Latest results on D_s^+ and Λ_c^+ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE at the LHC

STRANGENESS in QUARK MATTER, 11 JUNE 2019, BARI, ITALY

CHIARA ZAMPOLLI(*) for the ALICE COLLABORATION

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Outline

Introduction

The ALICE detector

Strange D meson and open charm baryon reconstruction

Results on D_s^+

Results on Λ_c^+

Summary and conclusions

For more details and information, see also:

- *Measurement of non-strange D-meson production and azimuthal anisotropy in Pb-Pb collisions with ALICE at the LHC*, S. Jaelani, Tue 11.06, 16:10, Heavy Flavour session
- *Measurement of D_s^+-meson production in Pb-Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV with ALICE at the LHC*, F. Catalano, Tue 11.06, 19:00, POSTER session
- *Measurement of D^0-meson R_{AA} and v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE*, S. Trogolo, Tue 11.06, 19:00, POSTER session
- *Measurement of the Λ_c^+ production in pp, p-Pb, and Pb-Pb collisions with ALICE Run-2 data*, L. Vermunt, Tue 11.06, 19:00, POSTER session

Motivations and previous results

High mass ($m_c \cong 1.3$ GeV, $m_b \cong 4.2$ GeV) → heavy-flavour quarks are produced in hard-partonic scattering processes during the initial stages of the collisions, before the creation of the QGP.

- $\tau_{prod} \approx 1/(2m_q) \approx 0.1_{q=c}$ $(0.03_{q=b})$ fm/c $\ll \tau_{QGP} \approx$ 0.3-1.5 fm/c at LHC.
  - They interact with the medium and experience the whole evolution of the system.
    - Energy loss, production mechanisms may depend on the interactions with the medium.

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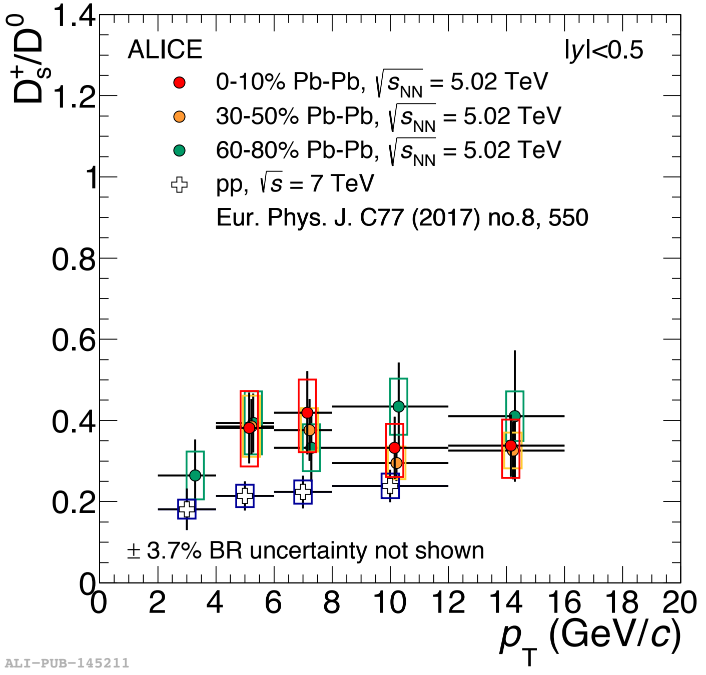
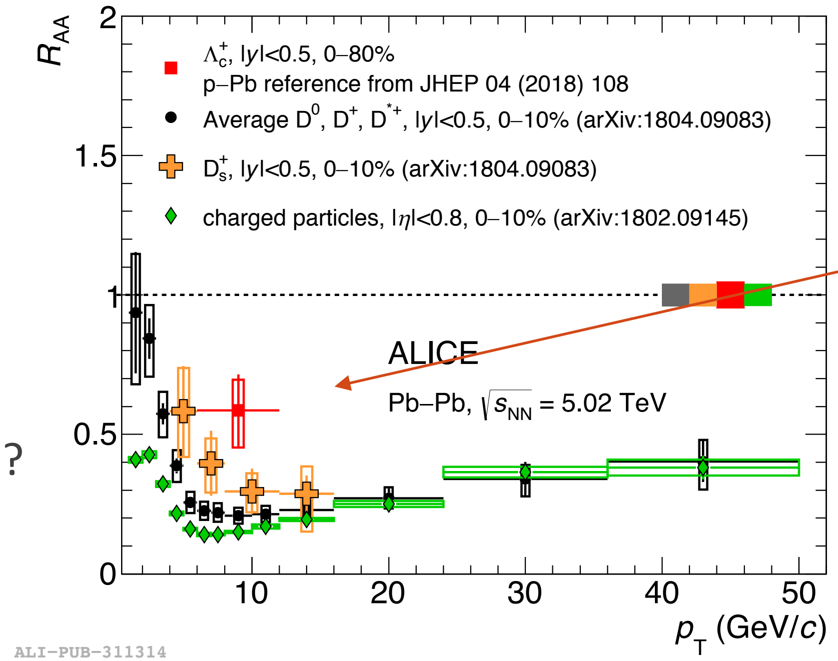
Strange to non-strange D mesons



JHEP 1810 (2018) 174

Strange D mesons produced more abundantly in the presence of the QGP?

Nuclear modification factor, $R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$



Phys.Lett. B793 (2019) 212-223

$\mathbf{D_s^+}$ less suppressed than non-strange **D** mesons?

$\mathbf{\Lambda_c^+}$ less suppressed than $\mathbf{D_s^+}$?

Hint of a hierarchy?

Recent CMS results on Λ_c^+ published in CMS PAS

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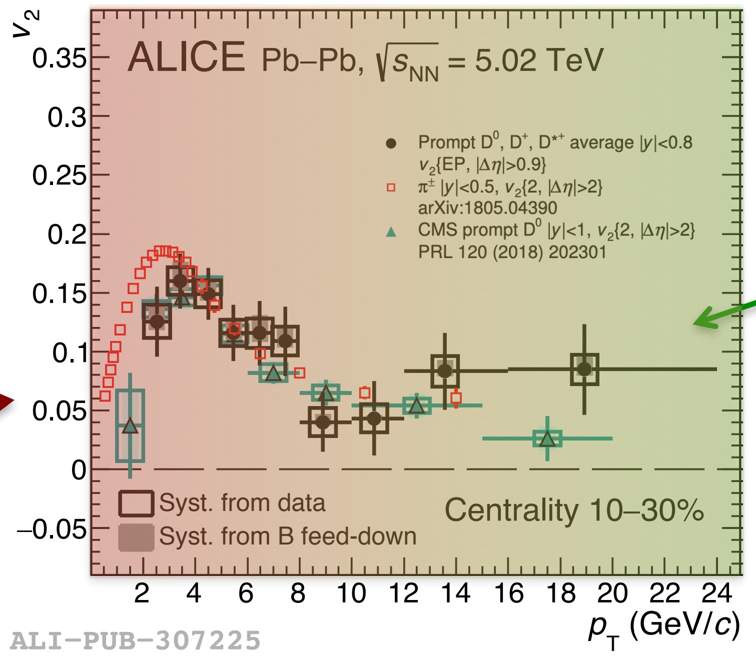
Elliptic flow,

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

Low p_T: Collective flow for charm and beauty. Coalescence as hadronization mechanism



arXiv:1809.09371

Cartoon, for illustration only

High p_T: Information on the path-length dependence of the heavy-quark **energy loss**

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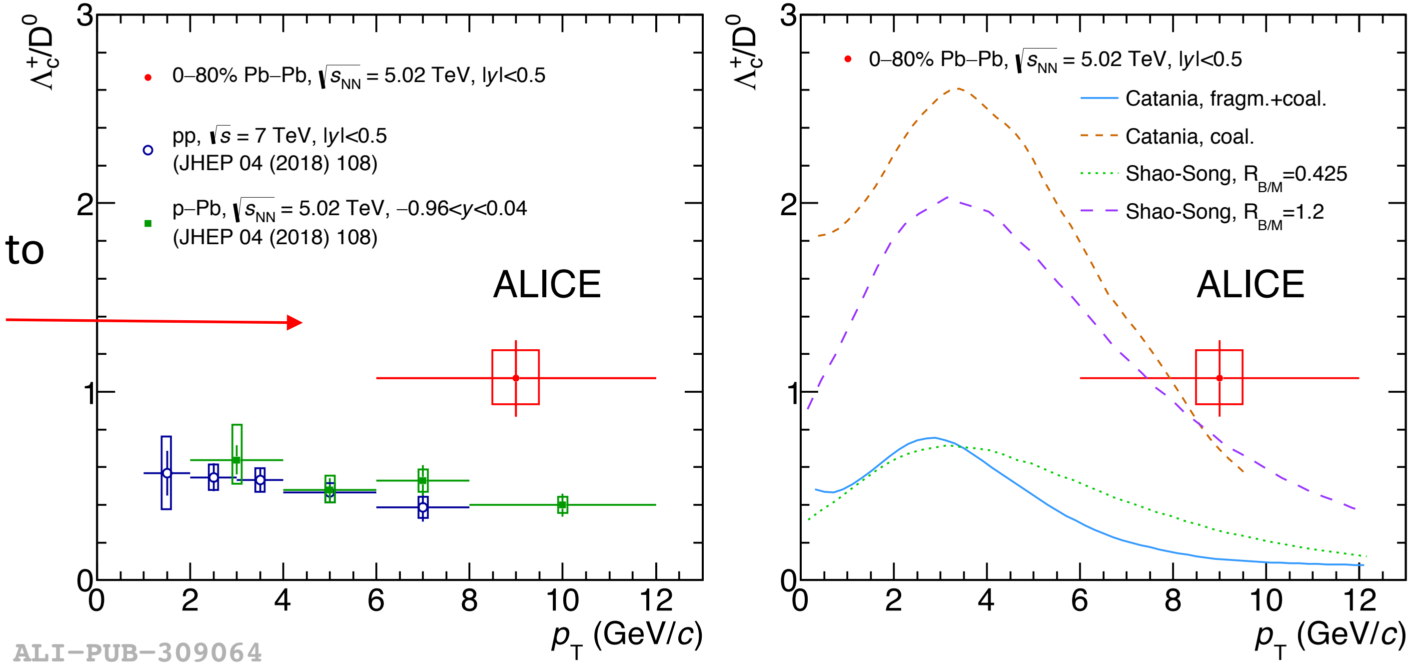
Baryon to meson ratio

Enhancement with respect to pp due to coalescence?



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Strange open-charm mesons (D_s^+) and open-charm baryons (Λ_c^+) are a major tool to study the charm-quark hadronization mechanisms inside the QGP

