Charm production and hadronisation in ALICE

B. Volkel
(on behalf of the ALICE collaboration)

19th International Conference on Hadron Spectroscopy and Structure
Mexico City (remote)
26 July 2021

Factorisation theorem

$$\mathrm{d}\sigma_{\mathrm{pp}\rightarrow\mathrm{h_c}+\mathrm{X}}(\sqrt{\mathrm{s}}) = \sum_{\mathrm{a,b}} \mathrm{d}x_1\mathrm{d}x_2 \cdot f_{\mathrm{a}}(x_1,\mu_{\mathrm{f}}) f_{\mathrm{b}}(x_2,\mu_{\mathrm{f}}) \cdot \hat{\sigma}_{\mathrm{a+b}\rightarrow\mathrm{c}+\hat{\mathrm{X}}}(x_1,x_2,\sqrt{\mathrm{s}},\mu_{\mathrm{r}},\mu_{\mathrm{f}}) \cdot D_{\mathrm{c}\rightarrow\mathrm{h_c}}(x_{\mathrm{c}},\mu_{\mathrm{f}})$$

Inclusive production of hadron h_c in proton-proton collisions at a centre-of-mass energy $\sqrt{s}$

Parton distribution functions (non-pert.)

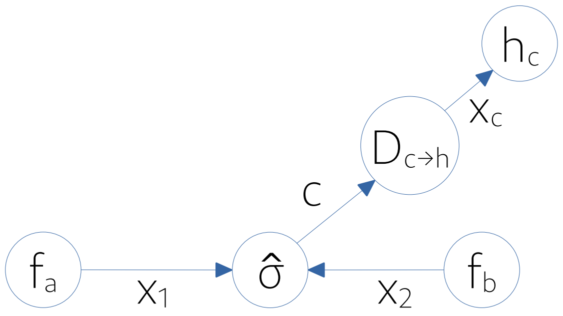
Probability to find parton a/b with energy fraction x_i in proton i

Partonic cross section (pert.)

Cross section of inclusive production of parton c

Fragmentation fraction (non. pert)

Probability that parton c fragments into hadron h_c carrying x_c of the parton's energy



Factorisation theorem

$$d\sigma_{\mathrm{pp}\to\mathrm{h_c}+\mathrm{X}}(\sqrt{\mathrm{s}}) = \sum_{\mathrm{a,b}} dx_1 dx_2 \cdot f_\mathrm{a}(x_1,\mu_\mathrm{f}) f_\mathrm{b}(x_2,\mu_\mathrm{f}) \cdot \hat{\sigma}_{\mathrm{a+b}\to\mathrm{c}+\hat{\mathrm{X}}}(x_1,x_2,\sqrt{\mathrm{s}},\mu_\mathrm{r},\mu_\mathrm{f}) \cdot D_{\mathrm{c}\to\mathrm{h_c}}(x_\mathrm{c},\mu_\mathrm{f})$$

Inclusive production of hadron h_c in proton-proton collisions at a centre-of-mass energy $\sqrt{s}$

Parton distribution functions (non-pert.)

Probability to find parton a/b with energy fraction x_i in proton i

Partonic cross section (pert.)

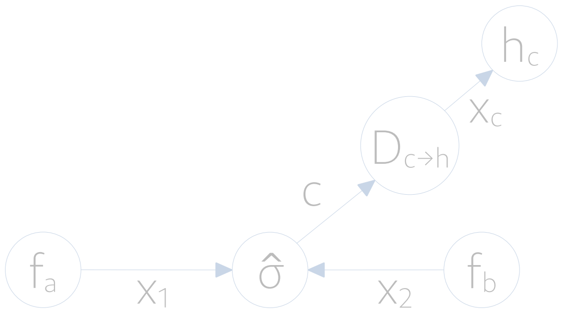
Cross section of inclusive production of parton c

Fragmentation fraction (non. pert)

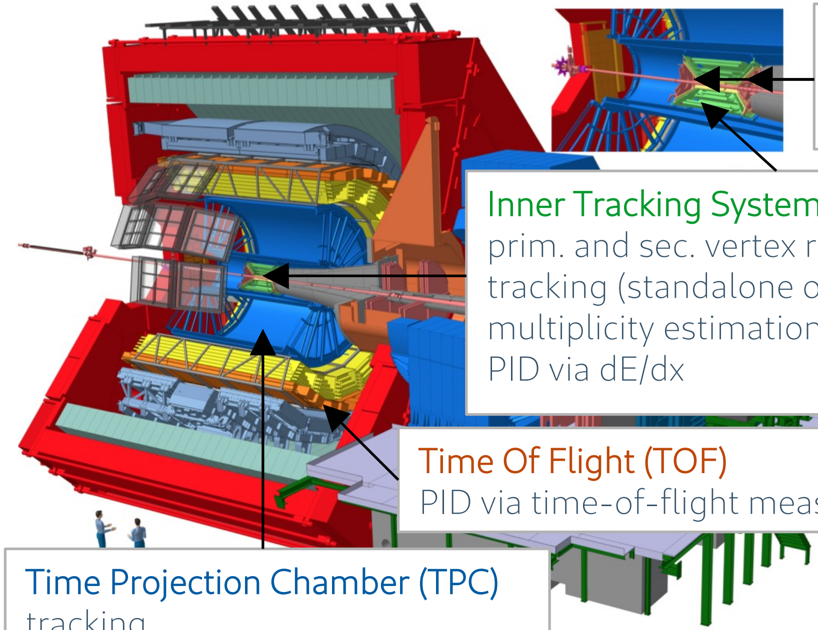
Probability that parton c fragments into hadron h_c carrying x_c of the parton's energy

Interest in hadron production and hadronisation mechanisms?!

- Charm quarks predominantly produced in hard interaction (in pp as well as in AA)
  → abundance directly reflected by abundance of charm hadrons
  → unique probes to study hadron production and hadronisation mechanisms
- Test and enhance understanding of QCD as a whole
- Are hadronisation mechanisms universal across collision systems?



ALICE detector and charm baryon reconstruction

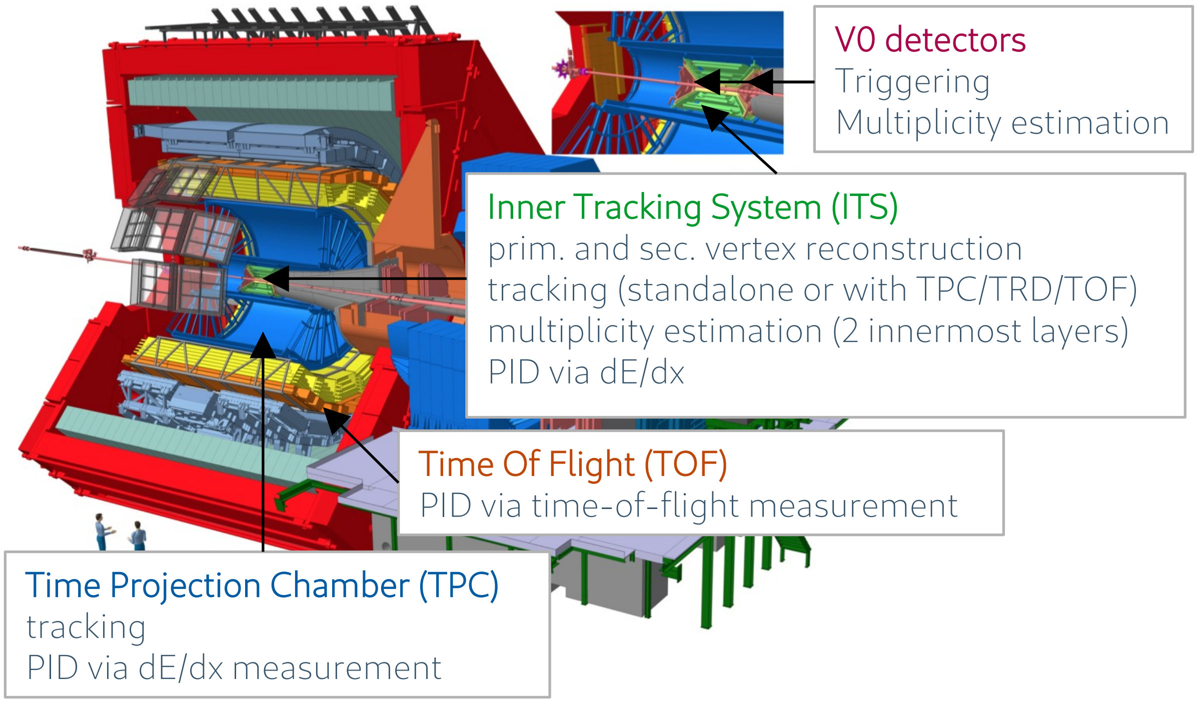


Charm baryons decay close to the interaction vertex

→ reconstruct charm baryons from their 2 or 3 tracks in central barrel, $|\eta| < 0.8$

