Charm cross section and fragmentation fractions in pp collisions with ALICE

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on behalf of the ALICE Collaboration

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VIRTUAL EDITION

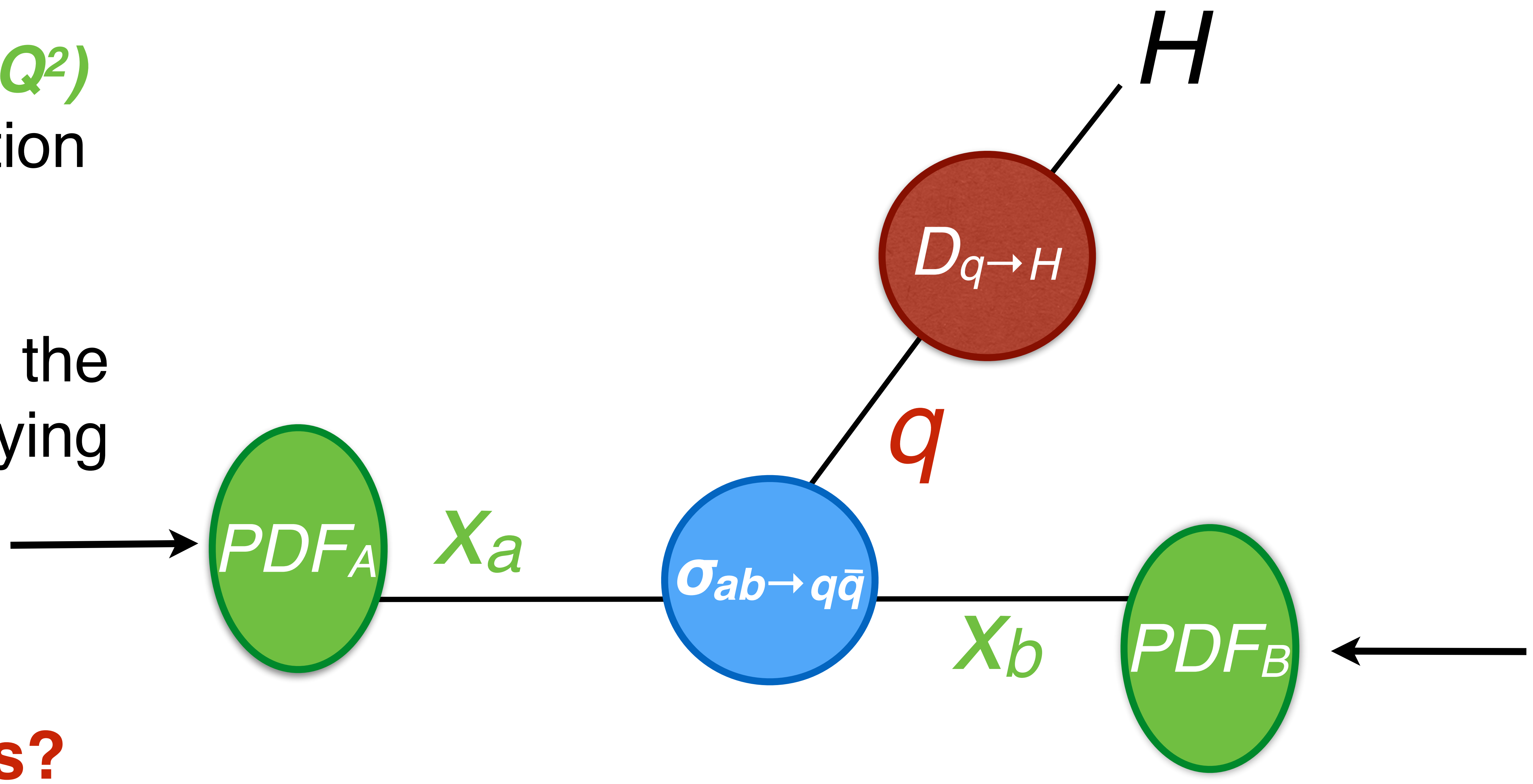
Factorization theorem

Factorization theorem: the p_T-differential cross sections are computed as the convolution of three terms:

$$d\sigma_{AB\rightarrow H} = \underbrace{PDF(x_a, Q^2)\ PDF(x_b, Q^2)}_{\text{1. Parton distribution functions}} \otimes \underbrace{\sigma_{ab\rightarrow q\bar{q}}\,(x_a, x_b, Q^2)}_{\text{2. Partonic cross section}} \otimes \underbrace{D_{q\rightarrow H}\,(z_q, Q^2)}_{\text{3. Fragmentation functions}}$$

- The parton distribution functions $\boldsymbol{PDF(x_a, Q^2), PDF(x_b, Q^2)}$ represent the probability to have each parton carrying a fraction $\boldsymbol{x_a}$, $\boldsymbol{x_b}$ within the colliding protons

- The quark fragmentation function $\boldsymbol{D_{q\rightarrow H}\,(z_q, Q^2)}$ represents the probability that the quark $\boldsymbol{q}$ fragments into the hadron $\boldsymbol{H}$, carrying a fraction $\boldsymbol{z_q}$ of the quark momentum ($p_H = z\ p_q$)



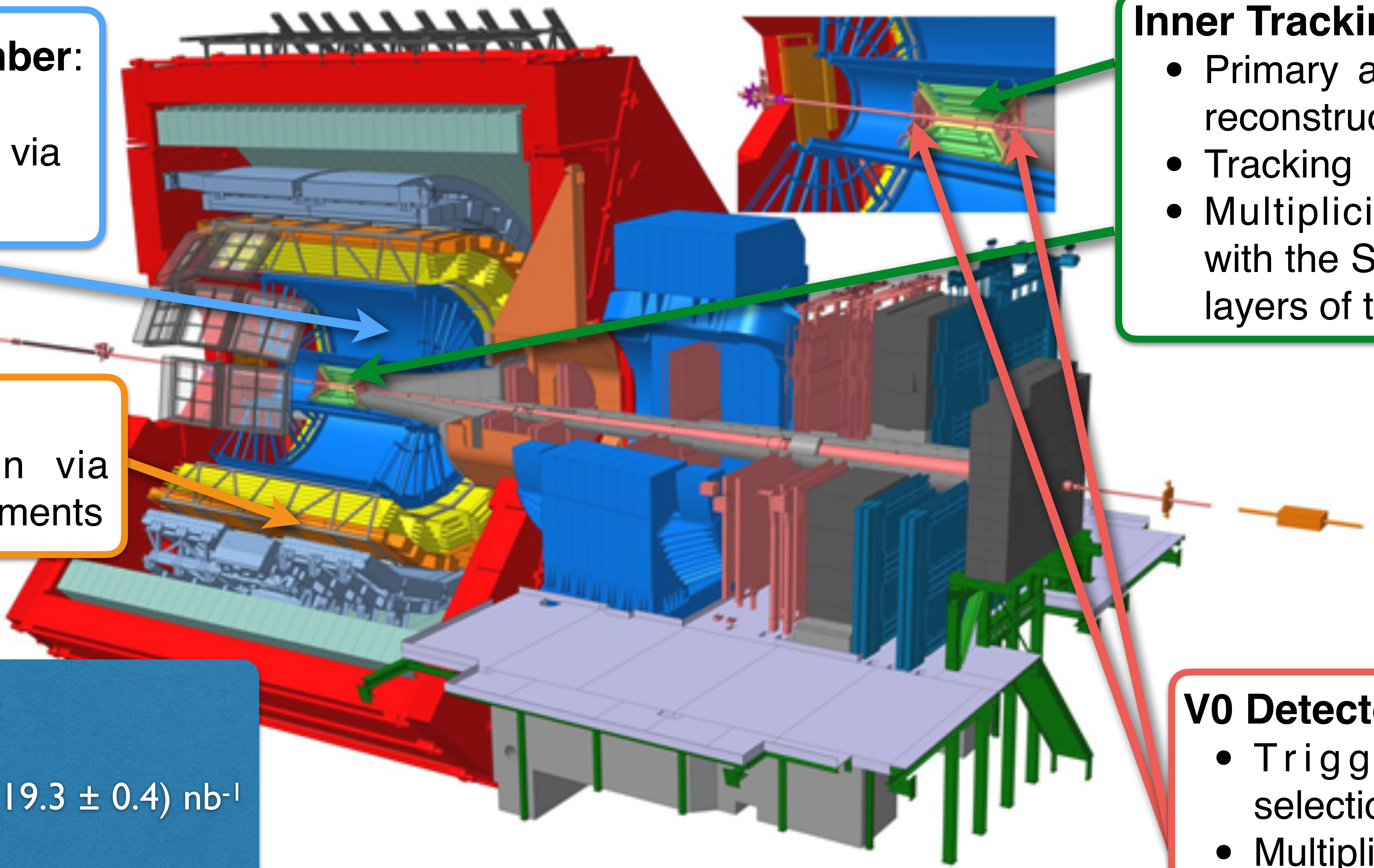
Is charm fragmentation the same for all collision systems?

- The study of charm baryon production is a powerful tool to investigate the modification of the hadronization mechanisms

ALICE detector

Time Projection Chamber:
- Track reconstruction
- Particle identification via dE/dx

Time of Flight:
- Particle identification via time-of-flight measurements



Inner Tracking System:
- Primary and decay vertices reconstruction
- Tracking
- Multiplicity measurement with the SPD (two innermost layers of the ITS)

V0 Detectors:
- Trigger and event selection
- Multiplicity measurement based on the V0 signal amplitude

Data Sample:
pp collisions @5.02 TeV
- 990M of MB events, L_{INT} = (19.3 ± 0.4) nb^{-1}
pp collisions @13 TeV:
- 1.8B of MB events, L_{INT} = (32 ± 1.6) nb^{-1}
p-Pb collisions @5.02 TeV:
- 600M of MB events, L_{INT} = (287 ± 11) μb^{-1}

