# Measurement of non–prompt $\Lambda_c^+$ production in pp collisions at $\sqrt{s} = 13$ TeV with ALICE

Accessing the hadronisation of the beauty quark

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MAX-PLANCK-INSTITUT FÜR PHYSIK

ALICE

# The factorisation approach

Hadrons that contain charm or beauty quarks are referred as heavy–flavour (HF);
The ***factorisation approach*** describes their production as a convolution of three terms:

Parton distribution functions:
→ non perturbative
→ parametrised using Deep Inelastic Scattering

Fragmentation Functions:
→ non perturbative
→ parametrised using $e^+e^-$ collisions

$$\sigma(\mathrm{pp} \rightarrow H_{\mathrm{Q}} + \mathrm{X}) = \sum_{\mathrm{i,j=q,\bar{q},g}} f(x_{\mathrm{i}}, Q^2) \otimes f(x_{\mathrm{j}}, Q^2) \otimes \sigma(\mathrm{ij} \rightarrow Q\bar{Q}) \otimes D(z_{\mathrm{Q}}, Q^2)$$

Partonic cross section
→ perturbative for HF–quarks
→ theoretical calculations are possible

Production of HF–hadrons → ideal probe to test pQCD and the factorisation approach.

# Charmed–hadron production

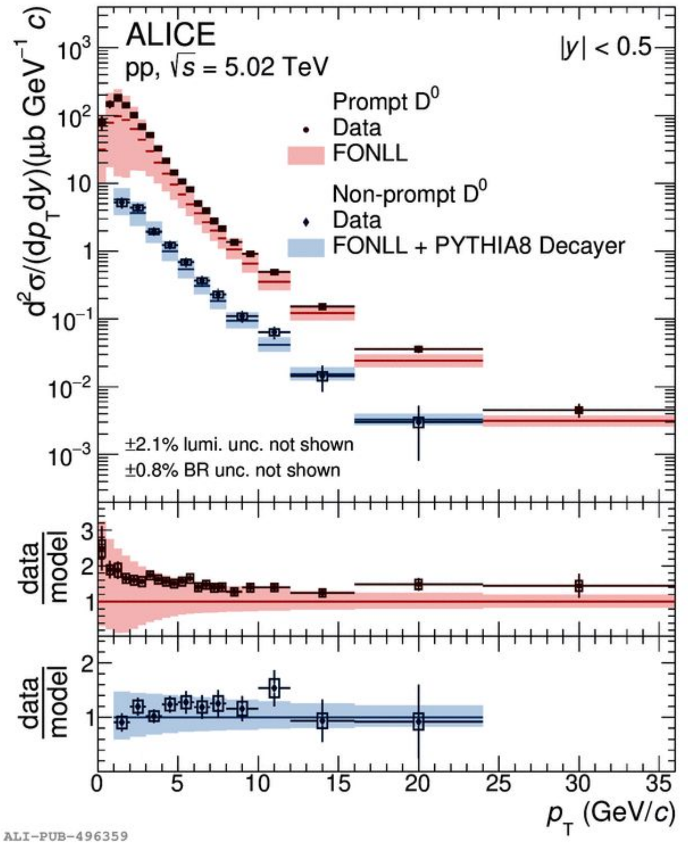
Charmed hadrons are classified according to their origin:

- **Prompt** → coming from:
  - hadronisation c quark
  - decay of excited charmed–hadron states.
- **Non–prompt** → coming from:
  - beauty hadron decay

Prompt and non–prompt cross sections D mesons:

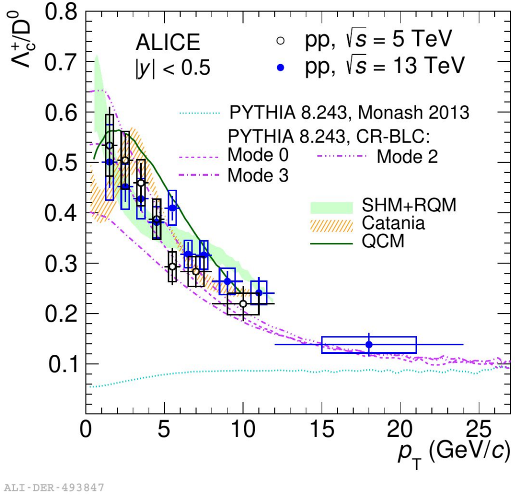
- Experimentally measured,
- consistent with pQCD calculations (FONLL).

The production of charmed–hadrons allows us to investigate the fragmentation process, e.g. via baryon/meson ratios.



# Hadronisation of the charm and beauty quarks

## Hadronisation of charm → prompt $\Lambda_c^+/D^0$




Recent measurements:
Enhanced baryon production in pp collisions w.r.t. $e^+e^-$.
The hadronisation of charm depends on the collision system![1,2]


[1] Phys. Rev. Lett. 128, 012001
[2] Phys. Rev. D 100, 031102(R)


## Hadronisation of beauty → ?

**Exclusive b–hadron measurements**
Challenging because of:

- Small beauty cross section;
- Small branching ratios.

**Non–prompt charmed hadrons**
in Nature: 5÷10 %, depending on the $p_T$.

Goal of this work: measure the non–prompt $\Lambda_c^+$ production in the $\Lambda_c^+ \to pK_S^0 \to p\pi^+\pi^-$ decay channel.

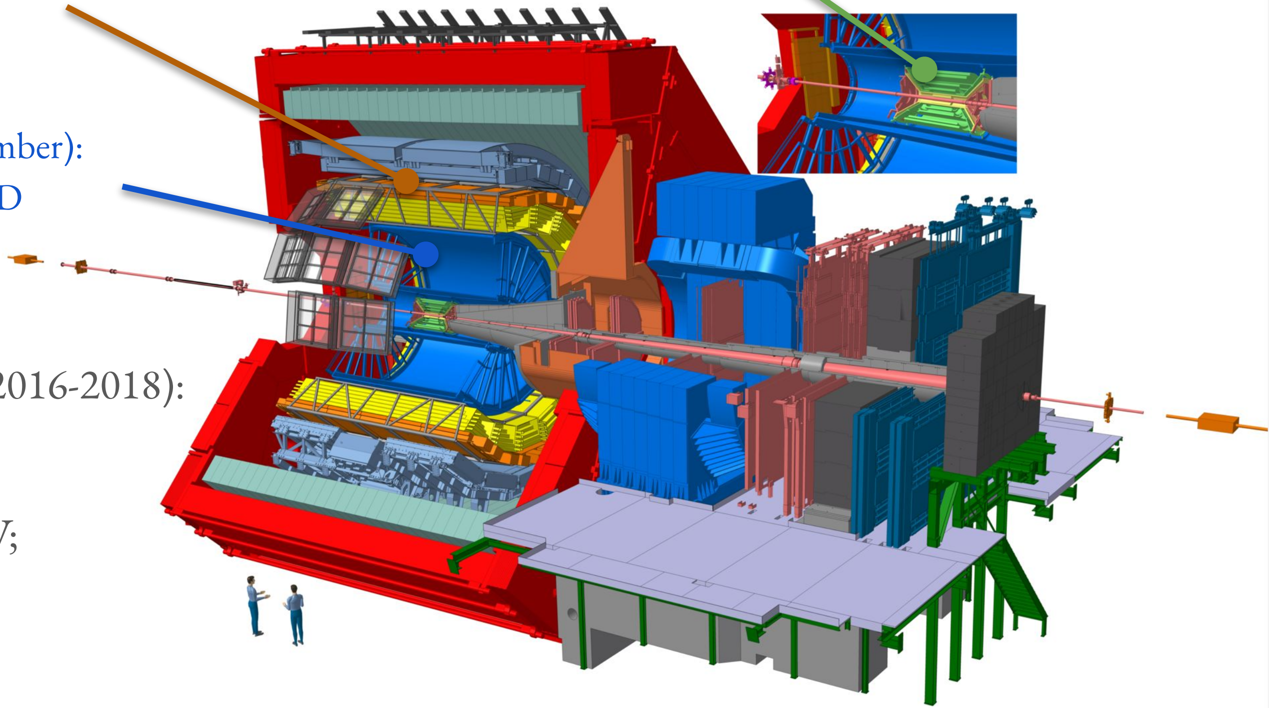
Access to the hadronisation mechanism in the beauty sector, via non–prompt $\Lambda_c^+/D^0$.

