ALICE charm fragmentation measurements in pp collisions at the LHC

ECFA WHF WG1

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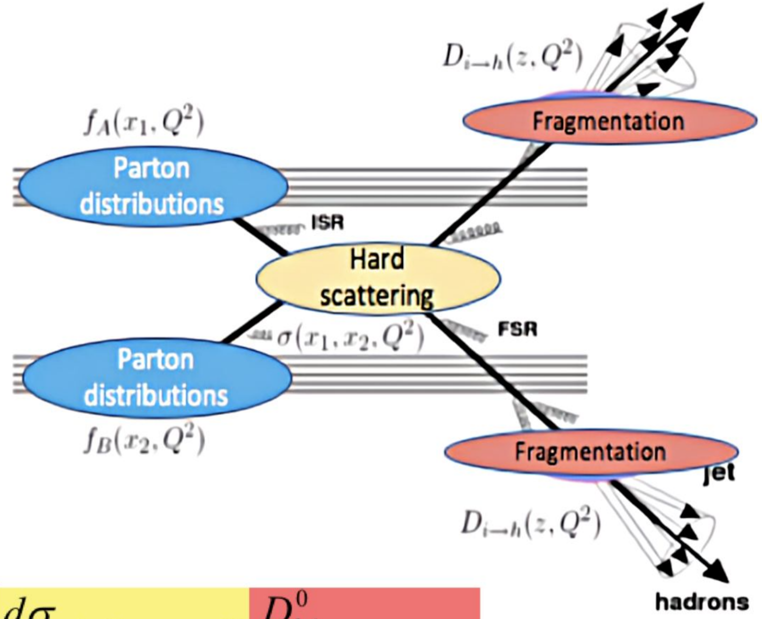
The factorization approach

Hard scattering:

- large quark mass provides hard scale
- pQCD can calculate cross sections down to low p_T



PDF → from ep collisions

FF → from e^+e^- collisions

$$\frac{d\sigma^h_{pp}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2)\frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{D^0_{h/c}}{\pi z_c}$$

Factorization of QCD holds if the non-perturbative part can be *"captured"* in universal PDF and FF

- generally assumed that the fragmentation functions are universal

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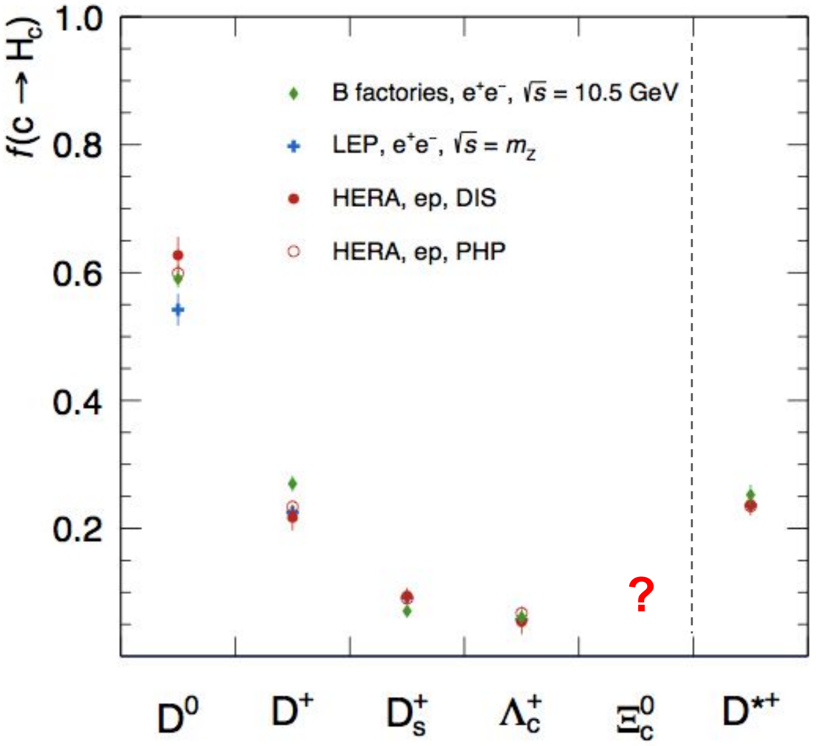
Results in e^+e^- and ep collisions



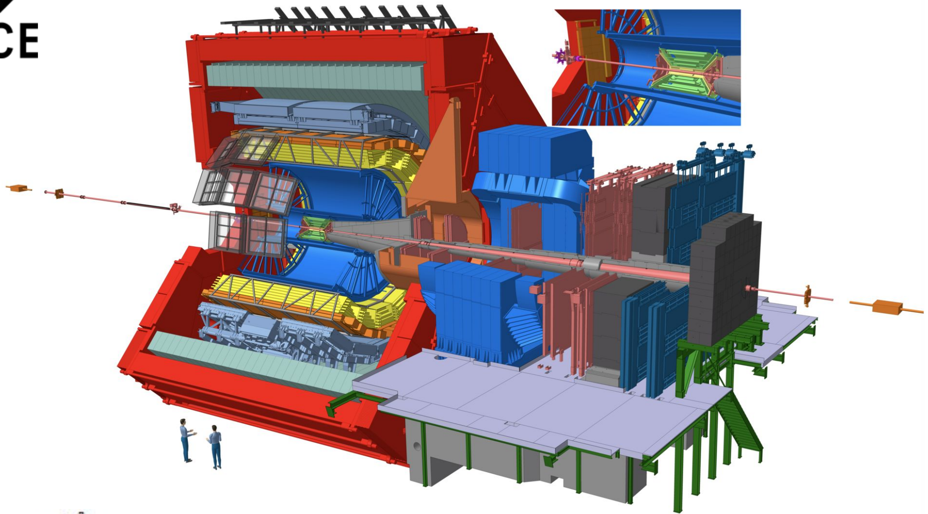
$$f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(\bar{s} \to \Xi^-)/f(\bar{s} \to \Lambda^0) \sim 0.004$$

- global analysis that include e^+e^- (B-factories and LEP), ep (HERA)
- very nice agreement across collision systems
- no Tevatron measurement of Λ_c

What about LHC results?

L. Gadalin: Eur. Phys. J. C75 (2015) 19
M. Lisovyi et al.: EPJ C 76 (2016) no.7, 397

A Large Ion Collider Experiment (ALICE)



$D^0 \to K^-\pi^+$

$D^+ \to K^-\pi^+\pi^+$

$D^{*+} \to D^0\pi^+$

$D_s^+ \to \phi\pi^+ \to K^-\pi^+\pi^+$

$J/\psi \to e^-e^+$

$J/\psi, \psi(2S) \to \mu^-\mu^+$

$\Upsilon(1S, 2S, 3S) \to \mu^-\mu^+$

$D \to e(\mu)X$

$B \to e(\mu)X$

$\Lambda_c^+ \to K_S^0 p$

$\Lambda_c^+ \to \pi^+K^-p$

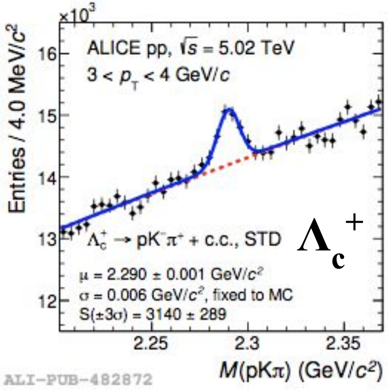
$\Xi_c^0 \to \Xi^-e^+\nu_e$

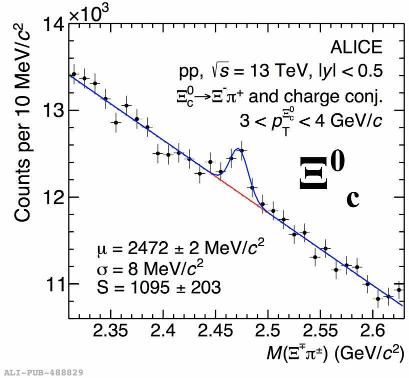
$\Xi_c^0 \to \Xi^-\pi^+$

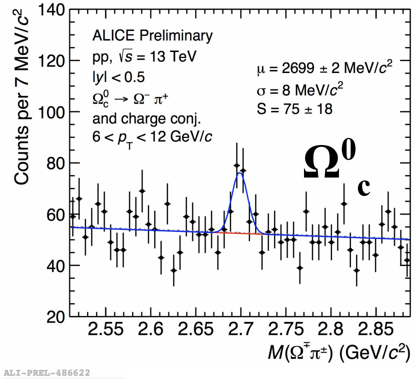
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$

$\Omega_c^0 \to \Omega^-\pi^+$

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







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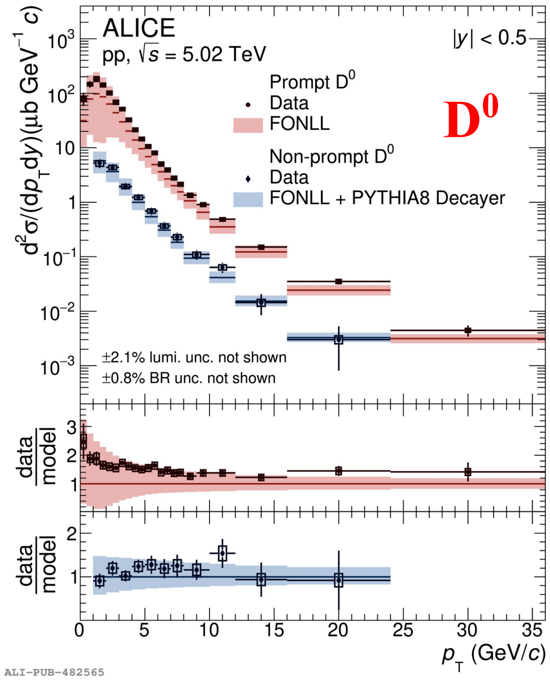
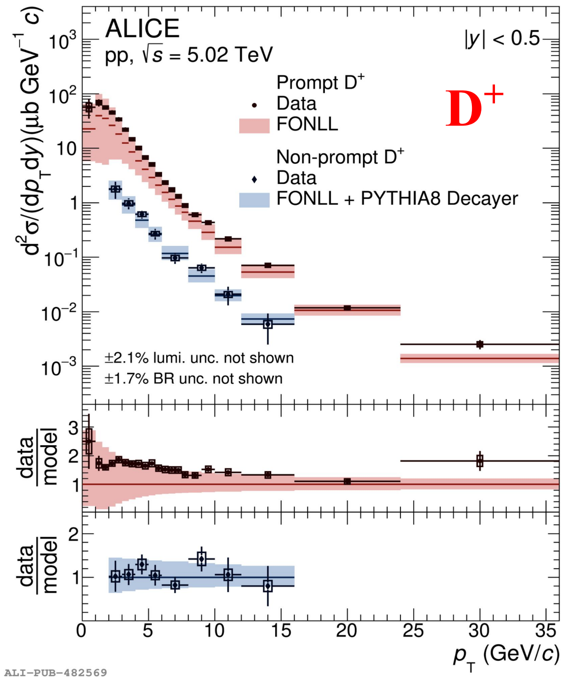
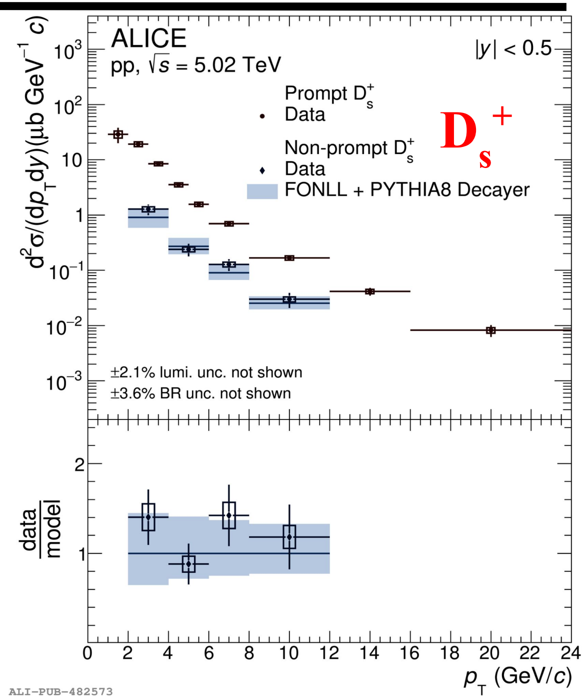
Open charm and beauty meson production







- Cross section measured in wide p_T range down to p_T = 0 for D^0 and D^+ meson

  → NLO pQCD calculations (FONLL and GM-VFNS) describe cross sections down to low p_T with fragmentation fractions extracted from e^+e^-

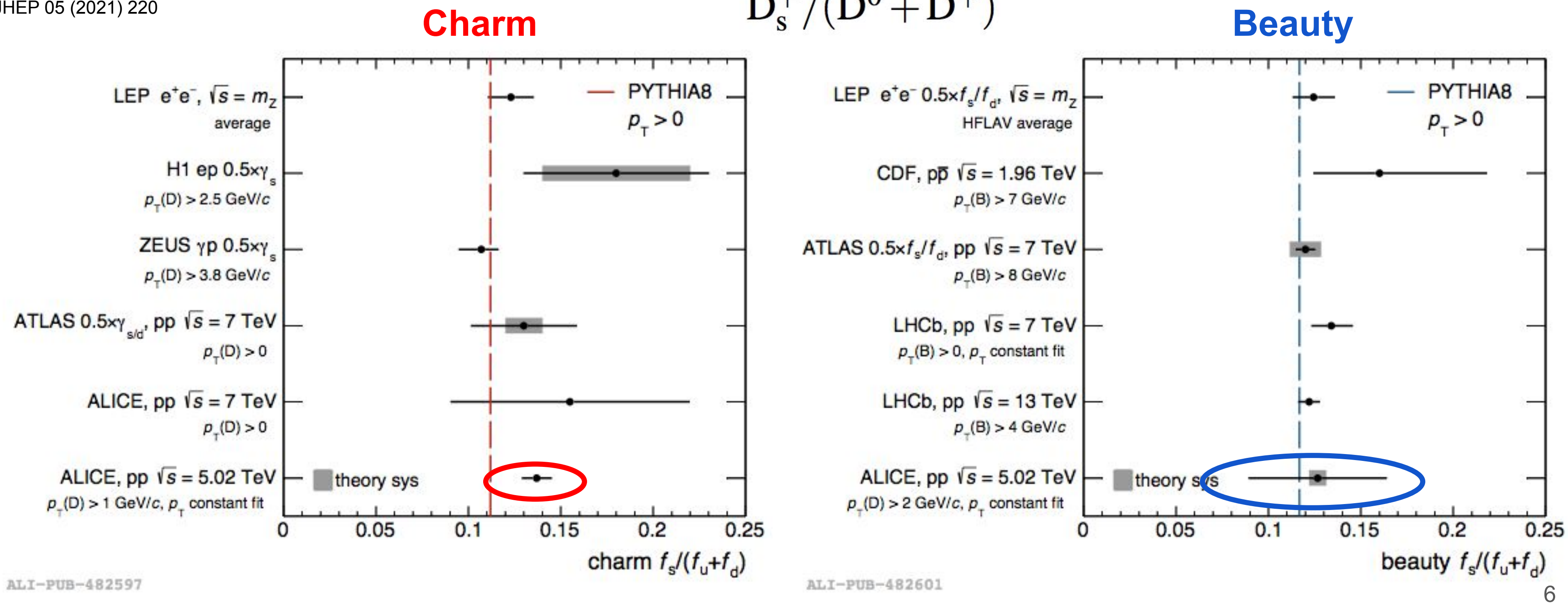
ALICE: JHEP 05 (2021) 220
FONNL: JHEP 1210 (2012) 137
GM-VFNS: EPJ C72 (2012) 2082

