Hadronisation studies at CERN

EMMI Collaboration Meeting : QCD at FAIR Workshop 2025

25th June 2025

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Introduction

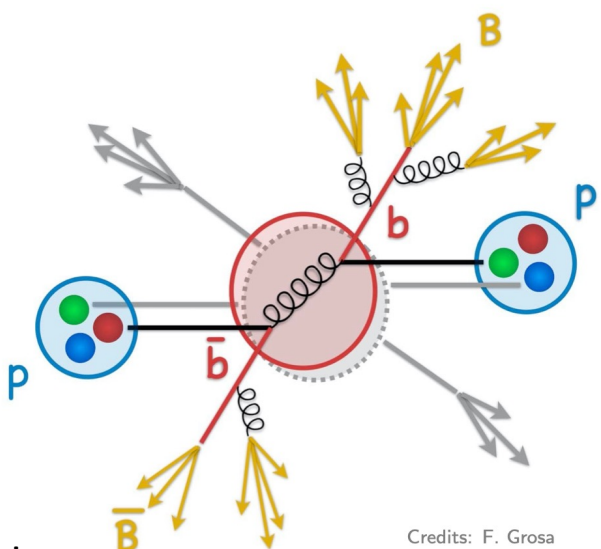
- The production of hadrdons can be described with the factorization approach :

$$\int \sigma_{(AB\to CX)} \propto PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{(ab\to cd)} \otimes D_c^C(z_c, Q^2)$$

- Parton distribution functions (non perturbative)
- Partonic cross section (perturbative)
- Fragmentation functions (non perturbative)

- Particle production ratios are sensitive to hadronization mechanisms

- Fragmentation functions are assumed to be universal across collision systems



Credits: F. Grosa

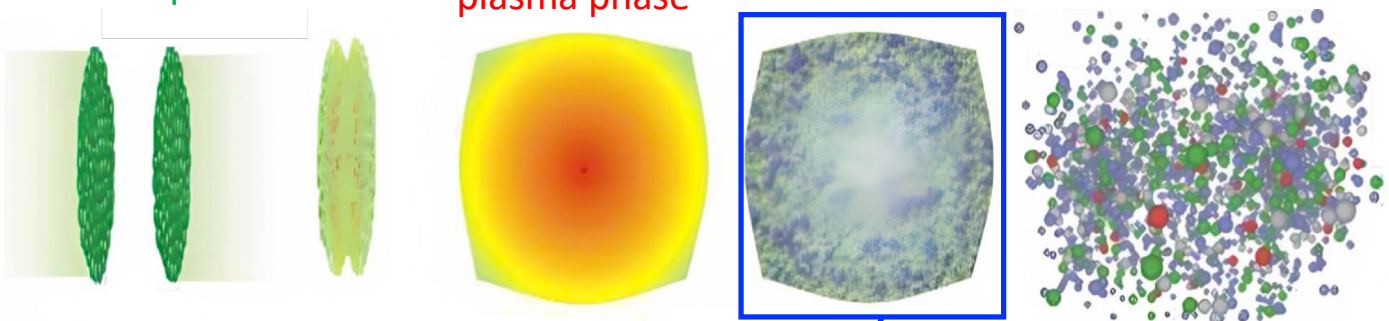
Introduction – Hadronisation in Pb-Pb

Initial phase

Quark-gluon plasma phase

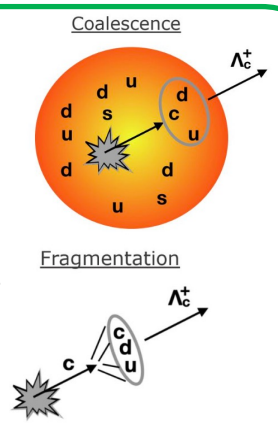
Hadronisation

Hadronic phase



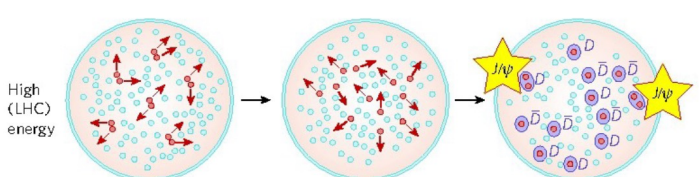
Mechanisms

- Coalescence: combination of quarks close in phase space
- Fragmentation: "break up" of charm quark

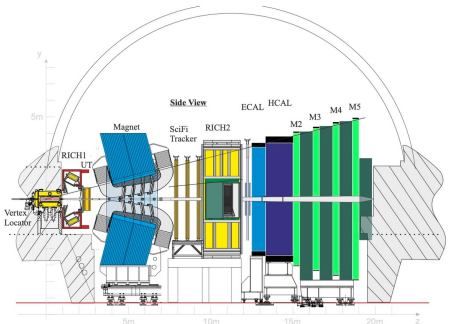


Models

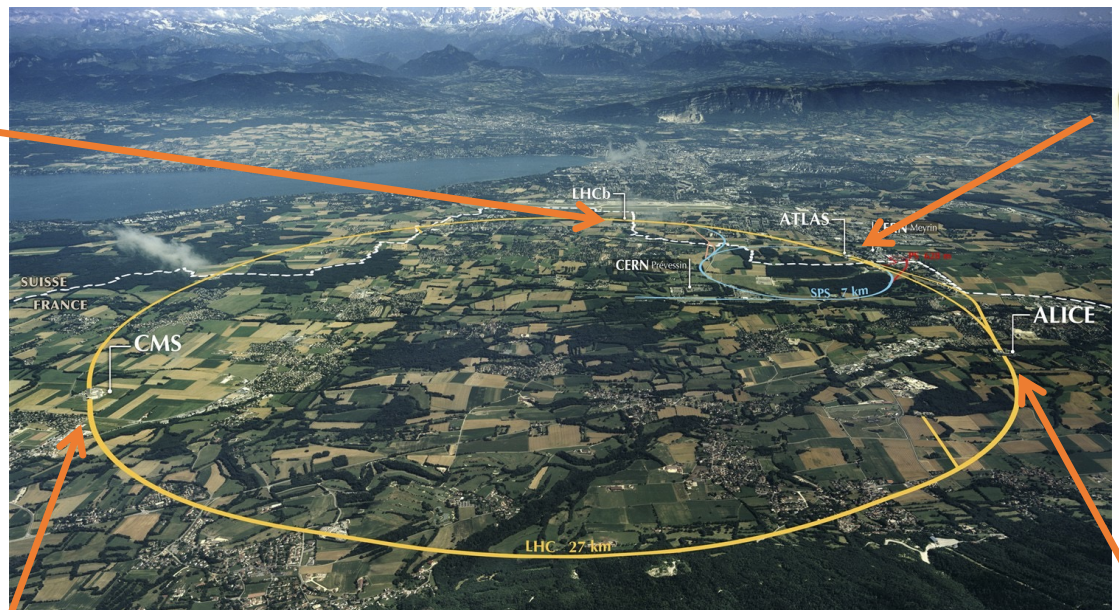
- Statistical hadronization : charm quarks distributed to hadrons according to thermal weights



Introduction – The LHC

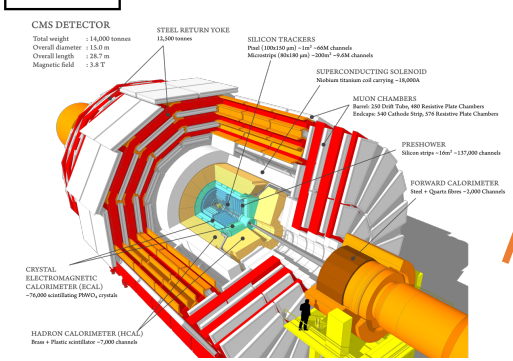


LHCb

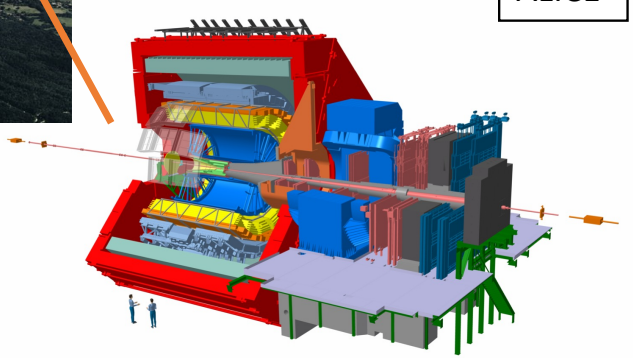


ATLAS

CMS

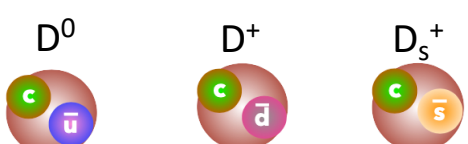


ALICE

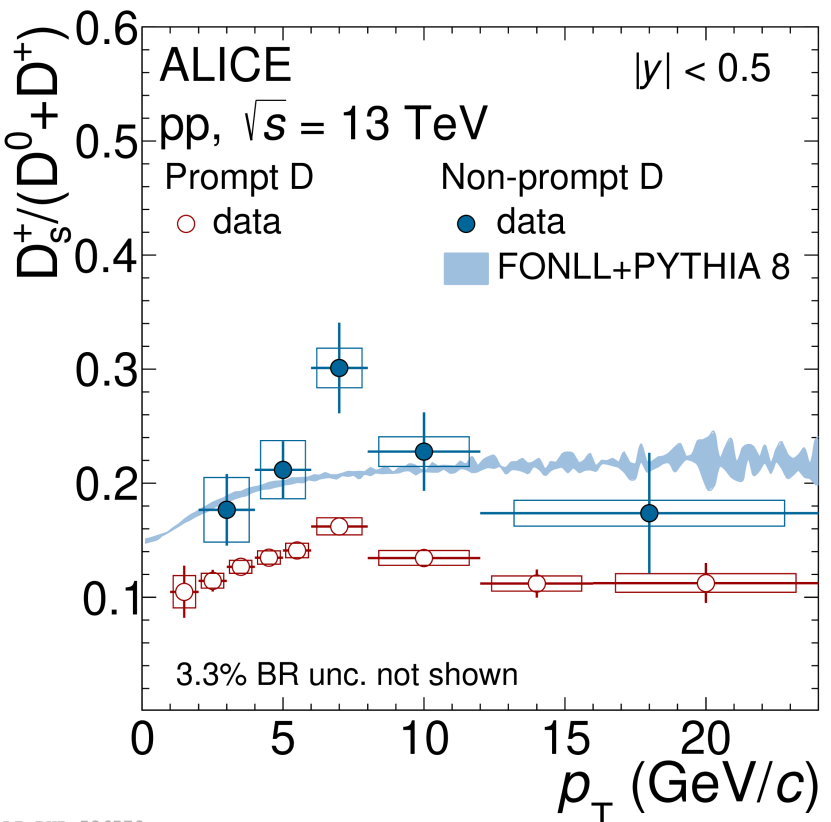


D-meson production in pp collisions

- Understanding the hadronization mechanism is necessary as enhancement in the strangeness is expected in QGP
- Prompt strange-to-non-strange meson ratio exhibit an increasing trend as a function of p_T up to ~8 GeV/c
- No significant trend visible in the non-prompt case
- FONLL calulation describe the data in the p_T range



