Heavy-flavour production and hadronization with ALICE at the LHC

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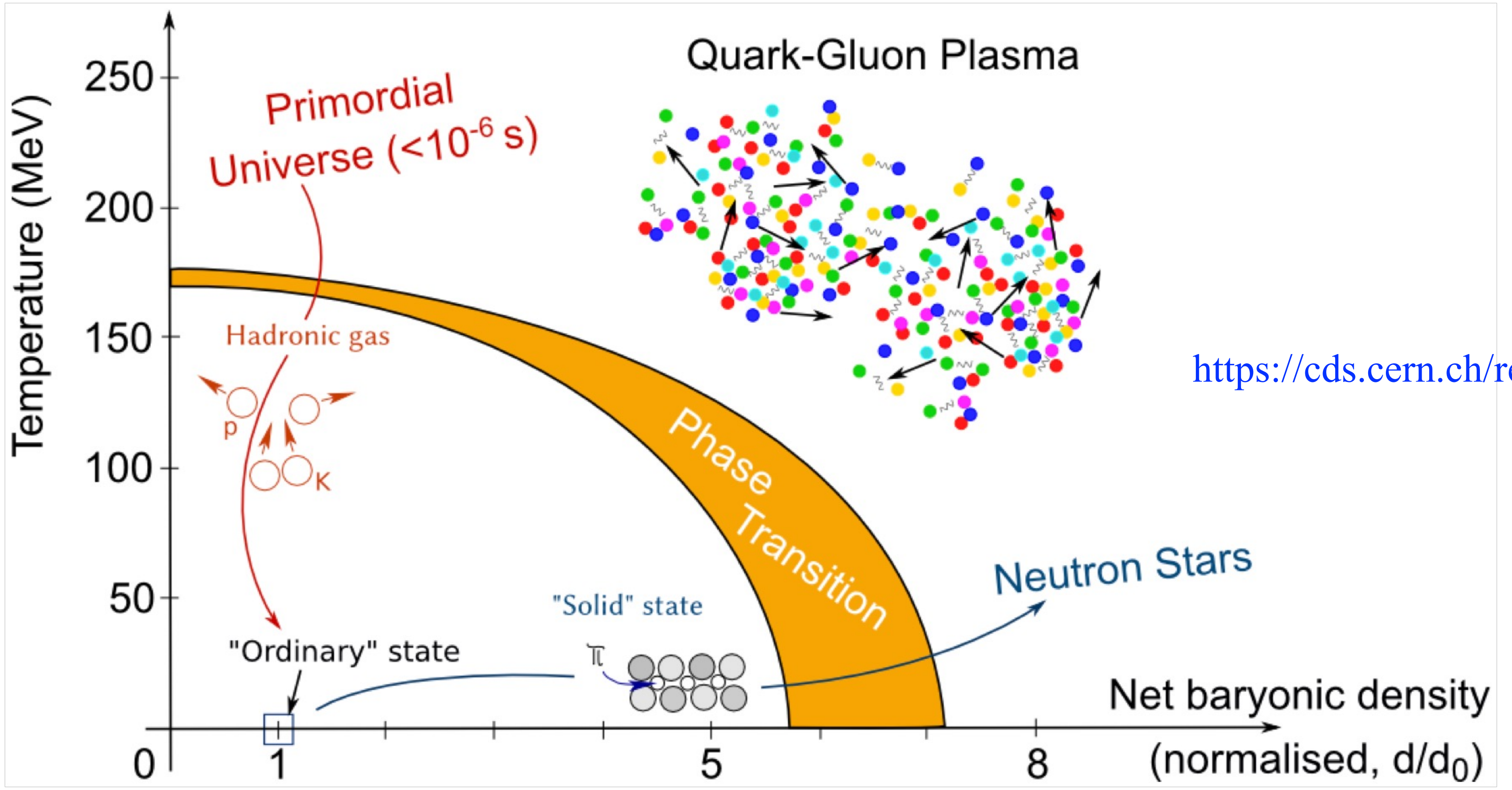
ALICE

The phase diagram of quantum chromodynamics (QCD)

- Quark-gluon plasma (QGP): deconfined phase of quarks and gluons
- Phase transition at LHC is a smooth crossover
  - Similar to early universe (~few μs after the Big Bang)

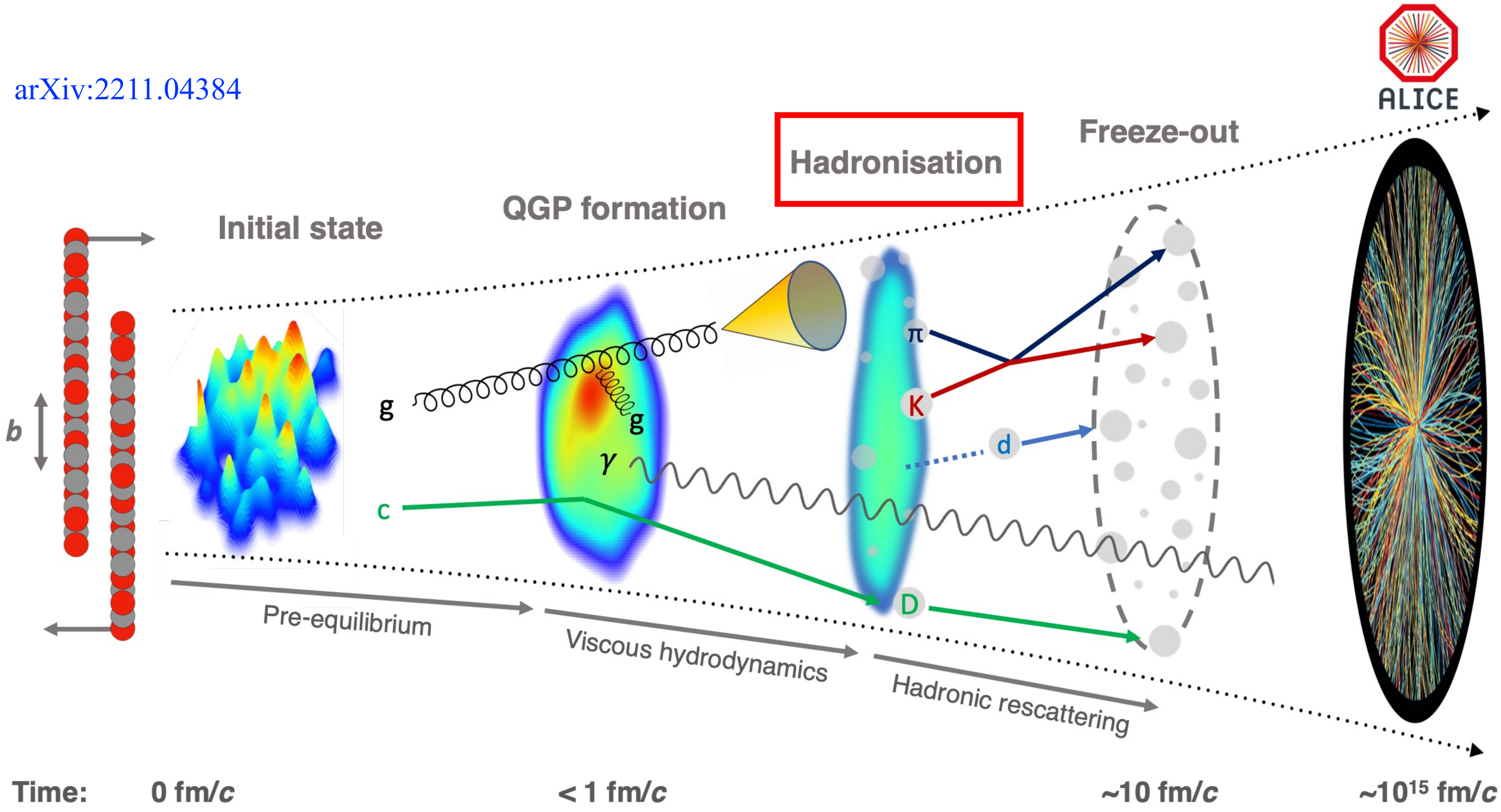


https://cds.cern.ch/record/2025215

Heavy-ion collisions

➢ Time evolution of ultra-relativistic heavy-ion collisions at LHC energies

arXiv:2211.04384

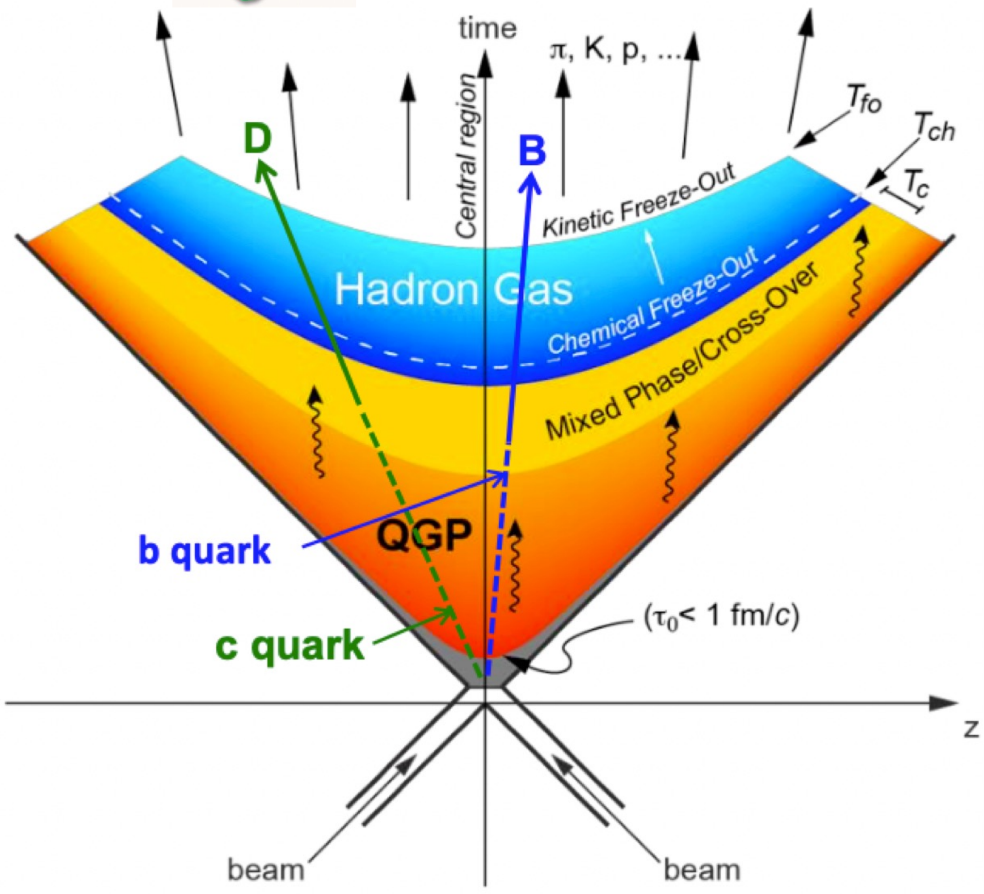


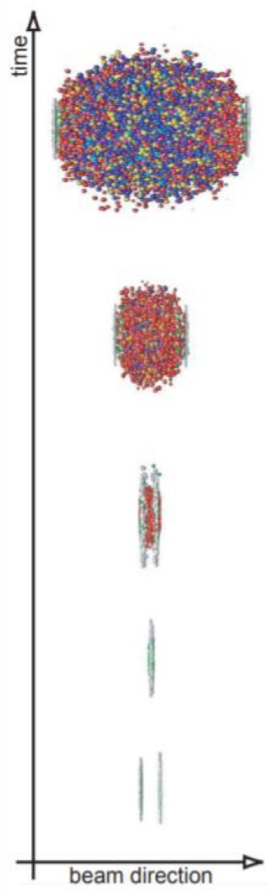
Heavy flavour: golden probes of the medium

- Charm and beauty quarks: golden probes of the medium
  - $m_{\mathrm{Q}} \gg \Lambda_{\mathrm{QCD}}$
    - Enable the evaluation of their production cross sections within pQCD
  - $m_{\mathrm{Q}} \gg T_{\mathrm{QGP}}$
    - Produced mainly in initial hard scatterings (high Q^2) at early stage of heavy-ion collisions
  - $\tau_{\mathrm{prob}} \approx \frac{1}{2m_{\mathrm{q}}} \approx 0.1_{q=c}(0.03)_{q=b}\ \mathrm{fm}/c <$ $\tau_{\mathrm{QGP}}(\approx 0.3-1.5\ \mathrm{fm}/c)$
    - Experience the full evolution of the QGP

- Charm
  $m_{\mathrm{c}} \approx 1.3\ \mathrm{GeV}/c^2$

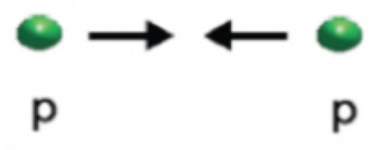
- Beauty
  $m_{\mathrm{b}} \approx 4.2\ \mathrm{GeV}/c^2$



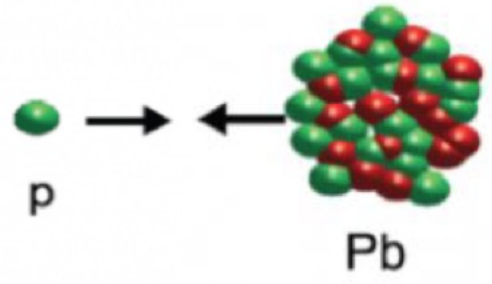


Physics motivations in different collision systems

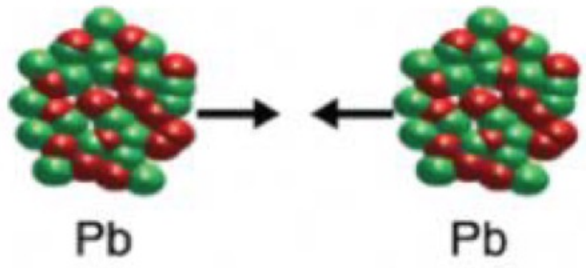
- pp collisions
  - Tests for pQCD calculations
  - Reference for heavy-ion collisions



- p-Pb collisions
  - Cold nuclear matter effects
    - Modification of parton distribution functions (PDF) in bound nucleons



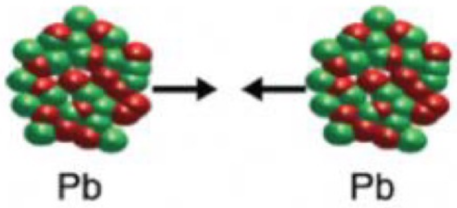
- Pb-Pb collisions
  - Hot nuclear matter effects
    - Energy loss in the QGP
    - Collective motion of the system
    - Modification of hadronization mechanisms



Heavy-flavour hadron formation in e^+e^- and Pb-Pb

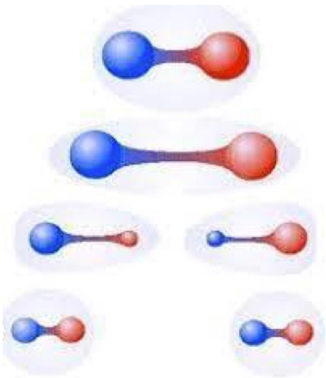
e^+ e^-

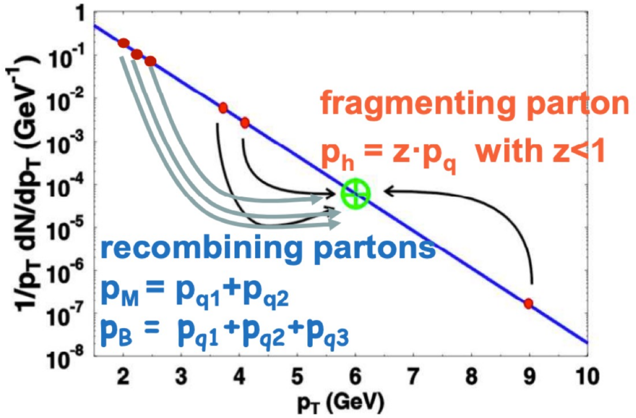
$\bullet\rightarrow\ \leftarrow\bullet$

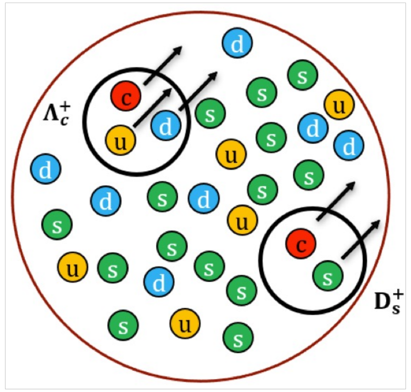


- “Point-like” object interaction
- Pure fragmentation

- QGP: complex large-size system
- Parton degrees of freedom
- Modification of hadronization mechanisms







Fragmentation Eur.Phys.J.C 78 (2018) 11, 983

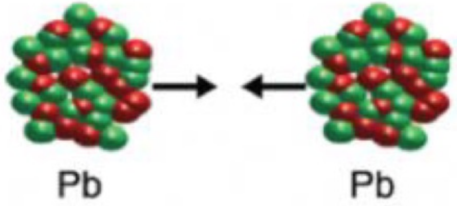
- Hard scattering $e^+e^- \rightarrow q\bar{q}$
- Color-potential string between q and $\bar{q}$
- Hadronization via multiple string breaking and formation of quark-antiquark pairs

Coalescence Phys.Lett.B 68 (1977) 459, Phys.Lett.B 73 (1978) 504 (erratum)

- Heavy quarks produced in hard scattering coalesce with light (di-) quarks from the system
- Expected to increase baryon production at low and intermediate p_T
- QGP: interplay coalescence (low p_T) vs. fragmentation (high p_T)

Heavy-flavour hadron formation in pp collisions

e^{+} e^{-}



- "Point-like" object interaction
- Pure fragmentation

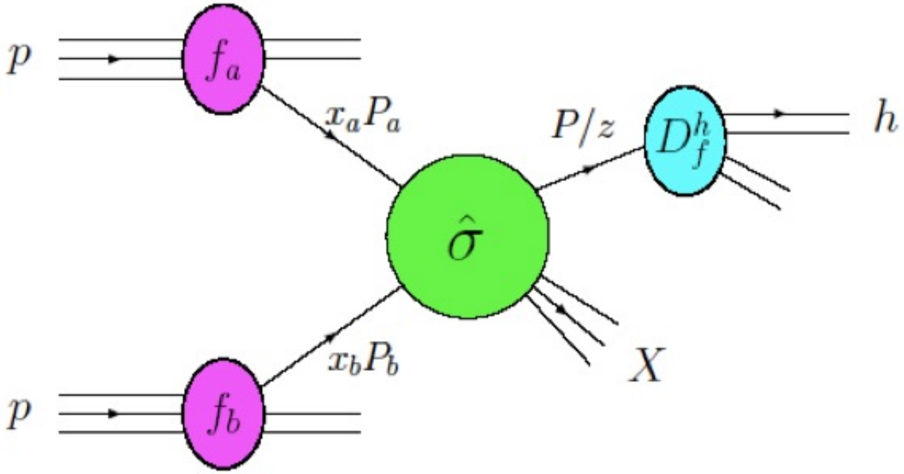
- Superposition of many "point-like object" collisions ?
- MPI and color reconnection modify hadronization ?

- QGP: complex large-size system
- Parton degrees of freedom
- Modification of hadronization mechanisms

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

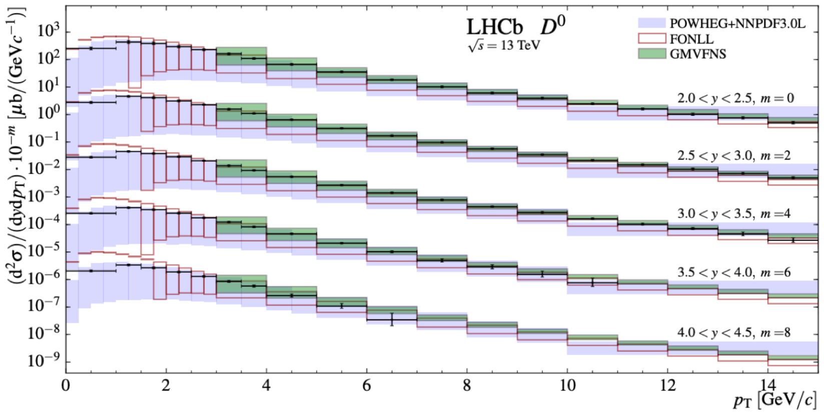
parton distribution function (PDF) (non-pertubative) | partonic cross section (pertubative) | hadronization by fragmentation (non-pertubative)

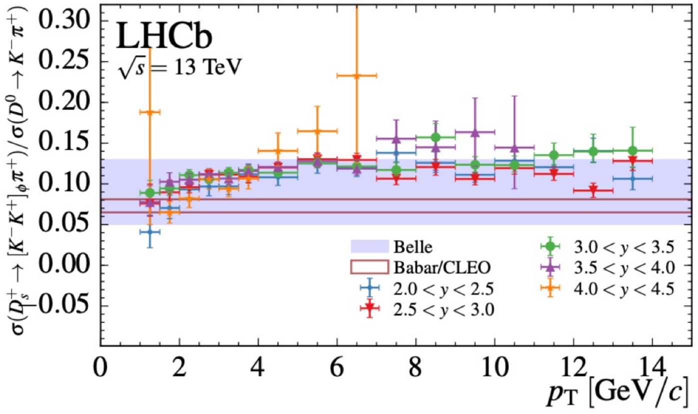
- Standard description of heavy-quark hadronization based on a factorisation approach
  - Ratios of particle species → ratios of fragmentation fractions
    - Sensitive to HF quark hadronisaton
  - Fragmentation fractions assumed universal among collision systems and constrained from $e^{+}e^{-}$ and $e^{-}p$ collisions



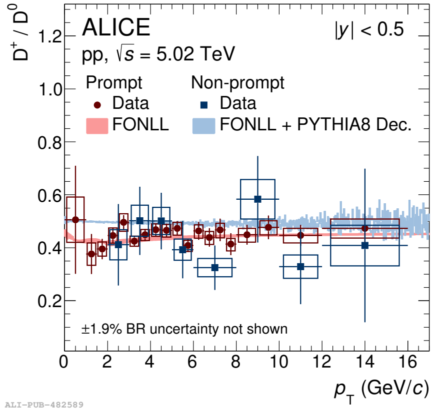
Factorization: a very successful framework

LHCb: JHEP 03 (2016) 159, JHEP 09 (2016) 013 (erratum), JHEP 05 (2017) 074 (erratum)