Charm and beauty fragmentation to mesons

- Ratio of fragmentation fraction (FF) to mesons with and w/o strange quark content similar for charm and beauty
- No significant dependence on energy and collision system

JHEP 05 (2021) 220

$D_s^+/(D^0+D^+)$



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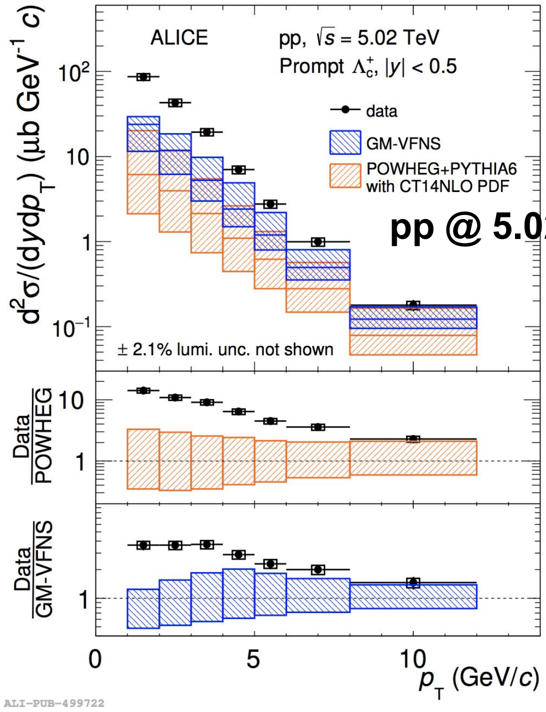
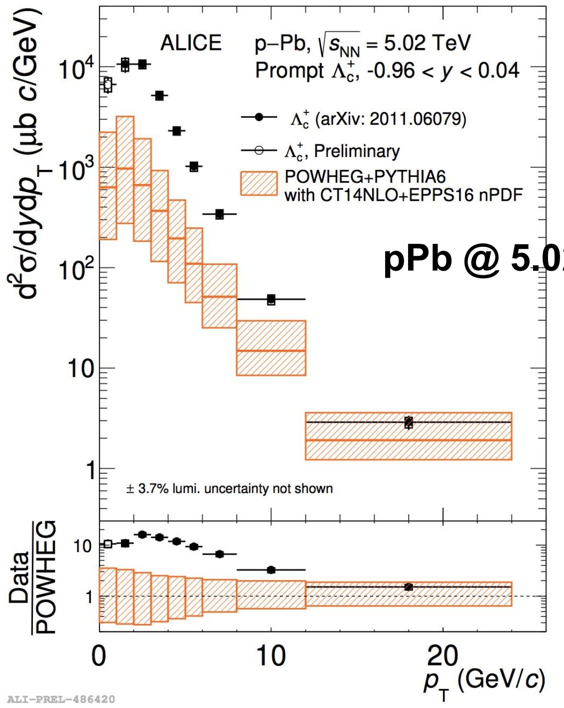
Precise Λ_c measurements in Run 2

PRL127(2021)202301
PRC104(2021)054905



pp @ 5.02 TeV



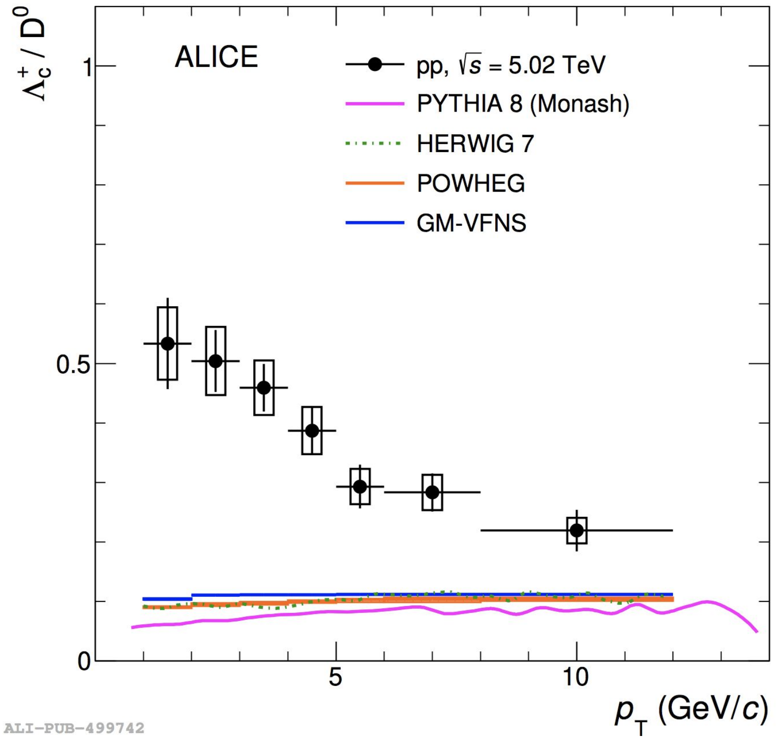
pPb @ 5.02 TeV

First measurements of Λ_c **down to p_T = 0** in pp and p-Pb collisions!

pQCD calculations underestimate data especially at low p_T

- FF used by GM-VFNS includes new input from Belle measurements (Phys. Rev. D **97**, 072005)

How do MC generators perform at LHC?



PRL127(2021)202301
PRC104(2021)054905

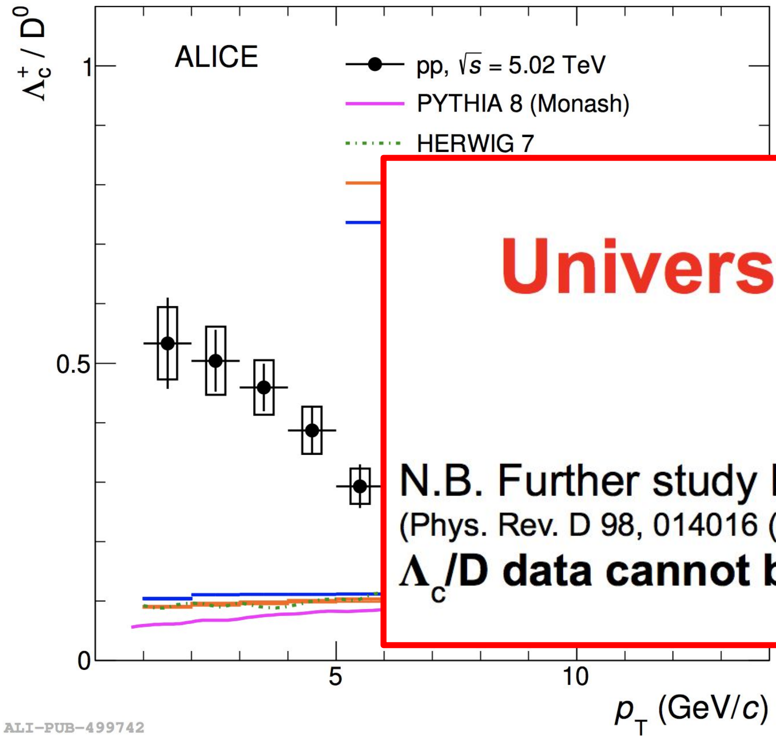
The MC generators

- **PYTHIA 8** with Monash tune and colour reconnection Eur. Phys. J. C74 no. 8, (2014) 3024
- **HERWIG 7** where hadronisation is implemented via clusters Eur. Phys. J. C58 (2008) 639–707
- **POWHEG** matched to PYTHIA 6 to generate the parton shower JHEP 09 (2007) 126
- **GM-VFNS** pQCD calculations → compute the ratios of the Λ_c and D^0 cross sections with the same choice of pQCD scales Phys. Rev. D 101 (2020) 114021

All implement fragmentation processes tuned on charm production measurements in e^+e^- collisions, → predict a value of the Λ_c/D^0 ~ 0.1, with a very mild p_T dependence.

Significantly underestimate the data at low p_T by a factor of about 6-10, while at high p_T the discrepancy is reduced to a factor of about 3.

How do MC generators perform at LHC?



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…rate the parton

…e the ratios of …he choice of

…n charm …predict a …endence.

…y a factor of about 6-10, while at high p_T the discrepancy is reduced to a factor of about 3.

Universality: where are you?

N.B. Further study by R. Maciula and A. Szczurek (Phys. Rev. D 98, 014016 (2018))

Λ_c/D data cannot be described by tweaking D and Λ_c FF

Any model with different assumption?

- **PYTHIA 8:** color reconnection (CR) allowed between partons from different MPIs.

- **Statistical:** total yields governed by mass of hadron states at a universal hadronization temperature.

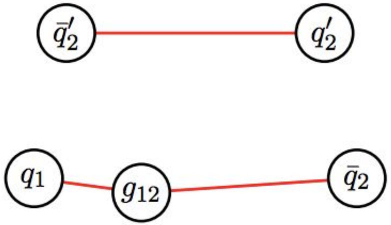
- **Coalescence:** combination of quarks close in phase-space.

A PYTHIA model with CR?

PYTHIA8 with String Formation beyond Leading Colour JHEP 1508 (2015) 003

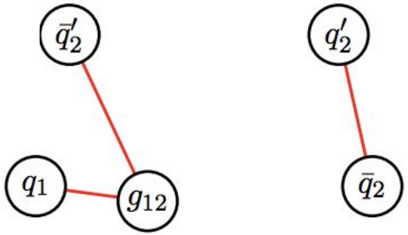
- Colour reconnection mode with SU(3) topology weights + string-length minimisation.
- ***A dynamical "QCD-inspired" way for coalescence?***

No CR



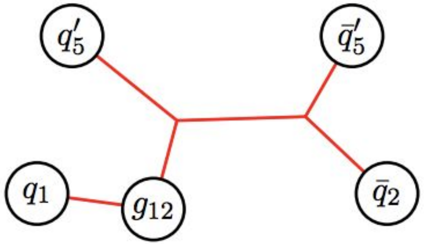
- Partons created in different MPIs do not interact

Old CR



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

New CR



- Minimization of the string length over all possible configurations
- Junction reconnection → enhance baryons
- Include CR with MPIs and with beam remnants

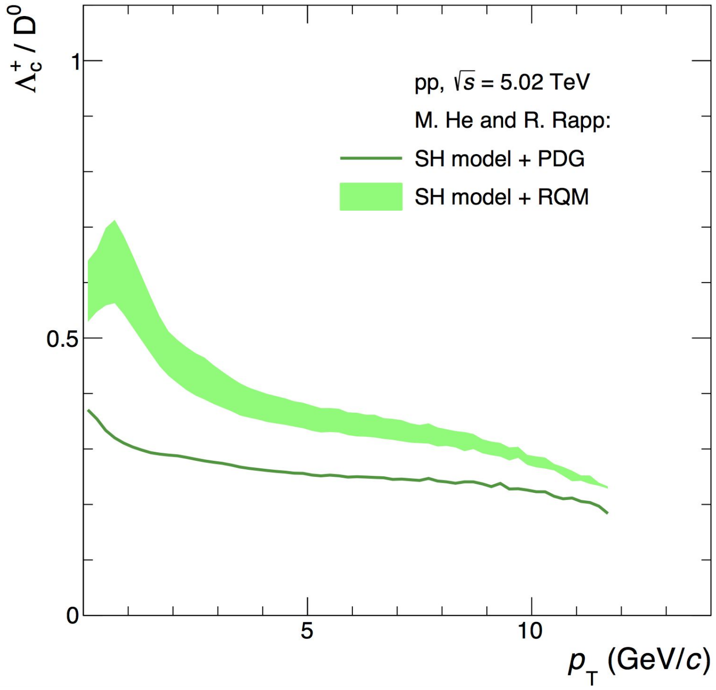
Higher mass baryon resonance states?

