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ALICE

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Charm hadronization measurements with the ALICE experiment

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QCD@Work
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Theory and Experiment
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Introduction

- Charm quarks are produced at the early stages of the collision due to their large mass → described by pQCD calculations
- ALICE measured a charmed baryon-to-meson ratio in pp higher than e^+e^- → non-universality of charm fragmentation?
- In this presentation the latest measurements in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV, and in p-Pb and Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV will be shown

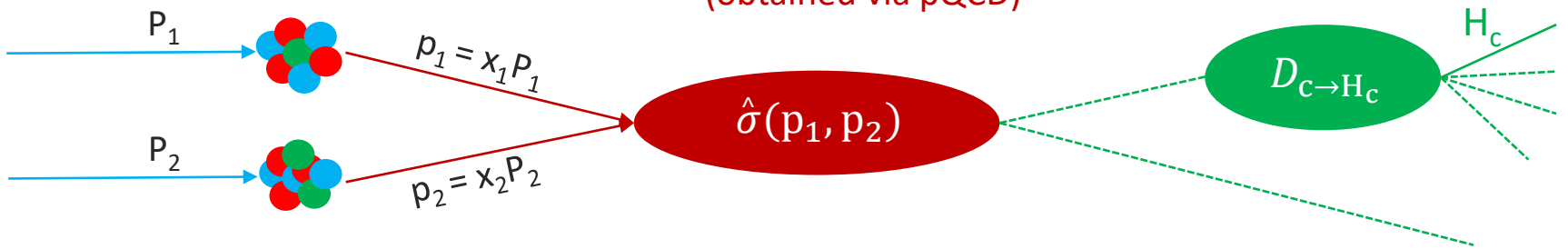
Heavy Flavour (HF) in pp collisions

$$\frac{\mathrm{d}\sigma^{\mathrm{Hc}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Hc}}} = f_1(x_1,\mu_f)\cdot f_2(x_2,\mu_f)\otimes\frac{\mathrm{d}\sigma^{c}}{\mathrm{d}p_{\mathrm{T}}c}(x_1,x_2,\mu_f,\mu_r)\otimes D_{\mathrm{c}\to\mathrm{H_c}}(z_c=\frac{p_{Hc}}{p_c},\mu_f^2)$$

Parton distribution functions (PDFs)

Hard scattering cross section (obtained via pQCD)

Fragmentation function (Hadronization)



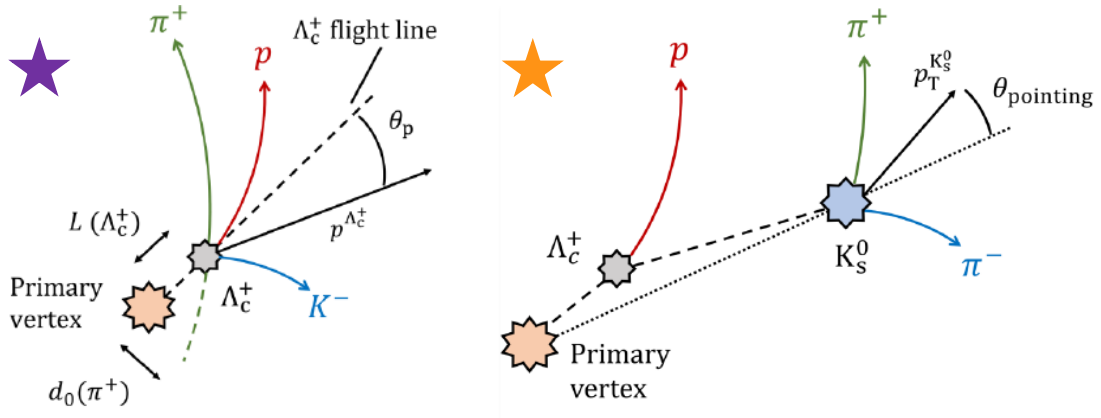
- Measurements in pp collisions are fundamental for testing perturbative QCD (pQCD) calculations
- Cross section computed with the factorization approach including:
  - Parton distribution functions
  - Hard scattering cross section
  - Fragmentation function
- Assumption of universal fragmentation functions (FF) ⟶ constrained from e^+e^- and ep

Heavy Flavour reconstruction

Measured hadrons	Reconstruction decays
D^0	$K^- \pi^+$
D^+	$K^- \pi^+ \pi^+$
D_s^+	$\Phi(\rightarrow K^+K^-)\,\pi^+$
Ξ_c^+	$\Xi^- \pi^+ \pi^+$
Ξ_c^0	$\Xi^- e^+ \upsilon_e$, $\Xi^- \pi^+$
Ω_c^0	$\Omega^- \pi^+$
Λ_c^+	$pK^- \pi^+$, $pK^0_s \rightarrow p\,\pi^+\,\pi^-$
$\Sigma_c^{0,++}$	$\pi^{-,+}\,\Lambda_c^+$

- Cross section measurements based on invariant-mass analysis → selection based on PID of daughter particles and decay topology
- Exploiting excellent impact parameter resolution provided by the ITS detector

Examples of heavy-flavour hadron reconstruction



Data samples:

pp

- $\sqrt{s}$ = 5.02 TeV → $L_{int} \approx 19\ nb^{-1}$
- $\sqrt{s}$ = 13 TeV → $L_{int} \approx 32\ nb^{-1}$

p-Pb and Pb-Pb

- $\sqrt{s_{NN}}$ = 5.02 TeV → $L^{pPb}_{int} \approx 287\ \mu b^{-1}$, $L^{PbPb}_{int} \approx 185\ \mu b^{-1}$

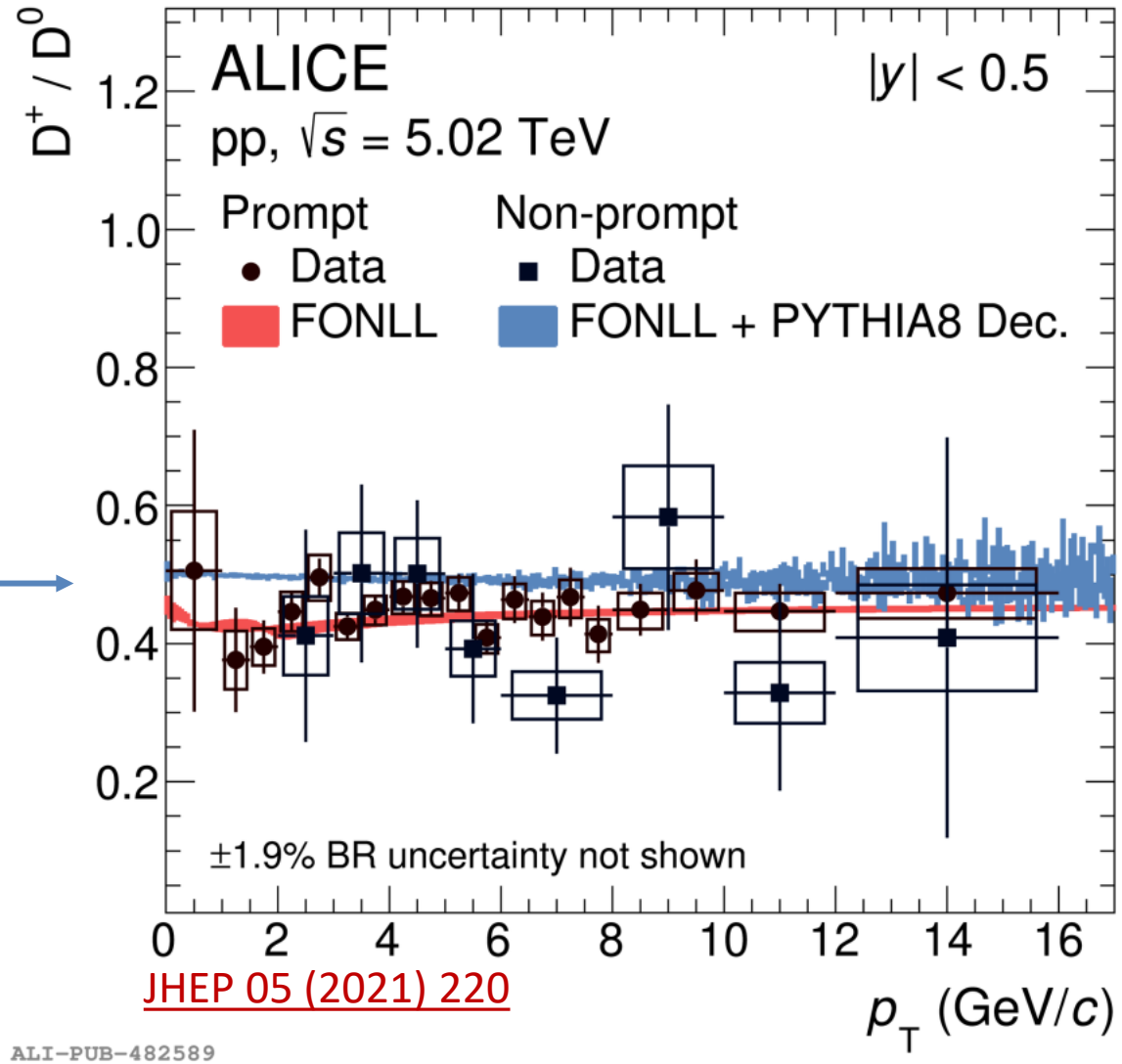
In the centrality intervals 0-10 and 30-50%

Meson-to-meson vs baryon-to-meson ratios

- Meson-to-meson ratio is p_T and collision system independent

- D^+/D^0 prompt and non-prompt ratios described well by pQCD-based models and they agree with measurements done at e^+e^- and ep

BUT…



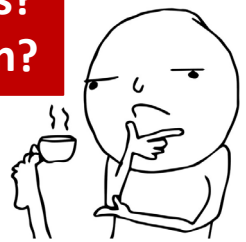
FONLL: JHEP 10 (2012) 137

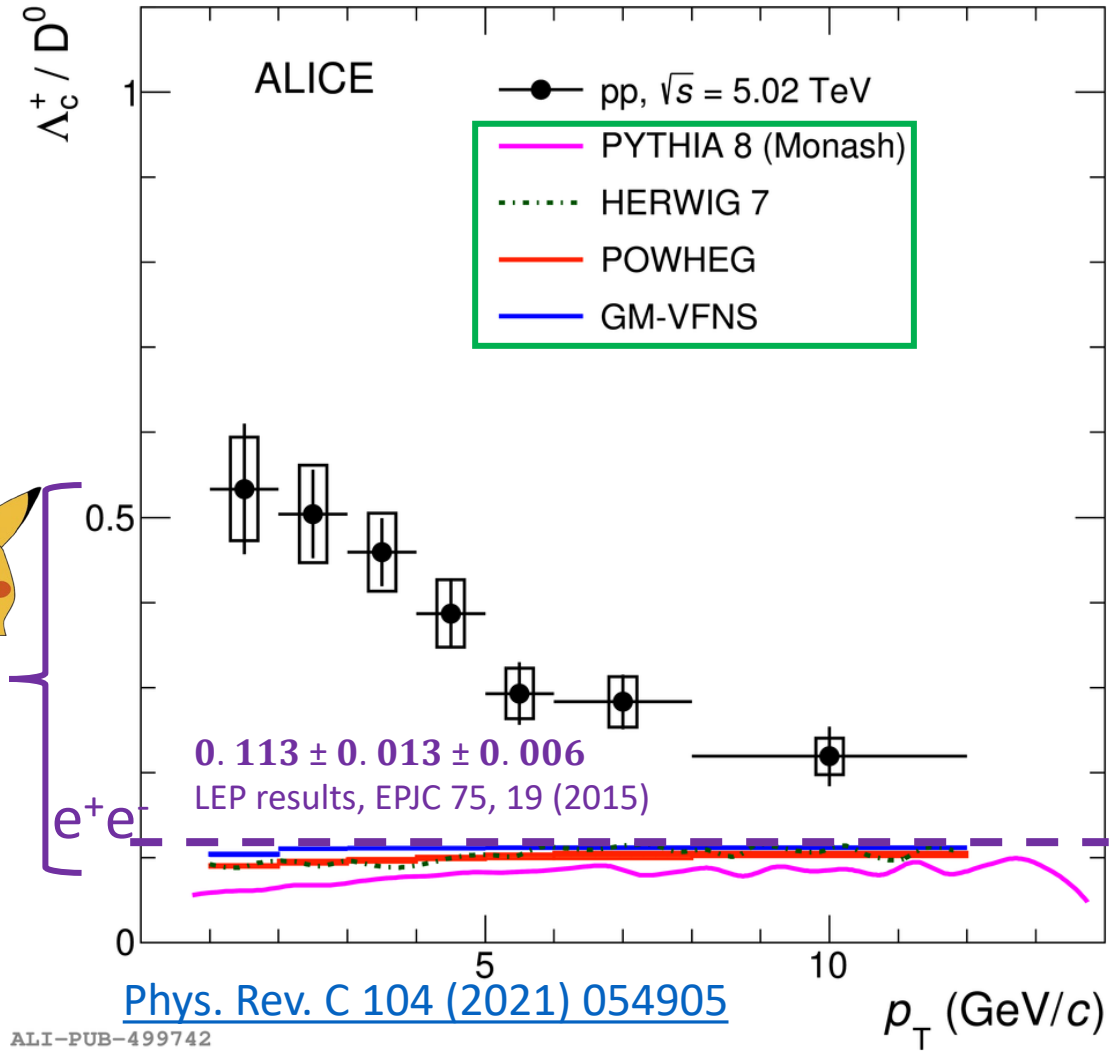
Meson-to-meson vs baryon-to-meson ratios

- Charmed baryon-to-meson ratio shows a significant p_T dependence → results up to 5x higher than e^+e^- measurements at low p_T

- All models adopting FF constraints from e^+e^-/ep measurements underestimate Λ_c^+/D^0 results

Other fragmentation mechanisms?
Non-universality of fragmentation?

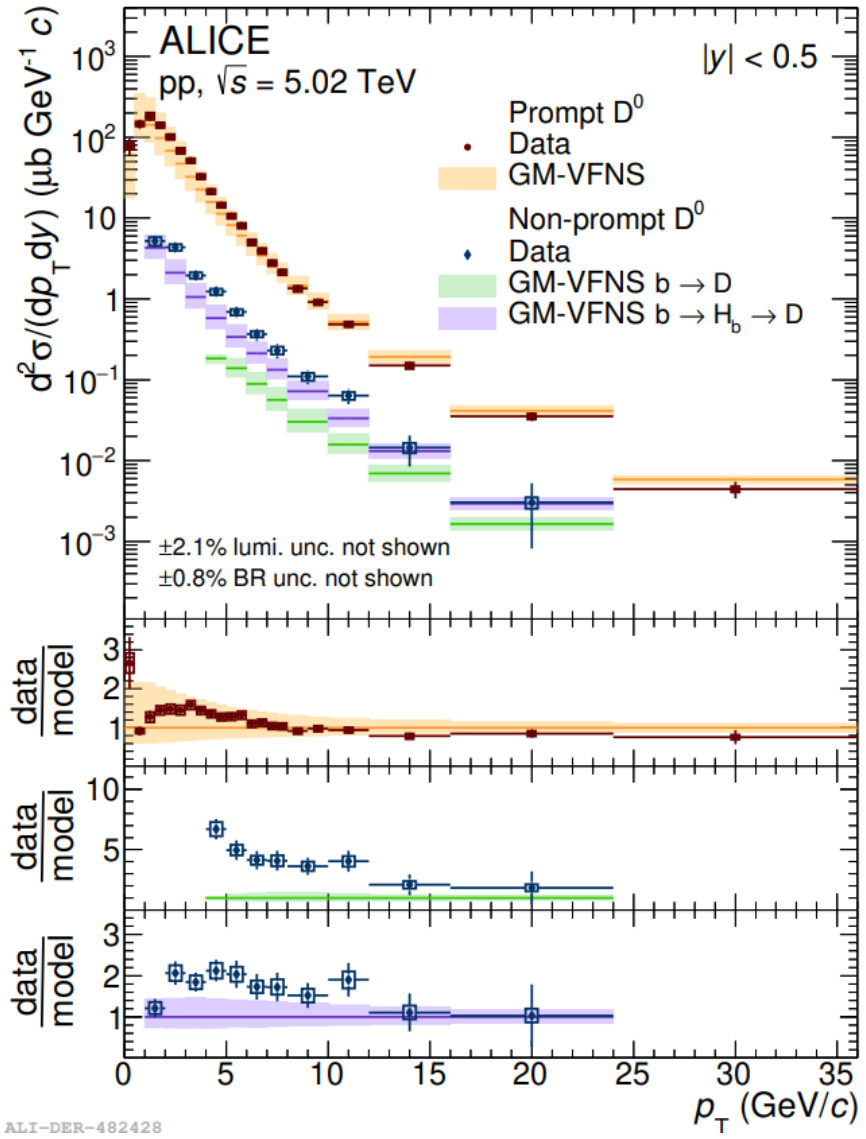


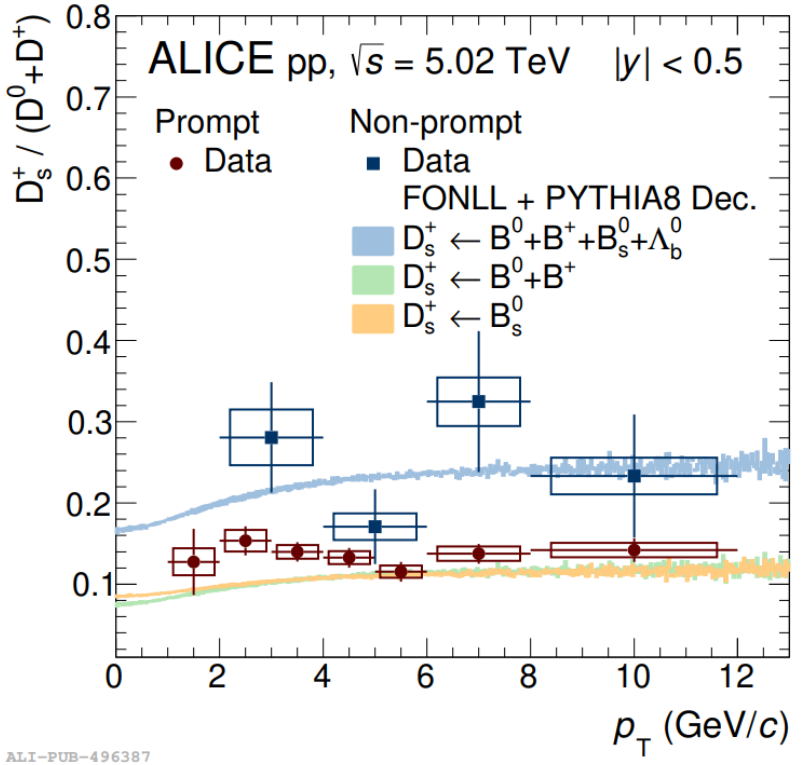


Phys. Rev. C 104 (2021) 054905

JHEP 05 (2021) 220

D mesons in pp collisions





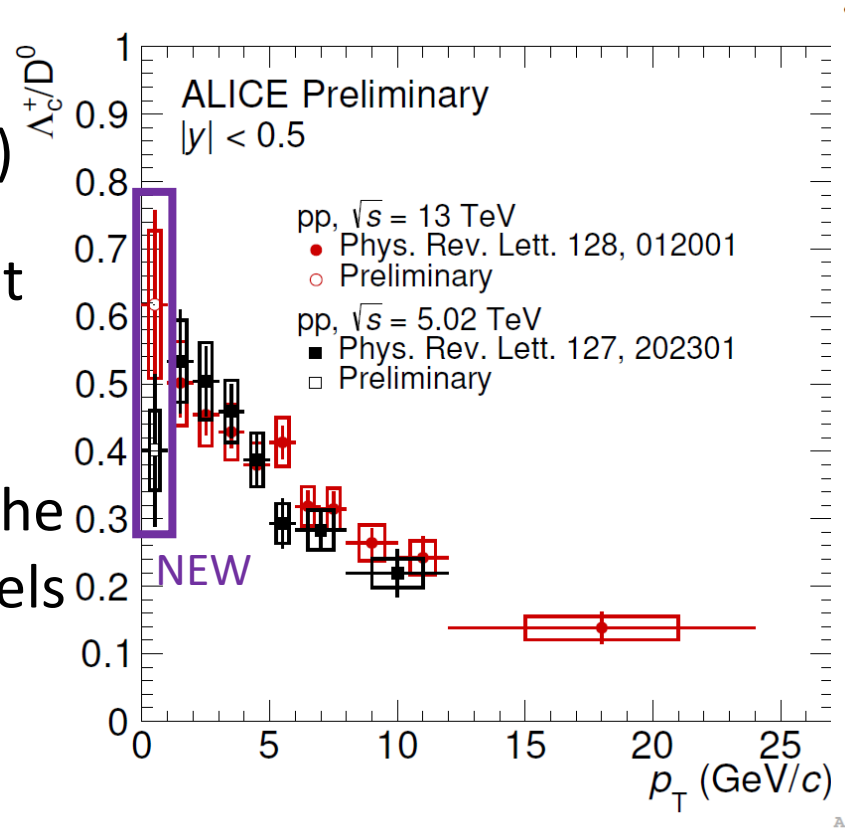
D$^{0,+}$ measured down to $p_T \approx 0$

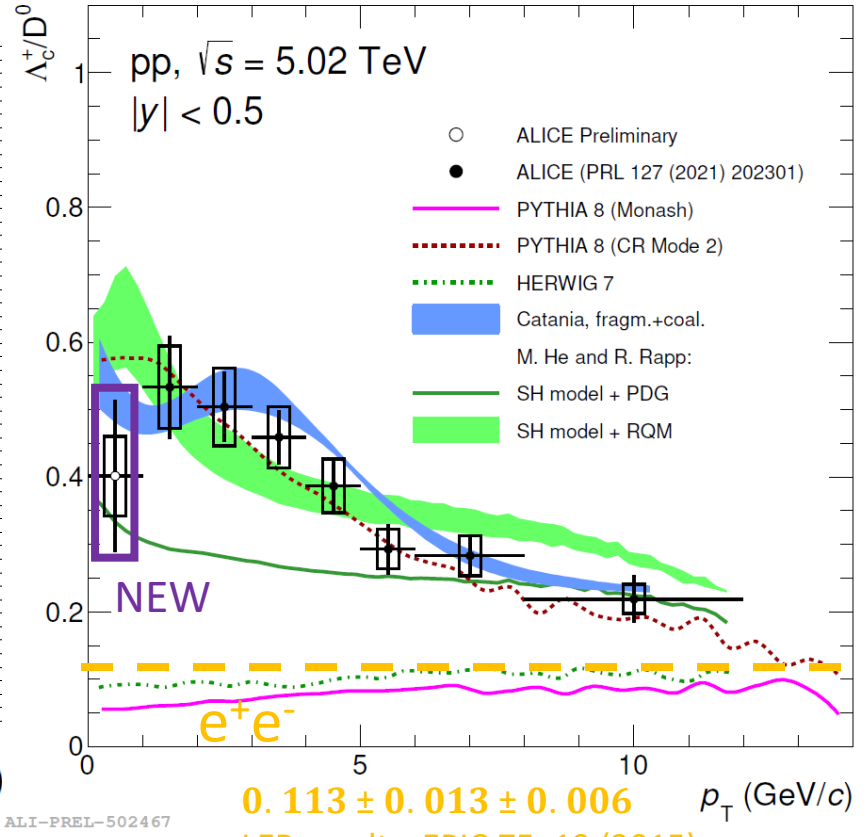
- Calculations based on factorization approach describe well prompt production
- GM-VFNS underestimates D mesons from b quarks
- Data provide good costraints for models → Results uncertainties lower than theory ones

Phys. Rev. Lett.128, 012001
Phys. Rev. Lett. 127, 202301

Λ_c^+ in pp collisions

- Prompt Λ_c^+/D^0 dependent on $p_T \longrightarrow$ centre of mass energy independent (5.02 and 13 TeV)
- New preliminary measurement performed down to $p_T \approx 0$
- Flat e^-e^+ trend not describing the decreasing trend vs $p_T \longrightarrow$ models e^-e^+ constrained included
- Models including enhanced heavy-flavour hadronization mechanisms provide a better description of the results





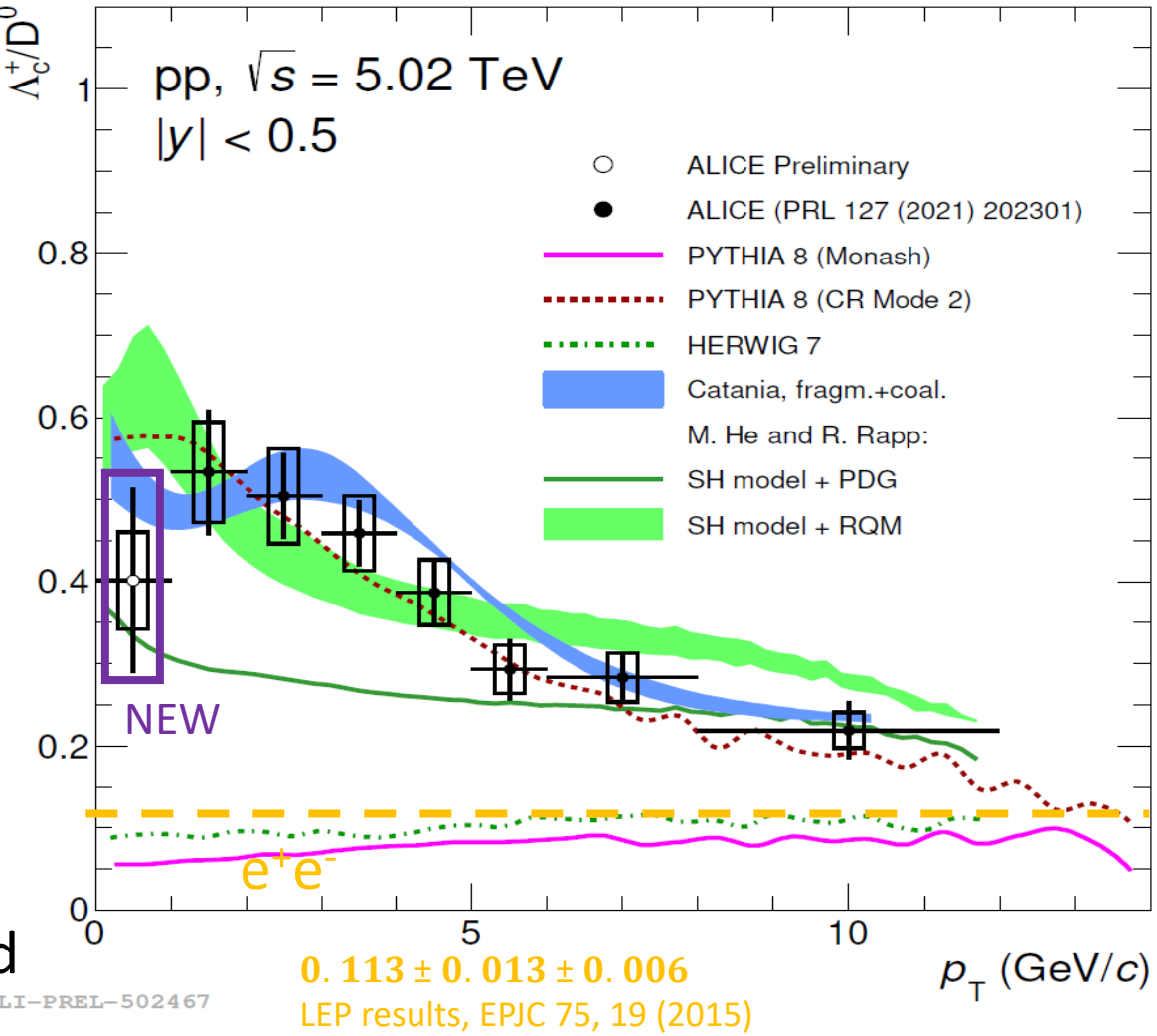
$0.113 \pm 0.013 \pm 0.006$
LEP results, EPJC 75, 19 (2015)

How do the models work?

Phys. Rev. Lett. 127, 202301

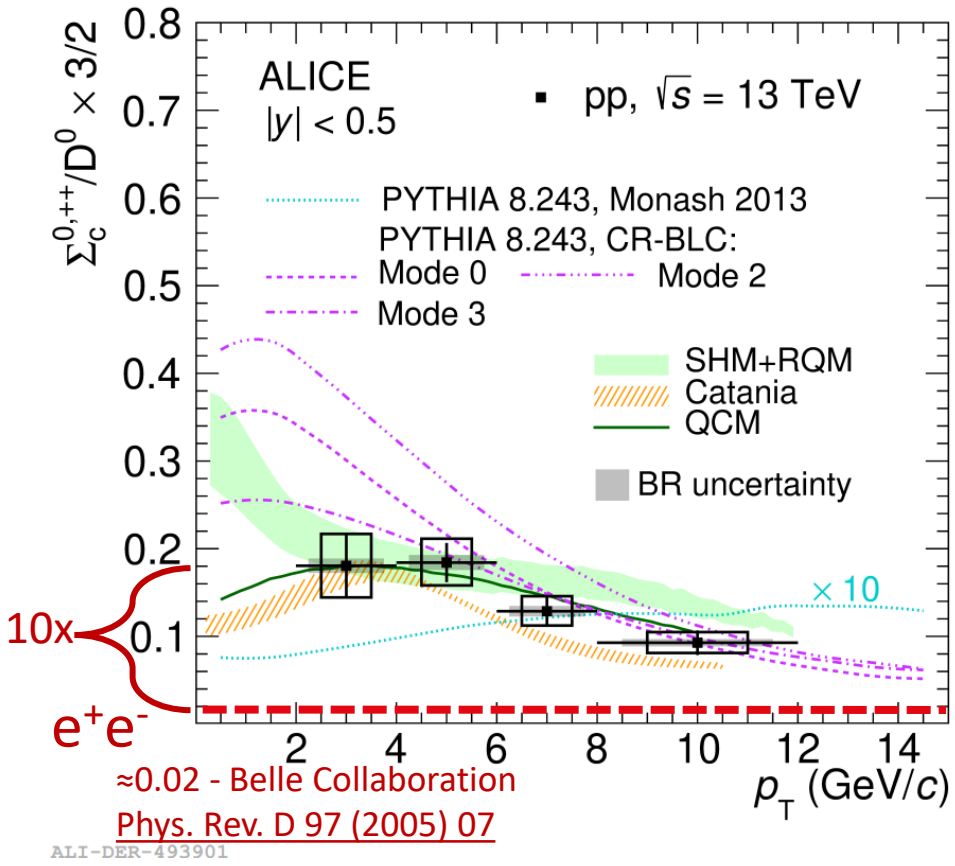
Λ_c^+ in pp collisions

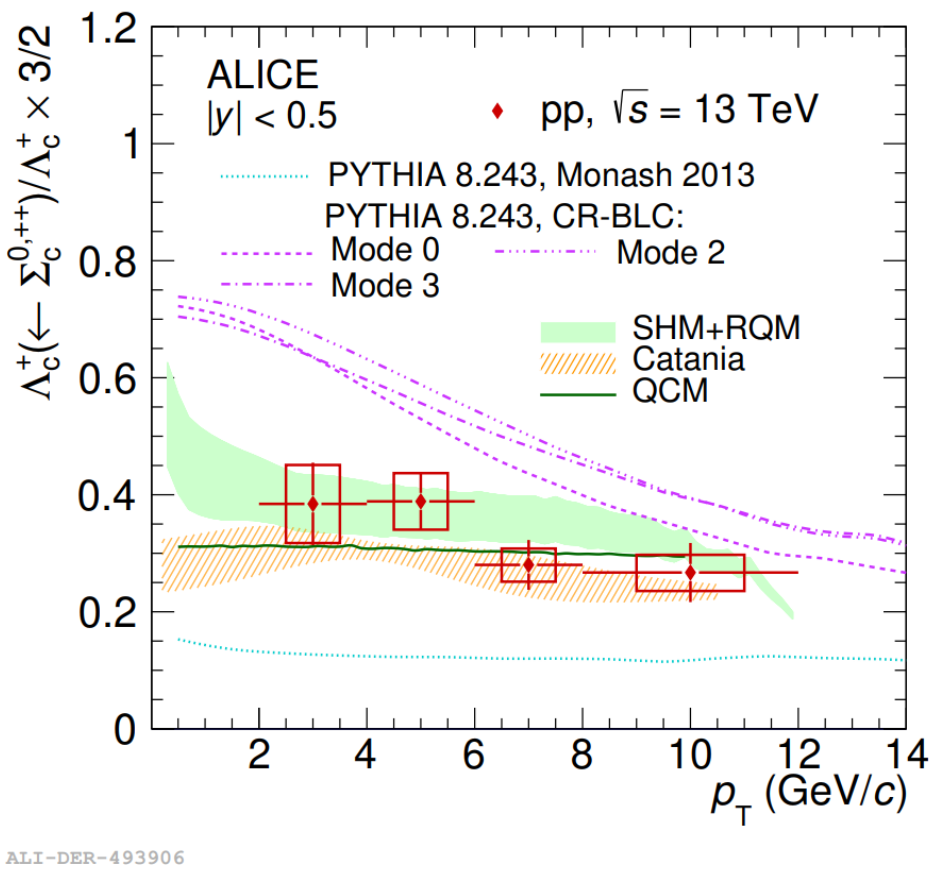
- PYTHIA8 with enhanced Colour Reconnection (CR)
  - ''Junction'' topology recombination between quarks and gluons
- Catania
  - Assumption of light quarks and gluons thermalised system
  - Hadron formation by: fragmentation + coalescence ← dominant at $p_T \approx 0$
- Statistical Hadronization Model and Relativistic Quark Model (SHM+RQM)
  - hadronization by statistical weights + enhanced set of excited charm baryons providing strong feed-down ← PDG/RQM define quantity of decaying additional baryons



Models References in next slide

Phys. Rev. Lett. 128 (2022) 012001 $\Sigma_c^{0,+,++}(2455)$ at $\sqrt{s}$ = 13 TeV





*Pythia8 with Monash: arXiv:1404.5630

*Pythia8 with Colour reconnection beyond leading colour (CR-BLC): JHEP 08 (2015) 003

*Statistical Hadronization Model with predictions of Relativistic Quark Model (SHM+RQM): Phys. Lett. B 795 (2019) 117–121

*Quark (re-)Combination Model (QCM): Eur. Phys. J. C 78 no. 4, (2018) 344

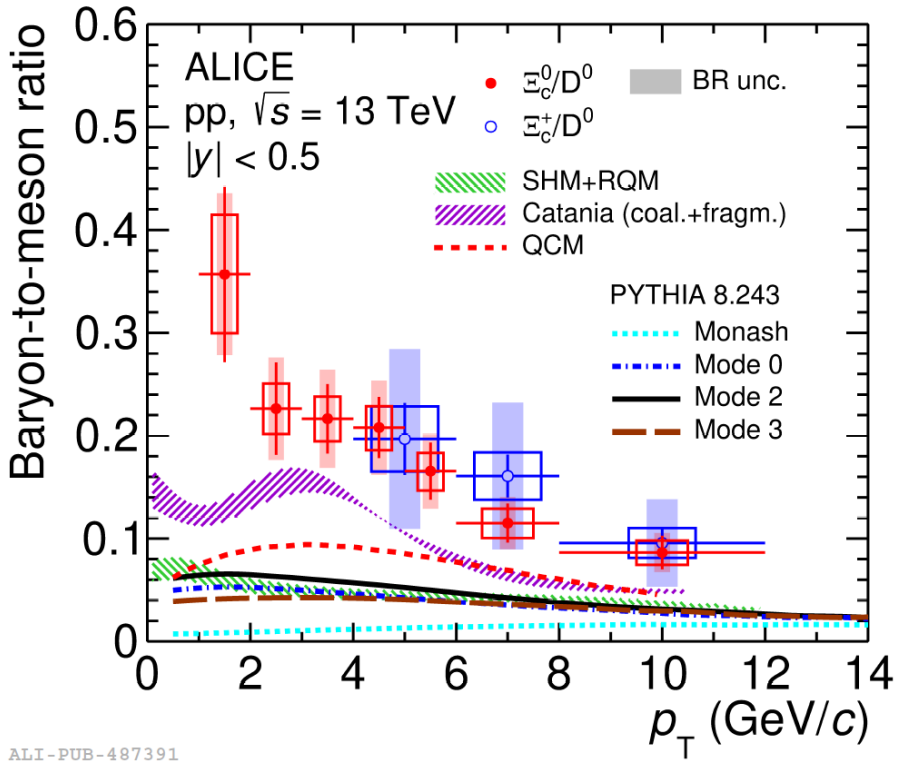
*Catania Model: arXiv:2012.12001

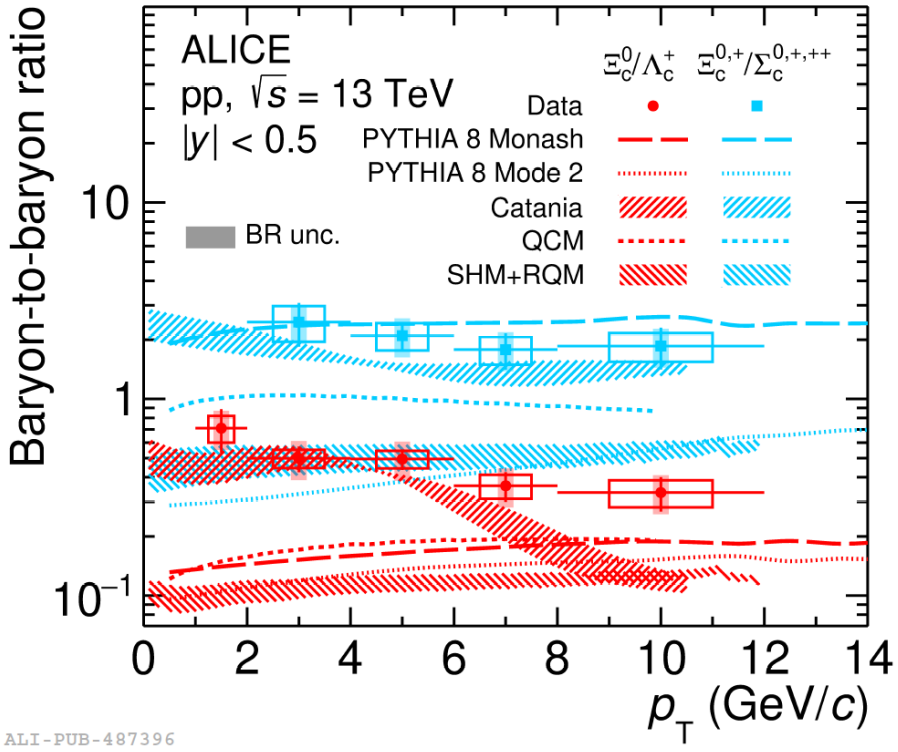
- Ratio larger than e^+e^- results → Underestimated by PYTHIA8 with Monash tune → $\Sigma_c^{0,+,++}/D^0$ shows a larger enhanchement compared to Λ_c^+/D^0
- SHM+RQM, QCM, Catania models describe well the experimental data

Strange charmed baryon production: $\Xi_c^{0,+}$

Phys. Rev. Lett. 127, 272001

- Ratio Ξ_c^0/D^0 enhanced by a factor ≈ 30 at low p_T considering PYTHIA8 with Monash tune
- All models underestimate the $\Xi_c^{0,+}/D^0$ ratios





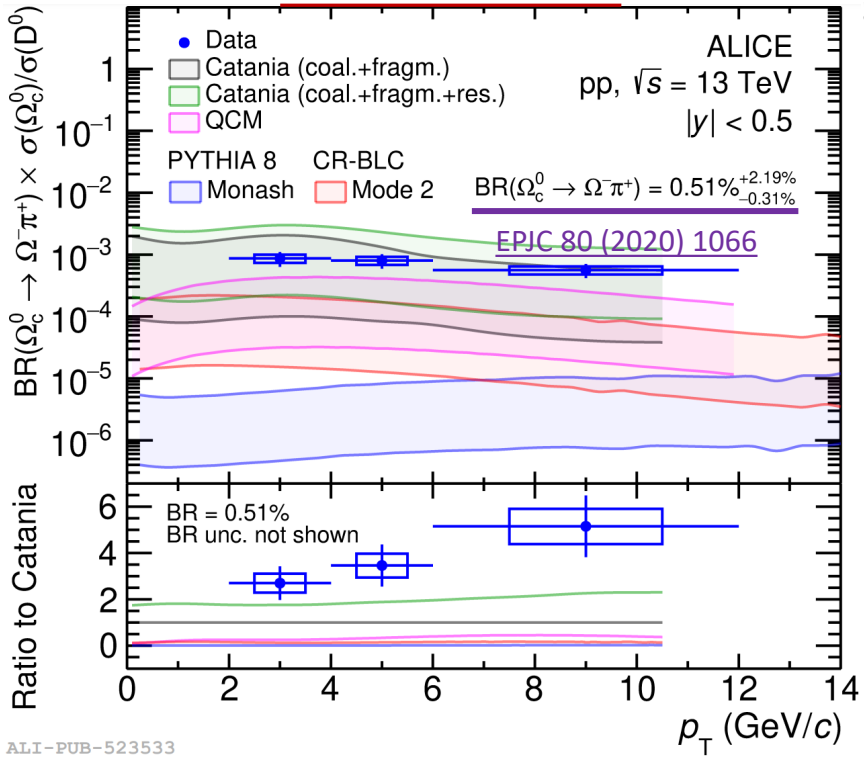
- $\Xi_c^0/\Sigma_c^{0,+,++}$ in pp agrees with PYTHIA8 Monash Tune → Similar enhancement in pp w.r.t. e^+e^- collisions?
- Catania model describes well baryon ratios → closer than other theories for the D^0 ratio

Doubly strange charmed baryon production: Ω_c^0

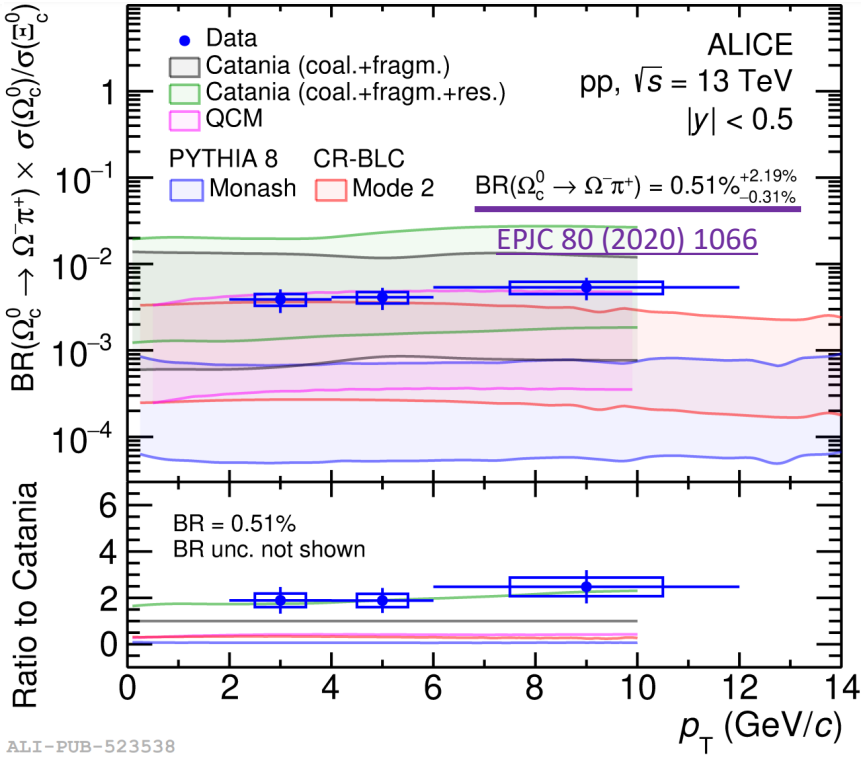
First measurement in pp collisions at $\sqrt{s}$ = 13 TeV

- Branching ratio (BR) of $\Omega_c^0 \rightarrow \Omega_c^- \pi^+$ from calculations → Used to scale model predictions
- Ω_c^0/D^0 and Ω_c^0/Ξ_c^0 are larger than theoretical predictions → Catania model closer to data in describing baryon-to-baryon ratio when adding higher mass resonance decays

NEW arXiv:2205.13993



NEW

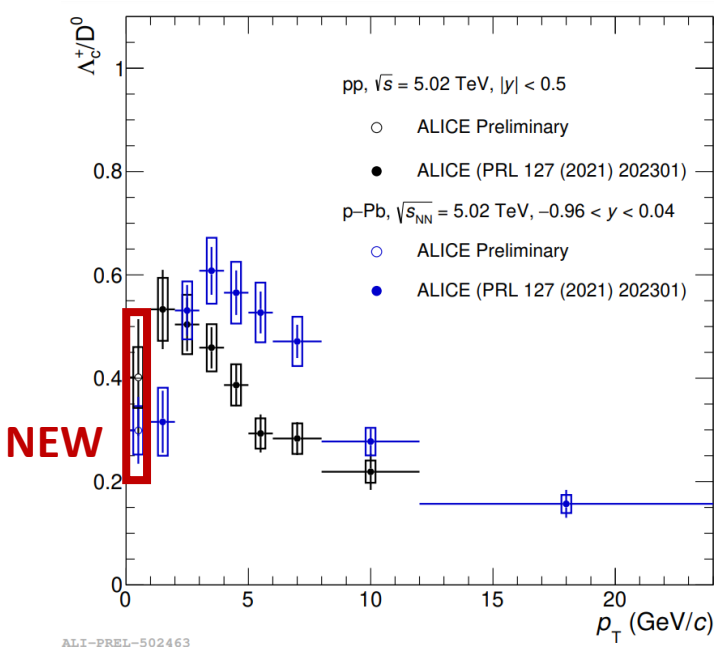


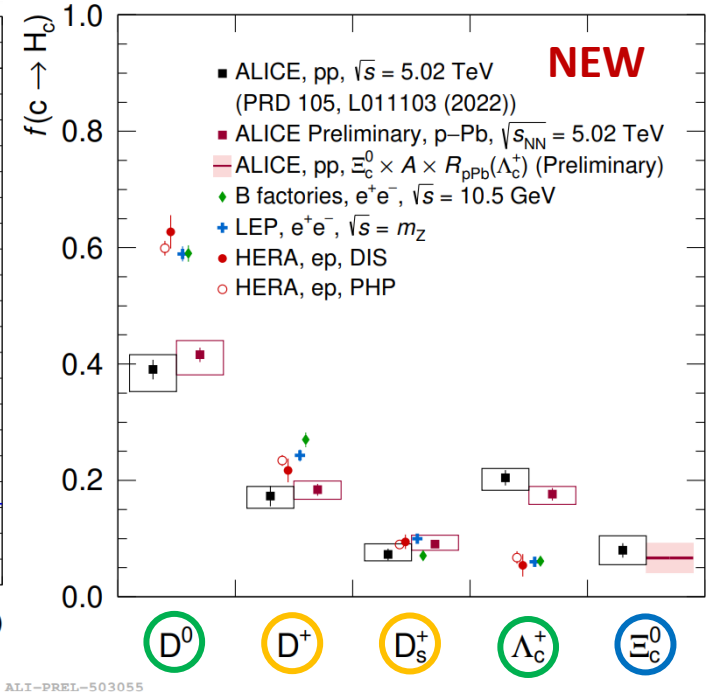
Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	BELLE (e^+e^- 10.52 GeV) visible
$BR(\Omega_c^0 \rightarrow \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(8.58 \pm 1.15 \pm 1.98) \times 10^{-4}$

PRD 97, 072005 (2018)

Significant contribution to charm production at LHC energies by Ω_c^0 ?

Λ_c^+/D^0 + charm fragmentation with pp and p-Pb





- Newly measured down to $p_T = 0$
- Extrapolated to $p_T = 0$ with PYTHIA+POWHEG
- Not measured, calculated with:

$$208 \cdot \sigma_{pp}(\Xi_c^0) \cdot R_{pPb}(\Lambda_c^+)$$

$$R_{pPb} = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

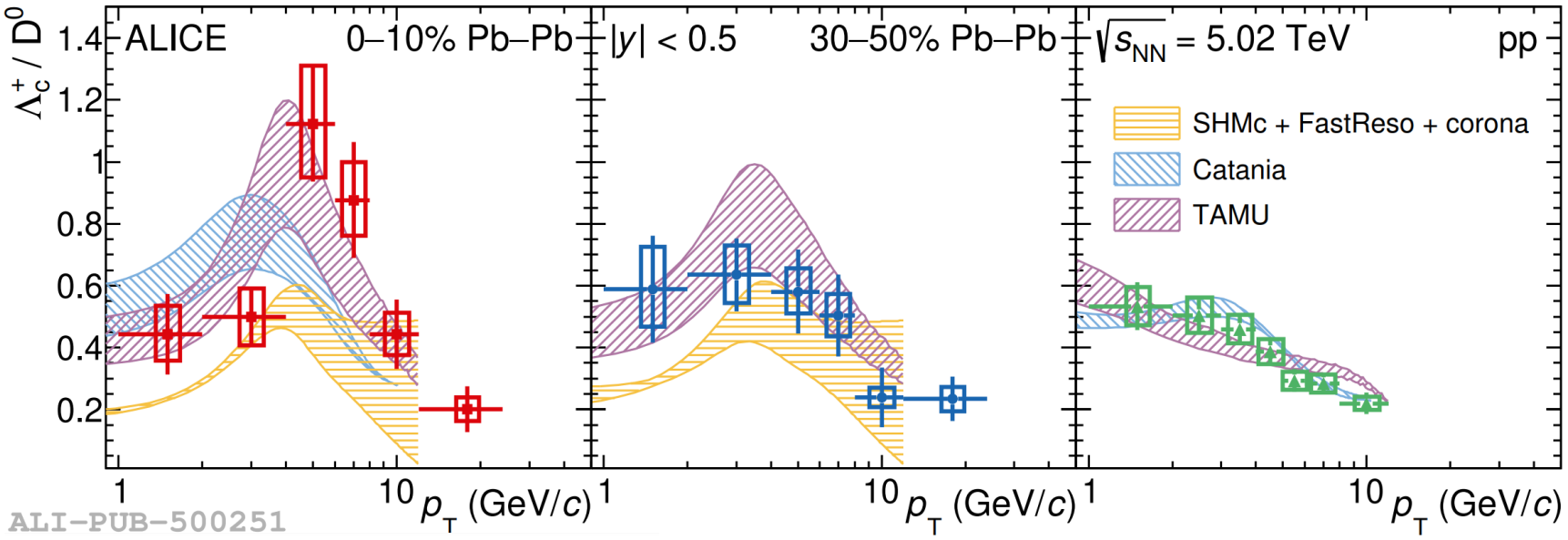
- Ratio Λ_c^+/D^0 in p-Pb collisions larger than in pp for $p_T > 3$ GeV/c ⟶ harder p_T spectrum
- Charm fragmentation fractions compatible in pp and p-Pb

Baryon enhancement compared to e^+e^- and ep measurements

arXiv:2112.08156

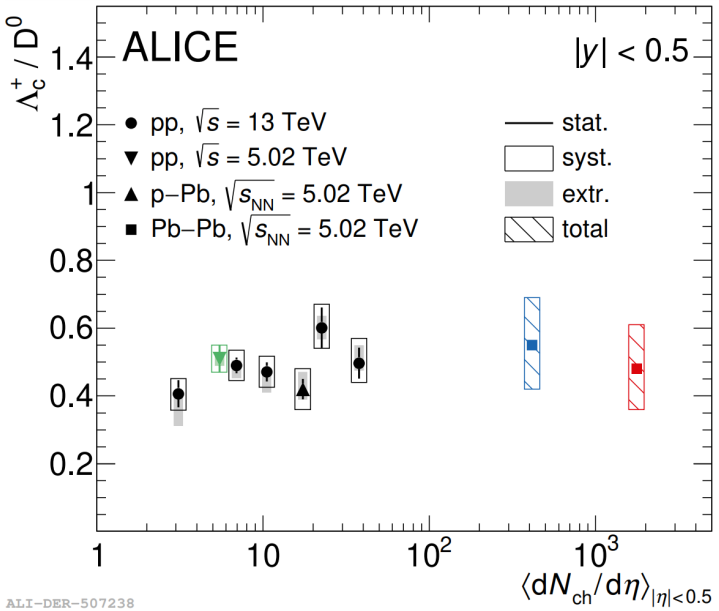
Λ_c^+/D^0 in pp and heavy ions

Phys.Lett.B 829 (2022) 137065



Λ_c^+/D^0 ratio showing different trend as a function of p_T for pp and Pb-Pb ⟶ 30-50% centrality interval is closer to pp

Radial flow causing dissimilar p_T shapes?



Phys. Rev. Lett. 124 (2020) 042301

- TAMU model describes better the results than Catania, which fails at low centrality

* Recombination approach for HF hadrons and baryons recovering thermal and chemical equilibrium + space-momentum correlations of heavy quarks with partons of expanding QGP

- The Λ_c^+/D^0 p_T-integrated ratio as a function of charged particle density does not show an enhancement between pp, p-Pb and Pb-Pb collision systems

Summary

- From the analysis of heavy-flavour baryons production we learned:
  - Additional hadronization mechanisms in pp could take place compared to e^+e^-/ep ⟶ models including enhanced production of baryons better describe the measurements

More studies needed to discriminate among different theoretical descriptions

  - Fragmentation fractions are not universal ⟶ baryon-to-meson ratios are not the same in different collisions systems

- New measurements will be performed opening new physics horizons thanks to:
  - RUN 3 higher statistics and improved tracking resolution
  - ALICE3: a new heavy-ion experiment for RUN 5 and 6

High accuracy B-hadron results down to 0 GeV/*c* | **Multi-charm baryons** | **Much more**

Thank you for your attention

ALICE

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Detector setup

- Inner Tracking System (ITS) and Time Projection Chamber (TPC) → charged particles tracking
- TPC and Time Of Flight (TOF) → Particle Identification (PID)
- V0 → centrality

Rapidity coverage
Central barrel → $|\eta| < 0.9$