ICHEP 2022 BOLOGNA

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Jianhui Zhu (INFN-Padova & CCNU)
for the ALICE Collaboration

Constraining hadronization with prompt and non-prompt charm baryons in small collision systems with ALICE at the LHC

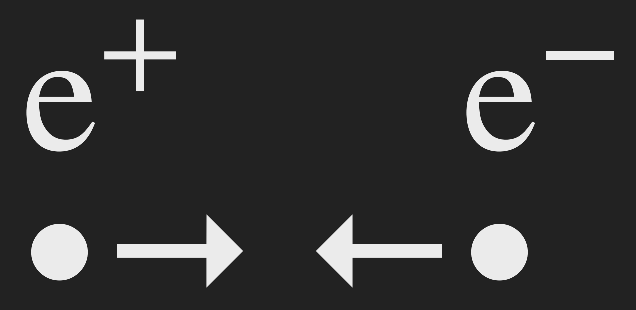
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

華中師範大學
CENTRAL CHINA NORMAL UNIVERSITY

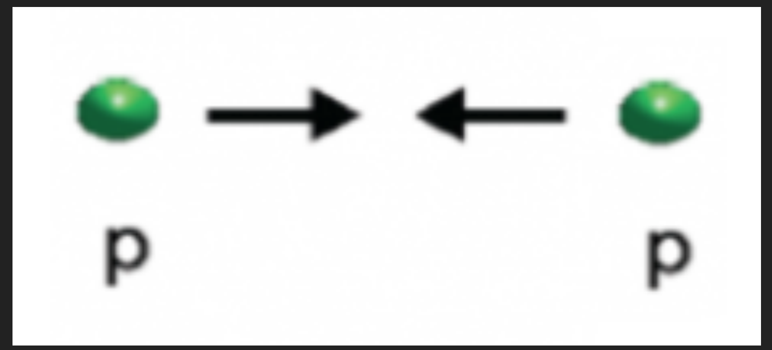
ALICE

Heavy-flavour hadron formation in small collision systems

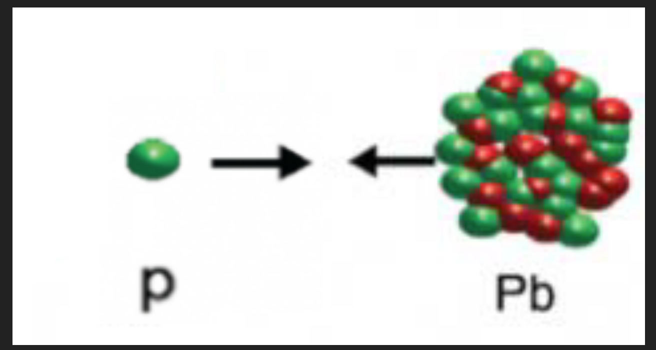
ALICE



- "Point-like" object interaction
- Pure fragmentation



- Superposition of many "point-like object" collisions ?
- MPI and color reconnection modify hadronization ?



- Cold nuclear matter effects
- Modified hadronization ?
- Radial flow ?

Heavy-flavour hadron production cross section based on factorisation approach

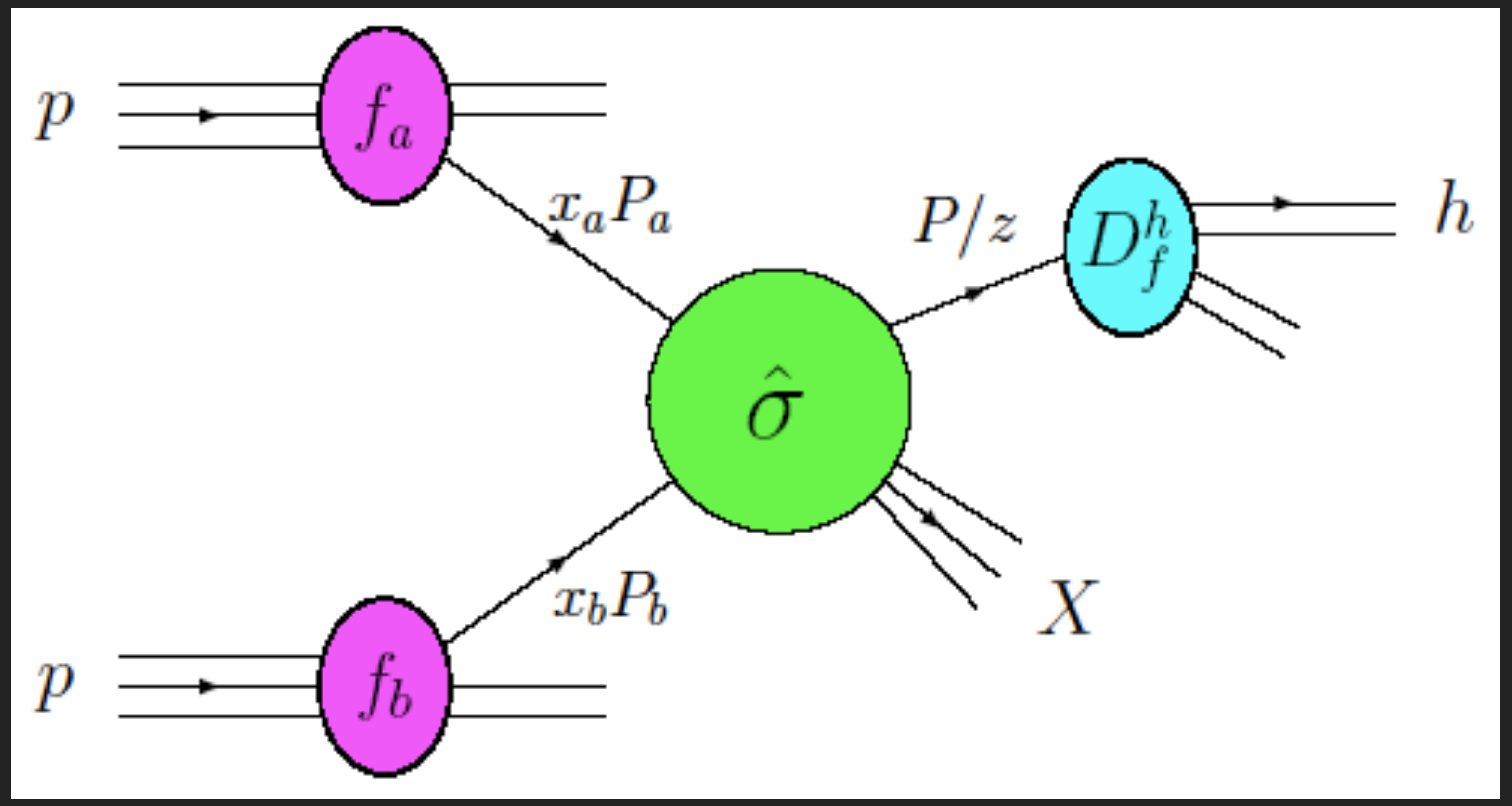
- Fragmentation functions assumed to be universal among collision systems and constrained from e^+e^- and e^-p collisions

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

parton distribution function (PDF) (non-perturbative)

partonic cross section (perturbative)

hadronisation by fragmentation (non-perturbative)



- Ratios of particle species -> ratios of fragmentation fractions, sensitive to heavy-quark hadronization

Charm-hadron reconstruction

- Particle identification of decay tracks
- Selections on the displaced decay topology
- Machine-learning (ML) techniques used

Charm mesons

$D^0 : D^0 \rightarrow K^-\pi^+$

$D^+ : D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} : D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$

$D_s^+ : D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$

Charm baryons

$\Lambda_c^+ : \Lambda_c^+ \rightarrow pK^-\pi^+, \Lambda_c^+ \rightarrow pK_s^0$

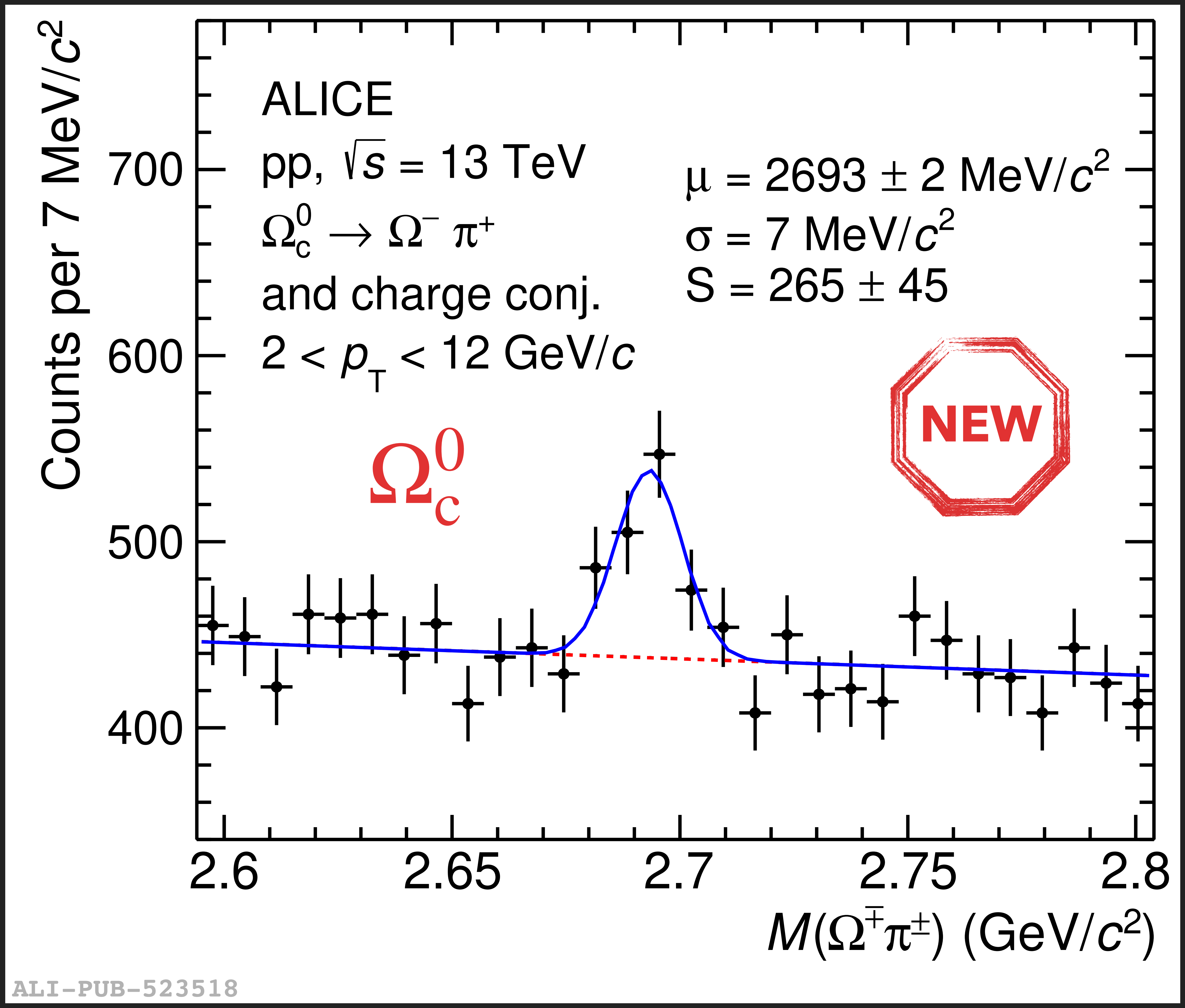
$\Sigma_c^{0,++} : \Sigma_c^0 \rightarrow \Lambda_c^+\pi^-, \Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