# The ALICE detector

TOF (Time Of Flight):
Particle Identification (PID)

ITS (Inner Tracking System):
Track and vertex reconstruction

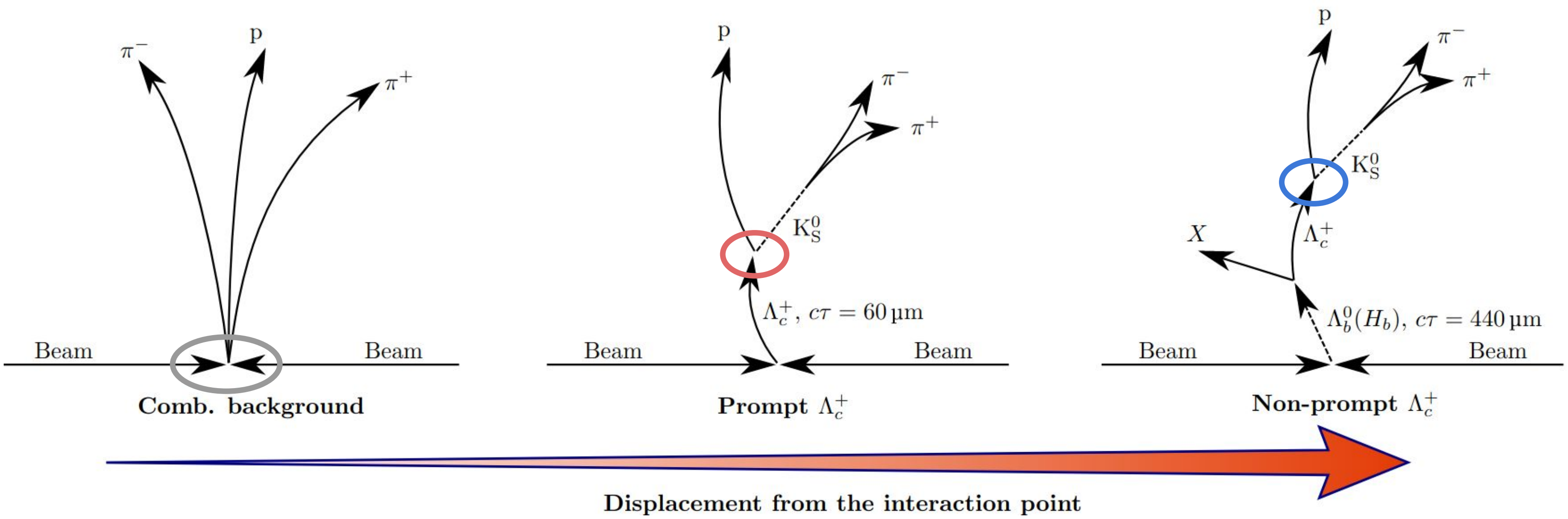
TPC (Time Projection Chamber):
Track reconstruction and PID



Data collected during the Run 2 (2016-2018):

Minimum Bias pp collisions;
Center-of-mass energy: $\sqrt{s}$ = 13 TeV;
$1.84 \times 10^9$ Events ($L_{int}$ = 32 $nb^{-1}$).

# Decay topologies: prompt, non–prompt and background




To separate the three contributions → Machine Learning (ML) method:

- Multi-class classification algorithm;
- Training variables: topology + PID.

# Machine Learning & Boosted Decision Trees

Machine Learning allows for more advanced selections.

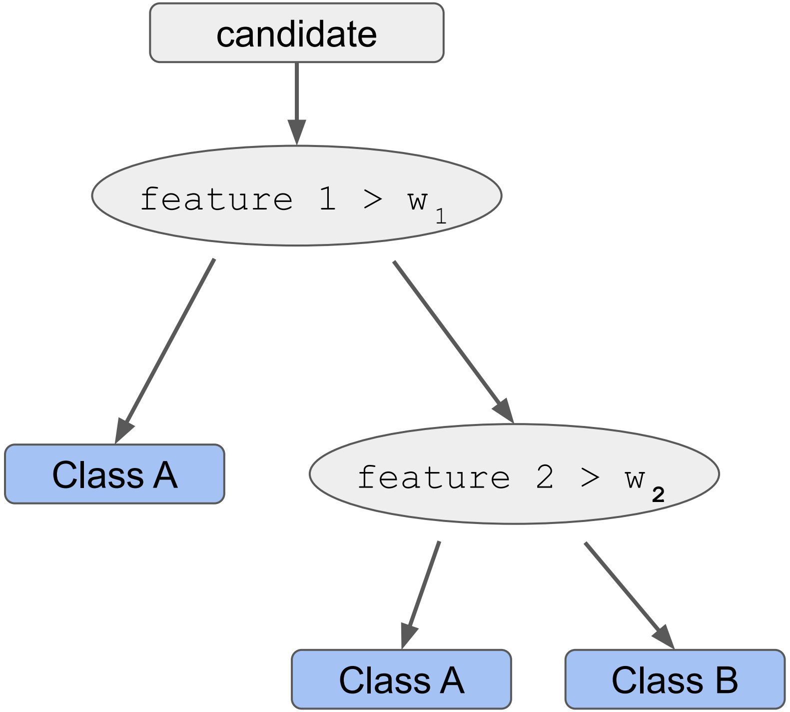
- Exploit high order correlation between the features;
- Easily handle multi–dimensional studies.

The use of ML is typically characterised by:

- Learning phase;
- hyperparameter optimisation;
- test of the model performance;
- application to unseen data.

In this work → Boosted Decision Trees (XGBoost):

- Simple;
- Performant.



