Charm-baryon hadronization mechanism and its multiplicity dependence with ALICE

Fang Tao (CCNU) for the ALICE Collaboration

tao.fang@cern.ch

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Motivation

The production heavy-flavor hadrons in collisons is calculated through a convolution of three components.

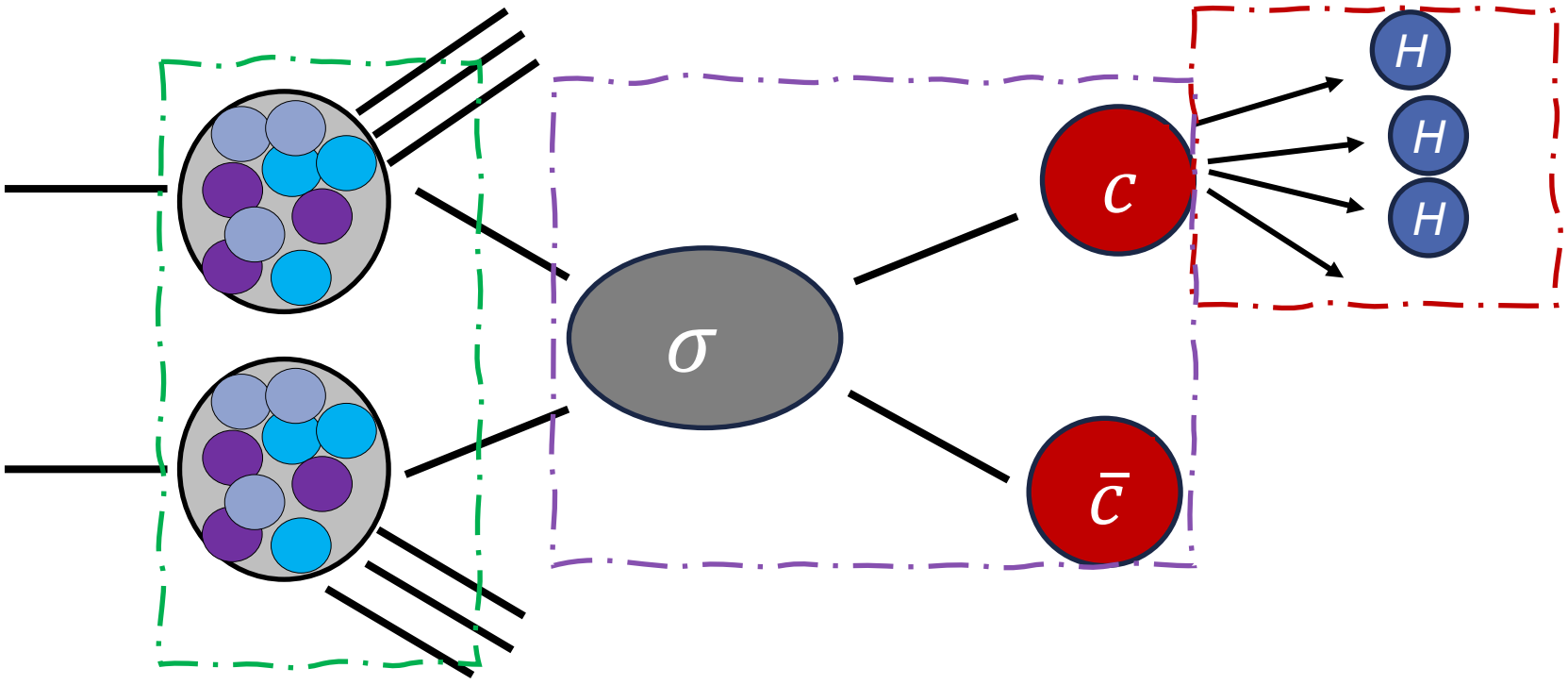
LINK

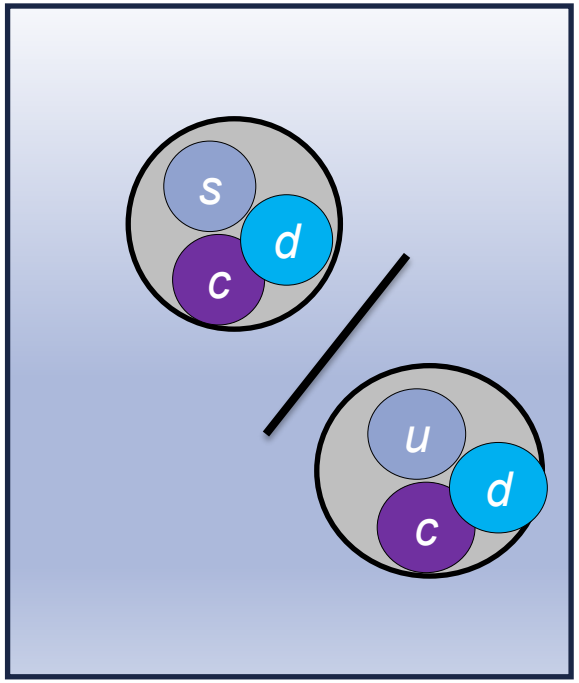
$$\sigma_{AB\to H} = \mathrm{PDF}(x_a, Q^2)\,\mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}}(x_a, x_b, Q^2) \otimes D_{q\to H}\,(z = p_{\mathrm{H}}/p_q\,, Q^2)$$

Parton distribution functions

Hard scattering cross section

Fragmentation function (hadronization)





The ratio of different hadron is an effective tool to probe charm hadronization

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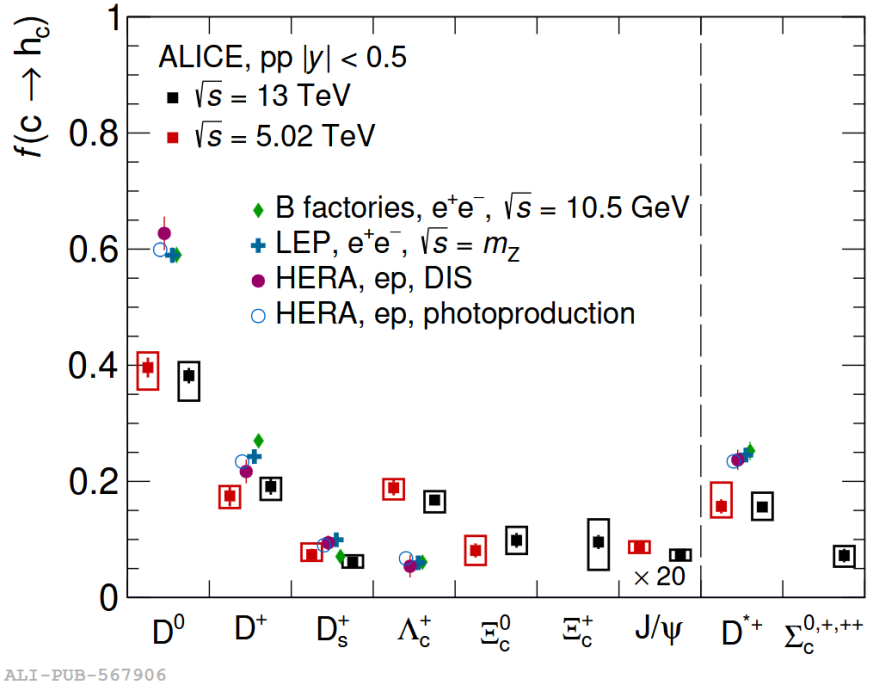
Parton distribution functions

Hard scattering cross section

Fragmentation function (hadronization)

JHEP12(2023)086



Charm-Quark fragmentation fractions into diff charm hadrons

Fragmentation Functions

- Derived from electron-positron (e^+e^-) or electron-proton (ep) collisions
- Considered **universal** across collision systems

Findings from the ALICE Experiment

- Significantly larger fraction of charm quarks hadronized into baryons compared to leptonic collisions.
- Baryon-to-Meson Ratio
  - Λ_c^+/D^0 significant enhancement in proton- proton (pp) collisions compared to low multiplicity e^+e^- and ep collisions.
  - p_{T}-differential Λ_c^+/D^0 ratio shows a multiplicity enhancement.
- Indication that hadronization process depends on collision system

