First measurement of $\Sigma_c^{0,++}$ production in hadronic collisions at the LHC

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On behalf of the ALICE Collaboration

Workshop *Quark-Gluon Plasma Characterisation with Heavy Flavour Probes*

Trento - 16th November 2021

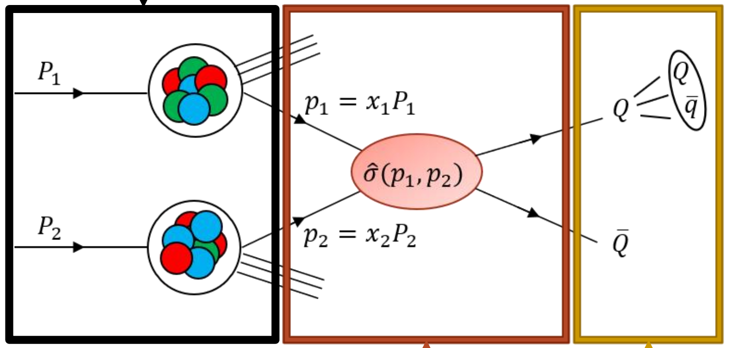
Heavy flavour (HF) production in pp collisions

$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{H_c}}}(p_{\mathrm{T}};\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z=p_{\mathrm{H_c}}/p_{\mathrm{c}},\mu_F)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)

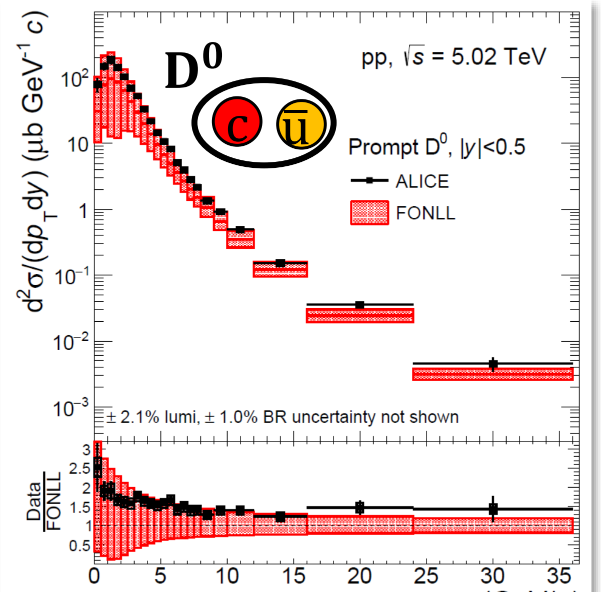


- The measurements of the **HF hadron production** are fundamental **tests** of **pQCD calculations**
- The standard description in pp collisions is based on the **factorization theorem**
  → **Fragmentation functions** assumed **universal** among energy and collision systems and constrained from e^+e^- and ep measurements
- **Ratios of particle species** → ratios of fragmentation fractions, sensitive to HF quark hadronization

$$\boldsymbol{f(\mathrm{c}\to\mathrm{H_c}) = \sigma(\mathrm{H_c})/\sigma(\mathrm{c\bar{c}})}$$

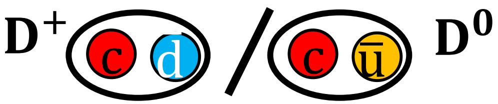
Heavy flavour (HF) production in pp collisions

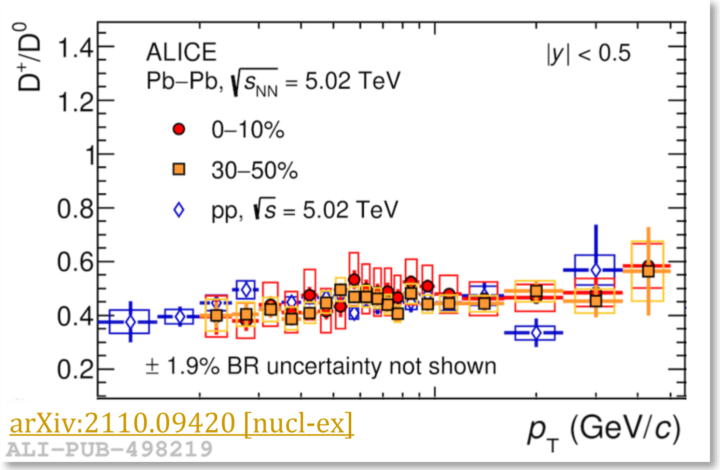
$\sqrt{s} = 5.02$ TeV



Eur.Phys.J. C79 (2019) no.5, 388

ALI-PUB-314115



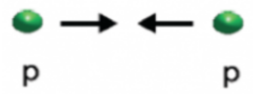


arXiv:2110.09420 [nucl-ex]

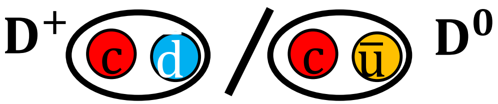
ALI-PUB-498219

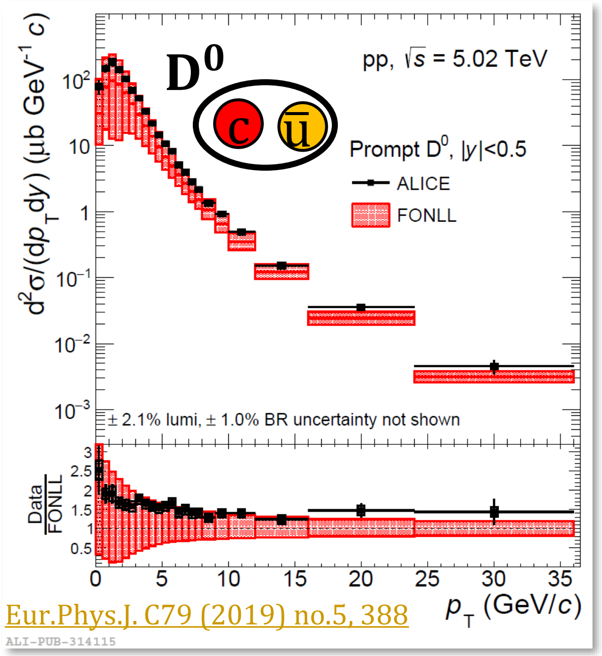
- Fragmentation functions constrained from e^+e^- measurements
- Theoretical models based on a factorisation approach describe the meson production within large uncertainties
- D-meson cross section on the upper edge of FONLL prediction
- D-meson ratios independent among collision systems and vs. p_T

Heavy flavour (HF) production in pp collisions



$\sqrt{s} = 5.02, 13$ TeV





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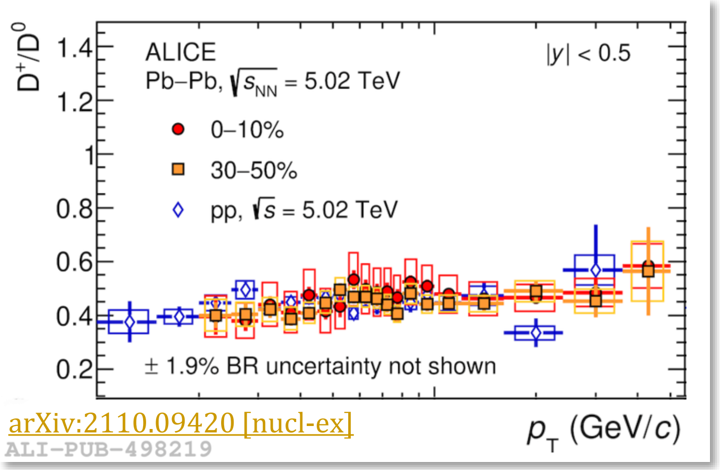

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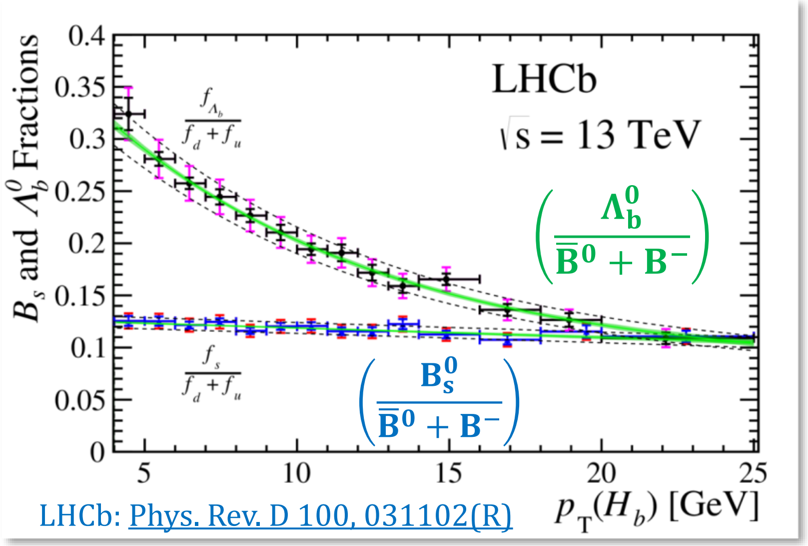
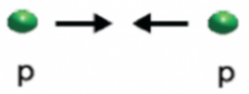


LHCb: Phys. Rev. D 100, 031102(R)

- Fragmentation functions constrained from e^+e^- measurements
- Theoretical models based on a factorisation approach describe the meson production within large uncertainties
- D-meson cross section on the upper edge of FONLL prediction
- D-meson ratios independent among collision systems and vs. p_T