# Separating prompt, non–prompt and comb background

In this case: 3 classes (prompt, non-prompt and background)
Binary classificators are combined

The model is provided with example candidates for each class:

- Background: data (sidebands)
- Signal (prompt and non–prompt): Monte Carlo (MC)

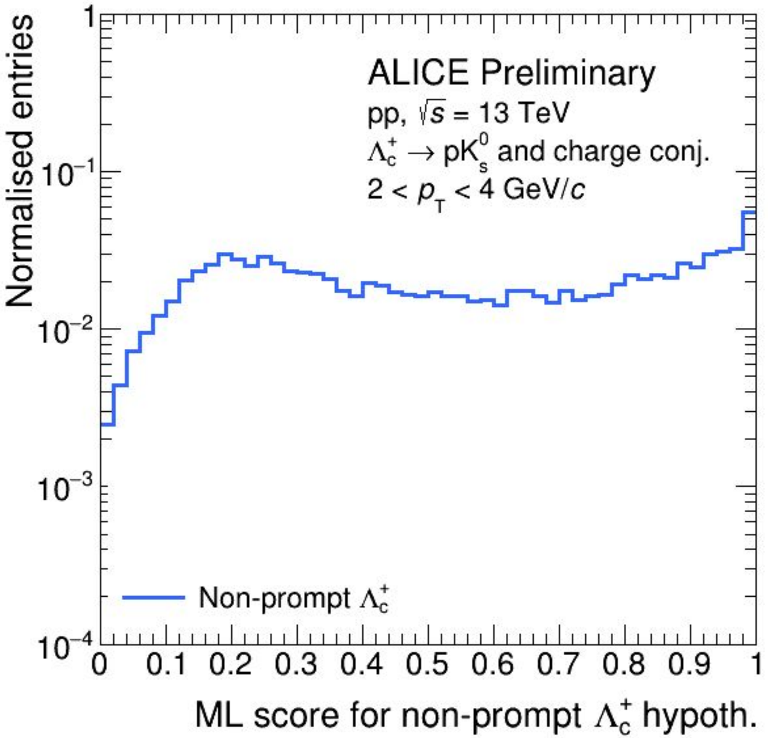
Output of the ML model: three scores

→ probability of belonging to each class.

Good separation between the three classes;

To measure the non–prompt contribution → selections:

- Large non–prompt score;
- Small background score.



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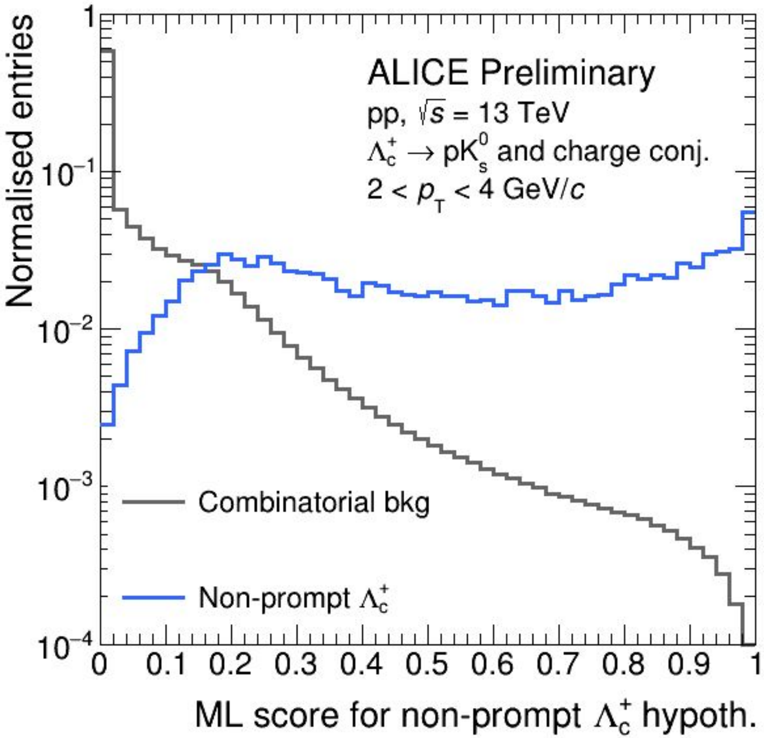

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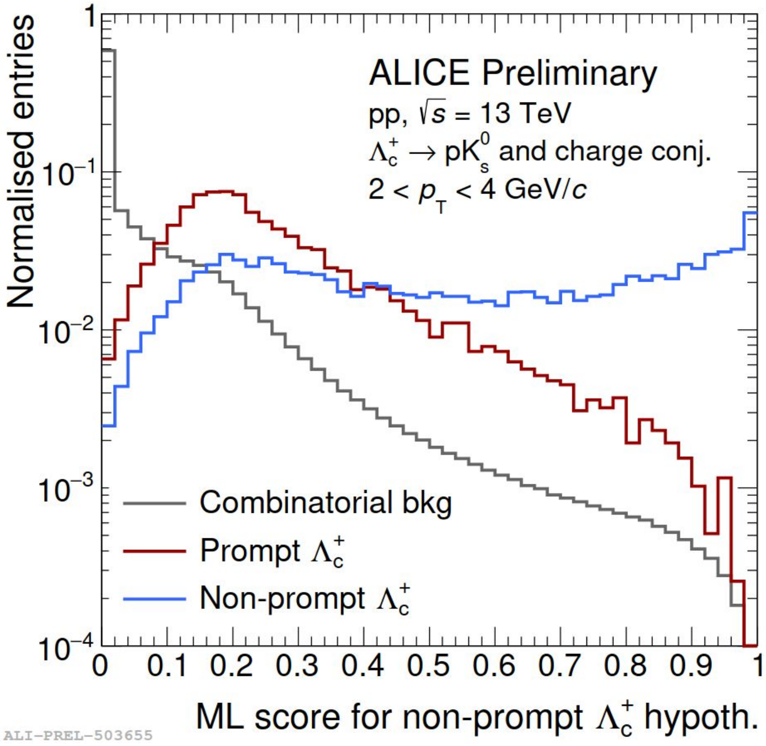

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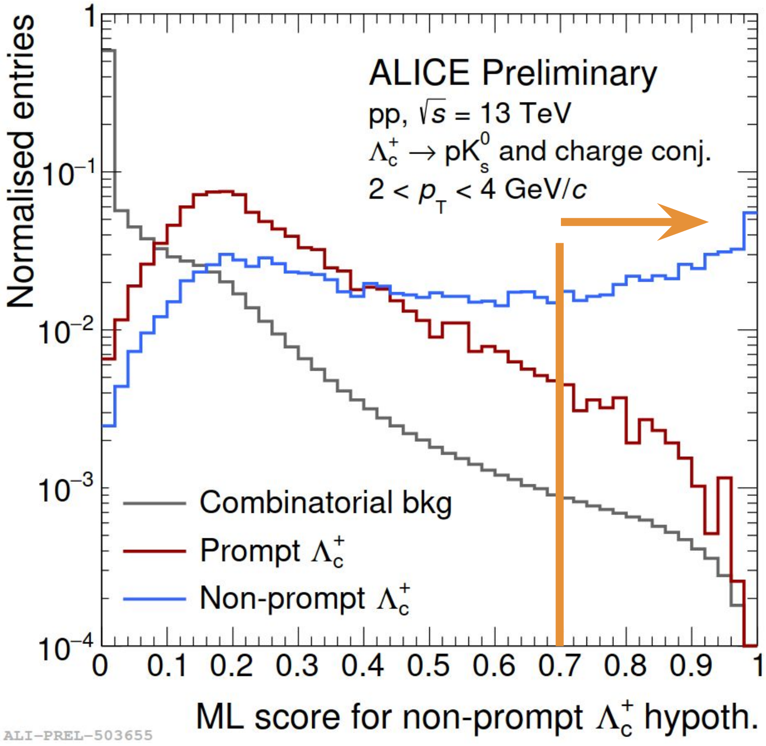


