10th International Workshop on Charm Physics (CHARM 2020)

Charm-baryon production and fragmentation fractions in pp collisions with ALICE

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on behalf of the ALICE Collaboration

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ALICE

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1954

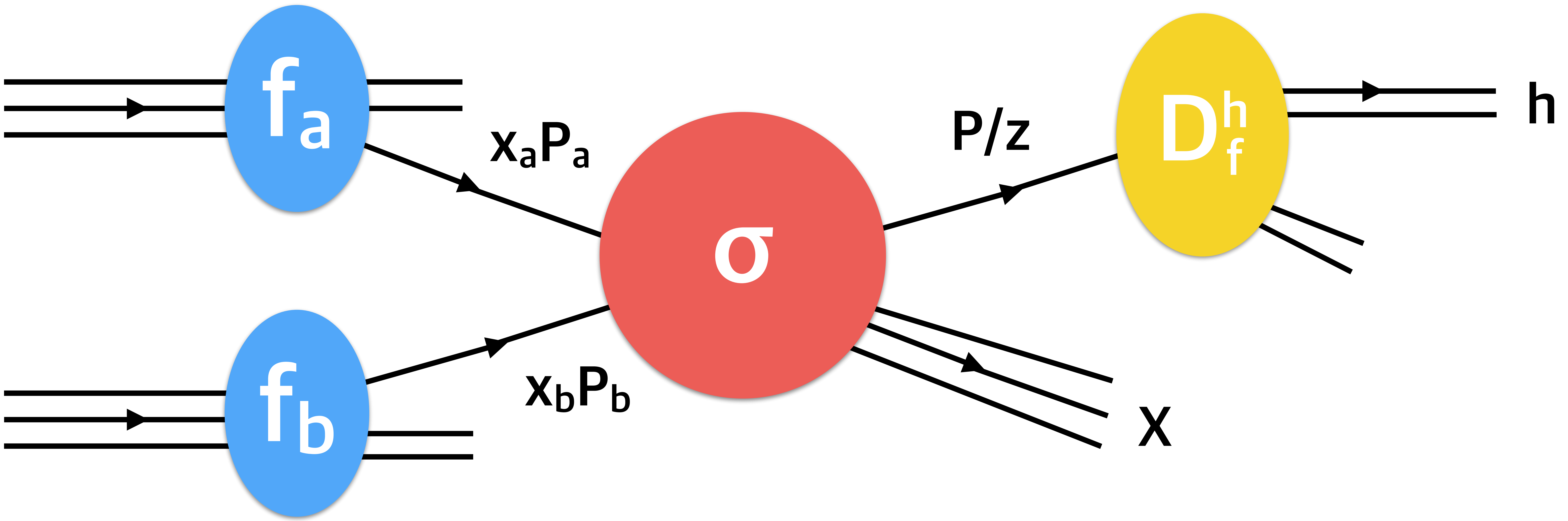
Heavy-flavour production

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

Initial state
Parton distribution function

pQCD partonic
cross section

Hadronisation by
fragmentation



- **pp collisions :** Test for pQCD calculations, baseline for nuclear collisions.

Heavy-flavour production

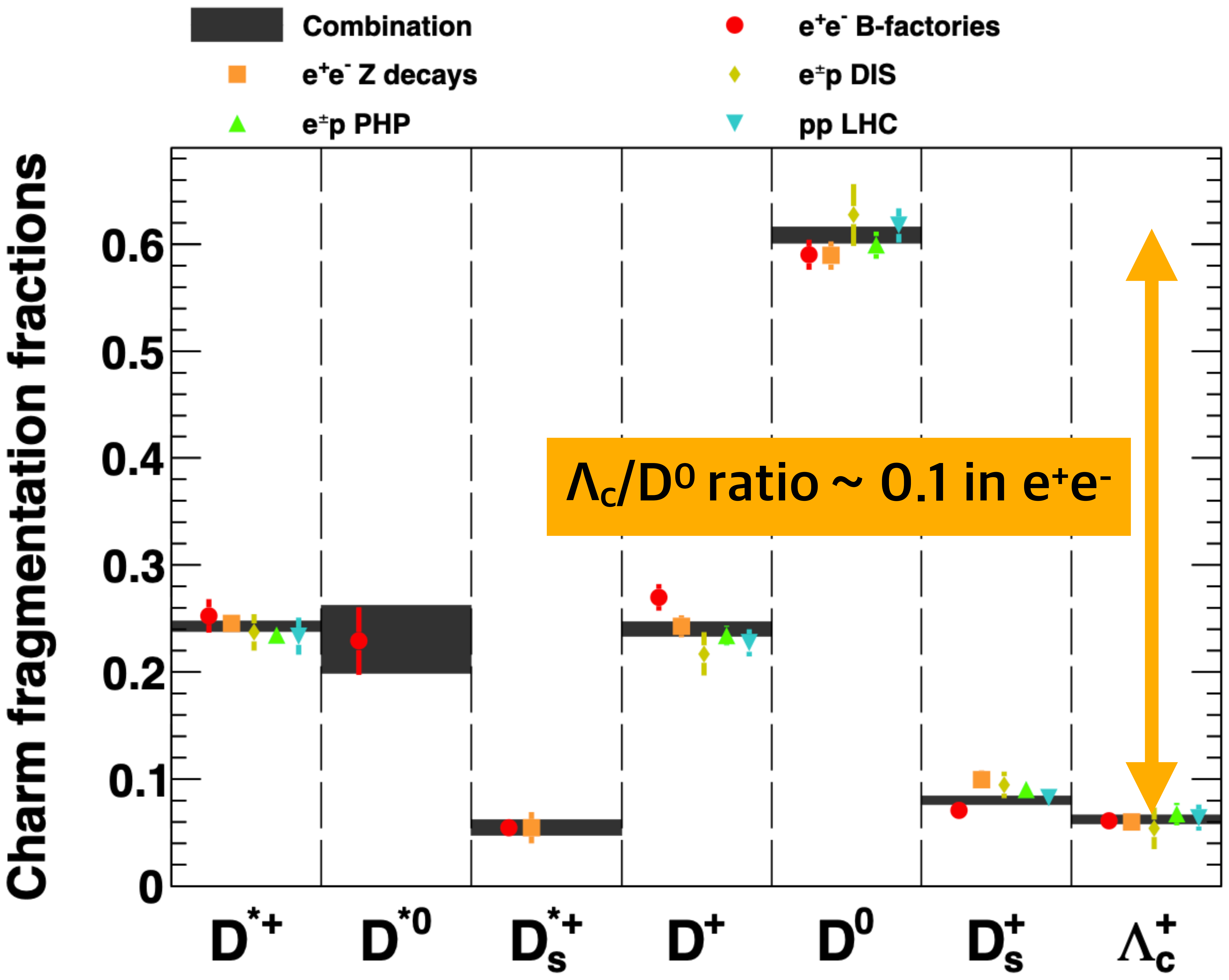
- **Charm fragmentation fraction**

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

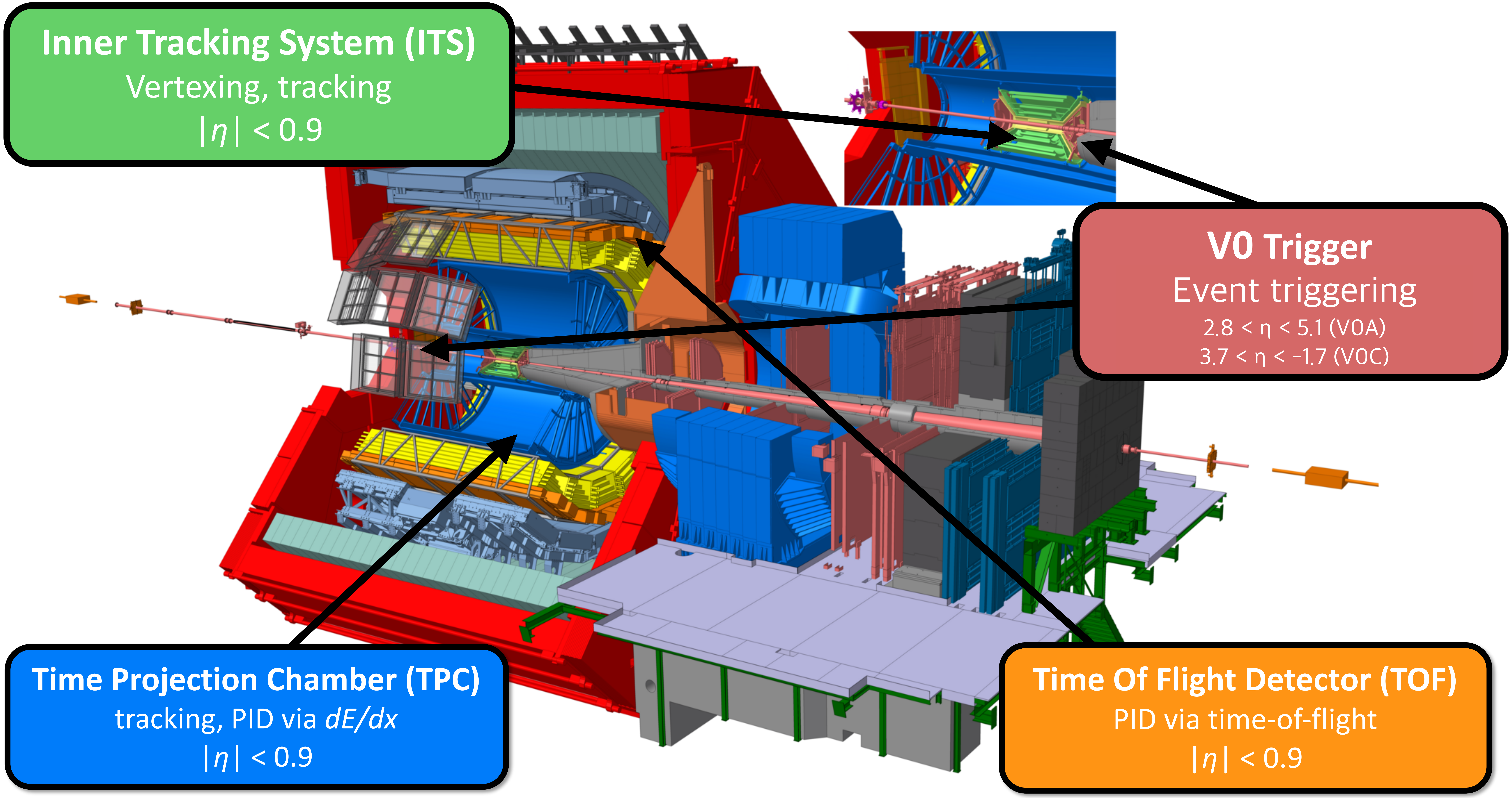
- Measurements in different collision systems and at different energies agree within uncertainties.
  ➡ Support the hypothesis that fragmentation fractions are independent of the collision systems?

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

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



ALICE Detector

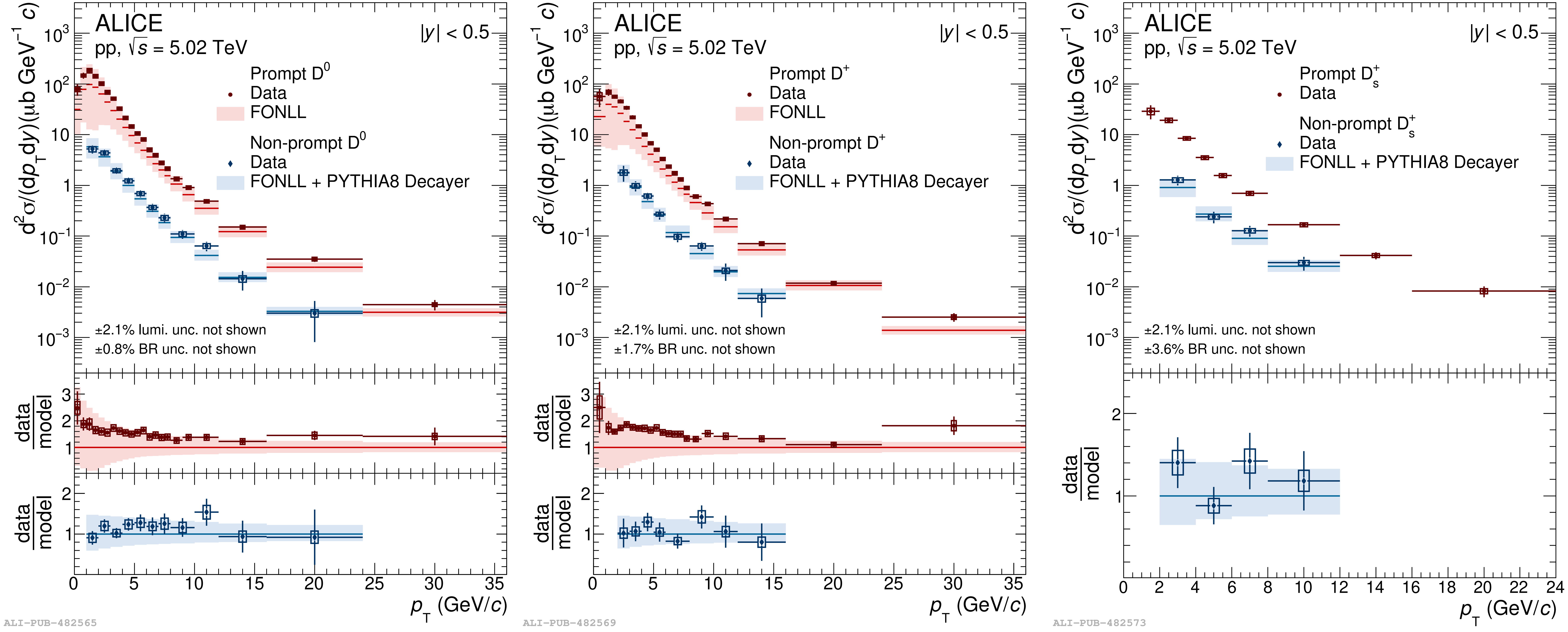


Charm-meson production

- **Comparison of p_T-differential production cross section of D meson with models**
  - **FONLL** : Fixed Order with Next to Leading Log resummation JHEP (2012) 137

➡ **NLO pQCD calculation with fragmentation fractions from e^+e^- can describe the charm-meson production!**

arXiv:2102.13601



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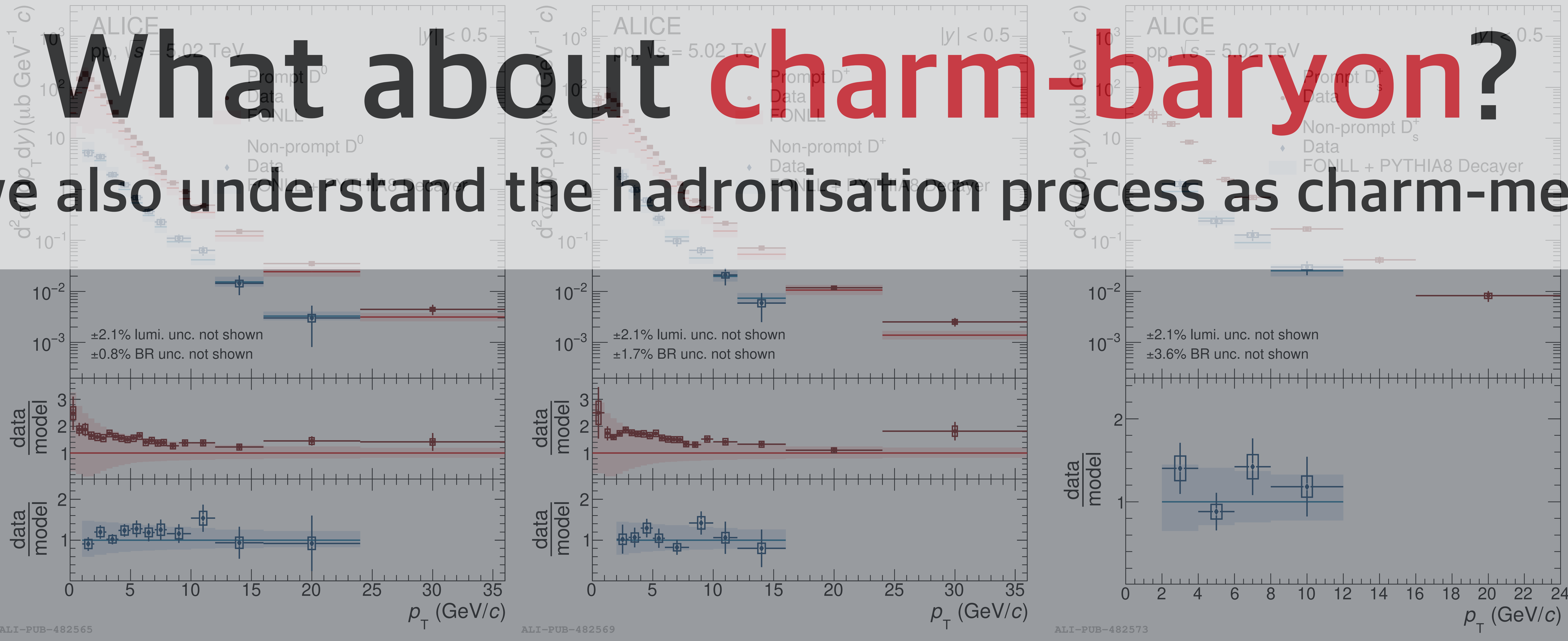


What about charm-baryon?

