Charmed baryon production with ALICE

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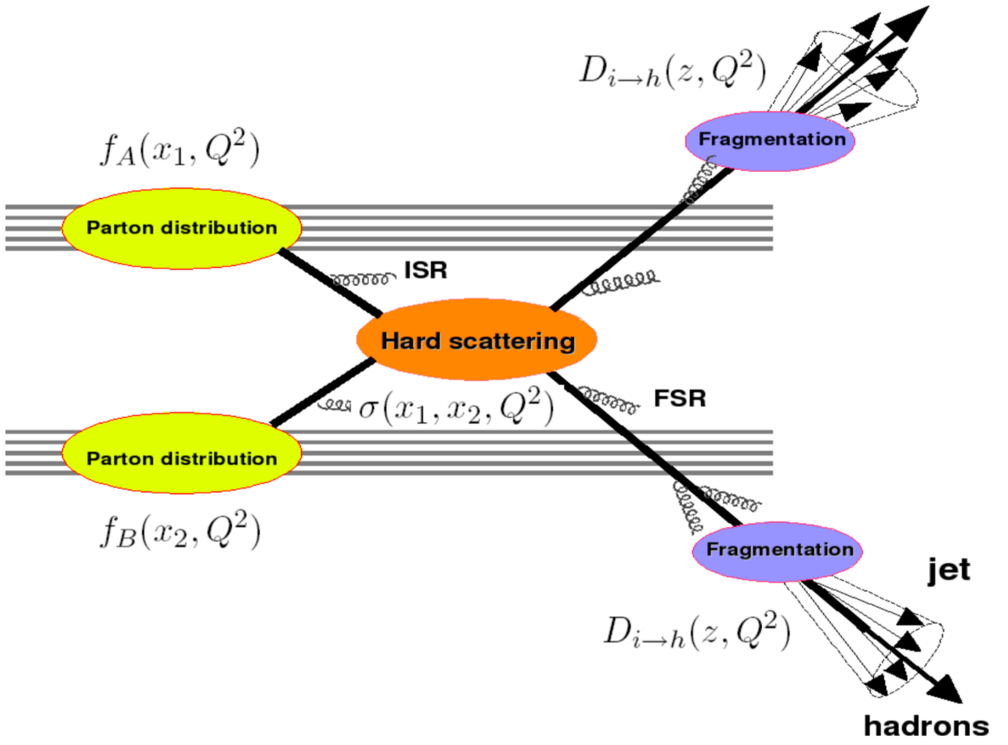
Laboratoire de Physique
Subatomique et de Cosmologie

Outline

- Physics motivations
- Charmed baryon production measurements in pp and p-Pb collisions 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
  - First measurement of Ξ_c^0 production in pp collisions at $\sqrt{s}$ = 7 TeV
- Future measurements with ALICE (Run 3/4)

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”:

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

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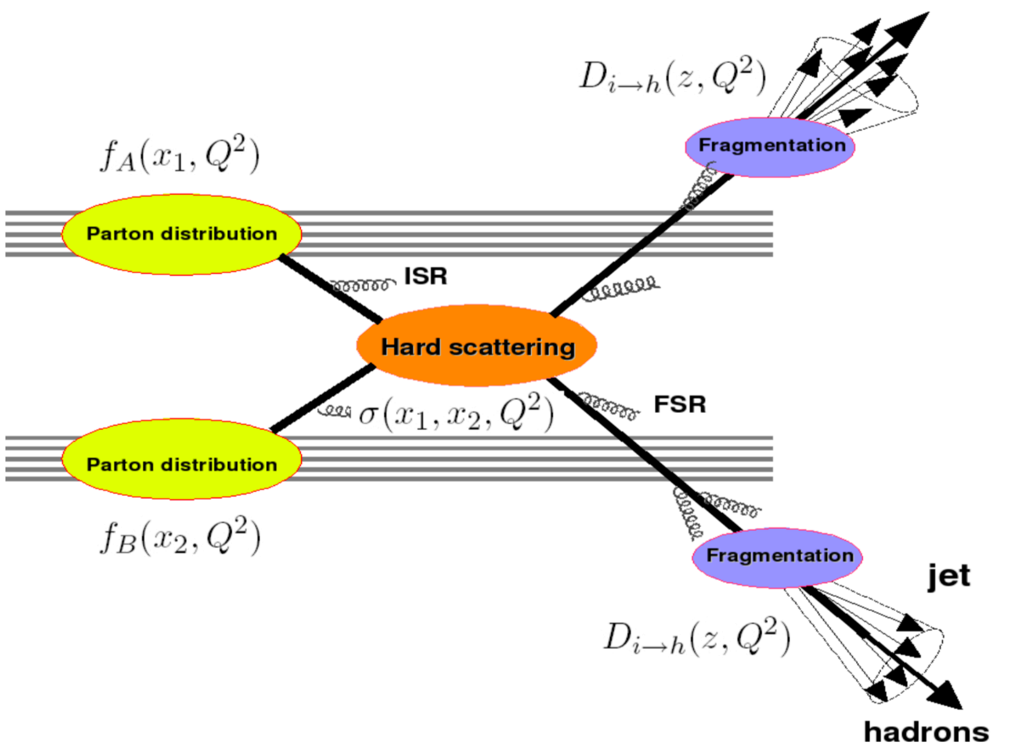

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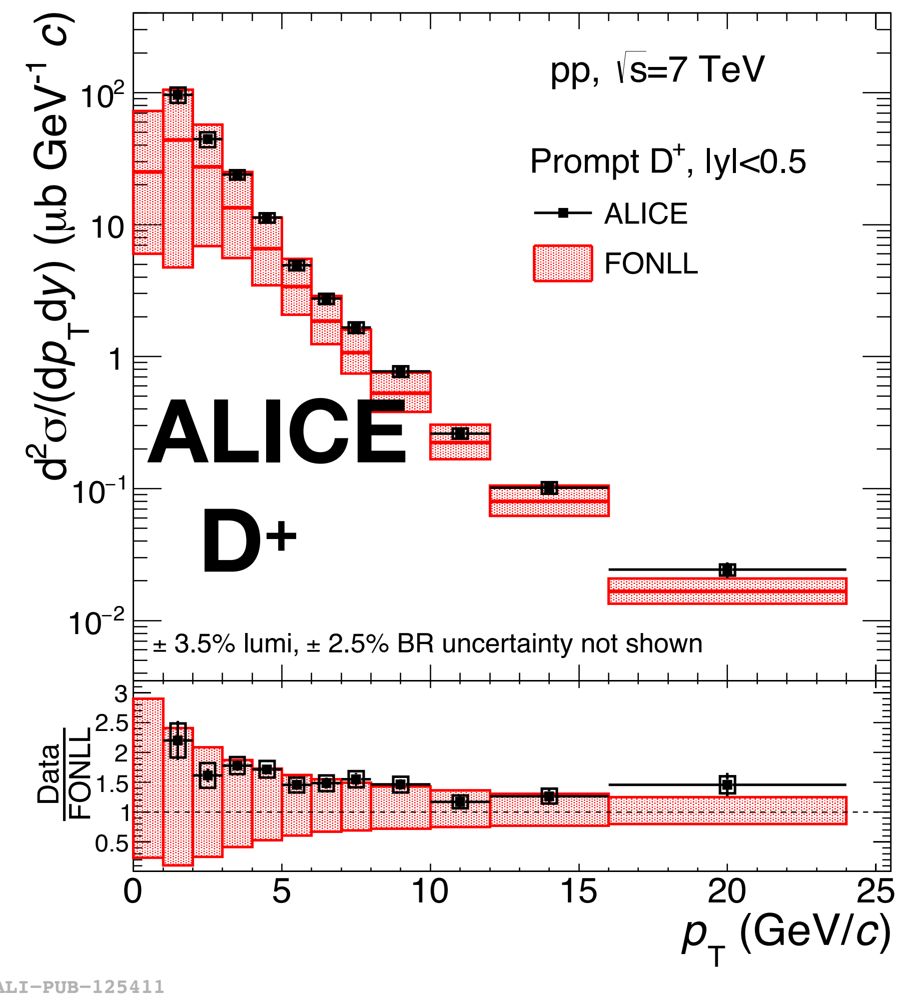
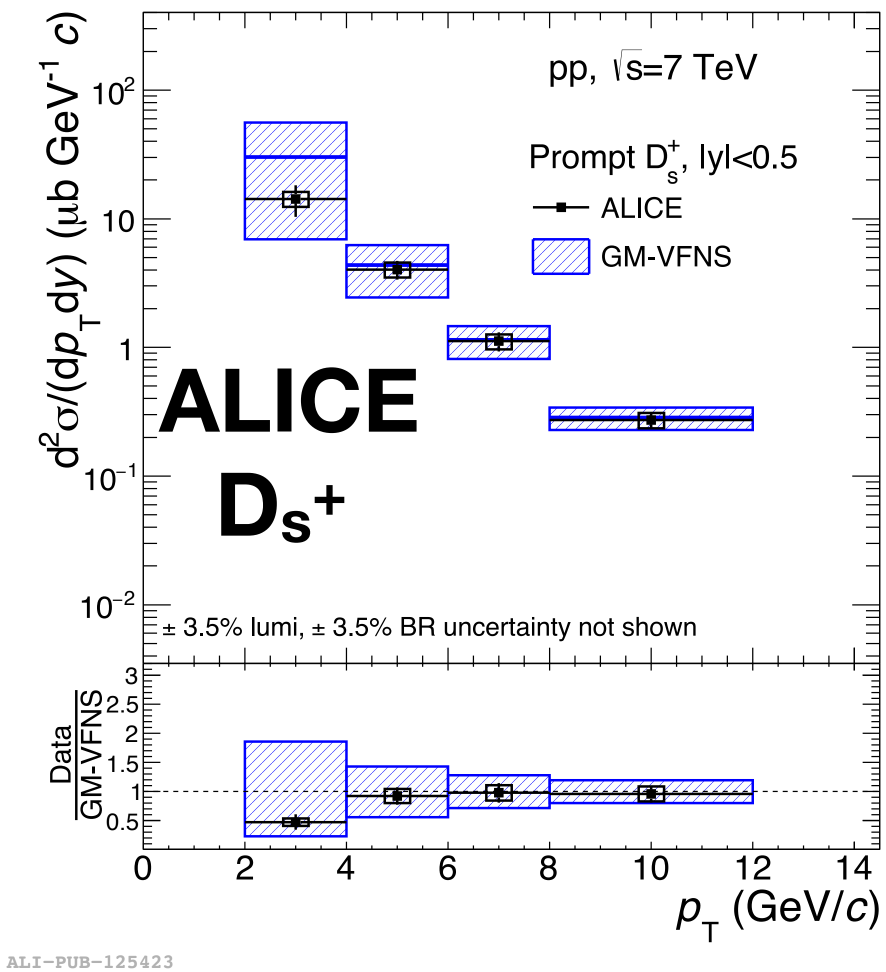
- Open heavy-flavour production measurements in pp collisions:
  - **Important test of pQCD-based calculations**
  - **Sensitive to fragmentation functions** determined from e^+e^- collisions
  - Sensitivity to **low-x gluon PDF** ($p_T \rightarrow 0$)

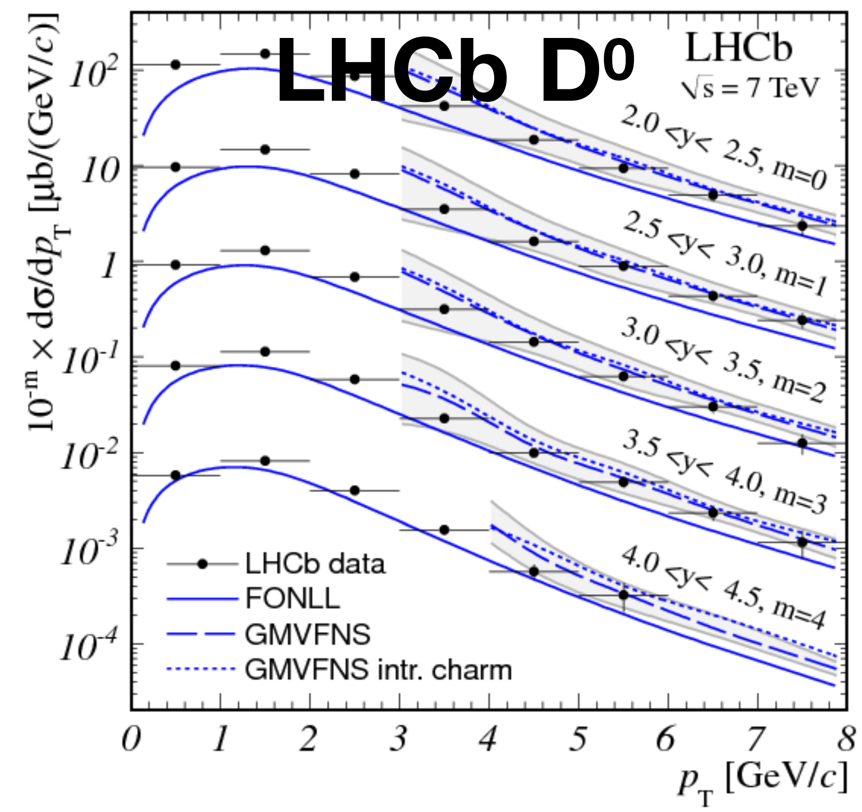
pp: Charm production at the LHC

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





LHCb: Nucl. Phys.B871 (2013) 1–20

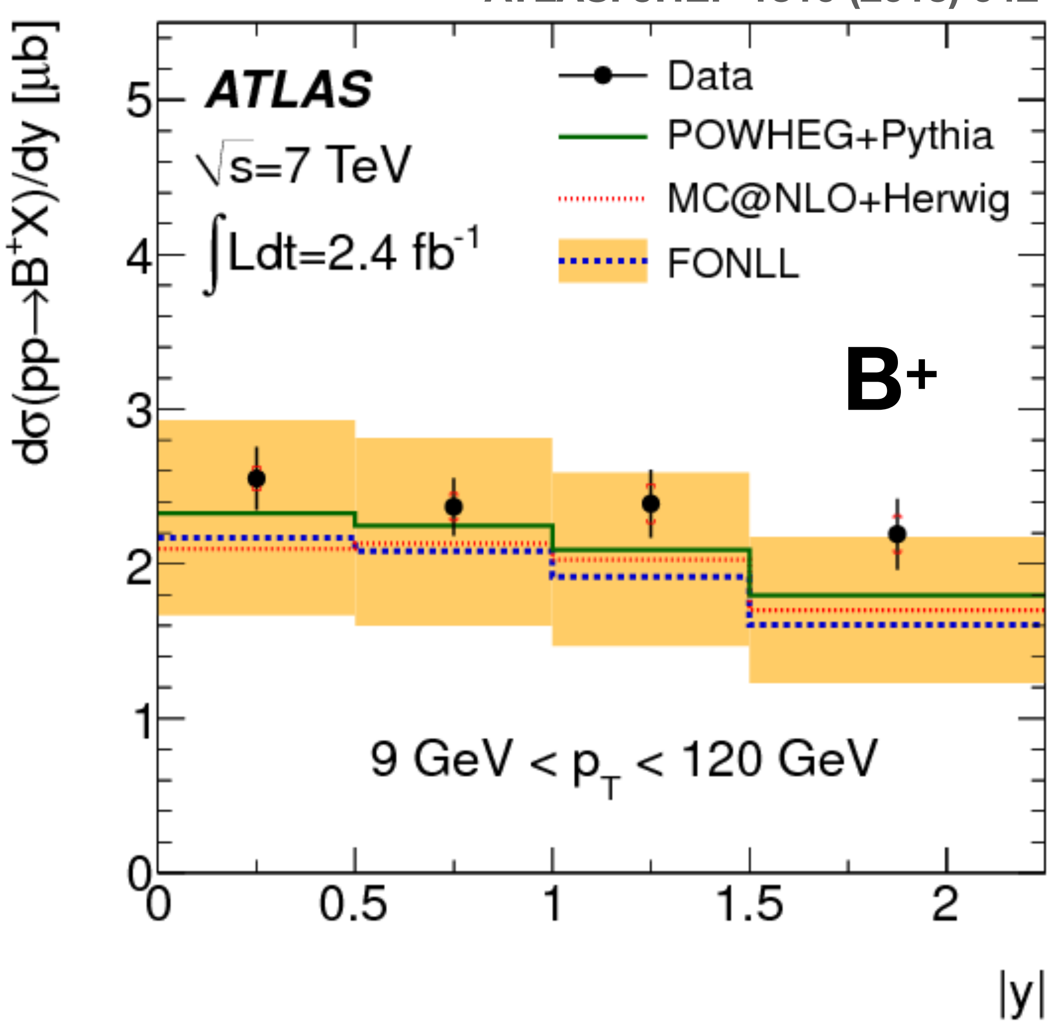


- Cross sections of D mesons at the LHC **in agreement with pQCD predictions** at central rapidity (ALICE) and forward rapidity (LHCb)
  - FONLL, GM-VFNS: Next-to-leading order with next-to-leading-log resummation
- Similar observation at 2.76 TeV, 5 TeV and 13 TeV

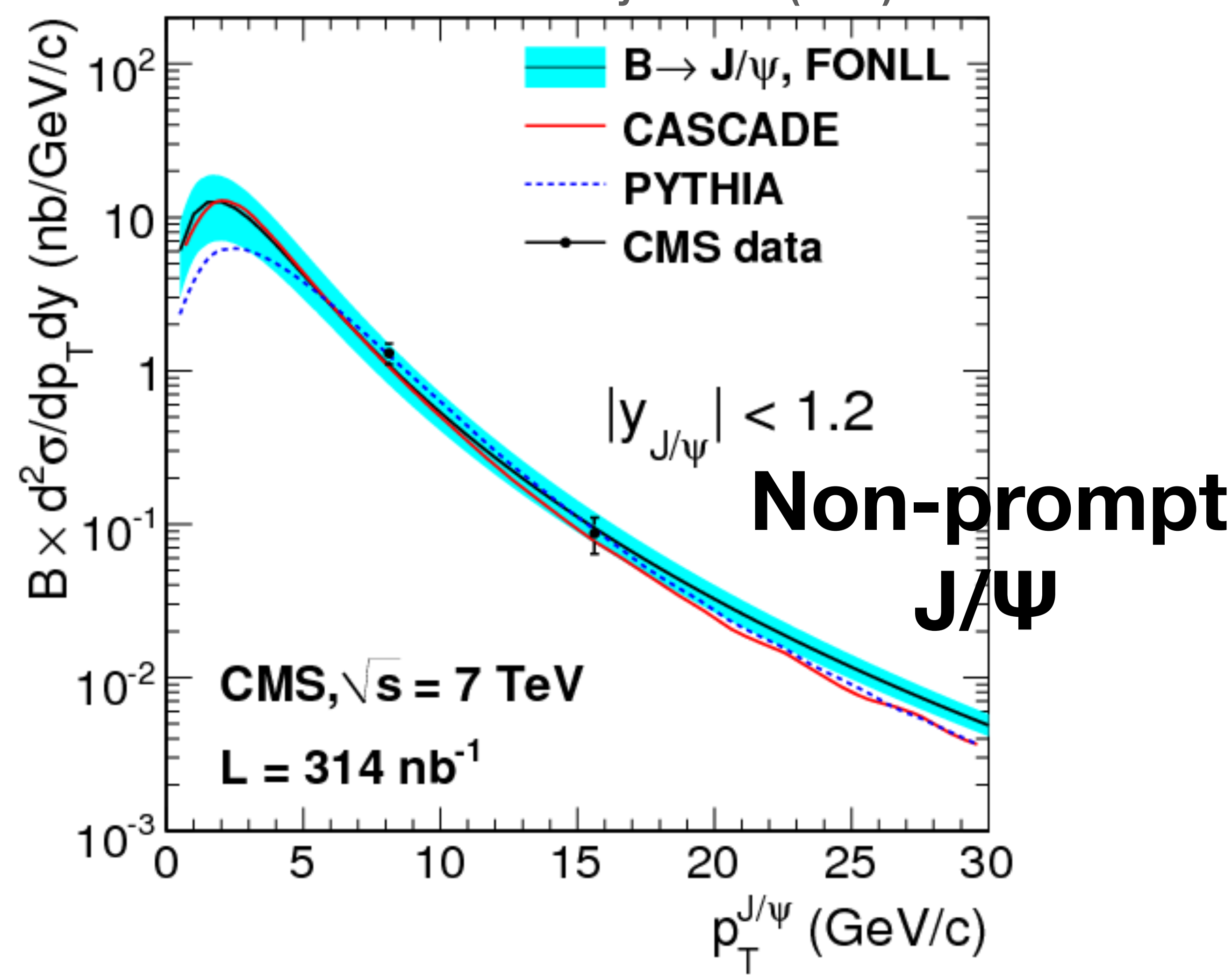
FONLL: M. Cacciari et al. JHEP 05 (1998), JHEP 10 (2012)
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082

pp: Beauty production at the LHC

ATLAS: JHEP 1310 (2013) 042



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



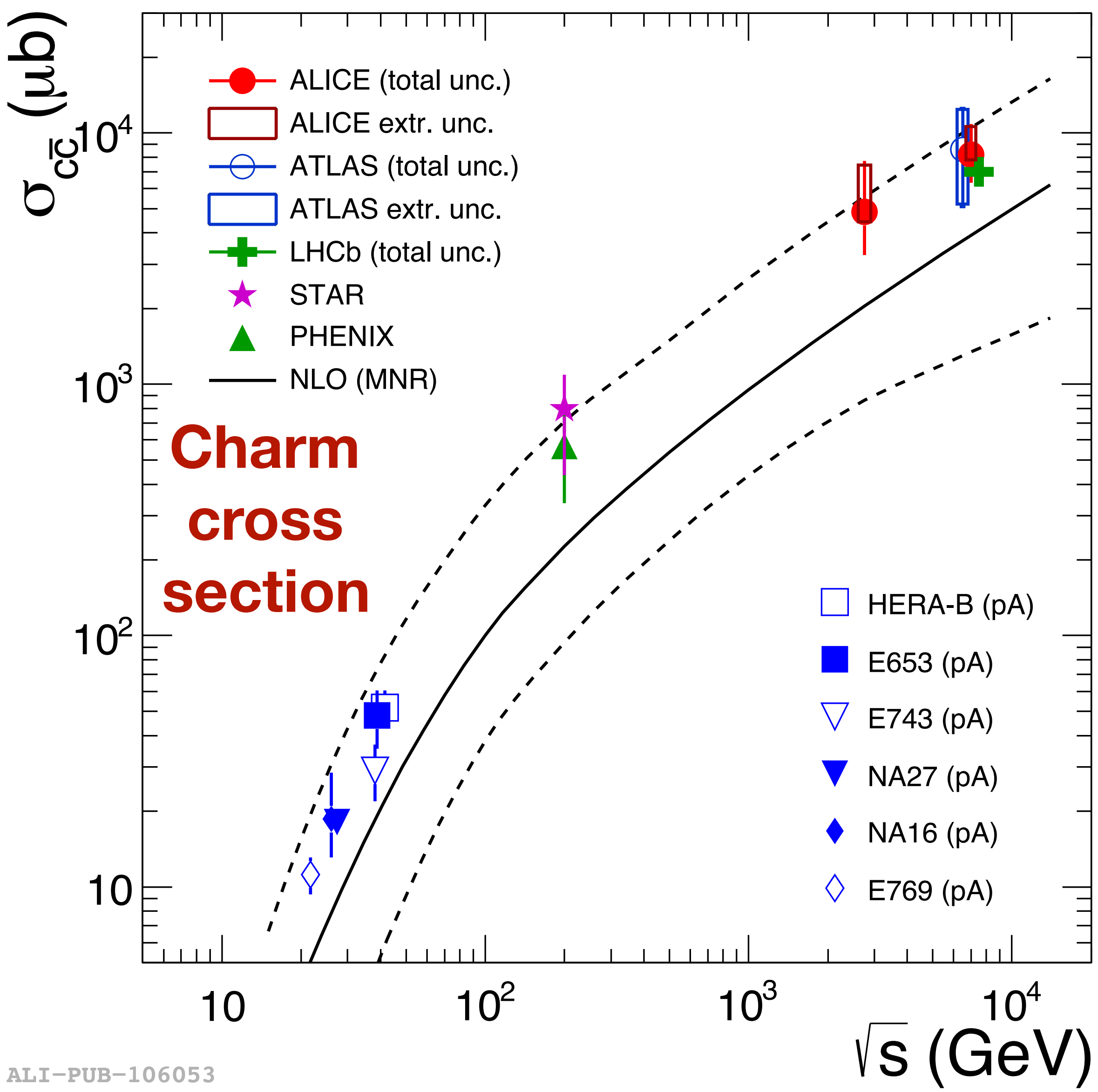
- Cross sections of B mesons at the LHC **in agreement with pQCD predictions**
  - FONLL, GM-VFNS: Next-to-leading order with next-to-leading-log resummation
  - POWHEG, MC@NLO: MC generators with next-to-leading order accuracy, with leading-log Parton shower
- **Similar agreement** of charm and beauty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

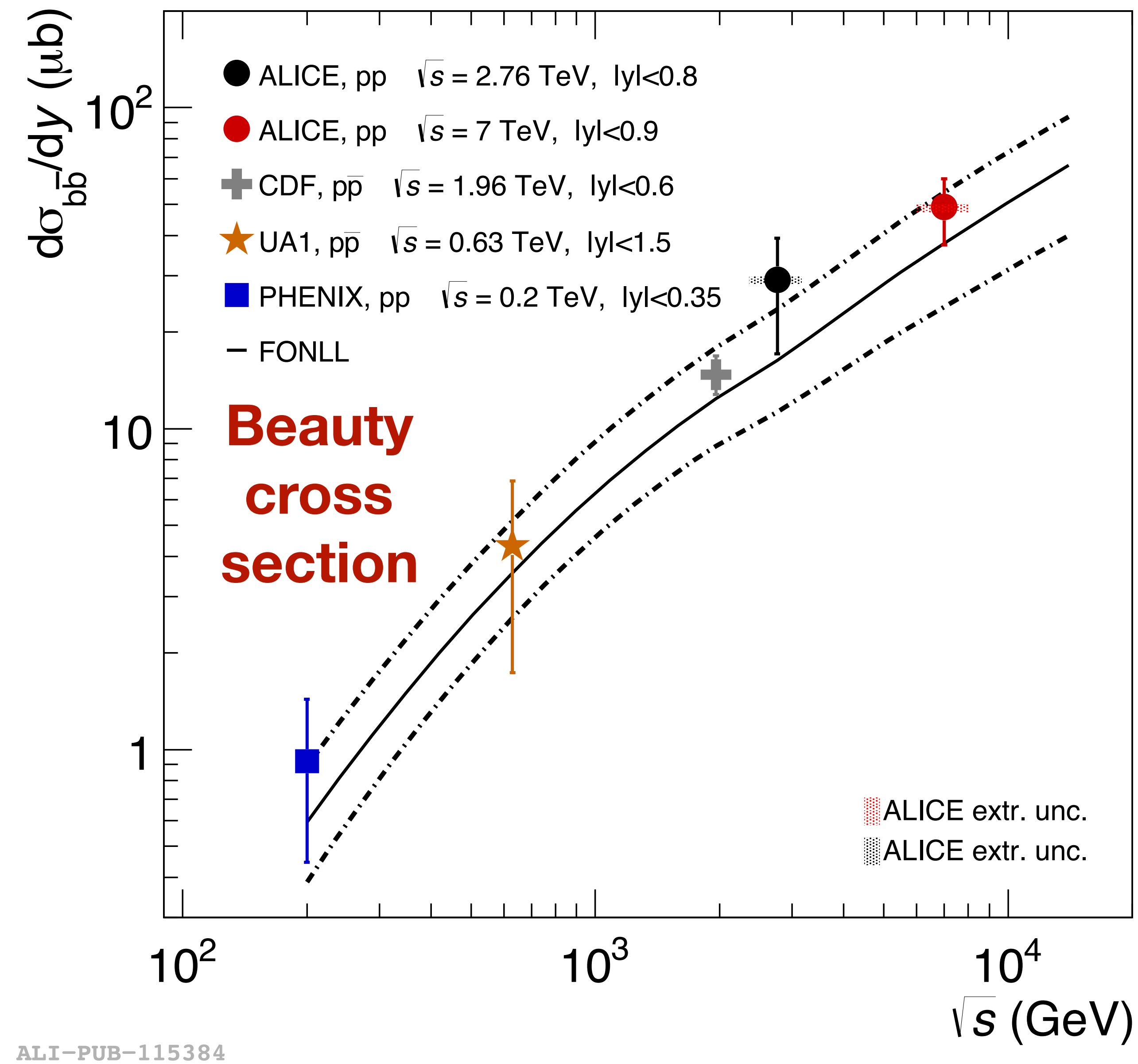
FONLL: M. Cacciari et al. JHEP 05 (1998), JHEP 10 (2012)
GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082

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



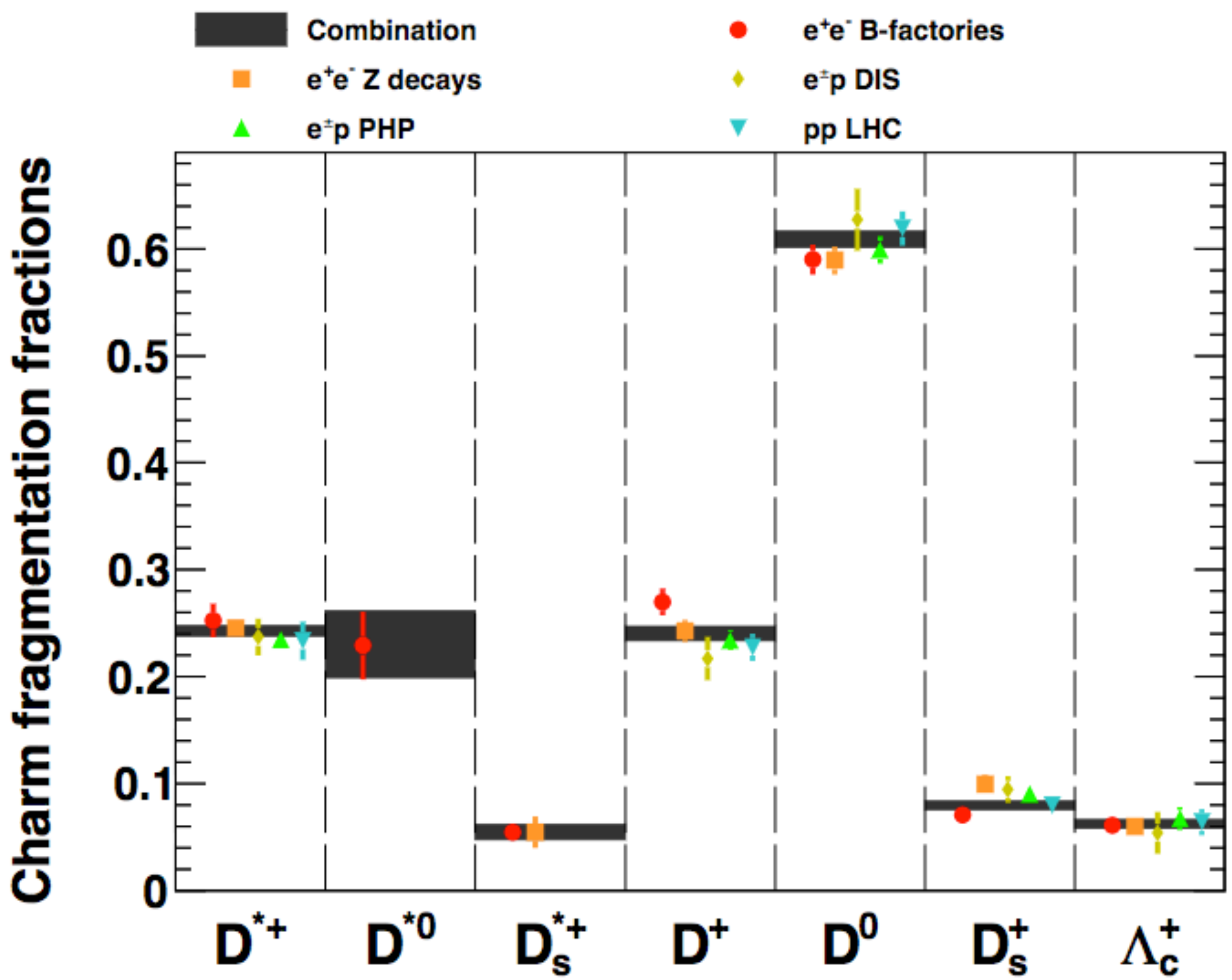


- Total charm and beauty cross section described well by predictions at NLO

pp: Charm quark fragmentation

Charmed hadron ratios sensitive to fragmentation process

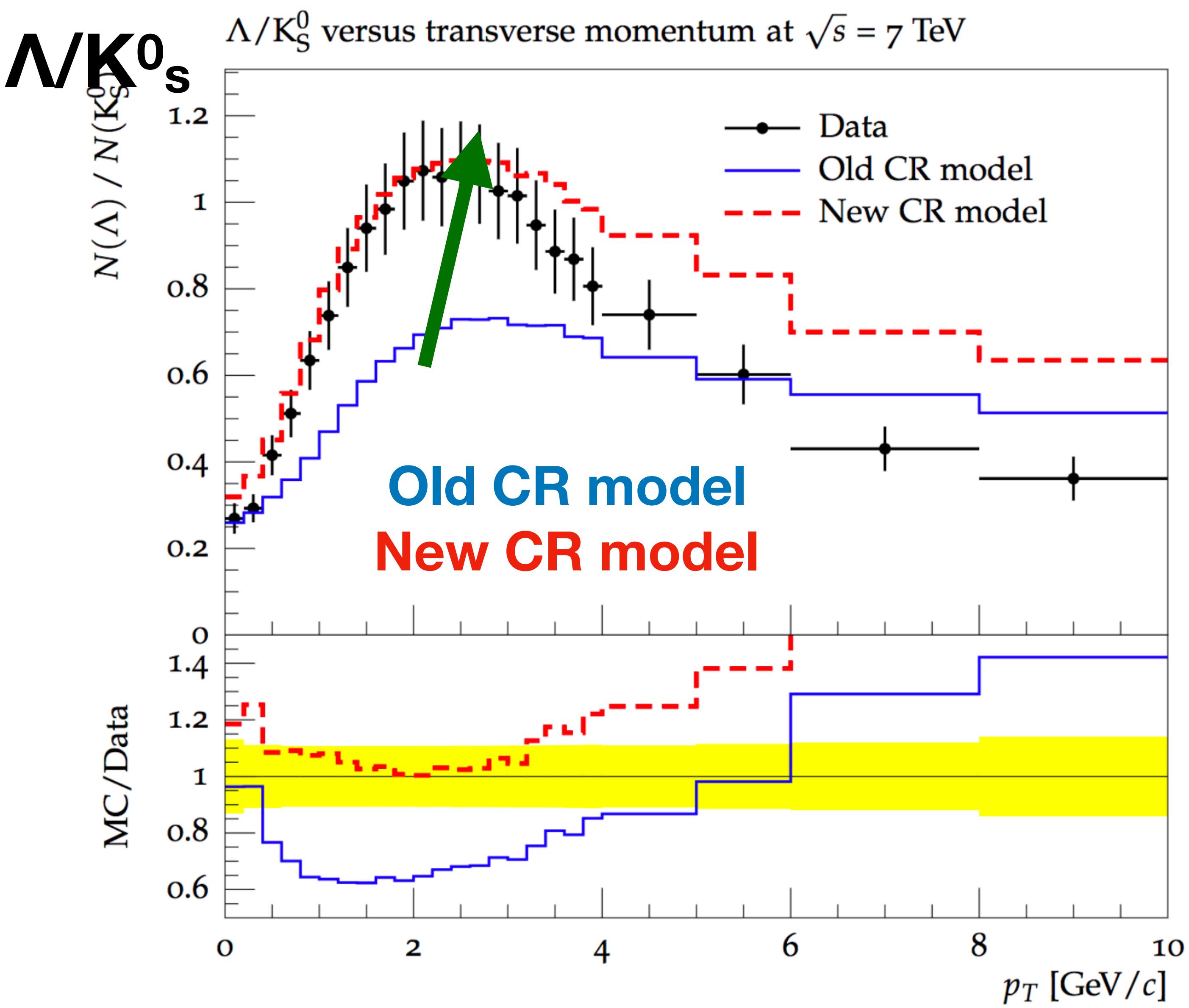
- *fragmentation fractions* **expected to be universal**
  → same in different systems, energies, etc
- Measurements in different collision systems (ee, ep, pp) and energies support this picture



EPJ C 76 (2016) no.7, 397

pp: Charm quark fragmentation

Can hadronisation be modified?



