The 19th International Conference on Strangeness in Quark Matter

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SQM2021

Jianhui Zhu (GSI & CCNU) for the ALICE Collaboration

Charm-baryon enhancement and charm fragmentation fractions in small systems measured with ALICE

GSI

CENTRAL CHINA NORMAL UNIVERSITY

ALICE

Motivation

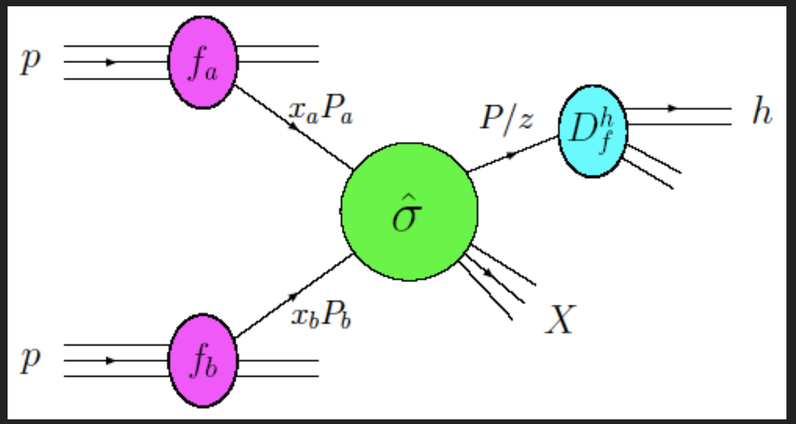
- Hadroproduction with factorisation approach, which works well for charm mesons :

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

initial state parton distribution function (PDF) (non-perturbative)

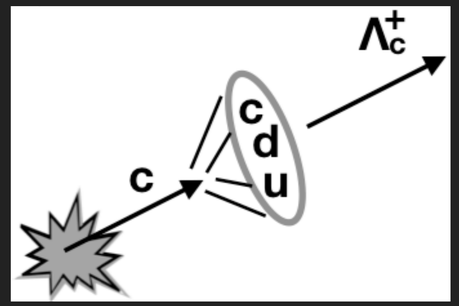
partonic cross section (perturbative)

hadronization by fragmentation (non-perturbative)

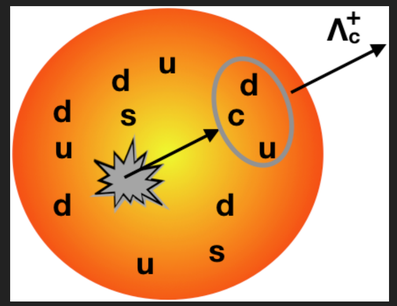


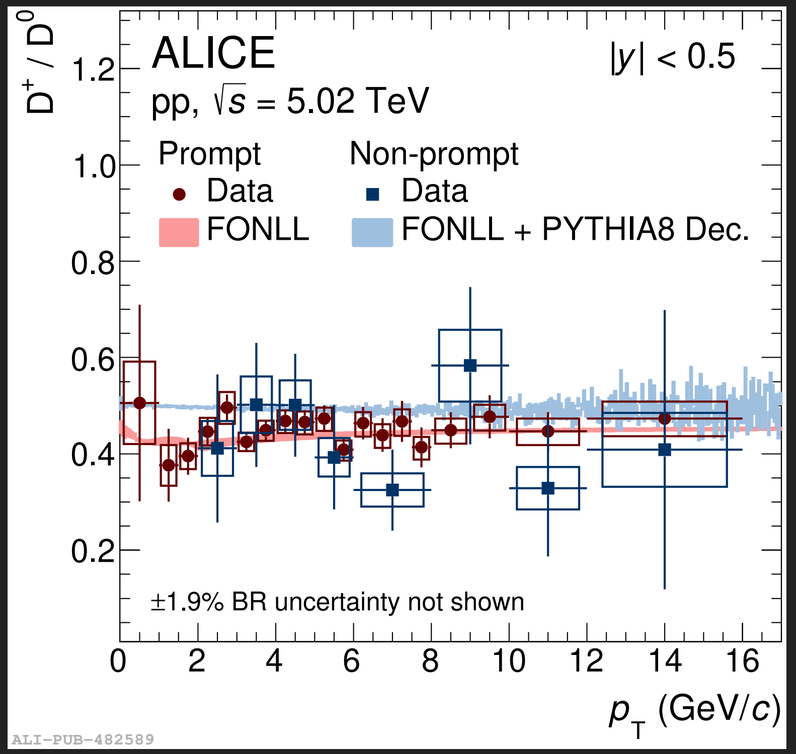
- pQCD models based on factorisation approach use fragmentation fractions (FF) tuned on e^+e^- and consider them universal
- Charm baryons essential for total charm cross section and FF measurement
- Charm baryon-to-meson & baryon-to-baryon yield ratio sensitive to hadronization

Fragmentation:



Coalescence:

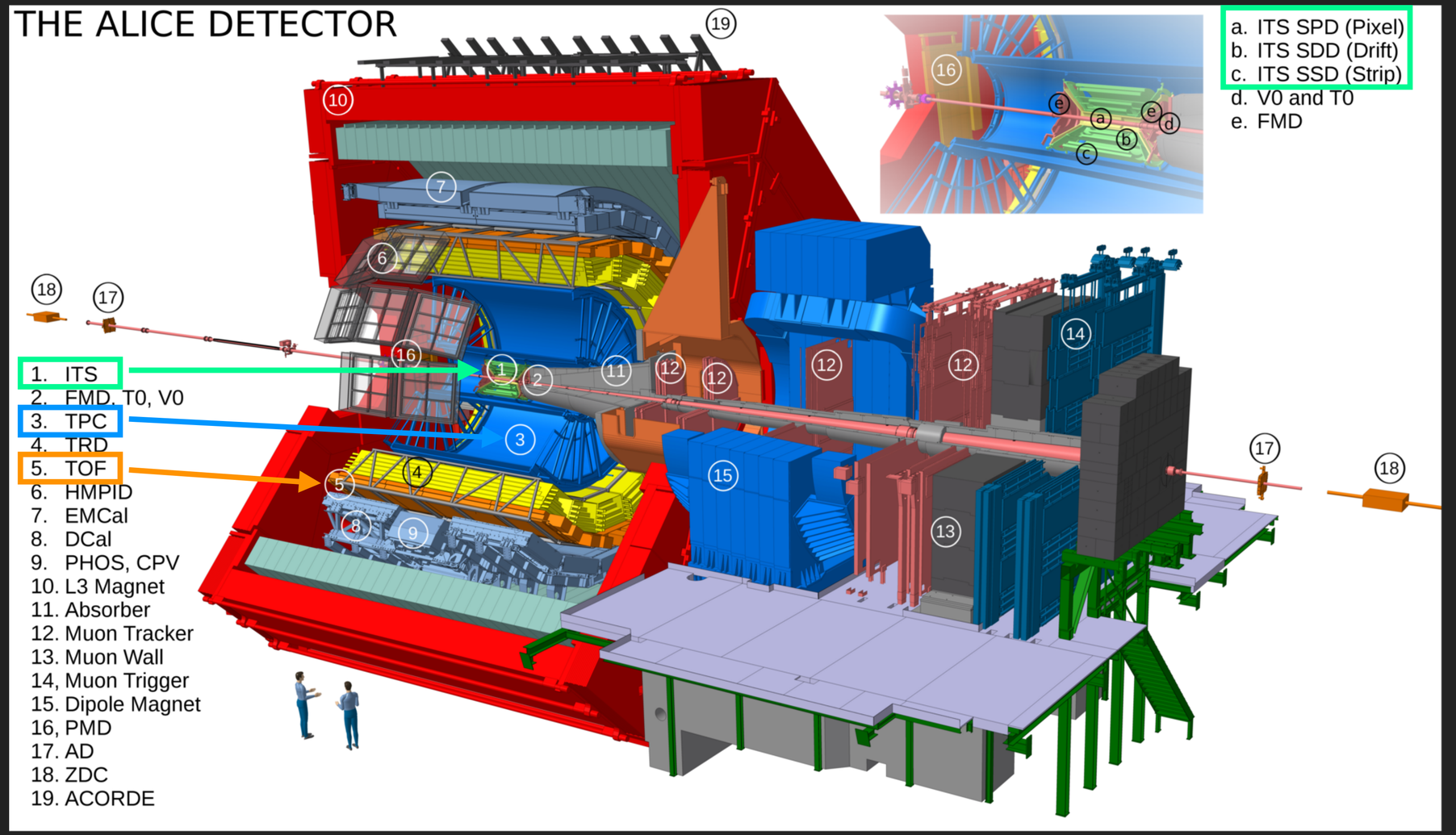




arXiv:2102.13601
Submitted to JHEP

ALICE detector

- 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

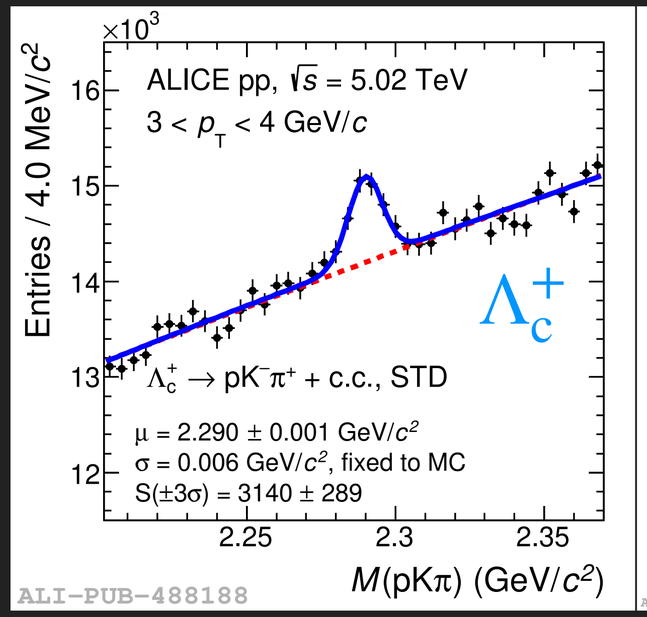
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2017	5.02	~20 nb^{-1}
	2016-2018	13	~32 nb^{-1}
p–Pb	2016	5.02	~0.3 nb^{-1}

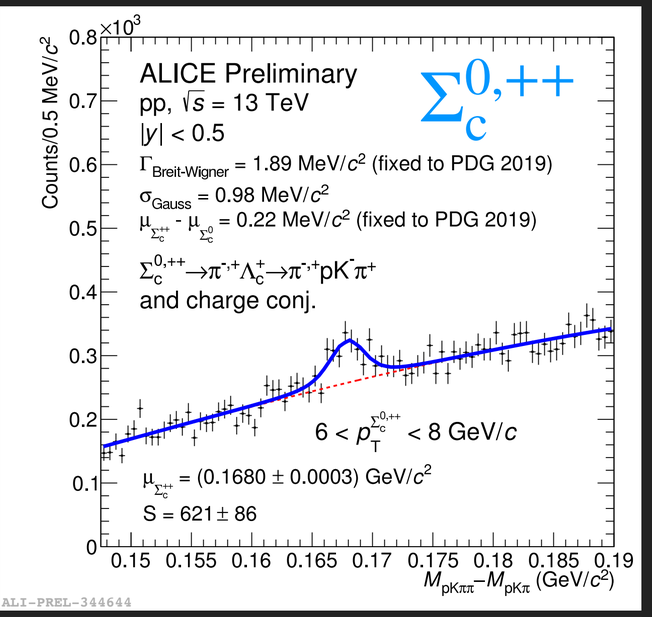
Hadronic decays:

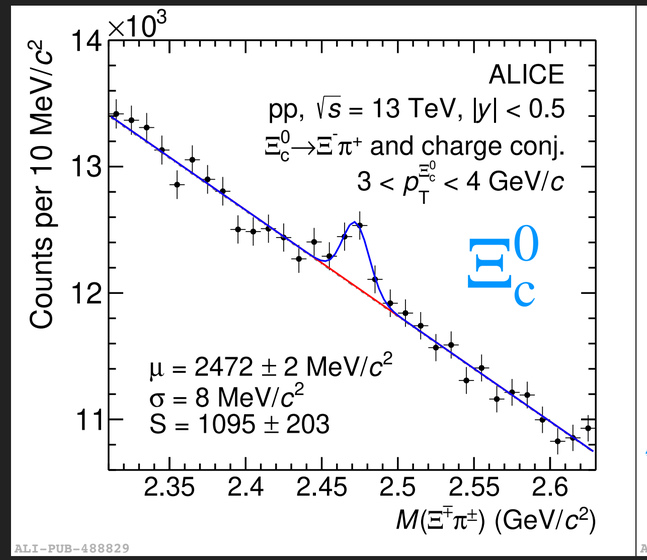
- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$ & $\Lambda_c^+ \rightarrow pK_s^0$
- $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ & $\Sigma_c^{++}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

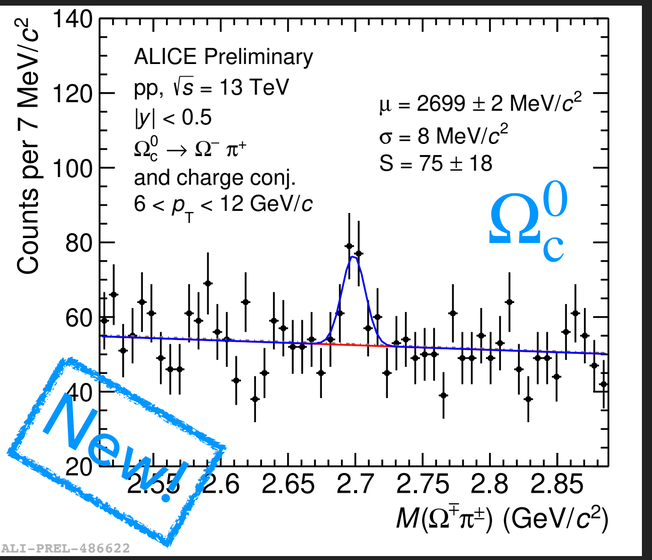
Semileptonic decays:

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



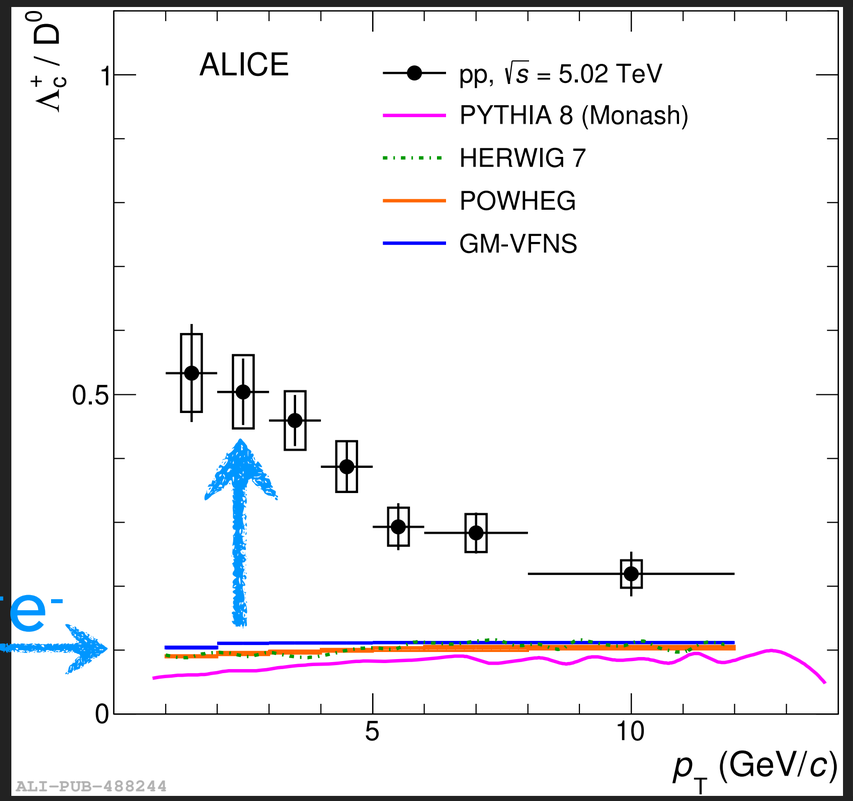


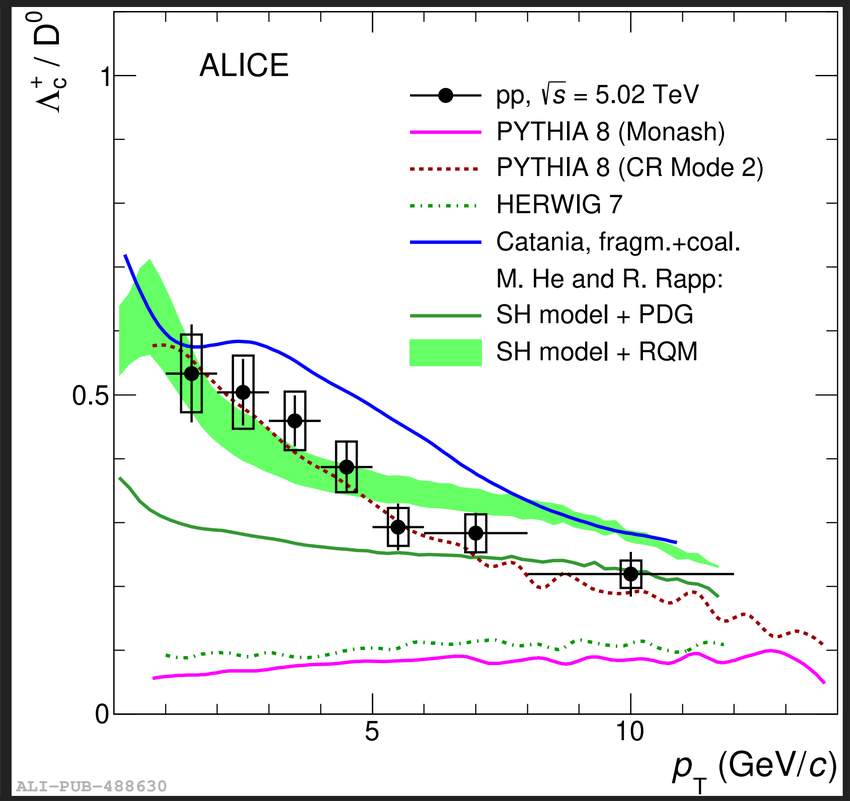




Λ_c^+/D^0 in pp@5.02 TeV

arXiv:2011.06078
arXiv:2011.06079





PYTHIA 8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA 8 Mode2
[JHEP 08 (2015) 003]
HERWIG 7
[Eur. Phys. J. C58 (2008) 639–707]
POWHEG
[JHEP 09 (2007) 126]
GM-VFNS
[Phys. Rev. D 101 (2020) 114021]
M. He and R. Rapp
[PLB 795 (2019) 117-121]
RQM
[Phys. Rev. D 84 (2011) 014025]
Catania
[arXiv:2012.12001]
[EPJC 78 no. 4, (2018) 348]

Models which describe e^+e^-, but not pp

- PYTHIA 8 with Monash tune
- HERWIG 7 with hadronisation implemented via clusters
- POWHEG matched to PYTHIA 6 to generate parton shower
- GM-VFNS pQCD calculation -> same choice of pQCD scales for Λ_c^+ and D^0

Models which describe pp

- PYTHIA 8 with color reconnection (CR) beyond leading color (BLC) approximation (Mode 0, Mode 2, Mode 3)
- Catania with coalescence+fragmentation slightly overestimates data
- M. He and R. Rapp (statistical hadronization model (SHM) approach)
  - SHM+RQM: SHM with augmented set of charm-baryon states according to relativistic quark model (RQM)

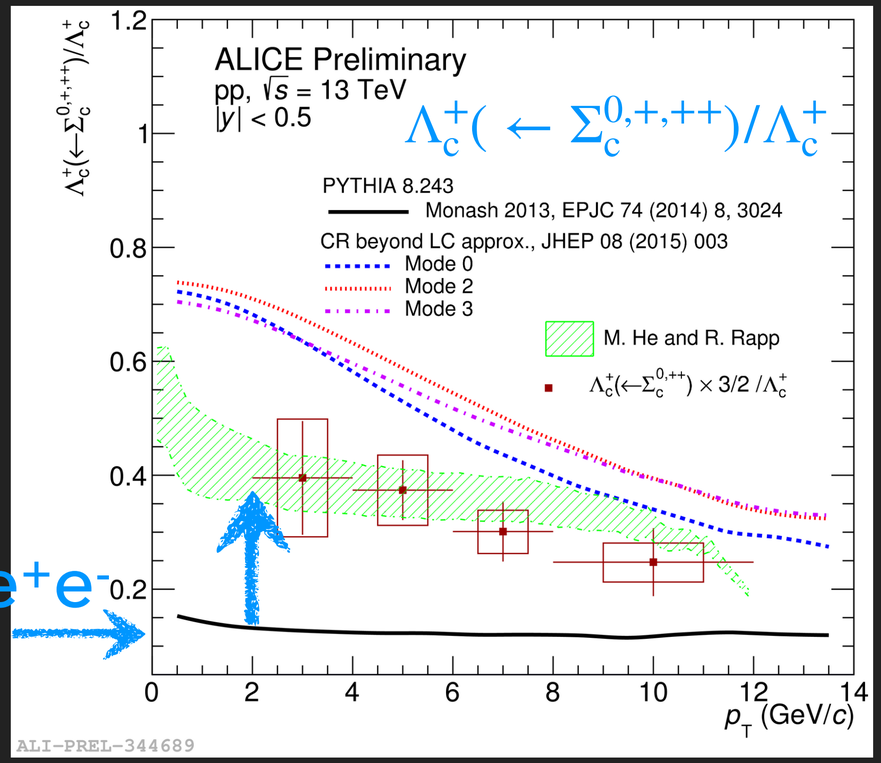
$\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$ in pp@13 TeV

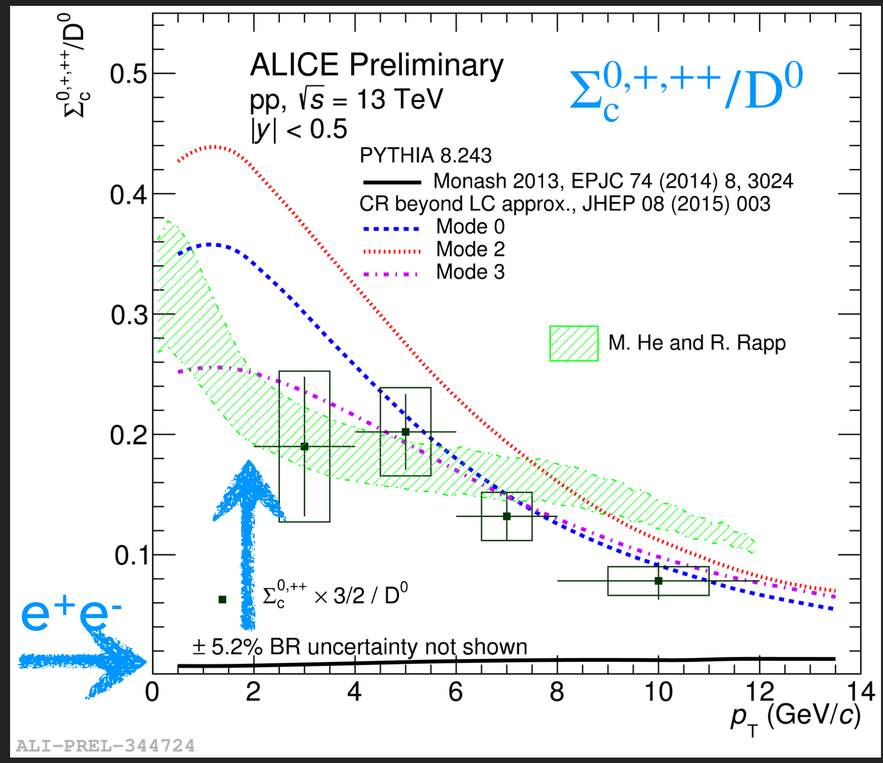
Λ_c^+/D^0 enhancement due to $\Sigma_c^{0,+,++}$ feed-down ?

- ~40% contribution from $\Sigma_c^{0,+,++}$ feed-down
- Λ_c^+/D^0 enhancement in pp can be only partially explained by $\Sigma_c^{0,+,++}$ feed-down
- Enhancement also found for $\Sigma_c^{0,+,++}$ in pp w.r.t. e^+e^-
- $\Sigma_c^{0,+,++}$ Largely underestimated by PYTHIA 8 Monash

PYTHIA 8 CR-BLC & SHM+RQM can describe Λ_c^+ and $\Sigma_c^{0,+,++}$

Do they also work for $\Xi_c^{0,+}$ and Ω_c^0 ?

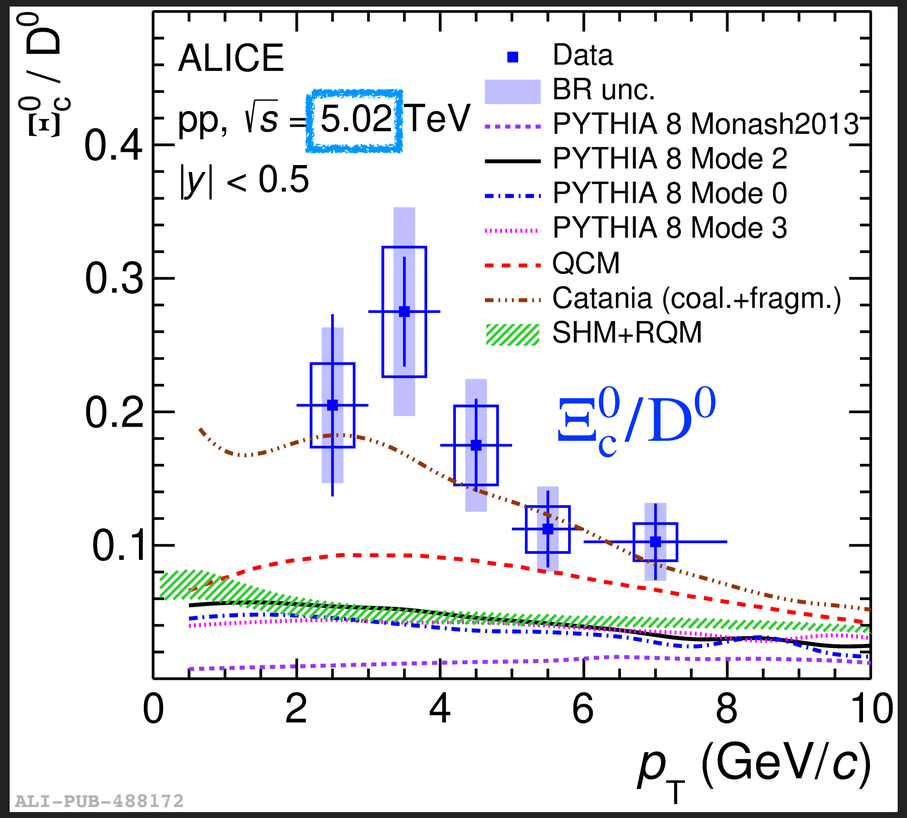




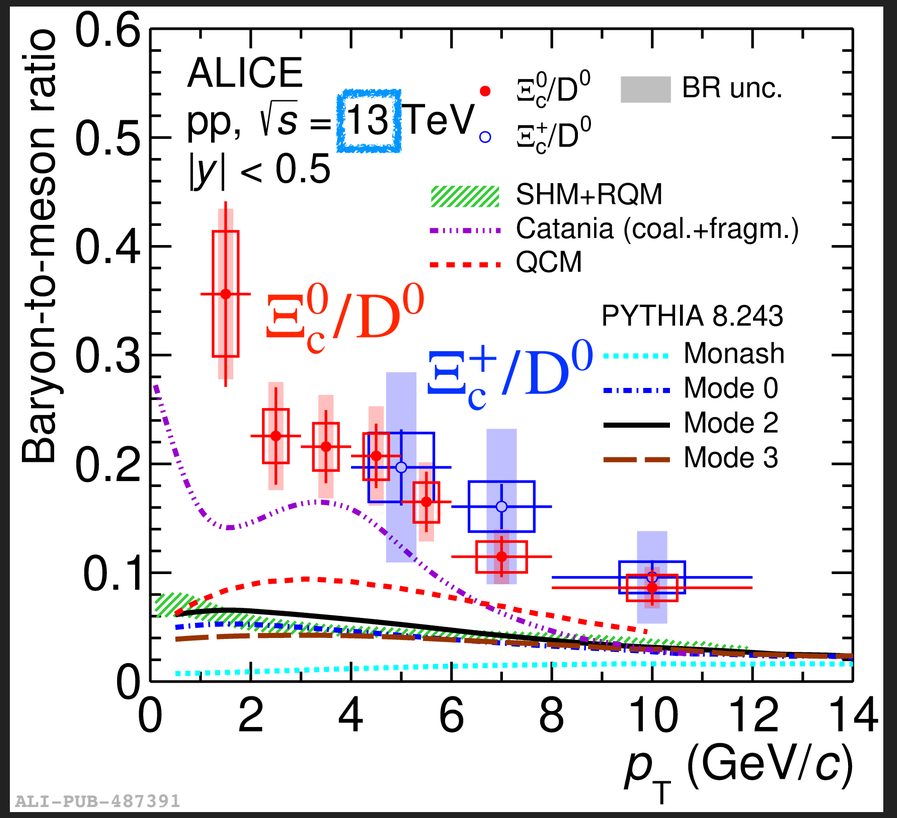
M. He and R. Rapp
[PLB 795 (2019) 117-121]