Do we also understand the hadronisation process as charm-meson?

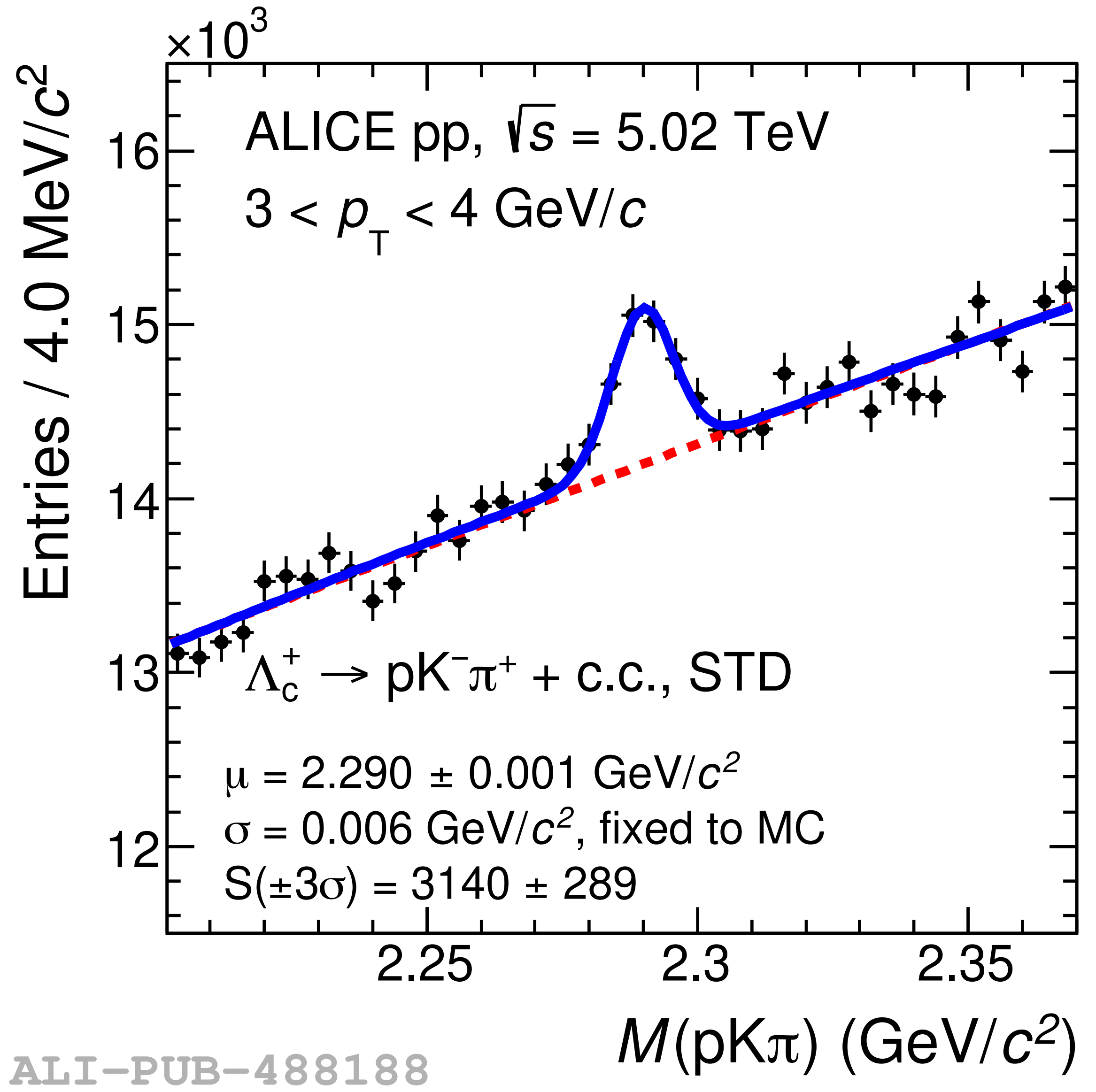
Charm-hadron in ALICE

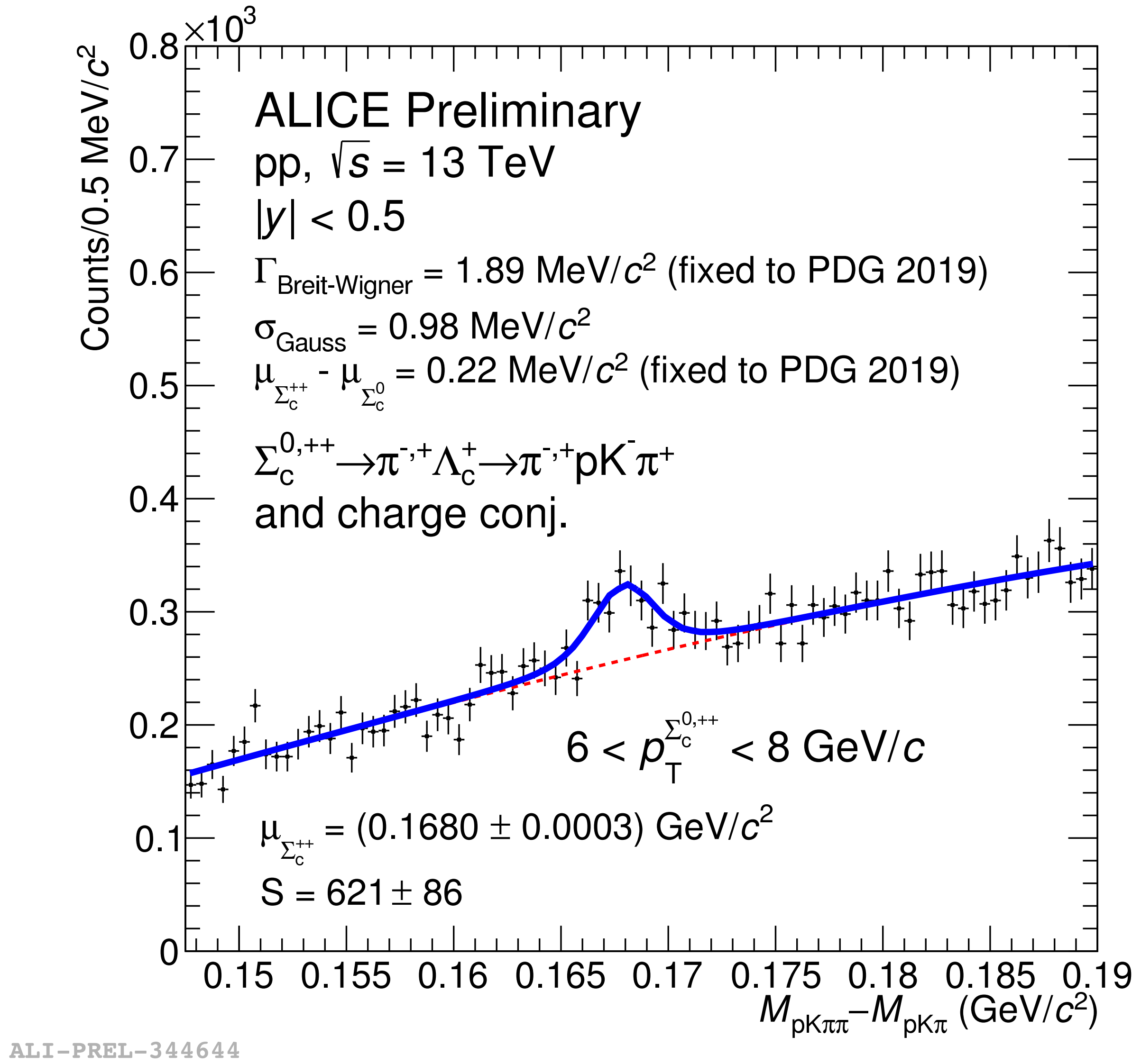
- **Data samples**

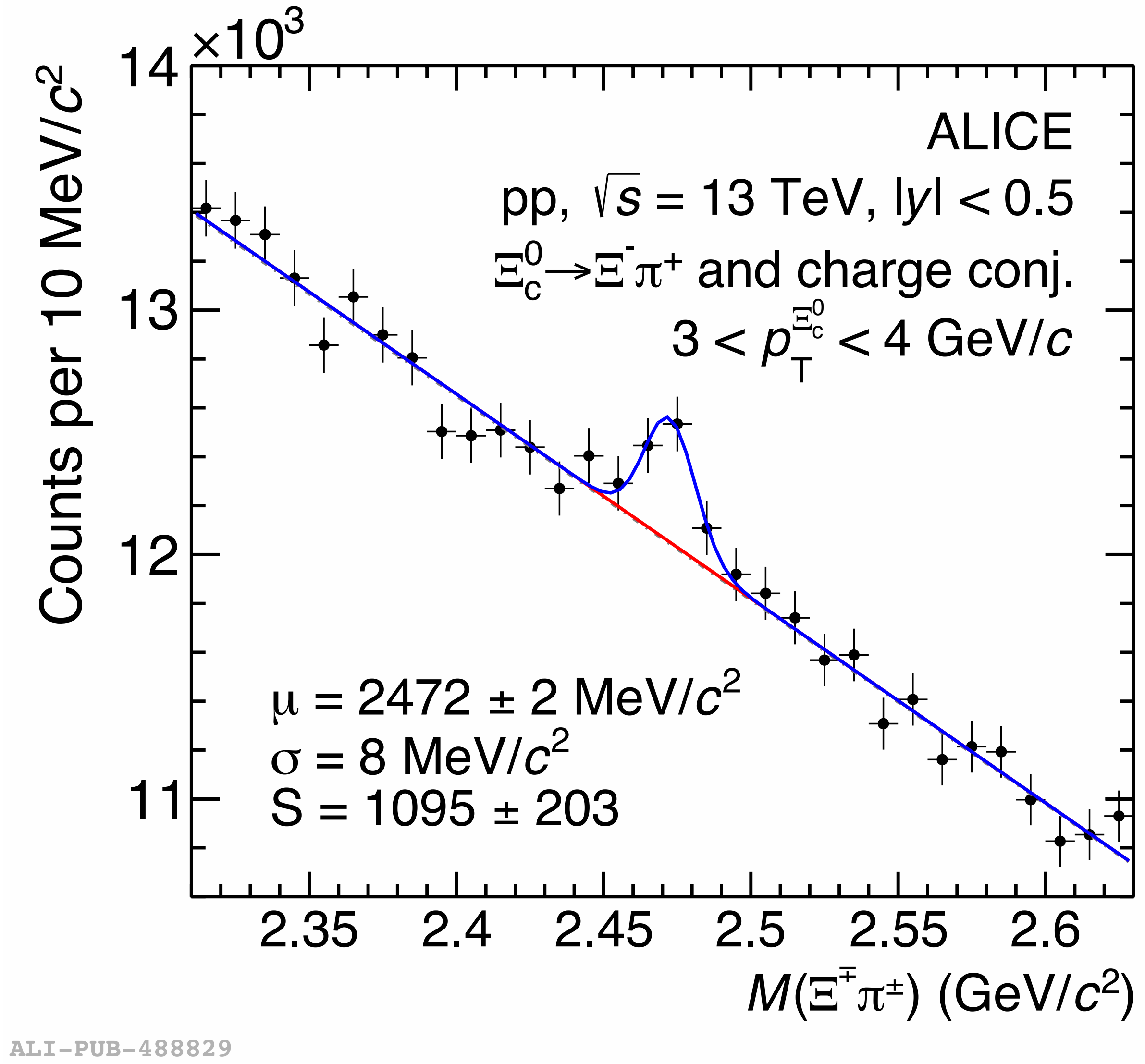
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2017	5.02	~20 nb^{-1}
	2016-2018	13	~32 nb^{-1}
p-Pb	2016	5.02	~0.3 nb^{-1}

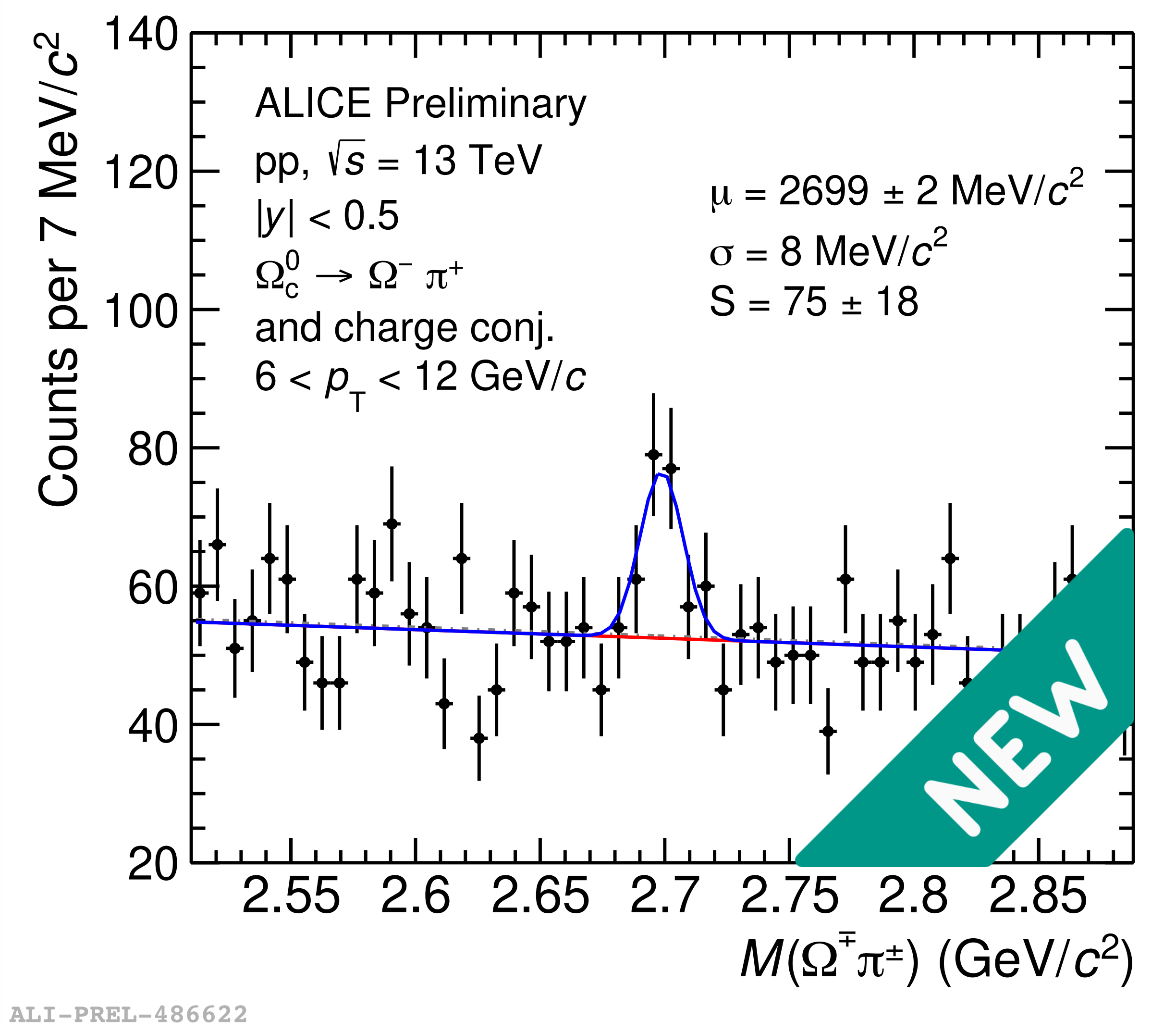
- **Hadronic decay**
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
  - $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ & $\Lambda_c^+ \rightarrow pK_s^0$
  - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
  - $\Xi_c^0 \rightarrow \Xi^-\pi^+$
  - $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
  - $\Omega_c^0 \rightarrow \Omega^-\pi^+$