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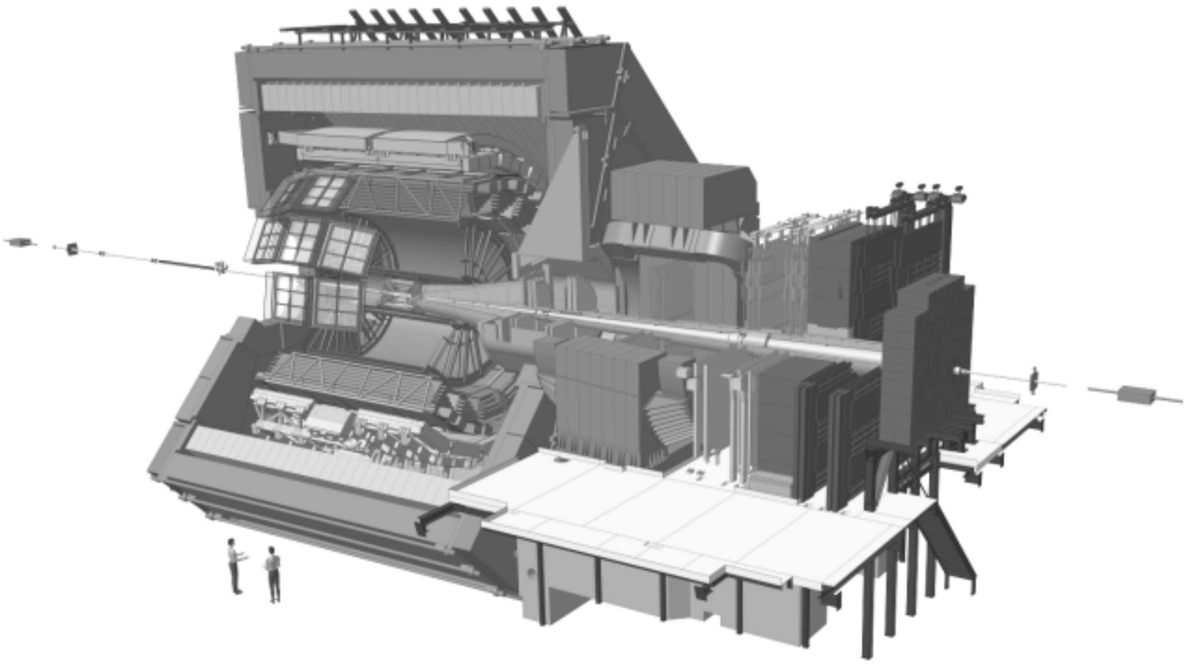
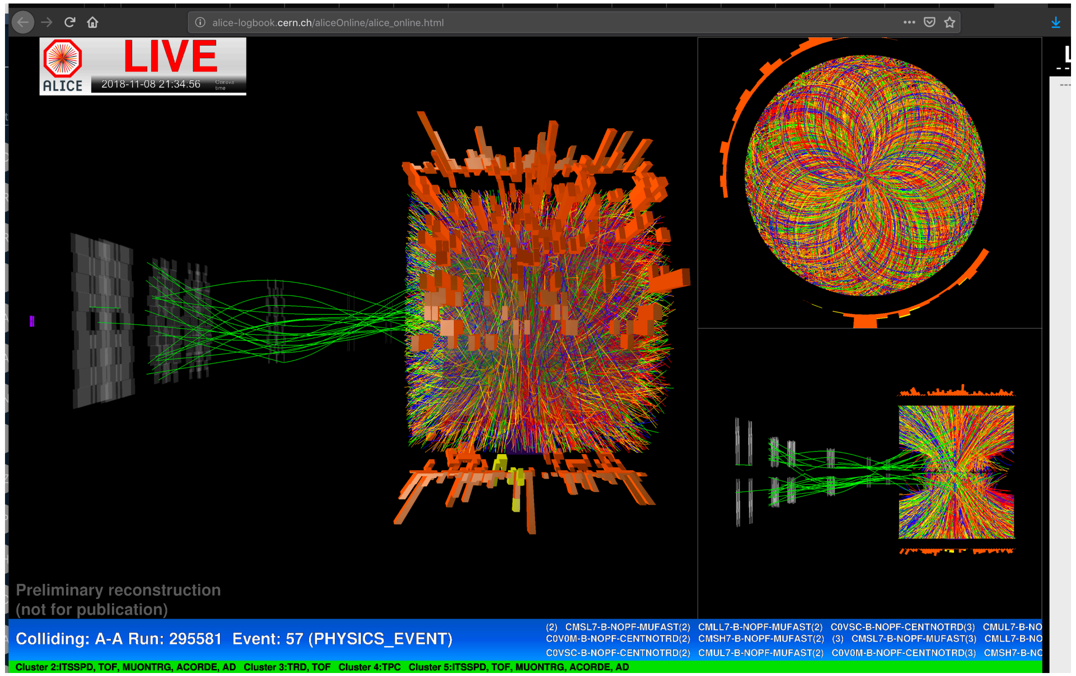
Results shown here will be based on the latest Run2 PbPb 2018 at $\sqrt{s_{NN}} = 5.02$ TeV data taking campaign, corresponding to $\mathcal{L} \approx 112.3$ μb^{-1} (0-10% central) and $\mathcal{L} \approx 49.0$ μb^{-1} (30-50% central)

- *More differential and more precise measurements*
- *Extended p_T range*

A Large Ion Collider Experiment

Dedicated Heavy Ion experiment





Online event display
(preliminary reconstruction)
on 08.11.2018

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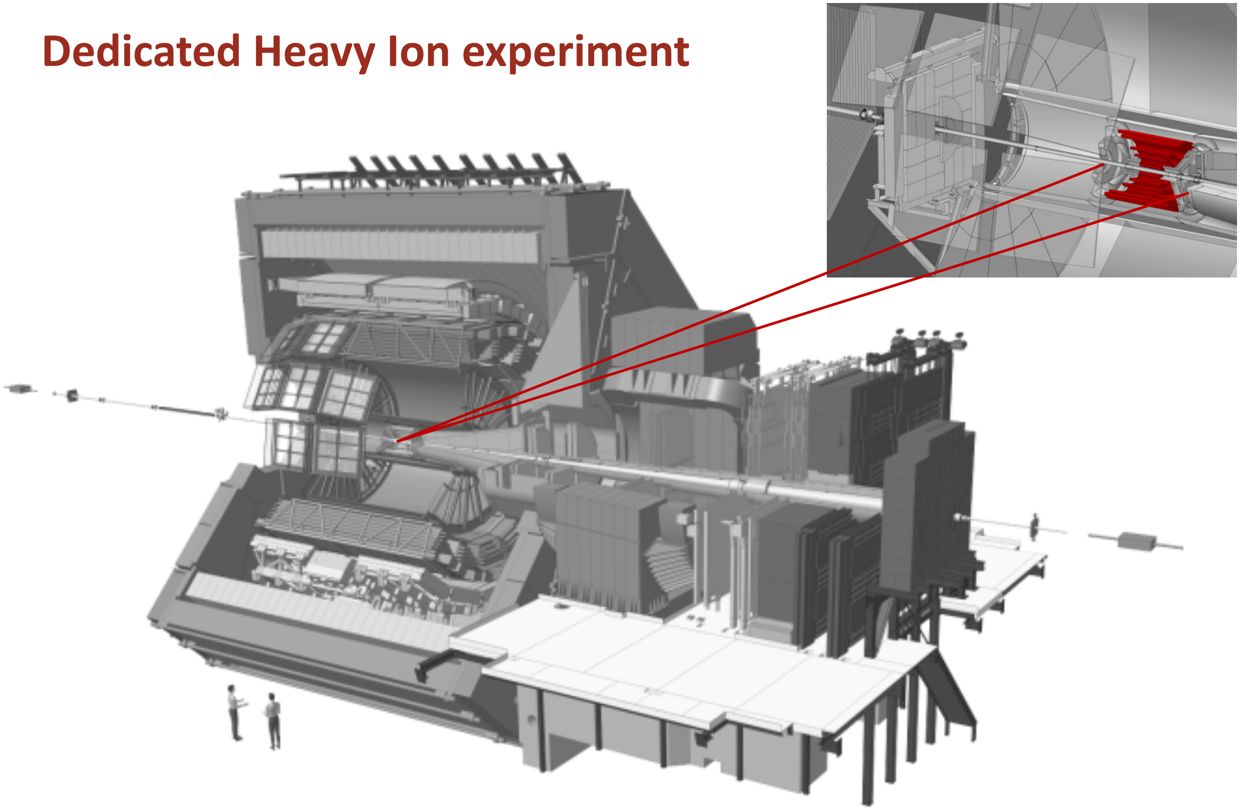

Inner Tracking System

- 6 layers, 3 technologies of silicon detectors.
- Reconstruction of primary and **secondary vertices**.
- Low-momentum tracking and hadron **P**article **ID**entification (dE/dx).

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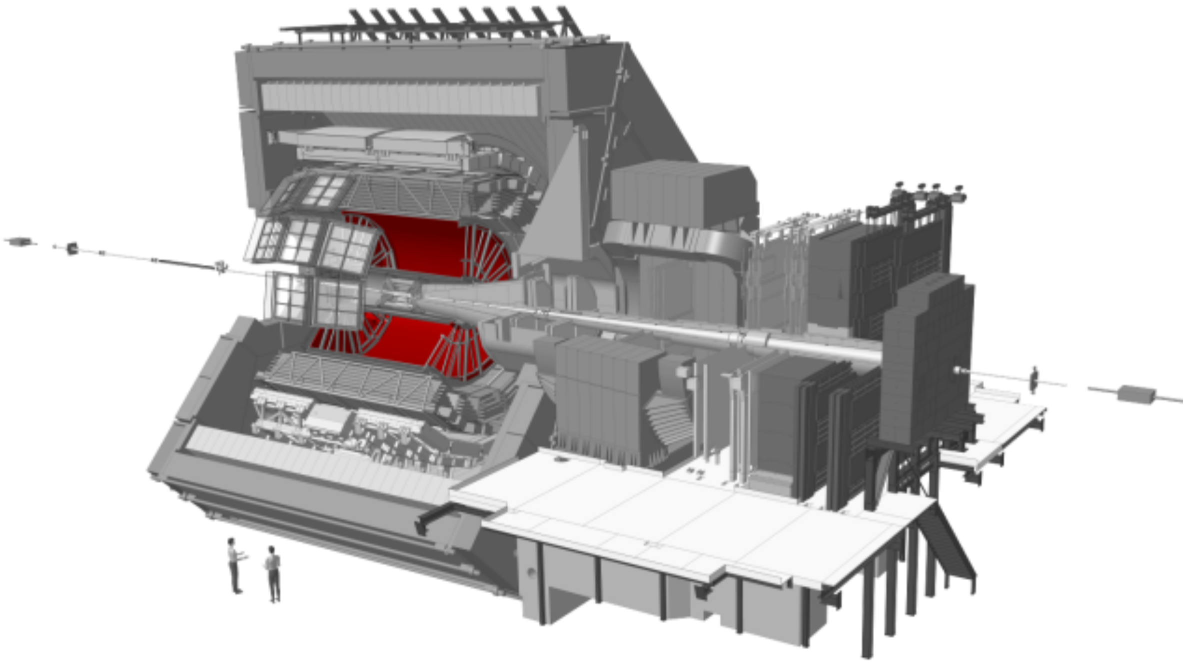

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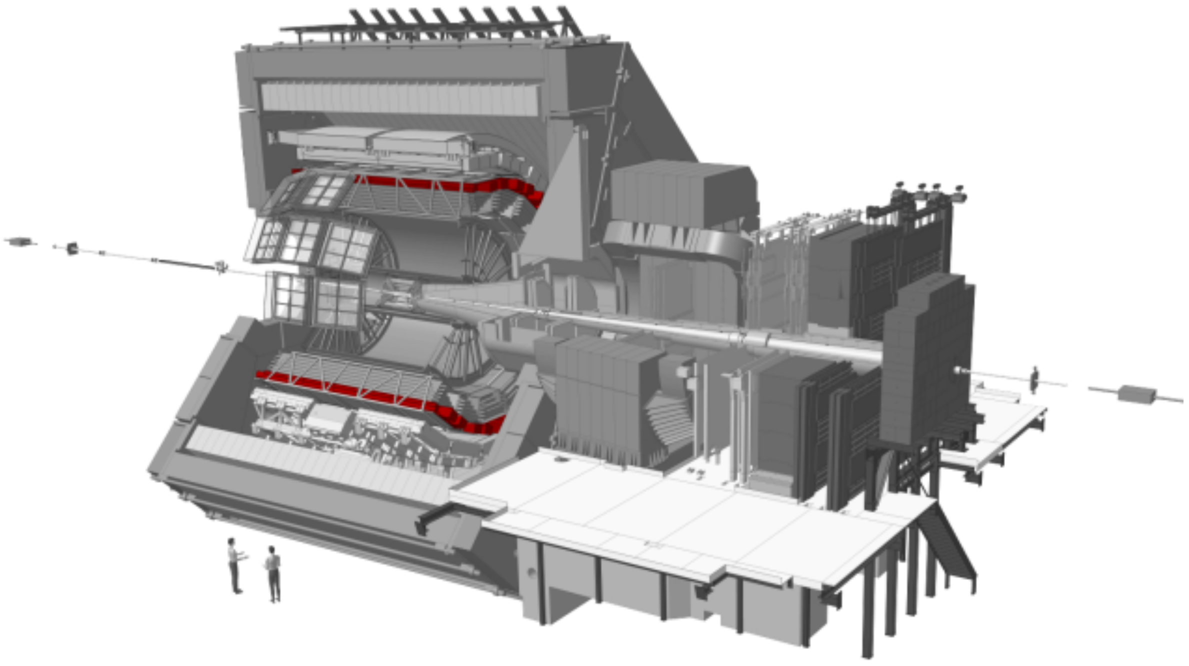
Time Projection Chamber

- MWPC.
- Tracking.
- **Hadron PID (dE/dx)**.

