

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

JaeYoon Cho^{*}

on behalf of the ALICE Collaboration

^{*} Inha University



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ALICE

Heavy-flavour hadronization

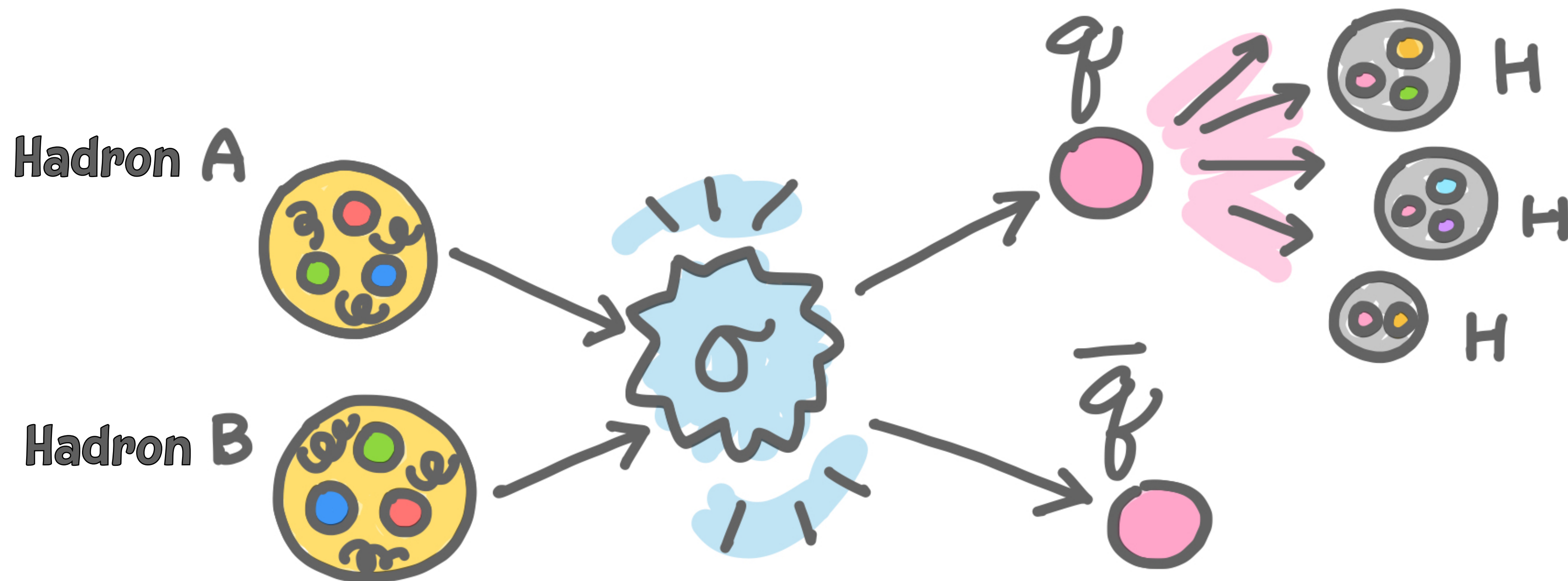
$$d\sigma_{AB \rightarrow h} = f_{i/A}(x_i, Q^2) \otimes f_{j/B}(x_j, Q^2) \otimes d\sigma_{ij \rightarrow q\bar{q}}(x_i x_j, Q^2) \otimes D_{q \rightarrow h}(z, Q^2)$$

Production cross section of HF hadrons

Parton distribution functions

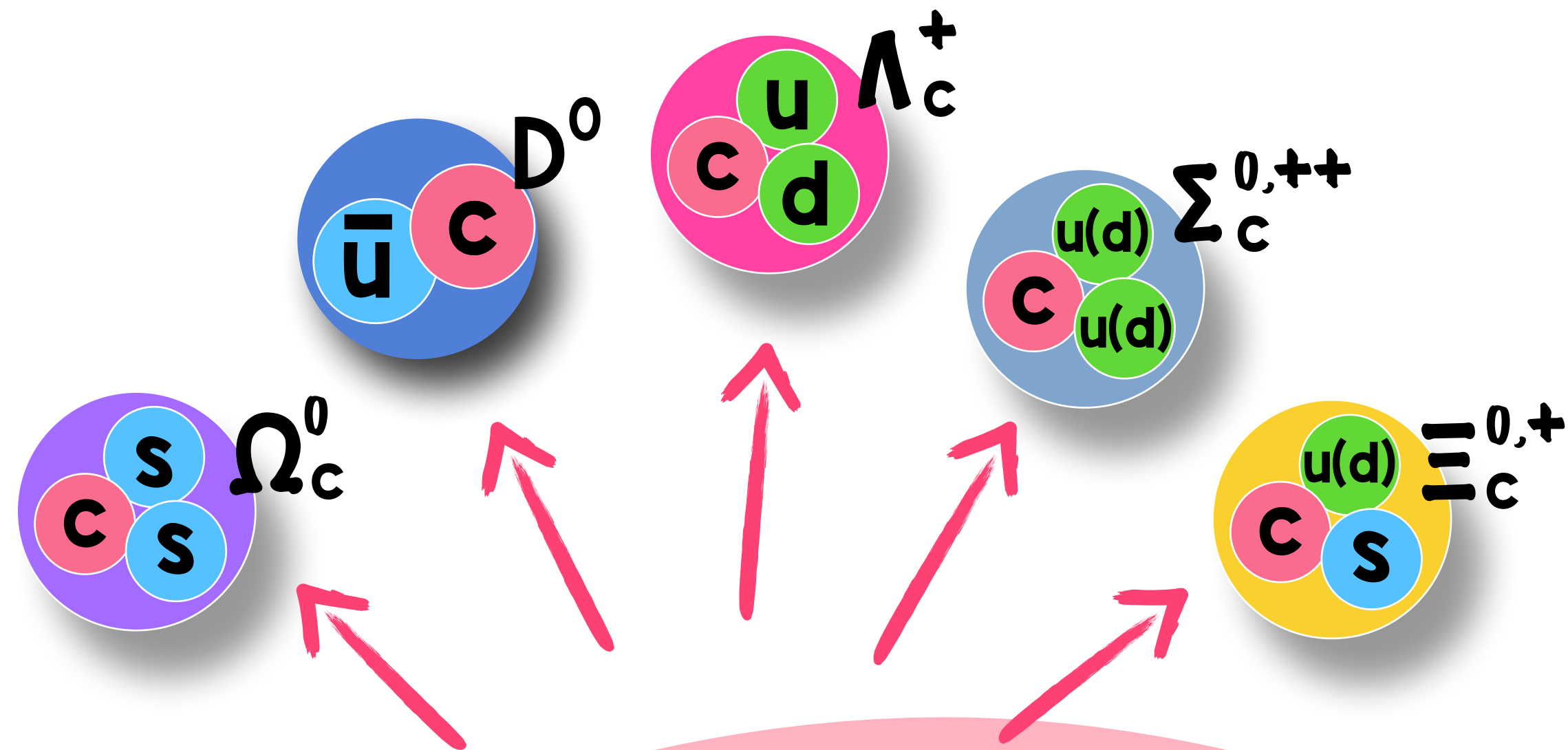
Hard-scattering cross section

Fragmentation function (Hadronization)



Heavy-flavour hadronization

Experimental observable

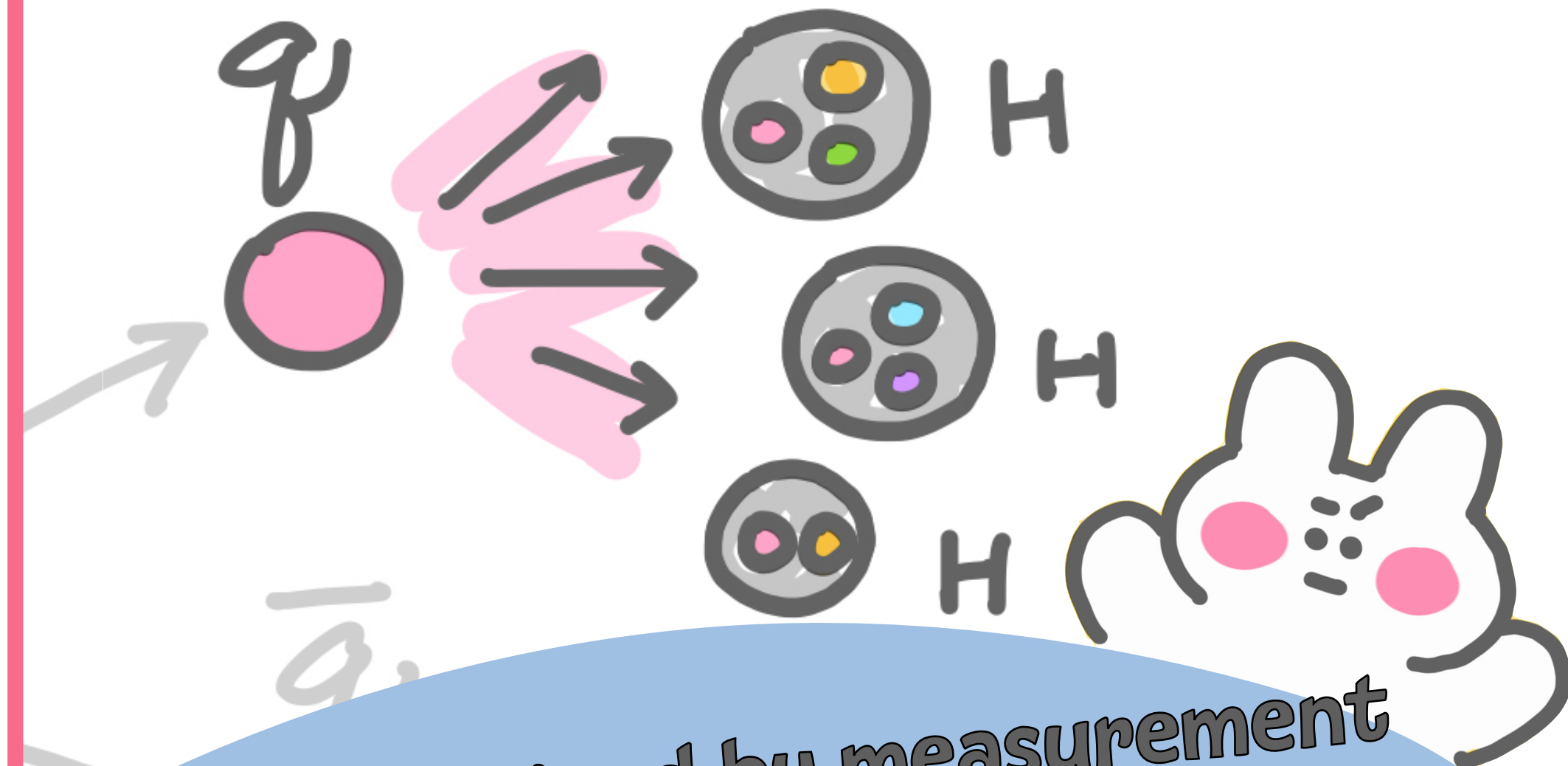


Production cross section ratio of hadron species is good probe of hadronization!

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

scattering section

Fragmentation function (Hadronization)



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

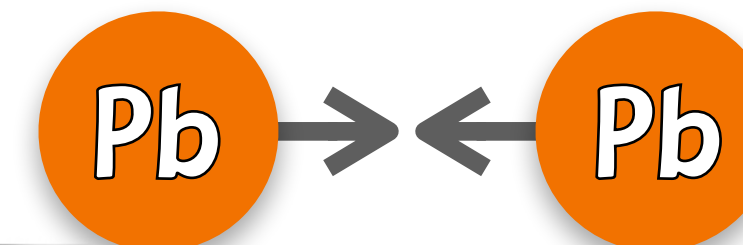
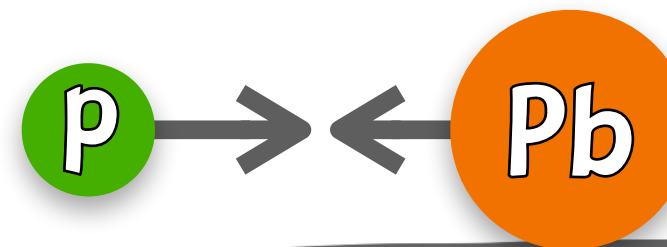
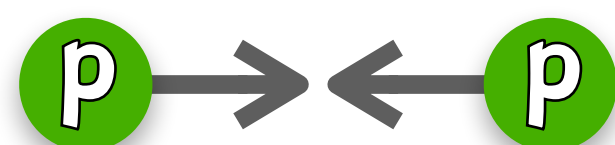



ALICE charm baryon measurements

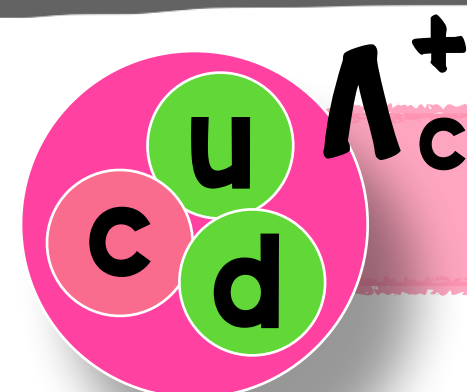
2.76 TeV, 5.02 TeV, 13 TeV
13.6 TeV

5.02 TeV

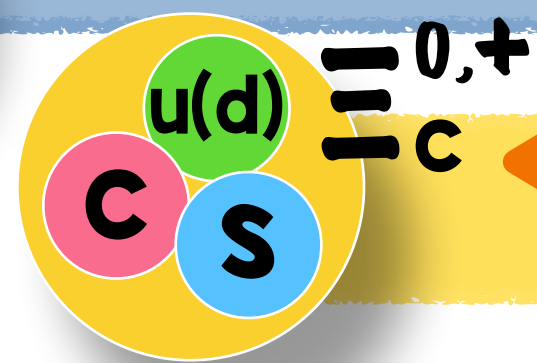
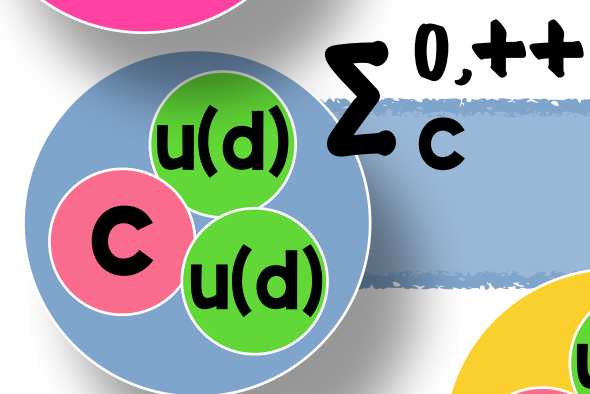
2.76 TeV, 5.02 TeV



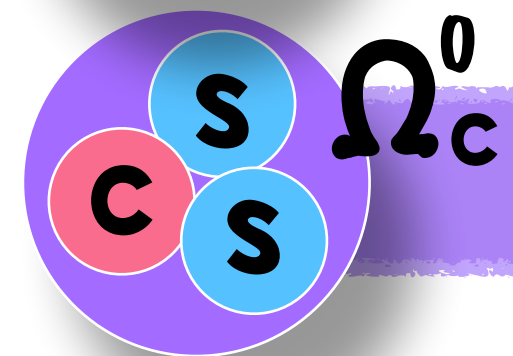
 Hadronic collisions



vs. event multiplicity 

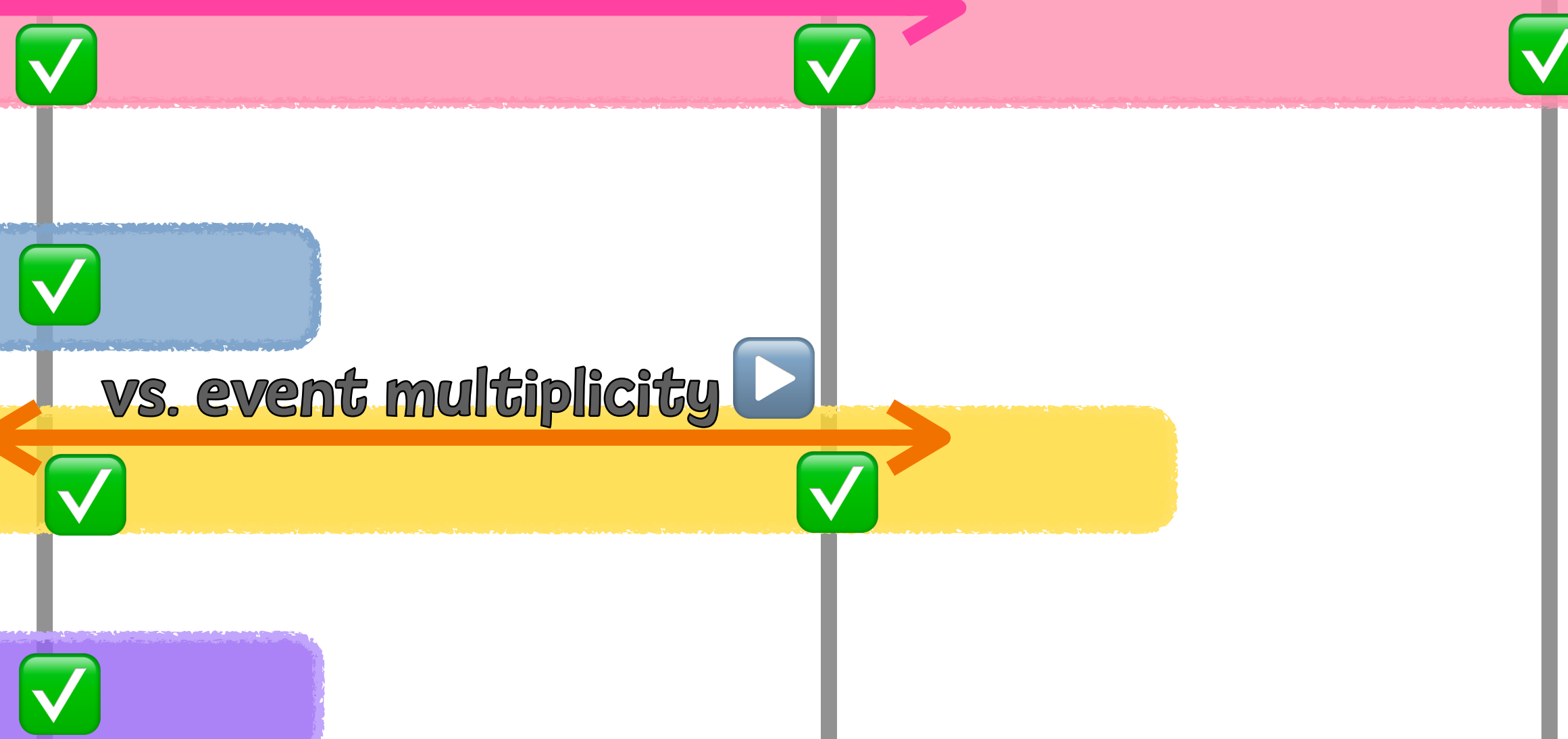


vs. event multiplicity 



 : Published

 : Preliminary



The ALICE experiment

TPC Time Projection Chamber
 $|\eta| < 0.9$
Particle identification
Tracking

ITS Inner Tracking System
 $|\eta| < 0.9$
Vertexing & 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



(Run 2)
ALICE Detector

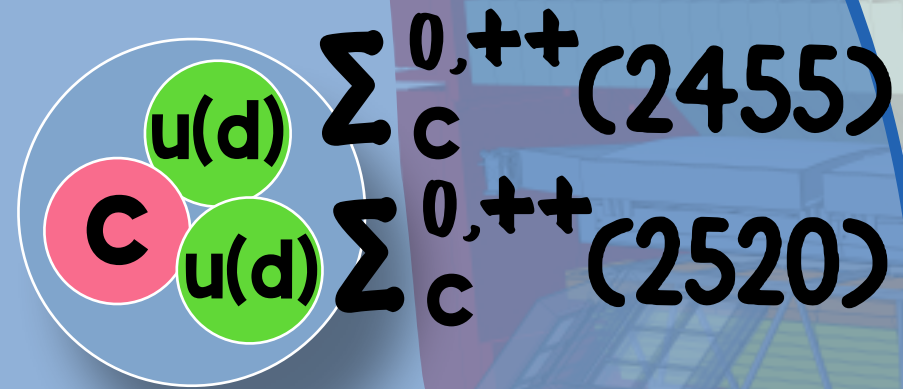


Charm baryon reconstruction

Charge conj. included for all measured hadrons

Hadronic decays

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



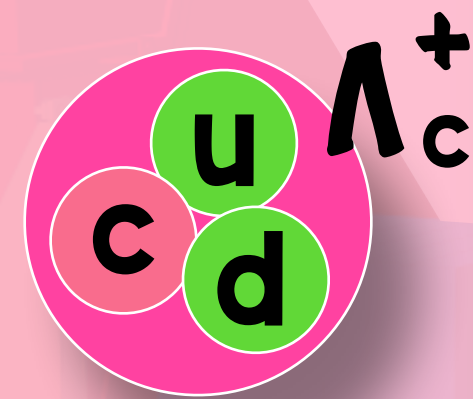
Hadronic decays

★ $\Lambda_c^+ \rightarrow p K^- \pi^+$

★ $\Lambda_c^+ \rightarrow p K_s^0$

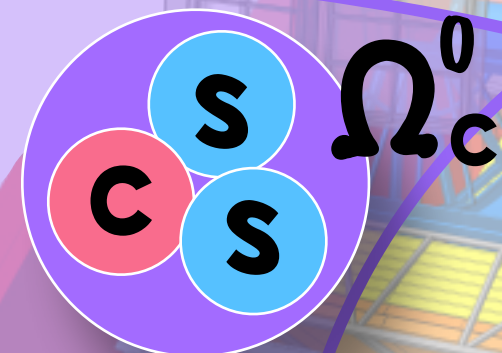
Semileptonic decays

★ $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$



Hadronic decays

★ $\Omega_c^0 \rightarrow \Omega^- \pi^+$



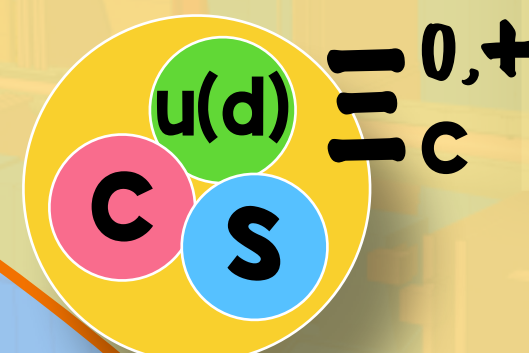
Semileptonic decays

★ $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$

Hadronic decays

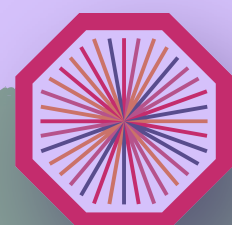
★ $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$

★ $\Xi_c^0 \rightarrow \Xi^- \pi^+$



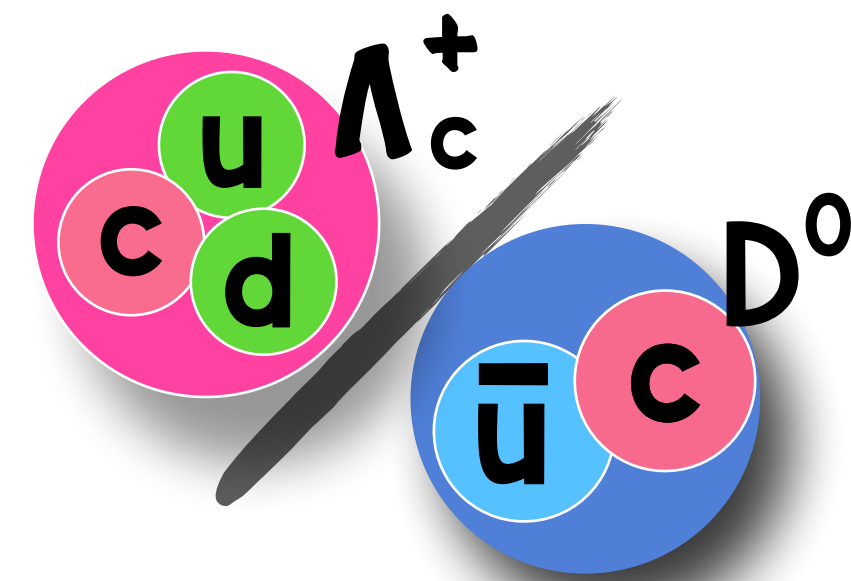
Semileptonic decays

★ $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$

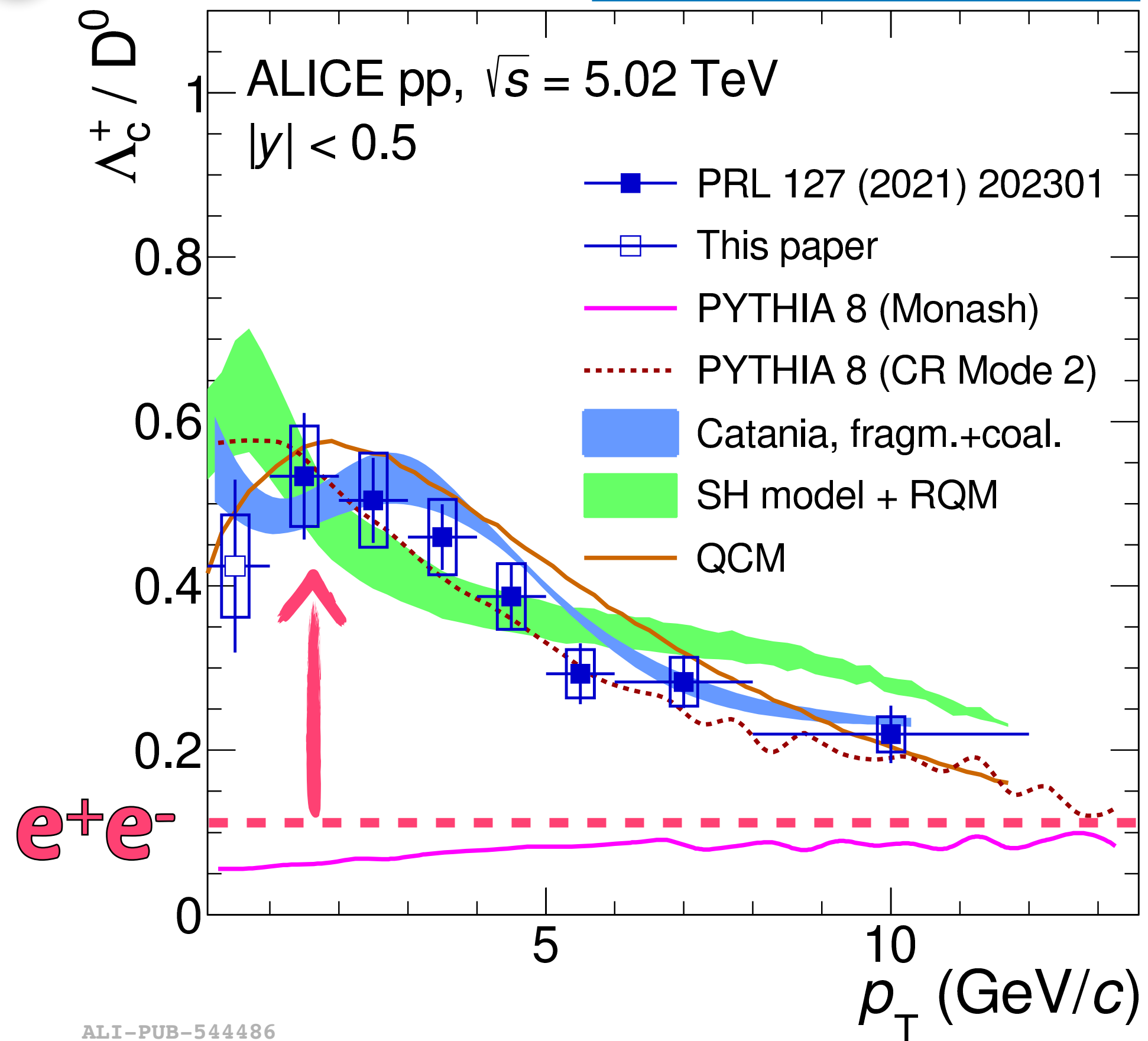


Λ_c^+ / D^0 in pp collisions

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

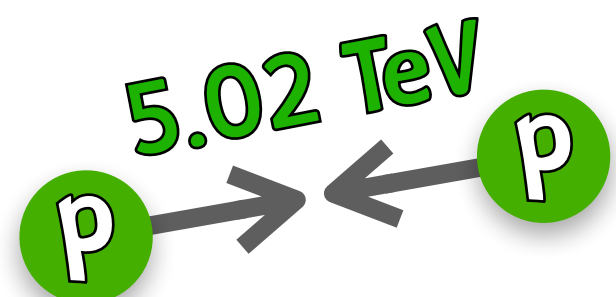
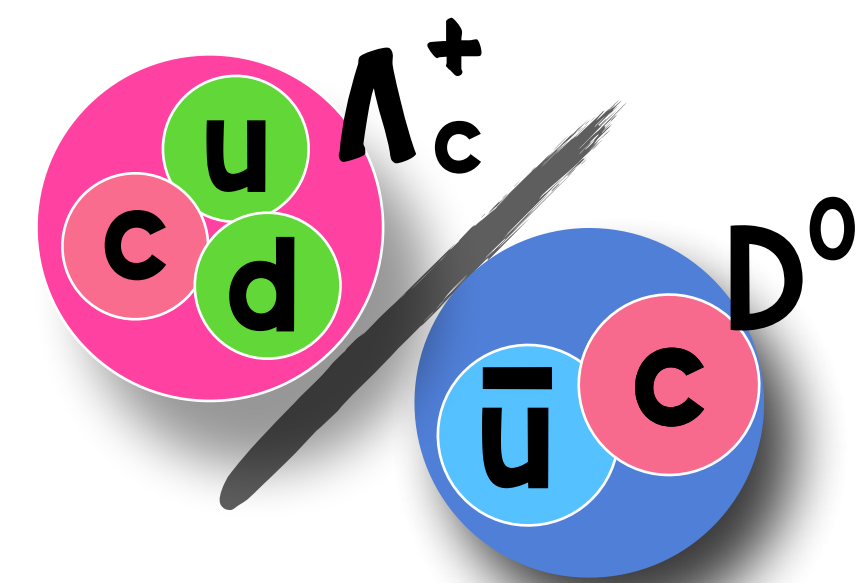
- ★ Significantly larger baryon-to-meson ratio at low and intermediate p_T and strong p_T dependence in pp collisions

ALI-PUB-544486

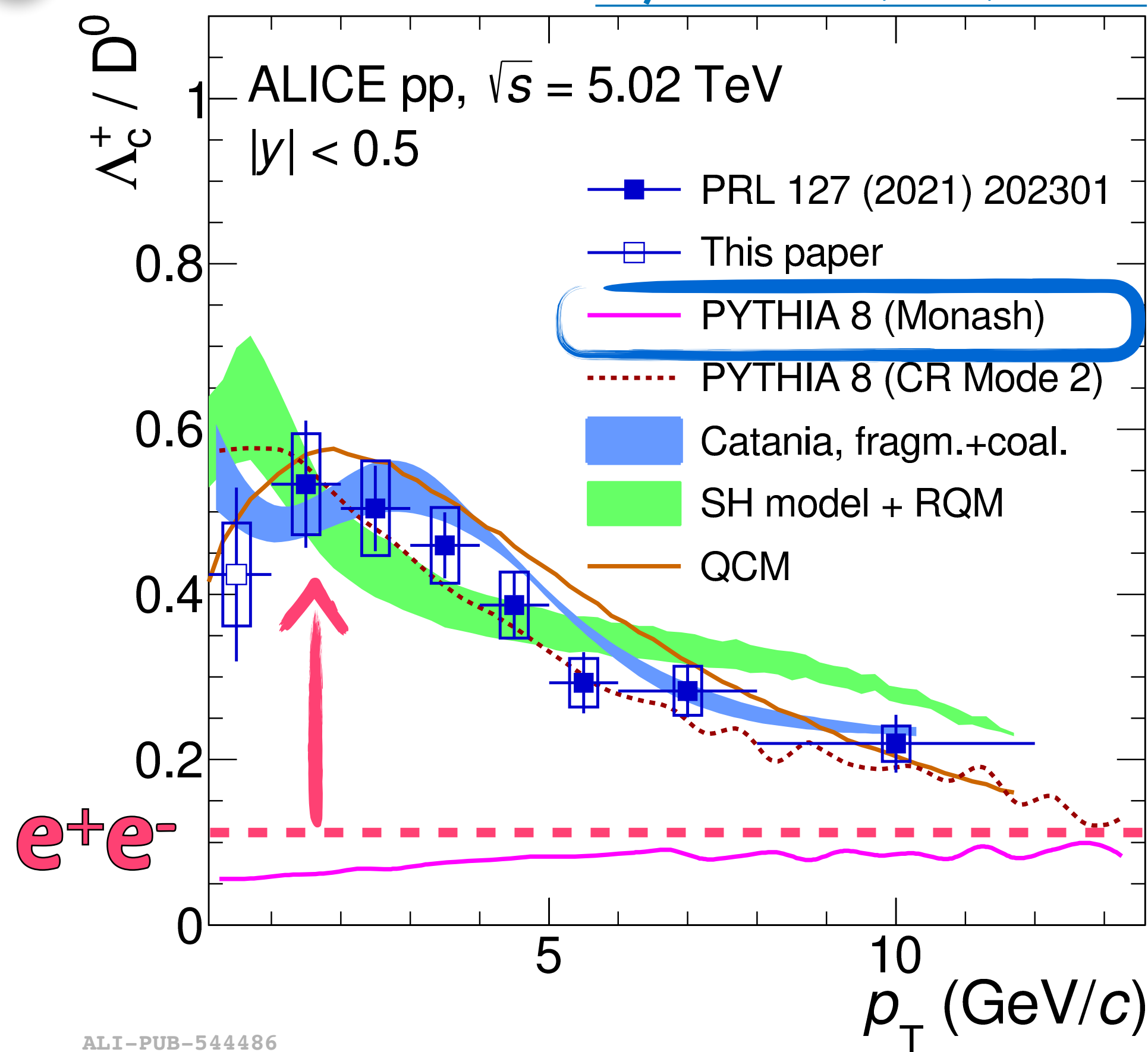


Λ_c^+ / D^0 in pp collisions

down to $p_T = 0$



Phys.Rev.C 107 (2023) 064901



ALI-PUB-544486

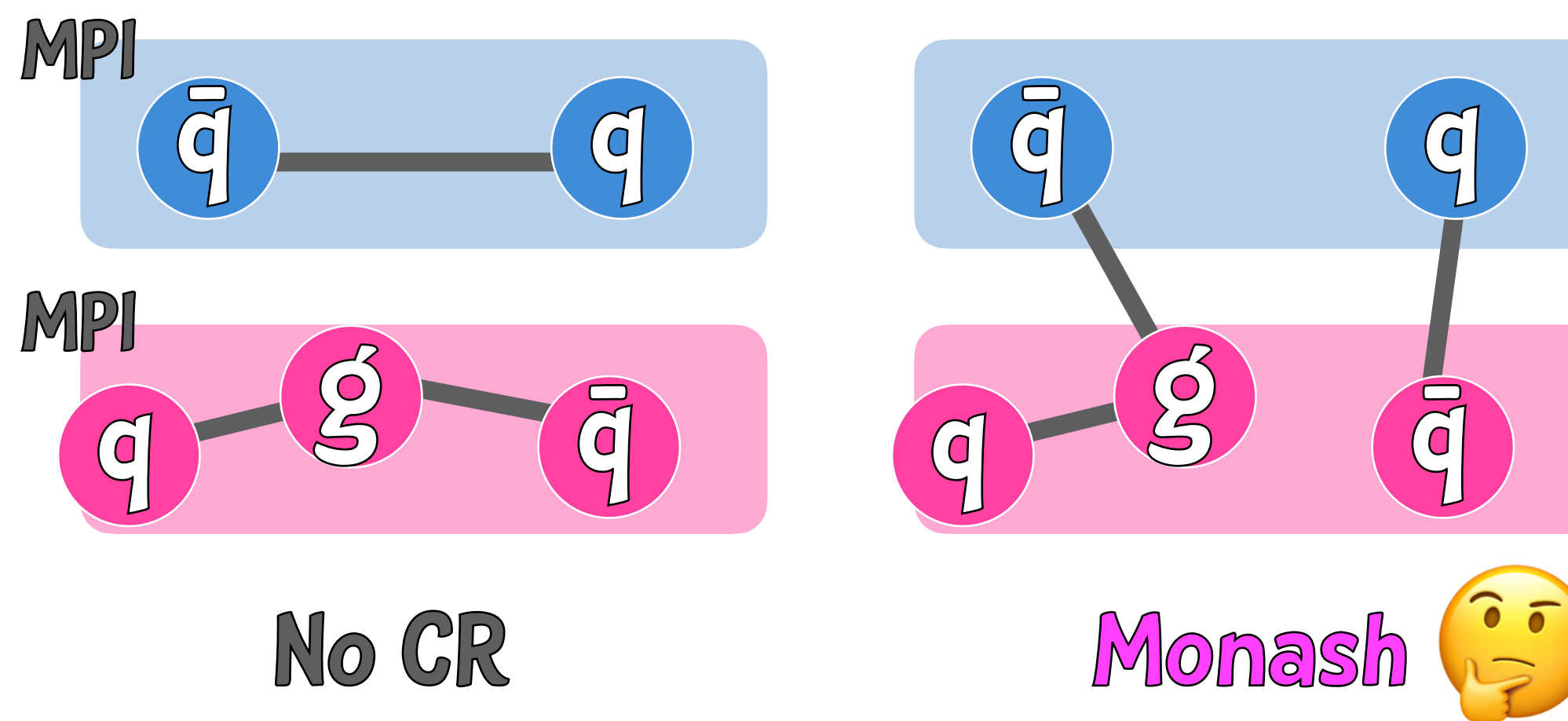
Model comparison

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

PYTHIA 8

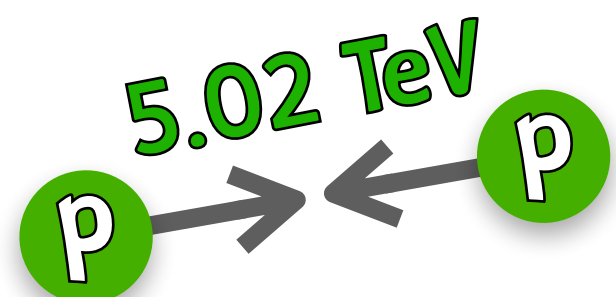
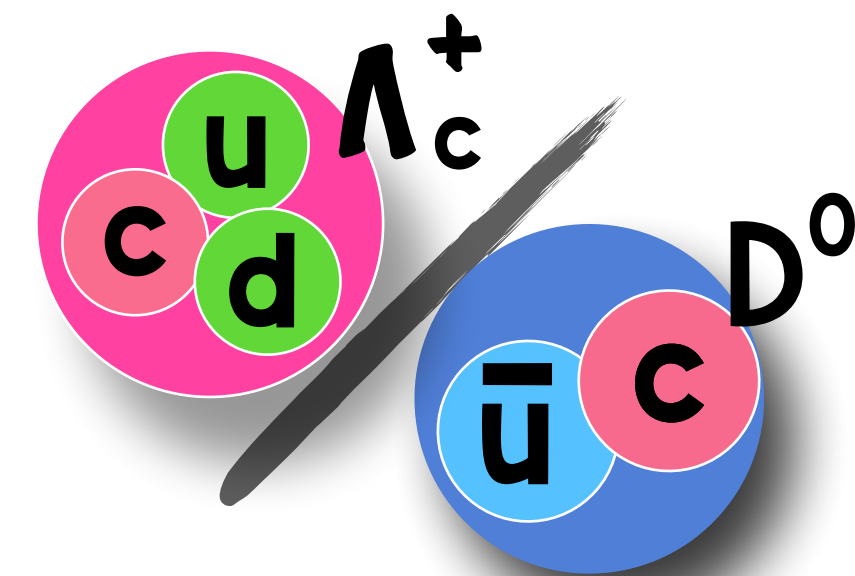
Allows colour reconnection (CR) between partons from different multiparton interactions (MPIs) to minimize the string length.

