Hard Probes 2018: International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Aix-Les-Bains, Savoie, France

30 September 2018 to 5 October 2018

Charm baryon production in pp, p-Pb and Pb-Pb collsions with ALICE at the LHC

E. Meninno* on behalf of the ALICE Collaboration

* University and INFN, Salerno

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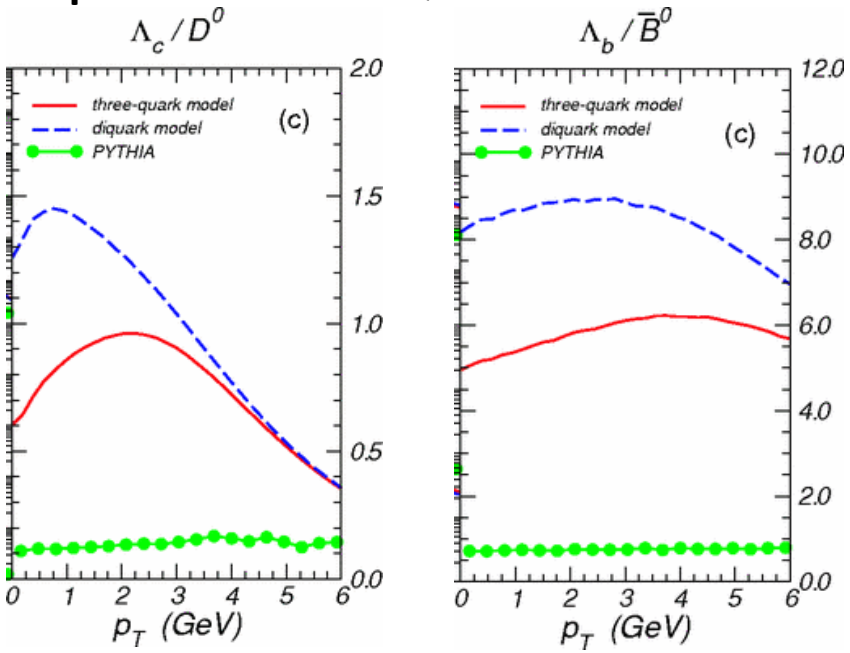
–New results in pp@5TeV

– Final results in Pb-Pb@5TeV

* University and INFN, Salerno

Physics motivations

- Charm is a powerful probe of the *Quark-Gluon-Plasma* (QGP)
  - Produced in hard partonic scattering processes in the early stages of the collision
- Charmed-baryon production in Heavy Ion (HI) collisions sensitive to the **hadronisation processes** in the QGP.



Y. Oh et al., PRC 79, 044905 (2009)

- Enhancement of Λ_c^+ / D^0 (and $\Lambda_b^+ / \bar{B}^0$) ratio predicted in coalescence models.
- Further enhancement expected if thermalised light diquark states exist in the QGP.

- Detailed studies in small systems (pp and p-Pb collisions) are required.

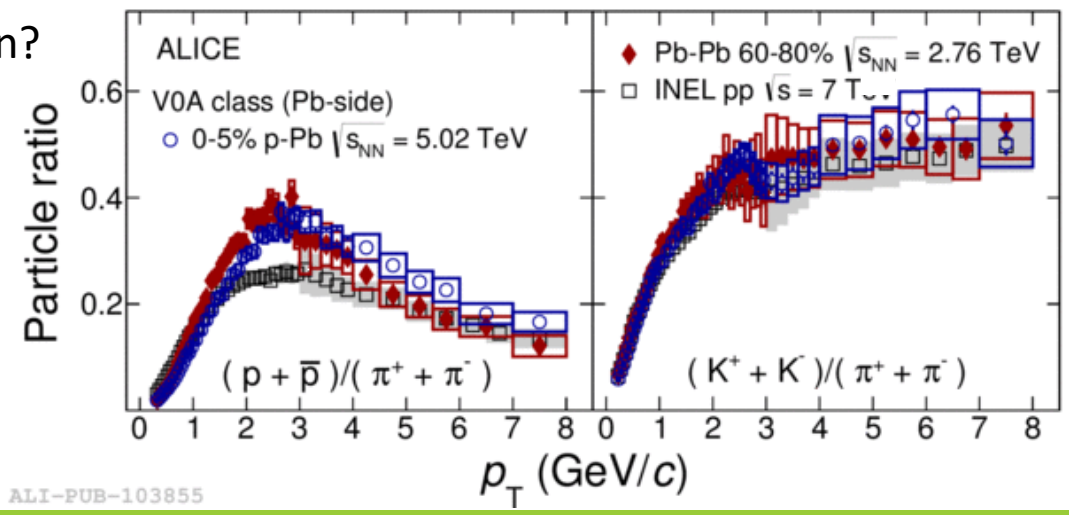
Physics motivations

- Measurement in pp collisions:
  - Important to test predictions from pQCD and models of hadronisation in vacuum.

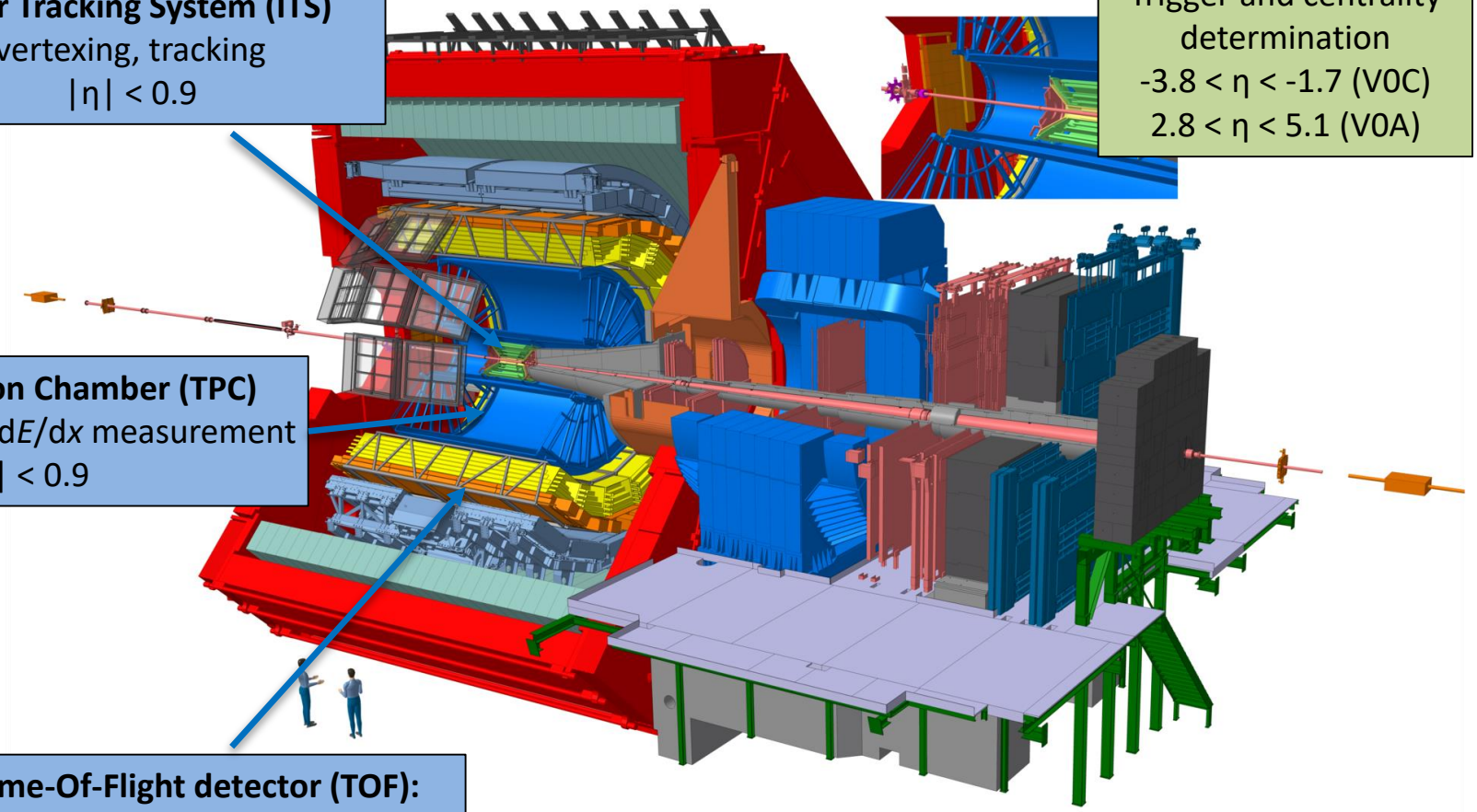
- Measurement in p-Pb collisions:
  - Important to distinguish cold-nuclear-matter (CNM) effects

- Study momentum and multiplicity dependence of charm hadron production
  -Enhancement of baryon/meson ratios p/π and Λ/K at intermediate p_T in High Multiplicity (HM) pp and p-Pb collisions.
  - Similar to what was observed in HI collisions
    mini-QGP?
    influence of colour reconnection?

Phys. Lett. B760 (2016) 720-735



The ALICE apparatus



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

V0
Trigger and centrality determination
$-3.8 < \eta < -1.7$ (V0C)
$2.8 < \eta < 5.1$ (V0A)

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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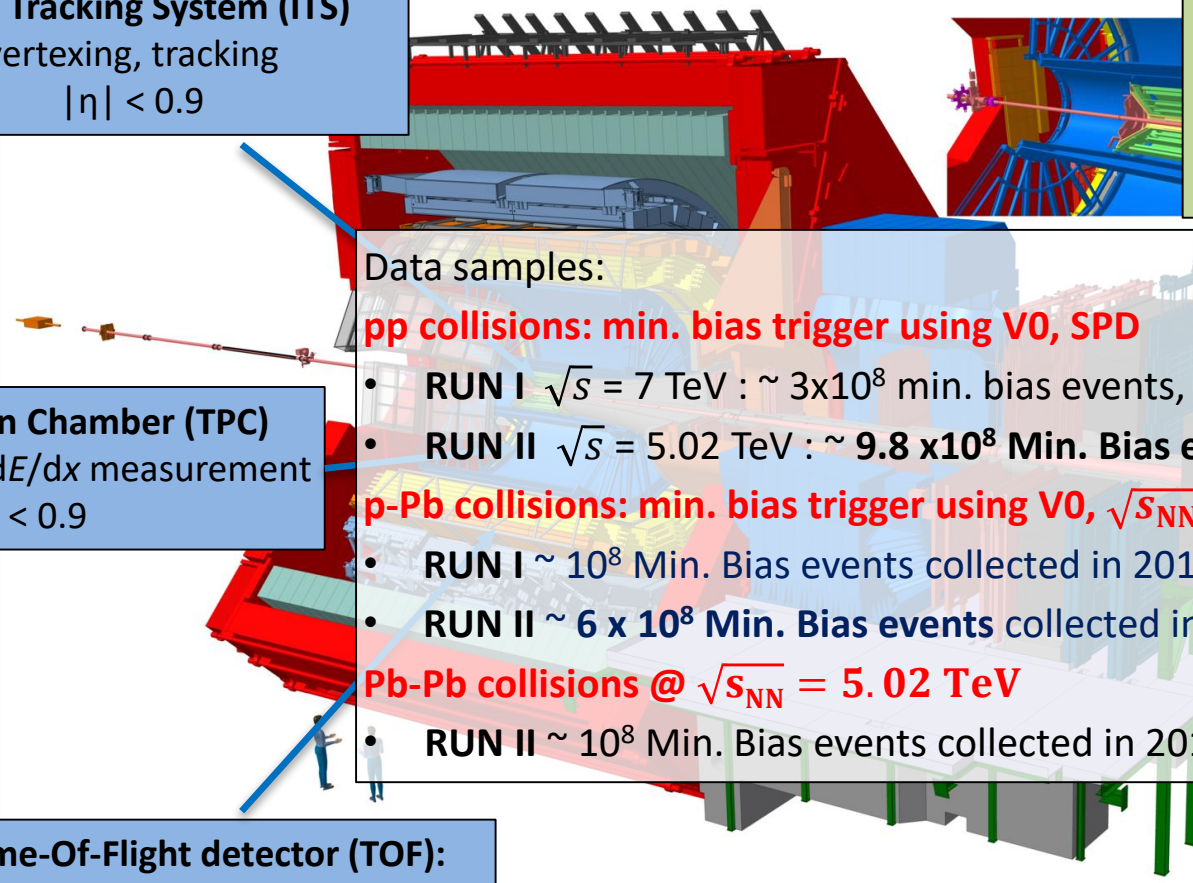


Time Projection Chamber (TPC)
Tracking, PID via d*E*/d*x* measurement
$|\eta| < 0.9$

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

Data samples:

pp collisions: min. bias trigger using V0, SPD

- **RUN I** $\sqrt{s}$ = 7 TeV : ~ 3x10^8 min. bias events, L_{int} = 6.0 nb^{-1}
- **RUN II** $\sqrt{s}$ = 5.02 TeV : ~ **9.8 x10^8 Min. Bias events**, L_{int} = 19.6 nb^{-1}

p-Pb collisions: min. bias trigger using V0, $\sqrt{s_{NN}}$ = 5.02 TeV:

- **RUN I** ~ 10^8 Min. Bias events collected in 2013, L_{int} = 48.6 μb^{-1}
- **RUN II** ~ **6 x 10^8 Min. Bias events** collected in 2016, L_{int} = 292 μb^{-1}

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

- **RUN II** ~ 10^8 Min. Bias events collected in 2015, L_{int} = 13.4 μb^{-1}

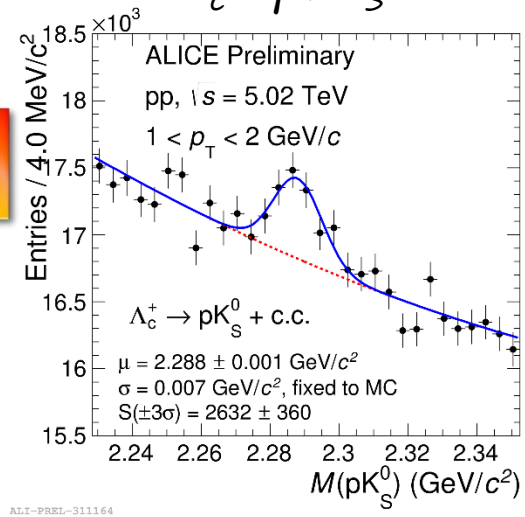
Charmed-hadron reconstruction

Hadronic decays

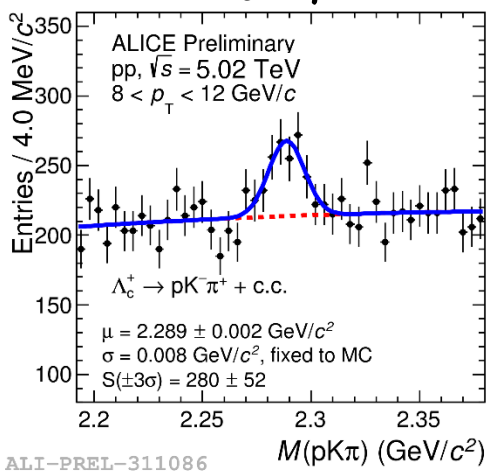
- **Reconstruction of secondary** vertex, displaced a few hundred of μm from primary vertex.
- Candidates selected applying topological selection and PID (using TPC and TOF)
- **Signal extraction** from invariant mass distribution, in several p_T intervals.

