Latest ALICE results on charm and beauty hadronization mechanisms in hadronic collisions

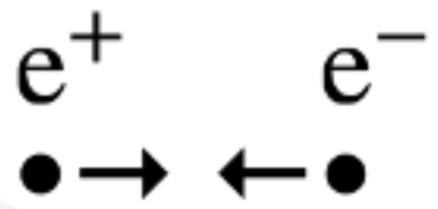
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Jianhui Zhu (INFN Padova)
on behalf of the ALICE Collaboration

ALICE

Heavy-flavour hadronization

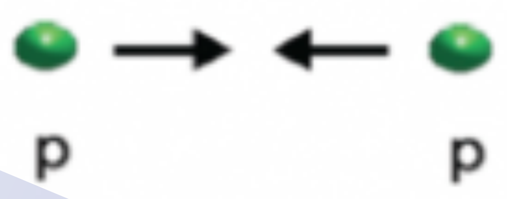
- Open heavy-flavour (HF) hadron production cross section calculated using the factorization approach
  - Ratios of particle species sensitive to hadronization

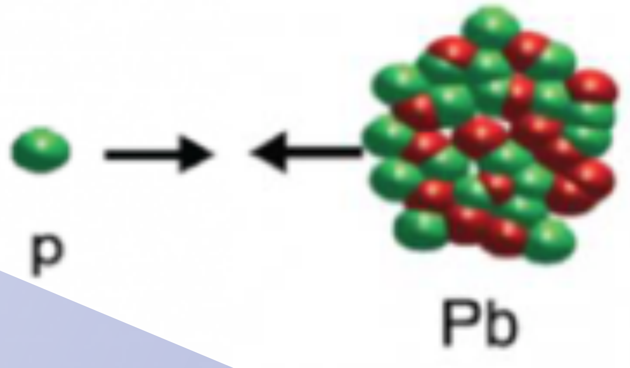


Vacuum

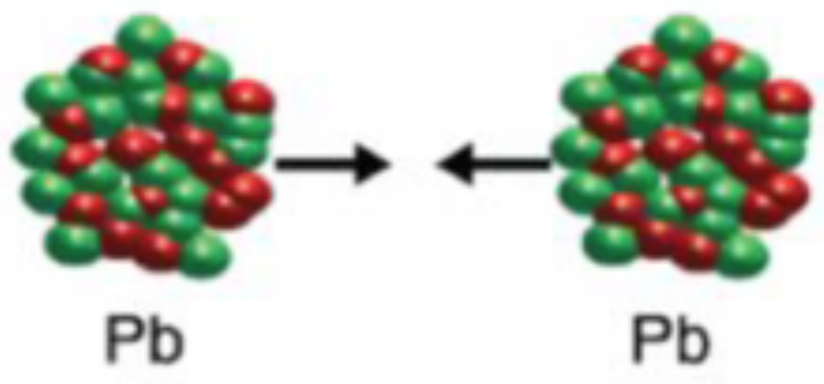
Not far from vacuum?

Or dense enough to alter hadronization?





System size



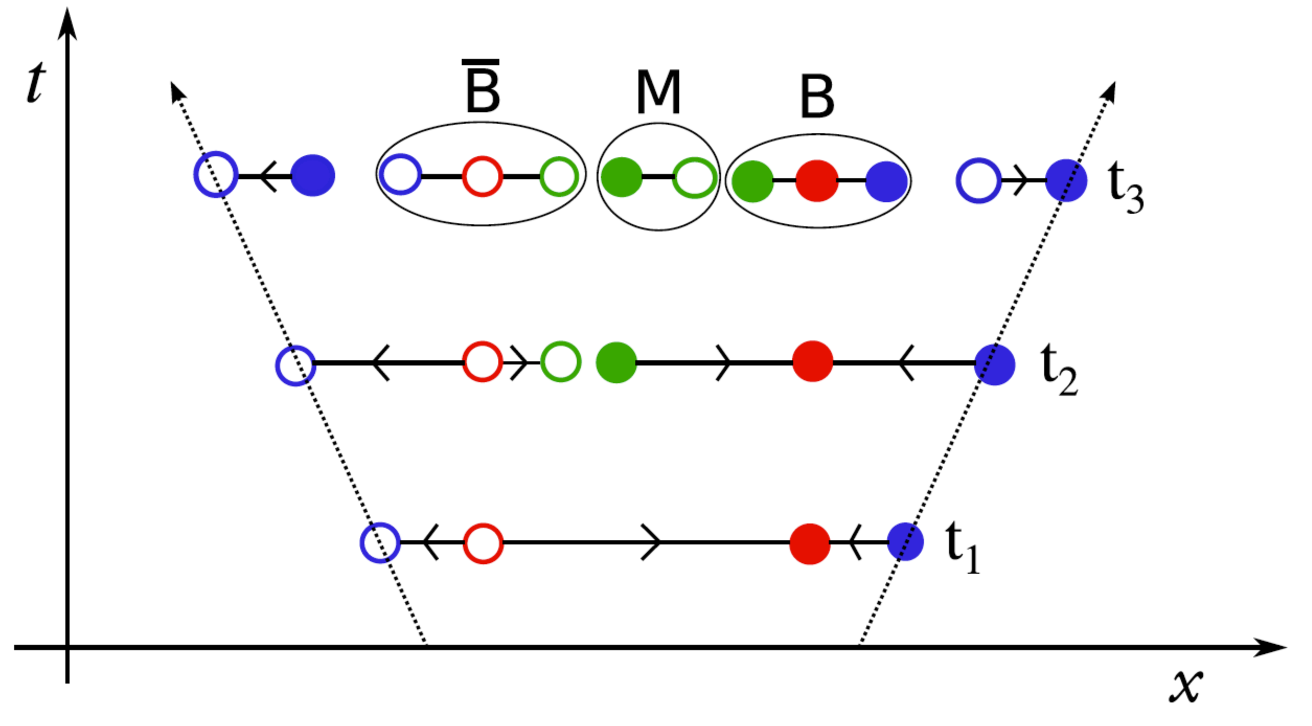
Dense, extended-size system

Open questions

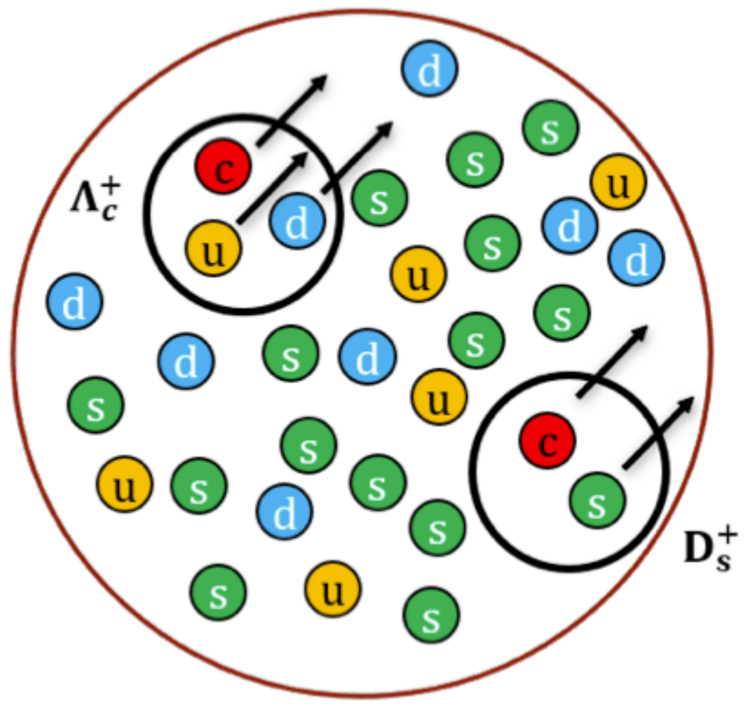
- Fragmentation fractions (FFs) universality violated already in pp collisions?
  - A system rich of quarks or gluons?
- Charm-strange baryons ($\Xi_c^{0,+}$ and Ω_c^0) production can not be described by models, which can describe Λ_c^+
  - Powerful constraints on models

Fragmentation

- Hard scattering $e^+e^- \rightarrow q\bar{q}$
- Color-potential string between q and $\bar{q}$
- Hadronisation via multiple string breaking and formation of quark-antiquark pairs



C. Bierlich, et al., *Eur.Phys.J.C 82 (2022) 228*



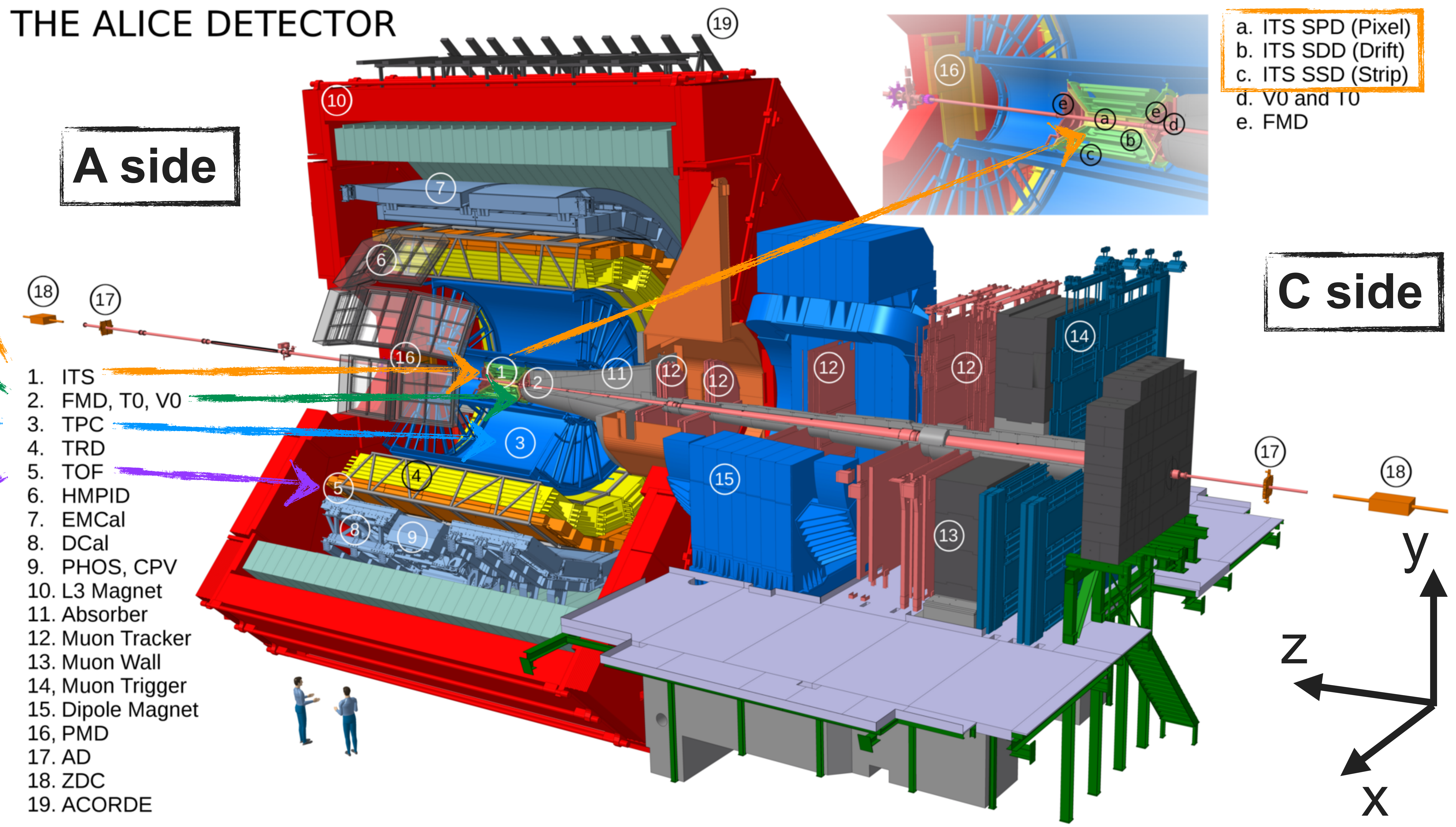
Coalescence

- Heavy-quarks coalescence with light (di-)quarks from the system
- Expected to increase baryon production at low and intermediate p_T

ALICE detector for Run 1 and Run 2

- Inner Tracking System (ITS)
  - $|\eta| < 0.9$
  - Tracking, vertexing, multiplicity
- V0
  - V0-A: $2.8 < \eta < 5.1$
  - V0-C: $-3.7 < \eta < -1.7$
  - Triggering, luminosity, multiplicity
- Time Projection Chamber (TPC)
  - $|\eta| < 0.9$
  - Tracking, PID
- Time-Of-Flight (TOF)
  - $|\eta| < 0.9$
  - Tracking, PID

System	Year(s)	$\sqrt{s_{NN}}$	L_{int}
pp	2017	5.02 TeV	~20 nb^{-1}
	2016 – 2018	13 TeV	~32 nb^{-1}
p–Pb	2016	5.02 TeV	~287 μb^{-1}
Pb–Pb (0-10%)	2018	5.02 TeV	~131 μb^{-1}
Pb–Pb (30-50%)	2018	5.02 TeV	~56 μb^{-1}



Charm-hadron reconstruction

Hadronic decays

- $D^0(\bar{u}c) \to K^-\pi^+$, BR $\approx 3.95\,\%$
- $D^+(\bar{d}c) \to K^-\pi^+\pi^+$, BR $\approx 9.38\,\%$
- $D^{*+}(\bar{d}c) \to D^0\pi^+$, BR $\approx 67.7\,\%$
- $D_s^+(\bar{s}c) \to \phi\pi^+ \to K^+K^-\pi^+$, BR $\approx 2.22\,\%$
- $D_{s1}^+(\bar{s}c) \to D^{*+}K_s^0$, BR unknown
- $D_{s2}^{*+}(\bar{s}c) \to D^+K_s^0$, BR unknown
- $\Lambda_c^+(udc) \to pK^-\pi^+$, BR $\approx 6.28\,\%$
- $\Lambda_c^+(udc) \to pK_s^0$, BR $\approx 1.59\,\%$
- $\Sigma_c^0(ddc) \to \Lambda_c^+\pi^-$, BR $\approx 100\,\%$
- $\Sigma_c^{++}(uuc) \to \Lambda_c^+\pi^+$, BR $\approx 100\,\%$
- $\Xi_c^+(usc) \to \Xi^-\pi^+\pi^+$, BR $\approx 2.9\,\%$
- $\Xi_c^0(dsc) \to \Xi^-\pi^+$, BR $\approx 1.43\,\%$
- $\Omega_c^0(ssc) \to \Omega^-\pi^+$, BR unknown

Semileptonic decays

- $\Lambda_c^+(udc) \to \Lambda e^+\nu_e$, BR $\approx 3.6\,\%$
- $\Xi_c^0(dsc) \to \Xi^- e^+\nu_e$, BR $\approx 1.04\,\%$
- $\Omega_c^0(ssc) \to \Omega^- e^+\nu_e$, BR unknown