- **Semileptonic decay**
  - $\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$
  - $\Xi_c^0 \rightarrow \Xi^- e^+\nu_e$









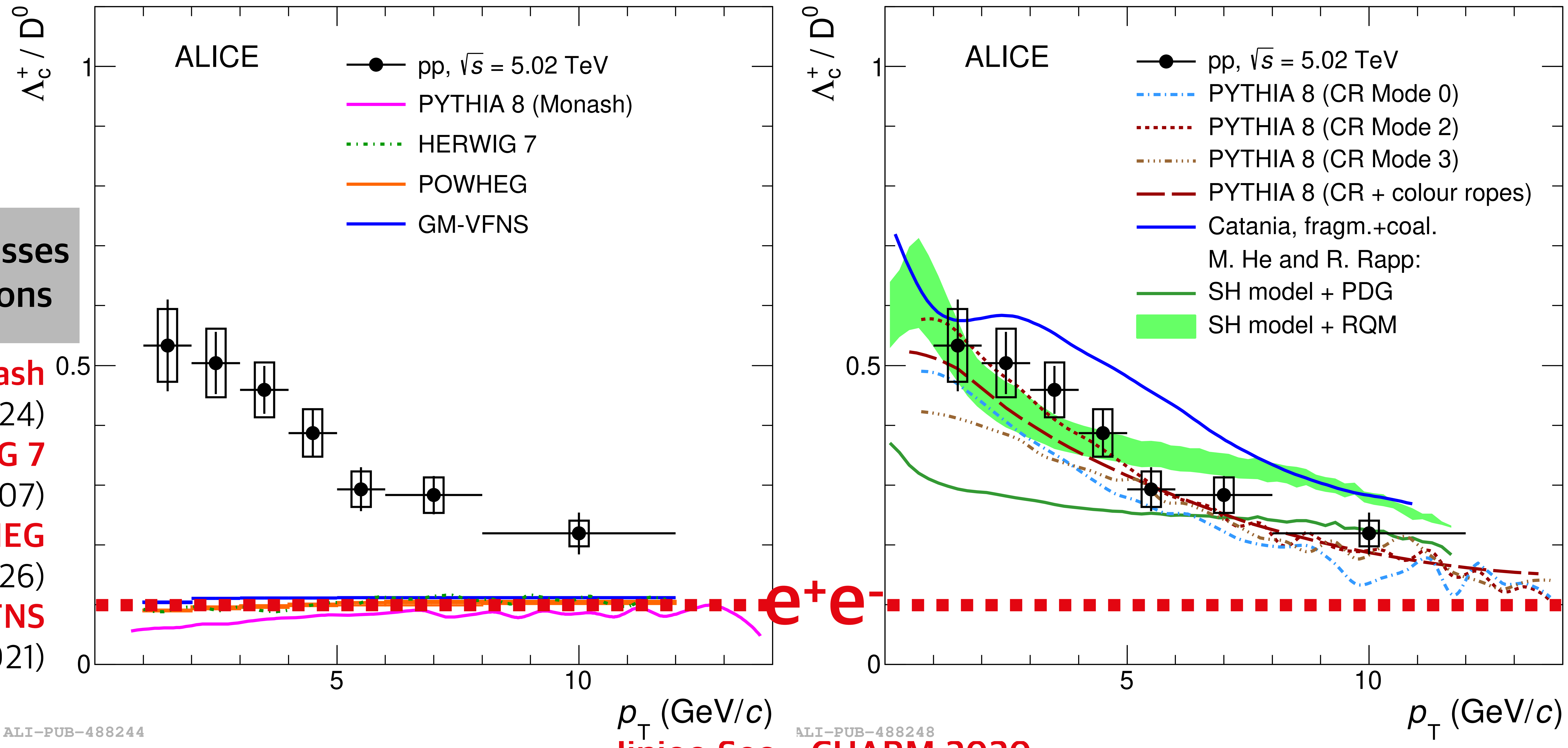
Λ_c^+ measurements in ALICE

- Λ_c^+/D^0 **in pp collisions at 5.02 TeV**
  - **PYTHIA 8 with CR modes including junctions** : baryon enhancement due to new CR topologies.
  - **Catania** : hadronisation via fragmentation + recombination of charm quark with light quarks in a hot QCD matter.
  - **SH model + RQM** : Consider additional excited charm baryon states expected by the RQM.

arXiv:2011.06079

Fragmentation processes tuned on e^+e^- collisions

PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
HERWIG 7
(EPJC58 (2008) 639-707)
POWHEG
(JHEP 09 (2007) 126)
GM-VFNS
(PRD 101 (2020) 114021)



Models that predict baryon enhancement

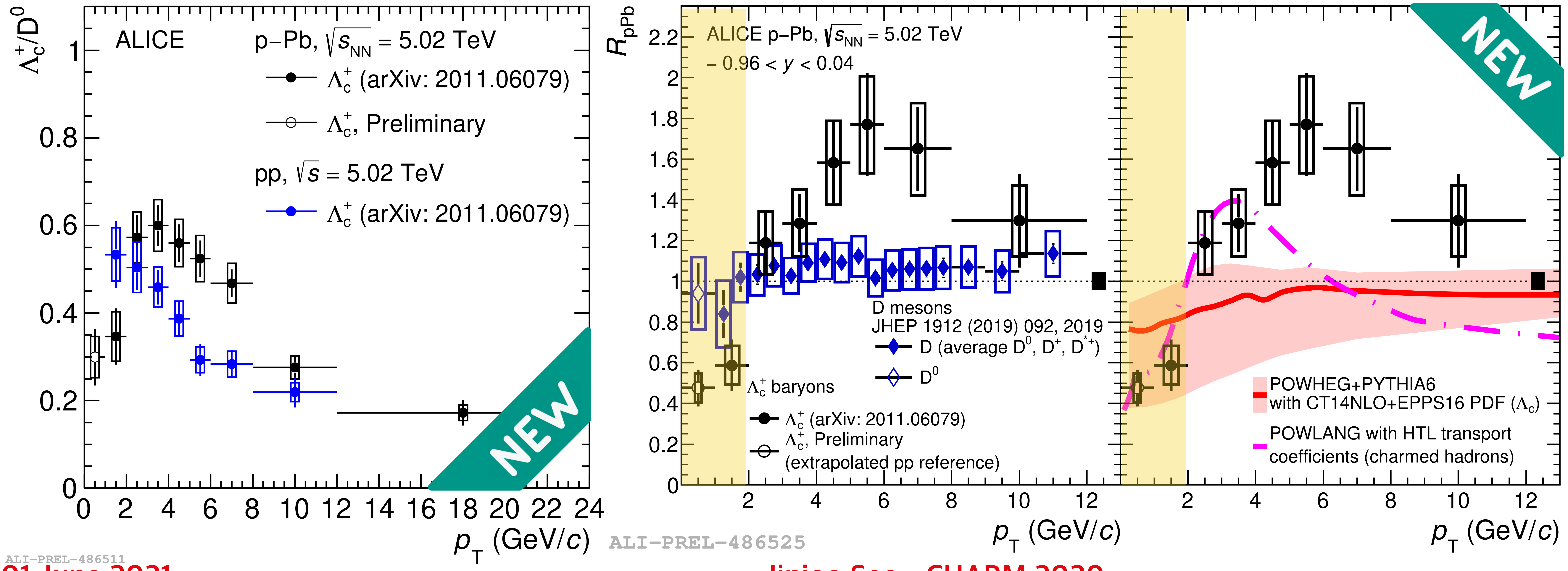
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
Catania
(arXiv:2012.12001)
M. He and R. Rapp
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)

Λ_c^+ measurements in ALICE

- **Λ_c^+ down to $p_T = 0$ in p-Pb collisions**
  - Λ_c^+/D^0 : larger in $3 < p_T < 8$ GeV/c and a lower in $p_T < 2$ GeV/c in p-Pb collisions with respect to pp collisions.
  - R_{pPb} : Systematically above unity in $p_T > 2$ GeV/c, below unity in $p_T < 2$ GeV/c.
    - **Significant suppression for the Λ_c^+ baryon in p-Pb collisions in $p_T < 2$ GeV/c**

➡ Possible modification due to radial flow or hadronisation mechanisms

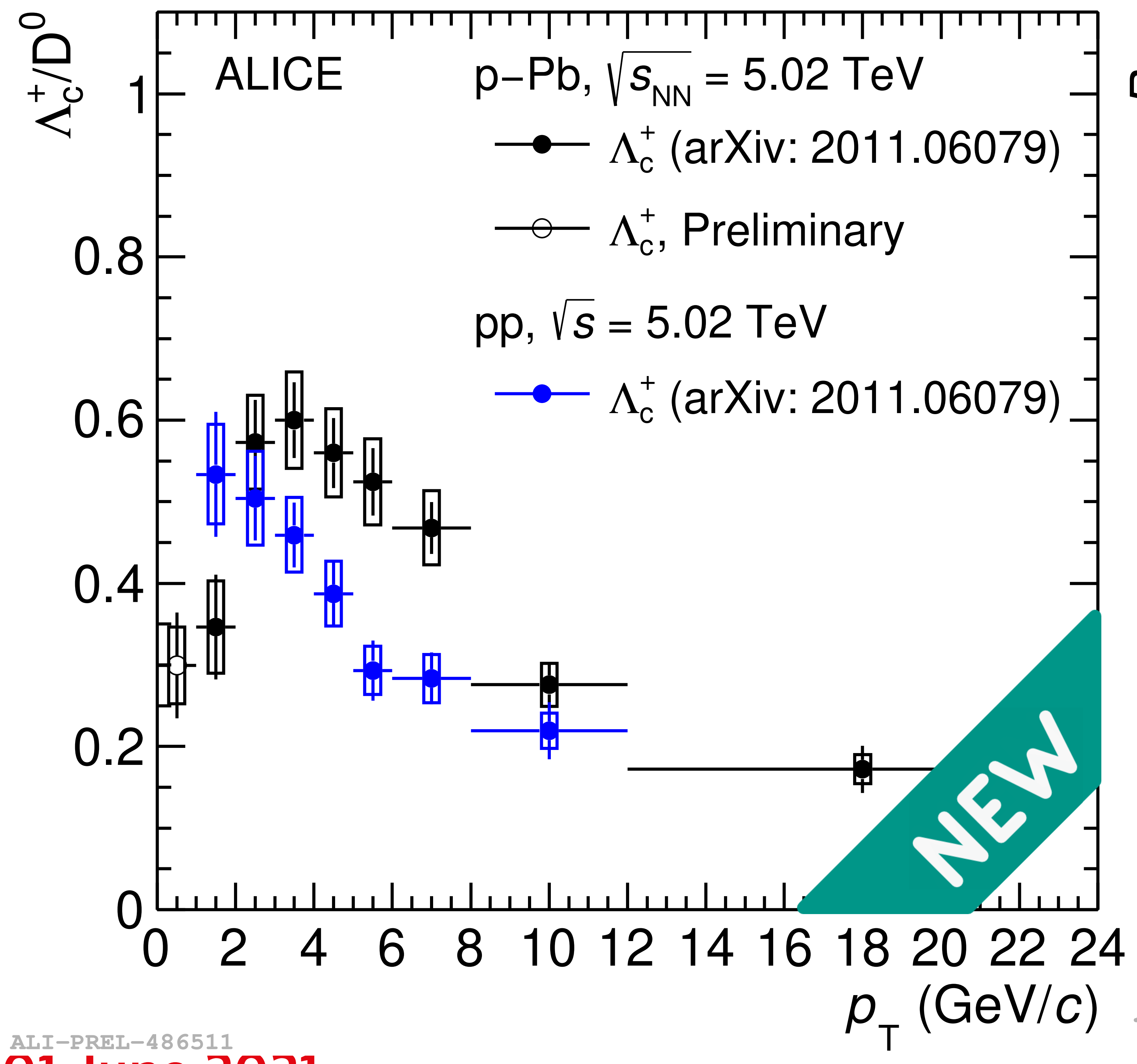
arXiv:2011.06079

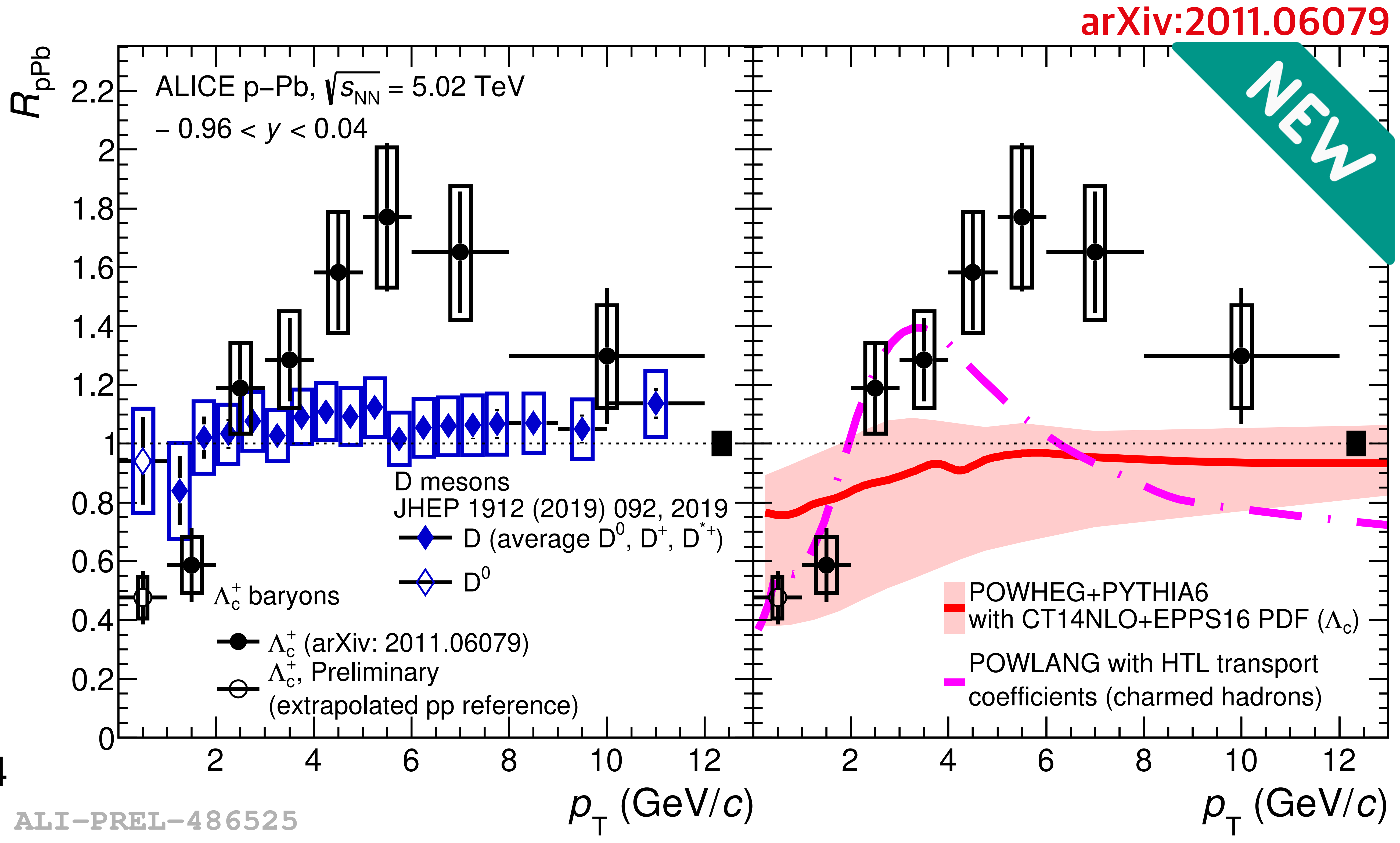


POWHEG
(EPJC 77 no. 3,(2017) 163)
PYTHIA6
(JHEP 09 (2007) 126)
POWLANG
(JHEP 03 (2016) 123)

Λ_c^+ measurements in ALICE

- Λ_c^+ **down to $p_T = 0$ 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.