$\Xi_c^{0,+}/D^0$ in pp@5.02 TeV and pp@13 TeV

Final on arXiv:2105.05616



Final on arXiv:2105.05187

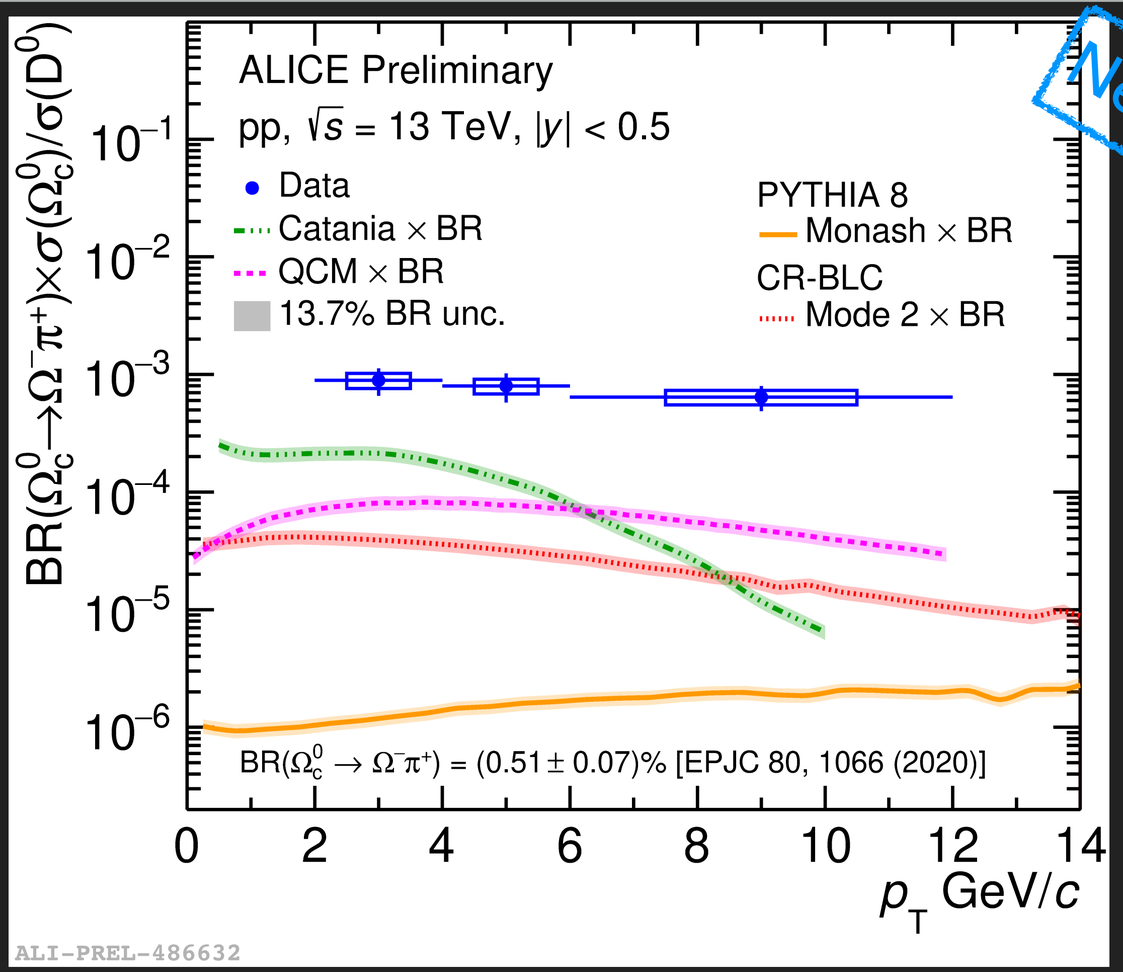


PYTHIA 8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA 8 Mode
[JHEP 08 (2015) 003]
QCM
[EPJC 78 no. 4, (2018) 344]
SHM
[PLB 795 (2019) 117-121]
RQM
[Phys. Rev. D 84 (2011) 014025]
Catania
[arXiv:2012.12001]
[EPJC 78 no. 4, (2018) 348]

- Underestimated by PYTHIA 8 CR-BLC, SHM+RQM, Quark (re-)combination mechanism (QCM)
- Described by Catania with coalescence+fragmentation
- No energy dependence of the ratio

$(BR \times \Omega_c^0)/D^0$ in pp@13 TeV

$BR(\Omega_c^0 \to \pi^+\Omega^-)$
Yu-Kuo Hsiao et al.
[EPJC 80, 1066 (2020)]

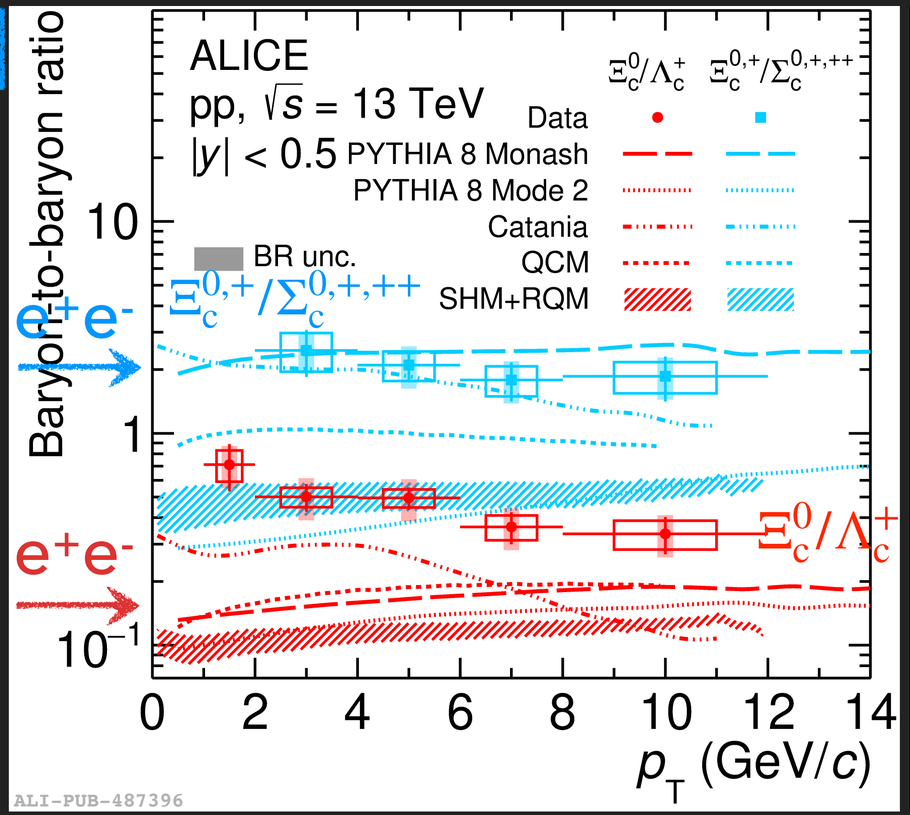


PYTHIA 8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA 8 Mode2
[JHEP 08 (2015) 003]
QCM
[EPJC 78 no. 4, (2018) 344]
Catania
[arXiv:2012.12001]
[EPJC 78 no. 4, (2018) 348]

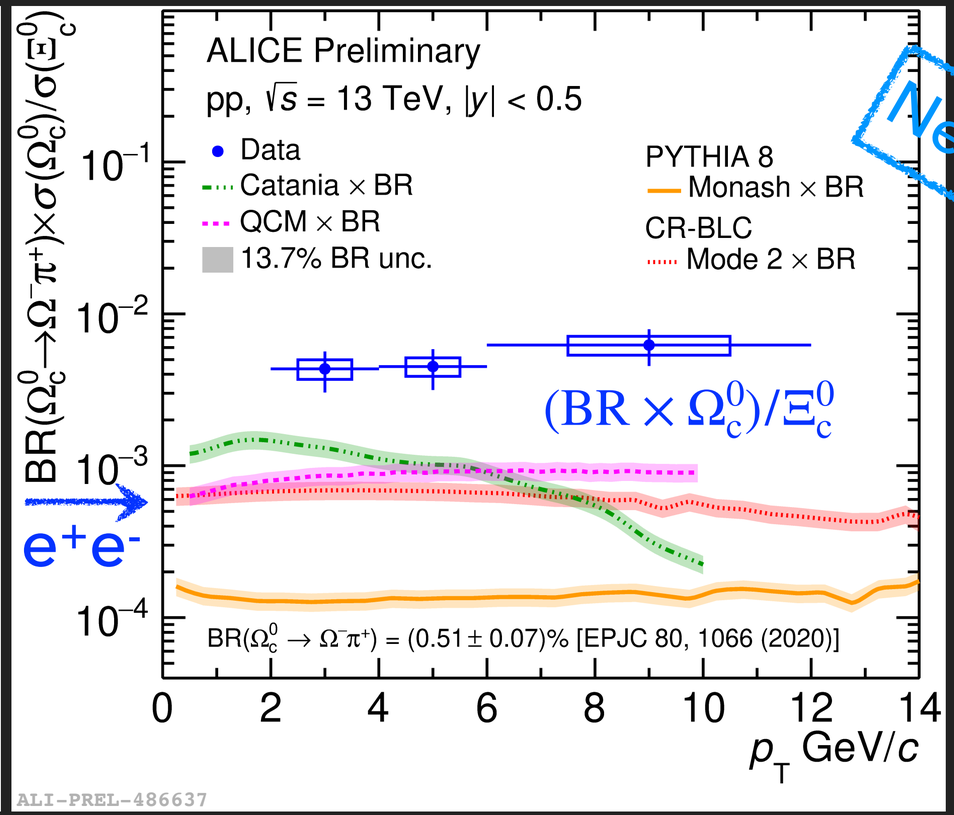
- $BR(\Omega_c^0 \to \pi^+\Omega^-) = (0.51 \pm 0.07)\,\%$ theoretical calculation, **not** measured
- **First** measurement of Ω_c^0 production at the LHC
- **Underestimated** by PYTHIA 8 CR-BLC, QCM, Catania (with coalescence)

Charm baryon-to-baryon in pp@13 TeV with models

Final on arXiv:2105.05187



Belle
[Phys. Rev. D 97, 072005 (2018)]



New!