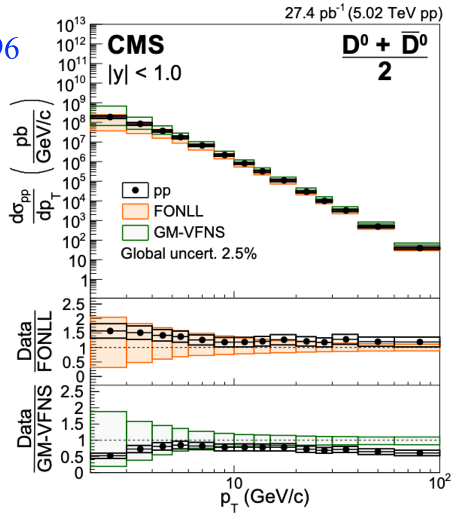




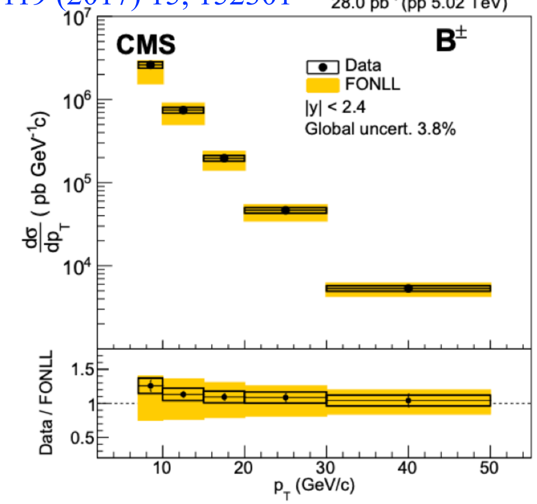
ALICE: JHEP 05 (2021) 220



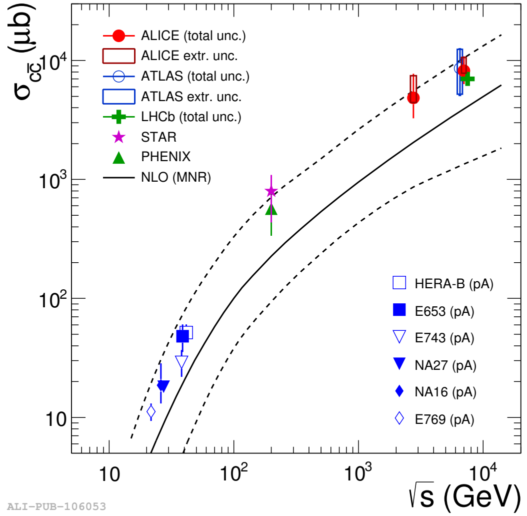
CMS: PLB 782 (2018) 474-496



CMS: PRL 119 (2017) 15, 152301



ALICE: PRC 94 (2016) 5, 054908



Only D mesons

- Plethora of data on open-charm and open-beauty meson production
  - vs. p_T and y (wide range)
  - In different collision energies
  - Relative abundance of charm meson species

→ Described by pQCD calculations relying on factorization

Charm fragmentation measured in e^+e^- and ep

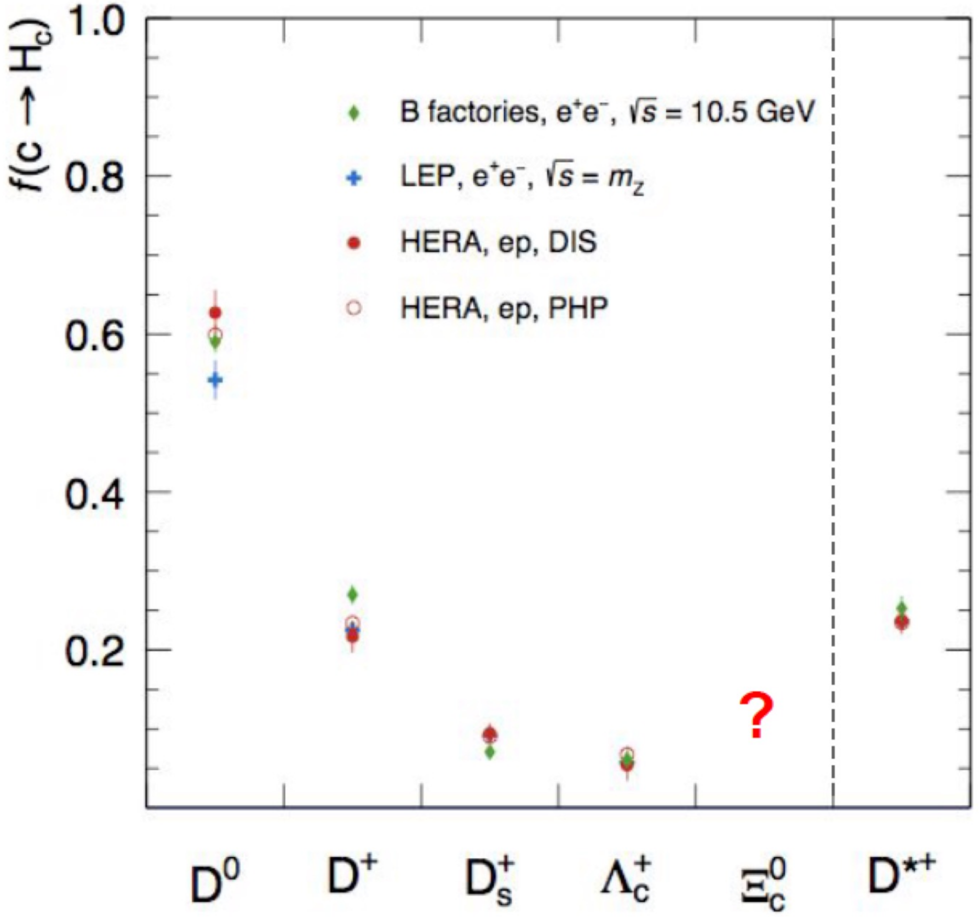
- Charm fragmentation fractions (FF)
  - $f(c \to H_c) = \sigma(H_c)/\sigma(c) = \sigma(H_c)/\sum_{w.d.} \sigma(H_c)$ (w.d.: weakly decaying)
  - Inputs used in a standard factorisation approach
- Production cross section of $\Xi_c^{0,+}$ are calculated under assumptions[1]:
  - $f(c \to \Xi_c^0)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda) \approx 0.004$

Average LEP FF

H_c	$f(c \to H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$
D^+	$22.5 \pm 1.0 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$
D^{*+}, double-tag	$24.4 \pm 1.3 \pm 0.2$
D^{*+}, combined	$23.6 \pm 0.6 \pm 0.3$

L. Gladilin, EPJC 75 (2015) 19

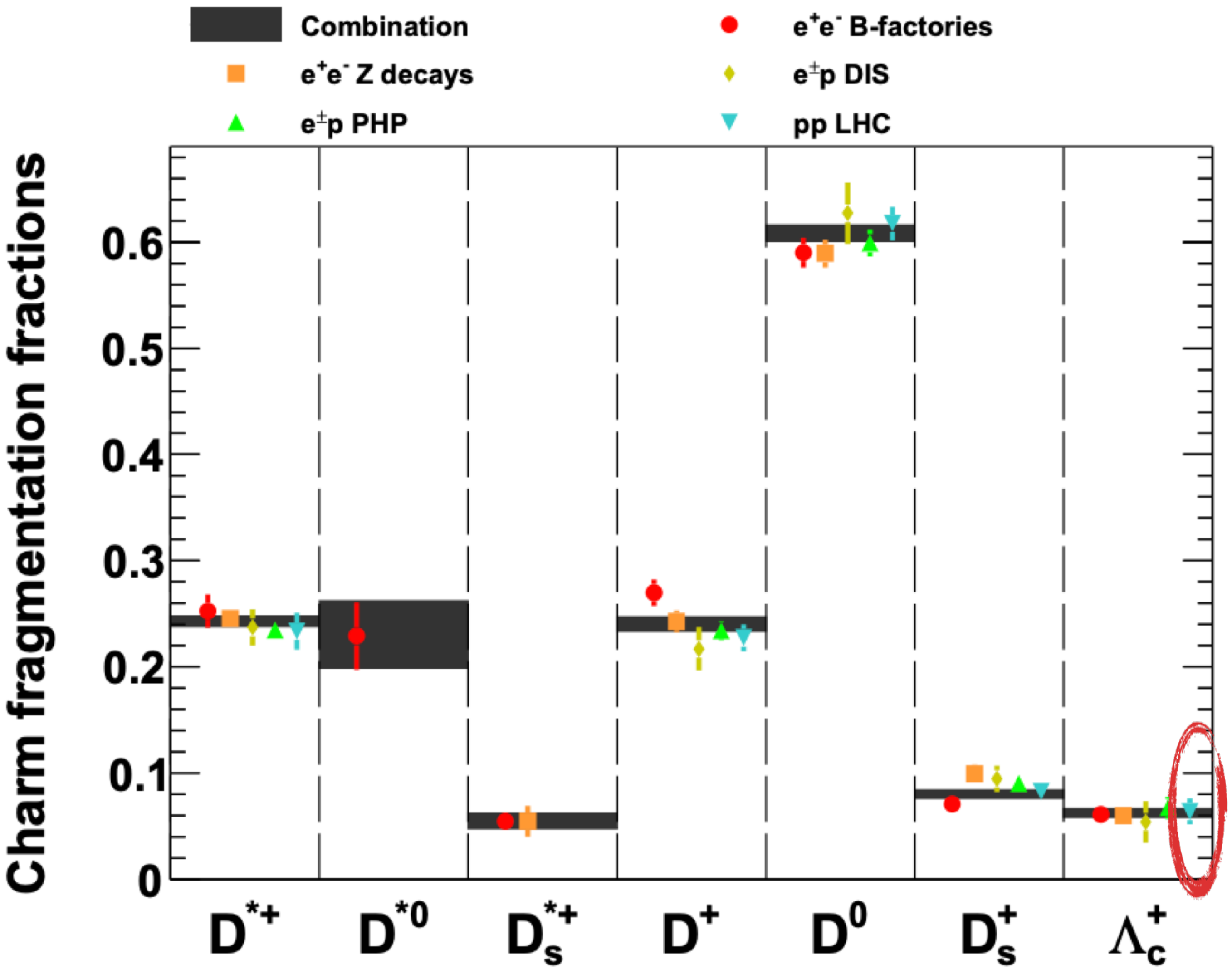
Sum of $f(c \to H_c)$ for D^0, D^+, D_s^+ and Λ_c^+: $[91.6 \pm 3.3(\text{stat} \oplus \text{syst}) \pm 1.0(\text{BR})]\%$



[1] M. Lisovyi, et al., EPJC 76 (2016) no.7, 397
[2] B factories: EPJC 76 no. 7, (2016) 397
[3] LEP: EPJC 75 no. 1, (2015) 19
[4] HERA: EPJC 76 no. 7, (2016) 397

Universality confirmed at the LHC in 2013

M. Lisovyi, A. Verbytskyi, O. Zenaiev, EPJC 76 (2016) no.7, 397



- Very nice agreement across collision systems (e^+e^-, ep and pp collisions)
- In 2013, only LHCb Λ_c^+ measurement at forward rapidity in pp@7 TeV[1] available at the LHC

Forward rapidity

[1] LHCb: Nucl.Phys.B 871 (2013) 1-20

Indication of non-universality by ALICE in 2017

https://cerncourier.com/a/alice-investigates-charm-quark-hadronisation

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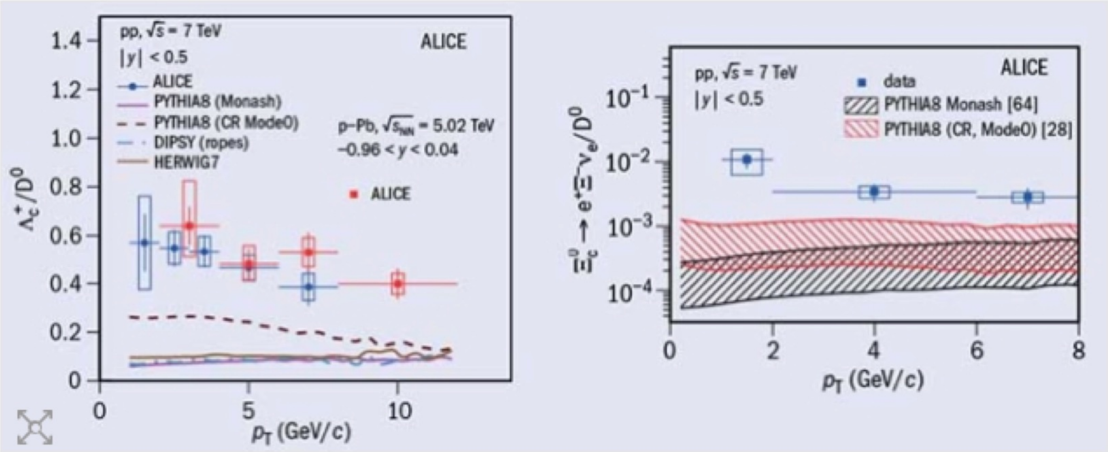
ALICE investigates charm-quark hadronisation

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 $\Xi^0_c \rightarrow e^+ \nu_e \Xi^-$ branching ratio (shaded bands).

- Measurements of Λ_c^+/D^0[1] and Ξ_c^0/D^0[2] from ALICE in 2017 much higher than calculations based on fragmentation fractions tuned on e^+e^- data
  - Indicate fragmentation of charm quark NOT well understood
  - Charm baryon studies suggested that charm hadronization might be not universal and depends on collision system

Central rapidity

[1] ALICE: JHEP 04 (2018) 108
[2] ALICE: PLB 781 (2018) 8-19

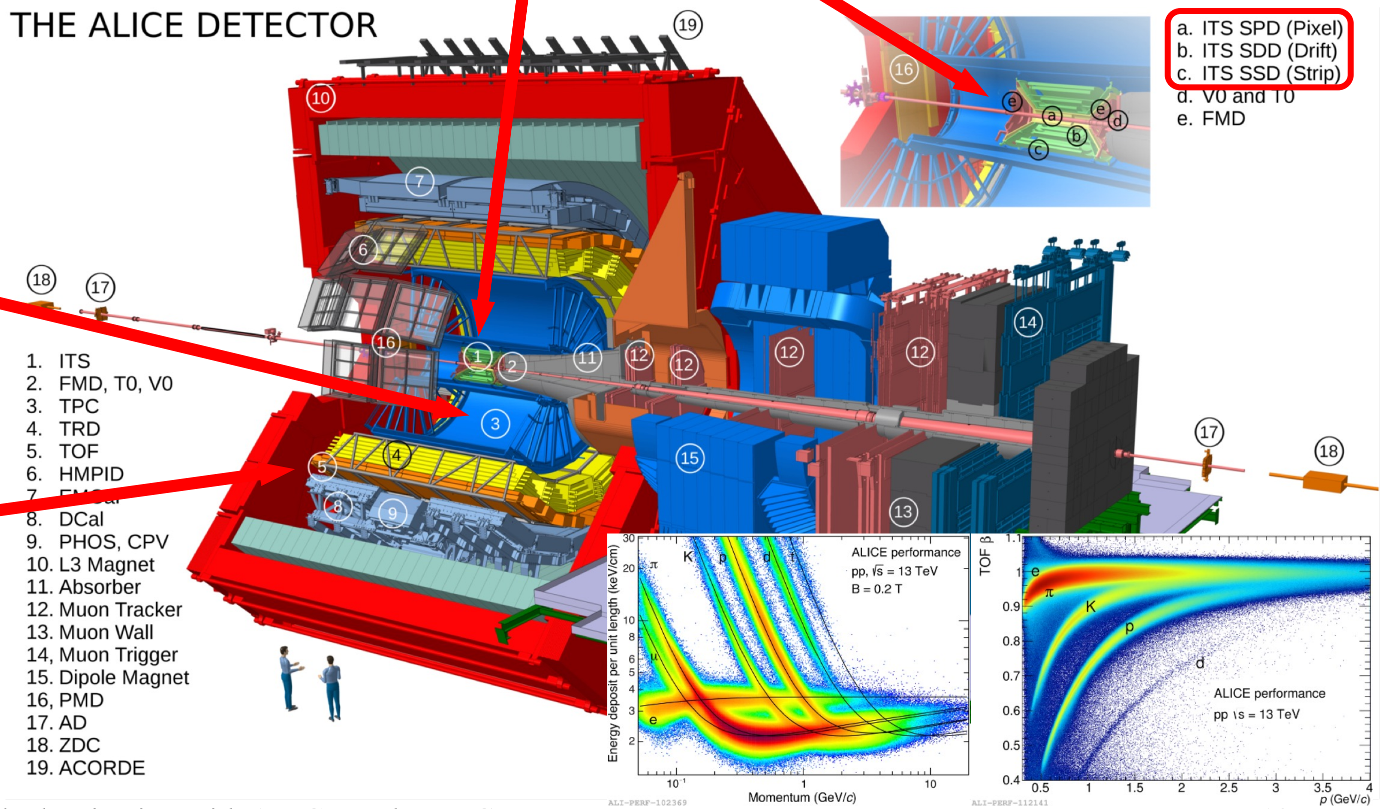
A Large Ion Collider Experiment (ALICE)

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int} (MB)
pp	2017	5.02	~ 19 nb^{-1}
	2016-2018	13	~ 33 nb^{-1}
p-Pb	2016	5.02	~ 0.3 nb^{-1}
Pb-Pb (0-10%)	2018	5.02	~ 0.13 nb^{-1}
Pb-Pb (30-50%)			~ 0.056 nb^{-1}

- Inner Tracking System (ITS)
  - $|\eta| < 0.9$
  - Tracking, vertex, particle identification (PID), multiplicity

- Time Projection Chamber (TPC)
  - $|\eta| < 0.9$
  - Tracking, PID

- Time-Of-Flight (TOF)
  - $|\eta| < 0.9$
  - Tracking, PID



Charm-hadron reconstruction

- Particle identification of decay tracks
- Selections on the displaced decay topology
- Machine-learning (ML) techniques used

D^0: $D^0 \longrightarrow K^-\pi^+$

D^+: $D^+ \longrightarrow K^-\pi^+\pi^+$

D^{*+}: $D^{*+} \longrightarrow D^0\pi^+ \longrightarrow K^-\pi^+\pi^+$

D_s^+: $D_s^+ \longrightarrow \phi\pi^+ \longrightarrow K^+K^-\pi^+$

} Charm mesons

Λ_c^+: $\Lambda_c^+ \longrightarrow pK^-\pi^+$, $\Lambda_c^+ \longrightarrow pK_s^0$

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

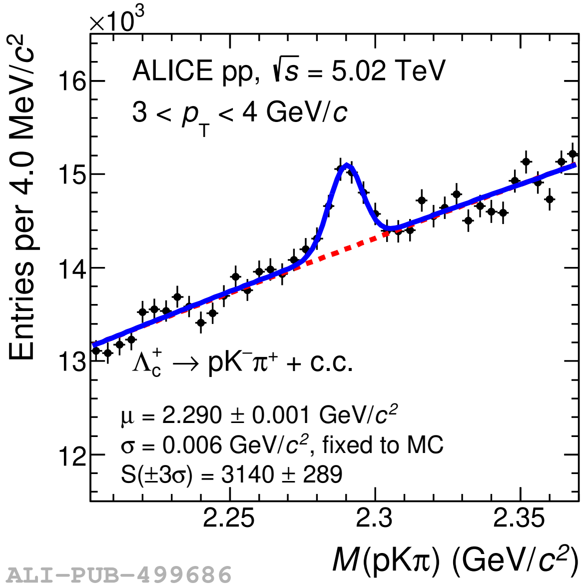
Ξ_c^0: $\Xi_c^0 \longrightarrow \Xi^-\pi^+$, $\Xi_c^0 \longrightarrow e^+\Xi^-\nu_e$

Ξ_c^+: $\Xi_c^+ \longrightarrow \Xi^-\pi^+\pi^+$

Ω_c^0: $\Omega_c^0 \longrightarrow pK^-\pi^+$, $\Omega_c^0 \longrightarrow e^+\Xi^-\nu_e$

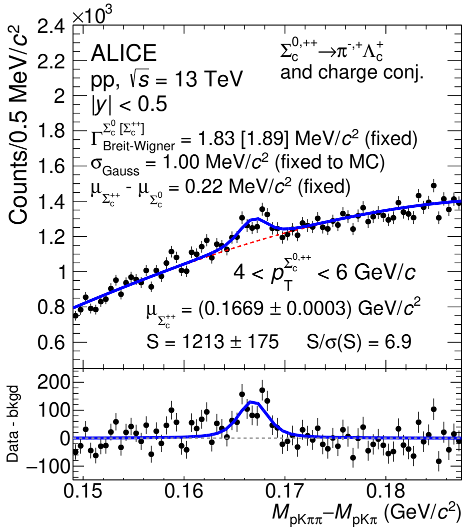
} Charm baryons

PRC 104 (2021), 054905



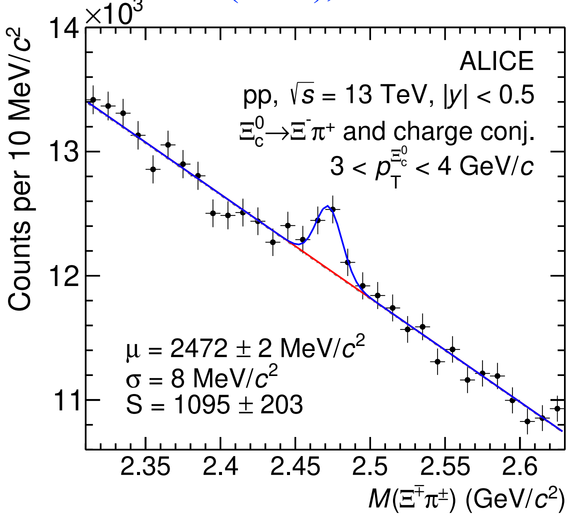
ALI-PUB-499686

PRL 128 (2022), 012001



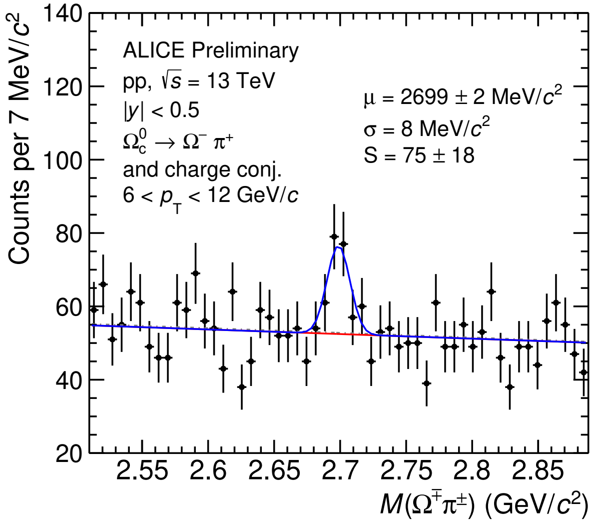
ALI-PUB-493832

PRL 127 (2021), 272001



ALI-PUB-488829

arXiv:2205.13993



ALI-PREL-486622

Charm mesons

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	$D^0(\bar{u}c)$	$D^+(\bar{d}c)$	$D^{*+}(\bar{d}c)$	$D_s^+(\bar{s}c)$	$\Lambda_c^+(udc)$	$\Sigma_c^0(ddc)$	$\Sigma_c^{++}(uuc)$	$\Xi_c^+(usc)$	$\Xi_c^0(dsc)$	$\Omega_c^0(ssc)$
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	—	151.2	60.7	—	—	136.6	45.8	80

D^0: $D^0 \longrightarrow K^-\pi^+$ (BR=3.95%)