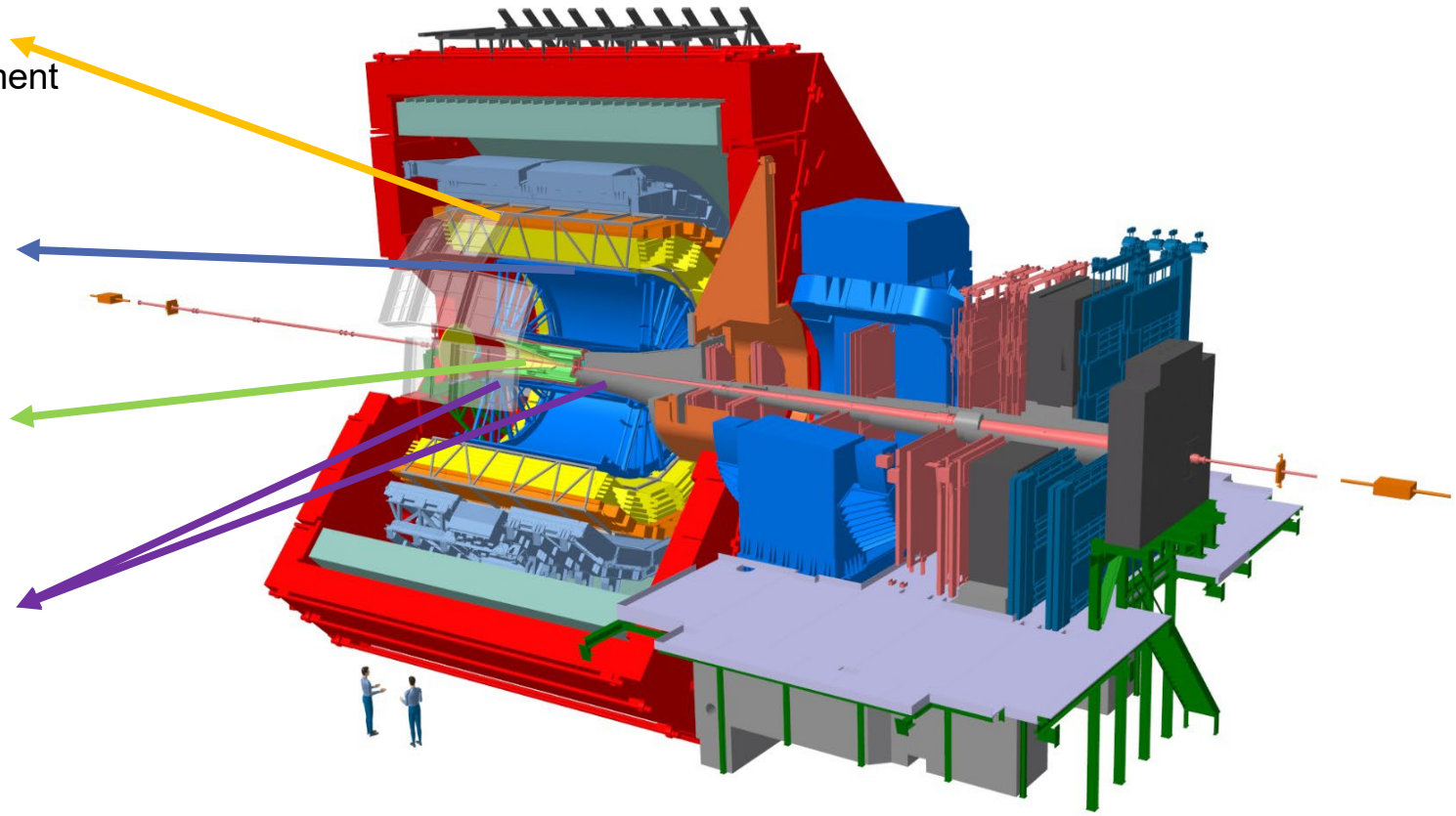
ALICE experiment in Run 2

Time Of Flight(TOF):
PID (particle Identification) via time-of-flight measurement
$|\eta| < 0.9$

Time Projection Chamber(TPC):
tracking, PID via dE/dx
$|\eta| < 0.9$

Inner Tracking System(ITS):
tracking, trigger, vertexing
$|\eta| < 0.9$

V0:
trigger, multiplicity estimator
$2.8 < |\eta| < 5.1$ (V0A)
$-3.7 < |\eta| < -1.7$ (V0C)



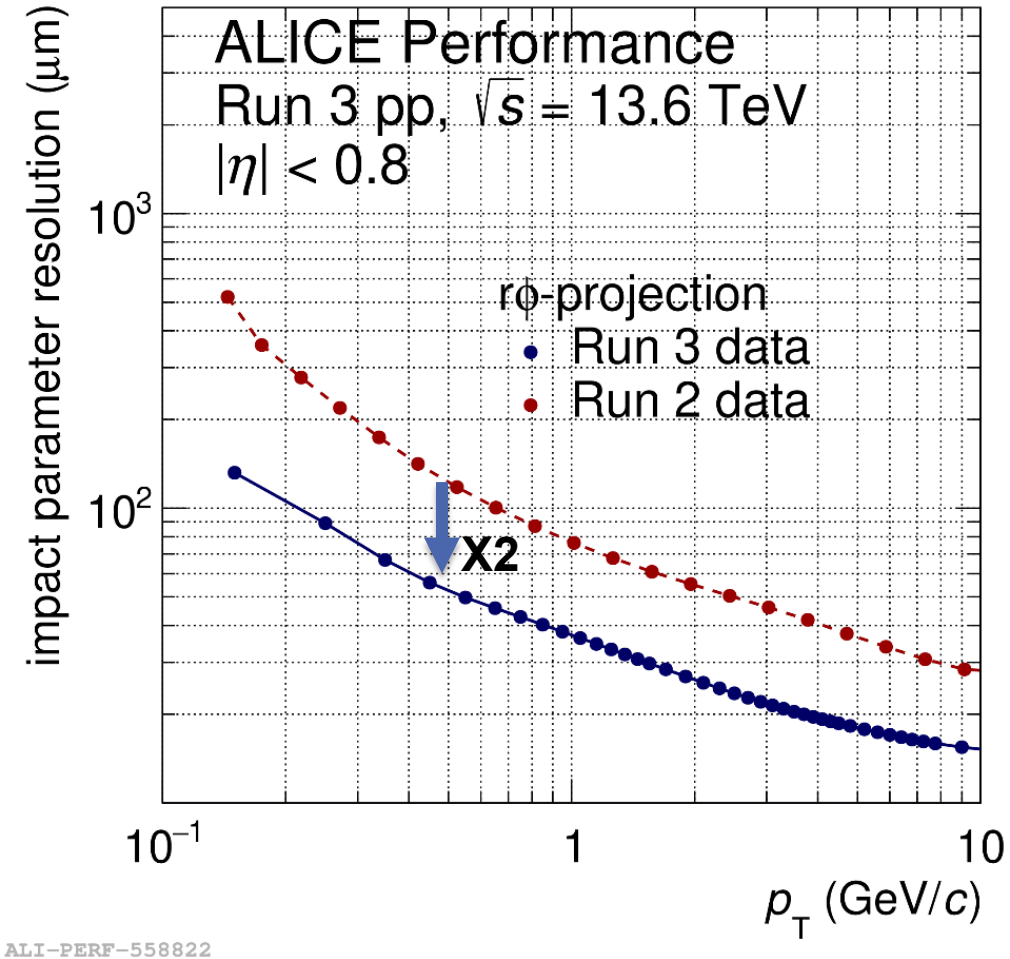
The major upgrades during Run 3

ITS: New ALPIDE pixel sensors used, significantly **improving resolution**.

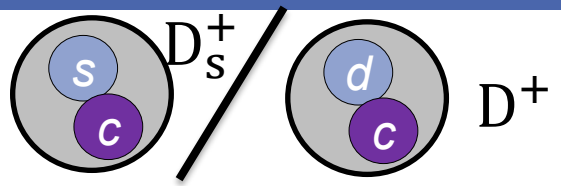
TPC: Gas Electron Multiplier (GEM) technology used, increases the TPC readout rate (× 50-100 times in Pb-Pb collisions, × 500-1000 times in pp collisions) allows collect **larger data sample**

