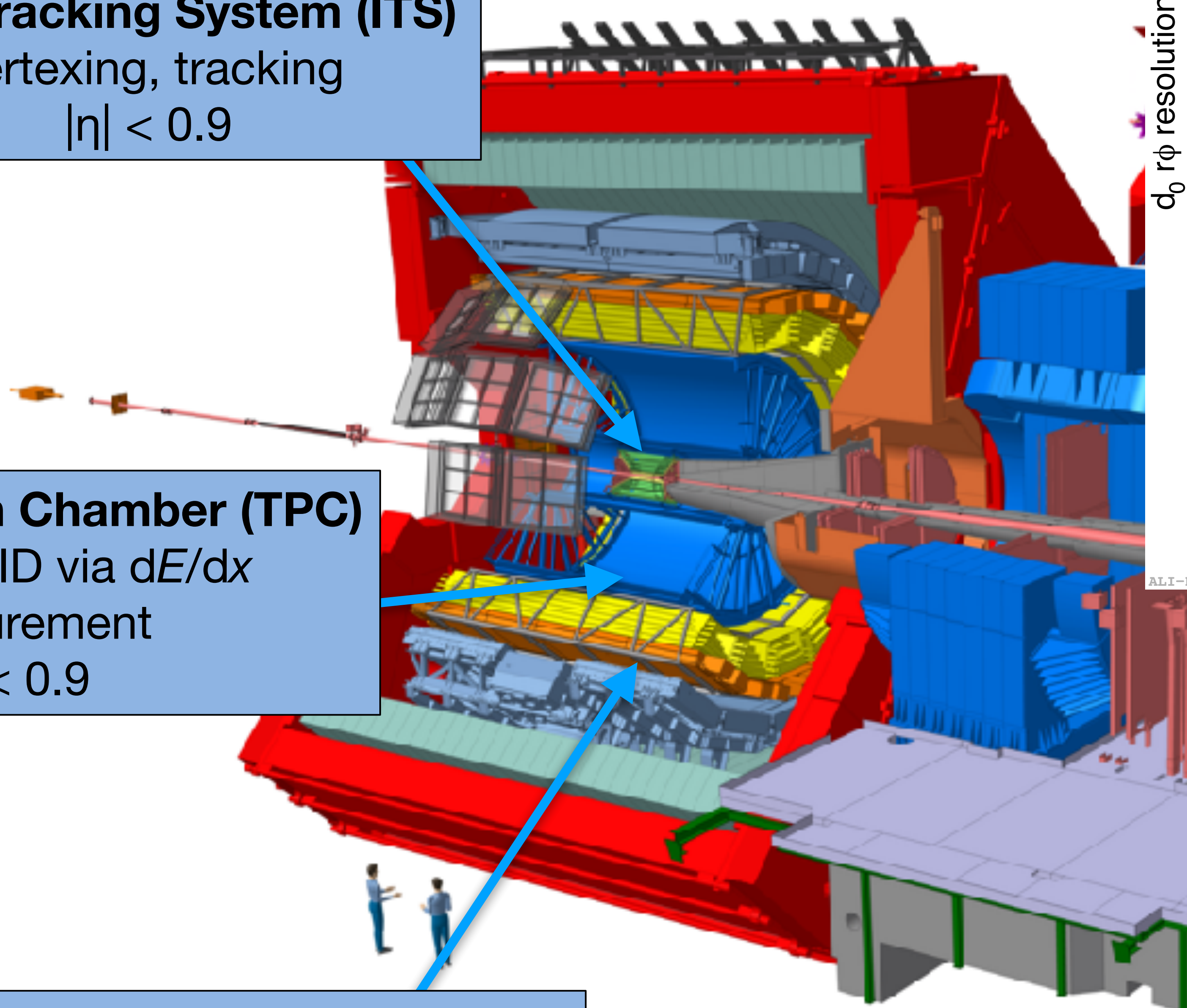
Note: here I touch on results in p-Pb collisions - see Elisa's talk tomorrow for more information/latest results in p-Pb!

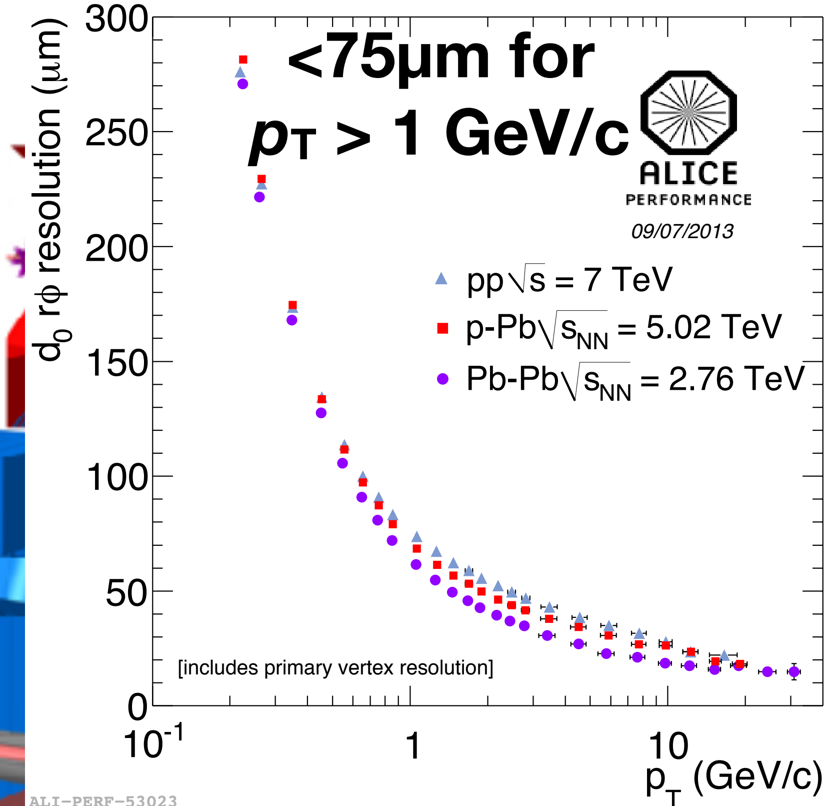
The ALICE apparatus

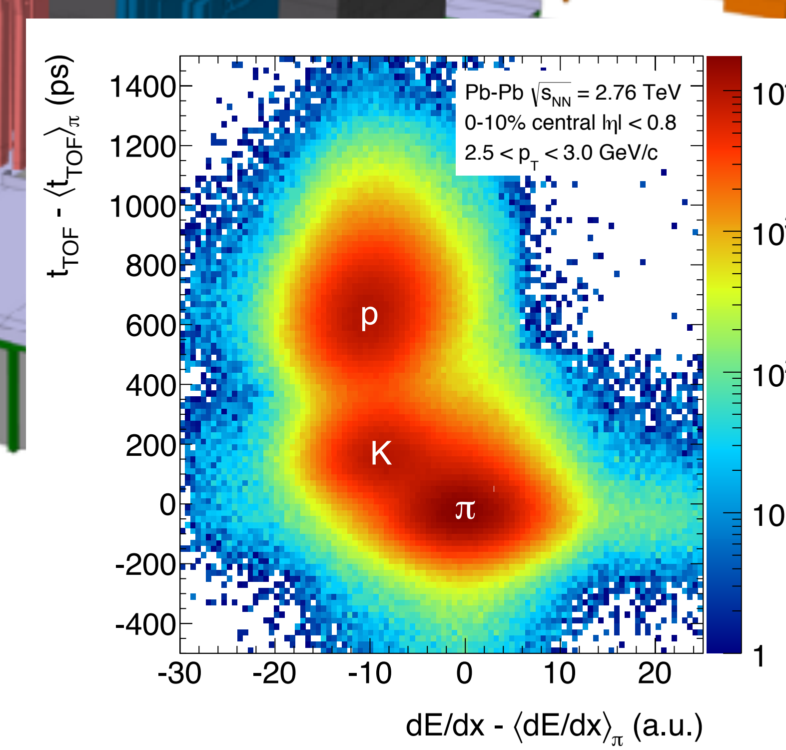
Inner Tracking System (ITS)
vertexing, tracking
|η| < 0.9

Time Projection Chamber (TPC)
Tracking, PID via d*E*/d*x* measurement
|η| < 0.9

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



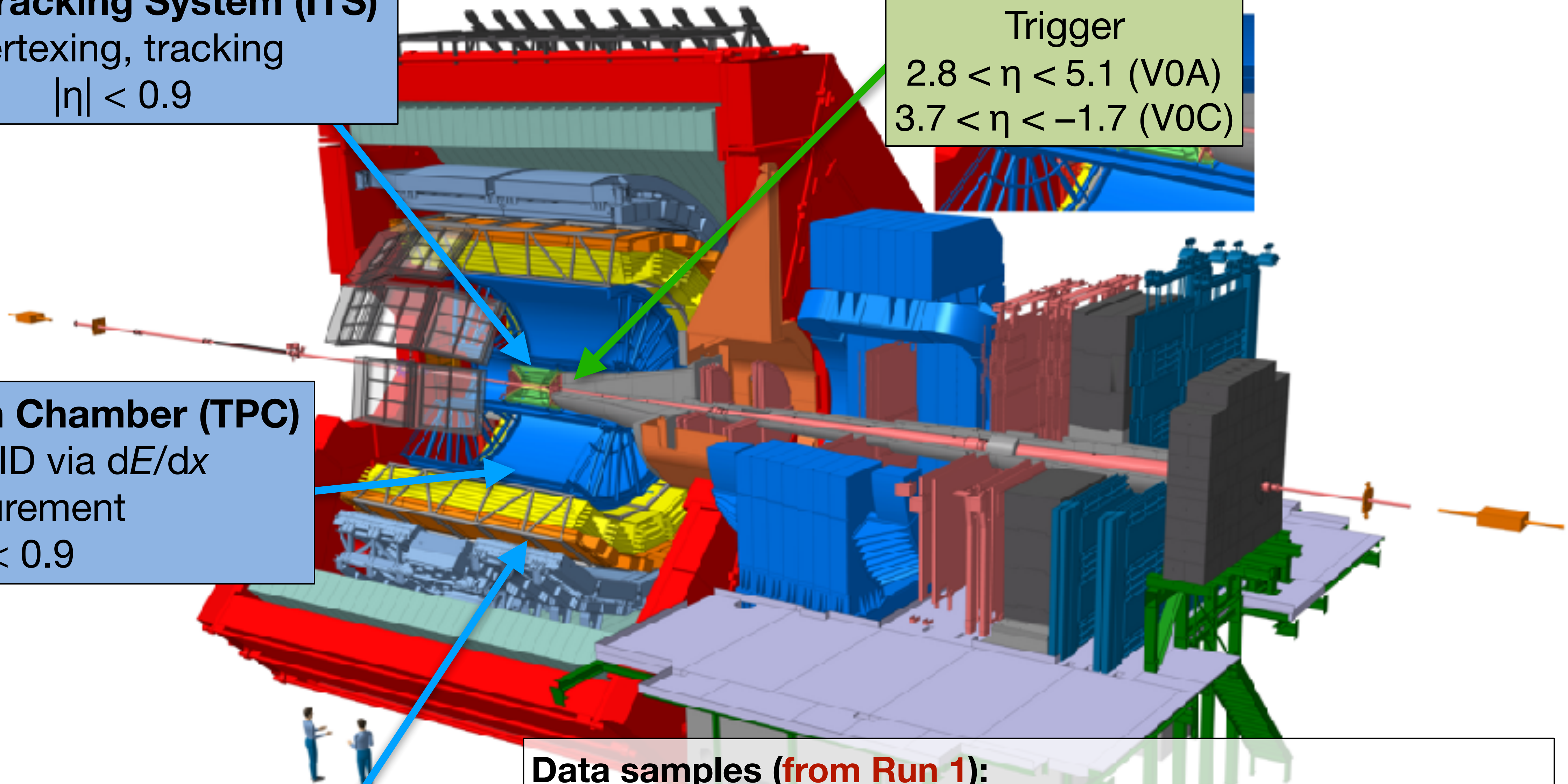




The ALICE apparatus

Inner Tracking System (ITS)
vertexing, tracking
$|\eta| < 0.9$

V0
Trigger
$2.8 < \eta < 5.1$ (V0A)
$3.7 < \eta < -1.7$ (V0C)



Time Projection Chamber (TPC)
Tracking, PID via d*E*/dx measurement
$|\eta| < 0.9$

Time-Of-Flight detector (TOF):
PID via time-of-flight measurement
$|\eta| < 0.9$

Data samples (from Run 1):

pp collisions: min. bias trigger using V0, SPD

- $\sqrt{s}$ **= 7 TeV :** ~4x10^8 min. bias events, L_{int} = 6.0 nb^{-1}

p-Pb collisions: min. bias trigger using V0

- $\sqrt{s_{NN}}$ **= 5.02 TeV :** ~10^8 min. bias events, L_{int} = 48.6 μb^{-1}

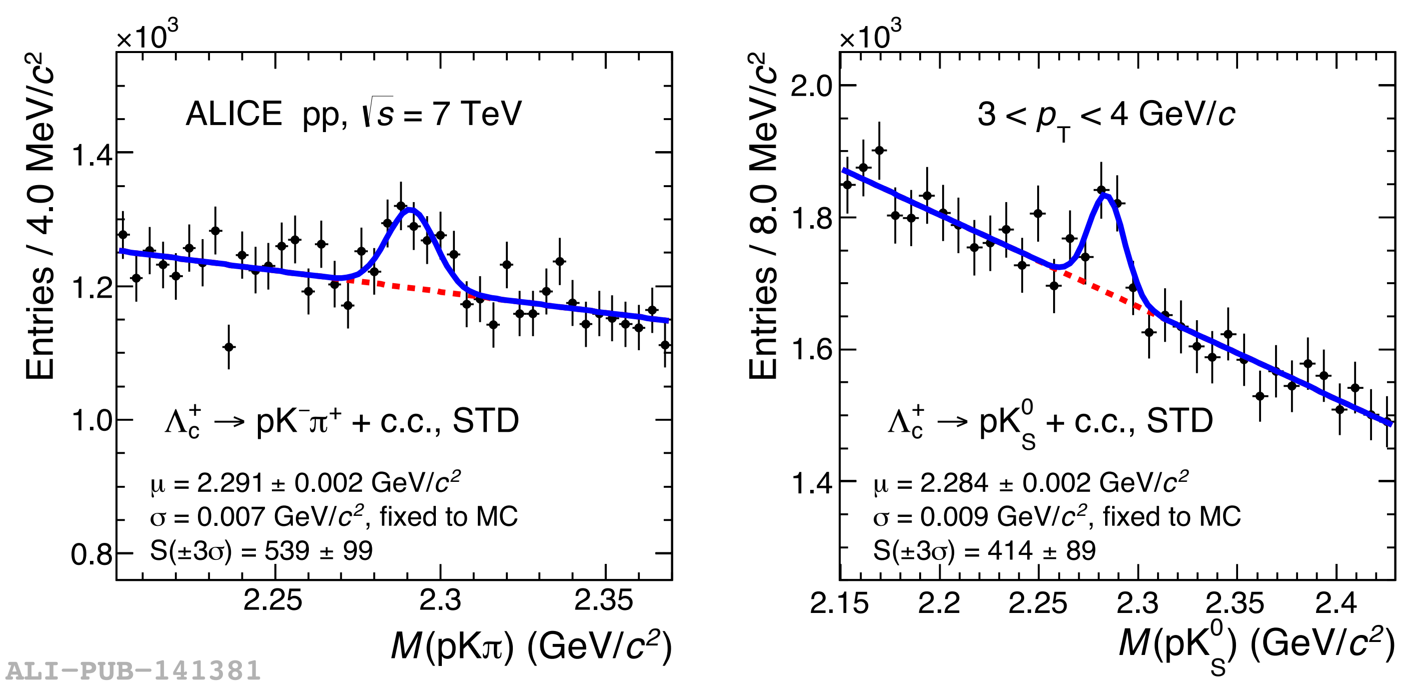
Charmed baryon reconstruction

Hadronic decays

- **PID** using TPC via d*E*/d*x* and TOF via time-of-flight measurement
  - nσ cuts, or Bayesian approach to identify particles
- **Cuts on decay topologies** exploiting decay vertex displacement from primary vertex
- **Signal extraction** via invariant mass distribution in bins of transverse momentum
- **B feed-down subtraction** using pQCD-based estimation of beauty-baryon production
- **Efficiency, acceptance** corrections

Λ_c^+ baryon
M = 2284 MeV/c^2
Quark content *udc*
$c\tau$ = 60 μm

Decay	Branching fraction (%)
$\Lambda_c^+ \rightarrow pK^-\pi^+$	6.35
$\Lambda_c^+ \rightarrow pK^0_S$	1.58



Charmed baryon reconstruction

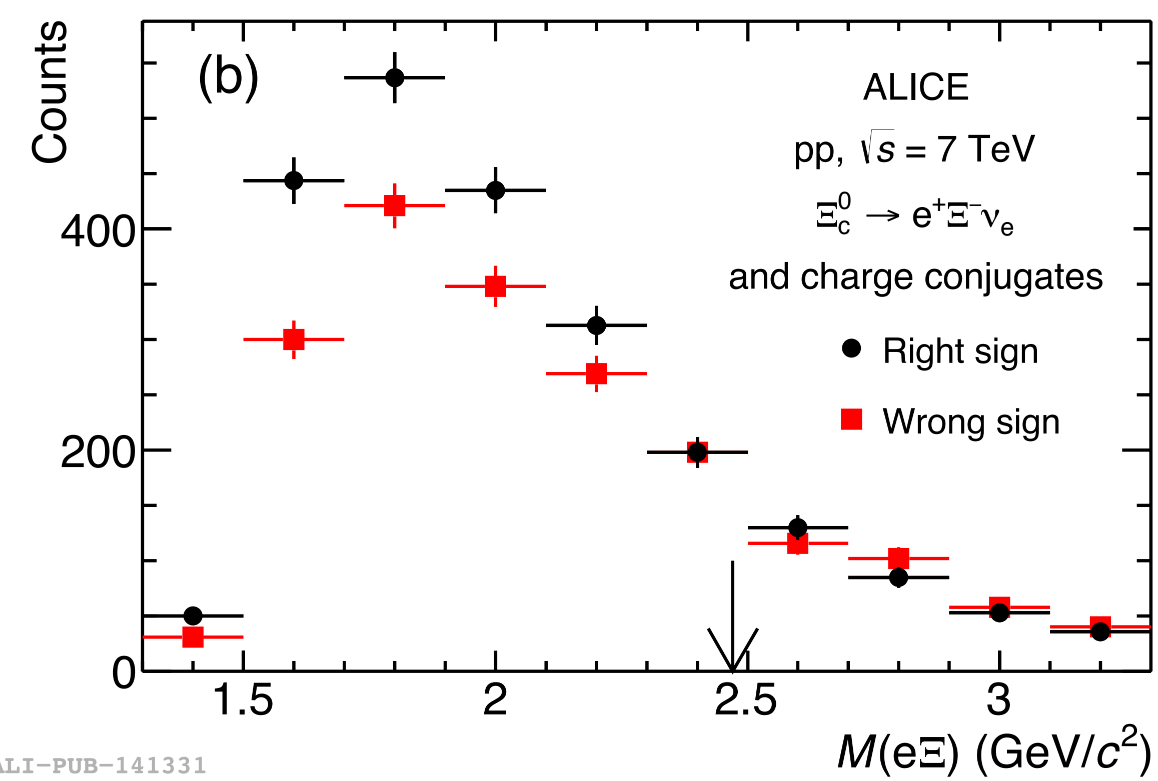
Semileptonic decays

- **PID** using TPC via dE/dx and TOF via time of flight measurement
  - Λ, Ξ candidates reconstructed
- **Wrong-sign (WS)** $e^-\Lambda$ ($e^-\Xi^-$) pairs subtracted from **right-sign (RS)** spectra $e^+\Lambda$ ($e^+\Xi^-$)
- Subtract contributions from:
  - $\mathbf{\Lambda_b^0}$ **($\mathbf{\Xi_b^0}$)** in wrong-sign spectra
  - $\mathbf{\Xi_c^{0,+}}$ in right-sign spectra for Λ_c^+ analysis
- **Unfold** $e^+\Lambda$($e^+\Xi^-$) p_T spectra to obtain Λ_c^+ (Ξ_c^0) spectra
- **B feed-down subtraction** using pQCD-based estimation of beauty baryon production **(Λ_c^+ only!)**
- **Efficiency, acceptance** corrections

Ξ_c^+ baryon
M = 2471 MeV/c^2
Quark content *usc*
$c\tau$ = 34 μm

Λ_c^+ baryon
M = 2284 MeV/c^2
Quark content *udc*
$c\tau$ = 60 μm

Decay	Branching fraction (%)
$\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$	3.6
$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$	**Unknown**

