CERN-LHC Seminar, 3rd August 2021

Jianhui Zhu (GSI&CCNU) for the ALICE Collaboration

Charm production and hadronisation at the LHC with ALICE

GSI

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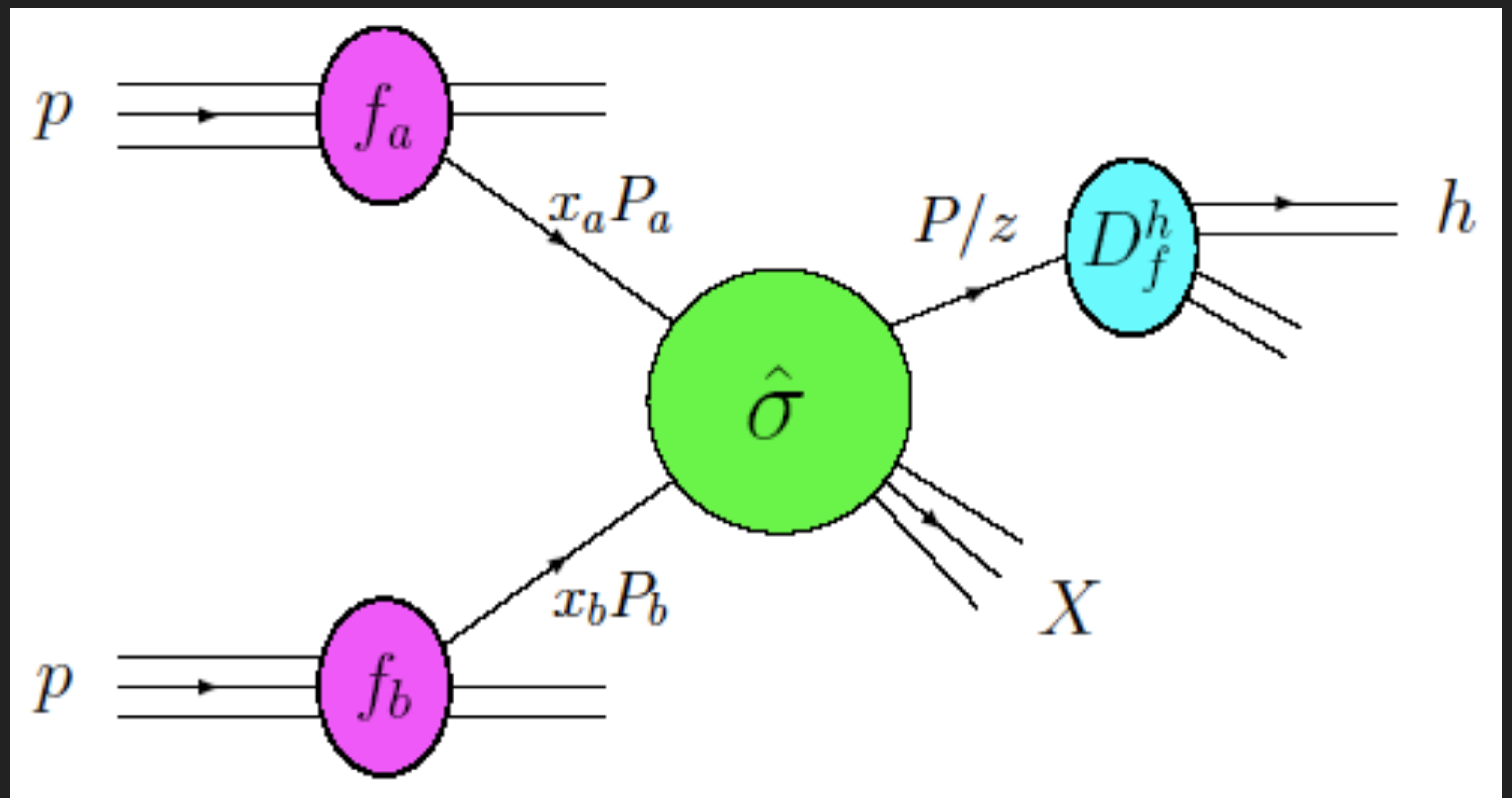
ALICE

Heavy-flavour production in pp collisions

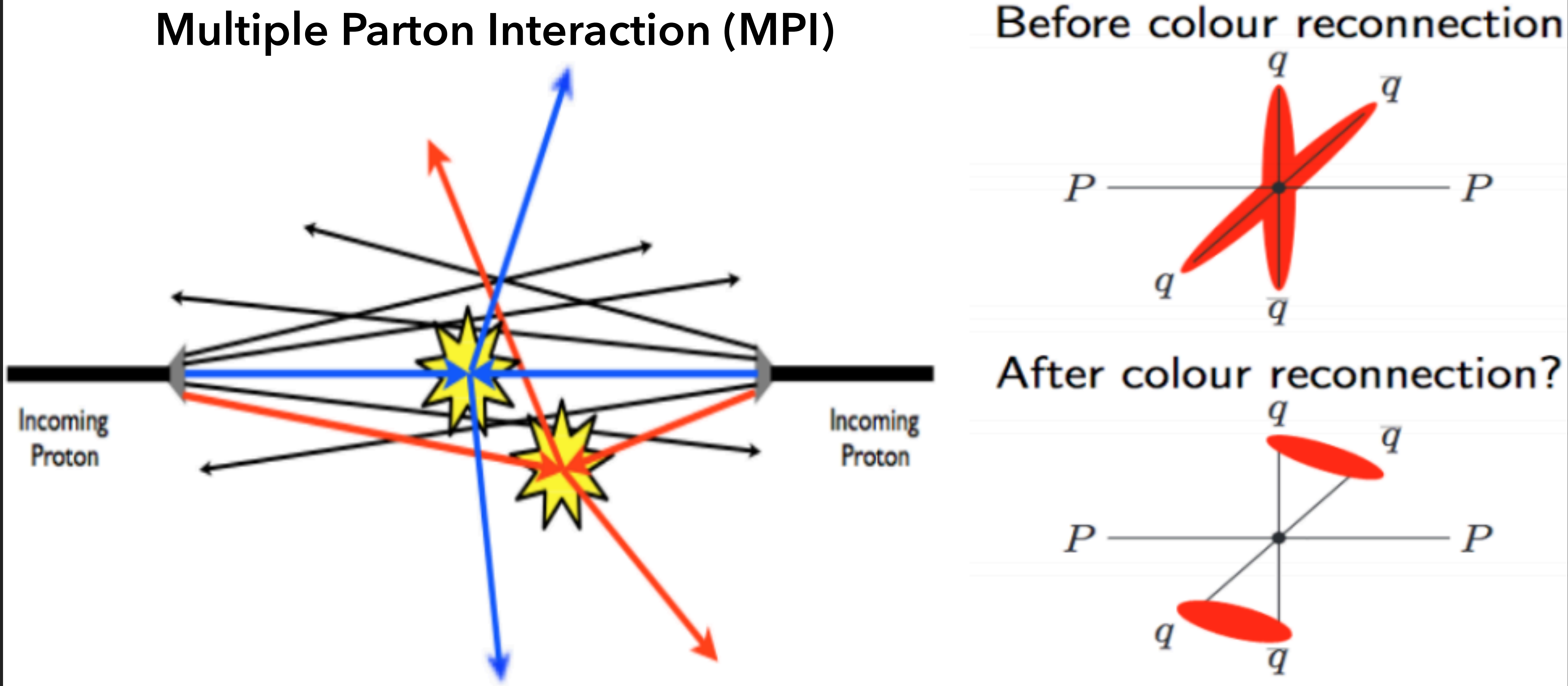
Hadroproduction described by factorisation approach, which works well for charm and beauty mesons :

$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_T;\mu_F;\mu_R) = PDF(x_a,\mu_F)PDF(x_b,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_a,x_b,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

parton distribution function (PDF) (non-perturbative) — partonic cross section (perturbative) — hadronisation by fragmentation (non-perturbative)



- Current pQCD calculations based on factorisation approach use fragmentation functions tuned on e^+e^- and ep measurements, assuming them universal across different collision energies and systems

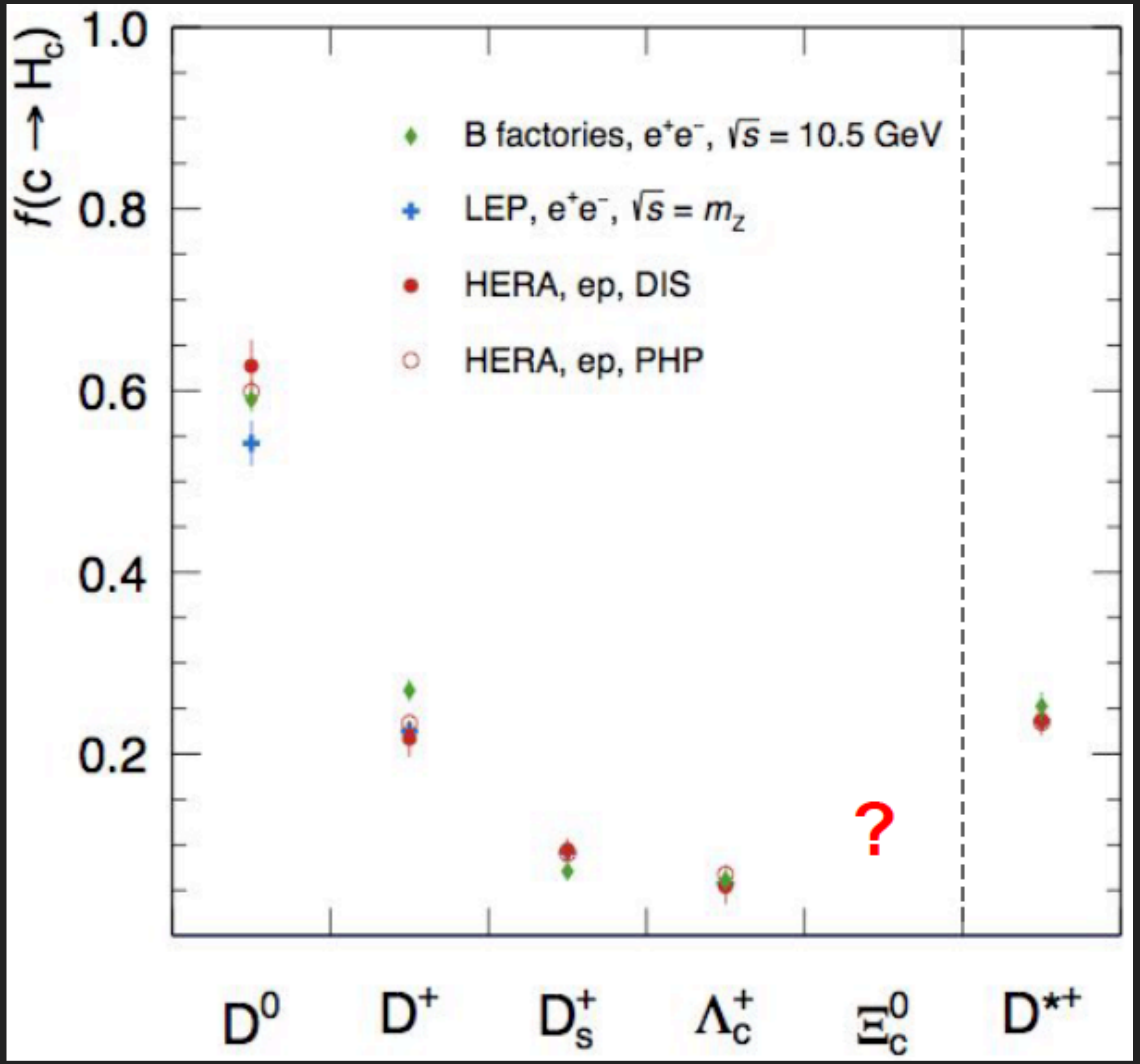


Is charm fragmentation universal at the LHC ?

- Investigate the charm baryon-to-meson & baryon-to-baryon yield ratio, which are sensitive to hadronisation mechanism

Charm fragmentation measured in e^+e^- and ep

- Charm fragmentation fractions (FF)
  - $f(\mathrm{c} \rightarrow \mathrm{H_c}) = \sigma(\mathrm{H_c})/\sigma(\mathrm{c}) = \sigma(\mathrm{H_c})/\sum_{\mathrm{w.d.}} \sigma(\mathrm{H_c})$ (w.d.: weakly decaying)
  - Inputs used in a standard factorisation approach
- Production cross section of $\Xi_c^{0,+}$ are calculated under assumptions[1]:
  - $f(\mathrm{c} \rightarrow \Xi_c^0)/f(\mathrm{c} \rightarrow \Lambda_c^+) = f(\mathrm{s} \rightarrow \Xi^-)/f(\mathrm{s} \rightarrow \Lambda) \approx 0.004$



Average LEP FF

H_c	$f(c \rightarrow H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$
D^+	$22.5 \pm 1.0 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$
D^{*+}, double-tag	$24.4 \pm 1.3 \pm 0.2$
D^{*+}, combined	$23.6 \pm 0.6 \pm 0.3$

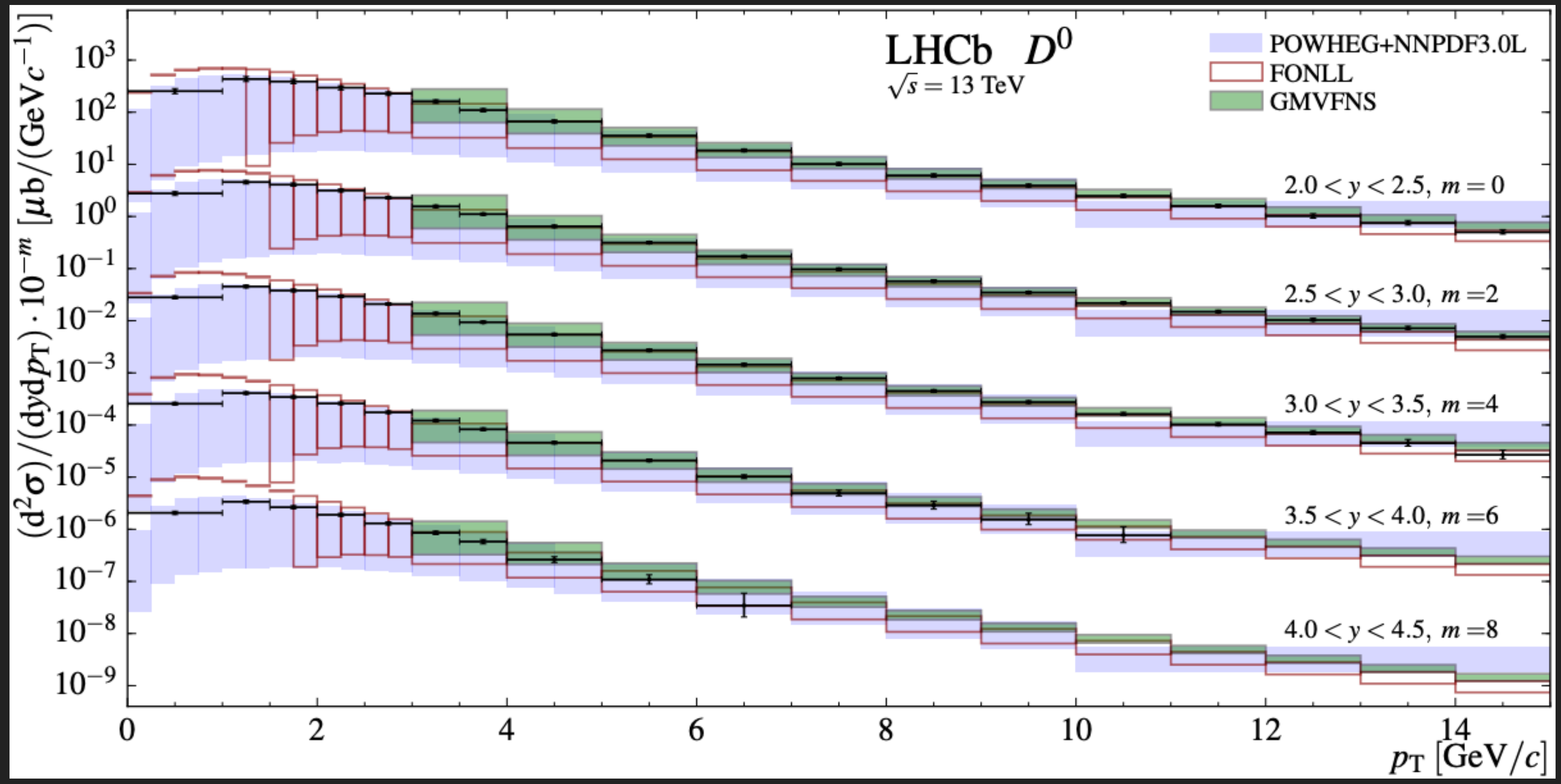
L. Gladilin, EPJC 75 (2015) 19

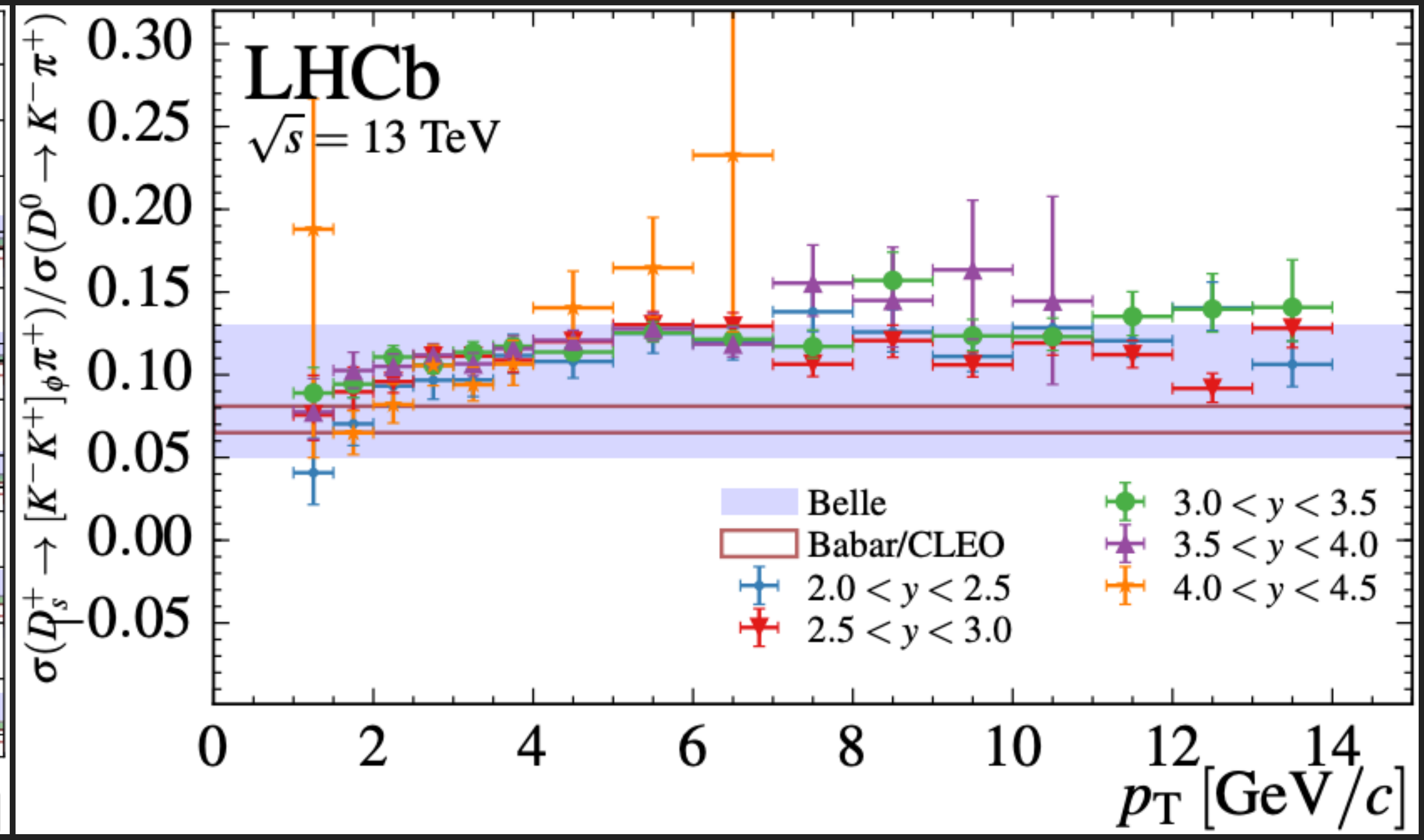
Sum of $f(\mathrm{c} \rightarrow \mathrm{H_c})$ for $\mathrm{D^0}$, $\mathrm{D^+}$, $\mathrm{D_s^+}$ and Λ_c^+: $91.6 \pm 3.3(\mathrm{stat} \oplus \mathrm{syst}) \pm 1.0(\mathrm{BR})$ %

[1] M. Lisovyi, et al., EPJC 76 (2016) no.7, 397
[2] B factories: EPJC 76 no. 7, (2016) 397
[3] LEP: EPJC 75 no. 1, (2015) 19
[4] HERA: EPJC 76 no. 7, (2016) 397

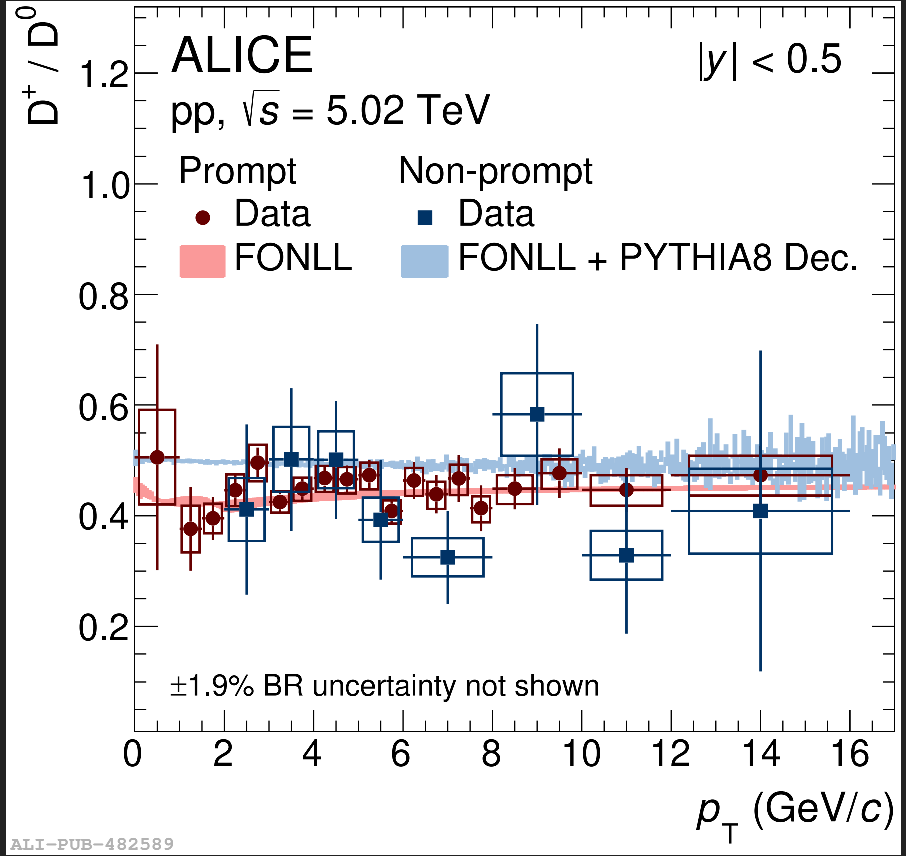
Factorisation: a very successful framework

LHCb: JHEP 03 (2016) 159, JHEP 09 (2016) 013 (erratum), JHEP 05 (2017) 074 (erratum)

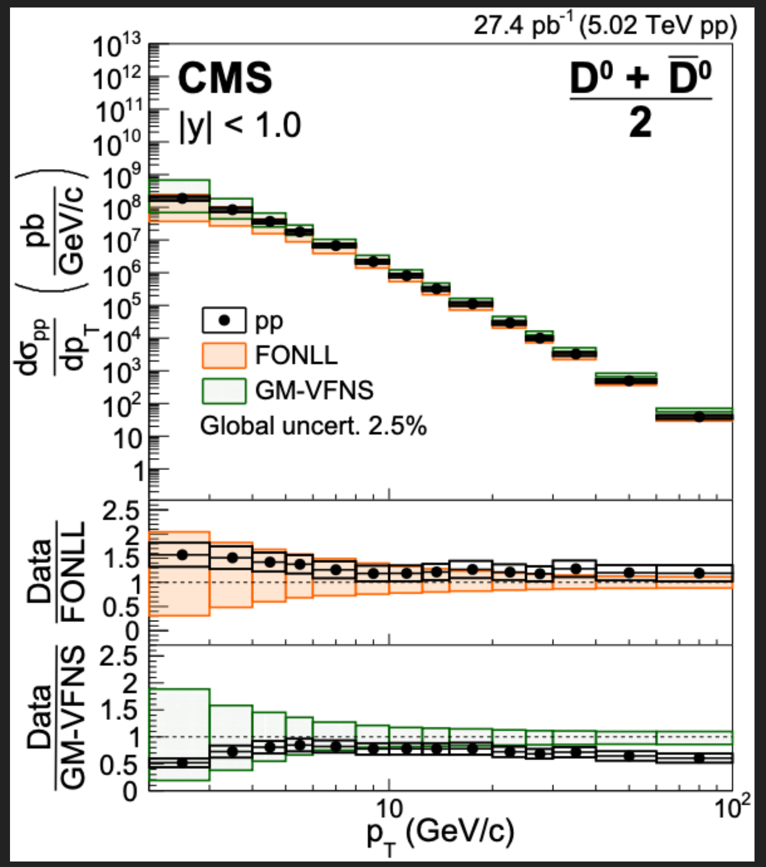




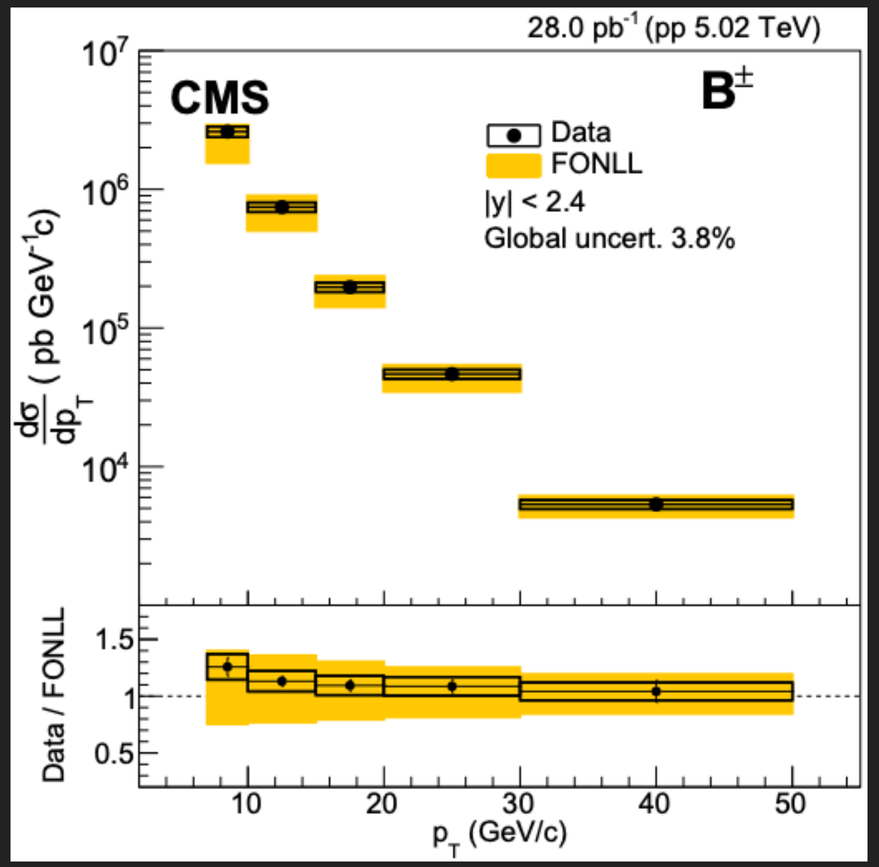
ALICE: JHEP 05 (2021) 220



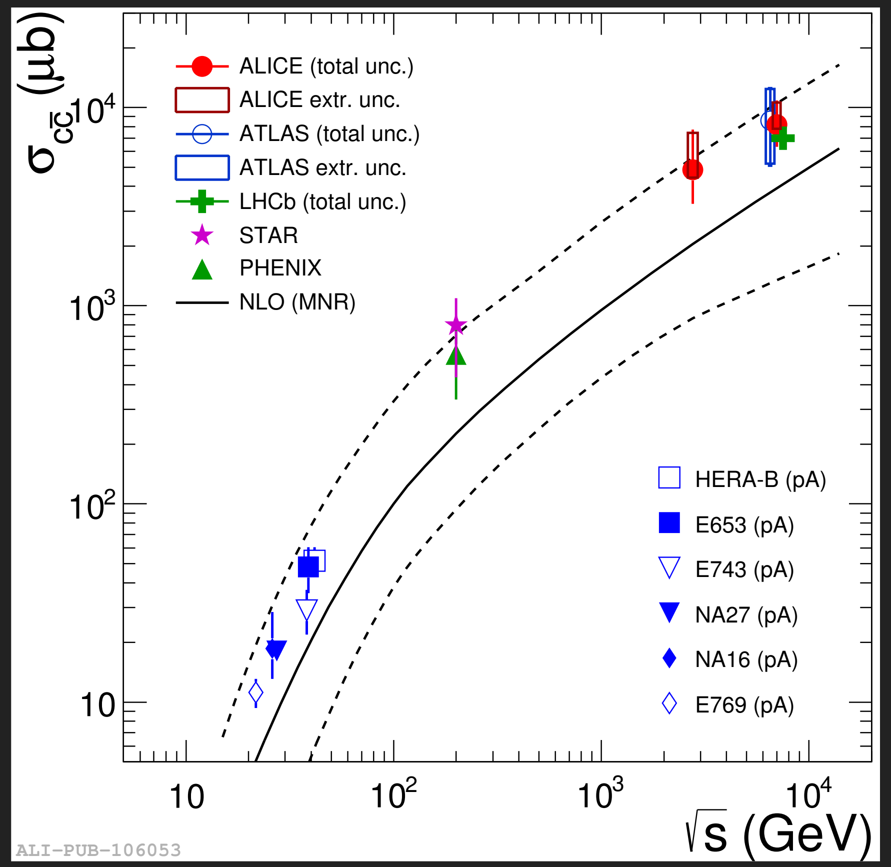
CMS: PLB 782 (2018) 474-496



CMS: PRL 119 (2017) 15, 152301



ALICE: PRC 94 (2016) 5, 054908

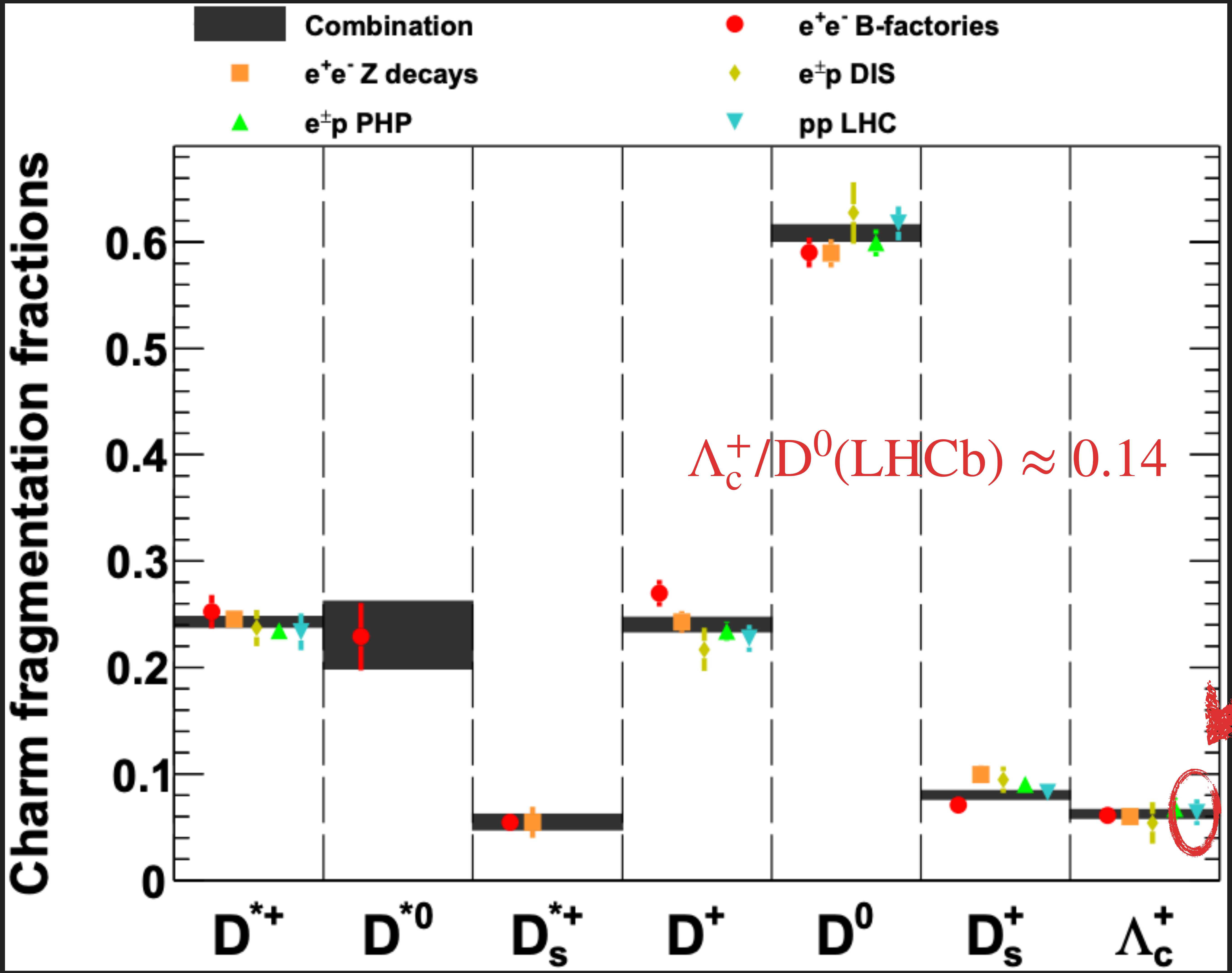


- Plethora of data on open-charm and open-beauty meson production
  - vs. p_T and y (wide range)
  - in different collision energies
  - relative abundance of charm meson species

→ Described by pQCD calculations relying on factorisation

Universality confirmed at the LHC in 2013

M. Lisovyi, A. Verbytskyi, O. Zenaiev, EPJC 76 (2016) no.7, 397



- Very nice agreement across collision systems (e^+e^-, ep and pp)
- In 2013, only LHCb Λ_c^+ measurement at forward rapidity in pp@7 TeV[1] available at the LHC

[1] LHCb: Nucl.Phys.B 871 (2013) 1-20

Role of hadronisation began to change in 2017

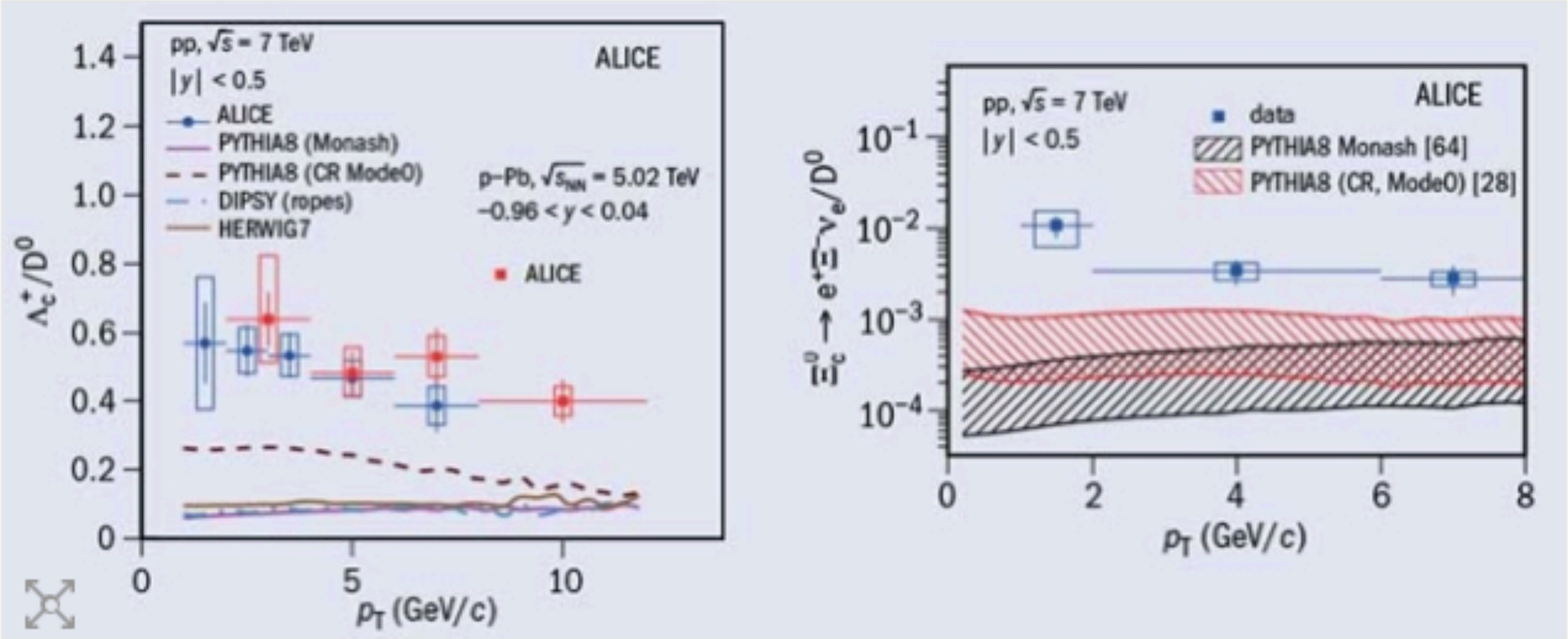
https://cerncourier.com/a/alice-investigates-charm-quark-hadronisation

CERNCOURIER | Reporting on international high-energy physics

STRONG INTERACTIONS | NEWS

ALICE investigates charm-quark hadronisation

16 February 2018



(Left) The Λ^+_c/D^0 baryon-to-meson ratio measured in pp and p–Pb collisions as a function of transverse momentum, compared with different event generators for pp collisions. (Right) The ratio of the p_T differential cross-sections of Ξ^0_c baryons (multiplied by the branching ratio into $e^+ \nu_e \Xi^-$) as a function of transverse momentum, showing the large uncertainty on the $\Xi^0_c \to e^+ \nu_e \Xi^-$ branching ratio (shaded bands).