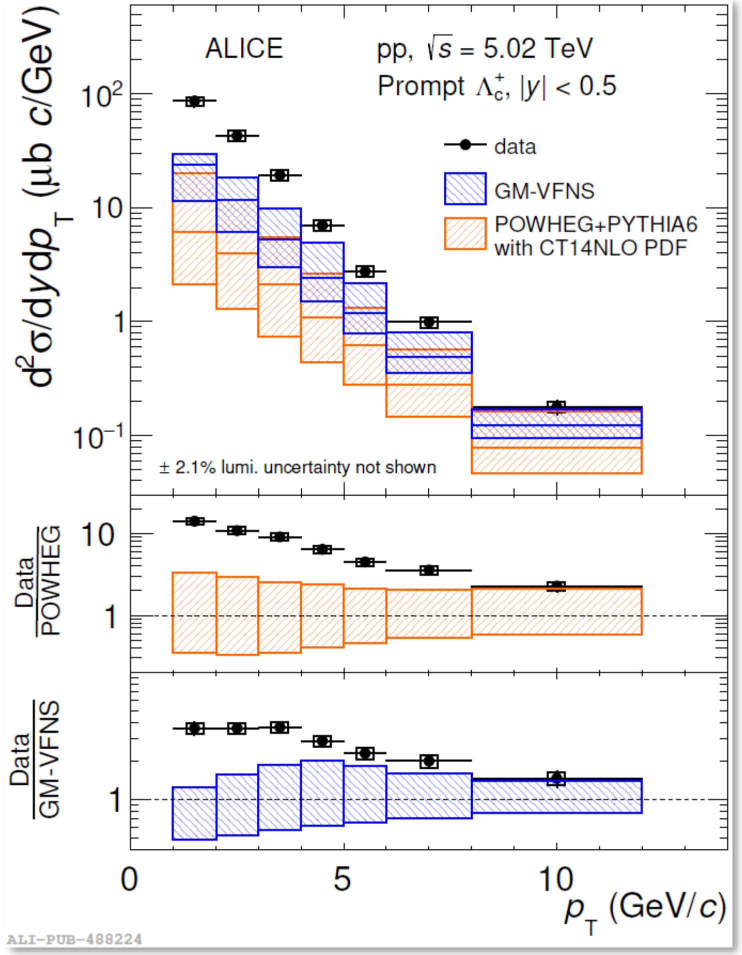
- Beauty baryon-to-meson:
  - ➢ Decreasing trend vs. p_T
  - ➢ Enhancement at low p_T with respect to $B_s^+/(\overline{B}^0 + B^-)$

Heavy flavour (HF) production in pp collisions

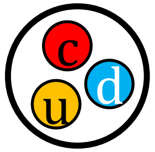


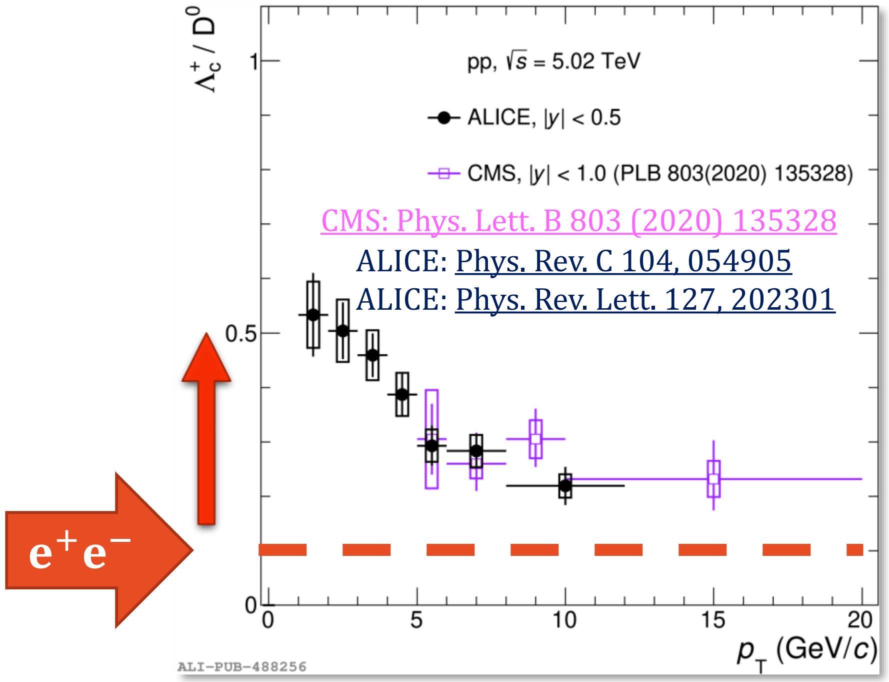
$\sqrt{s} = 5.02$ TeV

ALICE: Phys. Rev. C 104, 054905   ALICE: Phys. Rev. Lett. 127, 202301



Λ_c^+





- **Theoretical models** based on the same approach **significantly underestimate the baryon production**
- Λ_c^+/D^0 ratio:
  - → Significant decrease with p_T
  - → $\times$ 2.5 – 5 enhancement in pp collisions compared to e^+e^-

→ Further mechanisms playing a role?   **→ Non-universality of fragmentation functions?**

The role of Λ_c^+ and $\Sigma_c^{0,+,++}$

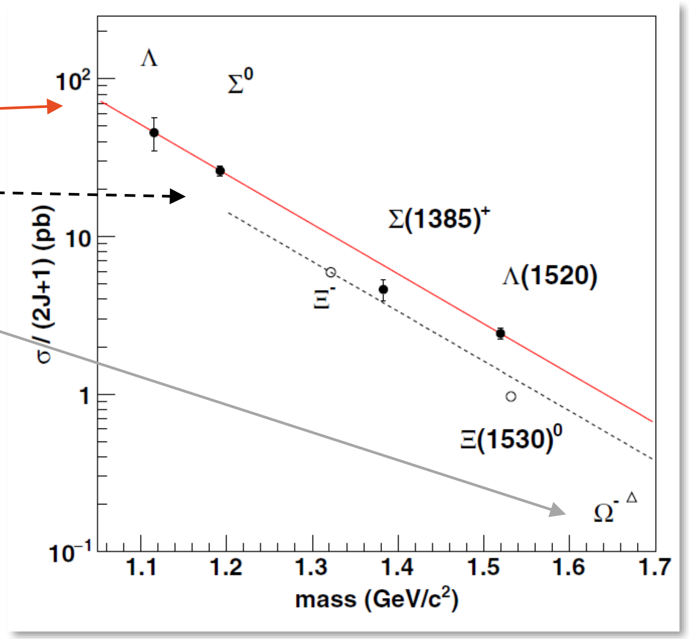
(PYTHIA 8)
$m(\mathrm{ud})_0 = 579\ \mathrm{MeV}/c^2$
$m(\mathrm{ud})_1 = 771\ \mathrm{MeV}/c^2$

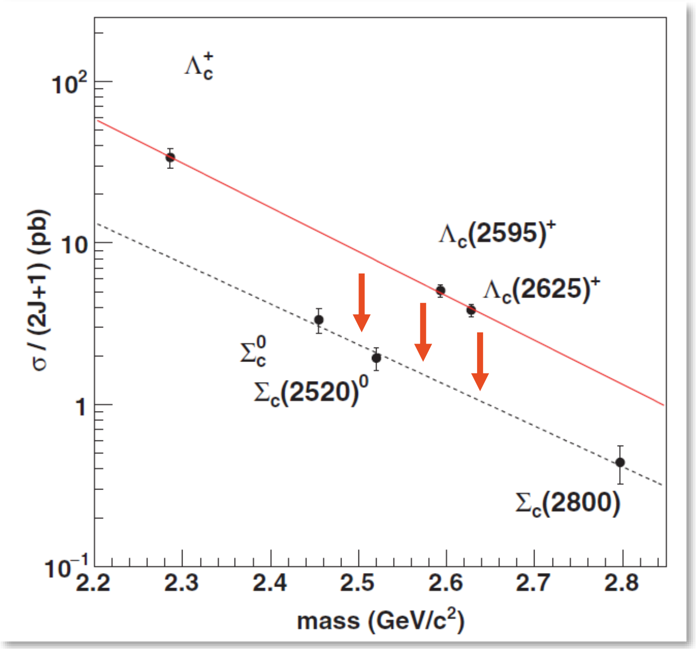
Belle, e^+e^- $\sqrt{s} = 10.52$ GeV
(Phys. Rev. D 97, 072005)

$f(m) = a_0 \exp(a_1 m)$

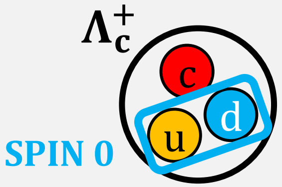
S = -1
S = -2
S = -3

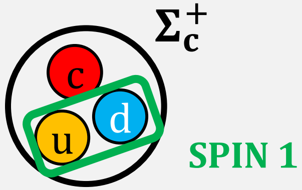
Hierarchy driven by $s\bar{s}$ pair creation





- In conventional fragmentation:
  - charm picks up a spin-0 $(\mathrm{ud})_0$ diquark $\rightarrow$ Λ_c^+ $(I = 0)$
  - charm picks up a spin-1 $(\mathrm{ud})_1$ diquark $\rightarrow$ Σ_c^+ $(I = 1)$





- $(\mathrm{ud})_1$ mass much larger than $(\mathrm{ud})_0$
  $\Rightarrow$ production of Σ_c states expected to be suppressed compared to Λ_c^+

- Σ_c-state production suppressed by ~3-4 times that of excited Λ_c^+ states in e^+e^- collisions at $\sqrt{s} = 10.52$ GeV