New results in pp@5TeV

$\Lambda_c \to pK^0_S$



$\Lambda_c \to pK\pi$



Baryon Λ_c^+
M = 2284 MeV/c²
Quark: *udc*
cτ = 60 µm

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

Charmed-hadron reconstruction

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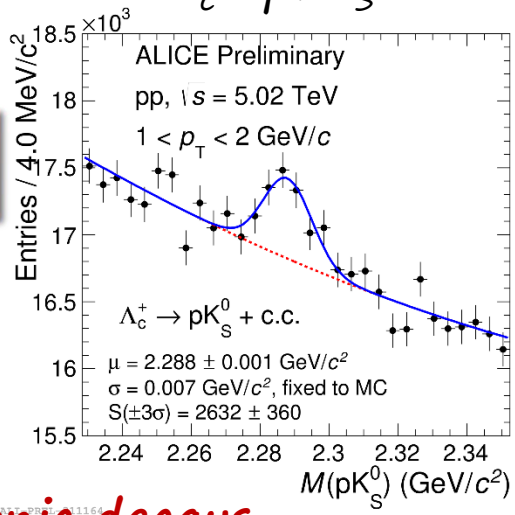
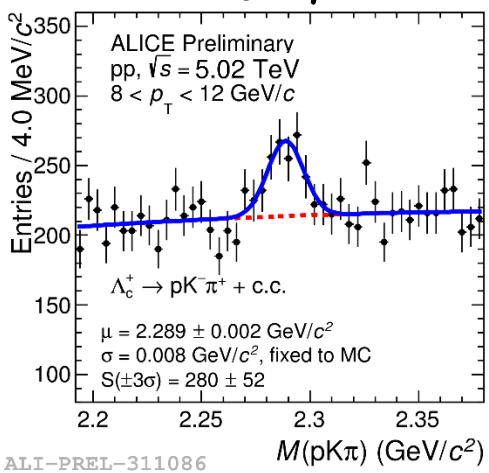


$\Lambda_c \to pK\pi$



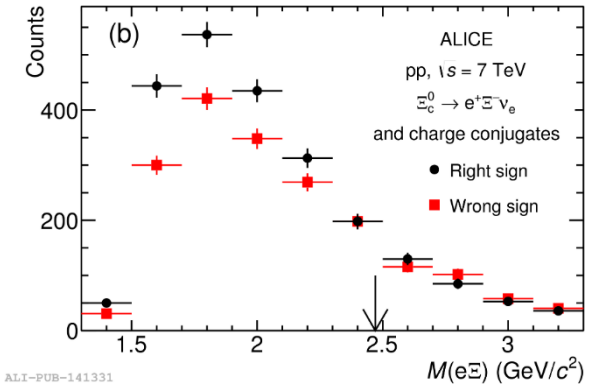
Baryon Λ_c^+
M = 2284 MeV/c²
Quark: *udc*
cτ = 60 μm

Baryon Ξ_c^+
M = 2471 MeV/c²
Quark: *usc*
cτ = 34 μm

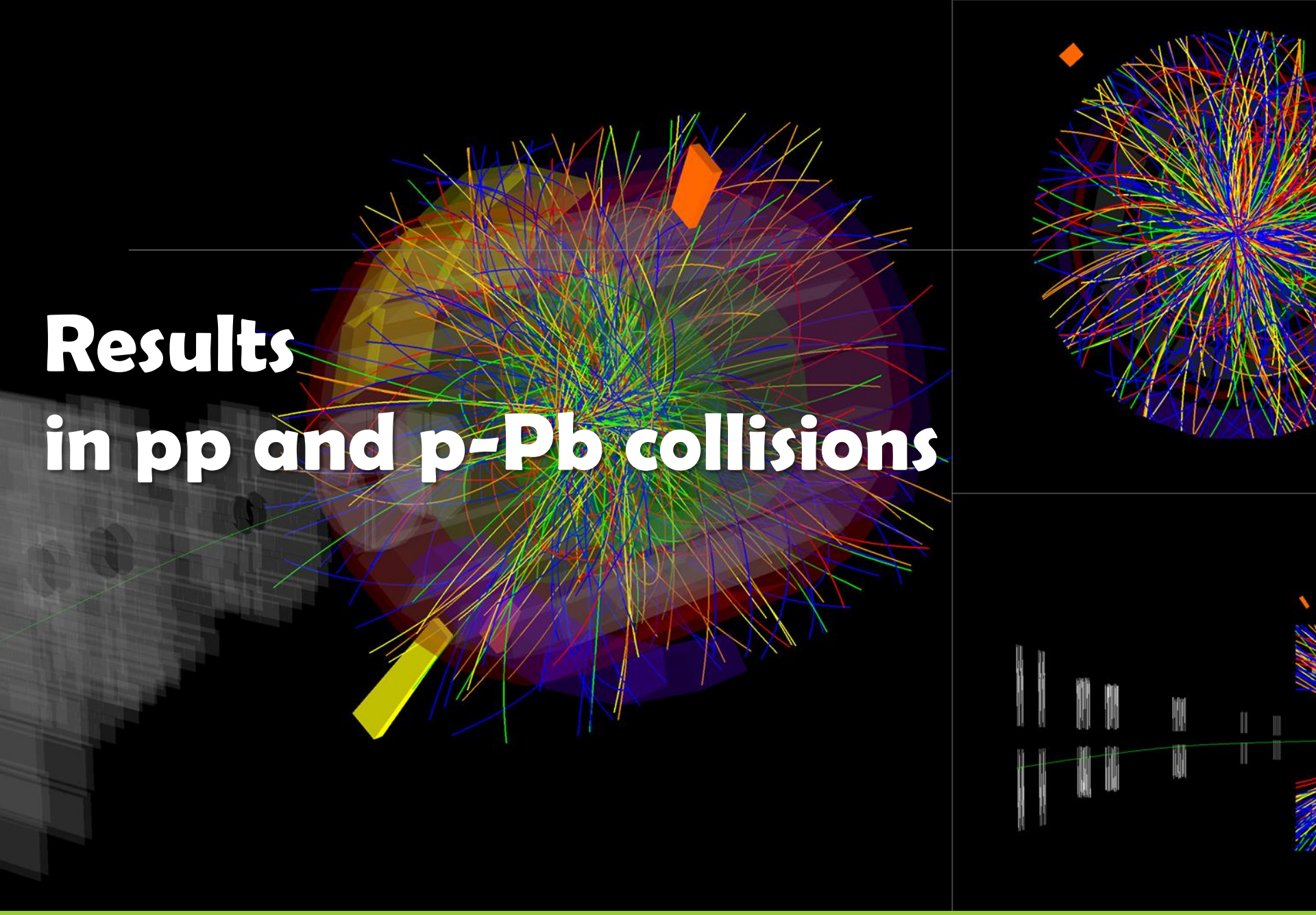
Decay	Branching fraction (%)
$\Lambda_c^+ \to pK^-\pi^+$	6.35
$\Lambda_c^+ \to pK^0_S$	1.58
$\Lambda_c^+ \to e^+\Lambda\nu_e$	3.6
$\Xi_c^0 \to e^+\Xi^-\nu_e$	Unknown

Semileptonic decays

- **Wrong-Sign (WS)** $e^-\Lambda$ ($e^-\Xi^-$) pairs subtracted from **Right-Sign (RS)** $e^+\Lambda$ ($e^+\Xi^-$) spectra, to estimate the combinatorial background.
- **Unfolding technique** used to convert the $e^+\Lambda$ ($e^+\Xi^-$) p_T spectrum in Λ_c^+ (Ξ_c^0)



Results in pp and p-Pb collisions

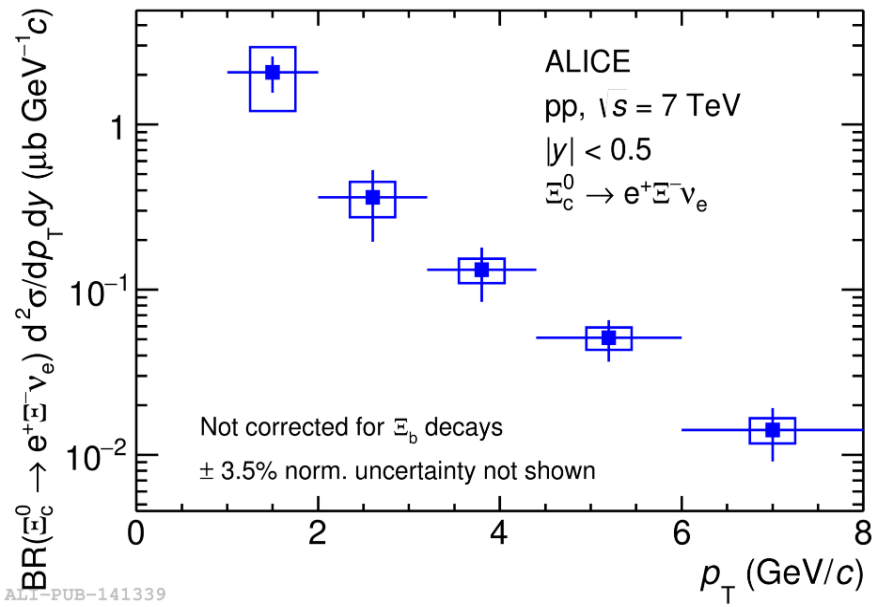


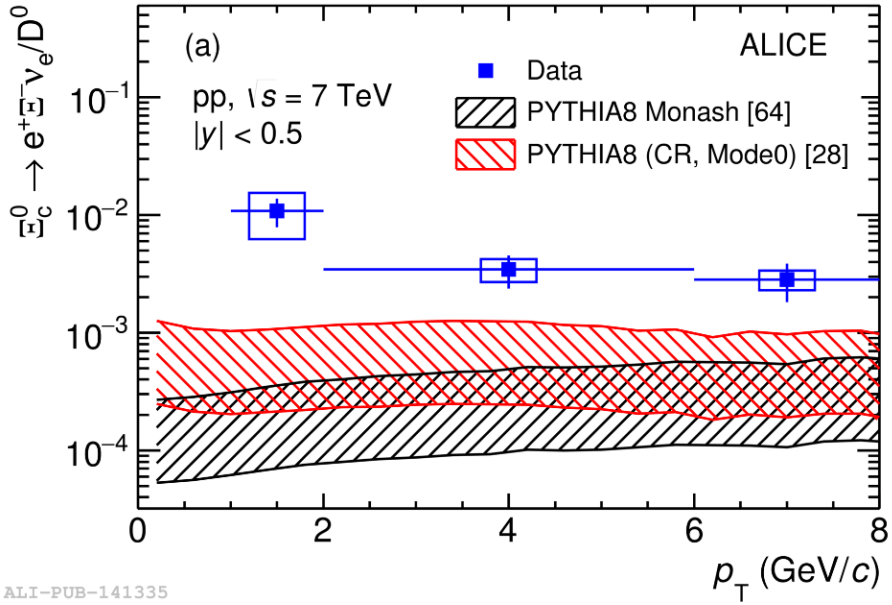
E. MENINNO

Results from Run1 for Ξ_c^0

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

Phys. Lett. B 781 (2018) 8-19





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

- Ξ_c^0 cross section x B.R.($\Xi_c^0 \to e^+\Xi^-\nu_e$) in $1 < p_T < 8$ GeV/c

  B.R.($\Xi_0^c \to e^+\Xi^-\nu_e$) not known, high uncertainty bands in the theoretical predictions.

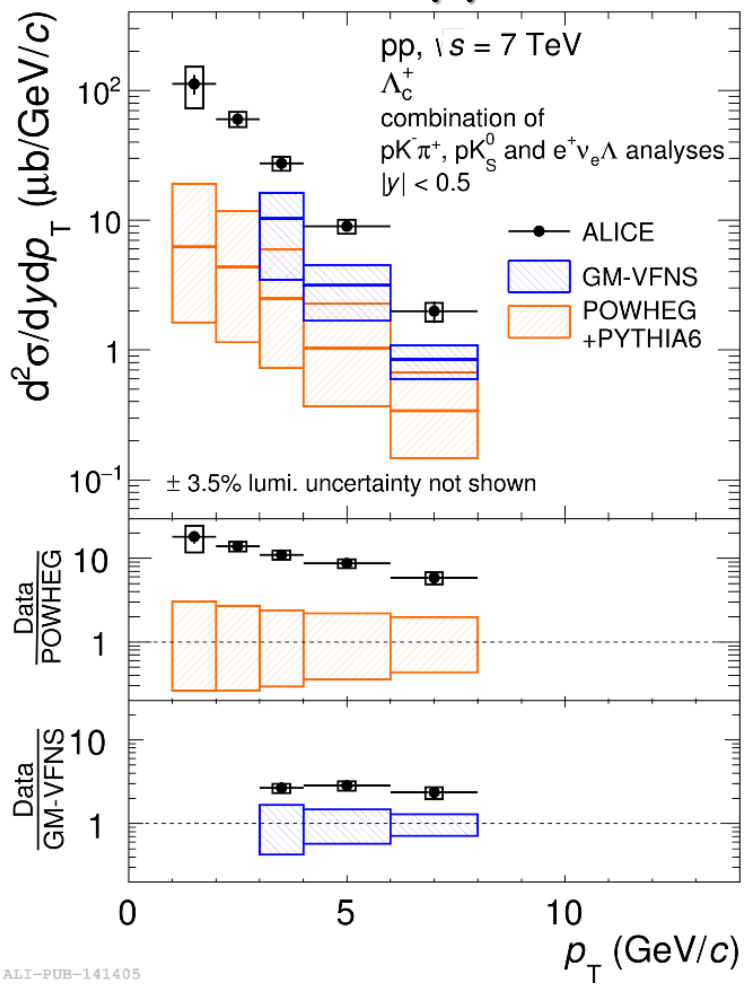
- Baryon/meson $\Xi_c^0 \to e^+\Xi^-\nu_e / D^0$ ratio higher than theoretical predictions.

- **PYTHIA8** with enhanced colour reconnection mechanisms closer to data.

Λ_c^+ cross section in pp collisions

JHEP 04 (2018) 108

pp@7TeV



GM-VFNS, **POWHEG**
(tuned on e^+e^- measurements) underestimate the measured cross section.

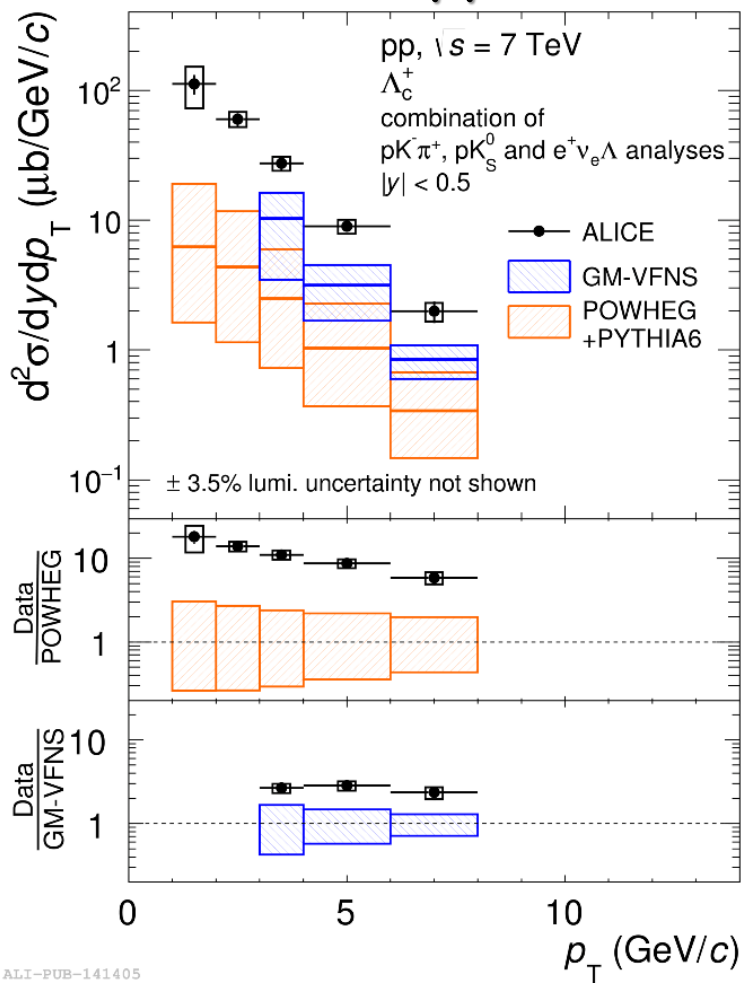
GM-VFNS
Eur. Phys. J. C41, 199 (2005)

POWHEG
JHEP0709, 126 (2007)