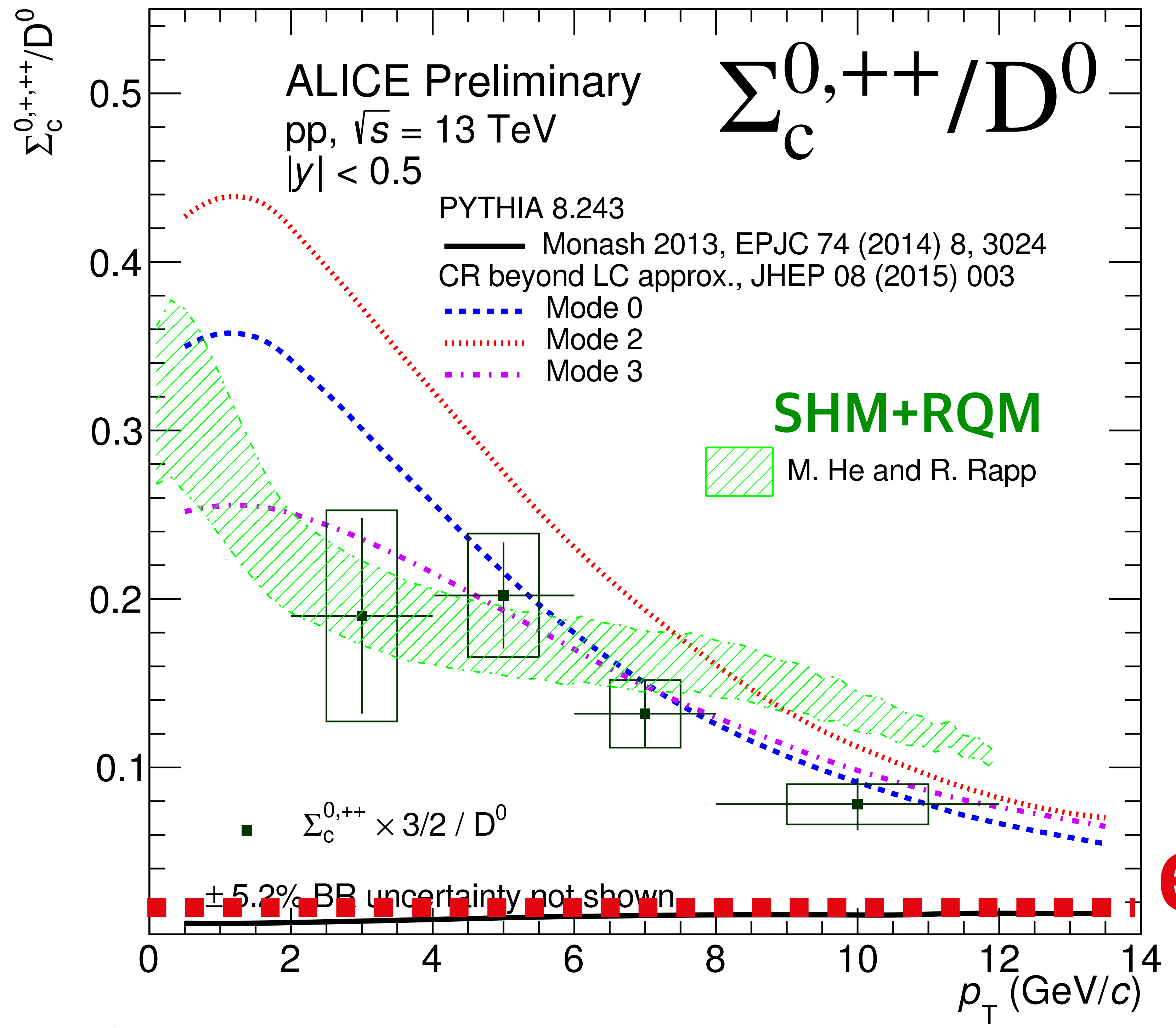


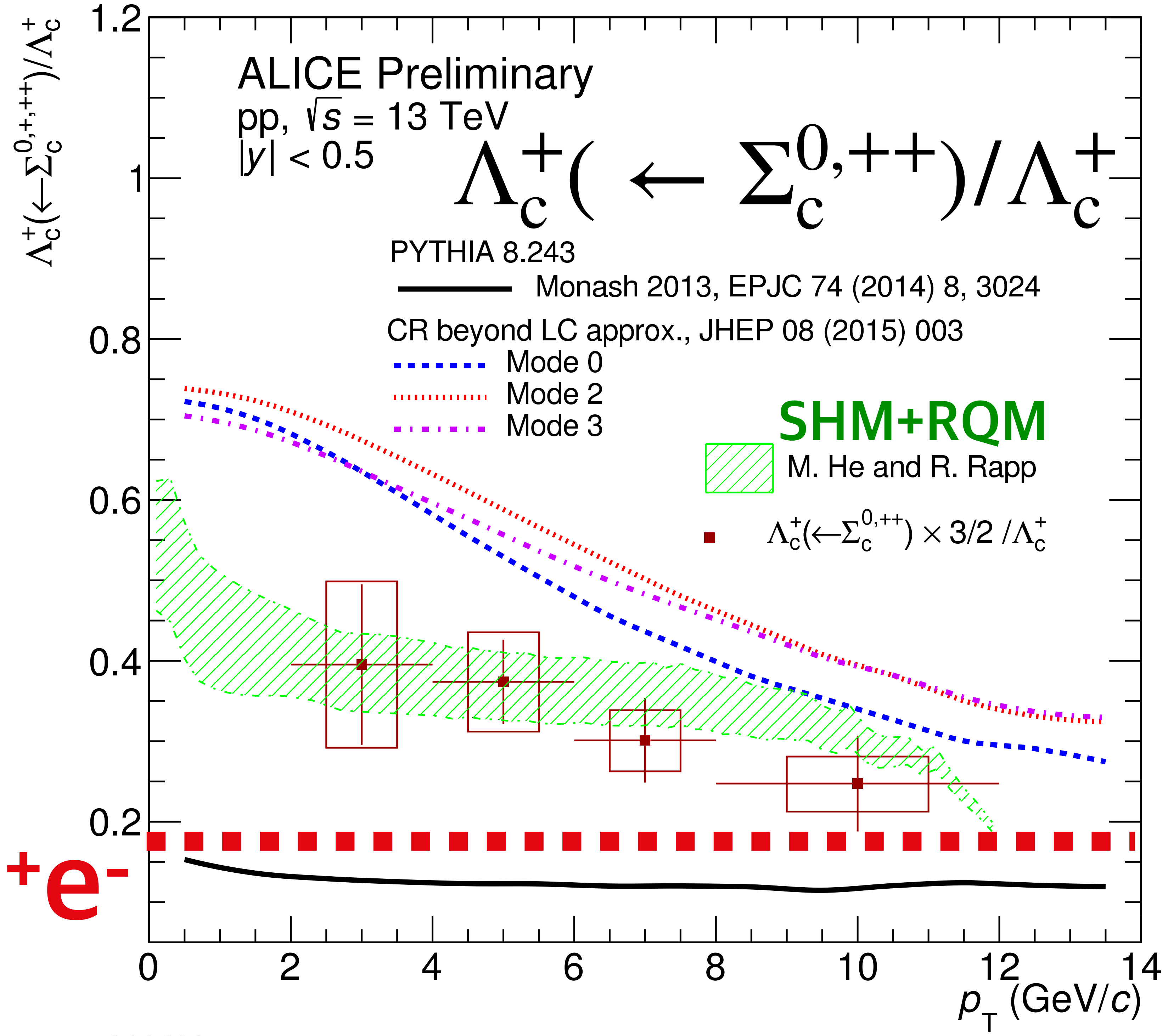


POWHEG
(EPJC 77 no. 3,(2017) 163)
PYTHIA6
(JHEP 09 (2007) 126)
POWLANG
(JHEP 03 (2016) 123)

$\Sigma_c^{0,++}$ measurements in ALICE

- $\Sigma_c^{0,++}/D^0$ **and** $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ **in pp collisions at 13TeV**
  - $\Sigma_c^{0,++}/D^0$ ratio shows remarkable difference between the pp and e^+e^- collisions.
  - $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ ratio significantly larger than e^+e^- collisions measurements.
  - **The larger feed-down from $\Sigma_c^{0,++}$ (~40%) partially explains the Λ_c^+/D^0 enhancement in pp collisions.**





e^+e^-

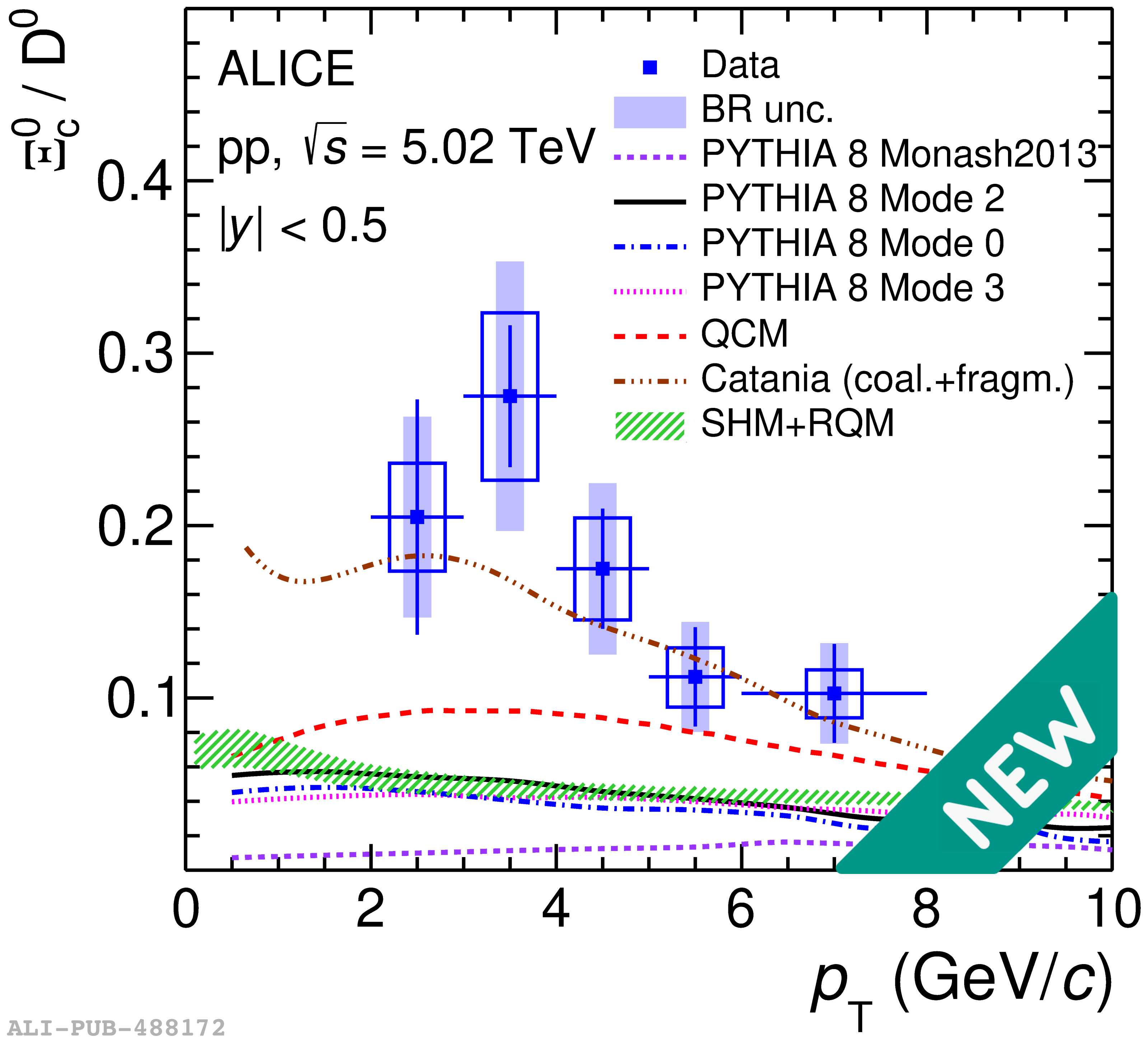
PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
M. He and R. Rapp
(PLB 795 (2019) 117-121)

$\Xi_c^{0,+}$ measurements in ALICE

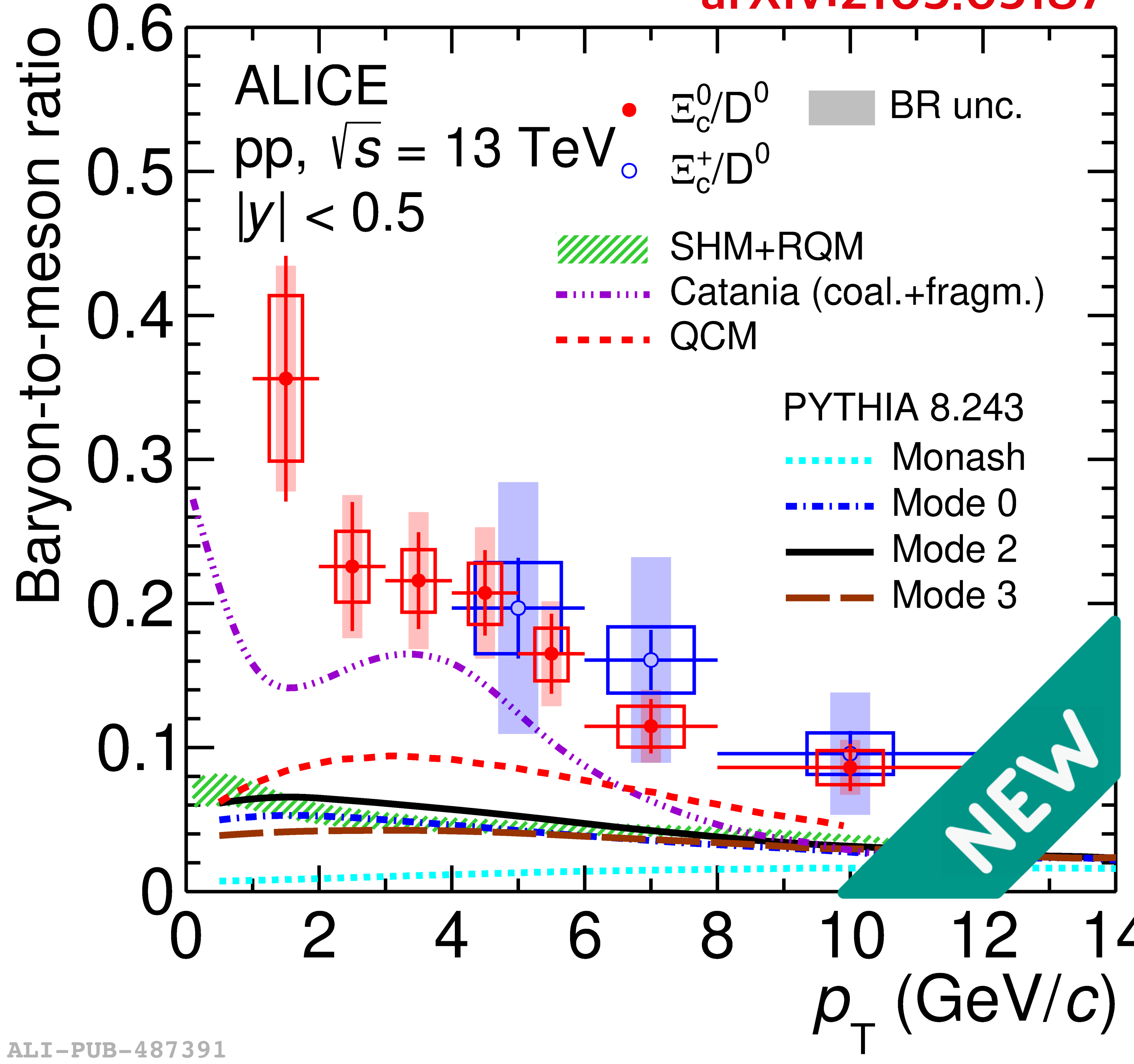
- **Baryon-to-meson ratio in pp collisions at 5.02 TeV and 13 TeV**
  - **PYTHIA 8 Monash**, **PYTHIA 8 CR tunes**, **SHM+RQM** and **QCM** : Significantly underestimate the ratios.
  - **Catania** : Describes better the ratios in the measured p_T interval.