→ suppress background contamination via decay topology and PID criteria

ALICE detector and charm baryon reconstruction



Charm baryons decay close to the interaction vertex

→ reconstruct charm baryons from their 2 or 3 tracks in central barrel, $|\eta| < 0.8$

→ suppress background contamination via decay topology and PID criteria

particles under study

baryon	m_{inv} [GeV/c^2]	$c\tau$ [μm]	decay (BR [%])
Λ_c^+	≈ 2.286	≈ 60	$pK^-\pi^+$ (6.28), $pK^0_S \to p\pi^+\pi^-$ (1.1)
$\Sigma_c^{0,++}$	≈ 2.454	-	$\Lambda_c^+\pi^{-,+}$ (≈ 100) (7.39 with only above Λ_c^+ decay channels)
Ξ_c^0	≈ 2.468	≈ 136	$\Xi^- e^+ \nu_e$ (1.8), $\Xi^-\pi^+$ (1.43)
Ξ_c^+	≈ 2.470	≈ 46	$\Xi^- 2\pi^+$ (2.86)
Ω_c^0	≈ 2.695	≈ 80	$\Omega^-\pi^+$ (0.51) (from theoretical calculations)

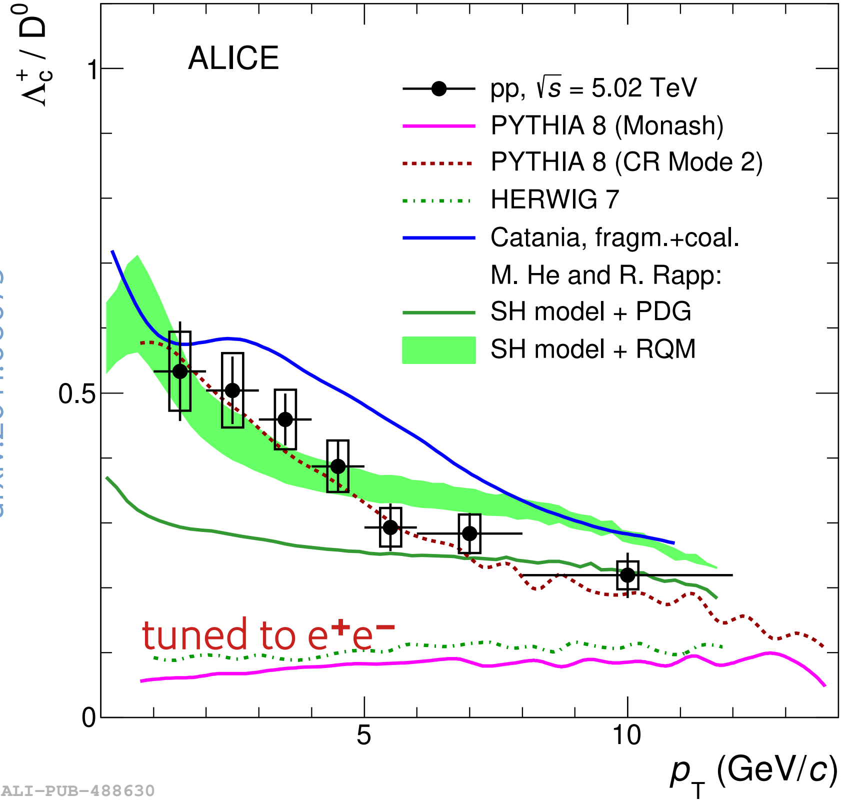
Particle Data Group (2020)

EPJC 80 (2020) 11, 1066

data samples

system	$\sqrt{s}$ [TeV]	N_{ev}	$\mathcal{L}_{\text{int}}$	baryon
pp	5.02	10^9	19.5 nb^{-1}	Λ_c^+, Ξ_c^0
pp	13	$1.9 \cdot 10^9$	32 nb^{-1}	Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0
p-Pb	5.02	$6 \cdot 10^8$	287 μb^{-1}	Λ_c^+

Λ^+_c measurements in pp and p-Pb



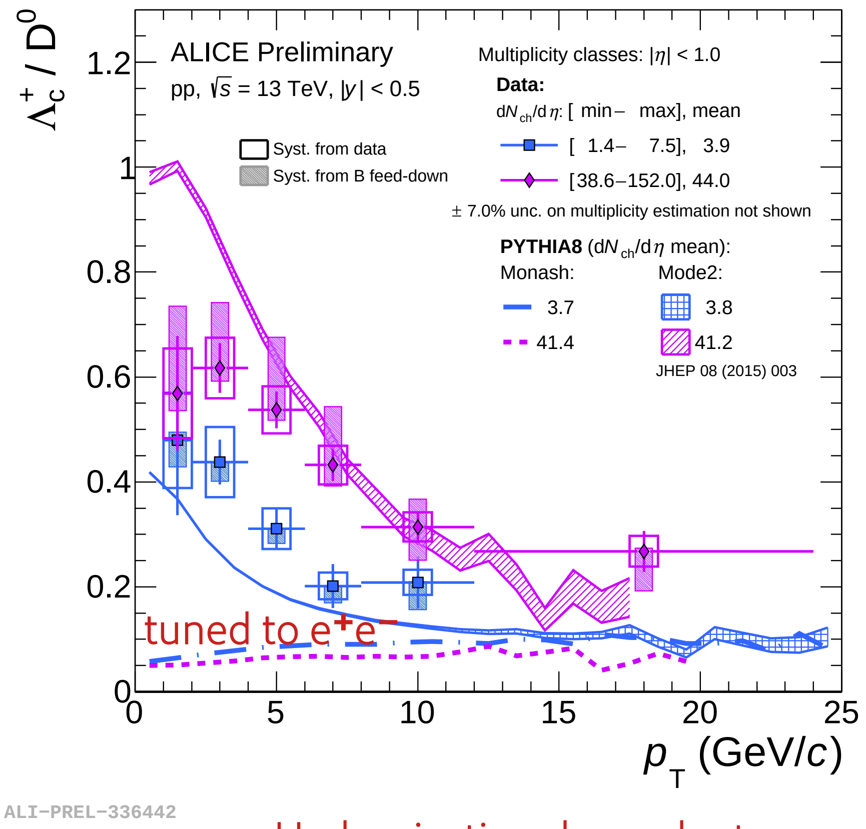
arxiv:2011.06079

ALI-PUB-488630

Suggesting that (charm) hadronisation is not universal across collision systems

- Pythia8 (Monash) and HERWIG7
  hadronisation tuned to results obtained in e^+e^-
  underestimates the data and does not reproduce the shape
- SHM(PDG)
  hadronisation effectively described via statistical approach
  develops shape but underestimates the data at low and intermediate p_T
- Catania
  fragmentation + partonic coalescence
  compatible order of magnitude,
  slightly overestimating the data
- SHM(RQM)
  augmented with excited baryon states from Relativistic Quark Model
  in agreement with data
- Pythia8 (CR Mode2)
  colour reconnection beyond leading colour
  in agreement with data

Λ^+_c measurements in pp and p-Pb (contd.)