Charge conjugates are included

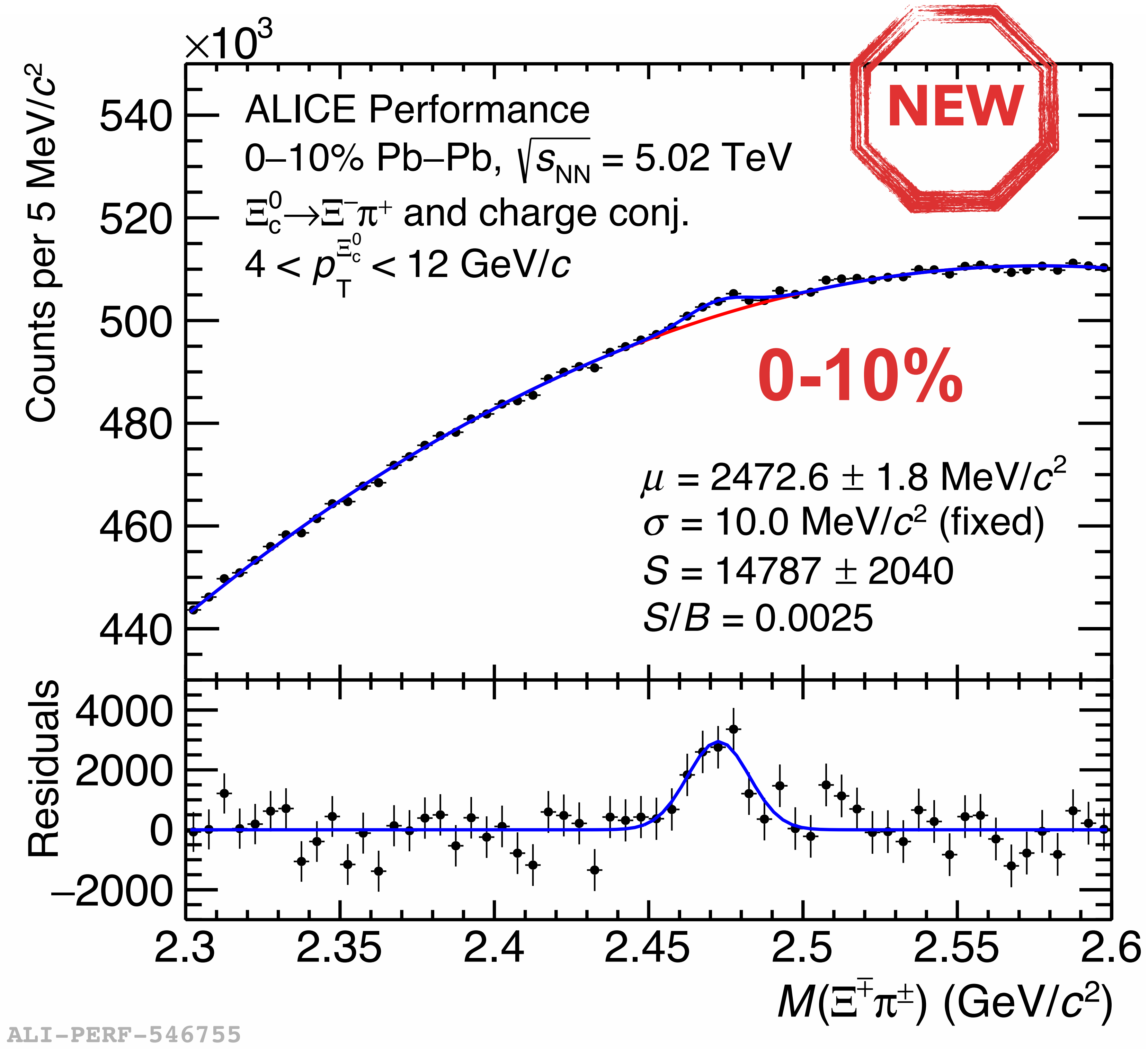
Prompt

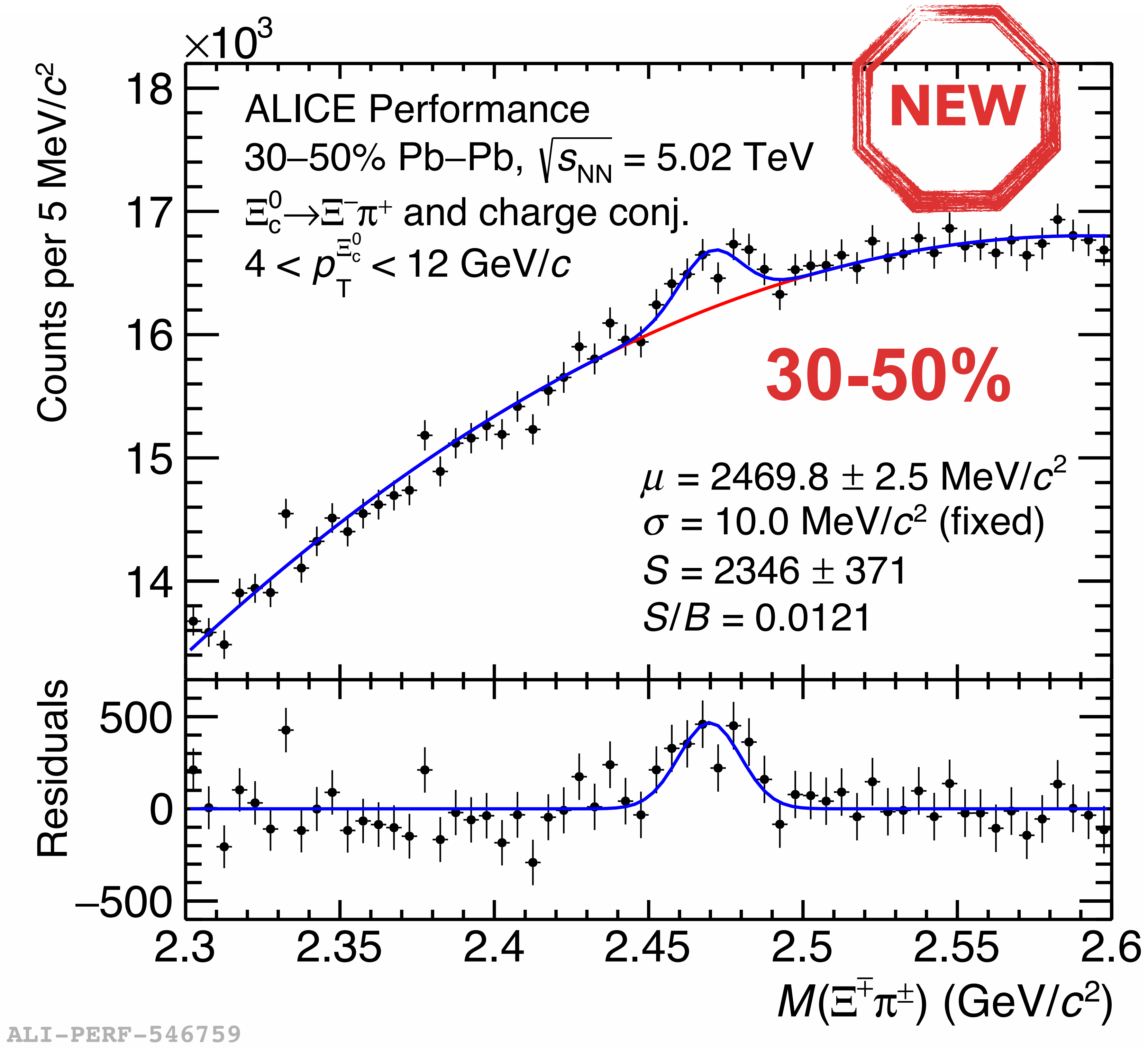
- $c \to$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$

Non-Prompt

- $b \to c \to$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$

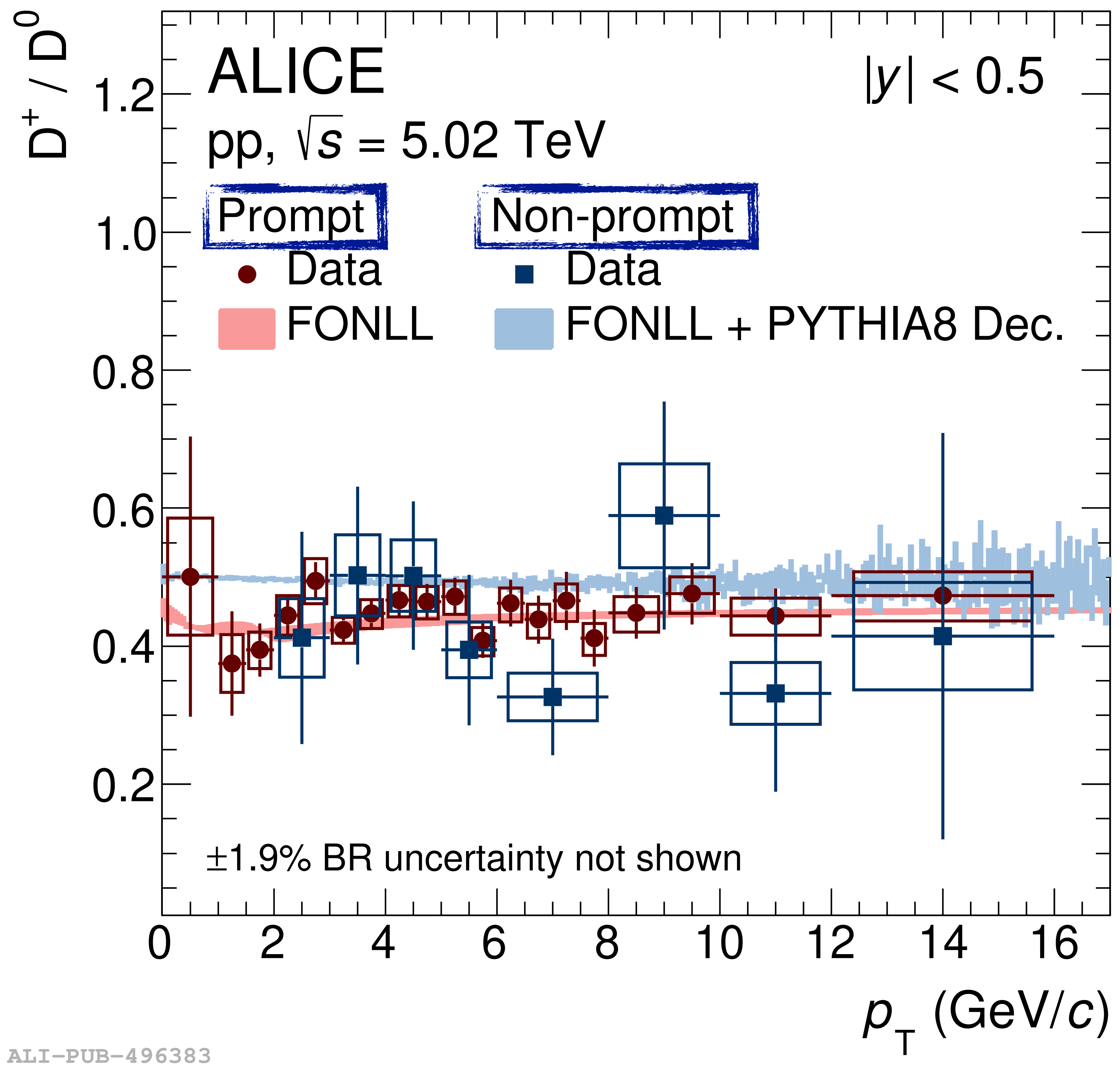
First observation of $\Xi_c^0(dsc)$ in Pb–Pb collisions