$\Xi_c^0 : \Xi_c^0 \rightarrow \Xi^-\pi^+, \Xi_c^0 \rightarrow e^+\Xi^-\nu_e$

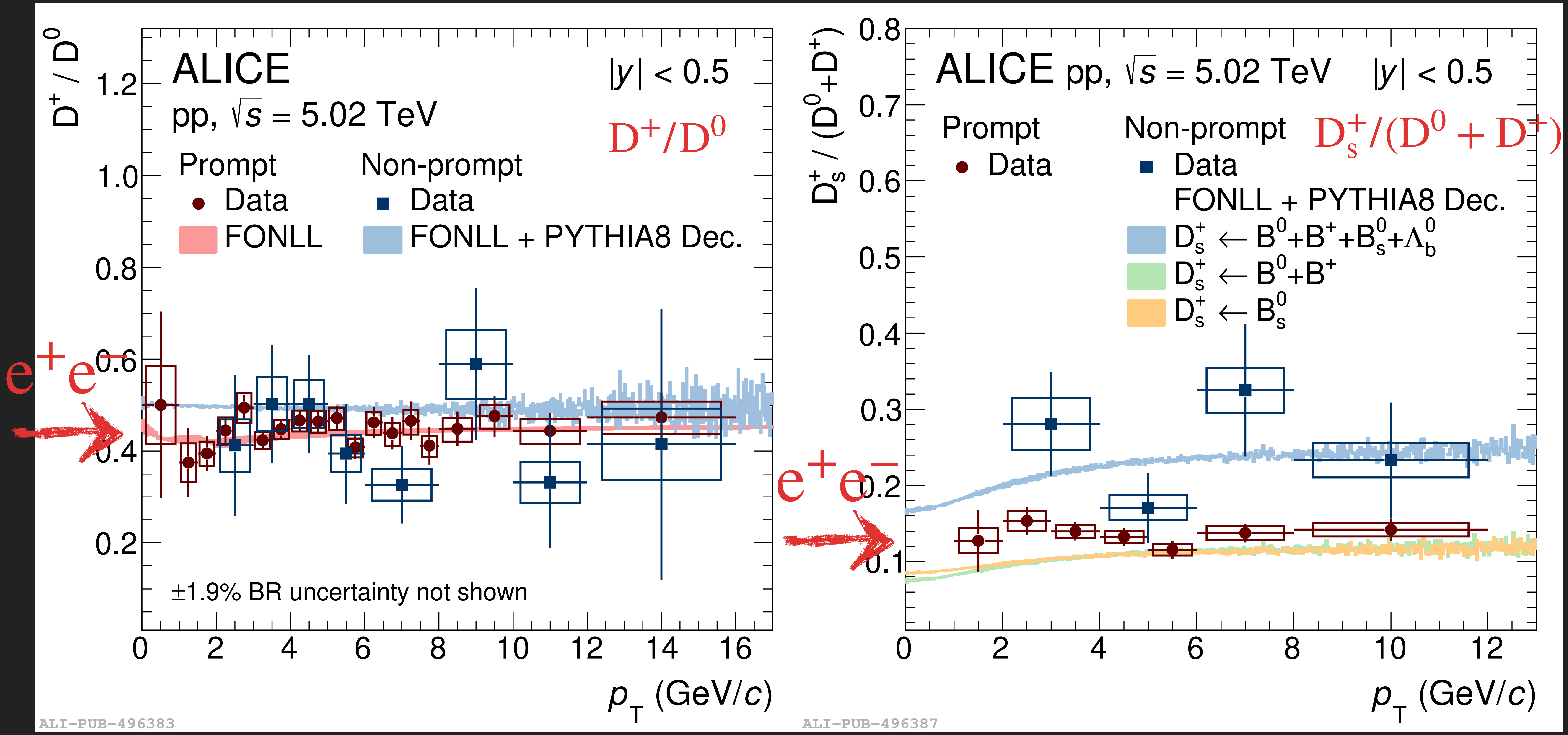
$\Xi_c^+ : \Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$

$\Omega_c^0 : \Omega_c^0 \rightarrow \Omega^-\pi^+$

arXiv:2205.13993



HF meson-to-meson production ratios in pp collisions



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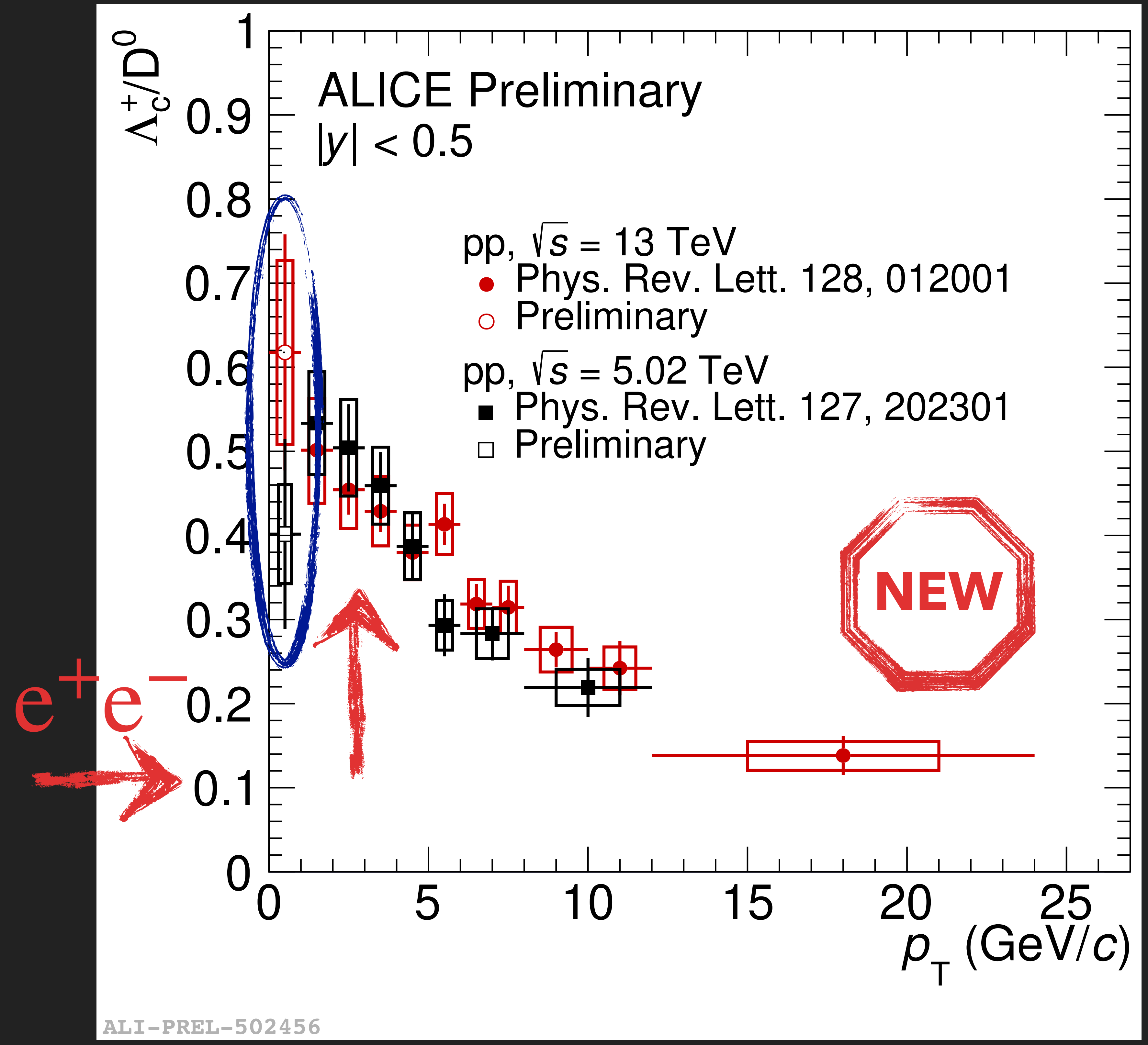
- Prompt and non-prompt D meson ratios independent of p_T and collision system
- Agreement with model calculations based on a factorisation approach and relying on universal fragmentation functions and with e^+e^- and e^-p measurements

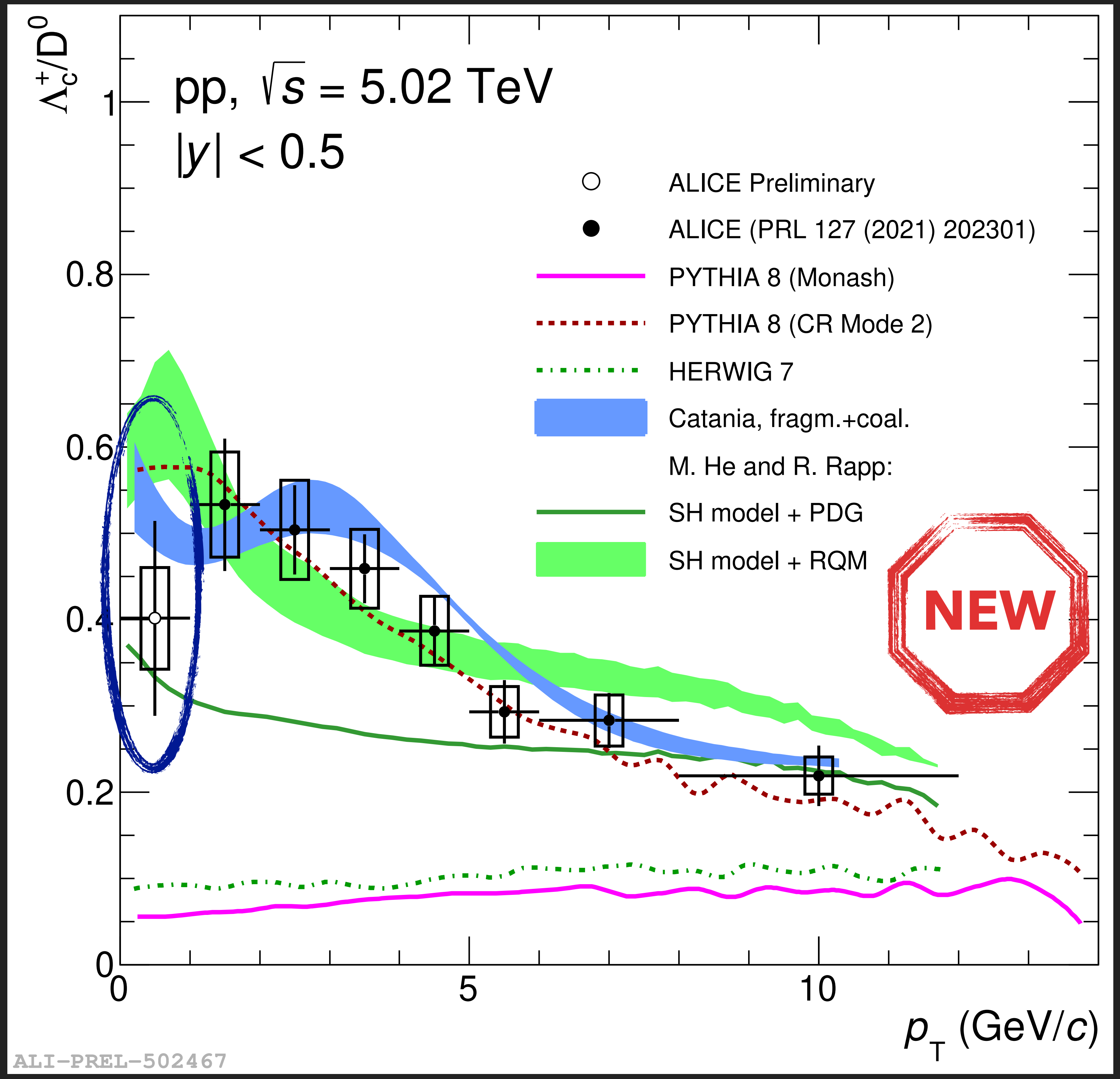
FONLL: M. Cacciari, et al., JHEP 10 (2012) 137
PYTHIA 8: P. Skands, et al., EPJC 74 (2014) 3024

Baryon-to-meson ratios: Λ_c^+/D^0 in pp collisions

- Λ_c^+/D^0 measured down to $p_T = 0$ in pp collisions
- Strong p_T dependence
- NO collision energy dependence
- Significantly higher than e^+e^- results



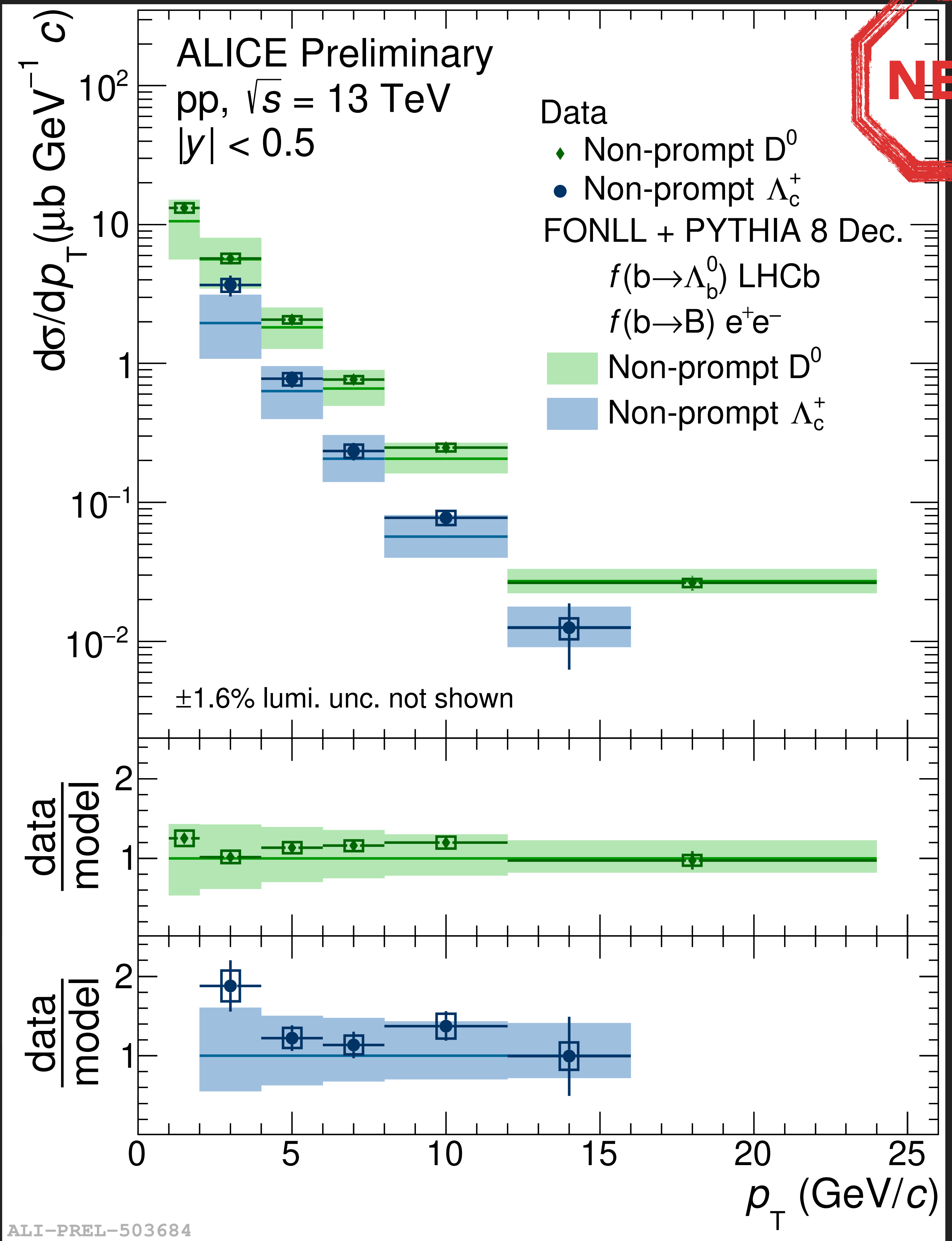
- Largely underestimated by PYTHIA 8 Monash[1]
  - PYTHIA 8 Monash: e^+e^- charm fragmentation functions
- Well described by PYTHIA 8 CR Mode2[2], SHM[3]+RQM[4], Catania[5]
  - PYTHIA 8 CR Mode2: color reconnection (CR) beyond leading color (BLC) approximation
  - Catania: transport model with hadronization via coalescence+fragmentation
  - SHM+RQM: statistical hadronization model (SHM) with augmented set of charm-baryon states according to relativistic quark model (RQM)