Λ_c^+ cross section in pp collisions

JHEP 04 (2018) 108

pp@7TeV

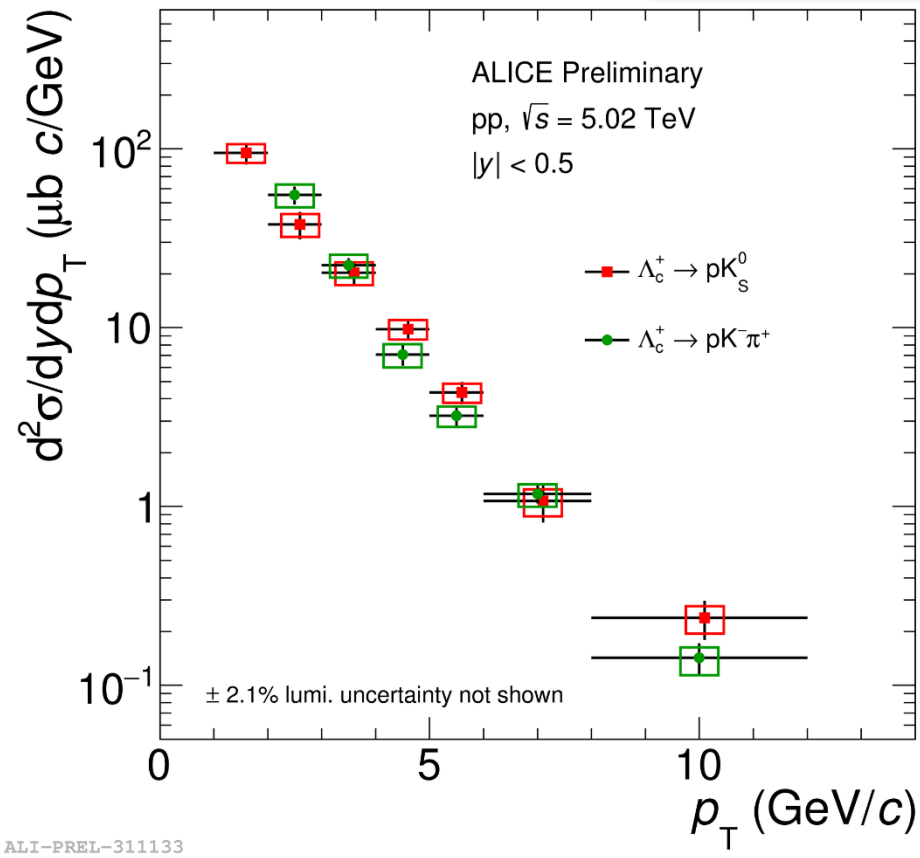


GM-VFNS
Eur. Phys. J. C41, 199 (2005)

POWHEG
JHEP0709, 126 (2007)

pp@5.02TeV (Run2)

New results



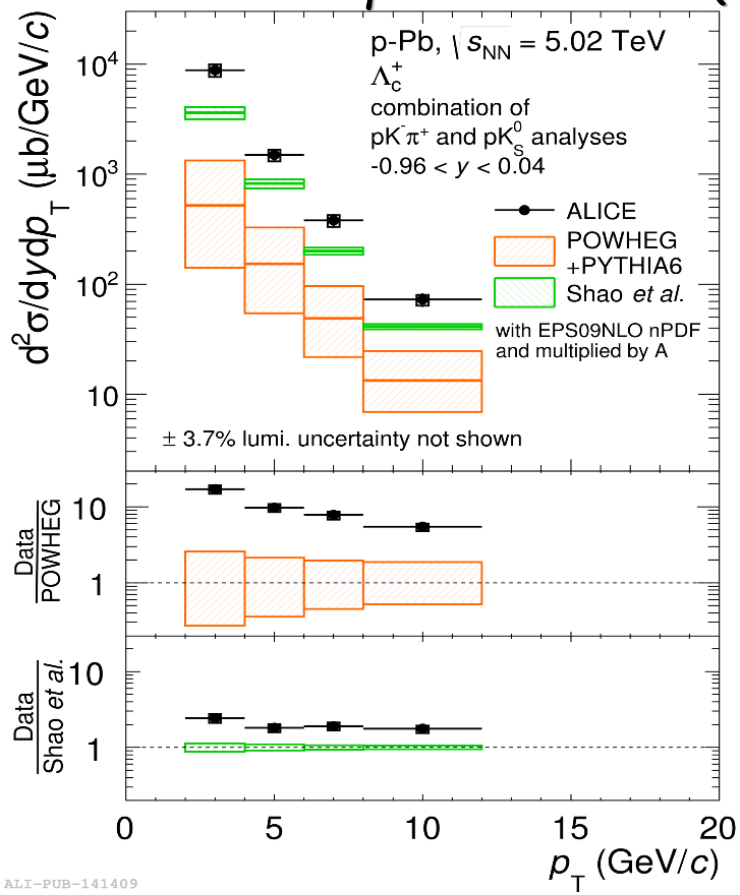
New measurement in pp@5TeV in wider p_T range

Important reference for Pb-Pb and p-Pb collisions.

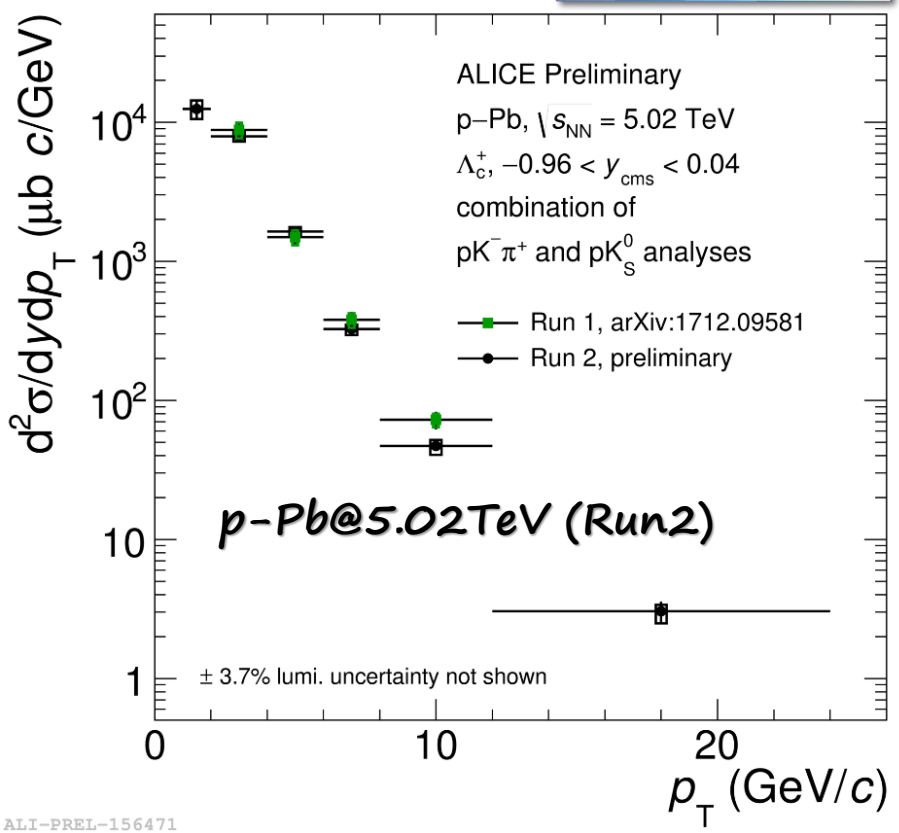
Λ_c^+ cross section in p-Pb collisions

JHEP 04 (2018) 108

p-Pb@5.02TeV (Run1)



Recent results from RunII



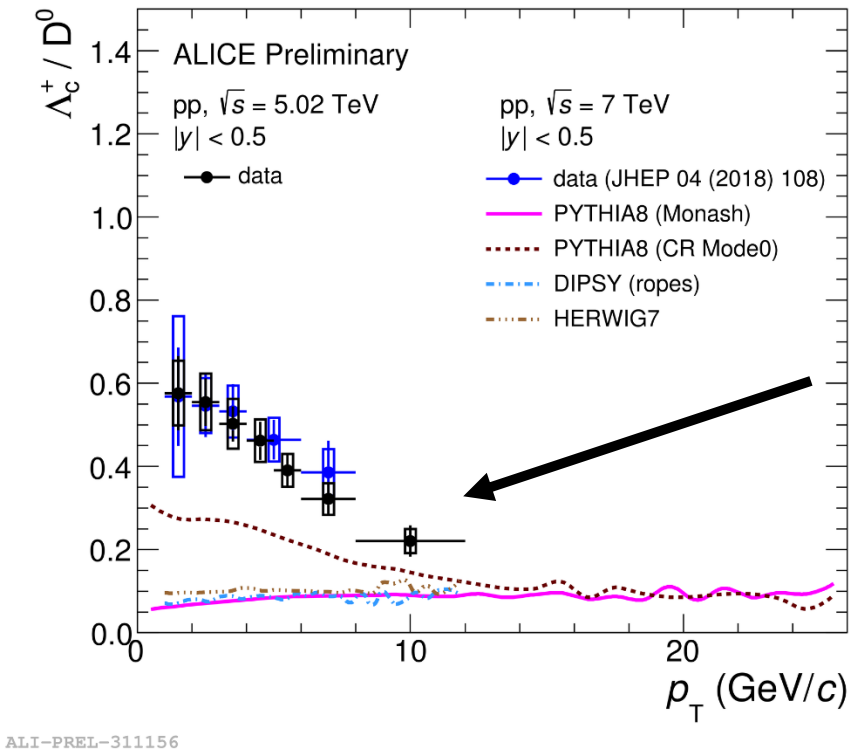
- Λ_c^+ p_T-differential cross section **underestimated** by theoretical models in p-Pb (and pp) collisions
- Improved precision and extended p_T range with Run II data.

POWHEG JHEP0709, 126 (2007)

Lansberg and Shao Eur. Phys. J. C77, no. 1, 1 (2017)

Results for Λ_c^+/D^0

pp@5.02TeV pp@7TeV



New measurement in pp@5TeV

No significant differences w.r.t pp@7TeV

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

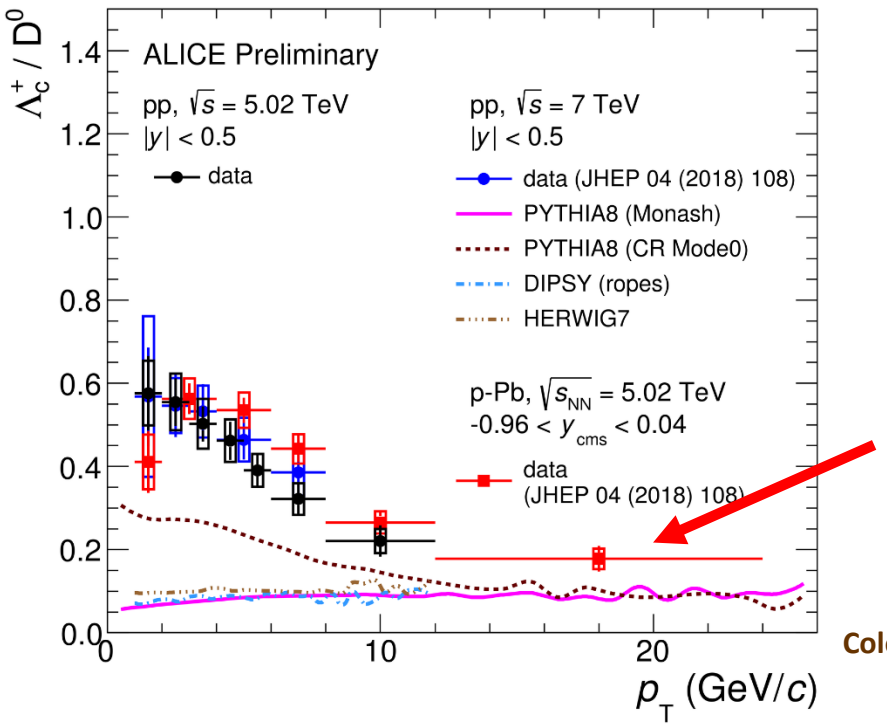
HERWIG7: Eur. Phys. J. C58 (2008) 639-707

- All the models underestimate our measurements.
  - PYTHIA8 with enhanced colour reconnection mode closer to data.

Results for Λ_c^+/D^0

p-Pb@5.02TeV

pp@5.02TeV pp@7TeV



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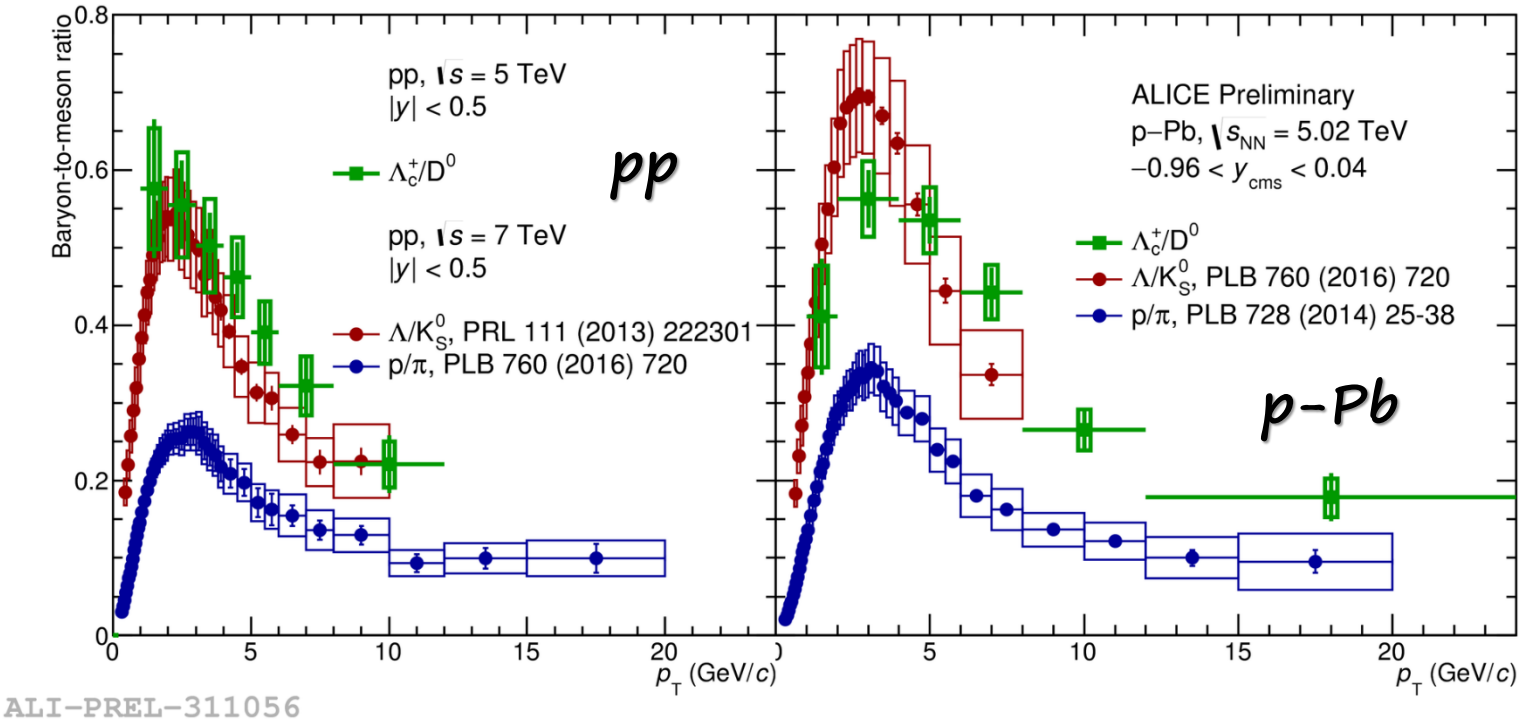
HERWIG7: Eur. Phys. J. C58 (2008) 639-707

- All the models underestimate our measurements.
  - PYTHIA8 with enhanced colour reconnection mode closer to data.
- p-Pb results agree with pp ones within uncertainties.

Results for Λ_c^+/D^0

Λ_c^+/D^0 vs Λ/K^0_S vs p/π

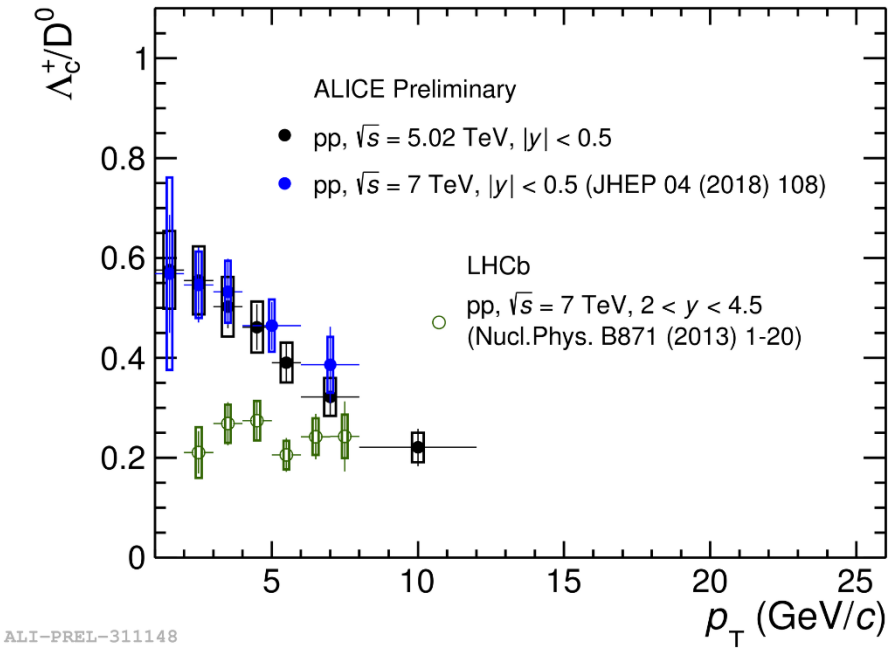


- Decreasing trend from p_T = 4 GeV/c observed in pp and p-Pb collisions.
- Similar trend to baryon-to-meson ratio in the light-flavour sector.