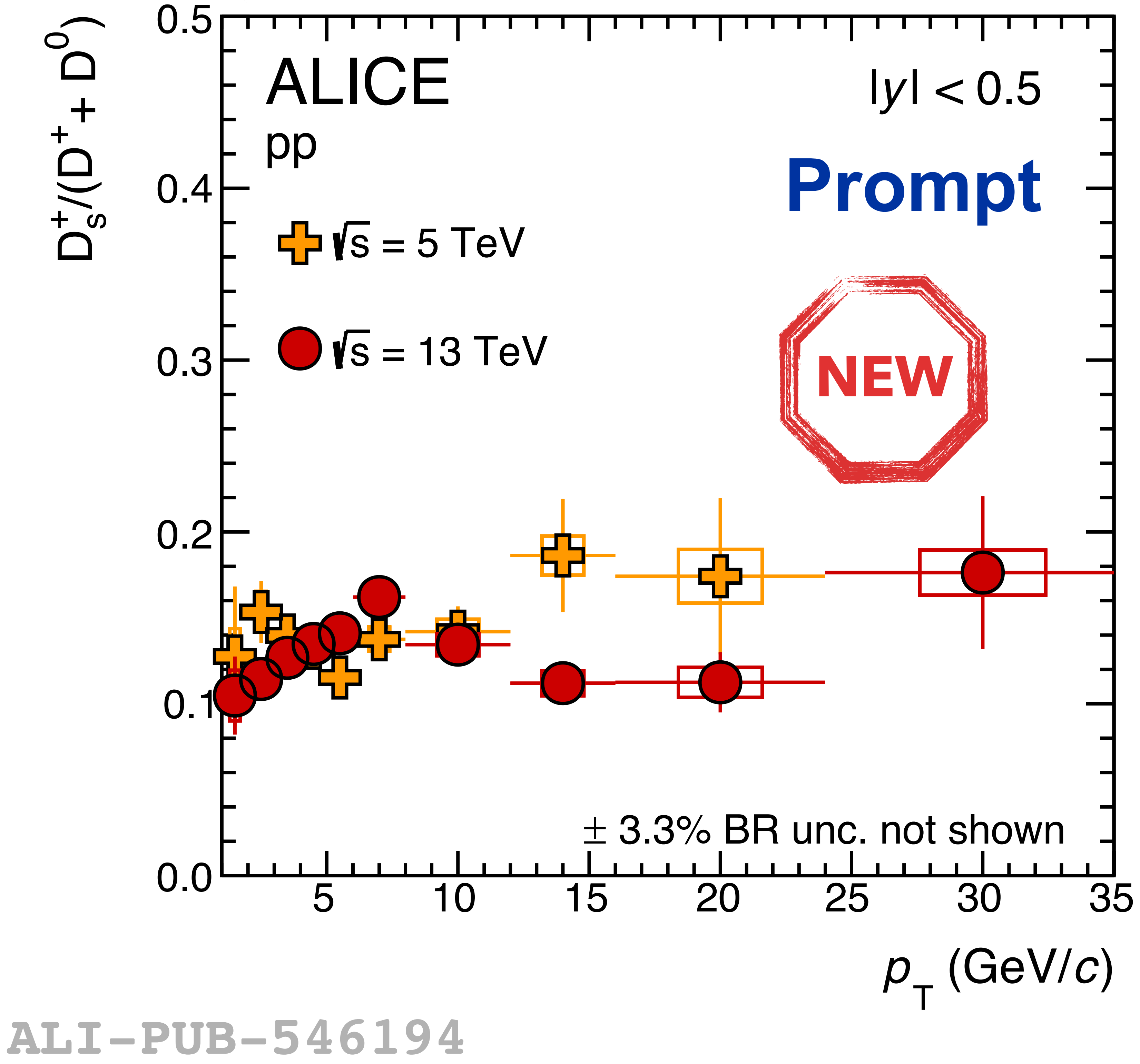


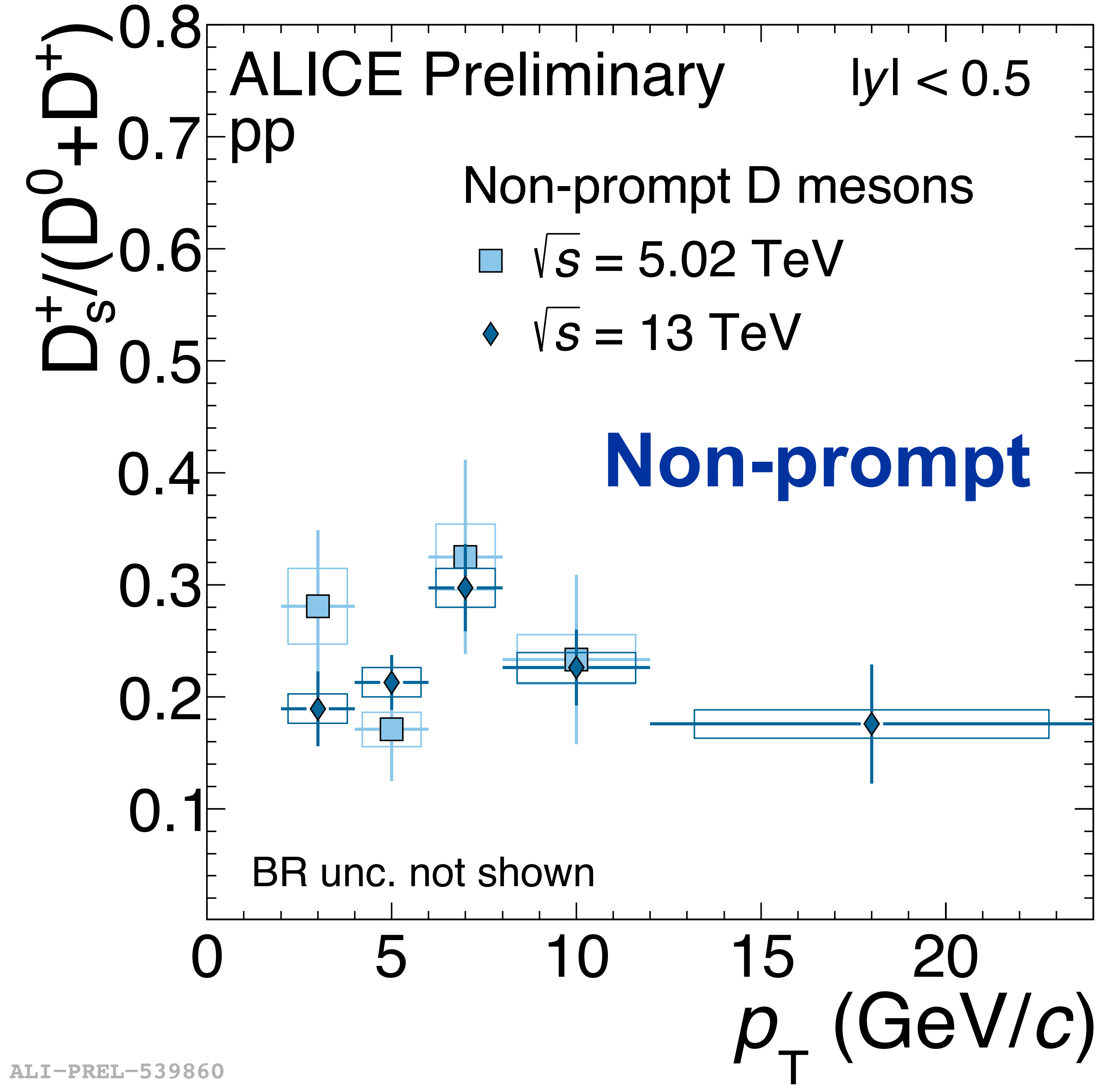
D-meson production in pp collisions

JHEP 05 (2021) 220



arXiv: 2308.04877





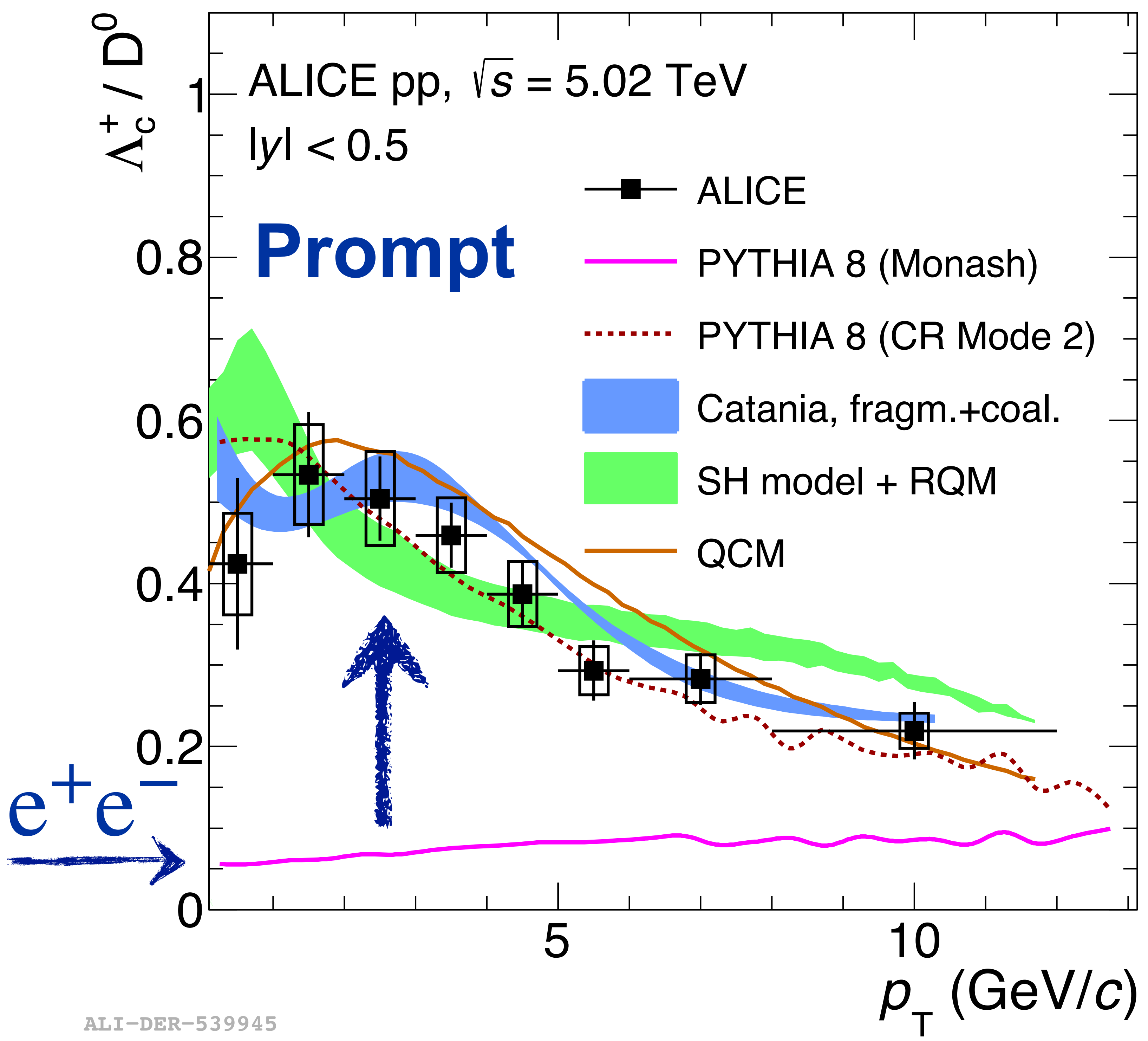
FONLL: *JHEP 05 (1998) 007* $f(c \rightarrow H_c)$: *Eur.Phys.J.C 75 (2015) 19*

HF poster:
Renu Bala

- No strong p_T dependence in prompt and non-prompt charm meson-to-meson yield ratios
- Well described by model calculations, based on factorization assuming FFs from e^+e^- collisions

