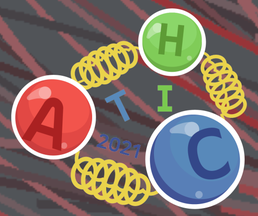


The 8th Asian Triangle Heavy-Ion Conference (ATHIC 2021)

Charm-baryon production and fragmentation fractions in pp collisions with ALICE

Jinjoo Seo
on behalf of the ALICE Collaboration

2021. 11. 07

ALICE

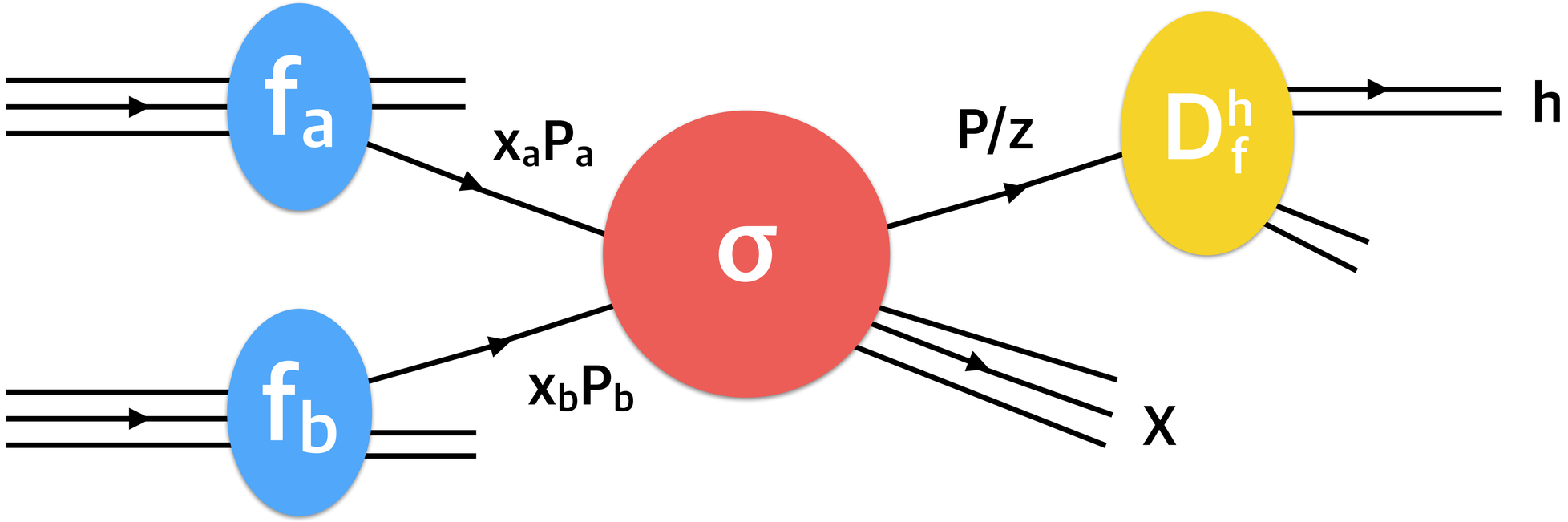
Heavy-flavour production

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

Initial state
Parton distribution function

pQCD partonic cross section

Hadronisation by fragmentation



- **pp collisions:** Test for pQCD calculations, baseline for nuclear collisions.

Heavy-flavour production

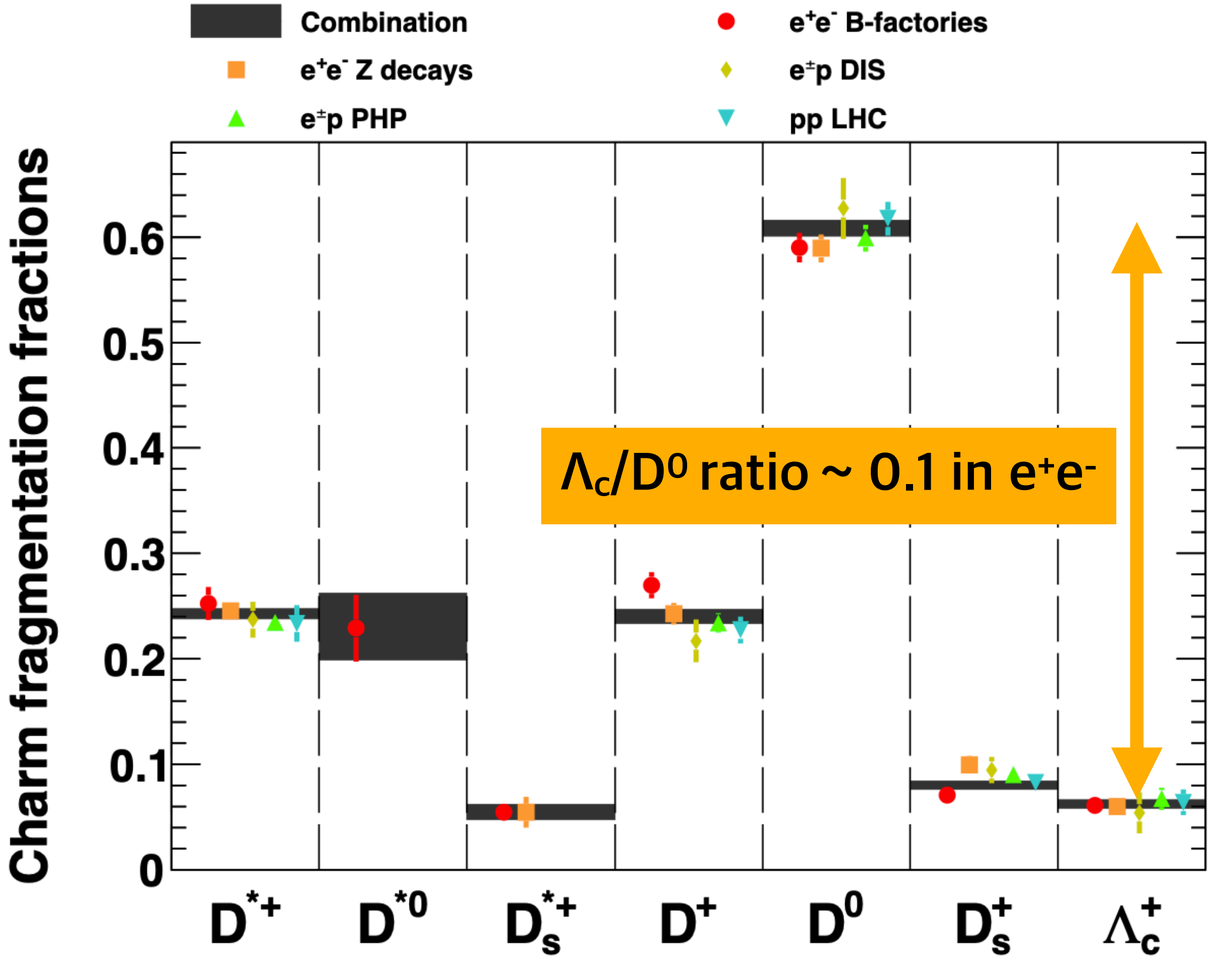
- **Charm fragmentation fraction**

$$f(\mathrm{c} \to \mathrm{H}) = \sigma(\mathrm{H})/\Sigma_{\mathrm{H}}\sigma(\mathrm{H})$$

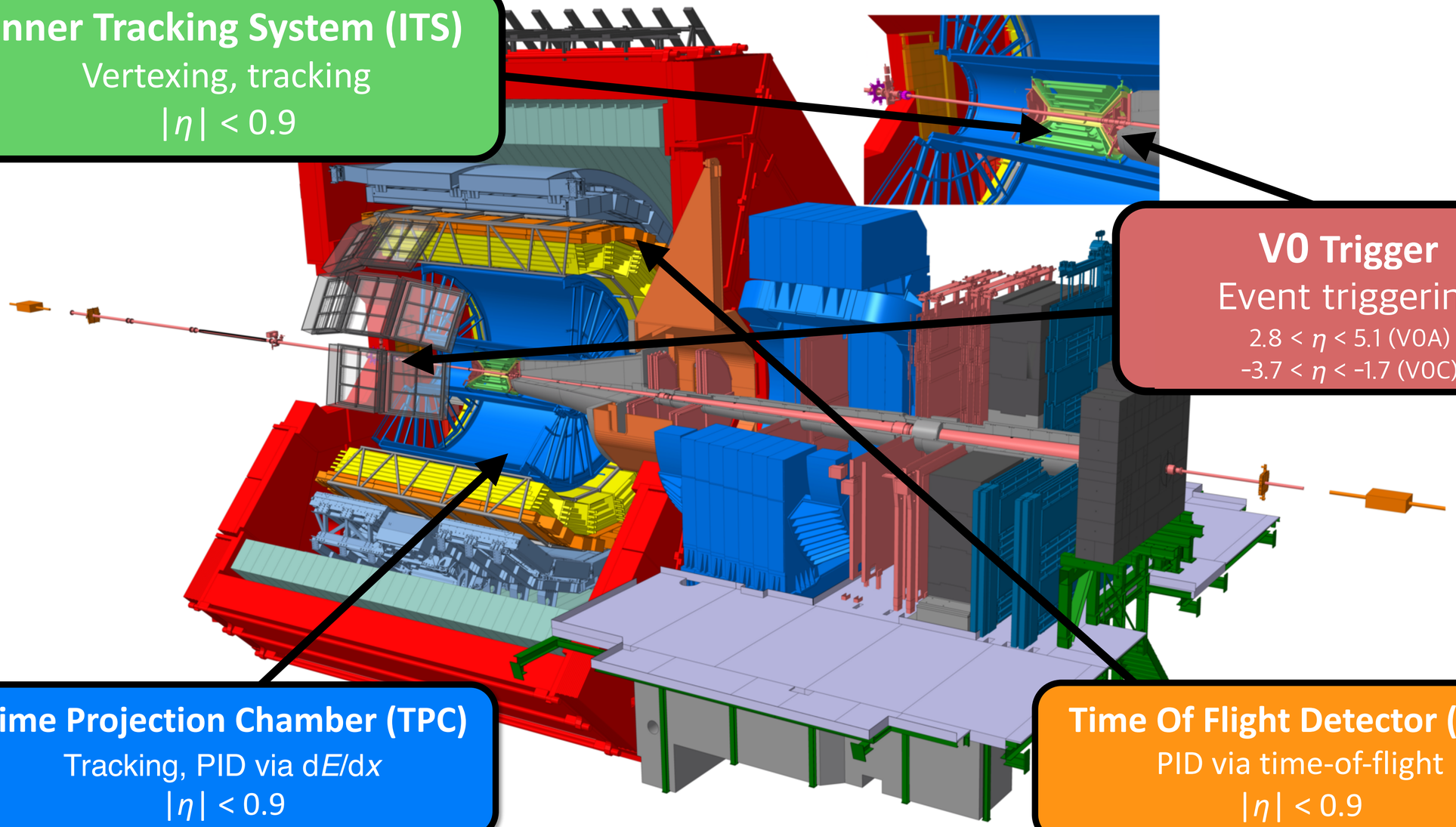
  - Measurements in different collision systems and at different energies agree within uncertainties.
    - ➡ Support the hypothesis that fragmentation functions are independent of the collision systems?