Tuned to e^+e^- and ep measurements

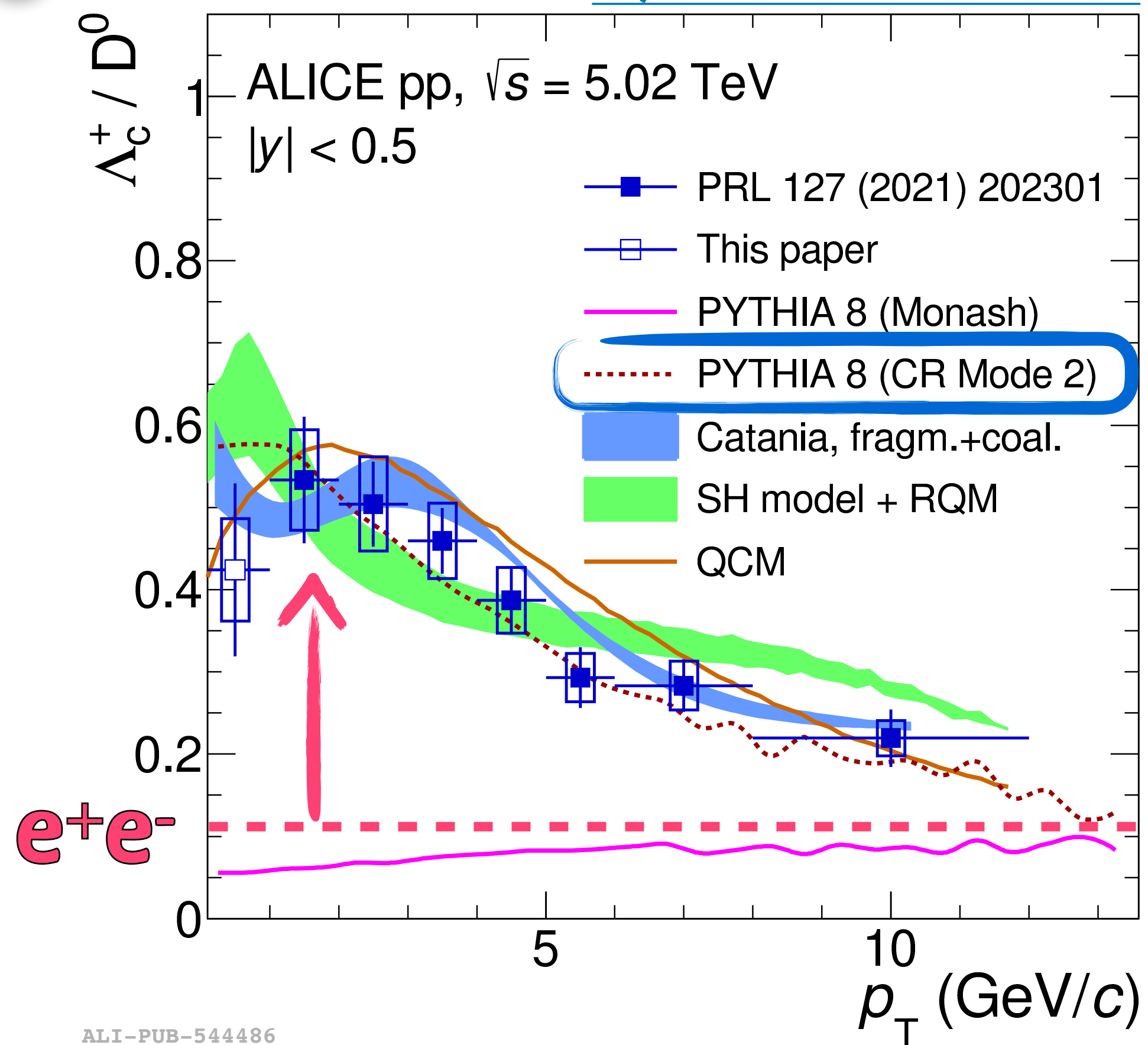


Λ_c^+ / D^0 in pp collisions

down to $p_T = 0$



Phys.Rev.C 107 (2023) 064901



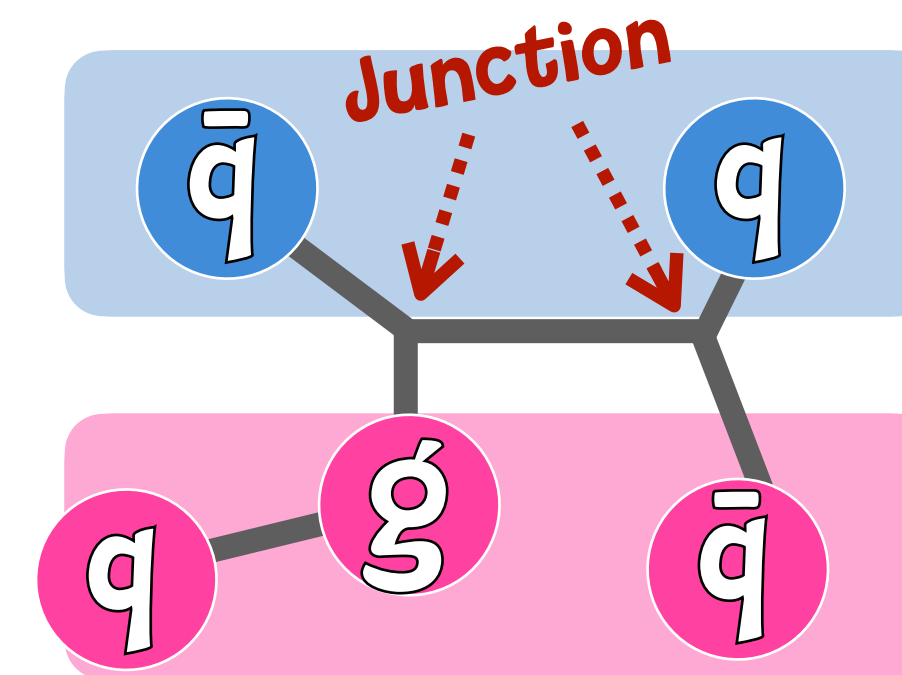
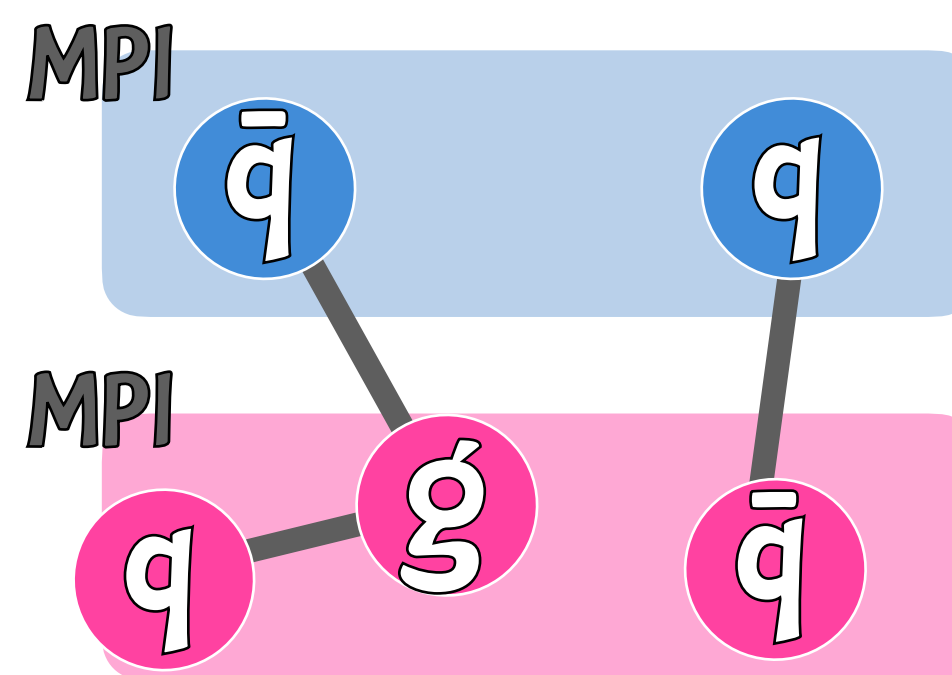
ALI-PUB-544486

Model comparison

CR Mode 2 : JHEP 08 (2015) 003

PYTHIA 8

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



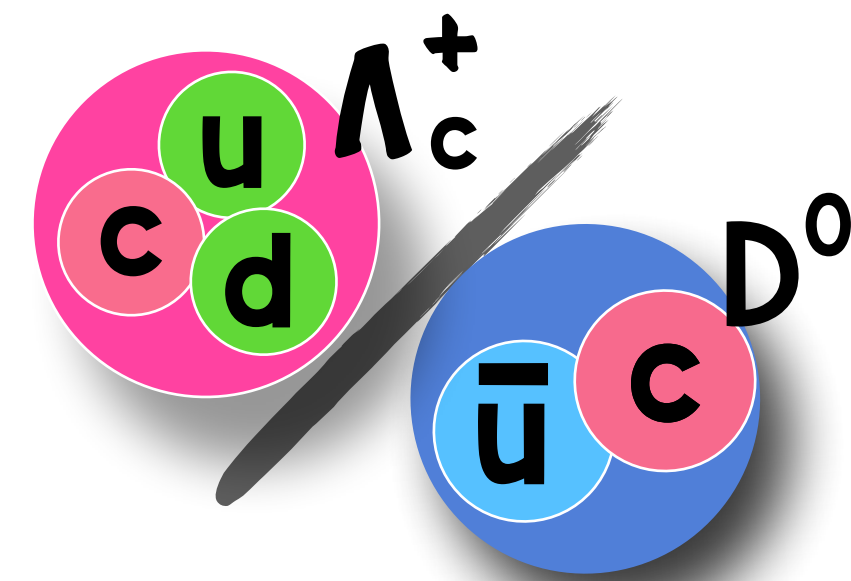
Monash

CR Mode 2

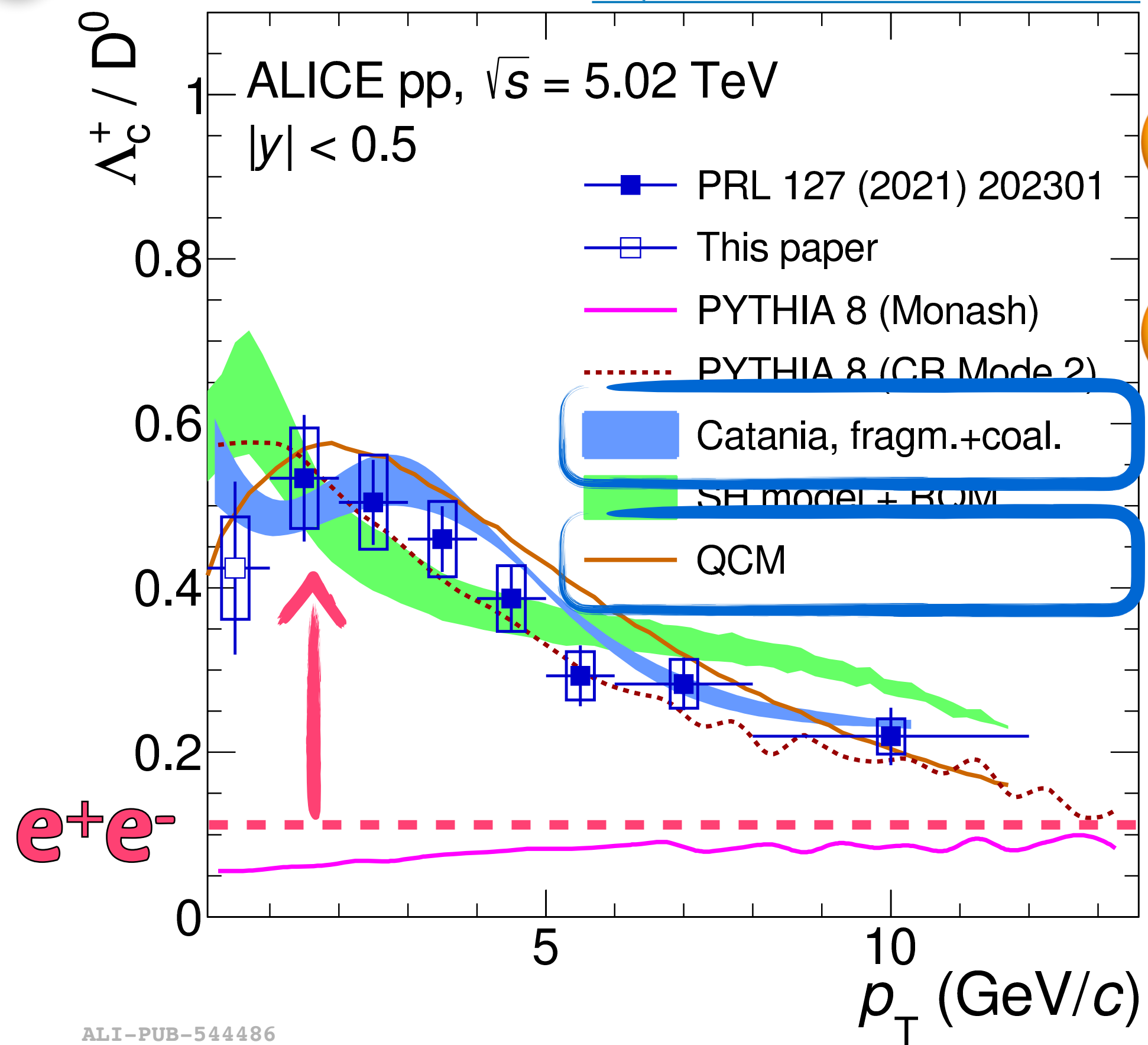


Λ_c^+ / D^0 in pp collisions

down to $p_T = 0$



Phys.Rev.C 107 (2023) 064901



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Model comparison

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

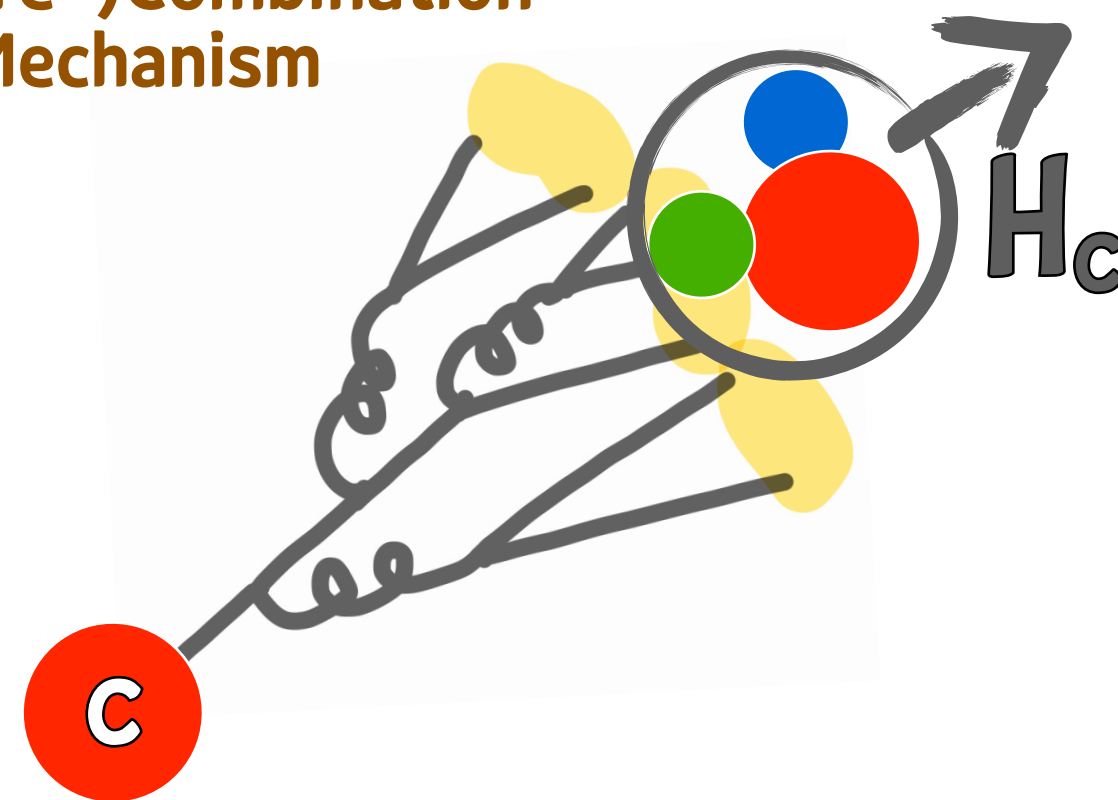
💖💖 Catania

Hadronization via both fragmentation and coalescence

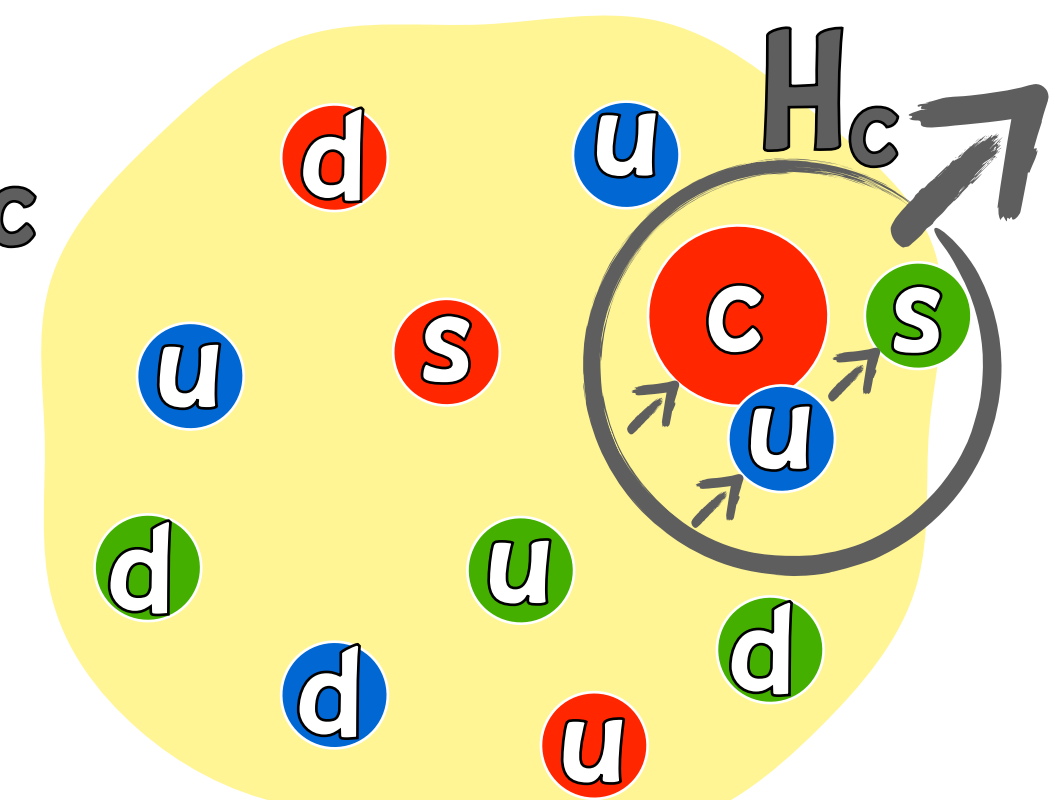
💖💖 QCM
Quark (re-)Combination Mechanism

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

Charm quark combines with light quarks close in space and momentum



Fragmentation

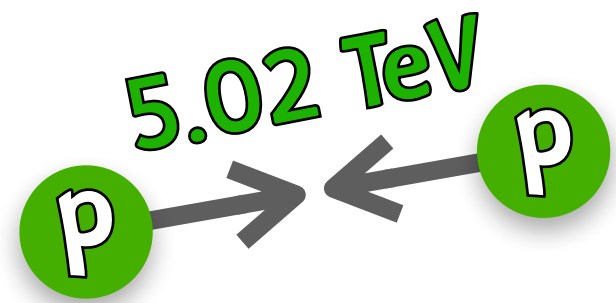
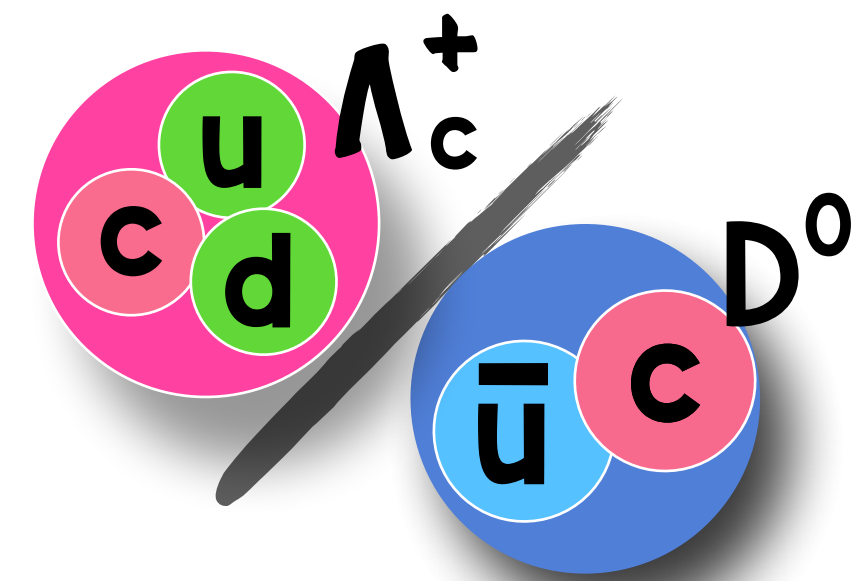


Coalescence



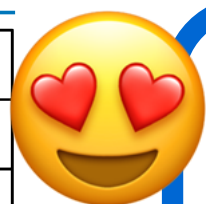
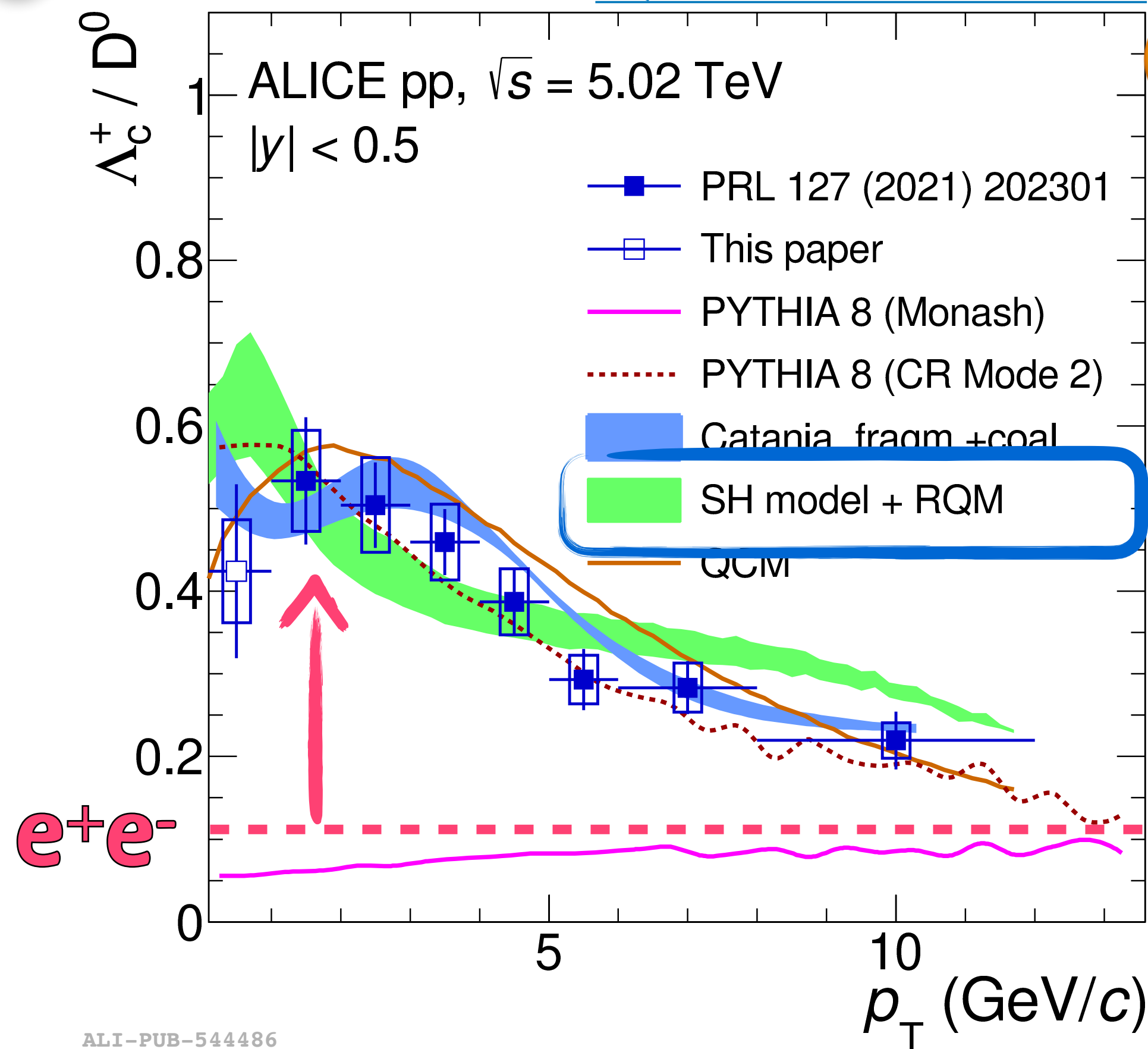
Λ_c^+ / D^0 in pp collisions

down to $p_T = 0$



Model comparison

Phys.Rev.C 107 (2023) 064901



Statistical model + RQM

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

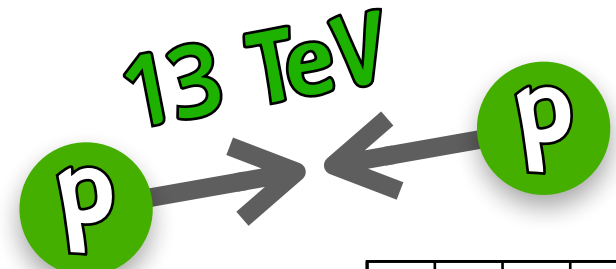
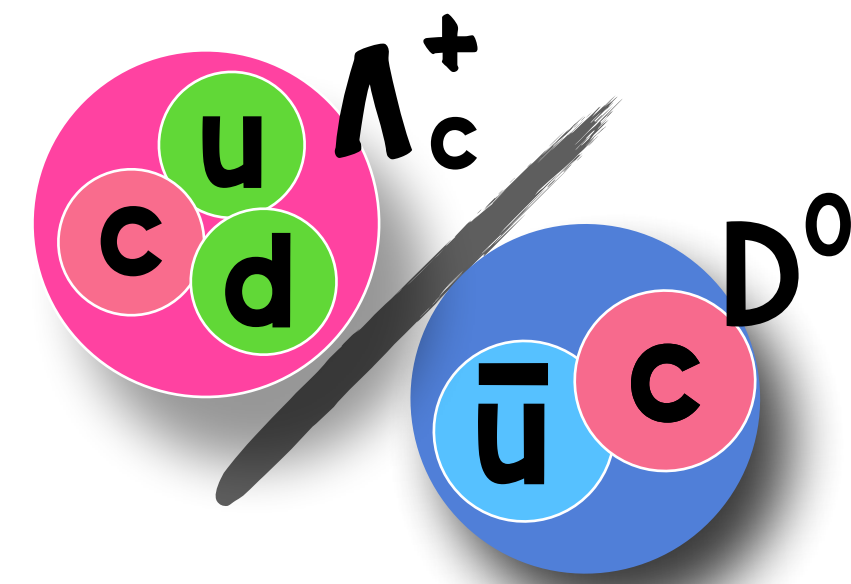
- ★ Hadronization driven by the species statistical weight
 - Weights are governed by the masses of hadron states at hadronization temperature
- ★ Feed-down from (not yet measured) charm baryon states
 - Takes a large enhanced set of charm baryon state beyond the current list of PDG into account
 - PDG : 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

ALI-PUB-544486

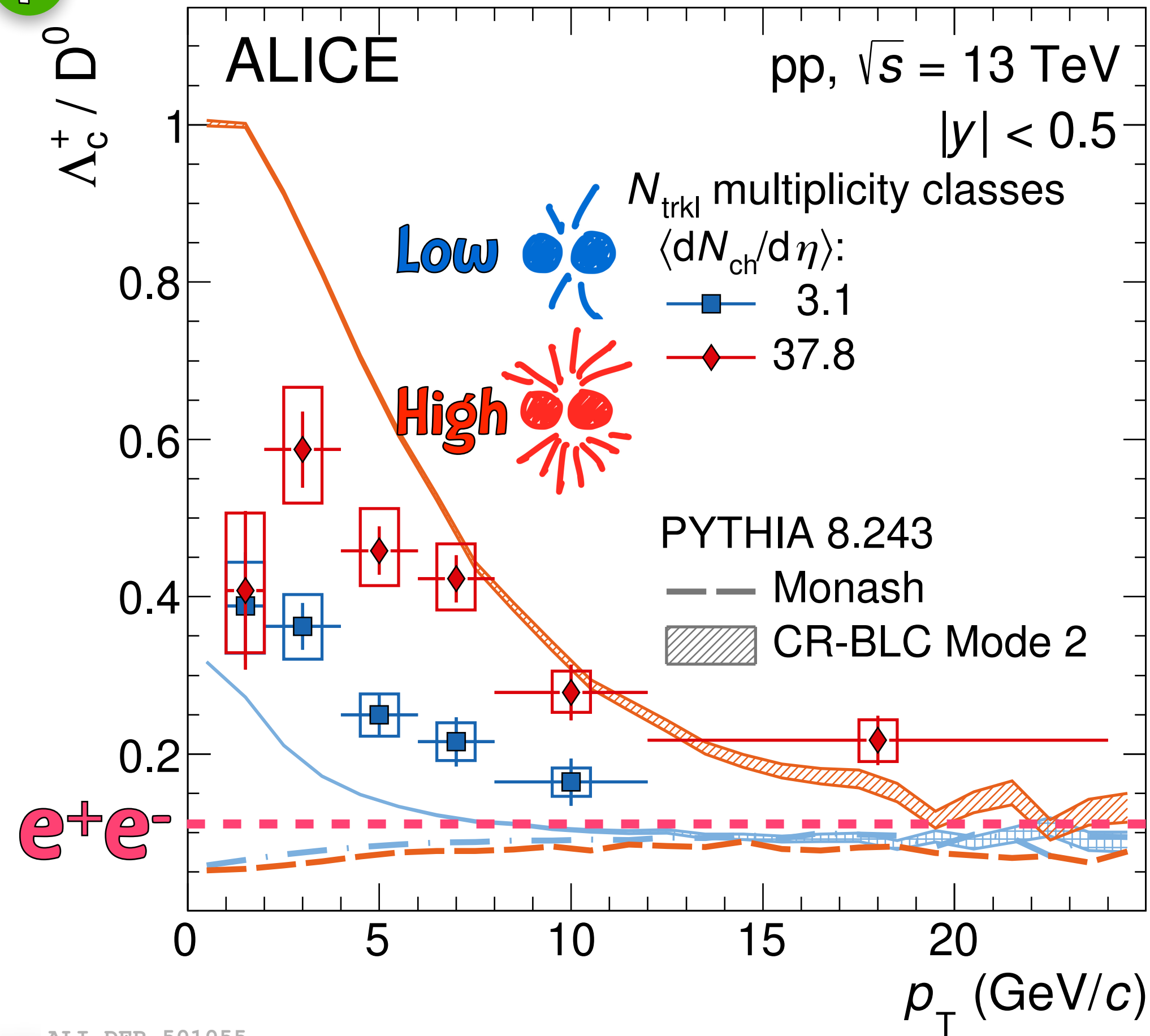


Λ_c^+ / D^0 vs. event multiplicity

in pp collisions



Phys.Lett.B 829 (2022) 137065



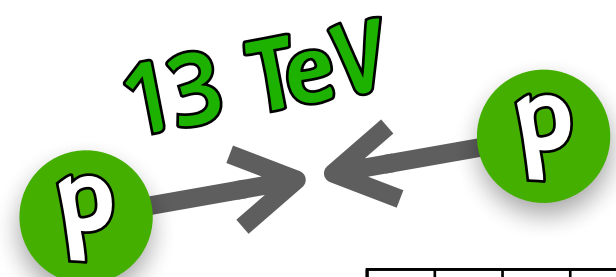
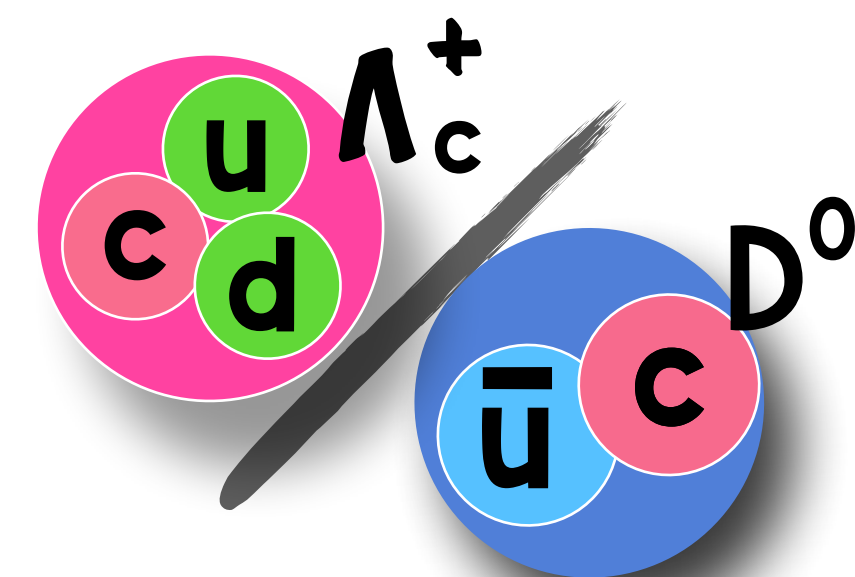
Multiplicity dependence in baryon-to-meson ratio