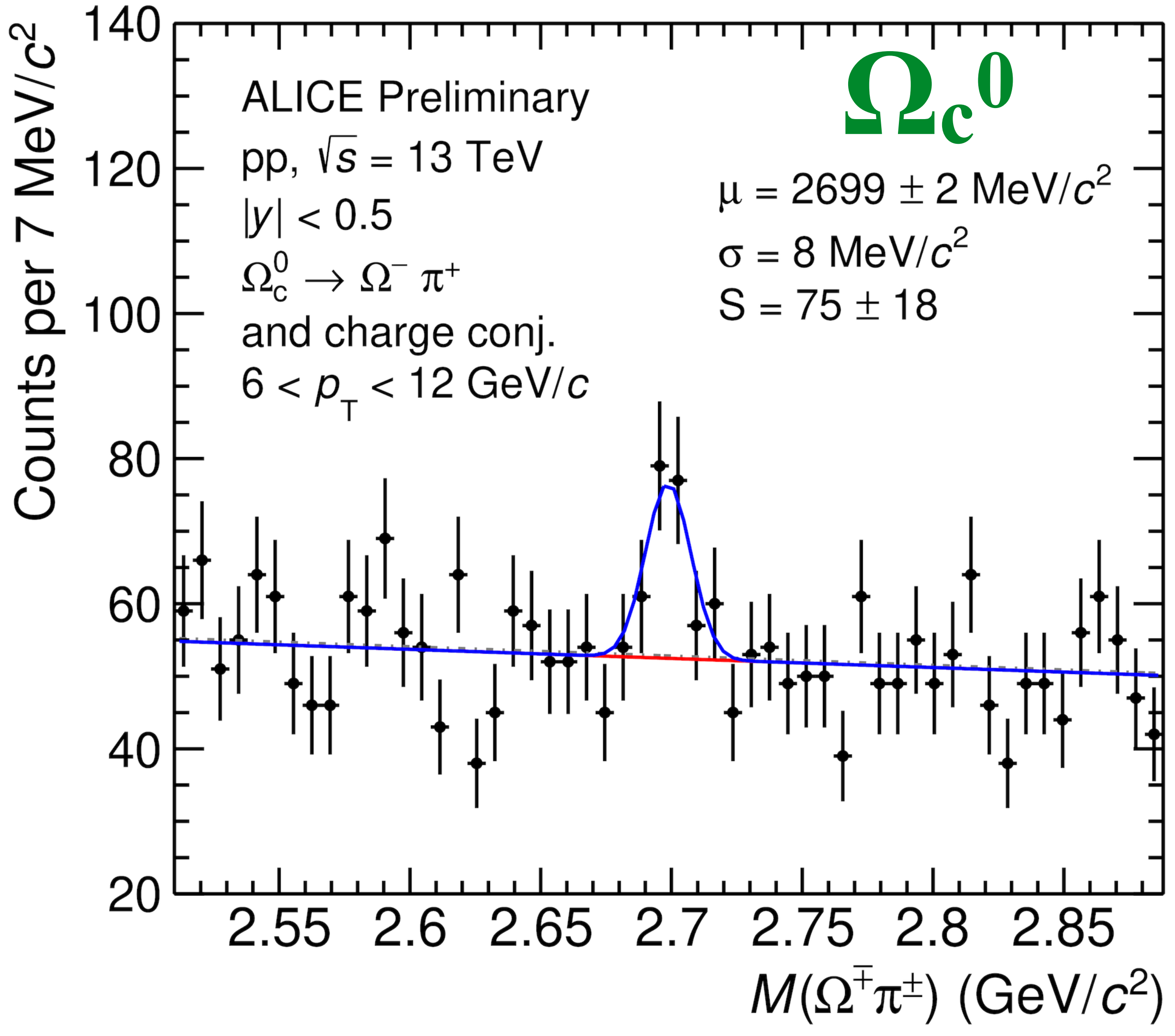
Charm-baryons reconstruction

The following charmed baryons are reconstructed:

Baryon	M (GeV/c²)	$c\tau$ (μm)	Decay	BR (%)
Λ_c^+	~2.286	~61	$pK^-\pi^+$, $pK^0_s(\longrightarrow \pi^+\pi^-)$	6.28% , 1.1%
Ξ_c^0	~2.468	~46	$\Xi^- e^+ \nu_e$, $\Xi^-\pi^+$	1.8% , 1.43%
Ξ_c^+	~2.471	~137	$\Xi^-\pi^+\pi^+$	2.86%
$\Sigma_c^{0,++}$	~2.454	/	$\Lambda_c^+\pi^{-,+}$	7.38% *
Ω_c^0	~2.695	~80	$\Omega^-\pi^+$	0.51% *

- HF candidates built combining **pairs or triplets of tracks** at midrapidity ($|\eta| < 0.8$) with the proper charge-sign combination
- **Topological** and **PID** selections to reduce the combinatorial background

NEW!



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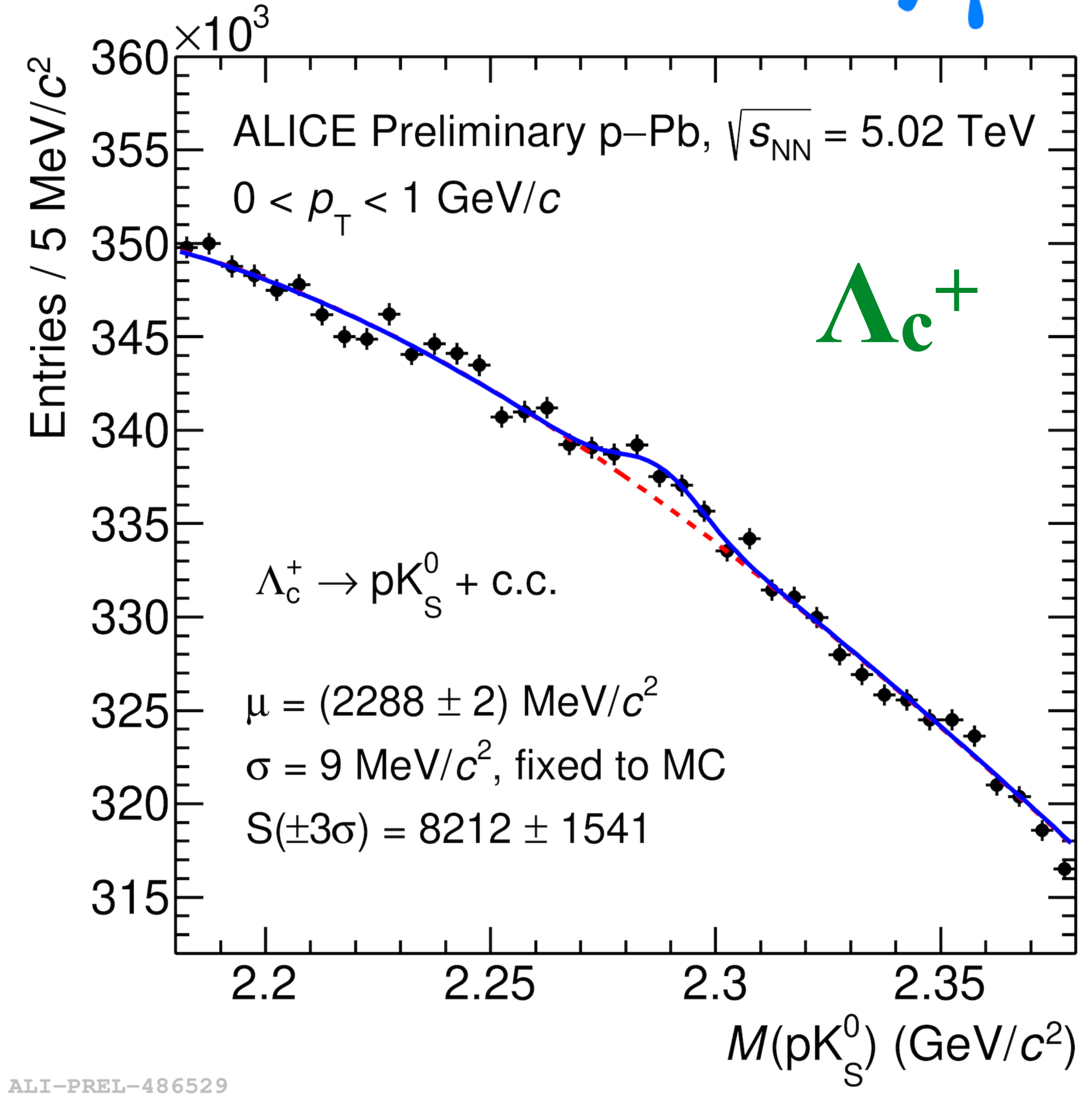


* The $\Sigma^{0,++}$ decays with a BR ~100% in Λ_c. The two Λ_c decay channels pKπ and pK^0_s are reconstructed

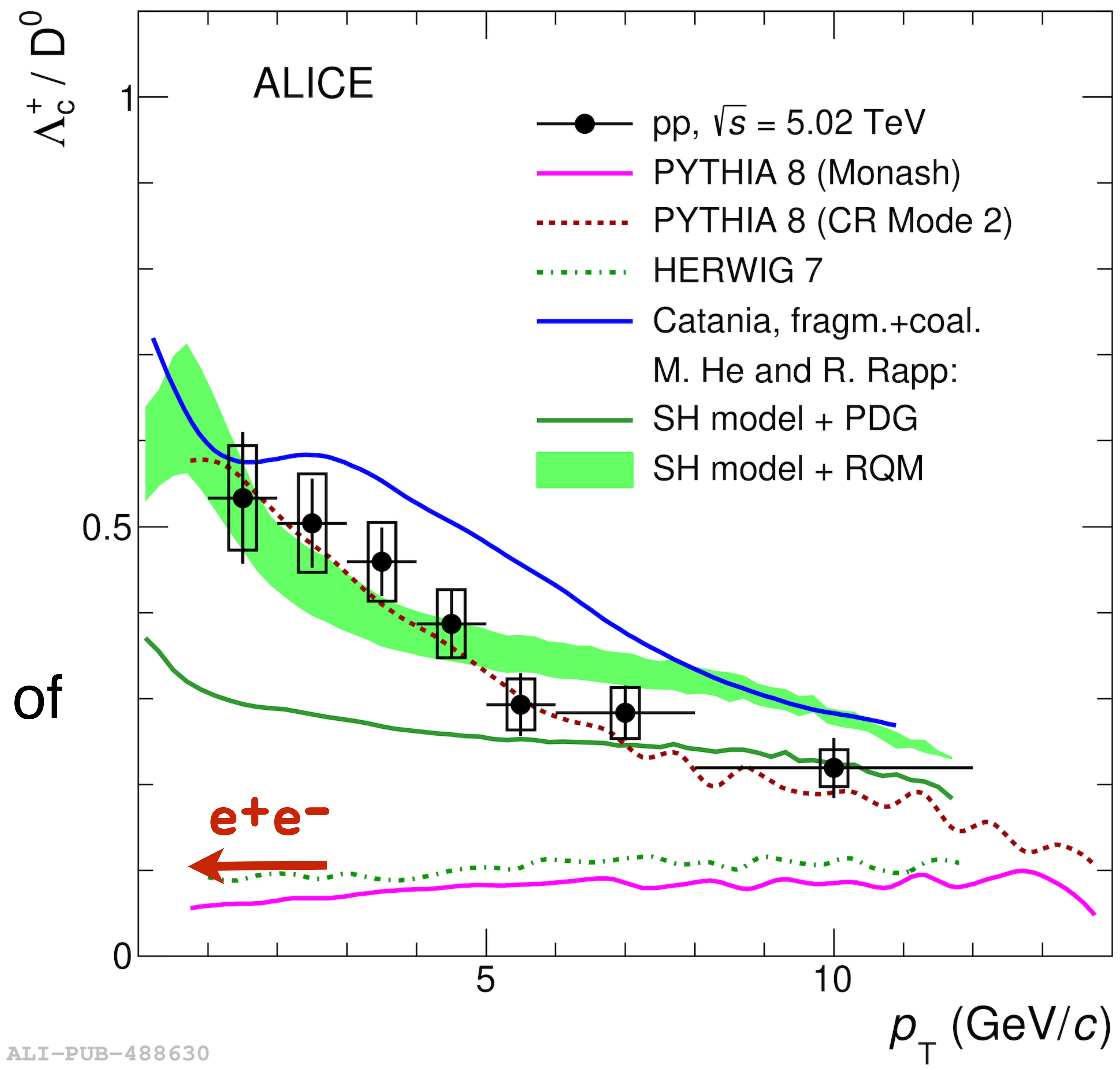
* BR($\Omega_c^0 \to \pi^+\Omega^-$) from theory calculations [Y. Hsiao et al. EPJC 80, 1066 (2020)]