- Measurements of Λ_c^+/D^0[1] and Ξ_c^0/D^0[2] from ALICE in 2017 much higher than calculations based on fragmentation fractions tuned on e^+e^- data
  - Indicate fragmentation of charm quark NOT well understood
  - Charm baryon studies suggested that charm hadronisation might not be universal and depends on collision system

[1] ALICE: JHEP 04 (2018) 108
[2] ALICE: PLB 781 (2018) 8-19

A Large Ion Collider Experiment (ALICE)

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int} (MB)
pp	2017	5.02	~19 nb^{-1}
	2016-2018	13	~33 nb^{-1}
p–Pb	2016	5.02	~0.3 nb^{-1}
Pb–Pb (0-10%)	2018	5.02	~0.13 nb^{-1}
Pb–Pb (30-50%)			~0.056 nb^{-1}

Inner Tracking System (ITS)

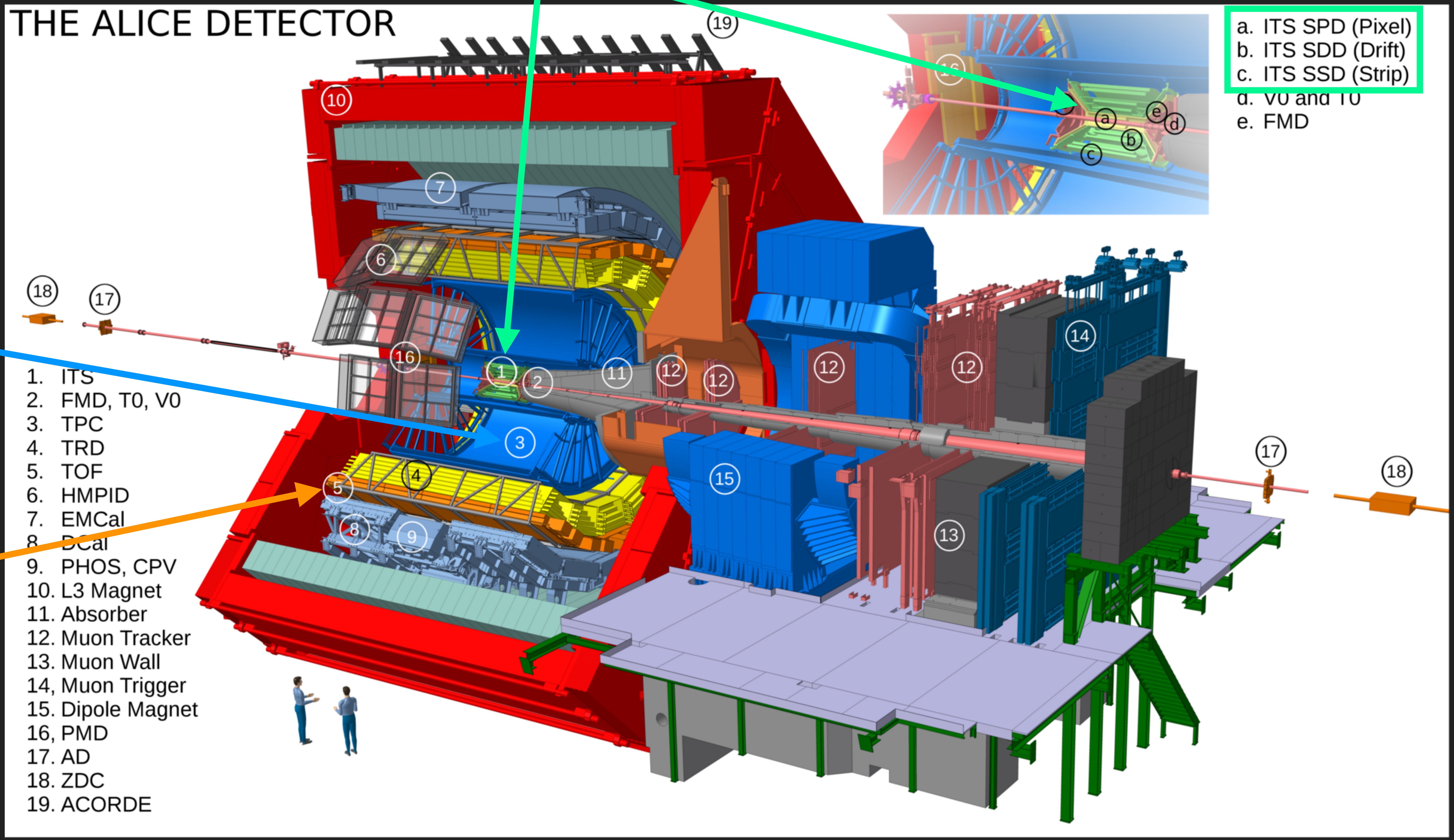
- $|\eta| < 0.9$
- Tracking, vertex, particle identification (PID), multiplicity

Time Projection Chamber (TPC)

- $|\eta| < 0.9$
- Tracking, PID

Time-Of-Flight (TOF)

- $|\eta| < 0.9$
- Tracking, PID



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

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

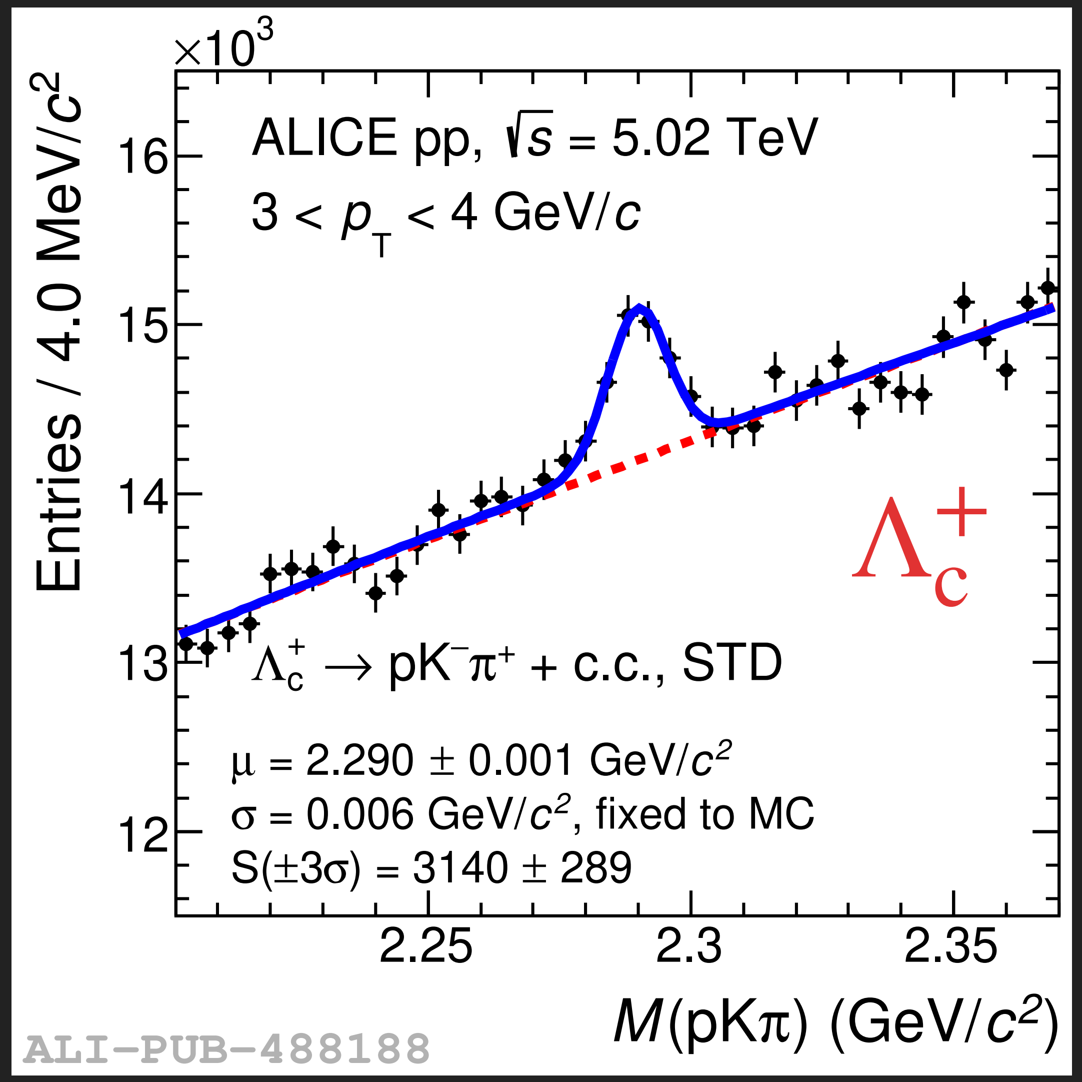
$\Sigma_c^{0,++} : \Sigma_c^0 \rightarrow \Lambda_c^+\pi^-, \Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

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

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

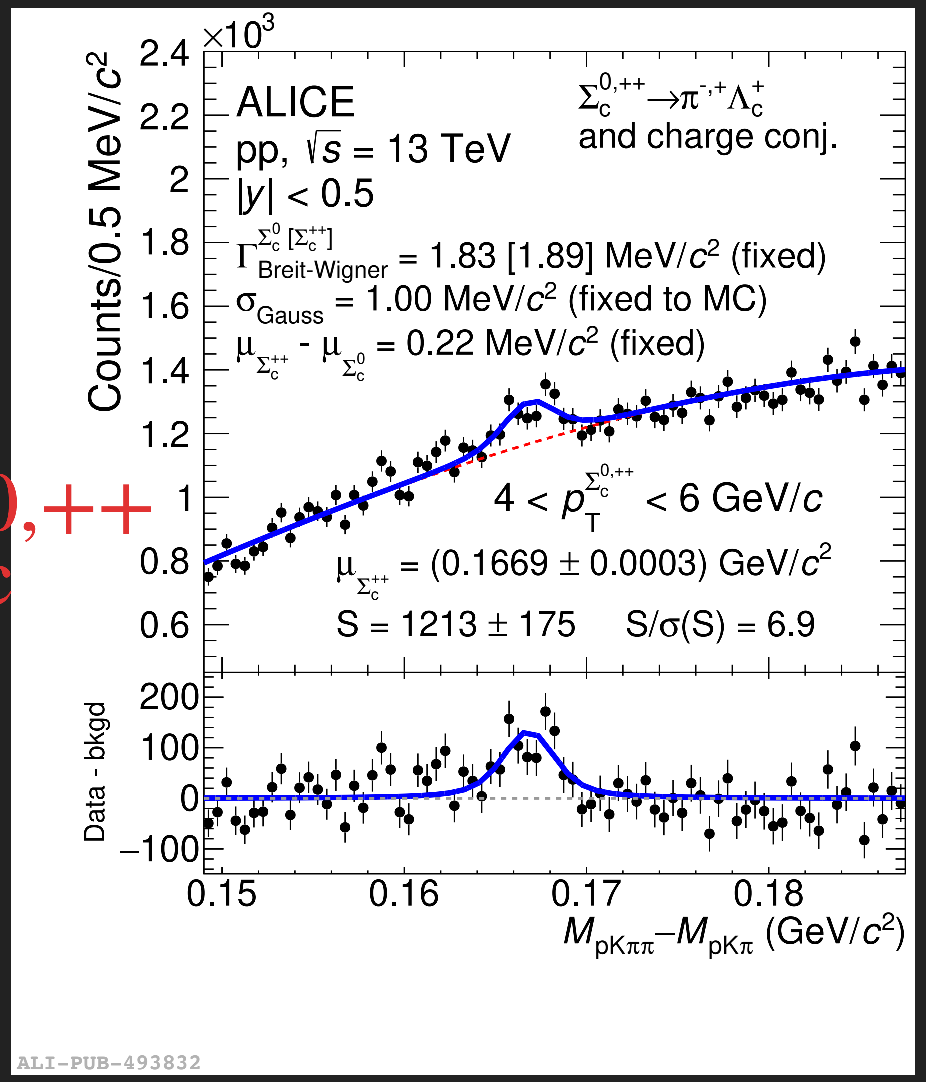
$\Omega_c^0 : \Omega_c^0 \rightarrow \Omega^-\pi^+$

arXiv:2011.06079

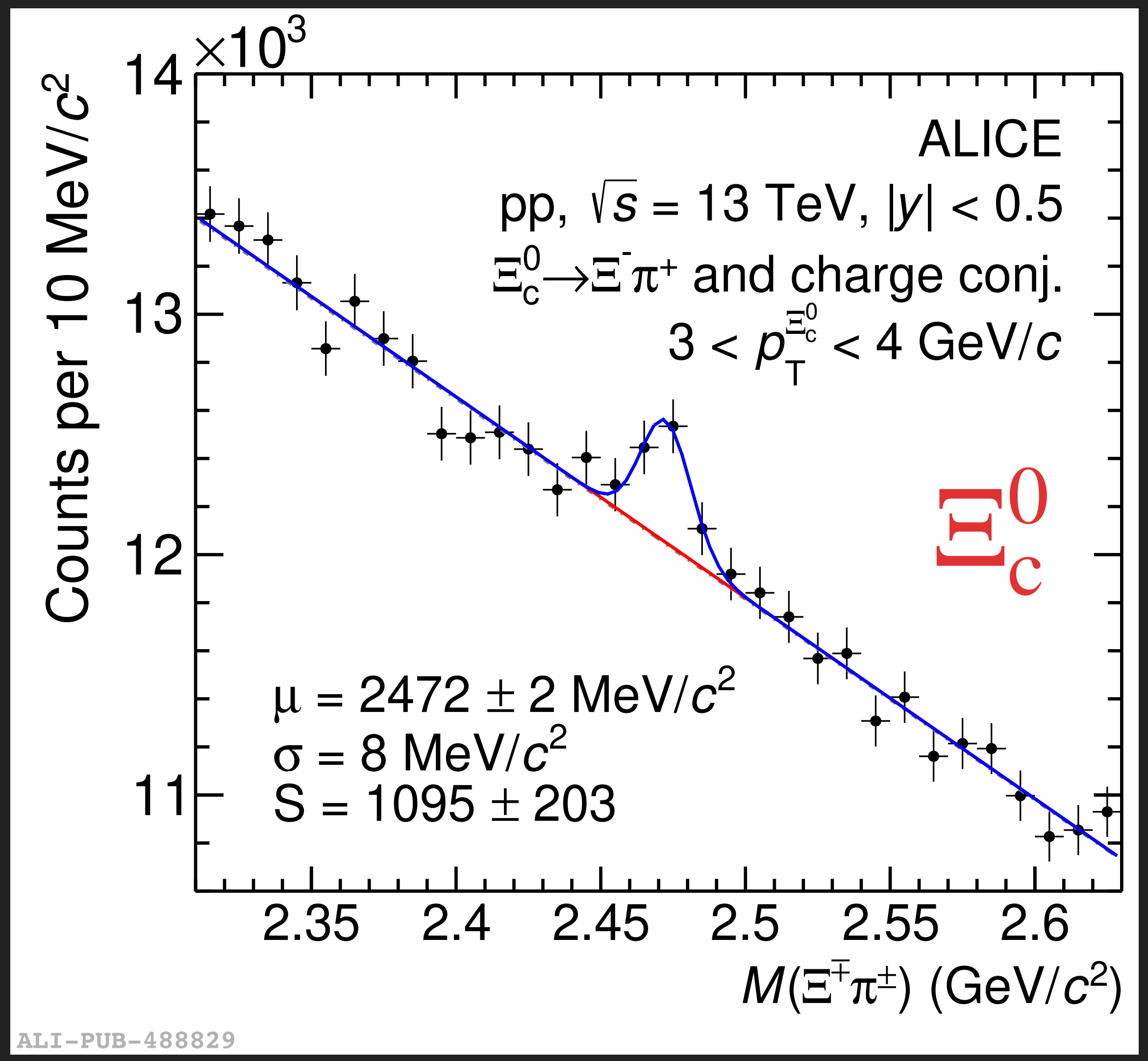


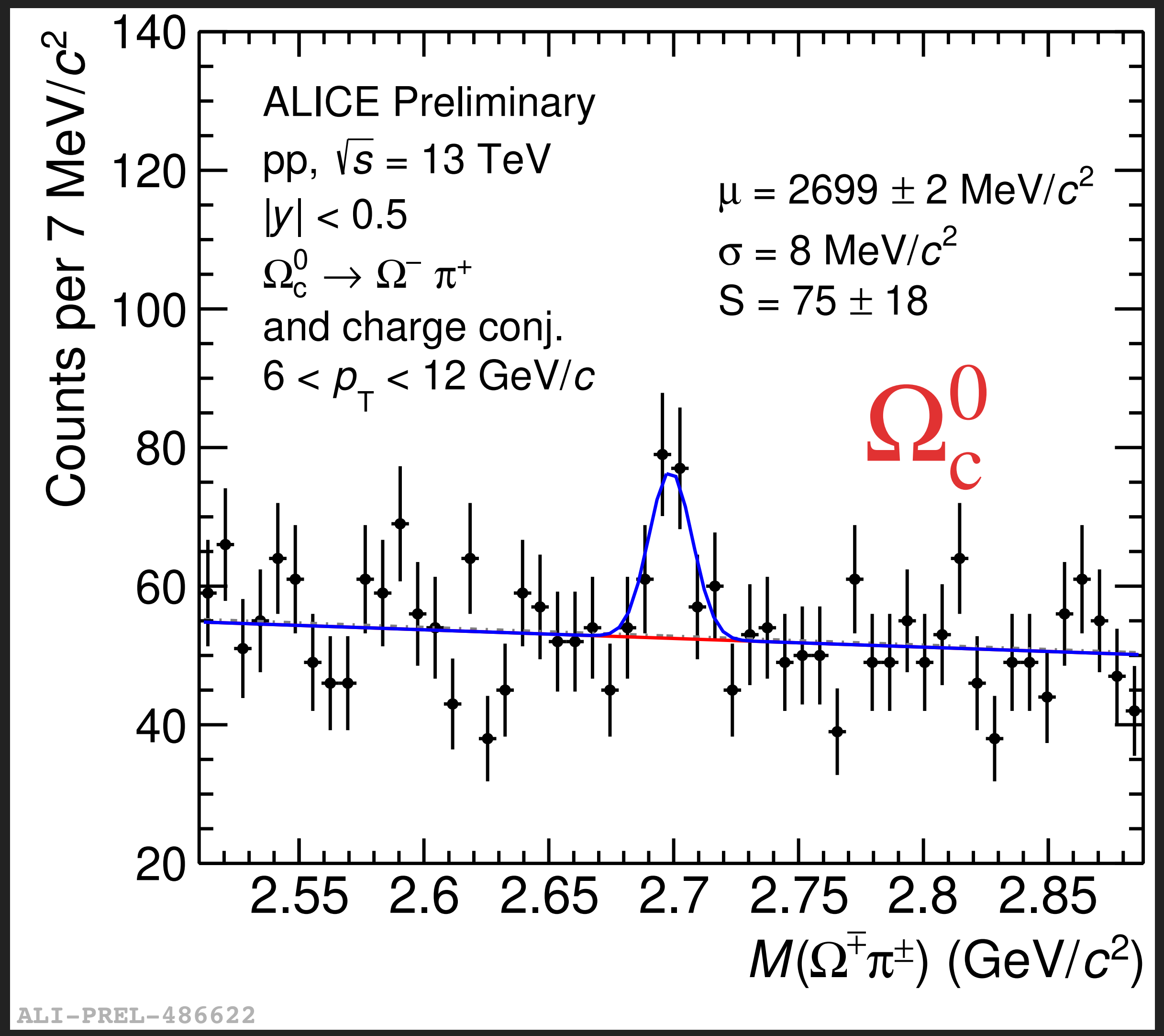
arXiv:2106.08278

$\Sigma_c^{0,++}$



arXiv:2105.05187





Charm mesons

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	D^0 ($u\bar{c}$)	D^+ ($d\bar{c}$)	D^{*+} ($d\bar{c}$)	D_s^+ ($s\bar{c}$)	Λ_c^+ (udc)	Σ_c^0 (ddc)	Σ_c^{++} (uuc)	Ξ_c^+ (usc)	Ξ_c^0 (dsc)	Ω_c^0 (ssc)
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	–	151.2	60.7	–	–	136.6	45.8	80

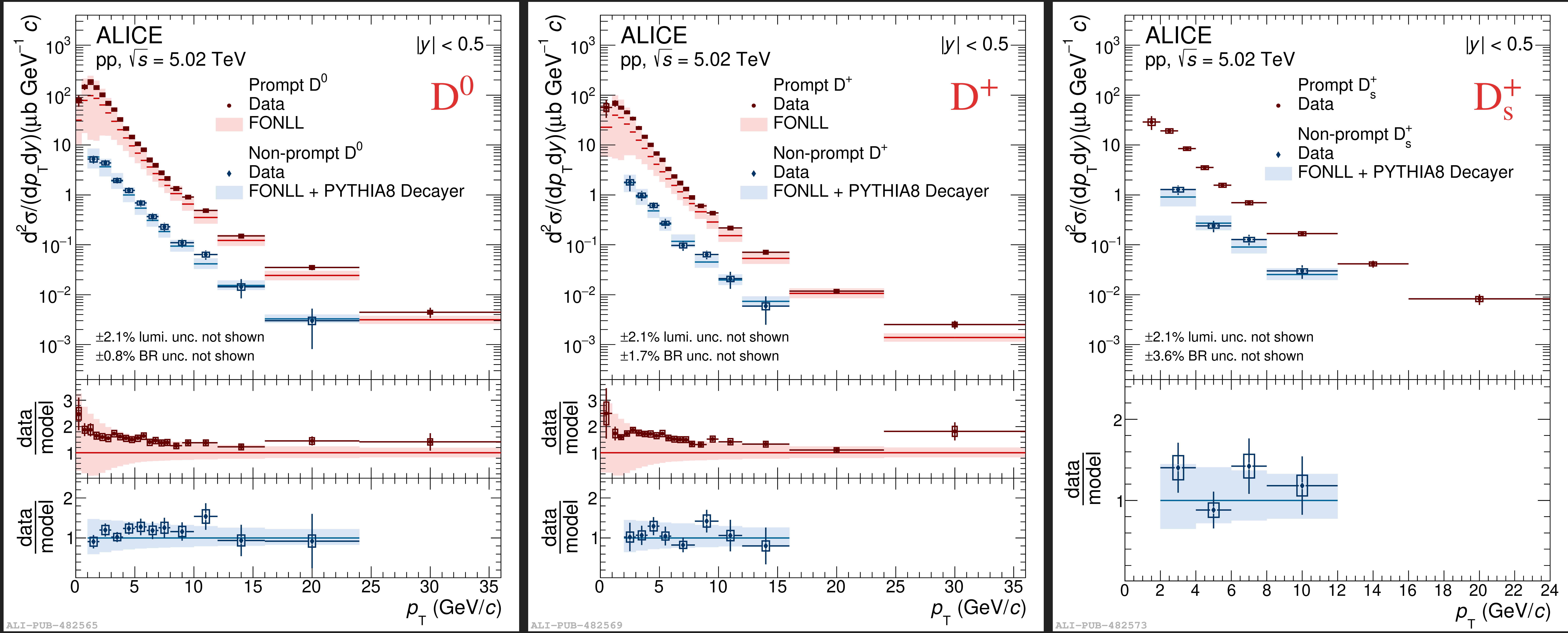
$D^0 \rightarrow K^-\pi^+$ (BR=3.95%)

$D^+ \rightarrow K^-\pi^+\pi^+$ (BR=9.38%)

$D^{*+} \rightarrow D^0\pi^+$ (BR=67.7%)

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR=2.24%)

Baseline measurements: D mesons



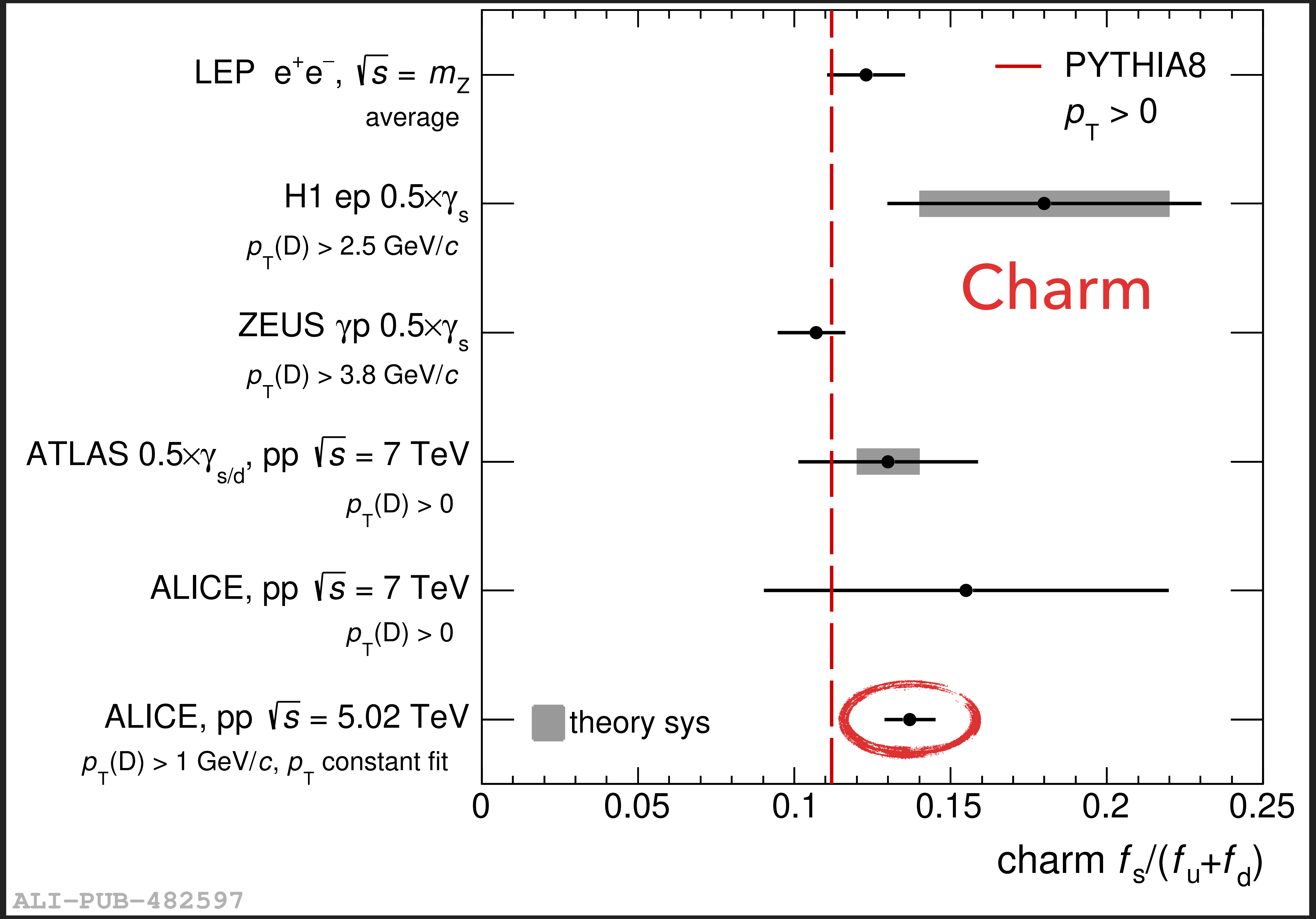
JHEP 05 (2021) 220

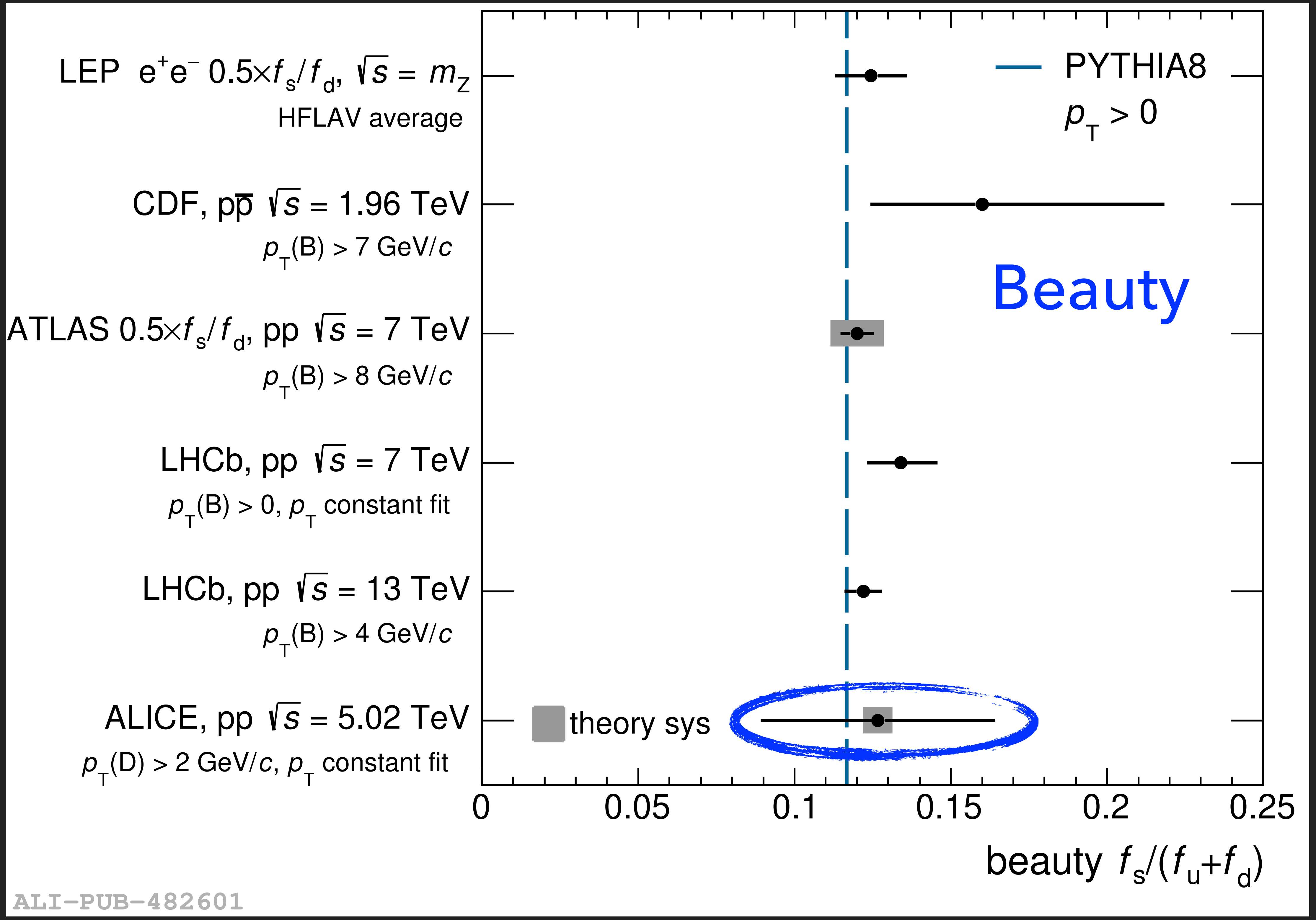
- D^0 and D^+ measured down to $p_T = 0$, D_s^+ measured down to $p_T = 1$ GeV/c
- pQCD calculations at NLO with FFs from e^+e^- in good agreement with prompt and non-prompt D mesons
  - FONLL (Fixed Order + Next-to-Leading Logarithms)[1]
  - GM-VFNS (General Mass Variable Flavour Number Scheme)[2]

