Investigation of charm-quark hadronization into baryons and its collision-system dependence with ALICE

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on behalf of the ALICE Collaboration

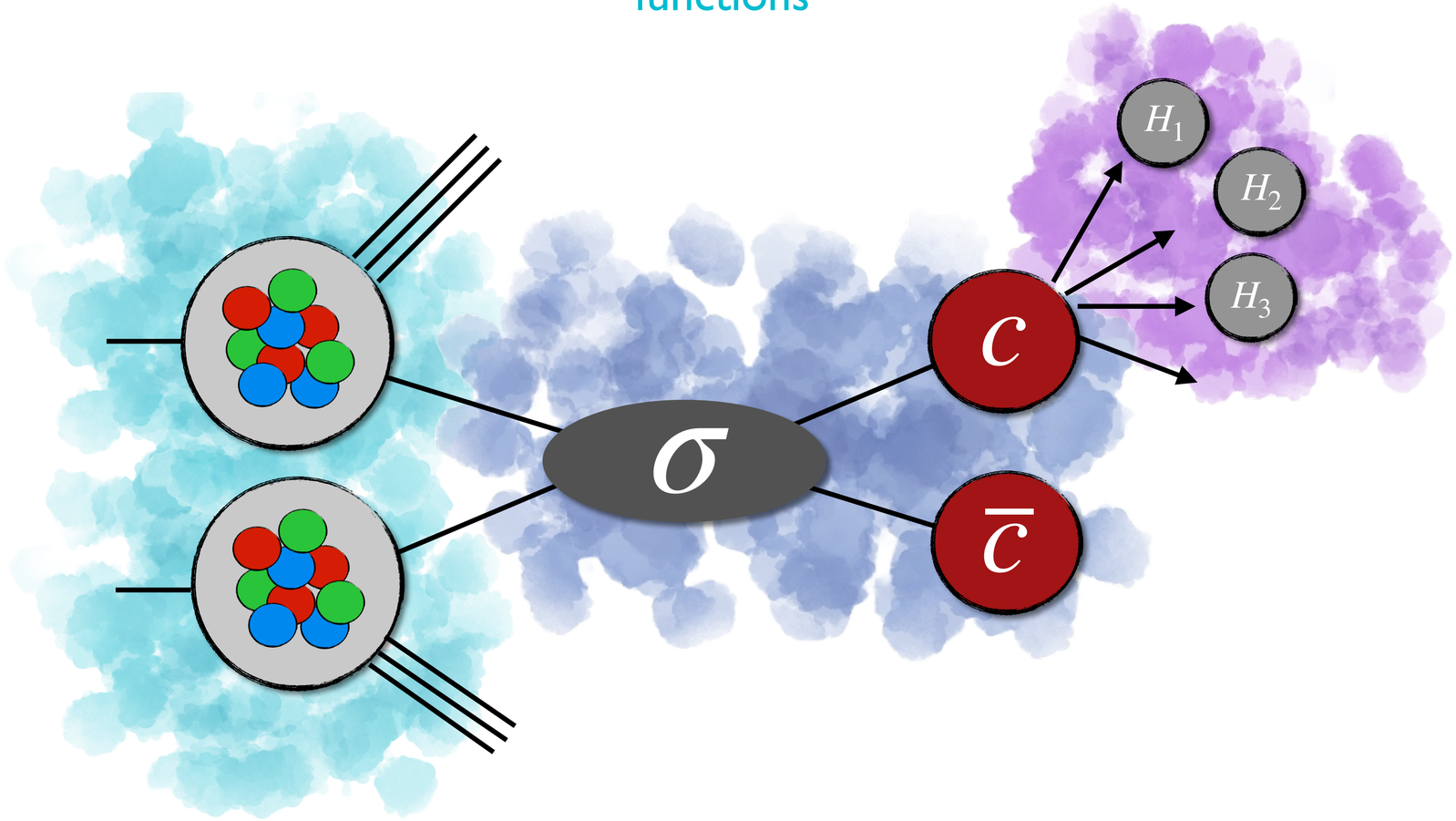
Probing charm hadronization

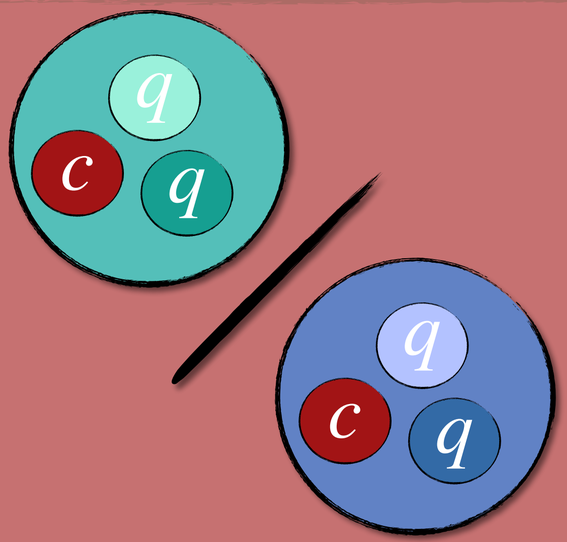
$$\sigma_{\mathrm{AB}\to\mathrm{H}} = \mathrm{PDF}(x_a, Q^2)\mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}}(x_a, x_b, Q^2) \otimes D_{q\to\mathrm{H}}(z = \mathrm{p_H}/\mathrm{p}_q, Q^2)$$

Parton distribution functions

Hard scattering cross section

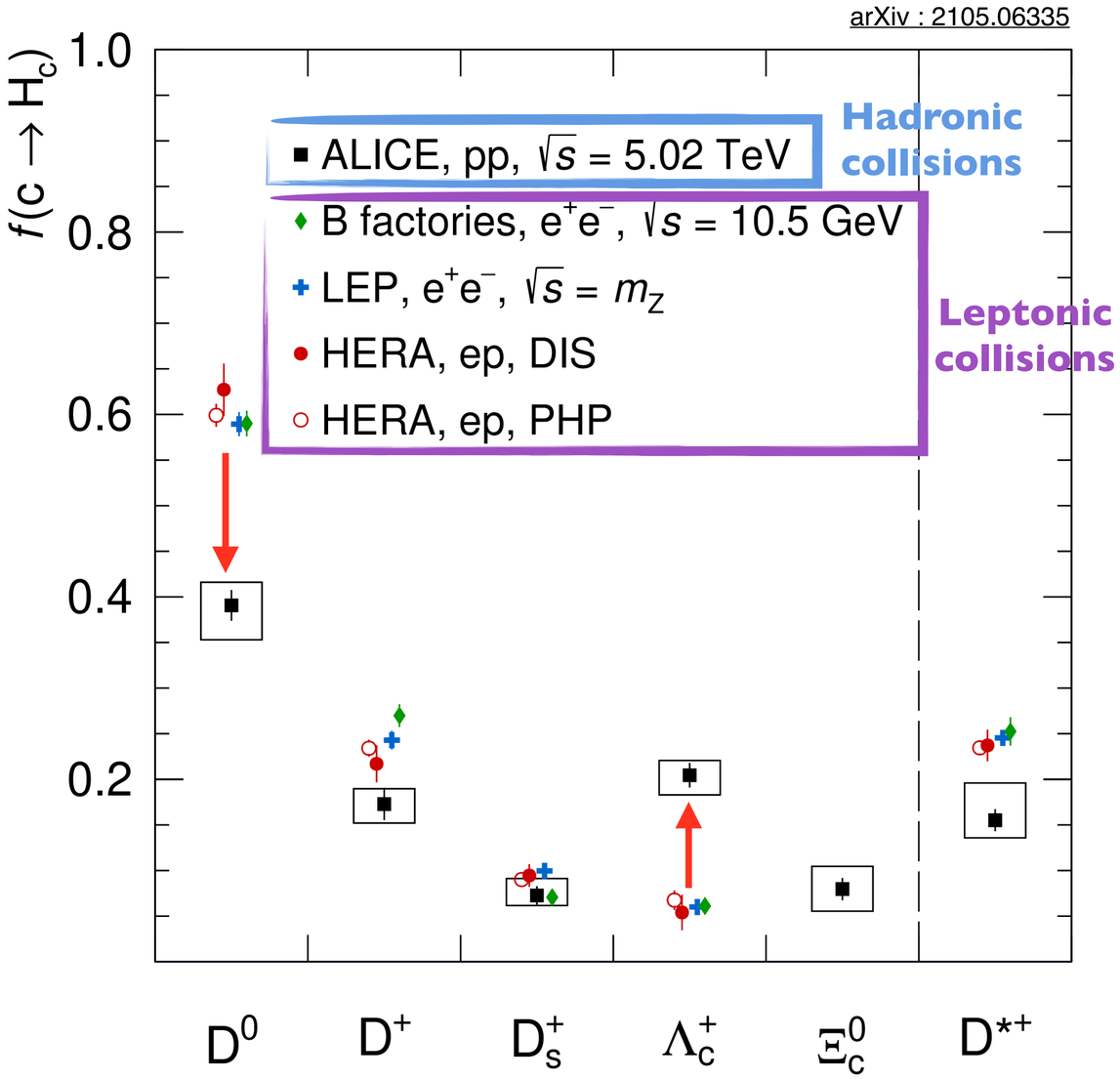
Fragmentation function (hadronization)





Production cross section ratio of different hadron species is an effective tool to probe charm hadronization

Testing universality of fragmentation functions



ALICE found a significantly larger fraction of charm quarks hadronising into baryons compared to leptonic collisions

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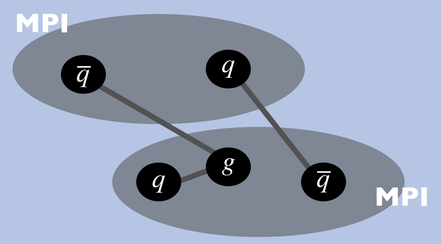
Indication that hadronization process depends on collision system

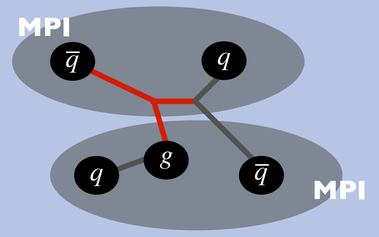
Modeling hadronization

PYTHIA 8

Hadronization via **fragmentation**, color reconnection between partons from different multiparton interactions



Monash tune
(tuned to e^+e^- measurements)
Eur.Phys.J. C 74 (2014) 3024

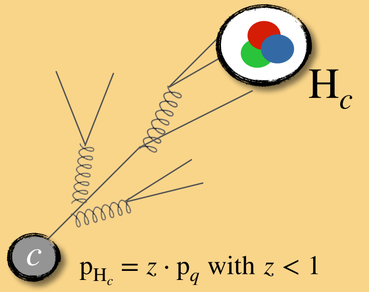


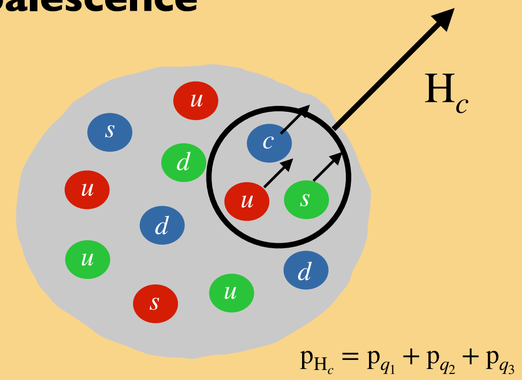
Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

Hadronization via both **fragmentation** and **coalescence**





SHM + RQM

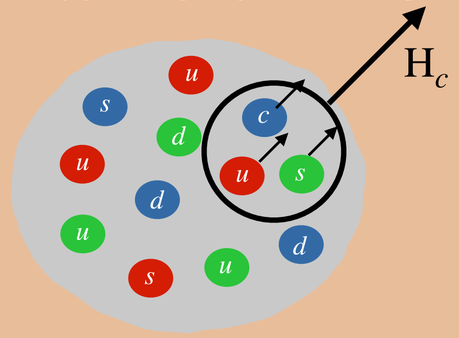
Phys.Lett.B 795 (2019) 117-121
Phys.Rev.D. 84 (2011) 014025

- Complexity of hadronization process replaced by **statistical weights** governed by hadron mass
- Feed-down from largely **augmented set of charm baryon stated** beyond the ones currently listed in the PDG, as predicted by Relativistic Quark Model

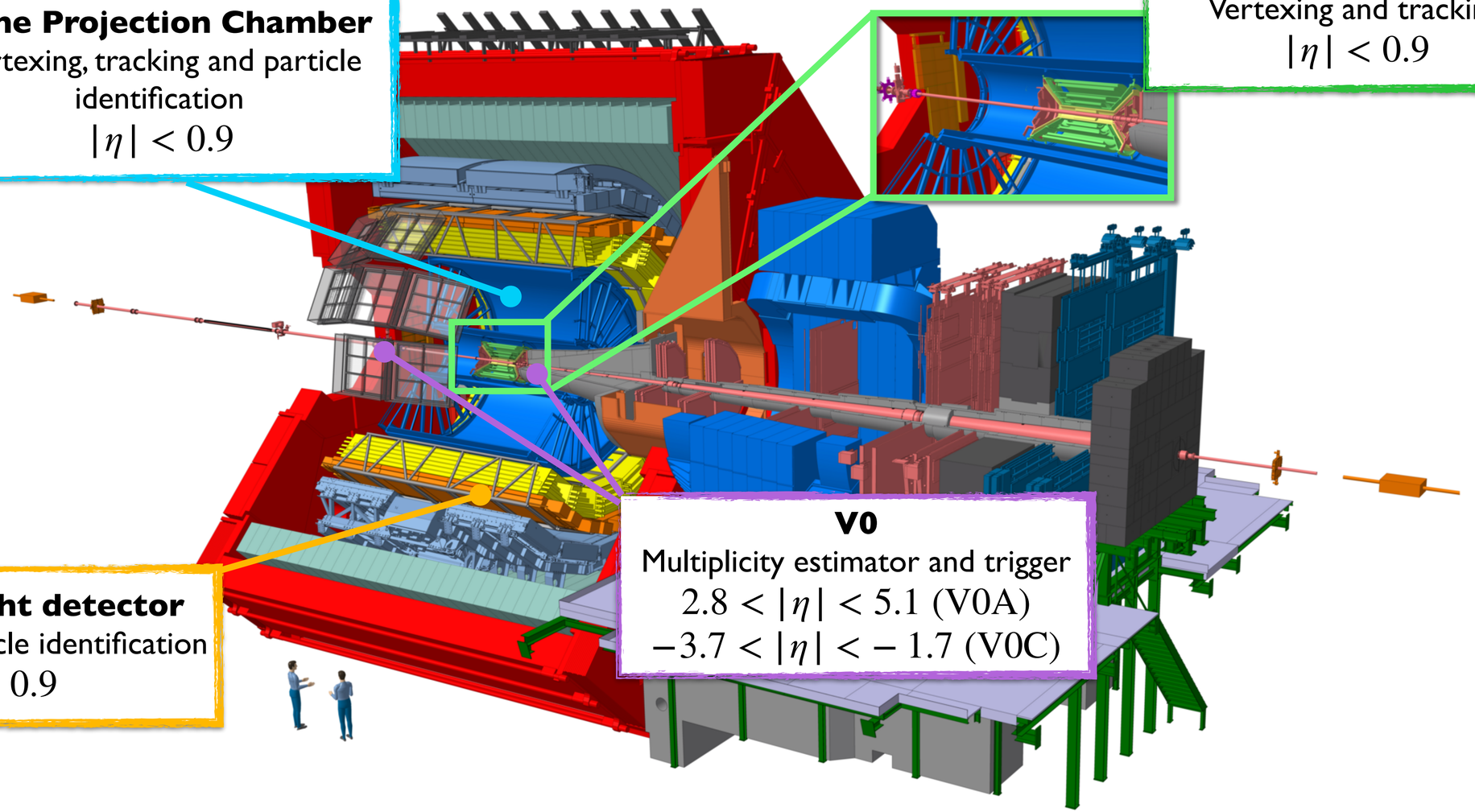
QCM

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

Quark (re-)Combination Mechanism
equal-velocity combination of charm quark and light quarks (spatial properties neglected)



