Study of charm baryon production and hadronization with ALICE

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Charm quarks hadronisation

hadronisation described by **factorisation approach**, which works well for charm and beauty mesons :

Nucl. Phys. B 263 (1986) 37

$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_{T};\mu_{F};\mu_{R}) = PDF(x_{a},\mu_{F})PDF(x_{b},\mu_{F}) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_{a},x_{b},\mu_{R},\mu_{F}) \otimes D_{c\to D}(z = p_{D}/p_{c}, \mu_{F})$$

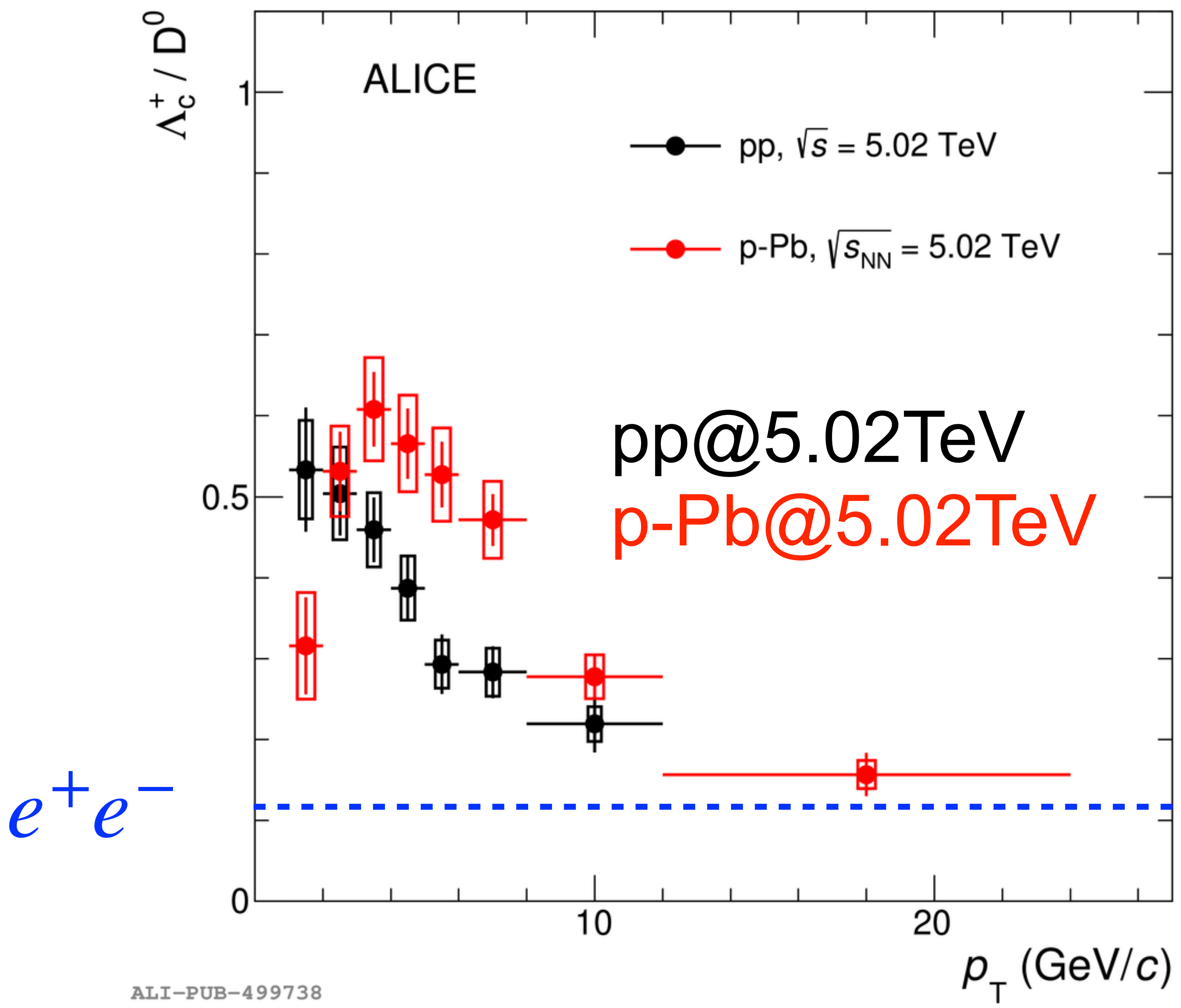
Parton distribution function(PDF) (non-perturbative)

Partonic cross section (perturbative)

hadronisation by fragmentation (non-perturbative)

c $m_{c} \approx 1.3\ \mathrm{GeV}/c^{2}$

Phys. Rev. C 104 (2021) 054905



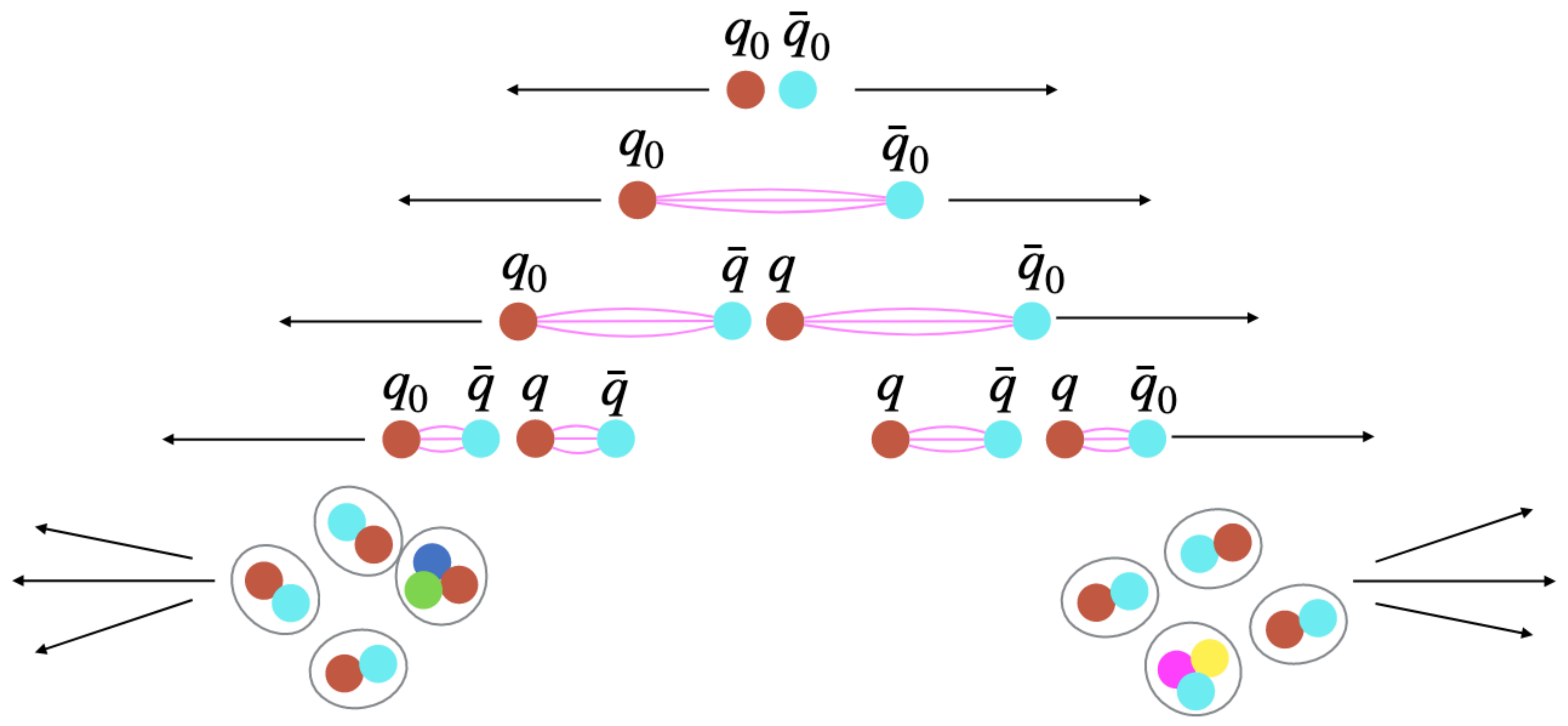
▸ **Ratios of particle species** → ratios of fragmentation fractions, sensitive to HF quark hadronisation

▸ Hadronisation mechanisms **vary** in different collision systems

Hadronisation mechanism

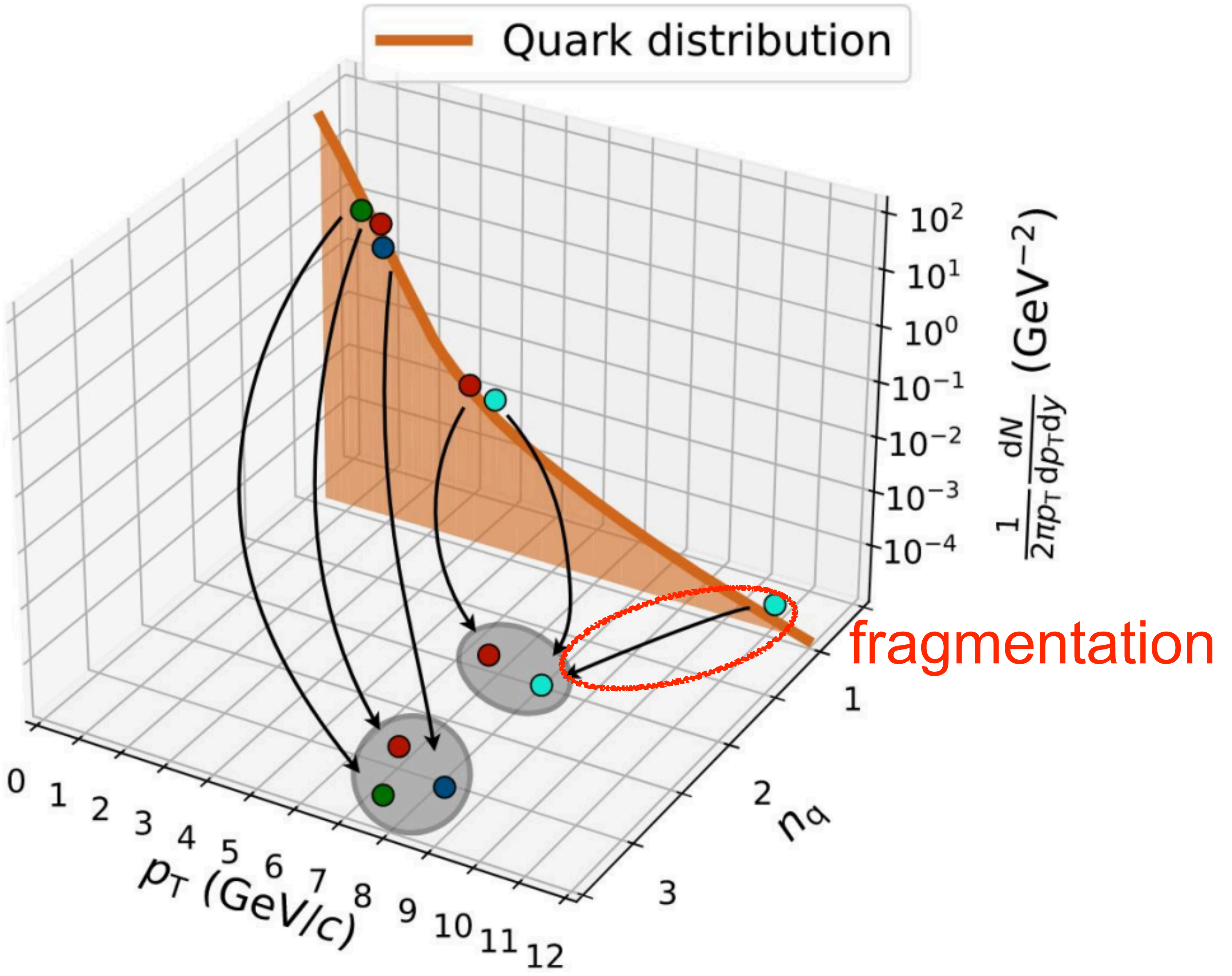
The hadronisation process is typically described via two different mechanisms:

Eur. Phys. J. C 85 (2025) 16,



(i) Fragmentation

https://indico.cern.ch/event/1139644/contributions/5344541/attachments/2711287/4708030/QM2023_openhf_fgrosa.pdf

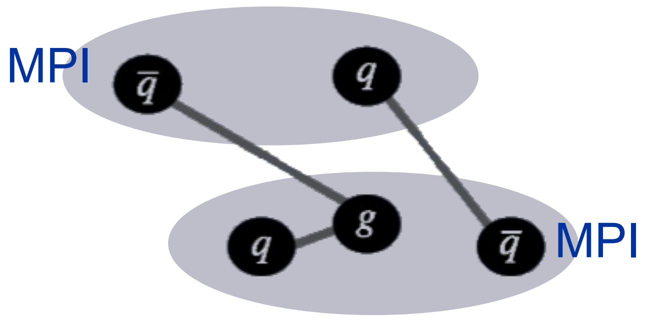


(ii)Recombination/coalescence

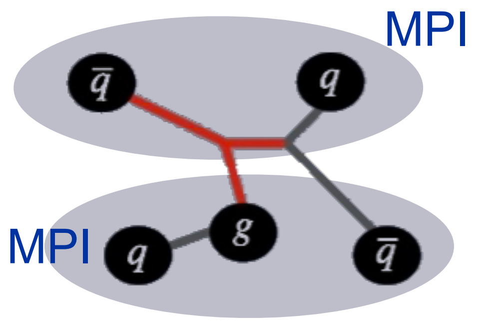
Modeling hadronization

PYTHIA 8

- Hadronization via **fragmentation**, **color reconnection** between partons from different multiparton interaction.



Monash
(tuned to e^+e^- measurements)
Eur. Phys.J. C 74 (2014) 3024



Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

POWLANG

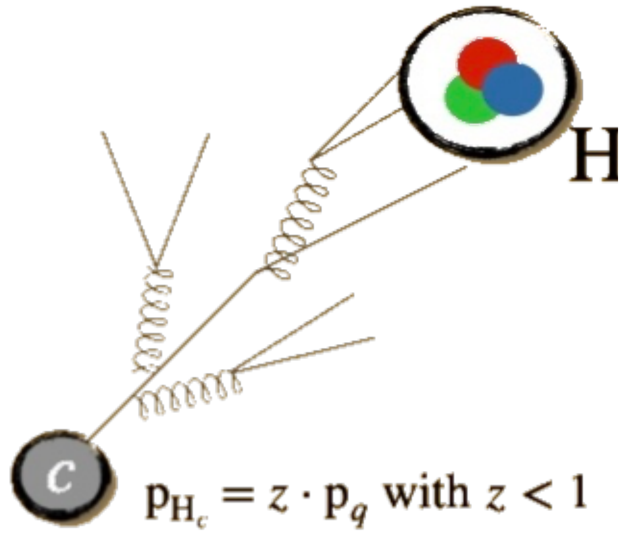
Phys. Rev. D 109 (2024)

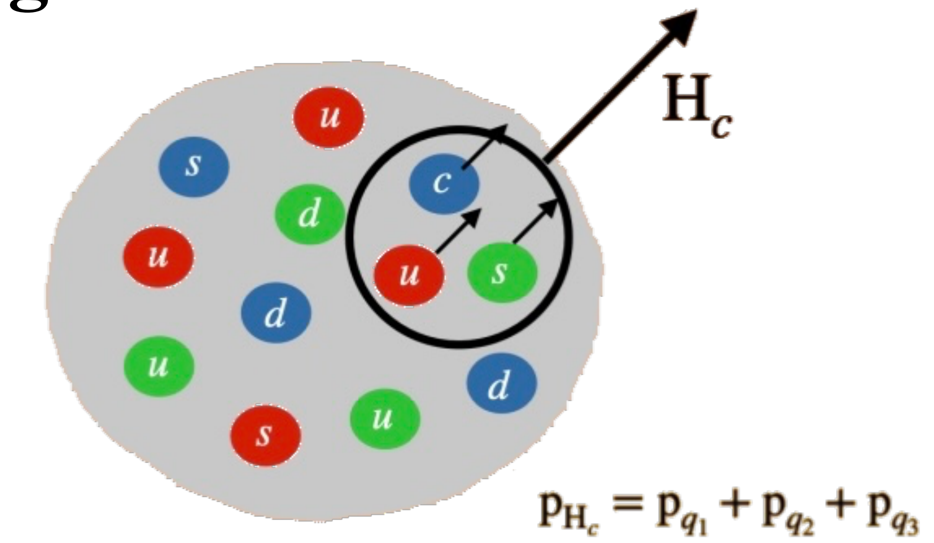
- Based on the idea of quark **recombination**, implementation of **PYTHIA** generated charm quarks within a **hydrodynamical** background.

CATANIA

Phys.Lett.B 821 (2021) 136622

- Hadronization via both **fragmentation** and **coalescence.**

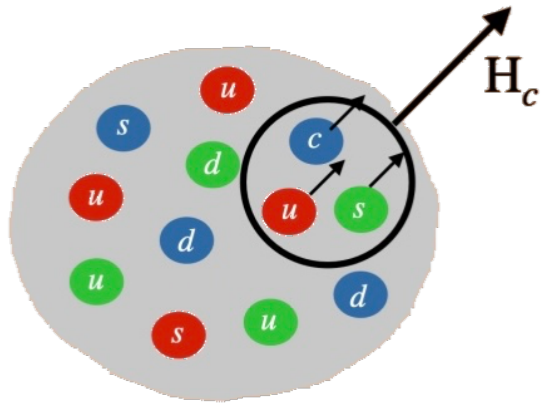




QCM

Eur.Phys.J.C 78 (2018) 344

- Quark (re-) Combination Mechanism **equal-velocity combination** of charm quark and light quarks (spatial properties neglected).



SHM+RQM

Phys.Lett.B 795 (2019) 117-121
Phys.Rev.D.84 (2011) 014025

Statistical Hadronization Model + Relativistic Quark Model

- Complexity of hadronization process replaced by **statistical weights** governed by hadron mass.
- Feed-down from largely **augmented set of charm baryon stated beyond** the ones currently listed in the **PDG**, as predicted by Relativistic Quark Model.