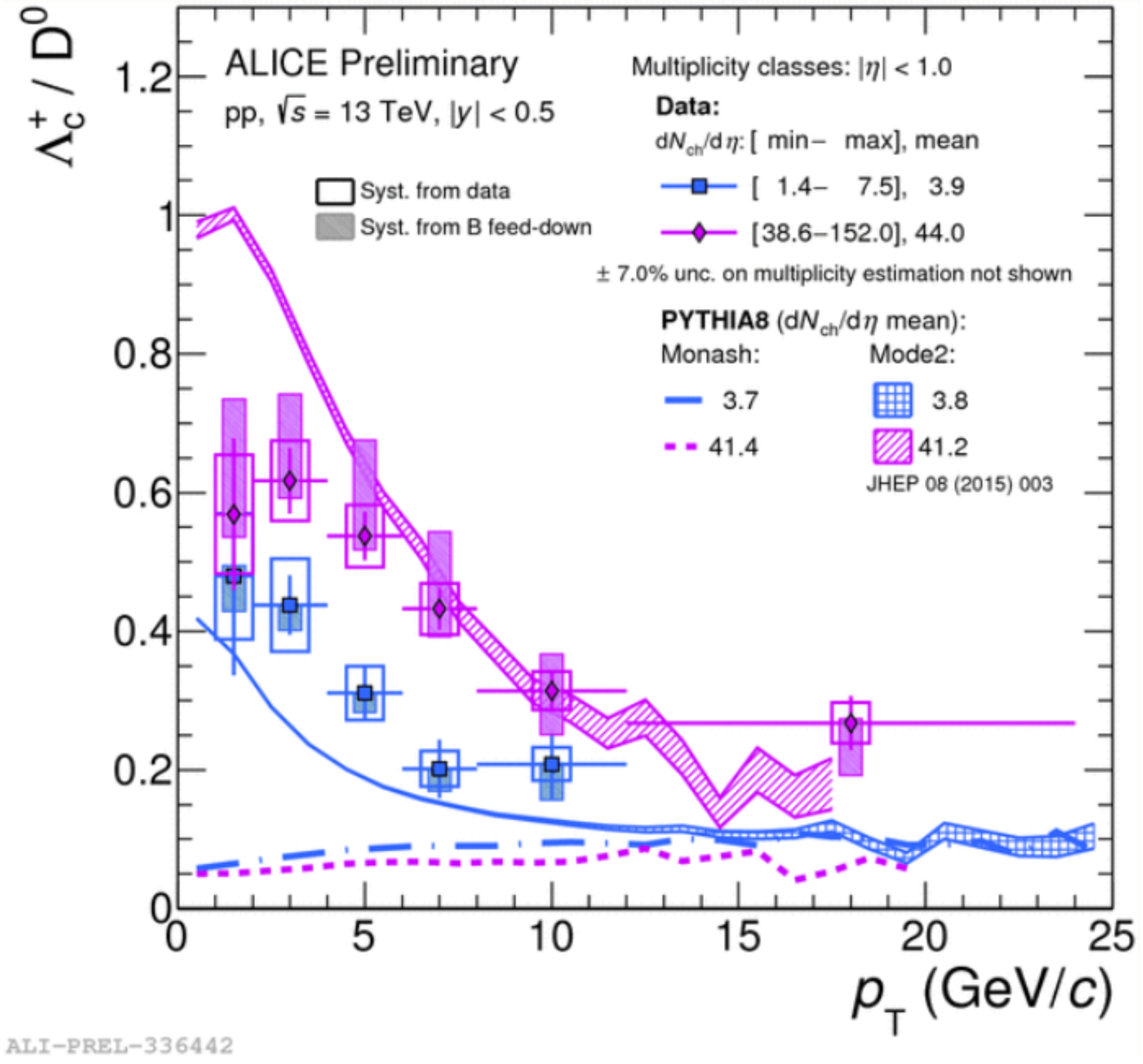
Λ_c^+ results in pp collisions

arXiv:2011.06078

- The charmed baryon-to-meson ratio Λ_c^+/D^0 in pp is enhanced with respect to e^+e^- collisions
- Strong p_T dependence observed

- **Monash tune:** simple string fragmentation model, with FF tuned on e^+e^- measurements. **Strongly underestimates the data**





- Which is the origin of the modification of the Λ_c^+/D^0 ratio?

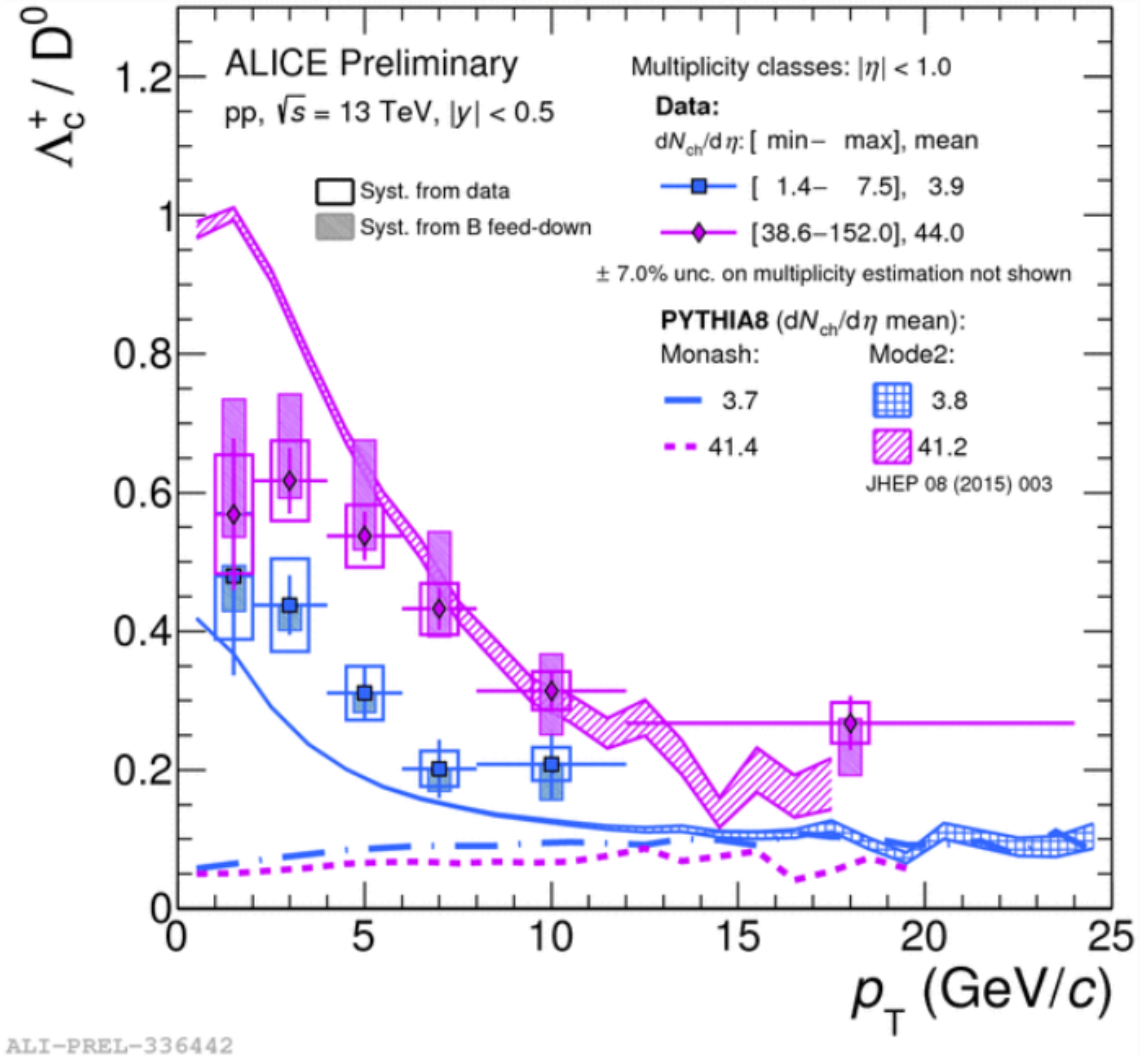
Which role does multiplicity play?

- Significant enhancement from low to high multiplicity
- Low multiplicity pp is still enhanced with respect to e^+e^-

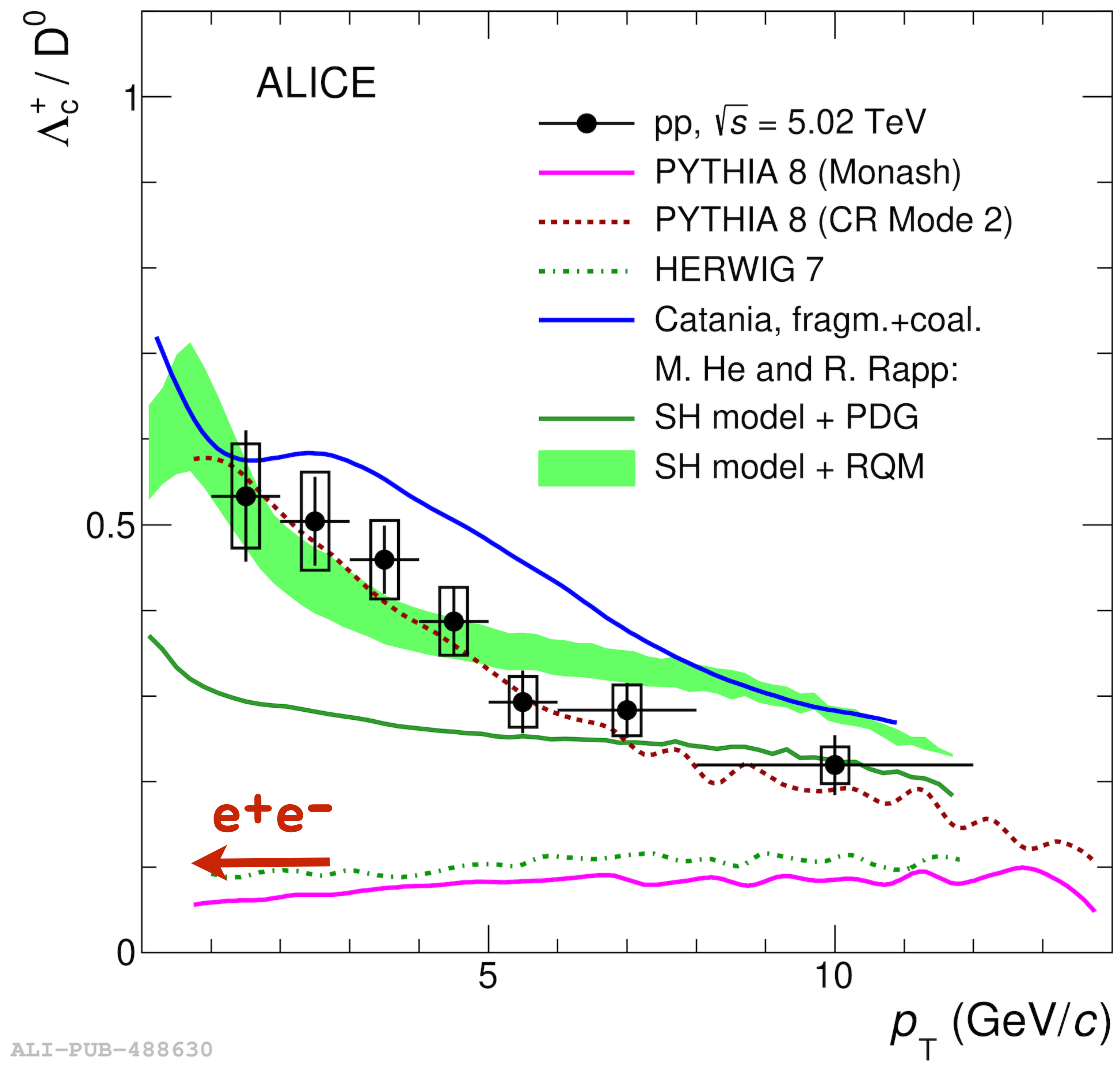
Λ_c^+ results in pp collisions

Mechanisms that enhance baryon formation needed to explain the observed results:

- **CR modes:** string formation beyond leading colour (LC) approximation
  Good data description. It can also describe the multiplicity dependence
  [Christiansen & Skands, JHEP 1508 (2015) 003]



[arXiv:2011.06078]



- **SHM + RQM:** decay of clusters in a purely statistical fashion, including additional excited baryon states predicted by the Relativistic Quark Model (RQM)
  Good data description [Hee & Rapp, PLB 795 117-121 (2019)]