  ➡ **Both of Fragmentation and coalescence process are important.**
  - The Ξ_c^0/D^0 ratios show no energy dependence.

arXiv:2105.05616



arXiv:2105.05187

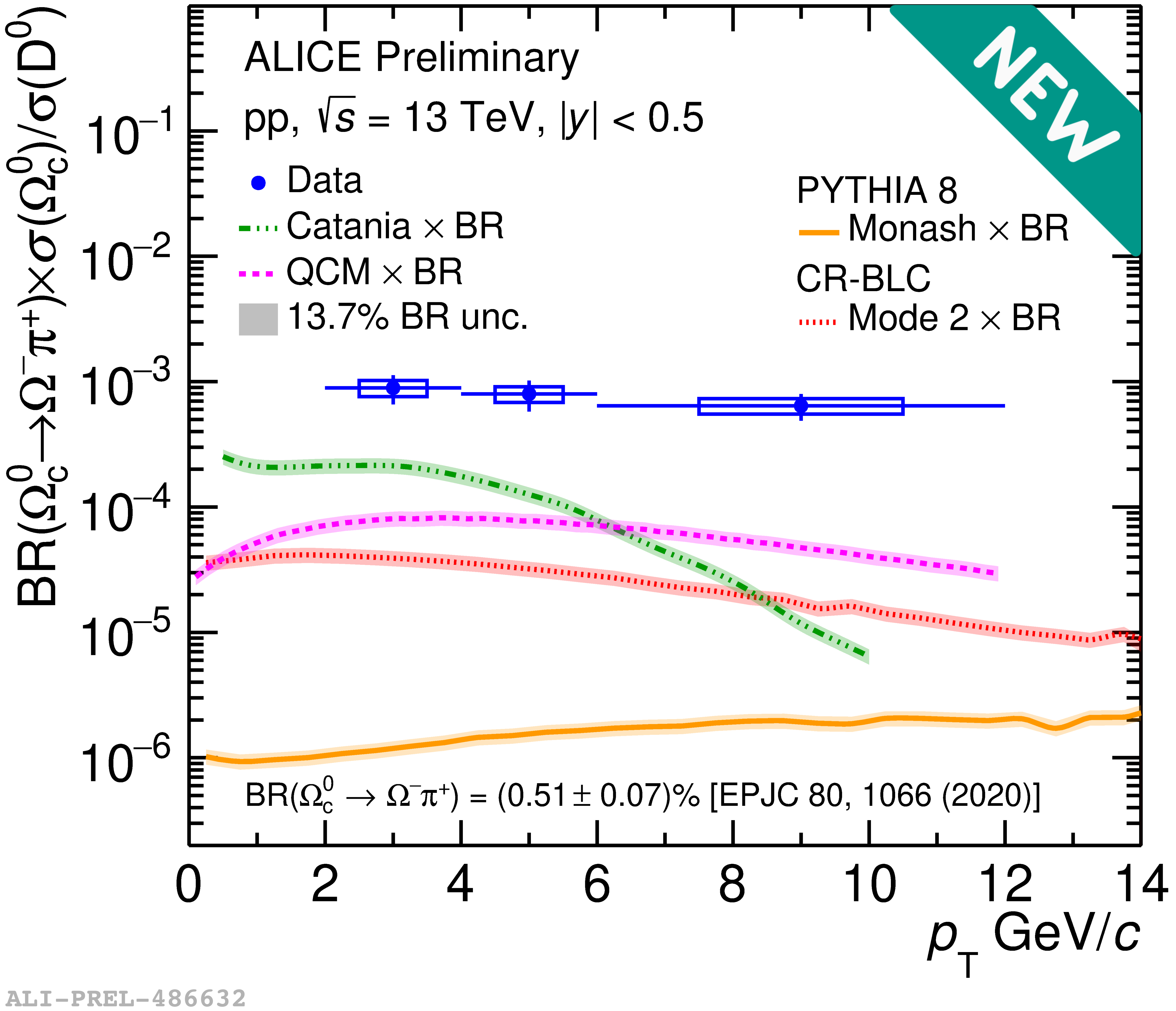


PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
SHM
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)
QCM
(EPJC 78 no.4, (2018) 344)
Catania
(arXiv:2012.12001)

Ω_c^0 measurements in ALICE

- $(\mathrm{BR}\times\Omega_c^0)/\mathrm{D}^0$ **ratio in pp collisions at 13TeV**
  - First measurement of Ω_c^0 production at the LHC
  - $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\,\%$
    - Theoretical calculation EPJC 80, 1006(2020)

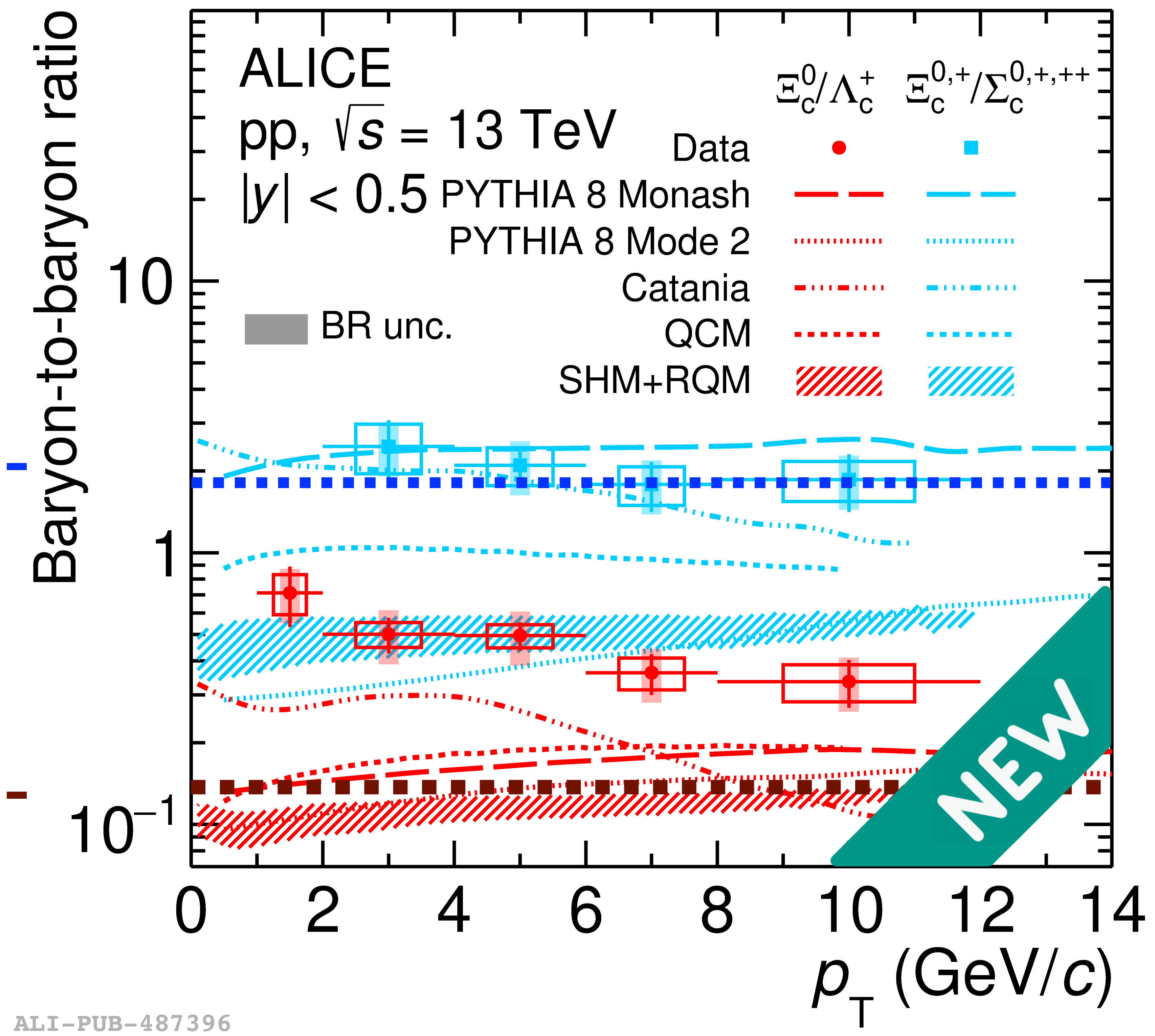
- **Model comparison**
  - **PYTHIA 8 Monash**
    - Largely underestimate the measurement.
  - **PYTHIA 8 CR tunes**
    - Underestimate the measurement.
  - **Catania** and **QCM**
    - Underestimate the measurement even though including the coalescence process.

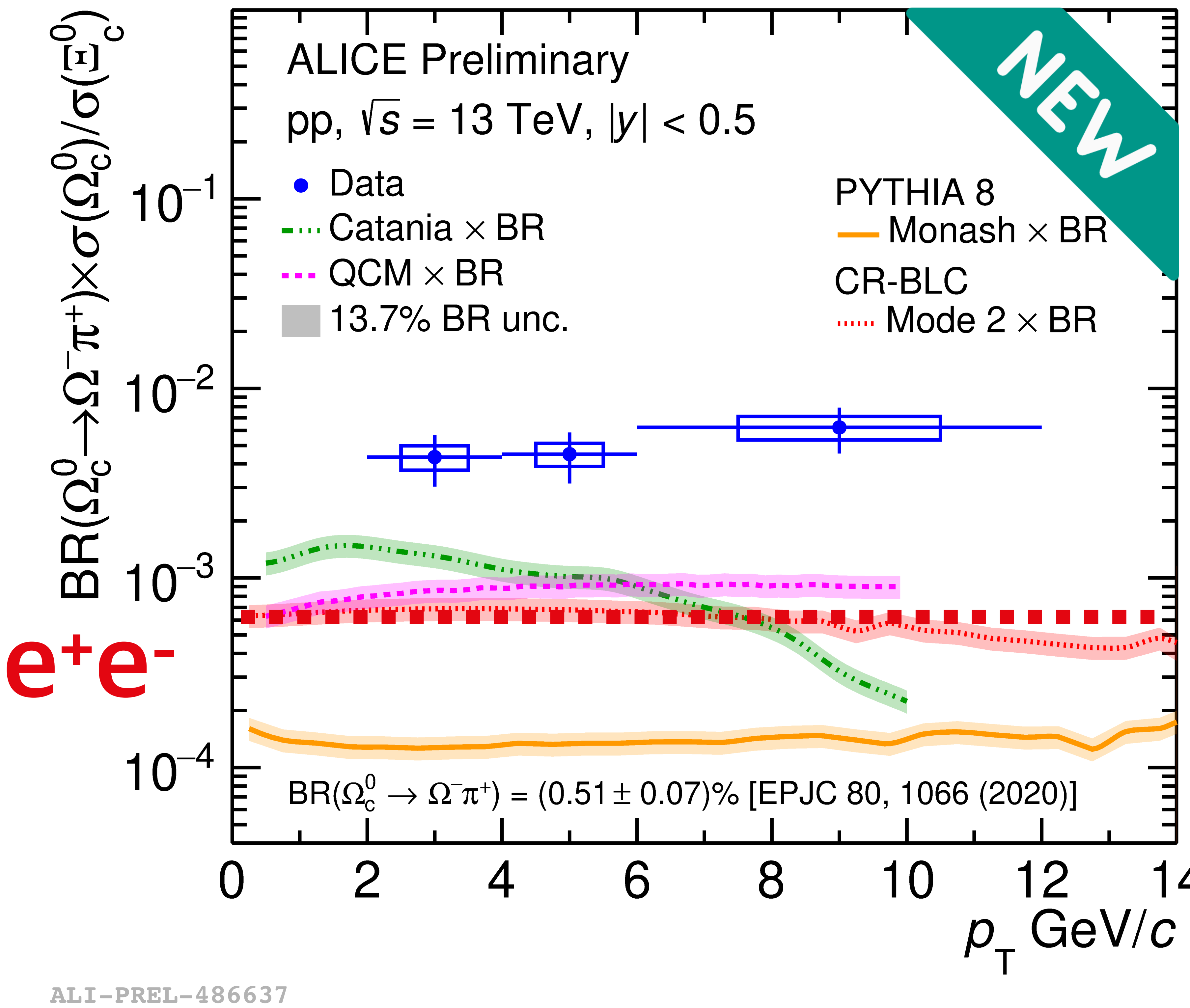


Charm baryon-to-baryon ratio

- **Charm baryon-to-baryon ratio in pp collisions at 13 TeV**
  - First measurement of charm baryon-to-baryon ratio yields at the LHC.
  - $\Xi_c^{0,+}/\Sigma_c^{0,++}$ ratio : **Catania** describes the magnitude and p_T shape, **Monash** describes the magnitude.
  - Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$, further enhancement for Ω_c^0 are shown w.r.t e+e- collisions.

arXiv:2105.05187





PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
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SHM
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)
QCM
(EPJC 78 no.4, (2018) 344)
Catania
(arXiv:2012.12001)
Belle
(PRD 97, 072005 (2018))