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

- Same FF used by FONLL, tuned on D^0 ALICE data + scaling for mass.
- Feed-down from augmented set of charm-baryon states based on relativistic quark model

□ PDG: 5 Λ_C (I=0) , 3 Σ_C (I=1), 8 Ξ_C (I=1/2), 2 Ω_C (I=0)➔ missing baryons?!
RQM: 18 extra Λ_C , 42 extra Σ_C, 62 extra Ξ_C, 34 extra Ω_C up to 3.5 GeV
➔ supported by lattice PRD 84 (2011) 014025; PoS LAT. 2014 (2015) 084; PLB 737 (2014) 210

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

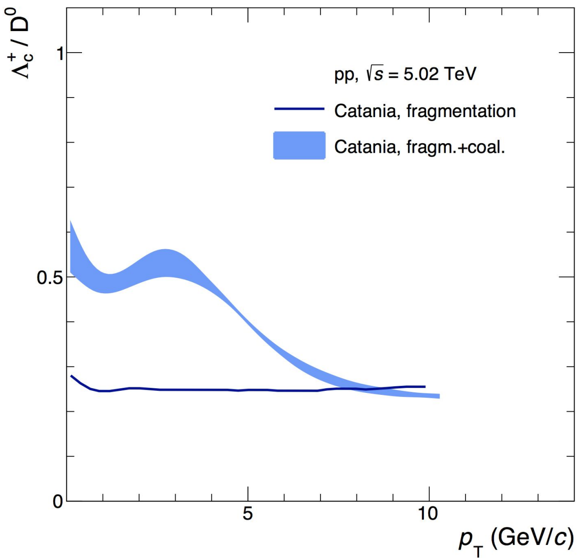


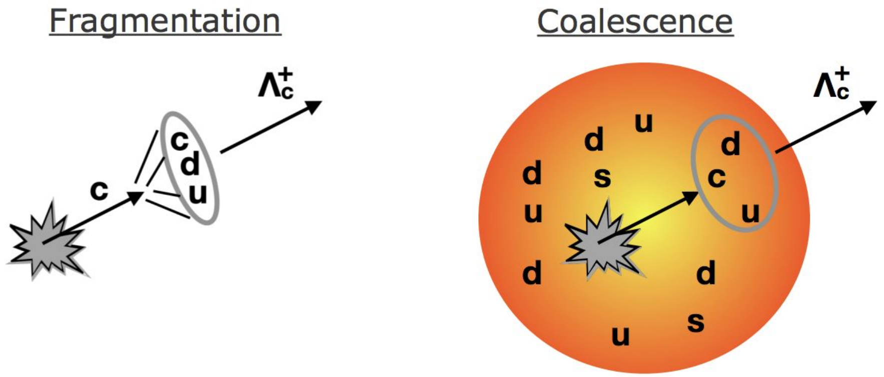
Coalescence in pp?

Catania: Transport model with hadronization via coalescence+fragmentation

- Quark-gluon plasma in pp collisions → quarks and gluons with thermal distributions
- Charm quark spectrum from FONLL
- Same first excited resonances as PDG

At $p_T \approx 0$, a charm quark mainly hadronizes via coalescence, while at high p_T fragmentation becomes dominant





PLB821(2021)136622
EPJC(2018)78:348

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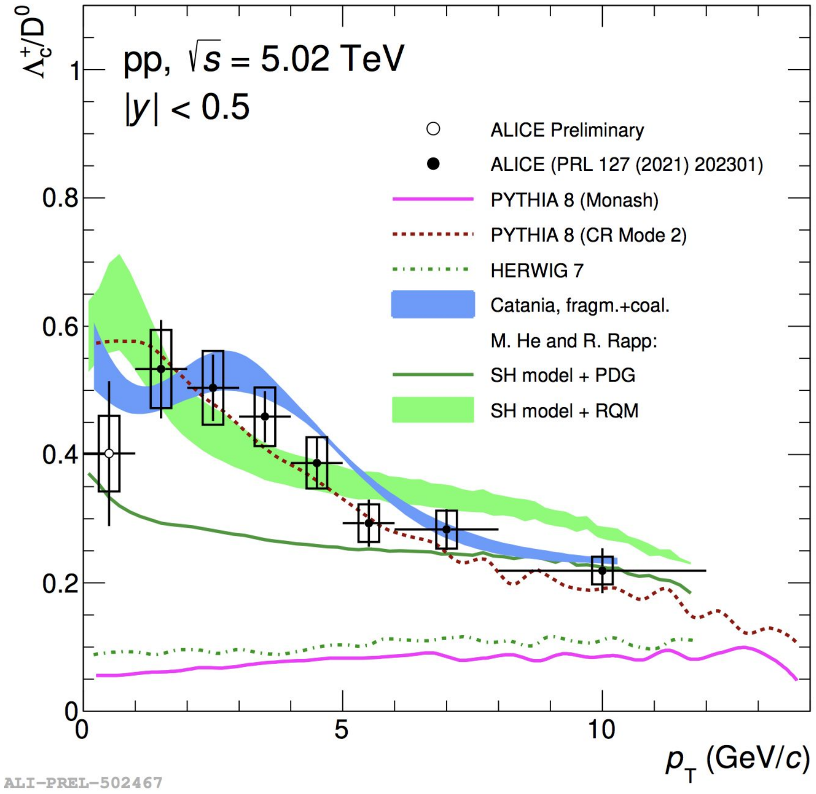
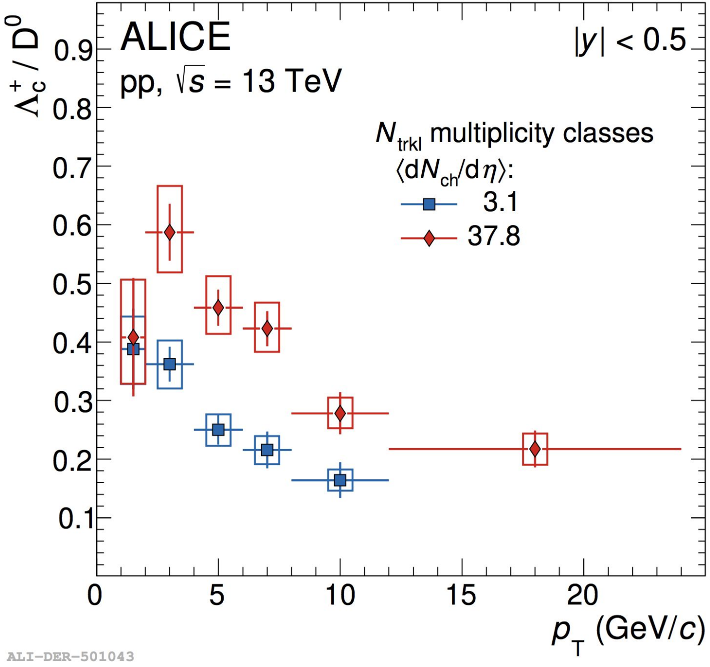
A comprehensive comparison



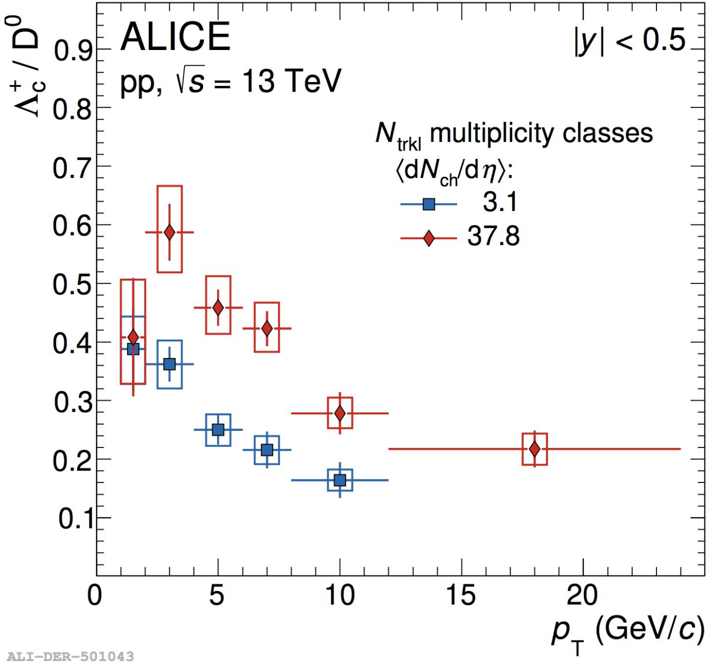
- New **CR tunes in PYTHIA 8** largely enhance the baryon yield. Similar measurements and prediction at different collision energy.
- **SHM+RQM** also enhance the baryon yield and better describe the data
- **Catania** is the model that enhances the baryon contribution more thanks to the coalescence approach

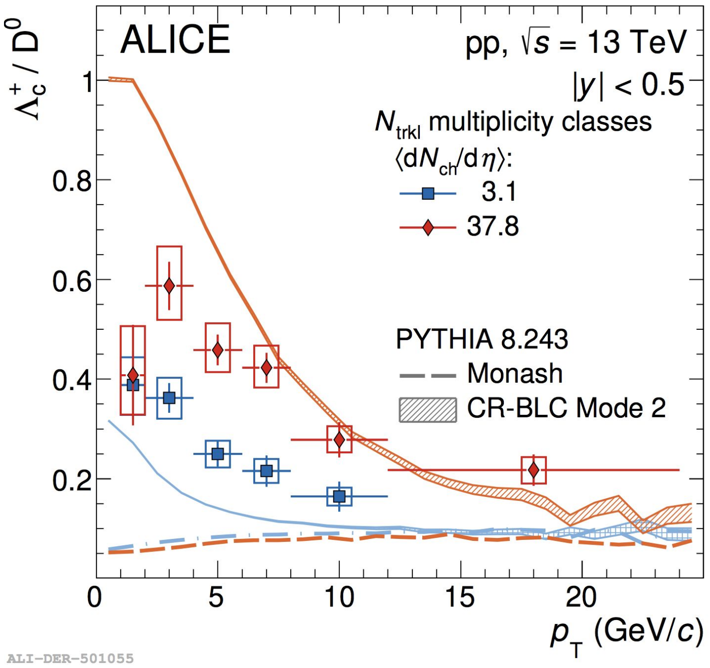
More differential....



- Enhancement observed for Λ_c/D^0 from low to high multiplicity

More differential....

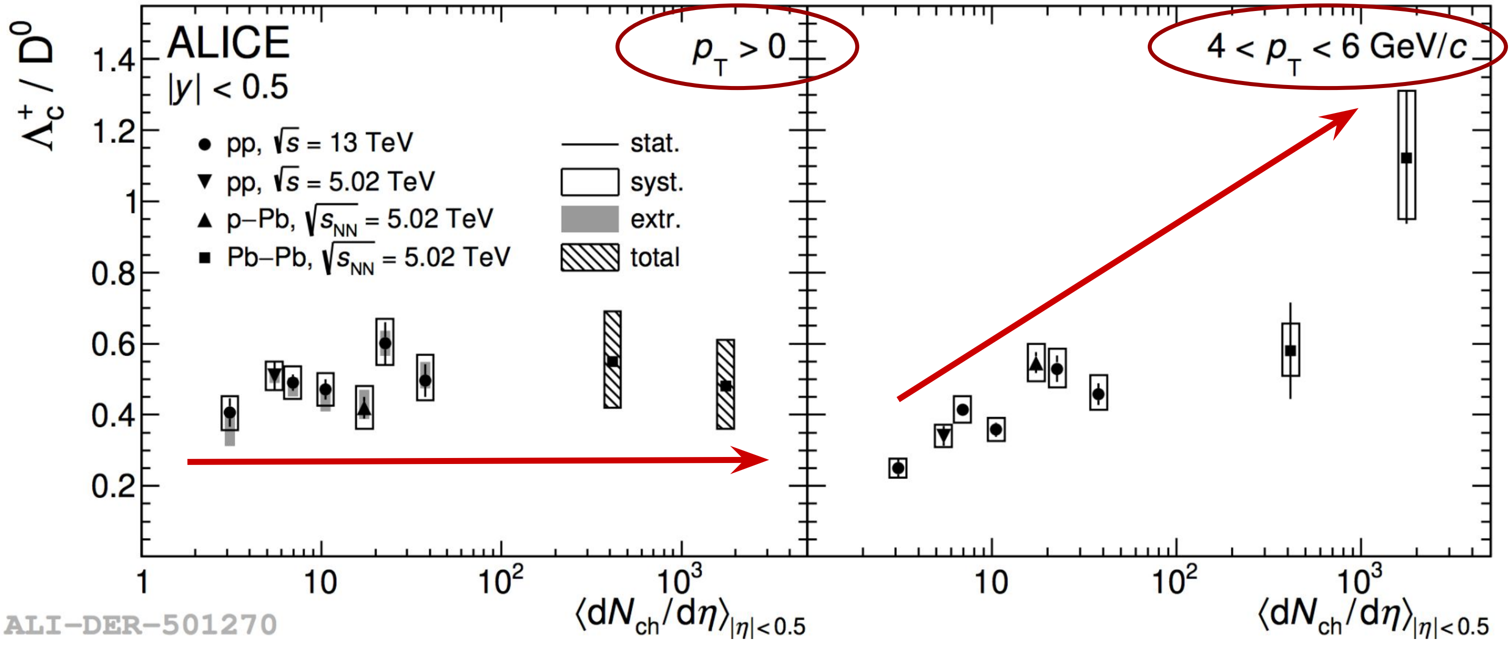




- Enhancement observed for Λ_c/D^0 from low to high multiplicity

- Pythia Mode 2: Multiplicity trend qualitatively in line with data
- no variation with mult. in default PYTHIA 8 (Monash)

The complete picture from pp to Pb-Pb



- ➢ no evident mult. dependence from very low (pp) to very high (most central Pb-Pb) multiplicity for $p_T > 0$
- ➢ no enhancement of total yield of Λ^+_c wrt D^0 in Pb-Pb wrt to pp collisions
  - a dense particle environment in pp: act as proxy for “collectivity”?
  - different hadronization mechanisms for baryons and mesons act in different momentum ranges? effect of system expansion?