[1] M. Cacciari, et al., JHEP 10 (2012) 137
[2] B. Kniehl, et al., EPJC 72 (2012) 2082
[3] PYTHIA8: P. Skands, et al., EPJC 74 (2014) 3024

Charm vs. beauty FF at the LHC: $D_s^+/(D^0 + D^+)$

- Ratio of fragmentation fraction to meson w/ and w/o strange quark similar for charm and beauty sector
- No significant dependence on collision system and energy





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Charm-quark $f_s/(f_u + f_d)$:

- Consistent with PYTHIA8 Monash tune[1] within 2.7σ

JHEP 05 (2021) 220

Beauty-quark $f_s/(f_u + f_d)$:

- Compatible with previous observations and PYTHIA8[1]

[1] PYTHIA8: EPJC 74 3024 (2014)
[2] LEP: EPJC 75 19 (2015)
[3] H1: EPJC 38 447-459 (2005)
[4] ZEUS: JHEP 09 058 (2013)
[5] ATLAS: Nucl. Phys. B 907 717-763 (2016)
[6] ALICE pp@7TeV: PLB 718 279-294 (2012)
[7] LEP: EPJC 81 (2021) 3, 226
[8] CDF: PRD 77 072003 (2008)
[9] ATLAS: PRL 115 262001 (2015)
[10] LHCb pp@7TeV: PRD 85 032008 (2012)
[11] LHCb pp@13TeV: PRD 100 031102 (2019)

Charm baryon: Λ_c^+

📖 P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	D^0 ($u\bar{c}$)	D^+ ($d\bar{c}$)	D^{*+} ($d\bar{c}$)	D_s^+ ($s\bar{c}$)	Λ_c^+ (udc)	Σ_c^0 (ddc)	Σ_c^{++} (uuc)	Ξ_c^+ (usc)	Ξ_c^0 (dsc)	Ω_c^0 (ssc)
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (µm)	122.9	311.8	–	151.2	60.7	–	–	136.6	45.8	80

$\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR=6.28%)

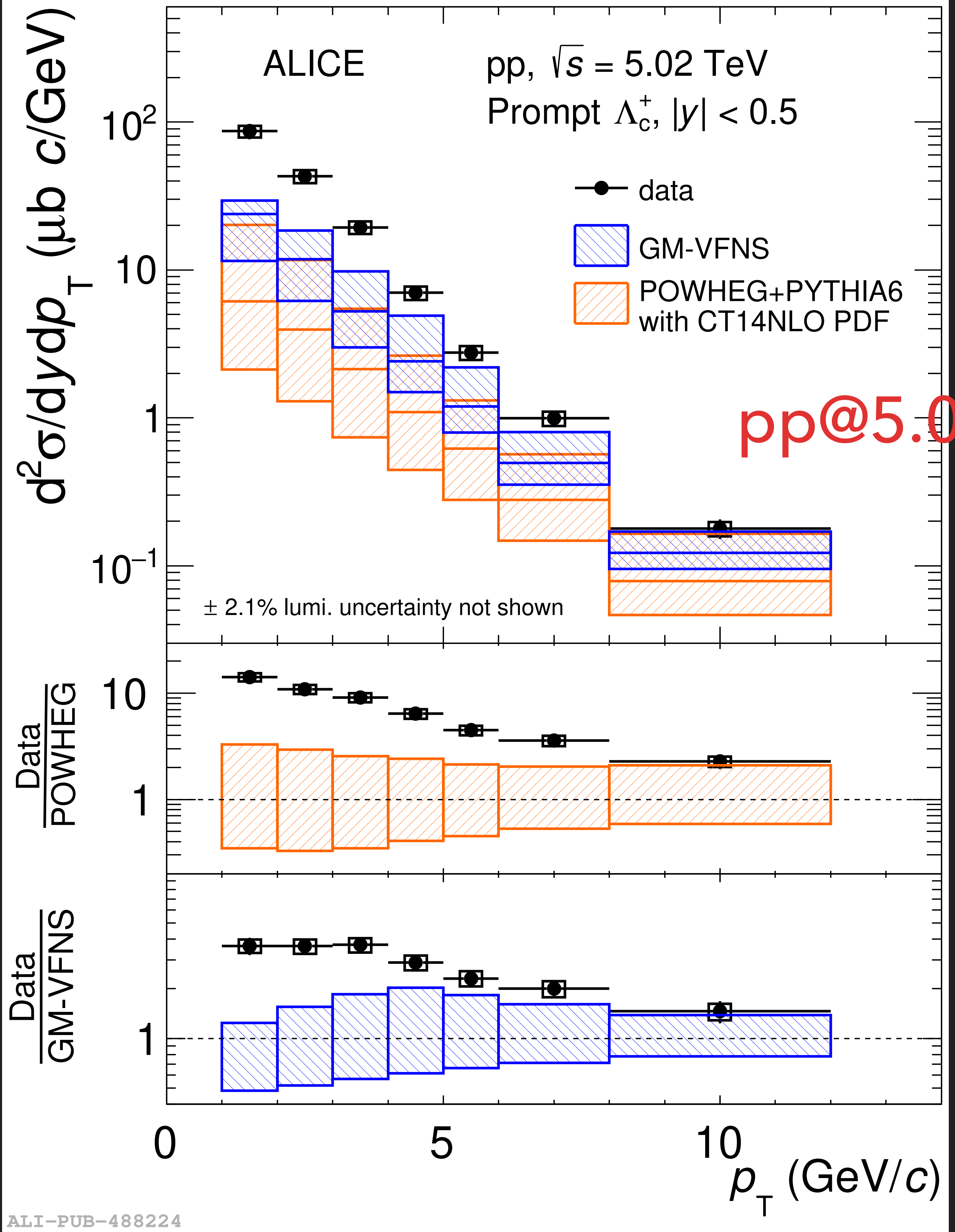
$\Lambda_c^+ \rightarrow pK_s^0$ (BR=1.59%)

Precise measurements of Λ_c^+ in pp and p–Pb collisions

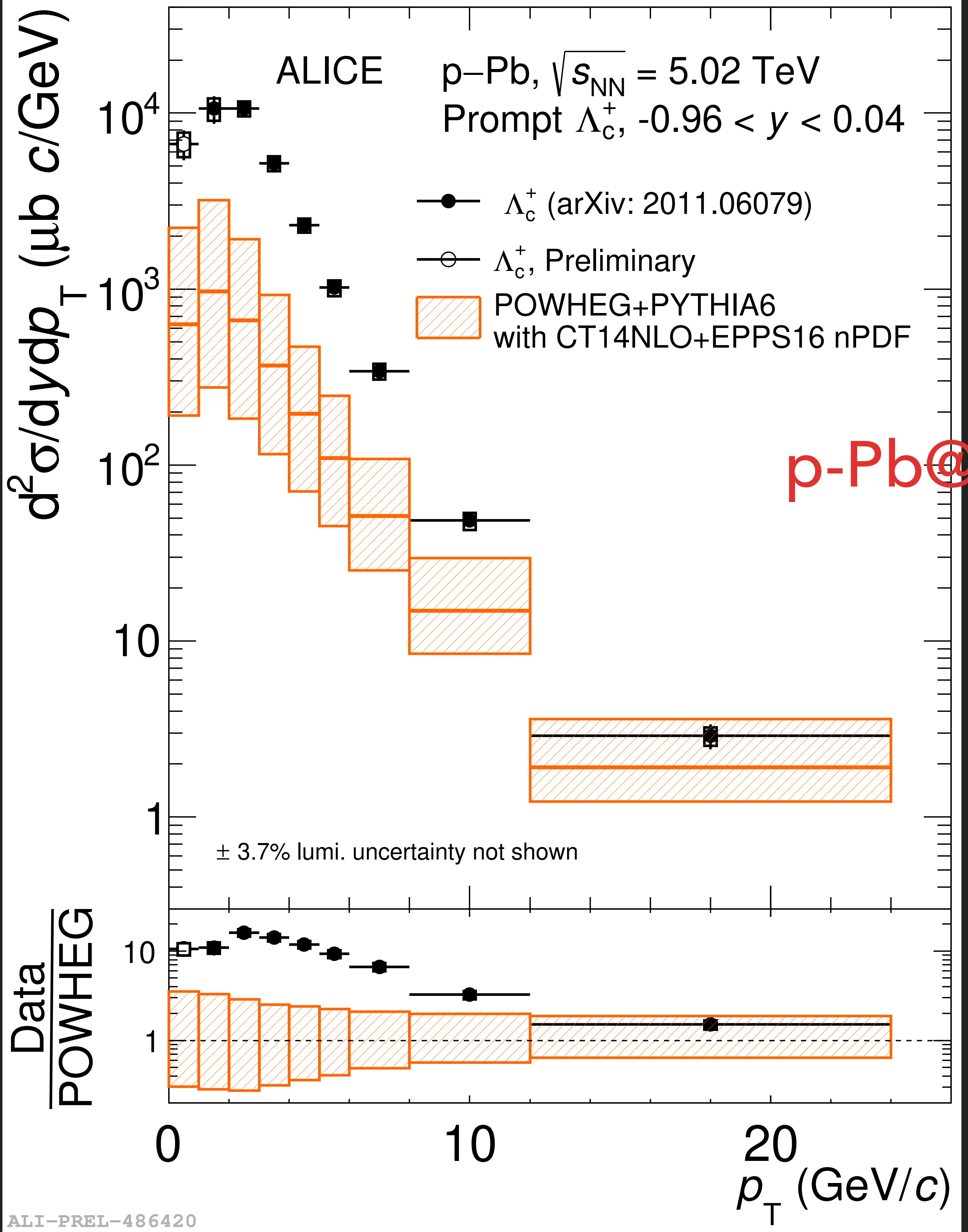
- First measurements of Λ_c^+ down to $p_T = 0$ in p-Pb collisions
- pQCD calculations underestimate data, especially at low p_T
  - Previous results in pp@7 TeV confirmed with larger statistics and extended p_T range
  - FF used by GM-VFNS includes new input from Belle measurements[1]

[1] Belle: Phys. Rev. D 97, 072005

arXiv:2011.06079
arXiv:2011.06078



pp@5.02 TeV

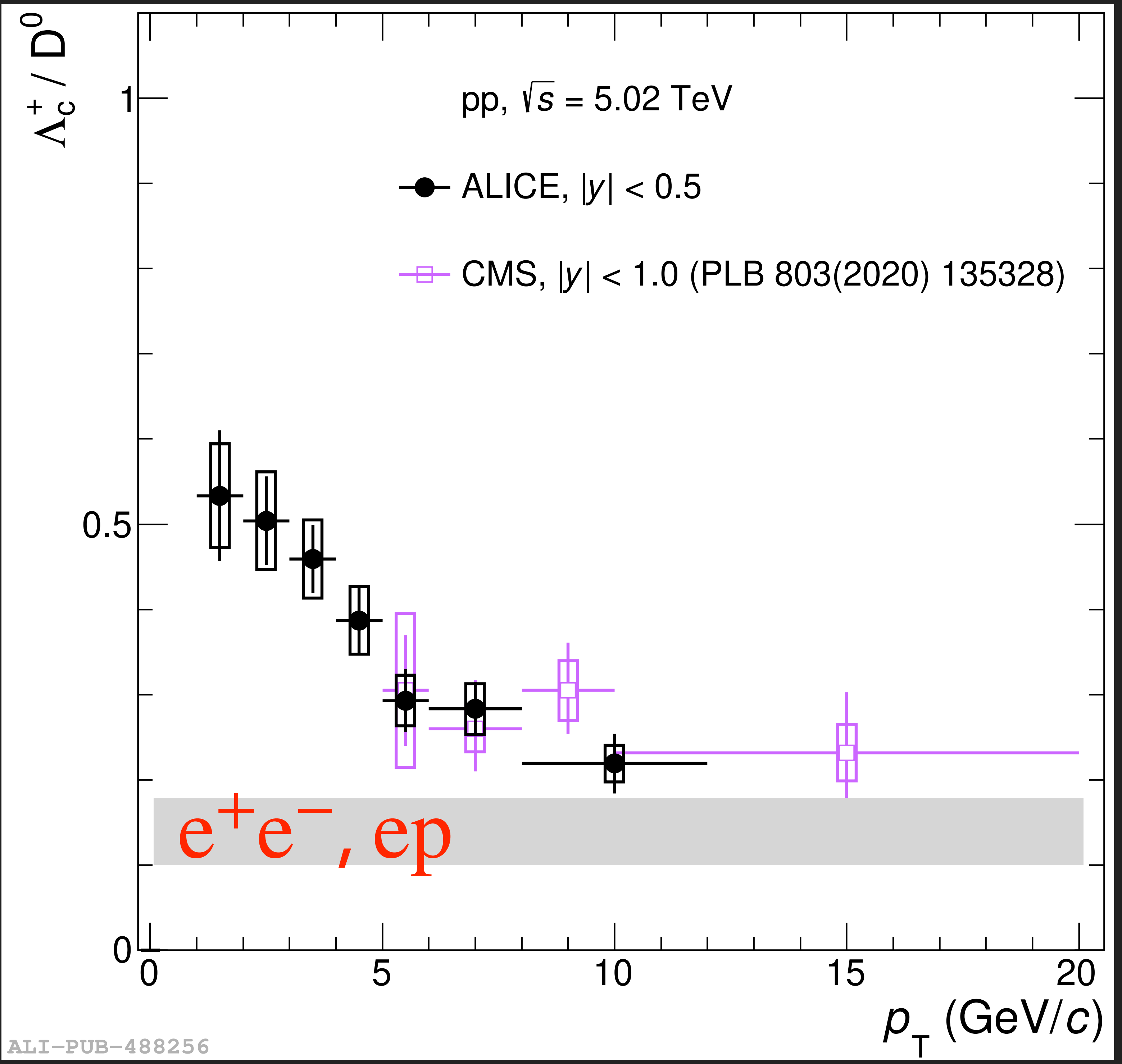


p-Pb@5.02 TeV

arXiv:2011.06079
arXiv:2011.06078

Precise measurements of Λ_c^+/D^0

arXiv:2011.06079 arXiv:2011.06078



- More precise and wider p_T range measurements (w.r.t. Run 1) highlight strong p_T dependence (CMS reaches higher p_T)
  - Low p_T significantly higher than e^+e^- and ep
  - High p_T approaches value measured in e^+e^- and ep

Precise measurements of Λ_c^+/D^0

arXiv:2011.06079 arXiv:2011.06078

- More precise and wider p_T range measurements (w.r.t. Run 1) highlight strong p_T dependence (CMS reaches higher p_T)
  - Low p_T significantly higher than e^+e^- and ep
  - High p_T approaches value measured in e^+e^- and ep
- Comparison with forward and backward rapidity measured by LHCb represents interesting trend
- All measurements from Run 2 at the LHC agree to draw conclusion that Λ_c^+/D^0 is higher in pp w.r.t. e^+e^- and ep

Precise measurements of Λ_c^+/D^0

arXiv:2011.06079 arXiv:2011.06078

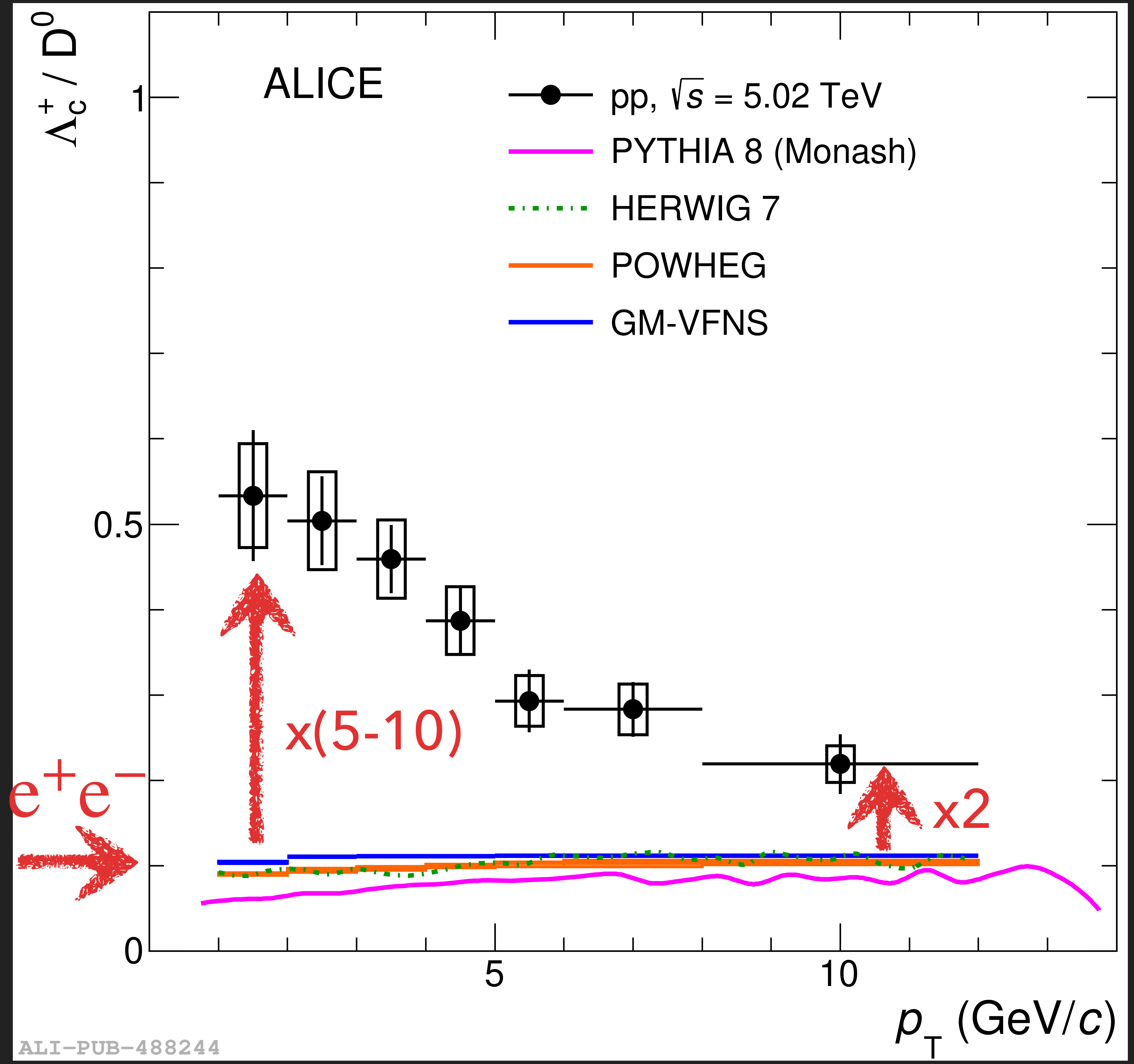
LHC Run 2 data confirm the indications observed previously

- Enhancement of Λ_c^+/D^0 → modification of charm hadronisation mechanism

- More precise and wider p_T range measurements (w.r.t. Run 1) highlight strong p_T dependence (CMS reaches higher p_T)
  - Low p_T significantly higher than e^+e^- and ep
  - High p_T approaches value measured in e^+e^- and ep
- Comparison with forward and backward rapidity measured by LHCb represents interesting trend
- All measurements from Run 2 at the LHC agree to draw conclusion that Λ_c^+/D^0 is higher in pp w.r.t. e^+e^- and ep

How do model calculations and MC generators perform at the LHC ?

arXiv:2011.06079
arXiv:2011.06078



- The MC generators
  - PYTHIA8 Monash tune[1] simple LUND string fragmentation
  - HERWIG7[2]: hadronisation implemented via clusters
  - POWHEG[3]: matched to PYTHIA6[4] to generate parton shower
- GM-VFNS[5]: pQCD calculations, compute the ratios of Λ_c^+ and D^0 cross sections with same choice of pQCD scales
- All implement fragmentation processes tuned on e^+e^-
  - $\Lambda_c^+/D^0 \approx 0.1$
  - NO p_T dependence
- At low p_T, significantly underestimate Λ_c^+/D^0
- At high p_T, discrepancy reduced

[1] PYTHIA8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
[2] HERWIG: M. Bahr, et al., EPJC 58 (2008) 639-707
[3] POWHEG: S. Frixione, et al., JHEP 09 (2007) 126
[4] PYTHIA6: T. Sjostrand, JHEP 05 (2006) 026
[5] GM-VFNS: B. Kniehl, et al., PRD 101 (2020) 114021

PYTHIA with new colour reconnection

ALICE

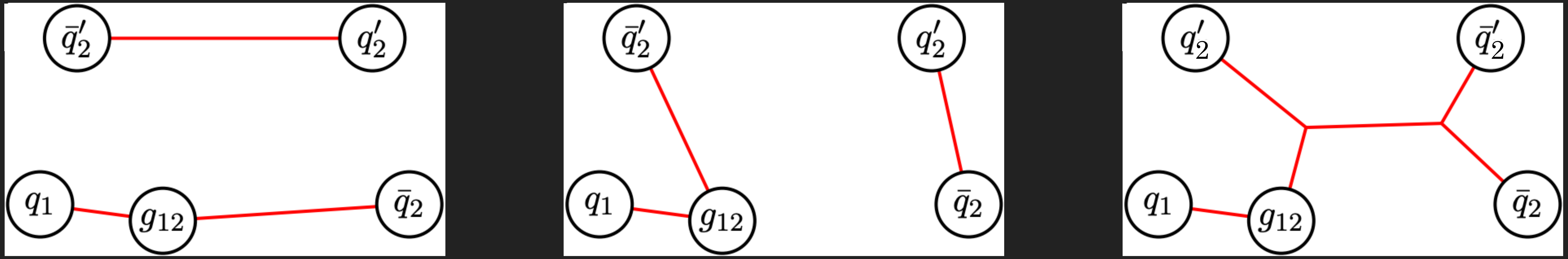
PYTHIA8[1,2]

J. Christiansen, P. Skands, JHEP 08 (2015) 003

- New CR model: colour reconnection beyond leading colour (CR-BLC) mode with SU(3) topology weights + string-length minimisation
  - The junction topology favours baryon formation
    - Primordial Λ_c^+ enhanced by factor ~2 with new CR model
    - Extra contribution from feed-down of Σ_c states (x20~30 more)

Particle	New CR model (N_{par}/N_{events}) string	junction	all	Old CR model N_{par}/N_{events} (all)
D^+	$5.3 \cdot 10^{-2}$	0	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$4.0 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$2.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^+	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^0	$2.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$

No CR | MPI-based CR (Old CR model) | More-QCD CR (New CR-BLC model)



No CR:
✳ Partons created in different scatterings do not interact

MPI-based CR (Old CR model):
✳ CR allowed between partons from different MPIs to minimize string length
✳ As implemented in Monash

More-QCD CR (New CR-BLC model):
✳ Uses a simple model of the colour rules of QCD to determine the formation of strings and introduce junctions
✳ Minimization of the string length over all possible configurations
✳ Include CR with MPIs and with beam remnants

[1] P. Skands, S. Carrazza and J. Rojo, EPJC 74 (2014) 3024
[2] J. Christiansen, P. Skands, JHEP 08 (2015) 003

Statistical hadronisation with augmented resonances

ALICE

Statistical Hadronisation Model (SHM) (M. He and R. Rapp)[1]

- SHM (M. He and R. Rapp), and FF from e^+e^-
  - Tuned on D^0 ALICE data + scaling for mass
- Feed-down from augmented set of charm-baryon states based on Relativistic Quark Model (RQM)[2]
  - RQM: extra 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c w.r.t. PDG2018[3]

M. He and R. Rapp, PLB 795 (2019) 117-121

r_i	D^+/D^0	D^{*+}/D^0	D_s^+/D^0	Λ_c^+/D^0
PDG(170)	0.4391	0.4315	0.2736	0.2851
PDG(160)	0.4450	0.4229	0.2624	0.2404
RQM(170)	0.4391	0.4315	0.2726	0.5696
RQM(160)	0.4450	0.4229	0.2624	0.4409

M. He and R. Rapp, PLB 795 (2019) 117-121

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

[1] M. He and R. Rapp, PLB 795 (2019) 117-121
[2] D. Ebert, R. Faustov and V. Galkin, PRD 84:014025, 2011
[3] PDG: PRD 98, no.3, 030001 (2018)

Coalescence from a partonic system

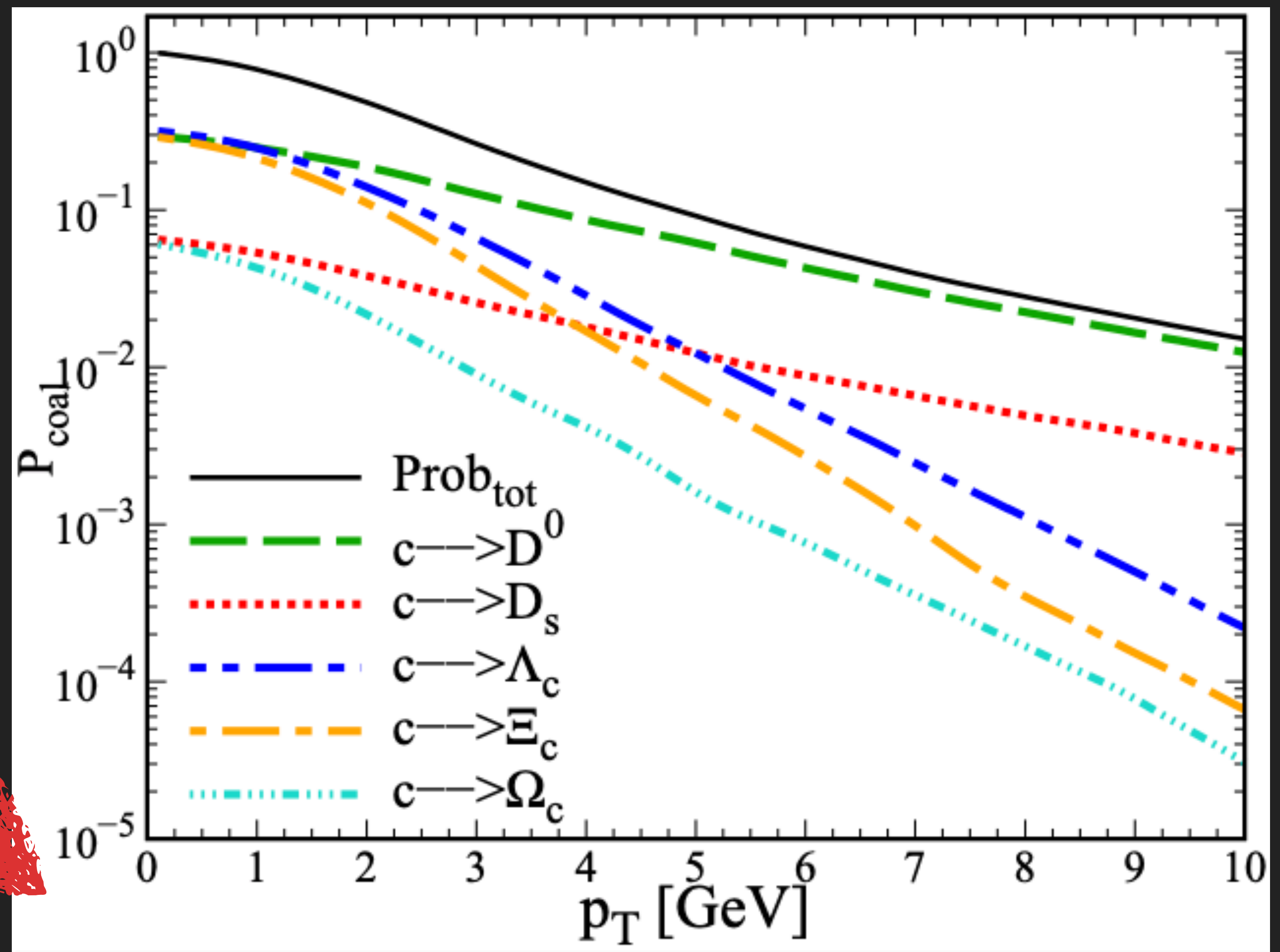
Catania[1,2]

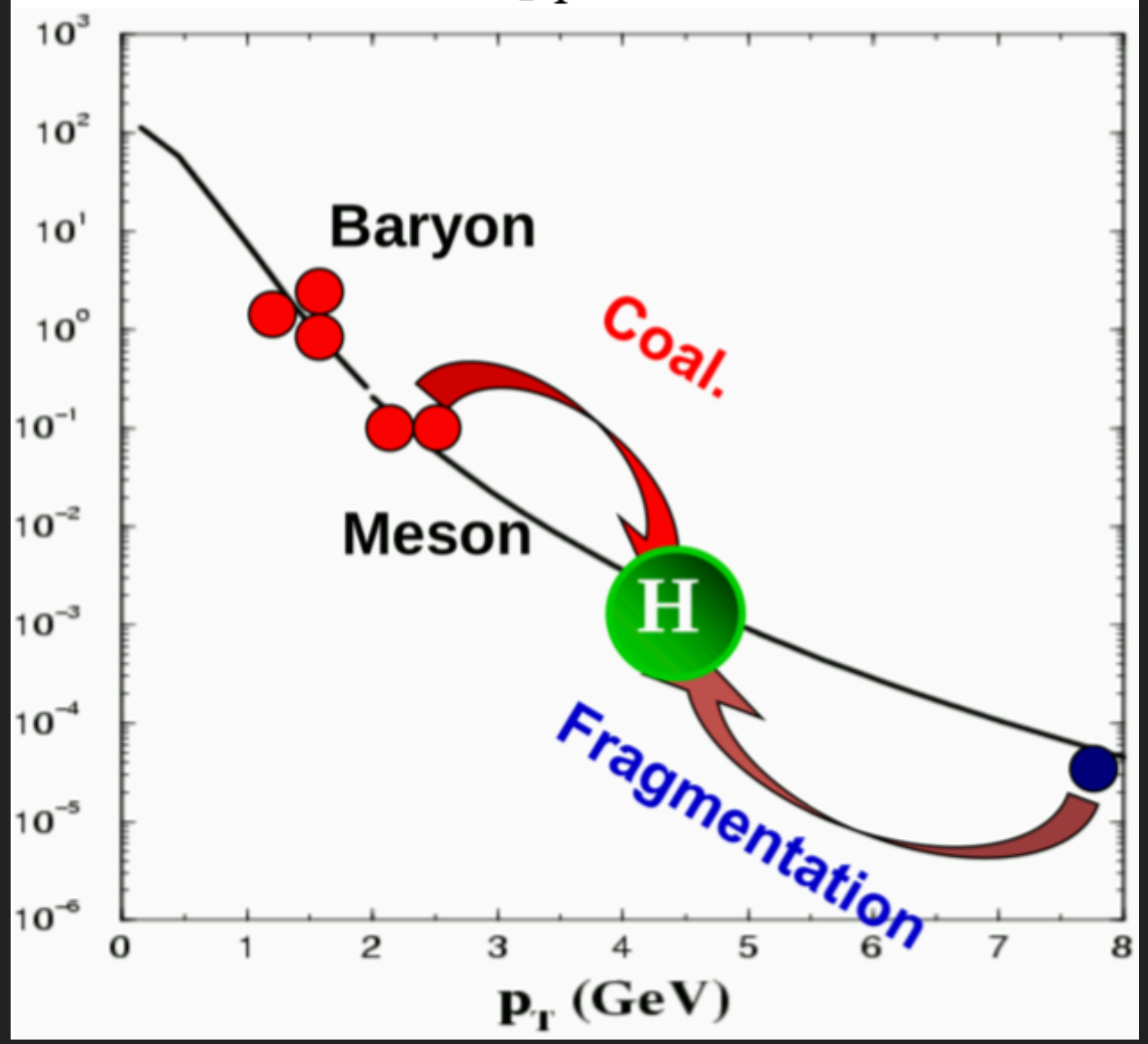
- Transport model with hadronization via coalescence+fragmentation
  - Assume a partonic system (QGP-like) in pp
  - Coalescence enhances baryon-to-meson yield ratio
- Charm quark spectrum from FONLL
- Same excited resonances as PDG
- At $p_{\mathrm{T}} \approx 0$, a charm quark can hadronize only by coalescence
- At high p_{T}, fragmentation becomes dominant

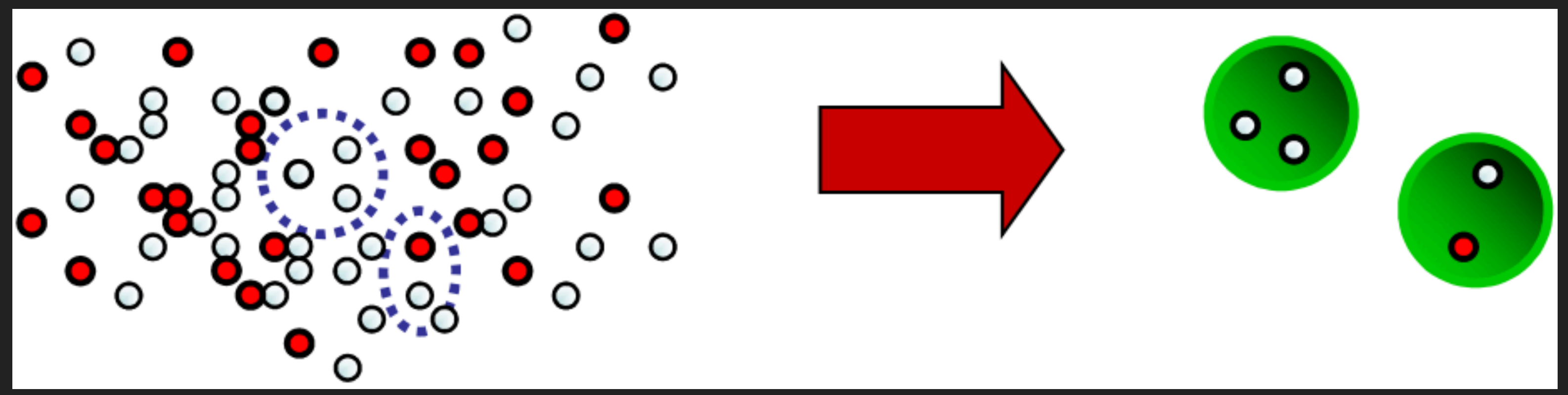
QCM: Quark (re-)Combination Mechanism[3]

- Charm combined with equal-velocity light quarks
  - Charm can pick up a co-moving light antiquark or two co-moving quarks
- A new scenario of low p_{T} charm quark hadronization in presence of underlying light quark source
  - Maybe related to creation of deconfined parton system in pp at LHC