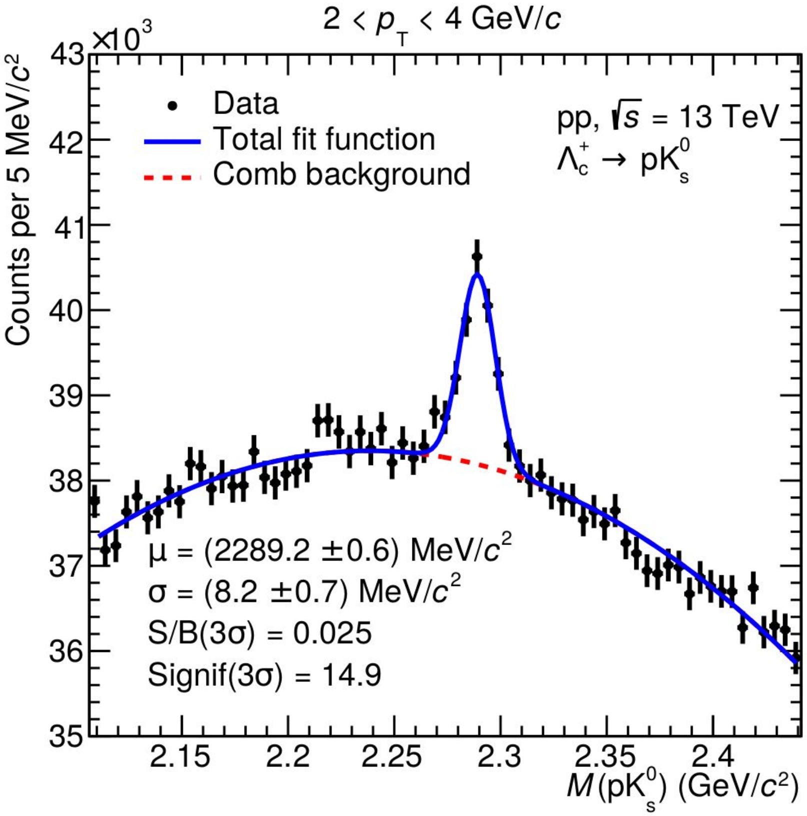
# Signal extraction

After the selections, fit the invariant mass distribution:
- signal → gaussian;
- background → parabola.

The fit gives the Raw Yield and the amount of background.

Can we separate the non–prompt from the prompt hadrons?

Not from the invariant mass distribution, but...



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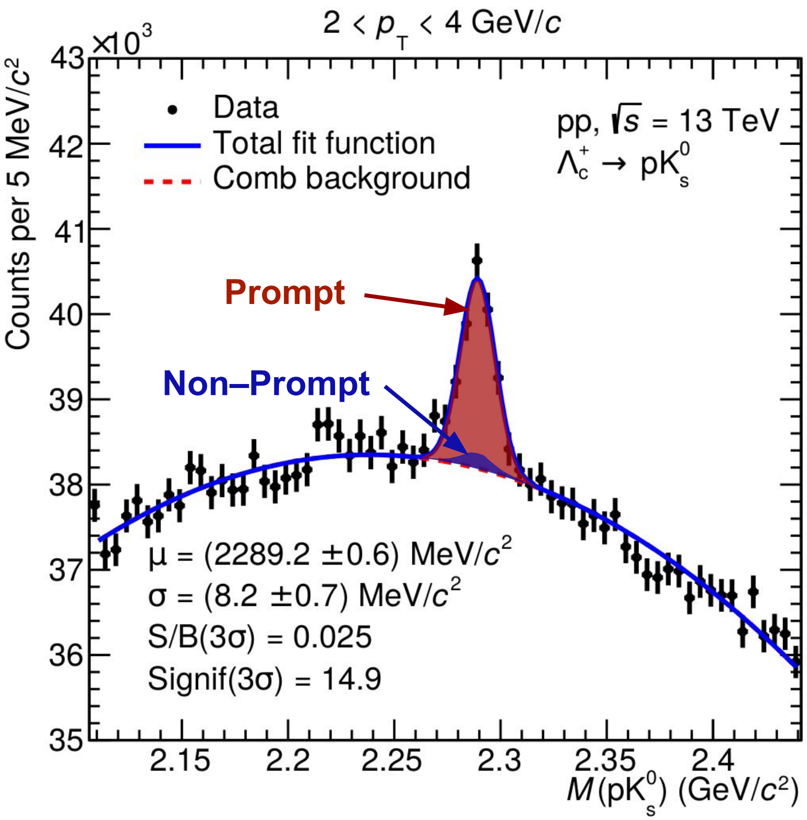

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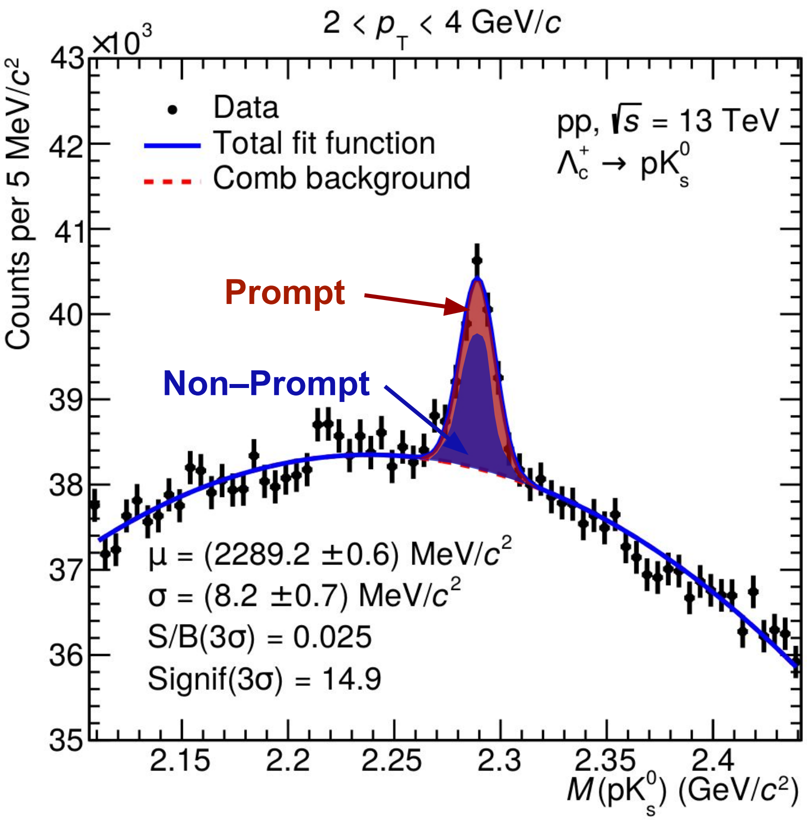