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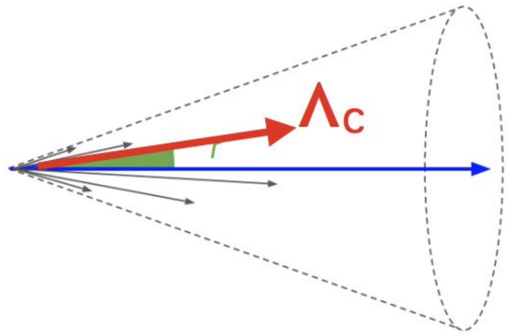
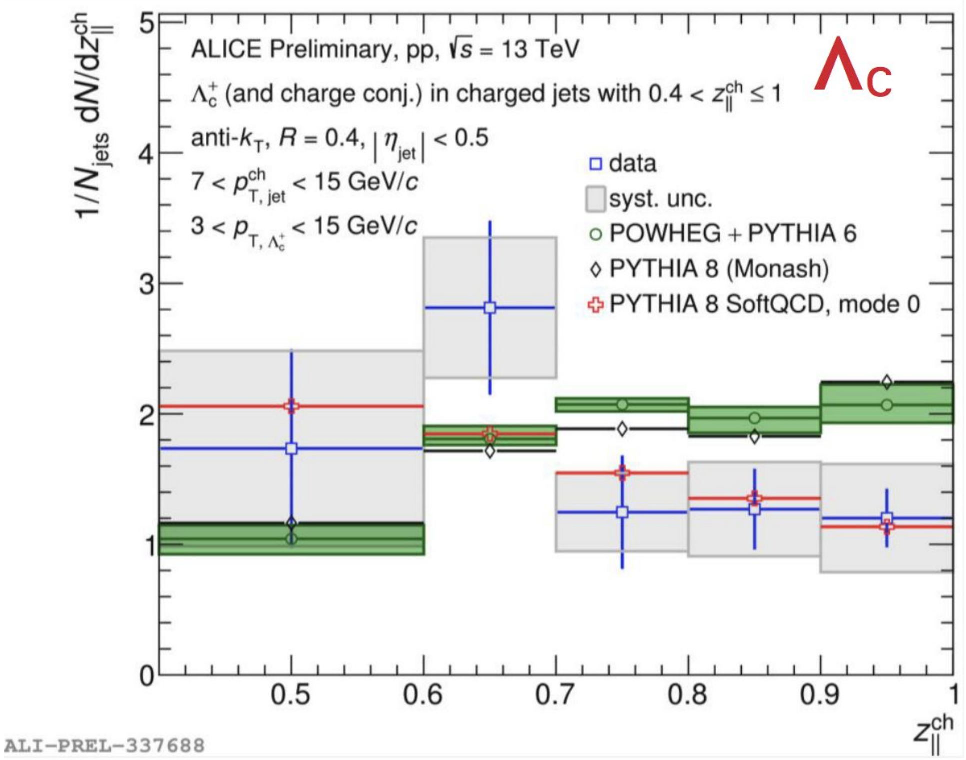
HF in jets: to look into fragmentation

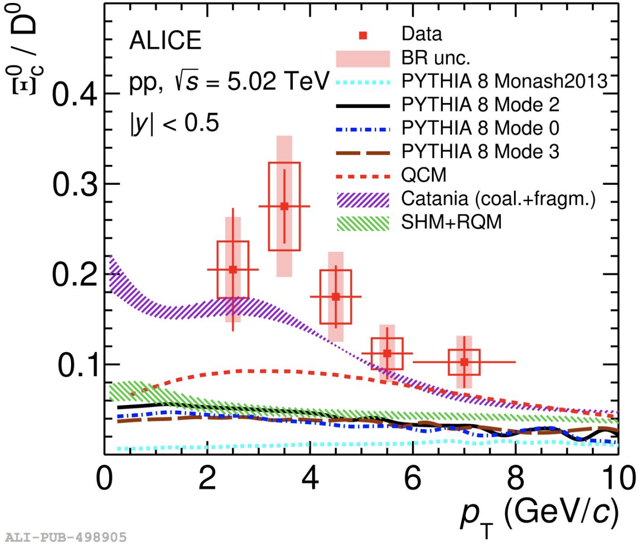


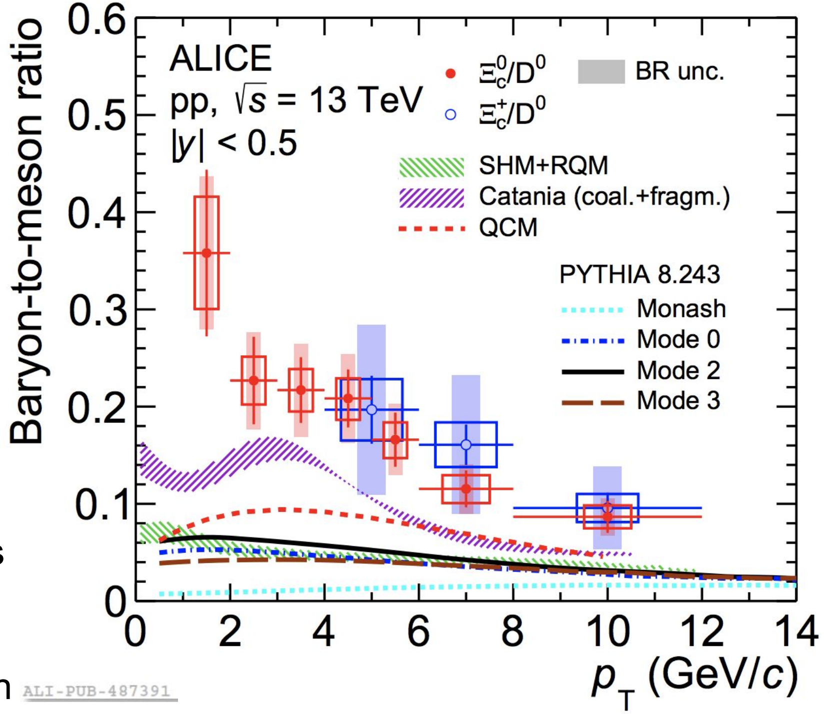


- Data point toward a softer fragmentation w.r.t. classic in vacuum fragmentation models in the low $p_{T,ch\text{-}jet}$ range (beyond Leading Color fragmentation needed)

$$z_{||} = \frac{\vec{p}_{jet} \cdot \vec{p}_{\Lambda_c^+}}{\vec{p}_{jet} \cdot \vec{p}_{jet}}$$

Heavier charmed baryons: Ξ_c





- **New PYTHIA CR tunes** do not describe the measurements of Ξ^0_c baryons. No strangeness enhancement in PYTHIA. Additional modelling is needed
- **SHM+RQM** also don't describe the data: not enough baryon resonances?
- **Catania** is the model that gets closer to the data also in this case. Indication of coalescence in pp collisions?

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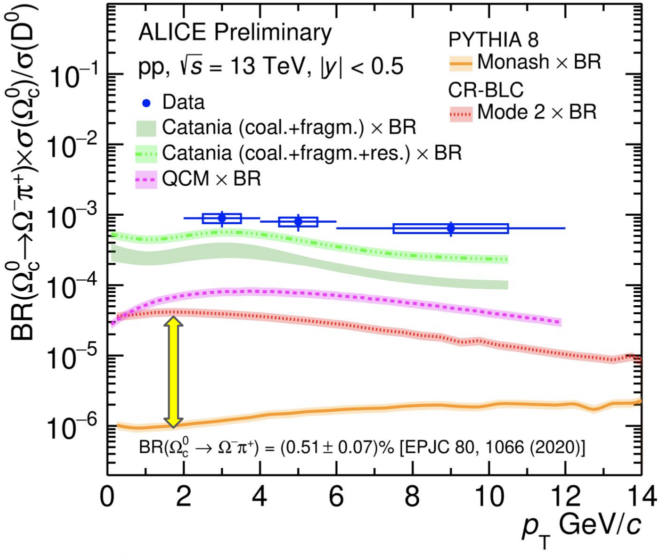
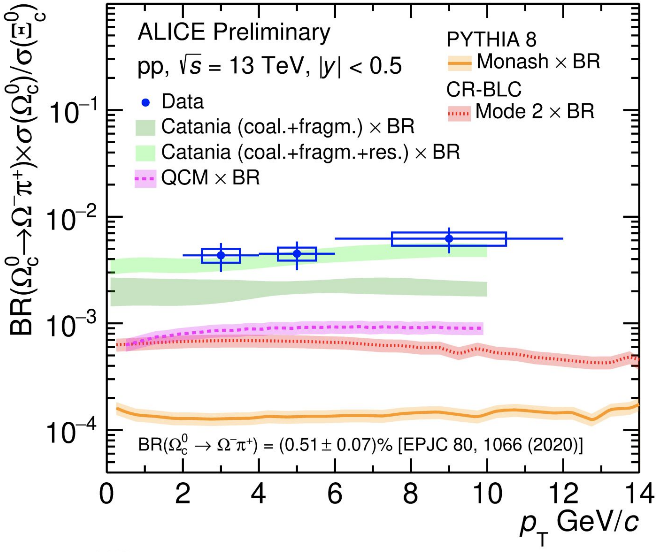
...and Ω^0_c

$BR(\Omega^0_c \to \pi^+\Omega^-)$ = (0.51 ± 0.07)% [Eur. Phys. J. C 80, 1066 (2020)]





- **Large enhancement observed** with enhanced CR tunes
- Only **Catania** gets closer to the data

Belle: Phys. Rev. D 97, 072005 (2018)

Ratio	ALICE (pp@13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^-@10.52 GeV) visible
$BR(\Omega^0_c \to \Omega^-\pi^+) \times \sigma(\Omega^0_c)/\sigma(\Lambda^+_c)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(9.70 \pm 1.27 \pm 0.66) \times 10^{-5}$
$BR(\Omega^0_c \to \Omega^-\pi^+) \times \sigma(\Omega^0_c)/\sigma(\Xi^0_c)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(5.82 \pm 0.78 \pm 1.34) \times 10^{-4}$

Charm fragmentation fraction at LHC

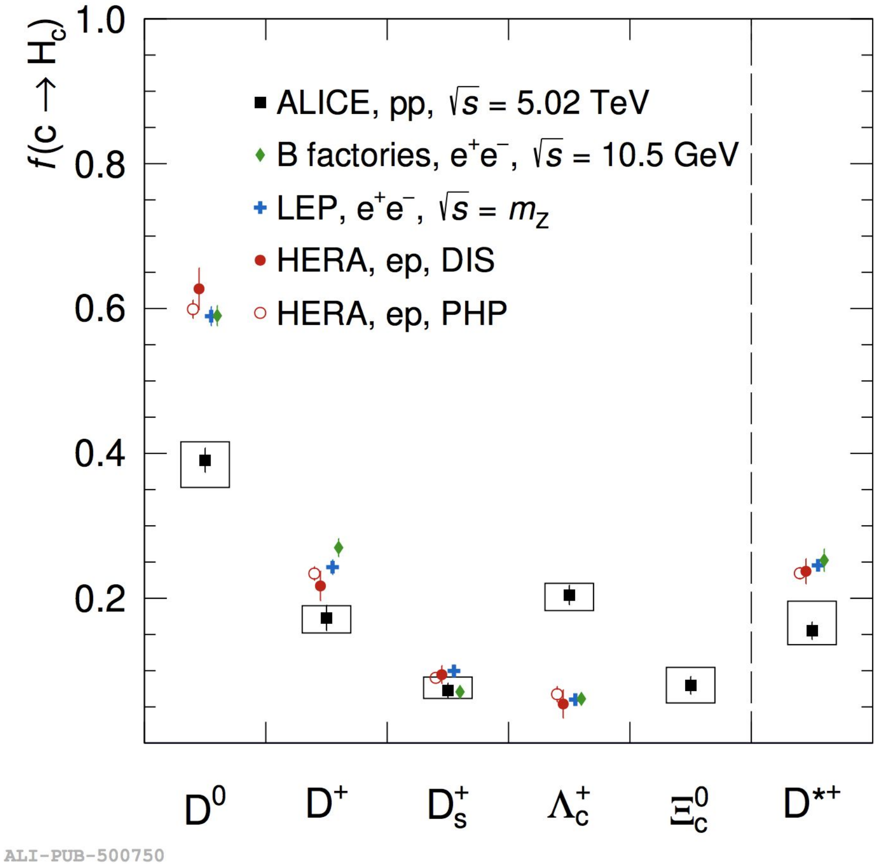
H_c	$f(c \to H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
2 x Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$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

- D^{*+} feeds into the D^0 and D^+ mesons

$$f(c \to \Xi_c^0)/f(c \to \Lambda_c^+) = 0.39 \pm 0.07(\text{stat})^{+0.08}_{-0.07}(\text{syst})$$

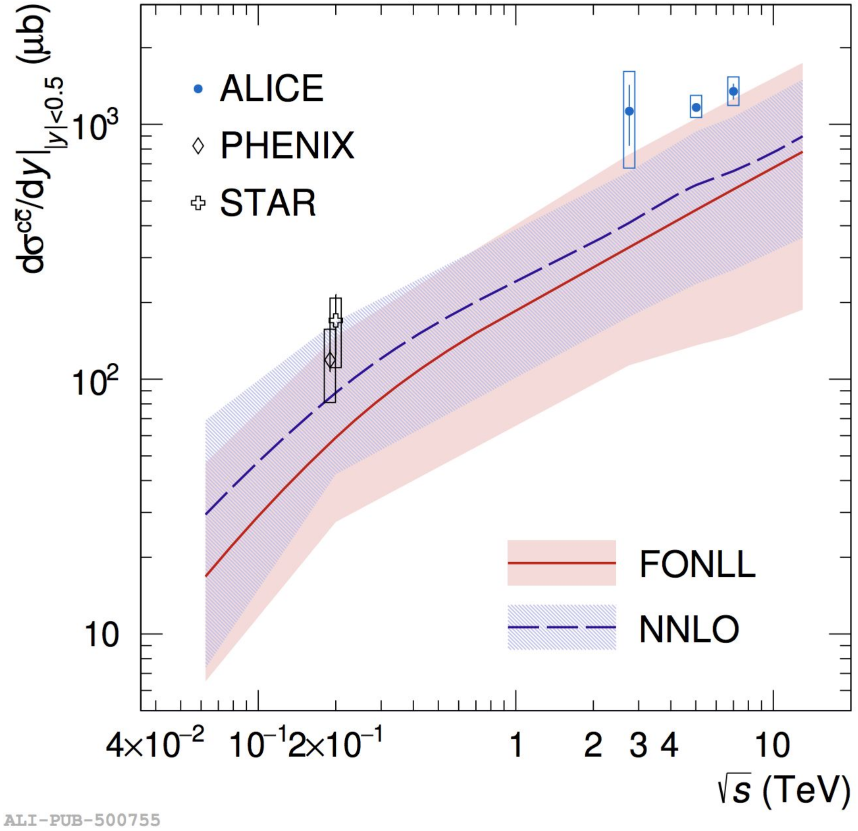
M. Lisovyi et al.: EPJC76(2016)no.7,397

$$f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda^0) \sim 0.004$$



PRD105,L011103(2022)

Charm production cross section at LHC



- New FF allowed to update the charm cross section measurements previously published at 7 and 2.76 TeV
- New measurements are 40% higher than the previous ones.
- Measurements barely compatible with the upper edge of the FONNL and NNLO calculations