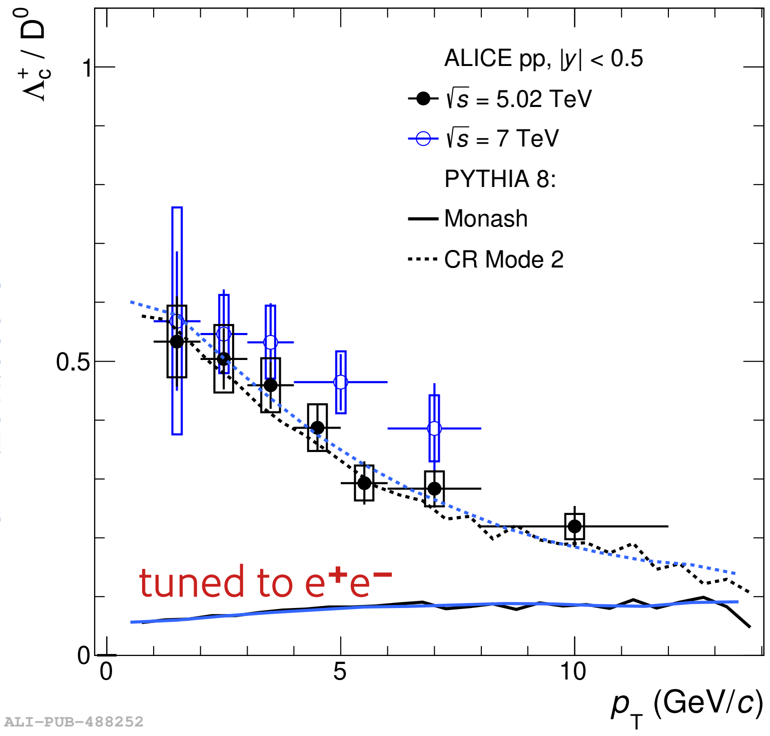


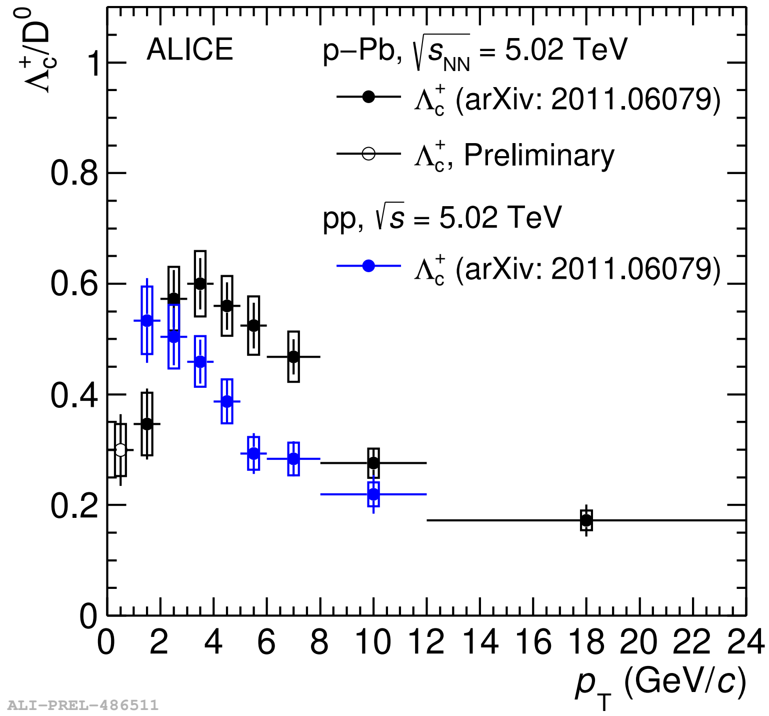
- As of now, multiple differential measurements, also in intervals of multiplicity (here two are shown, highest and lowest)
- Deviation of e^+e^--tuned prediction increases with multiplicity
- Pythia8 with CR Mode2 better approaches the measurements in both cases
- Data in the low multiplicity interval at lower p_T is still significantly above Pythia8 (Monash)

Hadronisation dependent on multiplicity and somewhat complexity of the system?
Peculiarity/impact of hadronisation mechanisms enhancing with multiplicity? Radial flow effects?

Λ^+_c measurements in pp and p-Pb (contd.)

arxiv:2011.06079

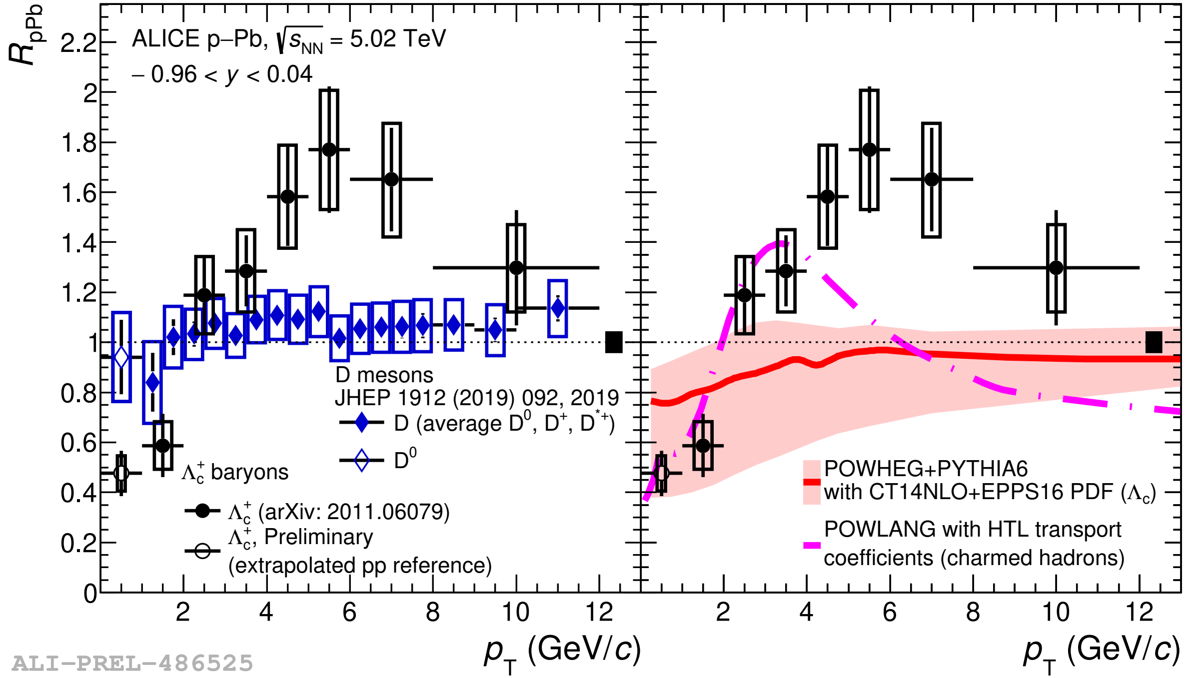




- Within uncertainties compatible ratio at 5.02 TeV and 7 TeV in pp

- p-Pb data has potentially larger shift in p_T
- First measurement of Λ^+_c in pp down to p_T=0

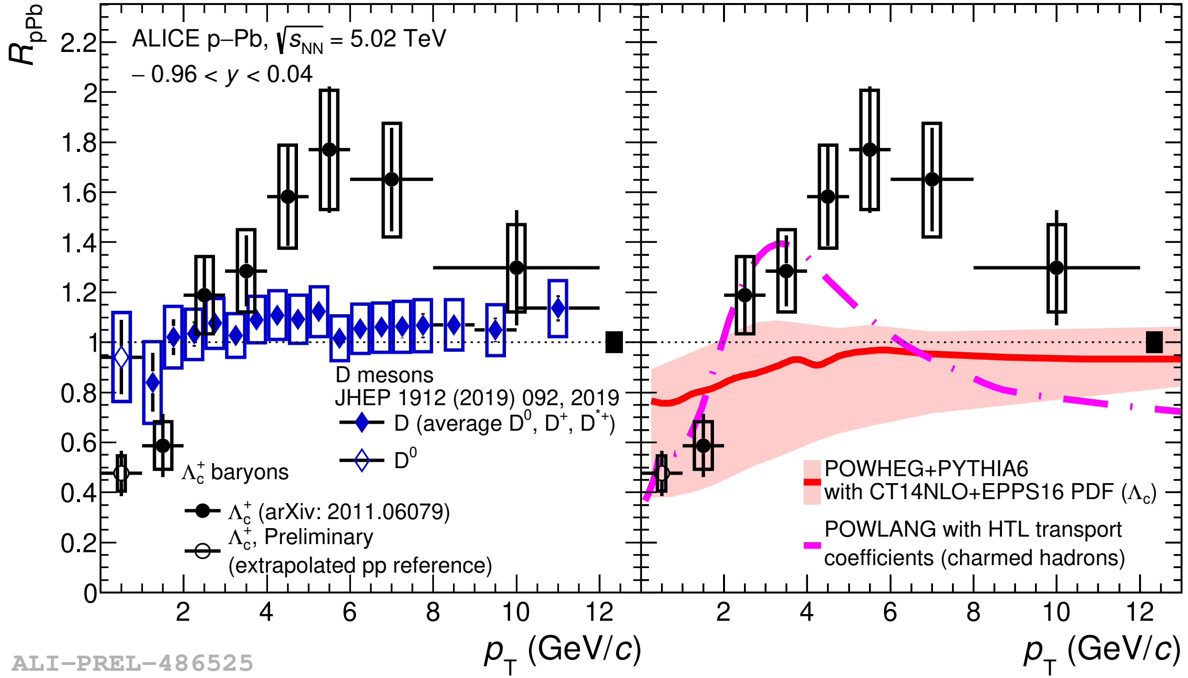
Λ^+_c measurements in pp and p-Pb (contd.)

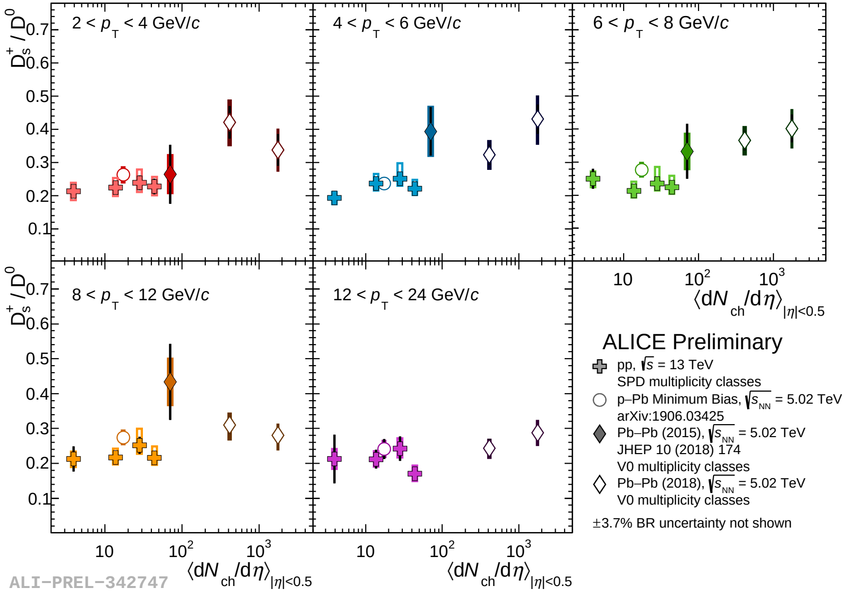


- POWHEG+Pythia6 with Cold Nuclear Matter effects underestimates the data for $p_T > 4$ GeV/c
- POWLANG (QGP in small systems) exhibits similar shape at lower p_T but underestimates the data at higher momenta

- D-meson R_{pPb} compatible with unity
- Λ^+_c suppressed at low p_T and enhanced at higher p_T in p-Pb compared to pp
  → due to increasing multiplicity?
  → flow effects?