Λ_c^+ / D^0 ratio vs LHCb

ALICE: pp@5.02TeV **pp@7TeV**

LHCb: pp@7TeV



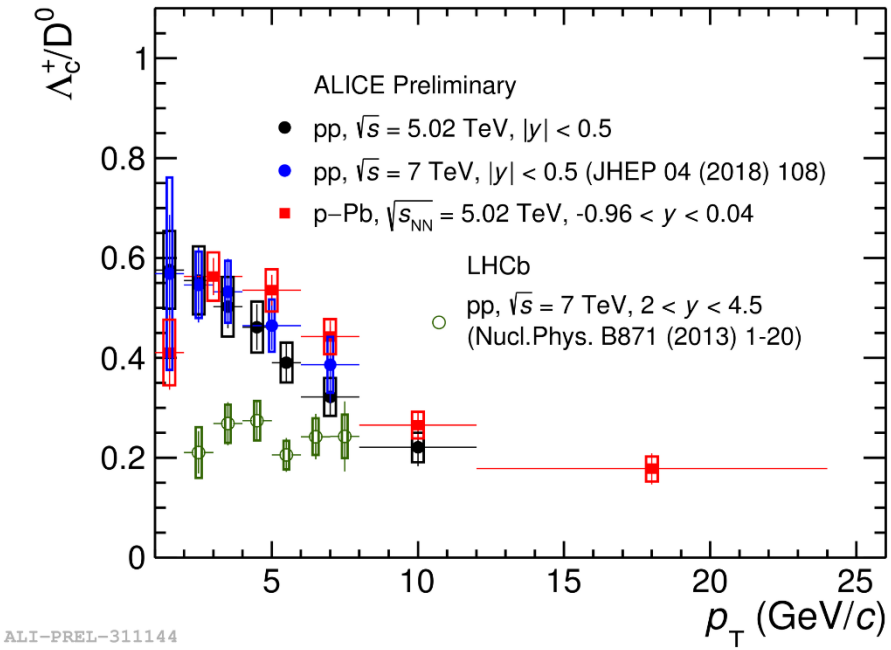
- ALICE measurements higher than LHCb in pp collisions.

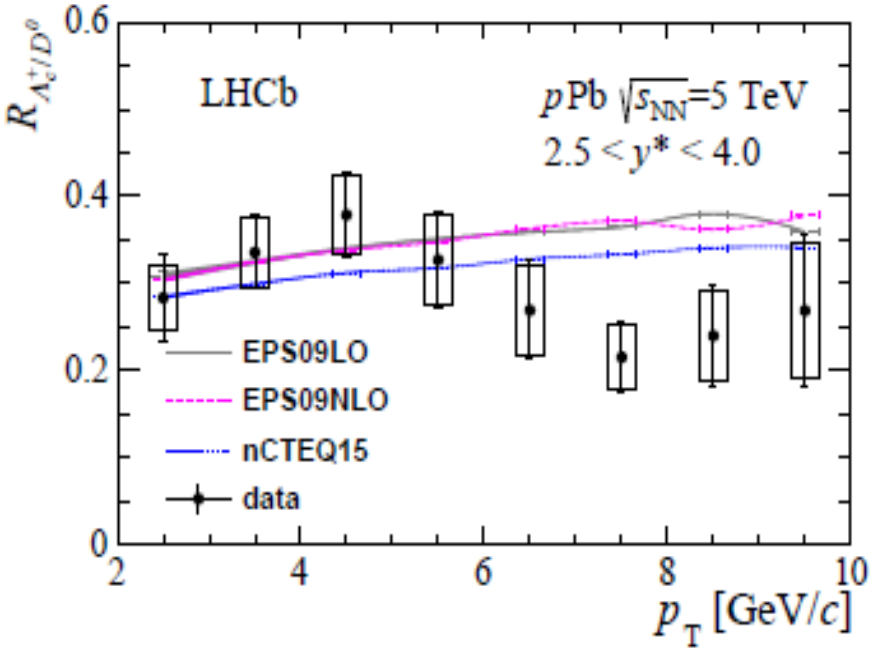
Λ_c^+ / D^0 ratio vs LHCb

ALICE: pp@5.02TeV pp@7TeV p-Pb@5.02TeV

LHCb: pp@7TeV

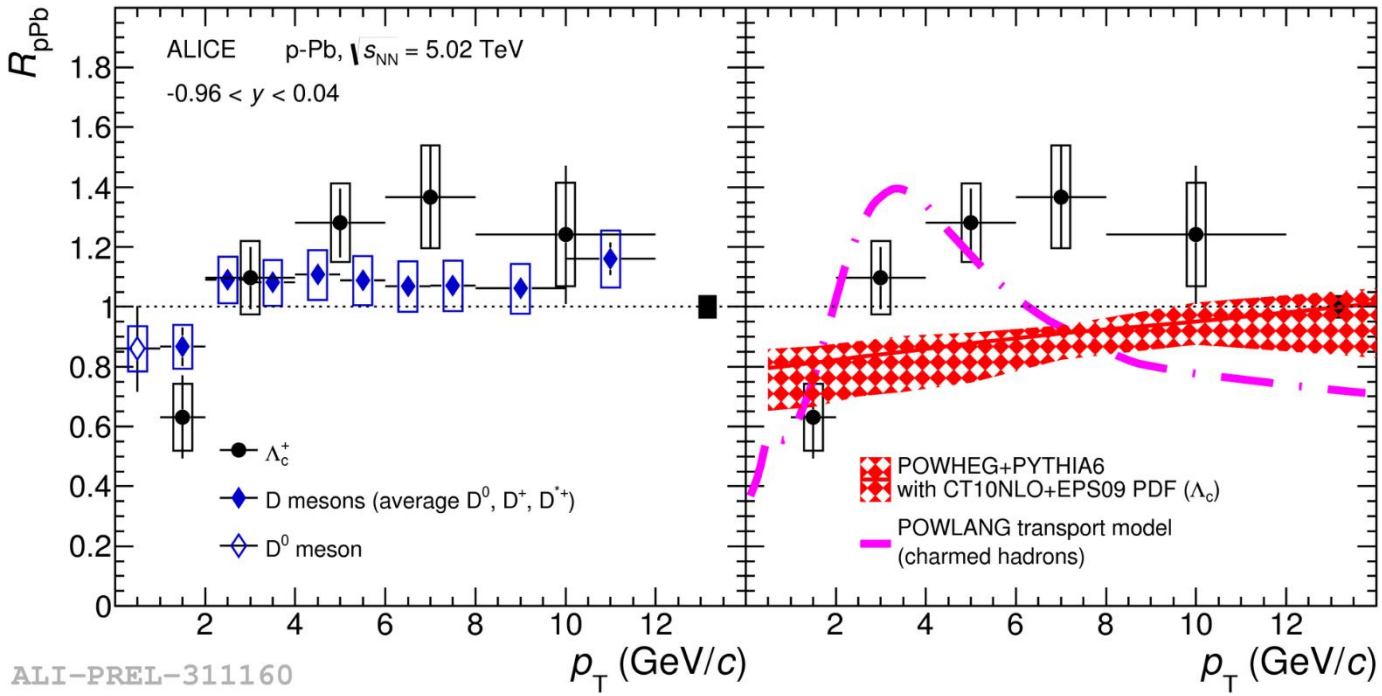
LHCb arXiv:1809.01404





- ALICE measurements higher than LHCb in pp collisions.
- Λ_c^+/D^0 in p-Pb collisions:
  - ALICE and LHCb points are closer than in pp collisions
  - Tendency for higher values at midrapidity than forward and backward rapidity.

Λ_c^+ nuclear modification factor R_{pPb}



$$R_{\mathrm{pPb}} = \frac{d\sigma_{\mathrm{pPb}}/dp_{\mathrm{T}}}{A \times d\sigma_{pp}/dp_{\mathrm{T}}}$$

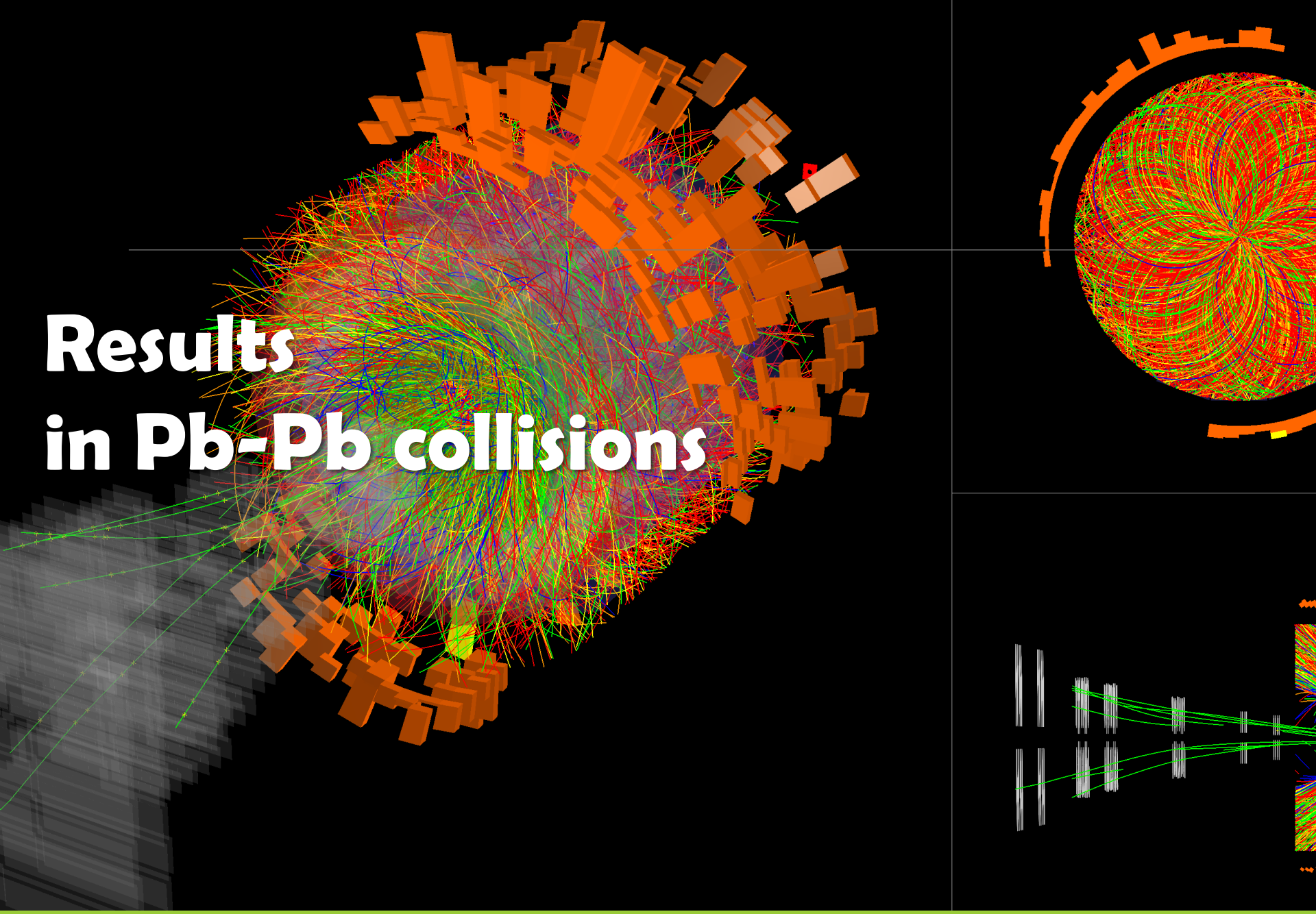
pp reference:
new measurement at 5 TeV

- Λ_c^+ R_{pPb} **compatible with unity**
- Compatible with D-meson R_{pPb}

- **Compatible with models within uncertainties:**
  - **POWHEG+PYTHIA6 with CT10NLO+EPS09 PDF - only CNM effects included**
  - **POWLANG – small QGP formation included**

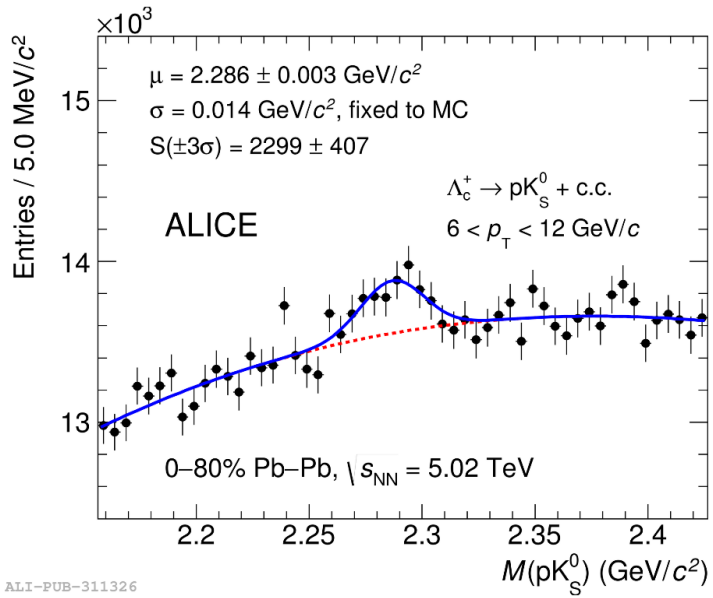
POWHEG +PYTHIA parton shower: JHEP 0709:126,2007
POWLANG: JHEP03(2016)123

Results in Pb-Pb collisions



First measurement of Λ_c production in Pb–Pb collisions at the LHC

New on arXiv! arXiv:1809.10922



- Analysis of $\Lambda_c^+ \rightarrow pK^0_S$ with topological cut selection in 0-80 % centrality and for $6 < p_T < 12$ GeV/*c*.