- **Catania:** quark hadronization via coalescence + fragmentation
  Slightly overestimate the data [Minissale, Plumari & Greco, arXiv:2012.12001]

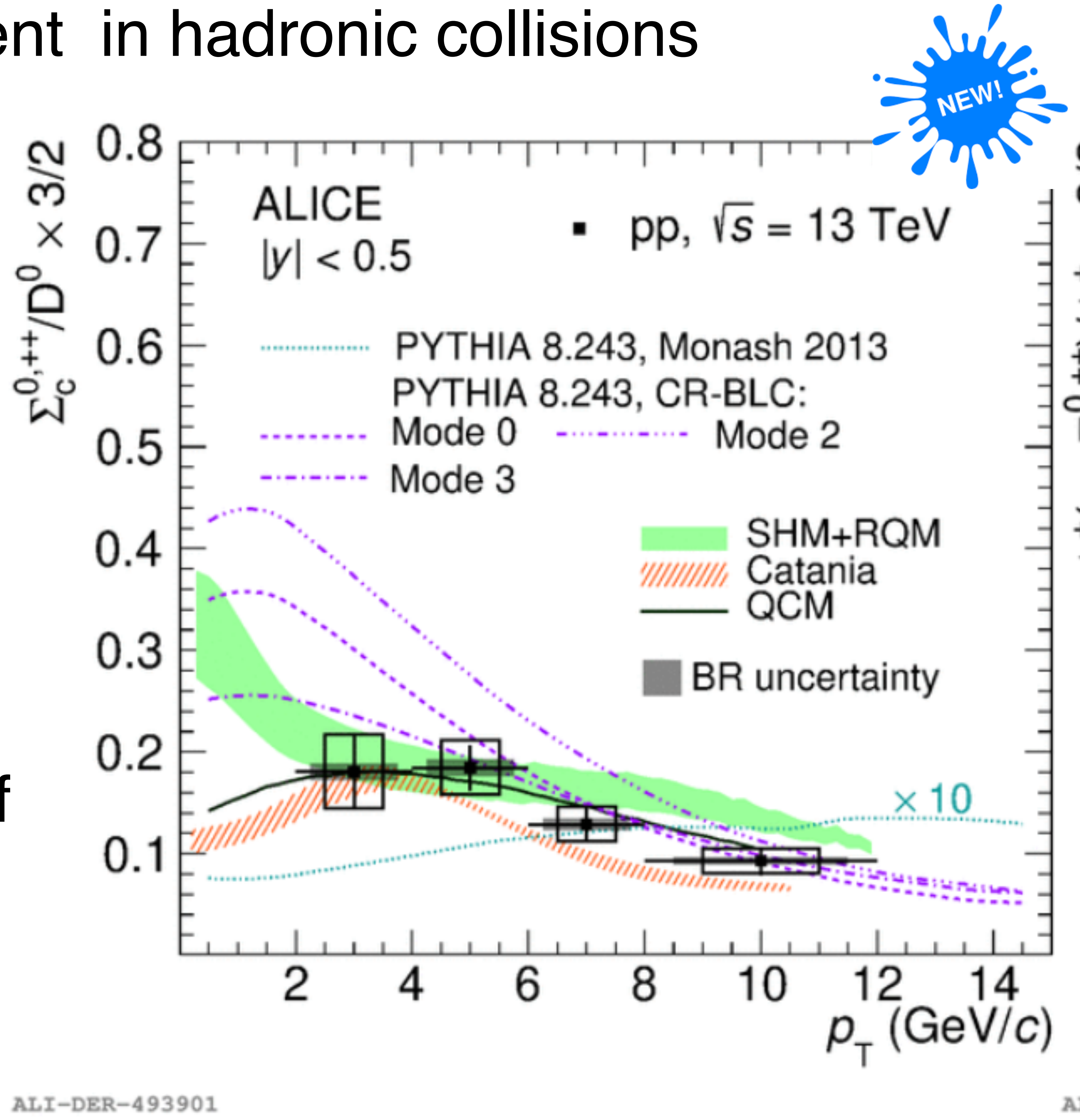
$\Sigma_c^{0,+,++}$ results in pp collisions

- First $\Sigma_c^{0,++}(2455)$ production measurement in hadronic collisions

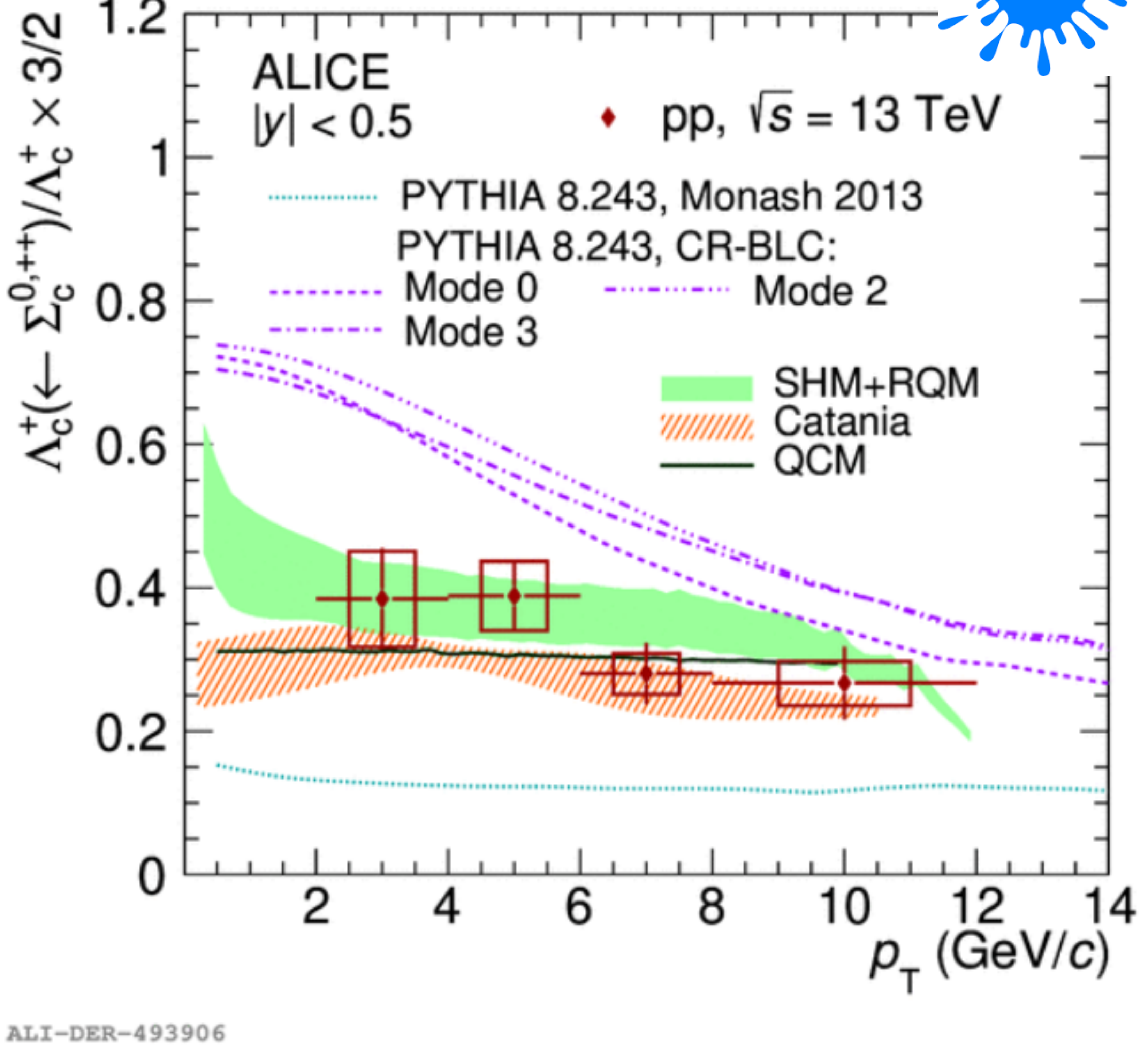
- The $\Sigma_c^{0,+,++}/D^0$ in pp is strongly enhanced with respect to Monash prediction tuned on e^+e^- collisions

- Effects of Σ_c feed-down on Λ_c^+/D^0

→ $\Sigma_c^{0,+,++}$ feed-down could explain part of the Λ_c enhancement in pp collisions
~40% of feeddown Λ_c from $\Sigma_c^{0,+,++}$



arXiv:2106.08278



- PYTHIA 8 Monash severely underpredicts both $\Sigma_c^{0,+,++}/D^0$ and $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratios
- PYTHIA 8 with CR describes $\Sigma_c^{0,+,++}/D^0$ but overestimates the $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio
- SHM+RQM describes both measurements
- Catania and **QCM** (pure coalescence) models also provide a good description of the data

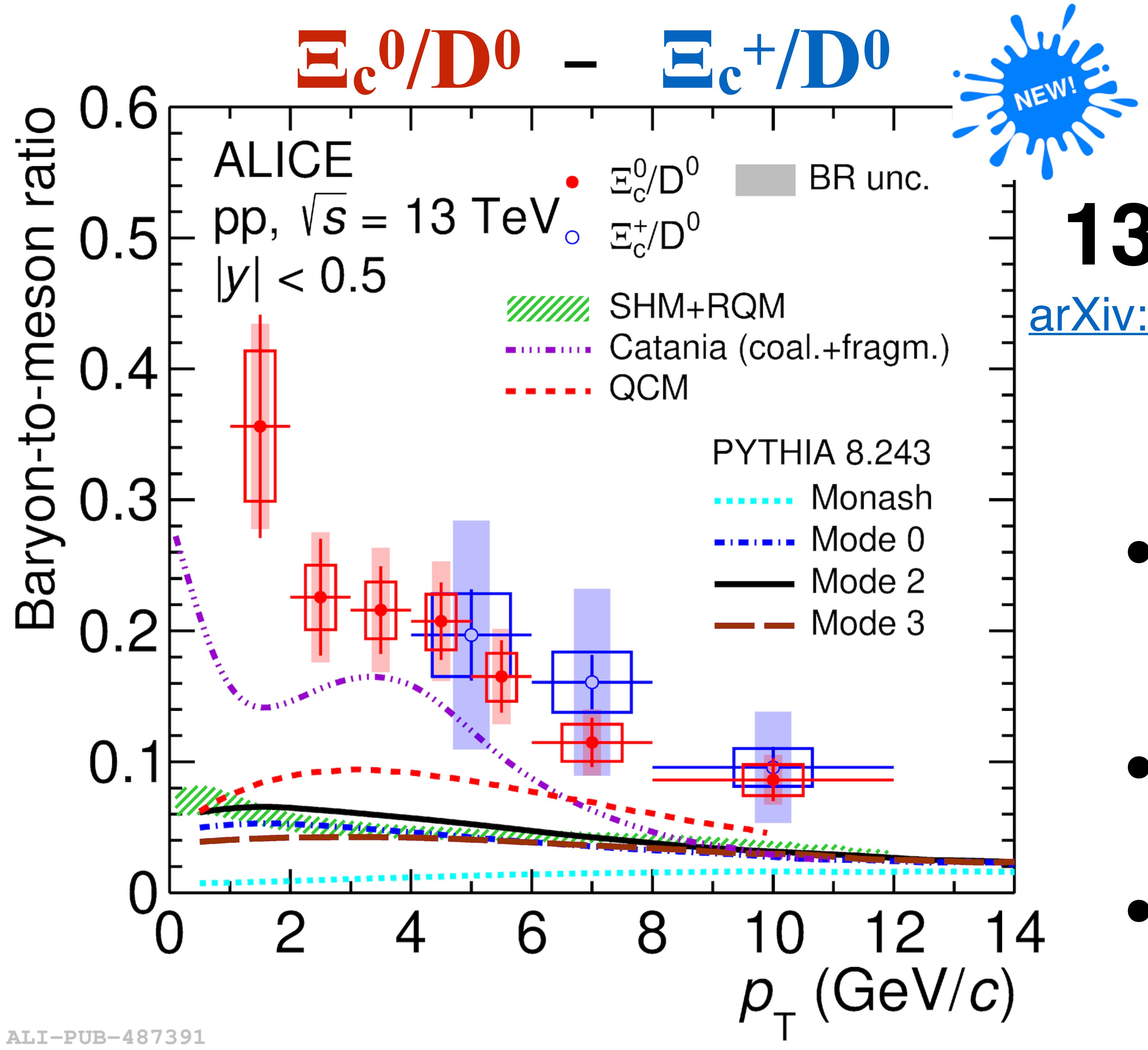
Song, Lii & Shao, EPJC 78 no. 4, (2018) 344