D^+: $D^+ \longrightarrow K^-\pi^+\pi^+$ (BR=9.38%)

D^{*+}: $D^{*+} \longrightarrow D^0\pi^+$ (BR=67.7%)

D_s^+: $D_s^+ \longrightarrow \phi\pi^+ \longrightarrow K^+K^-\pi^+$ (BR=2.24%)

HF meson-to-meson production ratios in pp collisions

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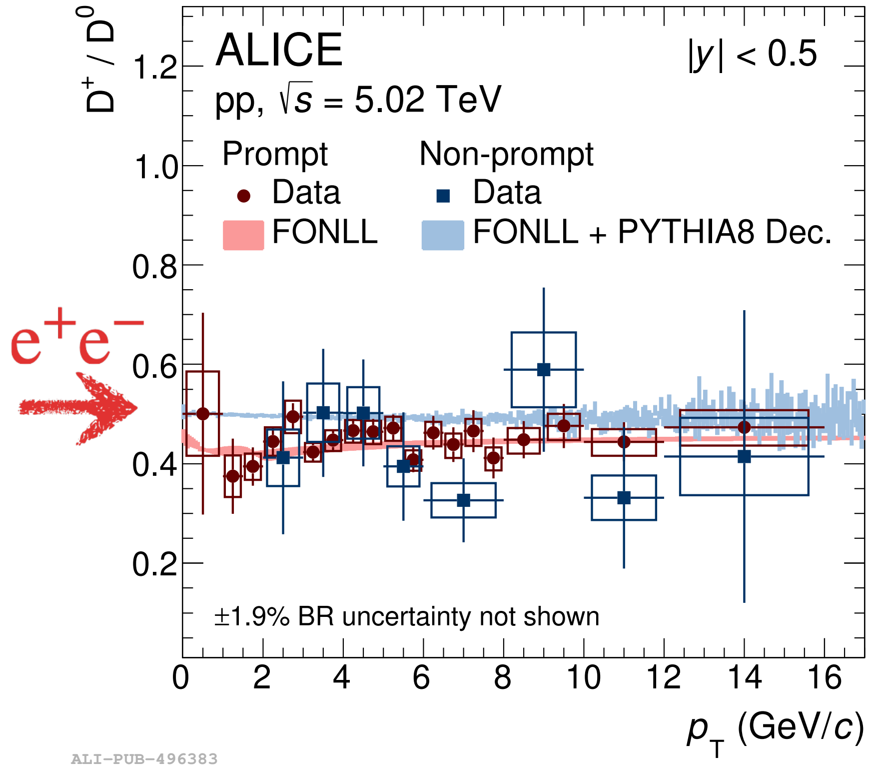
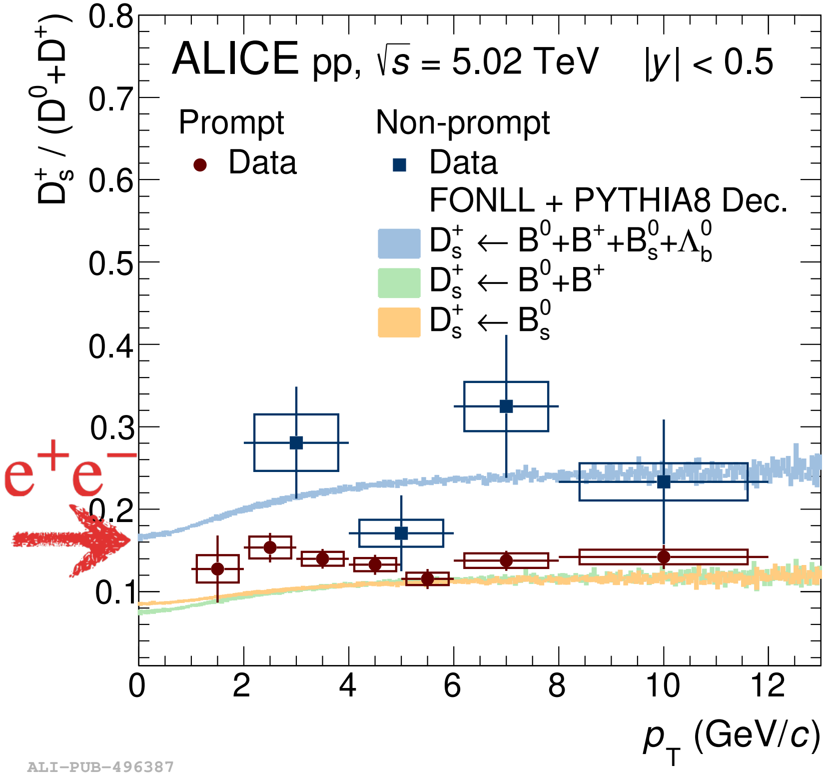
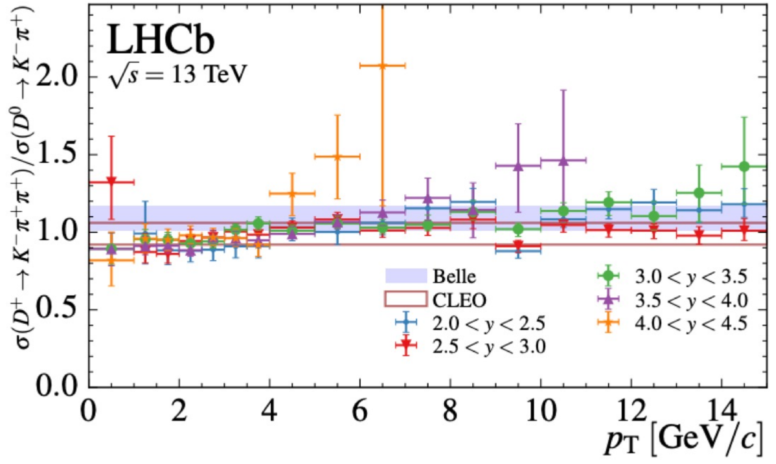
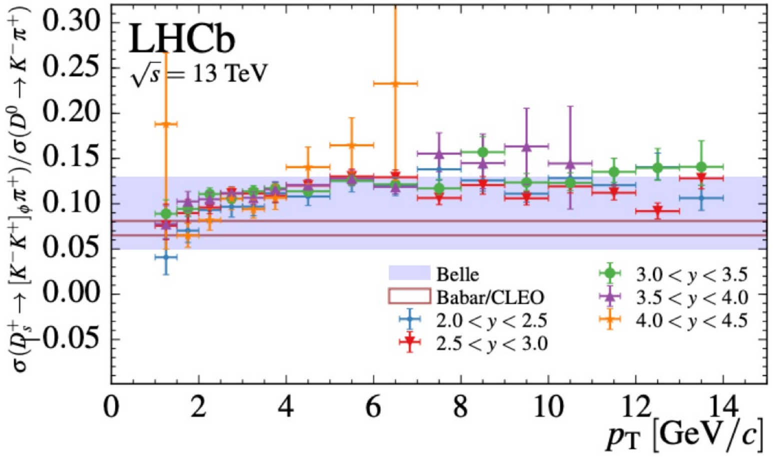
JHEP 05 (2021) 220





LHCb: JHEP 05 (2017) 074





- HF meson-to-meson ratios independent of meson p_T and collision system
- Agreement with model calculations (FONLL[1]) based on a factorisation approach and relying on universal fragmentation functions and with e^+e^- and e^-p measurements

[1] M. Cacciari, et al., JHEP 10 (2012) 137
[2] PYTHIA8: P. Skands, et al., EPJC 74 (2014) 3024

Charm baryon: Λ_c^+

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	$D^0(\bar{u}c)$	$D^+(\bar{d}c)$	$D^{*+}(\bar{d}c)$	$D_s^+(\bar{s}c)$	$\Lambda_c^+(udc)$	$\Sigma_c^0(ddc)$	$\Sigma_c^{++}(uuc)$	$\Xi_c^+(usc)$	$\Xi_c^0(dsc)$	$\Omega_c^0(ssc)$
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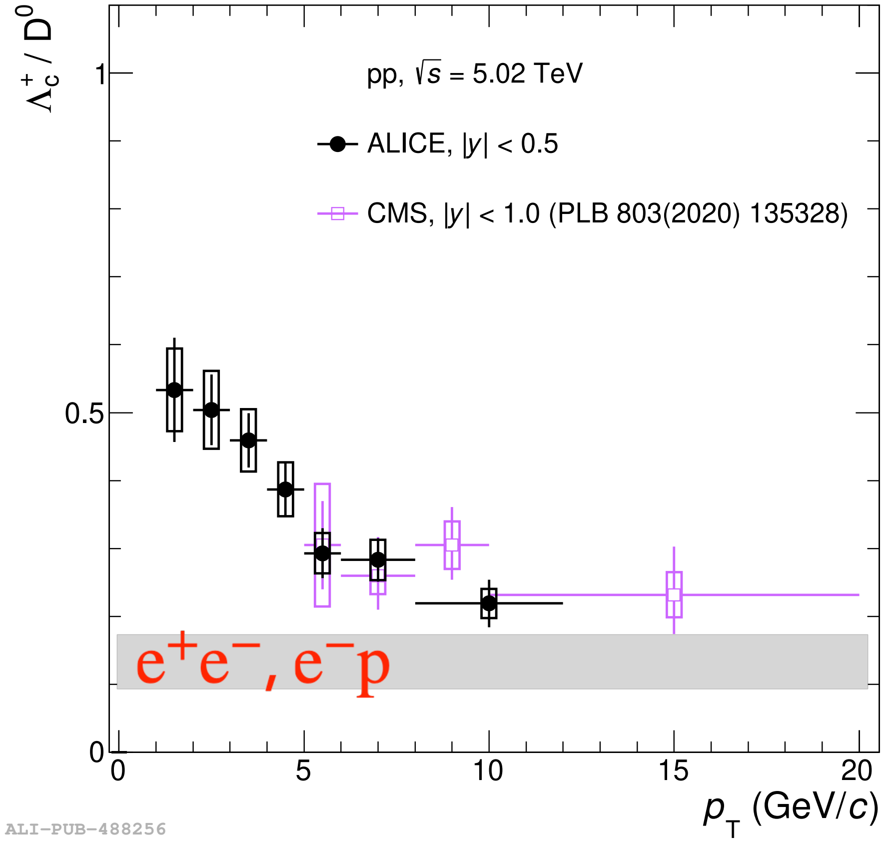
Lifetime (μm)	122.9	311.8	—	151.2	60.7	—	—	136.6	45.8	80

$\Lambda_c^+ \longrightarrow pK^-\pi^+$ (BR=6.28%)

$\Lambda_c^+ \longrightarrow pK_s^0$ (BR=1.59%)

Λ_c^+/D^0 in Run 2: more precise

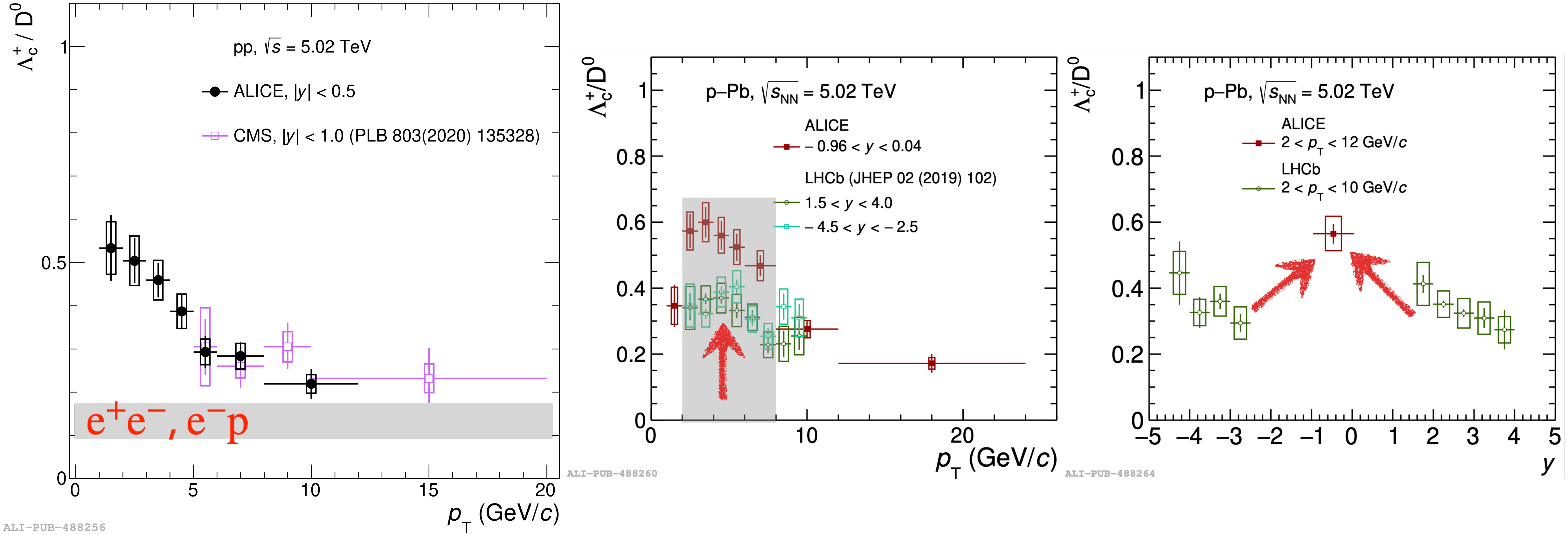
PRC 104 (2021), 054905 PRL 127 (2021), 202301



- More precise and wider p_T range measurements (w.r.t. Run 1) highlight strong p_T dependence (CMS reaches higher p_T)
  - Low p_T significantly higher than e^+e^- and e^-p
  - High p_T approaches value measured in e^+e^- and e^-p

Λ_c^+/D^0 in Run 2: more precise

PRC 104 (2021), 054905 PRL 127 (2021), 202301



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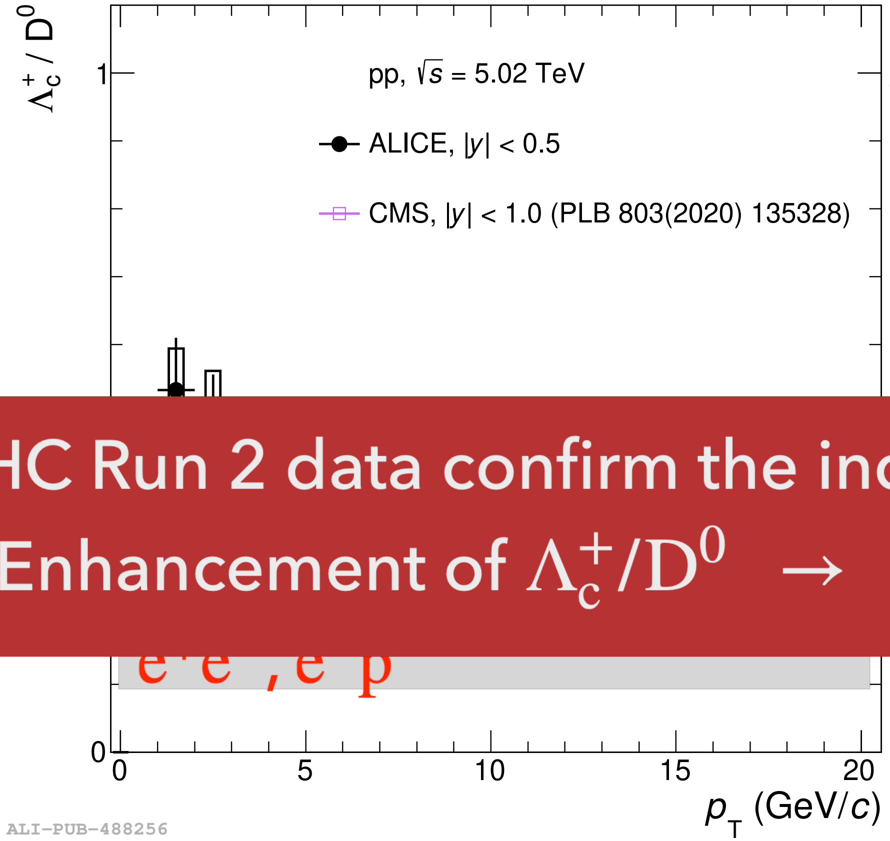
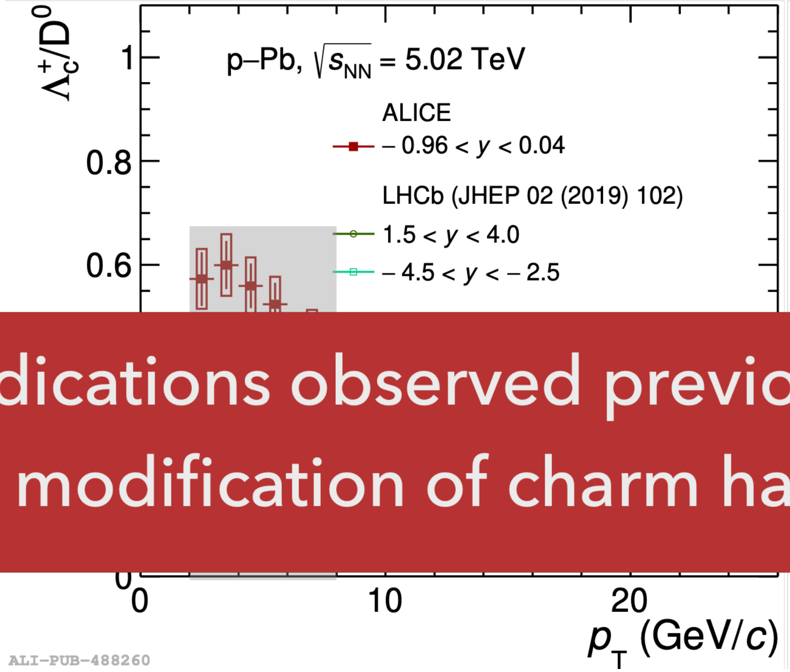
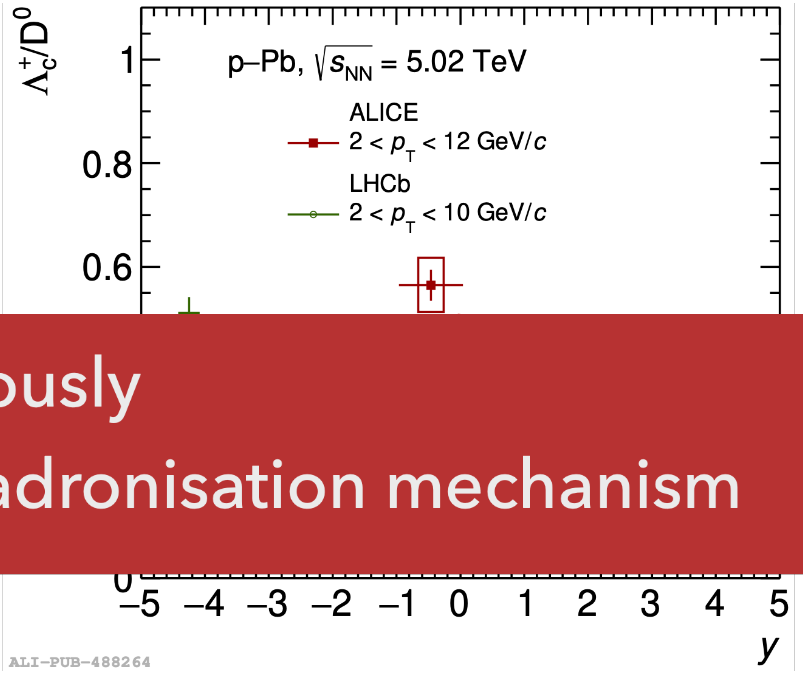
  - Low p_T significantly higher than e^+e^- and e^-p
  - High p_T approaches value measured in e^+e^- and e^-p
- Comparison with forward and backward rapidity measured by LHCb represents interesting trend
- All measurements from Run 2 at the LHC agree to draw conclusion that Λ_c^+/D^0 is higher in pp w.r.t. e^+e^- and e^-p

Λ_c^+/D^0 in Run 2: more precise

PRC 104 (2021), 054905 PRL 127 (2021), 202301





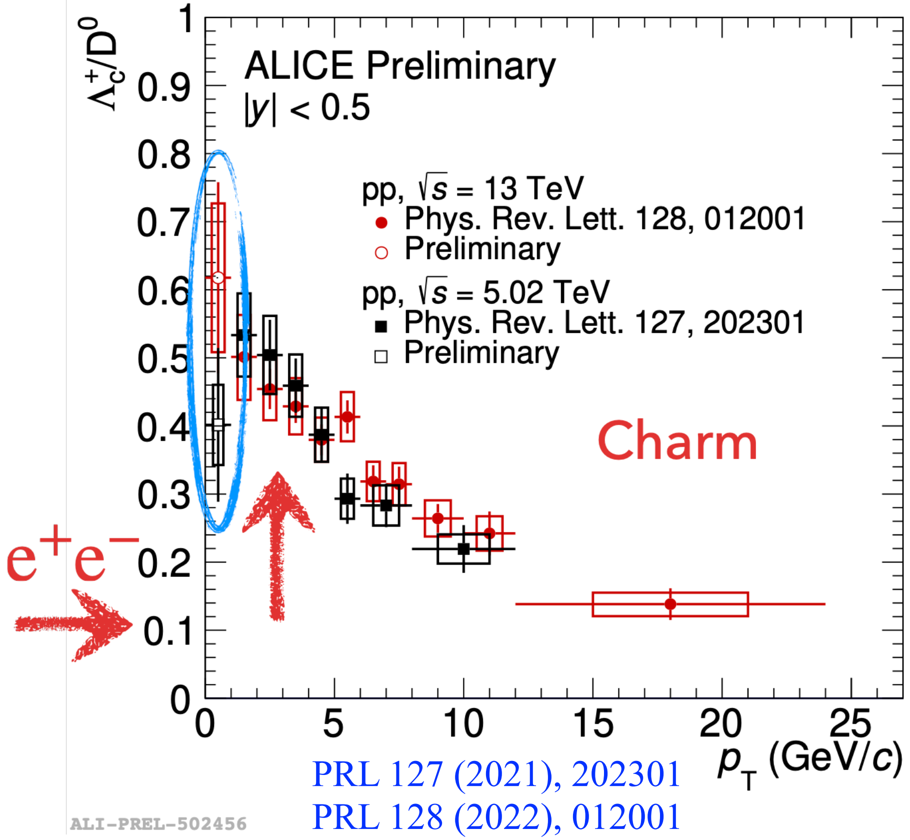


LHC Run 2 data confirm the indications observed previously

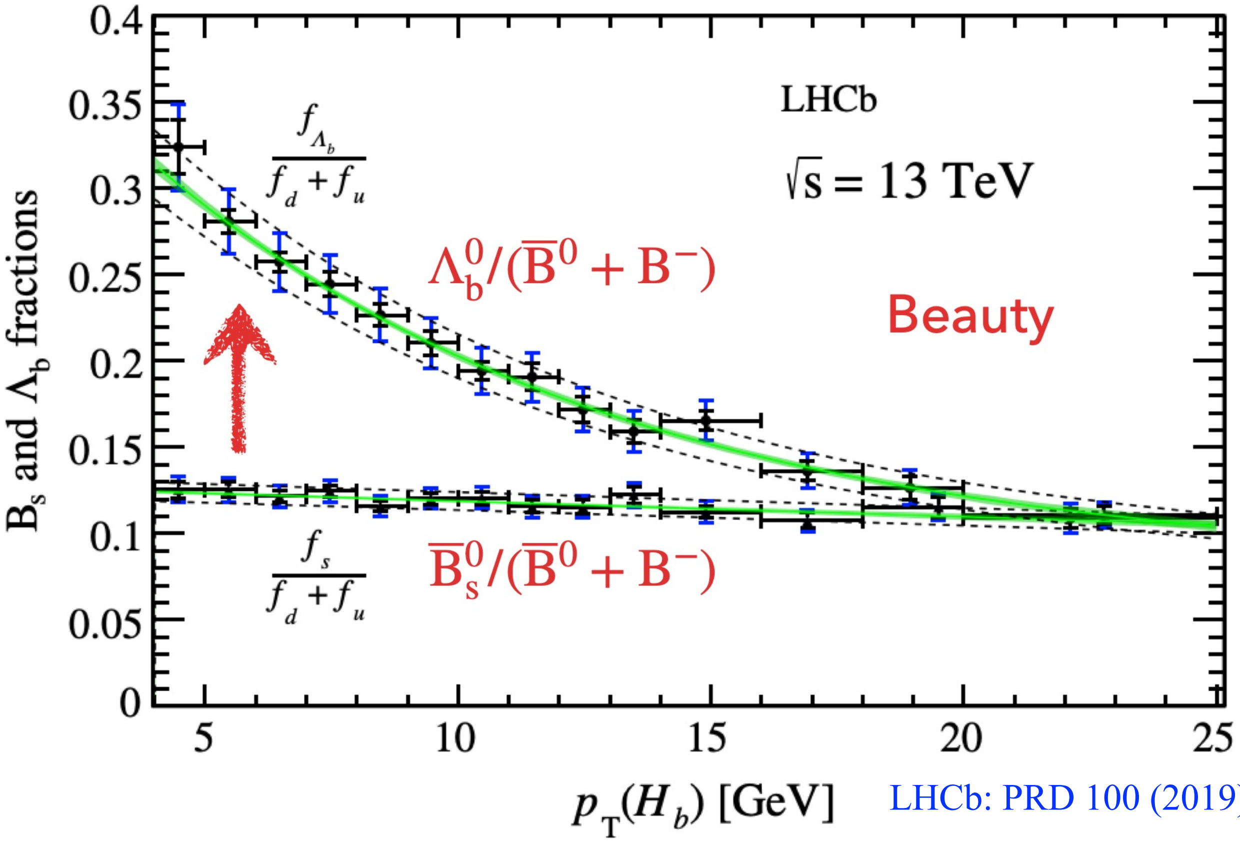
- Enhancement of Λ_c^+/D^0 → modification of charm hadronisation mechanism