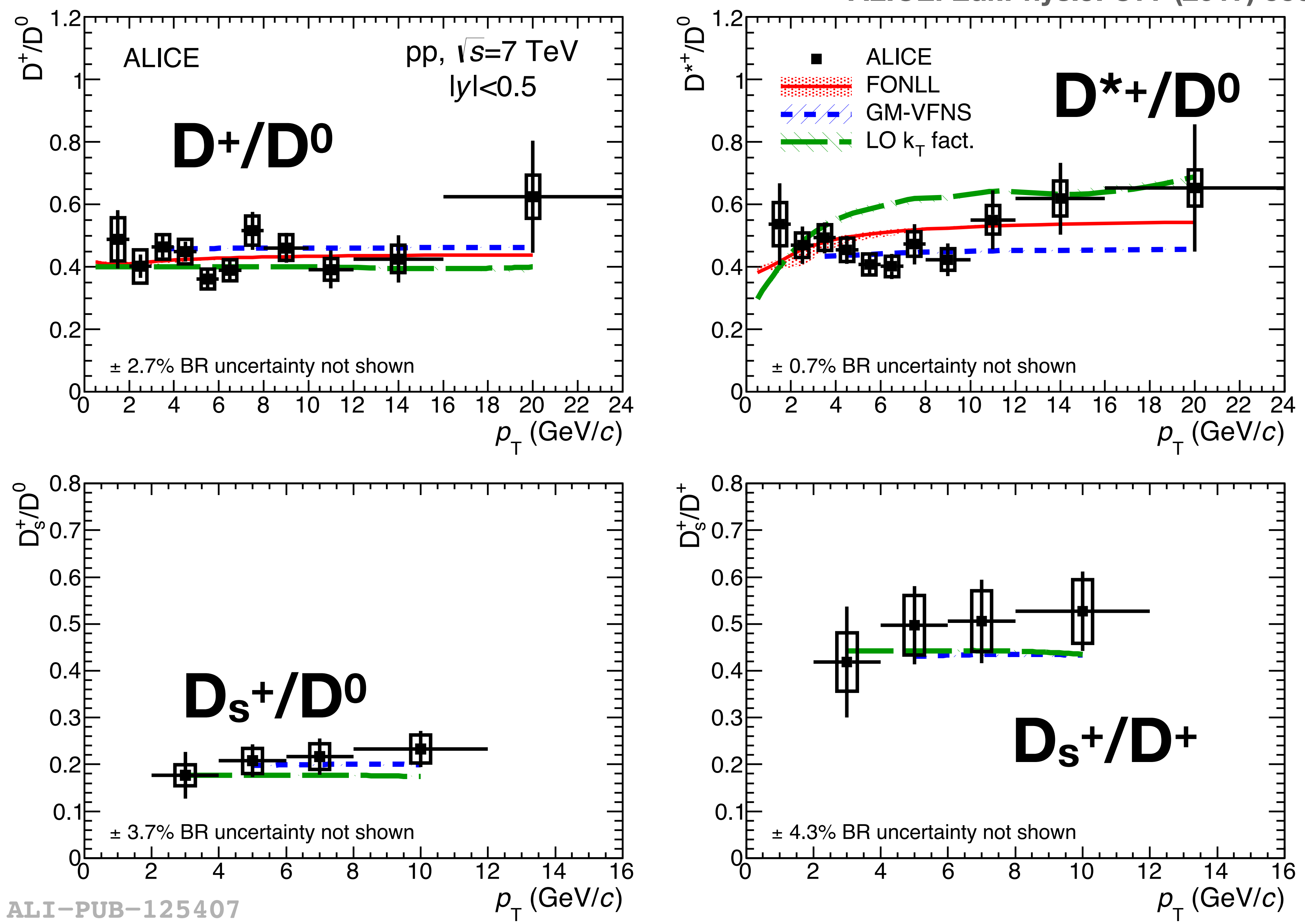
- **Multi-parton interactions,** coherence effects at LHC energies may affect hadronisation
- e.g. within PYTHIA, **enhanced colour reconnection** modes gives better agreement with measured Λ/K^0_s ratio
  - String formation beyond the leading-colour approximation, specific tuning of the colour reconnection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

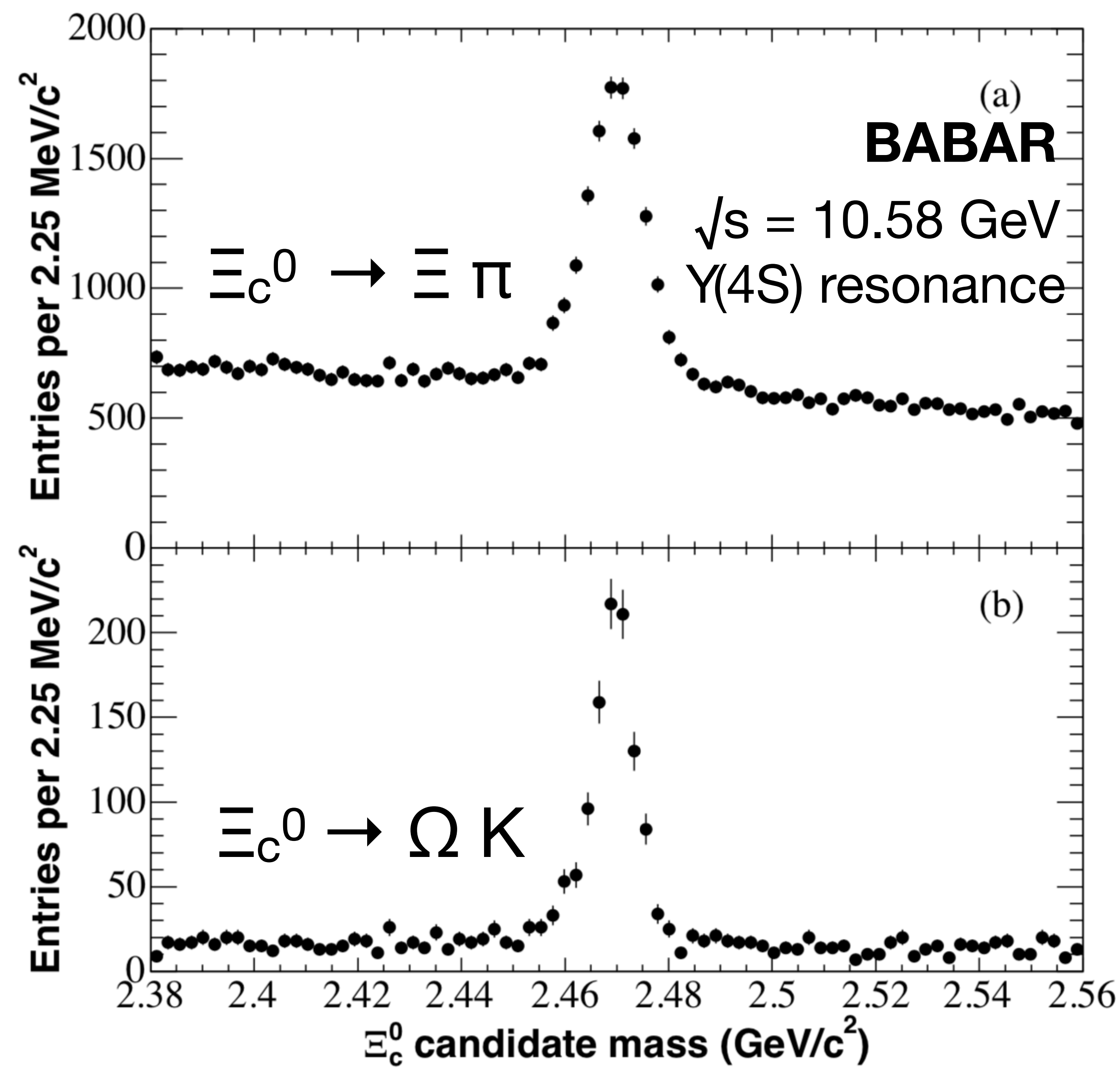
LHCb: Nuclear Physics, Section B 871 (2013), pp. 1-20
LHCb-CONF-2017-005

pp: 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)

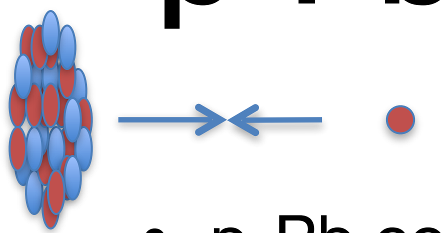
- Charm hadron *production* measurements in hadron collisions limited to low-mass mesons and baryons
    - Only Ξ_c^0 production measurements in e^+e^- collisions
- New measurements of charmed baryons could provide further insight into hadronisation mechanisms



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

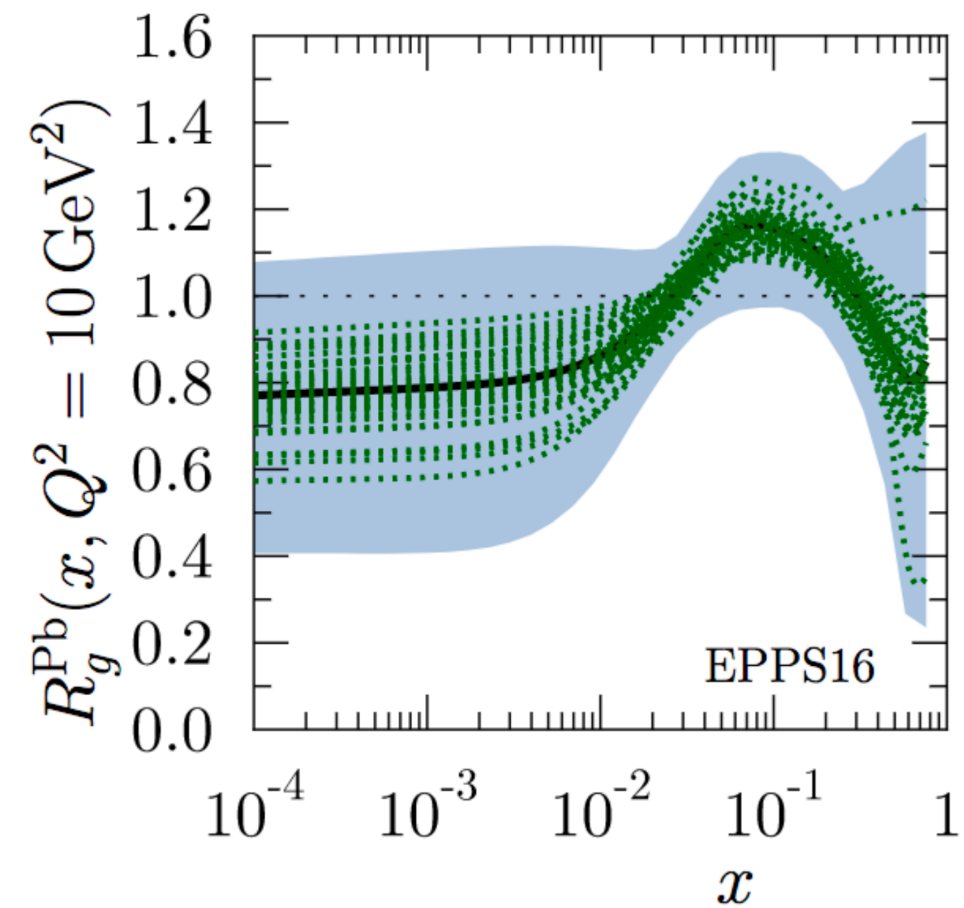
p-Pb collisions

p-Pb: Heavy-flavour production



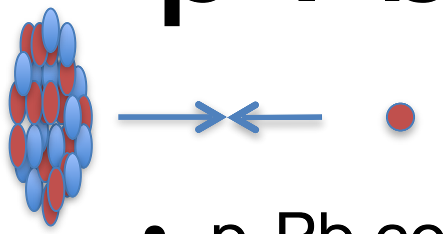
- p-Pb collisions traditionally used to **separate** ‘*hot*’ effects in Pb-Pb collisions (effects due to hot dense deconfined matter) from ‘*cold nuclear matter’* effects (effects due to the presence of a nuclei)
  - **Initial state effects:** modification of nuclear parton distribution
  - **Final-state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



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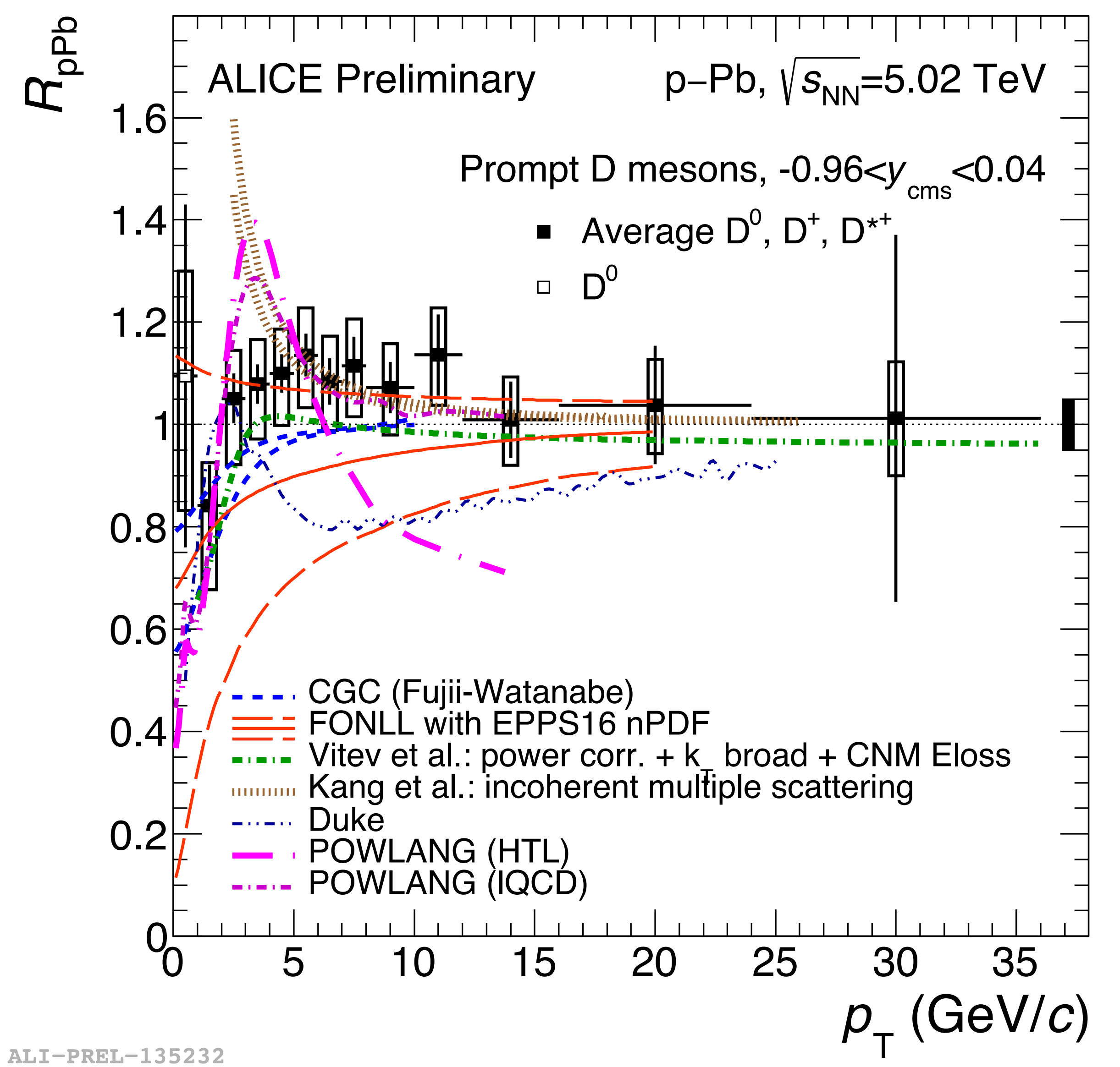
  - **Initial state effects:** modification of nuclear parton distribution
  - **Final-state effects:** (energy loss? Collectivity?)
- D-meson nuclear modification factor R_{pPb} indicates **minimal modification** to p_{T} spectrum w.r.t pp collisions

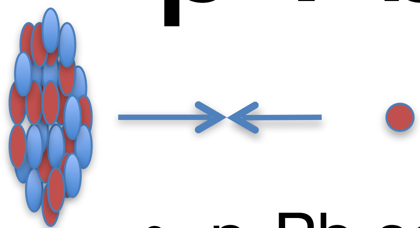
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

***$R_{\mathrm{pPb}} < 1$* = suppression**

***$R_{\mathrm{pPb}} > 1$* = enhancement**



p-Pb: Heavy-flavour production



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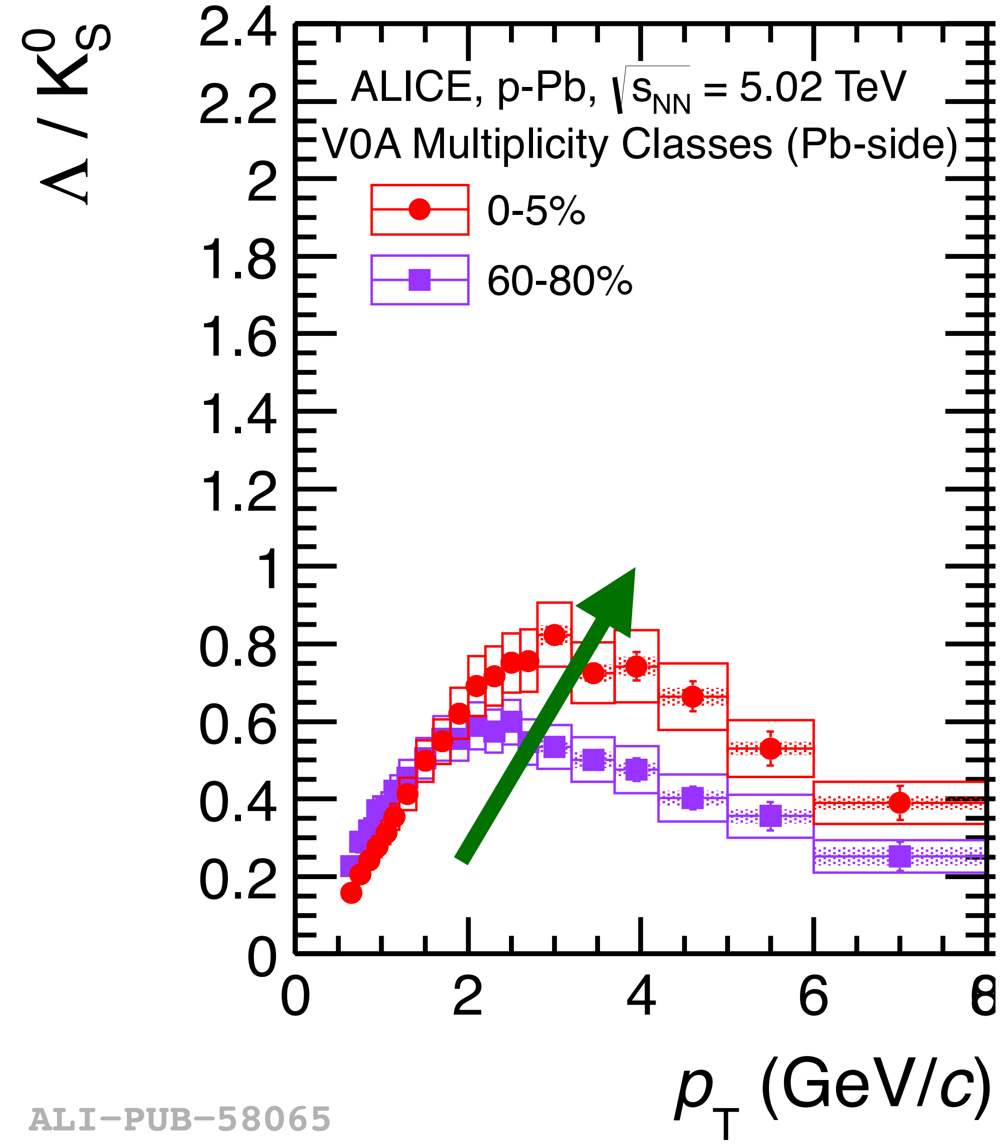
    - **Final-state effects:** (energy loss? Collectivity?)
- D-meson nuclear modification factor R_{pPb} indicates **minimal modification** to p_{T} spectrum w.r.t pp collisions
- **Modification to charmed baryon production in p-Pb collisions?**
    - (strange) Λ/K ratio increases towards higher multiplicity