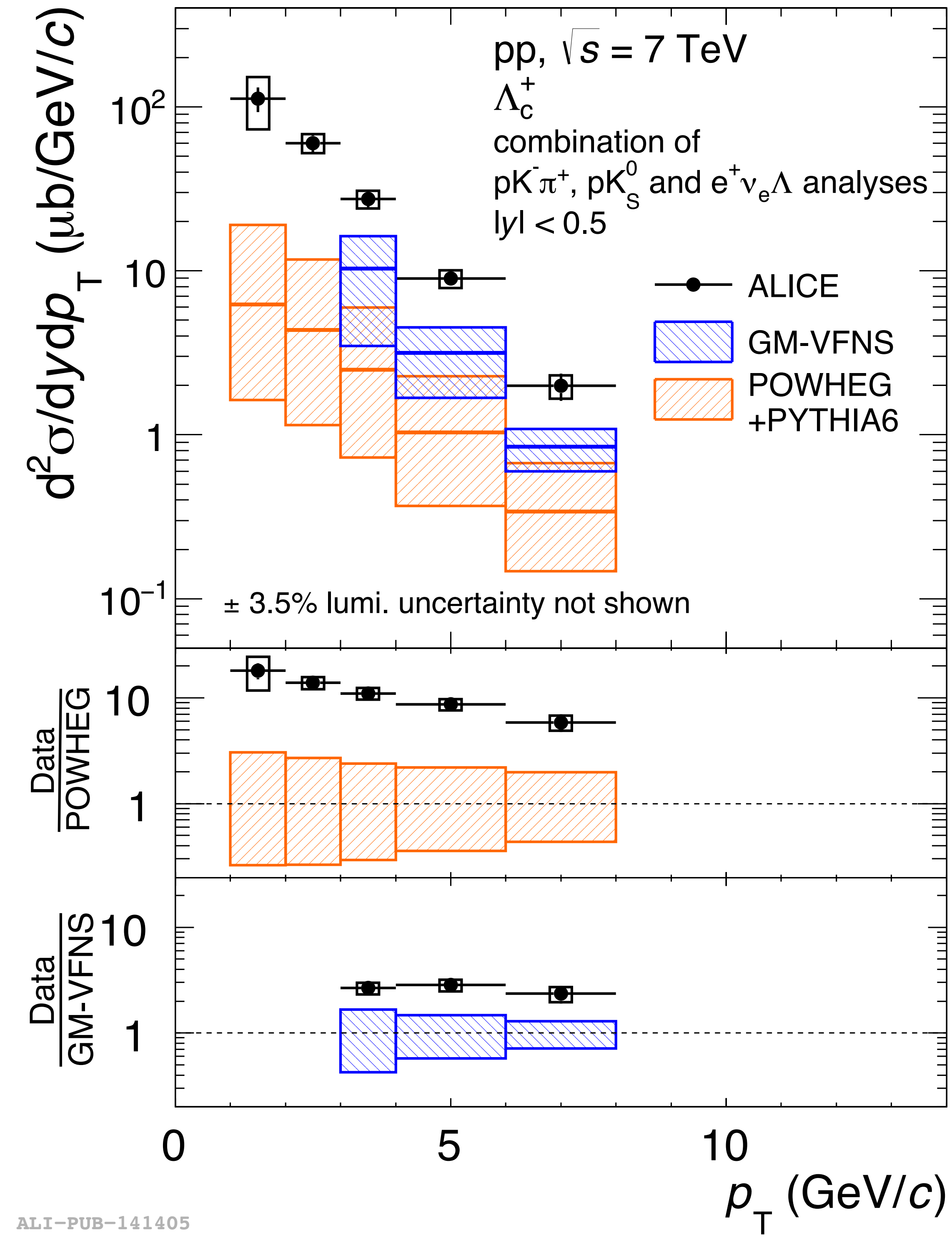


Results

Λ_c^+ p_T-differential cross section in pp collisions

- Λ_c^+ p_T-differential cross section **significantly underestimated** by theory
  - **GM-VFNS:** Next-to-leading order QCD with large logarithms resummed to all orders
    - Non-perturbative fragmentation estimated from e+e- collision data
      B.A. Kniehl, G. Kramer: Phys. Rev. D 74 (2006) 037502
  - **POWHEG:** MC generator with next-to-leading order accuracy
    - PYTHIA parton shower

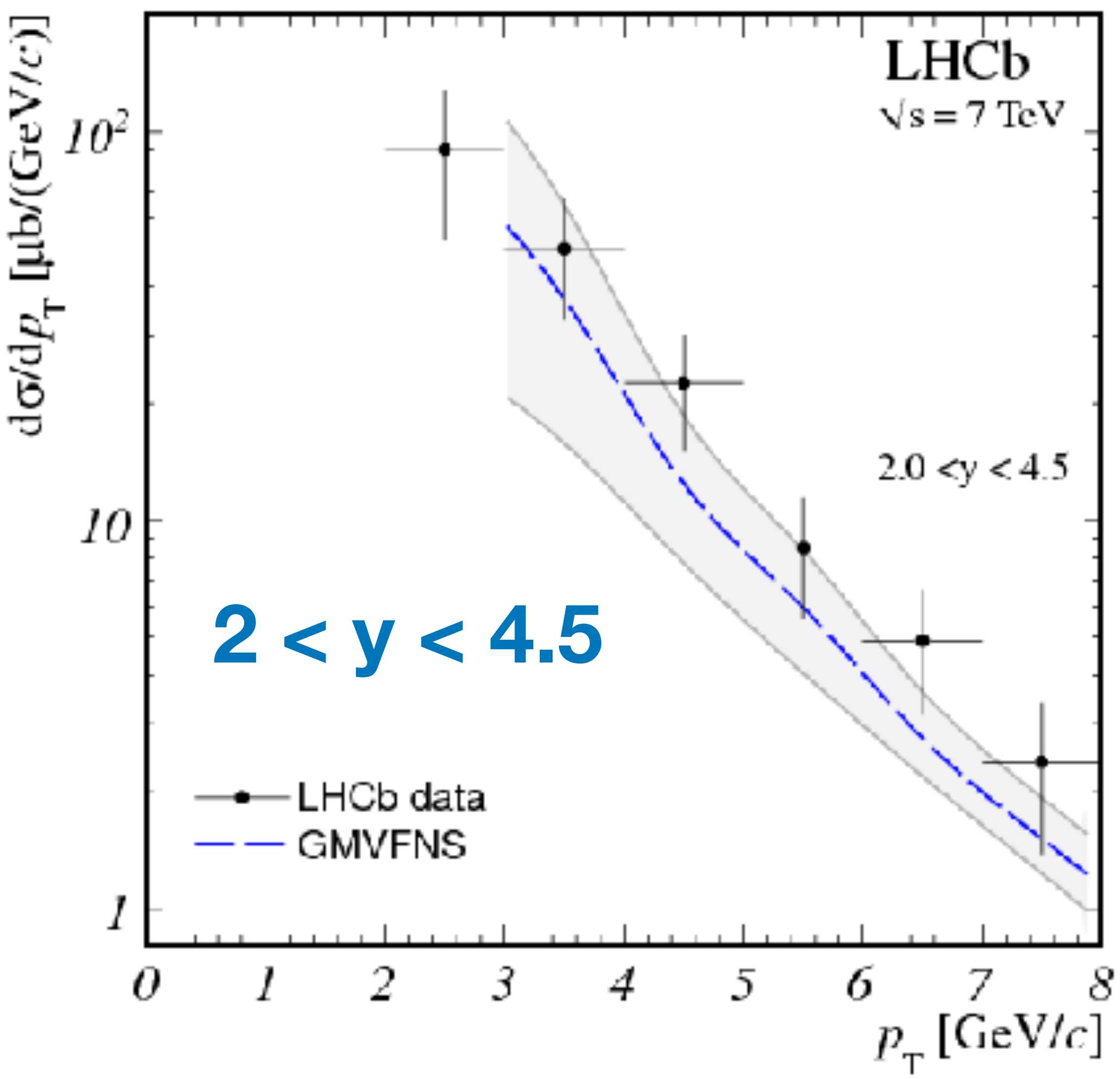
JHEP 1804 (2018) 108



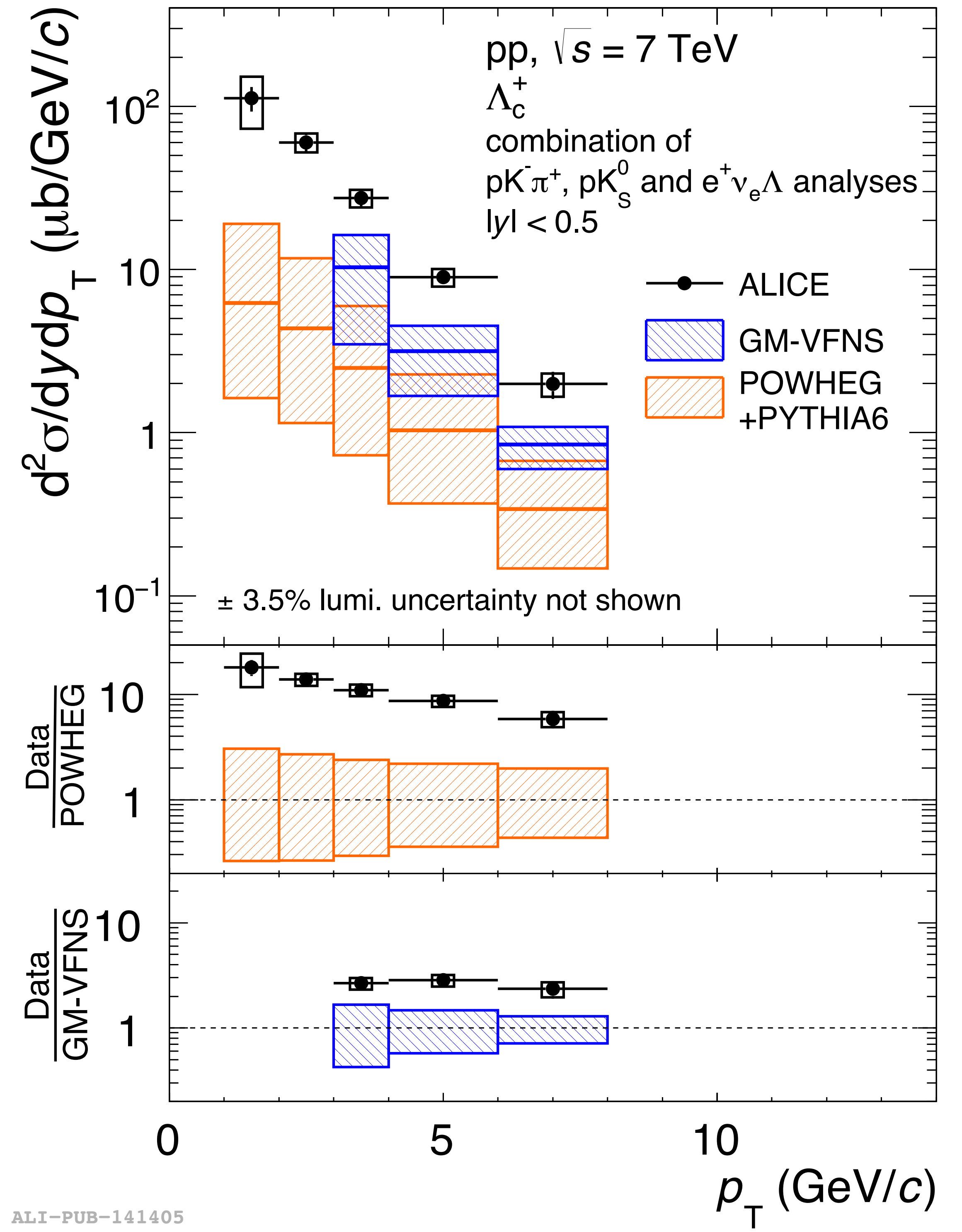
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082
POWHEG: S. Frixione et al.: JHEP 09 (2007) 126