ALICE, JHEP 12 (2023) 086
ALICE, JHEP 10 (2024) 110

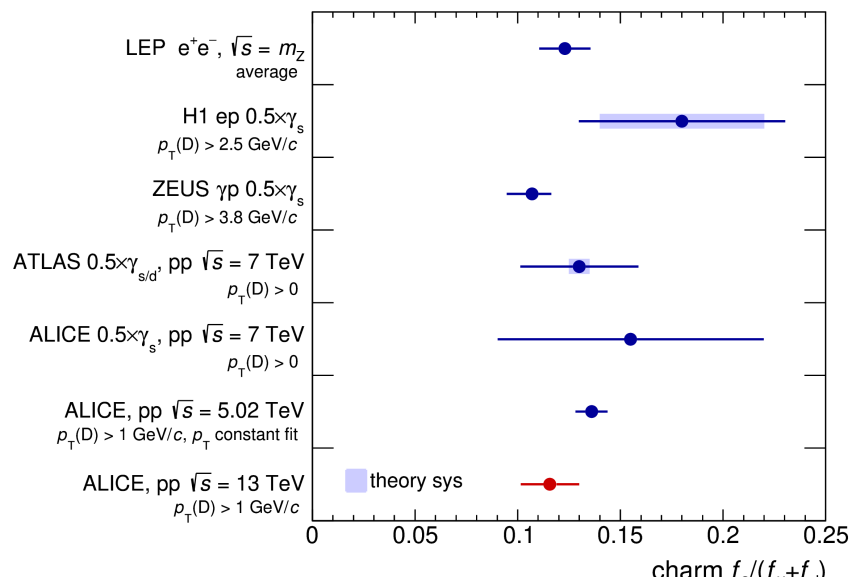


FONLL, JHEP 10 (2012) 137

D-meson production in pp collisions

ALICE, JHEP 12 (2023) 086
ALICE, JHEP 10 (2024) 110

- Results are compatible with the values found for e^+e^- collisions
  ➜ **Indicates universality of the fragmentation function for mesons**



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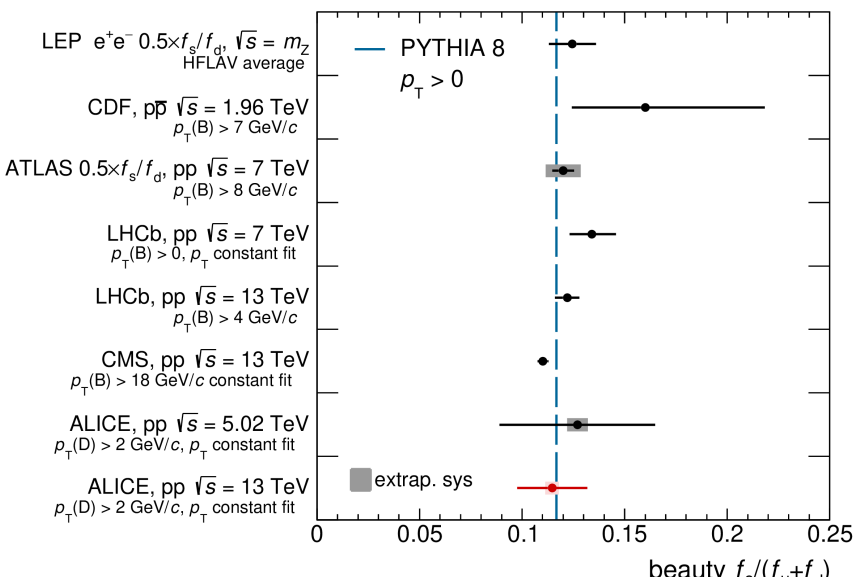
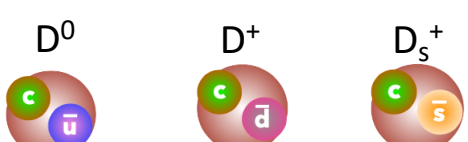


ALI-PUB-586583

Prompt

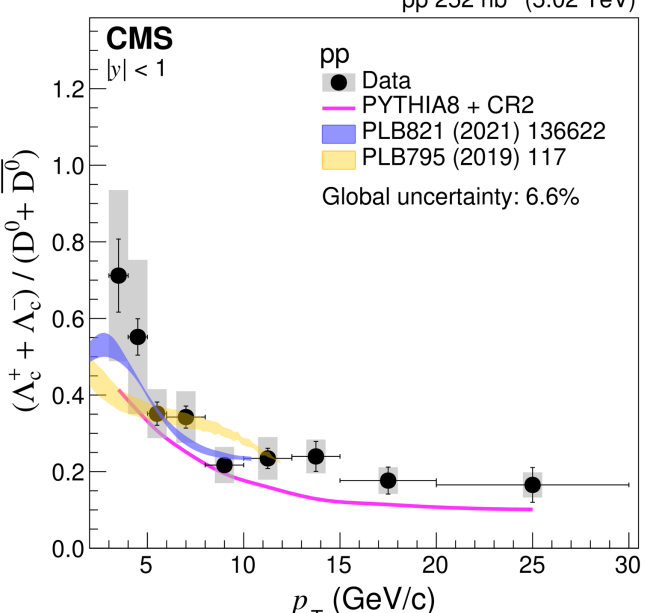


Non-Prompt

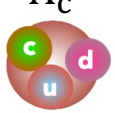
Λ_c^+ measurement in pp collisions

- The Λ_c^+/D^0 production in pp collisions shows a **decreasing trend with increasing p_T**
- The Λ_c^+/D^0 production in pp collisions in ALICE shows a similar **decreasing trend with increasing p_T**
- PYTHIA 8 predictions shows good agreement with data for $p_T < 10$ GeV/c, understimates data for $p_T > 10$ GeV/c

CMS, *JHEP 01 (2024) 128*

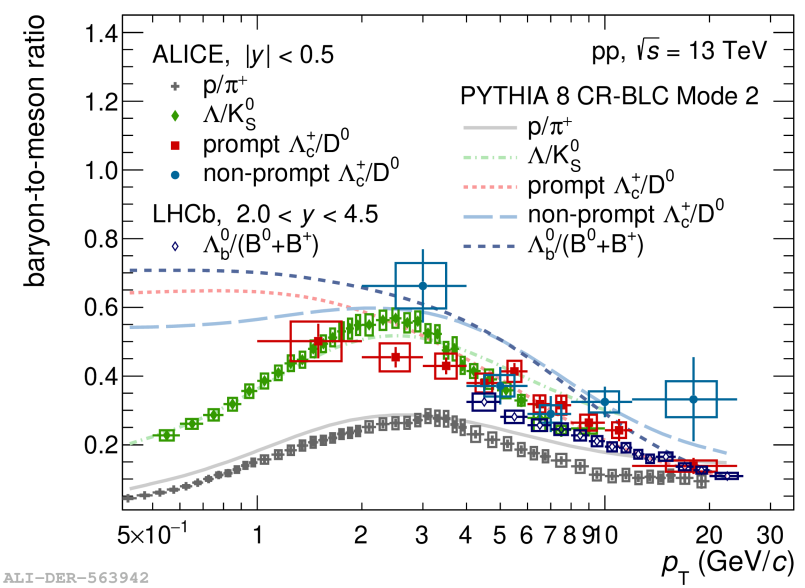


Λ_c^+



PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM, *Phys. Lett. B 795 (2019) 117*

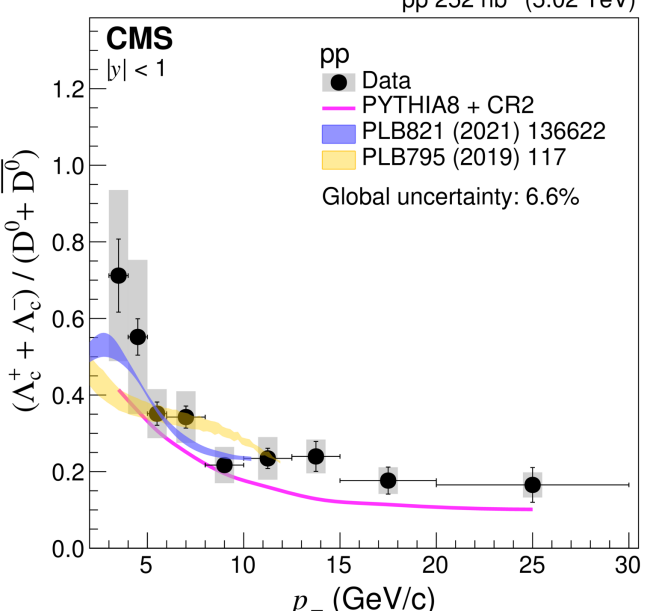
ALICE, *Phys. Rev. D (2023)108, 112003*
LHCb, *Phys. Rev. D (2019)100, 031102*

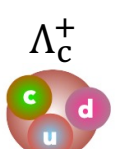


Λ_c^+ measurement in pp collisions

- Model with coalescence & fragmentation processes (PLB821(2021)136622) shows good agreement in the available p_T range and reproduces the trend
- Statistical hadronization model (PLB795(2019)117) shows also good agreement with data in the available range

