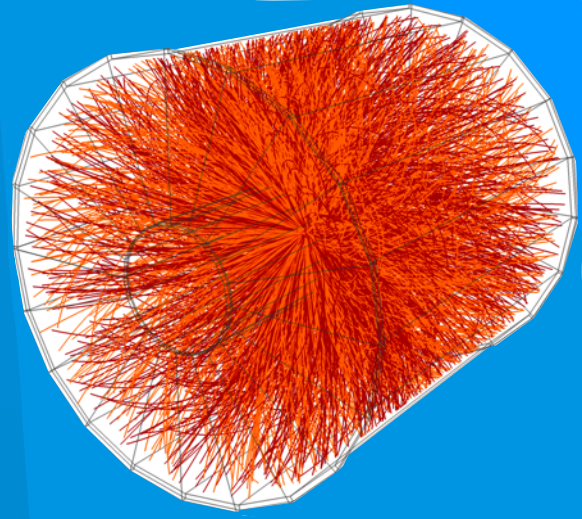
Measurement of Λ_c^+ production in Pb-Pb collisions with ALICE

Luuk Vermunt* (Utrecht University),
for the ALICE Collaboration



Workshop: Heavy-flavour hadronisation at the LHC
CERN, 03/03/2020

* luuk.vermunt@cern.ch

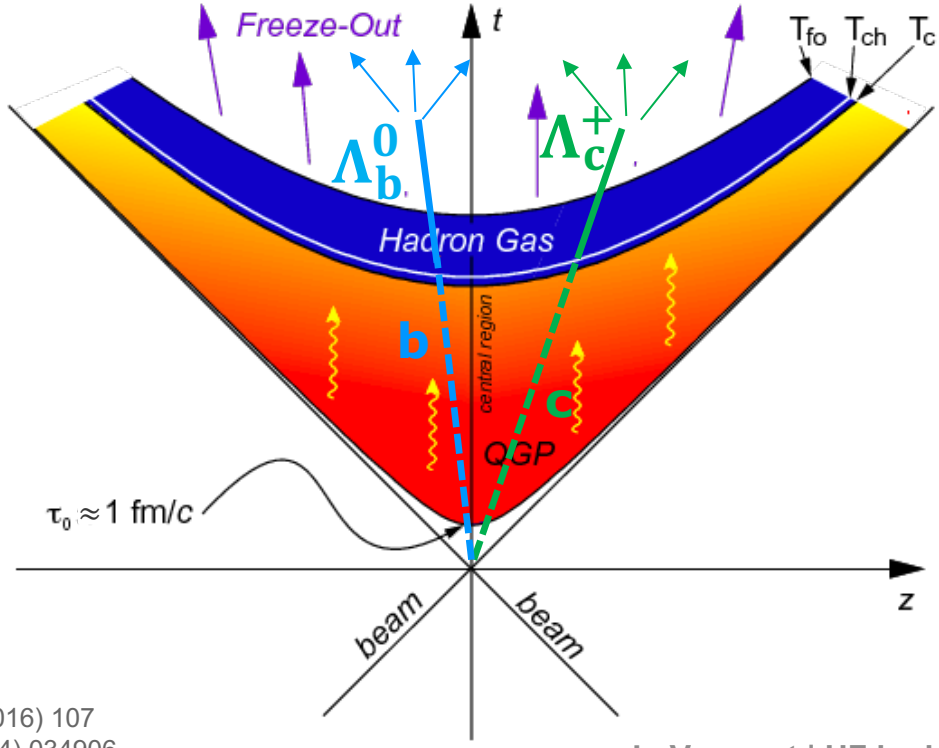
Heavy quarks in heavy-ion collisions

Heavy quarks (charm & beauty) are produced 'perturbatively' during initial stages of the collision.

- Experience the **full evolution** of the Quark-Gluon Plasma.

$$\tau_{\mathrm{prod}} \approx \frac{1}{2m_{\mathrm{q}}} \approx 0.1_{\mathrm{q=c}}\,(0.03)_{\mathrm{q=b}}\ \mathrm{fm}/c \quad \ll \quad \tau_{\mathrm{QGP}} \approx 0.3{-}1.5\ \mathrm{fm}/c$$ (at the LHC)[1,2]

- **Interact strongly** with the constituents of the medium.

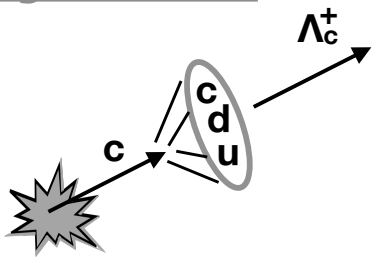


[1] Eur. Phys. J. C76 no. 3, (2016) 107
[2] Phys. Rev. C89 no. 3, (2014) 034906

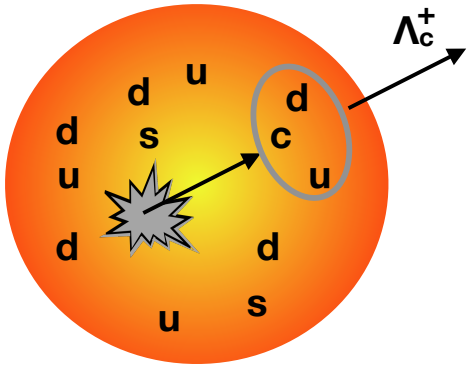
Charm-baryon measurements provide unique insights into **hadronisation processes** in the QGP

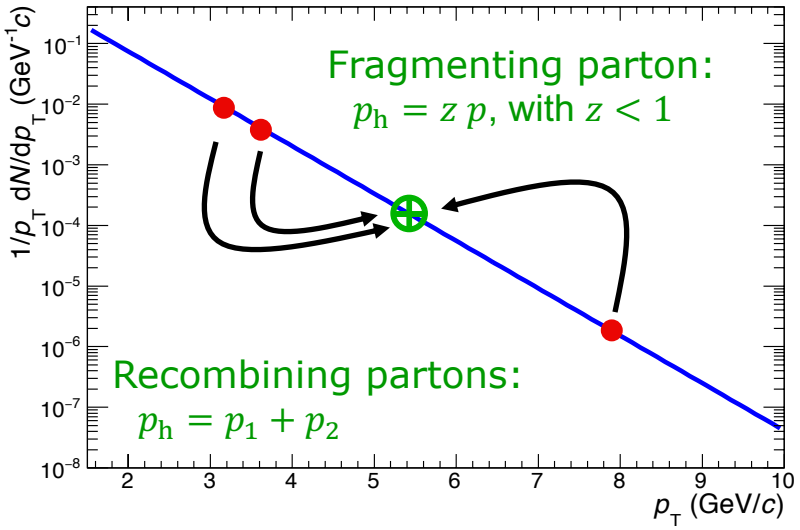
- **Pb-Pb:** Charm quarks may recombine with constituents of the medium and form charm-baryons at low/intermediate p_T.

Fragmentation



Recombination



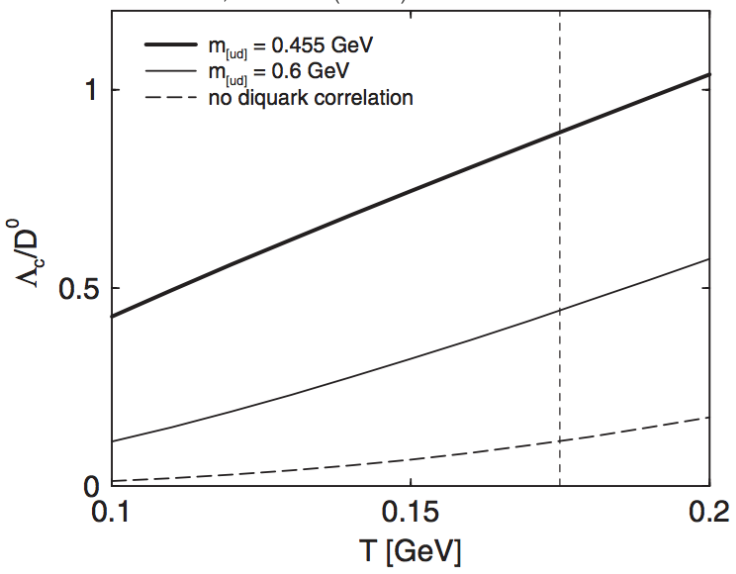


- Baryons are shifted to higher p_T than mesons, for same quark distribution.

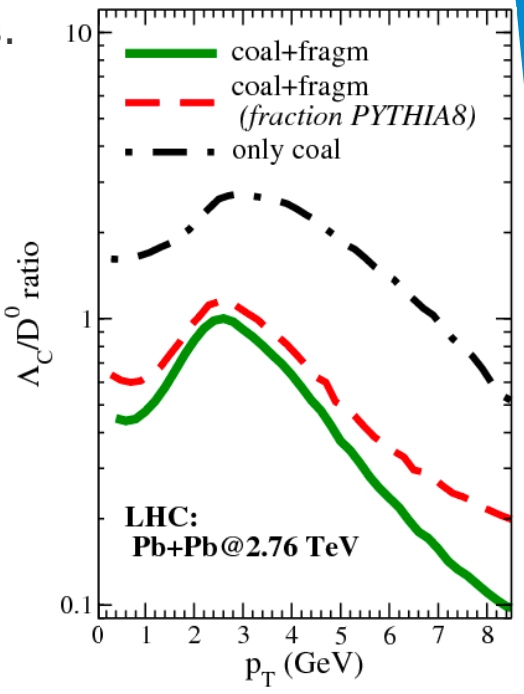
Charm-baryon measurements provide unique insights into **hadronisation processes** in the QGP

- **Pb-Pb:** Charm quarks may recombine with constituents of the medium and form charm-baryons at low/intermediate p_T.
  - **Enhancement** of baryon-to-meson (Λ_c^+ / D^0) ratio is predicted in **recombination** (or coalescence) models.
  - Further **enhancement** of baryon-to-meson ratio is expected if **light di-quark states** exist in the QGP.

PRL 100, 222301 (2008)

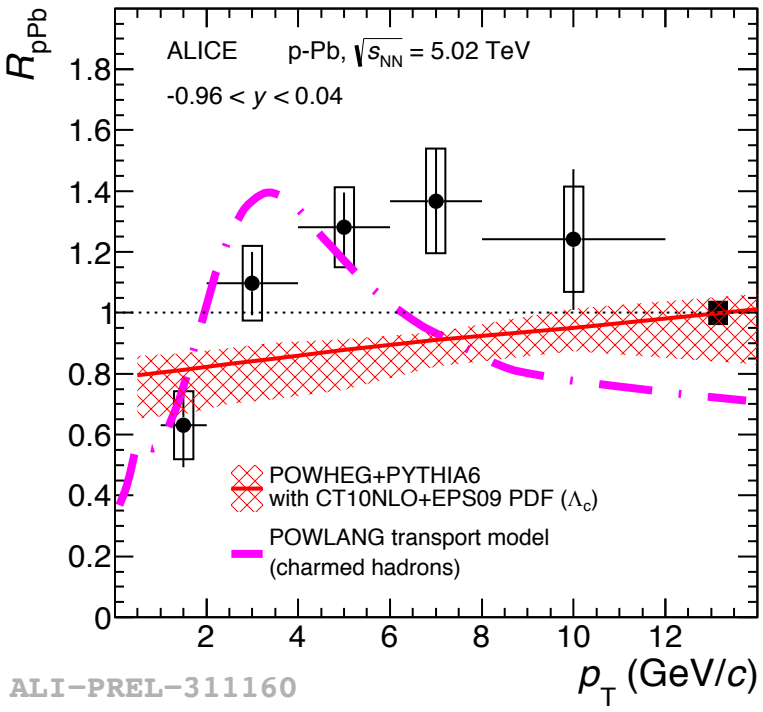


Eur. Phys. J. C (2018) 78:348

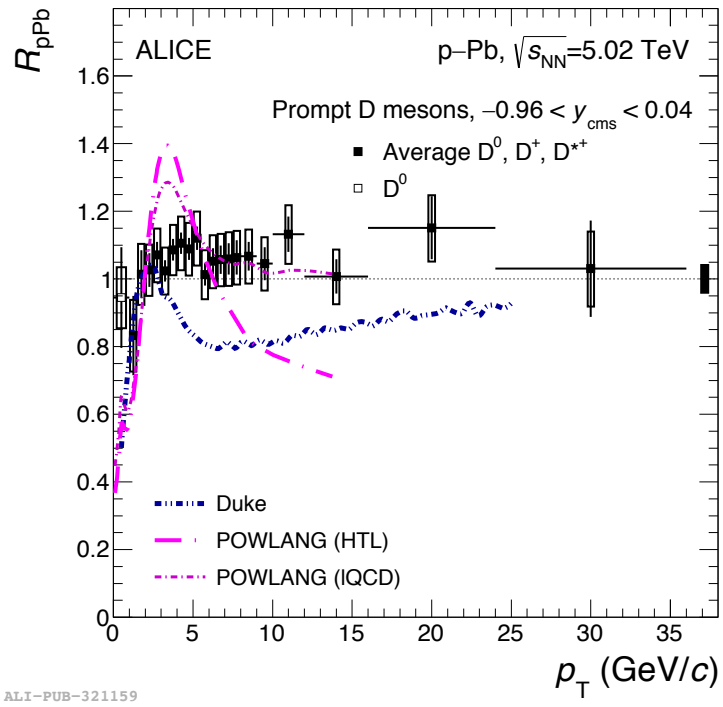


What did we learn from p-Pb?