[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., PLB 821 (2021) 136622

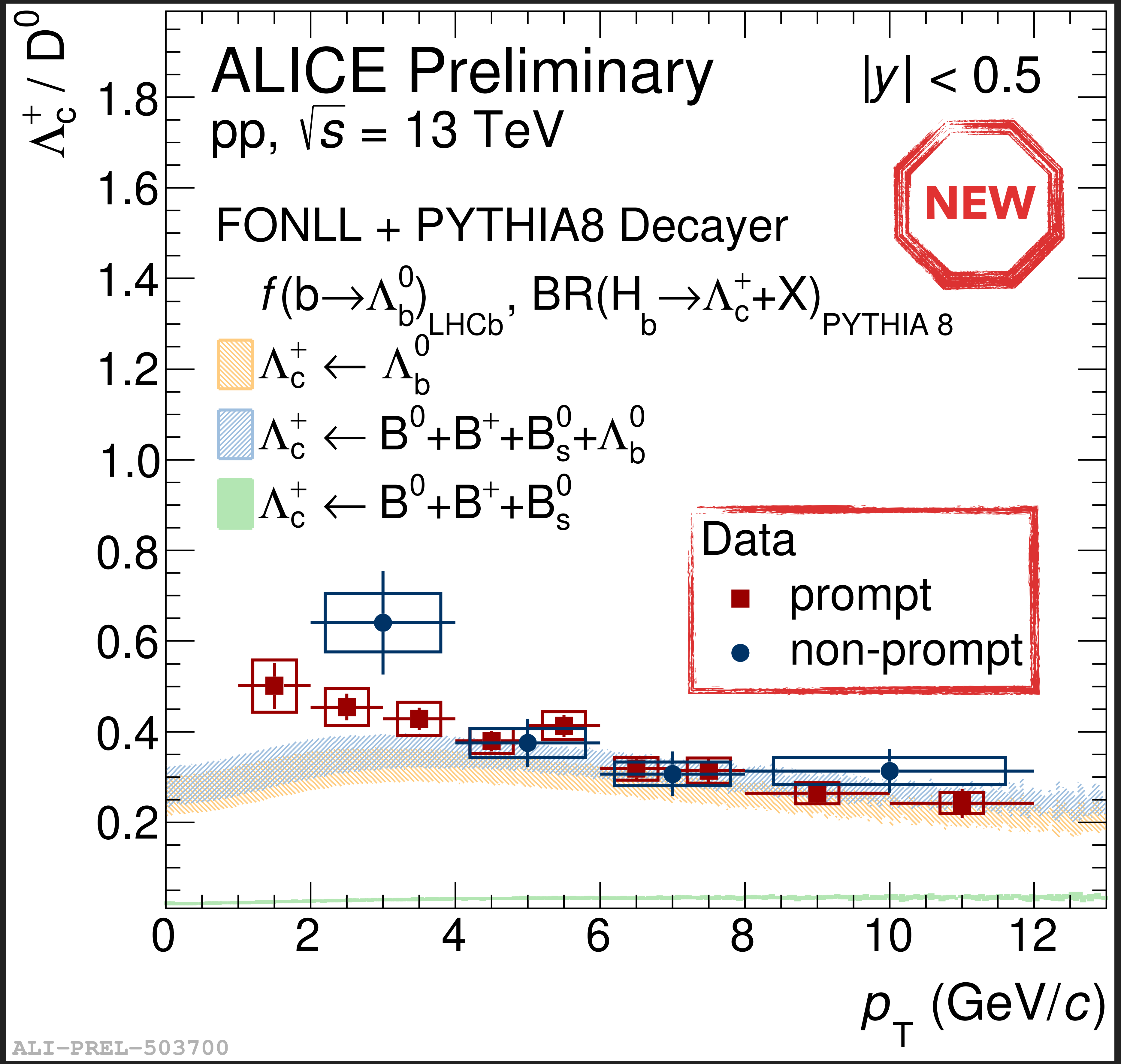
Non-prompt Λ_c^+ production in pp@13 TeV

ALICE



LHCb: Phys.Rev.D 100 (2019), 031102

Beauty: K. Demmich, tomorrow 17:45, "Strong Interactions and Hadron Physics"

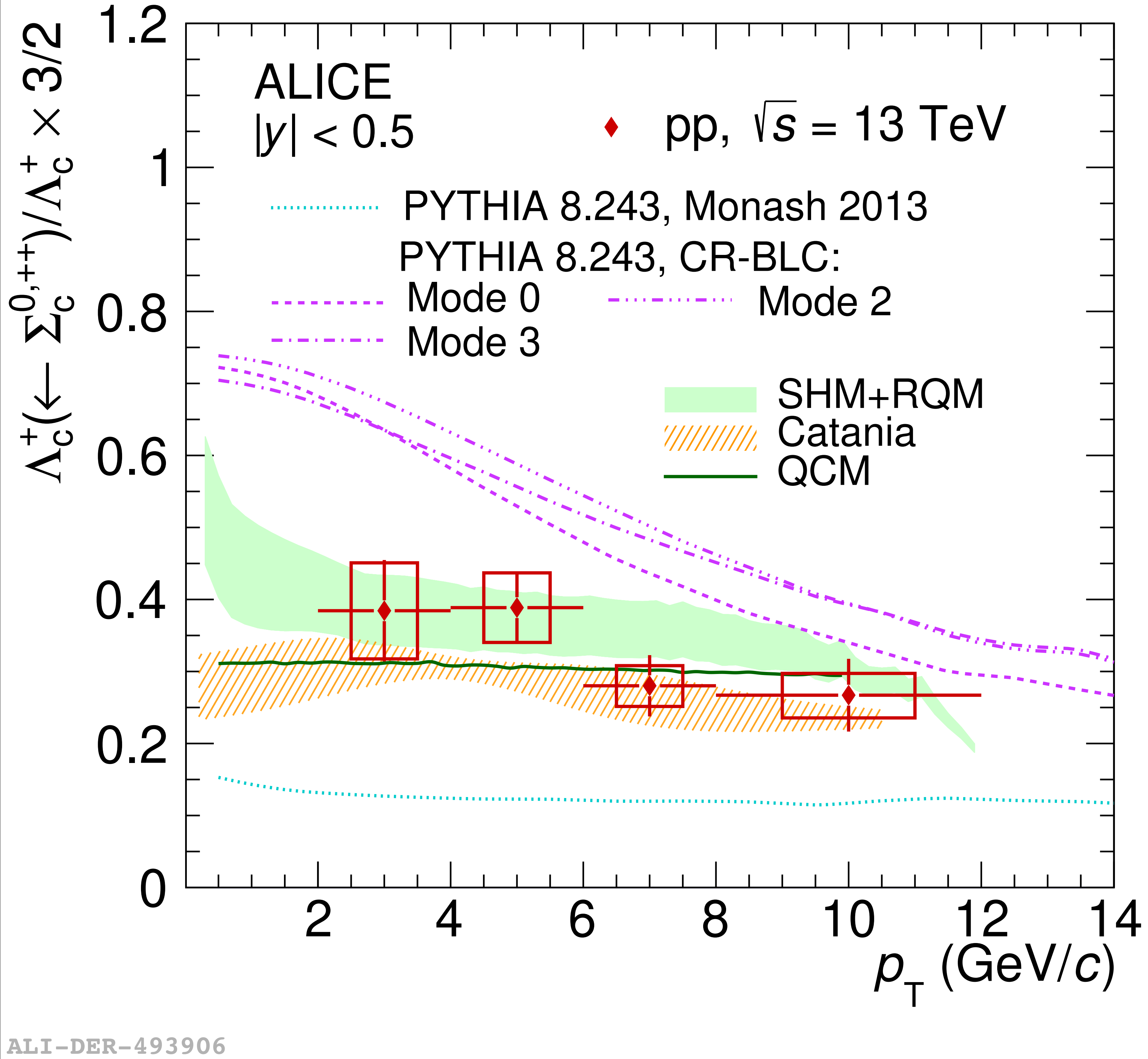


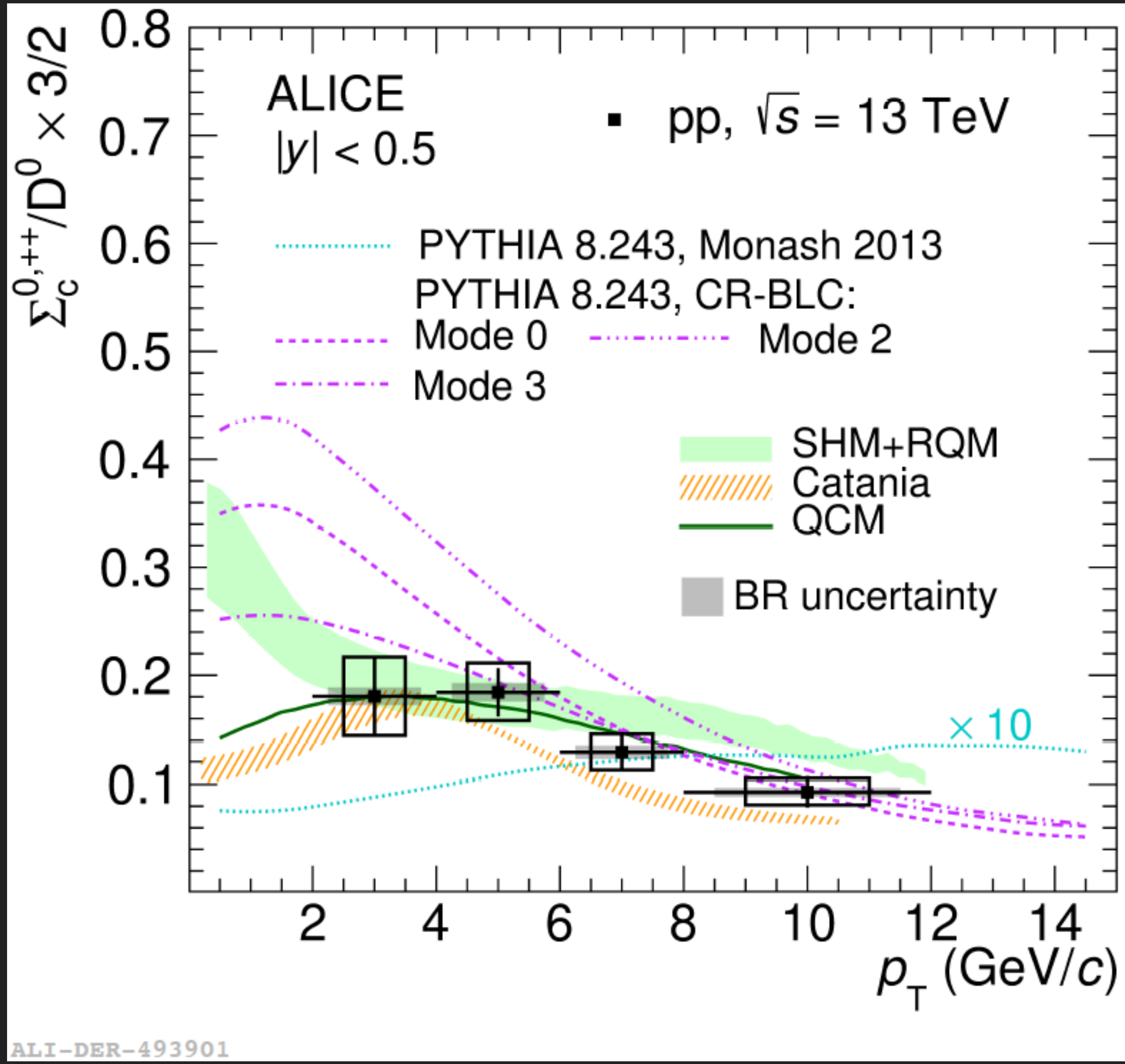
- p_{T} dependence well reproduced by theoretical calculations
  - Λ_b^0 fragmentation fractions measured by LHCb
  - Folding with $\mathrm{H_b} \rightarrow \Lambda_c^+ + \mathrm{X}$ decay from PYTHIA 8
- Non-prompt vs. prompt Λ_c^+/D^0
  - Similar baryon-to-meson ratio enhancement
- Non-prompt Λ_c^+/D^0 vs. models
  - Well reproduced by FONLL + PYTHIA 8 for $p_{\mathrm{T}} > 4\ \mathrm{GeV}/c$

