Charmed baryon production and fragmentation fractions in pp collisions with ALICE

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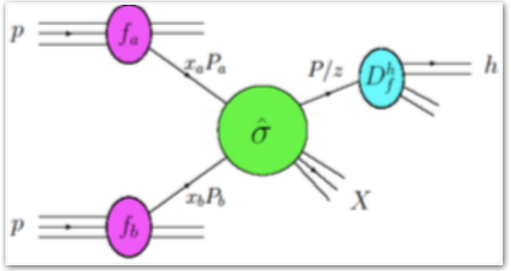
Heavy flavour production

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

initial state parton distribution function

pQCD partonic cross section

hadronization by fragmentation

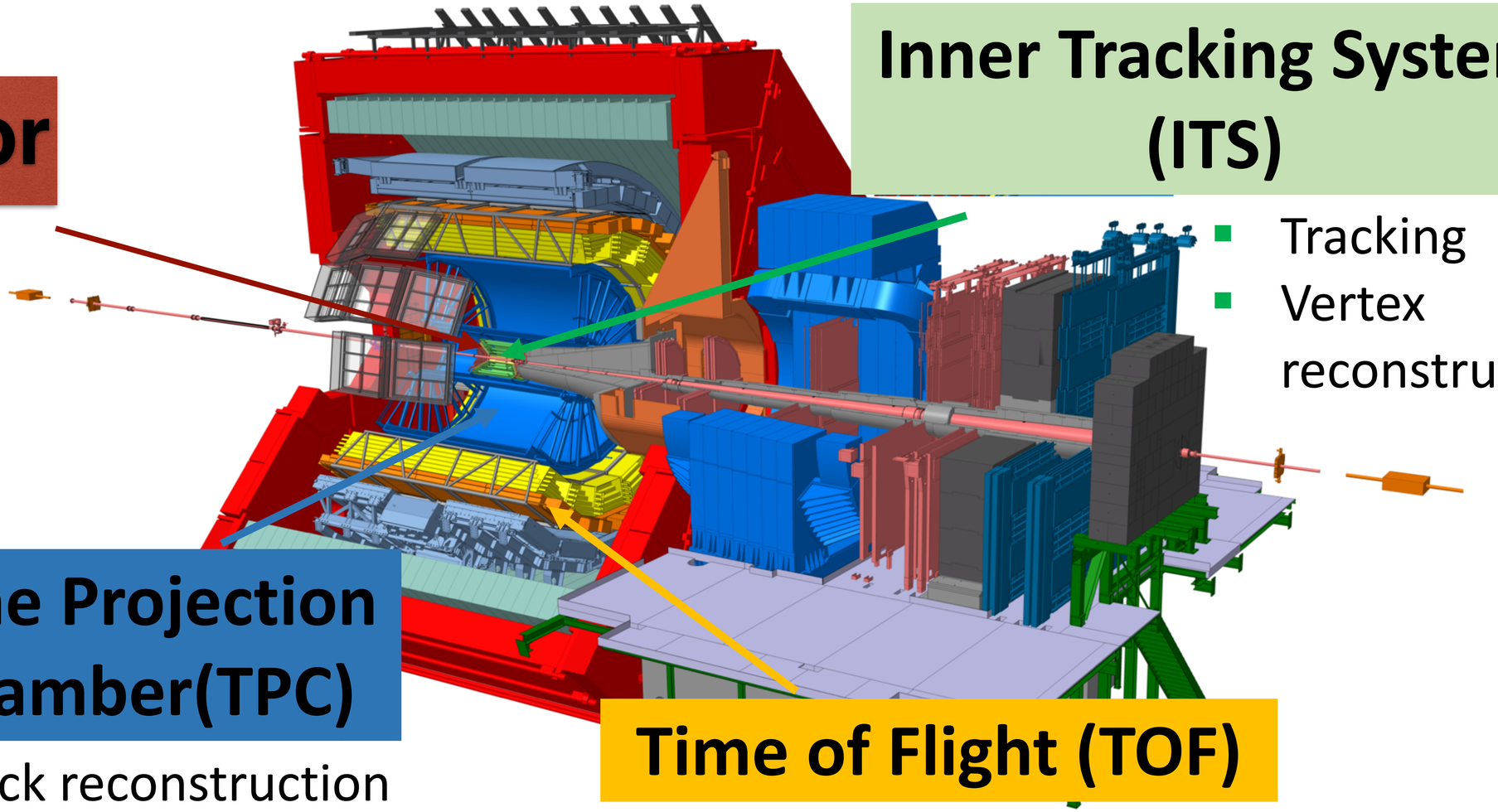


- pQCD models based on factorization approach use fragmentation functions measured in e^+e^- collisions considering them universal
- Charm baryons essential for total charm cross section and fragmentation fraction (FF) measurements
- Ratios of particle species: baryon-to-meson, baryon-to-baryon
  - Sensitive to HF quark hadronization

ALICE detector

V0 detector

- Event trigger



Inner Tracking System (ITS)

- Tracking
- Vertex reconstruction

Time Projection Chamber(TPC)

- Track reconstruction
- PID ($\mathrm{d}E/\mathrm{d}x$)

Time of Flight (TOF)

- PID (time-of-flight)

Charm-baryon reconstruction

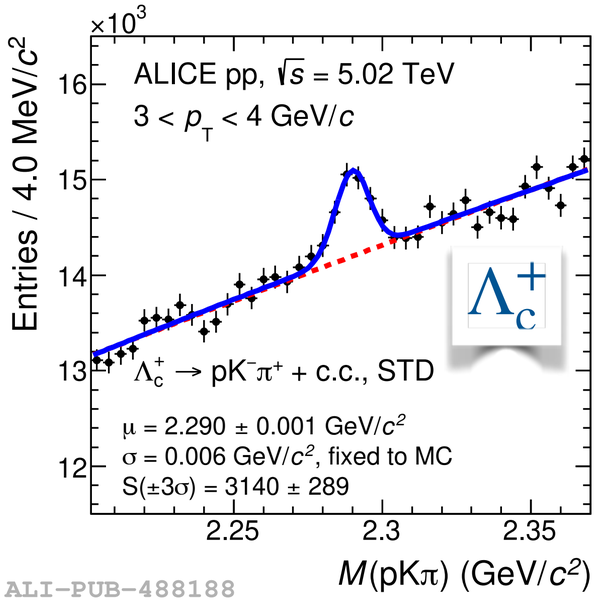
System	Year(s)	$\sqrt{s_{NN}}$(TeV)	L_{int}
pp	2017	5.02	~ 20 nb^{-1}
	2016-2018	13	~ 32 nb^{-1}
p-Pb	2016	5.02	~ 0.3 nb^{-1}

Hadronic decays:

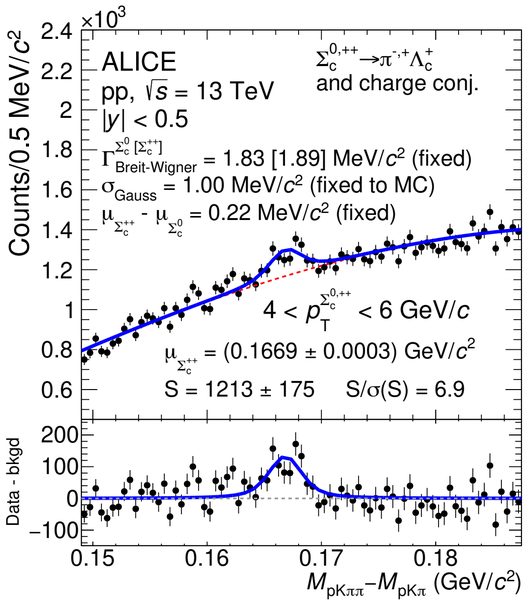
- $\Lambda_c^+ \to pK^-\pi^+$ & $\Lambda_c \to pK_s^0$
- $\Sigma_c^0 \to \Lambda_c^+\pi^-$ & $\Sigma_c^{++} \to \Lambda_c^+\pi^+$
- $\Xi_c^0 \to \Xi^-\pi^+$
- $\Xi_c^+ \to \Xi^-\pi^+\pi^+$
- $\Omega_c^0 \to \Omega^-\pi^+$

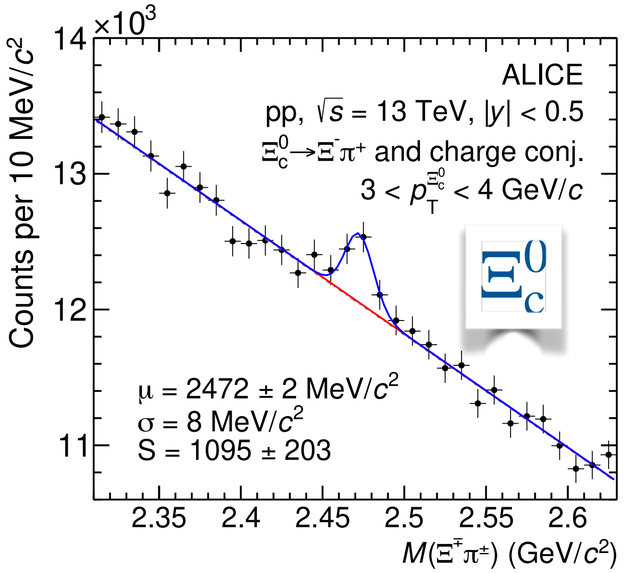
Semileptonic decays:

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



ALI-PUB-488188





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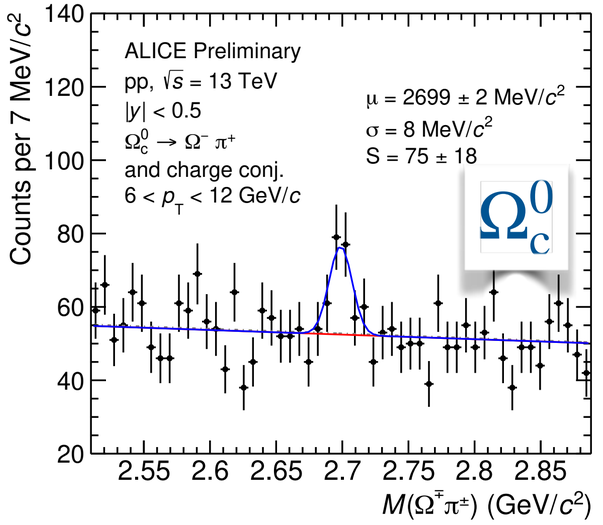
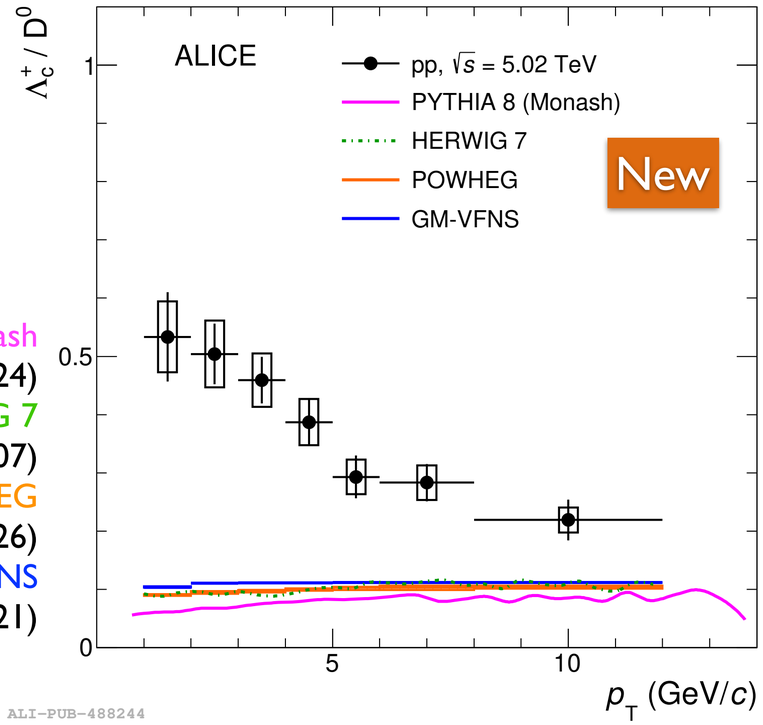


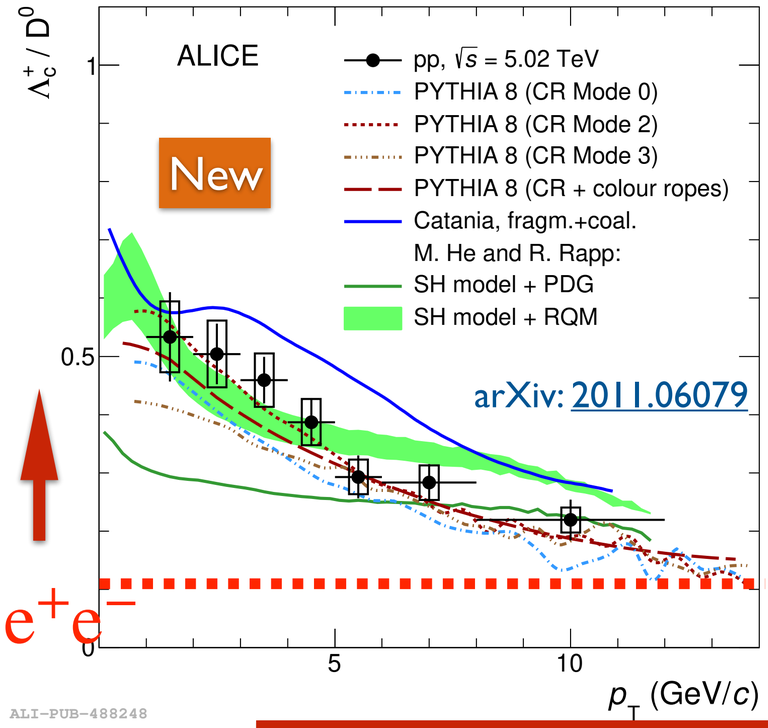
ALI-PREL-486622

Charm-baryons: Λ_c^+

- Λ_c/D^0 **in pp collisions at 5.02 TeV compared with models that enhance the baryon formation**
  - PYTHIA 8 with CR beyond leading color approximation (Mode 0, Mode 2, Mode3)
  - Catania with coalescence + fragmentation
  - M.He and R.Rapp+RQM: statistical hadronization model (SHM) approach

PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
HERWIG 7
(EPJC 58 (2008) 639-707)
POWHEG
(JHEP 09 (2007) 126)
GM-VFNS
(PRD 101 (2020) 114021)





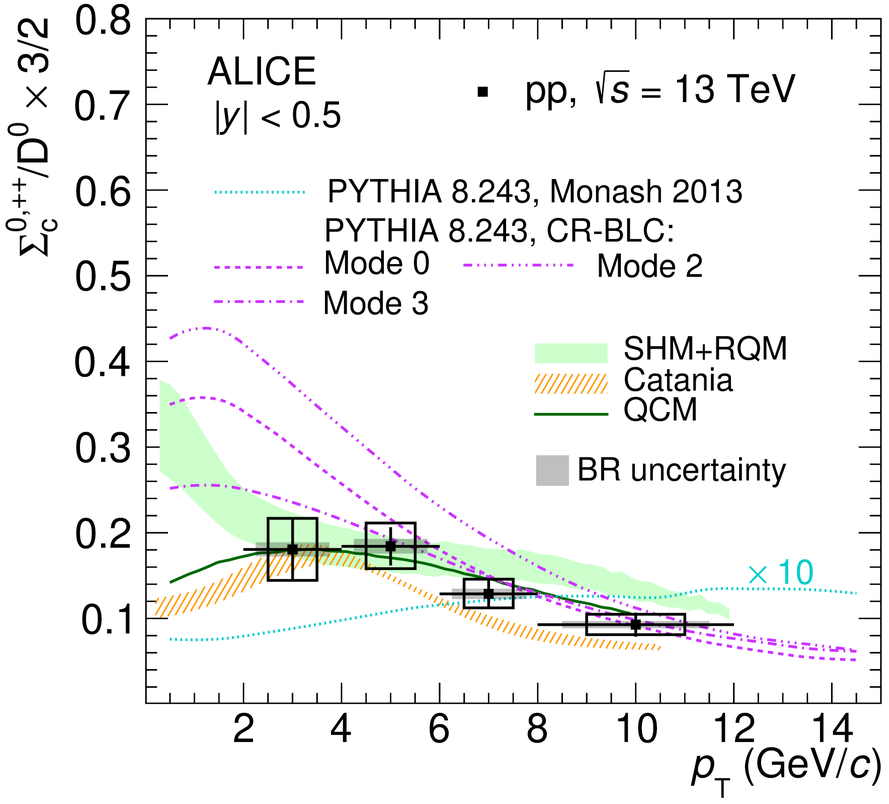
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
Catania
(arXiv: 2021.12001)
(EPJC 78 no. 4, (2018) 348)
M.He and R.Rapp
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)

- HERWIG 7 with hadronizationn implemented via clusters
- OWGHEG matched to PYTHIA 6 to generate parton shower
- GM-VFNS pQCD calculation: same choice of pQCD scales for Λ_c^+ and D^0

Charm baryon-to-meson ratio shows clear p_T dependence and is larger than e^+e^-

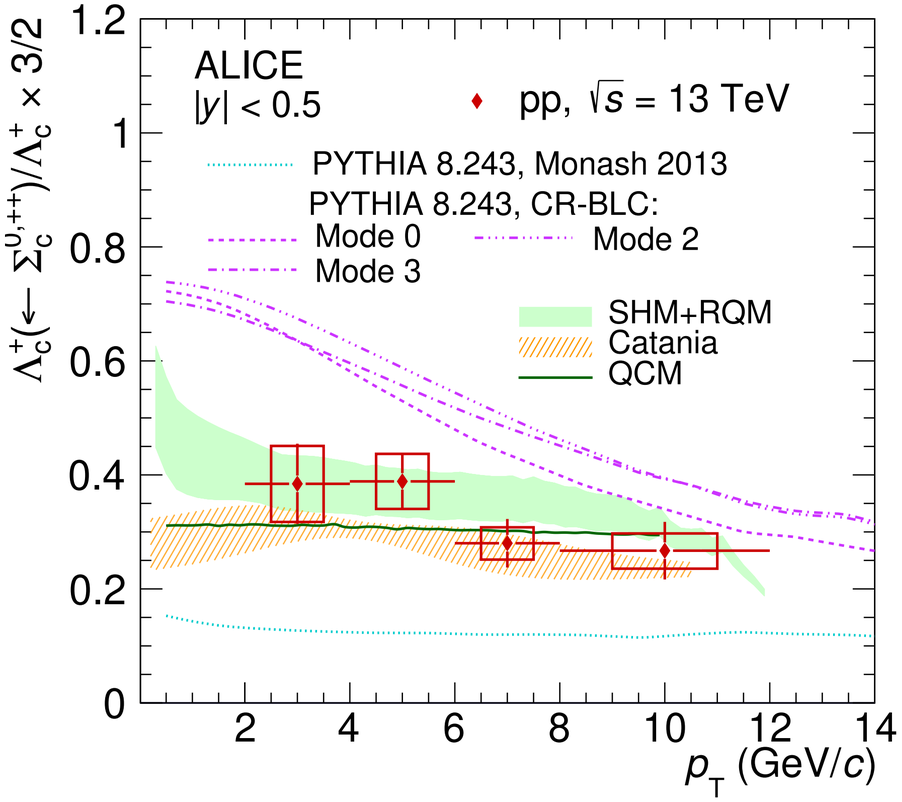
Charm-baryons: $\Sigma_c^{0,++}$

- **$\Sigma_c^{0,++}/D^0$ and $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ in pp collisions at 13 TeV**
  - $\Sigma_c^{0,++}/D^0$ partially accounts for the Λ_c^0/D^0 enhancement in pp collisions
  - $\Sigma_c^{0,++}/D^0$ is well described by SHM+RQM and QCM
  - $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ is overestimated by CR modes