- **Caveat**
  - In 2015, only LHCb Λ_c^+ measurement available.
    - Rapidity range : $2.0 < y < 4.5$

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



ALICE Detector



Inner Tracking System (ITS)
Vertexing, tracking
$|\eta| < 0.9$

V0 Trigger
Event triggering
$2.8 < \eta < 5.1$ (V0A)
$-3.7 < \eta < -1.7$ (V0C)

Time Projection Chamber (TPC)
Tracking, PID via dE/dx
$|\eta| < 0.9$

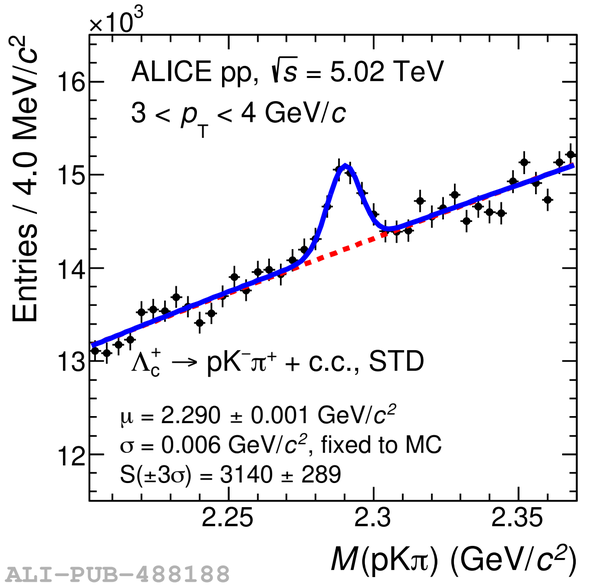
Time Of Flight Detector (TOF)
PID via time-of-flight
$|\eta| < 0.9$

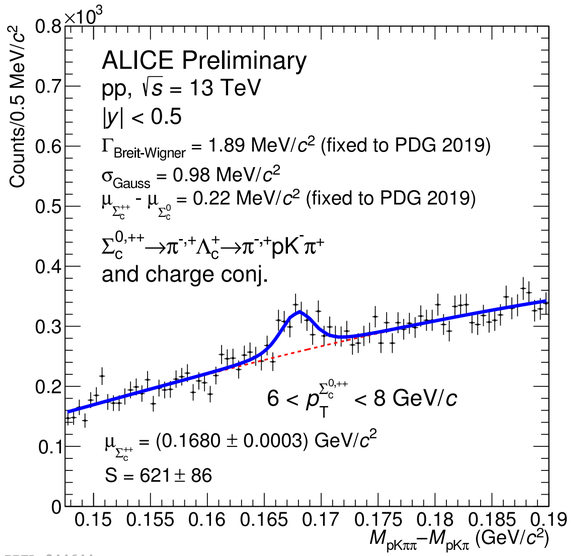
Charm-hadron in ALICE

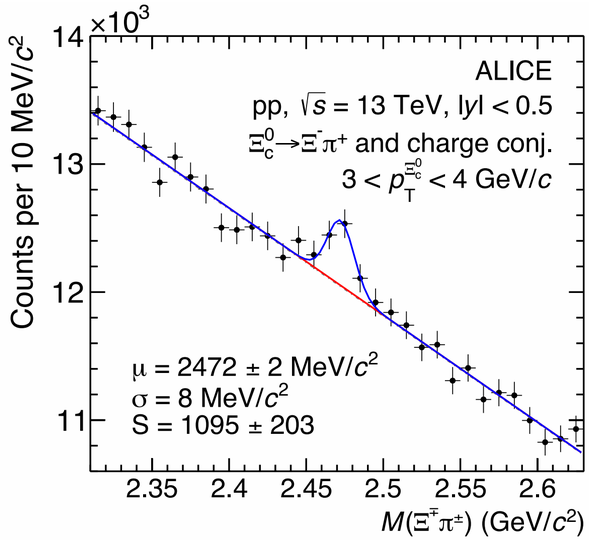
- **Data samples (Run 2)**

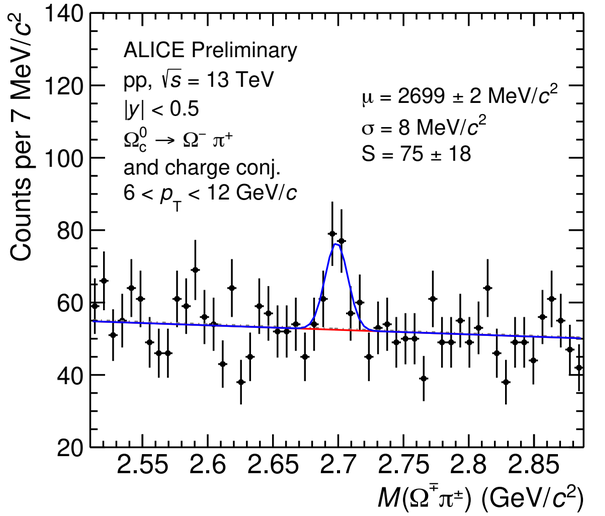
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2017	5.02	~20 nb^{-1}
	2016-2018	13	~32 nb^{-1}
p-Pb	2016	5.02	~0.3 nb^{-1}

- **Hadronic decay**
  - $D^0 \to K^-\pi^+$
  - $D^+ \to K^-\pi^+\pi^+$
  - $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
  - $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$
  - $\Lambda_c^+ \to pK^-\pi^+$ **&** $\Lambda_c^+ \to pK_S^0$
  - $\Sigma_c^{0,++} \to \Lambda_c^+\pi^{-,+}$
  - $\Xi_c^0 \to \Xi^-\pi^+$
  - $\Xi_c^+ \to \Xi^-\pi^+\pi^+$
  - $\Omega_c^0 \to \Omega^-\pi^+$
- **Semileptonic decay**
  - $\Lambda_c^+ \to \Lambda e^+\nu_e$
  - $\Xi_c^0 \to \Xi^- e^+\nu_e$





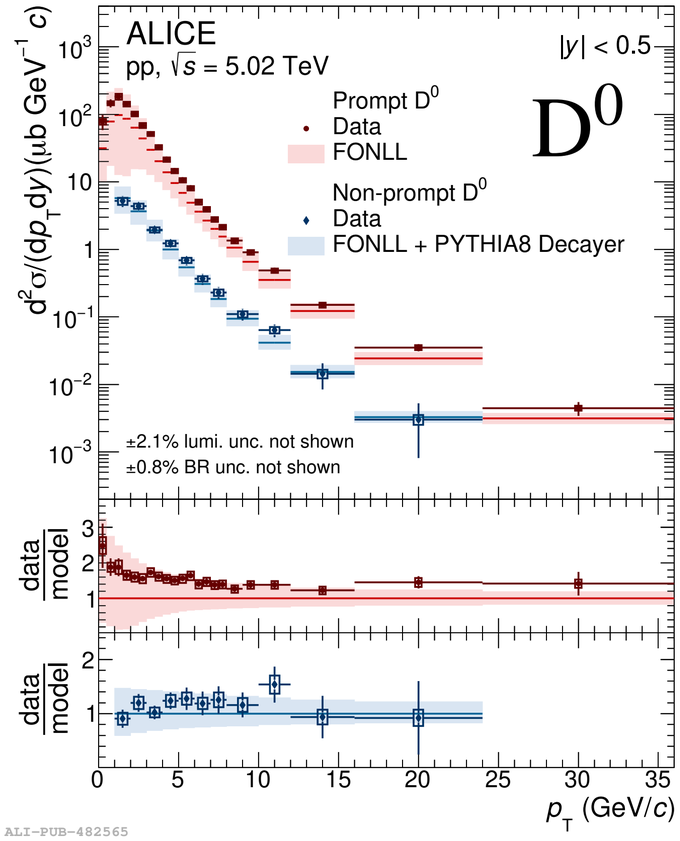


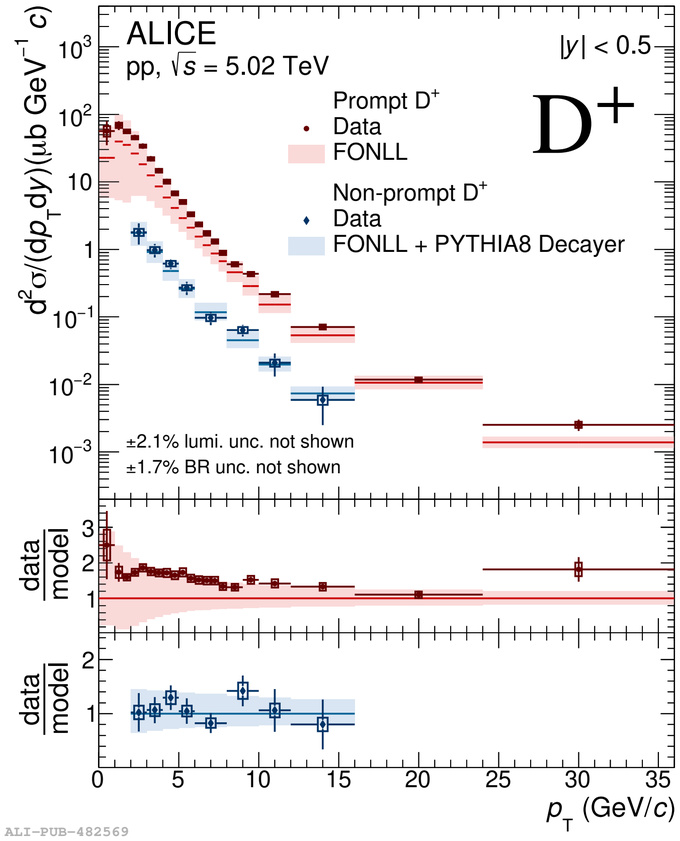


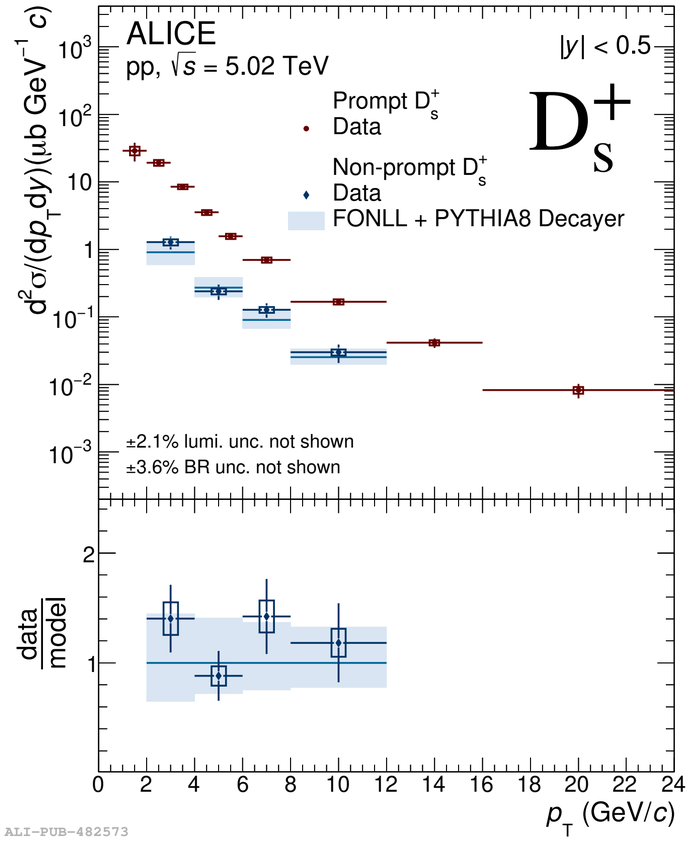
Charm-meson production

- **Comparison of p_T-differential production cross section of D meson with models**
  - **FONLL** : Fixed Order with Next to Leading Log resummation JHEP (2012) 137
    - ➡ **NLO pQCD calculation with fragmentation functions from e^+e^- can describe the charm-meson production!**

JHEP 05 (2021) 220





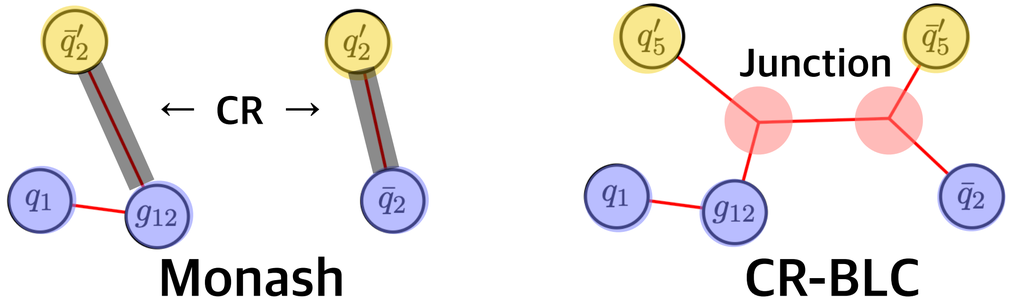


Λ_c^+ measurements in ALICE

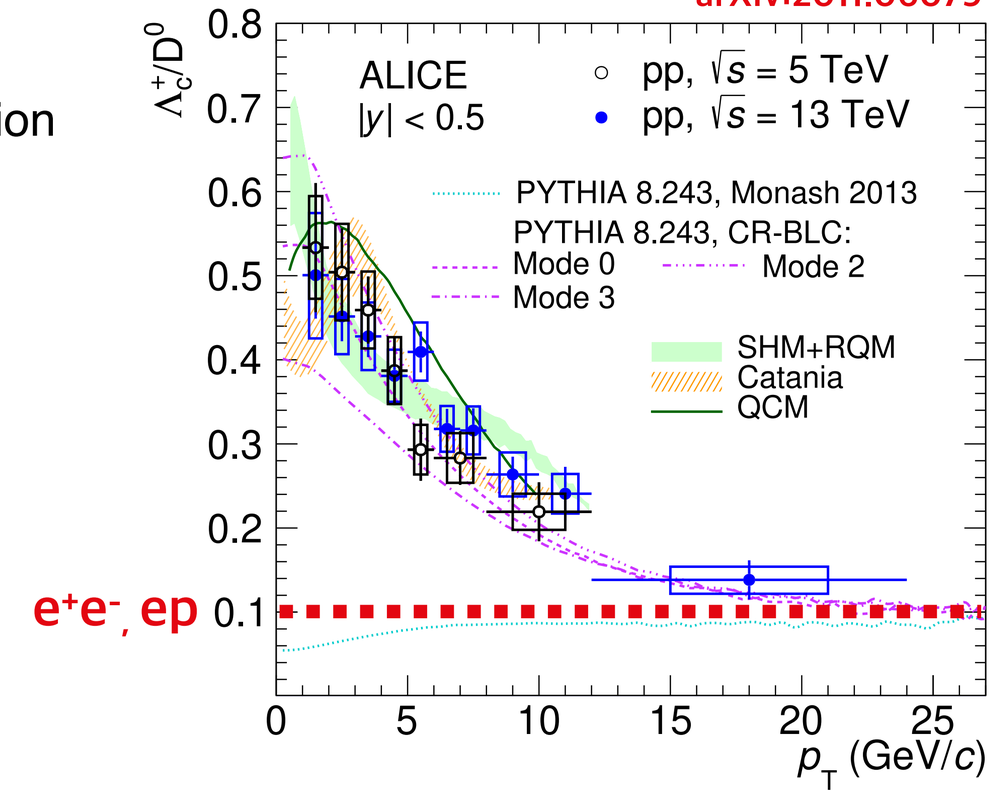
- Λ_c^+/D^0 **in pp collisions at 5.02 TeV and 13 TeV**
  - **PYTHIA 8, Monash** : Colour reconnection between partons from different multi-parton interactions.