Λ_c^+ p_T-differential cross section in pp collisions

LHCb: Nucl. Phys.B871 (2013) 1–20



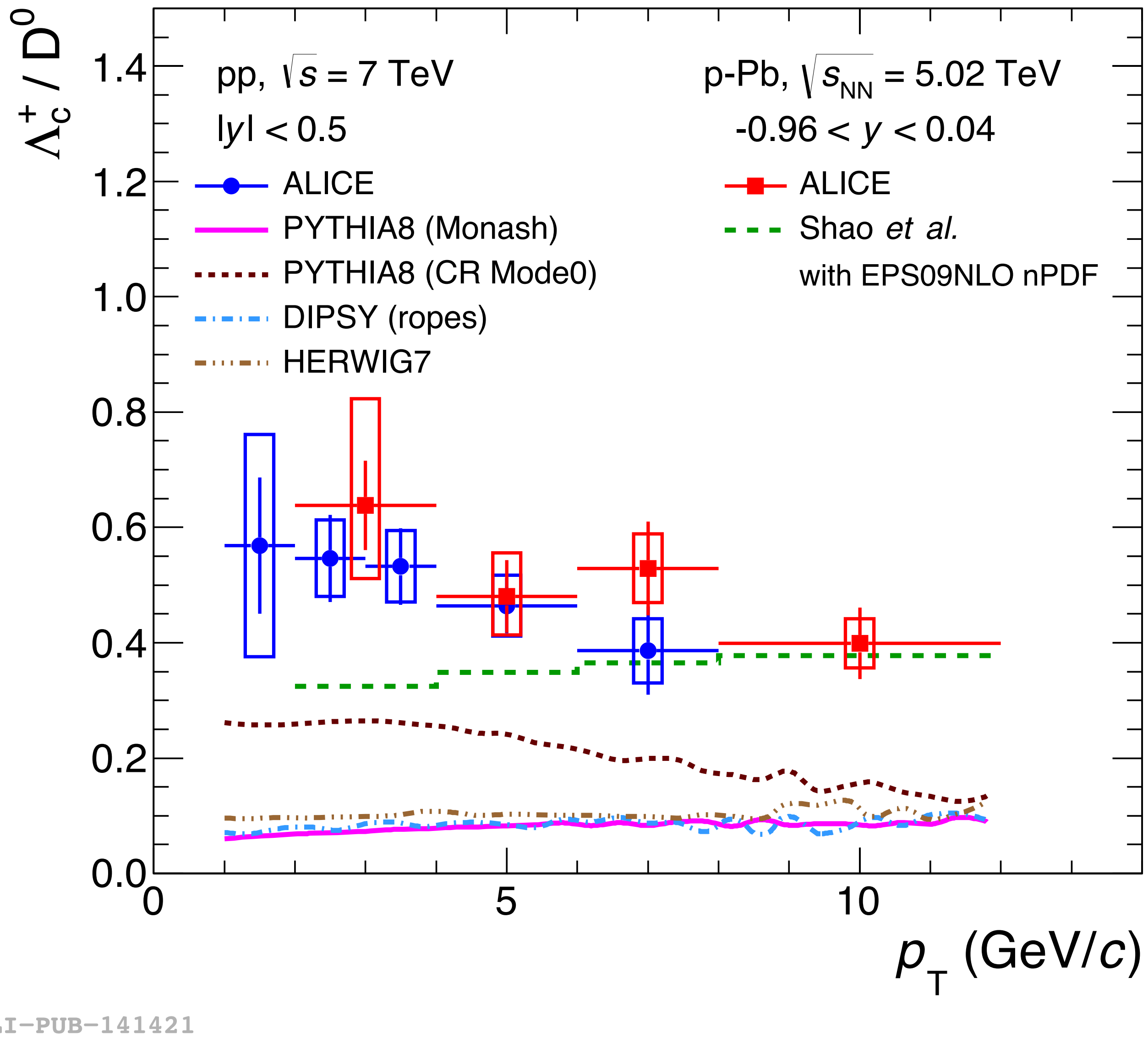
JHEP 1804 (2018) 108

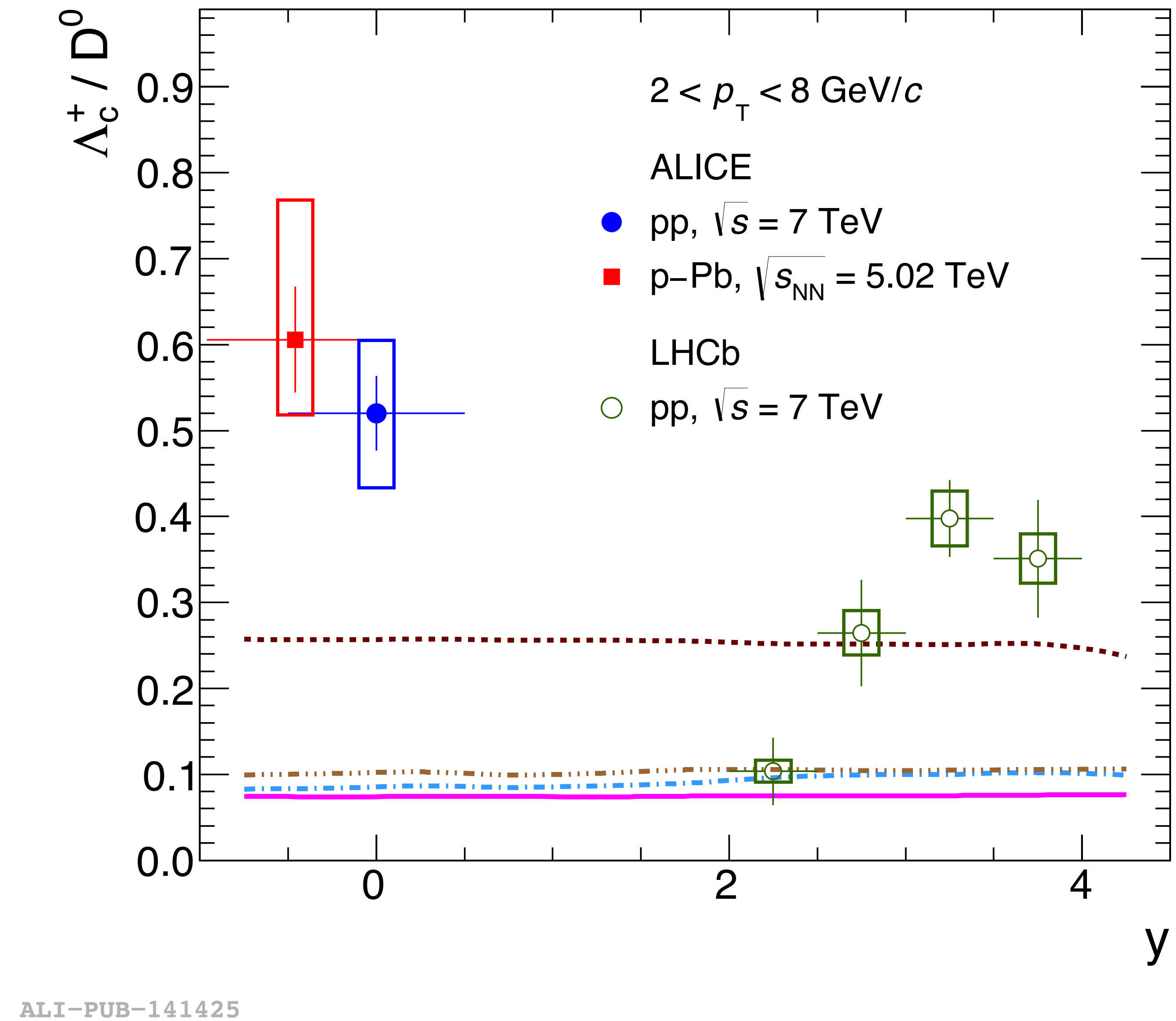


- Λ_c^+ production at forward rapidity described by GM-VFNS

Λ_c^+/D^0 baryon-to-meson ratio vs models

JHEP 1804 (2018) 108

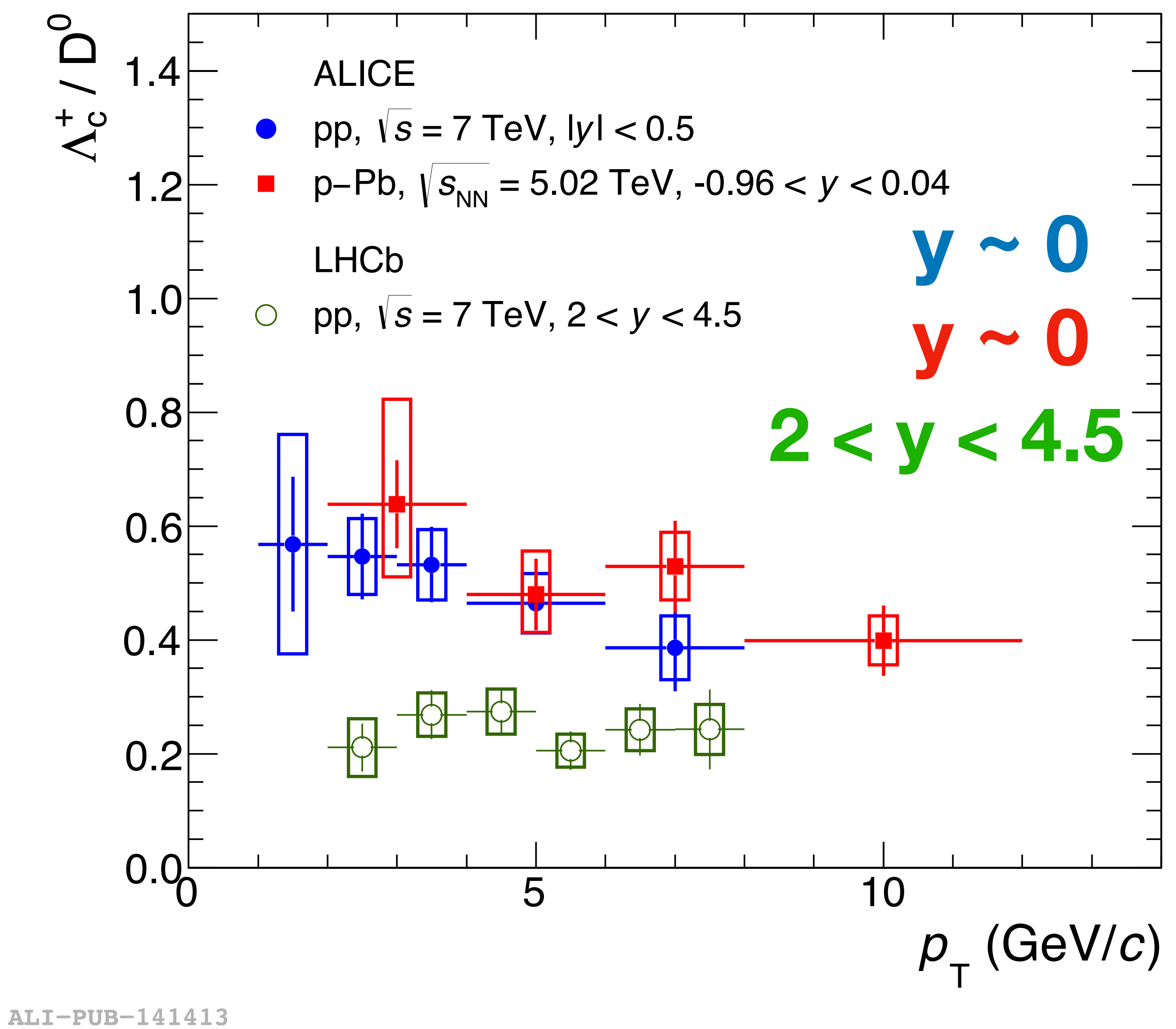


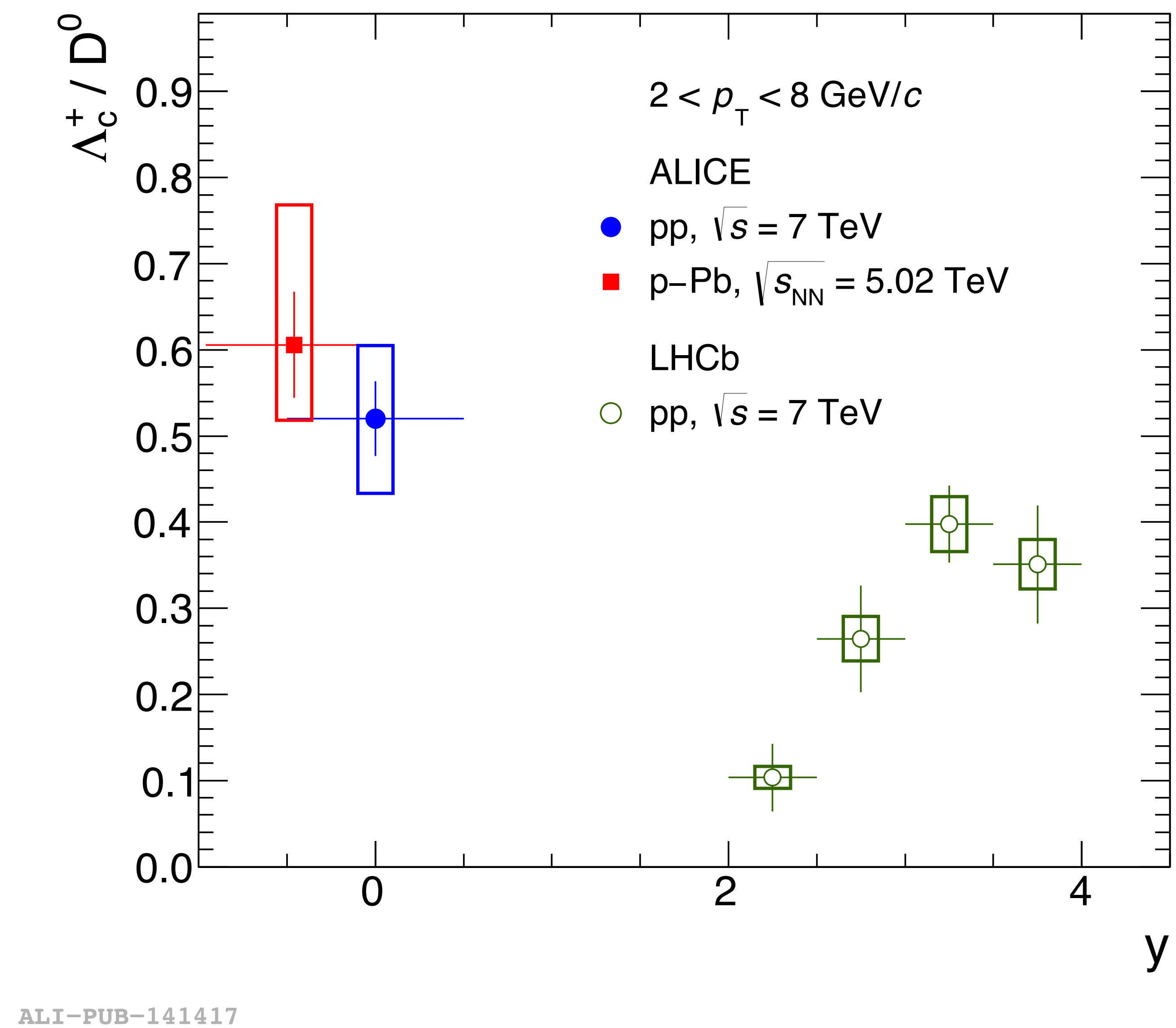


- Λ_c^+/D^0 ratio **higher than expectation** from MC
- **PYTHIA8 tune with enhanced colour reconnection** closer to data
  - String formation beyond the leading-colour approximation
- Flat rapidity trend predicted by models not in agreement with ALICE and LHCb measurements

Λ_c^+/D^0 baryon-to-meson ratio

JHEP 1804 (2018) 108





- ALICE measurement **systematically higher** than LHCb

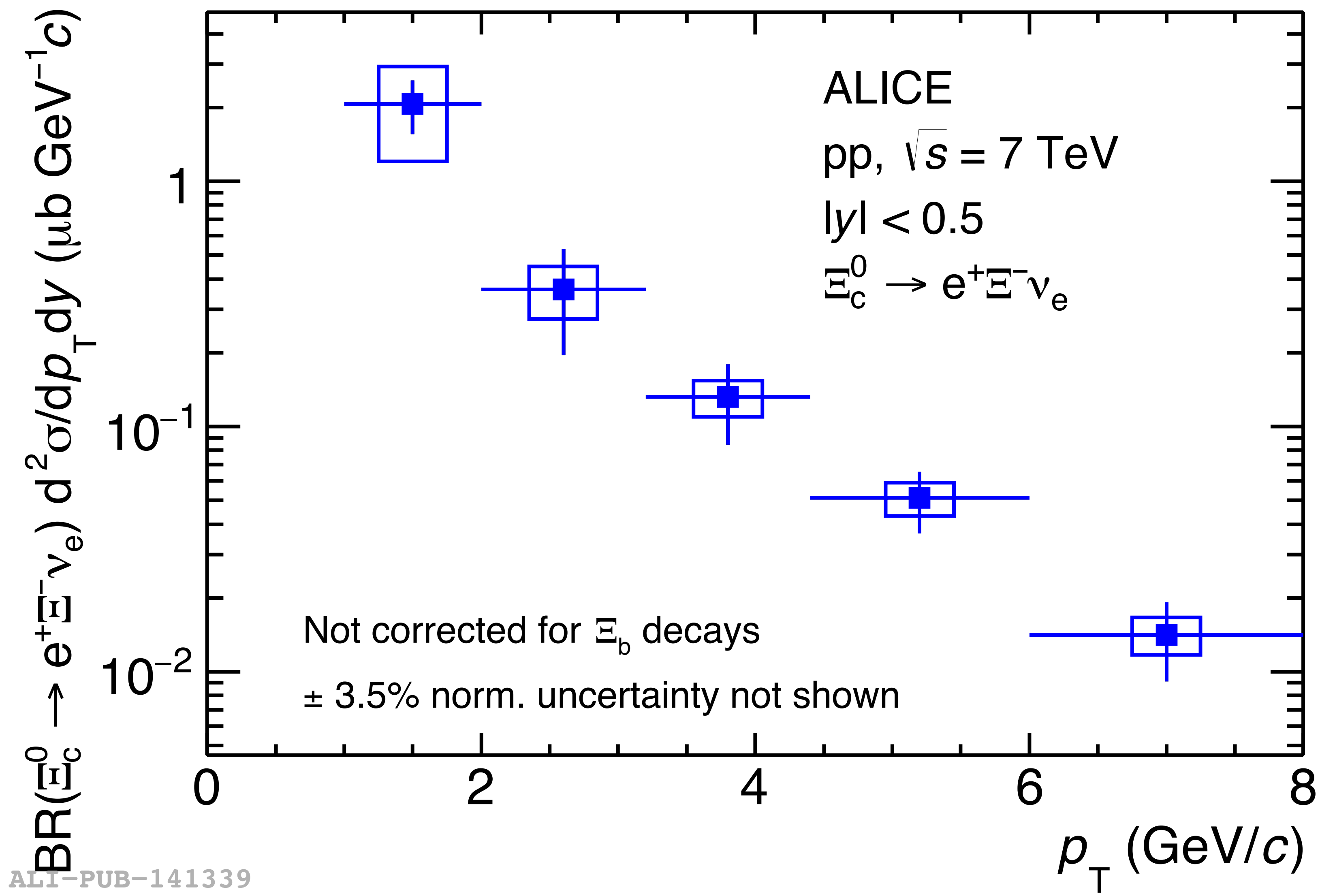
Λ_c^+/D^0 baryon-to-meson ratio

Measurement	Λ_c^+/D^0 ± stat. ± syst.	System	√s (GeV)	Kinematics
CLEO	0.119 ± 0.021 ± 0.019	ee	10.55	
ARGUS	0.127 ± 0.031 (stat.+syst.)	ee	10.55	
LEP average	0.113 ± 0.013 ± 0.006	ee	91.2	
ZEUS DIS	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp HERA I	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert\eta\rvert < 1.6$
ZEUS γp HERA II	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert\eta\rvert < 1.6$
ALICE	**0.543 ± 0.061 ± 0.160**	**pp**	**7000**	**$1 < p_T < 8$ GeV/c, $\lvert\eta\rvert < 0.5$**
ALICE	**$0.602 \pm 0.060^{+0.159}_{-0.087}$**	**pPb**	**5020**	**$2 < p_T < 12$ GeV/c, $\lvert\eta\rvert < 0.5$**

- Baryon-to-meson ratio ***higher than previous measurements*** in different collision systems + kinematic regimes (+ LHCb at ~0.2-0.3)
- For a more robust comparison it will be very important to measure the Λ_c^+ down to p_T=0 with good precision

Ξ_c^0 p_T-differential cross section in pp collisions

Phys.Lett. B781 (2018) 8-19



- Ξ_c^0 production cross-section-times-branching-ratio measured from $1 < p_T < 8$ GeV/c
  - Not feed-down corrected - includes $\Xi_b \rightarrow \Xi_c^0 X \rightarrow e^+\Xi^-\nu_e$

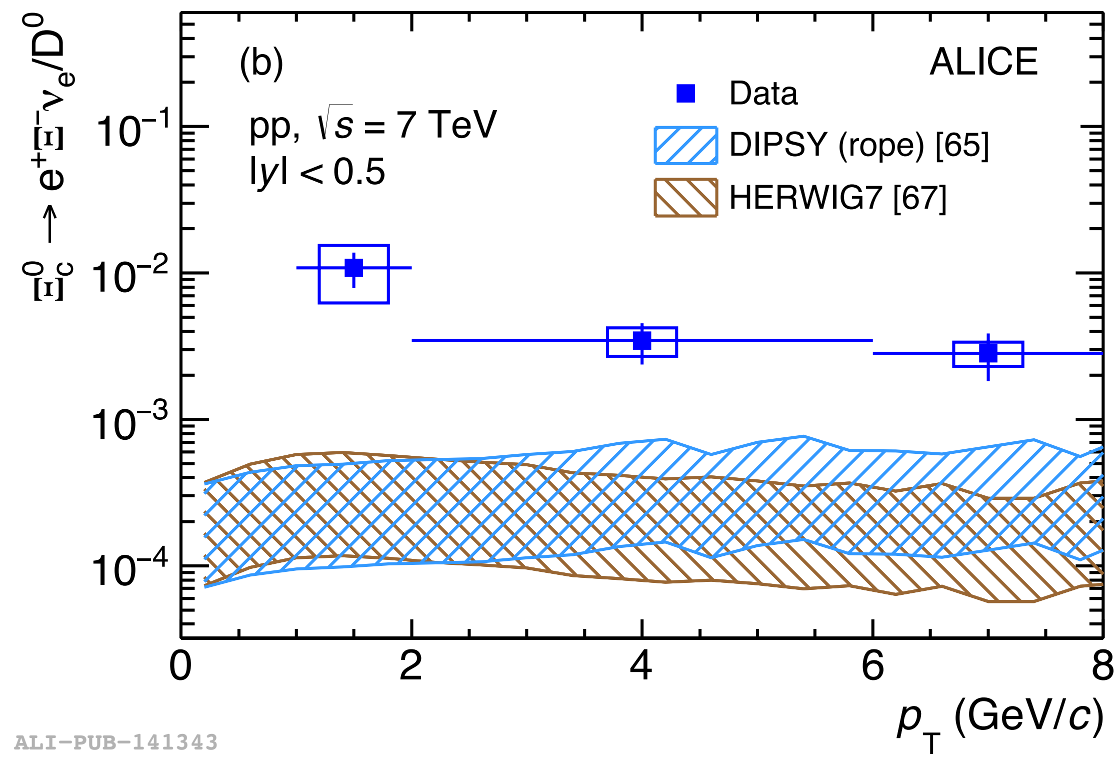
$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ /D^0 baryon-to-meson ratio

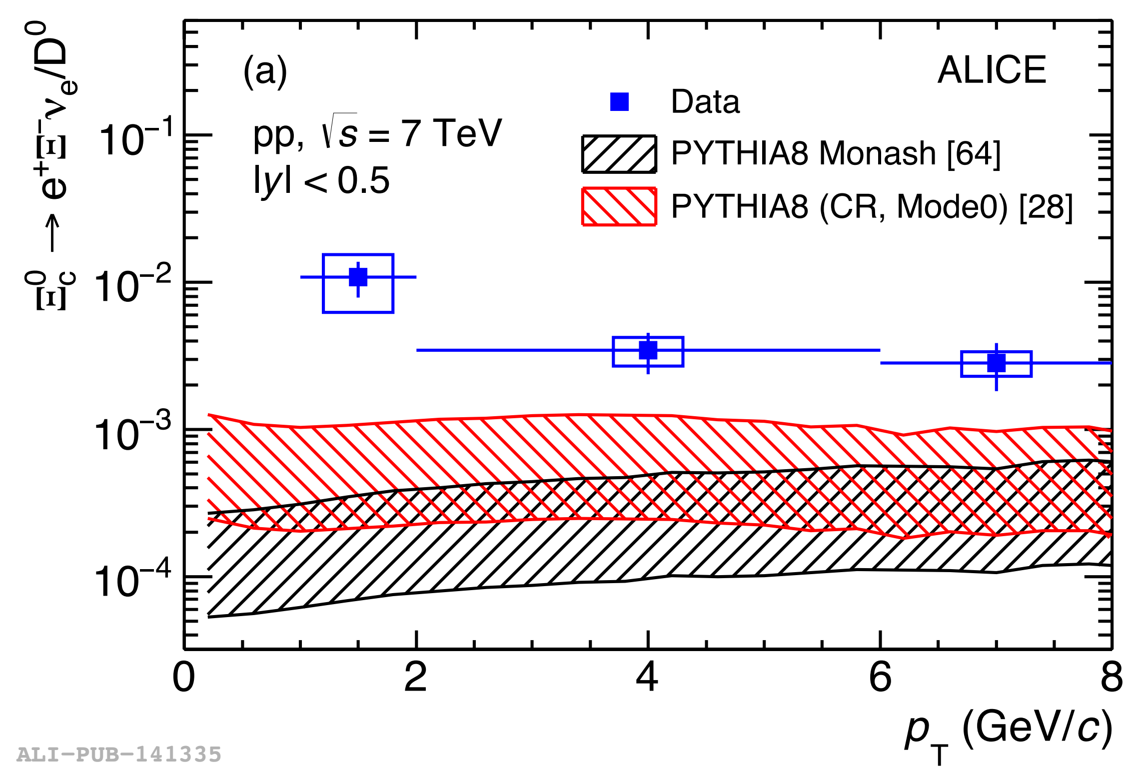
Phys.Lett. B781 (2018) 8-19

- Baryon-to-meson ratio $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ /D^0 **higher than expectation** from theory
- $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ branching ratio not known: range in prediction bands (0.83-4.2%) is the envelope of theoretical predictions

Phys. Rev. D40 (1989) 2955,
Phys. Rev. D43 (1991) 2939,
Phys. Rev. D53 (1996) 1457

- PYTHIA8 with enhanced colour reconnection closer to data





$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ /D^0 ($1 < p_T < 8$ GeV/c) = 7.0 +-1.5 (stat.) +- 2.6 (syst.) x 10^{-3}

Summary and perspectives

- First measurement by ALICE of charmed-baryon production in pp collisions intriguing;
  - Charmed-baryon production in pp collisions higher than expectations from e^+e^- collisions
  - V*iolation of fragmentation universality?*
- Run 2 data beginning to aid in answering some open questions

Larger pp datasets collected at 5 TeV, 13 TeV
Larger p-Pb dataset collected at 5 TeV

Summary and perspectives

- First measurement by ALICE of charmed-baryon production in pp collisions intriguing;
  - Charmed-baryon production in pp collisions higher than expectations from e^+e^- collisions
  - V*iolation of fragmentation universality?*
- Run 2 data beginning to aid in answering some open questions

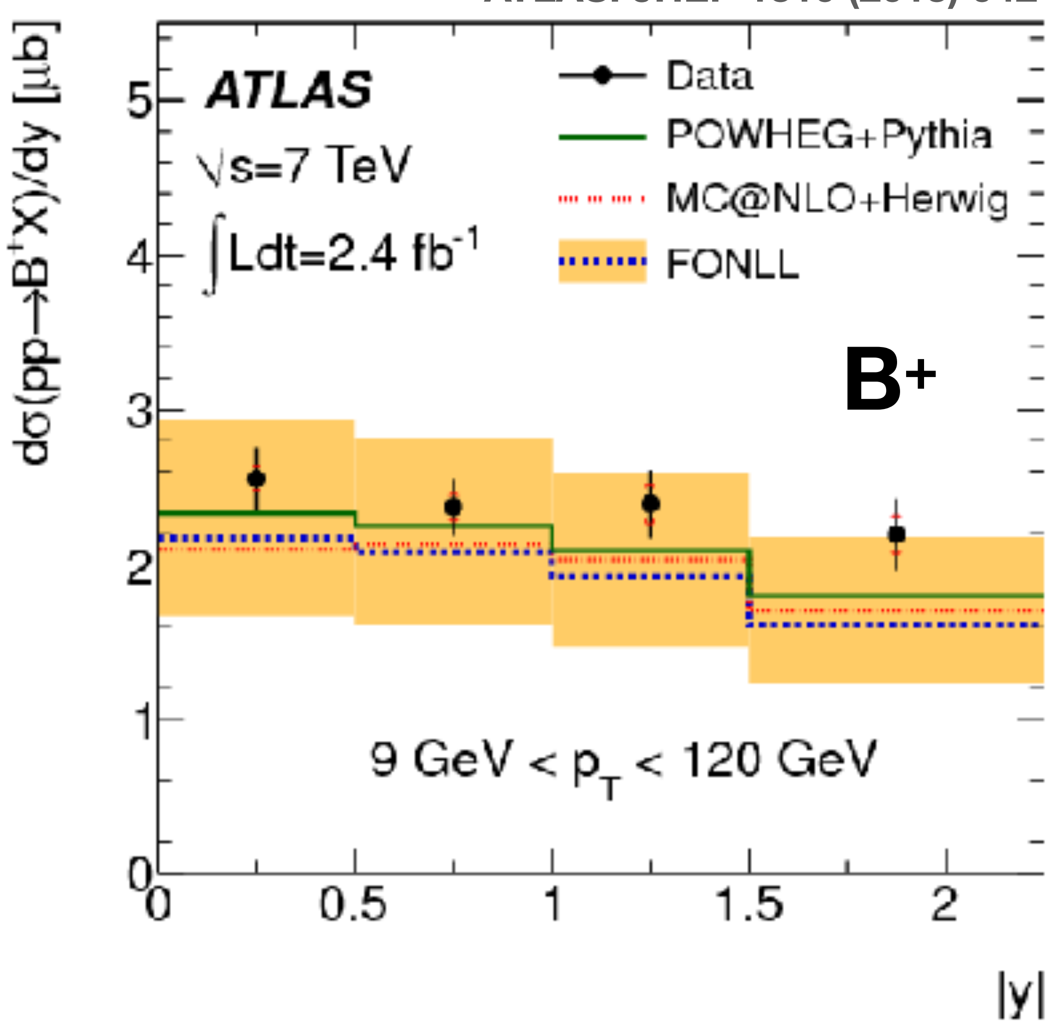
Larger pp datasets collected at 5 TeV, 13 TeV
Larger p-Pb dataset collected at 5 TeV

- ***p_T*-dependent baryon production?**
  - Fragmentation/coherence effects manifest themselves in different baryon-to-meson p_T shapes
  - Kinematic range covered by different measurements not exactly the same - important to extend measurement to p_T=0
- **Multiplicity-dependent baryon production?**
  - Baryon production could be modified at higher/lower multiplicities
- **Energy-dependent baryon production?**
  - Continuity from e^+e^- energies → LHC energies?