A Large **I**on **C**ollider **E**xperiment

Dedicated Heavy Ion experiment



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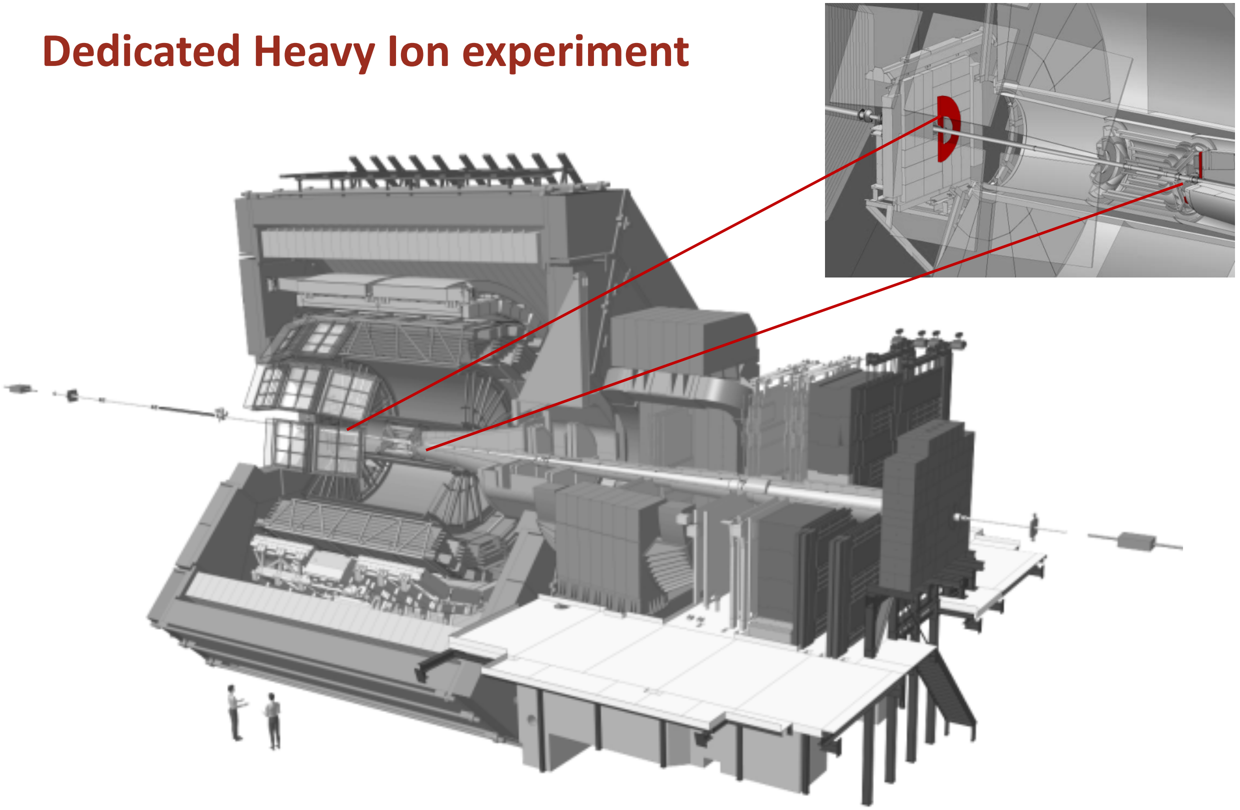
Time Of Flight
- MRPC.
- **Hadron PID (time of flight)**.

A Large Ion Collider Experiment

Dedicated Heavy Ion experiment



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Time Projection Chamber

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Time Of Flight

- MRPC.
- **Hadron PID (time of flight)**.

V0

- **Trigger (**MinBias and **centrality)**.

Reconstruction strategy

Reconstruction of D_s^+ and Λ_c^+

Invariant mass analysis of the decay topology.

- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ ($c\tau$ = 150 μm)
- $\Lambda_c^+ \rightarrow K^0_S p \rightarrow \pi^+\pi^- p$ ($c\tau$ = 60 μm)

Selections

- track reconstruction **quality**,
- on the displaced **topology** of the secondary vertex
- **geometrical** and **kinematical** properties of the decays

used to reduce the background contribution.

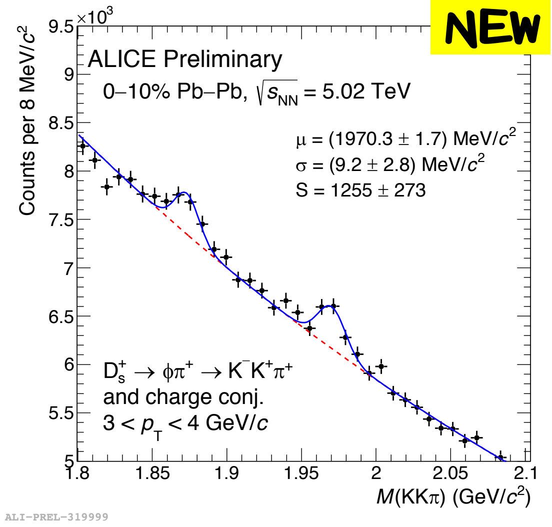
For the D_s^+:

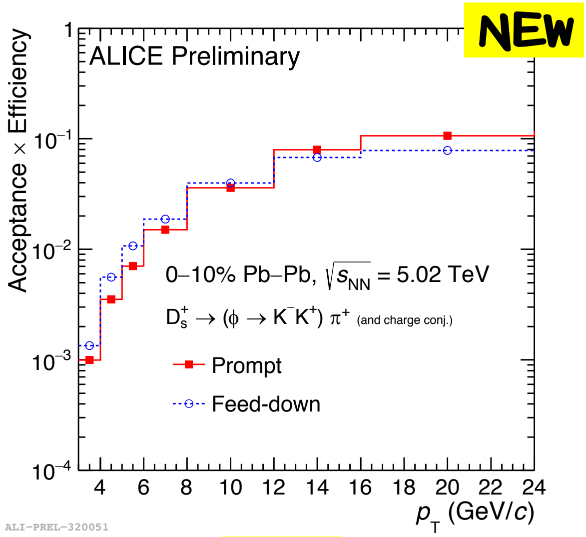
- **compatibility** between the invariant mass of the K^+K^- pair to the ϕ mass required.

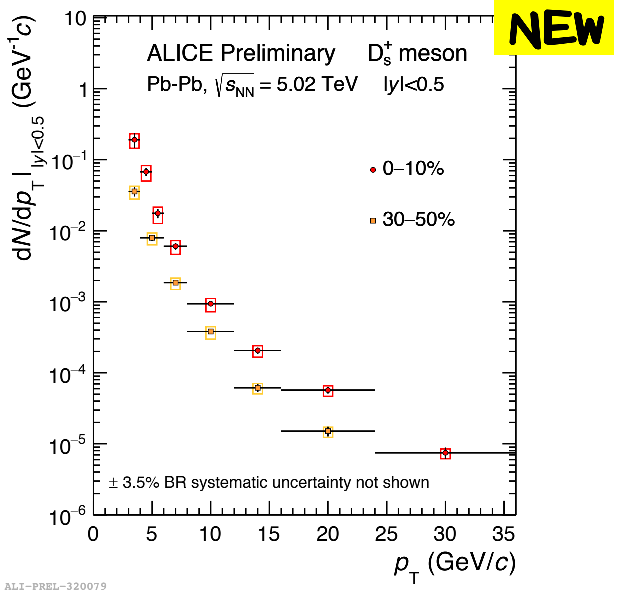
Hadron **Particle IDentification** from TPC and TOF applied using an n_σ selection

- $n_\sigma = (S_\alpha - \hat{S}(H_i)_\alpha)/\sigma^i_\alpha$.

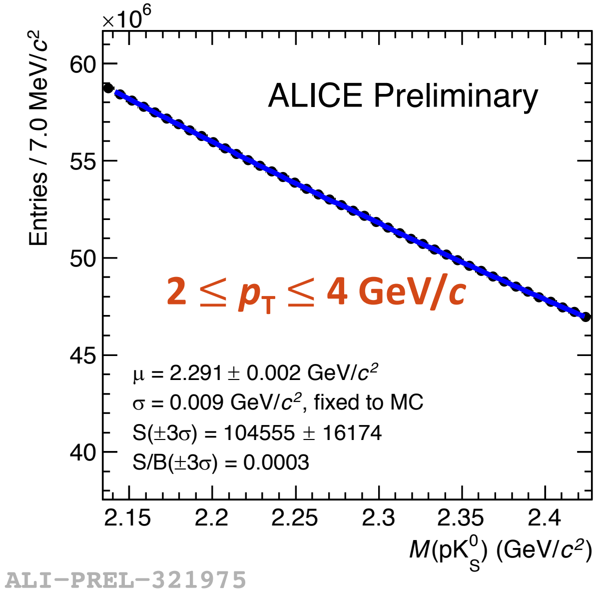
Feeddown from b-hadron decays subtracted using FONLL predictions.

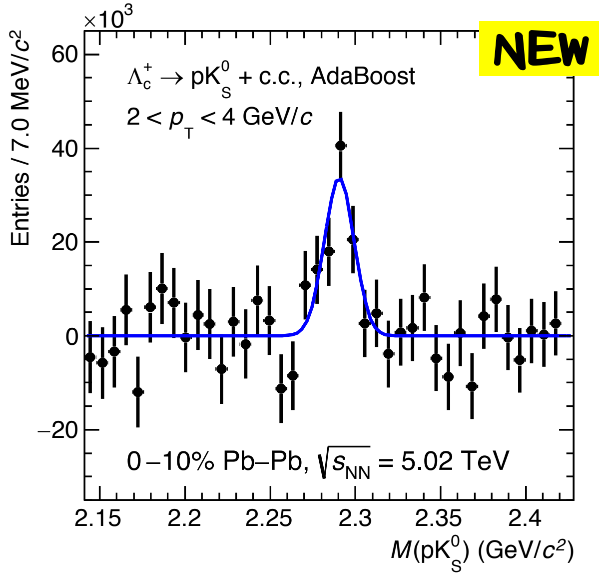






Reconstruction of D_s^+ and Λ_c^+





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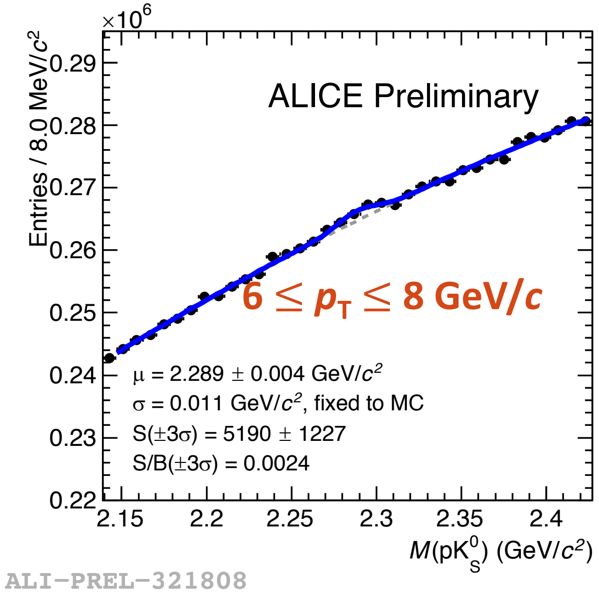
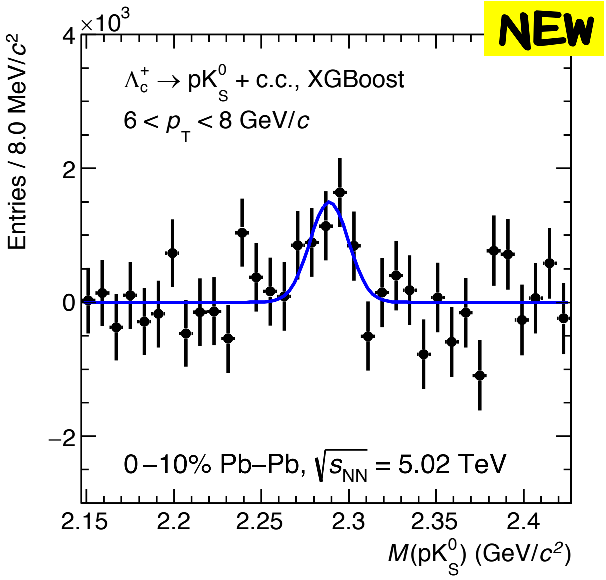




ALI-PREL-321808

NEW in PbPb

For the Λ_c^+, two different **machine-learning** algorithms were used to reduce the background:

- TMVA/Boosted Decision Trees (like for JHEP 04 (2018) 108) → *AdaBoost* in the following
- **New** MLHEP python package (more details in the backup) → *XGBoost* in the following

Topological, kinematical and PID training variables.