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

arXiv:1712.09581

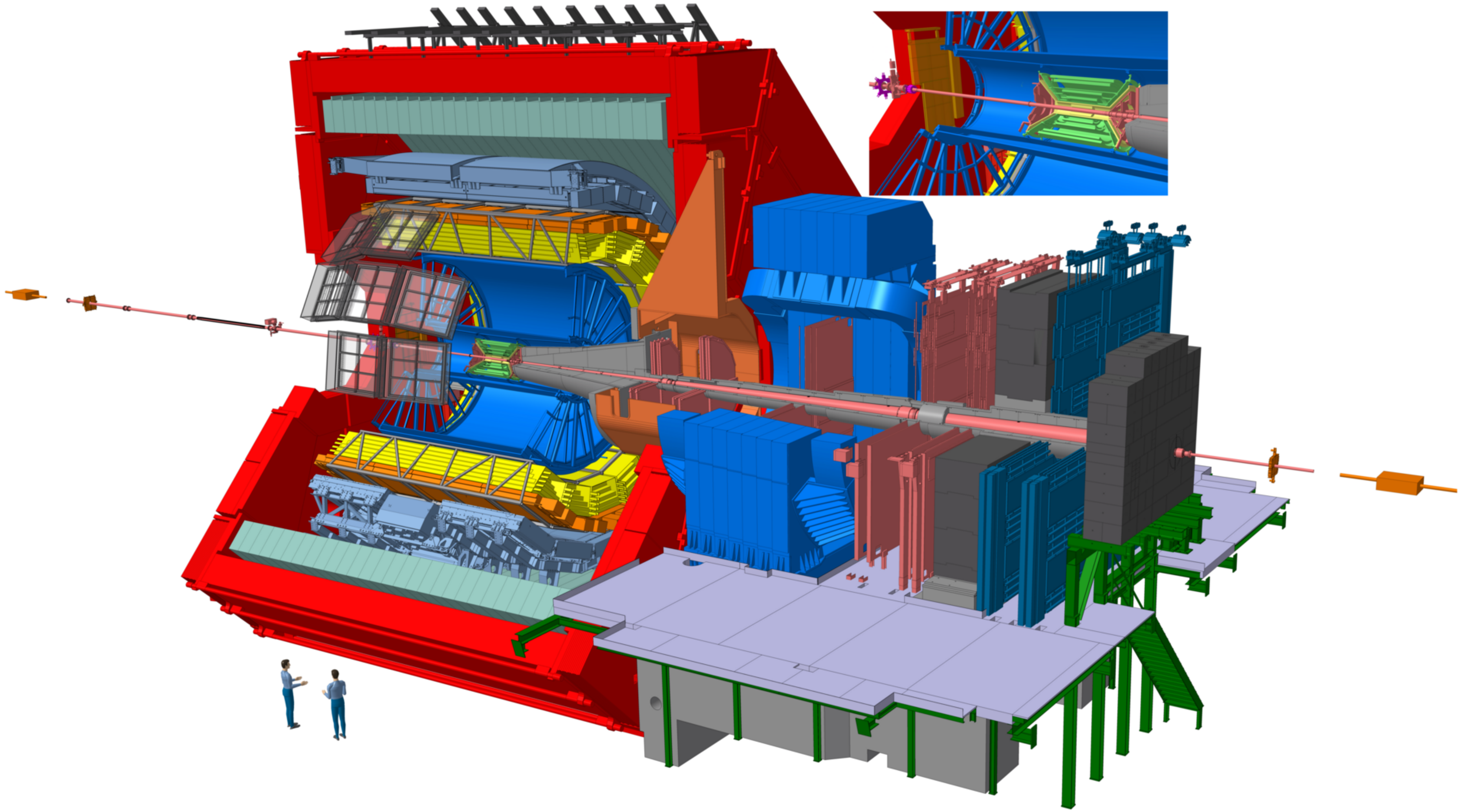
Accepted by JHEP

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

arXiv:1712.04242

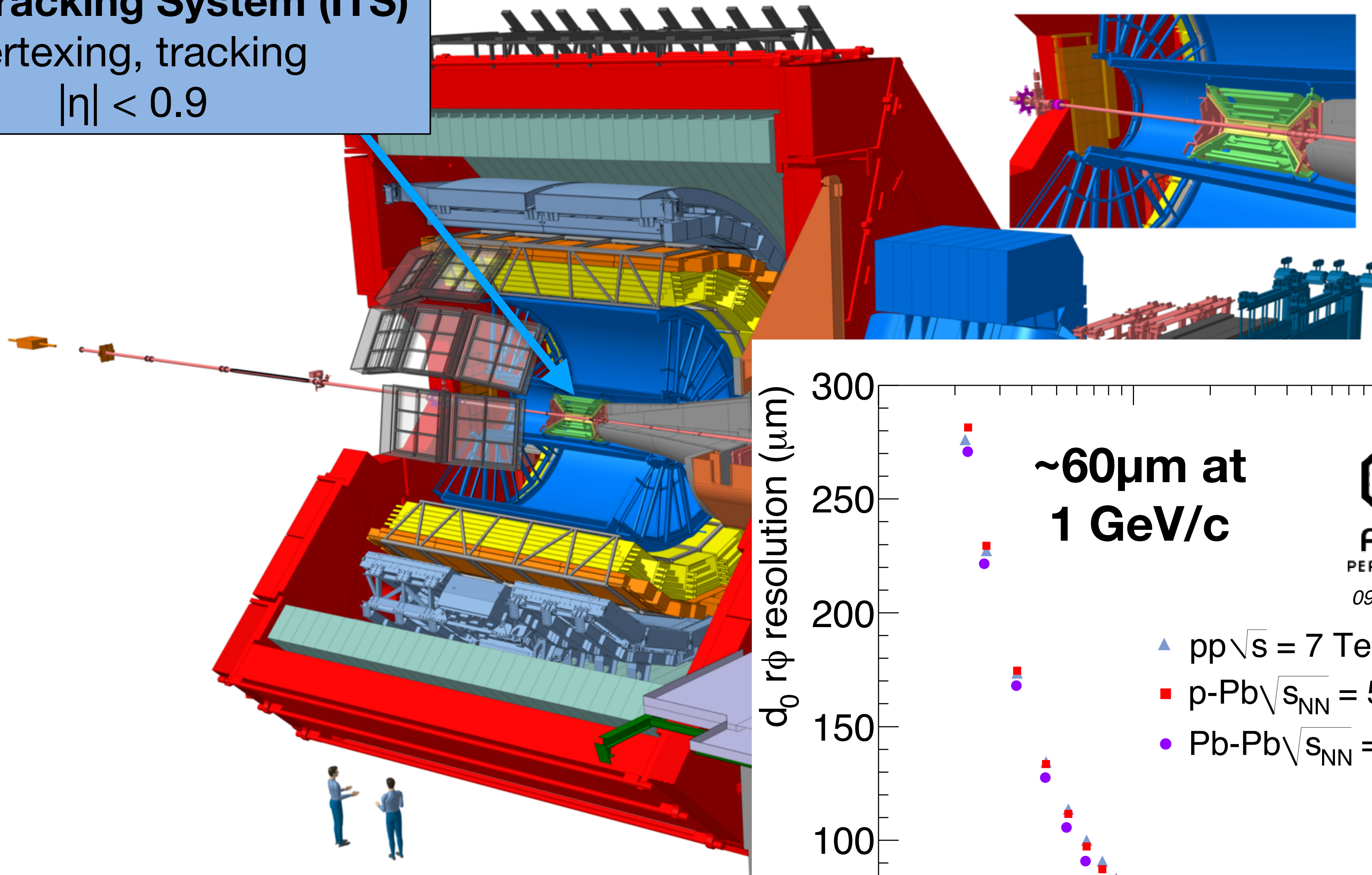
Submitted to PLB

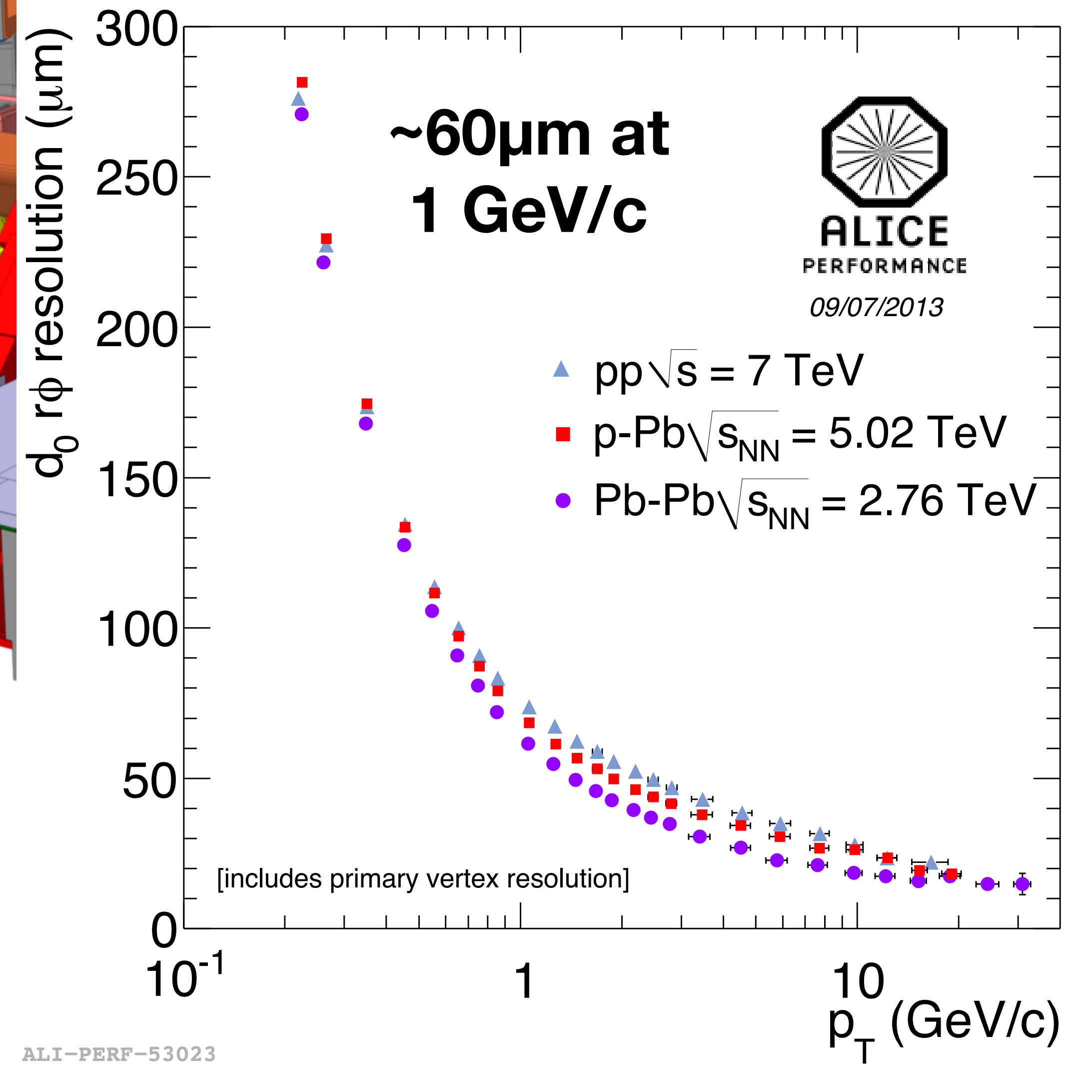
The ALICE apparatus



The ALICE apparatus

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





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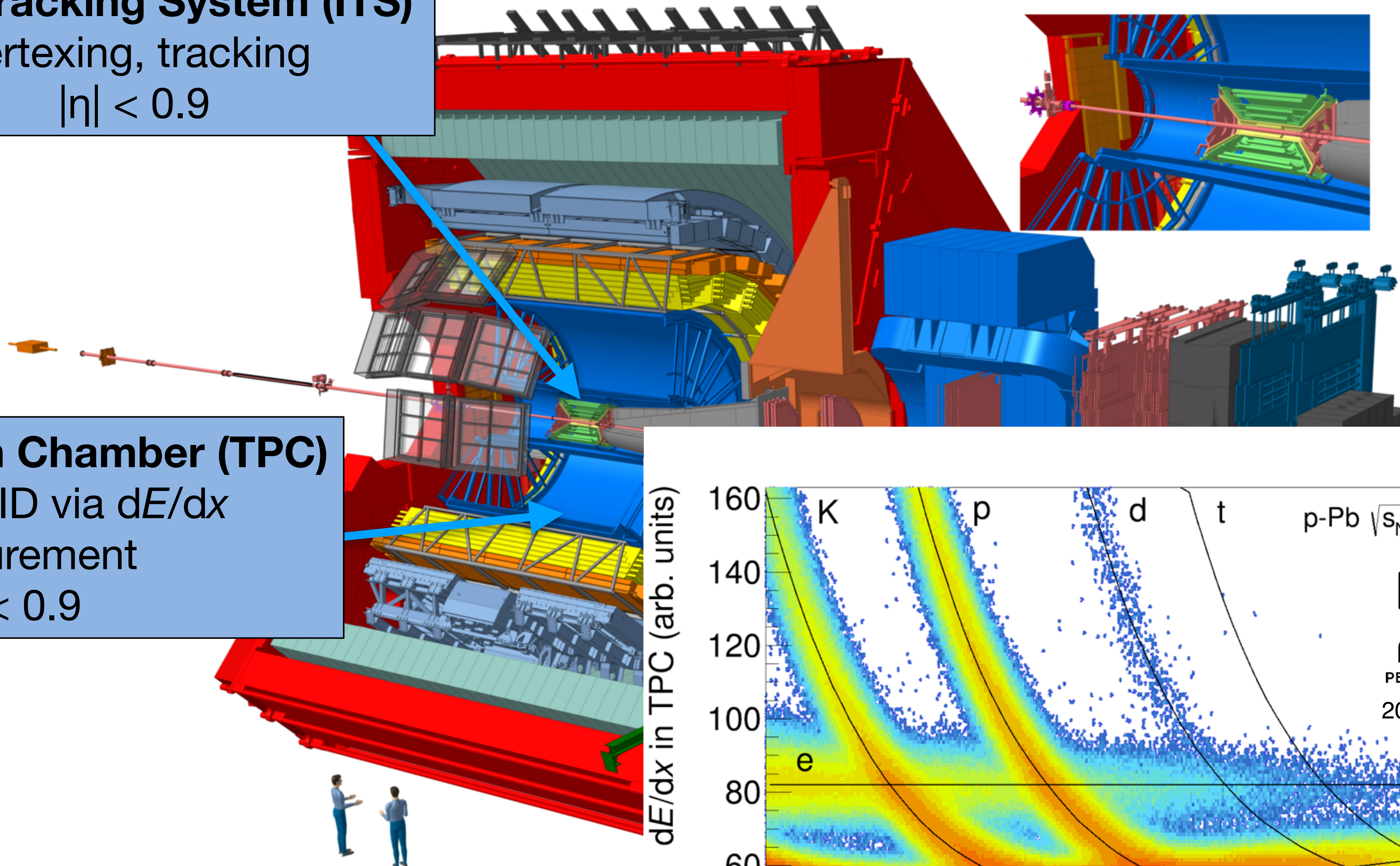
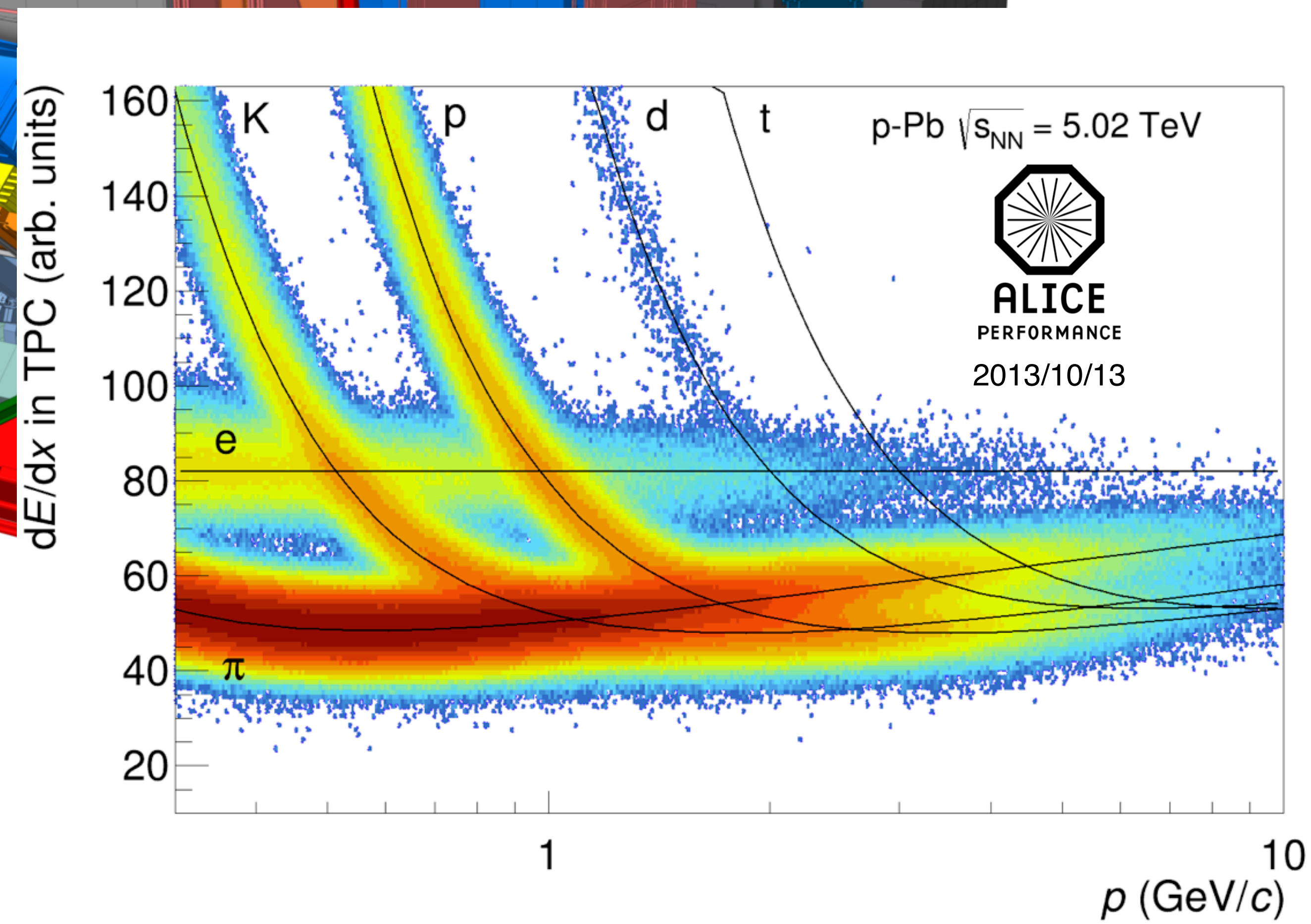


Time Projection Chamber (TPC)
Tracking, PID via d*E*/dx measurement
|η| < 0.9



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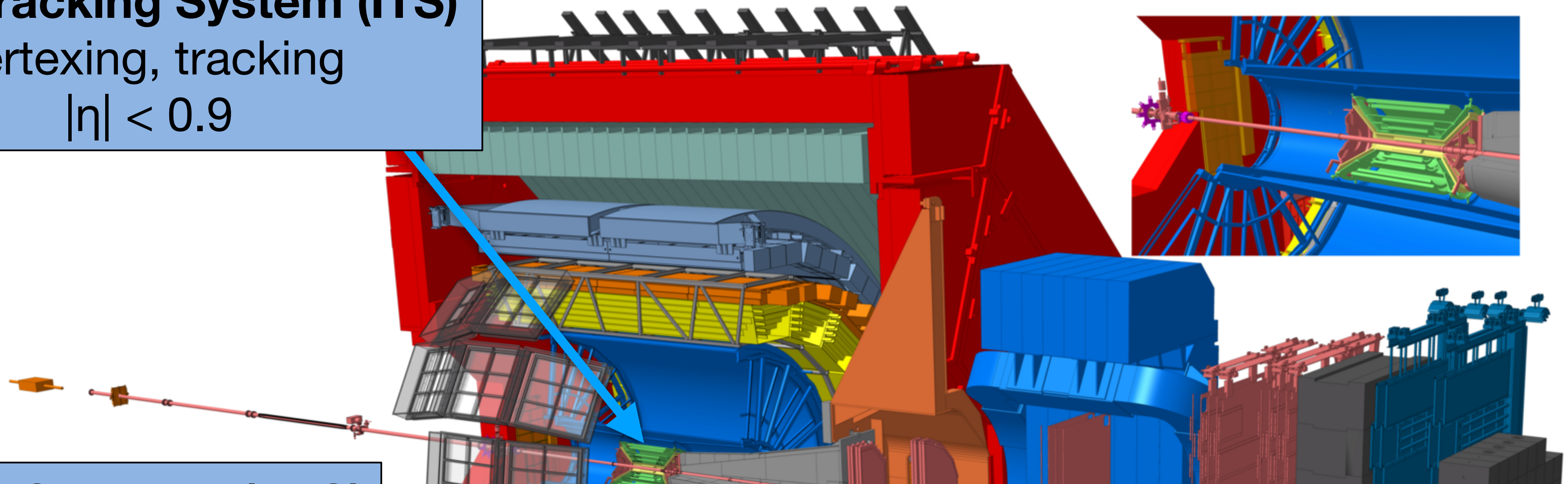
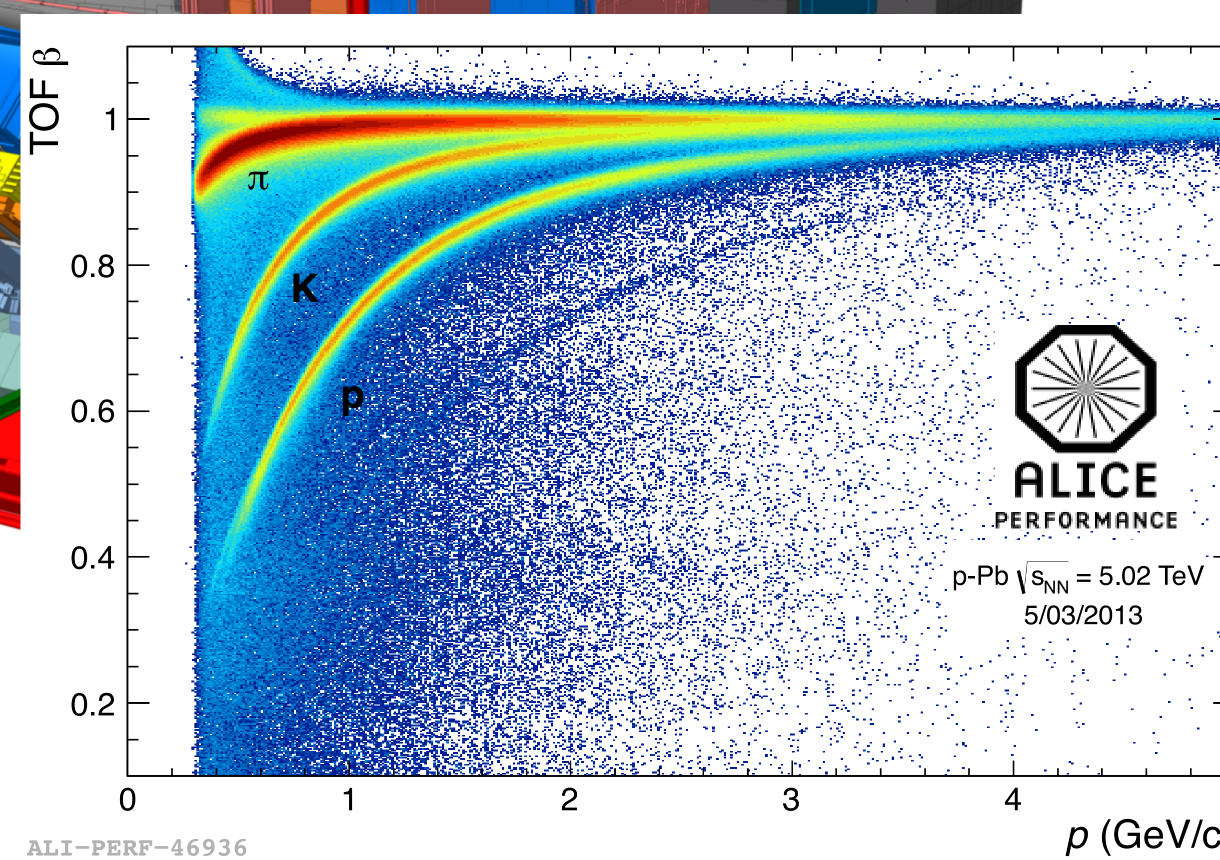
Time Projection Chamber (TPC)
Tracking, PID via d*E*/d*x* measurement
$|\eta| < 0.9$

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





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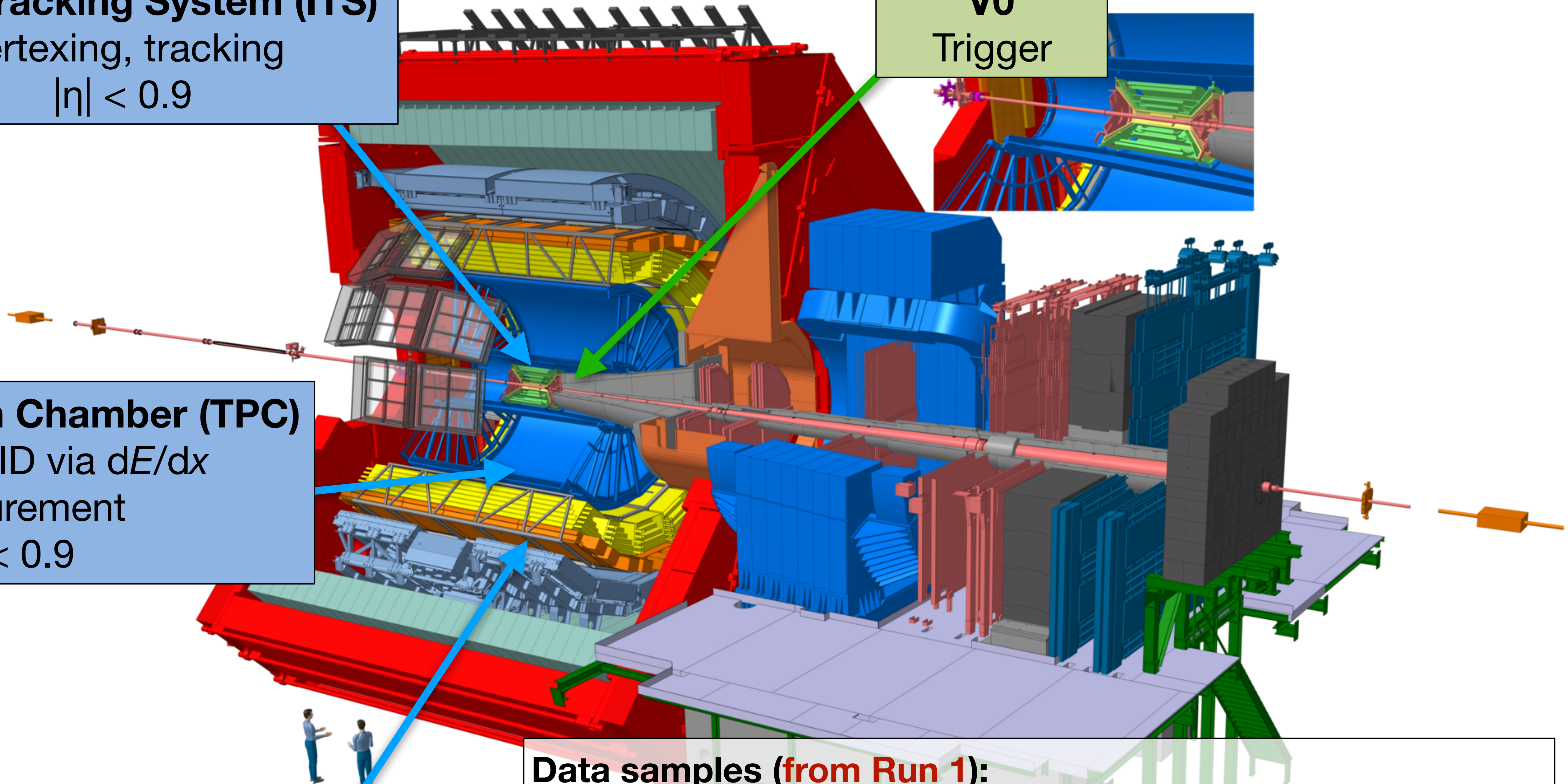
V0
Trigger



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 :** ~400x10^6 min. bias events, L_{int} = 6.0 nb^{-1}

p-Pb collisions: min. bias trigger using V0

- **$\sqrt{s_{NN}}$ = 5.02 TeV :** ~100x10^6 min. bias events, L_{int} = 48.6 μb^{-1}

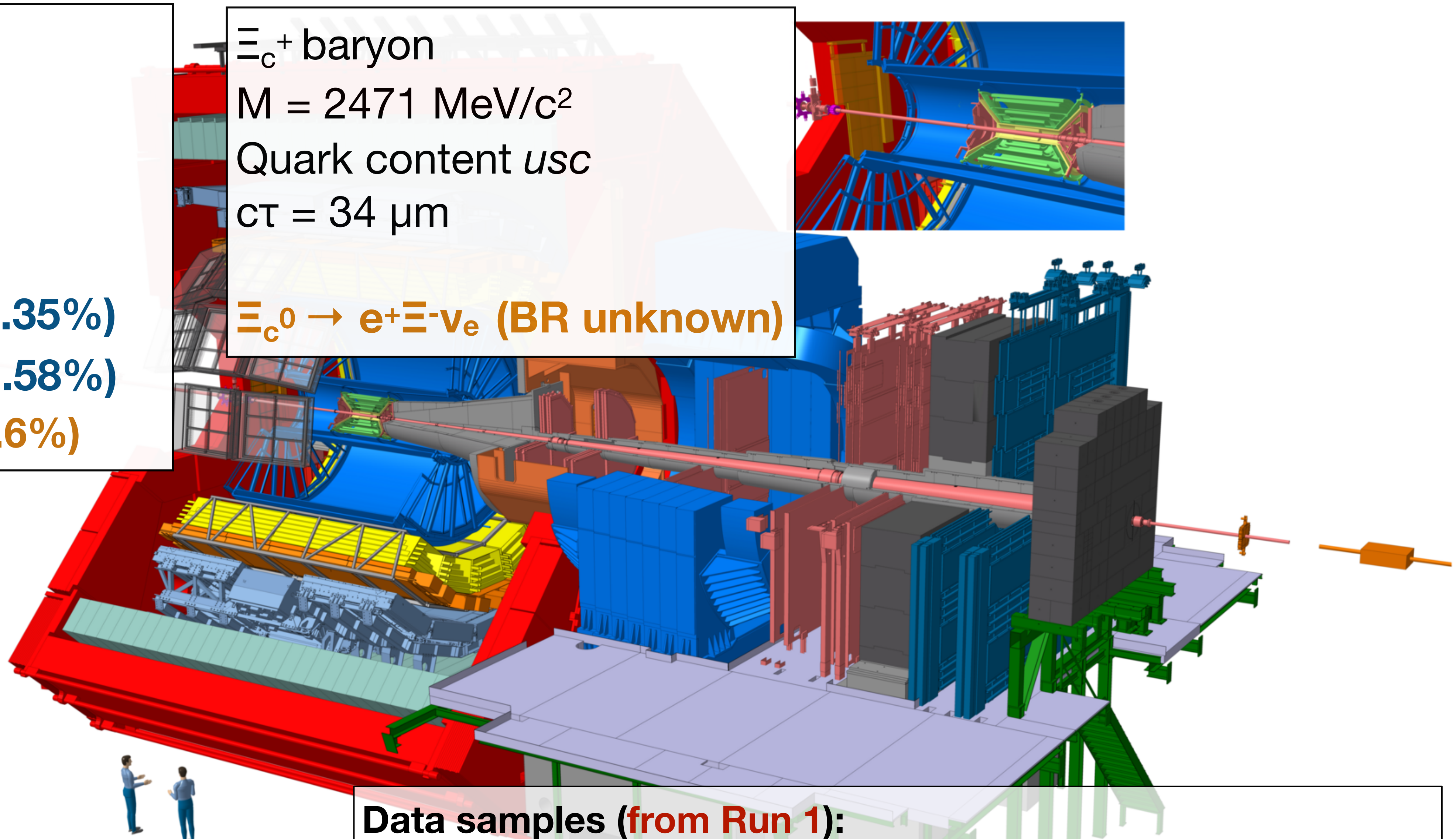
The ALICE apparatus

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

$\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR ~ 6.35%)
$\Lambda_c^+ \rightarrow pK^0_S$ (BR ~ 1.58%)
$\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$ (BR ~ 3.6%)

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

$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ (BR unknown)



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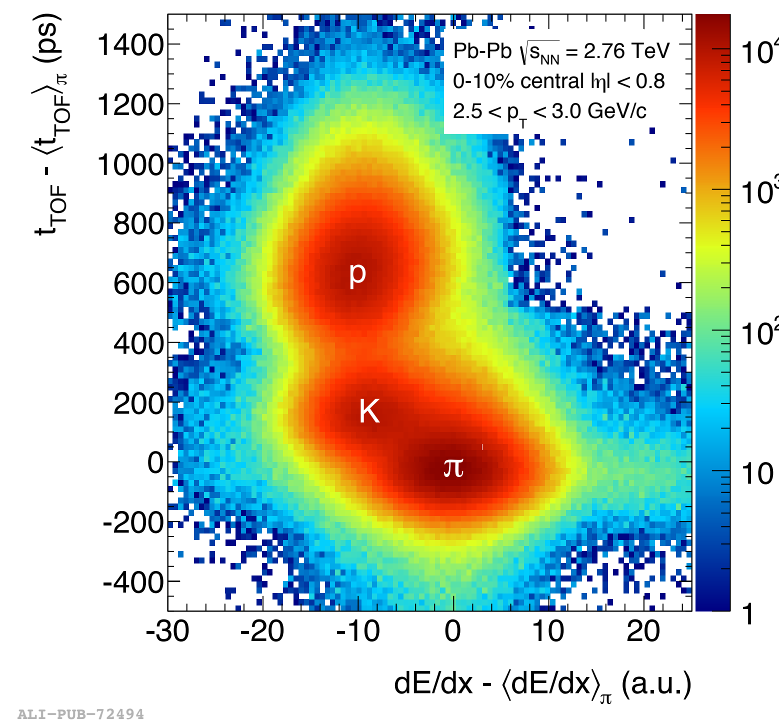
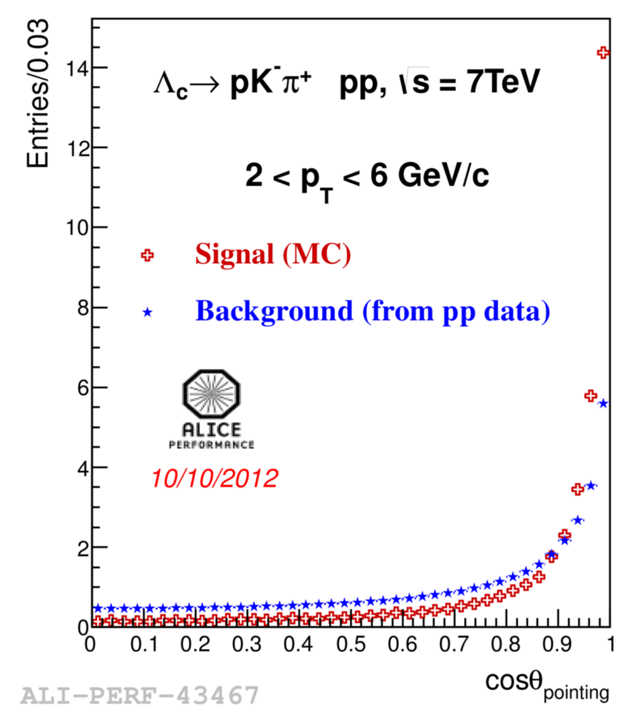
Charmed baryon reconstruction

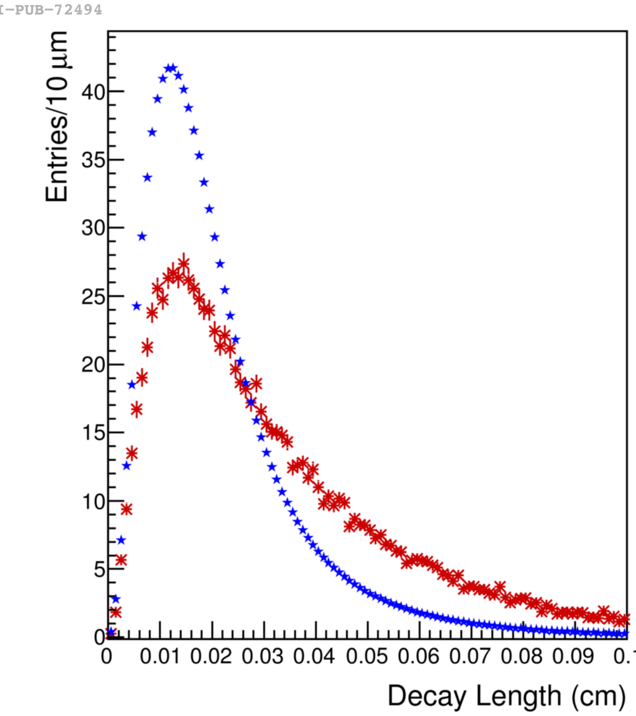
Hadronic decays

- **PID** using TPC via dE/dx 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 (BDT or rectangular cuts)
- **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

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





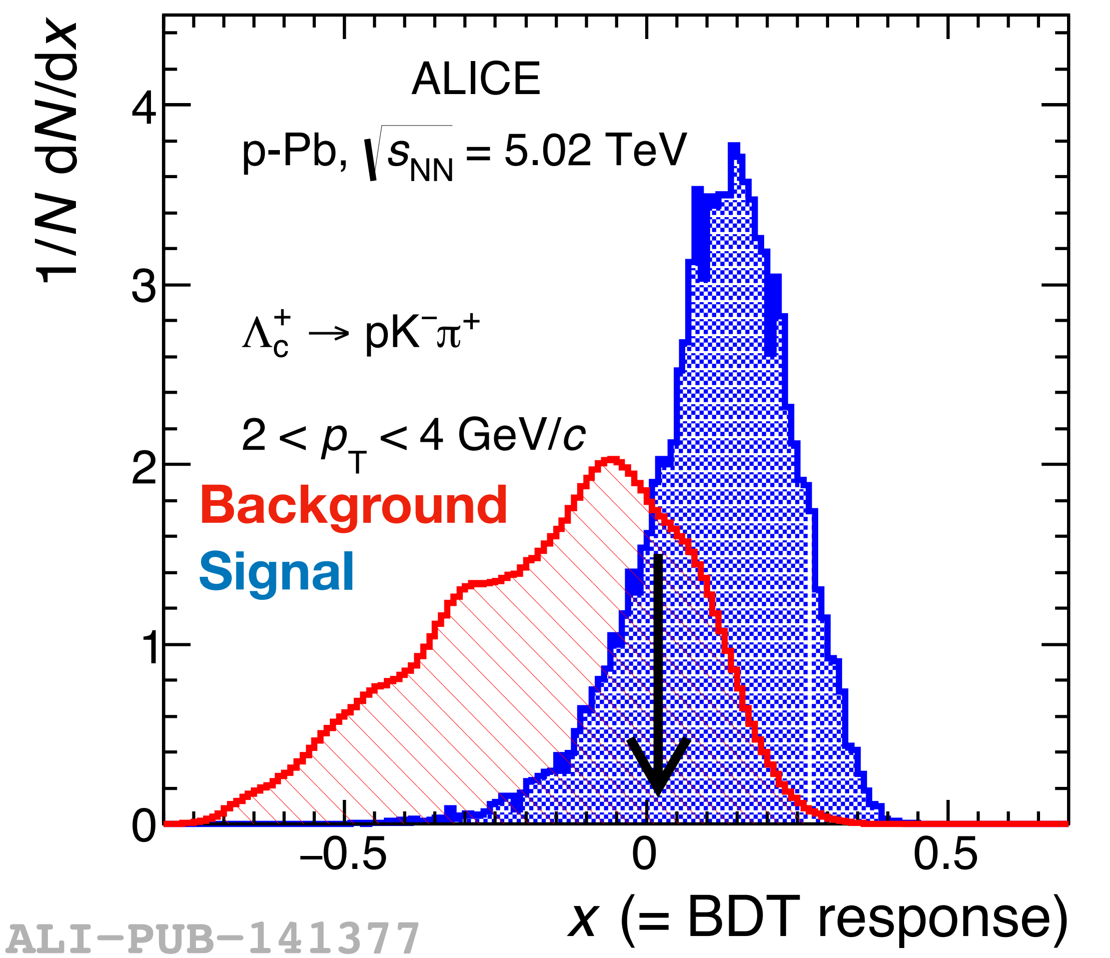


* See P. Antonioli CERN seminar "PID with a Bayesian approach in ALICE"

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



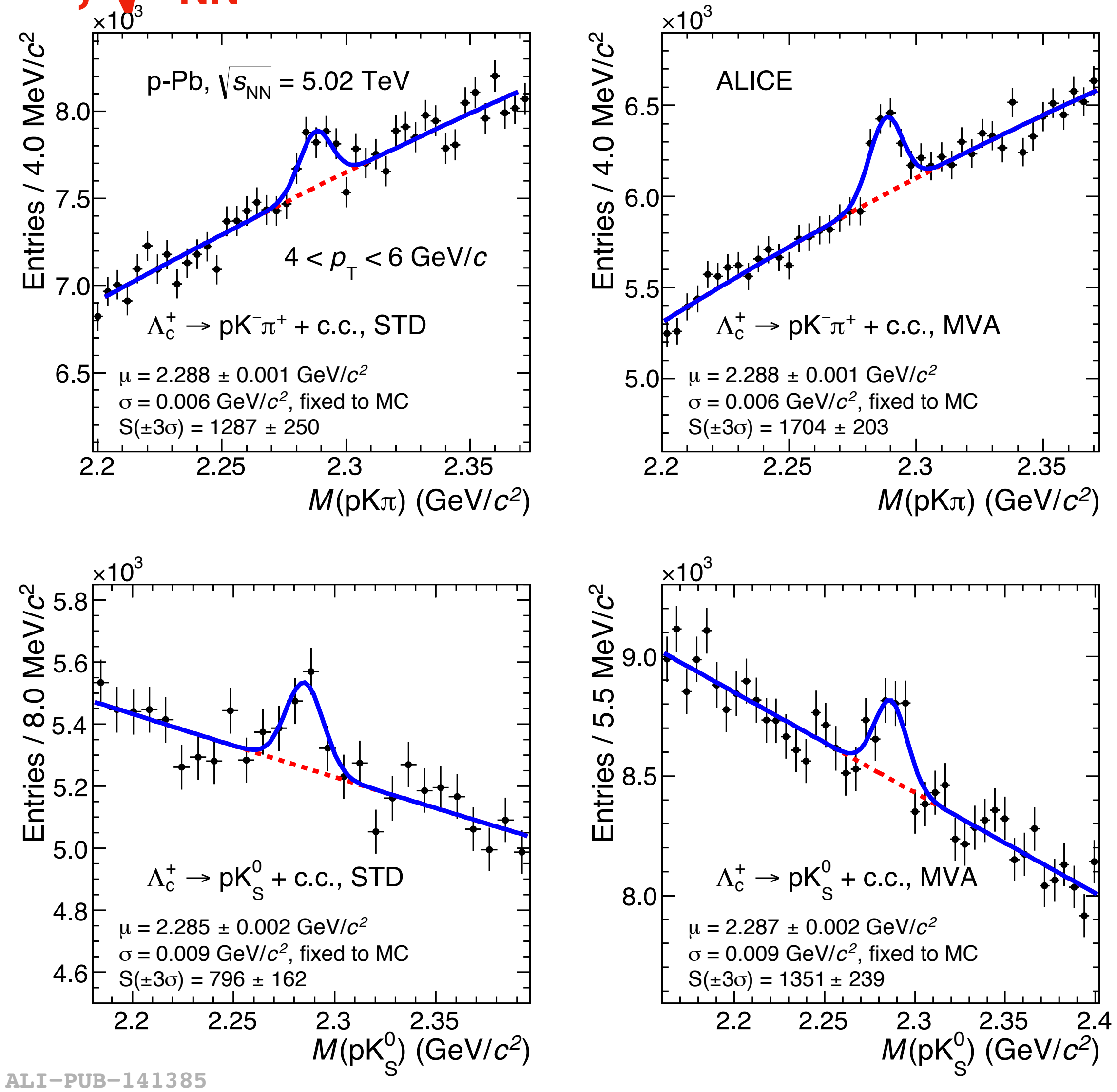
Analysis allows for slightly better statistical precision + gain in signal efficiency

TMVA: PoS(ACAT)040

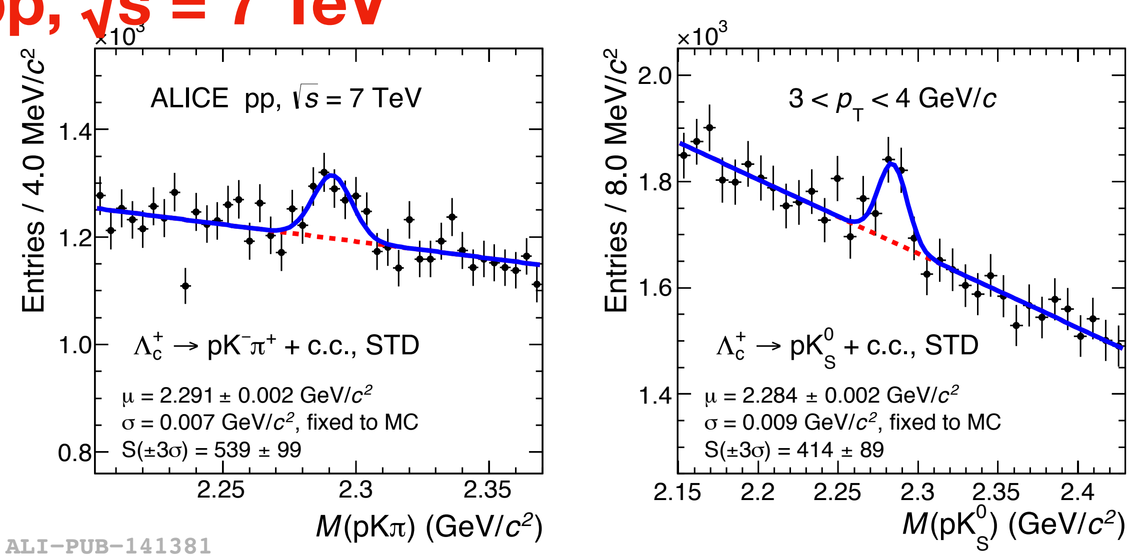
Charmed baryon signal extraction

Hadronic decays

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



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



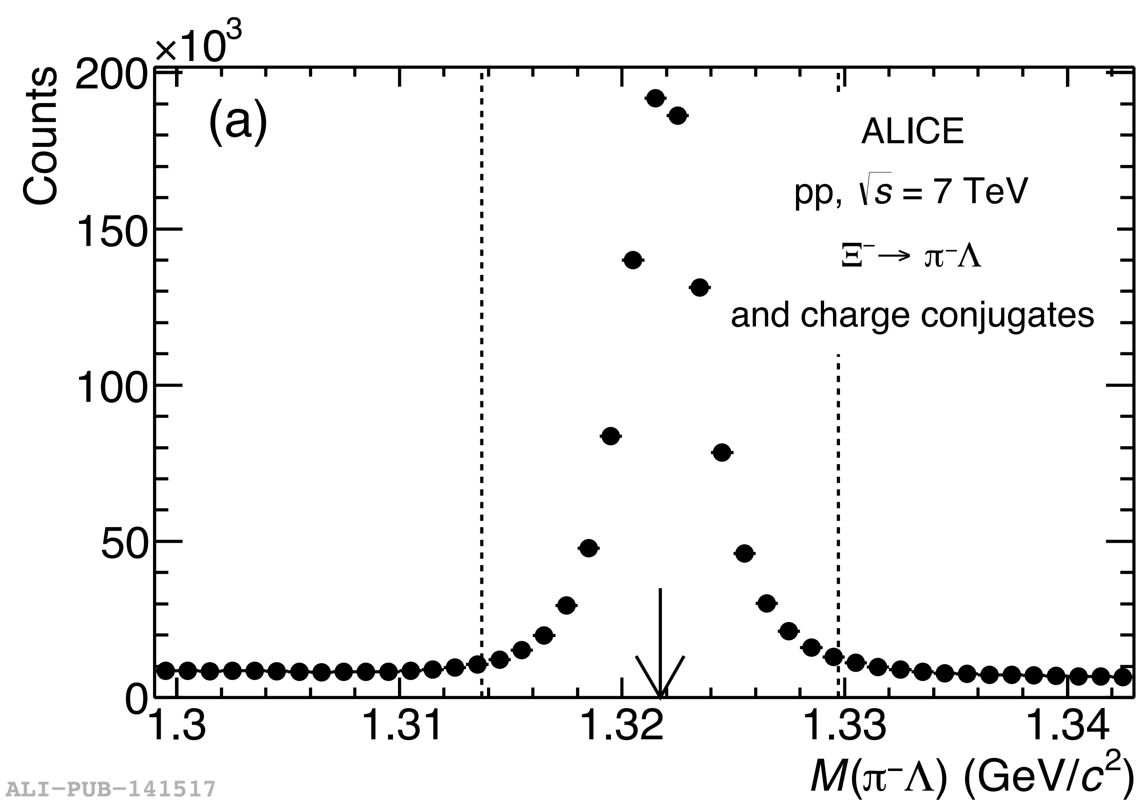
- Signal extracted from $2 < p_T < 12$ GeV/c in p-Pb collisions
- Signal extracted from $2 < p_T < 8$ GeV/c in pp collisions