Comparison of hadronization models

	Fragmentation	Recombination
PYTHIA 8	✔	✘
POWLANG	✔	✔
QCM	✘	✔
CATANIA	✔	✔

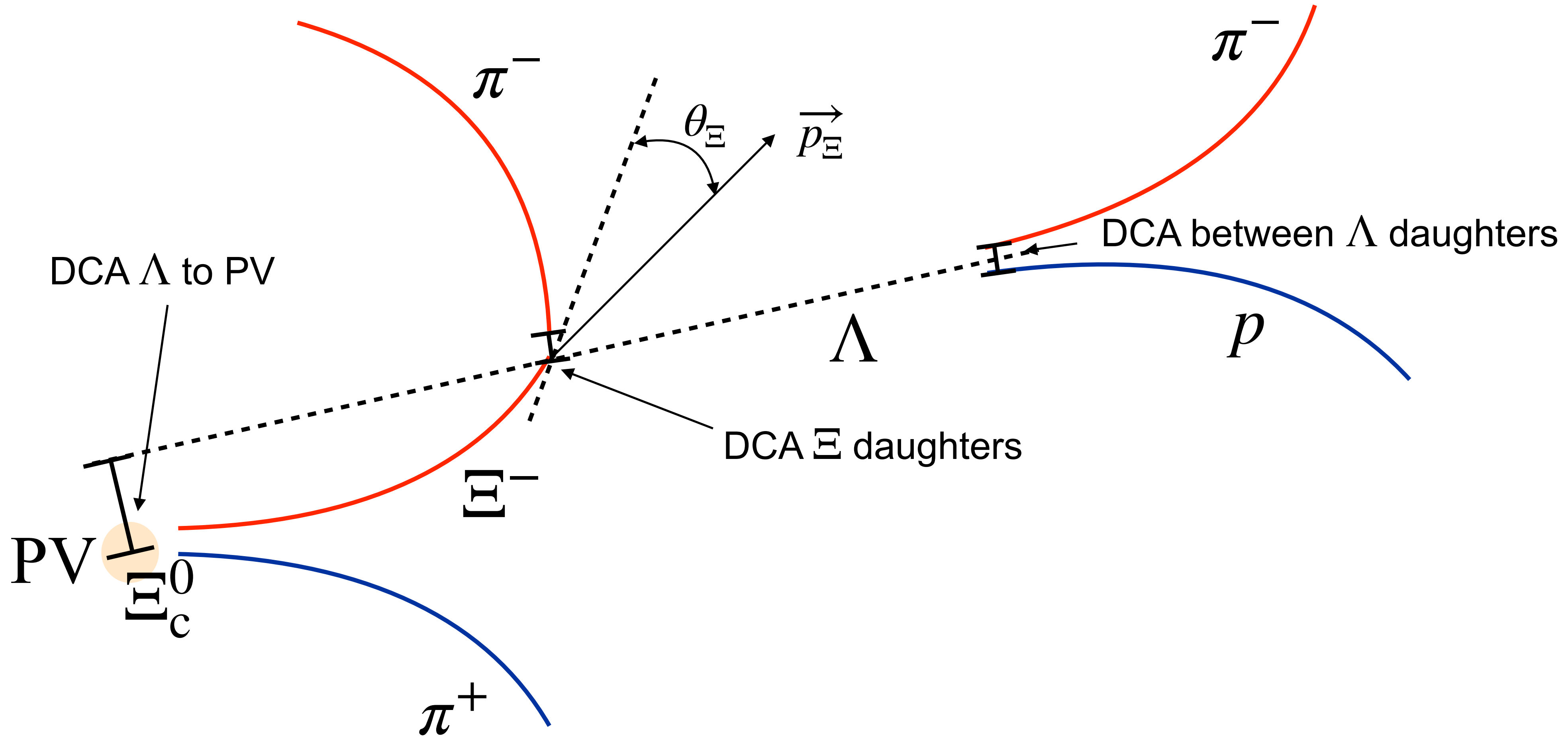
Charm baryons

	Charm Baryons					
	Λ_c^+(udc)	Σ_c^0(ddc)	Σ_c^{++}(uuc)	Ξ_c^+(usc)	Ξ_c^0(dsc)	Ω_c^0(ssc)
Strangeness	0			1		2
Mass(MeV/c^2)	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	60.7	—	—	136.6	45.8	80

Charm baryon reconstruction

Analysis strategy

- **Hadronic decay channel:**
  - $\Lambda_c^+ \to pK^-\pi^+$
  - $\Sigma_c^{0,+} \to \pi^{-,+}\Lambda_c^+$
  - $\Xi_c^0 \to \pi^+\Xi^- \to \pi^+(\pi^-\Lambda) \to \pi^+(\pi^-(p\pi^-))$
  - $\Omega_c^0 \to \pi^+\Omega^- \to \pi^+(K^-\Lambda) \to \pi^+K^-(p\pi^-))$



The sketch of $\Xi_c^0 \to \pi^+\Xi^-$

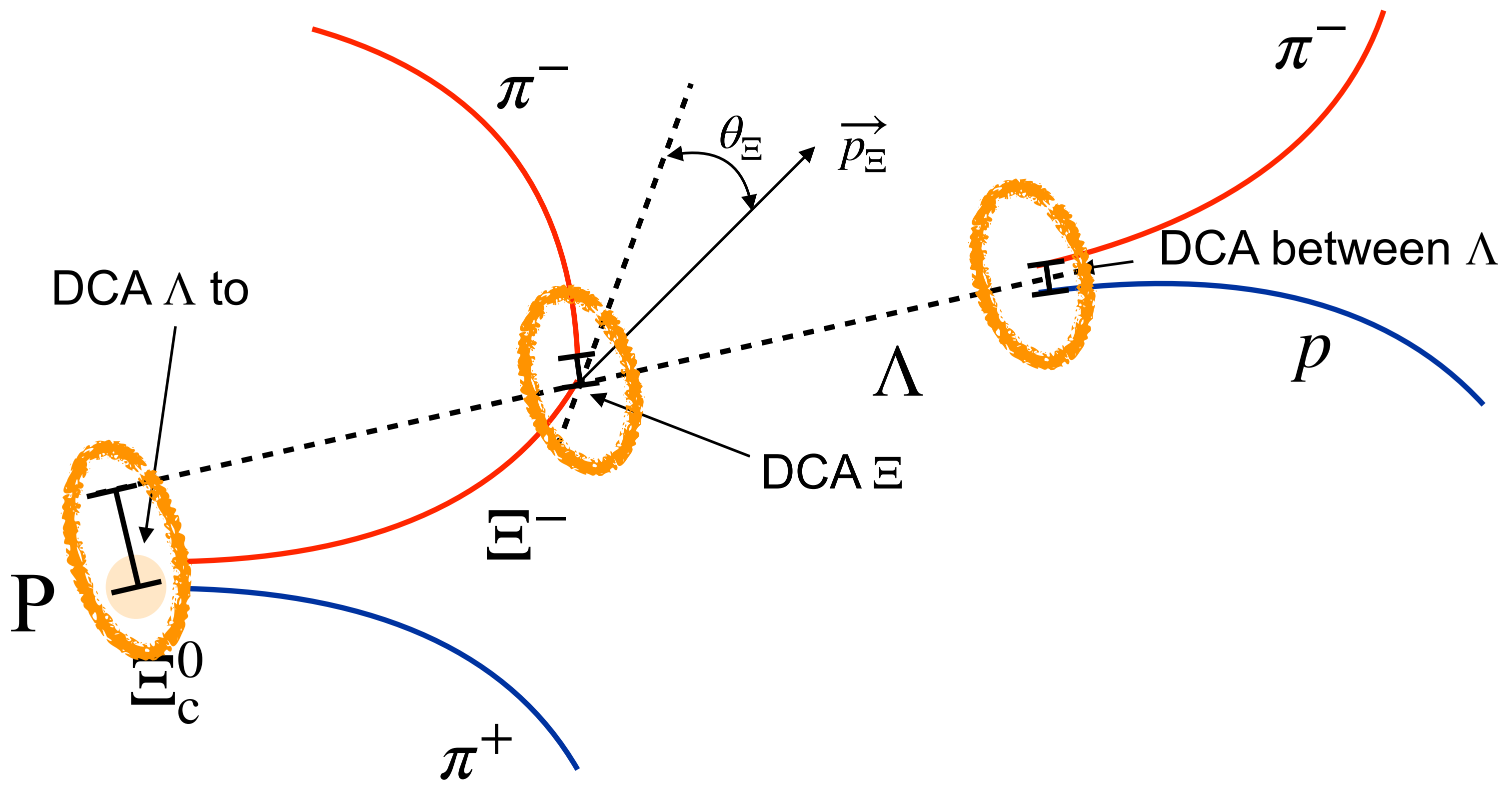
- **Analysis strategy for Ξ_c^0:**
  - Select $\pi^\pm$ and $\Xi^\mp$ (pre-selections)
  - Make pairs of $\pi^+\Xi^-$ and $\pi^-\Xi^+$ and fit the invariant mass to extract signal
  - Correct yield by Acc. x Eff.

$$\text{Acc.} \times \text{Eff.} = \frac{N^{\Xi_c^0}_{\text{MC,rec}}\big|_{|y|<0.8}\,(\text{with preselection and BDT cut})}{N^{\Xi_c^0}_{\text{MC,gen}}\big|_{|y|<0.8}}$$

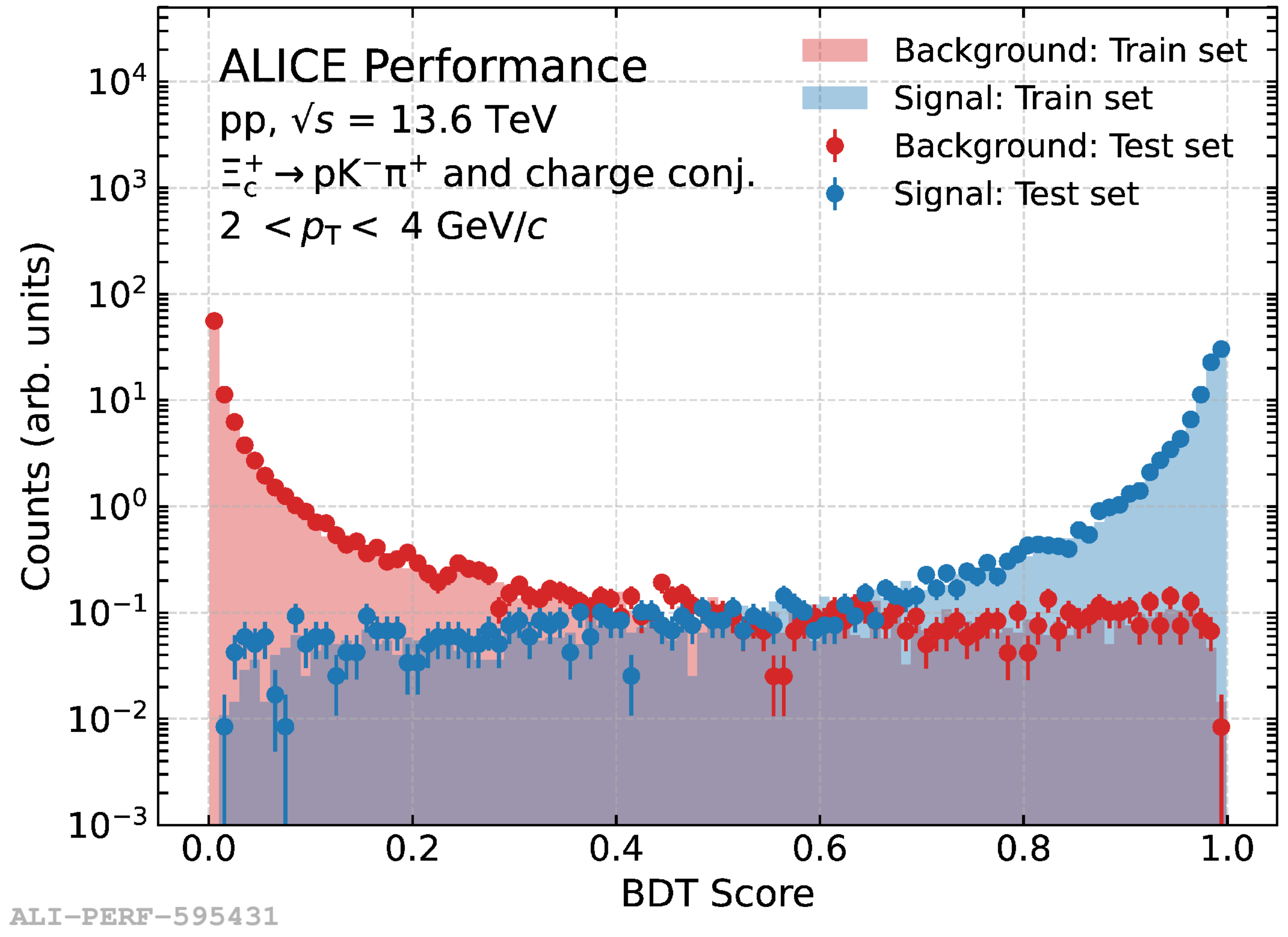
  - Feed-down subtraction

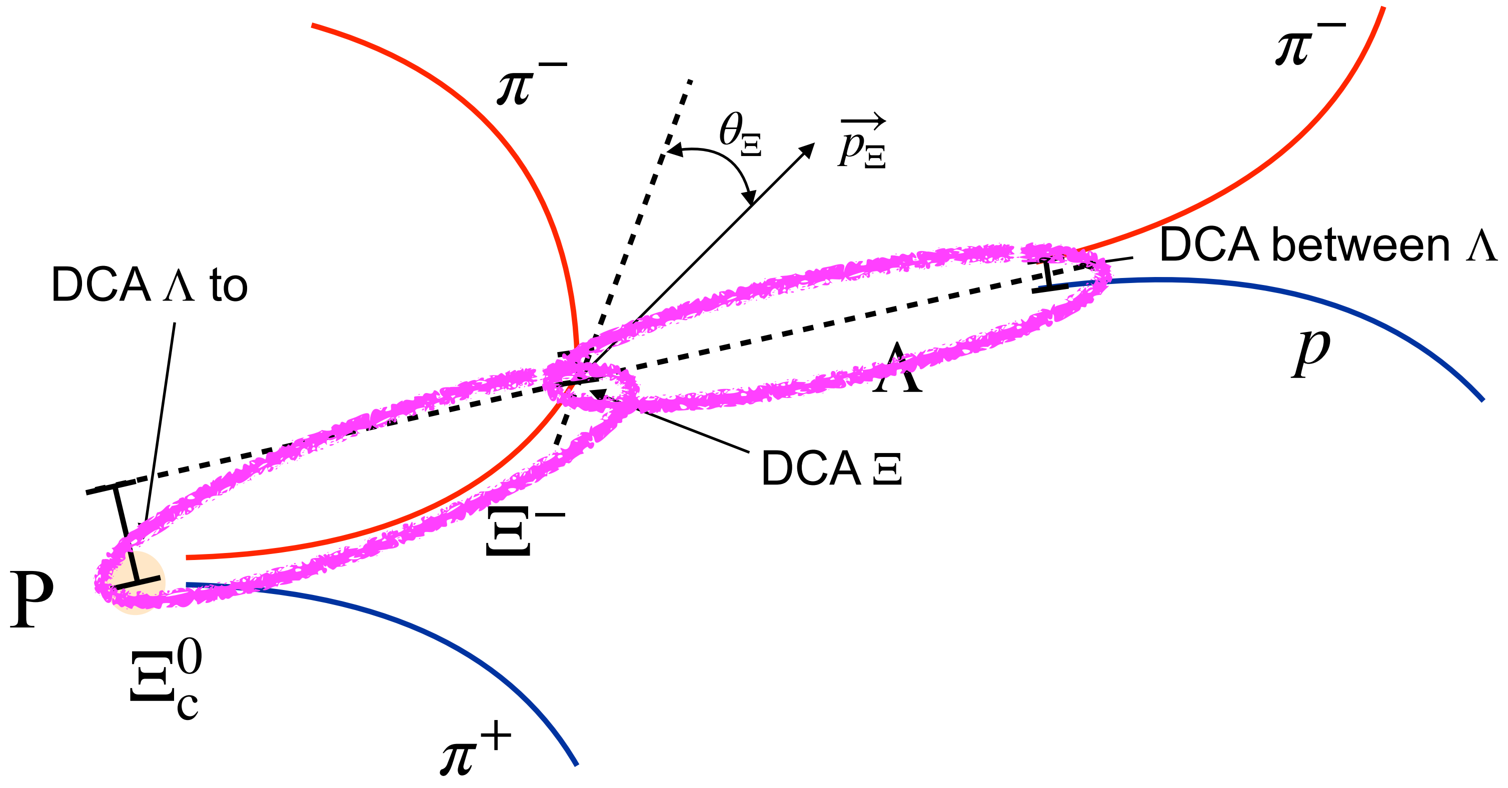
Reconstruction strategy for short-lived particles

- The **Kalman-Filter vertexing algorithm** was used for the reconstruction
  - ✓ Consideration of the particle full error matrix:
  - ✓ Use of powerful decay information:
    - ✓ Mass constraint (Adjust the momentum of daughter particles)
    - ✓ Vertex constraints (eg. χ^2_{geo} , χ^2_{topo} , $l/\Delta l$)



