Workshop on singly and doubly charmed baryons
LPNHE Paris
27th June 2018

Λ_c^+ production measurement in p-Pb and Pb-Pb collisions with the ALICE experiment at the LHC

E. Meninno* on behalf of the ALICE Collaboration

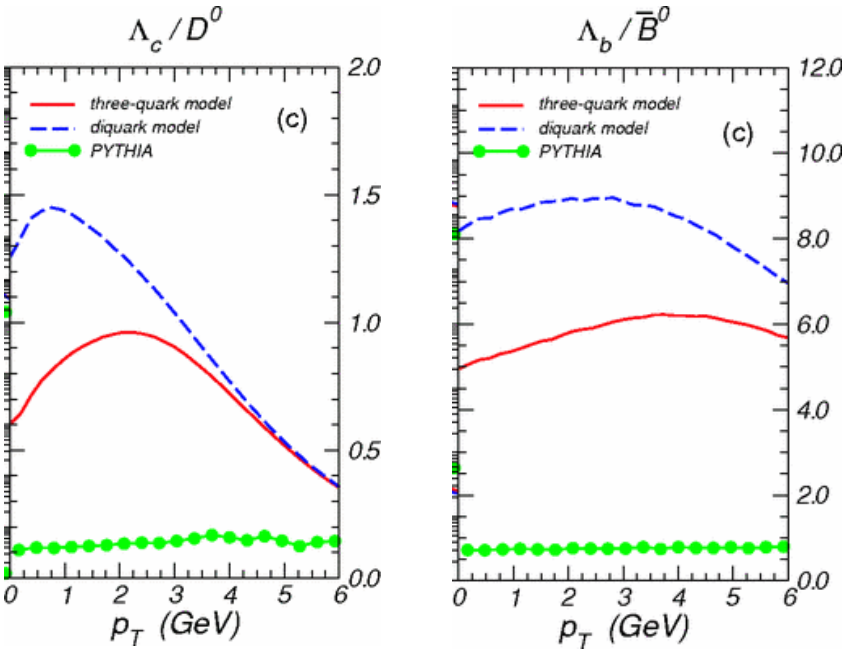
* University and INFN, Salerno

Outline

- Physics motivation for studying charmed hadrons
  - focus on p-Pb and Pb-Pb collisions
- The ALICE experiment
- Results in p-Pb and Pb-Pb collisions @ **5.02 TeV**
- ALICE upgrade
  - What we expect for Λ_c^+ ?

Physics motivations

- Charm is a very sensitive probe of the *Quark-Gluon-Plasma* (QGP), produced in heavy-ion collisions.
- Charmed-baryon production in Heavy Ion (HI) collisions could give an insight into the hadronisation processes in the QGP.



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

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

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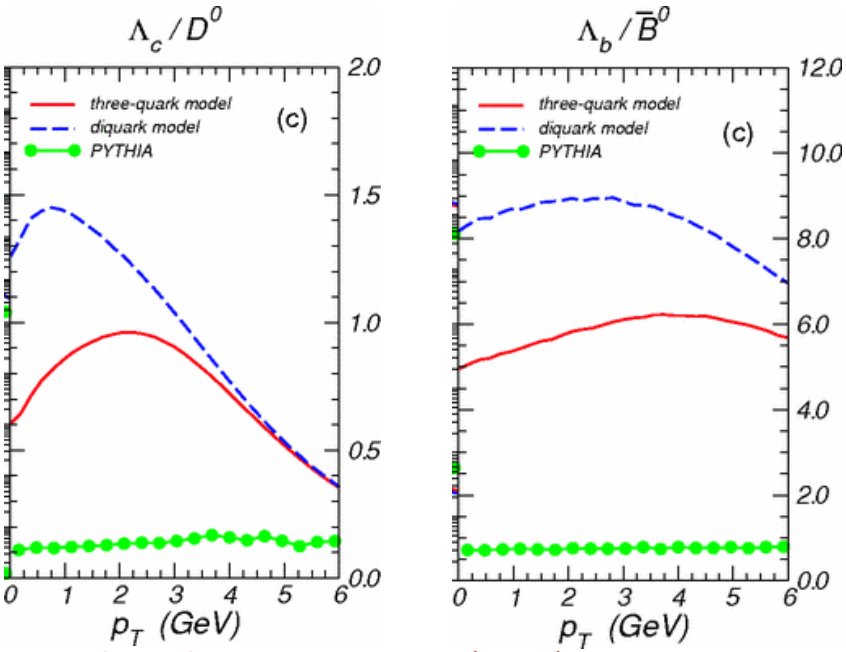

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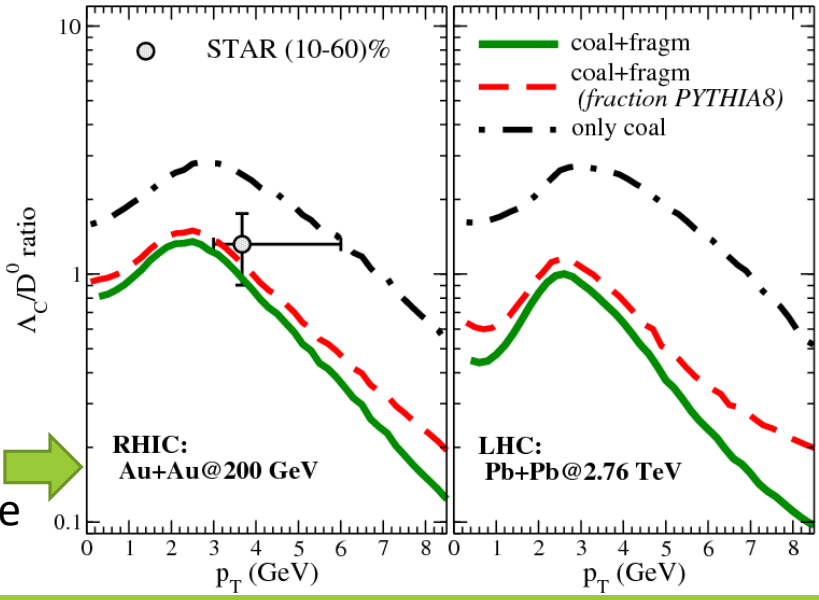

Coalescence plus fragmentation modelling: in the peak region quite good agreement with the experimental data by STAR.

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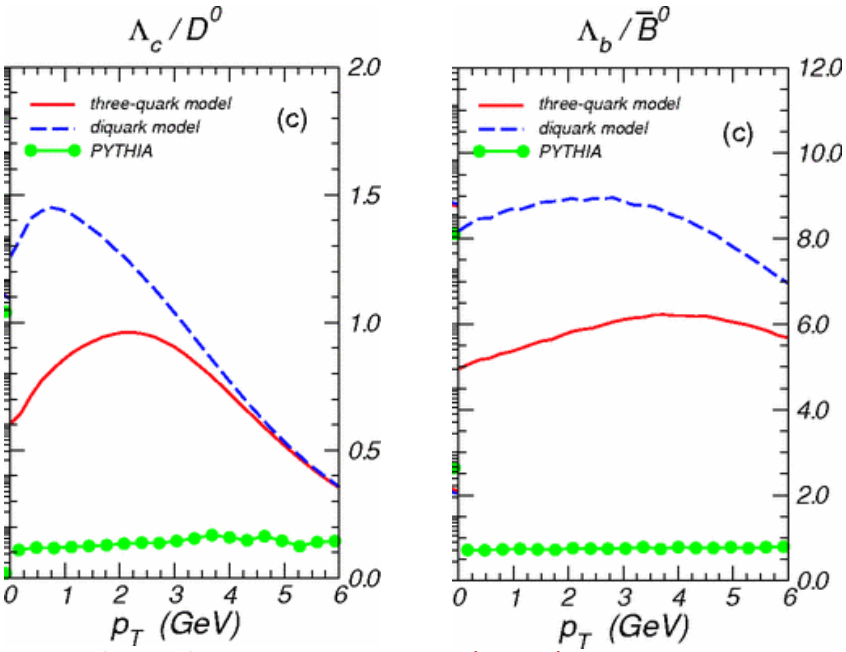

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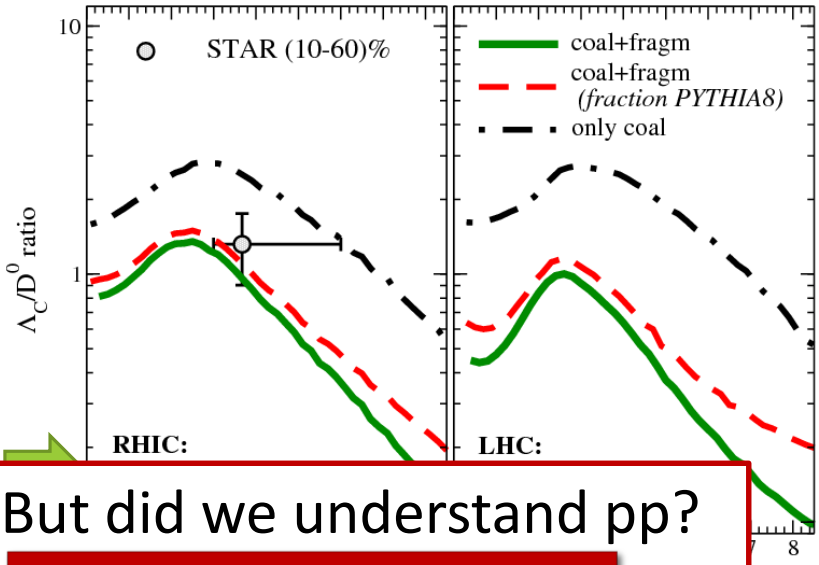


Coalescence plus fragmentation modelling: in the peak region quite good agreement with experimental data by STAR.

.. But did we understand pp?

See Jaime's Talk (Tue)

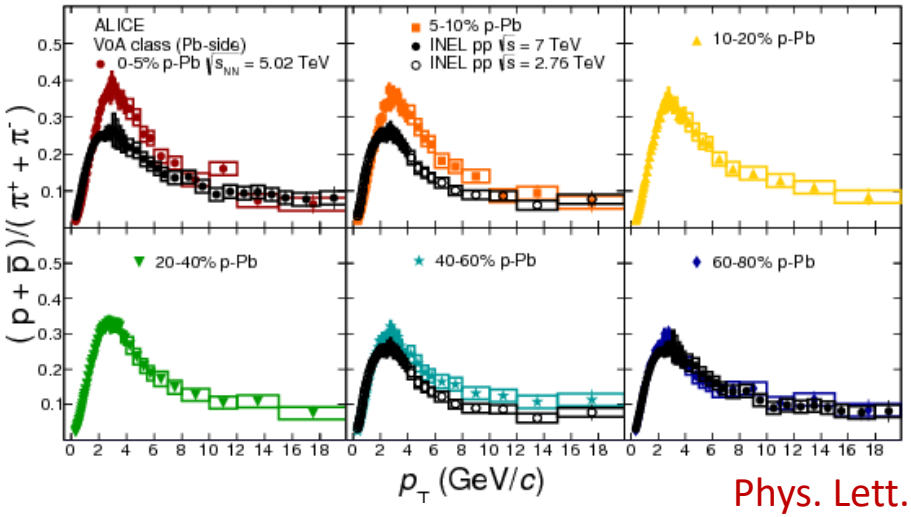
Physics motivations

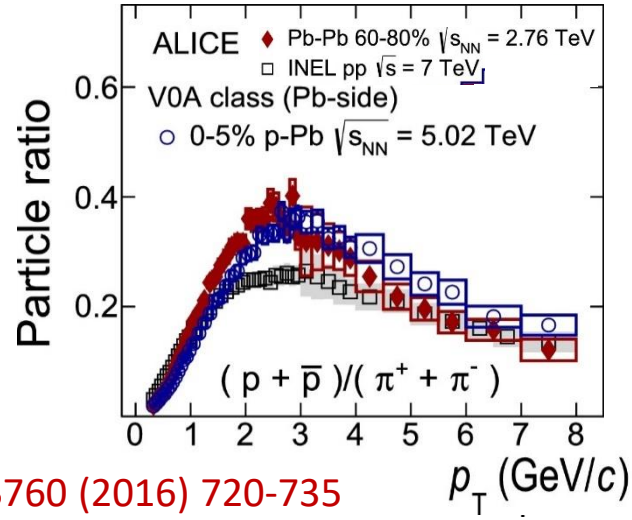
- Measurement in pp collisions: **See Jaime's Talk (Tue)**
  - Important to test predictions from pQCD and the models of hadronisation in vacuum.
- Measurement in p-Pb collisions:
  - Important to distinguish cold-nuclear-matter (CNM) effects, that can affect the charm hadron production.

Physics motivations

- Measurement in pp collisions: **See Jaime's Talk (Tue)**
  - 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.
- 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

    Possible explanations:
  - mini-QGP, influence of colour reconnection on hadronisation?