Heavier charm baryons: $\Sigma_c^{0,+,++}$ in pp@13 TeV

- Feed-down from $\Sigma_c^{0,+,++}$ partially explains Λ_c^+/D^0 enhancement
  - $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+ = 0.38 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$
- $\Sigma_c^{0,+,++}/D^0$ enhancement in pp w.r.t. e^+e^-

PRL 128 (2022) 1, 012001



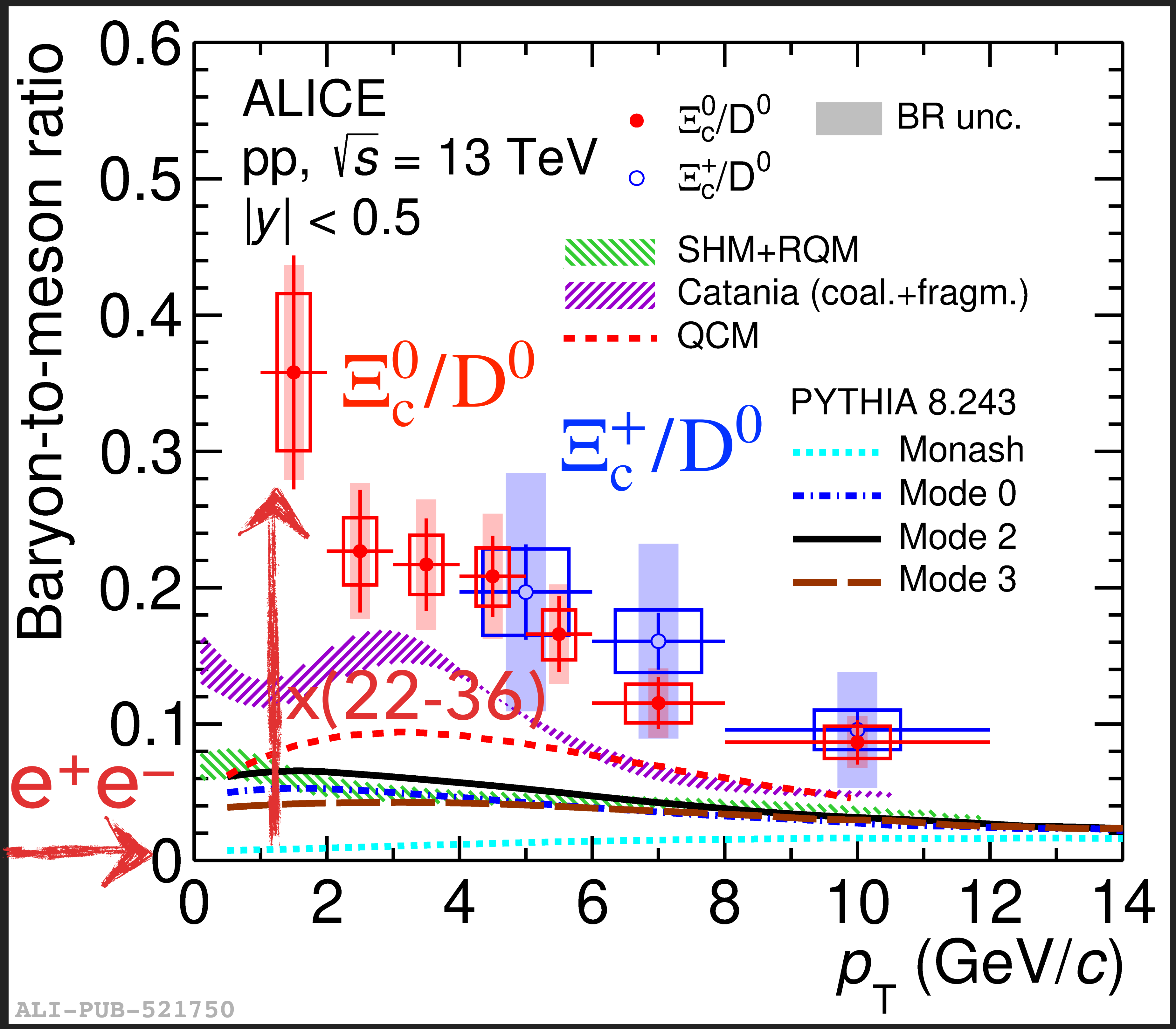


- PYTHIA 8 Monash[1] severely underestimates $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$
- PYTHIA 8 CR Modes[2] overestimate $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$, but describe $\Sigma_c^{0,+,++}/D^0$
- Well described by SHM[3]+RQM[4], Catania[5] and QCM[6]

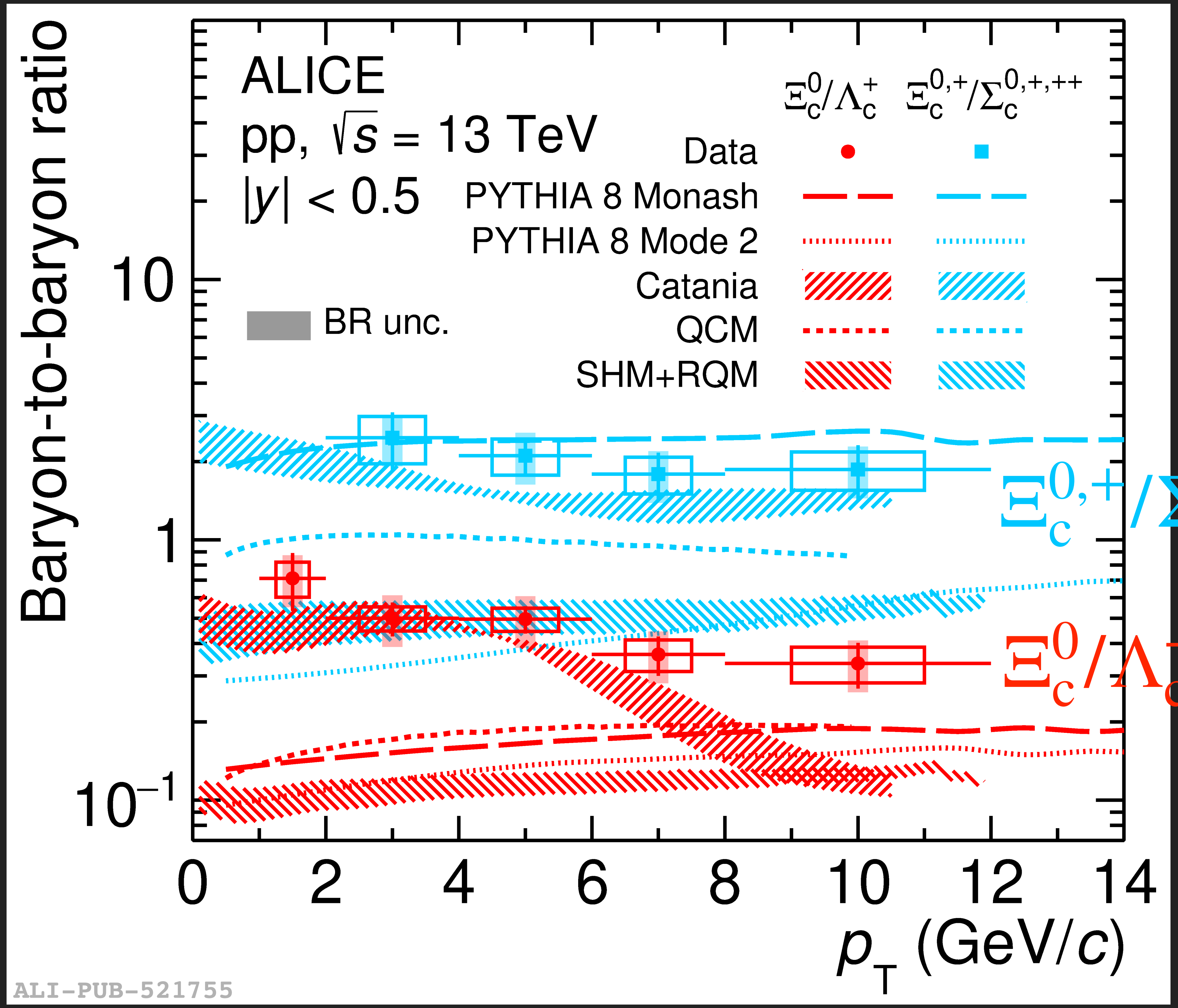
[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., PLB 821 (2021) 136622
[6] J. Song, et al., EPJC (2018) 78: 344

Strange-charm baryons: Ξ_c^0 and Ξ_c^+ in pp@5.02 and 13 TeV

- Ξ_c^0/D^0 in agreement with Ξ_c^+/D^0 and similar p_T trend as Λ_c^+/D^0
- Significantly underestimated by models[1,2,3,4,5]
  - Different from $D_s^+/(D^0 + D^+)$ $\rightarrow$ baryons are "strange" ?



PRL 127 (2021) 27, 272001



- Catania[6] gets close to measurements
- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ in agreement with PYTHIA 8 Monash
  - Similar suppression of $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$ in e^+e^- ?
  - Matter of similar (diquark) mass ?
    - $m(uu, ud, dd)_1 \approx m(us)_0$

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] J. Song, et al., EPJC (2018) 78: 344
[6] V. Minissale, et al., PLB 821 (2021) 136622
[7] Belle e+e-: PRD 97 (2018) 7, 072005