Ξ_c^0 and Ξ_c^+ results in pp collisions

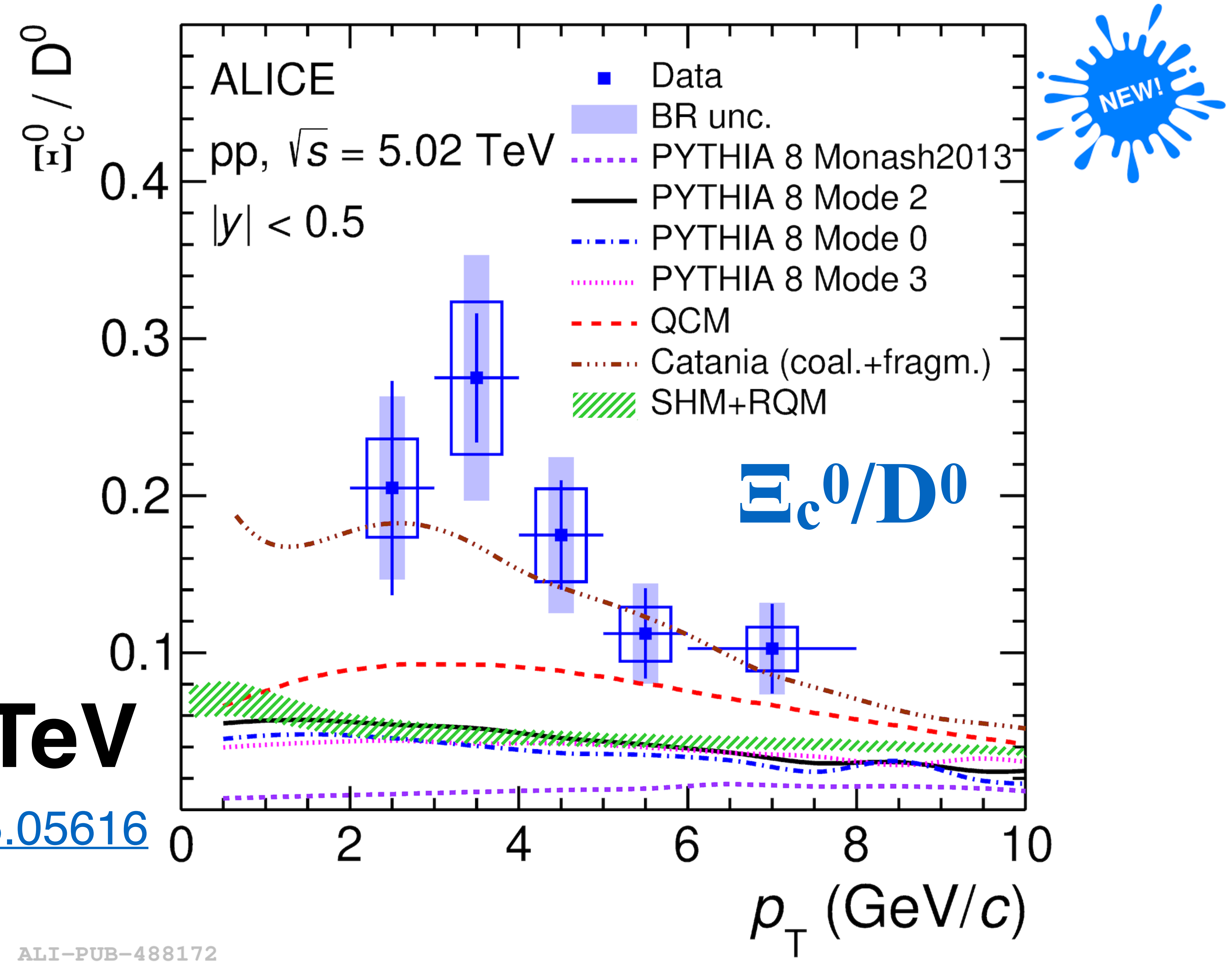
- $\Xi_c^{0,+}/D^0$ p_T dependence similar to that observed for the Λ_c^+/D^0
- Ξ_c^0/D^0 and Ξ_c^+/D^0 in agreement within the uncertainty

- Ξ_c^0/D^0 and Ξ_c^+/D^0 significantly underestimated by the **Monash Tune**
  Additional information on the non-universality of charm fragmentation

Ξ_c^0/D^0 – Ξ_c^+/D^0



13 TeV
arXiv:2105.05187



5.02 TeV
arXiv:2105.05616

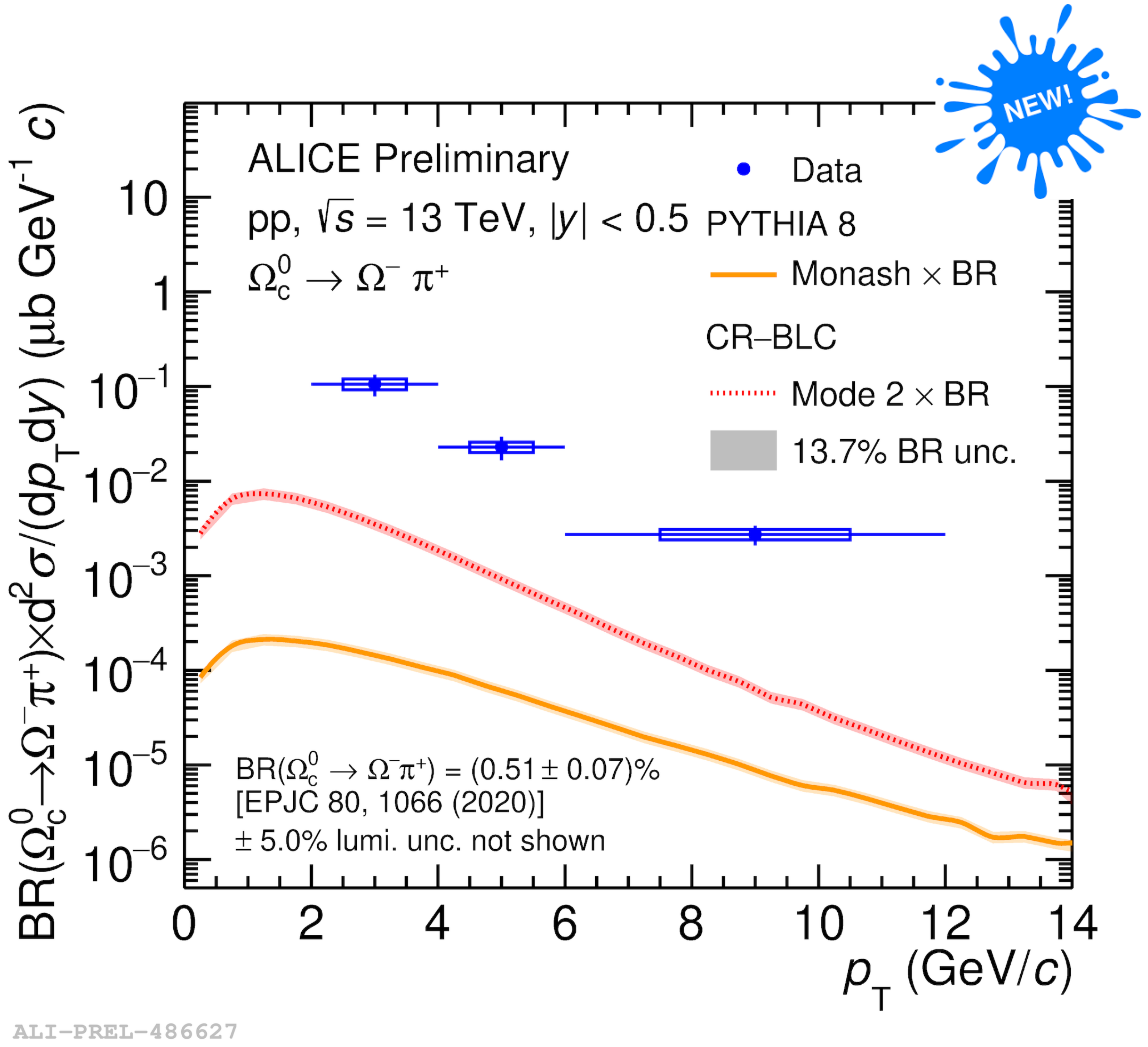
- **CR modes** and **SHM**: significantly larger cross sections w.r.t. Monash. The predictions still underestimate the data

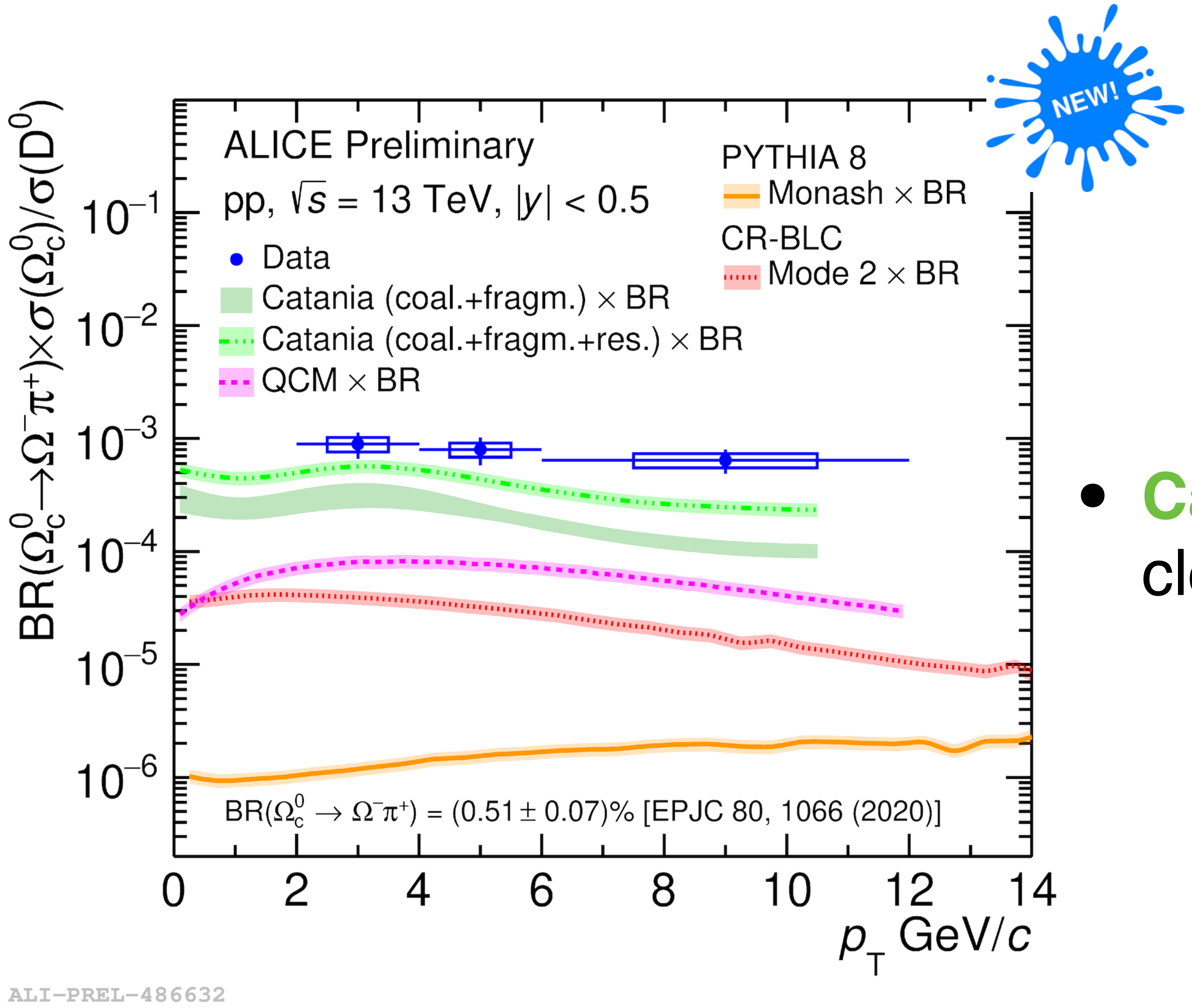
- **QCM**: Further enhancement but still underpredicts the measured ratio

