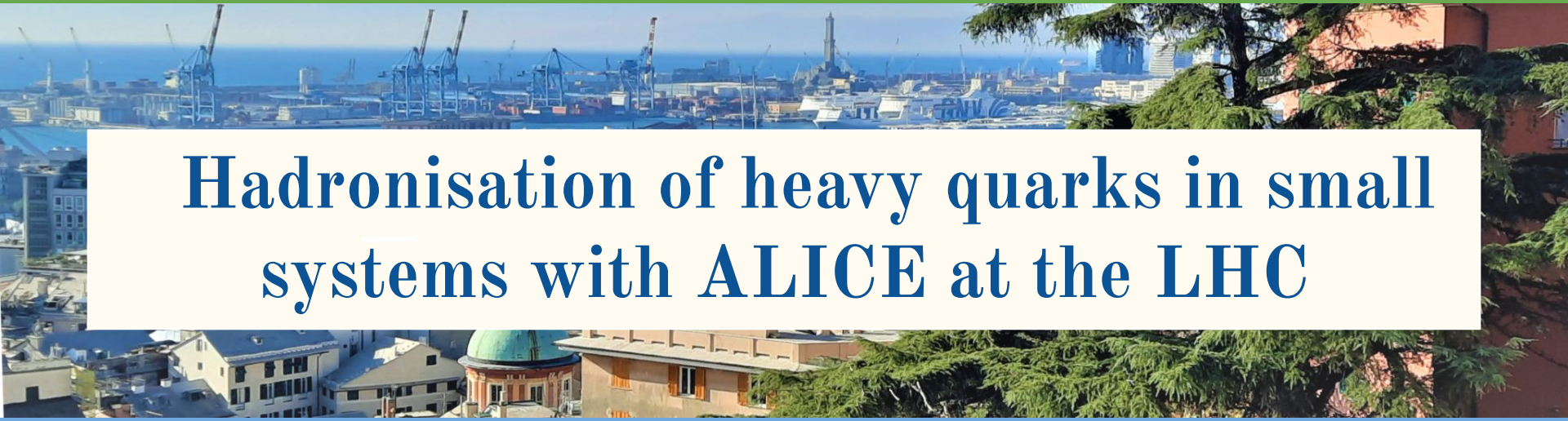


Hadronisation of heavy quarks in small systems with ALICE at the LHC

Tiantian Cheng, CCNU (WuHan), GSI (Darmstadt)

on behalf of the ALICE Collaboration

tiantian.cheng@cern.ch

June 9th, 2023

Introduction

- The production of heavy-flavour hadrons in hadronic collisions can be described by the factorization approach:

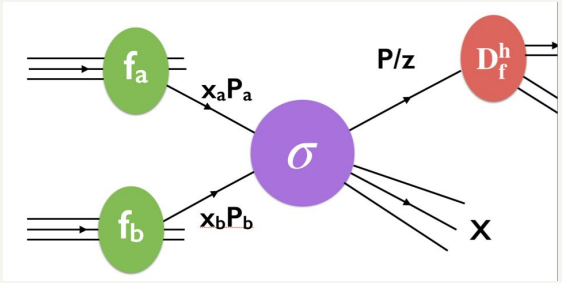
$$\frac{d\sigma^{D}}{dp_T^{D}}(p_T;\mu_F;\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_T^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)

  - **Test of perturbative QCD (pQCD)** calculations



heavy quarks:

c $m_c \sim 1.3$ GeV/c^2

b $m_b \sim 4.2$ GeV/c^2

Introduction

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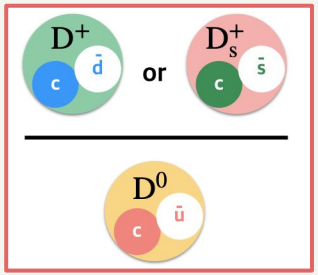
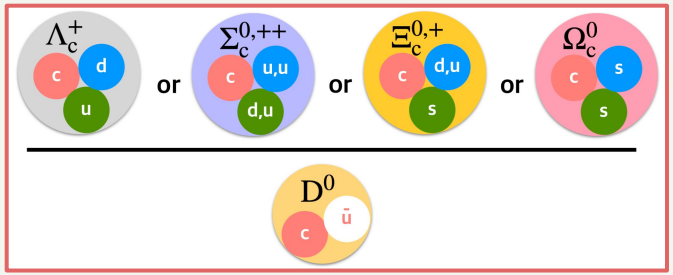
Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)

  - The yield ratios of hadrons are sensitive to the **HF hadronization process**
  - Measurements of **Fragmentation Fraction (FF)**





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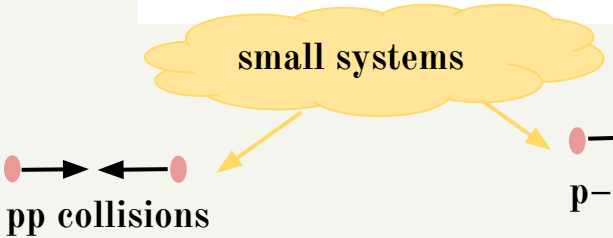
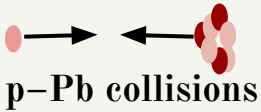


- Reference for p–Pb, Pb–Pb
- Test of pQCD calculations
- Study hadronisation



- Cold nuclear matter (CNM) effects
  - Modification of parton distribution functions (PDFs) in nuclei

heavy quarks:

c $m_c \sim 1.3$ GeV/c^2

b $m_b \sim 4.2$ GeV/c^2

The ALICE Experiment

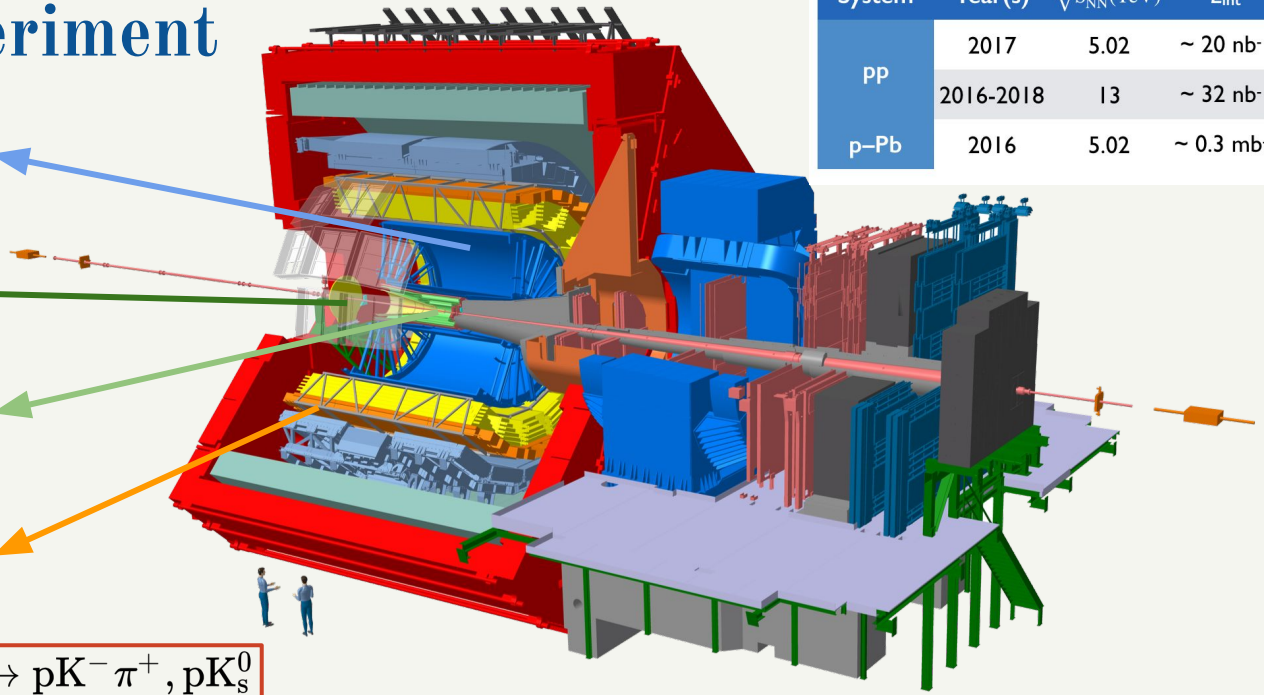
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
PP	2017	5.02	~ 20 nb^{-1}
	2016-2018	13	~ 32 nb^{-1}
p–Pb	2016	5.02	~ 0.3 mb^{-1}

Time Projection Chamber (TPC)
Tracking, PID via dE/dx

V0 detector
Triggering

Inner Tracking System (ITS):
Tracking and vertexing

Time-of-Flight (TOF)detector:
PID via time of flight



Talk: Clara Bartels
June 5th, 3:20 PM

$\Lambda_c^+(\mathrm{udc}) \to \mathrm{pK}^-\pi^+, \mathrm{pK}_s^0$

$\Sigma_c^{0,++}(\mathrm{ddc}, \mathrm{uuc}) \to \Lambda_c^+\pi^{-,+}$

$\Xi_c^0(\mathrm{dsc}) \to \Xi^-\mathrm{e}^+\nu_e, \Xi^-\pi^+$

$\Xi_c^+(\mathrm{usc}) \to \Xi^-\pi^+\pi^+$

$\Omega_c^0(\mathrm{ssc}) \to \Omega^-\pi^+$

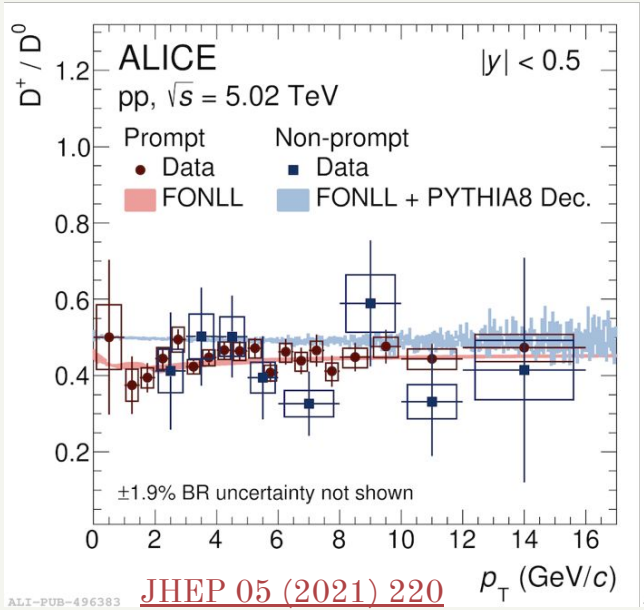
$\mathrm{D}^0(\bar{\mathrm{u}}\mathrm{c}) \to \mathrm{K}^-\pi^+$

$\mathrm{D}^+(\bar{\mathrm{d}}\mathrm{c}) \to \mathrm{K}^-\pi^+\pi^+$

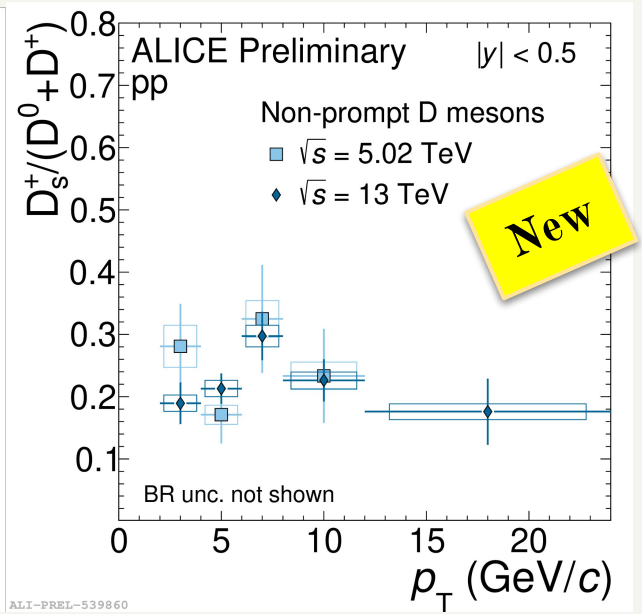
$\mathrm{D}_s^+(\bar{\mathrm{s}}\mathrm{c}) \to \Phi\pi^+ \to \mathrm{K}^+\mathrm{K}^-\pi^+$

Charm and beauty mesons in pp collisions

- Meson-to-meson yield ratios independent of p_T and collision energies
- Good agreement with model calculations
  - NLO pQCD calculations with fragmentation functions from e^+e^- and e^-p colliders, assumed to be **universal** across collision systems



JHEP 05 (2021) 220



First measurement of non-prompt D^+, D_s^+ in $|y| < 0.5$ in pp collisions at $\sqrt{s} = 13$ TeV

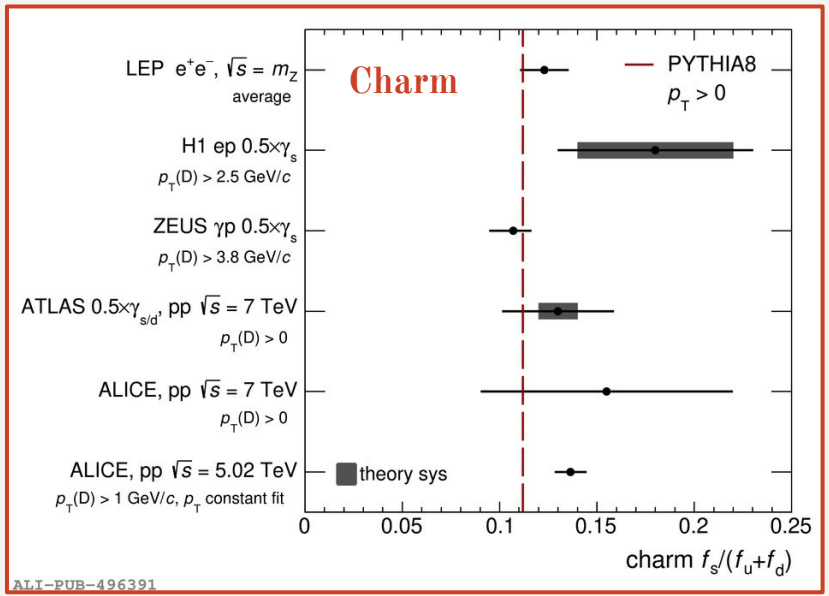
Meson sector: so far so good

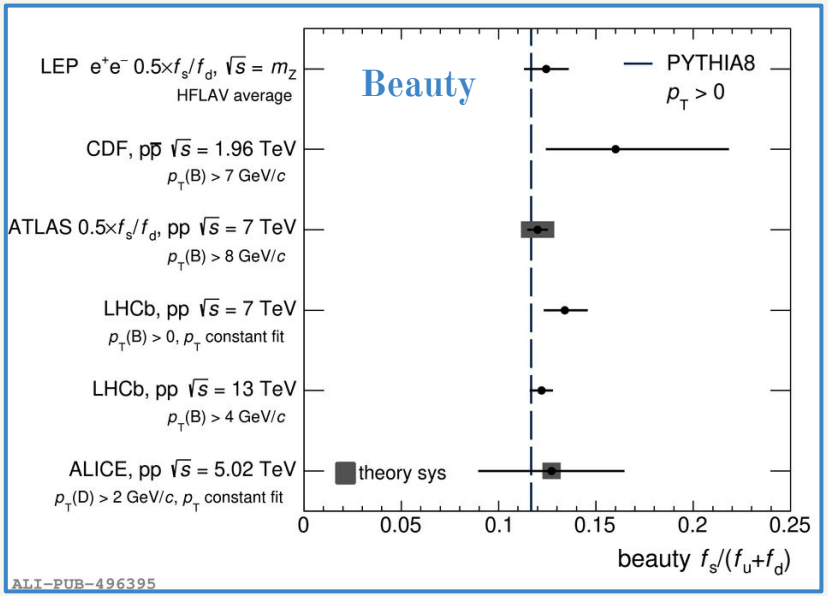
Charm and beauty fragmentation to mesons

- Fragmentation fraction ratios for charm and beauty mesons are compatible
- No significant dependence on energy and collision systems
  - From e^+e^- and e^-p to hadronic collisions

$$f_s/(f_u + f_d)$$

JHEP 05 (2021) 220



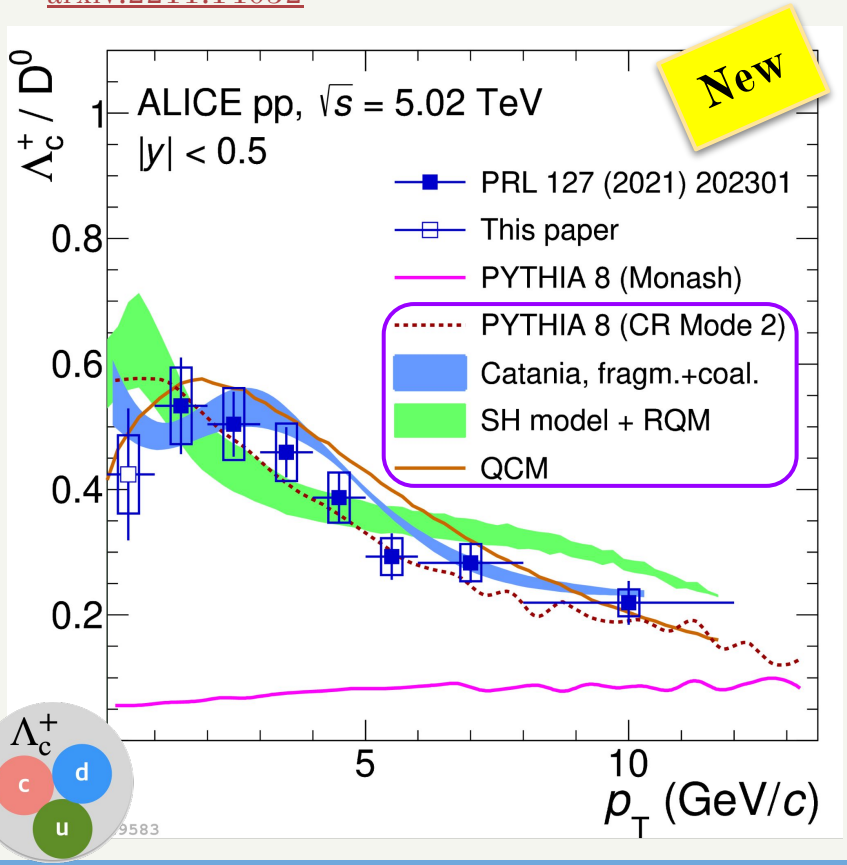


Charm baryon-to-meson yield ratio

5.02 TeV

pp collisions

arxiv:2211.14032



- Strong p_T dependence
- Ratio at low p_T much larger than predicted by string fragmentation models tuned on e^+e^- data
- Ratio qualitatively described by models with further baryon junctions increasing baryon production (PYTHIA 8 with CR_BLC modes), hadronization via coalescence (Catania, QCM), or feed-down from augmented set of higher-mass charm baryons (SH+RQM)

Baryon sector: the cool kid on the block

Charm baryon-to-meson yield ratio

5.02 TeV

pp collisions

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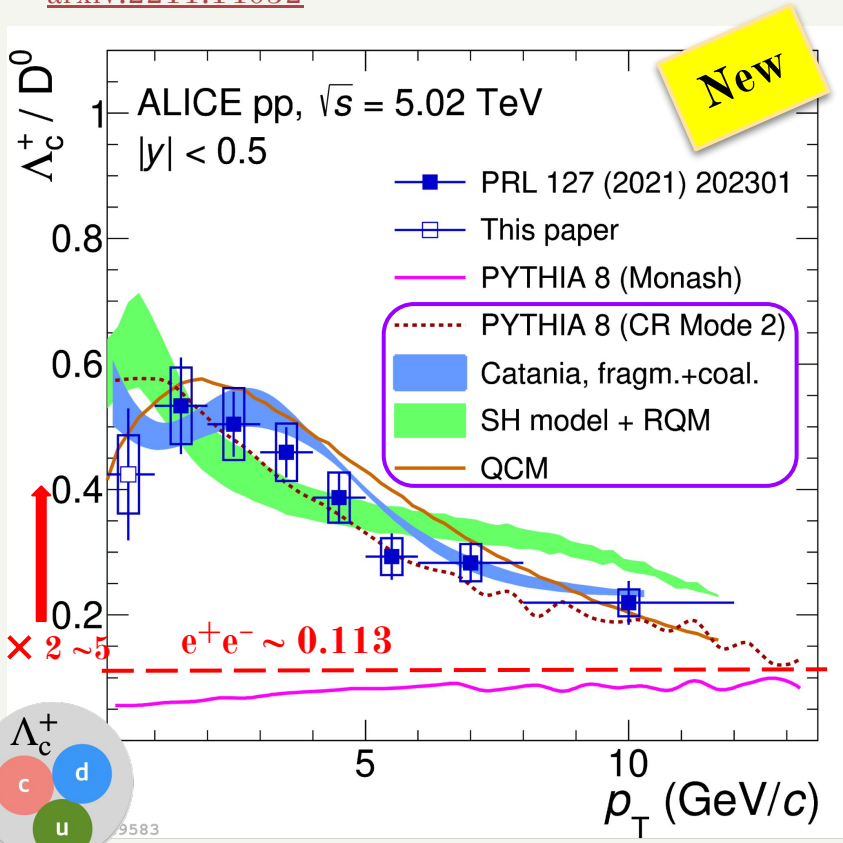

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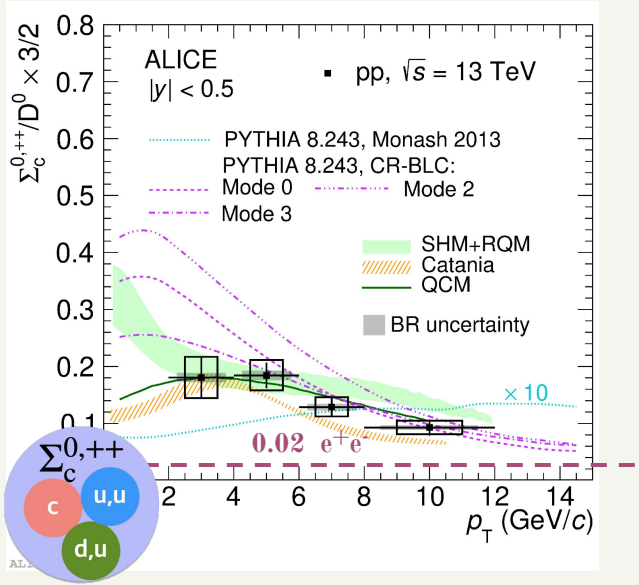
Ratio significantly higher w.r.t. e^+e^- and ep collisions

Charm baryon-to-meson yield ratio

13 TeV

pp collisions

PRL 128 (2022) 012001



Baryon-to-meson yield ratios

- Large enhancement of charm-baryon production in pp collisions w.r.t. e^+e^- collisions

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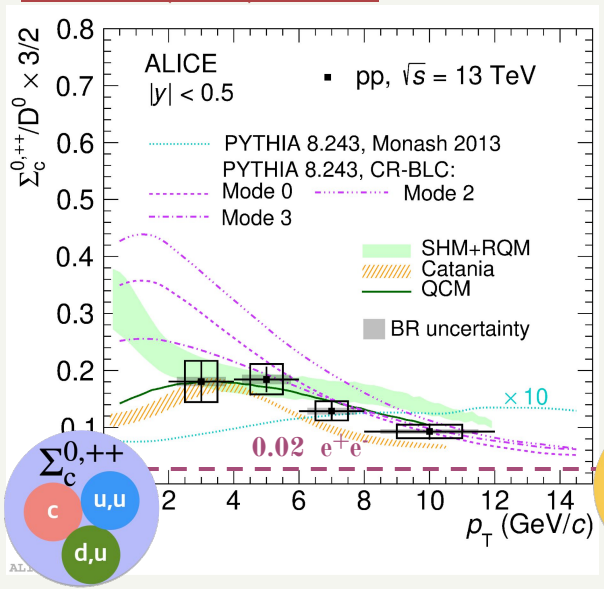
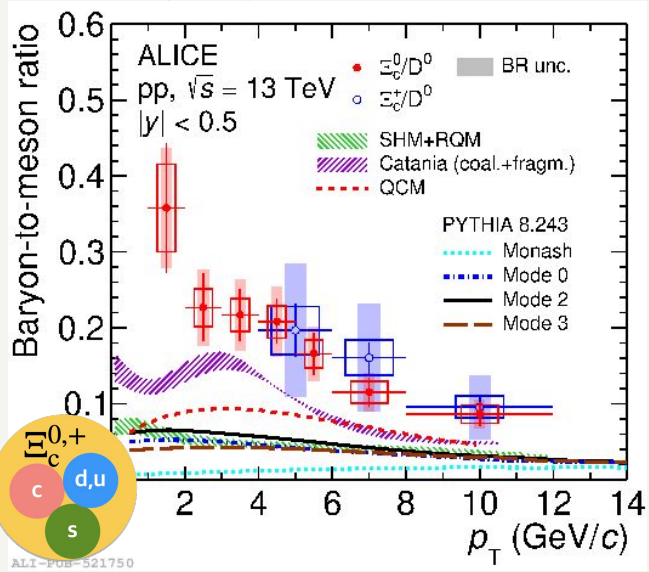


PRL 127 (2021) 272001



Baryon-to-meson yield ratios

- Large enhancement of charm-baryon production in pp collisions w.r.t. e^+e^- collisions
- Catania model (including hadronization via coalescence) describes better the shape of measured data

In the charm-strange sector, the enhancement is even larger

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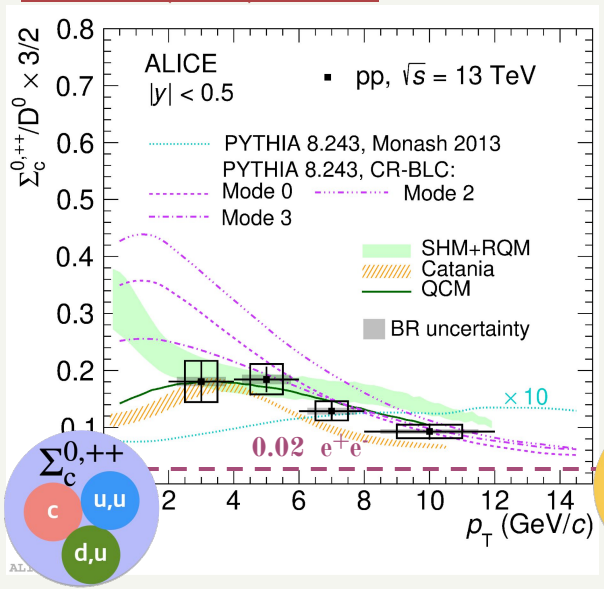
pp collisions

PRL 128 (2022) 012001



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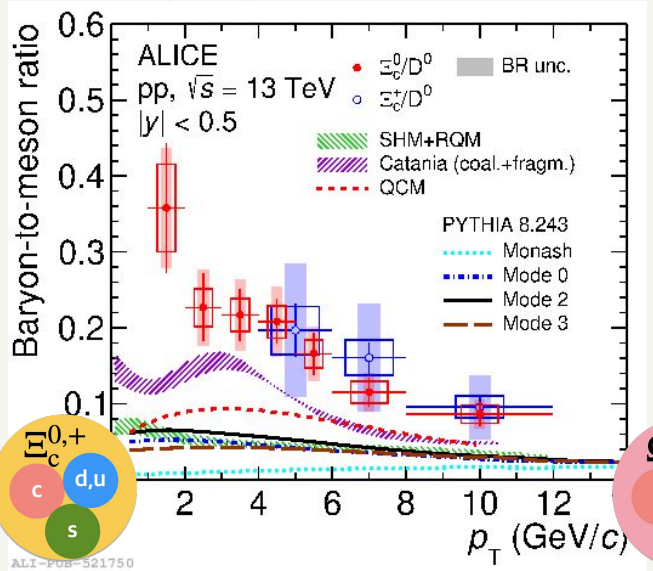
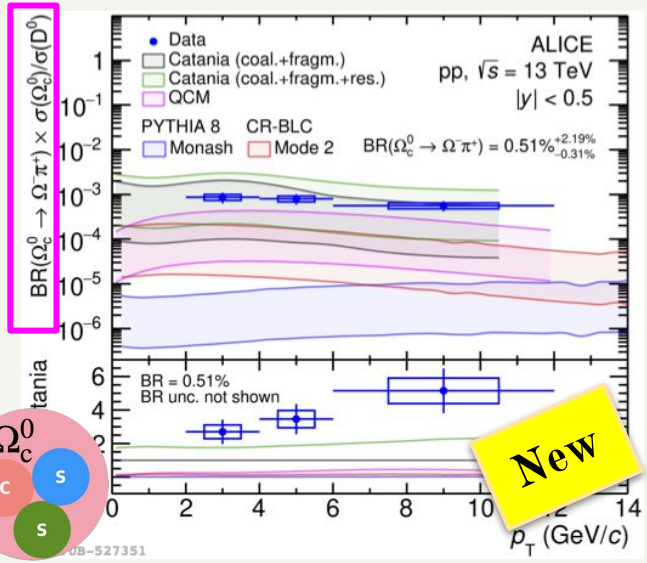


Accepted by PLB, arxiv:2205.13993



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$BR(\Omega_c^0 \to \Omega^-\pi^+)$ is not measured, theoretical calculation used Y.Hsiao et al. EPJC 80, 1066 (2020)

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13 TeV

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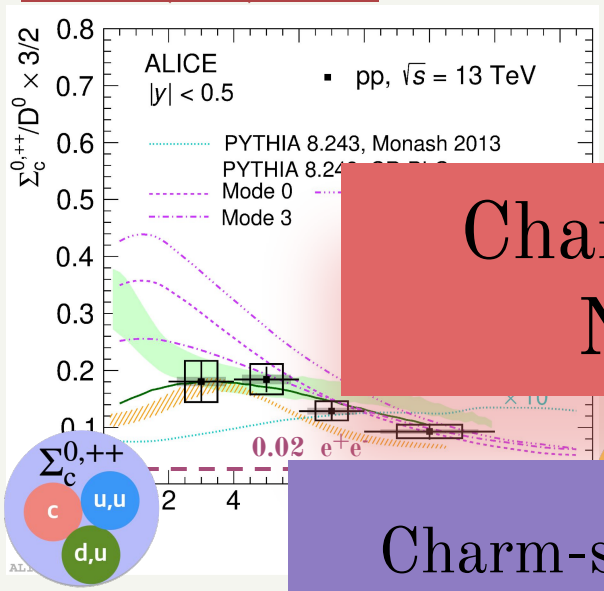
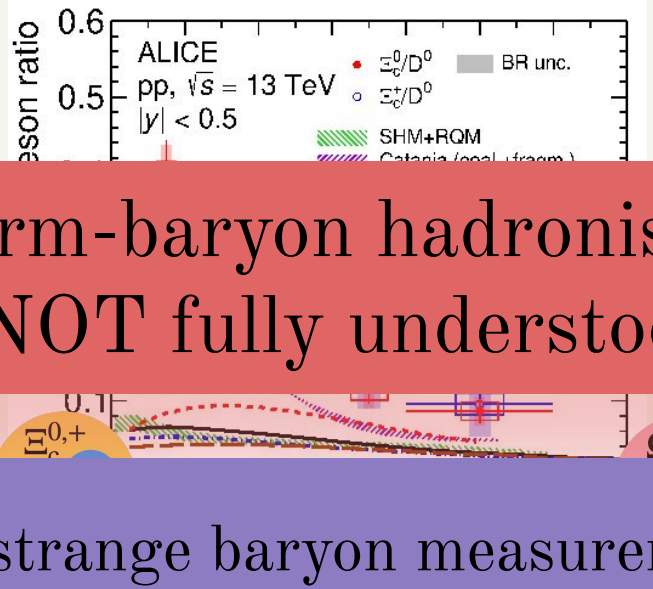
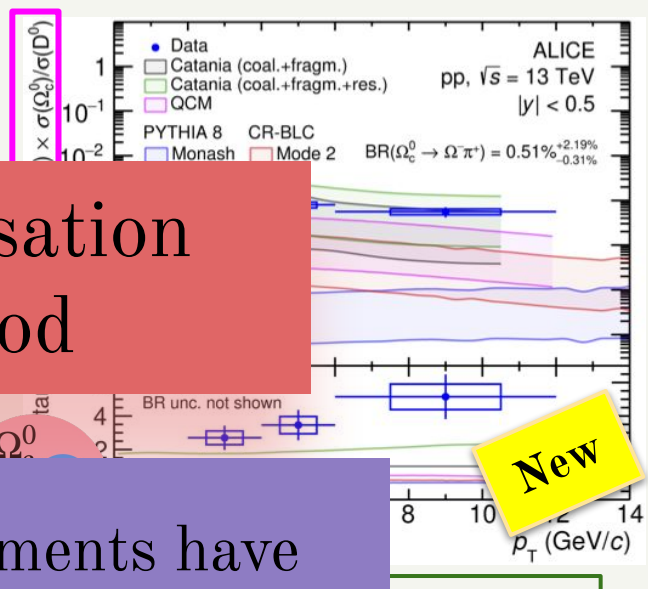






Charm-baryon hadronisation NOT fully understood

Charm-strange baryon measurements have large constraining power on model predictions!

Baryon-to

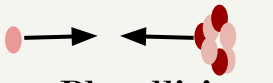
- Large
  w.r.t. e+e− collisions
- Catania model (including hadronization via coalescence) describes better the shape of measured data

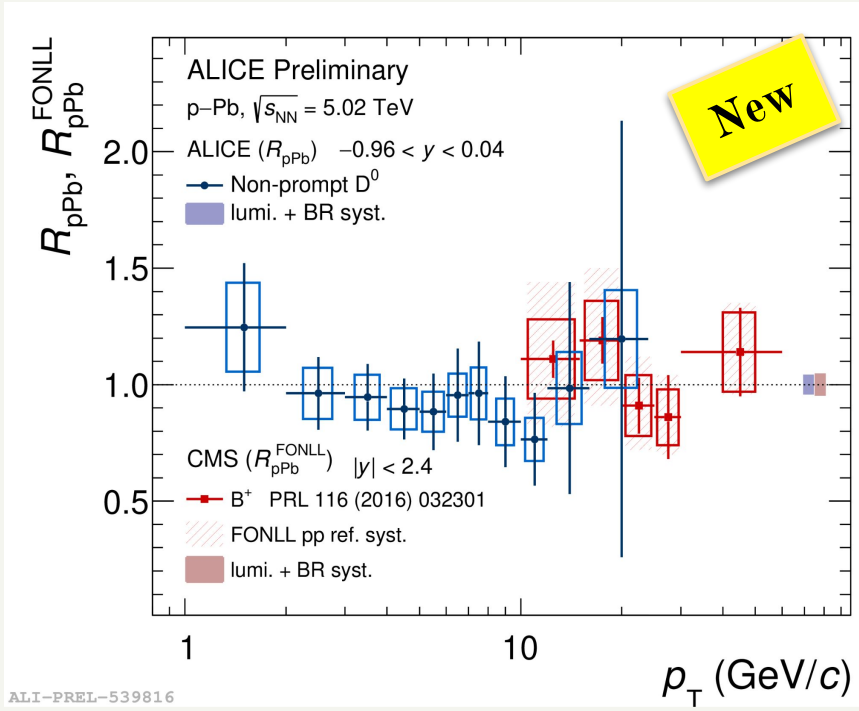
sector, en larger

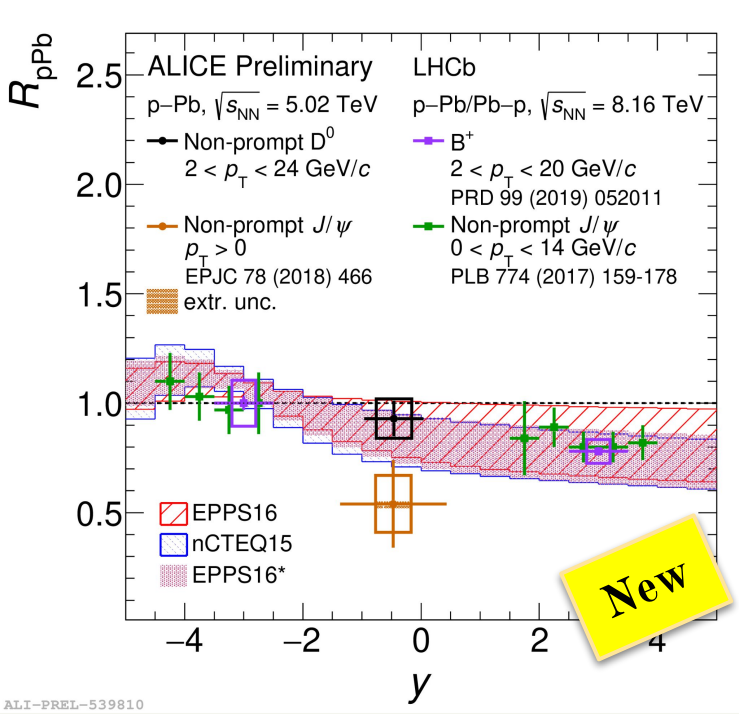
BR($\Omega_c^0 \to \Omega^-\pi^+$) is not measured, theoretical calculation used Y.Hsiao et al. EPJC 80, 1066 (2020)

Non-prompt R_{pA} of D^0

5.02 TeV



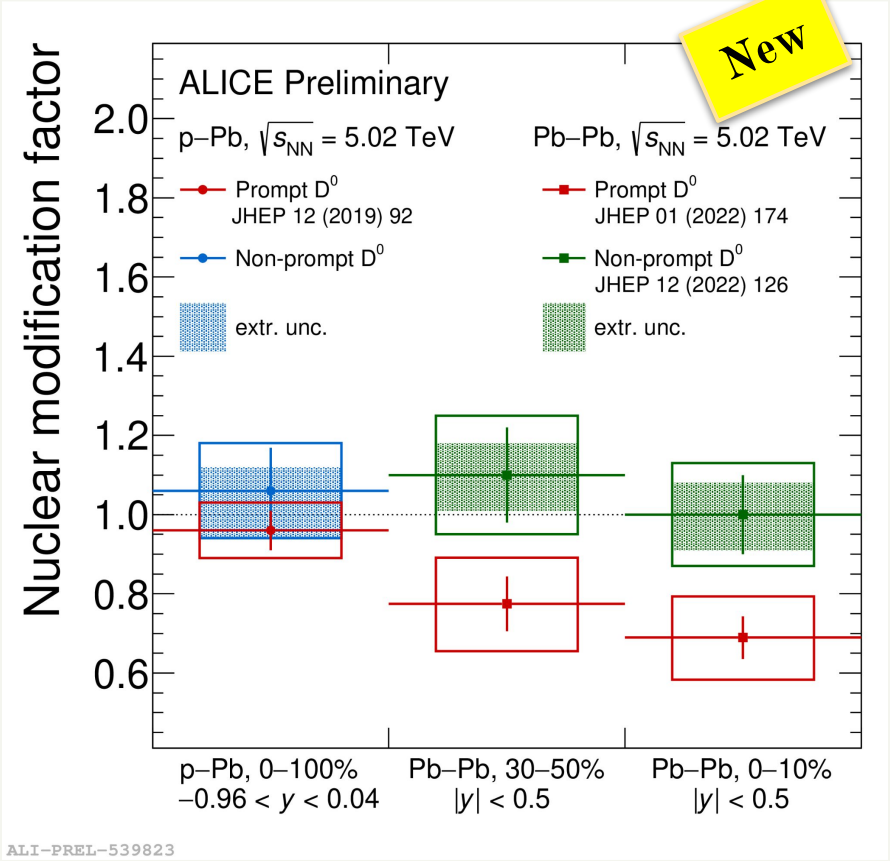




Nuclear modification factor

- Non-prompt D^0 R_{pPb} is in agreement with measurement of B^+ from CMS
- p_T–integrated non-prompt D^0 R_{pPb} agrees with the results of B^+, and non-prompt J/ψ from LHCb

Non-prompt R_{pA} of D^0



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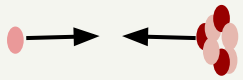
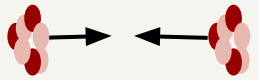


p–Pb collisions



Pb–Pb collisions

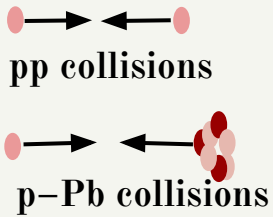
Nuclear modification factor

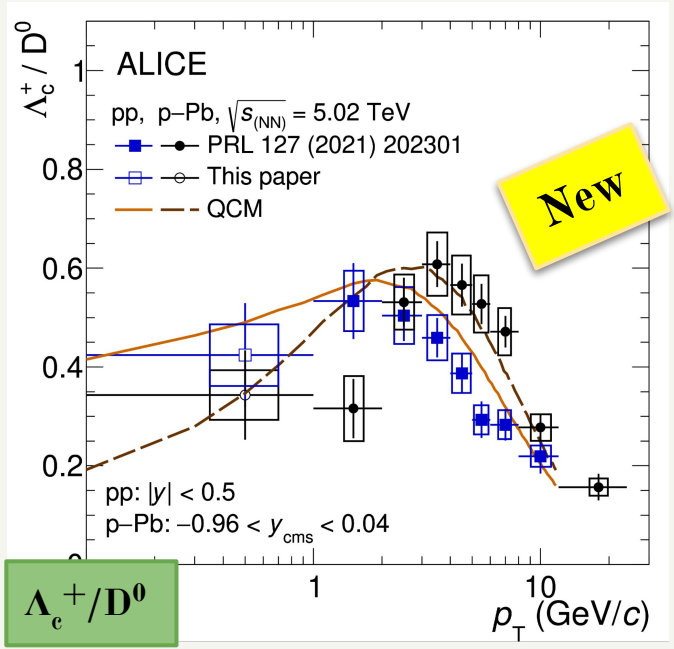
- p_T–integrated non-prompt D^0 R_{pPb} is compared with prompt D^0 in p–Pb and Pb–Pb, as well as non-prompt D^0 from Pb–Pb
- D^0 R_{pPb} in p–Pb is consistent with 1
- Deviation from unity in Pb–Pb expected to be due to hot nuclear effects
- **Study shadowing for beauty and charm**

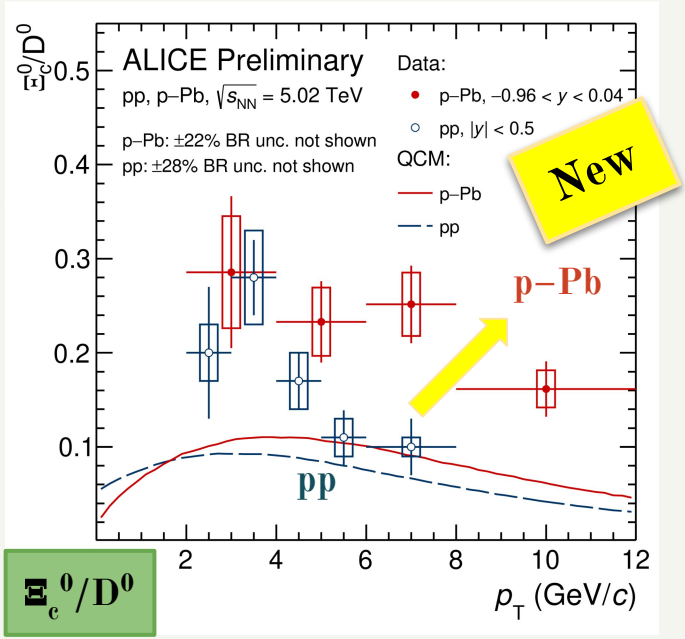
Charm baryon-to-meson yield ratios

First measurement of Ξ_c^0 production in p–Pb collisions

5.02 TeV





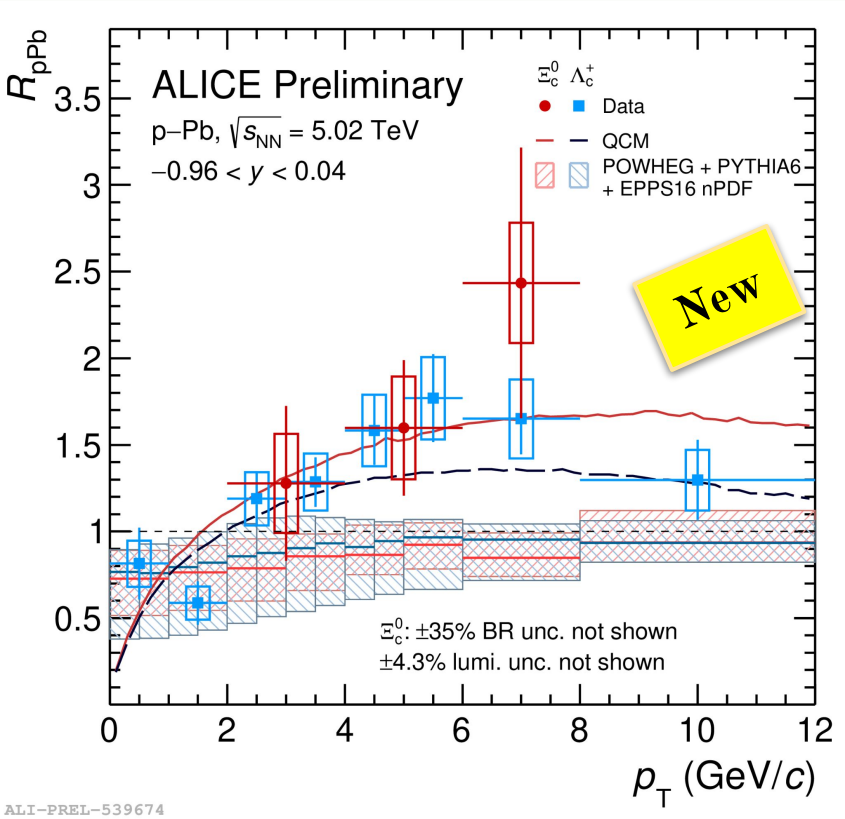


- Λ_c^+/D^0 in **p–Pb** collisions:
  - For $p_T > 3$ GeV/c, larger than in pp
  - For $p_T < 2$ GeV/c , tendency for smaller ratio
- Higher Ξ_c^0/D^0 in **p–Pb** collisions compared to pp collisions for $p_T > 6$ GeV/c ?

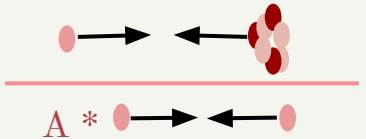
Hardening of p_T spectra w.r.t pp is predicted from QCM

Quark reCombation Mechanism (QCM)

Nuclear Modification factor



$$R_{\mathrm{p-Pb}} = \frac{\mathrm{d}\sigma_{\mathrm{p-Pb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{A}\cdot\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

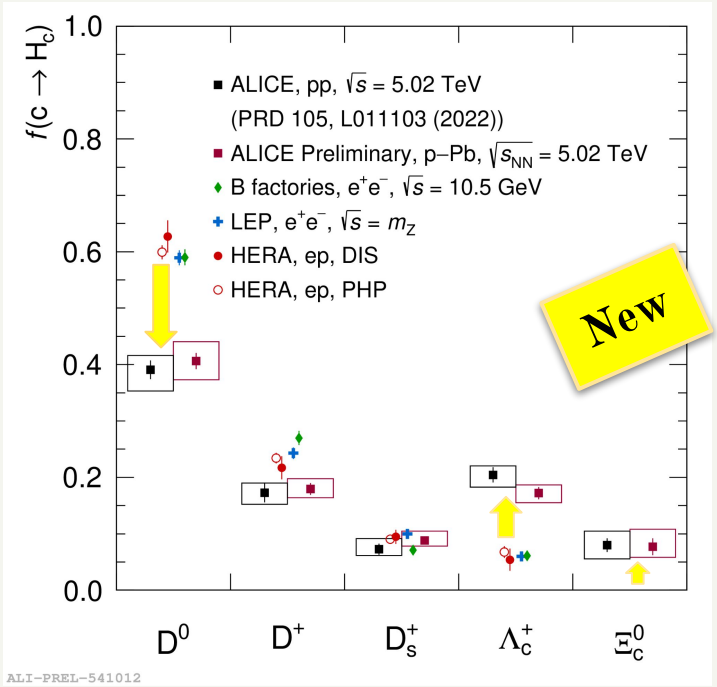


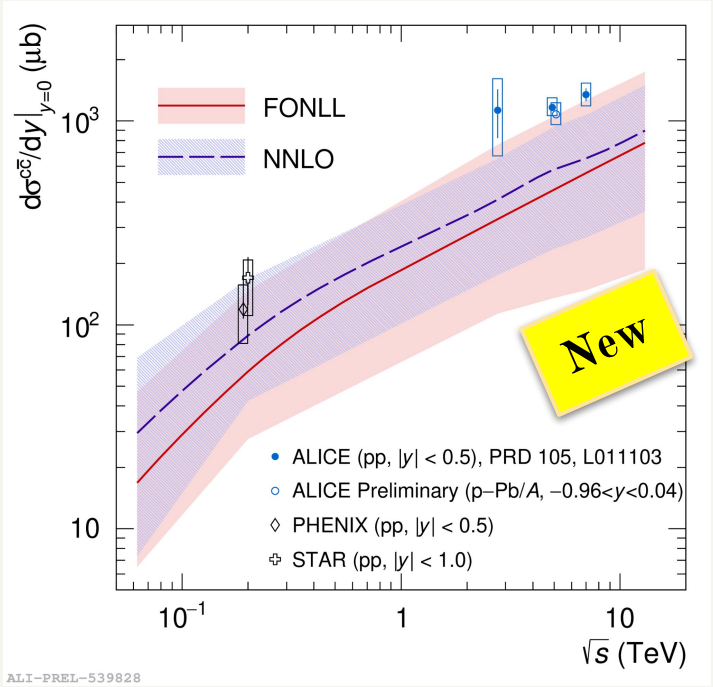
Nuclear modification factor

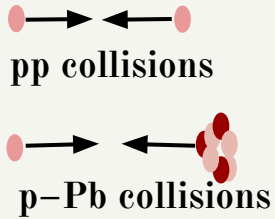
- If $R_{\mathrm{pPb}} = 1$: No modification w.r.t pp collisions
- Disentangle cold nuclear matter effect from final state effects

- $R_{\mathrm{pPb}}(\Lambda_c^+) \approx R_{\mathrm{pPb}}(\Xi_c^0)$
- $R_{\mathrm{pPb}}(\Lambda_c^+) < 1$ at low p_{T} and > 1 at intermediate p_{T}, as also observed in the strange sector (CMS: PRC 101, 064906)
- QCM prediction agrees with Ξ_c^0 measurement

Total charm cross section and fragmentation fractions





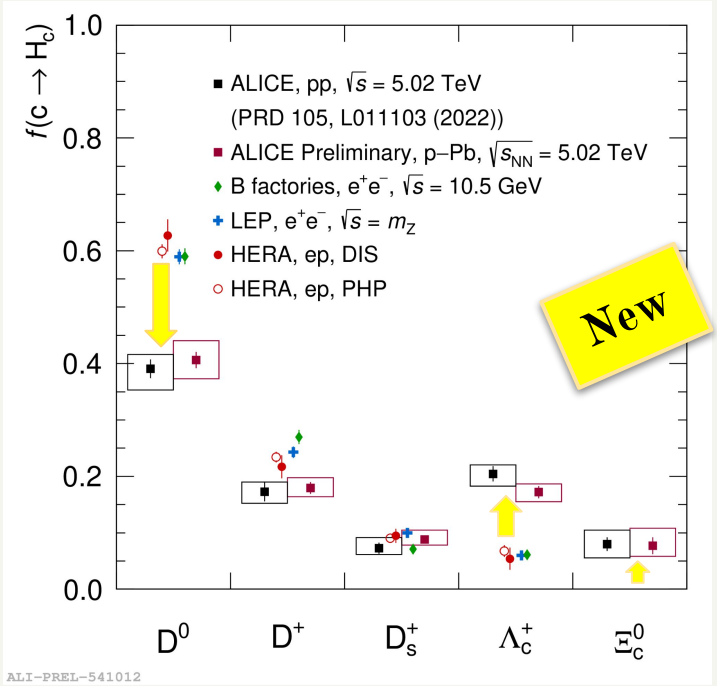


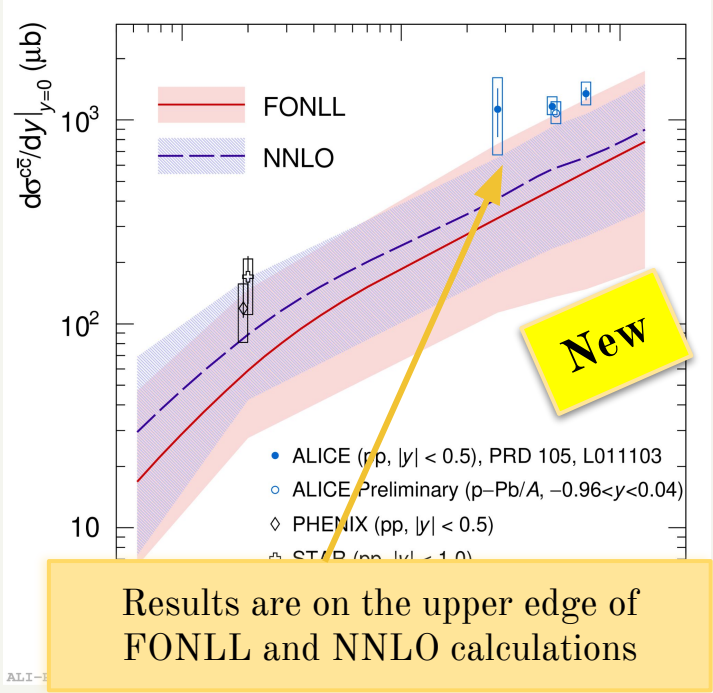
First measurement of Ξ_c^0 production and charm fragmentation fractions (FF) in p–Pb collisions

The universality of charm FF is broken

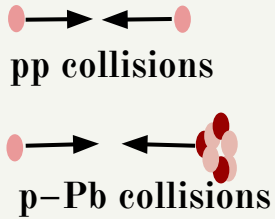
- No significant system dependence for charm fragmentation fractions
- Significant baryon enhancement in pp and p–Pb w.r.t. e^+e^- and e^-p collisions

Total charm cross section and fragmentation fractions





Results are on the upper edge of FONLL and NNLO calculations



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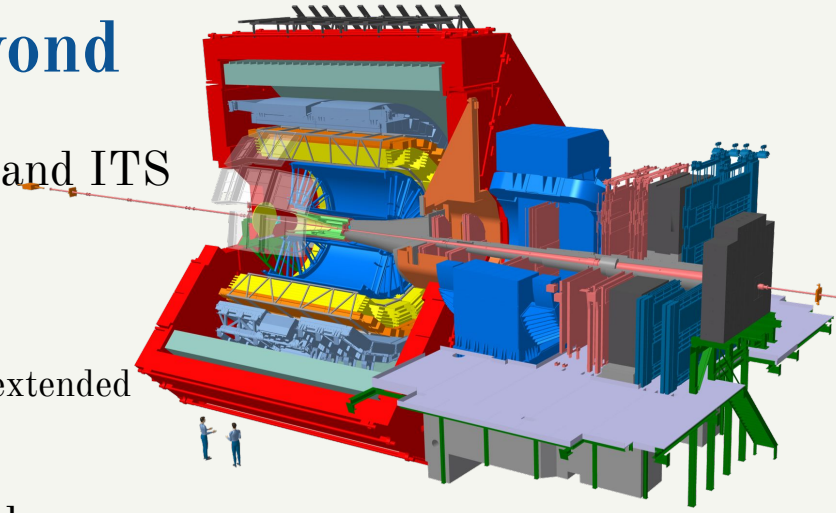
- No significant system dependence for charm fragmentation fractions
- Significant baryon enhancement in pp and p–Pb w.r.t. e^+e^- and e^-p collisions
- Total $c\bar{c}$ production at midrapidity is ~ 30% higher than previously published results

Summary

- Heavy–flavor hadron production
  - D–meson production well described using FF from e^+e^- measurements
  - Large enhancement of all charm-baryon production in pp collisions w.r.t. e^+e^- collisions

- Modified hadronisation mechanisms are needed w.r.t the vacuum string fragmentation picture to describe the heavy-flavor baryon measurements
  - Or additional charm baryon states should be considered

Outlook: LHC Run 3, 4 and beyond



- Larger data taking rate and upgraded TPC and ITS
  - Larger data samples in Run 3 than Run 2
  - Improved impact parameter resolution
  - Lead to more precise measurements, and with an extended p_{T} reach, of the observables studied in Run 2
- Direct reconstruction of beauty mesons and baryons
- Better constraints to theoretical models of the strongly interacting medium and hadronisation

	ITS 1	ITS 2	
Distance to interaction point (mm)	39	22	→ Closer to interaction point
X_0 (innermost layer) (%)	~1.14	~0.35	→ Lower material budget
Pixel pitch (μm^2)	50 × 425	27 × 29	→ Improved granularity
Readout rate (kHz)	1	100	→ Faster readout
Spatial resolution ($r\varphi \times z$) (μm^2)	11 × 100	5 × 5	→ Improved resolution

Thanks for your attention

ADDITIONAL SLIDES

Doubly strange charmed baryon production

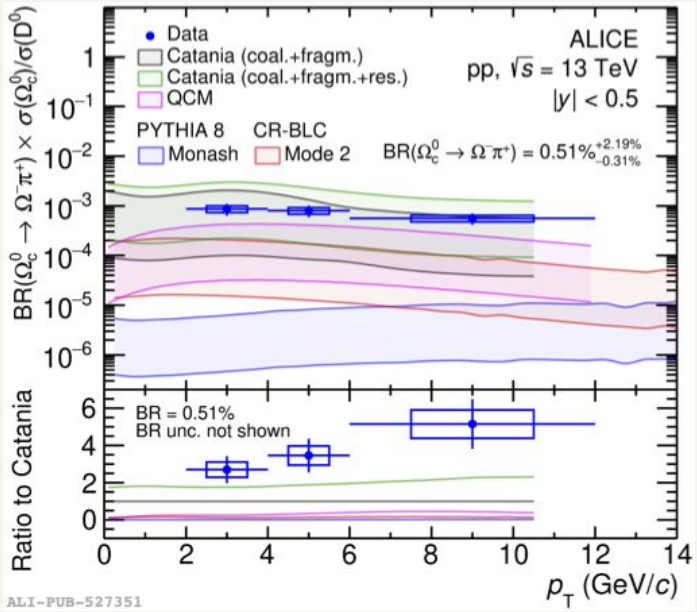
13 TeV

pp collisions

$(BR \times \Omega_c^0/D^0)$

arXiv:2205.13993
accepted by PLB

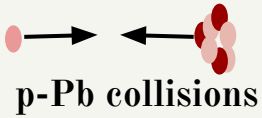
Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^- 10.52 GeV) [28] visible
$BR(\Omega_c^0 \to \Omega^- \pi^+) \times \sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(2.24 \pm 0.29 \pm 0.16) \times 10^{-4}$
$BR(\Omega_c^0 \to \Omega^- \pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$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

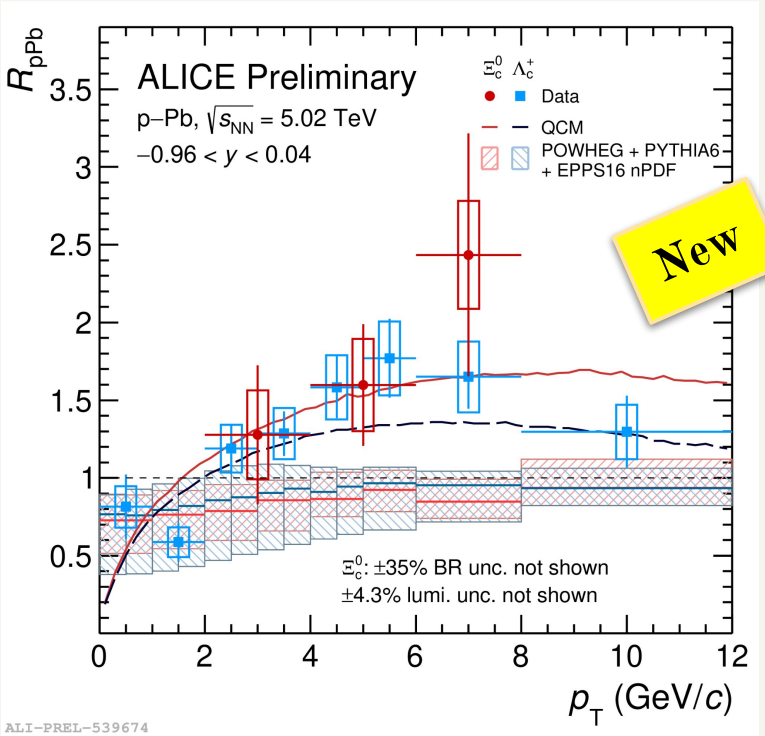


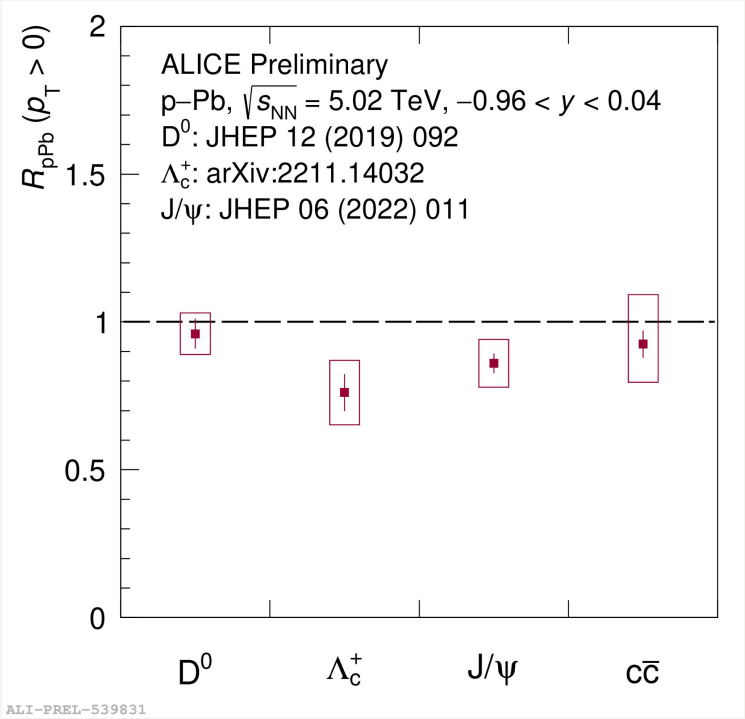
Sizeable contribution of Ω_c^0 to charm production at LHC energies?

- The hadronization process differs in pp and e^+e^- collisions
- Largely underestimated by PYTHIA 8 Monash[1]
  → Does not reproduce strangeness enhancement in pp
- PYTHIA 8 including CR-BLC[2] is not enough to describe the measurement
- Further enhancement with a simple coalescence model (QCM[3]) still shows a hint of underestimation
- Catania[4] is closer to data points → coalescence in pp?

Nuclear modification factor

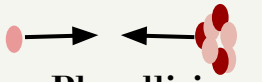






- Total charm RpPb is in agreement with unity
- Goal: Study modifications also in Pb-Pb collisions

Non-prompt Λ_c^+ production in p-Pb collisions



p–Pb collisions

First measurement of non–prompt baryon production in p-Pb collisions