The role of Λ_c^+ and $\Sigma_c^{0,+,++}$

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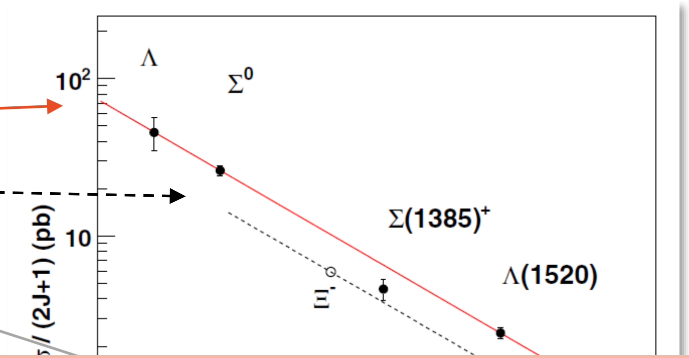

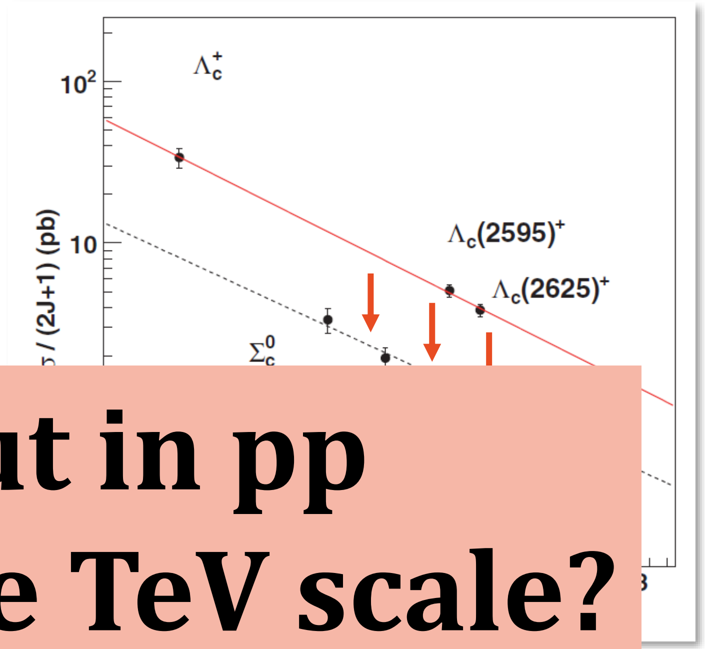

Hierarchy driven by $s\bar{s}$ pair creation

What about in pp collisions at the TeV scale?

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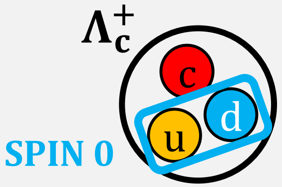

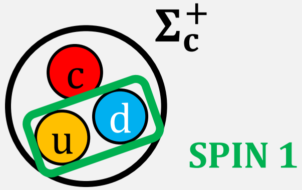

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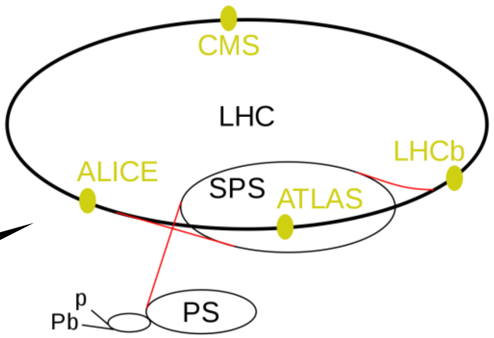
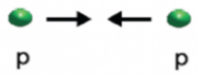
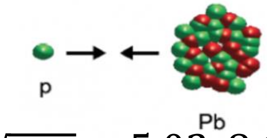
The ALICE apparatus in a nutshell



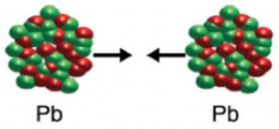
Time Projection Chamber (TPC): tracking, PID via dE/dx



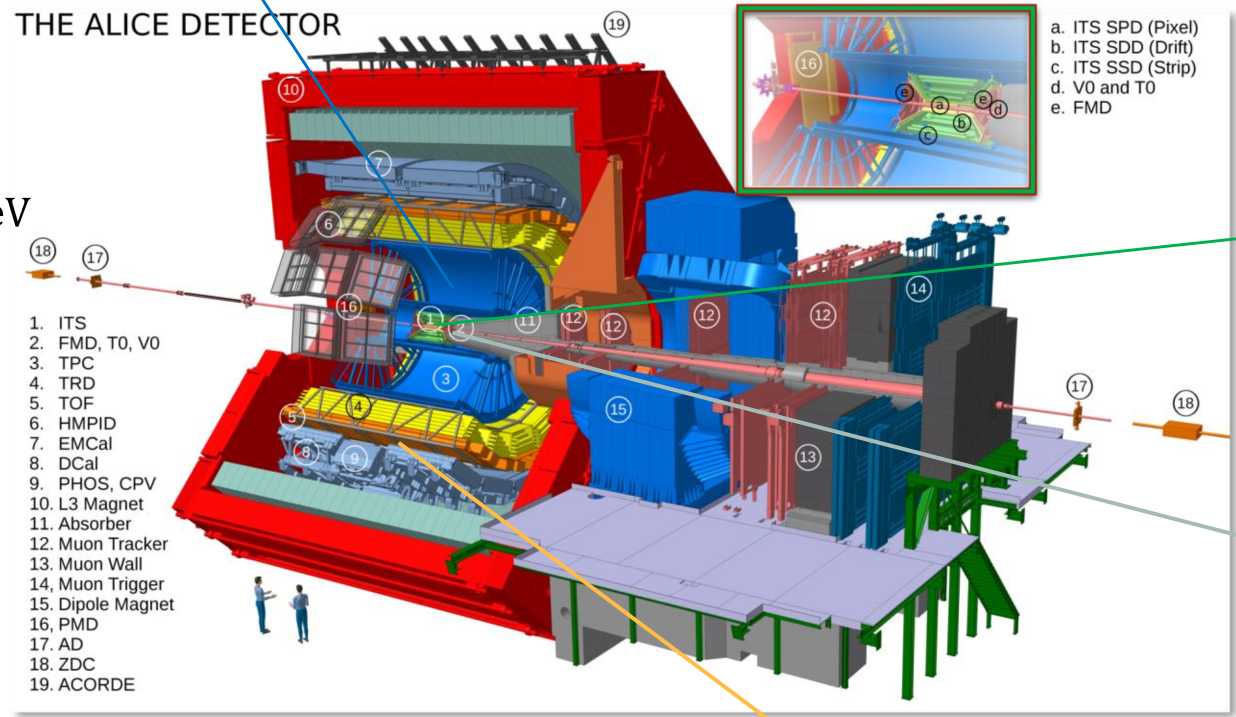
$\sqrt{s}$ = 2.76, 5.02, 7, 8, 13 TeV



$\sqrt{s_{\mathrm{NN}}}$ = 5.02, 8.16 TeV



$\sqrt{s_{\mathrm{NN}}}$ = 2.76, 5.02 TeV



Inner Tracking System (ITS): tracking, vertexing (primary, <u>secondary HF</u>), PID via dE/dx, trigger

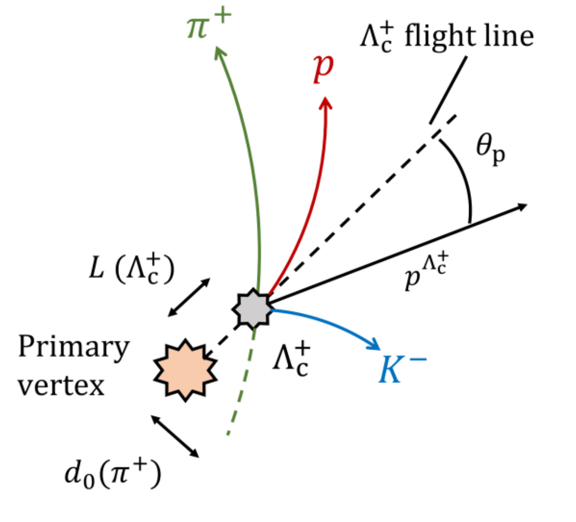
V0: trigger, centrality

T0: start time, luminosity determination

Central barrel coverage: $|\eta| < 0.9$
Muon spectrometer coverage: $-4 < \eta < -2.5$

Time Of Flight (TOF): PID via time of flight

$\Lambda_c^+ \rightarrow pK^-\pi^+$ reconstruction in ALICE



P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Mass (MeV/c^2)	$c\tau$ (μm)	Decay (BR)
Λ_c^+	2286.46 ± 0.14	60.7	$pK^-\pi^+$ ($(6.28 \pm 032)\%$)

- Variables linked to the displaced decay topology exploited
- Secondary vertex: 3D point of closest approach among identified p, K^-, π^+ tracks

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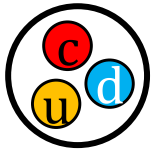

