Investigation of charm-quark hadronization into baryons in hadronic collisions with ALICE

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on behalf of the ALICE Collaboration

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ALICE

Heavy-flavour hadronization

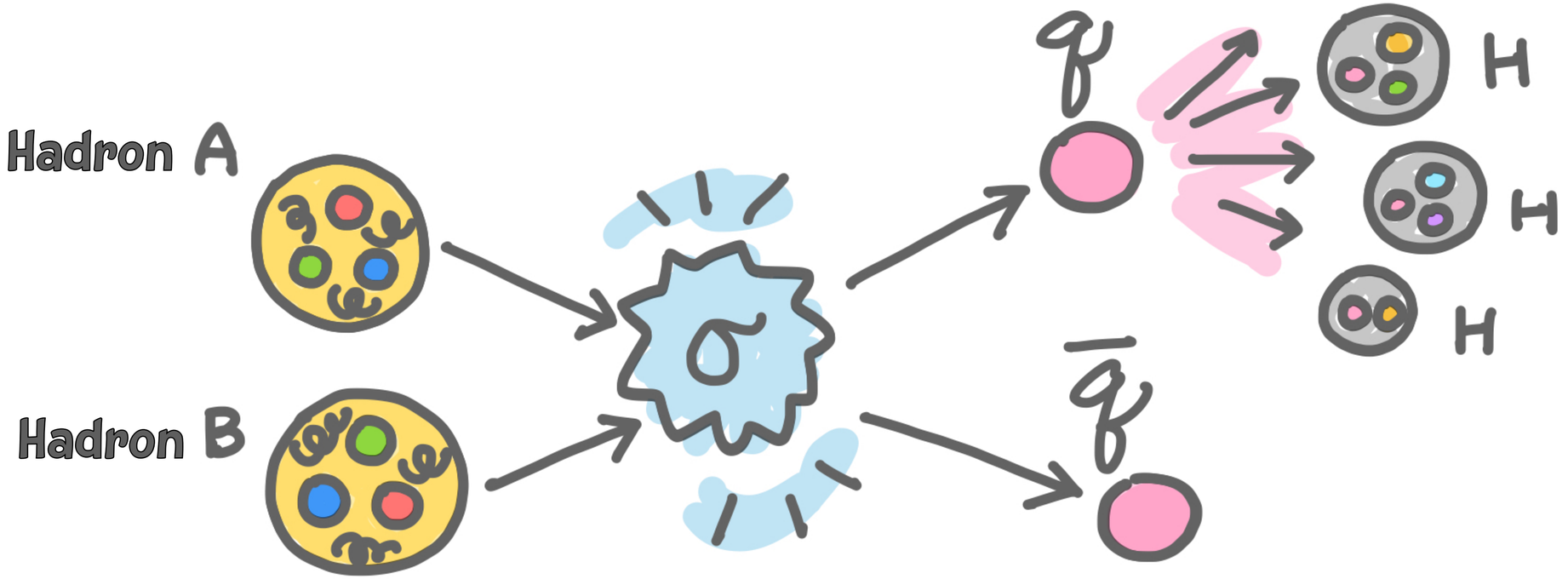
$$\mathrm{d}\sigma_{\mathrm{AB}\to\mathrm{h}} = f_{\mathrm{i/A}}(x_{\mathrm{i}}, \mathrm{Q}^2) \otimes f_{\mathrm{j/B}}(x_{\mathrm{j}}, \mathrm{Q}^2) \otimes \mathrm{d}\sigma_{\mathrm{ij}\to\mathrm{q\bar{q}}}(x_{\mathrm{i}}x_{\mathrm{j}}, \mathrm{Q}^2) \otimes D_{\mathrm{q}\to\mathrm{h}}(z, \mathrm{Q}^2)$$

Production cross section of HF hadrons

Parton distribution functions

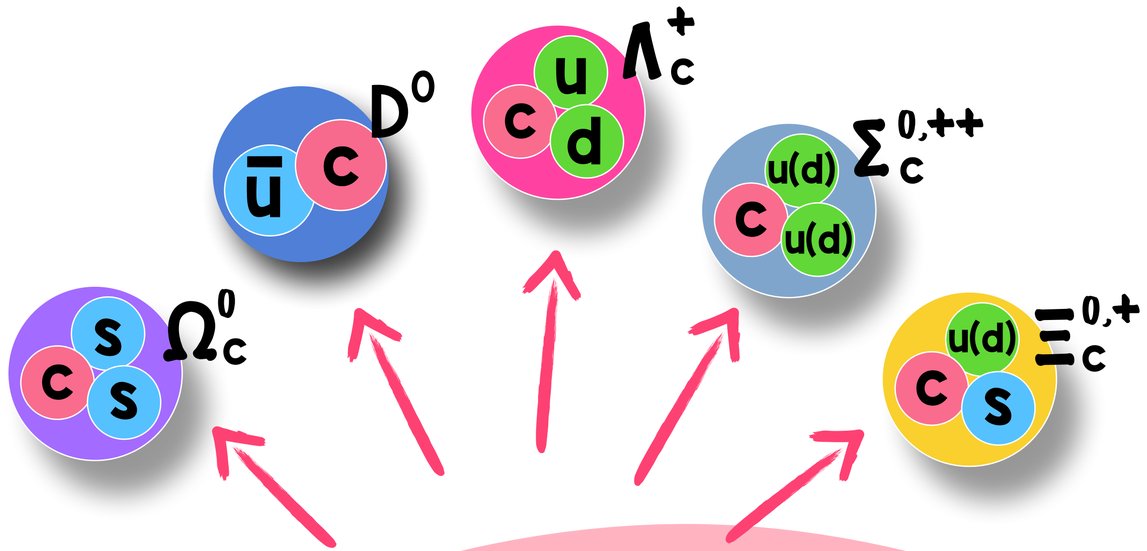
Hard-scattering cross section

Fragmentation function (Hadronization)



Heavy-flavour hadronization

Experimental observable



Production cross section ratio of hadron species is good probe of hadronization!

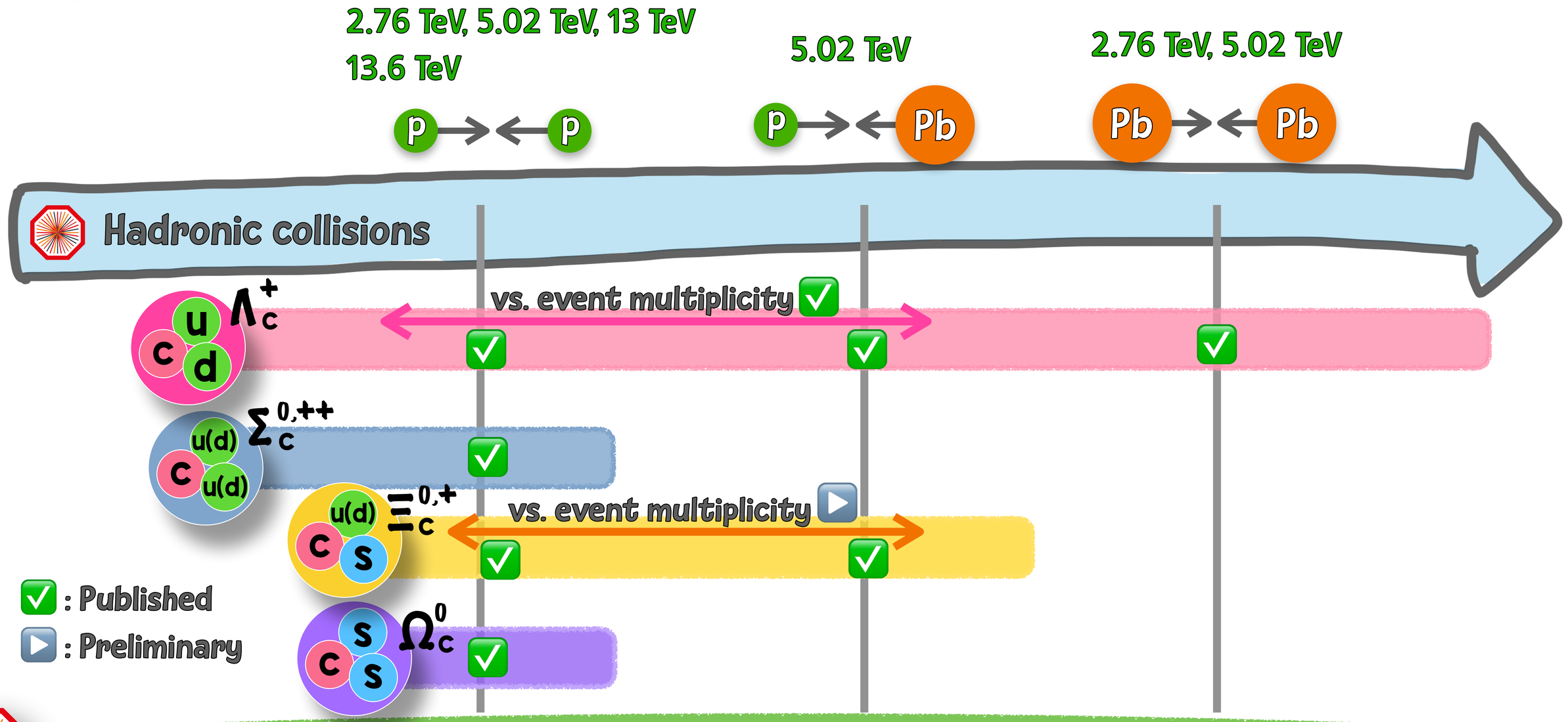
$$\rightarrow q\bar{q}(x_i x_j, Q^2) \otimes D_{q\rightarrow h}(z, Q^2)$$

scattering section

Fragmentation function (Hadronization)

FF is determined by measurement from leptonic collisions.
Is the hadronization universal among the collision systems?

ALICE charm baryon measurements



The ALICE experiment

ITS Inner Tracking System

$|\eta| < 0.9$
Vertexing & tracking

TPC Time Projection Chamber

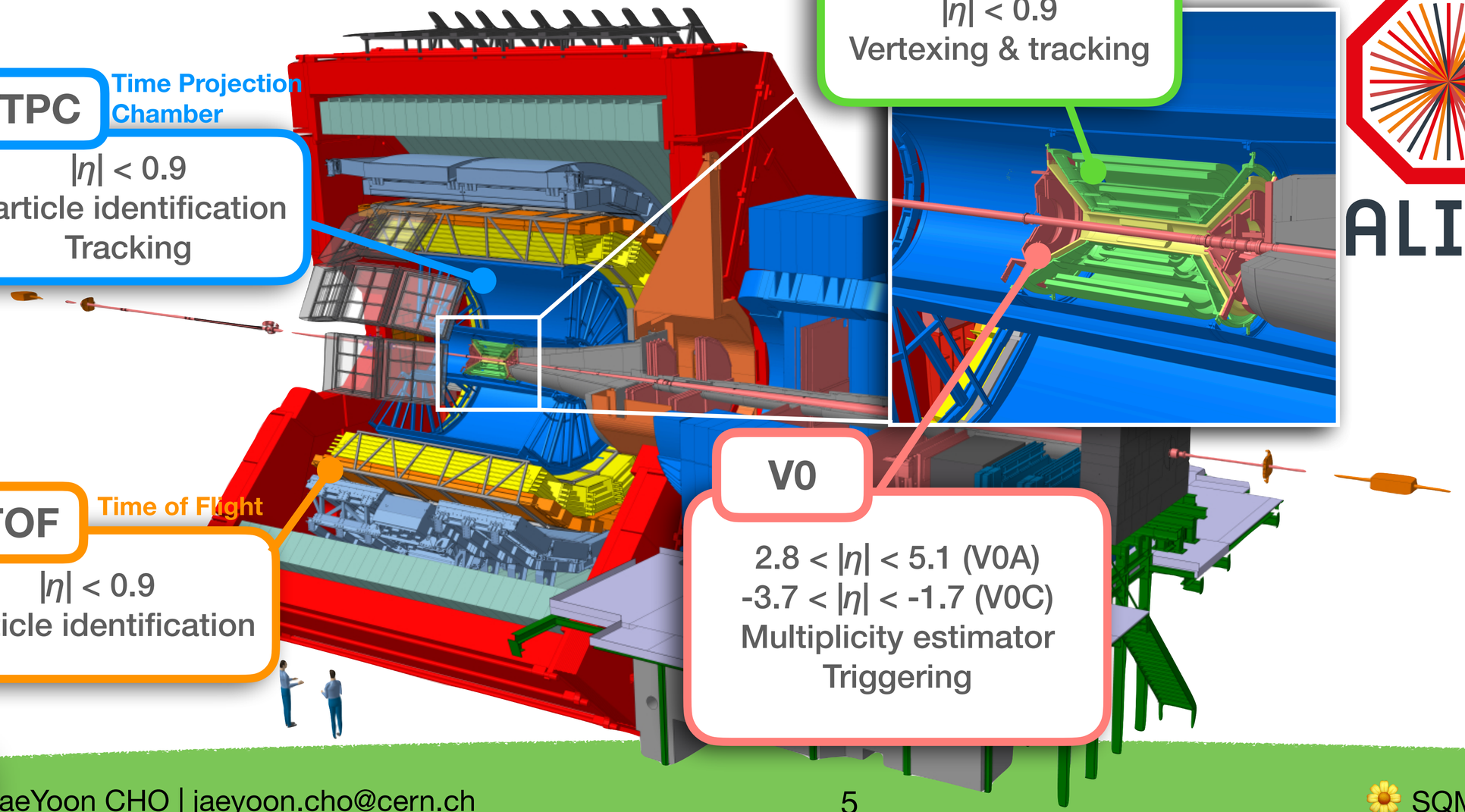
$|\eta| < 0.9$
Particle identification
Tracking

TOF Time of Flight

$|\eta| < 0.9$
Particle identification

V0

$2.8 < |\eta| < 5.1$ (V0A)
$-3.7 < |\eta| < -1.7$ (V0C)
Multiplicity estimator
Triggering



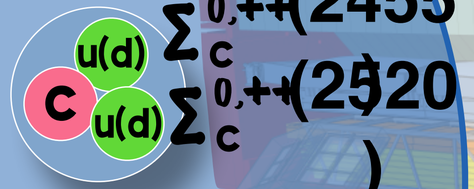
ALICE (Run 2) Detector

Charm baryon reconstruction

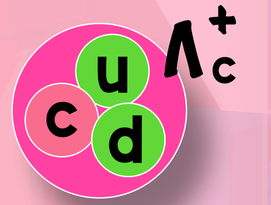
Charge conj. included for all measured hadrons

Hadronic decays

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



$\Sigma_c^{0,++}(2455)$
$\Sigma_c^{0,++}(2520)$



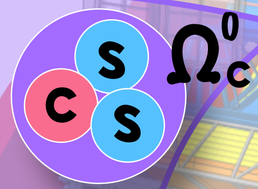
Λ_c^+

Hadronic decays

- $\Lambda_c^+ \to pK^-\pi^+$
- $\Lambda_c^+ \to pK_s^0$

Semileptonic decays

- $\Lambda_c^+ \to \Lambda e^+ \nu_e$



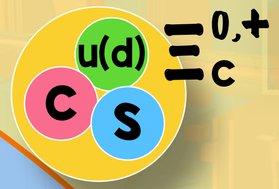
Ω_c^0

Hadronic decays

- $\Omega_c^0 \to \Omega^-\pi^+$

Semileptonic decays

- $\Omega_c^0 \to \Omega^- e^+ \nu_e$



$\Xi_c^{0,+}$

Hadronic decays

- $\Xi_c^+ \to \Xi^-\pi^+\pi^+$
- $\Xi_c^0 \to \Xi^-\pi^+$

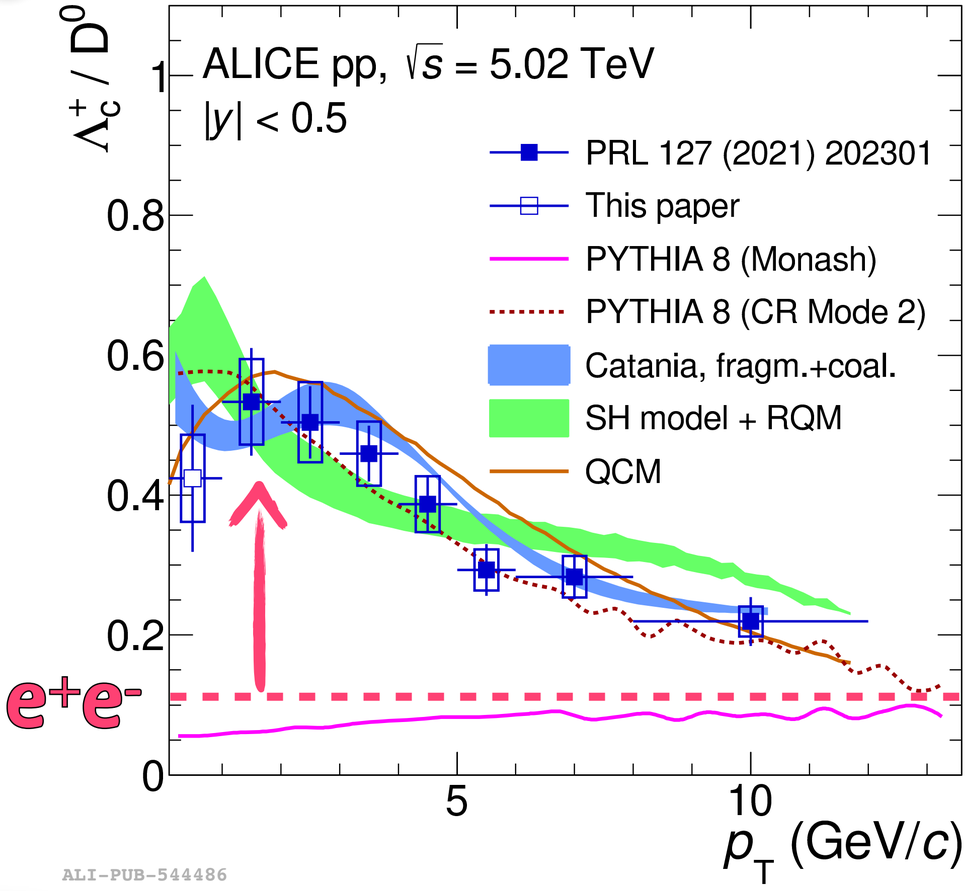
Semileptonic decays

- $\Xi_c^0 \to \Xi^- e^+ \nu_e$

Λ_c^+/D^0 in pp collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901



Measurements from e+e− collisions : Phys.Rev.D 43 (1991) 3599

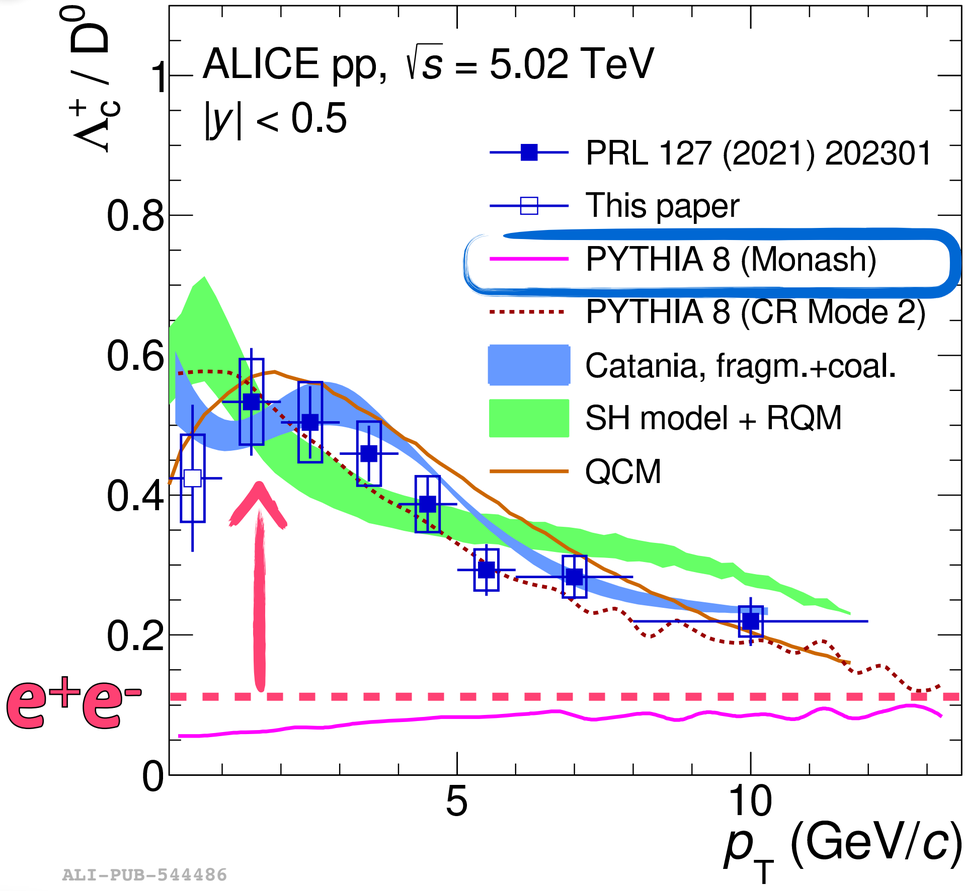
Comparing to e+e- collisions

⭐ Significantly larger baryon-to-meson ratio at low and intermediate p_T and strong p_T dependence in pp collisions