STAR: Phys. Rev. D 86 (2012) 072013

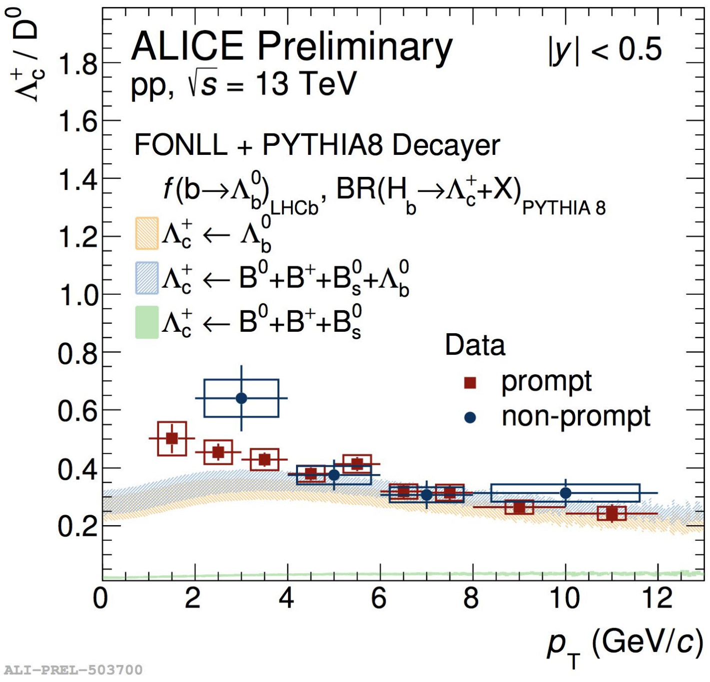
PHENIX: Phys. Rev. C 84 (2011) 044905

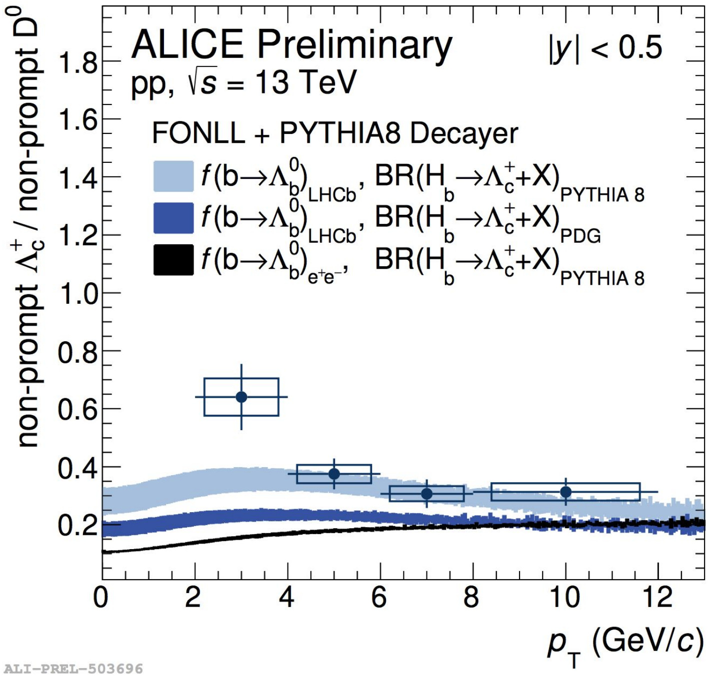
FONLL: JHEP 1210 (2012) 137

NNLO: JHEP 03 (2021) 029

PRD105,L011103(2022)

Non-prompt Λ_c in pp collisions





- Almost all the Λ_c^+ originate from Λ_b^0 decays (B-meson contribution is minor)
- Measurement underestimated in case of b-hadron FF from e^+e^- and in case of PDG decay table

LHCb: PRD100(2019)no.3,031102

Conclusion

- Charmed **baryons** studies at the LHC were a **big surprise**: we were looking for a baseline in pp to then look at an enhancement in Pb-Pb and we found something different from e^+e^- and ep
- Dependence of fragmentation fractions on collision systems is firmly established!
- The access at low p_T allow us to test hadronization models in the LHC *parton rich environment*

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- Dependence of fragmentation fractions on collision systems is firmly established!
- The access at low p_T allow us to test hadronization models in the LHC *parton rich environment*

$$\frac{d\sigma_{pp}^{h}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_{a}dx_{b}f_{a}(x_{a},Q^{2})f_{b}(x_{b},Q^{2})\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\frac{D_{h/c}^{0}}{\pi z_{c}}$$

The LHC is a perfect laboratory to study the dependence of the fragmentation fractions on the surrounding parton rich environment

BACKUP

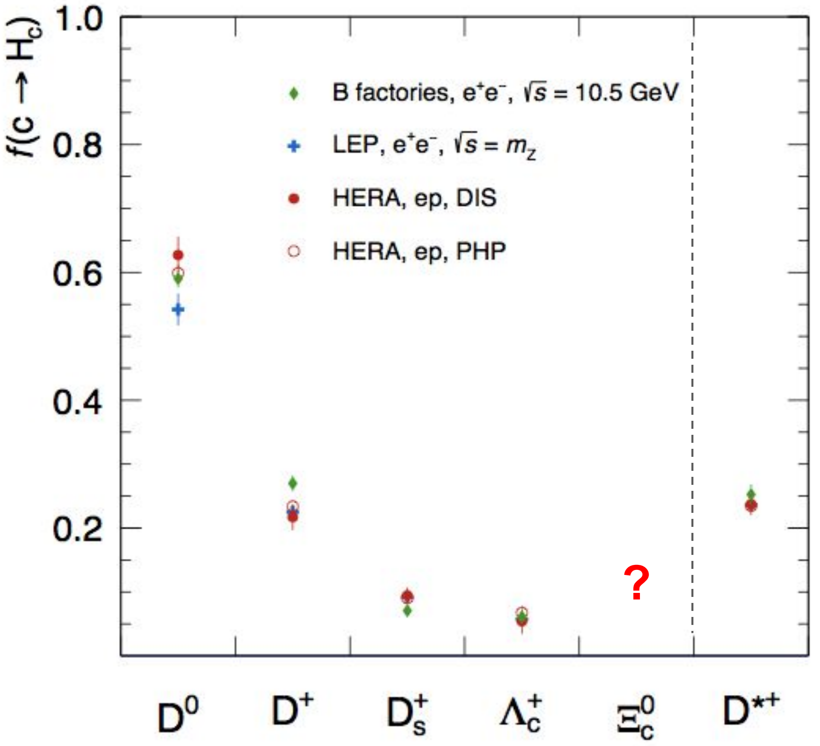
Historical snapshot

L. Gadalin: Eur. Phys. J. C75 (2015) 19
M. Lisovyi et al.: EPJ C 76 (2016) no.7, 397

Fragmentation fractions of charm quark used as default inputs in a standard factorization approach

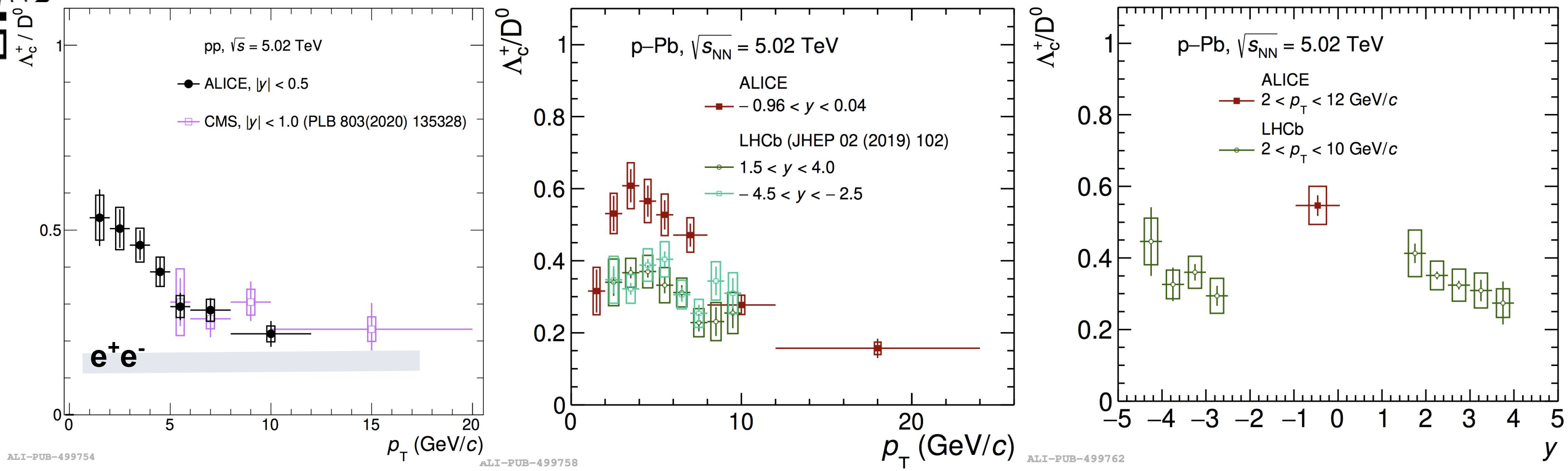
H_c	$f(c \to H_c)$ [%]	$f(b \to H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$	$58.7 \pm 2.1 \pm 0.8$
D^+	$22.5 \pm 1.0 \pm 0.5$	$22.3 \pm 1.1 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$	$13.8 \pm 0.9 \pm 0.6$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$	$7.3 \pm 0.8 \pm 0.4$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$	$23.3 \pm 1.0 \pm 0.3$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

$$f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda^0) \sim 0.004$$



Andrea Dubla

Precise Λ_c measurements in Run2



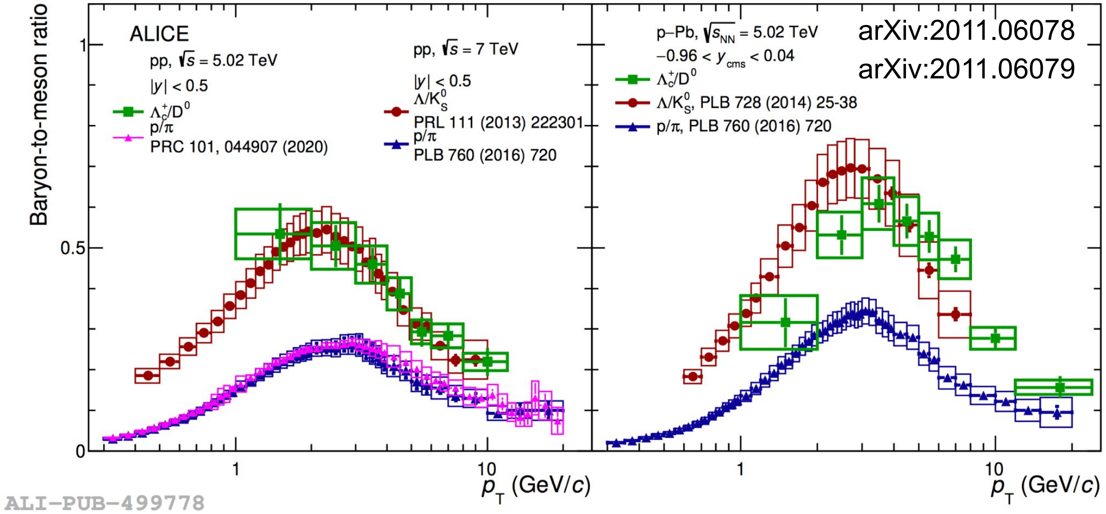
More precise measurements highlight a strong p_T dependence (CMS reaches higher p_T).

- Low p_T significantly higher than e^+e^-
- High p_T the Λ_c/D^0 ratio approaches the value measured in e^+e^-

Comparison with forward/backward rapidity measurements (LHCb) shows some interesting trend

- All experiments agree with the picture of higher baryon-to-meson ratios with respect to e^+e^-

Similarities or accidents

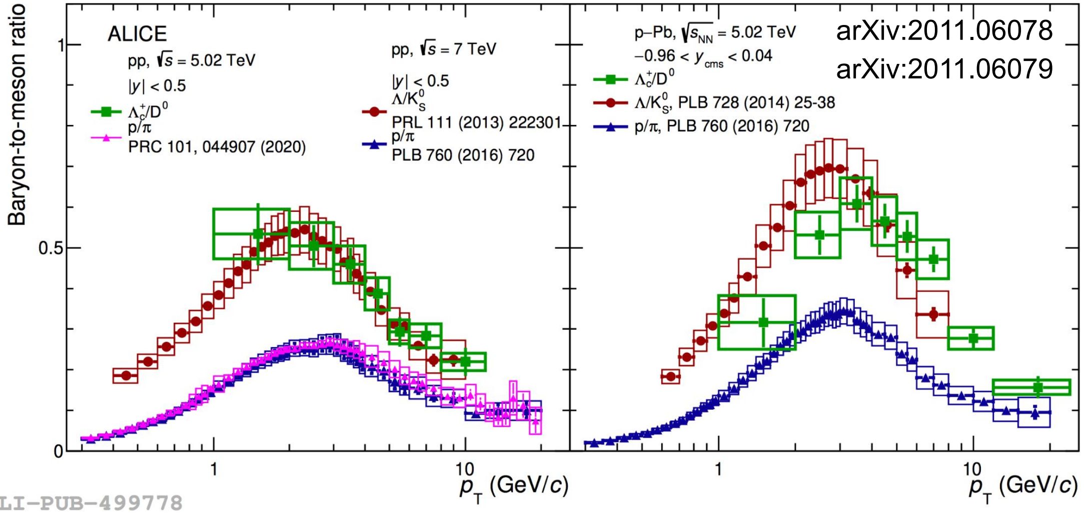


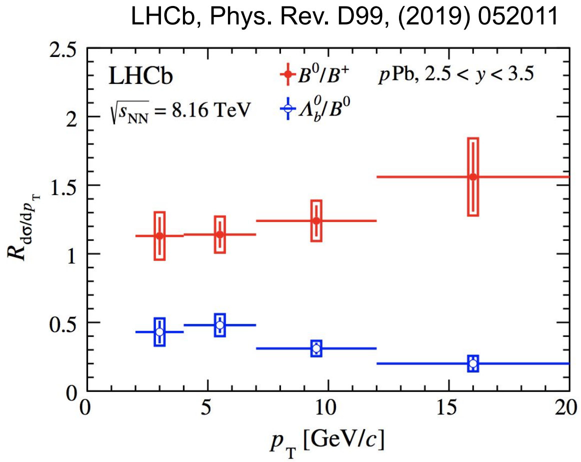
Comparison of the baryon-to-meson ratio in the heavy and the light sector show remarkably similar properties

- The Λ_c/D^0 ratio is consistent with the 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?