✓ **Predict baryon enhancement**

- **PYTHIA 8, CR-BLC** : CR with Junction connection topologies enhance baryon formation.



arXiv:2011.06079



e⁺e⁻, ep

PYTHIA 8 Monash
(EPJC 74 (2014) 3024)
PYTHIA 8 CR-BLC
(JHEP 08 (2015) 003)
Catania
(arXiv:2012.12001)
SHM
(PLB 795 (2019) 117-121)
RQM
(PRD 84 (2011) 014025)
QCM
(EPJC 78 no.4, (2018) 344)

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✓ **Predict baryon enhancement**

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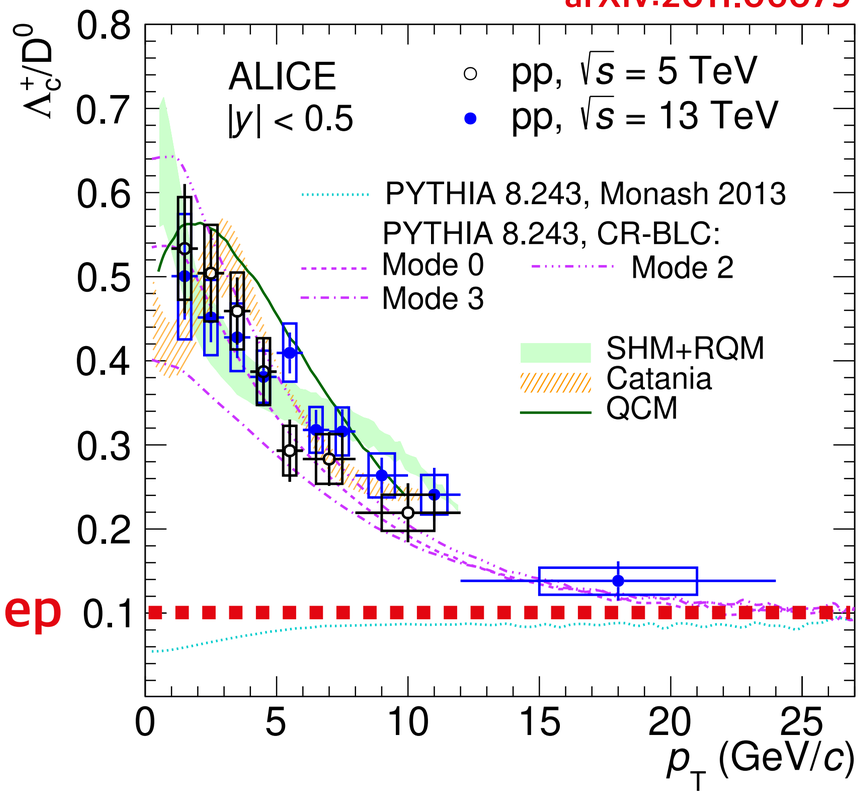
  - **SHM + RQM** : Consider additional excited charm baryon states expected by the RQM.

- **Statistical Hadronisation Model (SHM) + additional baryon states**
  - **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

arXiv:2011.06079



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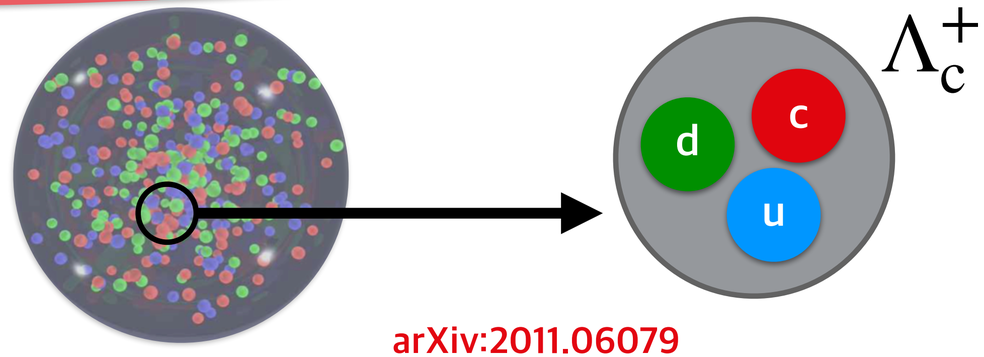
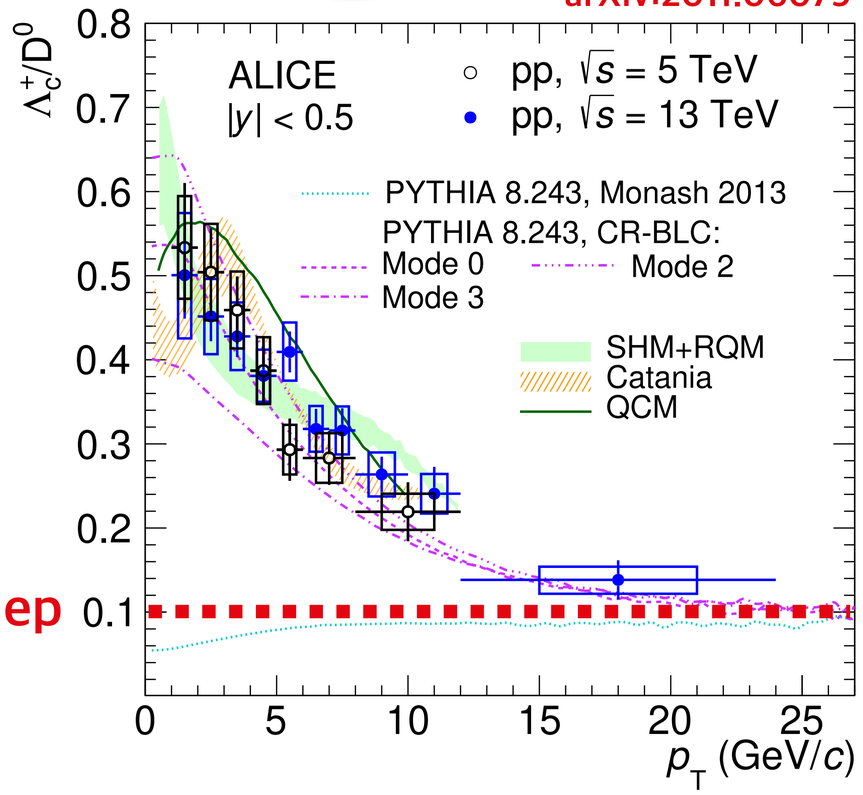
✓ **Predict baryon enhancement**

  - **PYTHIA 8, CR-BLC** : CR with Junction connection topologies enhance baryon formation.
  - **SHM + RQM** : Consider additional excited charm baryon states expected by the RQM.
  - **Catania** : Hadronisation via vacuum fragmentation + coalescence of charm quark with light quarks in a hot QCD matter.
  - **QCM** : Combination of charm quarks with co-moving light quarks



arXiv:2011.06079



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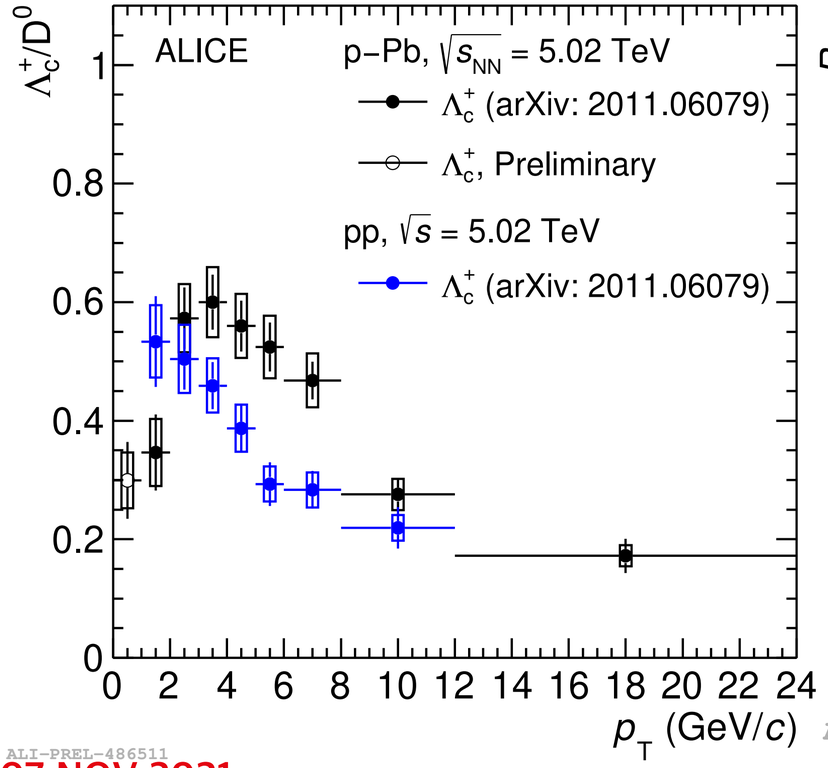
(EPJC 78 no.4, (2018) 344)

Λ_c^+ measurements in ALICE

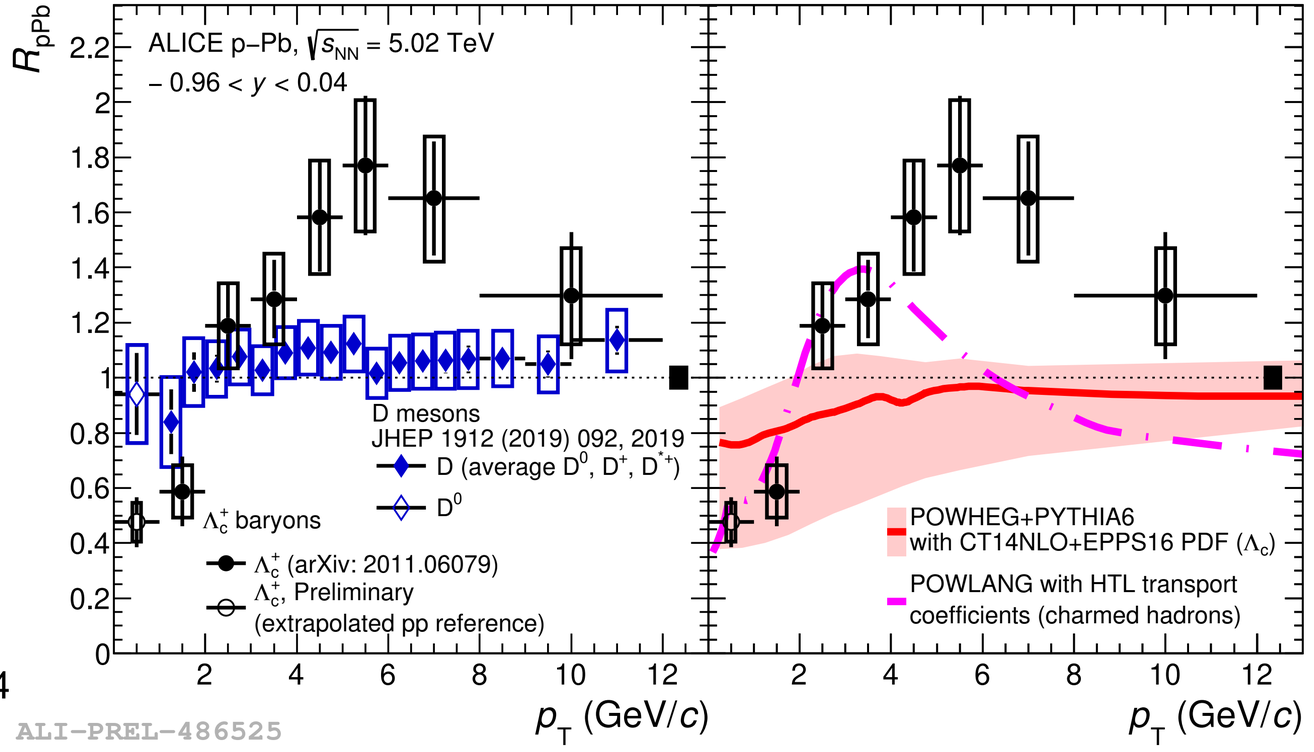
- Λ_c^+ **down to p_T = 0 in p-Pb collisions**
  - Λ_c^+/D^0 : larger in $3 < p_T < 8$ GeV/c and a lower in $p_T < 2$ GeV/c in p-Pb collisions with respect to pp collisions.
  - R_{pPb} : Systematically above unity in $p_T > 2$ GeV/c, below unity in $p_T < 2$ GeV/c.
    - **Significant suppression for the Λ_c^+ baryon in p-Pb collisions in $p_T < 2$ GeV/c**