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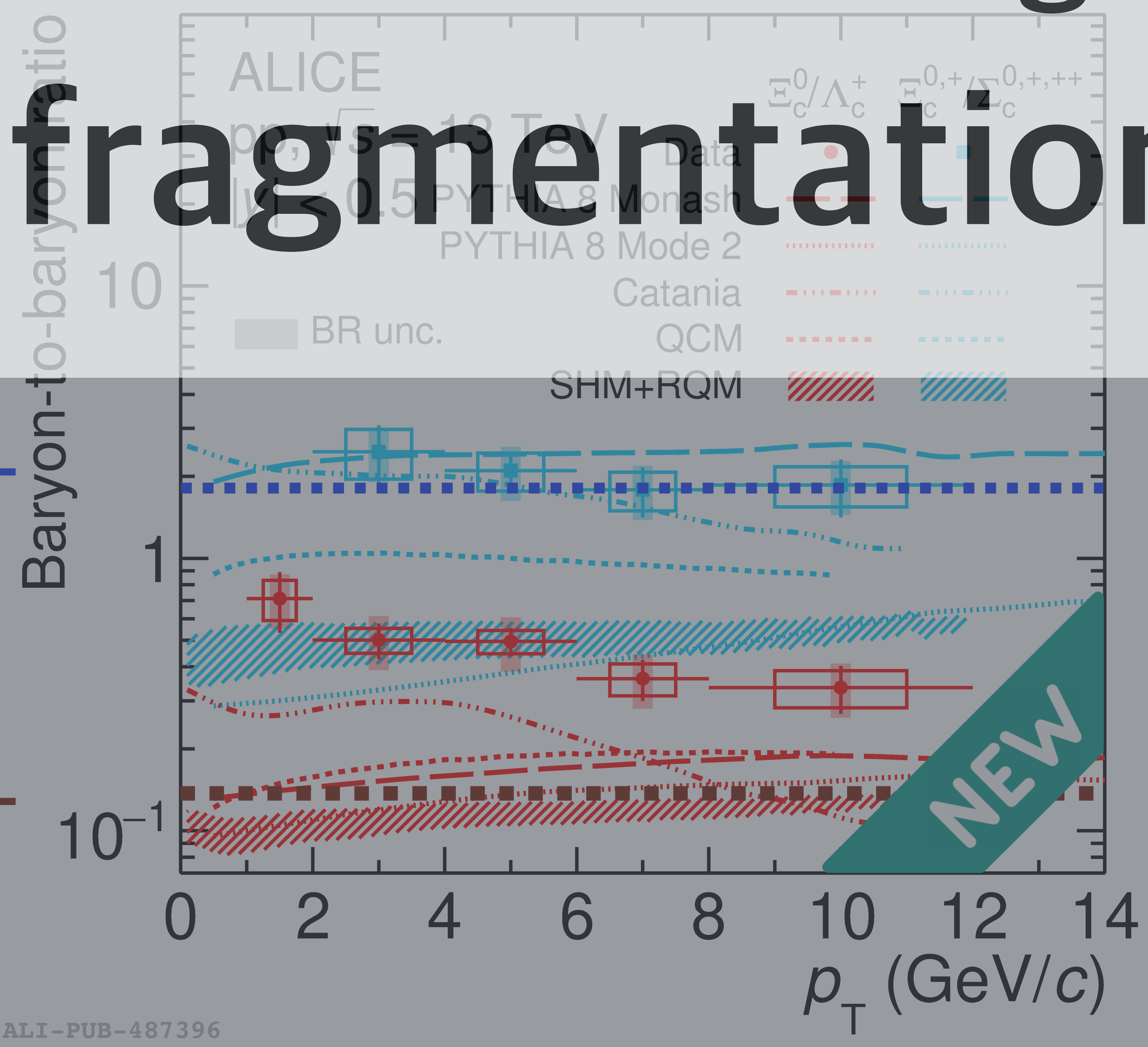
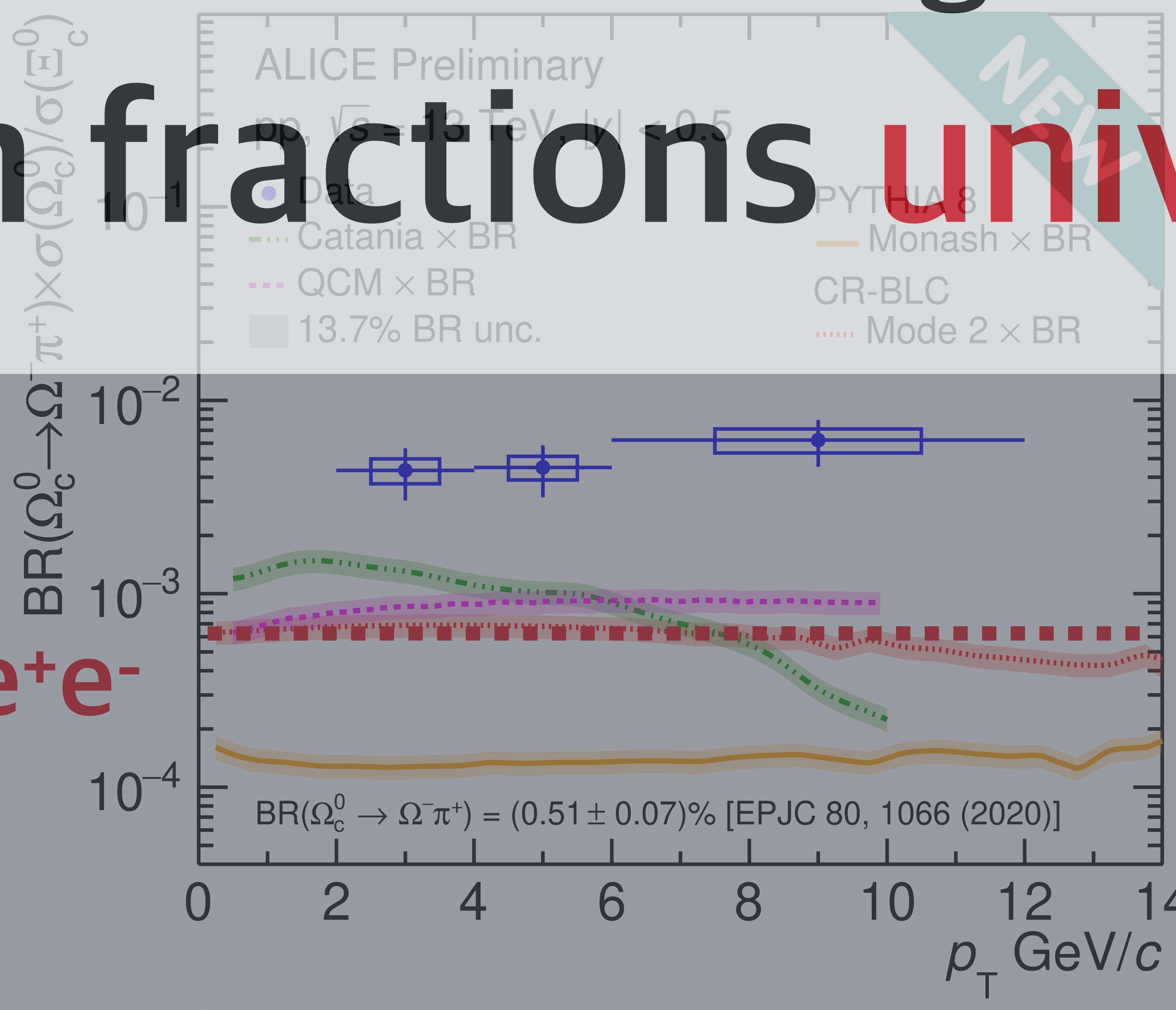
arXiv:2105.05187

We measure now all single charm hadron ground states!

Are fragmentation fractions universal?





PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
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SHM
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RQM
(PRD 84 (2011) 014025)
QCM
(EPJC 78 no.4, (2018) 344)
Catania
(arXiv:2012.12001)
Belle
(PRD 97, 072005 (2018))

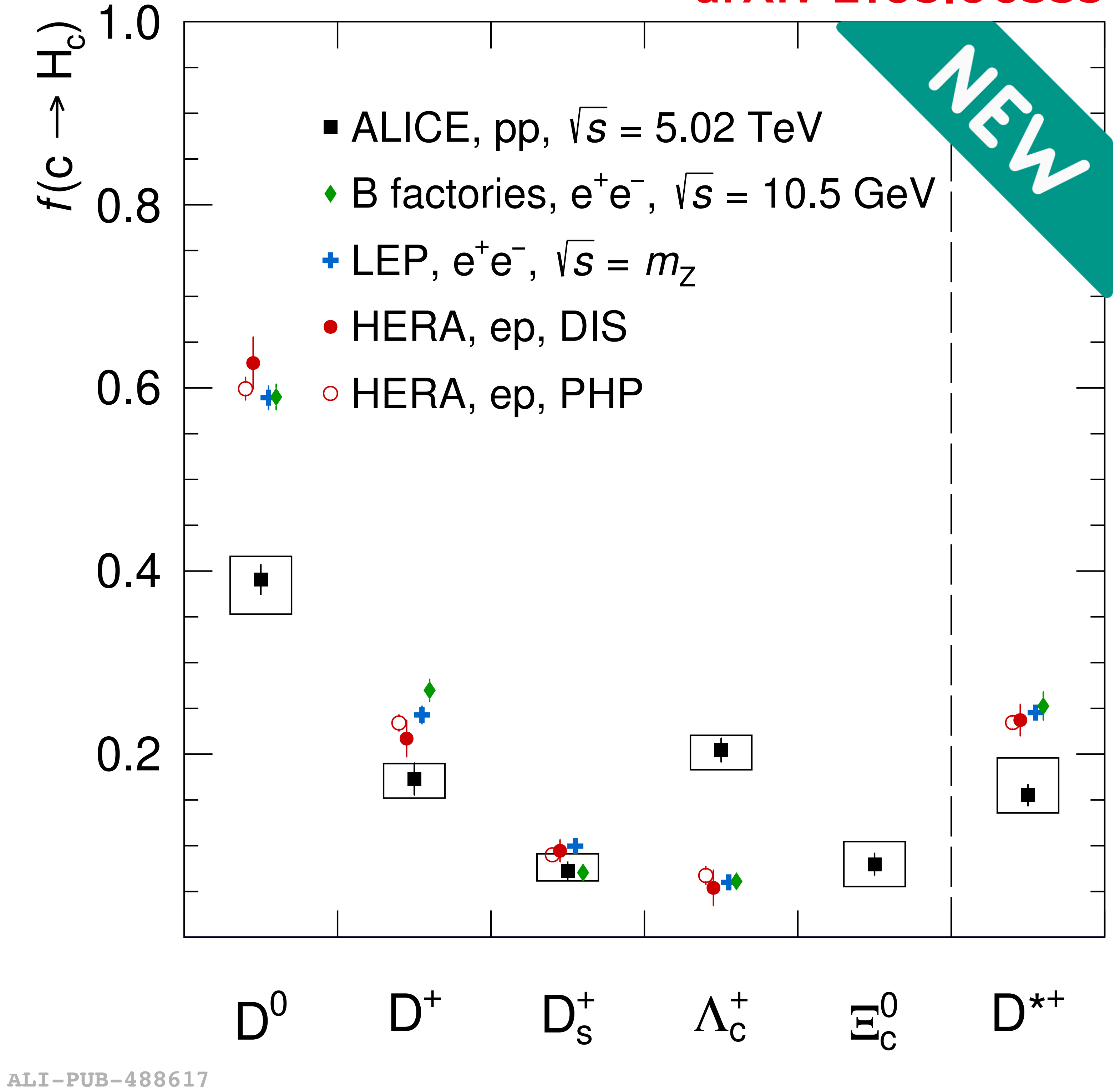
Charm fragmentation fractions

- **Charm fragmentation fractions**
  - Fragmentation fraction for the Ξ_c^0 baryon is measured for the first time.
  - Not counting the contribution of D^{*+}, which feeds into the D^0 and D^+ mesons.

H_c	$f(c \to H_c)[\%]$
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^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

+ Ξ_c^+ contribution is considered as Ξ_c^0 contribution

arXiv:2105.06335



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 are not universal!**

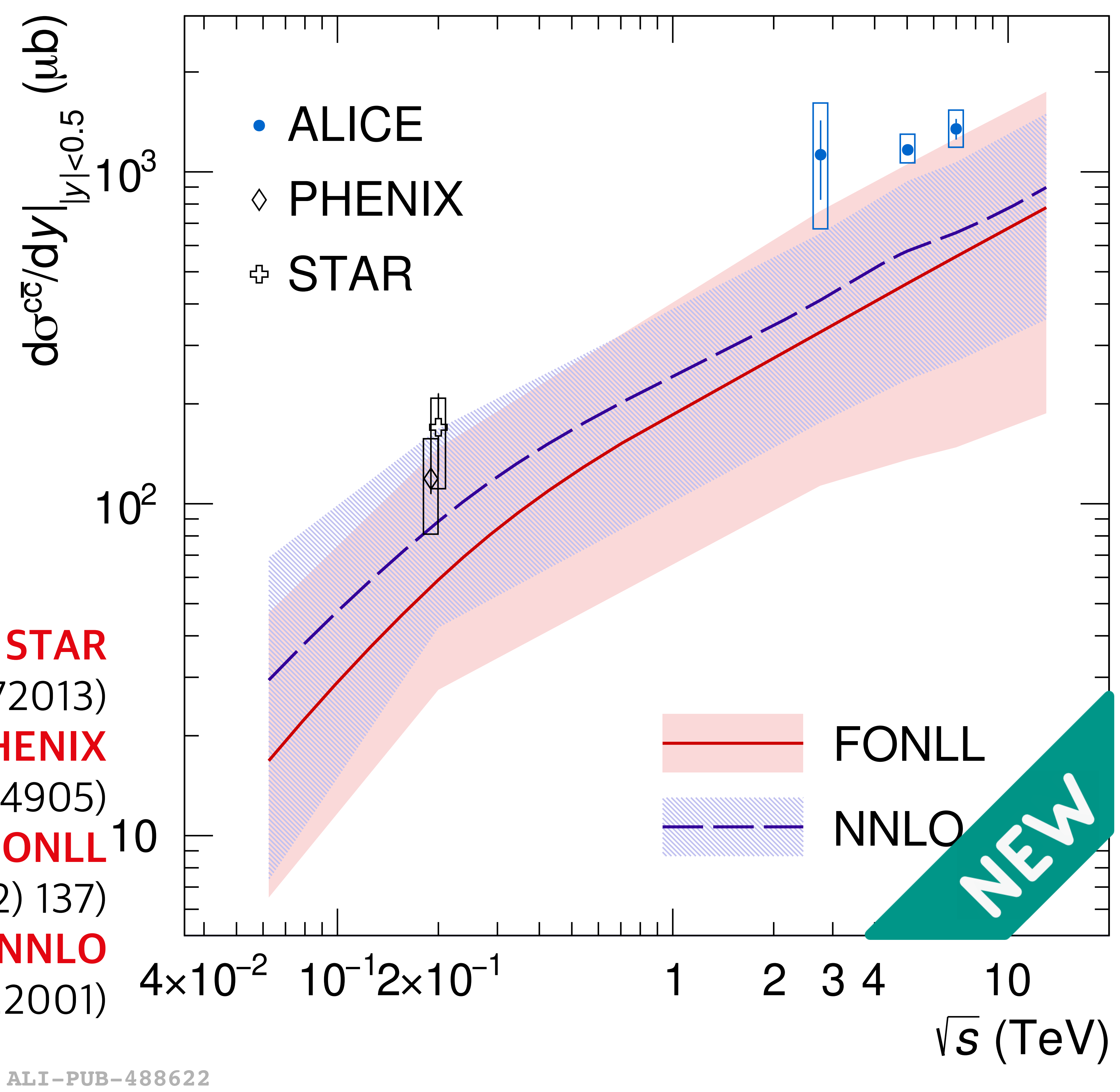
Charm production cross section

- **Charm production cross section at the LHC**
  - First measurement of charm production cross section per unit of rapidity at midrapidity in pp collisions at 5.02 TeV

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

  - According to new measured charm fragmentation fractions, updated charm cross section measurements in pp collisions at 2.76 TeV and 7 TeV are about **40% higher** than the previously published results.
  - All of measurements in ALICE with new charm fragmentation fractions lies at the upper edge of the pQCD calculations.

arXiv:2105.06335



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

Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and Ω_c^0 production cross section in pp collisions at 13 TeV.
- First measurement of Λ_c^+ down to p_T = 0 GeV/*c* in 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-baryon production.
- The charm fragmentation fractions are not universal.