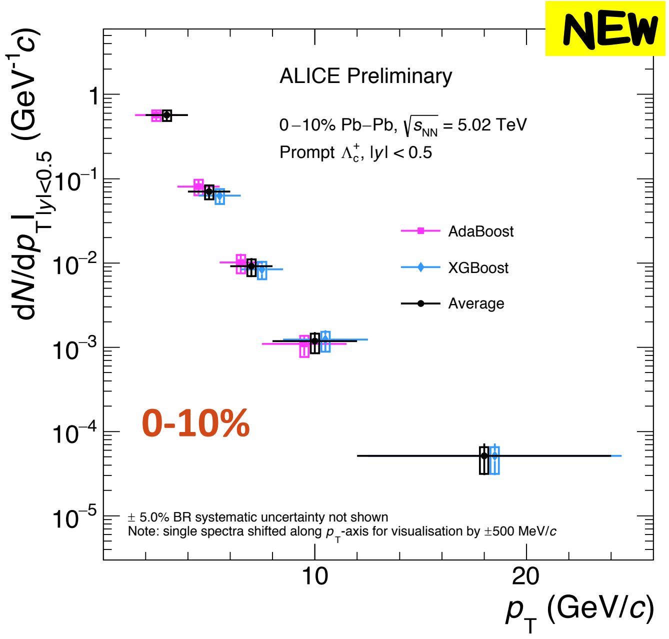
Background used for training taken from the side bands in data.

The invariant mass distribution was obtained after selecting on the ML algorithm response.

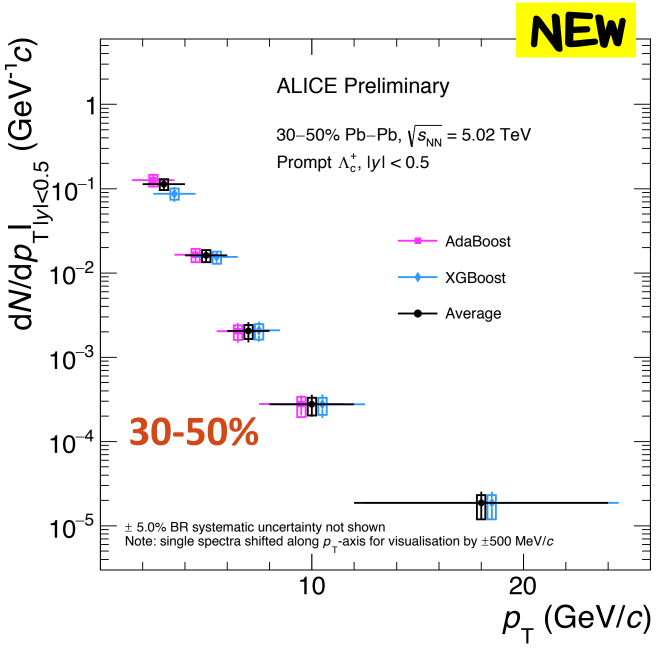
XGBoost under study also for D_s^+.

Reconstruction of D_s^+ and Λ_c^+

NEW in PbPb



ALI-PREL-321721



ALI-PREL-321729

Average result obtained by weighing the two results by the inverse of the sum in quadrature of the relative uncorrelated systematics (i.e. yield extraction).

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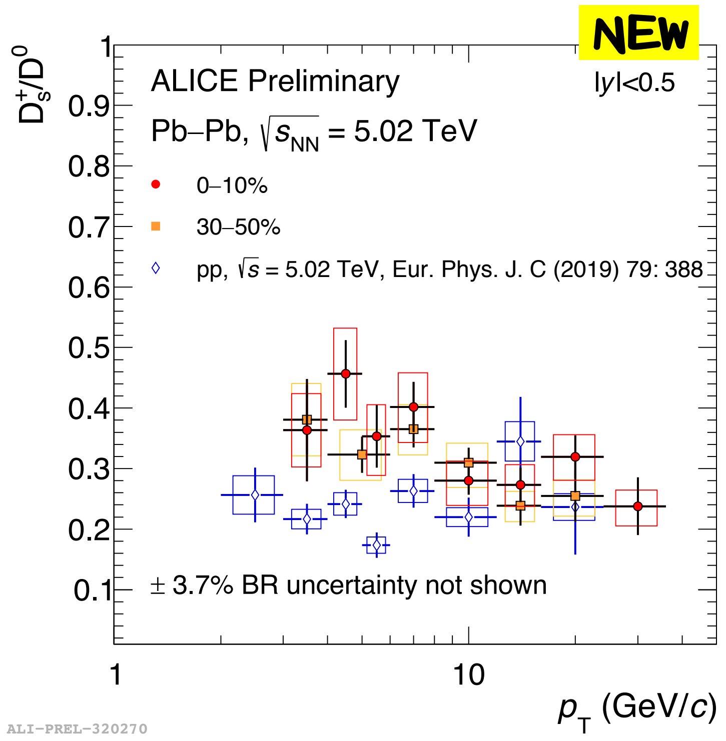
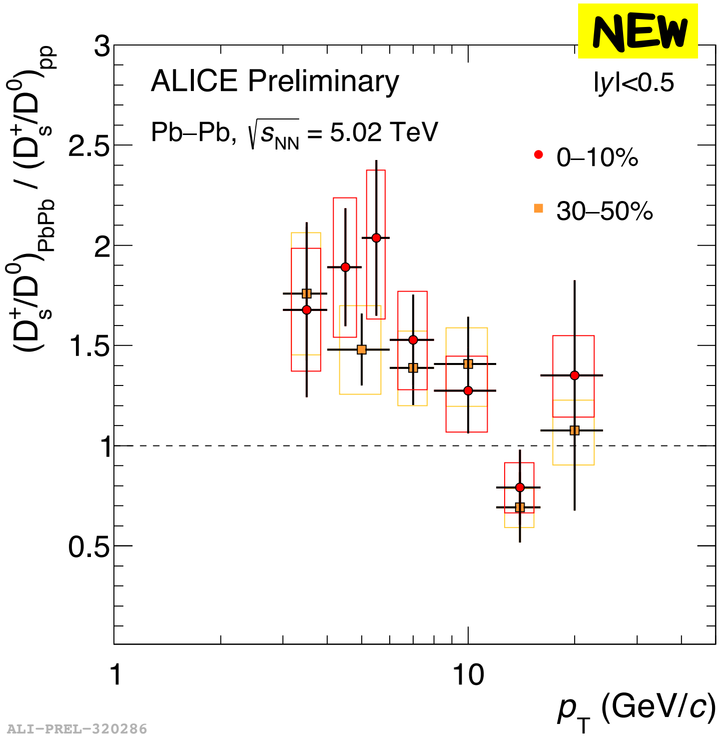
XGBoost under study also for D_s^+.

Results on D_s^+

Strange/non-strange charmed mesons



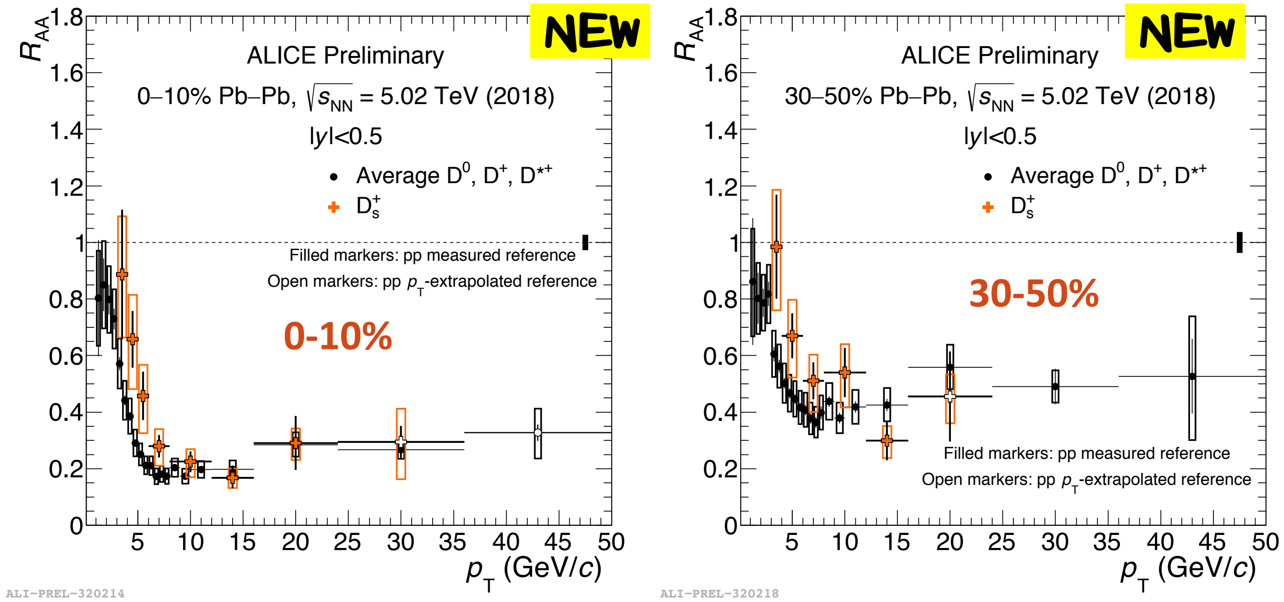


For both centralities, a hint of a higher D_s^+/D^0 ratio in Pb-Pb collisions than in pp collisions up to p_T = 6 GeV/c.

Behaviour in Pb-Pb compatible with the one in pp for higher transverse momentum.

Large uncertainties prevent from drawing strong conclusions.

D_s^+ R_{AA}



Similar patter of **strange** and **non-strange** charmed mesons, steeper and with stronger suppression in central collisions (up to 2x from $p_T \approx 5$ GeV/c).

R_{AA} of **strange**-charmed mesons higher than the one of **non-strange**-charmed mesons → enhancement of strangeness as expected in the QGP.

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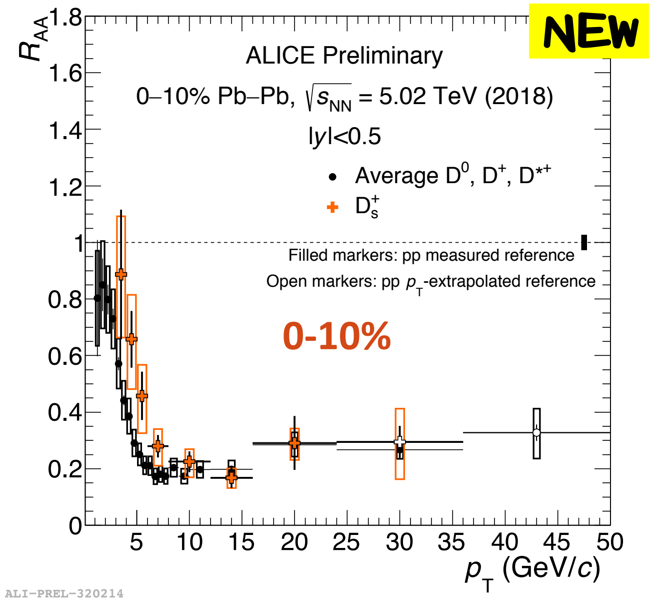