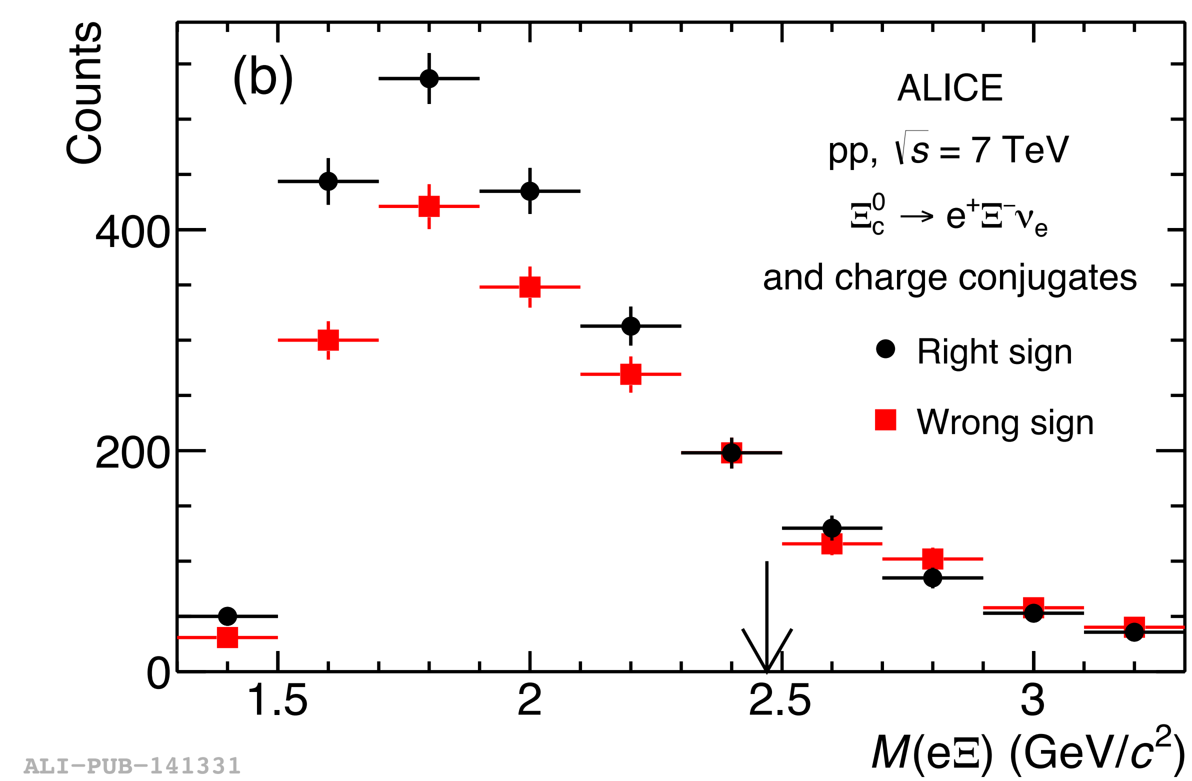
Charmed baryon reconstruction

Semileptonic decays

- **PID** using TPC via d*E*/d*x* and TOF via time of flight measurement
  - Λ, Ξ candidates reconstructed
  - Photonic electrons removed from electron candidate sample
  - eΛ (eΞ) pairs with opening angle < 90° constructed
- **Wrong-sign (WS)** $e^-\Lambda$ ($e^-\Xi^-$) pairs subtracted from **right-sign (RS)** spectra $e^+\Lambda$ ($e^+\Xi^-$)

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





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

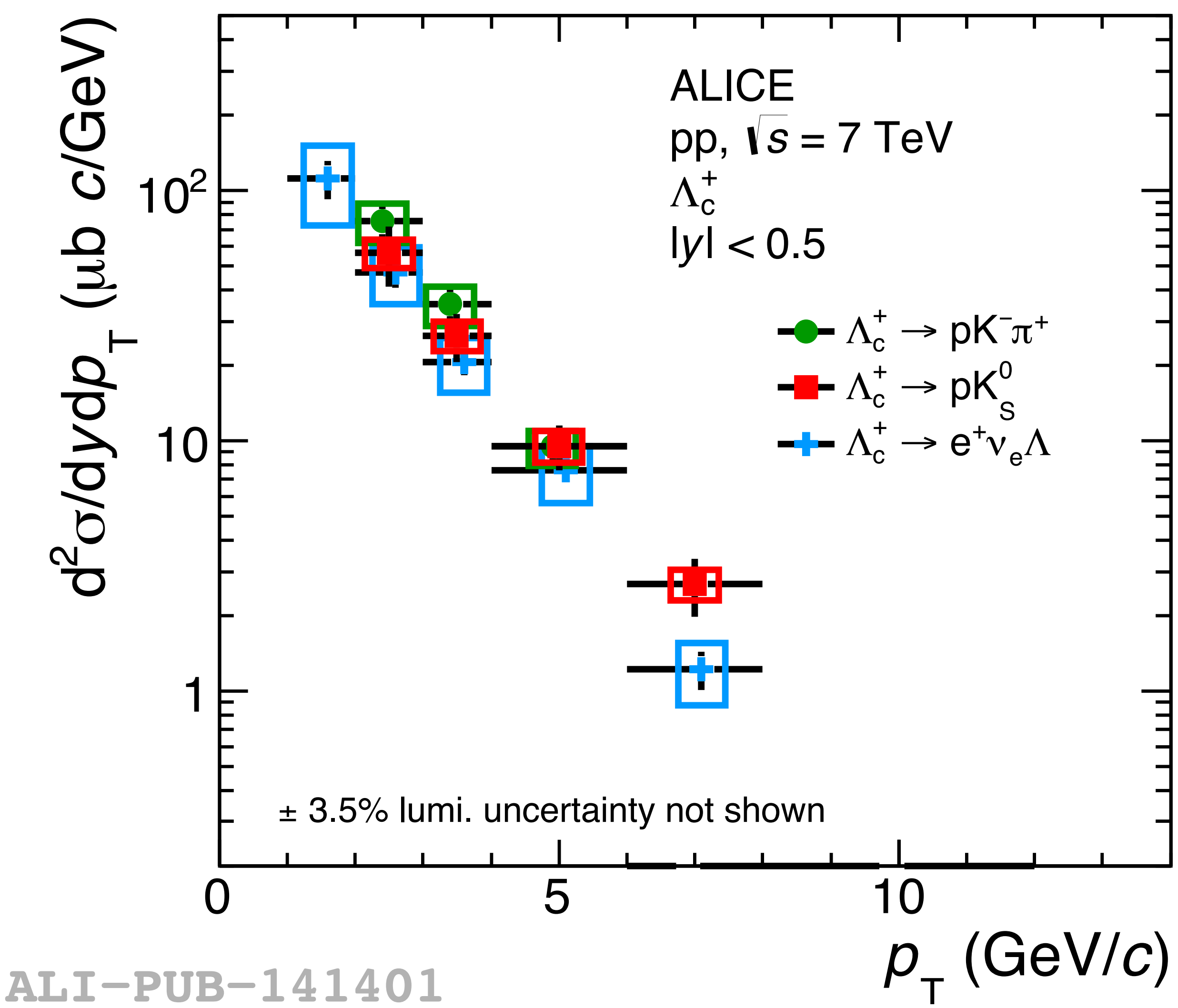
Systematic unc. source	$\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$		$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$	
	Low p_T (%)	High p_T (%)	Low p_T (%)	High p_T (%)
Yield extraction	17	17	5	5
Efficiency, acceptance	28	13	30	14
Missing neutrino momentum	3	11	29	10
B feed-down	negl.	$^{+1}_{-7}$	-	
BR	11		-	

Luminosity uncertainty = 3.5%

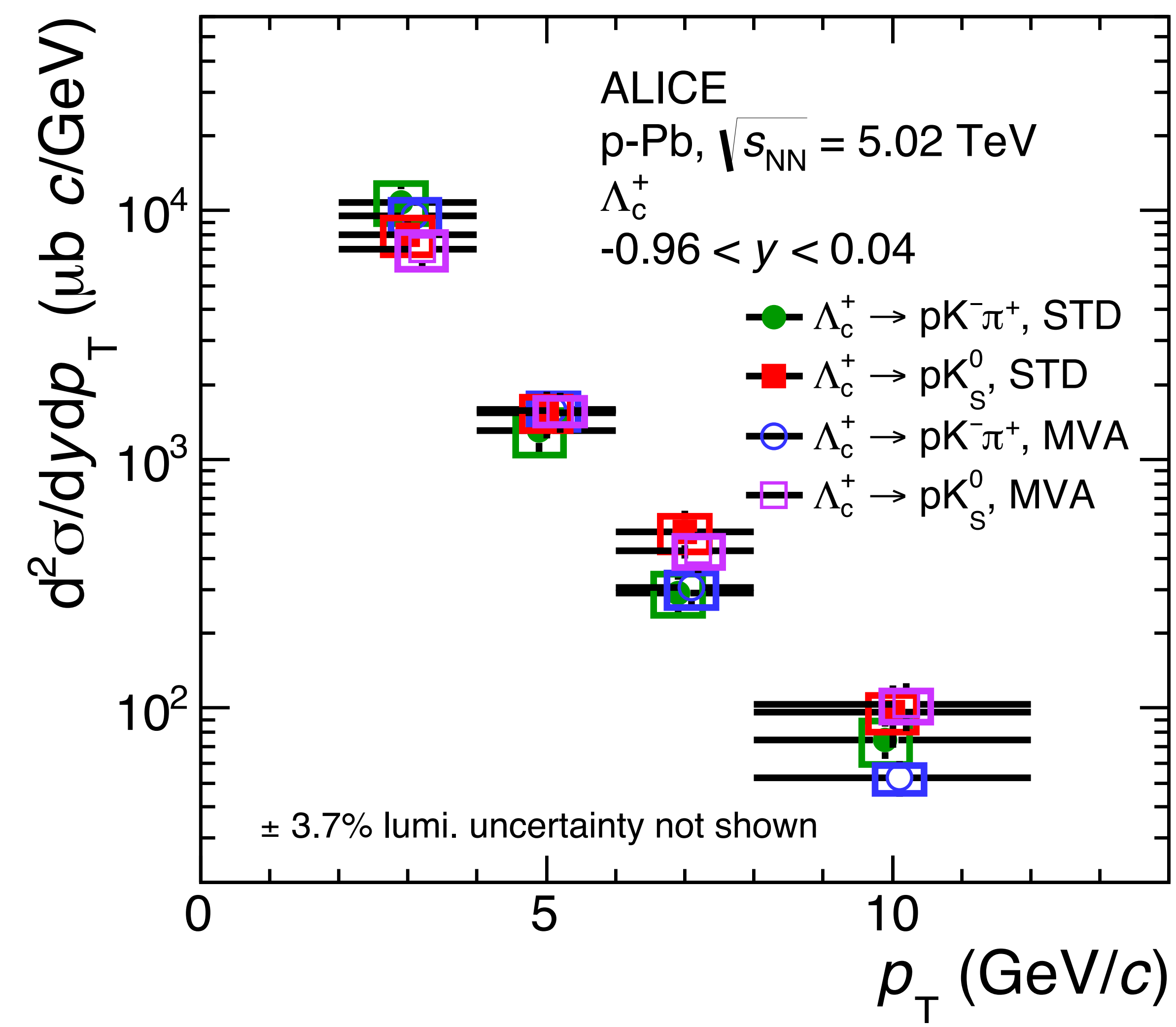
Results

Λ_c^+ p_T-differential cross sections

pp collisions



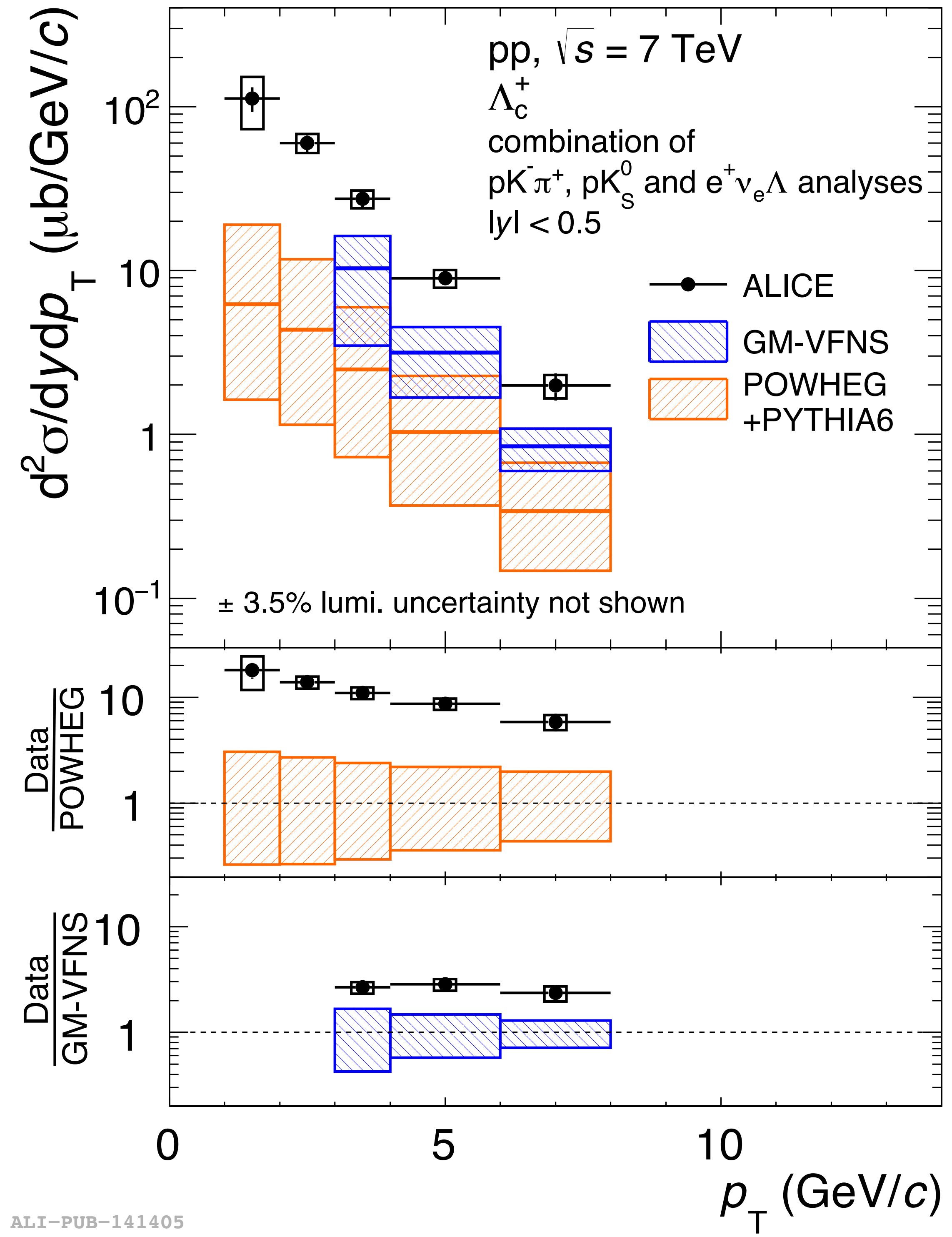
p-Pb collisions



- Good agreement between different decay channels + analysis methods

Λ_c^+ p_T-differential cross section in pp collisions

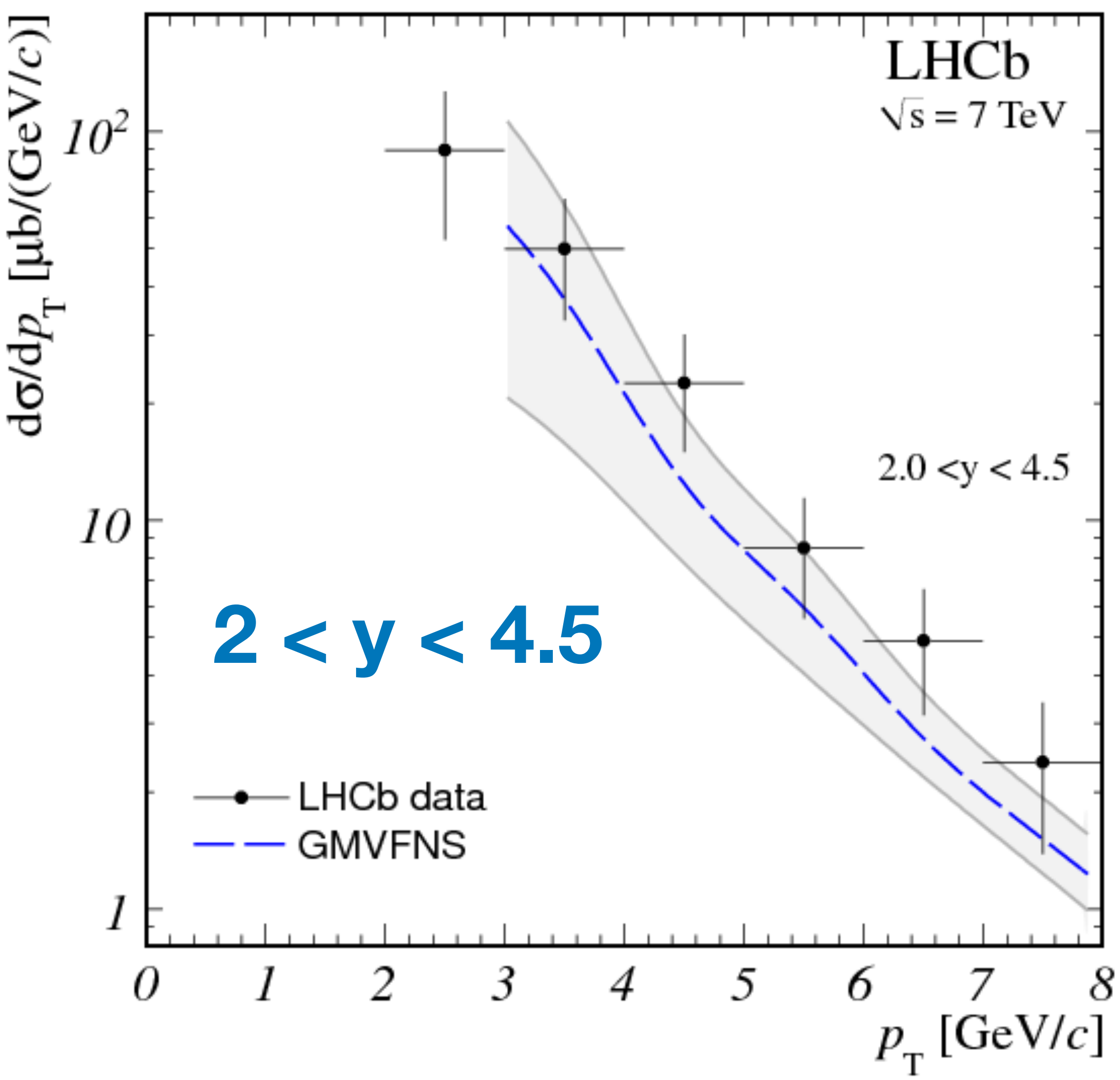
- Λ_c^+ p_T-differential cross section **significantly underestimated** by theory
  - **GM-VFNS:** Next-to-leading order QCD with logarithms resumed to next-to-leading order
    - Non-perturbative fragmentation estimated from e^+e^- collision data **B.A. Kniehl, G. Kramer: Phys. Rev. D 74 (2006) 037502**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

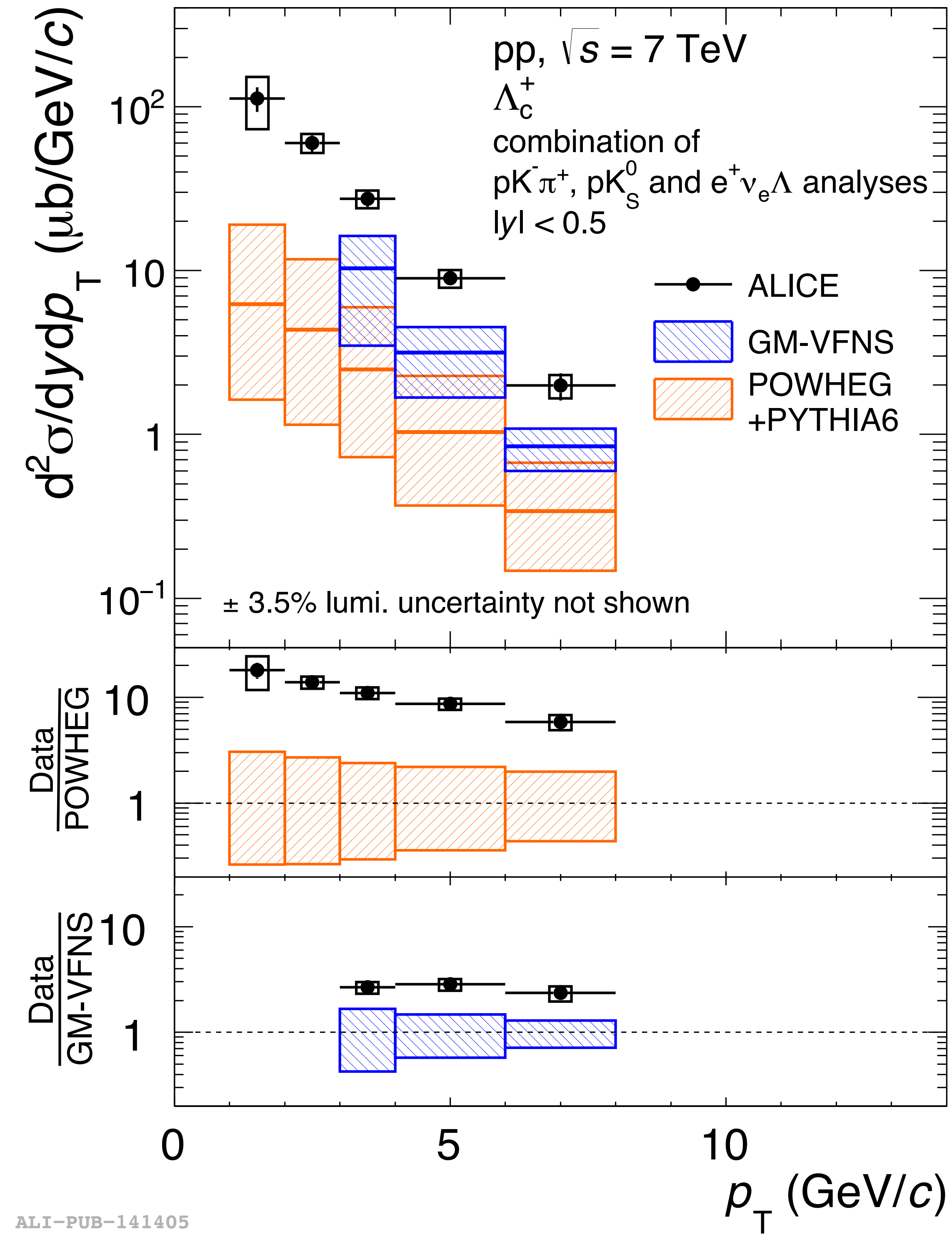


GM-VFNS: B.A. Kniehl et al. Eur. Phys. J. C 41 (2005), Eur. Phys. J. C 72 (2012) 2082
POWHEG: S. Frixione et al.: JHEP 09 (2007) 126

Λ_c^+ p_T-differential cross section in pp collisions

LHCb: Nucl. Phys.B871 (2013) 1–20

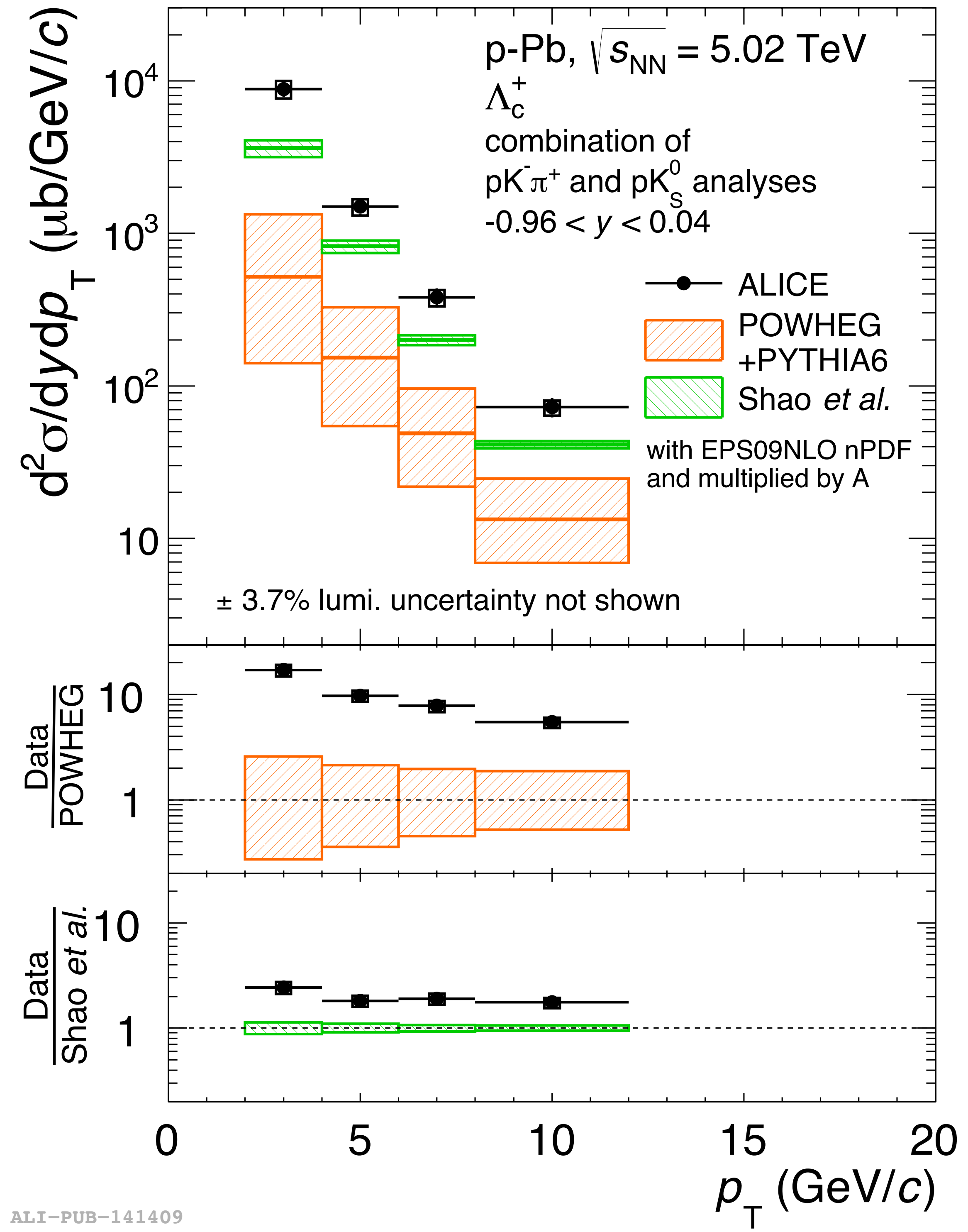




- Λ_c^+ production at forward rapidity described by GM-VFNS

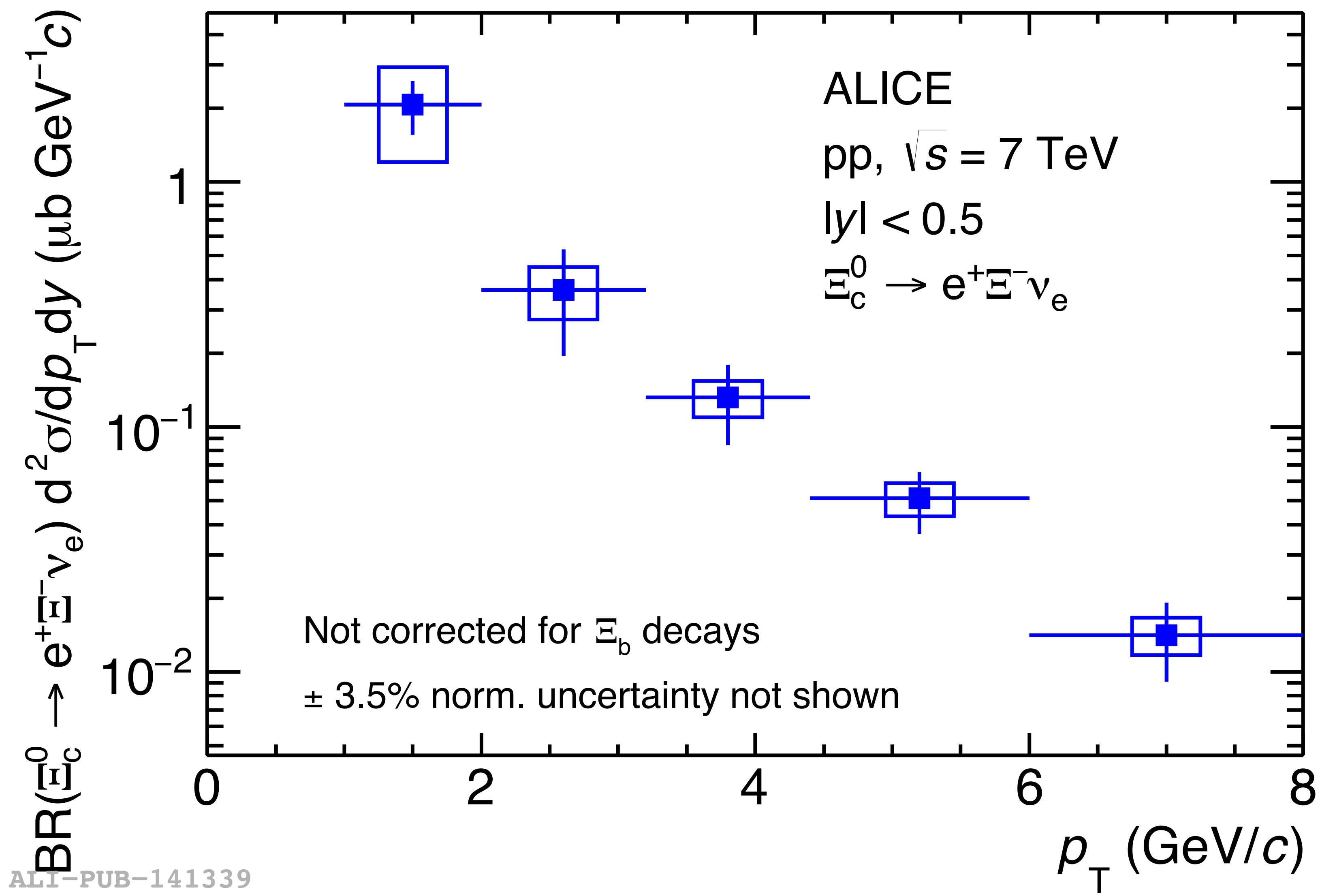
Λ_c^+ p_T-differential cross section in p-Pb collisions