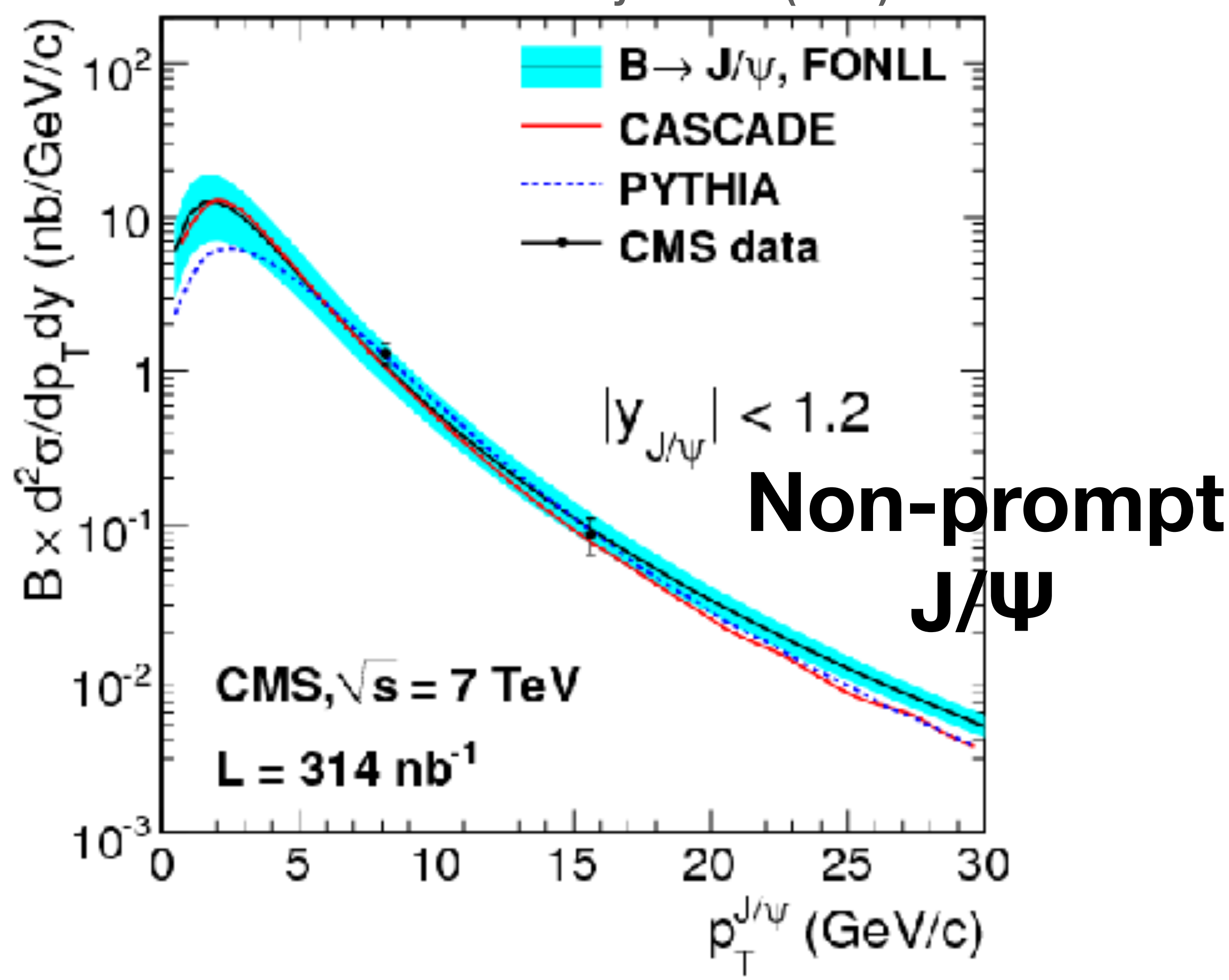
Backup

pp: Beauty production at the LHC

ATLAS: JHEP 1310 (2013) 042



CMS: Eur.Phys.J. C71 (2011) 1575



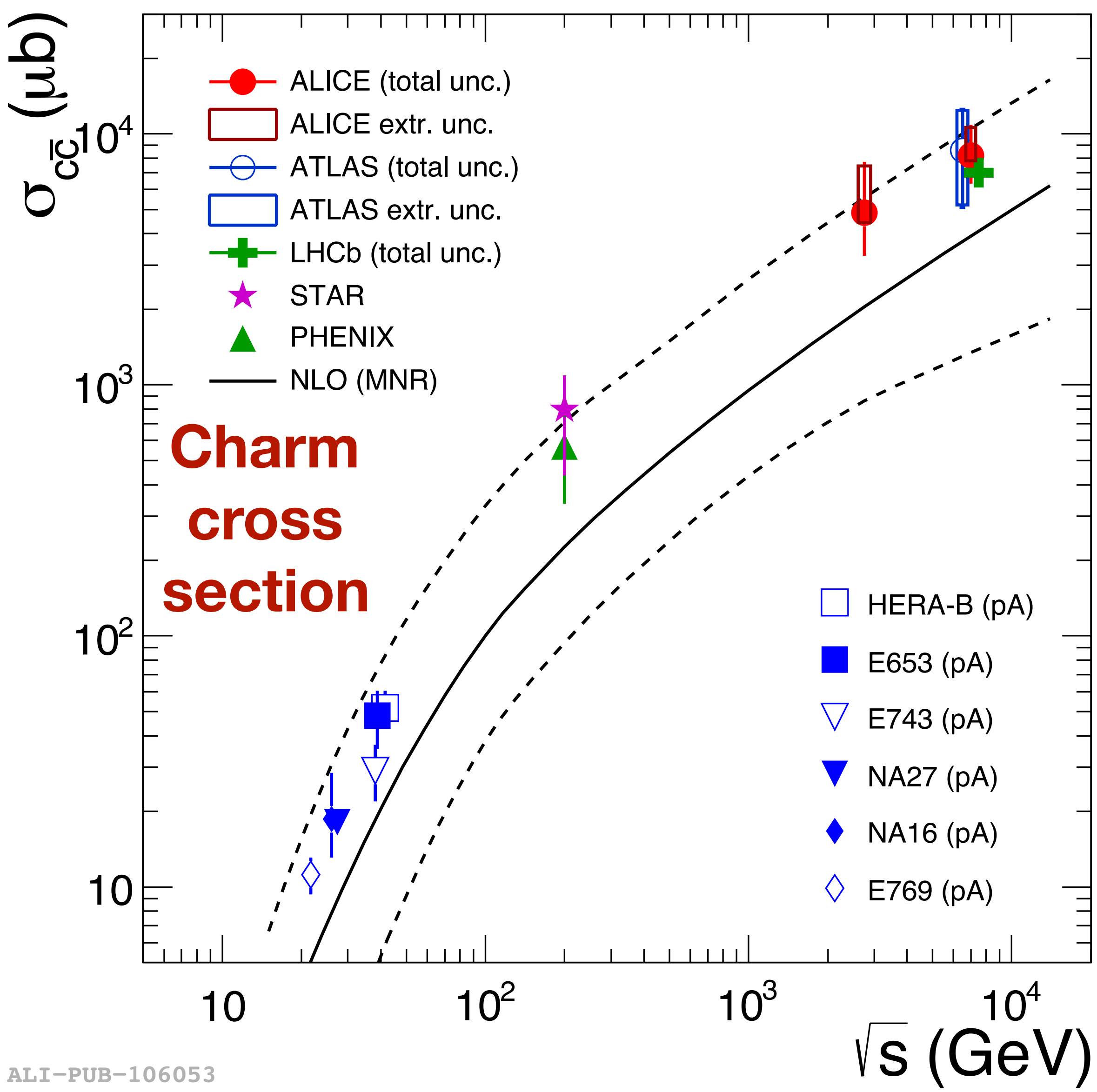
- Cross sections of B mesons at the LHC **in agreement with pQCD predictions**
  - FONLL, GM-VFNS: Next-to-leading order with next-to-leading-log resummation
  - POWHEG, MC@NLO: MC generators with next-to-leading order accuracy, with leading-log Parton shower
- **Similar agreement** of charm and beauty meson production with theory at **Tevatron**

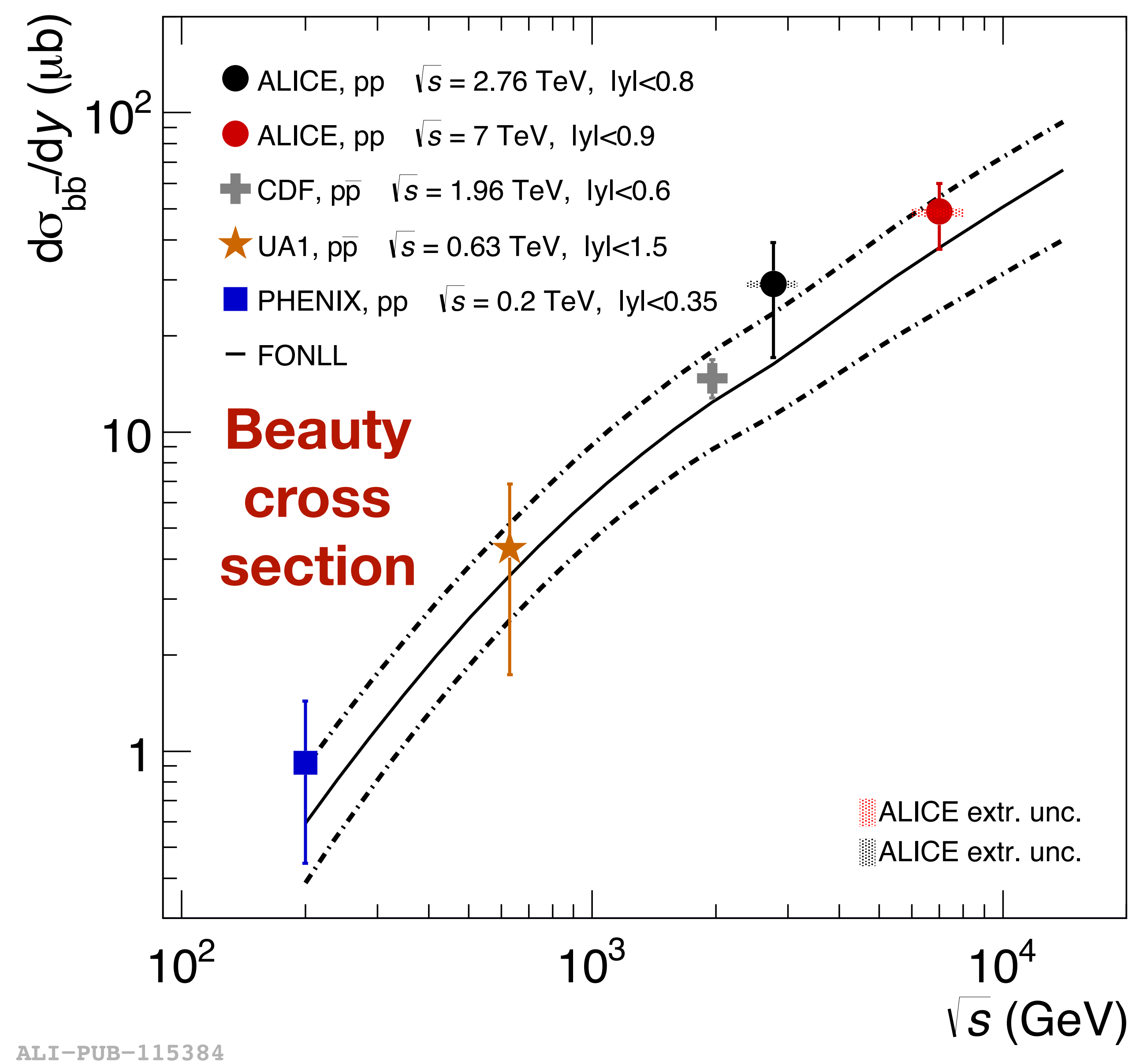
FONLL: M. Cacciari et al. JHEP 05 (1998), JHEP 10 (2012)
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082

POWHEG: S. Frixione et al. JHEP 09 (2007) 126
MC@NLO: JHEP 08 (2003) 007

pp: total charm and beauty cross section

ALICE: Phys. Rev. C 94 (2016) 054908
ALICE: Phys. Lett. B 763, (2016) 507-509

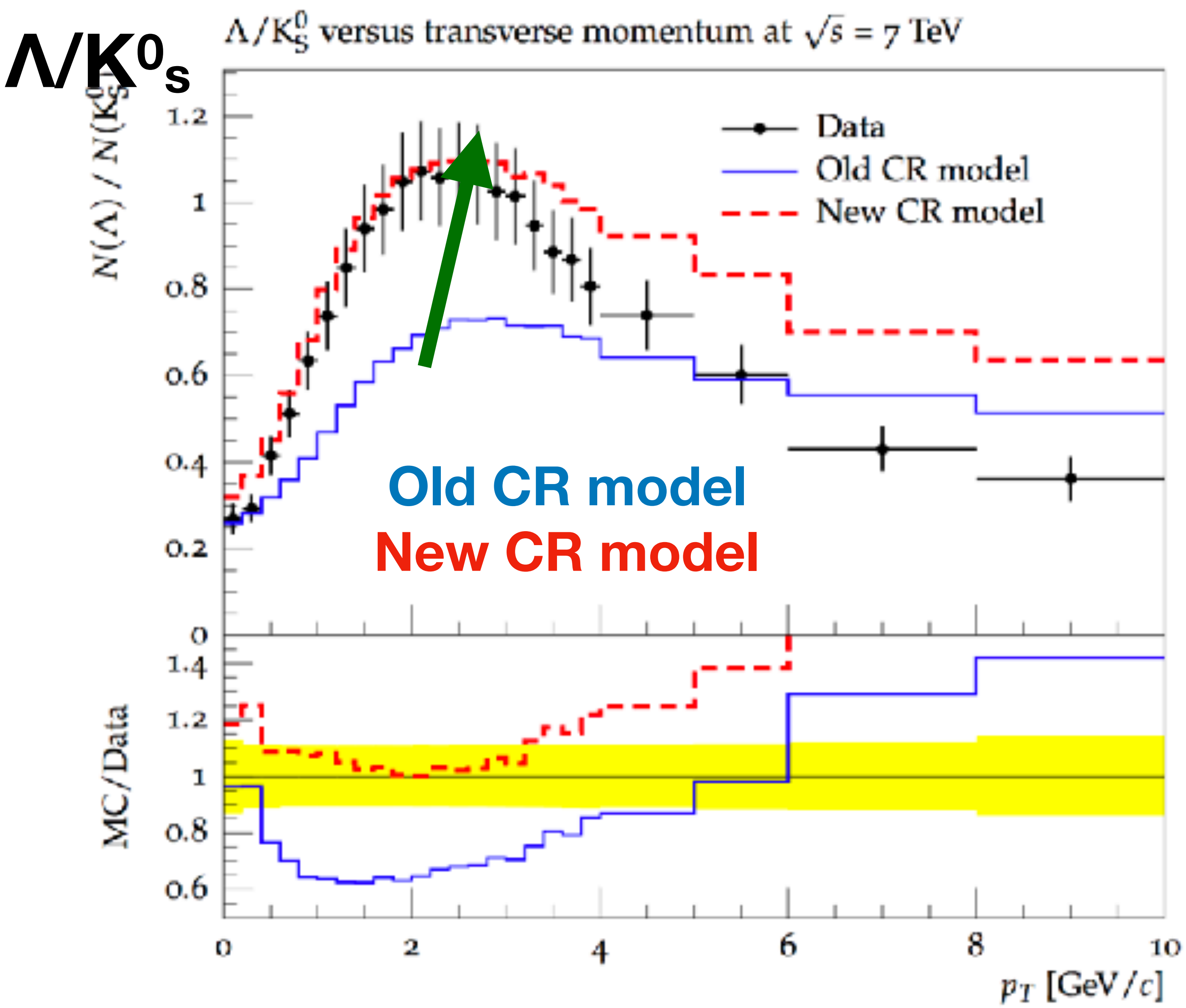




- Total charm and beauty cross section described well by predictions at NLO

pp: Charm quark fragmentation

Can hadronisation be modified?



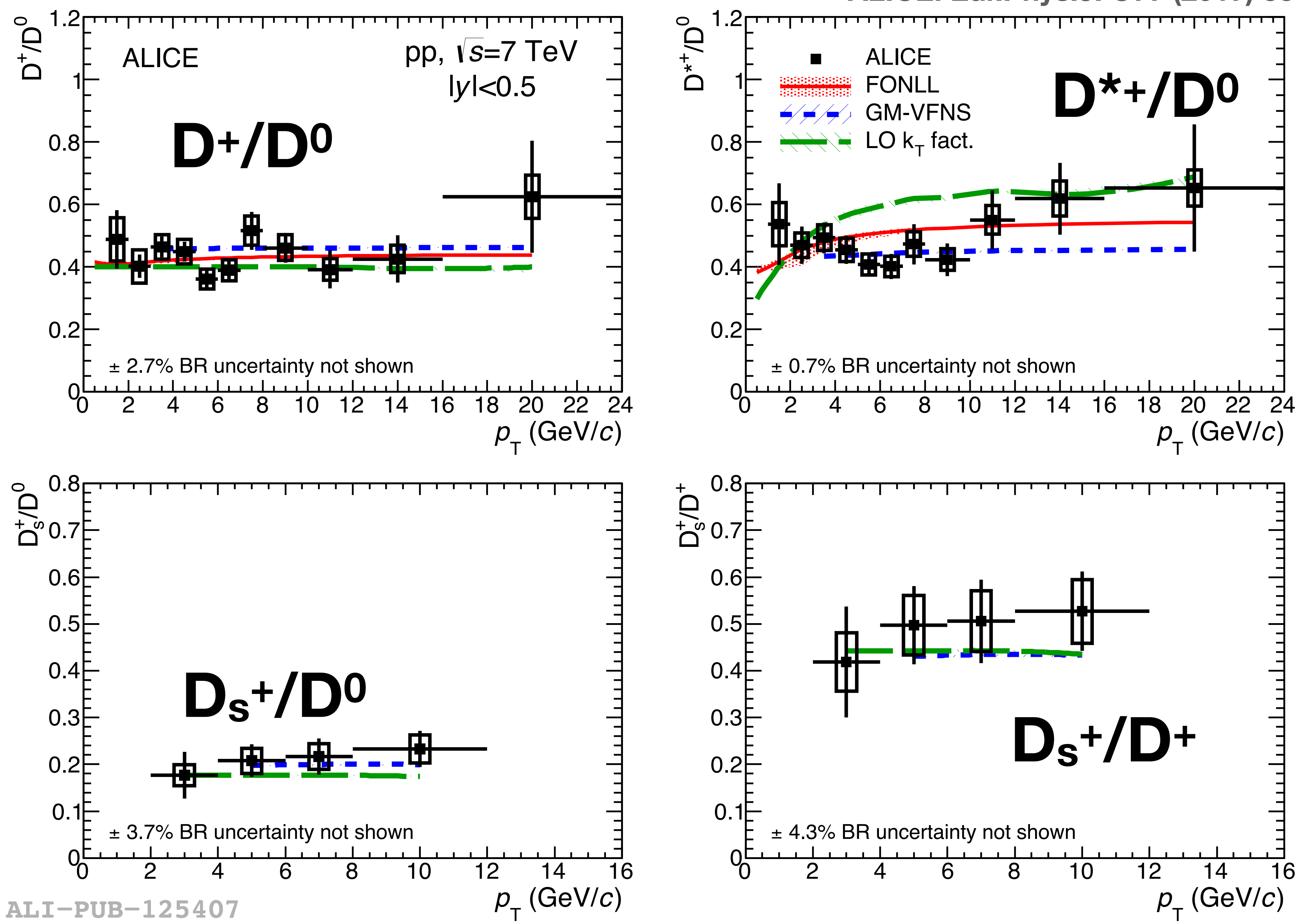
- **Multi-parton interactions**, coherence effects at LHC energies may affect hadronisation
- e.g. within PYTHIA, **enhanced colour reconnection** modes gives better agreement with measured Λ/K^0_s ratio
  - String formation beyond the leading-colour approximation, specific tuning of the colour reconnection 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

C. Bierlich, J.R. Christiansen, Phys. Rev. D 92 (2015) 094010
J.R. Christiansen, P.Z. Skands JHEP 08 (2015) 003

pp: D meson ratios

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



- Production ratios of D mesons **compatible with theoretical predictions** (in which charm fragmentation is based mainly on measurements in e^+e^- collisions)
- **Include Λ_c^+: Very few charmed baryon production measurements in hadron colliders**

LHCb: Nuclear Physics, Section B 871 (2013), pp. 1-20
LHCb-CONF-2017-005

pp($p\bar{p}$): Beauty baryon fragmentation

Indications that the fraction of b-baryons depends on the collision system

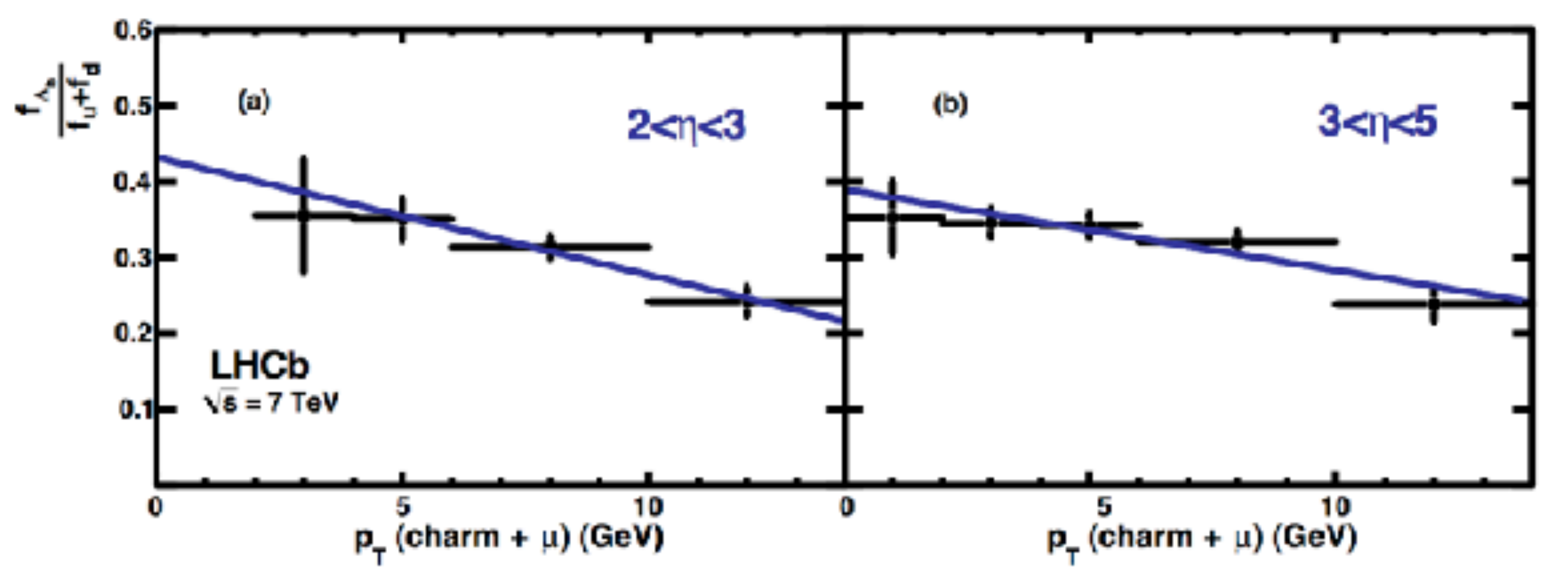
1. b-baryon fragmentation in $p\bar{p}$ collisions **over 2x that in e^+e^-** at Z resonance (though uncertainties large)