Paper coming soon



JHEP 1912 (2019) 092



- The Λ_c^+ R_{pPb} has large uncertainties but is **qualitatively described** by **POWHEG+PYTHIA6+EPS09** (CNM effects) and **POWLANG** (QGP formation).
- D-meson R_{pPb} compared to transport models (with "small size" QGP).
  - Trend suggested by the models **not supported** by the data.
  - Data excludes some pure CNM models, see talk P. Antonioli.

Duke: Nucl. Part. Phys. Proc. 276-278 (2016) 225–228
POWLANG: JHEP 03 (2016) 123
POWHEG+PYTHIA6: JHEP 09 (2007) 126
EPS09: JHEP 04 (2009) 065

ALICE publication: Λ_c^+ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015)

If charm quarks recombine with constituents of the medium, we expect:

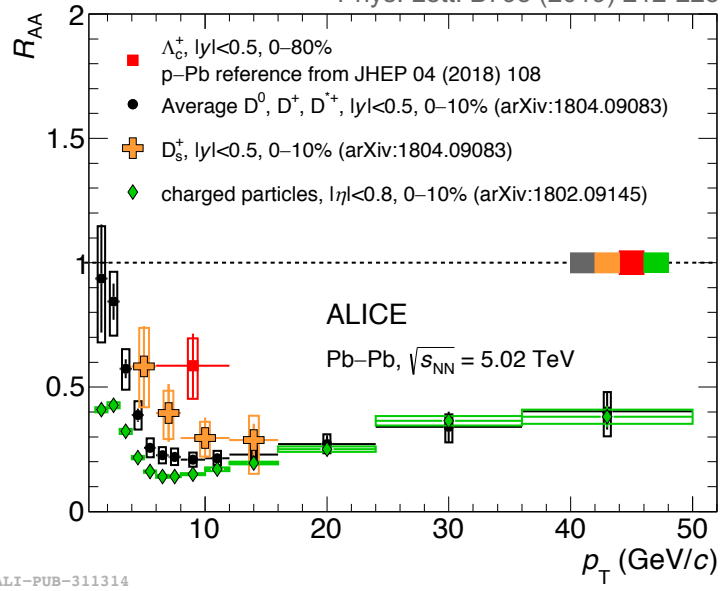
- Different nuclear modification compared to the charmed meson states ($R_{AA}(\mathbf{\Lambda_c^+}) > R_{AA}(\mathbf{D})$).

$$R_{AA}(p_T) = \frac{1}{< N_{coll}^{AA} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- Enhanced baryon-to-meson ratio compared to pp collisions at low/intermediate p_T.

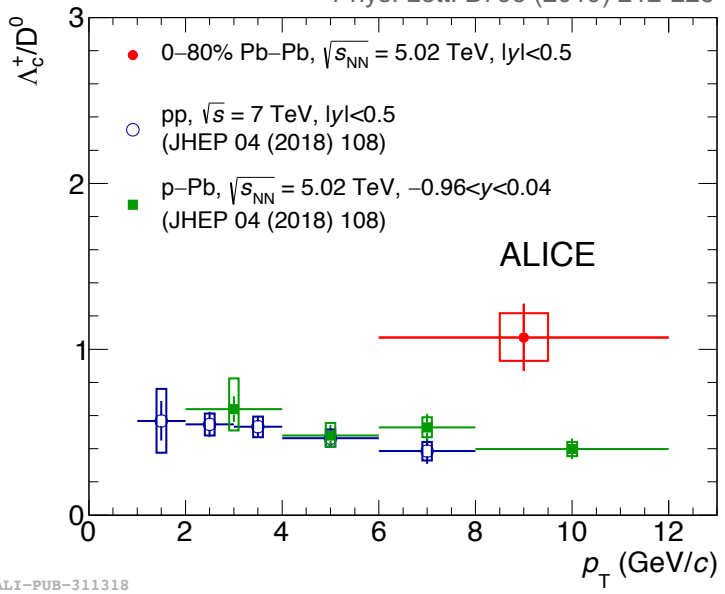
$$\left[\frac{\Lambda_c^+}{D^0}\right]_{Pb-Pb} > \left[\frac{\Lambda_c^+}{D^0}\right]_{pp}$$

Phys. Lett. B793 (2019) 212-223



ALI-PUB-311314

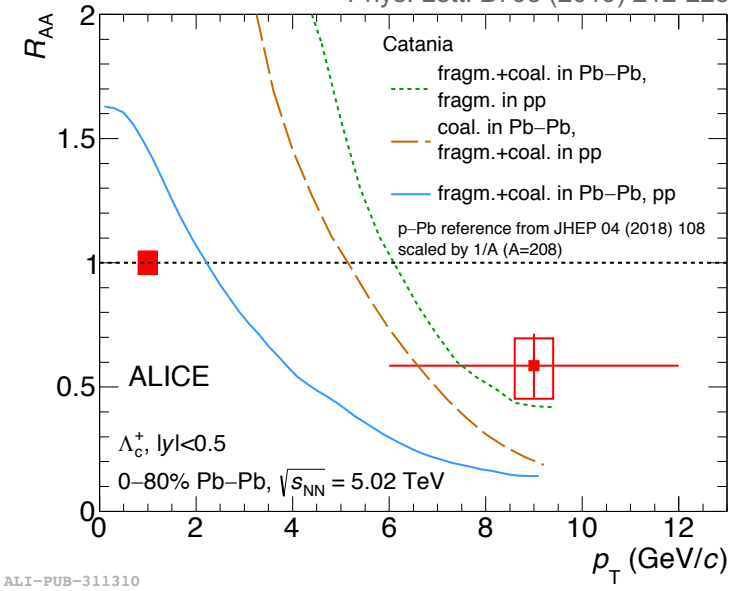
Phys. Lett. B793 (2019) 212-223



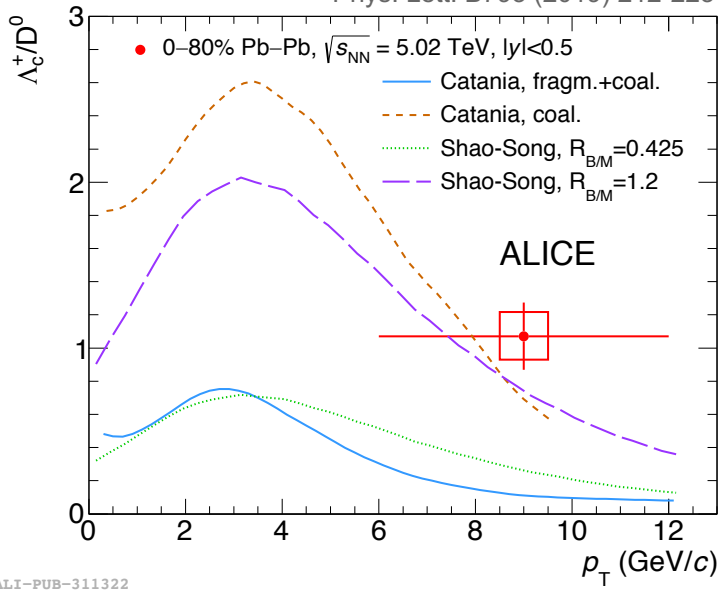
ALI-PUB-311318

ALICE publication: Λ_c^+ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015)

Phys. Lett. B793 (2019) 212-223



Phys. Lett. B793 (2019) 212-223



Phys. Lett. B793 (2019) 212-223:

- Hint of **hierarchy**: $R_{AA}(\mathrm{D}^0) < R_{AA}(\mathrm{D}_s^+) < R_{AA}(\Lambda_c^+)$.
- $\Lambda_c^+ / \mathrm{D}^0$ in p-Pb and Pb-Pb differ by about **two standard deviations**.
- Measured ratio is reproduced by models implementing a **pure coalescence scenario**.

Conclusions revisited later with new Pb-Pb 2018 preliminaries.

Open-charm baryon (Λ_c^+) measurements provide unique insights into hadronisation processes in the QGP

Results shown here are based on the **latest Run2 Pb-Pb 2018** at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV data taking campaign by **ALICE**, corresponding to $\mathcal{L} \approx 112.3\ \mu\mathrm{b}^{-1}$ (0-10% central) and $\mathcal{L} \approx 49.0\ \mu\mathrm{b}^{-1}$ (30-50% central):

- More differential measurements and improved statistical precision.
- Extended p_{T} range.

Reconstruction of Λ_c^+ baryons in ALICE

Invariant mass analysis of the decay

- $\Lambda_c^+ \longrightarrow K_S^0\ p \longrightarrow \pi^+\ \pi^-\ p \qquad (c\tau \approx 60\ \mu m,\ BR \approx 1.1\%)$

Candidates built **combining triplets of tracks** reconstructed at mid-rapidity ($|\eta| < 0.8$) with proper charge.

Reduction of the combinatorial background by exploiting two different **BDT** algorithms to improve the measurement

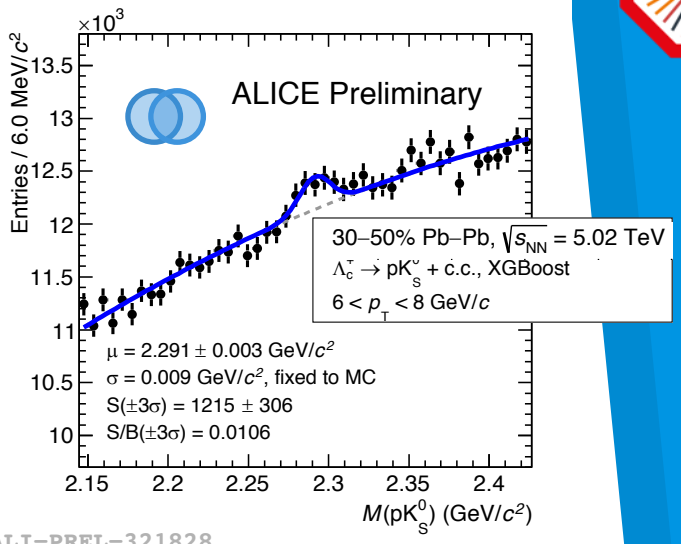
- The **TMVA** package ⟶ AdaBoost
- **Python-based analysis framework** ⟶ XGBoost

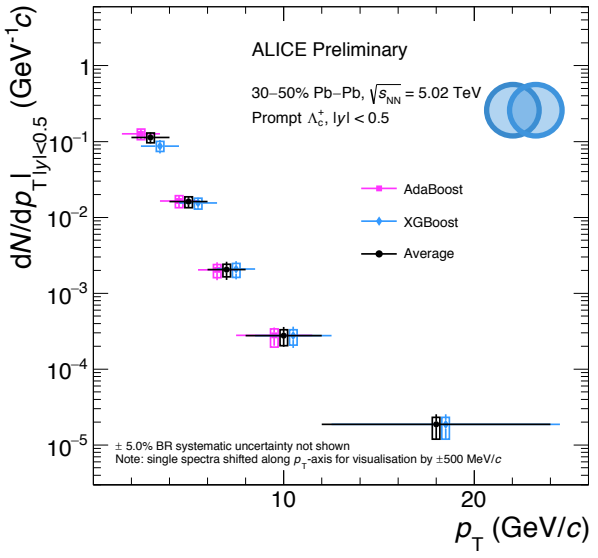
Topological, kinematical, and PID training variables.