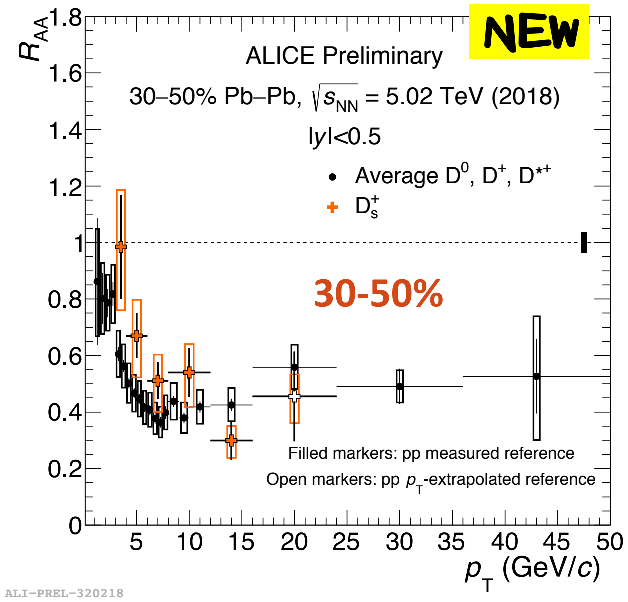

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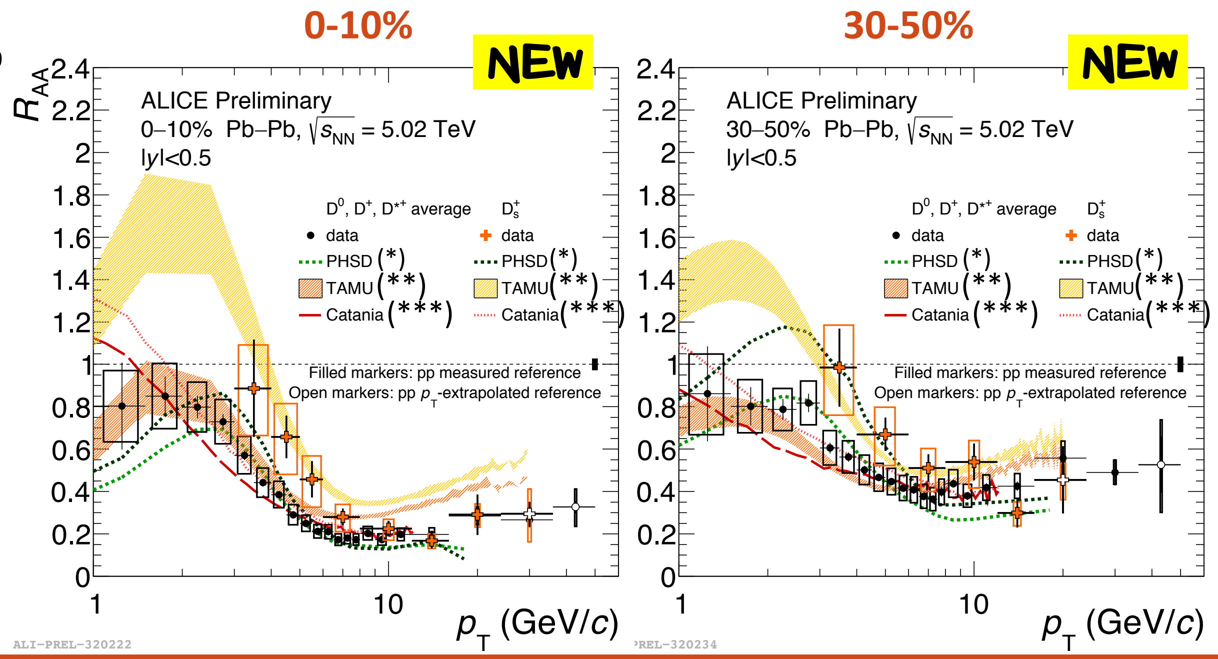
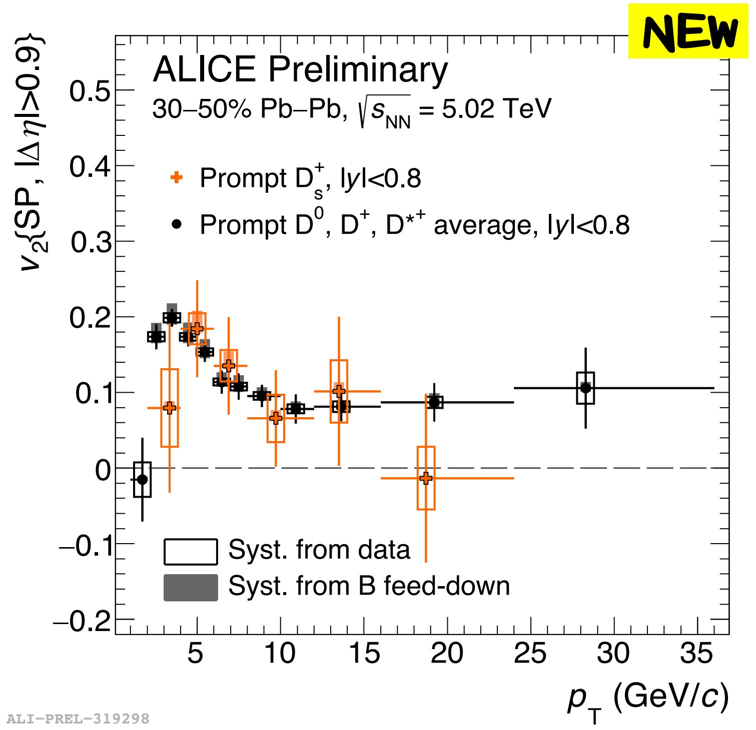


Comparison of R_{AA} of **strange**-charmed mesons to theoretical models of charm-quark transport in a hydrodynamically expanding medium.

The three models predict an increase of the D_s^+ with respect to **non-strange**-charmed mesons especially for $p_T < 5$ GeV/c.

(*) Phys. Rev. C 93, 034906 (2016)
(**) Phys. Lett. B 735, 445 (2014)
(***) Eur. Phys. J. C (2018) 78: 348

v_2 measurement



Similar v_2 magnitude for **strange** and **non-strange** D mesons, but large uncertainties.

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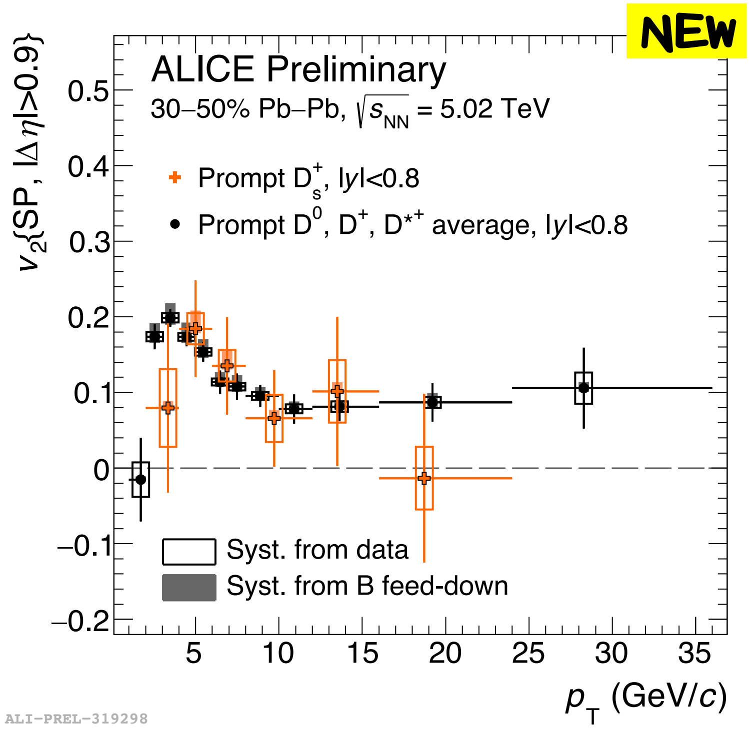

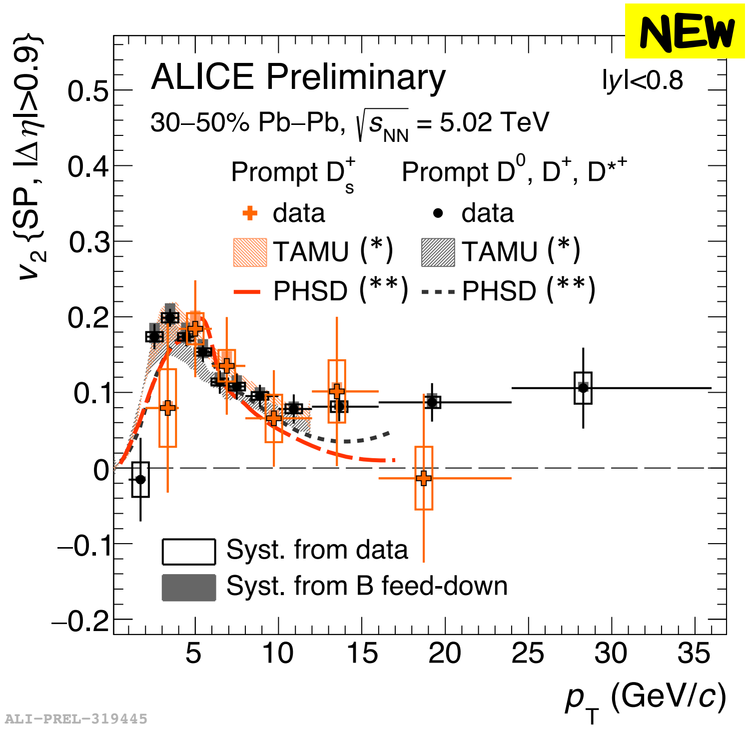

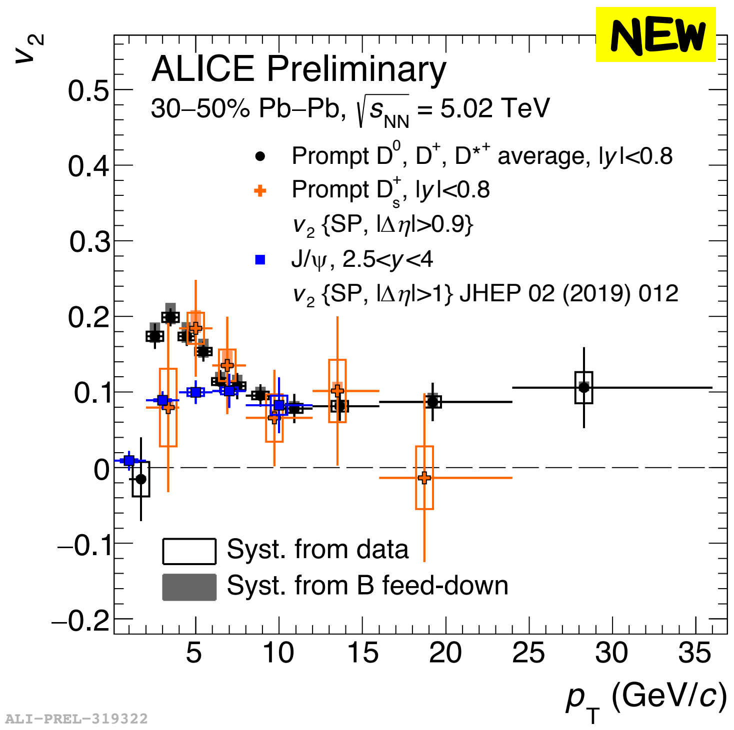

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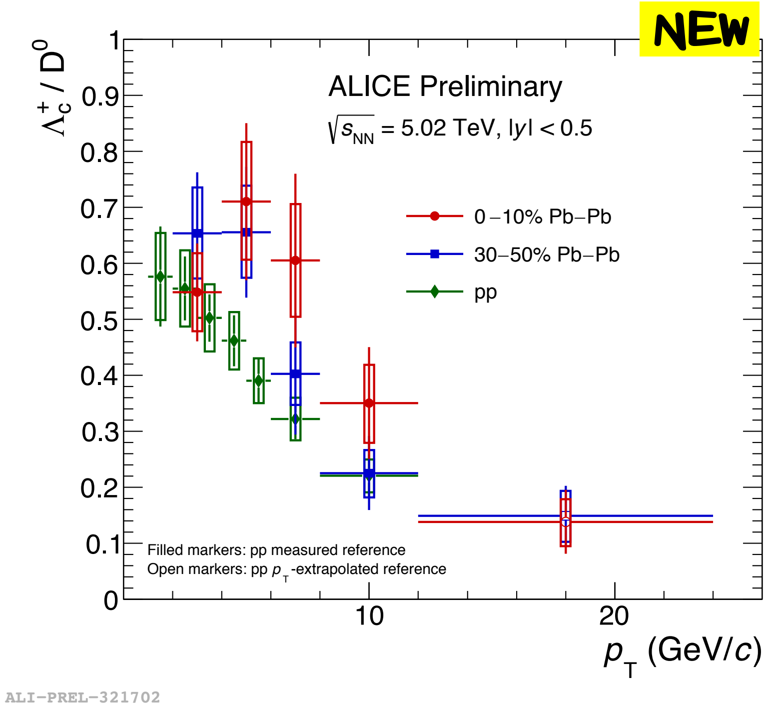
Hadronization via quark recombination included in both TAMU and PHSD models. Both show a good agreement with data.

Higher v_2 for **open charm** than **quarkonia**. Comparison to **strange D** mesons more difficult due to large uncertainties.

(*)Phys. Lett. B 735, 445 (2014)
(**) Phys. Rev. C 93, 034906 (2016)

Results on Λ_c^+

Baryon to meson ratio: Λ_c^+/D^0



Central collisions show a higher ratio than peripheral collisions, with a hint of decrease in the ratio at low p_T, but the uncertainties are large to draw a firm conclusion.

Hint to a higher Λ_c^+/D^0 in Pb-Pb collisions than in **pp** (especially at intermediate p_T).