V. Minissale, S. Plumari, V. Greco, arXiv:2012.12001



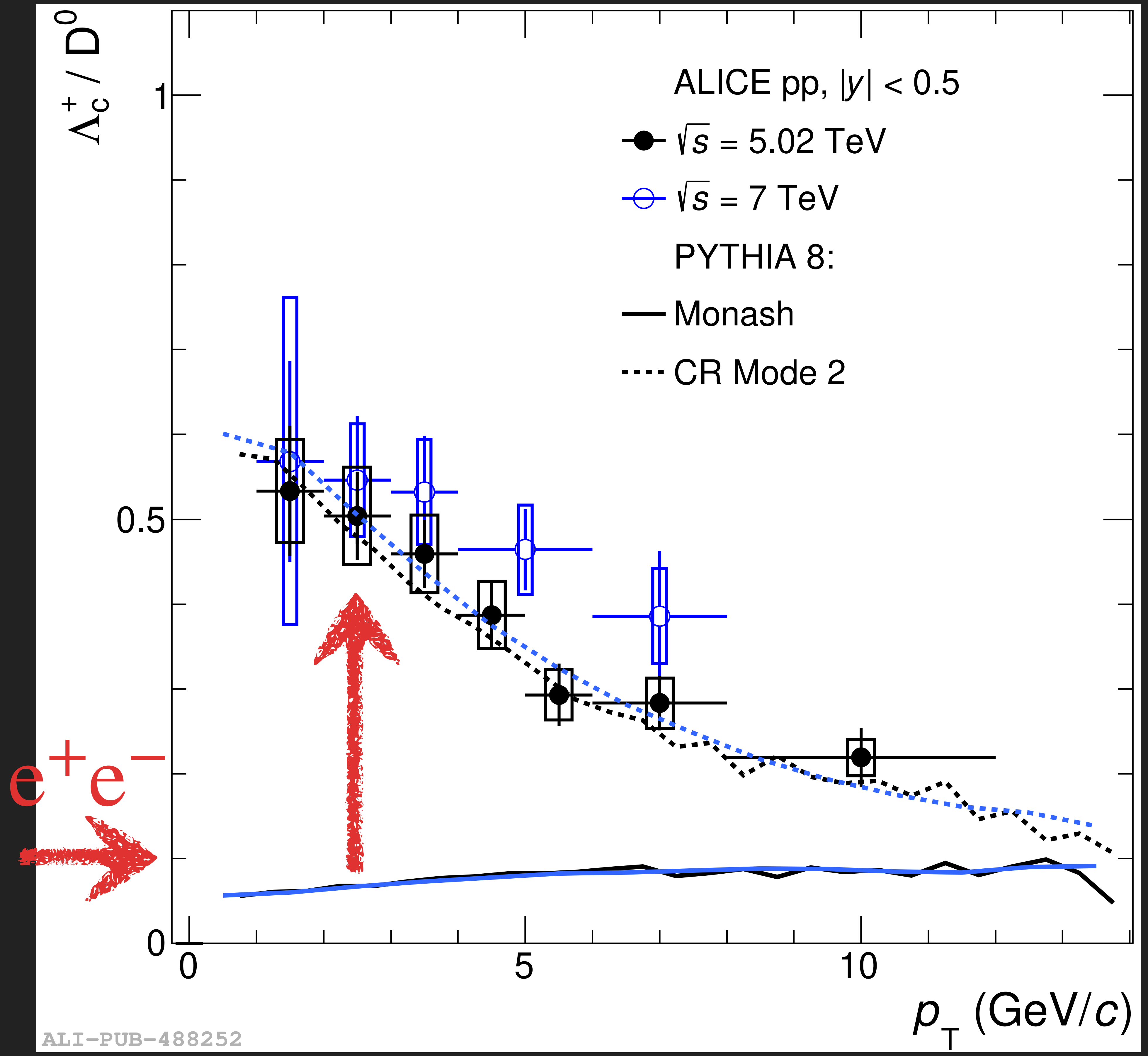




[1] V. Minissale, S. Plumari, V. Greco, arXiv:2012.12001
[2] S. Plumari, et al., EPJC (2018) 78:348
[3] J. Song, H. Li, F. Shao, EPJC (2018) 78: 344

Models with different assumptions compared with data

arXiv:2011.06079
arXiv:2011.06078



- PYTHIA8 CR-BLC tunes[2] largely enhance Λ_c^+ yield w.r.t. Monash tune[1]

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003

Models with different assumptions compared with data

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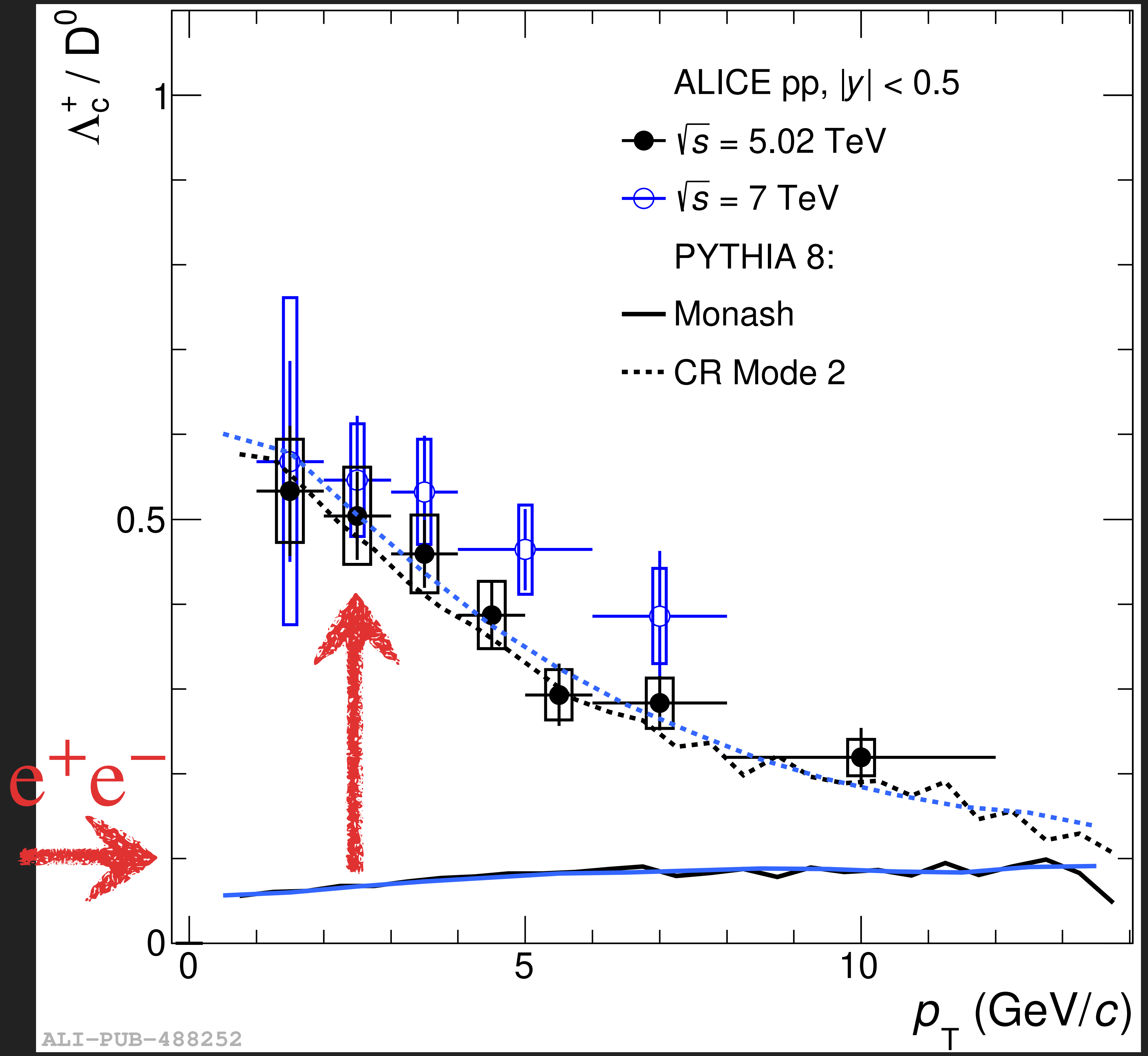
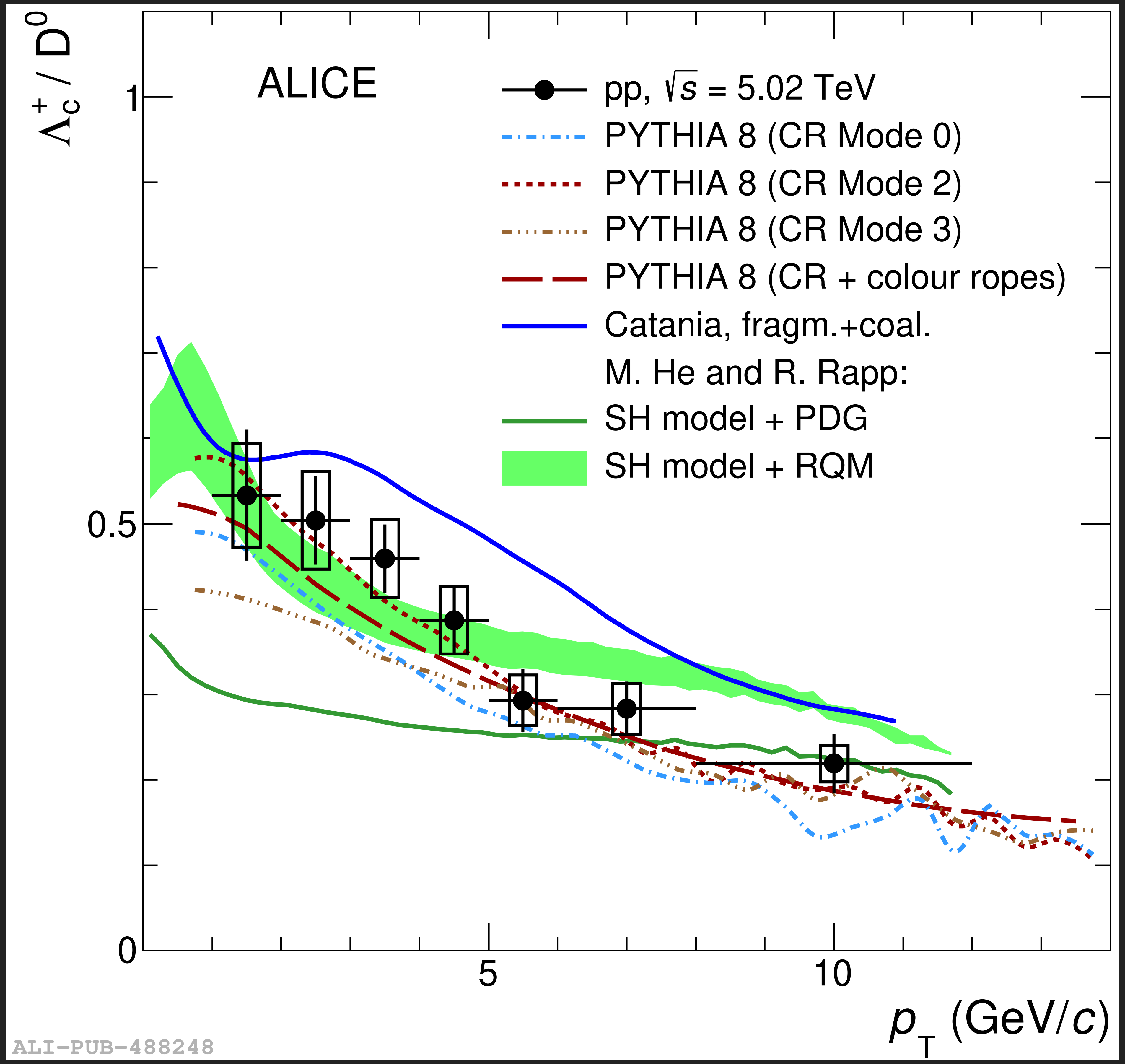


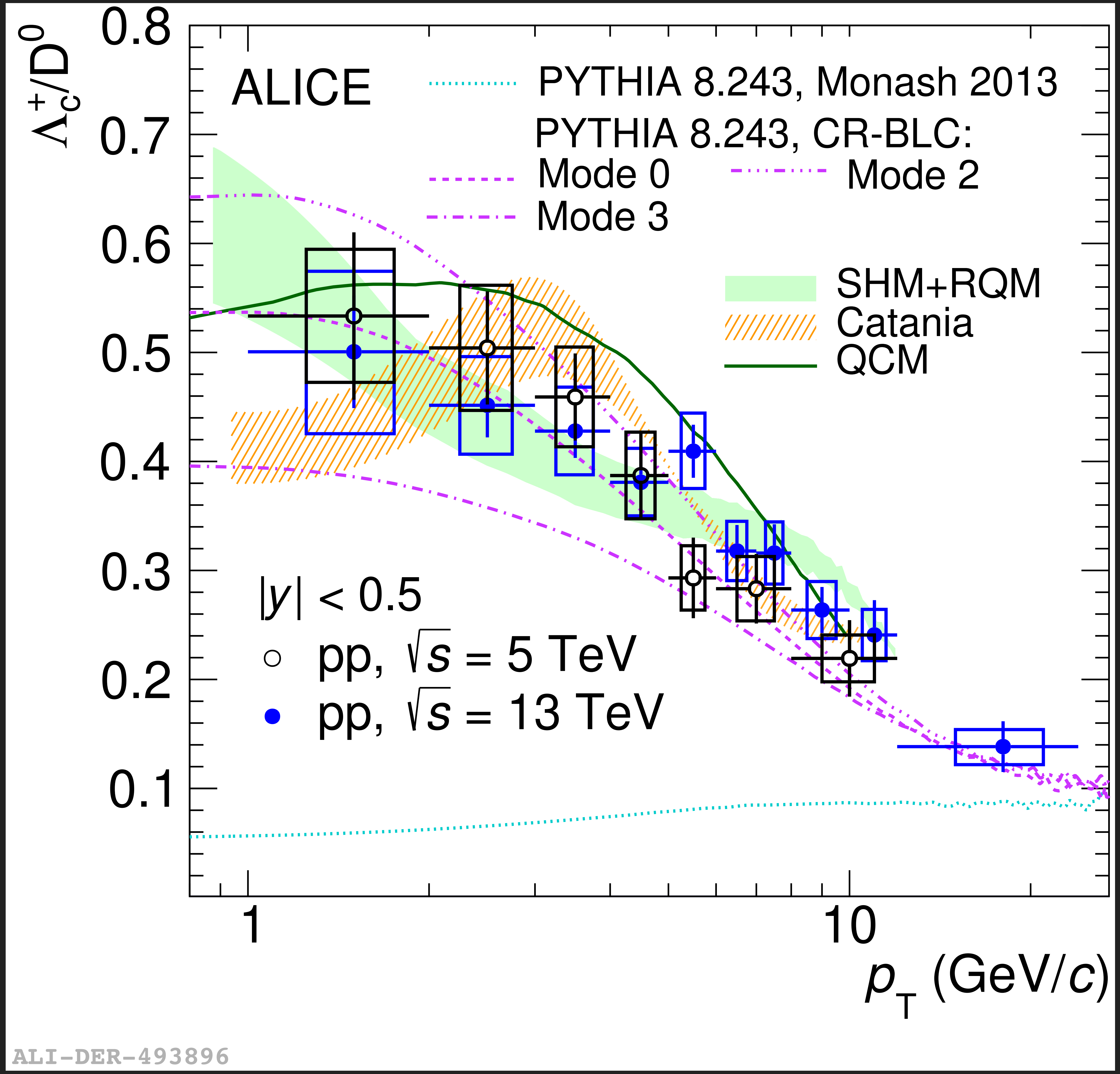


- PYTHIA8 CR-BLC tunes[2] largely enhance Λ_c^+ yield w.r.t. Monash tune[1]
- NO large differences between different CR-BLC tunes in PYTHIA8
- SHM[3]+RQM[4] enhance Λ_c^+ yield w.r.t. SHM+PDG and better describe data
- Catania[5] further enhances Λ_c^+ yield by coalescence approach, but tend to overestimate the measurement

[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., arXiv:2012.12001

Compare different collision energies

arXiv:2106.08278

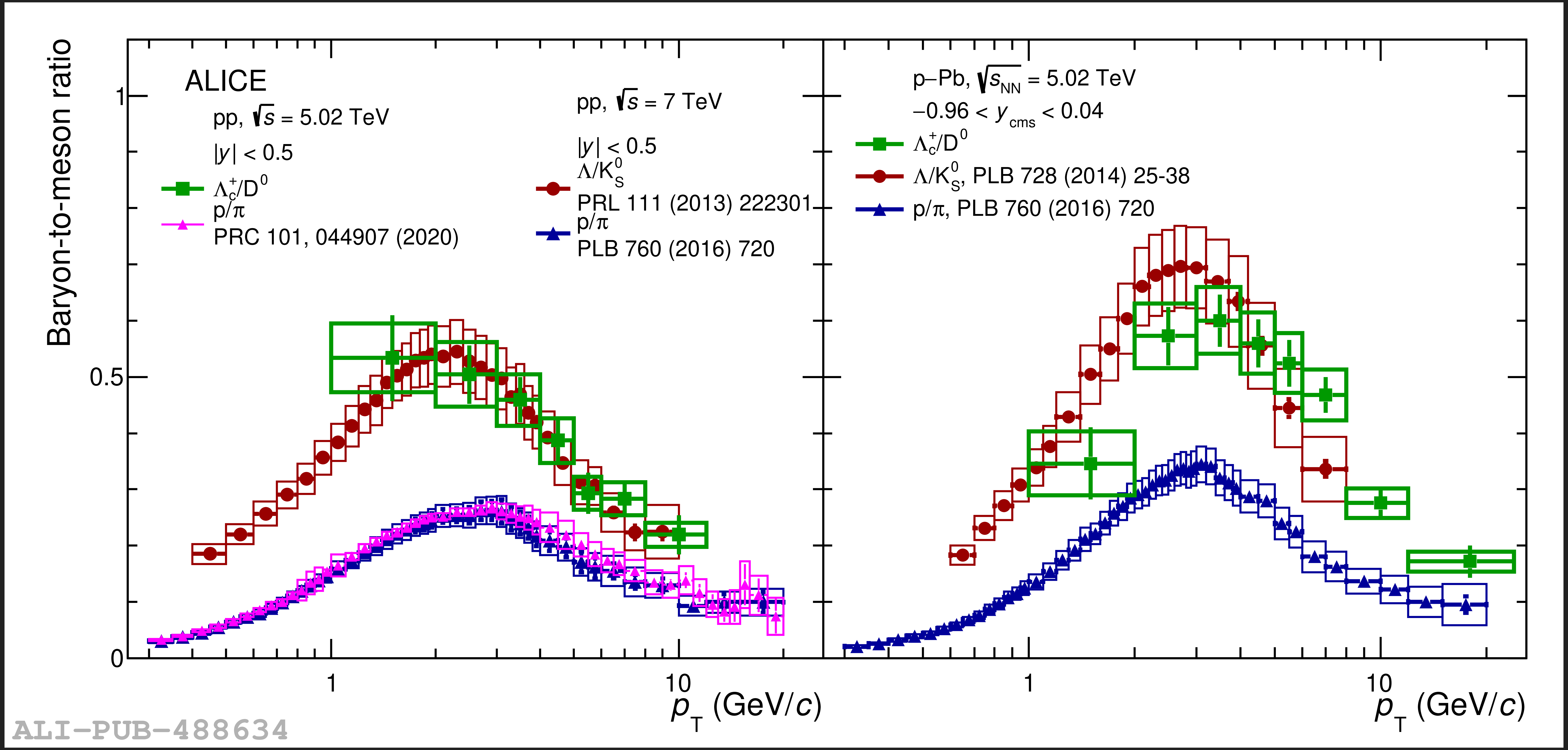


- Λ_c^+/D^0 in pp@5 TeV and pp@13 TeV
- NO collision energy dependence

Compare with light flavor (LF)

ALICE

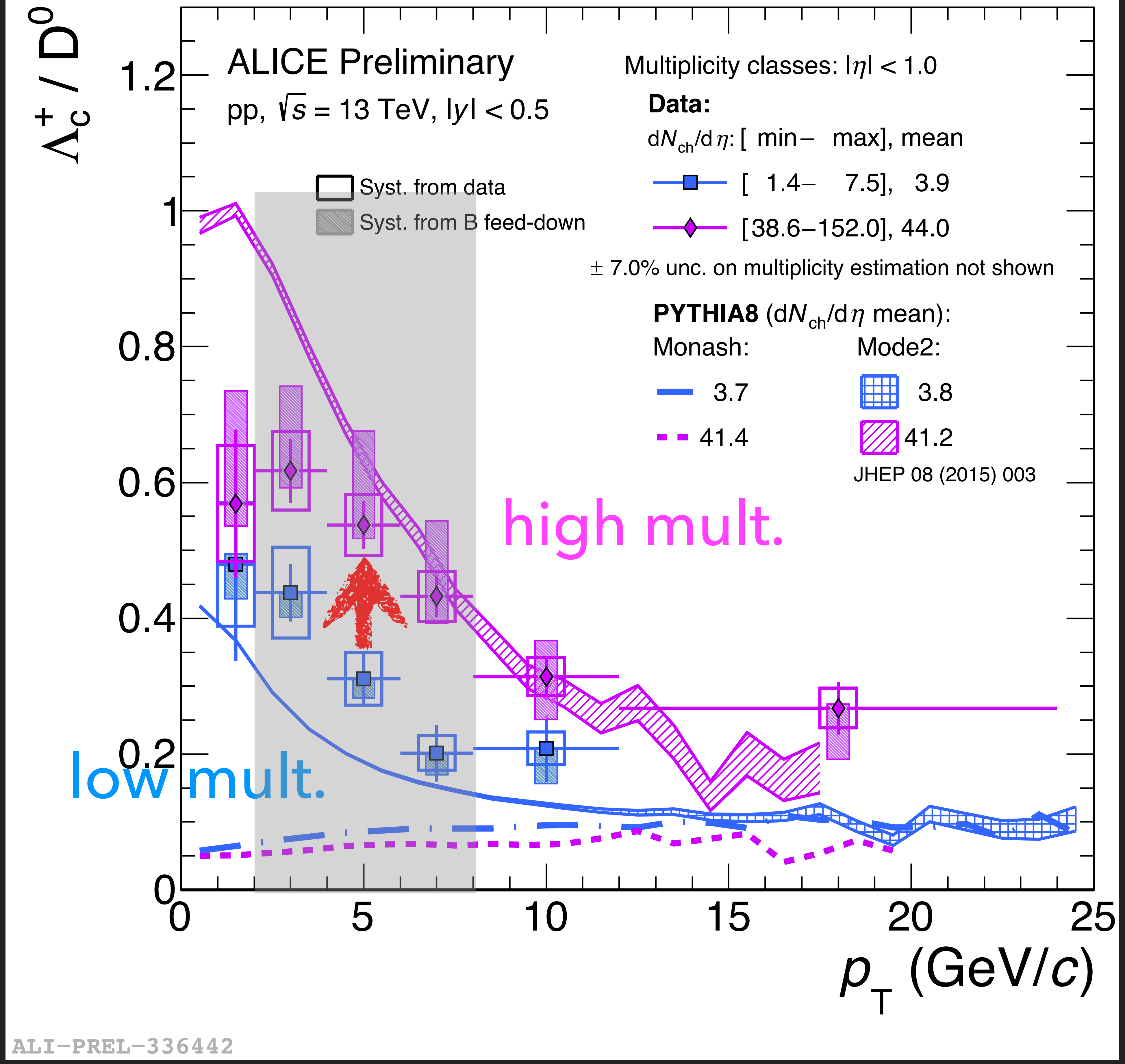
arXiv:2011.06078



- Comparison of baryon-to-meson yield ratio in heavy and light sector show similar properties
  - Λ_c^+/D^0 consistent with Λ/K^0_s both in magnitude and shape
  - Similar p_T trend observed for p/π

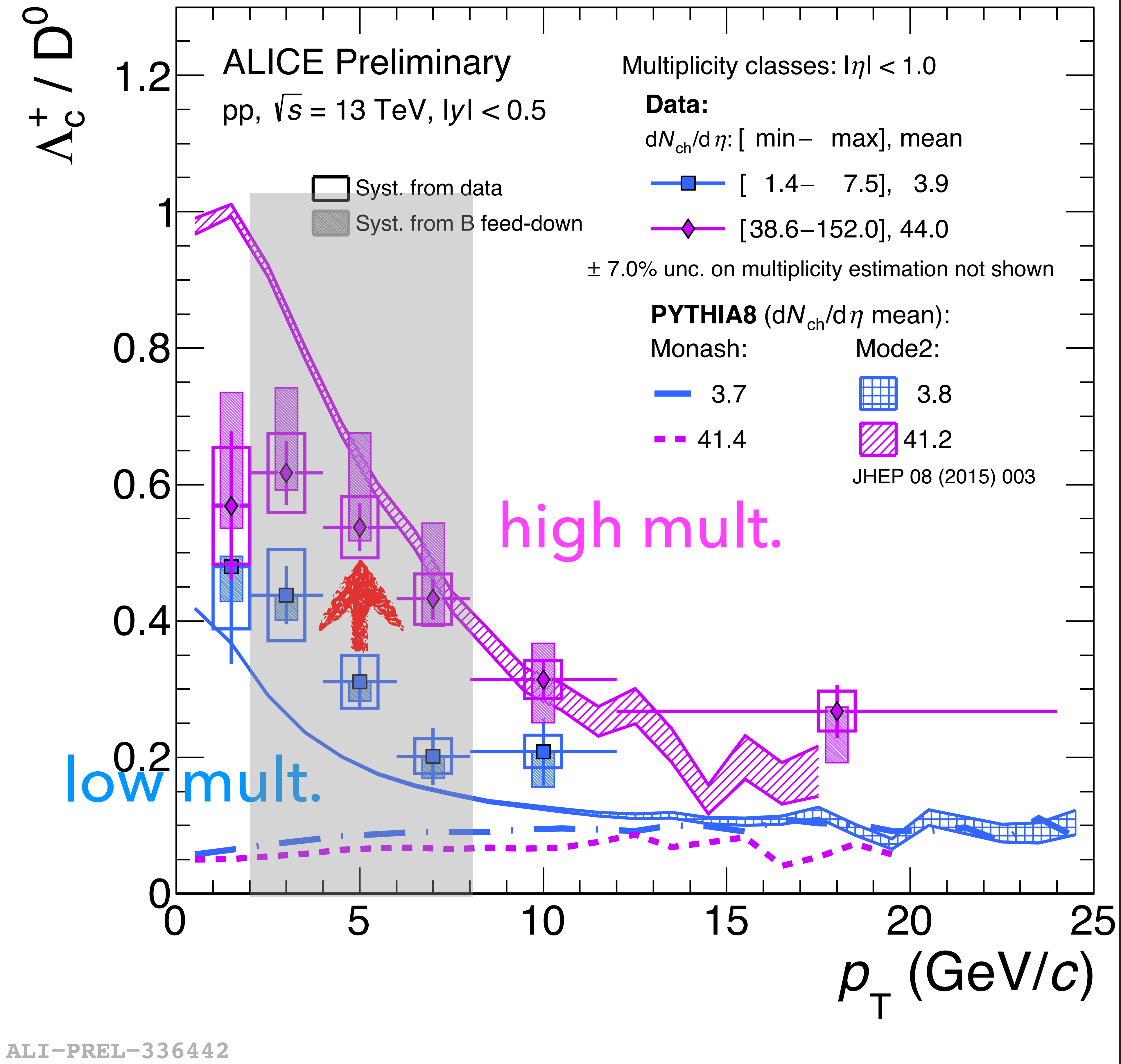
Hadronisation mechanisms similar for light and heavy quarks ?

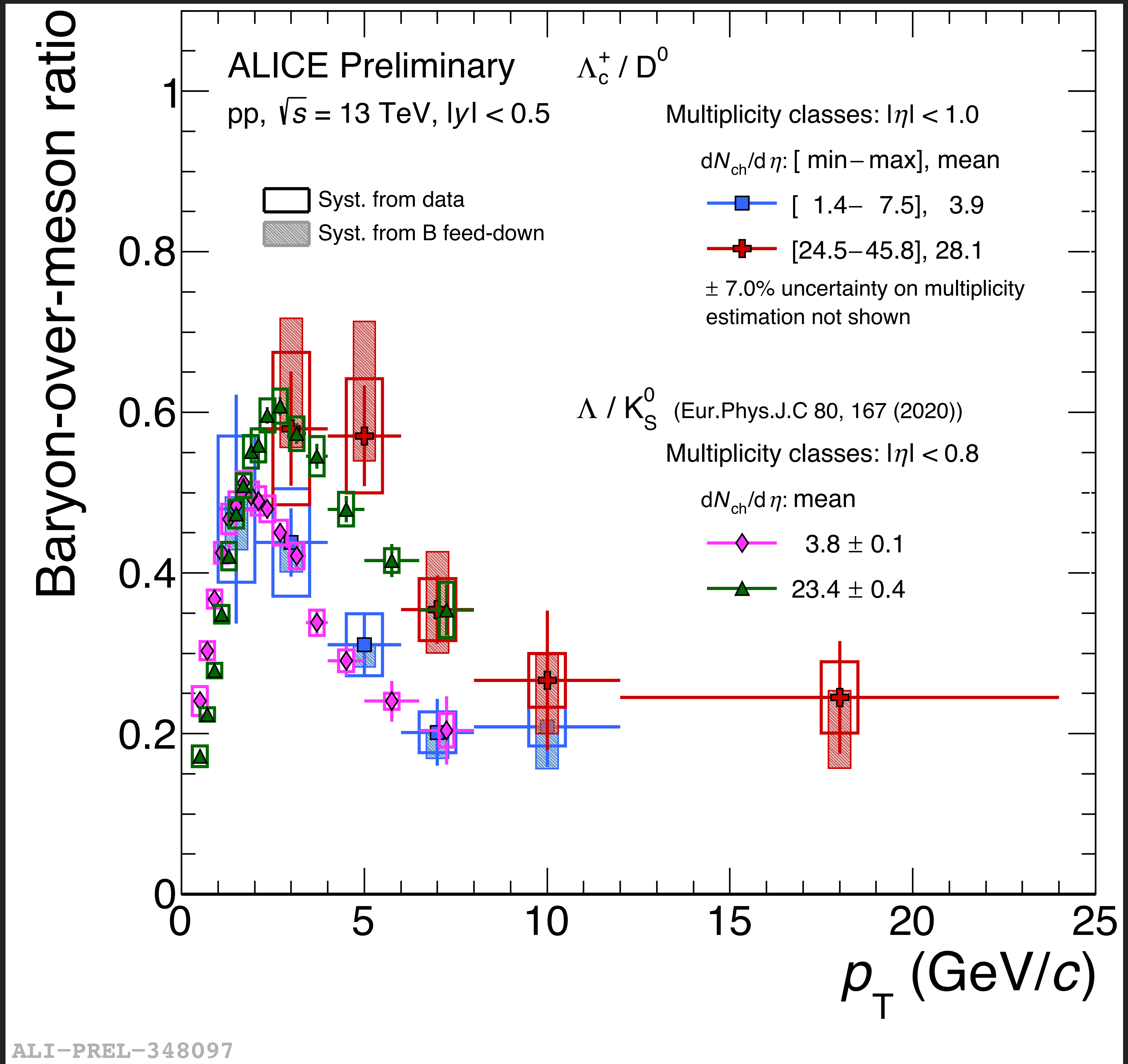
More differential measurements of Λ_c^+/D^0



- p_T-dependent enhancement of Λ_c^+/D^0 observed from low to high multiplicity
- PYTHIA8 Mode2: Multiplicity trend qualitatively in line with data
- PYTHIA8 Monash: NO variation with multiplicity

More differential measurements of Λ_c^+/D^0





- p_T-dependent enhancement of Λ_c^+/D^0 observed from low to high multiplicity
- PYTHIA8 Mode2: Multiplicity trend qualitatively in line with data
- PYTHIA8 Monash: NO variation with multiplicity

- Similar p_T-dependent enhancement of Λ_c^+/D^0 and Λ/K_S^0 observed from low to high multiplicity
  - Hadronisation mechanisms similar for light and heavy quarks ?

