SQM 2022
The 20th International Conference on Strangeness in Quark Matter

Constraining hadronization processes with charm baryons in pp and p—Pb collisions with ALICE

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on behalf of the ALICE Collaboration
* Inha University

2022. 06. 14

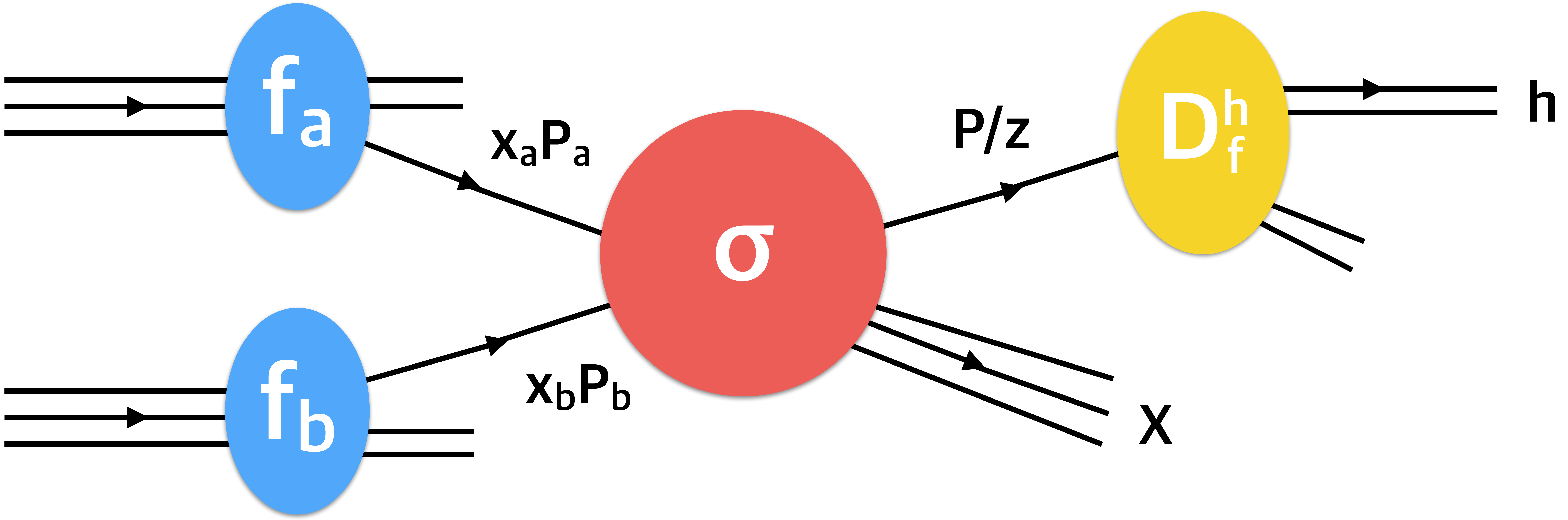
Heavy-flavour production

$$\frac{d\sigma^{\mathrm{D}}}{dp_{\mathrm{T}}^{\mathrm{D}}}(p_{\mathrm{T}};\mu_{\mathrm{R}};\mu_{\mathrm{F}}) = PDF(x_1, Q^2)PDF(x_2, Q^2) \otimes \frac{d\sigma^{\mathrm{c}}}{dp_{\mathrm{T}}^{\mathrm{c}}}(x_1, x_2, Q^2) \otimes D_{\mathrm{c}\to\mathrm{h}}(z = p_{\mathrm{h}}/p_c, Q^2)$$

Parton distribution function

Hard scattering cross section

Fragmentation function



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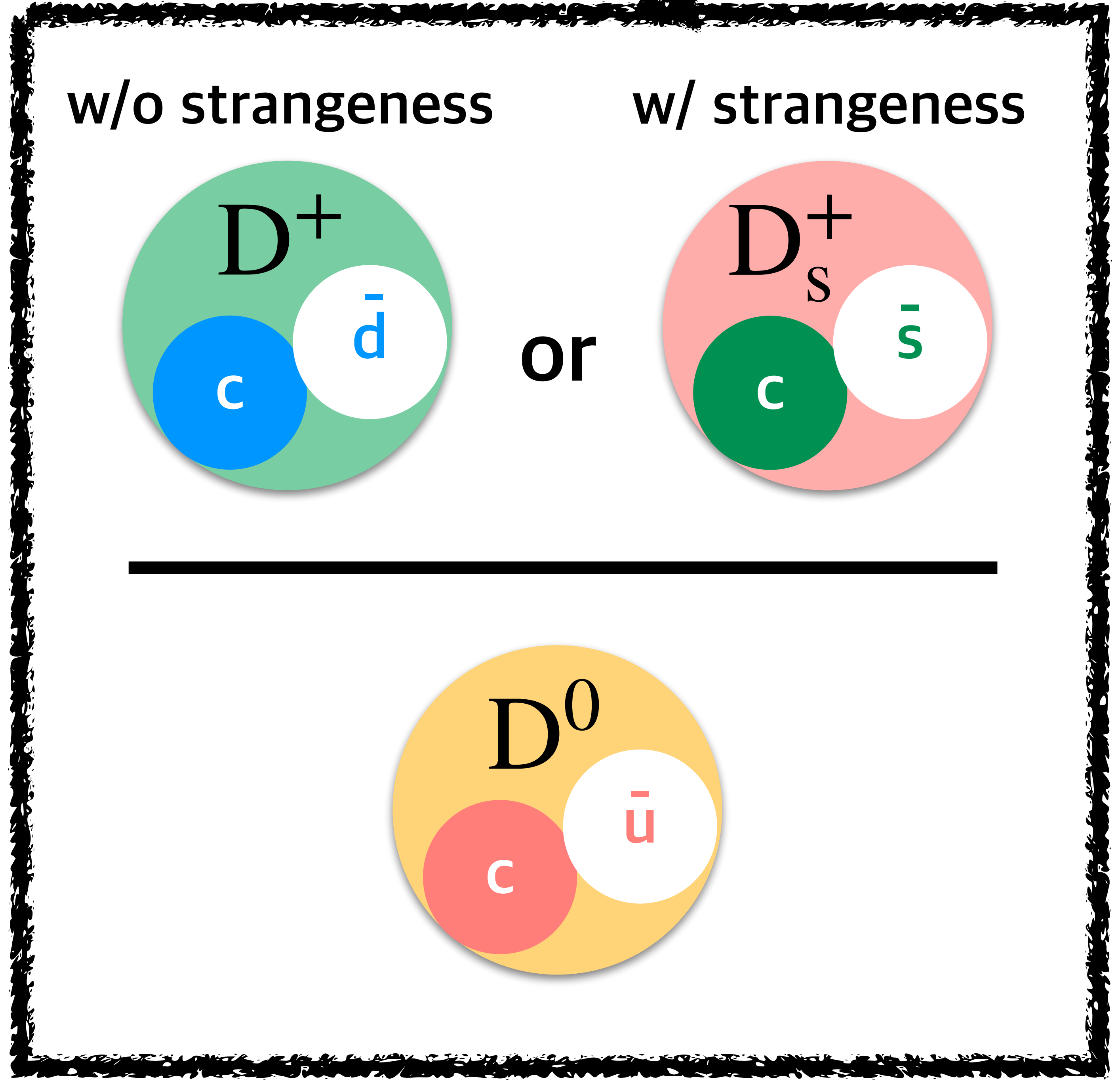
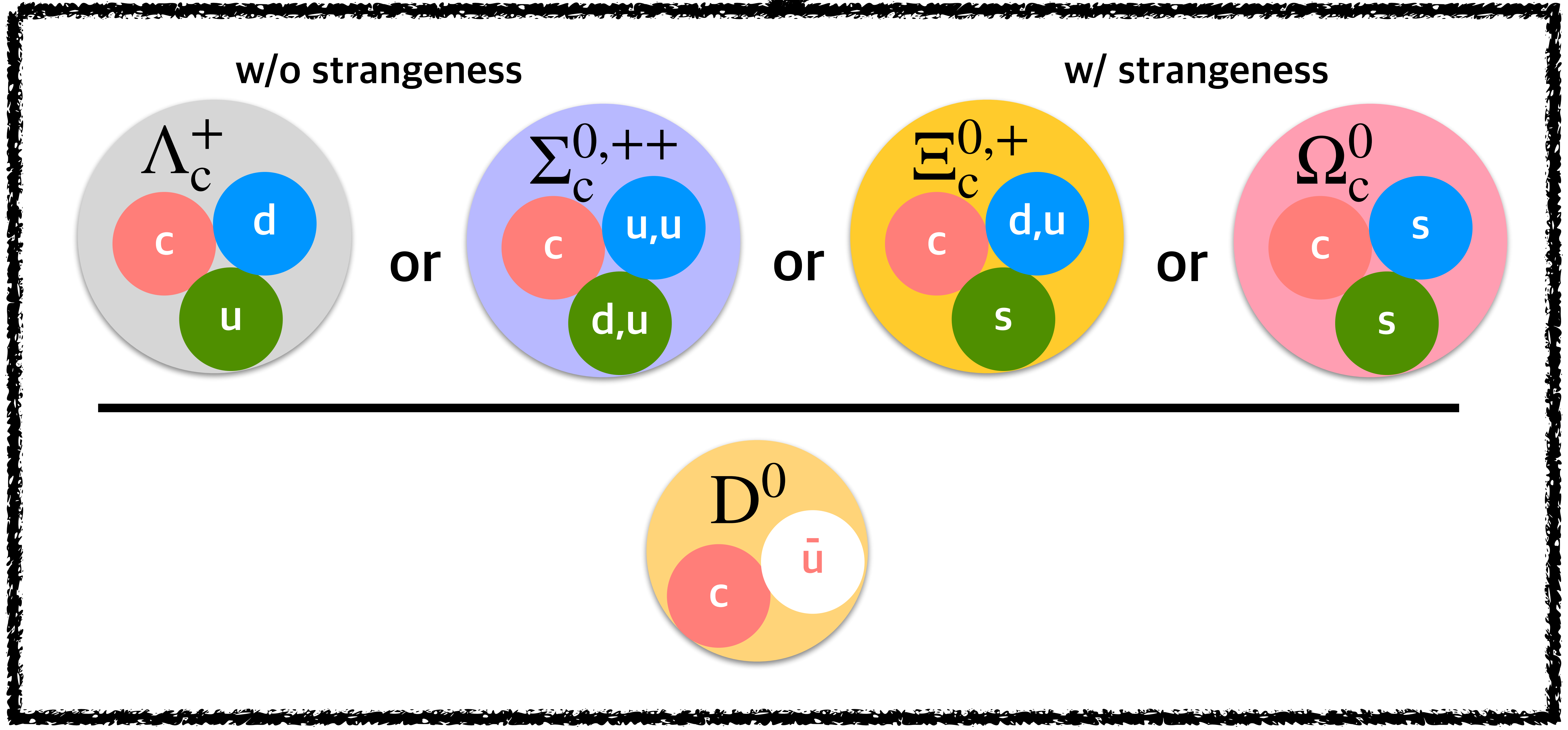
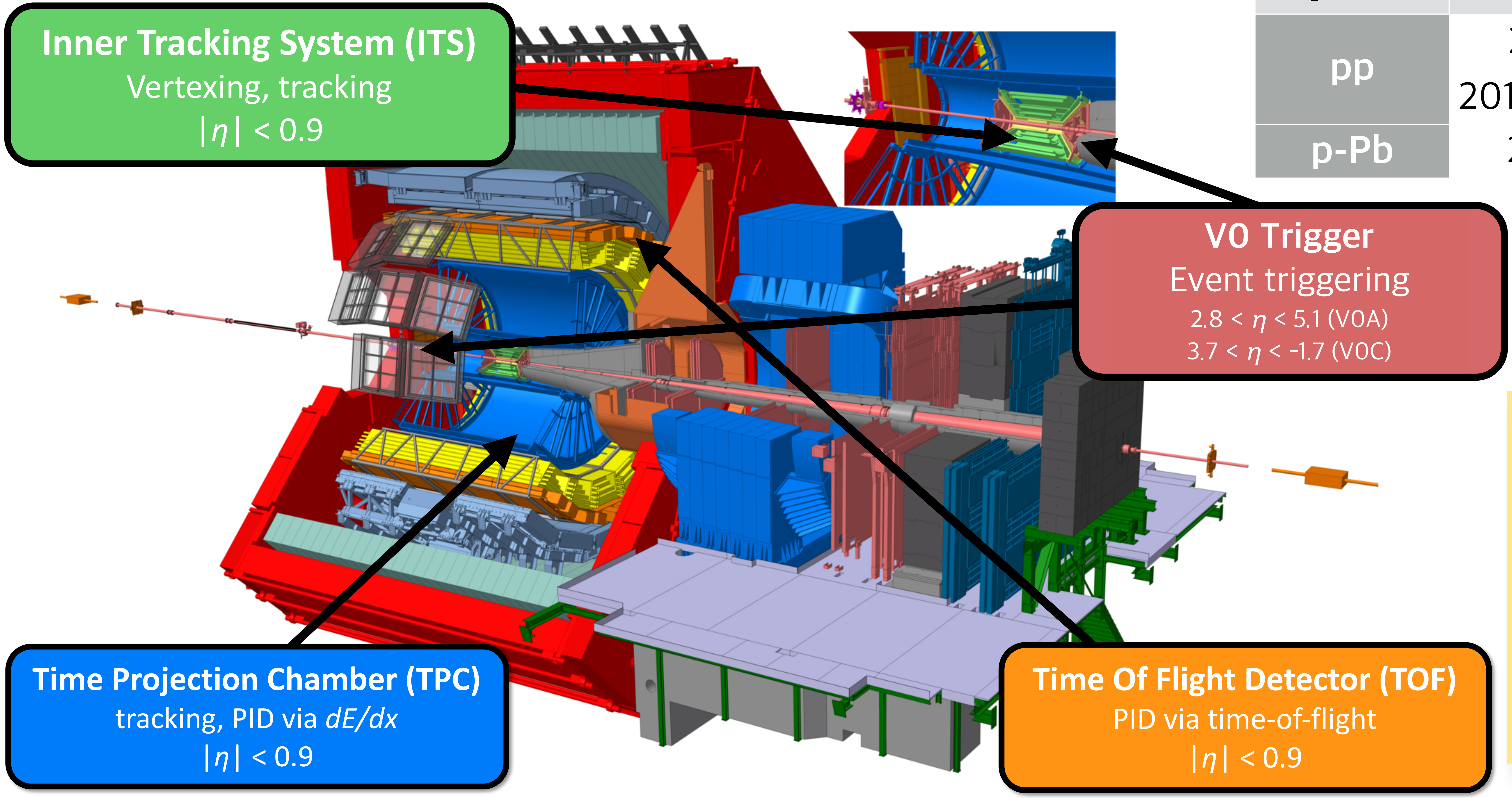
- **Hadron ratios (meson-to-meson, baryon-to-meson) are sensitive to fragmentations!**





ALICE Detector



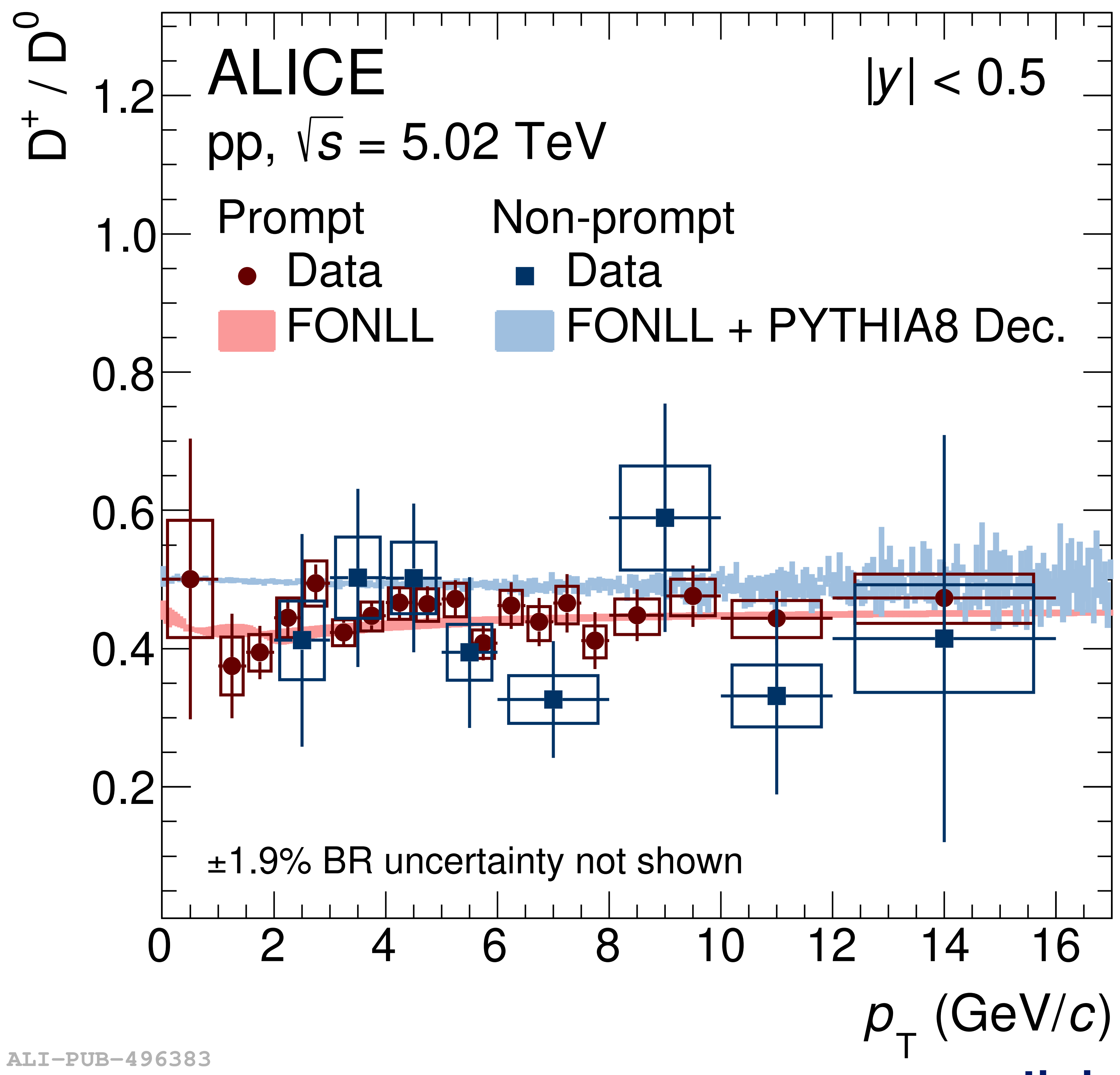
- **Data samples (Minimum-bias trigger)**

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2017	5.02	~19 nb^{-1}
	2016–2018	13	~32 nb^{-1}
p-Pb	2016	5.02	~0.3 mb^{-1}

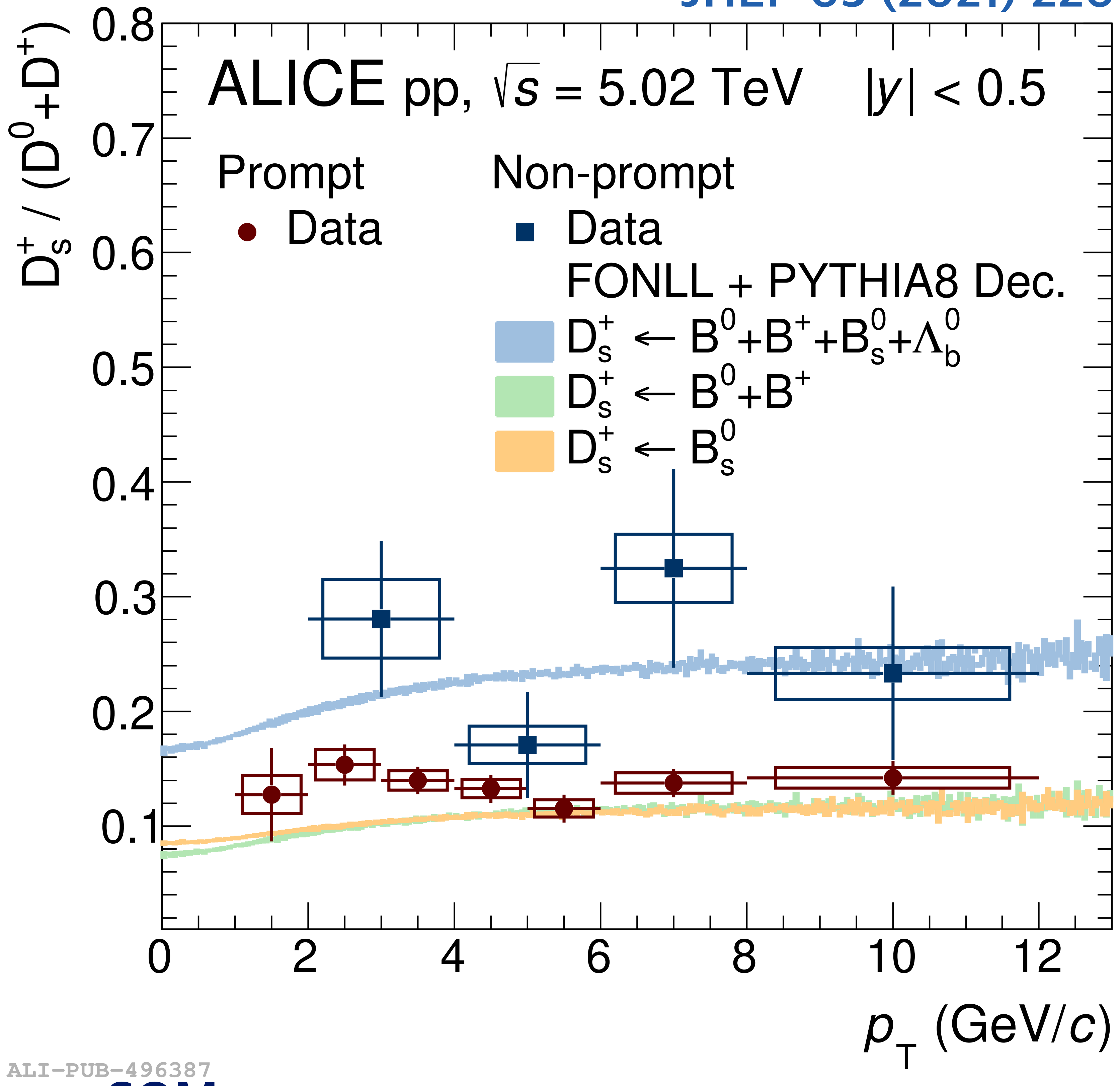
- **Charm-baryon decays**
  - $\Lambda_c^+ \rightarrow pK^-\pi^+, pK_s^0$
  - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
  - $\Xi_c^0 \rightarrow \Xi^-\pi^+, \Xi^-e^+\nu_e$
  - $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
  - $\Omega_c^0 \rightarrow \Omega^-\pi^+$

Charm and beauty meson production

- **Meson-to-meson ratios** are **independent** of p_T and **collisions system**
- Good agreement with model calculations
  - **NLO pQCD** calculation with **fragmentation functions** from **measurements at e^+e^- and ep colliders**, assumed to be **universal** across collision systems