- **Machine learning** (hipe4ml) used

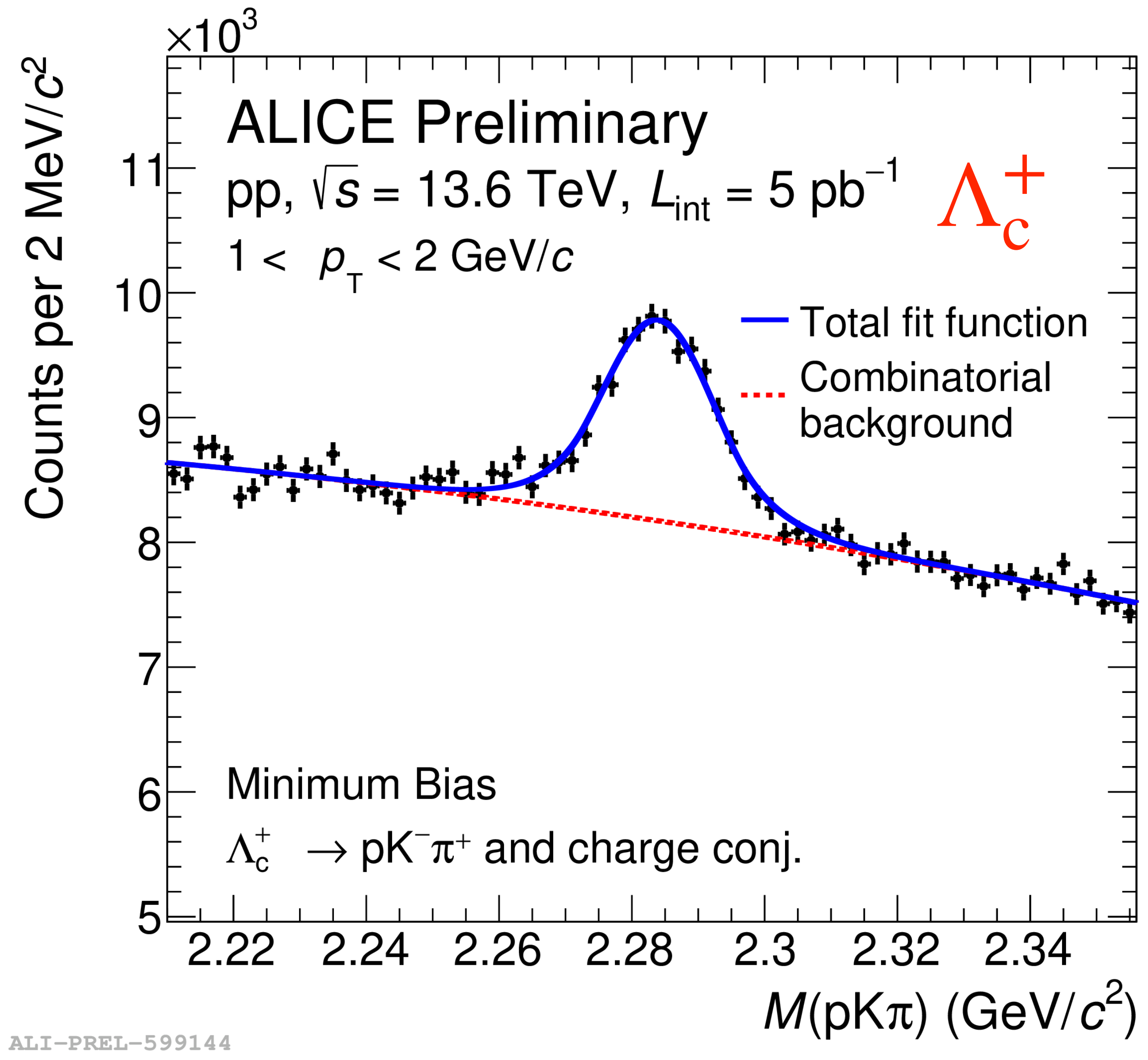


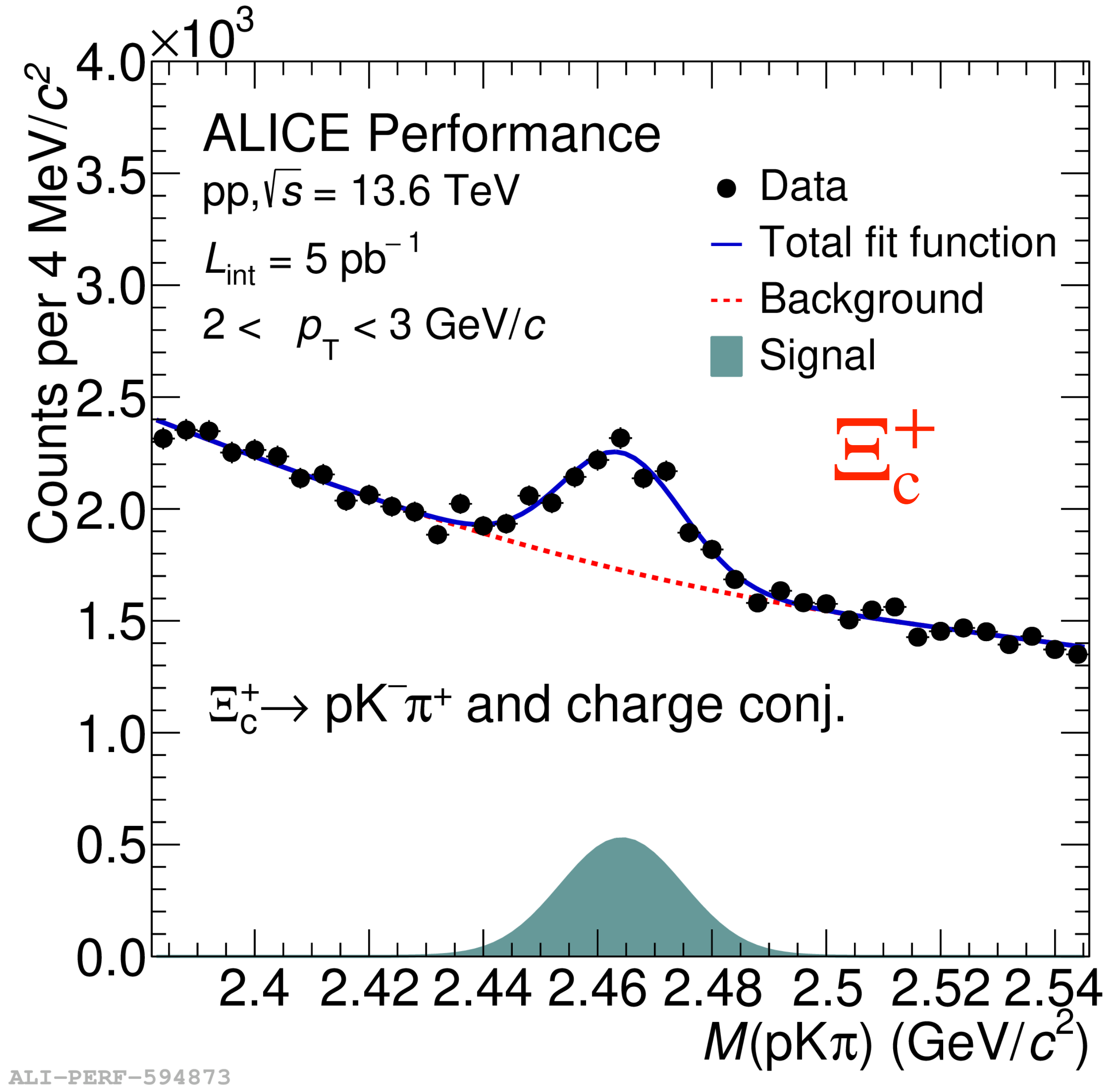


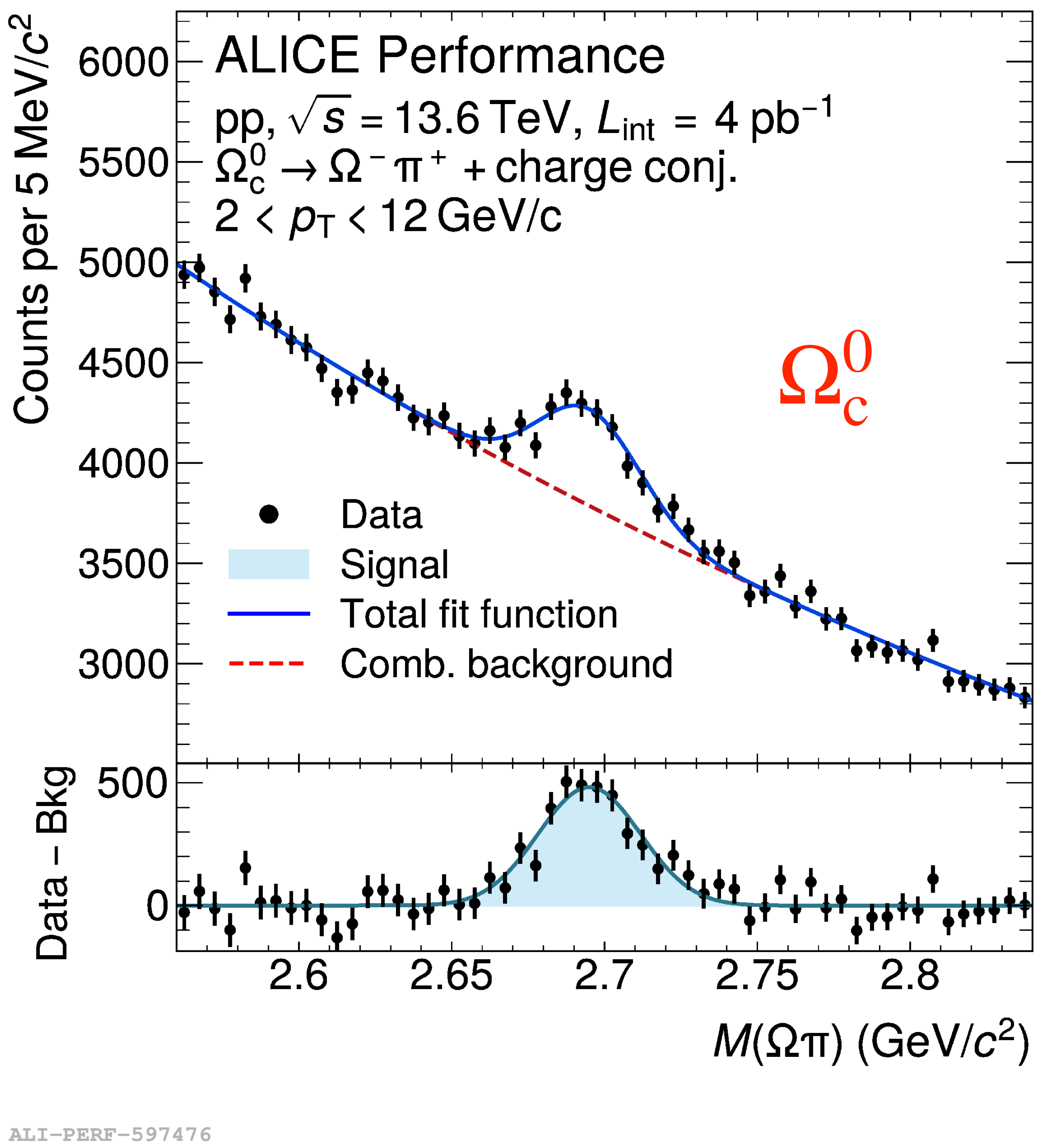
Charm baryon signal extracted in Run 3

Run2: $\mathscr{L}_{\mathrm{int}}$(MB pp, 13 TeV) = 32 nb^{-1} → Run3: $\mathscr{L}_{\mathrm{int}}$(MB pp, 13.6 TeV) = 6 pb^{-1}

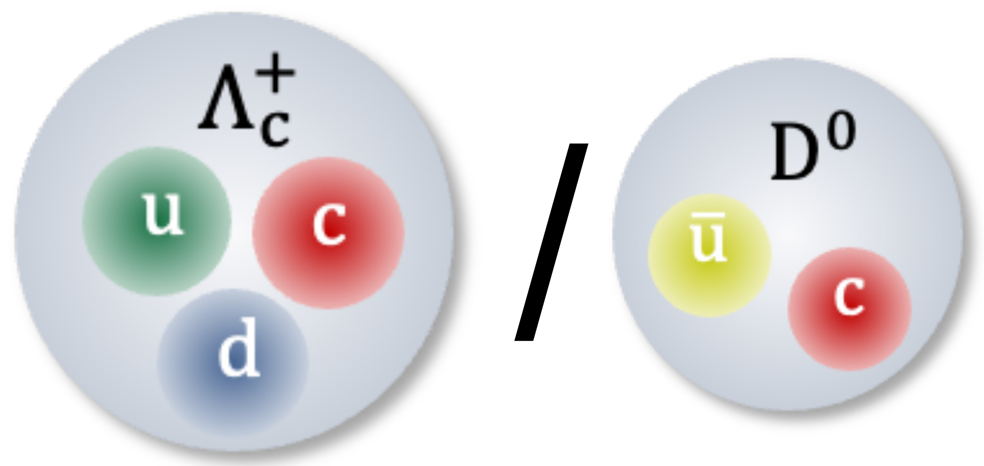
150x larger

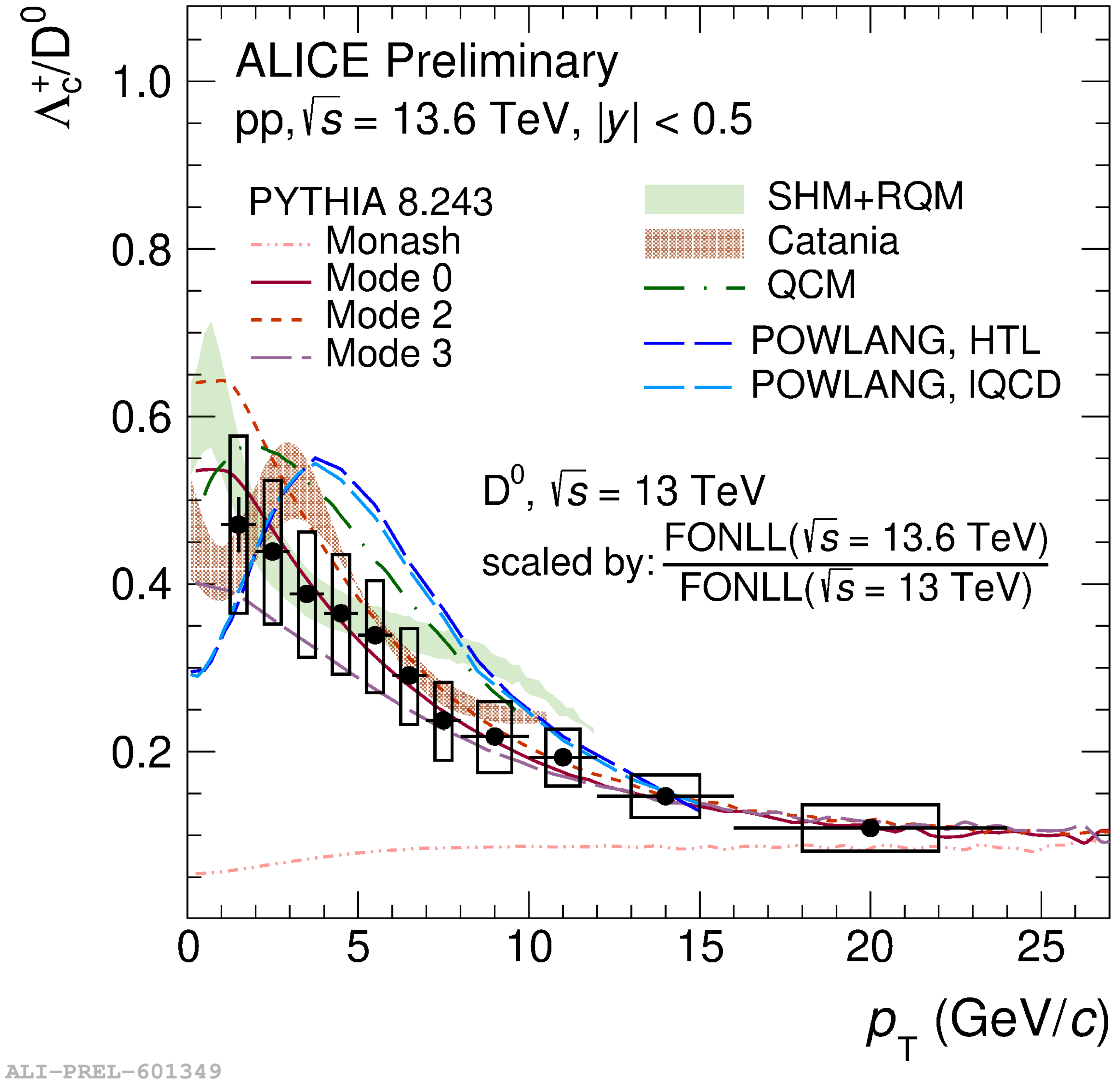






Λ_c^+/D^0 in pp collisions in Run 3





- **Decrease of the Λ_c^+/D^0 ratio with increasing pT**
  - Hadronisation of baryon and meson **differs**
- Monash underestimate the data
- Different hadronization mechanisms enhance baryon production and describe data

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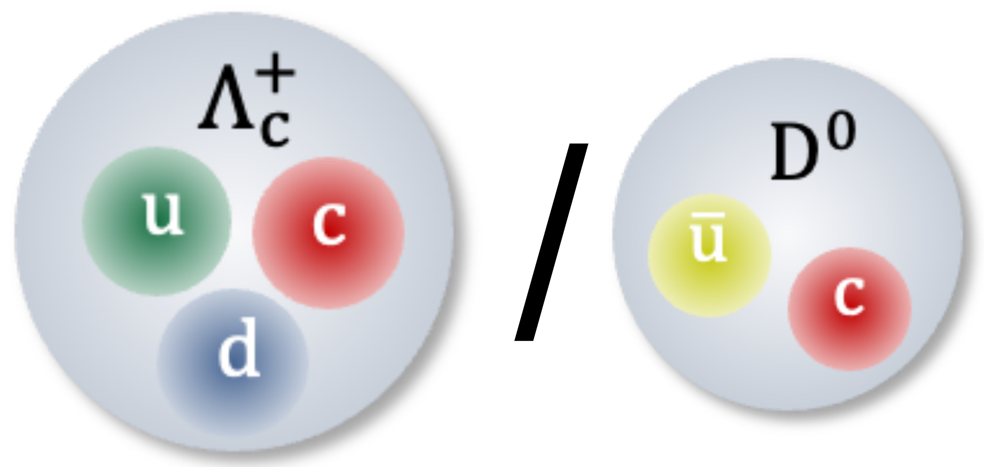

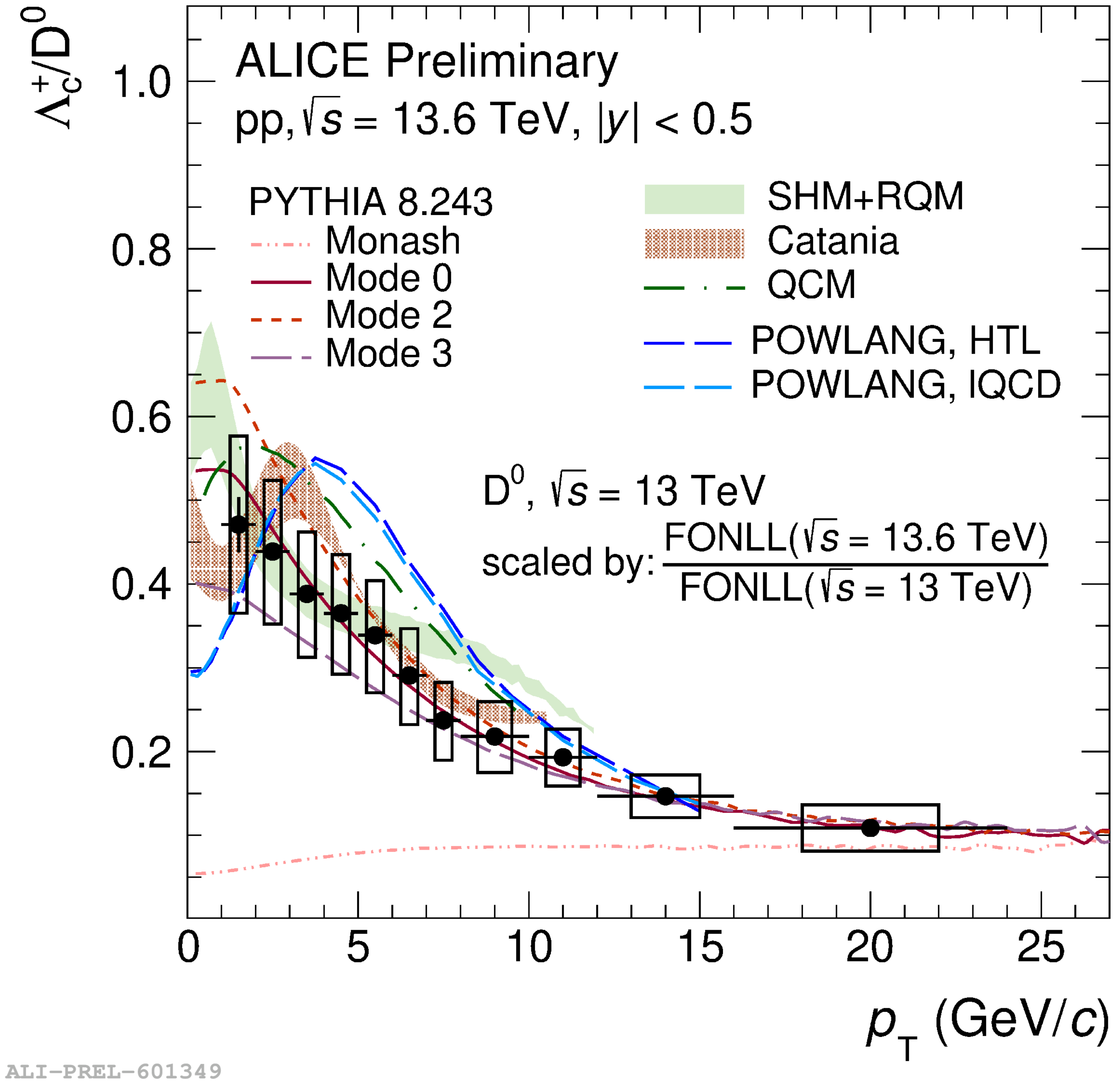

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  - PYTHIA 8 CR-BLC

    Color reconnection beyond leading color within the Lund string fragmentation model

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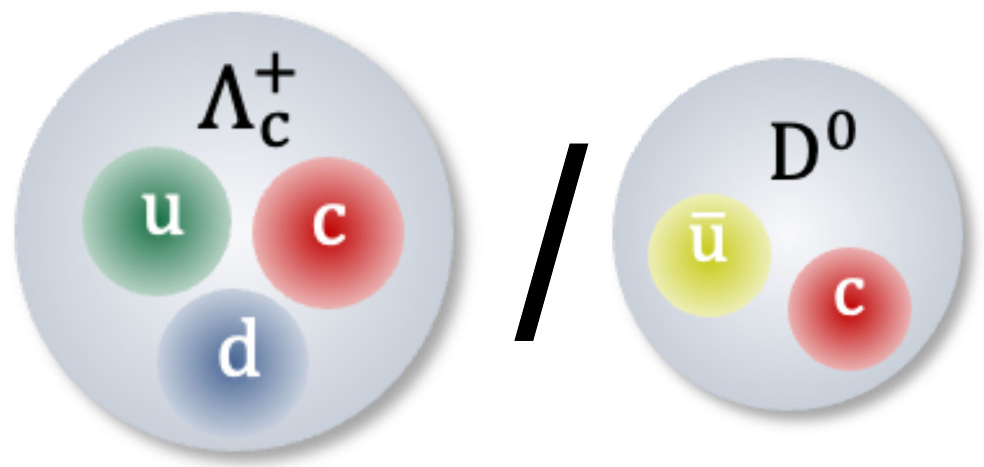