Heavier charm baryons: $\Sigma_c^{0,+,++}$

ALICE

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	D^0 ($u\bar{c}$)	D^+ ($d\bar{c}$)	D^{*+} ($d\bar{c}$)	D_s^+ ($s\bar{c}$)	Λ_c^+ (udc)	Σ_c^0 (ddc)	Σ_c^{++} (uuc)	Ξ_c^+ (usc)	Ξ_c^0 (dsc)	Ω_c^0 (ssc)
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	–	151.2	60.7	–	–	136.6	45.8	80

$\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$ (BR=100%, strongly decay)

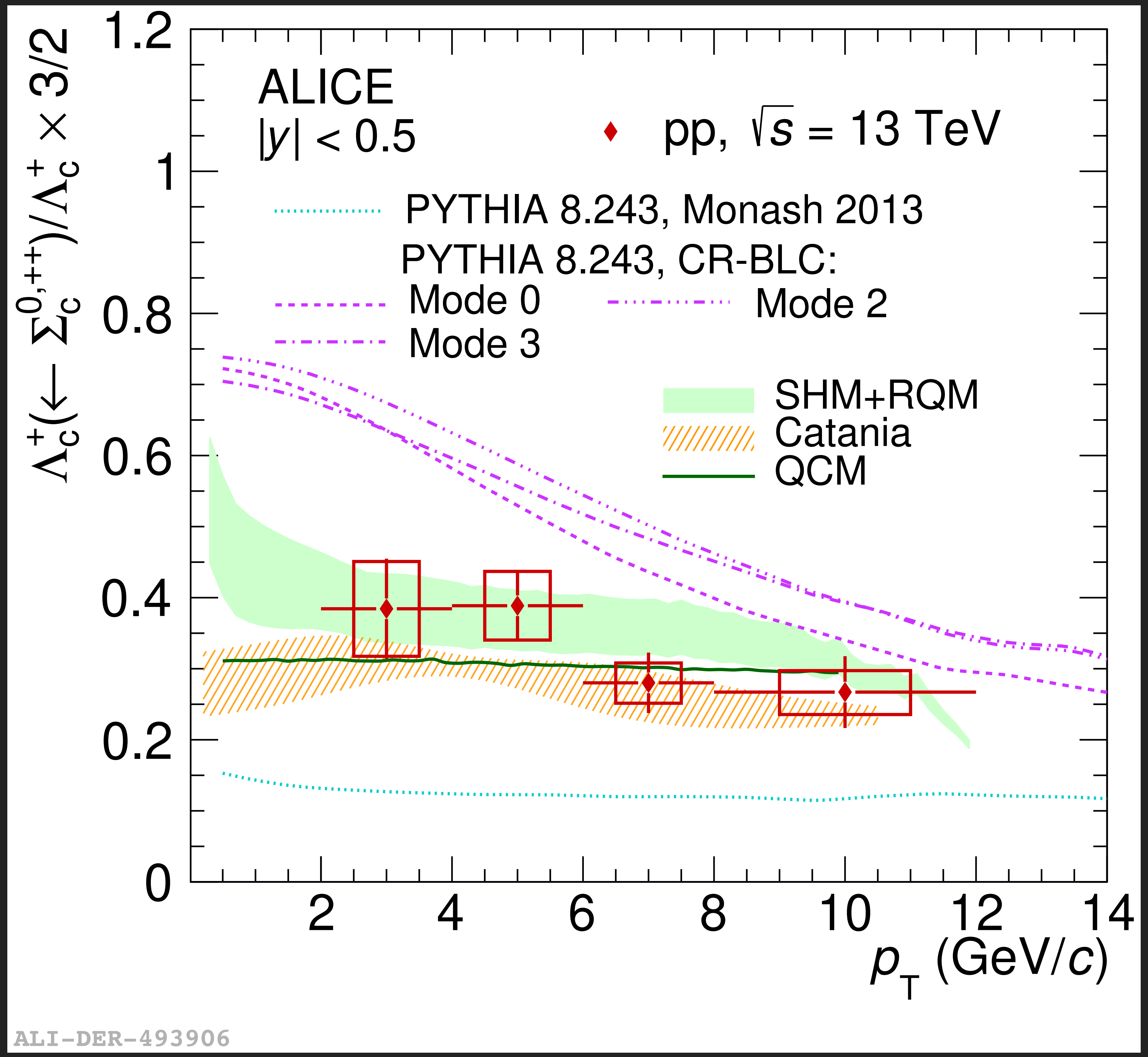
$\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ (BR=100%, strongly decay)

x3/2 to count Σ_c^+(udc)

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

- Effect of $\Sigma_c^{0,+,++}$ feed-down contribution on Λ_c^+/D^0 enhancement
  - ~40% contribution, only partially explained by $\Sigma_c^{0,+,++}$ feed-down

arXiv:2106.08278



- PYTHIA8 Monash[1] severely underestimates $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$
- PYTHIA8 CR Modes[2] overestimate $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$
- SHM[3]+RQM[4] describes both $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$
- Catania[5] and QCM[6] also provide good description of data

[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., arXiv:2012.12001
[6] J. Song, et al., EPJC (2018) 78: 344

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

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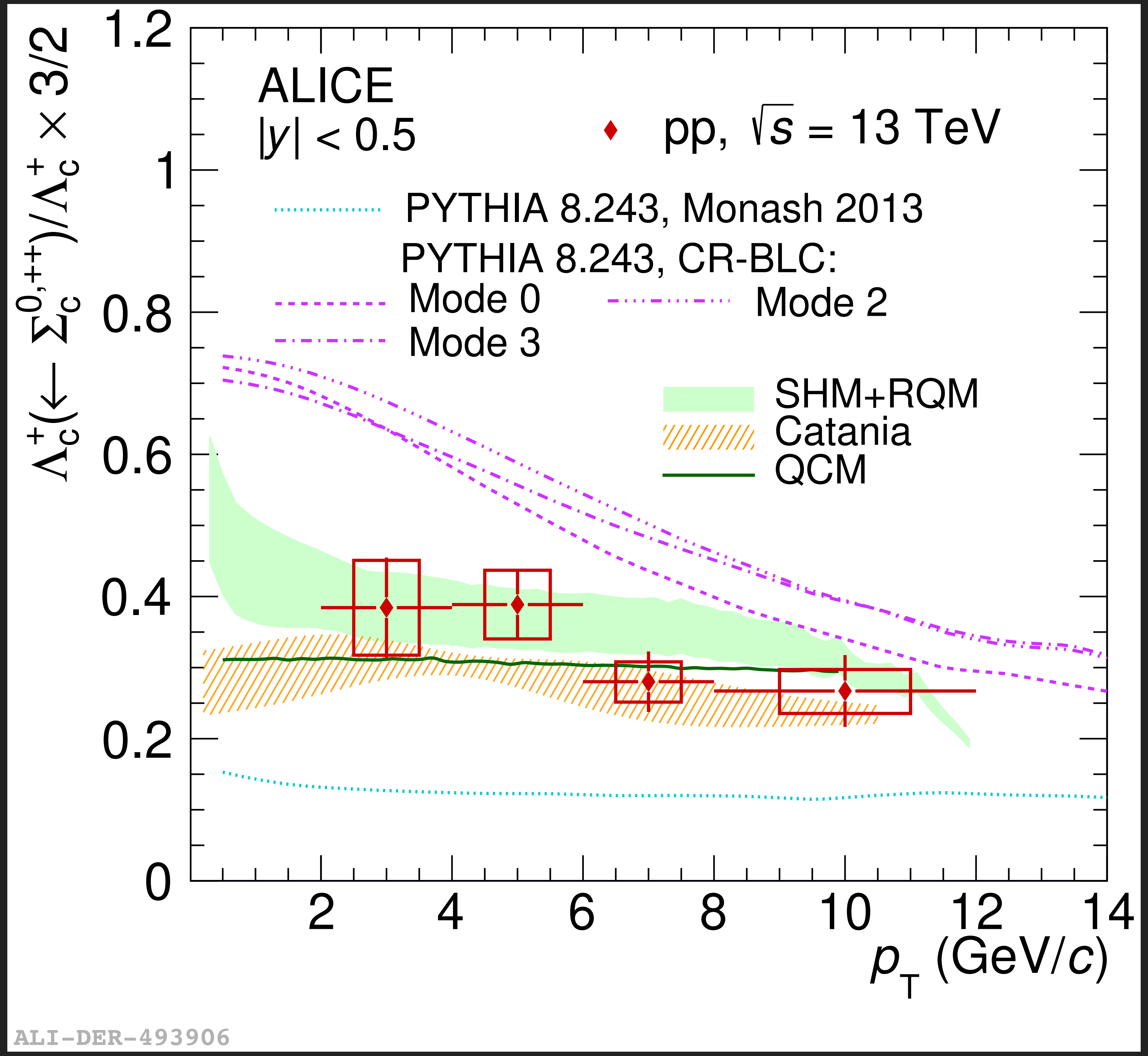

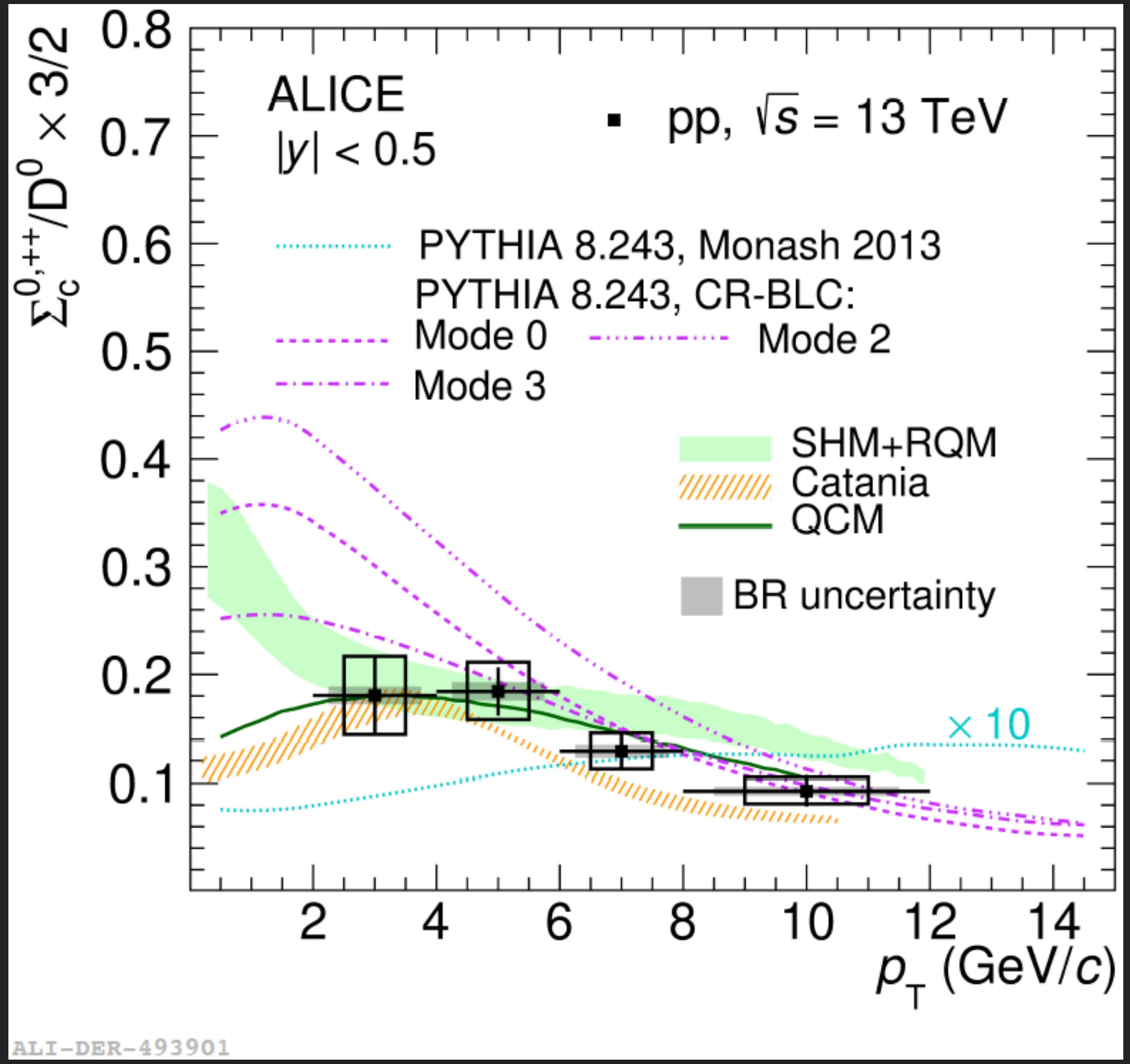

- PYTHIA8 Monash[1] severely underestimates $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$
- PYTHIA8 CR Modes[2] overestimate $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$, but describe $\Sigma_c^{0,+,++}/D^0$
- SHM[3]+RQM[4] describes both $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$
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[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., arXiv:2012.12001
[6] J. Song, et al., EPJC (2018) 78: 344

Heavier charm baryons: $\Xi_c^{0,+}$

ALICE

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	D^0 ($u\bar{c}$)	D^+ ($d\bar{c}$)	D^{*+} ($d\bar{c}$)	D_s^+ ($s\bar{c}$)	Λ_c^+ (udc)	Σ_c^0 (ddc)	Σ_c^{++} (uuc)	Ξ_c^+ (usc)	Ξ_c^0 (dsc)	Ω_c^0 (ssc)
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Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	–	151.2	60.7	–	–	136.6	45.8	80

$\Xi_c^0 \rightarrow \Xi^- \pi^+$ (BR=1.43%)

$\Xi_c^0 \rightarrow e^+ \Xi^- \nu_e$ (BR=1.8%)

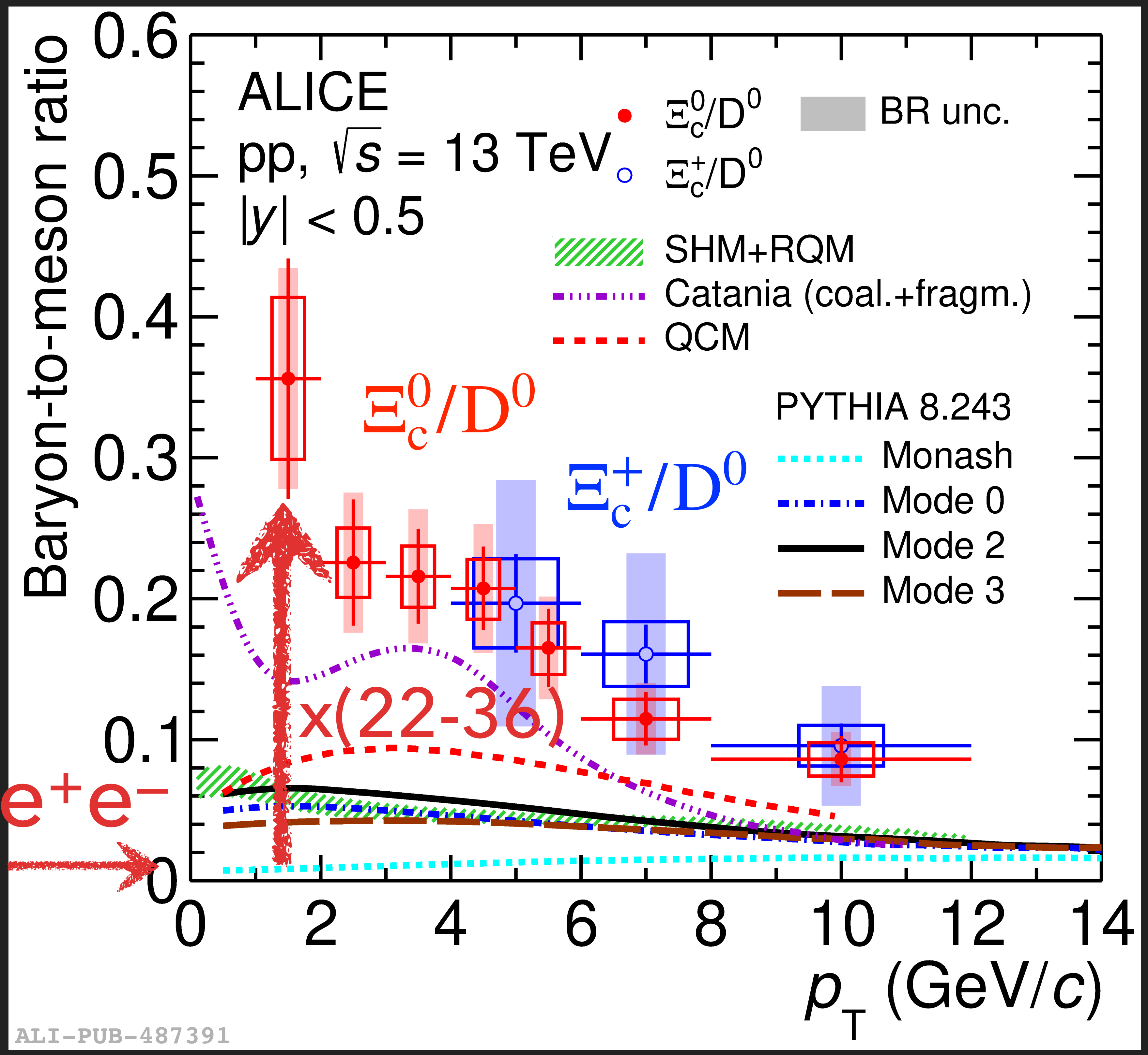
$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ (BR=2.86%[1])

[1] Belle: Phys. Rev. D 100, 031101 (2019)

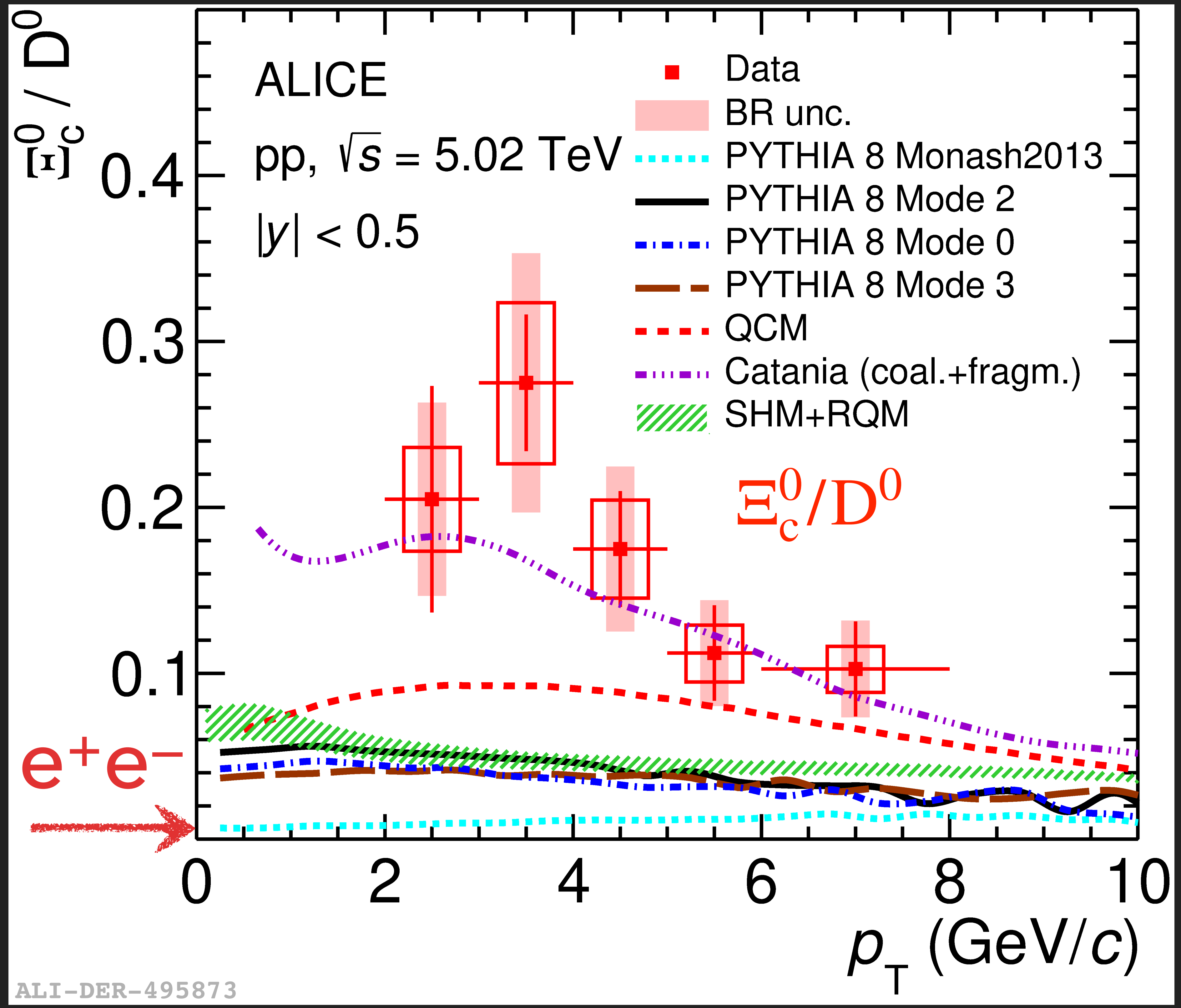
Heavier charm baryons: Ξ_c^0 and Ξ_c^+ in pp@5.02 and 13 TeV

- Ξ_c^0/D^0 in agreement with Ξ_c^+/D^0
- $\Xi_c^{0,+}/D^0$ similar p_T trend as Λ_c^+/D^0
- PYTHIA8 Monash[1] largely underestimates data

arXiv:2105.05187



arXiv:2105.05616



- 3 CR-BLC Modes[2] and SHM[3]+RQM[4] predict significantly larger ratio w.r.t. Monash, but largely underestimate data
- QCM[5], further enhanced, still NOT describe the data
- Catania[6] better describes measurements

[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., arXiv:2012.12001
[7] Belle e⁺e⁻: PRD 97 (2018) 7, 072005

Heavier charm baryon: Ω_c^0

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	D^0 ($u\bar{c}$)	D^+ ($d\bar{c}$)	D^{*+} ($d\bar{c}$)	D_s^+ ($s\bar{c}$)	Λ_c^+ (udc)	Σ_c^0 (ddc)	Σ_c^{++} (uuc)	Ξ_c^+ (usc)	Ξ_c^0 (dsc)	Ω_c^0 (ssc)
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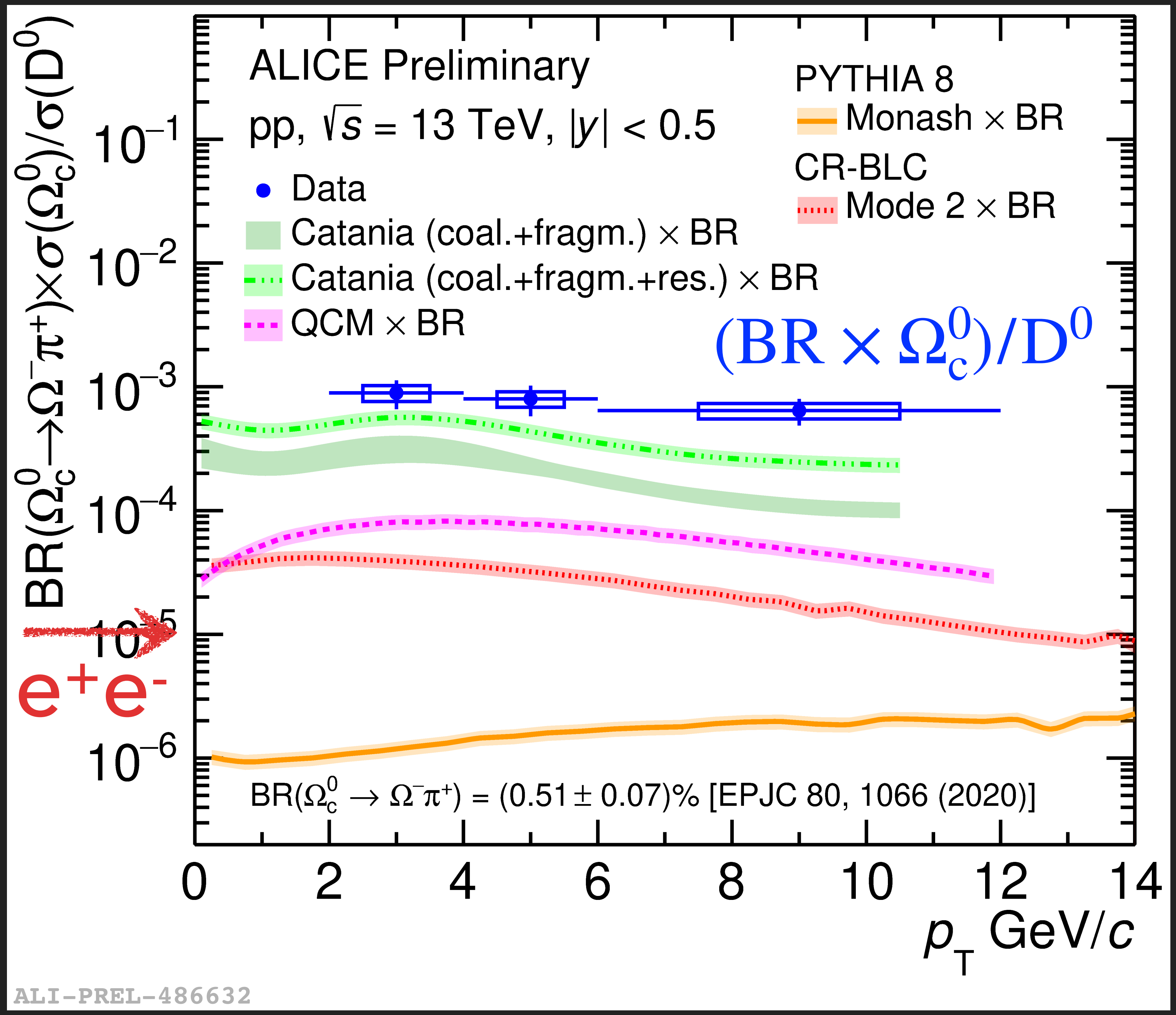
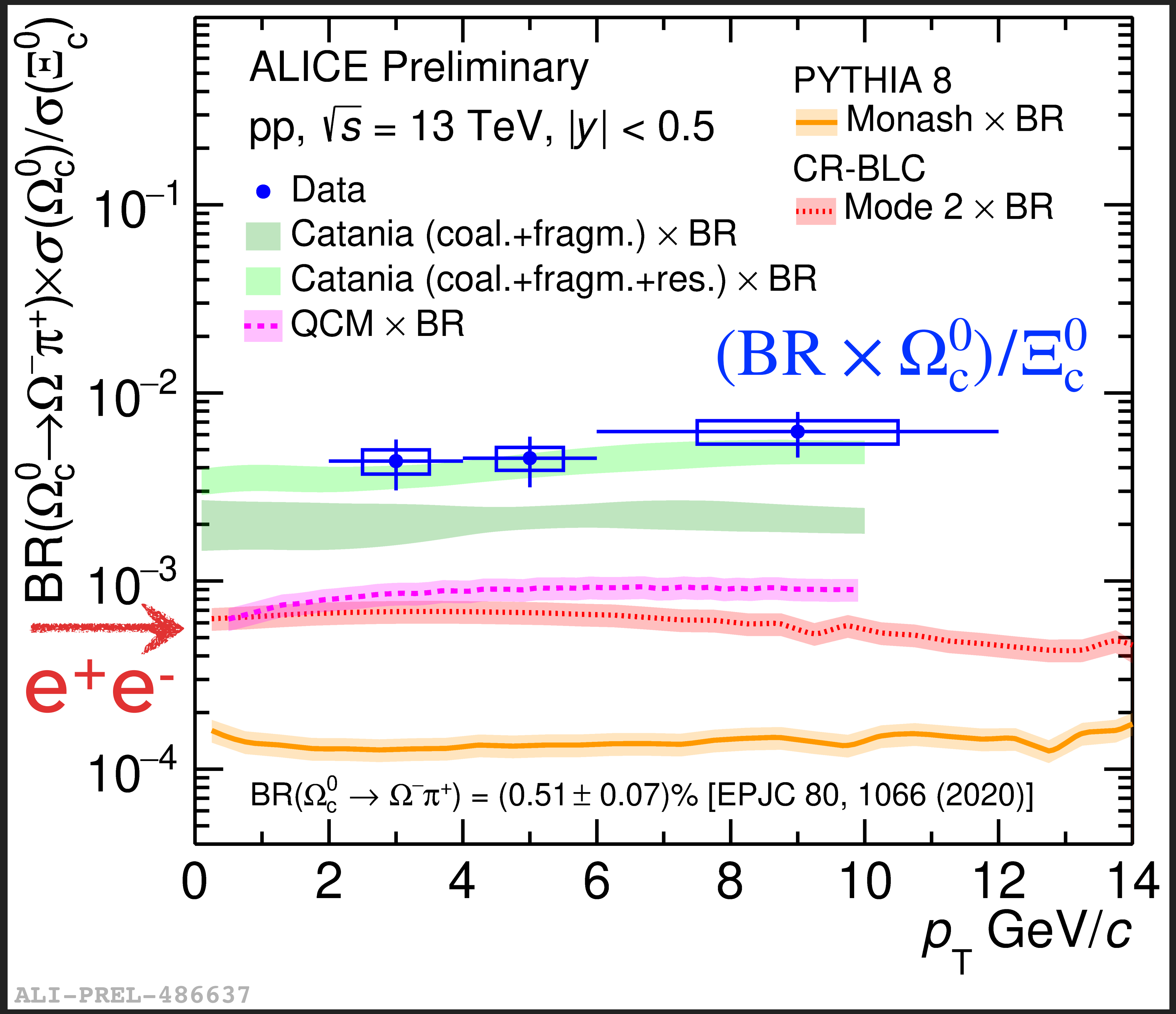
Lifetime (μm)	122.9	311.8	–	151.2	60.7	–	–	136.6	45.8	80

$\Omega_c^0 \to \Omega^-\pi^+$ (BR unknown)

Heavier charm baryons: Ω_c^0 in pp@13 TeV

- $BR(\Omega_c^0 \to \pi^+\Omega^-) = (0.51 \pm 0.07)$ % theoretical calculation
- PYTHIA8 Monash[1] largely underestimates Ω_c^0, also for Ω_c^0/D^0 and Ω_c^0/Ξ_c^0
  - ➡ Do not reproduce strangeness enhancement in pp
- PYTHIA8 CR-BLC[2] NOT enough to describe the measurement
- Further enhancement with simple coalescence QCM[3] still NOT describe data
- Catania[4] closer to data points, additional resonances decay considered





Coalescence in pp ?

[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., arXiv:2012.12001
[5] Belle e+e-: PRD 97 (2018) 7, 072005

Charm fragmentation fractions at the LHC

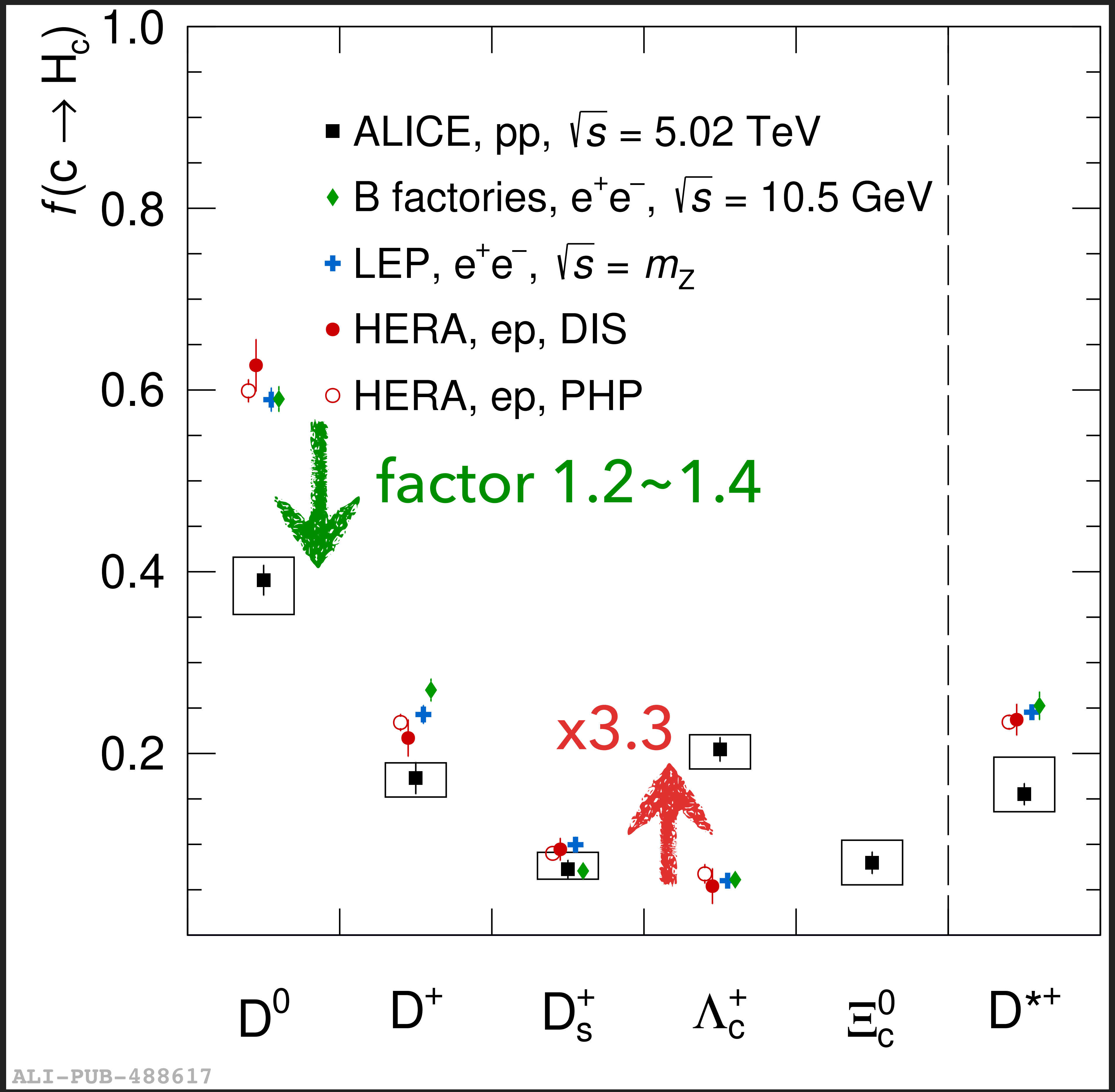
ALICE

- D^0 and D^+ down to 0, D_s^+ and Λ_c^+ down to 1 GeV/c, Ξ_c^0 down to 2 GeV/c
- Charm fragmentation fraction calculated as hadron-production cross section over sum of cross sections of all ground-states of charm hadrons : $f(c \rightarrow H_c) = \sigma(H_c)/\Sigma_i \sigma(H_{c,i})$

arXiv:2105.06335

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	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$	$\times$ 2 to include Ξ_c^+
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$	Feed into D^0 and D^+

arXiv:2105.06335



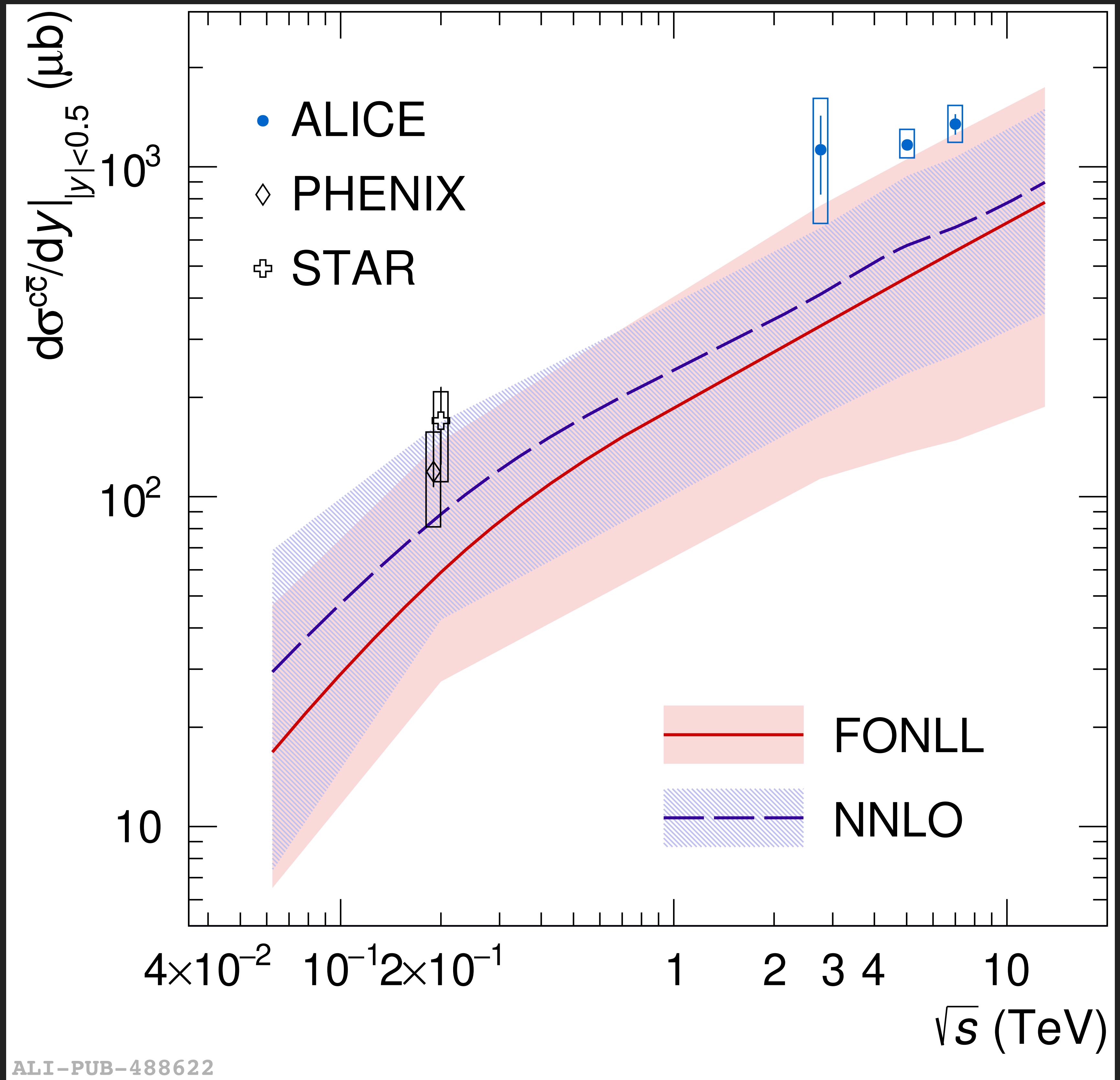
- e^+e^- and ep : $f(c \rightarrow \Xi_c^0)/f(c \rightarrow \Lambda_c^+) = f(s \rightarrow \Xi^-)/f(s \rightarrow \Lambda) \approx 0.004$ [1]
- pp: $f(c \rightarrow \Xi_c^0)/f(c \rightarrow \Lambda_c^+) = 0.39 \pm 0.07(\text{stat})^{+0.08(\text{syst})}_{-0.07(\text{syst})}$ [4]

Charm fragmentation fractions not universal!