Corrected for

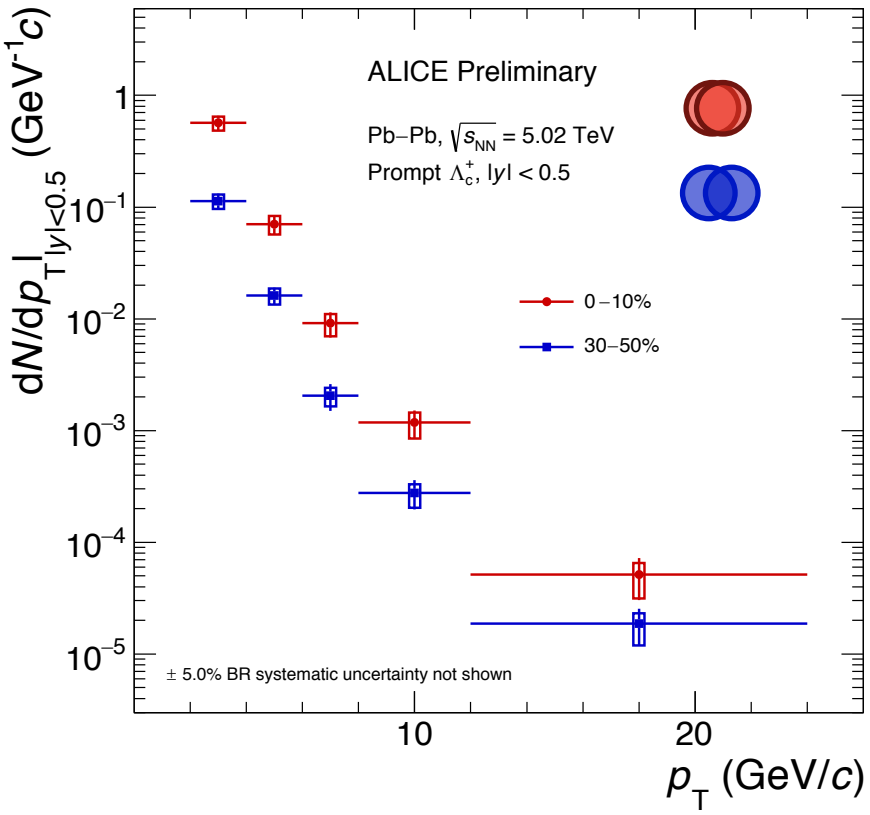
- **selection efficiency** using MC simulations.
- **feed-down subtraction** using FONLL predictions.

Average results obtained by weighting the two results by the inverse of the sum in quadrature of the relative uncorrelated systematics uncertainties.





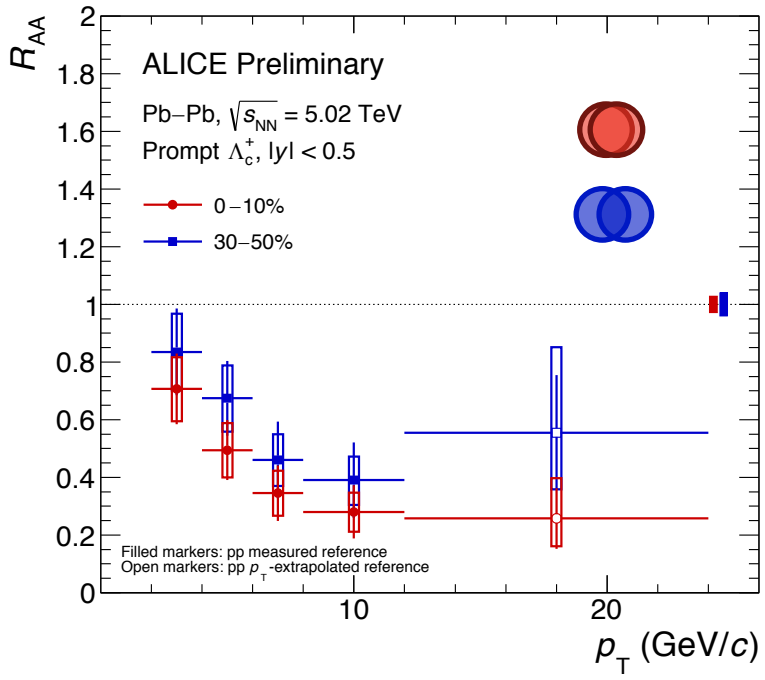
Λ_c^+ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



Big improvement with respect to measurement in Pb-Pb '15:

- From one p_T bin (6-12 GeV/c) to five bins in 2 and 24 GeV/c.
- From one big centrality interval (0-80%) to 0-10% and 30-50%.

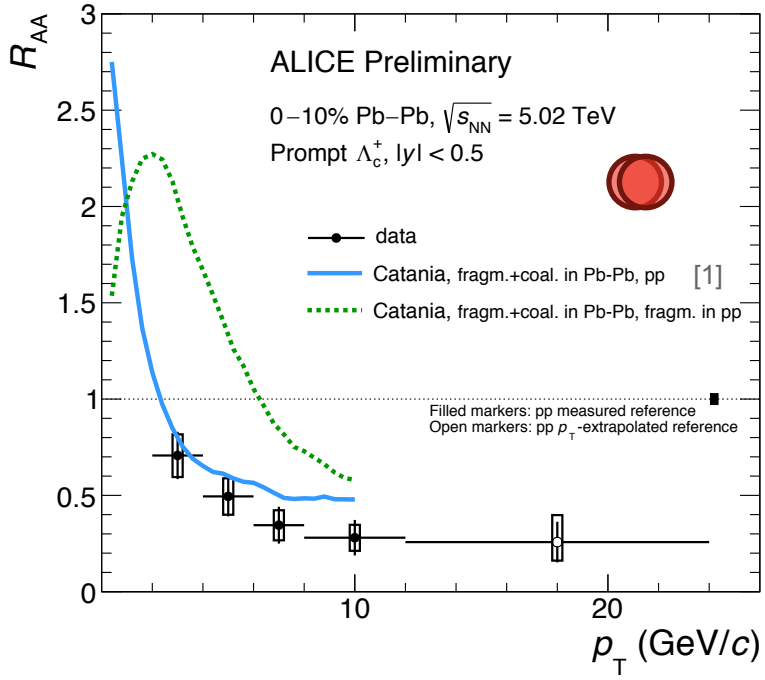
Λ_c^+ nuclear modification factor (R_{AA}) at $\sqrt{s_{NN}} = 5.02$ TeV

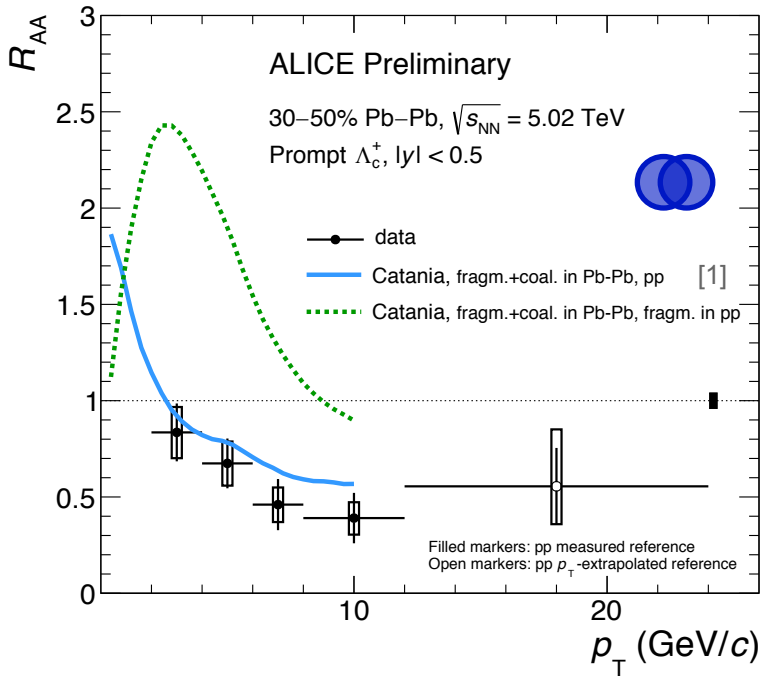


ALI-PREL-321861

- **Suppression observed** for the Λ_c^+ baryon in Pb-Pb collisions.
- Despite the compatibility within uncertainties, hint of larger suppression for central collisions by a factor ~1.5 up to $p_T = 12$ GeV/c.

Λ_c^+ nuclear modification factor (R_{AA}) at $\sqrt{s_{NN}} = 5.02$ TeV



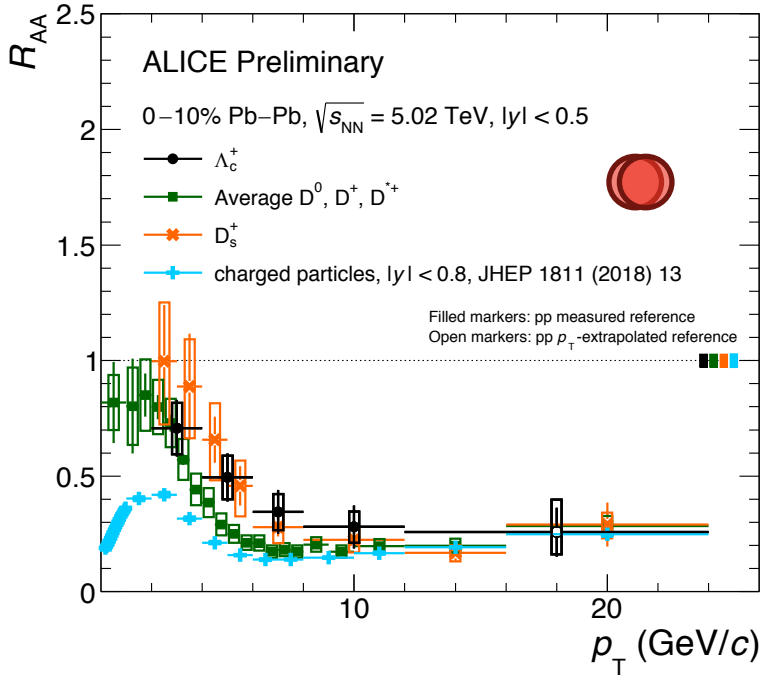


- Suppression observed for the Λ_c^+ baryon in Pb-Pb collisions.
- Despite the compatibility within uncertainties, hint of larger suppression for central collisions by a factor ~1.5 up to $p_T = 12$ GeV/c.
- Comparison to theory favours a scenario where both **fragmentation and recombination** are present in Pb-Pb and pp collisions.