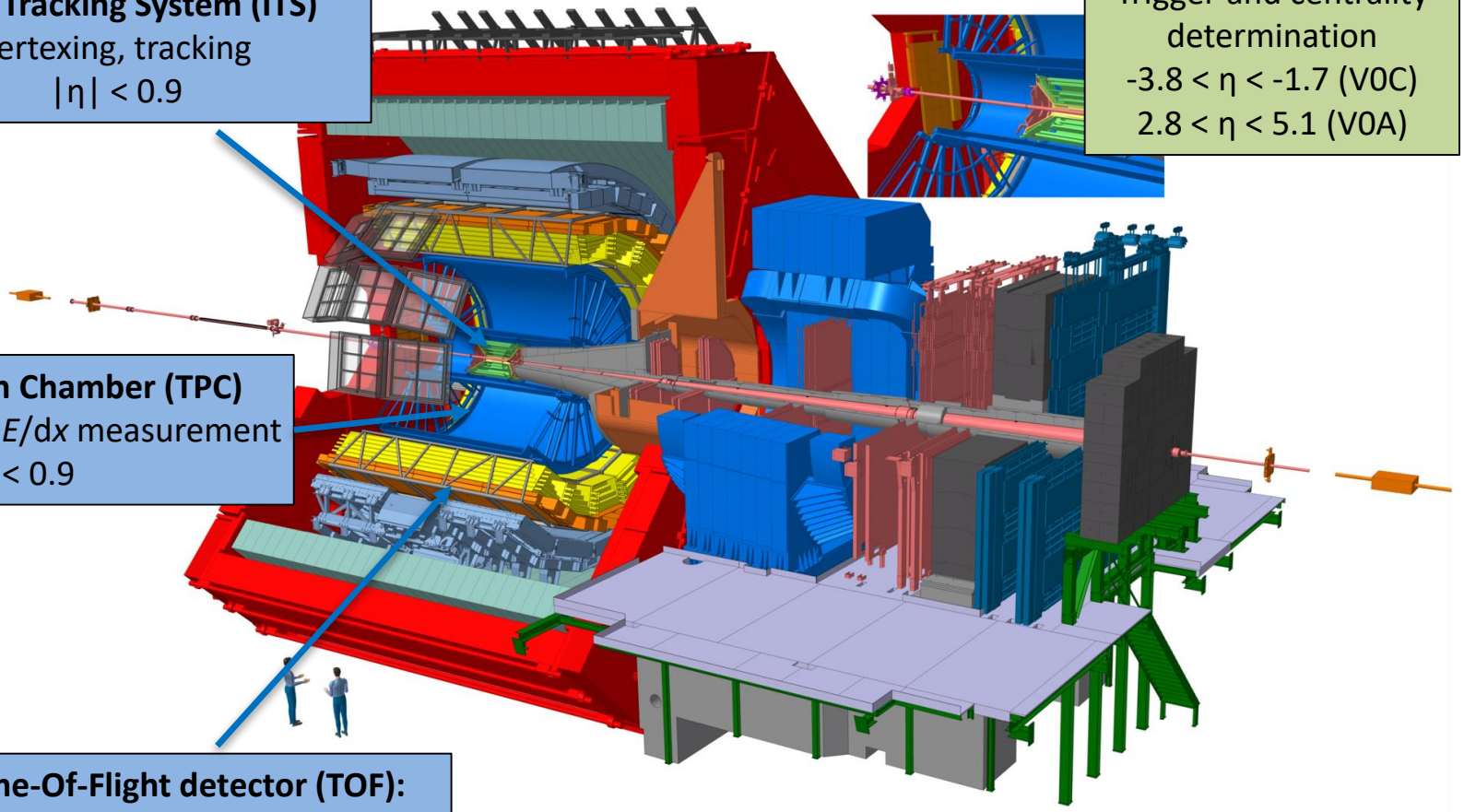


Phys. Lett. B760 (2016) 720-735

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
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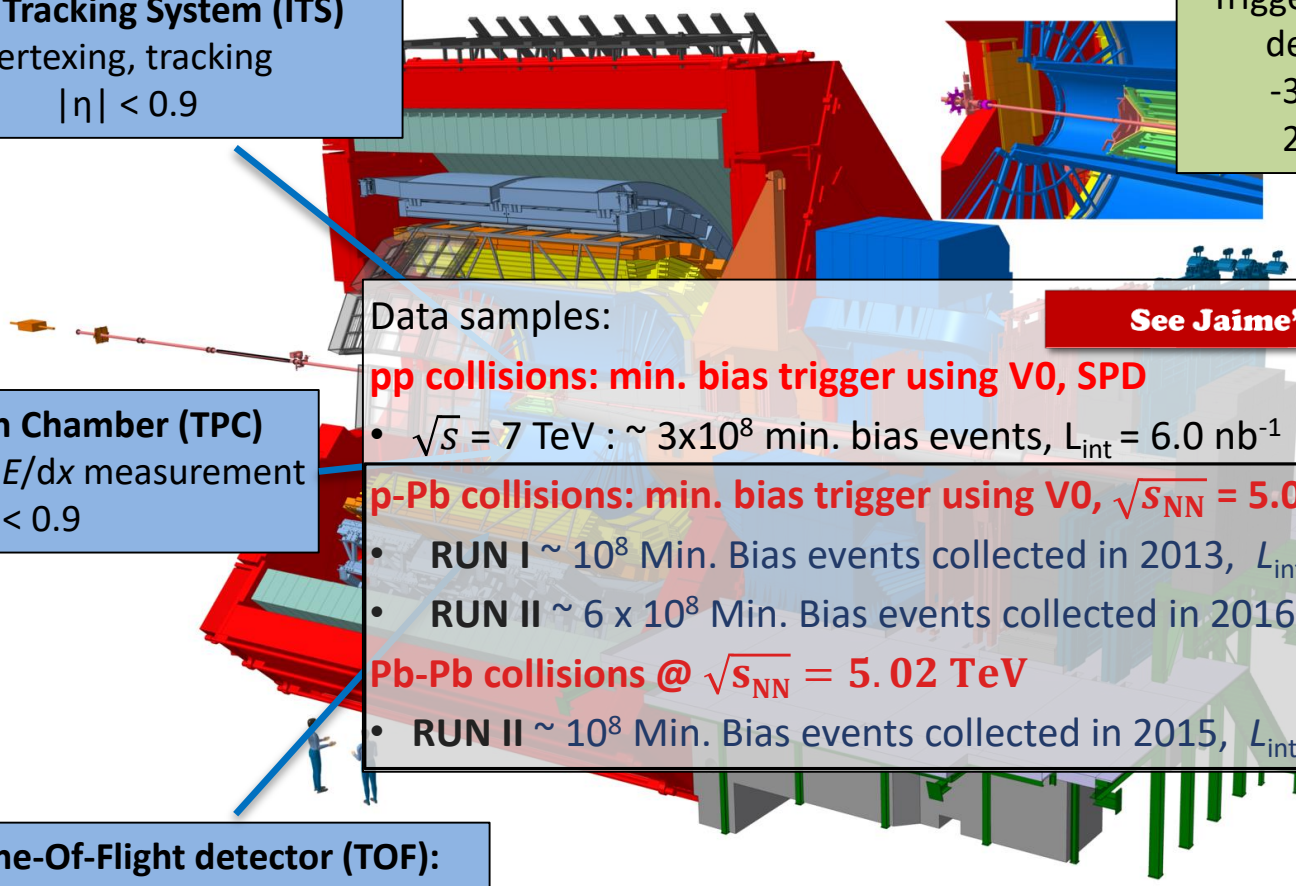

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Time-Of-Flight detector (TOF):
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$|\eta| < 0.9$

Data samples:

See Jaime's Talk (Tue)

pp collisions: min. bias trigger using V0, SPD

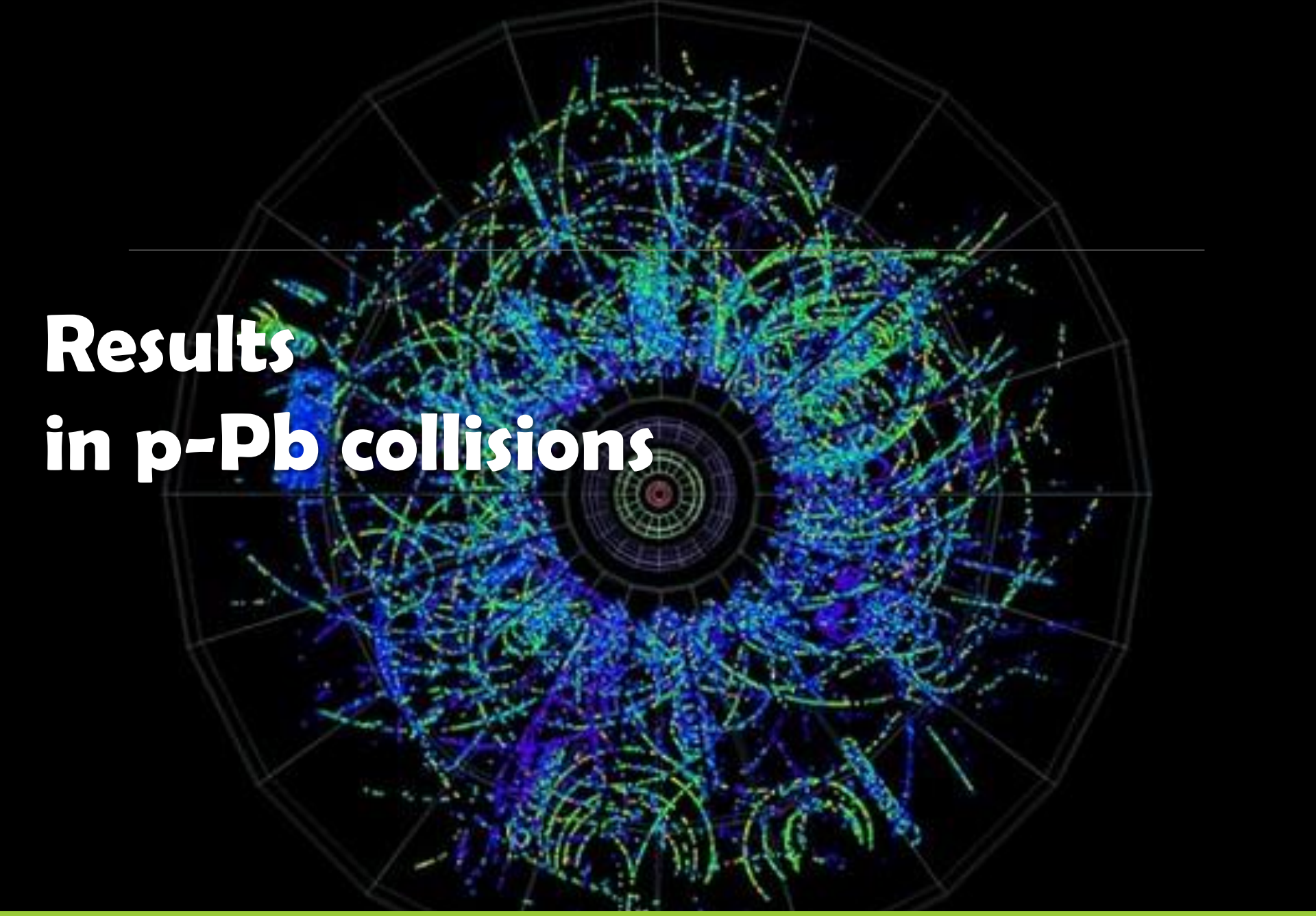
- $\sqrt{s}$ = 7 TeV : ~ 3x10^8 min. bias events, L_{int} = 6.0 nb^{-1}

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

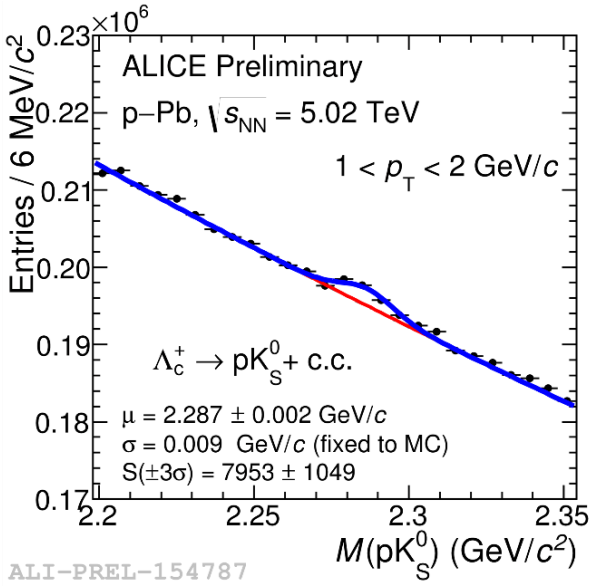
- **RUN II** ~ 10^8 Min. Bias events collected in 2015, L_{int} = 13.4 μb^{-1}