Double strange-charm baryon: $\mathrm{BR} \times \Omega_c^0$ in pp@13 TeV

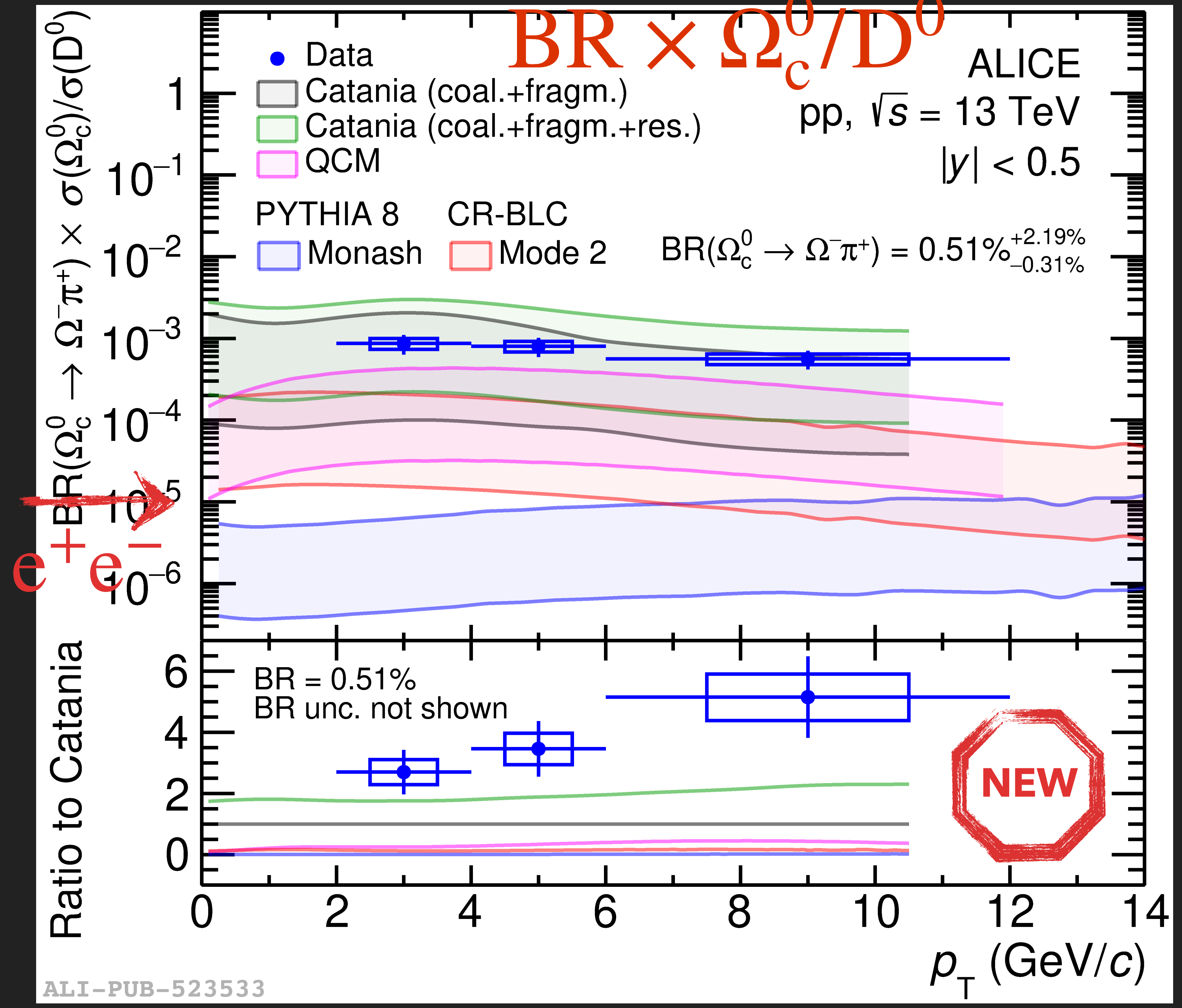
ALICE

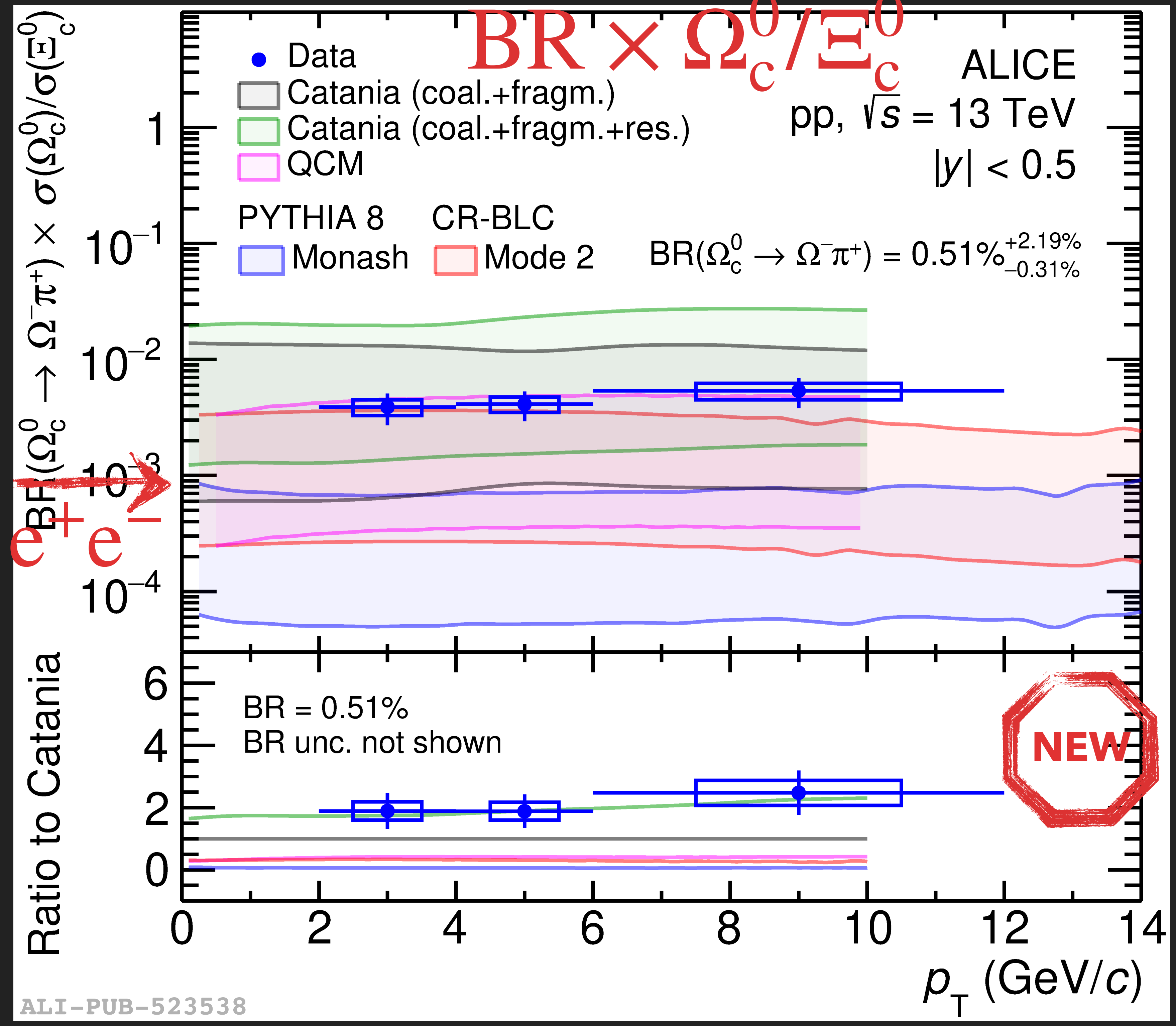
- Theoretical calculations: $\mathrm{BR}(\Omega_c^0 \rightarrow \pi^+\Omega^-) = 0.51^{+2.19}_{-0.31}\,\%$
- PYTHIA 8 Monash[1] largely underestimates Ω_c^0/D^0 and Ω_c^0/Ξ_c^0
  - ➡ Do not reproduce strangeness enhancement in pp
- PYTHIA 8 CR-BLC[2] NOT enough to describe the measurement
- Further enhancement with simple coalescence QCM[3] still shows a hint of underestimation
- Catania[4] closer to data points, additional resonances decay considered

Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^- 10.52 GeV) [28] visible
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(2.24 \pm 0.29 \pm 0.16) \times 10^{-4}$
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(8.58 \pm 1.15 \pm 1.98) \times 10^{-4}$

$$\frac{\Omega_c^0/\Lambda_c^+(pp)}{\Omega_c^0/\Lambda_c^+(e^+e^-)} \approx 9$$

$$\frac{\Omega_c^0/\Xi_c^0(pp)}{\Omega_c^0/\Xi_c^0(e^+e^-)} \approx 5$$



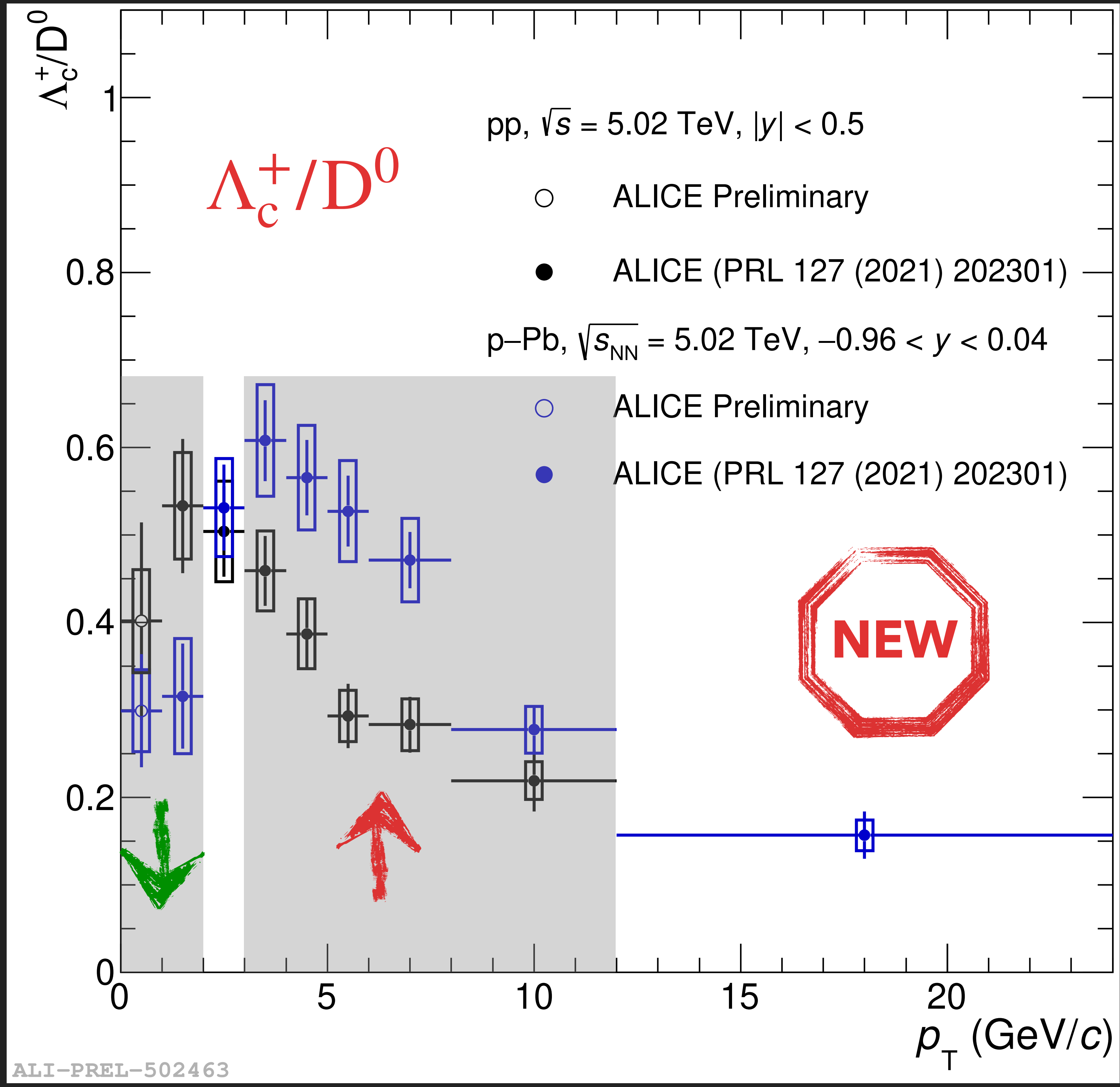


Sizeable contribution of Ω_c^0 to charm production at LHC energies ?

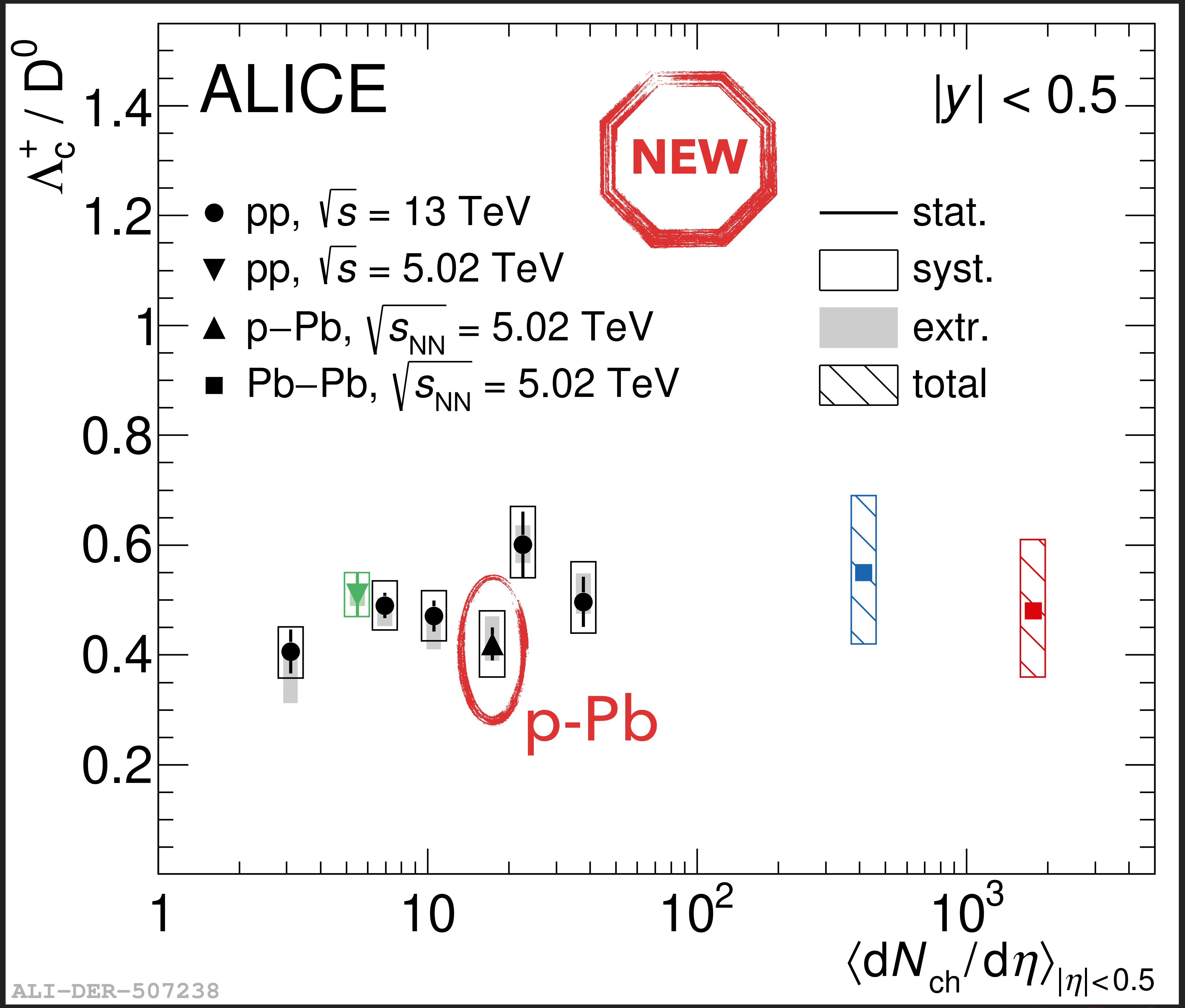
arXiv:2205.13993

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] J. Song, et al., EPJC (2018) 78: 344
[4] V. Minissale, et al., PLB 821 (2021) 136622
[5] Belle e+e−: PRD 97 (2018) 7, 072005

Λ_c^+/D^0 in p-Pb@5.02 TeV



pp: arXiv:2111.11948
Pb-Pb: arXiv:2112.08156



Pb-Pb results: F. Catalano, 7th July 14:30, Heavy Ions

- Fist measurement of Λ_c^+ down to $p_T = 0$ in p-Pb collisions
- Λ_c^+/D^0: hint of suppression in $p_T < 2$ and enhancement in mid-p_T
  - Similarities to strange sector[1,2]
  - Hardening of p_T by 3.7σ according to $\langle p_T \rangle$
  - Radial flow?