Charm-baryon production: Λ_c^+(udc) in pp collisions

Phys.Rev.C 107 (2023) 064901



PYTHIA 8 Monash: Eur.Phys.J.C 74 (2014) 3024

PYTHIA 8 CR Mode: JHEP 08 (2015) 003

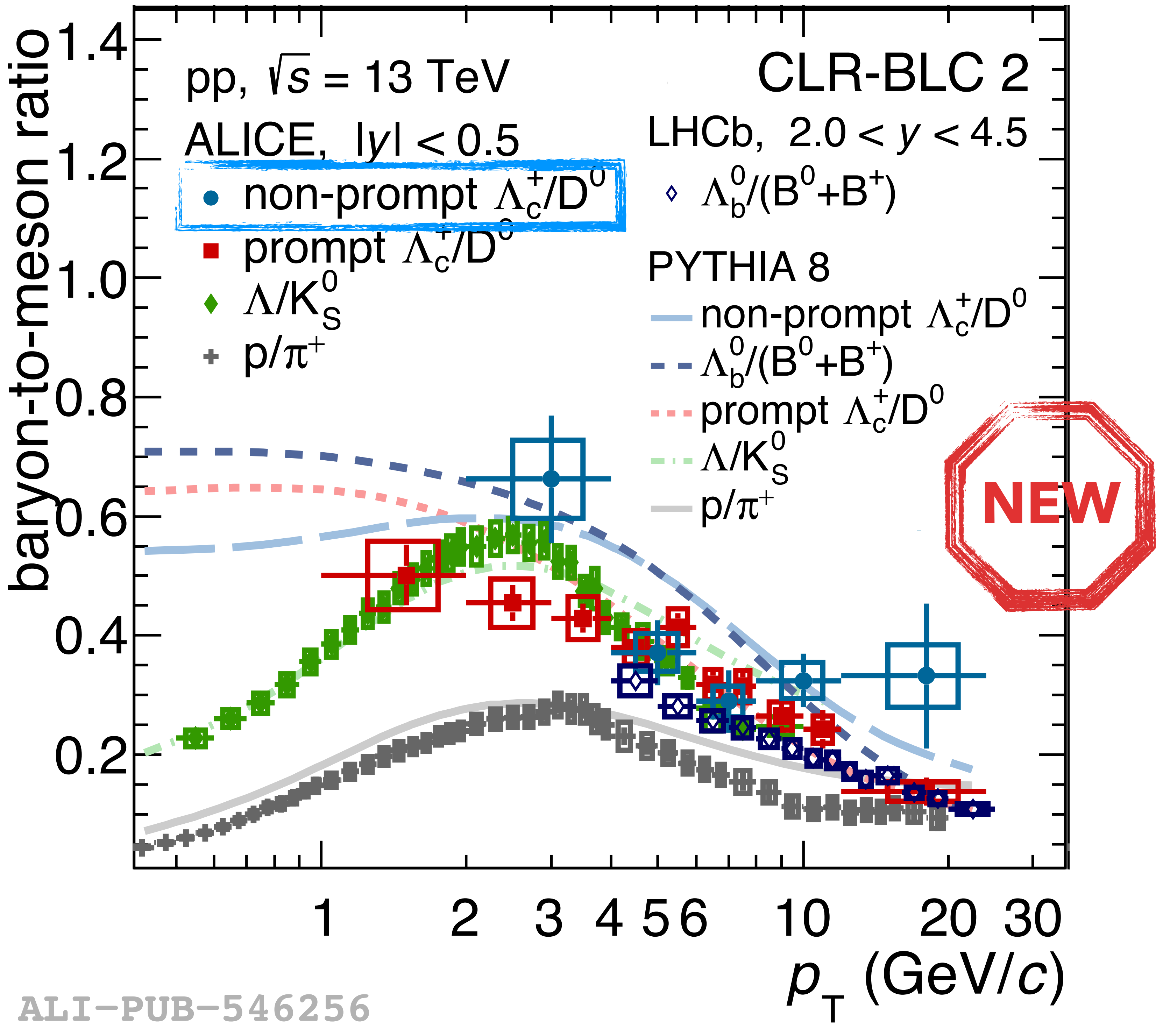
Catania: Phys.Lett.B 821 (2021) 136622

SHM: Phys.Lett.B 795 (2019) 117-121

RQM: Phys.Rev.D 84 (2011) 014025

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

arXiv: 2308.04873



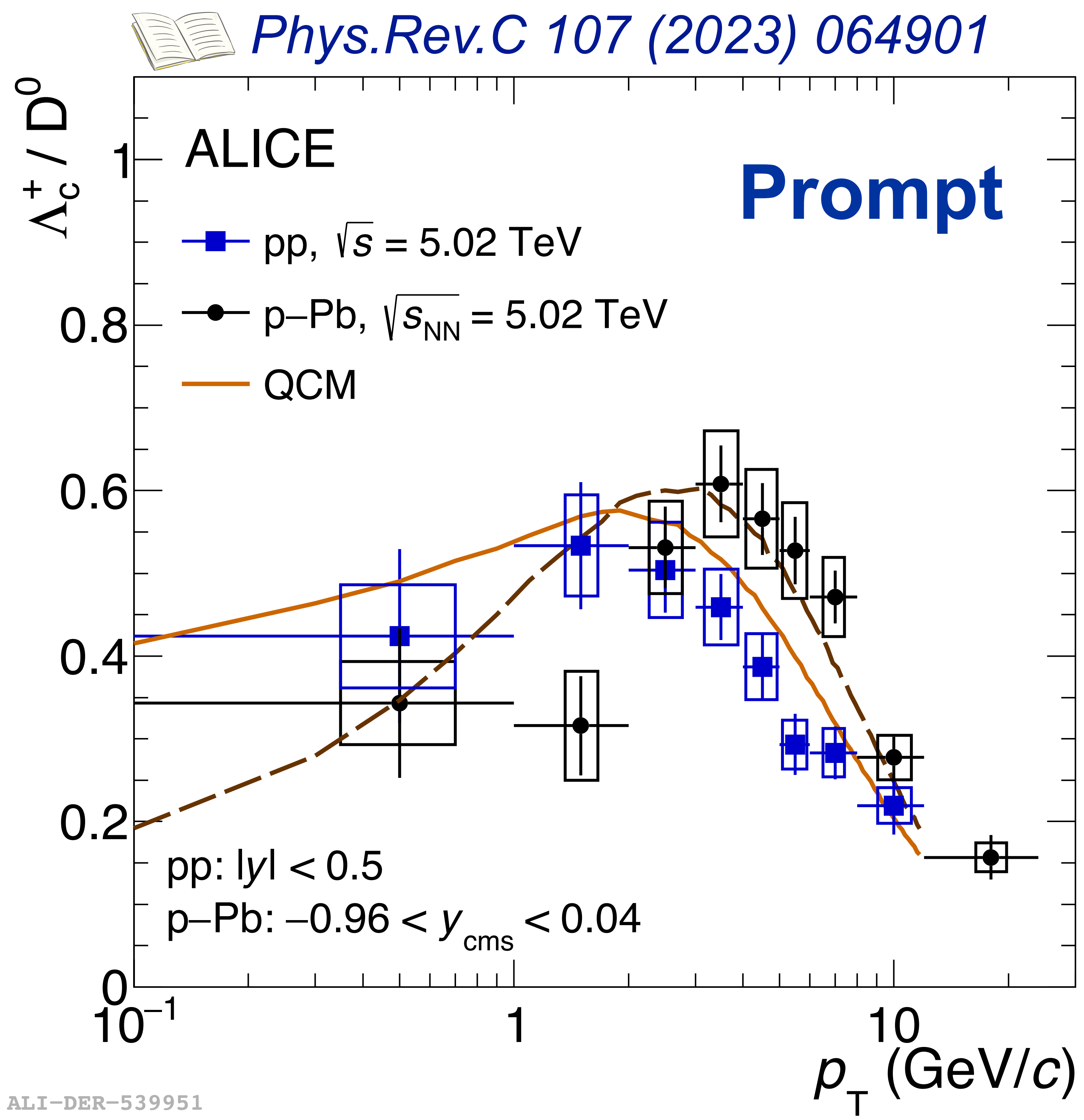
Prompt Λ_c^+/D^0 in pp collisions

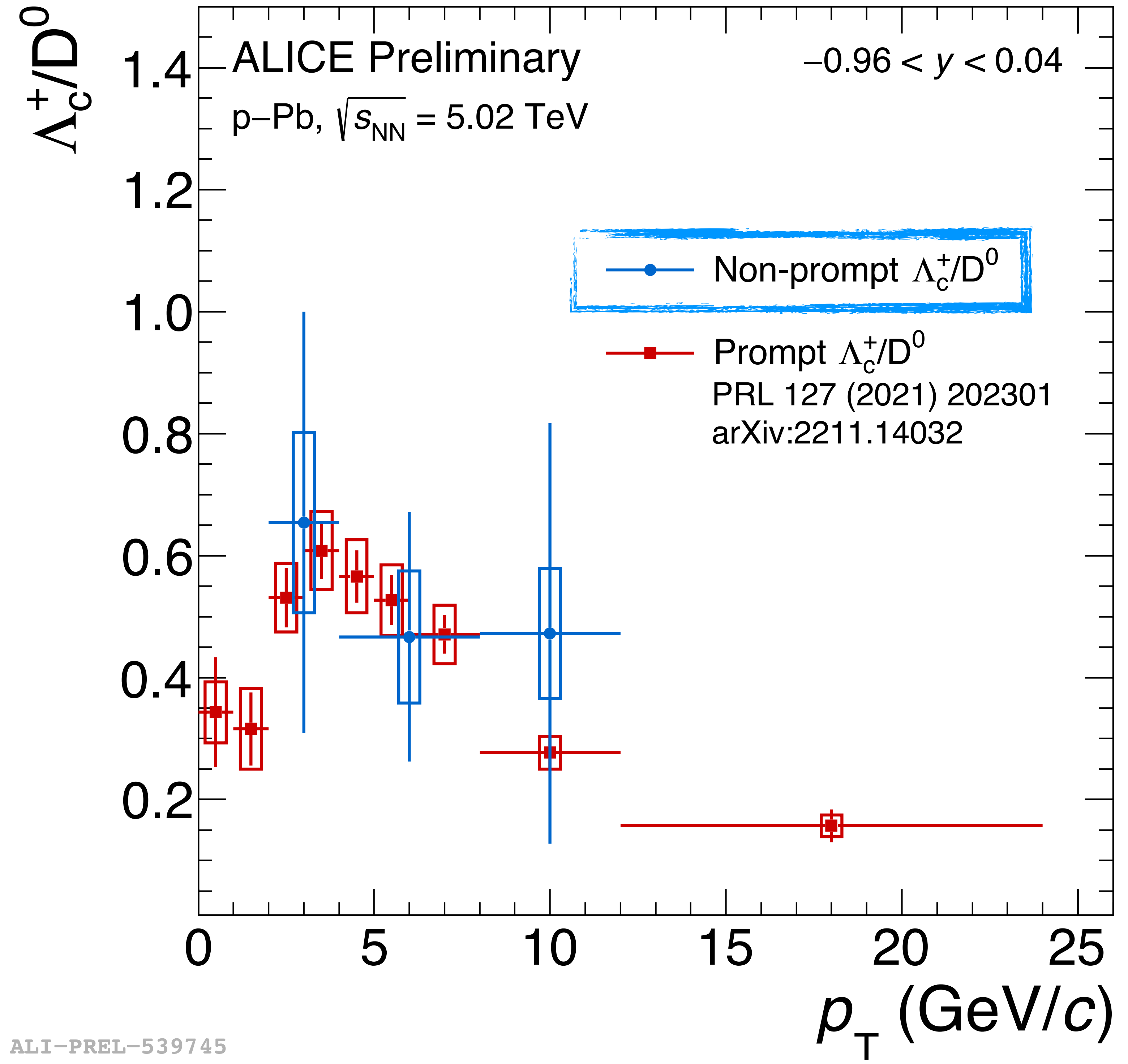
- First measurement down to $p_T = 0$
- Well described by model calculations, except PYTHIA 8 Monash based on FFs from e^+e^- collisions

Non-prompt Λ_c^+/D^0 in pp collisions

- First measurement of non-prompt Λ_c^+/D^0
- Beauty, charm, and strange hadrons show a similar p_T trend

Charm-baryon production: Λ_c^+(udc) in p–Pb collisions





Prompt Λ_c^+/D^0 in p–Pb collisions

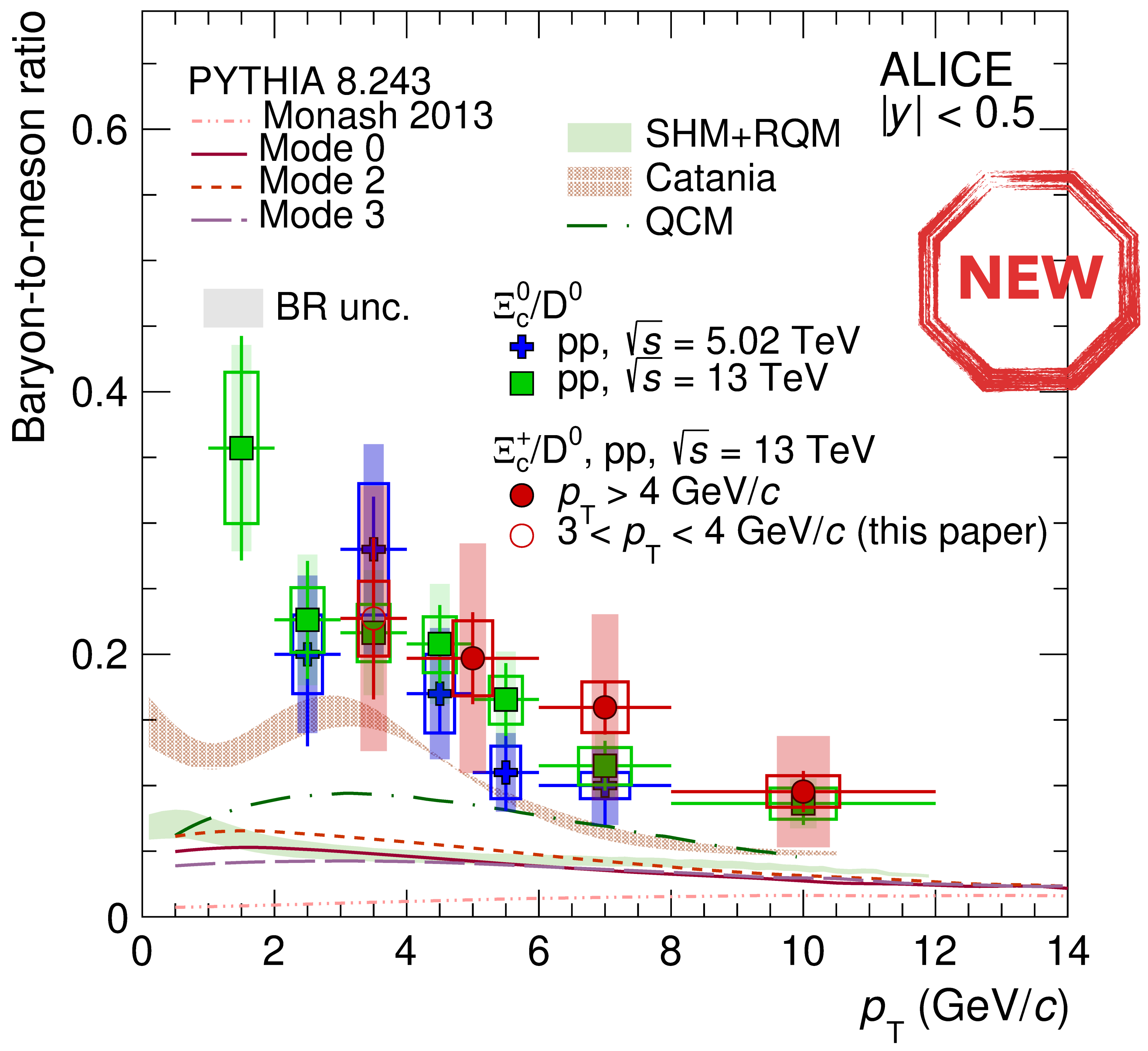
- First measurement down to $p_T = 0$
- Shift of peak towards higher p_T could be due to quark recombination or collective effects (e.g. radial flow)
- Well described by quark (re)combination model (QCM)

Non-prompt Λ_c^+/D^0 in p–Pb collisions

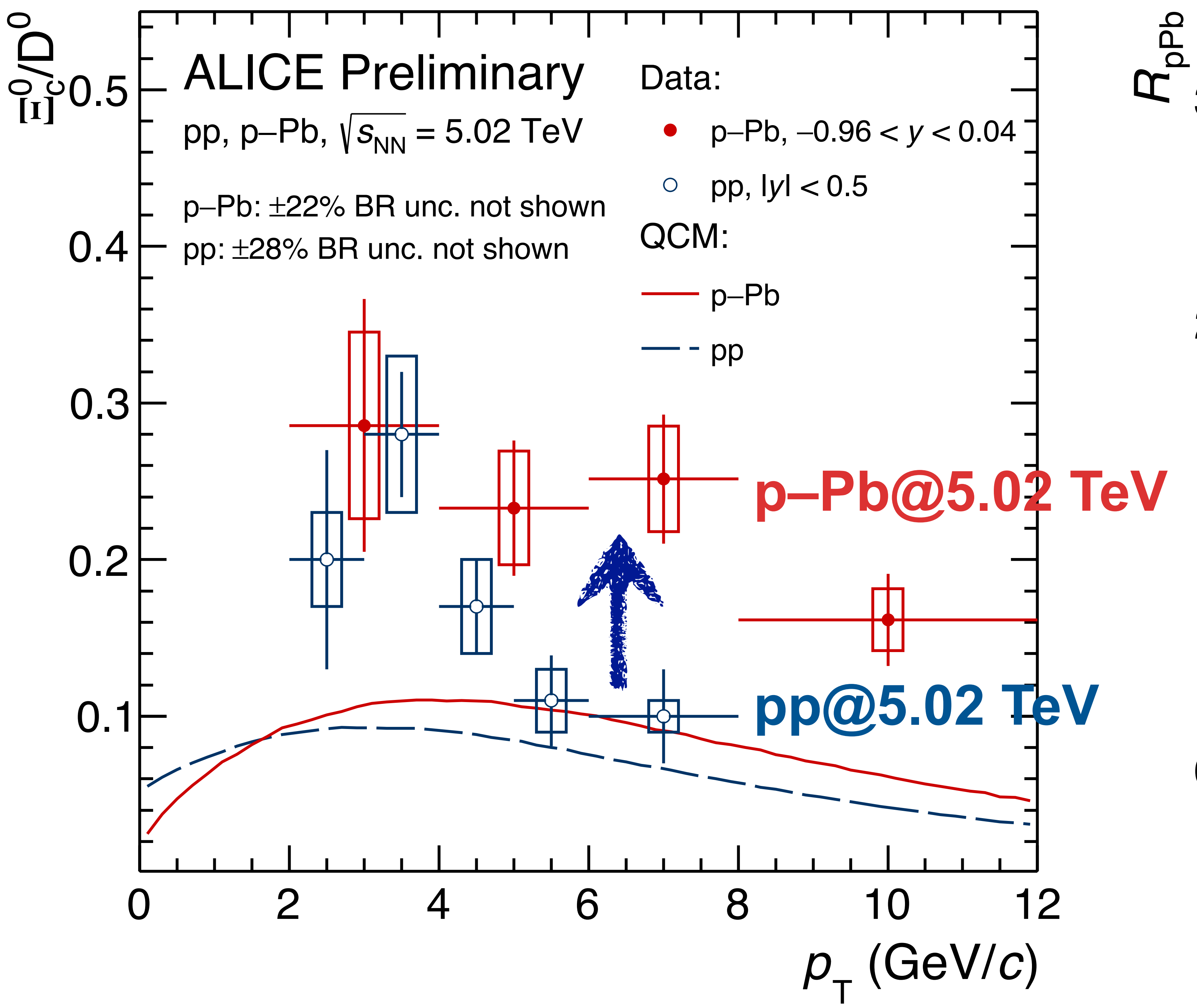
- First measurement of non-prompt Λ_c^+/D^0
- Similarity between prompt and non-prompt Λ_c^+/D^0 within uncertainties

Charm-baryon production: Ξ_c^0(dsc) and Ξ_c^+(usc)