Similarities or accidents





Comparison of the baryon-to-meson ratio in the heavy and the light sector show remarkably similar properties

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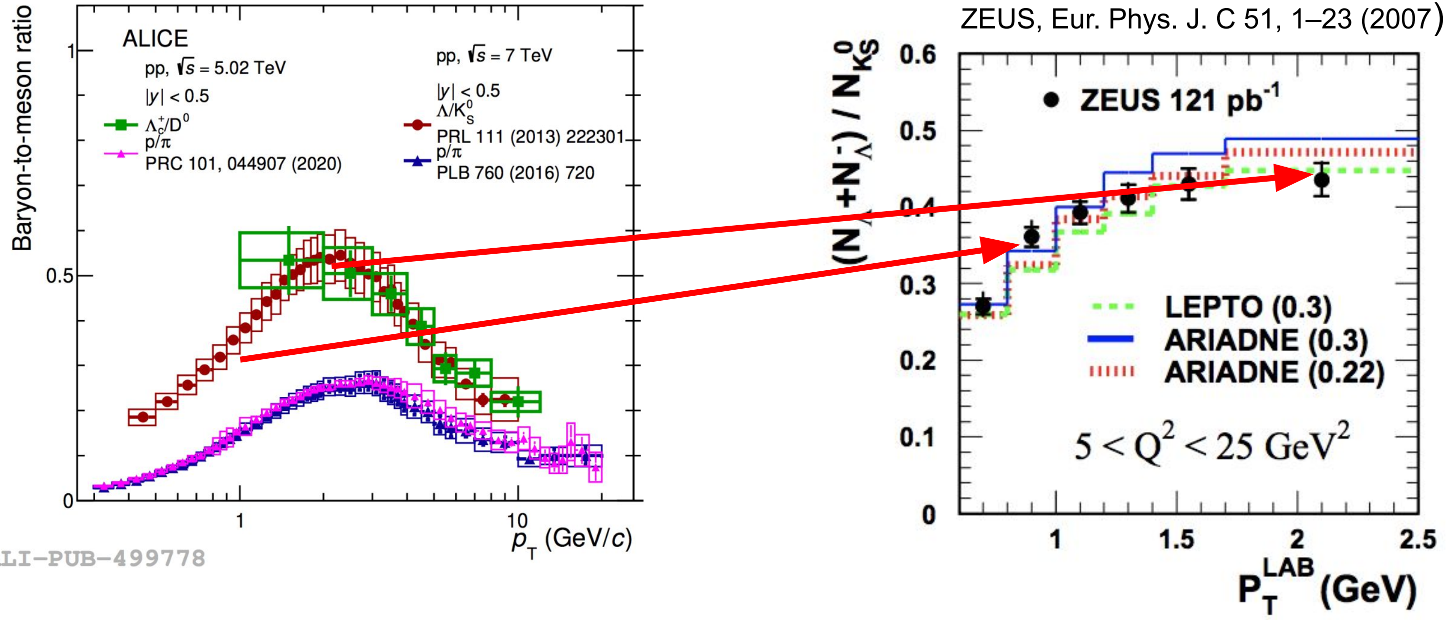
Hadronisation mechanisms similar for light and heavy quarks?

LHCb measurement of Λ_b/B^0 show also similarities in the beauty sector

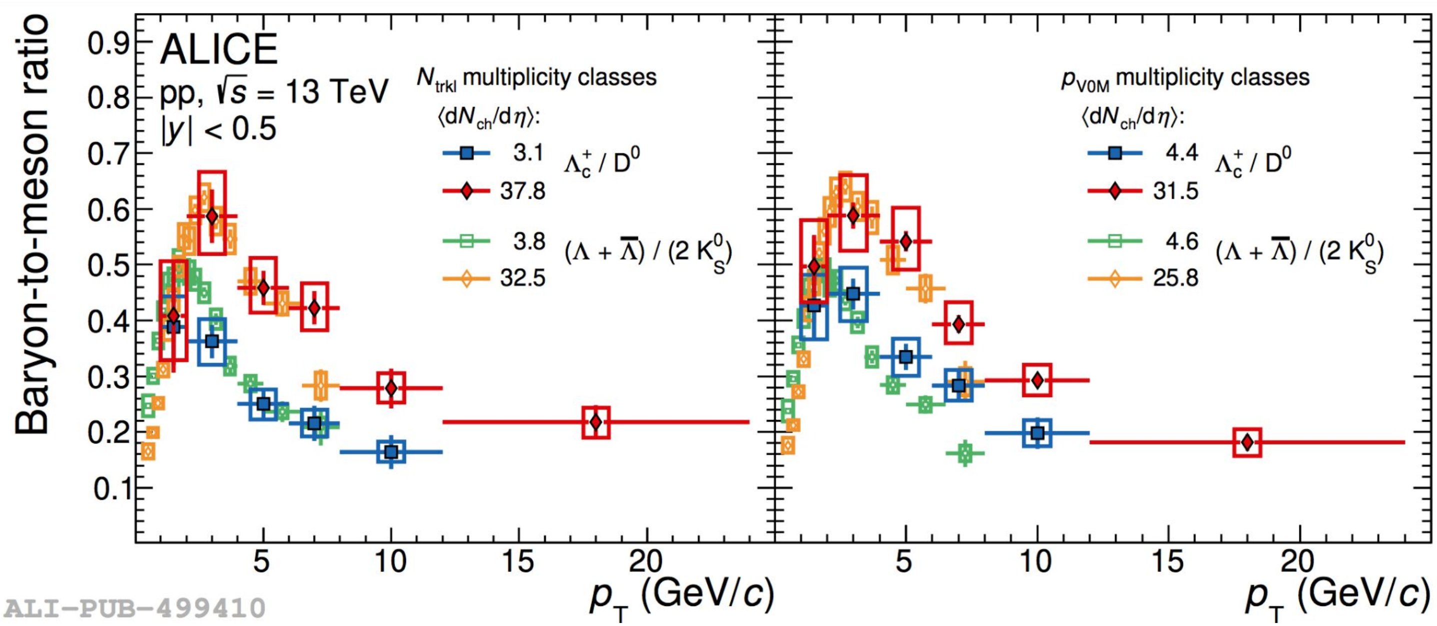
Similarities or accidents



Note in e^+e^- and ep (DIS) for the LF sector this was apparently already there...

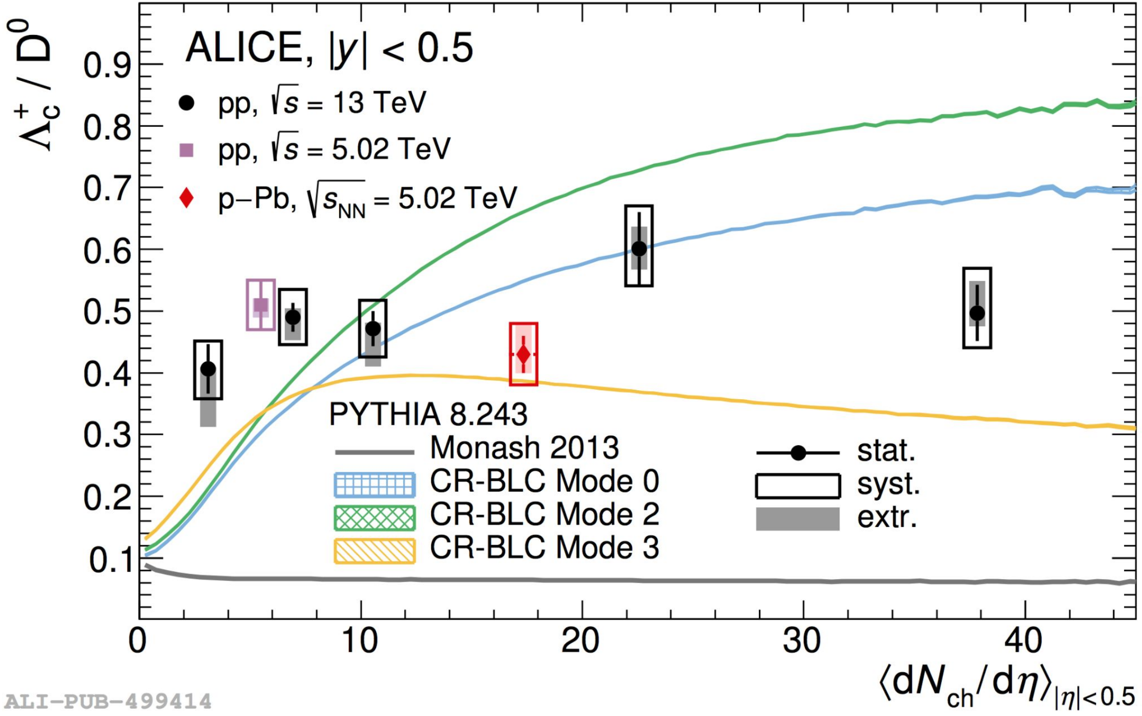
- larger values seen already at HERA in strange sector
- in e^+e^-(ep) baryon-to-meson measurements limited to p_T < 2 (2.5) GeV/c

More differential....



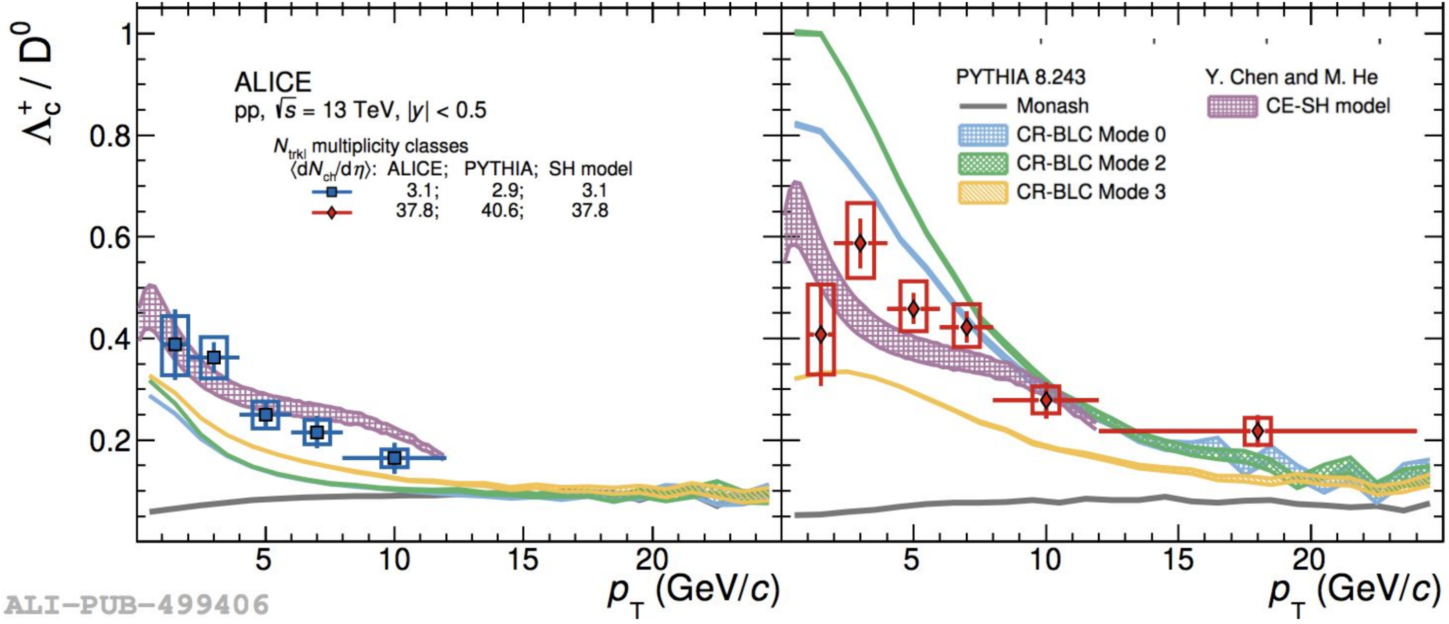
- Similar p_T-trend of baryon/meson ratios in HF and LF sectors and similar evolution with multiplicity is there a common kinematic scale / mechanism?

More differential....



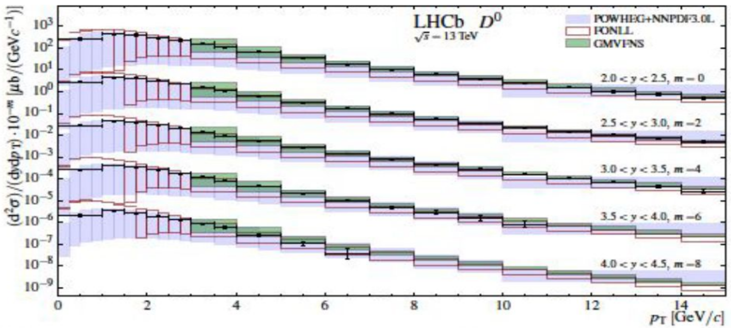
- Pythia Modes: increase of baryon-to-meson yield ratio depends on multiplicity

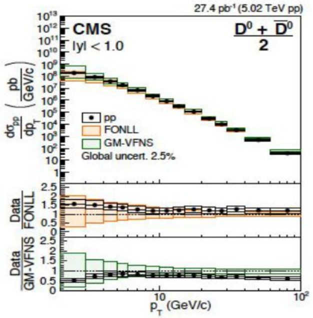
More differential....