➡ **Possible modification due to radial flow or hadronisation mechanisms**

arXiv:2011.06079



ALI-PREL-486511



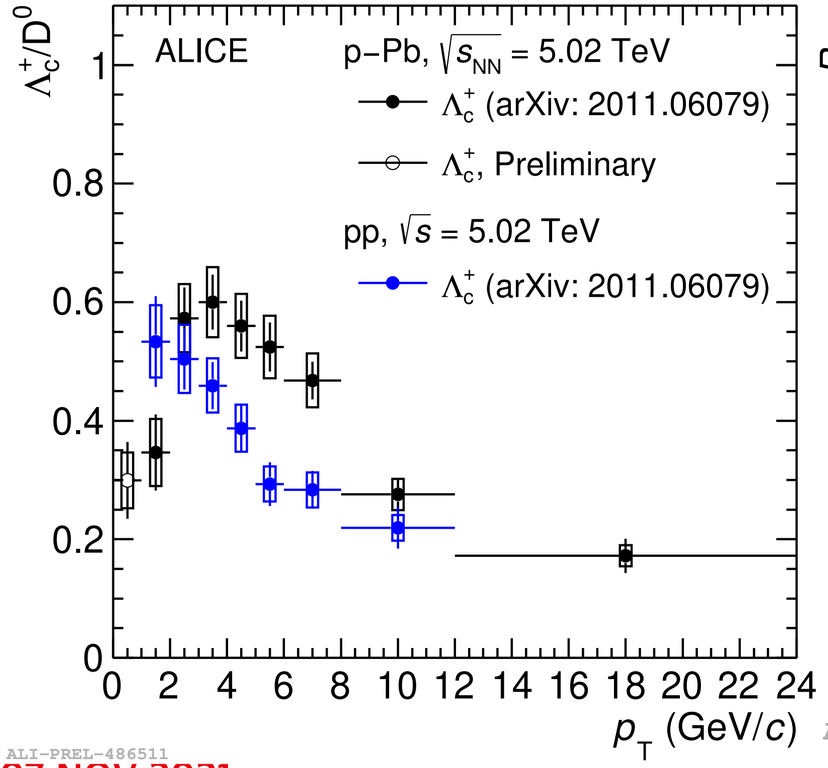
ALI-PREL-486525

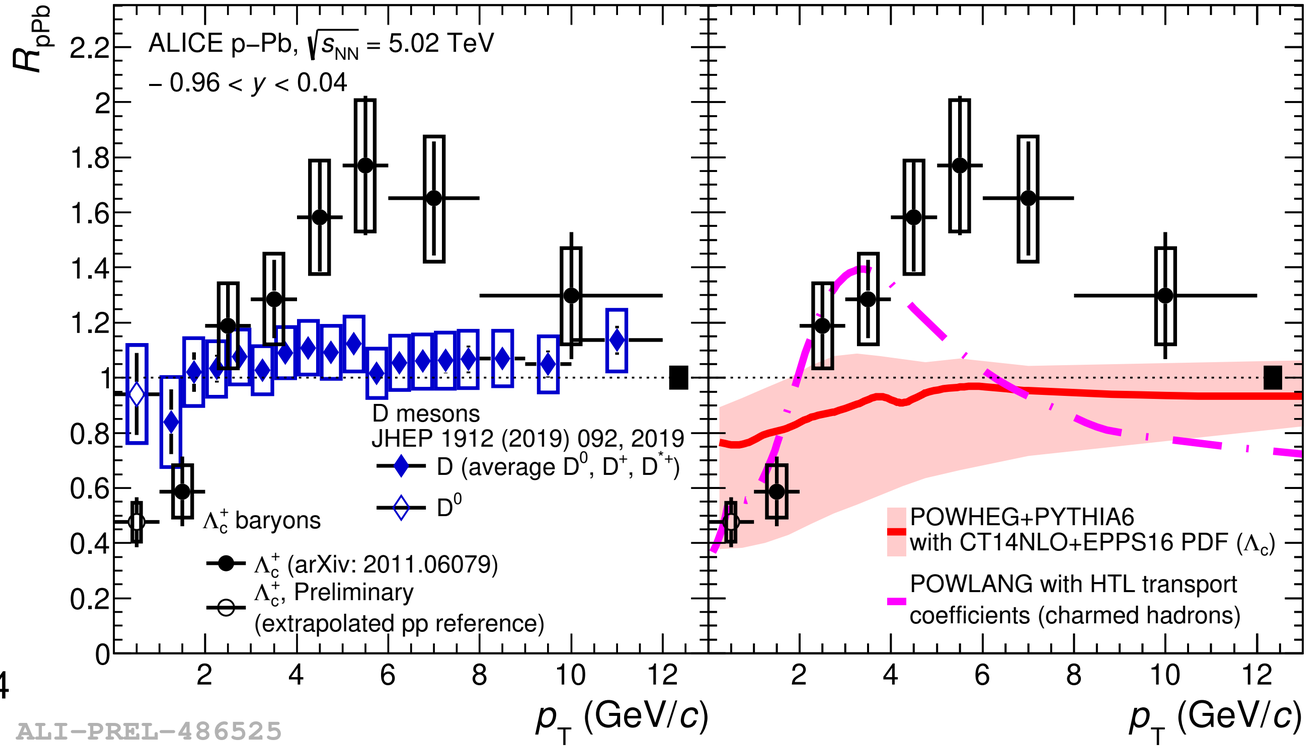
POWHEG
(EPJC 77 no. 3,(2017) 163)
PYTHIA6
(JHEP 09 (2007) 126)
POWLANG
(JHEP 03 (2016) 123)

Λ_c^+ measurements in ALICE

- Λ_c^+ **down to p_T = 0 in p-Pb collisions**
  - **POWHEG+PYTHIA6** : CNM effect + PYTHIA 6 Parton shower + EPPS16 parameterization for PDFs.
  - **POWLANG** : Hot deconfined medium in p-Pb collisions.
    - Describe the suppression at low p_T.

arXiv:2011.06079





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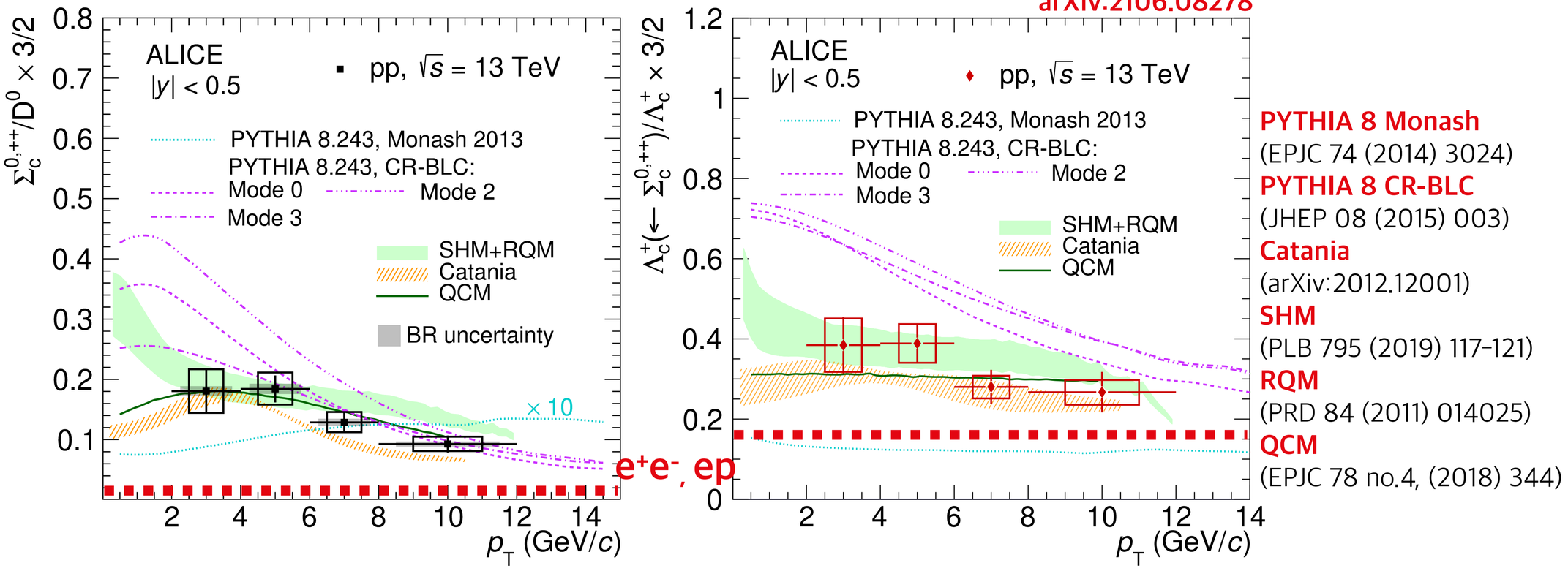
ALI-PREL-486525

$\Sigma_c^{0,++}$ measurements in ALICE

- $\Sigma_c^{0,++}/D^0$ **and** $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ **in pp collisions at 13 TeV**
  - $\Sigma_c^{0,++}/D^0$ ratio shows remarkable difference between the pp and e^+e^- collisions.
  - $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ ratio significantly larger than e^+e^- collisions measurements.
  - **The larger feed-down from $\Sigma_c^{0,++}$ (~40%) partially explains the Λ_c^+/D^0 enhancement in pp collisions.**

arXiv:2106.08278



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QCM
(EPJC 78 no.4, (2018) 344)

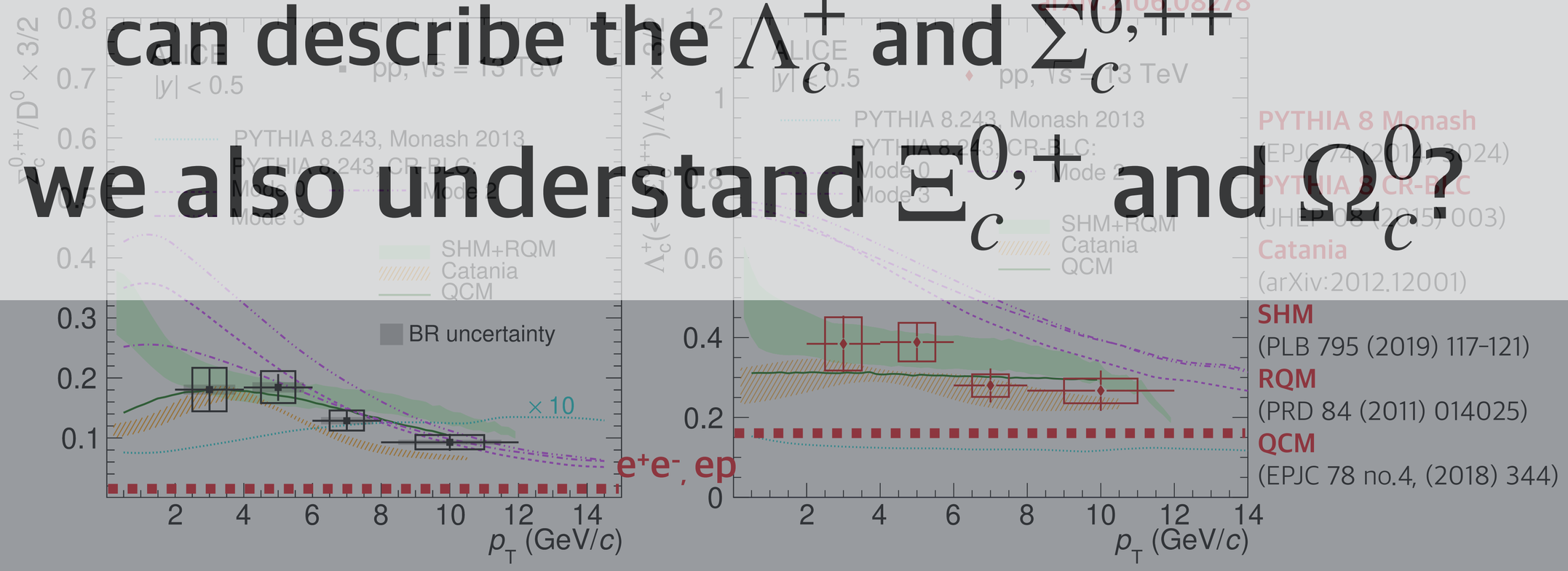
ALI-DER-493901 ALI-DER-493906

$\Sigma_c^{0,++}$ measurements in ALICE

- $\Sigma_c^{0,++}/D^0$ and $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ in pp collisions at 13 TeV
  - $\Sigma_c^{0,++}/D^0$ ratio shows remarkable difference between the pp and e^+e^- collisions.
  - $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ ratio significantly larger than e^+e^- collisions measurements.
  - The larger feed-down from $\Sigma_c^{0,++}$ (~40%) partially explains the Λ_c^+/D^0 enhancement in pp collisions.