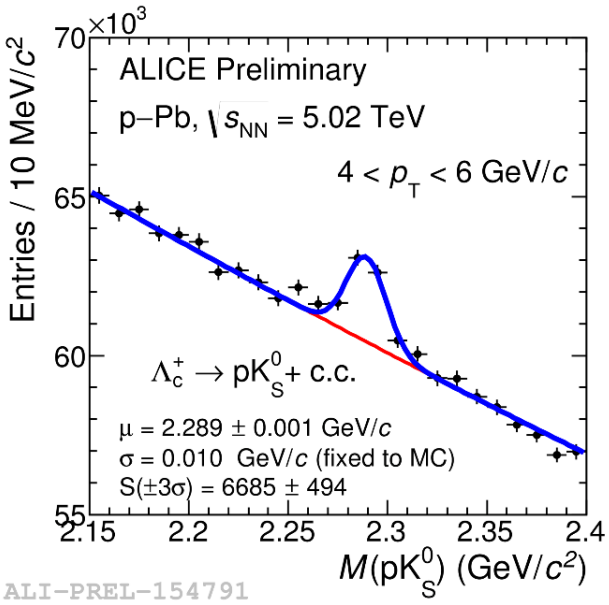


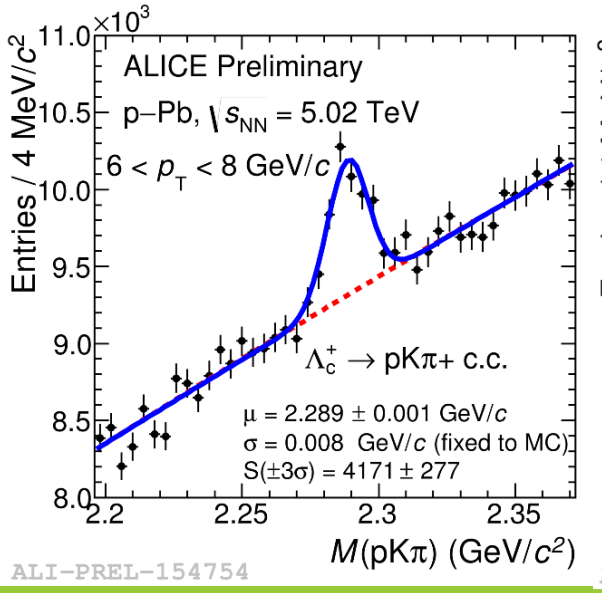
Results in p-Pb collisions

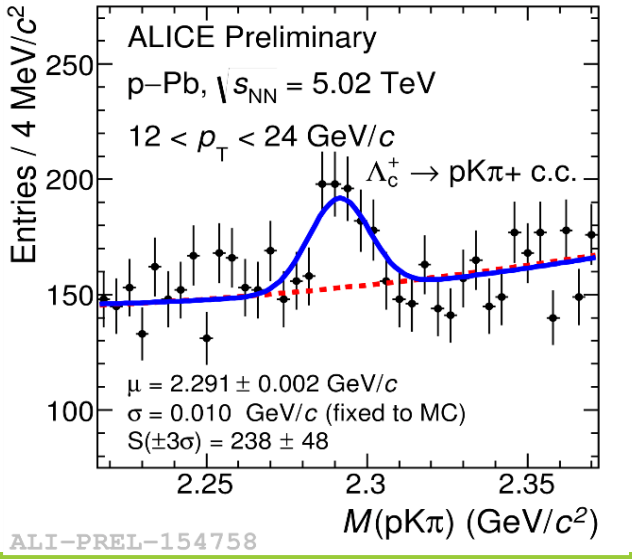
$\Lambda_c^+ \rightarrow pK^0_S$ and $\Lambda_c^+ \rightarrow pK^+\pi^-$ signal extraction in p-Pb

Recent results from RunII







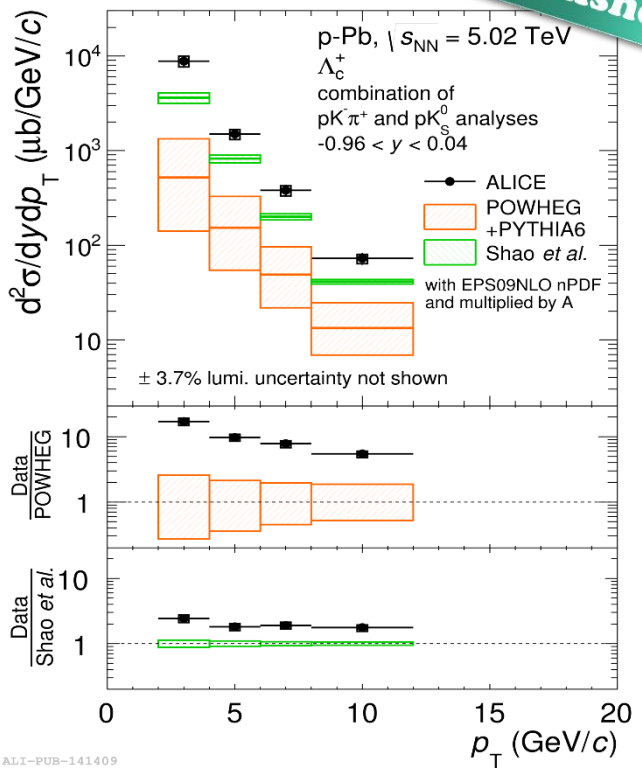


- Signal extracted via an invariant-mass analysis.
- Decay topology selection and Multivariate approach (Boosted Decision Tree) used.
- Signal extracted in 1-24 GeV/c
- Wider and finer binning with respect to Run I.

https://arxiv.org/abs/1712.09581

Λ_c^+ cross section

Published



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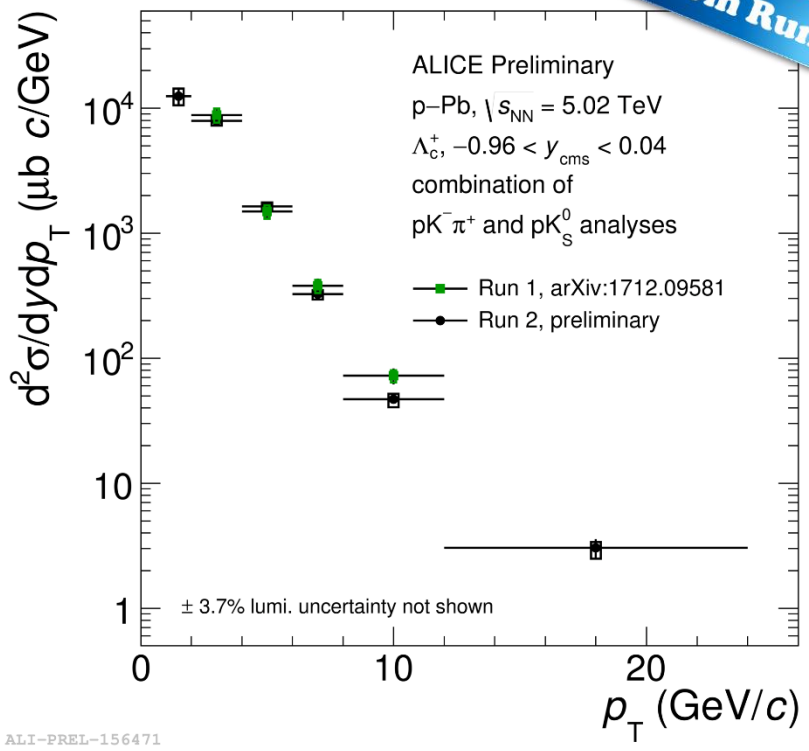


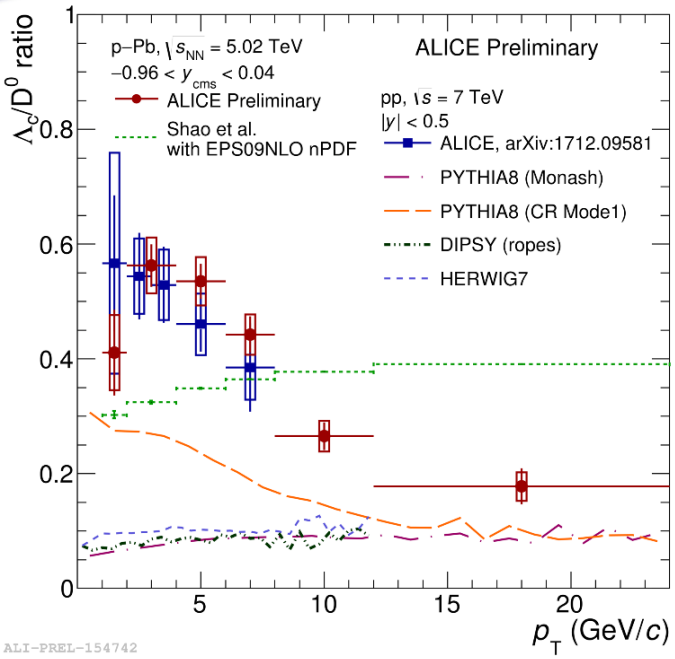
- Λ_c^+ p_T-differential cross section **underestimated** by theoretical models in p-Pb (and pp) collisions
- Improved precision and extended p_T range with Run II data.

POWEG JHEP0709, 126 (2007)

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

Λ_c^+ / D^0 ratio

Recent results from RunII



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**

- Λ_c^+ / D^0 ratio:
- pp result agrees with p-Pb one within the relatively large uncertainties.
- All the models underestimate our measurements.
  - PYTHIA8 with colour reconnection mode closer to data.

Λ_c^+ / D^0 ratio

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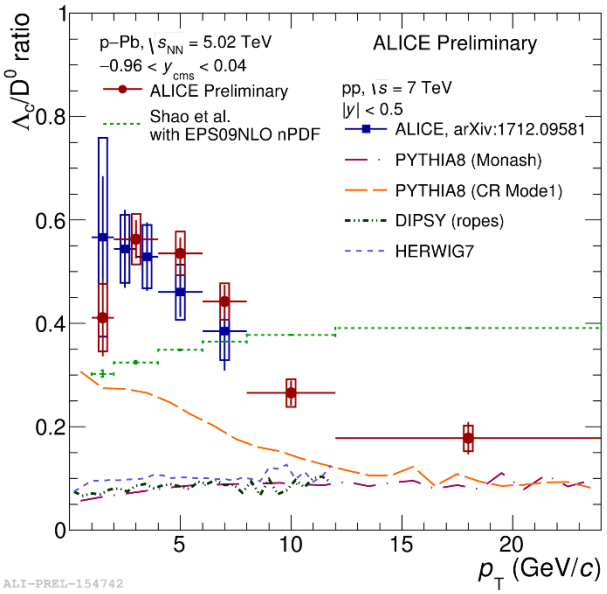
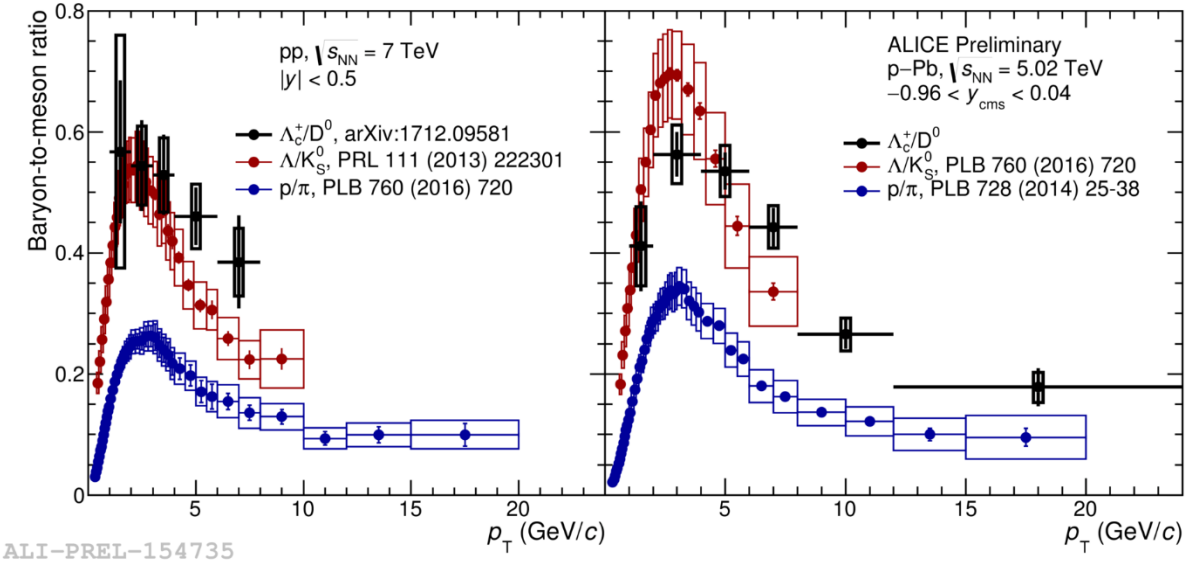


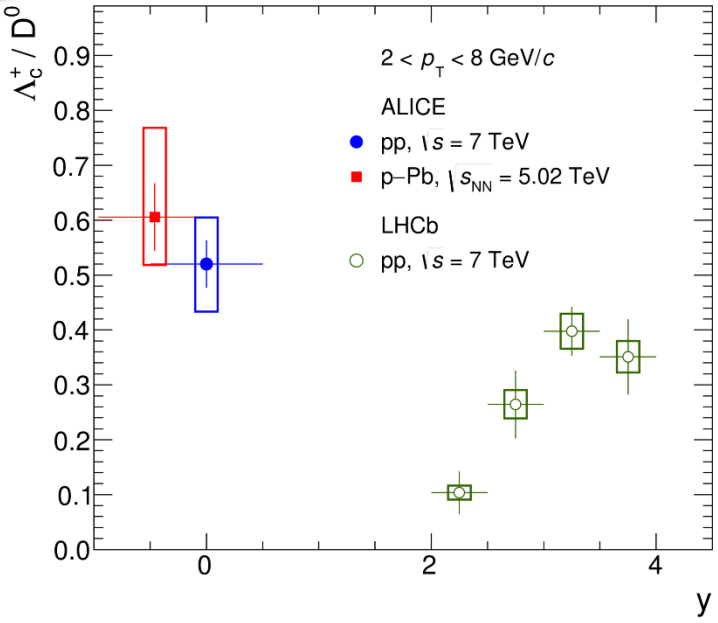


- Λ_c^+ / D^0 ratio:
- pp result agrees with p-Pb one within the relatively large uncertainties.
- All the models underestimate our measurements.
  - PYTHIA8 with colour reconnection mode closer to data.
- Decreasing trend from p_T = 4 GeV/c observed in the new results. Similar trend as baryon-to-meson ratio in the light-flavour sector.