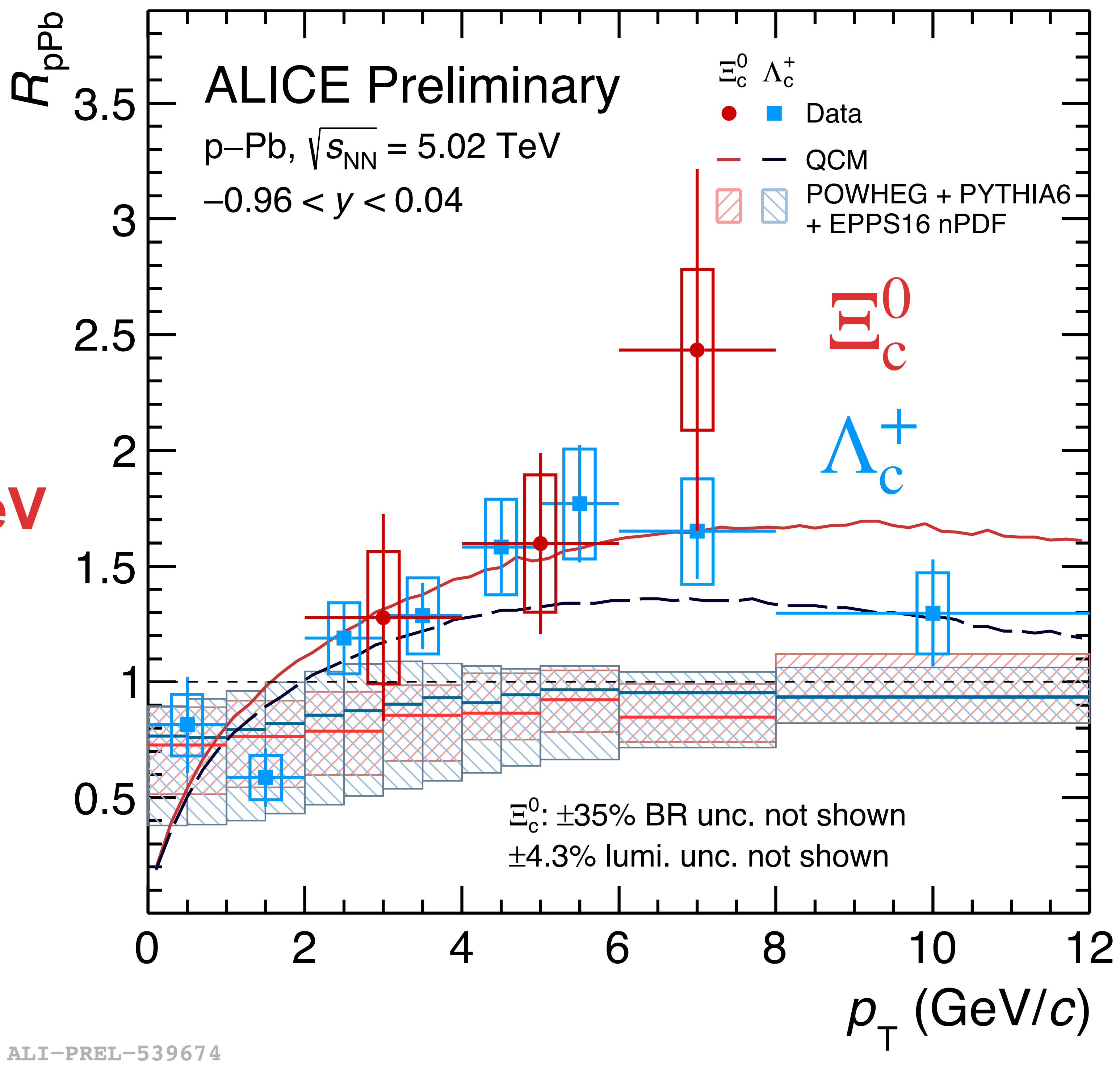
arXiv: 2308.04877



ALI-PUB-546202



ALI-PREL-539681



ALI-PREL-539674

Charm baryon-to-meson yield ratio Ξ_c^0/D^0

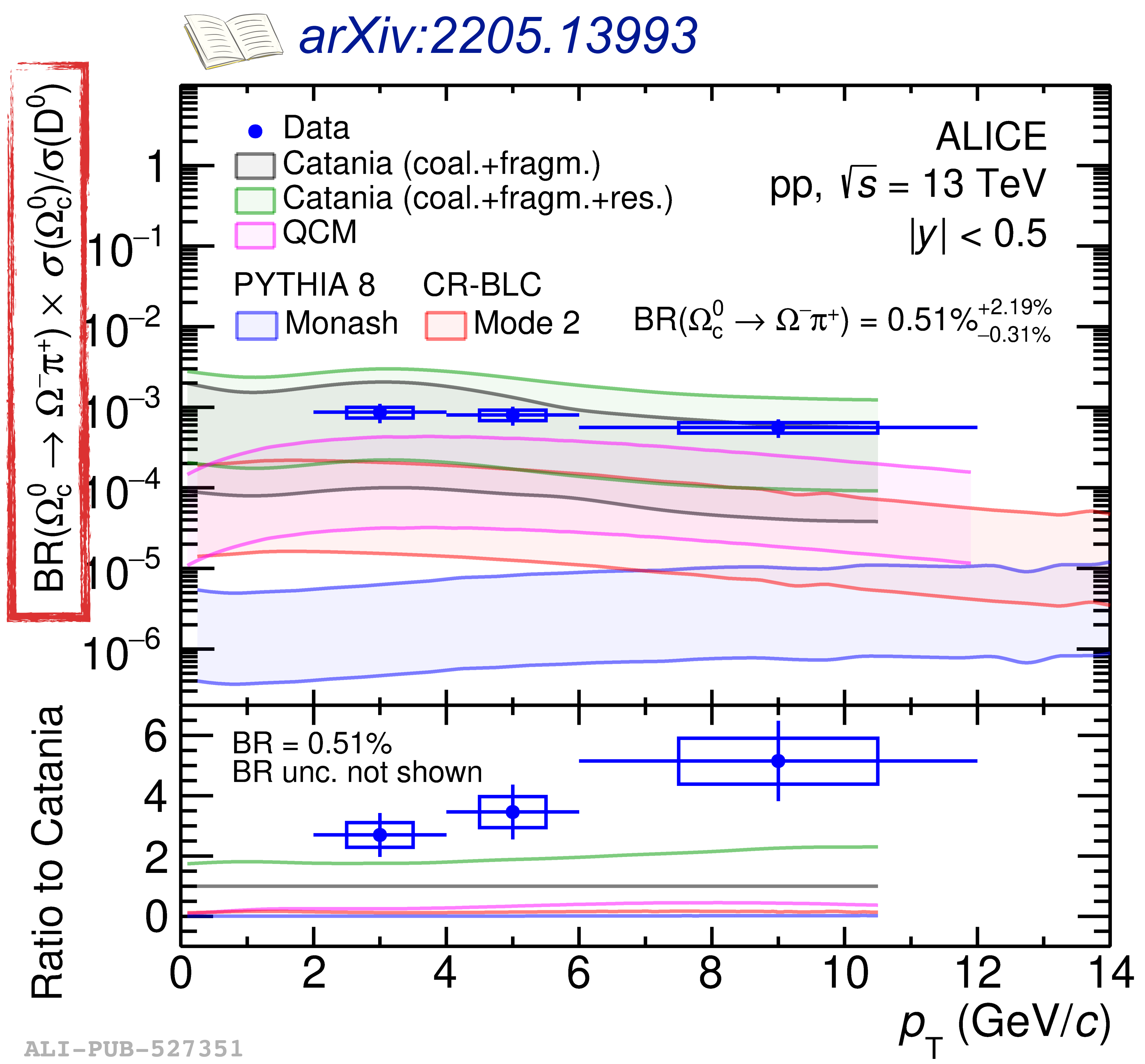
- Hint of enhancement at high p_T in p–Pb w.r.t. pp collisions
- Underestimated by QCM for both pp and p–Pb collisions

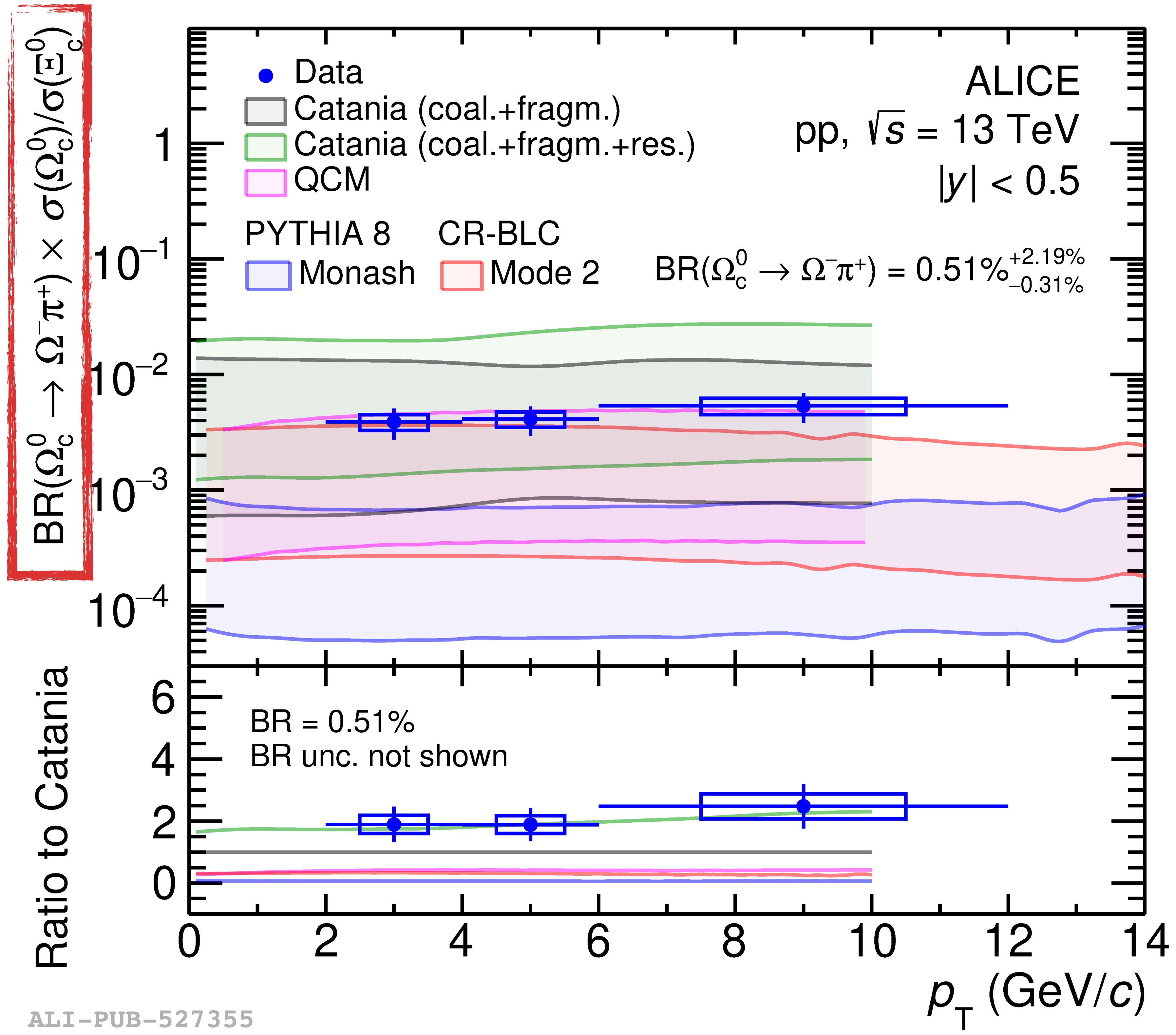
Nuclear modification factor R_{pPb}

- R_{pPb} of Λ_c^+ and Ξ_c^0 are compatible within uncertainties
- Described by QCM

Charm-baryon production: $\Omega_c^0(ssc)$ in pp collisions (I)

arXiv:2205.13993

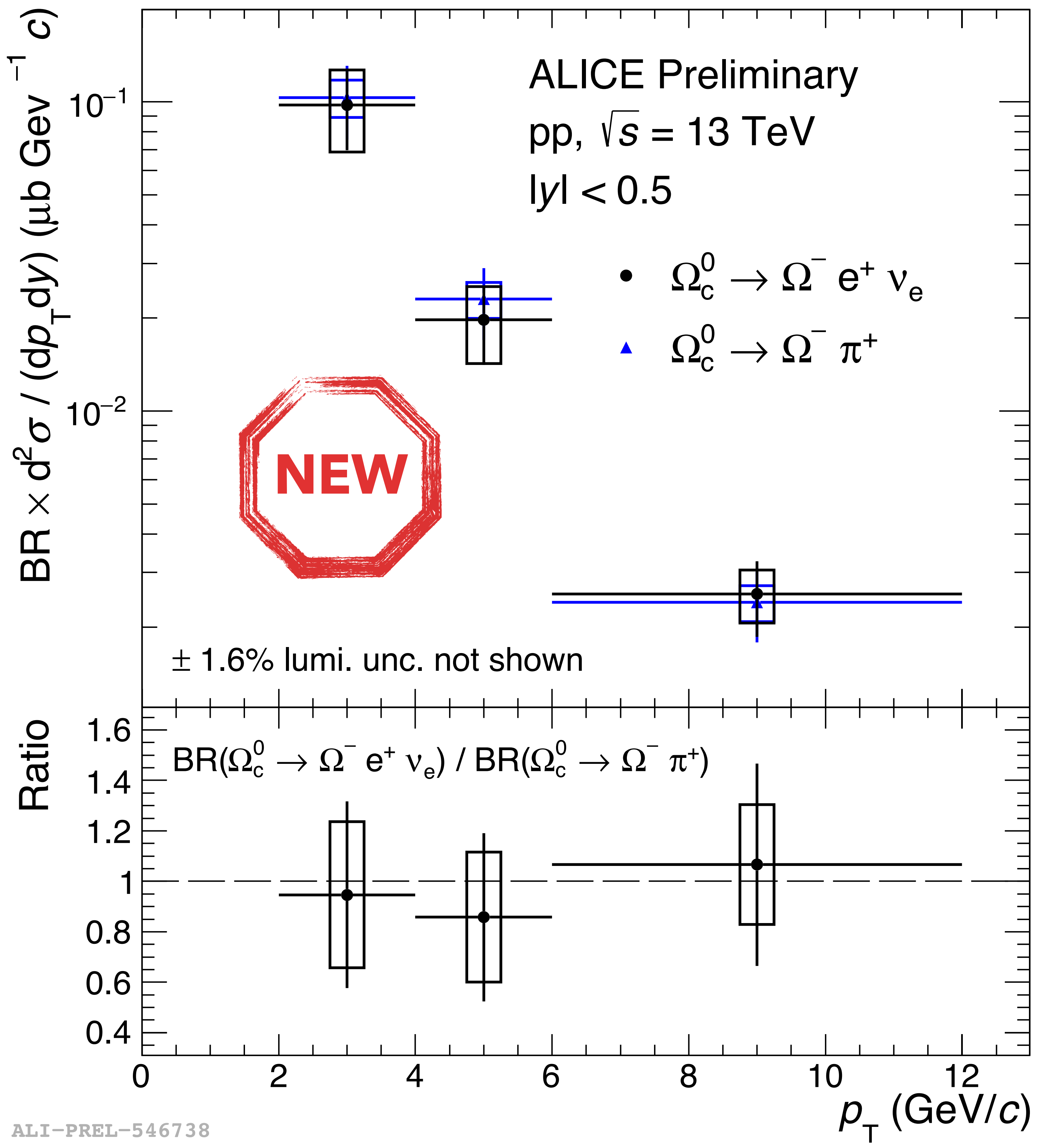




- No measurement of $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)$, loose bound from theoretical calculations
- Only Catania (coalescence + resonance decay) close to the data

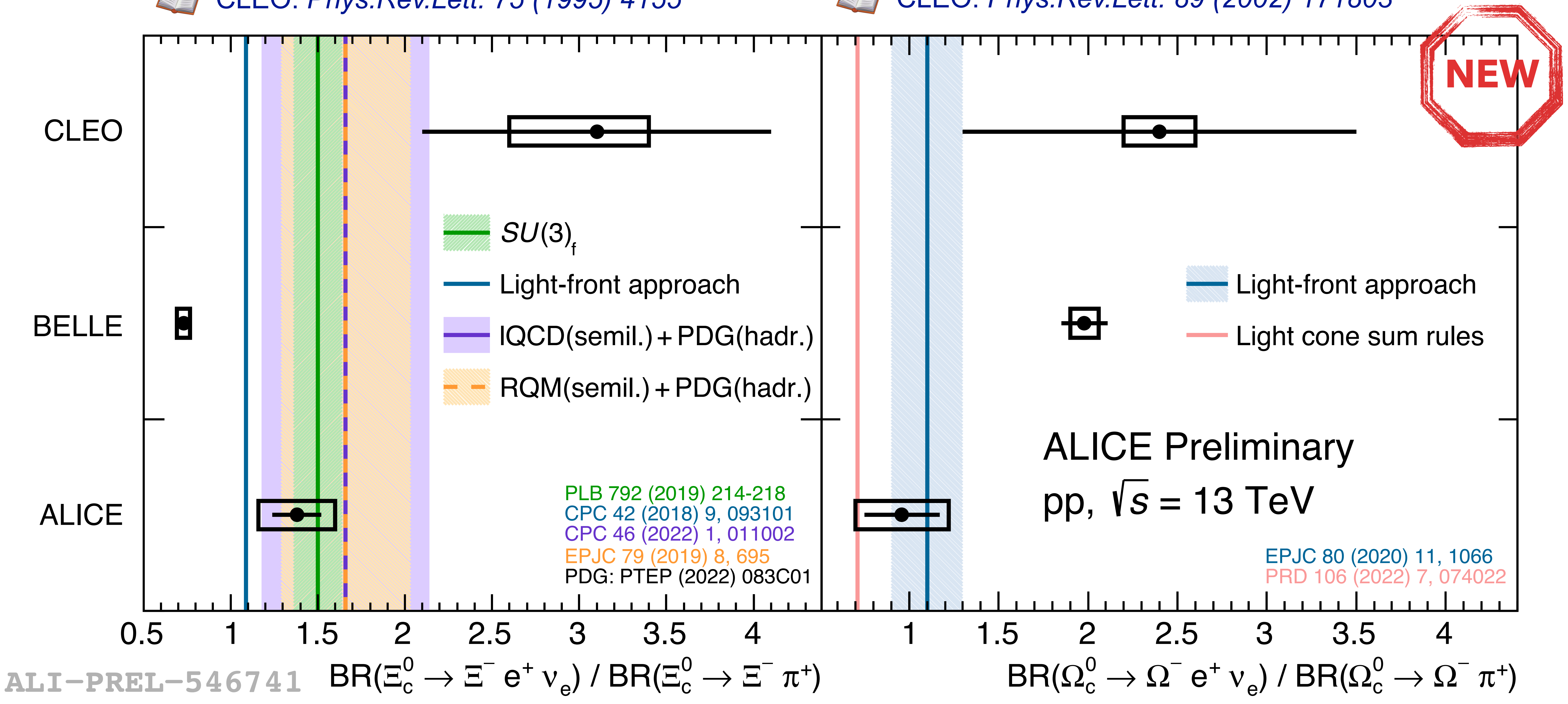
Extremely important to measure BR to discriminate models

Charm-baryon production: $\Omega_c^0(ssc)$ in pp collisions (II)



ALICE: *Phys.Rev.Lett. 127 (2021) 272001*
BELLE: *Phys.Rev.Lett. 127 (2021) 121803*
CLEO: *Phys.Rev.Lett. 75 (1995) 4155*

ALICE $\Omega_c^0 \to \Omega^-\pi^+$: *arXiv:2205.13993*
BELLE: *Phys.Rev.D 105 (2022) L091101*
CLEO: *Phys.Rev.Lett. 89 (2002) 171803*



First measurement of branching-fraction ratio of $\mathrm{BR}(\Omega_c^0 \to \Omega^- e^+ \nu_e)/\mathrm{BR}(\Omega_c^0 \to \Omega^- \pi^+)$ in ALICE