JHEP 05 (2021) 220

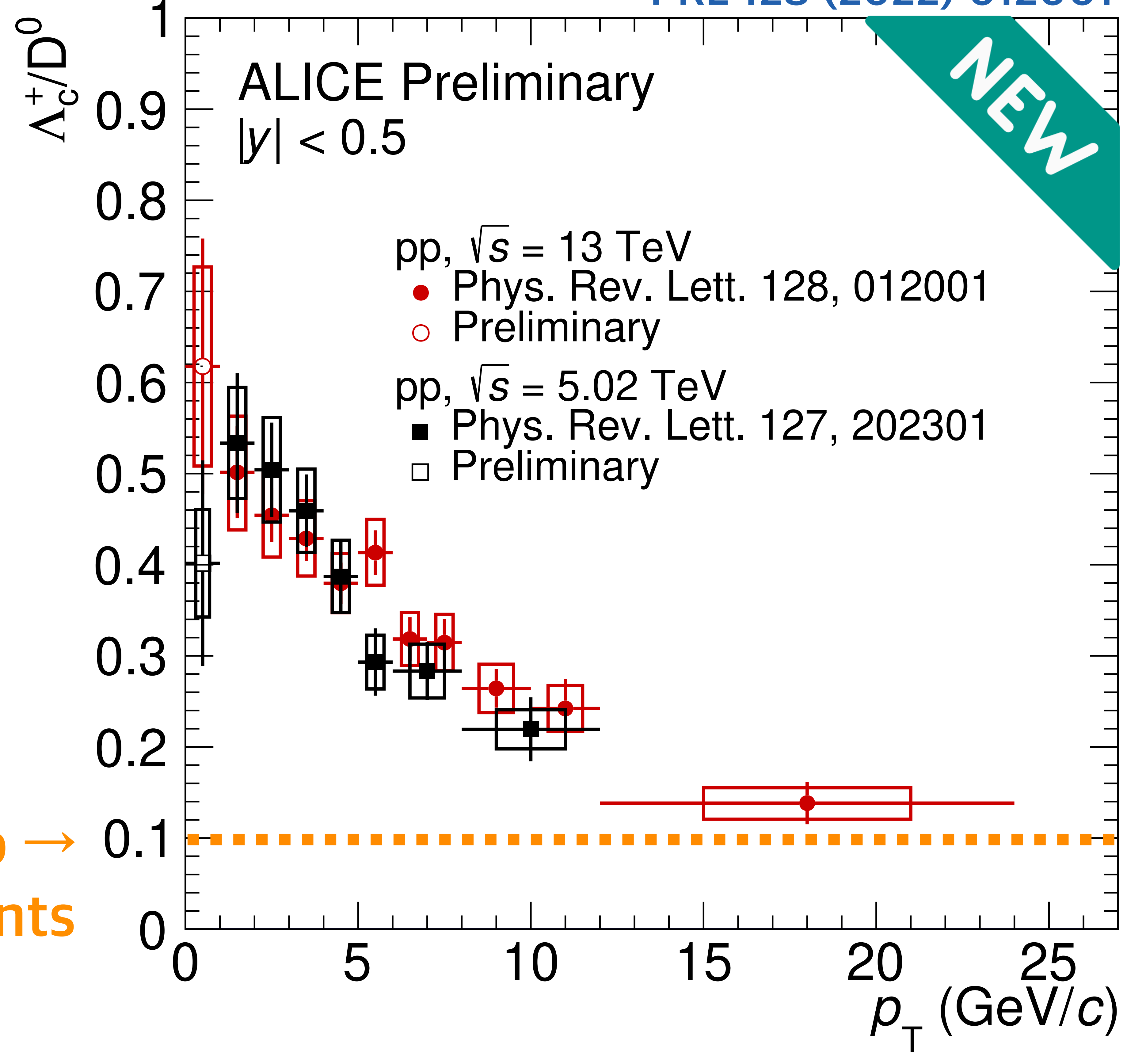


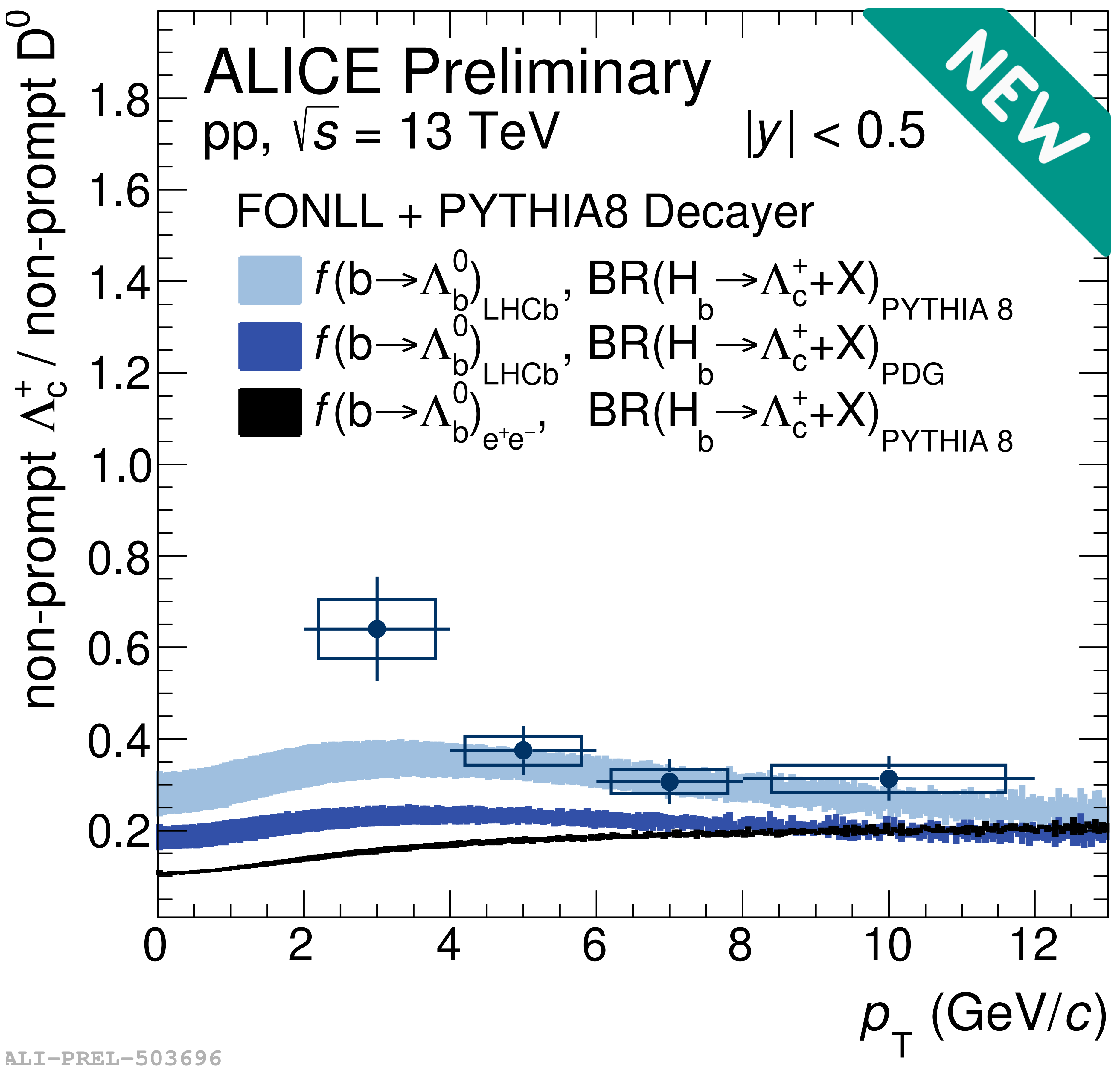
S. Politano
14 Jun 2022, 14:00

Λ_c^+ measurements in pp collisions

- Λ_c^+ measured down to $p_T = 0$ in pp collisions at √s = 5.02 TeV and 13 TeV
- **No difference** between √s = 5.02 TeV and 13 TeV within uncertainties

PRL 128 (2022) 012001



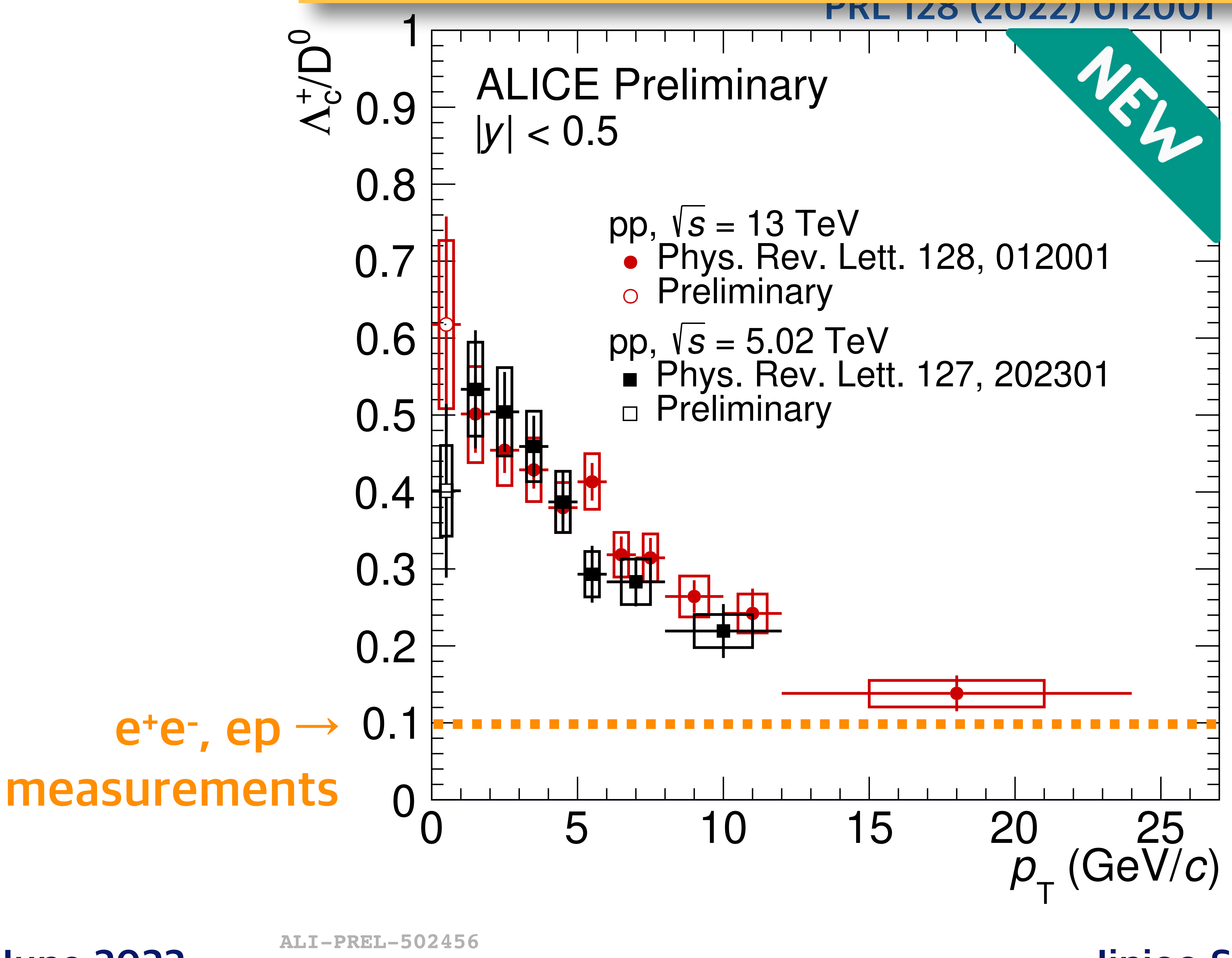


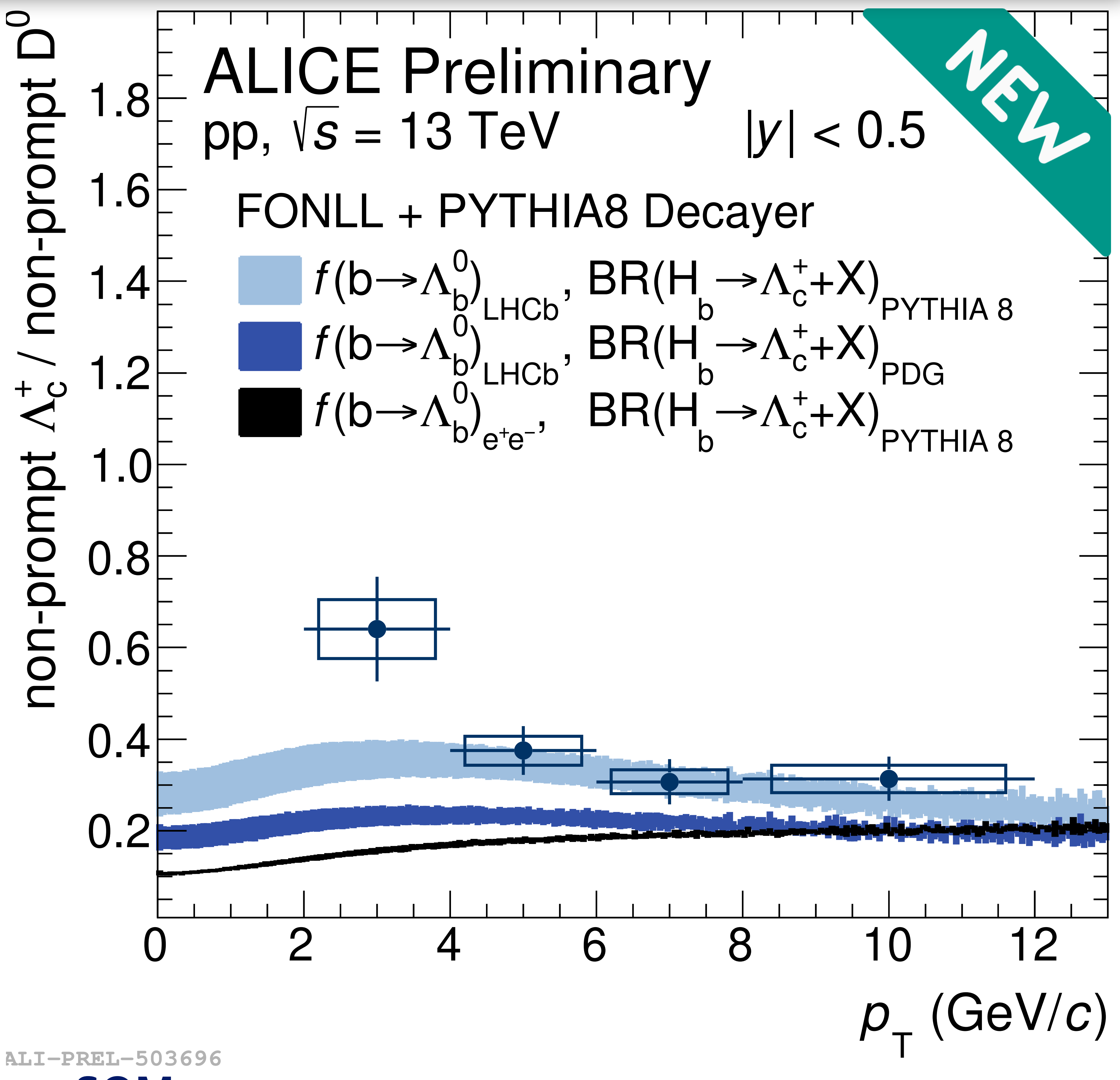
Λ_c^+ measurements in pp collisions

- Λ_c^+ measure
- **No differen**

- ***p_T* dependent** yield ratios
- **Enhancement at low *p_T*** w.r.t to e^+e^-, ep collisions
  - Similar enhancement for beauty measurements
  - ➡**Universality of charm fragmentation** among different collision system **broken**?

PRL 128 (2022) 012001



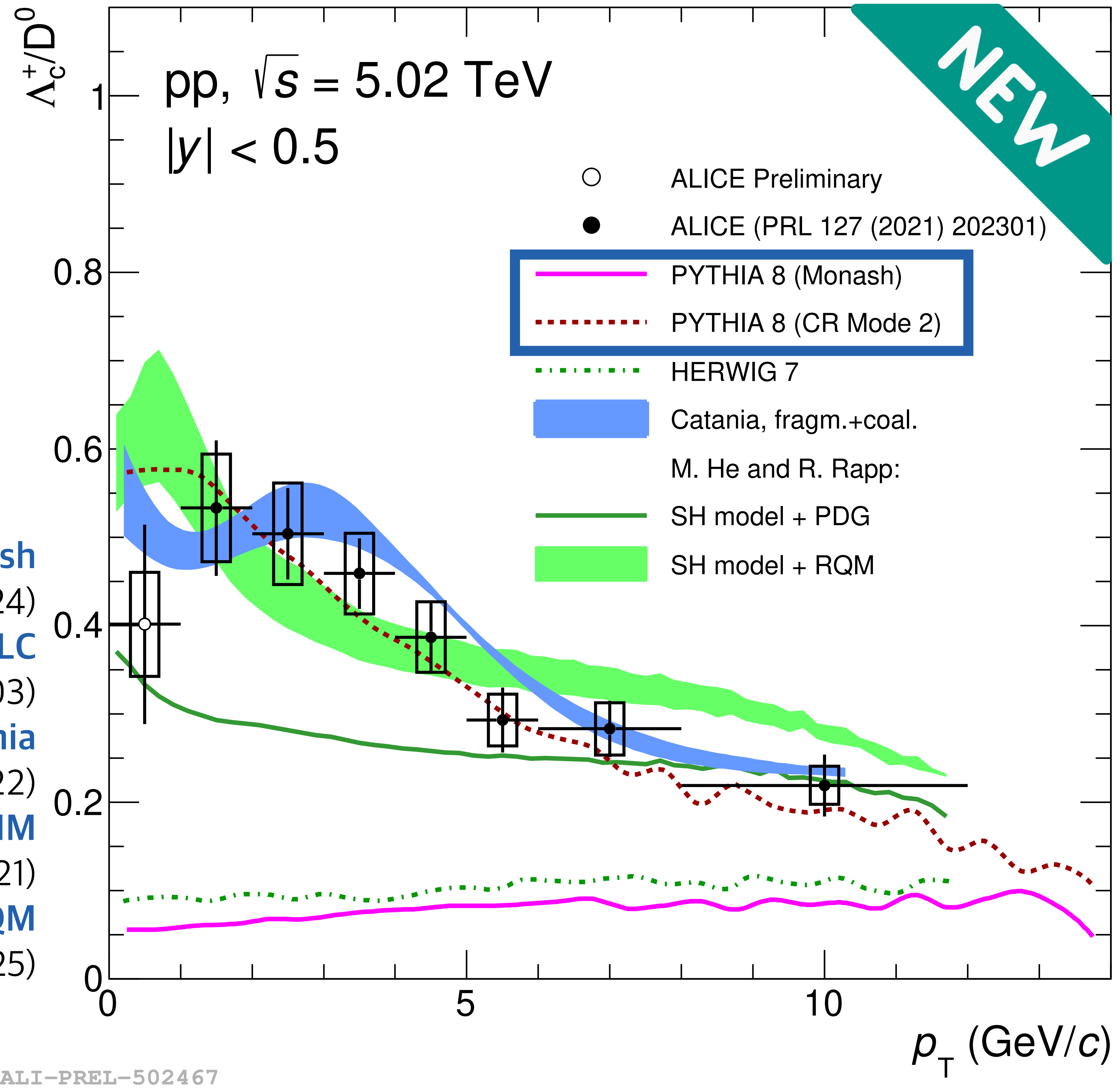


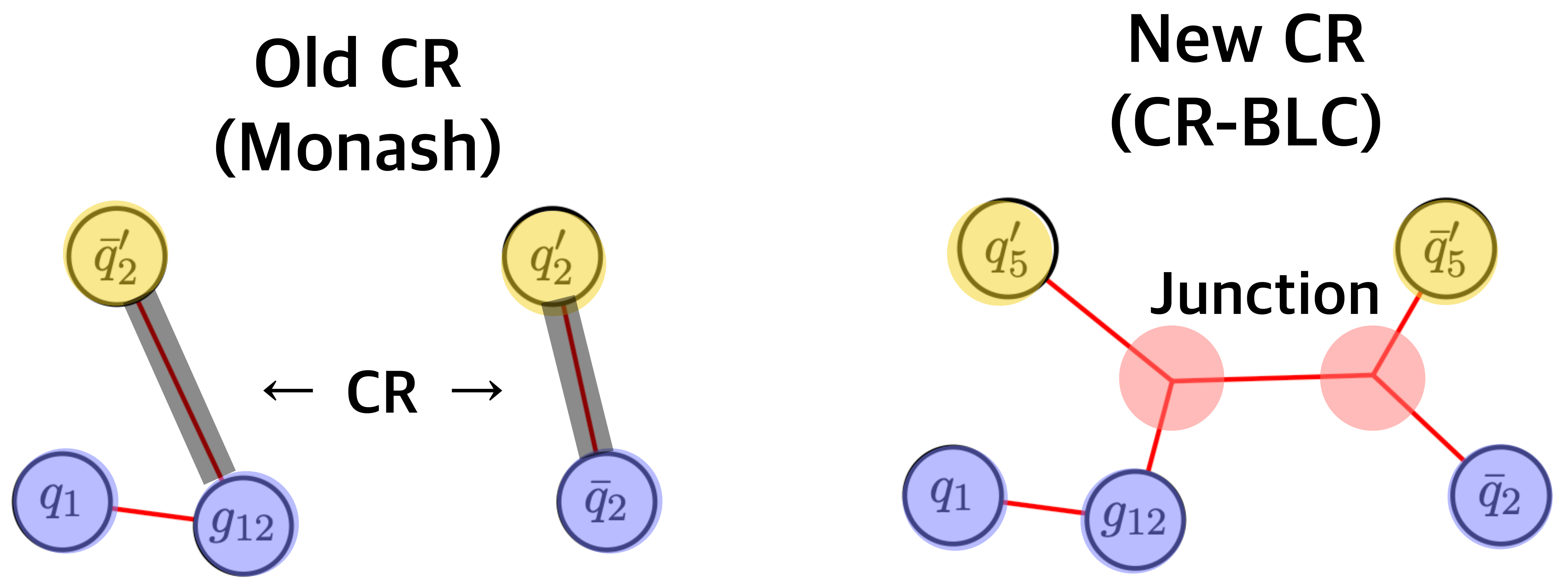
Λ_c^+ in comparison with models

- **PYTHIA 8 with Color Reconnection (CR) tunes**
  - Color reconnection mode with QCD SU(3) algebra + string-length minimization
  - Junction connection topologies enhance baryon formation

PRL 127 (2021) 202301

PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR-BLC
(JHEP 08 (2015) 003)
Catania
(PLB 821 (2021) 136622)
SHM
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)





- CR allowed between partons from different MPIs to minimize the string length
- Used in Monash tune

- Minimization of string length over all possible configurations
- Enhancement of baryons
- Used in CR mode tunes

Λ_c^+ in comparison with models

- **Catania model**
  - Charm quarks hadronize via fragmentation and coalescence with light quarks in a hot QCD matter
  - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra

PRL 127 (2021) 202301

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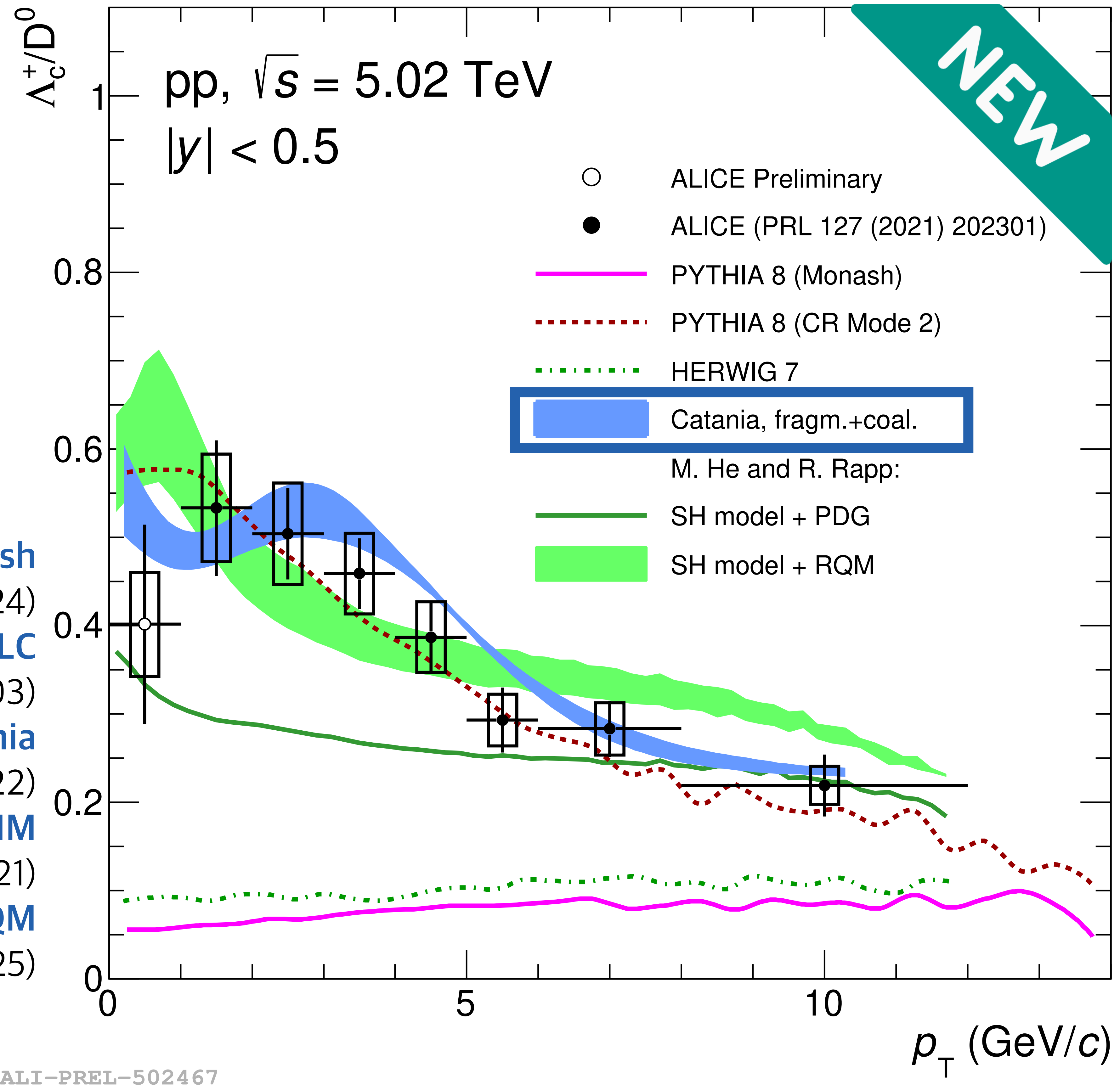
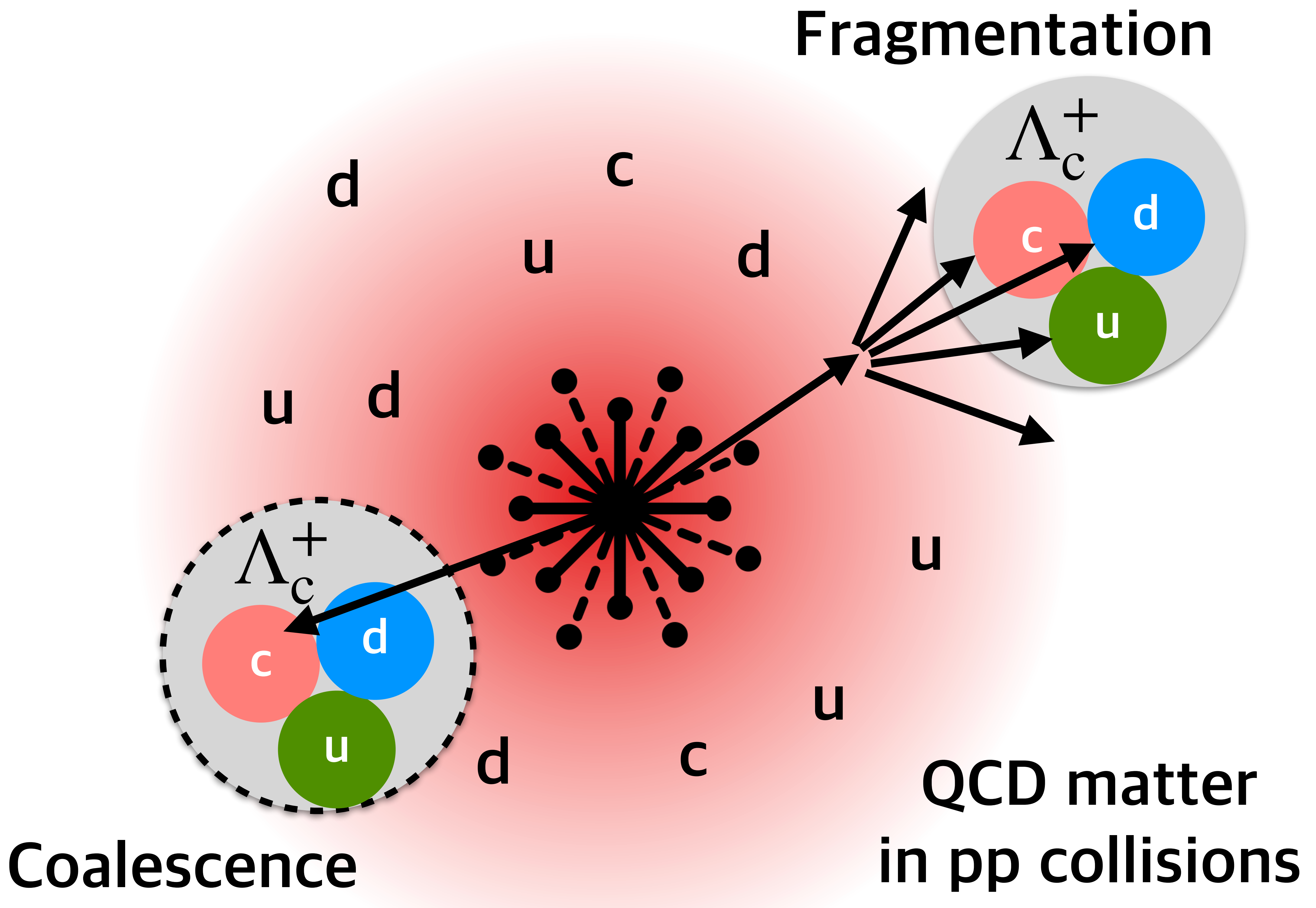
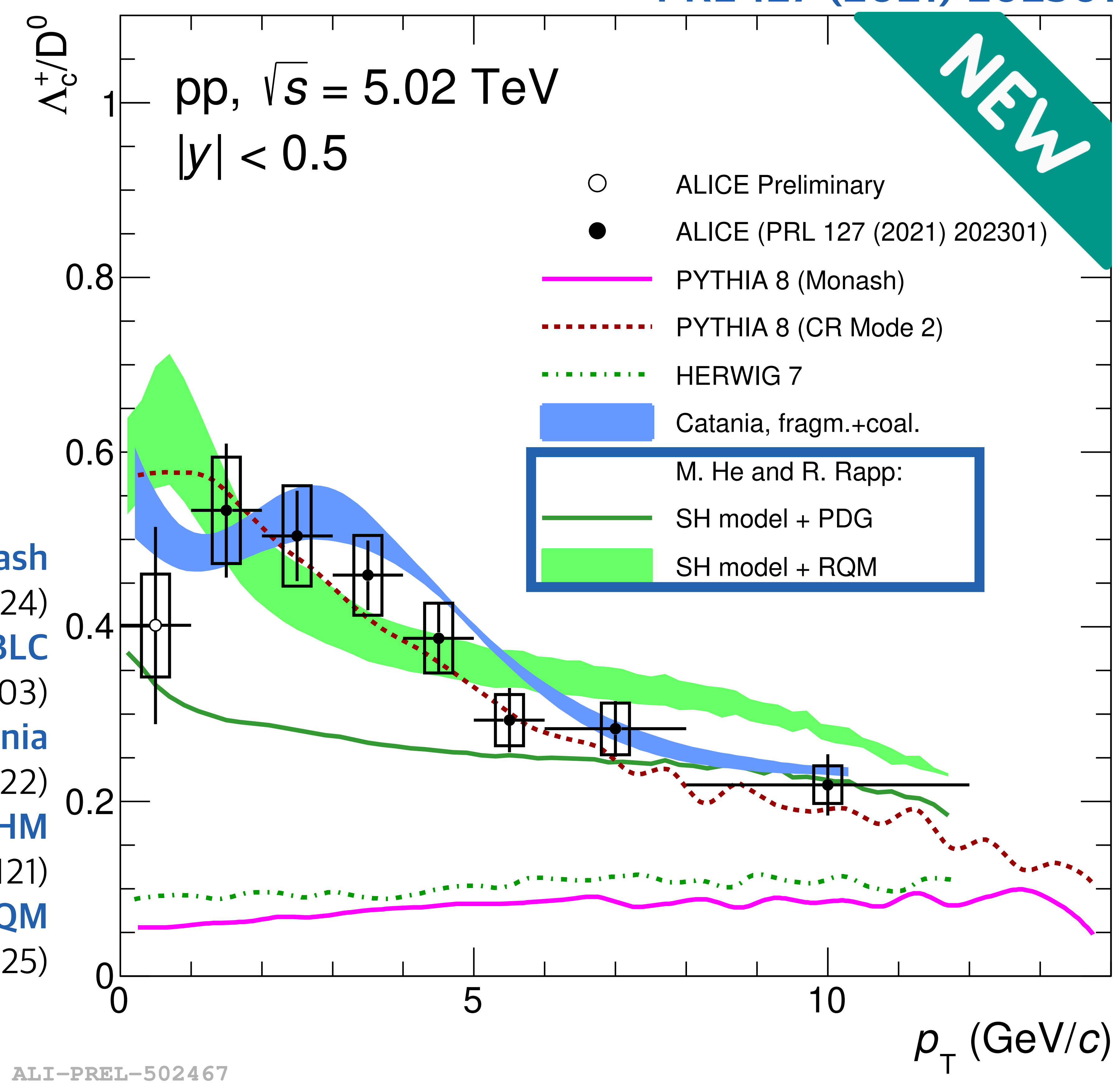




Λ_c^+ in comparison with models

- **Statistical Hadronization Model (SHM) + additional baryon states**
  - Hadronization by statistical weights governed by hadron masses at a hadronization temperature(T_H)
  - Strong feed-down from an augmented set of excited charm baryons

PRL 127 (2021) 202301



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RQM (PRD 84 (2011) 014025)

- **PDG:** 5Λc (I=0), 3Σc (I=1), 8Ξc (I=1/2), 2Ωc (I=0)
- **RQM (Relativistic Quark Model):**
  Additional 18Λc, 42 Σc, 62 Ξc, 34 Ωc (not yet measured)

n_i[10^{-4} fm^{-3}]	D^0	D^+	D^{*+}	D_s^+
PDG(170 MeV)	1.161	0.5908	0.5010	0.3165
RQM(170 MeV)	1.161	0.5908	0.5010	0.3165

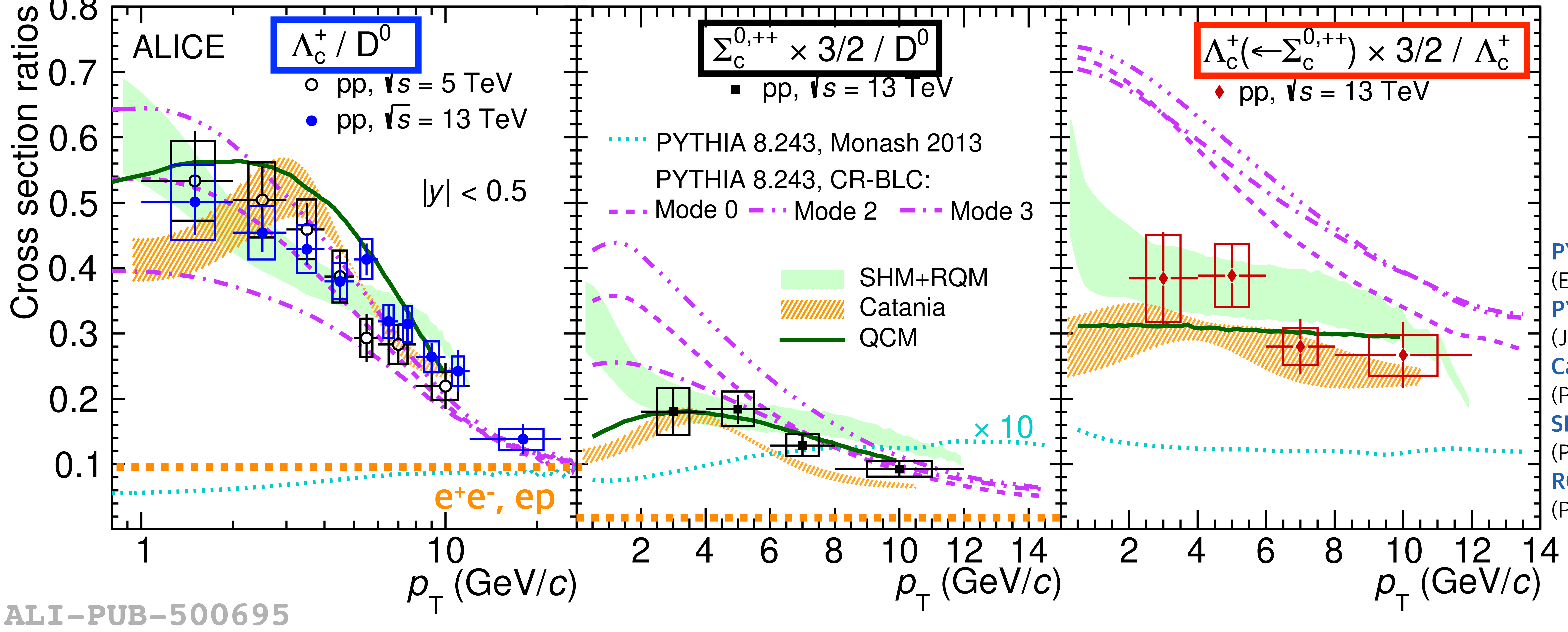
n_i[10^{-4} fm^{-3}]	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
PDG(170 MeV)	**0.3310**	**0.0874**	**0.0064**
RQM(170 MeV)	**0.6613**	**0.1173**	**0.0144**

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

- **Enhancement** in pp collisions than e+e- collisions and PYTHIA 8 Monash
- Well described by **SHM+RQM**, **Catania** and **QCM**
- The **feed-down from** $\Sigma_c^{0,++}$ **partially explains the** Λ_c^+/D^0 **enhancement** in pp collisions

PRL 128 (2022) 012001

$$\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+ = 0.38 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$$



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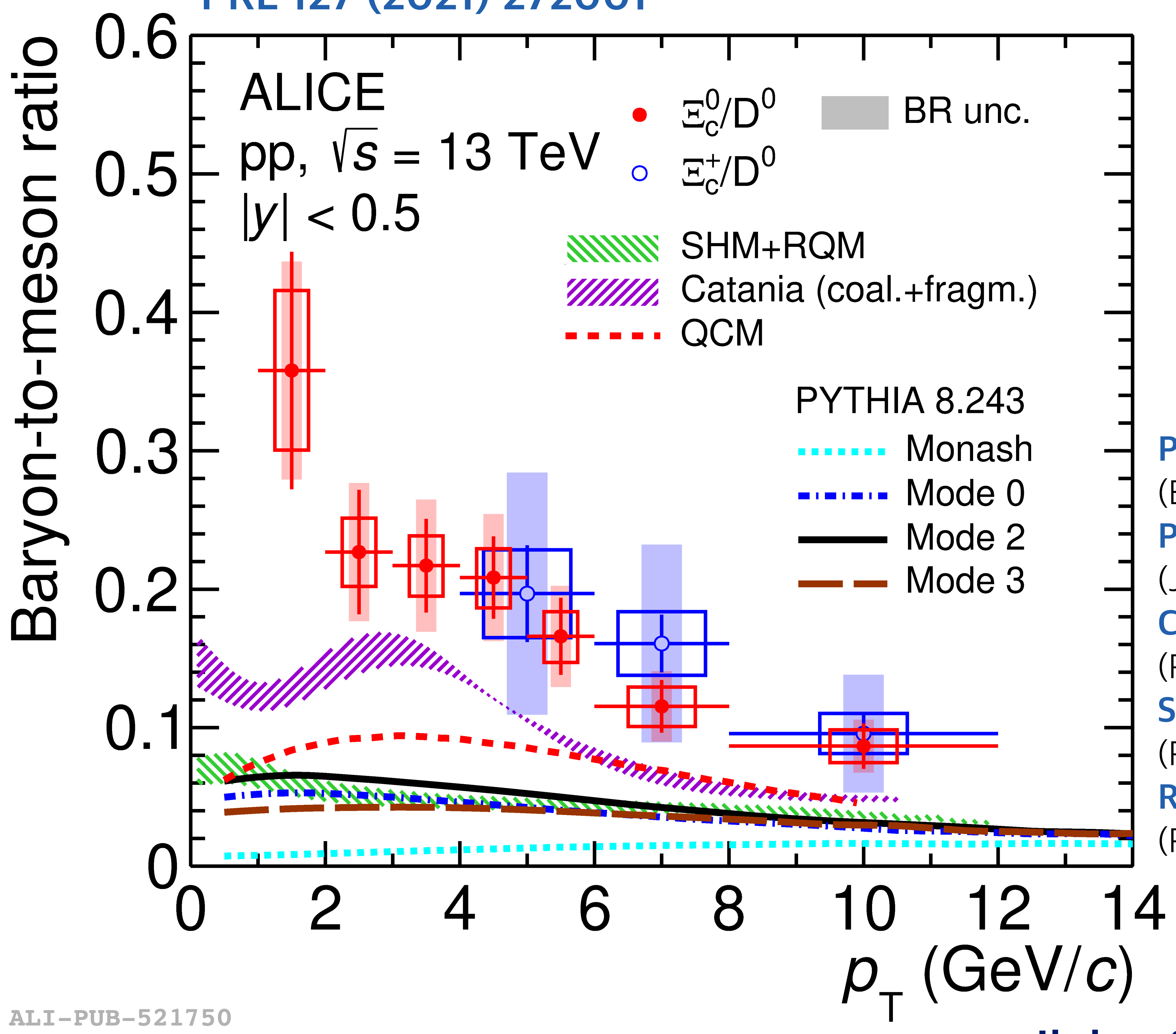
$\Xi_c^{0,+}$ measurements in pp collisions

- Underestimated by PYTHIA 8 Monash, PYTHIA 8 CR tunes, SHM+RQM and QCM
- **Described better** in the measured p_T interval by **Catania**

Ξ_c^0/D^0

Ξ_c^+/D^0

PRL 127 (2021) 272001



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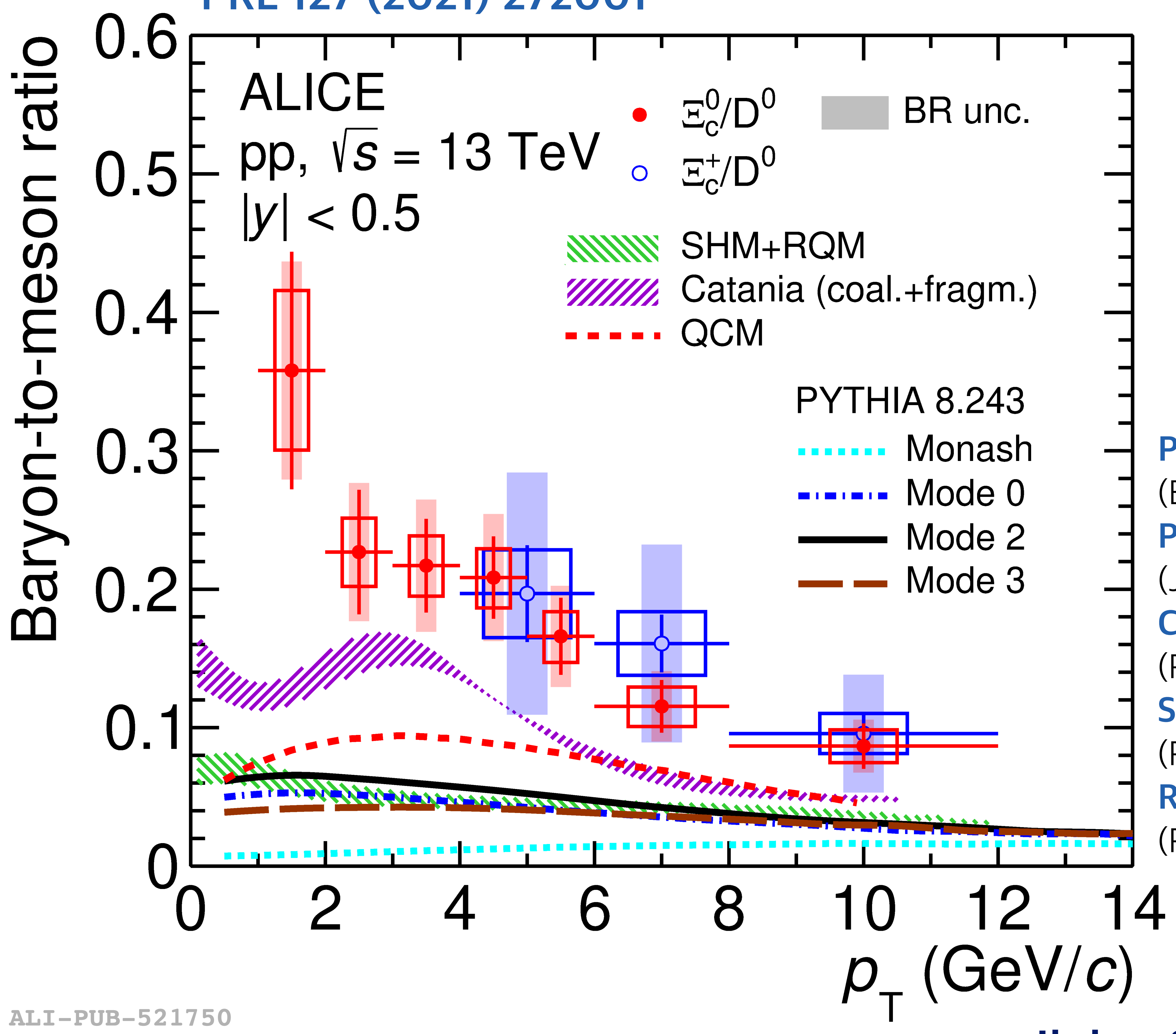
PRL 127 (2021) 272001

Ξ_c^0/D^0
Ξ_c^+/D^0



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- **PYTHIA 8 CR tunes**
  Few strangeness enhancement?
- **SHM + RQM**
  Not enough excited baryon?
- **Catania**
  Coalescence in pp collisions?

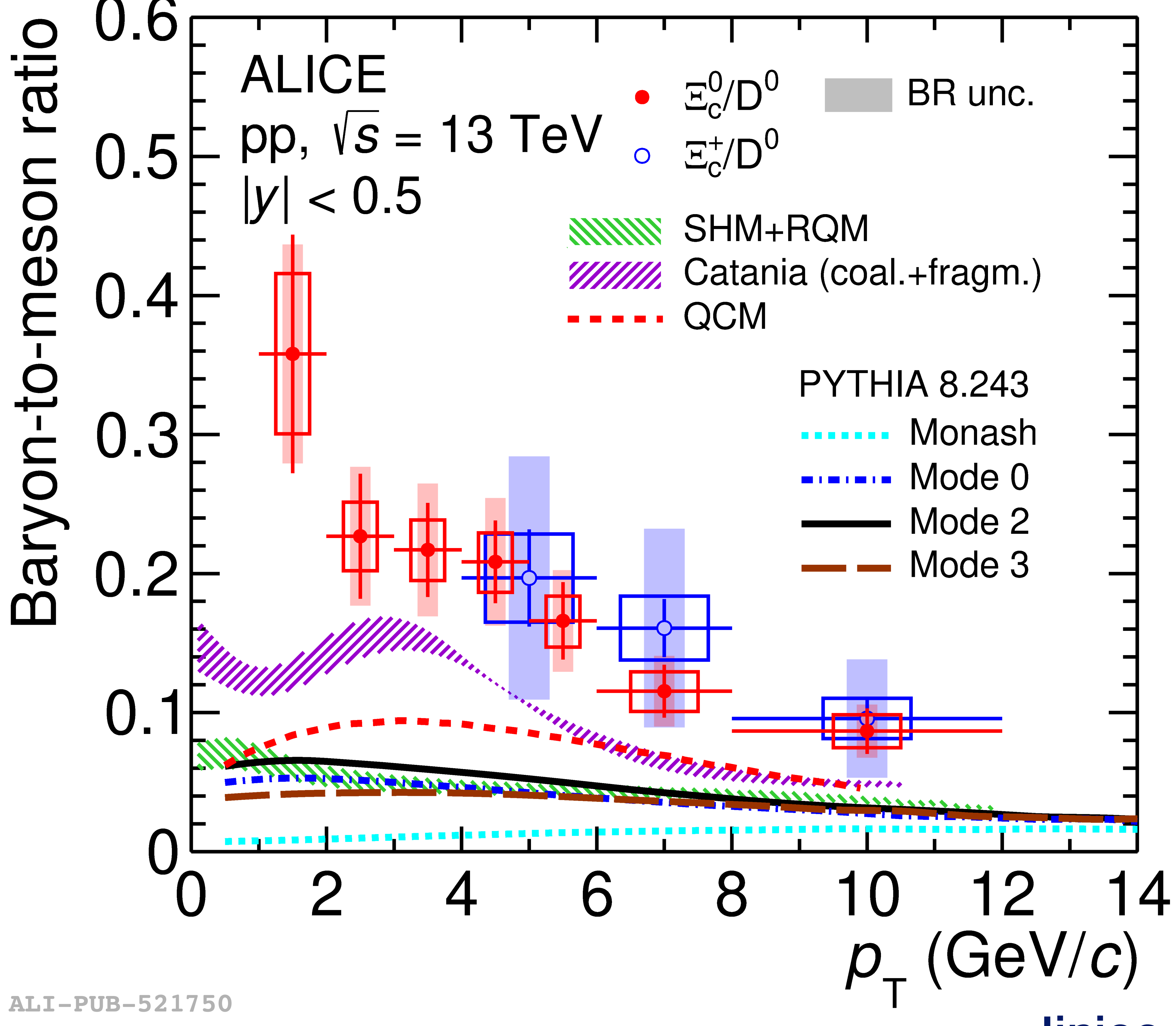
$\Xi_c^{0,+}$ measurements in pp collisions