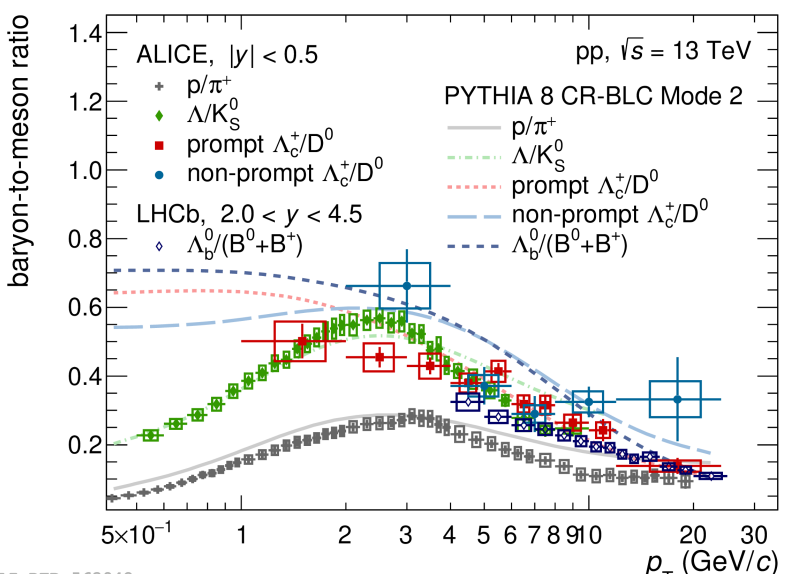
CMS, *JHEP 01 (2024) 128*





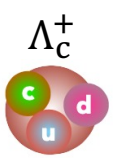
PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM, *Phys. Lett. B 795 (2019) 117*

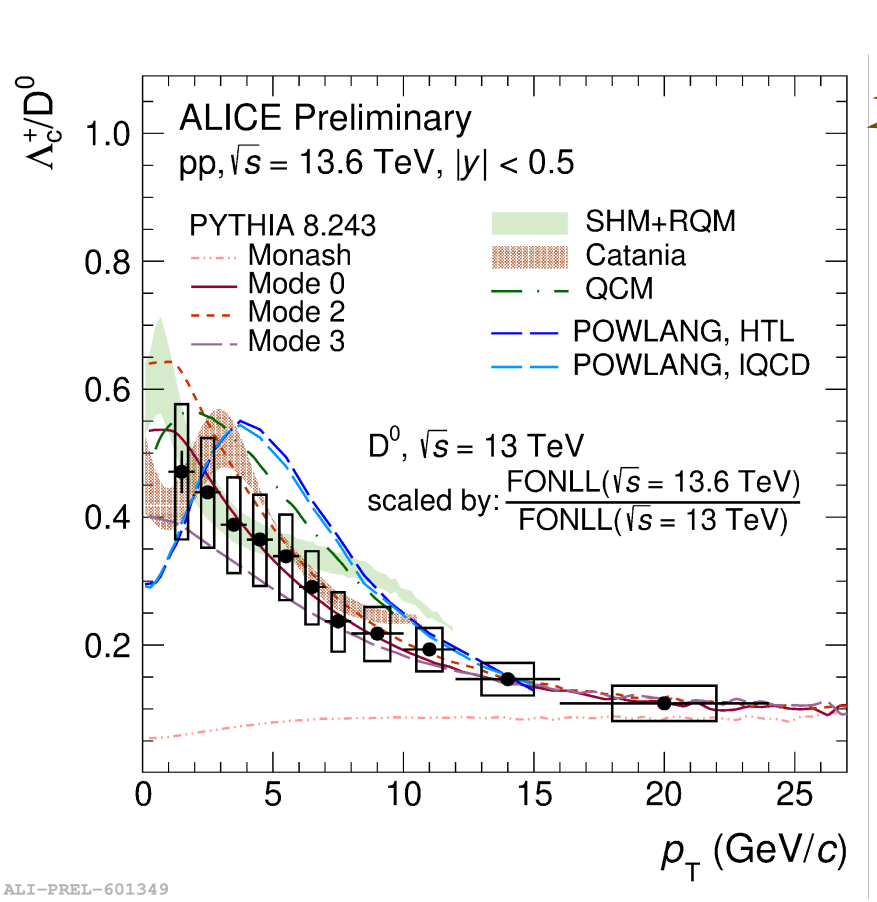
ALICE, *Phys. Rev. D (2023)108, 112003*
LHCb, *Phys. Rev. D (2019)100, 031102*



Λ_c^+ measurement in pp collisions

- Λ_c^+/D^0 production in pp collisions measured in Run 3
- Improvement in granularity and statistical precision
- Described by models with different hadronization mechanisms

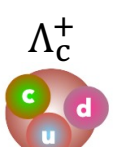


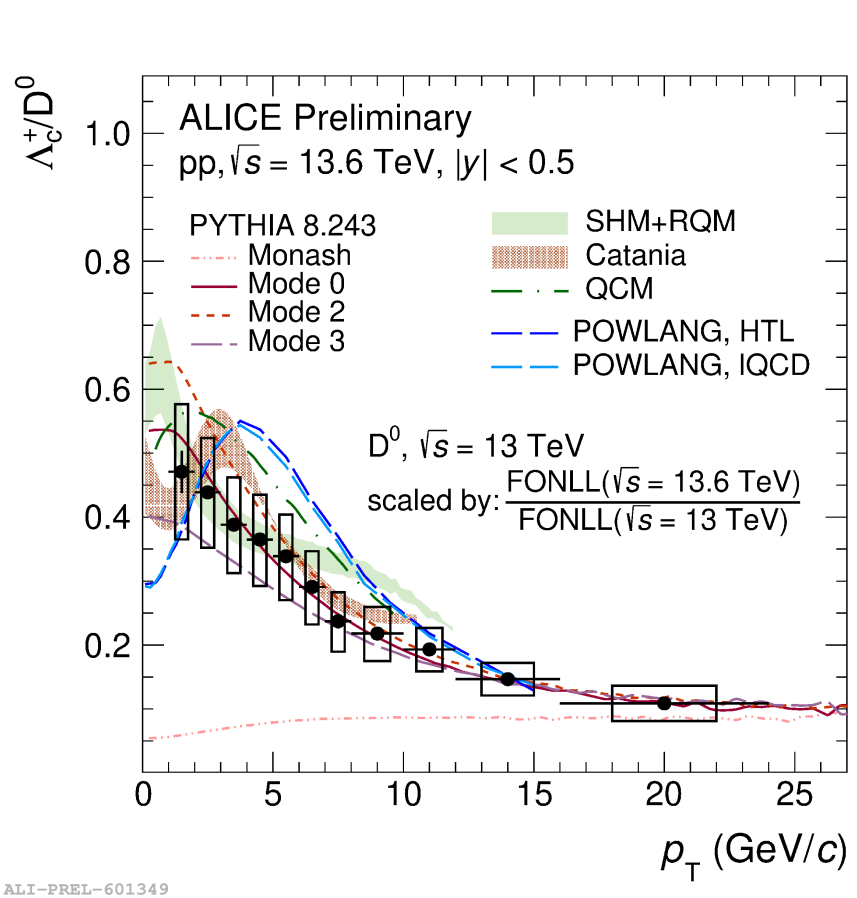


PYTHIA 8 MONASH, EPJC 74 (2014) 3024
PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM + RQM, *Phys. Lett. B 795 (2019) 117*
QCM, *EPJC 78, 2018 4, 344*
POWLANG, *arXiv:2306.02152*

Λ_c^+ measurement in pp collisions

- SHM + RQM : Statistical hadronization with feed-down from charm baryons based on Relativistic Quark model predictions
- Catania : Coalescence + in-vacuum fragmentation
- QCM : quark recombination model based on “equal quark-velocity” coalescence
- POWLANG : Expanding fireball assumed in pp collisions. Hadronisation via recombination with light quarks

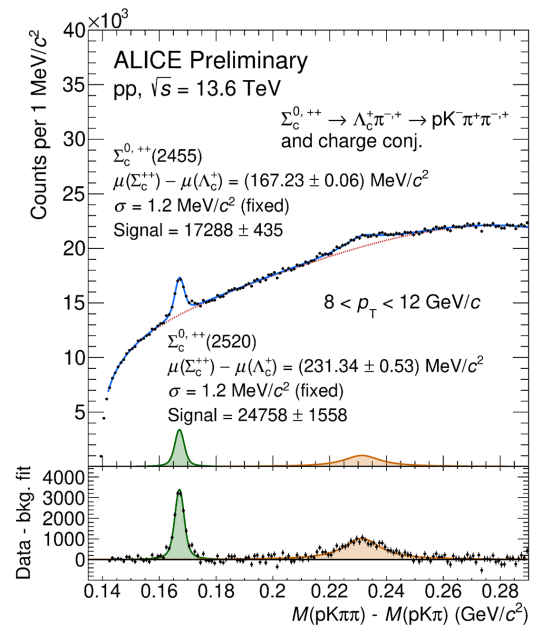


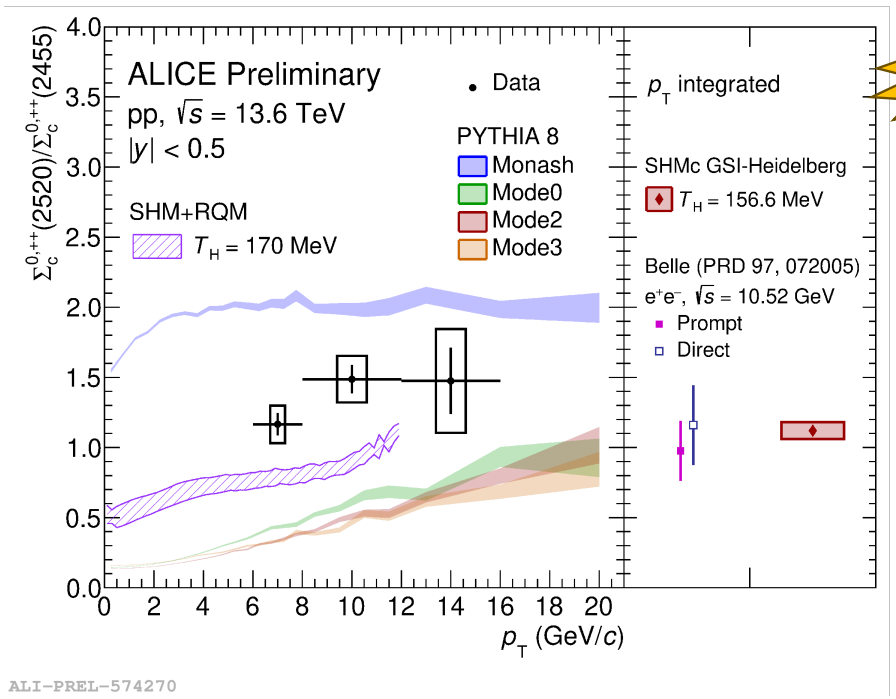


PYTHIA 8 MONASH, EPJC 74 (2014) 3024
PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM + RQM, *Phys. Lett. B 795 (2019) 117*
QCM, *EPJC 78, 2018 4, 344*
POWLANG, *arXiv:2306.02152*