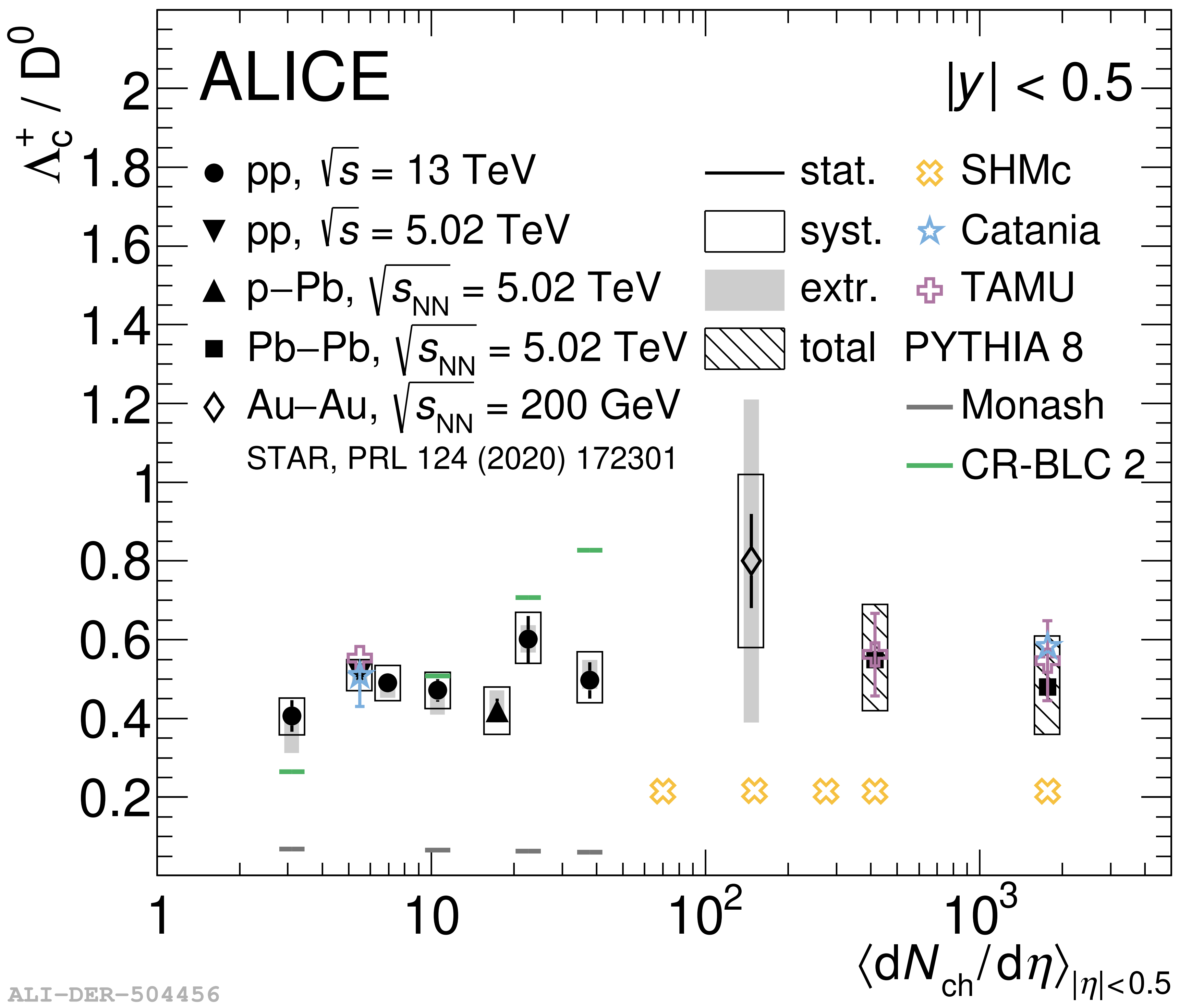
- Compatible with more precise measurement in Belle within 2.7σ, and with theoretical calculations
- Run 3 data taking will allow to reduce statistical and systematical uncertainties

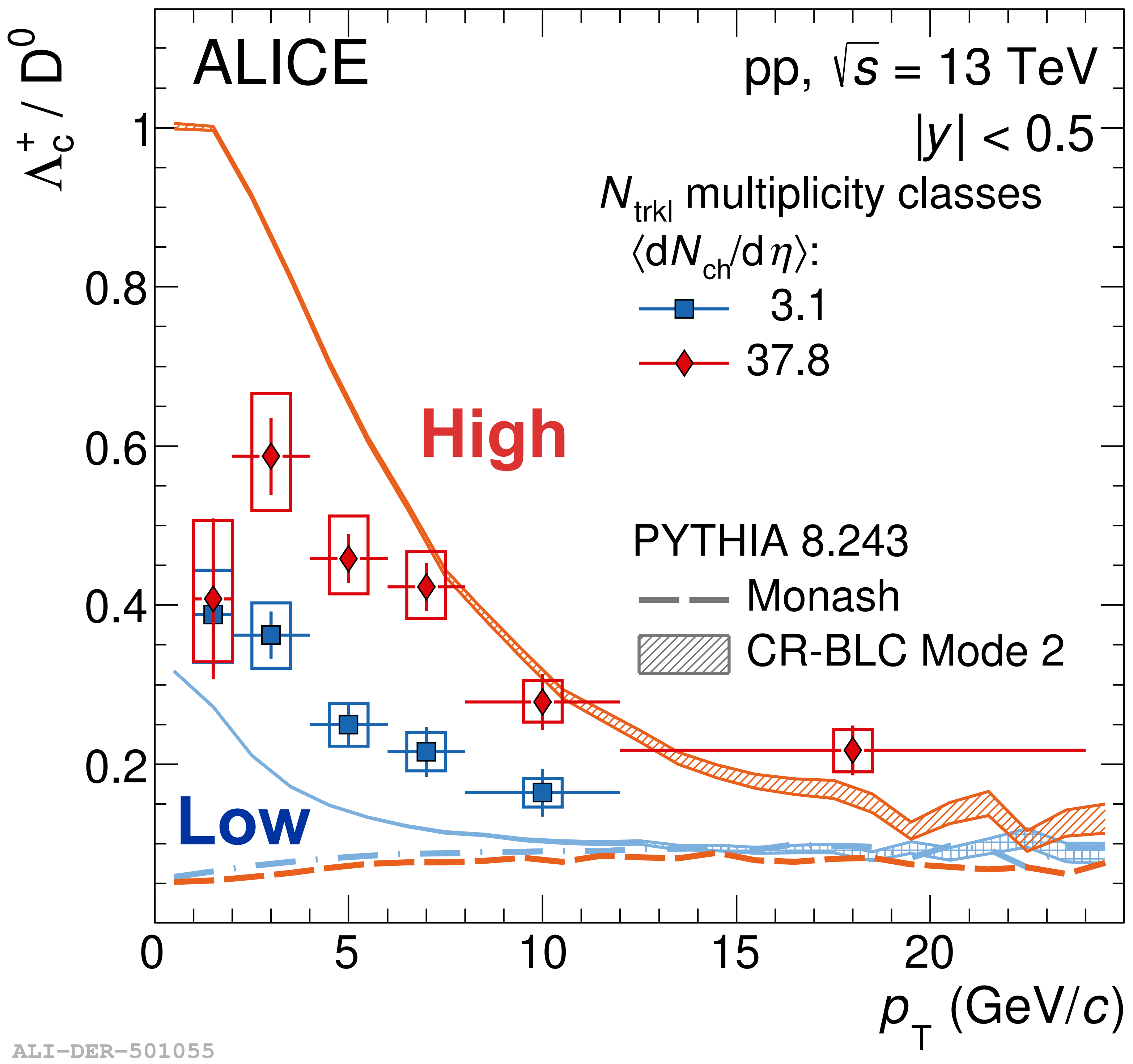
HF poster: Tiantian Cheng

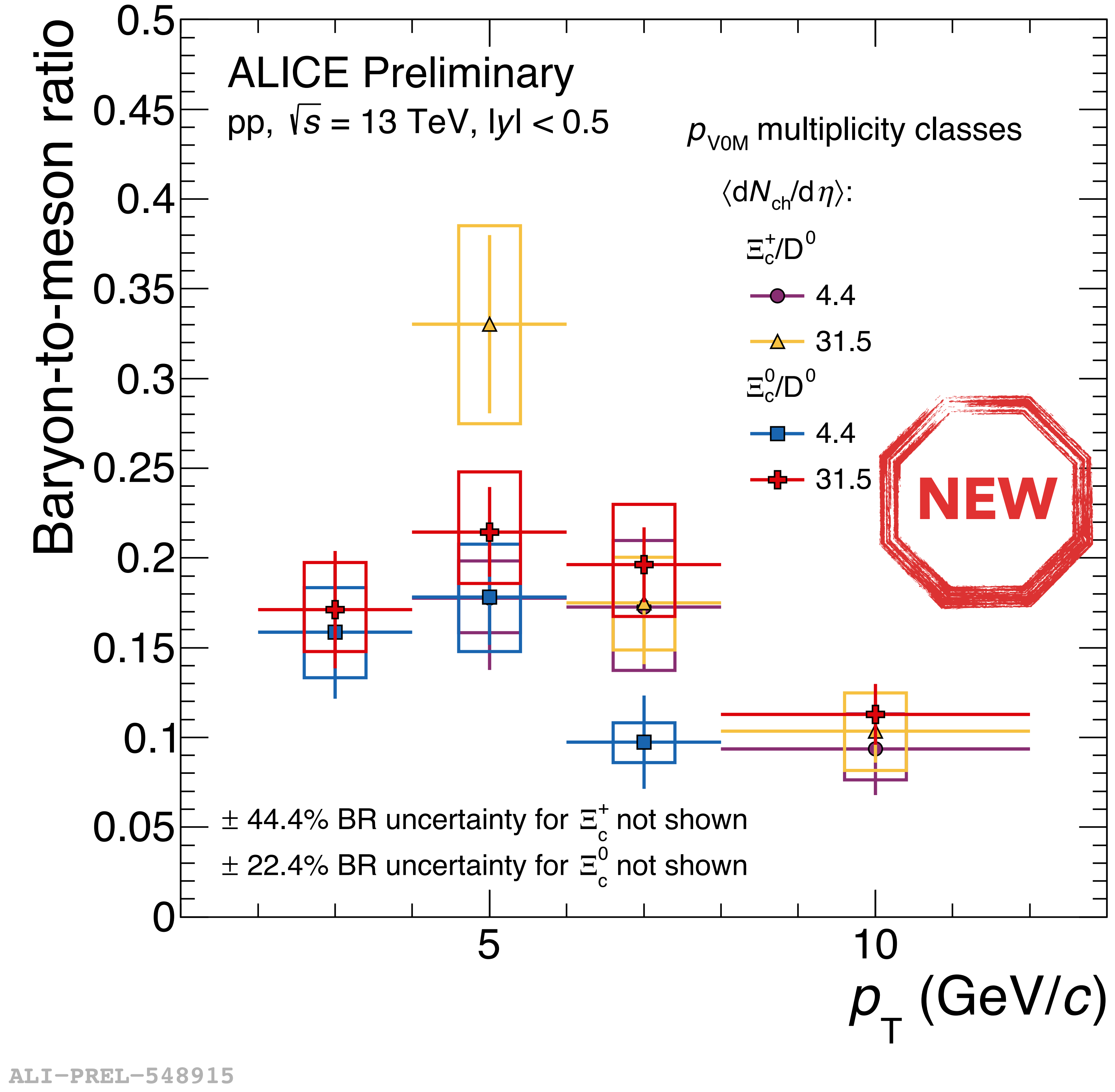
Charm-baryon production vs. event multiplicity

Phys.Lett.B 829 (2022) 137065

HF posters: Oveis Sheibani, Tao Fang, Chong Kim, Jaeyoon Cho







p_{T}-integrated Λ_c^+/D^0 vs. multiplicity

- No modification of overall production, difference between collision systems is due to momentum redistribution

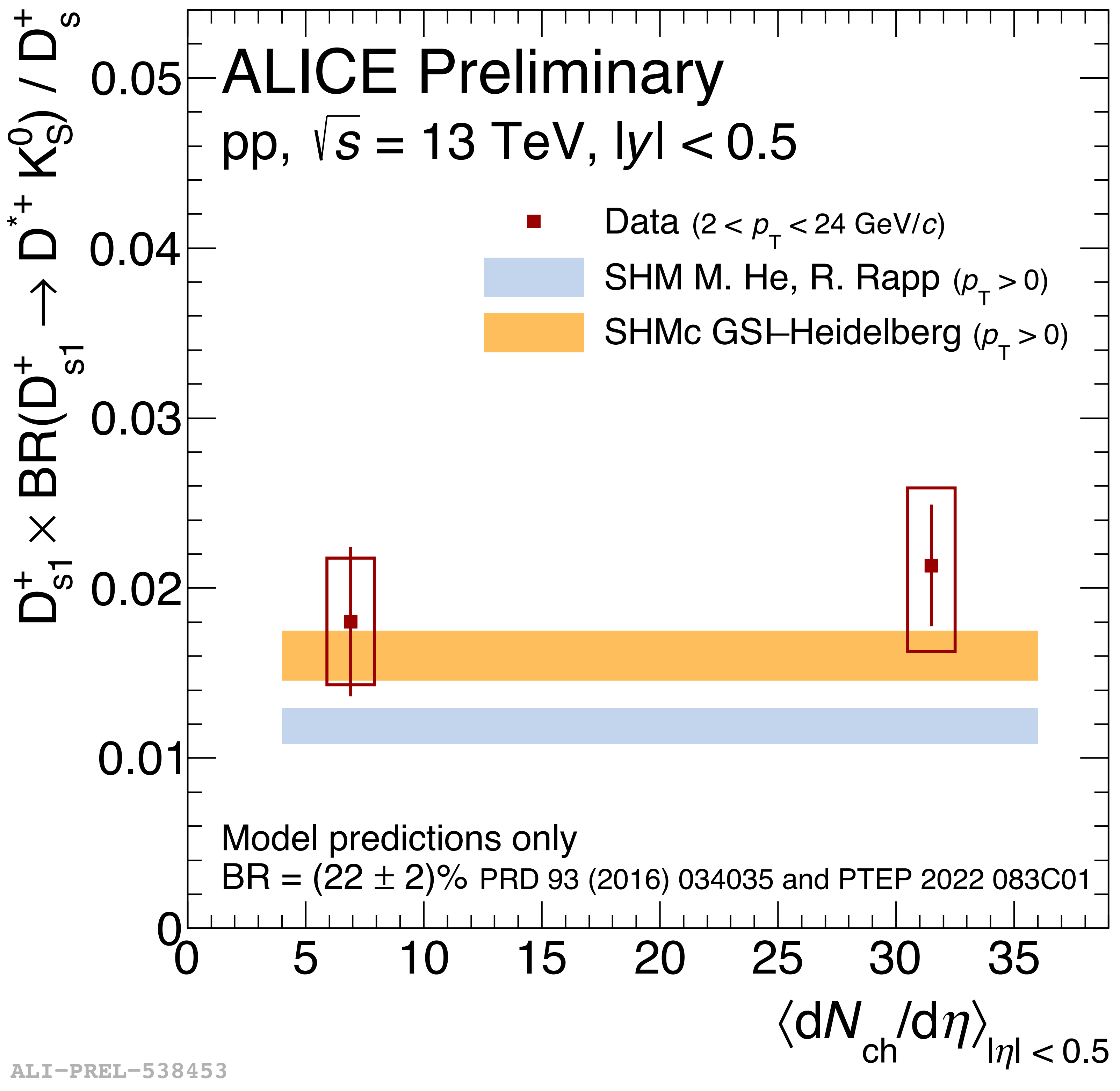
Λ_c^+/D^0 vs. p_{T} in different multiplicity