- More precise and wider p_T range measurements (w.r.t. Run 1) highlight strong p_T dependence (CMS reaches higher p_T)
  - Low p_T significantly higher than e^+e^- and e^-p
  - High p_T approaches value measured in e^+e^- and e^-p
- Comparison with forward and backward rapidity measured by LHCb represents interesting trend
- All measurements from Run 2 at the LHC agree to draw conclusion that Λ_c^+/D^0 is higher in pp w.r.t. e^+e^- and e^-p

Λ_c^+/D^0 down to $p_T = 0$ in pp collisions



PRL 127 (2021), 202301
PRL 128 (2022), 012001

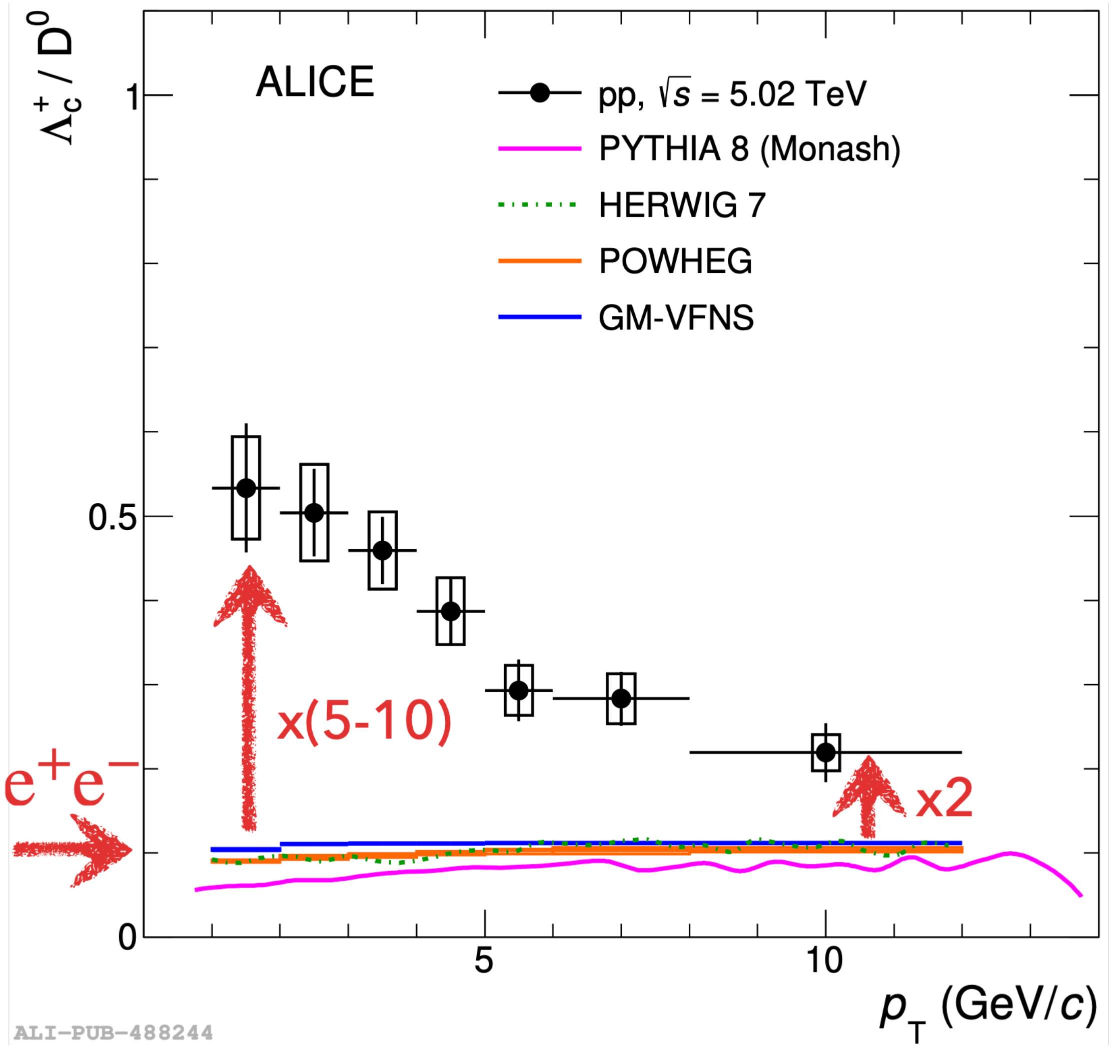


LHCb: PRD 100 (2019), 031102

- First measurements of Λ_c^+ down to $p_T = 0$ in pp@5.02 TeV and pp@13 TeV
- NO collision energy dependence
- Charm baryon-to-meson ratios significantly higher than e^+e^- results
  - PYTHIA 8 Monash (e^+e^- charm fragmentation functions)
- Beauty baryon-to-meson enhancement at low p_T also observed

How do model calculations and MC generators perform?

PRC 104 (2021), 054905   PRL 127 (2021), 202301



- The MC generators
  - PYTHIA8 Monash tune[1] simple LUND string fragmentation
  - HERWIG7[2]: hadronization implemented via clusters
  - POWHEG[3]: matched to PYTHIA6[4] to generate parton shower
- GM-VFNS[5]: pQCD calculations, compute the ratios of Λ_c^+ and D^0 cross sections with same choice of pQCD scales
- All implement fragmentation processes tuned on e^+e^-
  - $\Lambda_c^+/D^0 \approx 0.1$
  - NO p_T dependence
- At low p_T, significantly underestimate Λ_c^+/D^0
- At high p_T, discrepancy reduced

[1] PYTHIA8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
[2] HERWIG: M. Bahr, et al., EPJC 58 (2008) 639-707
[3] POWHEG: S. Frixione, et al., JHEP 09 (2007) 126
[4] PYTHIA6: T. Sjostrand, JHEP 05 (2006) 026
[5] GM-VFNS: B. Kniehl, et al., PRD 101 (2020) 114021

PYTHIA with new colour reconnection

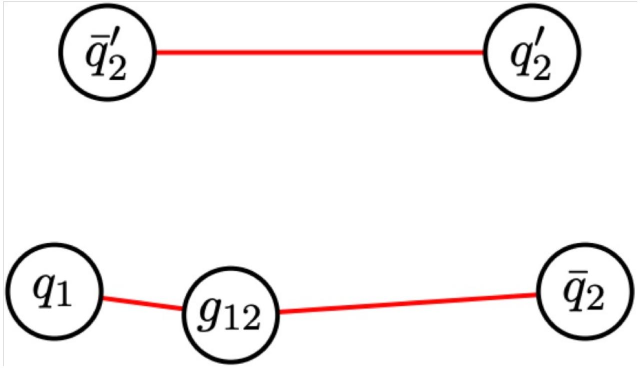
PYTHIA 8[1,2]

J. Christiansen, P. Skands, JHEP 08 (2015) 003

- New CR model: color reconnection beyond leading color (CR-BLC) mode with SU(3) topology weights + string-length minimisation
  - The junction topology favours baryon formation
    - Primordial Λ_c^+ enhanced by factor ~2 with new CR model
    - Extra contribution from feed-down of Σ_c states (×20~30 more)

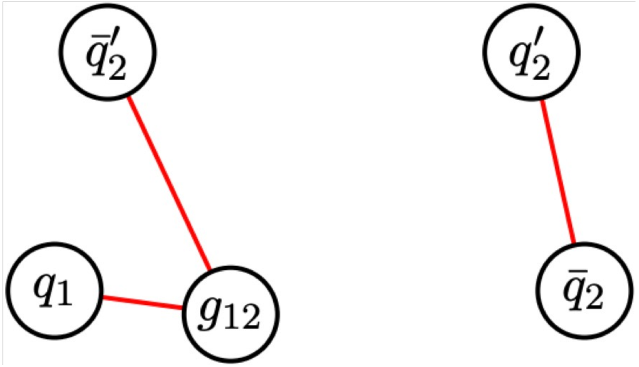
Particle	New CR model (N_{par}/N_{events}) string	junction	all	Old CR model N_{par}/N_{events} (all)
D^+	$5.3 \cdot 10^{-2}$	0	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$4.0 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$2.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^{+}	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^{0}	$2.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$

No CR



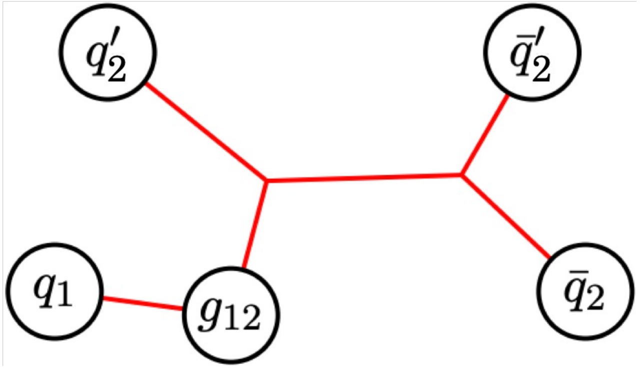
- Partons created in different scatterings do not interact

MPI-based CR
(Old CR model)



- CR allowed between partons from different MPIs to minimize string length
- As implemented in Monash

More-QCD CR
(New CR-BLC model)



- Uses a simple model of the colour rules of QCD to determine the formation of strings and introduce junctions
- Minimization of the string length over all possible configurations
- Include CR with MPIs and with beam remnants

[1] P. Skands, S. Carrazza and J. Rojo, EPJC 74 (2014) 3024
[2] J. Christiansen, P. Skands, JHEP 08 (2015) 003

Statistical hadronization with augmented resonances

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

r_i	D^+/D^0	D^{*+}/D^0	D_s^+/D^0	Λ_c^+/D^0
PDG(170)	0.4391	0.4315	0.2736	0.2851
PDG(160)	0.4450	0.4229	0.2624	0.2404
RQM(170)	0.4391	0.4315	0.2726	0.5696
RQM(160)	0.4450	0.4229	0.2624	0.4409

Statistical Hadronization Model and Relativistic Quark Model (SHM+RQM) (M. He and R. Rapp)[1]

- SHM (M. He and R. Rapp), and FF from e^+e^-
  - Tuned on D^0 ALICE data + scaling for mass
- Strong feed-down from an augmented set of excited charm baryons based on RQM[2]
  - PDG: $5\Lambda_c$, $3\Sigma_c$, $8\Xi_c$, $2\Omega_c$
  - RQM: extra $18\Lambda_c$, $42\Sigma_c$, $62\Xi_c$, $34\Omega_c$ w.r.t. PDG2018[3]

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

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

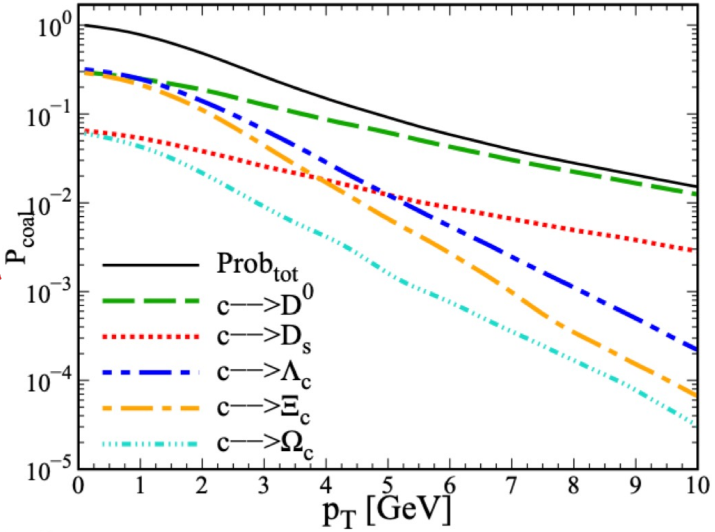
[1] M. He and R. Rapp, PLB 795 (2019) 117-121
[2] D. Ebert, R. Faustov and V. Galkin, PRD 84:014025, 2011
[3] PDG: PRD 98, no.3, 030001 (2018)

Coalescence from a partonic system

Catania[1,2]

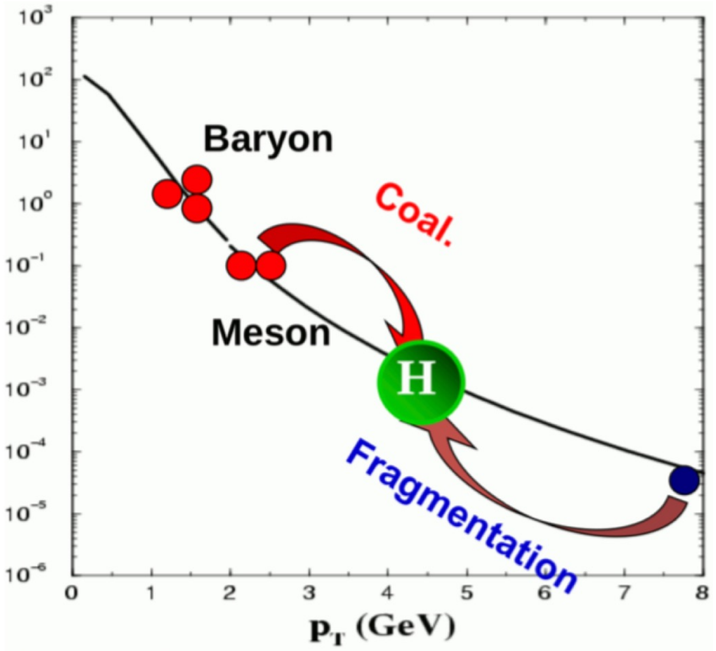
V. Minissale, S. Plumari, V. Greco, PLB 821 (2021) 136622

- Transport model with hadronization via coalescence+fragmentation
  - Assume a partonic system (QGP-like) in pp
  - Coalescence enhances baryon-to-meson yield ratio
- Total charm cross section $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y = 1.0$ mb used (higher than FONLL)
- Charm quark spectrum from FONLL
- Same excited resonances as PDG
- At $p_\mathrm{T} \approx 0$, a charm quark can hadronise only by coalescence
- At high p_T, fragmentation becomes dominant

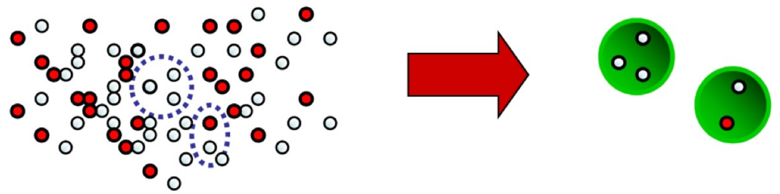


QCM: Quark (re-)Combination Mechanism[3]

- Charm combined with equal-velocity light quarks
  - Charm can pick up a co-moving light antiquark or two co-moving quarks

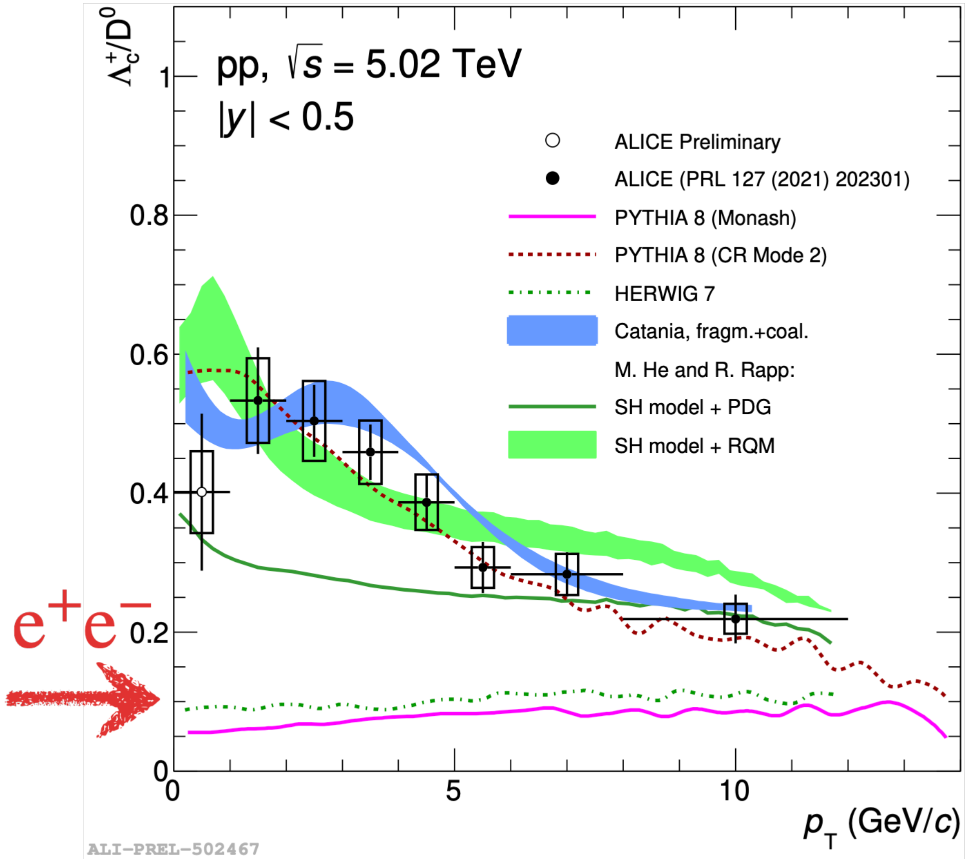


Both models maybe related to creation of deconfined parton system in pp



[1] V. Minissale, S. Plumari, V. Greco, arXiv:2012.12001
[2] S. Plumari, et al., EPJC (2018) 78:348
[3] J. Song, H. Li, F. Shao, EPJC (2018) 78: 344

Models with different assumptions compared with data

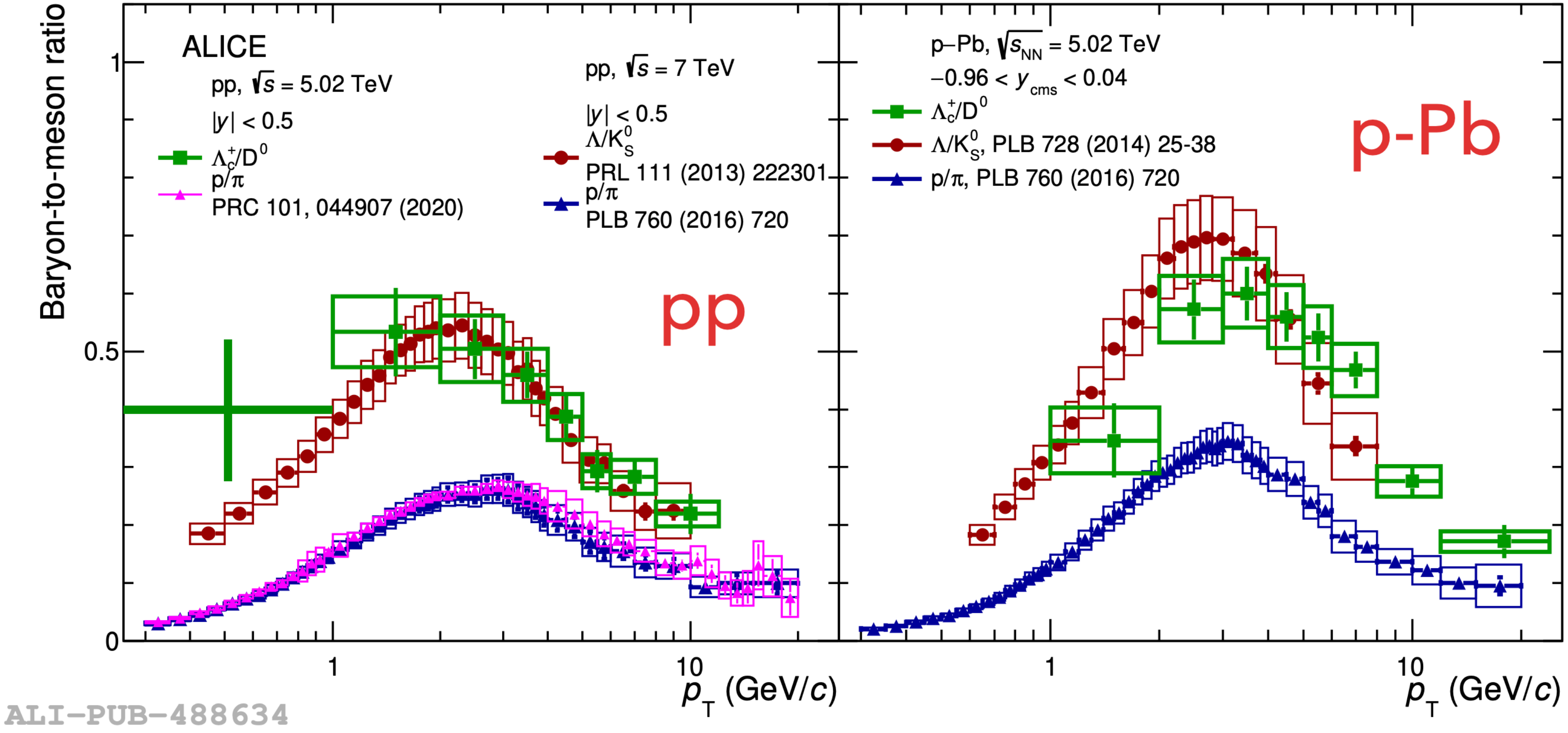


PRC 104 (2021), 054905
PRL 127 (2021), 202301

- PYTHIA8 CR-BLC tunes[2] largely enhance Λ_c^+ yield w.r.t. Monash tune[1]
- SHM[3]+RQM[4] enhance Λ_c^+ yield w.r.t. SHM+PDG and better describes data
  - Suggest yet-unobserved higher-mass charm-baryon states exist
- Catania[5] with coalescence approach describes data
  - Indicate coalescence exists in pp