$\Sigma_c^{0,++}(2520)$ measurement in pp collisions

- **→ first measurement of $\Sigma_c^{0,++}(2520)$ in ALICE**





Run 3 Result

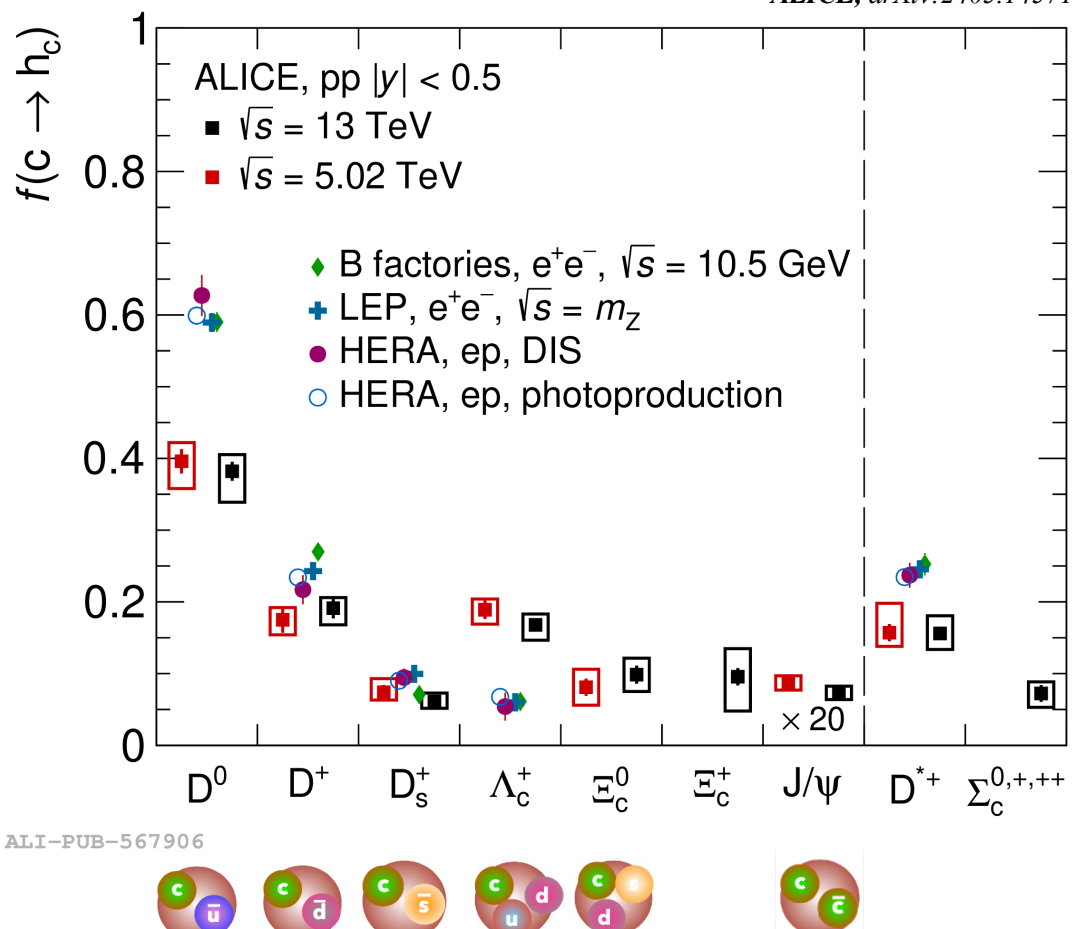
Pythia 8 (Monash), Eur. Phys. J. C 74 (2014)
Pythia 8 (Mode 0/2/3), JHEP 08 (2015) 003
SHM+RQM, Phys. Lett. B 795 (2019) 117-121
SHMc, Phys. Lett. B 797 (2019) 134836
Belle, Phys. Rev. D 97, 072005 (2018)

- Production ratio is consistent with p_T integrated results from e^+e^- experiments

Charm fragmentention functions

- Heavy-flavor charm mesons and baryons are used to evaluate the charm fragmentation fractions
- The values are consistent between pp and p–Pb collisions
- A difference is observed in pp and p–Pb collisions with respect to e^+e^- and ep collisions

ALICE, arXiv:2405.14571

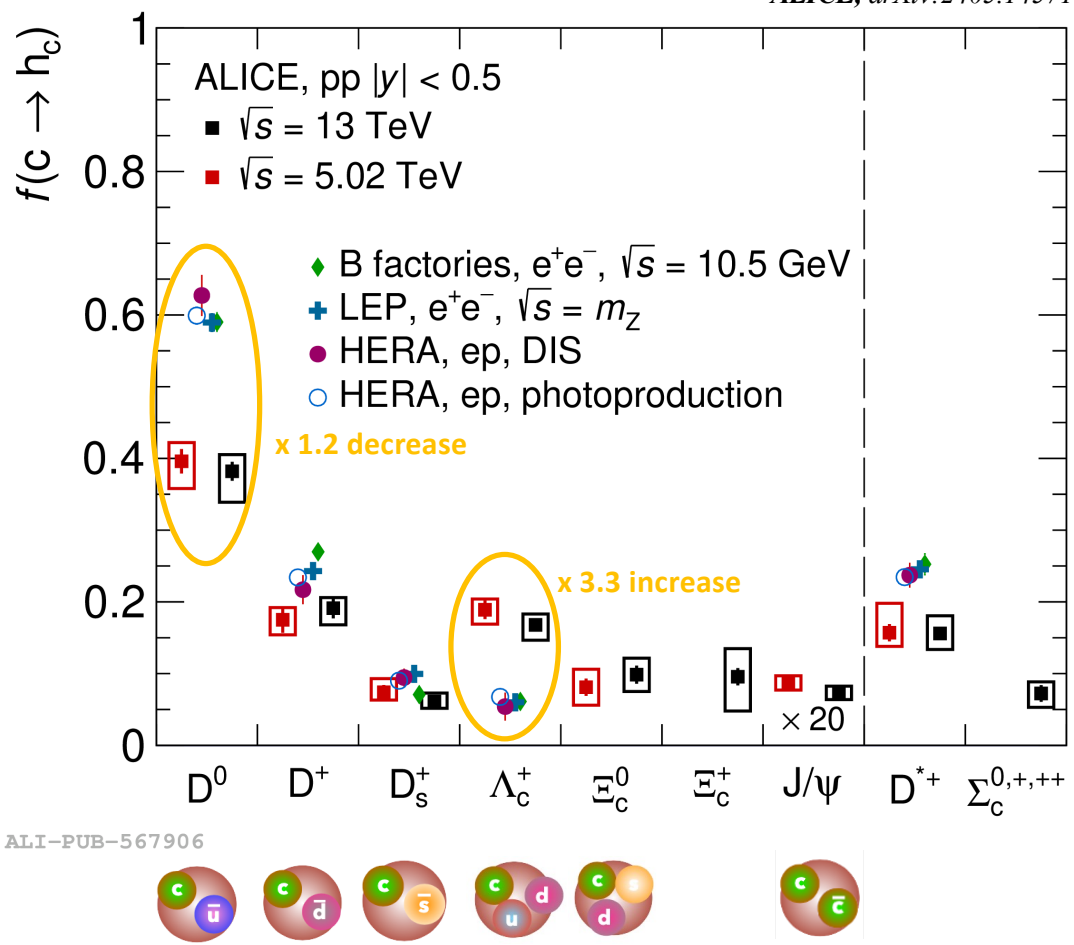


Charm fragmentention functions

- Heavy-flavor charm mesons and baryons are used to evaluate the charm fragmentation fractions
- The values are consistent between pp and p–Pb collisions
- A difference is observed in pp and p–Pb collisions with respect to e^+e^- and ep collisions
- Increase in Λ_c^+ production accompanied by a concomitant decrease in D^0

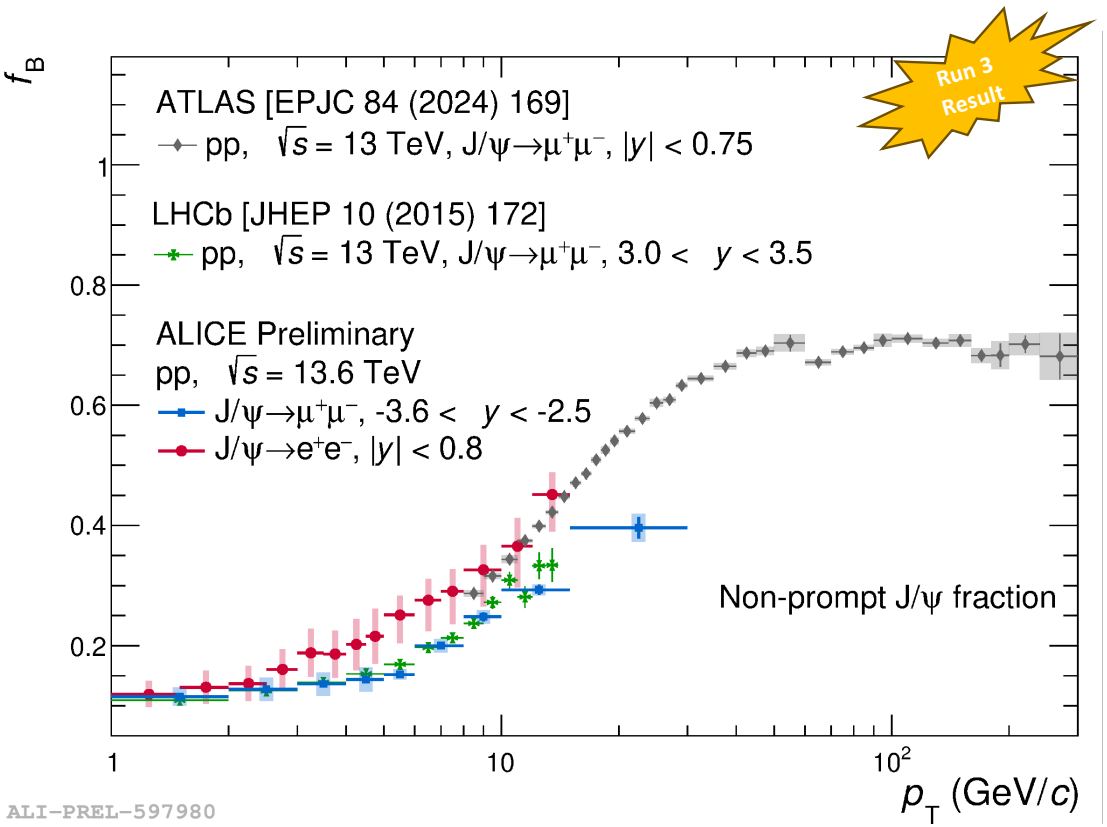
  → evidence that universality (i.e. collision-system independence) of parton-to-hadron fragmentation is not valid