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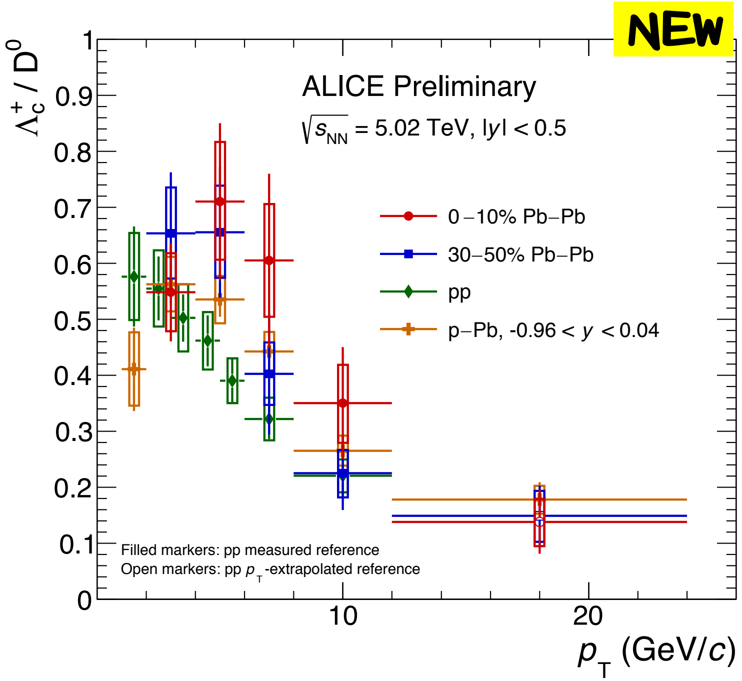

ALI−PREL−321706

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Same behaviour with respect to **p-Pb**.

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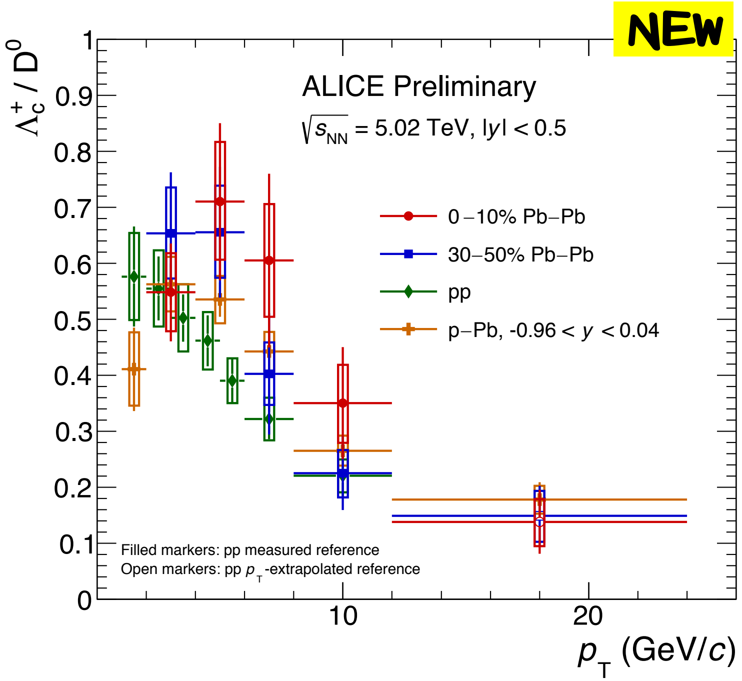
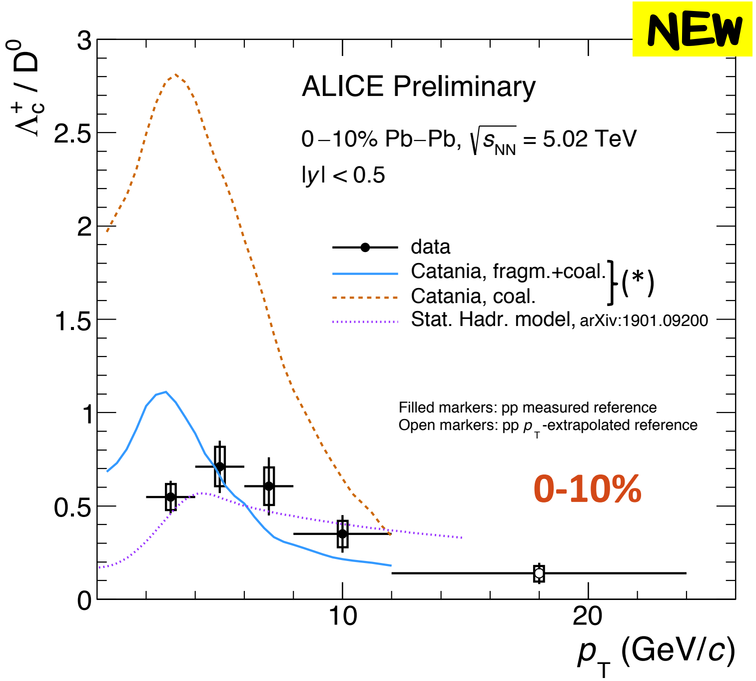
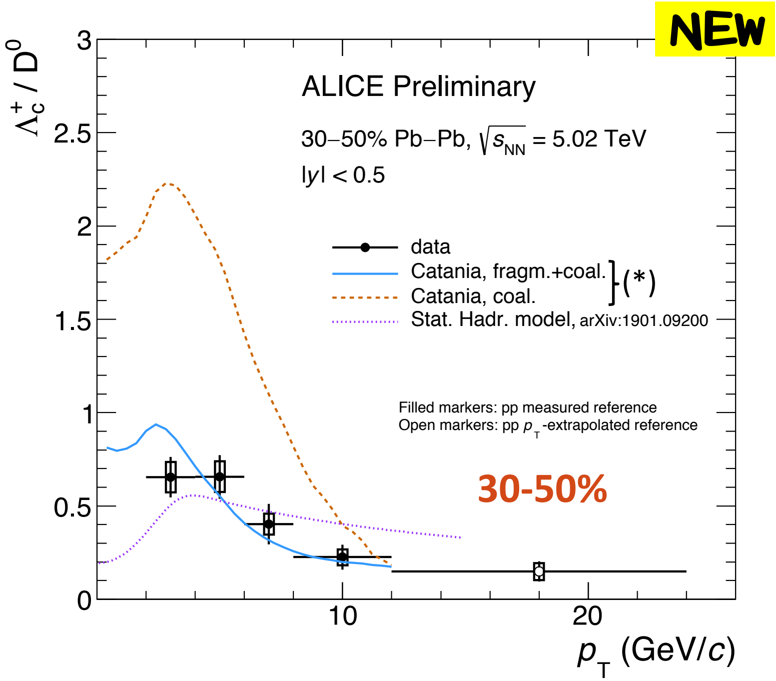


ALI-PREL-321706



ALI-PREL-321682



ALI-PREL-321686

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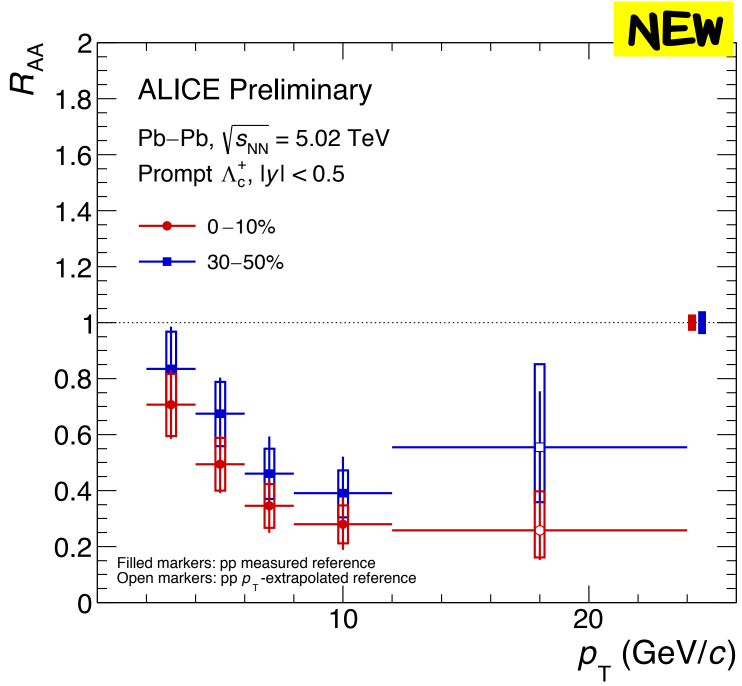
Hint to a higher Λ_c^+/D^0 in Pb-Pb collisions than in **pp** (especially at intermediate p_T).
Same behaviour with respect to **p-Pb**.

Comparison to Catania theory favours a scenario where both coalescence and fragmentation are present, for both centrality ranges.
Good agreement with statistical hadronization model.

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

Λ_c^+ R_{AA}



Despite compatibility within uncertainties, hint to a nuclear modification factor smaller for central collisions by ~1.5x up to p_T = 12 GeV/c.

Agreement within ~2σ with results from 2015 Pb-Pb data (PLB793 (2019) 212-223, see backup), but different centralities

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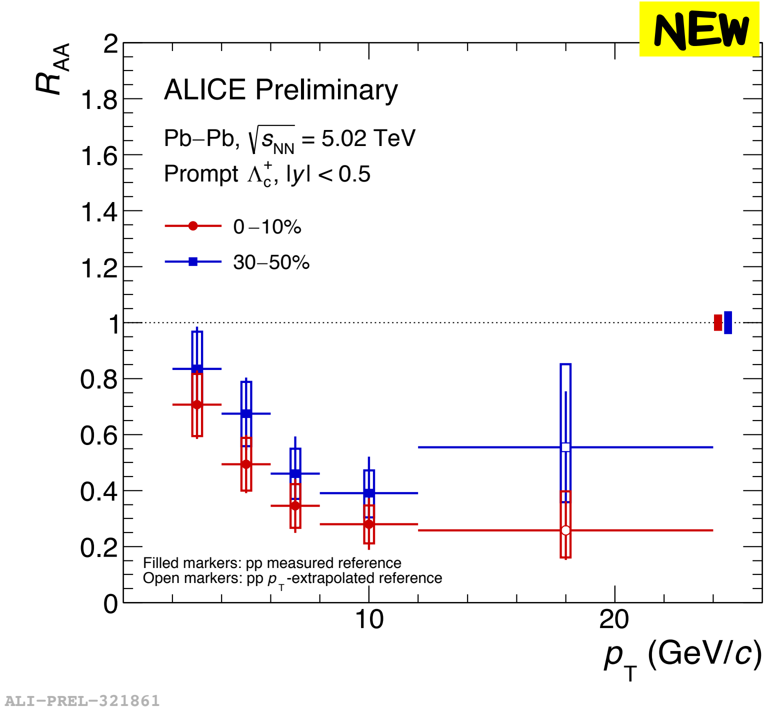