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

[1] PRC 104 (2021), 054905 [2] CMS: PRC 101 (2020), 064906

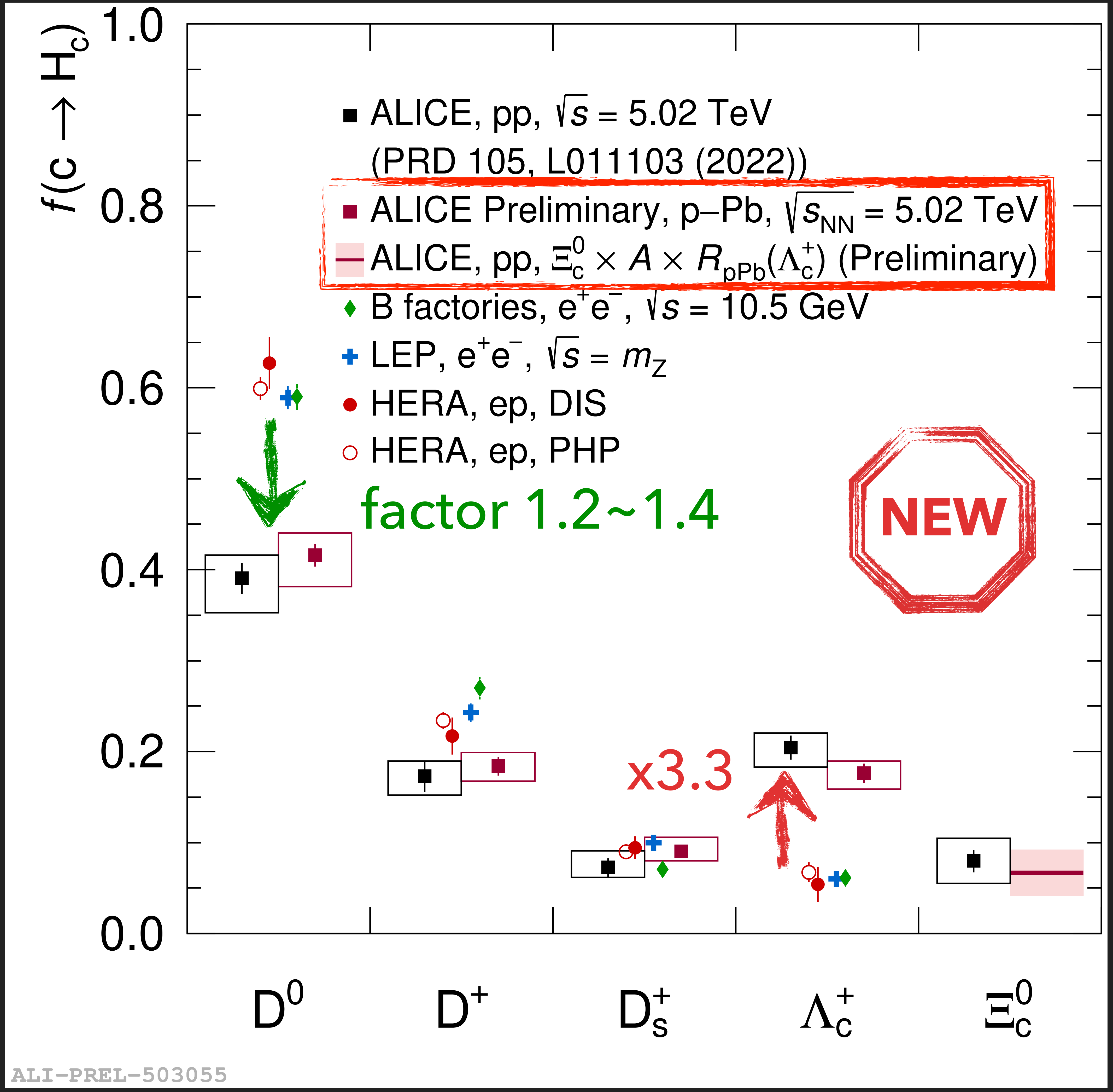
Charm fragmentation fractions

- Charm fragmentation fractions in hadronic collisions at 5.02 TeV
  - pp: PRD 105 (2022) 1, L011103
  - p-Pb:
    - D^0, Λ_c^+ (new): measured down to $p_\mathrm{T} = 0$
    - D^+, D_s^+: extrapolated to $p_\mathrm{T} = 0$ using POWHEG+PYTHIA
    - Ξ_c^0 not measured yet → $\sigma_{\mathrm{pp}}(\Xi_c^0) \times 208 \times R_{\mathrm{pPb}}(\Lambda_c^+)$

- pp and p-Pb results compatible
- Significant baryon enhancement w.r.t. e^+e^- and e^-p

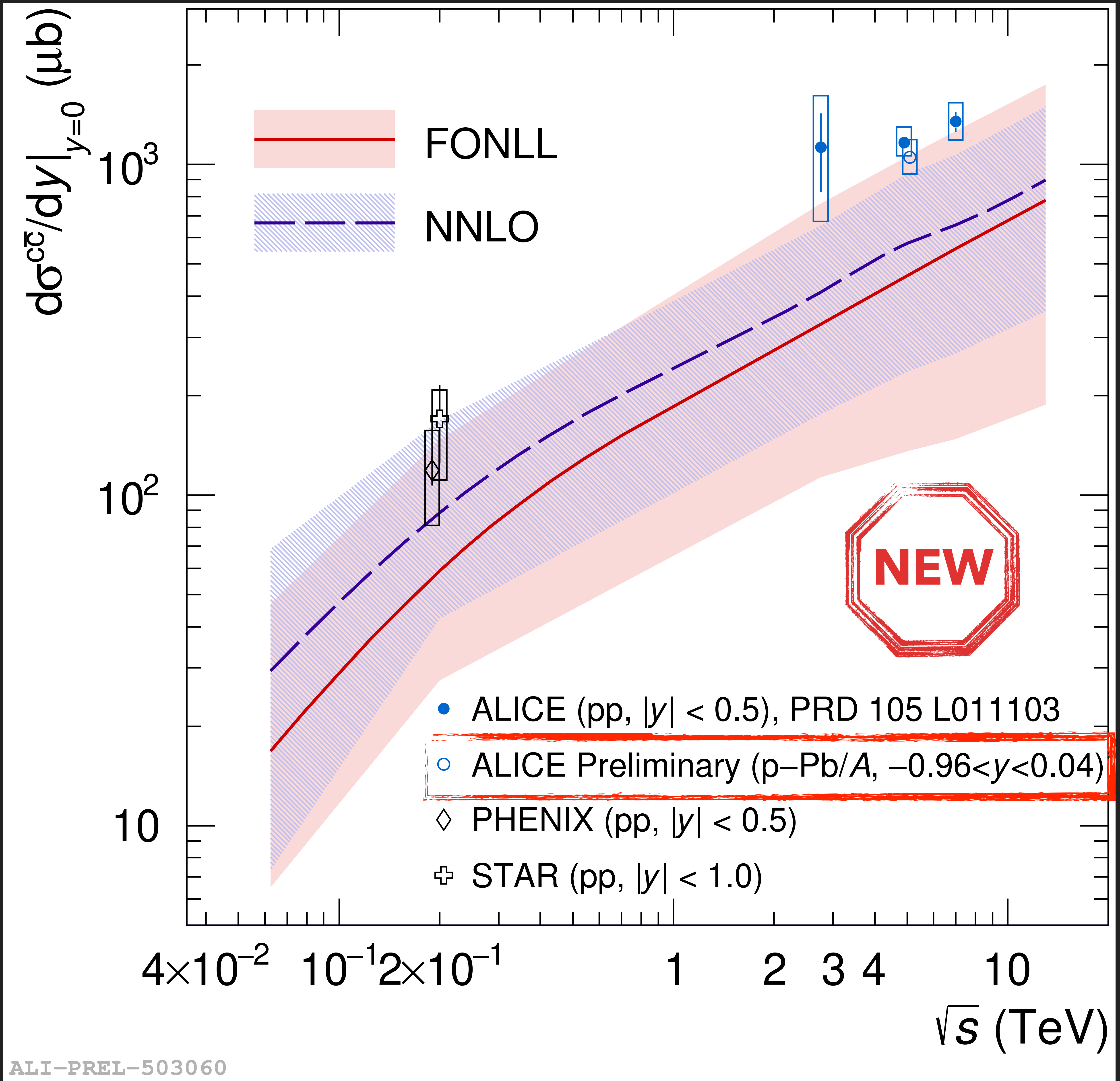
Charm fragmentation fractions are not universal

PRD 105 (2022) 1, L011103



[1] B factories: EPJC 76 no. 7, (2016) 397
[2] LEP: EPJC 75 no. 1, (2015) 19
[3] HERA: EPJC 76 no. 7, (2016) 397
[4] ALICE: JHEP 10 (2021) 159

$c\bar{c}$ production cross section



[1] STAR: Phys. Rev. D 86 (2012) 072013
[2] PHENIX: Phys. Rev. C 84 (2011) 044905
[3] FONLL: JHEP 10 (2012) 137
[4] Charm NNLO: PRL 118 (2017) 12, 122001

Sum of all charm hadron ground states

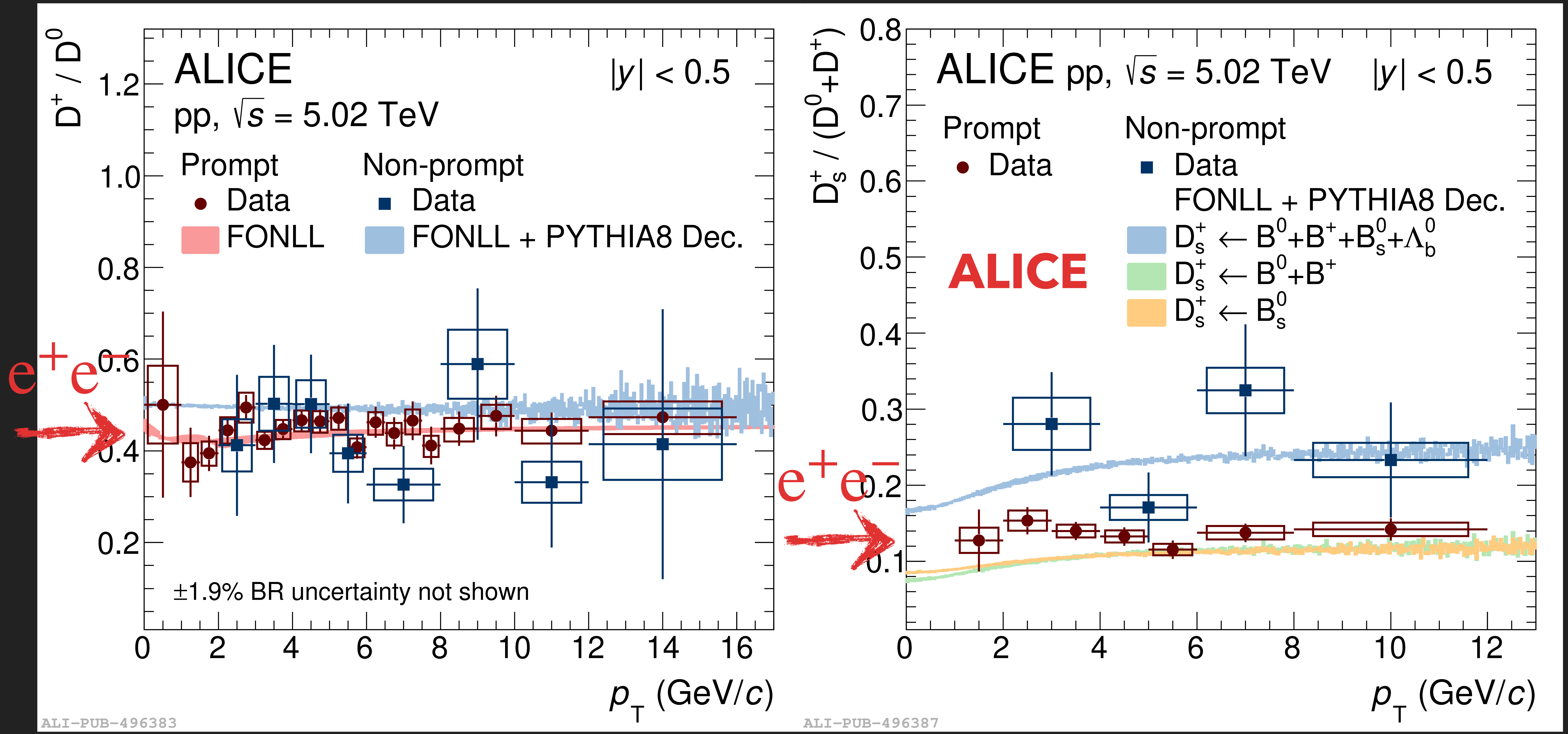
- Results in pp@2.76 & 7 TeV from D mesons updated with FFs from pp@5.02 TeV
  - ~40% increase driven by observed baryon enhancement
- On upper edge of FONLL[3] and NNLO[4] calculations