- ★ 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

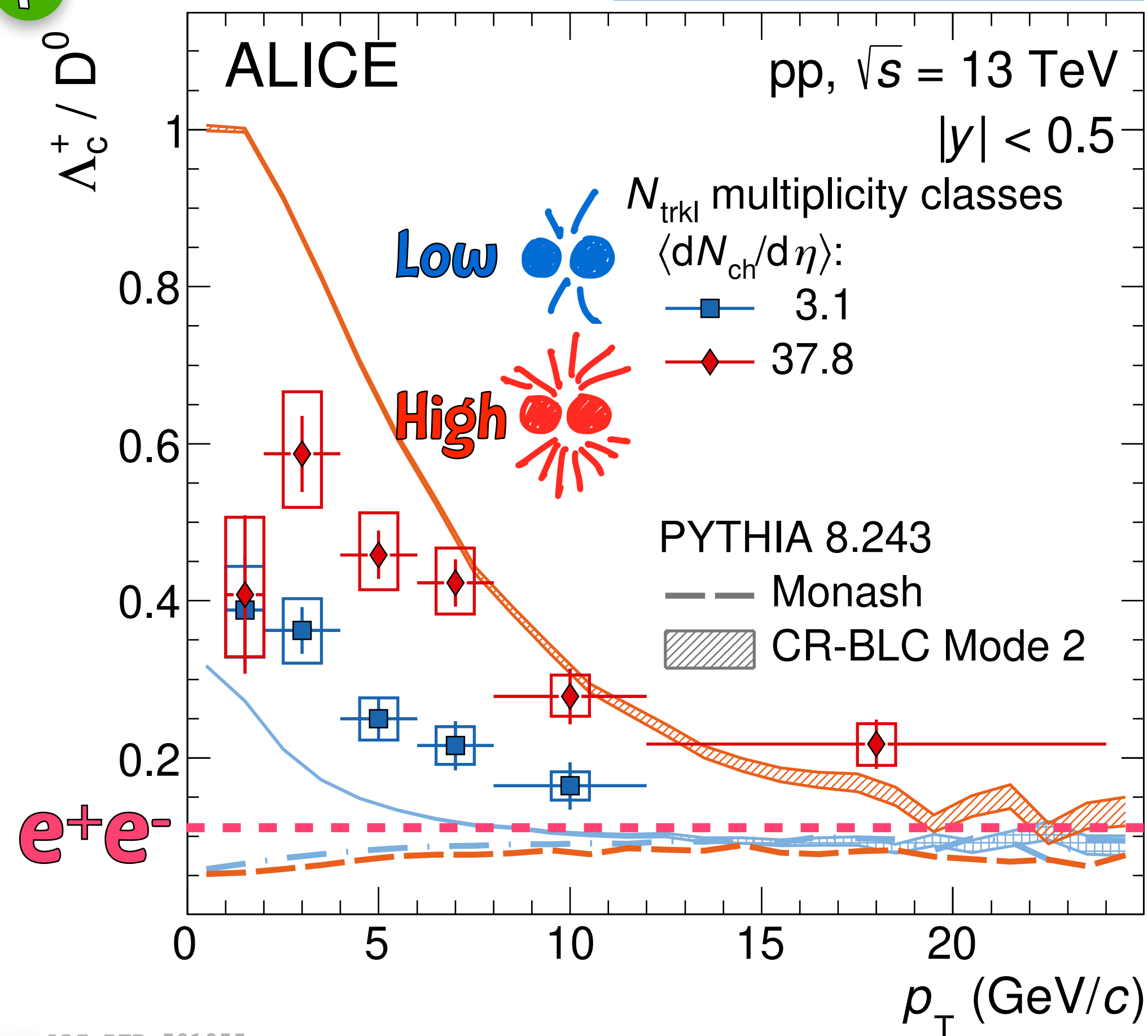
ALI-DER-501055

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

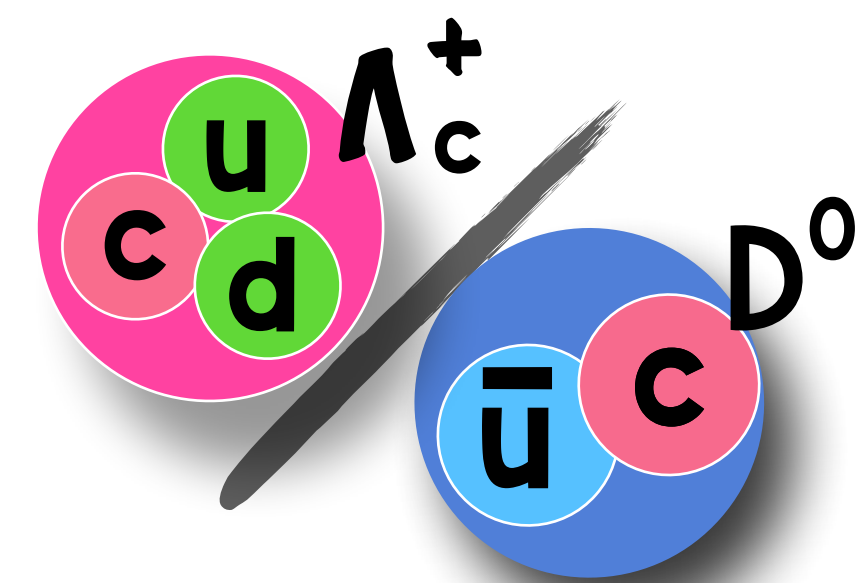
- ★ PYTHIA 8 Monash doesn't reproduce neither magnitude nor multiplicity dependence
- ★ PYTHIA 8 Mode 2 provides better description than Monash

ALI-DER-501055

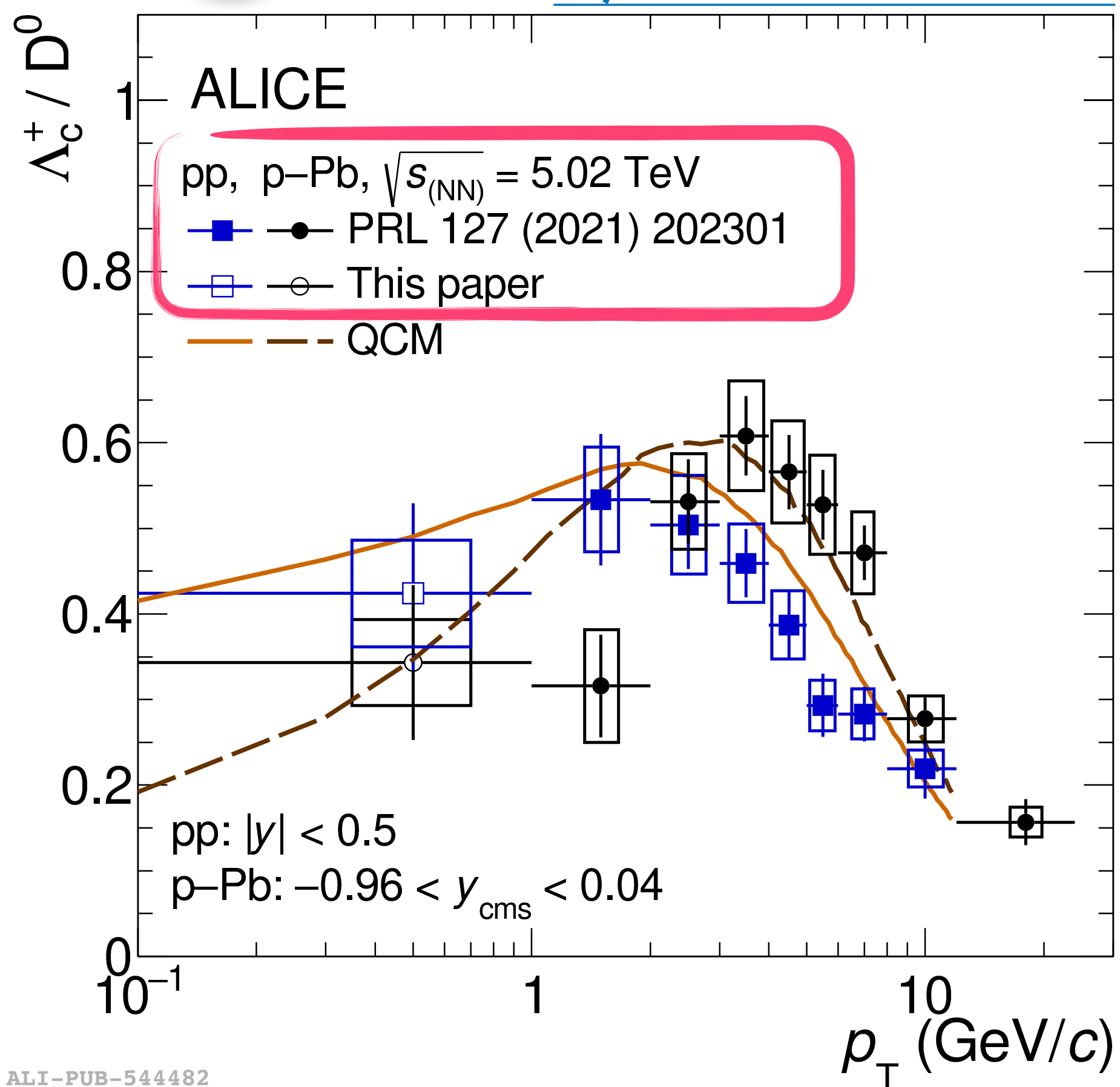


Λ_c^+ / D^0 in p-Pb collisions

down to $p_T = 0$



Phys.Rev.C 107 (2023) 064901



Collision system dependence

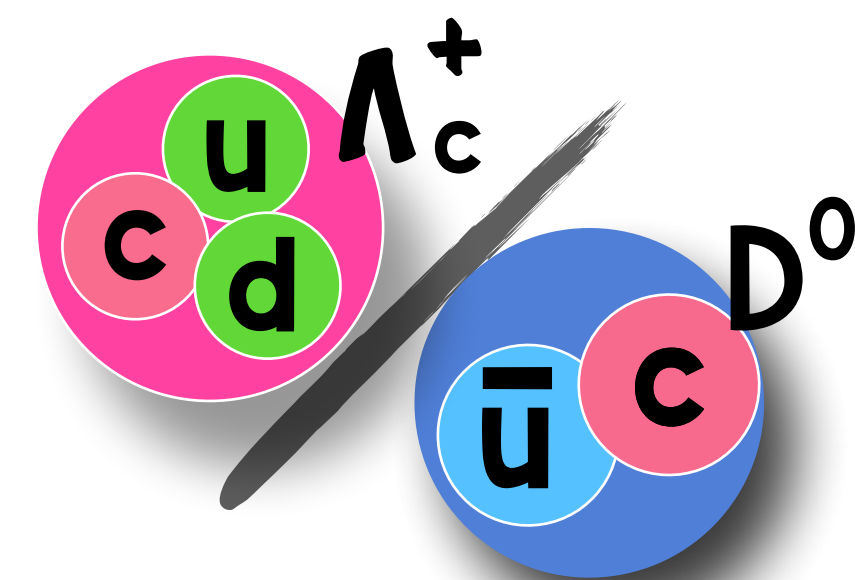
★ The overall magnitude of enhancement in Λ_c^+ / D^0 ratios with respect to e^+e^- collisions is similar between pp and p-Pb collisions within uncertainties

ALI-PUB-544482

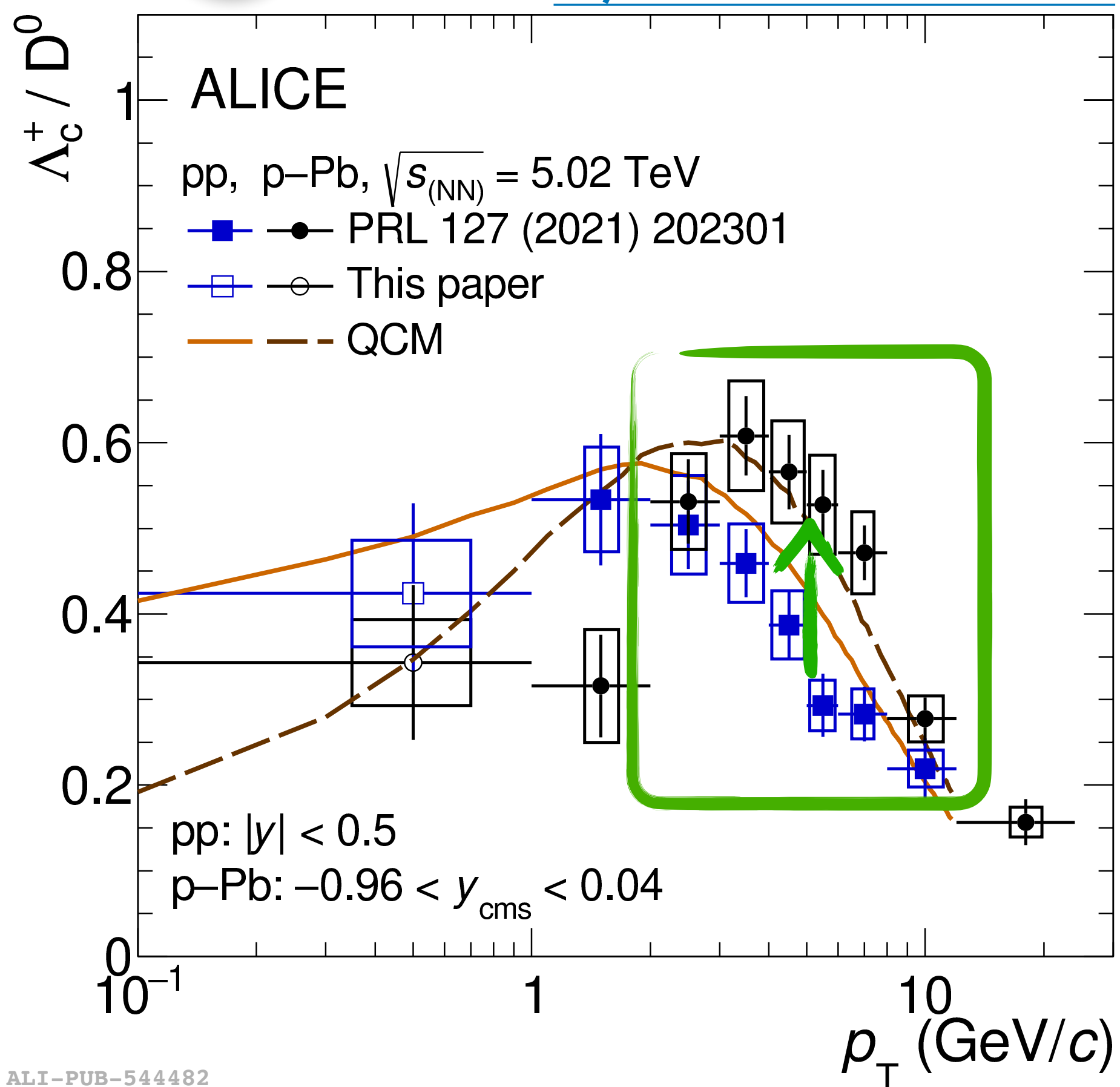


Λ_c^+ / D^0 in p-Pb collisions

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

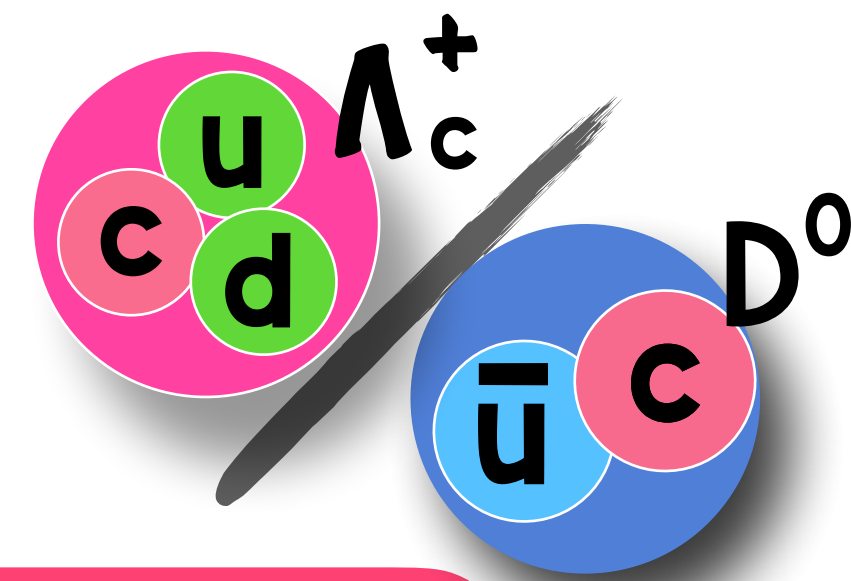
Modification of p_T spectra?

- ★ 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?

ALI-PUB-544482

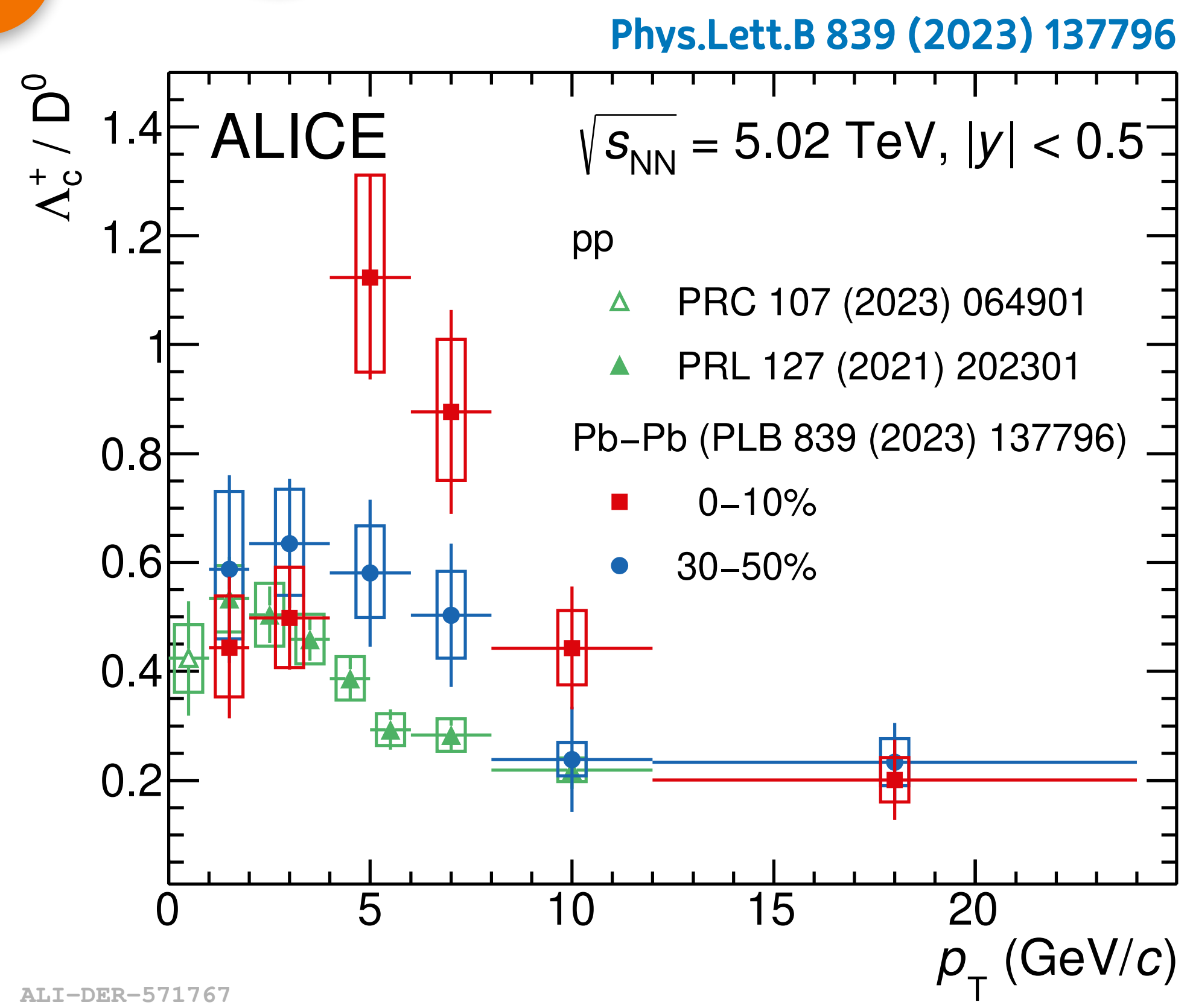


Λ_c^+ / D^0 in Pb-Pb collisions



Collision system dependence

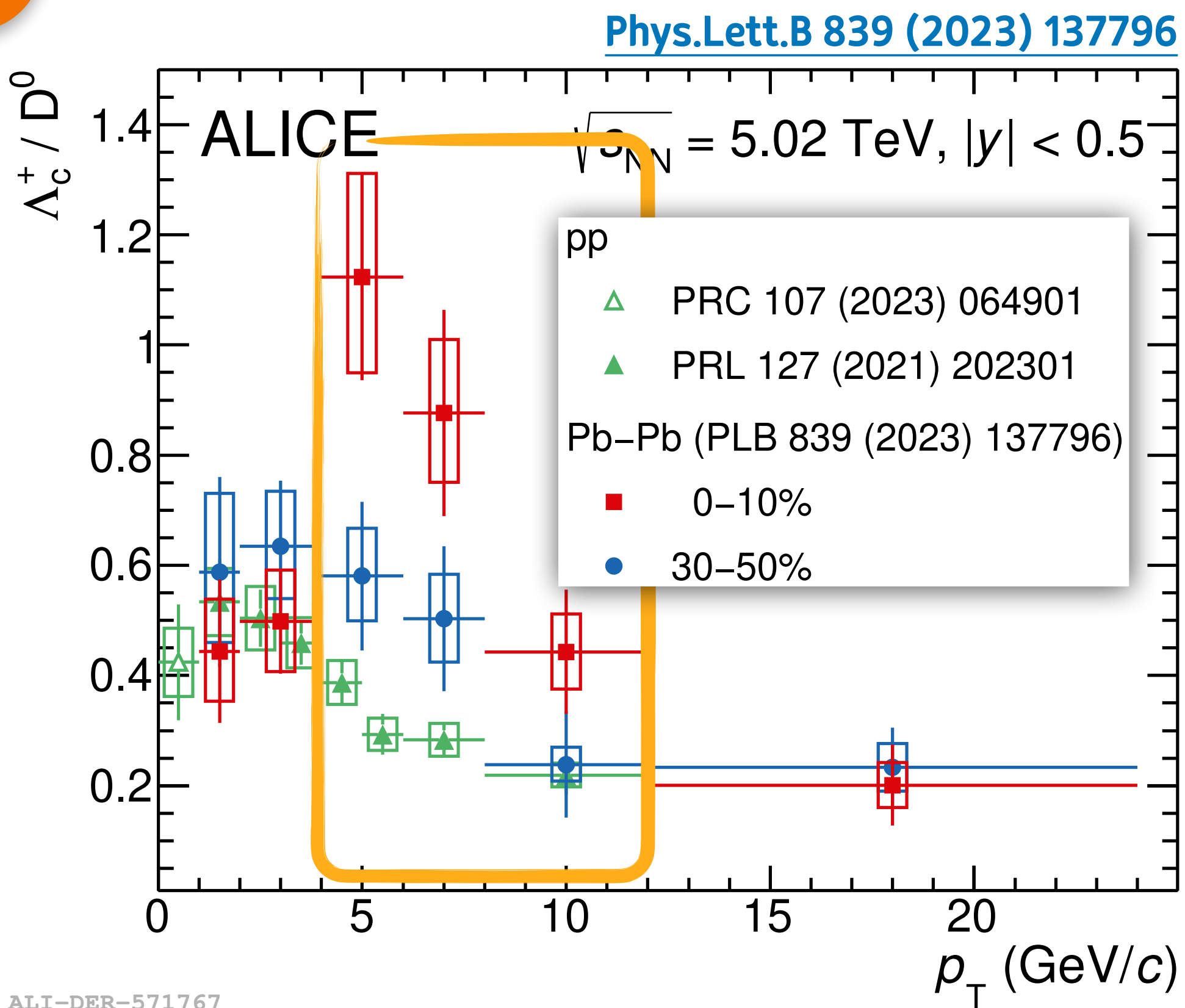
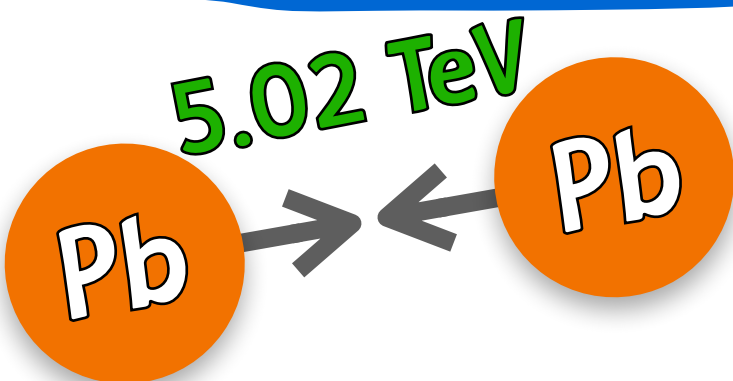
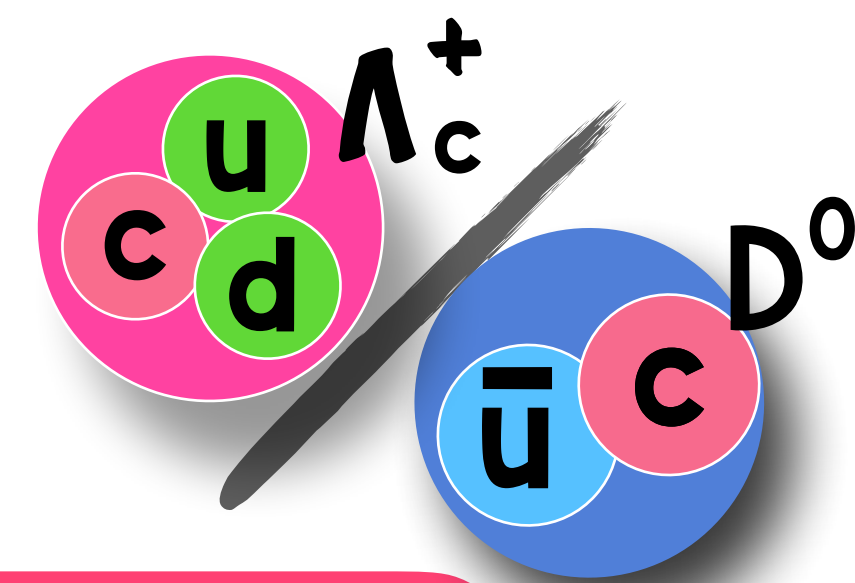
★ Indication for enhancement of Λ_c^+ / D^0 at intermediate p_T in Pb—Pb collisions with respect to pp collisions



ALI-DER-571767



Λ_c^+ / D^0 in Pb-Pb collisions



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 2.3σ for Pb—Pb 0-10% and by 2.4σ for Pb—Pb 30-50%
- ★ Due to recombination? Or radial flow?

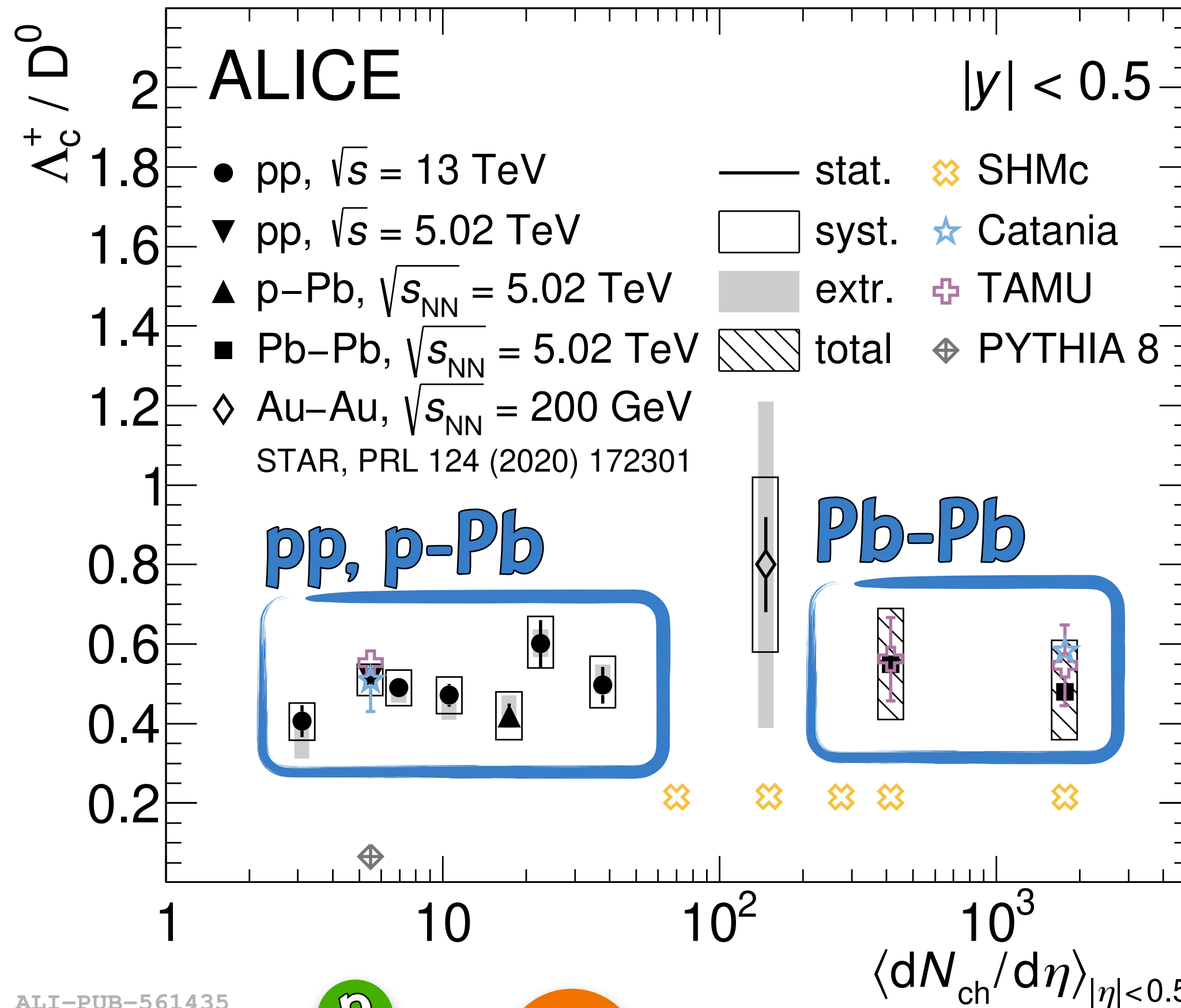
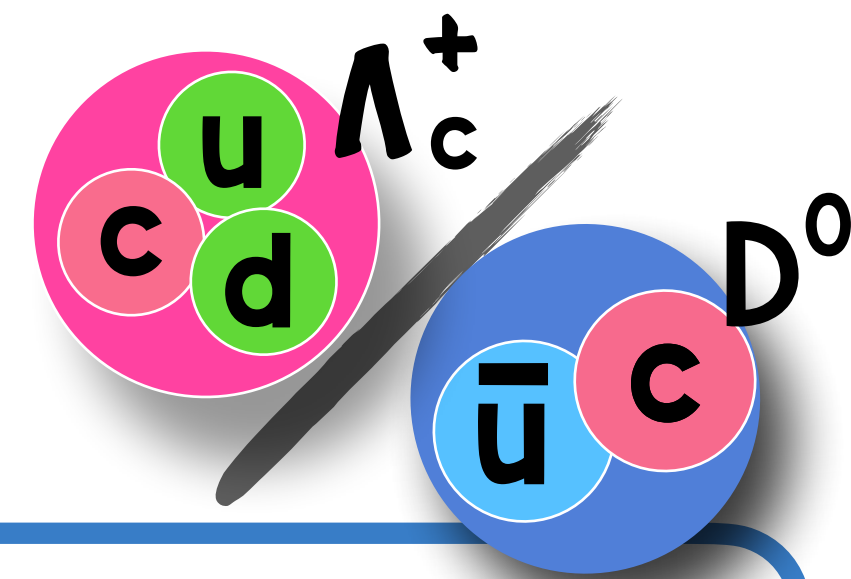
ALI-DER-571767



Λ_c^+ / D^0 in hadronic collisions

p_T integrated

Phys.Lett.B 839 (2023) 137796

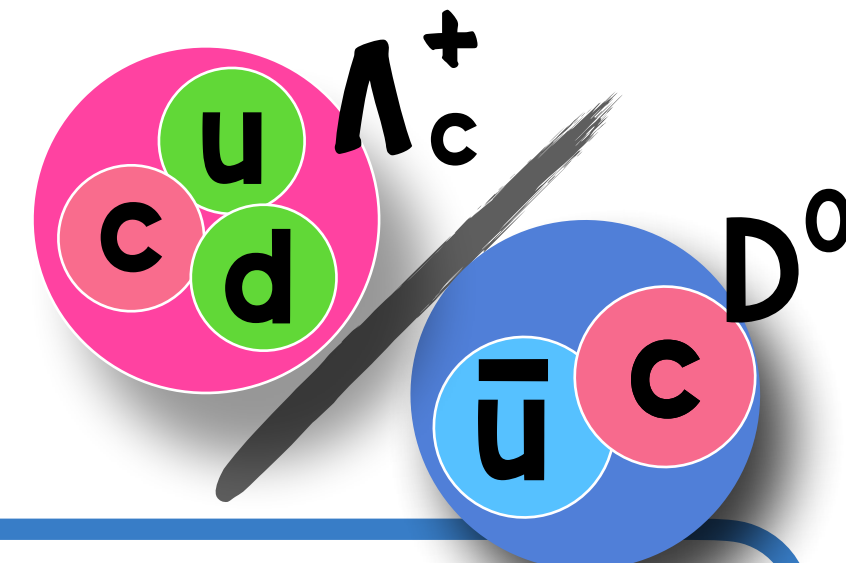


Among hadronic collisions

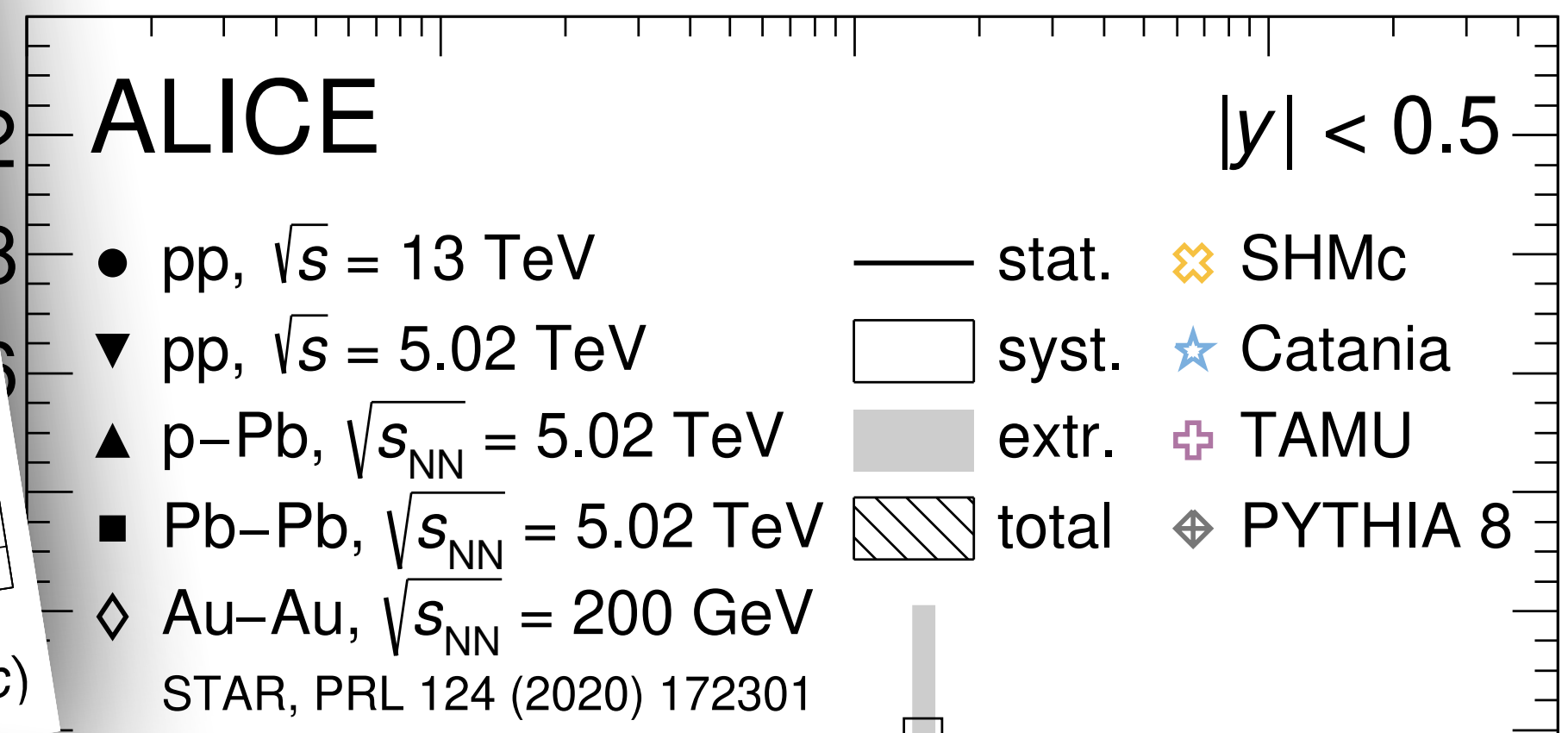
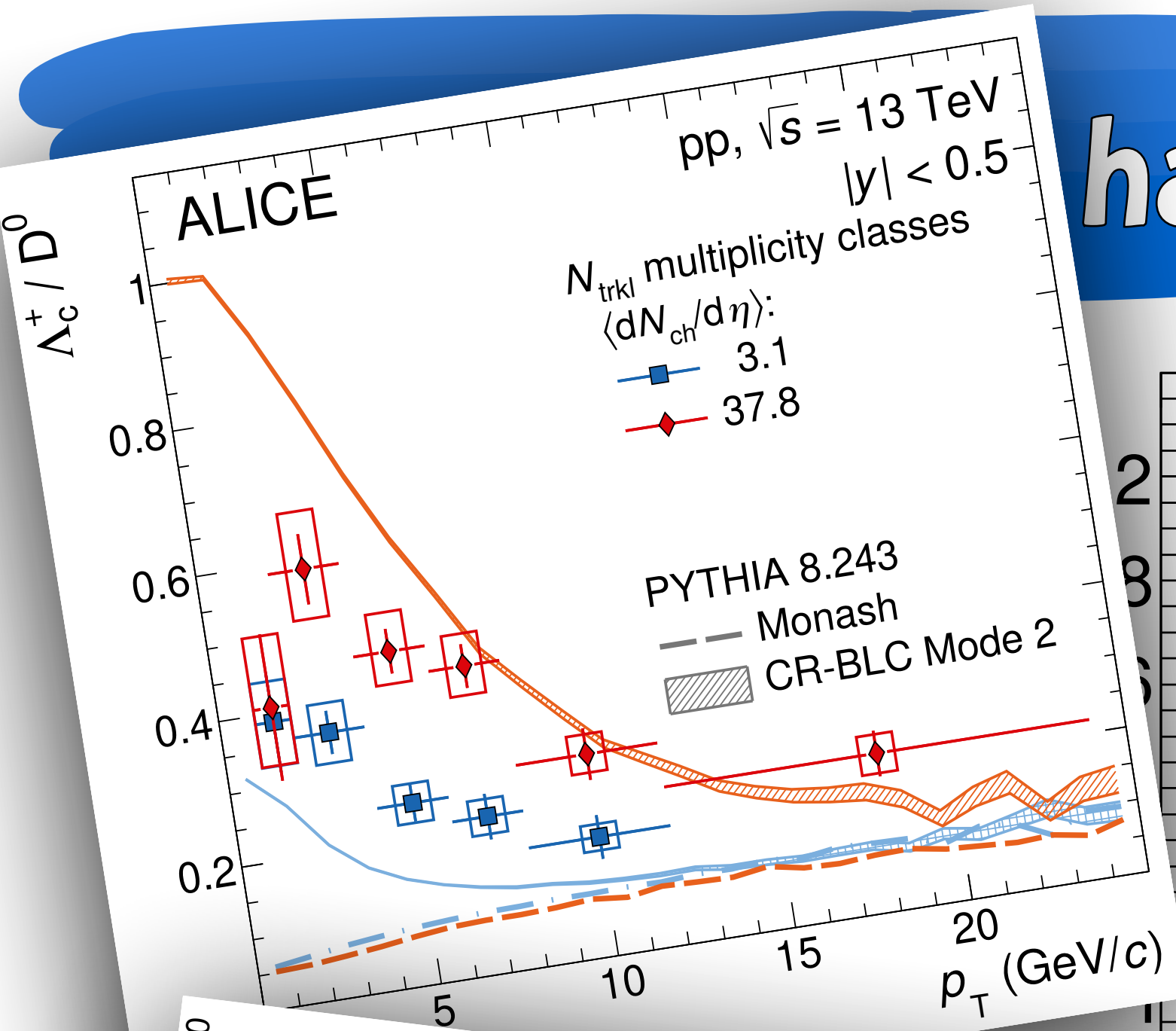
★ NO multiplicity dependence in p_T integrated Λ_c^+ / D^0 ratios within the uncertainty