The ALICE experiment in Run 2



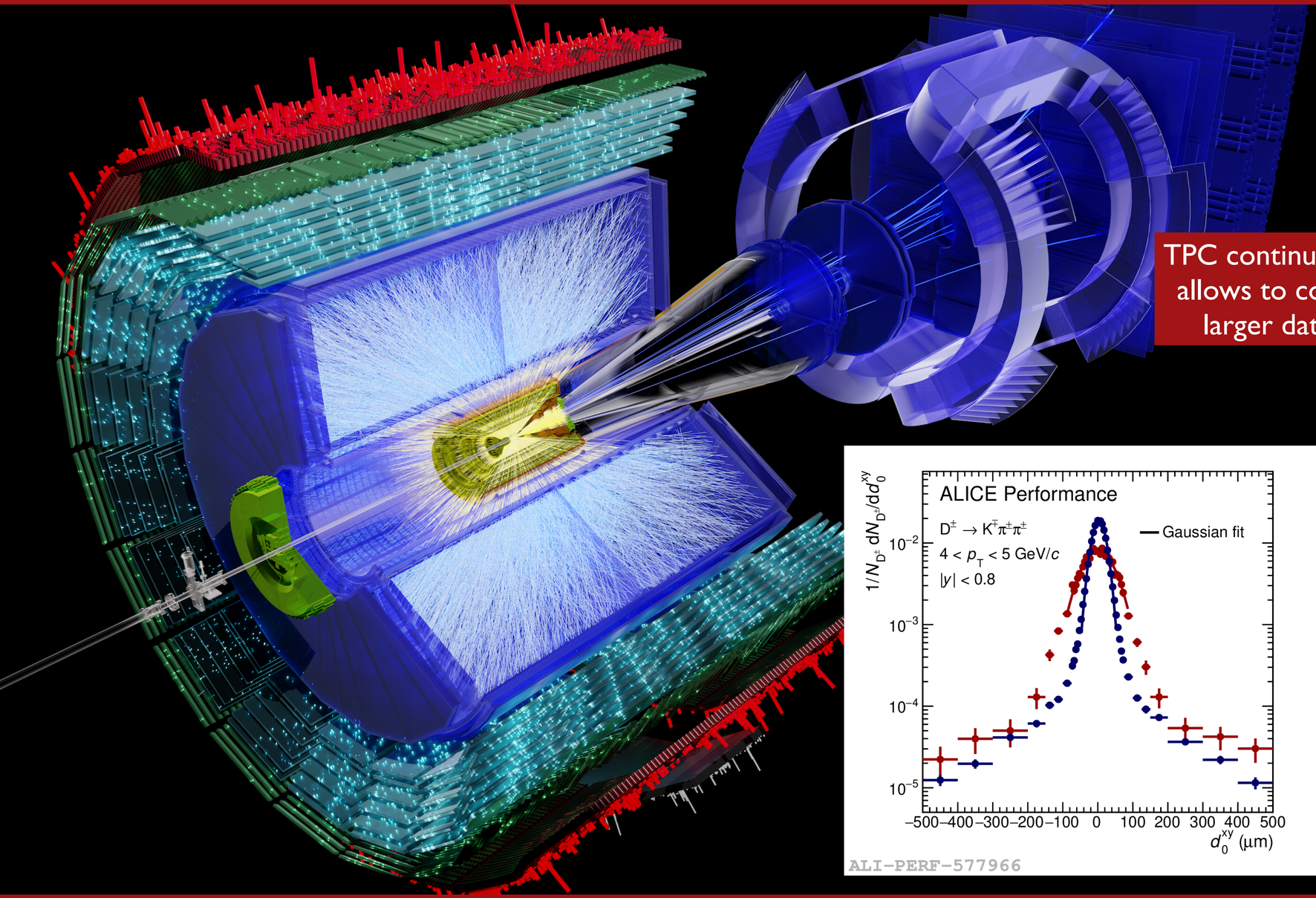
Time Projection Chamber
Vertexing, tracking and particle identification
$|\eta| < 0.9$

Inner Tracking System
Vertexing and tracking
$|\eta| < 0.9$

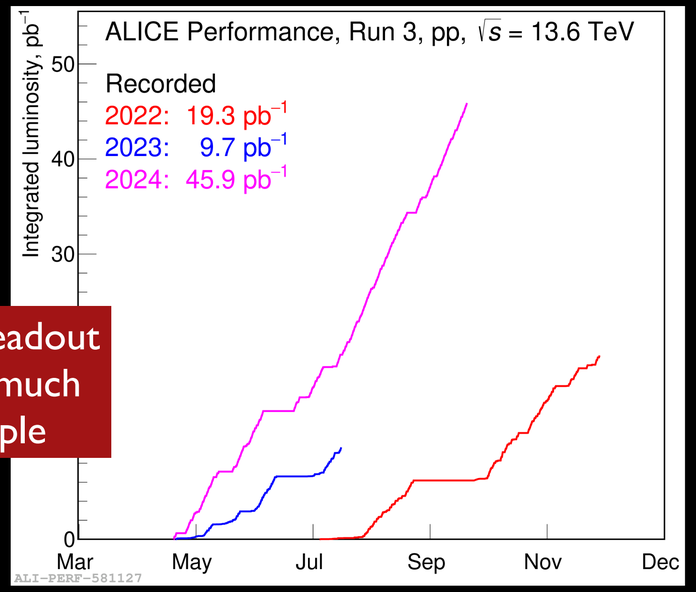
V0
Multiplicity estimator and trigger
$2.8 < |\eta| < 5.1$ (V0A)
$-3.7 < |\eta| < -1.7$ (V0C)

Time-Of-Flight detector
Tracking and particle identification
$|\eta| < 0.9$

Run 3

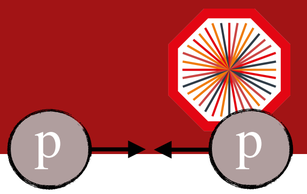


TPC continuous readout allows to collect much larger data sample

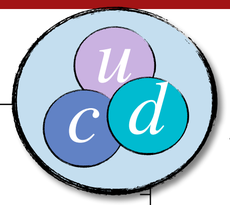


ITS upgrade improved pointing resolution

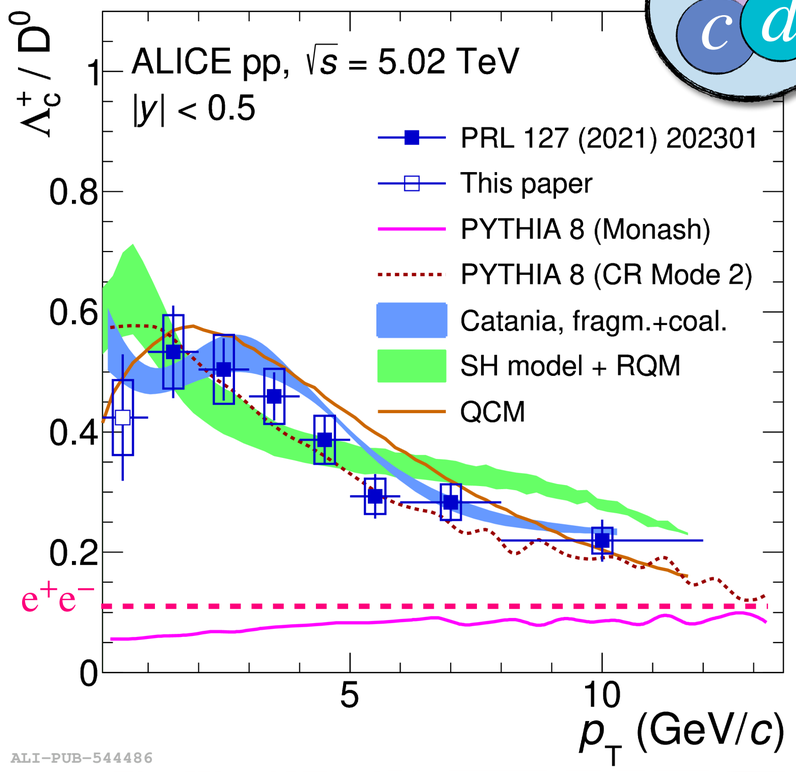
Measurements in pp collisions



Phys.Rev.C 107 (2023) 064901

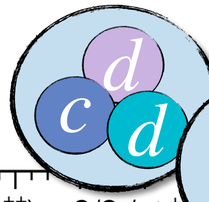


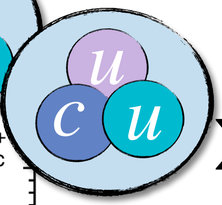
Λ_c^+



More about charm fragmentation in Jochen Klein's talk

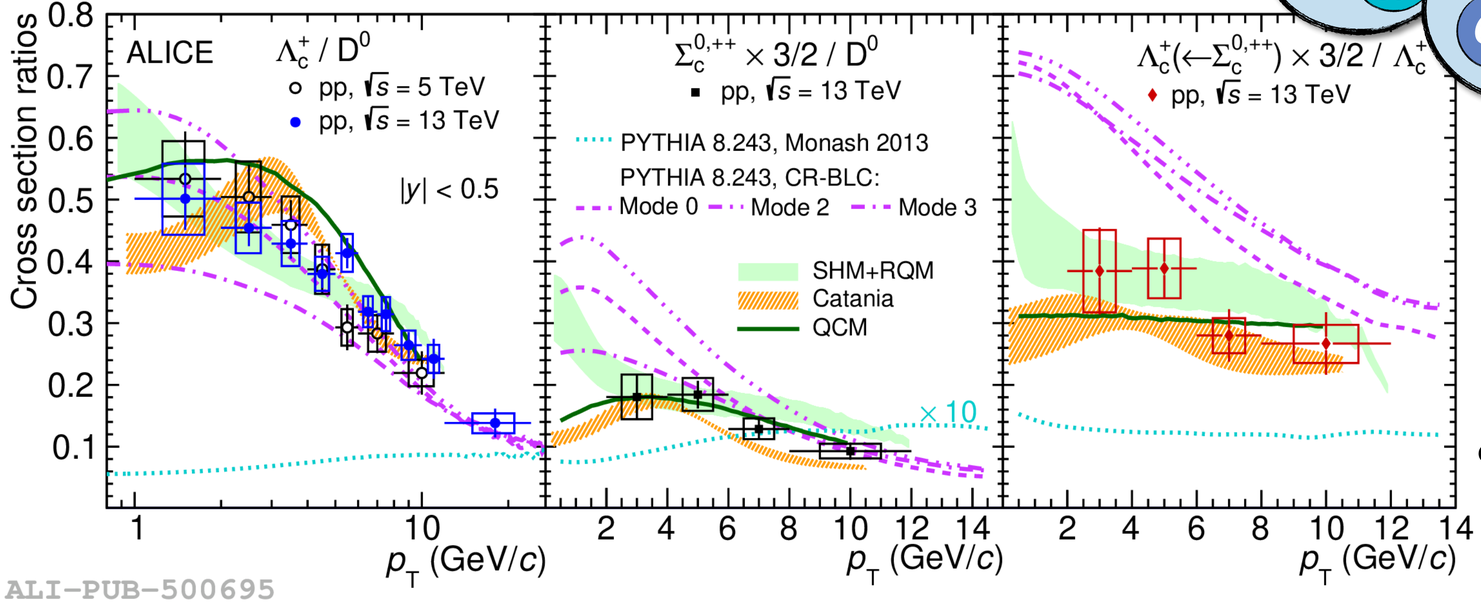
Σ_c^0





Σ_c^{++}

Phys.Rev.Lett. 128 (2022) 012001

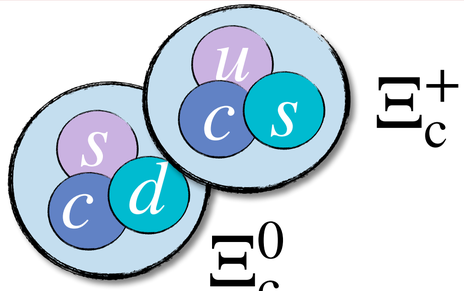


~40% of Λ_c^+ from $\Sigma_c^{0,++}$ decays → enhanced feed-down partially contributes to enhancement in Λ_c^+/D^0

- Predictions driven by charm-quark fragmentation processes measured in e^+e^- and e^-p collisions underestimate the data
- Baryon-to-meson ratio shows a clear p_T dependence, with larger baryon production at low and intermediate p_T
- PYTHIA 8 Mode 2, Catania, QCM and SHM+RQM successfully describe the data
- Measurements support the scenario of charm-quark hadronization in pp collisions via additional mechanisms than those in leptonic collisions

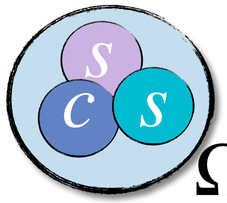
Measurement from e^+e^- collisions: Phys.Rev.Lett. 128 (2022) 012001