FIT: New Fast Interaction Trigger

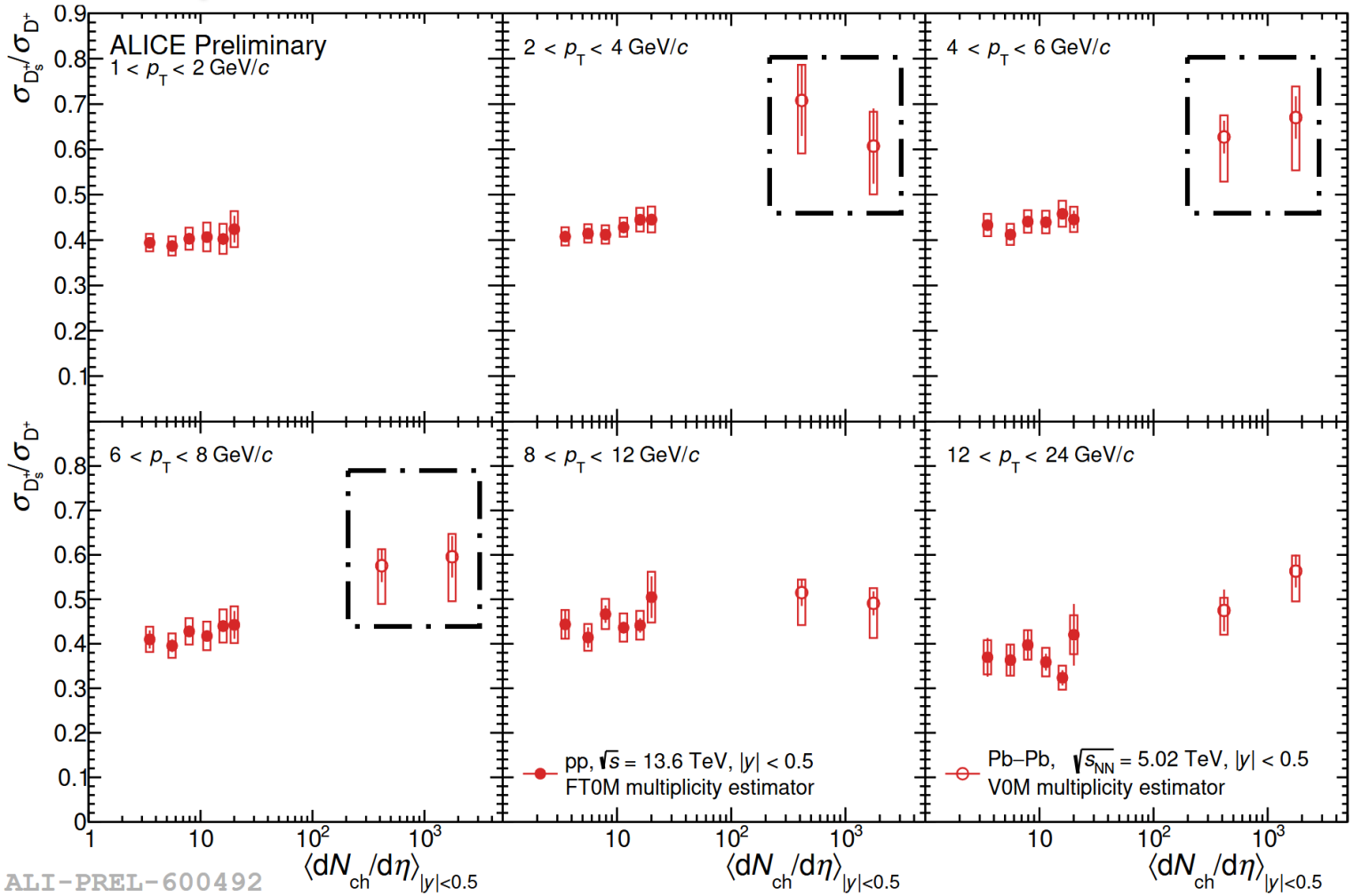
MFT: Muon Forward Tracker 2.5 <η < 3.6



D_s^+/D^+ ratio vs multiplicity



D_s^+ / D^+



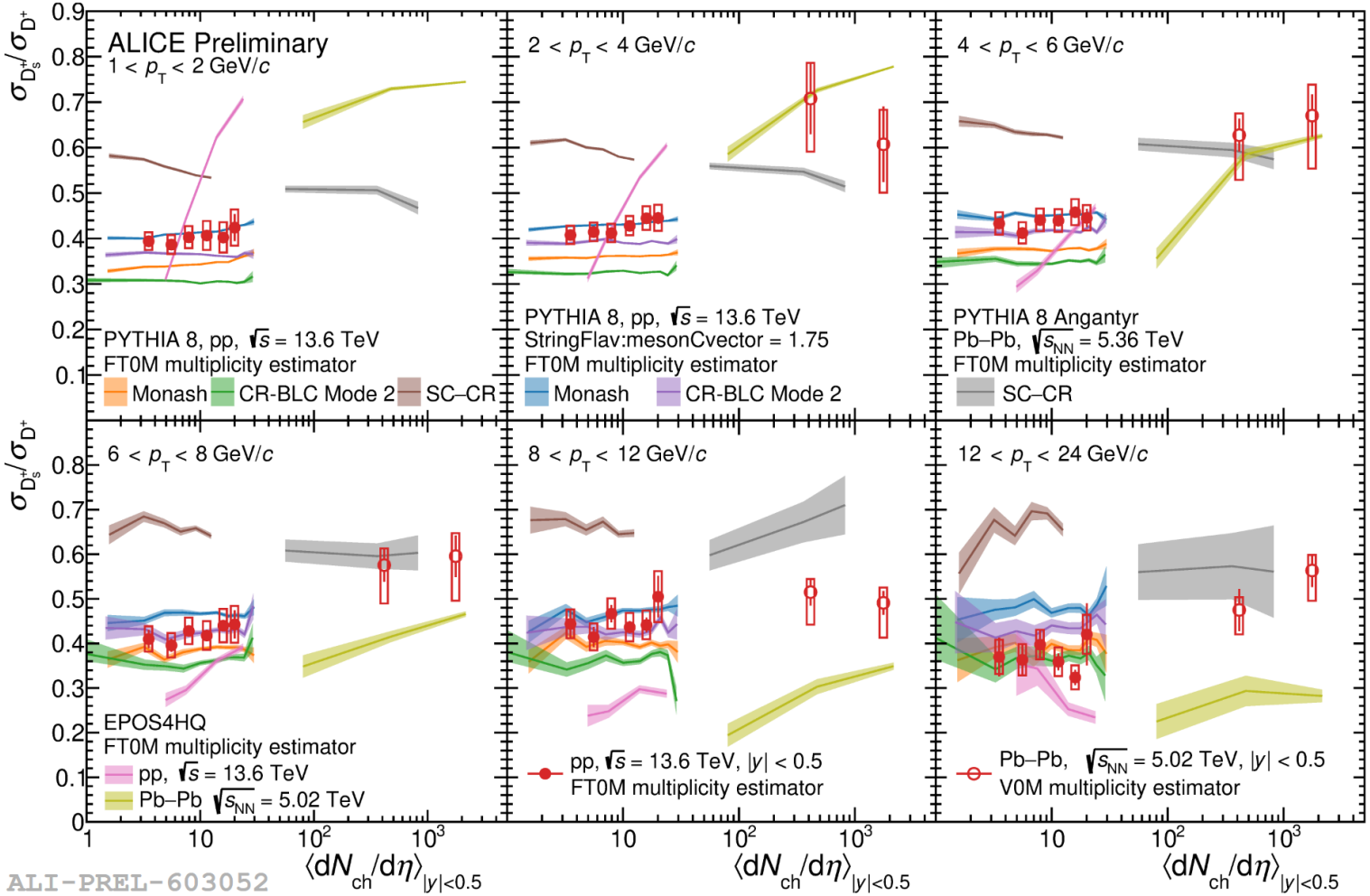
pp collisions:

- No multiplicity dependence observed in the D_s^+/D^+ ratios in pp collisions.

Pb-Pb collisions:

- Higher D_s^+/D^+ ratio at low/intermediate Pb-Pb collisions compared to pp collisions.
  - charm quarks recombination with strange quarks in the medium.

D_s^+/D^+ production vs multiplicity



pp collisions:

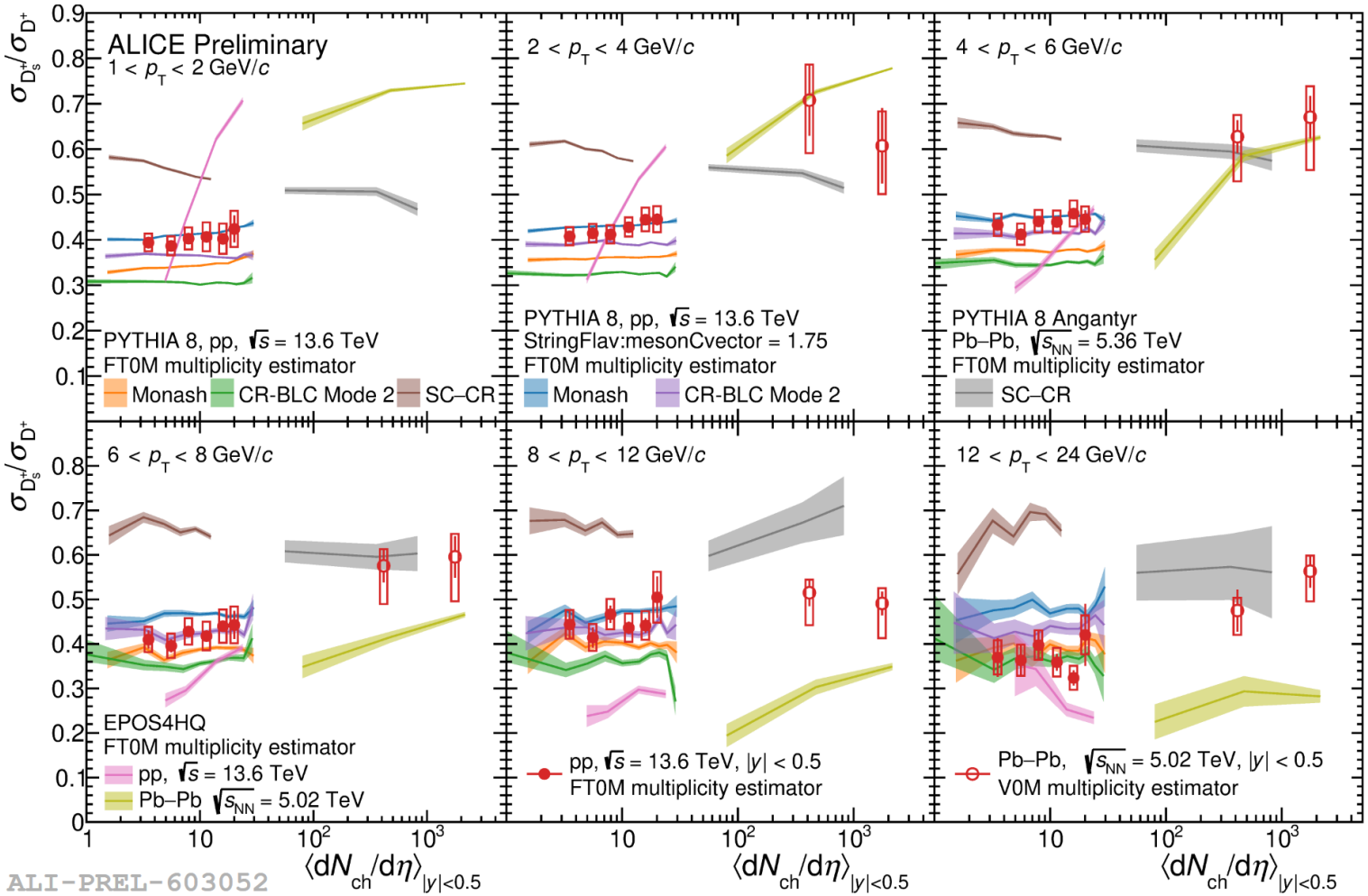
- D_s^+/D^+ ratios compatible with PYTHIA Monash and CR-BLC.

PYTHIA 8

Based on the Lund string fragmentation model

- **Monash Tune:** Tuned to e^+e^- measurements
- **CR Mode:** Junction topology beyond the leading colour approximation

D_s^+/D^+ production vs multiplicity



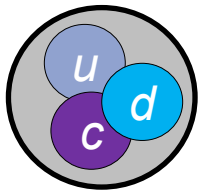
Pb-Pb collisions

- PYTHIA Angantyr and EPOS4HQ qualitatively reproduce the Pb-Pb measurements at low/intermediate but fail to describe the pp measurements.