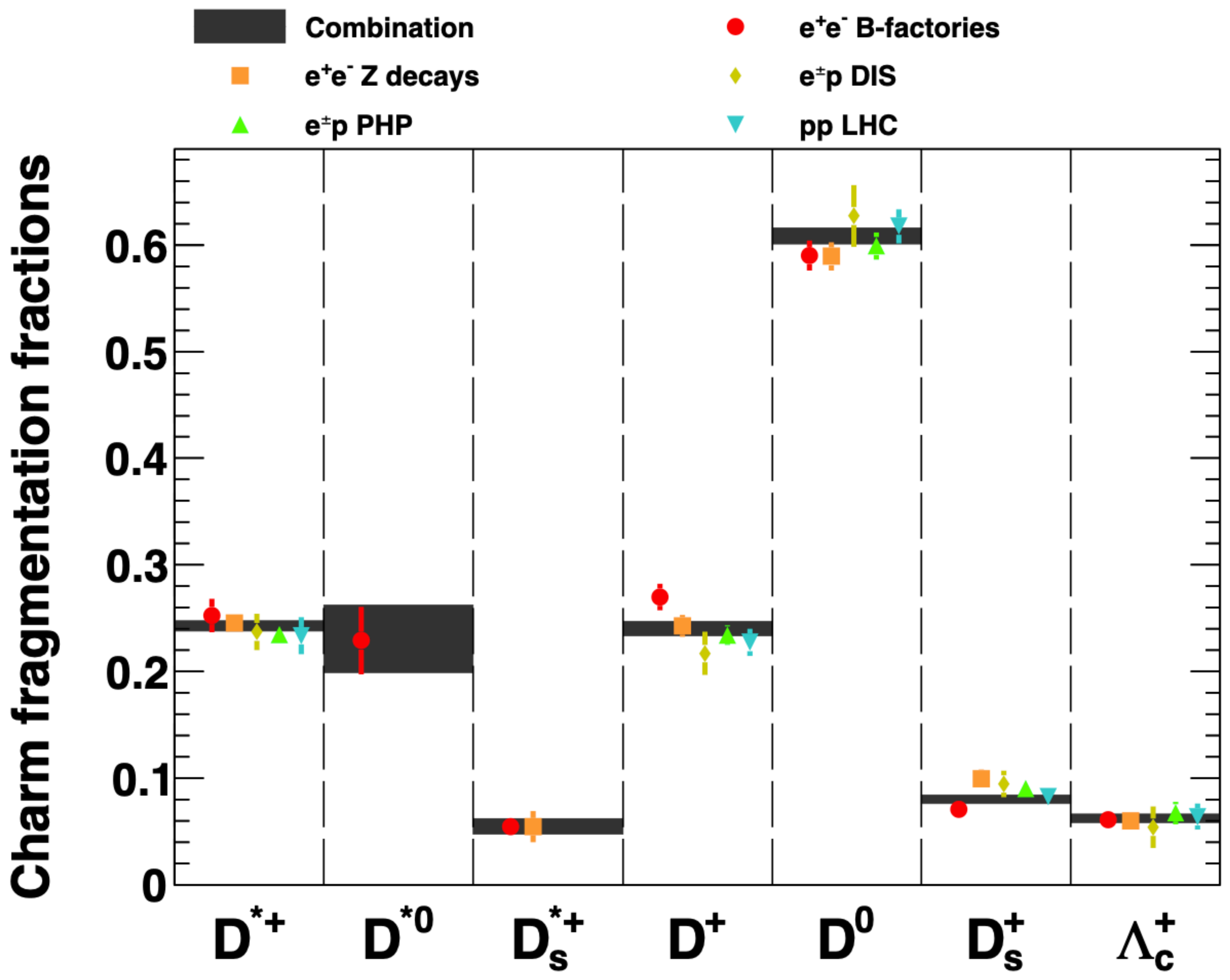
- ALICE upgrade for Run3+4 will offer the opportunity to explore, with higher precision, charm-baryon production measurements in a wider p_T region.

Back up

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
    - $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(c \to \Xi_c^0)/f(c \to \Lambda_c^+)$
      $= f(s \to \Xi^-)/f(s \to \Lambda) = 0.066$
    - $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+) = f(s \to \Omega^-)/f(s \to \Lambda) = 0.004$
    - $f(c \to \Omega_c^0)/f(c \to \Xi_c^0) = f(s \to \Omega^-)/f(s \to \Xi^-) = 0.062$

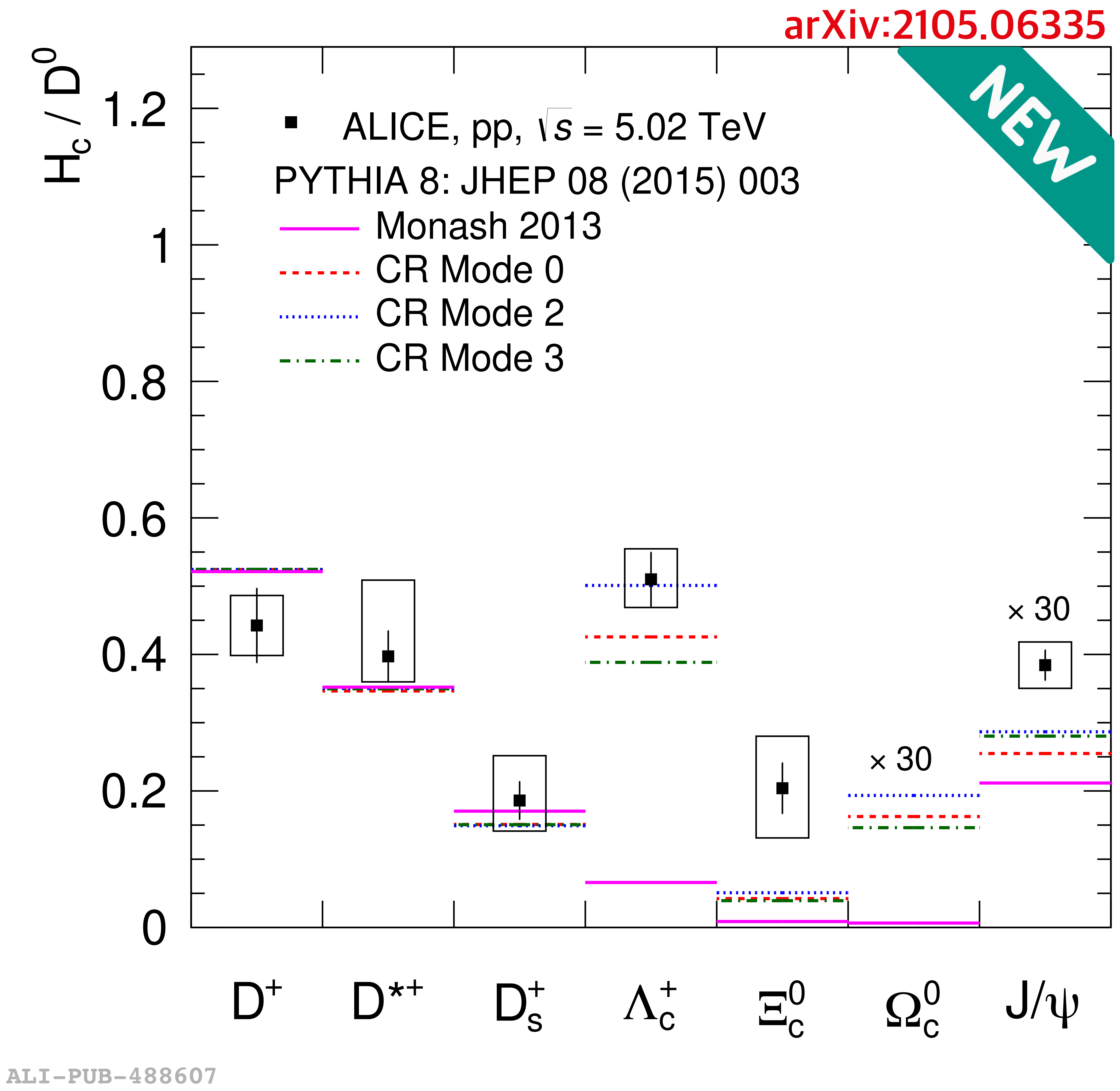
Eur. Phys. J. C76 (2016) no.7, 397

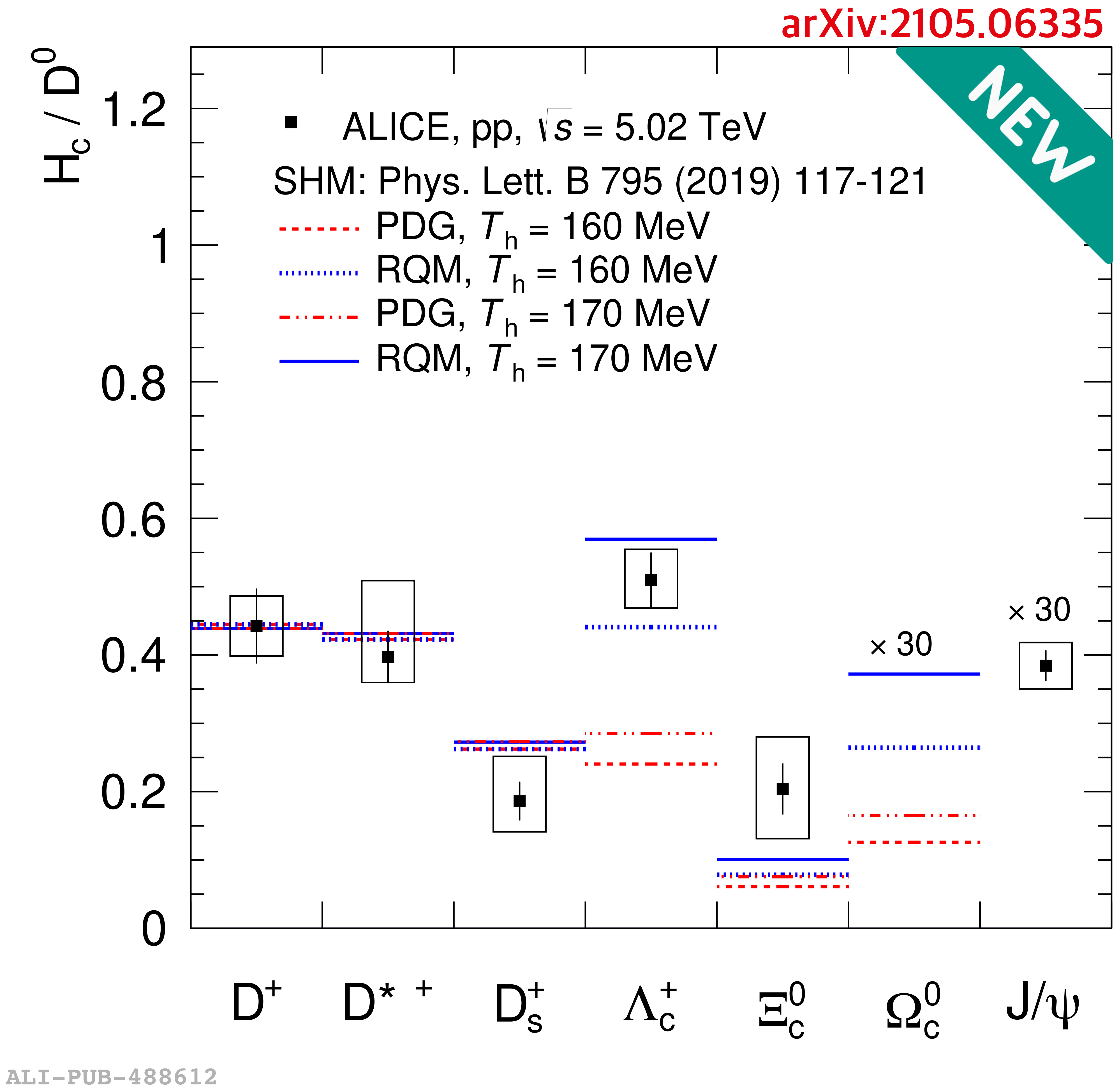


- **Caveat**
  - NO measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c)$ and $\sigma(\Omega_c)$.
  - In 2015, only LHCb Λ_c^+ measurement available.
    - Rapidity range : $2.0 < y < 4.5$

Charm hadron/D^0 Ratios

- **The ratio of p_T integrated cross sections of the various charm hadrons and D^0 meson**
  - SHM for charm baryon is sensitive to a hadronisation temperature.