ALI-DER-493901

arXiv: 1206.08278



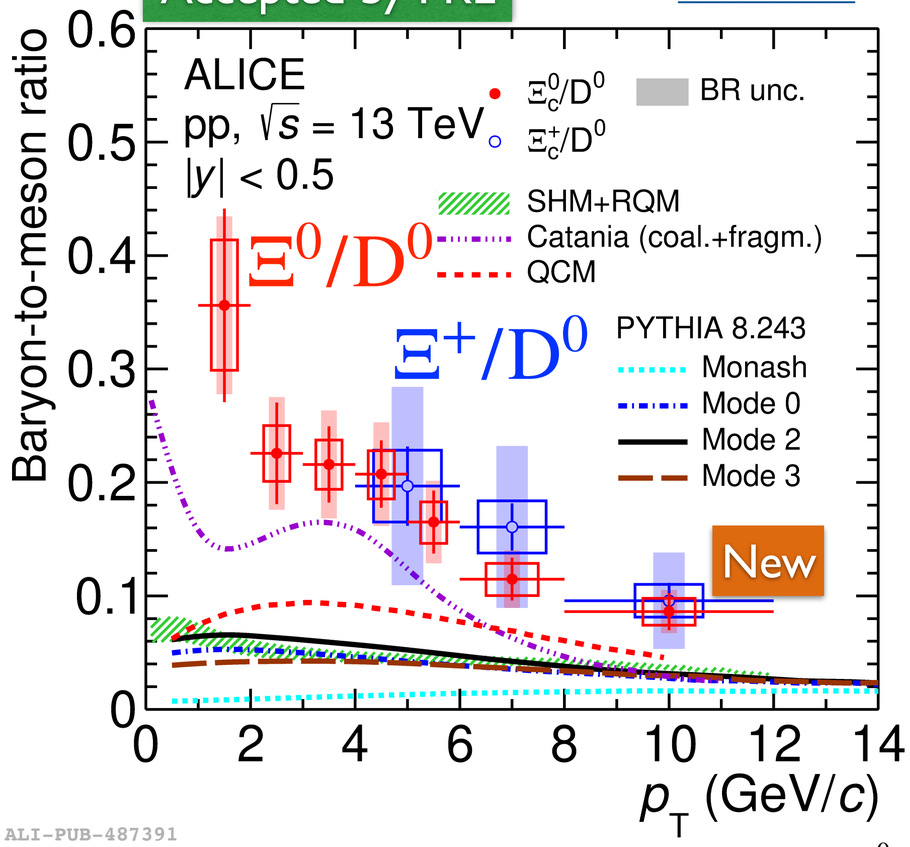
ALI-DER-493906

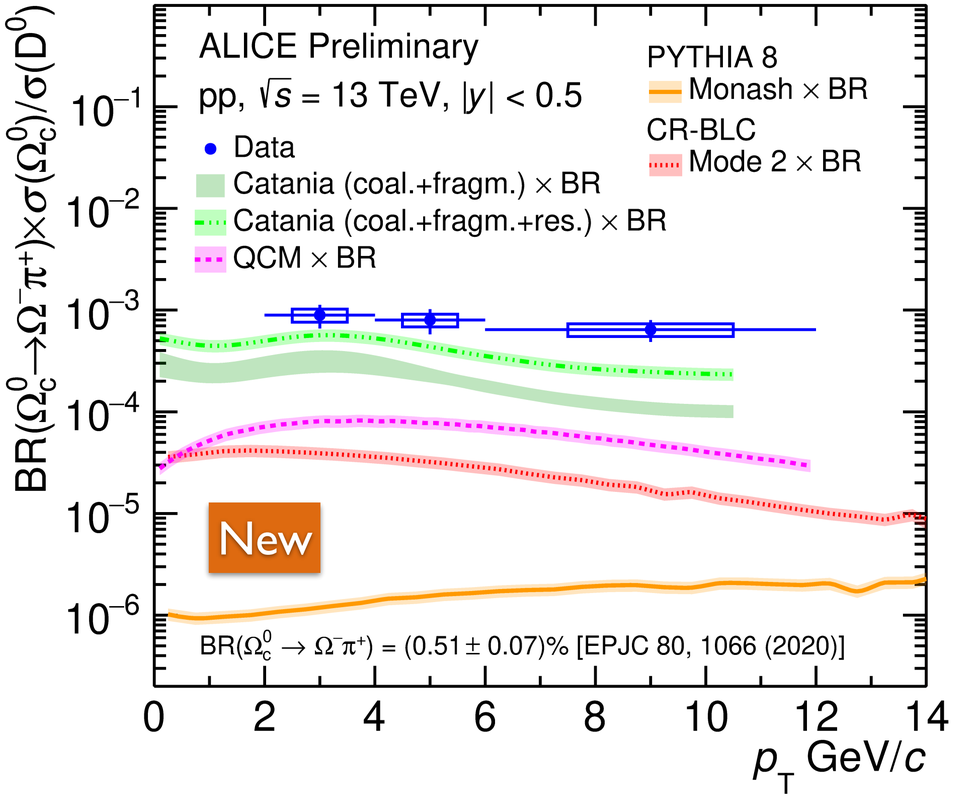
PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
(JHEP 08 (2015) 003)
SHM+RQM
(PLB 795 (2019) 117-121)
Catania
(arXiv: 2012.12001)
QCM
(EPJC 78 no.4, (2018) 344)

Charm-baryons: $\Xi_c^{0,+}$ & Ω_c^0

- $\Xi_c^{0,+}/D^0$, $(BR \times \Omega_c^0)/D^0$ **in pp collisions at 13 TeV**
  - PYTHIA 8: even with enhanced CR tunes, still underestimate the data
  - Coalescence models: largest Ω_c^0 enhancement

Accepted by PRL arXiv: 2105.05187





PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes(0,2,3)
(JHEP 08 (2015) 003)
SHM+RQM
(PLB 795 (2019) 117-121)
Catania
(arXiv: 2012.12001)
QCM
(EPJC 78 no.4, (2018) 344)

- $BR(\Omega_c^0 \to \pi^+\Omega^-) = (0.51 \pm 0.07)\,\%$ theoretical calculation (EPJC 80, 1006(2020))

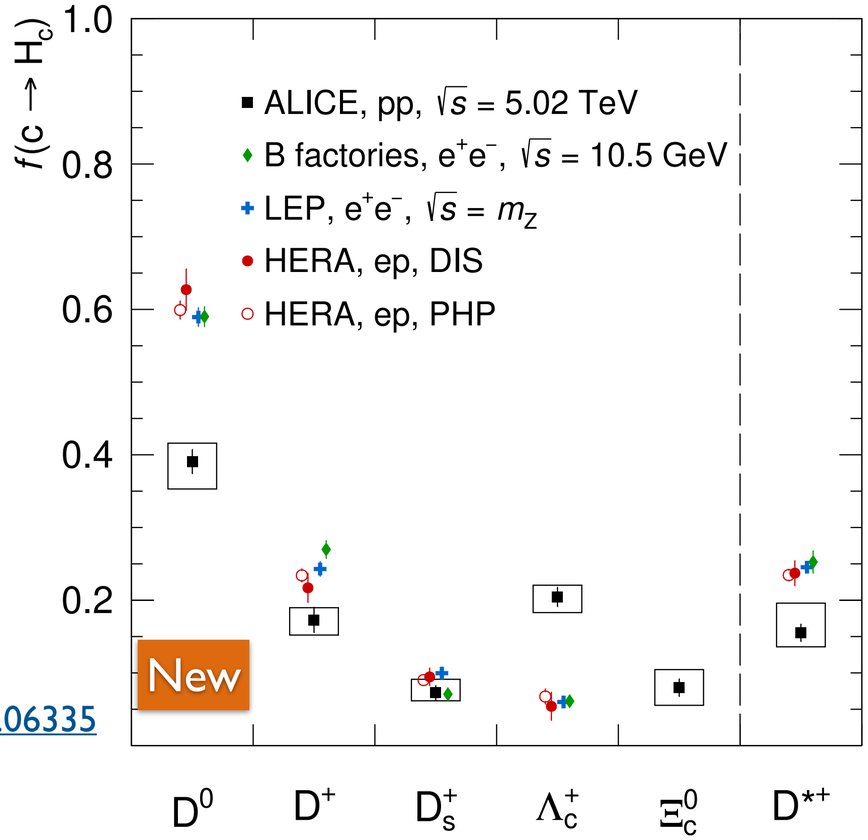
???