- **First** measurement of charm baryon-to-baryon yield ratio at the LHC
- All current models underestimate charm baryon-to-baryon yield ratios, except :
  - Catania (coalescence+fragmentation) describe $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$

pp@13 TeV vs. e^+e^-@10.52 GeV :

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

Charm fragmentation fractions in pp collisions at the LHC

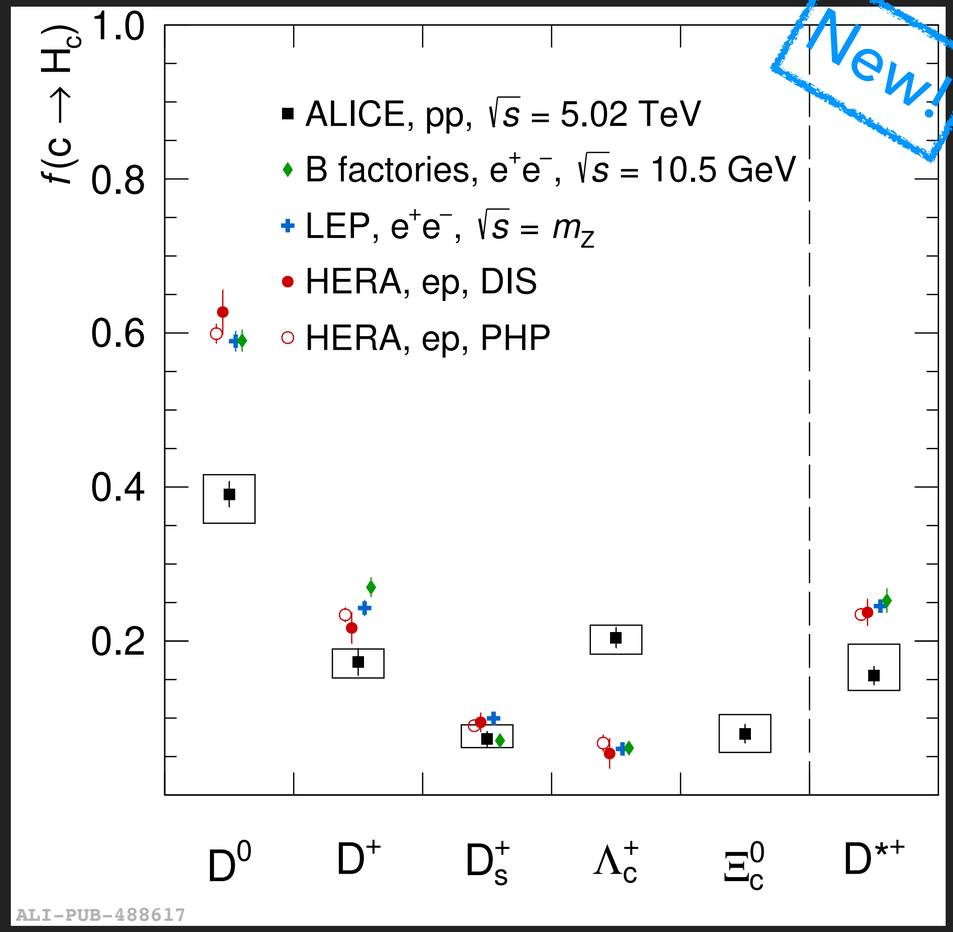
- NOW enable to measure charm FF and charm total cross section
  - D^0 and D^+ measured down to $p_{\mathrm{T}} = 0$
  - $\Xi_{\mathrm{c}}^{0,+}$ included for the first time

$\mathrm{H_c}$	$f(\mathrm{c} \to \mathrm{H_c})[\%]$
D^0	$39.1 \pm 1.7(\mathrm{stat})^{+2.5}_{-3.7}(\mathrm{syst})$
D^+	$17.3 \pm 1.8(\mathrm{stat})^{+1.7}_{-2.1}(\mathrm{syst})$
D_s^+	$7.3 \pm 1.0(\mathrm{stat})^{+1.9}_{-1.1}(\mathrm{syst})$
Λ_c^+	$20.4 \pm 1.3(\mathrm{stat})^{+1.6}_{-2.2}(\mathrm{syst})$
Ξ_c^0	$8.0 \pm 1.2(\mathrm{stat})^{+2.5}_{-2.4}(\mathrm{syst})$
D^{*+}	$15.5 \pm 1.2(\mathrm{stat})^{+4.1}_{-1.9}(\mathrm{syst})$

B factories
[EPJC 76 no. 7, (2016) 397]
LEP
[EPJC 75 no. 1, (2015) 19]
HERA
[EPJC 76 no. 7, (2016) 397]

Final on arXiv:2105.06335

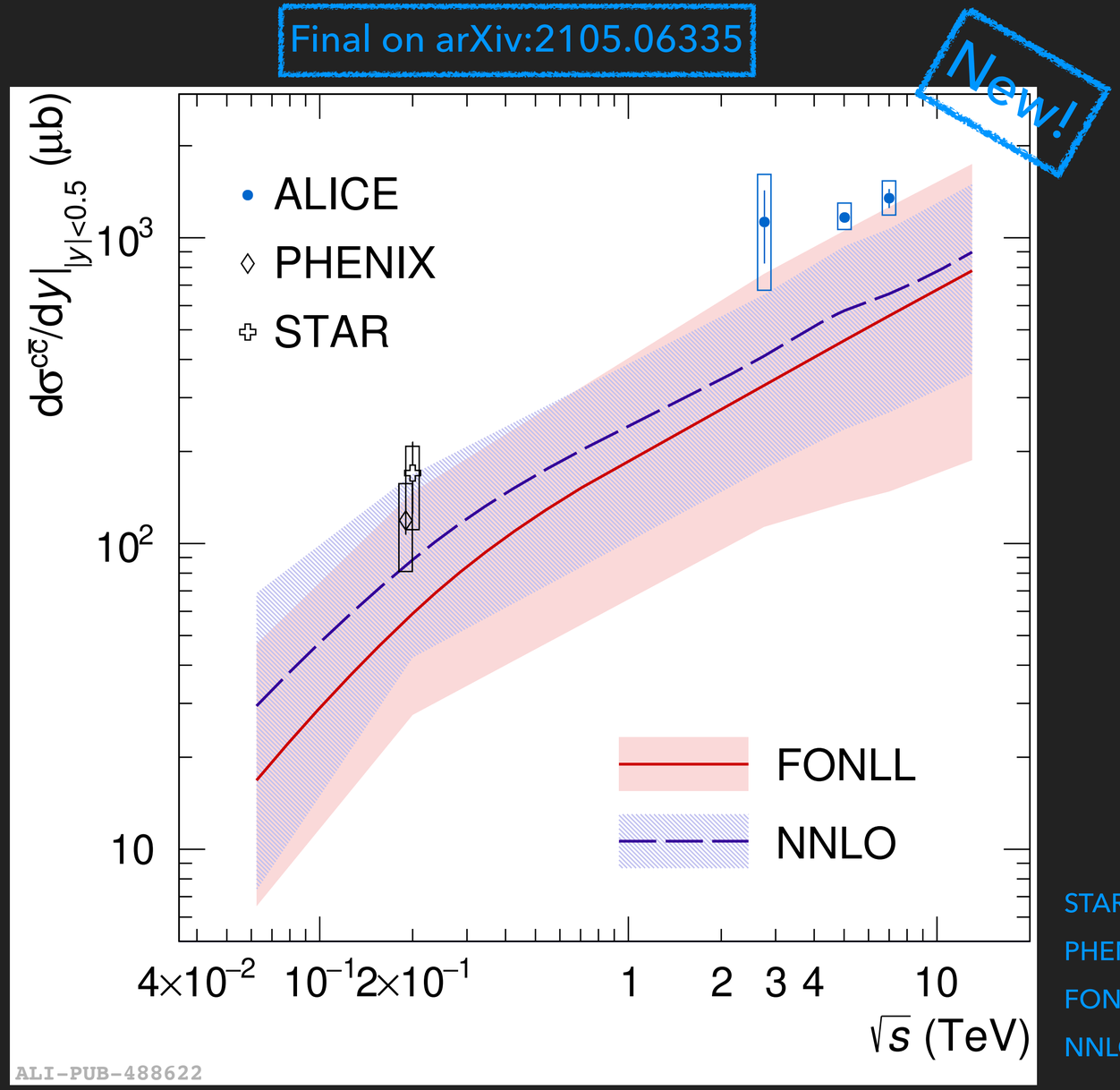
New!



- Consider twice Ξ_{c}^0 contribution to include Ξ_{c}^+
- Charm fragmentation fractions are not universal
- Sum of FFs add up to unity, not counting here D^{*+}, which feeds into D^0 and D^+

Charm total production cross section at the LHC

Final on arXiv:2105.06335



- New measurement of charm total cross section in pp@5.02 TeV

$$d\sigma^{c\bar{c}}/dy|_{|y|<0.5} = 1165 \pm 44(\text{stat})^{+133}_{-101}(\text{syst})\ \mu\text{b}$$

- Update charm total production cross sections in pp@2.76 TeV & pp@7 TeV according to new FFs
  - ~40% higher than previously published results

    pp@2.76TeV [JHEP 07 (2012) 191]

    pp@7TeV [EPJC 77 no. 8, (2017) 550]
- Ω_c^0 only used for systematic uncertainty
  - Assume same contribution as Ξ_c^0
- On upper edge of FONLL and NNLO calculations

STAR [Phys. Rev. D 86 (2012) 072013]

PHENIX [Phys. Rev. C 84 (2011) 044905]

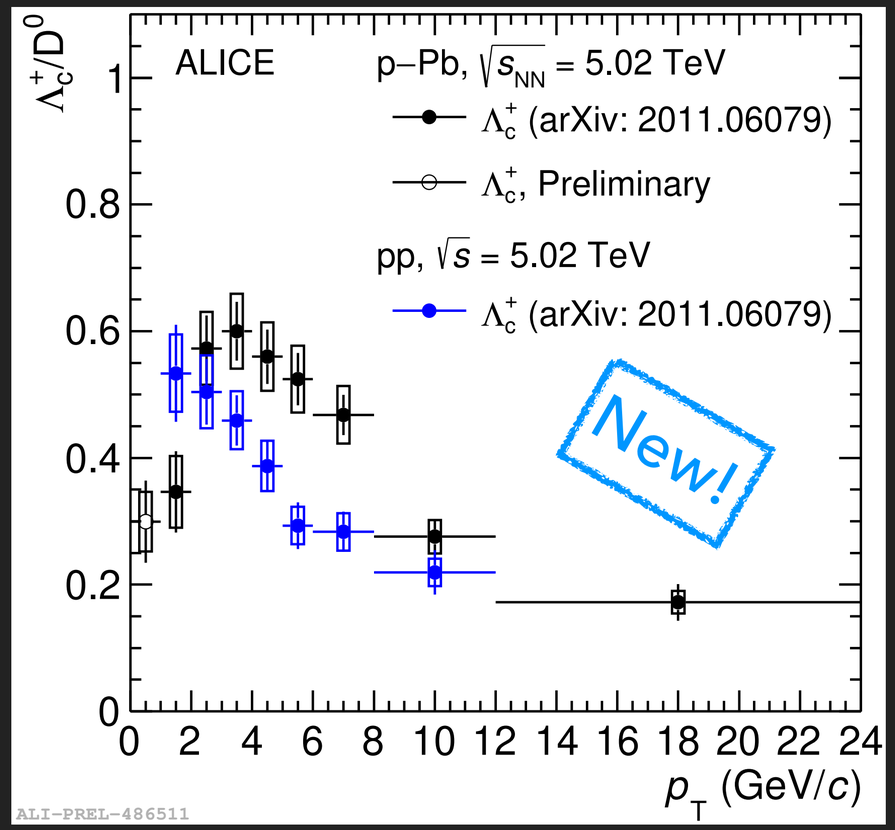
FONLL [JHEP 10 (2012) 137]

NNLO [PRL 118 (2017) 12, 122001]

Λ_c^+/D^0 and $R_{pPb}(\Lambda_c^+)$ in p-Pb@5.02 TeV

- **First** measurement of Λ_c^+ down to $p_T = 0$ in p-Pb collisions at LHC
- Λ_c^+/D^0 : larger in mid-p_T and lower in $p_T < 2$ GeV/c in p-Pb w.r.t. pp collisions