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., arXiv:2012.12001

Compare with light flavour (LF)



PRL 127 (2021), 202301

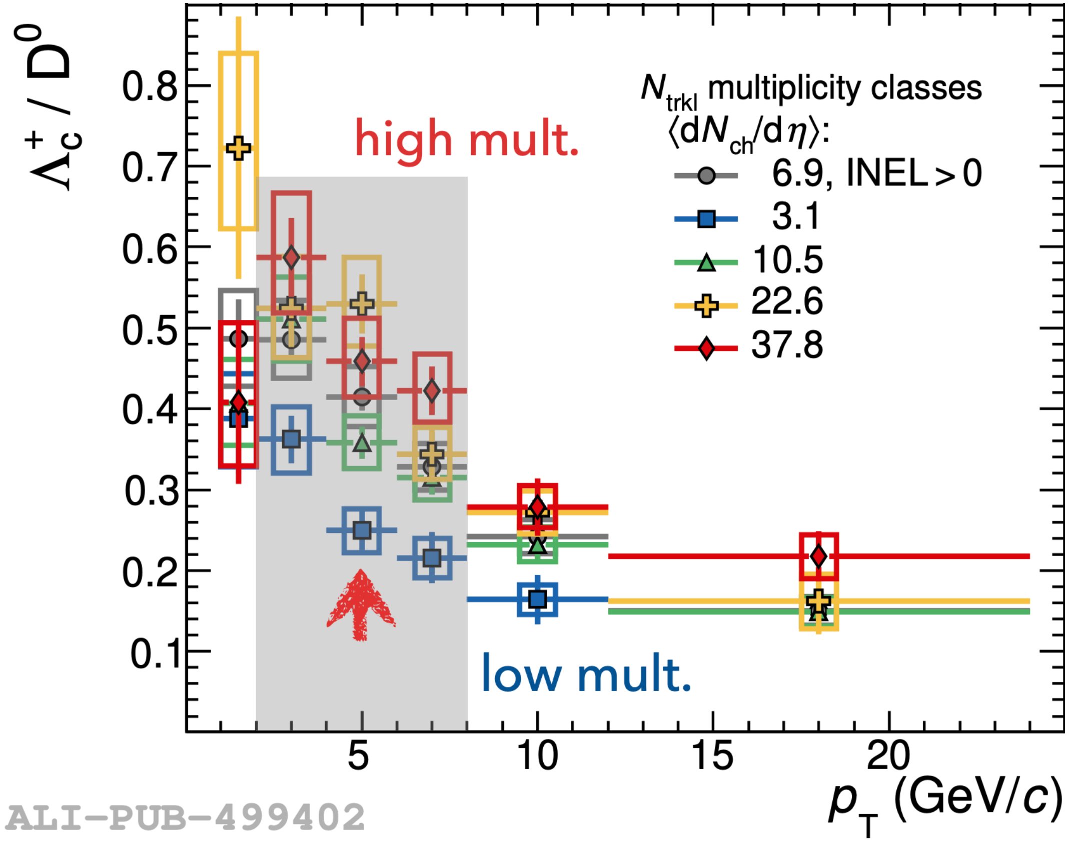
Common mechanism for light and charm baryon formation ?

- Comparison of baryon-to-meson yield ratio in heavy and light sector show similar properties
  - Λ_c^+/D^0 consistent with Λ/K^0_S both in magnitude and shape
  - Similar p_T trend observed for p/π

Caveat: Light-flavour hadrons have a significant contribution from gluon fragmentation
Low p_T light-flavour hadrons mainly originate from soft scattering process involving small momentum transfers

Λ_c^+/D^0 vs. p_T from low to high multiplicity

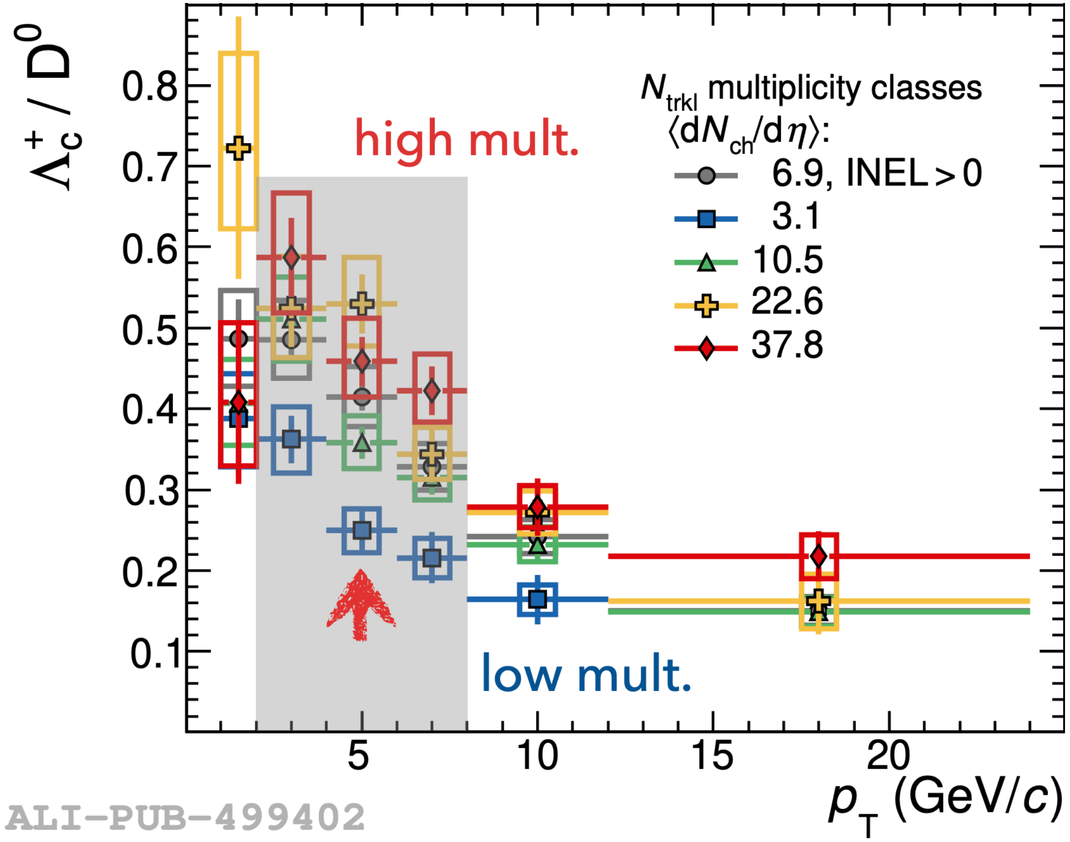
Phys.Lett.B 829 (2022) 137065



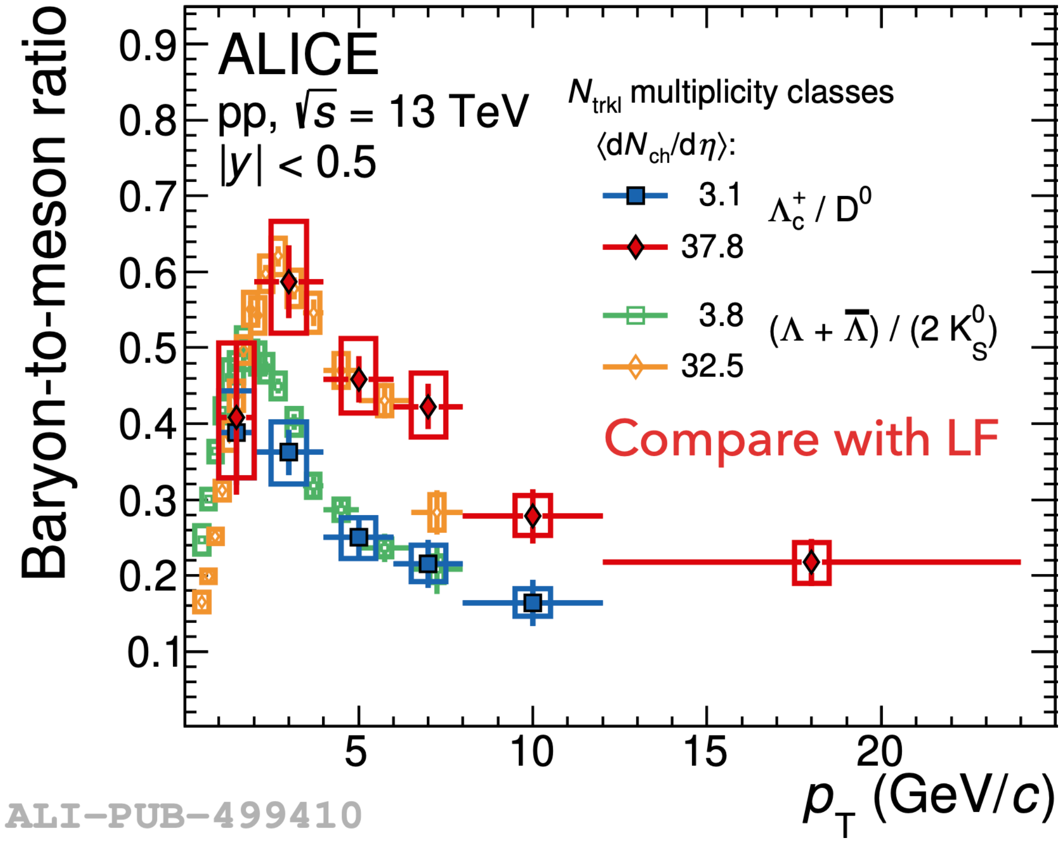
- p_T-dependent enhancement of Λ_c^+/D^0 observed from low to high multiplicity
- Lowest multiplicity still higher than measurements in e^+e^- and e^-p

Λ_c^+/D^0 vs. p_T from low to high multiplicity

Phys.Lett.B 829 (2022) 137065



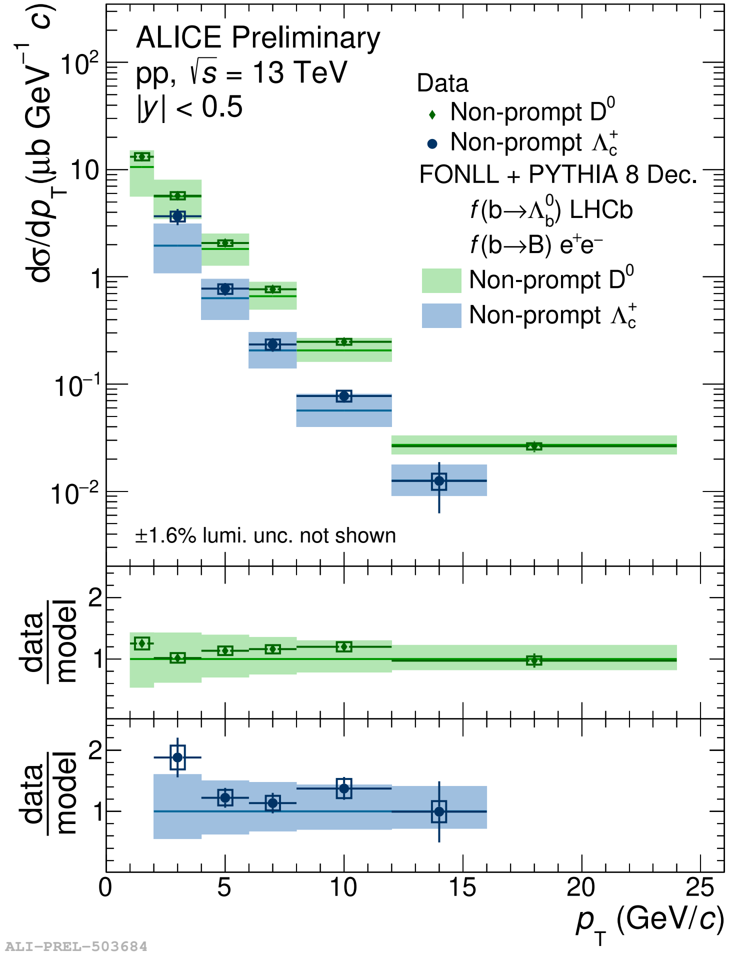
Phys.Lett.B 829 (2022) 137065

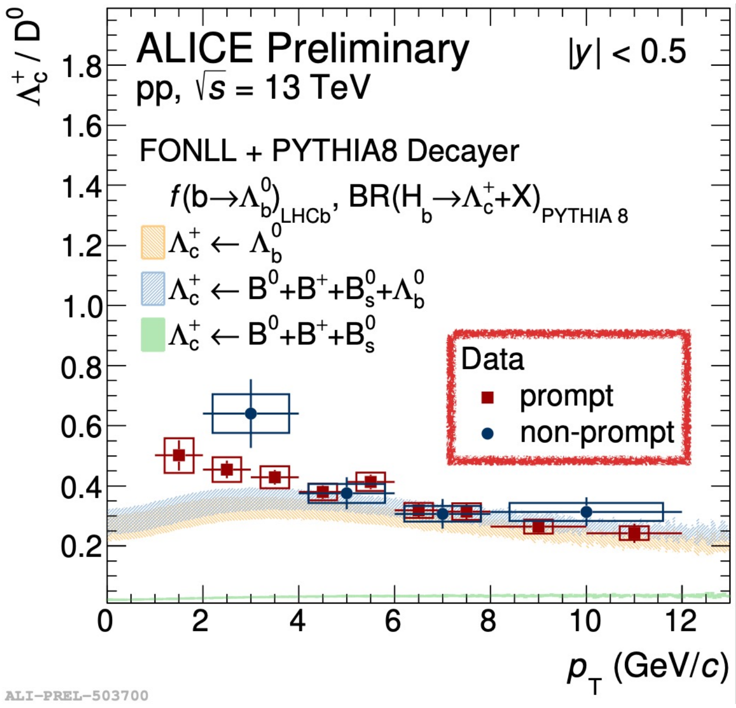


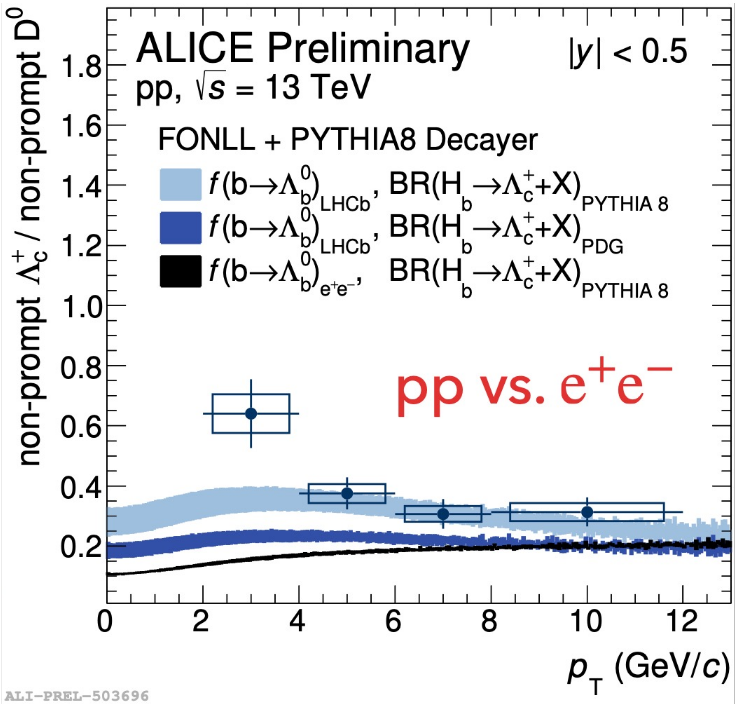
- p_T-dependent enhancement of Λ_c^+/D^0 observed from low to high multiplicity
- Lowest multiplicity still higher than measurements in e^+e^- and e^-p

- Similar p_T-dependent enhancement of Λ_c^+/D^0 and Λ/K_s^0 observed from low to high multiplicity
  - Common mechanism for light and charm baryon formation ?

Non-prompt Λ_c^+ production in pp@13 TeV







- p_T dependence well reproduced by theoretical calculations
  - Λ_b^0 fragmentation fractions measured by LHCb
  - Folding with $H_b \to \Lambda_c^+ + X$ decay from PYTHIA 8
- Non-prompt vs. prompt Λ_c^+/D^0
  - Similar baryon-to-meson ratio enhancement
- Non-prompt Λ_c^+/D^0 vs. models
  - Well reproduced by FONLL+PYTHIA8 for $p_T > 4$ GeV/c
- Non-prompt Λ_c^+/D^0: pp vs. e^+e^-
  - Enhanced beauty-baryon production in pp w.r.t. e^+e^-

Heavier charm baryons: $\Sigma_c^{0,+,++}$

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	$D^0(\bar{u}c)$	$D^+(\bar{d}c)$	$D^{*+}(\bar{d}c)$	$D_s^+(\bar{s}c)$	$\Lambda_c^+(udc)$	$\Sigma_c^0(ddc)$	$\Sigma_c^{++}(uuc)$	$\Xi_c^+(usc)$	$\Xi_c^0(dsc)$	$\Omega_c^0(ssc)$
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	—	151.2	60.7	—	—	136.6	45.8	80

$\Sigma_c^0 \longrightarrow \Lambda_c^+\pi^-$ (BR=100%, strongly decay)

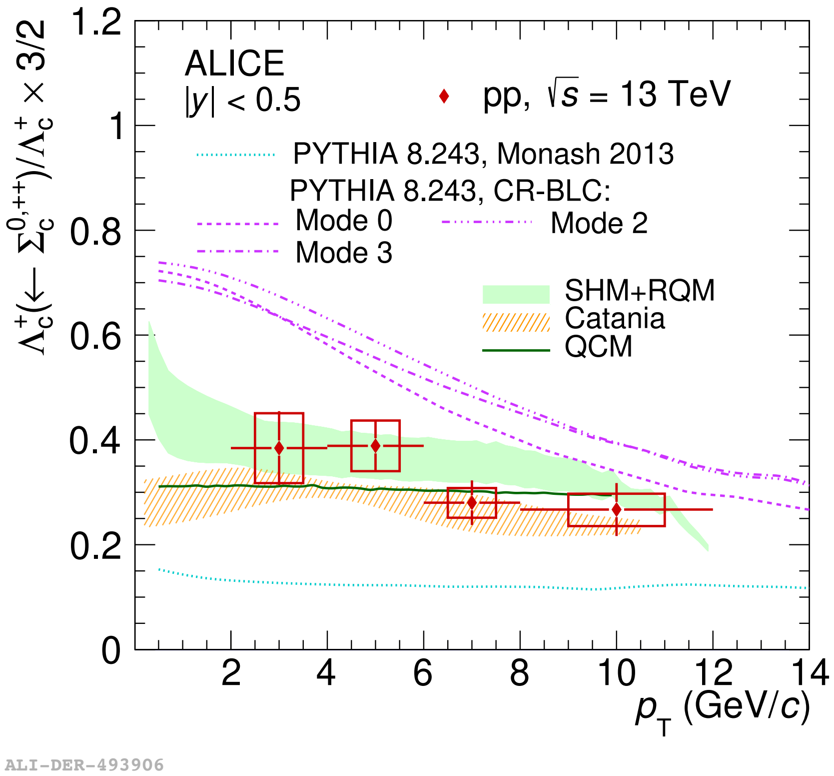
$\Sigma_c^{++} \longrightarrow \Lambda_c^+\pi^+$ (BR=100%, strongly decay)

$\times 3/2$ to count $\Sigma_c^+(udc)$

Heavier charm baryons: $\Sigma_c^{0,+,++}$ in pp@13 TeV

- Effect of $\Sigma_c^{0,+,++}$ feed-down contribution on Λ_c^+/D^0 enhancement
  - ~40% contribution, only partially explained by $\Sigma_c^{0,+,++}$ feed-down

PRL 128 (2022), 012001



- PYTHIA8 Monash[1] severely underestimates $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$
- PYTHIA8 CR Modes[2] overestimate $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$
- SHM[3]+RQM[4], Catania[5], and QCM[6] describe $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., arXiv:2012.12001
[6] J. Song, et al., EPJC (2018) 78: 344