Λ_c^+/D^0 in pp collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901



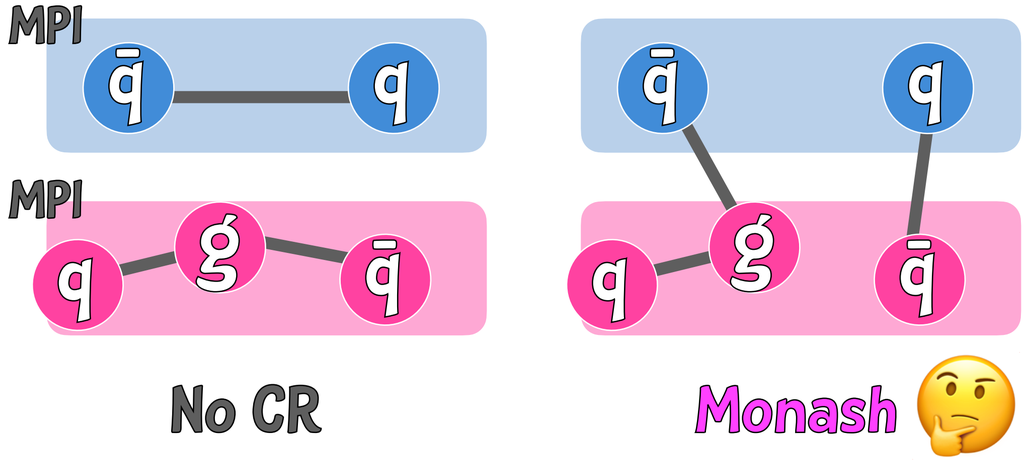
Model comparison

Monash : Eur.Phys.J.C 74 (2014) 3024

PYTHIA 8

Allows colour reconnection (CR) between partons from different multiparton interactions (MPIs) to minimize the string length.

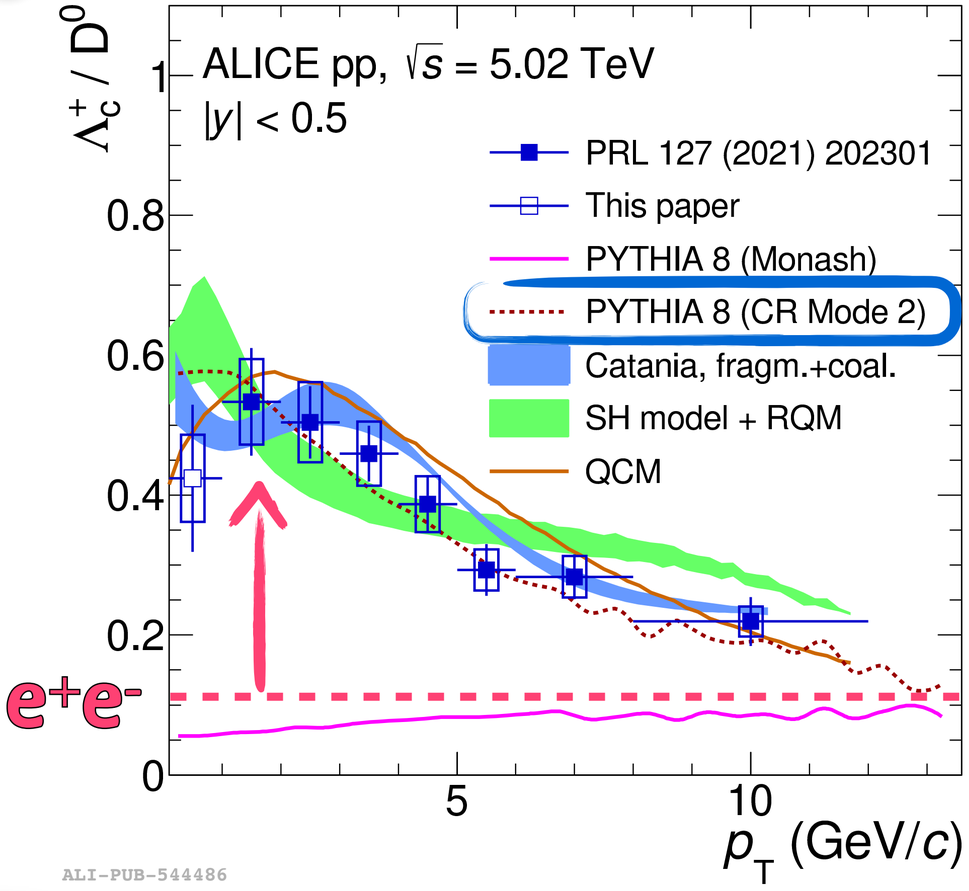
Tuned to e^+e^- and ep measurements



Λ_c^+/D^0 in pp collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901

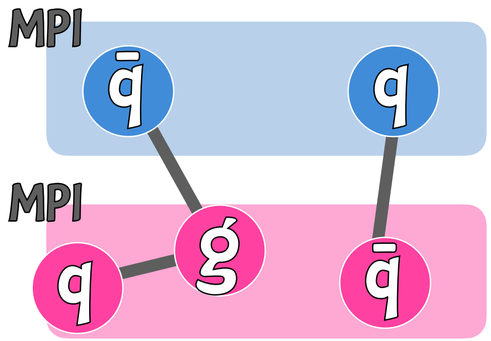


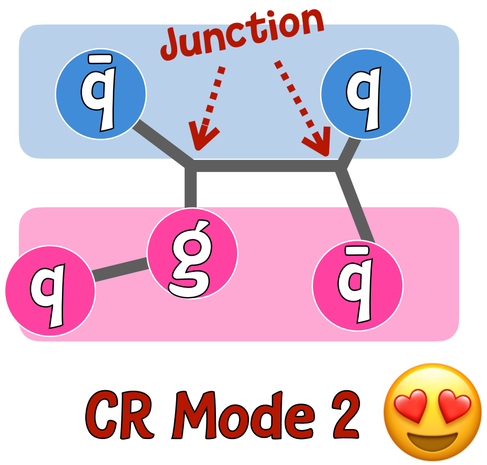
Model comparison

PYTHIA 8

CR Mode 2 : JHEP 08 (2015) 003

Allows CR for configurations beyond leading-colour approximation introducing *junctions*, to minimize string length, which **increase baryon production**





Λ_c^+/D^0 in pp collisions

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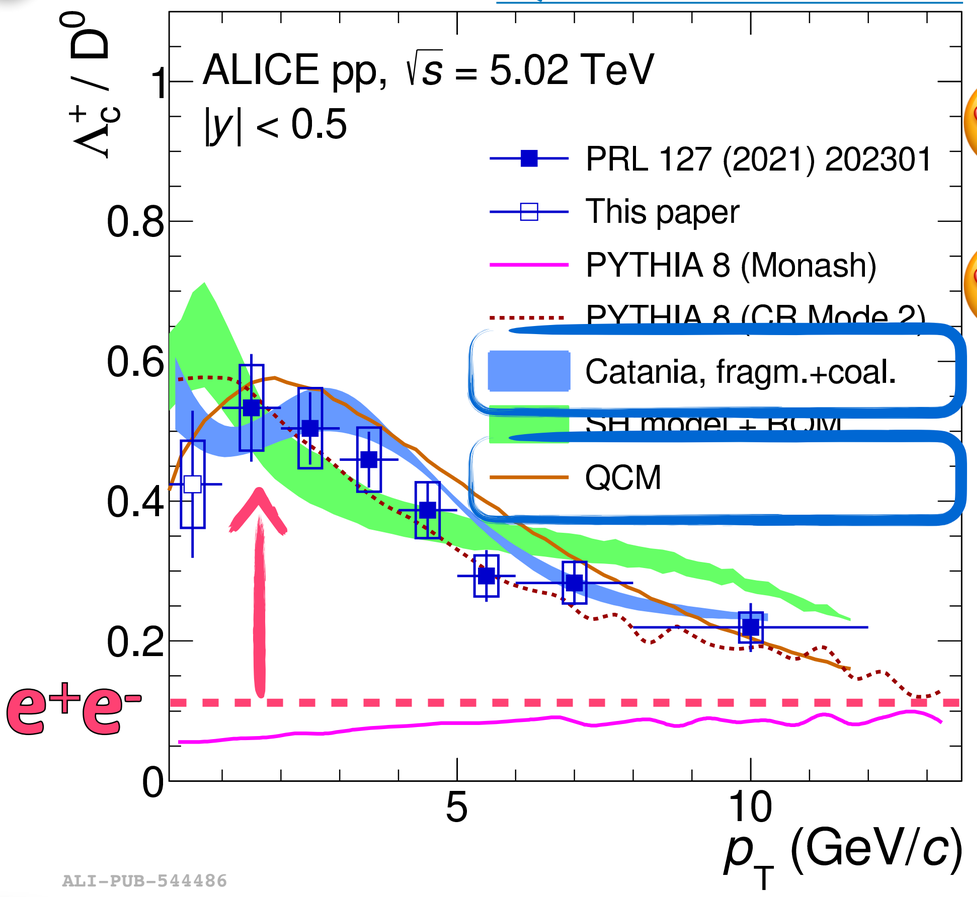


Model comparison

Catania : Phys.Lett.B 821 (2021) 136622

Catania

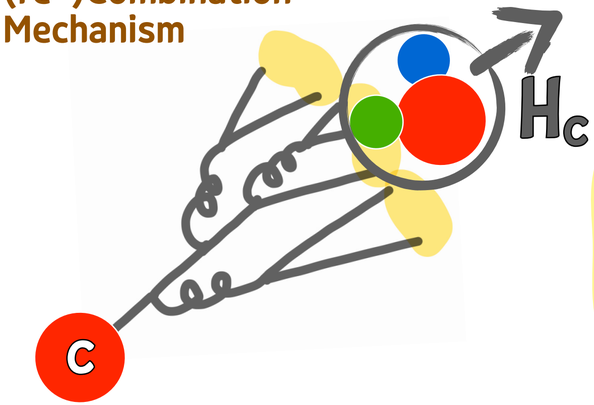
Hadronization via both fragmentation and coalescence

QCM : Eur.Phys.J.C 78 (2018) 344

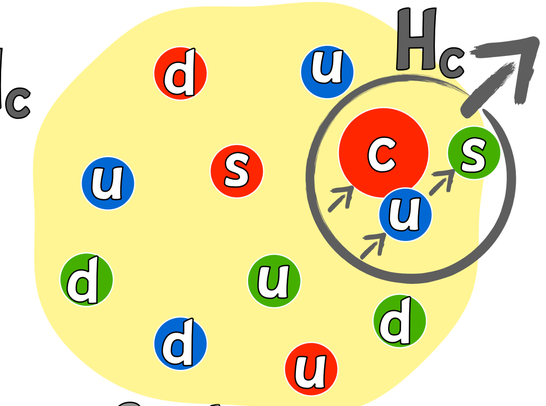
QCM

Quark (re-)Combination Mechanism

Charm quark combines with light quarks close in space and momentum



Fragmentation

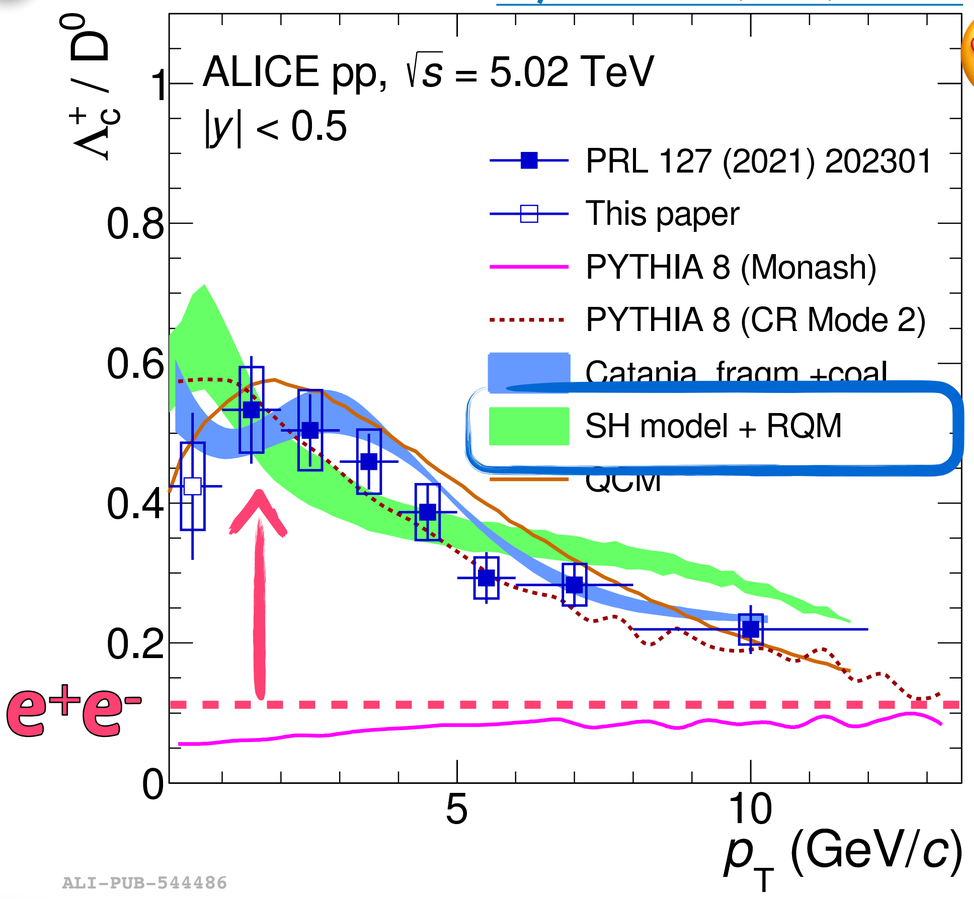


Coalescence

Λ_c^+/D^0 in pp collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901



Model comparison

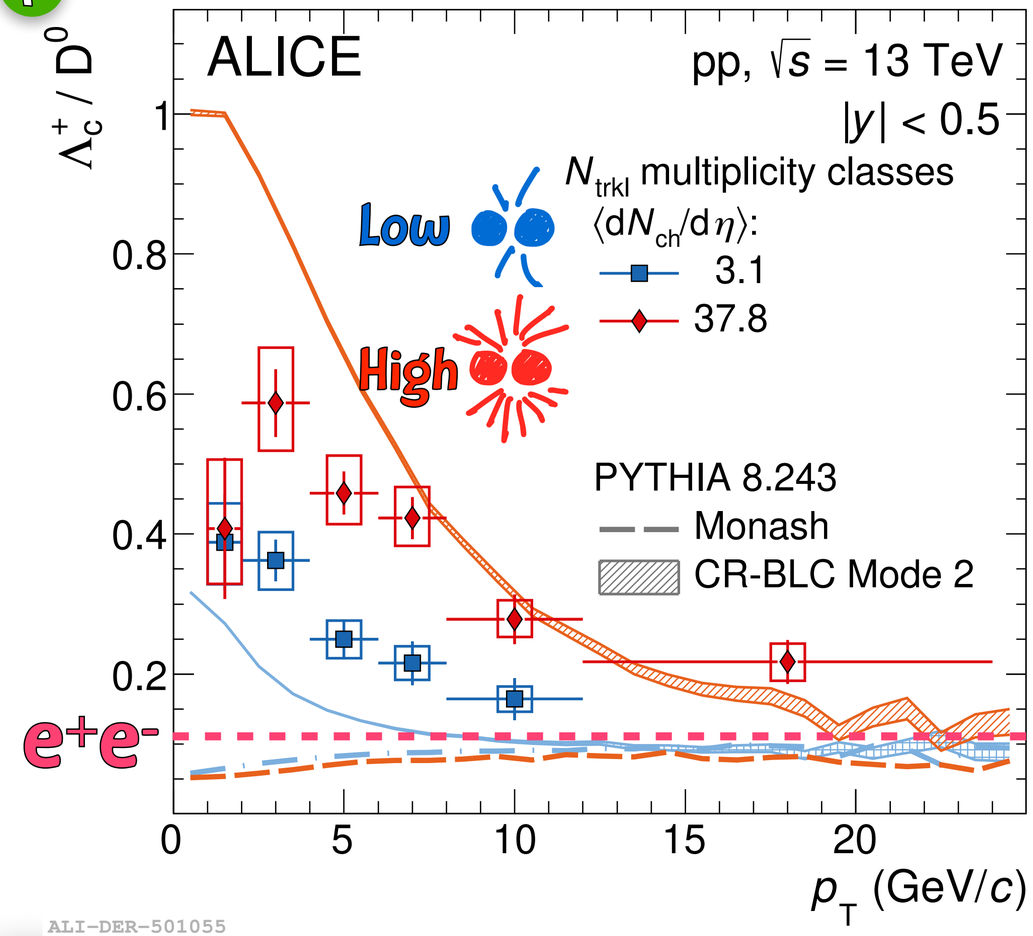
Statistical model + RQM

SHM : Phys.Lett.B 795 (2019) 117-121
RQM : Phys.Rev.D 84 (2011) 014025

- ⭐ Hadronization driven by the species statistical weight
  - Weights are governed by the masses of hadron states at hadronization temperature
- ⭐ Feed-down from (not yet measured) charm baryon states
  - Takes a large enhanced set of charm baryon state beyond the current list of PDG into account
  - PDG : 5 Λ_c , 3 Σ_c , 8 Ξ_c, 2 Ω_c states
  - RQM : Additional 18 Λ_c , 42 Σ_c , 62 Ξ_c, 34 Ω_c states