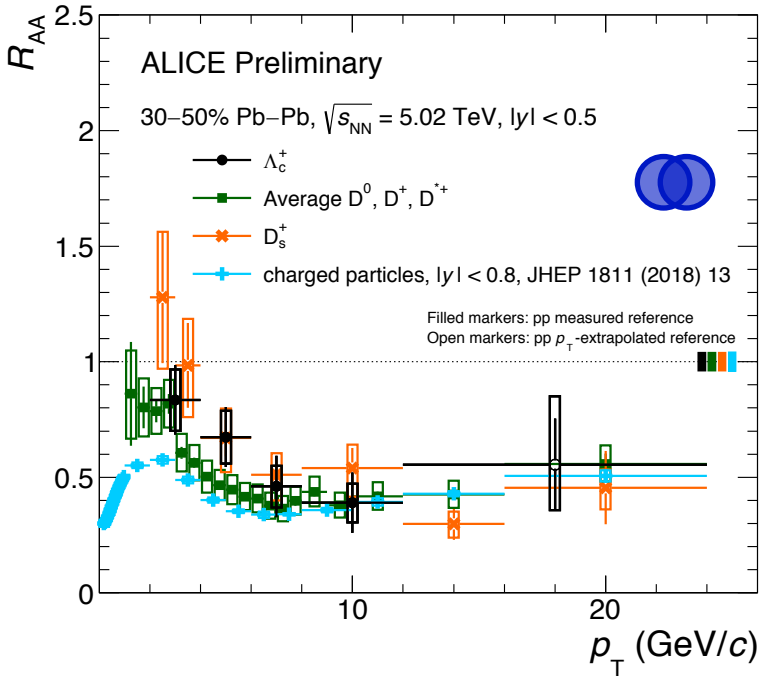
See talk of S. Plumari for more info.

[1] Catania: Eur. Phys. J. C (2018) 78: 348

ALICE's charm-family portrait of LHC Run-II



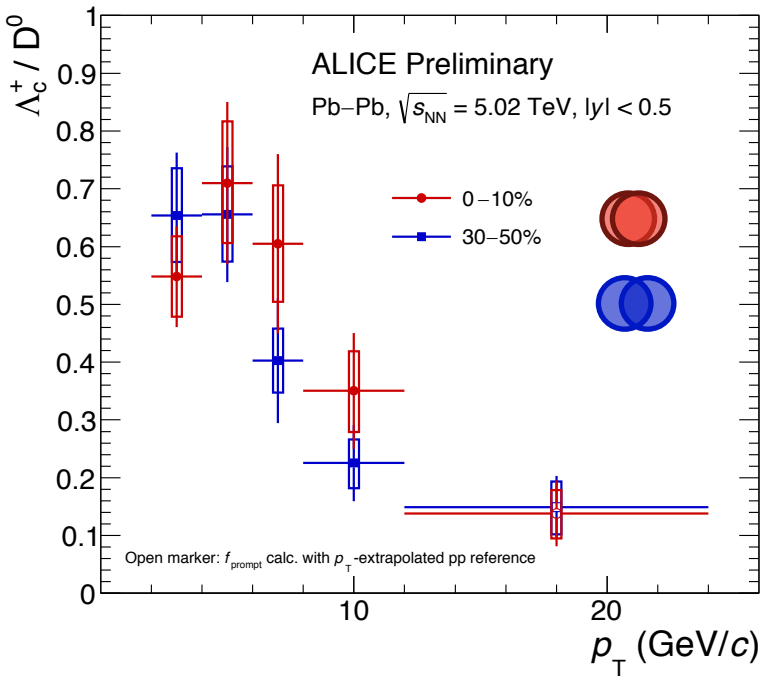
ALI-PREL-330734



ALI-PREL-321908

- Suppression observed for the Λ_c^+ baryon in Pb-Pb collisions.
- Despite the compatibility within uncertainties, hint of larger suppression for central collisions by a factor ~1.5 up to $p_T = 12$ GeV/c.
- Comparison to theory favours a scenario where both fragmentation and recombination are present in Pb-Pb and pp collisions.
- Nuclear suppression hierarchy: $R_{AA}(\mathbf{\Lambda_c^+}) \sim R_{AA}(\mathbf{D_s^+}) > R_{AA}(\mathbf{D}) > R_{AA}(\mathbf{h^\pm})$.

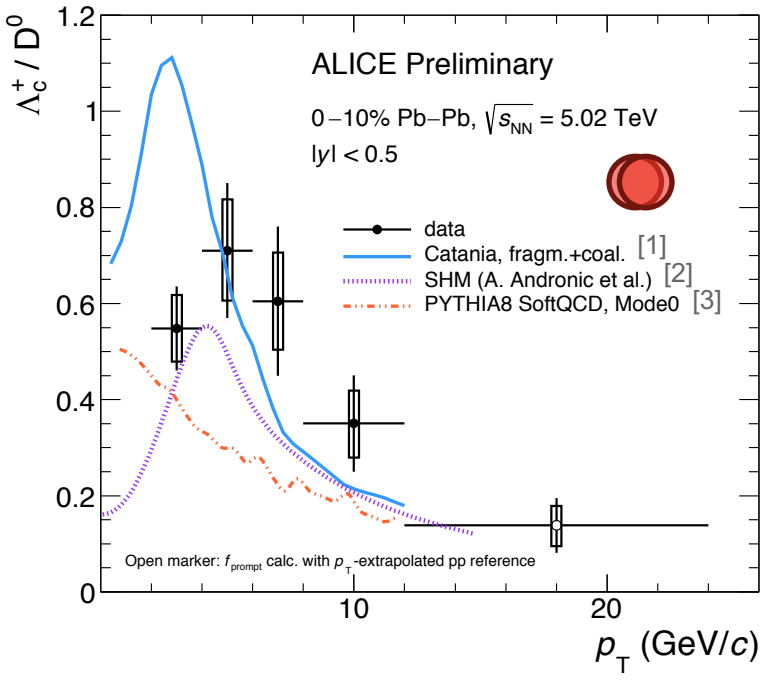
Baryon-to-meson ratio (Λ_c^+ / D^0) at $\sqrt{s_{NN}} = 5.02$ TeV



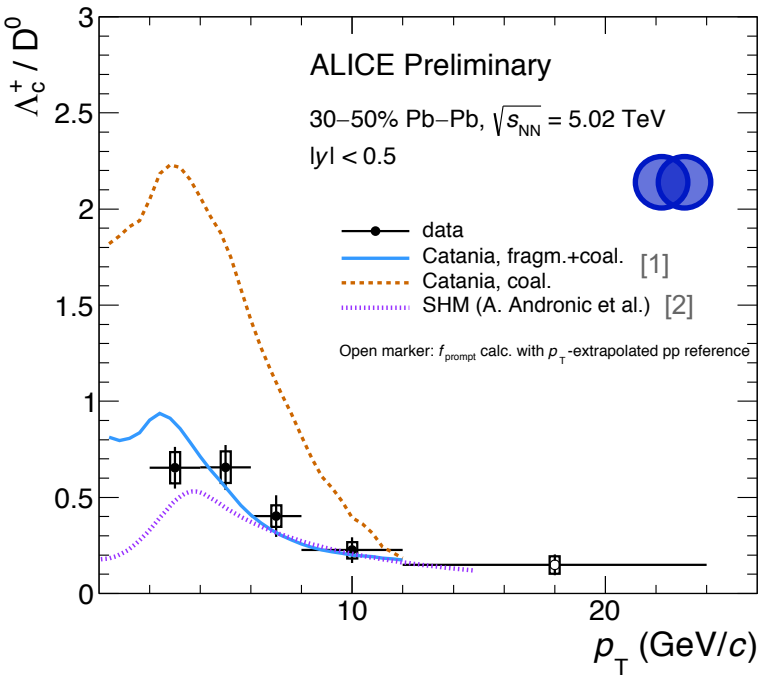
ALI-PREL-321690

- Central collisions (0-10%) show a hint of a larger ratio than semi-central collisions (30-50%) at intermediate p_T.

Baryon-to-meson ratio (Λ_c^+ / D^0) at $\sqrt{s_{NN}} = 5.02$ TeV



ALI-PREL-321835



ALI-PREL-321845

- Central collisions (0-10%) show a hint of a larger ratio than semi-central collisions (30-50%) at intermediate p_T.
- Λ_c^+ / D^0 ratio described by **statistical hadronisation model** and the Catania model including **fragmentation and recombination**.
- A pure coalescence model is clearly overshooting the data.

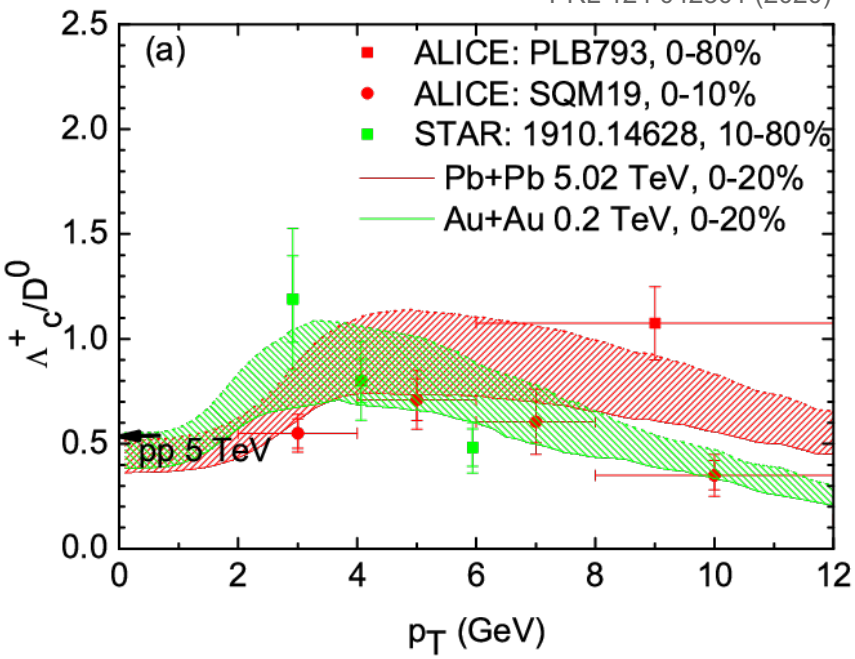
See talks of S. Plumari, A. Andronic, and P. Skands for more info.

[1] Catania: Eur. Phys. J. C (2018) 78: 348
[2] SHM: Phys Lett B797 (2019) 134836
[3] PYTHIA8 CR: JHEP 08 (2015) 003

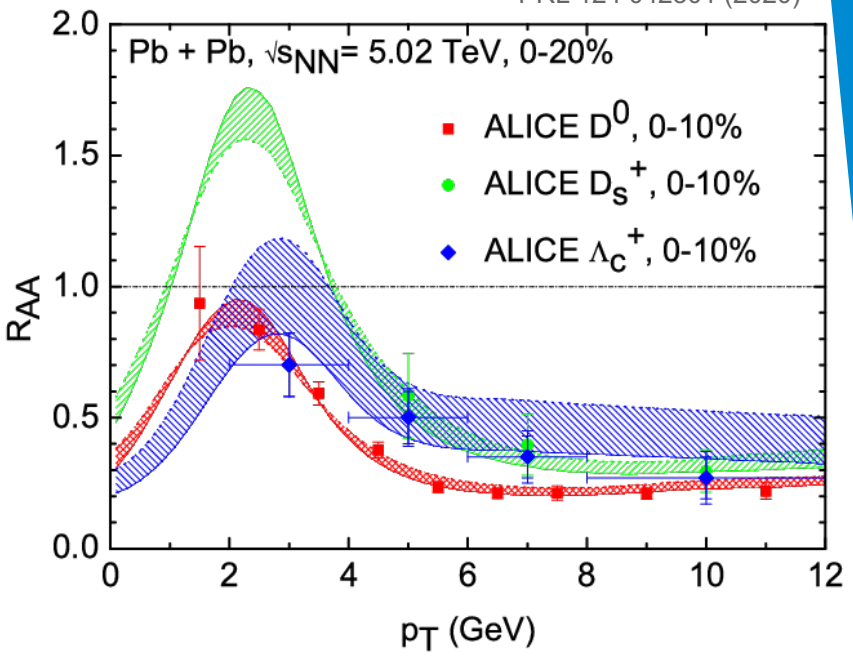
To “complete” the theoretical picture

- Recent predictions of Min He and Ralf Rapp compared to the ALICE and STAR measurements in AA collisions.
  - Including three new development in their non-perturbative hydro-Langevin-RRM framework (see [1] or talk of M. He for more info).
  - The Λ_c^+ / D^0 ratio tends to be slightly overpredicted, where the suppression hierarchy observed in R_{AA} is fairly well reproduced.