We measure now all single charm hadron ground states!

Are fragmentation functions **universal** across colliding systems?

Charm fragmentation fractions

- **Now** enable to measure charm FF and charm total cross section
  - D^0 and D^+ measured down to $p_{\mathrm{T}} = 0$
  - $\Xi^{0,+}$ included for the first time
  - Consider twice Ξ_{c}^0 contribution to included Ξ_{c}^+



arXiv: 2105.06335

ALI-PUB-488617

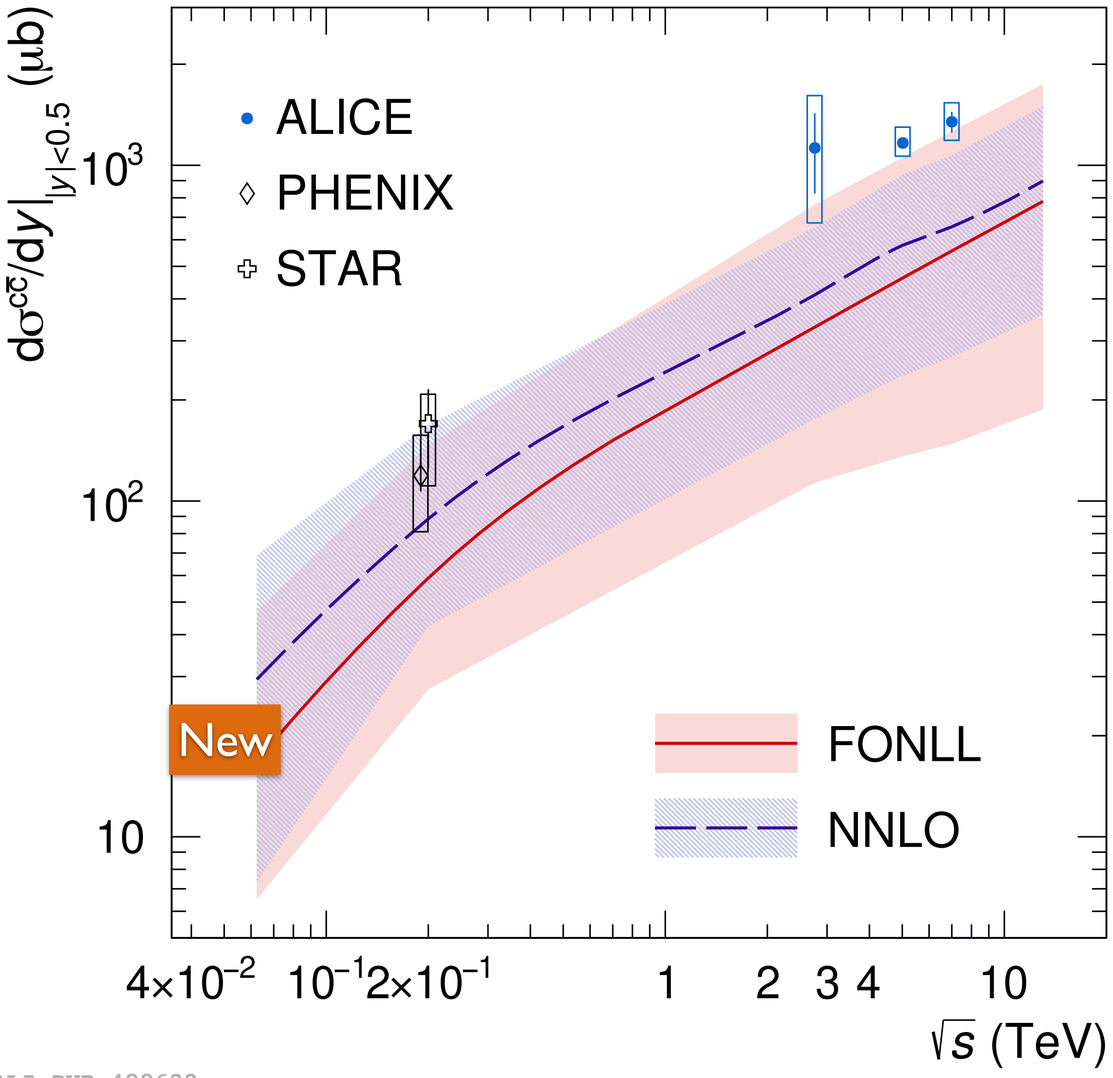
Fragmentation fraction $f(\mathrm{c} \to \mathrm{H_c})$ NOT universal
→Significant baryon enhancement in pp collisions

$\mathrm{H_c}$	$f(\mathrm{c} \to \mathrm{H_c})[\%]$
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^{*+}	$15.5 \pm 1.2(\mathrm{stat})^{+4.1}_{-1.9}(\mathrm{syst})$

- Sum of FFs add up to unity, not counting here D^{*+}, which feeds into D^0, D^+

Charm total production cross section

arXiv: 2105.06335



ALI-PUB-488622

- **First measurement total charm cross section in pp at 5.02 TeV**

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

- Results previously published in pp @2.76 and 7 TeV from D mesons

  updated with fragmentation fractions from 5.02 TeV analysis

  - 40% higher (pp@2.76 TeV JHEP 07 (2012) 191
    pp@7 TeV EPJC 77 no. 8, (2017) 550)

- Results on upper edge of FONLL and NNLO calculations

FONLL (JHEP 1210 (2012) 137)
NNLP PRL 118 (2017), JHEP 03 (2021) 029
PHENIX Phys. Rev. C 84 (2011) 044905
STAR Phys. Rev. D 86 (2012) 072013