Λ_c^+/D^0 vs. event multiplicity in pp collisions

Phys.Lett.B 829 (2022) 137065

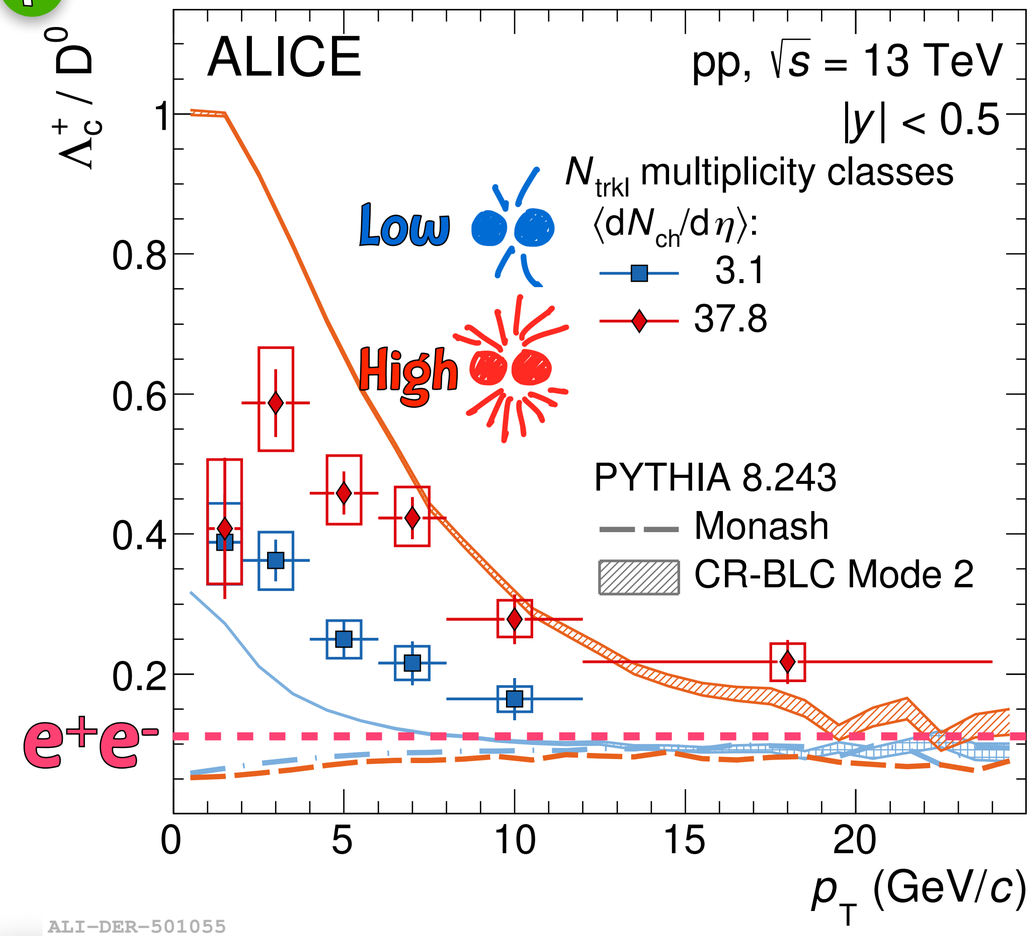


Multiplicity dependence in baryon-to-meson ratio

- **Significant multiplicity dependence**(5.3σ) for $p_T < 12$ GeV/c region going from lowest to highest multiplicity class
- Even in lowest multiplicity class, Λ_c^+/D^0 is much higher than e^+e^- collisions

Λ_c^+/D^0 vs. event multiplicity in pp collisions

Phys.Lett.B 829 (2022) 137065



Multiplicity dependence in baryon-to-meson ratio

- ⭐ **Significant multiplicity dependence**(5.3σ) for $p_T < 12$ GeV/c region going from lowest to highest multiplicity class
- ⭐ Even in lowest multiplicity class, Λ_c^+/D^0 is much higher than e^+e^- collisions

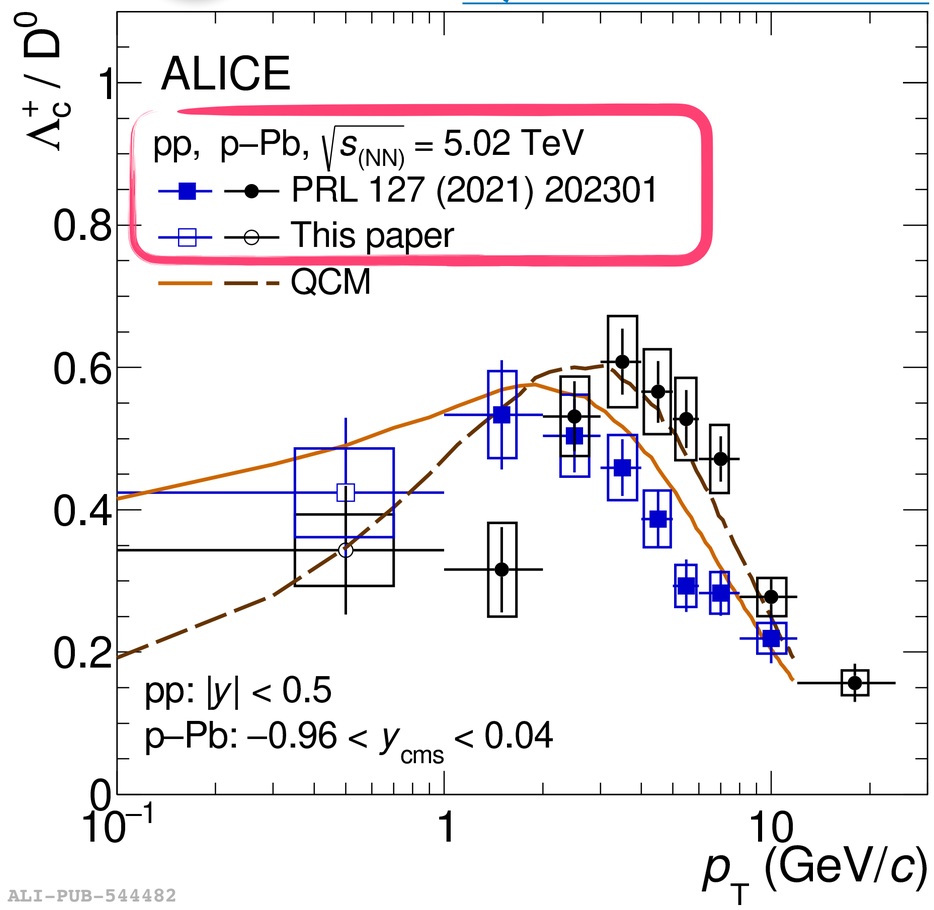
Model comparison

- ⭐ PYTHIA 8 Monash doesn't reproduce neither magnitude nor multiplicity dependence
- ⭐ PYTHIA 8 Mode 2 provides better description than Monash

Λ_c^+/D^0 in p-Pb collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901



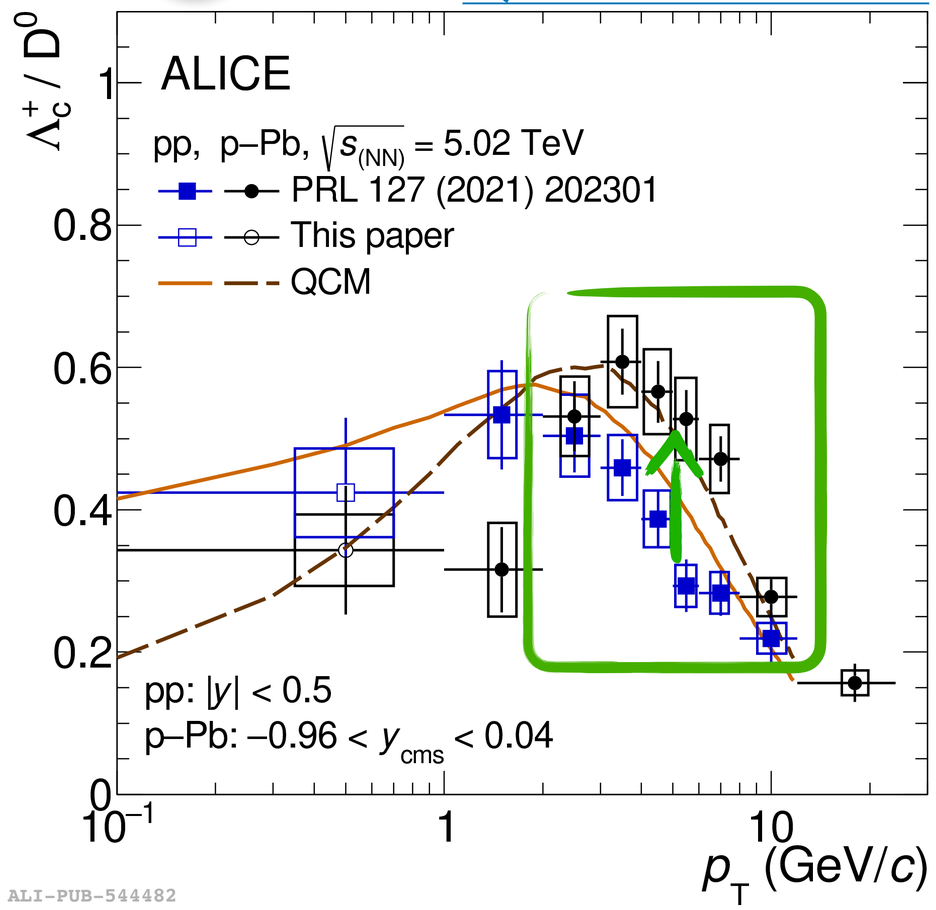
Collision system dependence

- The overall magnitude of enhancement in Λ_c^+/D^0 ratios with respect to e^+e^- collisions is similar between pp and p—Pb collisions within uncertainties

Λ_c^+/D^0 in p-Pb collisions

down to $p_T = 0$

Phys.Rev.C 107 (2023) 064901



Collision system dependence

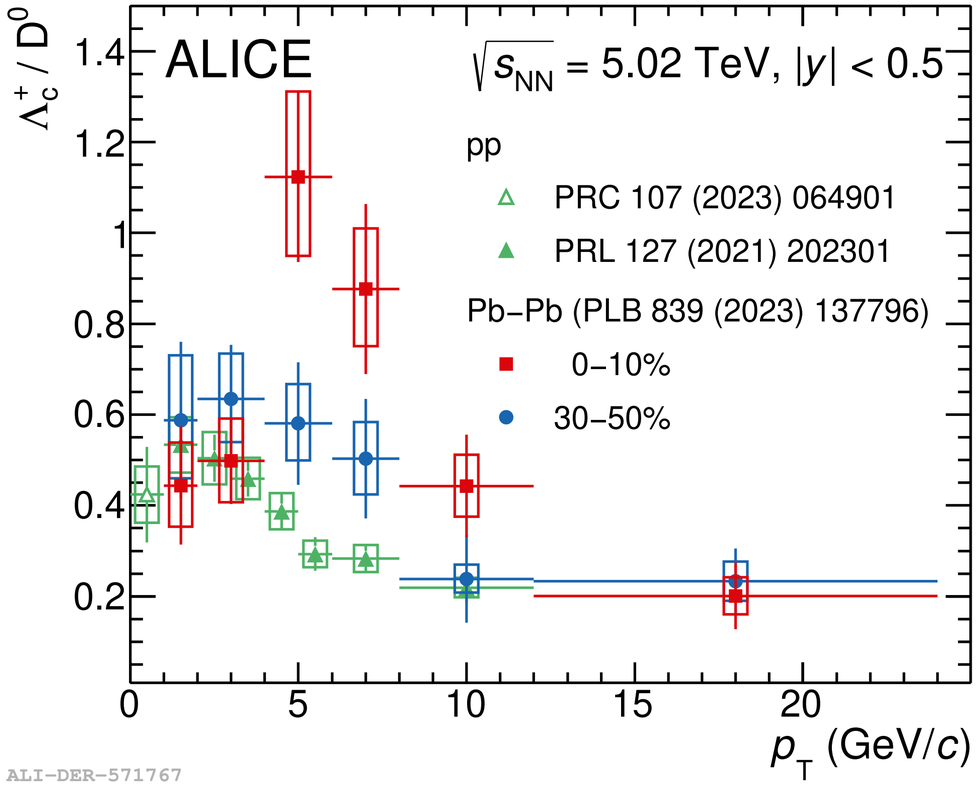
- The overall magnitude of enhancement in Λ_c^+/D^0 ratios with respect to e^+e^- collisions is similar between pp and p—Pb collisions within uncertainties

Modification of p_T spectra?

- The Λ_c^+/D^0 in p—Pb collisions is higher Λ_c^+/D^0 than that in pp collisions for $p_T > 3$ GeV/c
- Contribution from radial flow or different hadronization process?

Λ_c^+/D^0 in Pb-Pb collisions

Phys.Lett.B 839 (2023) 137796

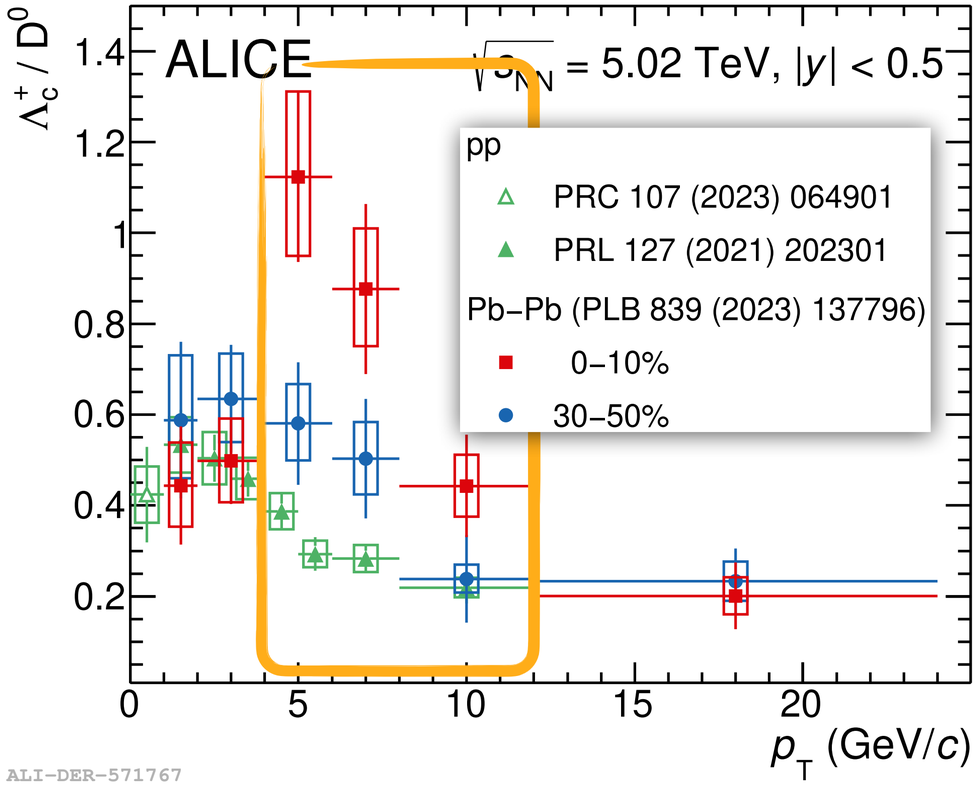


Collision system dependence

⭐ Indication for enhancement of Λ_c^+/D^0 at intermediate p_T in Pb—Pb collisions with respect to pp collisions

Λ_c^+/D^0 in Pb-Pb collisions

Phys.Lett.B 839 (2023) 137796



Collision system dependence

- Indication for enhancement of Λ_c^+/D^0 at intermediate p_T in Pb—Pb collisions with respect to pp collisions

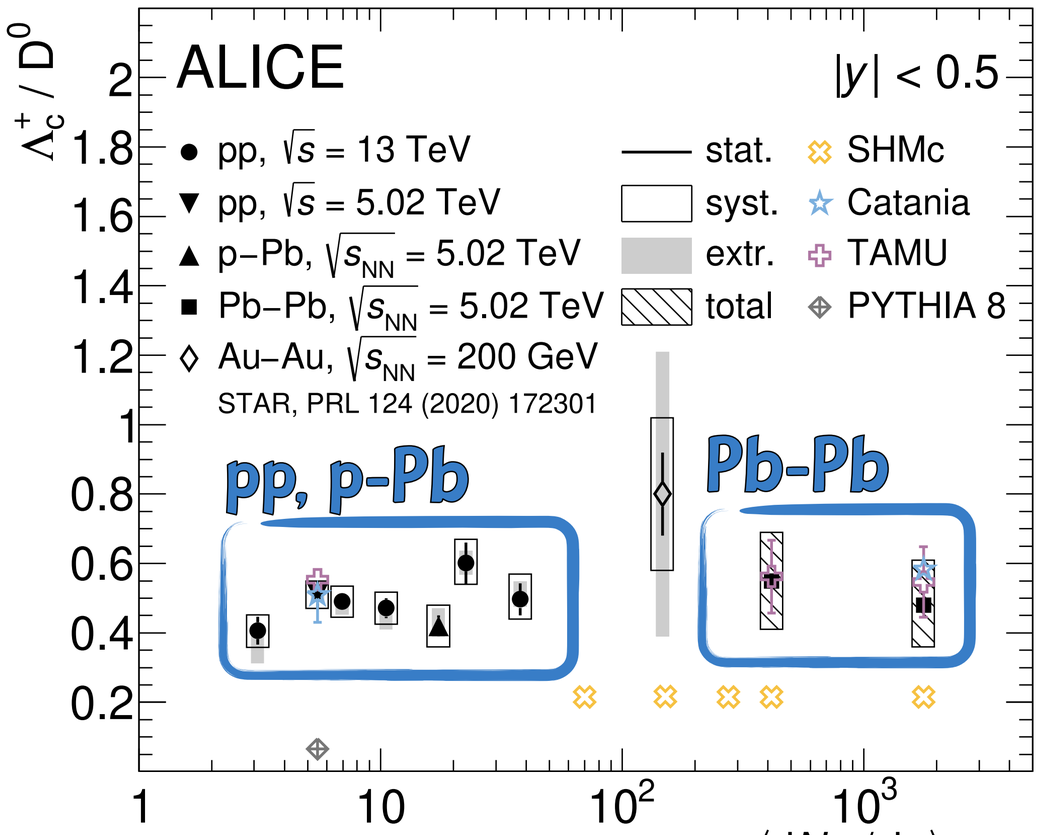
Modification of p_T spectra?

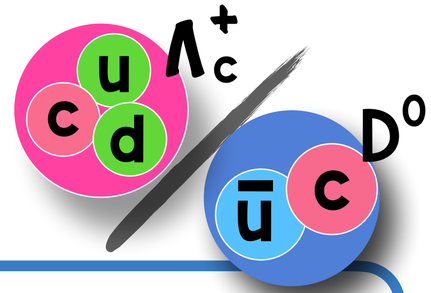
- In intermediate p_T region, the Λ_c^+/D^0 in Pb—Pb is higher than that in pp collisions
  - By 3.7σ for Pb—Pb 0-10% and by 2.0σ for Pb—Pb 30-50%
- Due to recombination? Or radial flow?