arXiv:2011.06078, arXiv:2011.06079

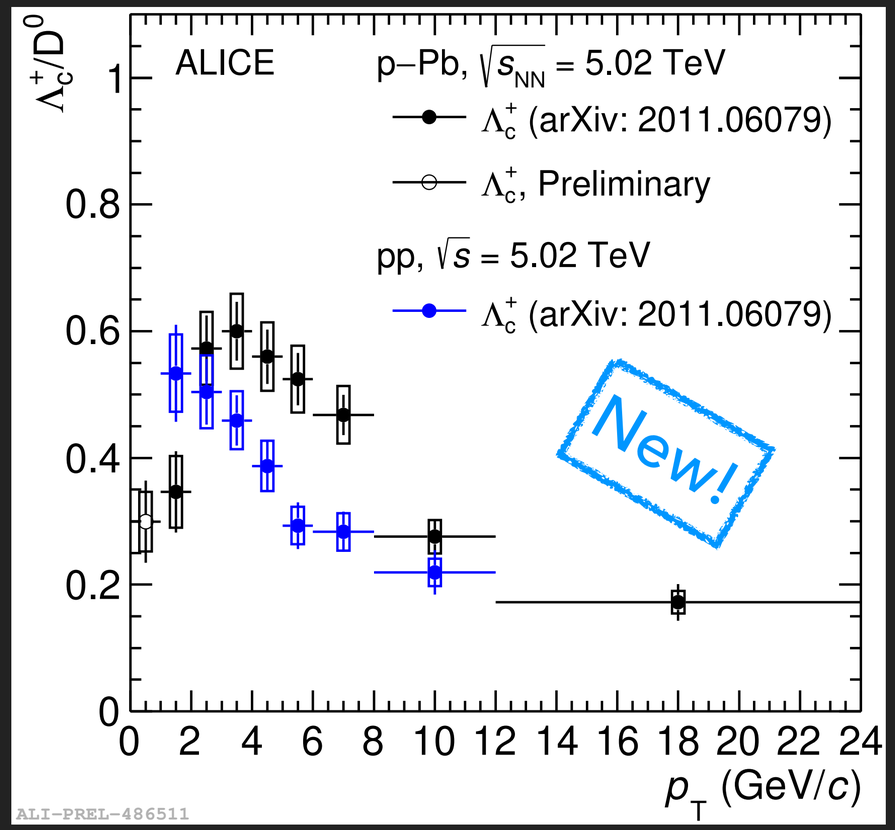


Λ_c^+/D^0 and $R_{pPb}(\Lambda_c^+)$ in p-Pb@5.02 TeV

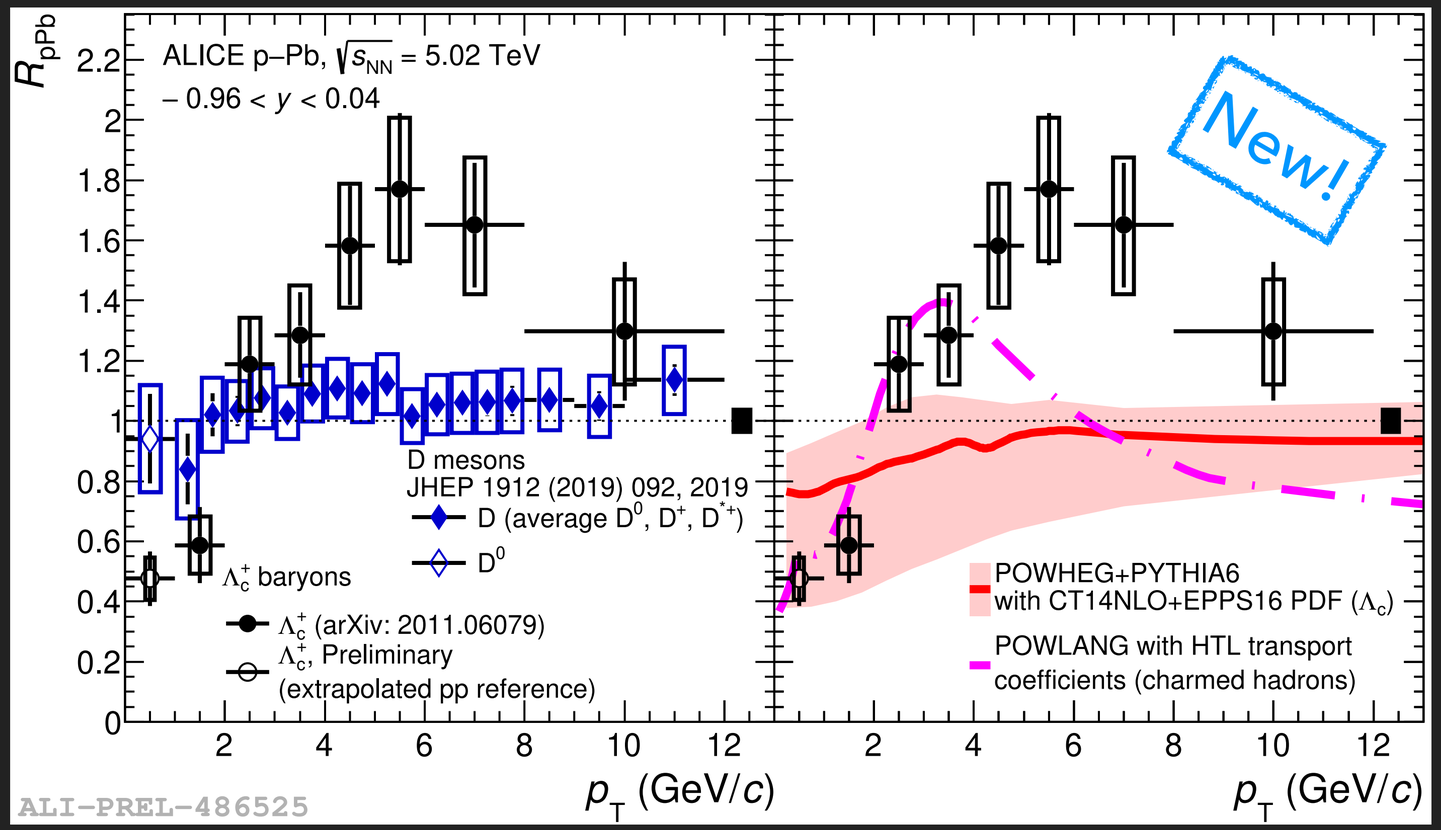
- **First** measurement of Λ_c^+ down to $p_T = 0$ in p-Pb collisions at LHC
- Λ_c^+/D^0 : larger in mid-p_T and lower in $p_T < 2$ GeV/c in p-Pb w.r.t. pp collisions

- Significant suppression for Λ_c^+ in $p_T < 2$ GeV/c in p-Pb w.r.t. pp collisions
- $R_{pPb}(\Lambda_c^+)$ systematically above unity in $p_T > 2$ GeV/c
- $R_{pPb}(\Lambda_c^+)$ cannot be described with two models
  - POWHEG+PYTHIA6: including only CNM effect [JHEP 09 (2007) 126] [EPJC 77 no. 3, (2017) 163]
  - POWLANG: QGP in small system [JHEP 03 (2016) 123]

arXiv:2011.06078, arXiv:2011.06079



arXiv:2011.06078, arXiv:2011.06079



Summary

- First measurement of $\Sigma_c^{0,+,++}$, $\Xi_c^{0,+}$, Ω_c^0 production cross section in pp@13 TeV and first measurement of Λ_c^+ down to $p_T = 0$ in p-Pb@5.02 TeV at the LHC
- Large enhancement of all charm baryons in pp than e^+e^- collisions
  - Current hadronization models not describe such enhancement for all charm baryons
- Charm fragmentation fractions are not universal
- Measure charm total cross section in pp@5.02 TeV using all measured single charm hadron states

BACKUP

Charm FF in e^+e^- & ep

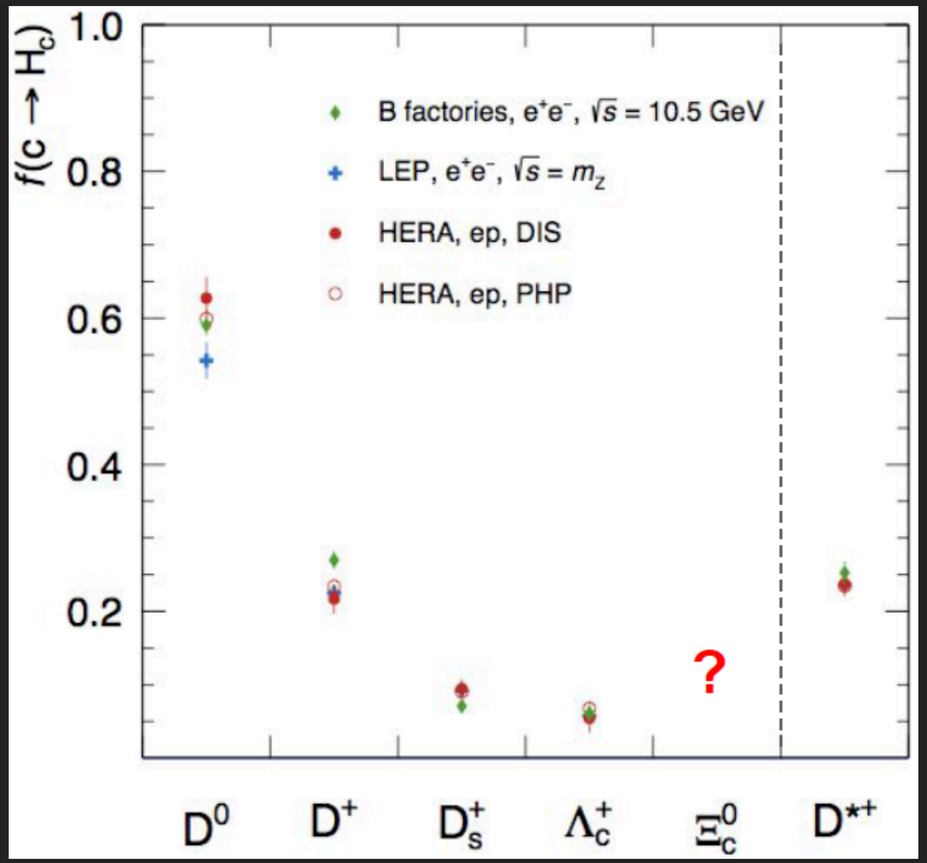
- Charm FF as important input for theoretical model calculation
- So far, charm hadronization models based on FF measured in e^+e^- & ep
- Lack of knowledge about production of $\Xi_c^{0,+}$ & Ω_c^0, assume:

  [EPJ C 76 (2016) no.7, 397]

  - $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(c \to \Xi_c^0)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda) \approx 0.004$
  - $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+) = f(s \to \Omega^-)/f(s \to \Lambda) \approx 0.066$
  - $f(c \to \Omega_c^0)/f(c \to \Xi_c^0) = f(s \to \Omega^-)/f(s \to \Xi^-) \approx 16.125$ (so large?)

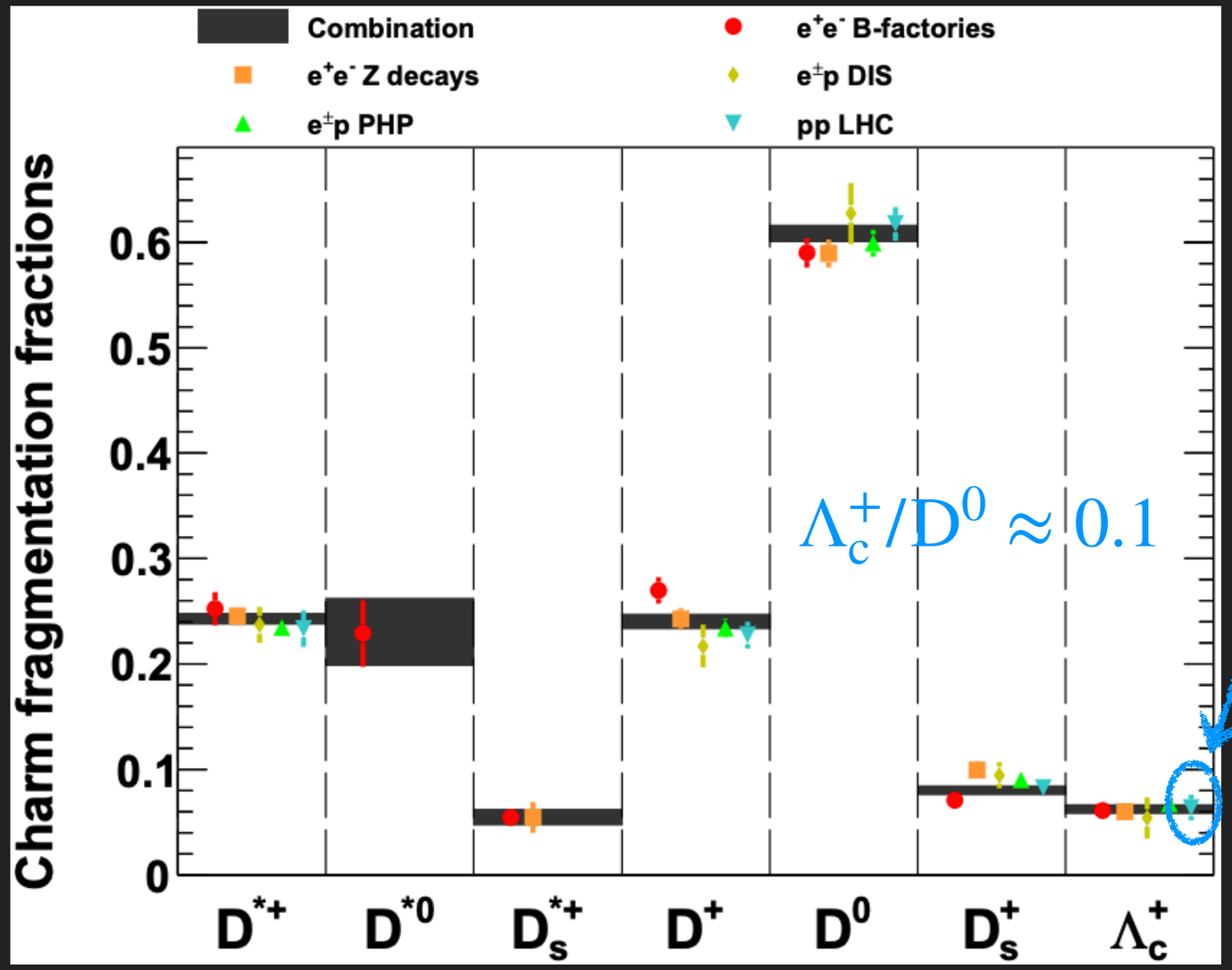
[Eur. Phys. J. C 75 (2015) 19]

H_c	$f(c \to H_c)$ [%]	$f(b \to H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$	$58.7 \pm 2.1 \pm 0.8$
D^+	$22.5 \pm 1.0 \pm 0.5$	$22.3 \pm 1.1 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$	$13.8 \pm 0.9 \pm 0.6$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$	$7.3 \pm 0.8 \pm 0.4$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$	$23.3 \pm 1.0 \pm 0.3$
D^{*+}, double-tag	$24.4 \pm 1.3 \pm 0.2$	$17.5 \pm 2.0 \pm 0.1$
D^{*+}, combined	$23.6 \pm 0.6 \pm 0.3$	$22.1 \pm 0.9 \pm 0.3$



Charm FF in e^+e^- & ep comparing with pp at LHC

[EPJ C 76 (2016) no.7, 397]



- In 2015, only LHCb Λ_c^+ measurement available at LHC for charm baryons
  - Consistent with e^+e^- -> FF universal
- So… everything fine and understood ?

CAVEAT:

- NO measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c^0)$, $\sigma(\Xi_c^+)$, $\sigma(\Omega_c^0)$

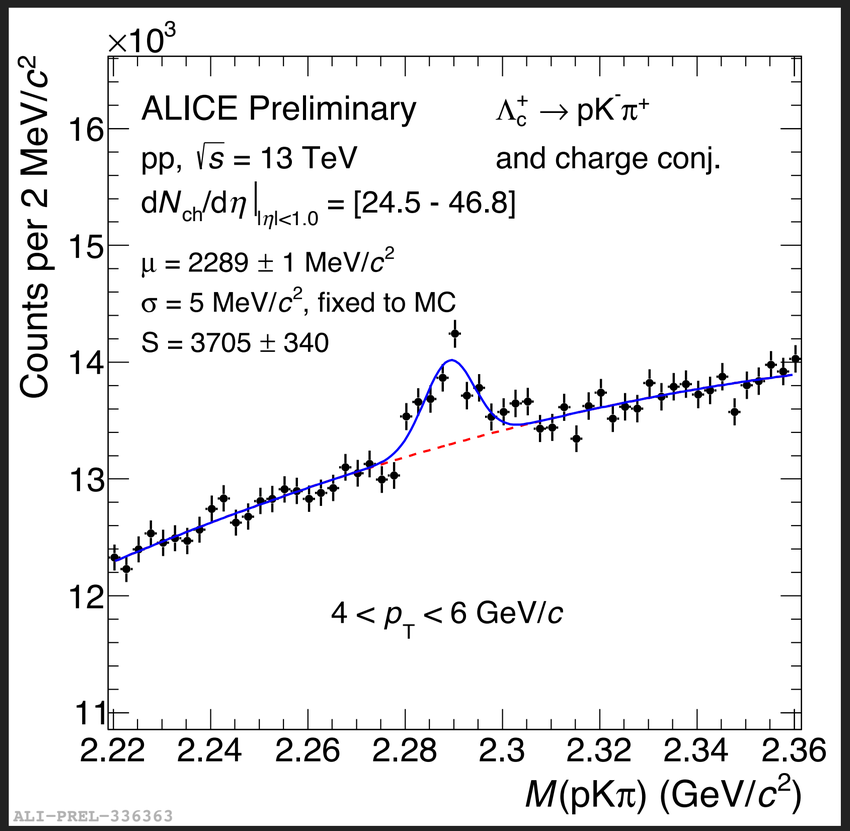
NOW, we have all of them in ALICE !