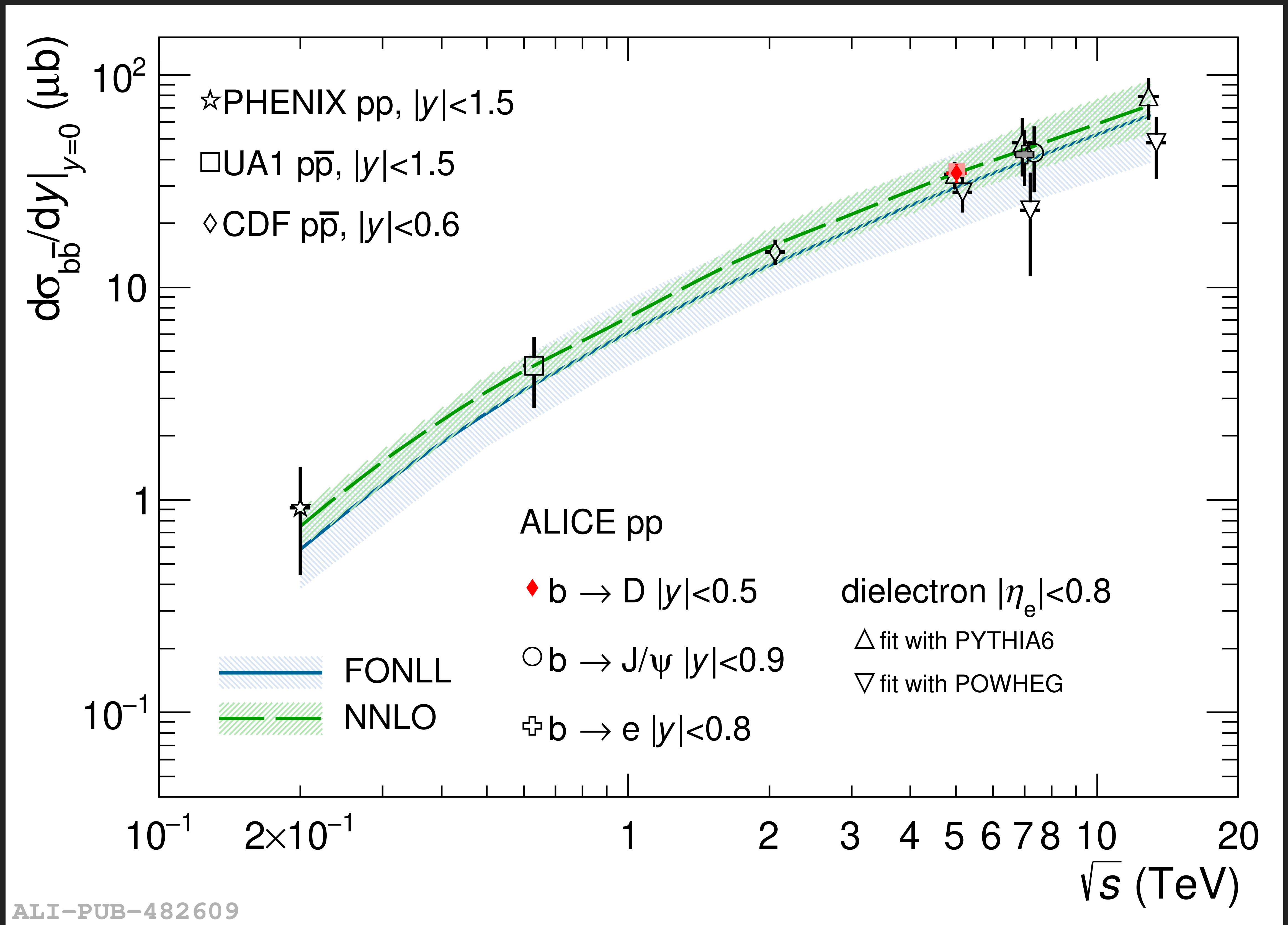
[1] B factories: EPJC 76 no. 7, (2016) 397 [2] LEP: EPJC 75 no. 1, (2015) 19 [3] HERA: EPJC 76 no. 7, (2016) 397 [4] ALICE: arXiv:2105.05616

Charm and beauty production cross section at the LHC

[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
[5] ALICE non-prompt D: JHEP 05 (2021) 220
[6] ALICE non-prompt J/ψ: JHEP 11 (2015) 065
[7] ALICE b→e: PLB 721 (2013) 13-23
[8] ALICE dielectrons: PRC 102 (2020) 5, 055204
[9] PHENIX: PRL (2009) 103, 082002
[10] UA1: PLB 256 (1991) 121-128
[11] CDF: PRL 91 (2003) 241804
[12] Beauty NNLO: JHEP 03 (2021) 029



arXiv:2105.06335



JHEP 05 (2021) 220

Charm:

- ~40% higher when charm baryons included
- On upper edge of FONLL[3] and NNLO[4] calculations

Beauty:

- Described widely by FONLL[3] and NNLO[12] calculations

Charm hadronisation vs. p_T in Pb-Pb

- D^+/D^0: flat distribution, NOT modified in QGP
- D_s^+/D^0: hint of enhancement at intermediate p_T in strangeness-rich QGP
- Λ_c^+/D^0: hint of further enhancement in Pb-Pb at intermediate p_T
  - Hadronisation mechanism? Radial-flow push in Pb-Pb?

Much more precise measurements in Run 3

Summary

- Charm hadronisation mechanisms need further investigations

Models	Λ_c/D^0 (no s)	Σ_c/D^0 (no s)	Ξ_c/D^0 (s)	Ω_c/D^0 (ss)
PYTHIA8 Monash	☹	☹	☹	☹
PYTHIA8 CR Mode	☺	☺	☹	☹
SHM+RQM	☺	☺	☹	–
QCM	☺	☺	☹	☹
Catania	☺	☺	☺	😐

Summary

- Charm hadronisation mechanisms need further investigations

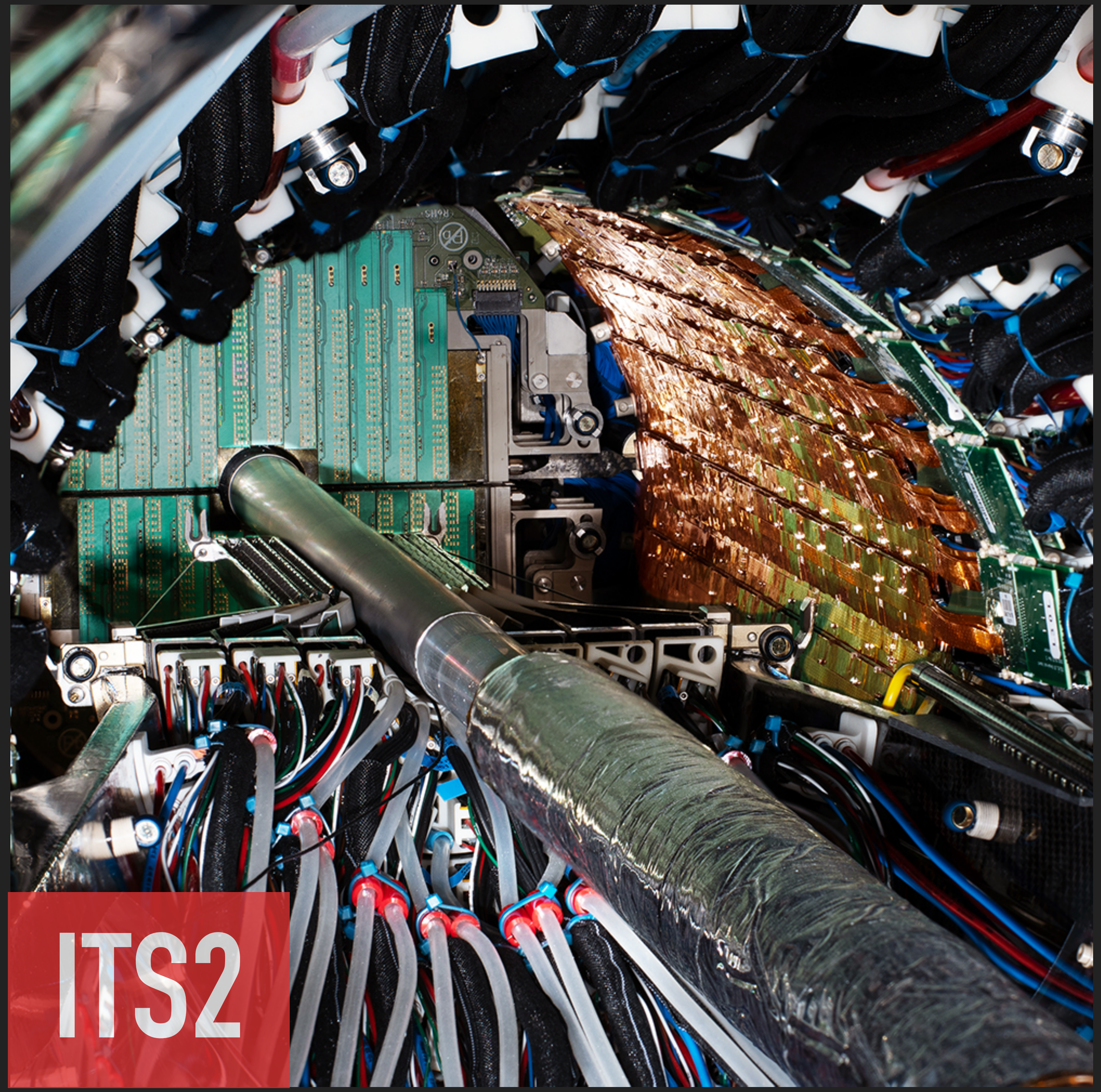
Models	Λ_c/D^0 (no s)	Σ_c/D^0 (no s)	Ξ_c/D^0 (s)	Ω_c/D^0 (ss)
PYTHIA8 Monash	☹	☹	☹	☹
PYTHIA8 CR Mode	☺	☺	☹	☹
SHM+RQM	☺	☺	☹	–
QCM	☺	☺	☹	☹
Catania	☺	☺	☺	😐

- Large enhancement of all charm baryons in pp collisions at LHC w.r.t. e^+e^- and ep collisions
    - ~40% charm quarks hadronise to charm baryons
- Charm fragmentation fractions are NOT universal
- Total charm cross sections in pp at different collision energies are on upper edge of FONLL and NNLO calculations

Outlook: Run 3

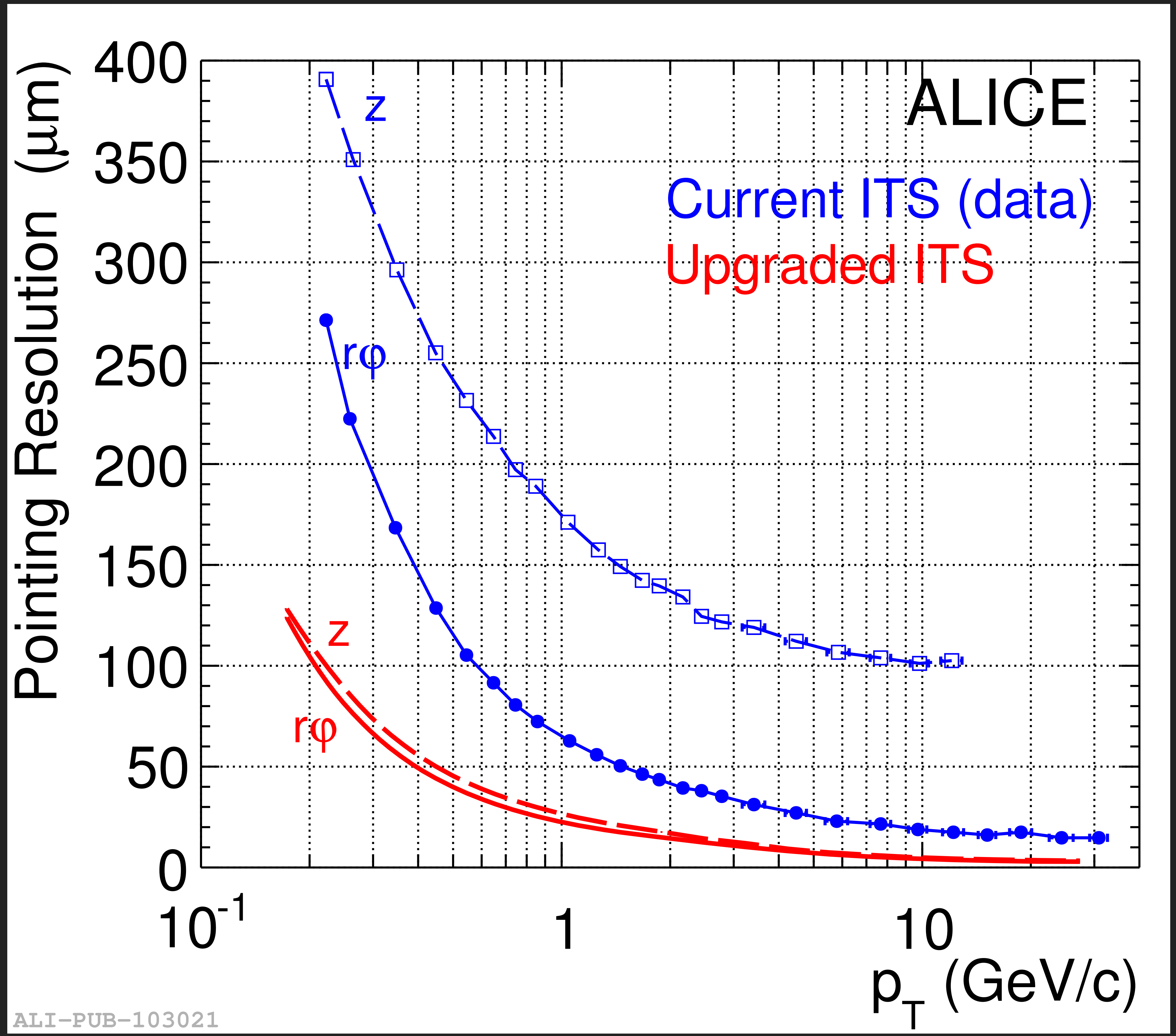
ALICE upgrade for Run 3

- Improved resolution with new silicon ITS2[1]



- Faster readout with GEM-based TPC readout (statistics ↑x100)
- Improvement in the precision of heavy flavor measurements

- Pointing resolution for ITS2 (charged pions)
  - x3 and x6 improvement in $r\varphi$ and z for 0.5 GeV/c
  - 40 μm for 0.5 GeV/c



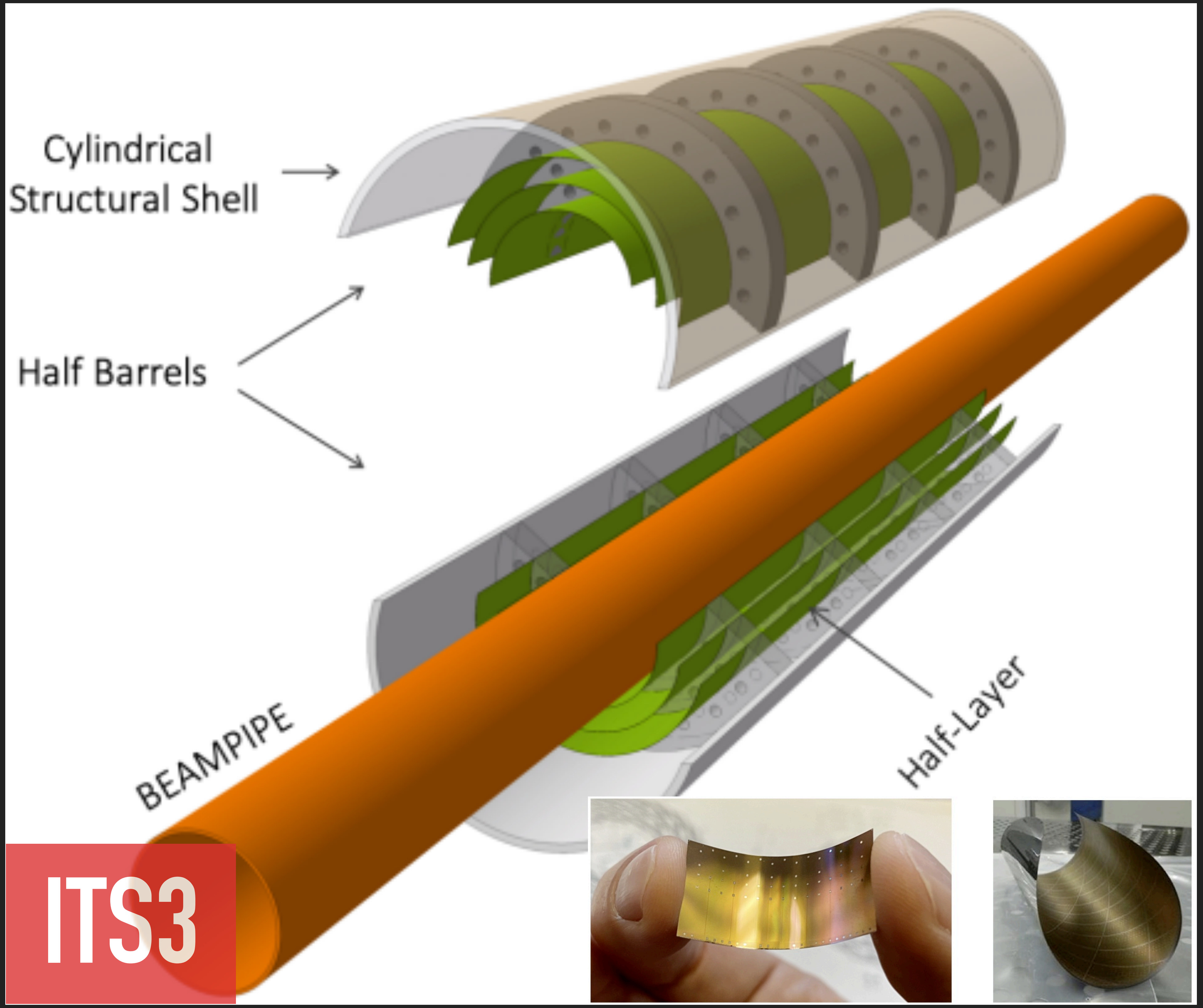
[1] ITS2 TDR: CERN-LHCC-2013-024

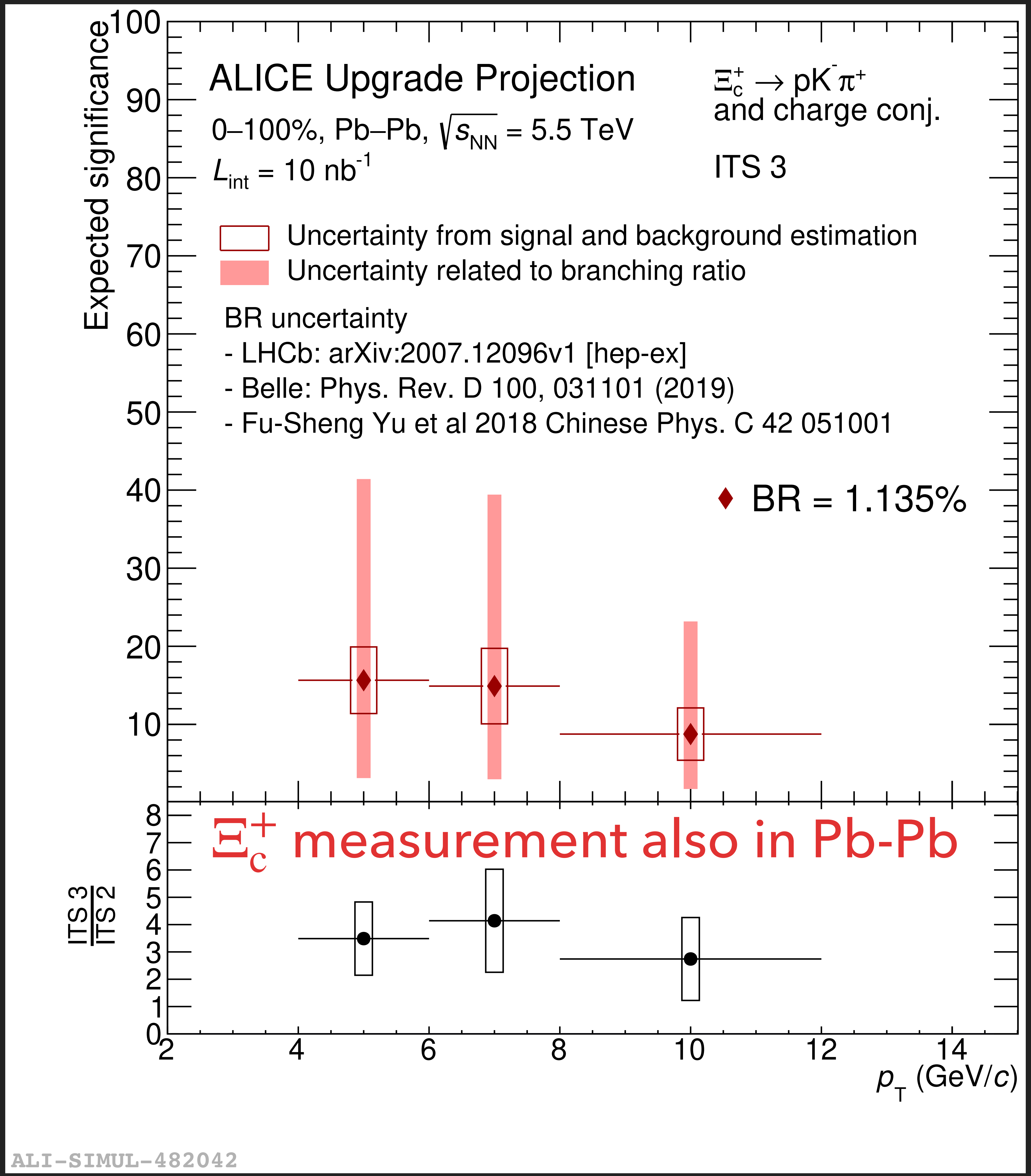
Outlook: Run 4

ALICE upgrade for Run 4

[1] ITS3 LoI: CERN-LHCC-2019-018

- Improvement of pointing resolution (x2) with ITS3[1] w.r.t. ITS2
- Increase of tracking efficiency for low-$p_{\rm T}$ particles and extension of the low-$p_{\rm T}$ reach

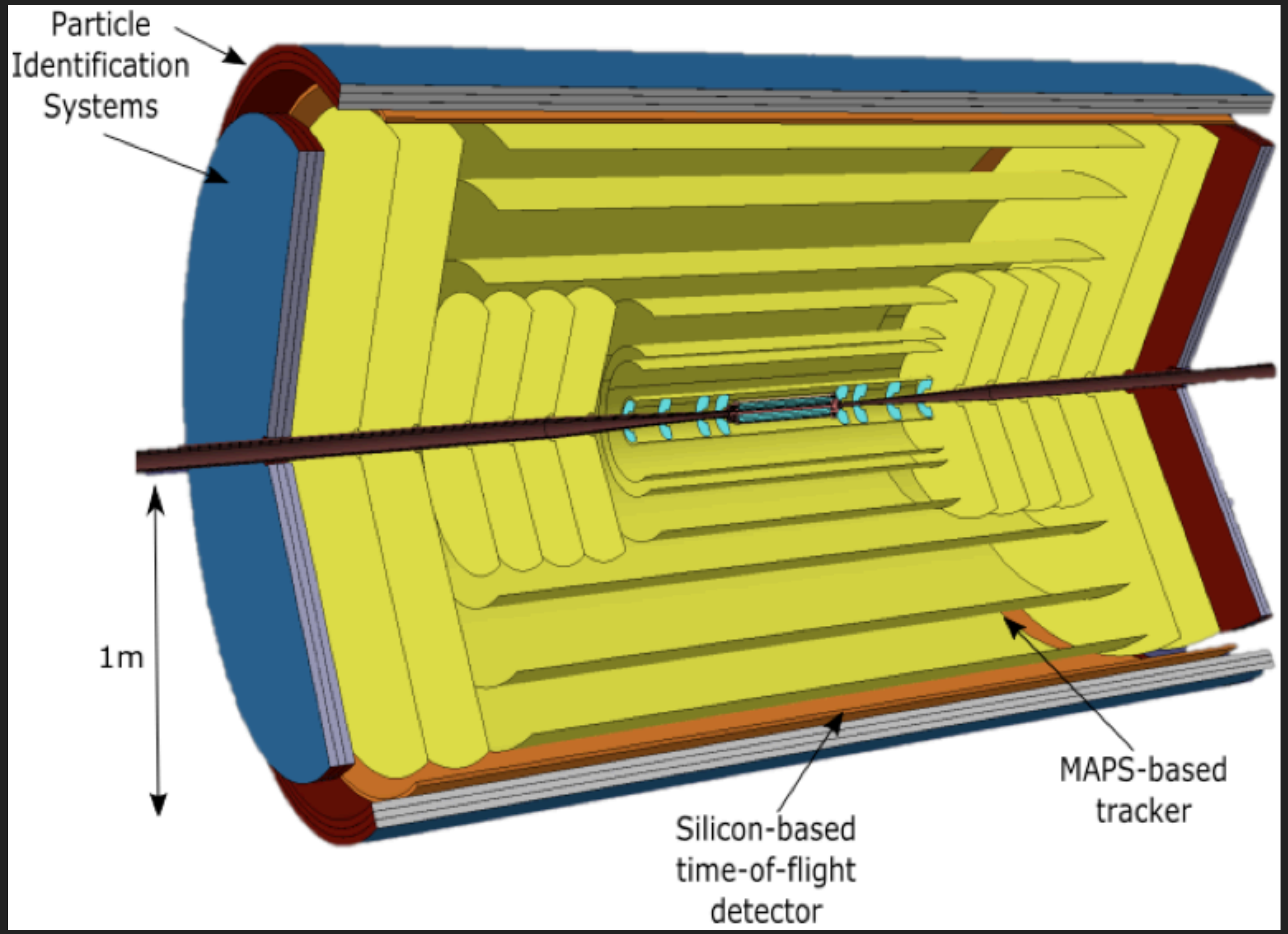




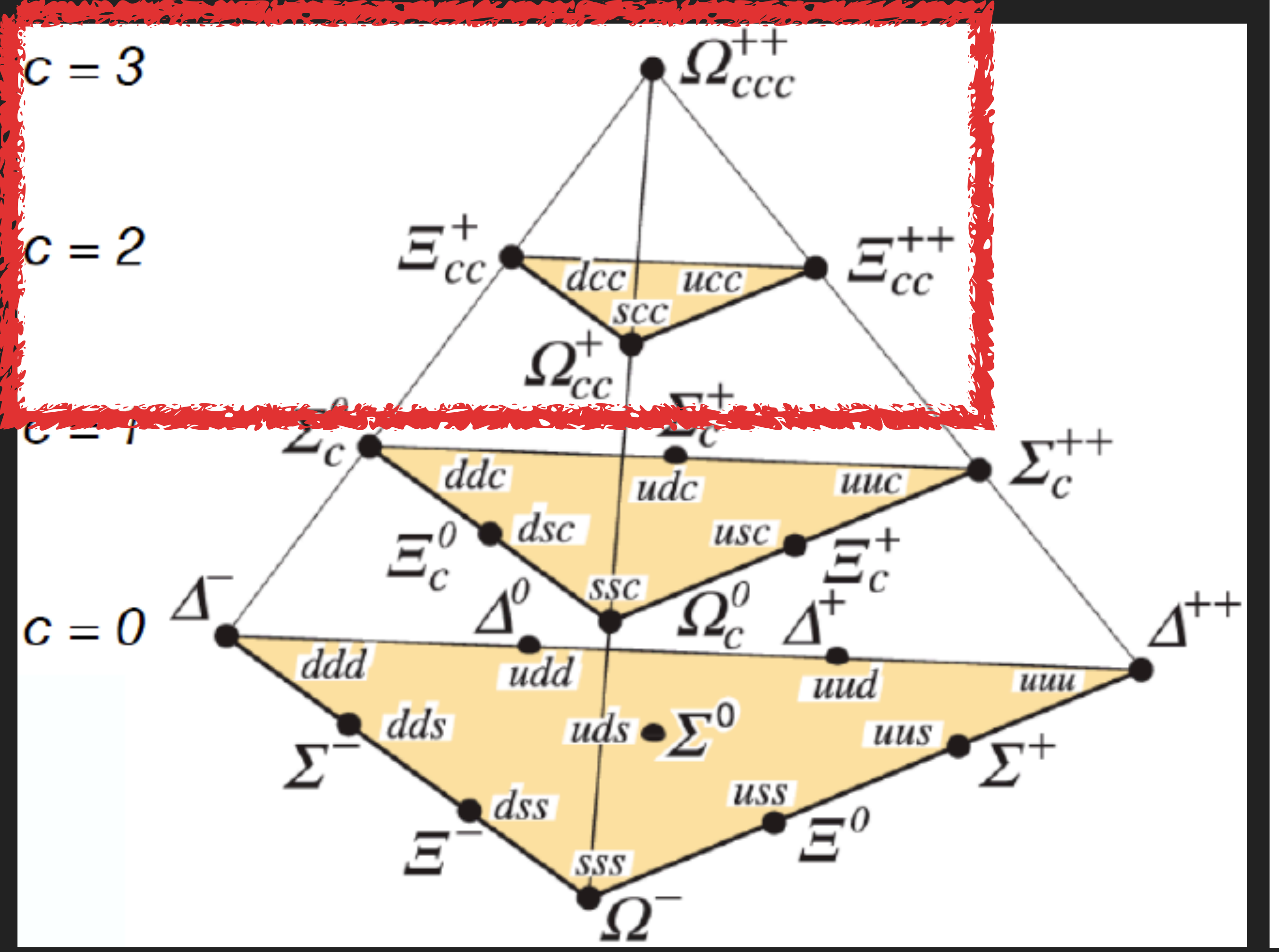
Ξ_c^+ measurement also in Pb-Pb

Outlook: Run 5 and beyond (ALICE 3)

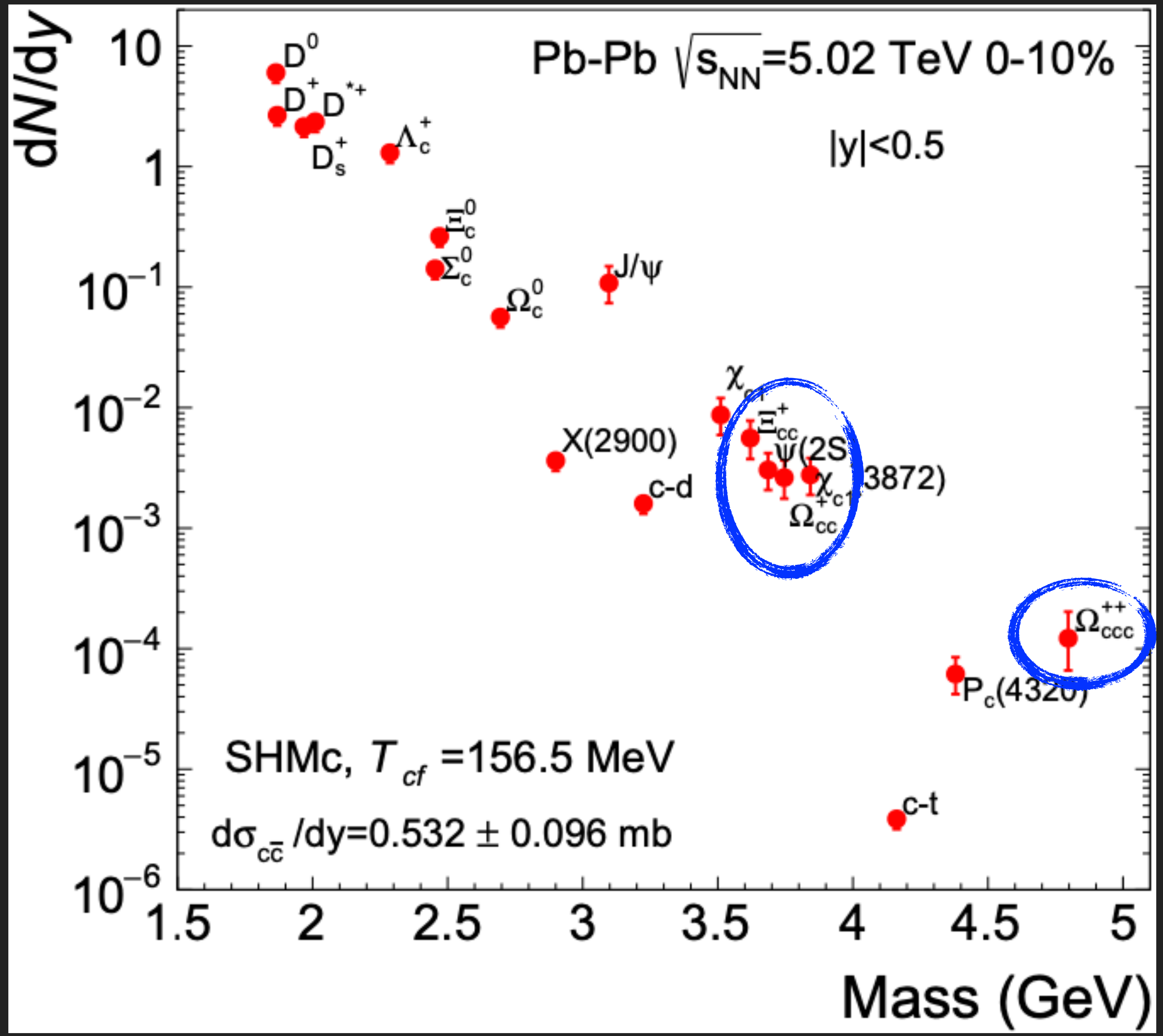
- For multi-charm in A-A collisions, expect large enhancement by 2~3 orders of magnitude
- Double charm baryons ($\sim \mathrm{fb}^{-1}$ region for pp)
  - $\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^{+}$
  - $\Xi_{cc}^{+} \to \Xi_c^{0} + \pi^{+}$
  - $\Omega_{cc}^{+} \to \Omega_c^{0} + \pi^{+}$