ALICE, arXiv:2405.14571



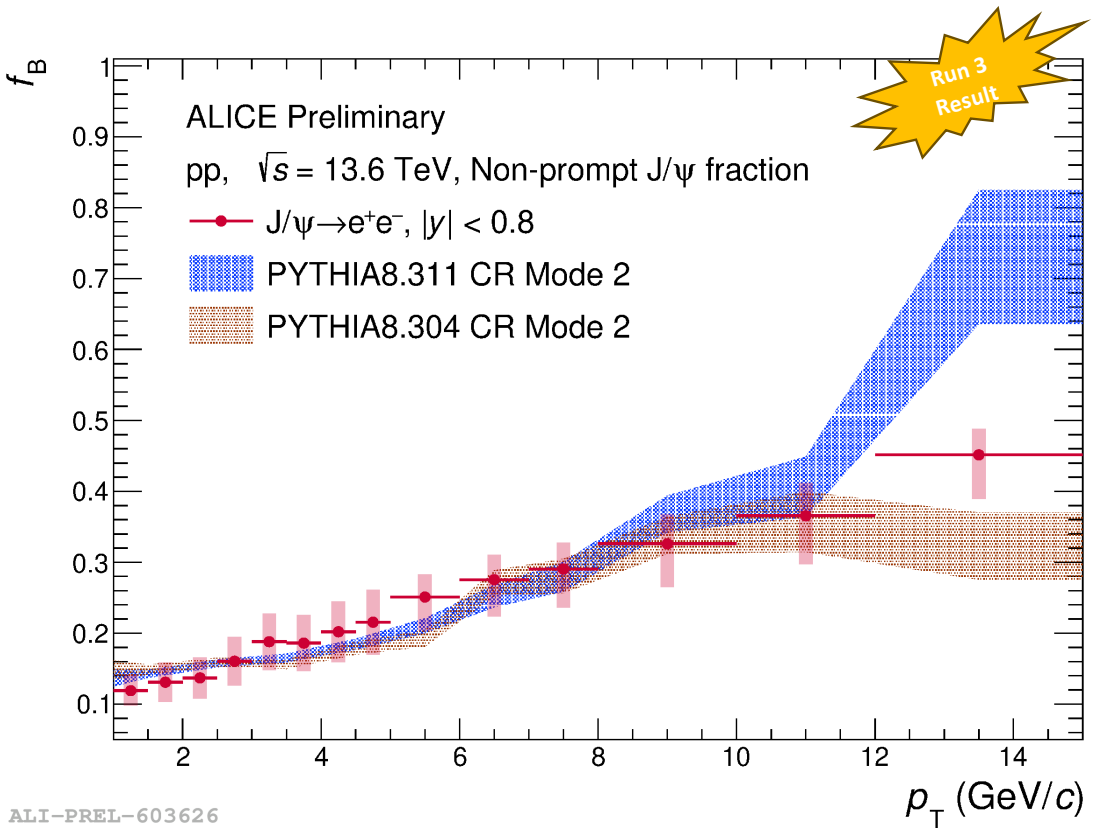
Non-prompt J/ψ fraction

- ALICE results are in agreement with results from ATLAS and LHCb experiments
- ALICE extends the ATLS results to low p_T
- The increase of f_B with p_T is more pronounced at mid rapidity compared to forward
  ➜ Indicates pairs are predominantly produced at midrapidity



Non-prompt J/ψ fraction

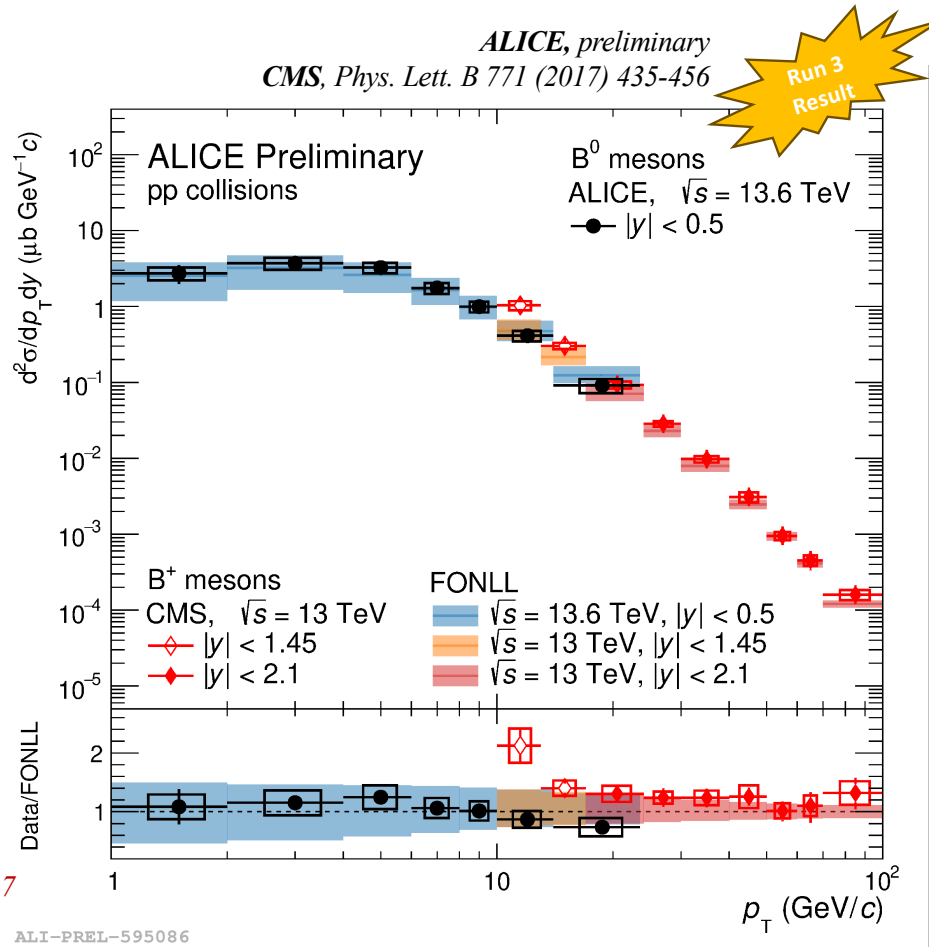
- PYTHIA calculations can describe the data at mid-rapidity within uncertainties
- New implementation in PYTHIA v8.310: production of quarkonia via NRQCD in a time-like parton shower
- No significant difference between PYTHIA versions within uncertainty until p_T = 11 GeV/c



PYTHIA 8.311 CR Mode 2, *EPJC (2024) 84, 432*
PYTHIA 8.304 CR Mode 2, *JHEP 08 (2015) 003*

B-meson production in pp collisions

- B^0 meson production cross section measured down to p_T = 1 GeV/c
- Results compatible with CMS measurements
- Results are compatible with FONLL predictions within uncertainties
- Constrains beauty hadronization



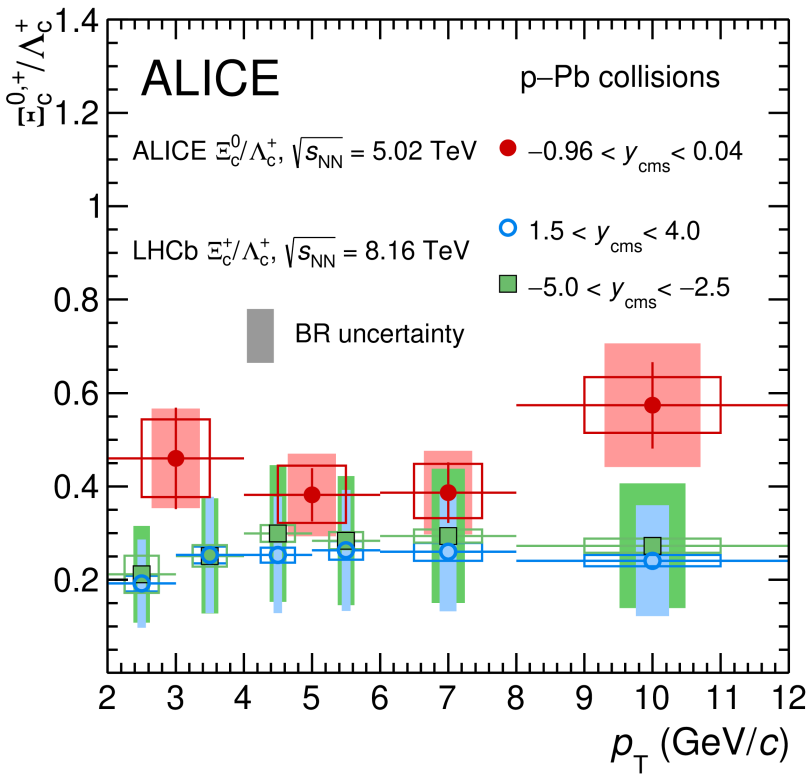
FONLL, JHEP 10 (2012) 137

Ξ_c^+ production in p–Pb collisions

- The Ξ_c^+/Λ_c^+ ratio show no significant p_T dependence for both p–Pb and Pb–p directions.
  → strong indication that the same processes govern hadronization in p–Pb and Pb–p collisions

- ALICE and LHCb points are compatible within uncertainties

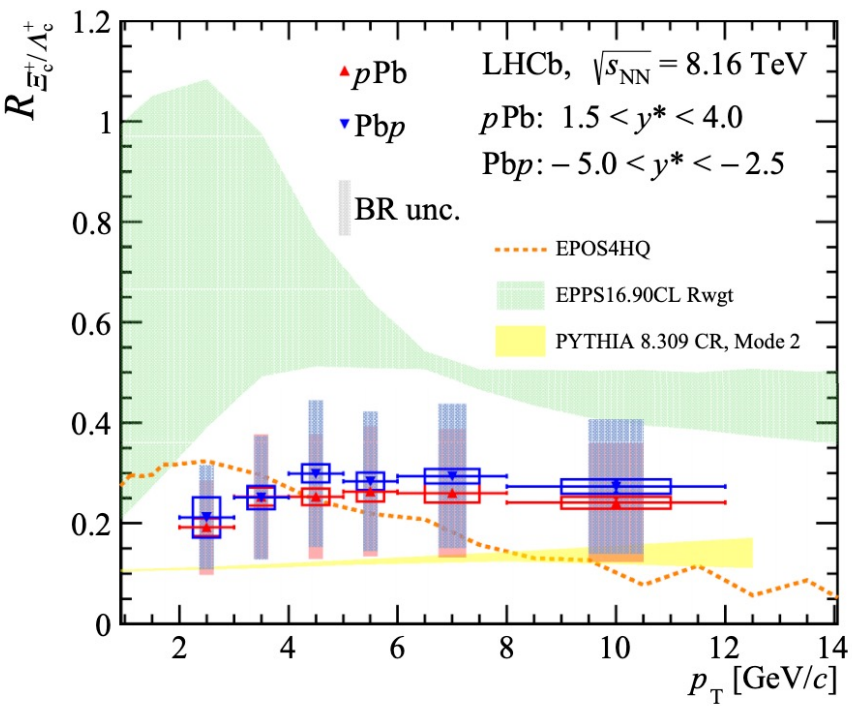
LHCb, Phys. Rev. C (2024) 109, 044901
ALICE, arXiv:2405.14538

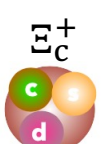


Ξ_c^+ production in p–Pb collisions

- The Ξ_c^+/Λ_c^+ ratio show no significant p_T dependence for both p–Pb and Pb–p directions.
  → strong indication that the same processes govern hadronization in p–Pb and Pb–p collisions
- ALICE and LHCb points are compatible within uncertainties
- The EPPS16 model significantly overestimates LHCb data but shows similar trend
- PYTHIA 8.3 calculations describe data within uncertainties
- EPOS4HQ calculations describe data within uncertainties but show different trend

LHCb, Phys. Rev. C (2024) 109, 044901



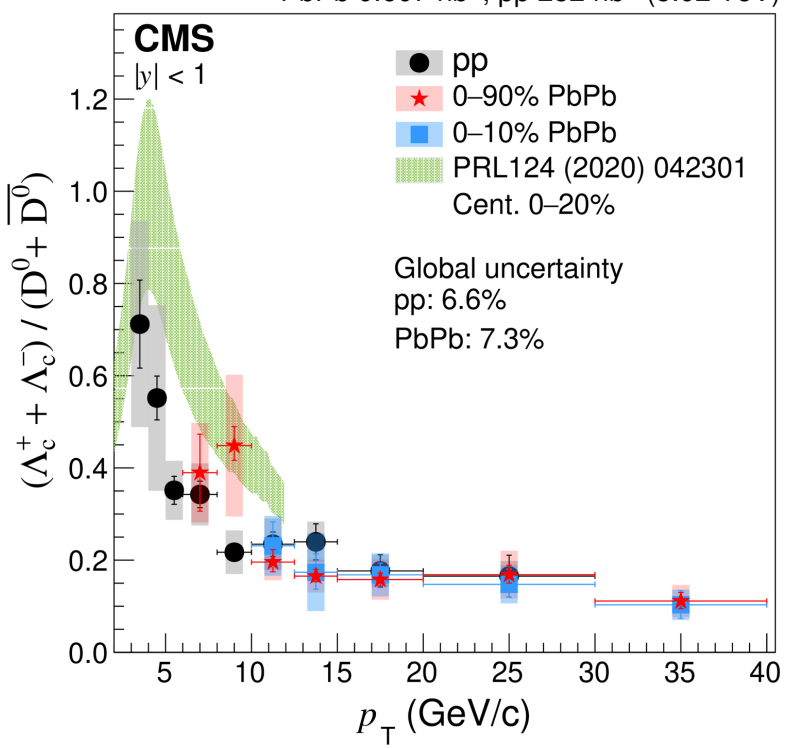


EPPS16, Eur. Phys. J. C 77 (2017) 163
PYTHIA8.3, J. High Energy Phys. 08 (2015) 003.
EPOS4HQ, Phys. Rev. C (2023) 108, 034904

Λ_c^+ measurement in pp & Pb–Pb collisions

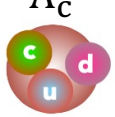
CMS, JHEP 01 (2024) 128

- The Λ_c^+/D^0 production in Pb–Pb collisions is compatible with the pp result
- Model prediction shows good agreement with the data in the overlapping p_T range ($10 < p_T < 12.5$ GeV/c)
- Both pp and Pb–Pb results tend toward the value found for e^+e^- collisions in this high p_T region
  → No significant contribution from coalescence at high p_T in Pb–Pb



M. He & R. Rapp, Phys. Rev. Lett. 124 (2020) 042301

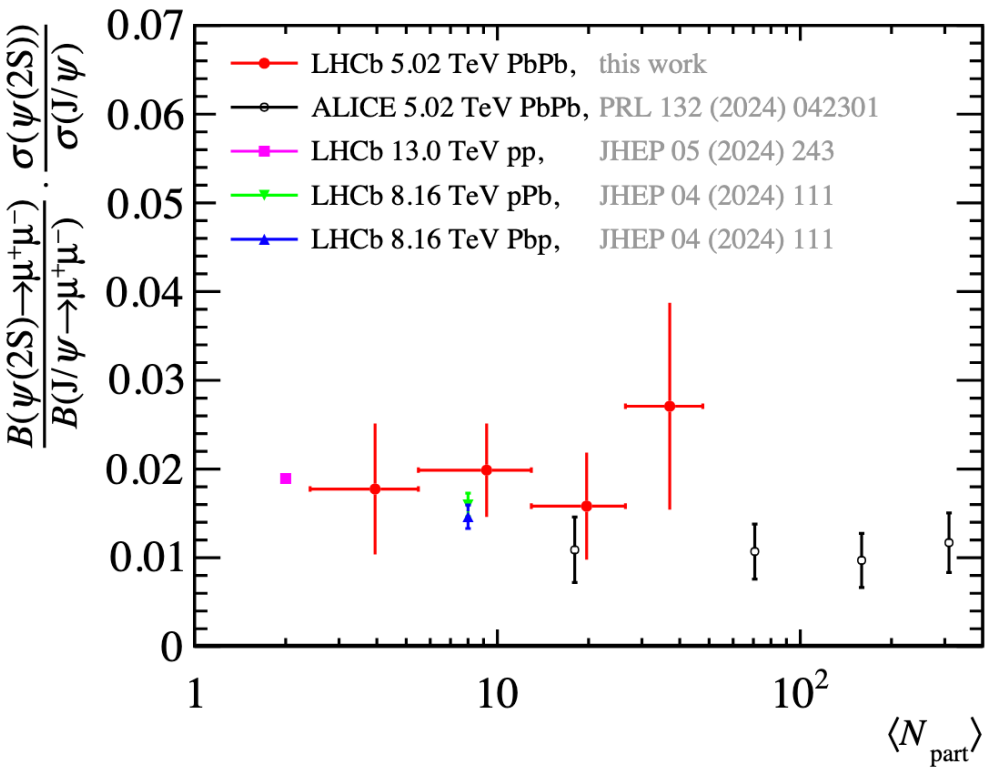
Λ_c^+



Charmonium production in Pb–Pb collisions

LHCb, arXiv:2411.05669

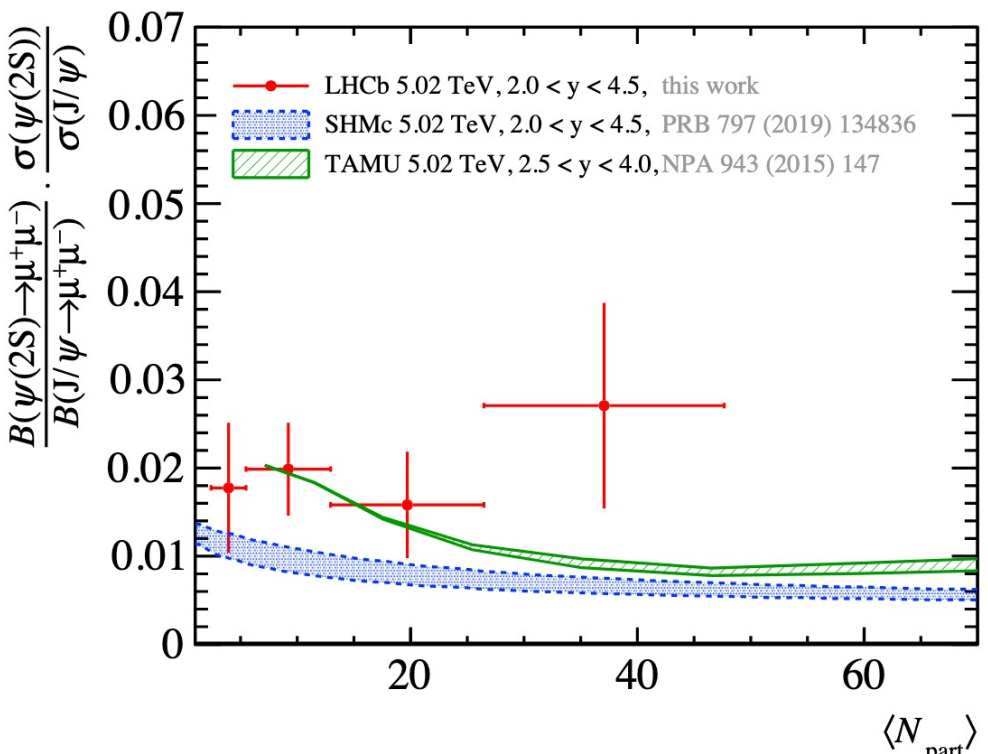
- First forward rapidity measurement of prompt charmonium production
- Flat J/ψ)to-ψ(2S) ratio observed as a function of multiplicity
- Compatible with other LHCb in pp and pPb and ALICE measurements in Pb-Pb