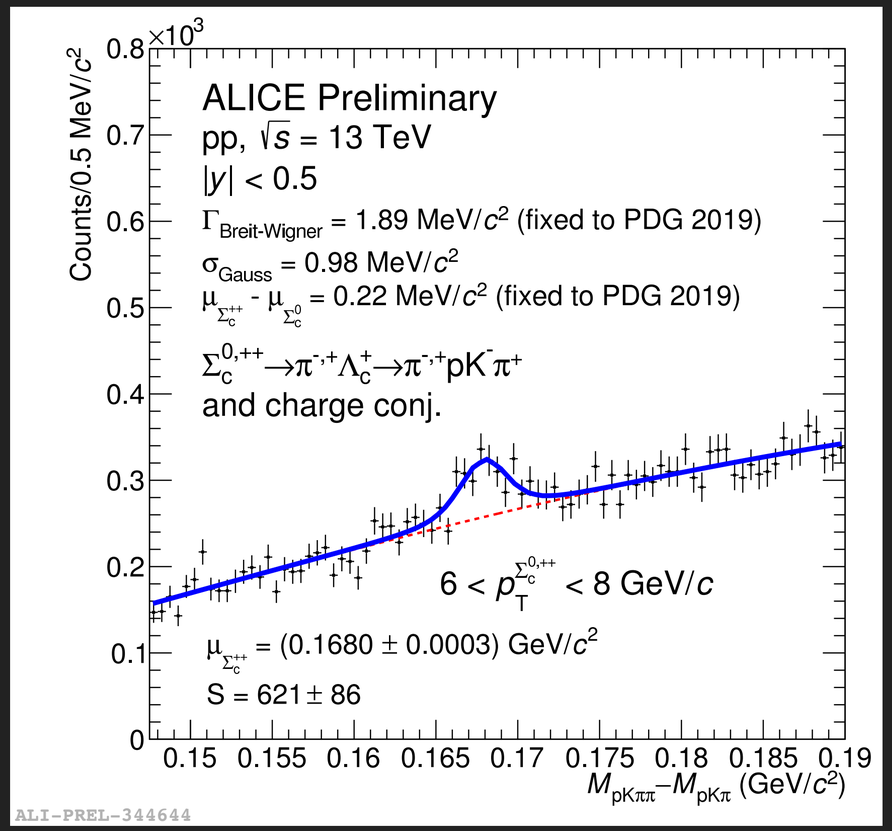
Charm-baryon reconstruction (I)

Hadronic decays:

- $\Lambda_c^+ \rightarrow pK^-\pi^+$ & $\Lambda_c^+ \rightarrow pK_S^0$
- $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ & $\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

- PID and topological selections
- Signal extraction via invariant mass analysis
- Acceptance x efficiency correction
- B feed-down subtraction



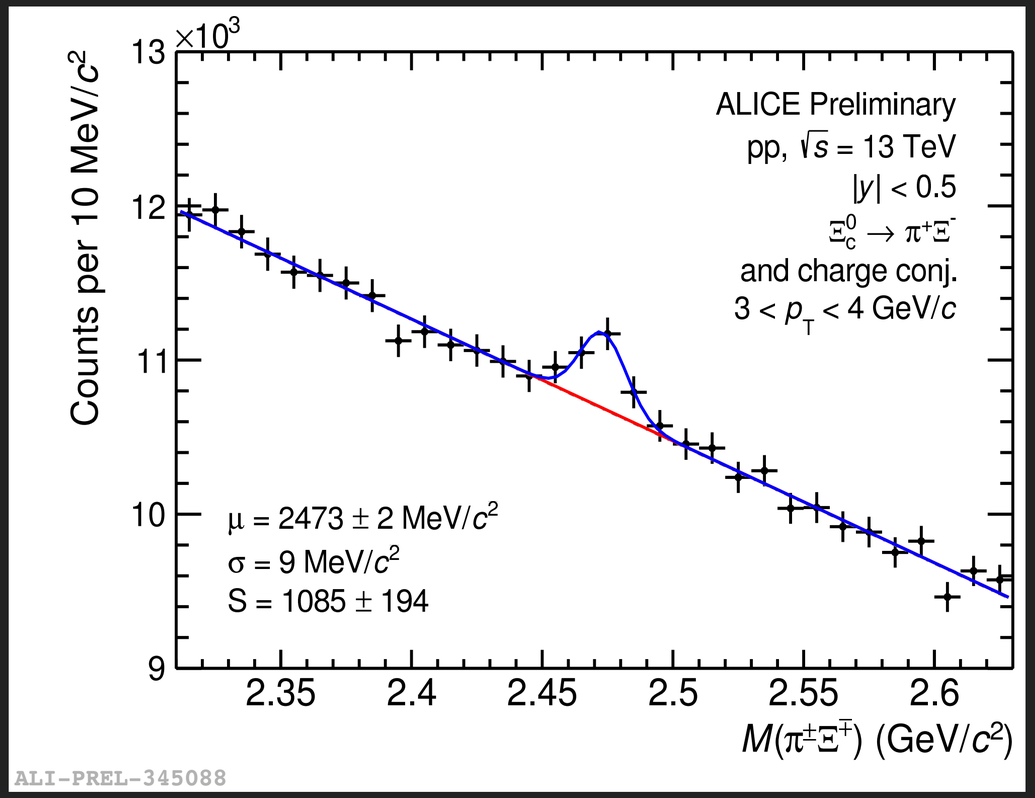


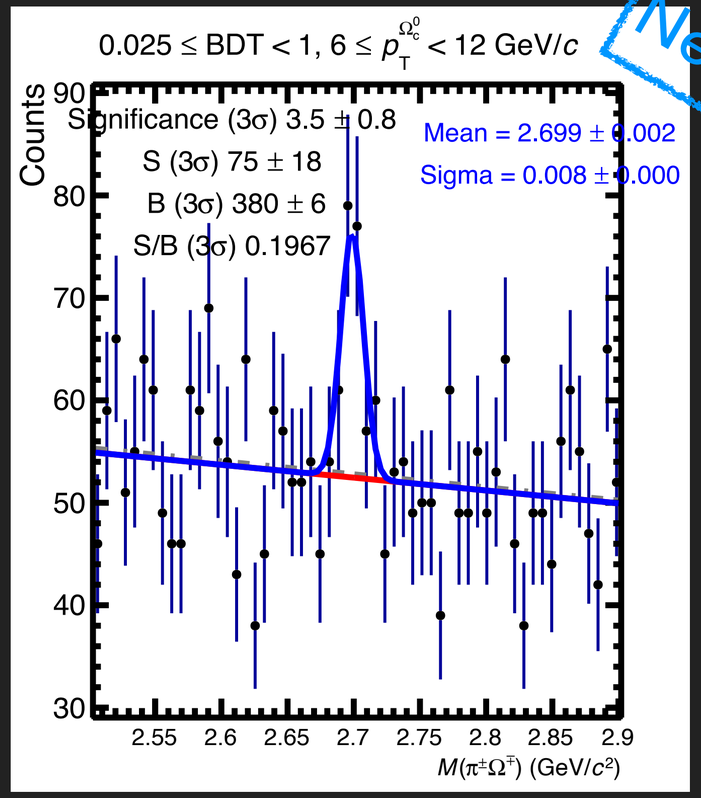
Charm-baryon reconstruction (II)

Hadronic decays:

- $\Xi_c^0 \rightarrow \Xi^-\pi^+$
- $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+$

- PID and topological selections
- Signal extraction via invariant mass analysis
- Acceptance x efficiency correction
- B feed-down subtraction

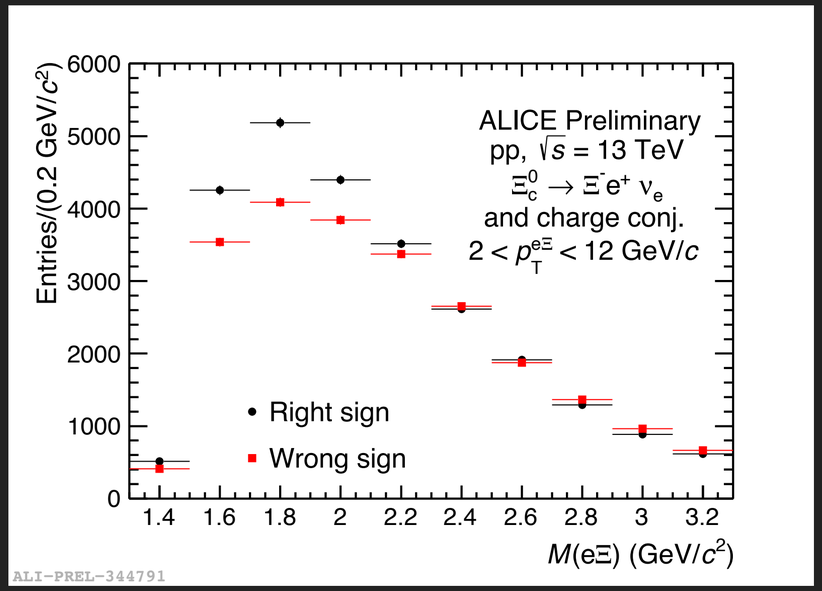


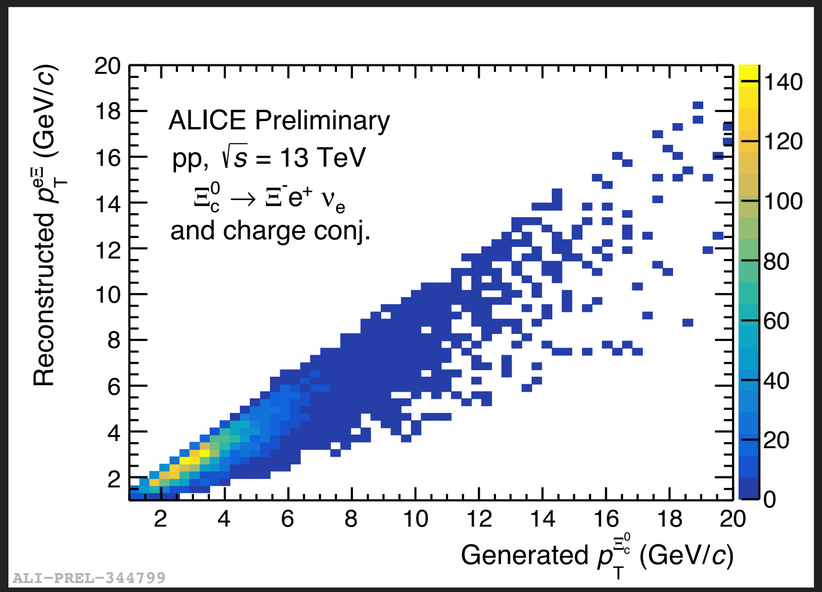


Charm-baryon reconstruction (III)

Semi-leptonic decay:

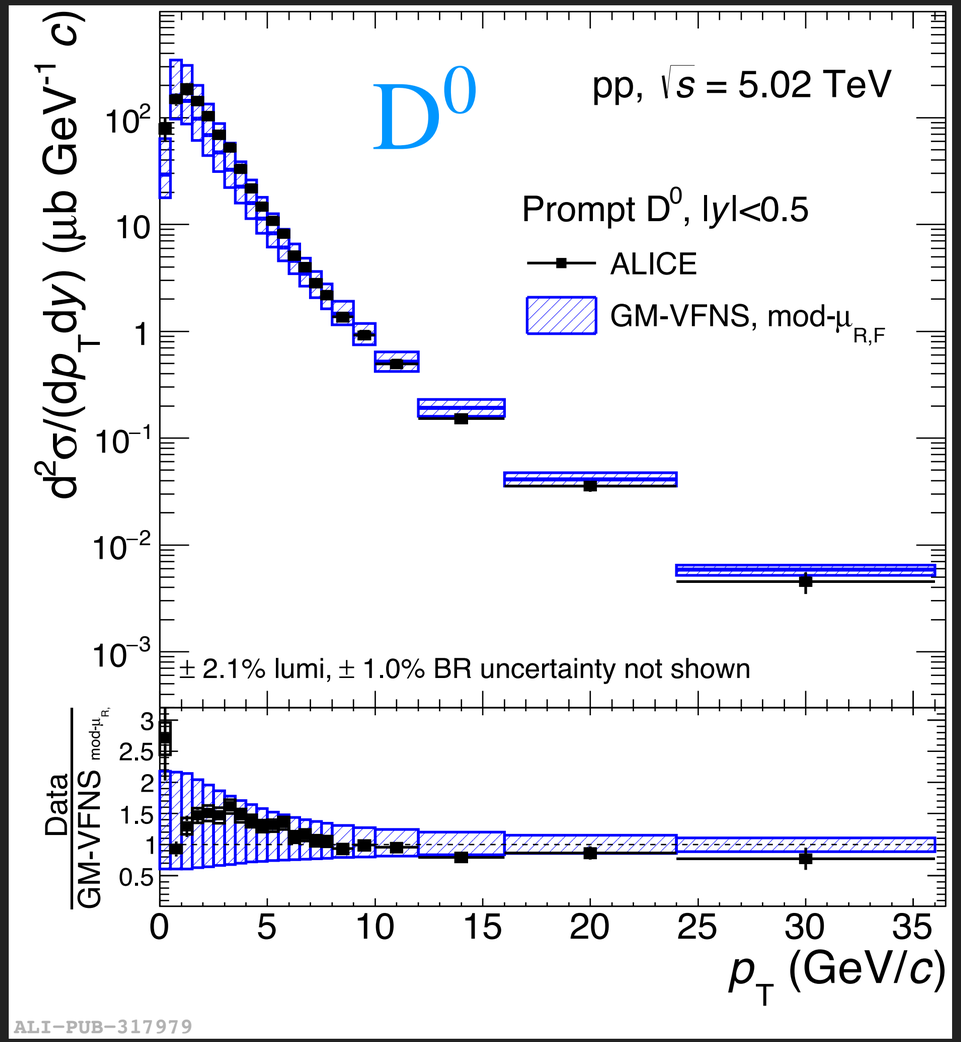
- $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$
- PID and topological selections
- Signal extraction via (Right-sign – Wrong-sign)
- Unfolding to convert p_T spectrum of $e^+\Xi^-$ into Ξ_c^0
- Acceptance x efficiency correction
- B feed-down subtraction