- 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



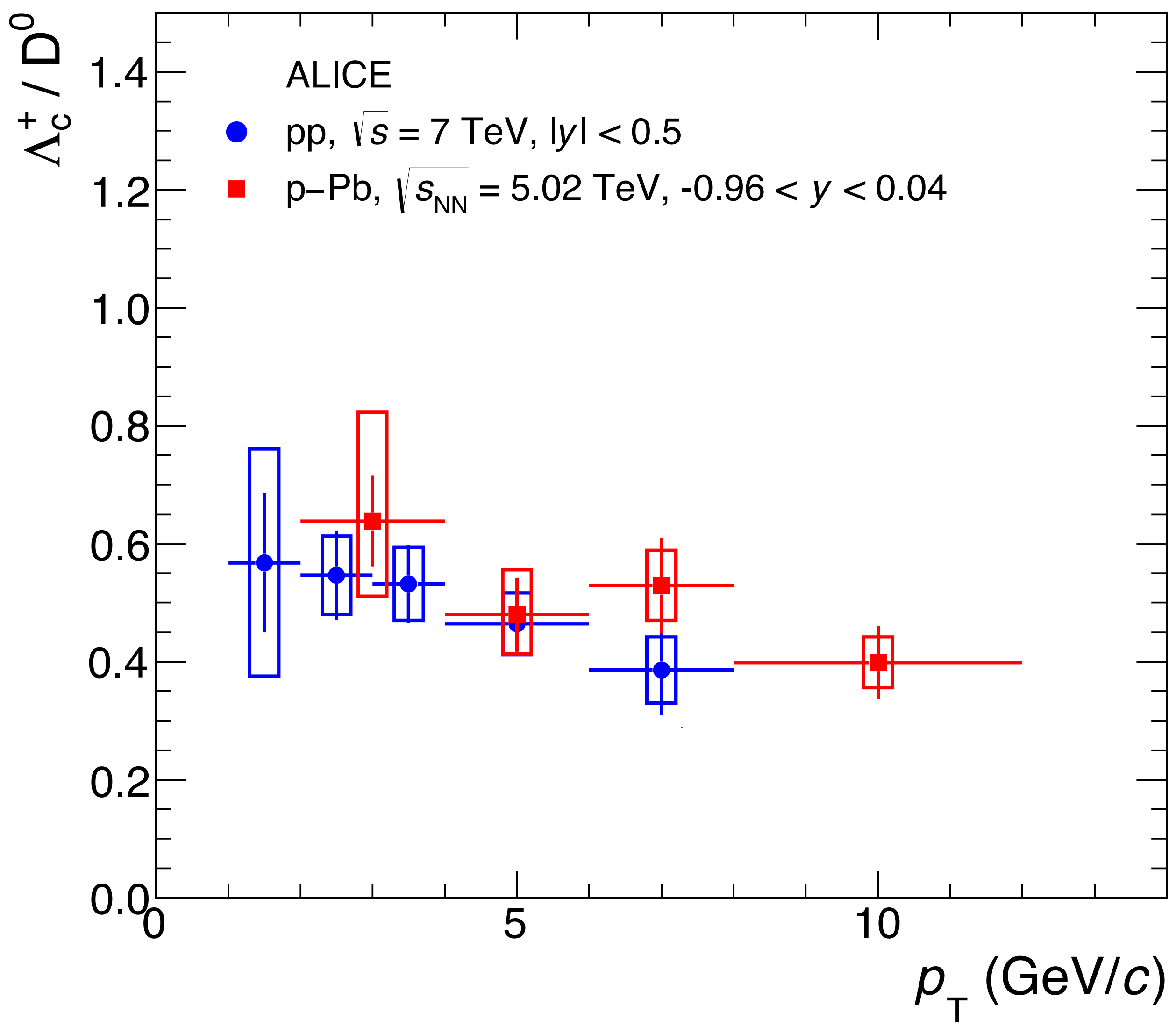
POWHEG: S. Frixione et al.: JHEP 09 (2007) 126
Shao et al: Eur. Phys. J. C 77 (2017)

Ξ_c^0 p_T-differential cross section in pp collisions

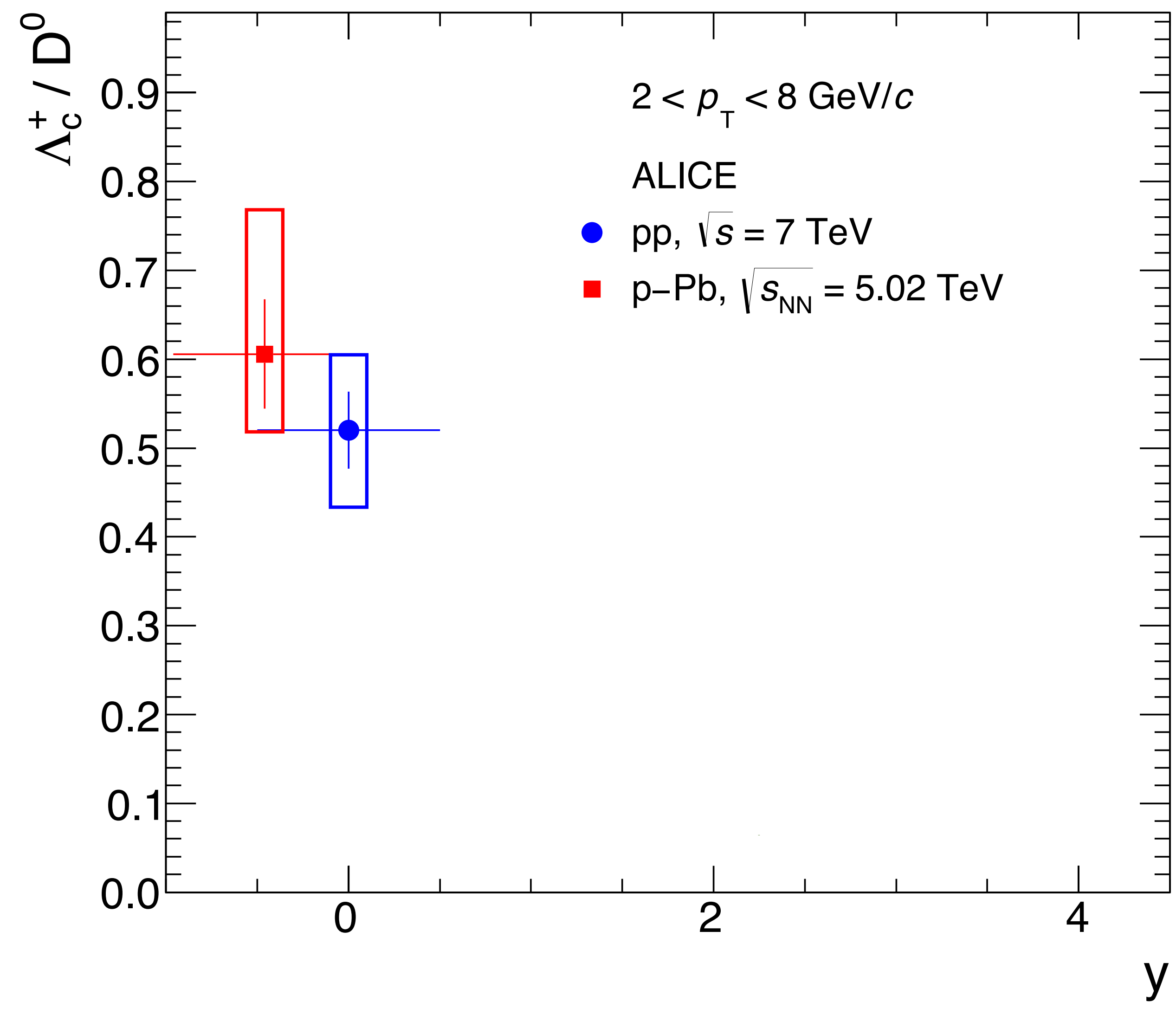


- Ξ_c^0 production cross-section-times-branching-ratio measured from $1 < p_T < 8$ GeV/c
    - Not feed-down corrected - includes $\Xi_b \rightarrow \Xi_c^0 X \rightarrow e^+\Xi^-\nu_e$

Λ_c^+/D^0 baryon-to-meson ratio



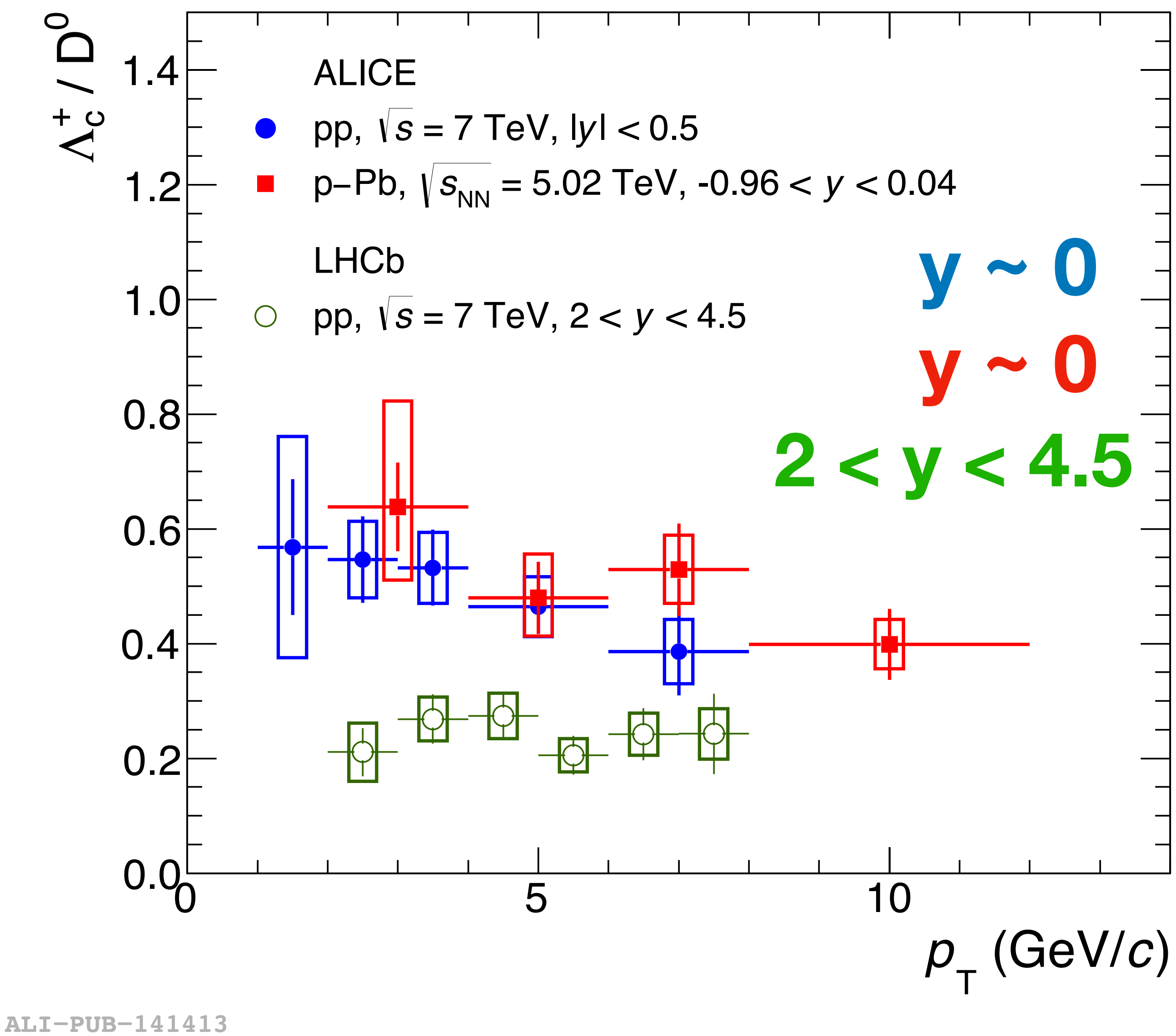
ALI-PUB-141413

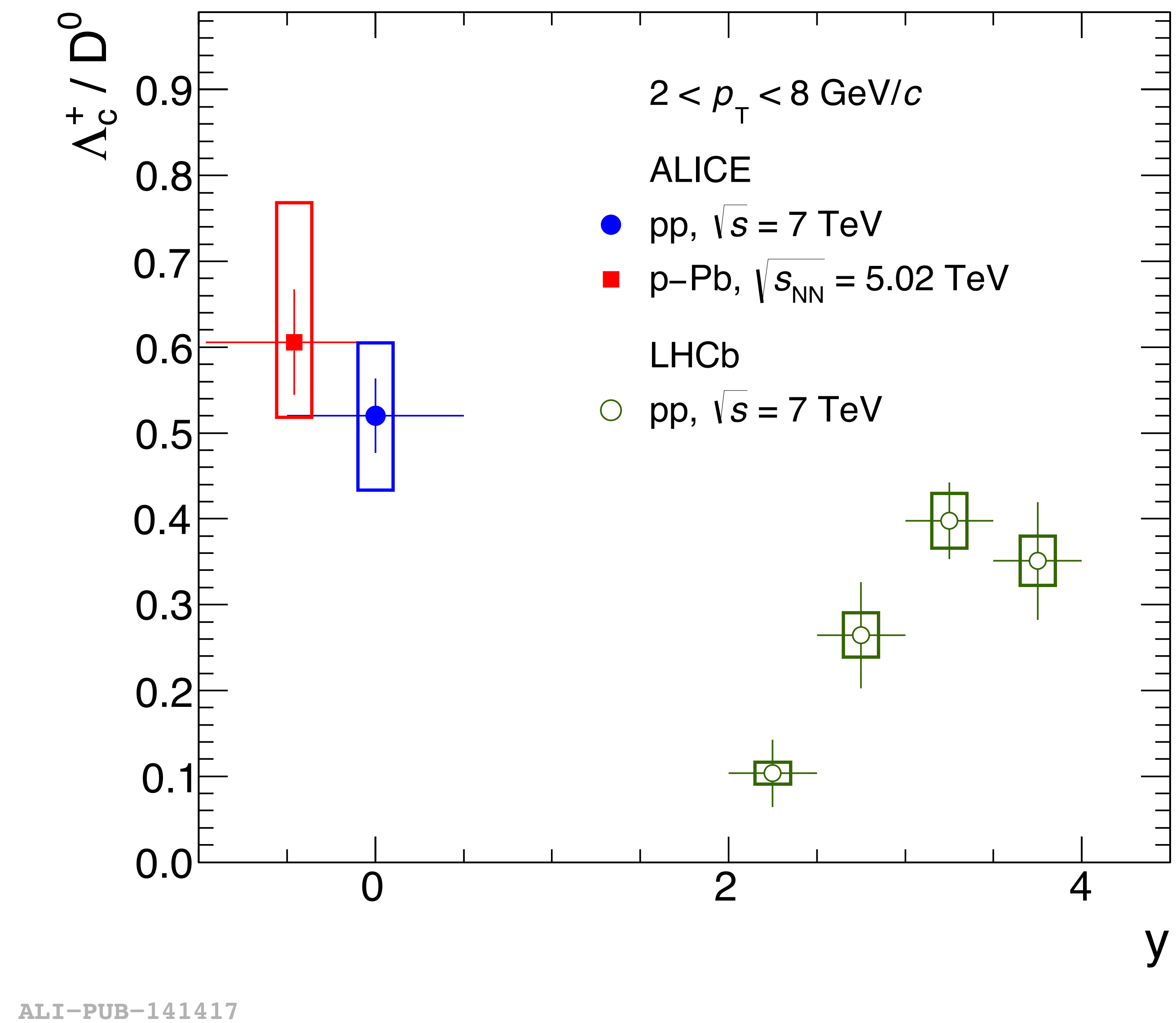


ALI-PUB-141417

- Λ_c^+/D^0 in pp and p-Pb collisions **compatible within uncertainties**

Λ_c^+/D^0 baryon-to-meson ratio





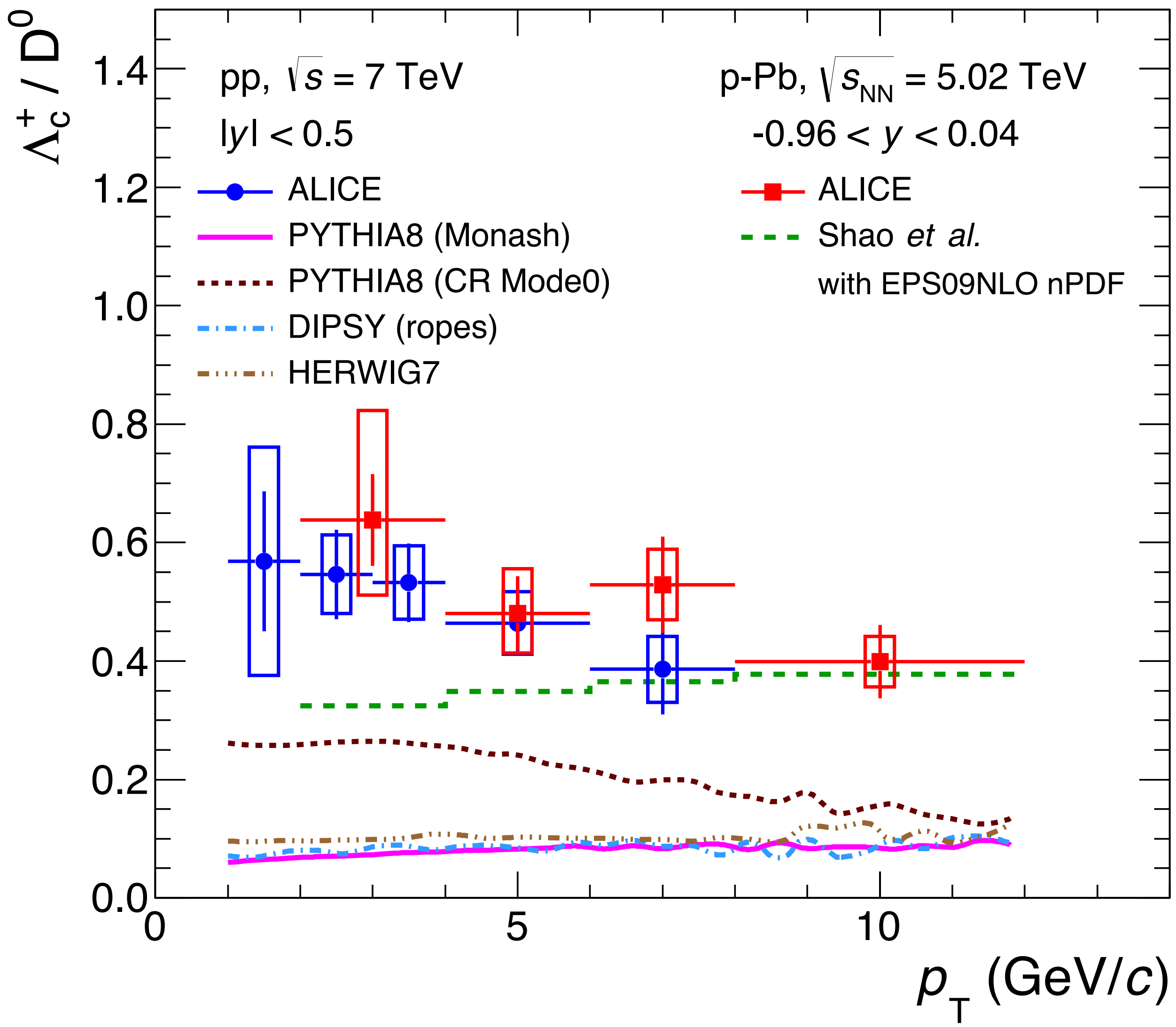
- Λ_c^+/D^0 in pp and p-Pb collisions **compatible within uncertainties**
- ALICE measurement **systematically higher** than LHCb

Λ_c^+/D^0 baryon-to-meson ratio

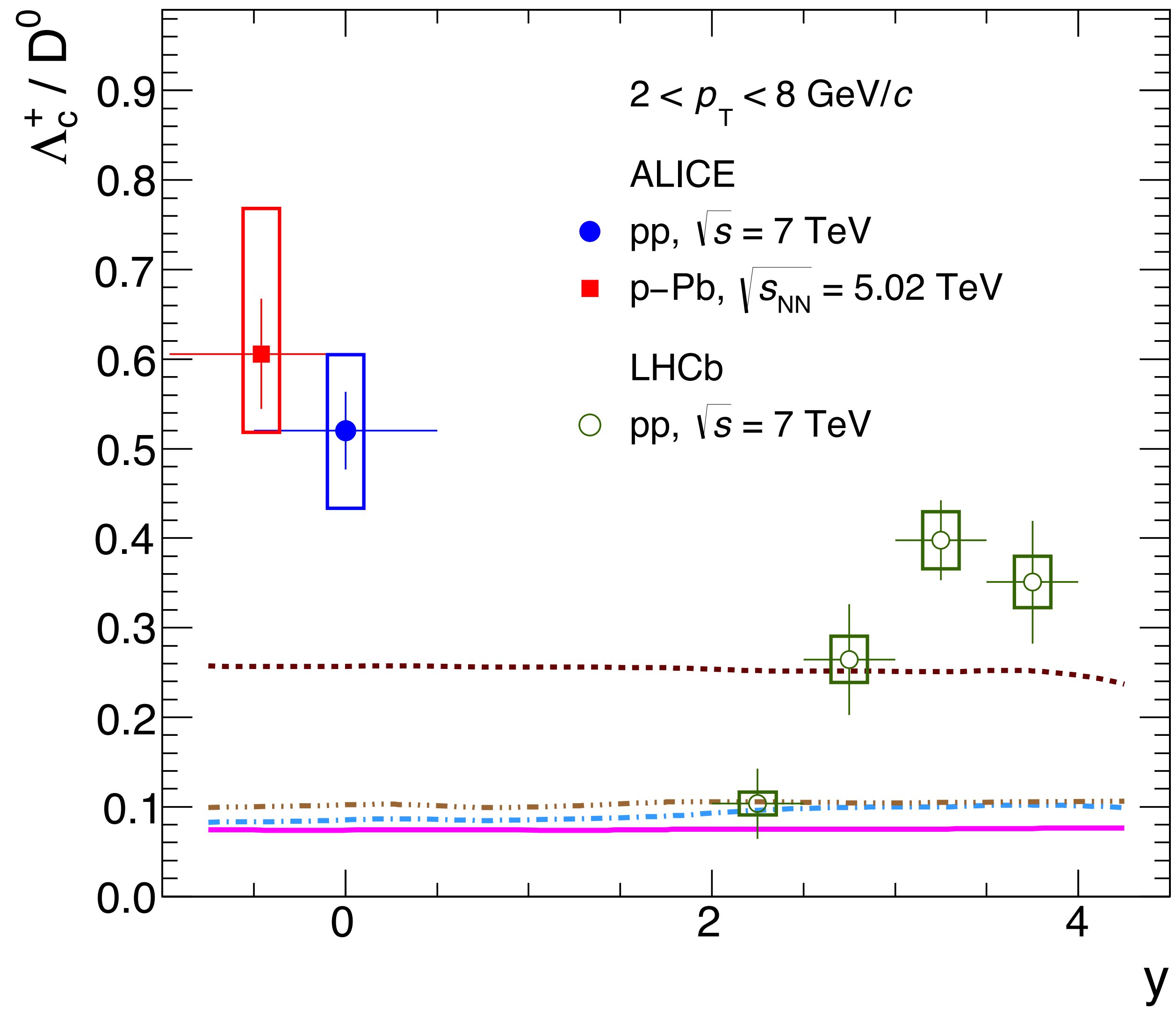
Measurement	Λ_c^+/D^0 ± stat. ± syst.	System	√s (GeV)	Kinematics
CLEO	0.119 ± 0.021 ± 0.019	ee	10.55	
ARGUS	0.127 ± 0.031 (stat.+syst.)	ee	10.55	
LEP average	0.113 ± 0.013 ± 0.006	ee	91.2	
ZEUS DIS	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
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, $\|\eta\| < 1.6$
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, $\|\eta\| < 1.6$
ALICE	**0.543 ± 0.061 ± 0.160**	**pp**	**7000**	**$1 < p_T < 8$ GeV/c, $\|\eta\| < 0.5$**
ALICE	**$0.602 \pm 0.060^{+0.159}_{-0.087}$**	**pPb**	**5020**	**$2 < p_T < 12$ GeV/c, $\|\eta\| < 0.5$**

- 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

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



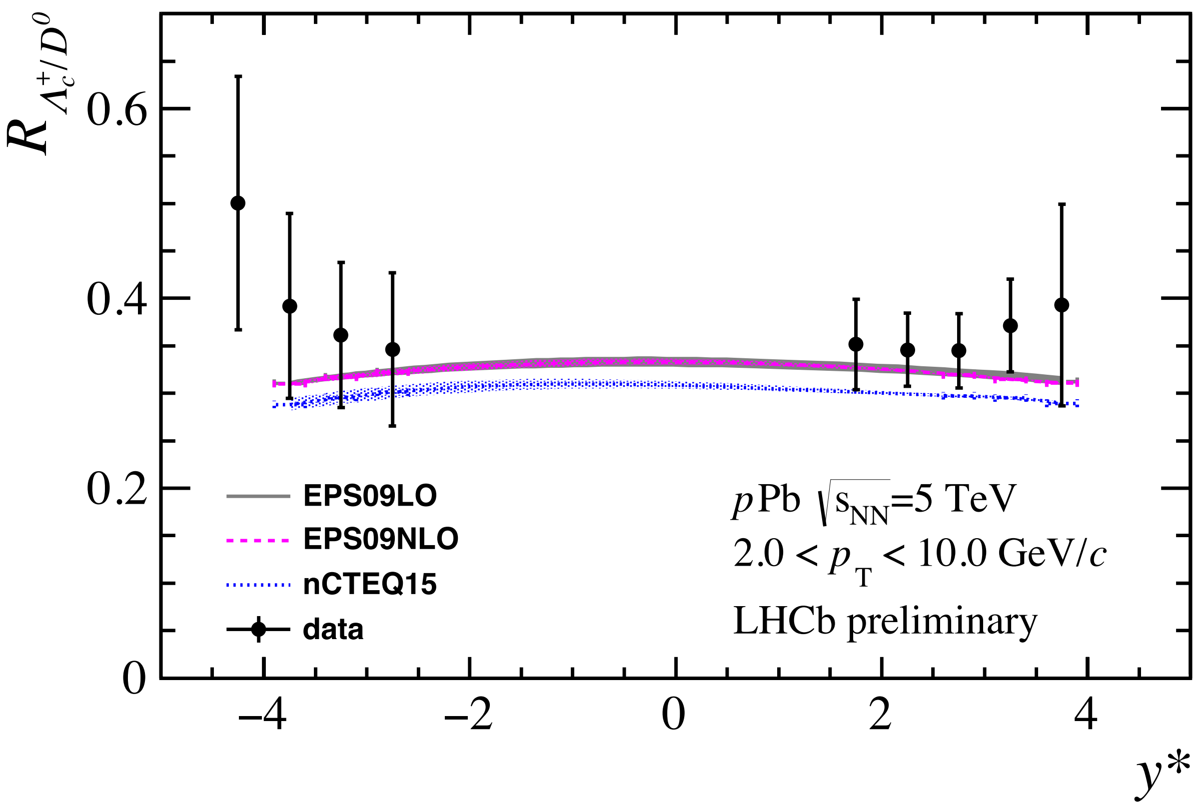
ALI-PUB-141421

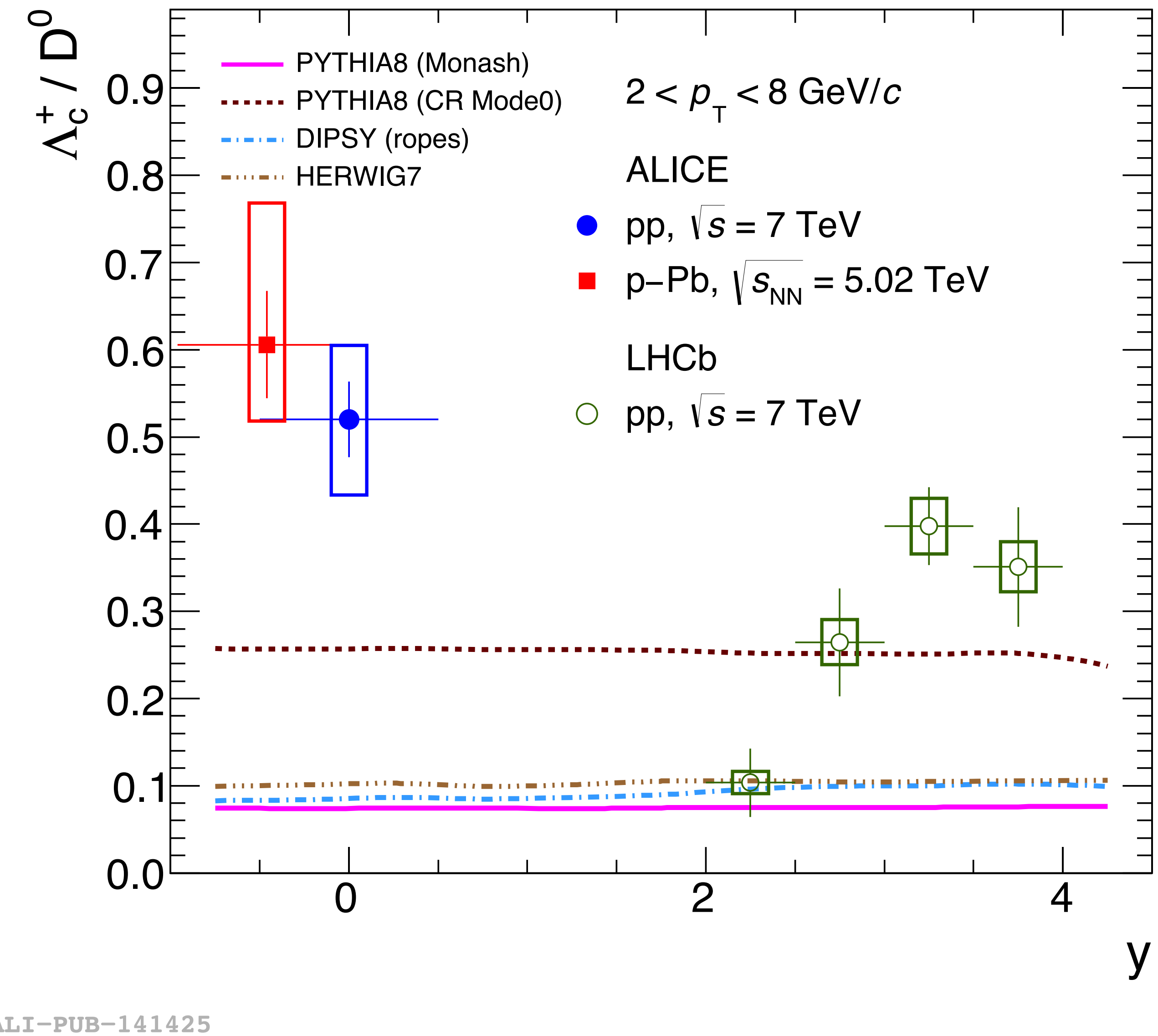


ALI-PUB-141425

- 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
- ***Shao et al.*** model (tuned on LHCb pp result) closer to data
- Flat rapidity trend predicted by models not reproduced by ALICE and LHCb measurements

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





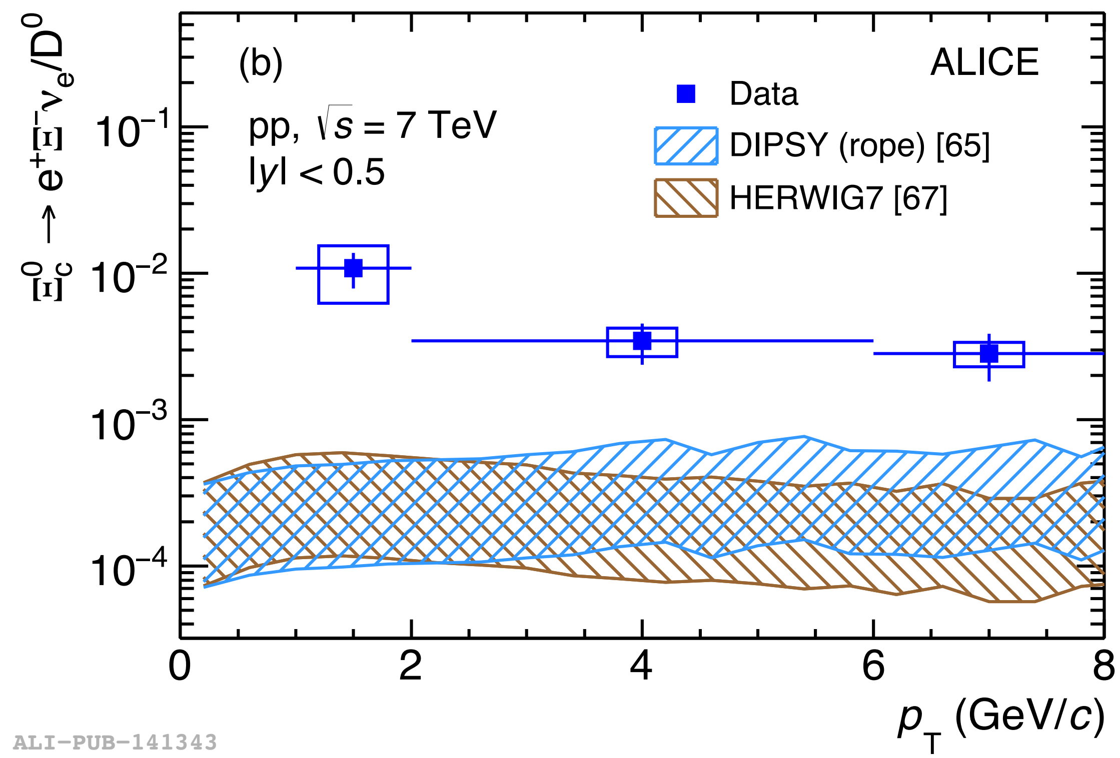
- Λ_c^+/D^0 in p-Pb collisions recently measured by the LHCb experiment shows a flatter trend with rapidity

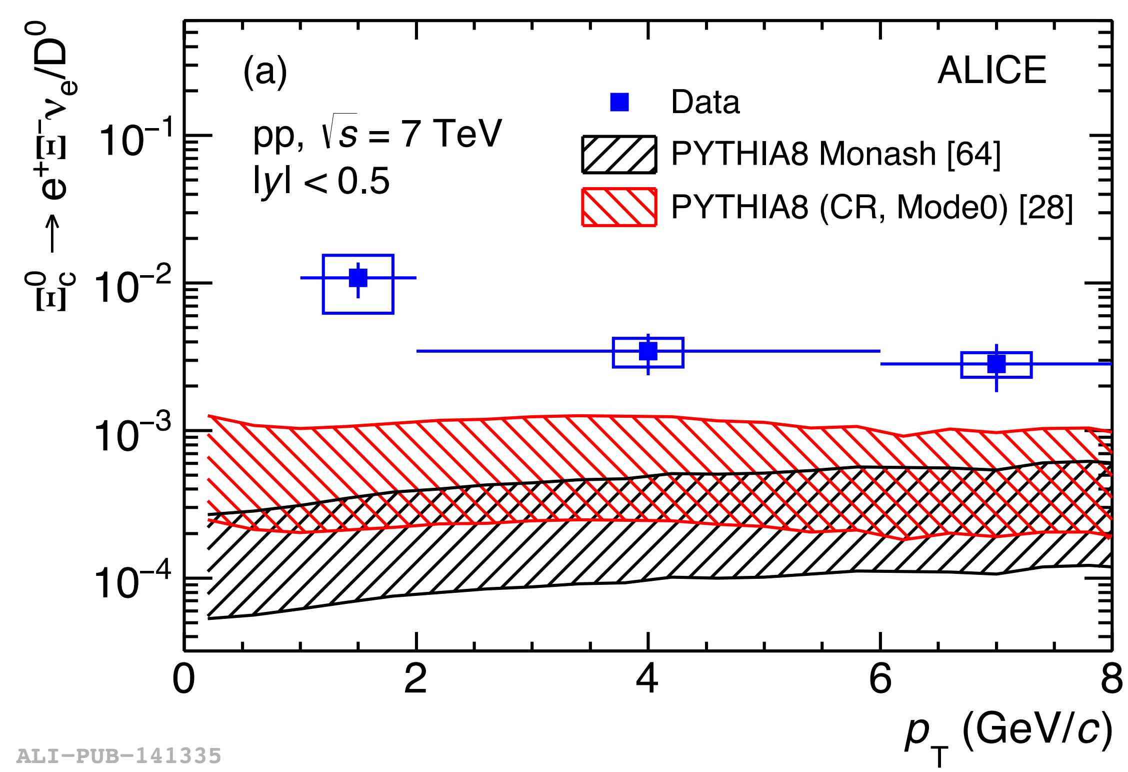
$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e / D^0$ baryon-to-meson ratio