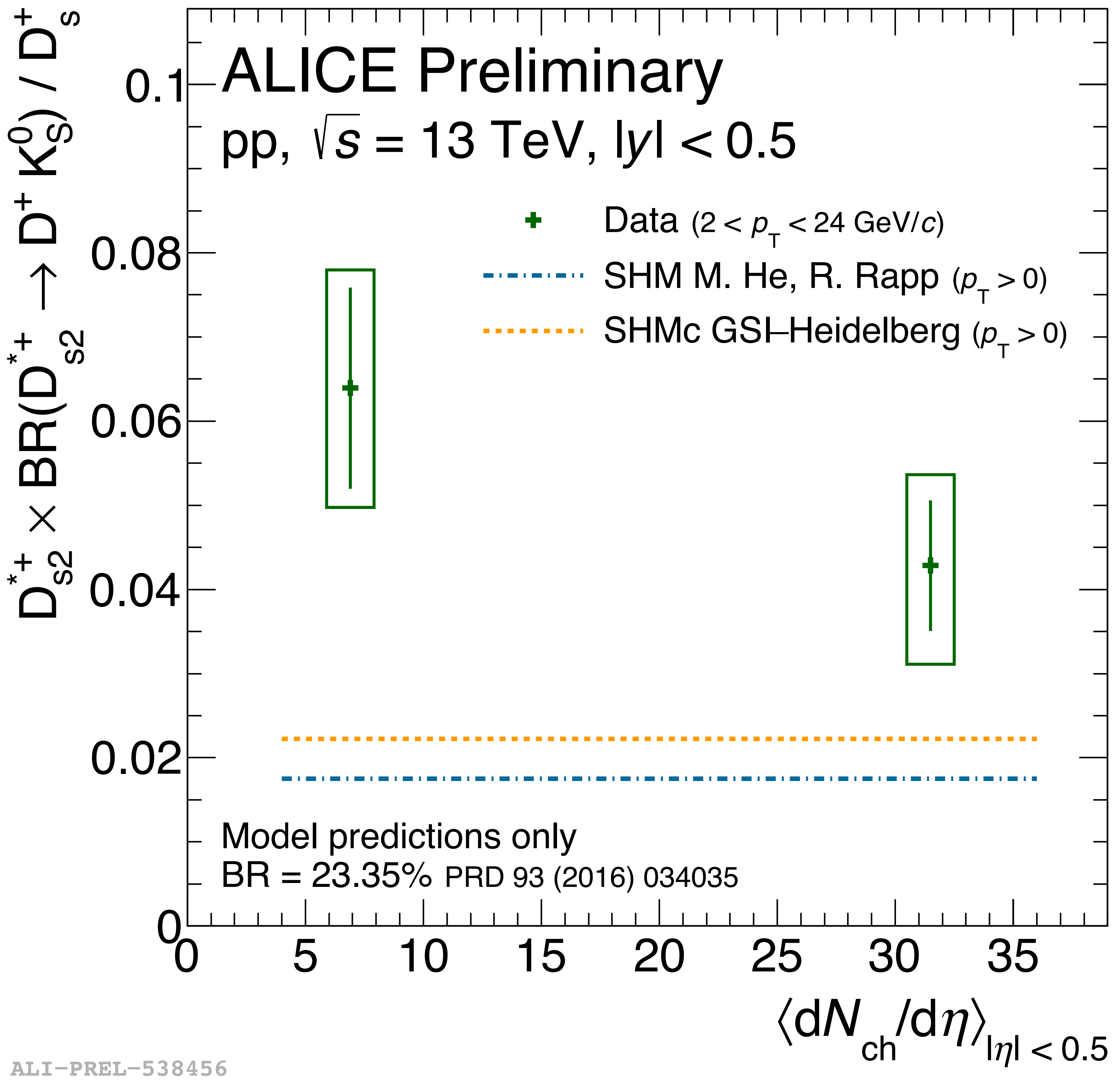
- Multiplicity-dependent enhancement with 5.3σ from lowest to highest multiplicity

$\Xi_c^{0,+}/D^0$ vs. p_{T} in different multiplicity

- No significant multiplicity dependence as a function of p_{T} within uncertainties

D_s^+ resonance production vs. event multiplicity



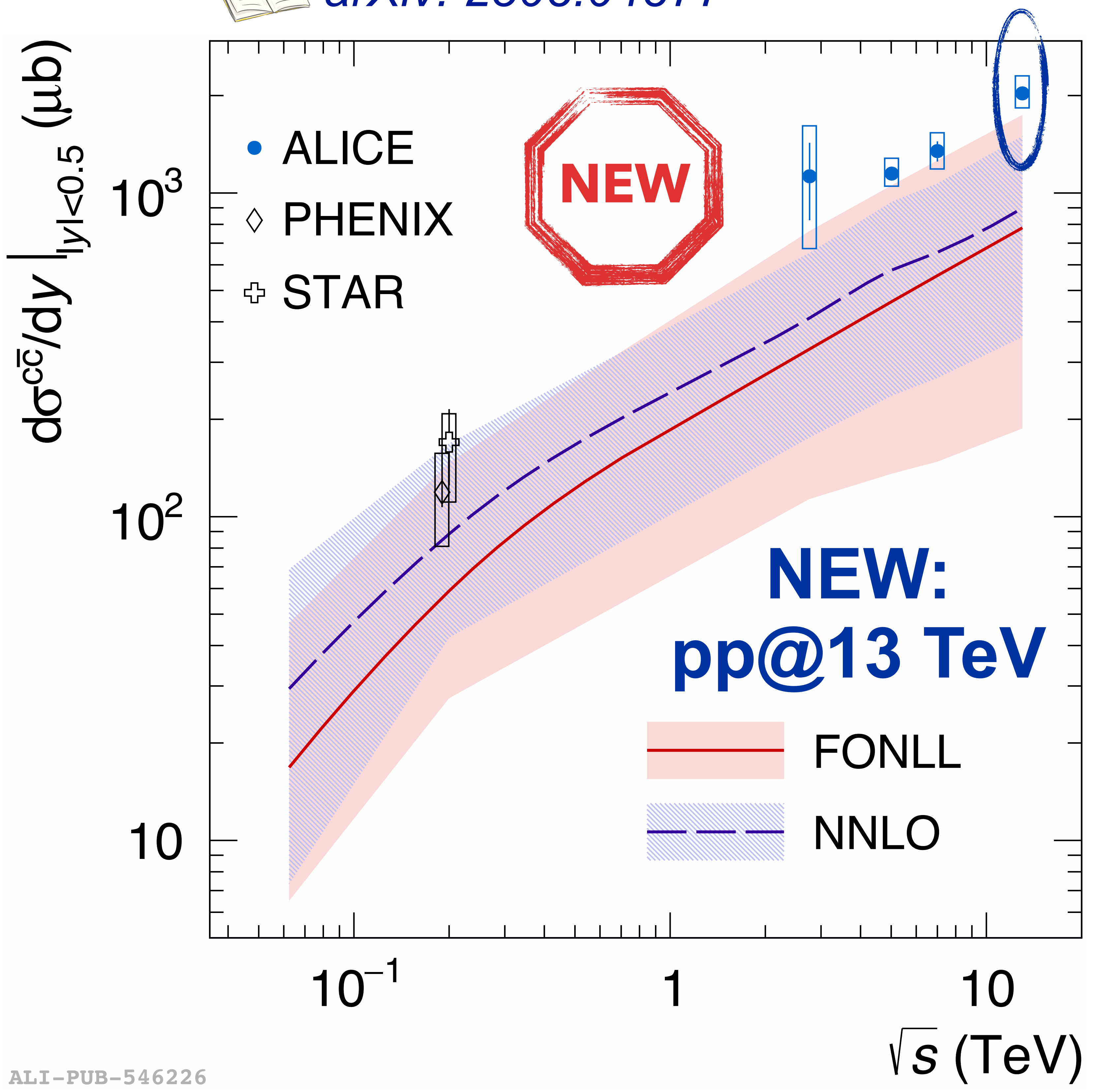


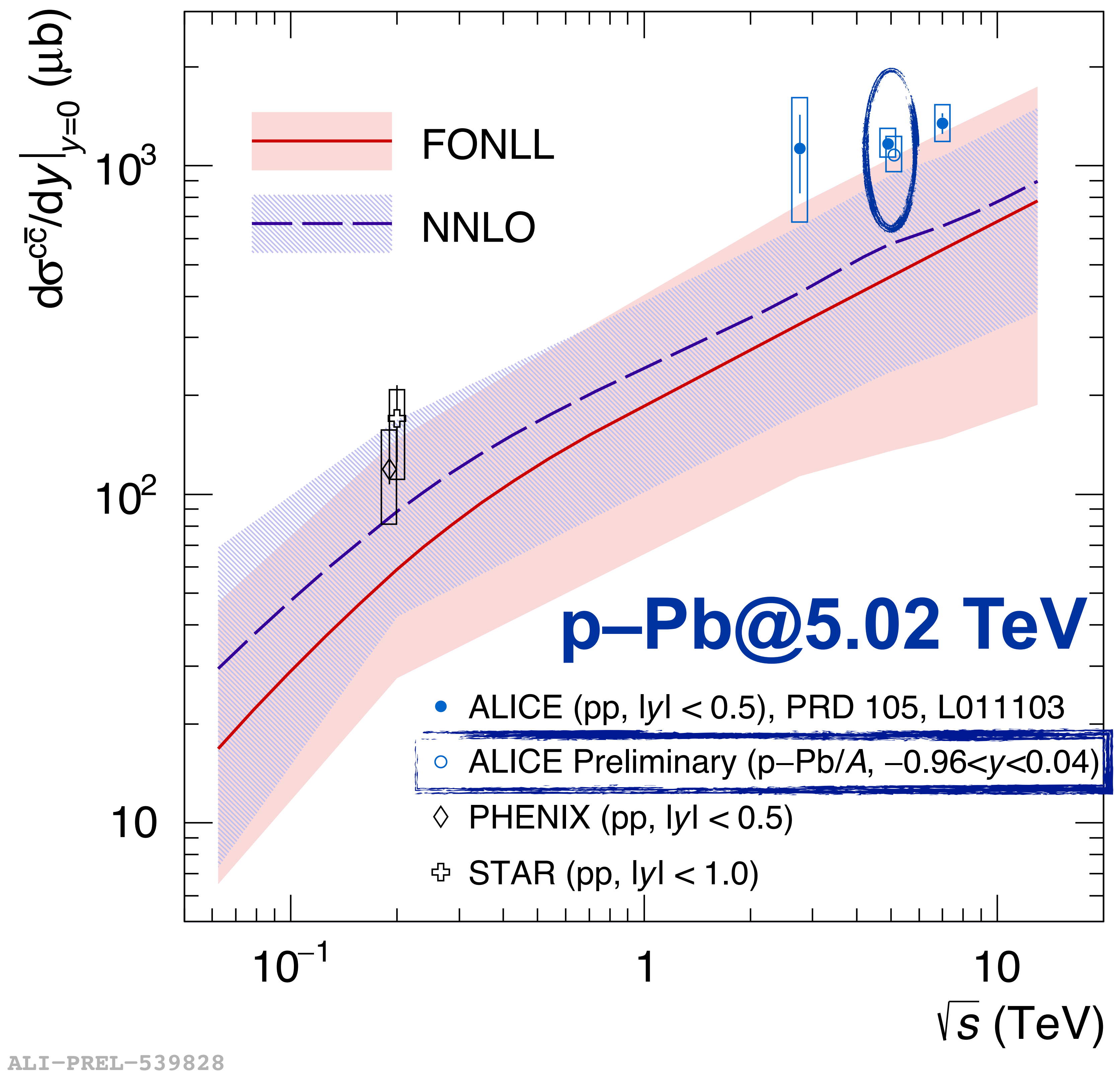
First measurement of D_s^+-resonance production in pp collisions

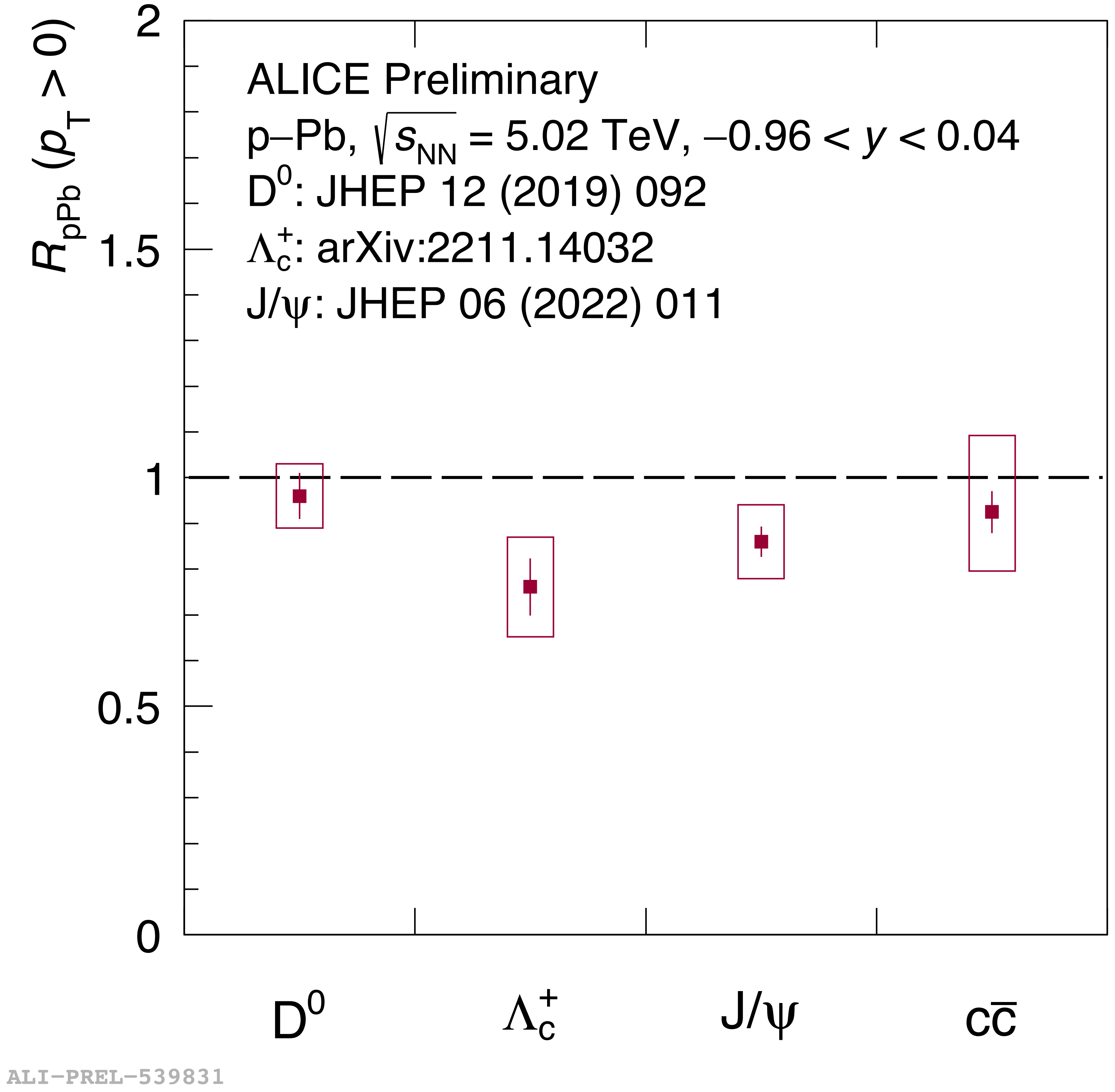
- No multiplicity dependence on D_{s1}^+/D_s^+ ratio
- Possible hint of decreasing trend as a function of multiplicity on D_{s2}^{*+}/D_s^+ ratio ➡ Need more precise measurement