Λ^+_c measurements in pp and p-Pb (contd.)



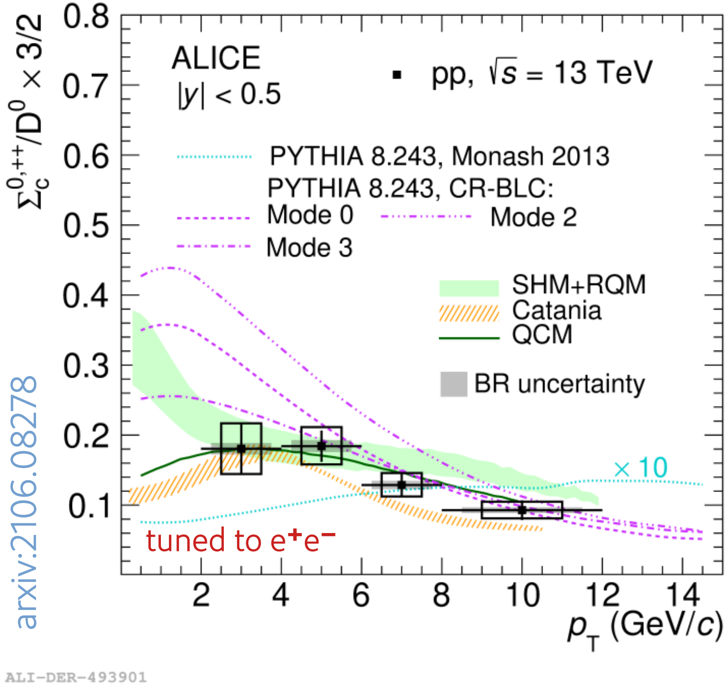


- D-meson R_{pPb} compatible with unity
- Λ^+_c suppressed at low p_T and enhanced at higher p_T in p-Pb compared to pp
  → due to increasing multiplicity?
  → flow effects?

- D-meson ratios compatible within uncertainties comparing pp, p-Pb and Pb-Pb systems

Production measurements of $\Sigma_c^{0,++}$ (first time in hadronic collisions!)

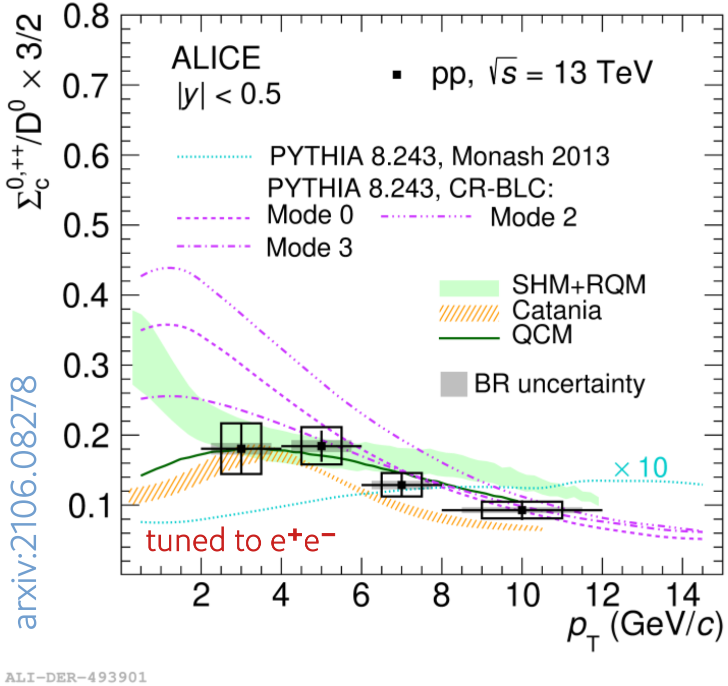
- Similar observation as in the case of Λ^+_c/D^0
  → Pythia8 (Monash) significantly underestimates the data
- p_T shape of the ratio less pronounced compared to Λ^+_c/D^0
- Pythia (CR-BLC) develops shape and approaches the data at medium and larger p_T
- Good approximation by SHM (RQM) and Catania predictions as well as by coalescence model QCM



Again: Suggesting non-universal hadronisation

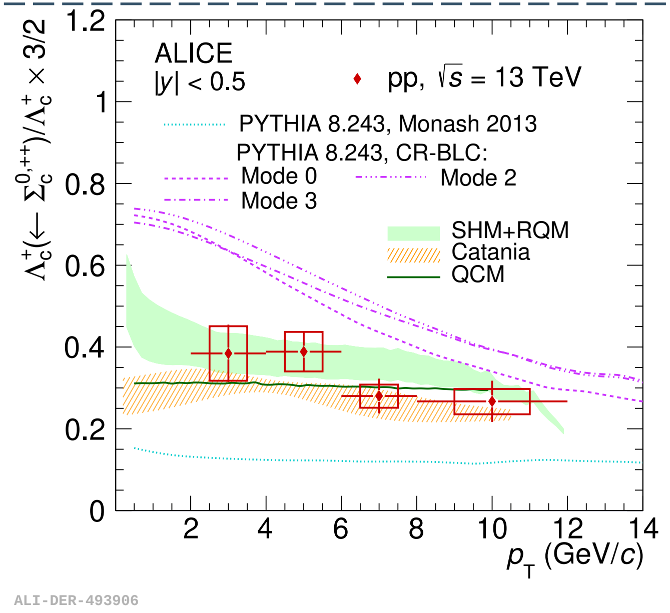
Production measurements of $\Sigma_c^{0,++}$ (first time in hadronic collisions!)

- Similar observation as in the case of Λ^+_c/D^0
  → Pythia8 (Monash) significantly underestimates the data
- p_T shape of the ratio less pronounced compared to Λ^+_c/D^0
- Pythia (CR-BLC) develops shape and approaches the data at medium and larger p_T
- Good approximation by SHM (RQM) and Catania predictions as well as by coalescence model QCM



arxiv:2106.08278

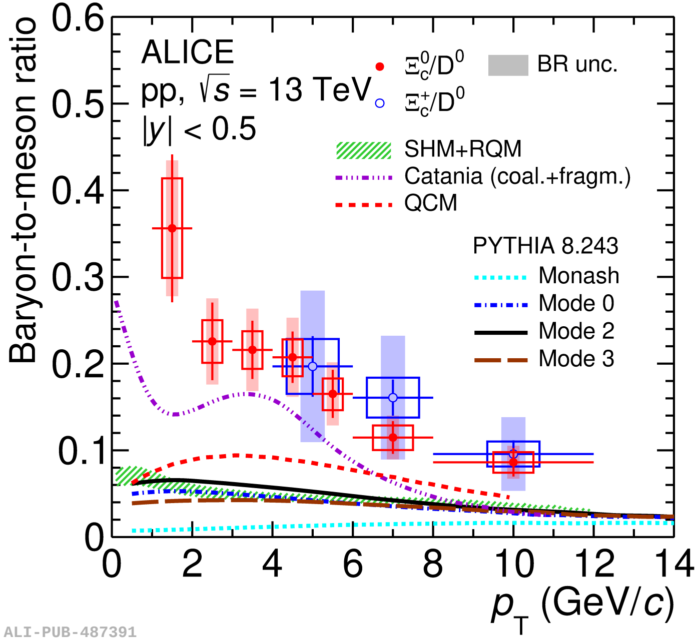
Again: Suggesting non-universal hadronisation