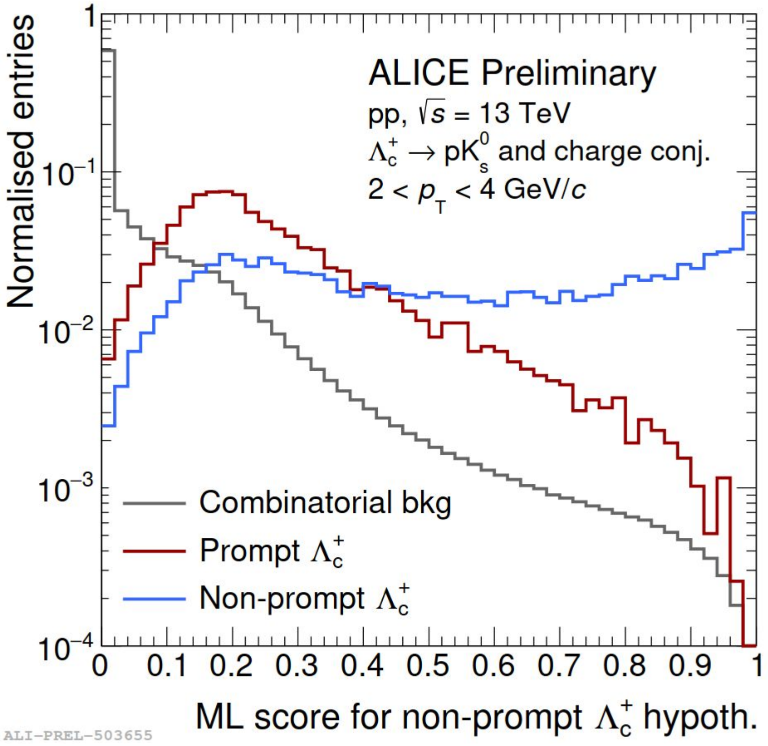
# Analysis strategy

Threshold changes → non–prompt fraction changes!

By construction, the selection efficiency is different for prompt and non–prompt.

Idea:

- study the raw yield using different selections;
- measure the selection efficiency
- combine the two and measure the prompt fraction



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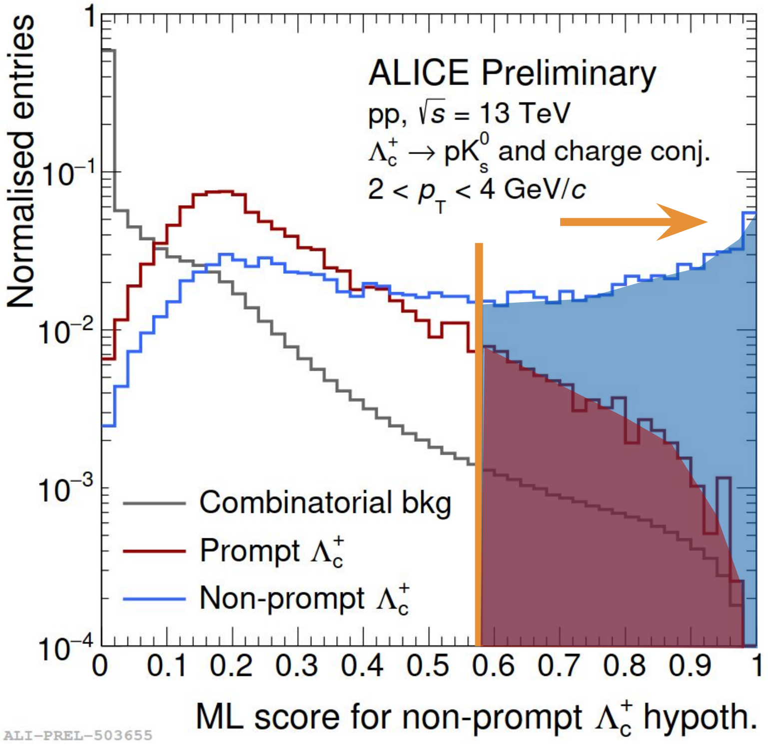

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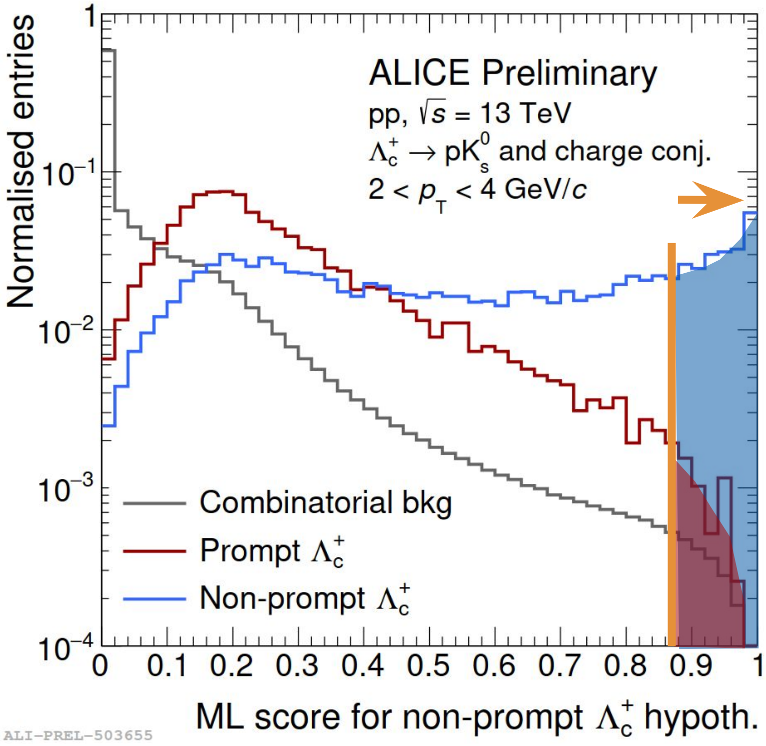


# Measuring the non–prompt fraction

Different selections → different proportions between prompt and non–prompt contributions.