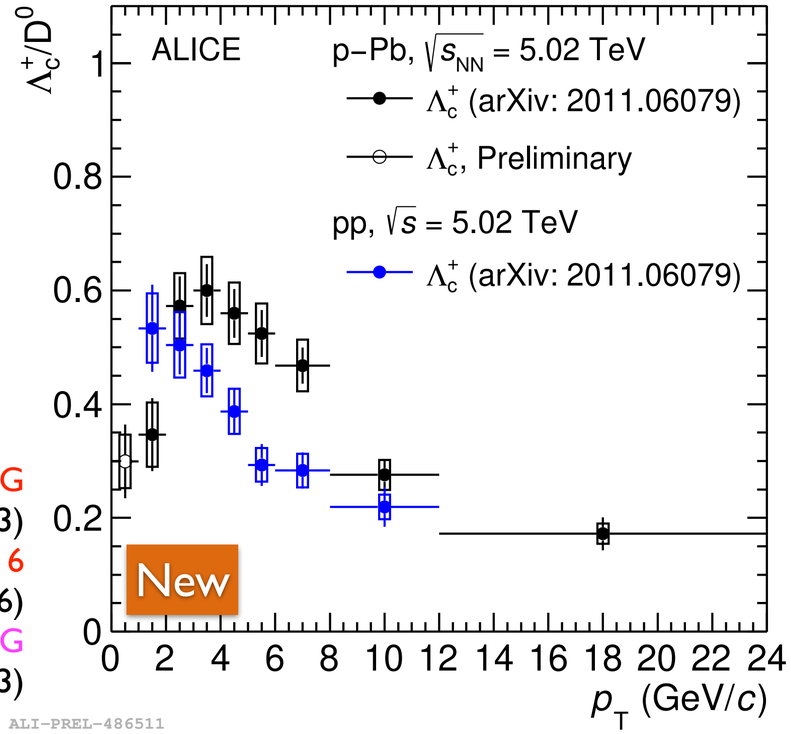
Baryon-to-meson ratio in p-Pb and Λ_c^+ R_{pPb}

- **First measurement of Λ_c^+ down to p_T = 0 in p-Pb collisions**
  - Λ_c^+/D^0: larger in mid-p_T and lower in $p_T < 2$ GeV/c in p-Pb collisions w.r.t. pp collisions
  - $R_{pPb}(\Lambda_c^+)$: systematically above unity in $p_T > 2$ GeV/c

    but significant suppression in $p_T < 2$ GeV/c

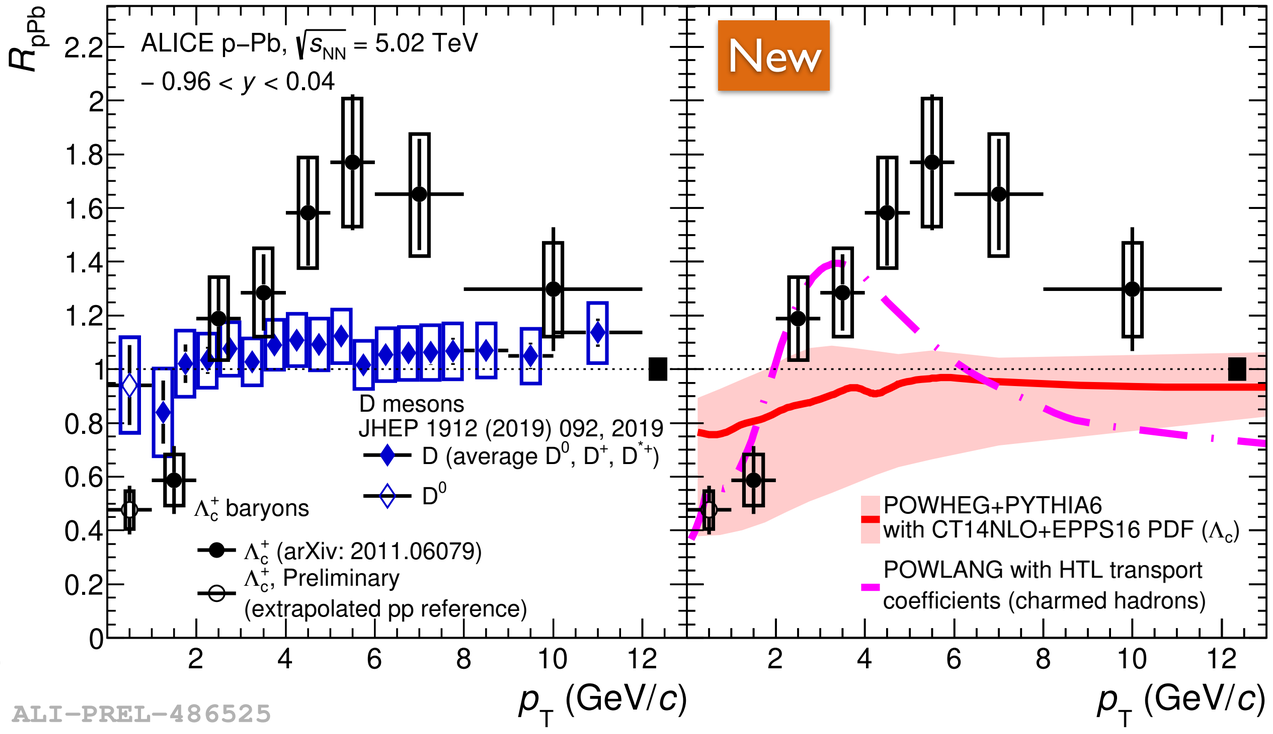
    ➡ Possible modification due to radial flow or hadronization mechanism?

arXiv: 2011.06079



ALI-PREL-486511

POWHEG (EPJC 77 no. 3, (2017) 163)
PYTHIA 6 (JHEP 09 (2007) 126)
POWLANG (JHEP 03 (2016) 123)



ALI-PREL-486525

Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0 production cross section in pp at 13 TeV
- First measurement of Λ_c^+ down to $p_T = 0$ in p-Pb at 5.02 TeV at the LHC

- Large enhancement of all charm-baryon production in pp collisions than e^+e^- collisions
- Charm fragmentation fractions are NOT universal
- Total charm cross section in pp@ 5.02 TeV using all measured charm hadron states

- ALICE upgrade for Run3/4 will offer the opportunity to further investigate the charm-baryon production

Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0 prod ection in pp at 13 TeV
- First measurement of Λ_c^+ down to $p_T =$ at the LHC

- Large enhancement of all charm n e^+e^- collisions
- Charm fragmentation fracti
- Total charm cross section n adron states