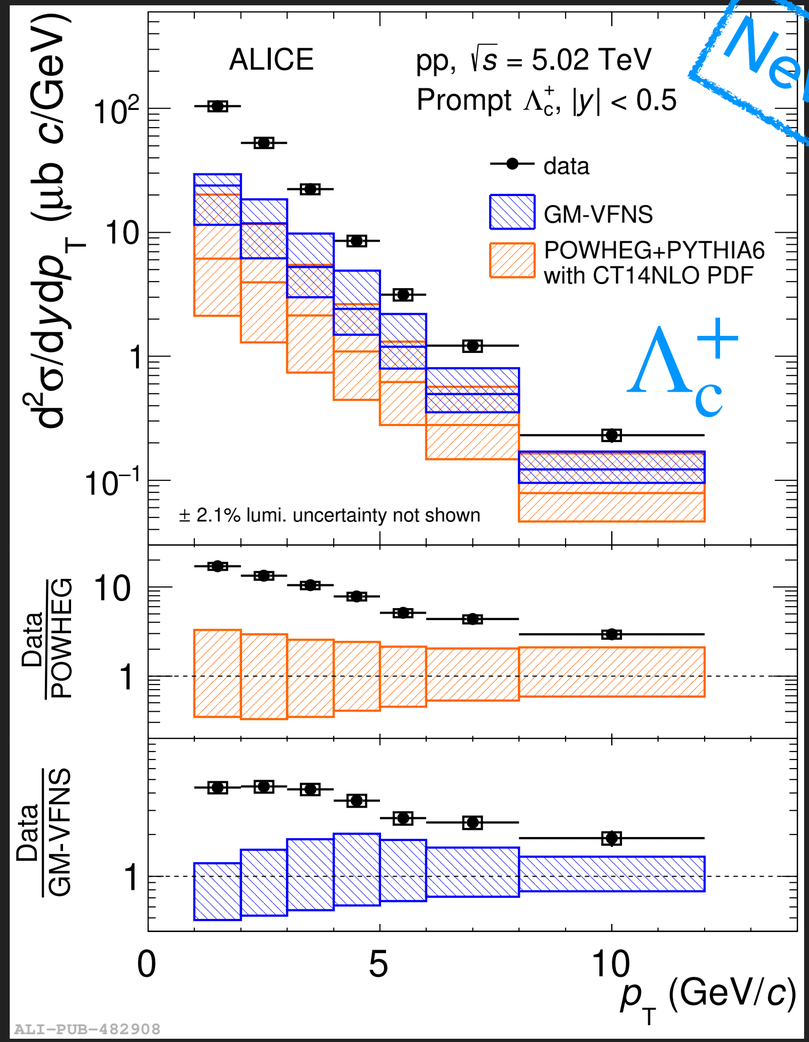


Λ_c^+ and D^0 in pp@5.02 TeV

Eur.Phys.J.C 79 (2019) 5, 388



arXiv:2011.06079



- General-mass variable-flavour-number scheme (GM-VFNS) pQCD calculation describes prompt D^0, but underestimates prompt Λ_c^+
  - GM-VFNS relies on hadron factorisation theorem

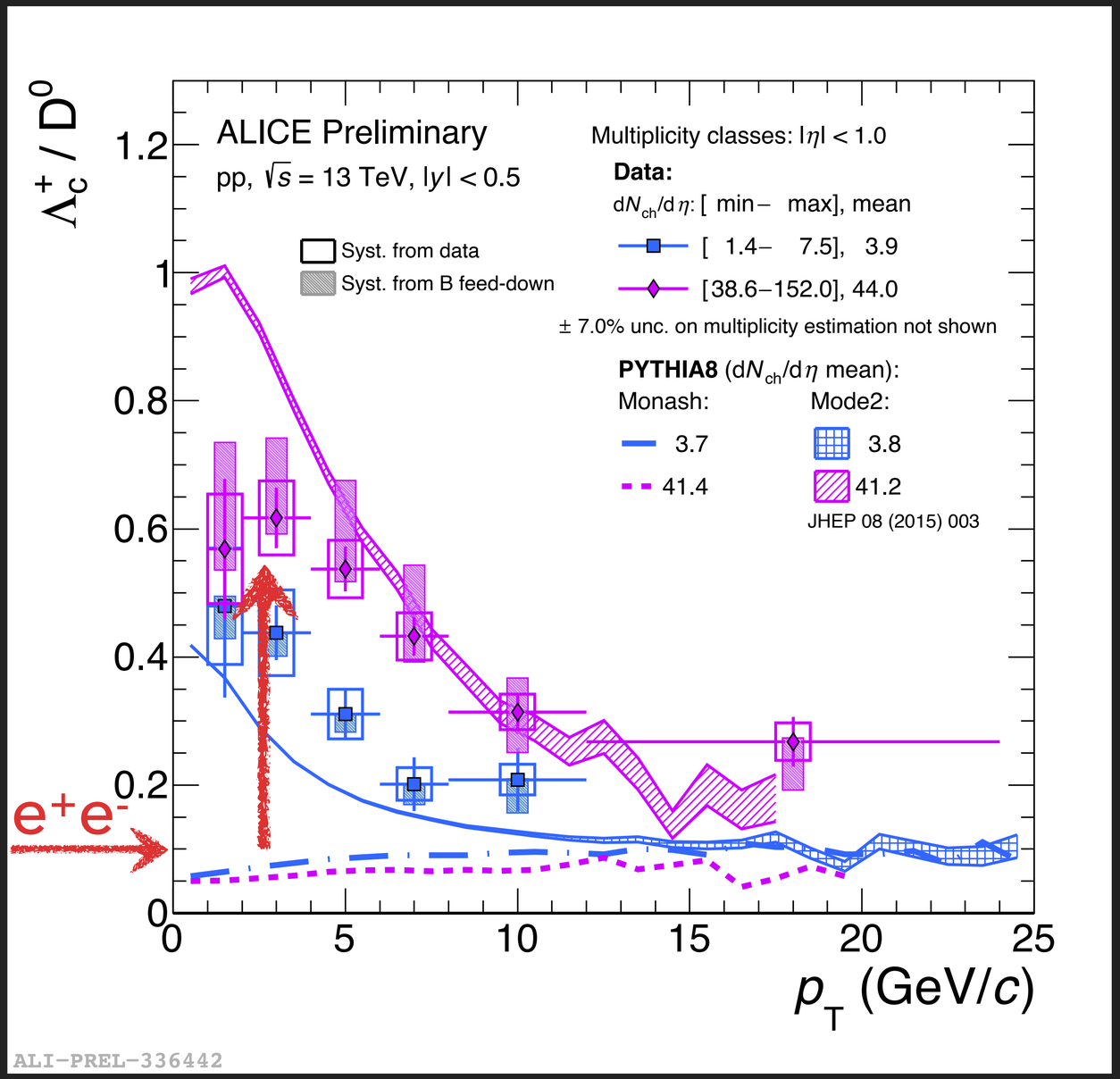
GM-VFNS
[JHEP 12 (2017) 021]
[Phys. Rev. D 101 (2020) 114021]

PYTHIA 6
[JHEP 05 (2006) 026]

POWHEG
[JHEP 09 (2007) 126]

CT14NLO PDF
[PRD 93 no. 3, (2016) 033006]

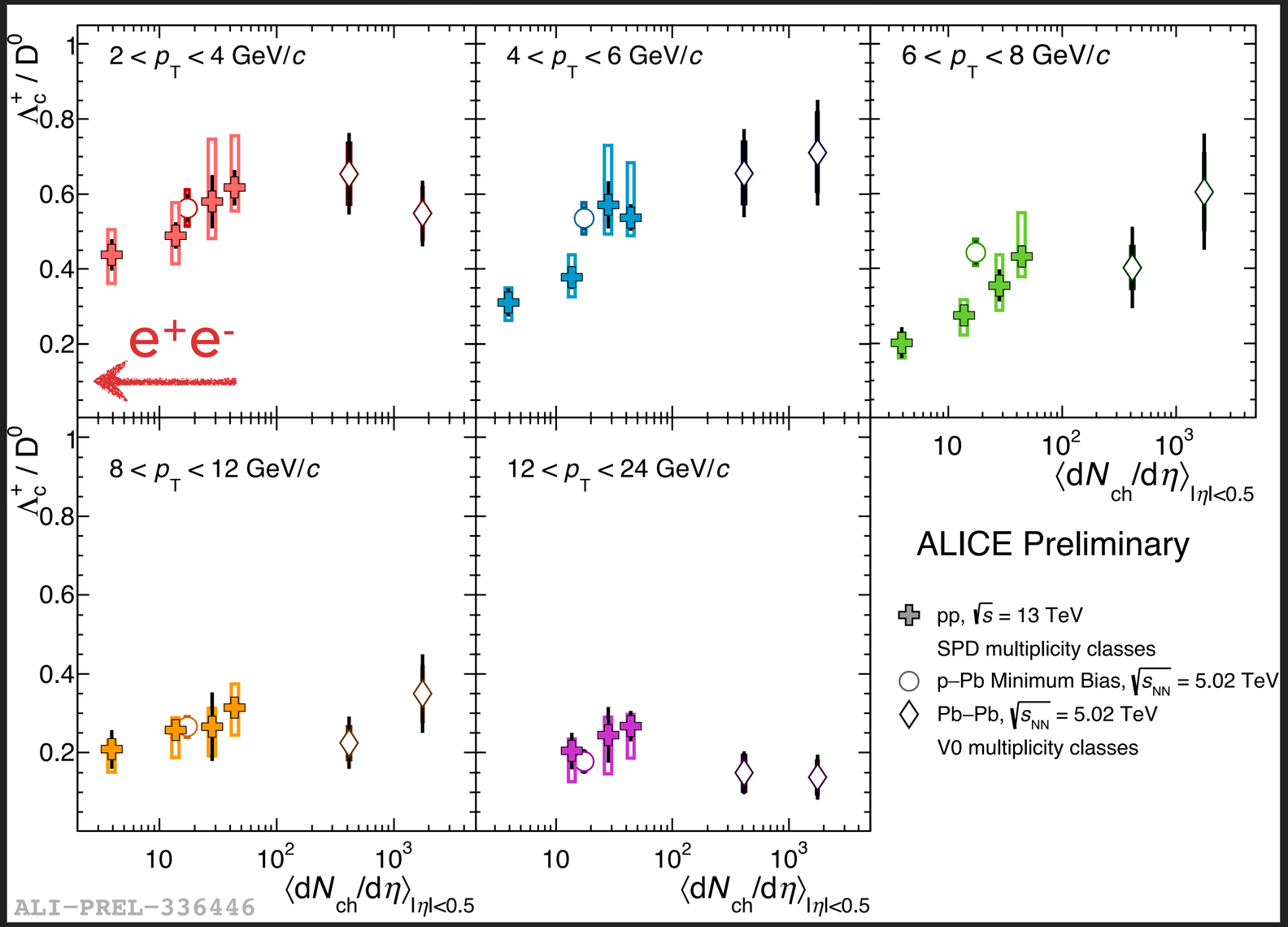
Λ_c^+/D^0 in pp@13 TeV



- Significant enhancement with increasing multiplicity
- Largely underestimated with PYTHIA 8 default tune (Monash), based on FF in e^+e^-
- Qualitatively described by PYTHIA 8 with colour reconnection (CR) beyond leading colour (BLC)
  - Colour reconnection effect seems to increase with increasing multiplicity
  - A dynamical "QCD-inspired" way for coalescence?