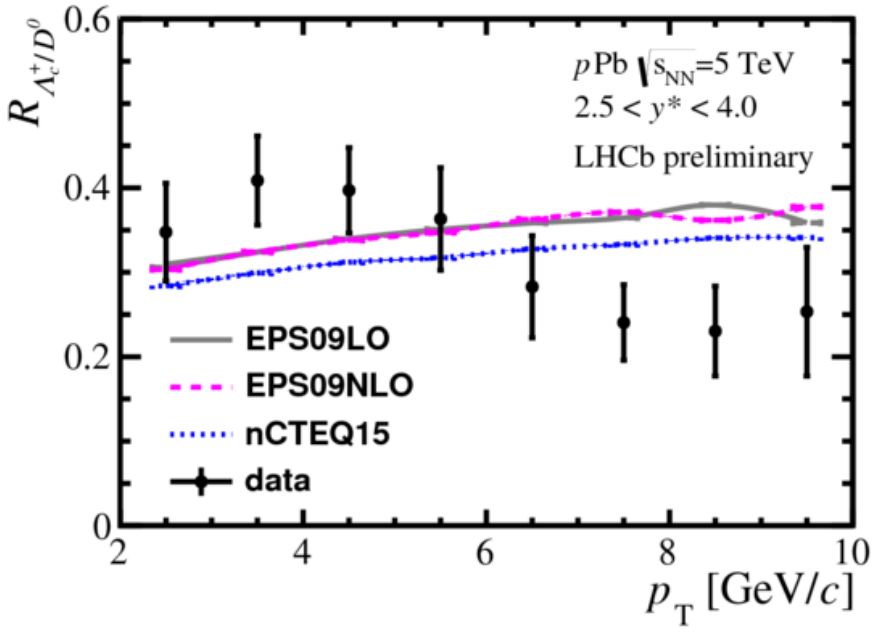
Λ_c^+ / D^0 ratio vs LHCb

Published

arXiv:1712.09581v1



CERN-LHCb-CONF-2017-005

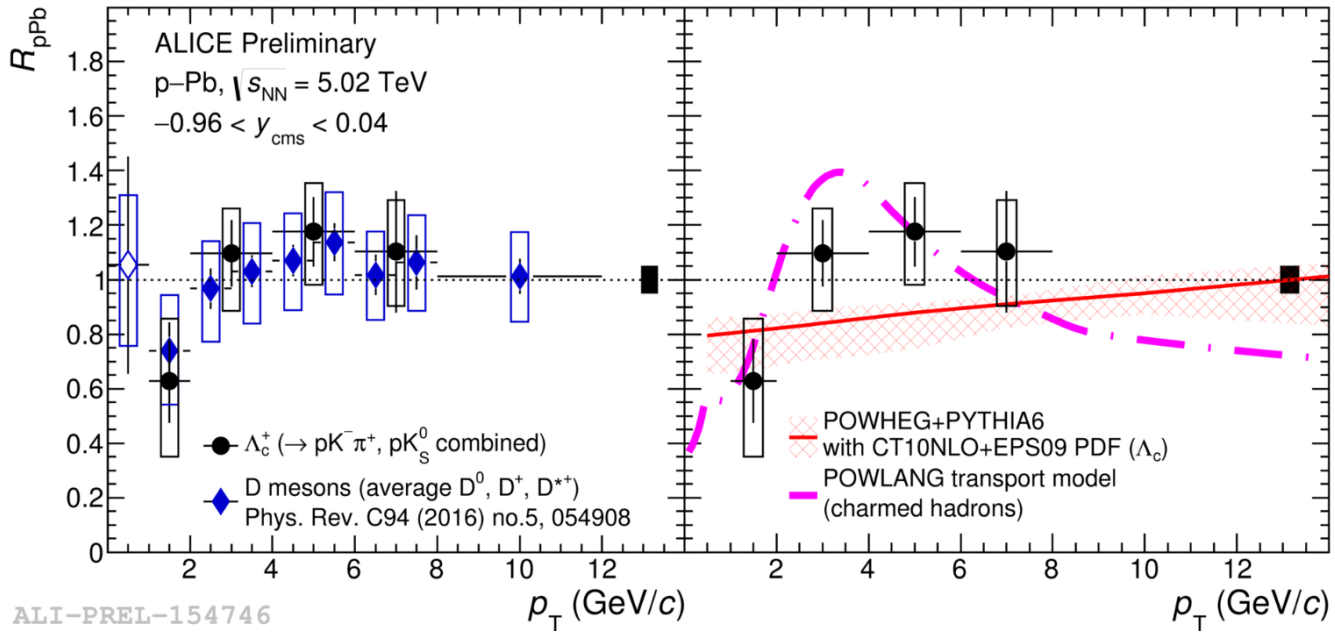


- Λ_c^+/D^0 in p-Pb collisions recently measured by the LHCb experiment shows a flatter trend with rapidity, differently from pp results.
- Tendency for higher values at midrapidity (ALICE) than forward and backward rapidity (LHCb).

Λ_c^+ nuclear modification factor R_{pPb}

Recent results from RunII

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

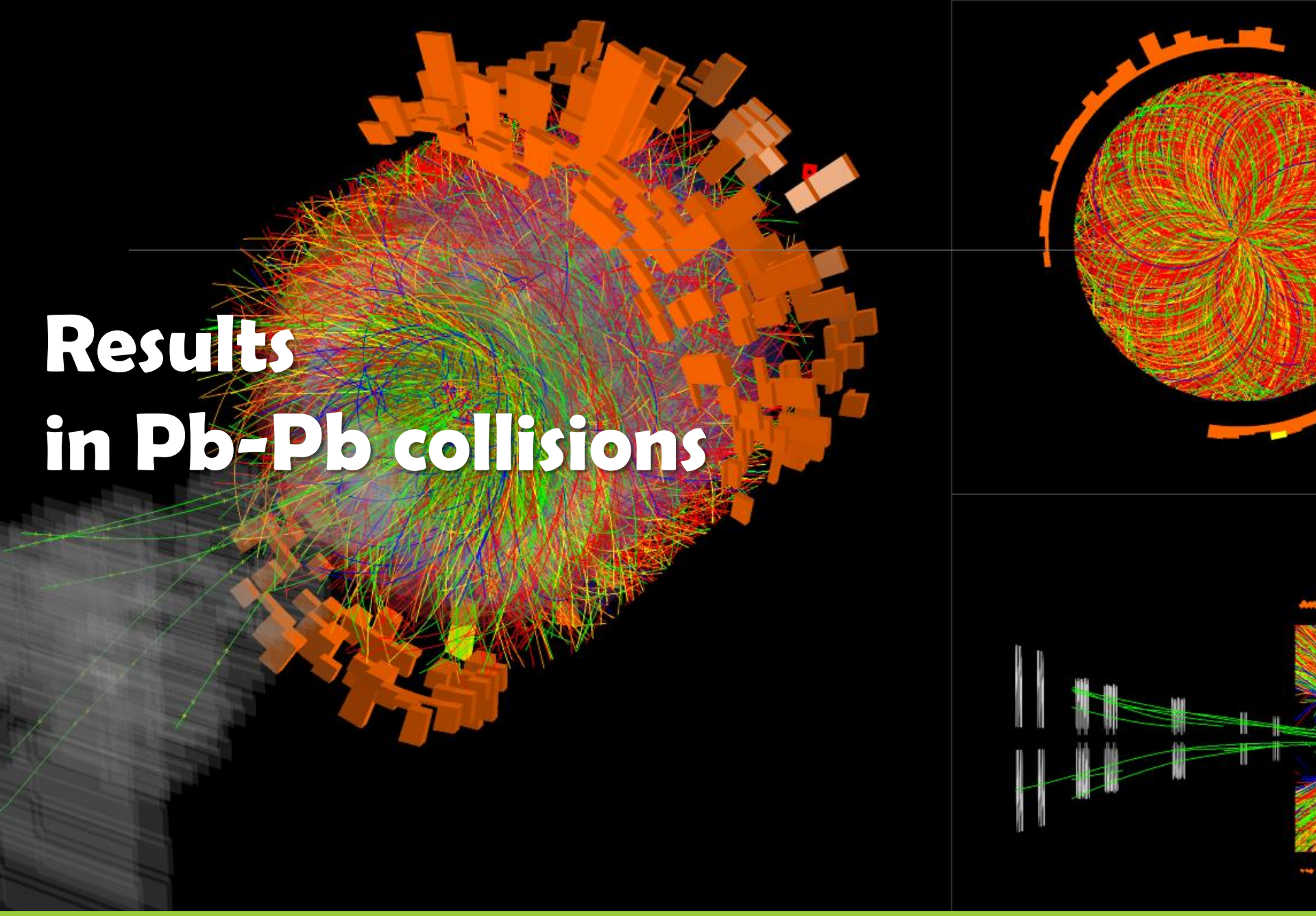


- Λ_c^+ R_{pPb} **compatible with unity**
- Compatible with D-meson R_{pPb}

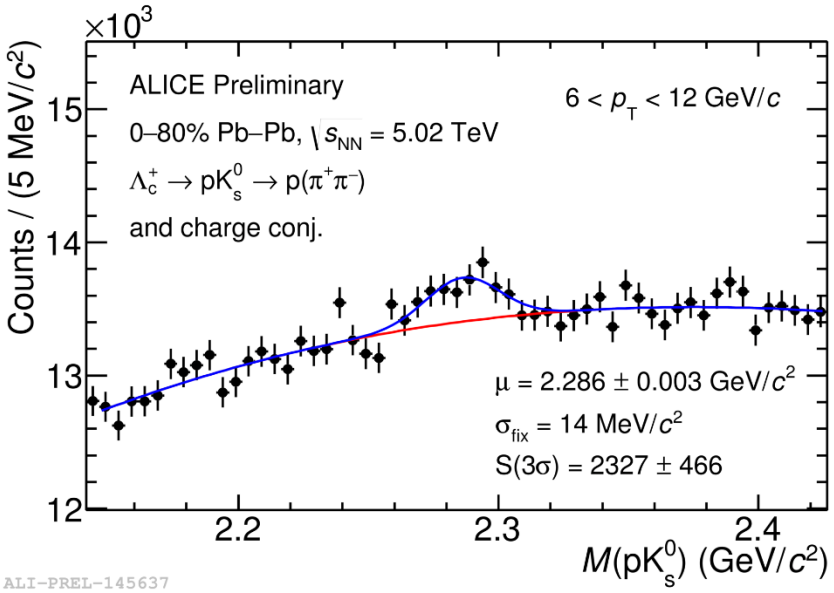
- **Compatible with models within uncertainties:**
  - **POWHEG+PYTHIA6 with CT10NLO+EPS09 PDF - only CNM effects included**
  - **POWLANG – small QGP formation included**

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

Results in Pb-Pb collisions



The first LHC measurement of Λ_c in HI collisions



- Analysis for 0-80 % centrality and for $6 < p_T < 12$ GeV/c
  - Waiting for 2018 Pb-Pb run: extend p_T interval, more differential measurements in p_T and centrality.