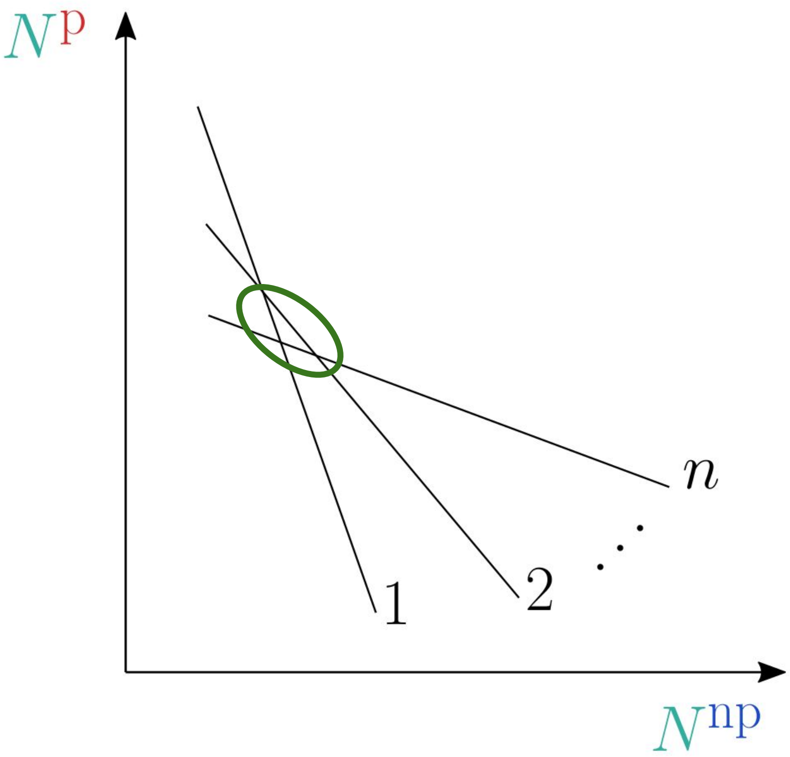
To measure the non–prompt fraction[1]:

- define many selections, for each:

$$Y_i = {\varepsilon_i}^{\mathrm{p}} N^{\mathrm{p}} + {\varepsilon_i}^{\mathrm{np}} N^{\mathrm{np}}$$

  Raw yields (from data),
  Efficiencies × acceptance (from MC),
  True yields (Unknown parameters).

- An overdetermined system of equation is defined.
- Solve numerically for $N^{\mathrm{p}}$ and $N^{\mathrm{np}}$.




[1] JHEP 05 (2021) 220

# Solving the system

The system to solve is:

$$\begin{cases} Y_1 & = \varepsilon_1^{\mathrm{p}} N^{\mathrm{p}} + \varepsilon_1^{\mathrm{np}} N^{\mathrm{np}} \\ & \dots \\ Y_n & = \varepsilon_n^{\mathrm{p}} N^{\mathrm{p}} + \varepsilon_n^{\mathrm{np}} N^{\mathrm{np}} \end{cases}$$

As the system is overdetermined, and there are statistical uncertainties, the quantity

$$\delta_i = Y_i - \varepsilon_i^{\mathrm{p}} N^{\mathrm{p}} - \varepsilon_i^{\mathrm{np}} N^{\mathrm{np}}$$

will be non–zero.

To find the best-fit true yields, a $\chi^2$ is defined,

$$\chi^2 = \boldsymbol{\delta}^T C^{-1} \boldsymbol{\delta}$$

Where C is the covariance matrix between the $\delta_i$

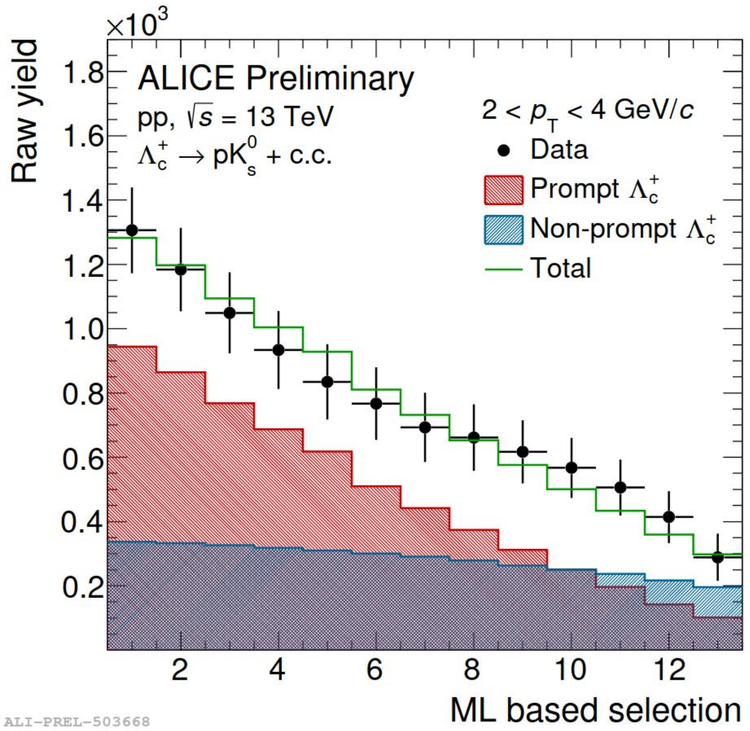
# Prompt and non–prompt contributions

Separation between prompt and non–prompt!

- The prompt contribution decreases rapidly;
- The non–prompt contribution is ~constant.

Tight selection → large non–prompt fraction:

$$f_{\rm np} = \frac{\varepsilon_i{}^{\rm np} N^{\rm np}}{\varepsilon_i{}^{\rm p} N^{\rm p} + \varepsilon_i{}^{\rm np} N^{\rm np}}$$

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# The non–prompt $\Lambda^+_c$ cross section

Non–prompt cross section:

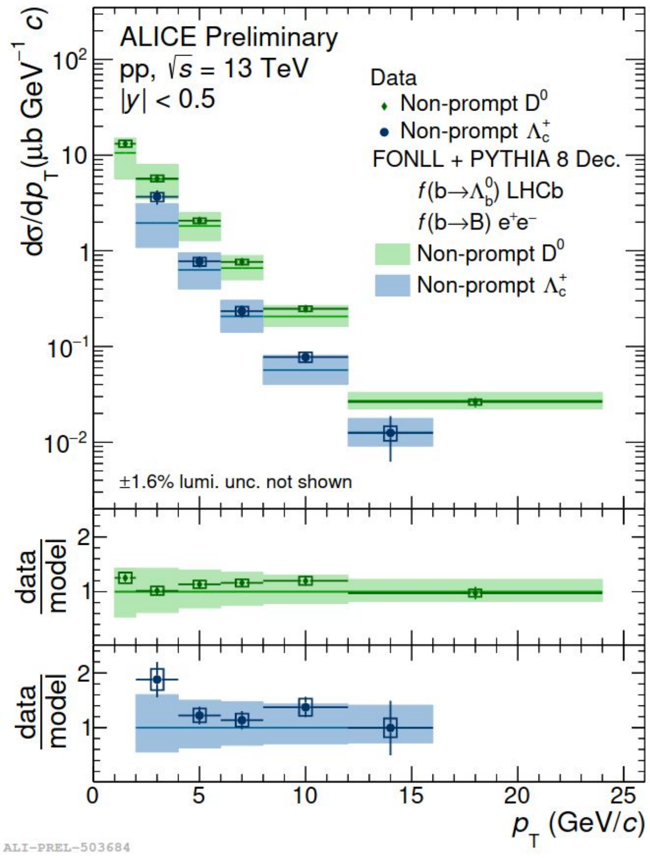
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}}\right)^{\mathrm{np}} = \frac{f^{\mathrm{np}} Y}{2\,\Delta p_\mathrm{T}\,\varepsilon^{\mathrm{np}}\,BR\,\mathcal{L}_{\mathrm{int}}}$$

Measured in 2 decay channels:
$\Lambda_c^+ \to \mathrm{pK^0_s}$ and $\Lambda_c^+ \to \mathrm{pK^-}\pi^+$.