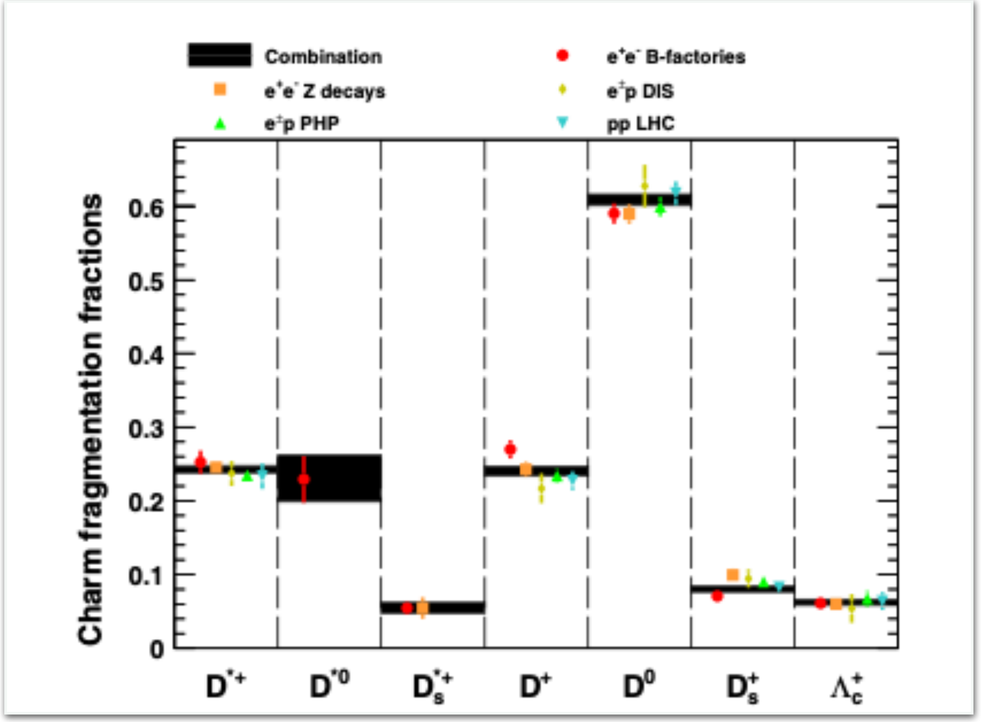
THANK YOU!

- ALICE upgrade for Run3/4 will offer investigate the charm-baryon production

Additional Slides

Charm FF in e^+e^- & ep

Eur. Phys. J, C76 (2016) no.7, 397

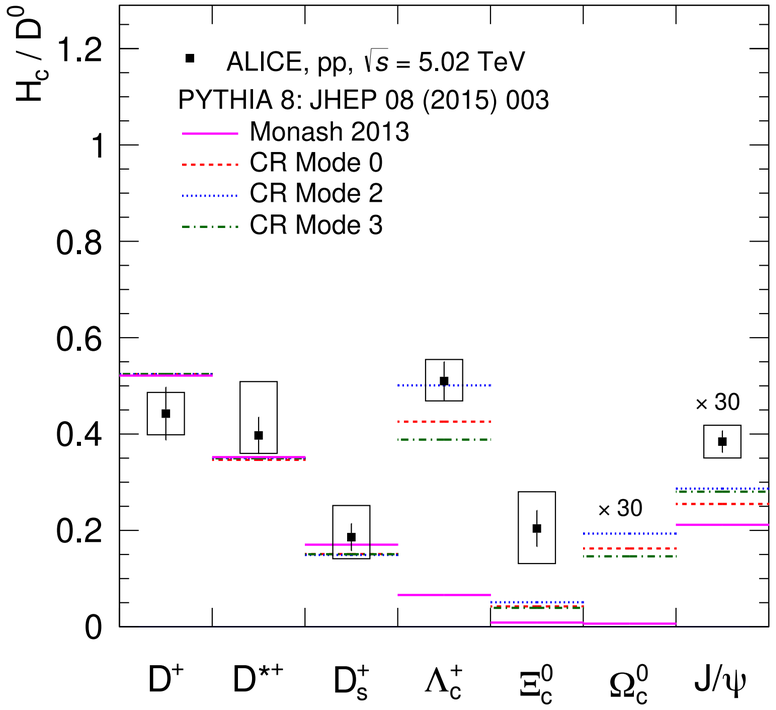


- In 2015, only LHCb Λ_c^+ measurement available at LHC for charm baryons
  - Consistent with e^+e^- - - - FF universal
- Caveat
  - No measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c)$, and $\sigma(\Omega_c)$
- But now we have all of them in ALICE

Charm H_c/D^0 ratios

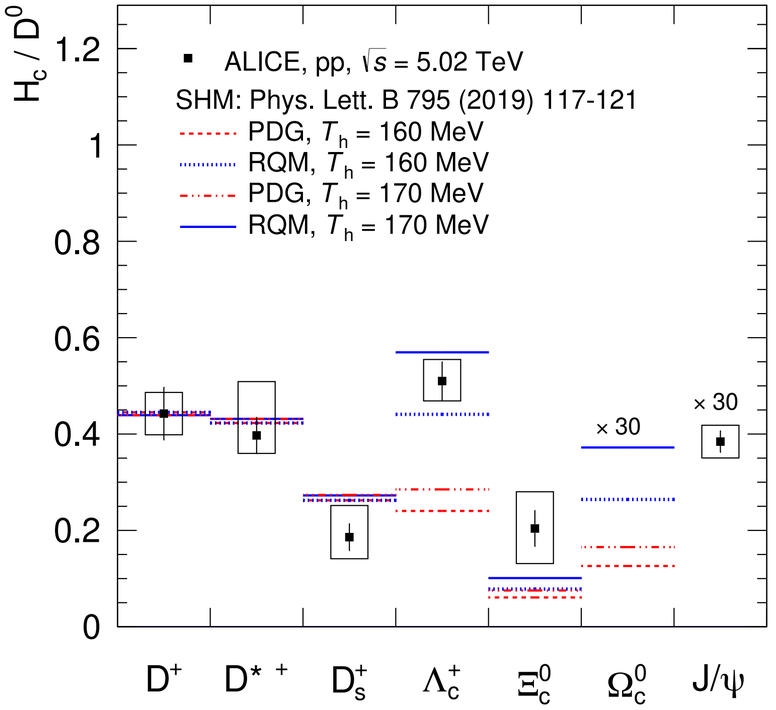
- PYTHIA 8 with different tunes similar for D mesons and describe measurements within uncertainties
- Large effect found in PYTHIA 8 CR-BLC for charm baryons formation
- SHM for charm mesons: small variations with two T_c and consistent with measurements
- SHM for charm baryons: significant variations with two T_c and large variations with RQM