Summary

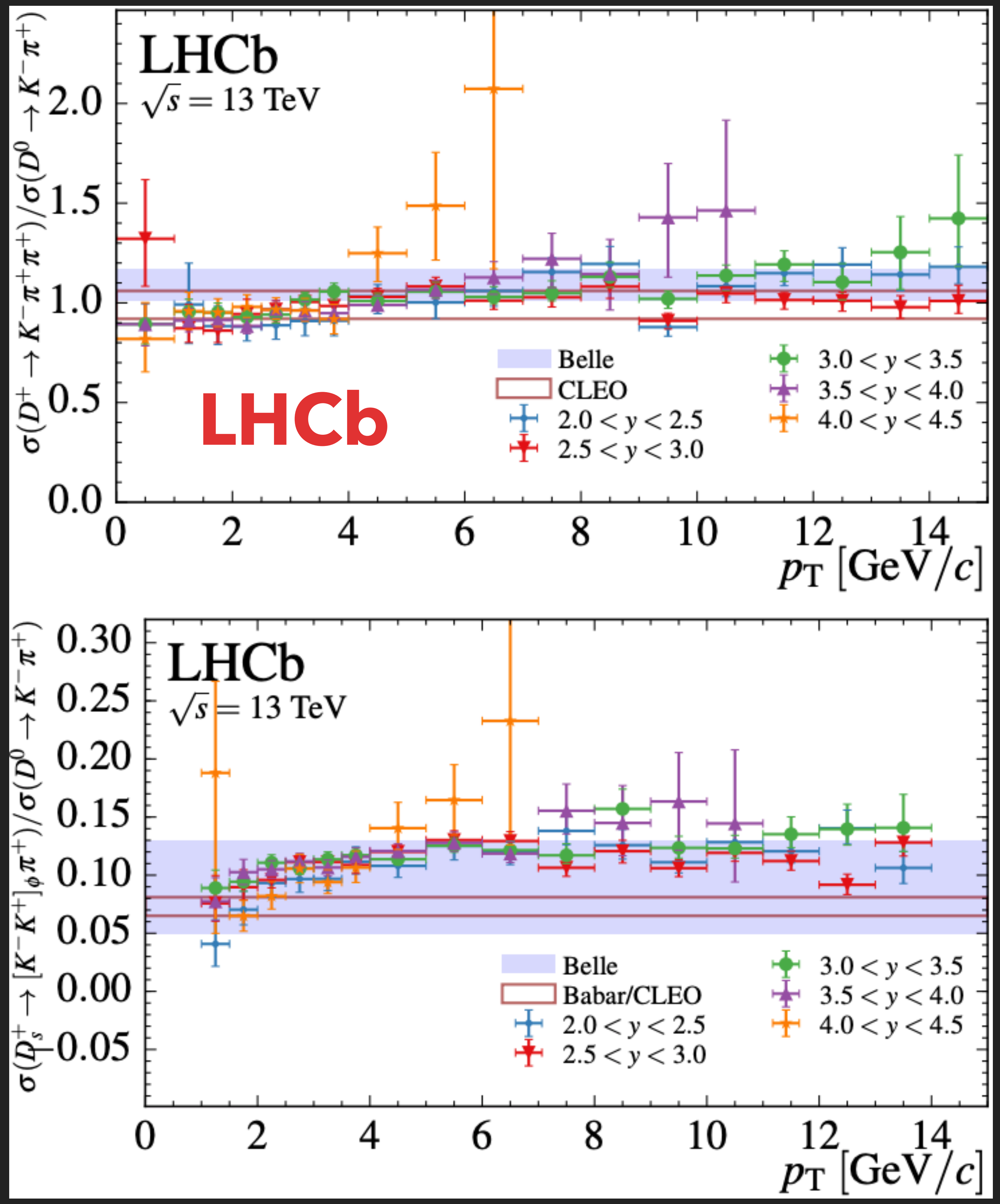
- Λ_c^+ was measured down to $p_T = 0$ in pp and p-Pb collisions
- Charm hadronisation mechanisms need further investigations
  - Coalescence in pp ?
- Evidence that the charm fragmentation fractions are not universal
- Re-distribution of p_T that acts differently for Λ_c^+/D^0, no modification of overall p_T-integrated yield ratio
  - Based on what was seen in strange sector ((multi-)strange baryon enhancement as a function of multiplicity), enhancement of $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 with multiplicity should be expected. Will we see it?
  - Same mechanism in all collision systems? Modified hadronisation? Radial flow?

BACKUP

HF meson-to-meson production ratios in pp collisions



JHEP 05 (2021) 220



LHCb: JHEP 05 (2017) 074

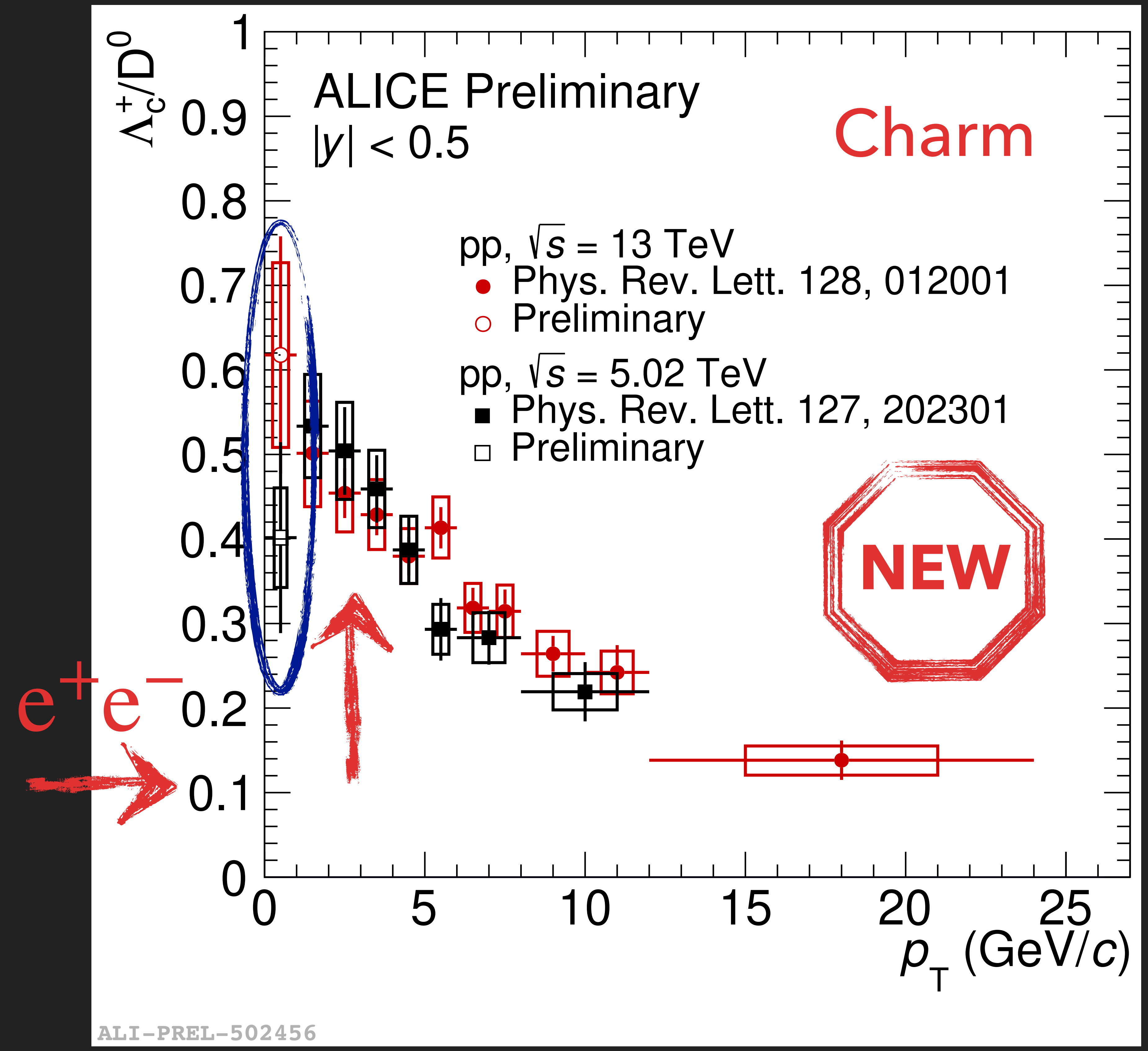
- Prompt and non-prompt D meson ratios independent of p_T and collision system
- Agreement with model calculations based on a factorisation approach and relying on universal fragmentation functions and with e^+e^- and e^-p measurements
- Compatible results between ALICE and LHCb

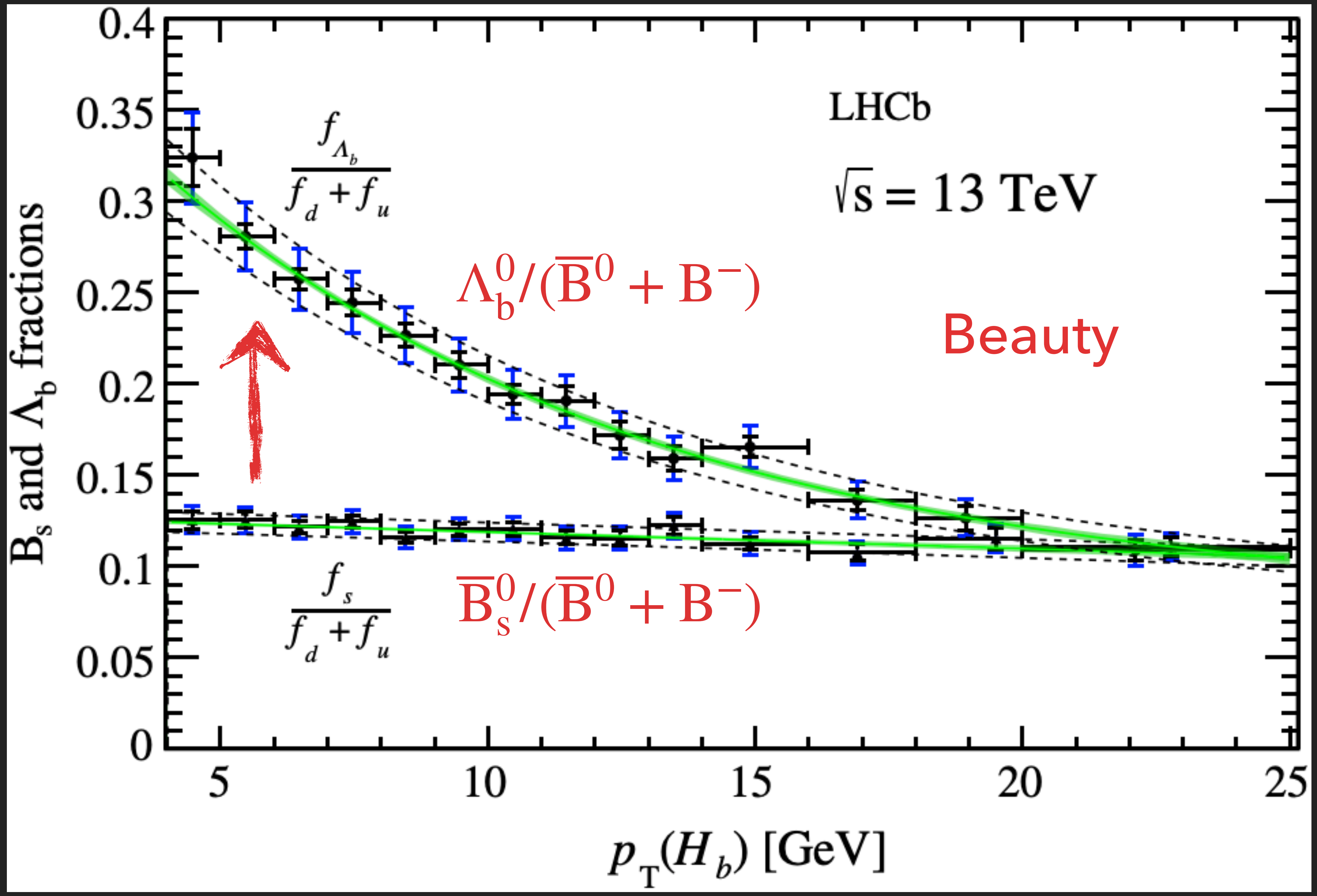
FONLL: M. Cacciari, et al., JHEP 10 (2012) 137
PYTHIA 8: P. Skands, et al., EPJC 74 (2014) 3024