Measurements in pp collisions

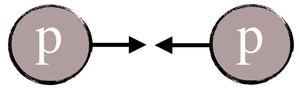


Ξ_c^+

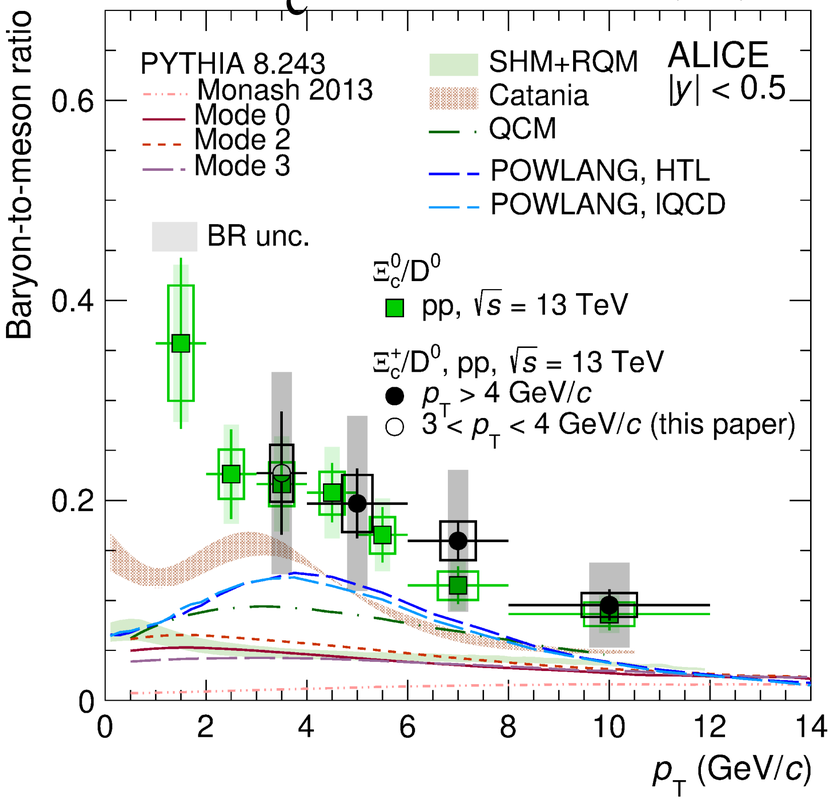
Ξ_c^0



Ω_c^0

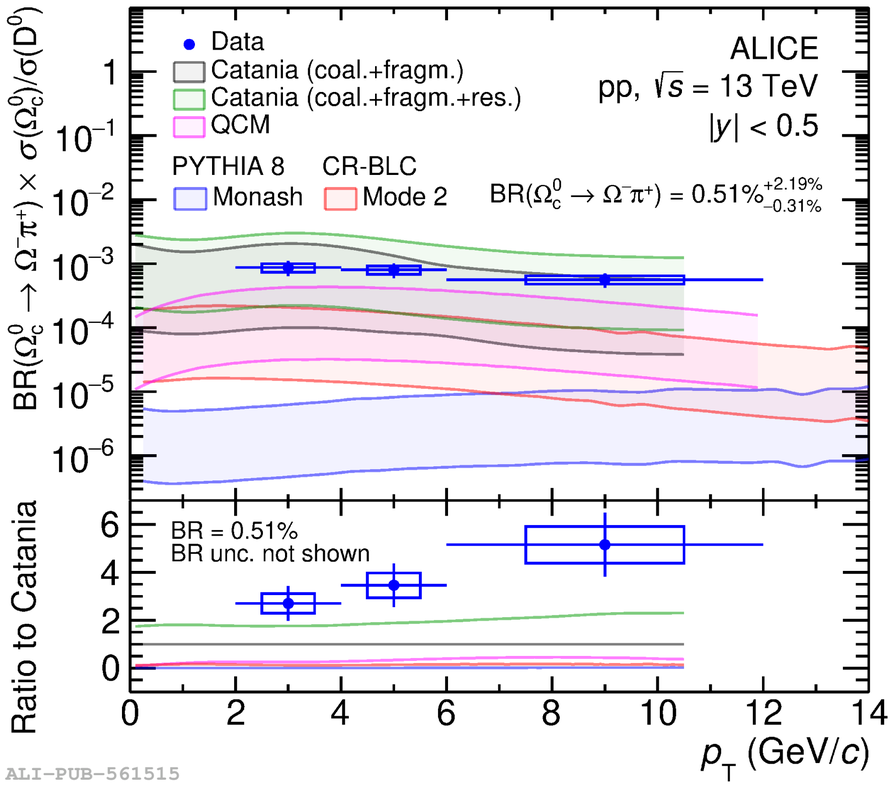


JHEP 12 (2023) 086



ALI-PUB-567881

Phys.Lett.B 846 (2023) 137625

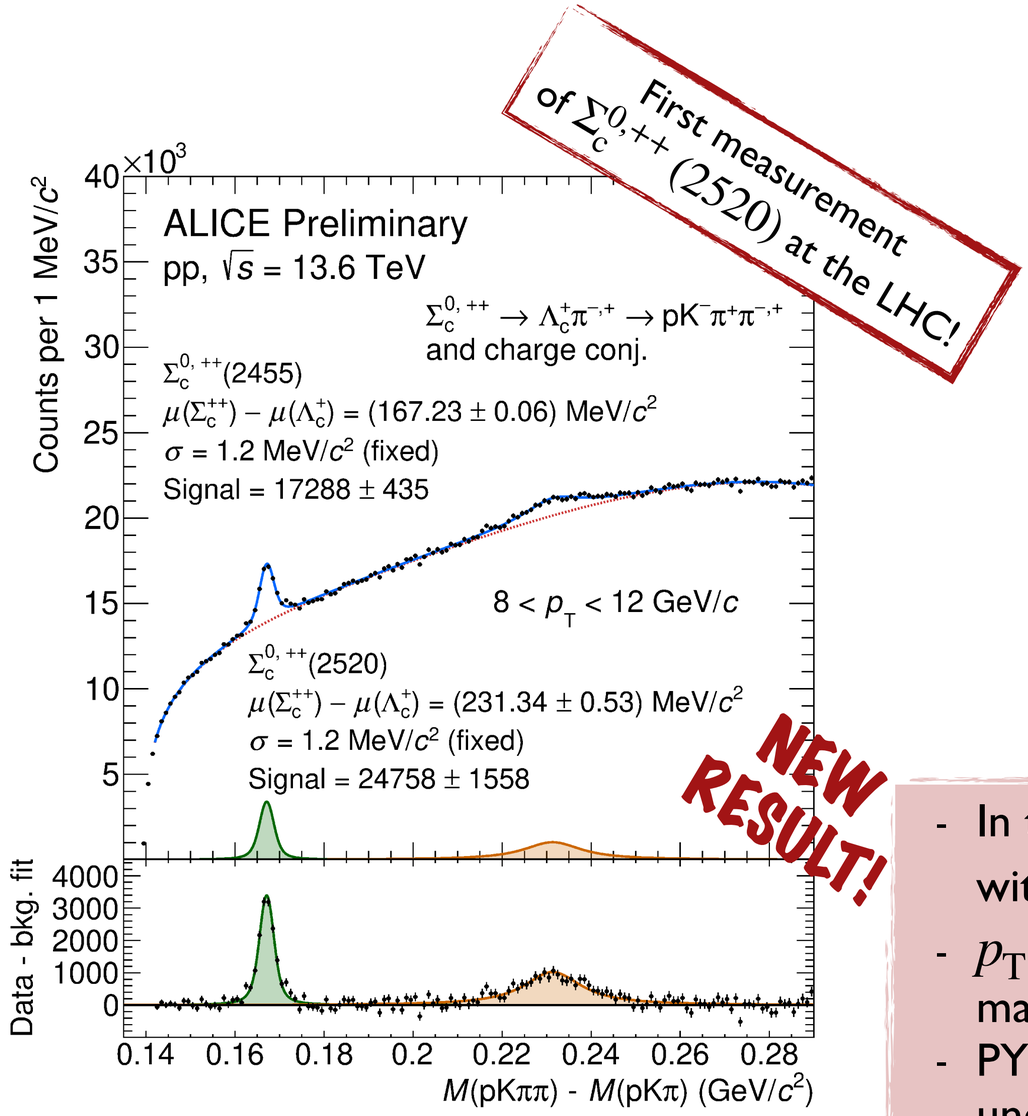


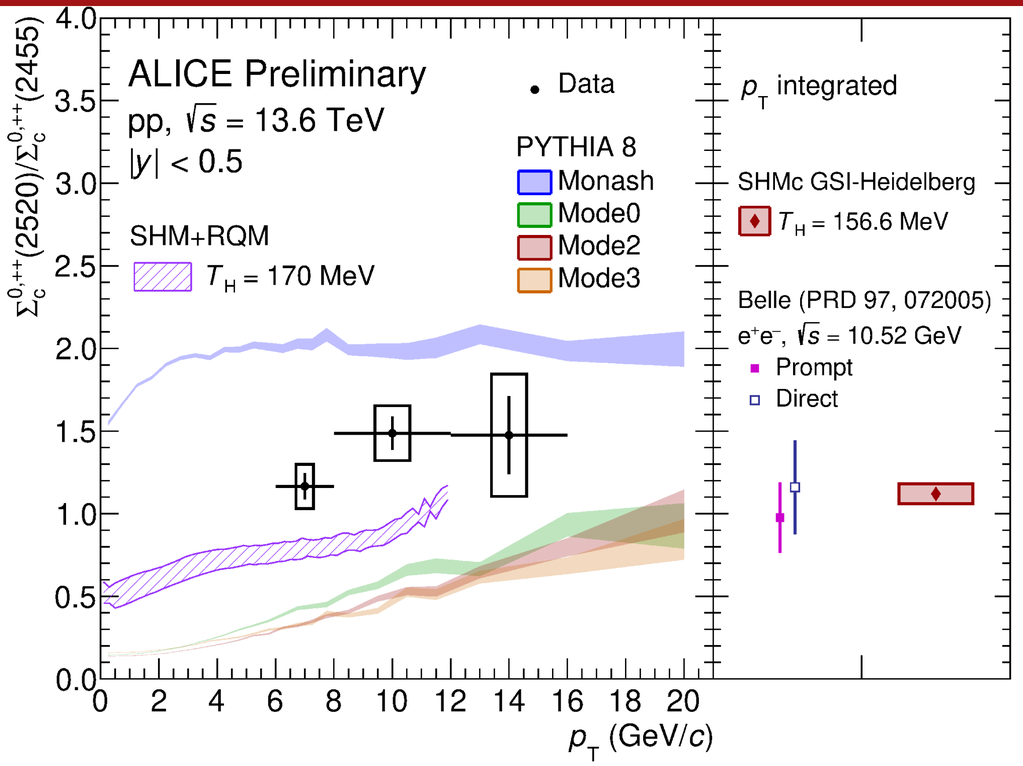
ALI-PUB-561515

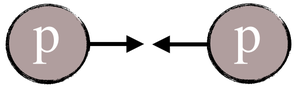
More about strangeness in heavy quark hadronisation in Fabio Catalano's talk

- Enhancement also in strange-charm-baryon-to-meson ratio in pp collisions
- **Poor description** from models successfully describing Λ_c^+/D^0 ratio, with theoretical predictions underestimating the data
  - Catania model gets closer to data
  - Coalescence even in pp collisions?
  - **Larger enhancement** for strange-charm baryons?
- Large uncertainty of Ω_c^0 **branching ratio** limits the effectiveness of the comparison with theoretical models

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

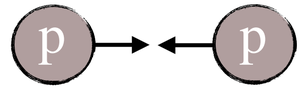


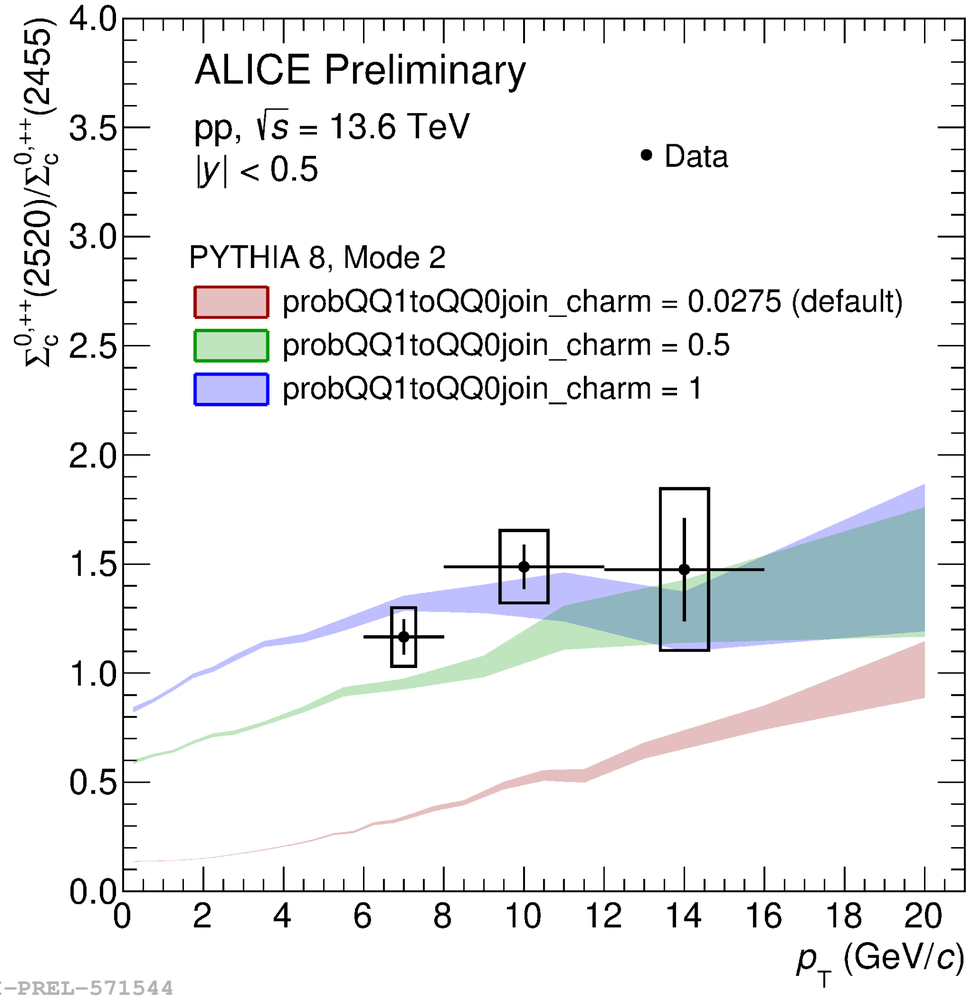




- In the investigated p_T region, ratios between the two $\Sigma_c^{0,++}$ states consistent with p_T integrated result from e^+e^- collisions within the uncertainties
- p_T integrated value compatible with SHM+RQM → measurements of higher mass resonances are a fundamental to validate such models
- PYTHIA 8 Monash overestimates the data, CR Modes and SHM+RQM underestimate the data