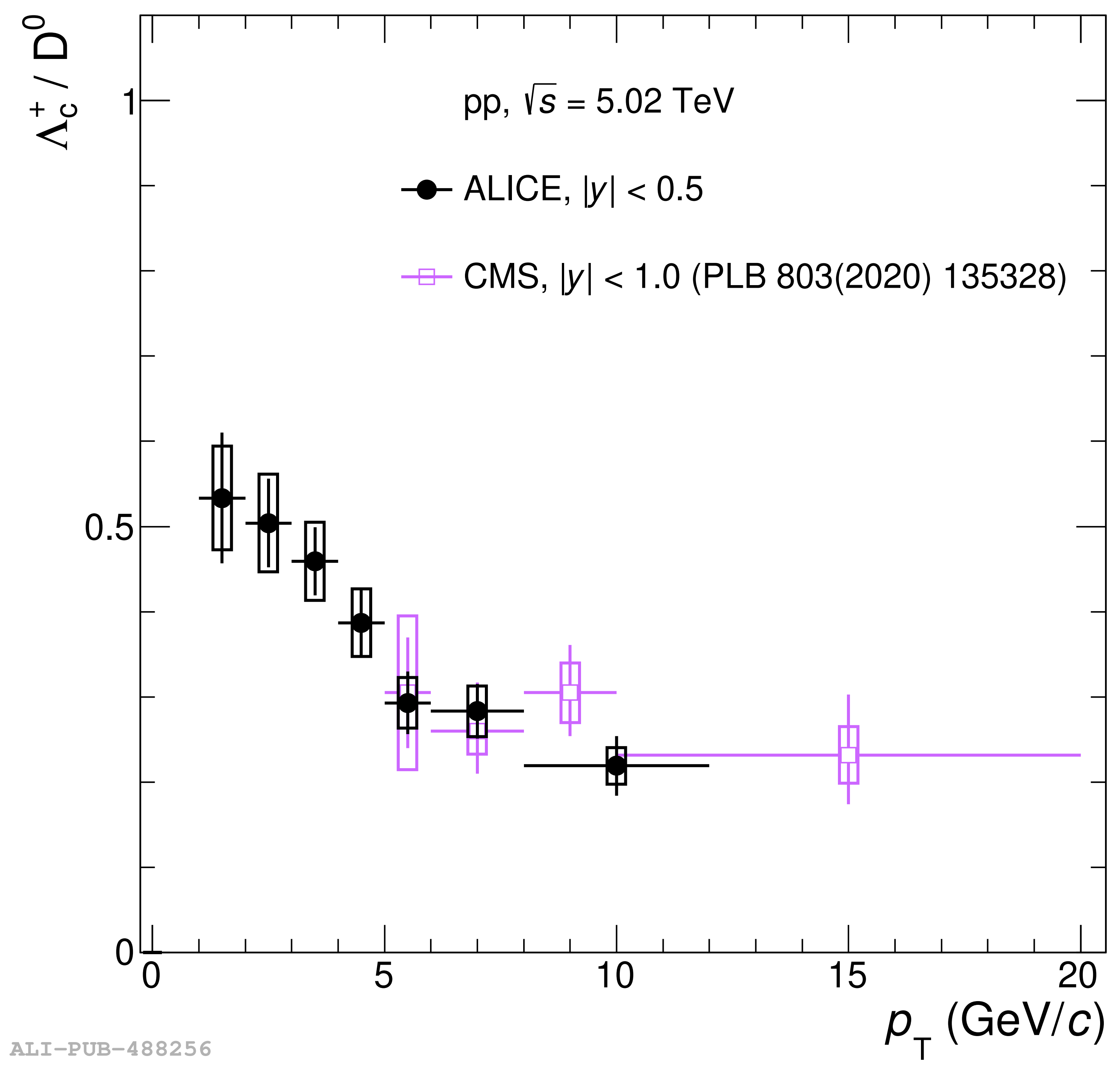




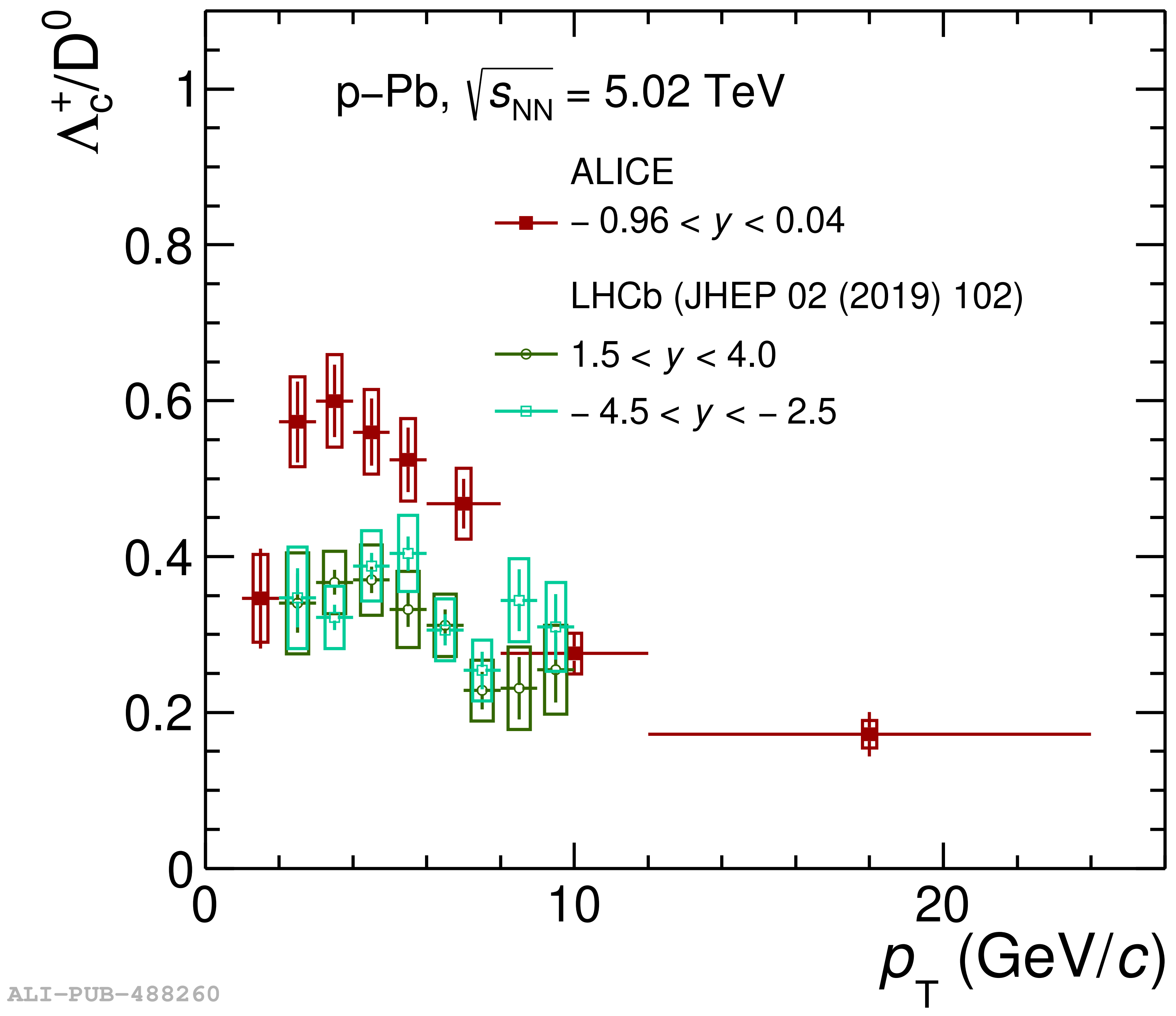
Λ_c^+ measurements comparison

- 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.

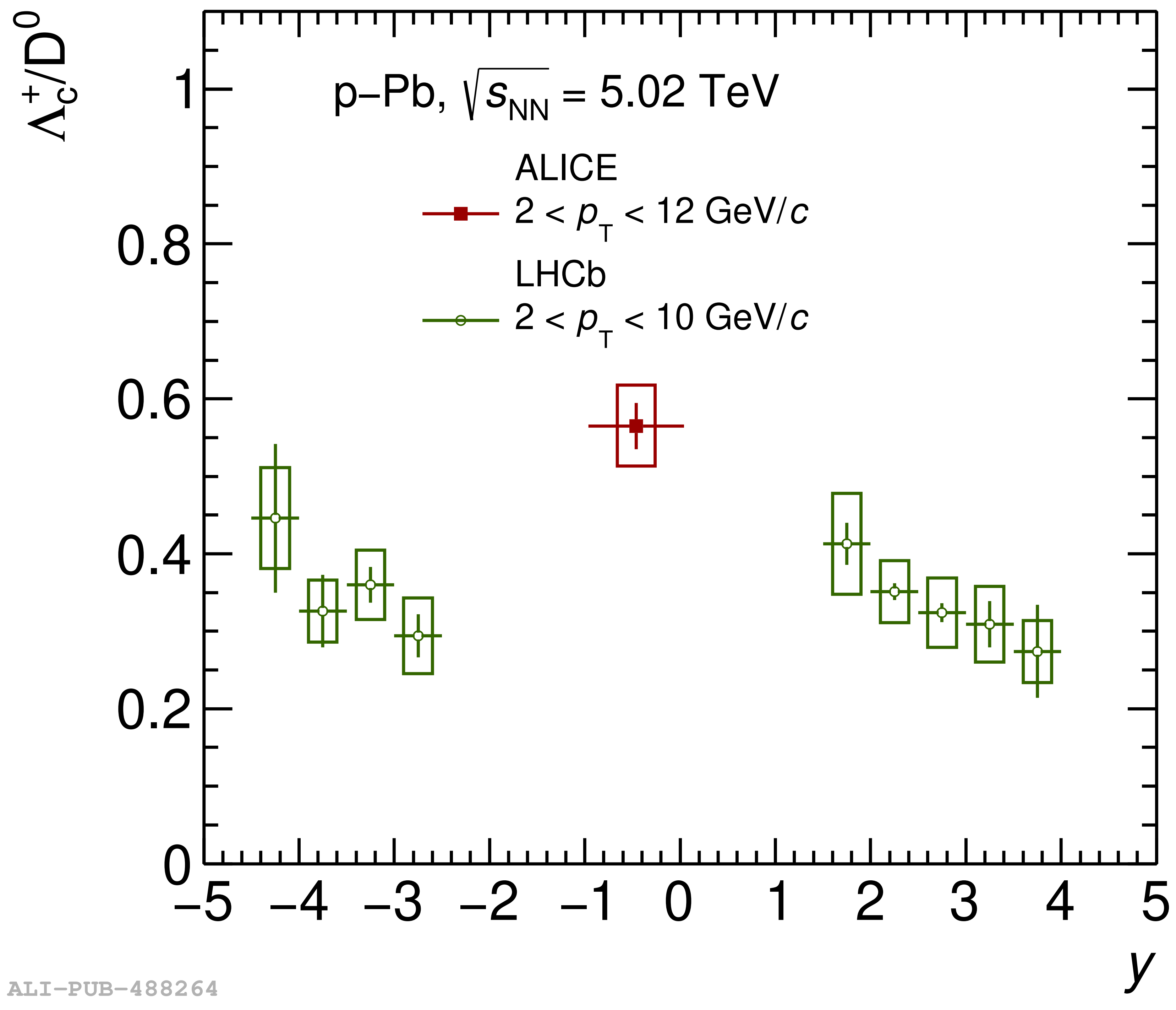
arXiv:2011.06079



arXiv:2011.06079

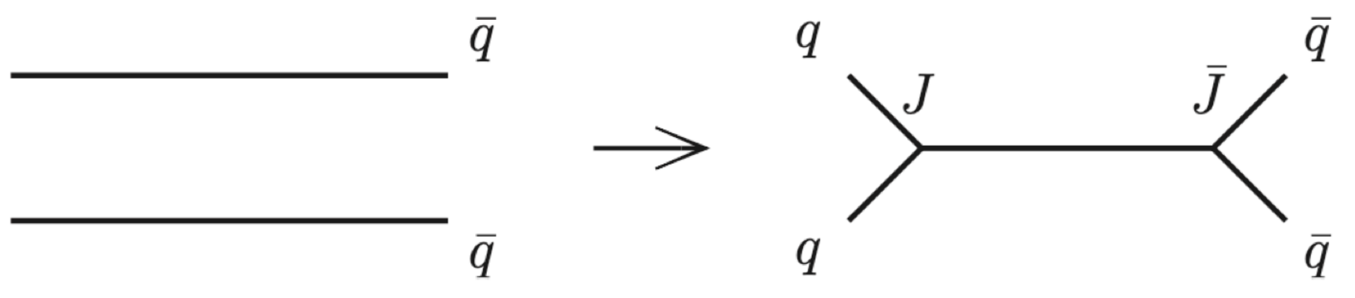


arXiv:2011.06079



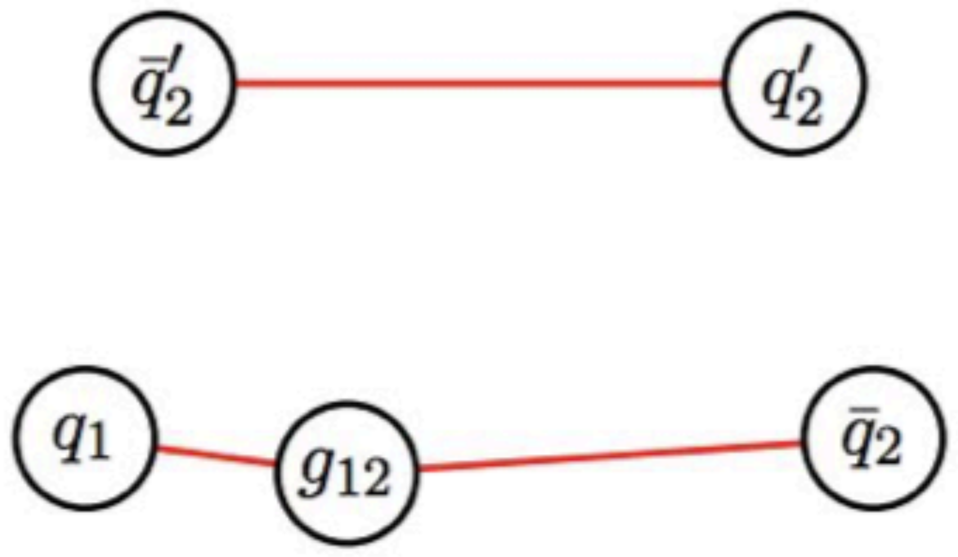
HF baryon enhance mechanism

- **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 dilation



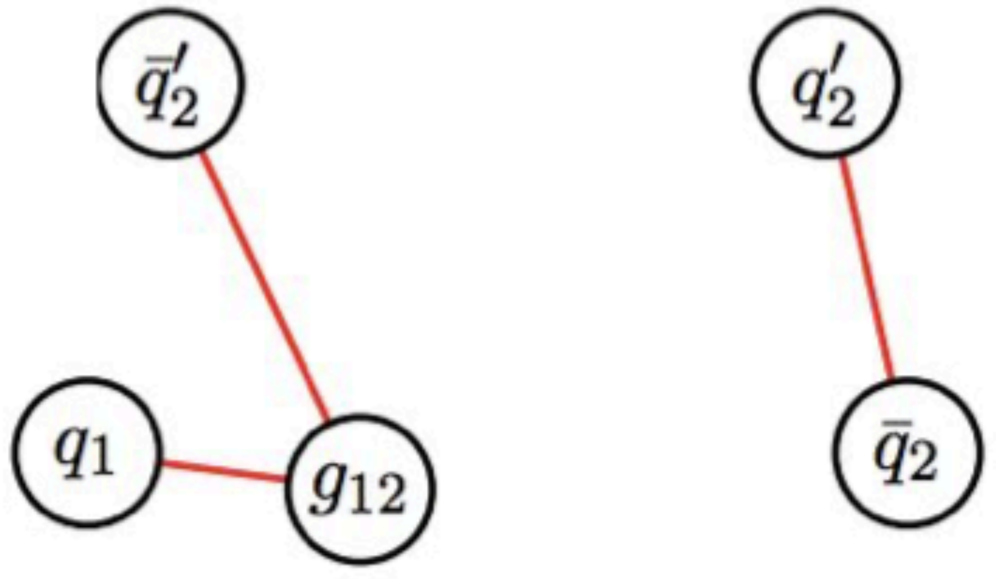
(b) Type II: junction-style reconnection

No CR



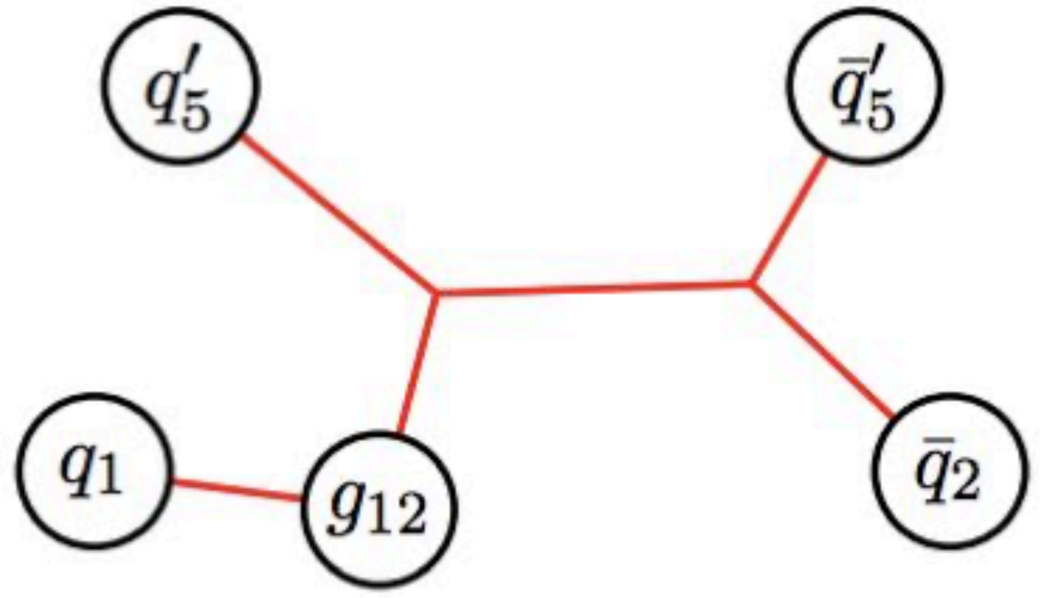
- Partons created in different MPIs do not interact

Old CR



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

New CR



- Simple model of QCD colour rules to determine the formation of strings
- Minimization of the string length over all possible configurations
- Include CR with MPIs and with beam remnants

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  - Junction connection topologies enhance baryon formation
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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)
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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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  - Junction connection topologies enhance baryon formation
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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