Theoretical model: FONLL[1] using:

- $\Lambda_b^0$ fragmentation fractions from LHCb[2],
- folding with $\mathrm{H_b} \to \Lambda_c^+ + \mathrm{X}$ decay from PYTHIA8.

For both non–prompt $\mathrm{D^0}$ mesons and $\Lambda_c^+$ baryons the data is compatible with the model!





[1] JHEP 03 (2001) 006
[2] Phys. Rev. D 100, 031102(R)

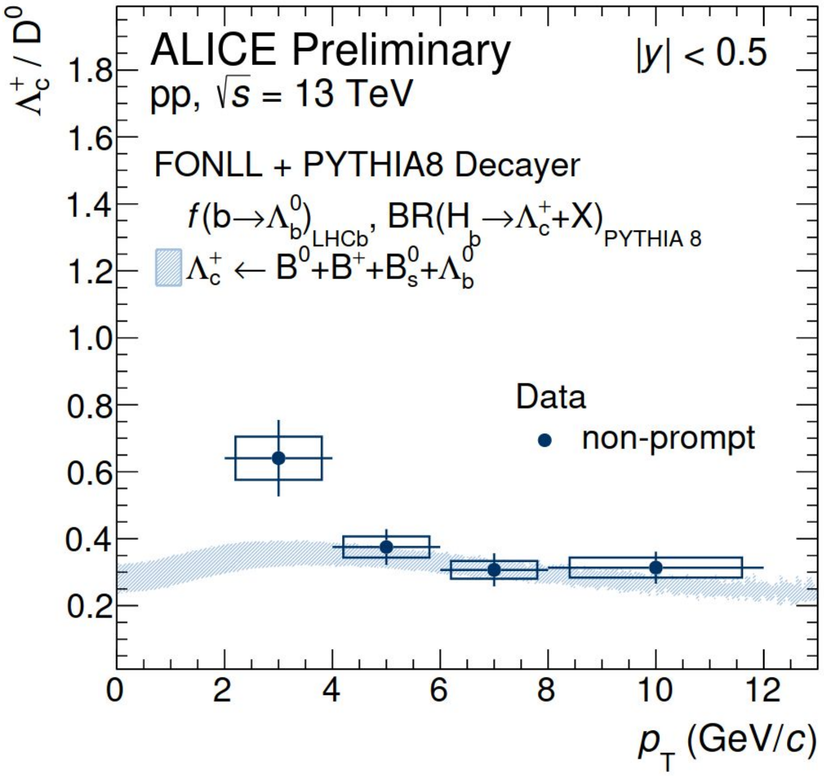
# The fragmentation of beauty

The fragmentation of beauty is accessible via:
non–prompt $\Lambda_c^+$/ non–prompt $D^0$ ratio

Major contributor to the $\Lambda_c^+$ yield: $\Lambda_b^0$
Minor contribution from B mesons.

Similar ratios for prompt and non–prompt.

Non–prompt $\Lambda_c^+ \approx \Lambda_b^0$.



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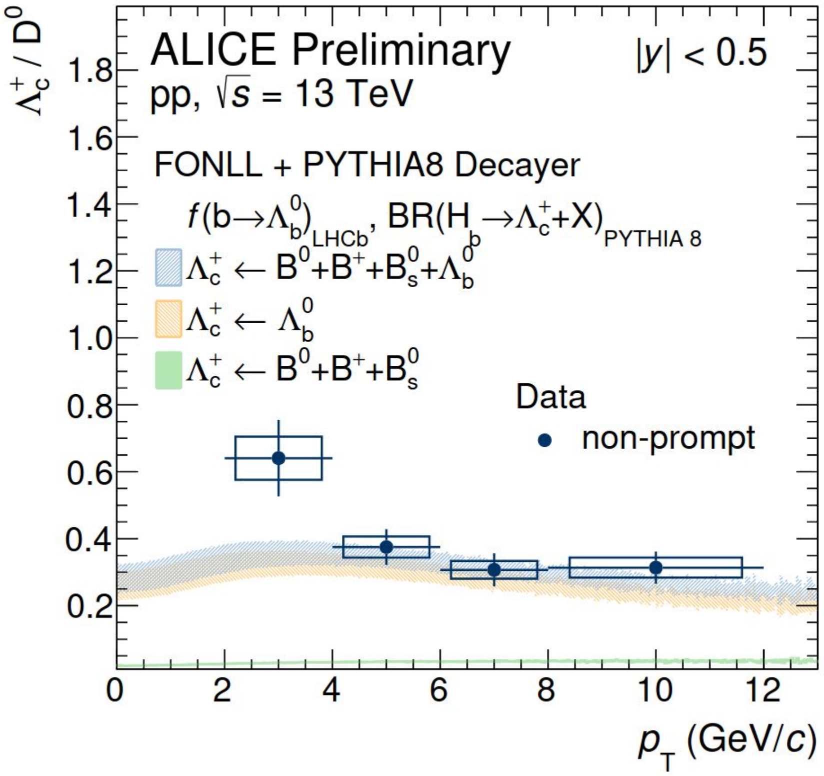

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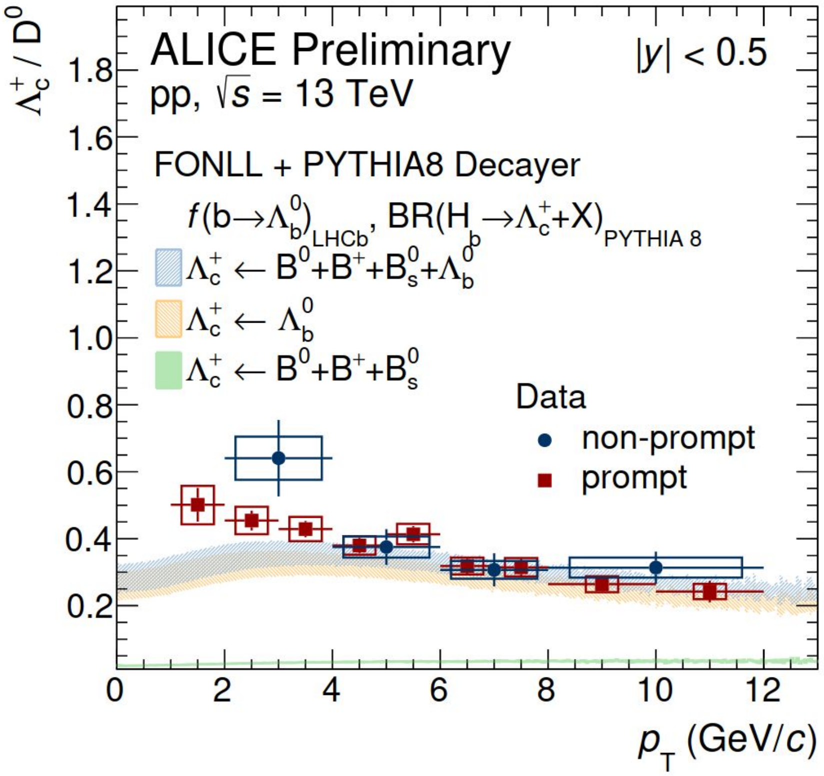