hadronic collisions

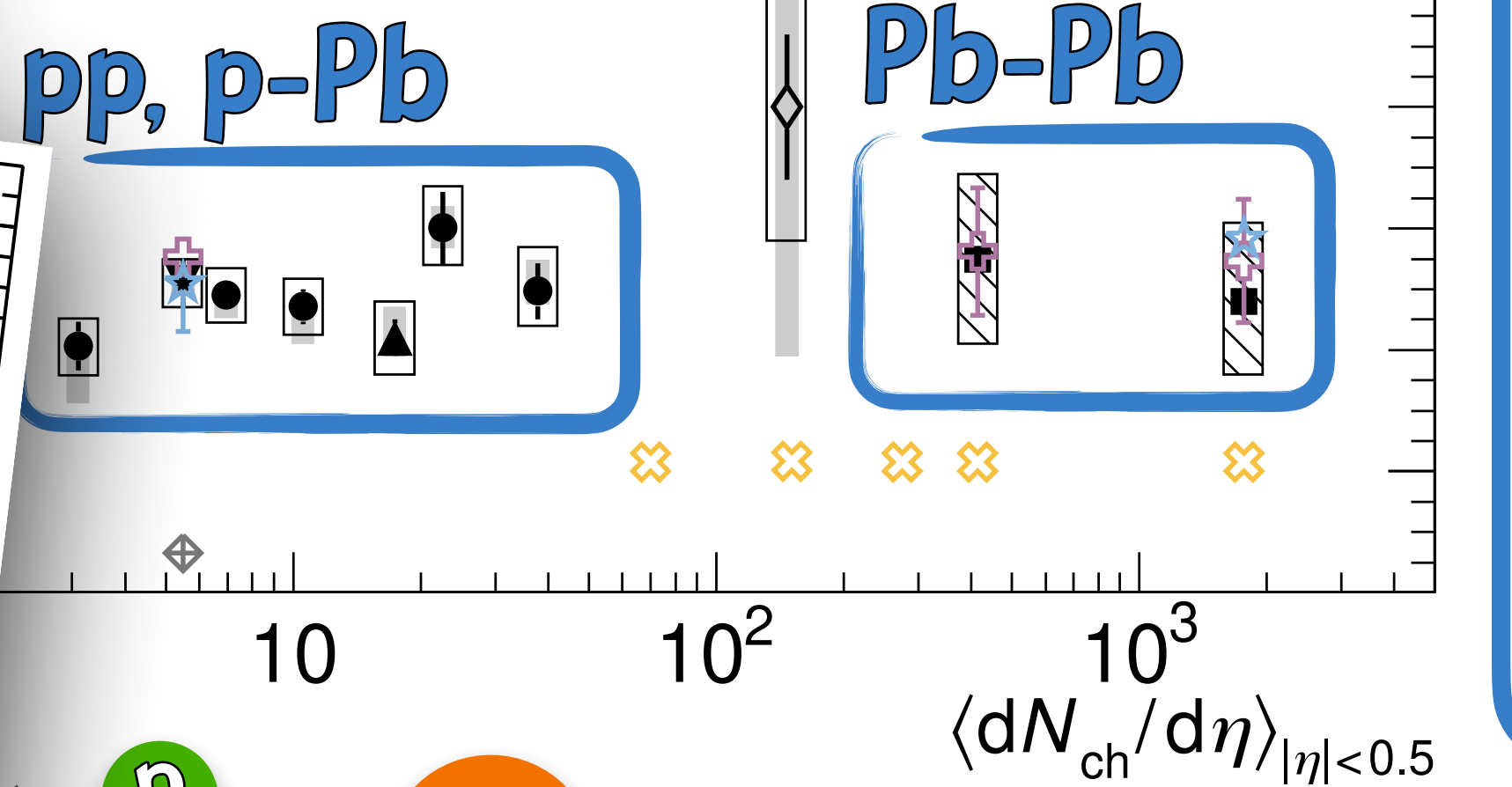
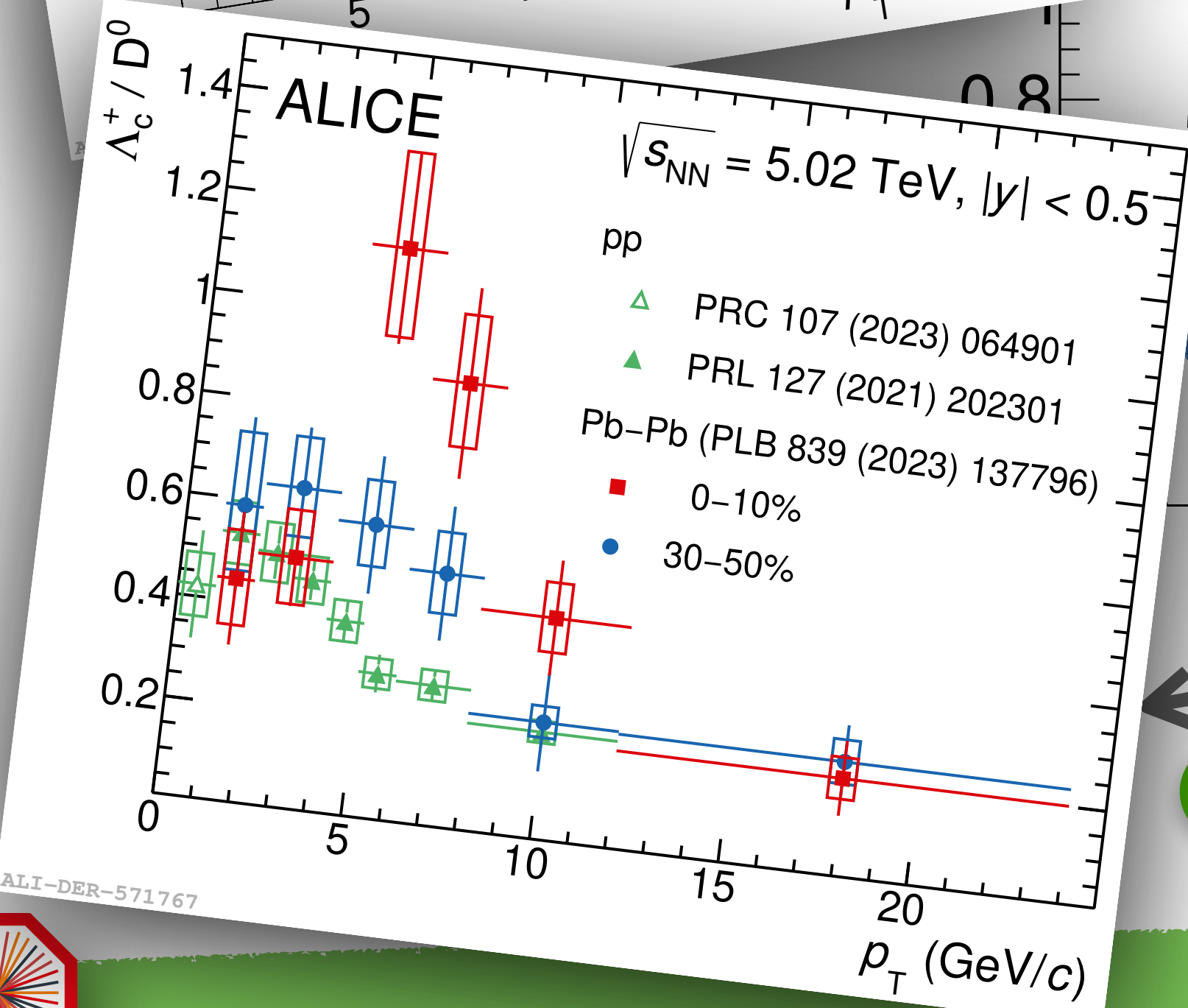


Phys.Lett.B 839 (2023) 137796

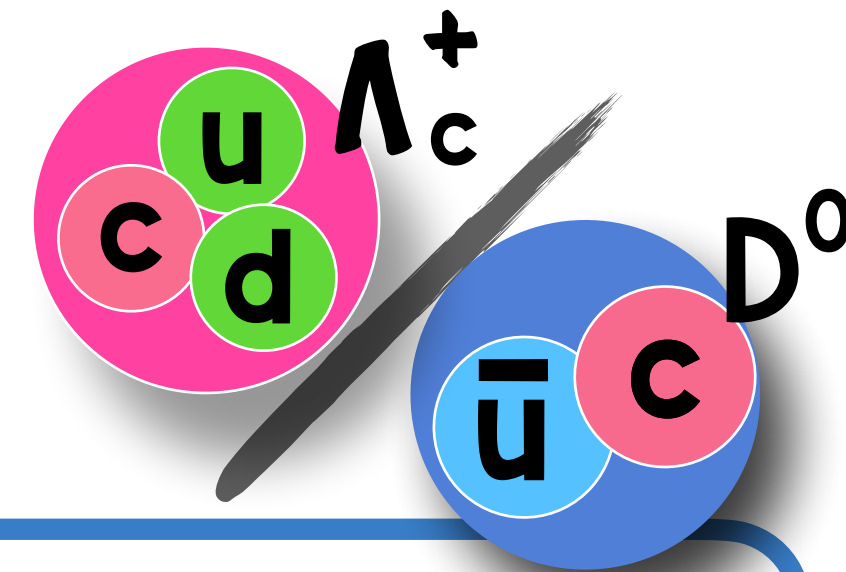


Among hadronic collisions

- ★ 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



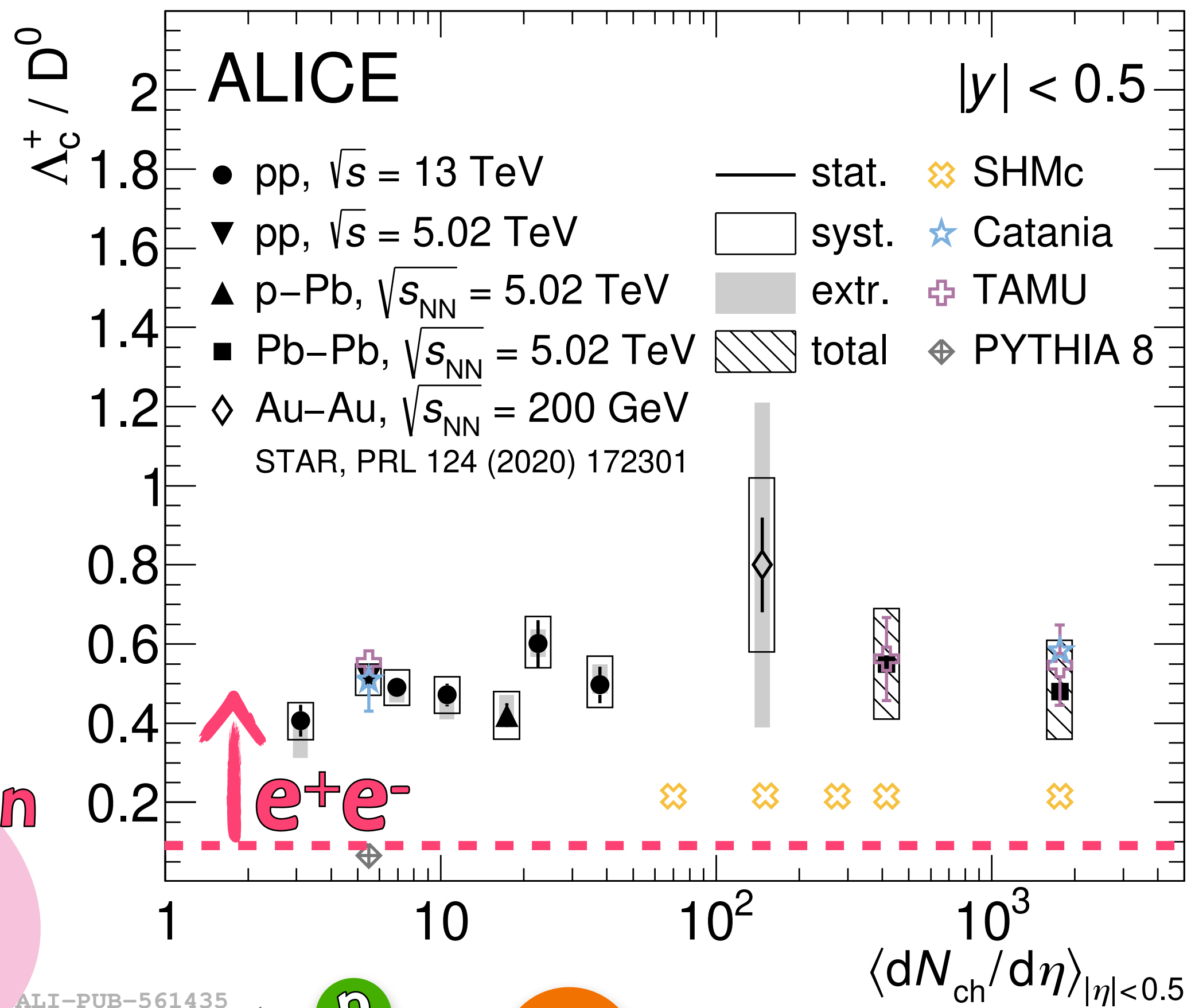
Phys.Lett.B 839 (2023) 137796

p_T integrated

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?



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

From Run 3 data



NEW!



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

★ First measurement

production at $\sqrt{s} = 13.6$ TeV

★ In meas

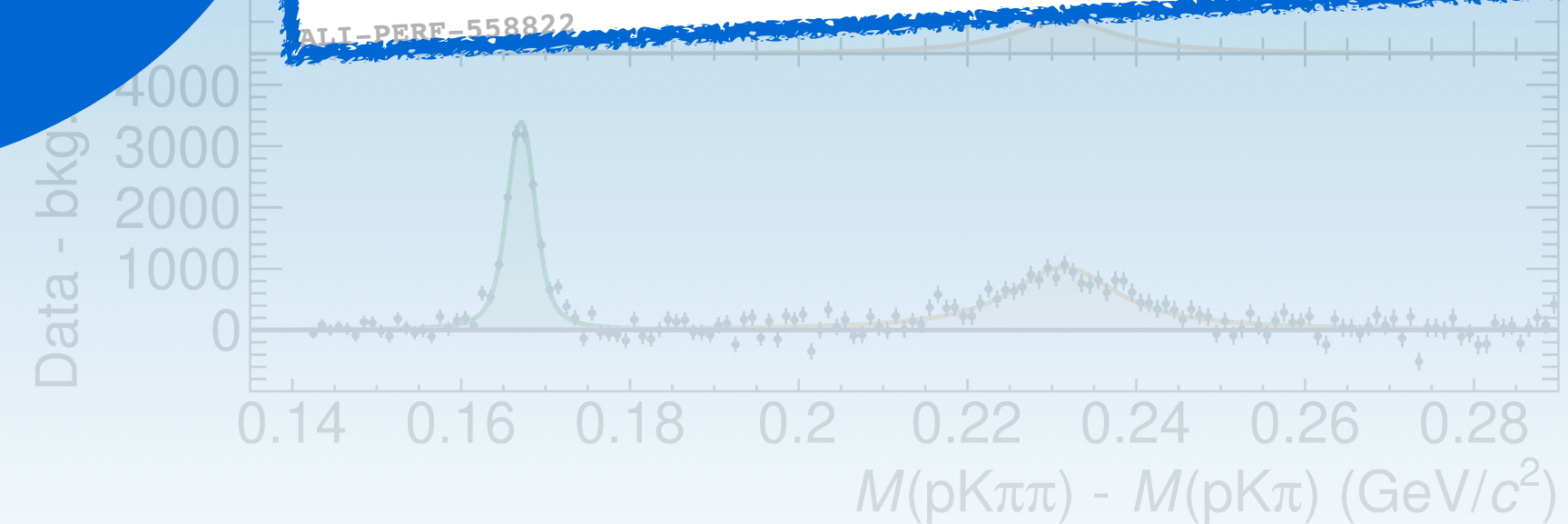
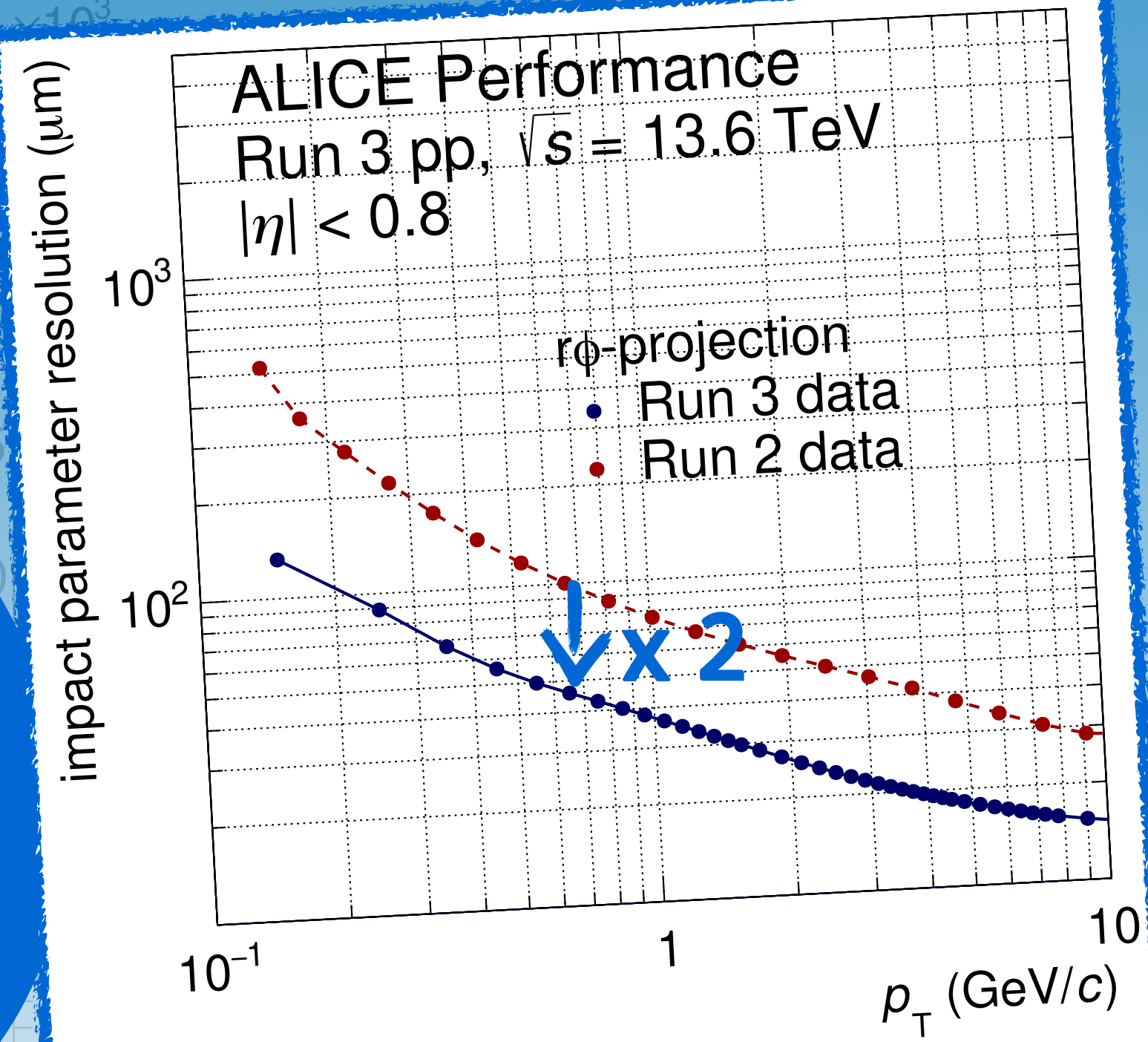
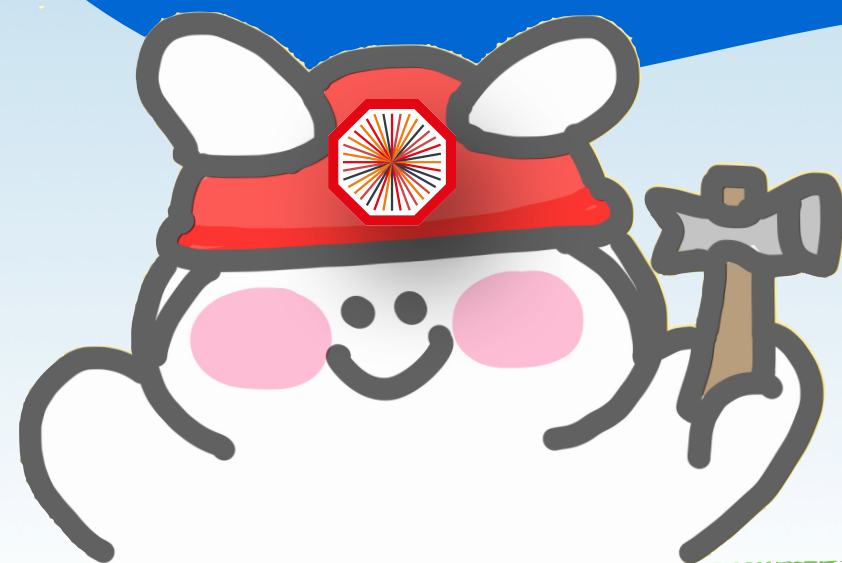
$\Sigma_c^{0,++}$ s

consist

uncerta

Comparing to Run 2 data,

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

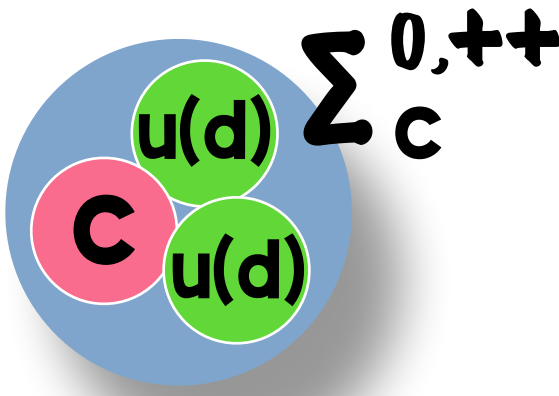


ALI-PREL-571534



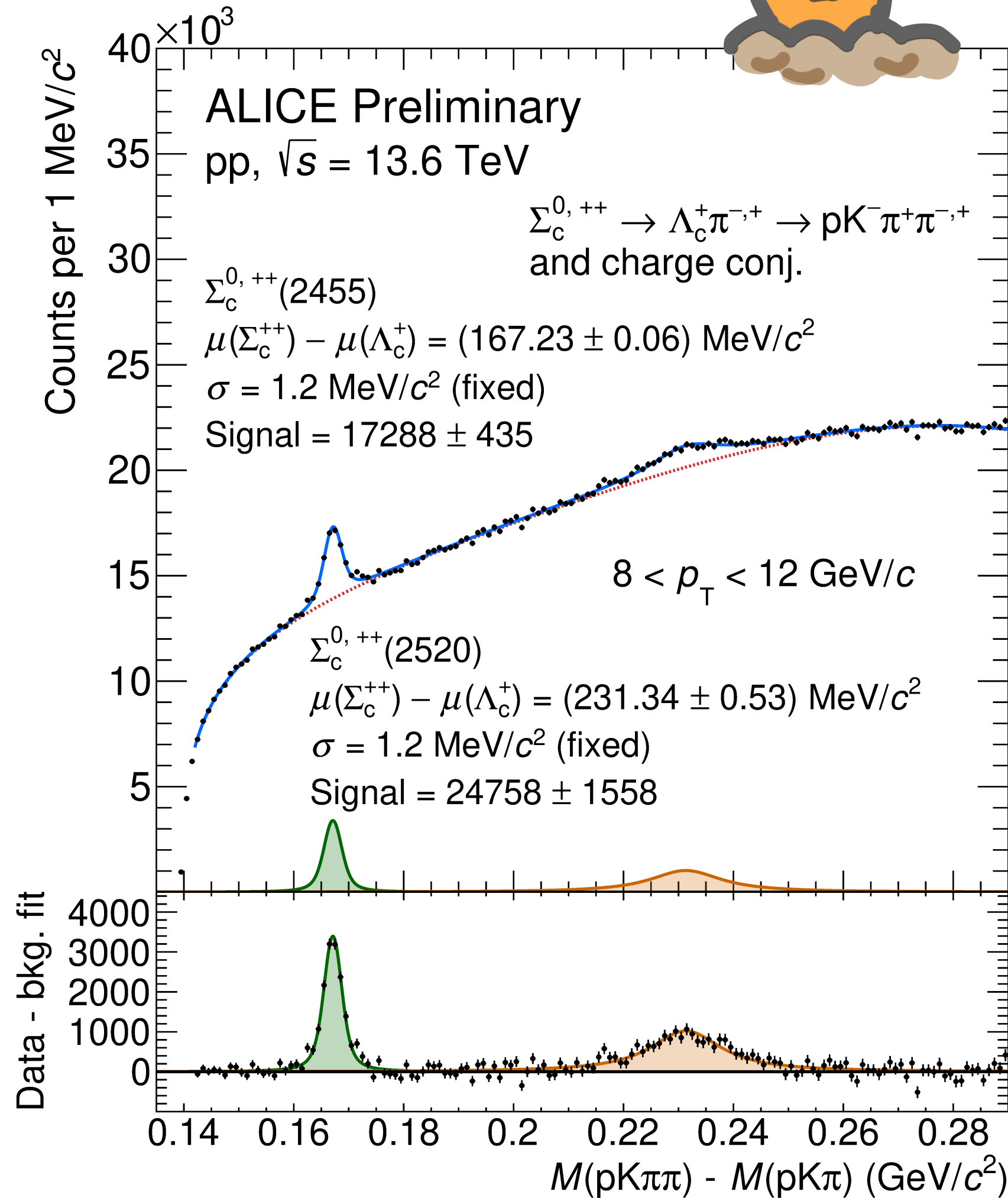
$\Sigma_c^{0,++}$ in pp collisions

From Run 3 data



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

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



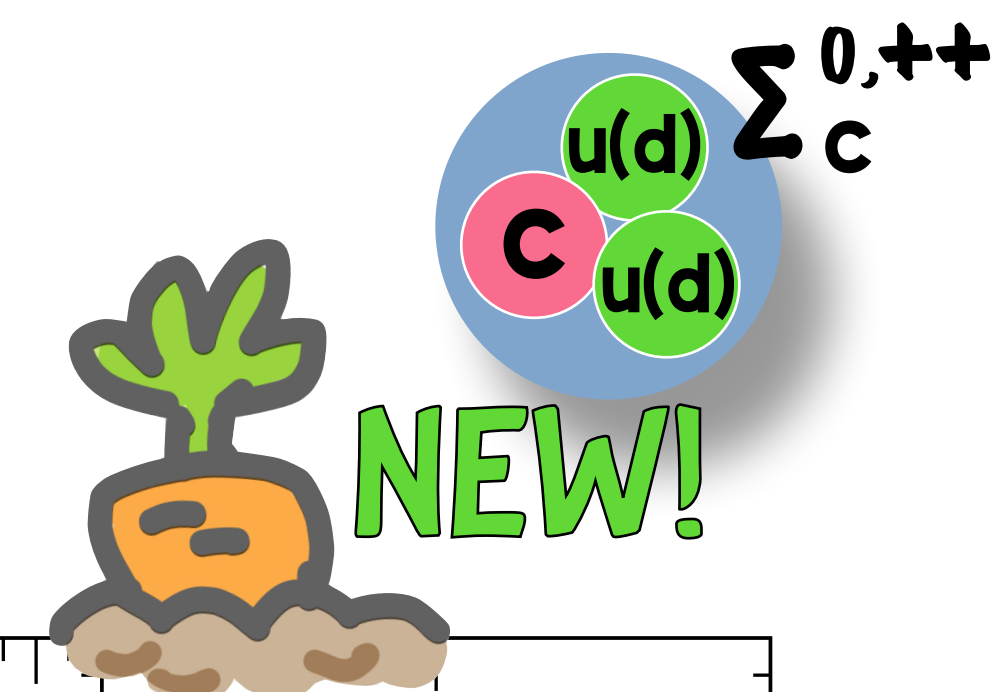
ALI-PREL-571534

Fresh results from Run 3 data!



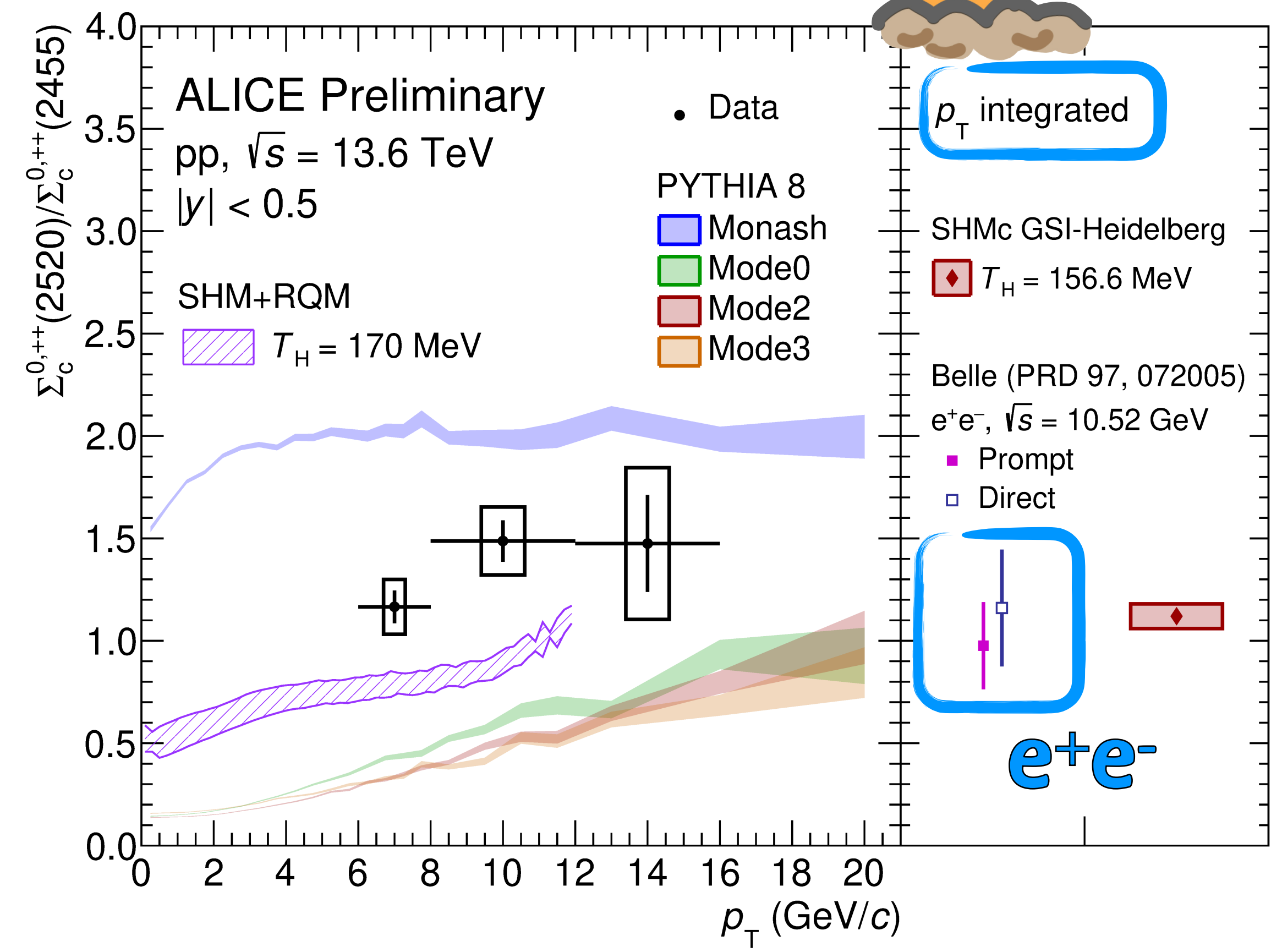
$\Sigma_c^{0,++}$ in pp collisions

From Run 3 data



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



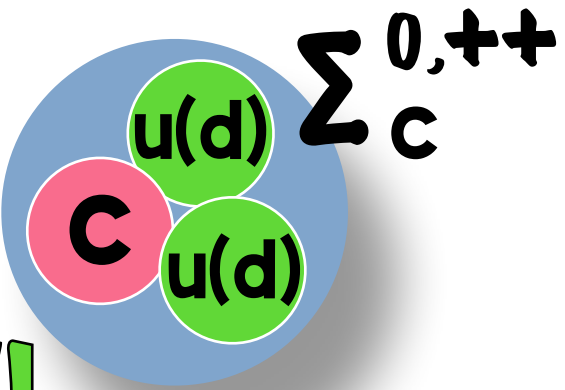
Model comparison

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

ALI-PREL-574270

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

From Run 3 data



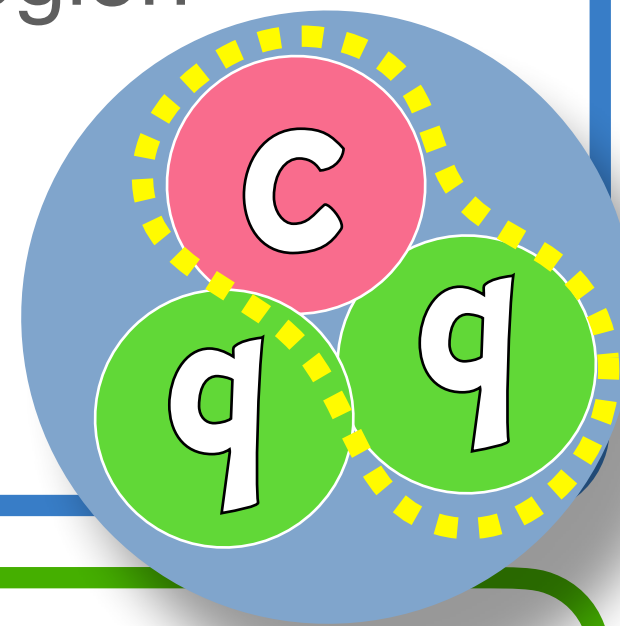
probQQ1toQQ0join : [arXiv : 2404.12040](#) and [arXiv : 2405.19137](#)

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

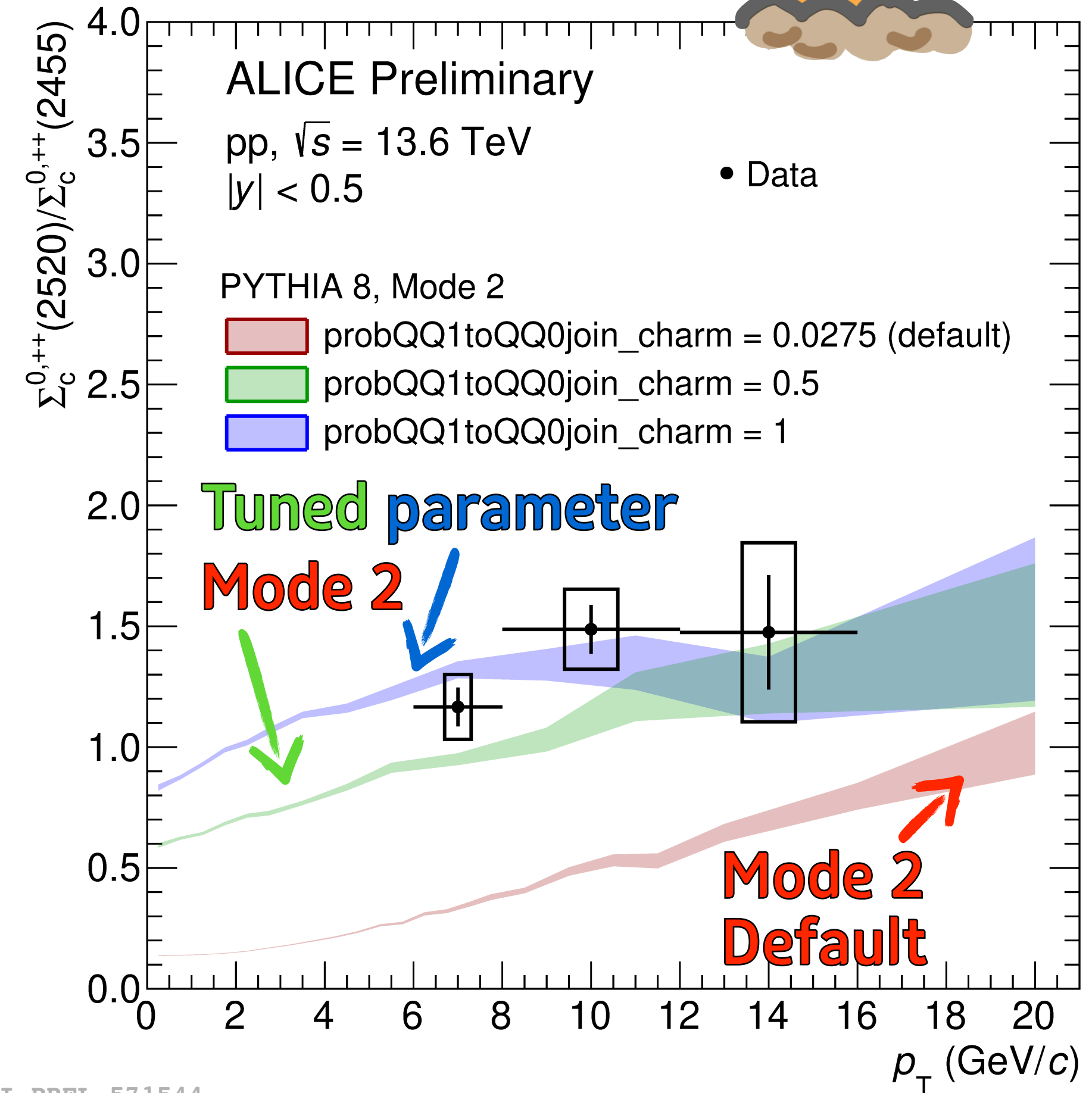


We have constraint power for model!