2. ***p_T* dependence** for $f_{\Lambda b}$ / (f_u + f_d) [3] ($f_q \equiv B(b \rightarrow B_q)$) at the LHC
   - Similar observation at the Tevatron in $p\bar{p}$ collisions

CDF: Phys.Rev.D77:072003,2008

Table 1: Fragmentation fractions of b quarks into weakly-decaying b-hadron species in $Z \to b\bar{b}$ decay, in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

b hadron	Fraction at Z [%]	Fraction at $\bar{p}p$[%]
B^+, B^0	40.4 ± 0.9	33.9 ± 3.9
B_s	10.3 ± 0.9	11.1 ± 1.4
b baryons	8.9 ± 1.5	21.2 ± 6.9



http://pdg.lbl.gov/2015/reviews/rpp2015-rev-b-meson-prod-decay.pdf

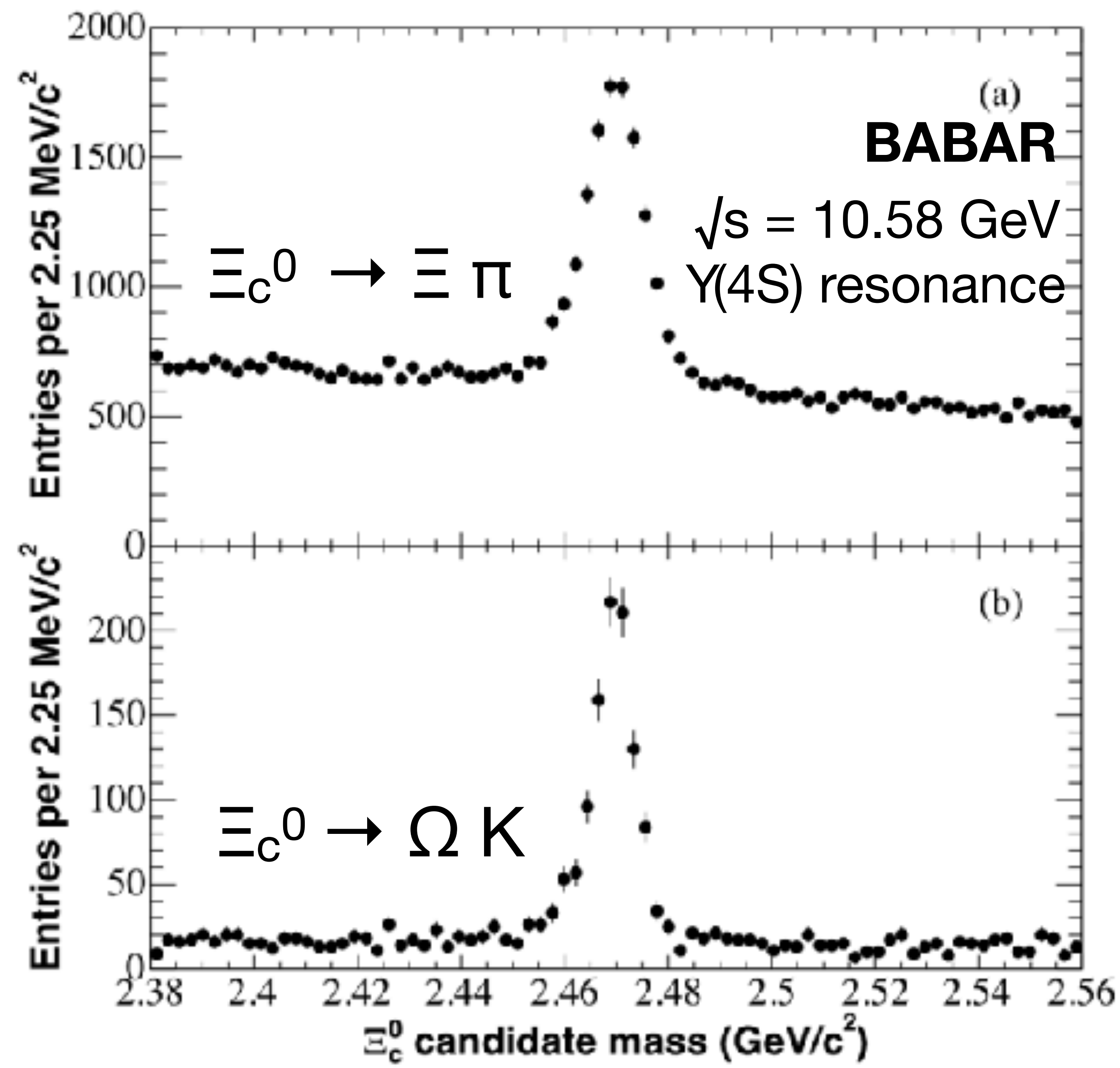
LHCb: Phys. Rev. D85 , 032008 (2012)

pp: Ξ_c^0 production

- Exotic charmed baryons in the news recently (Ξ_{cc}^{++}, Ω_c^0 resonances)

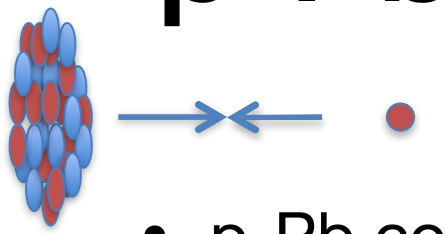
  LHCb: LHCb-PAPER-2017-018
  LHCb: Phys. Rev. Lett. 118, 182001 (2017)

- Charm hadron *production* measurements in hadron collisions limited to low-mass mesons and baryons
  - Only Ξ_c^0 production measurements in e^+e^- collisions
- New measurements of charmed baryons could provide further insight into hadronisation mechanisms



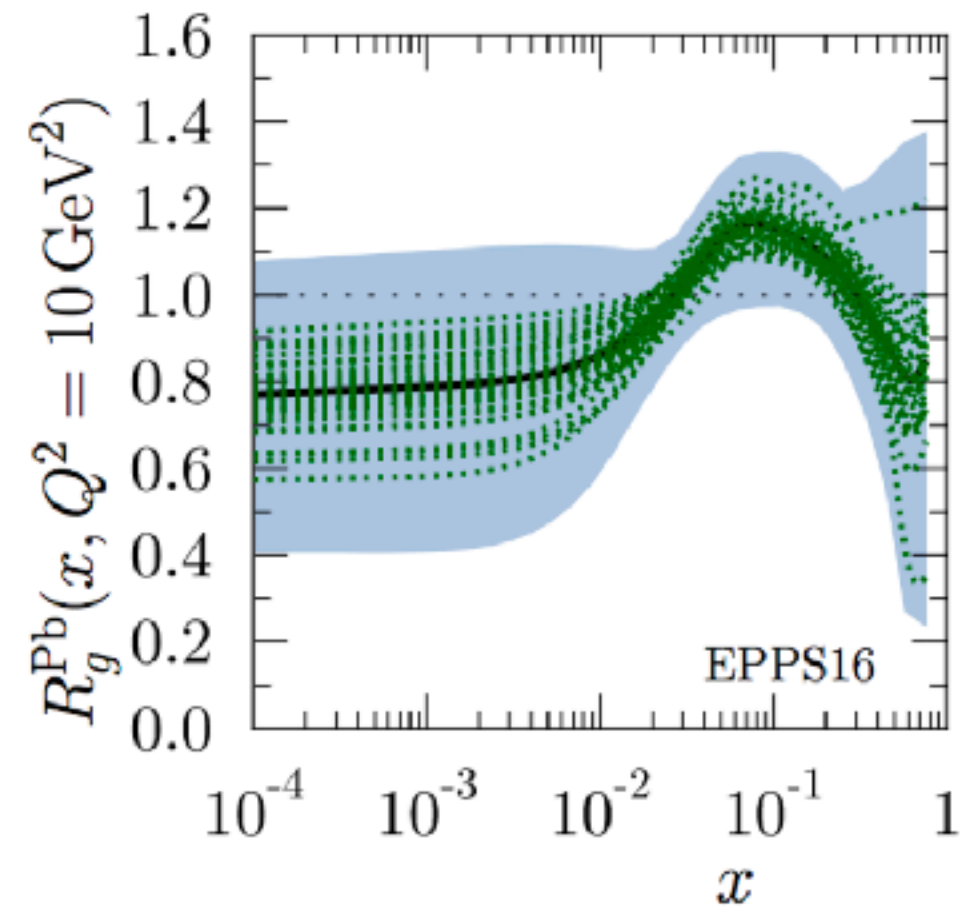
ARGUS: Phys. Lett. B247 (1990) 121
ARGUS: Phys. Lett. B303 (1993) 368.
CLEO: Phys. Rev. Lett. 74 (1995) 3113.
ARGUS: Phys. Lett. B342 (1995) 397. 12
BABAR: Phys. Rev. Lett. 95 (2005) 142003

p-Pb: Heavy-flavour production



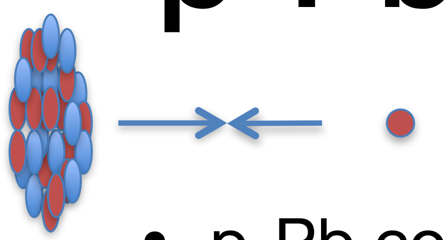
- p-Pb collisions traditionally used to **separate** '*hot*' effects in Pb-Pb collisions (effects due to hot dense deconfined matter) from '*cold nuclear matter*' effects (effects due to the presence of a nuclei)
    - **Initial state effects:** modification of nuclear parton distribution
    - **Final-state effects:** (energy loss? Collectivity?)

K. J. Eskola: Eur.Phys.J. C77 (2017) no.3, 163



$$f_i^N(x_i, Q^2) = R_i^N(x_i, Q^2) f_i(x_i, Q^2)$$

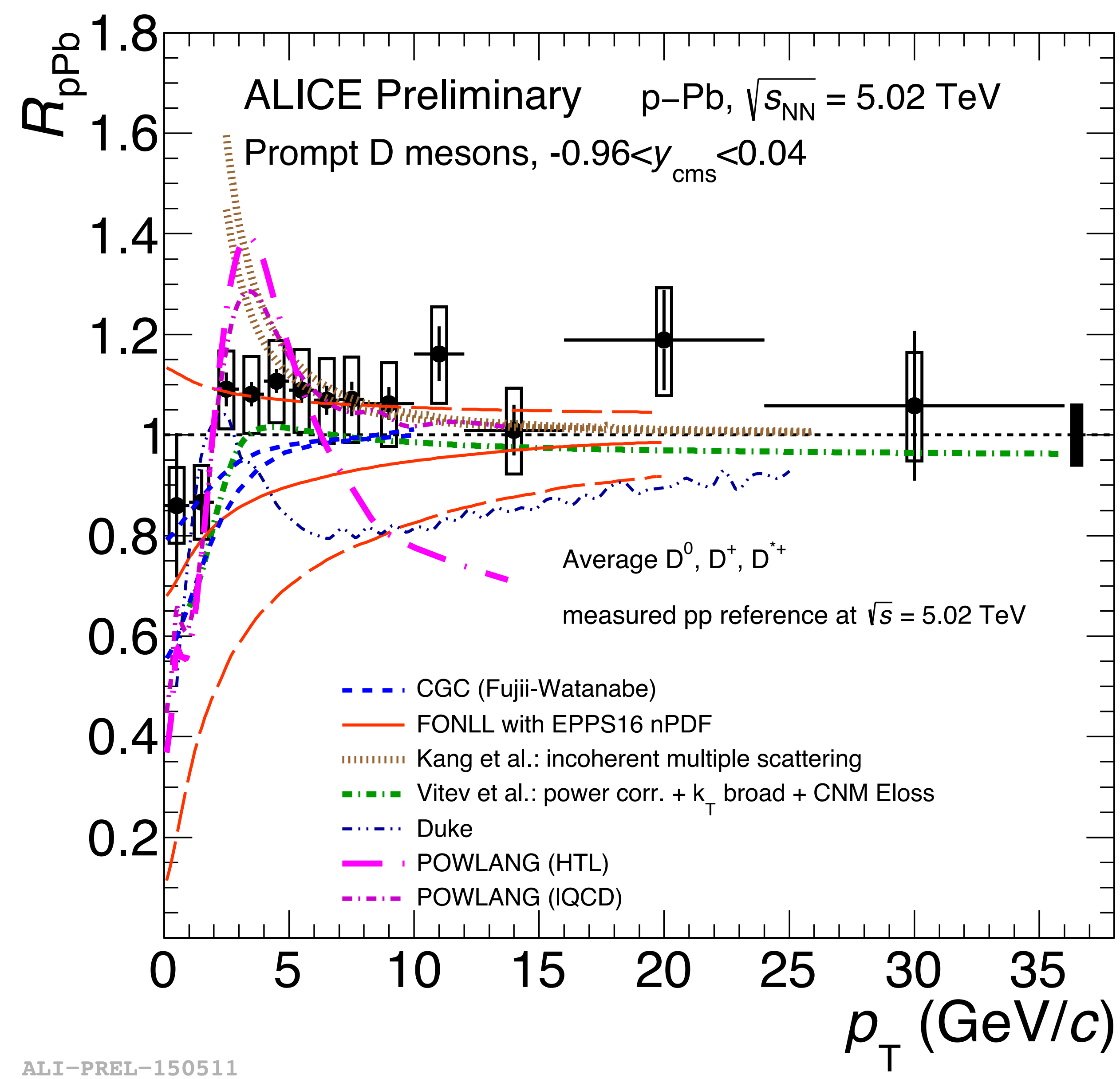
p-Pb: Heavy-flavour production



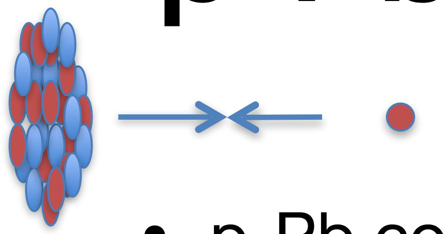
- p-Pb collisions traditionally used to **separate** ‘*hot*’ effects in Pb-Pb collisions (effects due to hot dense deconfined matter) from ‘*cold nuclear matter*’ effects (effects due to the presence of a nuclei)
  - **Initial state effects:** modification of nuclear parton distribution
  - **Final-state effects:** (energy loss? Collectivity?)
- D-meson nuclear modification factor R_{pPb} indicates **minimal modification** to p_{T} spectrum w.r.t pp collisions

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

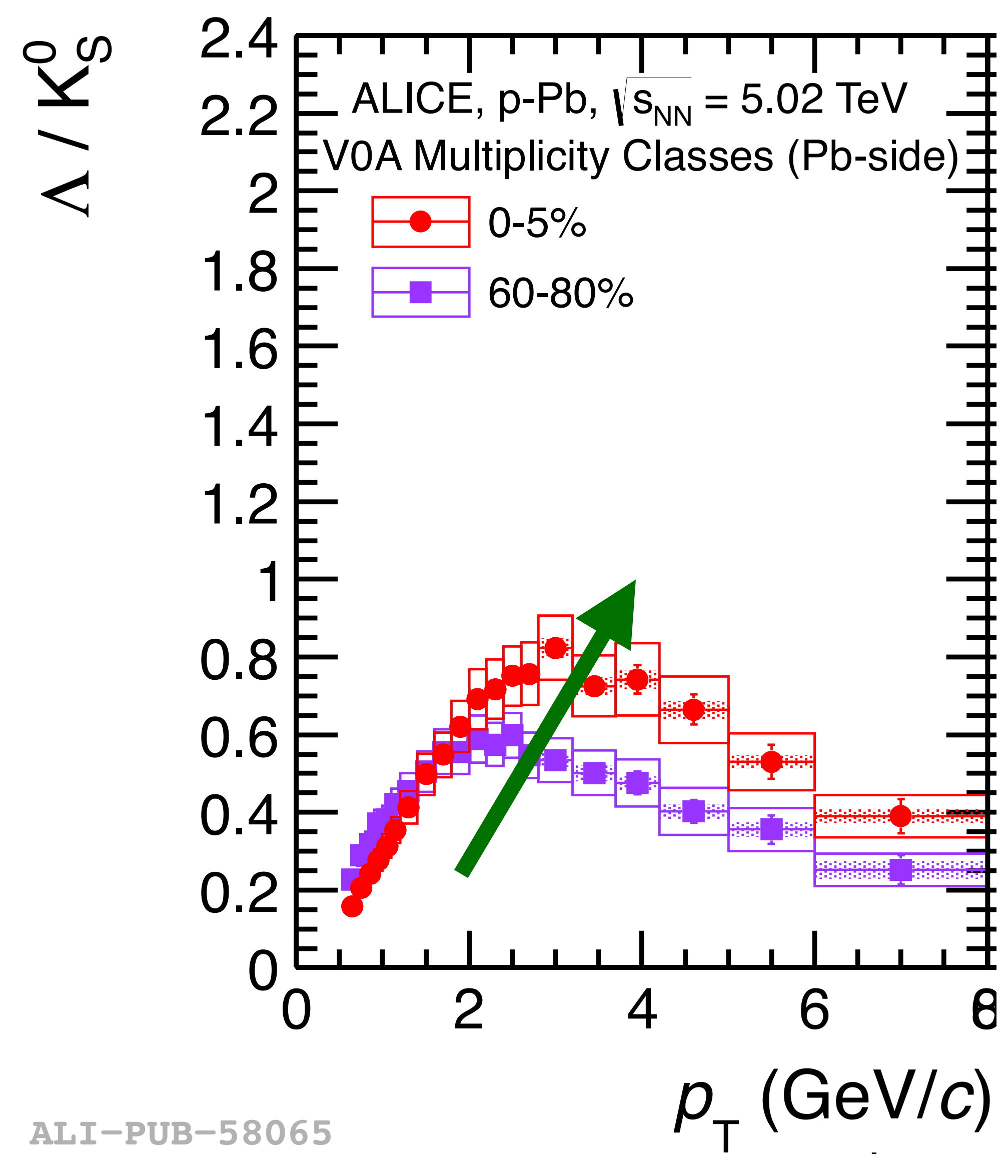
R_{pPb} < 1 = suppression
R_{pPb} > 1 = enhancement