- **Catania** model is the one that better describes both the measured $\Xi_c^{0,+}/D^0$ ratio

Ω_c^0 results in pp collisions

- First Ω_c^0 production cross section
  $BR(\Omega_c^0 \rightarrow \pi^+\Omega^-) = (0.51 \pm 0.07)\%$ from theory calculations [Y. Hsiao et al. EPJC 80, 1066 (2020)]
- No clear p_T dependence observed in the Ω_c^0/D^0 ratio
- **Monash Tune** strongly underestimate the Ω_c^0 production cross section and the Ω_c^0/D^0 ratio
- The enhancement predicted by the **CR mode** is not enough to describe the measurement
- Further enhancement observed with the simple coalescence **QCM**. Still cannot represent the data





- **Catania** model is the one that gets closer to the data for the Ω_c^0 as well

Ω_c^0 results in pp collisions

- First Ω_c^0 production cross section

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- No clear p_T dependence observed in the Ω_c^0/D^0 ratio

- **Monash Tune** strongly underestimate the Ω_c^0 production cross section and the Ω_c^0/D^0 ratio
- The enhancement predicted by the **CR mode** is not enough to describe the measurement
- Further enhancement observed with the simple coalescence **QCM**. Still cannot represent the data

	Monash	CR modes	SHM + RQM	QCM	Catania
Λ_c^+	Underestimate	Good	Good	/	Slightly overestimate
$\Sigma_c^{0,++}$	Underestimate	Good	Good	Good	Good
$\Lambda_c^+ (\leftarrow \Sigma_c^{0,++})$	Underestimate	Overestimate	Good	Good	Good
Ξ_c^0	Underestimate	Underestimate	Underestimate	Underestimate	Good
Ξ_c^+	Underestimate	Underestimate	Underestimate	Underestimate	Slightly underestimate
Ω_c^0	Underestimate	Underestimate	/	Underestimate	Slightly underestimate

- **Coalescence also in pp collisions?**

Charm production cross section

- First measurement of the charm cross section in **pp collision at $\sqrt{s}$ = 5.02 TeV** at midrapidity ($|y| < 0.5$). Measured hadron cross sections in pp collisions at 5.02 TeV:

  D^0, D^+, D_s^+, Λ_c^+, Ξ_c^0

- Extrapolation of the cross section down to zero p_T for D_s^+, Λ_c^+ and Ξ_c^0

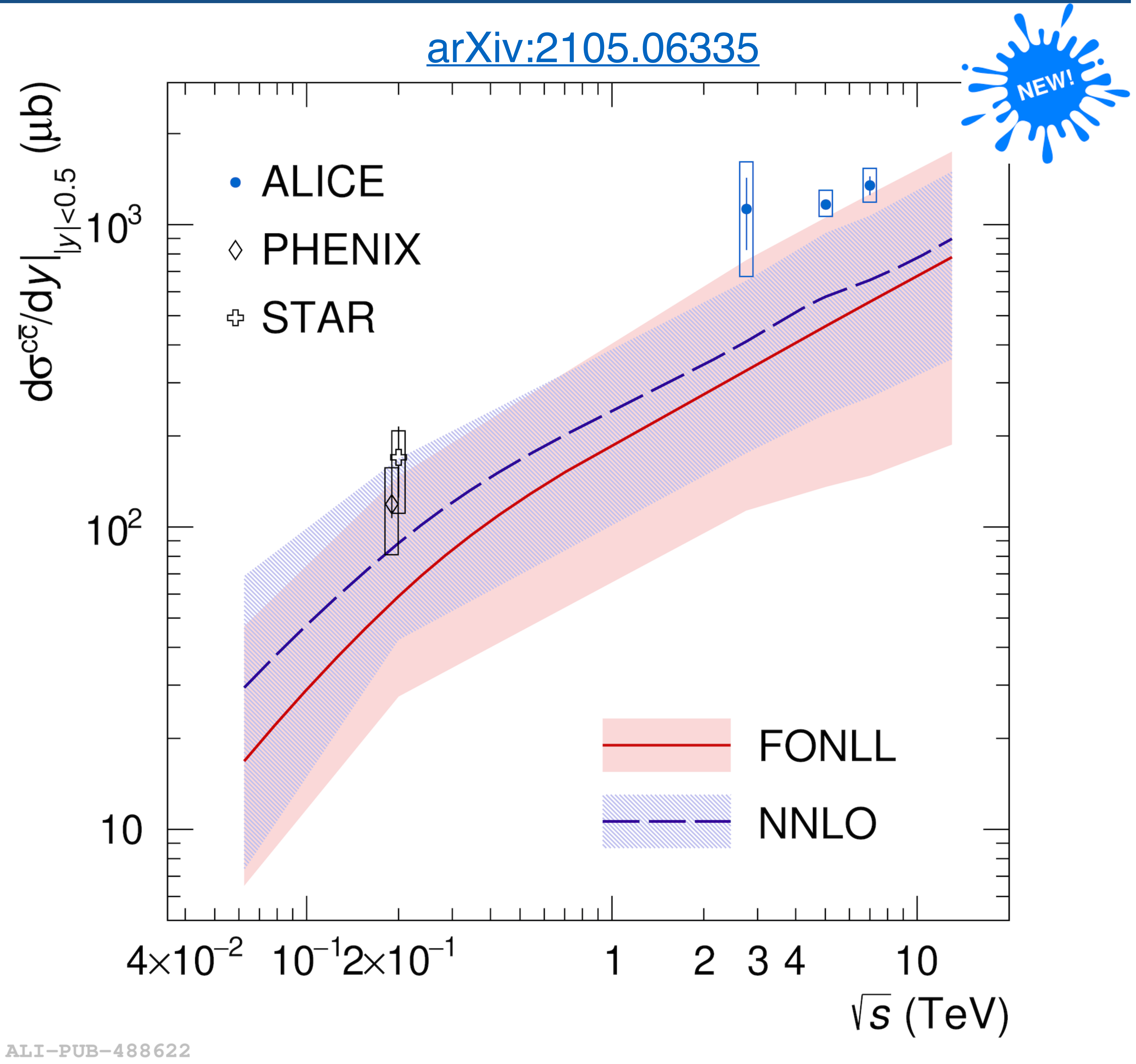
- The contribution of the Ξ_c^0 was multiplied by a factor of 2 in order to account for the contribution from the Ξ_c^+

- Ω_c^0 not measured in pp collision at 5.02 TeV
  → add an asymmetric systematic uncertainty assuming the Ω_c^0 contribution equal to the one of Ξ_c^0

- Measured cross section:

$$\boxed{\mathrm{d}\sigma^{c\bar{c}}/\mathrm{dy}|_{|\mathrm{y}|<0.5} = 1165 \pm 44(\mathrm{stat})^{+134}_{-101}(\mathrm{syst})\ \mu\mathrm{b}}$$

arXiv:2105.06335



- Charm cross section measurements at 2.76 and 7 TeV updated using the D^0 FF at 5.02 TeV
- Measurements compatible with the upper edge of the FONNL and NNLO calculations

Charm fragmentation fractions

- Measurement of the charm fragmentation fractions in **pp collision at √s = 5.02 TeV** at midrapidity (|y| < 0.5)

- The hadron fragmentation fraction is calculated as the ratio of the hadron-production cross section over the sum of cross sections of all known ground states of charm hadrons

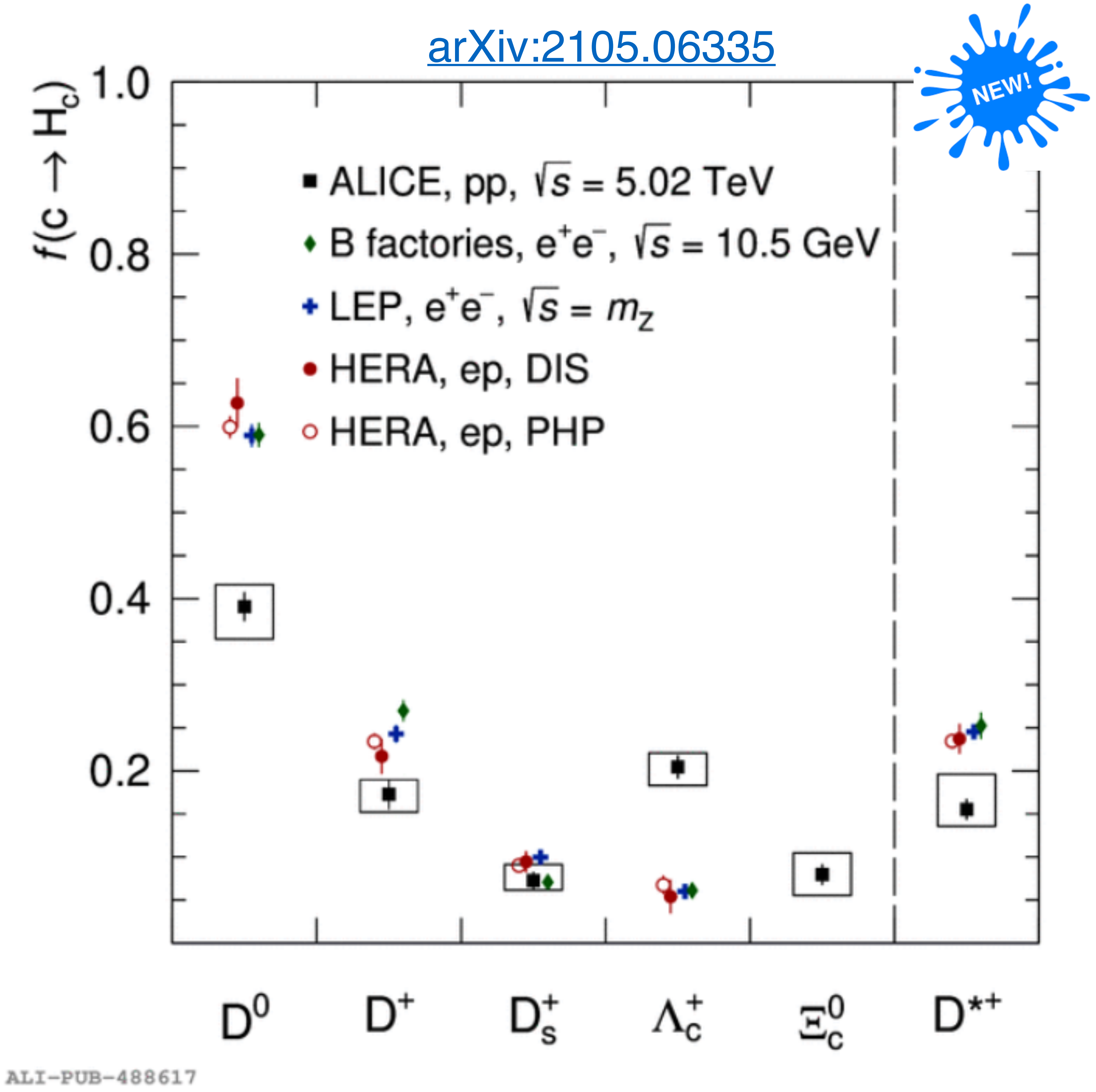
$$\boxed{f(c \rightarrow H_c) = \sigma(H_c)/\Sigma_i \sigma(H_{c,i})}$$