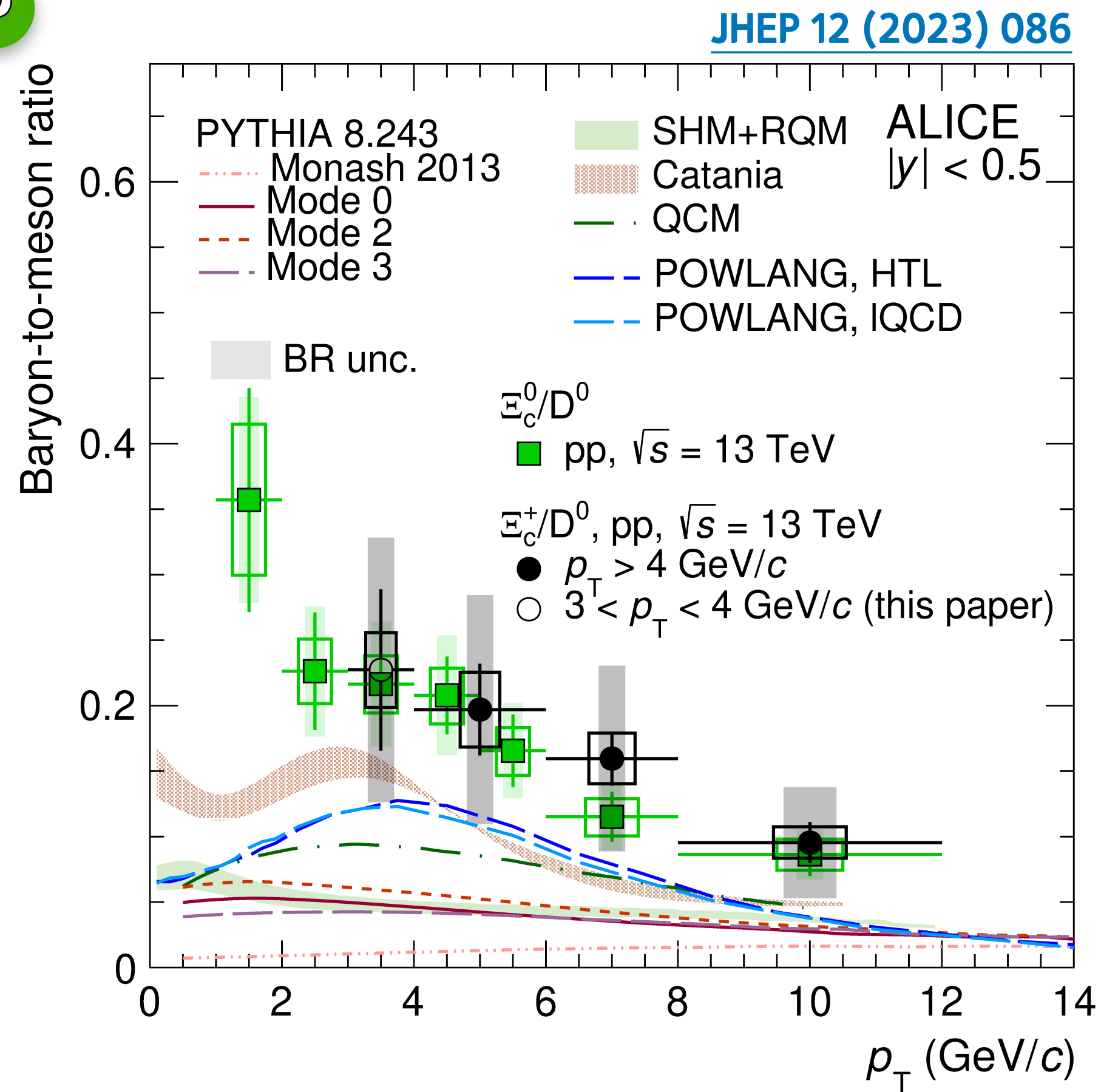
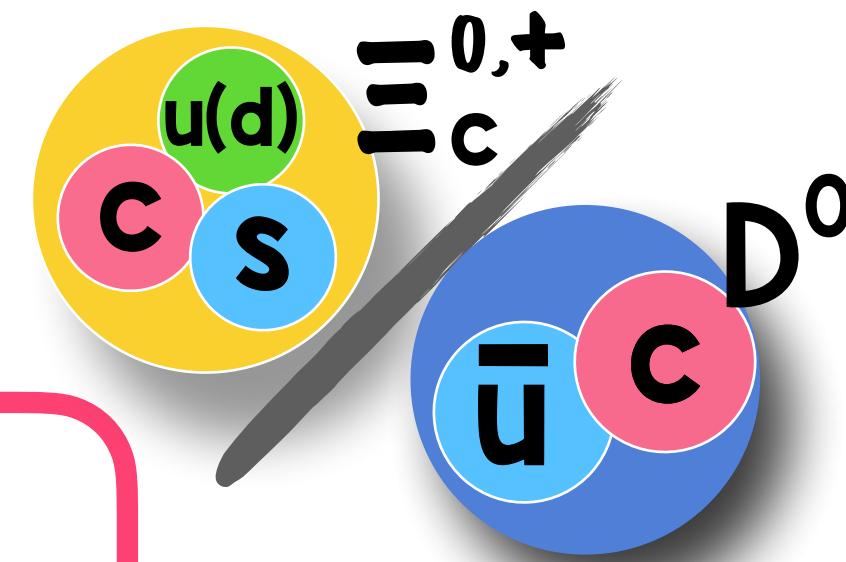
Model comparison

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



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

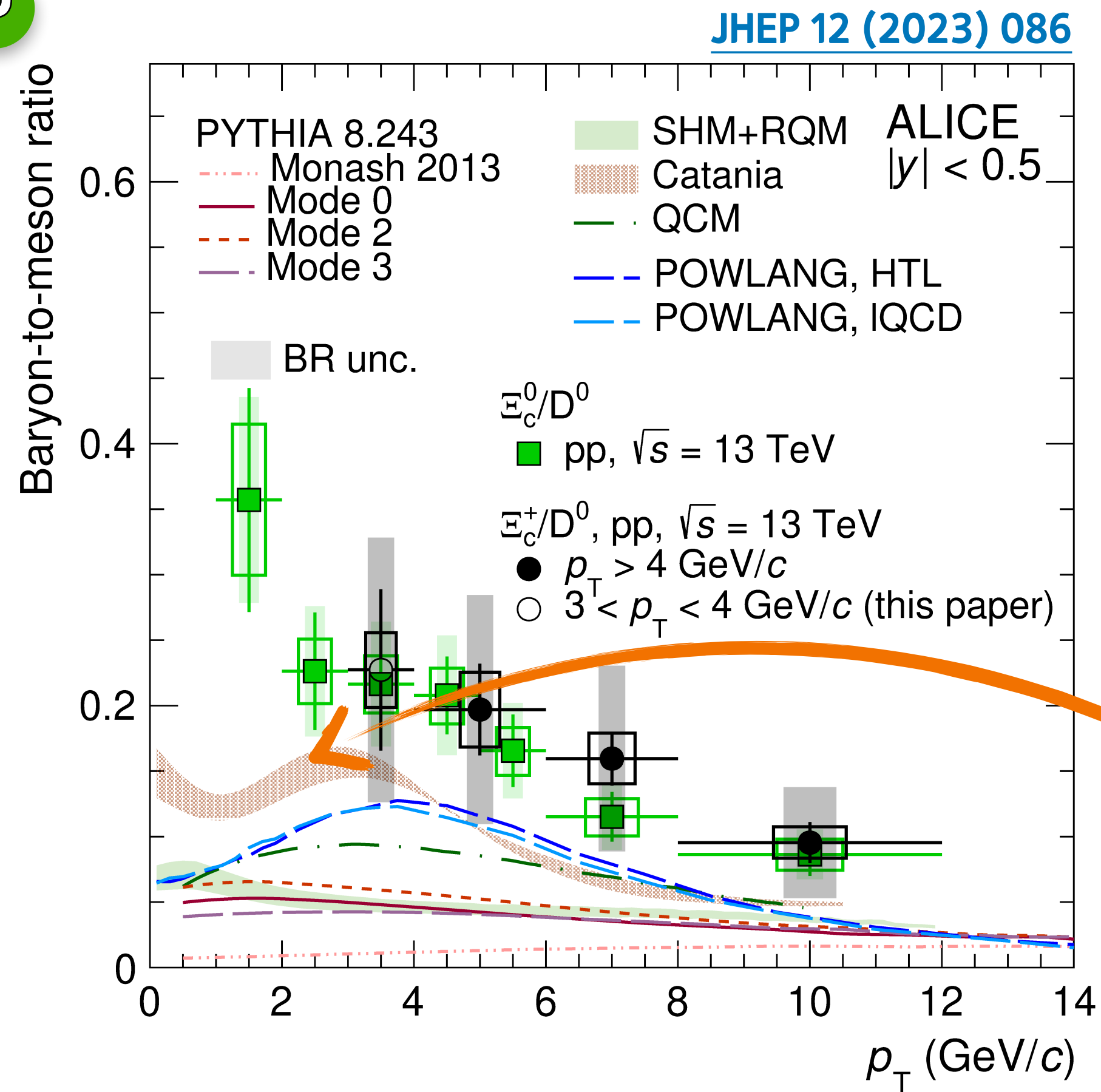
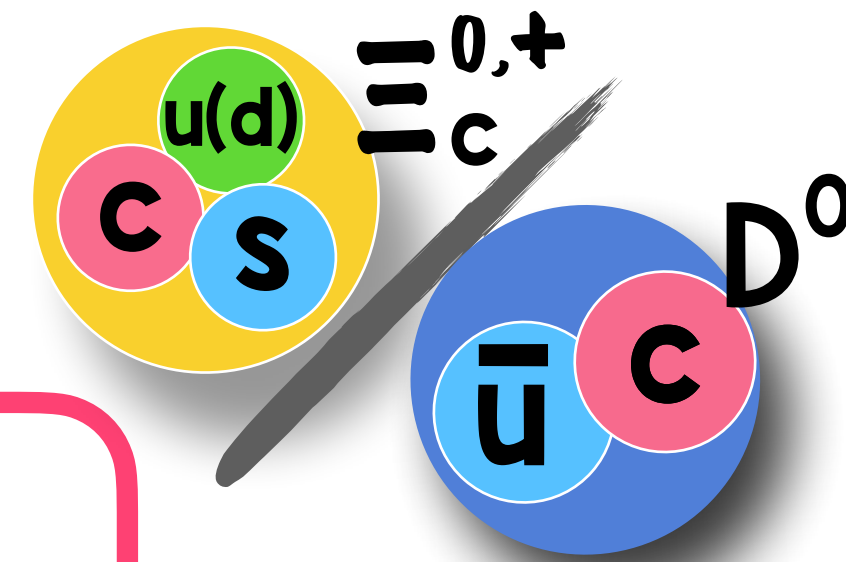
★ Poor description from models 🤔

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



ALI-PUB-567881

Comparing to e^+e^- collisions

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

Model comparisons

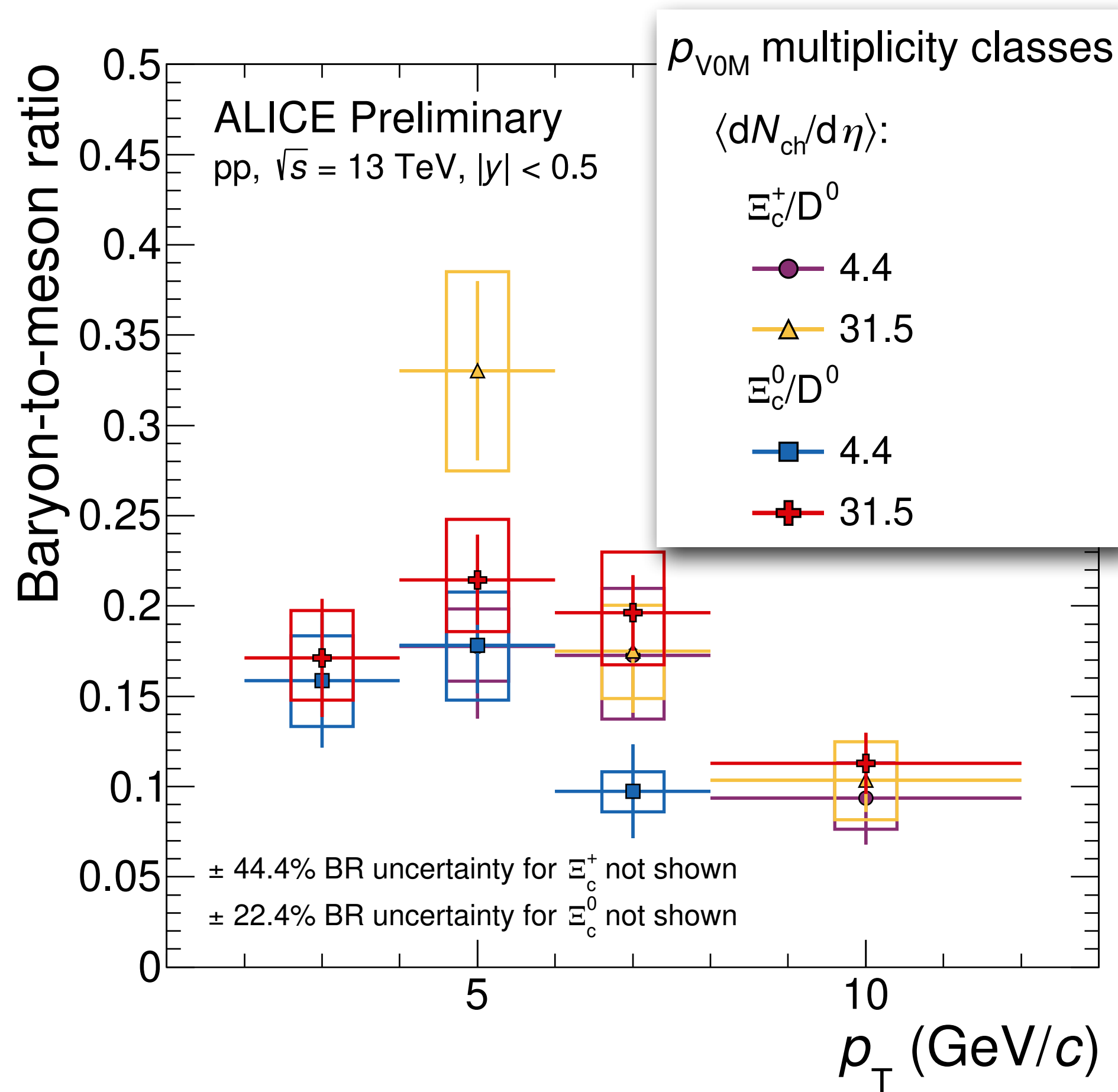
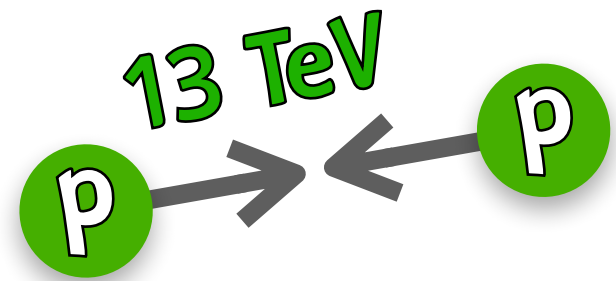
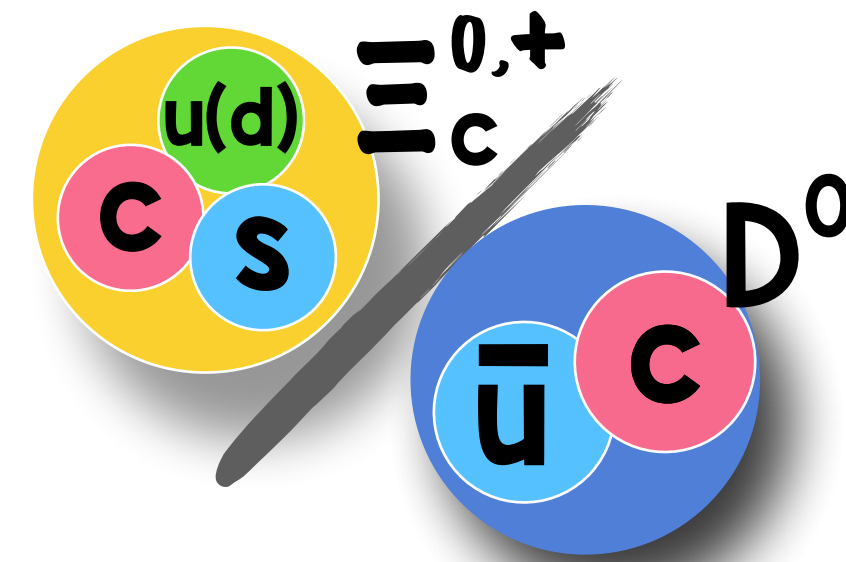
★ Poor description from models 🤔 which describe well the Λ_c^+/D^0 ratio

- Much larger enhancement than for non-strange baryons?
- ★ **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



Multiplicity dependence?

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

Poster

200. JaeYoon Cho

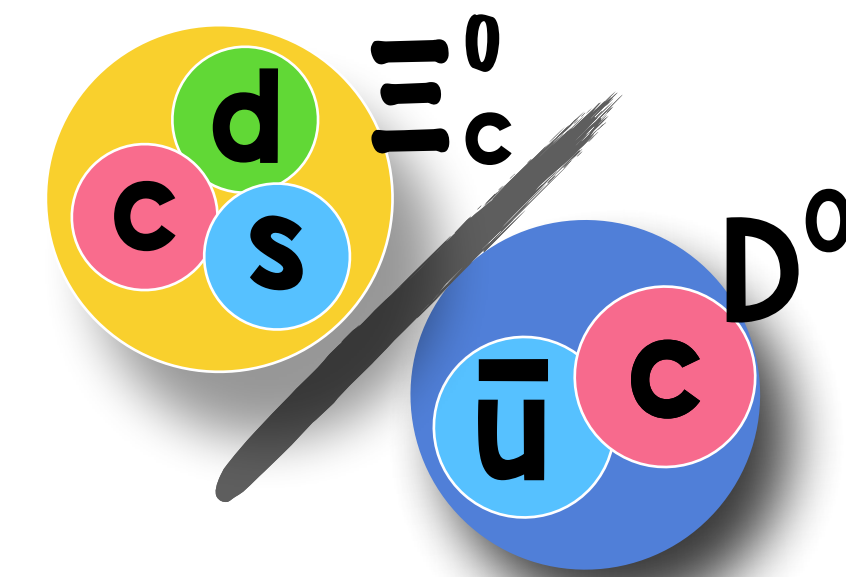
Ξ_c^+ vs. multiplicity in pp collisions



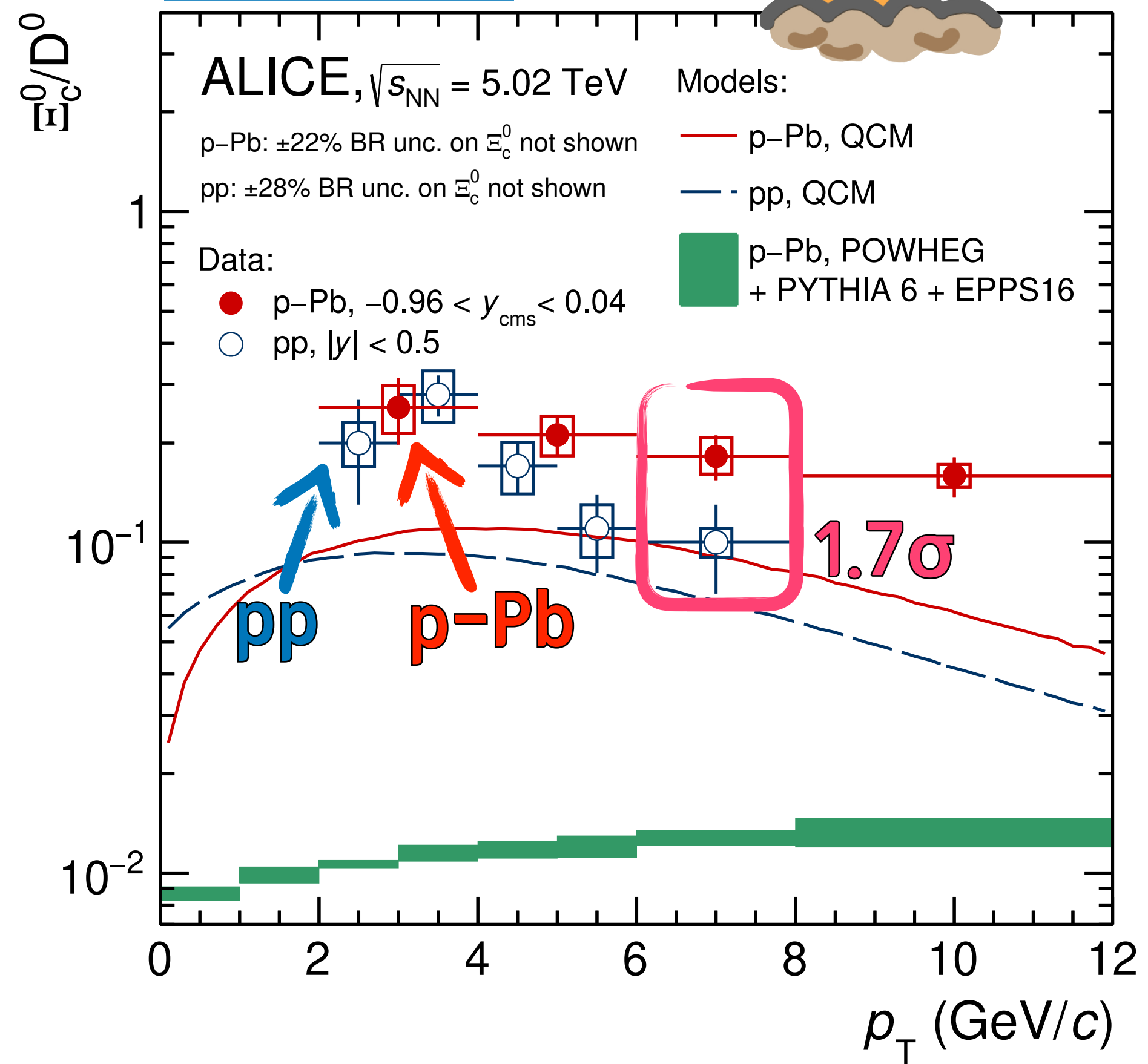
ALI-PREL-548915



Ξ_c^0/D^0 in p-Pb collisions



arXiv : 2405.14538



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

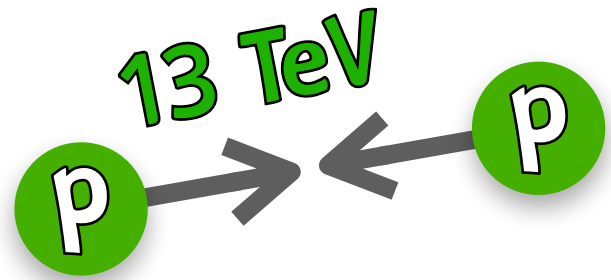
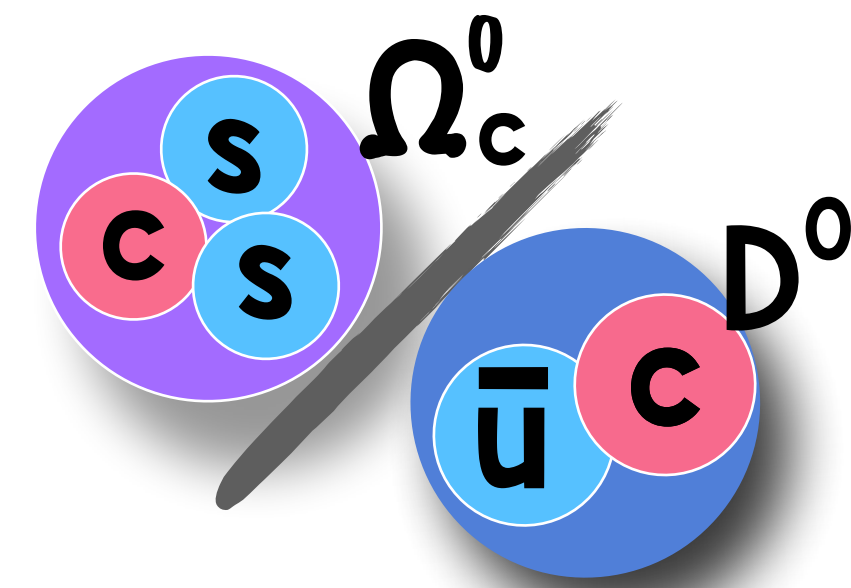
Model comparison

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

ALI-PUB-571011



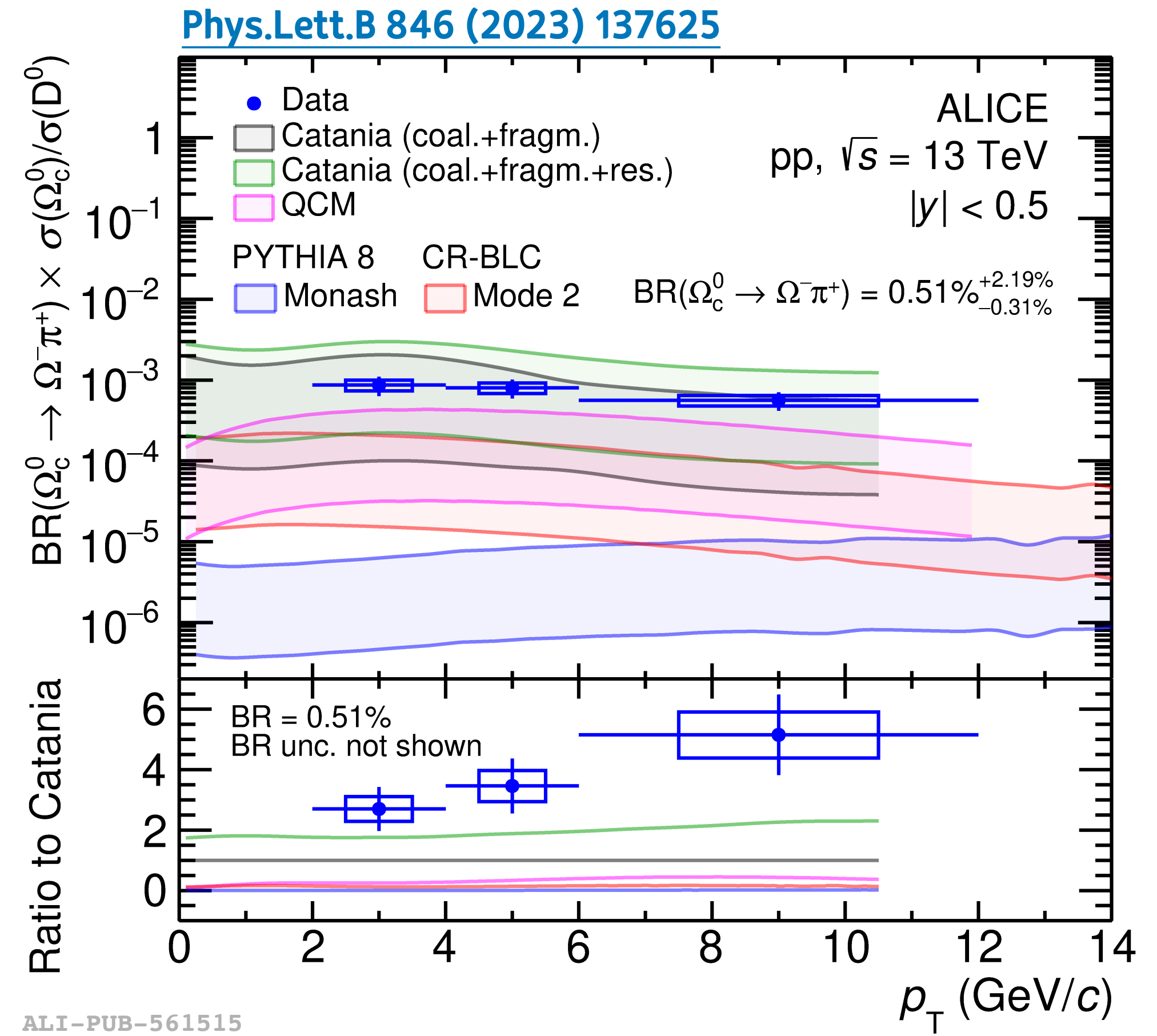
Ω_c^0/D^0 in pp collisions



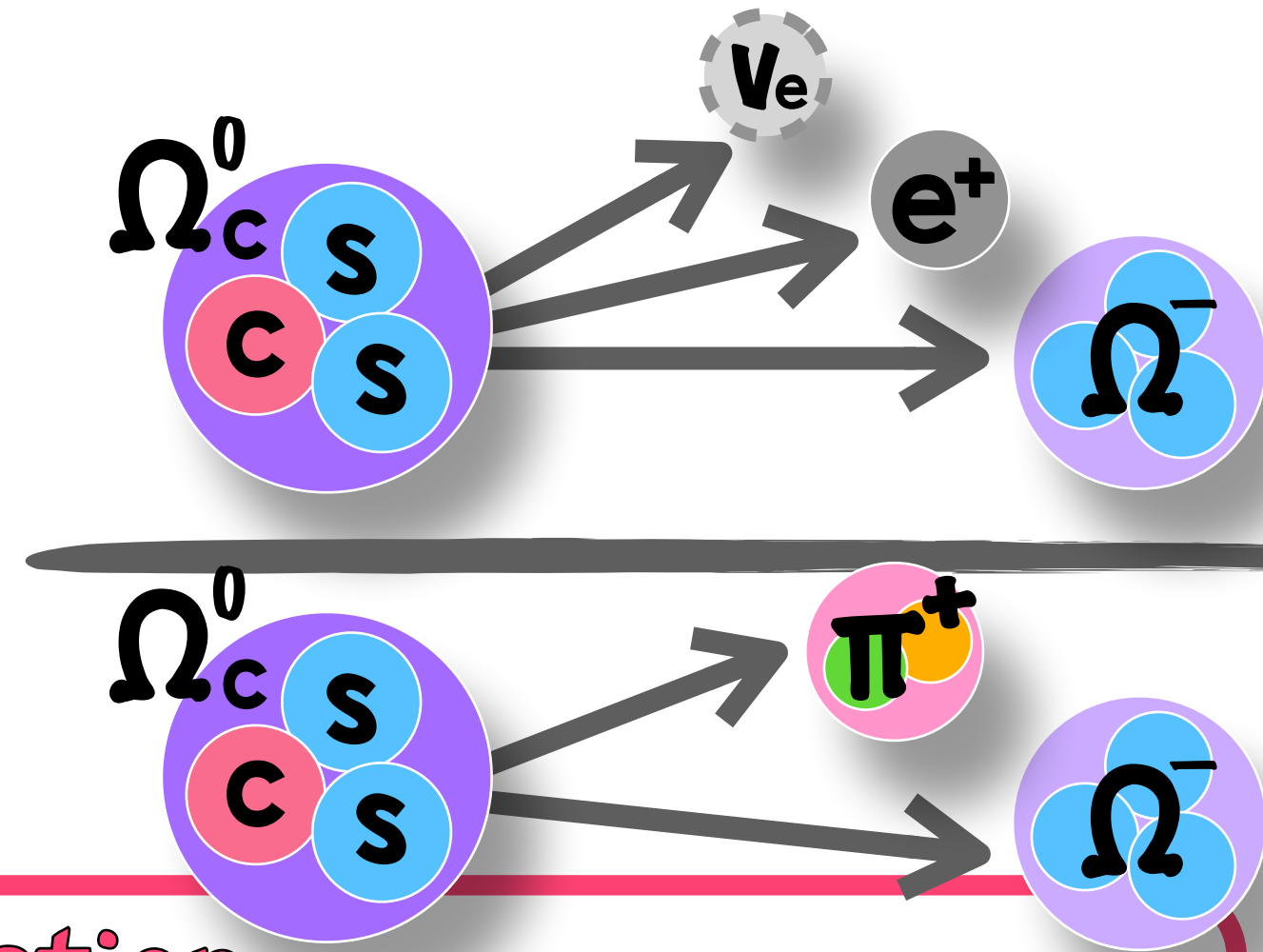
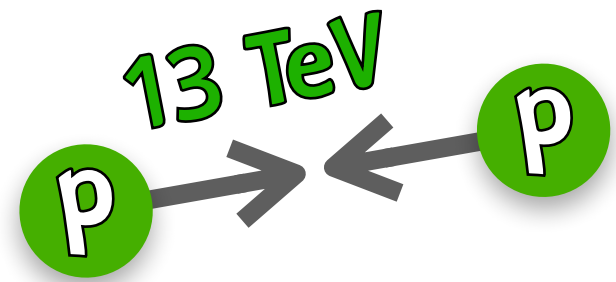
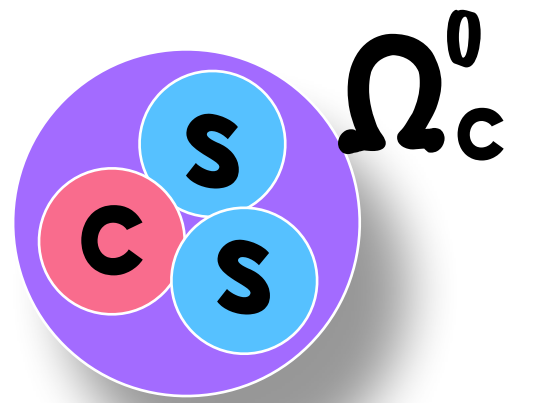
BR \times Ω_c^0/D^0 and model comparison

- ★ No measurement of BR($\Omega_c^0 \rightarrow \Omega^- \pi^+$)
 - BR($\Omega_c^0 \rightarrow \Omega^- \pi^+$) = $(0.51^{+2.19}_{-0.31})$ % 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 \(2020\)](#)