p-Pb: Heavy-flavour production

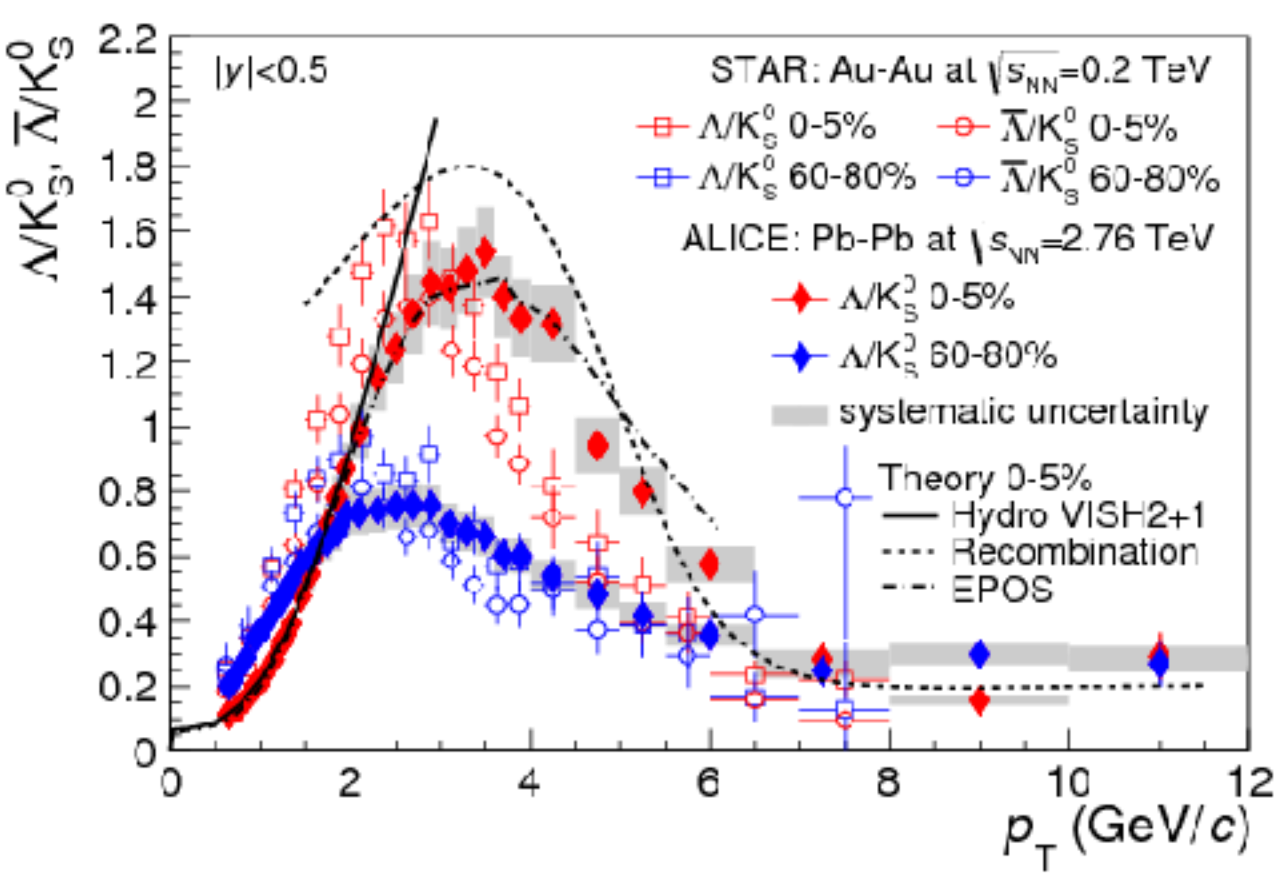


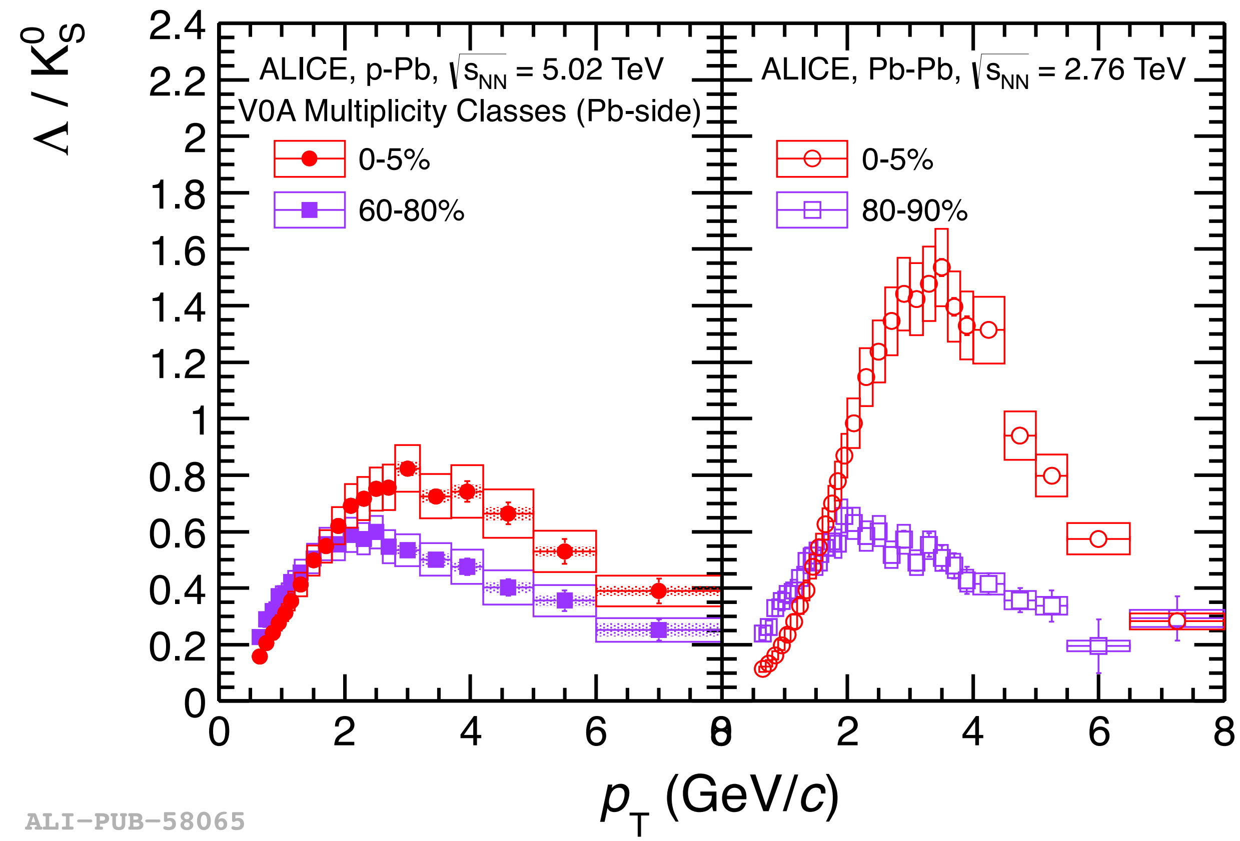
- p-Pb collisions traditionally used to **separate** '*hot*' effects in Pb-Pb collisions (effects due to hot dense deconfined matter) from '*cold nuclear matter*' effects (effects due to the presence of a nuclei)
    - **Initial state effects:** modification of nuclear parton distribution
    - **Final-state effects:** (energy loss? Collectivity?)
- D-meson nuclear modification factor R_{pPb} indicates **minimal modification** to p_T spectrum w.r.t pp collisions
- **Modification to charmed baryon production in p-Pb collisions?**
    - (strange) Λ/K ratio increases towards higher multiplicity



Strange baryon-to-meson ratio

- Enhancement in the baryon-to-meson ratio is also expected if coalescence has a role to play in hadronisation
  - Proton/pion and Λ/K^0_S ratios **enhanced in Pb-Pb collisions**
  - A similar enhancement is seen in high multiplicity p-Pb collisions



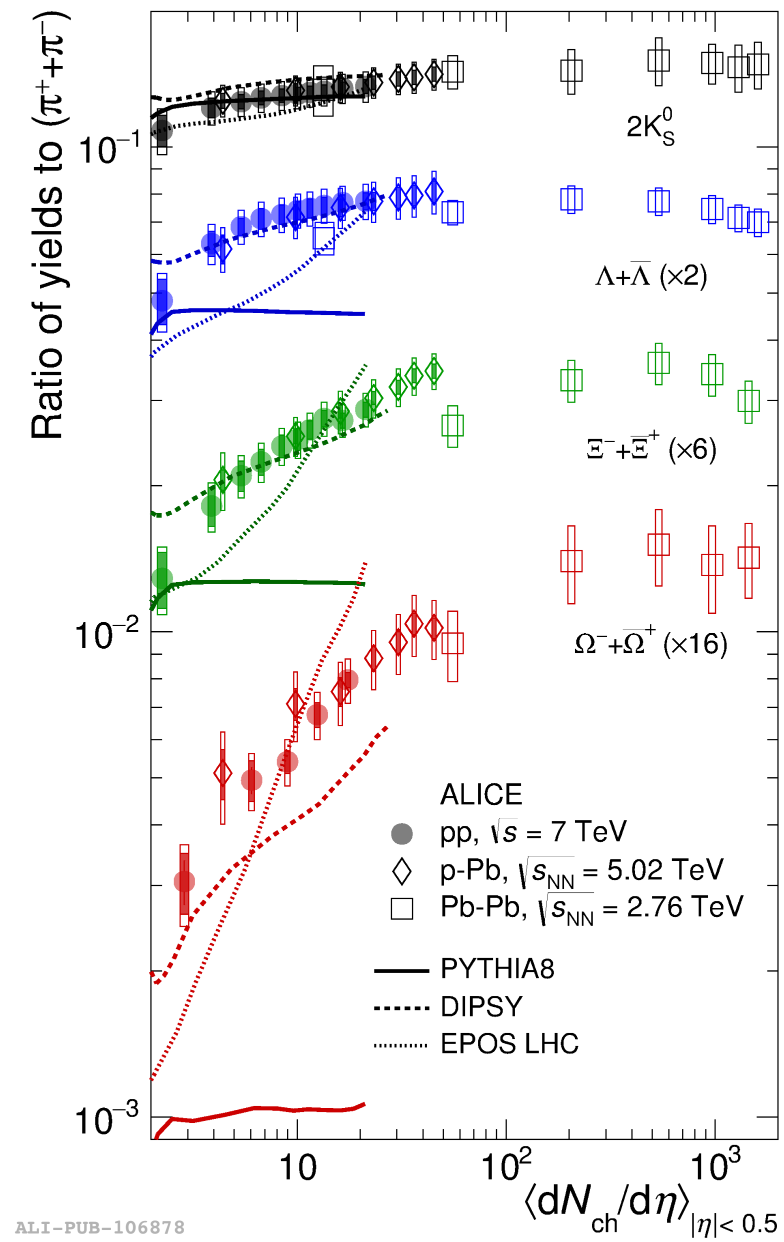


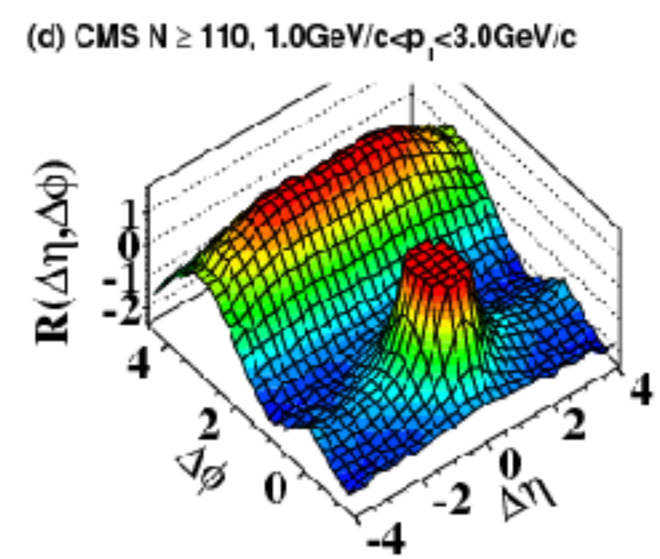
Coalescence? flow? Interplay between both effects?

pp and p-Pb collisions

- Many of these studies fit into the broader scope of understanding many 'Pb-Pb-like' phenomena emerging in high multiplicity pp/p-Pb collisions:
  - Di-hadron azimuthal correlations to large Δη
    CMS: JHEP 09 (2010) 091
    ALICE: Phys. Lett. B 719 (2013) 29
    ALICE: Phys. Lett. B 726 (2013) 164
    ATLAS: Phys. Rev. Lett. 110 (2013) 182302
  - Mass-dependent azimuthal anisotropy
    ALICE: Phys. Lett. B 726 (2013) 164-177
    CMS: Phys. Lett. B 765 (2017) 193
  - Evolution of average p_T vs. multiplicity
    ALICE: Phys. Lett. B 728 (2014) 25
    CMS: Eur. Phys. J. C 74 (2014) 2847
  - Strangeness enhancement…
    ALICE: Nature Physics 13, 535–539 (2017)

What is the origin of the continuity of phenomena seen from small to large systems?

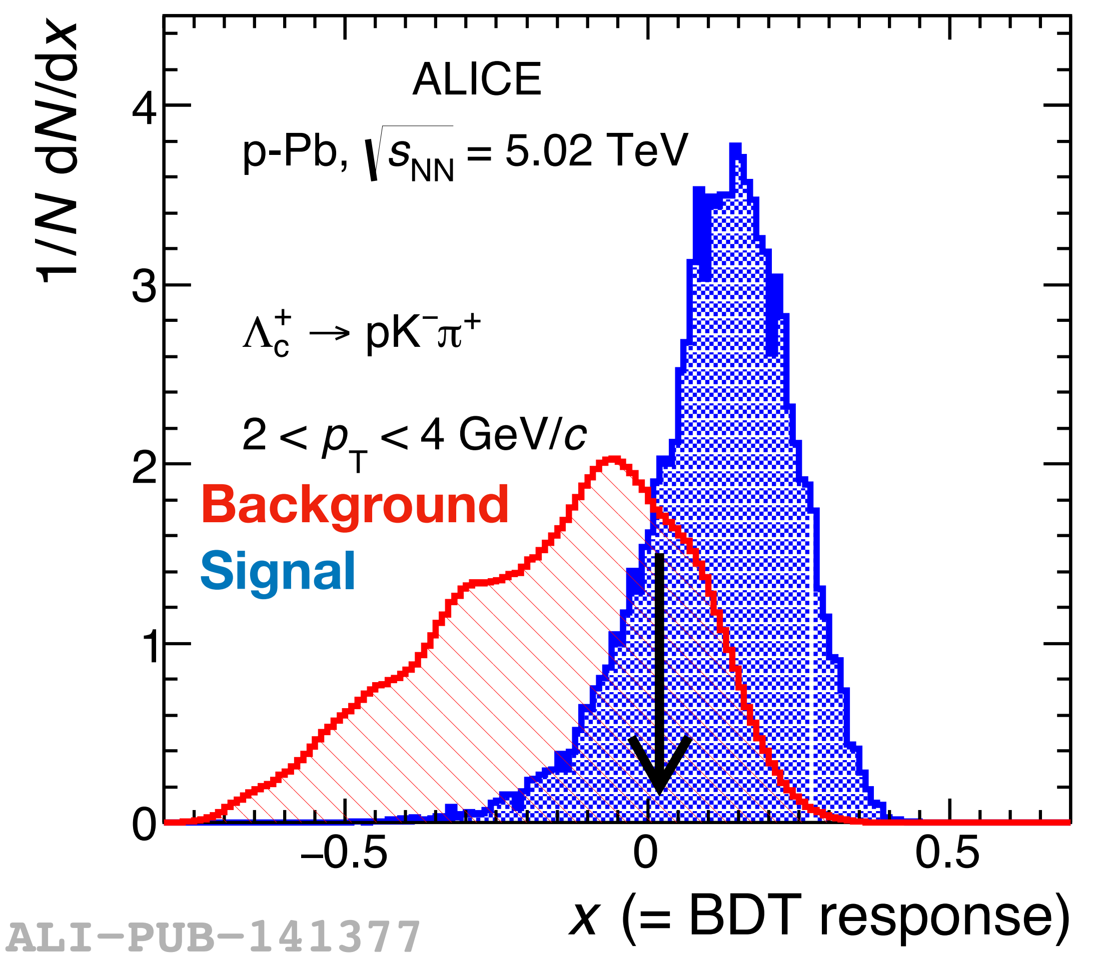




Charmed baryon BDT analysis

Hadronic decays

- BDT analysis performed for the $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^0_S$ in p-Pb collisions
- BDT trained on **simulated signal sample**, and **background sample from simulation or data**
  - Input variables include p_T of decay products, topological properties of decay, and PID variables
- Final result merged with std. analysis taking into account correlation between analyses



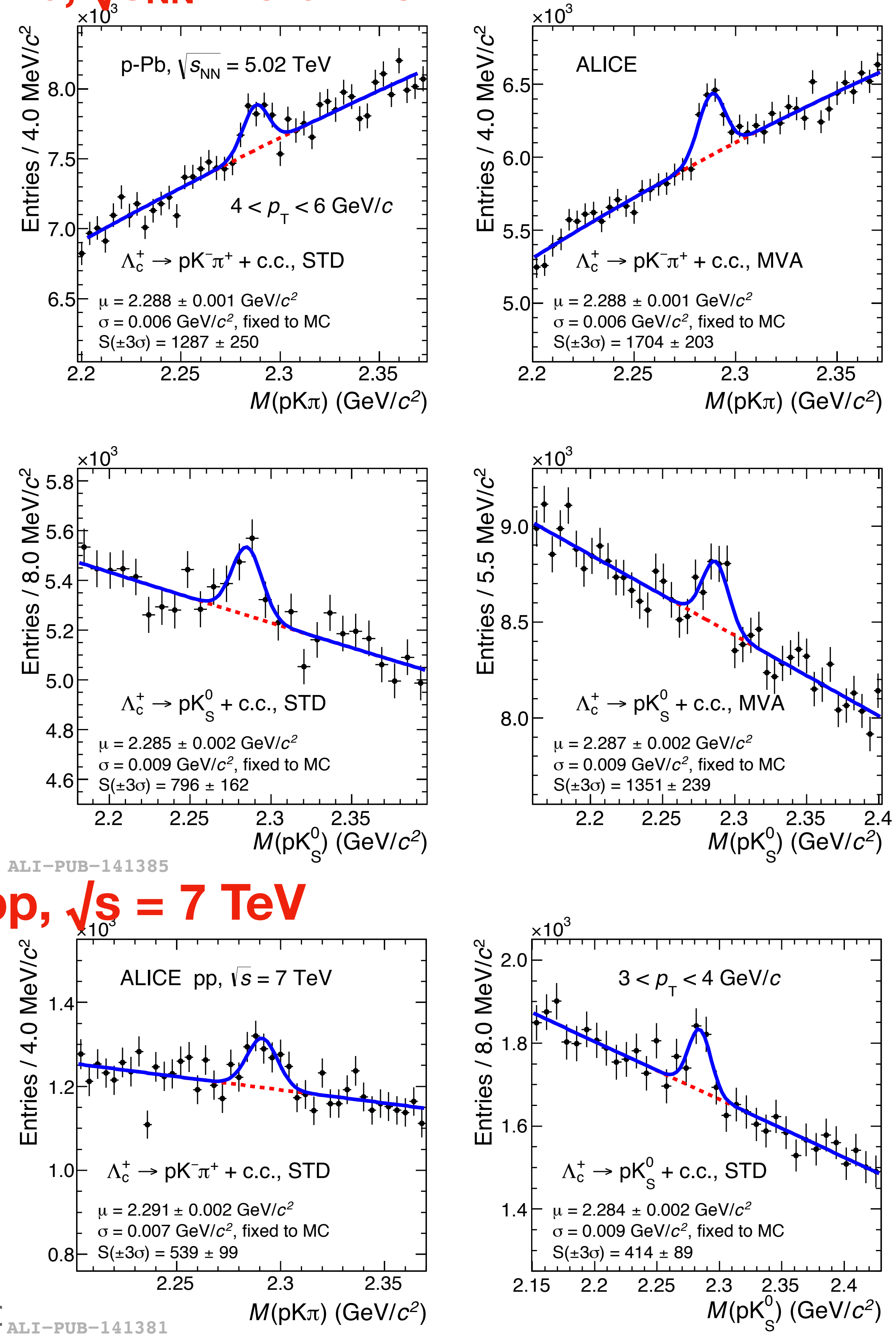
Analysis allows for slightly better statistical precision + gain in signal efficiency

TMVA: PoS(ACAT)040

Charmed baryon signal extraction

Hadronic decays

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



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

- Signal extracted from 2 < p_T < 12 GeV/c in p-Pb collisions
- Signal extracted from 2 < p_T < 8 GeV/c in pp collisions

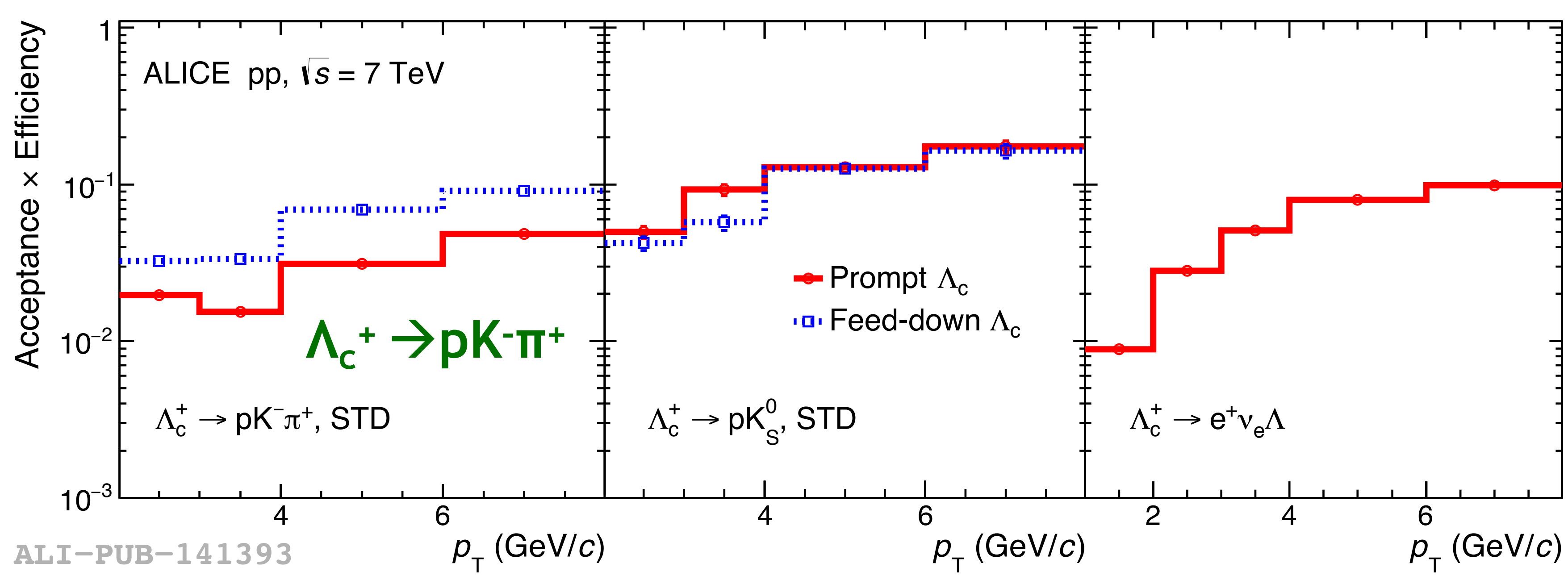
p_T-differential cross section measurement (Λ_C^+)

Correction factor for feed-down - fraction from beauty decays
using pQCD-based estimation of beauty baryon production
< 8% correction

Extracted raw yield in the fiducial acceptance

$$\frac{d^2\sigma^{\Lambda_c^+}}{dp_T dy} = \frac{1}{2c_{\Delta y}\Delta p_T} \frac{1}{BR} \frac{f_{prompt} \cdot N^{\Lambda_c}_{|y|<y_{fid}}}{(A \times \varepsilon)_{prompt}} \frac{1}{\mathcal{L}_{int}}$$