Λ_c^+/D^0 in hadronic collisions

p_T integrated

Phys.Lett.B 839 (2023) 137796

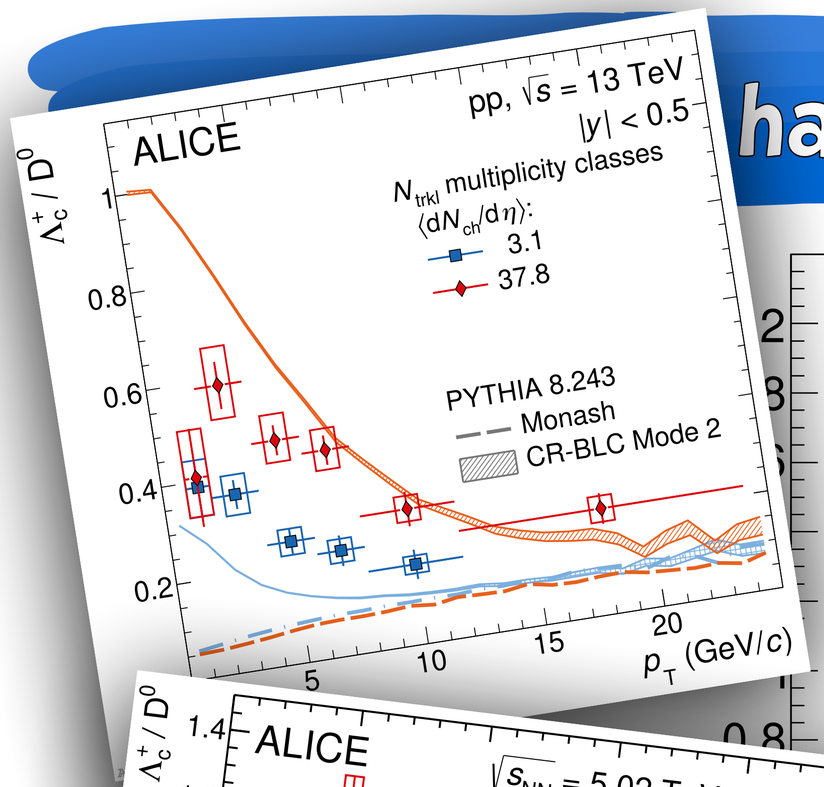


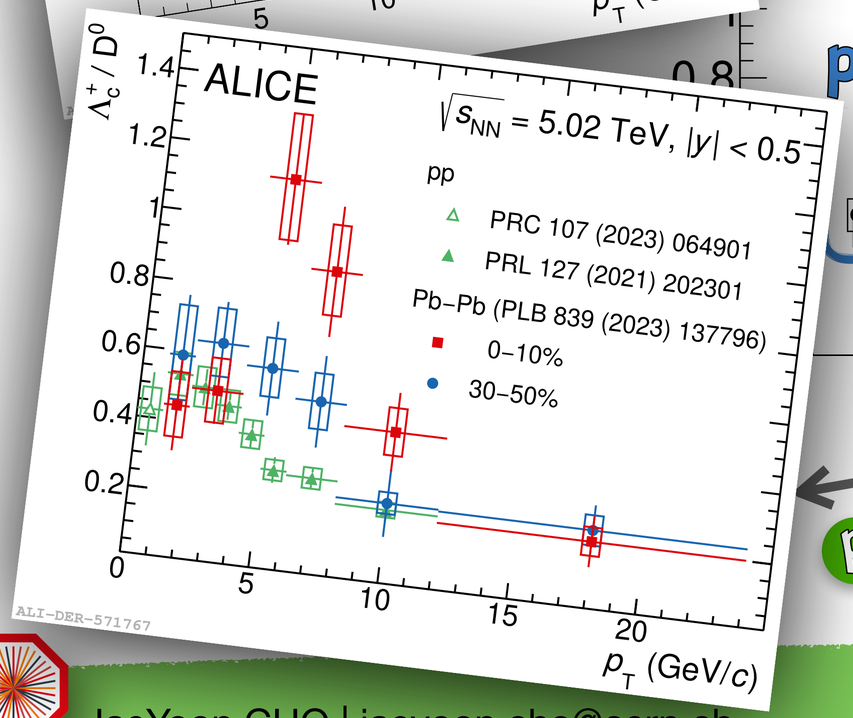


Among hadronic collisions

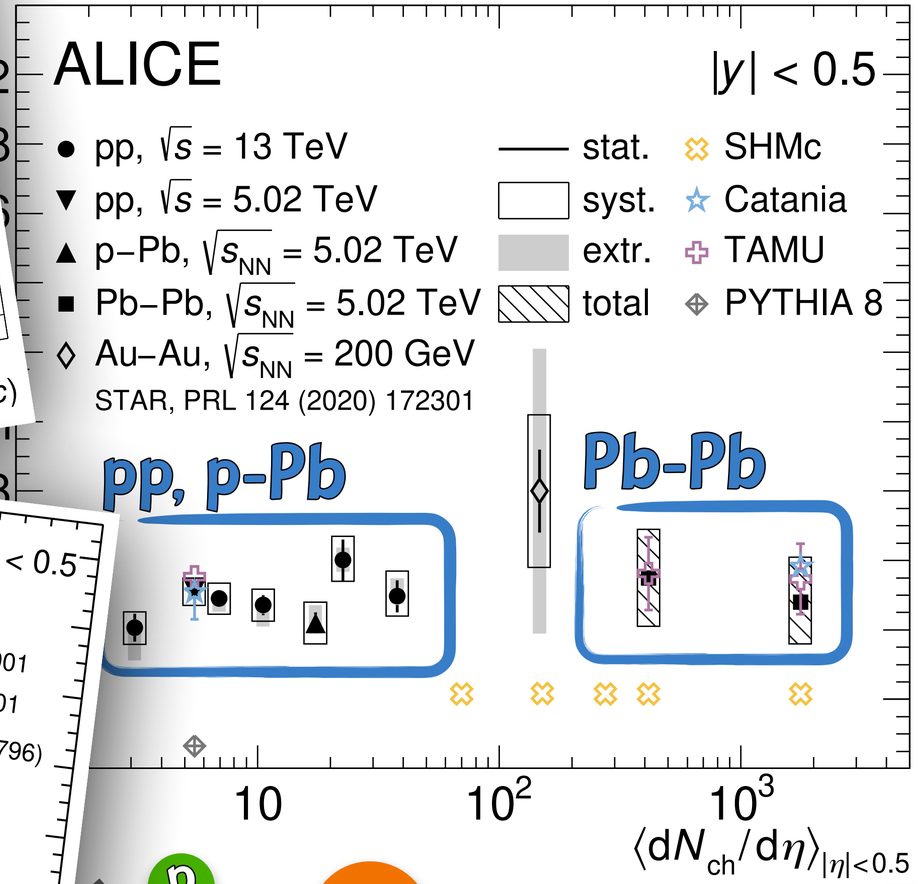
⭐ **NO multiplicity dependence in p_T integrated Λ_c^+/D^0 ratios within the uncertainty**

hadronic collisions





Phys.Lett.B 839 (2023) 137796



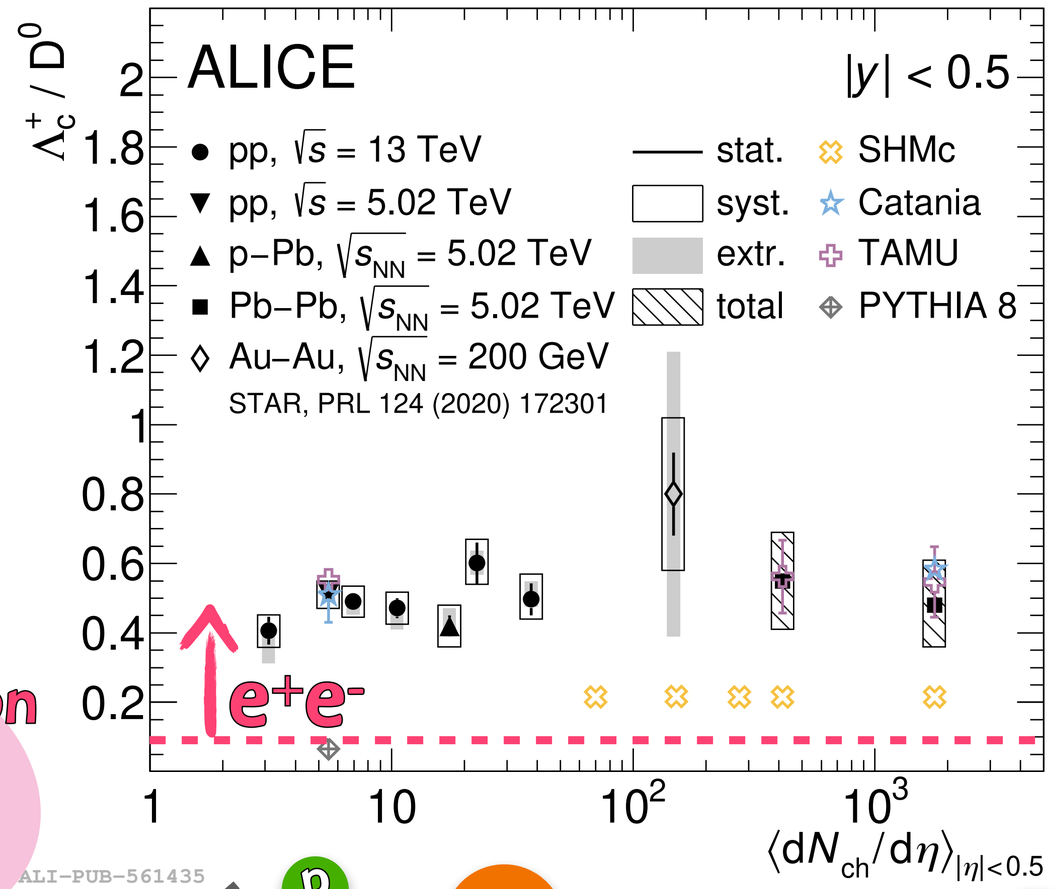
Among hadronic collisions

- ⭐ **NO multiplicity dependence in p_T integrated Λ_c^+/D^0 ratios** within the uncertainty
- ⭐ Observed multiplicity dependence in p_T differential Λ_c^+/D^0 ratios
  - Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?

Λ_c^+/D^0 in hadronic collisions

p_T integrated

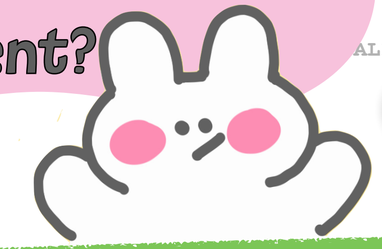
Phys.Lett.B 839 (2023) 137796



Comparing to e^+e^- collisions

- Significant difference between leptonic collisions and hadronic collisions

Different hadronization process in parton rich environment?

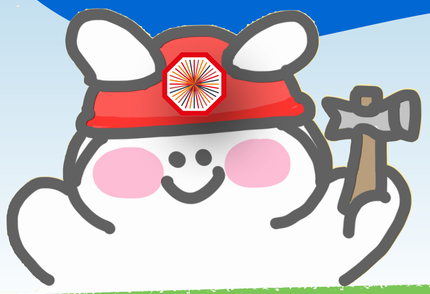


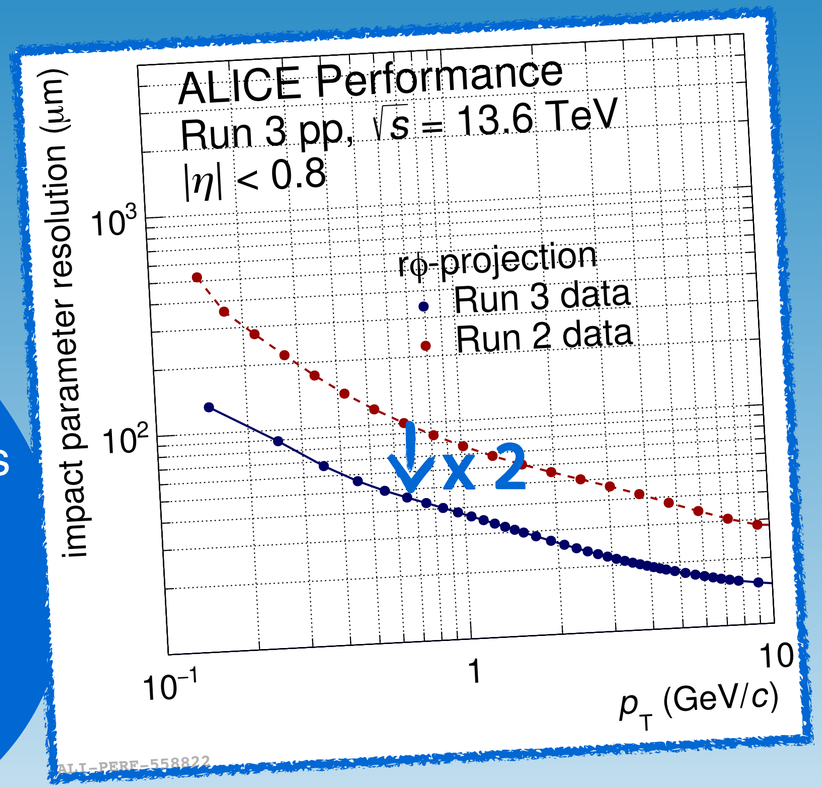
Among hadronic collisions

- **NO multiplicity dependence in p_T integrated** Λ_c^+/D^0 ratios within the uncertainty
- Observed multiplicity dependence in p_T differential Λ_c^+/D^0 ratios
  - Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?

Comparing to Run 2 data,

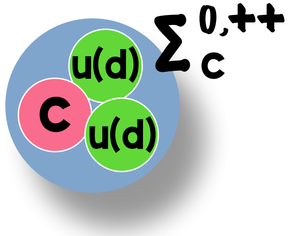
- ⭐ **Larger data sample** thanks to TPC continuous readout
- ⭐ **Improved resolution** thanks to upgraded tracking detector during Long Shutdown 2





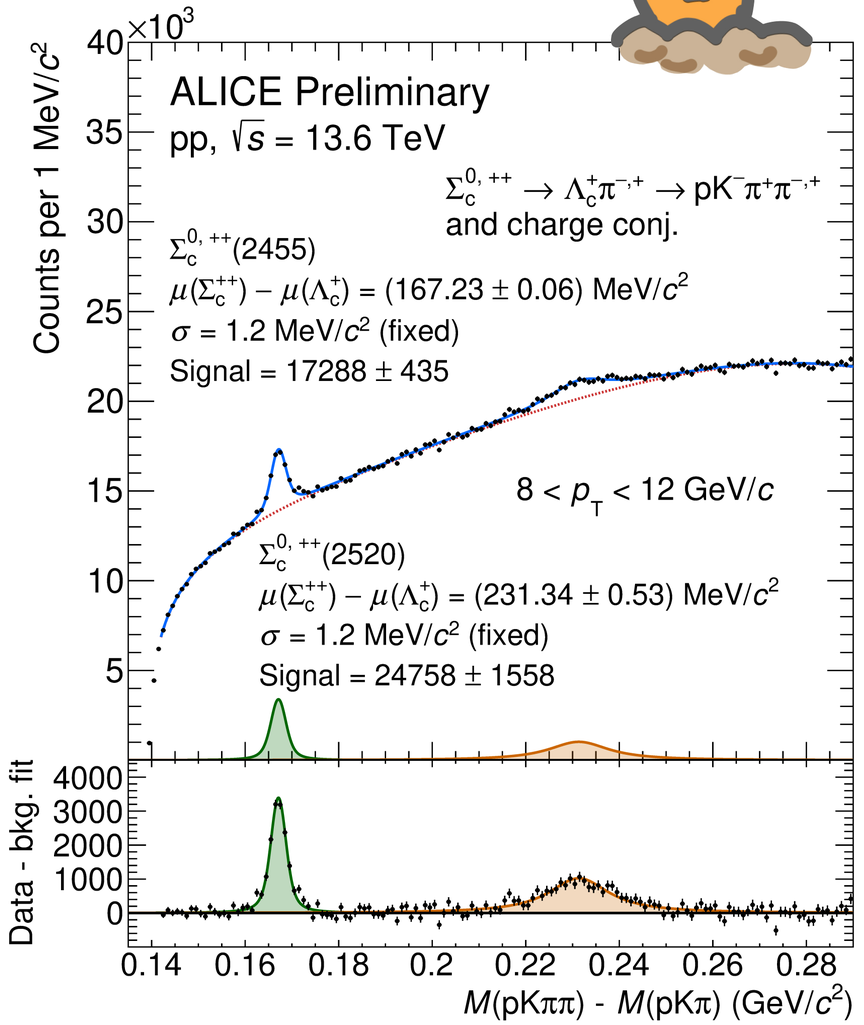
$\Sigma_c^{0,++}$ in pp collisions

From Run 3 data NEW!



$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ yield ratio

- First measurement of the $\Sigma_c^{0,++}(2520)$ relative production at the LHC

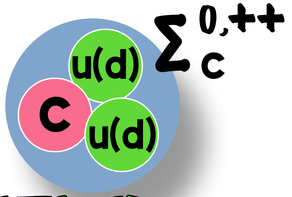


Fresh results from Run 3 data!

ALI-PREL-571534

$\Sigma_c^{0,++}$ in pp collisions

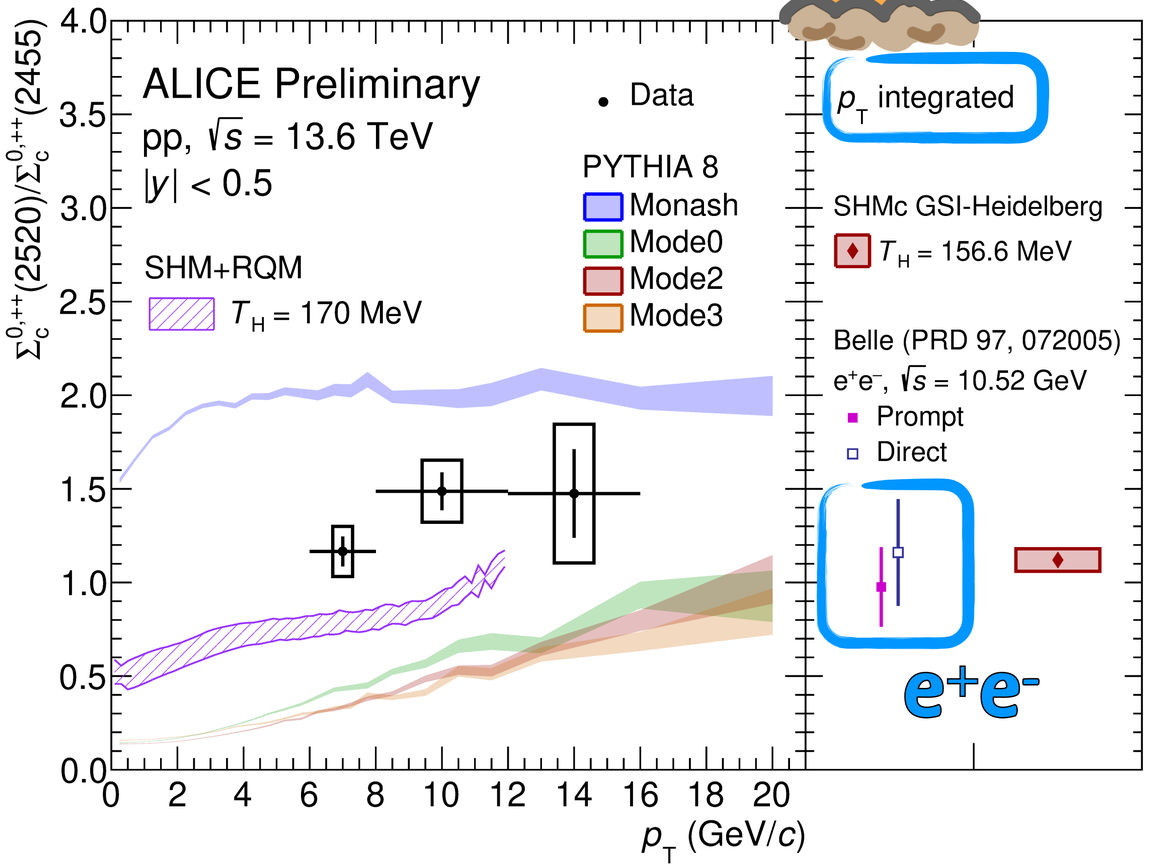
From Run 3 data



NEW!