Heavier charm baryons: $\Sigma_c^{0,+,++}$ in pp@13 TeV

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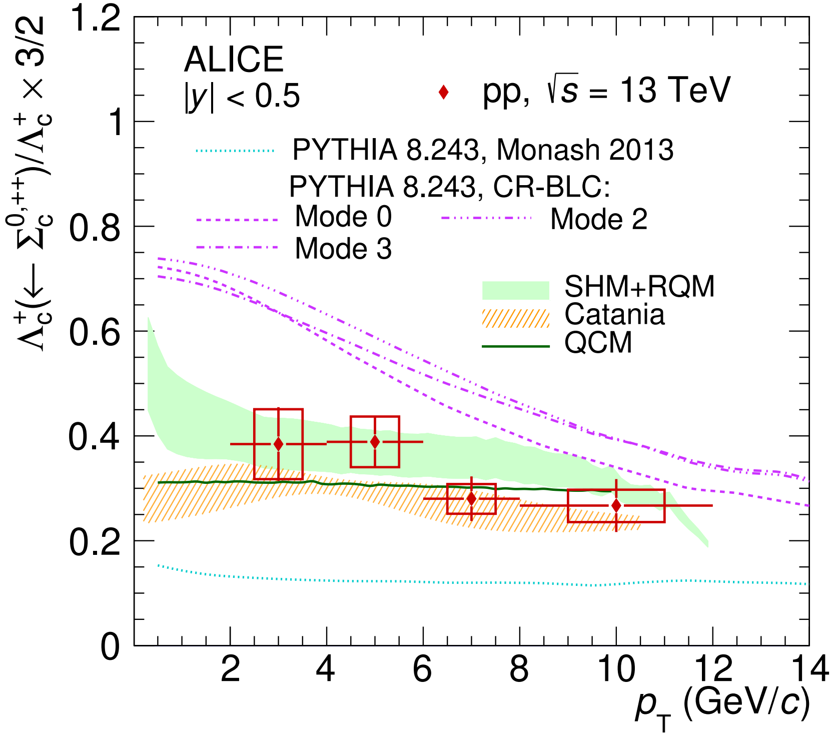
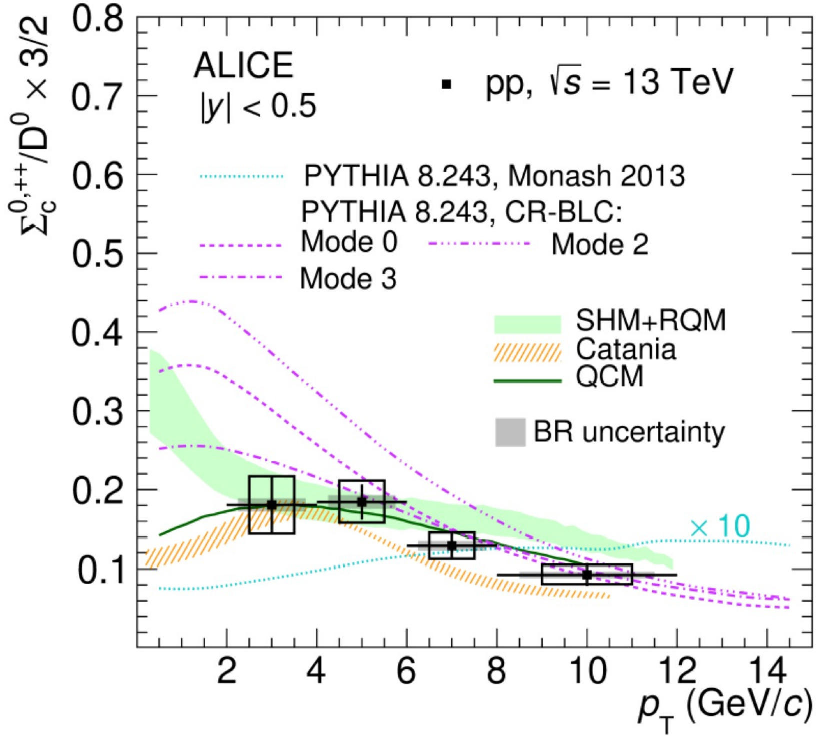
PRL 128 (2022), 012001





- PYTHIA8 Monash[1] severely underestimates $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$
- PYTHIA8 CR Modes[2] overestimate $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$, but describe $\Sigma_c^{0,+,++}/D^0$
- SHM[3]+RQM[4], Catania[5], and QCM[6] describe $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ and $\Sigma_c^{0,+,++}/D^0$

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., arXiv:2012.12001
[6] J. Song, et al., EPJC (2018) 78: 344

Strange-charm baryons: $\Xi_c^{0,+}$

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	$D^0(\bar{u}c)$	$D^+(\bar{d}c)$	$D^{*+}(\bar{d}c)$	$D_s^+(\bar{s}c)$	$\Lambda_c^+(udc)$	$\Sigma_c^0(ddc)$	$\Sigma_c^{++}(uuc)$	$\Xi_c^+(usc)$	$\Xi_c^0(dsc)$	$\Omega_c^0(ssc)$
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	—	151.2	60.7	—	—	136.6	45.8	80

$\Xi_c^0 \longrightarrow \Xi^-\pi^+$ (BR=1.43%)

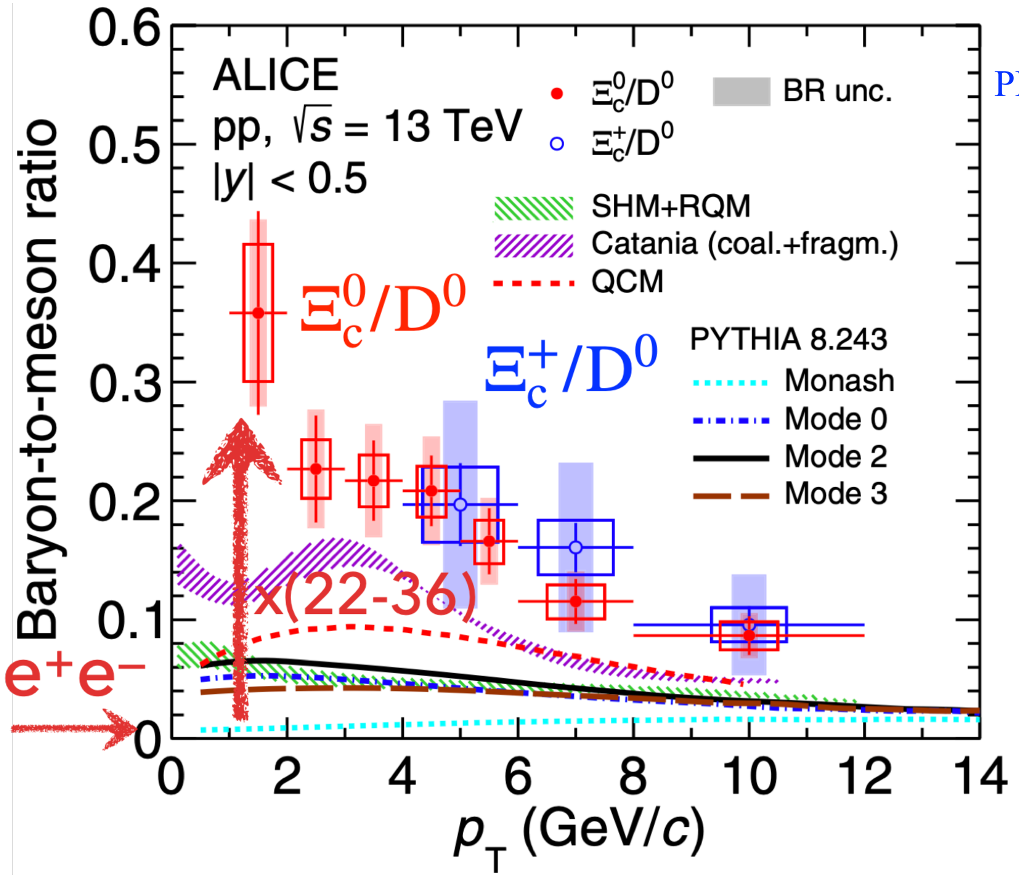
$\Xi_c^0 \longrightarrow e^+\Xi^-\nu_e$ (BR=1.8%)

$\Xi_c^+ \longrightarrow \Xi^-\pi^+\pi^+$ (BR=2.86%[1])

[1] Belle: Phys. Rev. D 100, 031101 (2019)

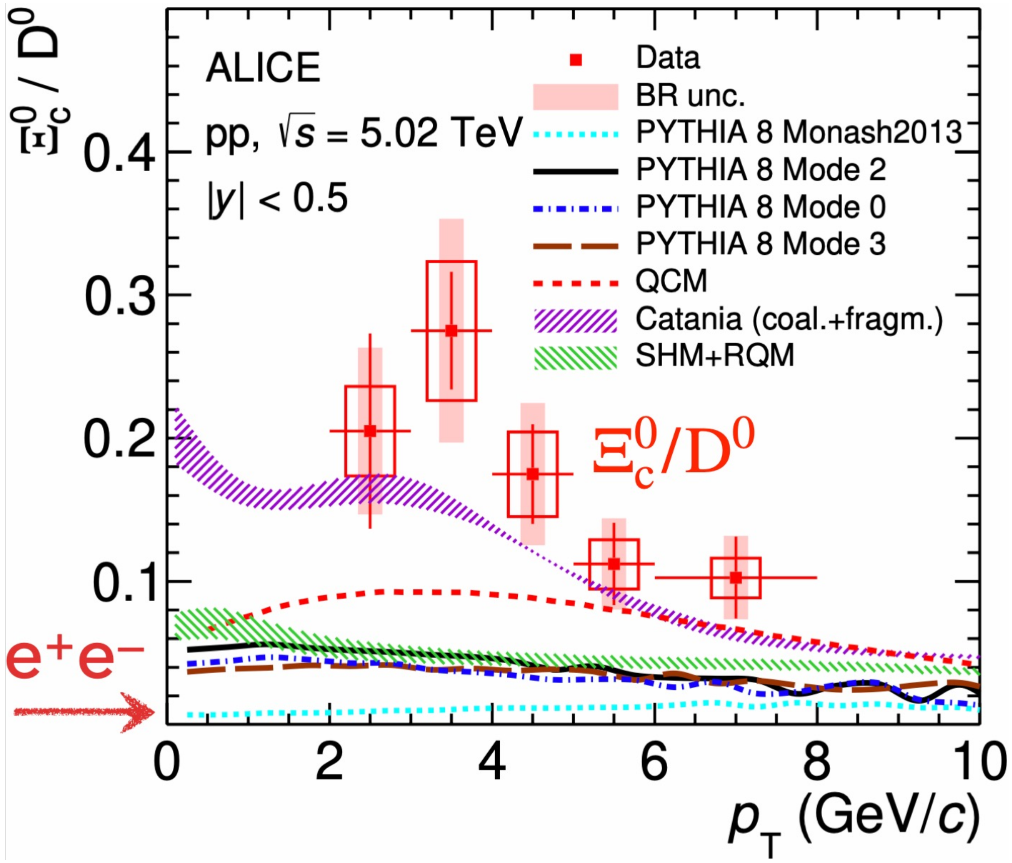
Strange-charm baryons: Ξ_c^0 and Ξ_c^+ in pp collisions

- Ξ_c^0/D^0 in agreement with Ξ_c^+/D^0
- PYTHIA8 Monash[1] largely underestimates data



PRL 127 (2021), 272001

JHEP 10 (2021) 159



- 3 CR-BLC Modes[2] and SHM[3]+RQM[4] predict significantly larger ratio w.r.t. Monash, but largely underestimate data
- QCM[5], further enhanced, still NOT describe the data
- Catania[6] better describes measurements

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] J. Song, et al., EPJC (2018) 78: 344
[6] V. Minissale, et al., arXiv:2012.12001
[7] Belle e+e−: PRD 97 (2018) 7, 072005

Double strange-charm baryon: Ω_c^0

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

	Charm mesons				Charm baryons					
	$D^0(\bar{u}c)$	$D^+(\bar{d}c)$	$D^{*+}(\bar{d}c)$	$D_s^+(\bar{s}c)$	$\Lambda_c^+(udc)$	$\Sigma_c^0(ddc)$	$\Sigma_c^{++}(uuc)$	$\Xi_c^+(usc)$	$\Xi_c^0(dsc)$	$\Omega_c^0(ssc)$
Strangeness	0			1	0			1		2
Mass (MeV/c^2)	1864.83	1869.65	2010.26	1968.34	2286.46	2453.75	2453.97	2467.94	2470.90	2695.20
Lifetime (μm)	122.9	311.8	—	151.2	60.7	—	—	136.6	45.8	80

$\Omega_c^0 \longrightarrow \Omega^-\pi^+$ (BR unknown, theoretical calculations: BR $= 0.51^{+2.19}_{-0.31}\%$ [1-5])

[1] EPJC 80 no. 11, (2020) 1066
[2] PRD 98 no. 7, (2018) 074011
[3] PRD 56 (1997) 2799-2811
[4] PRD 101 no. 9, (2020) 094033
[5] PRD 97 no. 7, (2018) 072005

Double strange-charm baryon: Ω_c^0 in pp@13 TeV

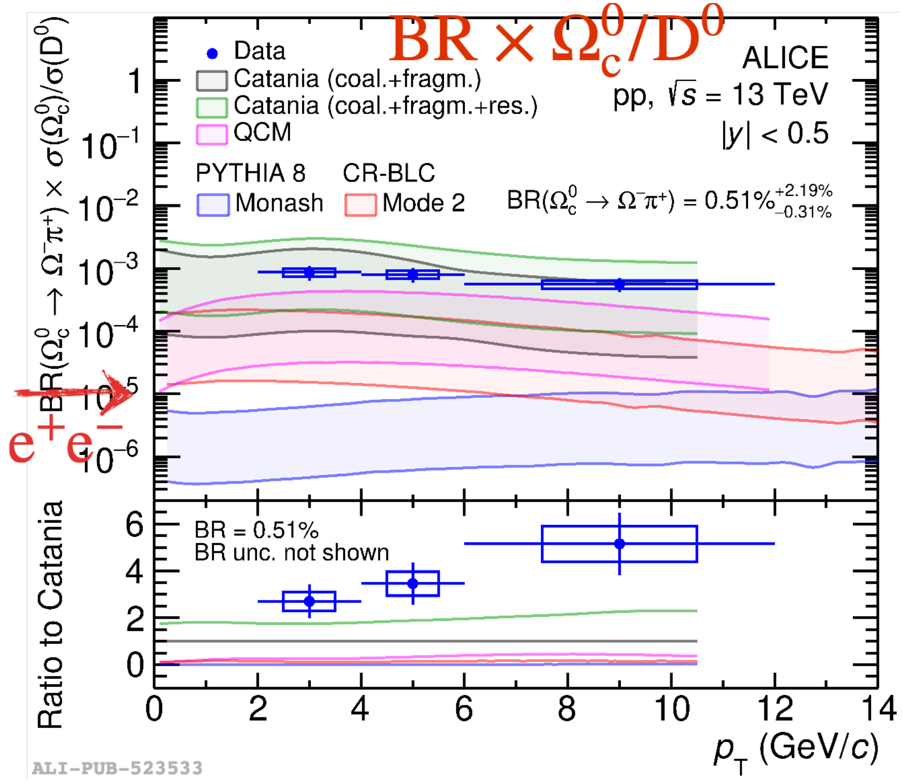
- Theoretical calculations: $BR(\Omega_c^0 \to \pi^+\Omega^-) = 0.51^{+2.19}_{-0.31}\%$
- PYTHIA8 Monash[1] largely underestimates Ω_c^0/D^0 and Ω_c^0/Ξ_c^0
  - Do not reproduce strangeness enhancement in pp
- PYTHIA8 CR-BLC[2] NOT enough to describe the measurement
- Further enhancement with simple coalescence QCM[3] still shows a hint of underestimation
- Catania[4] closer to data points, additional resonances decay considered

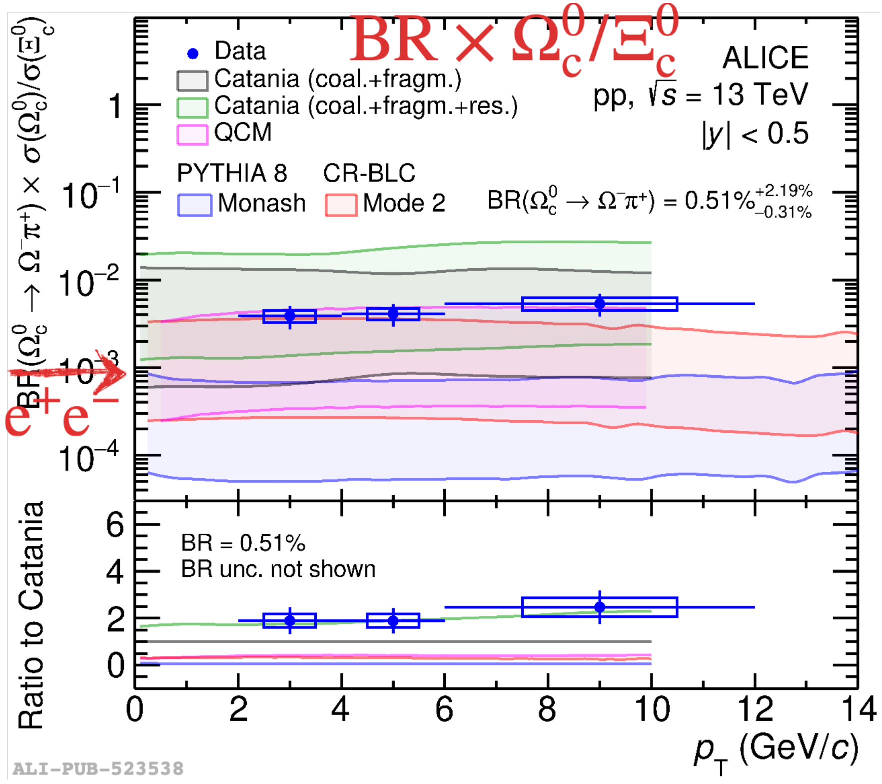
arXiv:2205.13993

Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^- 10.52 GeV) [28] visible
$BR(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(2.24 \pm 0.29 \pm 0.16) \times 10^{-4}$
$BR(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(8.58 \pm 1.15 \pm 1.98) \times 10^{-4}$

$$\frac{\Omega_c^0/\Lambda_c^+(pp)}{\Omega_c^0/\Lambda_c^+(e^+e^-)} \approx 9$$

$$\frac{\Omega_c^0/\Xi_c^0(pp)}{\Omega_c^0/\Xi_c^0(e^+e^-)} \approx 5$$



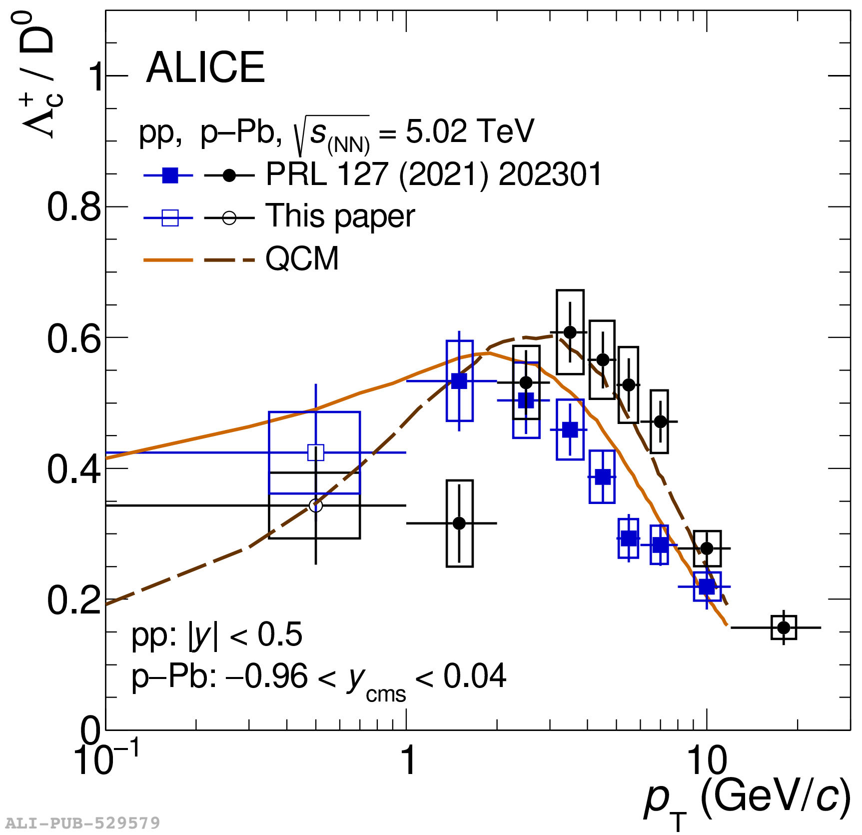


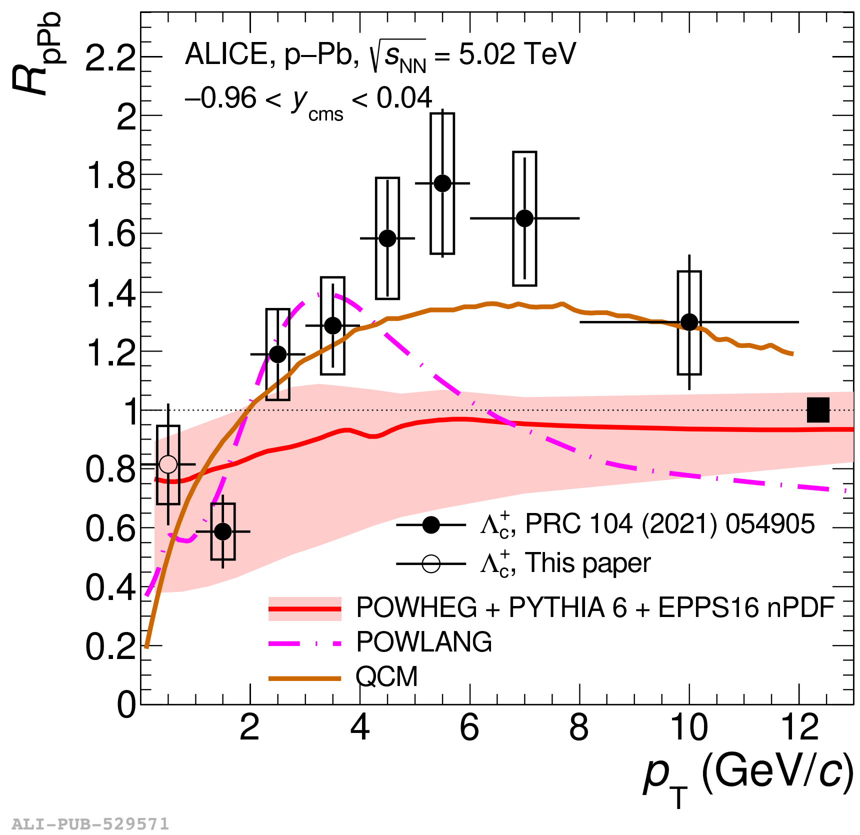
Sizeable contribution of to charm production at LHC energies ?