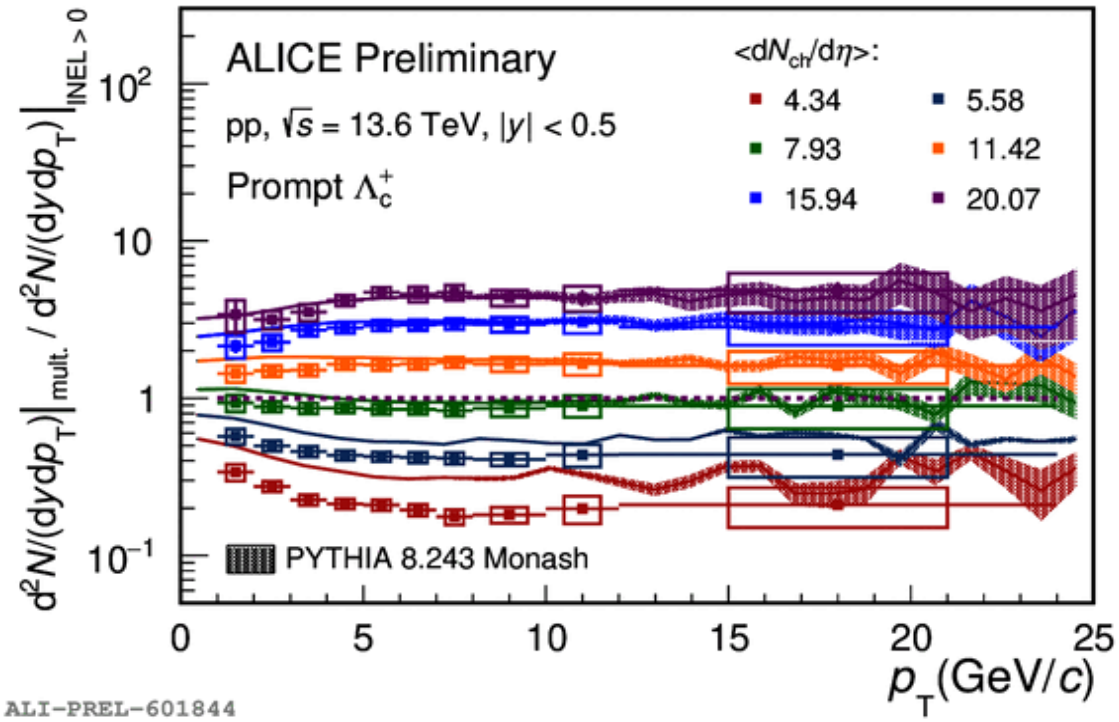
Models

- **PYTHIA 8 Angantr**: extended from a successful pA framework, that simulates non-collective particle production.
- **EPOS4HQ:** fragmentation + coalescence + resonance + UrQMD

Charm baryon production vs multiplicity



Λ_c^+



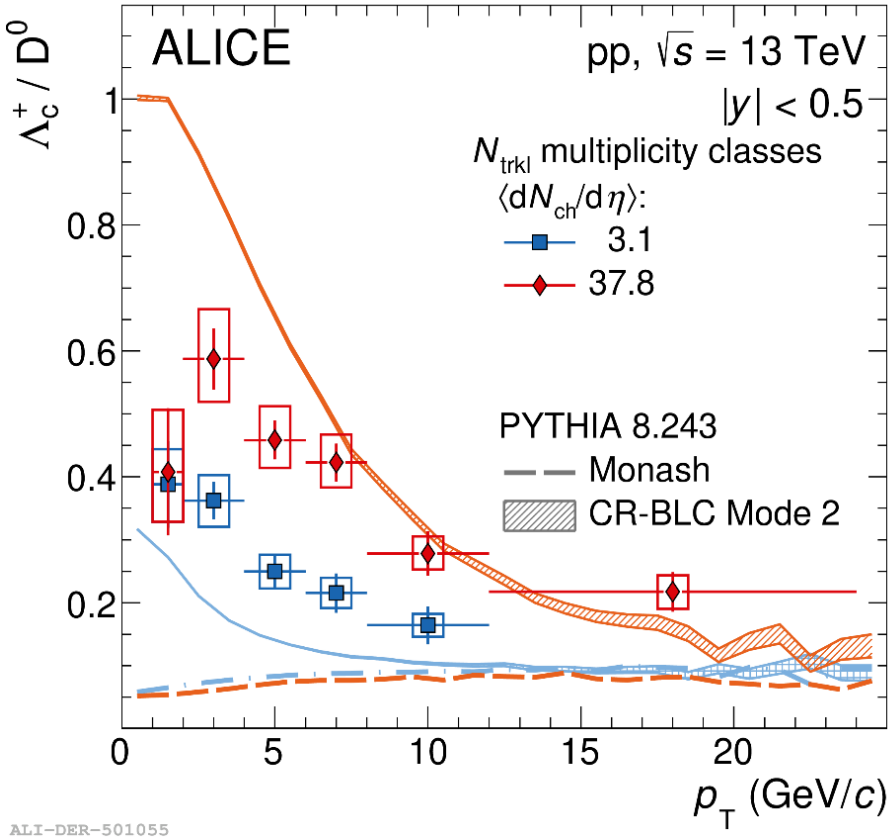
Different charged-particle multiplicity classes / multiplicity-integrated class

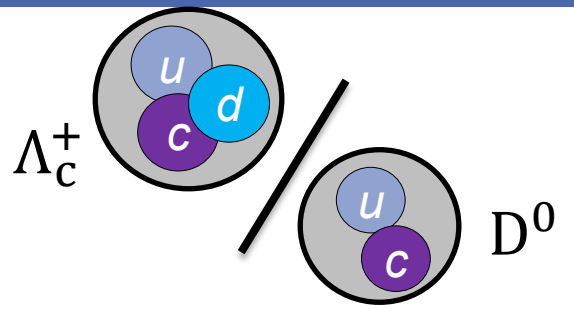
Multiplicity-Dependent of Λ_c^+

- p_T -differential yields of Λ_c^+ increase from the lowest to the highest multiplicity class.
- Ratios to INEL>0 increase (decrease) with increasing p_T for the highest (lowest) multiplicity class
  - Hardening of the p_T spectra with the increasing multiplicity.
- Data qualitatively described by PYTHIA8 Monash.

Charm baryon-to-meson vs multiplicity

Phys.Lett.B 829 (2022) 137065



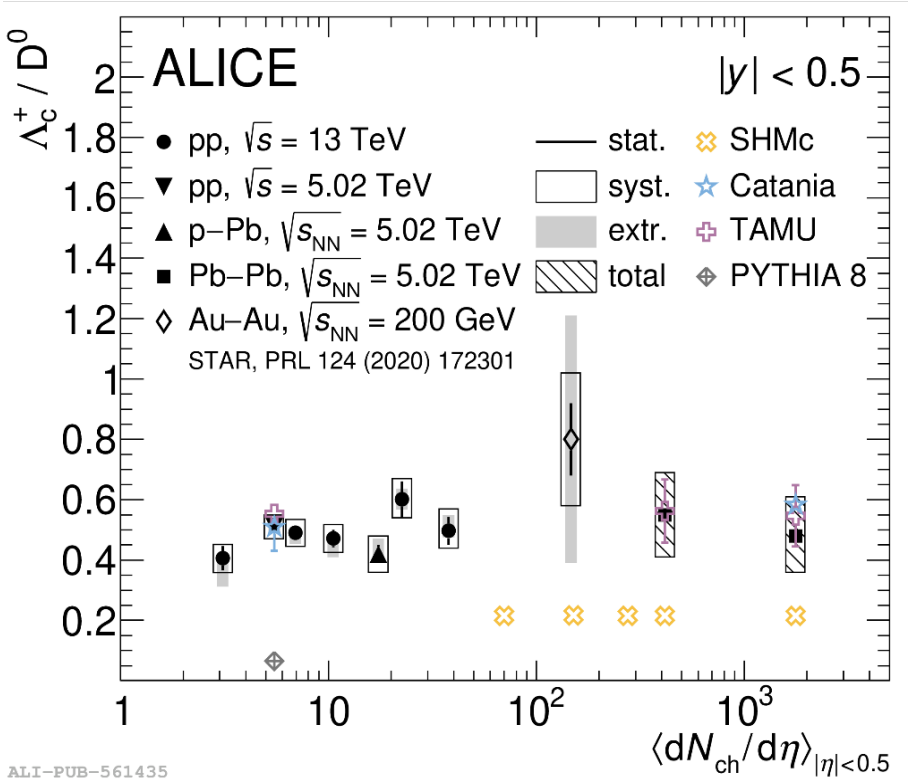


Multiplicity-Dependent of Λ_c^+/D^0

- Significant(5.3σ) enhancement from the lowest to the highest multiplicity class.
- In pp collision at lowest multiplicity Λ_c^+/D^0 ratio steal enhanced compared to (e^+e^-) collisions.
- PYTHIA CR-BLC capture the trend of the Λ_c^+/D^0 ratio, qualitatively describing the increasing ratios with multiplicity.