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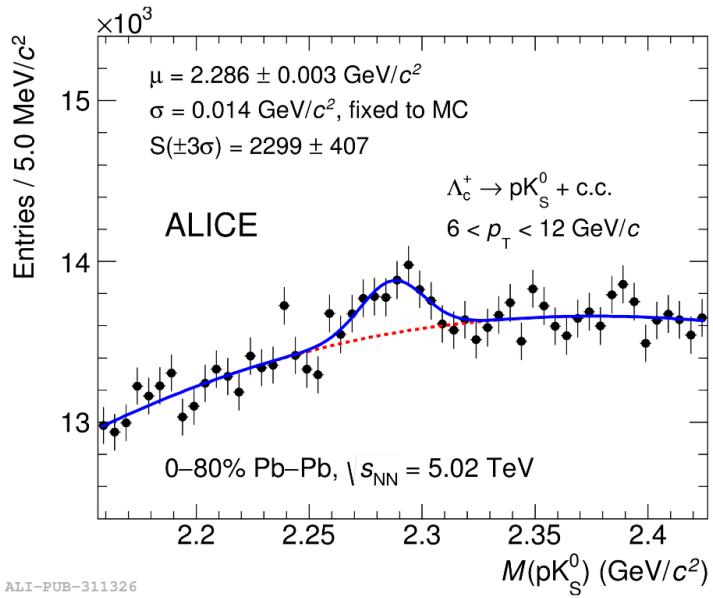
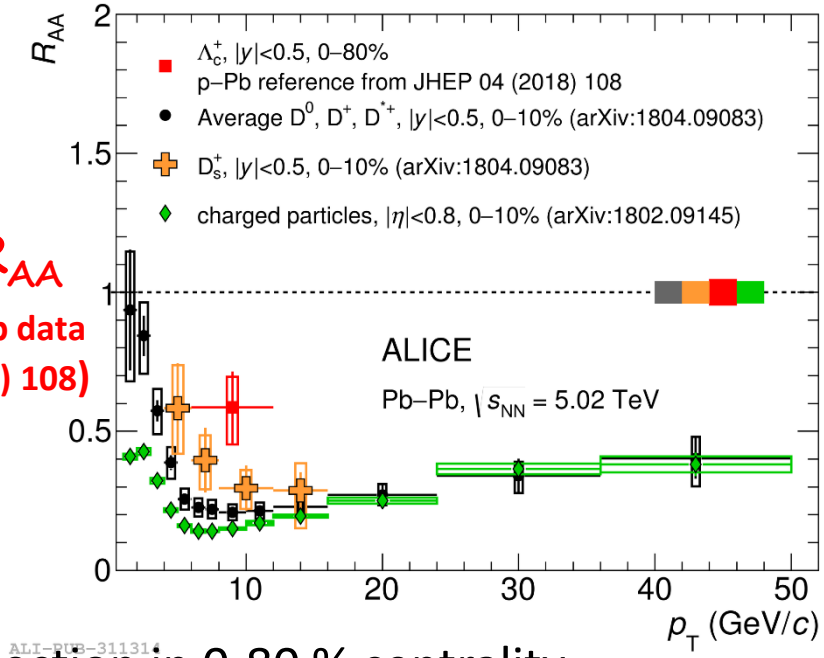


Λ_c^+ R_{AA}

Reference: p-Pb data (JHEP 04 (2018) 108)



- Analysis of $\Lambda_c^+ \rightarrow pK^0_S$ with topological cut selection in 0-80 % centrality and for $6 < p_T < 12$ GeV/*c*.
- Λ_c^+ R_{AA} in 0-80% for $6 < p_T < 12$ GeV/*c* higher (1.7σ) than that of D^0 mesons.
- Suggested hierarchy **Λ_c^+ R_{AA} > D_s^+ R_{AA} > non-strange D-meson R_{AA}?**
  - ➡ baryon production increased by hadronisation via coalescence

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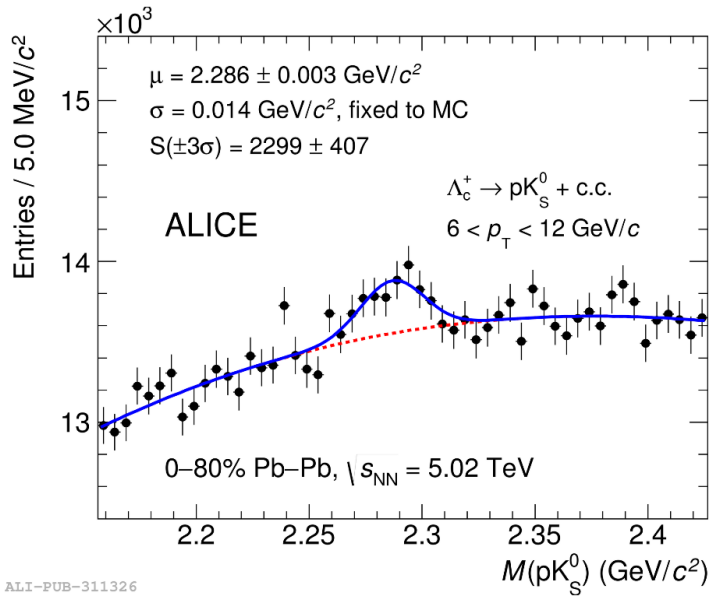
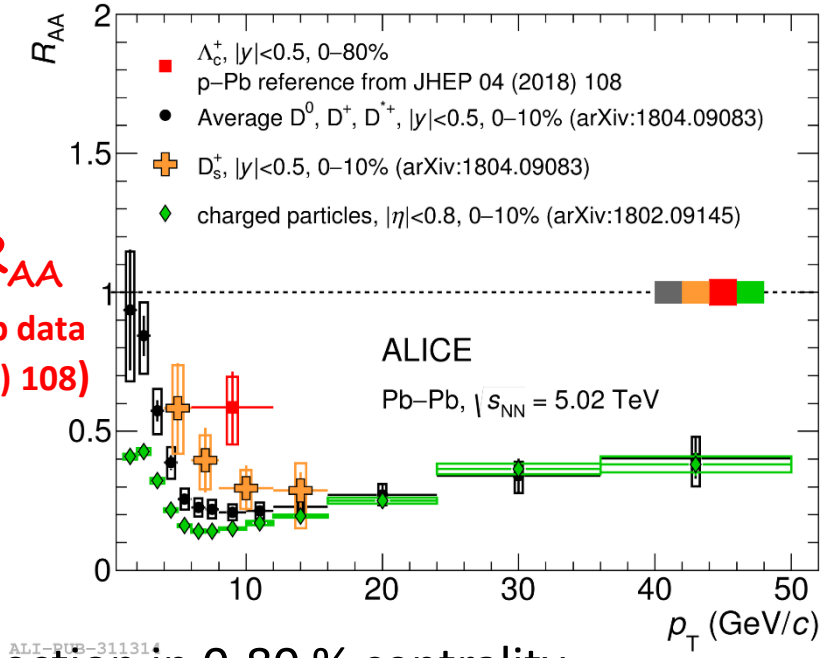


Λ_c^+ R_{AA}

Reference: p-Pb data (JHEP 04 (2018) 108)



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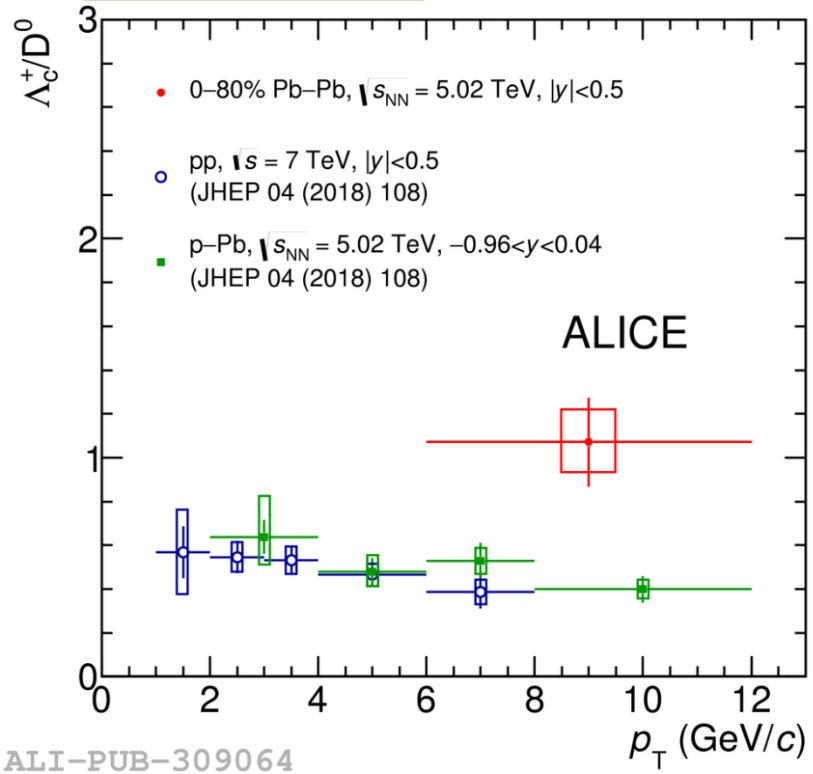
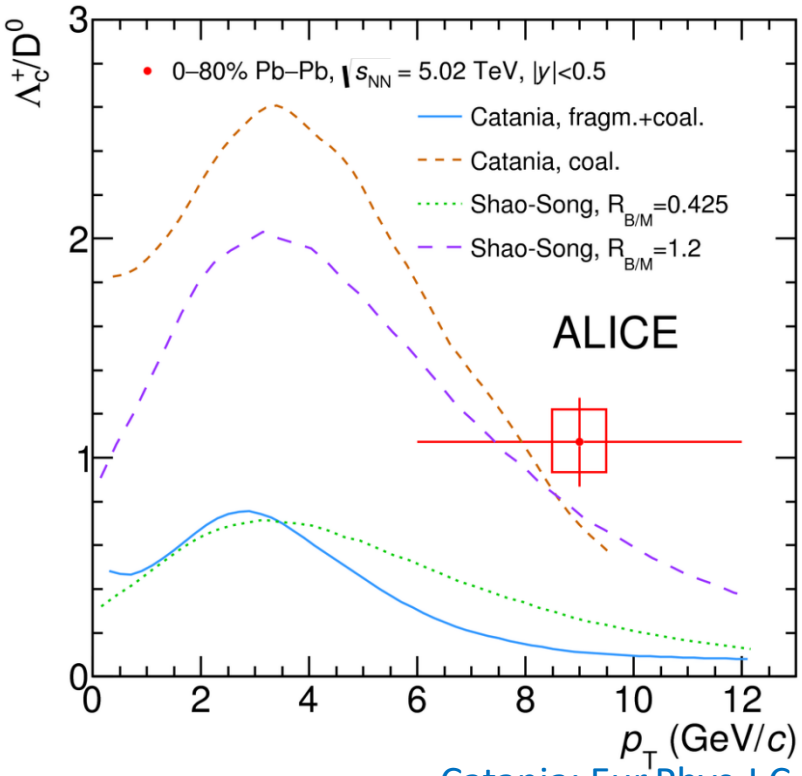
- Λ_c^+ R_{AA} in 0-80% for $6 < p_T < 12$ GeV/c higher (1.7σ) than that of D^0 mesons.
- Suggested hierarchy **Λ_c^+ R_{AA} > D_s^+ R_{AA} > non-strange D-meson R_{AA}?**
  - ➡ baryon production increased by hadronisation via coalescence
- Waiting for 2018 Pb-Pb run: extend p_T interval, finer granularity in p_T and centrality.

First measurement of Λ_c production in Pb-Pb collisions at the LHC

arXiv:1809.10922





Catania: Eur.Phys.J.C (2018) 78:348
Shao-Song: Phys. Rev. C 97, 064915

- Λ_c^+/D^0 higher (2σ) than that in pp and p-Pb collisions.
- Λ_c^+/D^0 results described by **model calculations including only coalescence.**

First measurement of Λ_c production in Pb-Pb collisions at the LHC

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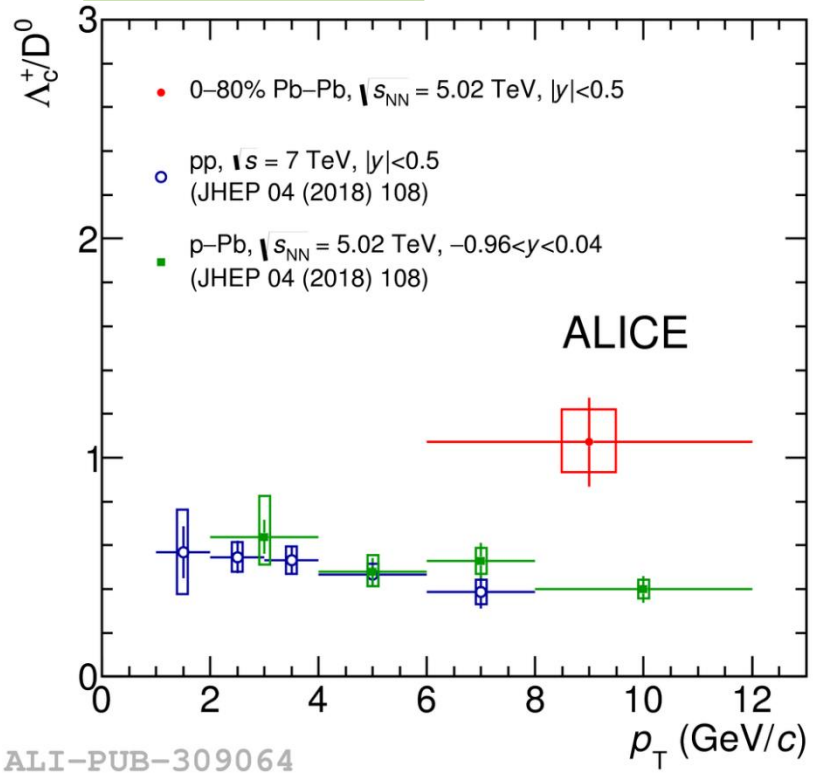

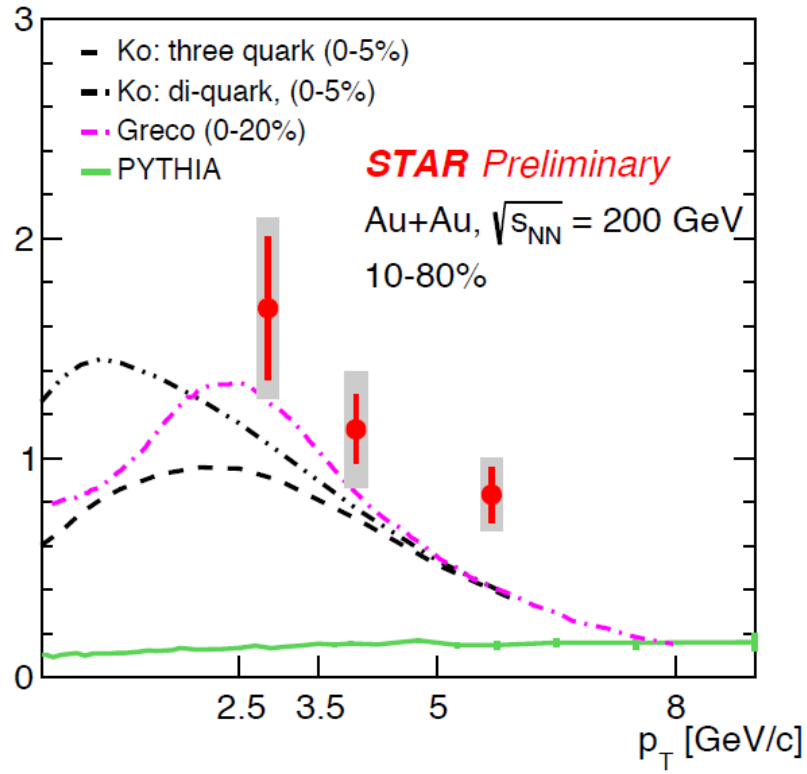

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- Λ_c^+/D^0 results described by **model calculations including only coalescence.**
  Catania: Eur.Phys.J.C (2018) 78:348
- Λ_c^+/D^0 in $6 < p_T < 12$ GeV/c similar to STAR values in 3-6 GeV/c.

Conclusions

Measurements of charmed baryons with ALICE in pp and p-Pb collisions

- New measurements in pp@5 TeV, more p_T –differential and covering a wider p_T range. Important reference for Pb-Pb
- Production higher than theoretical predictions, tuned on e^+e^- measurements.
    - violation of fragmentation universality?
- Λ_c^+/ D^0 in p-Pb : similar p_T trend as baryon to meson ratio observed in light flavour sector.
- Λ_c^+ R_{pPb} compatible with unity, with D mesons and with models including CNM effects or small QGP formation.

Conclusions

Measurements of charmed baryons with ALICE in pp and p-Pb collisions

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Λ_c analysis in Pb-Pb collisions

- Λ_c^+/D^0 : Hint of enhancement (2σ) with respect to pp and p-Pb collisions.
  - Λ_c^+/D^0 in Pb-Pb described by models including hadronisation via coalescence
- Λ_c^+ R_{AA} *:* hint of hierarchy Λ_c^+ R_{AA} > D_s^+ R_{AA} > D^0 R_{AA}

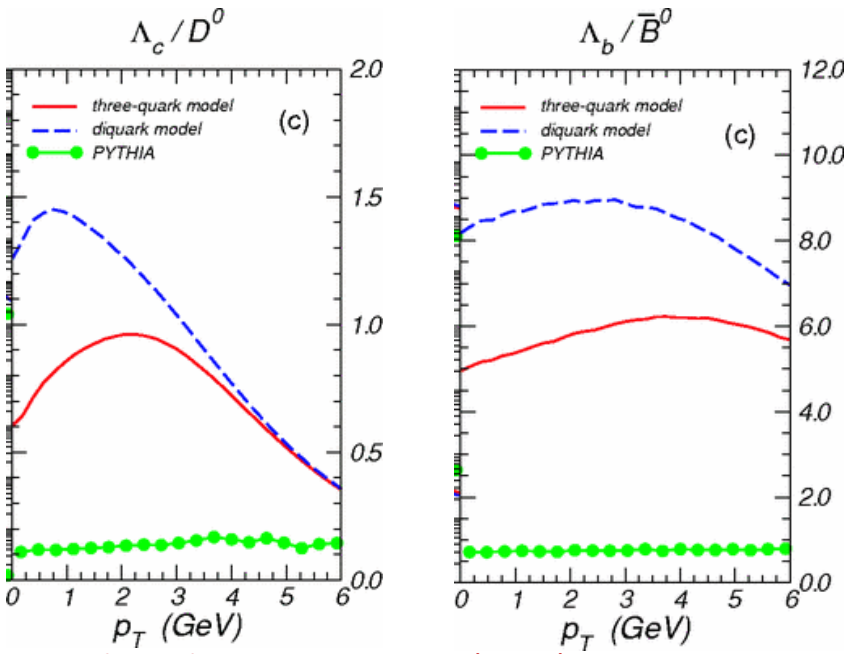
- **Still large uncertanties: Waiting for 2018 Pb-Pb data**


Thank You!