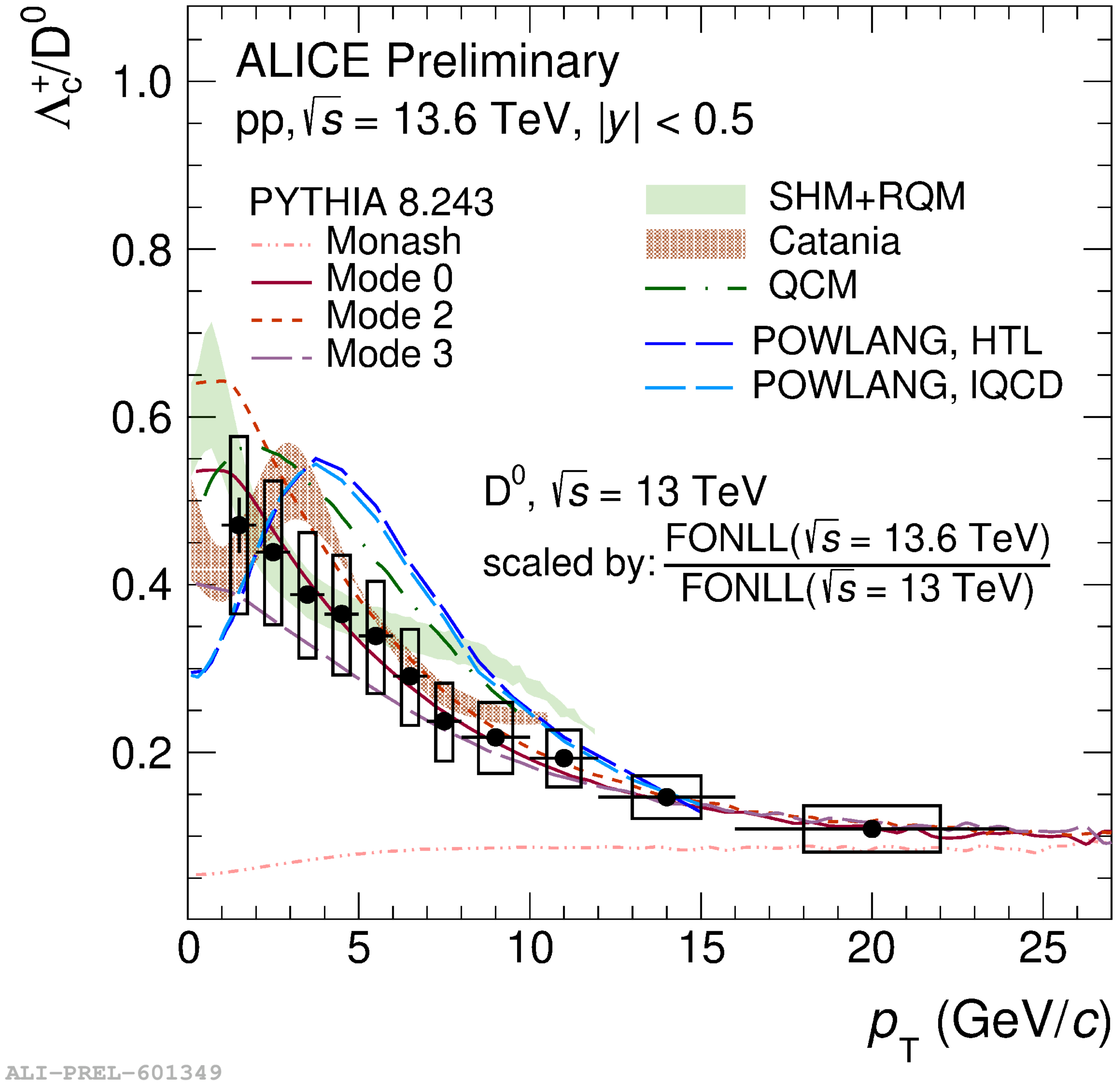

ALI-PREL-601349

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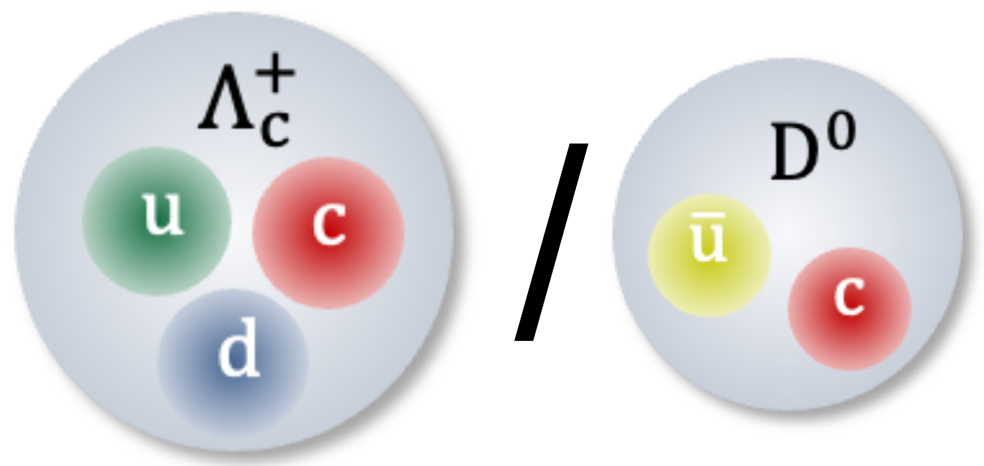
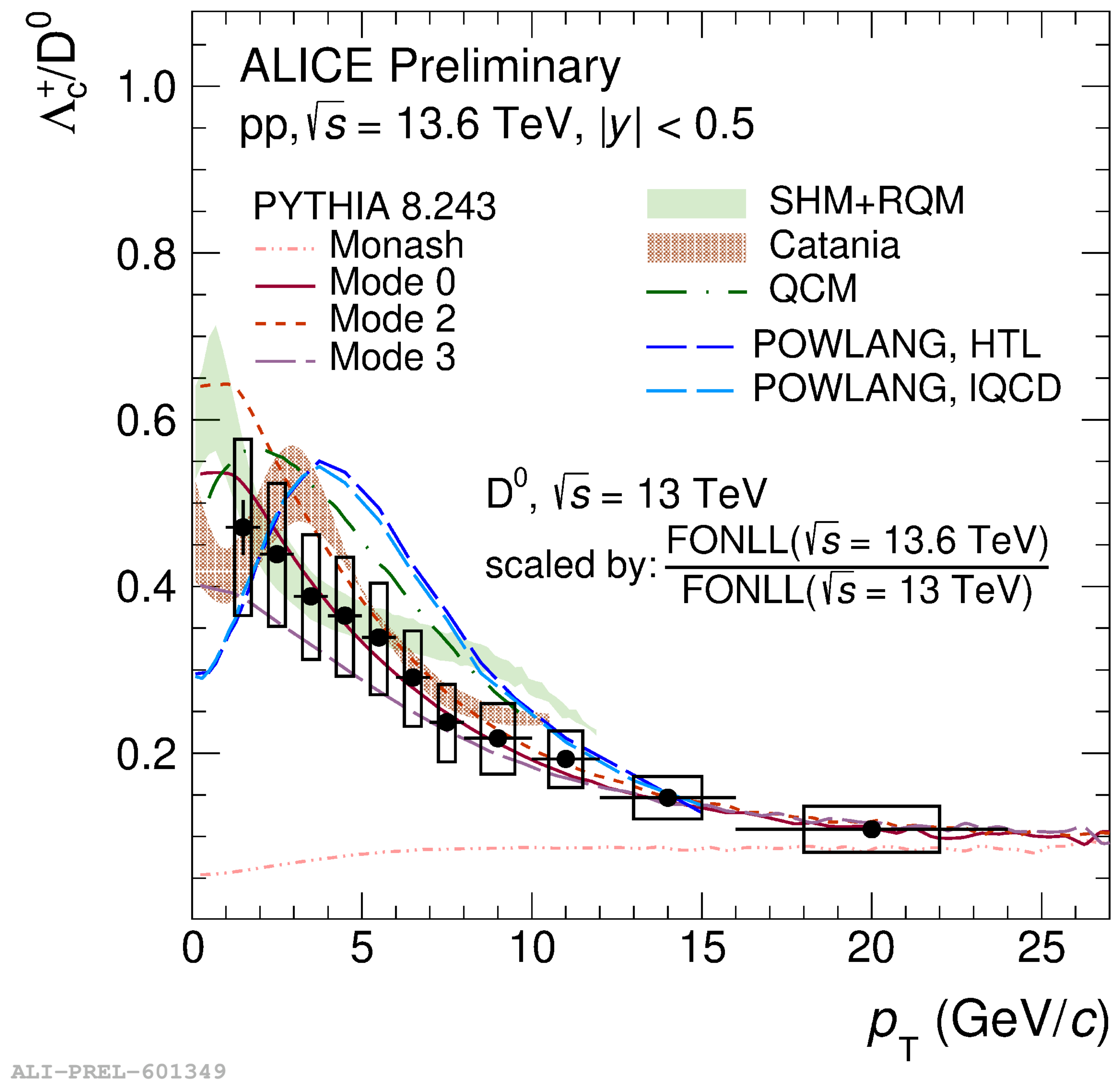
  Increased feed-down from additional baryon states predicted by RQM

Λ_c^+/D^0 in pp collisions in Run 3





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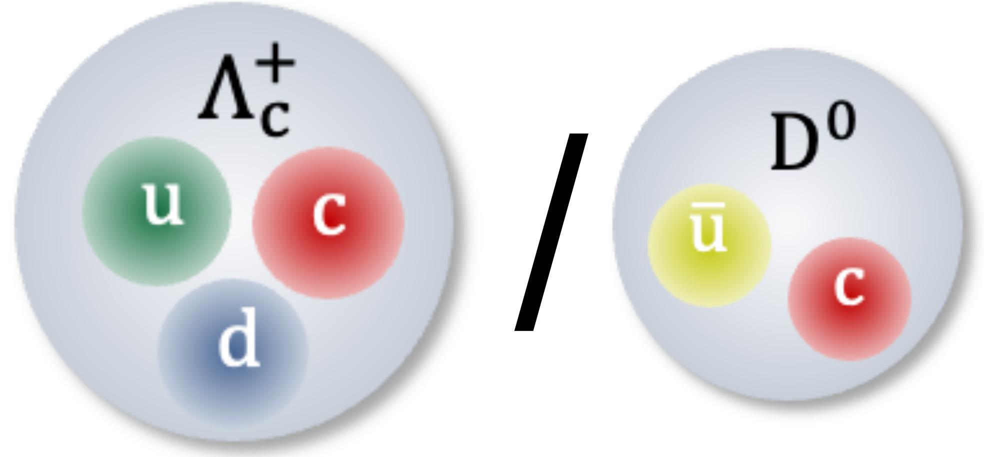
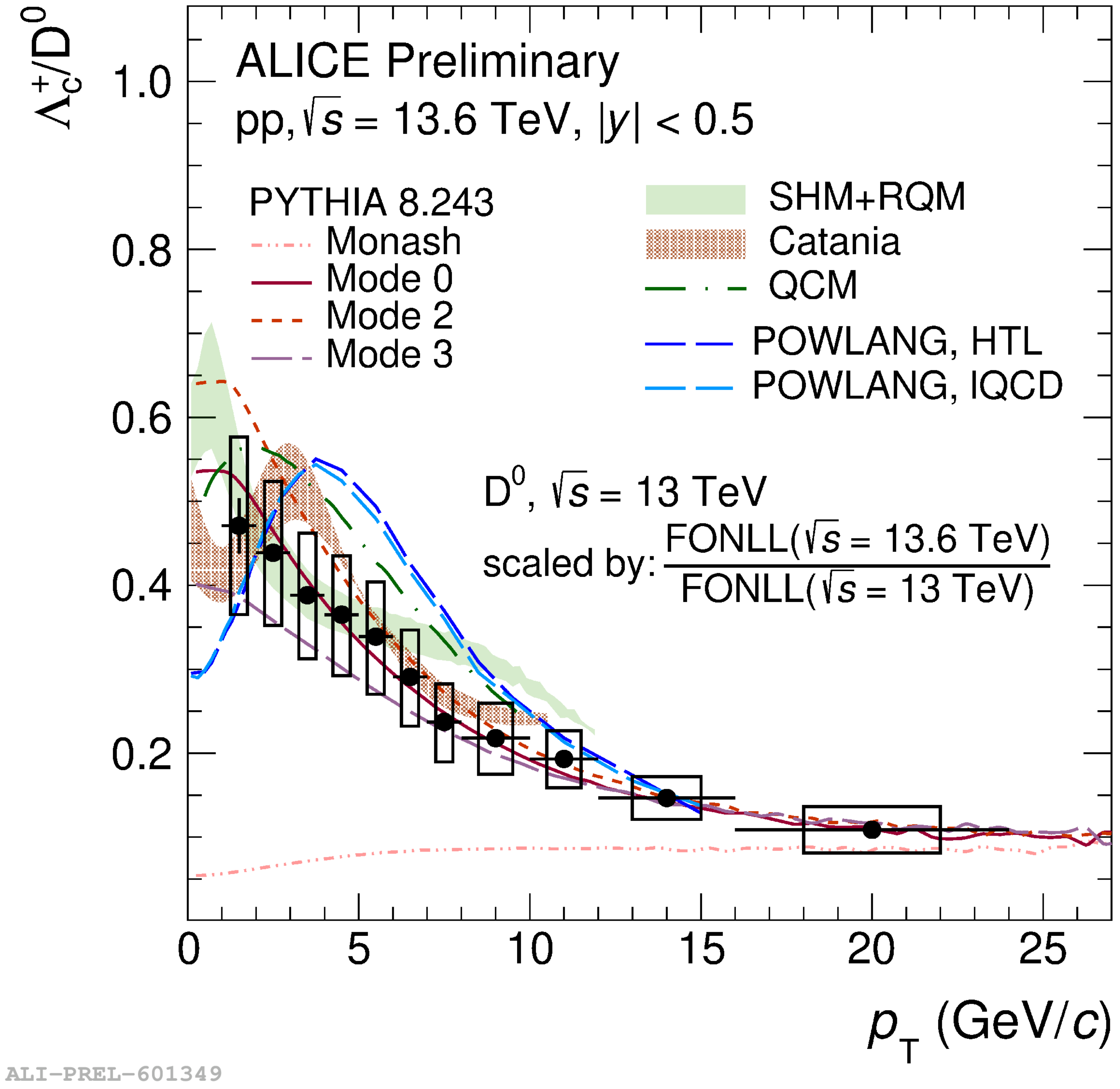
  - Catania

    Assumes an expanding medium formation in small collision systems, hadronization via **coalescence** and fragmentation

Λ_c^+/D^0 in pp collisions in Run 3





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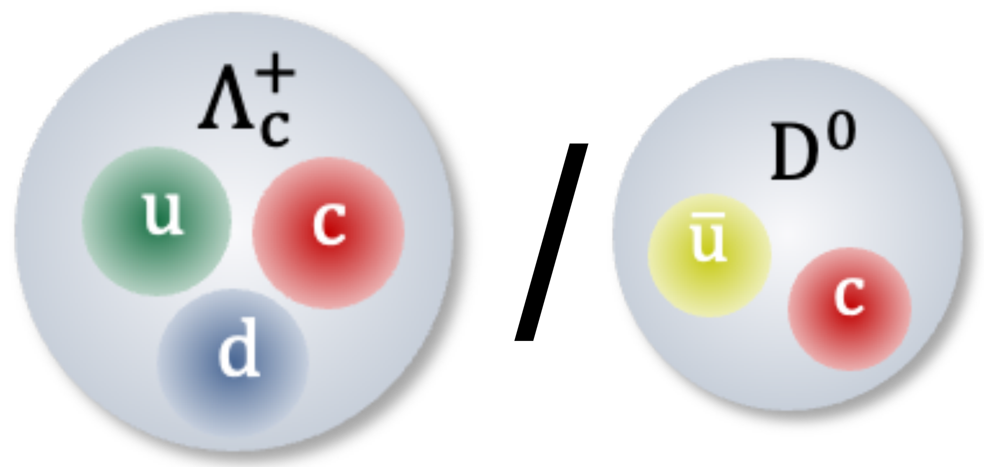
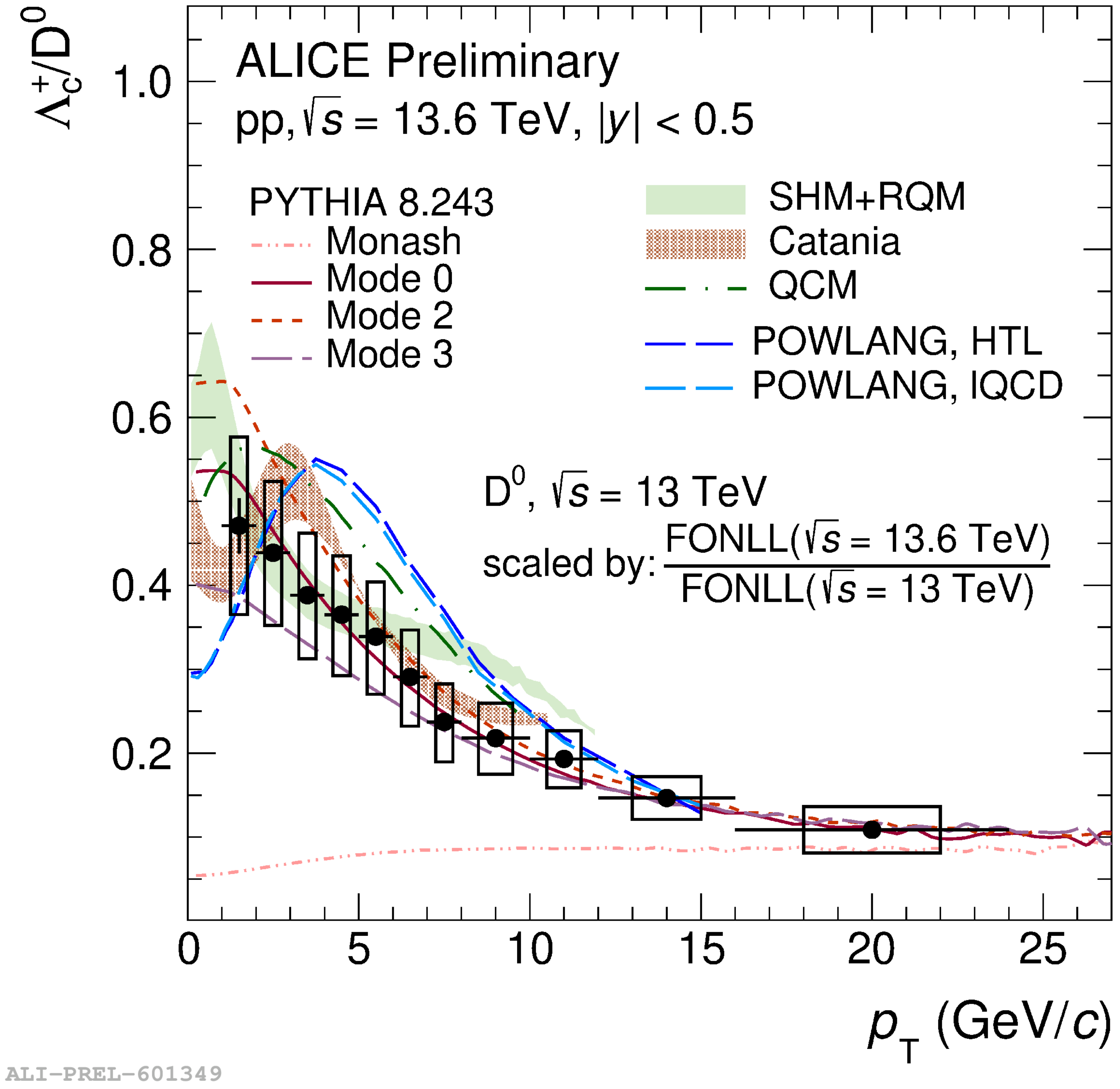
  - Quark (re)Combination model

  Charm quark is combined with a co-moving light antiquark or two quarks.