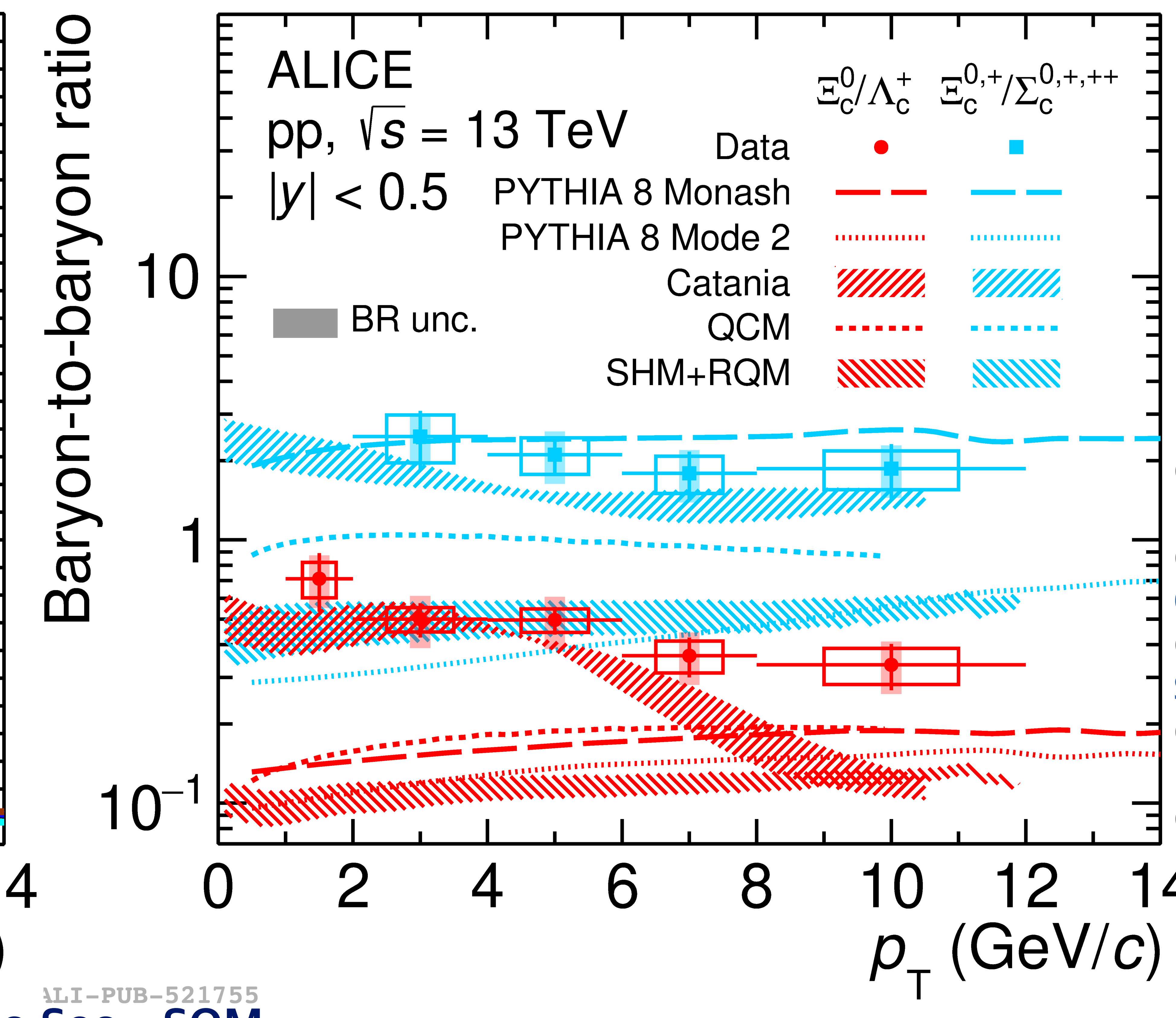
- Underestimated by PYTHIA 8 Monash, PYTHIA 8 CR tunes, SHM+RQM and QCM
- **Described better** in the measured p_T interval by **Catania**
- $\Xi_c^{0,+}/\Sigma_c^{0,++}$ **in agreement with Monash**

PRL 127 (2021) 272001

Ξ_c^0/D^0

Ξ_c^+/D^0





Ξ_c^0/Λ_c^+

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

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

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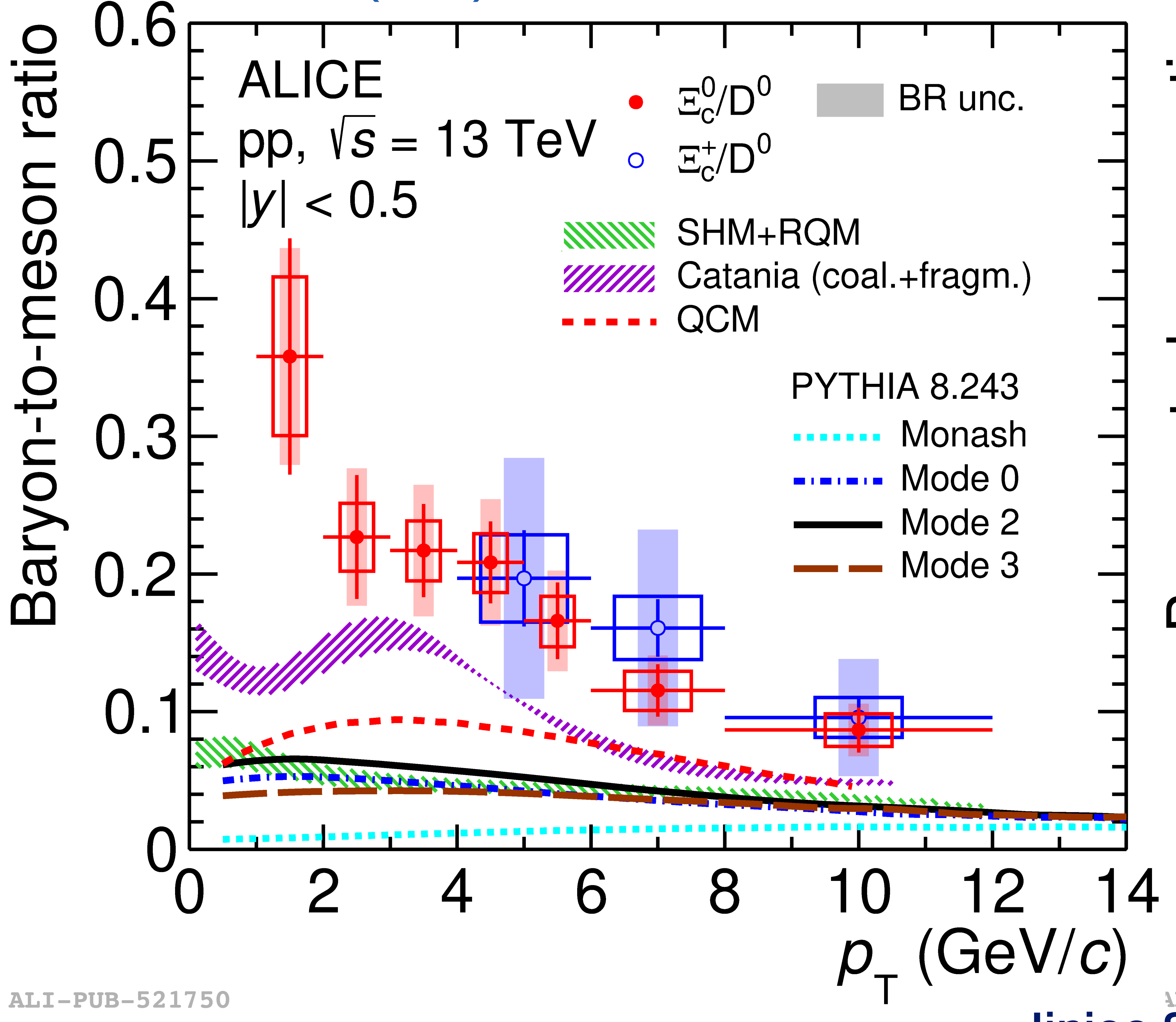
- **Described better** in the measured p_T interval by **Catania**
- $\Xi_c^{0,+}/\Sigma_c^{0,++}$ **in agreement with Monash**

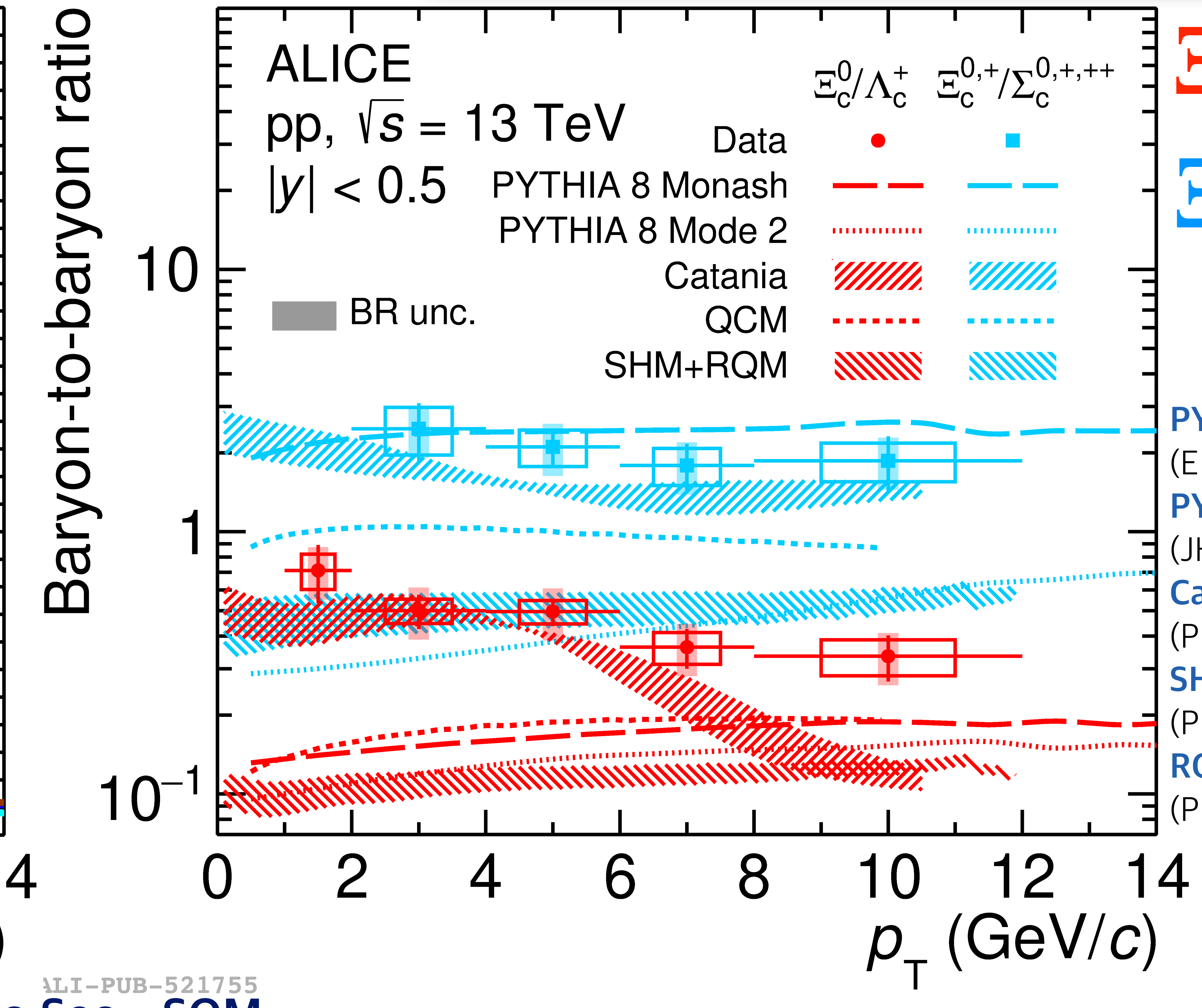
- **Similar suppression** of $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$ in e^+e^- collisions?
- **matter of similar (diquark) mass?** $(m(uu,ud,dd)_1 \sim m(us)_0)$

PRL 127 (2021) 272001

Ξ_c^0/D^0

Ξ_c^+/D^0





Ξ_c^0/Λ_c^+

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

PYTHIA 8 Monash (EPJC 74 (2014) 3024)
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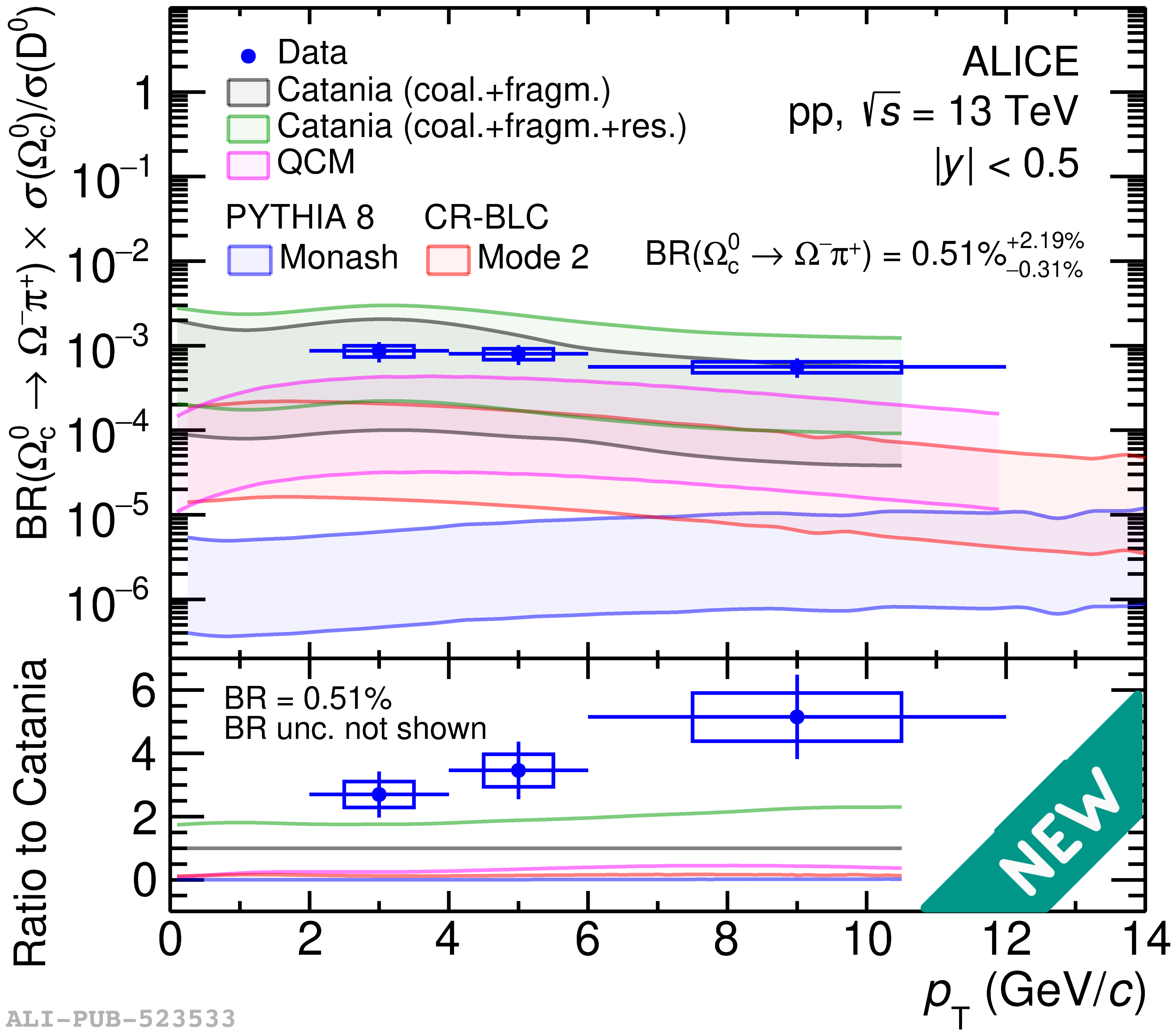
Ω_c^0 measurements in pp collisions

- Only **Catania** gets closer to the measurements considering the **additional resonance states**
  ✓No measurement of $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)$ → A theoretical calculation used to scale the models: $0.51\ \%^{+2.19\%}_{-0.31\%}$

Ratio	ALICE (pp@13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^-@10.52 GeV) visible
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(9.70 \pm 1.27 \pm 0.66) \times 10^{-5}$
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(5.82 \pm 0.78 \pm 1.34) \times 10^{-4}$

arXiv:2205.13993



PYTHIA 8 Monash
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PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
QCM
(EPJC 78 no.4, (2018) 344)
Catania
(PLB 821 (2021) 136622)
Branching ratio of Ω_c^0
(EPJC 80, 1066 (2002))

ALI-PUB-523533

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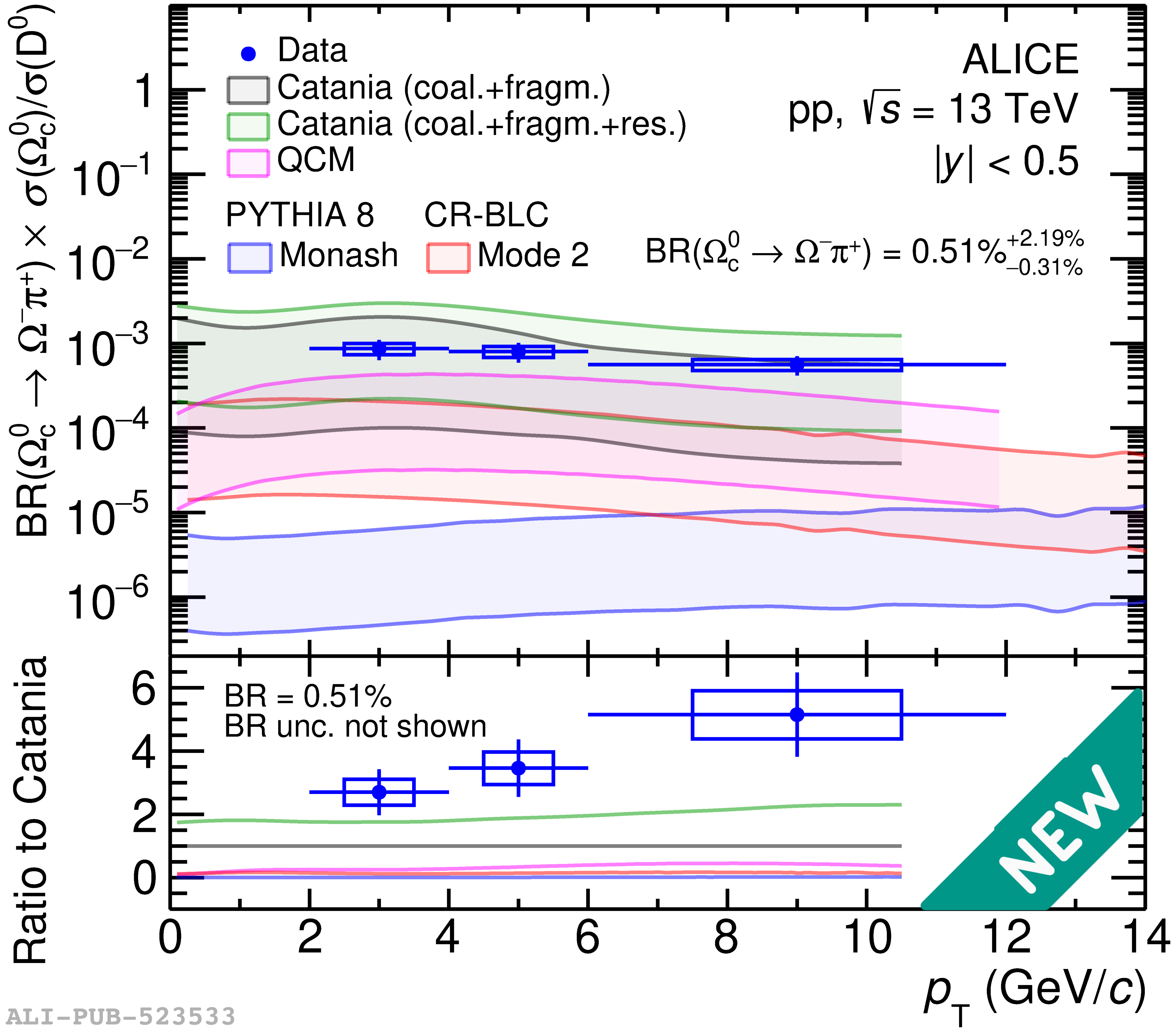
Sizeable contribution of Ω_c^0
to charm production at **LHC energies?**

arXiv:2205.13993



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Sizeable contribution of Ω_c^0
to charm production at **LHC energies?**

Charm baryon with strangeness
are mostly **underestimated**
by model that describe Λ_c^+/D^0 yield ratio

arXiv:2205.13993

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(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
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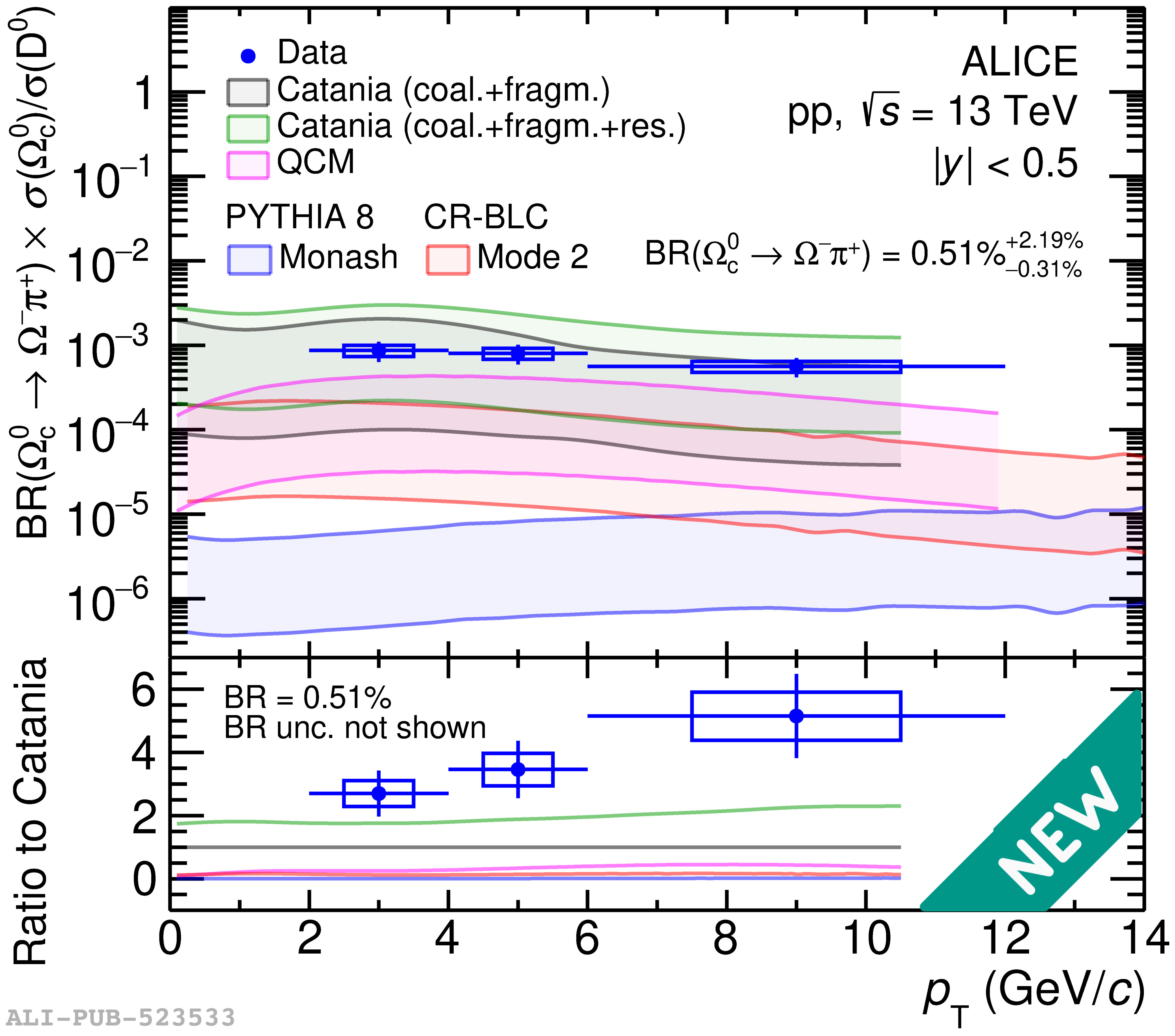


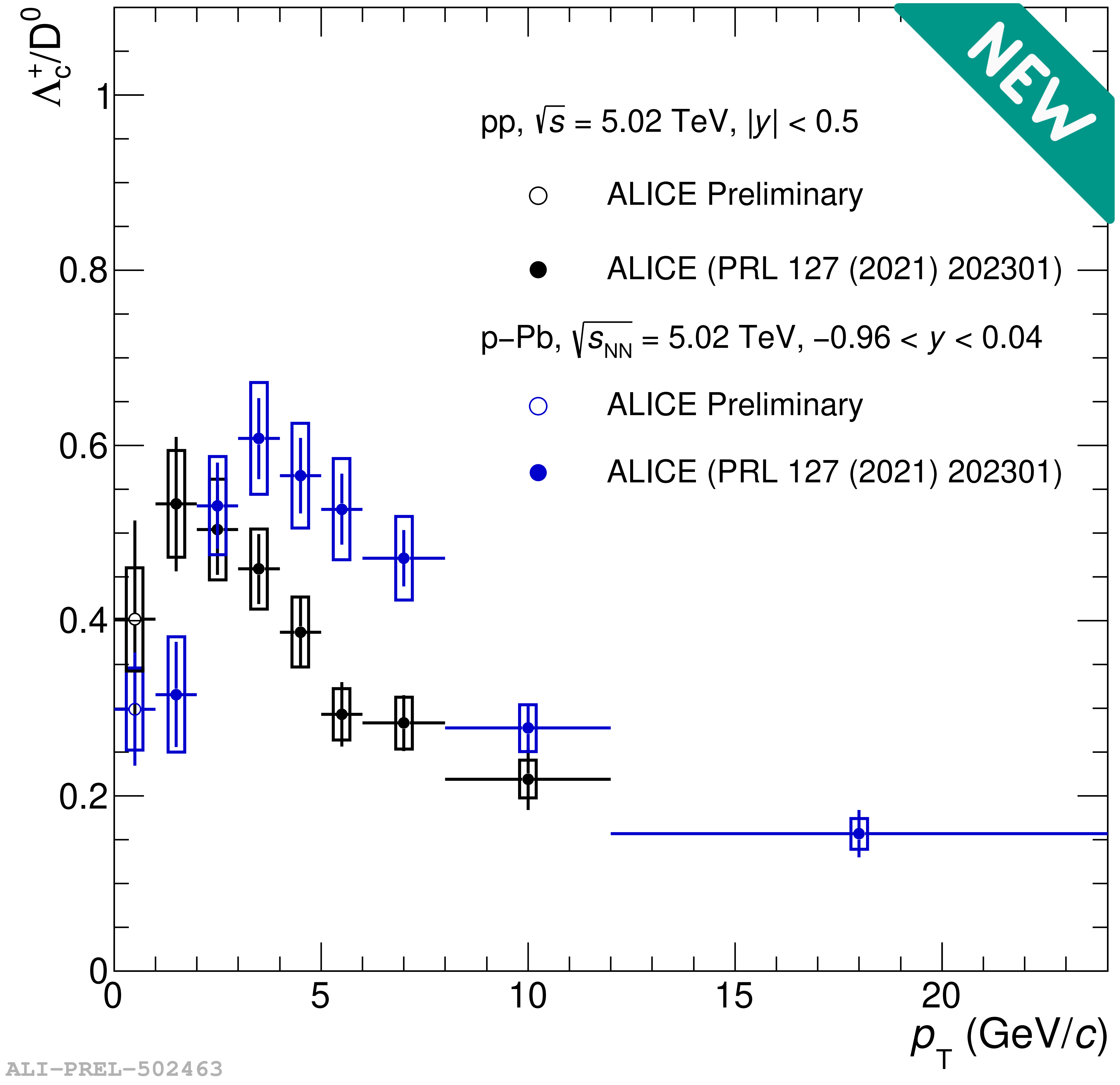
Λ_c^+ measurements in p-Pb collisions

- **Larger in p_T > 3 GeV/c** and **lower in p_T < 2 GeV/c** in **p–Pb** collisions than in pp collisions