$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ yield ratio

- First measurement of the $\Sigma_c^{0,++}(2520)$ relative production at the LHC
- In the measured p_T region, the ratios between two $\Sigma_c^{0,++}$ states in **p_T integrated e^+e^- collisions** and pp collisions are consistent with each others within the uncertainties



ALI-PREL-574270

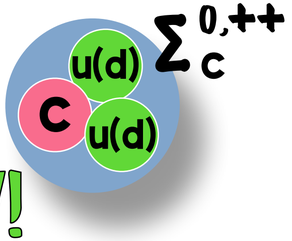
Model comparison

- PYTHIA 8 **Monash** overestimate data
- PYTHIA 8 **Mode 0, 2, 3** and **SHM+RQM** underestimate data

$\Sigma_c^{0,++}$ in pp collisions

From Run 3 data

NEW!

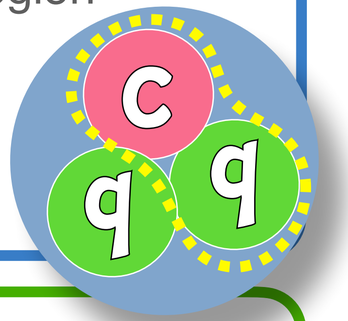


probQQ1toQQ0join : arXiv : 2404.12040 and arXiv : 2405.19137

Tune on parameter?

- PYTHIA 8 Mode 2 tune with modified parameter related to amount of suppression for heavy diquark spin 1 state with respect to spin 0 can catch the data in measured p_T region

We have constraint power for model!



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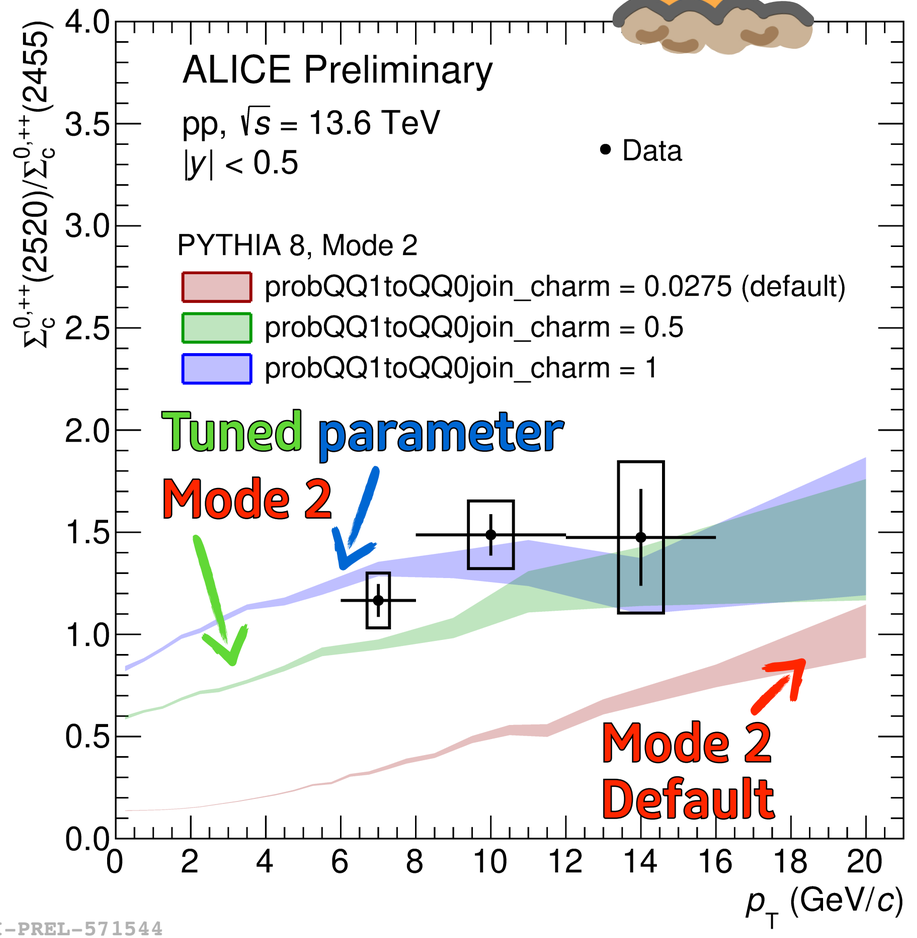
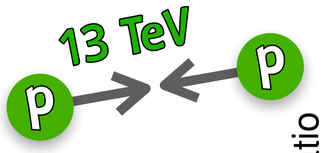
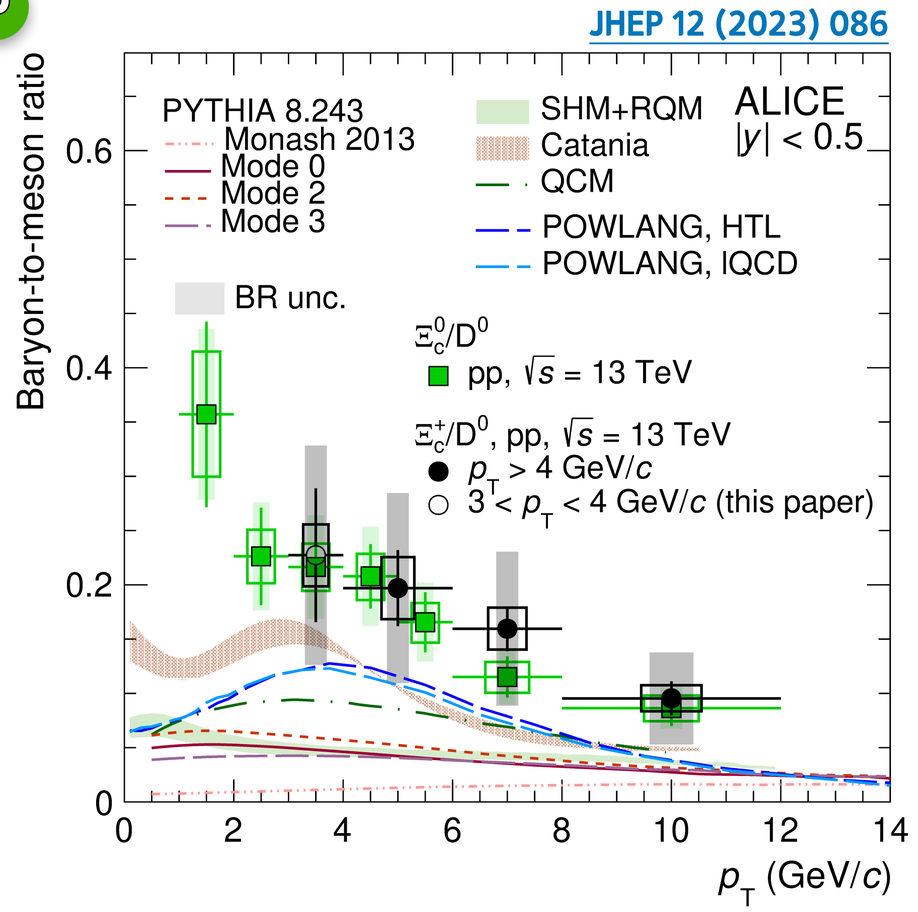


ALI-PREL-571544

$\Xi_c^{0,+}/D^0$ in pp collisions





ALI-PUB-567881

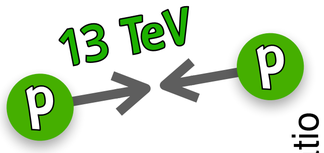
Comparing to e⁺e⁻ collisions

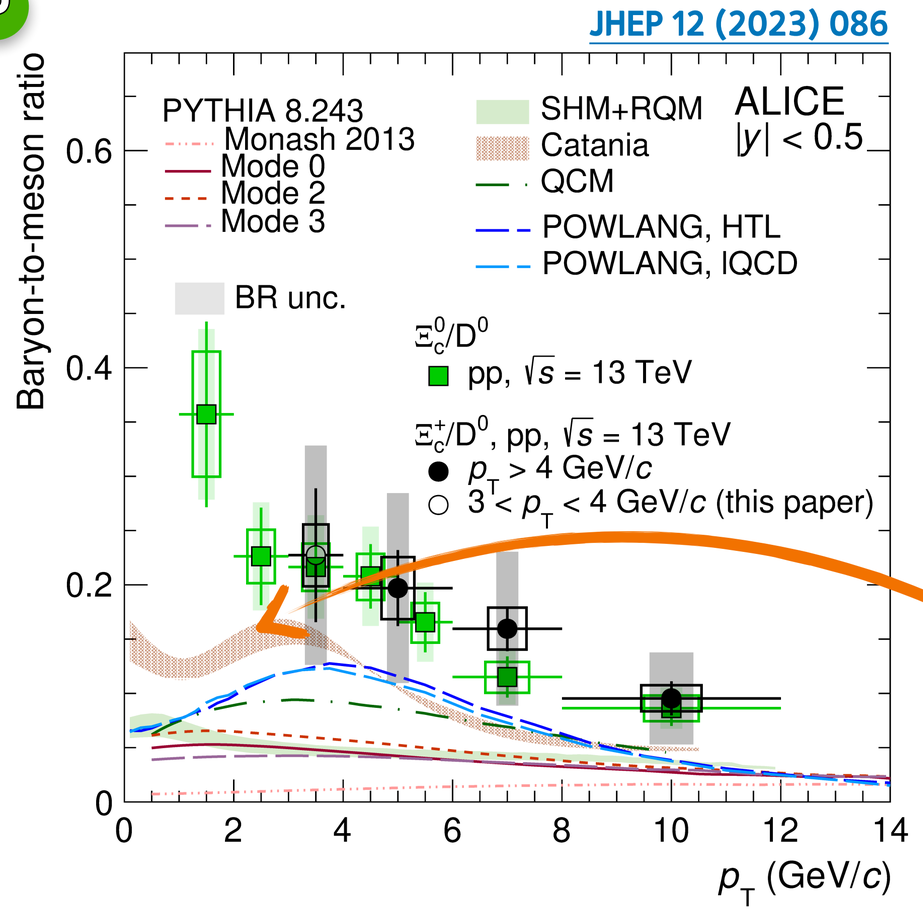
- Enhancement in $\Xi_c^{+,0}/D^0$ ratio in pp collisions

Model comparisons

- **Poor description from models** which describe well the Λ_c^+/D^0 ratio
  - Much larger enhancement than for non-strange baryons?

$\Xi_c^{0,+}/D^0$ in pp collisions





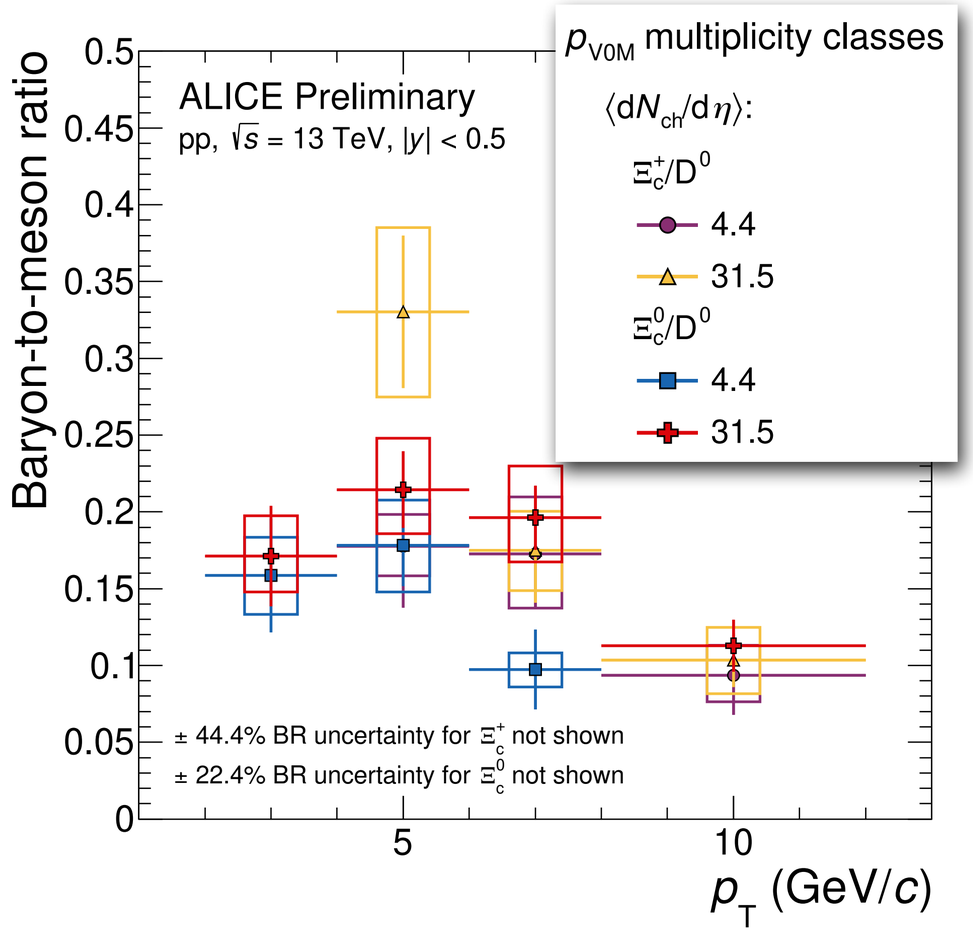
Comparing to e⁺e⁻ collisions

- Enhancement in $\Xi_c^{+,0}/D^0$ ratio in pp collisions

Model comparisons

- **Poor description from models** which describe well the Λ_c^+/D^0 ratio
  - Much larger enhancement than for non-strange baryons?
- **Catania** gets closer to data
  - Both coalescence and fragmentation in hadronization process even in pp collisions?

$\Xi_c^{0,+}/D^0$ vs. event multiplicity in pp collisions



ALI-PREL-548915

Multiplicity dependence?

- ⭐ No strong multiplicity dependence in $\Xi_c^{0,+}/D^0$ ratio with in the current uncertainty

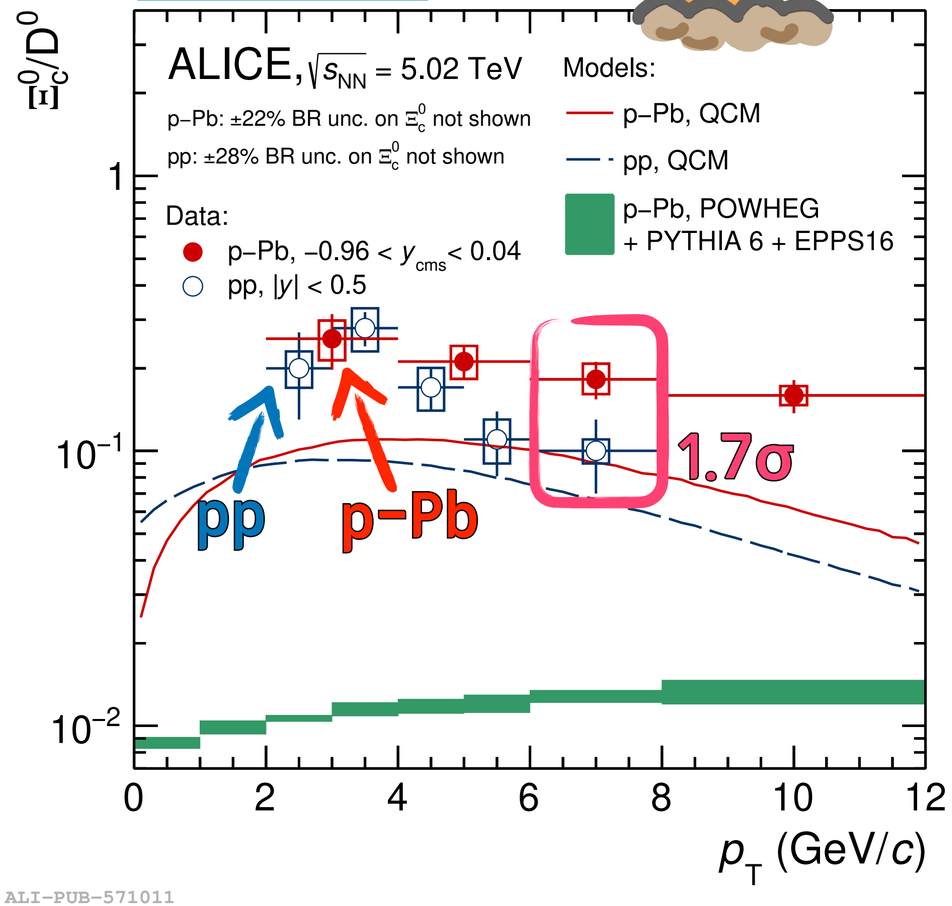
Poster

200. JaeYoon Cho

Ξ_c^+ vs. multiplicity in pp collisions

Ξ_c^0/D^0 in p-Pb collisions

arXiv : 2405.14538



ALI-PUB-571011

Modification of p_T spectra?

- Hint of enhanced Ξ_c^0/D^0 ratio in p—Pb collisions than that in pp collisions?
- Precision is not enough to conclude possible effect as shown for Λ_c^+/D^0 in p—Pb collisions

Model comparison

- Underestimated by QCM in both pp and p—Pb collisions

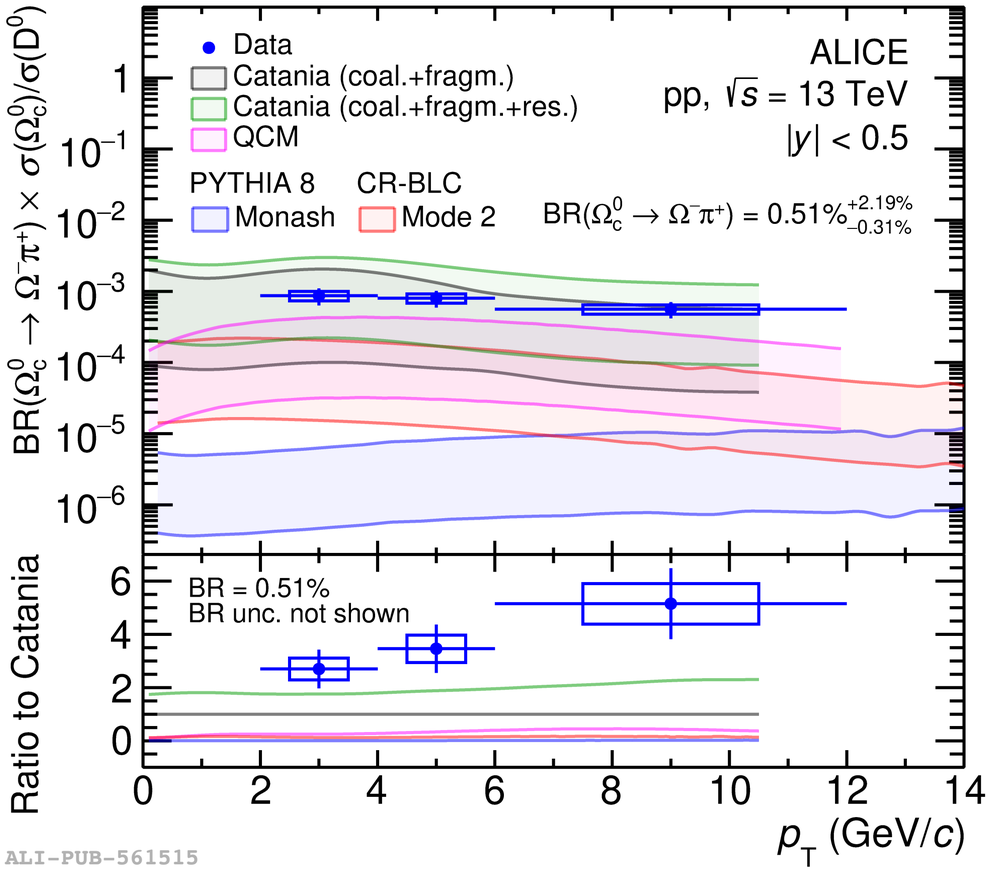
Ω_c^0/D^0 in pp collisions

$BR \times \Omega_c^0/D^0$ and model comparison

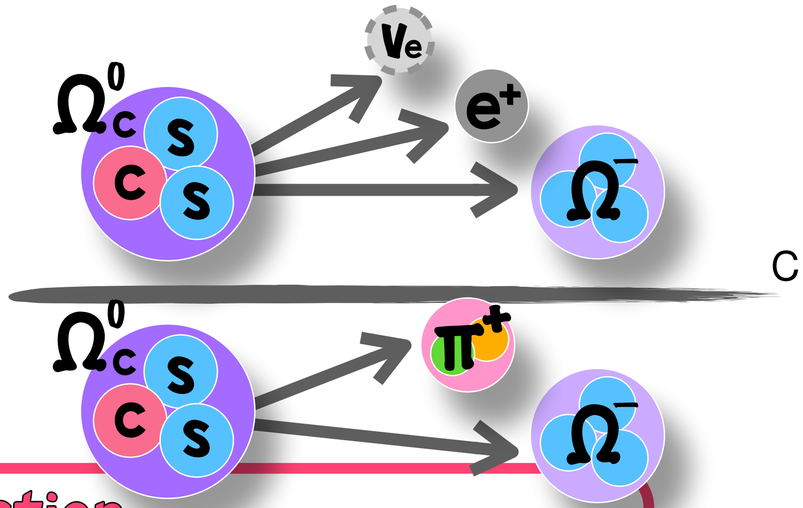
- ⭐ No measurement of $BR(\Omega_c^0 \to \Omega^-\pi^+)$
  - $BR(\Omega_c^0 \to \Omega^-\pi^+) = (0.51^{+2.19}_{-0.31})\,\%$ from theory calculations
- ⭐ **Catania (+resonance states)** is closer to data
- ⭐ BR measurement is needed!