Λ_c^+/D^0 in pp collisions in Run 3





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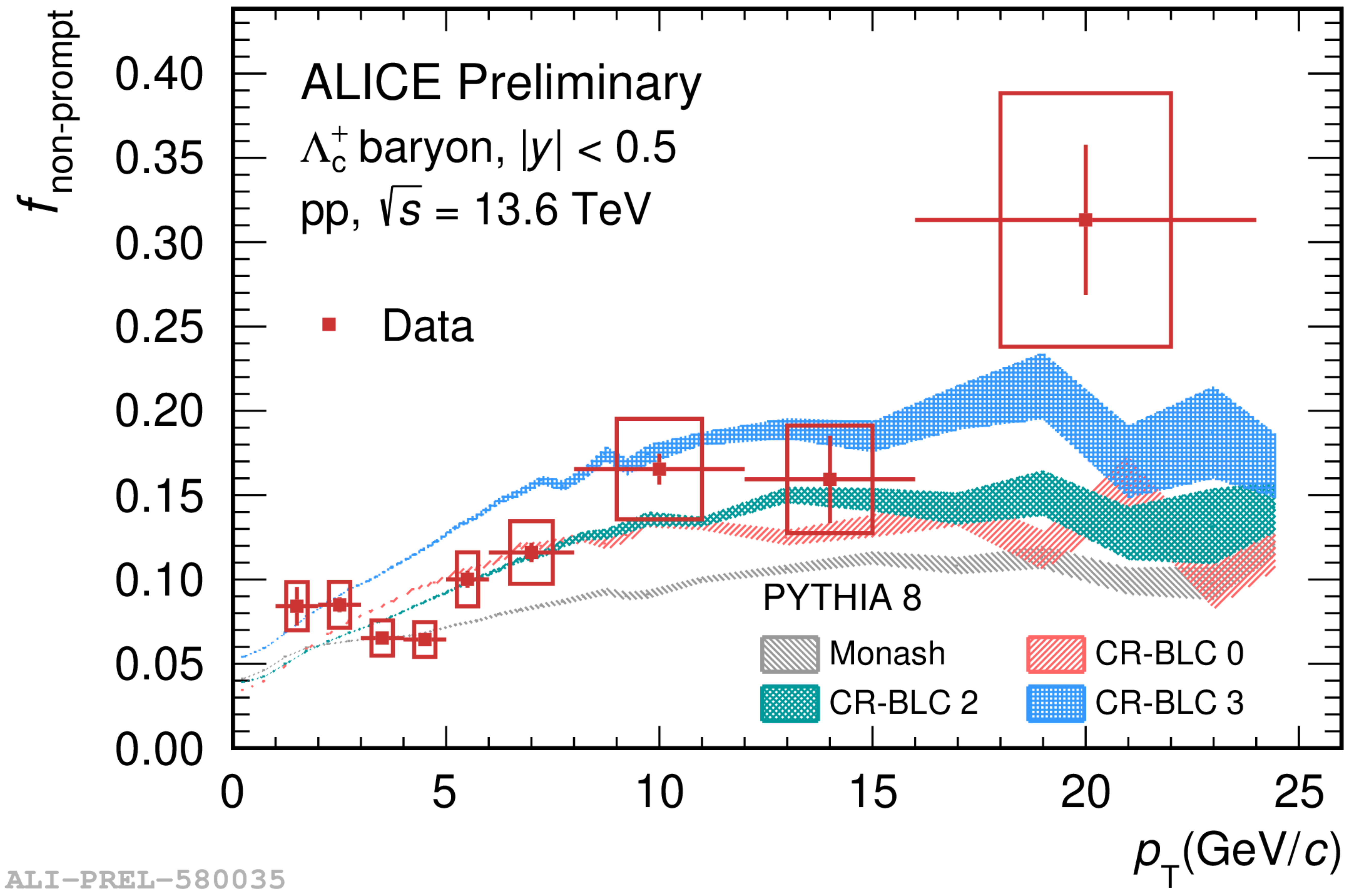
  - Quark (re)Combination model
  - POWLANG

Assumed Expanding fireball in pp collisions.
Hadronisation via recombination with light quarks
Charm-baryon formation enhanced thanks to diquark excitations.

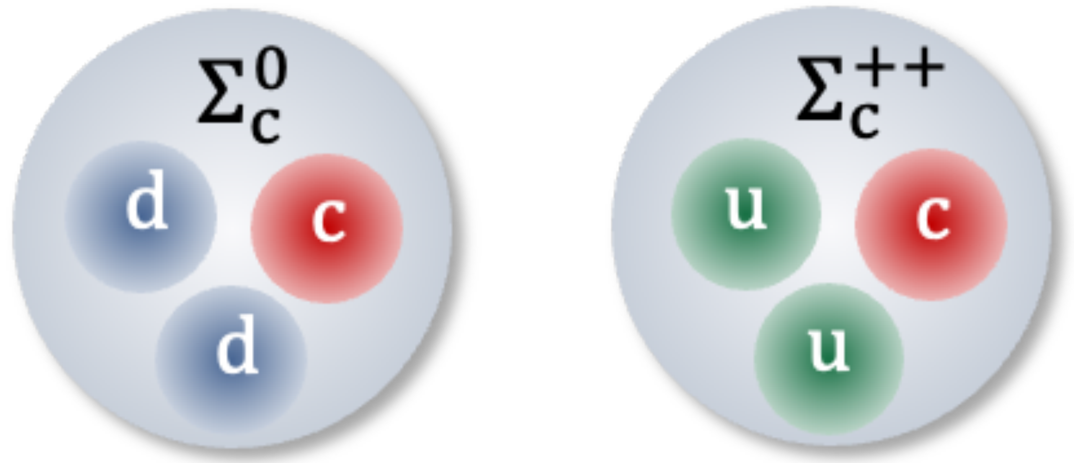
Λ_c^+ non-prompt fraction



PYTHIA8 Monash underestimates the Λ_c^+ non-prompt fraction.

A better agreement with the data is achieved with PYTHIA with CR-BLC tunes

$\Sigma_c^{0,++}(2520)$ in Run 3

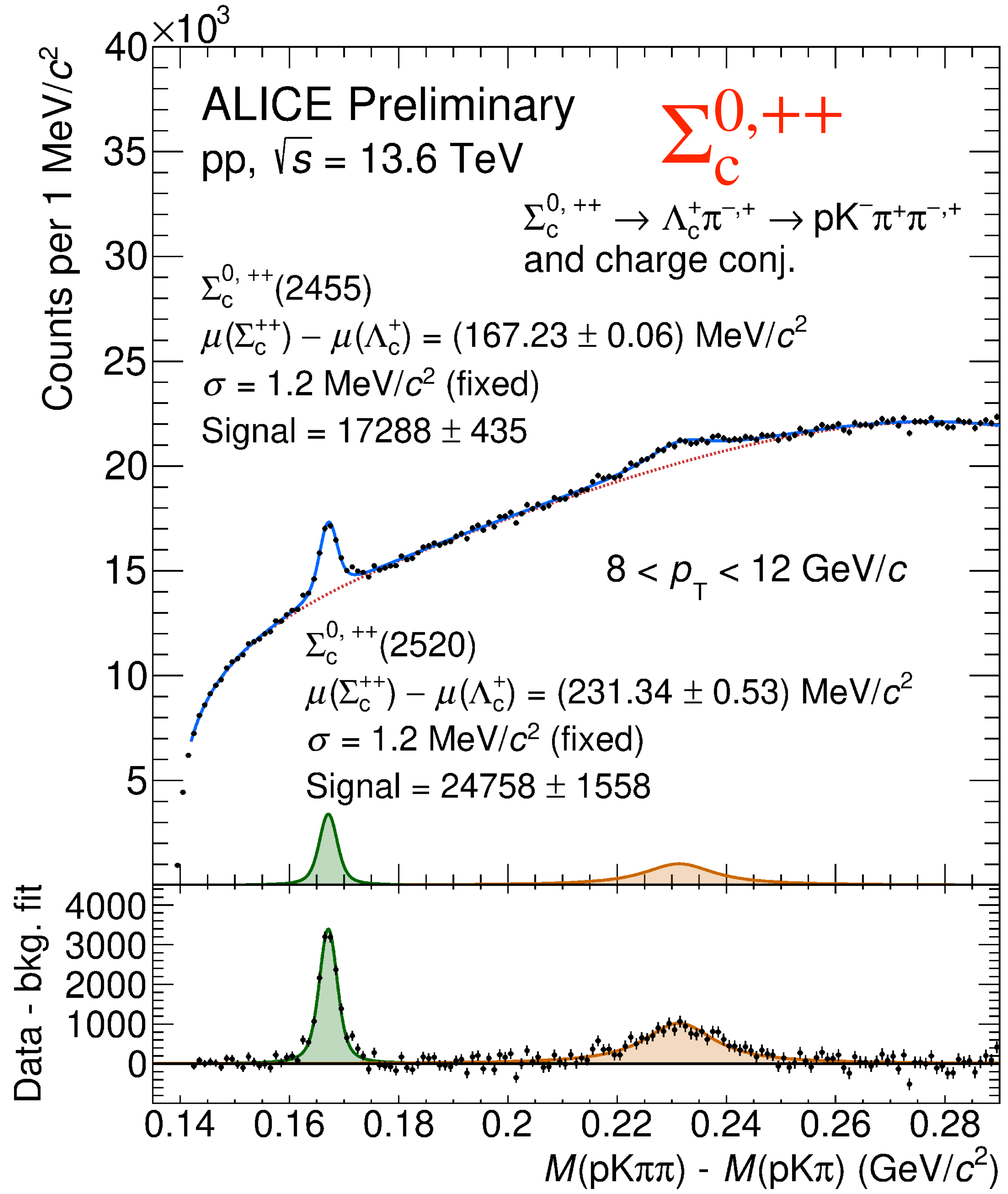


First production measurement of $\Sigma_c^{0,++}(2520)$ at the LHC

2455 $J = 1/2$

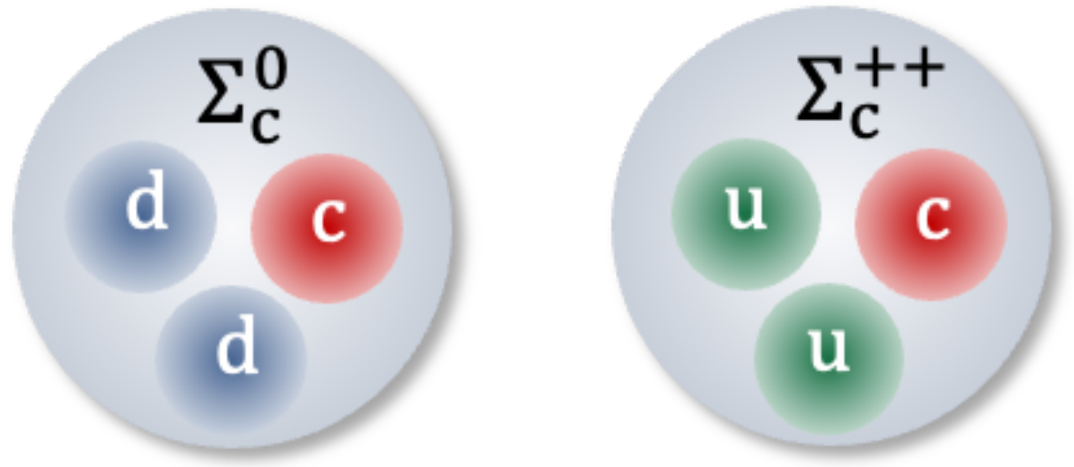
2520 $J = 3/2$

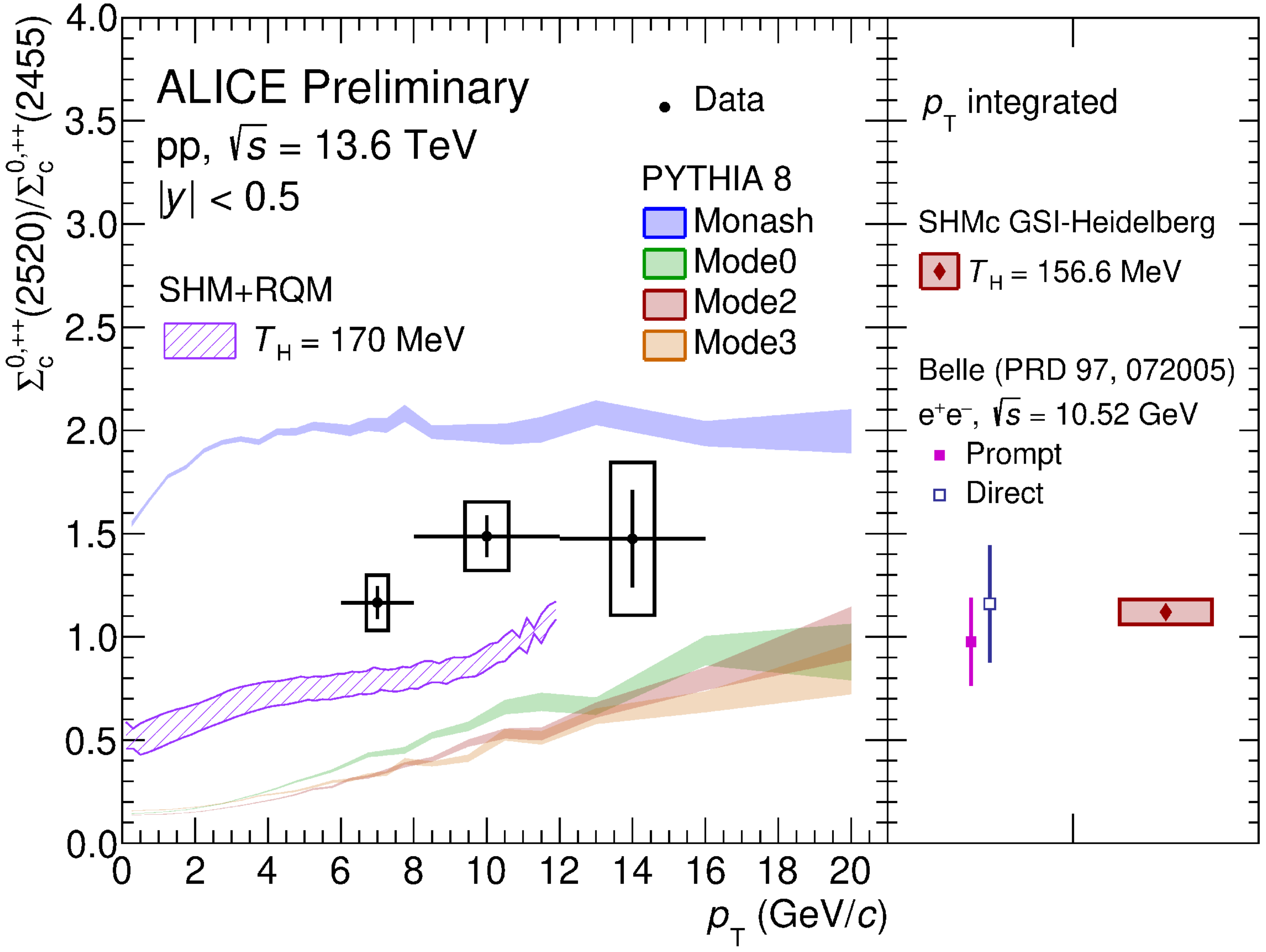
$\Sigma_c^{0,++}$ **states**



ALI-PREL-571534

$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$

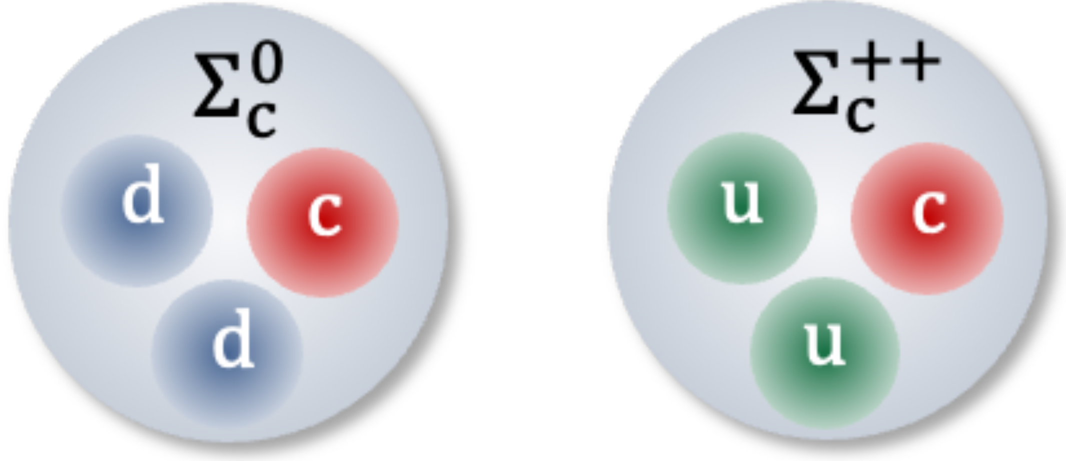


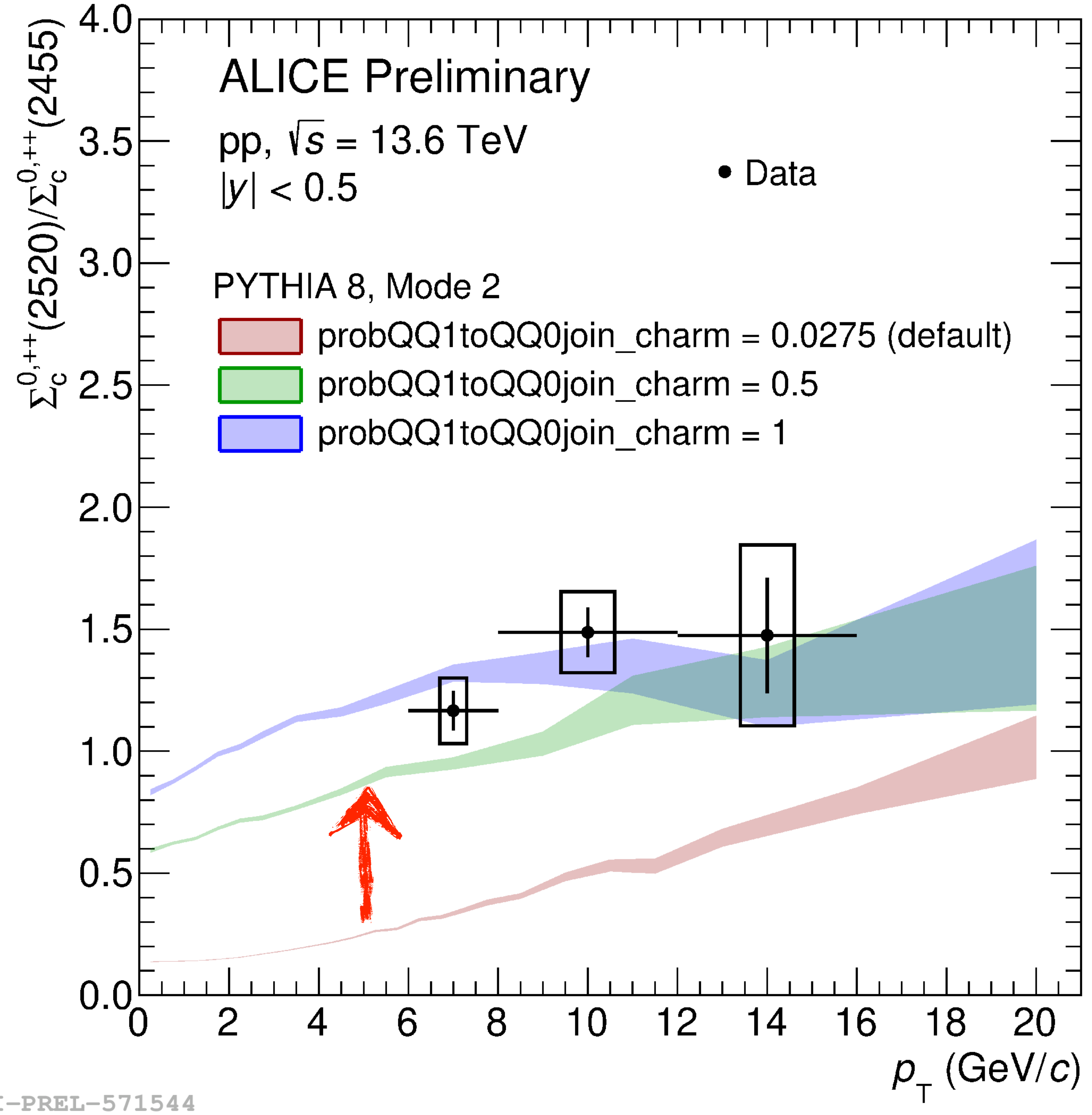


ALI-PREL-574270

- Ratio of cross sections in $6 < p_T < 16$ GeV/c **consistent** with integrated p_T results from e^+e^- collisions within the uncertainties
  - SHMc GSI+Heidelberg predictions compatible with measured data (different p_T range)
- Comparison with Models as a function of p_T
  - PYTHIA 8 Monash overestimates
  - Underestimate by CR Modes and SHM+RQM