Charm baryon−to−meson vs multiplicity

Phys.Lett.B 839 (2023) 137796



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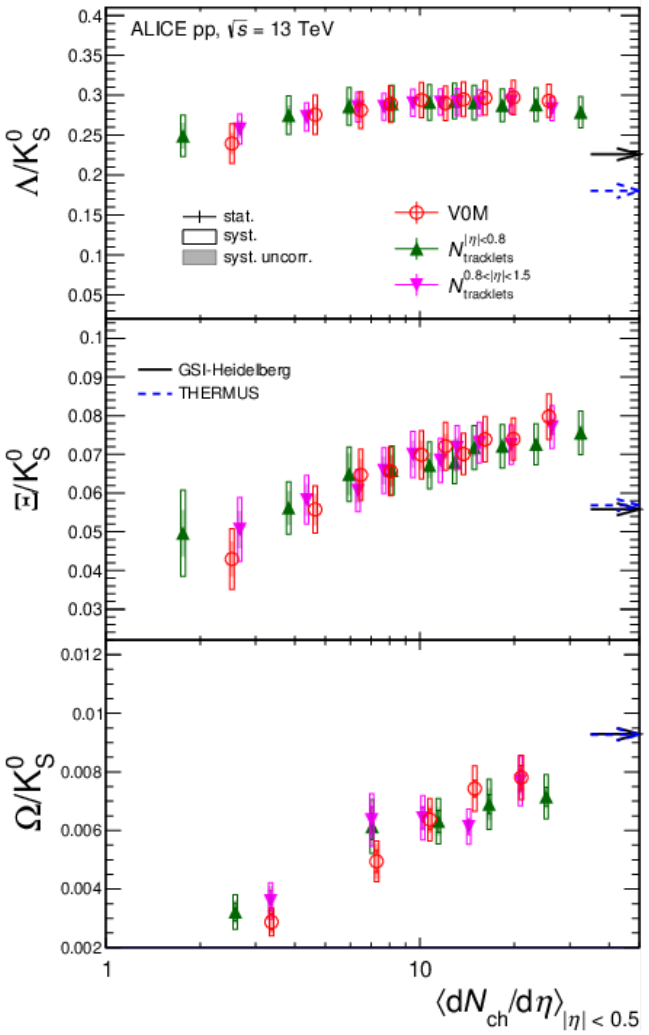
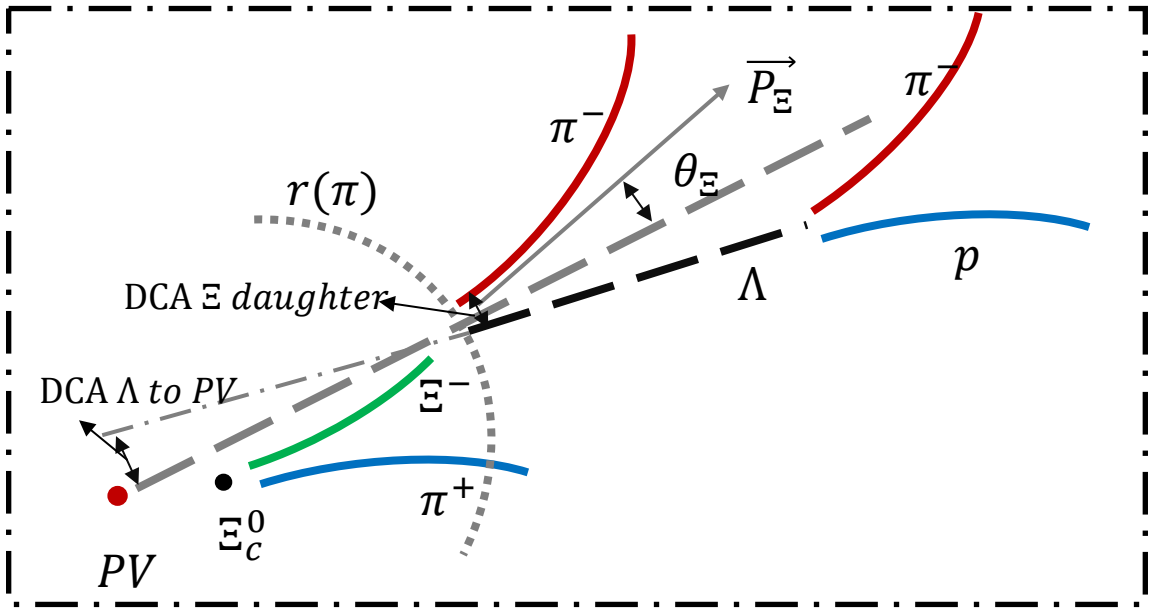
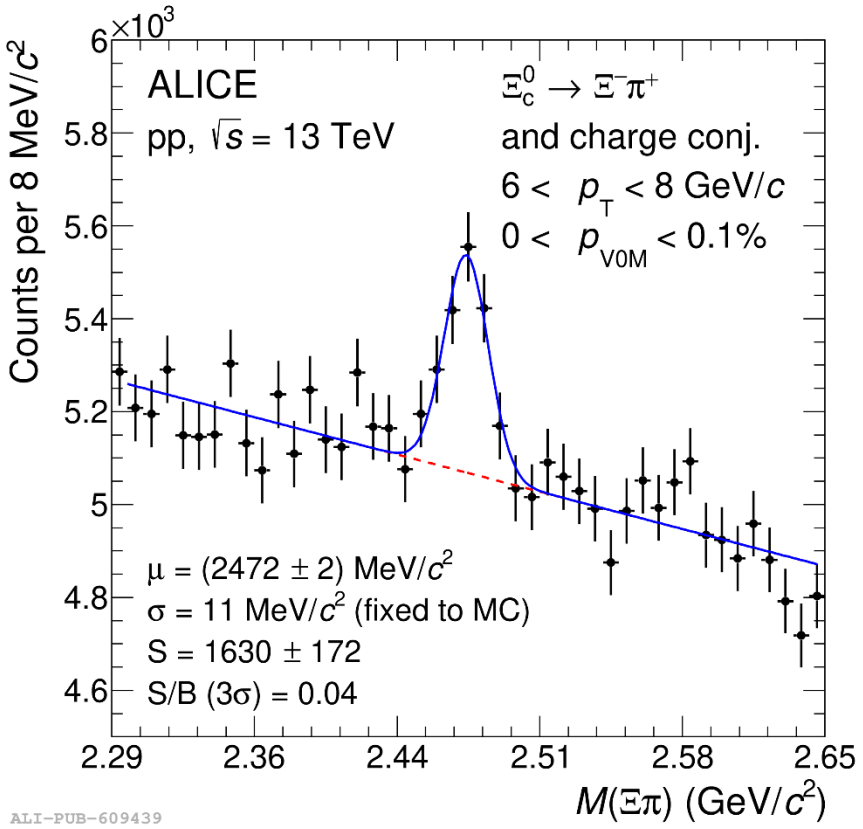


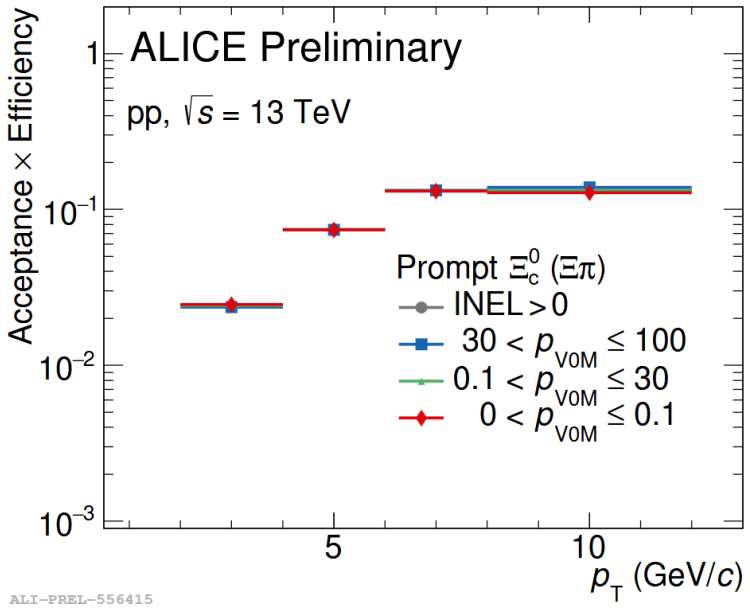
p_T -integrated yields of Λ_c^+/D^0 ratio in difference collision system

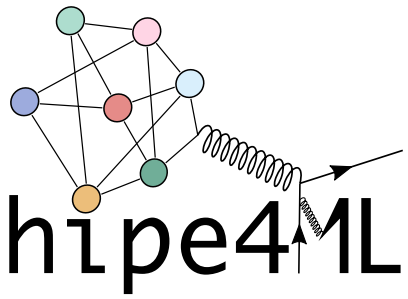
- No significant multiplicity dependence observed within the current uncertainties, flat trend reproduced by models
- Similar to Λ_c^+/K_s^0 with weak multiplicity dependence. Interestingly, a clear multiplicity dependence in the multi-strange baryon-to-meson yield ratios Ξ/K_s^0 and the Ω/K_s^0.