Theoretical calculation for BR : Y.Hisao et al. EPJC 80, 1066 (2020)

Phys.Lett.B 846 (2023) 137625



Ω_c^0 in pp collisions

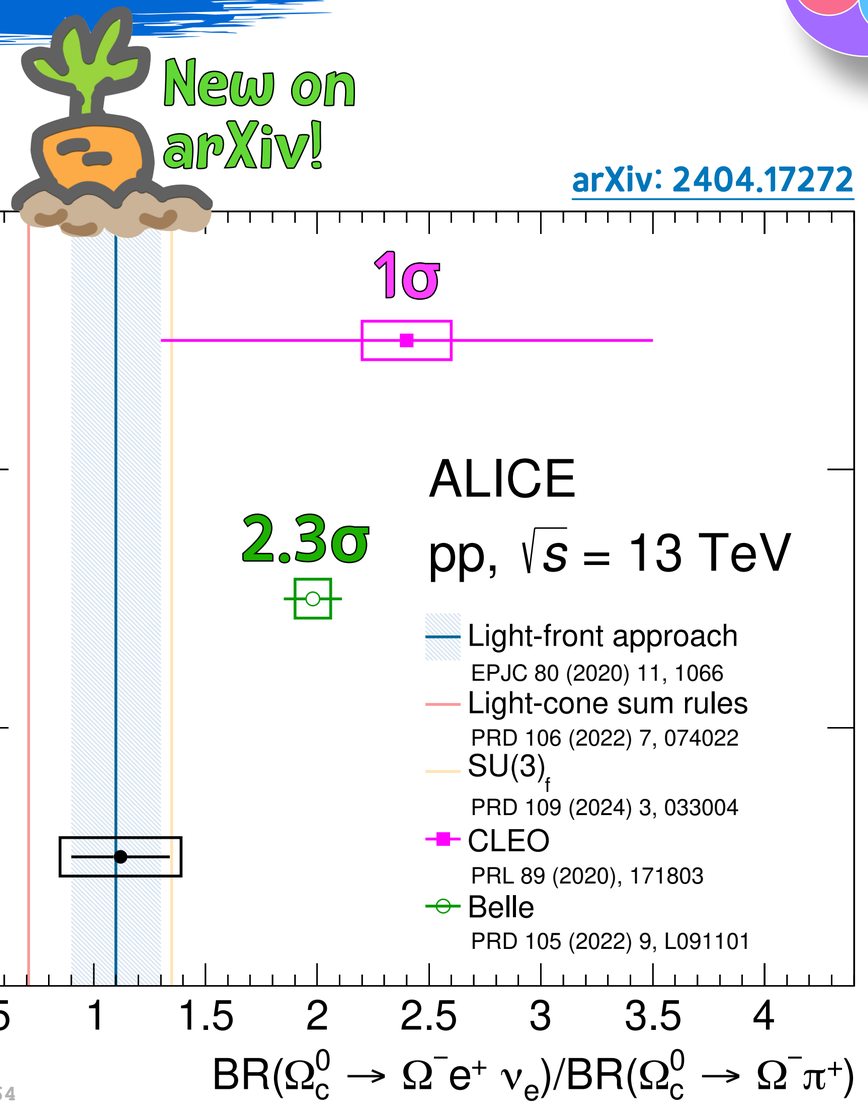


Branching fraction

- Measured ratio is

$$\mathrm{BR}(\Omega_c^0 \to \Omega^- e^+ \nu_e)/\mathrm{BR}(\Omega_c^0 \to \Omega^- \pi^+) = 1.12 \pm 0.22\ (\mathrm{stat.}) \pm 0.27\ (\mathrm{syst.})$$

- Agreement with measurement from CLEO Collaboration and model calculations within 1σ and within 2.3σ from BELLE measurement

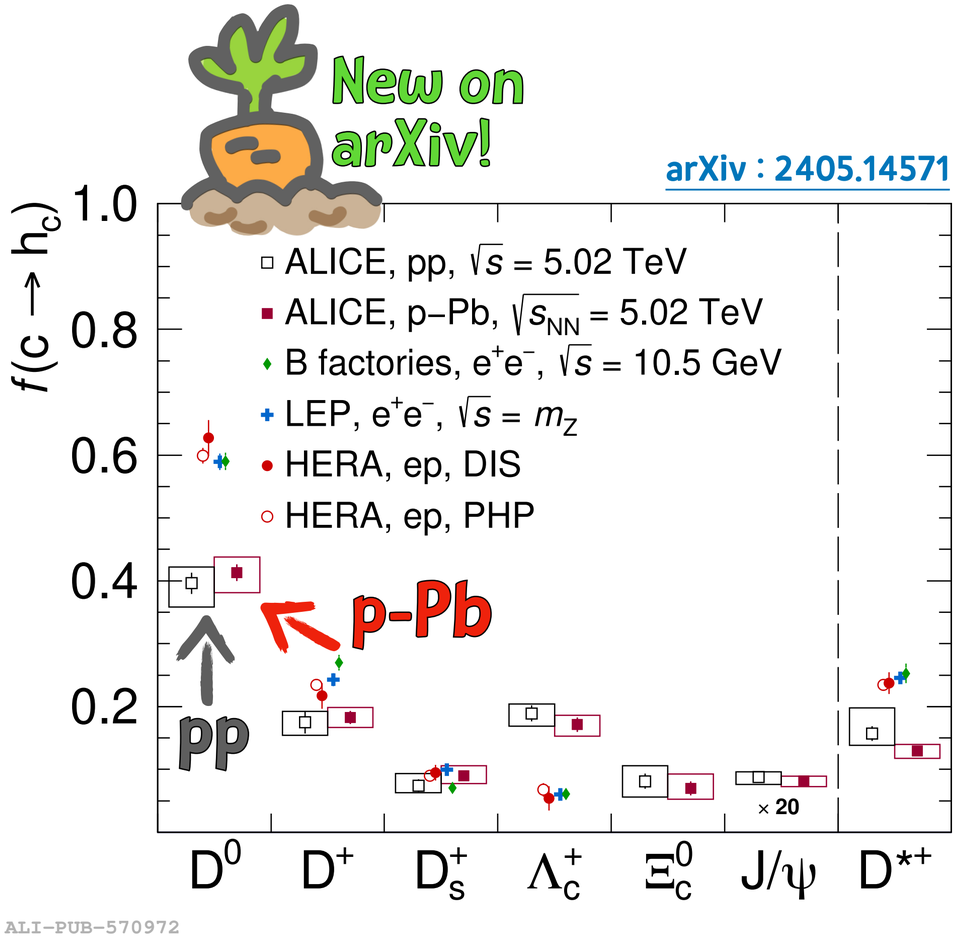


Charm fragmentation fraction

Charm fragmentation fraction

In hadronic collisions

⭐ Fragmentation fractions in pp and p—Pb collisions are consistent with each others

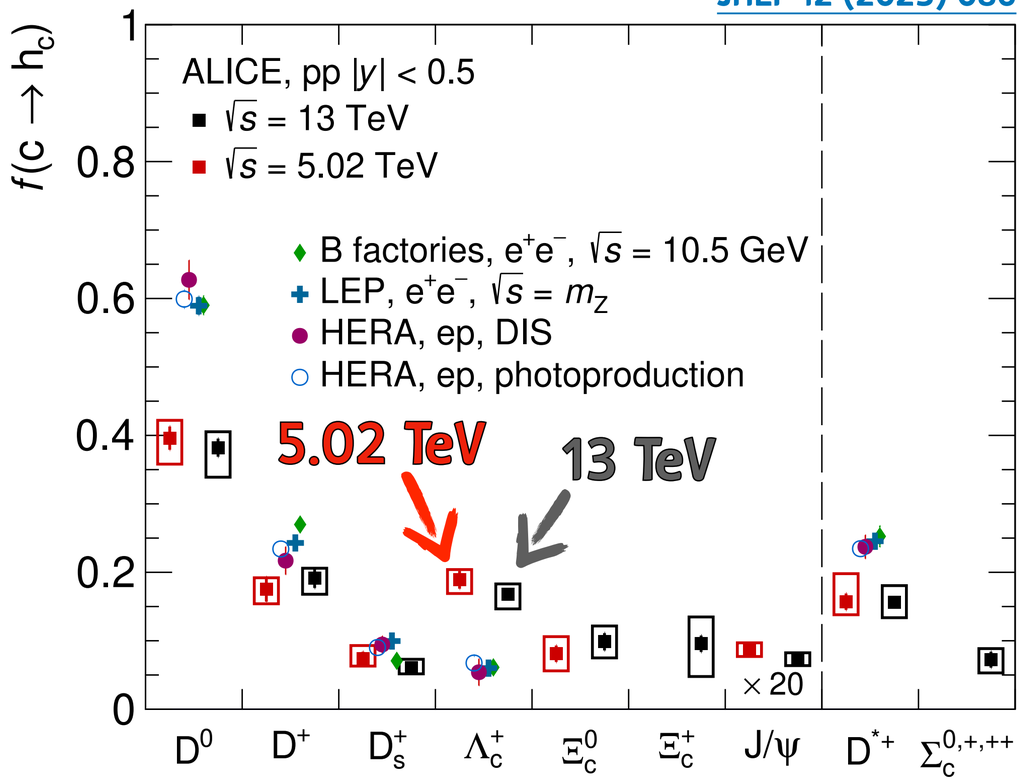


Charm fragmentation fraction

For different collisions energy

⭐ No energy dependence within the uncertainties

JHEP 12 (2023) 086



Charm fragmentation fraction

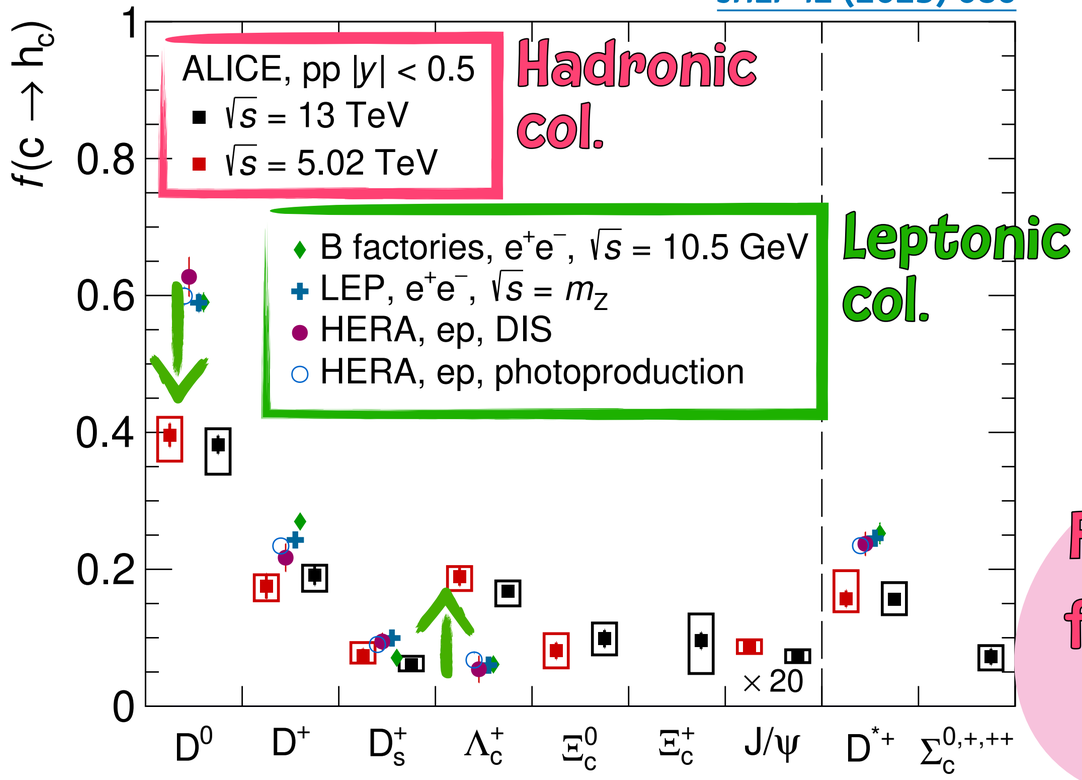
In different collisions energy

- No energy dependence within the uncertainties

Comparing to e⁺e⁻ collisions

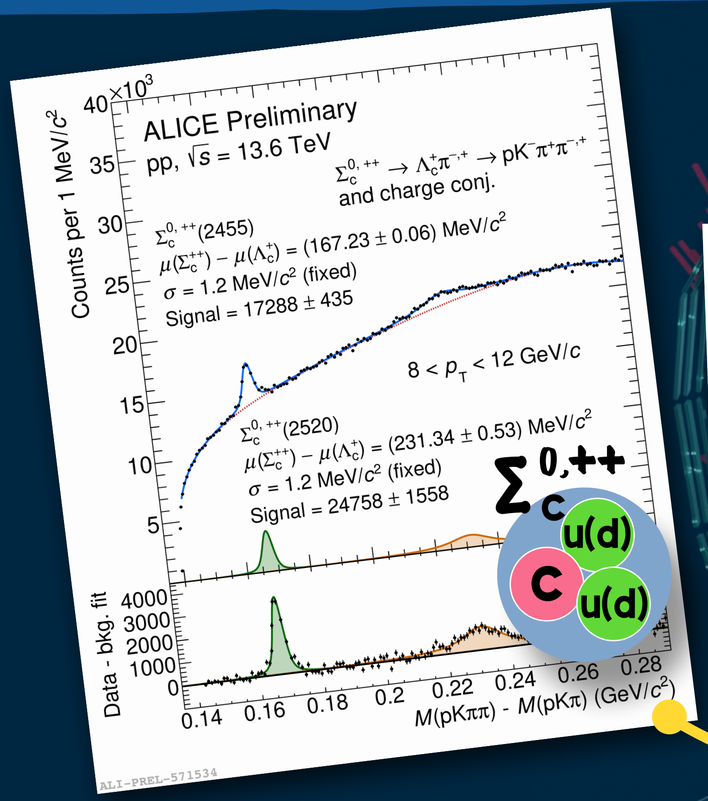
- Significantly increased baryon production, decreased meson production
- Indicate **different hadronization mechanism in hadronic collisions** with respect to leptonic collisions

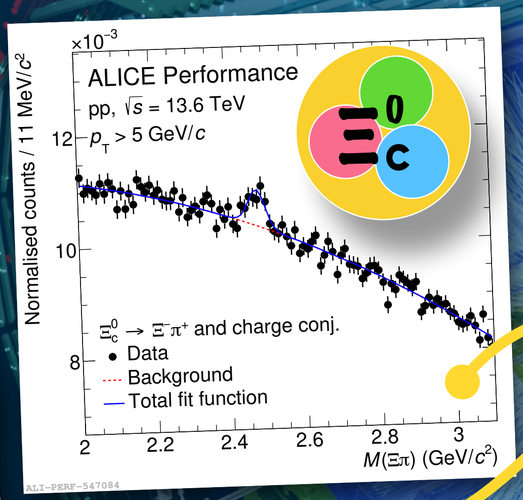
JHEP 12 (2023) 086

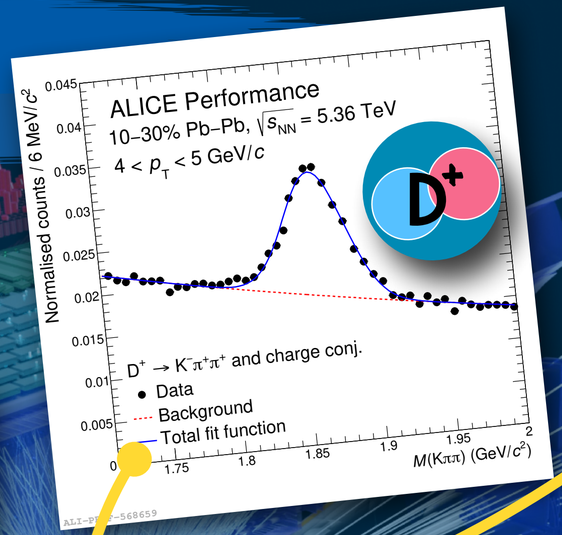


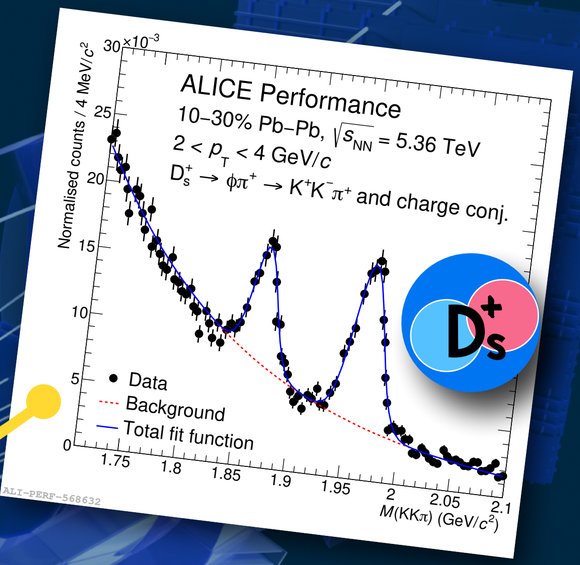
Fragmentation function is NOT universal

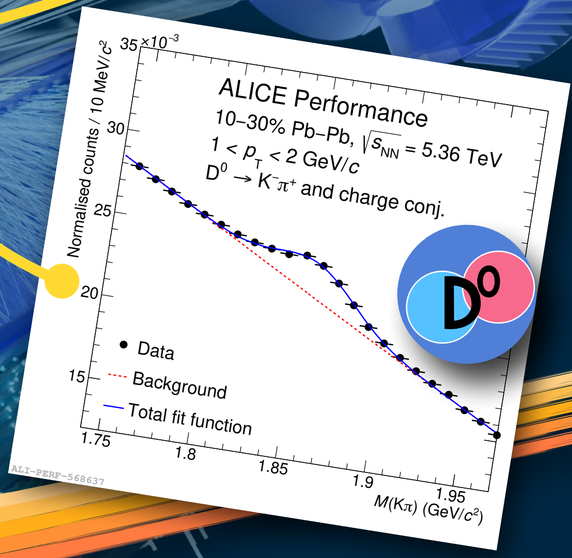
Outlook : HF in ALICE Run 3











Successfully done !