Backup

Physics motivations

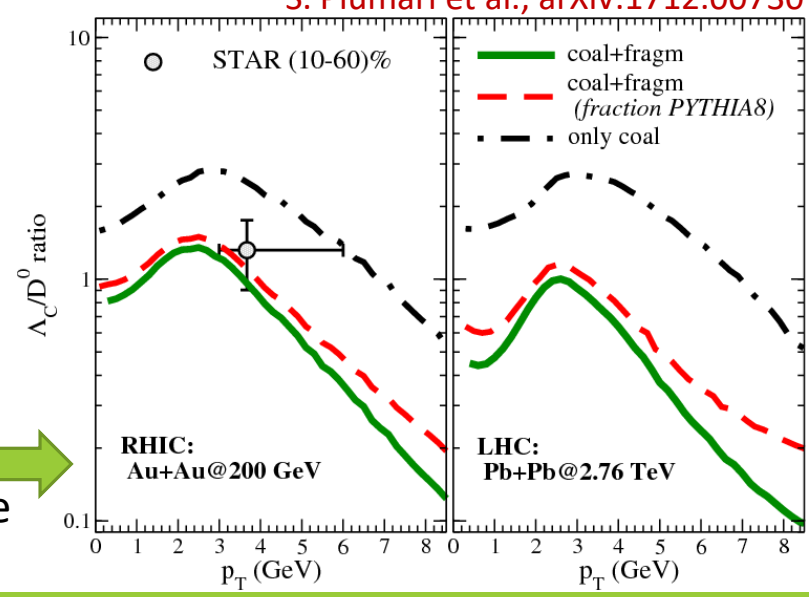
- Charm is a very sensitive probe of the *Quark-Gluon-Plasma* (QGP)
  - Produced in hard partonic scattering in the early stages of the collisions.
- Charmed-baryon production in Heavy Ion (HI) collisions could give an insight into the hadronisation processes in the QGP.



Y. Oh et al., PRC 79, 044905 (2009)

Enhancement of Λ_c^+ / D^0 (and $\Lambda_b^+ / \bar{B}^0$) ratio is predicted in coalescence models. Further enhancement is expected if thermalised light diquark states exist in the QGP.

S. Plumari et al., arXiv:1712.00730

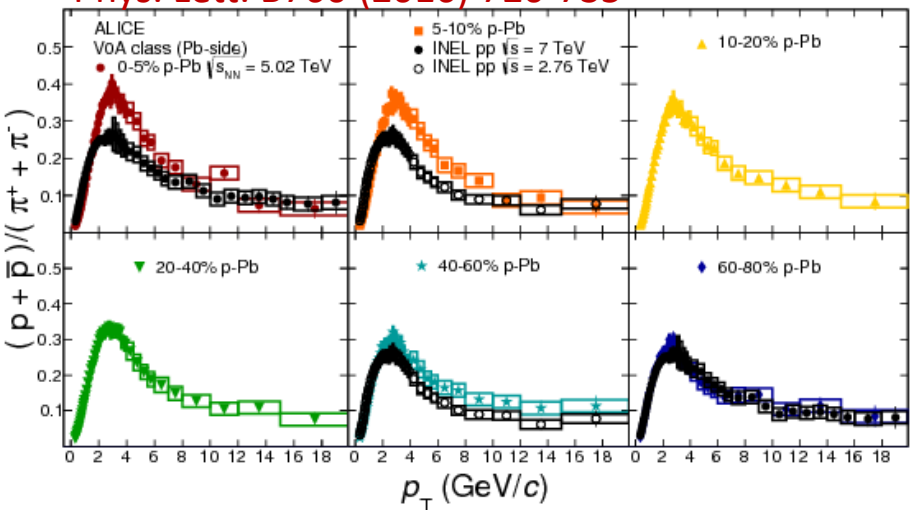


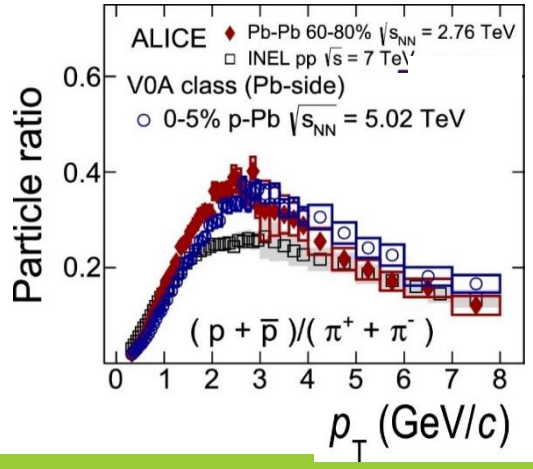
Coalescence plus fragmentation modelling: in the peak region quite good agreement with the experimental data by STAR.

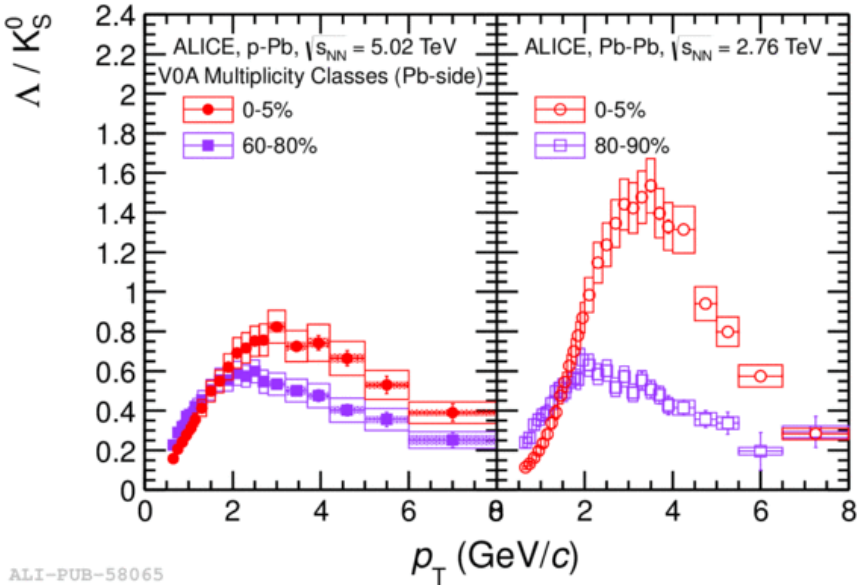
Physics motivations

- ALICE and CMS observed enhancement of baryon/meson ratio at intermediate p_T in High Multiplicity (HM) pp and p-Pb collisions.
  - Similar to what was observed in HI collisions

Phys. Lett. B760 (2016) 720-735







Physics motivations

- Measurement in pp collisions:
  - Important to test predictions from pQCD and the models of hadronisation in vacuum.
- Measurement in p-Pb collisions:
  - Important to distinguish cold-nuclear-matter (CNM) effects, that can affect the charm hadron production.

- Baryon/meson ratio particularly sensitive to the fragmentation process.
  - Differences observed in pp collisions (CDF+LHCb) with respect to e^+e^- collisions (LEP) in the beauty sector http://pdg.lbl.gov/2017/reviews/rpp2017-rev-b-meson-prod-decay.pdf

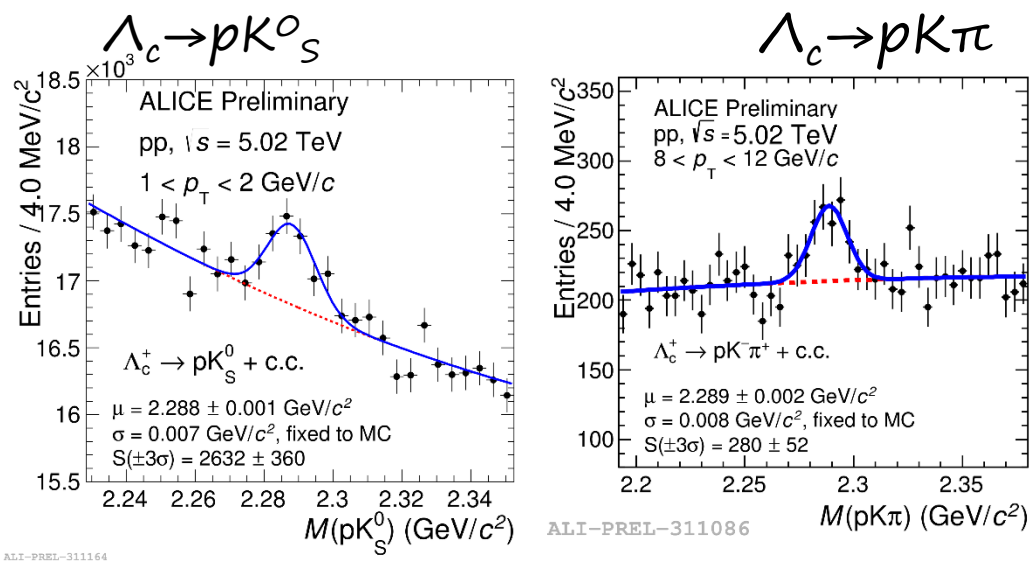
→ hint of non-universal fragmentation fractions for baryons in the beauty sector

Charmed-hadron reconstruction

Hadronic decays

- **Reconstruction of secondary** vertex, displaced a few hundred of μm from primary vertex.
- Candidate selected applying topological selection and PID (using TPC and TOF)
  - $N\sigma$ cuts, Bayesian approach

- **Signal extraction** from invariant mass distribution, in several p_T intervals.

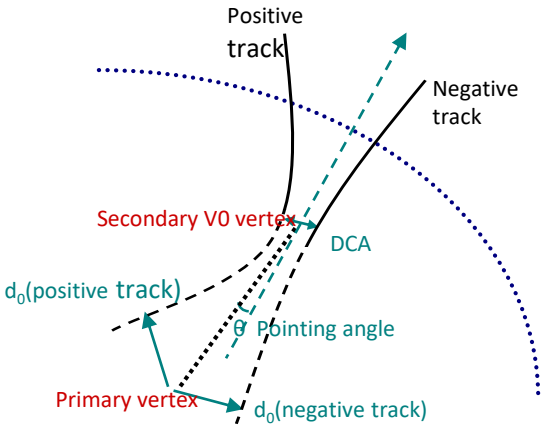


Baryon Λ_c^+
M = 2284 MeV/c^2
Quark: *udc*
$c\tau$ = 60 μm

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

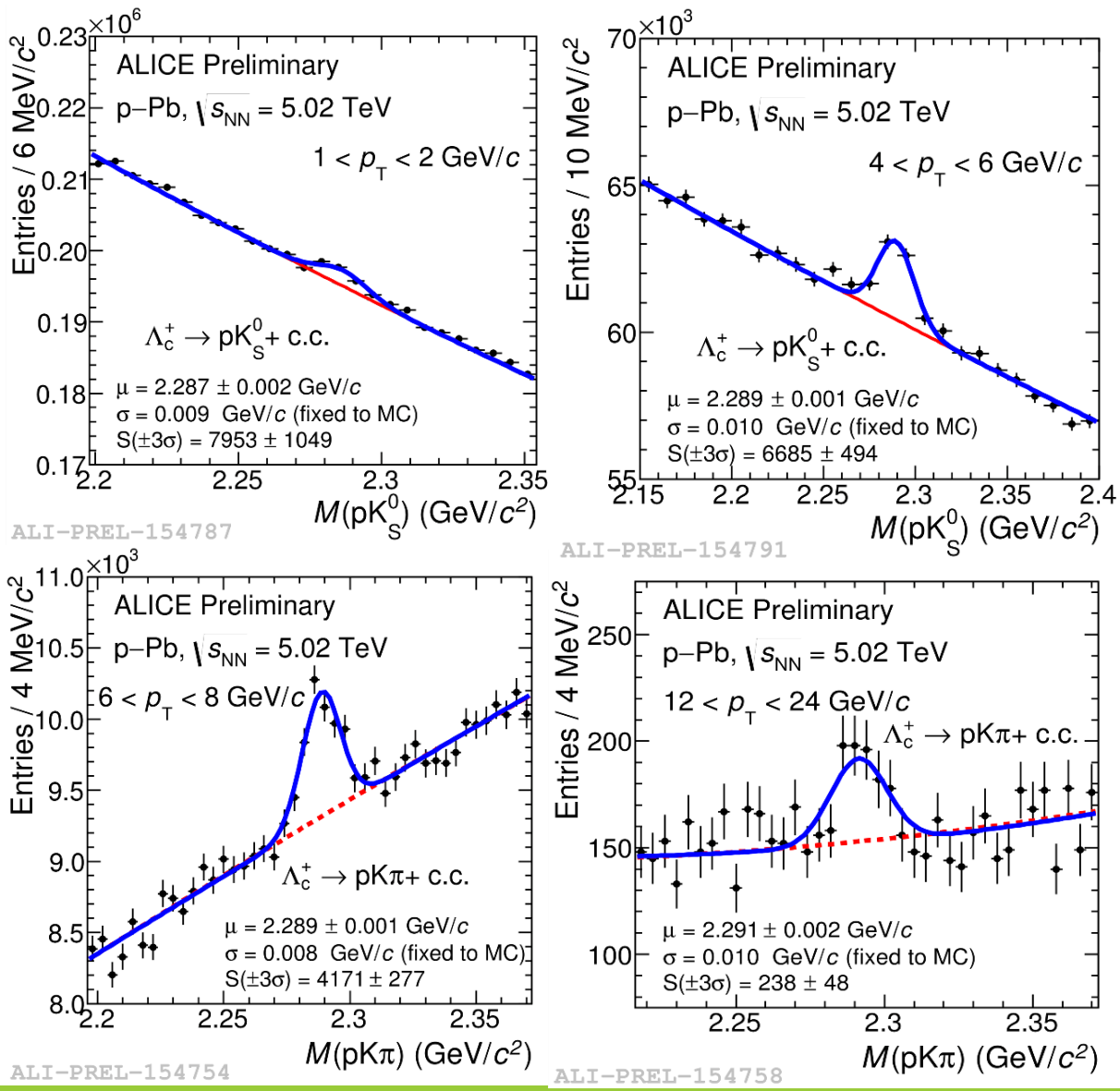
- Subtraction of contribution from beauty hadrons **(feed-down)**.

- Corrections for acceptance and efficiency.