PRL 124 042301 (2020)

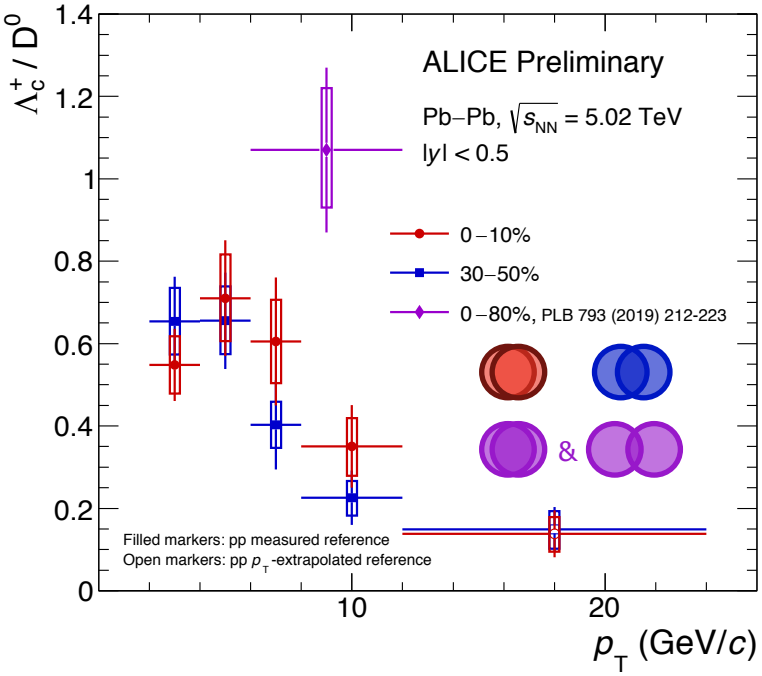


PRL 124 042301 (2020)



[1] PRL 124 042301 (2020)

Λ_c^+ / D^0 and Λ_c^+ R_{AA} compared to Pb-Pb 2015 publication



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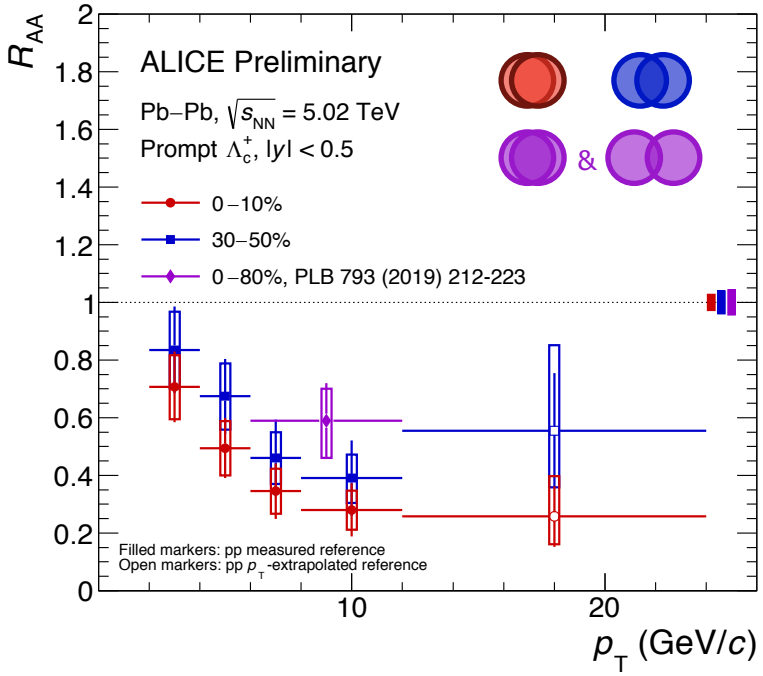
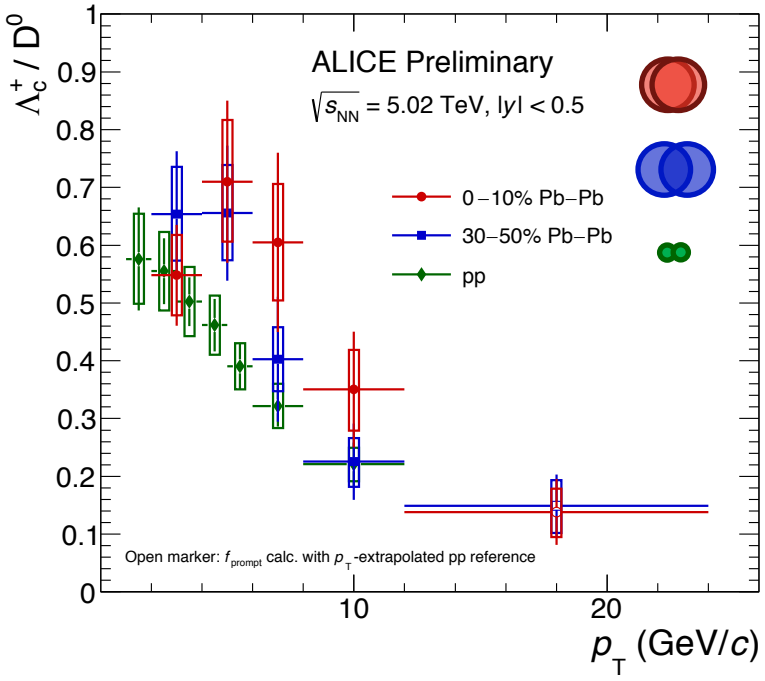


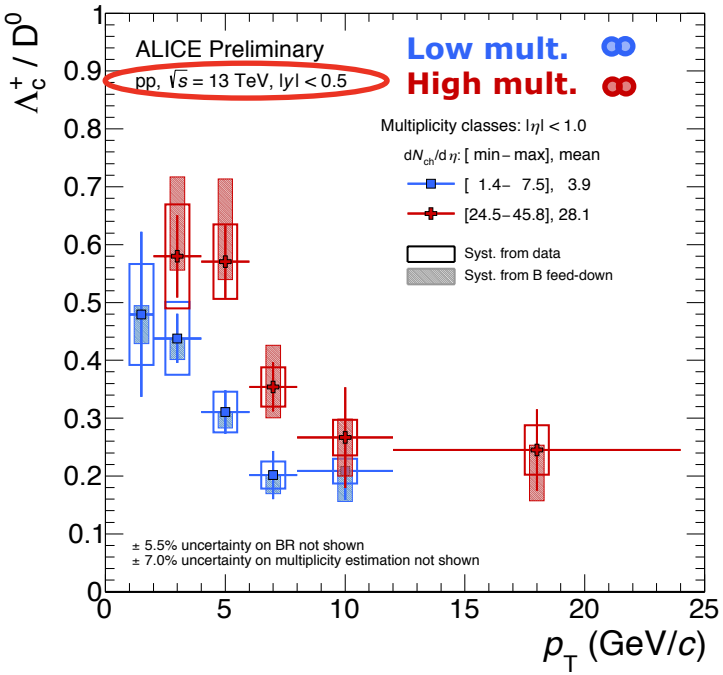
ALI-PREL-321868

Phys. Lett. B793 (2019) 212-223 improved physics message:

- Hint of **hierarchy**: $R_{AA}(D^0) < R_{AA}(D_s^+) \sim R_{AA}(\Lambda_c^+)$.
- Λ_c^+ / D^0 in p-Pb and Pb-Pb …
  - are compatible within statistical uncertainties.
- Measured ratio is reproduced by models implementing …
  - a frag+coal scenario, a Langevin-RRM approach, and the SHM.

Baryon-to-meson ratio (Λ_c^+ / D^0) compared to pp collisions

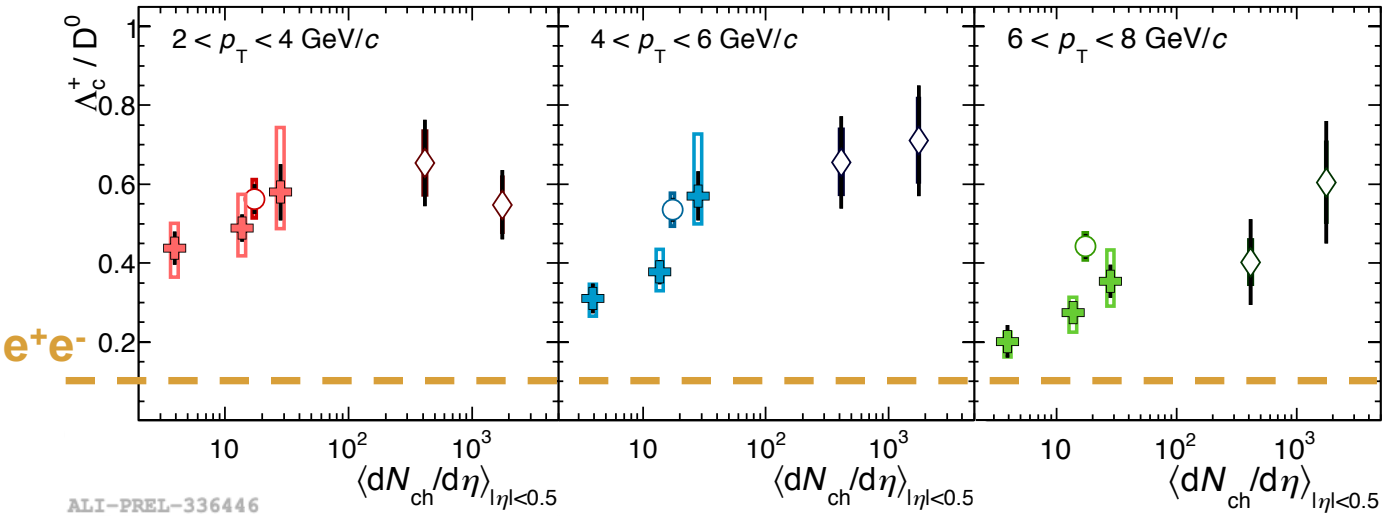


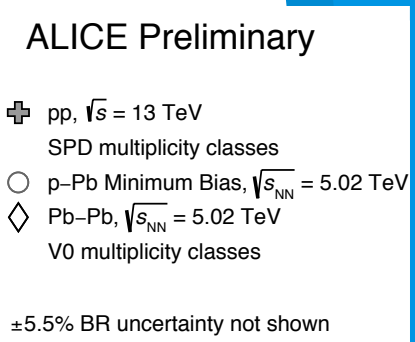


ALI-PREL-321702

- Hint of higher Λ_c^+ / D^0 ratio in Pb-Pb (**0-10%** and **30-50%**) collisions w.r.t. **pp** collisions.
  - Understanding of pp data is fundamental. Ratio is underestimated by models with fragmentation parameters derived from e^+e^- collision data.
- Λ_c^+ / D^0 shows an enhancement from low to high multiplicity in pp 13 TeV collisions.
- See talk of P. Antonioli for more info.

Λ_c^+ / D^0 versus multiplicity across the colliding systems





Smooth increase from pp to p-Pb to Pb-Pb multiplicities

- High pp multiplicity ~ Pb-Pb
- Low pp multiplicity > e^+e^-

In **qualitative agreement** with the hypothesis of **recombination** that **saturates already in pp?**

Summary and outlook

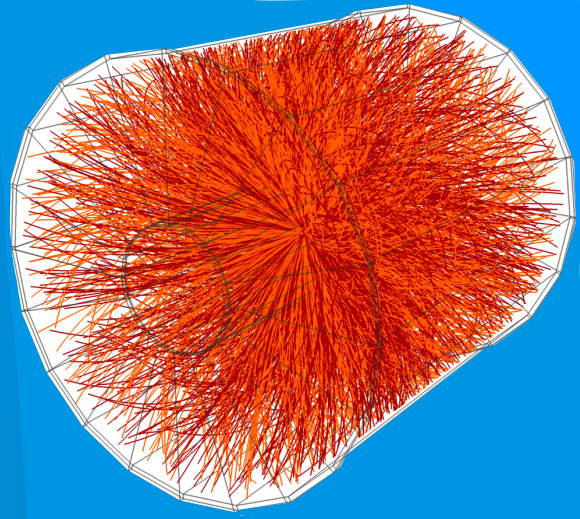
Pb-Pb: Λ_c^+ / D^0 and Λ_c^+ R_{AA} are measured in the range $2 \leq p_T \leq 24$ GeV/c for the 0-10% and 30-50% centrality classes in Pb-Pb collisions.