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] J. Song, et al., EPJC (2018) 78: 344
[4] V. Minissale, et al., arXiv:2012.12001
[5] Belle e^+e^-: PRD 97 (2018) 7, 072005

p-Pb collisions

Λ_c^+/D^0 and $R_{\mathrm{pPb}}(\Lambda_c^+)$ vs. p_T in p-Pb



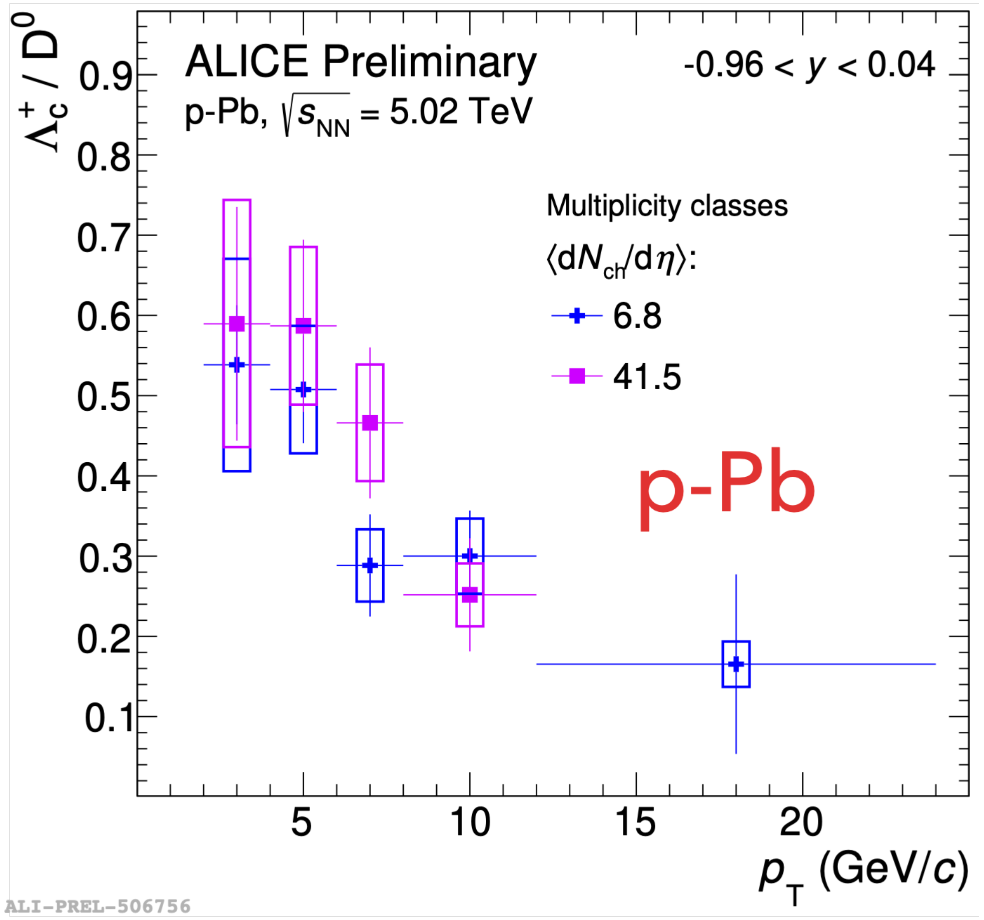


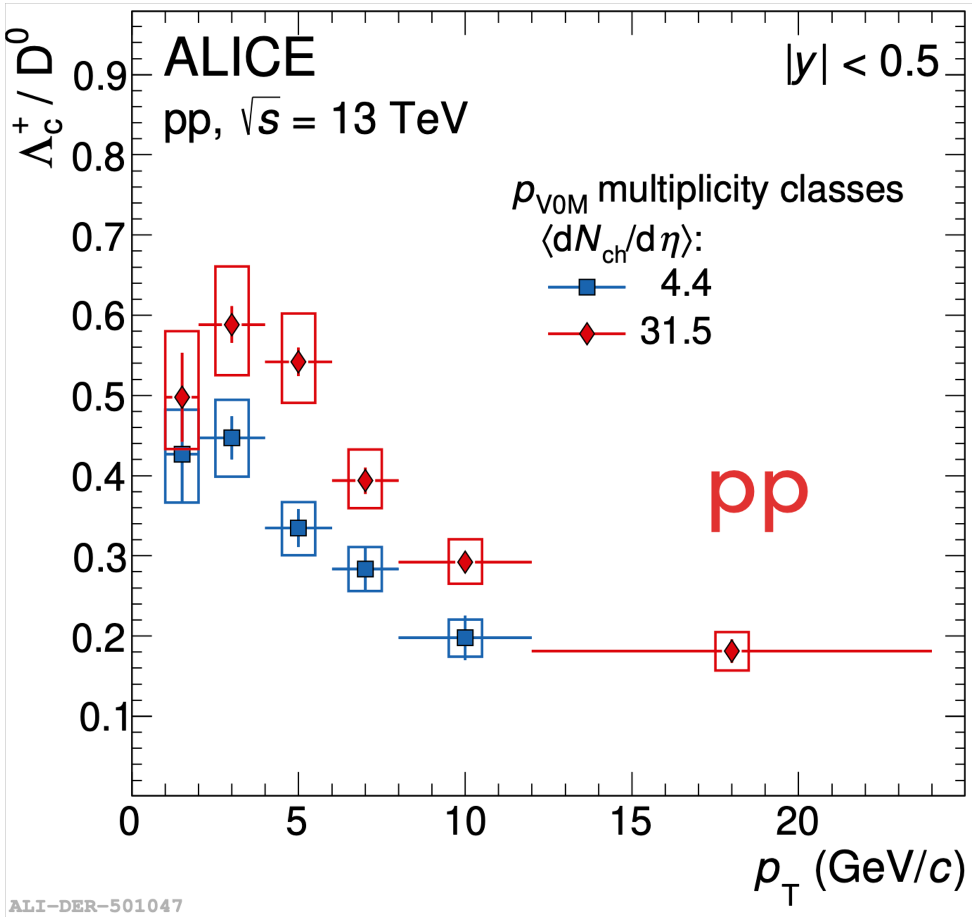
arXiv:2211.14032

- Fist measurement of Λ_c^+ down to 0
- Λ_c^+/D^0: significant suppression in $p_T < 2$ and enhancement in mid-p_T
  - Similarities with strange sector[1,2]
- $R_{\mathrm{pPb}}(\Lambda_c^+)$: significant suppression in $p_T < 2$, enhancement in mid-p_T
  - POWHEG[3]+PYTHIA6: only CNM effect[4] included
  - POWLANG[5]: QGP in small system
  - QCM [6]: CNM effect not included

[6] QCM: PRC 97 (2018) 064915
[1] PRC 104 (2021), 054905 [2] CMS: PRC 101 (2020), 064906 [3] POWHEG: JHEP 09 (2007) 126 [4] EPPS16: EPJC 77, (2017) 163 [5] POWLANG: JHEP 03 (2016) 123

Λ_c^+/D^0 vs. p_T from low to high multiplicity in p-Pb





Λ_c^+/D^0 vs. p_T in different multiplicity in p-Pb

- No significant separation between lowest and highest multiplicity
- Compatible with pp results within the large uncertainties
- More precise measurements needed

Λ_c^+/D^0 vs. p_T in different multiplicity in pp

- Significant enhancement from lowest to highest multiplicity

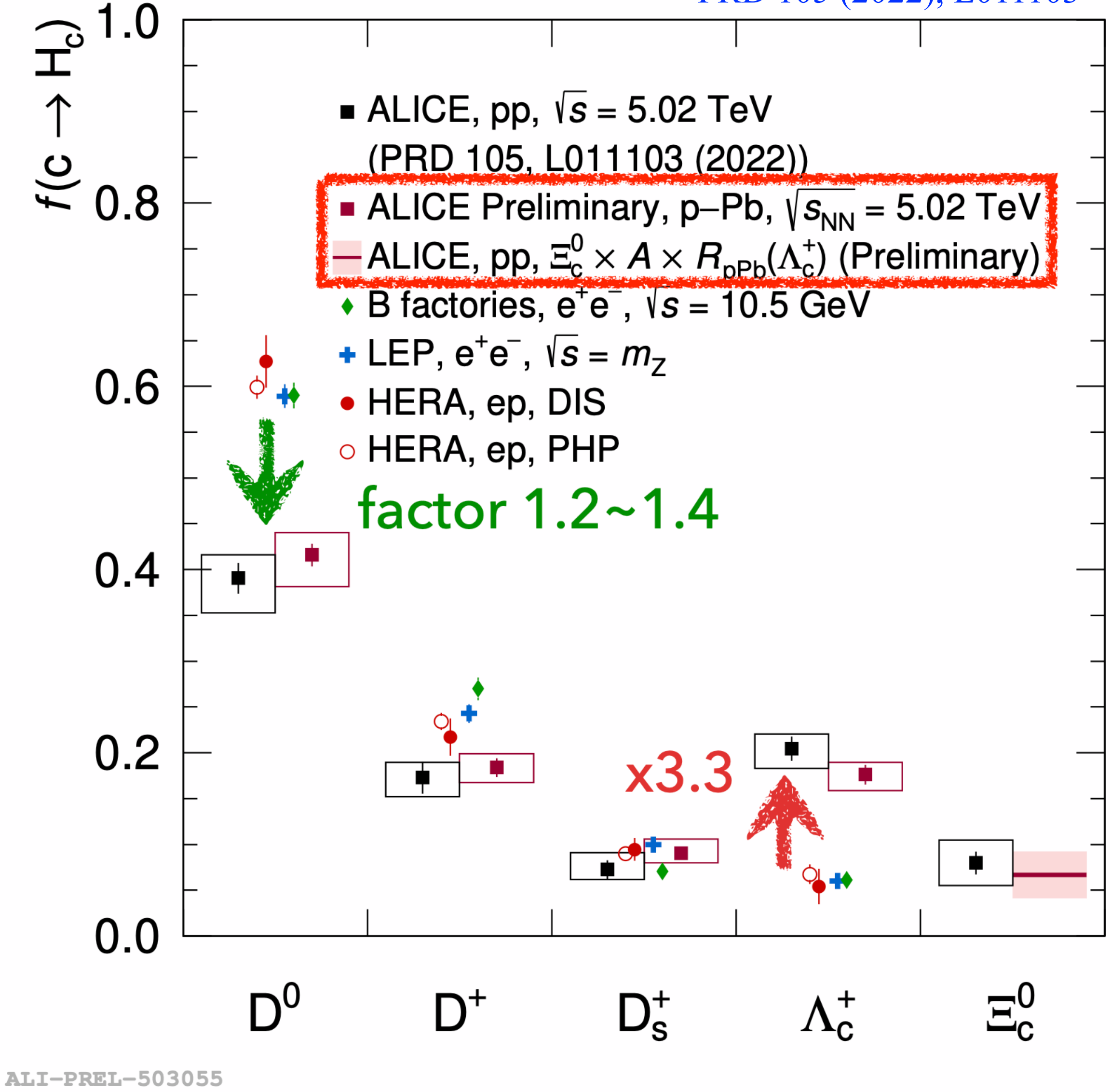
Charm fragmentation fractions

- Charm fragmentation fractions in hadronic collisions at 5.02 TeV
  - pp: PRD 105 (2022) 1, L011103
  - p-Pb:
    - D^0, Λ_c^+ (new): measured down to $p_T = 0$
    - D^+, D_s^+: extrapolated to $p_T = 0$ using POWHEG+PYTHIA
    - Ξ_c^0 not measured $\rightarrow \sigma_{pp}(\Xi_c^0)\times 208\times R_{pPb}(\Lambda_c^+)$

- pp and p-Pb results compatible
- Significant baryon enhancement w.r.t. e^+e^- and e^-p

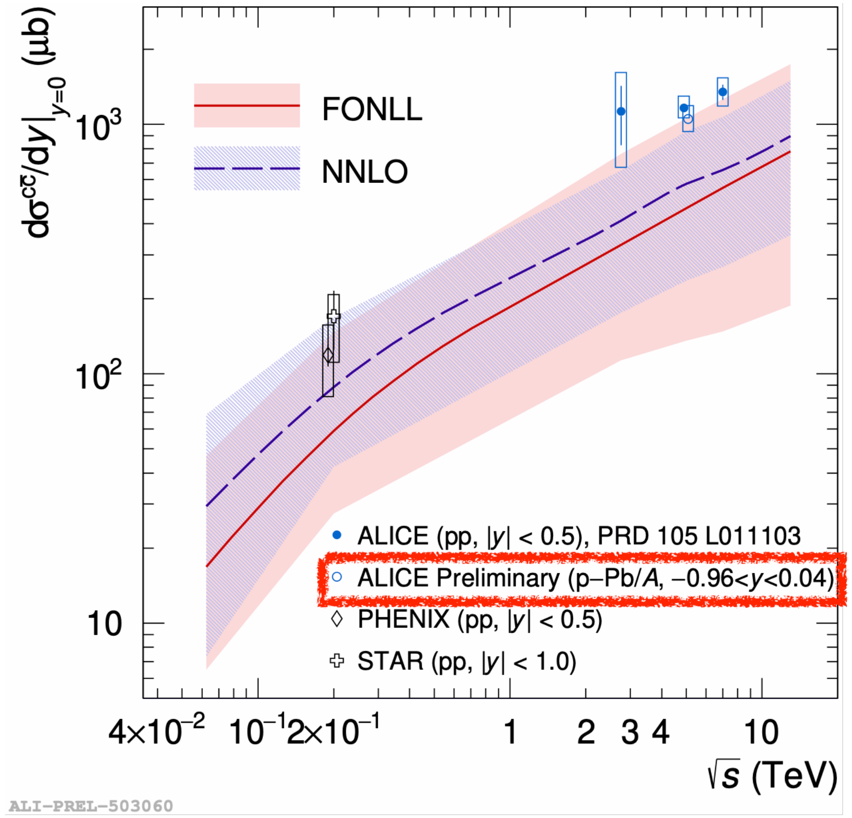
Charm fragmentation fractions not universal !

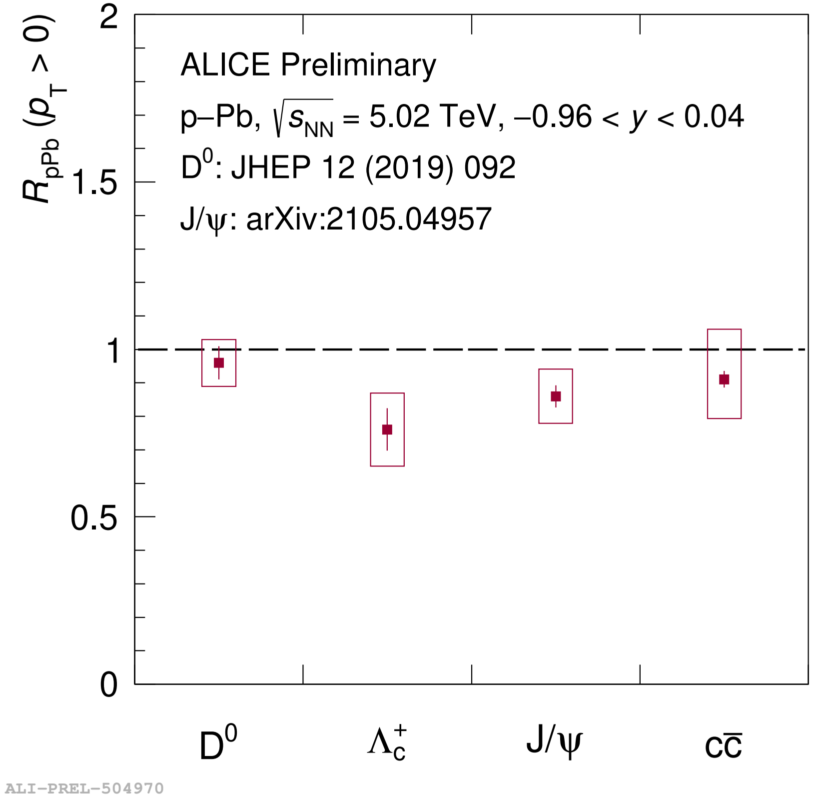
PRD 105 (2022), L011103



[1] B factories: EPJC 76, (2016) 397 [2] LEP: EPJC 75, (2015) 19 [3] HERA: EPJC 76, (2016) 397 [4] ALICE: JHEP 10 (2021) 159

$c\bar{c}$ production cross section and R_{pPb}





- Results in pp@2.76 & 7 TeV from D mesons updated with FFs from pp@5.02 TeV
  - ~40% increase driven by observed baryon enhancement
- On upper edge of FONLL[3] and NNLO[4] calculations

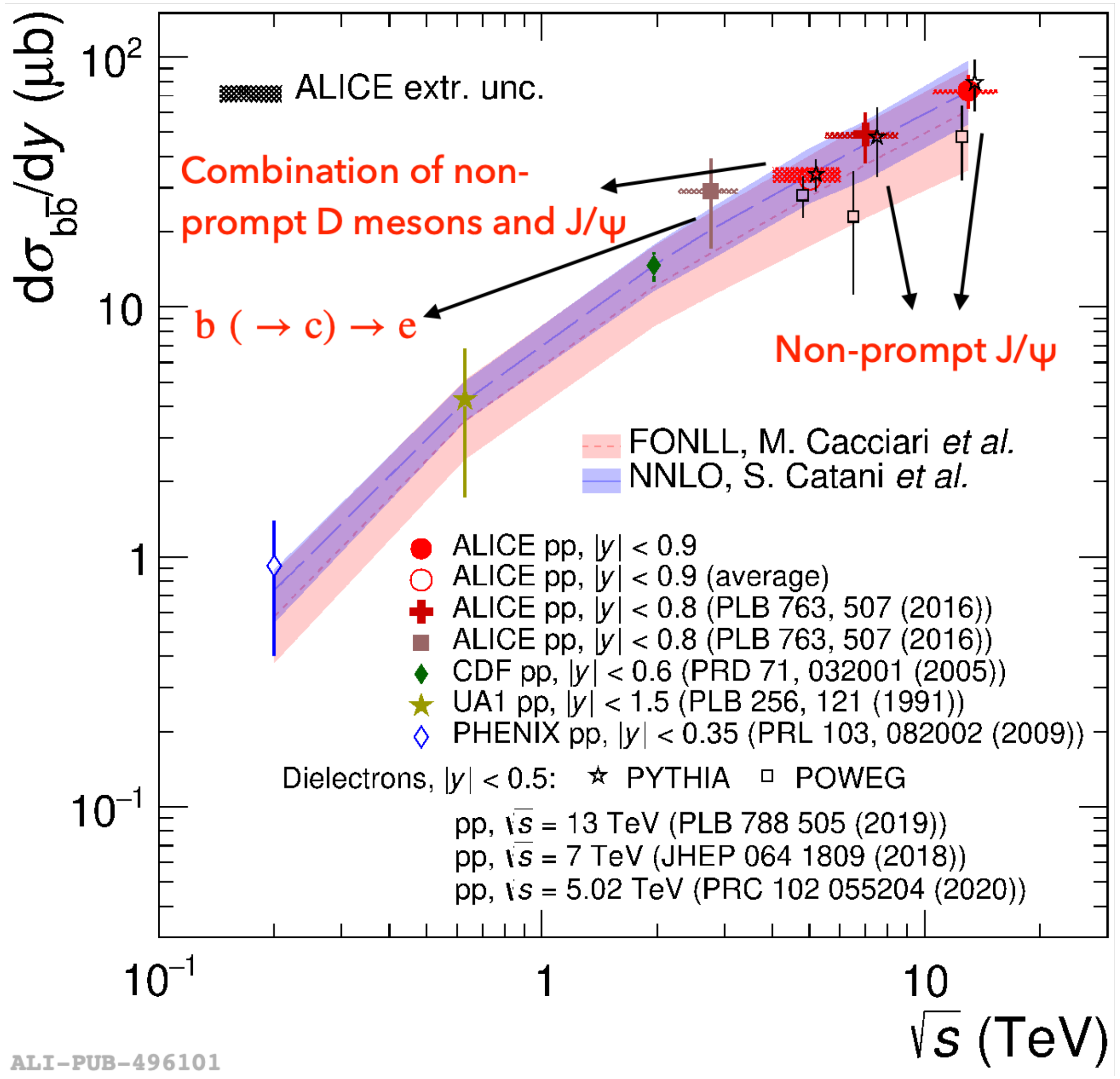
Nuclear shadowing effect

- p-Pb not obvious, $R_{\mathrm{pPb}}(c\bar{c})$ compatible with unity
- $c\bar{c}$ in Pb-Pb would be interesting to see this effect

[1] STAR: Phys. Rev. D 86 (2012) 072013
[2] PHENIX: Phys. Rev. C 84 (2011) 044905
[3] FONLL: JHEP 10 (2012) 137
[4] Charm NNLO: PRL 118 (2017) 12, 122001
[5] ALICE non-prompt D: JHEP 05 (2021) 220
[6] ALICE non-prompt : JHEP 11 (2015) 065
[7] ALICE b→e: PLB 721 (2013) 13-23
[8] ALICE dielectrons: PRC 102 (2020) 5, 055204
[9] PHENIX: PRL (2009) 103, 082002
[10] UA1: PLB 256 (1991) 121-128
[11] CDF: PRL 91 (2003) 241804

$b\bar{b}$ production cross section

- Described widely by FONLL[1] and NNLO[2] calculations

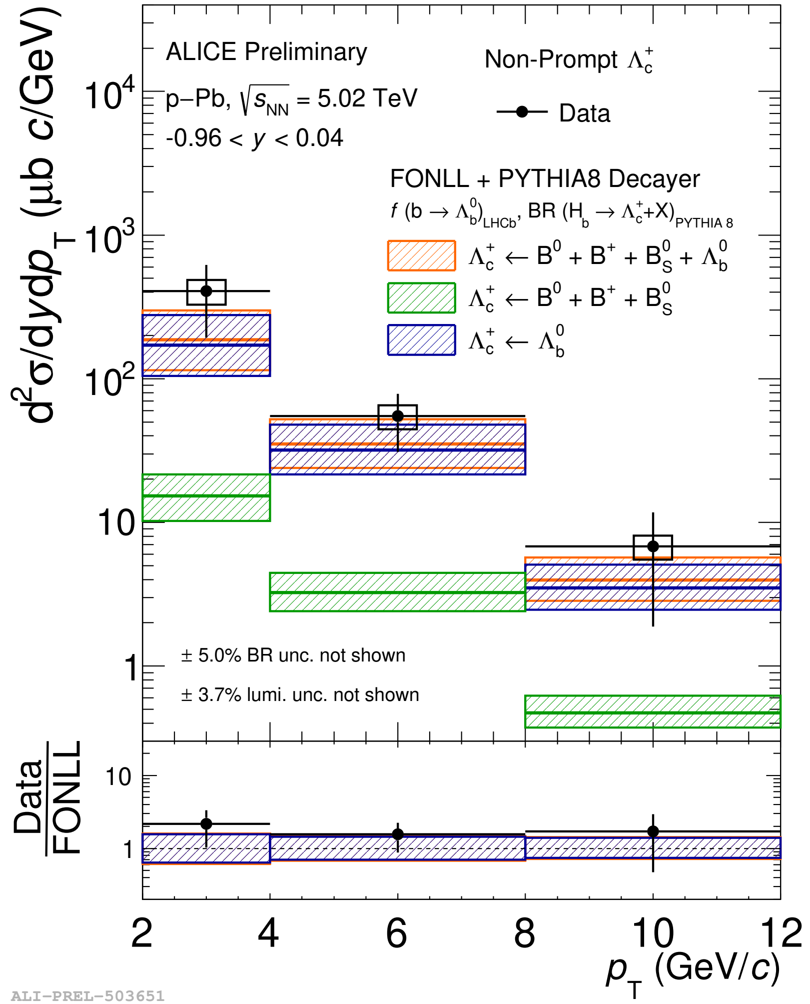


JHEP 03 (2022) 190

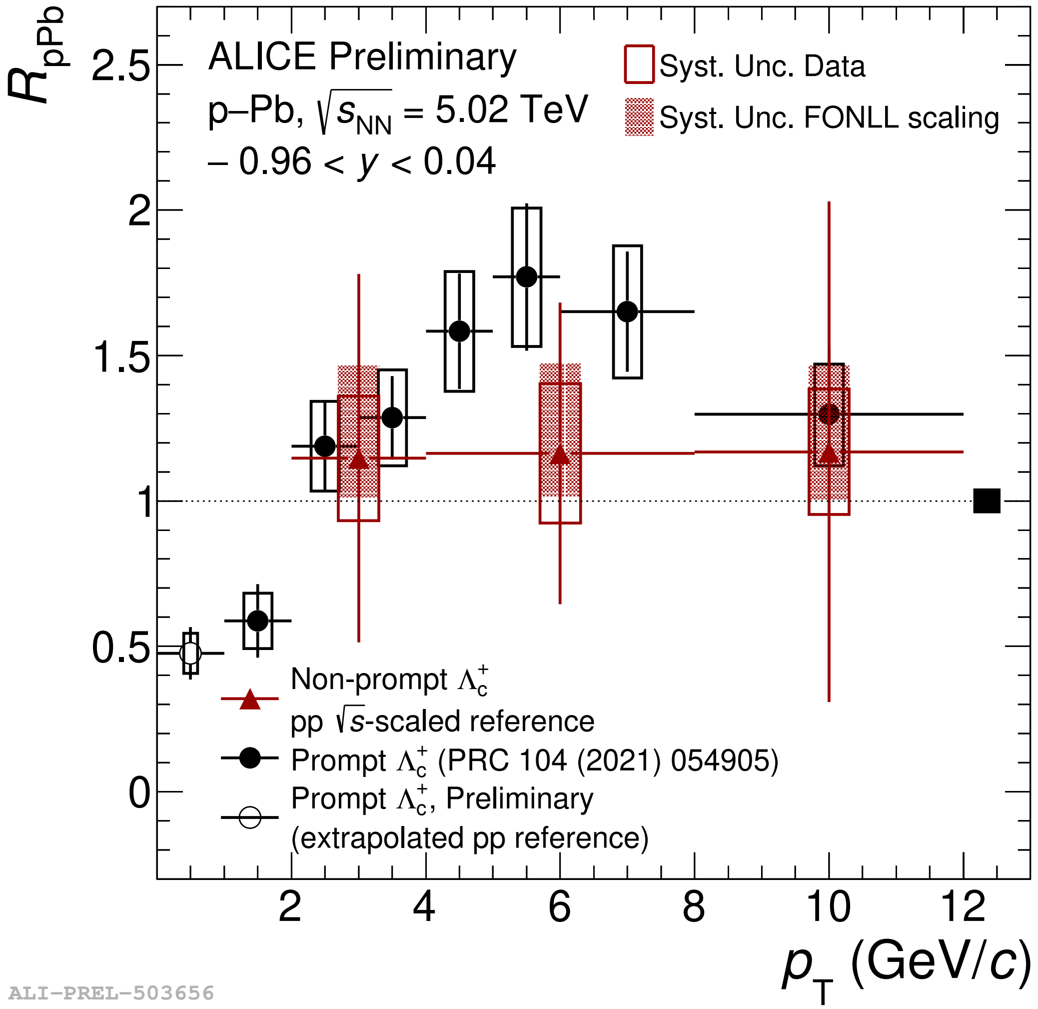
[1] FONLL: JHEP 10 (2012) 137
[2] Beauty NNLO: JHEP 03 (2021) 029