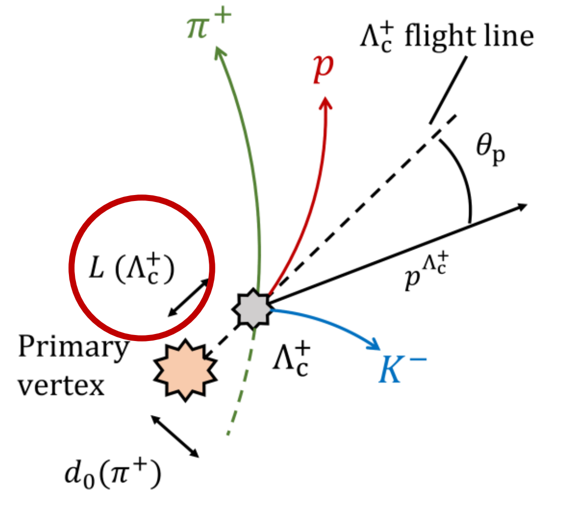

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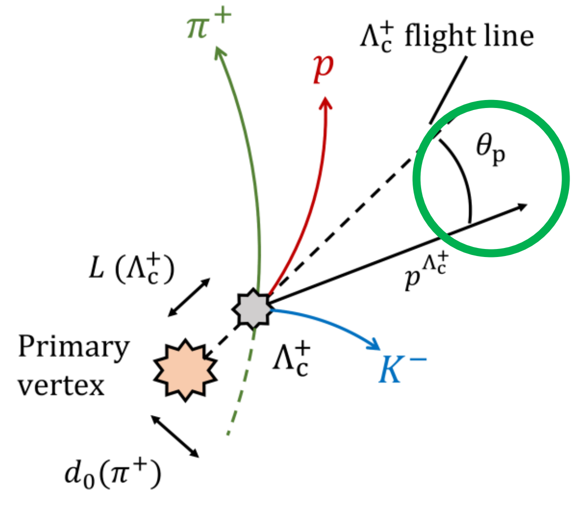
Examples

Decay length *L*

- Distance between beam interaction point and secondary vertex
- Intrinsic displacement of Λ_c^+ baryons

$\Lambda_c^+ \to pK^-\pi^+$ reconstruction in ALICE



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Examples

Decay length *L*

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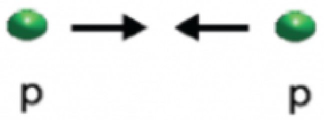
- Intrinsic displacement of Λ_c^+ baryons

Cosine of pointing angle ($\cos\theta_p$)

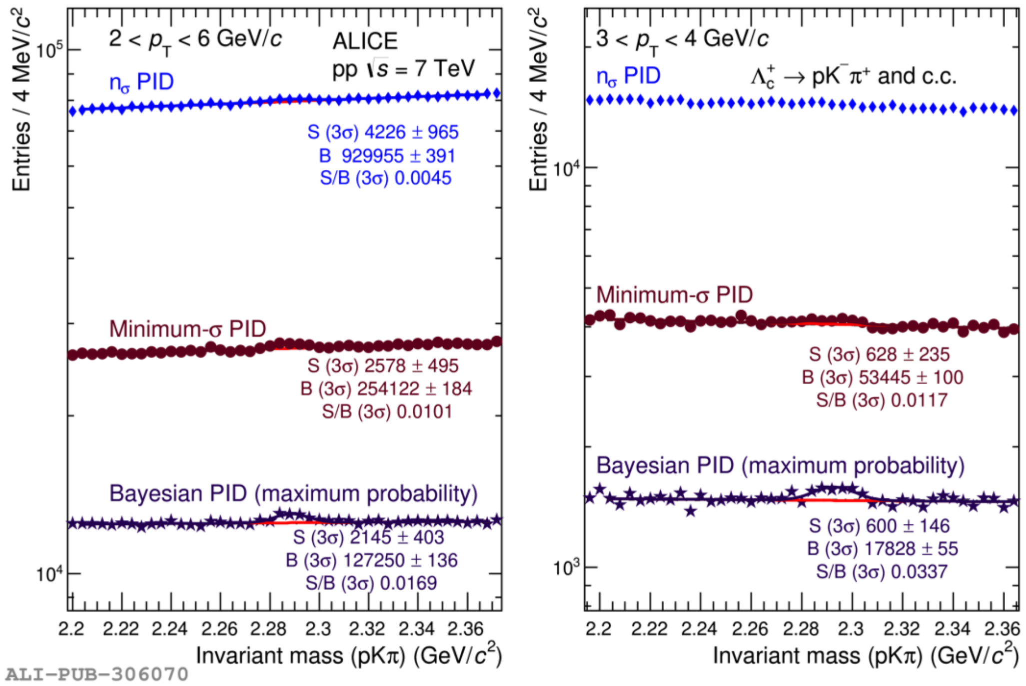
- Angle between the Λ_c^+ flight-line and the reconstructed momentum
- $\cos\theta_p = 1$ for signal (smearing due to resolution)

$\Lambda_c^+ \rightarrow pK^-\pi^+$: Bayes PID



$\sqrt{s} = 7$ TeV

Eur. Phys. J. Plus 131 (2016) 168



- × 7 more background rejection
- × 3 larger signal-to-background

- Method to better exploit the PID capabilities of the full apparatus (TPC and TOF in this analysis)
- Detector signals expressed in terms of probabilities:

$$P_\alpha(S_\alpha|H_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\left(S_\alpha - \hat{S}_\alpha(H_i)\right)^2}{2\sigma^2}}, \quad i\text{: species, } \alpha\text{: detector}$$

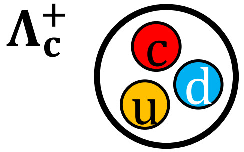
- Total likelihood = product of detector probabilities
- Posterior probability from the **Bayes' theorem**:

$$P(H_i|\vec{S}) = \frac{P(\vec{S}|H_i)C(H_i)}{\sum_{k=e,\mu,\pi,\ldots} P(\vec{S}|H_k)C(H_k)}$$

Likelihood

Prior ↔ measured p, K^-, π^+ relative abundances

$\Lambda_c^+ \to pK_s^0$ reconstruction in ALICE



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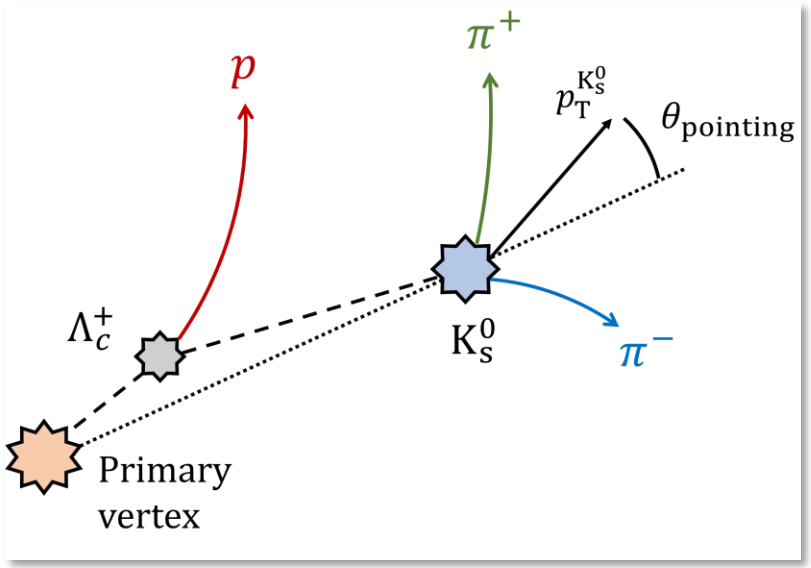
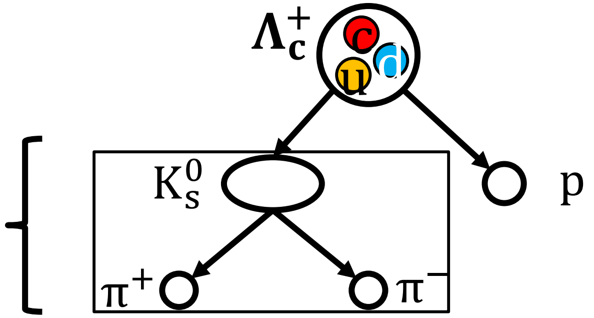


	Mass (MeV/c^2)	$c\tau$ (μm)	Decay (BR)
Λ_c^+	2286.46 ± 0.14	60.7	pK_s^0 (1.59 %)

BR (total) = 1.1 %

BR = 69.2 %

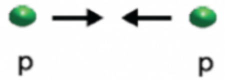


"V0" decay topology

- Λ_c^+ secondary vertex not reconstructed → K_s^0 propagation to primary vertex not precise enough
- Exploited variables (examples):
  - "bachelor" proton track:
    - → Impact parameter
    - → $\cos\theta^*$ (angle in Λ_c^+ rest frame w.r.t. Λ_c^+ momentum)
    - → PID in TPC, TOF
  - K_s^0:
    - → Invariant mass
    - → $\cos\theta_p$
    - → $c\tau$

BDT (AdaBoost, XGBoost) applied to optimise the signal-to-background separation

$\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$ reconstruction in ALICE

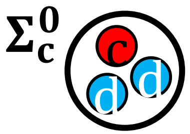


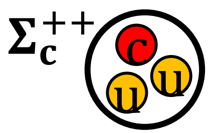
$\sqrt{s}$ = 13 TeV

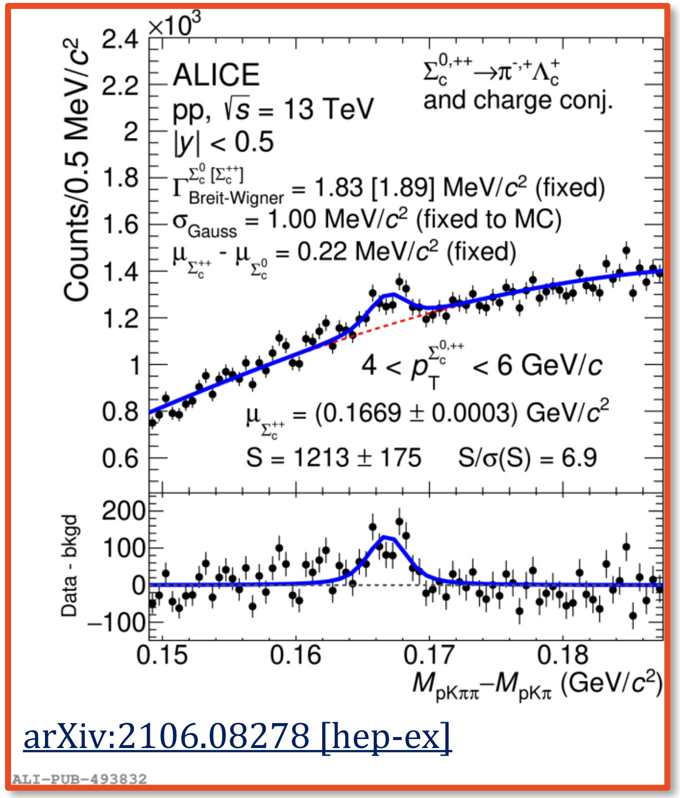
- BR$(\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}) \approx 100\%$
  - ➢ Strong decay
  - ➢ No displacement from the primary vertex ⇒ no topological selections