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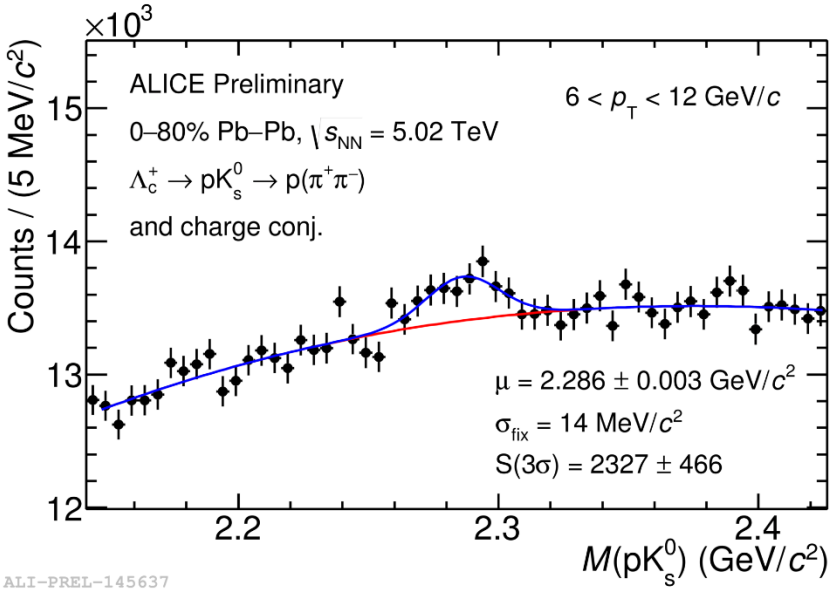

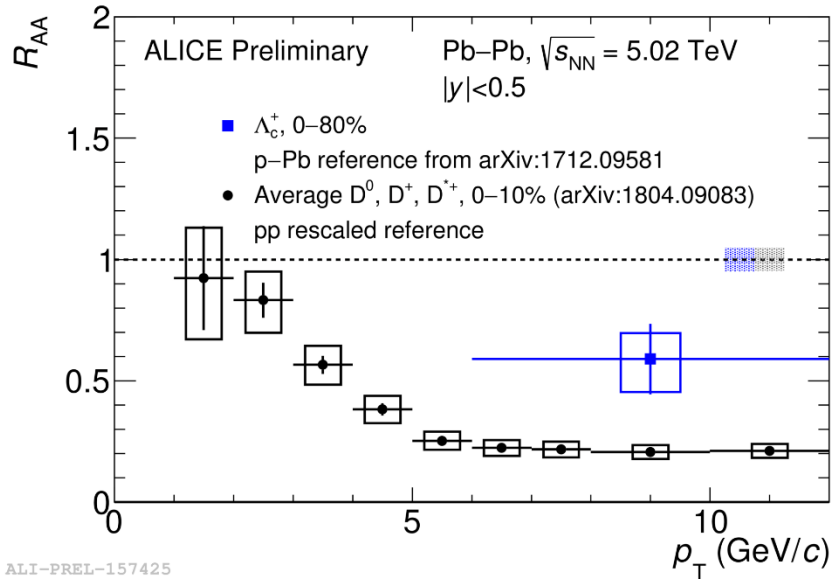

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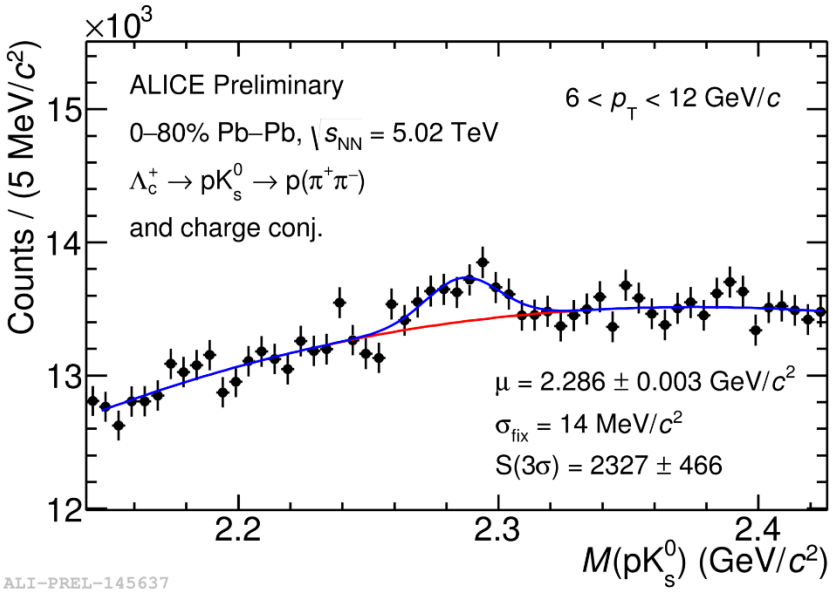

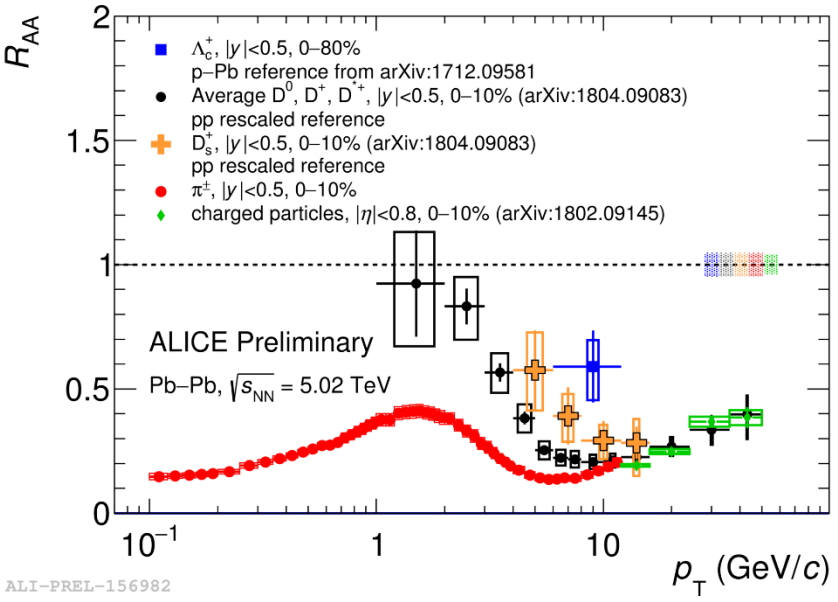

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- Hint for Λ_c^+ R_{AA} in 0-80% larger than D-meson R_{AA} in 0-10 % centrality class.
  - ➡ Suggested hierarchy Λ_c^+ R_{AA} > D_s^+ R_{AA} > non-strange D-meson R_{AA} > pion R_{AA} ?

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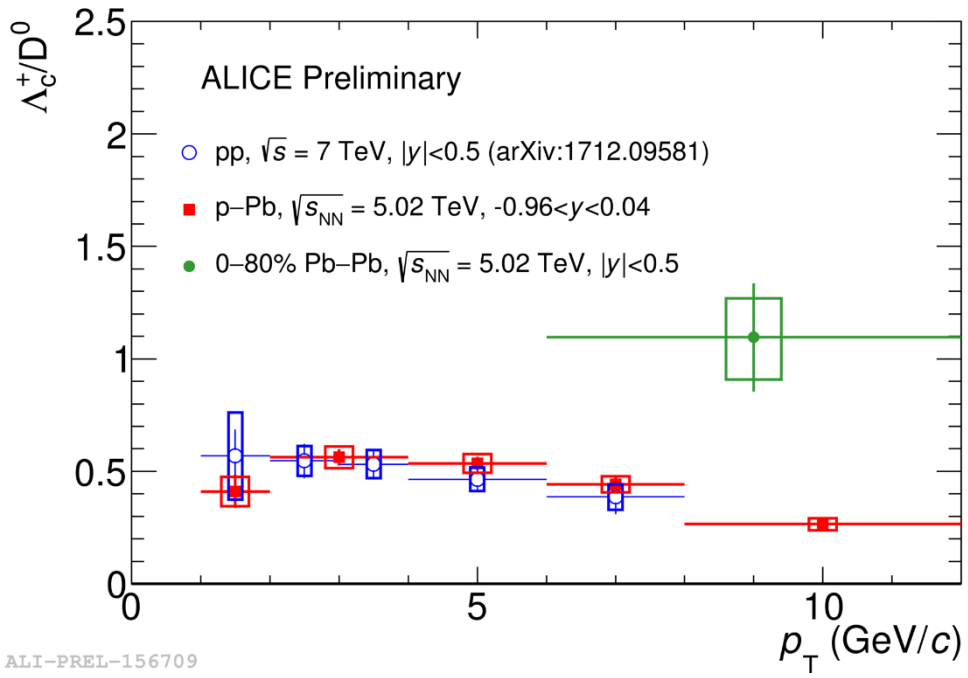

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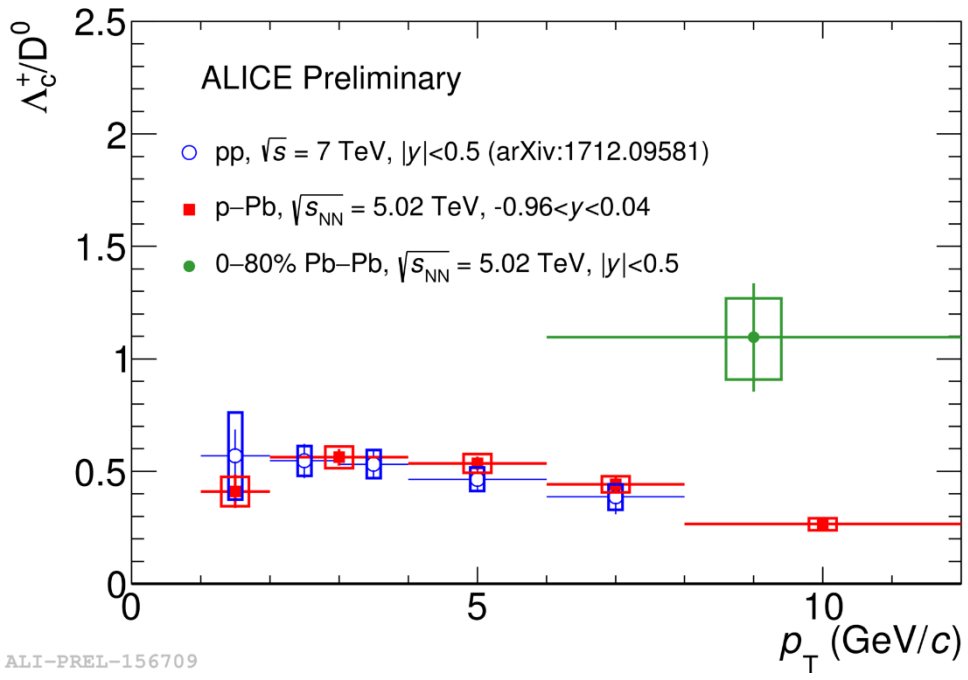
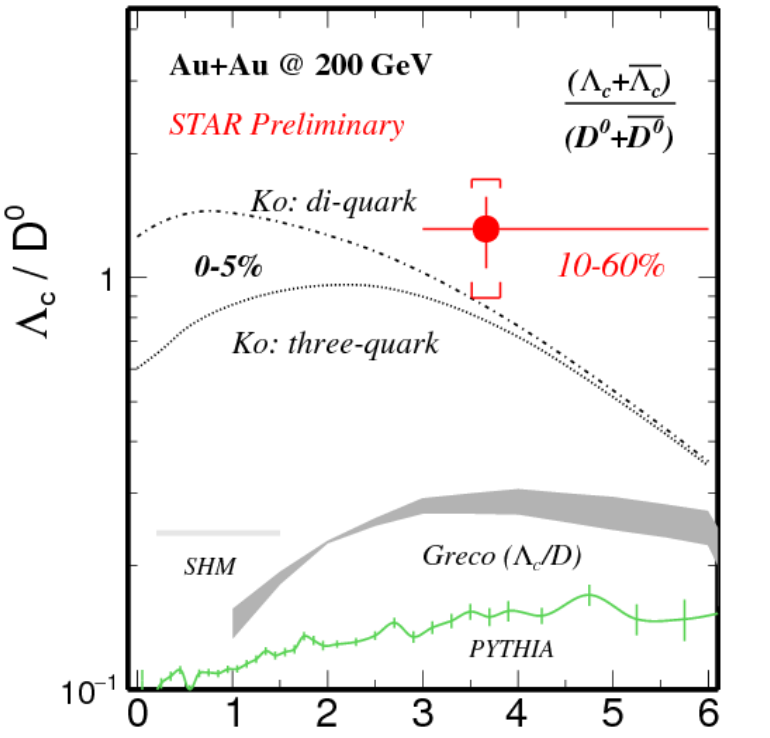
- Uncertainty is dominated by the statistical component.

The first LHC measurement of Λ_c in HI collisions

Nucl. Phys. A967, 928 (2017), 1704.04353





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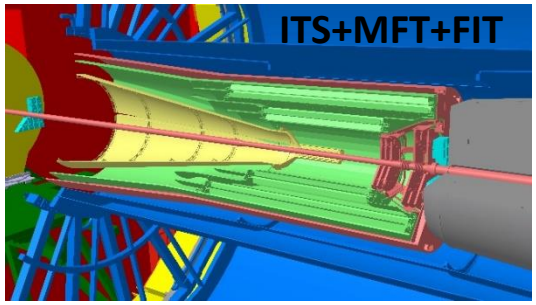
- Λ_c^+/D^0 in $6 < p_T < 12$ GeV/c similar to STAR value in 3-6 GeV/c.