- **Compatible p_T-integrated Λ_c^+/D^0 ratio** in pp and p–Pb collisions within uncertainties

M. Volkl
14 Jun 2022, 11:50

PRL 127 (2021) 202301

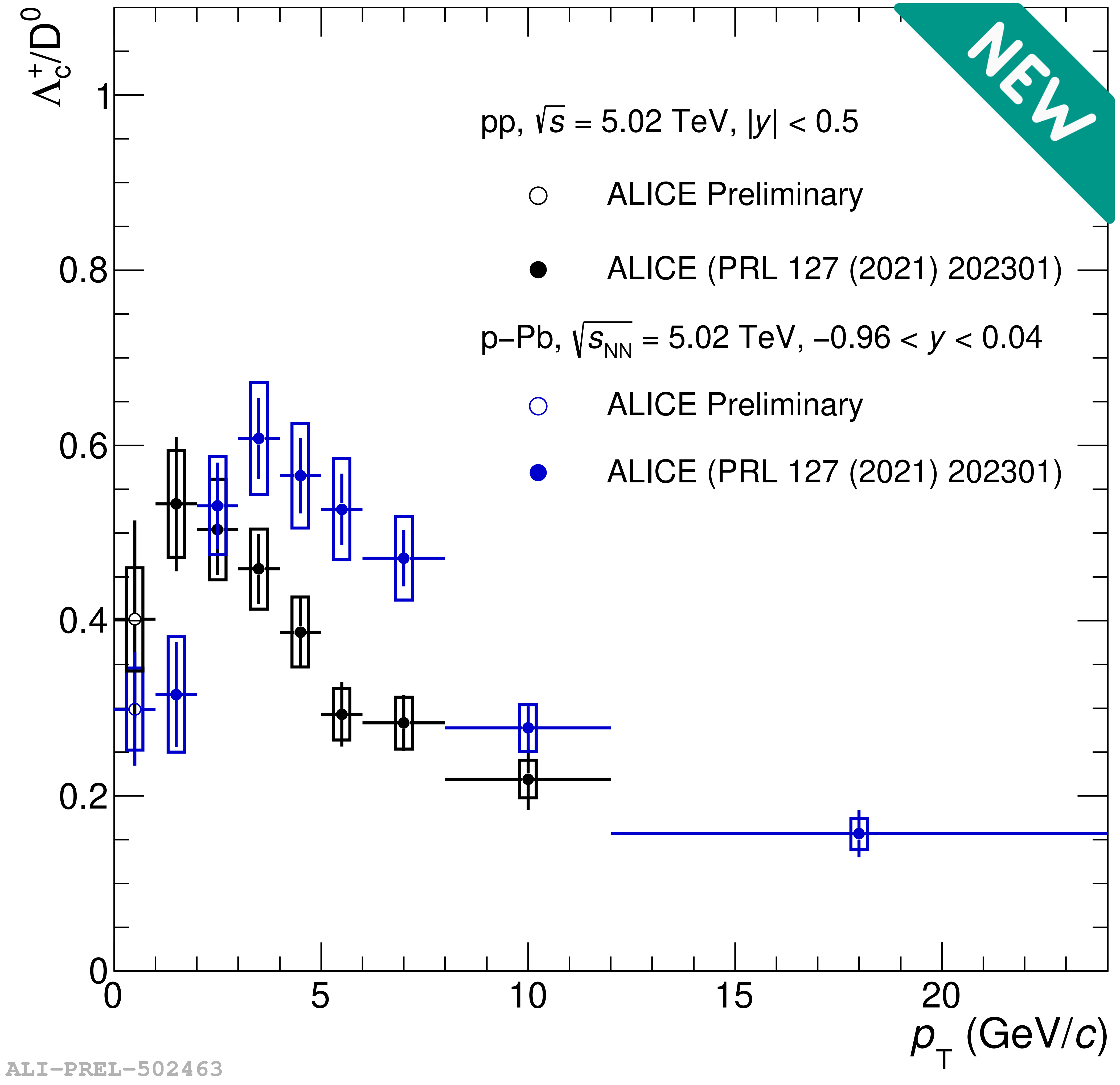


Λ_c^+ measurements in p-Pb collisions

- **Larger in p_T > 3 GeV/*c*** and **lower in p_T < 2 GeV/*c*** in **p–Pb** collisions than in pp collisions
  - **Radial flow?**
  - **Different hadronization mechanism?**
- **Compatible p_T-integrated Λ_c^+/D^0 ratio** in pp and p–Pb collisions within uncertainties

M. Volkl
14 Jun 2022, 11:50

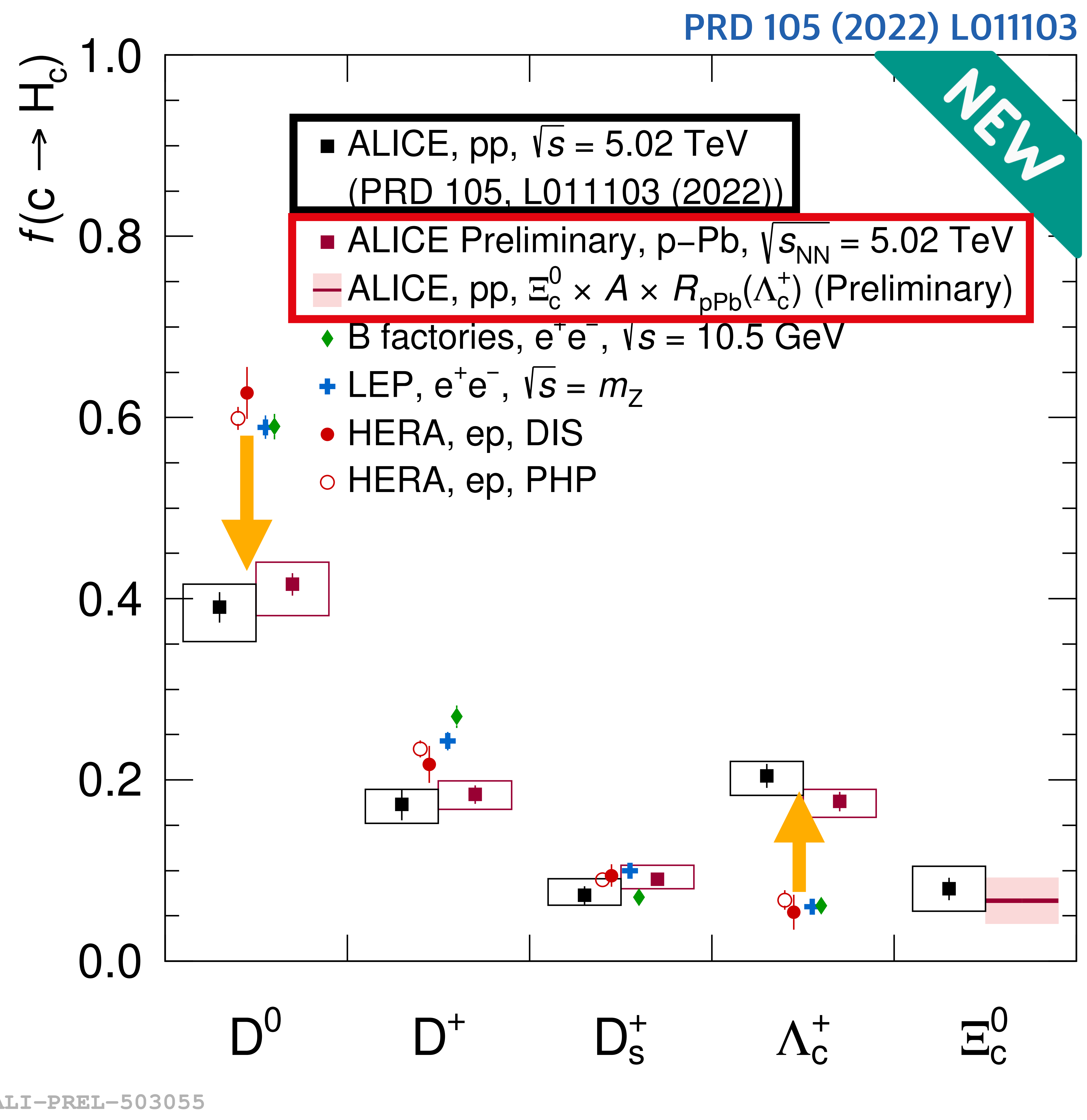
PRL 127 (2021) 202301



Charm fragmentation fractions

- **pp:** Phys. Rev. D 105, L011103 (2022)
- **p-Pb**:
  - D^0, Λ_c^+(new): measured down to $p_T = 0$
  - D^+, D_s^+: extrapolated to $p_T = 0$ using POWHEG+PYTHIA
  - Ξ_c^0: not measured yet
    → $\sigma_{pp}(\Xi_c^0) \times 208 \times R_{pPb}(\Lambda_c^+)$

- pp and p-Pb results are **compatible**
- **Significant baryon enhancement** with respect to e+e- and e-p collisions



B factories
(EPJC 76 no.7, (2016) 397)
LEP
(EPJC 77 no.1, (2015) 19)
HERA
(EPJC 76 no.7, (2016) 397)

Charm fragmentation fractions

- **Charm production cross section** at midrapidity in pp collisions at √s = 5.02 TeV including all the charm hadron ground states

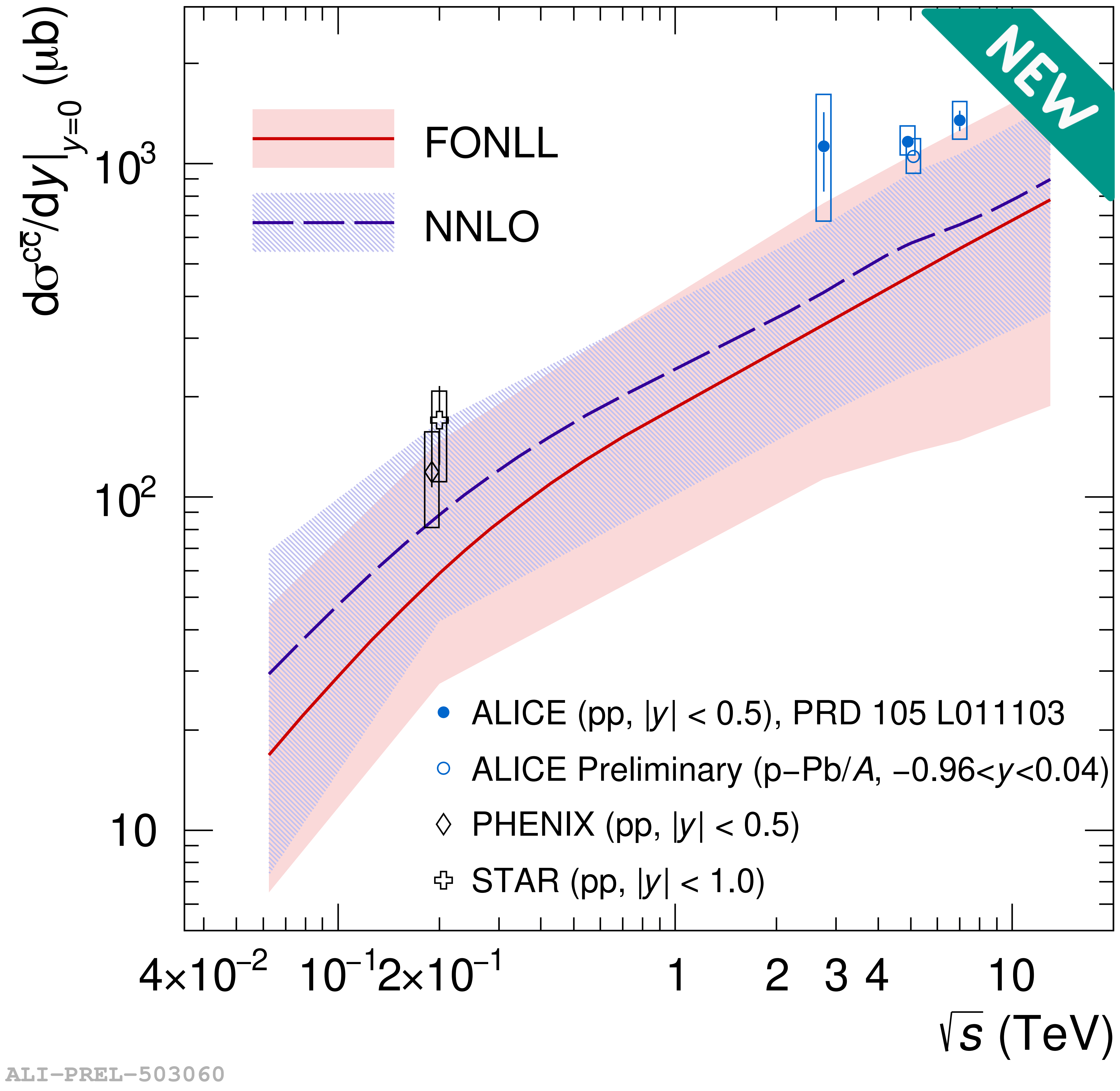
$$d\sigma^{c\bar{c}}/dy\,|_{|y|<0.5} = 1165 \pm 44(\text{stat})^{+134}_{-101}(\text{syst})\,\mu\text{b}$$

- **Charm production cross section** in p-Pb collisions at √s = 5.02 TeV

$$d\sigma^{c\bar{c}}/dy\,|_{-0.96<y<-0.04} = 1057.5 \pm 28.6(\text{stat})^{+103.6}_{-76}(\text{syst})\,\mu\text{b}$$

- Updated charm production cross section lie at the **upper edge of the pQCD calculations**

PRD 105 (2022) L011103



STAR
(PRD 86 (2012) 072013)
PHENIX
(PRC 84 (2001) 044905)
FONLL
(JHEP 10 (2012) 137)
NNLO
(PRL 118 (2017) 12, 122001)

Summary

Medium? Z, Q^2?

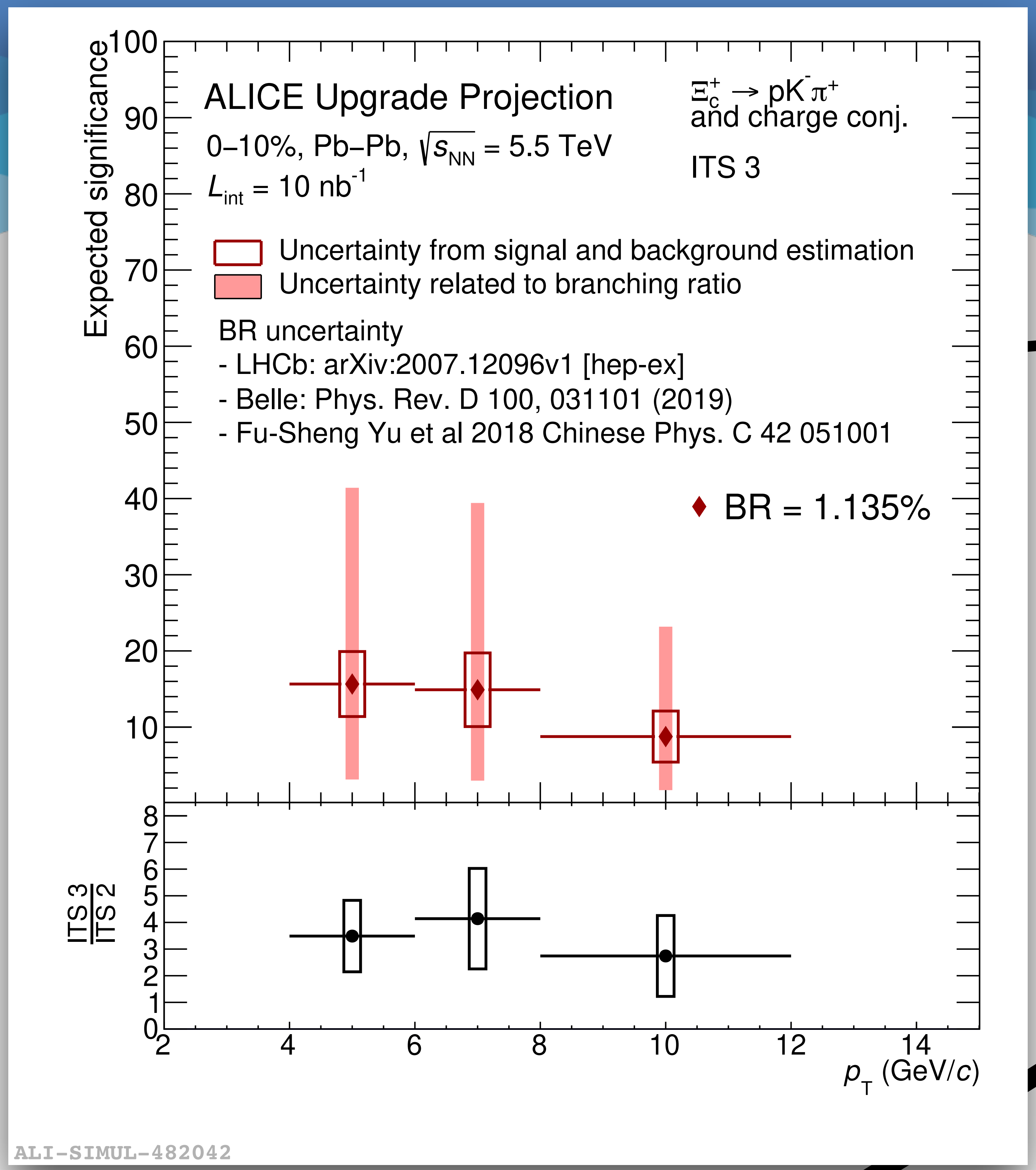
$$\frac{d\sigma^{\rm D}}{dp_{\rm T}^{\rm D}}(p_{\rm T};\mu_{\rm R};\mu_{\rm F}) = PDF(x_1,Q^2)PDF(x_2,Q^2) \otimes \frac{d\sigma^{\rm c}}{dp_{\rm T}^{\rm c}}(x_1,x_2,Q^2) \otimes D_{{\rm c}\rightarrow{\rm h}}(z = p_{\rm h}/p_c, Q^2)$$

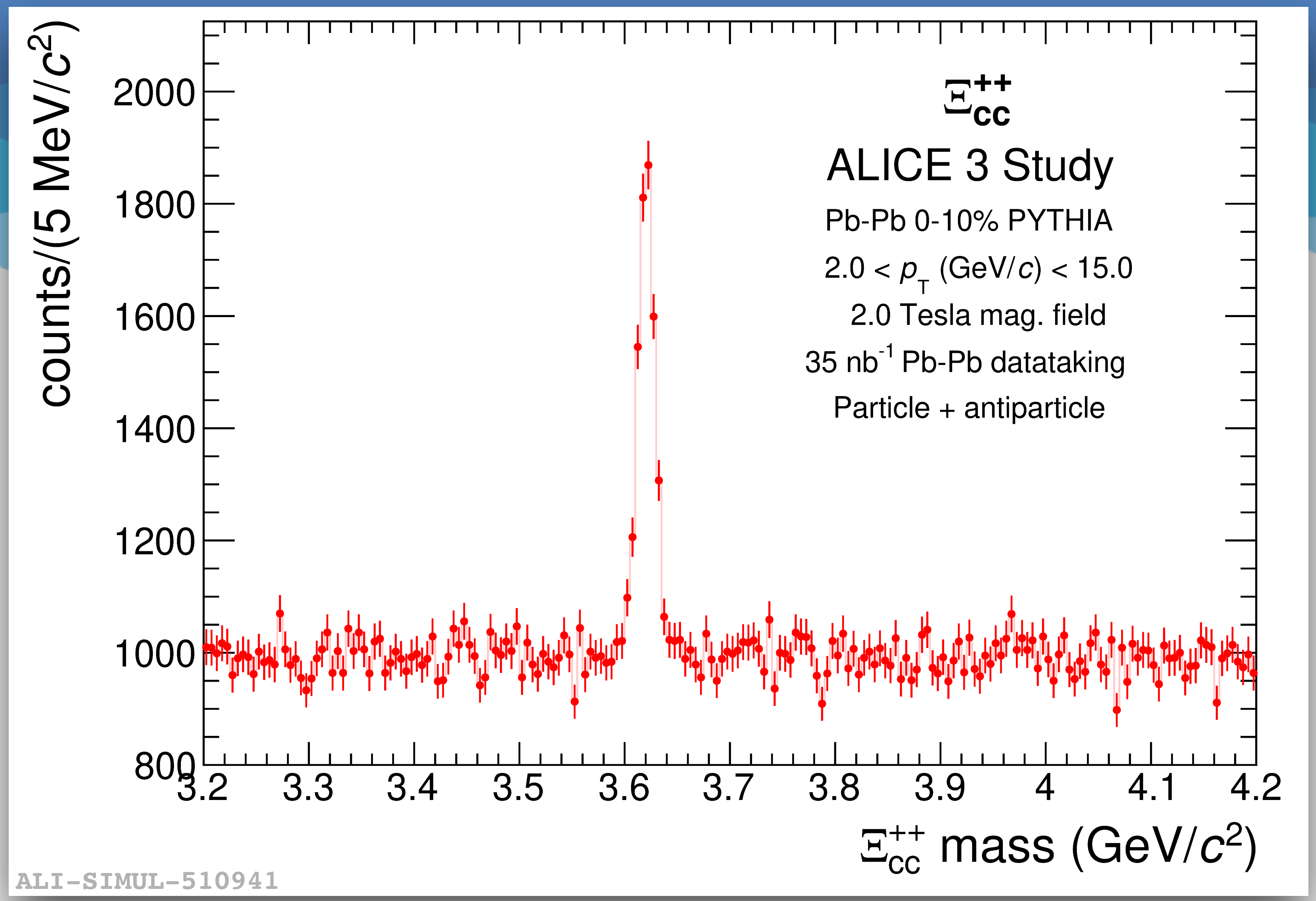
Parton distribution function | Hard scattering cross section | Fragmentation function

- **ALICE measured all of single-charm hadron ground states.**
- Λ_c^+ **was measured down to p_T = 0 GeV/*c* in pp and p-Pb collisions at 5.02 TeV.**
- **Large enhancement of all charm-baryon production in pp collisions w.r.t e^+e^- collisions.**
- **None of the models describes the enhancement of all charm baryons.**
- **The charm fragmentation fractions are not universal.**

➡How can we provide stronger and more differential constraints on hadronization?