	Σ_c^0	Σ_c^+	Σ_c^{++}
m (MeV/c^2)	2453.75 ± 0.14	2452.9 ± 0.4	2453.97 ± 0.14
Γ (MeV/c^2)	$1.83^{+0.11}_{-0.19}$	< 4.6 (90% CL)	$1.89^{+0.09}_{-0.18}$
Δm with Λ_c^+ (MeV/c^2)	167.290 ± 0.017	166.4 ± 0.4	167.510 ± 0.017
Δm with Σ_c^0 (MeV/c^2)	-	-0.9 ± 0.4	0.220 ± 0.013

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

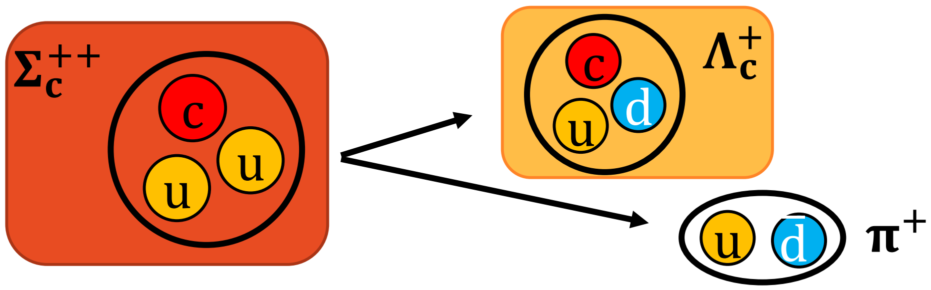






arXiv:2106.08278 [hep-ex]

- $\Delta M \equiv M(\text{pK}^-\pi^+\pi^{-,+}) - M(\text{pK}^-\pi^+)$ distribution
  - → $\pi^{-,+}$ momentum resolution dominates
- Σ_c^0 and Σ_c^{++} contributing to the signal
- Signal fit function: sum of two Voigt
  - → Convolution of Breit-Wigner (Γ width) and Gauss (σ resolution)



Cross section measurement

$$\mathcal{L}_{int.} = 32\ nb^{-1}$$
$$BR(pK^-\pi^+) = 100\% \cdot 6.28\%$$
$$BR(pK^0_s) = 1.59\% \cdot 69.20\% = 1.10\%$$

$$\left.\frac{d\sigma^H}{dp_T}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta p_T}\cdot\frac{f_{prompt}\, N^H_{|y|<y_{fid.}}}{\alpha_y(acc\times\varepsilon)_{prompt}}\cdot\frac{1}{BR}\cdot\frac{1}{\mathcal{L}_{int.}}$$

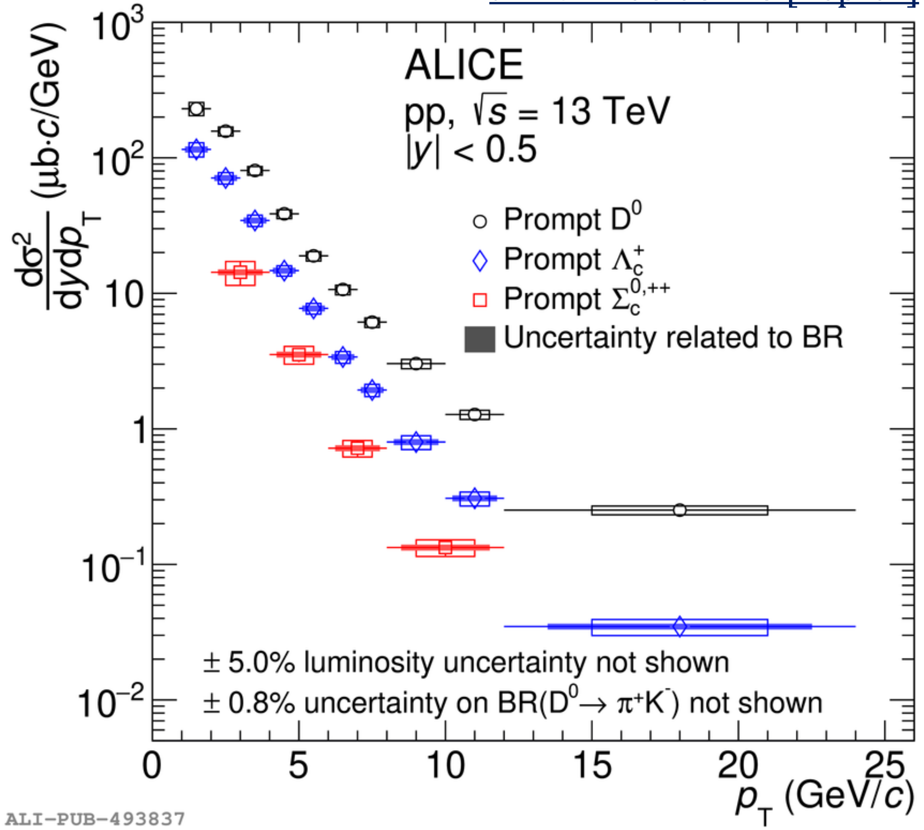
Signal measured from invariant mass fits

Prompt fraction (f_{prompt})

- Correction for fraction of prompt baryons out of all reconstructed
- Correction based on MC simulations ($\alpha_y(acc \times \varepsilon)$), FONLL calculations (b-quark cross section) and LHCb measurements (b-quark fragmentation functions)

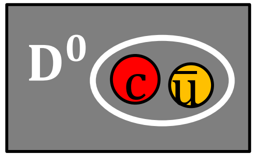
$\alpha_y(acc \times \varepsilon)$ → efficiency from MC simulations

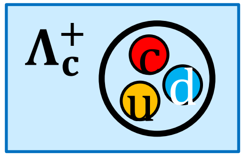
arXiv:2106.08278 [hep-ex]

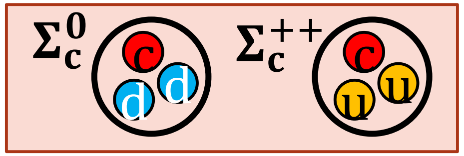


ALI-PUB-493837

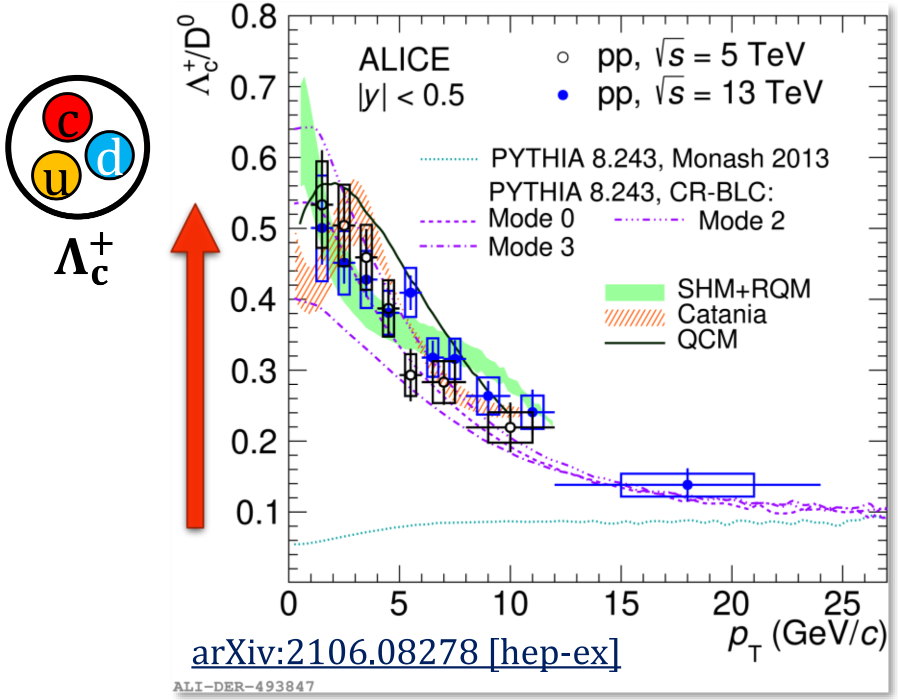
- Final result: average of cross sections measured exploiting the $\Lambda_c^+ \rightarrow pK^-\pi^+$ channel (this work) and the $\Lambda_c^+ \rightarrow pK^0_s$