Setting constraints on PYTHIA





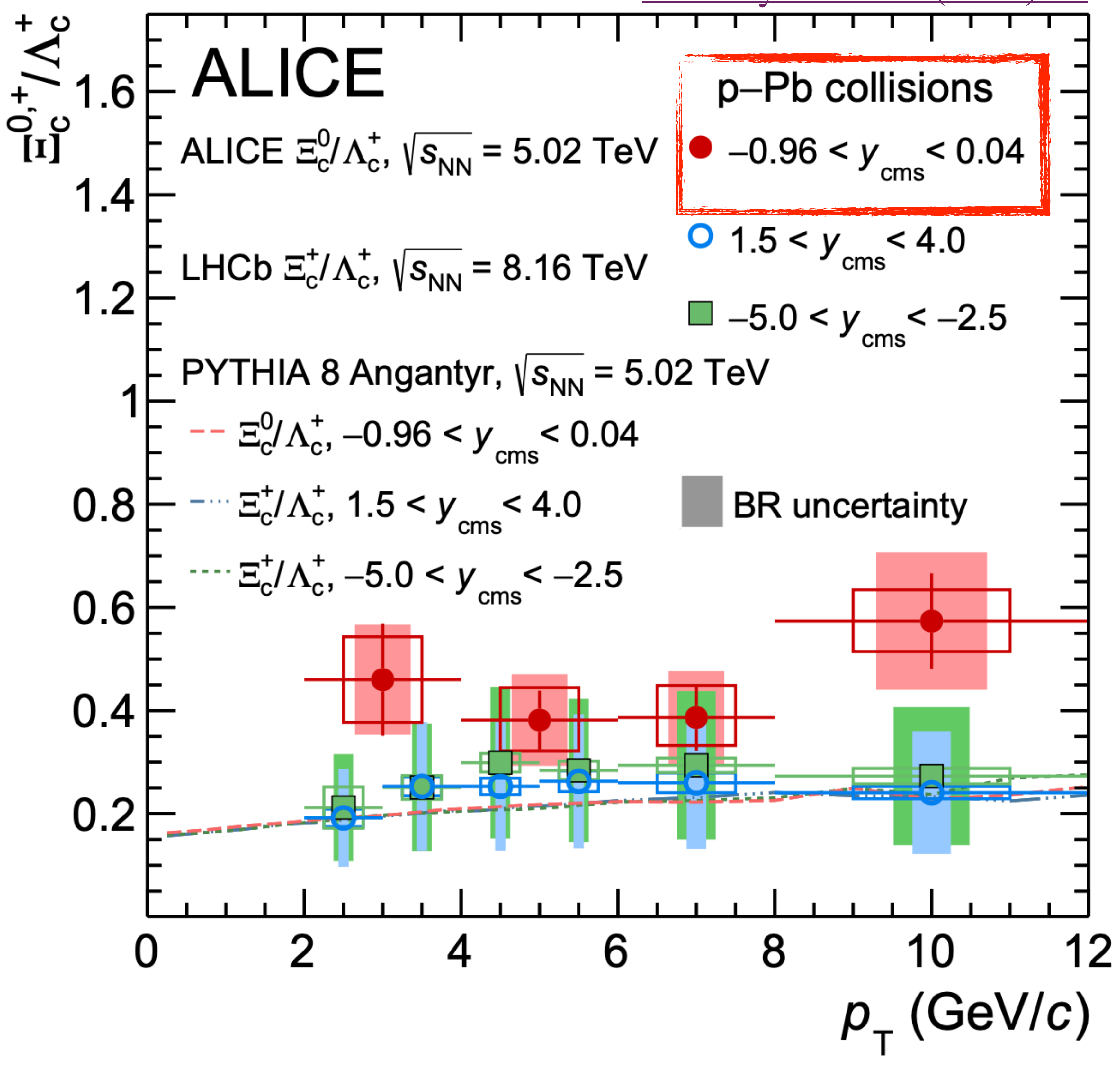
ALI-PREL-571544

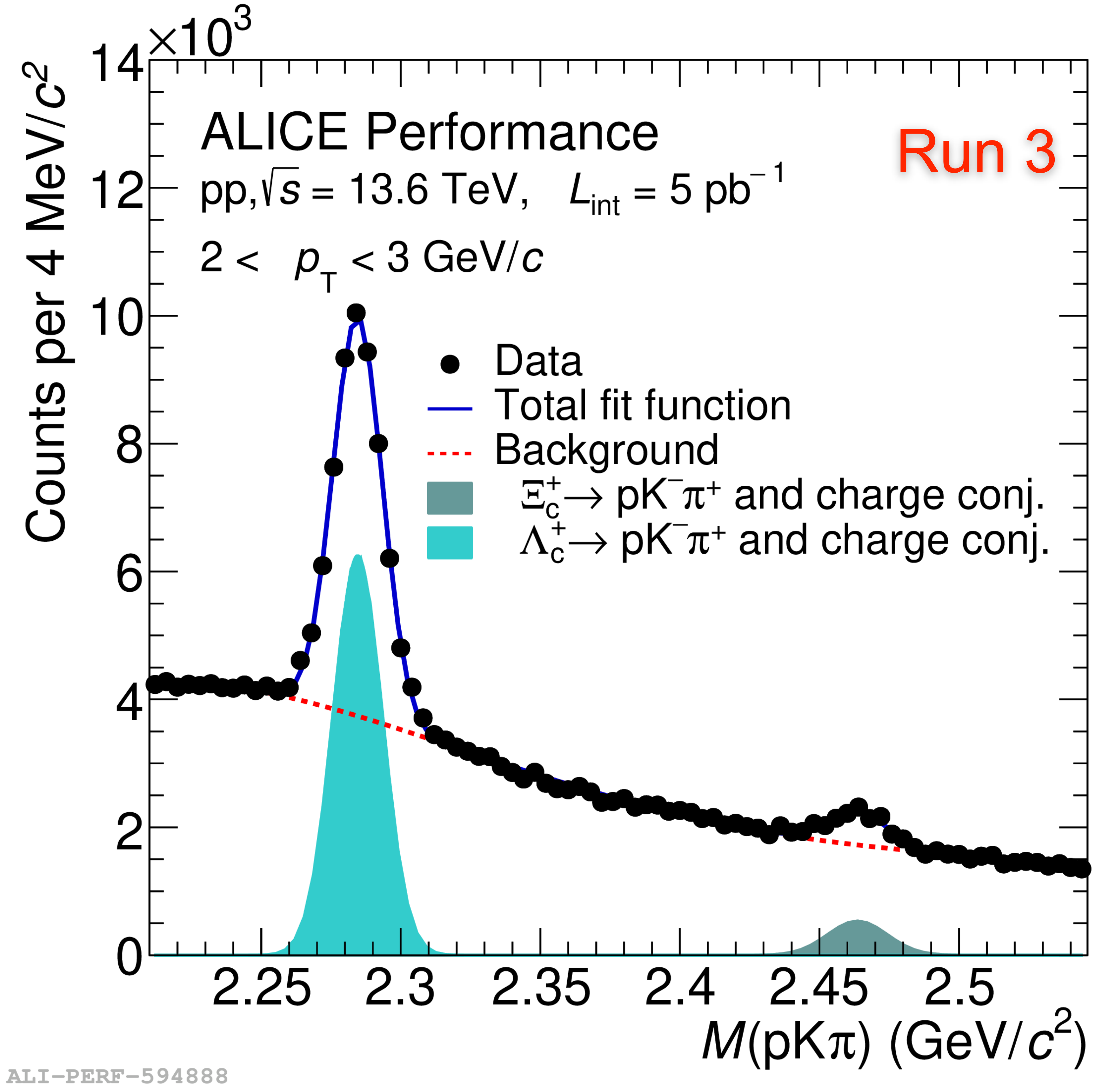
- PYTHIA 8 Mode 2 with tuned parameters agrees with data
  - probQQ1toQQ0join_charm
    - Probability of forming in junction diquark (cq) with spin 1 over spin 0
    - $$\frac{P_{\mathrm{cp}}(\mathrm{spin}=1)}{P_{\mathrm{cp}}(\mathrm{spin}=0)}$$
- **First measurement** of the relative production of the baryon **resonance** $\Sigma_c^{0,++}$**(2520)** at the LHC
  - Add further inputs to constrain hadronization

$\Xi_c^+ \to pK^-\pi^+$ in pp in Run 3

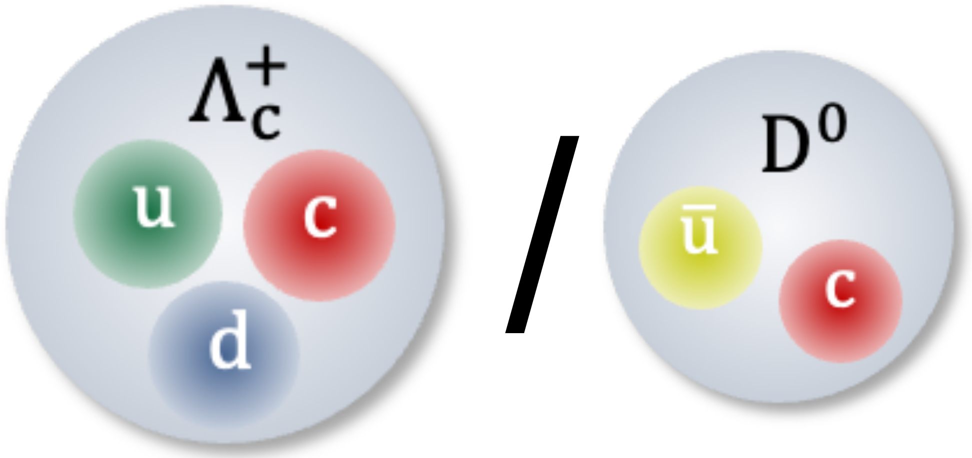
- Same decay channel of $\Lambda_c^+ \to pK^-\pi^+$ gives advantages of unc. cancellation for Ξ_c^+/Λ_c^+
- **Outlook**: possibility of precise rapidity dependence of Ξ_c^+/Λ_c^+ ratio in pp collisions

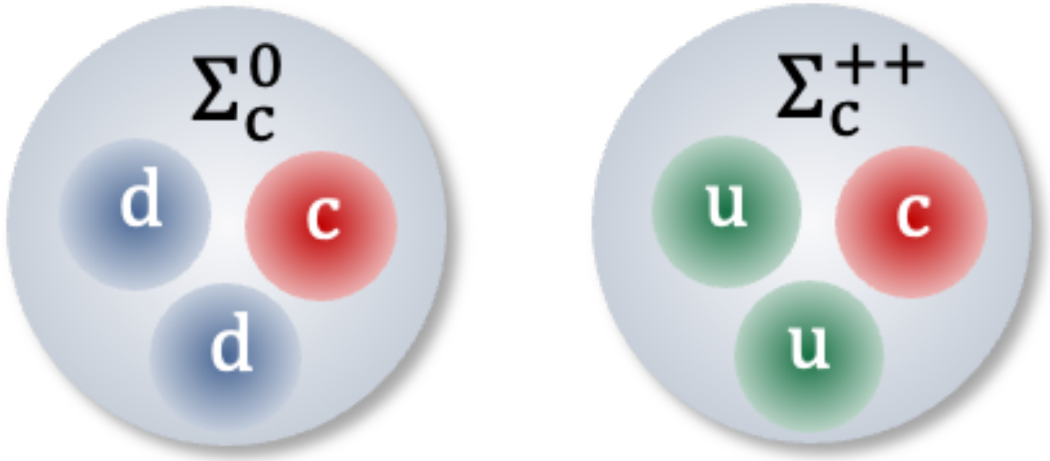
Eur. Phys. J. C 85 (2025) 86





Summary



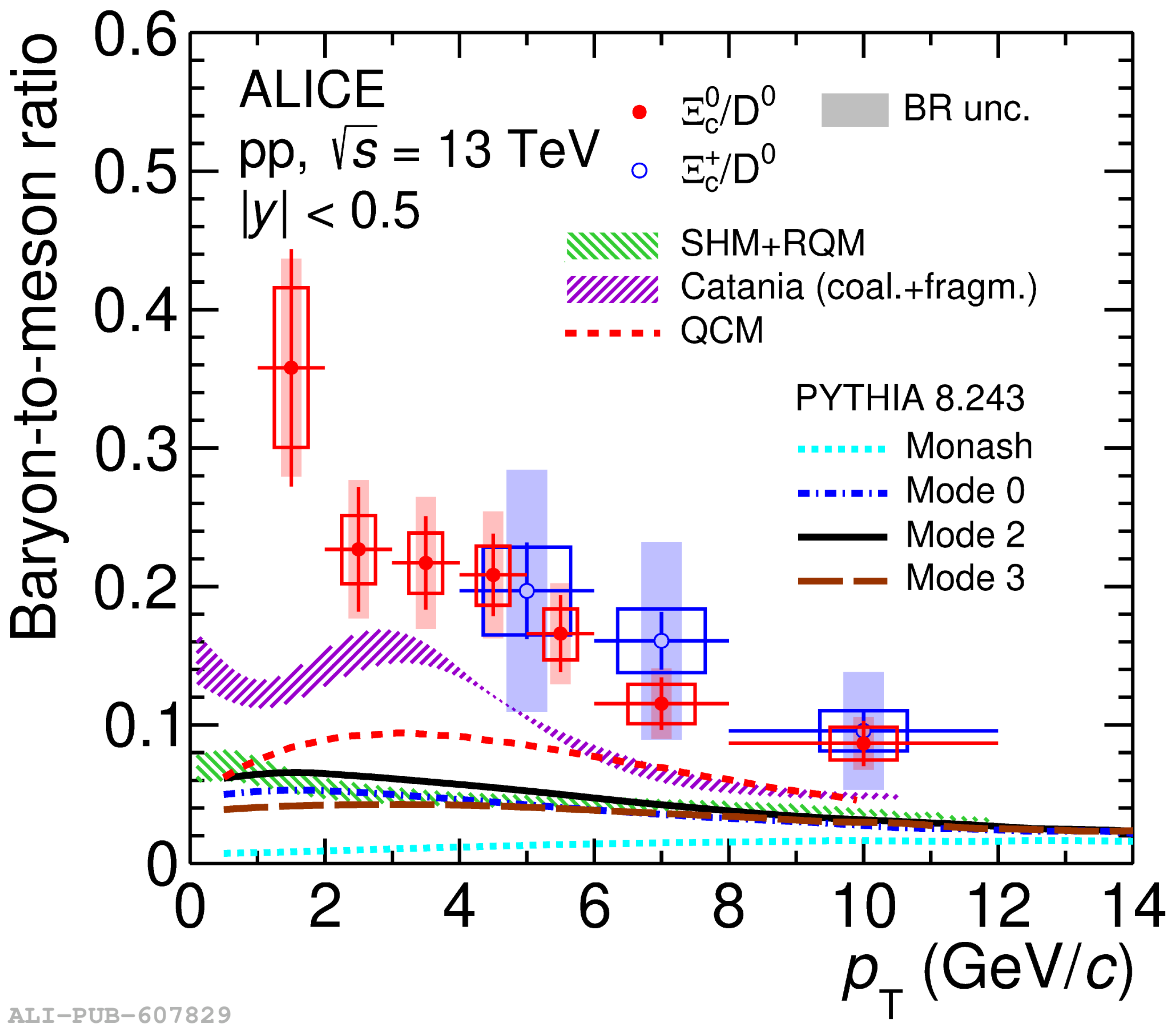


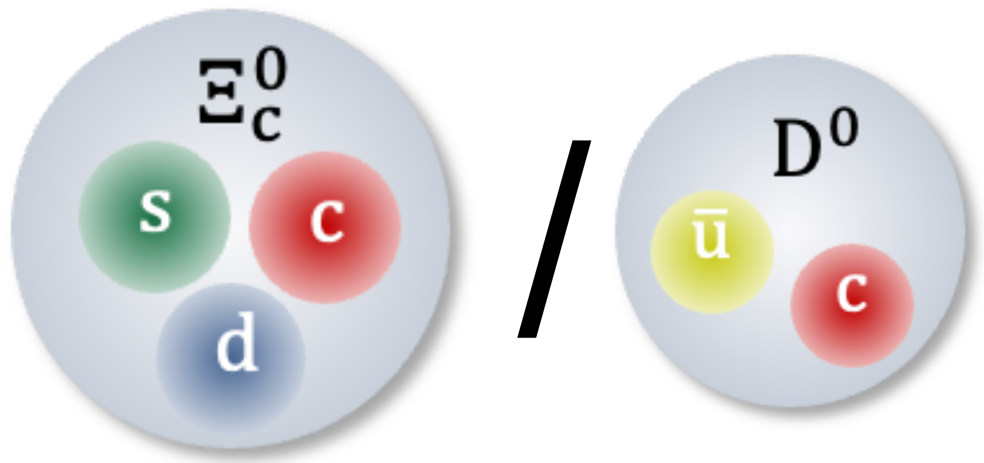
pp, $\sqrt{s} = 13.6$ TeV	Λ_c^+/D^0	Λ_c^+ non-prompt fraction	$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$
Monash	✘	✘	✘
CR Mode 2	✔	✔	✔ (parameter tuned)
POWLANG	✔	—	—
QCM	✔	—	—
CATANIA	✔	—	—
SHM+RQM	✔	—	✘