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



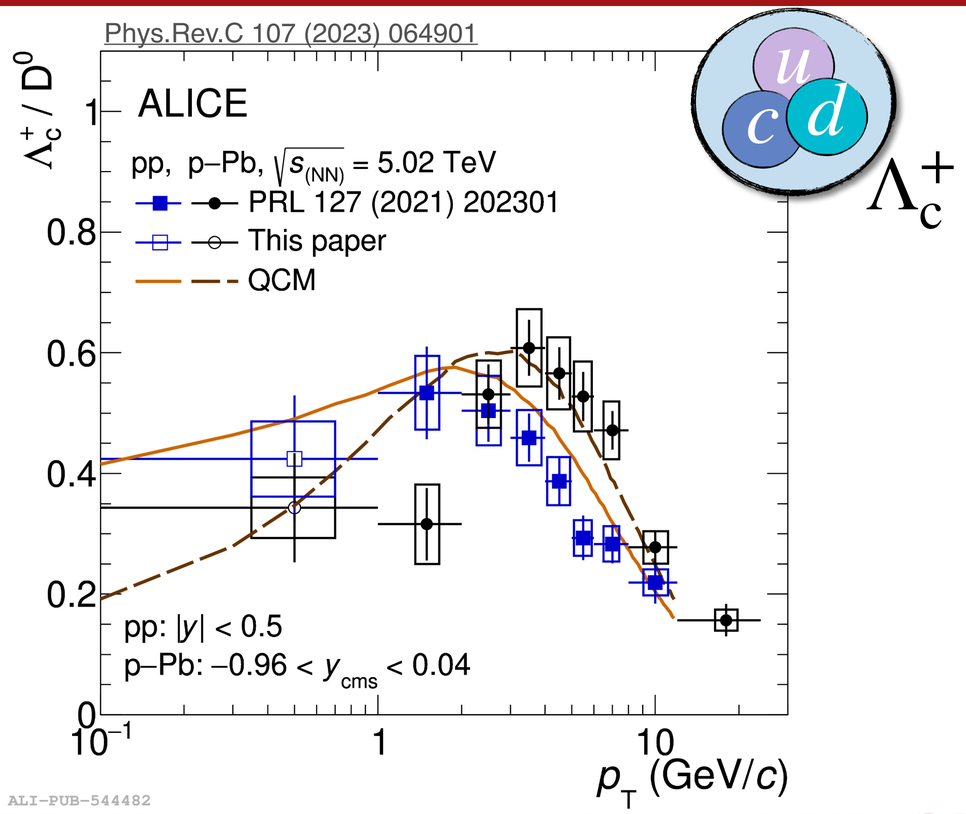


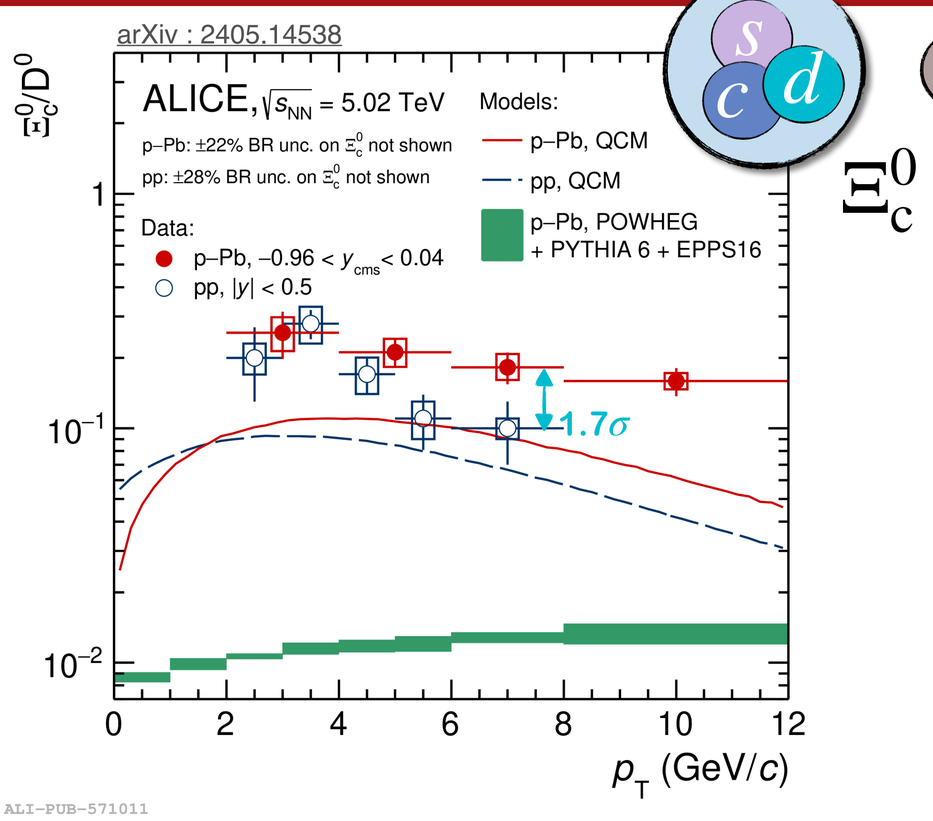
New constraint on model

- Available charm-quark hadronization models fail to describe experimental observations for $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$
- In the PYTHIA fragmentation scenario, the suppression of Σ_c production relative to Λ_c is attributed to the need to form a junction containing a spin $S = 1$ charm-light diquark instead of $S = 0$
- In PYTHIA 8 Mode 2 the amount of suppression is tuned by the model parameter **`probQQ1toQQ0join_charm`** → Σ_c measurements needed to tune the model

JHEP 08 (2015) 003 and arXiv : 2405.19137

Measurements in p–Pb collisions

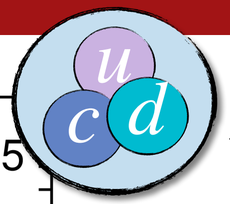




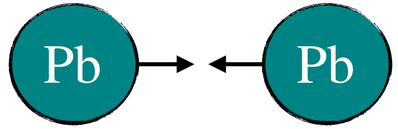
- Similar magnitude in the enhancement of Λ_c^+/D^0 in pp and p–Pb collisions wrt e^+e^- collisions
- Shift of distribution peak towards higher p_T could be attributed to radial flow
- QCM describes the magnitude of the ratio and predicts the hardening of Λ_c^+ spectrum in p-Pb collisions

- Hint of enhanced Ξ_c^0/D^0 ratio in p–Pb collisions wrt pp collisions
- Higher precision needed to draw conclusions as done for Λ_c^+/D^0
- QCM underestimates Ξ_c^0 cross section and Ξ_c^0/D^0 by same amount

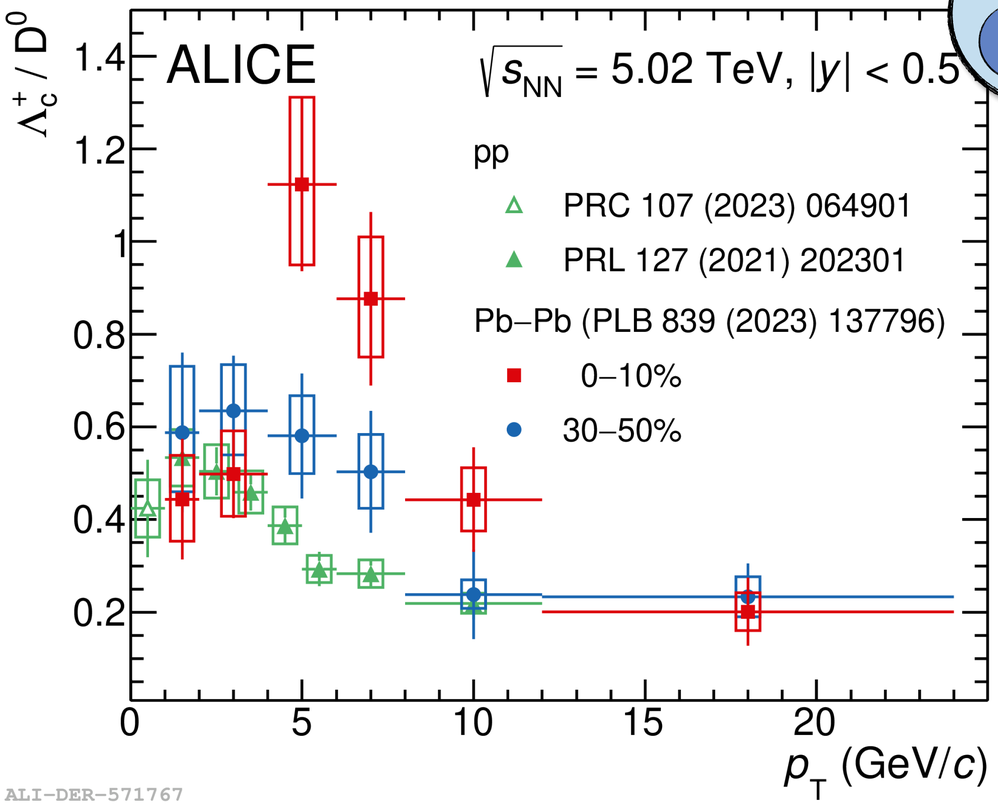
Measurements in Pb–Pb collisions



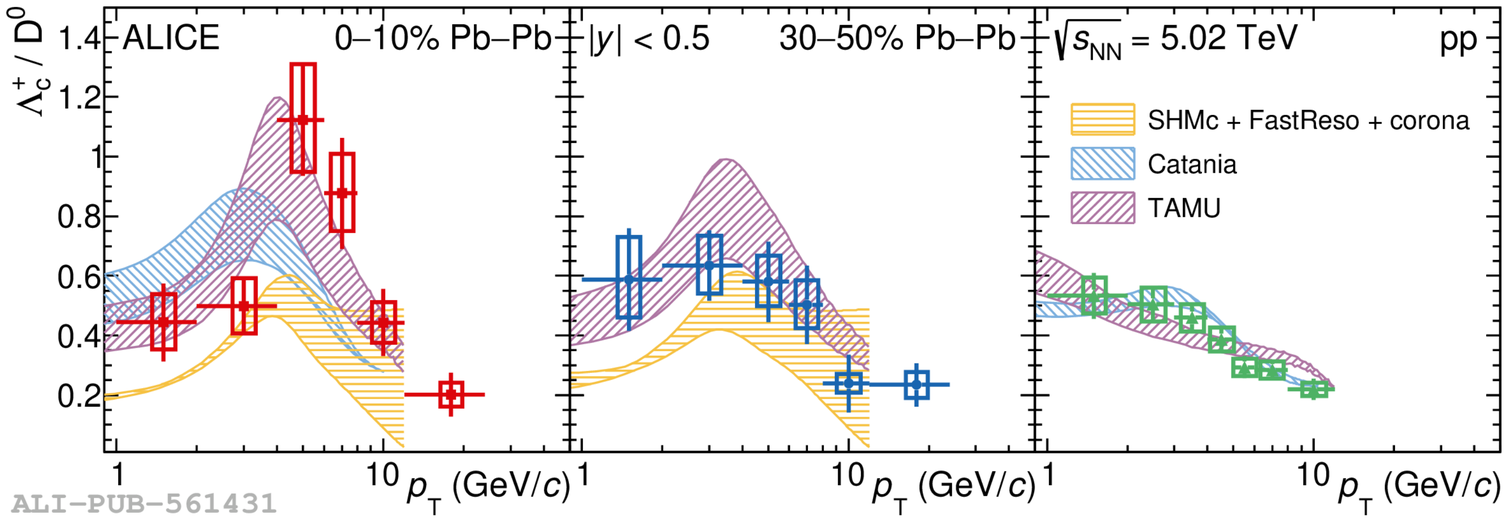
Λ_c^+



Phys.Lett.B 839 (2023) 137796

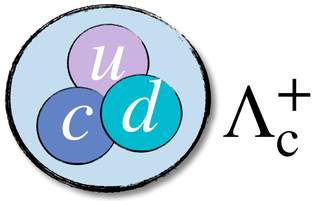


Phys.Lett.B 839 (2023) 137796

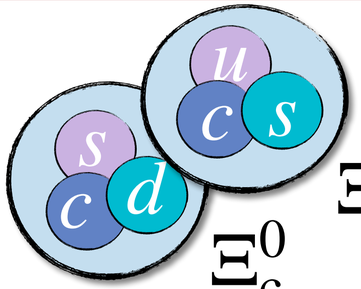


- Λ_c^+/D^0 ratio increases from pp to mid-central and central Pb–Pb collisions at intermediate p_T with a significance of 3.7σ, with a peak increasing in magnitude and shifting towards higher p_T values
- Observed behaviour could be the result of modification of p_T spectra due to recombination and/or radial flow
- Theoretical calculations including both fragmentation and coalescence describe the measurements