Charm and beauty baryon-to-meson ratio in pp collisions

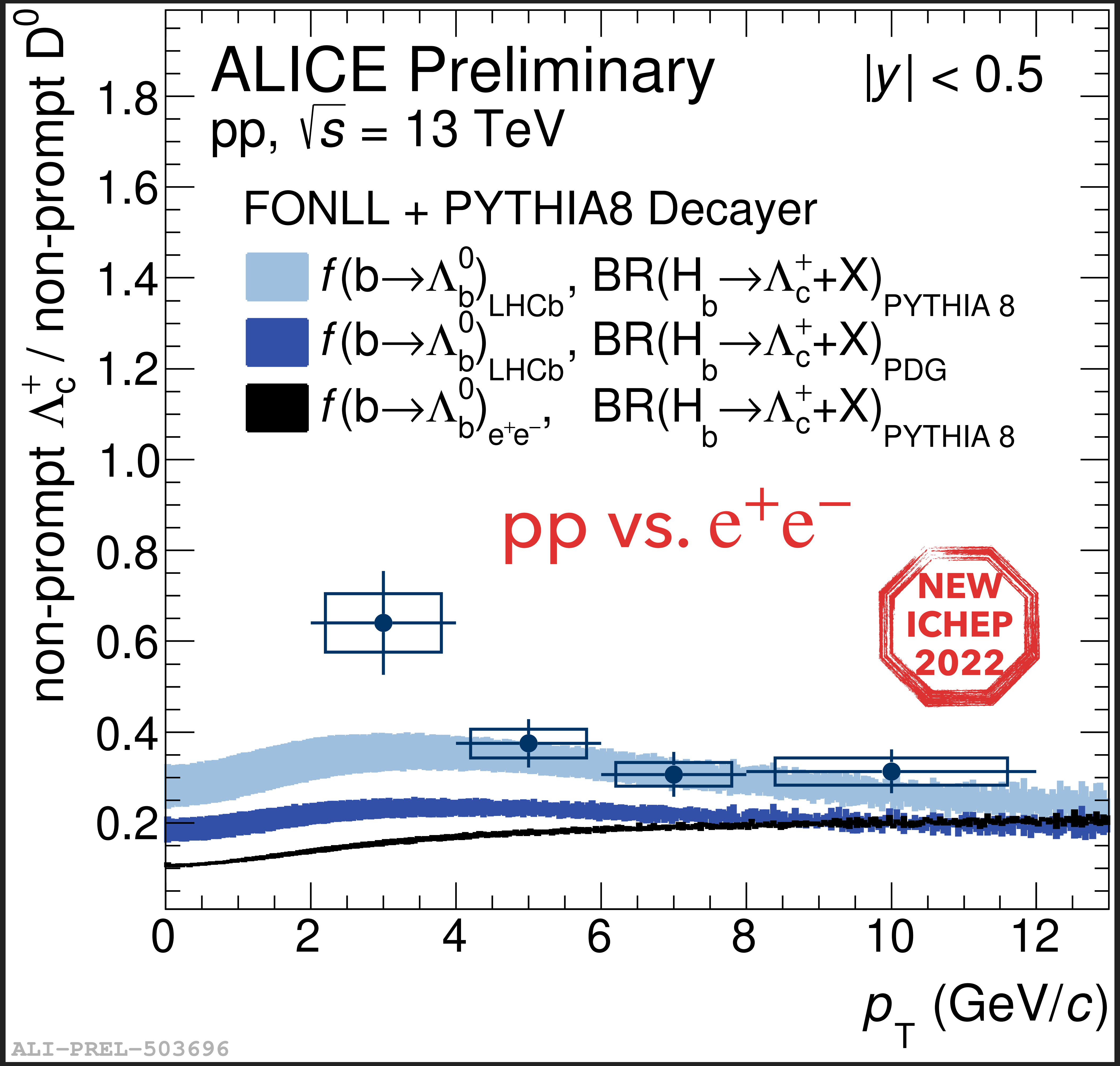
- Charm baryon-to-meson ratios significantly higher than e^+e^- results
  - PYTHIA 8 Monash (e^+e^- charm fragmentation functions)
- Beauty baryon-to-meson enhancement at low p_T also observed

LHCb: Phys.Rev.D 100 (2019), 031102





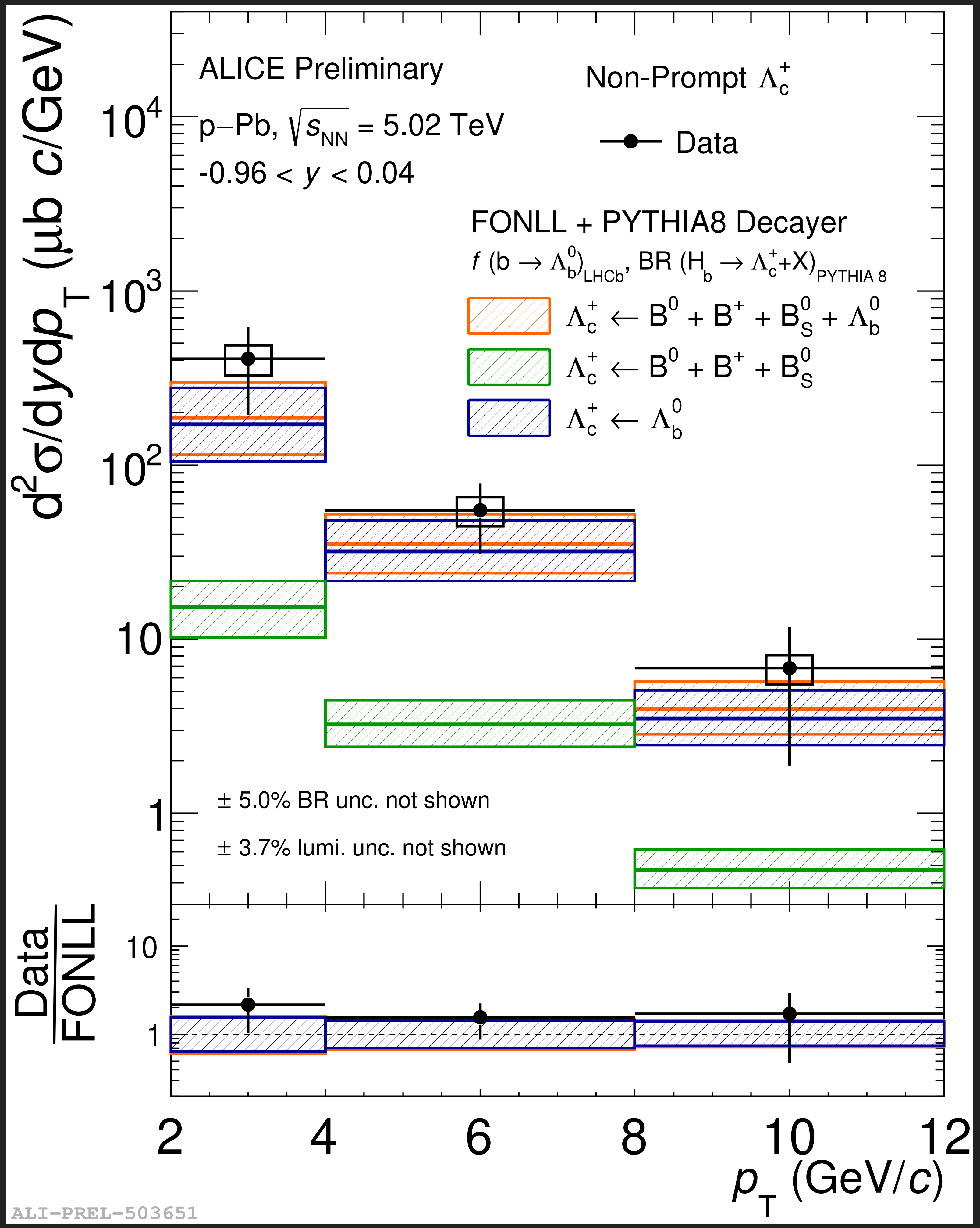
Non-prompt Λ_c^+/D^0 ratio in pp@13 TeV

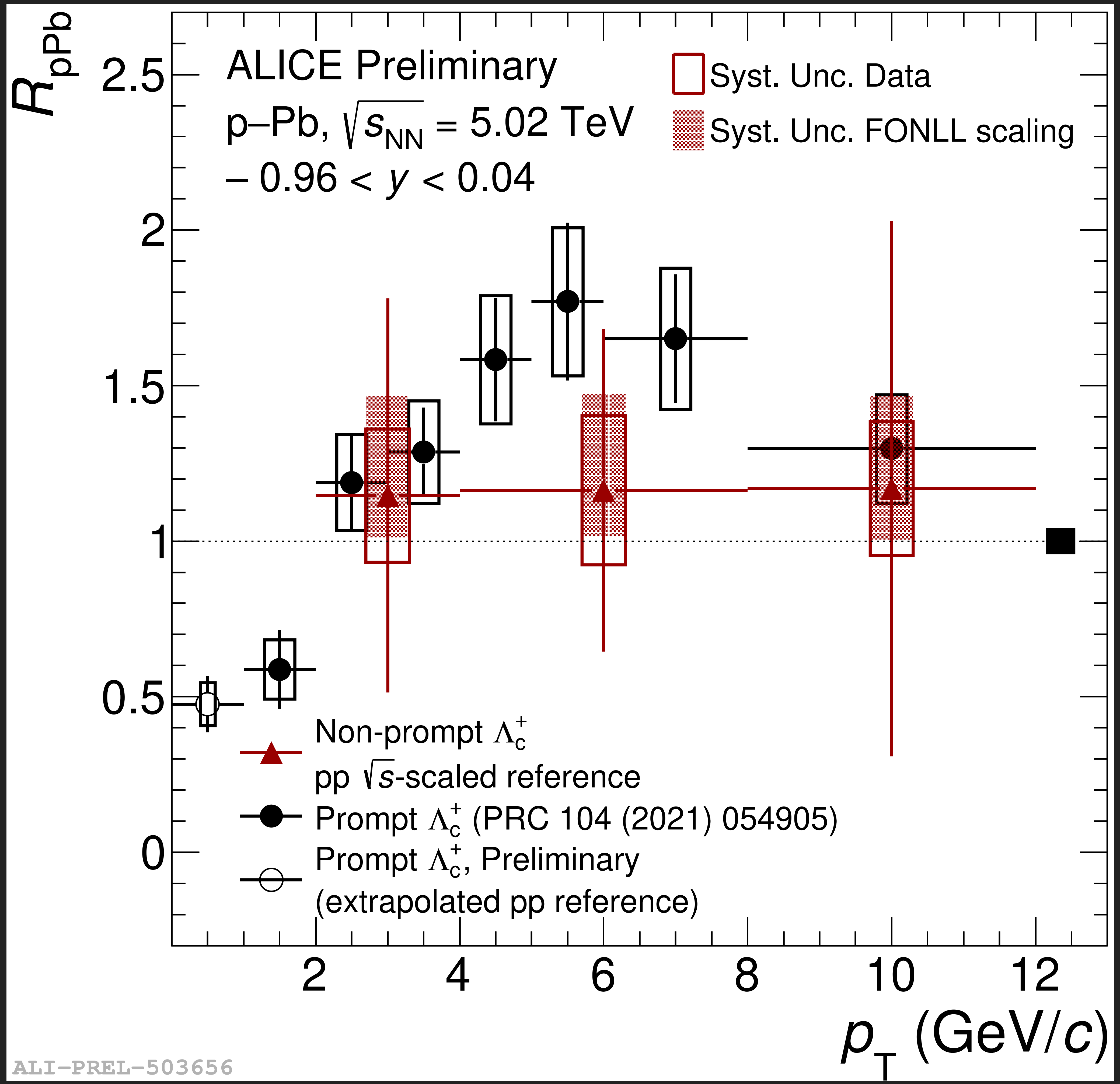


LHCb: Phys.Rev.D 100 (2019), 031102

- Non-prompt Λ_c^+/D^0: pp vs. e^+e^-
  - Enhanced beauty-baryon production in pp w.r.t. e^+e^- (different hadronization mechanism?)

Non-prompt Λ_c^+ production in p-Pb@5.02 TeV





- Non-prompt Λ_c^+
  - p_T dependence well reproduced by theoretical calculations, same as pp
- Non-prompt Λ_c^+ R_{pPb}
  - Compatible with unity and with prompt Λ_c^+ R_{pPb} within the large uncertainties