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

Do we also understand $\Xi_c^{0,+}$ and Ω_c^0?



e^+e^-, ep

PYTHIA 8 Monash
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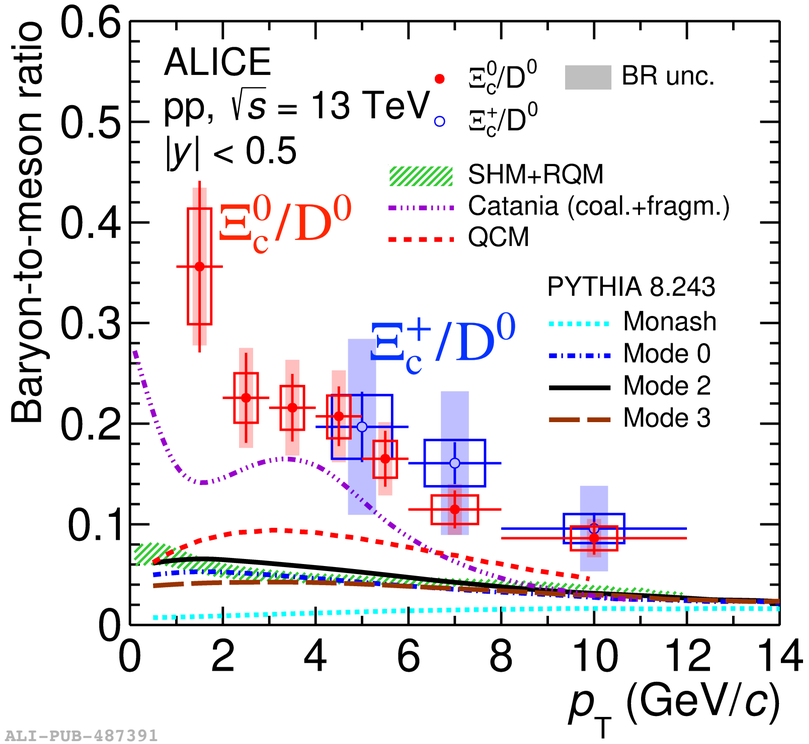
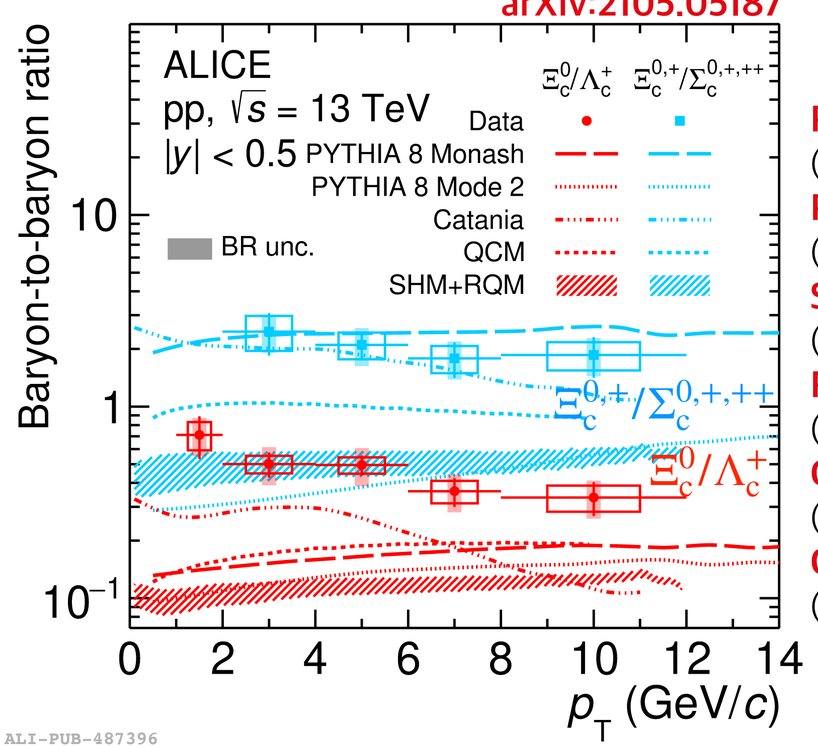
(EPJC 78 no.4, (2018) 344)

$\Xi_c^{0,+}$ measurements in ALICE

- $\Xi_c^{0,+}$ **measurements in pp collisions at 13 TeV**
  - **PYTHIA 8 Monash**, **PYTHIA 8 CR tunes**, **SHM+RQM** and **QCM** : Significantly underestimate the ratios.
  - **Catania** : Describes better the ratios in the measured p_T interval.
  - $\Xi_c^{0,+}/\Sigma_c^{0,++}$ ratio : **Monash** describes the magnitude.
    - Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$ are shown w.r.t e^+e^- collisions.



arXiv:2105.05187



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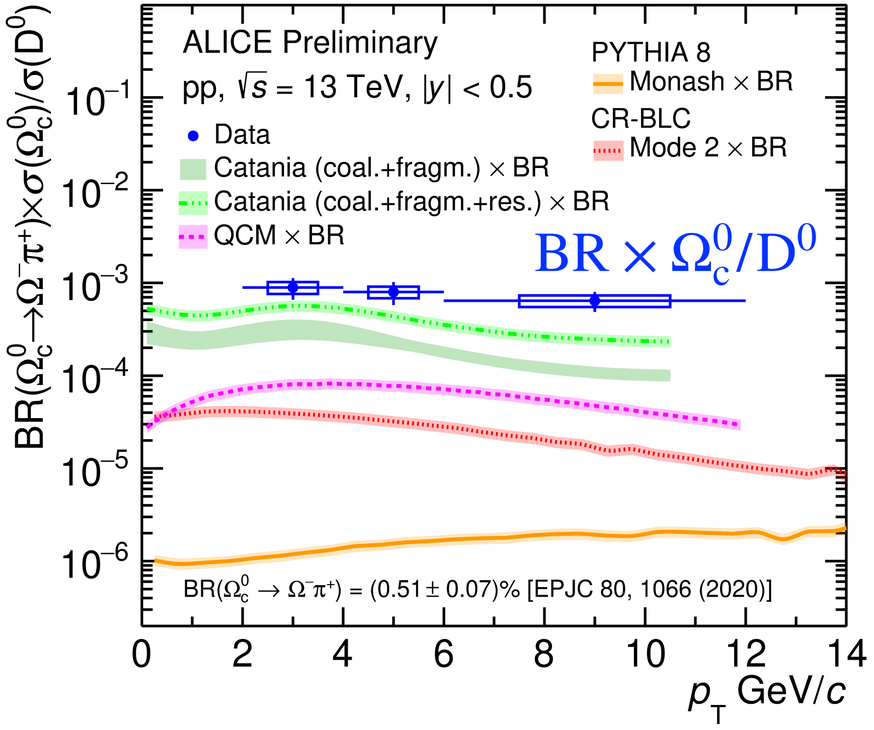
Catania
(arXiv:2012.12001)

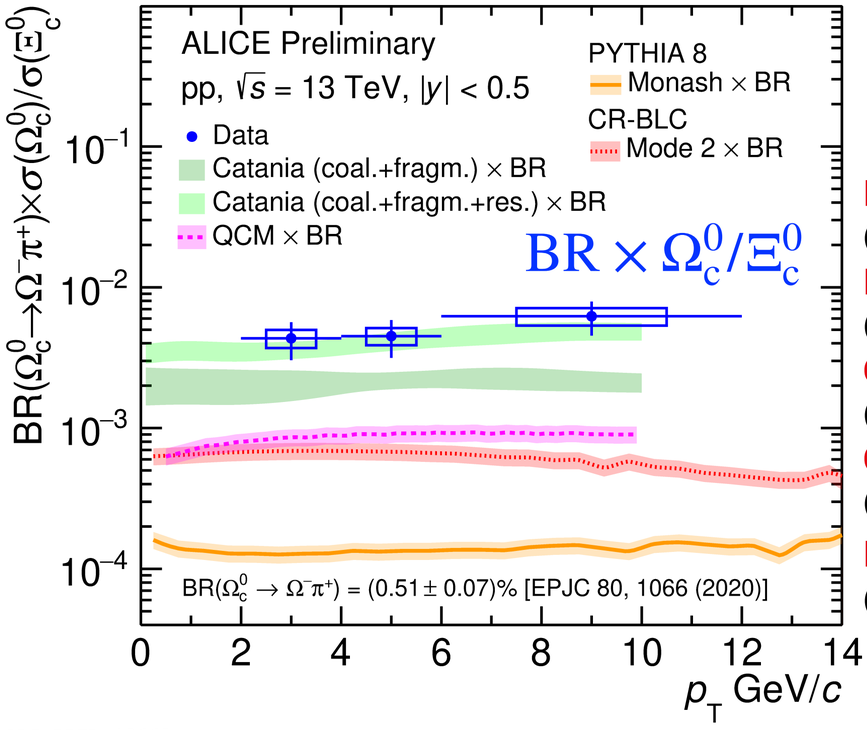
Ω_c^0 measurements in ALICE

- **Ω_c^0 measurements in pp collisions at 13 TeV**

  ✓No measurement of $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)$ → A theoretical calculation used to scale the models: (0.51 ± 0.07)%

  - **PYTHIA 8 Monash, CR-BLC :** Underestimate the measurement.
  - **Catania(w/o res.), QCM** : Underestimate the measurement even though including the coalescence process.
  - **Catania(w/ res.)** : Closer to the measurements considering the additional resonance states.





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QCM
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Catania
(arXiv:2012.12001)
Branching ratio of Ω_c^0
(EPJC 80, 1066 (2002))

ALI-PREL-486632

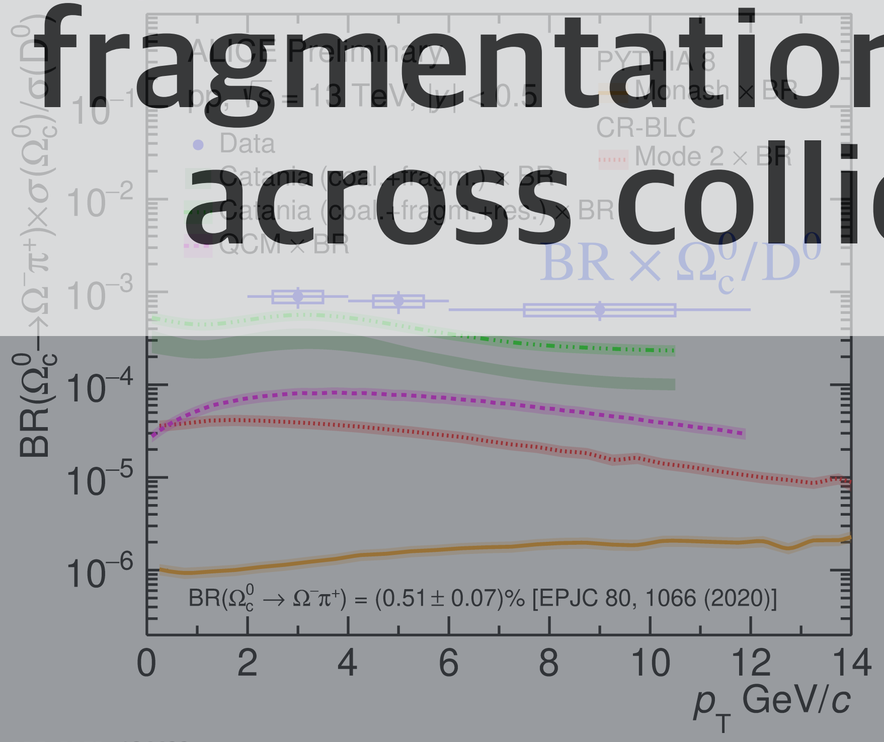
ALI-PREL-486637

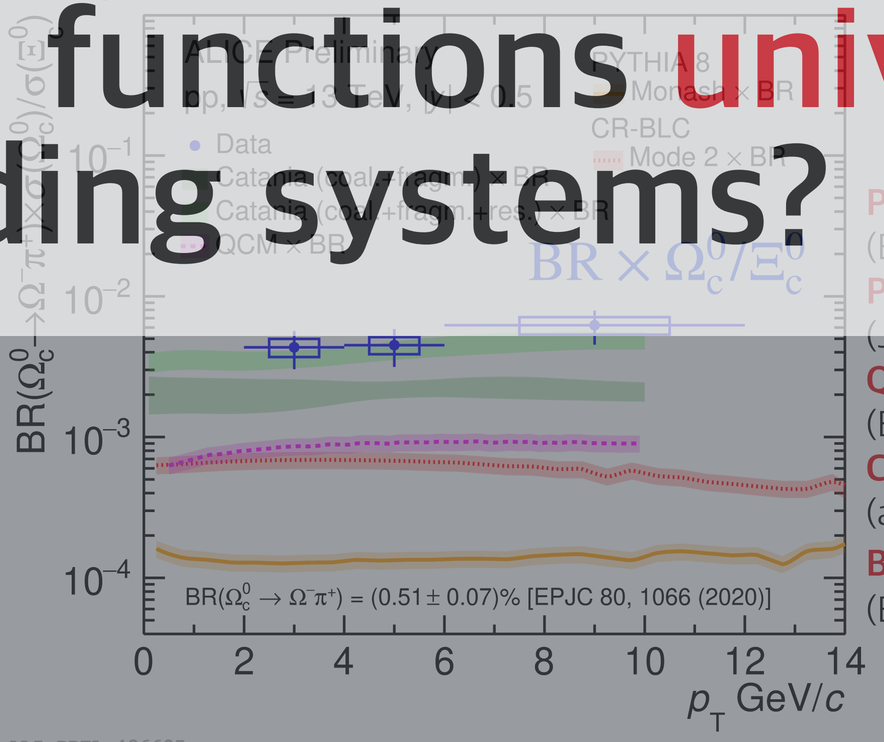
Ω_c^0 measurements in ALICE

- Ω_c^0 **measurements in pp collisions at 13 TeV**
  - ✓No measurement of $\mathrm{BR}(\Omega_c^0 \to \Omega^- \pi^+)$ → A theoretical calculation used to scale the models: (0.51 ± 0.07)%
  - **PYTHIA 8 Monash, CR-BLC :** Underestimate the measurement.
  - **Catania(w/ res.) (QCM) :** Underestimate the measurement even though including the coalescence process.
  - **Catania(w/ res.)** : Closer to the measurements considering the additional resonance states.