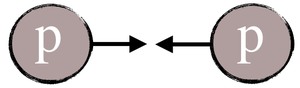
Event multiplicity dependence



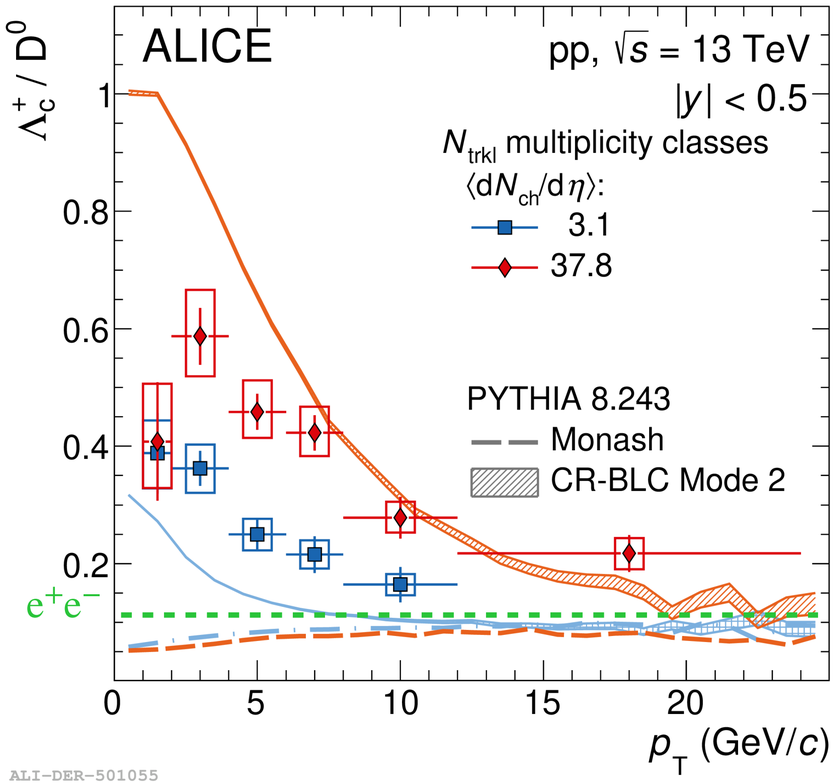
Λ_c^+



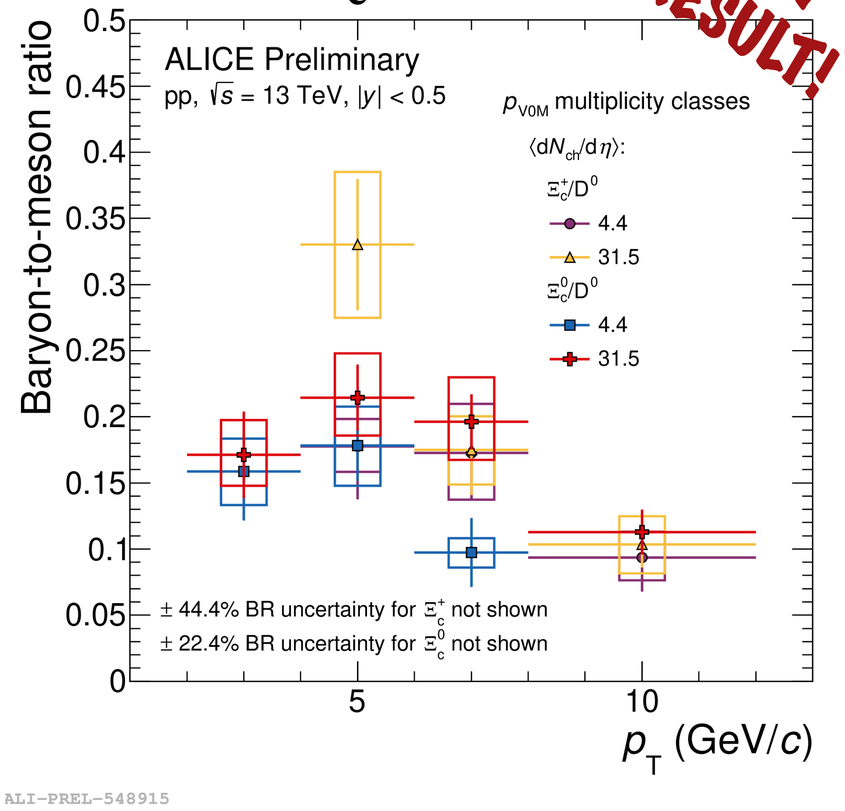
Ξ_c^+ Ξ_c^0



Phys.Lett.B 829 (2022) 137065

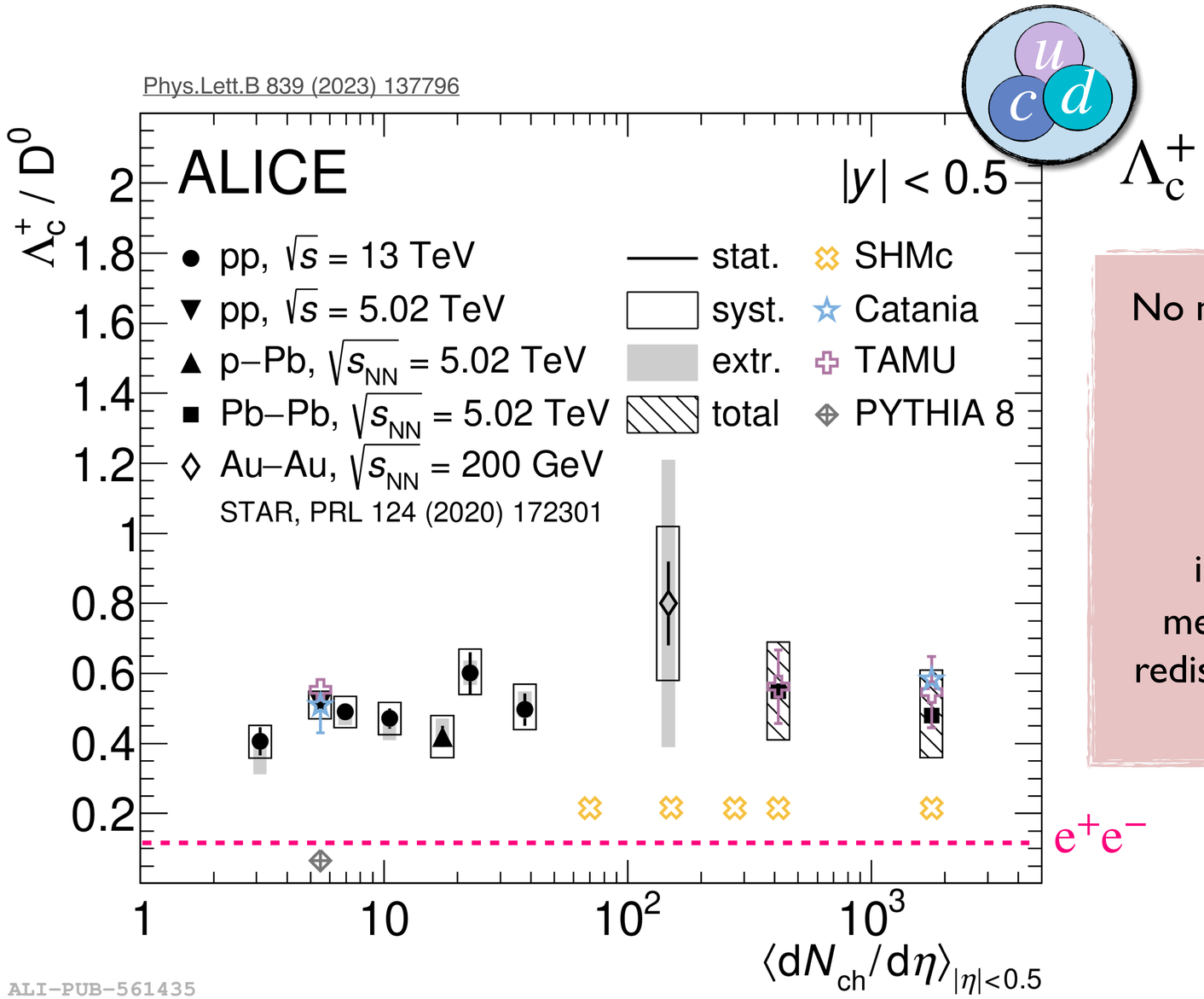


NEW RESULT!



- Significant multiplicity-dependent enhancement of the Λ_c^+/D^0 ratio with a significance of 5.3σ for $1 < p_T < 12$ GeV/c from lowest to highest multiplicity class
- Measured Λ_c^+/D^0 ratio in the lowest multiplicity interval is higher than in e^+e^- collisions
- PYTHIA 8 Monash fails to describe the Λ_c^+/D^0 ratio, Mode 2 catches its trend but not the magnitude
- No strong multiplicity dependence of Ξ_c^0/D^0 with the current uncertainties

Event multiplicity dependence



Λ_c^+

e^+e^-

No multiplicity dependence of p_T integrated Λ_c^+/D^0 ratio within the uncertainties

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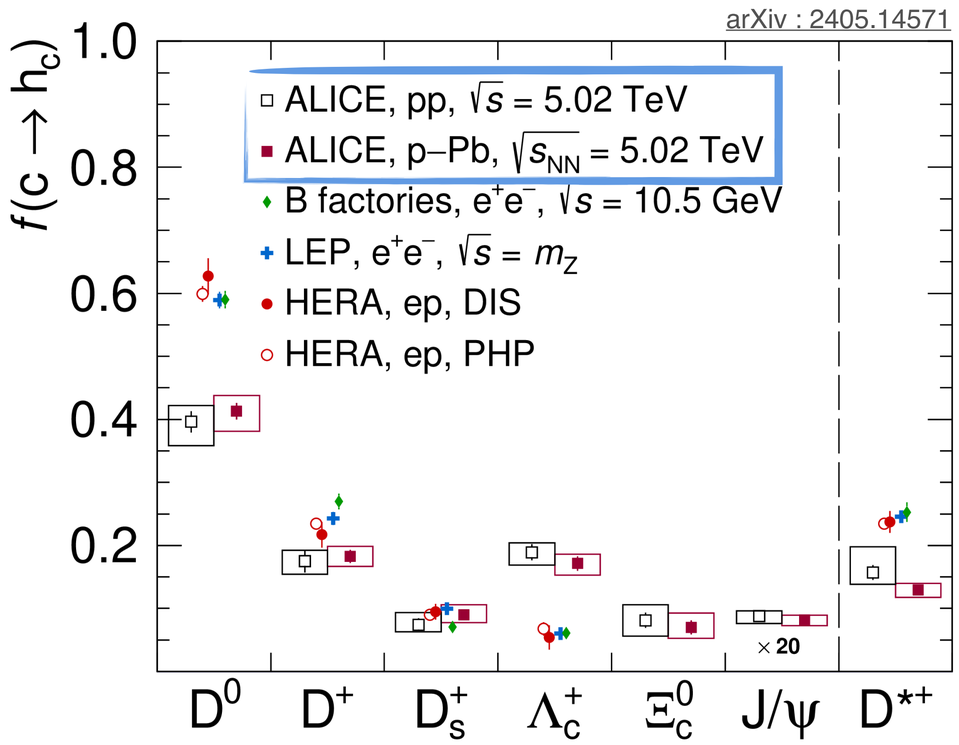
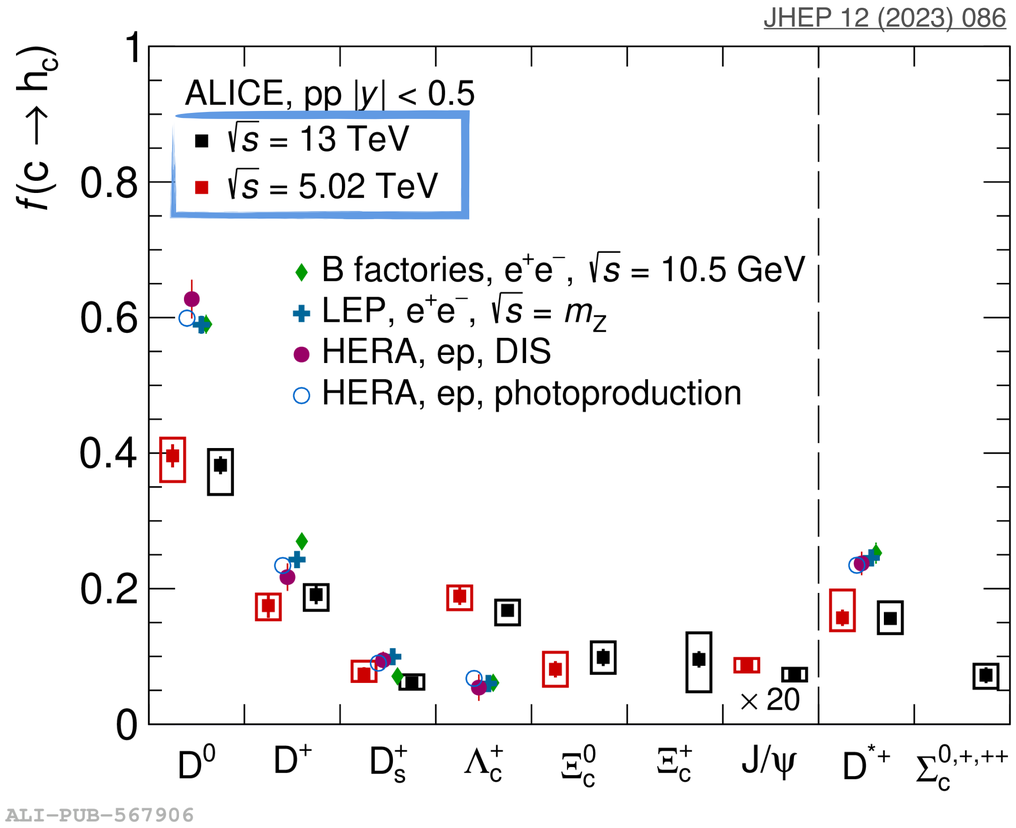
increase in baryon-to-meson ratio observed in the measured p_T range is likely to be due to a different p_T redistribution between meson and baryons rather than to an enhancement in the overall baryon yield

Charm fragmentation fractions





Fragmentation fractions in pp and p–Pb collisions are consistent with each other

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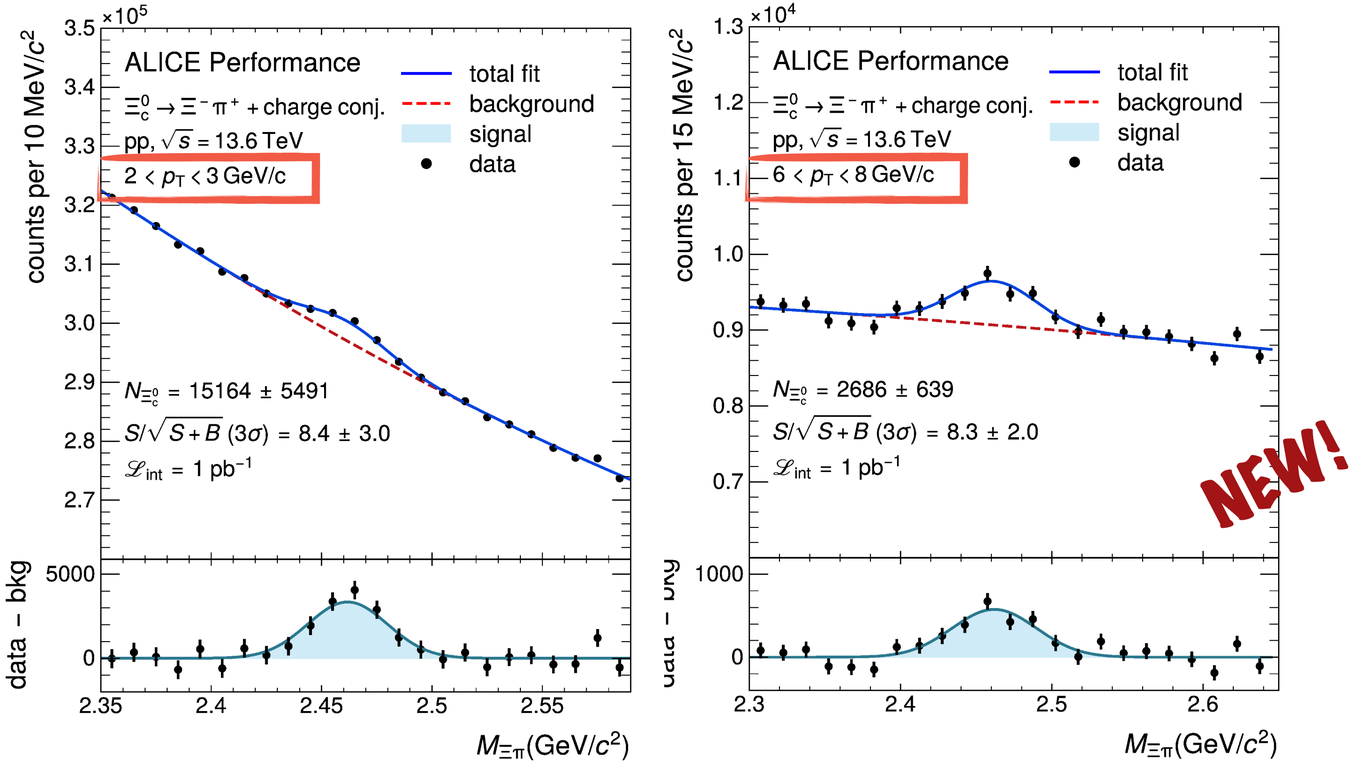
No modification of charm hadronization process due to different hadronic collision system size

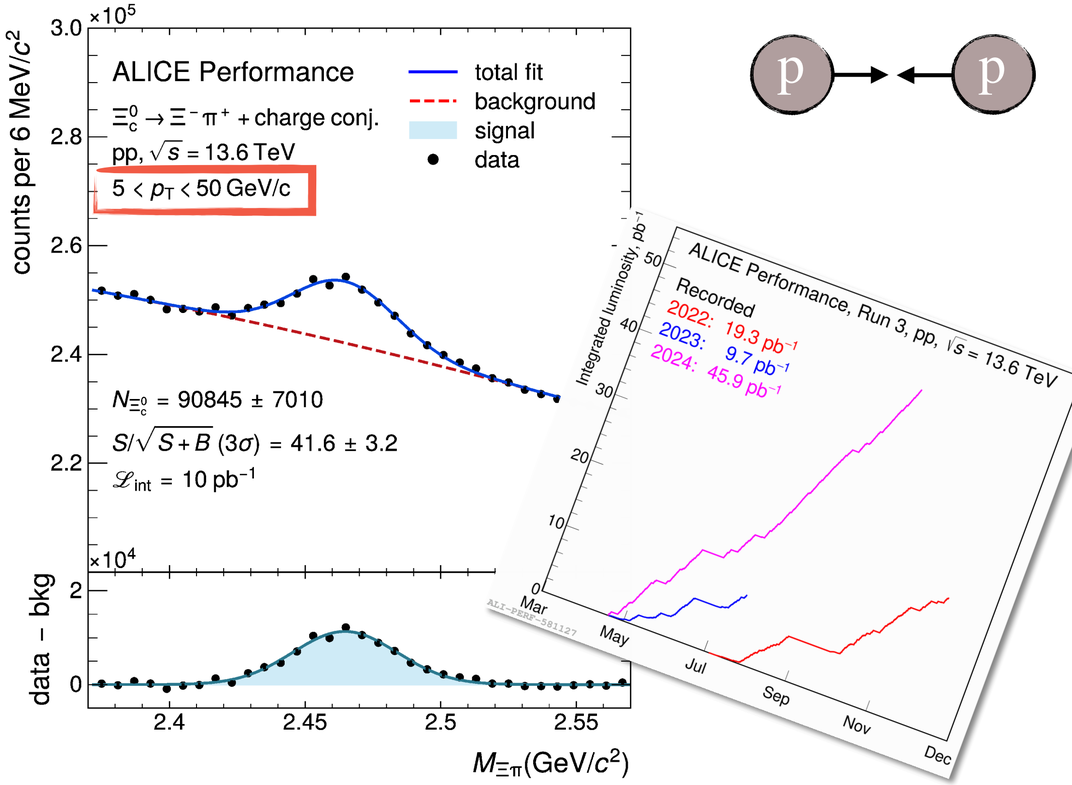
Fragmentation fractions do not show energy dependence within the uncertainties

Outlook: Ξ_c^0 in Run 3 and charm baryon software trigger



ALI-PERF-578561

I-PERF-578566



ALI-PERF-578571

Large statistics for Ξ_c^0 analysis already available!