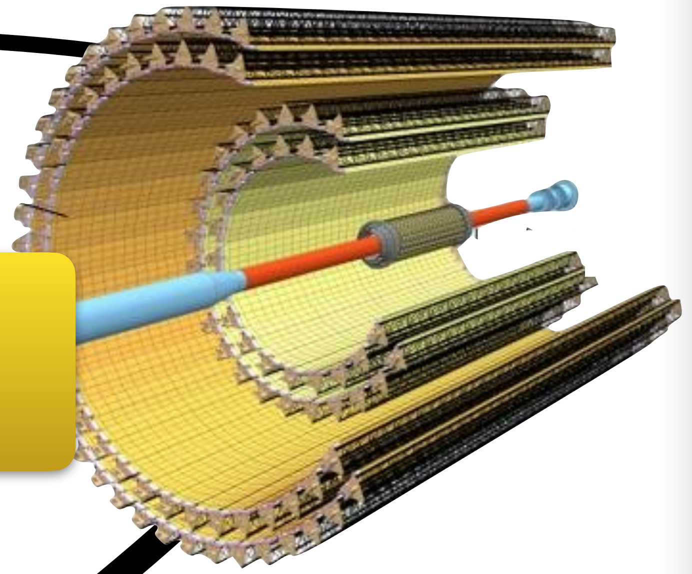
Outlook





2022

ALICE 2
(+ ITS2 & ⋯)



2026

2029

ALICE 2.1
(+ ITS3 & FoCal)

D. Kim
14 Jun 2022, 17:10

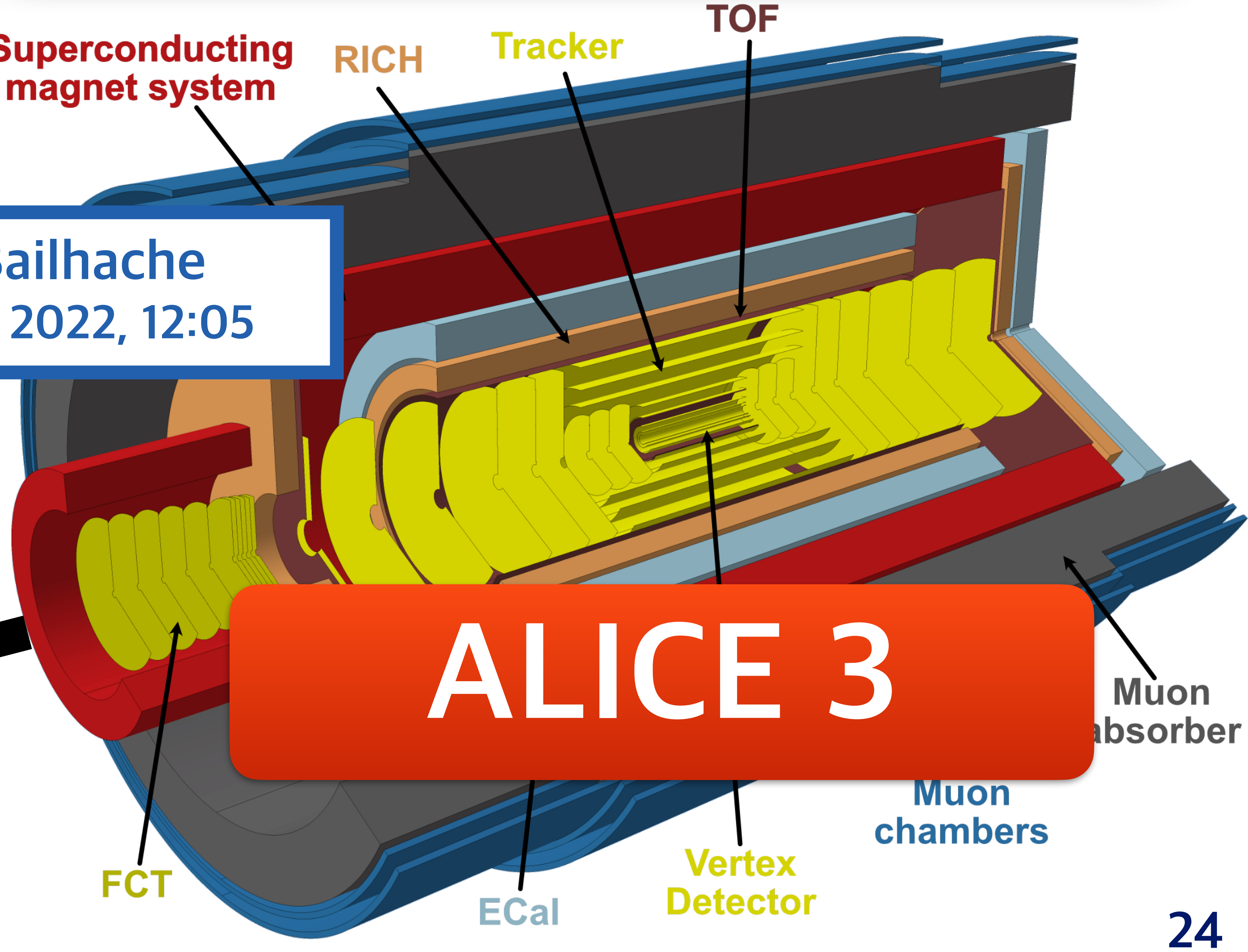
A. Yuncu
15 Jun 2022, 08:40

R. Bailhache
16 Jun 2022, 12:05

2033

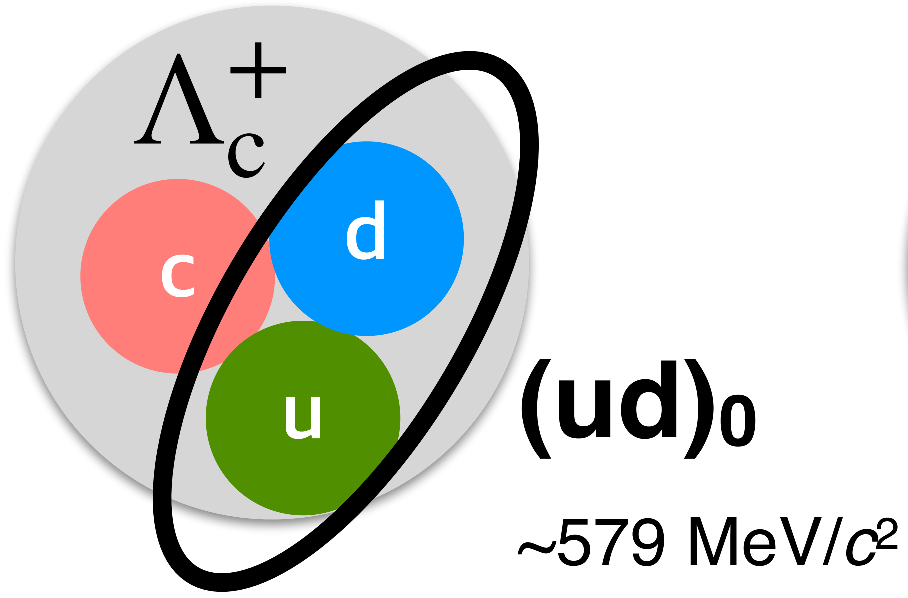
2035

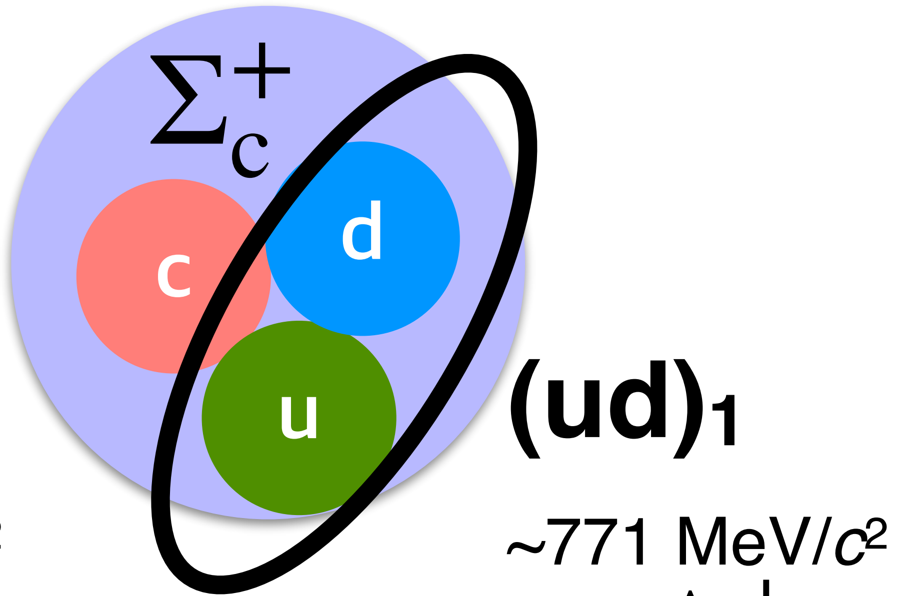
ALICE 3



BACK UP

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





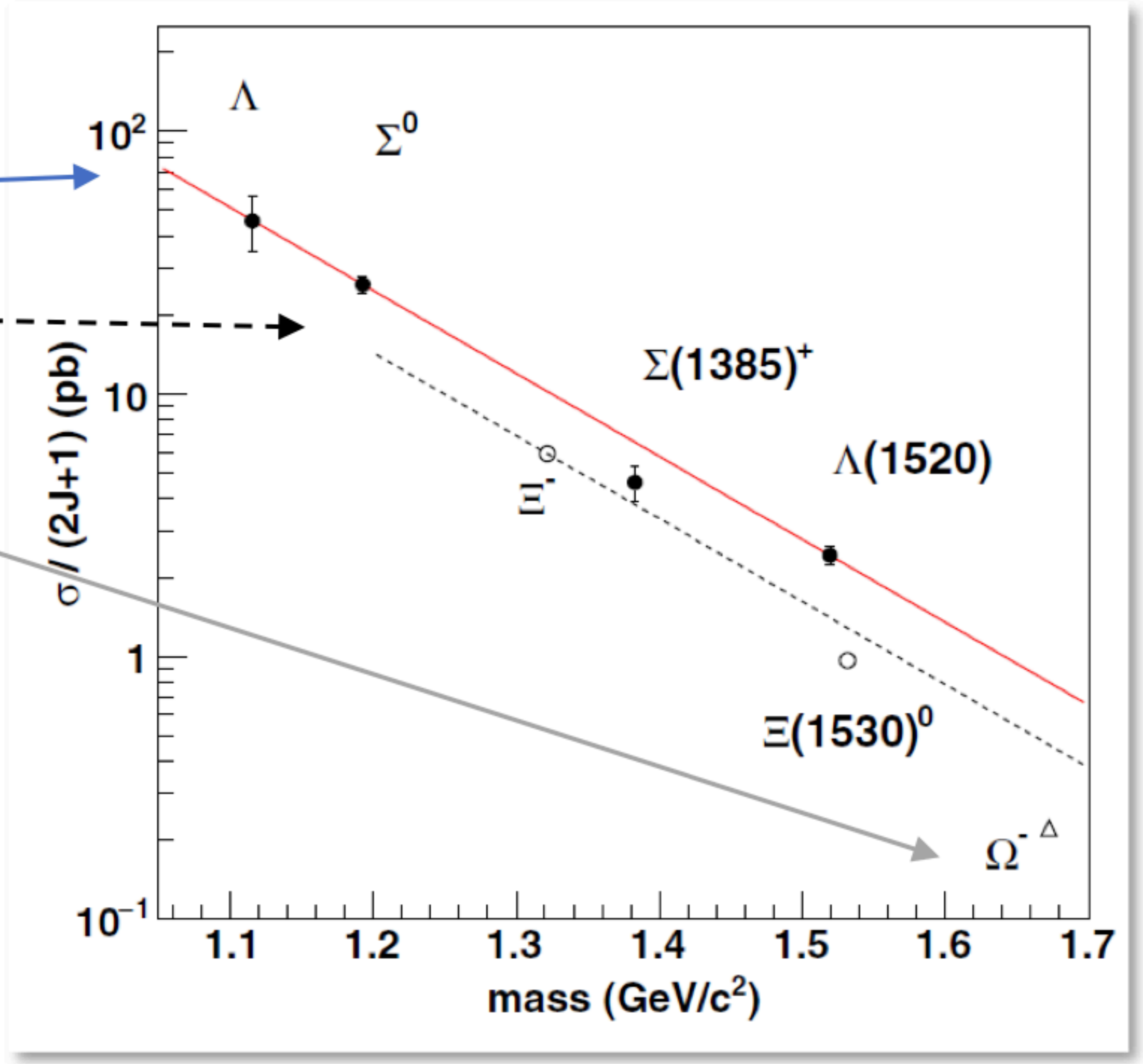
- In conventional fragmentation
  - Charm picks up a spin-0 $(ud)_0$ diquark -> Λ_c^+ ($I = 0$)
  - Charm picks up a spin-1 $(ud)_1$ diquark -> Σ_c^+ ($I = 1$)
- $(ud)_1$ mass much lager than $(ud)_0$ → production of Σ_c^+ states expected to be suppressed compared to Λ_c^+

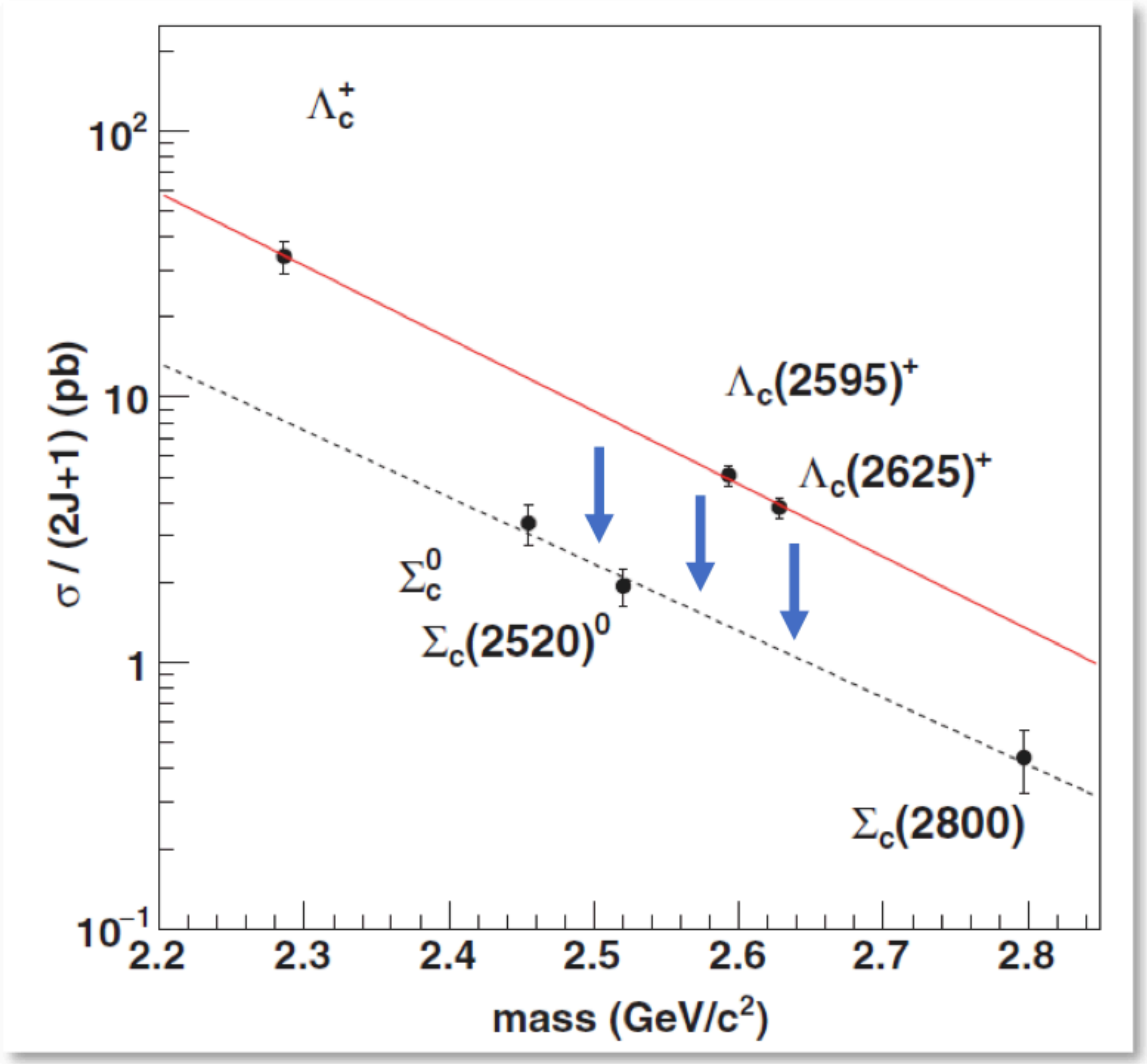
$f(m) = a_0 \exp(a_1 m)$

S = -1

S = -2

S = -3

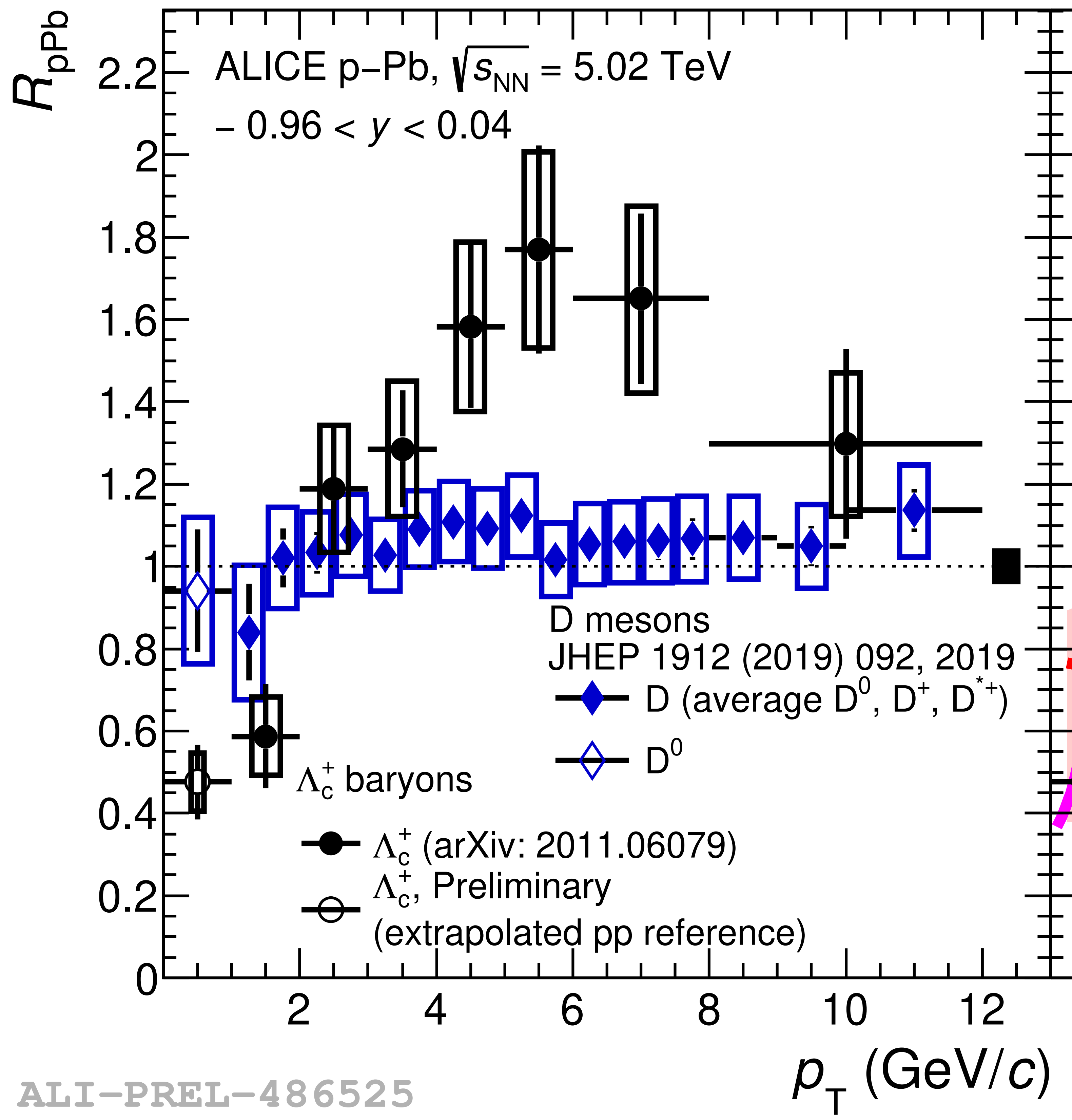


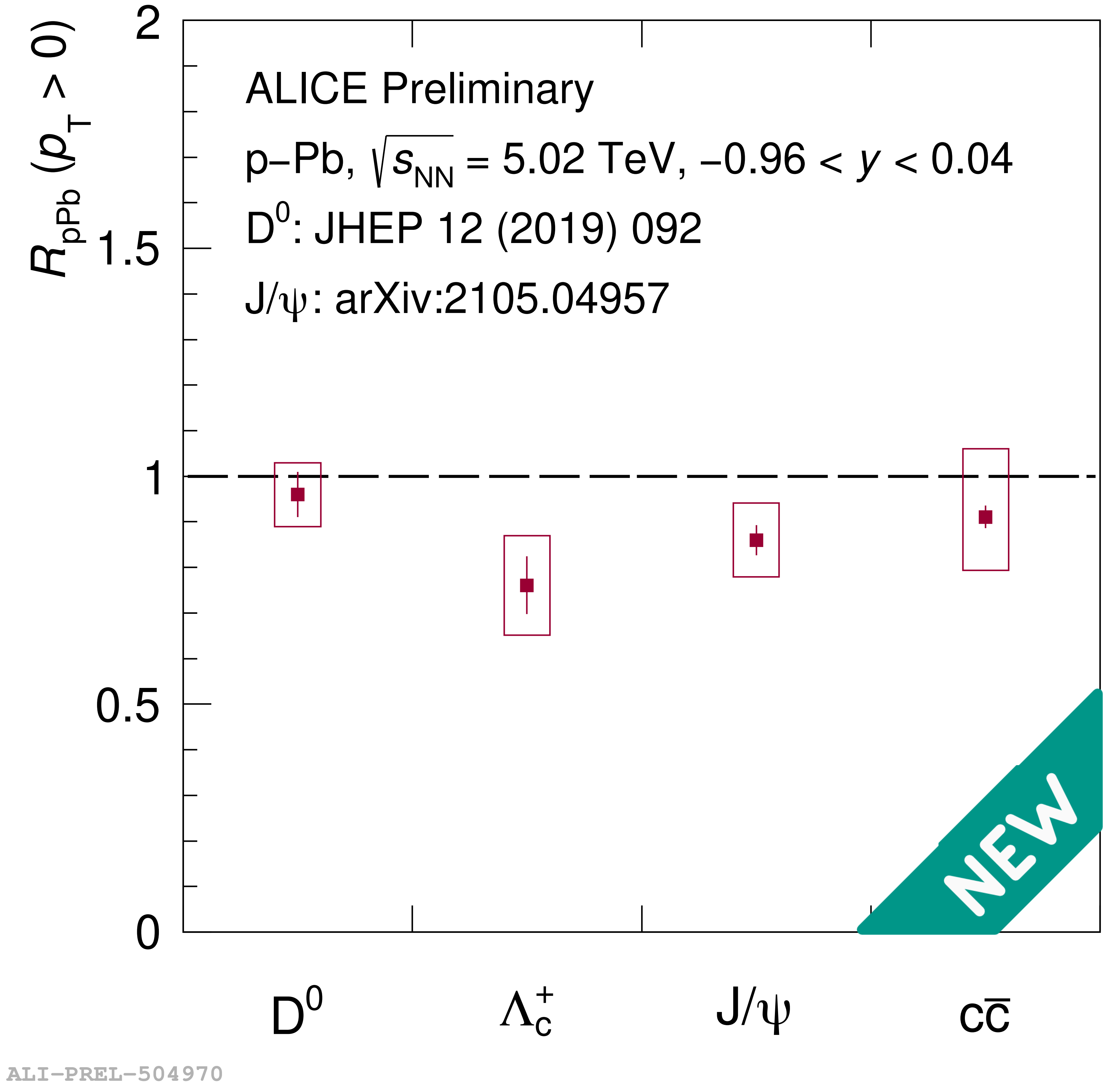


Hierarchy driven by $s\bar{s}$ pair creation

Λ_c^+ measurements in p-Pb collisions

- **POWHEG+PYTHIA6** : CNM effect + PYTHIA 6 Parton shower + EPPS16 parameterization for PDFs.
- **POWLANG** : Hot deconfined medium in p-Pb collisions.
  - Describe the suppression at low p_T.