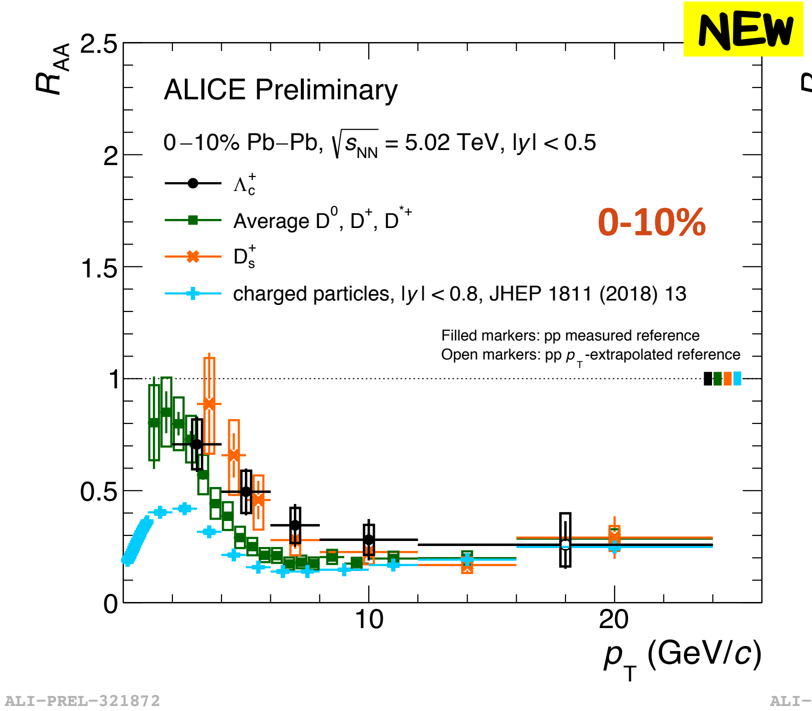

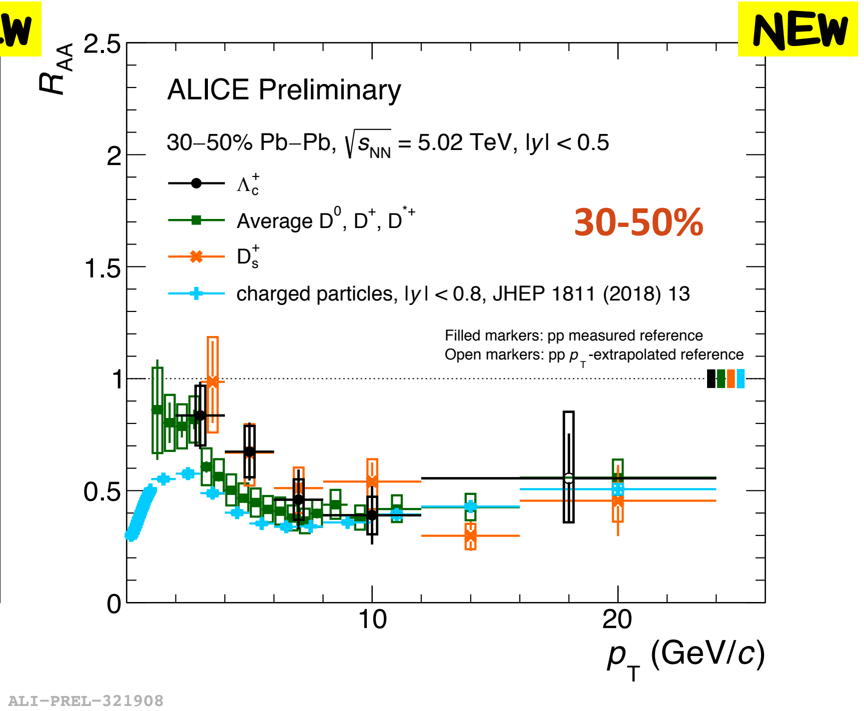

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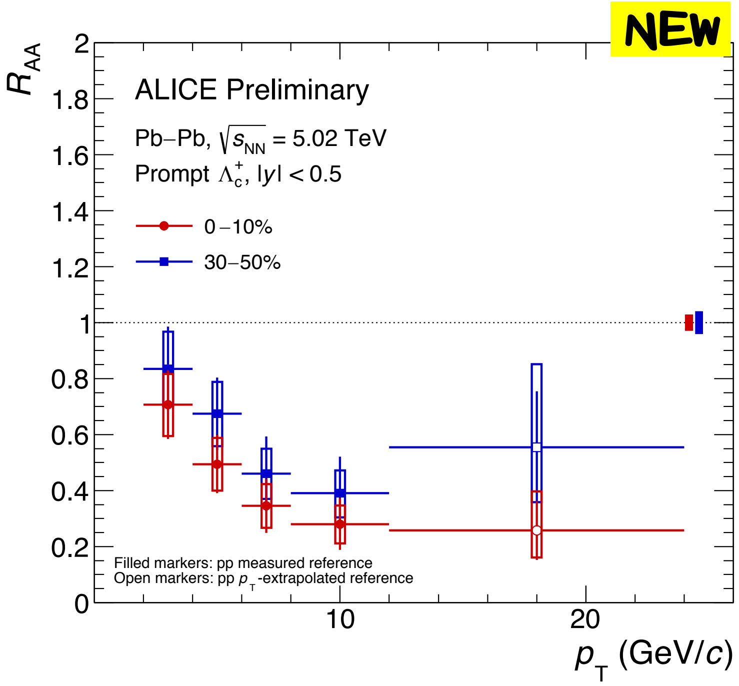
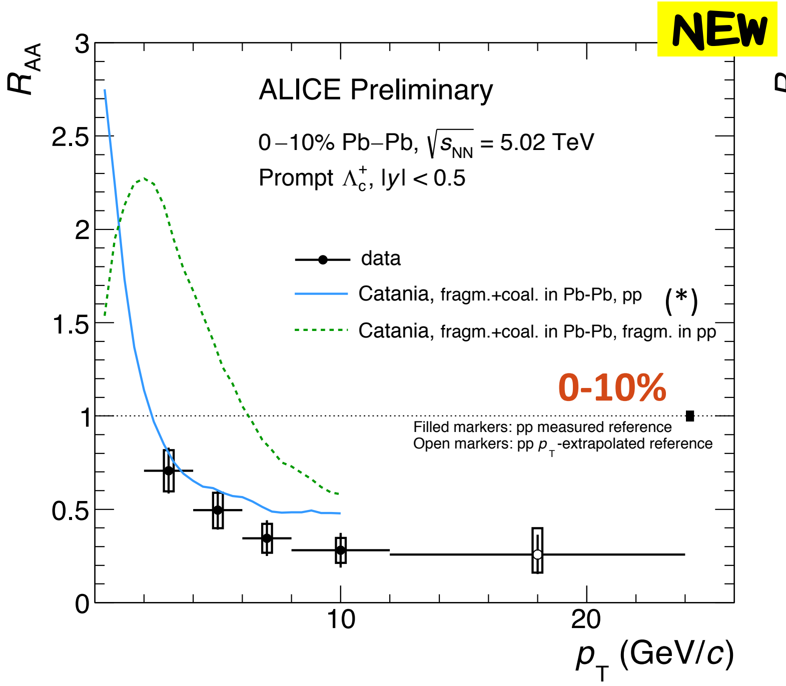
Comparison to charged particles and non-strange D mesons suggests a higher Λ_c^+ R_{AA}. Comparison to D_s^+ less straightforward due to uncertainties.

Λ_c^+ R_{AA}



ALI-PREL-321861



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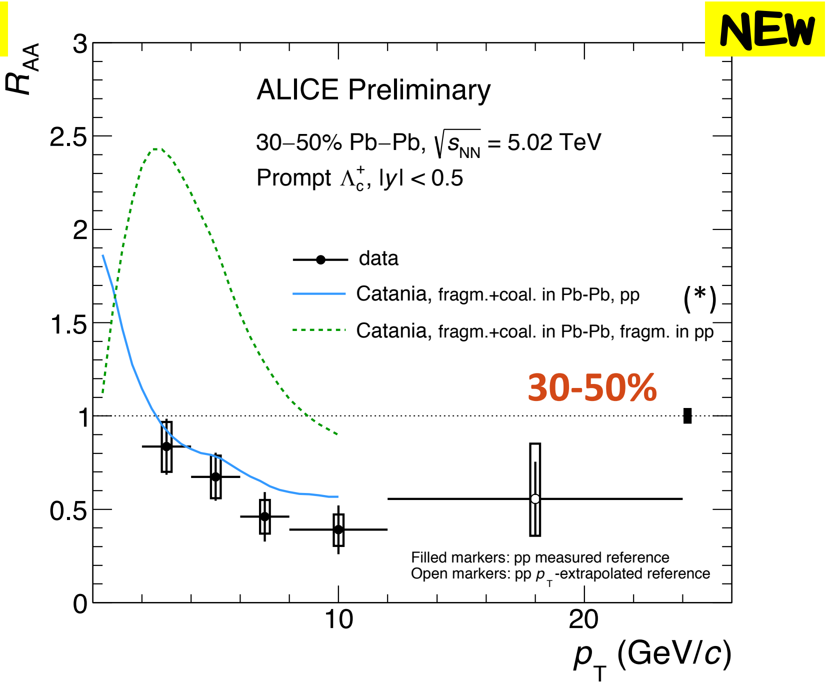


ALI-PREL-321845

Despite compatibility within uncertainties, hint to a nuclear modification factor smaller for central collisions by ~1.5x up to p_T = 12 GeV/c.

Agreement within ~2σ with results from 2015 Pb-Pb data (PLB793 (2019) 212-223, see backup), but different centralities

Similarly to Λ_c^+/D^0, the comparison to theory favours a scenario where both coalescence and fragmentation are present, for both centrality ranges.

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

Summary and Conclusions

2018 Pb-Pb data taking allowed for **new, more precise measurements** in the sector of open charm:

- **D_s^+ ratio to non-strange D-mesons and R_{AA}** was measured in the range $3 \leq p_T \leq 35$ GeV/c in the 0-10% and $3 \leq p_T \leq 25$ GeV/c in the 30-50% most central Pb-Pb collisions
- **D_s^+ v_2** was measured in the range $2 \leq p_T \leq 24$ GeV/c in the 30-50% most central Pb-Pb collisions

→ *Results indicate the **strangeness enhancement** expected in heavy-ion collisions*

- **Λ_c^+/D^0** and **Λ_c^+ R_{AA}** was measured in the range $2 \leq p_T \leq 24$ GeV/c in the 0-10% and 30-50% most central Pb-Pb collisions

→ *Results in agreement with models that foresee both **coalescence and fragmentation**, and for the Λ_c^+/D^0 good agreement with **SHM** is also found*

Outlook:

ALICE upgrade for Run3+4 with new ITS (7 layer pixel detector, pointing resolution $\sim$20 μm at p_T = 1 GeV/c) and TPC (GEM, continuous readout at 50 kHz) will offer the opportunity to explore with more precision a wide p_T range of open heavy flavour observables including new ones (e.g. Λ_b^+), to better constrain hadronisation mechanisms.

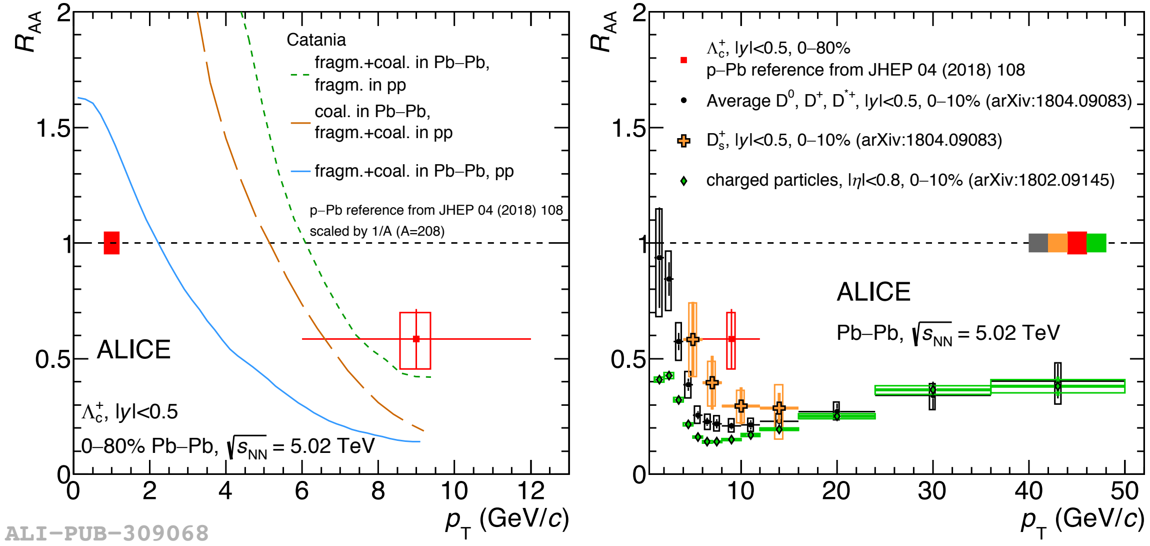
Backup

Introduction: motivations

Due to their high mass ($m_c \cong 1.3$, $m_b \cong 4.2$ GeV), heavy flavour quarks are produced in hard partonic scattering processes during the initial stages of the collisions, before the creation of the QGP.