We measure now all single charm hadron ground states!

Are fragmentation functions universal across colliding systems?





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(arXiv:2012.12001)
Branching ratio of Ω_c^0
(EPJC 80, 1066 (2002))

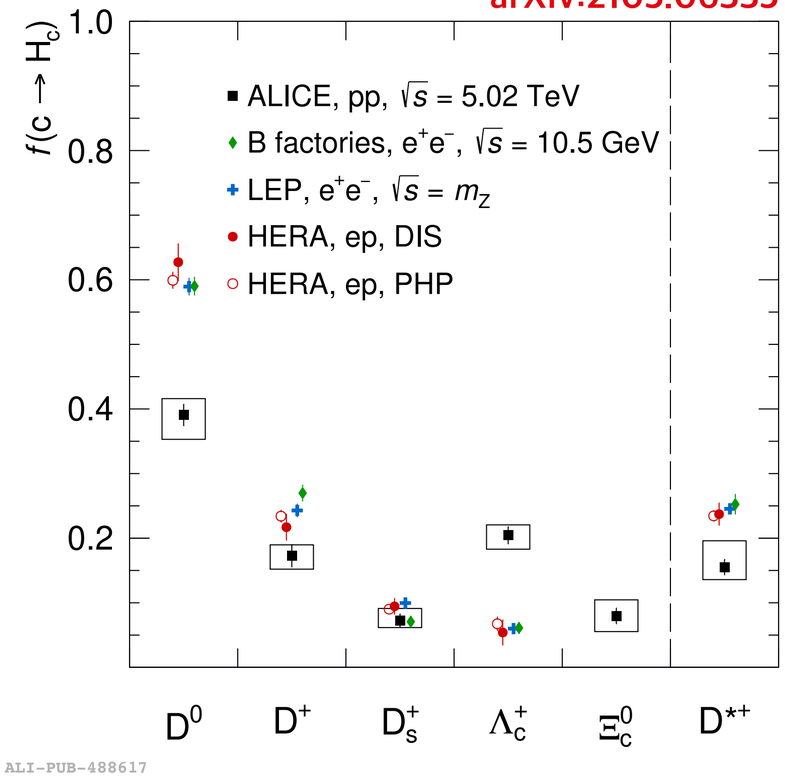
Charm fragmentation fractions

- **Charm fragmentation fractions**
  - Fragmentation fraction for the Ξ_c^0 baryon is measured for the first time.
  - Not counting the contribution of D^{*+}, which feeds into the D^0 and D^+ mesons.

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^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

+ Ξ_c^+ contribution is considered as Ξ_c^0 contribution

arXiv:2105.06335



B factories
(EPJC 76 no.7, (2016) 397)
LEP
(EPJC 77 no.1, (2015) 19)
HERA
(EPJC 76 no.7, (2016) 397)

➡ **Charm fragmentation fractions are not universal**

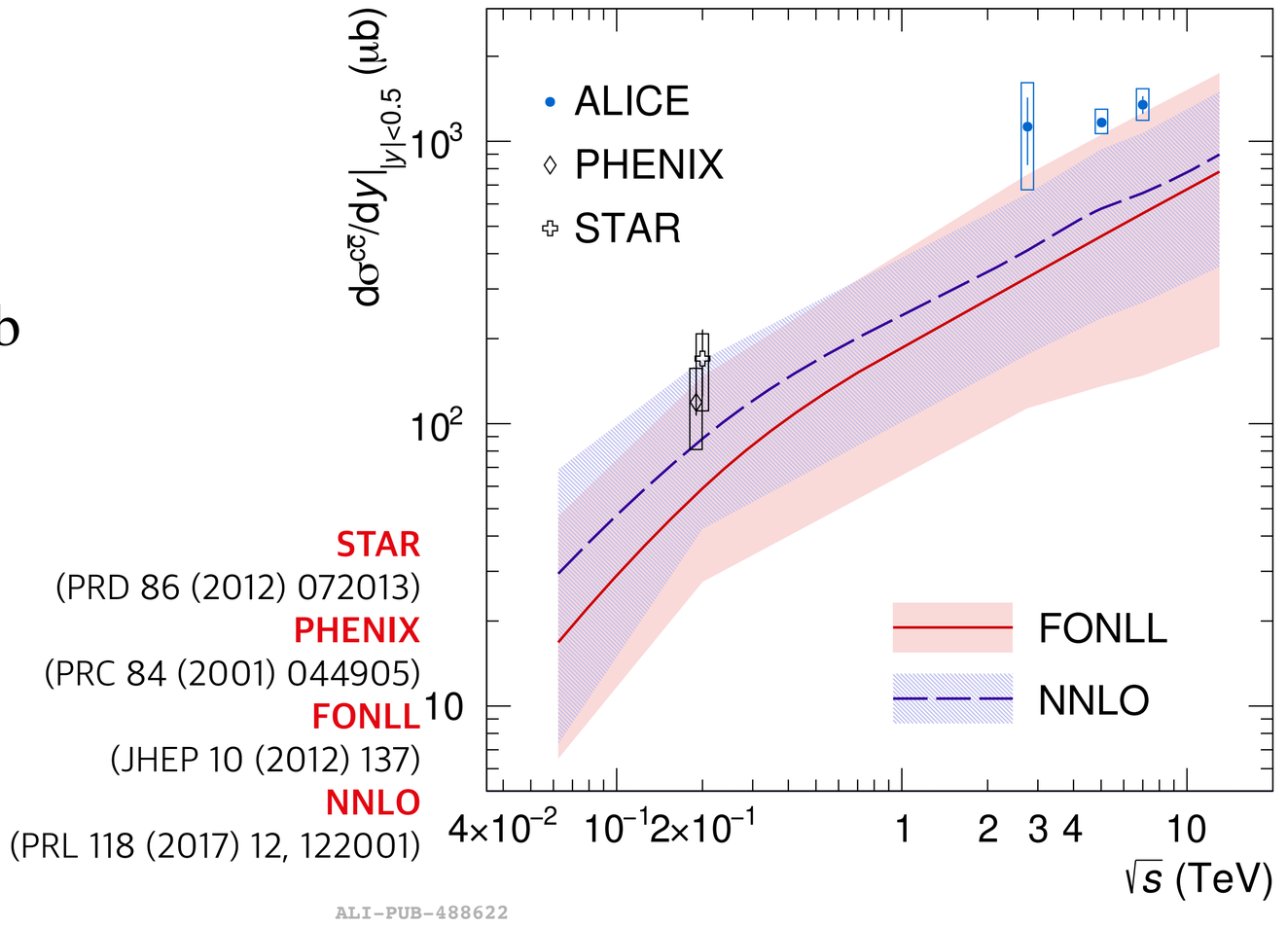
Charm production cross section

- **Charm production cross section at the LHC**
  - First measurement of charm production cross section, including all the ground state charm hadron measurements, per unit of rapidity at midrapidity in pp collisions at 5.02 TeV

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

  - According to new measured charm fragmentation fractions, updated charm cross section measurements in pp collisions at 2.76 TeV and 7 TeV are about **40% higher** than the previously published results.
  - Charm cross section measurements exploiting updated fragmentation fractions lies at the upper edge of the pQCD calculations.

arXiv:2105.06335



STAR
(PRD 86 (2012) 072013)
PHENIX
(PRC 84 (2001) 044905)
FONLL
(JHEP 10 (2012) 137)
NNLO
(PRL 118 (2017) 12, 122001)

ALI-PUB-488622

Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and Ω_c^0 production cross section in pp collisions at 13 TeV.
- First measurement of Λ_c^+ down to p_T = 0 GeV/c in p-Pb collisions at 5.02 TeV.

- Large enhancement of all charm-baryon production in pp collisions w.r.t e^+e^- collisions.
- None of the models describe the enhancement of charm-baryon production rates.
  - ✓ Modeling of charm baryons with a strange quark is challenging.
- The charm fragmentation fractions are not universal across colliding systems.

- ALICE is ready for data-taking with Run 3 and Run 4.
  - ✓ Higher statistics, better precision and more differential measurements for charm baryons awaiting!

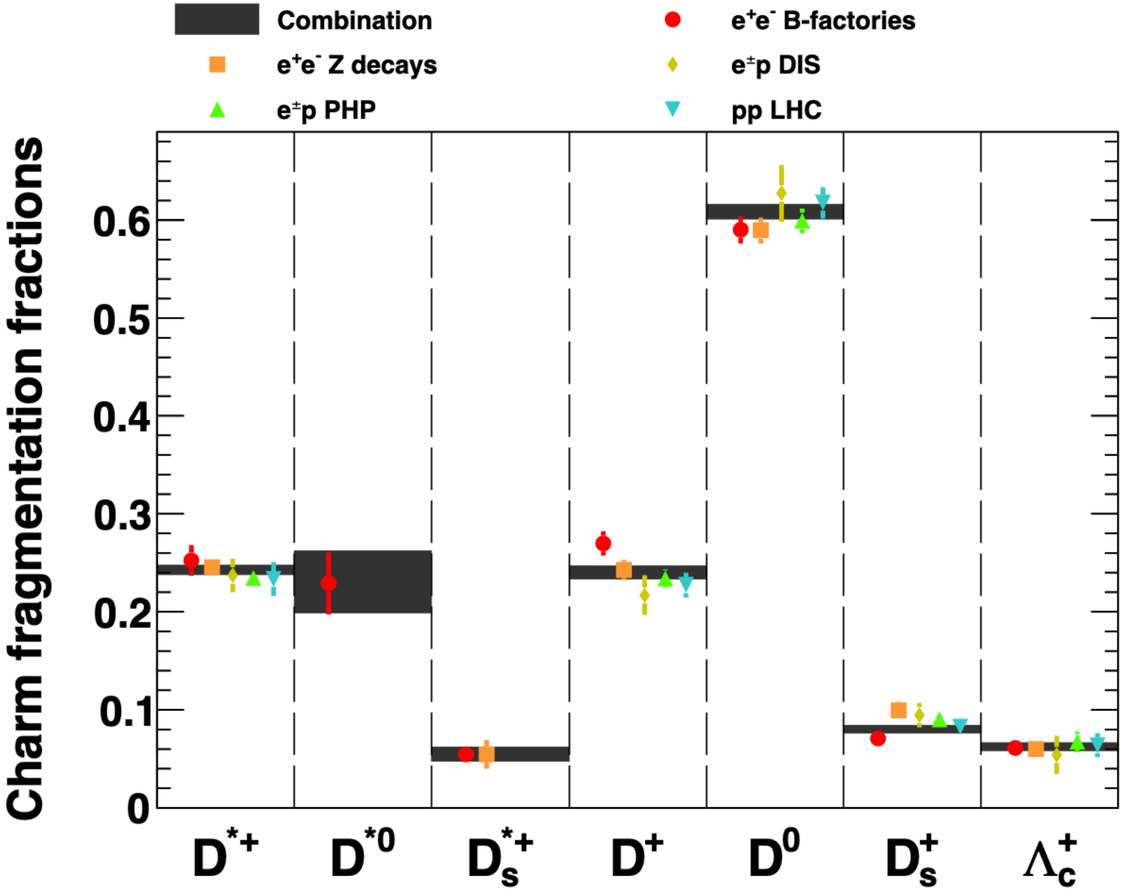
Back up

Charm FF in e^+e^- & ep

- **Charm fragmentation fraction**
  - Assumption is needed due to lack of knowledge about production of $\Xi_c^{0,+}$ and Ω_c^0
    - $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(c \to \Xi_c^0)/f(c \to \Lambda_c^+)$
      $= f(s \to \Xi^-)/f(s \to \Lambda) = 0.066$
    - $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+) = f(s \to \Omega^-)/f(s \to \Lambda) = 0.004$
    - $f(c \to \Omega_c^0)/f(c \to \Xi_c^0) = f(s \to \Omega^-)/f(s \to \Xi^-) = 0.062$