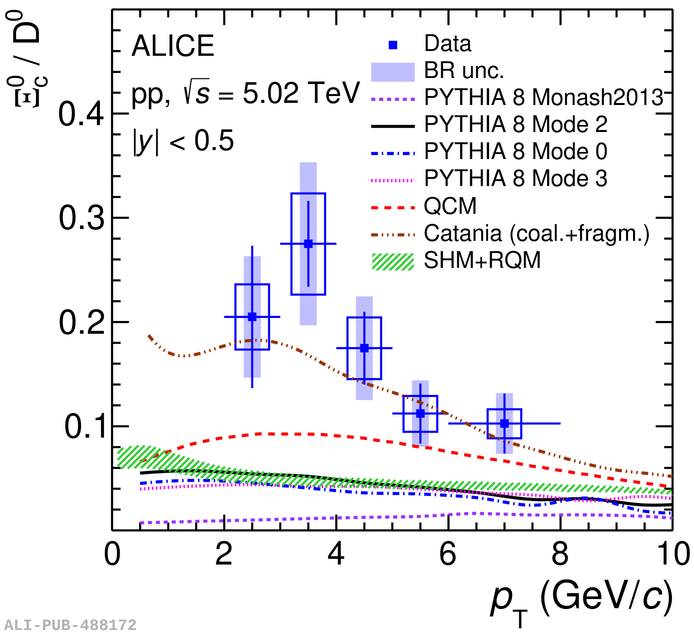
Substantial Λ^+_c feed-down fraction could contribute to increased Λ^+_c/D^0 ratio

NEW production measurements of Ξ^{+}_{c} and Ξ^{0}_{c}

arxiv:2105.05187



arxiv:2105.05616

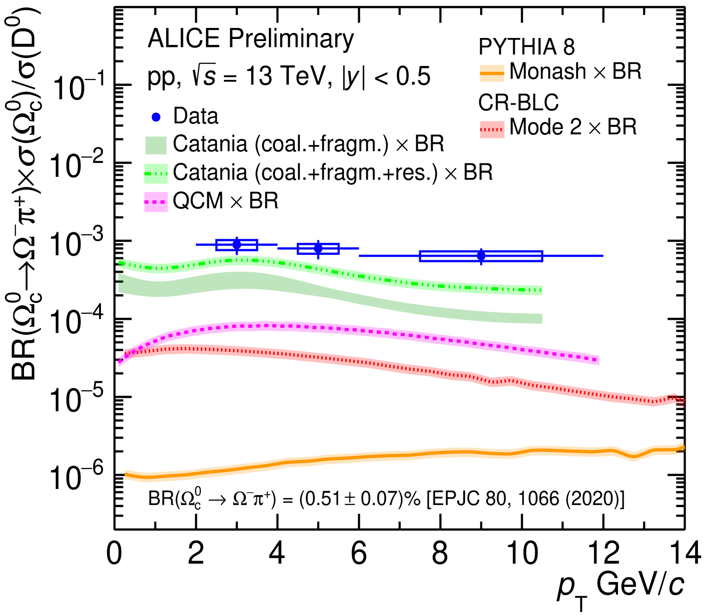


- p_T shape of ratios similar in shape compared to Λ^{+}_{c}/D^{0}
- This time, also colour reconnection is not capable of describing the data

Again: Suggesting non-universal hadronisation

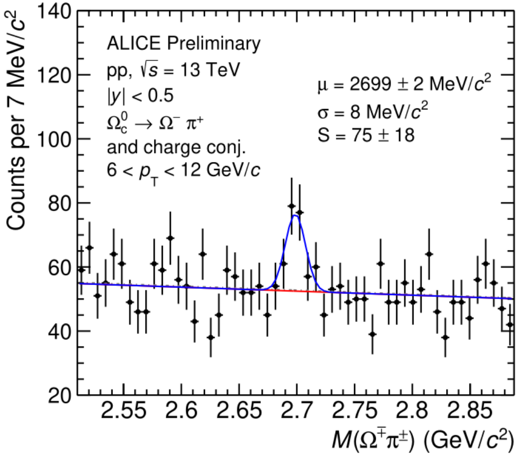
- All predictions **but Catania** underpredict the data, in particular significantly at low p_T
- Compatible ratios measured for Ξ^{+}_{c}/D^{0} and Ξ^{0}_{c}/D^{0} as measured at 13 TeV

Production measurements of Ω^0_c **(first time in hadronic collisions!)**



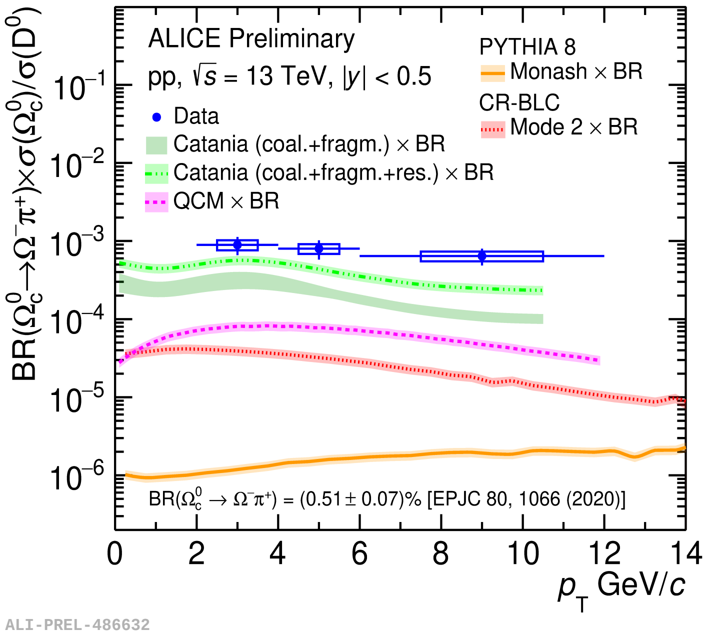
Theoretical prediction of BR($\Omega^0_c \rightarrow \Omega^- \pi^+$):
EPJC 80 (2020) 11, 1066

Again: Suggesting non-universal hadronisation



- Measured baryon-to-meson ratio flat within uncertainties
- All predictions but Catania underpredict the Ω^0_c/D^0 ratio

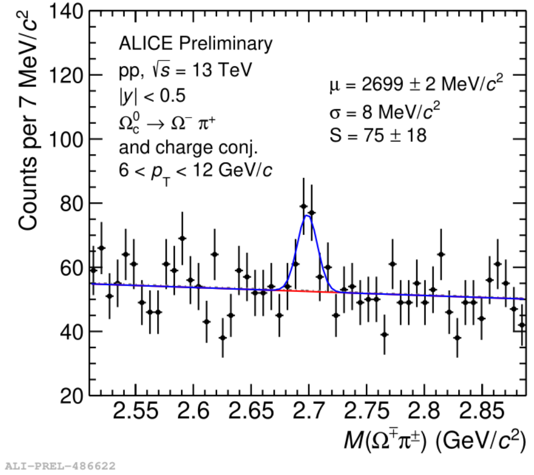
Production measurements of Ω^0_c (first time in hadronic collisions!)

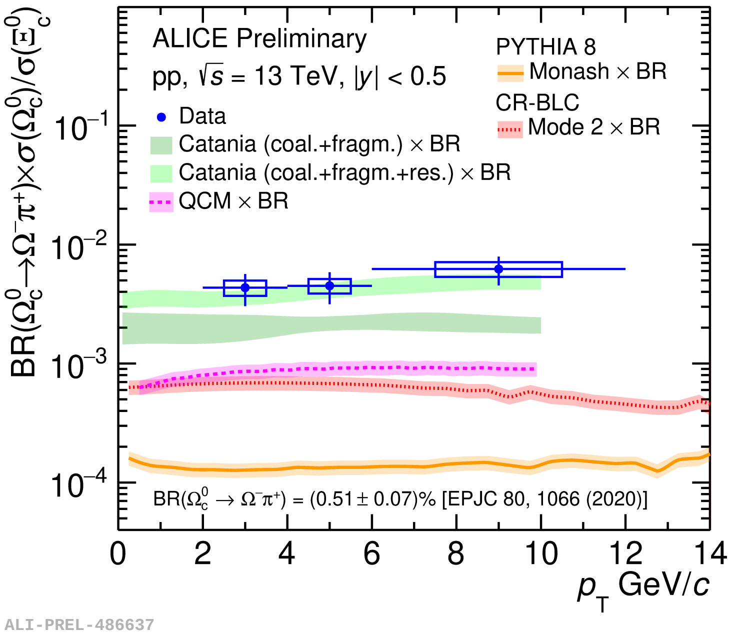


- Measured baryon-to-meson ratio flat within uncertainties
- All predictions but Catania underpredict the Ω^0_c/D^0 ratio

Theoretical prediction of $BR(\Omega^0_c \to \Omega^- \pi^+)$: EPJC 80 (2020) 11, 1066