Ω_c^0 in pp collisions



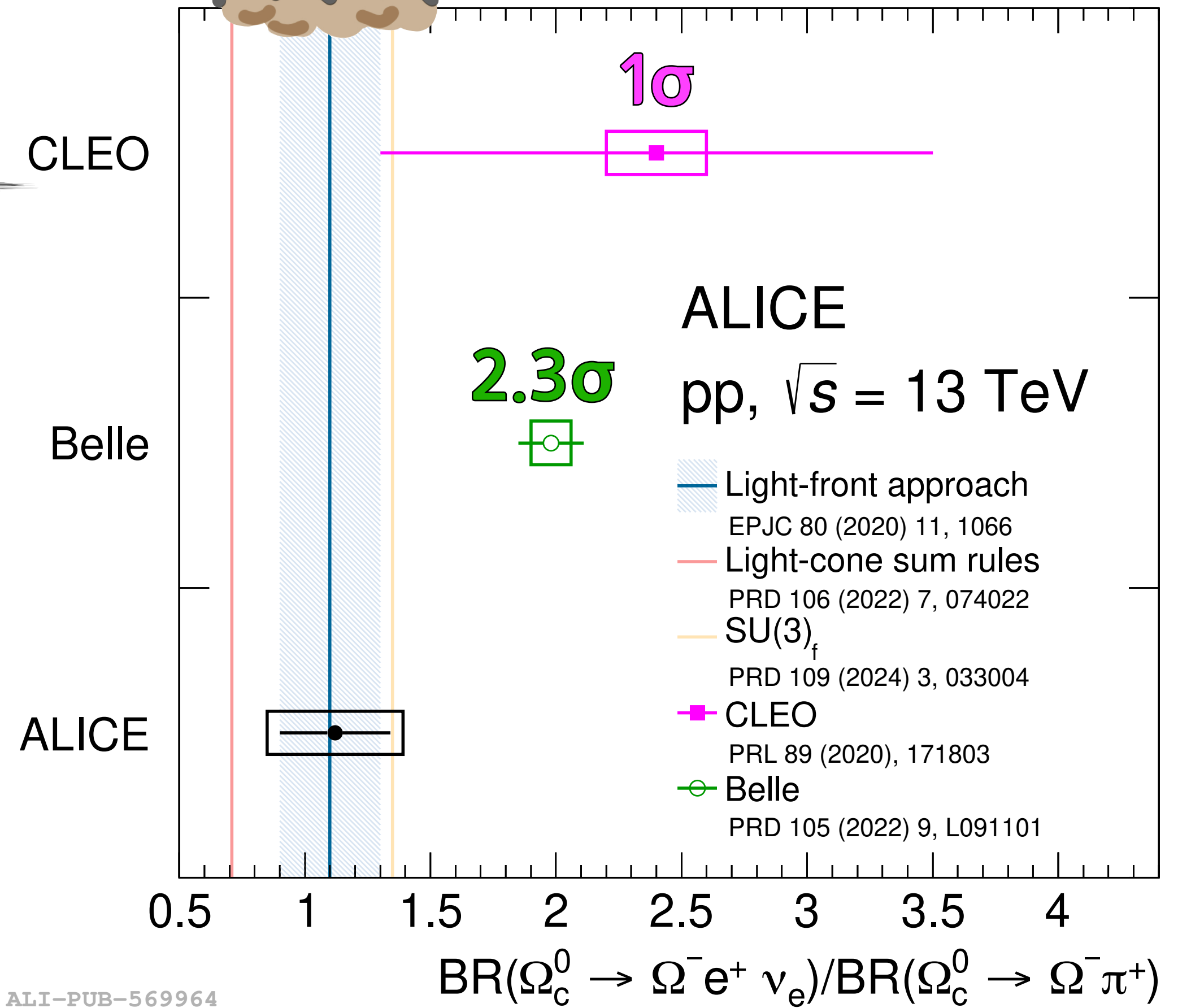
Branching fraction

★ Measured ratio is

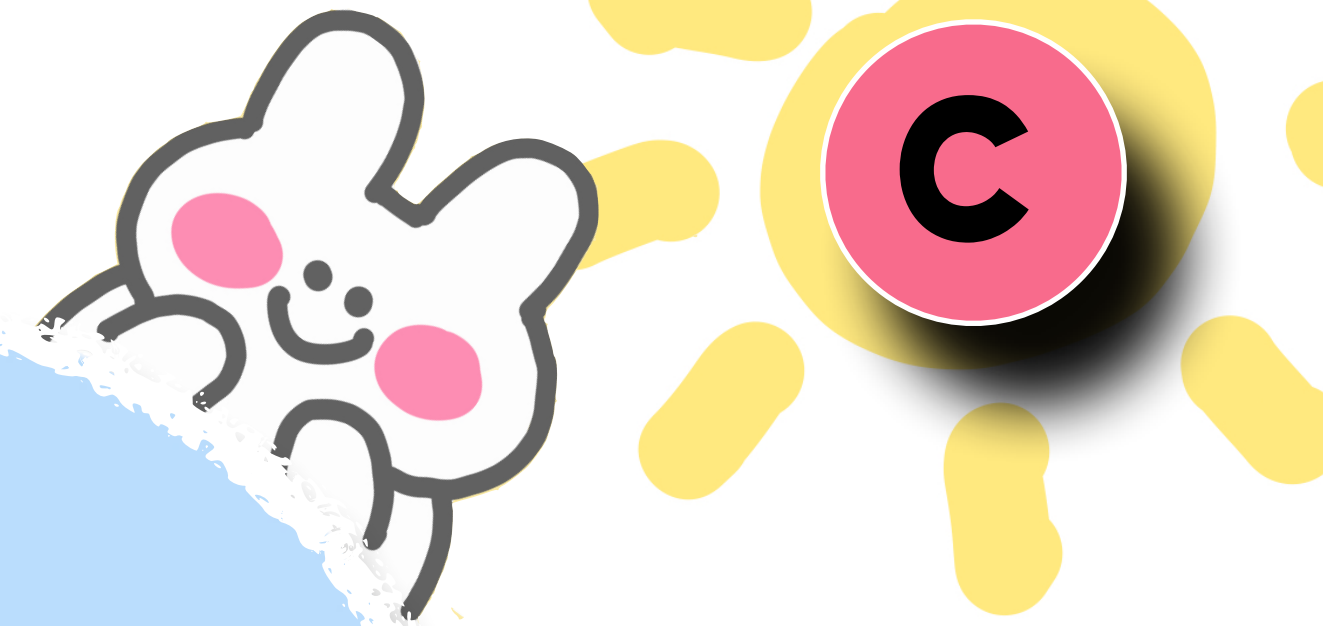
$$\frac{\text{BR}(\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e)}{\text{BR}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = 1.12 \pm 0.22 \text{ (stat.)} \pm 0.27 \text{ (syst.)}$$

★ Agreement with measurement from CLEO

Collaboration and model calculations within 1σ and within 2.3σ from BELLE measurement

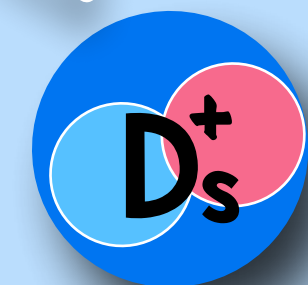
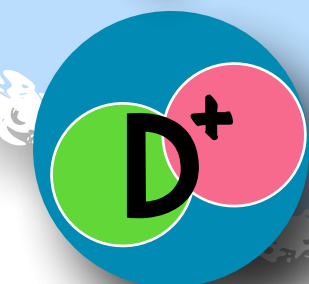
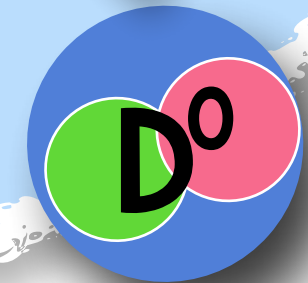
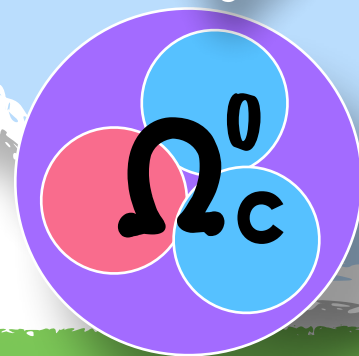
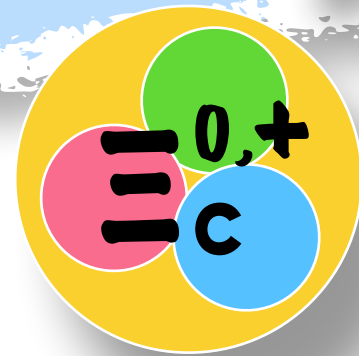
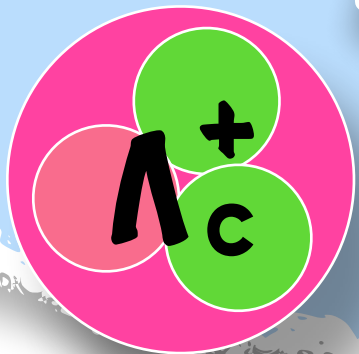


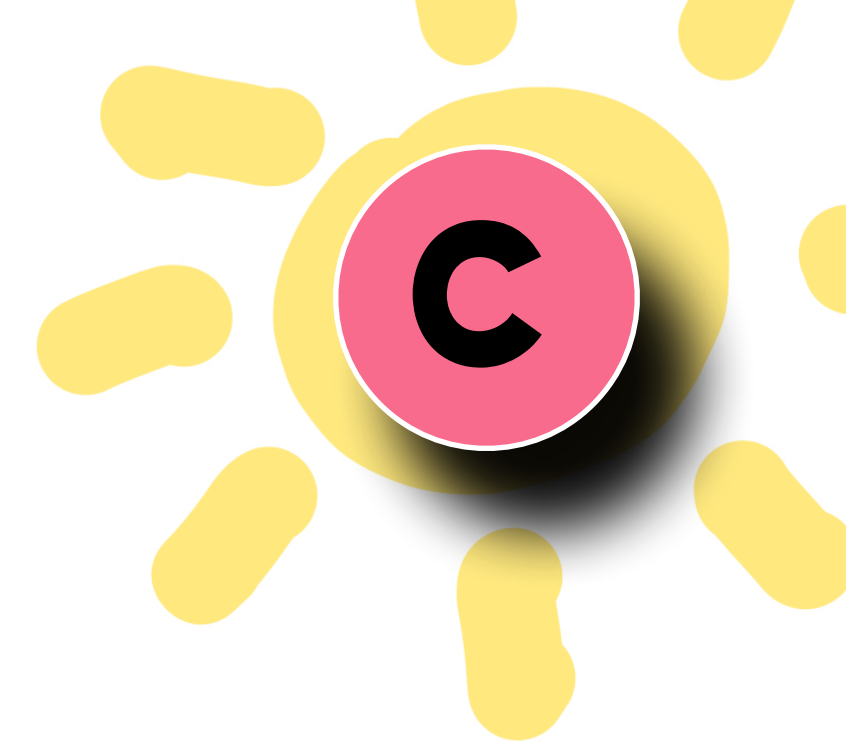
Charm fragmentation fraction



Probability of a charm quark to produce a hadron h_c

$$f(c \rightarrow h_c)$$





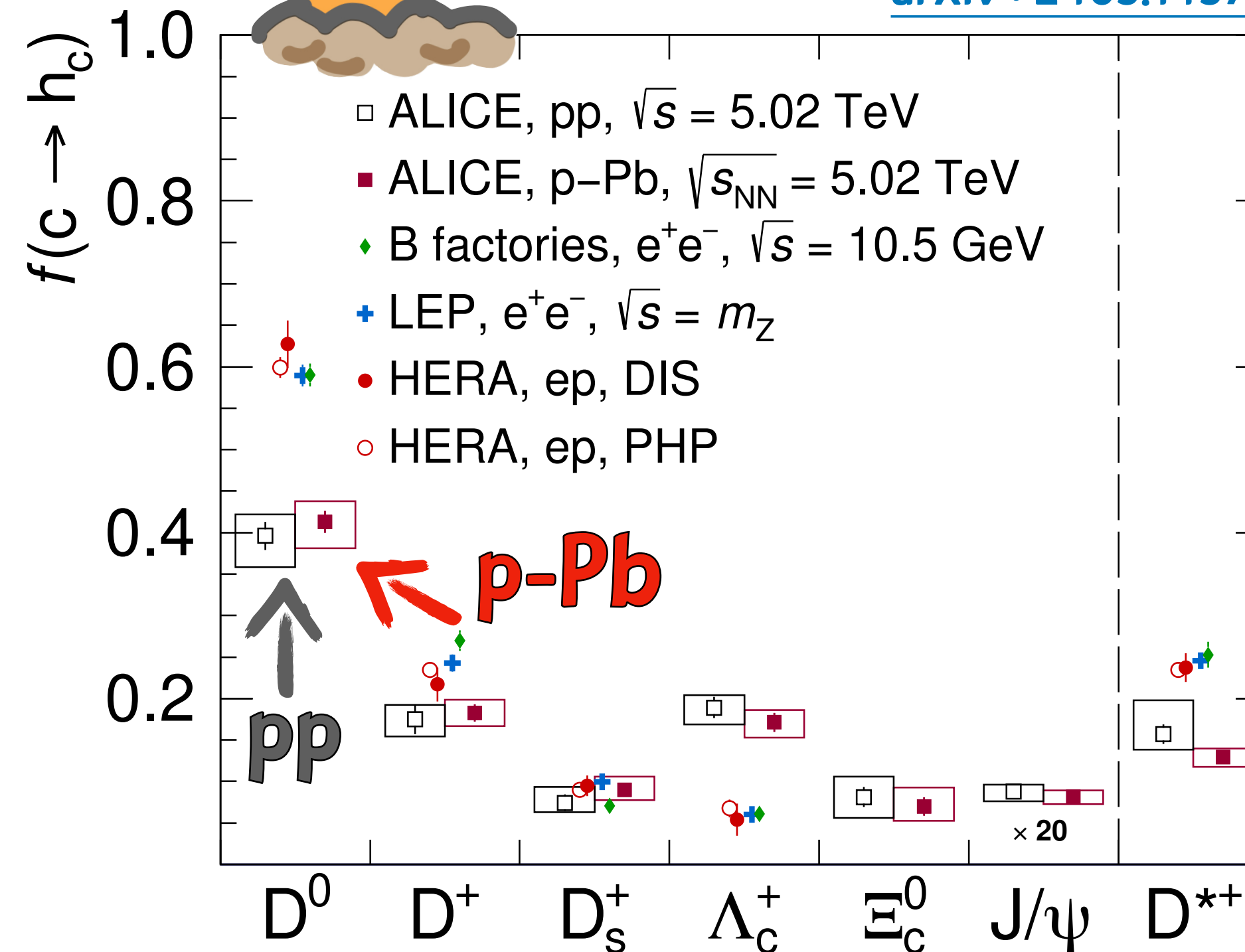
Charm fragmentation fraction

In hadronic collisions

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

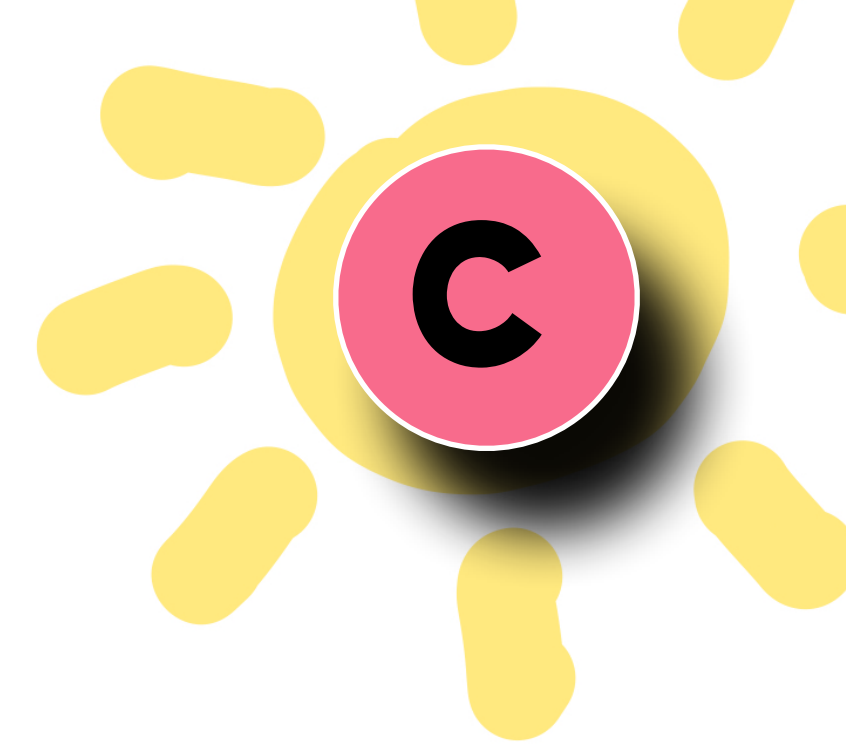


[arXiv : 2405.14571](https://arxiv.org/abs/2405.14571)



ALI-PUB-570972



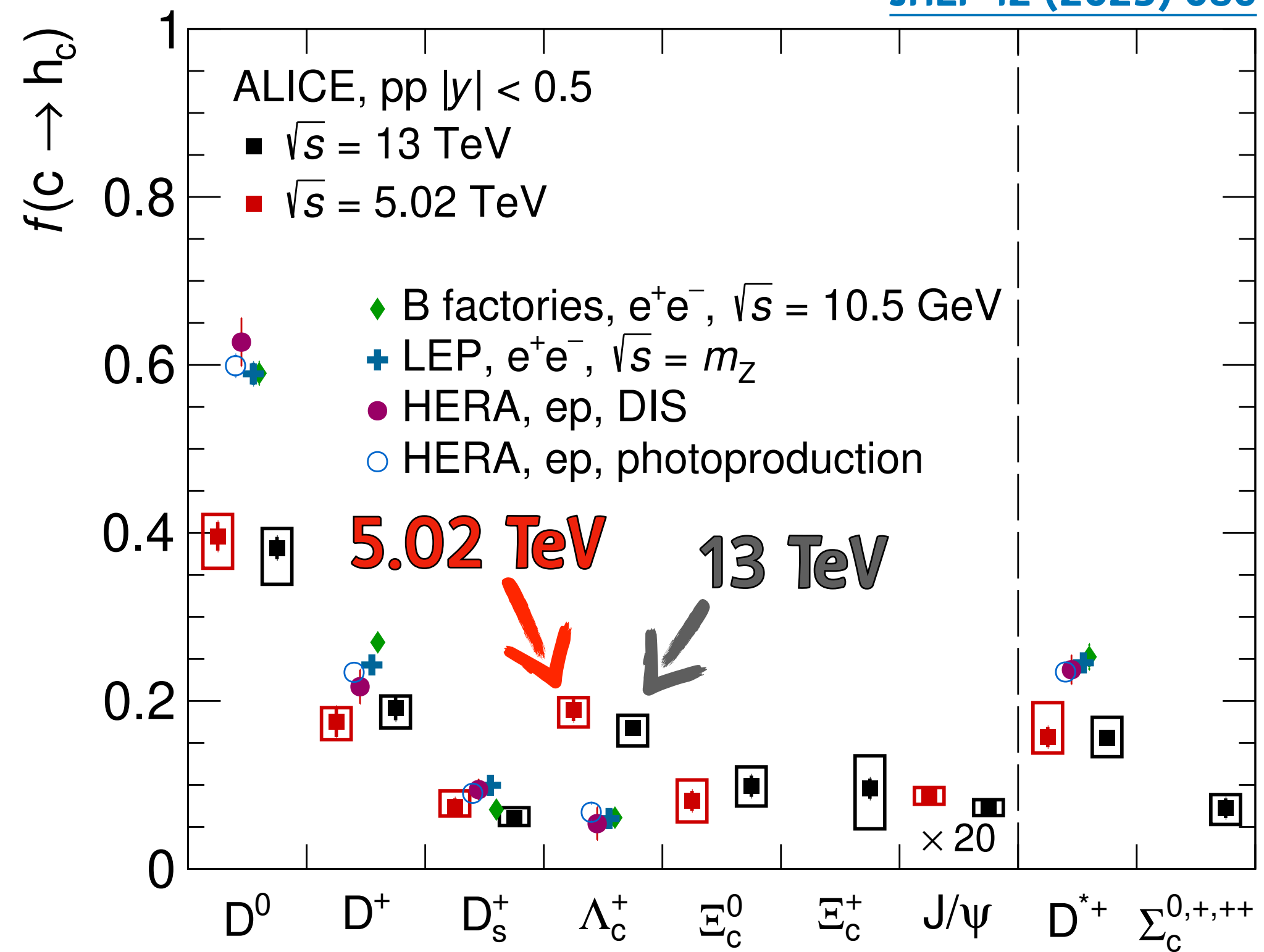


Charm fragmentation fraction

For different collisions energy

★ No energy dependence within the uncertainties

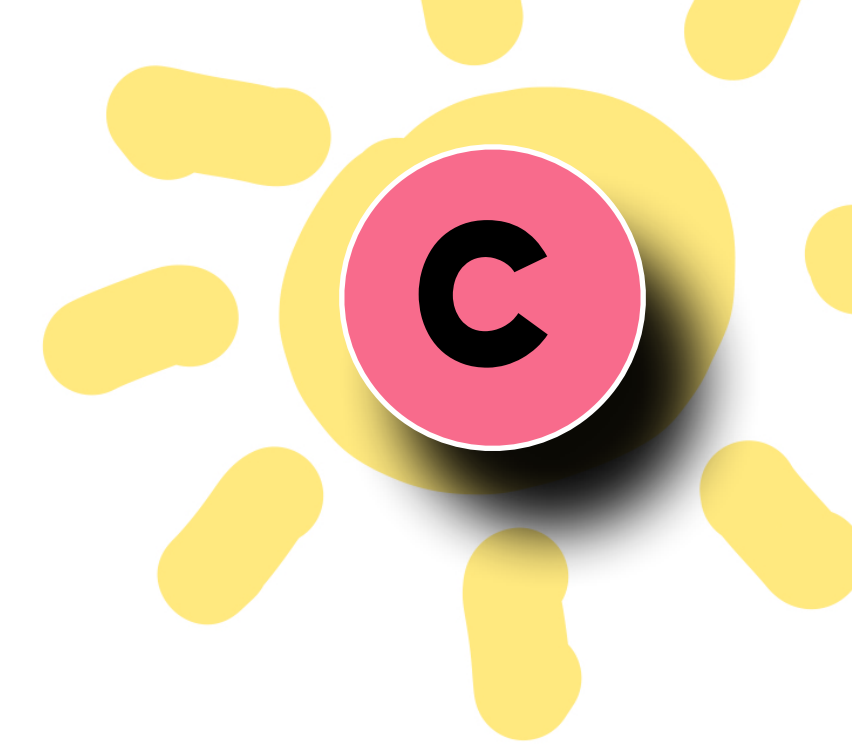
JHEP 12 (2023) 086



ALI-PUB-567906



Charm fragmentation fraction



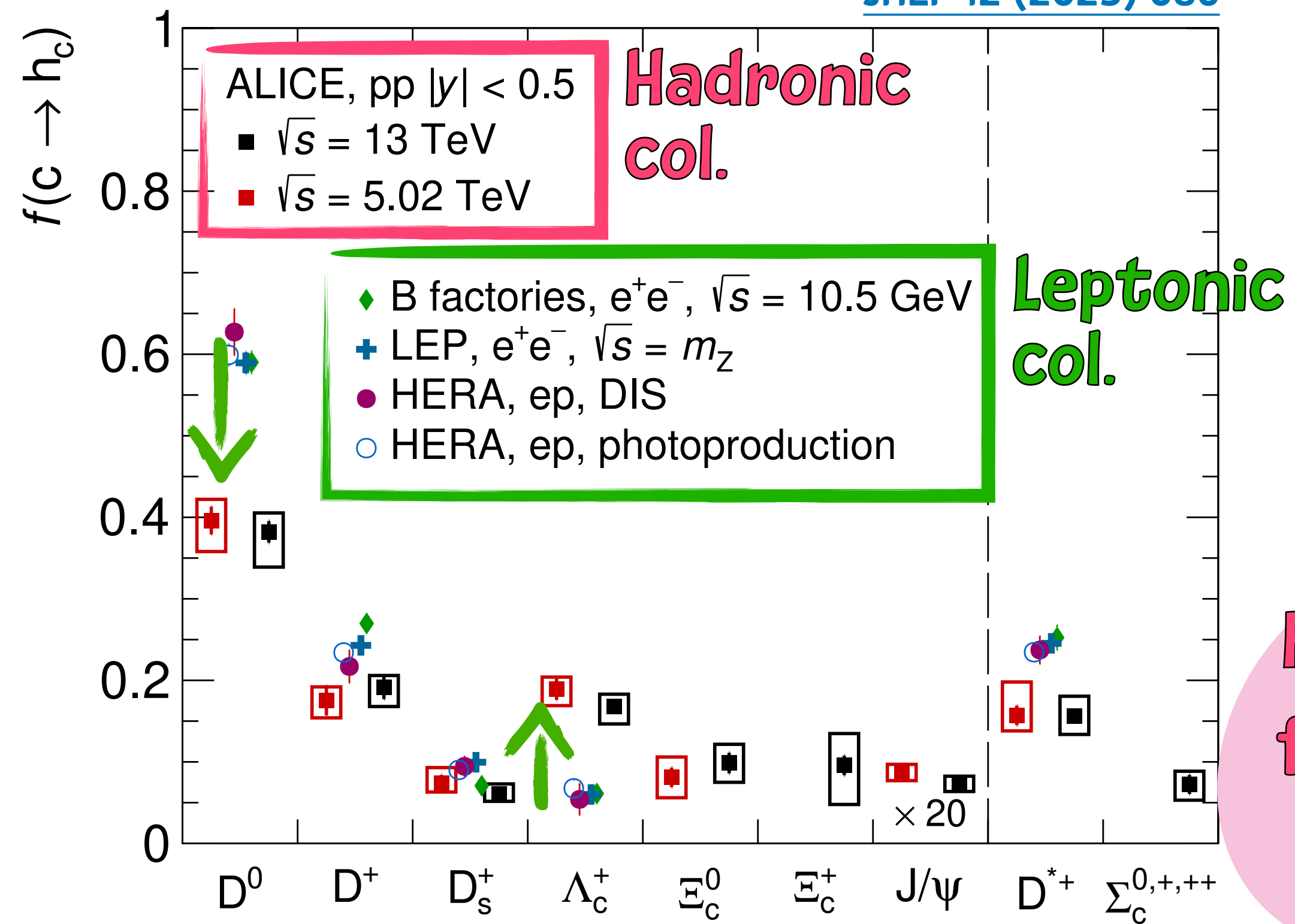
In different collisions energy

★ 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

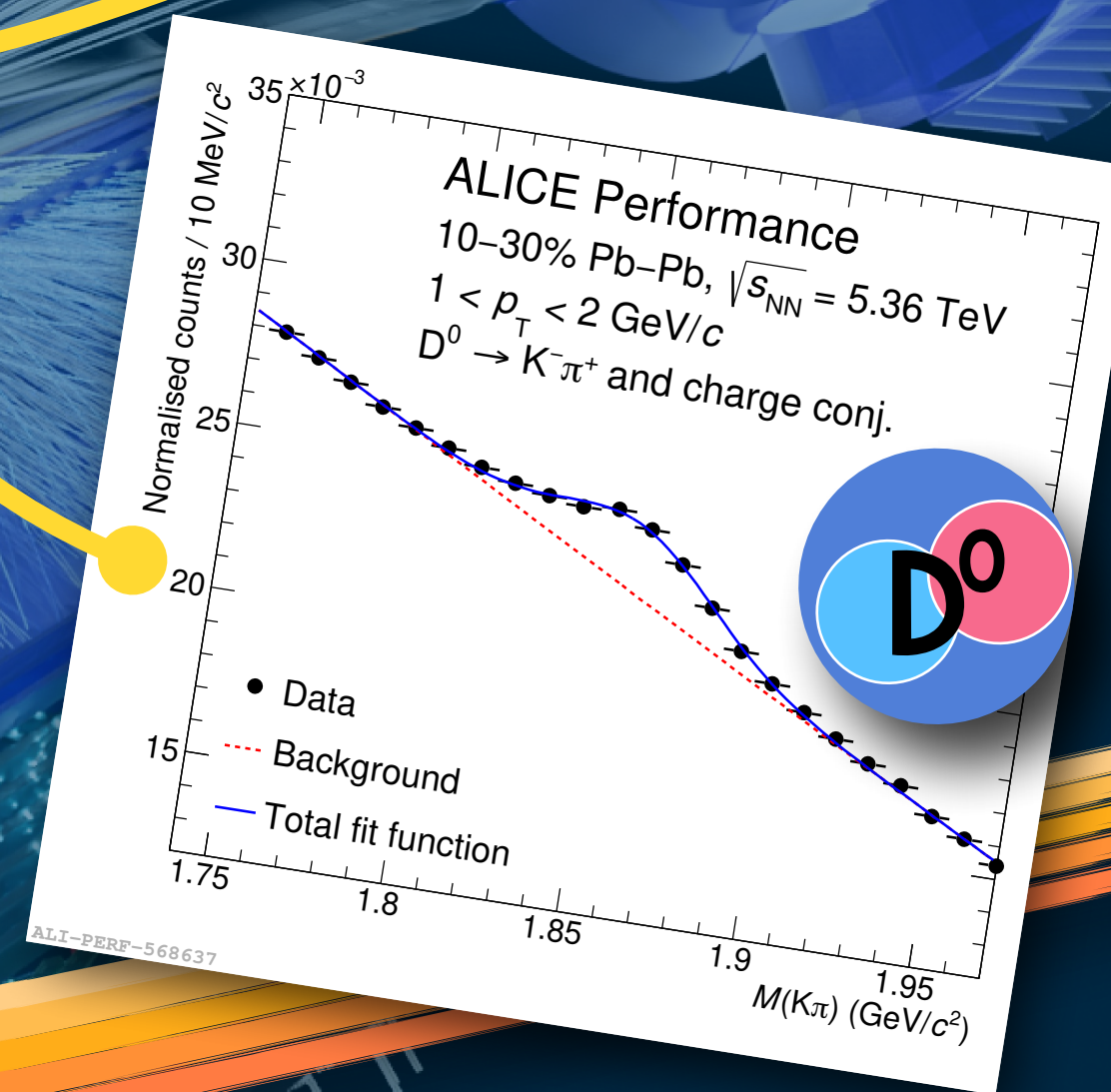
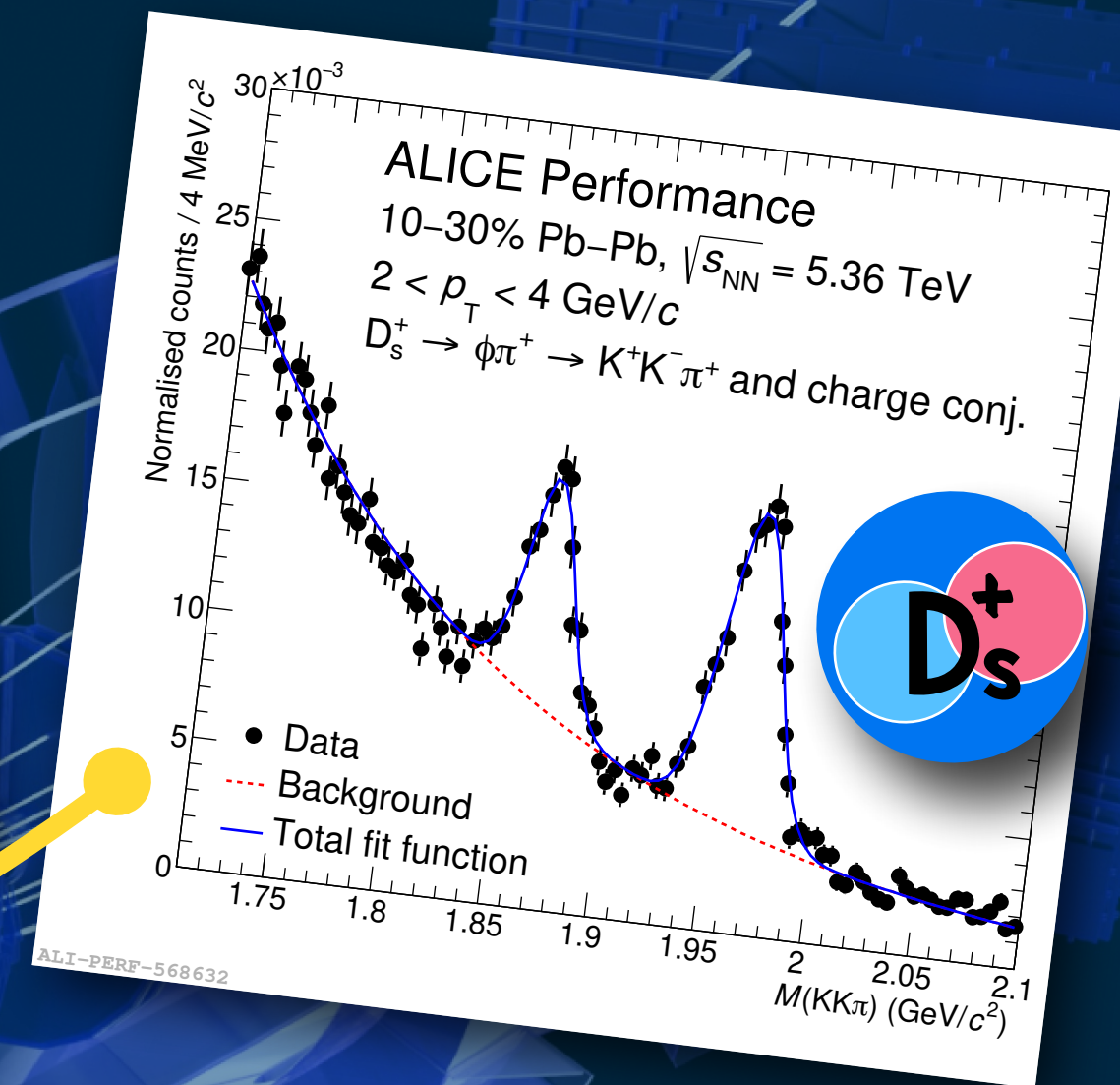
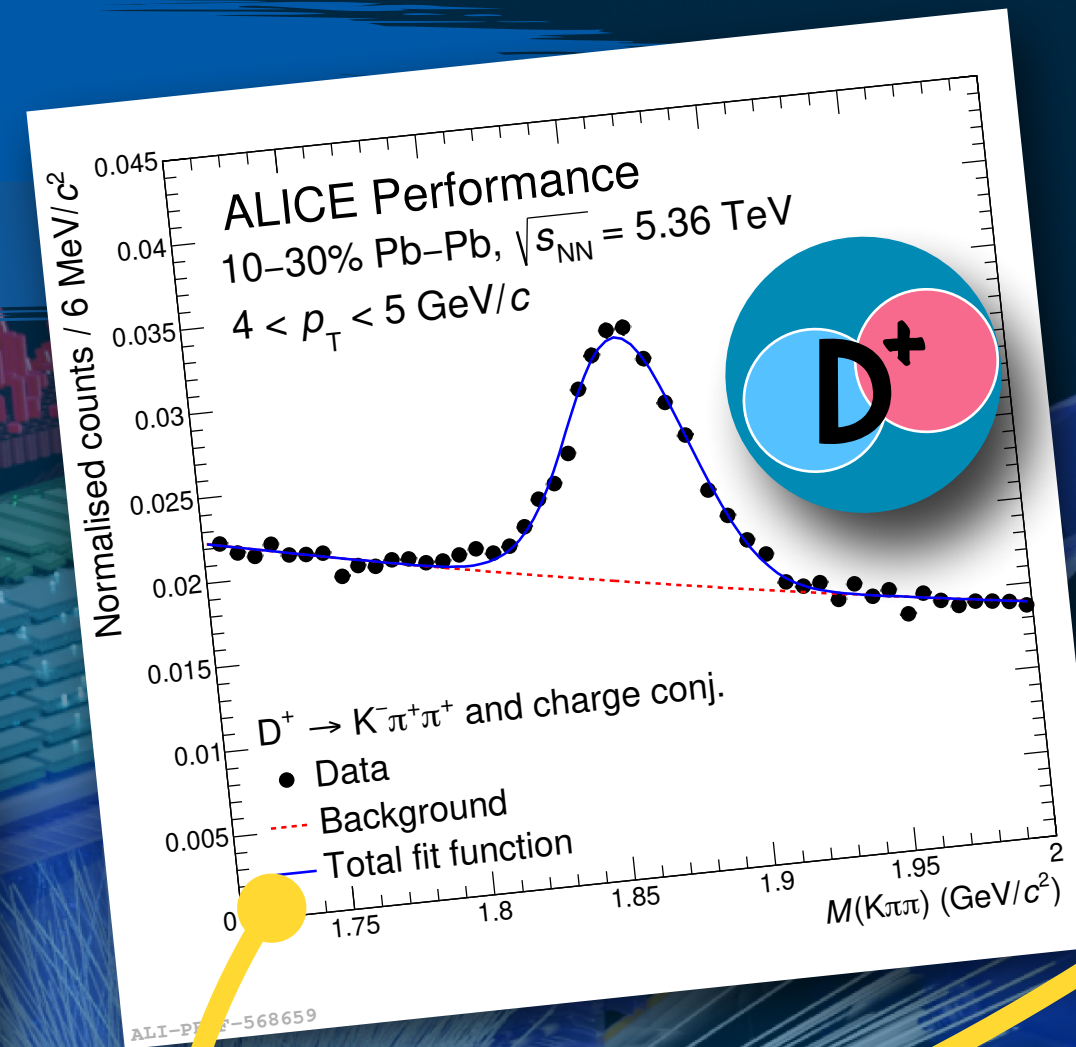
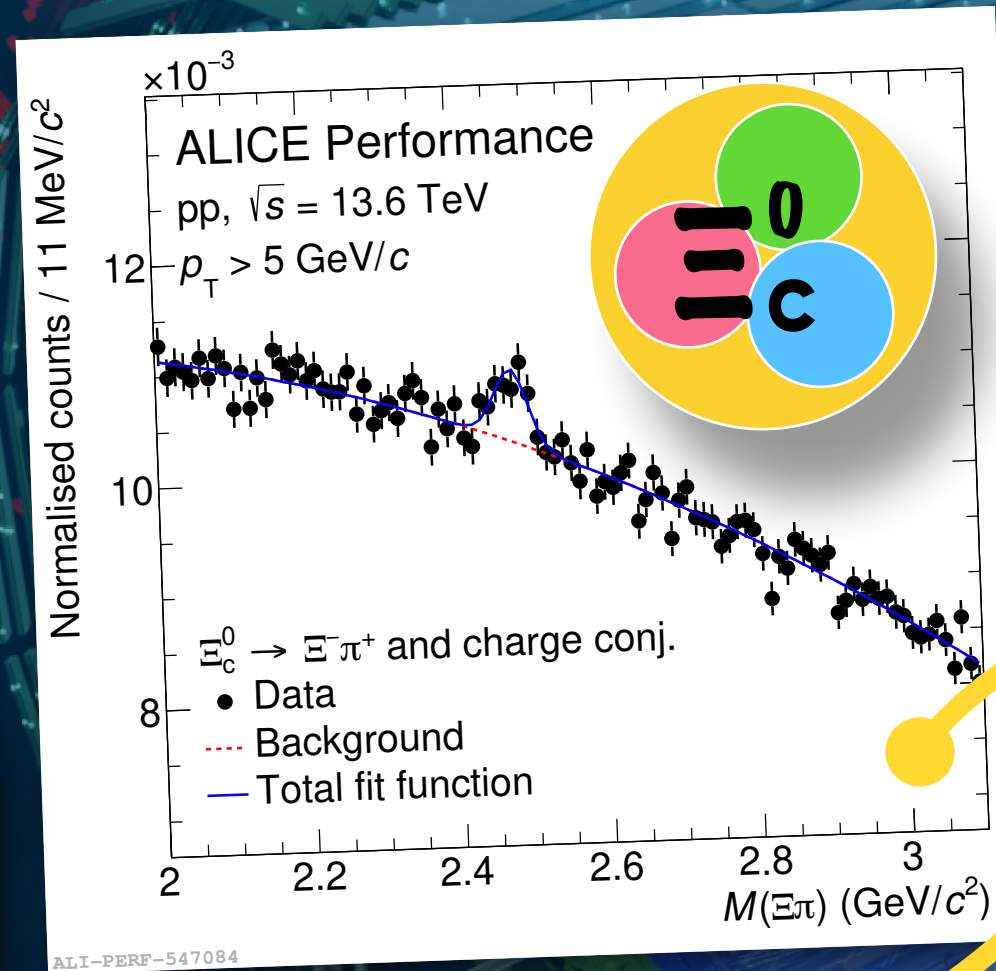
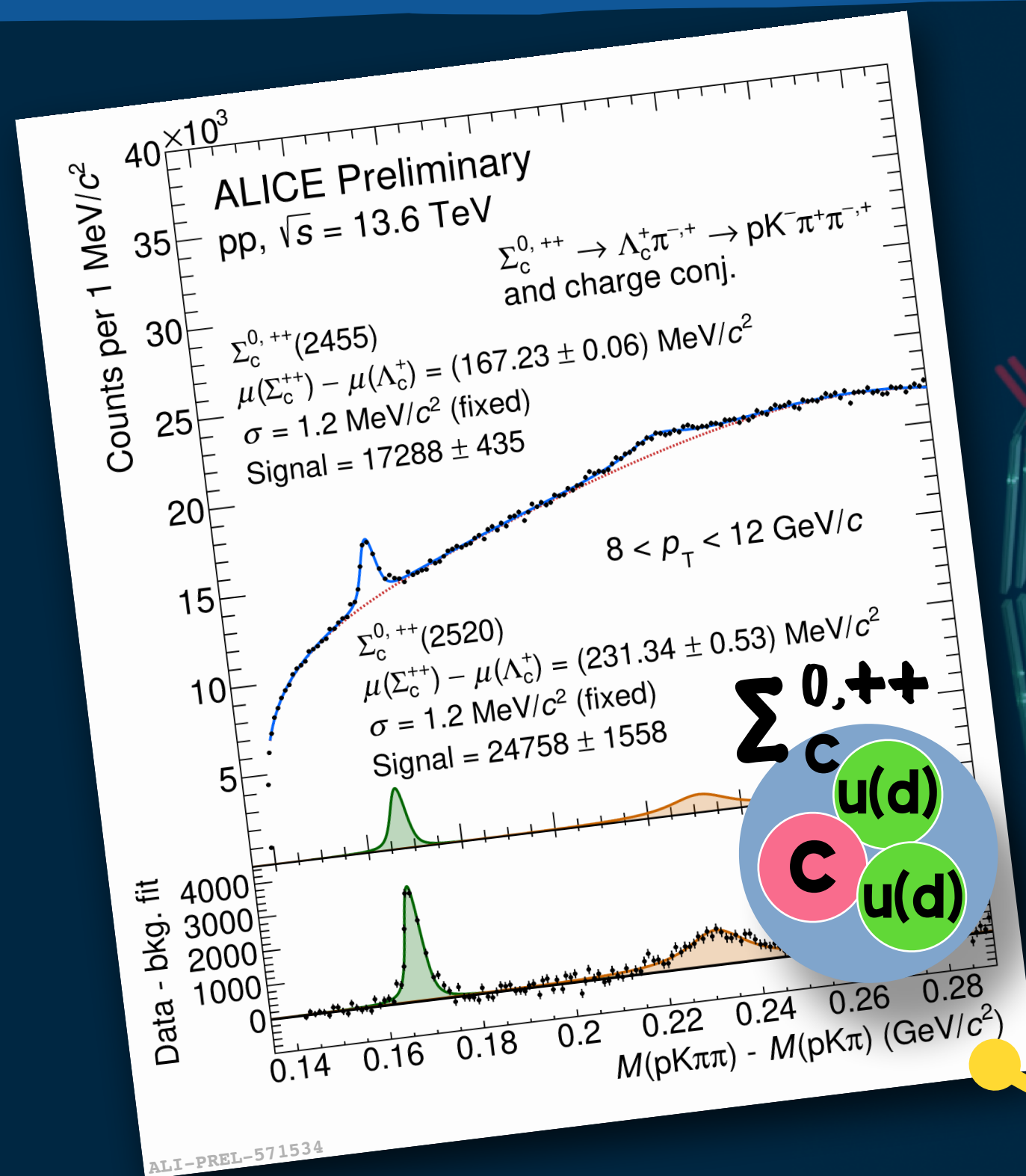


ALI-PUB-567906

Fragmentation function is NOT universal



Outlook : HF in ALICE Run 3



Successfully done!