Efficiency x acceptance for prompt Λ_C^+

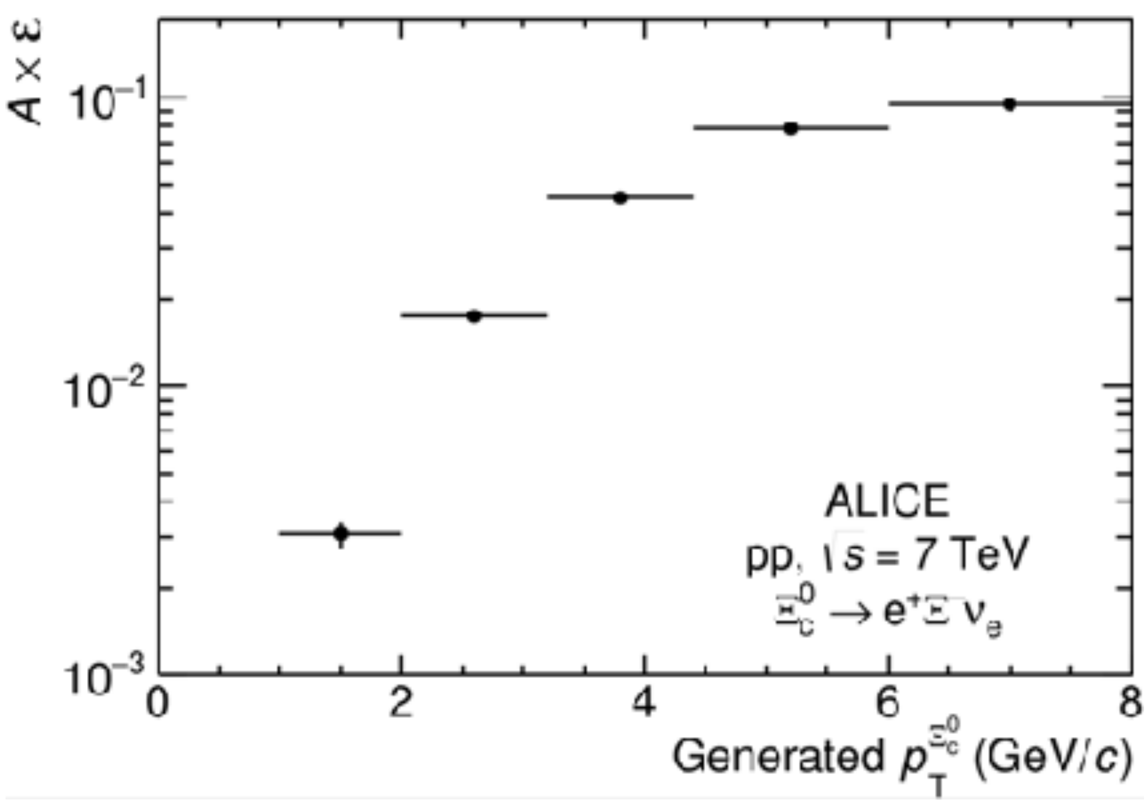


p_T-differential cross section measurement (Ξ_C^0)

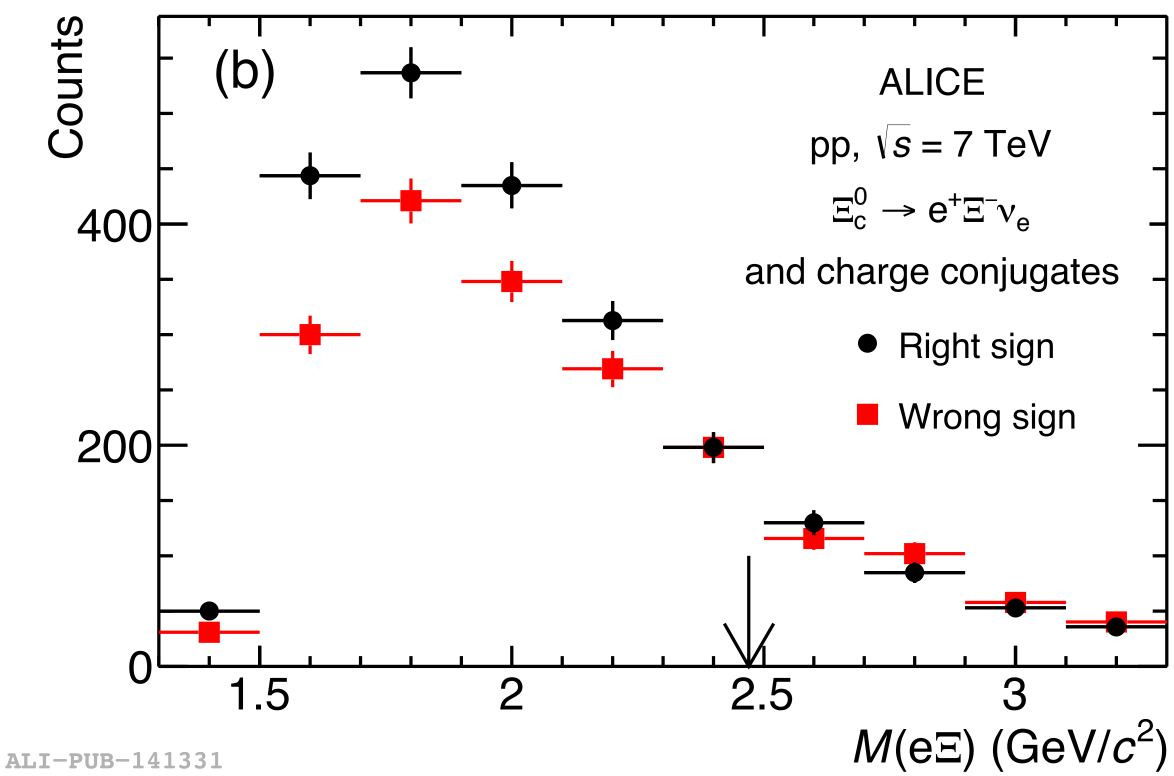
Extracted raw yield in the fiducial acceptance

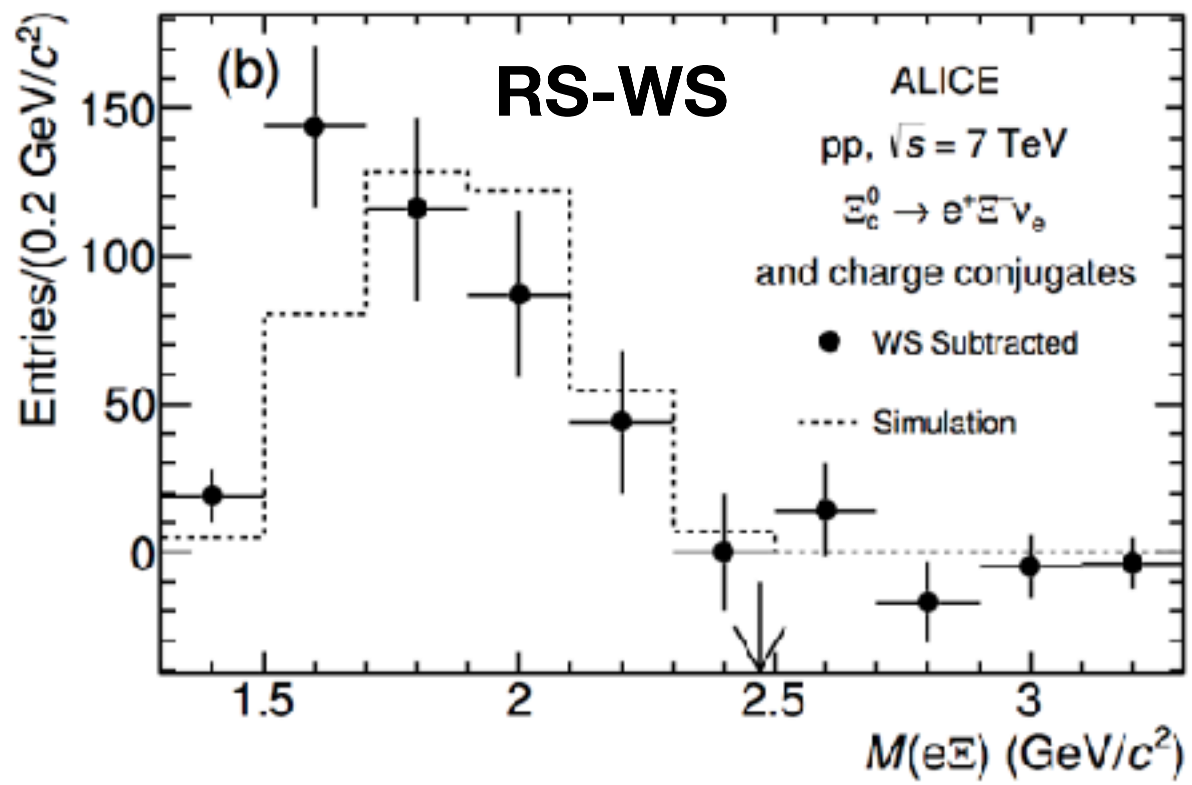
$$\mathrm{BR} \cdot \frac{\mathrm{d}^2\sigma^{\Xi_c^0}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} = \frac{N_{\Xi_c^0}}{2 \cdot \Delta p_\mathrm{T} \Delta y \cdot (A \times \varepsilon) \cdot L_\mathrm{int} \cdot \mathrm{BR}_{\Xi^-}}$$

Efficiency x acceptance for Ξ_C^0



Semileptonic RS-WS subtraction





- Wrong-sign subtracted eΞ spectrum shape in agreement with expectation from simulation

Charmed baryon corrections

Semileptonic decays

- Correct for:
  - **$\Lambda_b^0 \rightarrow e^- \Lambda_c^+ \bar{\nu}_e \rightarrow e^- \Lambda X$ ($\Xi_b^0 \rightarrow e^- \Xi^- \nu_e X$) contribution** in wrong-sign spectra:
    - Λ_b^0 contribution from Λ_b^0 measurement by CMS* - **up to 10% correction**
    - **Ξ_b^0 production not measured -** contribution estimated from BR($b \rightarrow \Xi_b$)· BR($\Xi_b \rightarrow \Xi^- l^- \nu X$) and BR($b \rightarrow \Lambda_b^0$)·BR($\Lambda_b^0 \rightarrow \Lambda l^- \nu X$) measurements in e^+e^- collisions* - **Up to 2% correction**
  - **$\Xi_c^{0,+} \rightarrow e^+ \Xi^{-,0} \nu \rightarrow e^+ \Lambda \pi^{-,0} \nu$ contribution** in right-sign spectra for Λ_c^+ measurement (2 methods):
    1. Determined from measured Ξ_c^0 cross section and measured BR($\Xi_c^+ \rightarrow e^+ \Xi^0 \nu_e$)/BR($\Xi_c^0 \rightarrow e^+ \Xi^- \nu_e$) ratio
    2. $c\tau(\Lambda_c^+ \rightarrow \Lambda + X) < c\tau(\Xi_c \rightarrow \Xi + X \rightarrow \Lambda + X)$ - MC fit to Λ distance from primary vertex

    → **$\Xi_c^{0,-}$ feed-down fraction = 0.46 ± 0.06**
- **Unfold** $e^+\Lambda(e^+\Xi^-)$ p_T spectra to obtain Λ_c^+ (Ξc0) spectra
- **B feed-down subtraction** using pQCD-based estimation of beauty baryon production **(Λ_c^+ only!)**
- **Efficiency, acceptance** corrections

* CMS: Phys. Lett. B714 (2012) 136–157
ALEPH: Phys. Lett. B384 (1996) 449
ALEPH: Eur. Phys. J. C2 (1998) 197
Phys. Rev. Lett. 74 (1995) 3113

Systematic uncertainties in pp collisions

Hadronic decay analyses

Systematic unc. source	$\Lambda_c^+ \rightarrow pK^-\pi^+$		$\Lambda_c^+ \rightarrow pK^0_S$	
	Low p_T (%)	High p_T (%)	Low p_T (%)	High p_T (%)
Yield extraction	11	4	7	9
Tracking efficiency	4	3	7	5
Cut efficiency	11	12	5	6
PID efficiency	4	4	5	5
MC pT shape	2	2	negl.	1.5
B feed-down	$^{+1}_{-4}$	$^{+2}_{-11}$	negl. -2	$^{+1}_{-4}$
BR	5.1		5.0	

Similar for p-Pb (backup)

Semileptonic decay analyses

Systematic unc. source	$\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$		$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$	
	Low p_T (%)	High p_T (%)	Low p_T (%)	High p_T (%)
Yield extraction	17	17	5	5
Efficiency, acceptance	28	13	30	14
Missing neutrino momentum	3	11	29	10
B feed-down	negl.	$^{+1}_{-7}$	-	
BR	11		-	

Luminosity uncertainty = 3.5%

Systematic uncertainties in p-Pb collisions

STD analysis

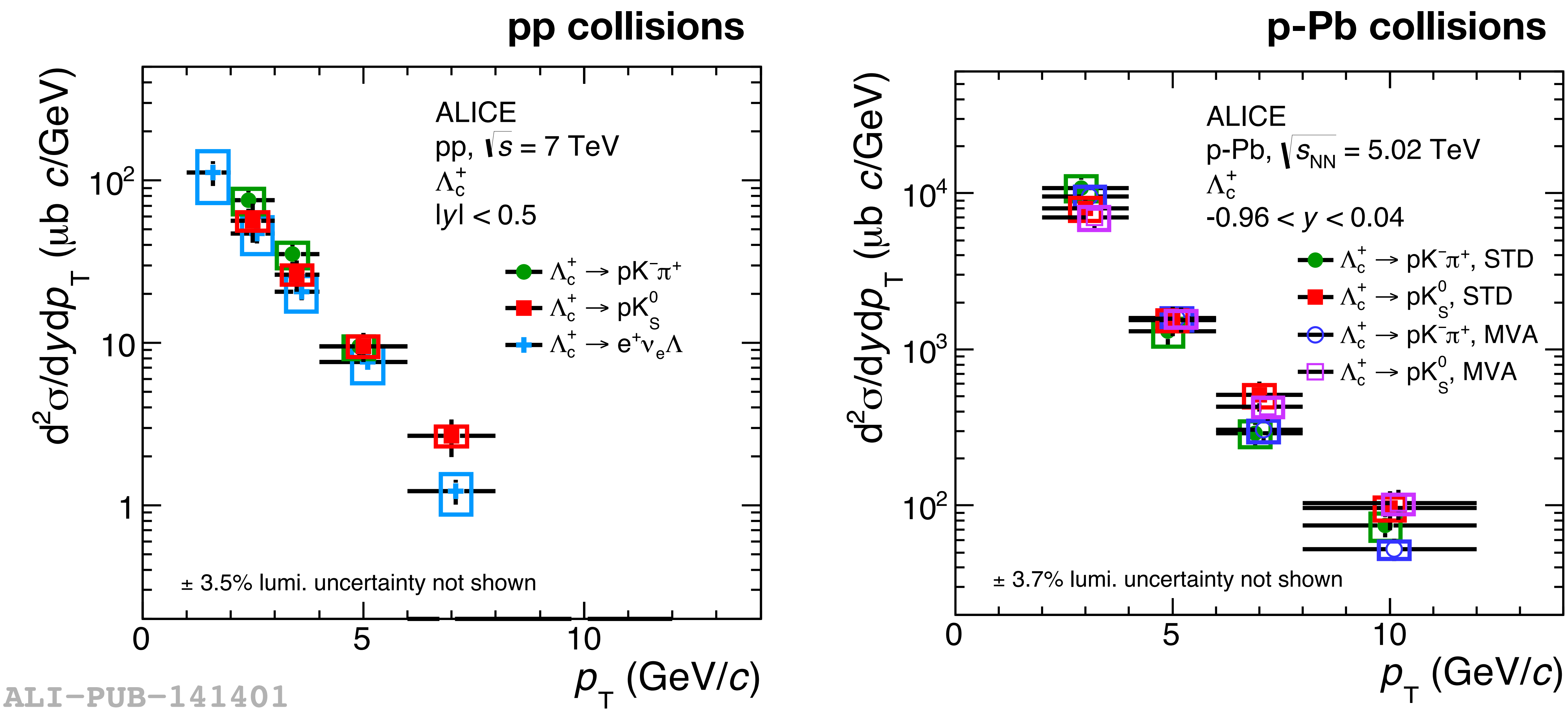
	$\Lambda_c^+ \to pK^-\pi^+$		$\Lambda_c^+ \to pK^0_S$	
Systematic unc. source	**Low p_T (%)**	**High p_T (%)**	**Low p_T (%)**	**High p_T (%)**
Yield extraction	10	11	10	10
Tracking efficiency	10	7	10	6
Cut efficiency	9	12	5	7
PID efficiency	6	6	6	6
MC pT shape	2	2	1	3
B feed-down	+1 -5	+2 -10	negl.	negl.
BR	5.1		5.0	

BDT analysis

	$\Lambda_c^+ \to pK^-\pi^+$		$\Lambda_c^+ \to pK^0_S$	
Systematic unc. source	**Low p_T (%)**	**High p_T (%)**	**Low p_T (%)**	**High p_T (%)**
Yield extraction	7	4	11	8
Tracking efficiency	10	7	10	6
Cut efficiency	8	6	5	8
PID efficiency	negl.	negl.	negl.	negl.
MC pT shape	negl.	3	negl.	negl.
B feed-down	+1 -5	+2 -10	negl. -3	+2 -7
BR	5.1		5.0	

Luminosity uncertainty = 3.7%

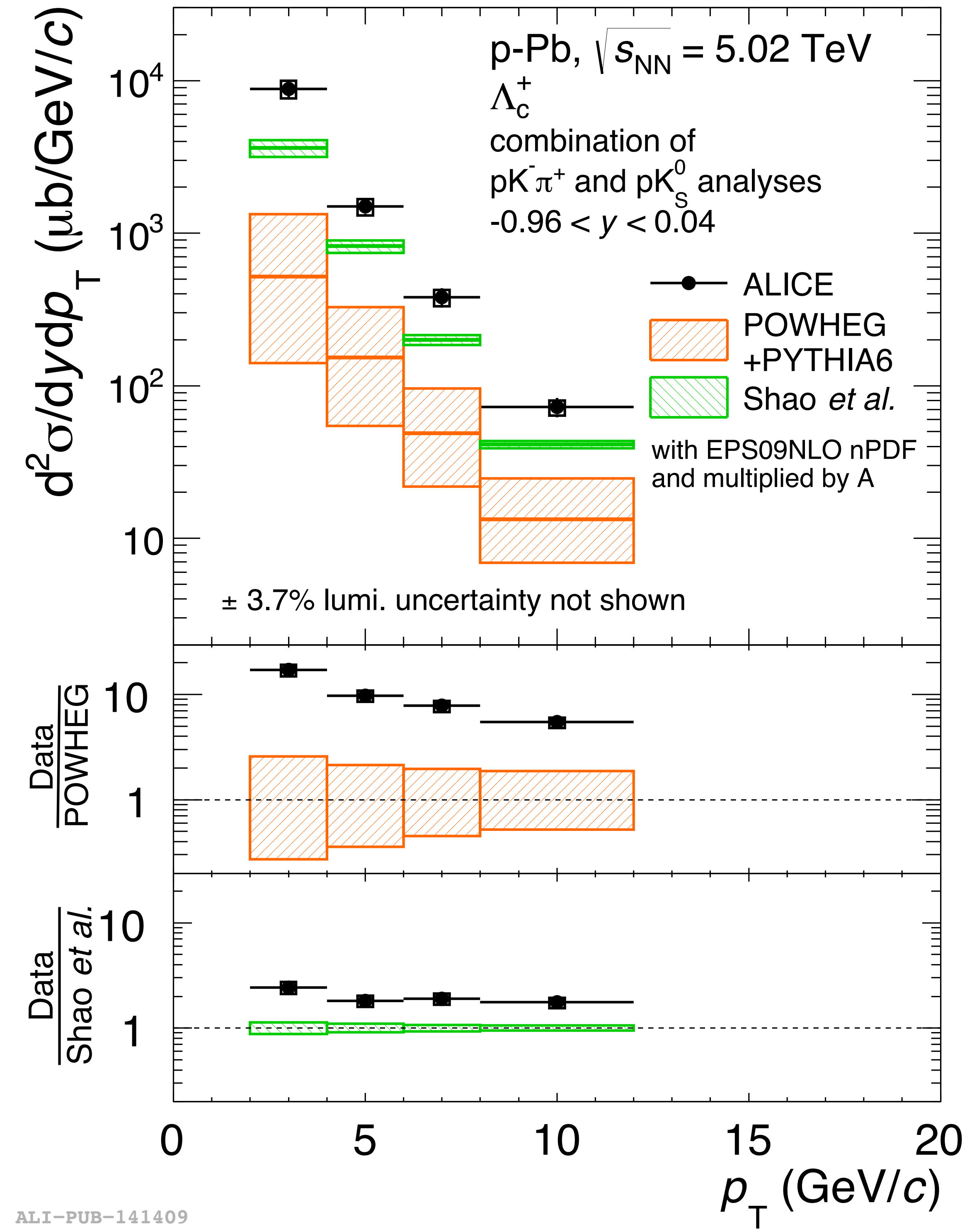
Λ_c^+ p_T-differential cross sections



- Good agreement between different decay channels + analysis methods

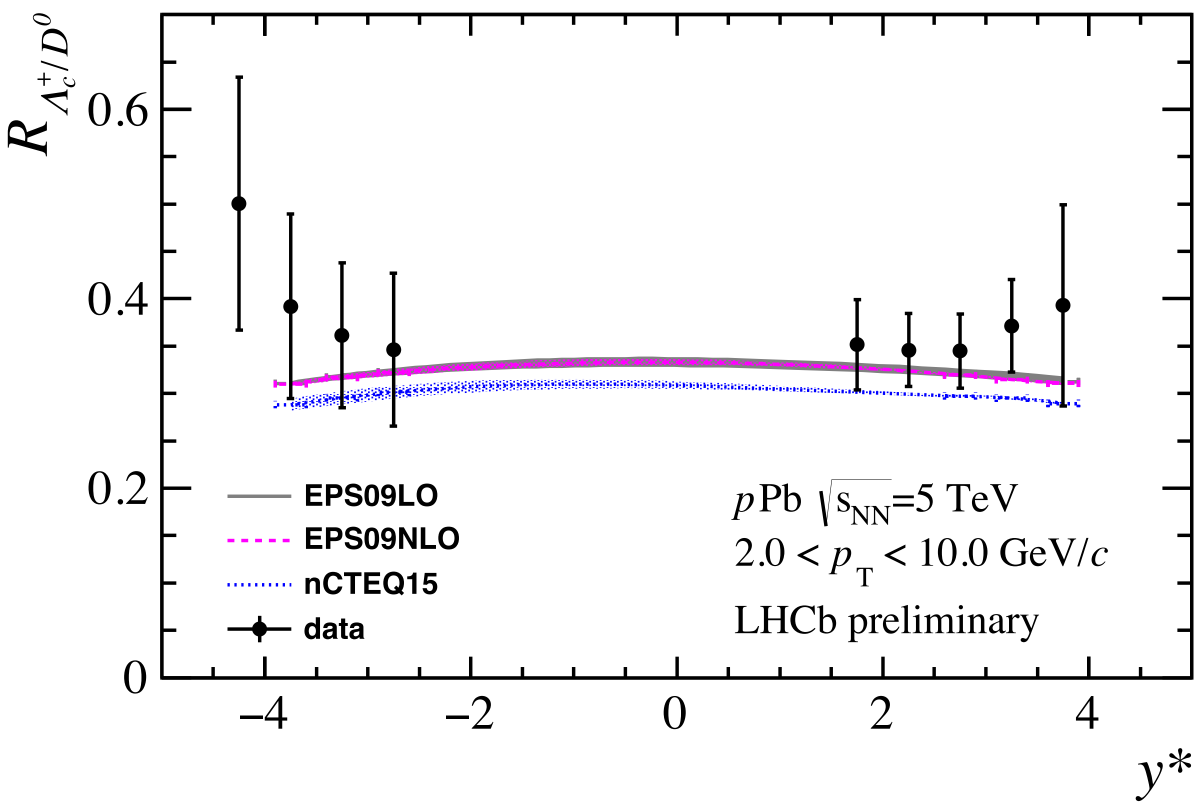
Λ_c^+ p_T-differential cross section in p-Pb collisions