Ξ_c^0 reconstruction

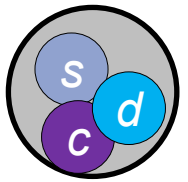








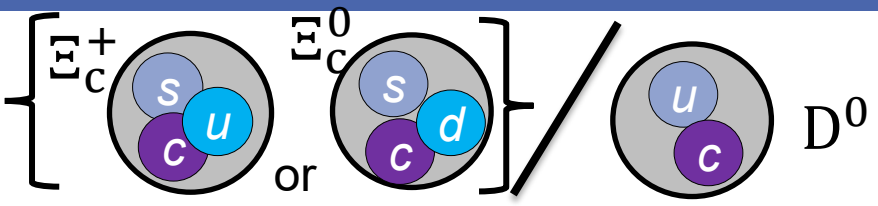
Analysis strategy

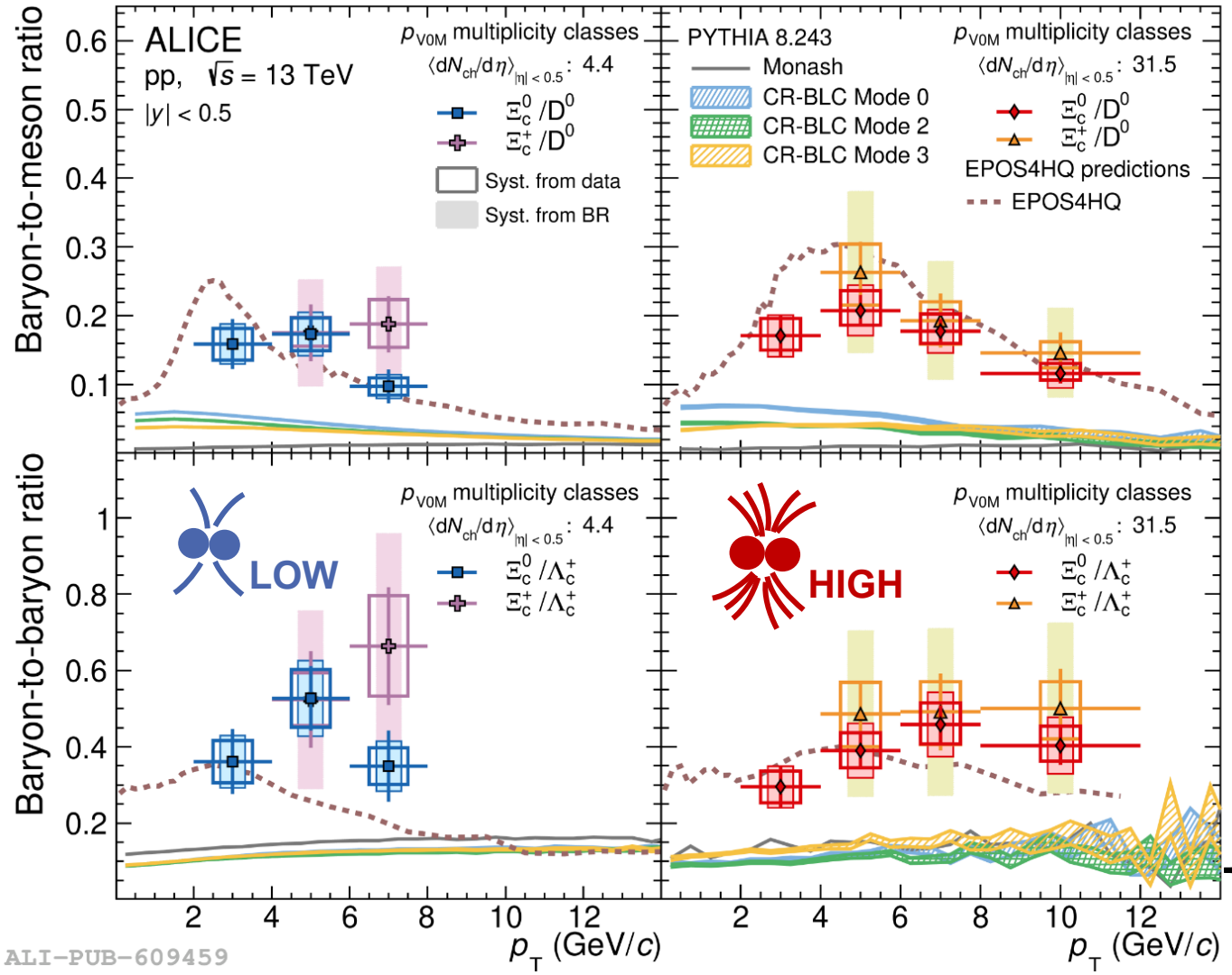


Ξ_c^0

ML: Reduce background
Raw yield: Fit inv. mass distribution
Efficiency correction: MC simulation
Feed-down substruction
Result: Corrected yields

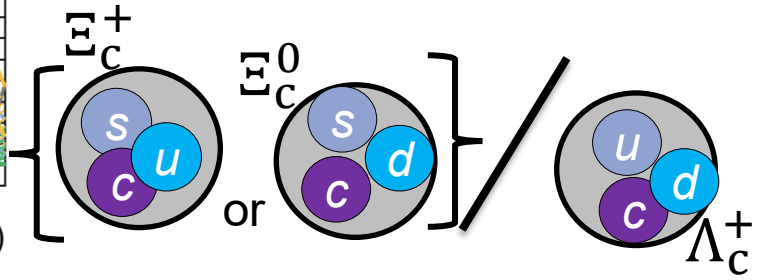
Baryon-to-meson and Baryon-to-baryon vs multiplicity





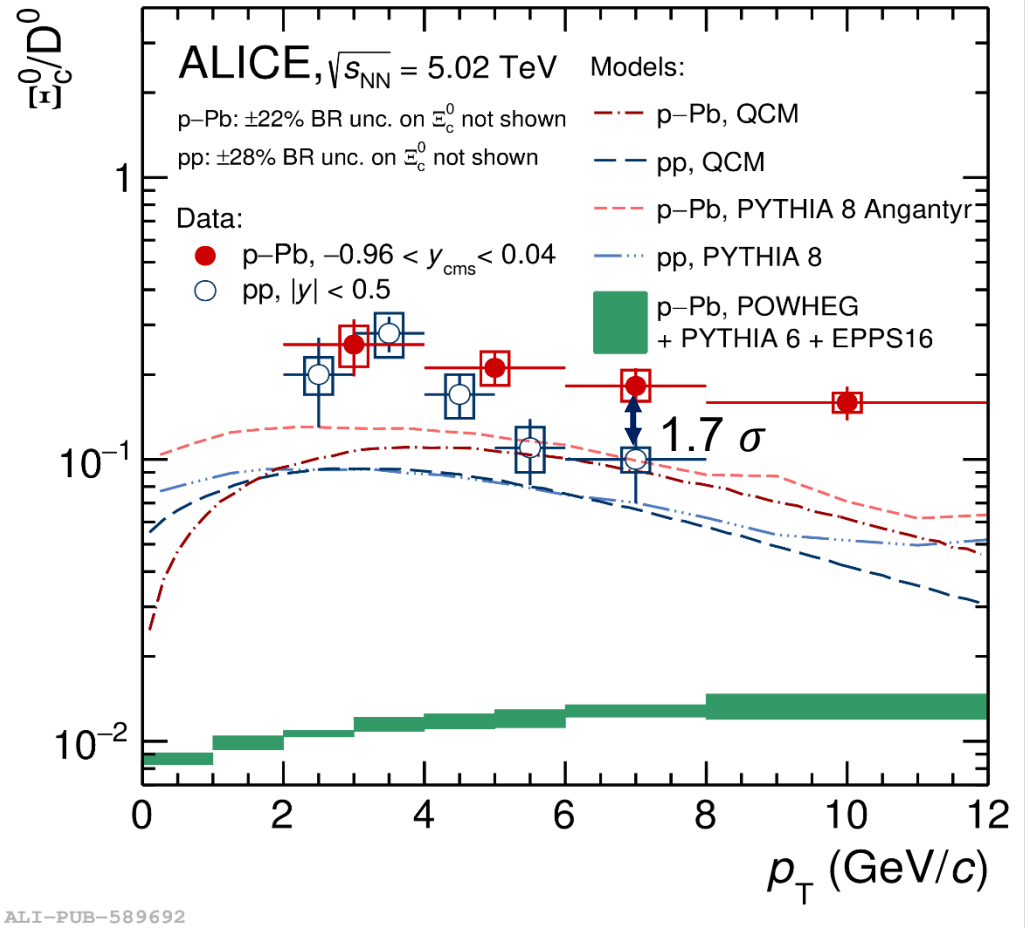
Multiplicity-Dependent of $\Xi_c^{0,+}/\mathrm{D}^0$ and $\Xi_c^{0,+}/\Lambda_c^+$ in pp collisions

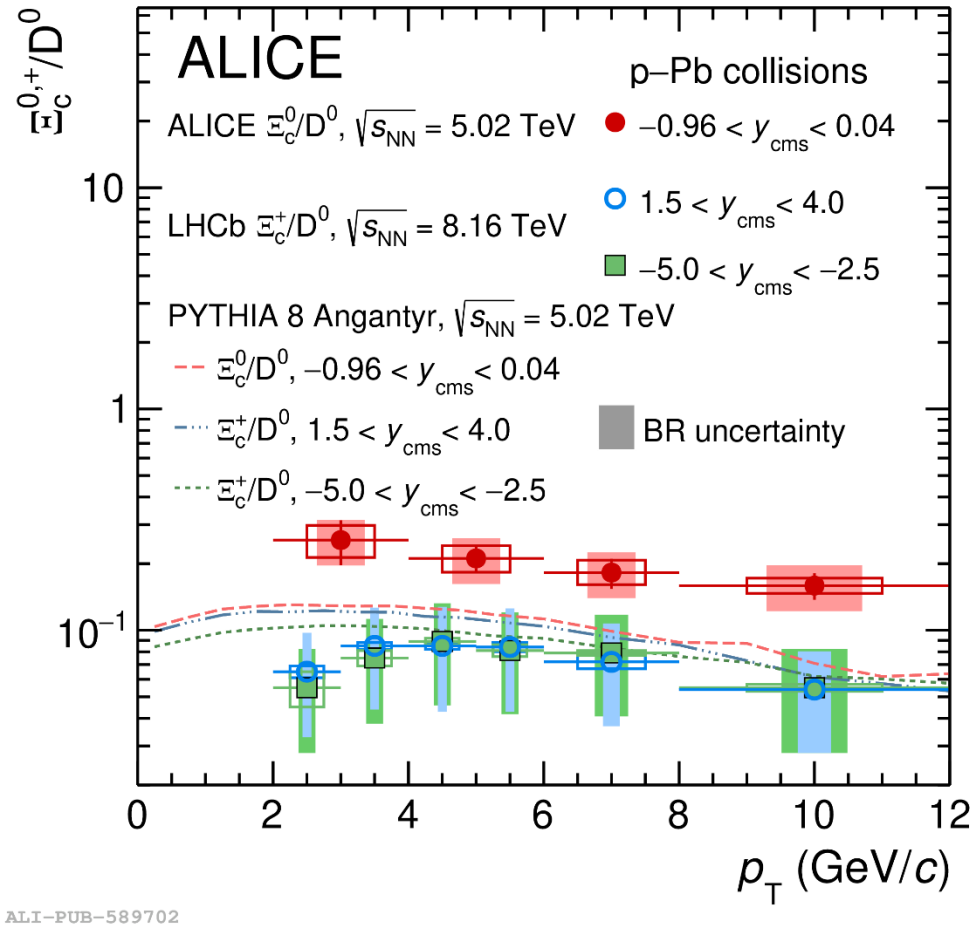
- No significant multiplicity dependence observed due to the limited precision
- The EPOS4HQ prediction describes the $\Xi_c^{0,+}/\mathrm{D}^0$ ratio as a function of p_T and multiplicity, while the PYTHIA 8.2 **Monash** tune and **CR-BLC** modes underestimated of the measurement.