- Ongoing measurement of Ξ_c^0 cross section on $\mathscr{L}_{\rm int} = 1\ {\rm pb}^{-1}$ dataset → 30 times larger statistics compared to full Run 2 sample
- $\mathscr{L}_{\rm int}$ target: $10\ {\rm pb}^{-1}$ (full 2023)

Charm baryon dedicated software trigger

- $\Xi_c^0 \to \Xi^-\pi^+$ (CF), $\Omega_c^0 \to \Xi^-\pi^+$ (SCS) and $\Omega_c^0 \to \Xi^-{\rm K}^+$ (DCS)
- Deployed starting from 2023 data taking

CF → Cabibbo Favoured, SCS → Singly Cabibbo Suppresses, DCS → Doubly Cabibbo Suppressed

Summary and outlook

Charm baryons have been measured in various collision systems, investigating the yield dependence on p_{T} and event multiplicity

- Charm-quark hadronization in parton rich environments happens via **additional mechanisms** wrt leptonic collisions
- Larger enhancement at **low and intermediate** p_{T}, hardening of baryon-to-meson ratio distribution in larger collision systems ascribable to recombination and/or radial flow
- Larger enhancement for **strange**-charm-baryons?
- Hint of **different** p_{T} **redistribution** between meson and baryons for different multiplicity classes
- Charm fragmentation fractions do not show a dependence neither on the hadronic collision **system size** nor on the collision **energy** within the uncertainties

Large Run 3 statistics

- extended p_{T} reach
- increased measurements granularity
- improved precision
- new particles now accessible at the LHC

Better understanding of charm and beauty hadronization

More about beauty in Andrea Tavira Garcia's talk

STAY TUNED!

BACKUP

SHM + RQM

SHM + RQM

Phys.Lett.B 795 (2019) 117-121

Phys.Rev.D. 84 (2011) 014025

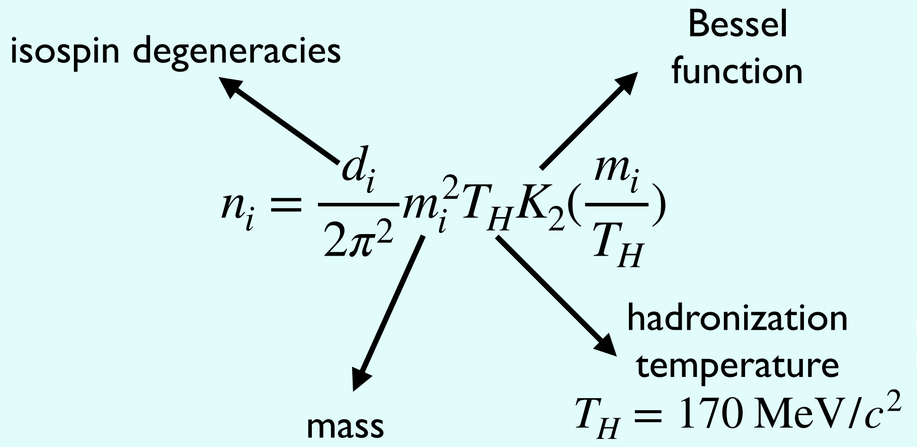
- Complexity of hadronization process replaced by statistical weights governed by the hadron mass
- Feed-down from a largely augmented set of charm baryon stated beyond the ones currently listed in the PDG
- The Relativistic Quark Model predicts the existence of a set of excited charm baryons using a relativistic description of a bound object composed of a heavy quark and a light diquark

CHARM BARYONS

- PDG: 6 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
- RQM: extra 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c (up to a mass of 3.5 GeV/c)

Phys.Rev.D. 84 (2011) 014025

HADRON THERMAL DENSITIES

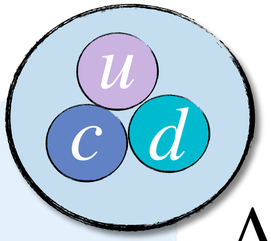


Phys.Lett.B 795 (2019) 117-121

Charm baryons decay channels measured by ALICE

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

$\Lambda_c^+ \to pK_S^0$

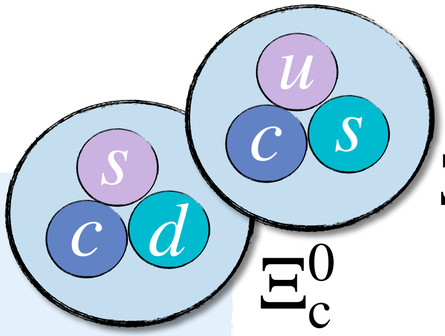


Λ_c^+

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

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

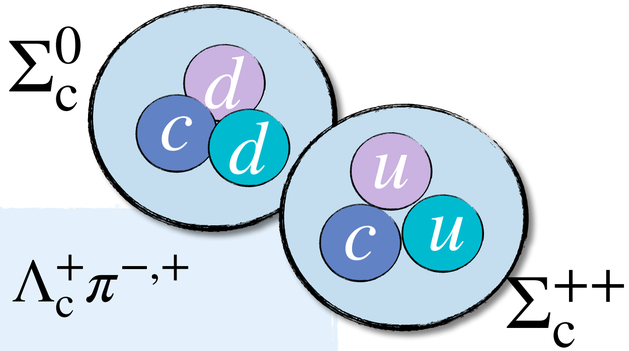
$\Xi_c^0 \to \Xi^- e^+ \nu_e$



Ξ_c^+

Ξ_c^0

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

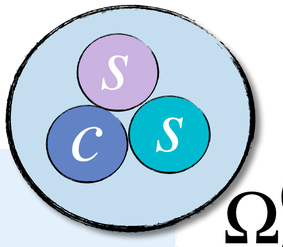


Σ_c^0

Σ_c^{++}

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

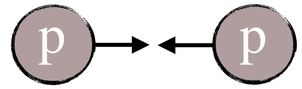
$\Omega_c^0 \to \Omega^- e^+ \nu_e$



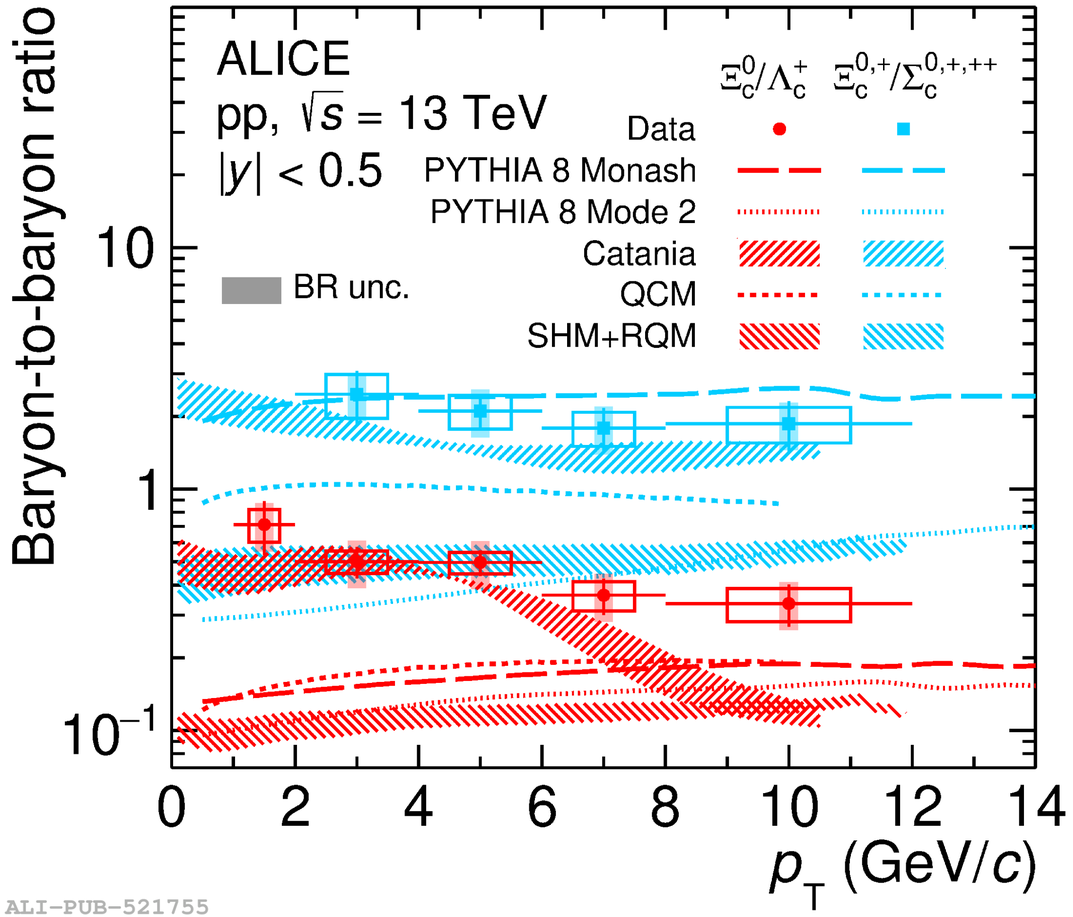
Ω_c^0

Charge conj. included
for all the measured hadrons

Baryon-to-baryon ratio in pp collisions



Phys.Rev.Lett. 127 (2021) 272001



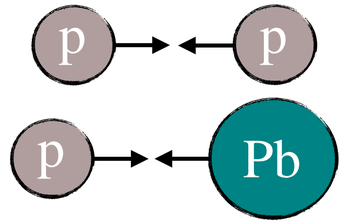
Ξ_c/Λ_c

- No significant p_T dependence
- All the models underestimate the data

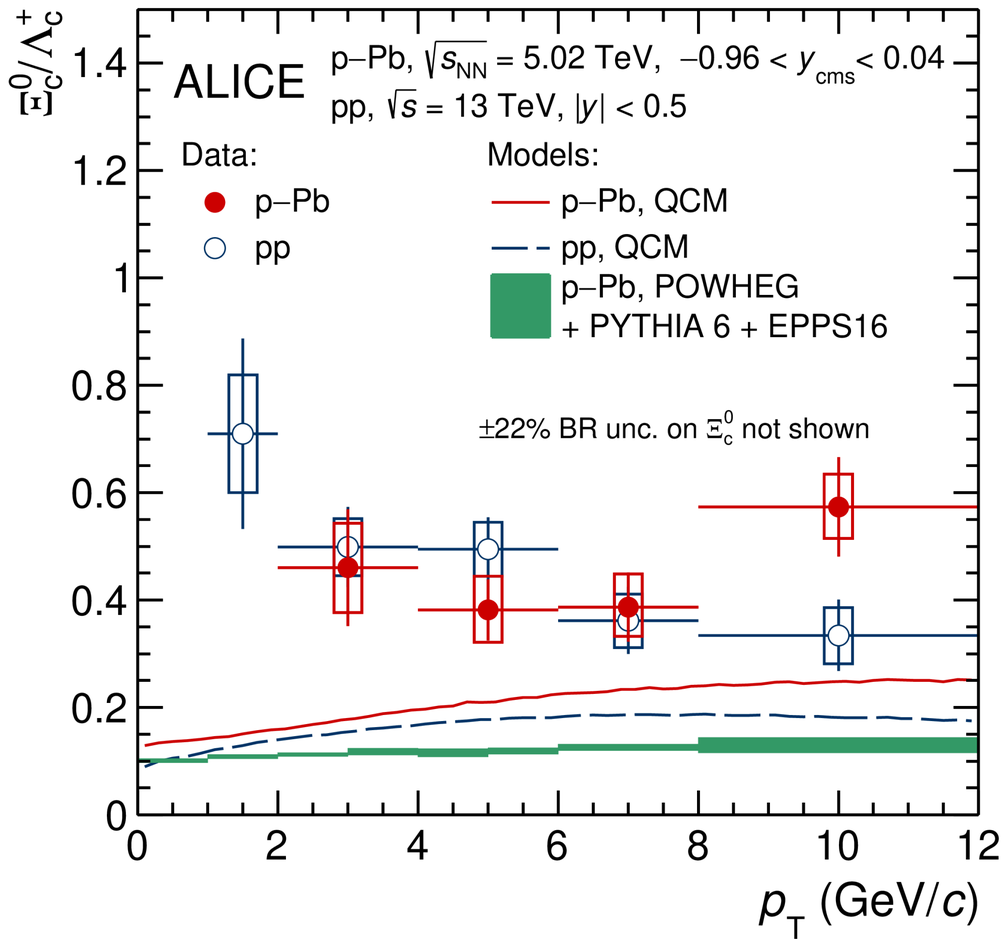
Ξ_c/Σ_c

- No significant p_T dependence
- All the models underestimate the data except for PYTHIA 8 Monash, that underestimates by a similar amount the $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$ cross sections