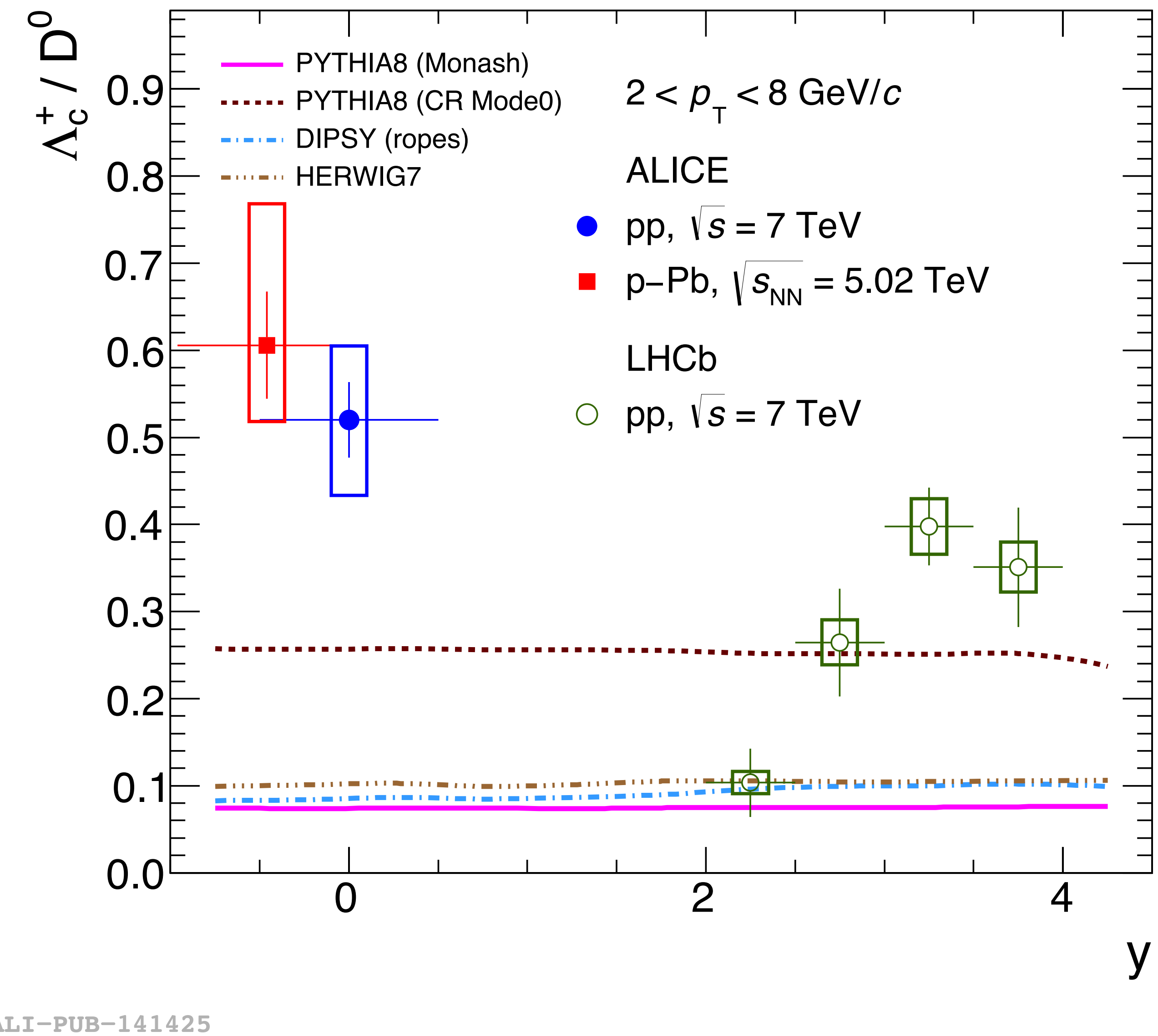
- Λ_c^+ p_T-differential cross section **significantly underestimated** by theory
    - **POWHEG:** MC generator with next-to-leading order accuracy
        - PYTHIA parton shower
    - **Shao *et al.*** : Data-driven model tuned on pp data at forward rapidity
        - Parameterises scattering amplitude using fit to LHCb Λ_c^+ cross section in pp collisions ($2 < y < 4.5$, $\sqrt{s} = 7$ TeV, $2 < p_T < 8$ GeV/c)
    - Both models include EPS09 parameteristion of nuclear PDF



POWHEG: S. Frixione et al.: JHEP 09 (2007) 126
Shao et al: Eur. Phys. J. C 77 (2017)

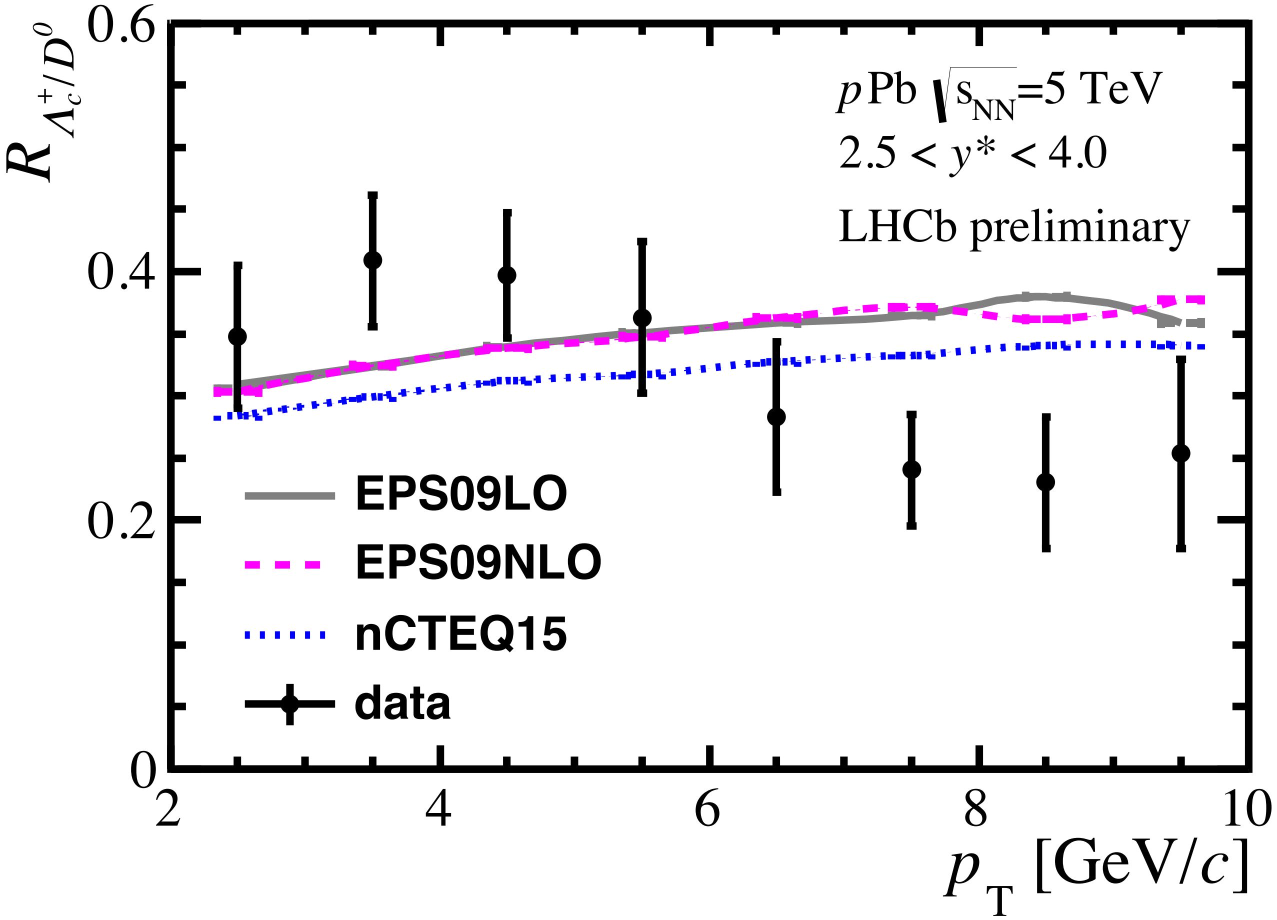
Λ_c^+/D^0 baryon-to-meson ratio vs models

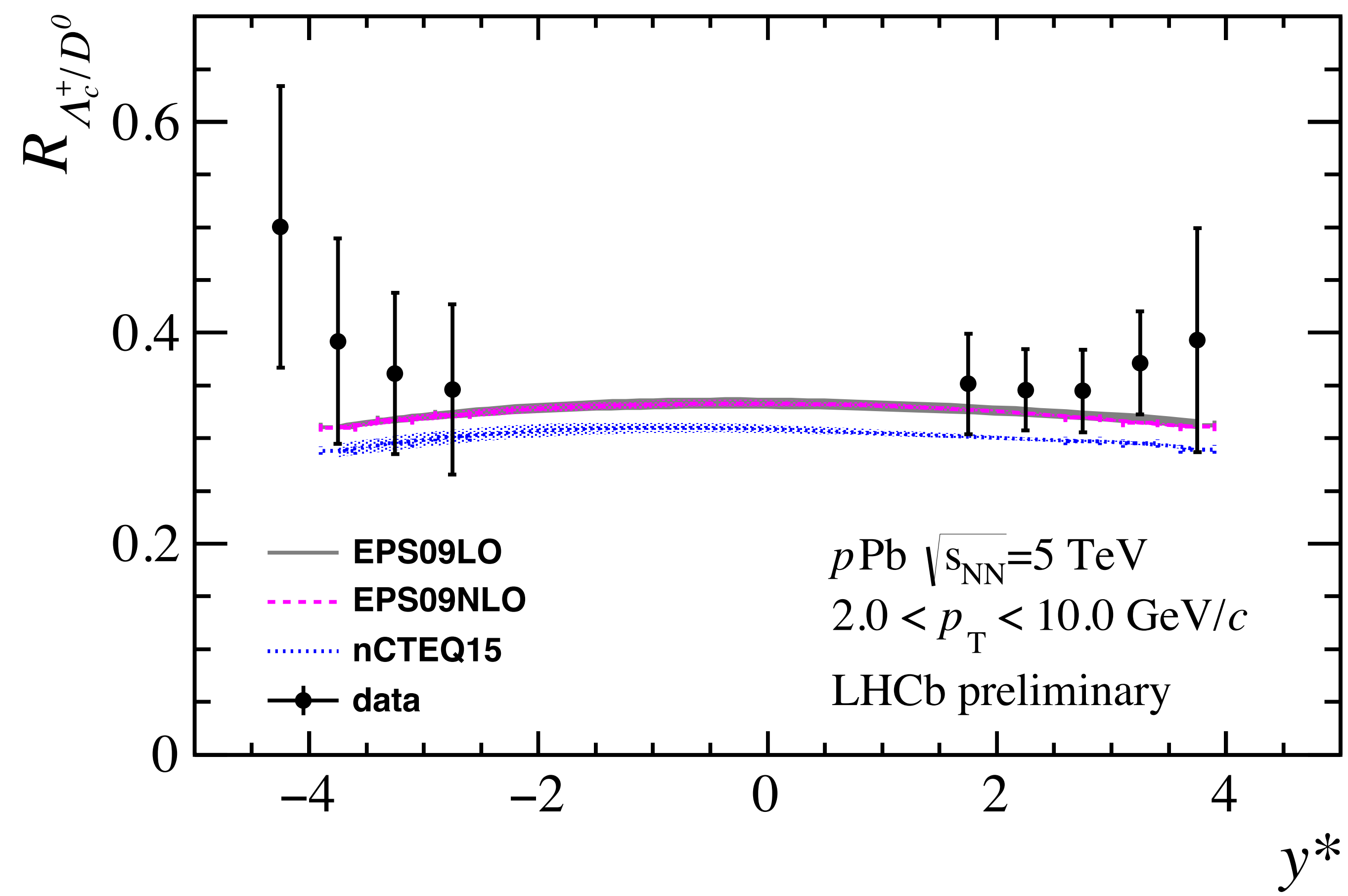




- Λ_c^+/D^0 in p-Pb collisions recently measured by the LHCb experiment shows a flatter trend with rapidity

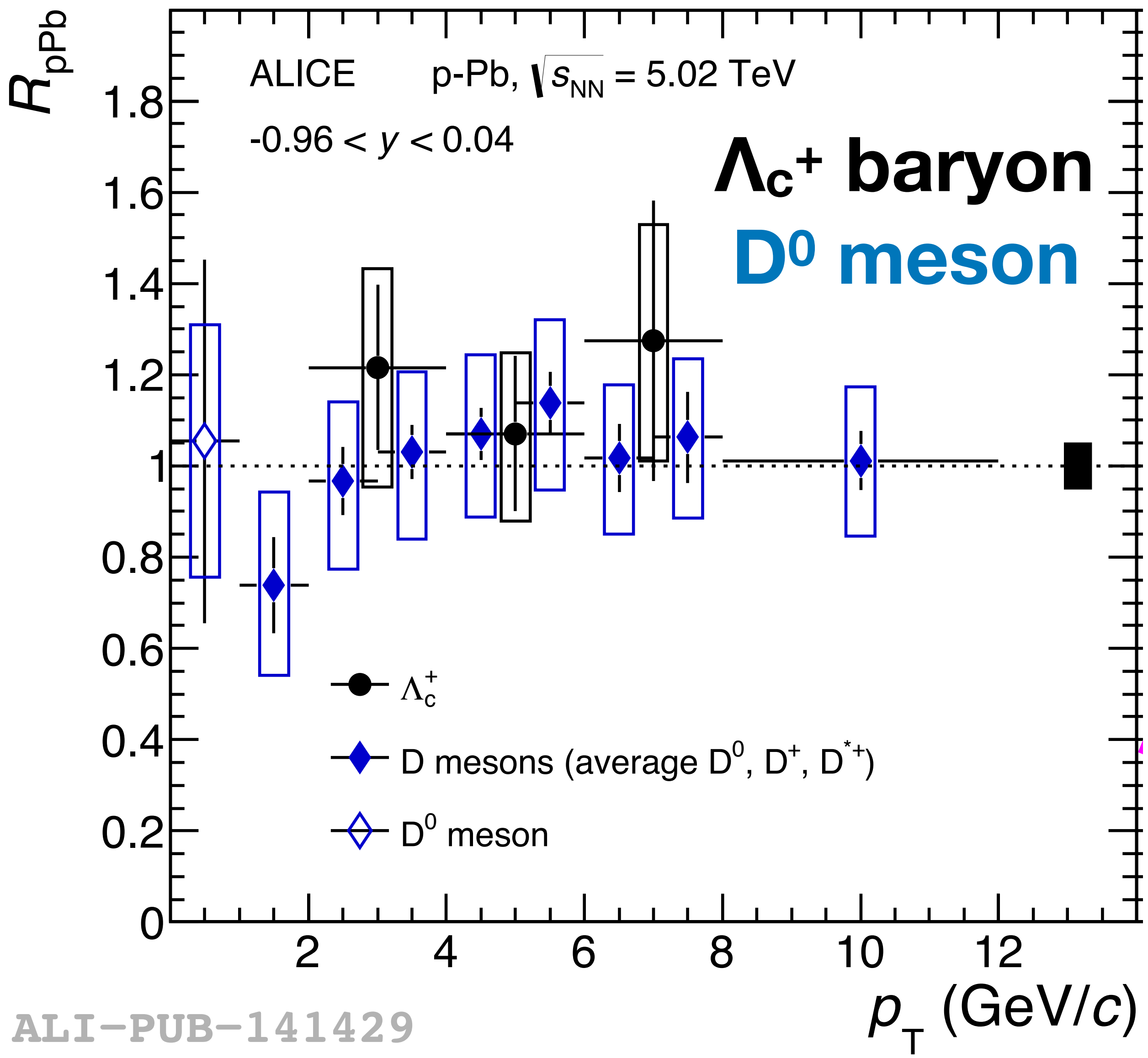
LHCb Λ_c^+/D^0 in p-Pb collisions





- Lc/D0 in p-Pb collisions measured by the LHCb experiment shows a flatter trend with rapidity

Λ_c^+ nuclear modification factor R_{pPb}



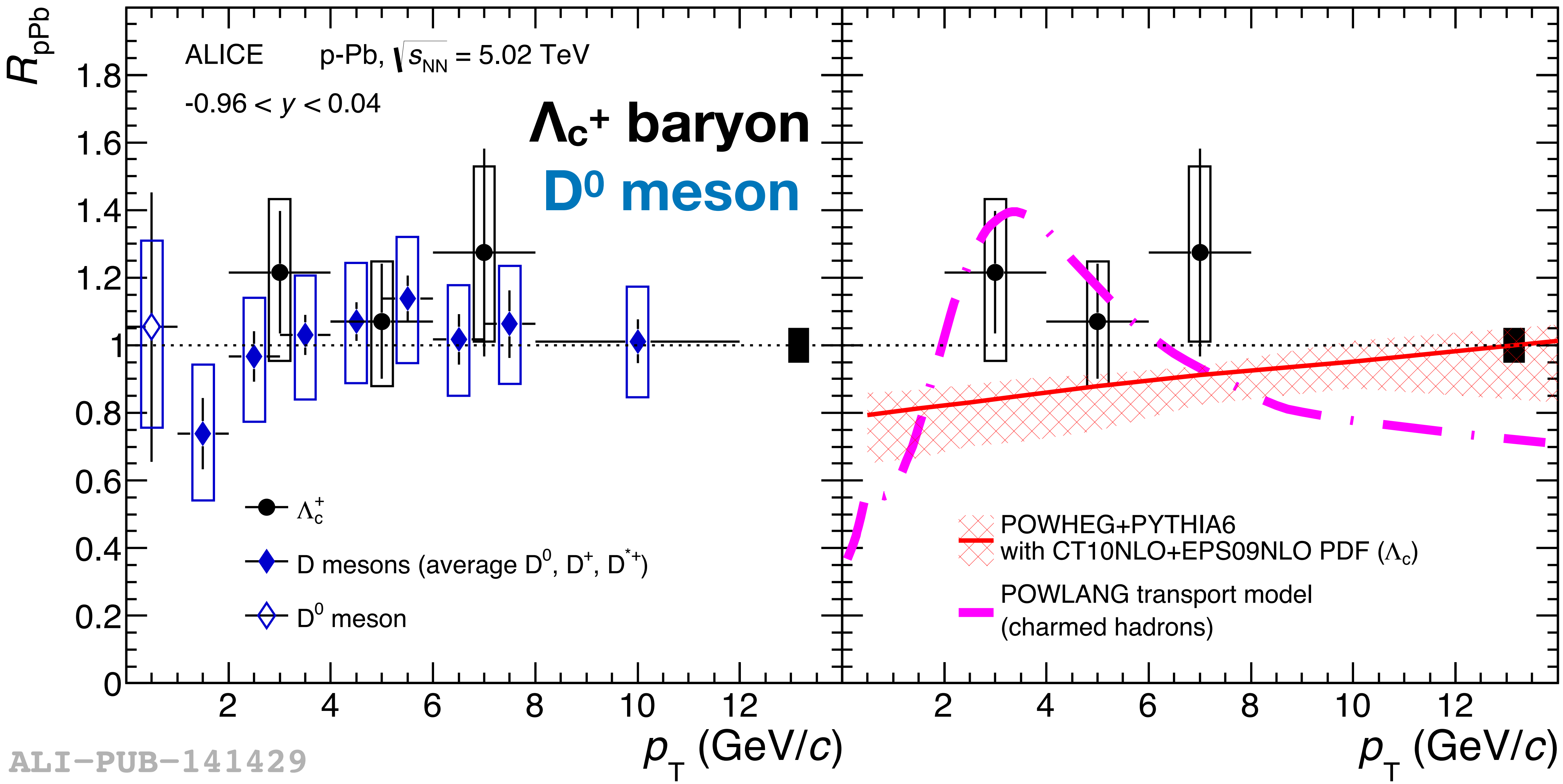
$$R_{pPb}(p_T) = \frac{1}{A} \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

R_{pPb} < 1 = suppression
R_{pPb} > 1 = enhancement

- Λ_c^+ nuclear modification factor R_{pPb}
  - consistent with unity
  - Consistent with D-meson R_{pPb}

Minimal modification w.r.t pp collisions within uncertainties

Λ_c^+ nuclear modification factor R_{pPb}



- Λ_c^+ R_{pPb} consistent **with models** assuming **cold nuclear matter** effects, or **'hot' medium** effects
  - **POWHEG + PYTHIA with CT10NLO+EPS09 PDF** - parameterisation of nuclear PDF
  - **POWLANG** – 'small-size' QGP formation, collisional energy loss only

POWHEG: JHEP 09 (2007) 126
POWLANG: JHEP 03 (2016) 123