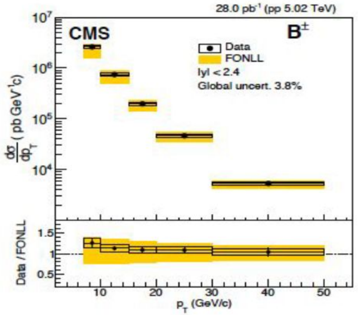


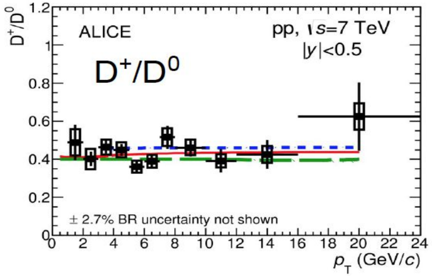
- SH model with Multiplicity dependence derived from reduced volume size towards smaller multiplicity.
- Pythia Mode 2: Multiplicity trend qualitatively in line with data - no variation with mult. in default PYTHIA 8 (Monash)

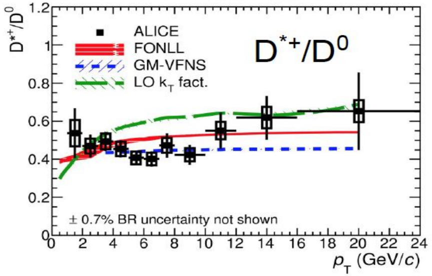
Factorization a very successful framework

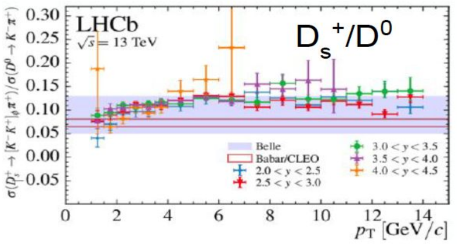


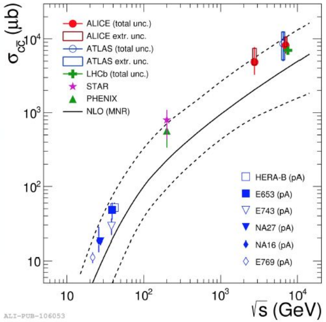












Plethora of data indicating that open-charm and open-beauty meson production

- vs. p_T and y (wide range covered)
- at very different collision energies
- charm meson species relative abundances

→ *is described by pQCD calculations relying on the factorisation approach*

Is it really the case?

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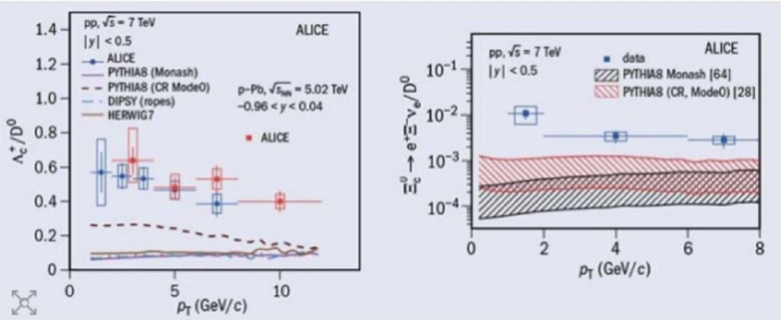
ALICE investigates charm-quark hadronisation

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).

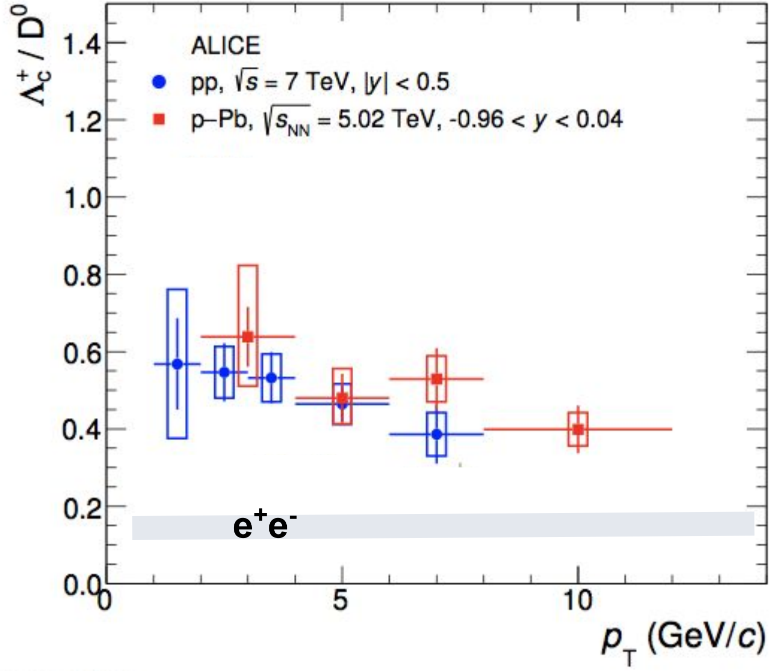
The results (see figure) are compared with the expectations obtained from perturbative QCD calculations and Monte Carlo event generators. None of the models reproduce the data, indicating that the fragmentation of charm quarks is not well understood. A similar pattern is seen when comparing the Ξ^0_c/D^0 baryon-to-meson ratio with predicted values (see figure, right), where the latter have a sizable uncertainty due to the unknown branching ratio of the decay.

These two results suggest that charmed baryon formation might not be universal, and that the baryon/meson ratio depends on the collision system. Hints of non-universality of the fragmentation functions are also seen when comparing beauty-baryon production measurements at the Tevatron and LHC with those at LEP. The ratios measured in pPb collisions are similar to the result in pp collisions.

Andrea Dubla

A sensitive quantity: Λ_c/D^0

JHEP 1804 (2018) 108



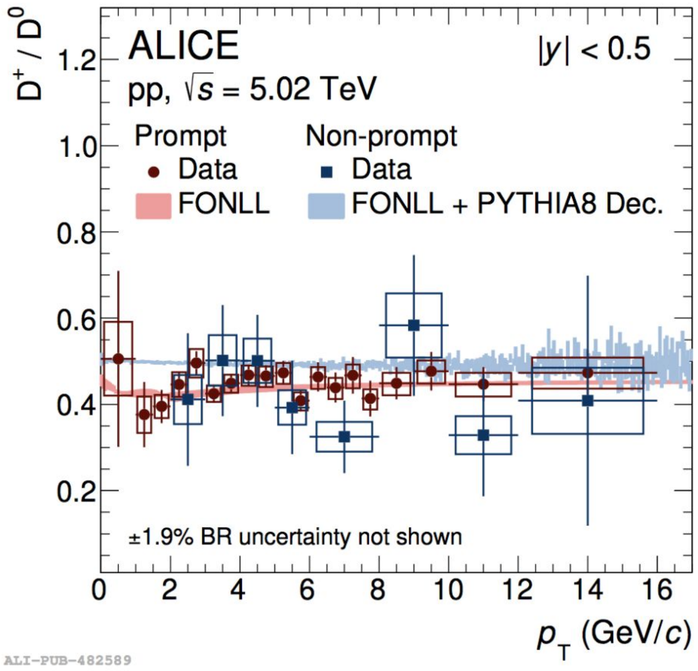
ALI-PUB-141413

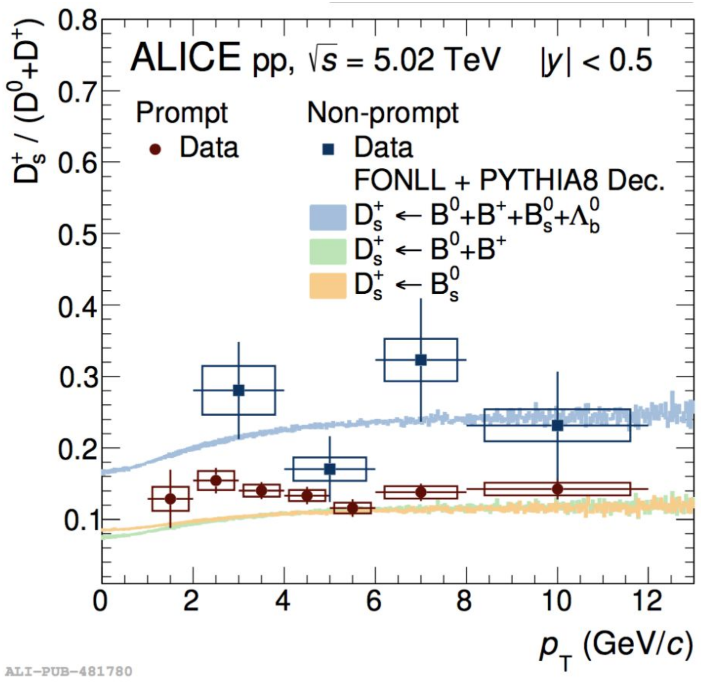
	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320

- no drastic change between pp and p-Pb
- "tension" with e^+e^- and ep results (p_T integrated)
- Do the √s and/or the collision system play a role?

"fragmentation to heavy-flavour baryons is **not** well understood"

Meson-to-meson yield ratios





- D-meson production ratios compatible with pQCD with fragmentation fractions extracted from e^+e^-

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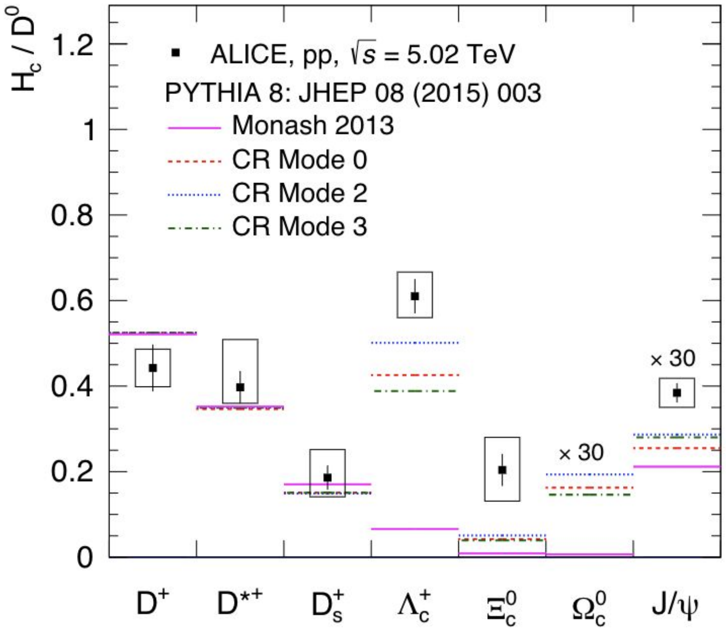
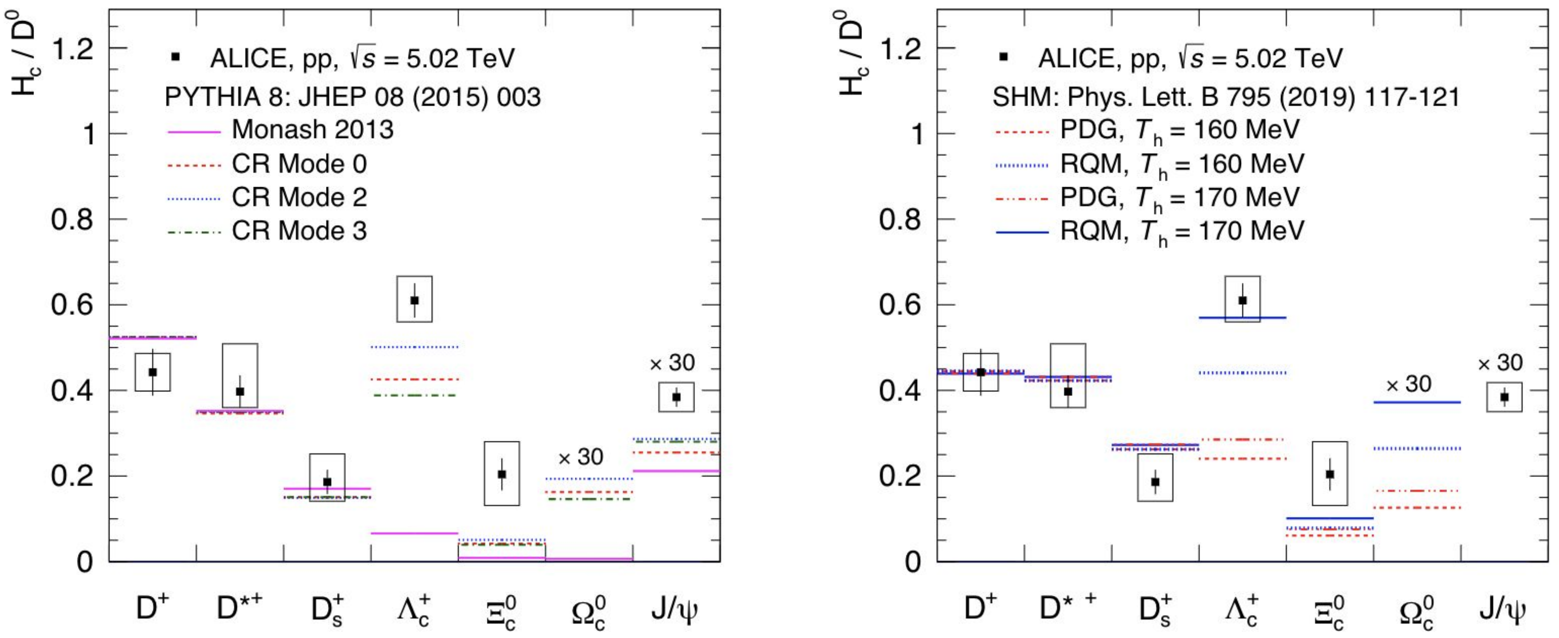
Integrated yield - model comparison



- open charm meson ratios the PYTHIA 8 generator predictions with the different tunes are fairly similar and describe the measurements within uncertainty

- Significant differences in the PYTHIA 8 predictions are observed when comparing them with the measured baryon-to-meson ratios.

Integrated yield - model comparison

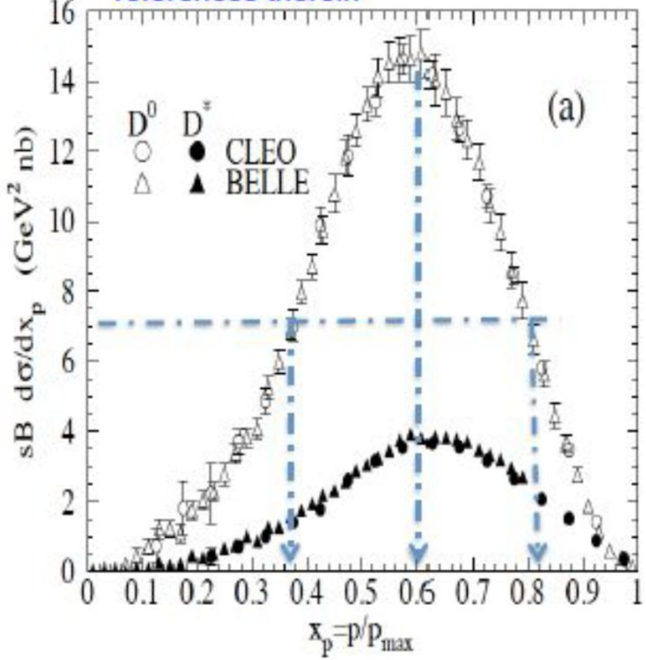


- two hadronisation temperatures leads to small variations in the meson-to-meson ratios, which are described by the model calculations → significant variations are observed in the baryon sector.