Baryon-to-baryon ratio in pp and p–Pb collisions



arXiv : 2405.14538

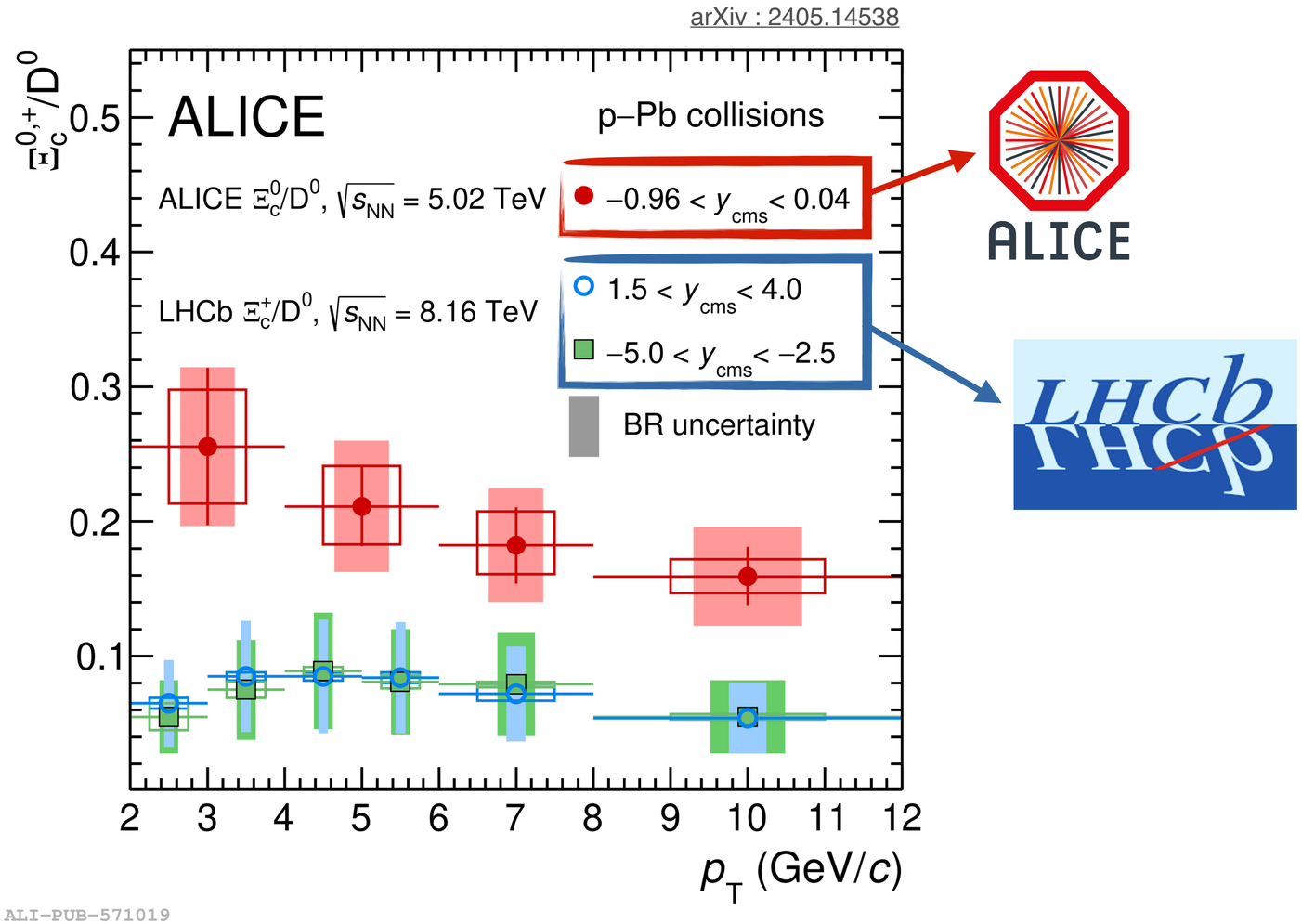


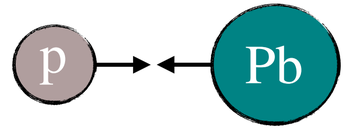
ALI-PUB-571015

Ξ_c/Λ_c

- No significant p_T dependence both in pp and p–Pb collisions
- Results in pp and p–Pb collisions are compatible within the uncertainties
- Both QCM and PYTHIA 6 + POWHEG underestimate the data

Rapidity dependence of baryon-to-meson ratio



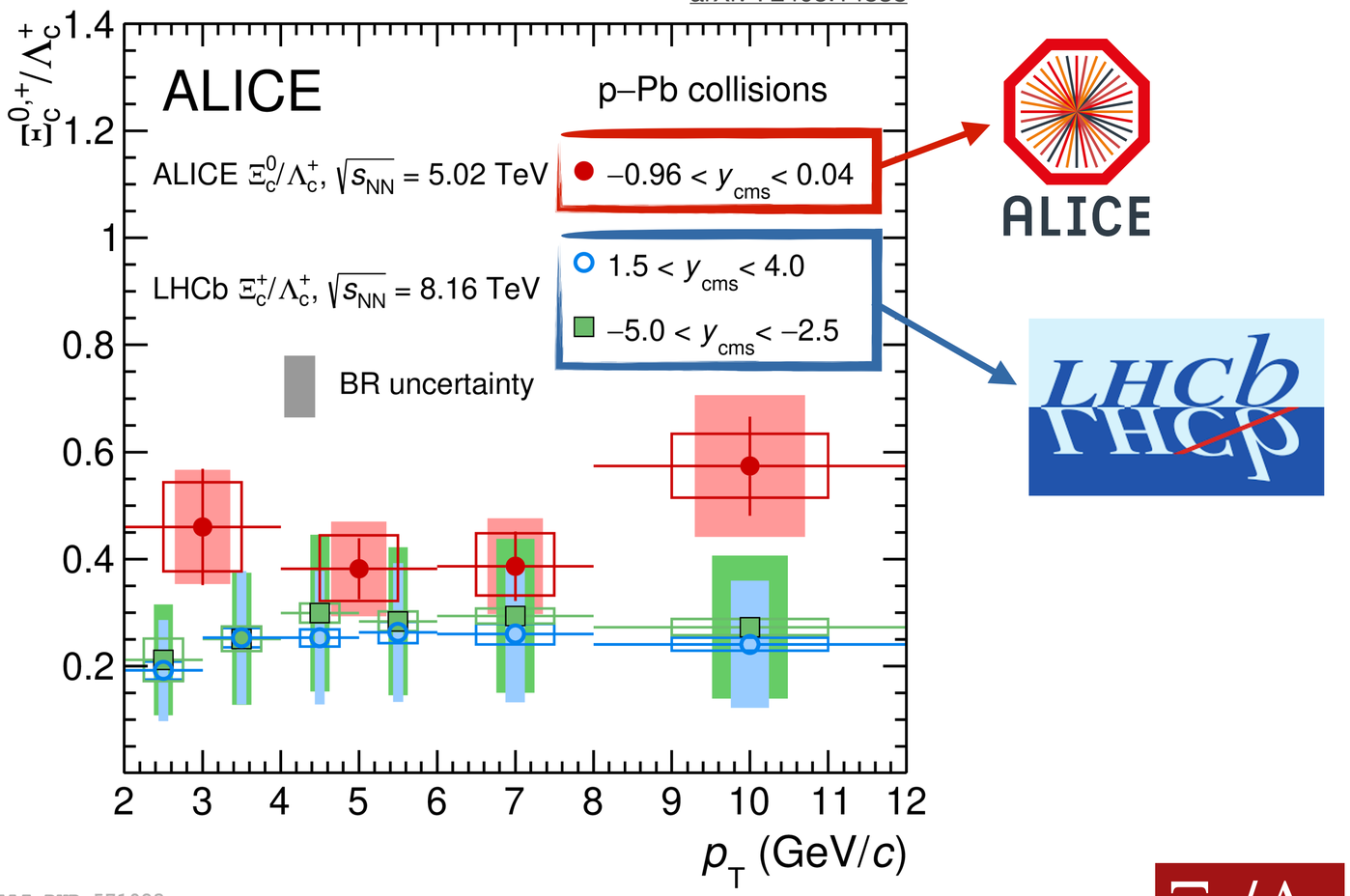


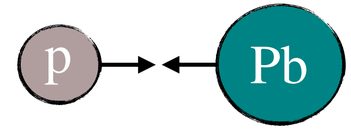
Ξ_c/D^0

- Hint of rapidity dependence
- Yield ratio at mid rapidity larger than measurements at forward and backward rapidities in the full p_T range (differences ranging from 1.5σ to 2.0σ)

Rapidity dependence of baryon-to-baryon ratio

arXiv : 2405.14538





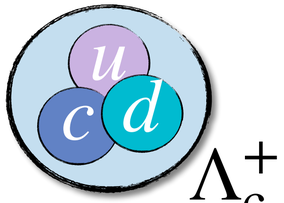
ALICE

LHCb

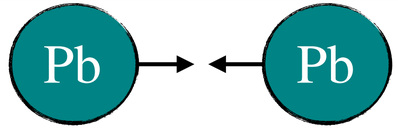
Ξ_c/Λ_c

Results are compatible within uncertainties at mid, forward and backward rapidity, with 1.1σ difference for $2 < p_T < 4$ GeV/c^2

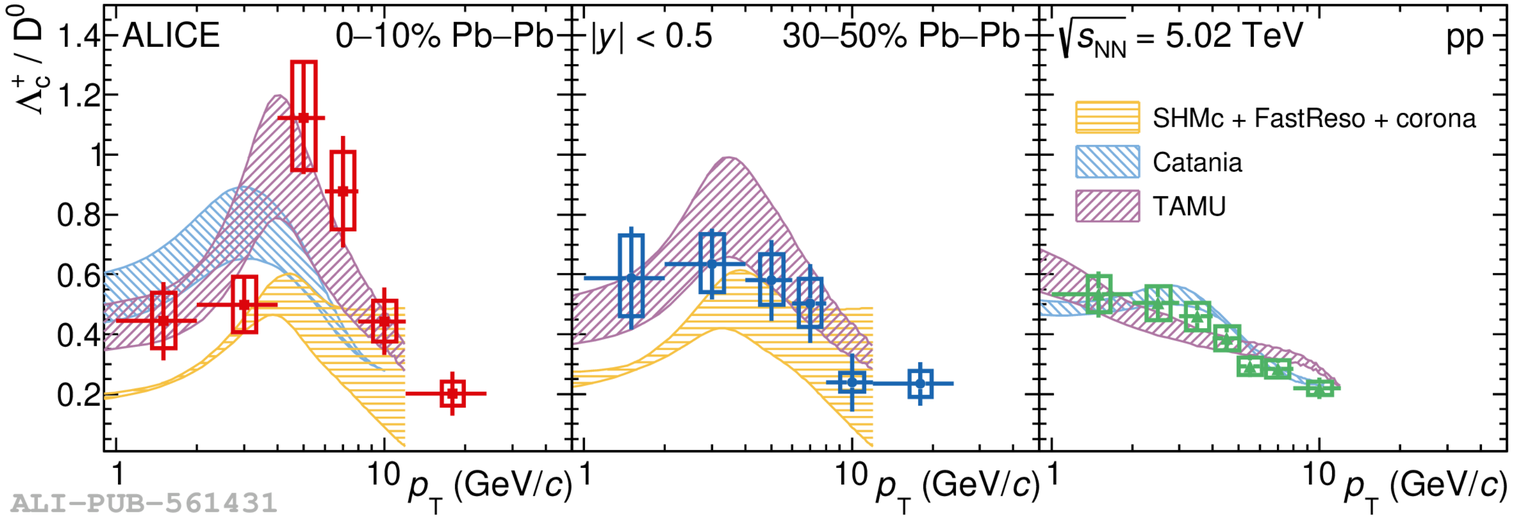
Comparison to theoretical models in Pb–Pb collisions



Λ_c^+



Phys.Lett.B 839 (2023) 137796

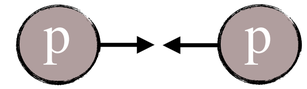


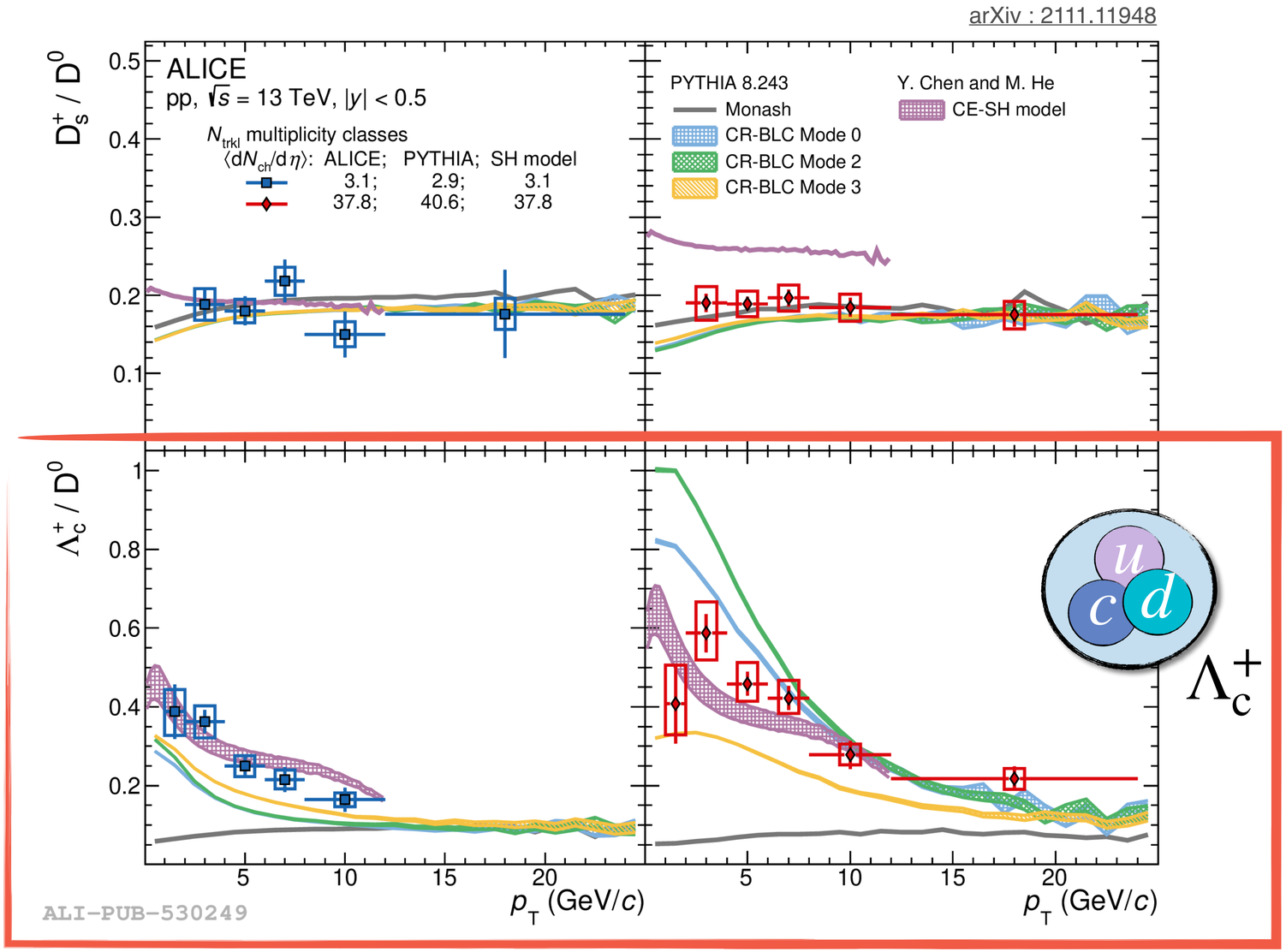
SHM
- Consider only charm hadrons from PDG
- Core-corona approach

CATANIA
- QGP formation both in pp and p–Pb collisions
- Hadronization via coalescence or fragmentation
- Charm-quark transport via Boltzmann equation

TAMU
- Hadronization primarily via coalescence (Resonance Recombination Model), but fragmentation is also included
- Charm-quark transport via Langevin equation
- SHM approach for pp collisions