$\Lambda_c^+ \to pK^0_S$ and $\Lambda_c^+ \to pK^+\pi^-$ signal extraction in p-Pb

Recent results from RunII

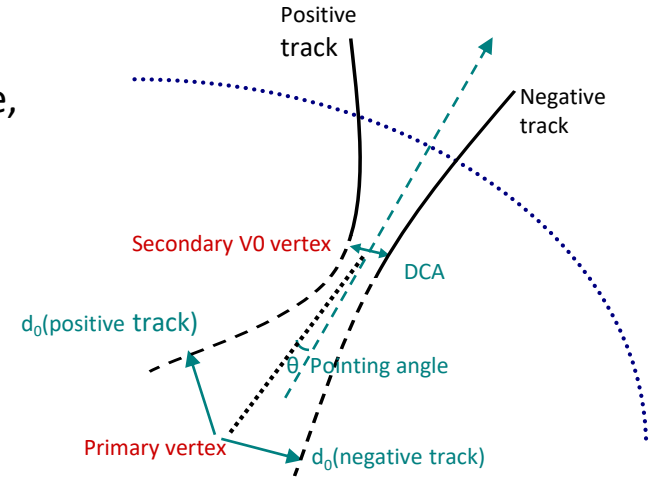


- Signal extracted via an invariant-mass analysis.
- Decay topology selection and Multivariate approach (Boosted Decision Tree) used.
- Signal extracted in 1-24 GeV/c
- Wider and finer binning with respect to Run I.

https://arxiv.org/abs/1712.09581

$\Lambda_c \rightarrow pK^0_S$ analysis strategy

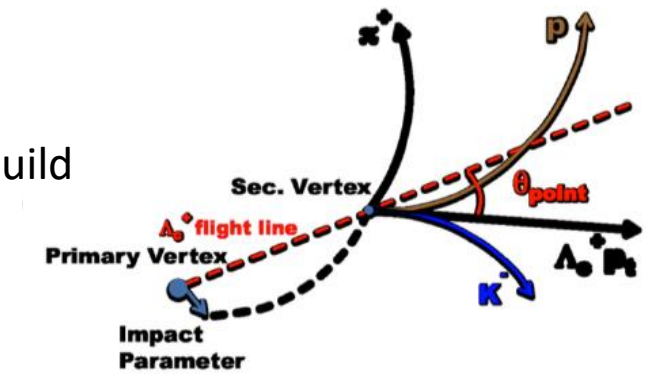
$\Lambda_c \rightarrow pK^0_S$ B.R = (1.58 ± 0.08)%
and $K^0_S \rightarrow \pi^+\pi^-$ B.R = (69.20 ± 0.05)%



- K^0_S candidate reconstructed from pairs of opposite-sign tracks forming a vertex displaced from the interaction vertex, according to track selection and topological cuts:
  - Distance of closest approach (DCA), Cosine of pointing angle, p_T(K^0_S daughters), d_0(K^0_S daughters) , $m_{inv}(\pi^+\pi^-)$
- Proton candidates are selected, according to track quality selection and **PID** (the main selection, using TPC and TOF)
- **Built Λ_c candidate, combining K^0_S and proton candidates**
- Further selection to improve signal extraction, via two methods:
  - **Topological cuts on several variables (standard analysis - STD)**
  - **Cut on multivariate discriminator (TMVA)**
- Feed-down correction
- Efficiency and acceptance corrections
- Cross section estimate

$\Lambda_c \rightarrow pK\pi$ analysis strategy

$\Lambda_c \rightarrow pK\pi$ B.R = (6.35 ± 0.33)%



- ***$pK\pi$ candidate building***

Pairs of opposite charge tracks selected. Third track added to build a triplet and secondary vertex of the triplet estimated.
Cuts applied: high-quality single track cuts, cuts on p_T daughters, quality of reconstructed vertex, DCA, cosine of Λ_c pointing angle (angle between the Λ_c flight line and the momentum of the reconstructed Λ_c candidate), Bayesian PID.

- Further selection to improve signal extraction, via two methods:
  - **Topological cuts on several variables (standard analysis - STD)**
  - **Cut on multivariate discriminator (TMVA)**

- Feed-down correction
- Efficiency and acceptance corrections
- Cross section estimate

Charmed-hadron reconstruction

Semileptonic decays

- **Wrong-Sign (WS)** $e^-\Lambda$ ($e^-\Xi^-$) pairs subracted from **Right-Sign (RS)** $e^+\Lambda$ ($e^+\Xi^-$) spectra, to estimate the combinatorial background.

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

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

- PID for electrons using TOF and TPC.

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

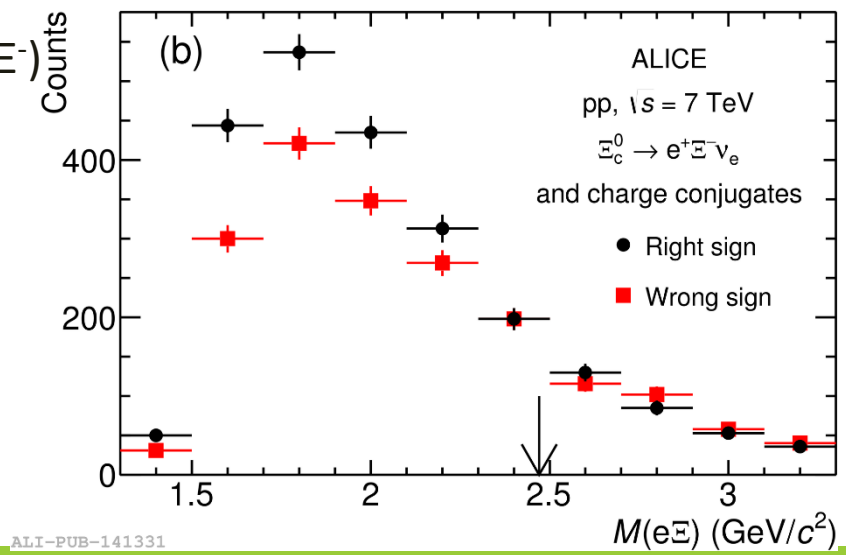
- Subtracted contributions from:
  - Λ_b^0 (Ξ_b^0) in WS spectra
  - Ξ_c^+ in RS spectra, for Λ_c^+ analysis.

- **Unfolding technique** used to convert the $e^+\Lambda$ ($e^+\Xi^-$) p_T spectrum in Λ_c^+ (Ξ_c^0)

- Subtraction of contribution from beauty hadrons (**only for Λ_c^+**)

- Corrections for acceptance and efficiency

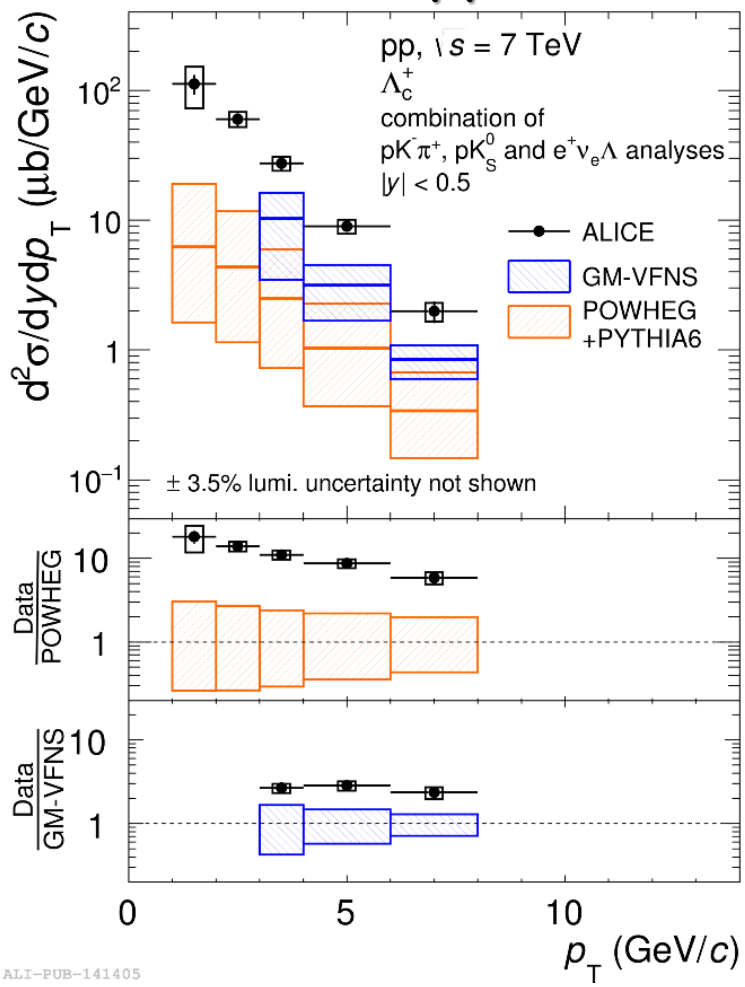
Phys. Lett. B 781 (2018) 8-19



Λ_c^+ cross section in pp collisions

JHEP 04 (2018) 108

pp@7TeV

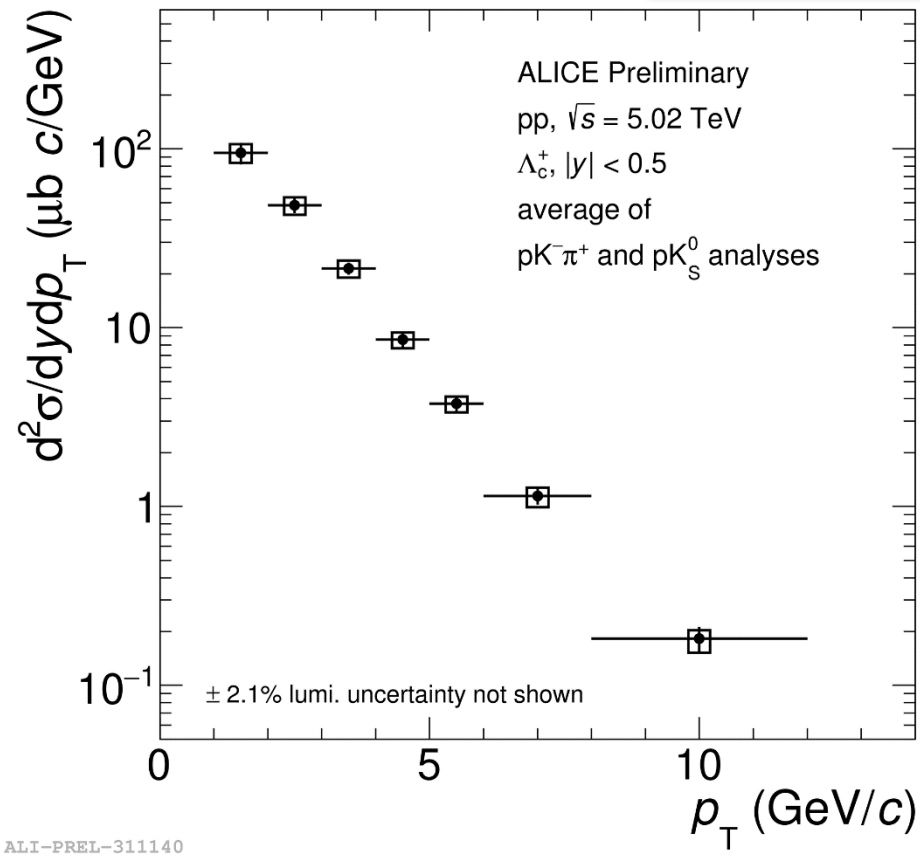


GM-VFNS
Eur. Phys. J. C41, 199 (2005)

POWHEG
JHEP0709, 126 (2007)

pp@5.02TeV (Run2)

New results



New measurement in pp@5TeV in wider p_T range

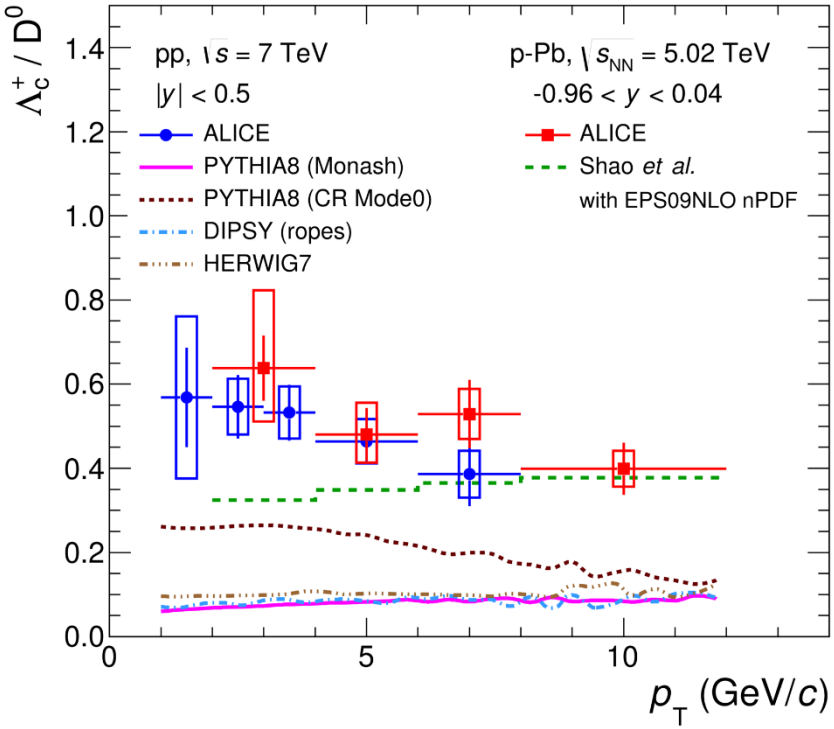
Important reference for Pb-Pb and p-Pb collisions.

Results from Run 1

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

On arXiv since 29/12/2017! https://arxiv.org/abs/1712.09581

JHEP very positively replied last week with very few comments



PYTHIA8 (Monash) Eur. Phys. J. C74, no. 8, 3024
PYTHIA8 (CR Model) JHEP 1508 (2015) 003
DIPSY Phys. Rev. D92, no. 9, 094010 (2015)

- **Λ_c^+ / D^0 ratio higher than previous measurements in e^+e^- and ep, and at lower centre-of-mass energies.**
- Predictions from event generators PYTHIA, DIPSY and HERWIG underpredict the pp measurements
- Only **PYTHIA8** with enhanced colour reconnection mechanisms increases the ratio at about 0.3 and predicts a slightly decreasing trend versus p_T .
- p-Pb measurements compared with **Lansberg and Shao** model (tuned on LHCb pp data)

Lansberg and Shao Eur. Phys. J. C77, no. 1, 1 (2017)

Results from Run 1

- $(\Lambda_c^+ / D^0)_{pp} = 0.543 \pm 0.061\ (stat) \pm 0.160\ (syst)$.
- $(\Lambda_c^+ / D^0)_{p\text{-}Pb} = 0.603 \pm 0.060\ ^{+0.159}_{-0.087}\ (syst)$

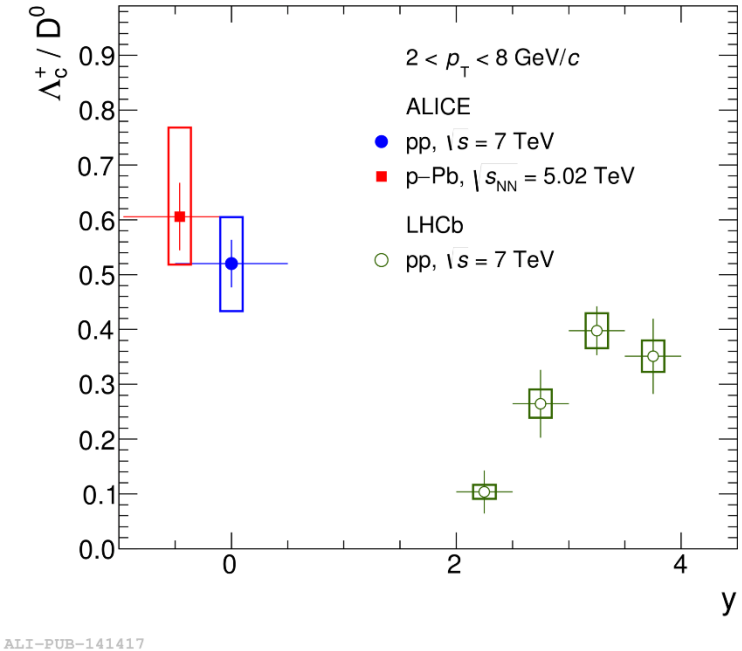
Λ_c^+ / D^0 ratio higher than previous measurements in e^+e^- and ep, and at lower centre-of-mass energies:

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
CLEO	$0.119 \pm 0.021 \pm 0.019$	ee	10.55	
ARGUS	0.127 ± 0.031	ee	10.55	
LEP average	$0.113 \pm 0.013 \pm 0.006$	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, $\lvert\eta\rvert < 1.6$