PDG, Prog. Theor. Exp. Phys., 083C01 (2020)



A. Andronic, et al., JHEP 07 (2021) 035

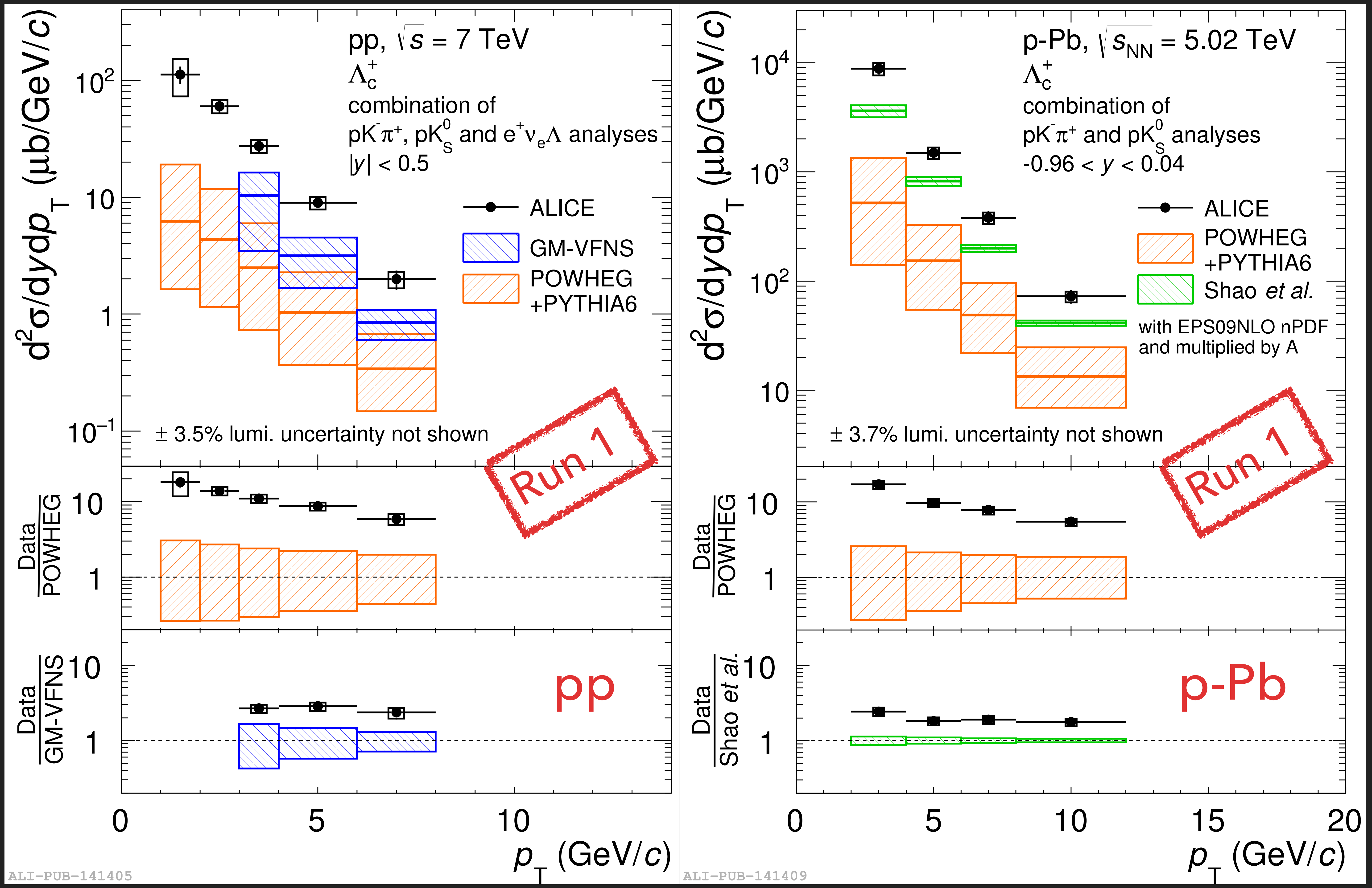


- Triple charm baryon
  - $\Omega_{ccc}^{++} \to \Omega_{cc}^{+} + \pi^{+}$
- LoI in preparation

BACKUP

A first indication of hadronisation universality breaking

JHEP 1804 (2018) 108



- pQCD calculations underestimate Λ_c^+ baryon production, but in good agreement with D mesons
- Note: GM-VFNS (General Mass Variable Flavour Number Scheme)[1,2] uses FF tuned from e^+e^- data
- Same considerations of comparisons with models hold in p-Pb collisions
- Shao et al. model[5] based on pp LHC data (LHCb) + nPDF[6]

[1] GM-VFNS: EPJC 41 (2005) 199-212
[2] GM-VFNS: EPJC 72 (2012) 2082
[3] POWHEG: JHEP 09 (2007) 126
[4] PYTHIA6: JHEP 05 (2006) 026
[5] Shao et al.: EPJC 77 no. 1, (2017) 1
[6] EPS09NLO: JHEP 04 (2009) 065

A sensitive hadronisation quantity: Λ_c^+/D^0

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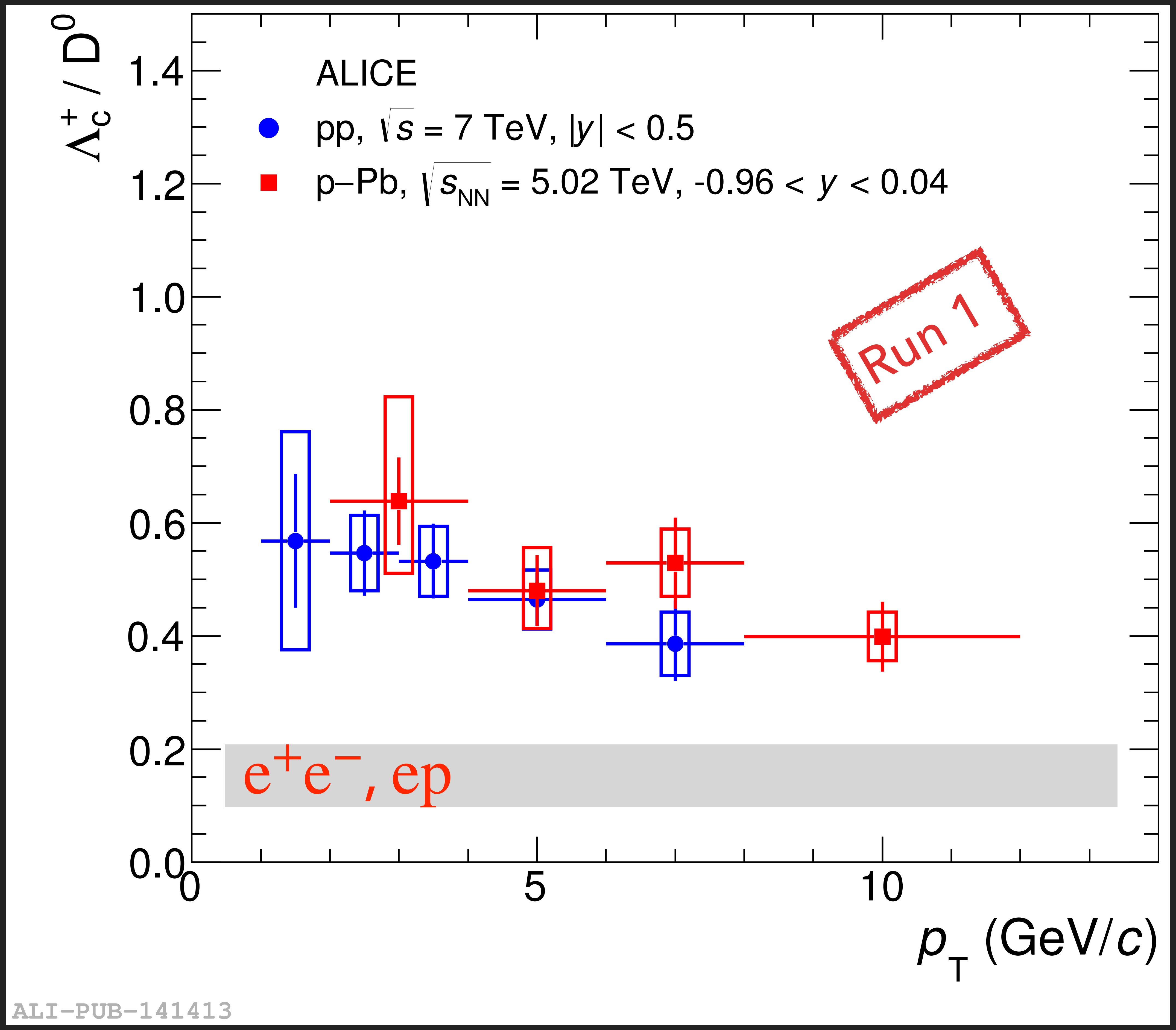

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	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [1]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [2,3]	0.127 ± 0.031	ee	10.55
LEP average [4]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [5]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [6]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320
ZEUS γp, HERA II [7]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320

- No significant change from pp to p-Pb
- "Tension" with e^+e^- and ep results
- Due to collision system and/or energy ?

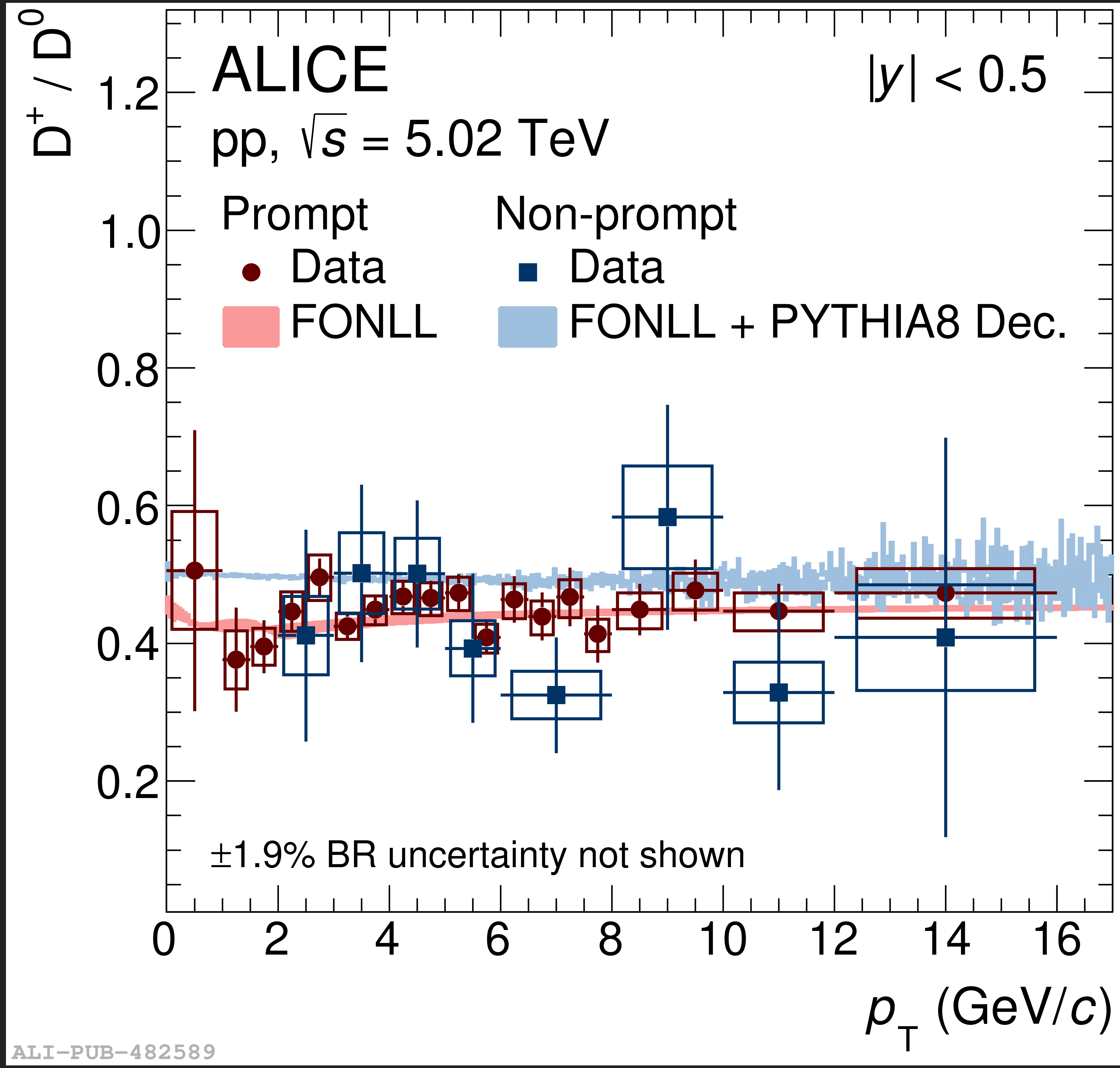
Charm fragmentation to baryons not well understood

[1] CLEO: PRD 43 (1991) 3599-3610
[2] ARGUS: PLB 207 (1988) 109-114
[3] ARGUS: Z. Phys. C 52 (1991) 353-360
[4] LEP: EPJC 75 no. 1, (2015) 19
[5] ZEUS DIS: JHEP 11 (2010) 009
[6] HERA I: EPJC 44 (2005) 351-366
[7] HERA II: JHEP 09 (2013) 058

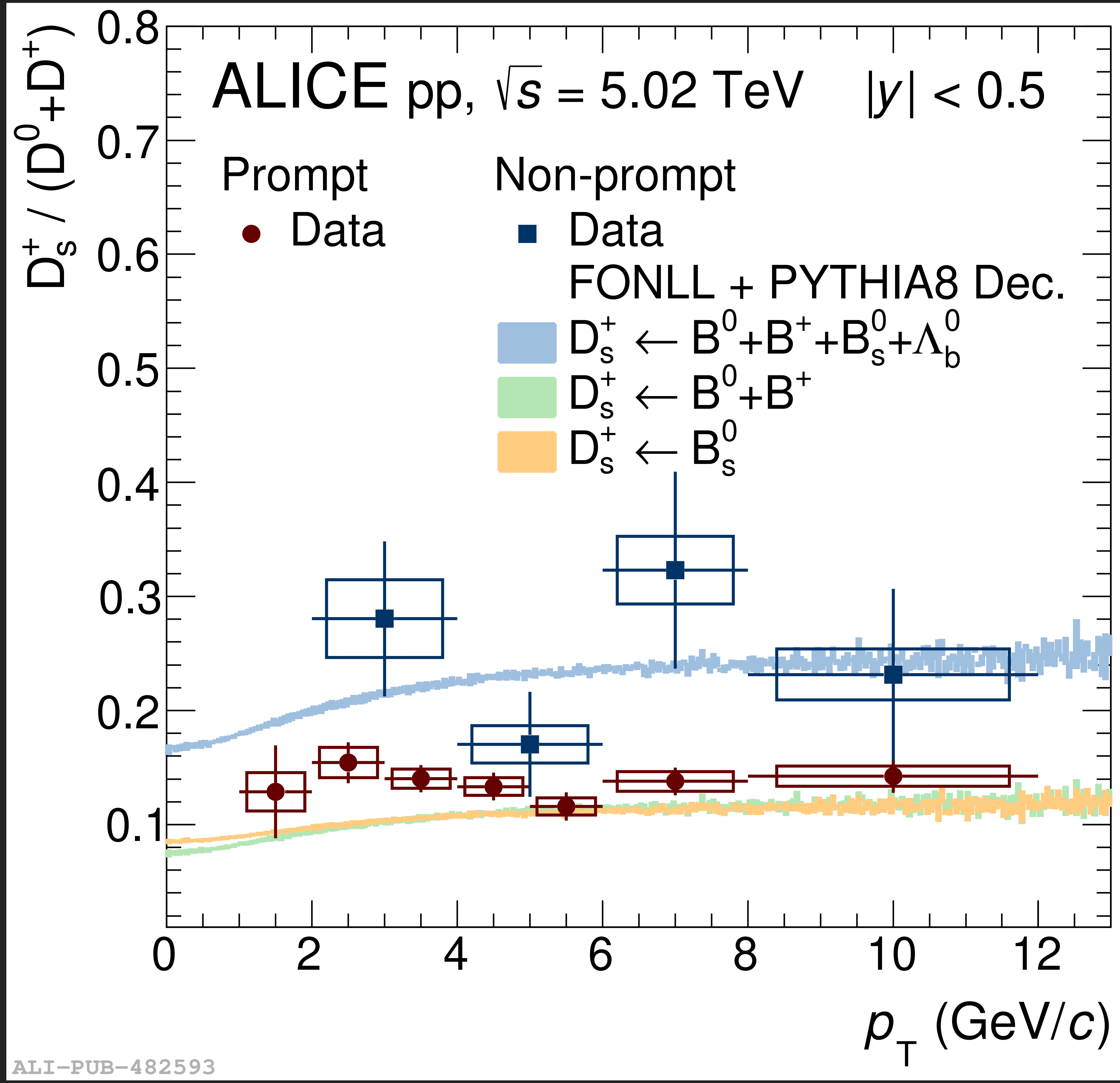
Charm meson-to-meson yield ratio

- D-meson production ratios flat in p_T and in good agreement with pQCD using FF extracted from e^+e^-
  - D^+/D^0: compatible prompt and non-prompt
  - $D_s^+/(D^0 + D^+)$: higher for non-prompt D mesons, substantial contribution from $b \rightarrow c\bar{c}s$ weak decays

JHEP 05 (2021) 220

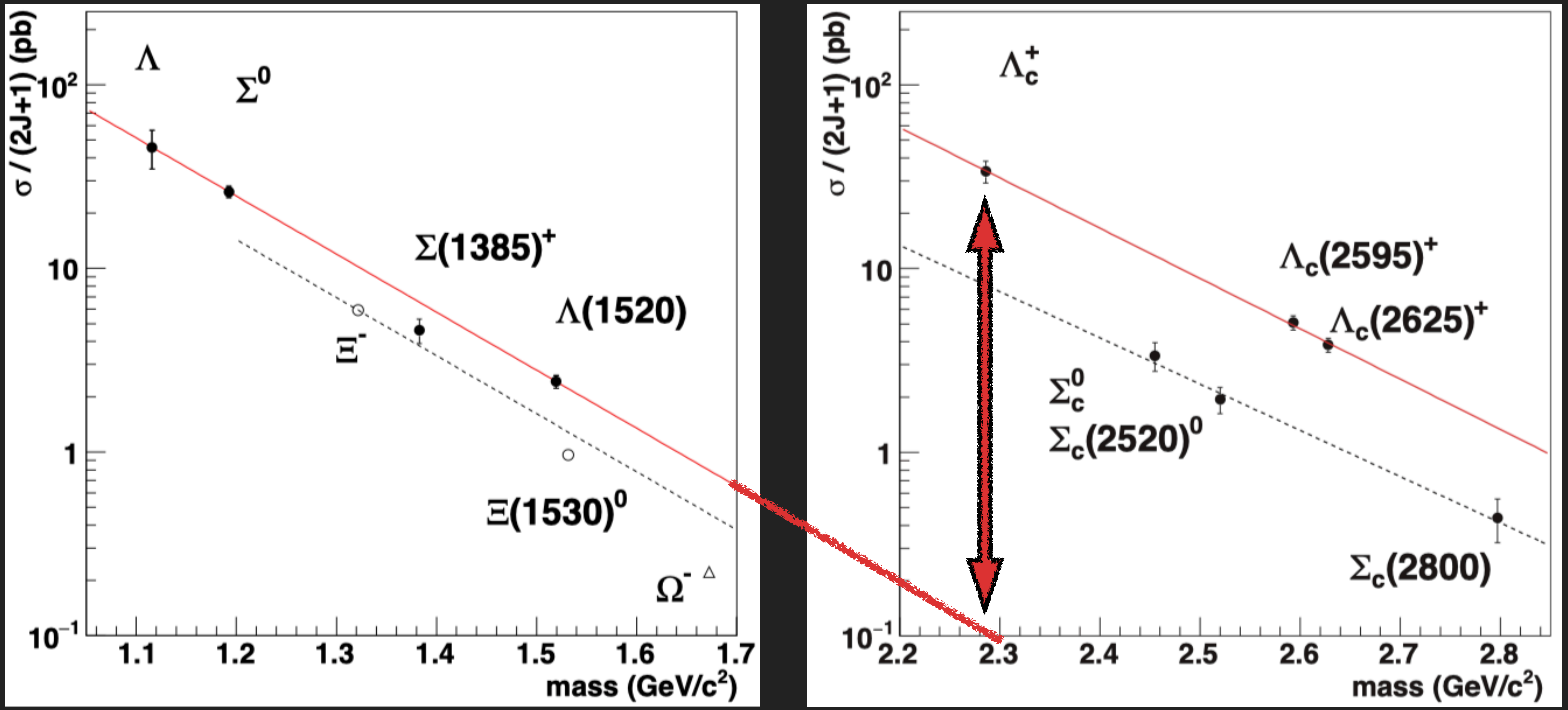


JHEP 05 (2021) 220



Σ_c suppression from spin-1 diquark suppression in e^+e^-

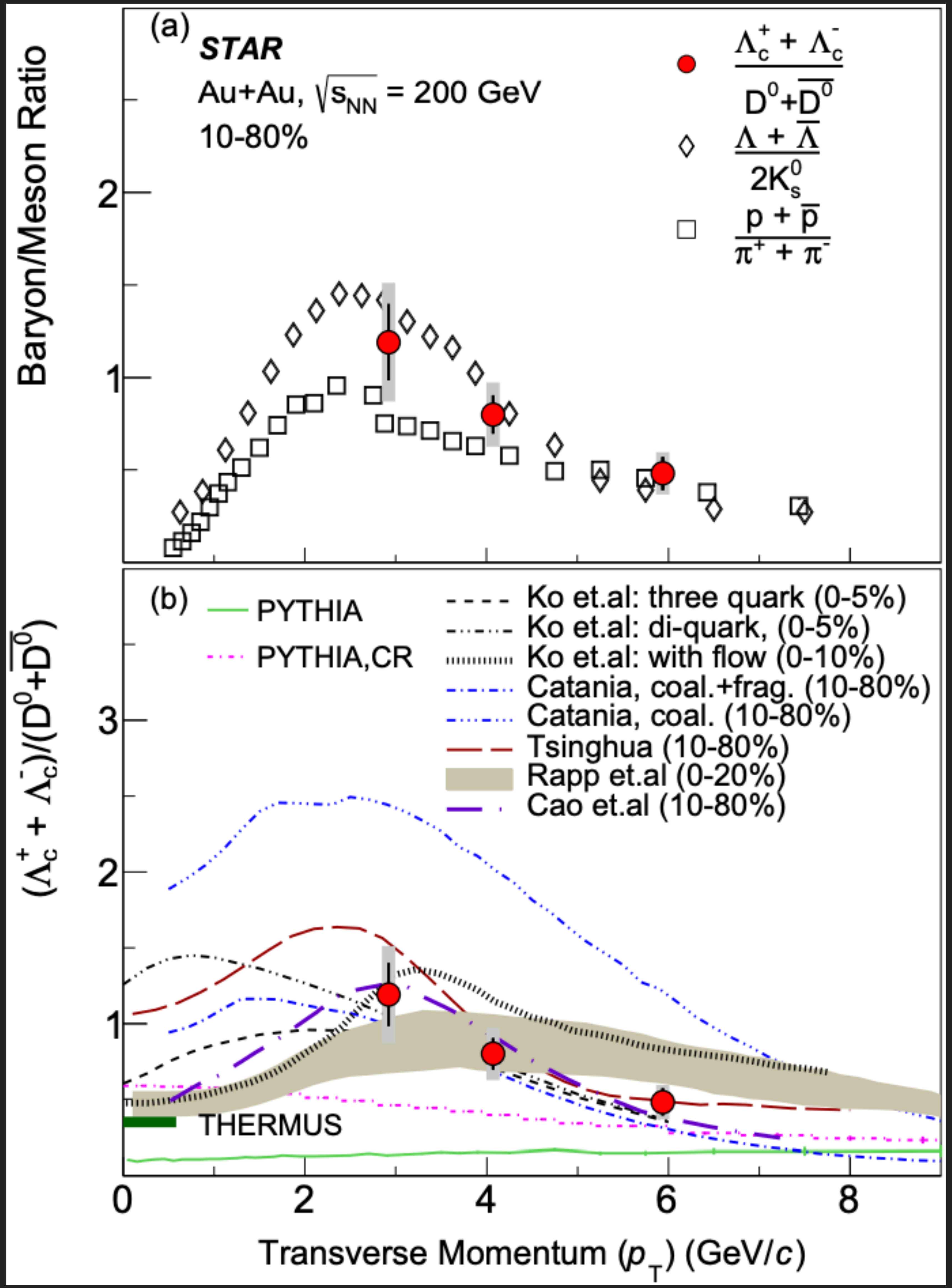
Belle: PRD 97, 072005 (2018)



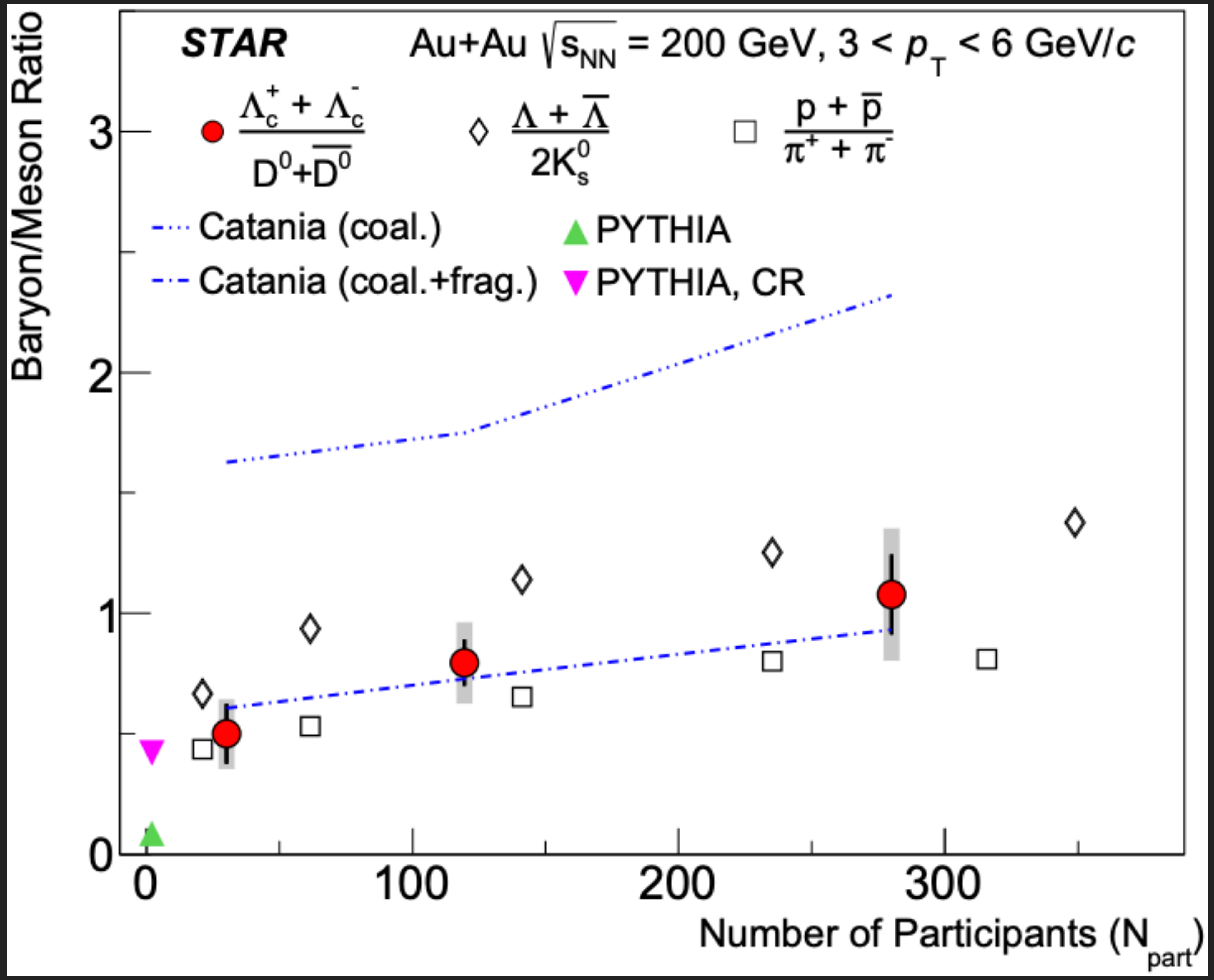
- Λ_c production rate higher than extrapolation of hyperon curve to charm mass window
  - ➡ Different production mechanism, points to important role of diquark production for charm baryons
- Λ_c and Σ_c cross-section difference support charm baryon production from diquark degrees of freedom and a spin-0 diquark component for Λ_c

Λ_c^+ in Au–Au collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ at RHIC

PRL 124 (2020) 17, 172301



PRL 124 (2020) 17, 172301



Charm baryon-to-baryon yield ratio

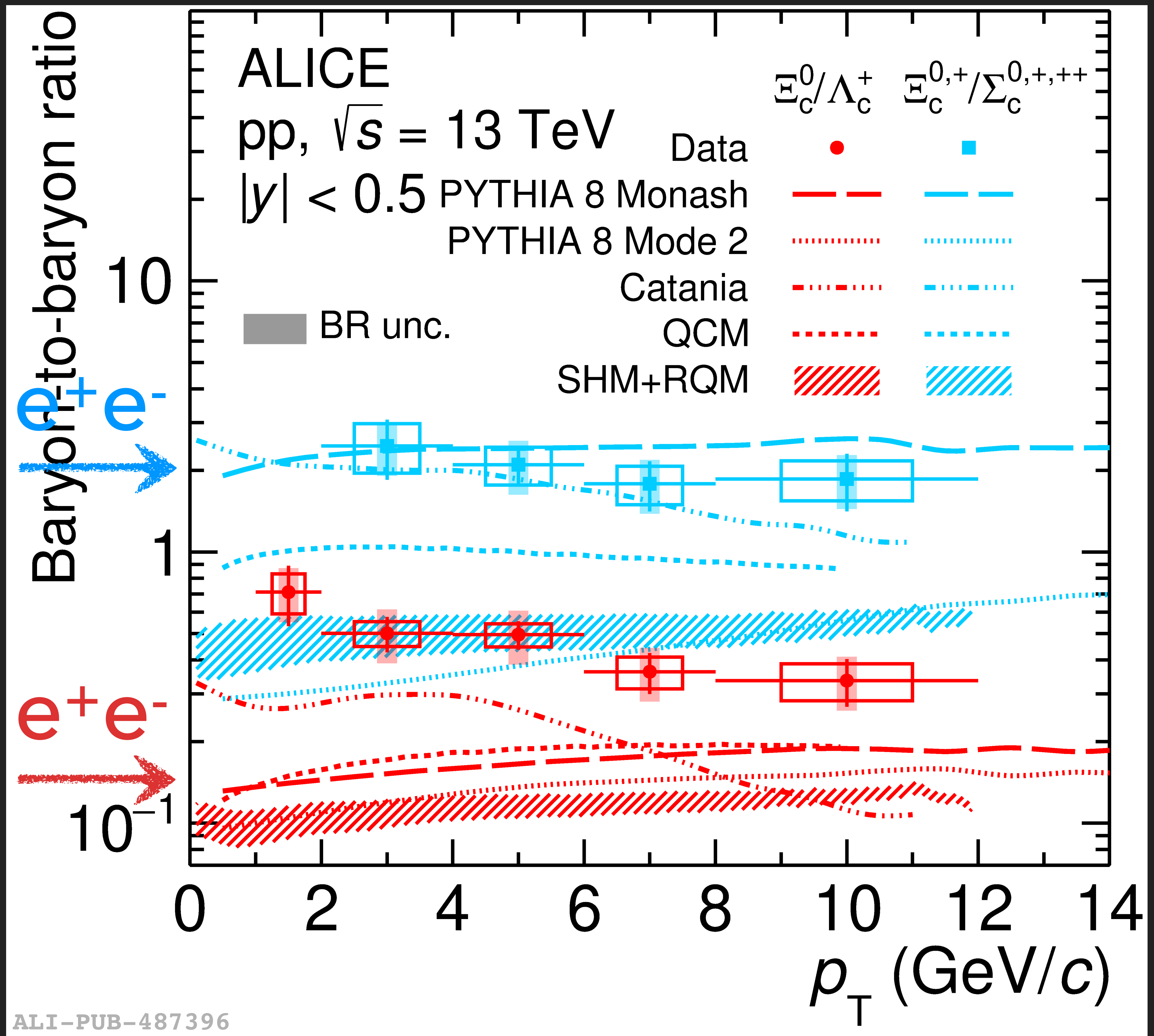
pp vs. models :

- Largely underestimated by PYTHIA8 Monash[1], CR-BLC[2], QCM[3], SHM[4]+RQM[5]
- Catania[6] closer to data points, especially resonances decay considered