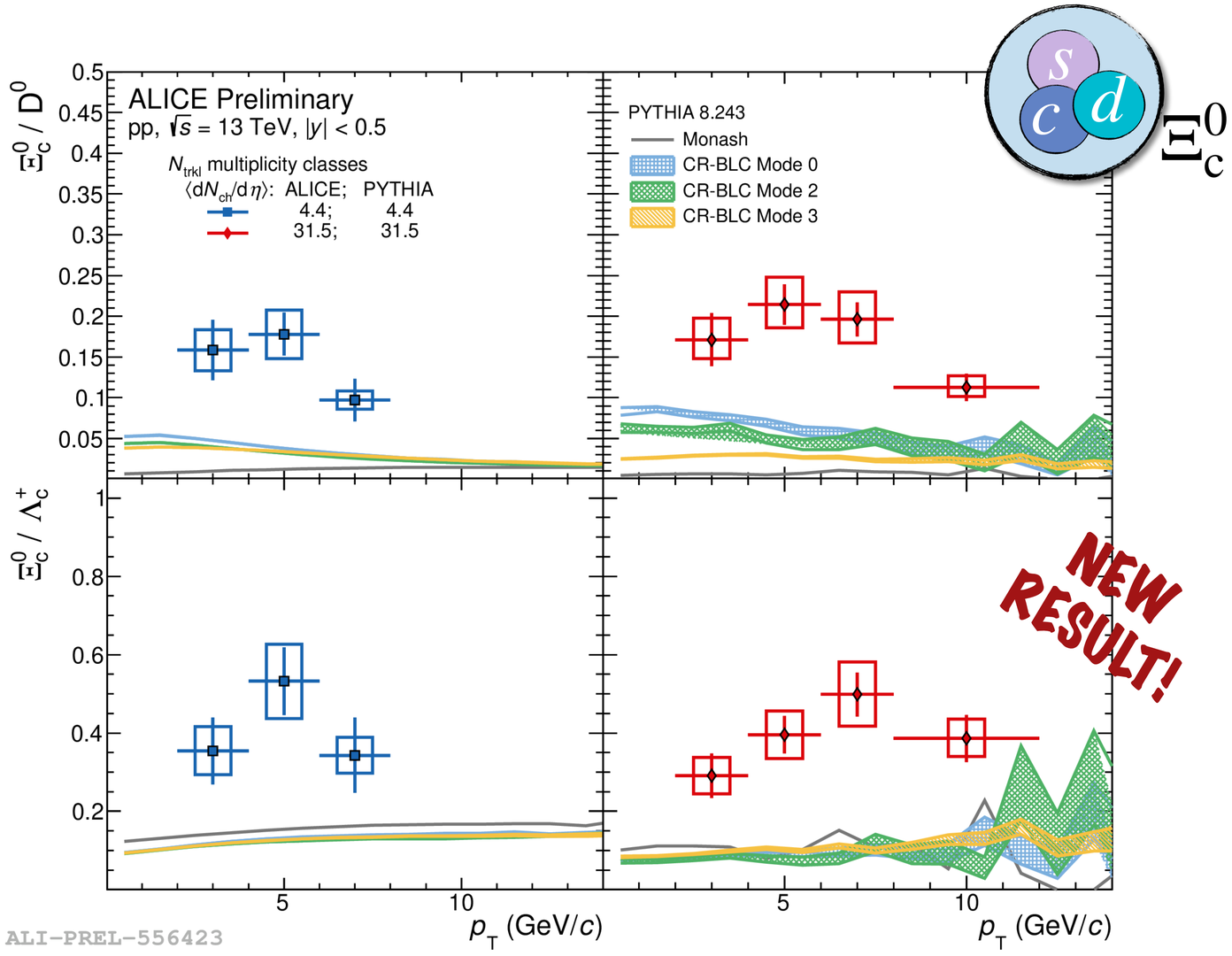
Multiplicity dependence and comparison to theoretical models

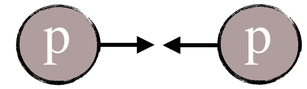




- PYTHIA 8 Monash does not reproduce the Λ_c^+/D^0 ratio and does not show multiplicity dependence
- PYTHIA CR-BLC describes the Λ_c^+/D^0 decreasing trend with p_T and is closer to the overall magnitude
- SHM+RQM reproduces the multiplicity dependence

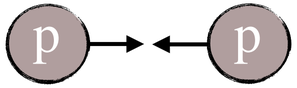
Multiplicity dependence and comparison to theoretical models



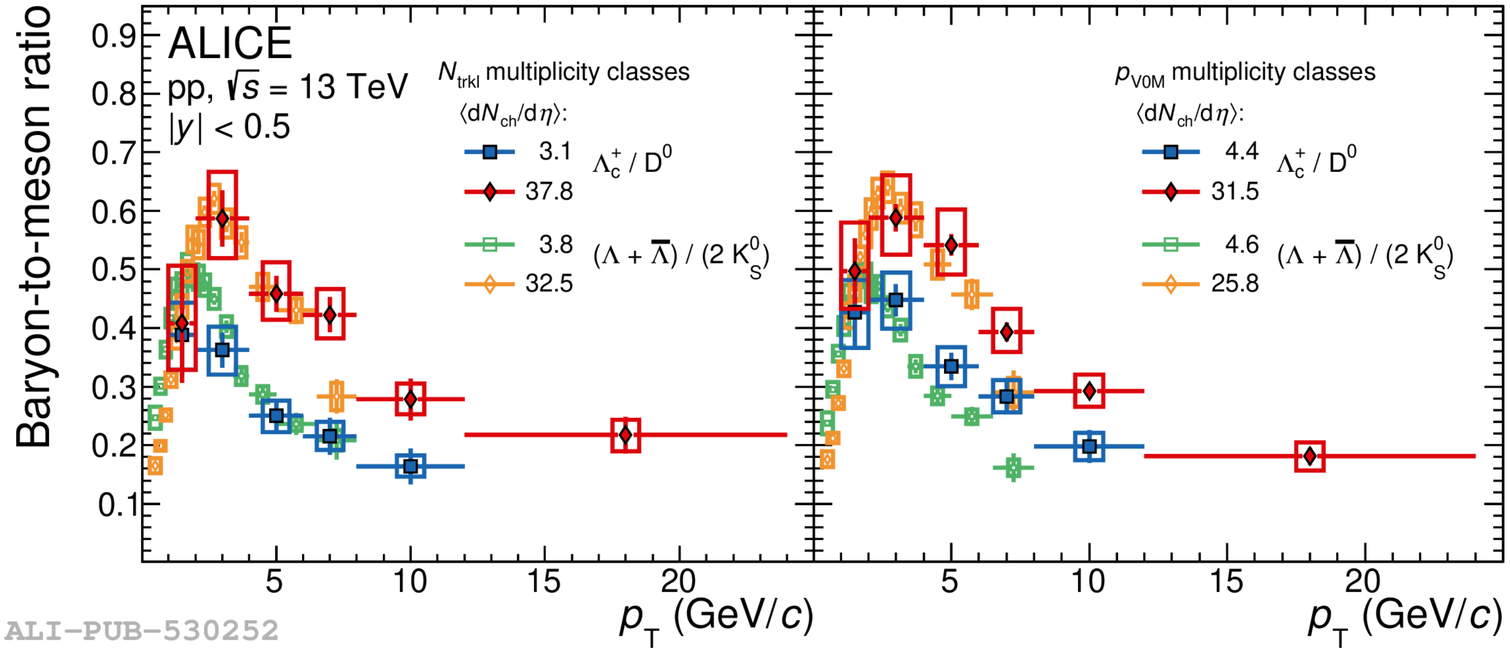


- No strong multiplicity dependence of Ξ_c^0/D^0 and Ξ_c^0/Λ_c^+ ratios within the uncertainties
- All PYTHIA 8 models underestimate the data
- Larger disagreement between PYTHIA CR-BLC prediction and data for Ξ_c^0/D^0 with respect to Λ_c^+/D^0 (slide 13)

Comparison to light-flavour hadrons

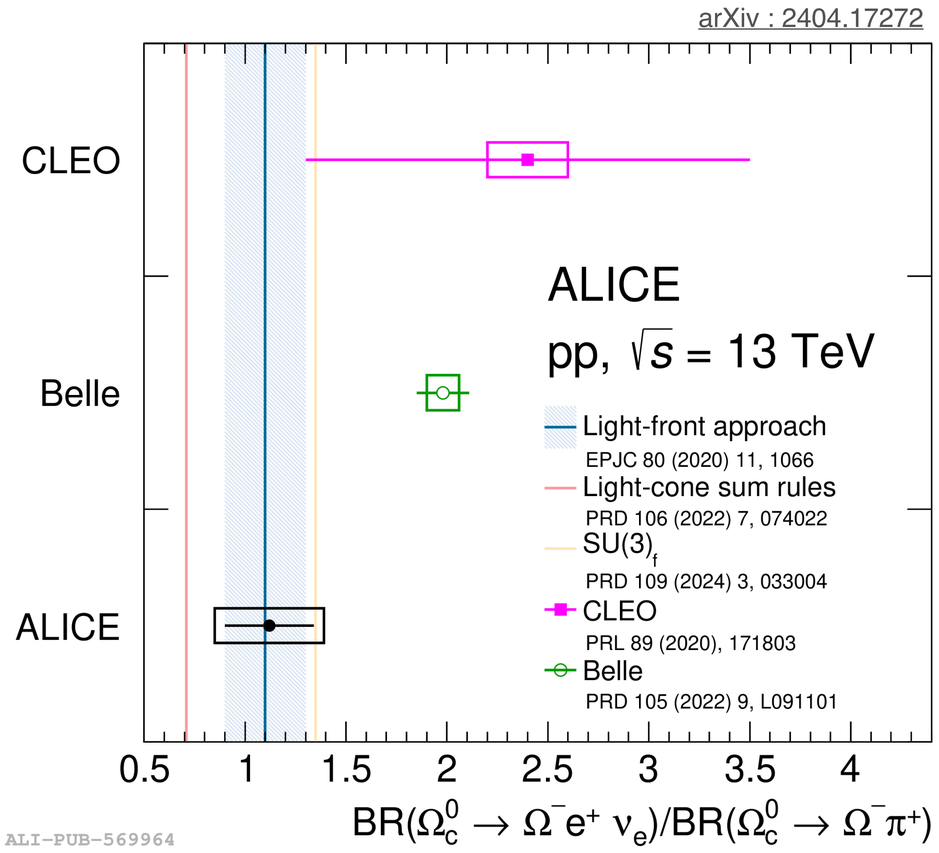


Phys.Lett.B 829 (2022) 137065



- Baryon-to-meson ratio in the charm sector are compared to those in the light-flavour sector
- Ratios show a similar trend as a function of p_{T} and similar enhancement with $< \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta >$
- Hint at a possible common mechanism for light- and charm-baryon formation in pp collisions at LHC energies

Strange charm baryon branching ratios



Ξ_c^0

Phys.Rev.Lett. 127 (2021) 272001

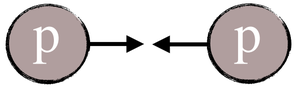
ALICE measurement

$$BR(\Xi_c^0 \to \Xi^- e^+ \nu_e)/BR(\Xi_c^0 \to \Xi^- \pi^+) = 1.38 \pm 0.14\,(stat) \pm 0.22\,(syst)$$

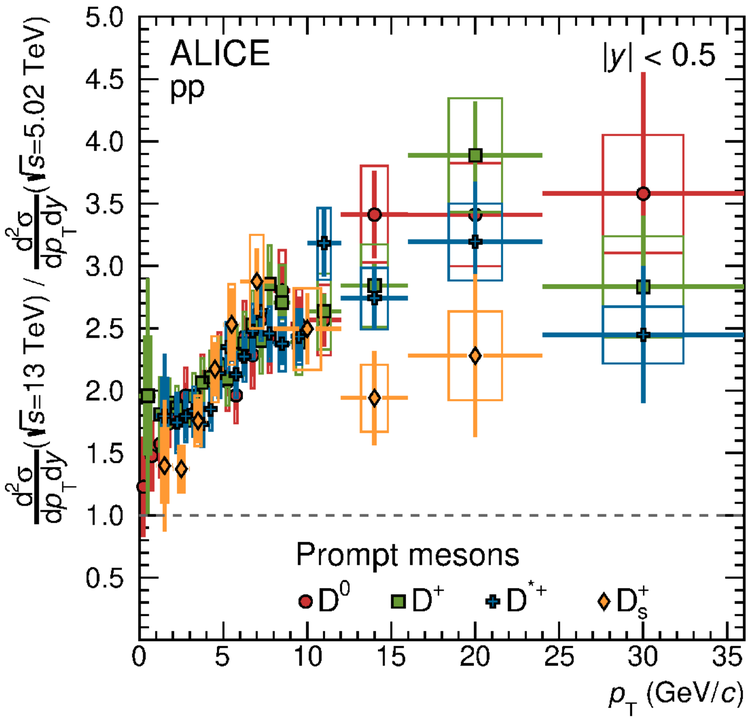
Ω_c^0

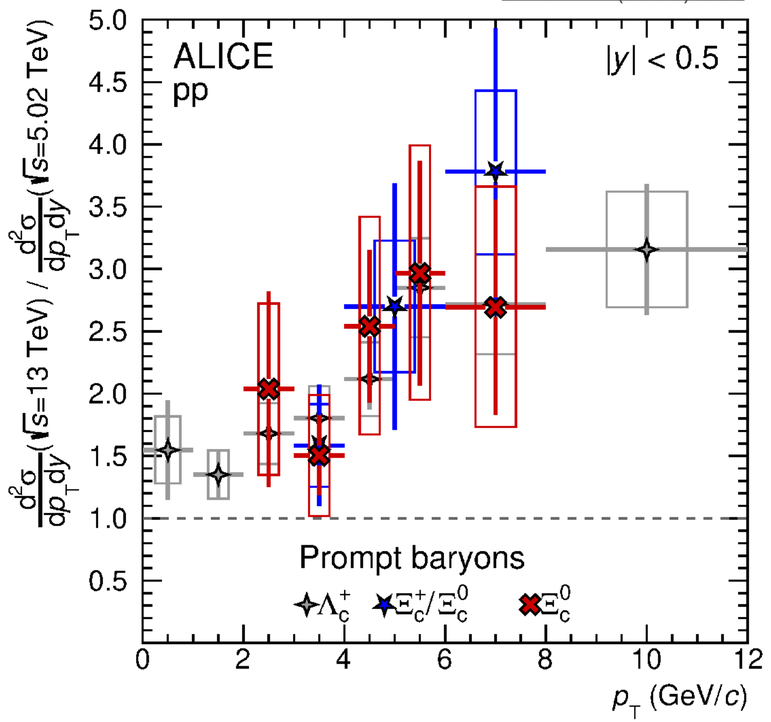
- Recent ALICE measurement of $BR(\Omega_c^0 \to \Omega^- e^+ \nu_e)/BR(\Omega_c^0 \to \Omega^- \pi^+)$
- Theoretical prediction used for $\Omega_c^0 \to \Omega^- \pi^+$ analysis
  $BR(\Omega_c^0 \to \Omega^- \pi^+) = (0.51^{+2.19\%}_{-0.31\%})\,\%$
- Poor theoretical knowledge of Ω_c^0 BR
- Tension between BELLE and LHCb BR fraction measurements for Cabibbo-suppressed decay channels
  BELLE: $BR(\Omega_c^0 \to \Xi^- \pi^+)/BR(\Omega_c^0 \to \Omega^- \pi^+) = 0.253 \pm 0.052\,(stat.) \pm 0.030\,(syst.)$
  LHCb: $BR(\Omega_c^0 \to \Xi^- \pi^+)/BR(\Omega_c^0 \to \Omega^- \pi^+) = 0.1581 \pm 0.0087\,(stat) \pm 0.0043\,(syst) \pm 0.0015\,(ext)$
- Ω_c^0 dedicated software trigger will provide data to perform new measurements of BR fractions

Energy dependence in hadron production



JHEP 12 (2023) 086





ALI-PUB-567886

- Increasing trend going from low to high p_{T} for given hadron species
- Compatible p_{T} spectrum hardening between mesons and baryons from $\sqrt{s} = 5.02$ TeV to $\sqrt{s} = 13$ TeV → no energy dependence in baryon-to-meson ratios