ALICE upgrade

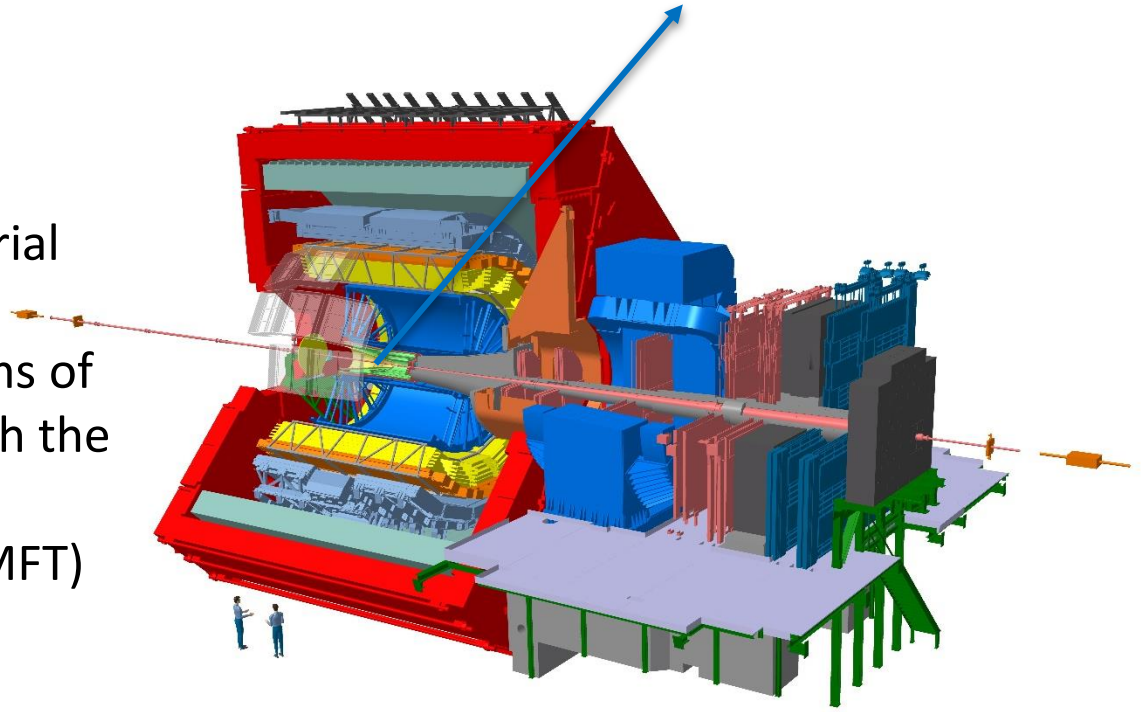
Data taking will start in 2021

- 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)



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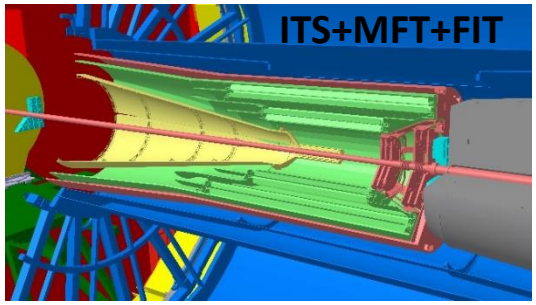

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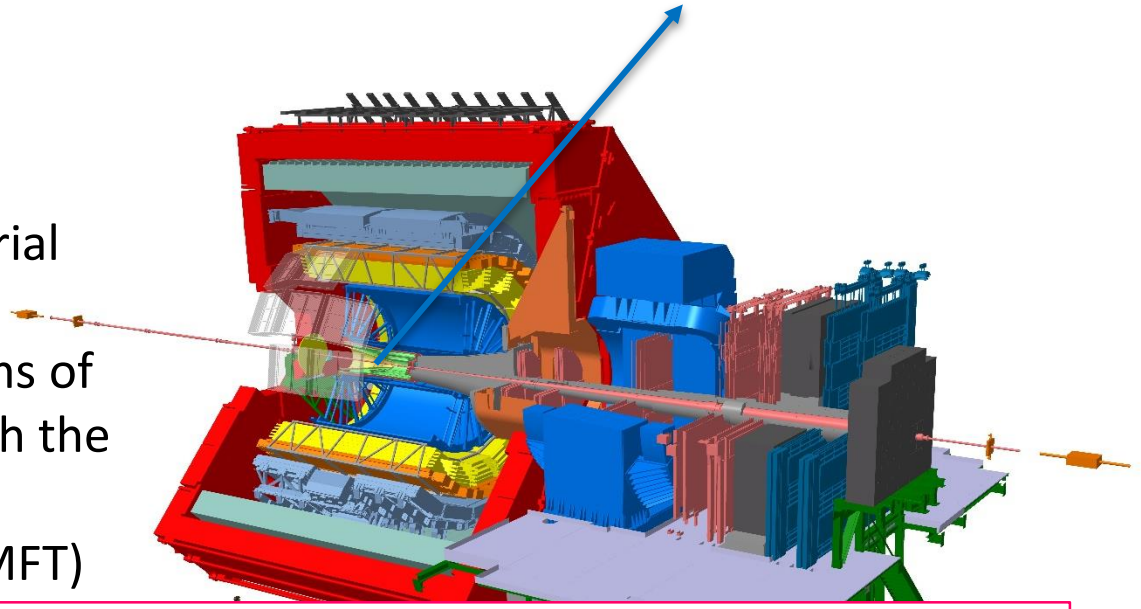
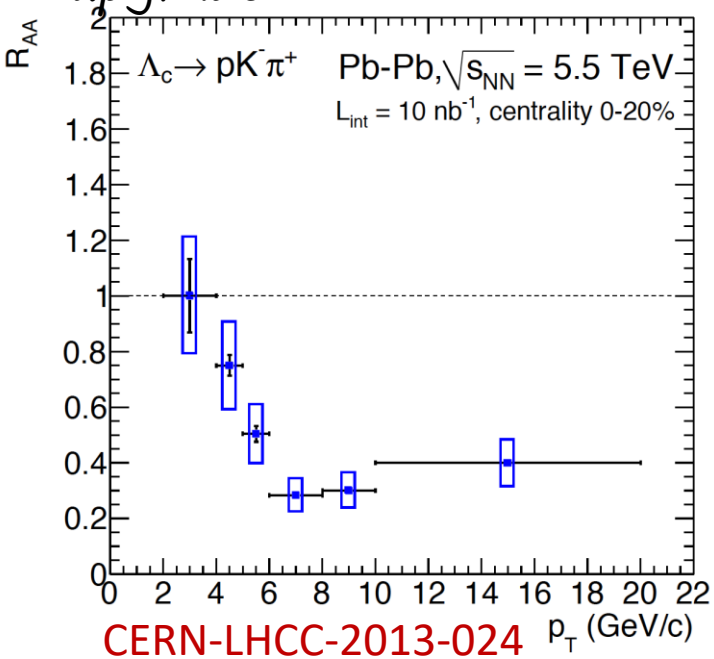


Main physics goal of the ALICE upgrade:

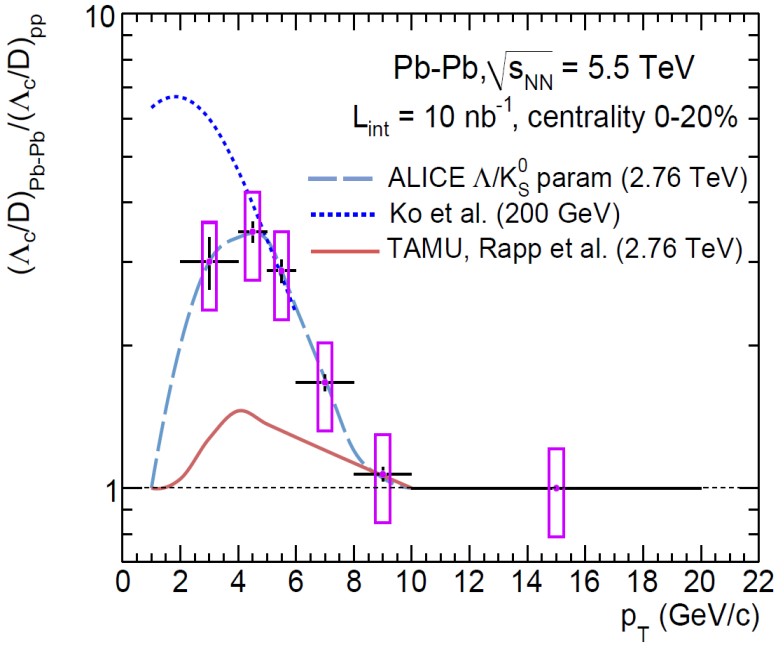
Charm and beauty-hadron measurements down to very low p_T

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*.**

Conclusions

Λ_c analysis in pp collisions

See Jaime's Talk (Tue)

- **Analysis started on larger data sets, collected at 5 TeV and 13 TeV**

Λ_c analysis in p-Pb collisions

- Λ_c^+/ D^0 higher than MC predictions (as already observed).
- Λ_c^+/ D^0: similar p_T trend than 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.

Λ_c analysis in Pb-Pb collisions

- Indication of enhancement with respect to pp and p-Pb collisions.
- Λ_c^+/ D^0: large uncertainty, waiting for 2018 Pb-Pb data.
- Λ_c^+/D^0 similar to STAR value in 3-6 GeV/*c*.

- ***Λ_c measurement in Pb-Pb collisions down to low p_T: one of the main goal of the ALICE upgrade***

Thanks for your attention

Backup

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
- 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

    Possible explanations:
  - mini-QGP, influence of colour reconnection on hadronisation?

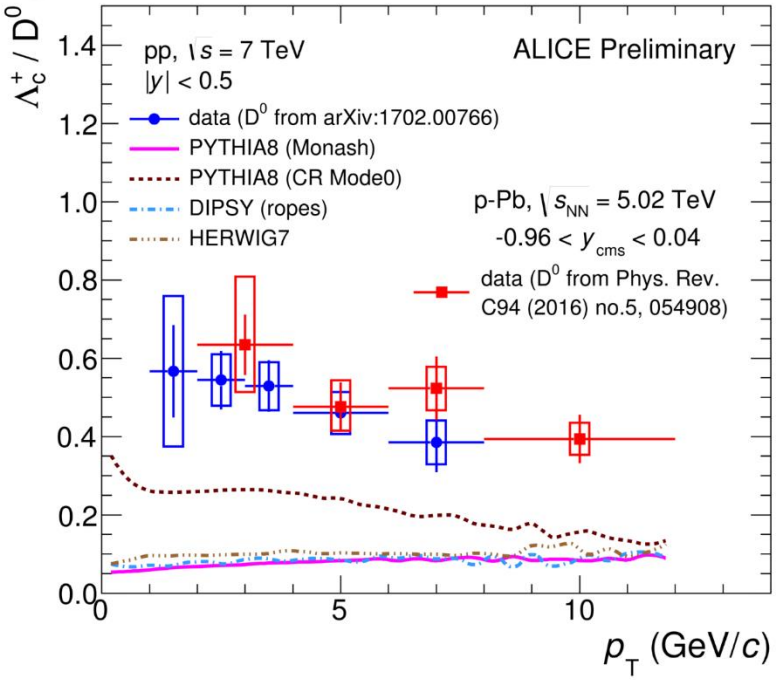
- Baryon/meson ratio particularly sensitive to the fragmentation process.
  - Differences observed in pp collisions (CDF+LHCb) with respect to e^+e^- collisions (LEP) in the beauty sector http://pdg.lbl.gov/2015/reviews/rpp2015-rev-b-meson-prod-decay.pdf

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

See Jaime's Talk (Tue)

Λ_c^+ / D^0 ratio

Results from RunI



Λ_c^+ / D^0 ratio:

- Agreement in pp and p-Pb collisions
- All the models underestimate our measurements
  - PYTHIA8 with colour reconnection mode closer to data
- Models however well describe the D^0 cross section

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**

- Λ_c/D^0 also larger than previous measurements at lower centre of mass energies and with different collisions systems, on which all the theoretical predictions are based!