- **Caveat**
  - NO measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c)$ and $\sigma(\Omega_c)$.
  - In 2015, only LHCb Λ_c^+ measurement available.
    - Rapidity range : $2.0 < y < 4.5$

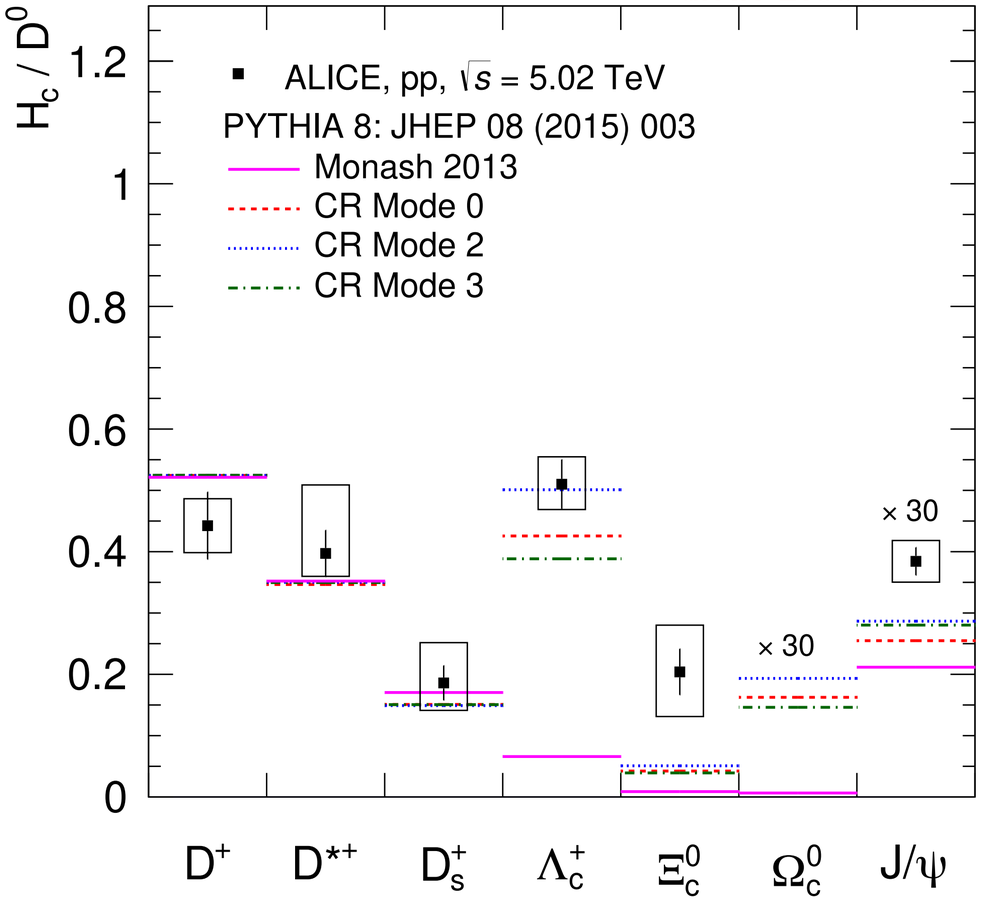
Eur. Phys. J. C76 (2016) no.7, 397



Charm hadron/D⁰ Ratios

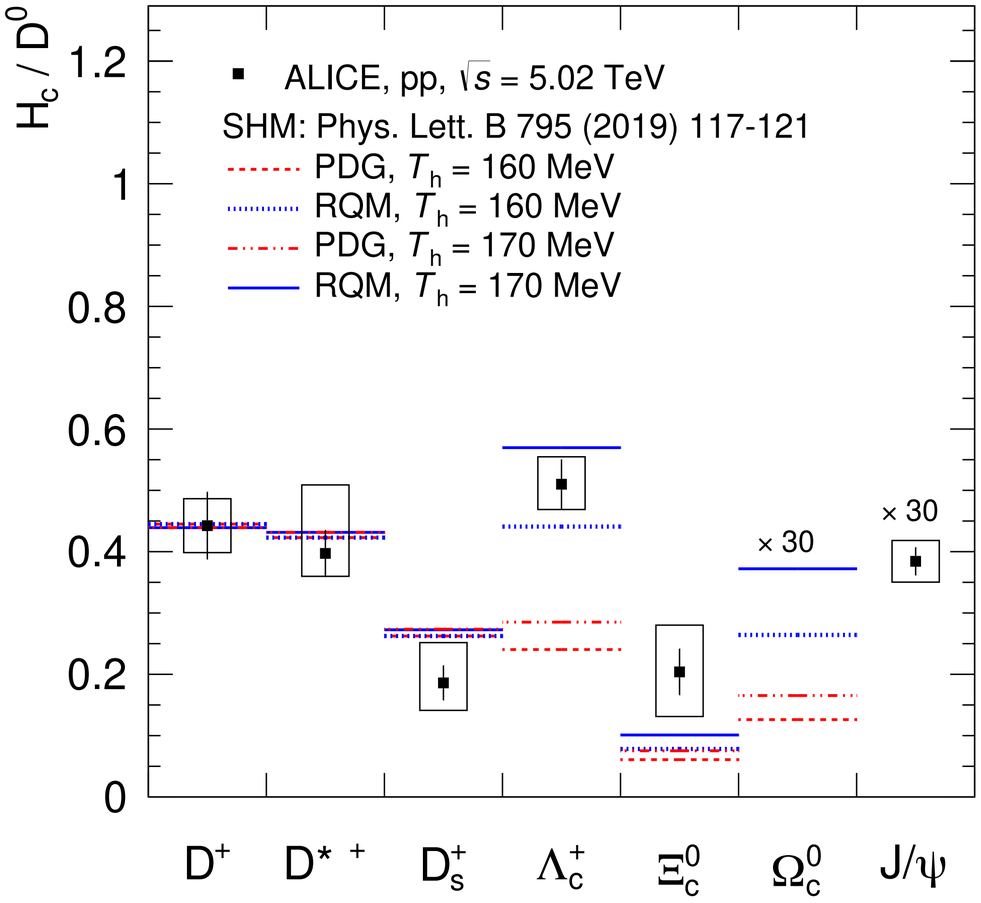
- **The ratio of p_T integrated cross sections of the various charm hadrons and D⁰ meson**
  - SHM for charm baryon is sensitive to a hadronisation temperature.

arXiv:2105.06335



ALI-PUB-488607

arXiv:2105.06335

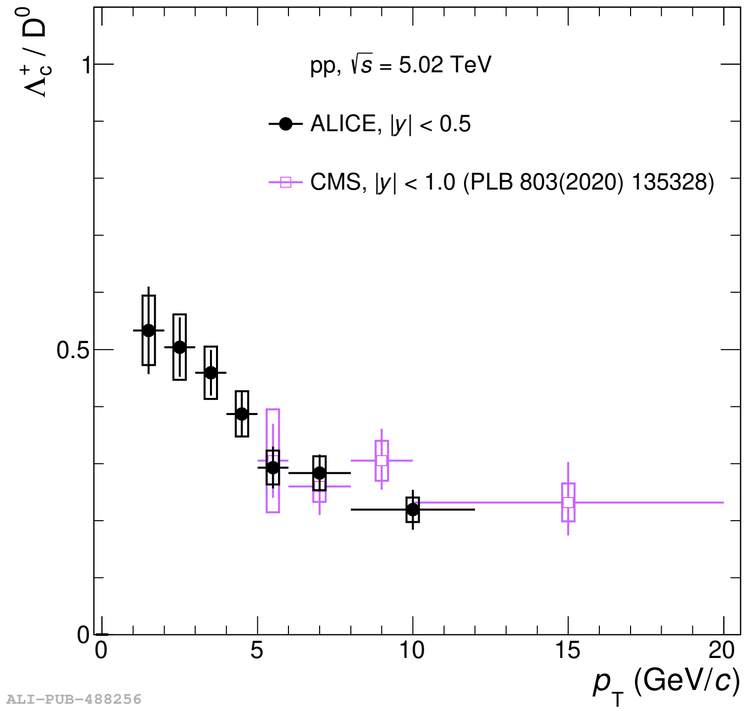


ALI-PUB-488612

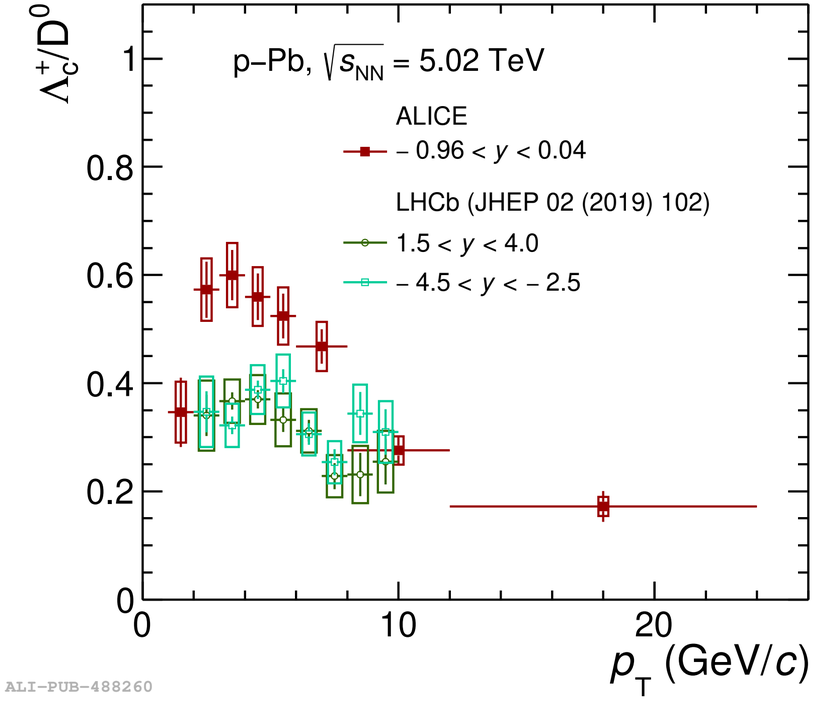
Λ_c^+ measurements comparison

- Λ_c^+/D^0 **in pp at 5.02 TeV (ALICE vs CMS)**
  - ALICE and CMS measurements are consistent.
- Λ_c^+/D^0 **in p-Pb at 5.02 TeV (ALICE vs LHCb)**
  - Suggest an enhancement of the ratio at mid rapidity with respect to forward and backward rapidity.