Thanks for your attention

Back up

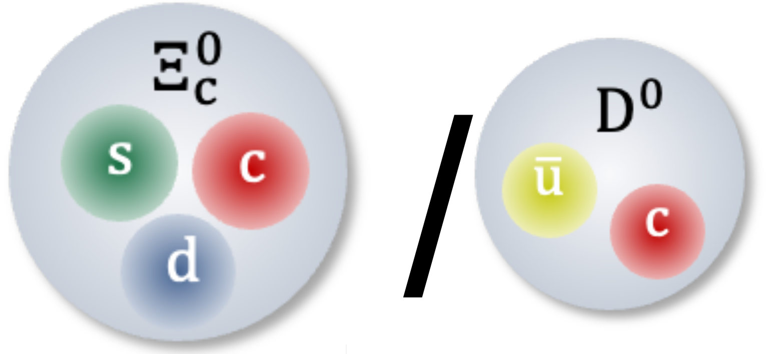
$\Xi_c^{0,+}/D^0$ in pp collisions



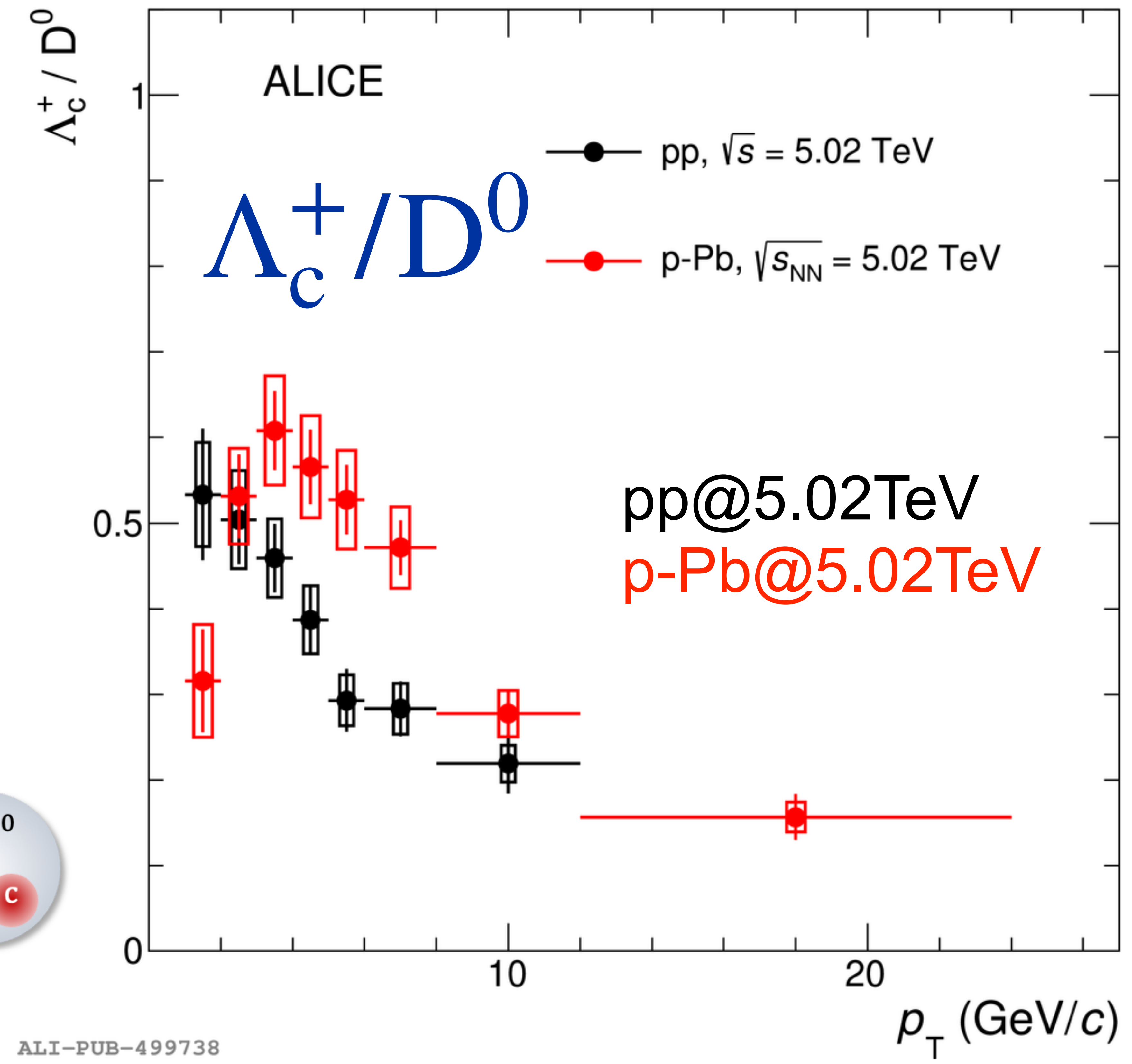


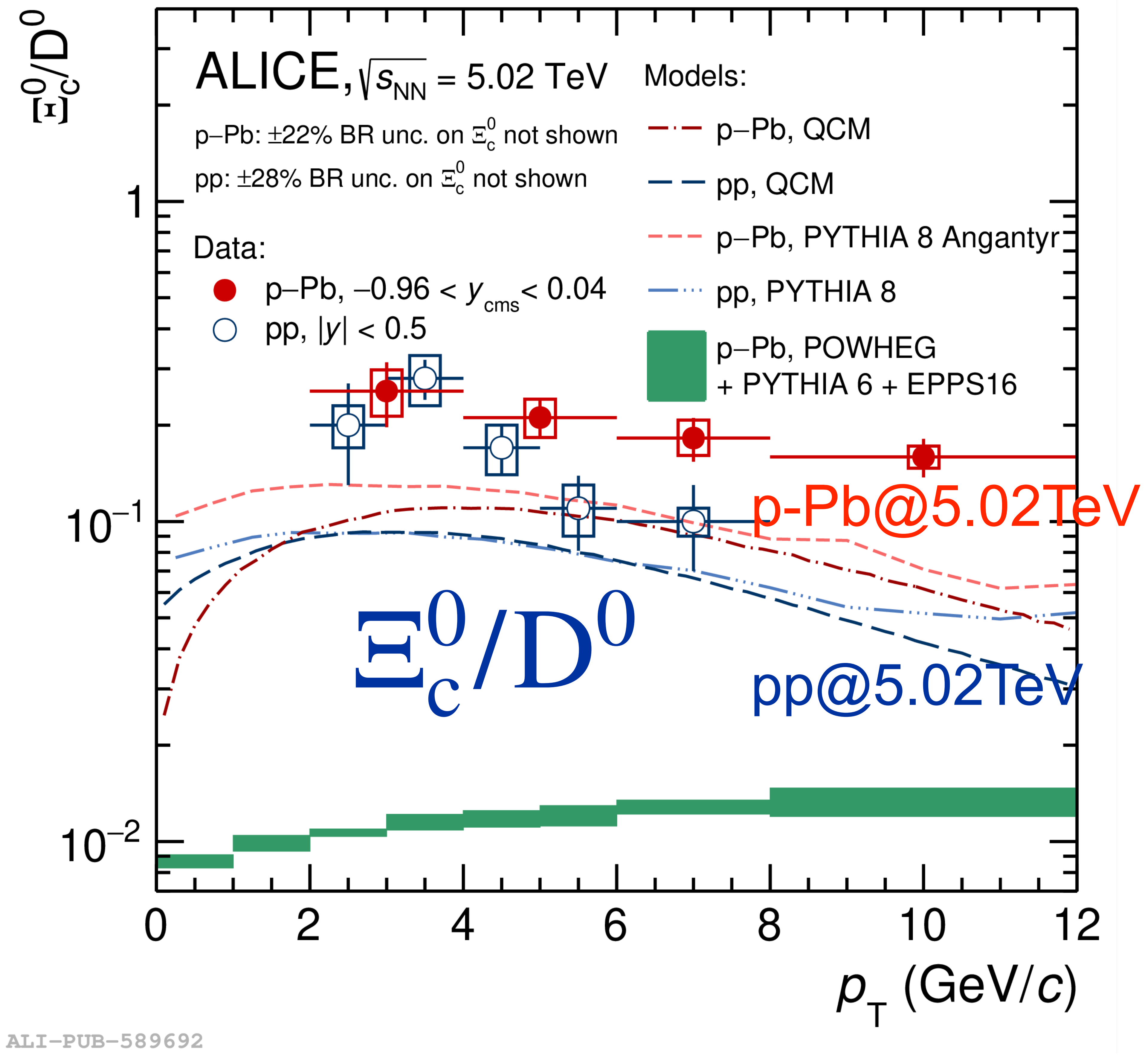
- Ξ_c^0/D^0 p_T dependence is **similar to the Λ_c^+/D^0 ratio**
- **Significantly underestimated by** PYTHIA.
  - CR modes give a similar pT dependence
- SHM+RQM can describe the Λ_c^+/D^0 ratio **but underpredict Ξ_c^0/D^0**
- Coalescence included models can't describe the data
  - QCM is tuned to reproduce the Λ_c^+/D^0 ratio in pp
  - Catania is closer to the measurement

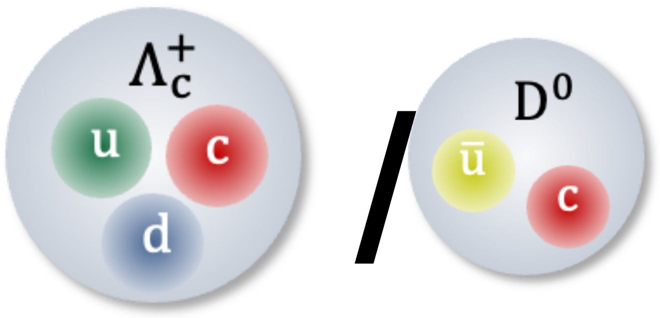
Λ_c^+/D^0, Ξ_c^0/D^0 in pp and p-Pb collisions



Phys. Rev. C 104 (2021) 054905

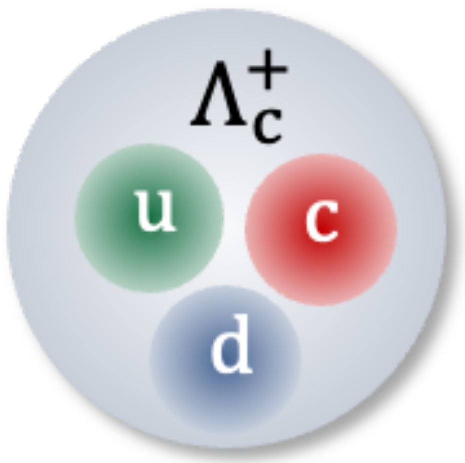


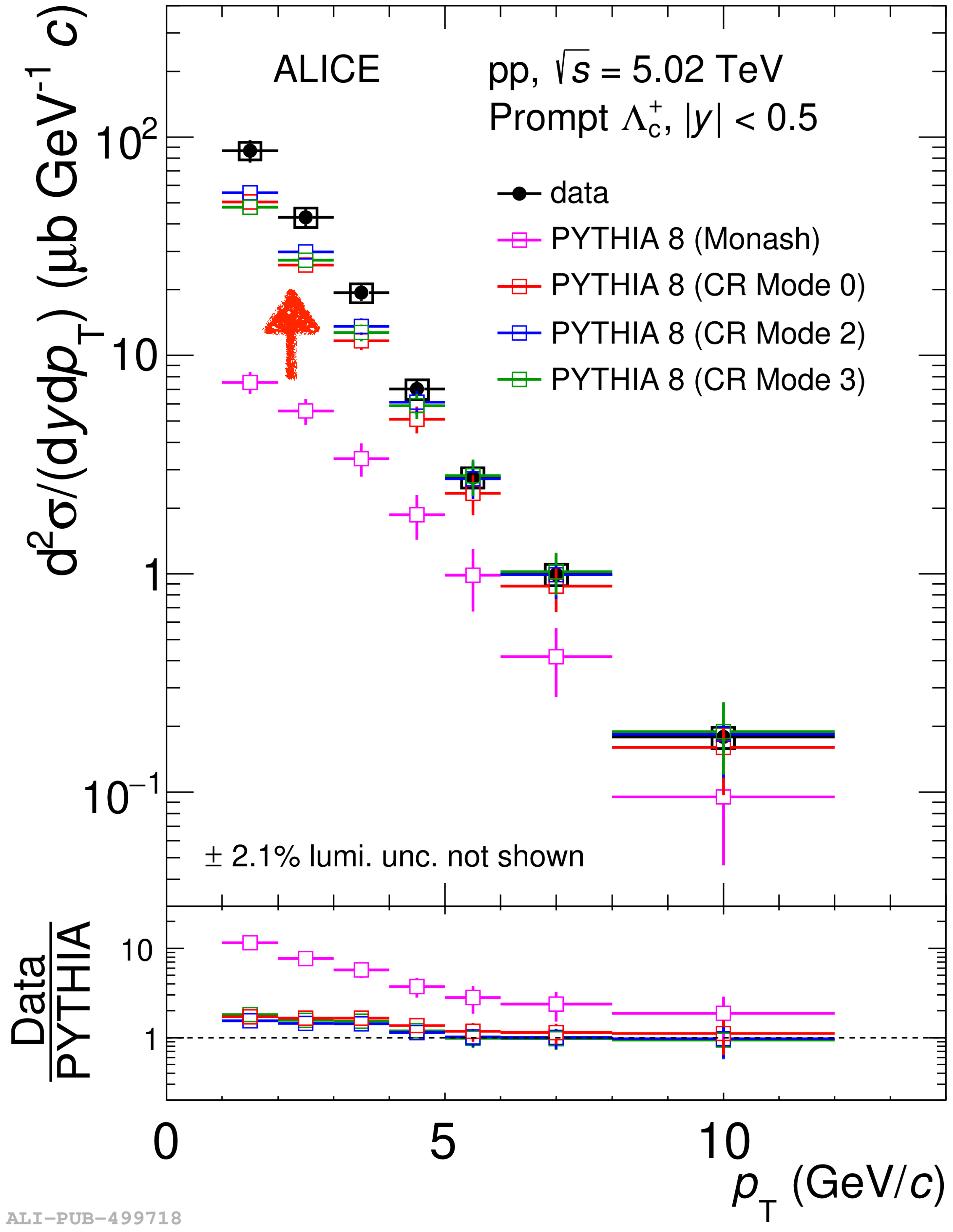




- **Enhancement** at high p_T in p–Pb w.r.t. pp collisions
- **Underestimated** by PYTHIA and QCM for both pp and p–Pb collisions

Λ_c^+ production in pp collisions in Run 2



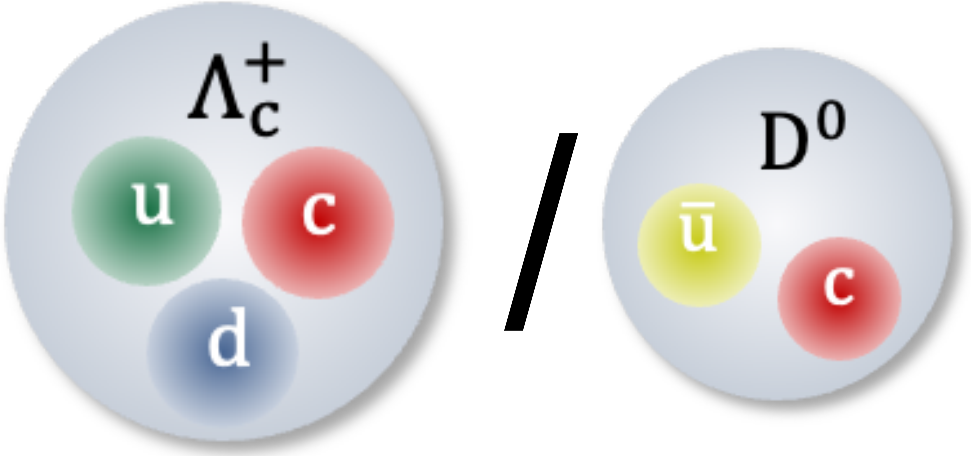


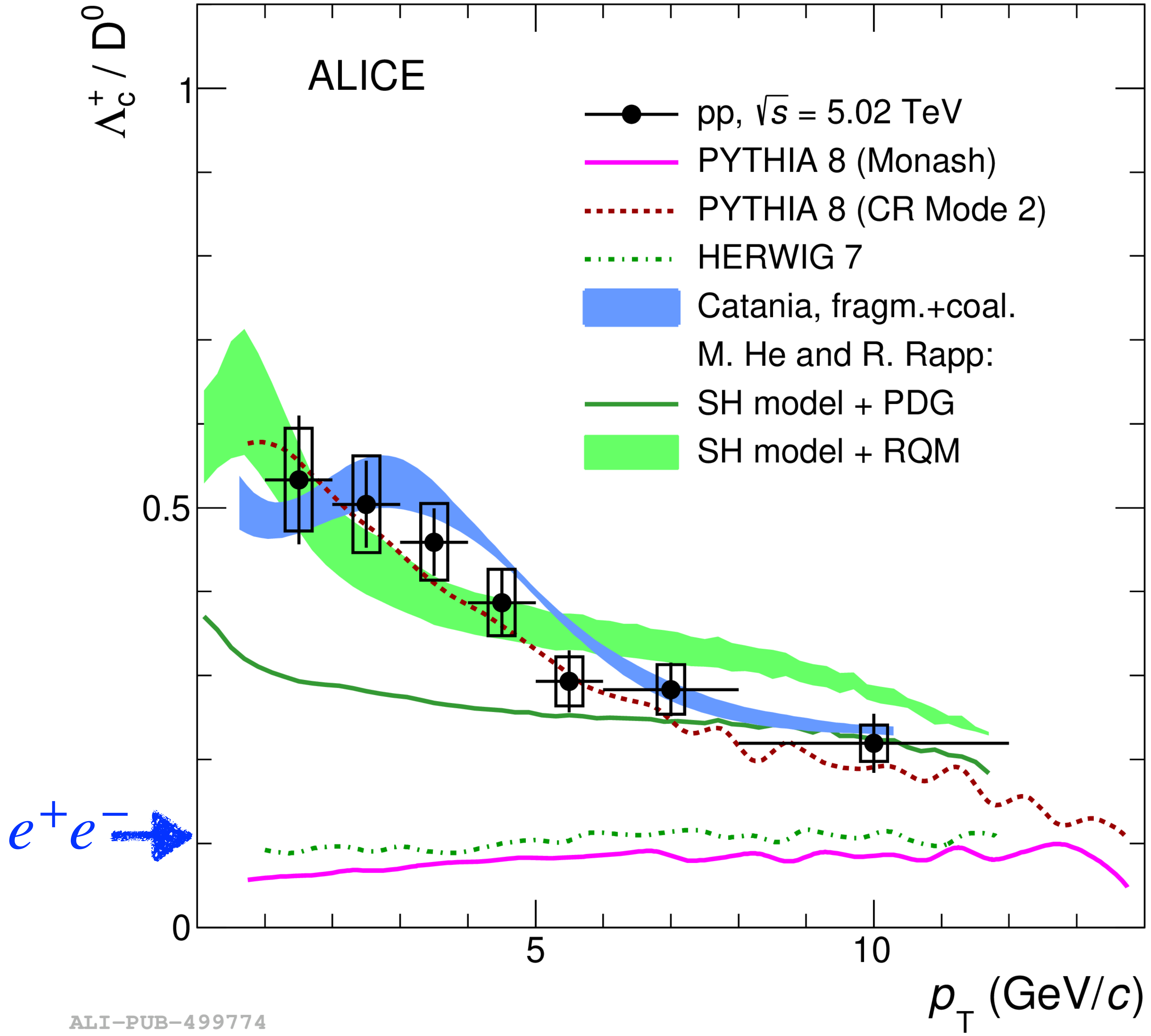
- **All PYTHIA 8** tunes **underestimate** the measured p_T differential prompt Λ_c^+ cross section.