- 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}

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

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

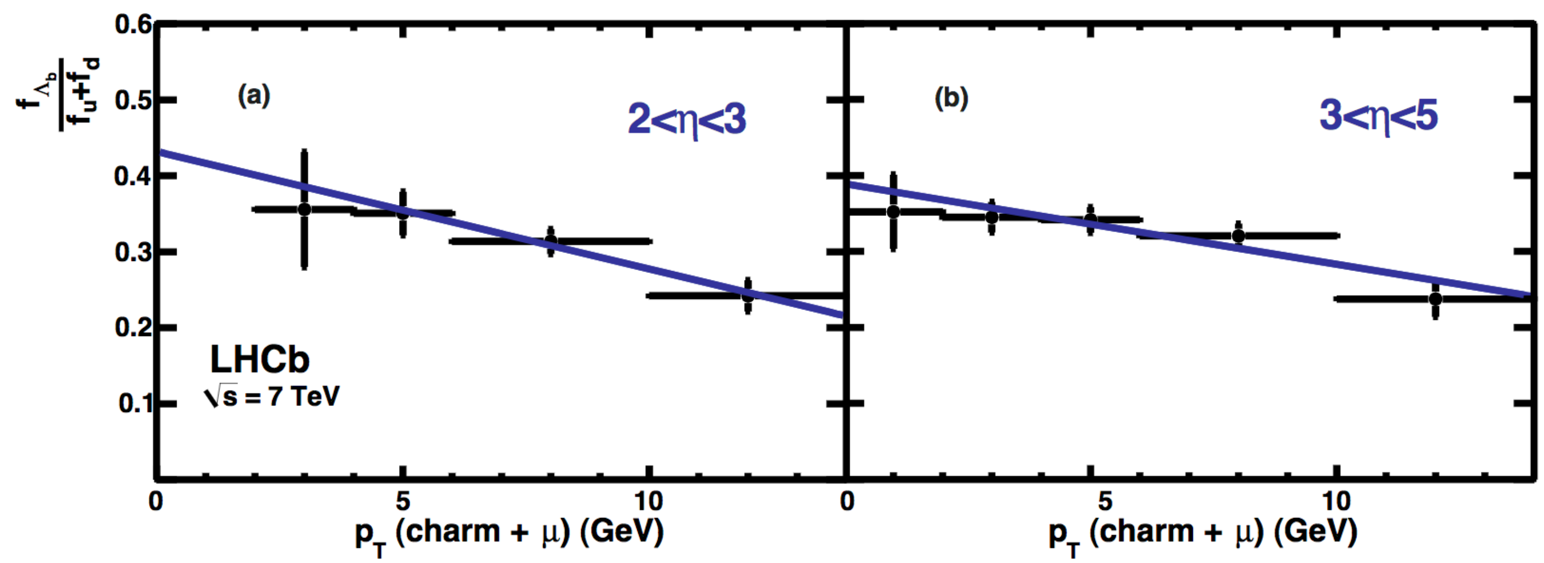
1. b-baryon fragmentation in $p\bar{p}$ collisions **over 2x that in e+e-** at Z resonance (though uncertainties large)

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 $Z \rightarrow b\bar{b}$ decay, in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

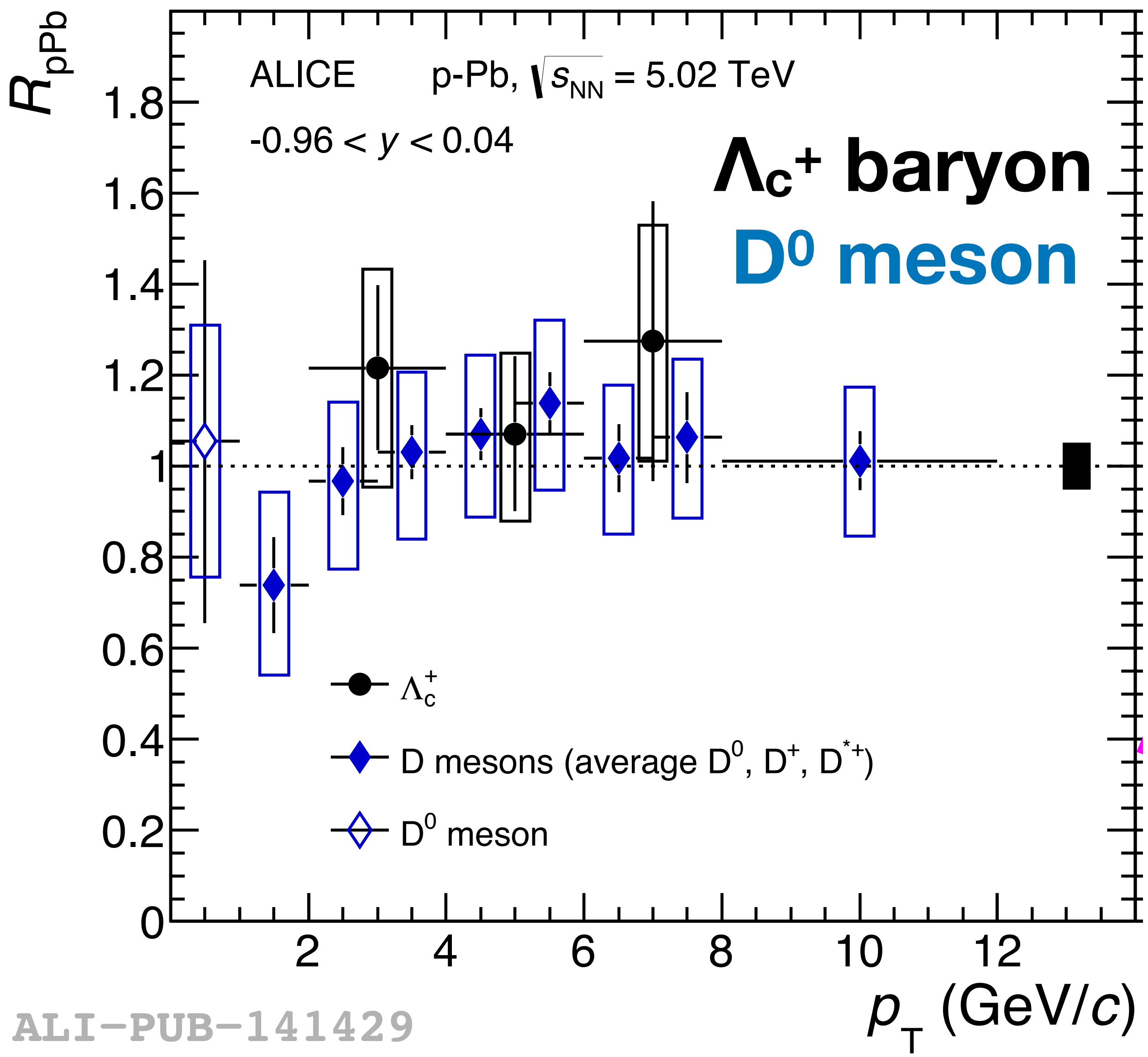
b hadron	Fraction at Z [%]	Fraction at $\bar{p}p$[%]
B^+, B^0	40.4 ± 0.9	33.9 ± 3.9
B_s	10.3 ± 0.9	11.1 ± 1.4
b baryons	8.9 ± 1.5	21.2 ± 6.9



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

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

Λ_c^+ nuclear modification factor R_{pPb}



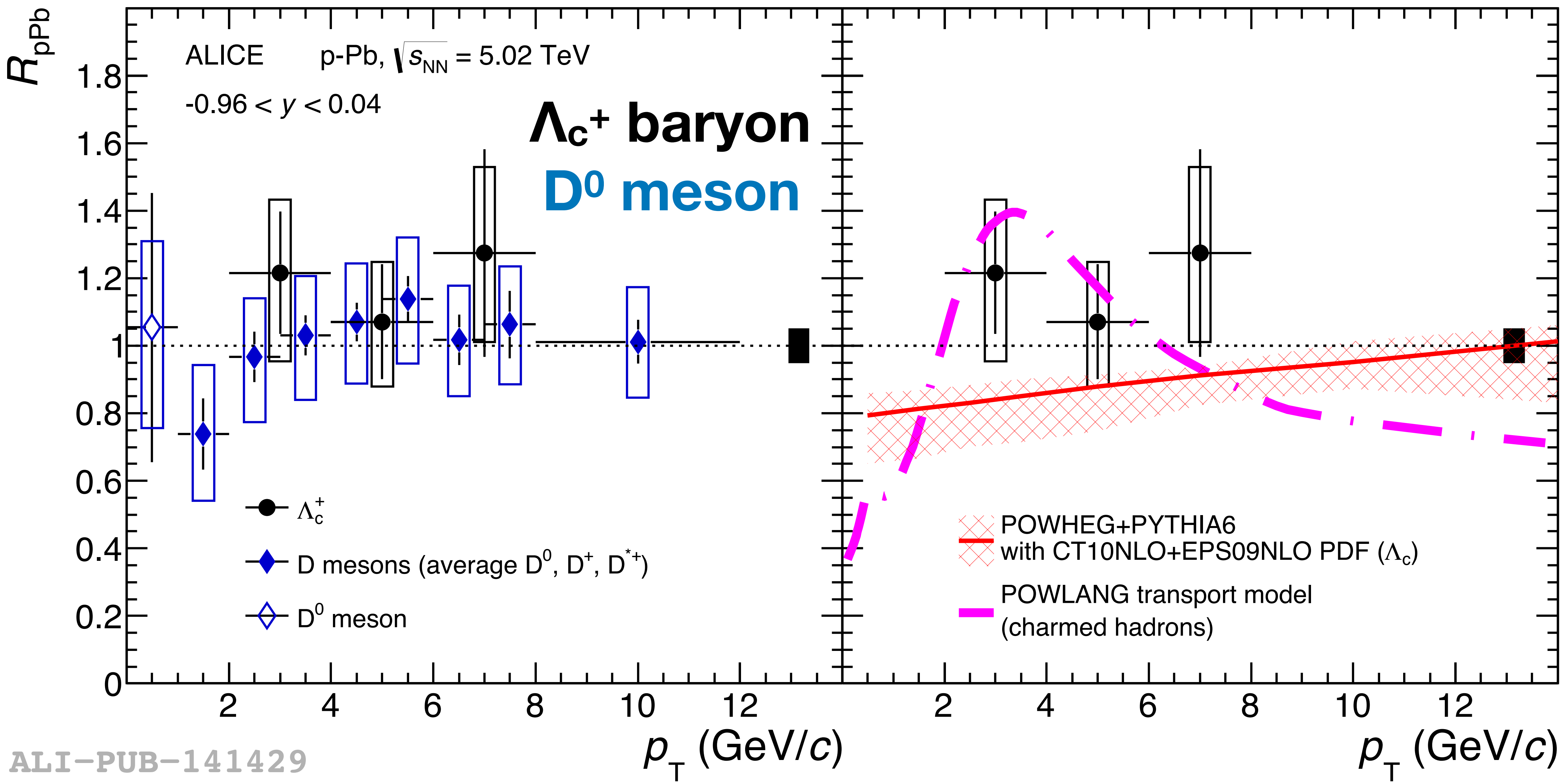
$$R_{pPb}(p_T) = \frac{1}{A} \frac{d\sigma_{pPb} / dp_T}{d\sigma_{pp} / dp_T}$$

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

Summary and perspectives in pp and p-Pb collisions

- Λ_c^+ baryon production in p-Pb collisions similar to that in pp collisions
- Charmed baryon production in pp collisions higher than expectations from e^+e^- collisions
  - Is baryon formation different in pp collisions than in e^+e^-/ep collisions?
- Run 2 data will aid in answering some open questions

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

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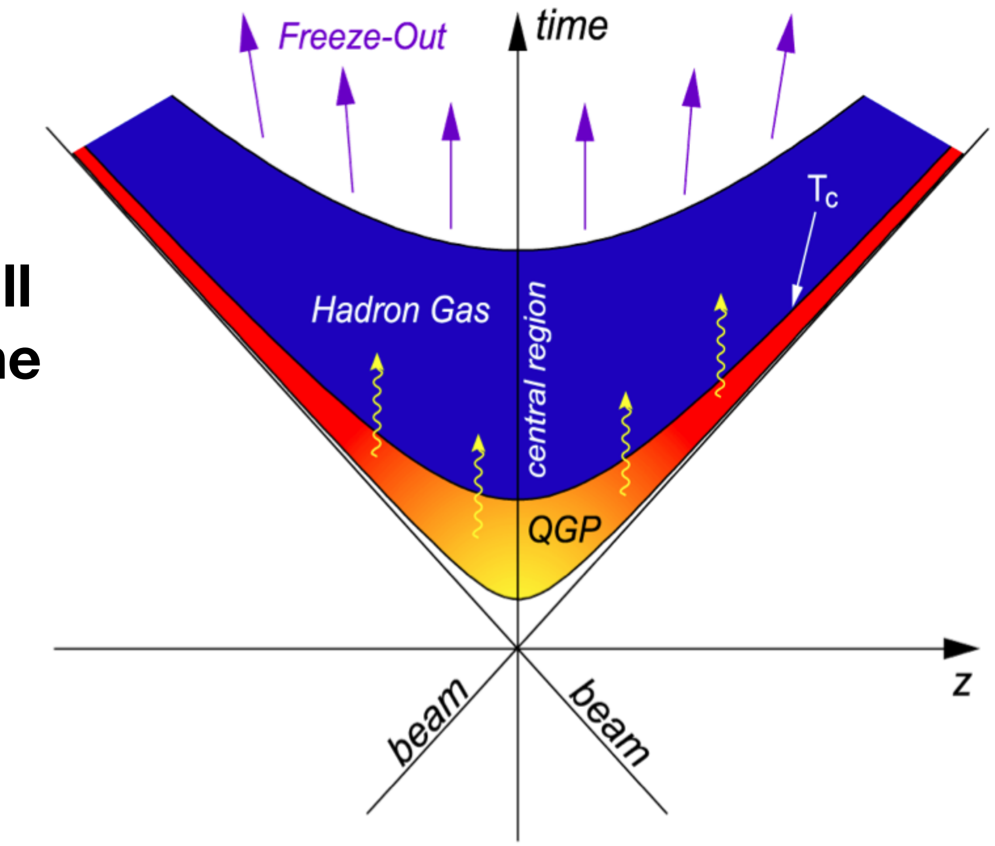
Larger pp datasets collected at 5 TeV, 13 TeV
Larger p-Pb dataset collected at 5 TeV

- ***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?**
  - Modification to baryon production could increase at higher multiplicities
- **Energy-dependent baryon production?**
  - Continuity from e^+e^- energies → LHC energies?

Pb-Pb: Heavy-flavour production

- Heavy-flavour provide unique probe of the hot, dense matter created in **heavy-ion collisions**
  - High Q^2
  - Short formation time
  - Minimal in-medium formation/annhilation

→ **Experience full evolution of the system**



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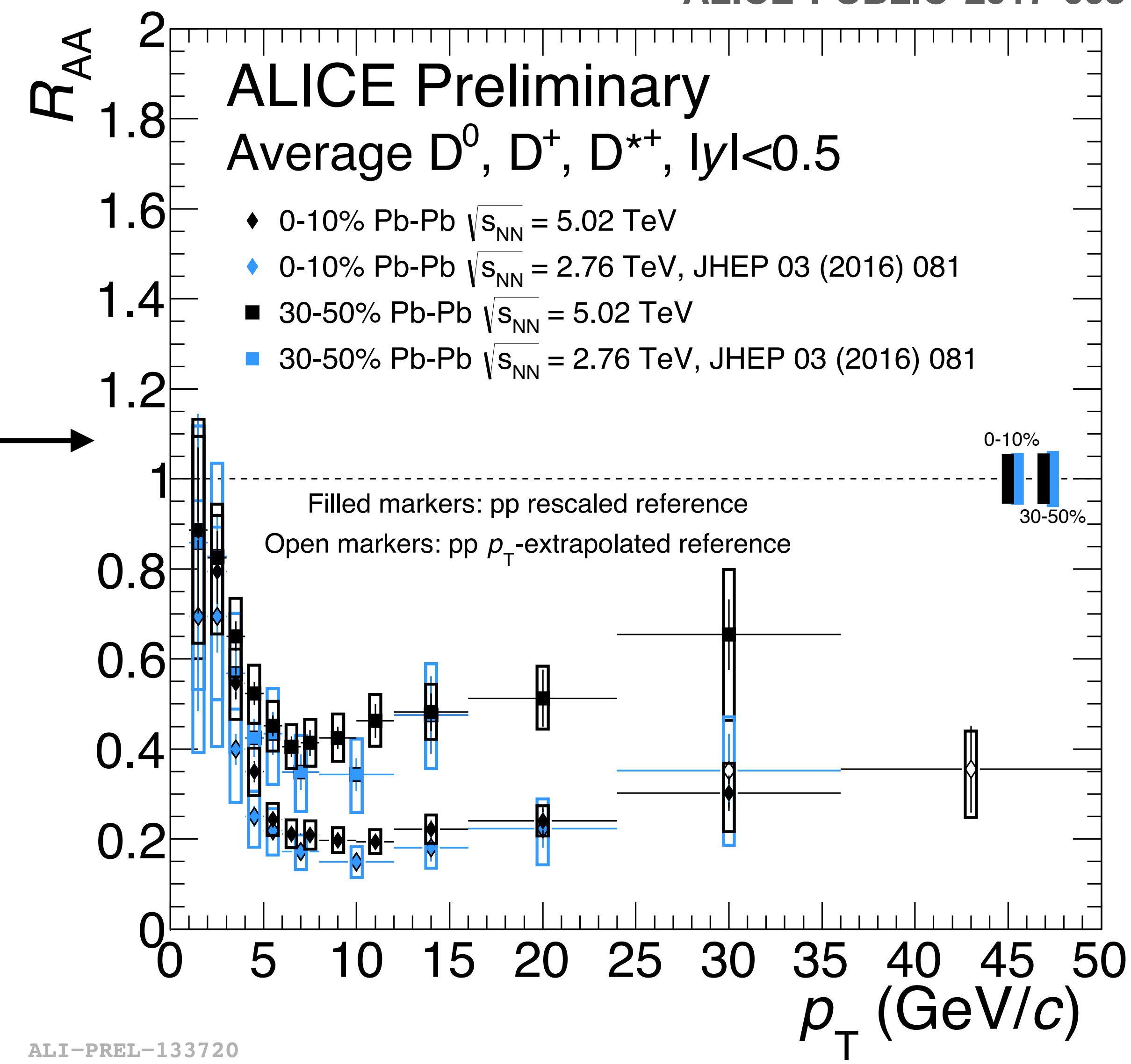
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}/dp_T}$$

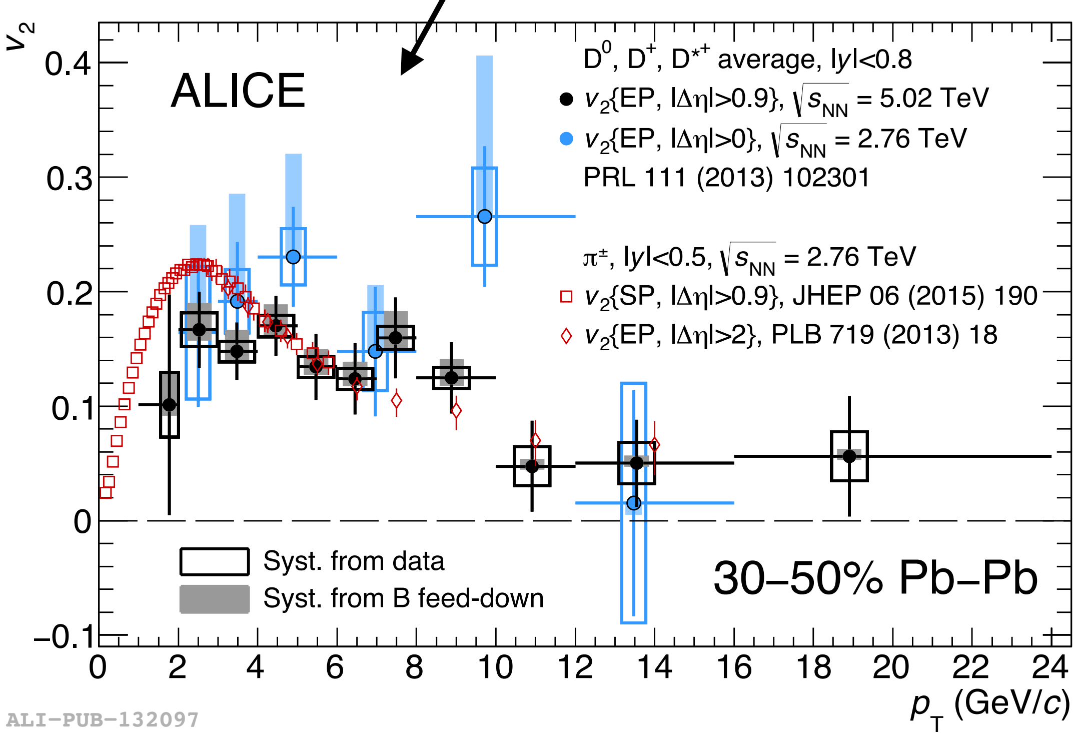
ALICE-PUBLIC-2017-003

Probe deconfined phase…

- **Significant** charm-quark energy loss →



- Charm quarks **participate in the collective motion** of the system



$$\frac{d^2N}{d\varphi\, dp_T} = \frac{dN}{2\pi\, dp_T}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos n(\varphi - \Psi_n)\right]$$

$$\rightarrow\ v_2 = \langle \cos[2(\varphi - \Psi_2)]\rangle$$

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Probe deconfined phase…

- **Significant** charm-quark energy loss
- Charm quarks **participate in the collective motion** of the system

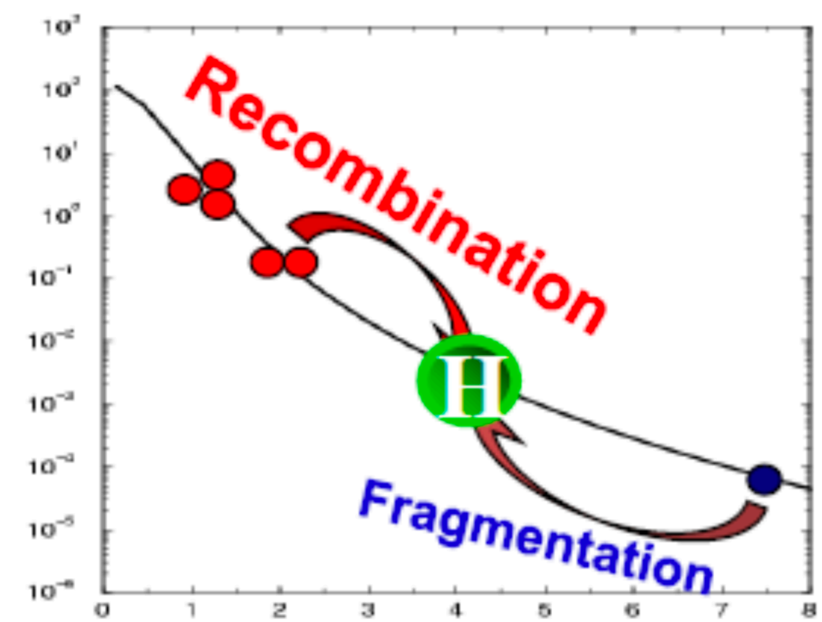
…as well as hadronisation

- Hadronisation through recombination (coalescence) of heavy quarks with light quarks close in phase space

  —> Modifies relative hadron abundances

  —> Modifies hadron p_T spectra

- D_s and charmed baryons (e.g. Λ_c) particularly sensitive to **hadronisation via coalescence**



Pb-Pb: D_s production

- **Enhanced strangeness** in Pb-Pb collisions - an enhancement of D_s with respect to non-strange D mesons expected from models including **coalescence** as hadronisation mechanism

  → **hint of enhancement** seen in Pb-Pb collisions

  → same observation by STAR in Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

STAR: arXiv:1704.04364

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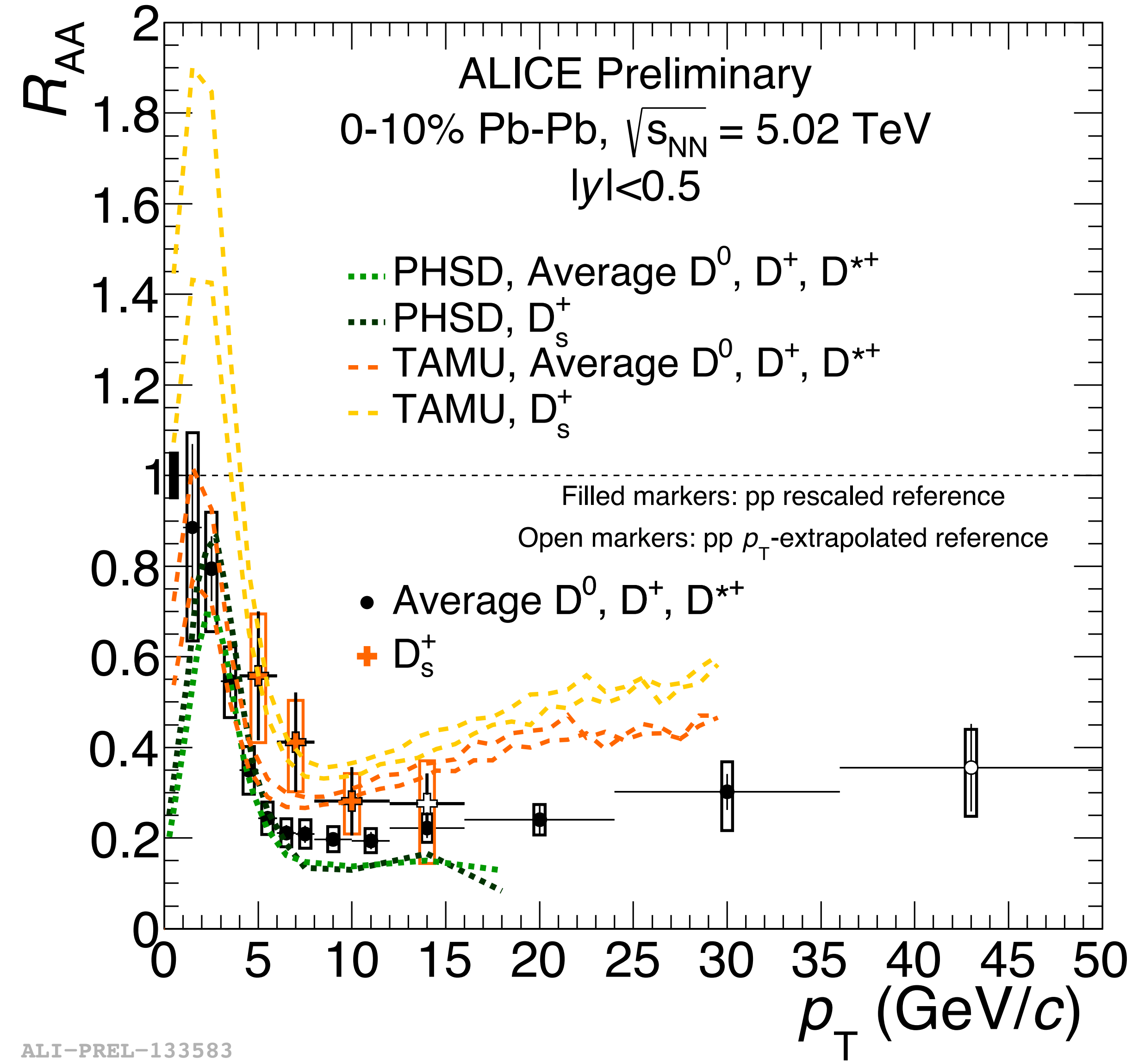

Pb-Pb: Heavy baryon-to-meson ratio

- The **baryon-to-meson ratio** in the charm sector in Pb-Pb collisions is a sensitive probe of:
  - **Hadronisation mechanisms** in the Quark-Gluon Plasma
  - Possible existence of [ud] **bound diquark states** in the Quark-Gluon Plasma

Lee et al.: Phys.Rev.Lett. 100 (2008) 222301
Ko et al.: Phys.Rev. C79 (2009) 044905
Plumari et al.: arXiv:1712.00730

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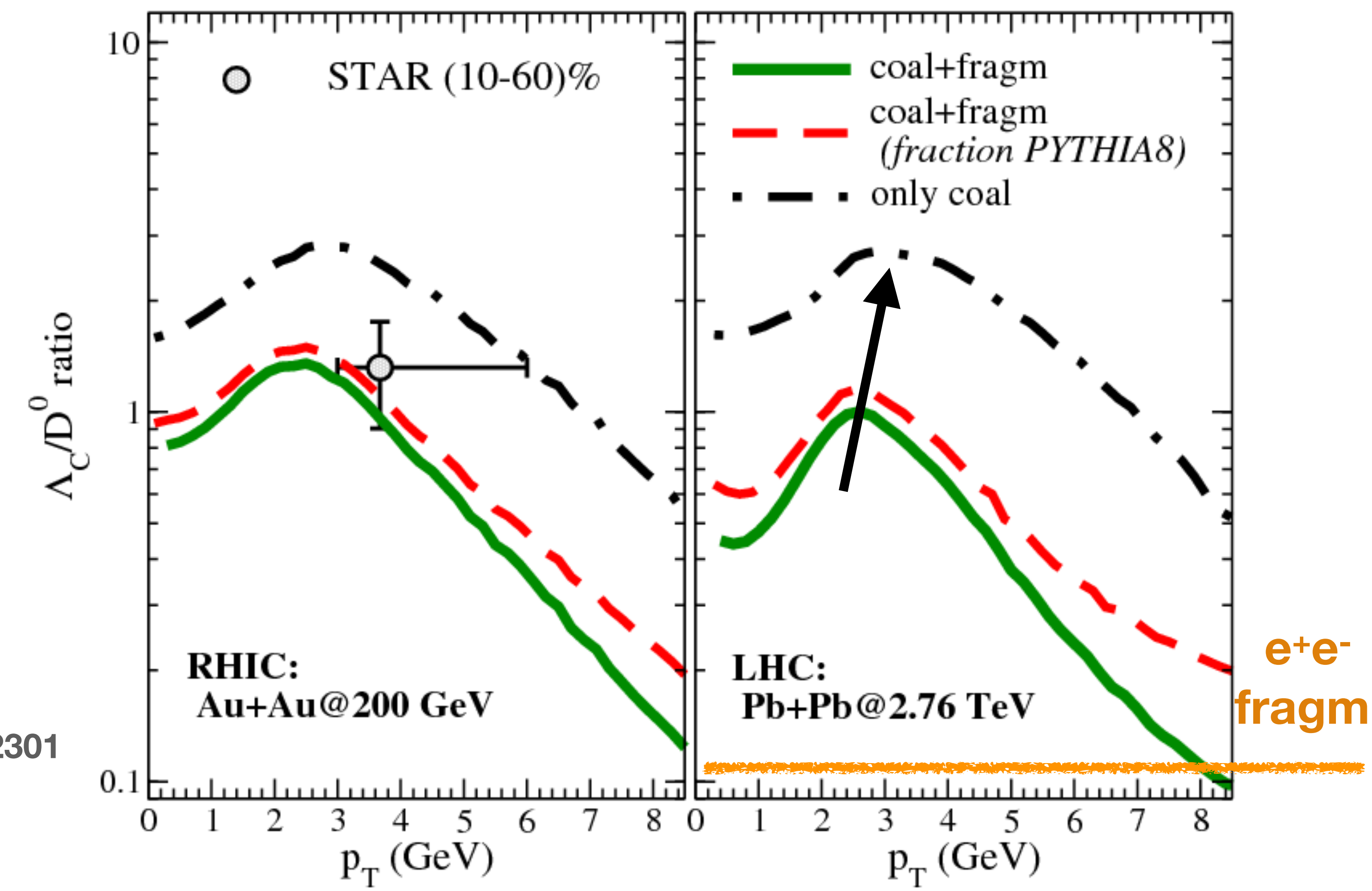

- First measurement of the Λ_c/D^0 ratio in AA collisions by STAR shows a **significant enhancement** with respect to pure fragmentation

STAR: arXiv:1704.04364

  - Reference measurement in pp or pA collisions **essential** for interpretation of results

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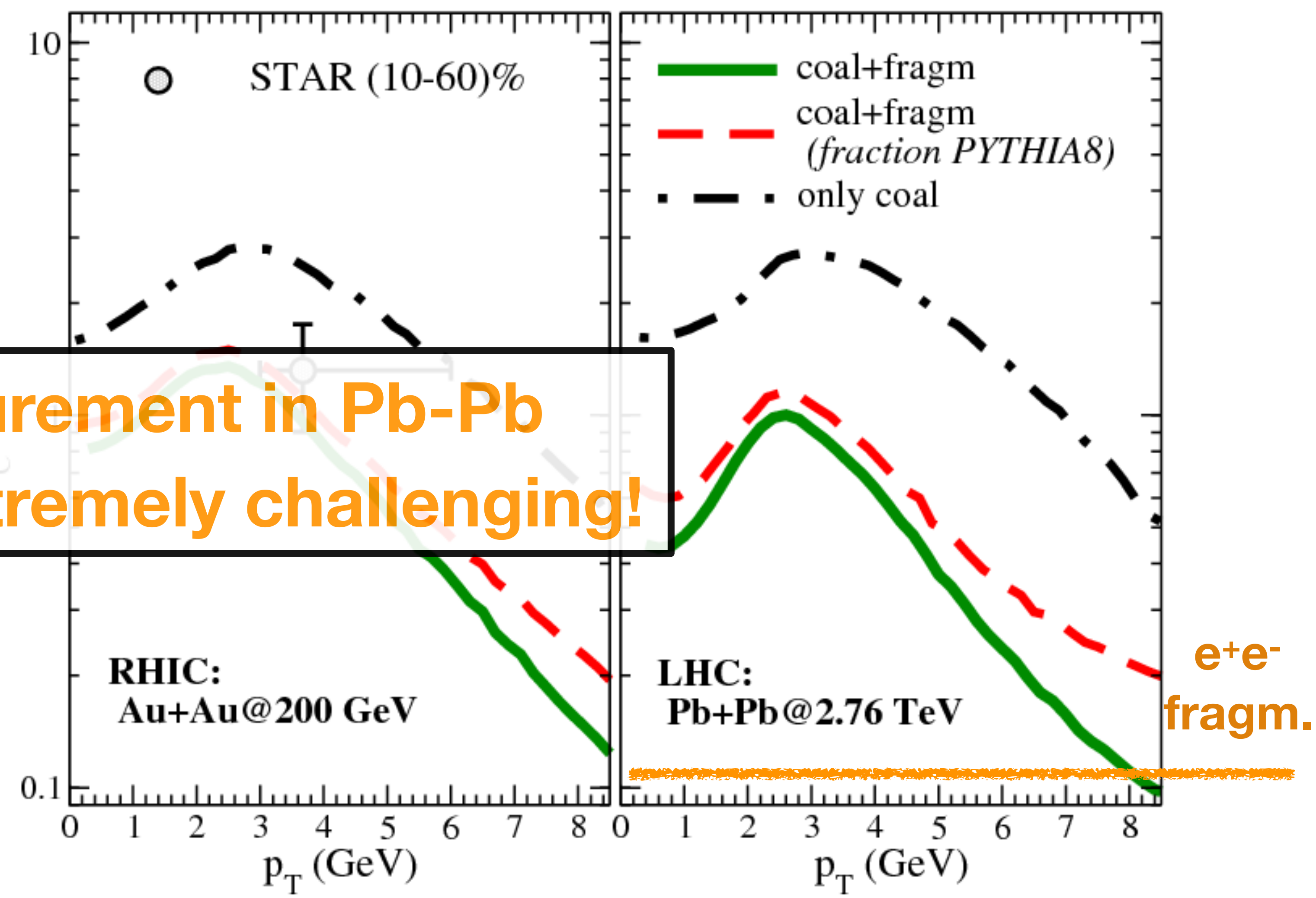

Λ_c^+ measurement in Pb-Pb collisions extremely challenging!