ALICE is here !

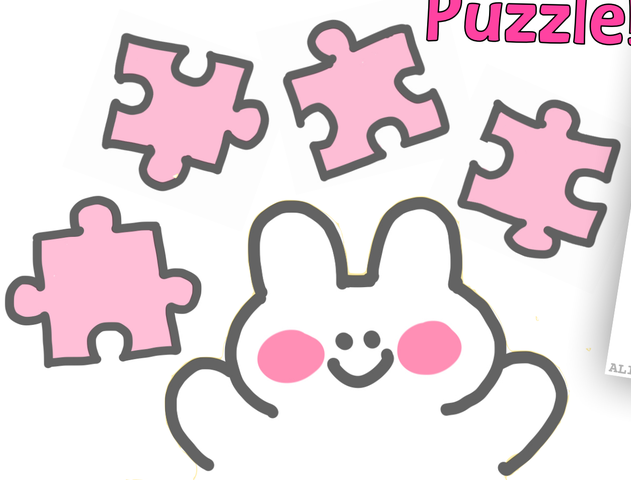
Run 2
2015-2018

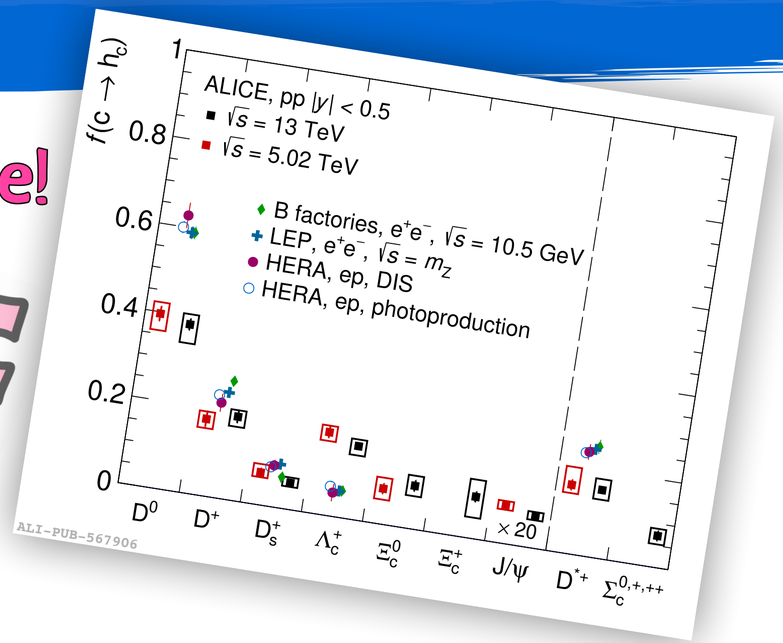
Long Shutdown 2

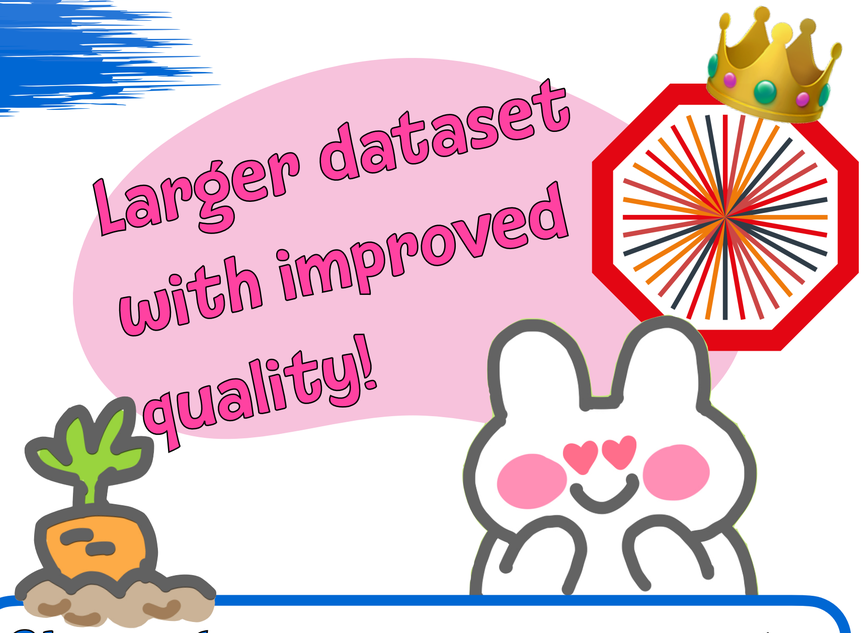
Run 3
2022-2025

ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV

Summary







Charm baryon measurement with Run 2 data

- ⭐ Charm baryons were measured in various collision system with Run 2 data
- ⭐ **Significantly enhanced charm baryon-to-meson ratio** in hadronic collisions with respect to leptonic collisions
- ⭐ **Charm fragmentation function is not universal!**

Charm baryon measurement with Run 3 data

- ⭐ **Precise measurement**
- ⭐ More differential measurement and extended p_T reach
- ⭐ Better understanding of charm hadronization!

Stay tuned!

BACK UP

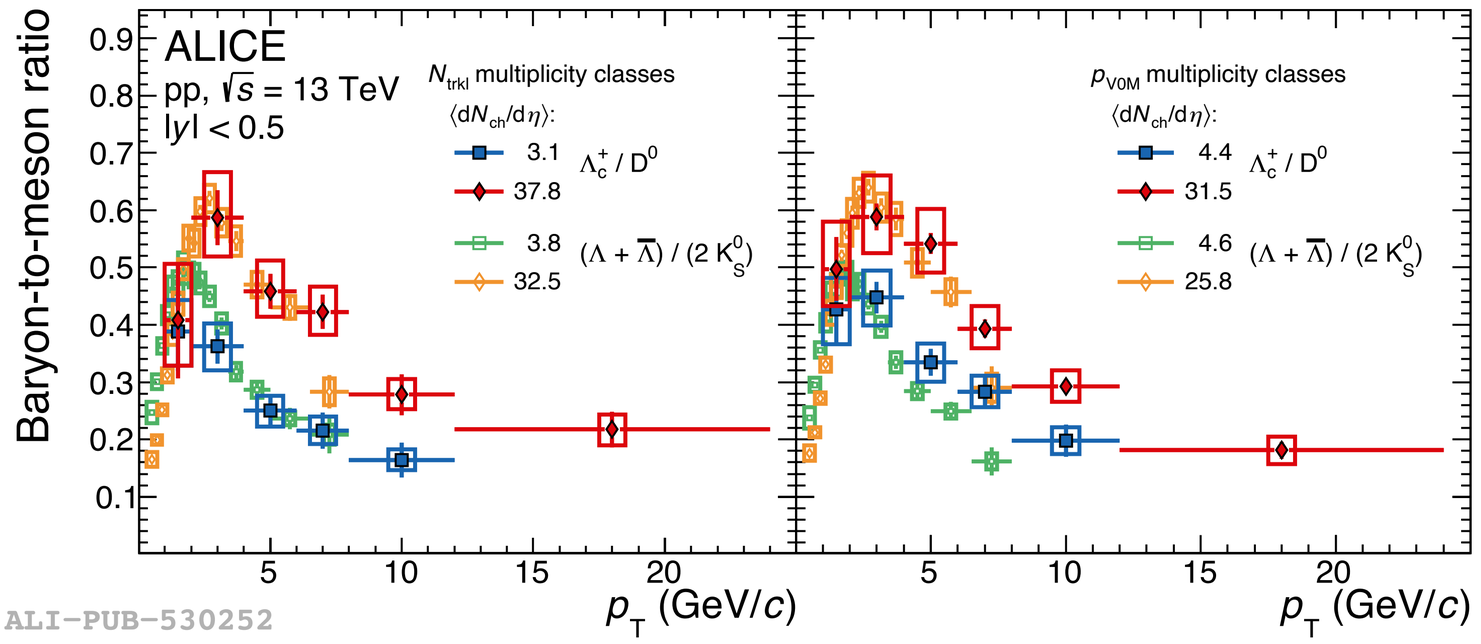
SQM2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

인하대학교 1954 INHA UNIVERSITY

ALICE

Λ_c^+/D^0 vs. event multiplicity in pp collisions

Phys.Lett.B 829 (2022) 137065

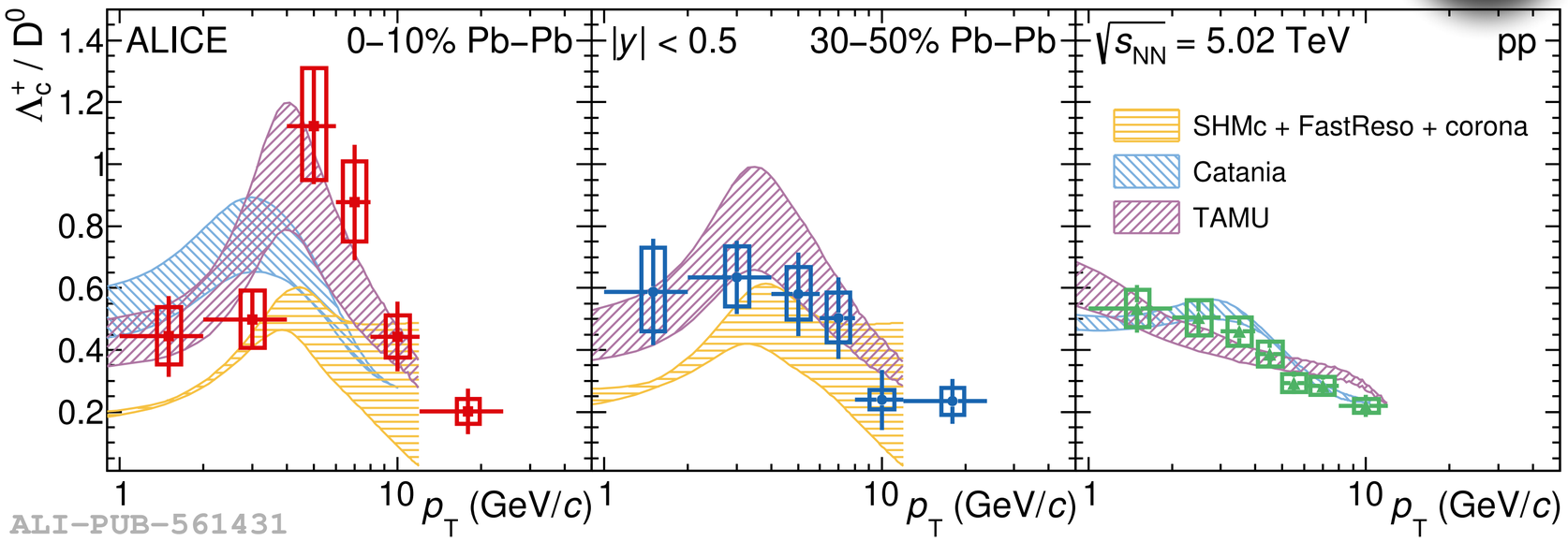


Comparing to baryon-to-meson ratio of light-flavour hadrons

- ⭐ Similar p_T shape and magnitude of the ratios
- ⭐ Similar hadron production mechanism in light- and heavy-flavour hadrons?

Λ_c^+/D^0 in Pb-Pb collisions

Phys.Lett.B 839 (2023) 137796



Catania

- QGP formation in both pp and Pb—Pb collisions
- Consider both coalescence and fragmentation for hadronization

SHMc

- Consider only charm meson and charm baryon
- Core-corona approach

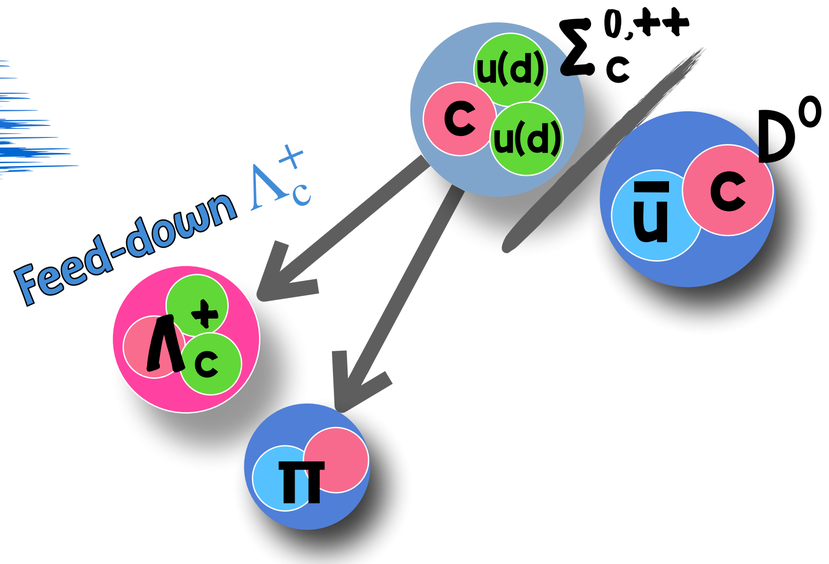
TAMU

- Exploit SHM for pp collisions
- Consider both coalescence and fragmentation for hadronization for Pb—Pb collisions
- Consider excited state baryon from RQM for both pp and Pb-Pb collisions

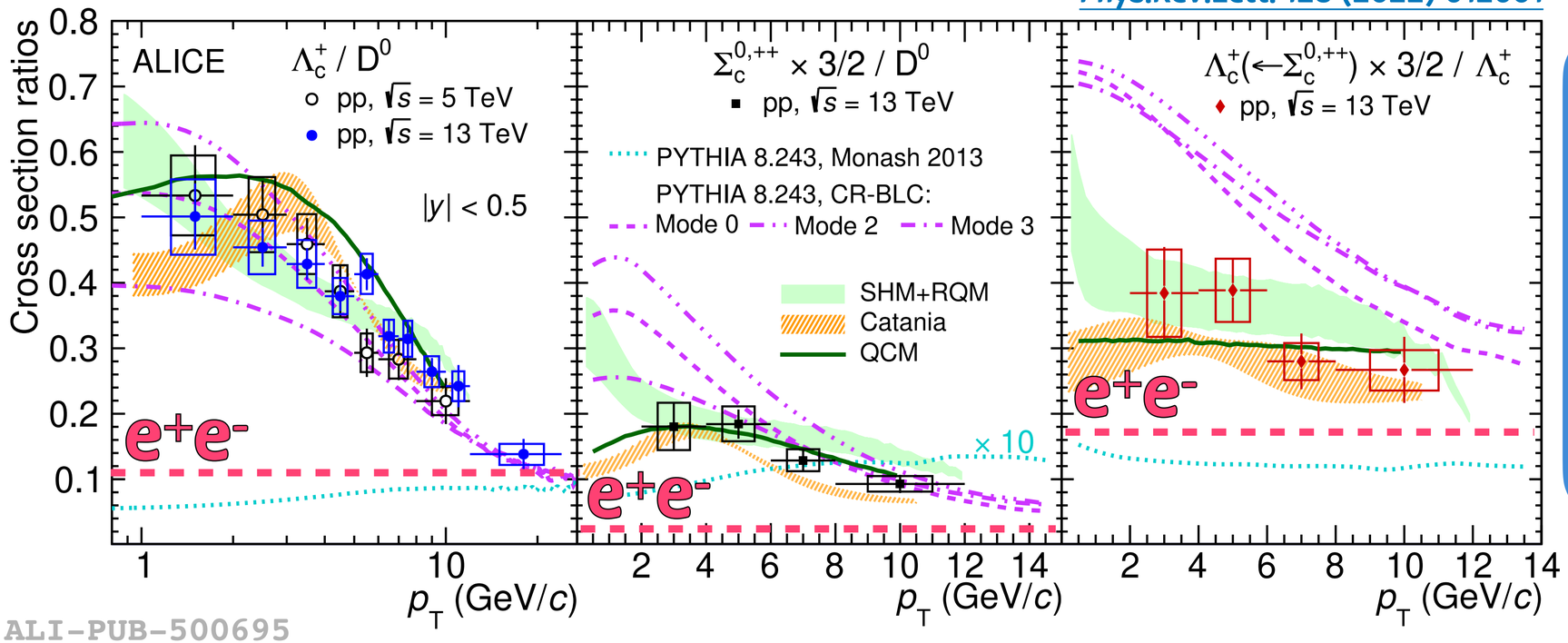
$\Sigma_c^{0,++}/D^0$ in pp collisions

Comparing to e^+e^- collisions

⭐ Remarkably enhanced baryon-to-meson ratio and strong p_T dependence in pp collisions



Phys.Rev.Lett. 128 (2022) 012001



ALI-PUB-500695

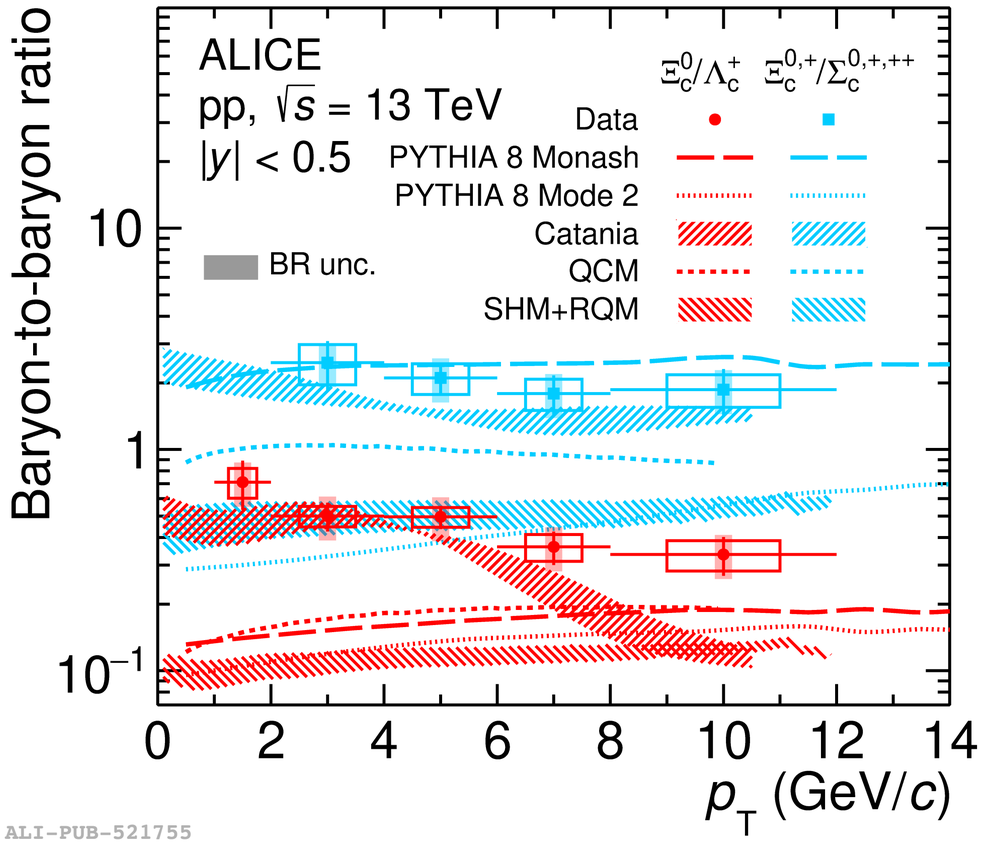
Feed-down Λ_c^+ from $\Sigma_c^{0,++}$

⭐ ~ 40% of Λ_c^+ from $\Sigma_c^{0,++}$ decay

⭐ Enhanced feed-down partially contribute to enhancement in Λ_c^+/D^0 in pp collisions

$\Xi_c^{0,+}$ in pp collisions

Phys.Rev.Lett. 127 (2021) 272001



Production yield ratio to Λ_c^+

- ⭐ No strong p_T dependence
- ⭐ Models underestimate data

Production yield ratio to $\Sigma_c^{0,+,++}$

- ⭐ No strong p_T dependence
- ⭐ Catania and PYTHIA 8 Monash describe the data
  - Both Catania and PYTHIA 8 Monash underestimate the $\Xi_c^{0,+}/D^0$ ratio
  - Similar amount of suppression for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$?