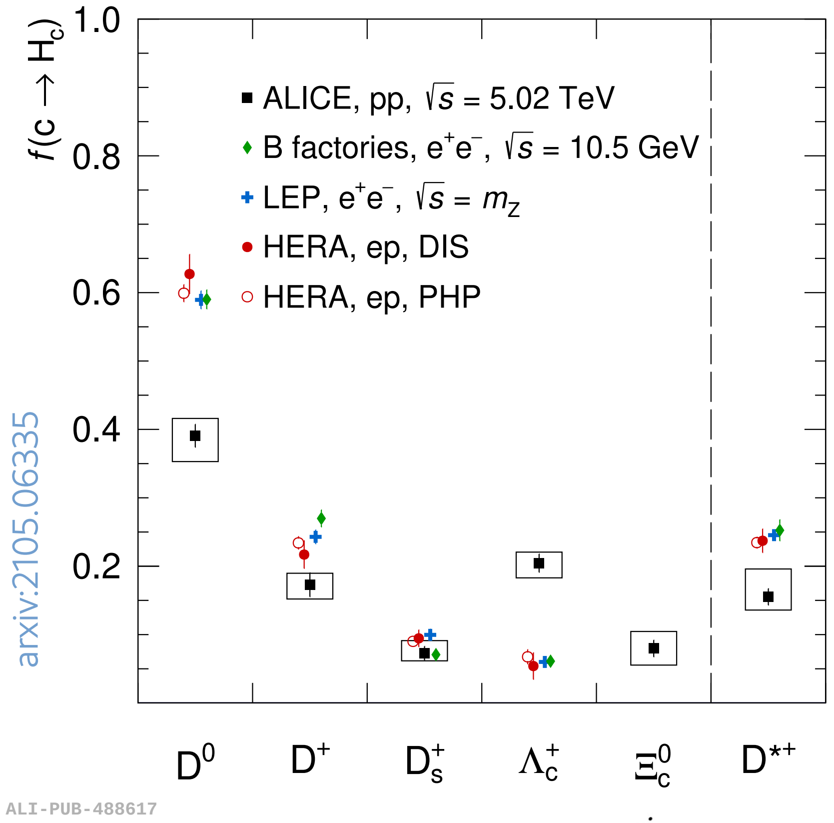
Again: Suggesting non-universal hadronisation





- Baryon-to-baryon ratio
- Measured ratio flat within uncertainties
- All predictions but Catania undershoot the Ω^0_c/Ξ^0_c ratio

Charm fragmentation fractions (FF)

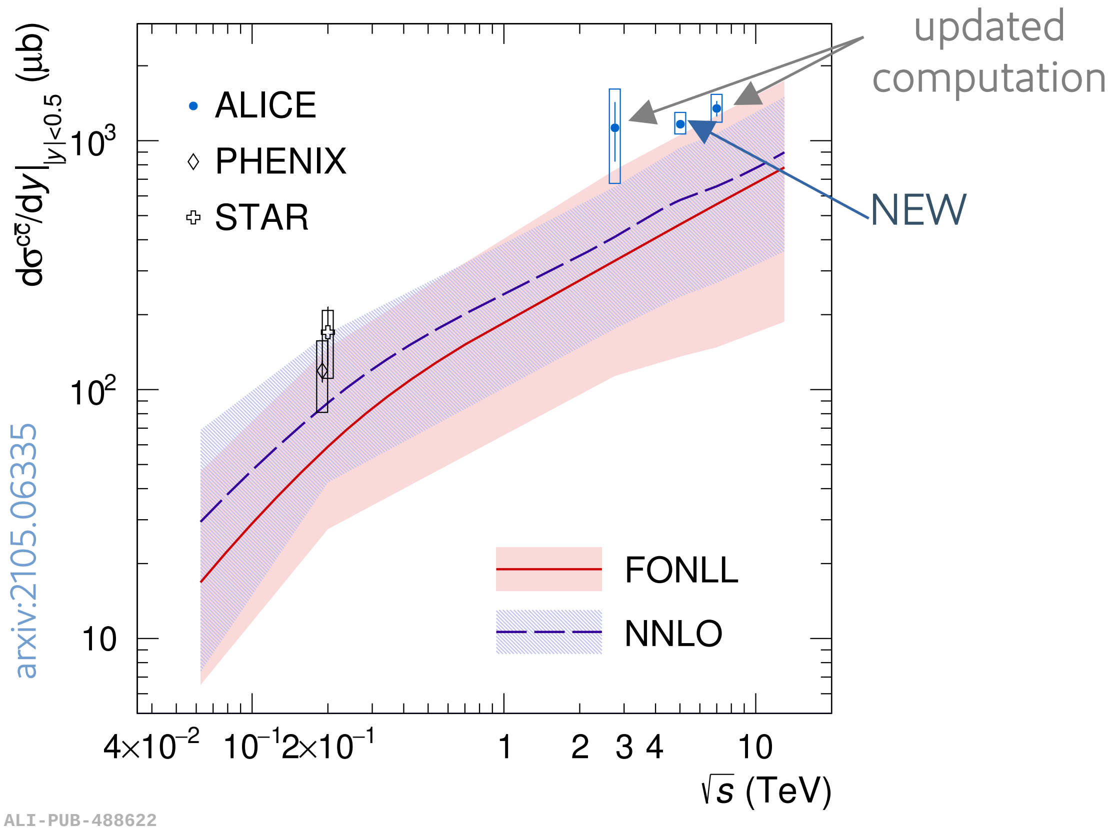


$$f(c \rightarrow h_c^j) = \frac{\sigma(h_c^j)}{\sum_i \sigma(h_c^i)}$$

- First time accounting for charmed baryons in hadronic collisions (all in $|y| < 0.5$)
  → Ξ^0_c contribution sizeable
  → Λ^+_c significantly differs from measurements in smaller systems
  → decrease of D^0 FF due to measurements of Λ^+_c/D^0 ratio
- D^{*+} feeds into D^0 and D^+

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	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

New and updated charm cross section measurements



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

- Use production cross sections of D^0, D^+, D^+_s, Λ^+_c, Ξ^0_c
- **First time accounting for charmed baryons in hadronic collisions**
- Recomputed cross sections (at 2.76 and 7 TeV) **increase by 40%** due to measurement of charm baryon-to-meson ratios
- Measurements on upper edge of predictions (still compatible within uncertainties)

- Account for Ξ^+_c by scaling Ξ^0_c by factor of 2
- Add asymmetric errors to account for possible sizeable contribution of Ω^0_c

Conclusions

- First measurements of production of $\Sigma_c^{0,++}$ and Ω^0_c in hadronic collisions
- First time taking charmed baryons (Λ^+_c and Ξ^0_c) into account for charm cross section calculation
- New and updated measurements of charm cross section and production measurement

Conclusions

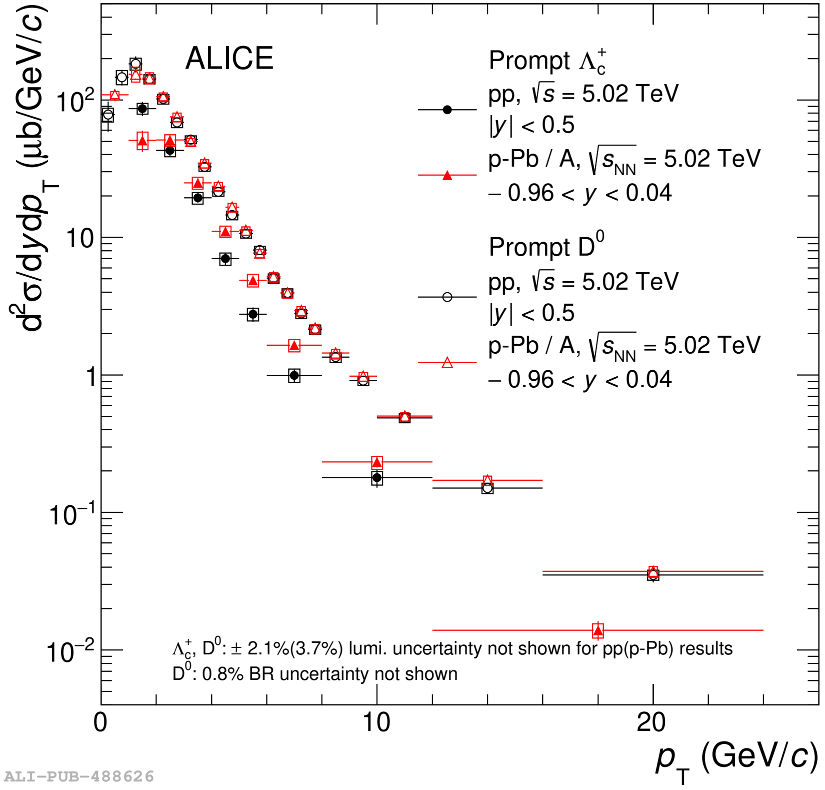
- First measurements of production of $\Sigma_c^{0,++}$ and Ω^0_c in hadronic collisions
- First time taking charmed baryons (Λ^+_c and Ξ^0_c) into account for charm cross section calculation
- New and updated measurements of charm cross section and production measurement
- Non-universality of charm-baryon hadronisation
  → Significant different fragmentation fractions measured in pp collisions at $\sqrt{s}$ = 5.02 TeV wrt. measurements at e^+e^- and e^-p colliders
- Different model predictions
  - Pythia8 (CR-BLC) well describes Λ^+_c/D^0 ratio but fails to describe $\Xi_c^{0,+}/D^0$, Ω^0_c/D^0 and Ω^0_c/Ξ^0_c
  - SHM(RQM) yields overall good approximations but fails to describe $\Xi_c^{0,+}/D^0$
  - Catania (coalescence + fragmentation) is as of now able to describe ratios best across different baryons
- Future measurements down to $p_T = 0$ might show actual enhancement or could for instance reveal flow-like behaviour in pp collisions