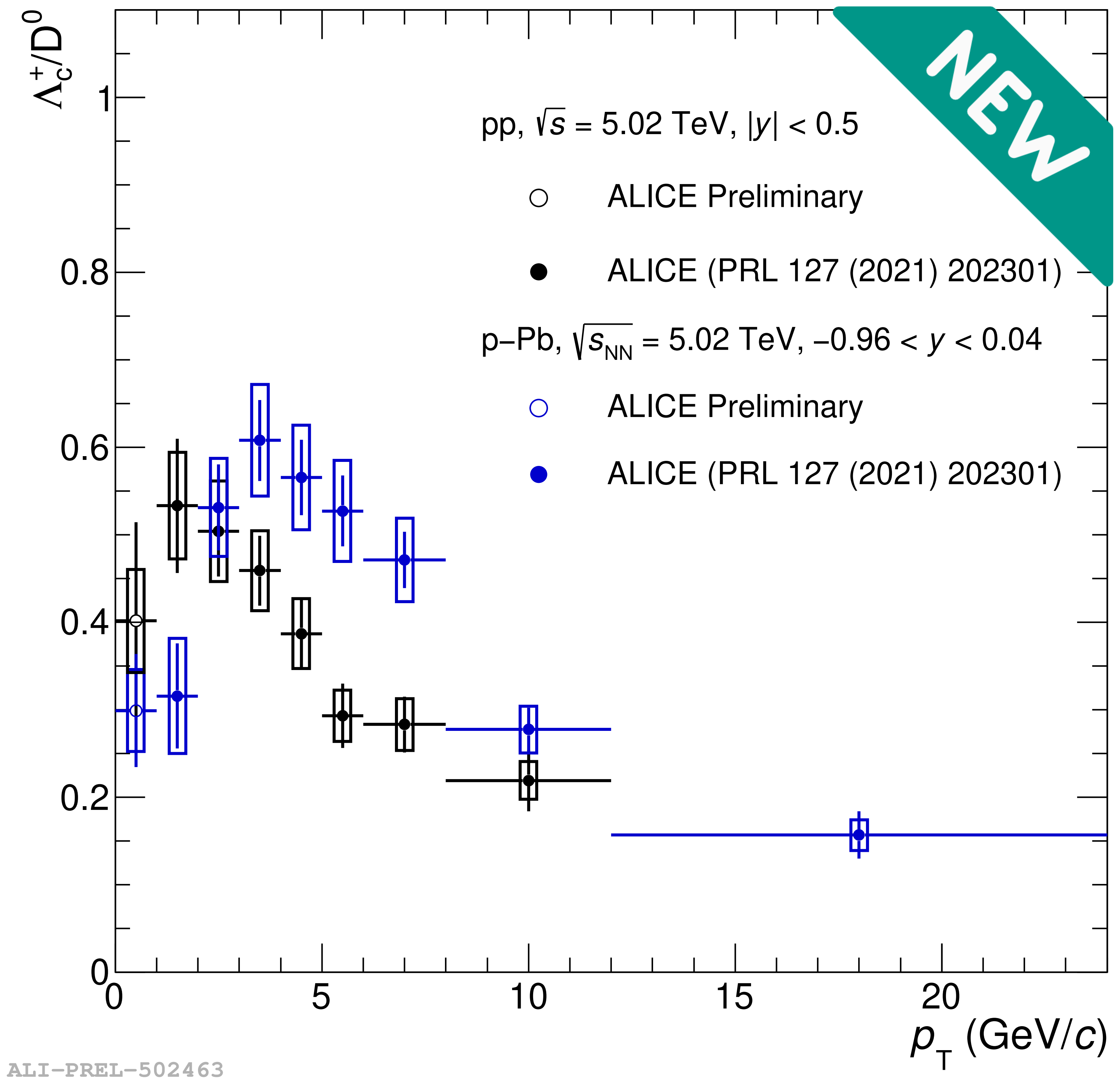


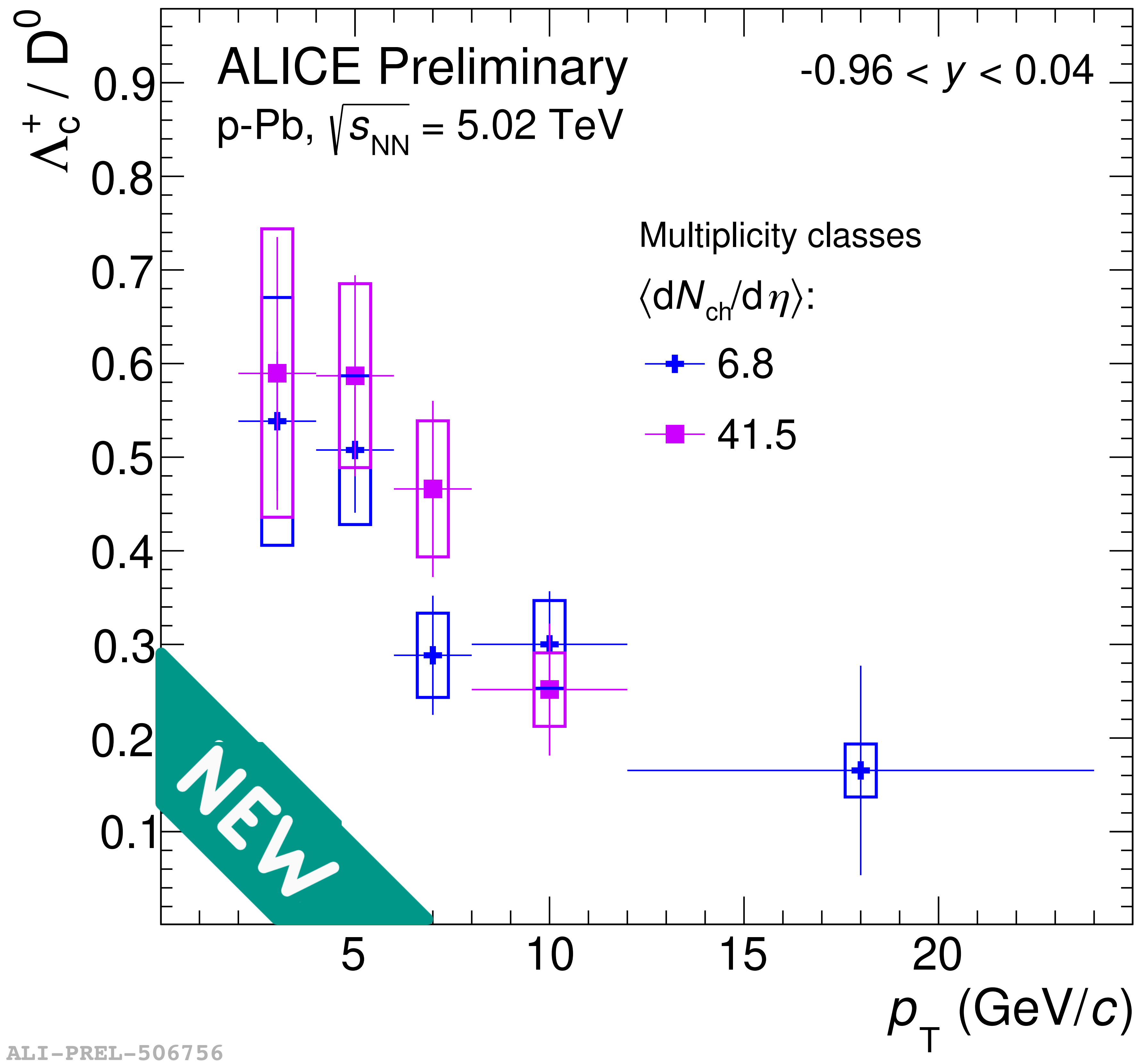


Λ_c^+ measurements in p-Pb collisions

- **Larger in p_T > 8 GeV/*c*** and **lower in p_T < 2 GeV/*c*** in **p-Pb** collisions than in pp collisions
- **Compatible p_T-integrated Λ_c^+/D^0 ratio** in pp and p-Pb collisions within uncertainties
- **Week significant multiplicity dependence** of Λ_c^+/D^0 ratio in p-Pb collisions with current precision

PRL 127 (2021) 202301





Heavy-flavour production

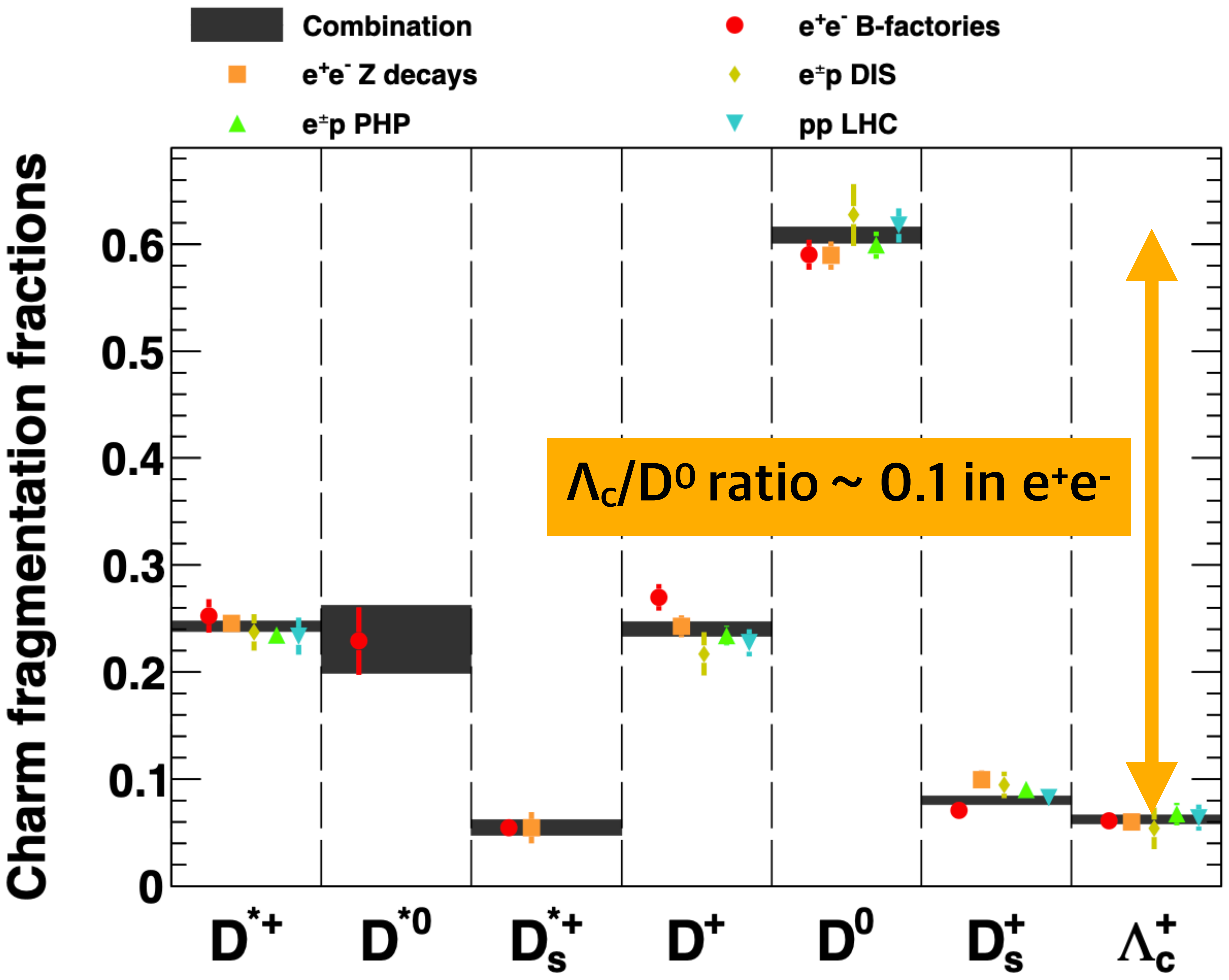
- **Charm fragmentation fraction**

$$f(c \rightarrow H) = \sigma(H)/\Sigma_H \sigma(H)$$

  - Measurements in different collision systems and at different energies agree within uncertainties.
    ➡ Support the hypothesis that fragmentation functions are independent of the collision systems?

- **Caveat**
  - In 2015, only LHCb Λ_c^+ measurement available.
    - Rapidity range : $2.0 < y < 4.5$

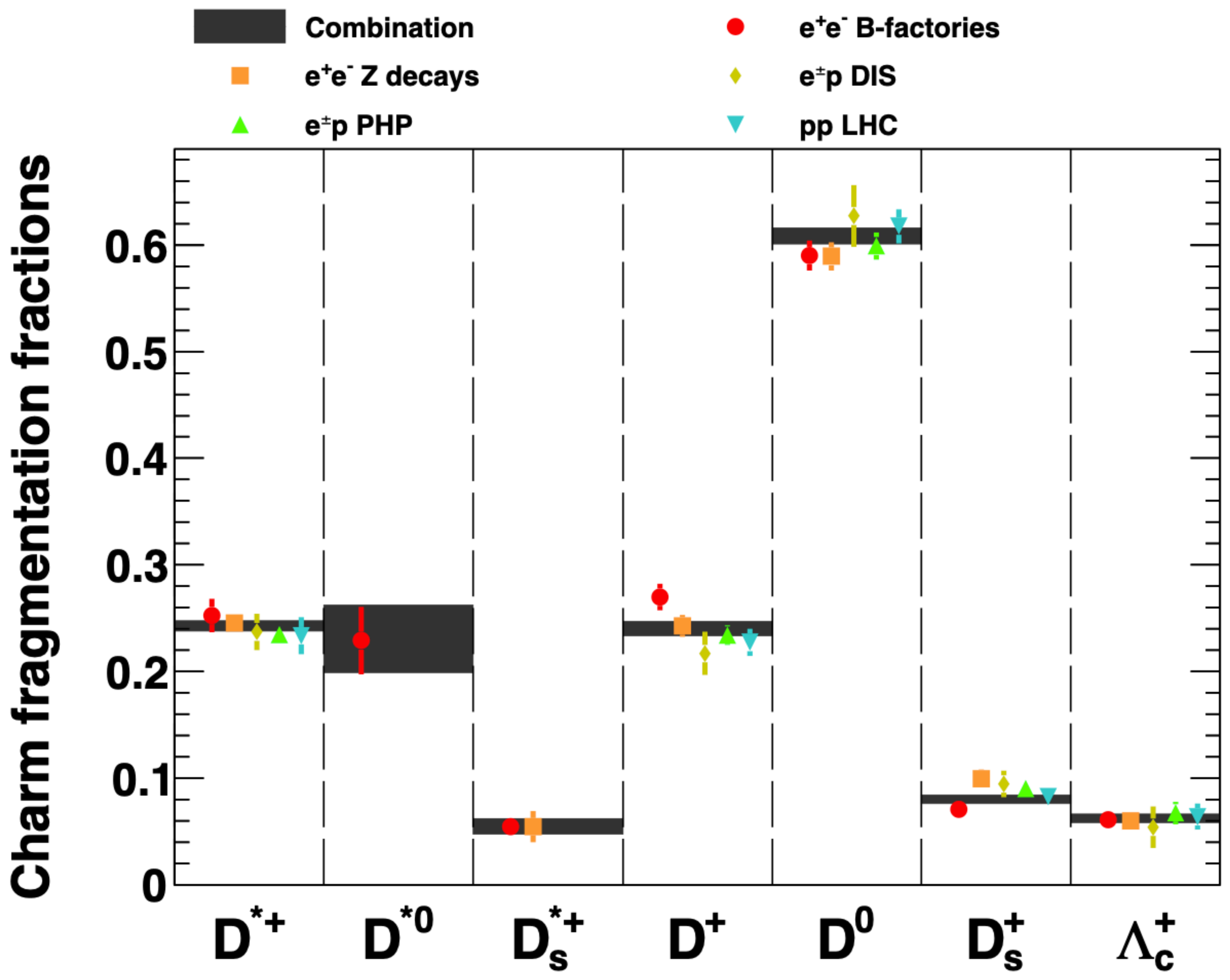
Eur. Phys. J. C76 (2016) no.7, 397



Charm FF in e^+e^- & ep

- **Charm fragmentation fraction**
  - Assumption is needed due to lack of knowledge about production of $\Xi_c^{0,+}$ and Ω_c^0
    - $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(c \to \Xi_c^0)/f(c \to \Lambda_c^+)$
      $= f(s \to \Xi^-)/f(s \to \Lambda) = 0.066$
    - $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+) = f(s \to \Omega^-)/f(s \to \Lambda) = 0.004$
    - $f(c \to \Omega_c^0)/f(c \to \Xi_c^0) = f(s \to \Omega^-)/f(s \to \Xi^-) = 0.062$

Eur. Phys. J. C76 (2016) no.7, 397

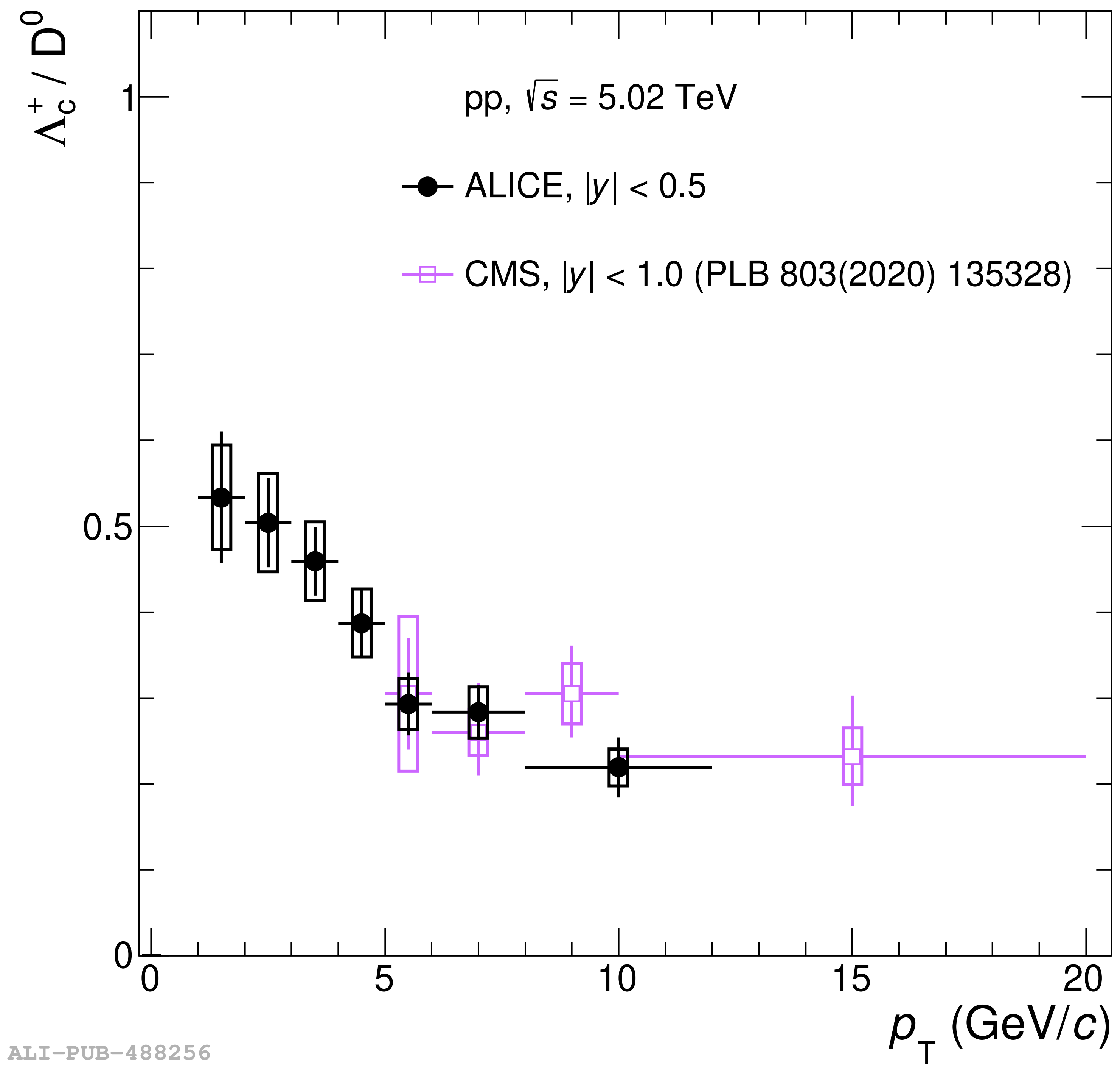


- **Caveat**
  - NO measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c)$ and $\sigma(\Omega_c)$.
  - In 2015, only LHCb Λ_c^+ measurement available.
    - Rapidity range : $2.0 < y < 4.5$

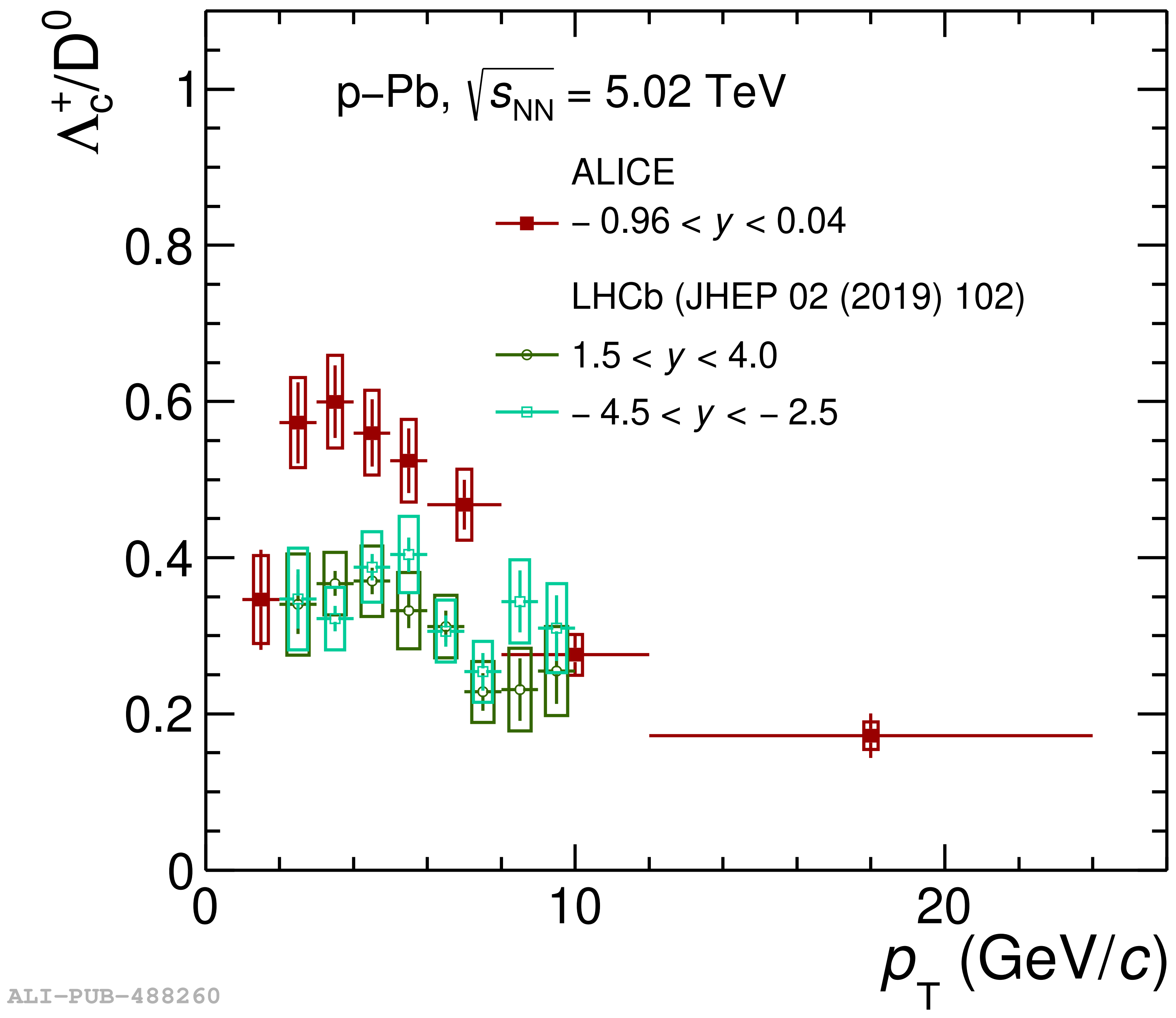
Λ_c^+ measurements comparison

- Λ_c^+/D^0 **in pp at 5.02 TeV (ALICE vs CMS)**
  - ALICE and CMS measurements are consistent.
- Λ_c^+/D^0 **in p-Pb at 5.02 TeV (ALICE vs LHCb)**
  - Suggest an enhancement of the ratio at mid rapidity with respect to forward and backward rapidity.