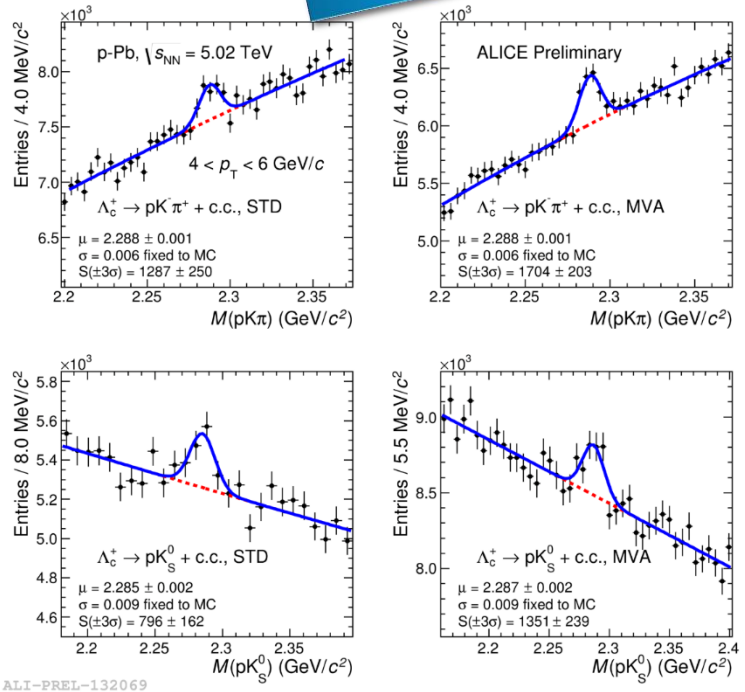
i.e. ZEUS: JHEP11 009, 2010
LHCb: Nucl Phys B871 (2013) 1-20

Charmed-hadron reconstruction

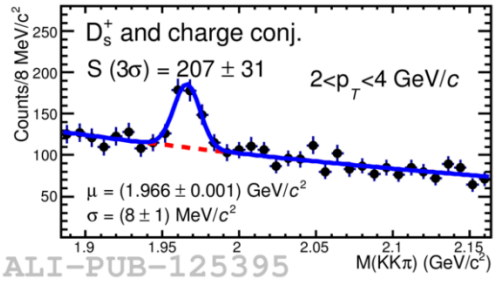
Charm from hadronic decays

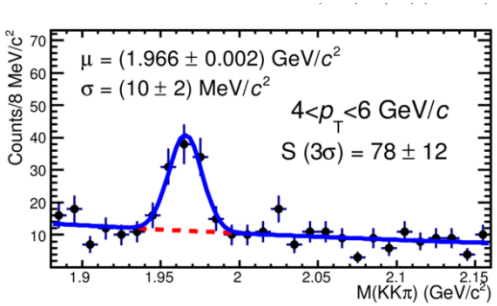
- **Reconstruction of secondary vertex**, displaced from the primary vertex by few hundred μm
- Candidates selected applying **topological selections** and **PID** (using TPC and TOF)
  - Using of **MultiVariate Approach**

Recent results from RunI



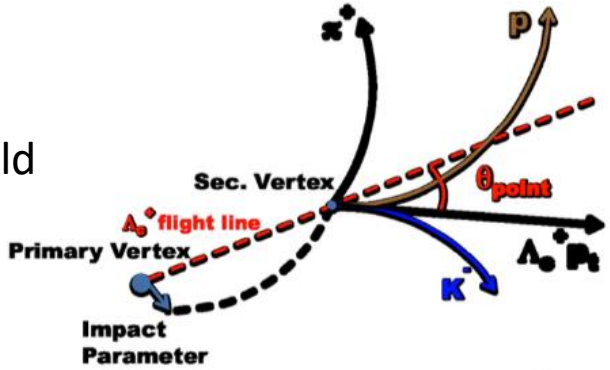
- Signal extraction via **invariant mass**





$\Lambda_c \rightarrow pK\pi$ analysis strategy

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



- ***pKπ 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.

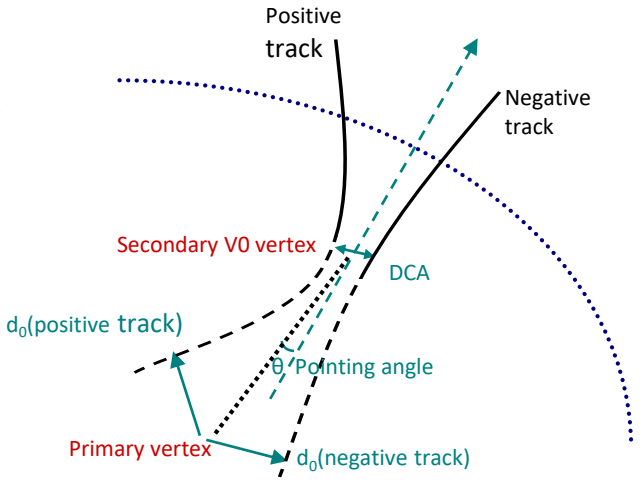
- Further selection to improve signal extraction, via two methods:
  - **Topological cuts on several variables (standard analysis - STD)**
  - **Cut on multivariate discriminator (TMVA)**

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

$\Lambda_c \rightarrow pK^0_S$ 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, $p_T(K^0_S \text{ daughters}), d_0(K^0_S \text{ daughters})$, $m_{inv}(\pi^+\pi^-)$
- 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**



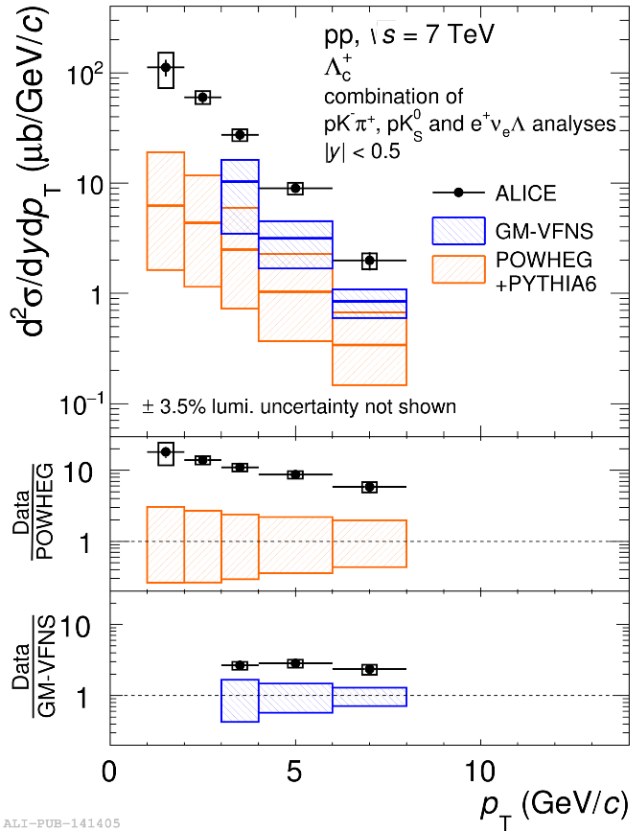
- Further selection to improve signal extraction, via two methods:
  - **Topological cuts on several variables (standard analysis - STD)**
  - **Cut on multivariate discriminator (TMVA)**
- Feed-down correction
- Efficiency and acceptance corrections
- Cross section estimate

Results at Run 1

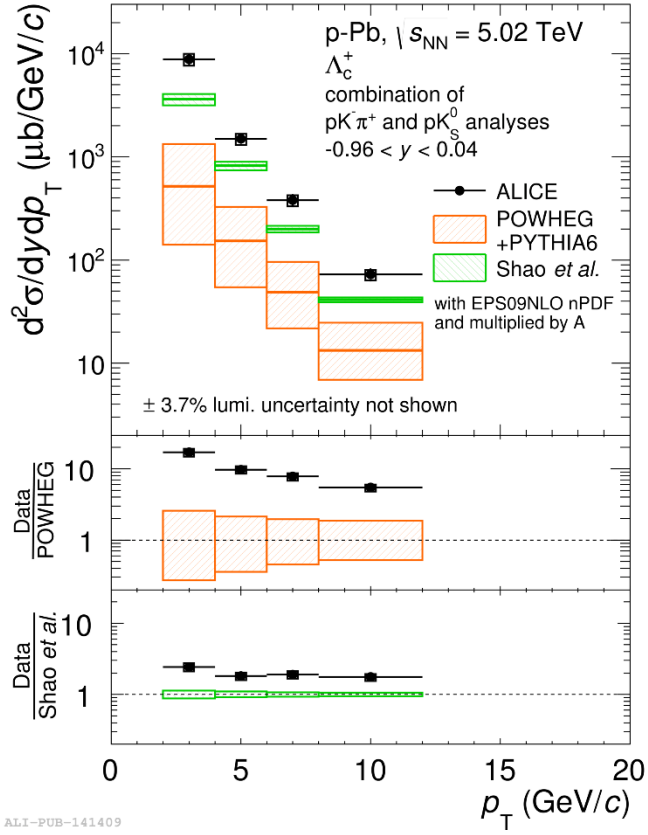
Λ_c^+ production in pp collisions at $\sqrt{s}$ = 7 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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

pp



p-Pb



GM-VFNS, Lansberg and Shao predictions and POWEG calculations underestimate significantly the measured cross sections.

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

POWEG JHEP0709, 126 (2007)

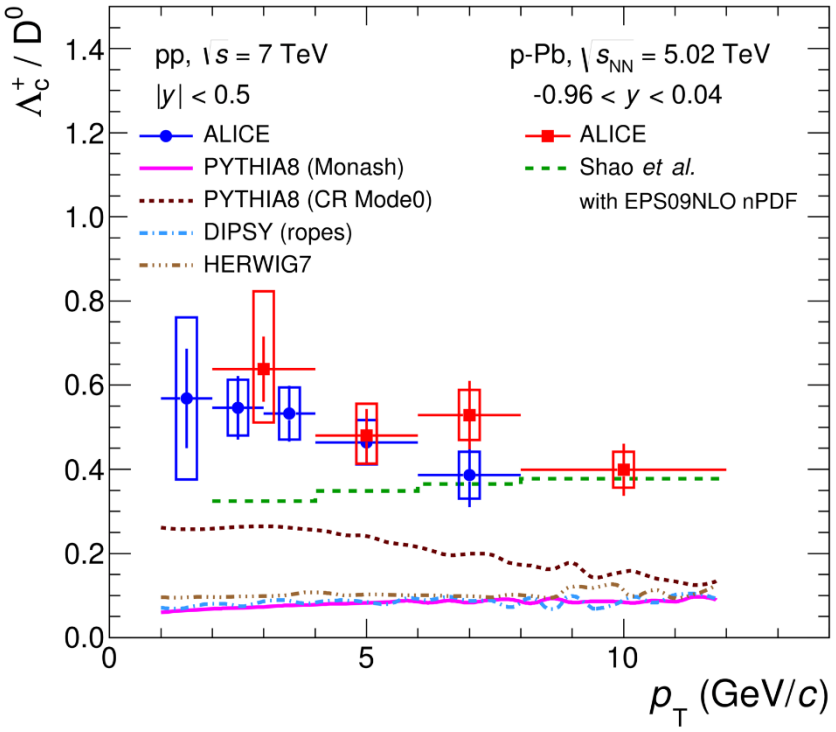
Lansberg and Shao
Eur. Phys. J. C77, no. 1, 1 (2017)

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



- **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)

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

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

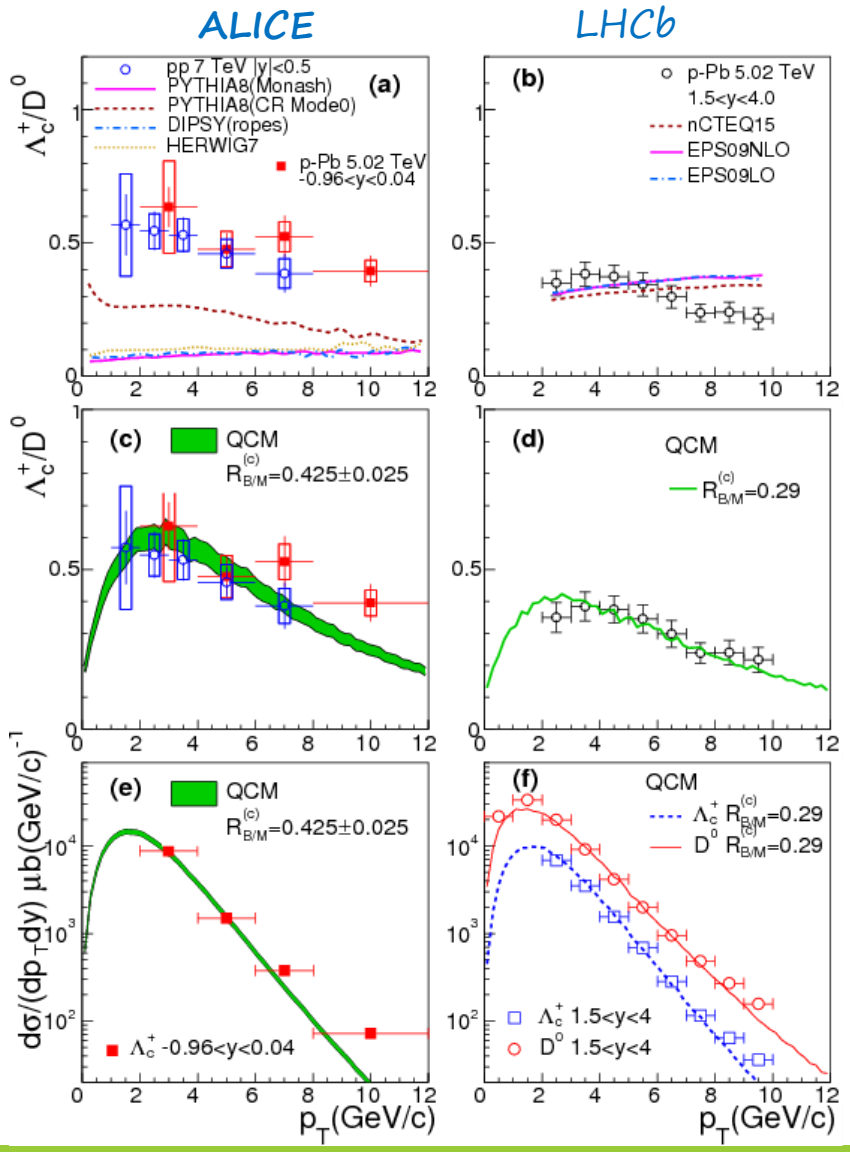
Results from Run 1

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

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	$1 < Q^2 < 1000\ \text{GeV}^2$, $0 < p_T < 10\ \text{GeV}/c$, $0.02 < y < 0.7$
ZEUS γp, HERA I	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320	$130 < W < 300\ \text{GeV}$, $Q^2 < 1\ \text{GeV}^2$, $p_T > 3.8\ \text{GeV}/c$, $\lvert\eta\rvert < 1.6$
ZEUS γp HERA II	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320	$130 < W < 300\ \text{GeV}$, $Q^2 < 1\ \text{GeV}^2$, $p_T > 3.8\ \text{GeV}/c$, $\lvert\eta\rvert < 1.6$