- Big improvement with respect to Pb-Pb 2015 analysis: physics message of comparison to theory updated!
- Compatible with p-Pb within statistical uncertainties.
- Results in agreement with models that foresee both fragmentation and recombination.

ALICE upgrade for Run3+4 will offer the opportunity to explore, with higher precision, open charmed baryon measurements in a wider p_T region (including new physics channels, e.g. Λ_b^+).

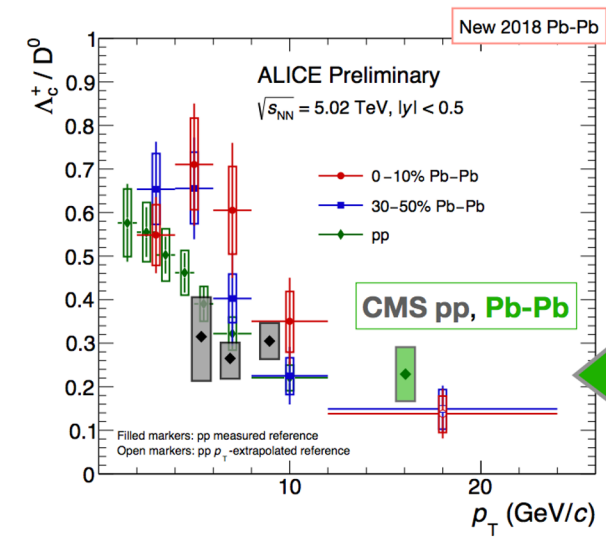
- **New ITS**: 7 layer pixel detector, pointing resolution $\sim 20\ \mu m$ at $p_T = 1$ GeV/c.
- **New TPC**: using GEM and continuous readout at 50 kHz.

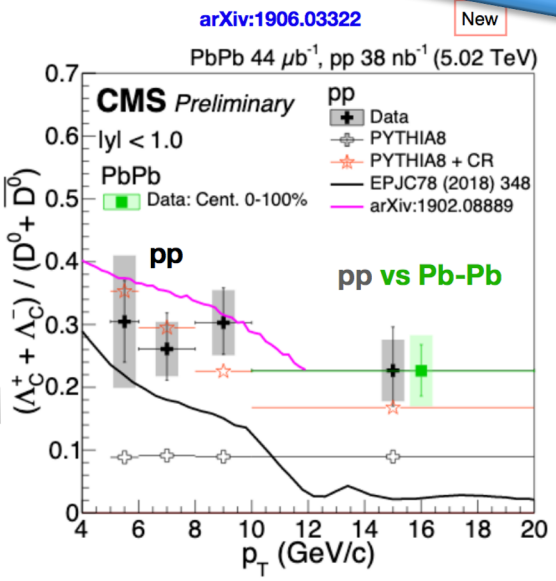
Additional slides



Comparison ALICE with CMS and STAR

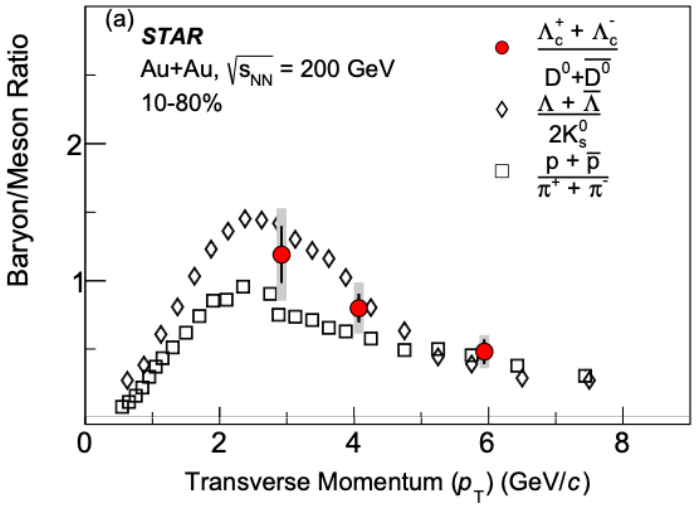
C. Terrevoli at SQM19

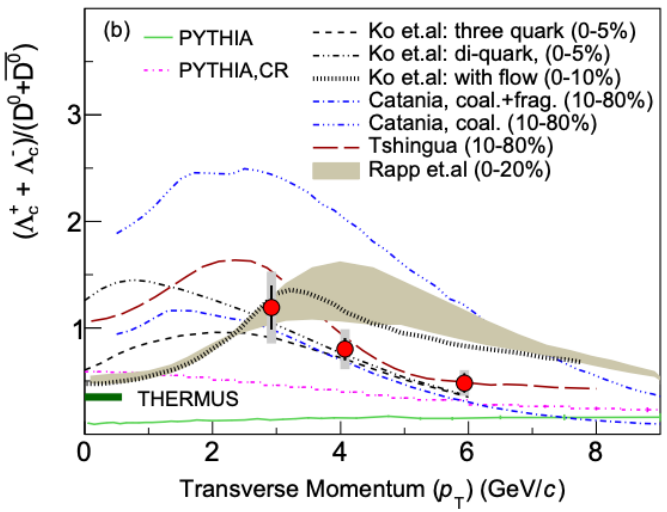




ALICE: hint of **larger Λ_c/D^0 in Pb-Pb w.r.t. to pp** for **4 <p_T< 6 GeV/c**

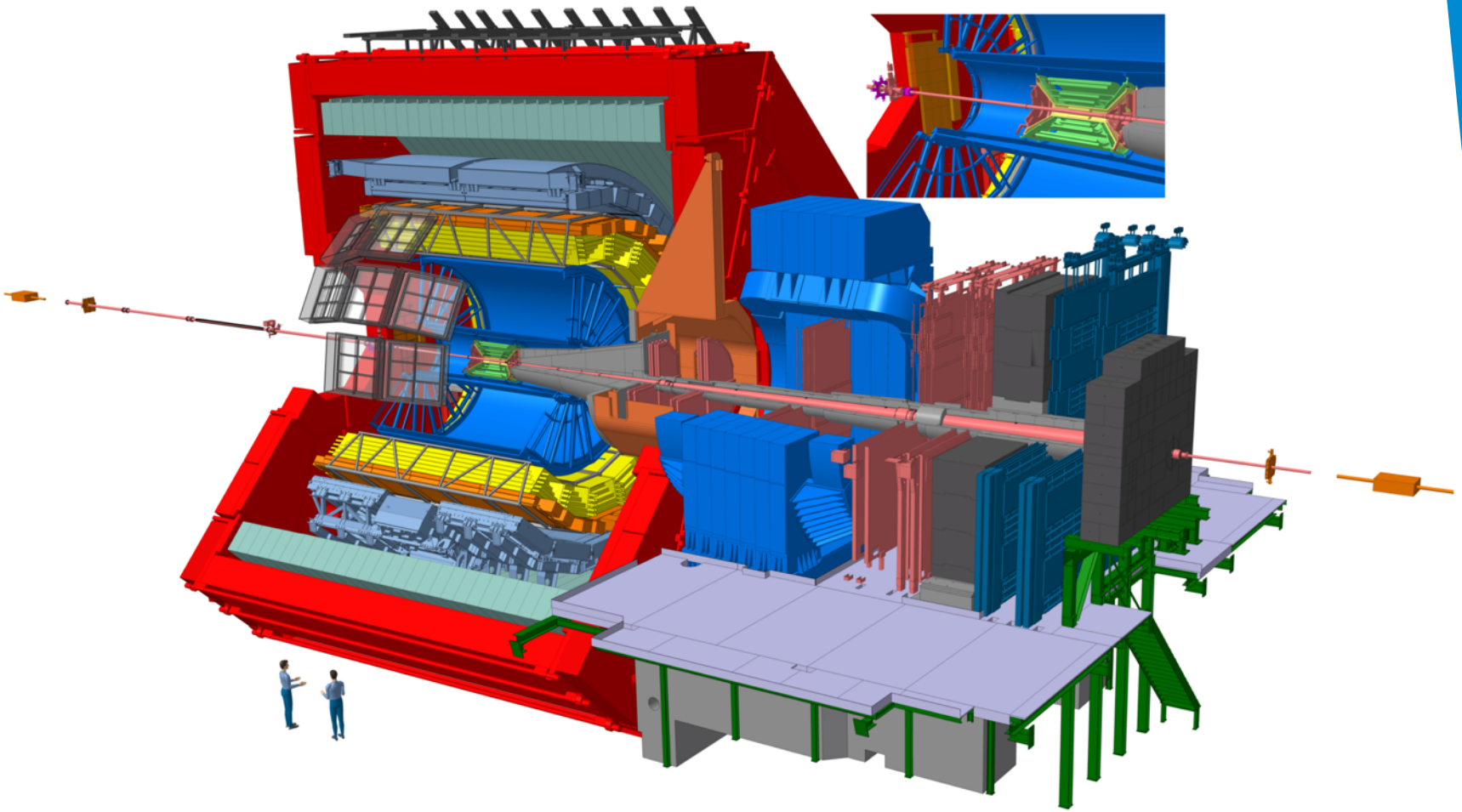
- **CMS: similar Λ_c/D^0 in Pb-Pb and pp at high p_T**
- **CMS** and **ALICE** agreement in pp and Pb-Pb (slightly different p_T and centrality ranges)





A Large Ion Collider Experiment (ALICE)

A dedicated heavy-ion experiment

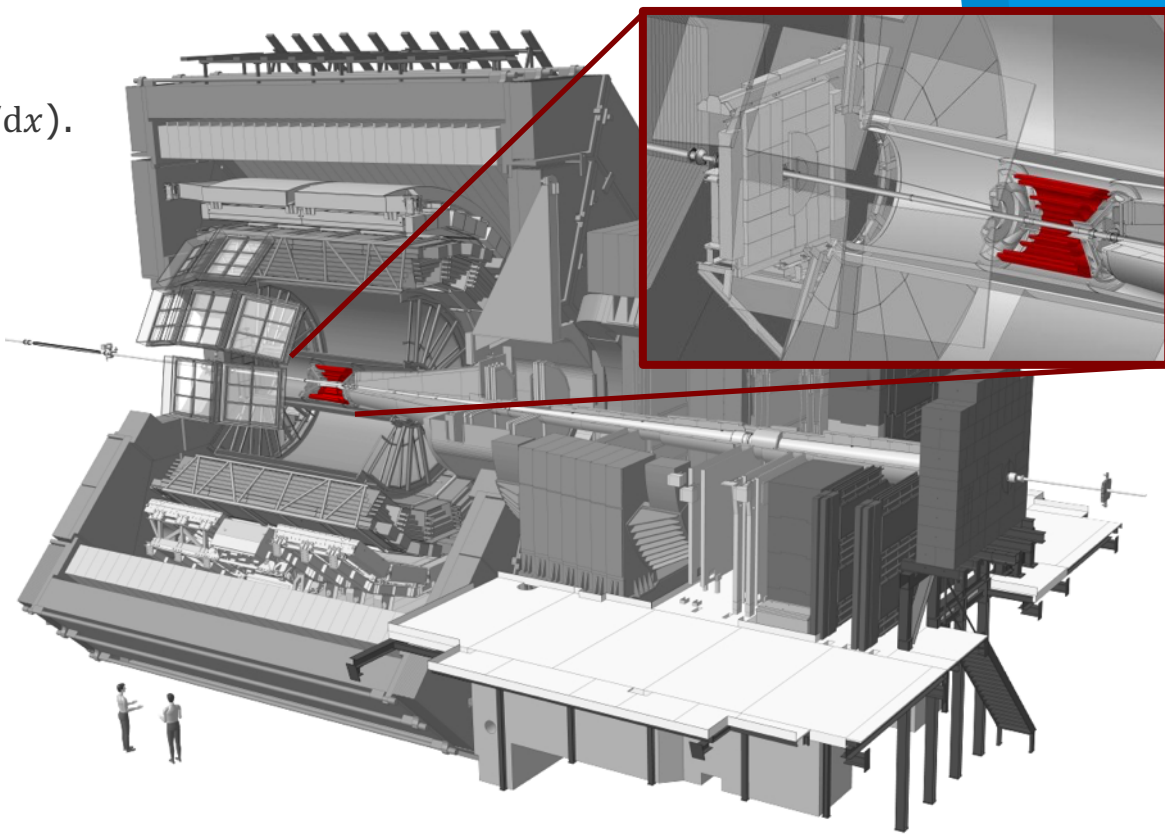


A Large Ion Collider Experiment (ALICE)