Charm production in pp and p–Pb collisions

arXiv: 2308.04877



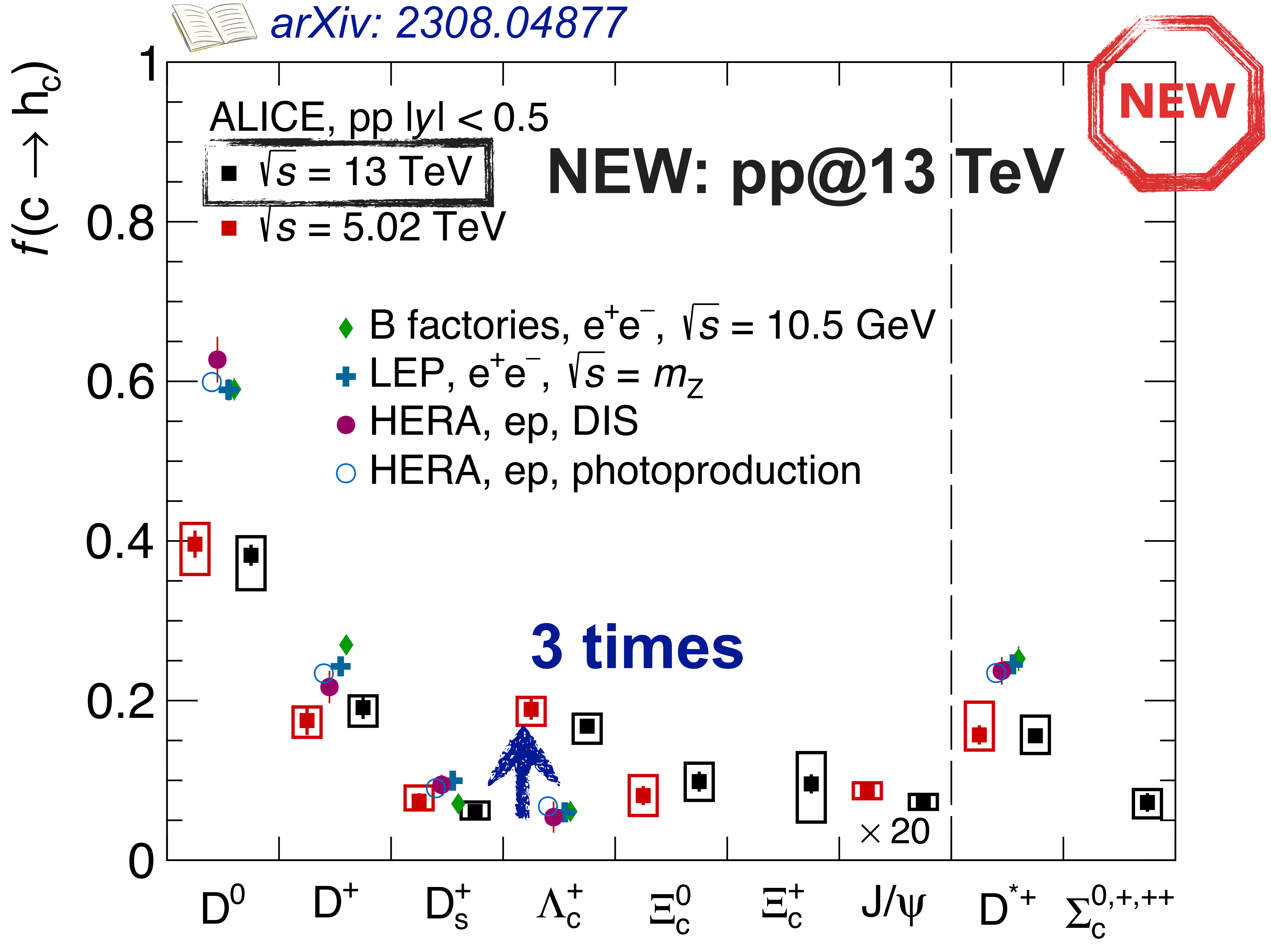


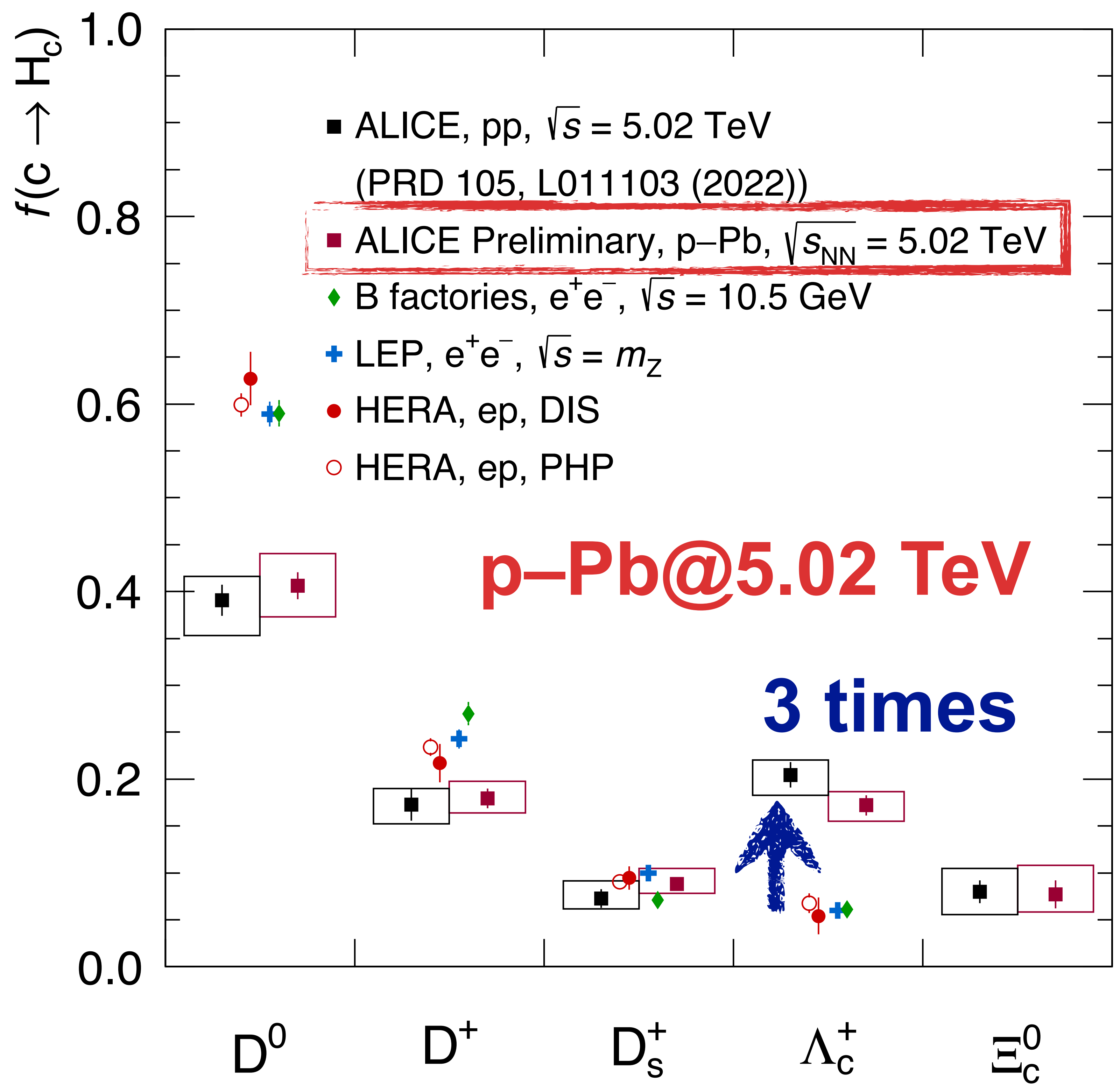


- $\sigma(c\bar{c})$ at midrapidity at the upper bound of state-of-the-art pQCD calculations
- No significant difference in the overall production of charm between pp and p–Pb collisions

Charm fragmentation fractions in pp and p–Pb collisions

arXiv: 2308.04877



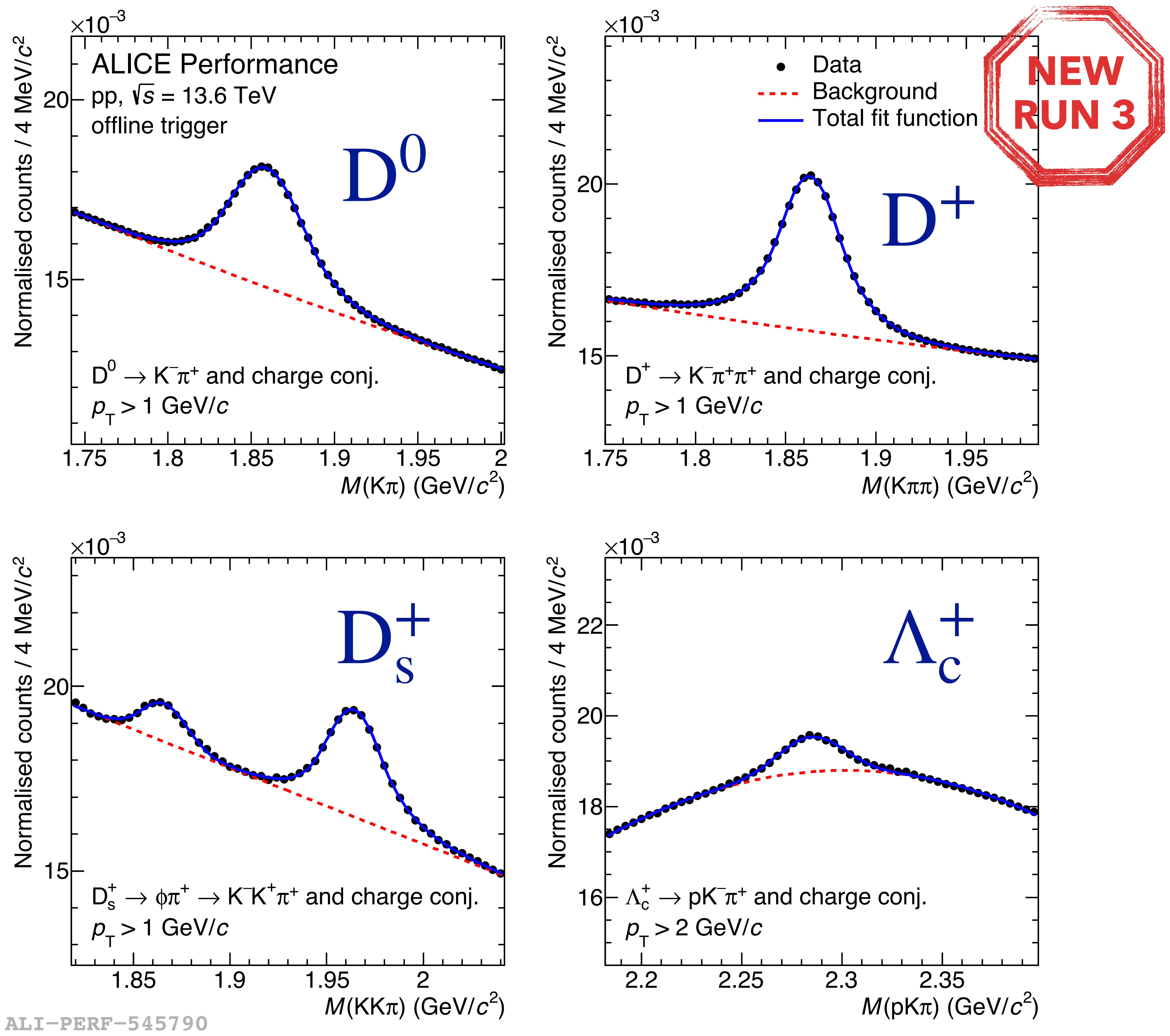


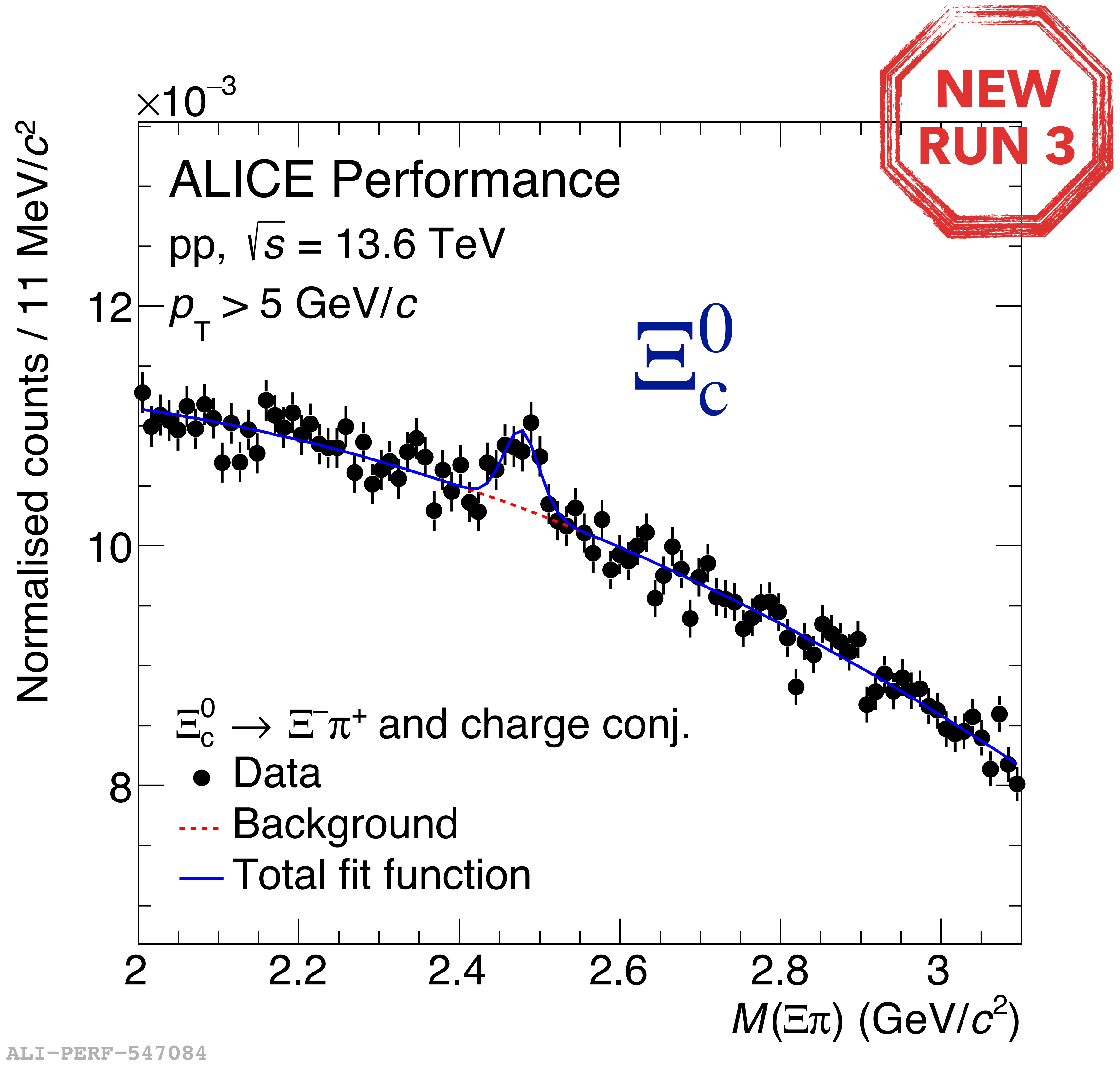
- Independent of centre-of-mass energy: pp@5.02 TeV and pp@13 TeV
- Consistent with system size: pp and p–Pb collisions
- Significant enhancement for charm baryons in pp and p–Pb w.r.t. e^+e^- and e^-p collisions

Fragmentation fractions universality is challenged

Outlook: Run 3 data

- More precise measurements of charm-baryon production with Run 3 data





Summary

- Investigate heavy-flavour (HF) hadronization mechanisms with Run 2 data
  - Assumption of universal parton-to-hadron fragmentation fractions not valid at LHC energies
  - HF hadronization mechanisms in small collision systems at LHC need further investigations
    - Resonance decay? Coalescence? Radial flow?
  - Access to exclusive measurement of beauty
  - The measurement of Ξ_c^0 production in Pb–Pb collisions with Run 2 data is coming soon

Backup