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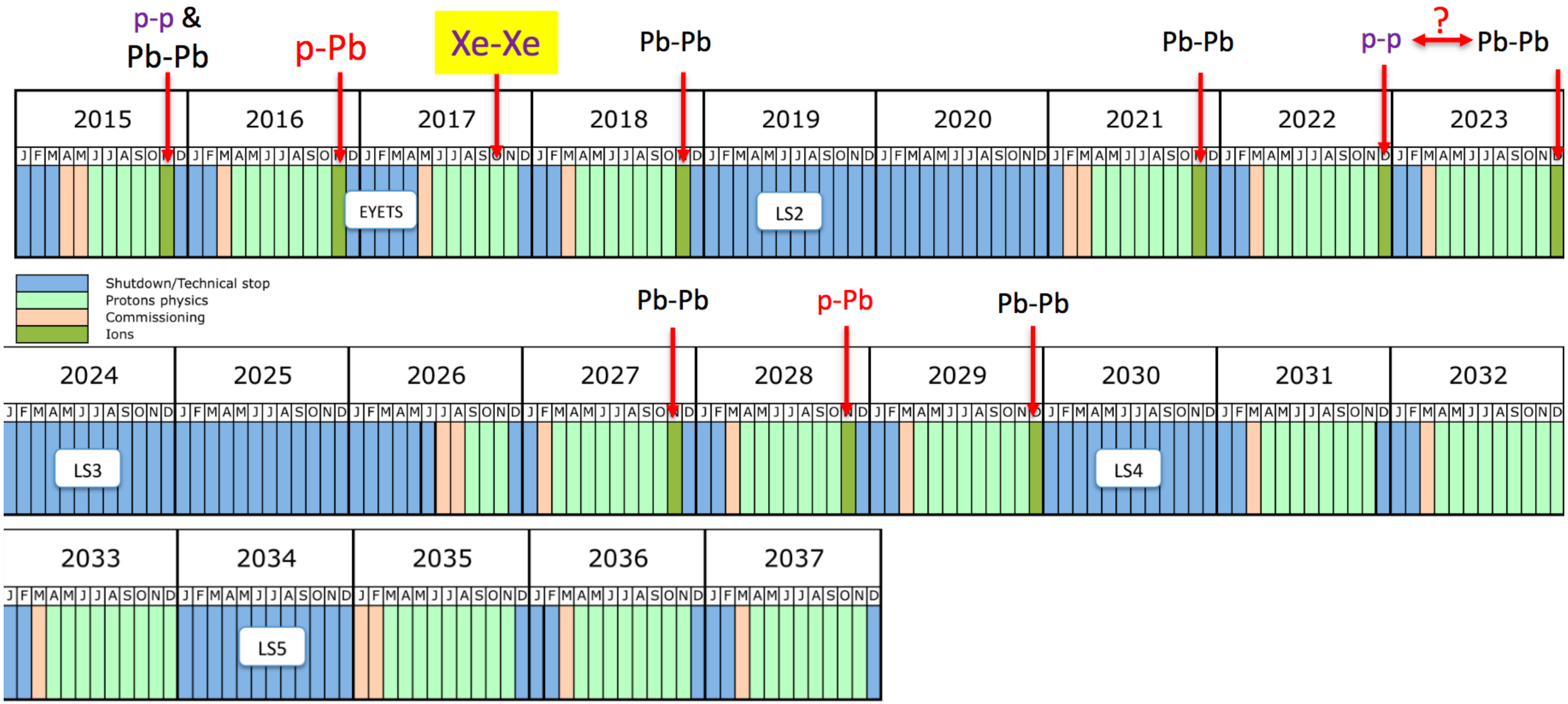
Towards Run 3 and 4



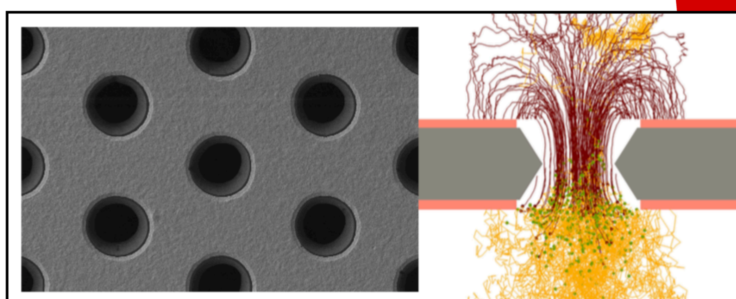
J. M. Jowett, workshop on the physics of HL-LHC, and perspectives at HE-LHC, CERN, 30/10/2017

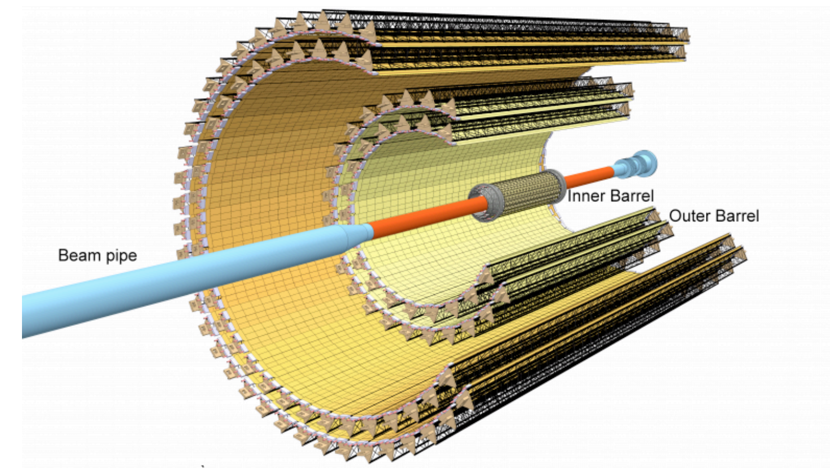
- Large upgrade to the ALICE apparatus for run 3 and 4, to exploit the higher interaction rate
- 50kHz Pb-Pb interaction rate foreseen
- Requested ALICE luminoisty of 10 nb^{-1} (+3 nb^{-1} at low ALICE B field)

—> **50-100x** min. bias Pb-Pb sample from run 2

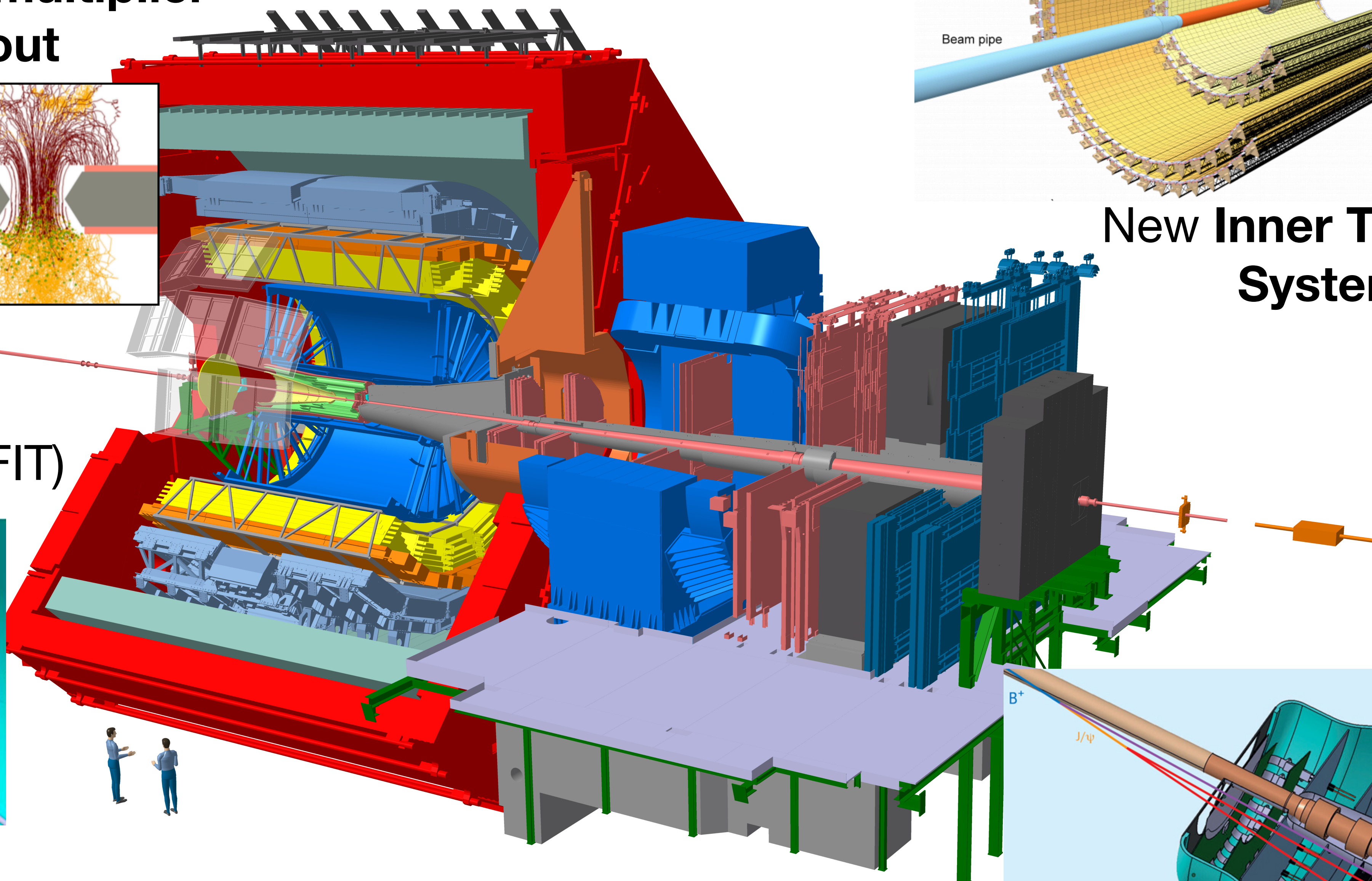
ALICE upgrade

Replace TPC wire chambers with **gas electron multiplier** (GEM) **readout**

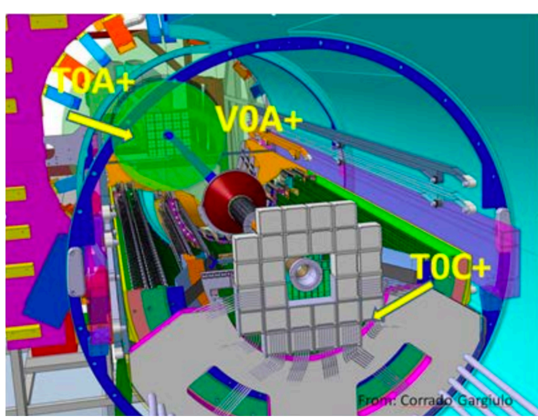


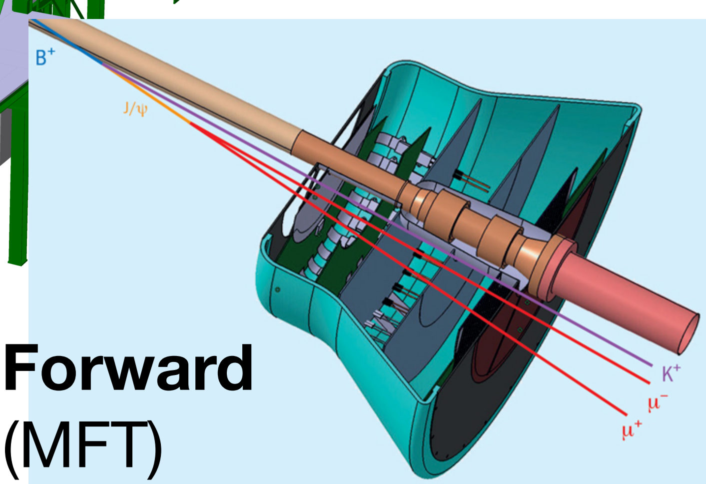


New **Inner Tracking System**



New **forward interaction trigger** (FIT)





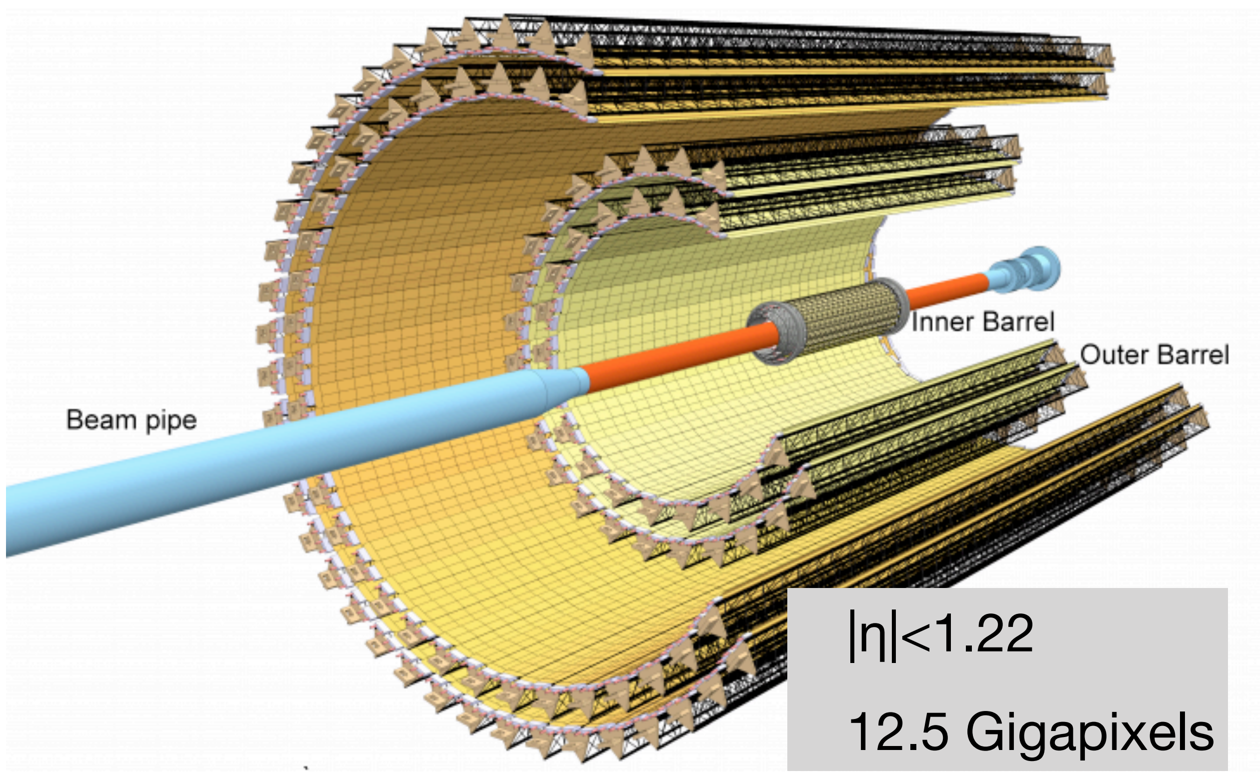
New **Muon Forward Tracker** (MFT)

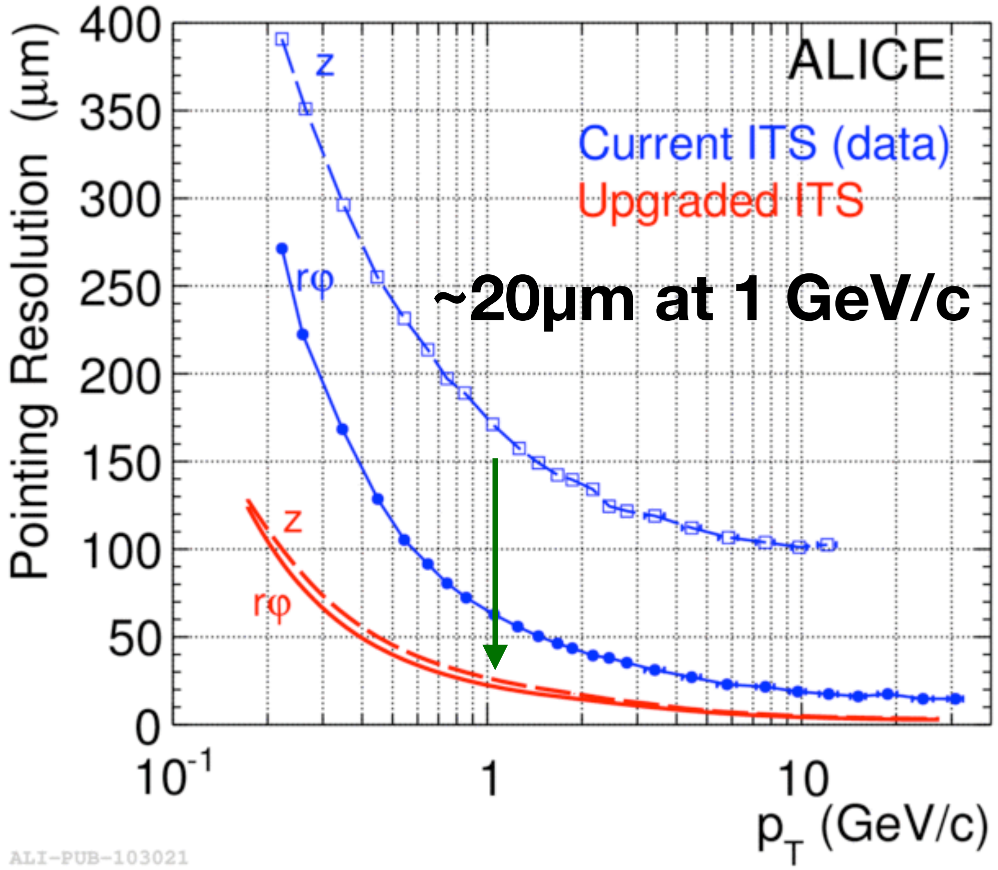
+ New beam pipe
+ New readout architecture
+ Major computing system upgrade (O2 project)

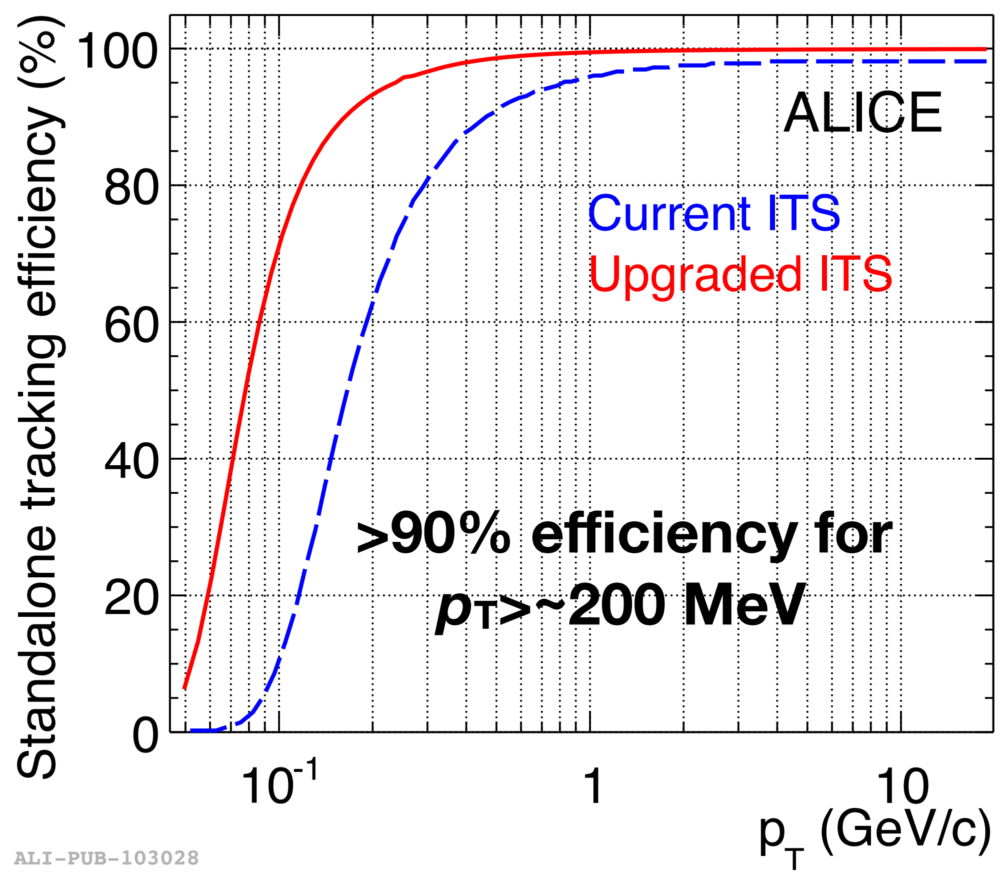
Upgrade LOI: J.Phys. G41 (2014) 087001

ITS upgrade

- 7 layer silicon pixel detector (Monolithic Active Pixel Sensors)
  - **Closer to interaction point**
    - 39mm —> 22mm
  - **Reduced material budget**
    - e.g. inner barrel X/X^0 per layer ~1.14% —> 0.3%
  - **Reduced pixel size**
    - 50μm x 425μm —> 28μm x 28μm



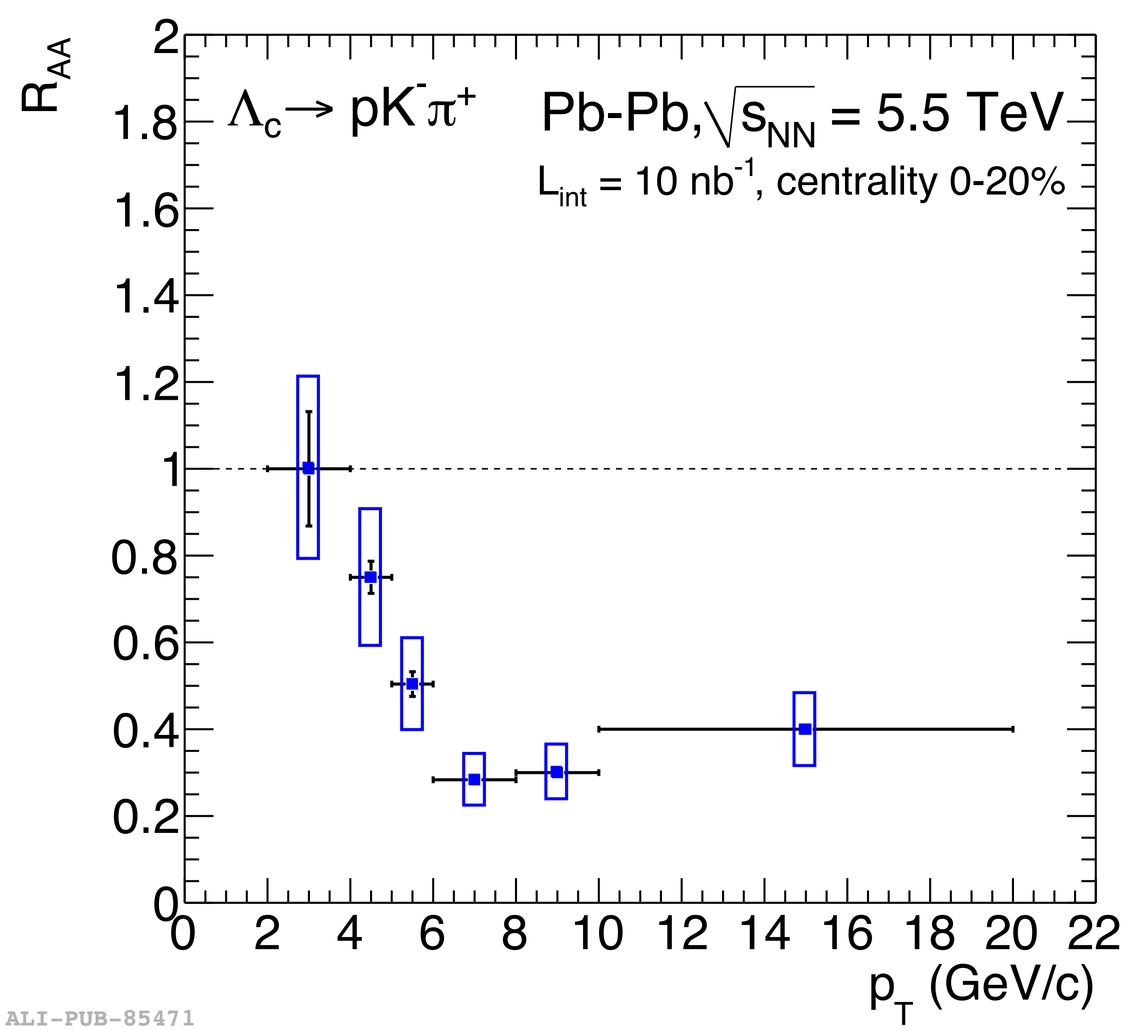




Run 3+4 projection: Λ_c^+/D^0

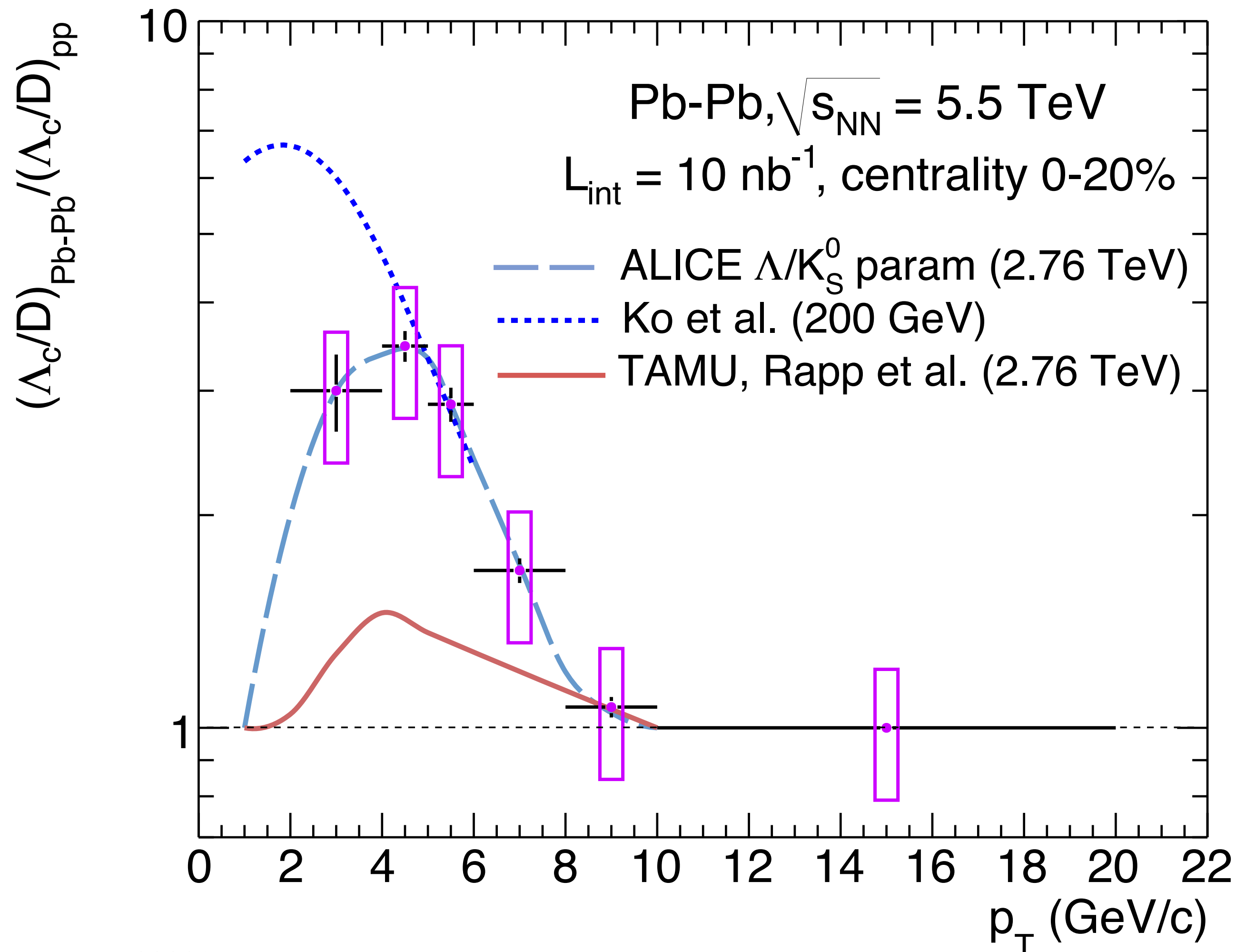
- Λ_c^+ baryon will be accessible down to low p_T in Pb-Pb collisions → *sensitive to baryon formation via coalescence*

ITS upgrade TDR: J. Phys. G 41 (2014) 087002



ALI-PUB-85471

Rapp et al.: arXiv:1204.4442
Ko et al.: Phys. Rev. C 79, 044905

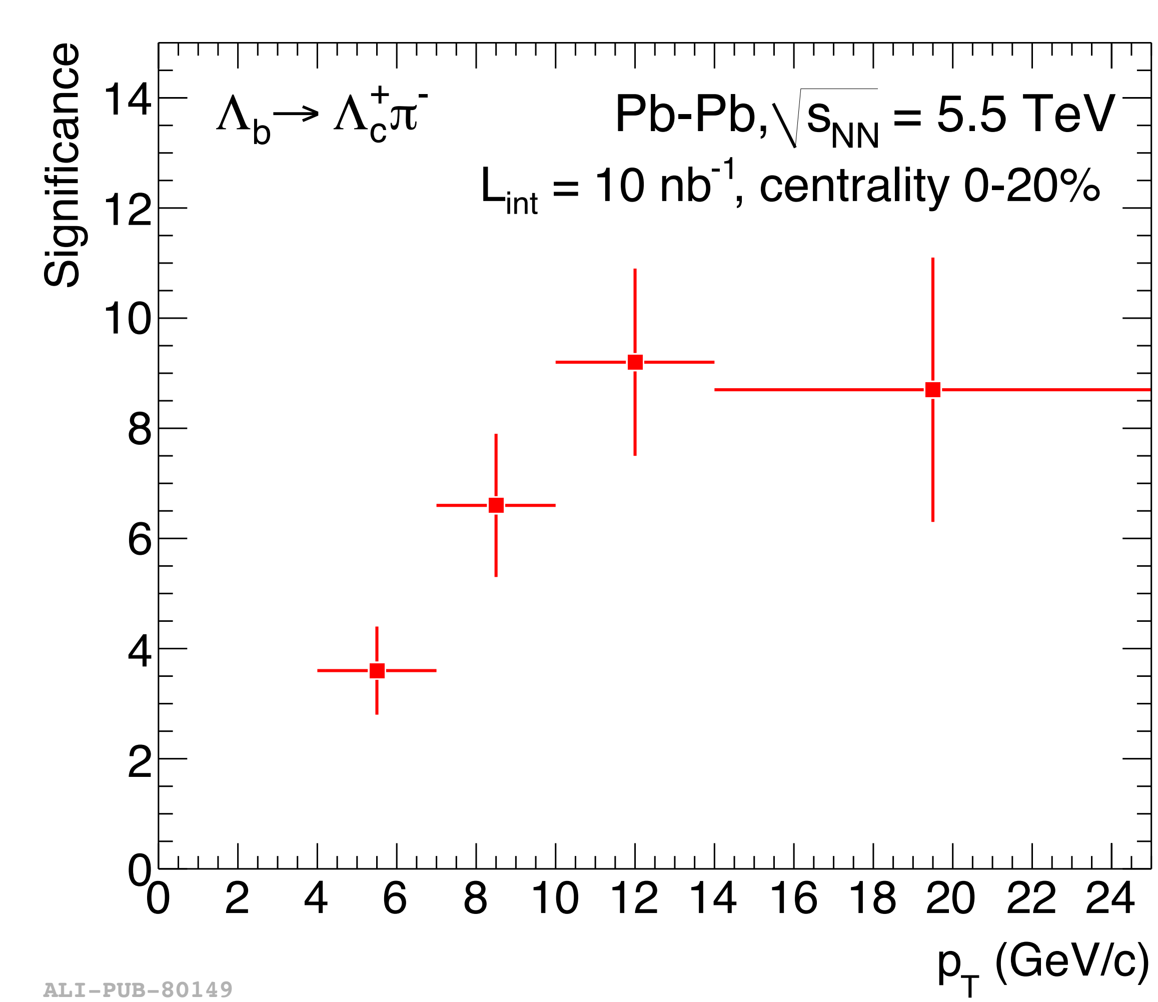


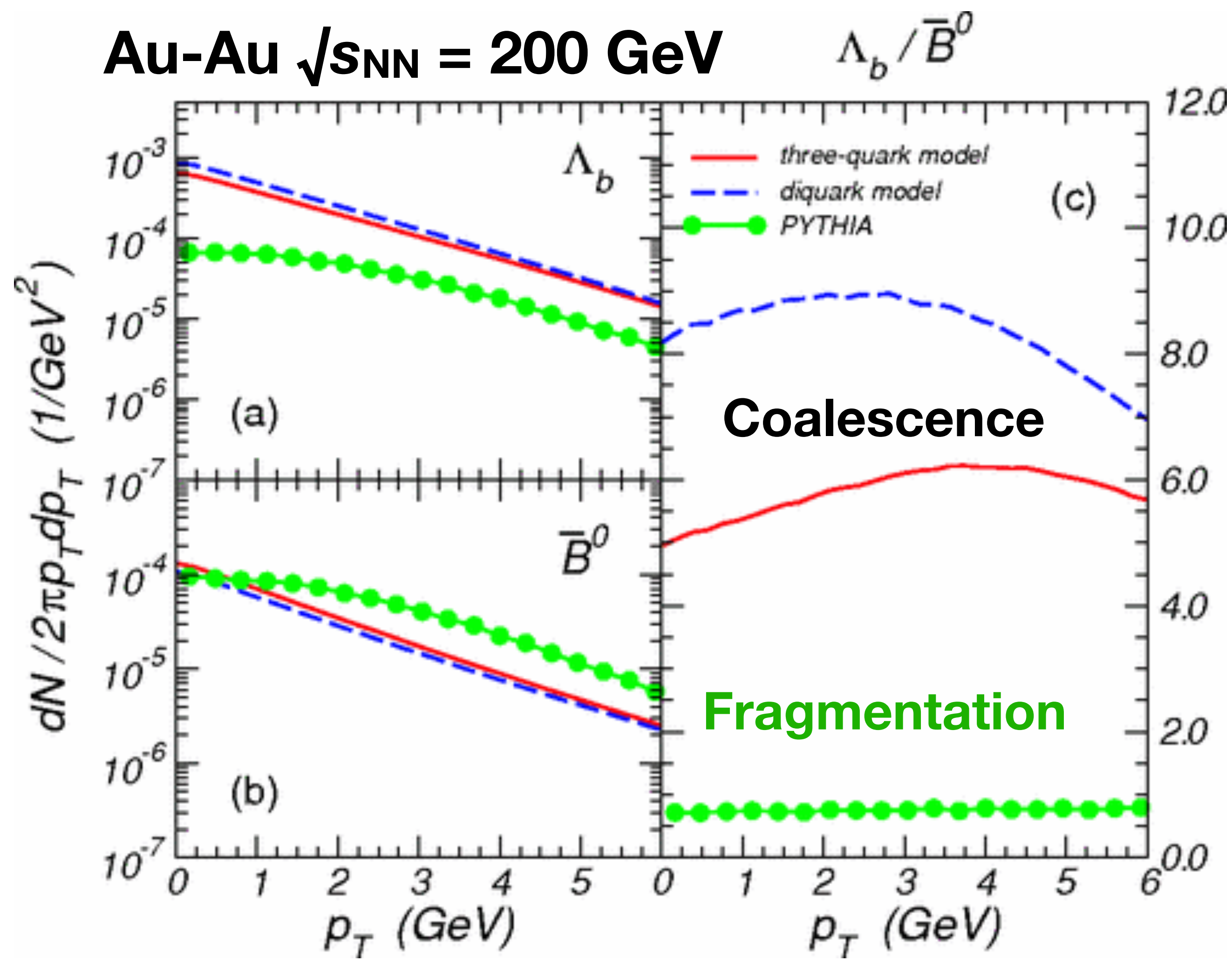
ALI-PUB-80329

Run 3+4 projection: beauty baryons

- Λ_c^+ baryon will be accessible down to low p_T in Pb-Pb collisions → *sensitive to baryon formation via coalescence*
- Λ_b^0 accessible down to 4 GeV/*c* → *also sensitive to hadronisation mechanisms*
- Further studies incorporating multivariate analysis techniques (BDTs) to measure Λ_c^+ and Λ_b^0 production with improved precision are ongoing