ALICE is here!



Run 2
2015-2018

Long Shutdown 2

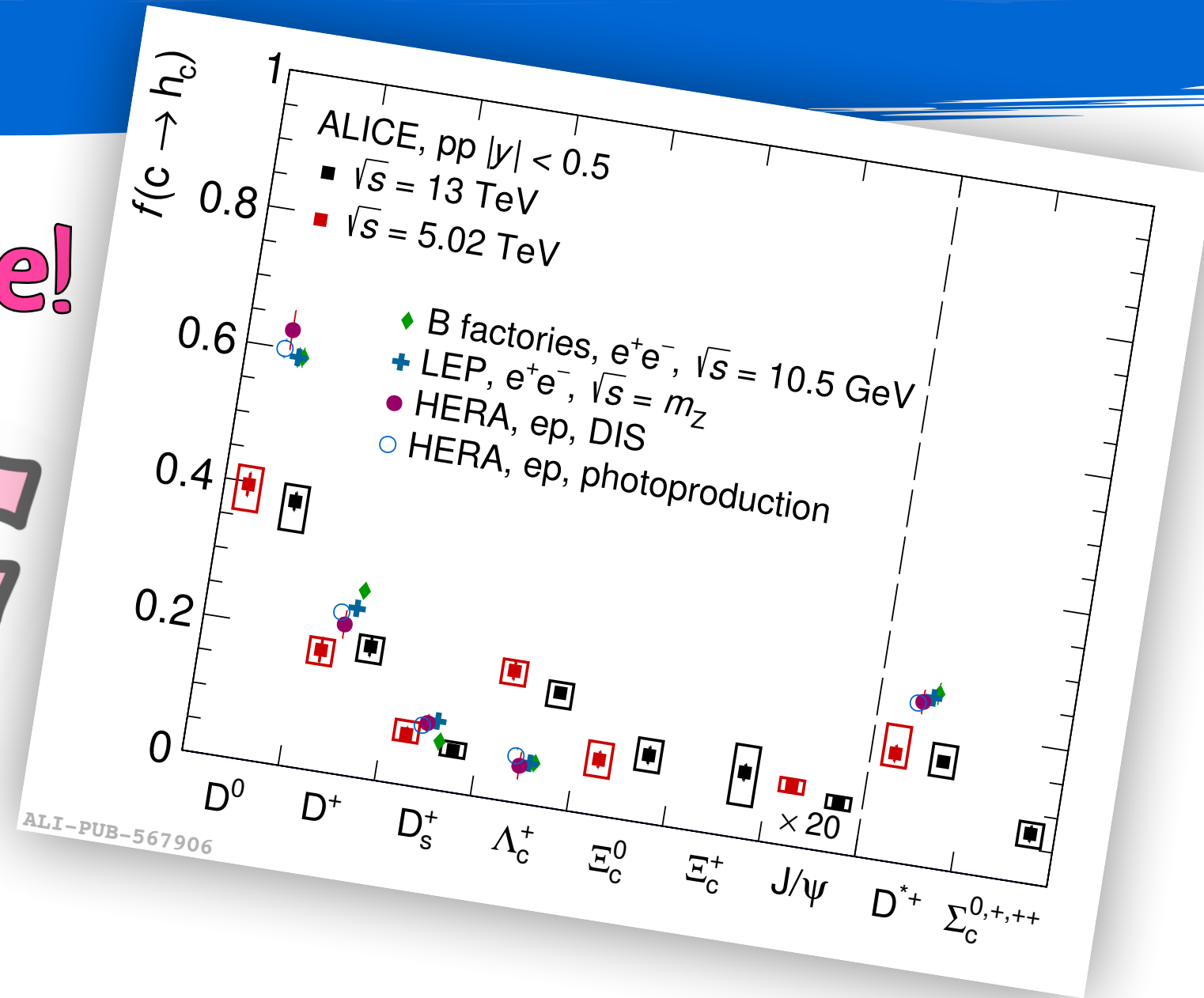
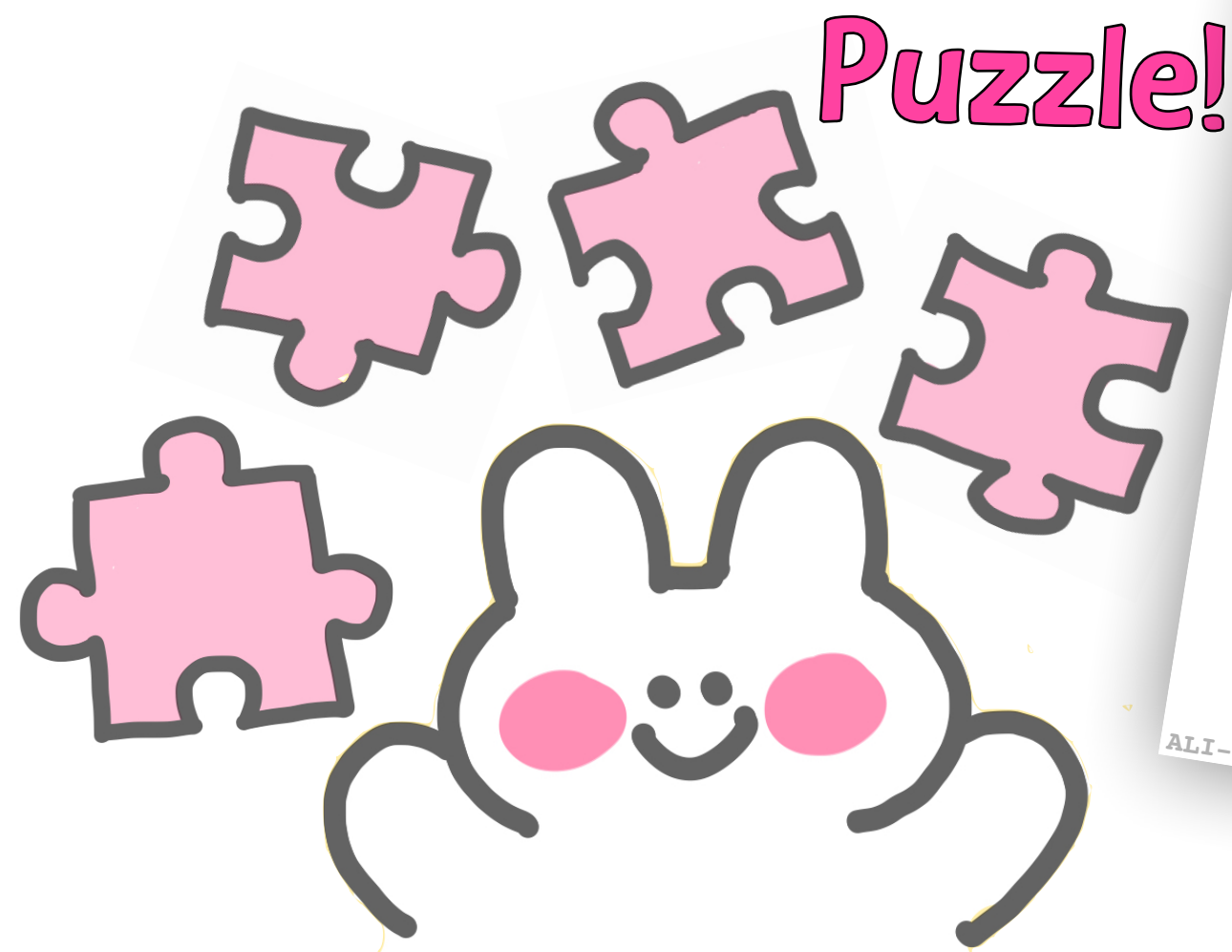
Run 3
2022-2025



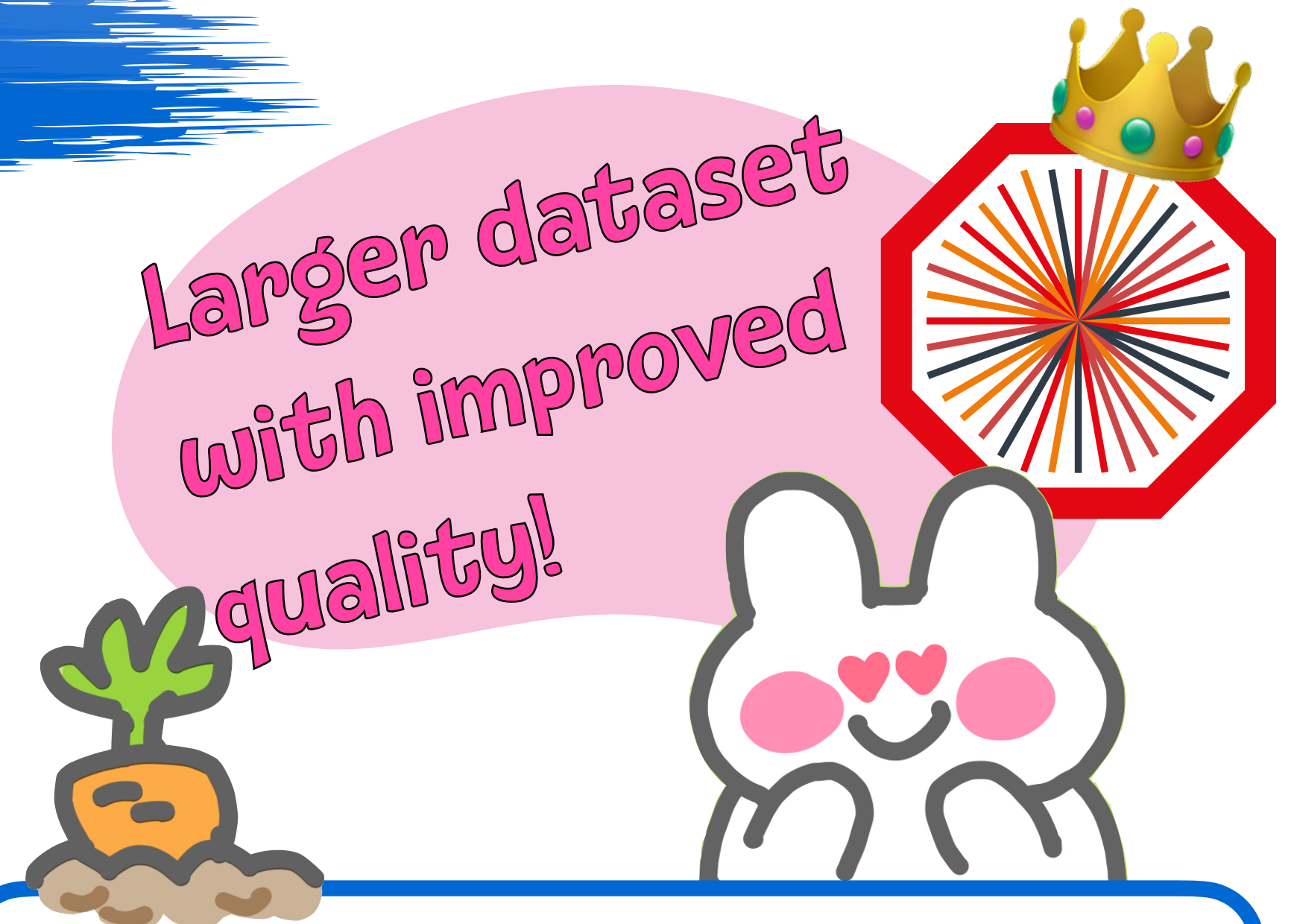
ALICE

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

Summary



Larger dataset
with improved
quality!



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

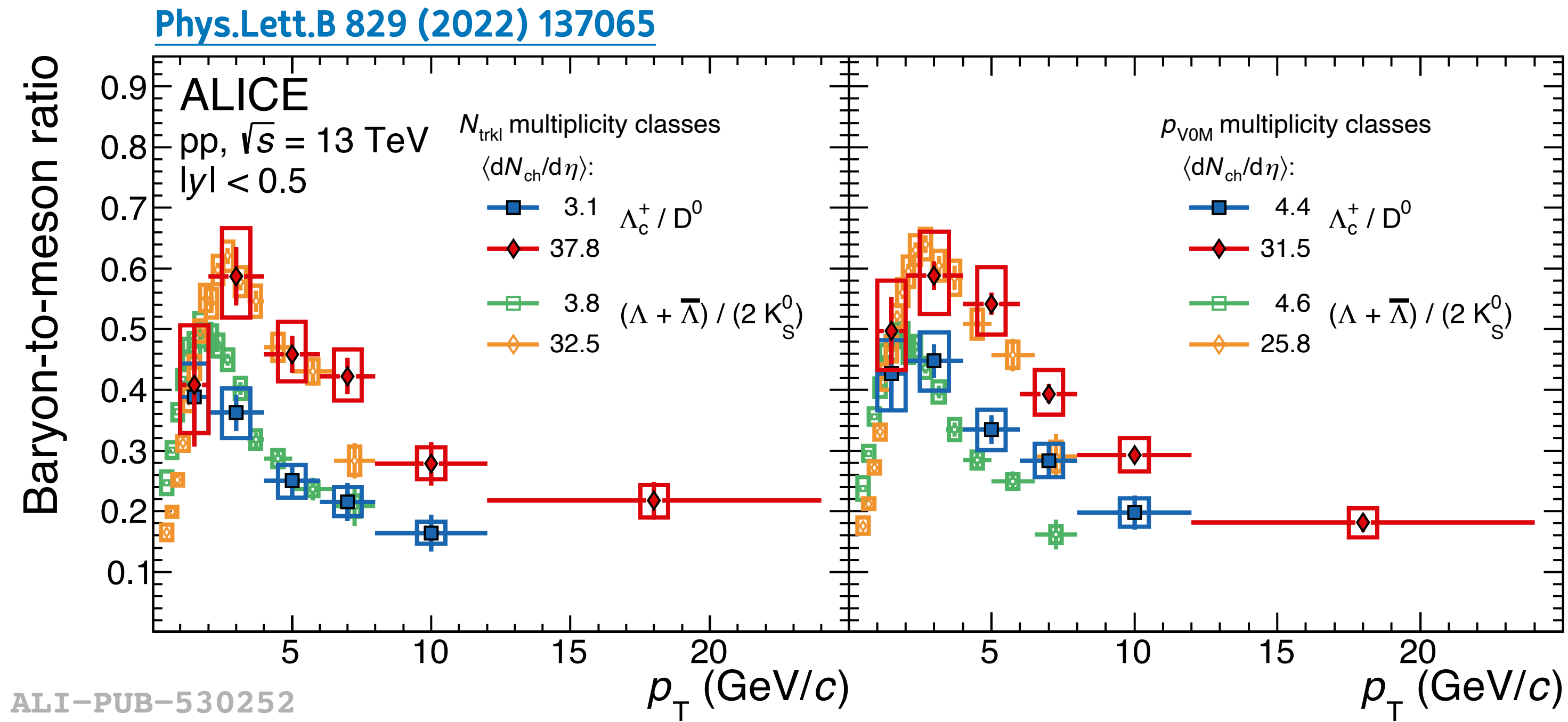
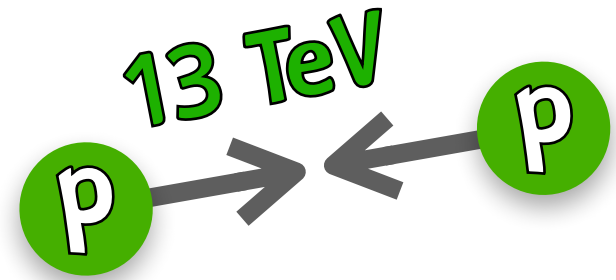
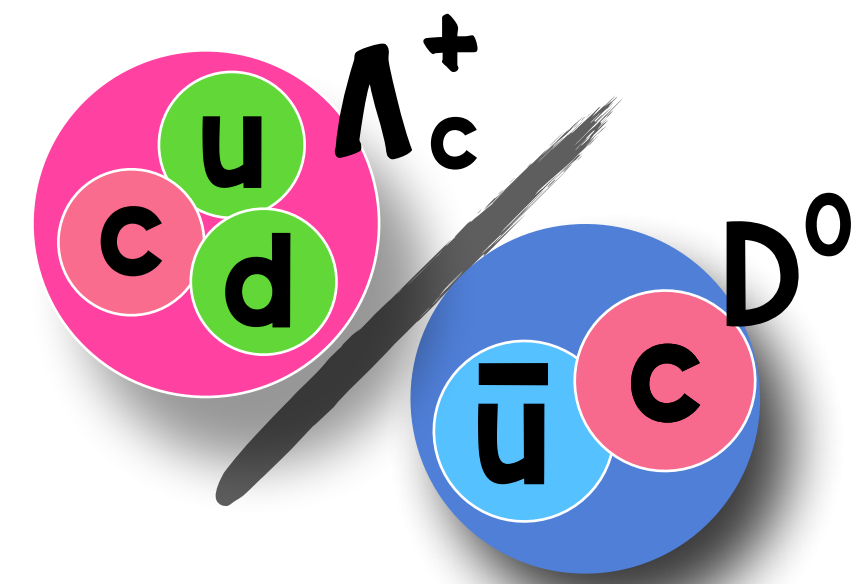
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France



ALICE

Λ_c^+ / D^0 vs. event multiplicity

in pp collisions

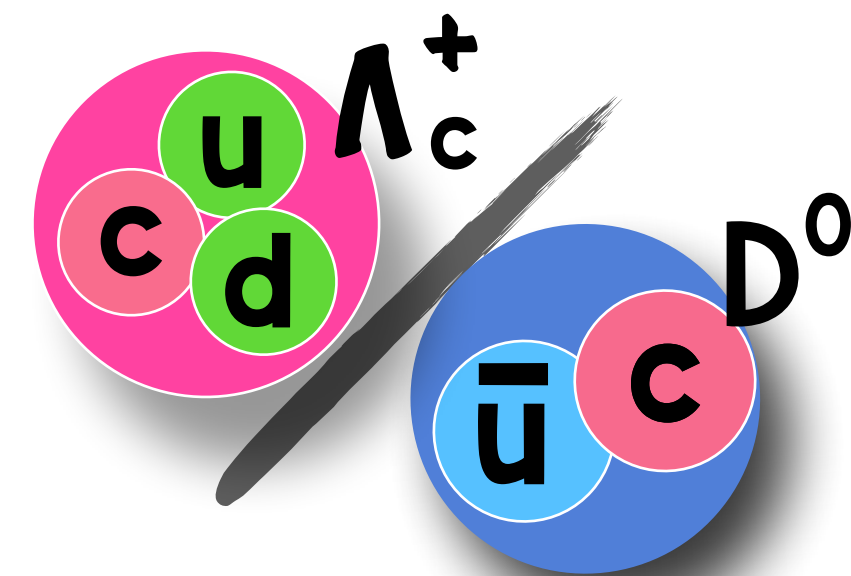


Comparing to baryon-to-meson ratio of light-flavour hadrons

- ★ 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



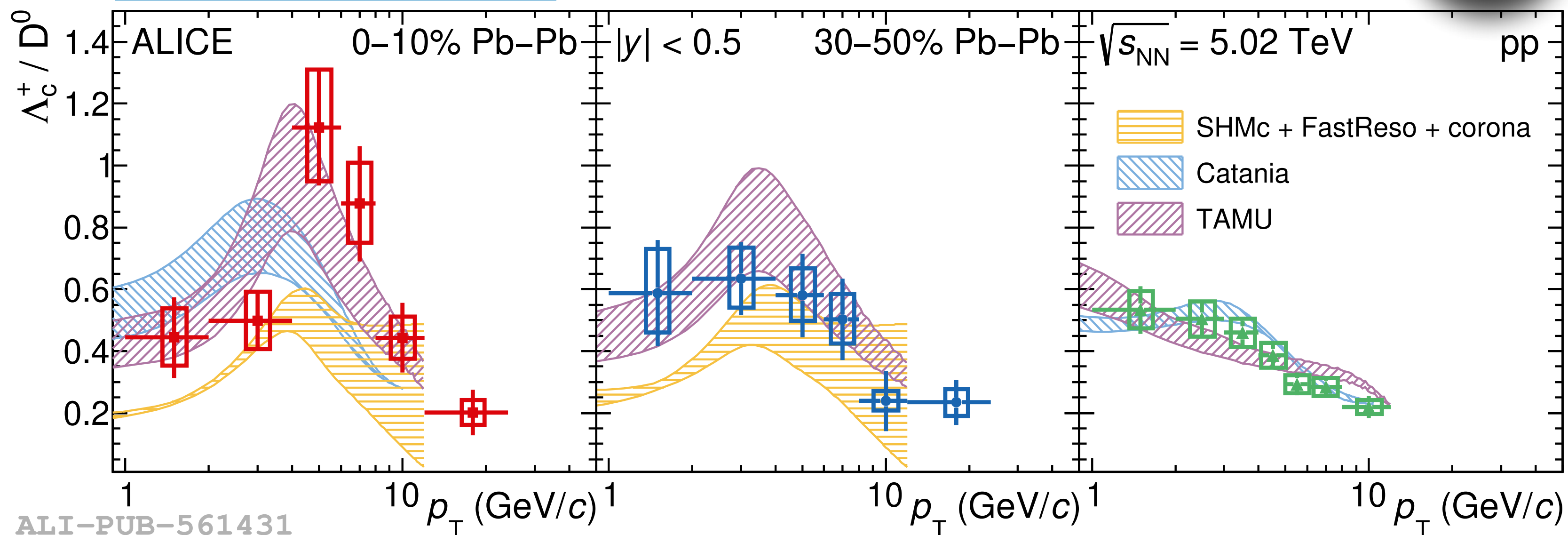
Catania

- ★ 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

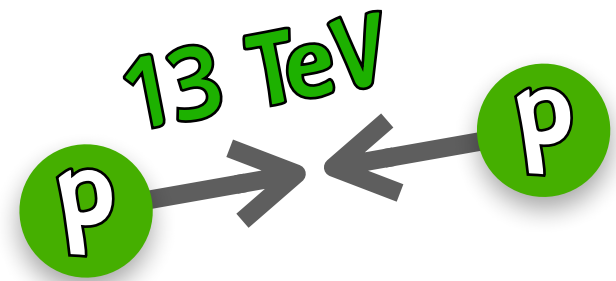
Phys.Lett.B 839 (2023) 137796



TAMU

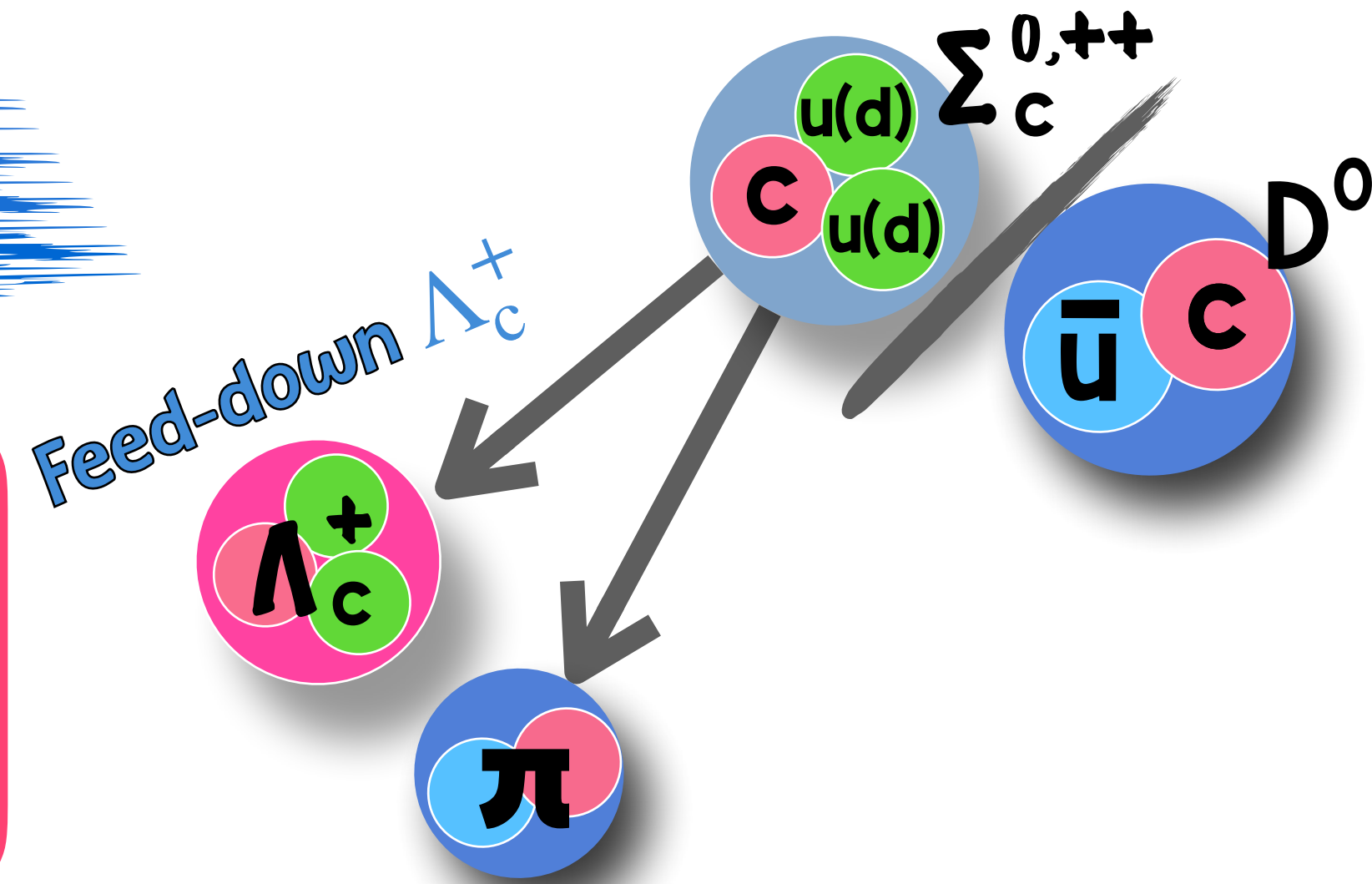
- ★ Exploit SHM for pp collisions
- ★ Consider both coalescence and fragmentation for hadronization for Pb—Pb collisions
- ★ Consider excited state baryon from RQM for both pp and Pb-Pb collisions

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

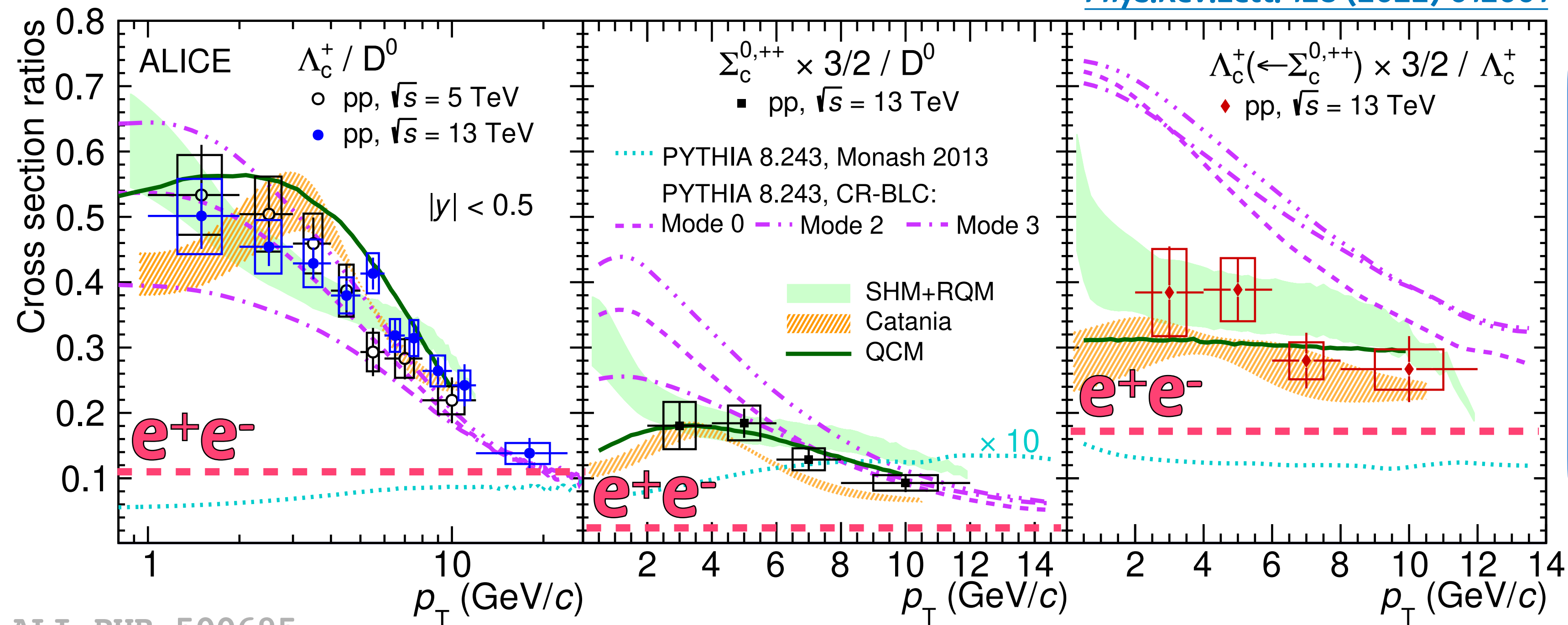


Comparing to e^+e^- collisions

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



Phys.Rev.Lett. 128 (2022) 012001



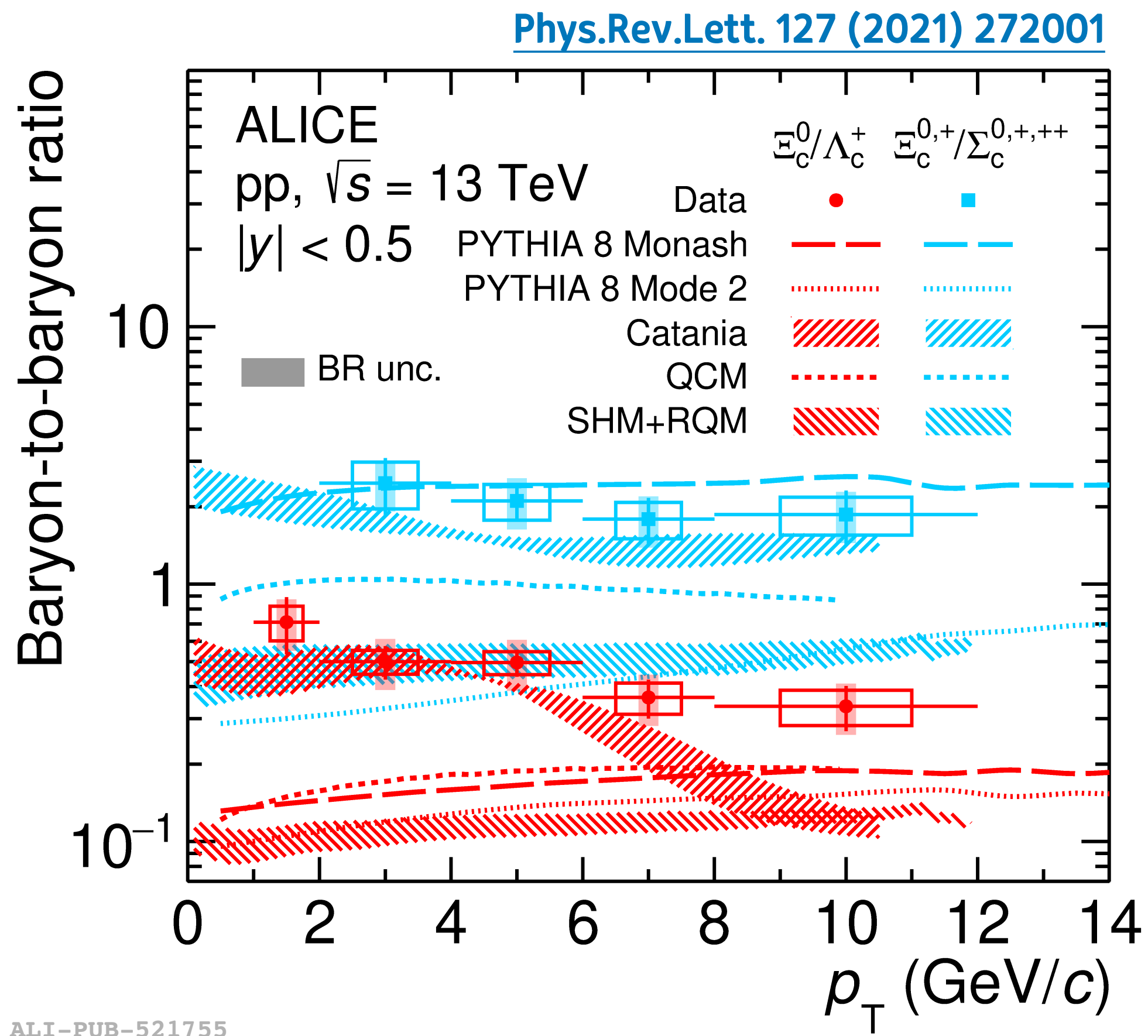
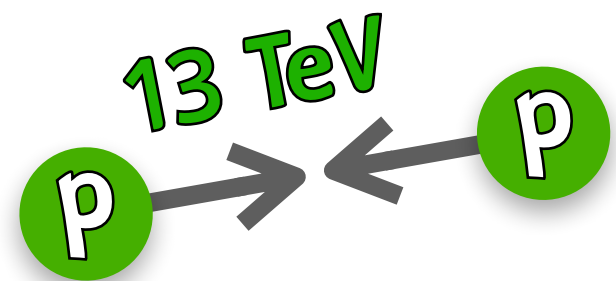
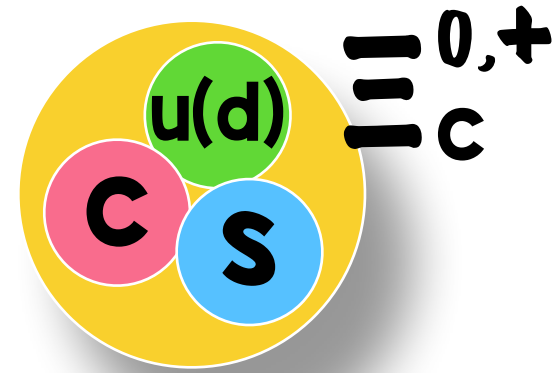
Feed-down Λ_c^+ from $\Sigma_c^{0,++}$