$\Xi_c^{0,+}/D^0$ in p-Pb collisions

Eur. Phys. J. C 85 (2025) 86





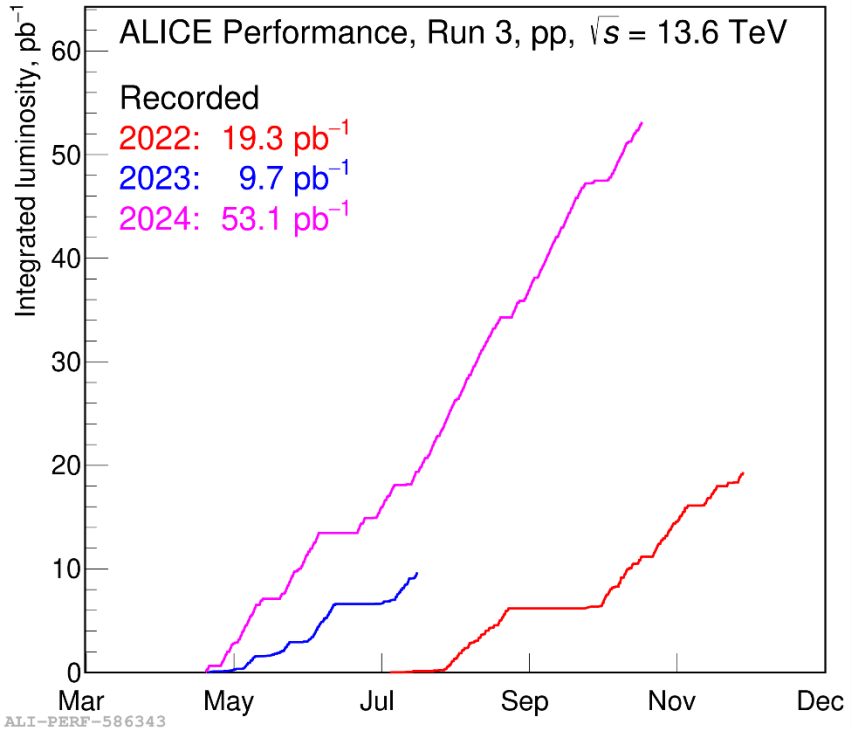
- Hint of enhanced Ξ_c^0/D^0 ratio in p-Pb collisions with pp collisions
- QCM underestimates Ξ_c^0/D^0 ratio, PYTHIA 8 Angantyr improves the description

- Yield ratio at midrapidity larger than the forward and backward rapidities in full p_T range(difference from 1.5σ to 2.0σ)

Outlook

Run3 improvement

- **Statistical significance**: exploiting the large data sample of pp collisions at 13.6TeV being collected (Run 2 MB sample was 36 nb-1,high-multiplicity one to about 6 pb-1)
- **Precision**: Systematic reduced
- **Multiplicity**: Studies from lower-multiplicity to higher-multiplicity reg.



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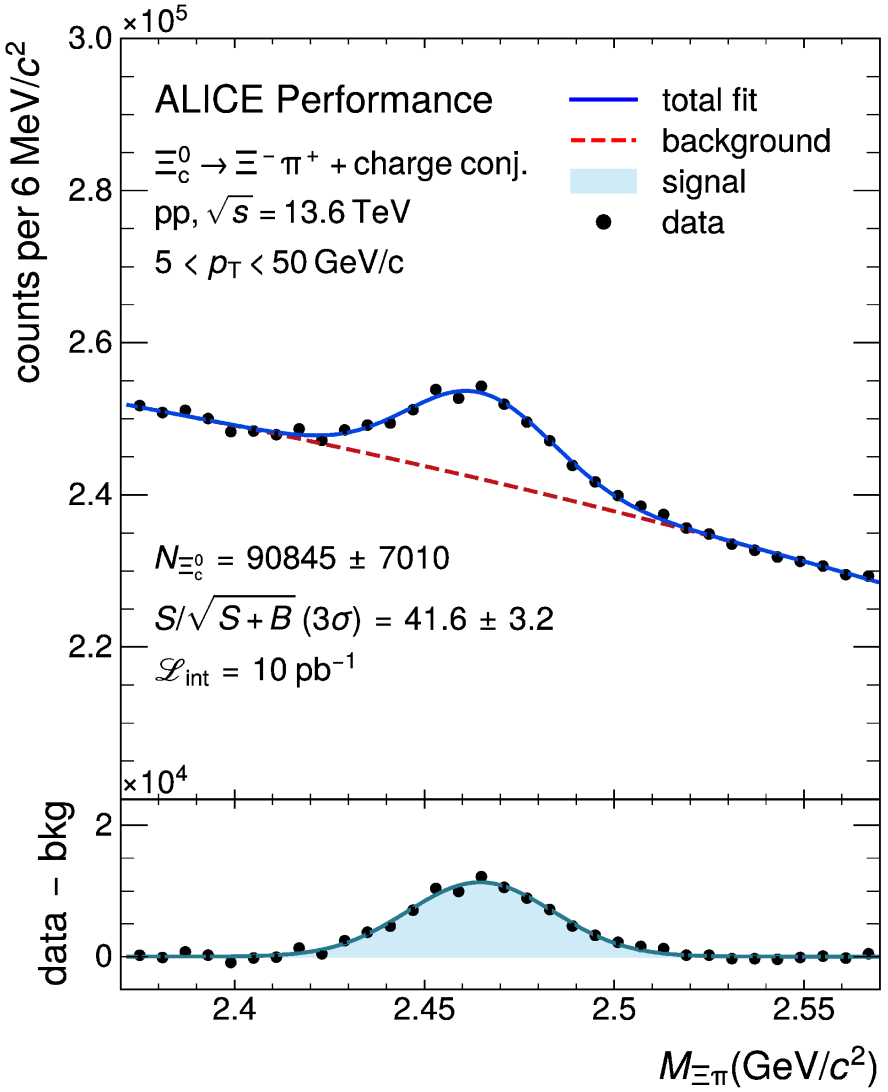

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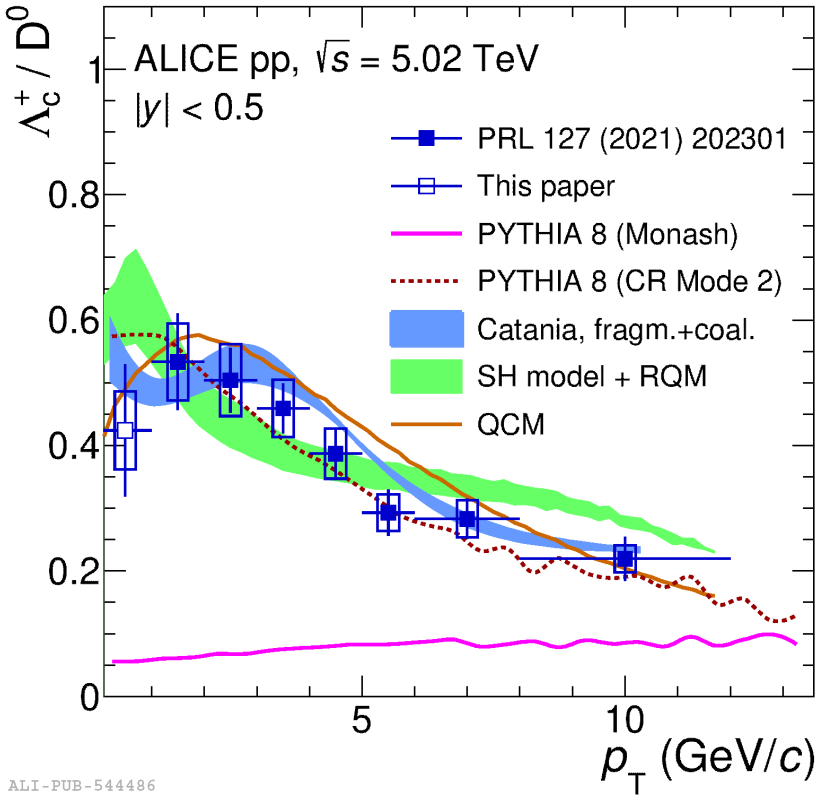
Summary

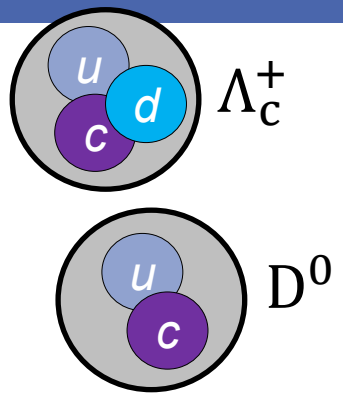
- Charm hadronization may not a universal process across different collision systems.
- No multiplicity dependence is observed in the $\mathbf{D_s^+/D^+}$ ratio in pp collisions, but the ratio is enhanced in Pb-Pb collisions.
- The p_{T}-differential $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ ratio shows a multiplicity enhancement, but integrated yields do not have significant multiplicity dependence.
- No significant multiplicity dependence is observed in either $\mathbf{\Xi_c^{0,+}/D^0}$ or $\mathbf{\Xi_c^0/\Lambda_c^+}$ within uncertainties.
- More charm-baryon measurements ongoing in Run 3 ….

Back up

Measurements in pp collisions

PhysRevC.107.064901





Monash tuned to e^+e^-

Baryon-to-Meson Ratio: The baryon-to-meson ratio shows a clear dependence on p_T, with enhanced at low and intermediate p_T. Models such **as PYTHIA 8 Mode 2, Catania, QCM, and SHM+RQM** successfully describe the observed data

PYTHIA 8

Based on the Lund string fragmentation model

- **Monash Tune:** Tuned to e^+e^- measurements
- **CR Mode 2:** Junction topology beyond the leading colour approximation
- Angantr: extended from a successful pA framework, that simulates non-collective particle production.

CATANIA

fragmentation + coalescence

SHM + RQM

- **Statistical Hadronization Model (SHM):**All quarks reach thermal equilibrium and undergo hadronization to form the final hadronic states. heavy quarks hadronization follows a statistical distribution.
- **Relativistic Quark Model (RQM):** Used to predict unobserved excited charm states (especially baryons) that feed down to ground-state hadrons.