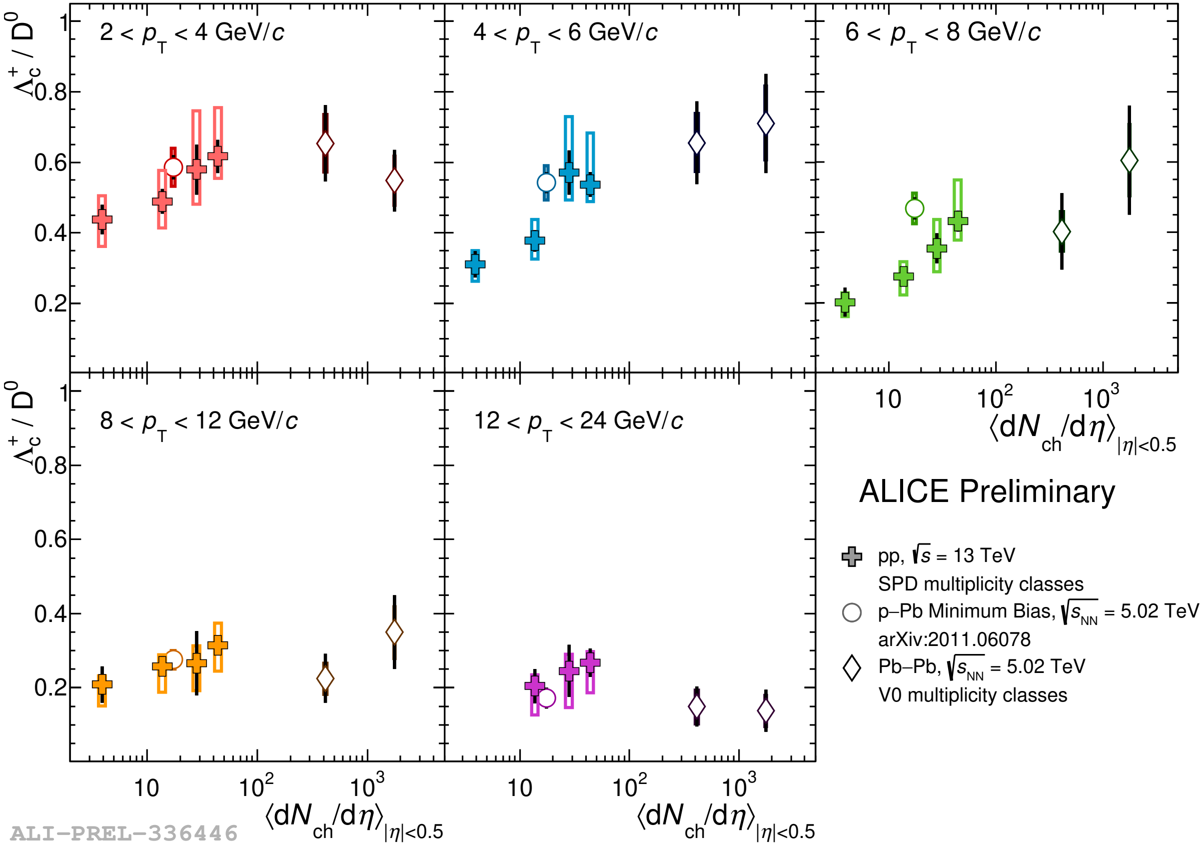
BACKUP

Model predictions

- Pythia8: Comput. Phys. Commun. 178 (2008) 852-867
- Pythia8 (Monash): EPJC 74 (2014) 8, 3024
- Pythia8 (CR-BLC): JHEP 1508 (2015) 003
- Catania: arxiv:2012.12001
- QCM: EPJC 78 (2018) 4, 344
- SHM (RQM): PLB 795 (2019) 117-121
- POWHEG+Pythia6 (CNM): JHEP 03 (2016) 123,
- POWLANG: JHEP 09 (2007) 126, EPJC 77 (2017) 3, 163
- ...