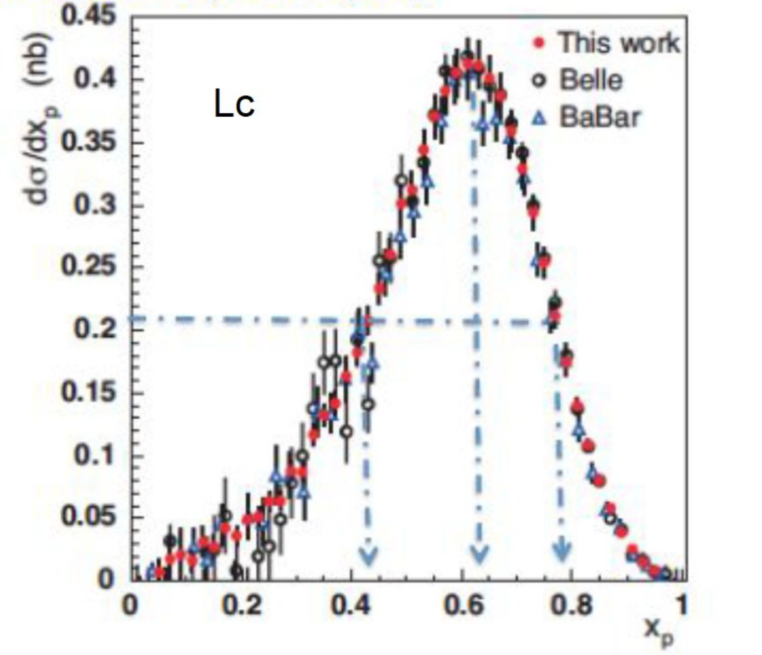
- The additional baryon states in the RQM almost double the fraction of the ground-state Λ_c in the system relative to the PDG scenario. Ξ^0_c/D^0 ratio is also observed to increase by a factor 1.3

D0 and Lc FF in e+e-

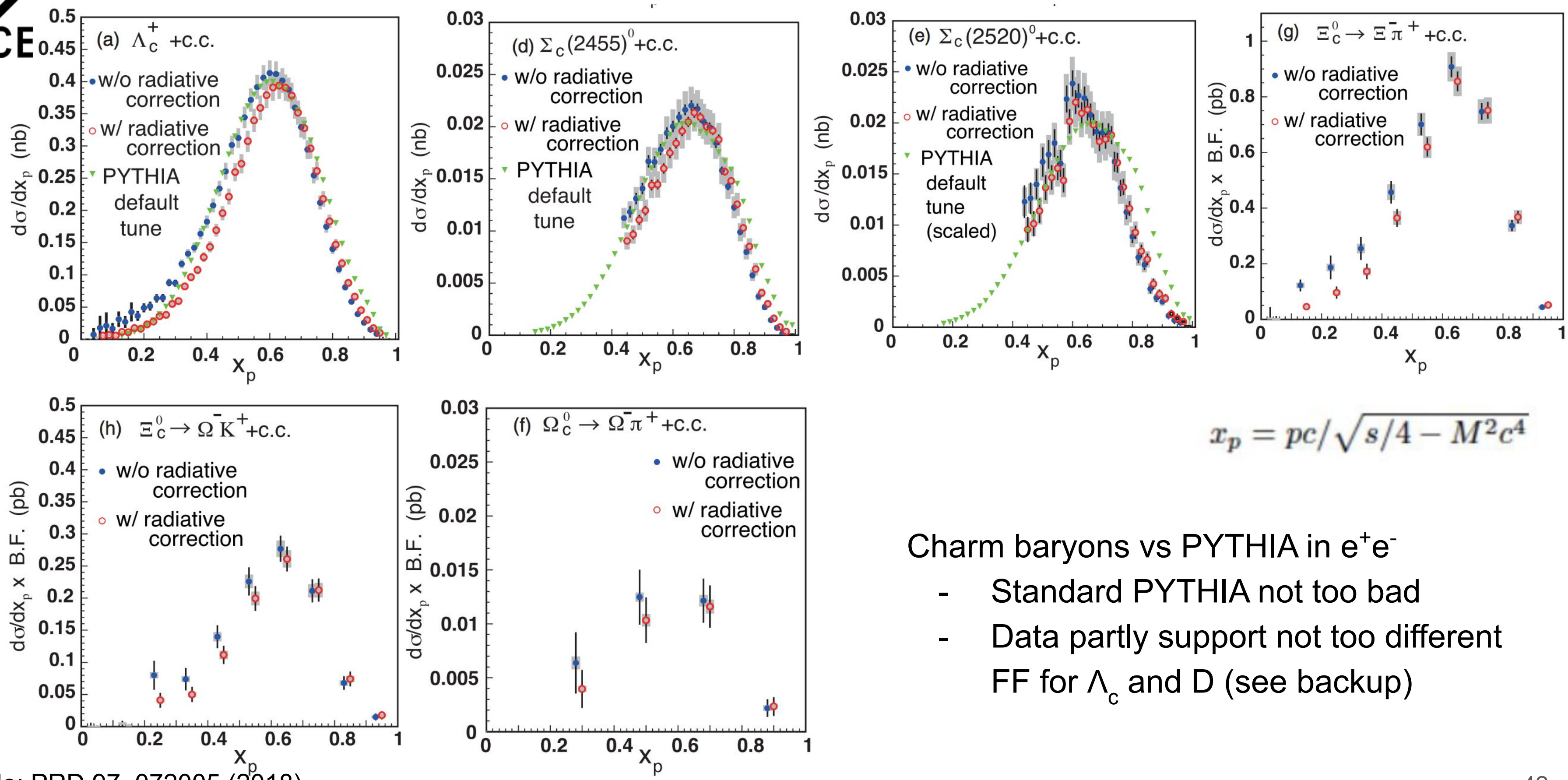
PDG 2019 fragm. funct. review, and references therein



Belle, PRD 97, 072005 (2018), PRD 73, 032002 (2006)
BaBar, PRD 75, 012003 (2007)



Are there model calculations?



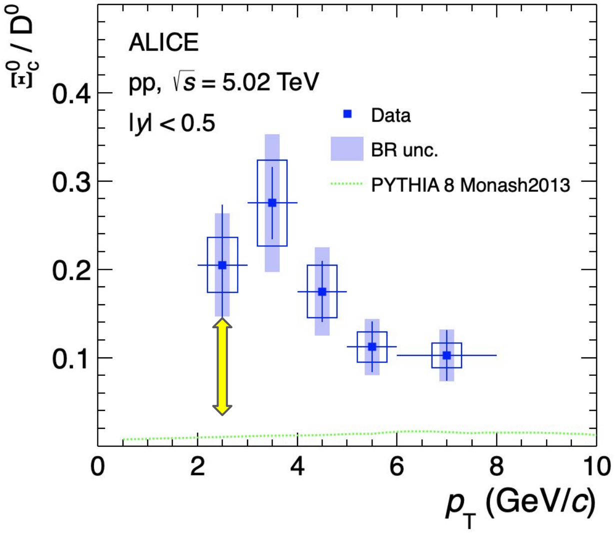
$$x_p = pc/\sqrt{s/4 - M^2c^4}$$

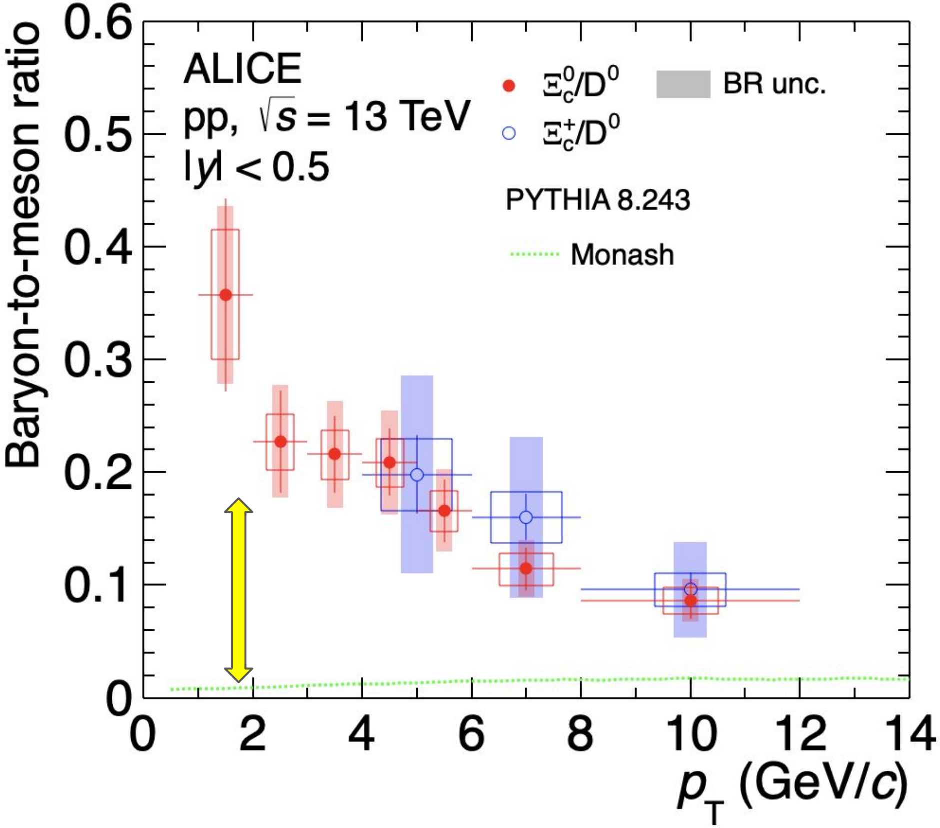
Charm baryons vs PYTHIA in e^+e^-

- Standard PYTHIA not too bad
- Data partly support not too different FF for Λ_c and D (see backup)

Belle: PRD 97, 072005 (2018)

Strange-charm baryons

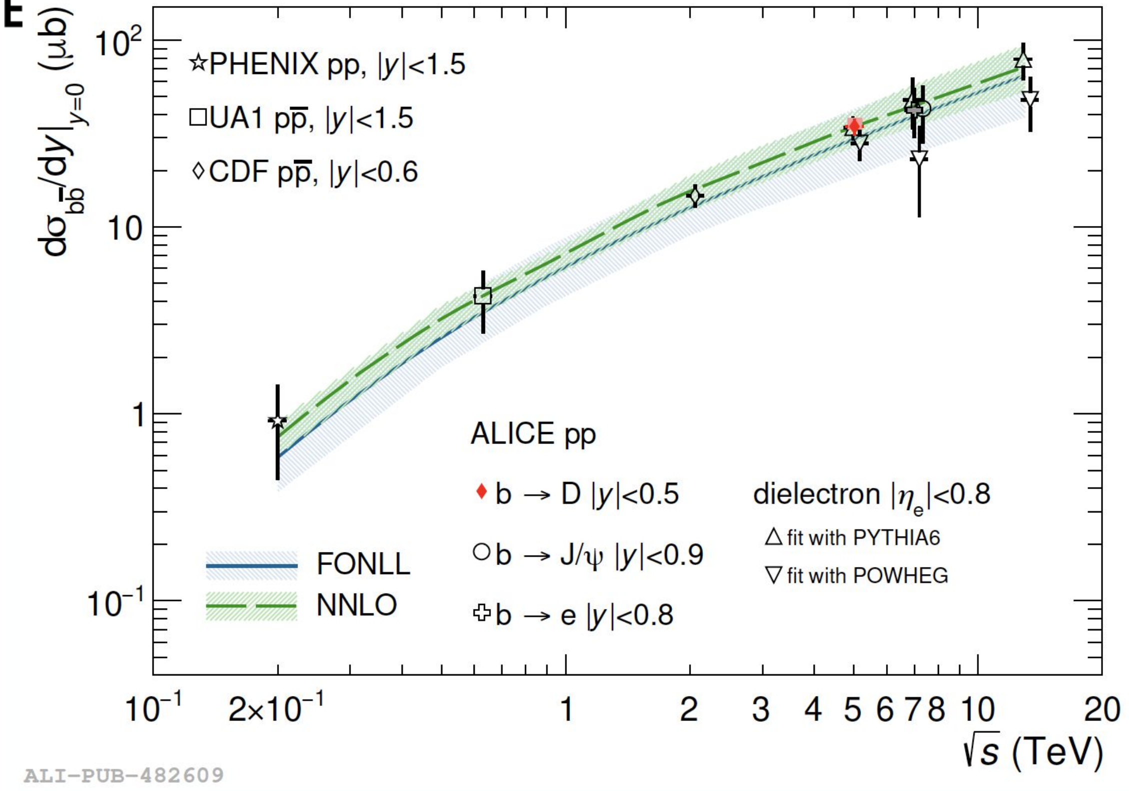




Monash tune significantly underestimates the data by a factor of about 20 in the low p_T region and by a factor of about 7 in the highest p_T interval

Ξ^+_c measured to be consistent with Ξ^0_c

Beauty production cross section at LHC



→ Measurements described over a wide range of energy by FONLL and the more precise NNLO calculations

ALICE Non-prompt D: arXiv:2102.13601

ALICE Non-prompt J/ψ: JHEP 11 (2015) 065

ALICE b→e: PLB 721 (2013) 13-23

ALICE Dielectrons: arXiv:2005.11995

PHENIX: PRL (2009) 103, 082002

UA1: PLB 256 (1991) 121–128

CDF: PRL 91 (2003) 241804

FONLL: JHEP 1210 (2012) 137

NNLO: JHEP 03 (2021) 029