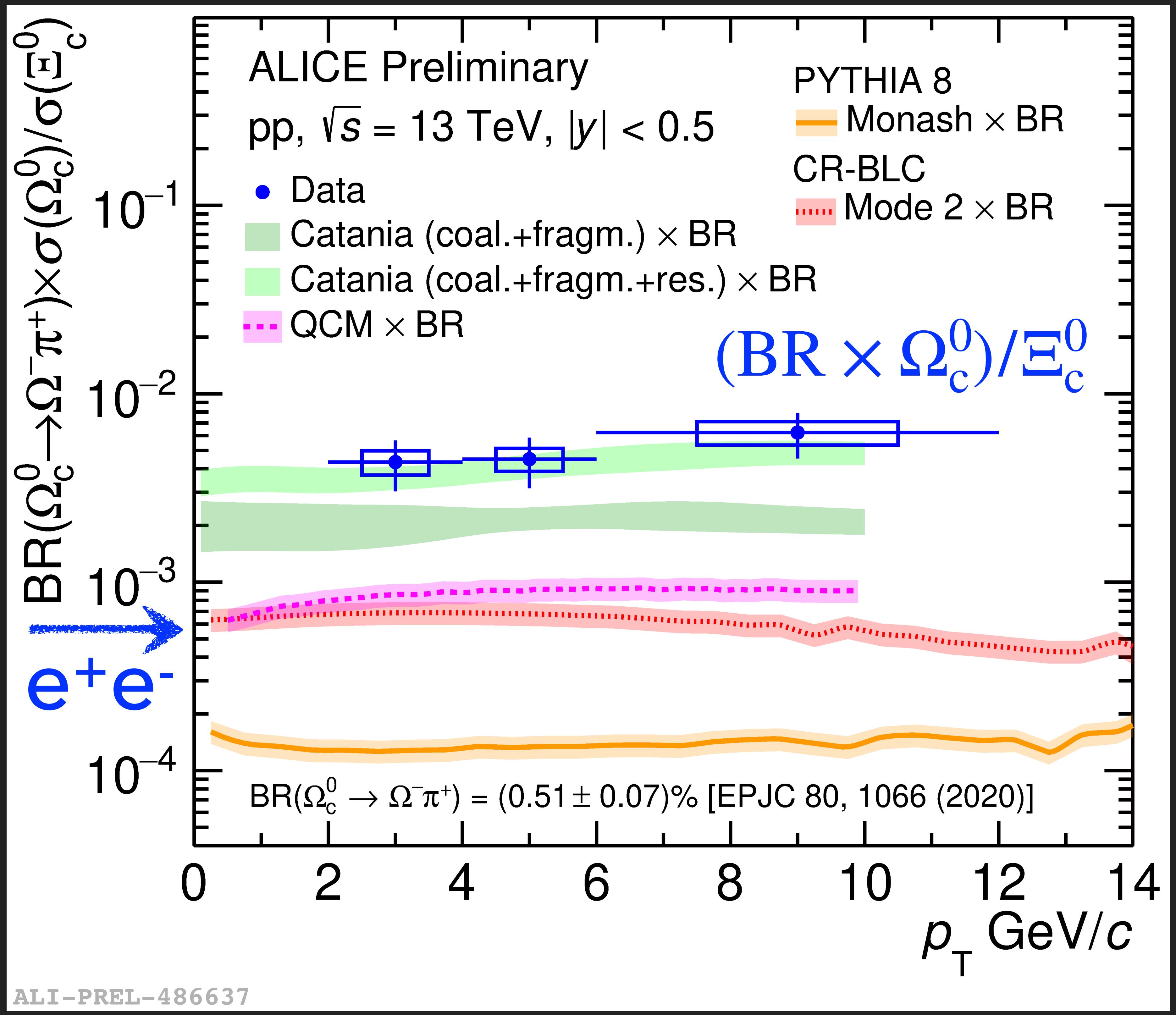
pp vs. e^+e^- :

- Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$
- Further enhancement for Ω_c^0

[1] PYTHIA8 Monash: EPJC 74 (2014) 3024
[2] PYTHIA8 Mode2: JHEP 08 (2015) 003
[3] QCM: EPJC 78 no. 4, (2018) 344
[4] SHM: PLB 795 (2019) 117-121
[5] RQM: PRD 84 (2011) 014025
[6] Catania pp: arXiv:2012.12001
[7] Catania NN: EPJC 78 no. 4, (2018) 348

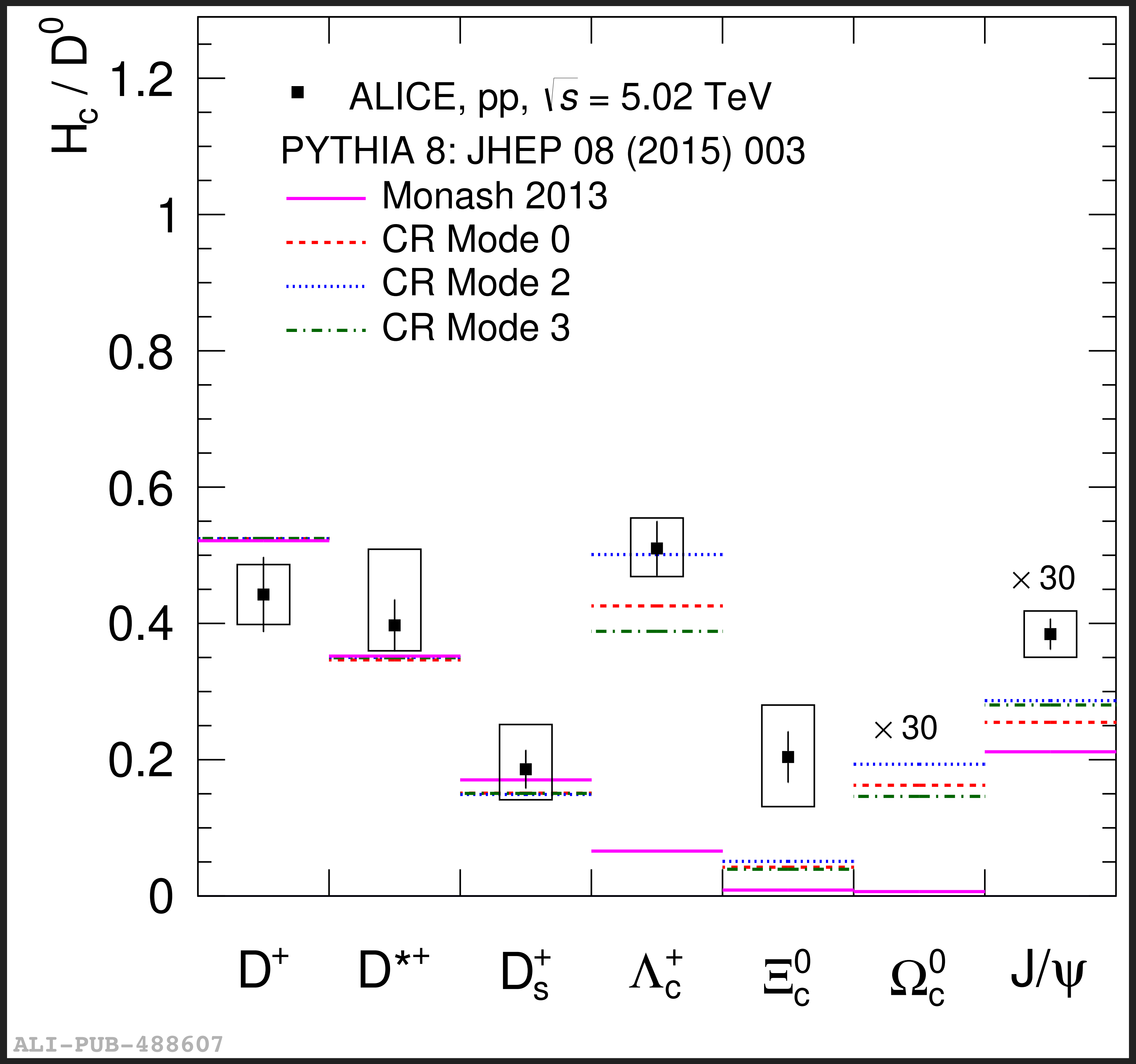


arXiv:2105.05187

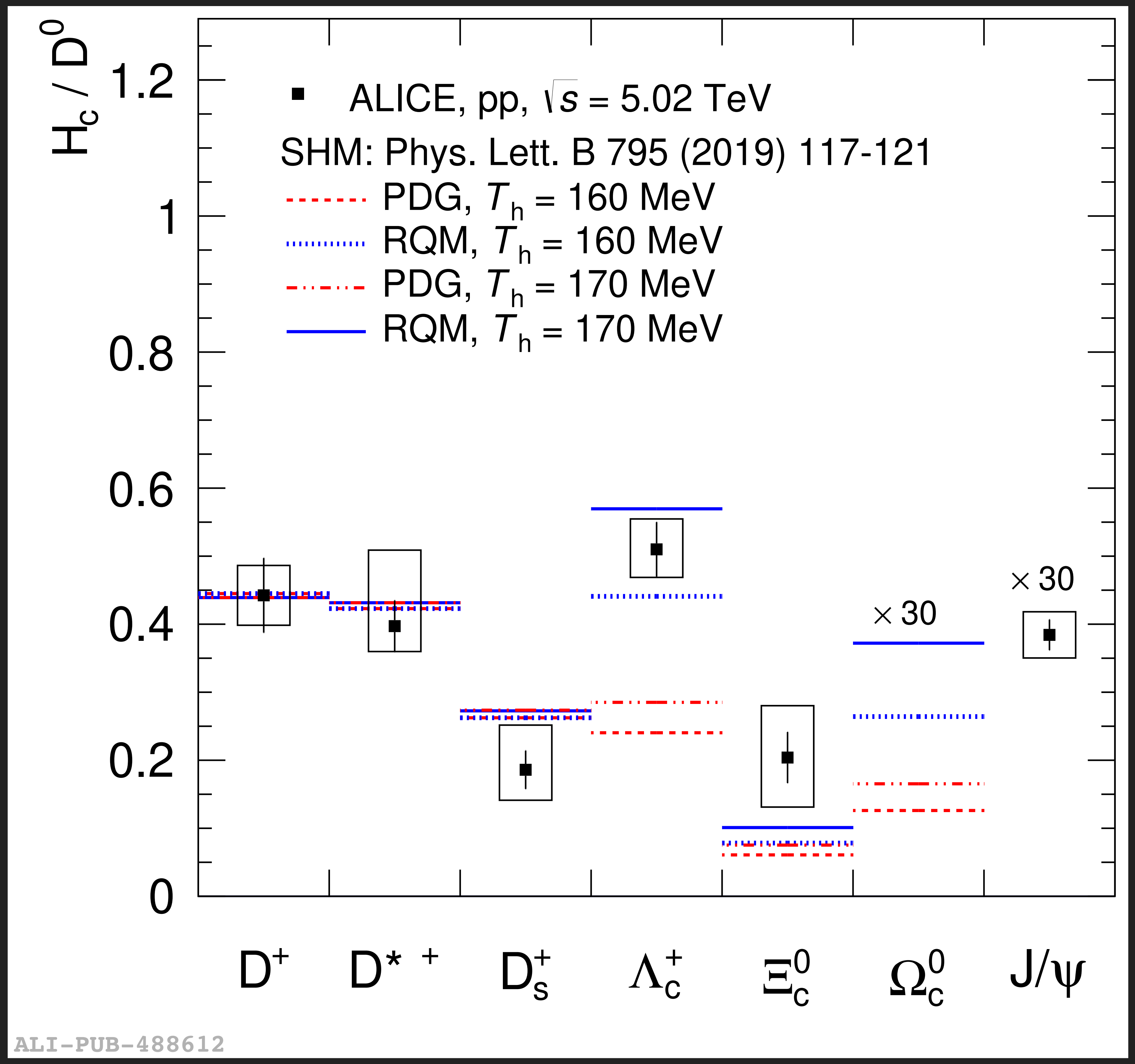


Integrated production yield vs. D^0 in pp@5.02 TeV

- PYTHIA8 with different tunes similar for D mesons and describe measurements within uncertainties
- Large effect found in PYTHIA8 CR-BLC for charm baryons formation
  - Only describe Λ_c^+, underestimate Ξ_c^0
- SHM for charm mesons : small variations with two hadronisation temperatures and consistent with measurements
- SHM for charm baryons : significant variations with two hadronisation temperatures and large variations with RQM
  - SHM+RQM describes Λ_c^+, but not Ξ_c^0



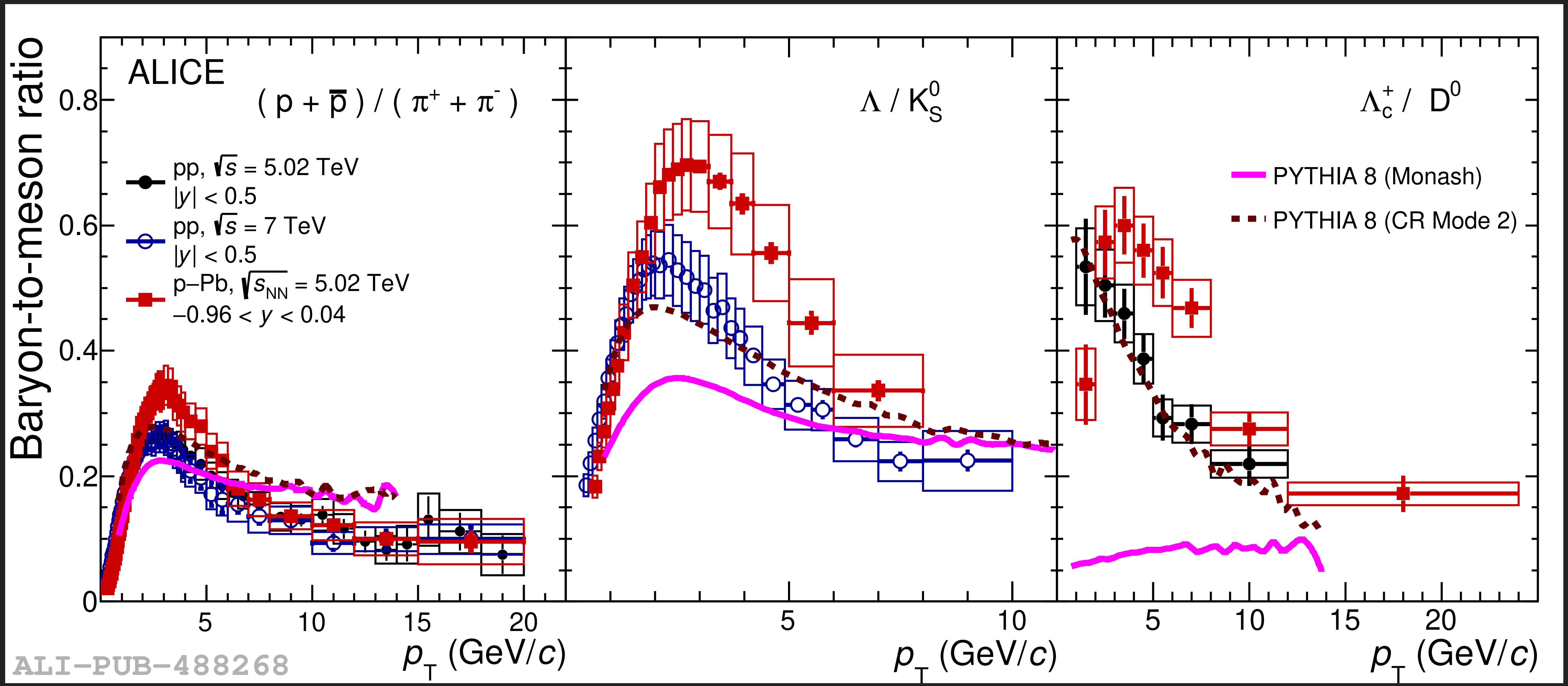
arXiv:2105.06335



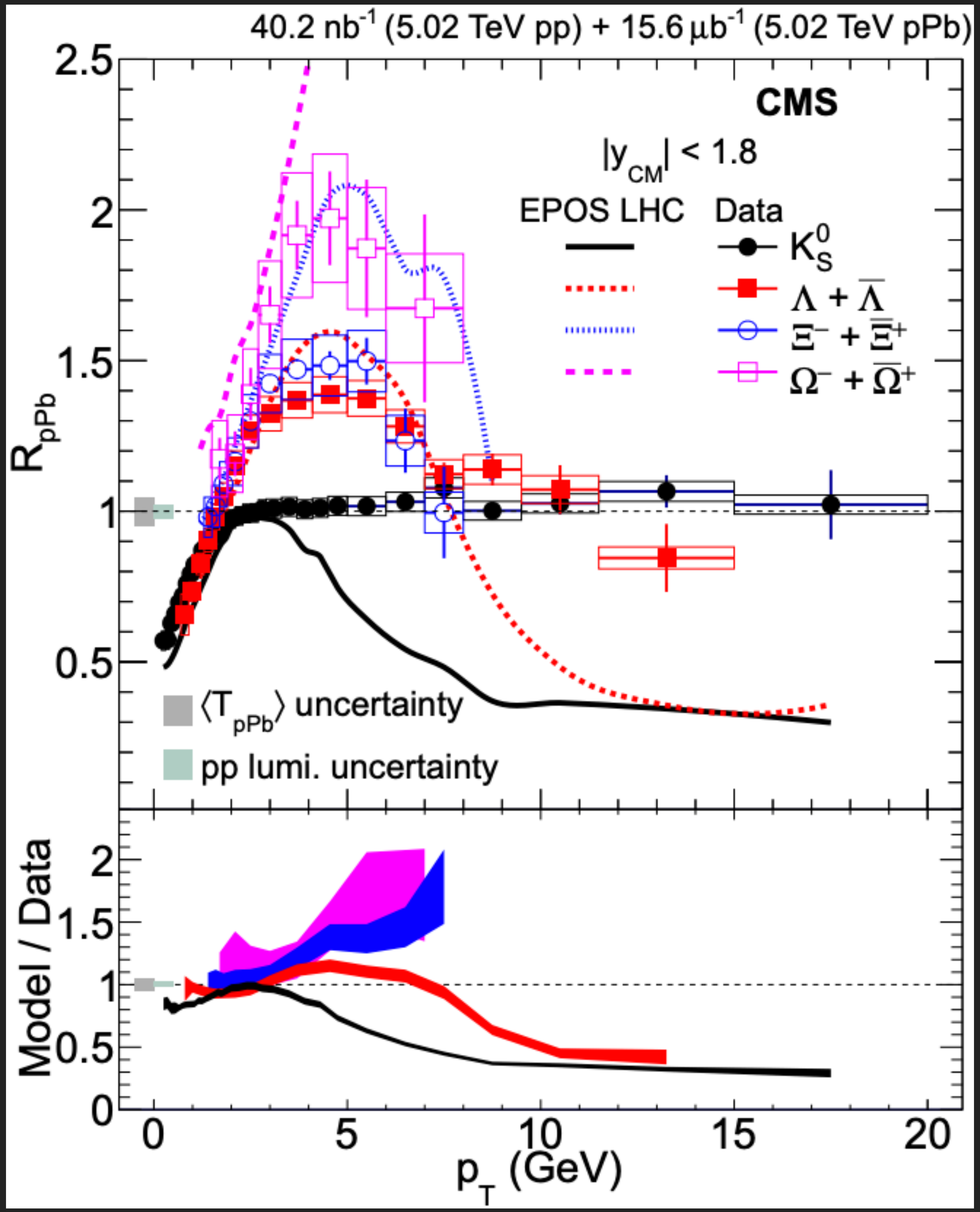
arXiv:2105.06335

Strange hadronisation in p-Pb collisions

arXiv:2011.06079

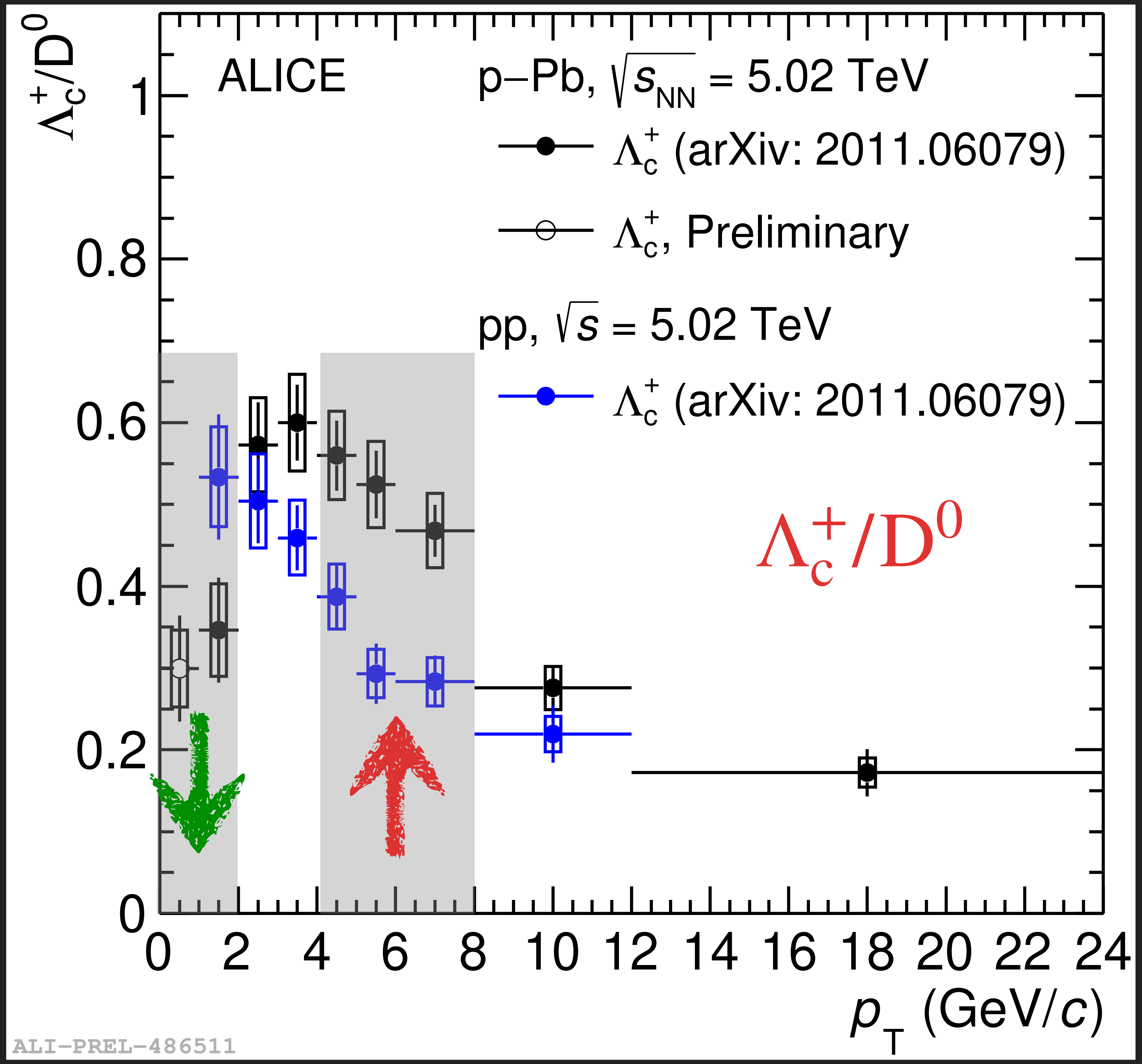


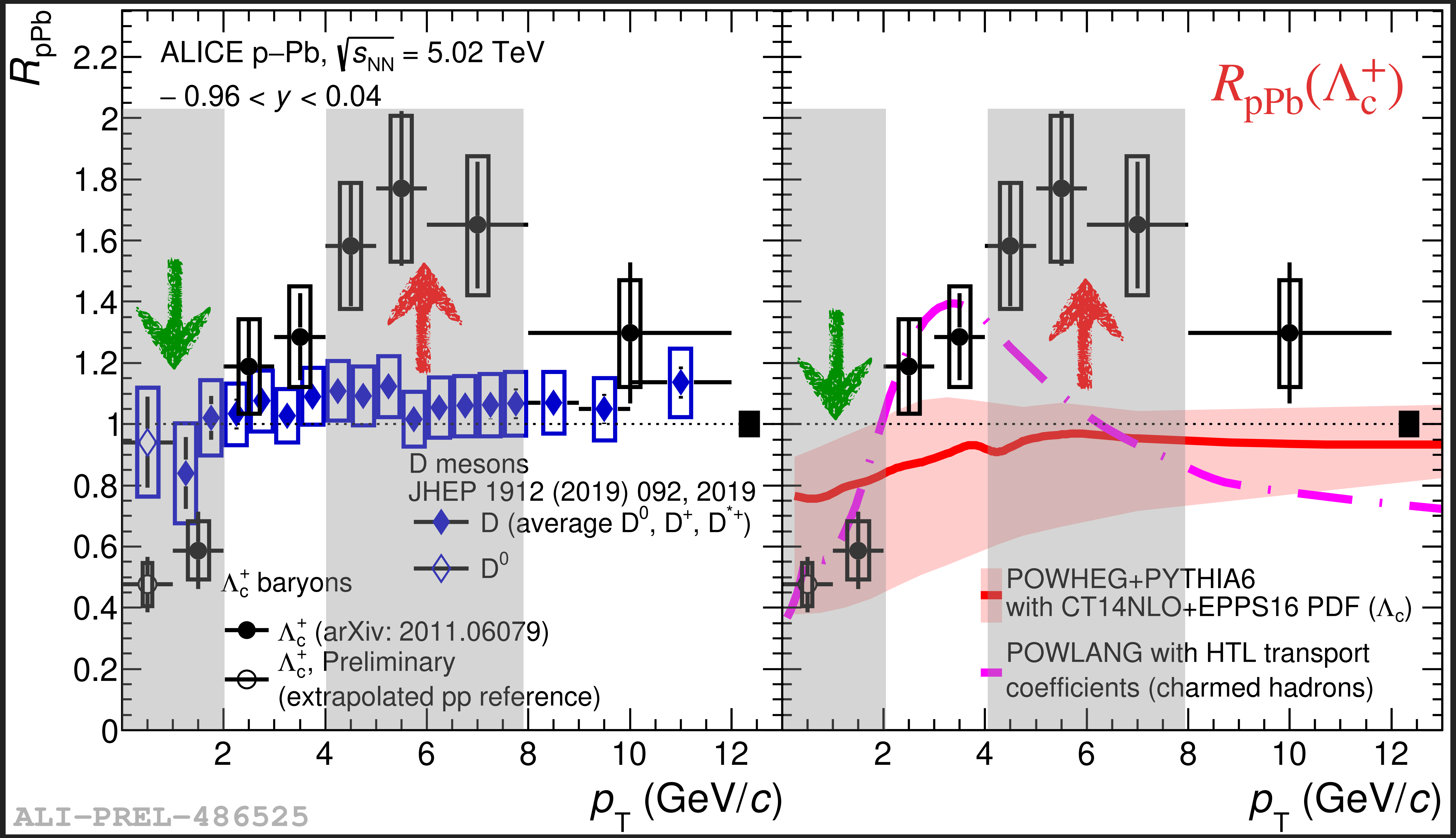
Phys.Rev.C 101 (2020) 6, 064906



Charm hadronisation in p-Pb collisions

ALICE



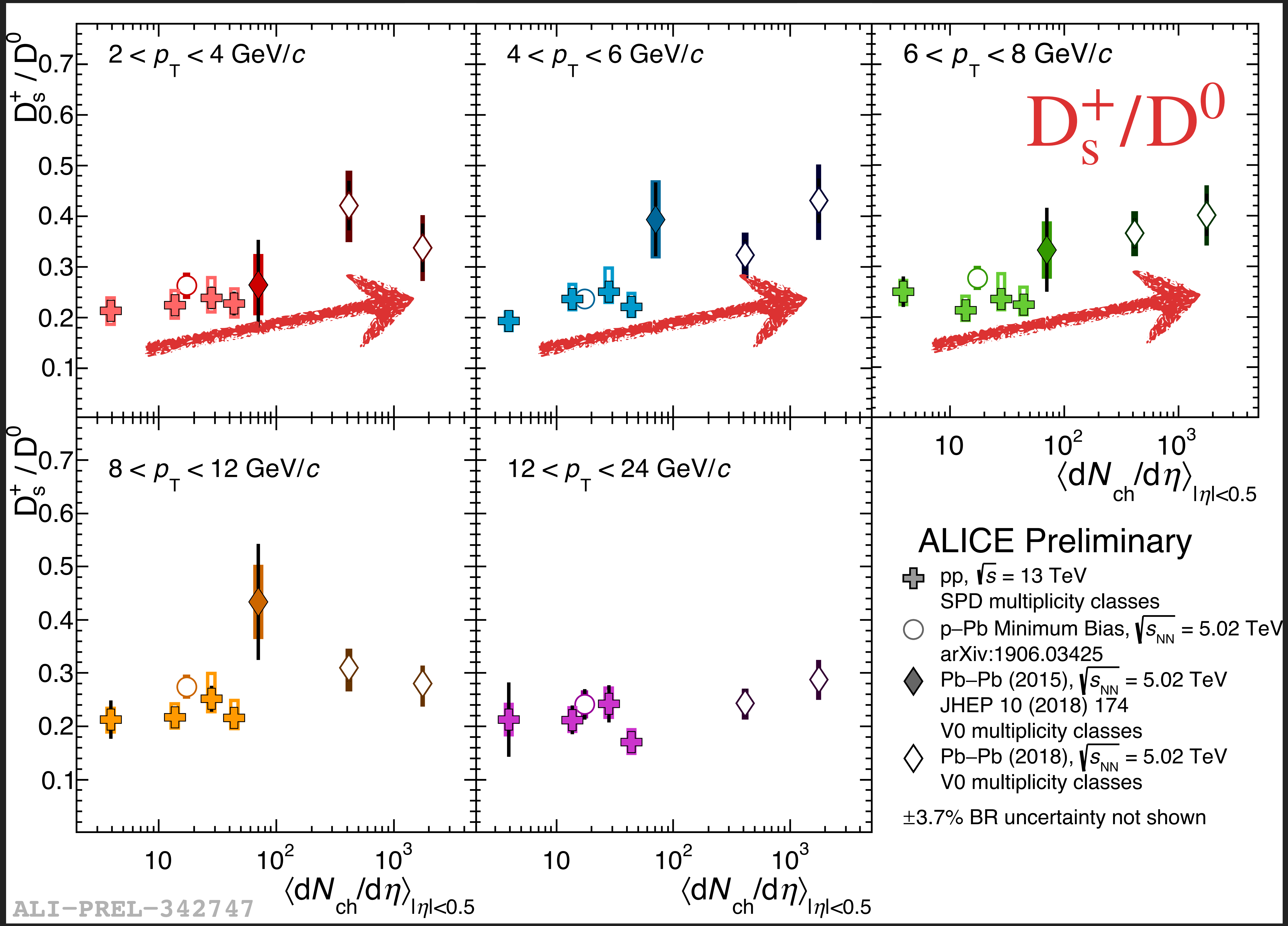


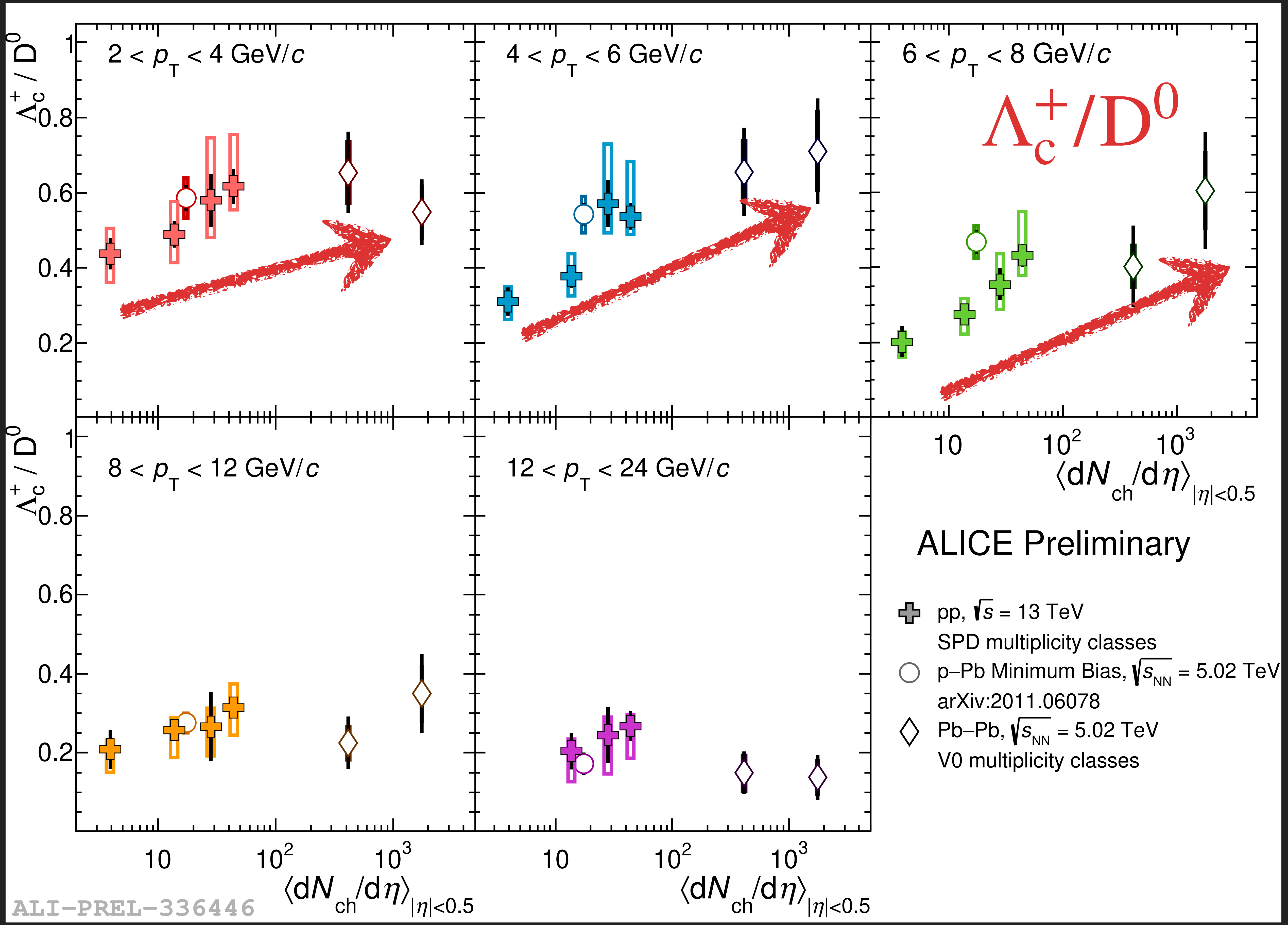
- Fist measurement of Λ_c^+ down to 0
- Λ_c^+/D^0: significant suppression in $p_T < 2$ and enhancement in mid-p_T
  - Similarities with strange sector[1,2]

- $R_{pPb}(\Lambda_c^+)$: significant suppression in $p_T < 2$, enhancement in mid-p_T
  - POWHEG[3]+PYTHIA6: only CNM effect[4] included
  - POWLANG[5]: QGP in small system

[1] arXiv:2011.06079 [2] CMS: PRC 101 (2020) 6, 064906 [3] POWHEG: JHEP 09 (2007) 126 [4] EPPS16: EPJC 77 no. 3, (2017) 163 [5] POWLANG: JHEP 03 (2016) 123

Charm hadronisation vs. multiplicity from pp to Pb–Pb





- D_s^+/D^0: strangeness enhancement (w.r.t. non-strangeness) at low and intermediate p_T
- Λ_c^+/D^0: baryon enhancement (w.r.t. meson) at low and intermediate p_T
- What about strangeness+baryon ($\Xi_c^{0,+}$ and Ω_c^0) ?