★ $\sim 40\%$ of Λ_c^+ from $\Sigma_c^{0,++}$ decay
 ★ Enhanced feed-down partially contribute to enhancement in Λ_c^+/D^0 in pp collisions

ALI-PUB-500695



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



ALI-PUB-521755

Production yield ratio to Λ_c^+

- ★ No strong p_T dependence
- ★ Models underestimate data

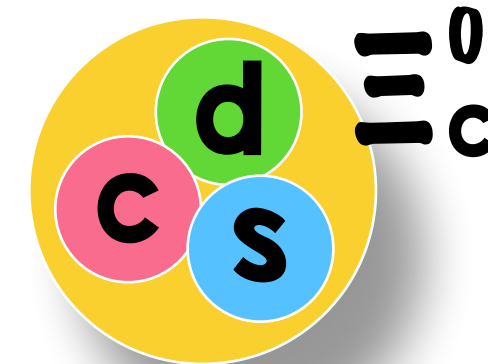
Production yield ratio to $\Sigma_c^{0,+,++}$

- ★ 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

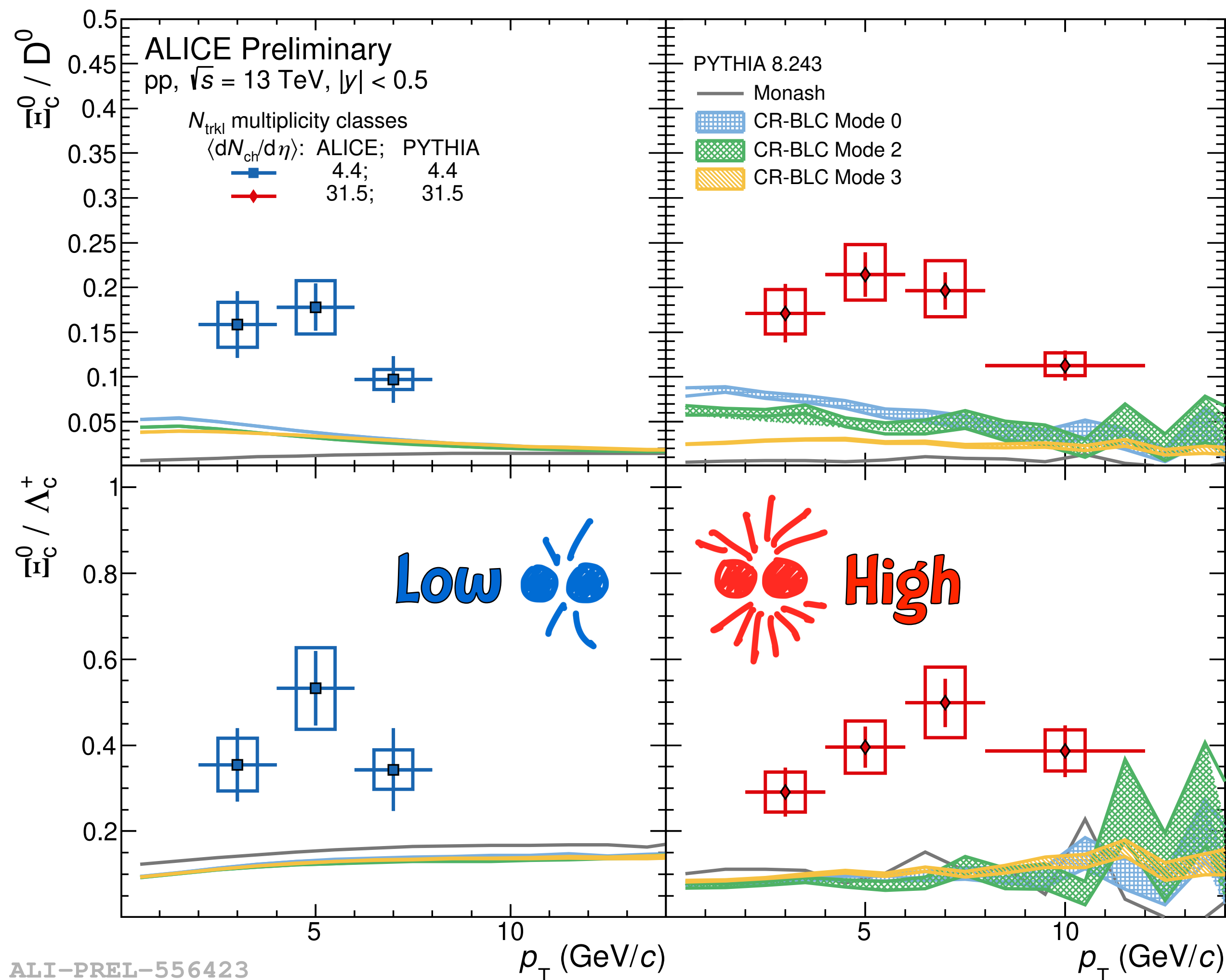


Production yield ratio to D^0 and Λ_c^+

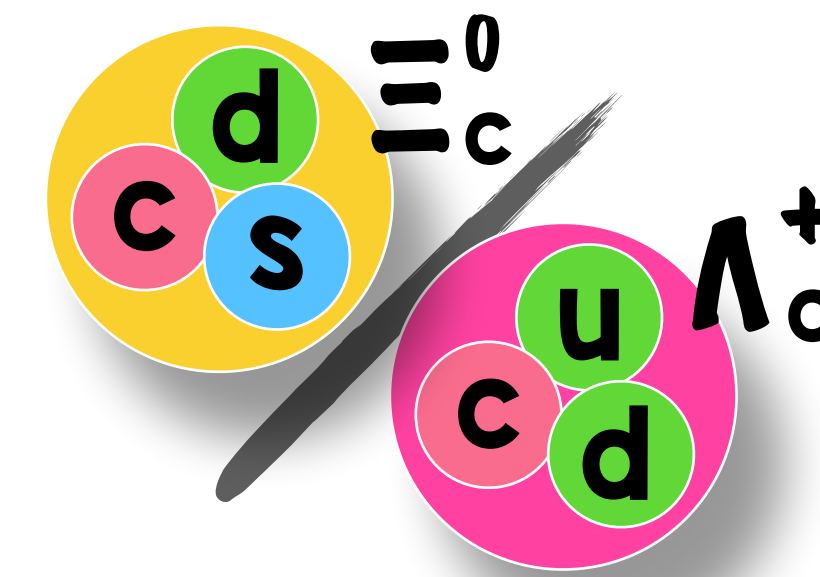
★ No strong multiplicity dependence in baryon-to-meson and baryon-to-baryon ratio within the uncertainties

Model comparison

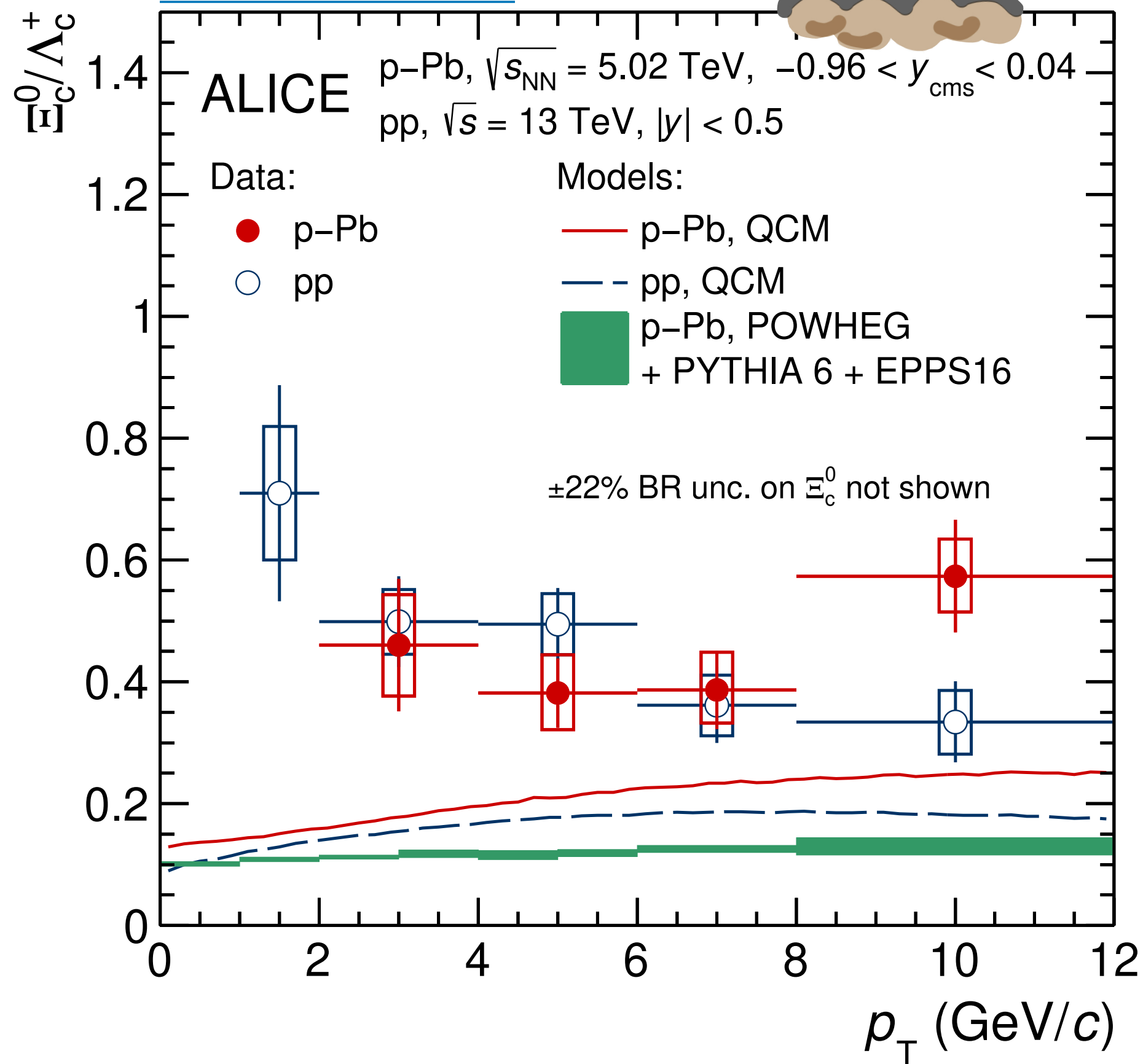
- ★ PYTHIA 8 Monash doesn't reproduce neither magnitude nor multiplicity dependence
- ★ PYTHIA 8 CR-BLC tunes, which describe the Λ_c^+ / D^0 ratio significantly underestimate the data



Ξ_c^0/Λ_c^+ in p-Pb collisions



arXiv : 2405.14538



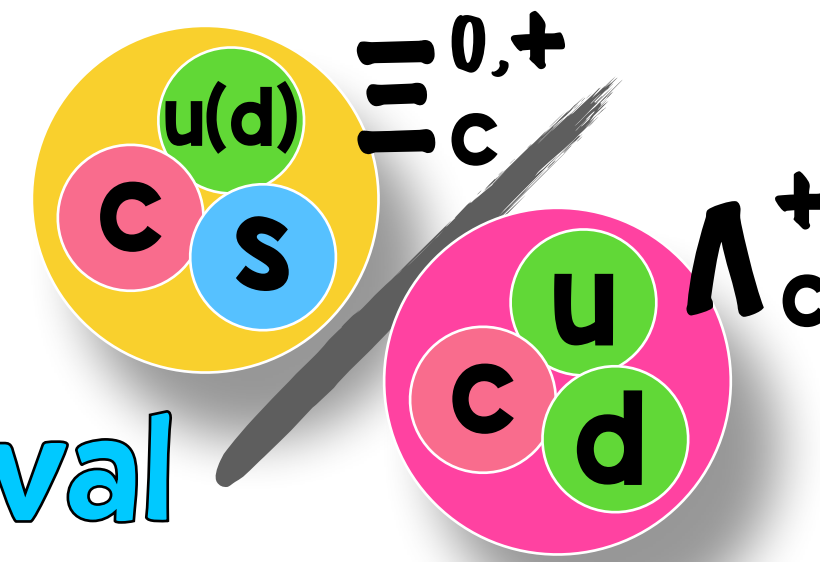
Production yield ratio to Λ_c^+

- ★ 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**

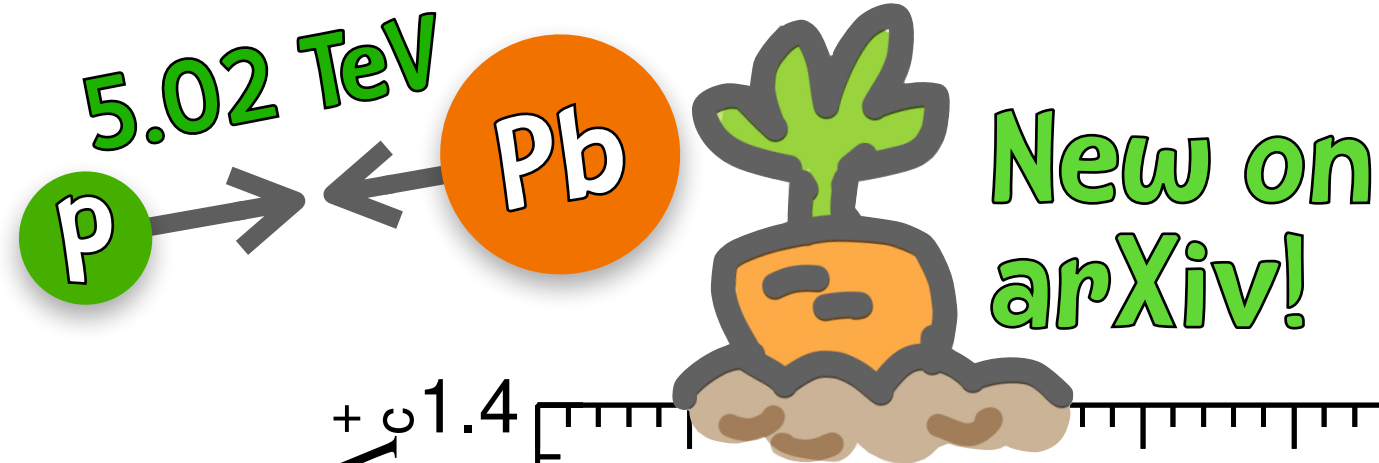
ALI-PUB-571015



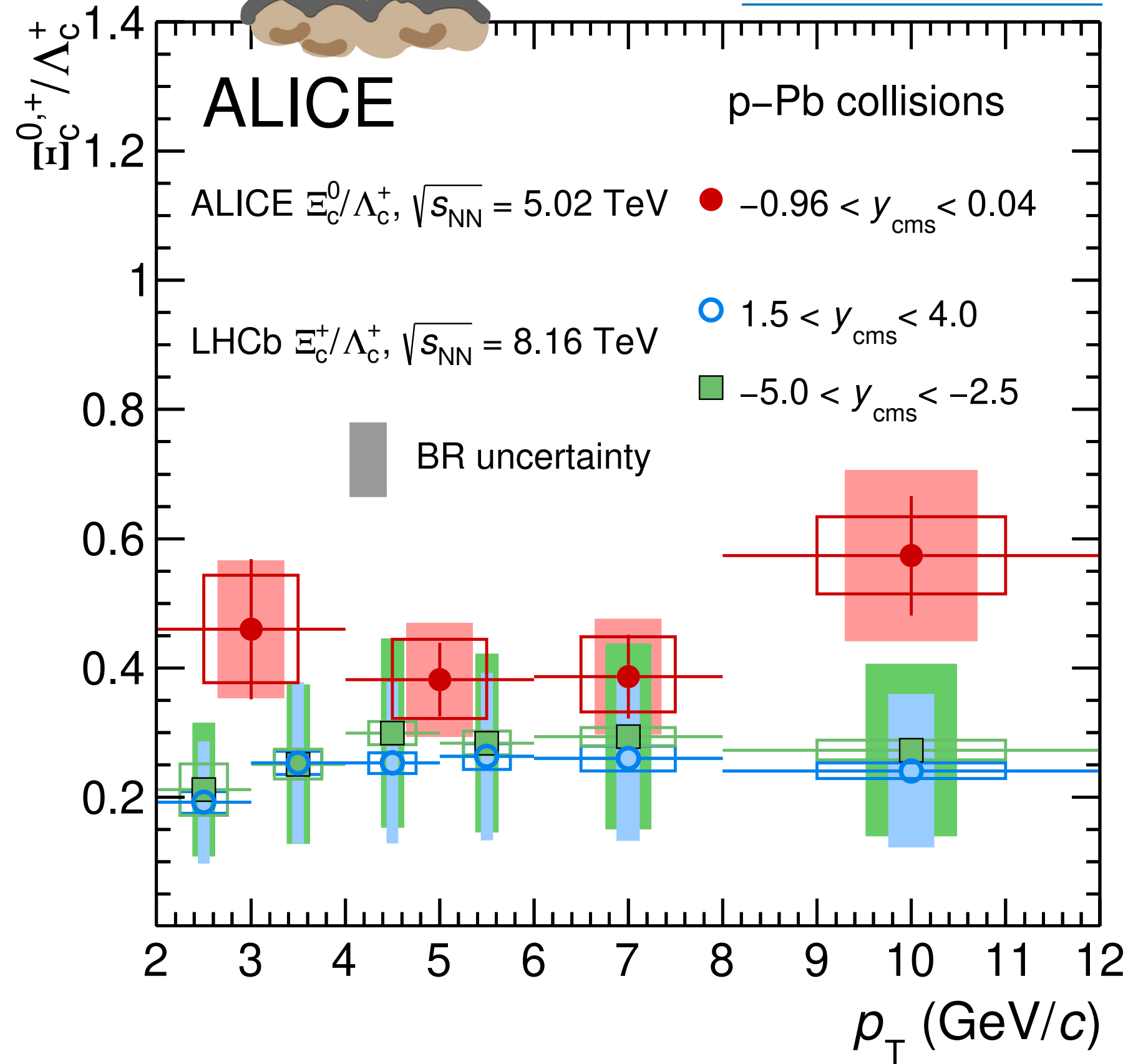
Ξ_c^0/Λ_c^+ in p-Pb collisions



in different rapidity interval



arXiv : 2405.14538



ALICE, 5.02 TeV
 Ξ_c^0 measurement

● $-0.96 < y_{cms} < 0.04$



LHCb, 8.16 TeV
 Ξ_c^+ measurement

○ $1.5 < y_{cms} < 4.0$

■ $-5.0 < y_{cms} < -2.5$

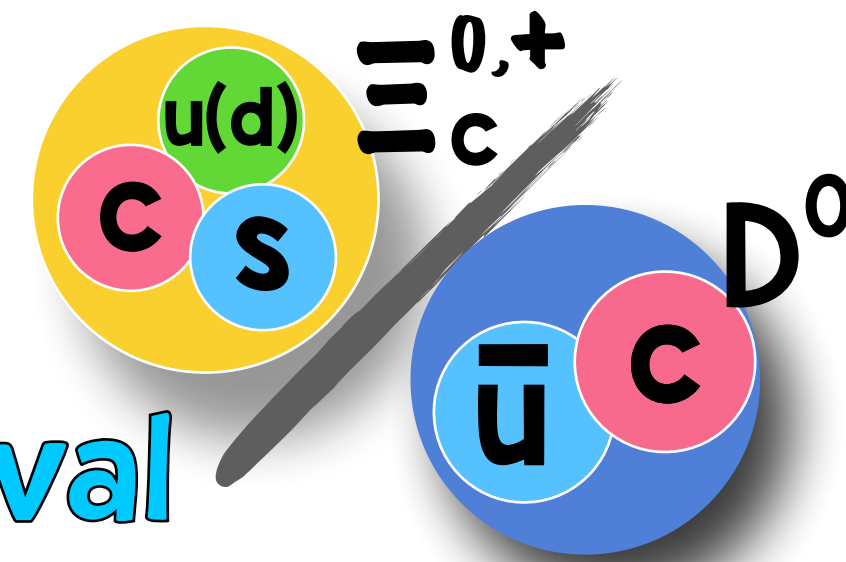
Production yield ratio to Λ_c^+

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

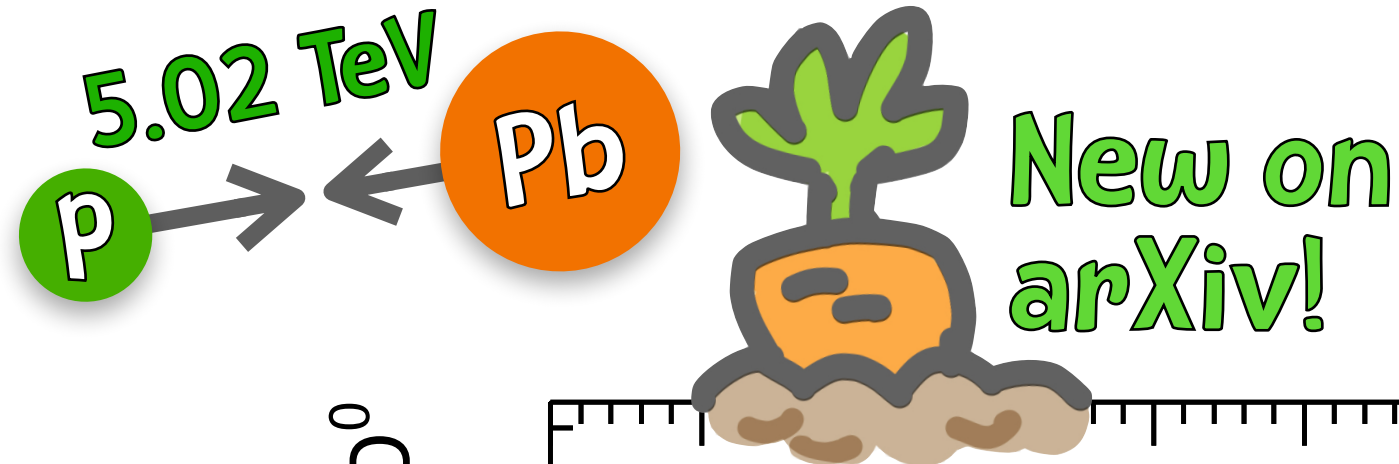
- 1.1 σ difference at 2-4 GeV/c p_T interval

ALI-PUB-571023

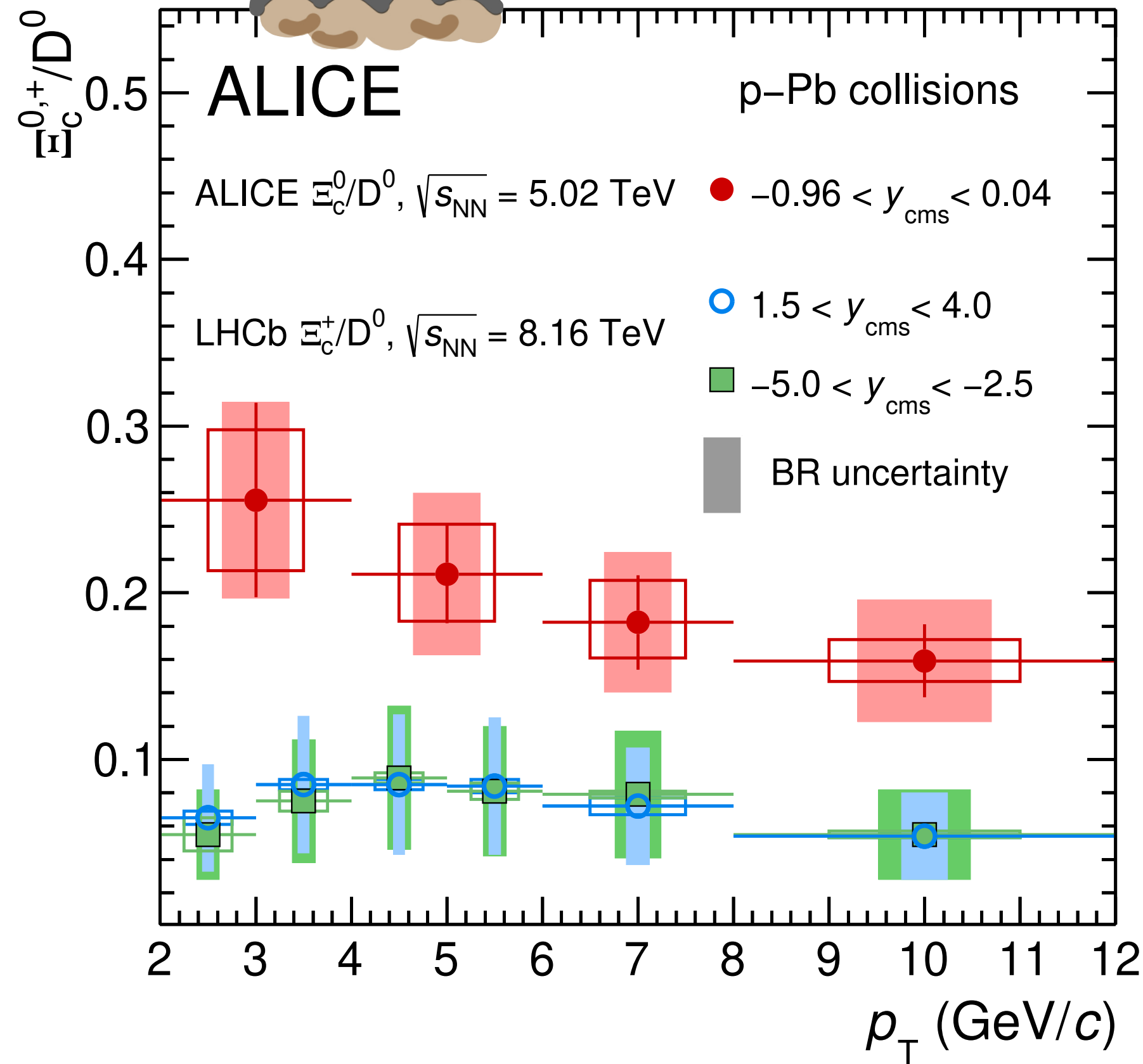
Ξ_c^0/Λ_c^+ in p-Pb collisions



in different rapidity interval



arXiv : 2405.14538



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

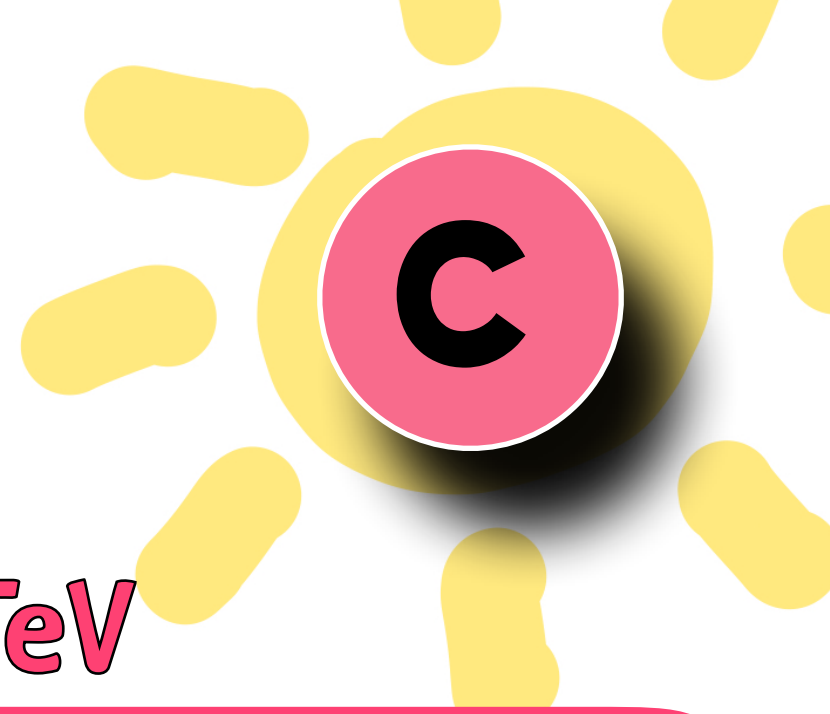
★ Hint of rapidity dependence?

- 1.5 σ to 2.0 σ difference across the different p_T interval

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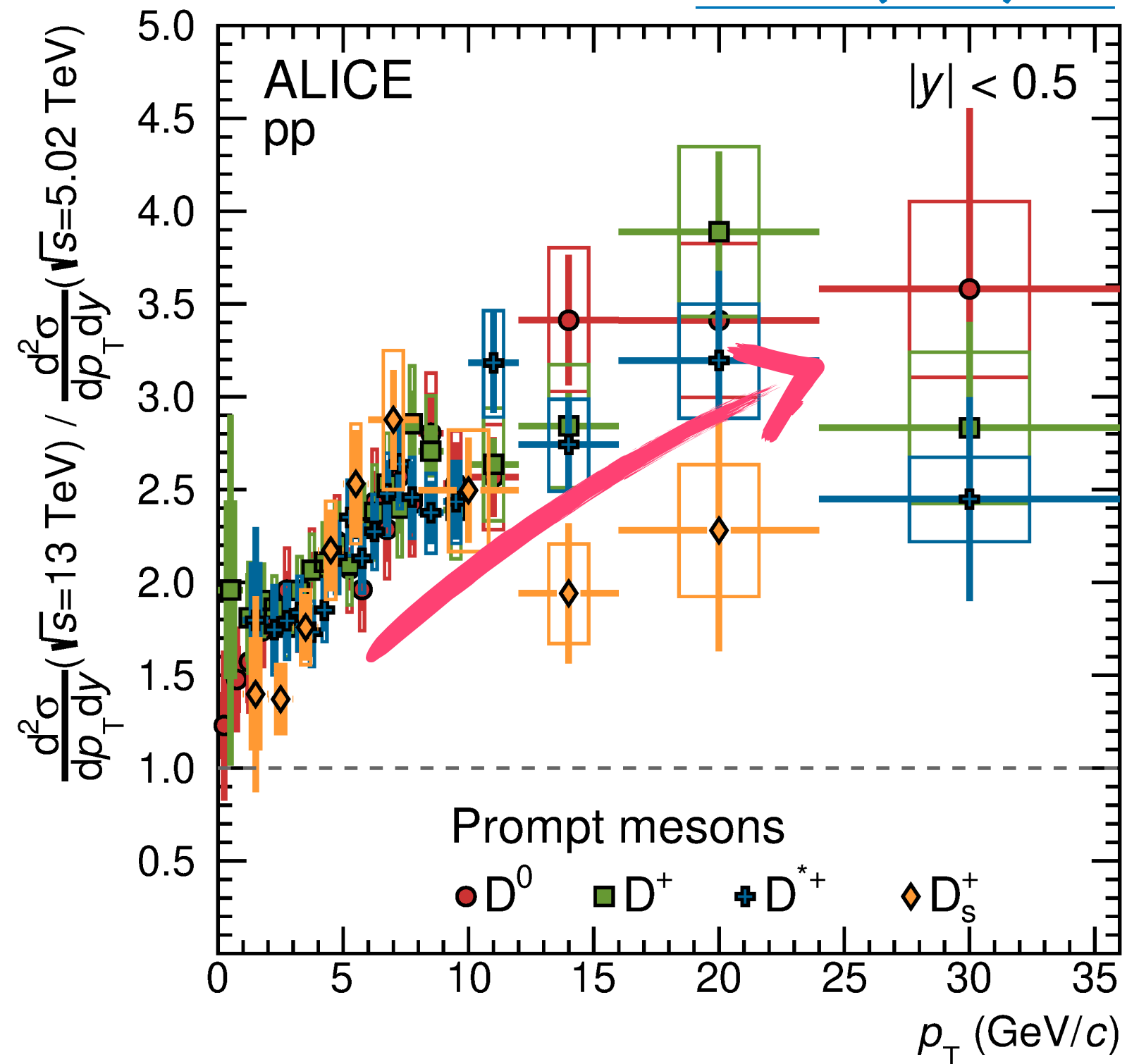
Energy dependence in hadron production



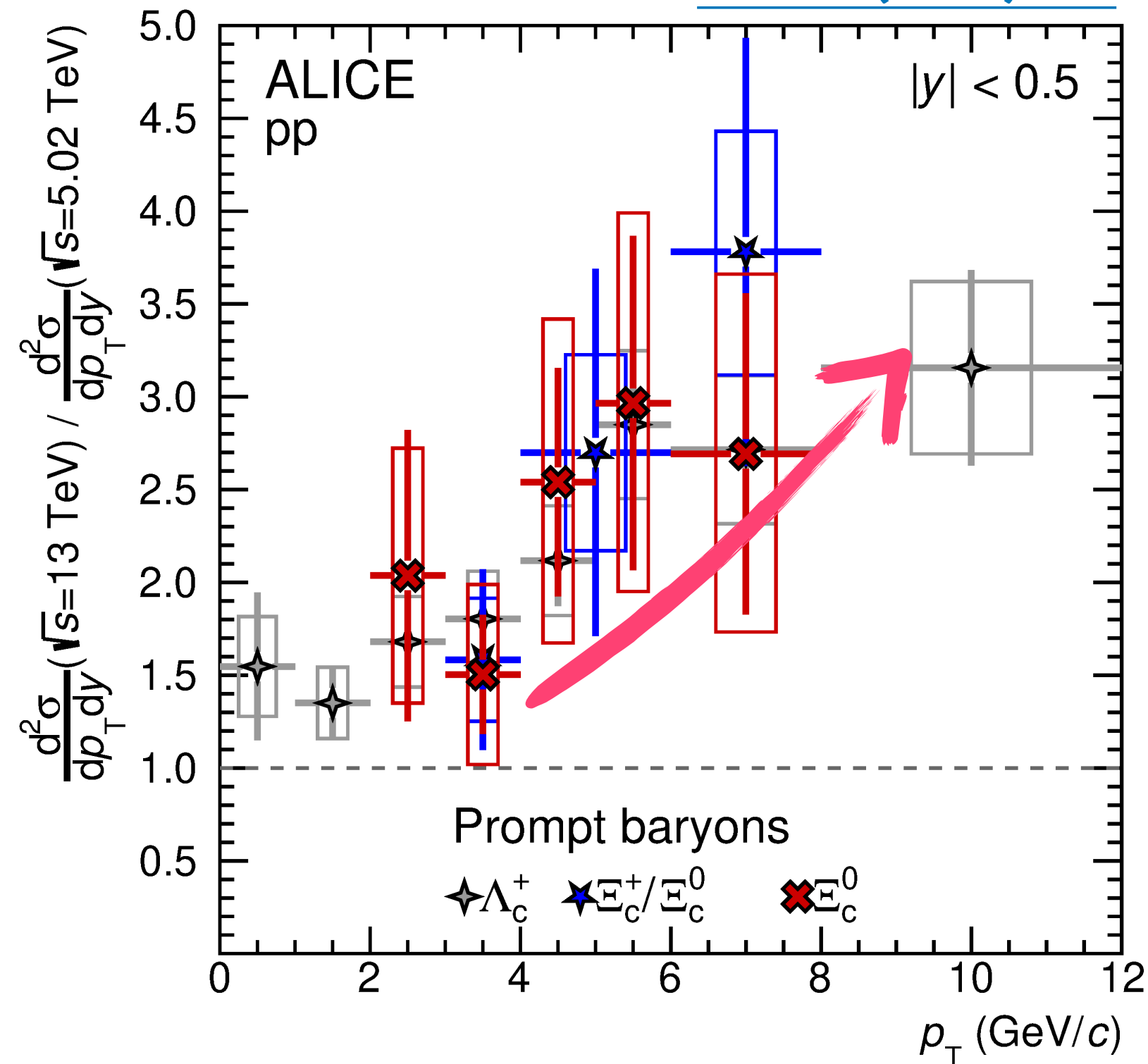
● D^0
 ■ D^+
 + D^{*+}
 ◆ D_s^+

★ Λ_c^+
 ★ E_c^+/E_c^0
 ✕ E_c^0

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13 TeV / 5.02 TeV

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

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