Charm hadron ratios



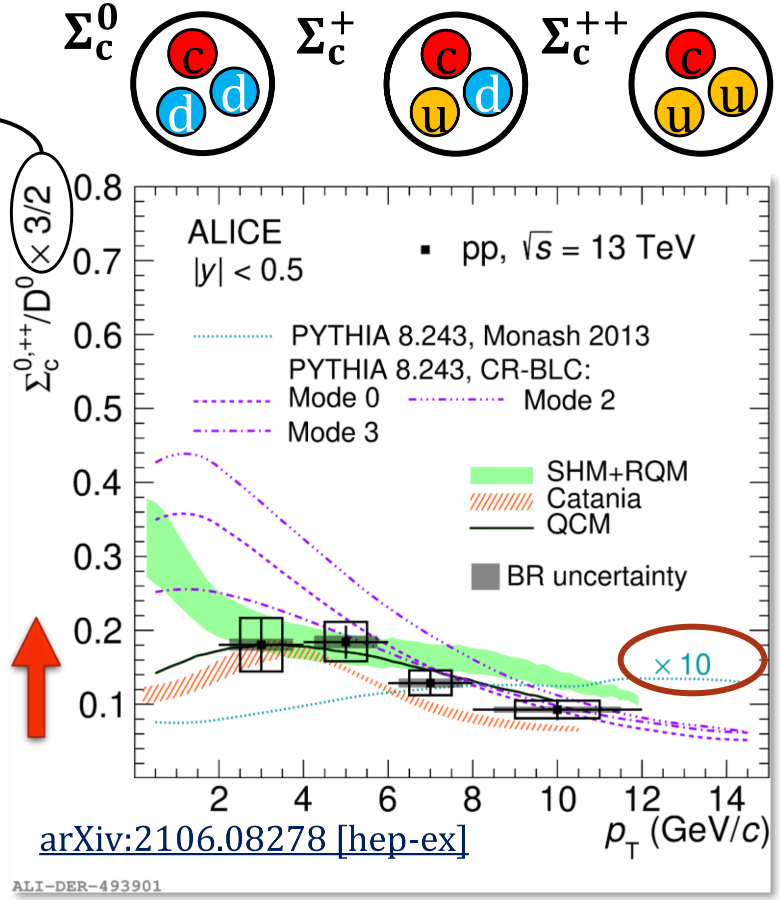
arXiv:2106.08278 [hep-ex]

$\frac{\Lambda_c^+}{D^0}$

e^+e^-

Factor × 3/2 : isospin symmetry assumed

$\frac{\Sigma_c^{0,+,++}}{D^0}$



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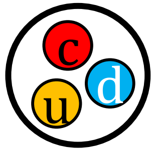
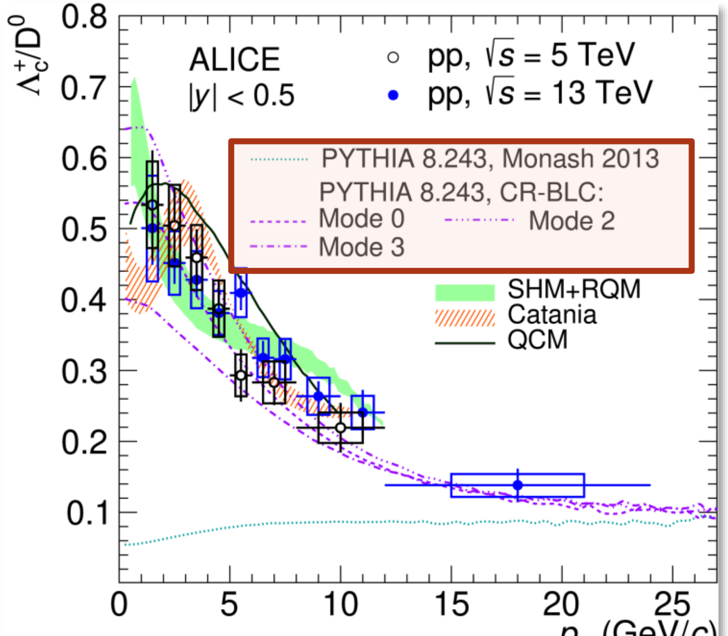


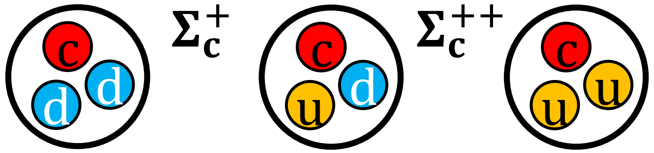
Λ_c^+

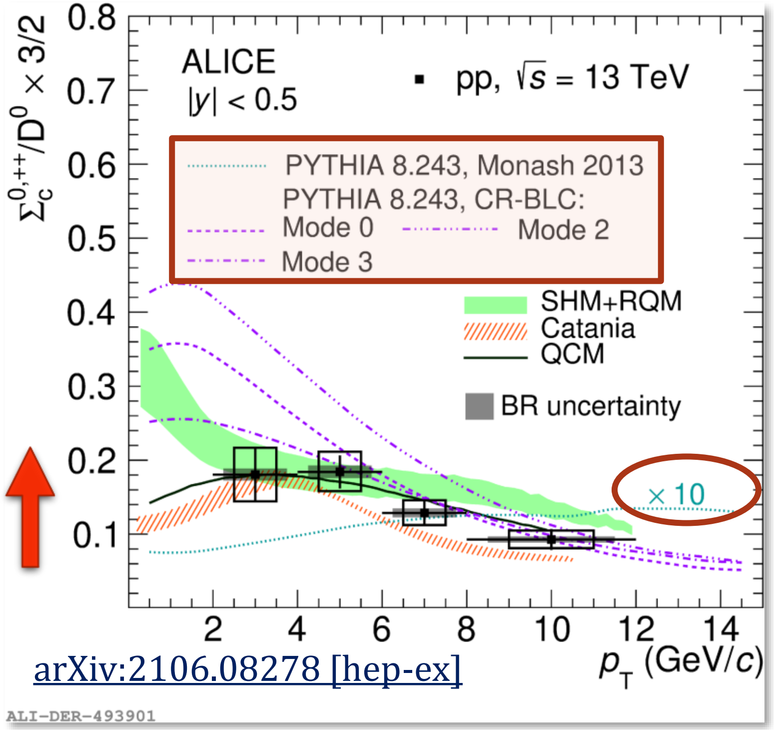


[arXiv:2106.08278 [hep-ex]](https://arxiv.org/abs/2106.08278)

[(PYTHIA 8 CR-BLC) J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003]()

Σ_c^0 Σ_c^+ Σ_c^{++}





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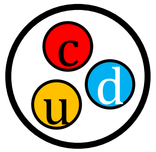
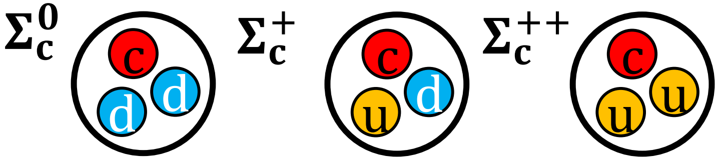
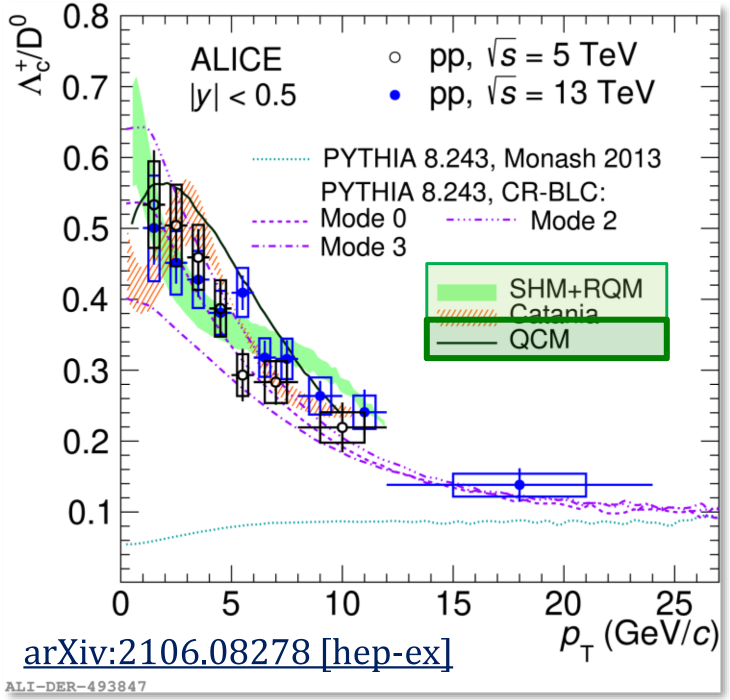


Λ_c^+

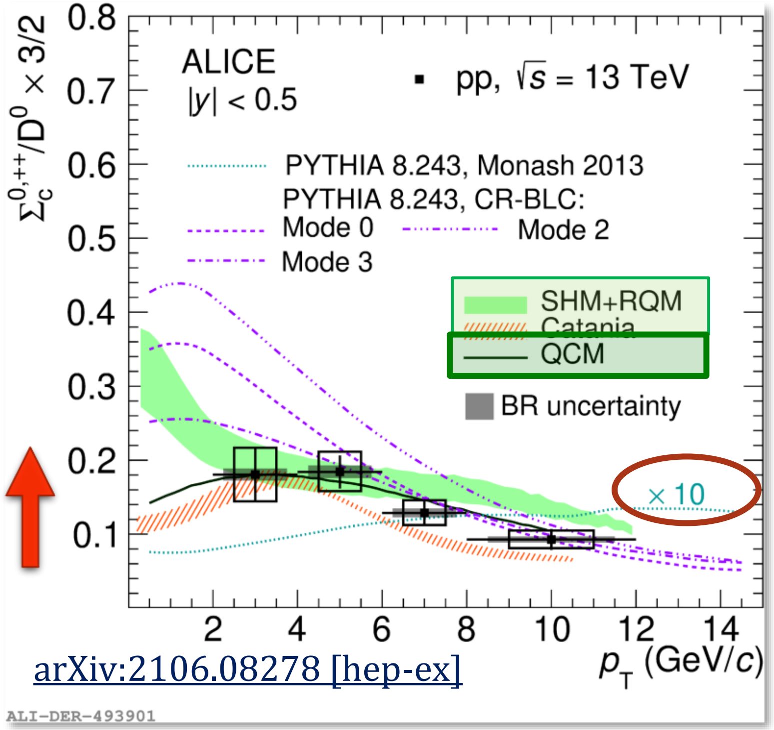




arXiv:2106.08278 [hep-ex]