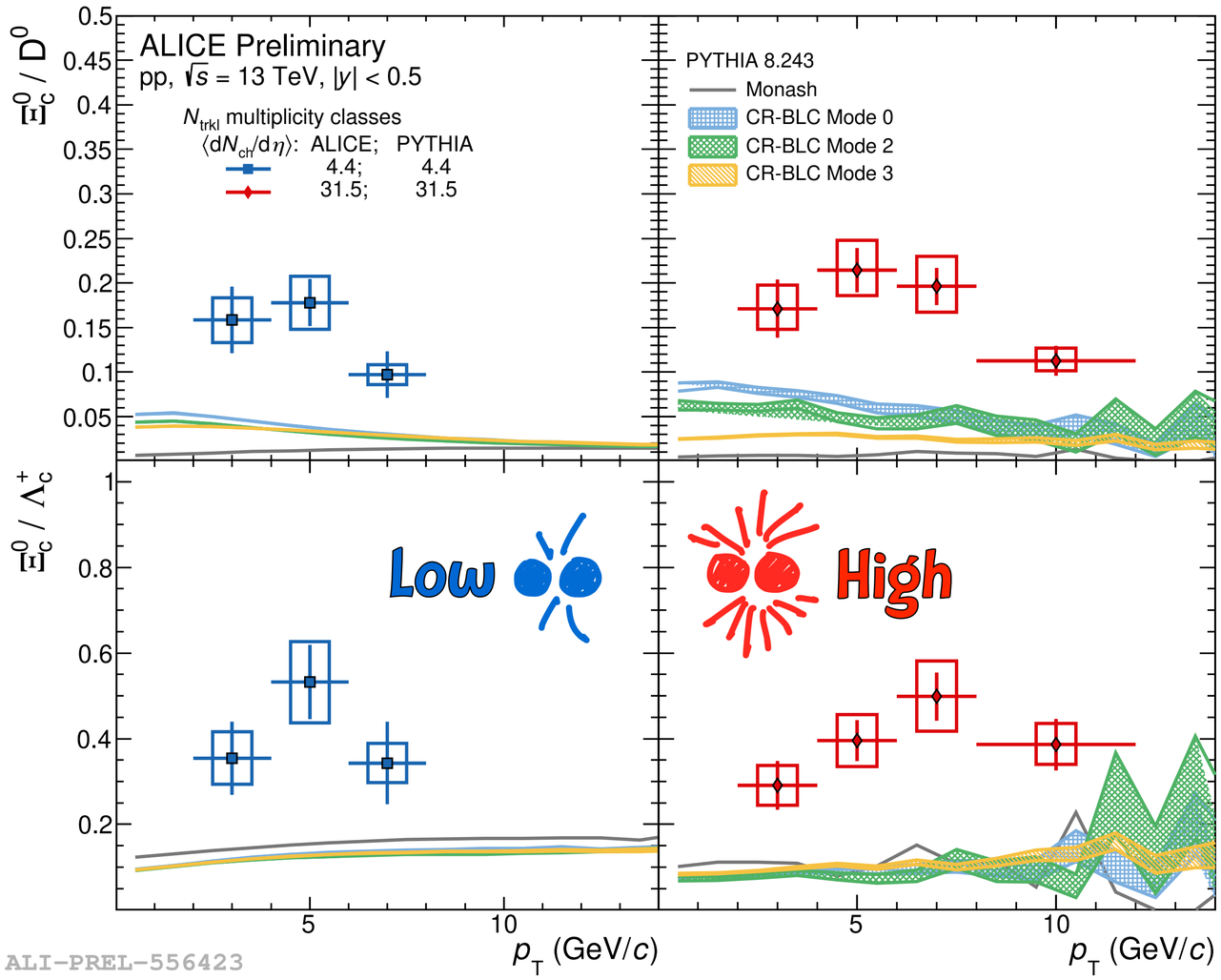
Ξ_c^0 vs. event multiplicity in pp collisions

Production yield ratio to D^0 and Λ_c^+

- No strong multiplicity dependence in baryon-to-meson and baryon-to-baryon ratio within the uncertainties

Model comparison

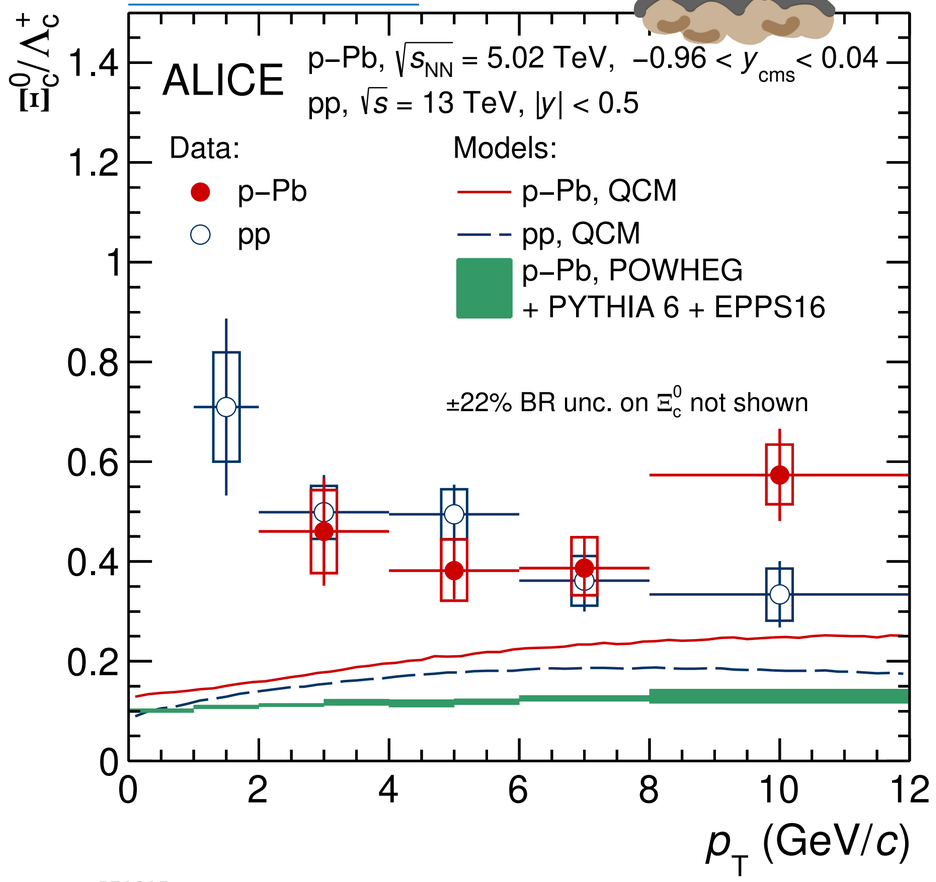
- PYTHIA 8 Monash doesn't reproduce neither magnitude nor multiplicity dependence
- PYTHIA 8 CR-BLC tunes, which describe the Λ_c^+/D^0 ratio significantly underestimate the data



Ξ_c^0/Λ_c^+ in p-Pb collisions

New on arXiv!

arXiv : 2405.14538



ALI-PUB-571015

Production yield ratio to Λ_c^+

- ⭐ No strong p_T dependence in both pp and p—Pb collisions
- ⭐ Similar magnitude of Ξ_c^0/Λ_c^+ in p-Pb collisions with respect to pp collisions
  - No appreciable additional modification of the hadronization process going from pp to p-Pb collisions
- ⭐ Underestimated by both **QCM** and **POWHEG+PYTHIA 6**

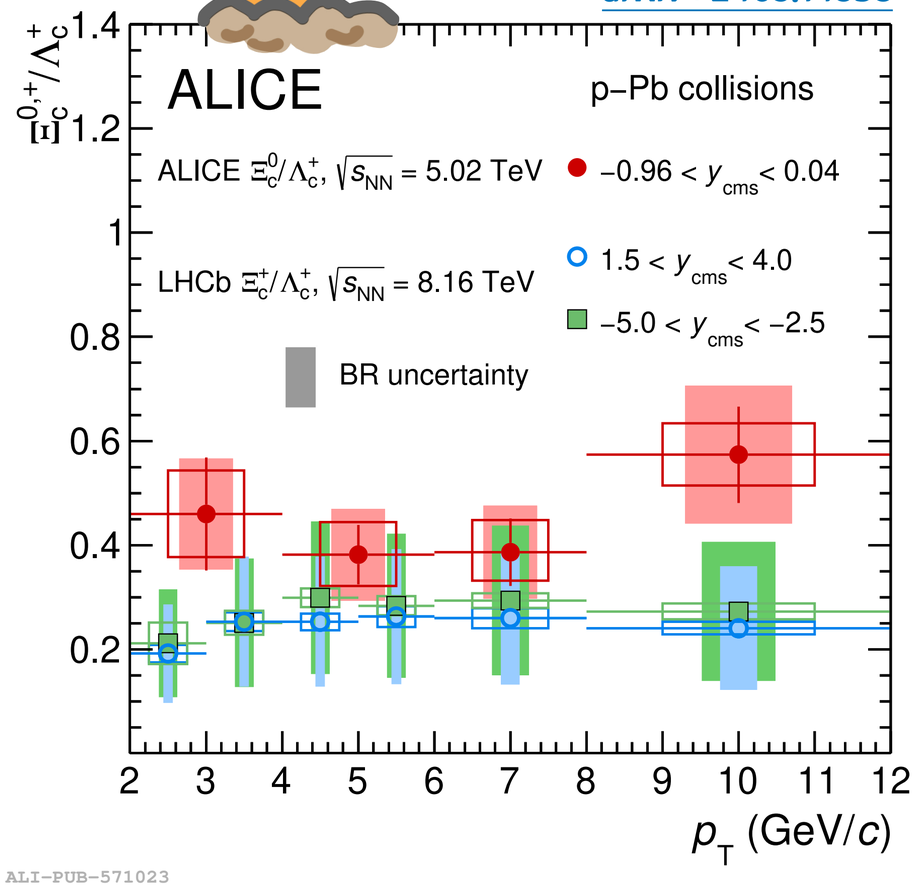
Ξ_c^0/Λ_c^+ in p-Pb collisions

in different rapidity interval

5.02 TeV p Pb

New on arXiv!

arXiv : 2405.14538



ALI-PUB-571023

ALICE, 5.02 TeV
Ξ_c^0 measurement

- $-0.96 < y_{cms} < 0.04$

LHCb, 8.16 TeV
Ξ_c^+ measurement

- $1.5 < y_{cms} < 4.0$
- $-5.0 < y_{cms} < -2.5$

Production yield ratio to Λ_c^+

⭐ Ratios are compatible at **mid**, **forward** and **backward** rapidity within the uncertainties

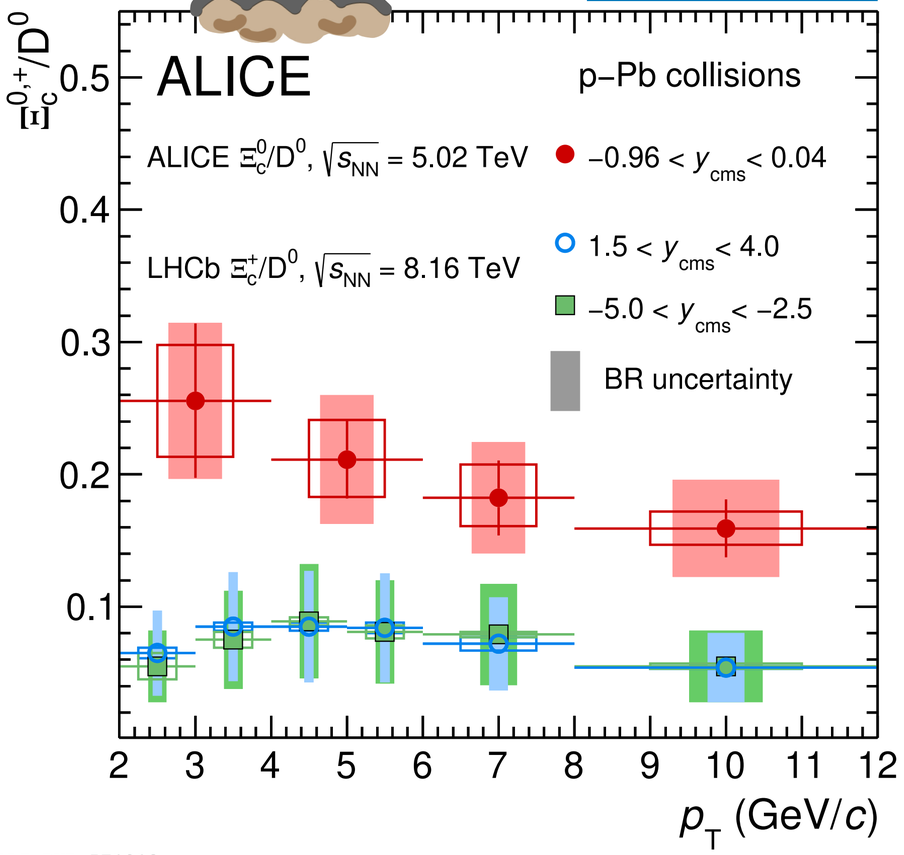
- 1.1σ difference at 2-4 GeV/c p_T interval

Ξ_c^0/Λ_c^+ in p-Pb collisions

in different rapidity interval

New on arXiv!

arXiv : 2405.14538



ALI-PUB-571019

ALICE, 5.02 TeV
Ξ_c^0 measurement

- $-0.96 < y_{cms} < 0.04$

LHCb, 8.16 TeV
Ξ_c^+ measurement

- $1.5 < y_{cms} < 4.0$
- $-5.0 < y_{cms} < -2.5$

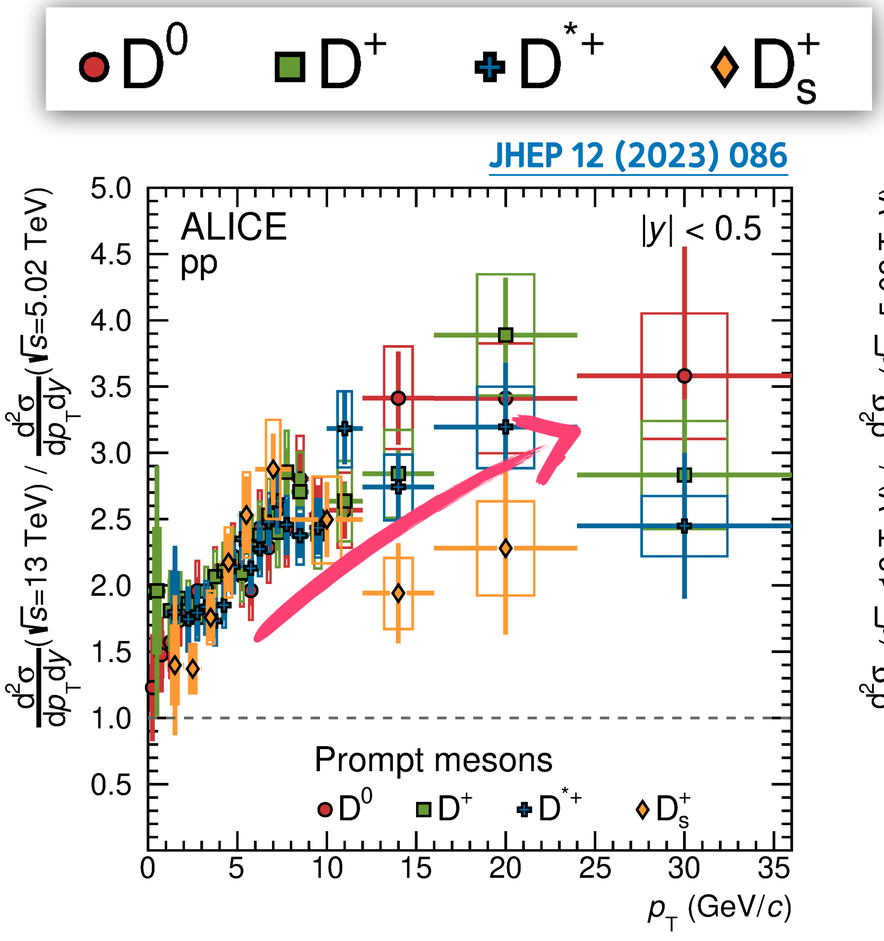
Production yield ratio to D^0

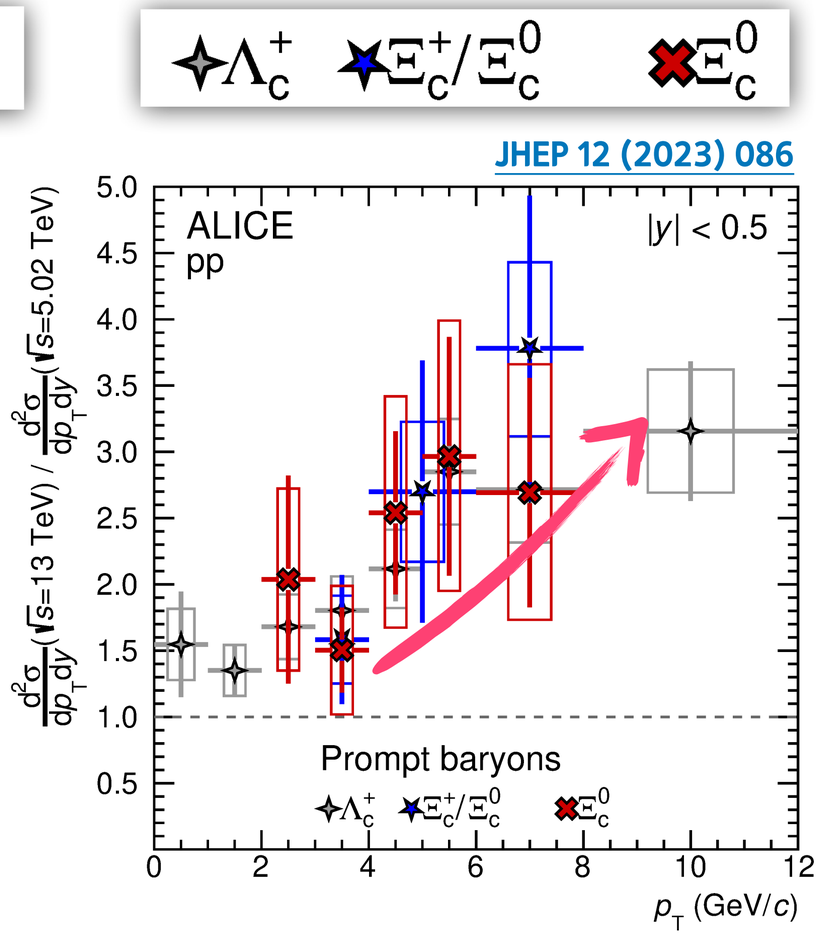
- ⭐ Hint of rapidity dependence?
  - 1.5σ to 2.0σ difference across the different p_T interval

Energy dependence in hadron production

C

13 TeV / 5.02 TeV





ALI-PUB-567886

Production cross section ratio between different collision energy

- ⭐ increasing trend going from low to high p_T region for given hadron species
- ⭐ Similar energy dependence in baryon and meson production
  → No energy dependence in baryon-to-meson ratios