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

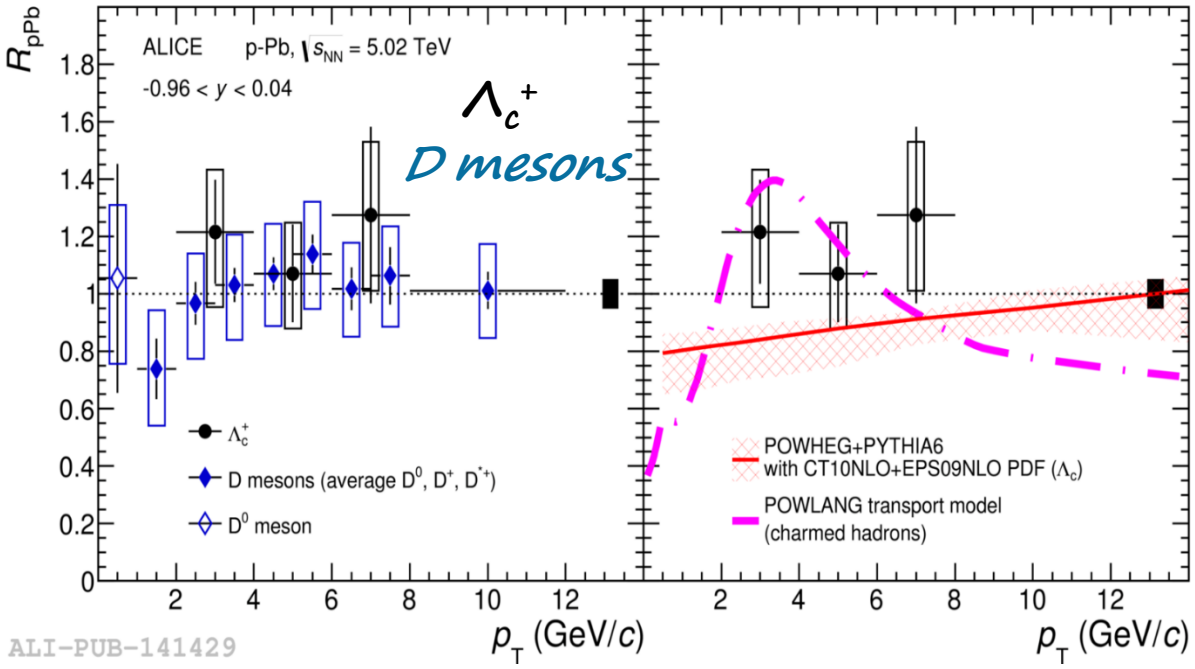
- $R^{(c)}_{B/M}$ relative production of single-charm baryons to single-charm mesons, treated as parameter of the model.

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

Results at 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



- Λ_c^+ R_{pPb} **compatible with unity**
- Compatible with D-Meson R_{pPb}
  - **Phys. Rev. C 94, 054908**

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

- Comparison with theory: -POWHEG+PYTHIA6 with CT10NLO+EPS09 PDF - **only CNM effects included**
  -POWLANG – **small QGP formation included**

Current precision of measurements not enough to constrain the models

The first LHC measurement of Λ_c in HI collisions

Pb-Pb

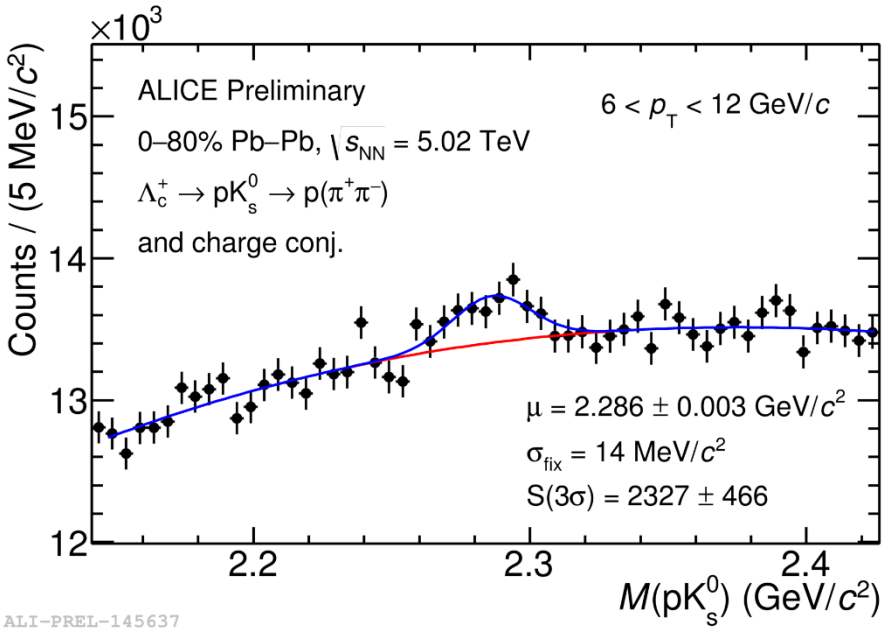
- **Data set:** **Pb-Pb**@5.02TeV (2015)
  LHC150
  110 M events in (0-100)% centrality interval

- 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



ALICE in Run 3 and Run 4

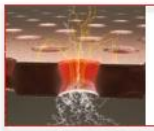
New Inner Tracking System (ITS)

- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

New Muon Forward Tracker (MFT)

- CMOS Pixels, MAPS technology
- Vertex tracker at forward rapidity

S. Siddhanta, Tue. 9:40



New TPC Readout Chambers (ROCs)

- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

New Fast Interaction Trigger (FIT) Detector

- Centrality, event plane

I.G. Bearden, Poster 66

FoCal proposal (Run 4)

N. Novitzky, Poster 771

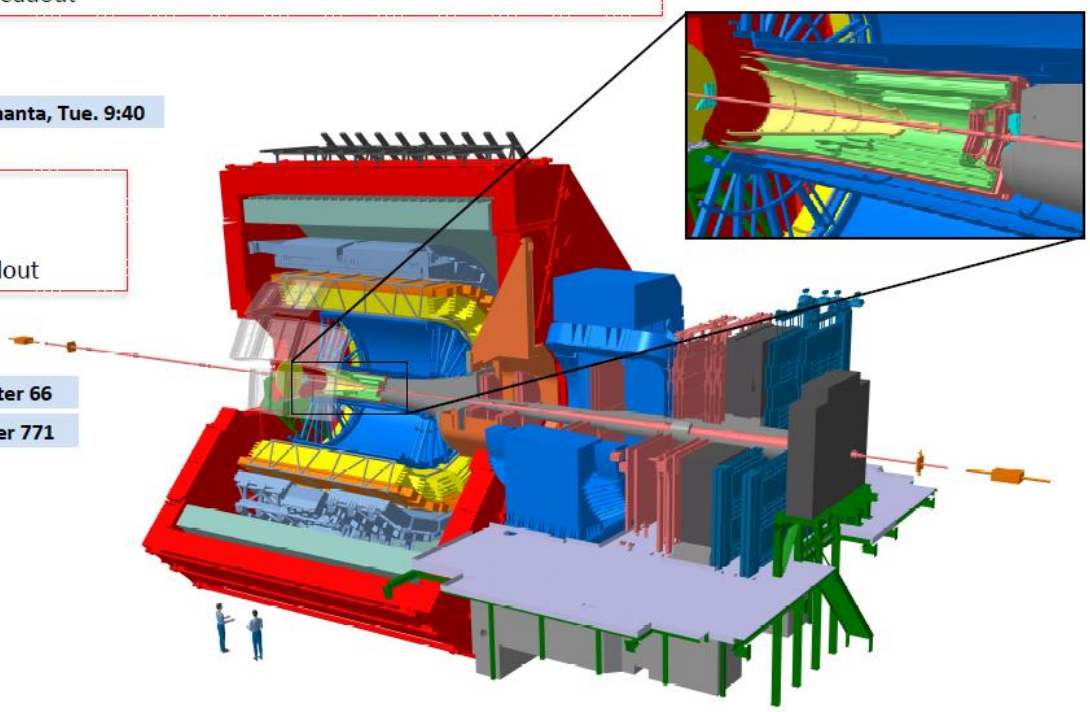
- Measure forward direct photons

Readout upgrade

- TOF, TRD, MUON, ZDC, Calorimeters

Integrated Online-Offline system (O^2)

- Record MB Pb-Pb data at 50 kHz



ALICE muon physics – current topics and upgrade motivations

Current topics: Low-mass dimuons, quarkonium states, heavy-flavor single muons, single muons and dimuons from W/Z bosons. Wealth of results published - 38 Muon Pub. / 193 ALICE Pub. ~20% (as of February 2018).

Upgrade motivations:

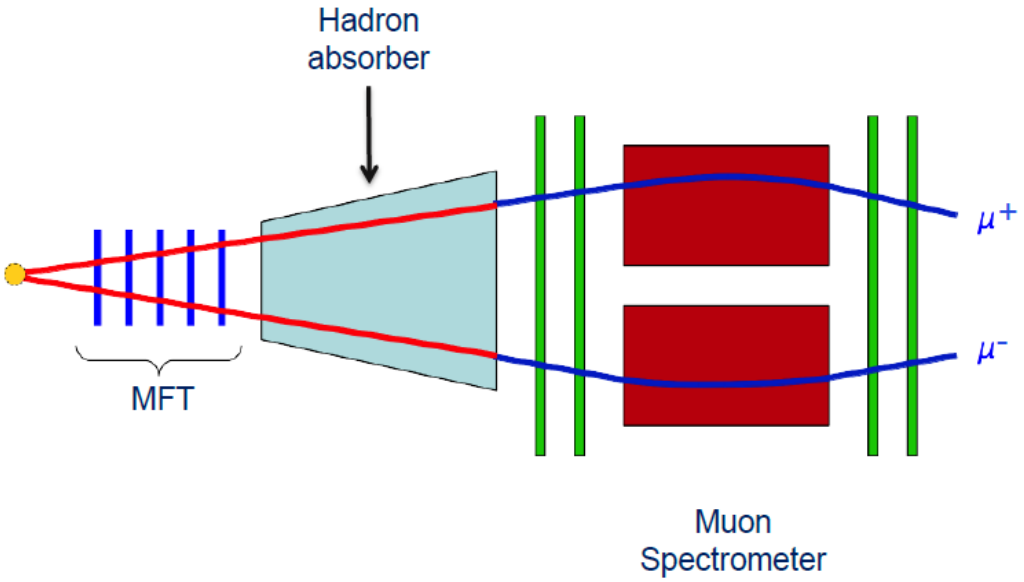
- **Reduce background from non-prompt sources**
  - Presently, there are large statistical uncertainties due to the large dimuon background from combinatorial π/K, charm and beauty semi leptonic decays . In particular, ψ(2S) measurements are limited by a poor significance of the ψ(2S) signal, namely in Pb-Pb collisions. Drell-Yan production is not accessible
- **Determine the muon production vertex**
  - No charm/beauty separation in single muons possible currently
  - No separation of prompt/non-prompt J/ψ in the present scenario: we miss an important source of information for the study of beauty
- **Improve mass resolution for light neutral resonances**
  - Limited resolution on the dimuon opening angle in the current scenario
- **Faster read-out to cope with the interaction rates expected after LS2**
  - Integrated luminosity during 1 month of Pb-Pb is limited to 1 nb^{-1} due to the present read-out electronics

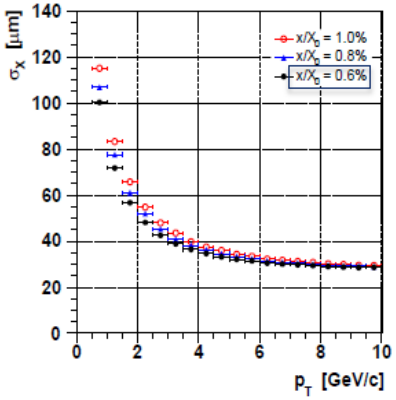
Muon Forward Tracker

Readout upgrade

The MFT Concept

Muon tracks are extrapolated and **matched to the MFT tracks** before the absorber





CERN-LHC-2015-001

High pointing accuracy gained by the single muon tracks in the transverse direction after matching with the MFT tracks. Pseudo-rapidity window reduces to
$2.5 < \eta < 3.6$