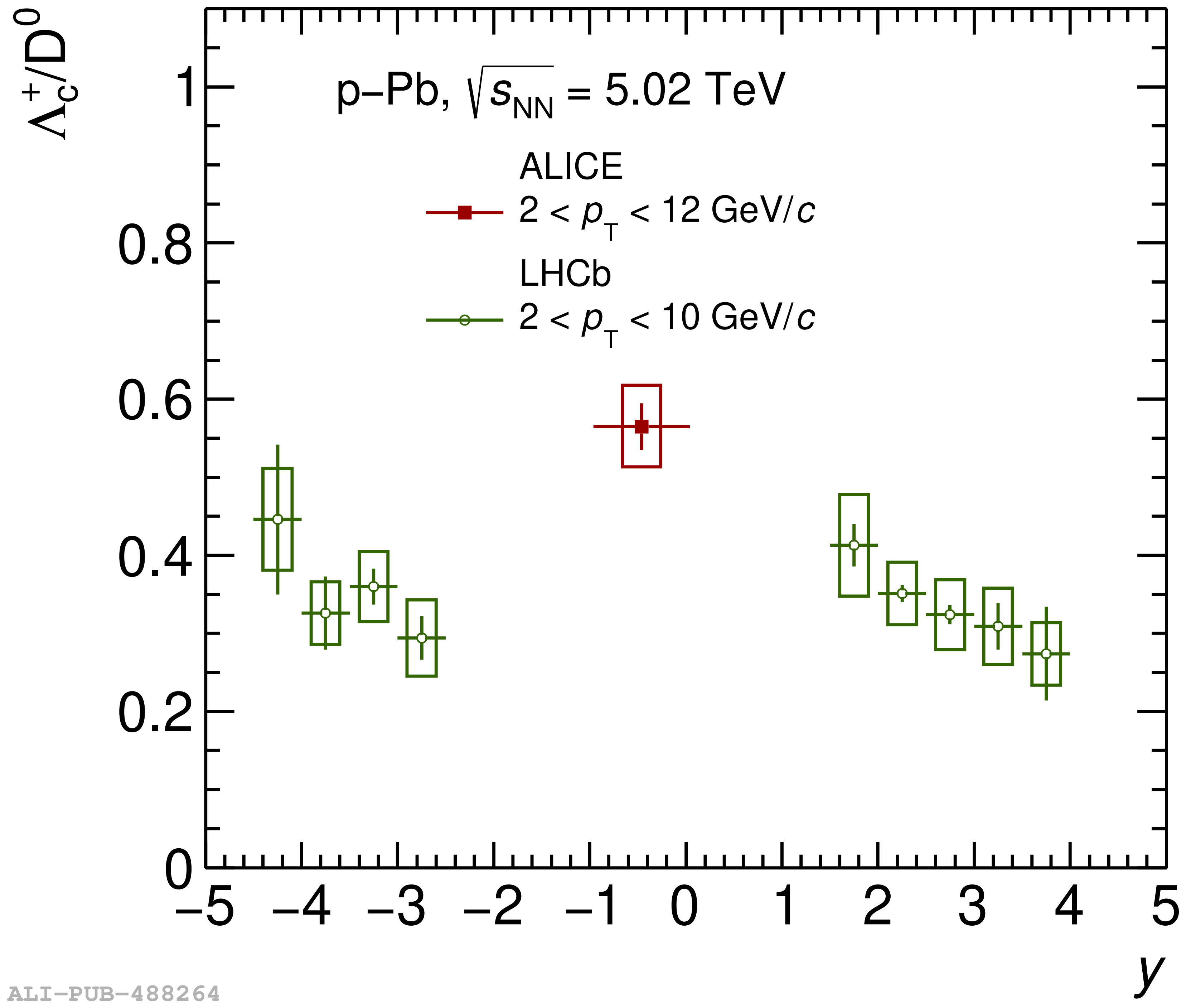
arXiv:2011.06079



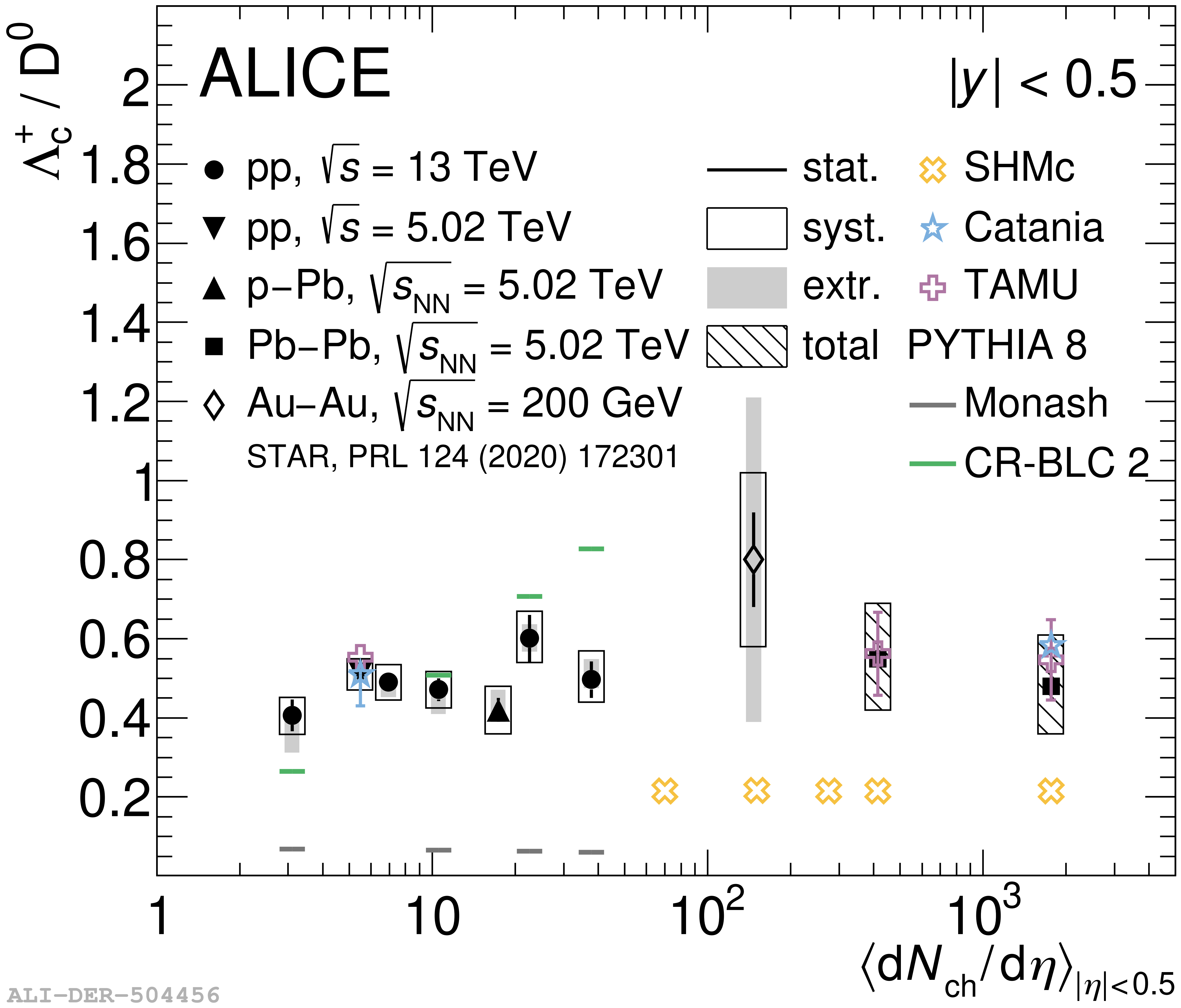
arXiv:2011.06079



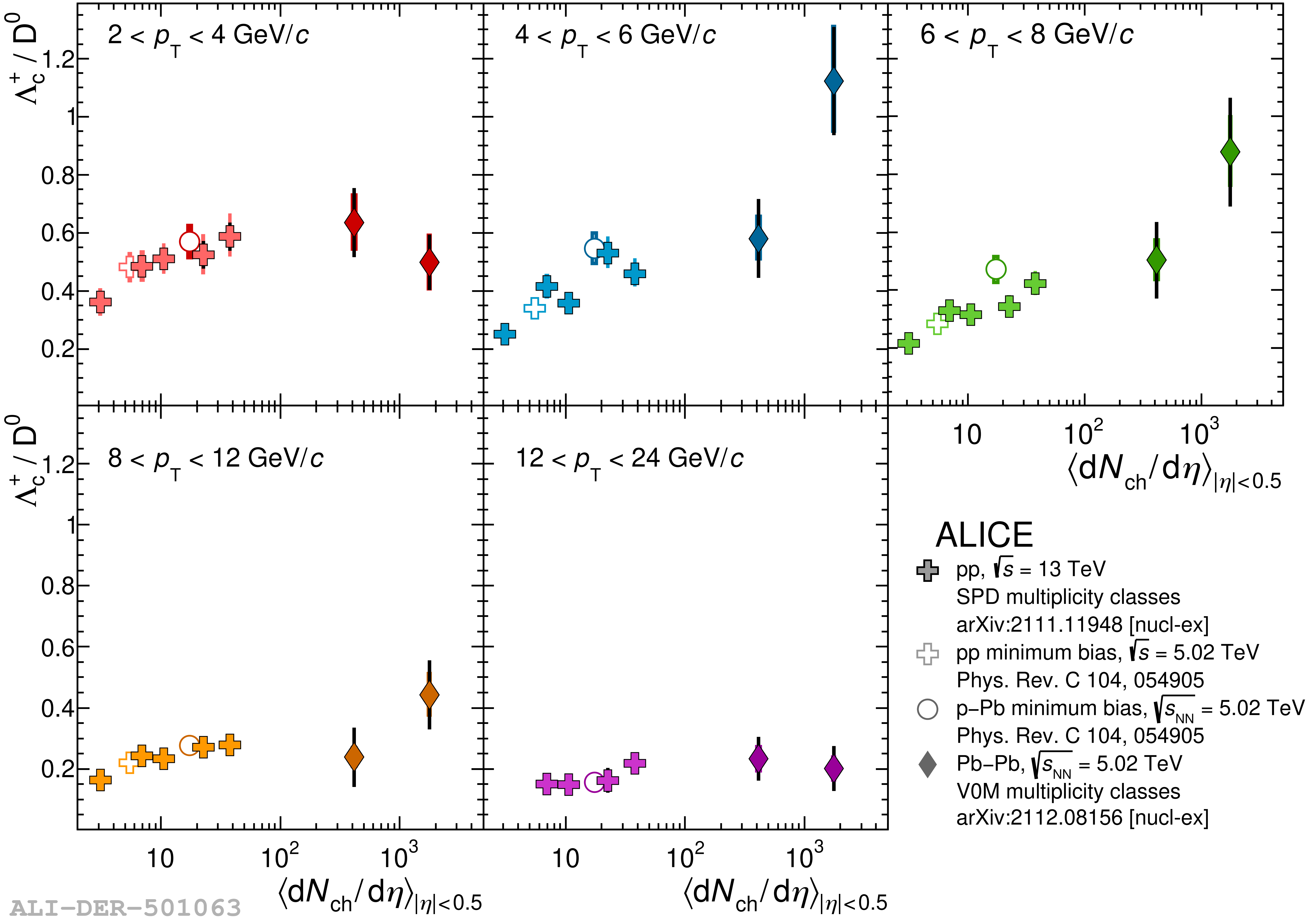
arXiv:2011.06079



Multiplicity dependence of Λ_c^+/D^0

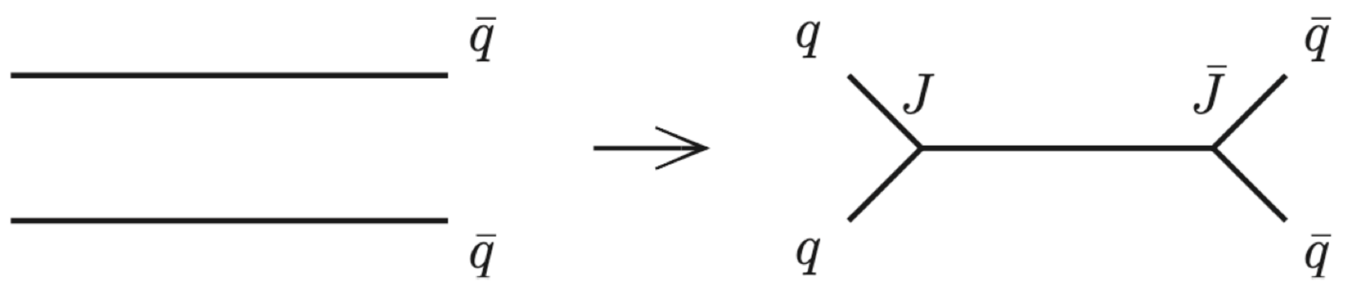


Multiplicity dependence of Λ_c^+/D^0



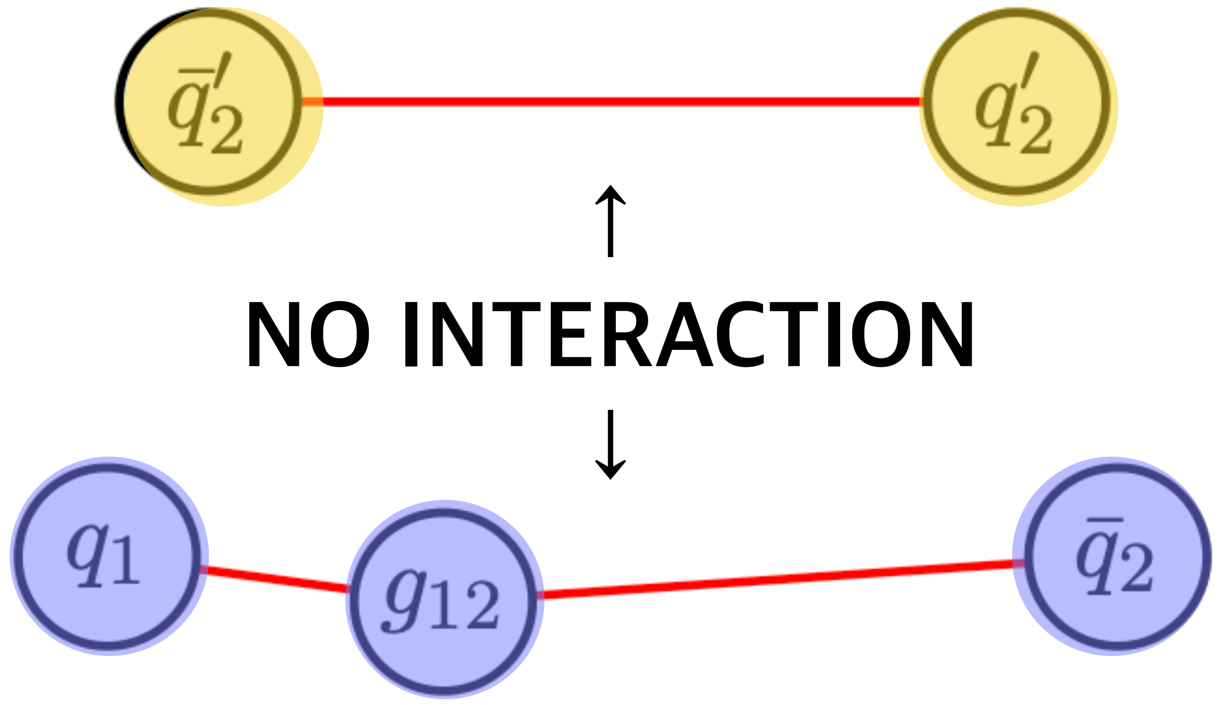
HF baryon enhance mechanism

- **PYTHIA 8 with Colour Reconnection (CR) tunes** JHEP 08 (2015) 003
  - Colour reconnection mode with QCD SU(3) algebra + string-length minimization
  - Junction connection topologies enhance baryon formation
  - Mode parameters : string reconnection, connection causality of dipoles, time dilatic



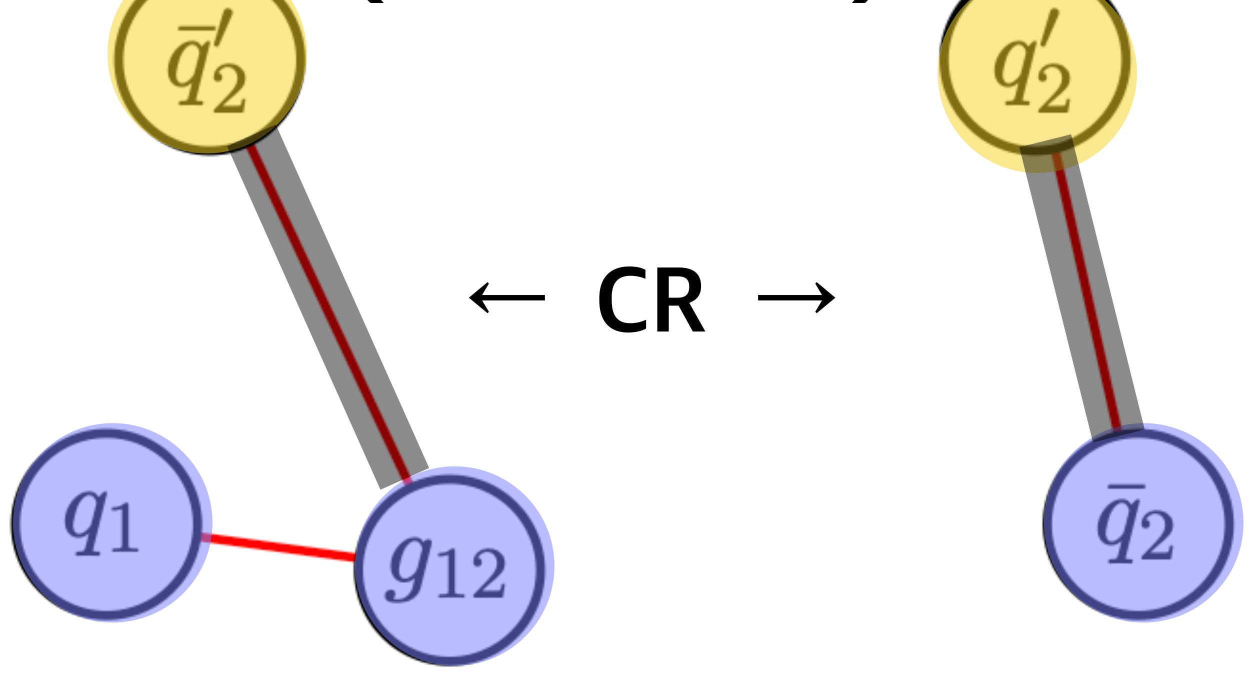
(b) Type II: junction-style reconnection

No CR



- Partons created in different MPIs do not interact each other

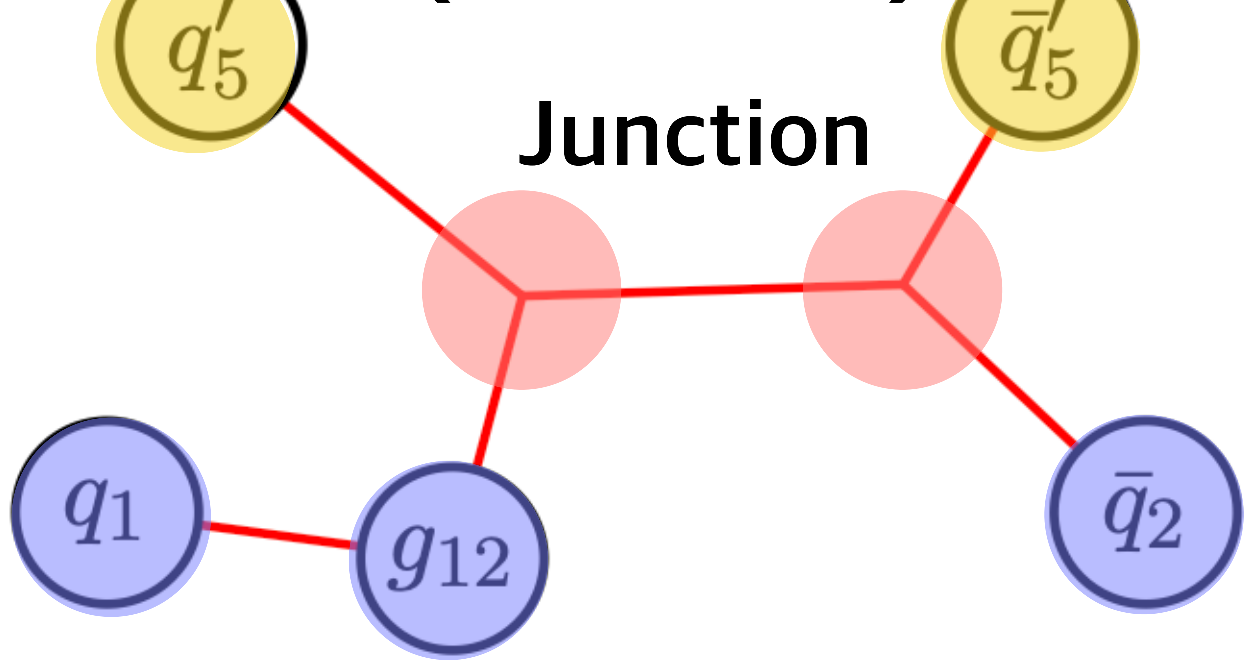
Old CR (Monash)



- CR allowed between partons from different MPIs to minimize the string length

- Used in Monash tune

New CR (CR-BLC)



- Minimization of string length over all possible configurations
- Enhancement of hadrons

- Used in CR mode X tunes

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- **Statistical Hadronisation Model (SHM) + additional baryon states** PLB 795 (2019) 117-121
  - **PDG :** 5 Λ_c (I=0), 3 Σ_c (I=1), 8 Ξ_c (I=1/2), 2 Ω_c (I=0)
  - **RQM (Relativistic Quark Model) :** Add 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c PRD 84 (2011) 014025

n_i $(\cdot 10^{-4}\ \mathrm{fm}^{-3})$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
PDG(170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
PDG(160)	0.4996	0.2223	0.2113	0.1311	0.1201	0.0304	0.0021
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144
RQM(160)	0.4996	0.2223	0.2113	0.1311	0.2203	0.0391	0.0044

HF baryon enhance mechanism

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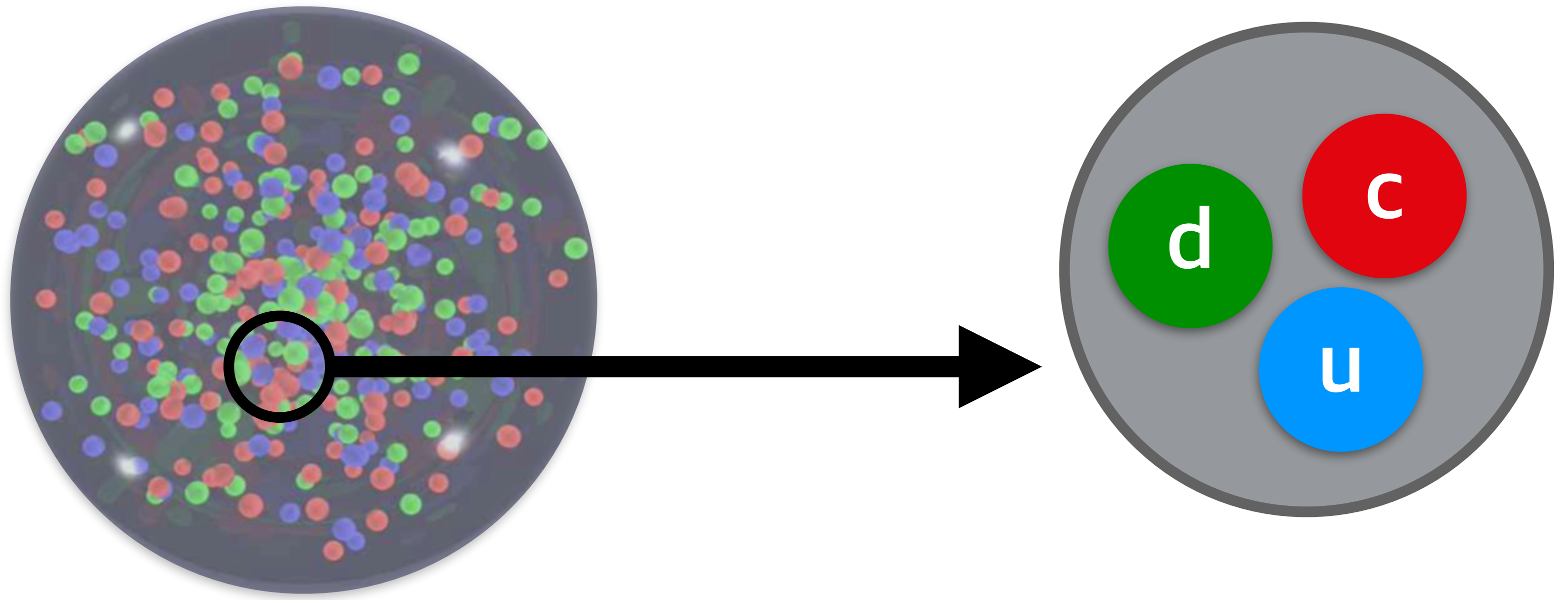
- **Quark Recombination Mechanism (QCM)** EPJC 78 no.4, (2018) 344
  - Combination of charm quarks with co-moving light quarks



HF baryon enhance mechanism

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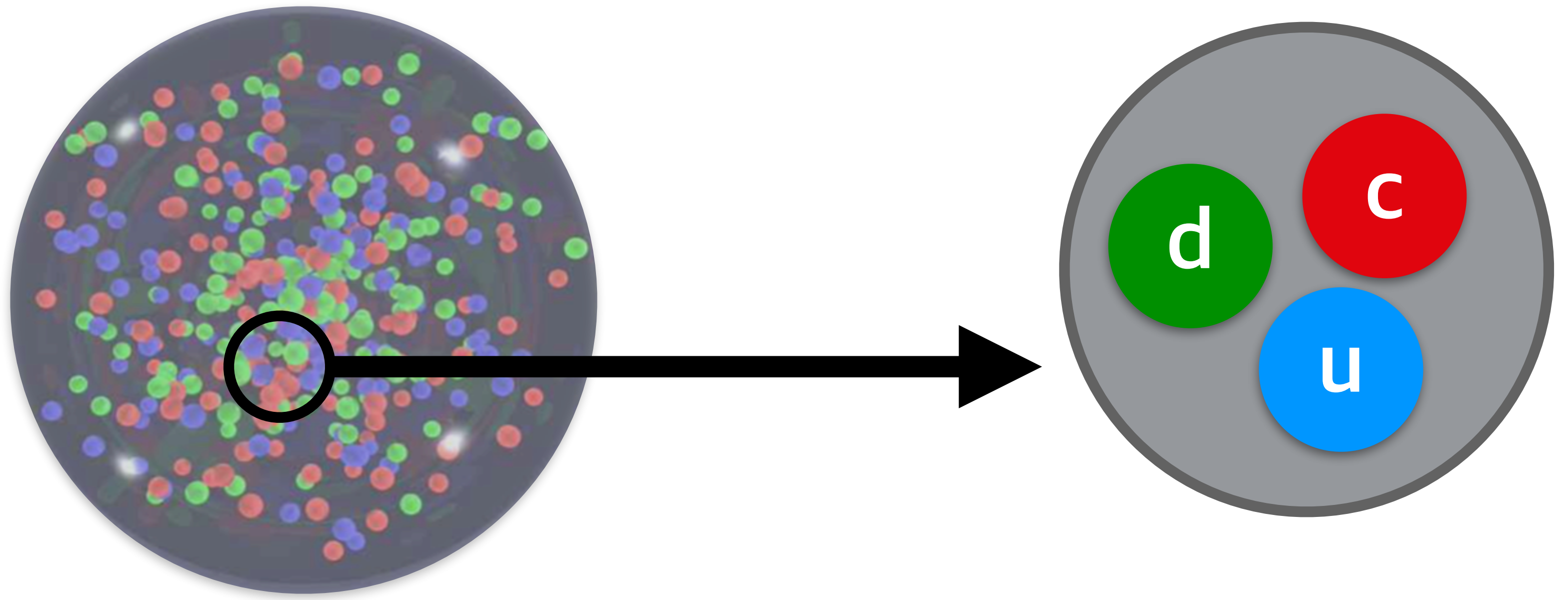

- **Catania model** arXiv:2012.12001
  - Coalescence process of heavy quarks with light quark based on the Wigner formalism + fragmentation process
  - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra