Constraining hadronization mechanisms via charm-hadron production with ALICE

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Windows on the Universe

30th Anniversary of the Rencontres du Vietnam

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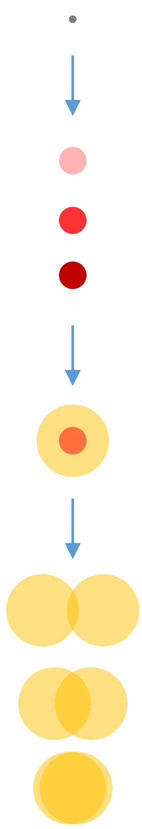
For the ALICE Collaboration

1. Introduction Motivation

- **Heavy flavor production**
  - e^+e^- vs. pp: from vacuum-like system to complex colliding systems, with multi-parton interactions (MPI)
  - pp vs. p–A vs. A–A
    - a. pp: reference for “larger” systems, a test of pQCD, study hadronization...
    - b. p–A: disentangle the initial state effect (shadowing, color glass condensate...)
    - c. A–A: characterization of QGP (collectivity, in-medium energy loss, hadronization...)



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    c. A–A: characterization of QGP (collectivity, in-medium energy loss, hadronization...)
  - Describing heavy-flavor production with factorization approach (i.e., large Q^2)

$$\frac{d\sigma^{pp\to Hq}}{dp_T} = f_i(x_1,\mu_f^2)\, f_j(x_2,\mu_f^2) \times \frac{d\sigma^{ij\to q}}{dp_T}(x_1, x_2, \mu_f^2) \times D_{q\to Hq}\left(z_q = \frac{p_{Hq}}{p_q}, \mu_f^2\right)$$

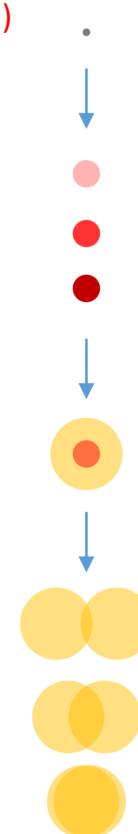
Parton distribution functions (PDFs)

Hard scattering cross section (via pQCD)

Fragmentation function (hadronization)

a. Among the ingredients, fragmentation functions are:
   a-1. Parameterized from e^+e^- and e^-p collisions
   a-2. Assumed to be universal independent of collision systems (e^+e^-, e^-p, pp, p–Pb and Pb–Pb)

b. Yield ratios of charm hadrons are sensitive to heavy-flavor hadronization mechanism

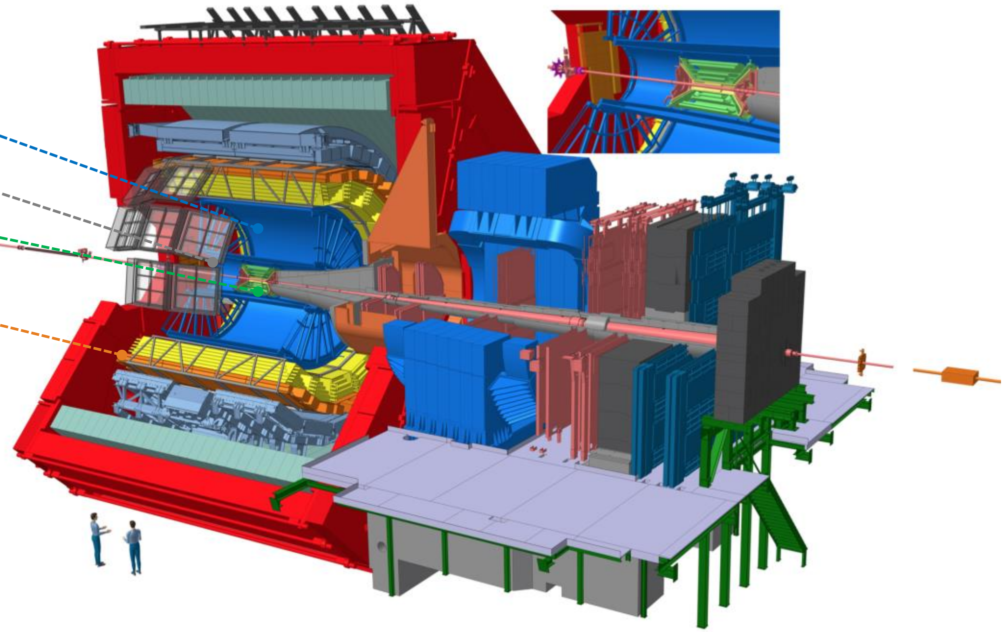


1. Introduction

ALICE detector

ALICE apparatus in Run 1 and 2 (2010-2018)

TPC	tracking, PID via dE/dx
V0	triggering, centrality
ITS	tracking and vertexing
TOF	PID via time of flight



Data samples

System	Energy (TeV)	L $_{\text{int}}$
pp	$\sqrt{s}$ = 5.02	~ 19 nb^{-1} (MB)
	$\sqrt{s}$ = 13	~ 32 nb^{-1} (MB)
p–Pb	$\sqrt{s_{\text{NN}}}$ = 5.02	~ 287 μb^{-1} (MB)
Pb–Pb	$\sqrt{s_{\text{NN}}}$ = 5.02	~ 130 μb^{-1} (0-10%)
		~ 56 μb^{-1} (30-50%)

Channels under study in pp, p–Pb, and Pb–Pb

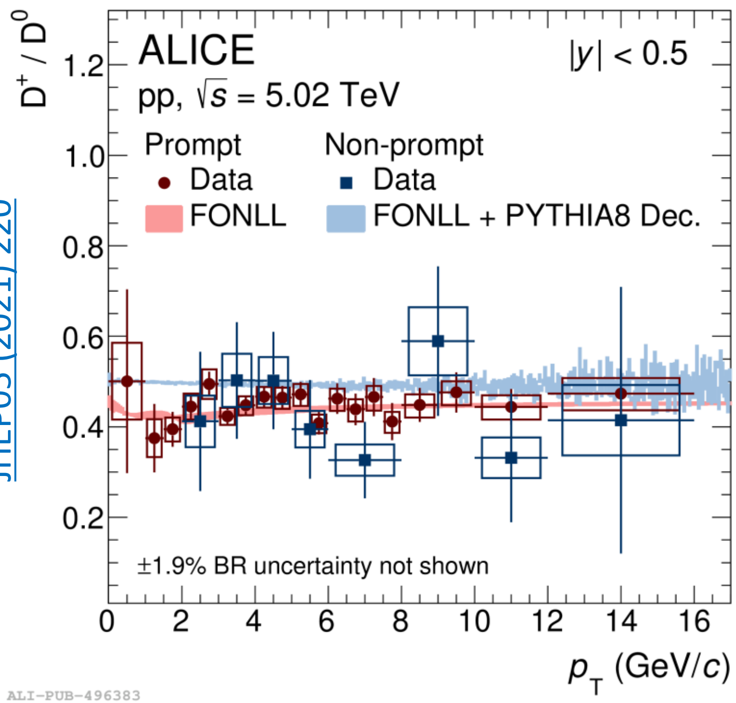
Mesons		Baryons	
D^0 ($\bar{u}c$) → $K^-\pi^+$	D_s^+($\bar{s}c$) → $\Phi\pi^+$ → $K^-K^+\pi^+$	Λ_c^+(udc) → $pK^-\pi^+$, pK_s^0	Ξ_c^+ (usc) → $\Xi^-\pi^+\pi^+$
D^+($\bar{d}c$) → $K^-\pi^+\pi^+$	D_{s1}^+($\bar{s}c$) → $D^{*+}K_s^0$ → $D^0\pi^+\pi^-\pi^+$	$\Sigma_c^{0,++}$ (ddc, uuc) → $\Lambda_c^+\pi^{-,+}$	Ω_c^0 (ssc) → $\Omega^-\pi^+$
D^{*+}($\bar{d}c$) → $D^0\pi^+$ → $K^-\pi^+\pi^+$	D_{s2}^+($\bar{s}c$) → $D^+K_s^0$ → $D^0\pi^+\pi^-\pi^+$	Ξ_c^0 (dsc) → $\Xi^-e^+\nu_e$, $\Xi^-\pi^+$	

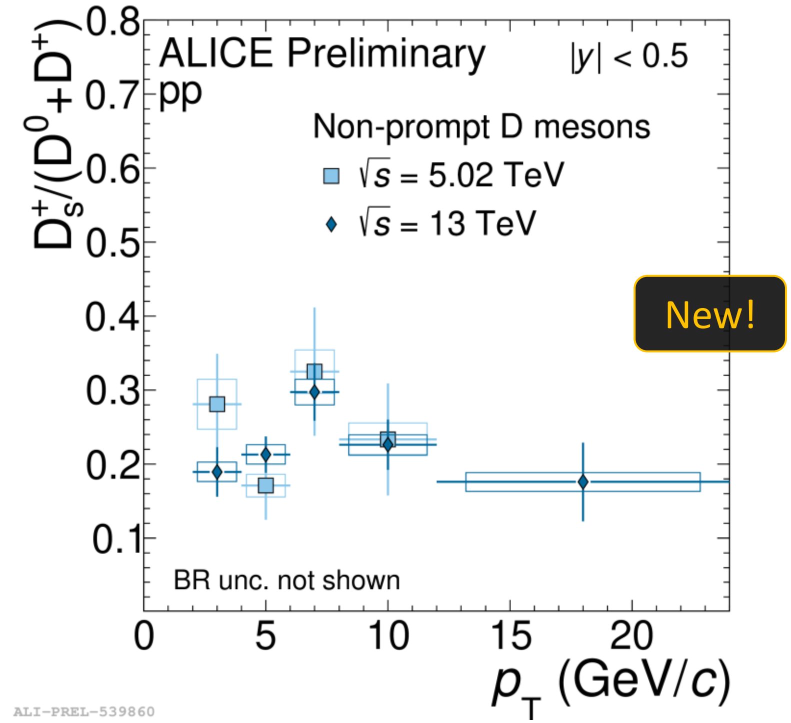
2. Charm @ ALICE

Prompt/Non-prompt D mesons in pp @ √s = 5.02 and 13 TeV

FONLL: JHEP 05 (1998) 007 / FONLL + PYTHIA8: JHEP 03 (2001) 006

JHEP05 (2021) 220





- D^+/D^0 measured down to p_T ~ 0 and $D_s^+/(D^0 + D^+)$ measured down to p_T = 2 GeV/c:

  non-prompt D-mesons: access to beauty meson production mechanisms

- No significant p_T dependence: independent of prompt/non-prompt, center-of-mass energies

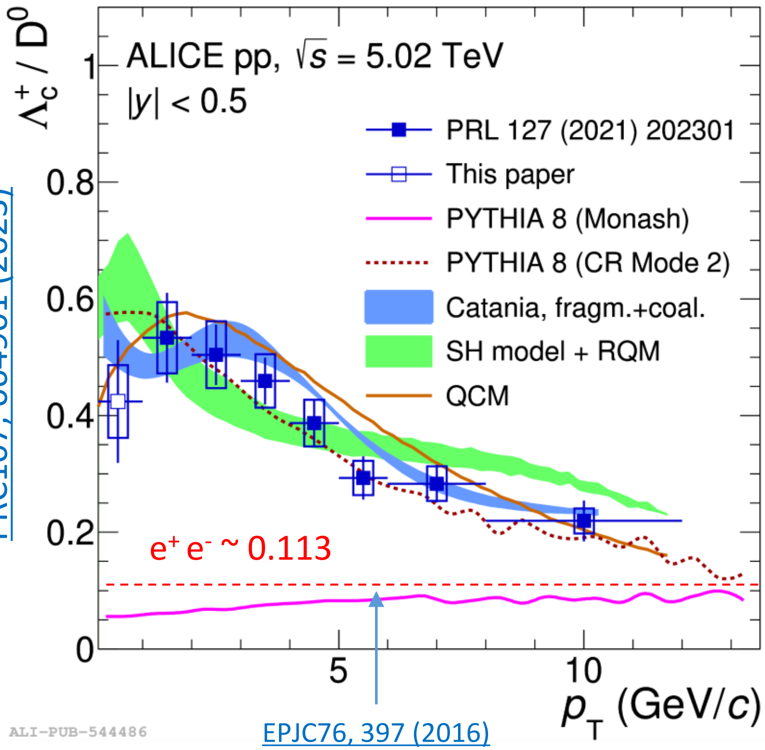
- Good agreement with pQCD (FONLL) calculations:

  supports factorization approach and universal fragmentation functions from e^+e^- / e^-p

2. Charm @ ALICE

Prompt Λ_c^+/D^0 in pp @ √s = 5.02 TeV

PRC107, 064901 (2023)



EPJC76, 397 (2016)

PYTHIA 8 (Monash) / Eur. Phys. J. C 74, 3024 (2014)
Based on fragmentation functions from e^+e^-

PYTHIA 8 (CR Mode 2) / J. High Energy Phys. 08 (2015) 003
Color reconnection beyond leading order,
Introduce new junction topologies which results in increased baryon

Catania / Phys. Lett. B 821, 136622 (2021)
Thermalized system of gluons, light quarks and antiquarks (QGP).
Hadronization via coalescence and fragmentation

SH model / Phys. Lett. B 795, 117 (2019)
Replaces complexity of hadronization by thermo-statistical weights, governed by the masses of hadrons at a universal hadronization "temperature"

QCM / Chin. Phys. C 45, 113105 (2021)
Charm is combined with co-moving light antiquark or two quarks.
Abundances of charm baryon species are determined by thermal weights

– Significant baryon enhancement vs. e^+e^- result

a. A model based on e^+e^-/e-p fragmentation functions cannot describe the data

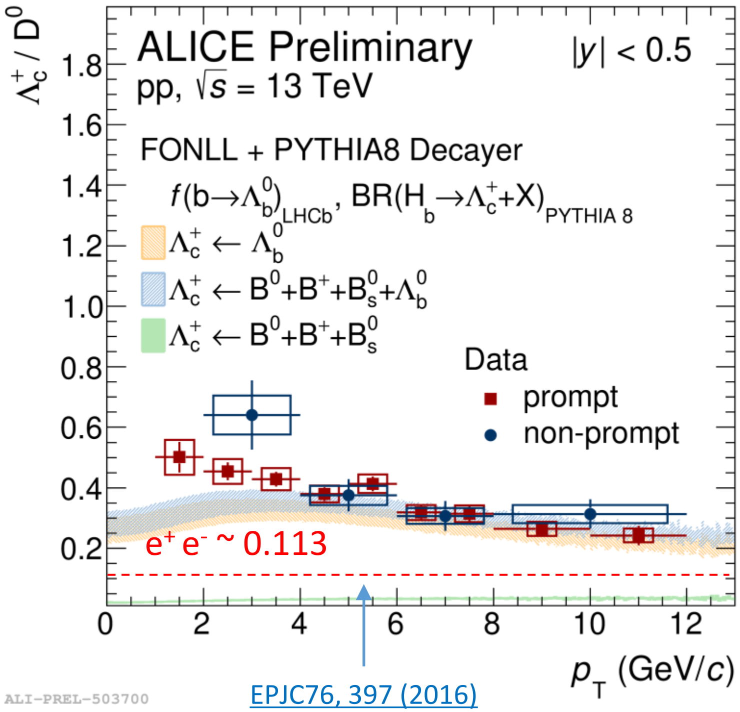
b. Models based on either modified hadronization mechanisms or augmented feed-down from higher mass states reproduces the data

c. Suggests further hadronization mechanisms at play

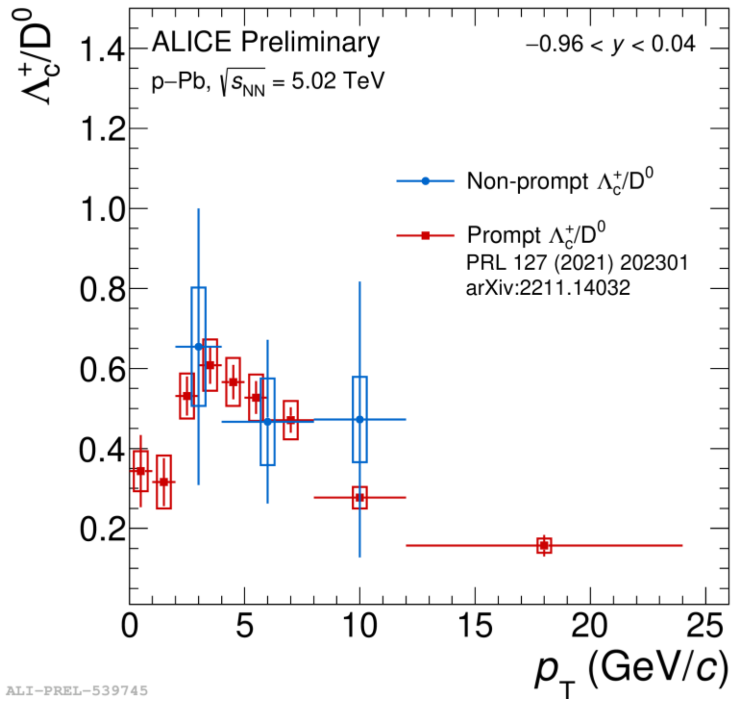
2. Charm @ ALICE

Prompt/Non-prompt Λ_c^+/D^0 in pp @ $\sqrt{s}$ = 13 TeV and in p–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

FONLL + PYTHIA8: JHEP 03 (2001) 006



EPJC76, 397 (2016)



– Agreement within the uncertainties for prompt/non-prompt, in both pp and p–Pb collisions:

  similar baryon enhancement independent of system compared to e^+e^-

– Non-prompt Λ_c^+ and D^0 data described by simulations

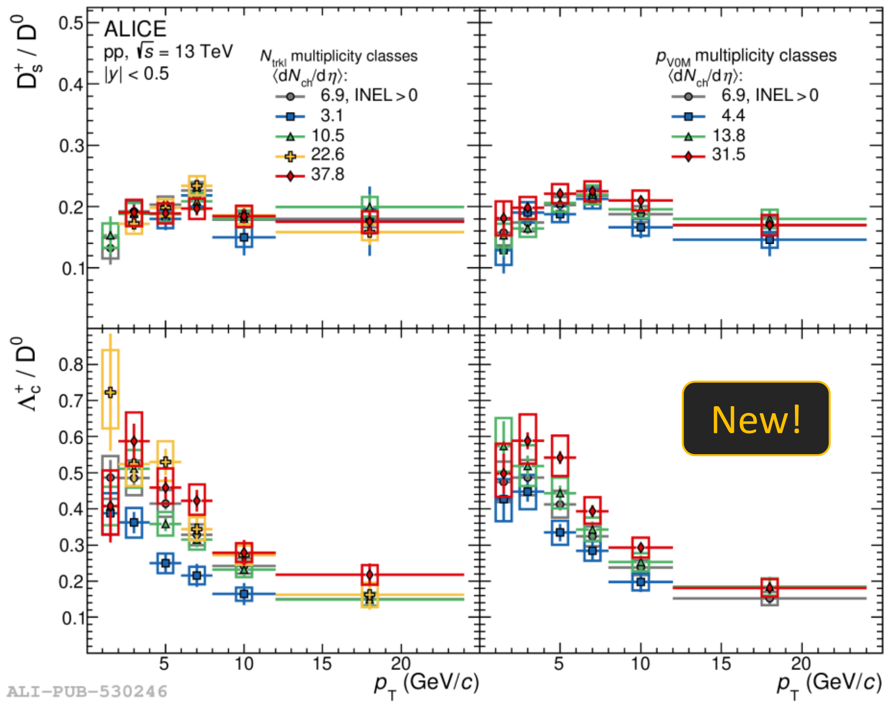
  a. The model (FONLL + PYTHIA8 decayer) utilizes frag. functions measured by LHCb

  b. Most of Λ_c^+ from Λ_b^0 decays

2. Charm @ ALICE

D_s^+/D^0 and Λ_c^+/D^0 vs. event multiplicity in pp @ √s = 13 TeV

PLB829, 137065 (2022)

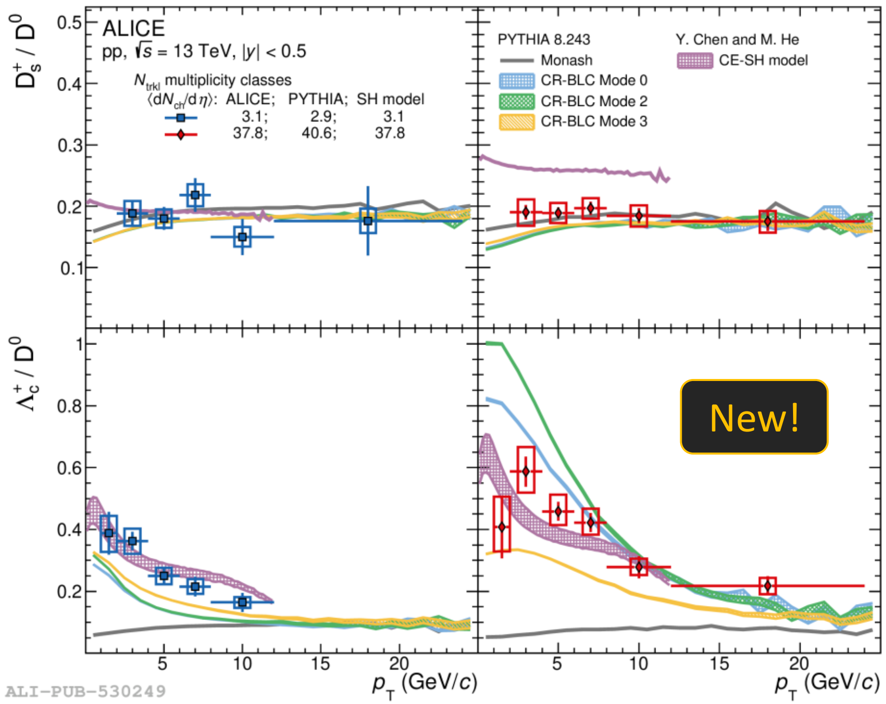


- D_s^+/D^0 : no dependence on either p_T or multiplicity
- Λ_c^+/D^0 : enhancement in the high multiplicity vs. low (significance of 5.3σ in $1 < p_T < 12$ GeV/c)

2. Charm @ ALICE

D_s^+/D^0 and Λ_c^+/D^0 vs. event multiplicity in pp @ $\sqrt{s}$ = 13 TeV

PLB829, 137065 (2022)



- PYTHIA8 Monash: Phys. J. C 74(8) (2014) 3024
- PYTHIA8 CR-BLC: JHEP08 (2015) 003
- CE-SH: PLB815 (2021) 136144

– D_s^+/D^0 : no dependence on either p_T or multiplicity

– Λ_c^+/D^0 : enhancement in the high multiplicity vs. low (significance of 5.3σ in $1 < p_T < 12$ GeV/c)

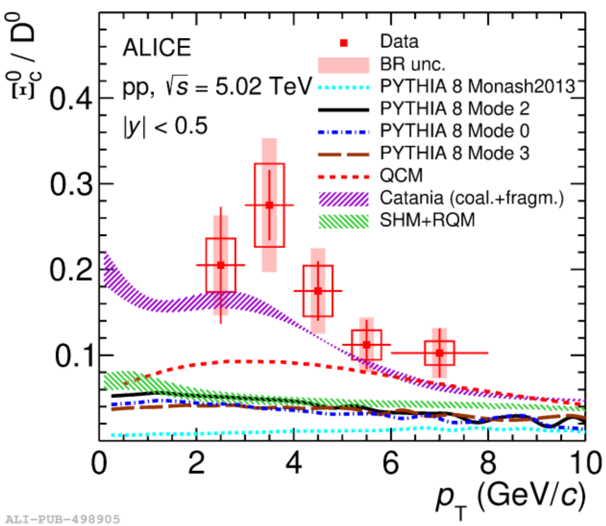
a. PYTHIA 8 CR-BLC: qualitative description; CE-SH: reproduces the whole measurement

b. Comparison to Λ/K_s^0 (backup): similar shape and magnitude – common mechanism between light and charm?

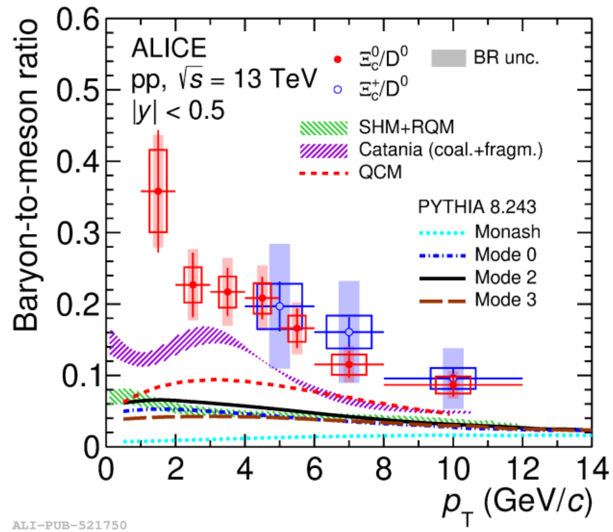
2. Charm @ ALICE

Ξ_c^0/D^0, Ξ_c^+/D^0, and Ω_c^0/D^0 in pp @ $\sqrt{s}$ = 5.02 and 13 TeV

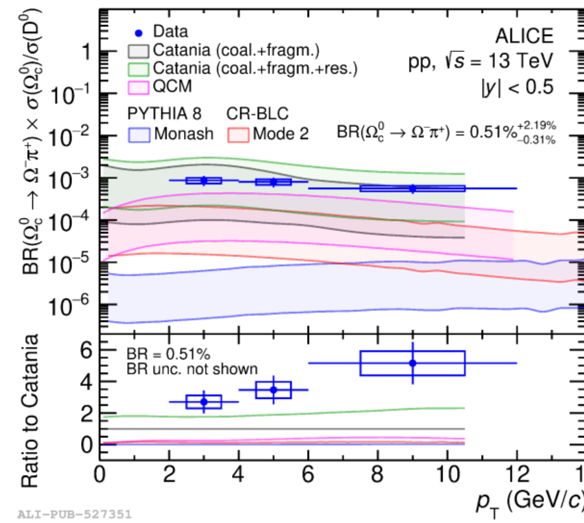
JHEP 10 (2021) 159



PRC127, 272001 (2021)



arXiv:2205.13993



- Catania: PLB821, 136622 (2021)
- PYTHIA8 Monash 2013: EPJC74 (2014) 3024
- PYTHIA8 CR Mode: JHEP 08 (2015) 003
- QCM: EPJC78 (2018) 344
- SHM: PLB795, 117 (2019)

– Compared to the previously shown Λ_c^+/D^0:

a. Even larger baryon enhancement vs. models

b. No significant energy difference in the Ξ_c^0 baryon enhancement

c. Most models fail to describe the Ξ_c^0 data, only Catania in agreement down to p_T ~ 2 GeV/c

d. For Ω_c^0/D^0, Catania with higher mass resonance decays shows best description

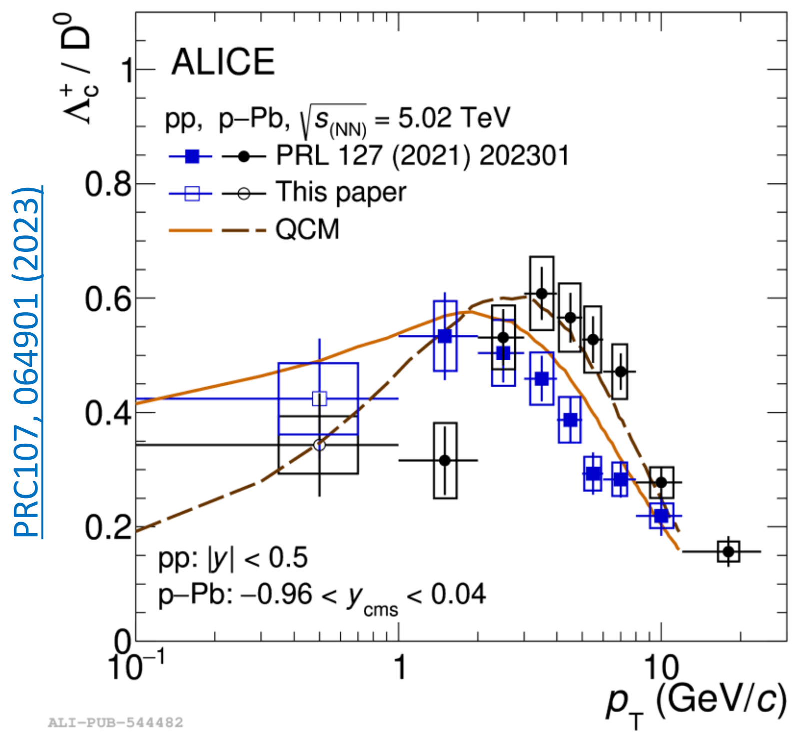
e. Still long way to go to fully describe charm-baryon production in pp

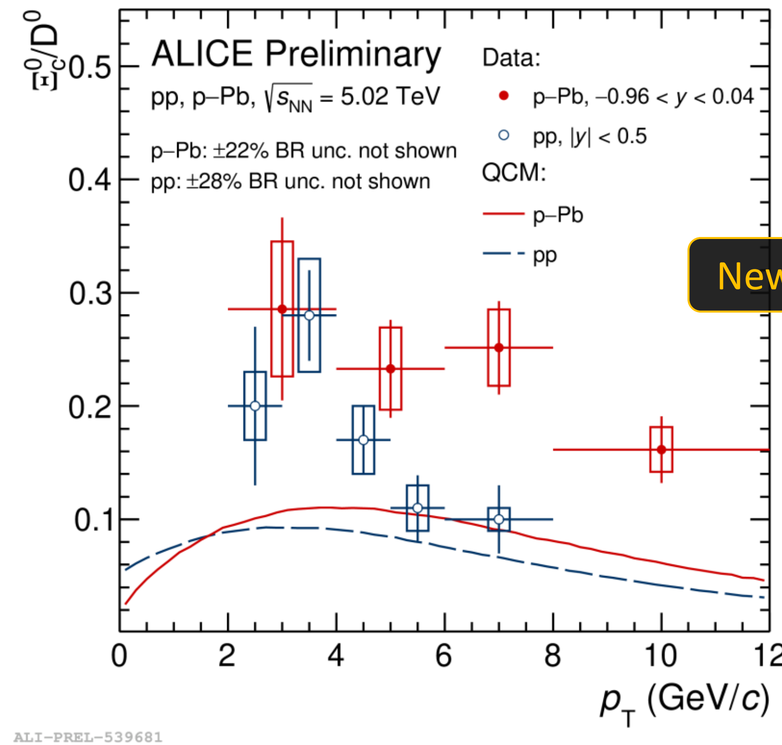
2. Charm @ ALICE

Λ_c^+/D^0 and Ξ_c^0/D^0 in pp and p–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

QCM: PRC97, 064915 (2018)

PRC107, 064901 (2023)





New!

– Λ_c^+/D^0 and Ξ_c^0/D^0 :

a. In both Λ_c^+ and Ξ_c^0 p–Pb ratio is larger than pp for $p_T > 3$ GeV/c (for Λ_c^+ opposite for $p_T < 2$ GeV/c); possible contribution from collective effects, as radial flow

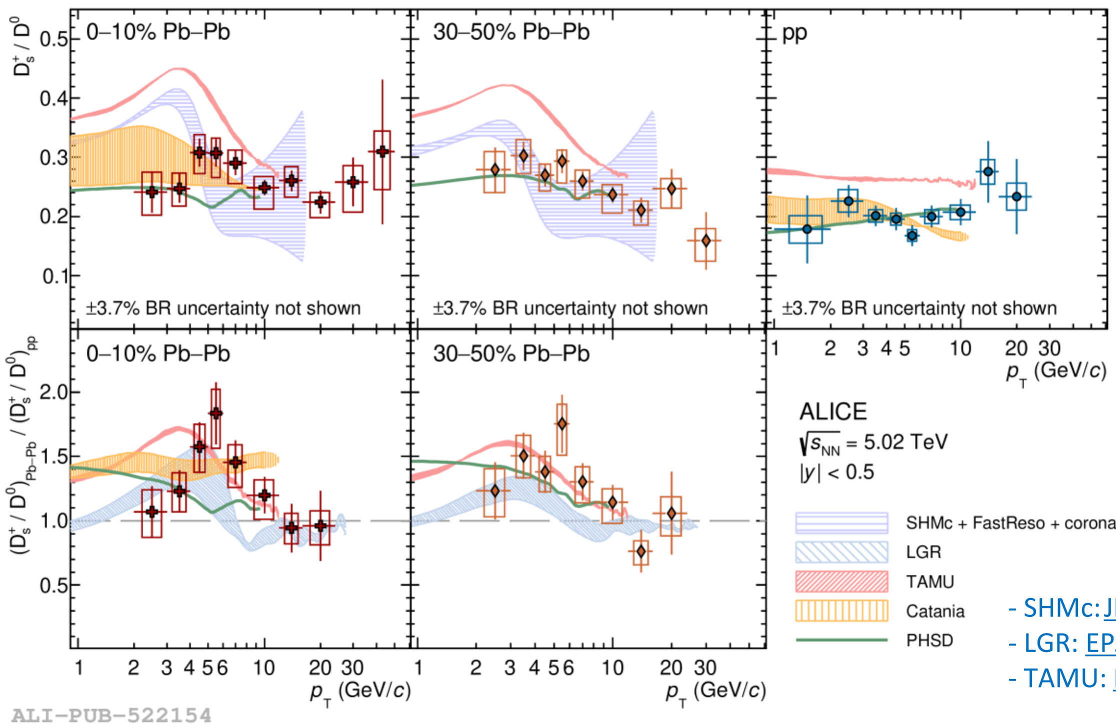
b. QCM well describes both pp and p–Pb for Λ_c^+/D^0, but it tends to underestimate the Ξ_c^0/D^0 ratio

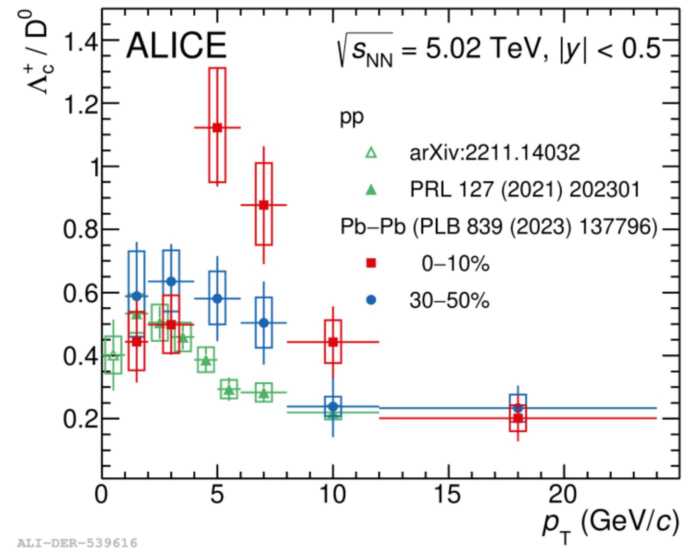
2. Charm @ ALICE

D_s^+/D^0 and Λ_c^+/D^0 in Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

PLB827, 136986 (2022)

arXiv:2112.08156 (PbPb)





- SHMc: JHEP07 (2021) 035
- LGR: EPJC80(7) (2020) 671
- TAMU: PRL124 (2020) 042301
- Catania: PRC96(4) (2017) 044905
- PHSD: PRC93(3) (2016) 034906

– D_s^+/D^0 : higher ratio in Pb–Pb than pp, by 2.3σ (0-10%) and by 2.4σ (30-50%) in the $2 < p_T < 8$ GeV/c

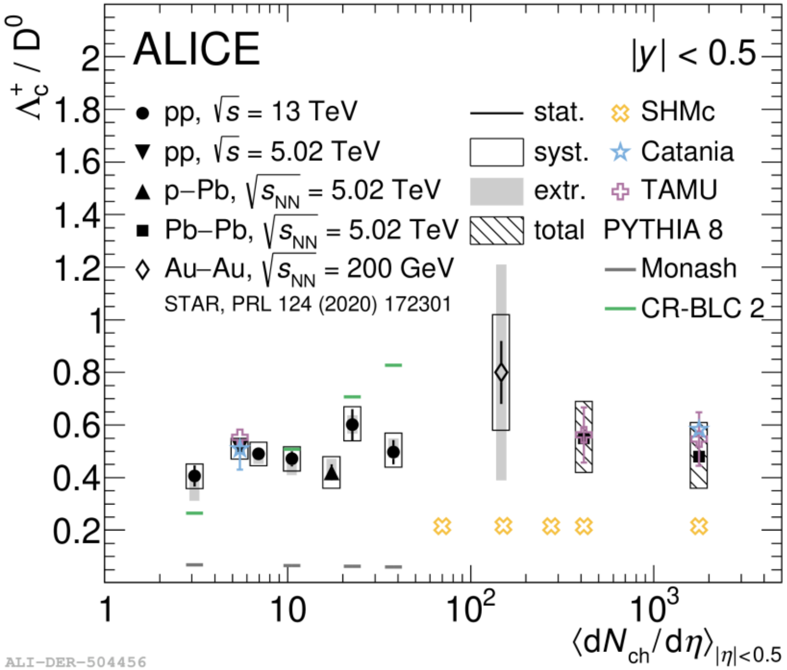
→ The double ratio > 1 can be D formation via coalescence in strange-quark rich environment

– Λ_c^+/D^0 : higher ratio in Pb–Pb than pp, by 3.7σ (0-10%) and by 2.0σ (30-50%) in the $4 < p_T < 8$ GeV/c

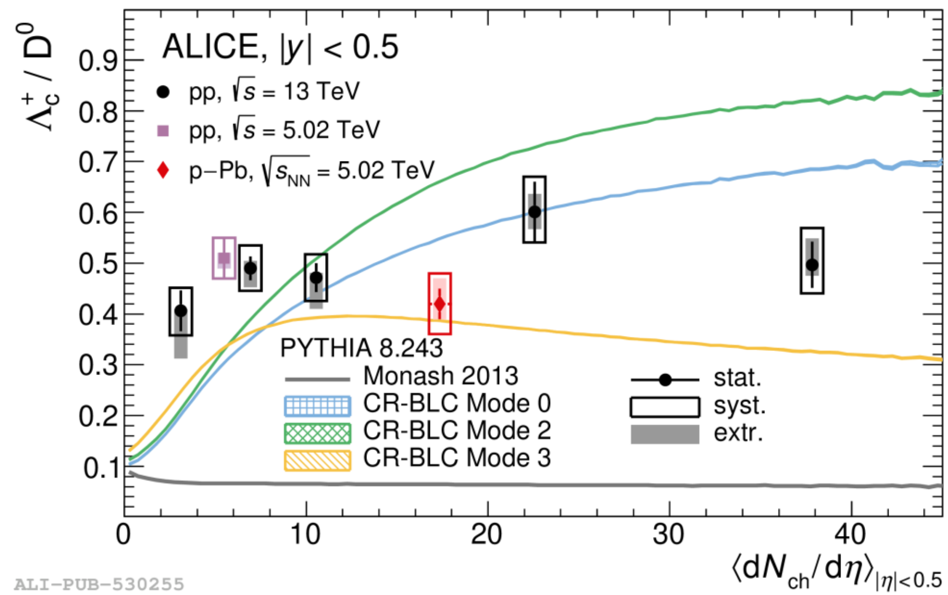
→ Could be due to the presence of relevant contribution of coalescence to Λ_c^+ hadronization

2. Charm @ ALICE

Λ_c^+/D^0 p_T integrated yield from pp to Pb–Pb



PLB829, 137065 (2022)



- SHMc: JHEP07 (2021) 035
- Catania: PRC96(4) (2017) 044905
- TAMU: PRL124 (2020) 042301
- PYTHIA8 Monash 2013: EPJC74 (2014) 3024
- PYTHIA8 CR-BLC: JHEP08 (2015) 003

– p_T - integrated Λ_c^+/D^0 yield vs. charged-particles multiplicity

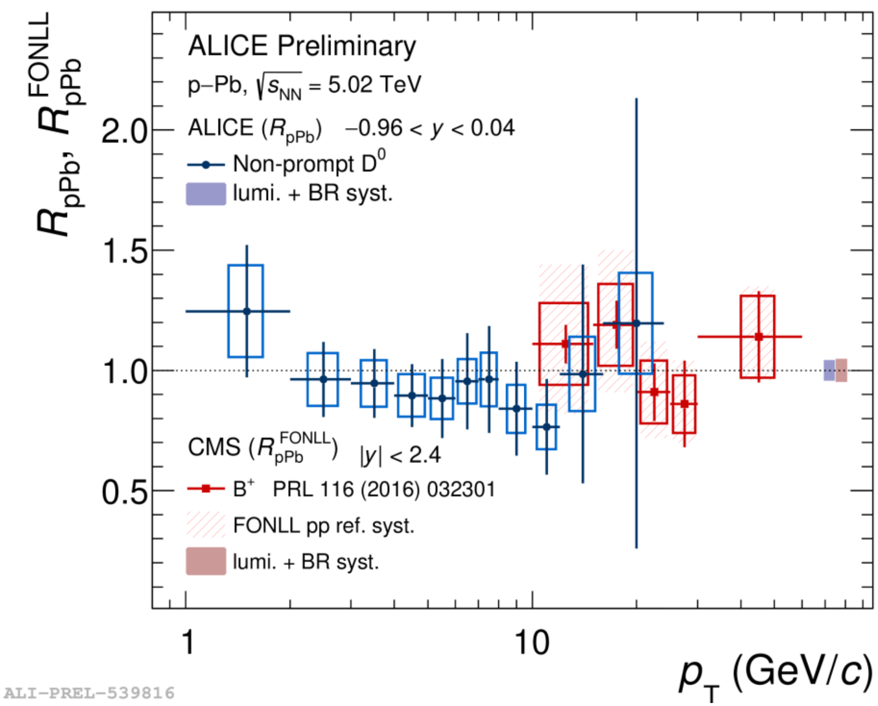
a. No significant difference by multiplicity, energy, and collision system: the multiplicity hierarchy observed in the $1 < p_T < 12$ GeV/c interval in pp is due to momentum redistribution, but no modification of the overall yield?

b. The cannot (can) be reproduced by PYTHIA8 Monash (CR-BLC)

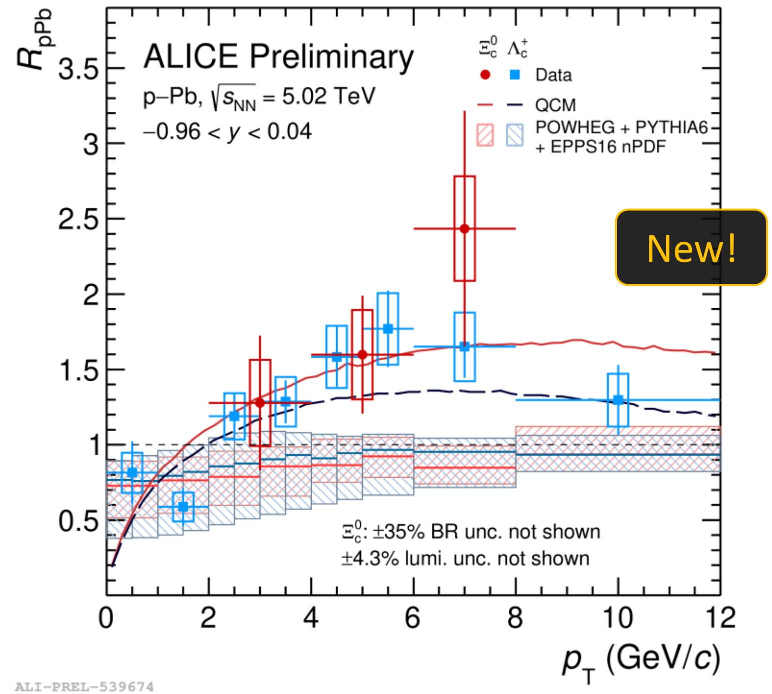
2. Charm @ ALICE

R_{pPb}, Non-prompt D^0, Λ_c^+, and Ξ_c^0 @ $\sqrt{s_{NN}}$ = 5.02 TeV

FONLL: JHEP 05 (1998) 007



QCM: EPJC78 (2018) 344 / POWHEG: arXiv:0709.2092



- R_{pPb} of non-prompt D^0: in agreement with CMS B^+ measurement for the common p_T range;

  p_T integrated non-prompt D^0 R_{pA} also agrees with LHCb B^+ and non-prompt J/ψ (backup)

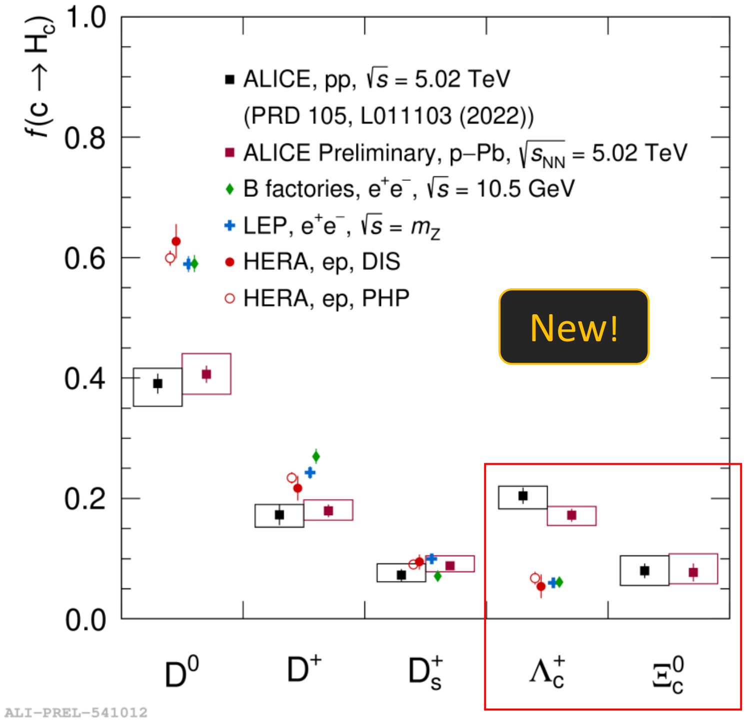
- R_{pPb} of Λ_c^+ and Ξ_c^0:

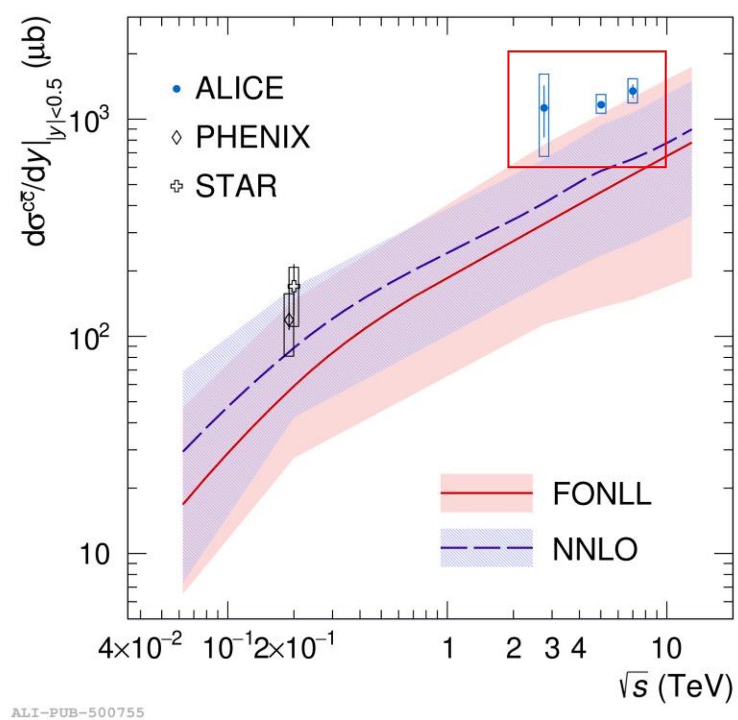
  a. Agree with each other within the uncertainties

  b. Well described by QCM

2. Charm @ ALICE

Fragmentation fractions in pp and p–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV





PRD105, L011103 (2022)

- FONLL: JHEP05 (1998) 007
- NNLO: PRL118, 122001 (2017)

– Fragmentation fraction:

a. Significant baryon enhancement in pp and p–Pb, compared to e⁺e⁻ and e⁻p

b. No significant system dependence between pp and p–Pb

– Charm production cross section:

a. Measured at midrapidity ($|y| < 0.5$) as a sum of ground state hadron production cross sections

b. No significant system dependence between pp and p–Pb; lies on the upper edge of pQCD uncertainty

Summary

- **Charm production with ALICE**
  - Meson-to-meson ratio: no significant p_T dependence regardless of system or energy
  - Baryon-to-meson ratio
    a. Significant enhancement vs. e^+e^- : models based on e^+e^- cannot describes the result, suggests modified hadronization mechanism
    b. Multiplicity dependence observed in pp
  - R_{pA}: no (clear) p_T dependence for meson (baryon)
  - Fragmentation fraction: significant baryon enhancement vs e^+e^-, questions universal fragmentation functions across collision systems
- **Ongoing: ALICE Run 3**
  - Better data in both quantity and quality:
    about × 50-100 larger data samples than Run2, upgraded TPC/ITS, and improved primary vertex resolution
  - Upgraded reconstruction capability:
    direct reconstruction of beauty hadrons, reconstruction of complex decay channels,
    Run 2 measurements with improved precision…