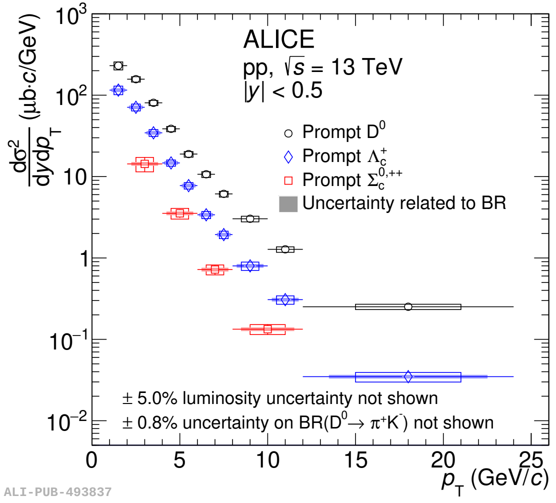
Complementary material Λ^{+}_{c}

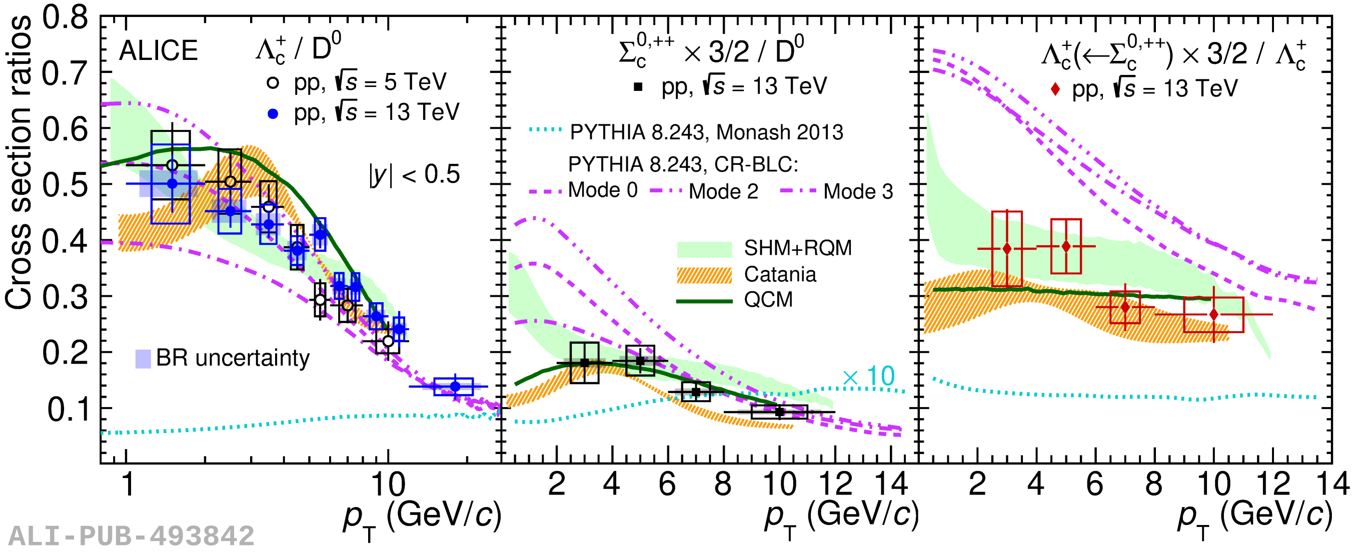




Complementary material $\Sigma_c^{0,++}$

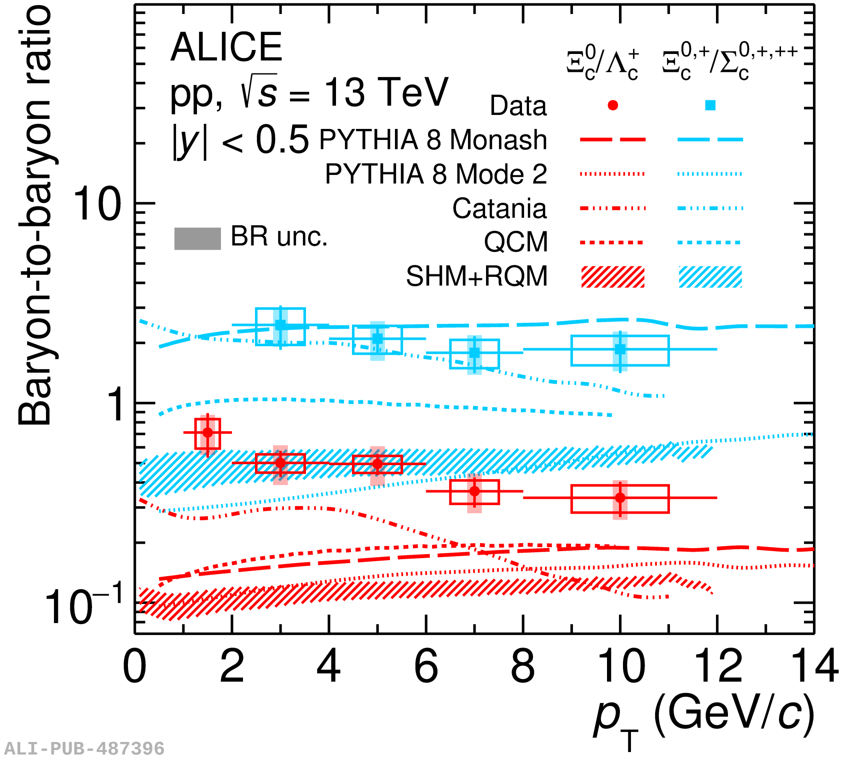
arxiv:2106.08278



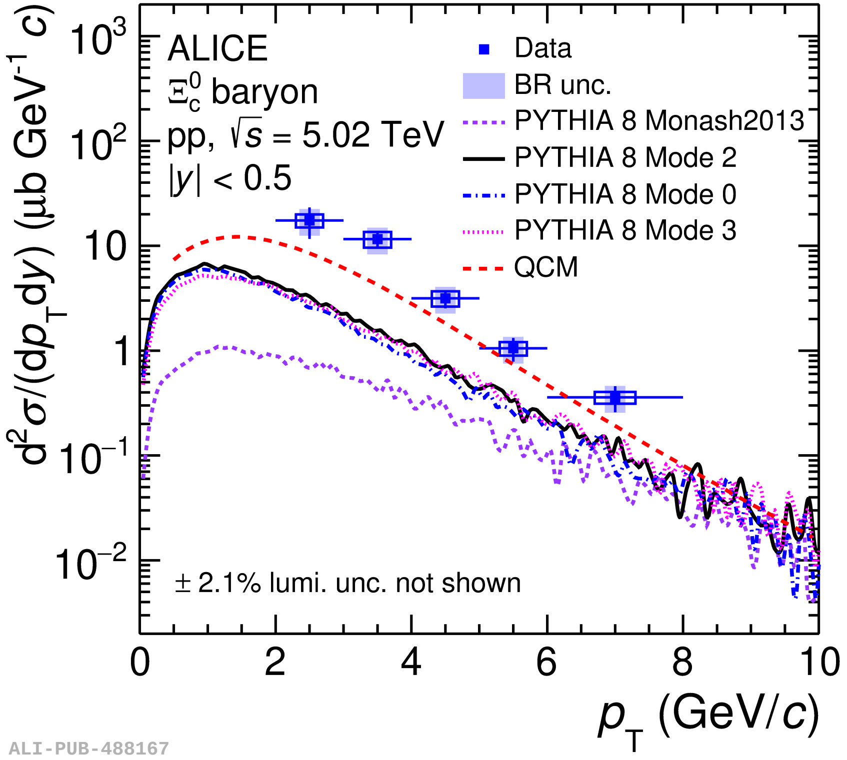


Complementary material $\Xi_c^{0,+}$

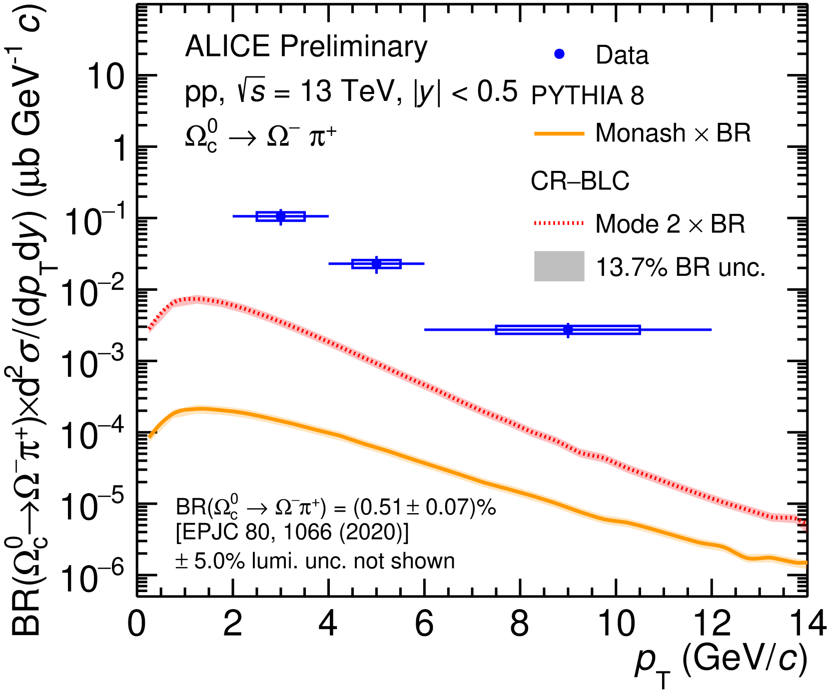
arxiv:2105.05187



arxiv:2105.05616

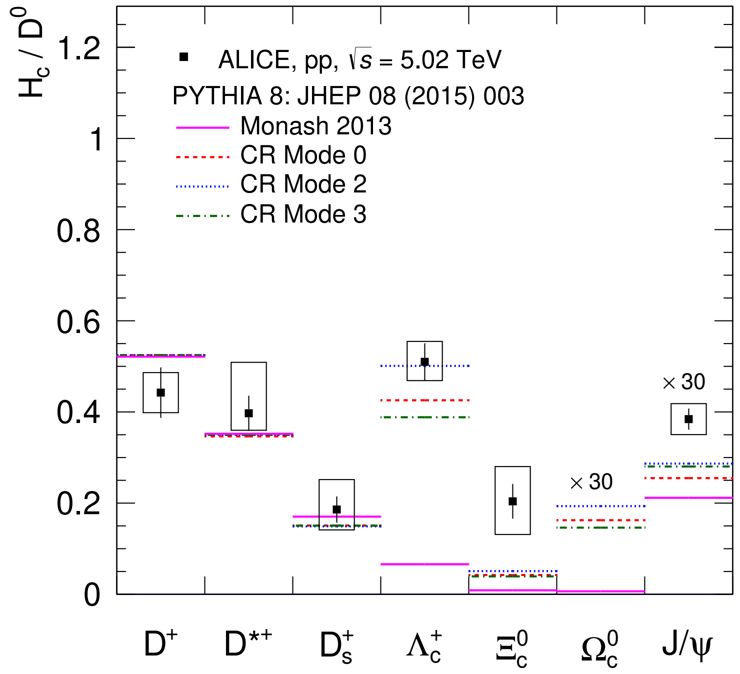


Complementary material Ω^0_c

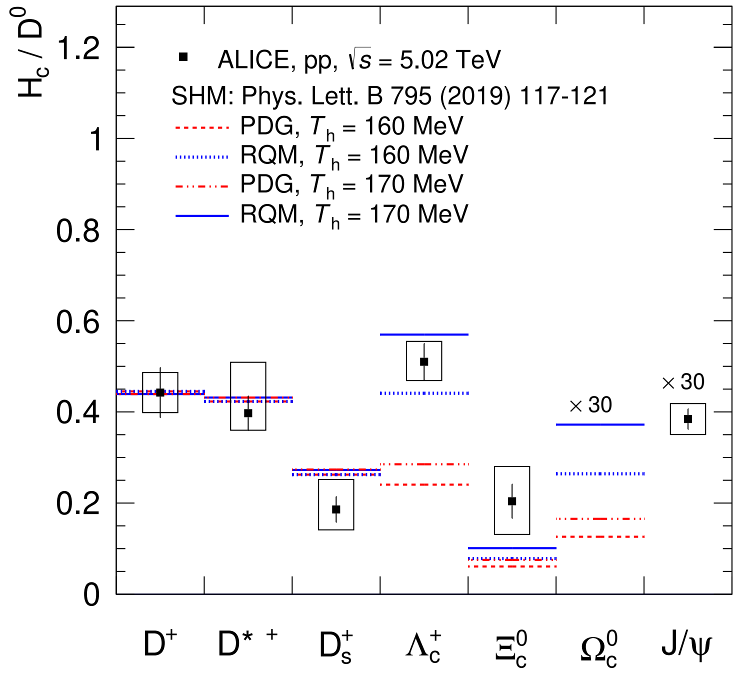


ALI-PREL-486627

Complementary material fragmentation functions



ALI-PUB-488607



ALI-PUB-488612

- Comparison to Pythia8 CR-BLC and SHM

Complementary material charm cross section

- Theory comparisons
  - FONLL: JHEP 05 (1998) 007, JHEP 03 (2001) 006, JHEP 10 (2012) 137
  - NNLO: PRL 118 (2017) 12, 122001, EPJC 78 (2018) 5, 359, PRL 110 (2013) 252004
-