(SHM+RQM) M. He, R. Rapp: PLB 795 (2019) 117-121

(QCM) J. Song, H. Li, F. Shao: Eur. Phys. J. C (2018) 78: 344



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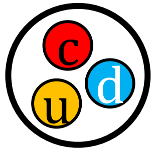
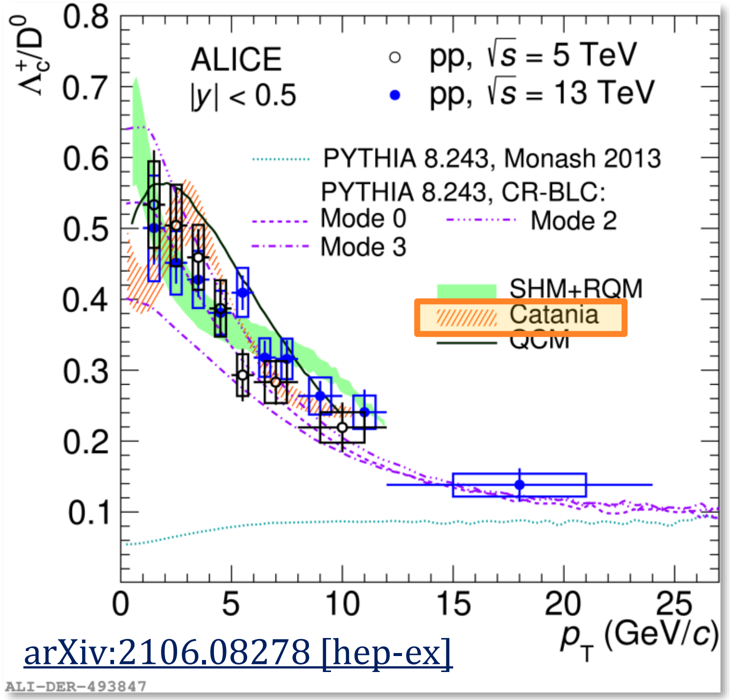
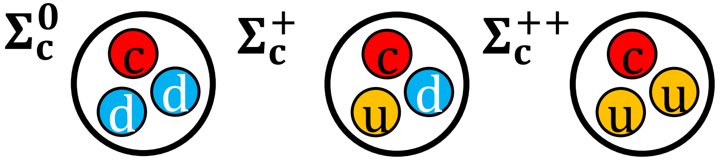


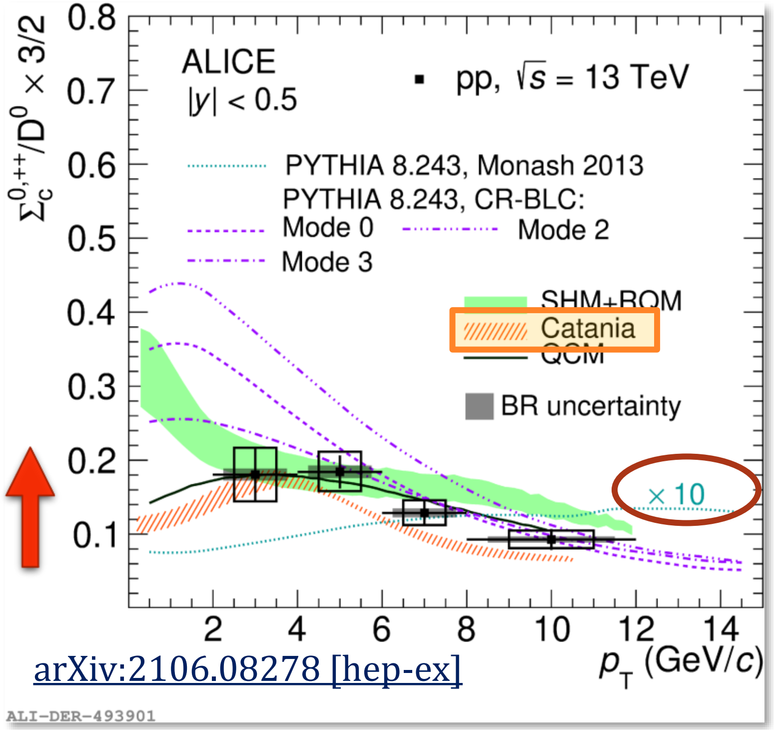
Λ_c^+



arXiv:2106.08278 [hep-ex]

(Catania) V. Minissale, S. Plumari, V. Greco: arXiv:2012.12001





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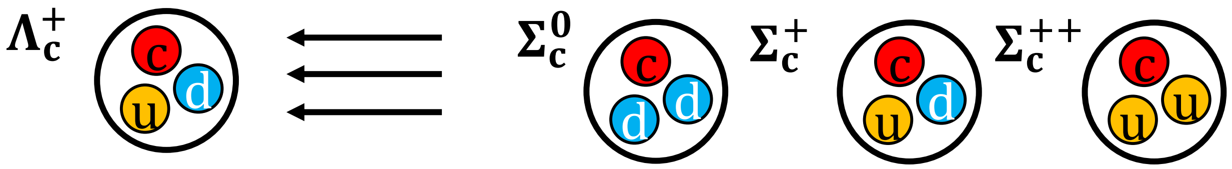
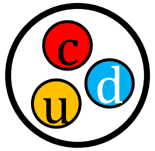
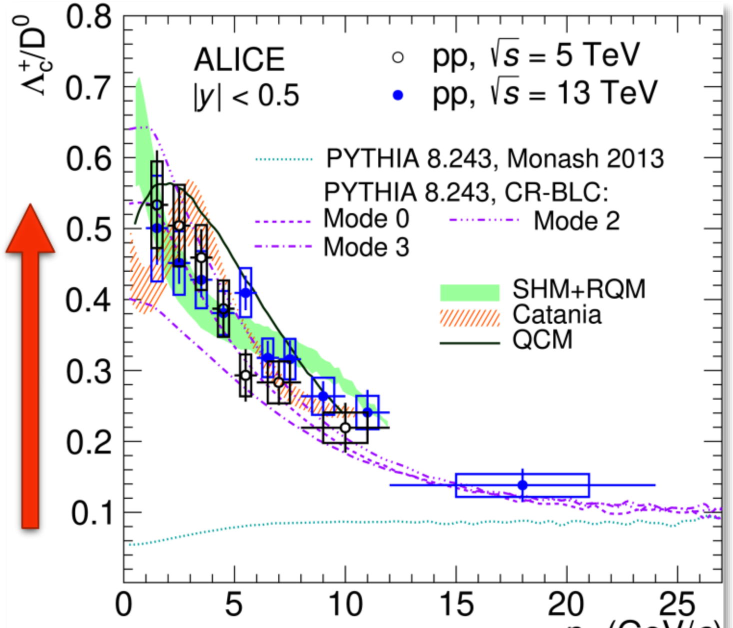




Λ_c^+

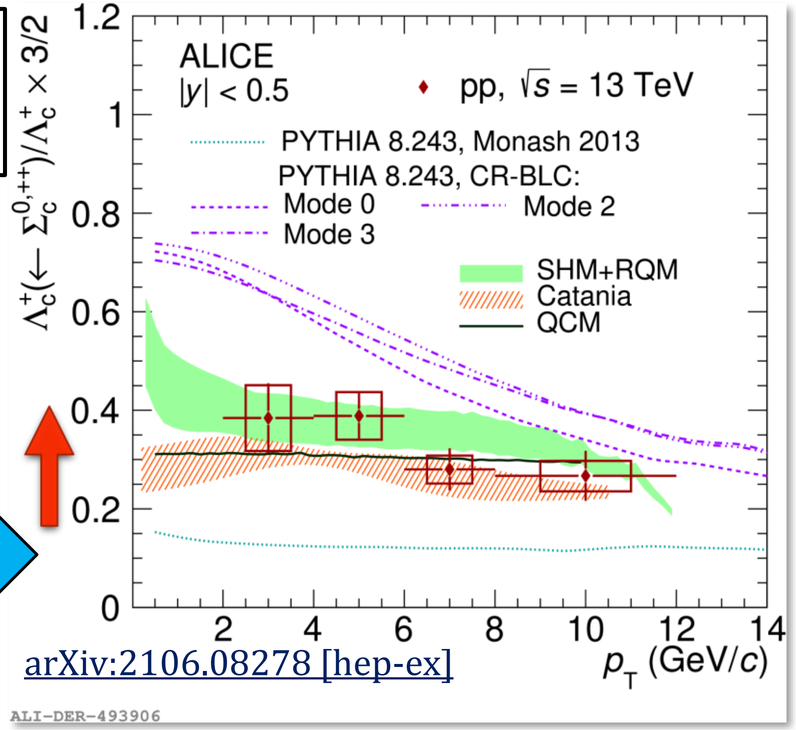


[arXiv:2106.08278 [hep-ex]]

$$\frac{\Lambda_c^+}{D^0}$$

e^+e^-

$$\frac{\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}}{\Lambda_c^{0+}}$$



[arXiv:2106.08278 [hep-ex]]

- First measurement of Λ_c^+ fraction from $\Sigma_c^{0,+,++}$ decays in pp collisions at the LHC:
  $\mathbf{0.38 \pm 0.06(stat.) \pm 0.06(syst.)}$

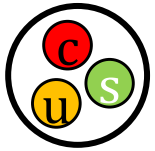
No more «di-quark» penalty factor for $\Sigma_c^{0,+,++}$ formation

→

Canonical fragmentation in pp collisions at the TeV scale fully overcome by new hadronization processes?