A dedicated heavy-ion experiment

Inner tracking system (ITS)

- Tracking, vertexing, and PID ($\mathrm{d}E/\mathrm{d}x$).
- $|\eta| < 0.9$



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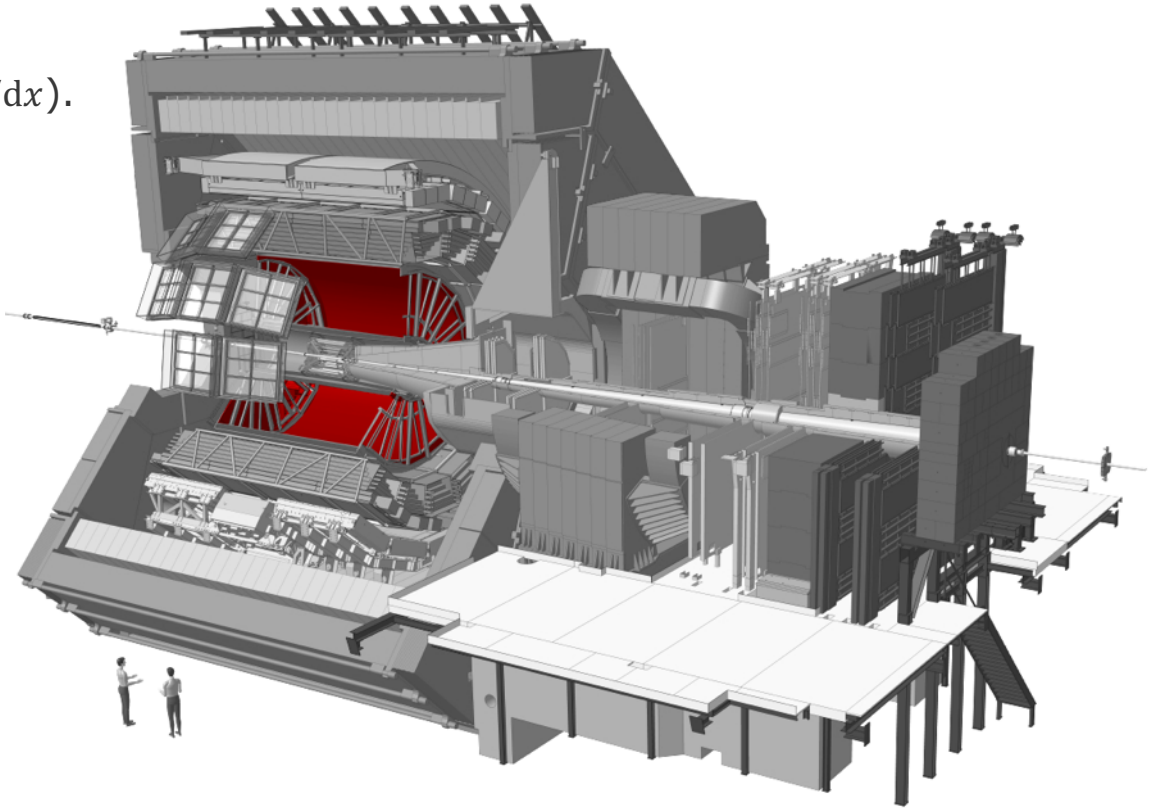

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- PID (time-of-flight).
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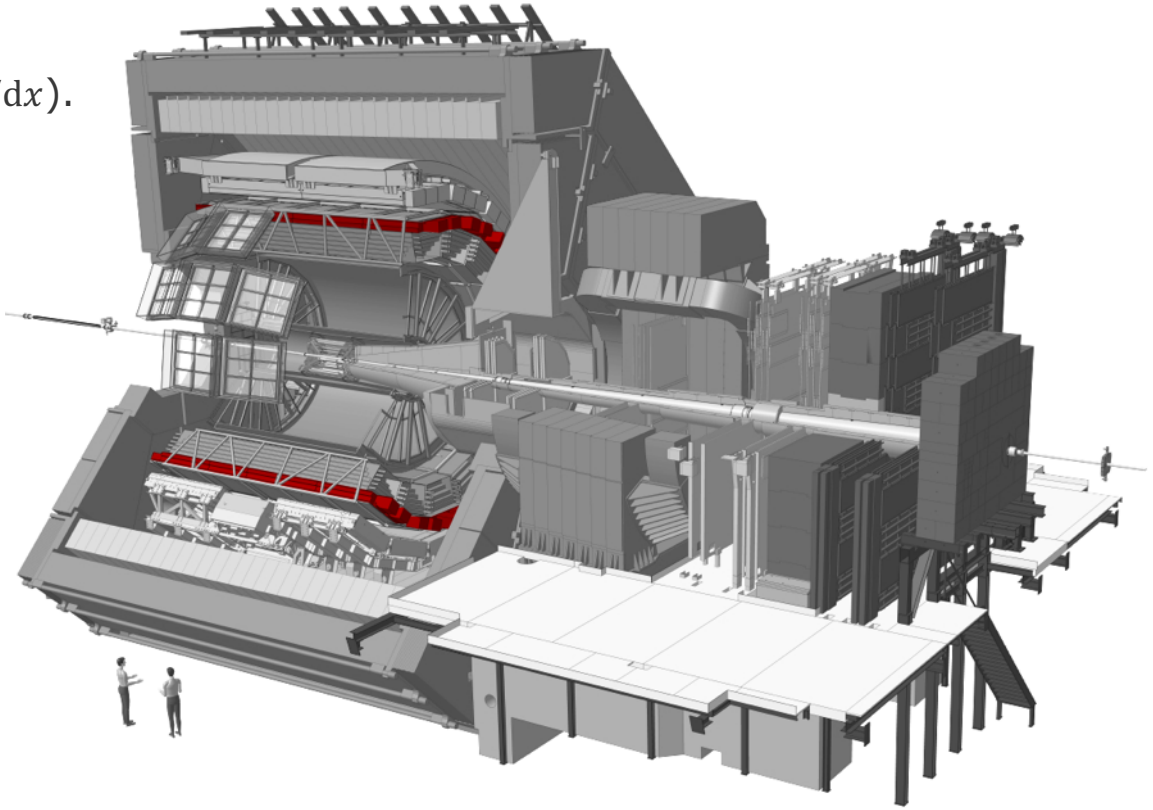

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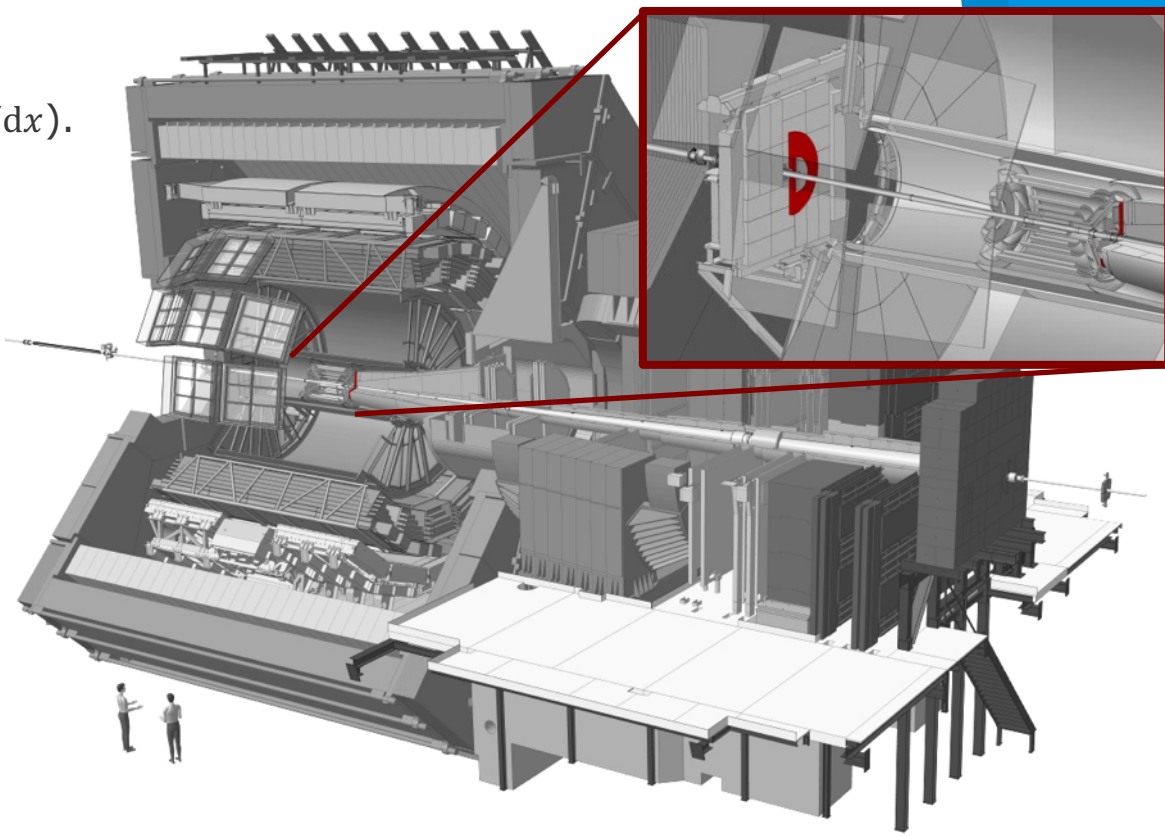
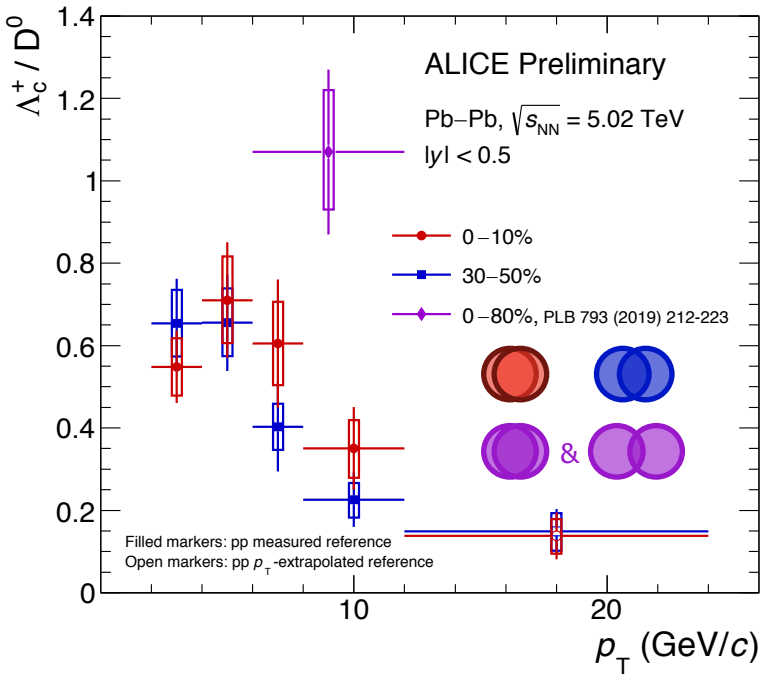
V0