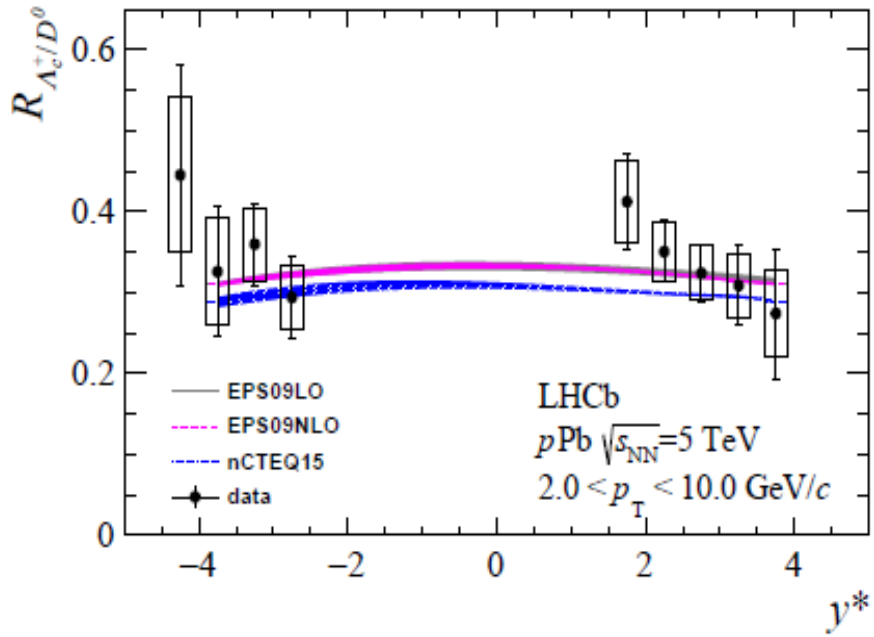
Λ_c^+ / D^0 ratio vs LHCb

Published

arXiv:1712.09581v1



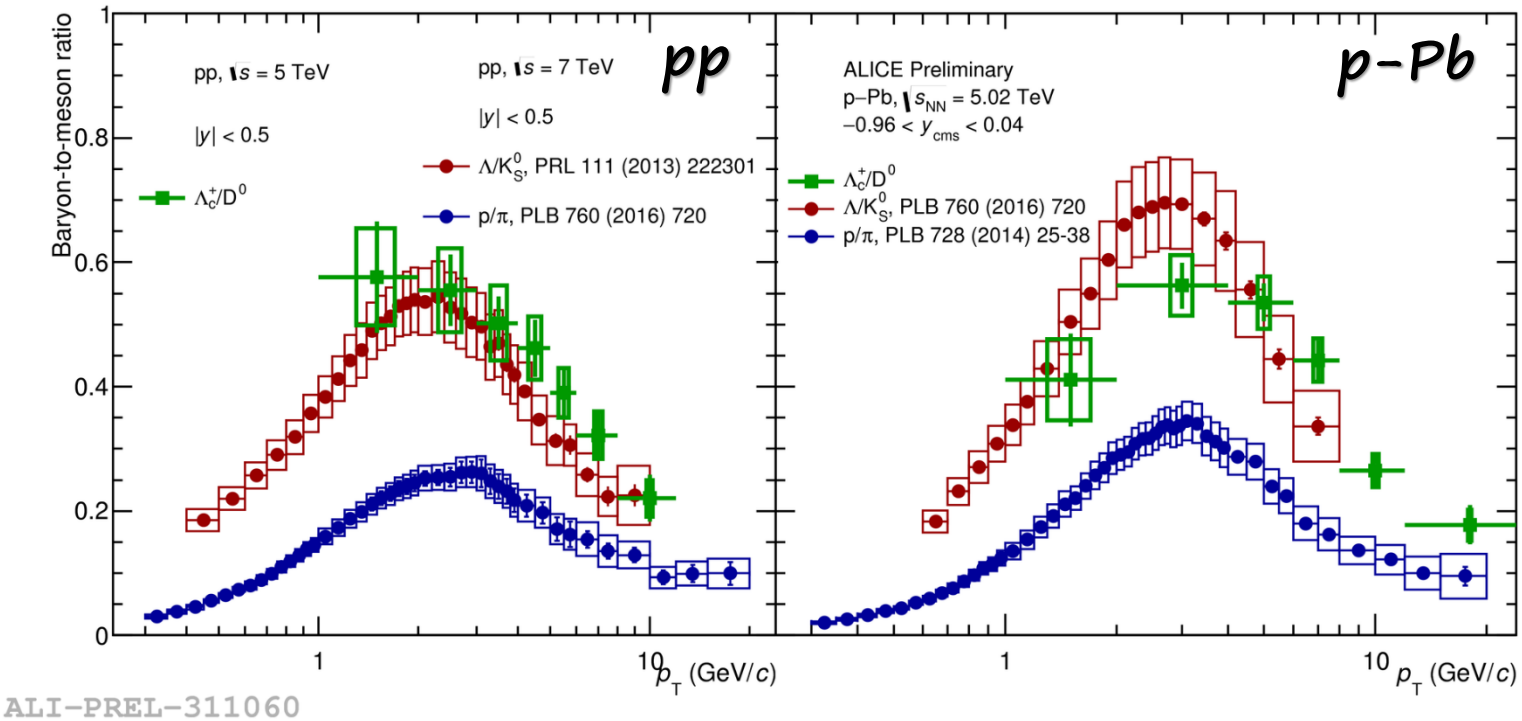
arXiv:1809.01404



- Λ_c^+/D^0 in p-Pb collisions recently measured by the LHCb experiment shows a flatter trend with rapidity, differently from pp results.
- Tendency for higher values at midrapidity (ALICE) than forward and backward rapidity (LHCb).

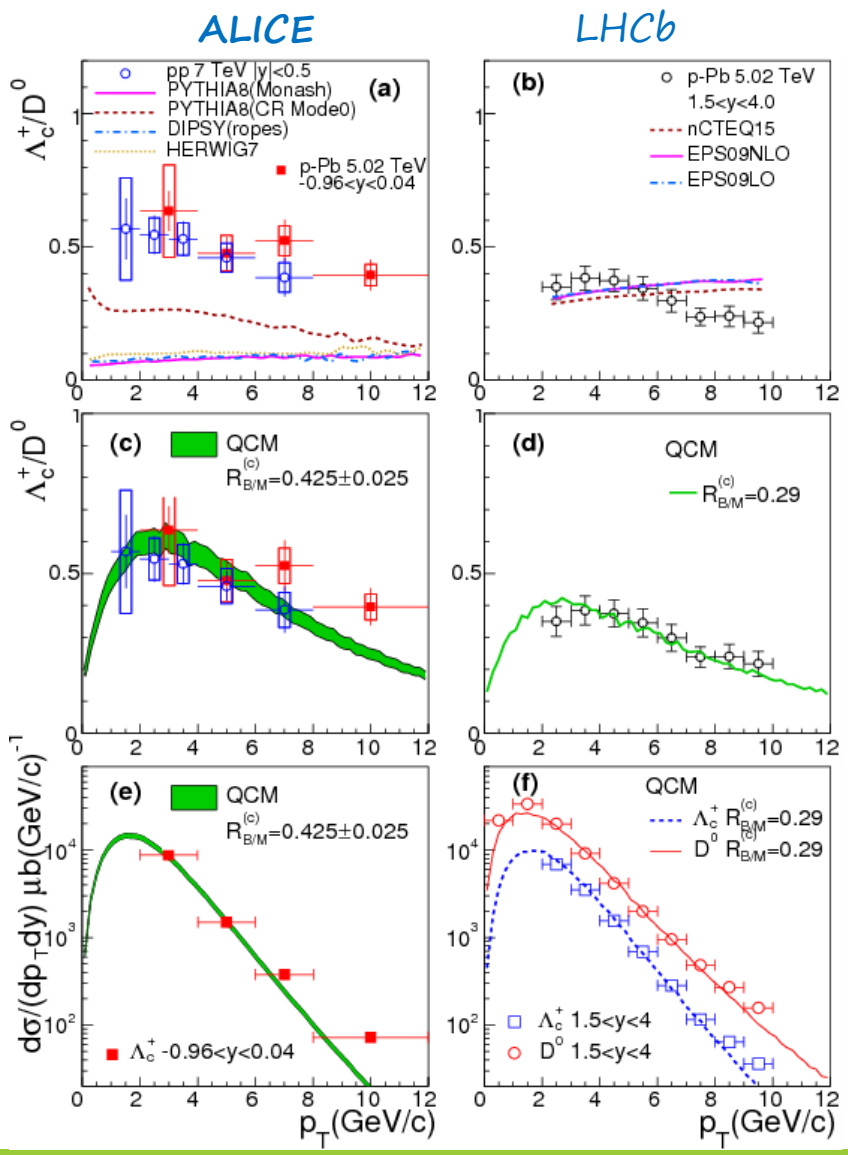
Results for Λ_c^+/D^0

Λ_c^+/D^0 vs Λ/K^0_S vs p/π



- Decreasing trend from p_T = 4 GeV/c observed in pp and p-Pb collisions.
- Similar trend to baryon-to-meson ratio in the light-flavour sector.

Theorists at work after our paper



Hai-hong Li et al., arXiv:1712.08921

- Predictions using hadronization via recombination model reproduce ALICE results at central rapidity and the LHCb ones at forward rapidity in p-Pb collisions. LHCb-CONF-2017-005

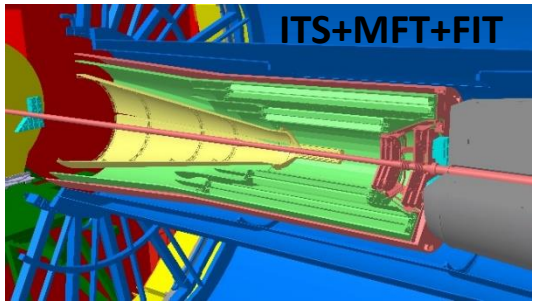
- $R^{(c)}_{B/M}$ relative production of single-charm baryons to single-charm mesons, treated as parameter of the model.

- Initial p_T distributions of light and charm quarks are input of the models.

ALICE upgrade

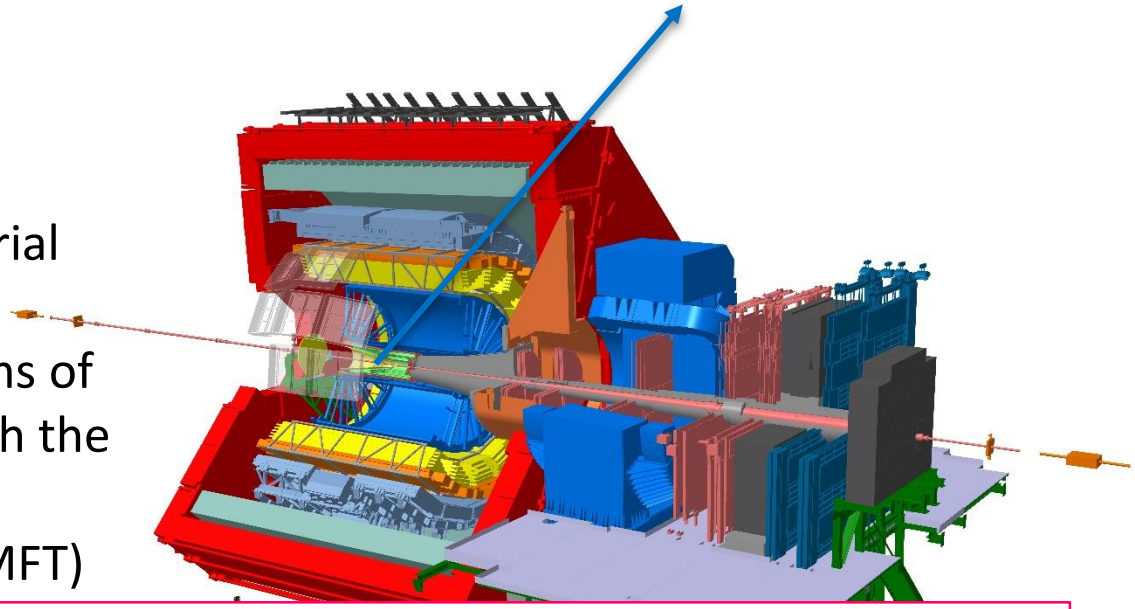
Data taking will start in 2021

- Significant upgrade forseen, aiming at:
  - Improve impact parameter resolution by a factor 3
  - Improve vertexing and tracking at low p_T
  - 50 kHz interaction rate in Pb-Pb (now < 10 kHz)



How?

- New smaller radius beam pipe
- New inner tracking system:
  - high resolution, low material budget
- Upgrade of the readout systems of most subdetectors to copy with the high rate
- New Muon Forward Tracker (MFT)

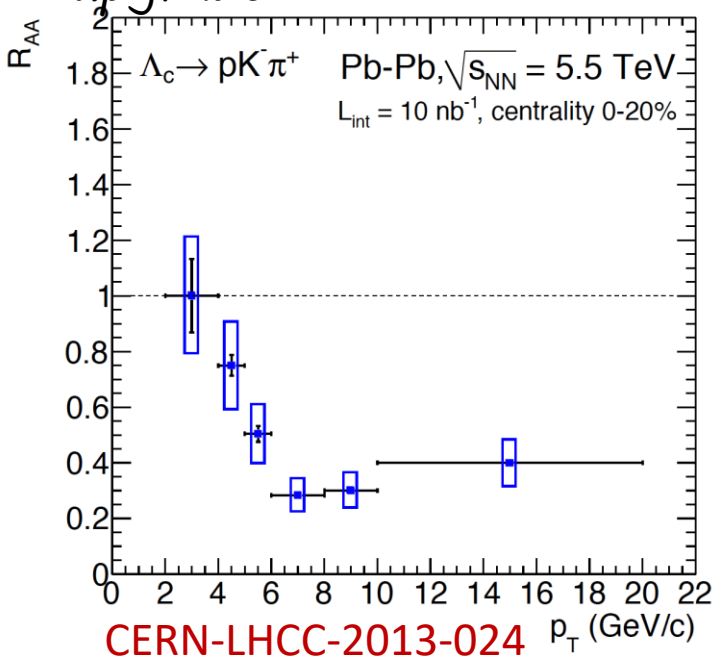


Main physics goal of the ALICE upgrade:

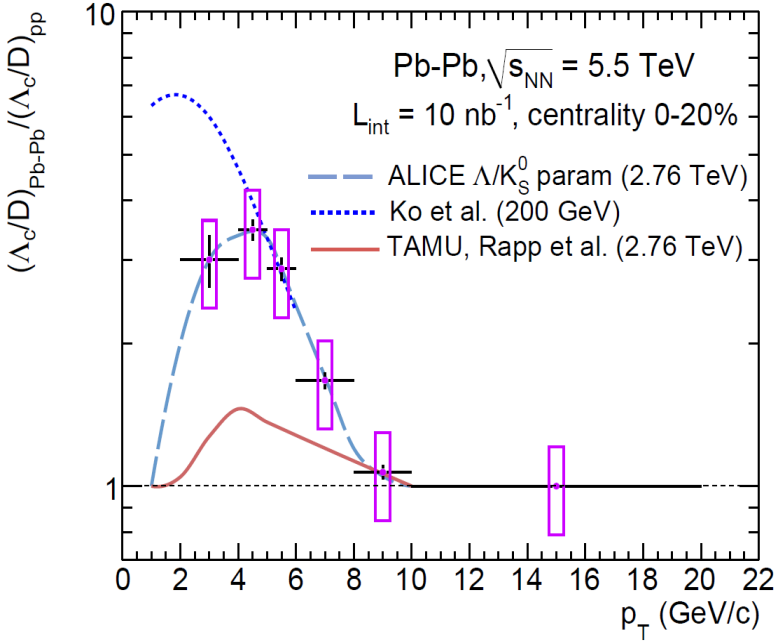
Charm and beauty-hadron measurements down to very low p_T

ALICE upgrade

- **Λ_c^+ measurement in Pb-Pb collisions:** one of the main goal of the ALICE upgrade



CERN-LHCC-2013-024



- Λ_c^+/D^0 baryon/meson ratio and Λ_c^+ baryon R_{AA} will be measured in charm sector with the upgraded ITS.
- Improvement in spatial resolution allows for a cleaner vertex identification.

➡ **Λ_c^+ production measurable down to 2 GeV/*c*.**

The first LHC measurement of Λ_c in HI collisions

Pb-Pb

- **Data set:** **Pb-Pb**@5.02TeV (2015)
  LHC150
  110 M events in (0-100)% centrality interval

- Λ_c->pK^0_S STD analysis performed in 0-80% centrality interval and in $6 < p_T(\Lambda_c) < 12$ GeV/c
- (82 M analized events)
  - For others p_T bins and centrality intervals better to wait for 2018 Pb-Pb data

- Cuts applied on:

DCA(K^0_S daughters), Armenteros variable, $\cos\theta_{CSM}$proton, $\cos\theta_{POINTING}K^0_S$, d_0(proton), PID for proton (using TPC and TOF)

- Clear peak for $6 < p_T < 12$ GeV/*c* with significance around 5, after cut optimzation procedure