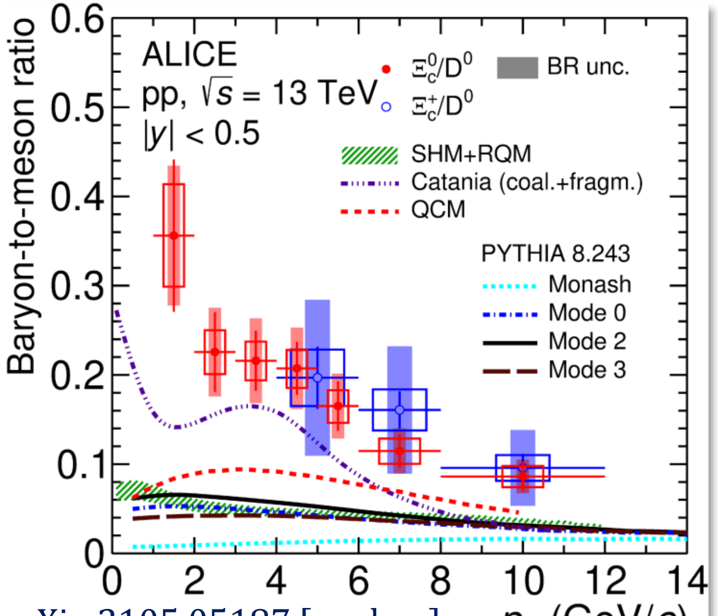
Charm hadron ratios

More on A. Rossi's talk "*Charm hadronization in pp and p-Pb collisions*"



Ξ_c^+

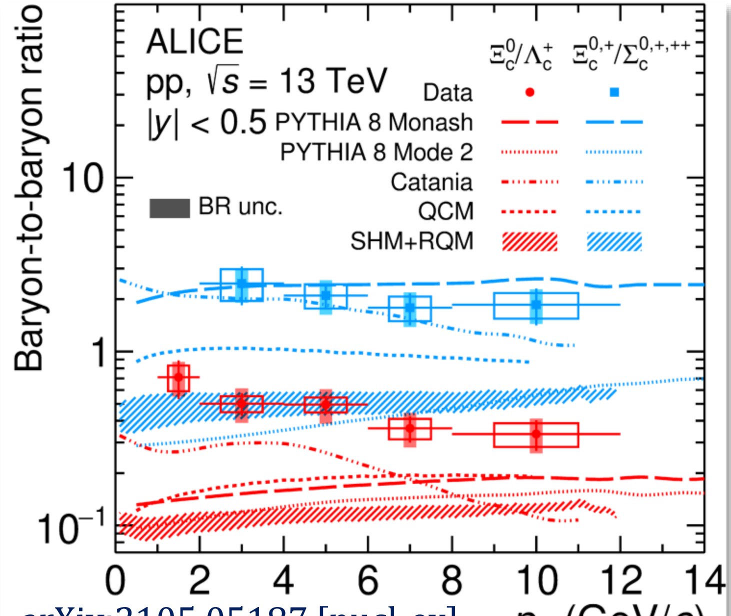
$\frac{\Xi_c^{0,+}}{D^0}$



arXiv:2105.05187 [nucl-ex]

$\frac{\Xi_c^{0,+}}{\Sigma_c^{0,+,++}}$

$\frac{\Xi_c^{0,+}}{\Lambda_c^+}$



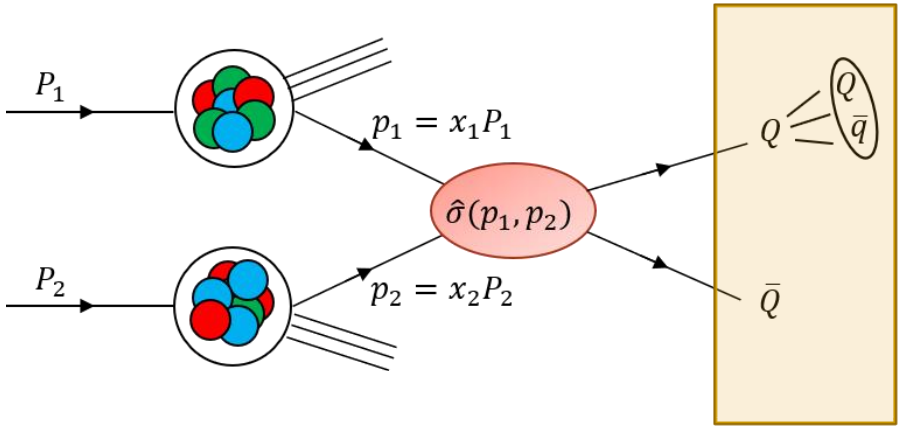
arXiv:2105.05187 [nucl-ex]

- $\Xi_c^{0,+}/D^0$ significantly larger in pp collisions at TeV scale than e^+e^- collisions
- $\Xi_c^{0,+}/D^0$ significantly underestimated by all the models describing $\Lambda_c^+, \Sigma_c^{0,+,++}/D^0$ ratios
  → only Catania (coalescence + fragmentation) gets close to the data

- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio in line with PYTHIA Monash (↔ e^+e^-)
  → similar suppression in e^+e^- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$?
  → matter of similar (di-quark) mass? $(m(\mathrm{uu,ud,dd})_1 \simeq m(\mathrm{us})_0)$

Summary

- Standard picture for the **heavy flavour production** in pp collisions based on the factorization approach, assuming **universal fragmentation functions**
- Recent results from LHC show that this **assumption** is **no more valid** in **hadronic collisions** at LHC
- Joint effort between theory and experiments to investigate the baryon enhancement in hadronic collisions



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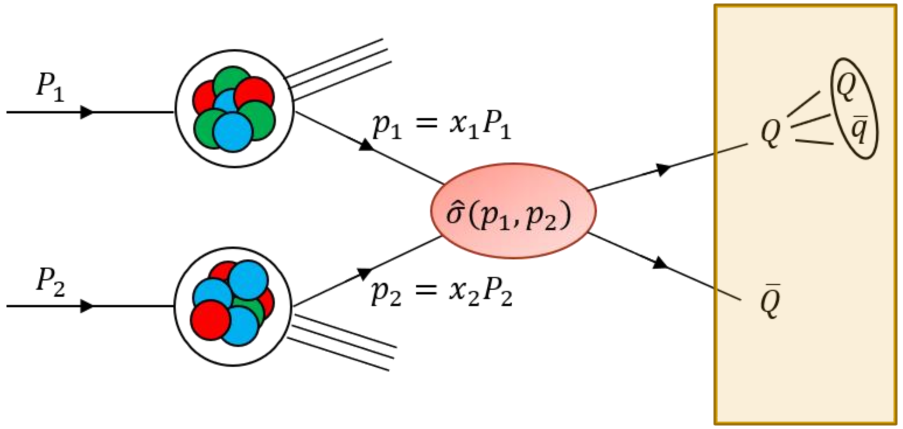
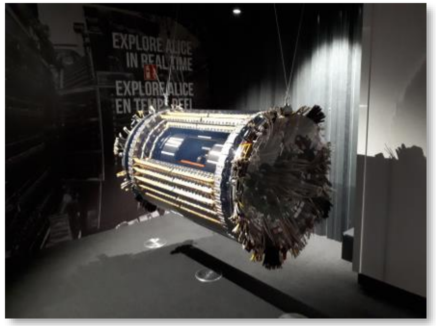
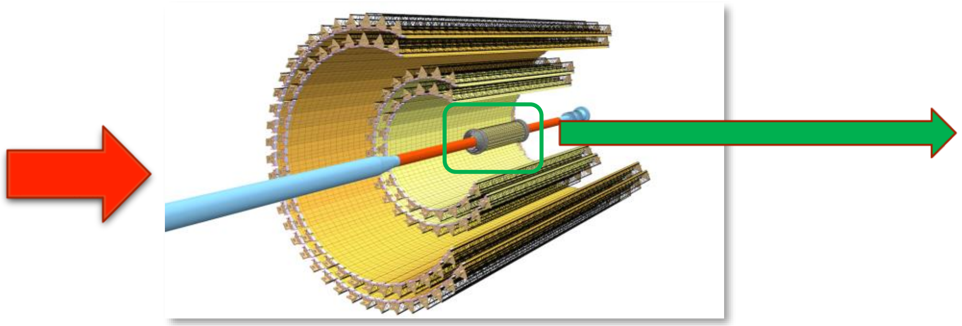


Run 3, 4 data taking starting in early 2022
→ larger statistics
→ upgraded detectors

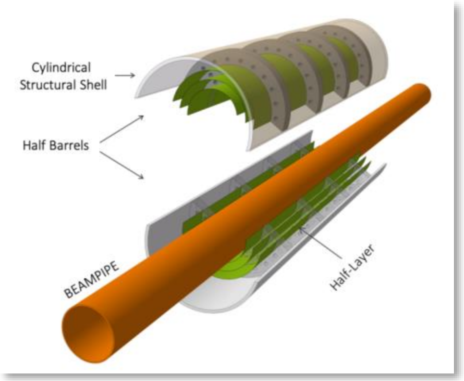
ITS 1 (ALICE exhibition)



ITS 2



ITS 3



Thank you very much for the attention!

Backup