H_c	$f(c \rightarrow H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

2x to account for the Ξ_c^+

feeds into the D^0 and D^+ mesons

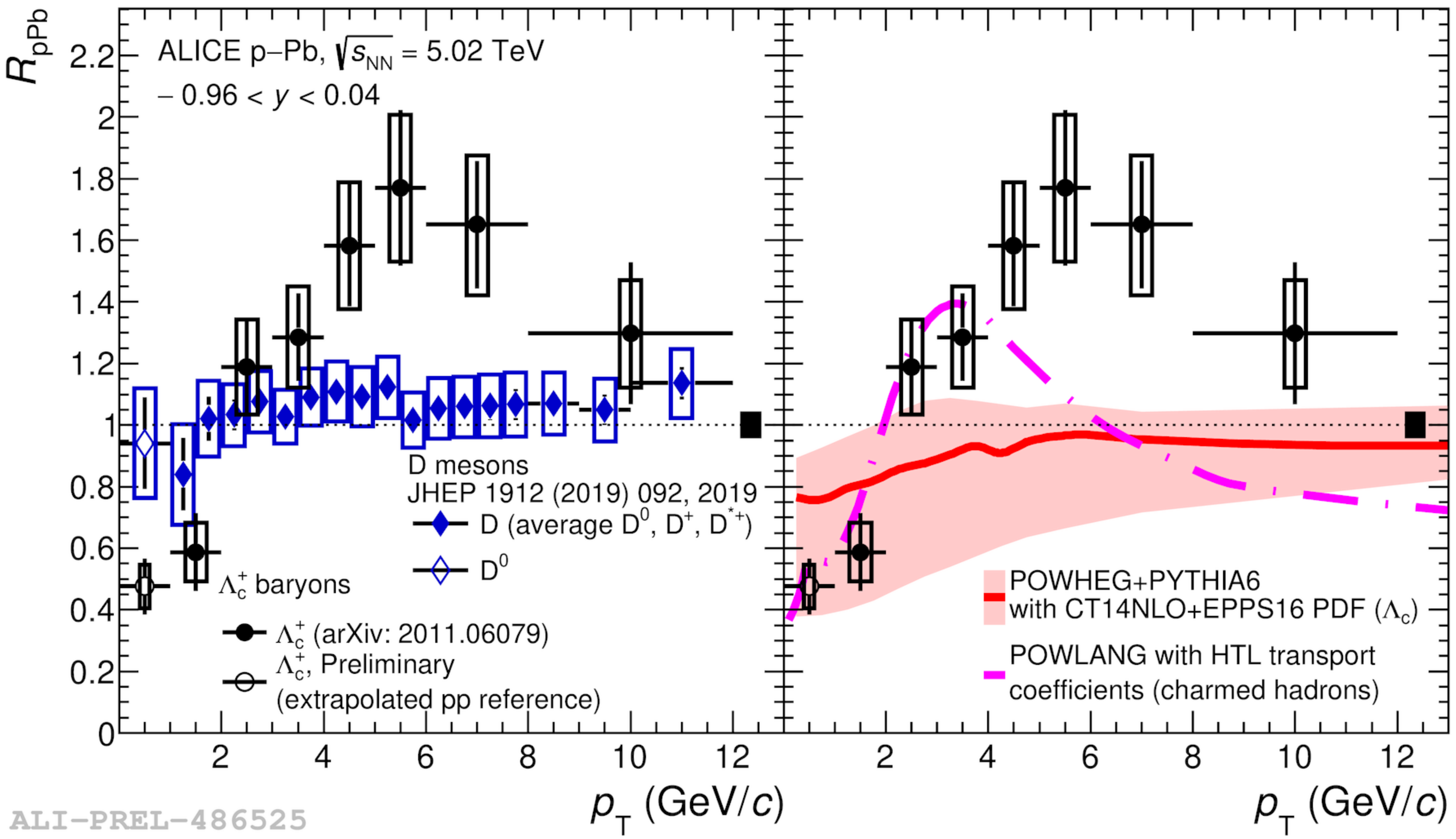
arXiv:2105.06335



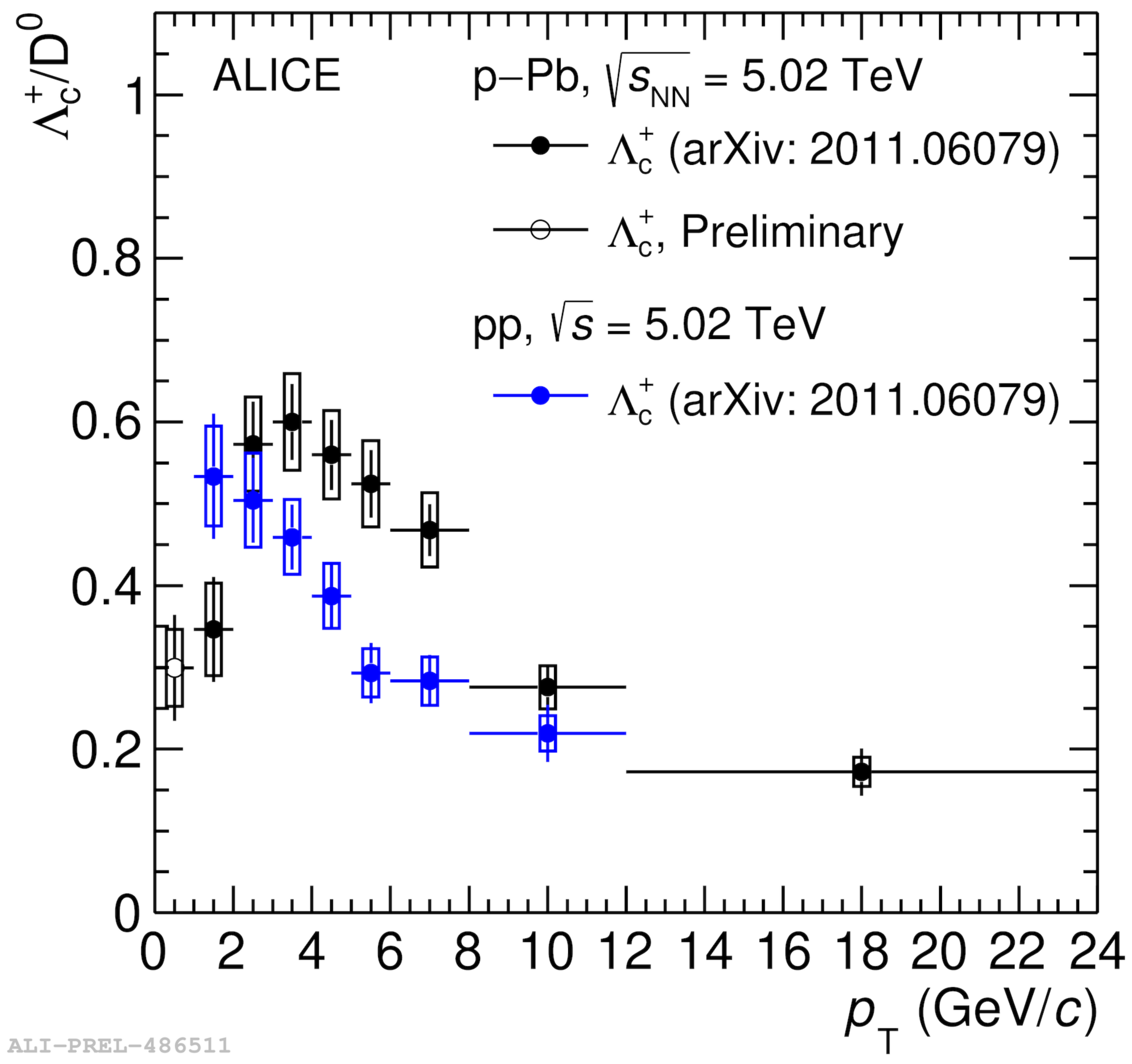
- **Charm fragmentation fractions not universal!**

Λ_c in p-Pb collisions

- First measurement of Λ_c down to zero p_T in p-Pb collisions at 5.02 TeV
- Λ_c^+/D^0: significant difference w.r.t. to pp
  → Cold Nuclear Matter (CNM) effects, radial flow or multiplicity dependence of hadronisation?



[arXiv:2011.06079](https://arxiv.org/abs/2011.06079)



$R_{pPb}(\Lambda_c^+)$ cannot be described in the full p_T range by the models:

- **POWHEG+PYTHIA6**: including only CNM effect
  Frixione, Ridolfi & Nason, JHEP 09 (2007) 126
- **POWLANG**: QGP in small system
  Beraudo et al. JHEP 03 (2016) 123

Conclusions

- Non-universality of the charm fragmentation fractions
  → Strong enhancement of the baryon-over-meson ratio in pp collisions w.r.t. e^+e^- collisions
  → Simple string fragmentation model (PYTHIA Monash), with FF tuned on e^+e^- measurements cannot describe data
  → New models with additional hadronization mechanism for charm quark under investigation
  → Catania model provides a decent description of all the measured hadron over meson ratios.

- Charm cross section and charm fragmentation fractions in pp collisions at 5.02 TeV at midrapidity
  → Measurements compatible with the upper edge of the FONNL and NNLO calculations

- Λ_c^+ cross section measurement in p-Pb collisions at 5.02 TeV extended down to zero p_T
  → Toward charm cross section in p-Pb collisions at midrapidity

BACKUP

Charmed baryons reconstructions

The following charmed baryons are reconstructed:

Baryon	M (GeV/c^2)	$c\tau$ (μm)	Decay	BR (%)
Λ_c^+	$\sim$2.286	$\sim$61	$pK^-\pi^+$, $pK_s^0(\longrightarrow \pi^+\pi^-)$	6.28% , 1.1%
Ξ_c^0	$\sim$2.468	$\sim$46	$\Xi^- e^+ \nu_e$, $\Xi^-\pi^+$	1.8% , 1.43%
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Ω_c^0	$\sim$2.695	$\sim$80	$\Omega^-\pi^+$	0.51% *

- HF candidates built combining **pairs or triplets of tracks** at midrapidity (|η| < 0.8) with the proper charge-sign combination.
- **Topological** and **PID** selections to reduce the combinatorial background.

Hadronic decay channels:

Raw Yield
- Fit of the invariant

Efficiency
- MC simulations

Prompt fraction
- FONLL predictions

Results:
- Cross section
- Corrected yields

* The $\Sigma^{0,++}$ decays with a BR ~100% in Λ_c. The two Λ_c decay channels pKπ and pK^0_s are reconstructed.

* BR($\Omega_c^+ \rightarrow \pi^+\Omega^-$) from theory calculations. [Y. Hsiao et al. EPJC 80, 1066 (2020)]

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- **Topological** and **PID** selections to reduce the combinatorial background.