QCM

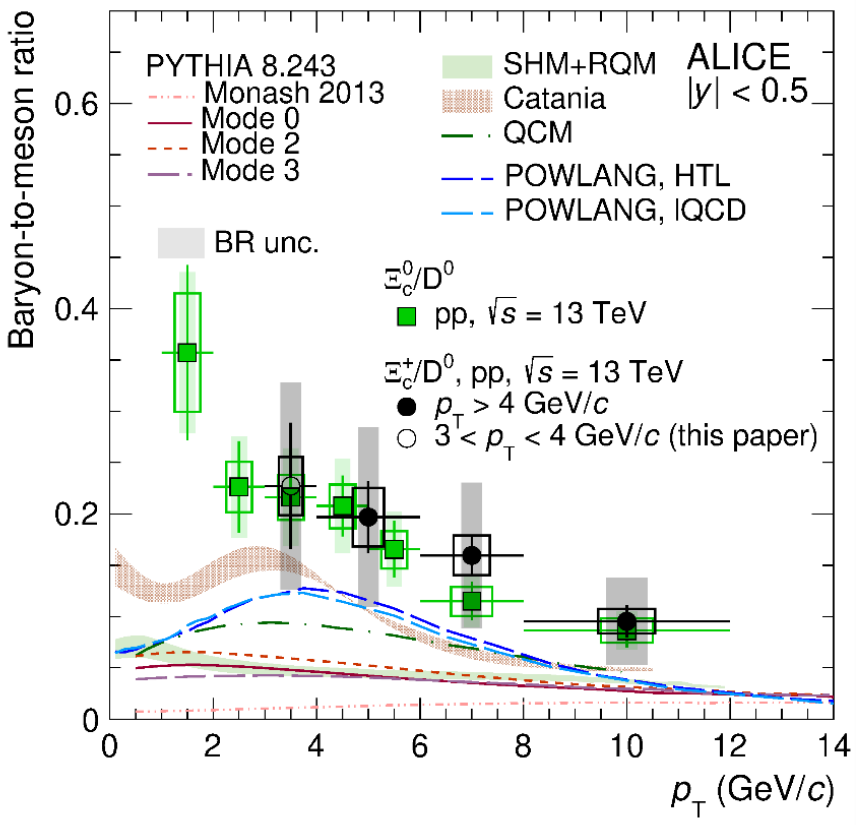
Pure coalescence, **e**qual-velocity combination of charm quark and light quarks

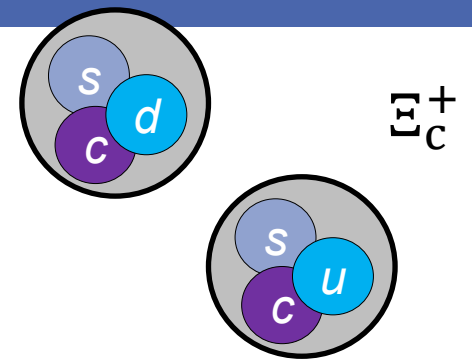
EPOS4HQ

fragmentation + coalescence + resonance + UrQMD

Measurements in pp collisions

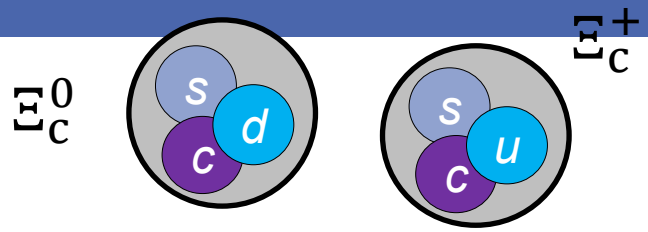
JHEP12(2023)086

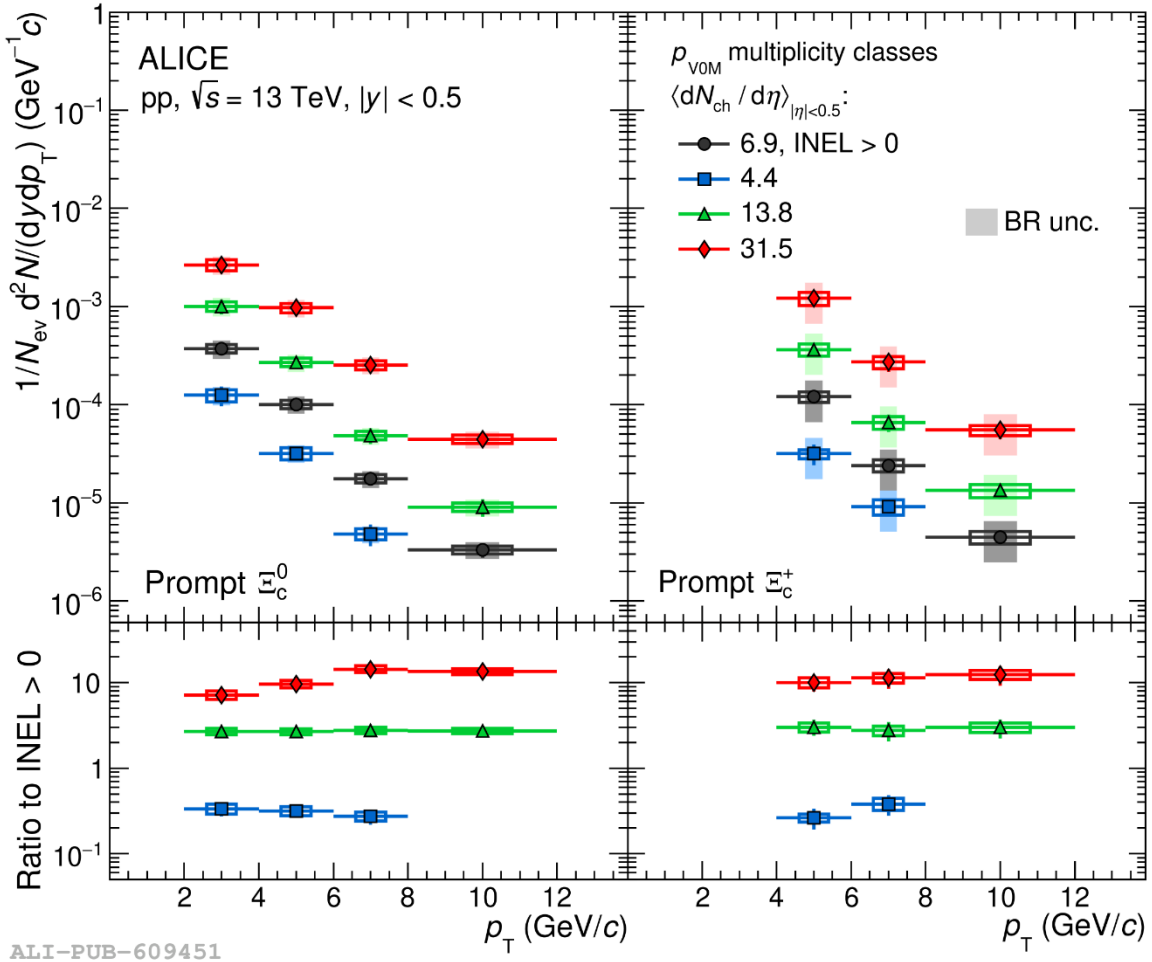


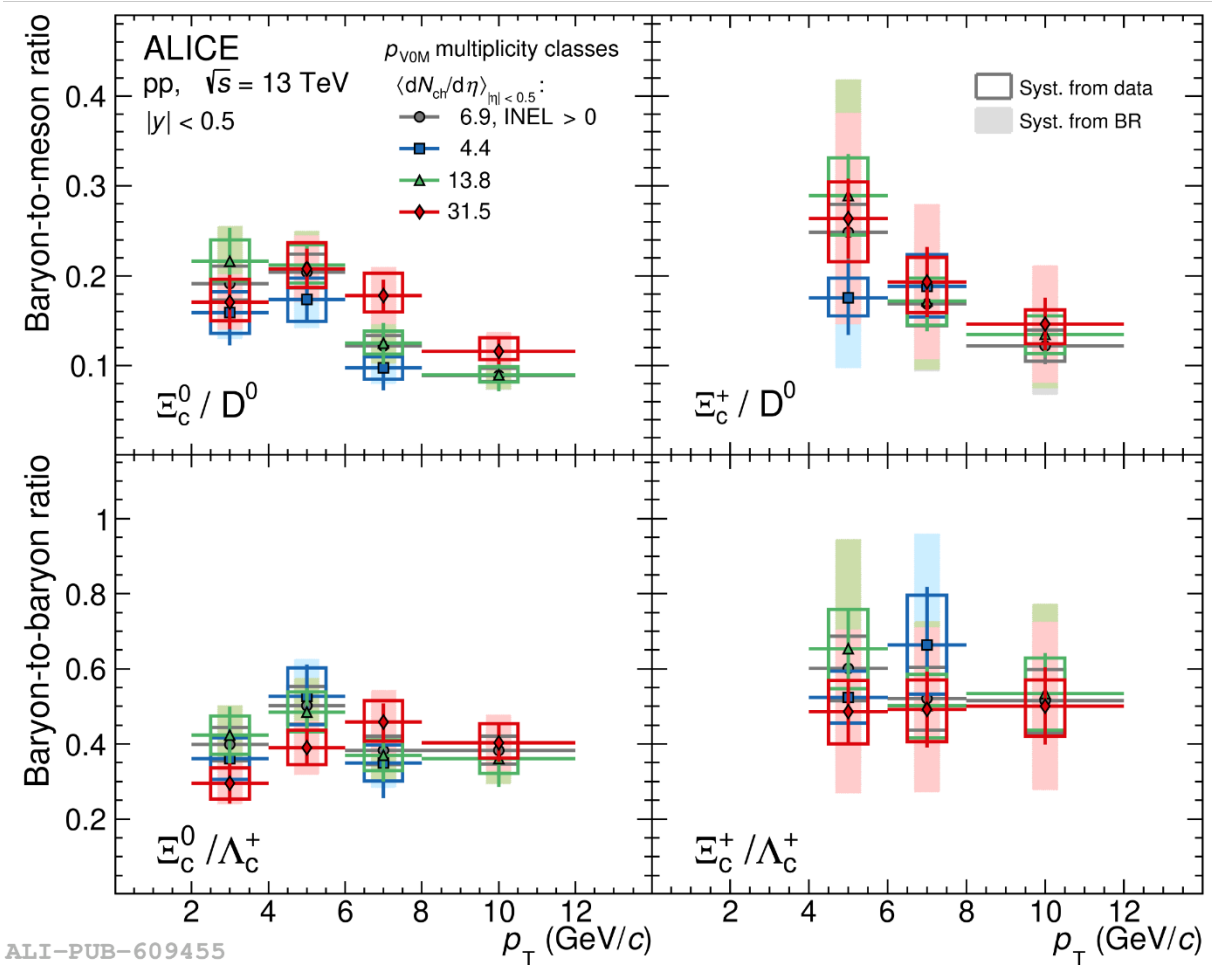


Strange-Charm Baryons: At low and intermediate pT show a clear enhancement, most models steal underestimate the ratio, despite the relatively large uncertainties in data

Measurements in pp collisions







Measurements in p-Pb collisions