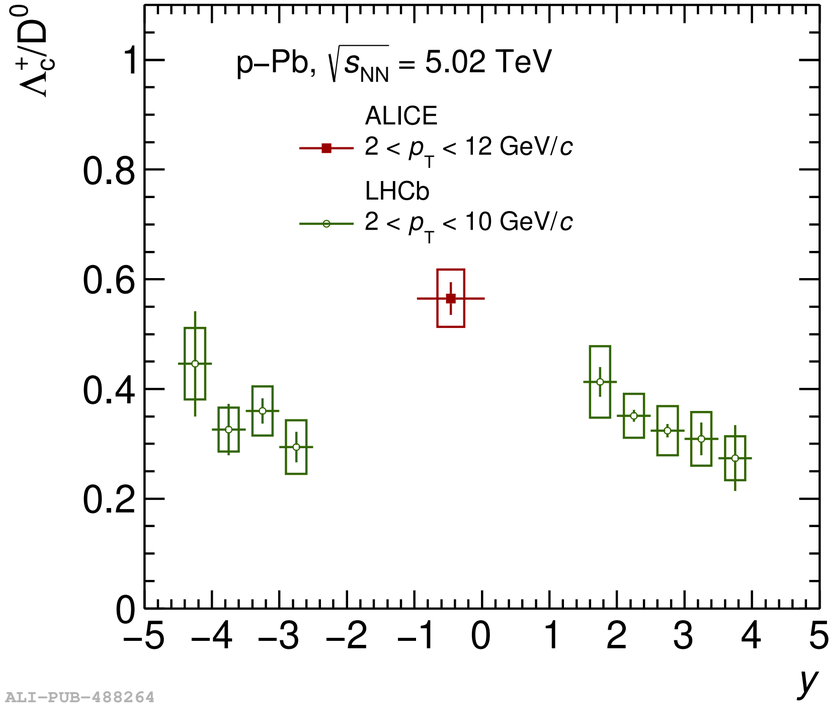
arXiv:2011.06079



arXiv:2011.06079



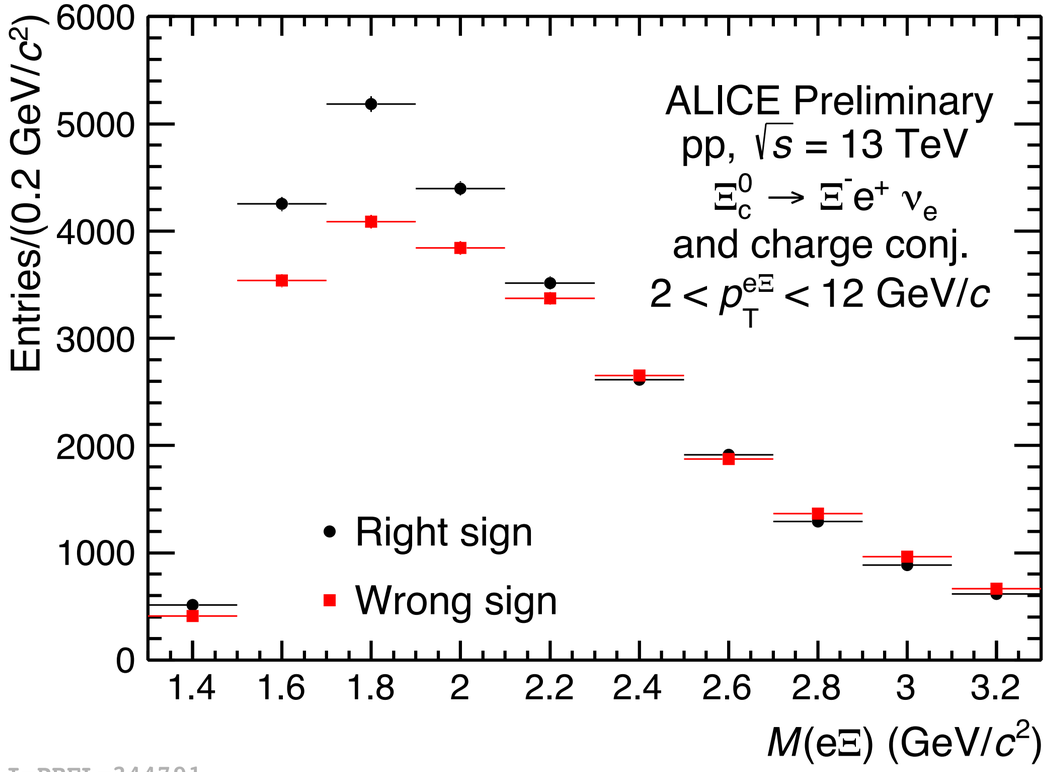
arXiv:2011.06079



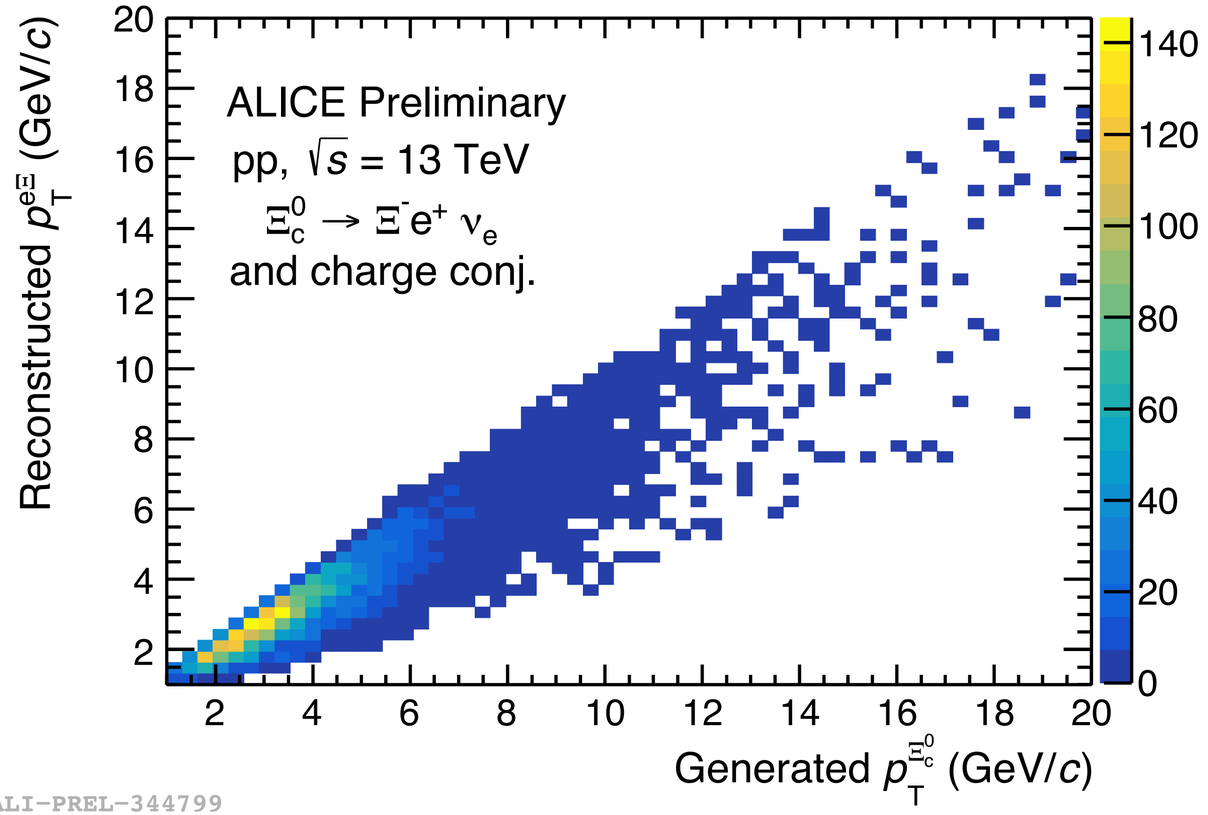
$\Xi^0_c \rightarrow e^+\Xi^-\nu_e$

- Unfolding

- **Unfolding**
  - The p_T of eΞ pairs is corrected for the missing momentum of the neutrino using unfolding techniques.
  - Convergence of the Bayesian unfolding is achieved after three iterations.



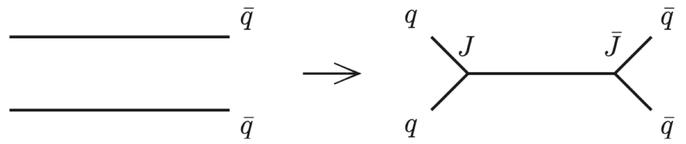
ALI-PREL-344791



ALI-PREL-344799

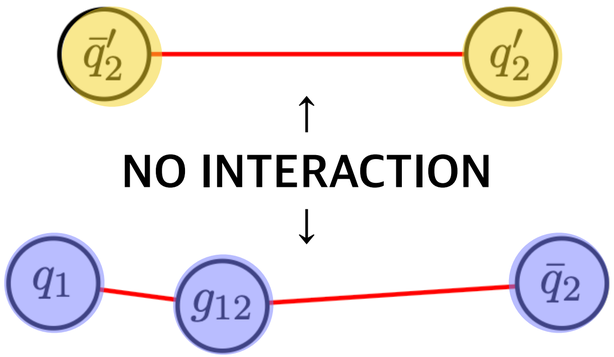
HF baryon enhance mechanism

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



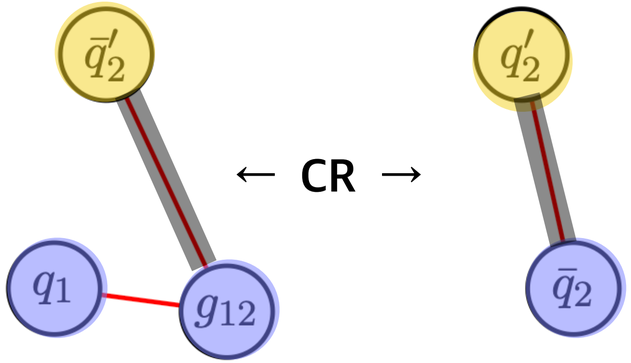
(b) Type II: junction-style reconnection

No CR



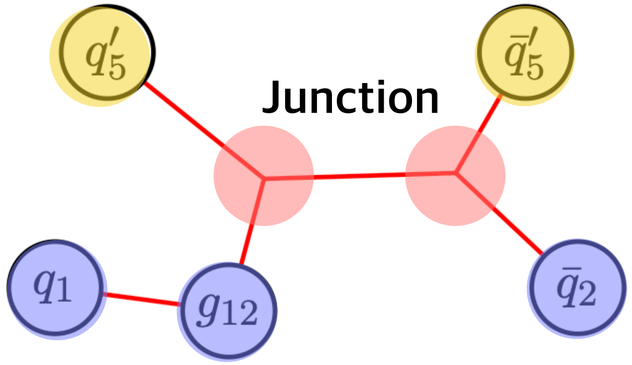
- Partons created in different MPIs do not interact each other

Old CR



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

New CR



- Minimization of string length over all possible configurations
- Enhancement of hadrons
- Used in CR mode X tunes

HF baryon enhance mechanism

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- **Statistical Hadronisation 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

n_i $(\cdot 10^{-4}$ 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

HF baryon enhance mechanism

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

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  - 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 Wigner formalism + fragmentation process
  - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra

Model

Model	HQ production	Medium modelling	Quark-medium interaction	HQ hadronization	Tuning of medium coupling	References
BAMPS el.	MC@NL0 No PDF shadowing	3d+1 expansion parton cascade	Transport with Boltzmann rad. + coll.	Frag.	RHIC (then scaled by dN/dη	https://arxiv.org/abs/1408.2964
TAMU	FONLL EPS09 (NLO) PDF shadowing	2d+1 expansion parton cascade	Transport with Langevin coll. only Diffusion in hadronic phase Improved space-mom correlation	Frag. + Rec.	Assume 1-QCD U potential	https://arxiv.org/abs/1401.3817
POWLANG	POWLANG EPS09 (NLO) PDF shadowing	2d+1 expansion with viscous fluido-dyn evolution	Transport with Langevin coll. only	Frag. + Rec.	Assume 1-QCD U potential	https://arxiv.org/abs/1410.6082
Catania	FONLL EPS09 (NLO) PDF shadowing	2d+1 expansion parton cascade	Transport with Langevin coll. only	Frag. + Rec. (different from TAMU?)	Assume 1-QCD U potential	https://arxiv.org/pdf/1712.00730.
LIDO	FONLL EPS09 (NLO) PDF shadowing	2d+1 rel. fluido-dynamics	Transport with Langevin + empirical transport coefficients to capture the non-perturbative part. (Boltzmann)	Frag. + Rec.	Coefficients fixed with Bayesian analysis to LHC D and B results	https://arxiv.org/pdf/1806.08848.

Model

Model	HQ production	Medium modelling	Quark-medium interaction	HQ hadronization	Tuning of medium coupling	References
PHSD	Pythia + string melting		Microscopic covariant transport Dynamical Quasiparticle Model	Local covariant transition rates		https://arxiv.org/pdf/1908.00451.
MC@ sHQ+ EPOS2	FONLL EPS09 (NLO) PDF shadowing	3d+1 expansion (EPOS model)	Transport with Boltzmann coll. (+rad when mentioned)	Frag. + Rec.	QGP transport coefficients fixed at LHC, adapted for RHIC	https://arxiv.org/abs/1305.6544
WHDG	FONLL no PDF shadowing	Glauber model nuclear overlap No fluido-dyn evol.	rad. + coll.	Frag.	RHIC (then scaled by dN/dη	
Vitev et al.	Non-zero mass VFNS no PDF shadowing	Glauber model nuclear overlap Ideal fluido-dyn Bjorken expansion	rad. + coll. In medium meson dissociation	Frag.	RHIC (then scaled by dN/dη	
CUJET3		Semi quark gluon monopole plasma	rad.	Frag.	Model parameters tuned on light flavor data	https://arxiv.org/abs/1704.04577

PYTHIA

Parameter	Monash	Mode 0	Mode 2	Mode 3
StringPT:sigma	= 0.335	= 0.335	= 0.335	= 0.335
StringZ:aLund	= 0.68	= 0.36	= 0.36	= 0.36
StringZ:bLund	= 0.98	= 0.56	= 0.56	= 0.56
StringFlav:probQQtoQ	= 0.081	= 0.078	= 0.078	= 0.078
StringFlav:ProbStoUD	= 0.217	= 0.2	= 0.2	= 0.2
StringFlav:probQQ1toQQ0join	= 0.5, 0.7, 0.9, 1.0	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275
MultiPartonInteractions:pT0Ref	= 2.28	= 2.12	= 2.15	= 2.05
BeamRemnants:remnantMode	= 0	= 1	= 1	= 1
BeamRemnants:saturation	-	= 5	= 5	= 5
ColourReconnection:mode	= 0	= 1	= 1	= 1
ColourReconnection:allowDoubleJunRem	= on	= off	= off	= off
ColourReconnection:m0	-	= 2.9	= 0.3	= 0.3
ColourReconnection:allowJunctions	-	= on	= on	= on
ColourReconnection:junctionCorrection	-	= 1.43	= 1.20	= 1.15
ColourReconnection:timeDilationMode	-	= 0	= 2	= 3
ColourReconnection:timeDilationPar	-	-	= 0.18	= 0.073

JHEP 08 (2015) 003, arXiv:1505.01681v1