Semi-leptonic decay channel:

Raw Yield
- Subtraction of the Wrong-Sign pairs from the Right-Sign ones

Efficiency
- MC simulations

Unfolding
- event generator and transport code simulations

Results:
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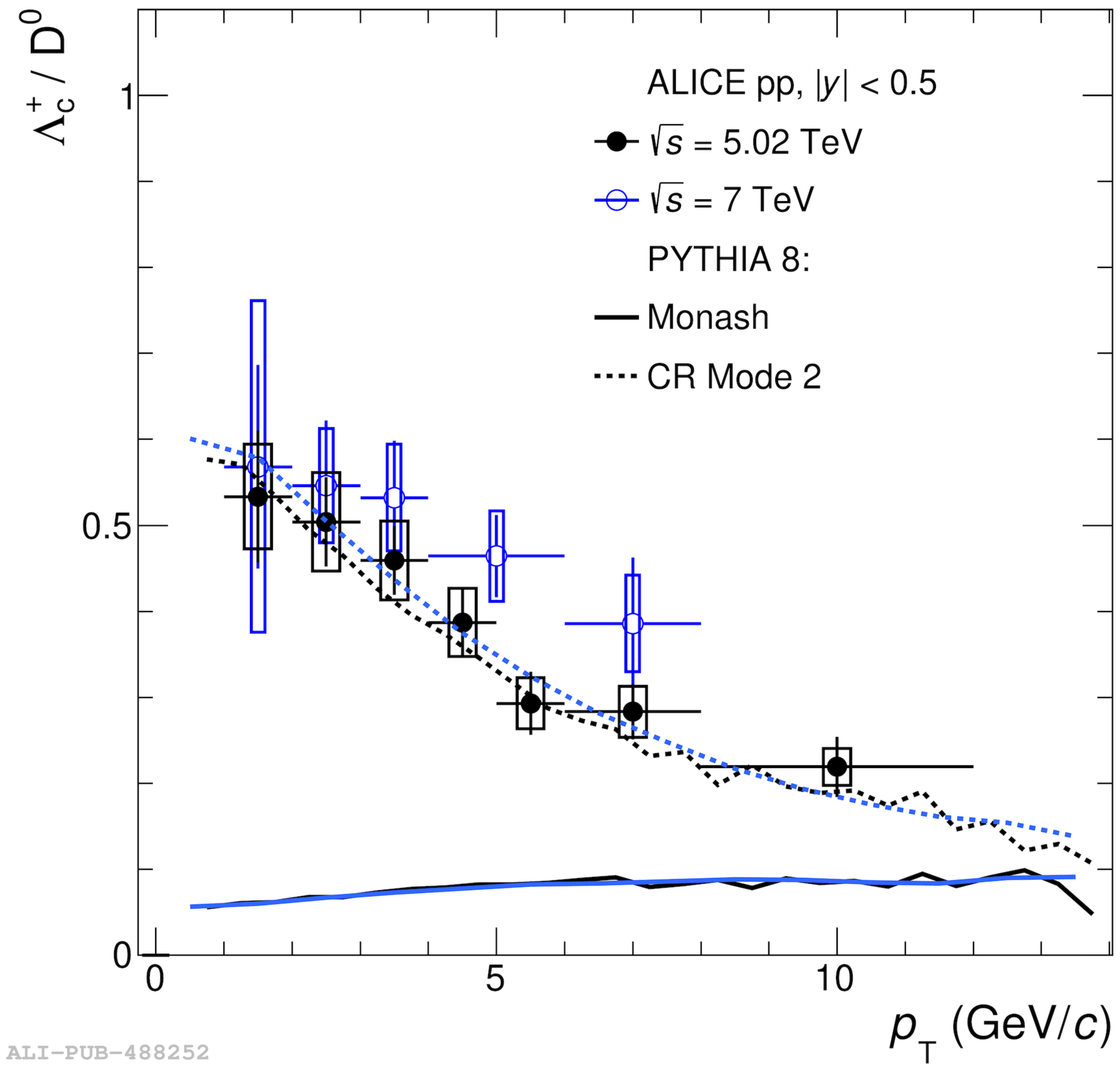
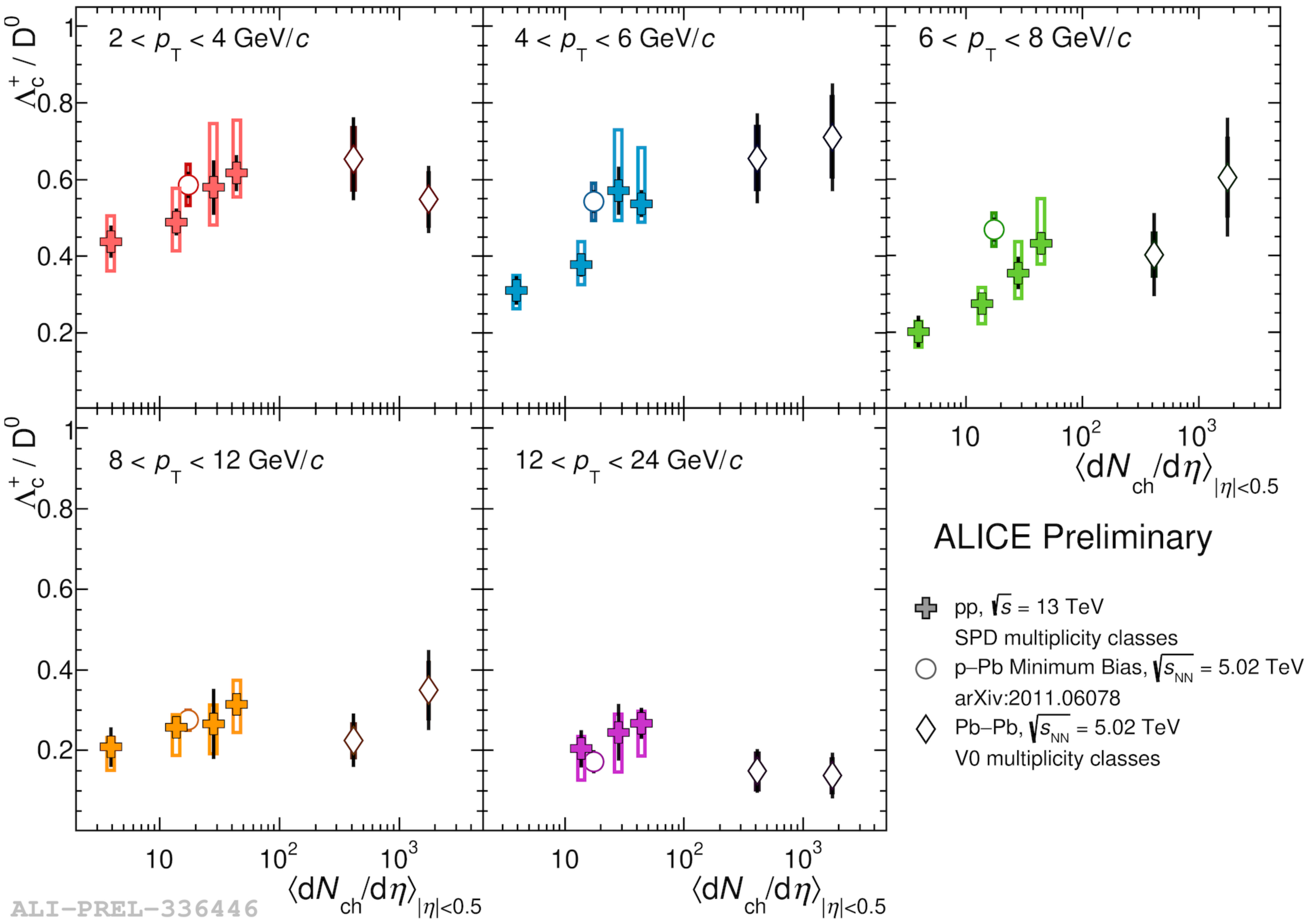
[Y. Hsiao et al. EPJC 80, 1066 (2020)]

Λ_c^+ results



Λ_c^+ production



$\Sigma_c^{0,+,++}$ results

- The Λ_c^+/D^0 ratio measured in pp collisions at 13TeV is compatible with the one observed at 5TeV.

- First production measurement for $\Sigma_c^{0,++}(2455)$ in hadronic collisions.

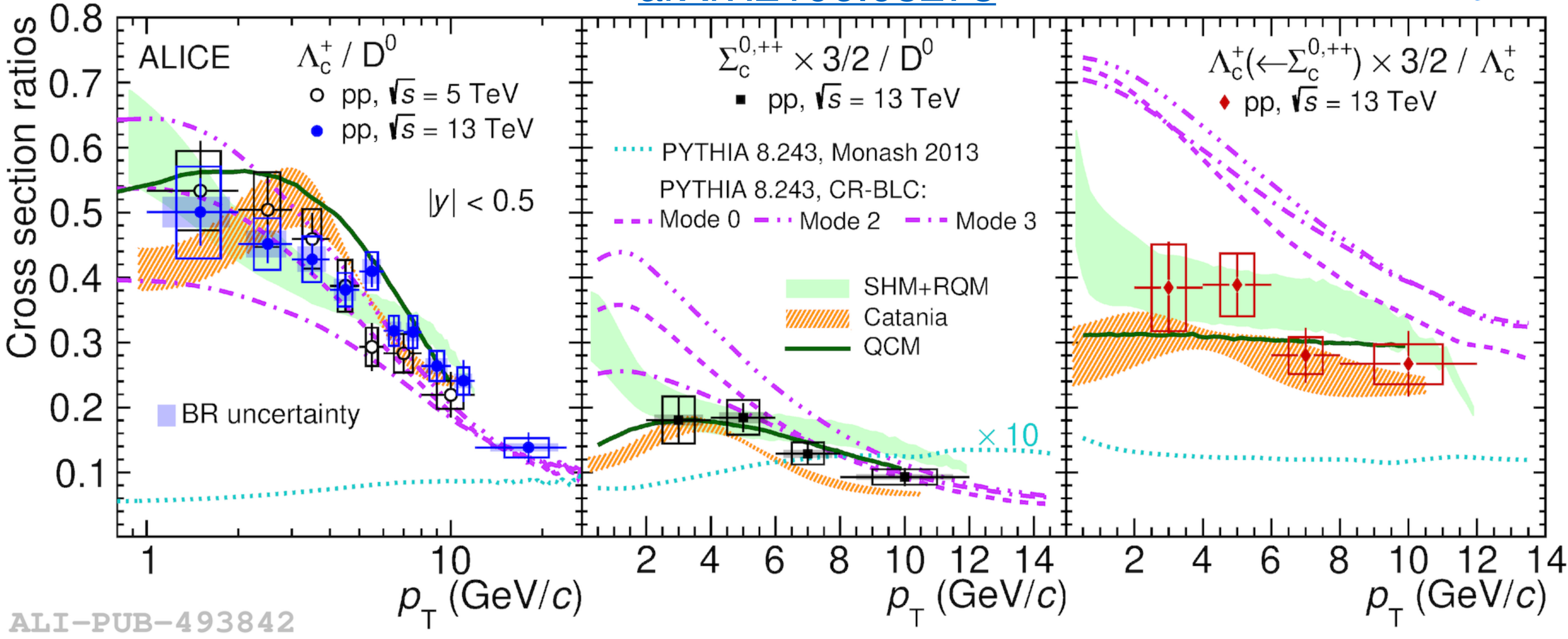
NEW!

arXiv:2106.08278

- Effects of Σ_c feed-down on Λ_c^+/D^0.

  → $\Sigma_c^{0,+,++}$ feed-down could explain part of the Λ_c enhancement in pp collisions.

  ~40% of feeddown Λ_c from $\Sigma_c^{0,+,++}$



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EPJC 78 no. 4, (2018) 344

Ξ_c^0 and Ξ_c^+ production