arXiv: 2105.06335



ALI-PUB-488607

arXiv: 2105.06335



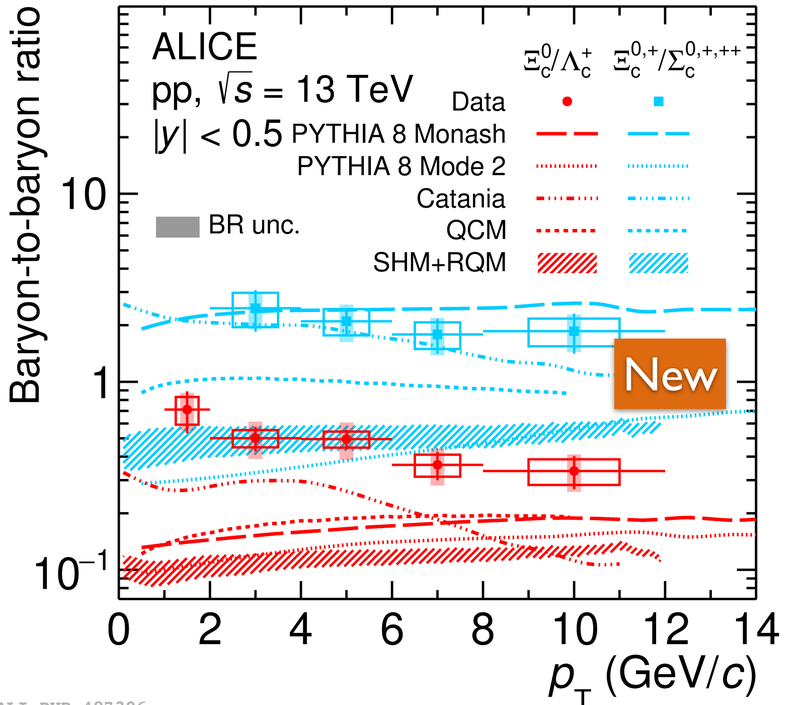
ALI-PUB-488612

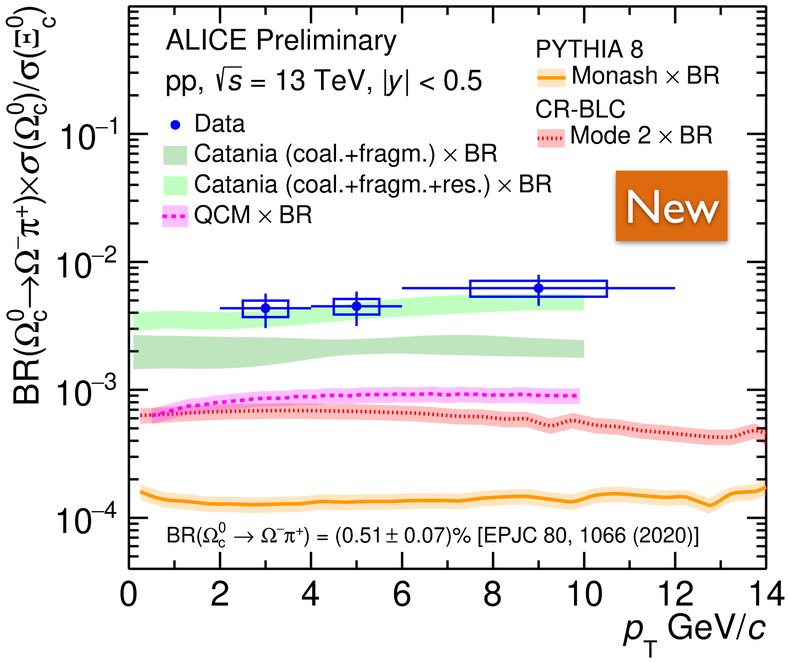
Charm-baryon $\Xi_c^{0,+}$ & Ω_c^0

- Ξ_c^0/Λ_c^+, $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$, $(BR \times \Omega_c^0)/D^0$ **in pp collisions at 13 TeV**
  - $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$: Catania and Monash describe the magnitude
- **First** measurement of charm baryon-to-baryon yield ratios at the LHC
- Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$, further enhancement for Ω_c^0 w.r.t e^+e^- collisions

PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes(0,2,3)
(JHEP 08 (2015) 003)
SHM+RQM
(PLB 795 (2019) 117-121)
Catania
(arXiv: 2012.12001)
QCM
(EPJC 78 no.4, (2018) 344)

arXiv: 1205.05187



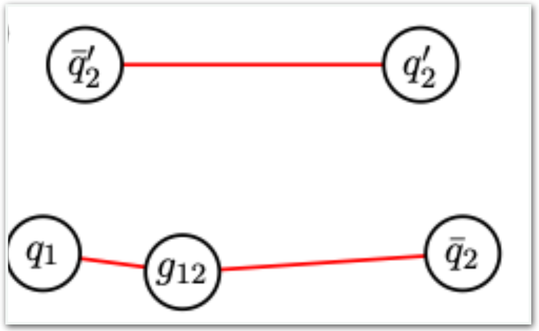


- $BR(\Omega_c^0 \to \pi^+\Omega^-) = (0.51 \pm 0.07)\,\%$ theoretical calculation (EPJC 80, 1006(2020))

HF baryon enhancement mechanism

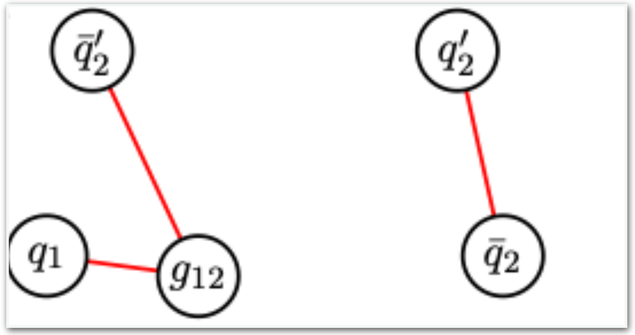
- **PYTHIA 8 with Colour Reconnection (CR) tunes** JHEP 08 (2015) 003
  - Colour reconnection mode with QCD SU(3) topology weights + string-length minimization
  - Junction connection topologies enhance baryon formation
  - Mode parameters: string reconnection, connection causality of dipoles, time dilation

No CR



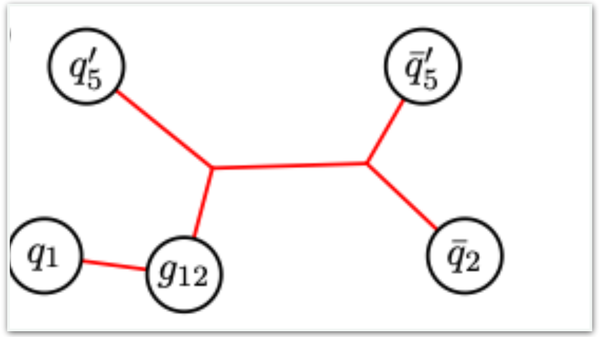
- Partons created in different MPIs do not interact

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 configuration
- Enhancement of hadrons
- Used in CR mode X tunes

HF baryon enhancement mechanism

- **Statistical Hadronization Model (SHM) + additional baryon states** PLB 795 (2019) 117-121
  - PDG: 5 Λ_c(I=0), 3 Σ_c(I=1), 8 Ξ_c(I=1/2), 2 Ω_c (I=0)
  - RQM (Relativistic Quark Model): Add 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c PRD 84 (2011) 014025

- **Quark Recombination Mechanism (QCM)** EPJC 78 no. 4 (2018) 344
  - Combination of charm quarks with co-moving light quarks

- **Catania model** arXiv: 2012.12001
  - Coalescence process of heavy quarks with light quark based on the Winger formalism + fragmentation process
  - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra

Charmed baryons

Particle	Mass	Valence quarks
Λ_c^+	2.286	udc
$\Sigma_c^{0,++}$	2.455	ddc, uuc
Ξ_c^+	2.467	usc
Ξ_c^0	2.471	dsc
Ω_c^0	2.695	ssc
Ξ_c^{++}	3.621	ucc