Charmonium production in Pb–Pb collisions

LHCb, arXiv:2411.05669

- TAMU model prediction is in relatively good agreement with the data
- SHMc model prediction slightly underestimates the data but shows a similar flat trend

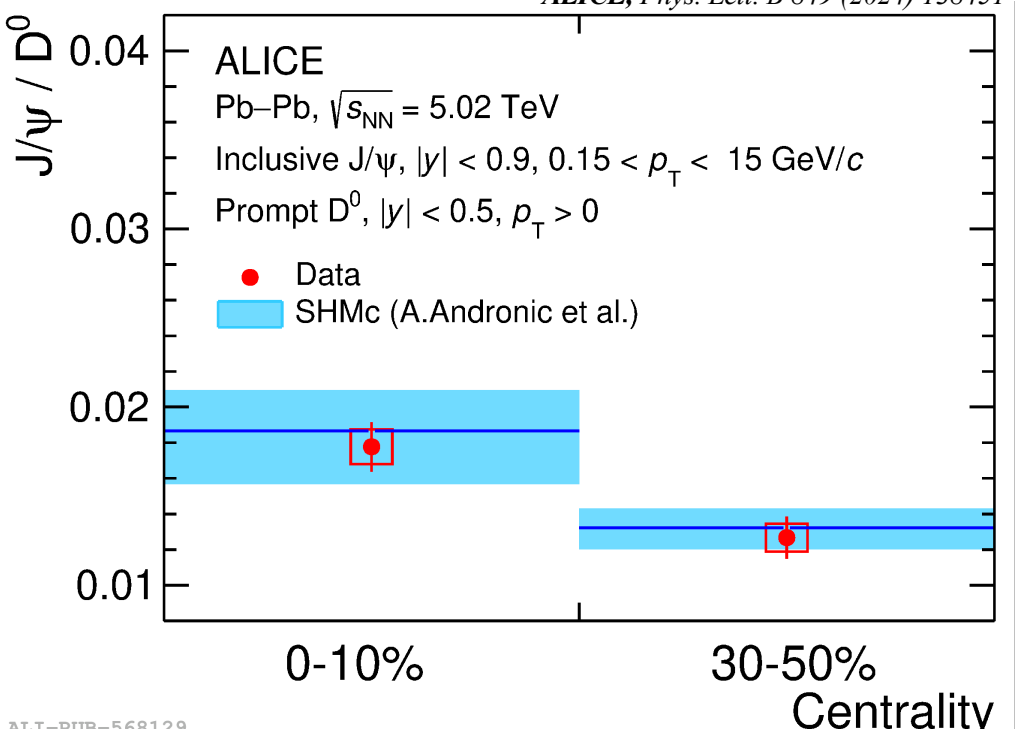


SHMc, Phys. Lett. B 797 (2019) 134836
TAMU, Nucl.Phys.A 943 (2015) 147-158

Charmonium production in Pb–Pb collisions

- The J/ψ/D^0 provides tight constraint to models because uncertainties related to the $c\bar{c}$ cross section cancel out
  → parameter-free prediction relying only on deconfined and thermalized charm quarks
- The ratio is sensitive to the hadronisation mechanisms of the different charm hadron
- The ratio is higher in most central collisions
- SHMc model predictions describe the data well
  → **hints that both J/ψ and D^0 are produced via the coalescence of charm quarks**

ALICE, Phys. Lett. B 849 (2024) 138451



SHMc, Phys. Lett. B 797 (2019) 134836

Conclusions

- The measurement of many heavy flavor species offers a solid ground to test the pQCD models and the factorization approach
  ➜ breaking of universal hadronisation for all systems

- A comprehensive description of all experimental observations is still missing

- Run 3 data allows more precise measurements with smaller uncertainties, as well as access to **higher mass hadrons** whose production has not been measured before
  ➜ First Run 3 results are starting to be shown

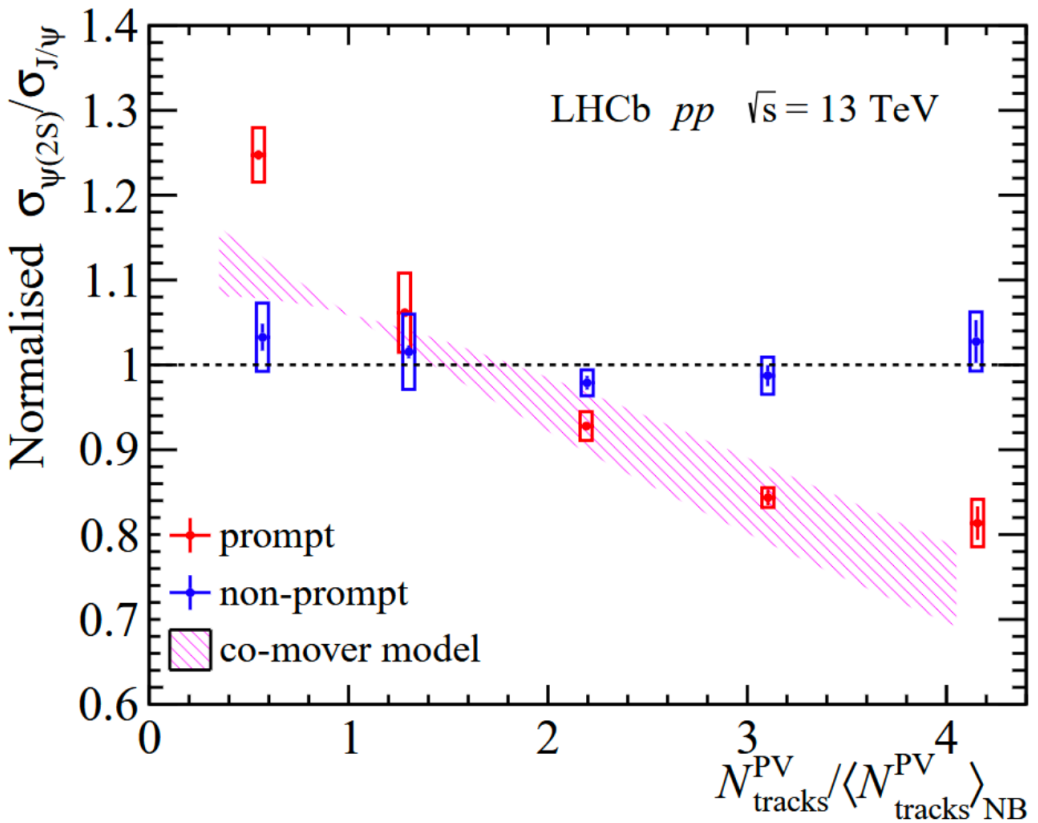
THANK YOU FOR YOUR ATTENTION !

More stuff…

Charmonium production in pp collisions

- First forward rapidity measurement of prompt charmonium production
- Flat J/ψ)to-ψ(2S) ratio observed as a function of multiplicity
- Compatible with other LHCb in pp and pPb and ALICE measurements in Pb-Pb

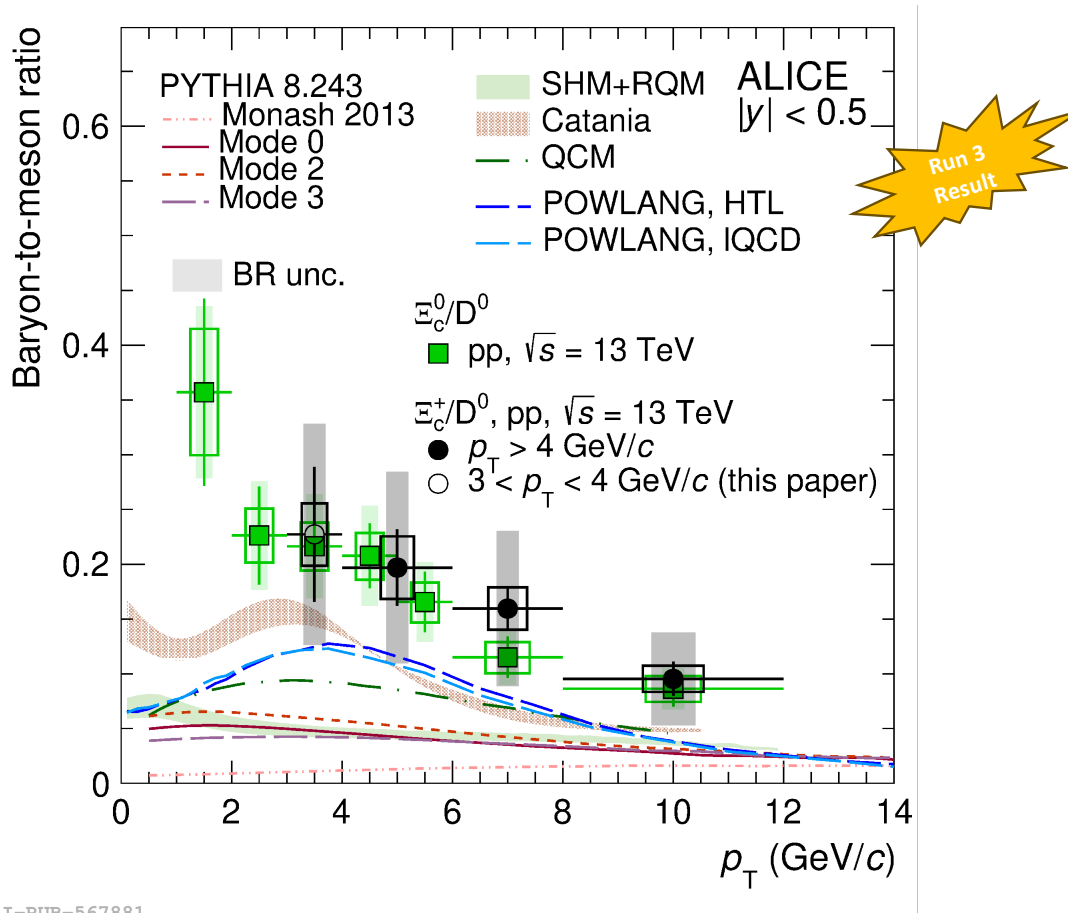
LHCb, *JHEP 05 (2024) 243*



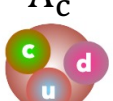
Comover*, Phys. Lett. B731 (2014) 57*

Ξ_c^+ measurement in pp collisions

- Ξ_c^+/D^0 production in pp collisions measured in Run 2
- Models that describe Λ_c^+/D^0 ratio underestimate Ξ_c^+/D^0
- Even greater enhancement of charm-strange baryon production w.r.t. e+e− collisions