Non-prompt Λ_c^+ production in p-Pb@5.02 TeV

- Non-prompt Λ_c^+
  - p_T dependence well reproduced by theoretical calculations, same as pp



- Non-prompt Λ_c^+ R_{pPb}
  - Compatible with unity and with prompt Λ_c^+ R_{pPb} within the large uncertainties

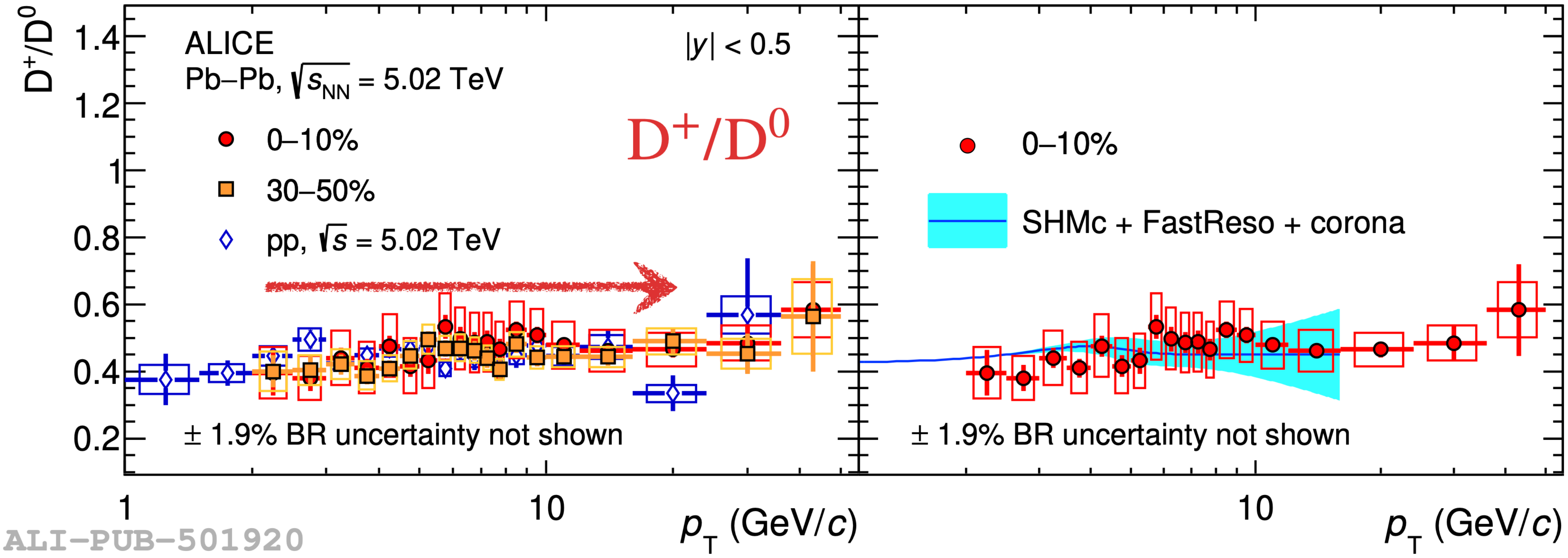


Pb-Pb collisions

Non-strange charm meson to probe hadronization

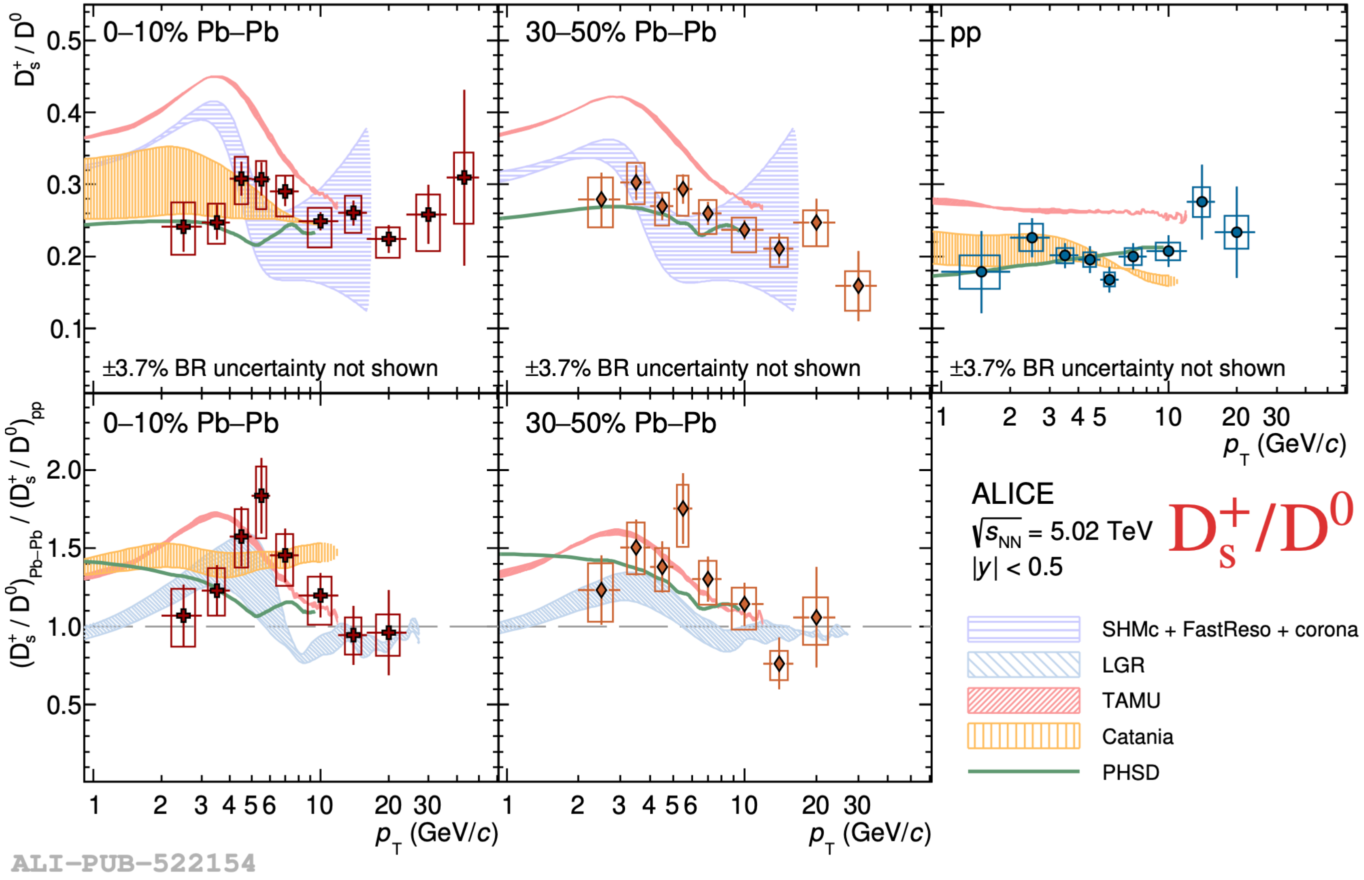
- D^+/D^0: flat distribution, NOT modified in QGP, described by SHMc
  - p_T spectra of charm hadrons are modelled with a core-corona approach
  - Resonance decays computed with FastReso package
  - Low p_T: dominated by the core contribution described with a Blast-Wave function
  - High p_T: corona contribution more relevant and is parametrised from pp measurements

JHEP 01 (2022) 174



Strange-charm meson to probe hadronization

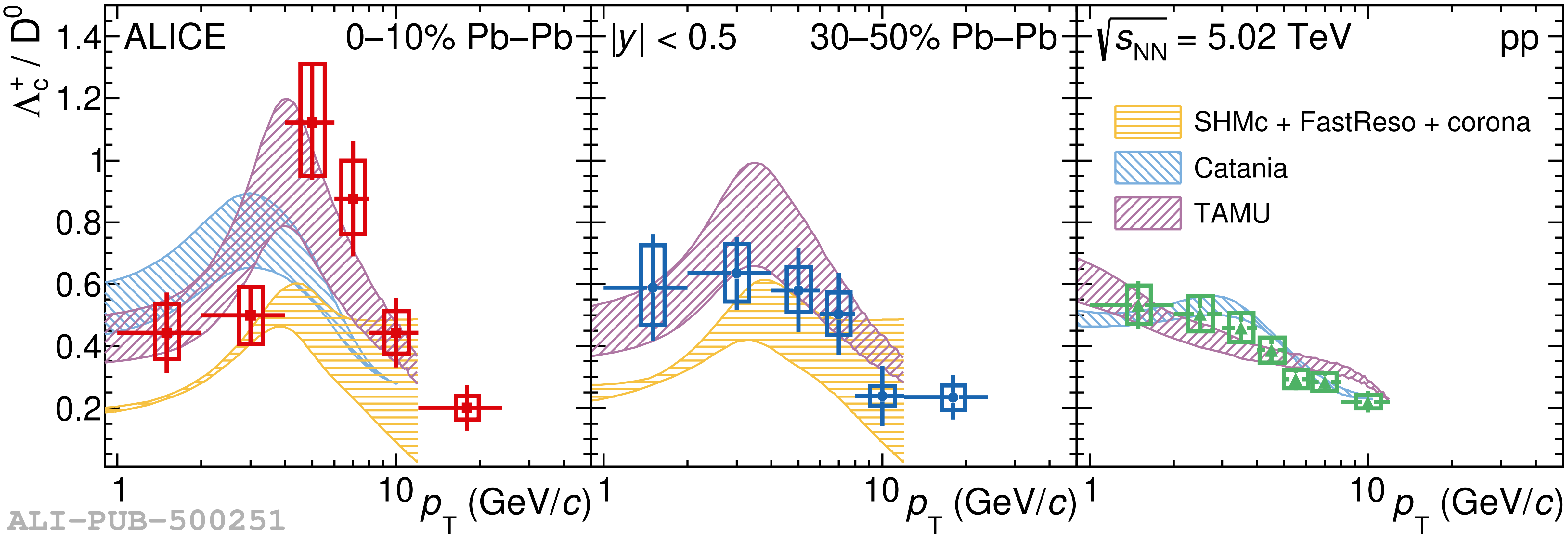
- D_s^+/D^0: hint of enhancement in $2 < p_T < 8$ GeV/c in 0-10% (30-50%) Pb-Pb by 2.3σ (2.4σ)
- Described by models including strangeness enhancement and fragmentation + recombination
  - TAMU (coalescence implemented with a Resonance Recombination Model) significantly overestimates data
  - Catania and LGR (coalescence implemented with Wigner formalism) describe data
  - PHSD (coalescence implemented with MC) describe data



Phys.Lett.B 827 (2022) 136986

Non-strange charm baryon to probe hadronization

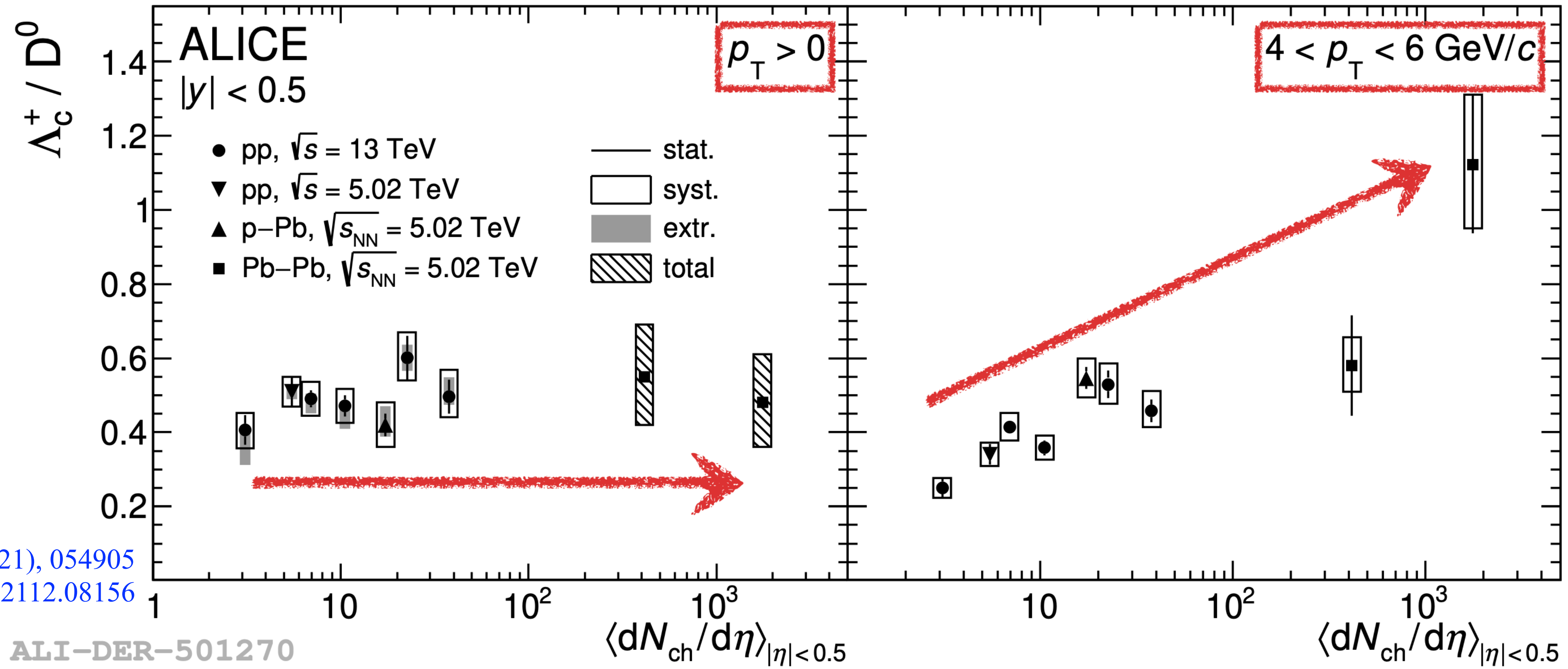
arXiv:2112.08156



- Λ_c^+/D^0: enhanced in $4 < p_T < 8$ GeV/c for central Pb-Pb w.r.t. pp by 3.7σ
  - Also seen for light-flavour baryon-to-meson ratios
  - Described by TAMU
  - The shapes of the Catania and SHMc predictions agree qualitatively

$\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 vs. p_T in Pb-Pb with Run 3 data to further constrain hadronization processes

Λ_c^+/D^0 vs. multiplicity for integrated and intermediate p_T



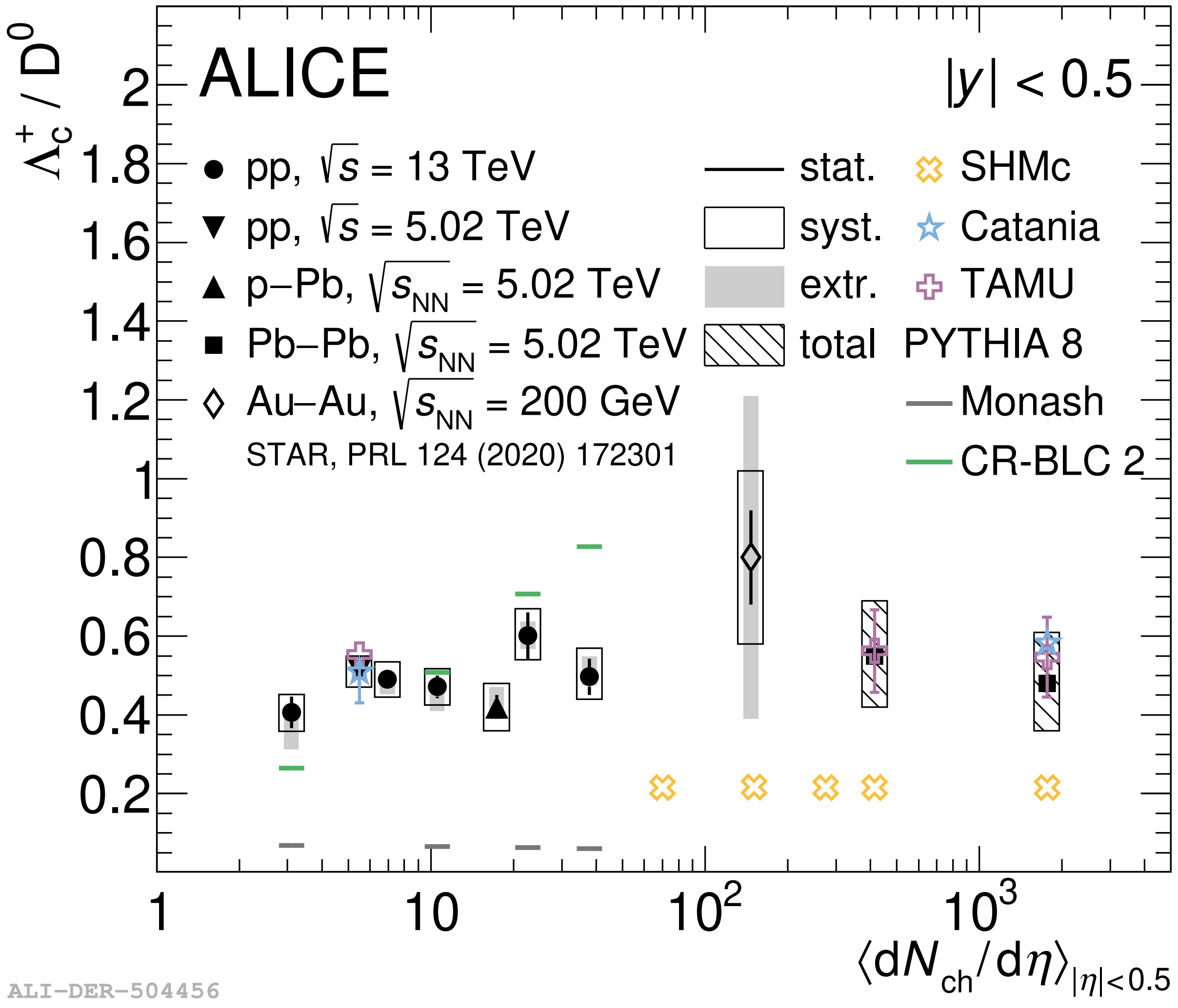
Phys.Rev.C 104 (2021), 054905
arXiv:2112.08156

- p_T-integrated Λ_c^+/D^0 ratio compatible with a flat behaviour versus event multiplicity, similar to Λ/K_S^0
- Re-distribution of p_T that acts differently for baryons and mesons, no modification of overall p_T-integrated yield
- Same mechanism in all collision systems? Modified hadronization? Radial flow?

$\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 vs. multiplicity for integrated and intermediate p_T with Run 3 data to further constrain hadronization processes

p_{T}-integrated Λ_c^+/D^0 vs. multiplicity comparing with models

- Flat trend reproduced by models implementing fragmentation+coalescence and SHM predictions
- PYTHIA 8 CR-BLC 2 predicts enhancement with multiplicity



Phys.Lett.B 829 (2022) 137065

Summary

- Precise measurements of charm and beauty **meson** production provide strong constraints on pQCD calculations

- Charm and beauty **baryon** production measurements indicate that assumption of universal parton-to-hadron fragmentation fractions not valid at LHC energies

- Charm hadronization mechanisms in pp collisions need further investigations
  - Coalescence in pp?

- Charm hadron yield ratios in Pb-Pb can be described by models including both coalescence and fragmentation processes

- Re-distribution of p_{T} that acts differently for Λ_{c}^{+} in p-Pb and Pb-Pb w.r.t. pp, no modification of overall p_{T}-integrated yield
  - Same mechanism in all collision systems? Modified hadronization? Radial flow?

Backup

Summary

➢ Charm hadronization mechanisms need further investigations

	Models	Λ_c^+/D^0 (no s)	$\Sigma_c^{0,+,++}/D^0$ (no s)	$\Xi_c^{0,+}/D^0$ (s)	Ω_c^0/D^0 (ss)
pp	PYTHIA8 Monash	☹️	☹️	☹️	☹️
	PYTHIA8 CR Mode	👌	👌	☹️	☹️
	SHM+RQM	👌	👌	☹️	—
	QCM	👌	👌	☹️	☹️
	Catania	👌	👌	👌	😐

	Models	D^+/D^0 (no s)	D_s^+/D^0 (s)	Λ_c^+/D^0 (no s)
Pb-Pb	SHMc	👌	☹️	☹️
	TAMU	—	☹️	👌
	Catania	—	👌	☹️
	LGR	—	👌	—
	PHSD	—	👌	—