ITS upgrade TDR: J. Phys. G 41 (2014) 087002





Ko et al.: Phys.Rev. C79 (2009) 044905

Summary

- Charmed baryon production measurements sensitive to **hadronisation mechanisms**

  → **pp collisions:** test of fragmentation/ effects beyond leading colour approximation

  → **p-Pb collisions:** Measure 'cold' nuclear matter effect on baryon production

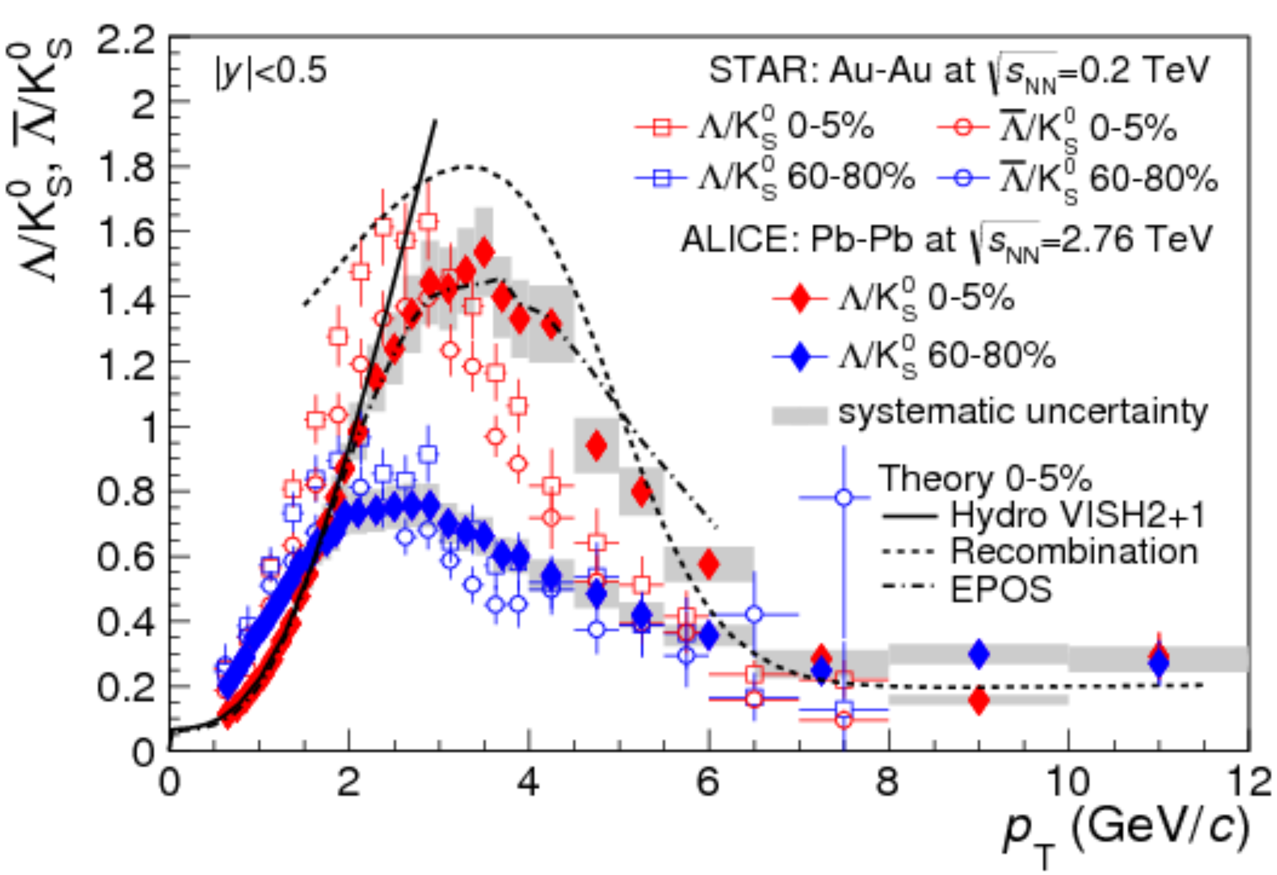
  → **Pb-Pb collisions:** Quantify the role of hadronisation via coalescence

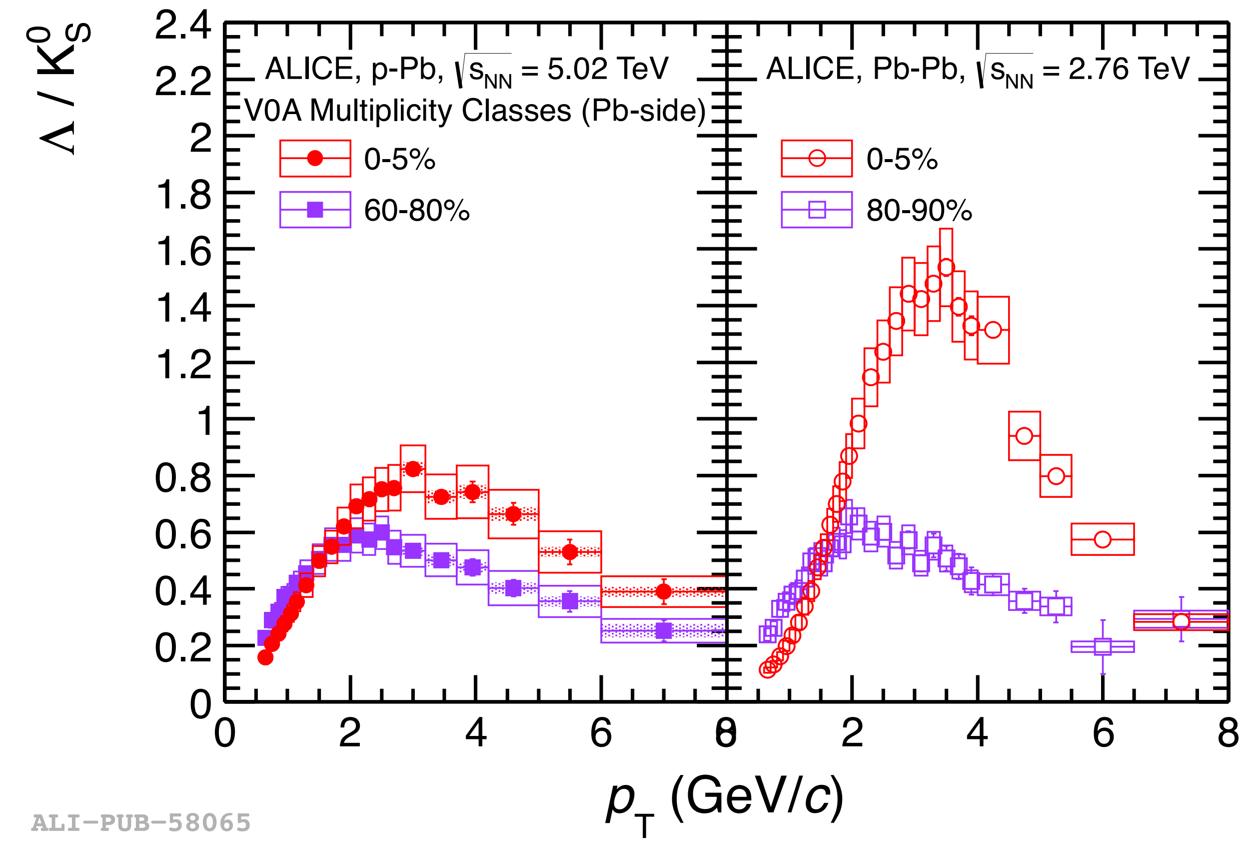
- First measurement by ALICE of charmed baryon production in pp and p-Pb collisions intriguing; *violation of fragmentation universality?*
- **Near future:** more precise/differential measurements in pp and p-Pb collisions will help in answering open questions (+ first Λ_c^+ measurement in Pb-Pb collisions with run 2 data expected)
- **Run 3 and 4:** Precise measurement of charmed baryon production in Pb-Pb collisions after the ALICE upgrade

Backup

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

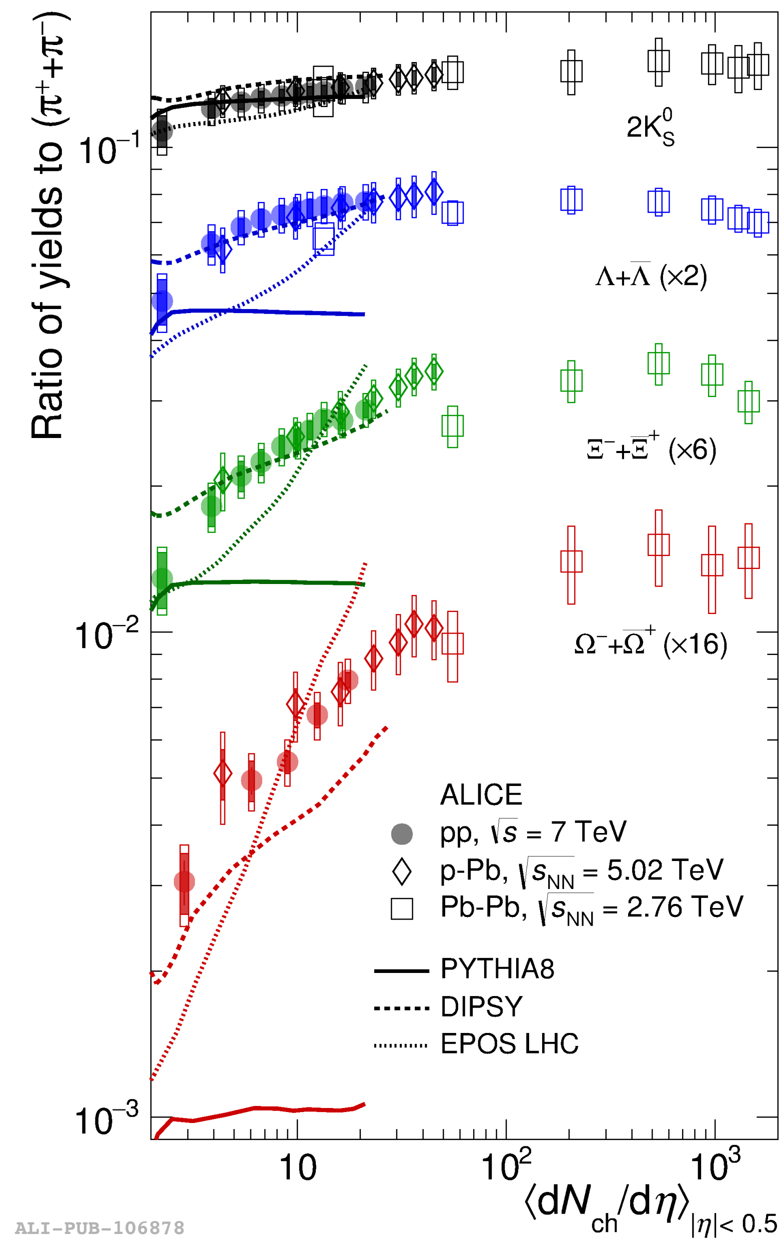


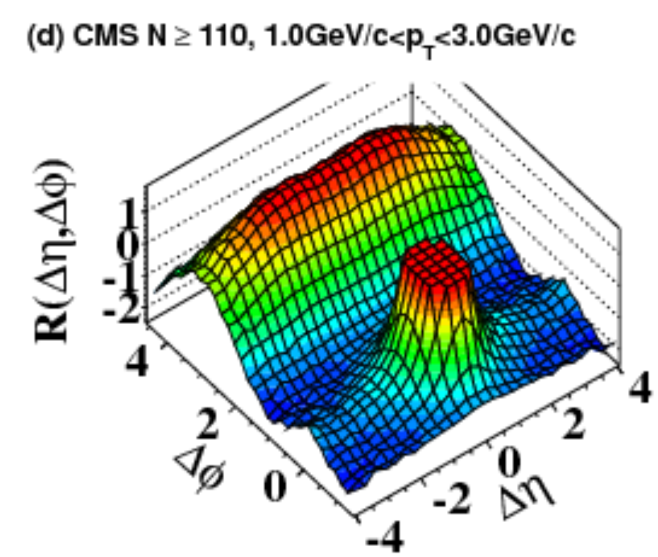


Coalescence? flow? Interplay between both effects?

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?

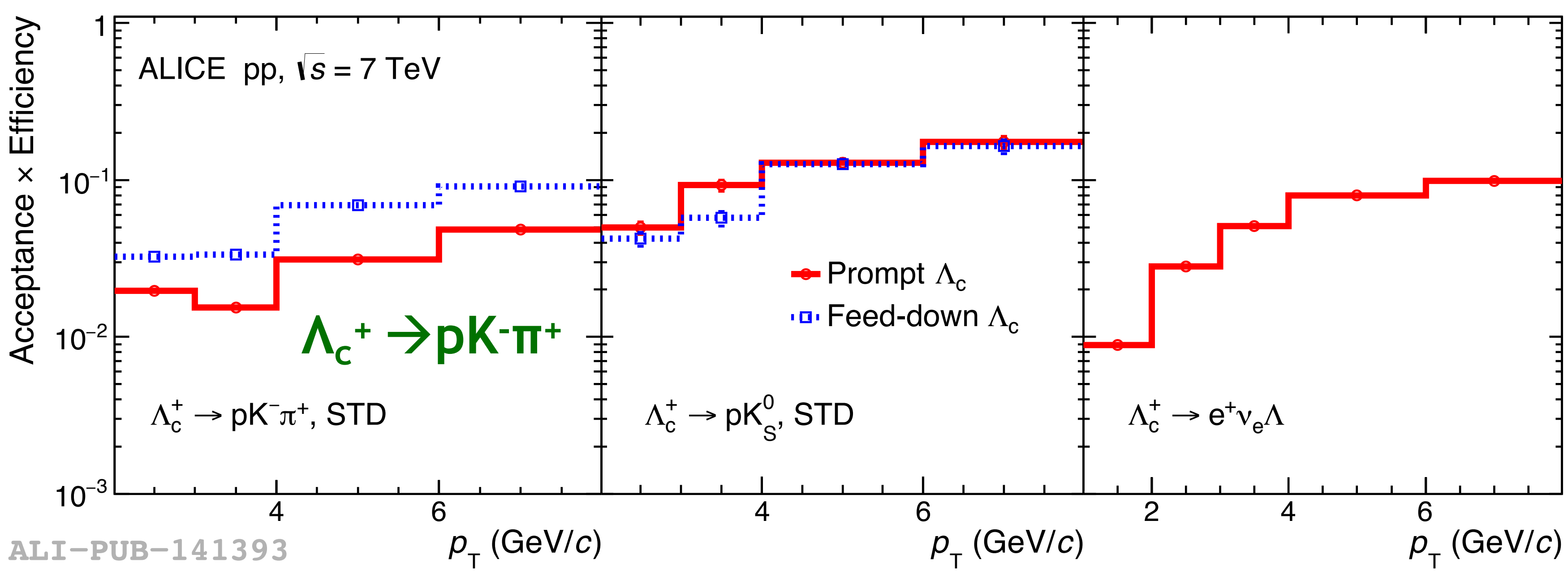
p_T-differential cross section measurement (Λ_C^+)

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^+

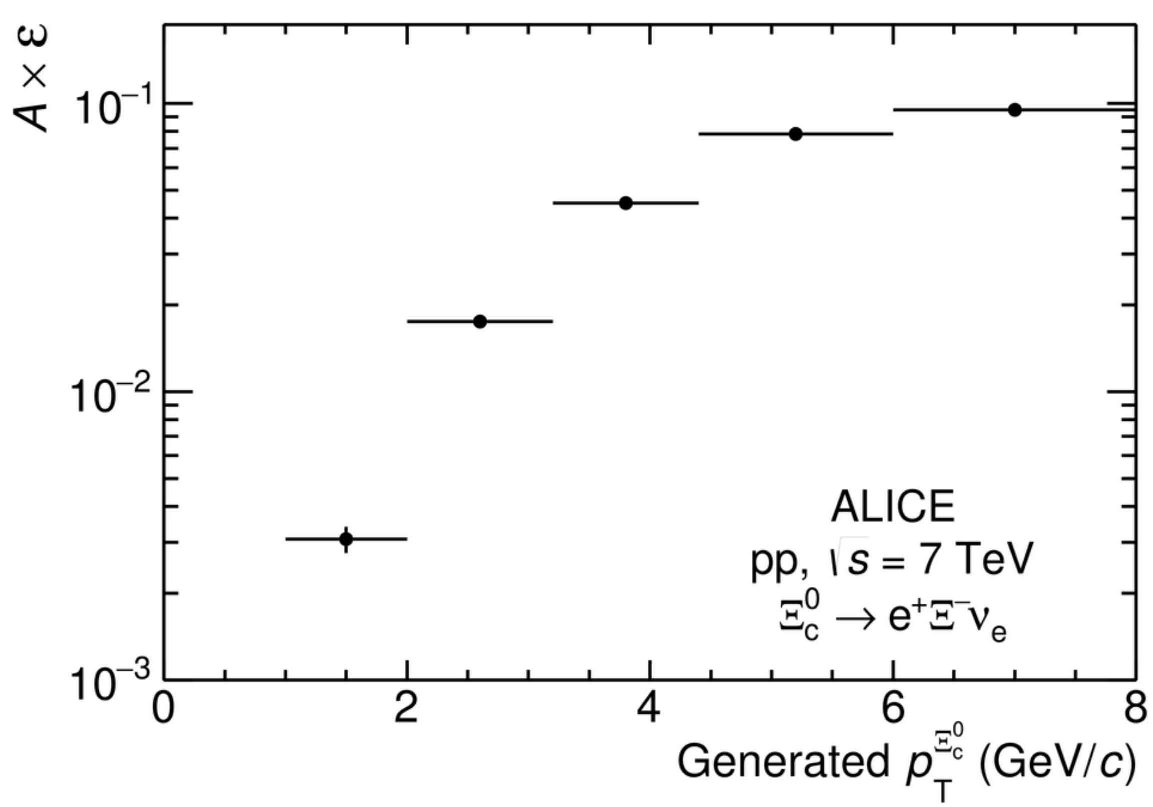


p_T-differential cross section measurement (Ξ_C^0)

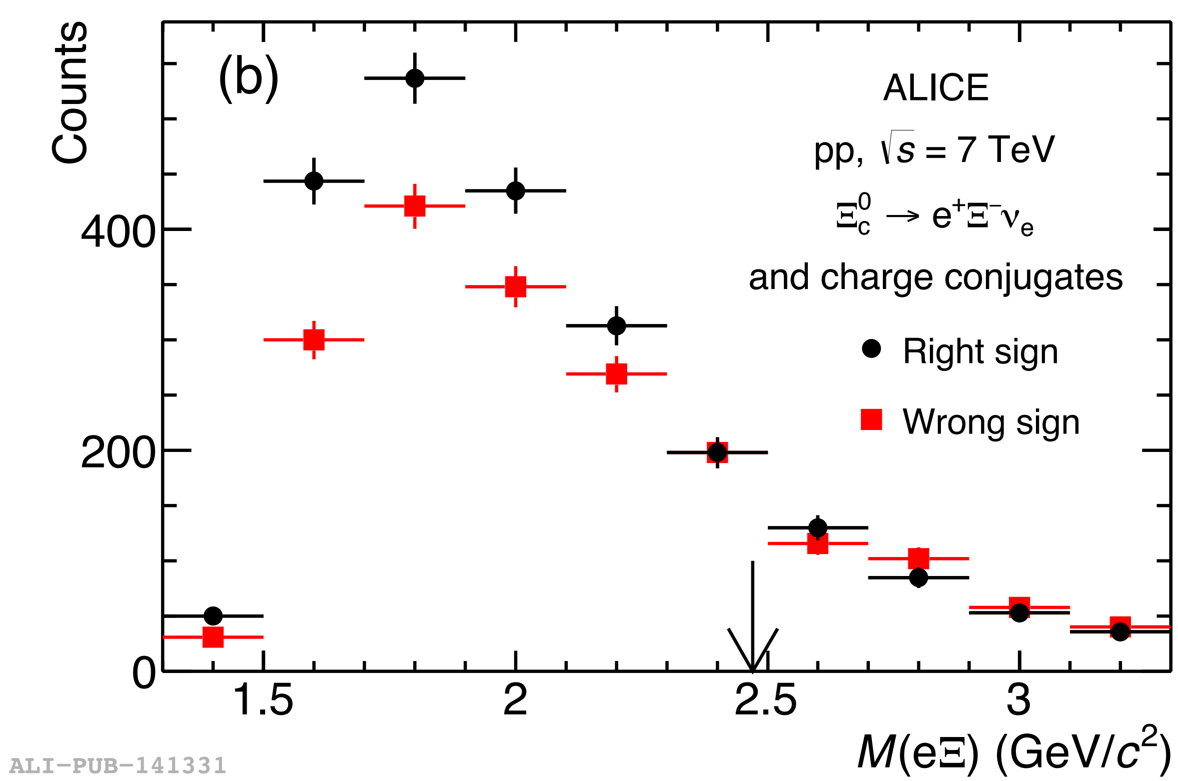
Extracted raw yield in the fiducial acceptance

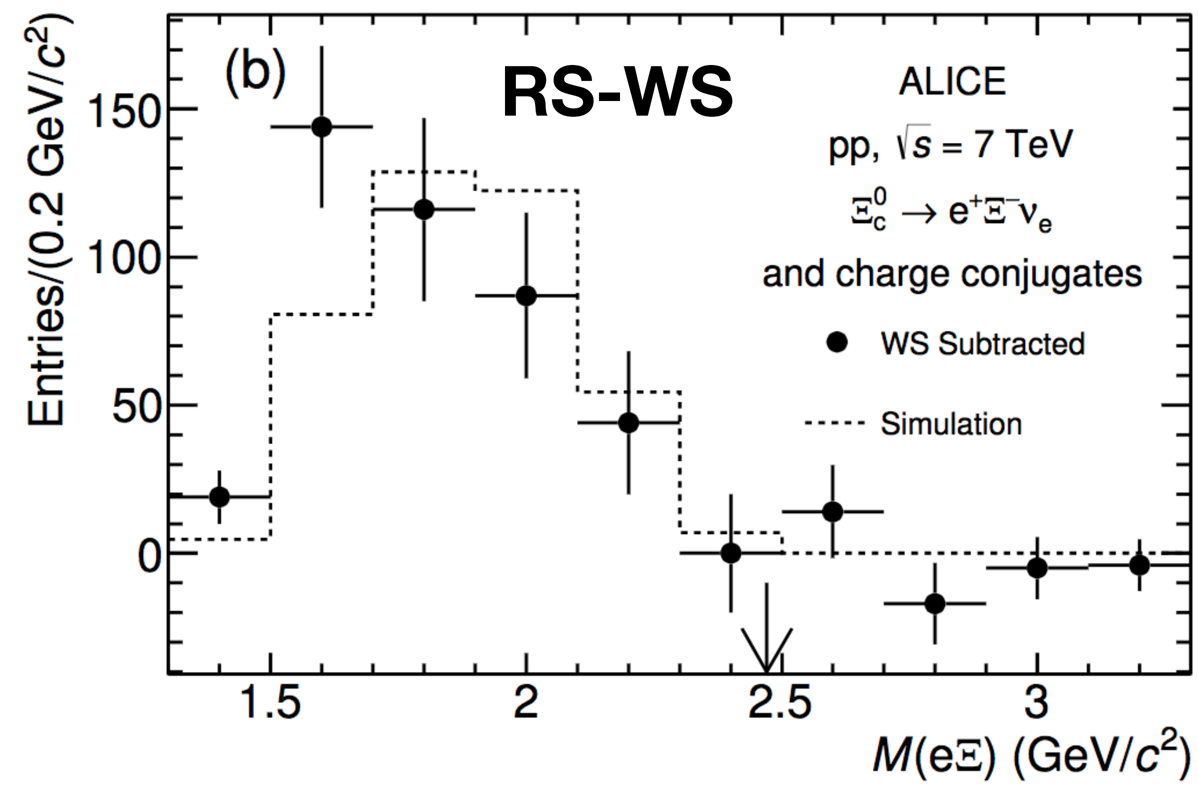
$$\mathrm{BR}\cdot\frac{\mathrm{d}^2\sigma^{\Xi_c^0}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}=\frac{N_{\Xi_c^0}}{2\cdot\Delta p_\mathrm{T}\Delta y\cdot(A\times\varepsilon)\cdot L_\mathrm{int}\cdot\mathrm{BR}_{\Xi^-}}$$

Efficiency x acceptance for Ξ_C^0



Semileptonic RS-WS subtraction





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

Systematic uncertainties in p-Pb collisions

STD analysis

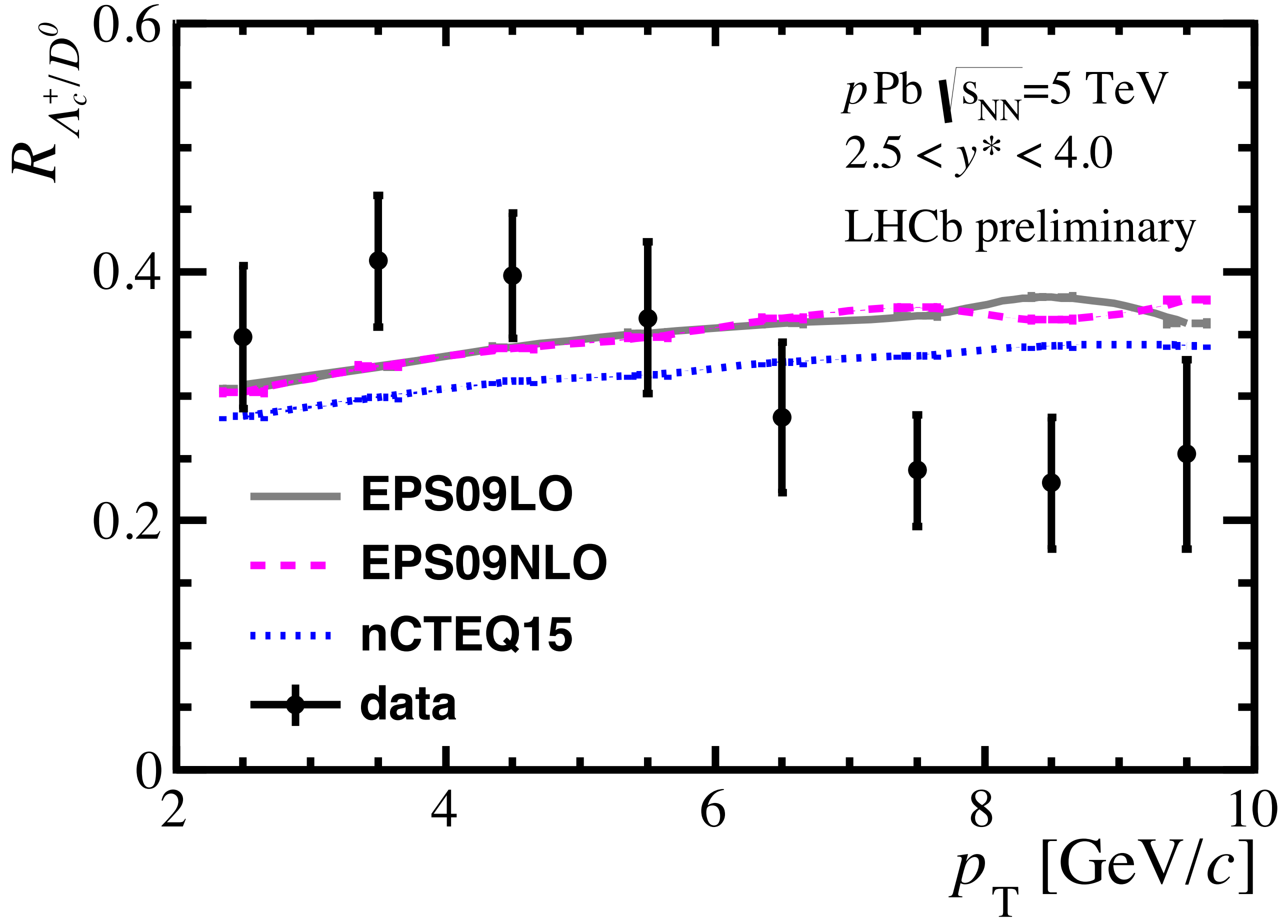
	$\Lambda_c^+ \to pK^-\pi^+$		$\Lambda_c^+ \to pK^0_S$	
Systematic unc. source	**Low p_T (%)**	**High p_T (%)**	**Low p_T (%)**	**High p_T (%)**
Yield extraction	10	11	10	10
Tracking efficiency	10	7	10	6
Cut efficiency	9	12	5	7
PID efficiency	6	6	6	6
MC pT shape	2	2	1	3
B feed-down	+1 -5	+2 -10	negl.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

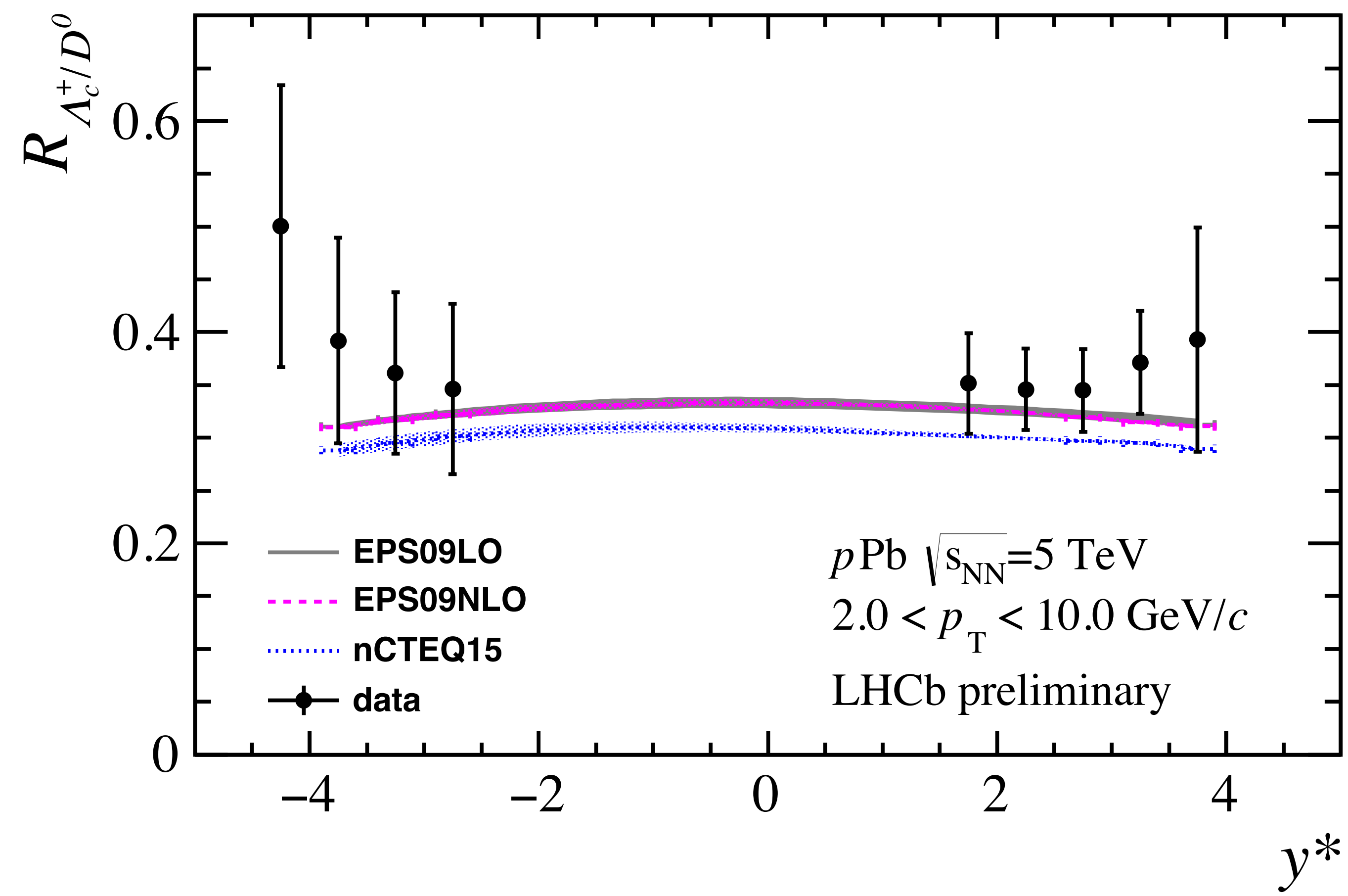
BDT analysis

	$\Lambda_c^+ \to pK^-\pi^+$		$\Lambda_c^+ \to pK^0_S$	
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%

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