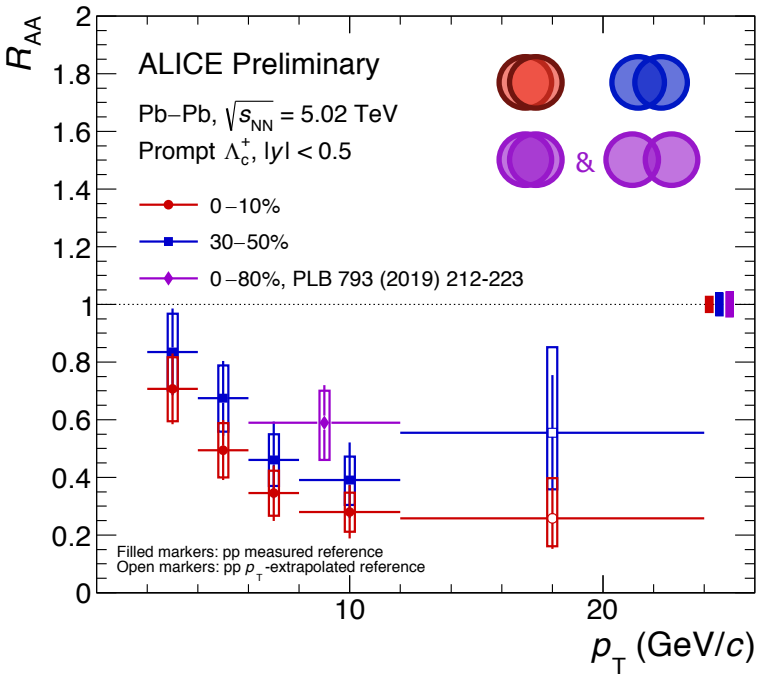
- Trigger, centrality, and event-plane estimation.



Λ_c^+ / D^0 and Λ_c^+ R_{AA} compared to Pb-Pb 2015 publication



ALI-PREL-321698



ALI-PREL-321868

- Λ_c^+ / D^0: ~1.9σ (0-10%) and ~2.8σ (30-50%) difference between 2015 and 2018.
- R_{AA}: ~1.2σ (0-10%) and ~0.6σ (30-50%) difference between 2015 and 2018.

NB1: For sigma calculation 2018 p_T bins merged to 6-12 GeV/c.
NB2: 2015 analysed in a different centrality range.

Λ_c^+ / D^0 in pp collisions

Preliminary at **5 TeV** compatible with published measurement at **7 TeV**.

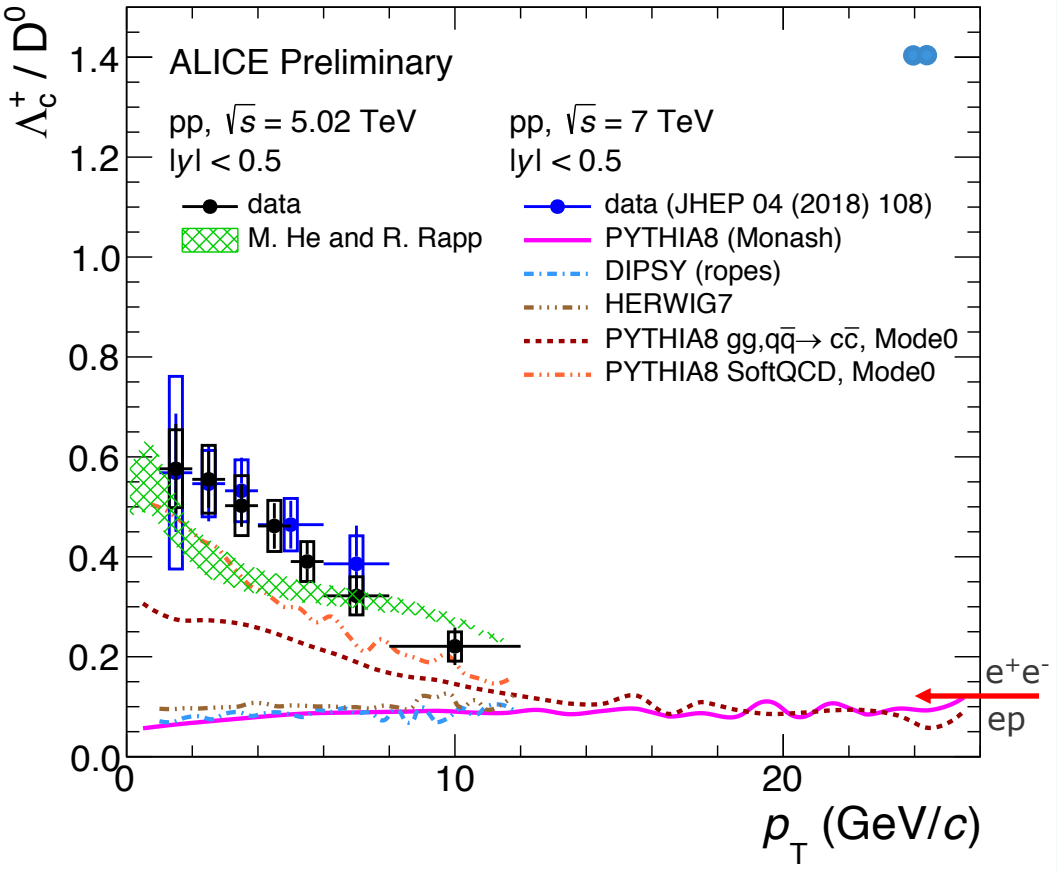
- Higher than previous measurements in ee and ep collisions at lower centre-of-mass energies (~0.12).

Theory predictions (from JHEP 04 (2018) 108) underpredict the measurement:

- Event generators **PYTHIA8**, **DIPSY**, and **HERWIG7** significantly too low.
- **PYTHIA8** with enhanced colour reconnection Mode0 increases the ratio and catches the p_T trend.
- New: **PYTHIA8** Mode0 using SoftQCD doing an even better job.

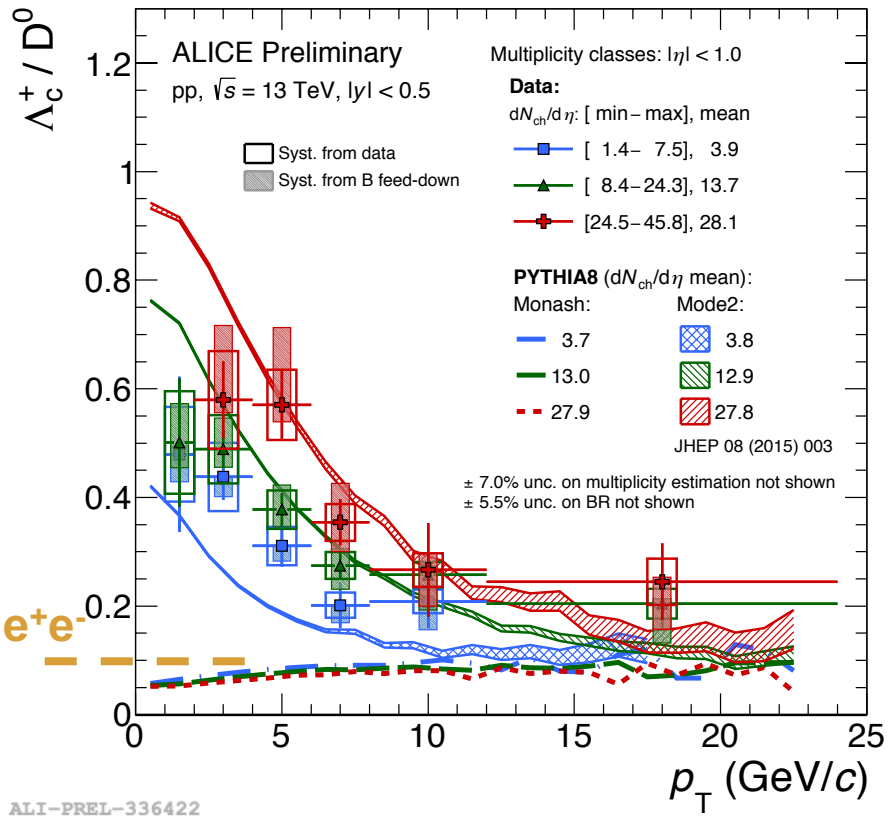
New: Prediction from **M. He & R. Rapp**:

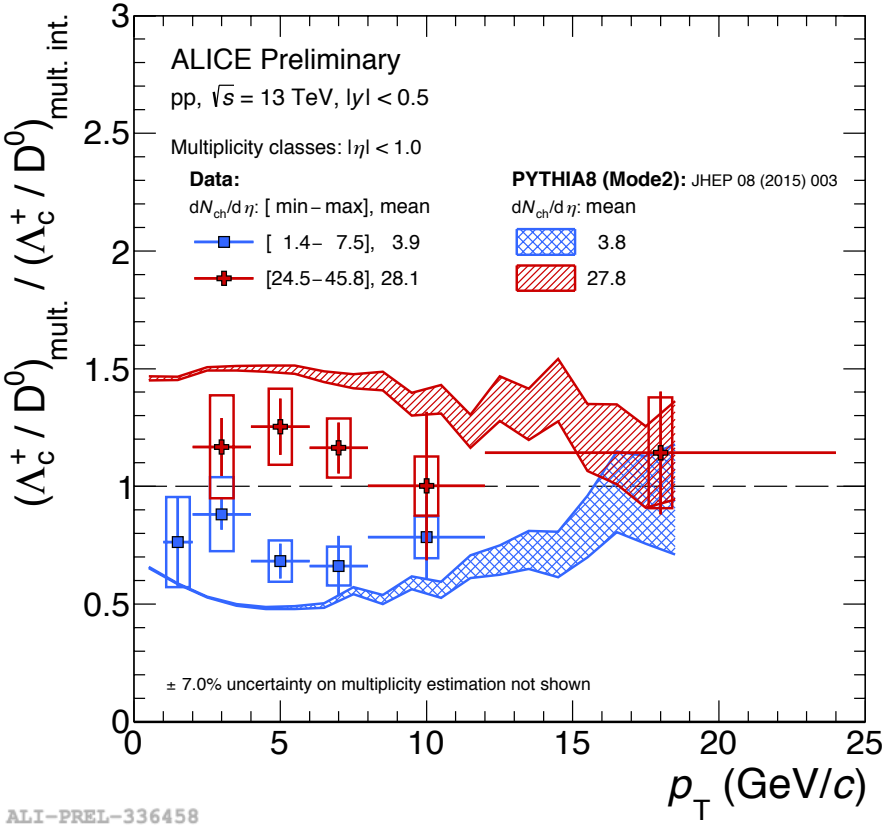
- Statistical hadronisation model, taking into account an increased set of charm-baryon states.
- Moving from 0.22 (std PDG) to 0.57, becoming compatible with ALICE data.



[1] PYTHIA8: Eur. Phys. J. C (2014) 74:3024
[2] DIPSY: JHEP 08 (2011) 103
[3] HERWIG7: Eur. Phys. J. C58 (2008) 639-707
[4] PYTHIA8 CR: JHEP 08 (2015) 003
[5] He & Rapp: 1902.08889

Λ_c^+ / D^0 in pp collisions versus multiplicity





Largely underestimated when comparing to the default PYTHIA8 tune (Monash).

Good agreement when colour-reconnection processes are included between partons created in different MPI's (Mode2).

- **Alternative description, doesn't require a QGP-like medium in pp.**

Baryon-to-meson ratio (Λ_c^+ / D^0) in ee and ep collisions

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55	
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55	
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2	
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	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 [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert\eta\rvert < 1.6$