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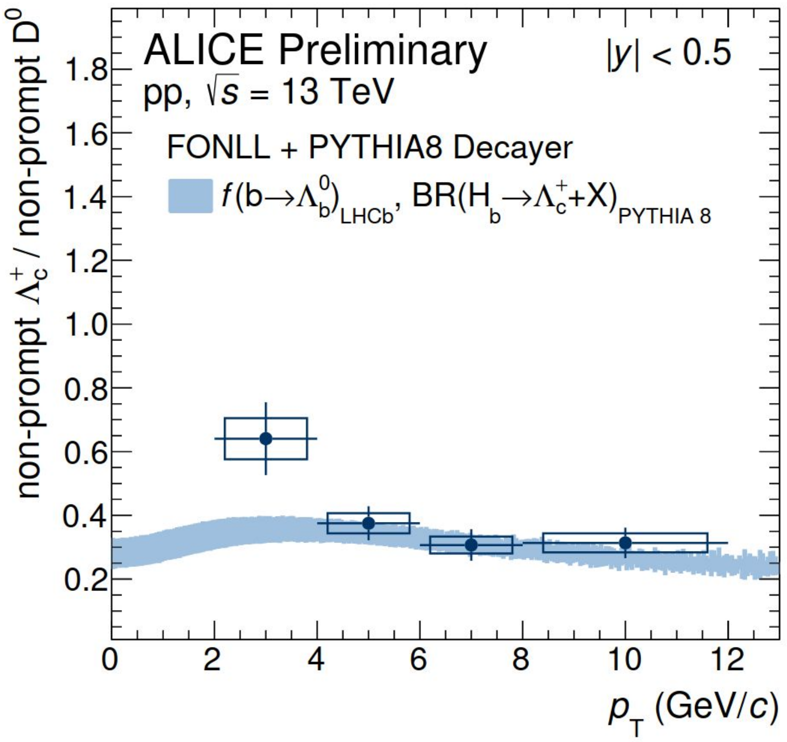
FONLL tested using fragmentation fractions from
- **LHCb**[1] (pp collisions),
- **$e^+e^-$ collisions**,

and folded with the $H_b \to \Lambda_c^+ + X$ decay, using:
- PDG decay table (only measured decays),
- PYTHIA8 decay table (also unmeasured decays).

Enhanced beauty–baryon production w.r.t $e^+e^-$ collisions.

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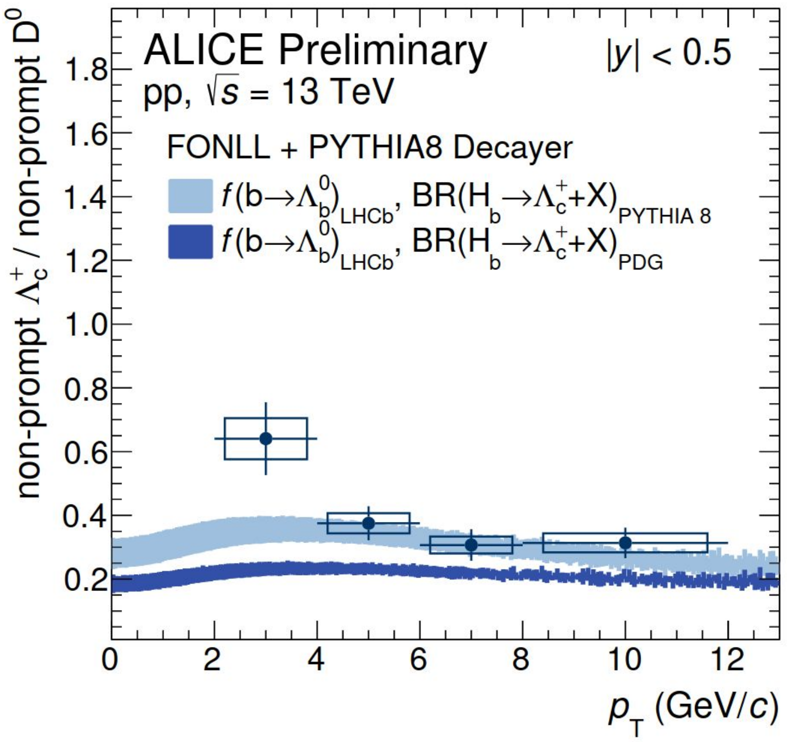


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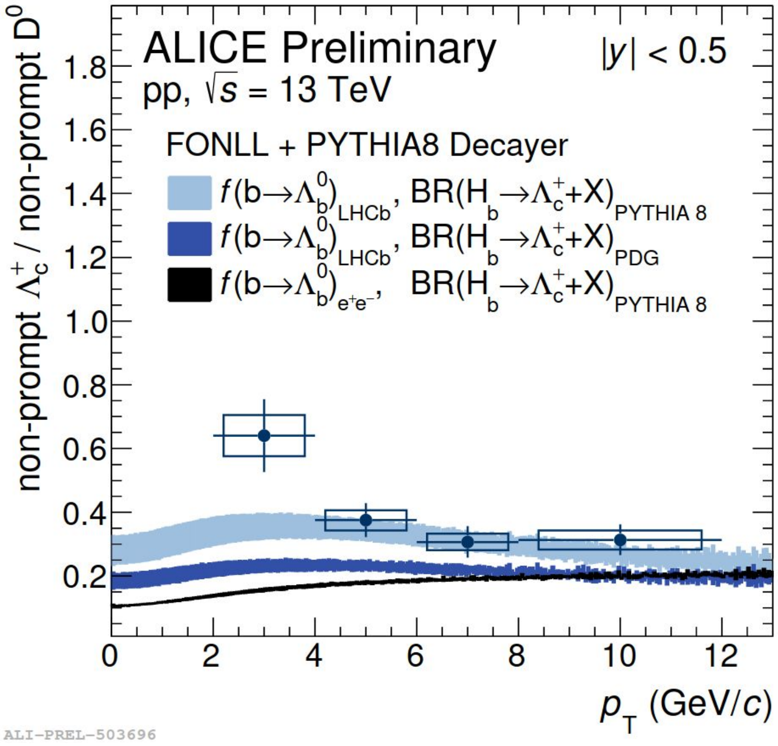


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# Conclusions

Results:

- First measurement of non–prompt $\Lambda_c^+$ cross section;
- $\Lambda_c^+/D^0$ : better agreement with the PYTHIA decay table: indication of missing decay in the PDG;
- Non–prompt $\Lambda_c^+/D^0$ $\rightarrow$ hadronisation of beauty is not independent of the collision system.

Outlook

- Improve the measurement with the Run 3 data;
- Study the non–prompt $\Lambda_c^+$ production in Pb–Pb collisions to characterize the QGP.