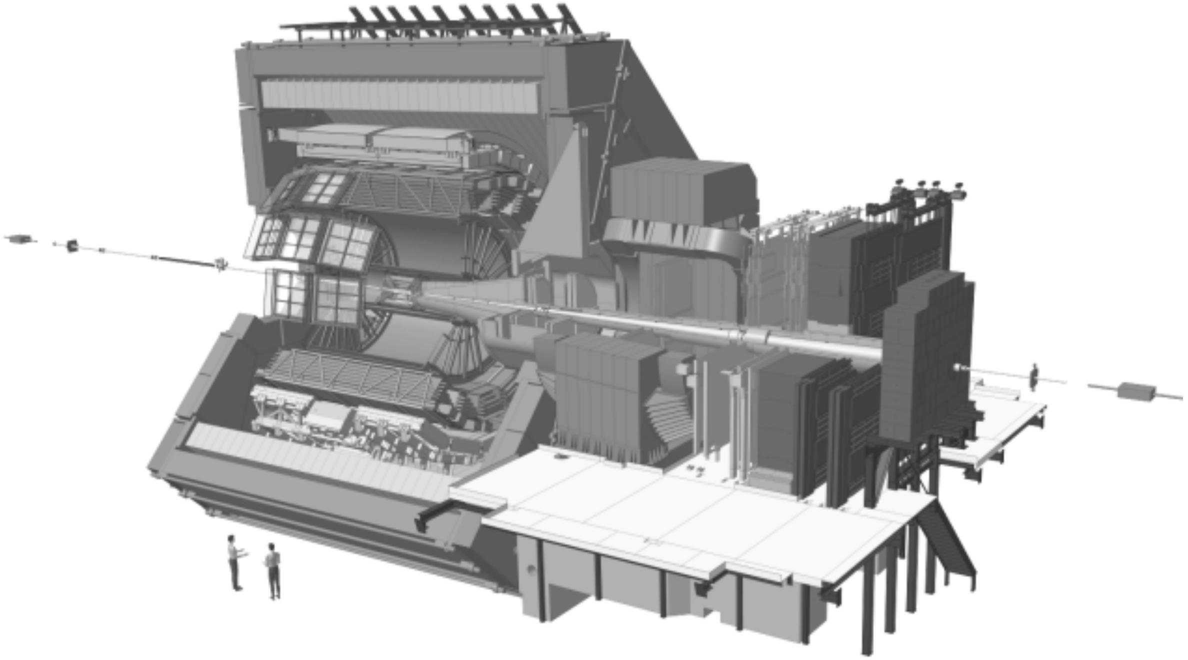
- $\tau_{prod} \approx 1/(2m_q) \approx 0.1_{q=c}$ $(0.03_{q=b})$ fm/c $\ll \tau_{QGP} \approx 0.3$-$1.5$ fm/c at LHC.
  - They interact with the medium and experience the whole evolution of the system.
    - Energy loss, production mechanisms may depend on the interactions with the medium.

Strange open-charm mesons and open-charm baryons are a major tool to study the charm-quark hadronization mechanisms inside the QGP



arXiv:1809.10922

A Large Ion Collider Experiment



Dedicated Heavy Ion experiment

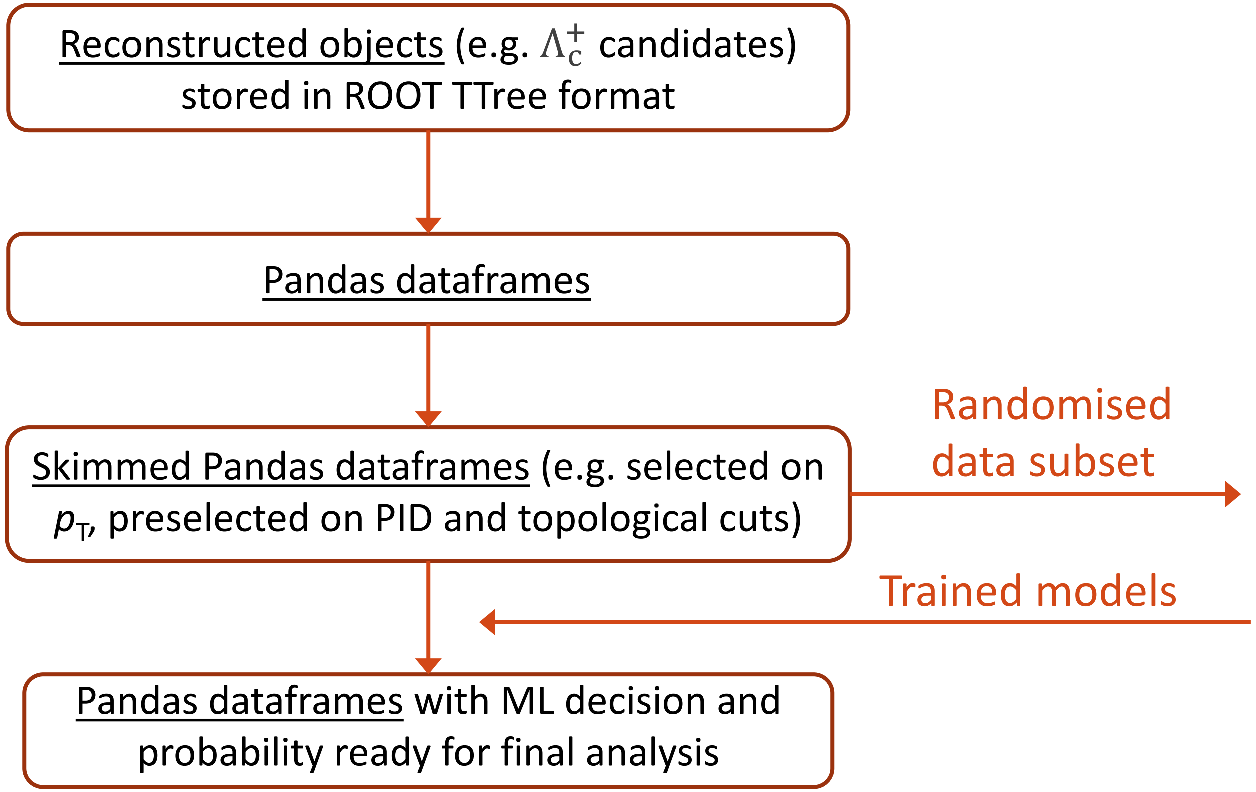
- Tracking detectors with geometrical acceptance $|\eta| < 0.9$ and full ϕ.
- Precision tracking capabilities in $|\eta| < 0.9$ down to very low momenta (100 MeV/*c*, low B field).
- Different particle identification detectors, some with limited geometrical acceptance
- Excellent hadron identification from low to high momenta.
- Tracking detectors optimized for extremely high charged track multiplicities → low event rate capability.

MLHEP python-based package

General purpose Python package for performing parallelized analysis over large datasets and Machine Learning (ML) optimization with Scikit, Keras and XGBoost.

https://github.com/ginnocen/MachineLearningHEP*

Software optimized for the use with local servers/clusters with large RAM, SSD storage and GPU boards



ML optimisation

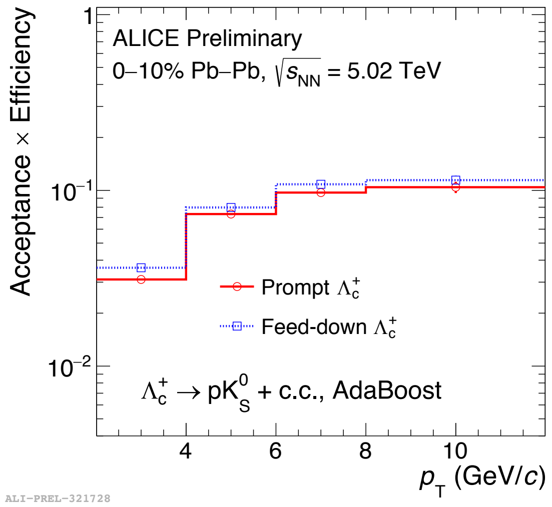
- ML sample preparation
- training/testing
- ML performance studies (ROC, cross validation, learning curves..)
- Significance optimisation

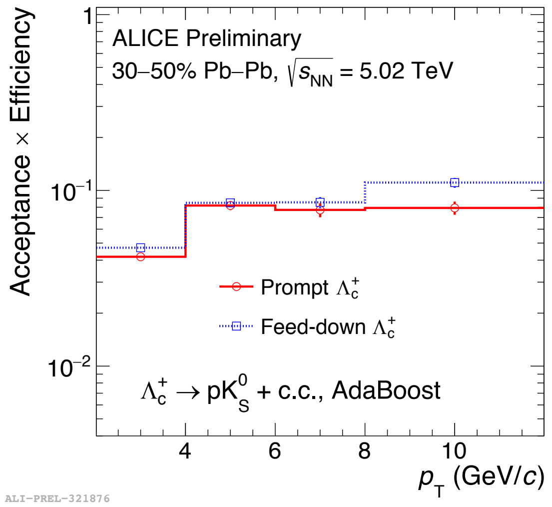
Efficiency x Acceptance, Λ_c^+

0-10%

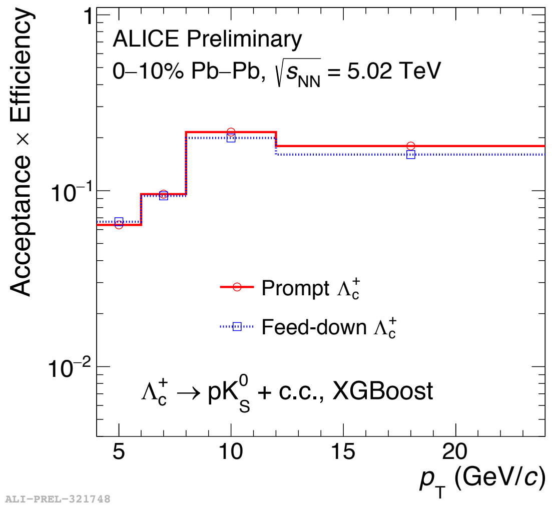
30-50%

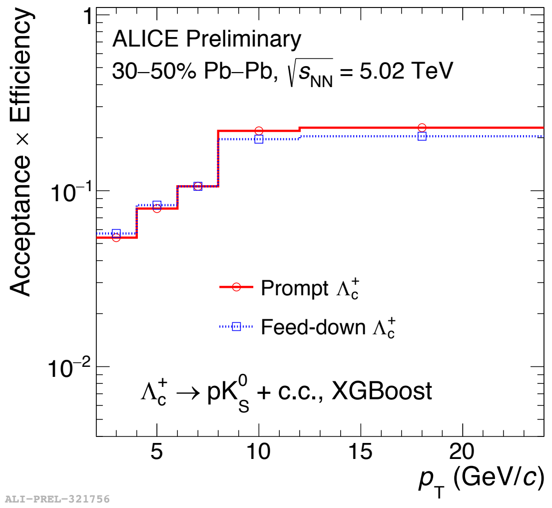
AdaBoost



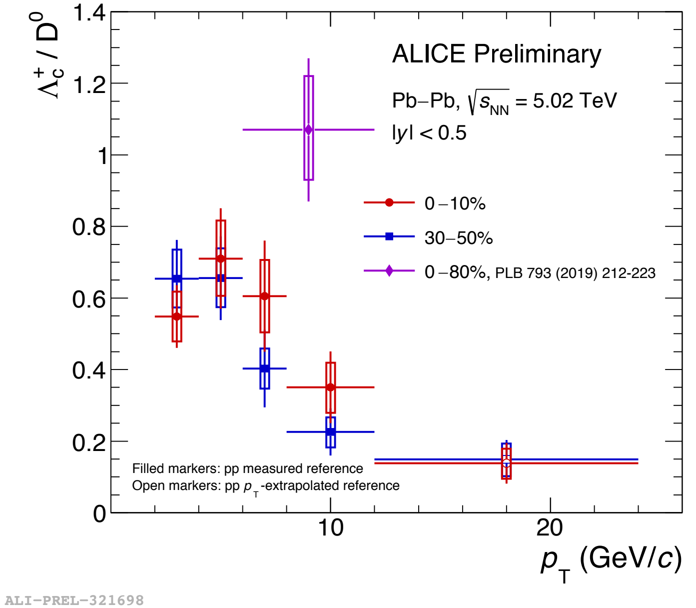


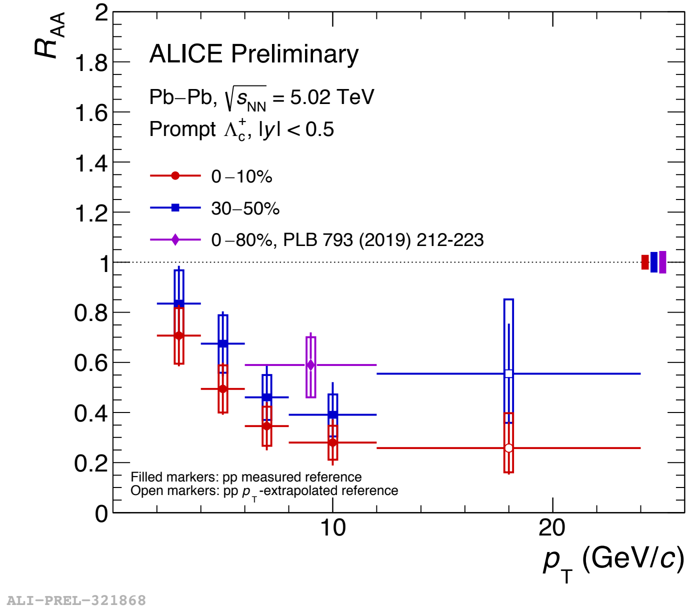
XGBoost





Λ_c^+/D^0 and Λ_c^+ R_{AA}: comparison to 2015





$\sim 2 - 2.8\ \sigma$ difference between 2015 and 2018 (central and semi-central respectively, once 2018 is done in [6, 12] too).

N.B.: 2015 data analyzed in a different centrality range

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