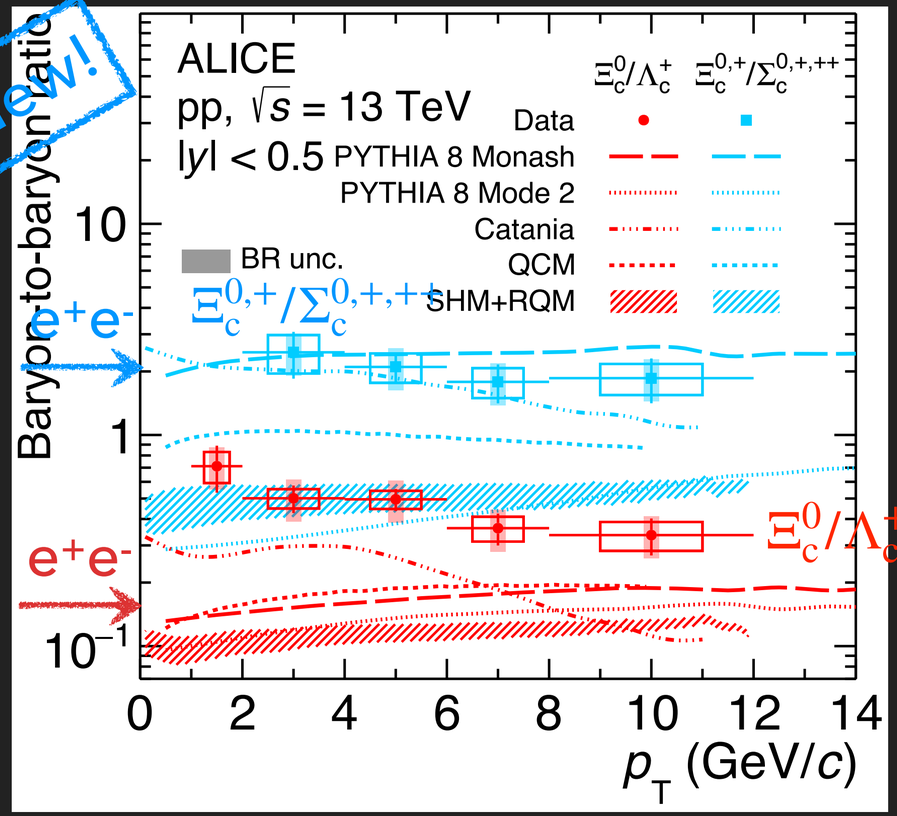
PYTHIA 8
[Comput. Phys. Commun. 178 (2008) 852]
PYTHIA 8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA 8 Mode2
[JHEP 08 (2015) 003]

Λ_c^+/D^0 vs. multiplicity in pp, p–Pb and Pb–Pb collisions

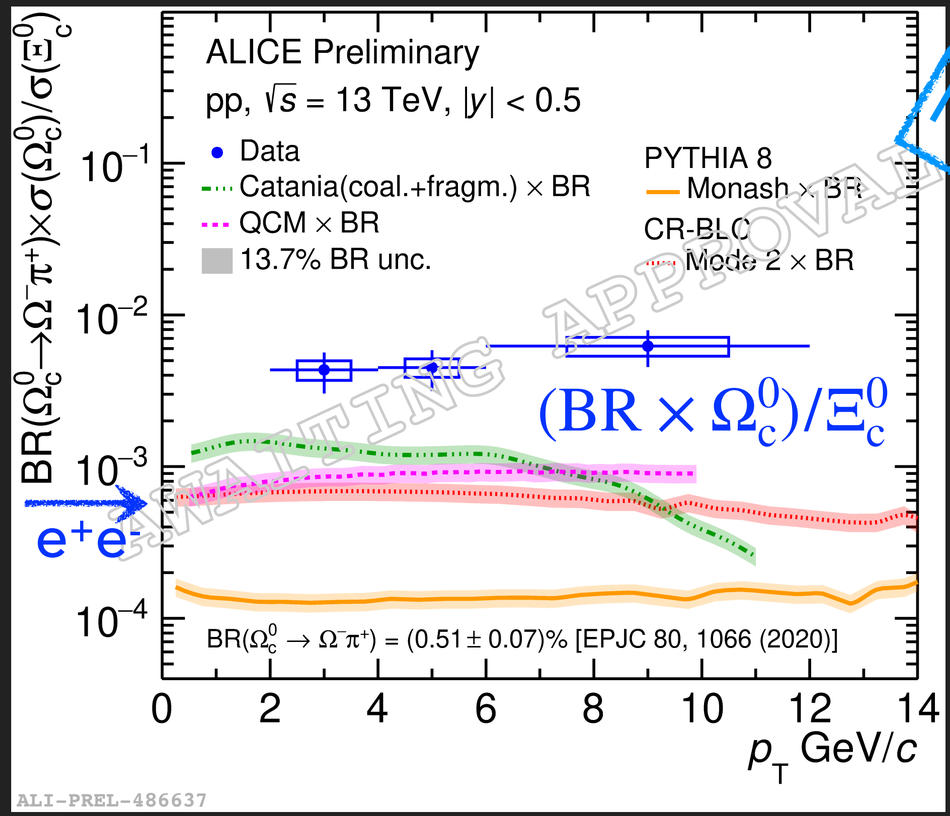


- At intermediate p_T, Λ_c^+/D^0 increases smoothly from low multiplicity pp to Pb-Pb
  - Low multiplicity pp > e^+e^-
  - High multiplicity pp ~ Pb-Pb

Charm baryon-to-baryon in pp@13 TeV with models (II)



Belle
[Phys. Rev. D 97, 072005 (2018)]



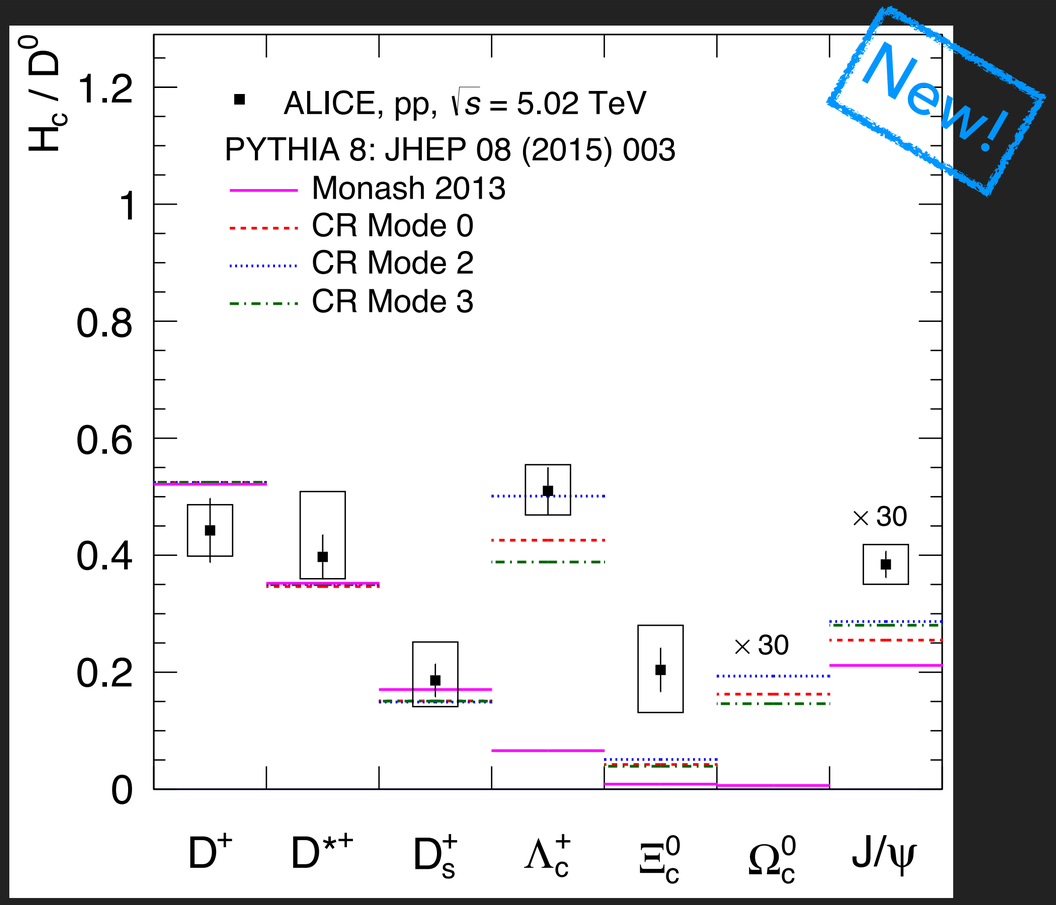
- Ξ_c^0/Λ_c^+ : ALICE/Belle ≈ 0.59/0.17 ≈ 3.5
- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$: ALICE/Belle ≈ 2.28/2.08 ≈ 1.1
- $(BR \times \Omega_c^0)/\Xi_c^0$: ALICE/Belle ≈ 0.0043/0.00058 ≈ 7.4

PYTHIA 8 Monash underestimates $(BR \times \Omega_c^0)/\Xi_c^0$ in pp@13 TeV

pp@13 TeV vs. e^+e^-@10.52 GeV :

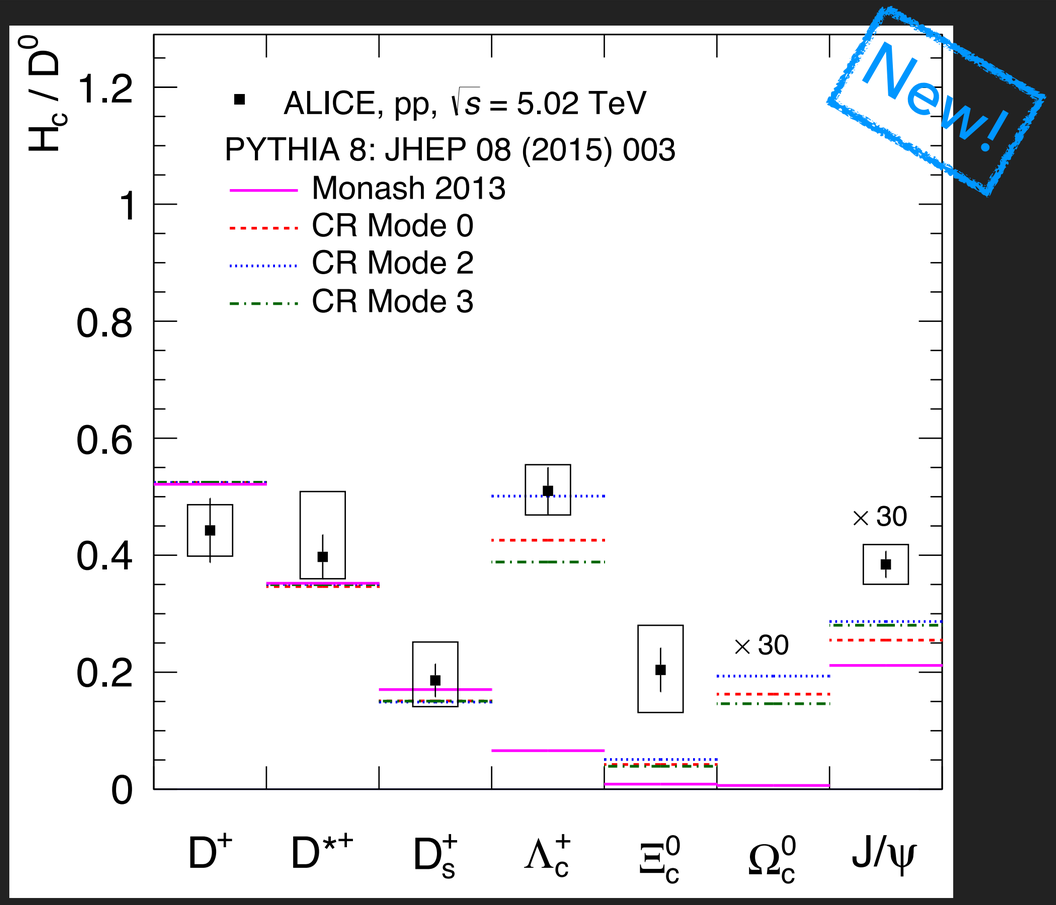
- Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$
- Further enhancement for Ω_c^0

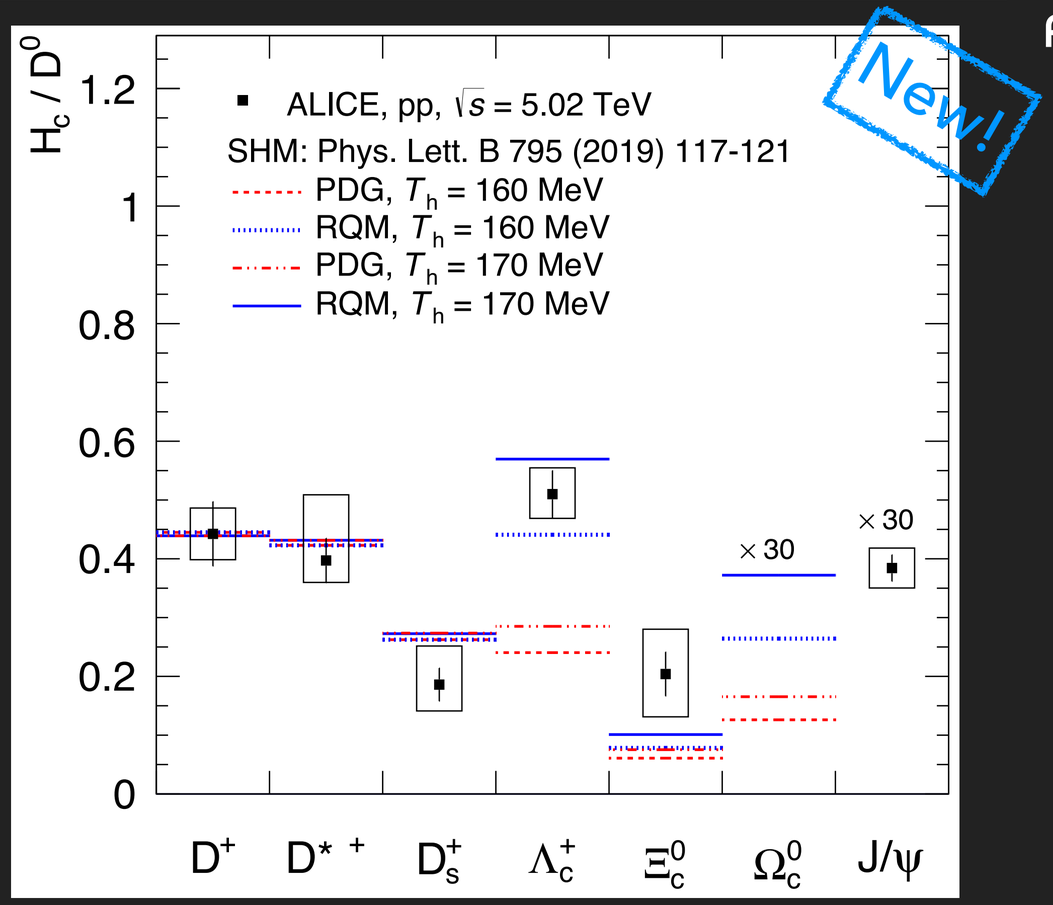
Integrated production vs. D^0 in pp@5.02 TeV



- PYTHIA 8 with different tunes similar for D mesons and describe measurements within uncertainties
- Large effect found in PYTHIA 8 CR-BLC for charm baryons formation
  - Only describe Λ_c^+
  - Underestimate Ξ_c^0 and Ω_c^0

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





- 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 for Ξ_c^0