- **Monash** tune significantly underestimates the data
  - The discrepancy becomes **smaller at high p_T**

- All three CR modes **enhance** the Λ_c^+ production and yield **a similar magnitude and shape**

Λ_c^+/D^0 in pp collisions in Run 2

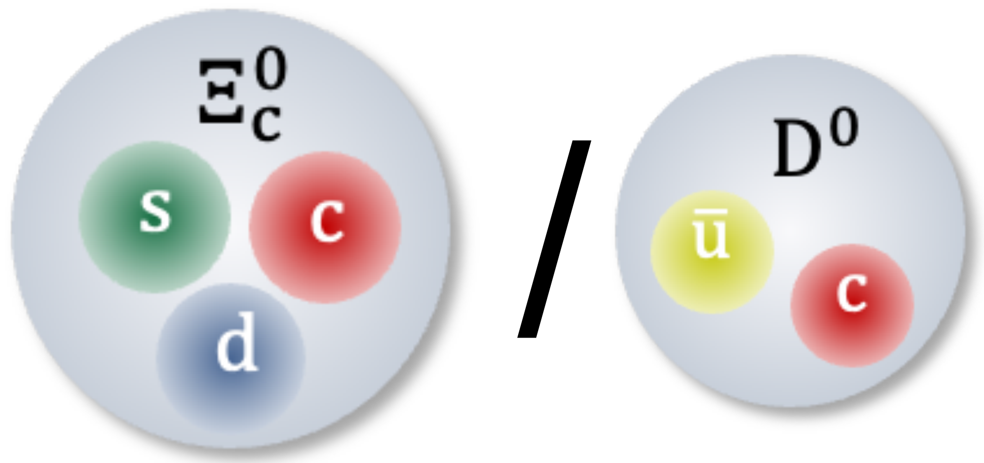


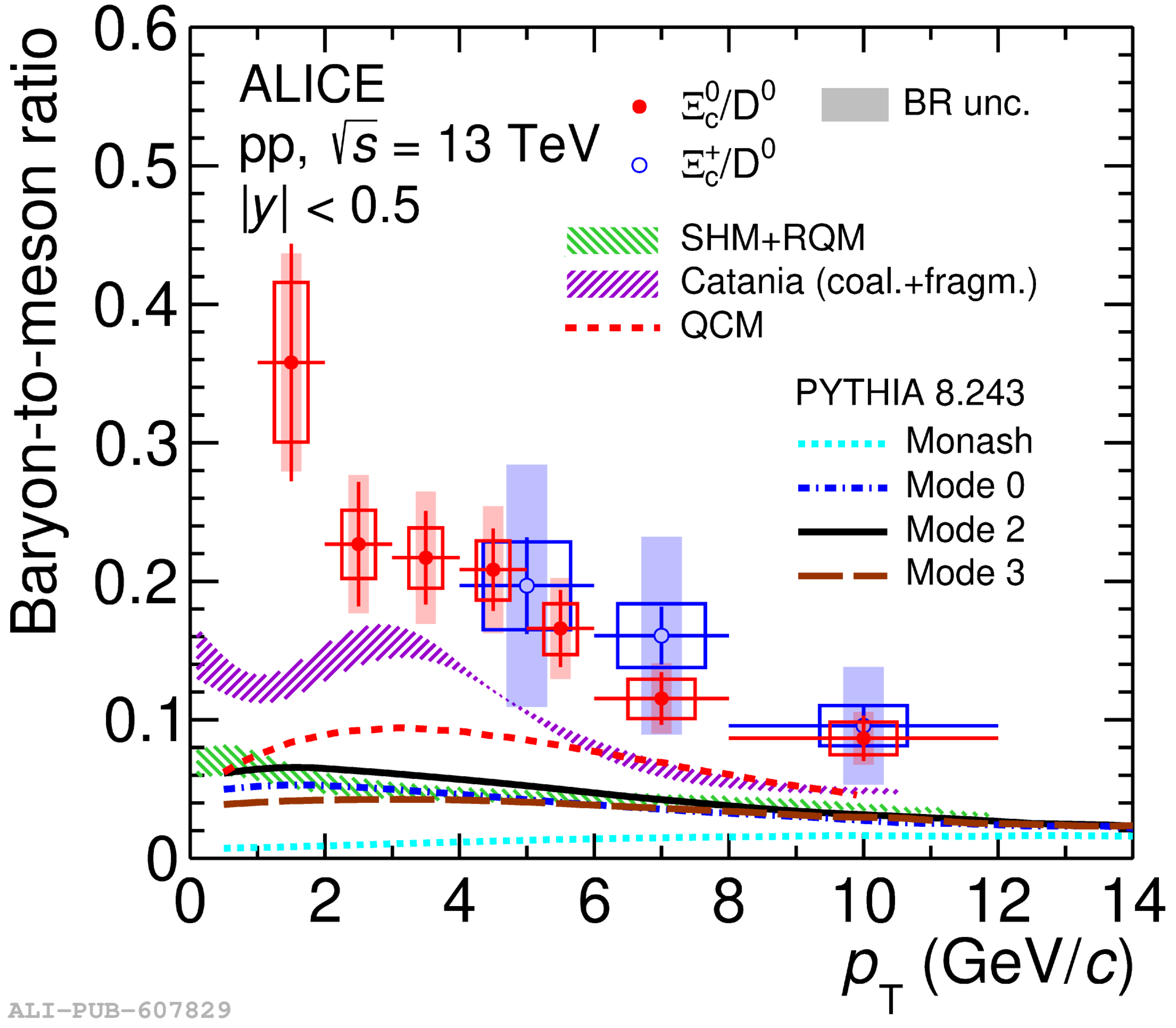


- **Decrease of the Λ_c^+/D^0 ratio with increasing pT**
  - Hadronisation of baryon and meson **differs**
- **Monash** and **HERWIG** tuned on e^+e^- collisions underestimate the data
- **Mode 2** is consistent with the measured Λ_c^+/D^0 ratio
- **SHM+PDG underpredicts the data**
- **SHM+RQM** and **Catania** describe both the magnitude and the p_T shape

ALICE

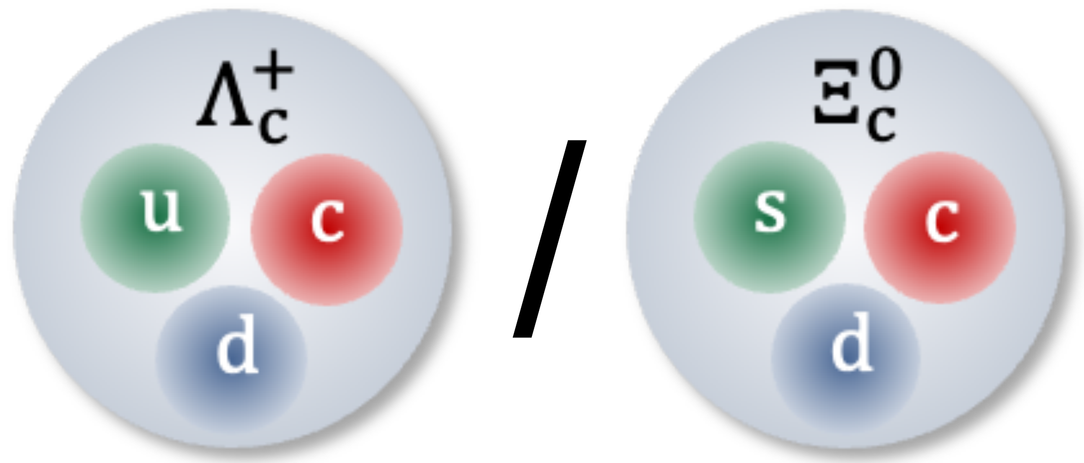
$\Xi_c^{0,+}/D^0$ in pp collisions in Run 2

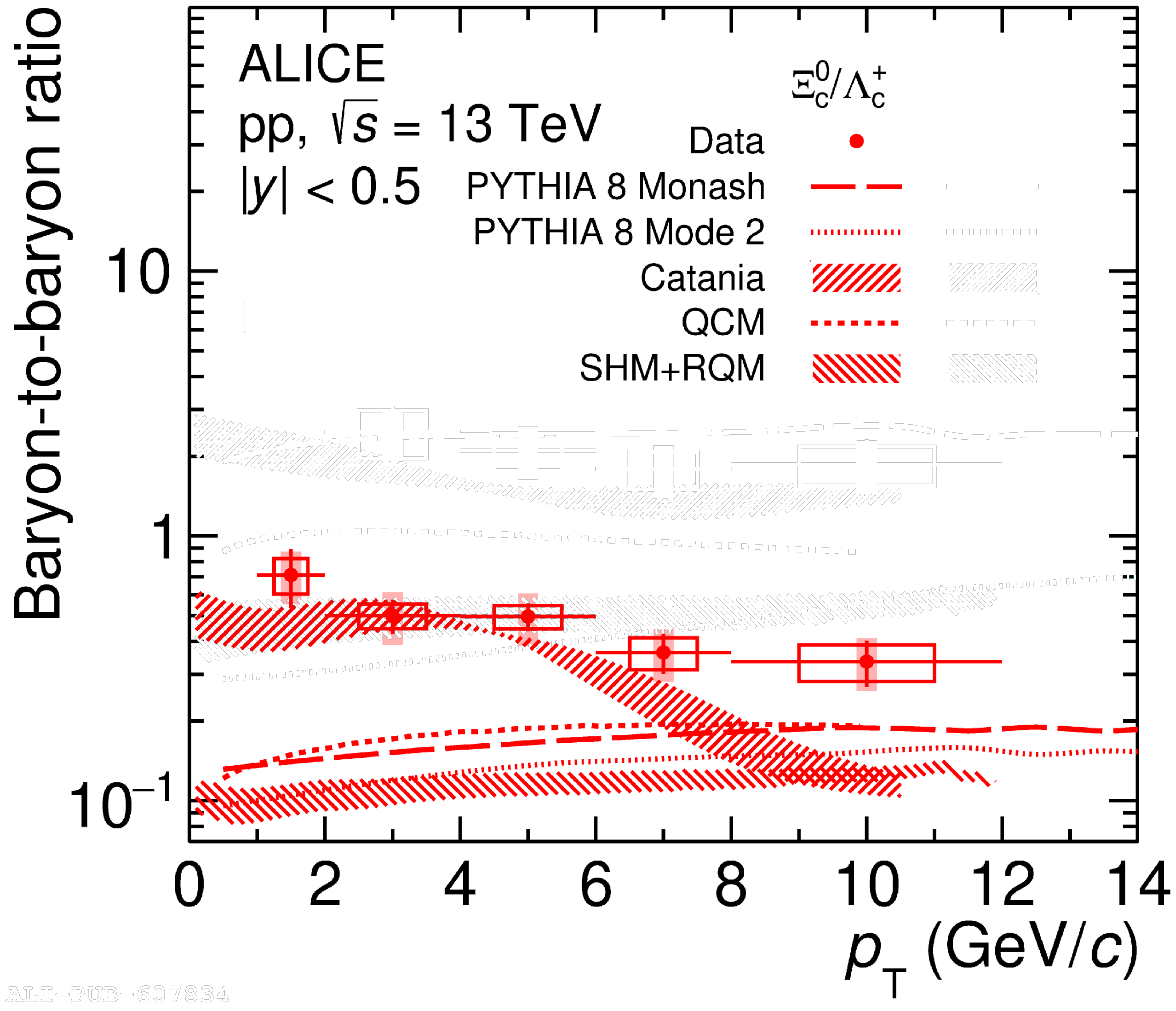




- Ξ_c^0/D^0 p_T dependence is **similar to the Λ_c^+/D^0 ratio**
- **Significantly underestimated by** PYTHIA.
  - CR modes give a similar pT dependence
- SHM+RQM can describe the Λ_c^+/D^0 ratio **but underpredict Ξ_c^0/D^0**
- Coalescence included models can't describe the data
  - QCM is tuned to reproduce the Λ_c^+/D^0 ratio in pp
  - Catania is closer to the measurement

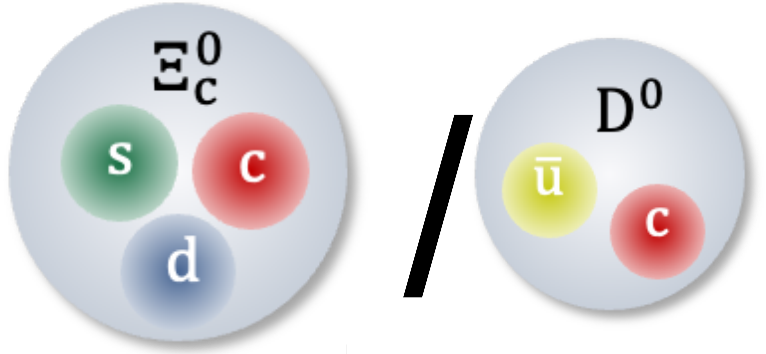
Ξ_c^0/Λ_c^+ in pp collisions in Run 2



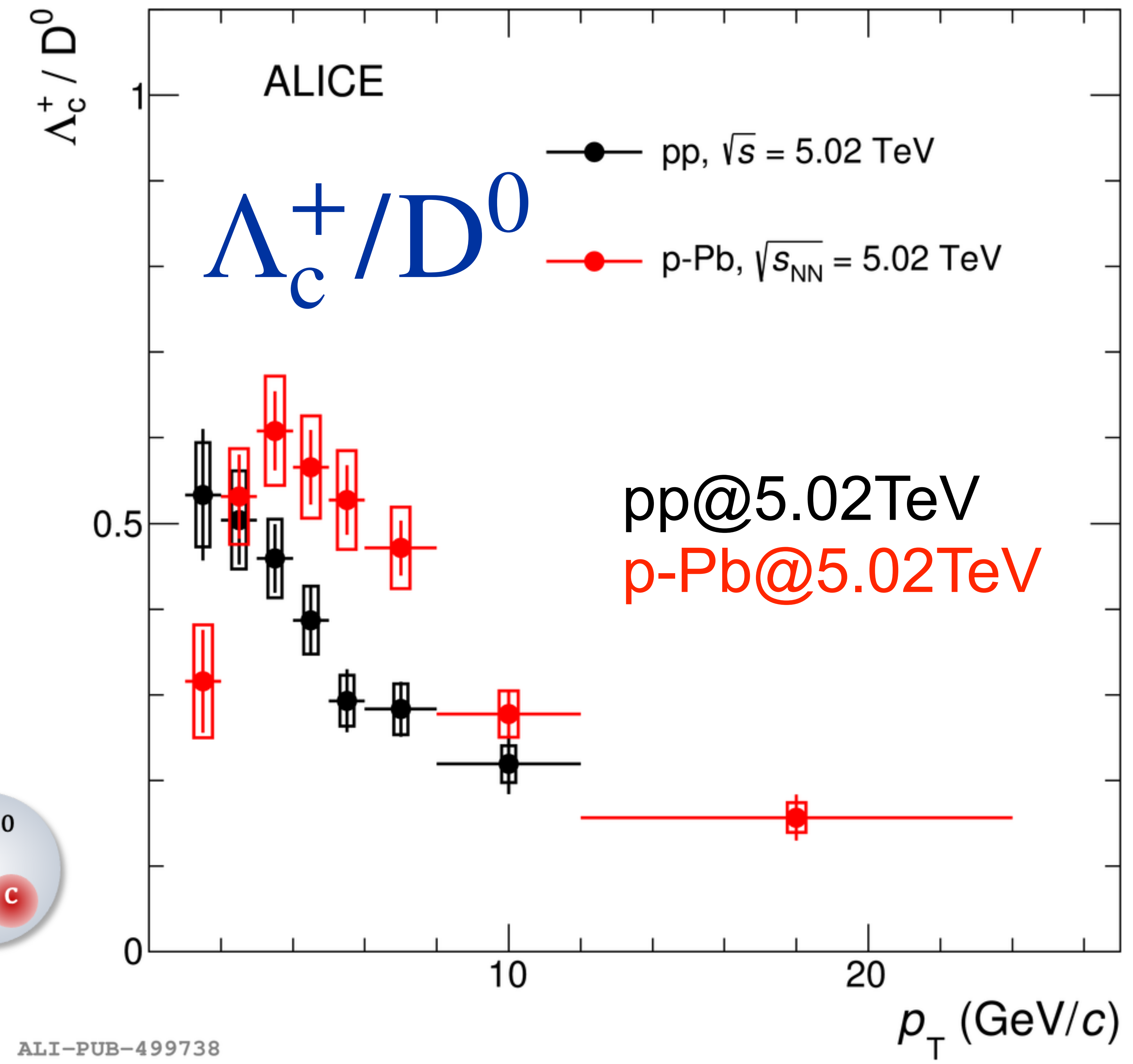


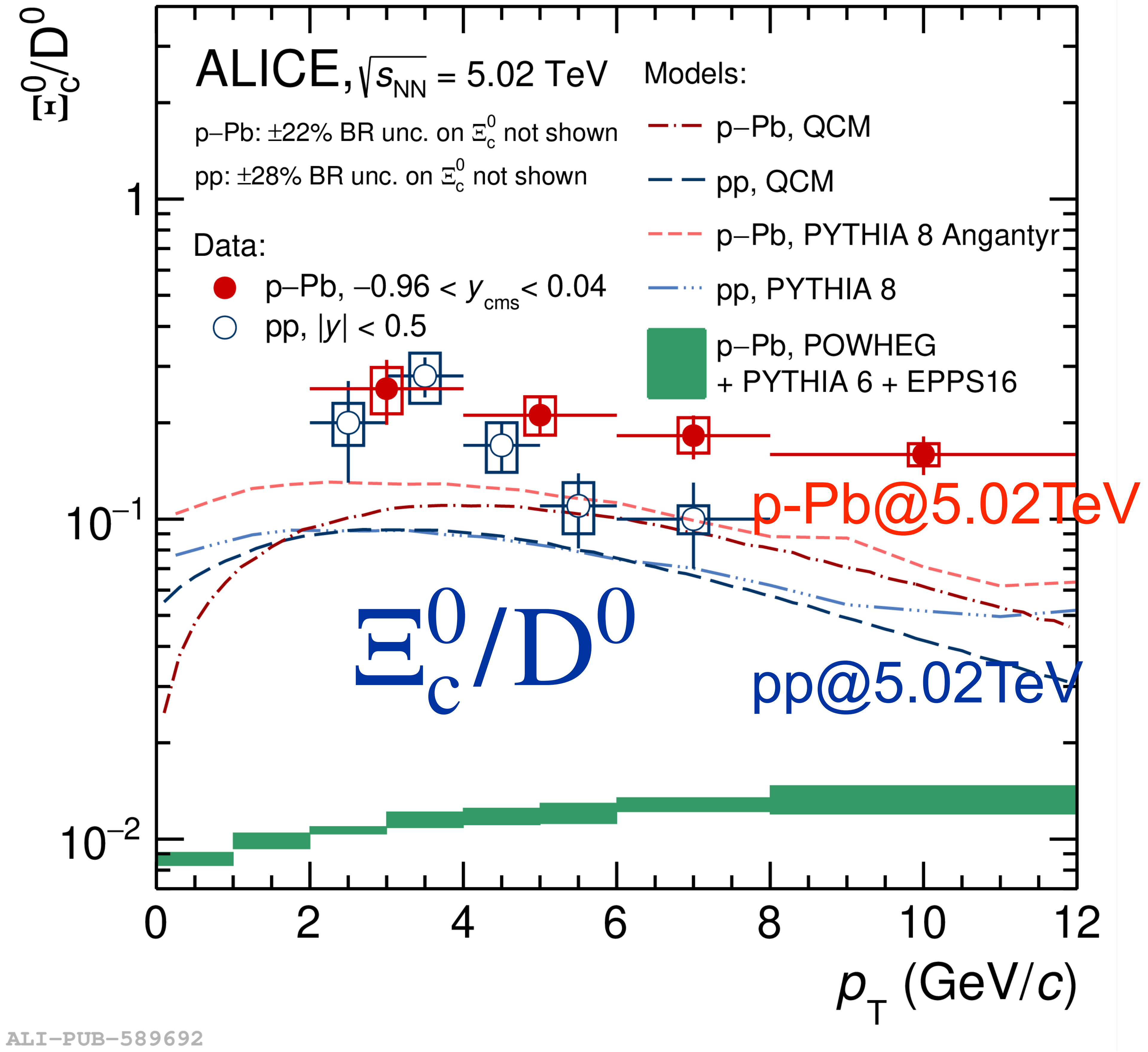
- The Ξ_c^0/Λ_c^+ ratio is approximately 0.5
- **No significant pT dependence.**
- All the models **can't describe** the measured ratio.

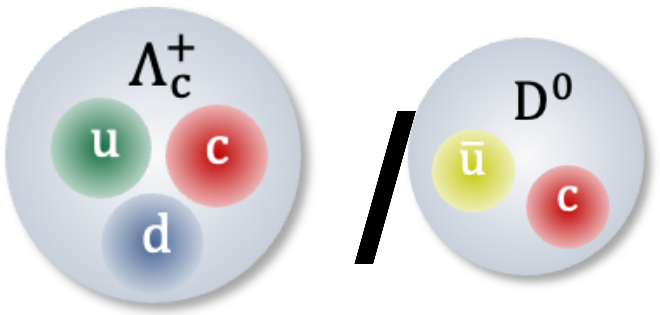
Λ_c^+/D^0, Ξ_c^0/D^0 in pp and p-Pb collisions



Phys. Rev. C 104 (2021) 054905







- **Enhancement** at high p_T in p–Pb w.r.t. pp collisions
- **Underestimated** by PYTHIA and QCM for both pp and p–Pb collisions