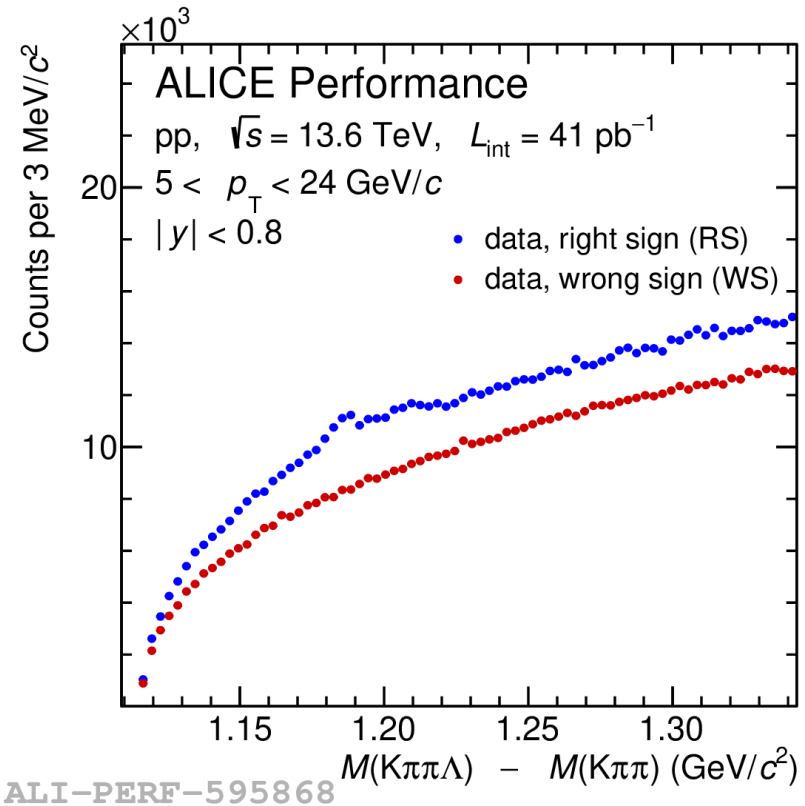
Λ_c^+

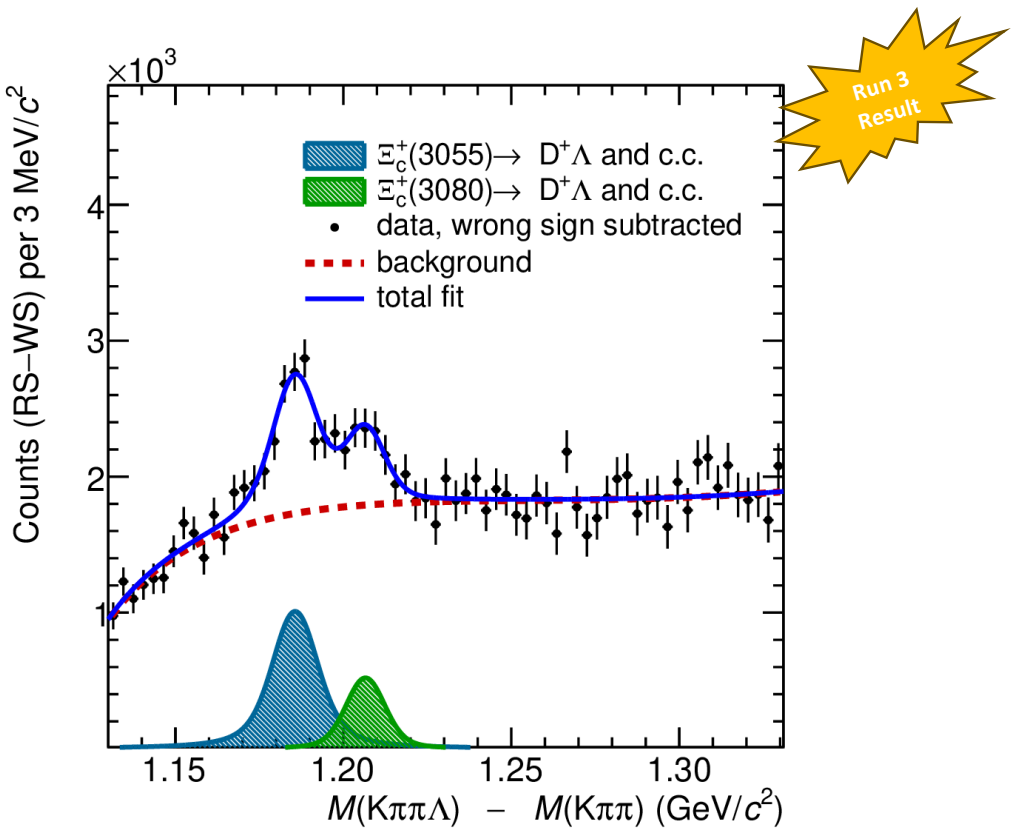


PYTHIA 8 MONASH, EPJC 74 (2014) 3024
PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM + RQM, *Phys. Lett. B 795 (2019) 117*
POWLANG, *arXiv:2306.02152*

$\Xi_c^+(3055, 3080)$ observation in pp collisions

- First measurement of $\Xi_c^+(3055, 3080)$ production in ALICE thanks to Run 3 statistics!

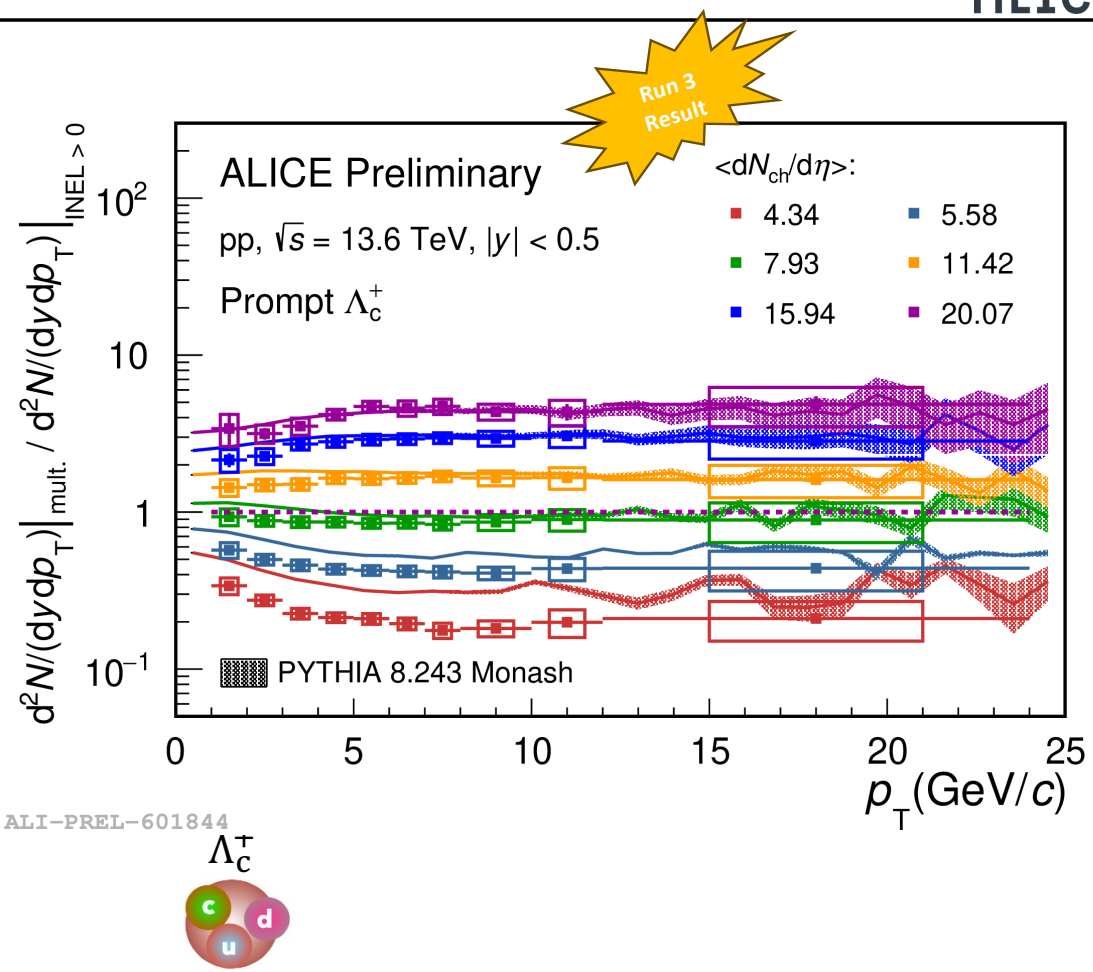




ALI-PERF-595868

Λ_c^+ measurement in pp collisions

- First measurement of Λ_c^+ production vs multiplicity in Run 3
- Ratios to minimum-bias class increase (decrease) with increasing p_T for the high (low) multiplicity classes
  ➔ Hardening of the p_T spectra as multiplicity increases
- PYTHIA 8 Monash overestimates relative Λ+c production in low multiplicity

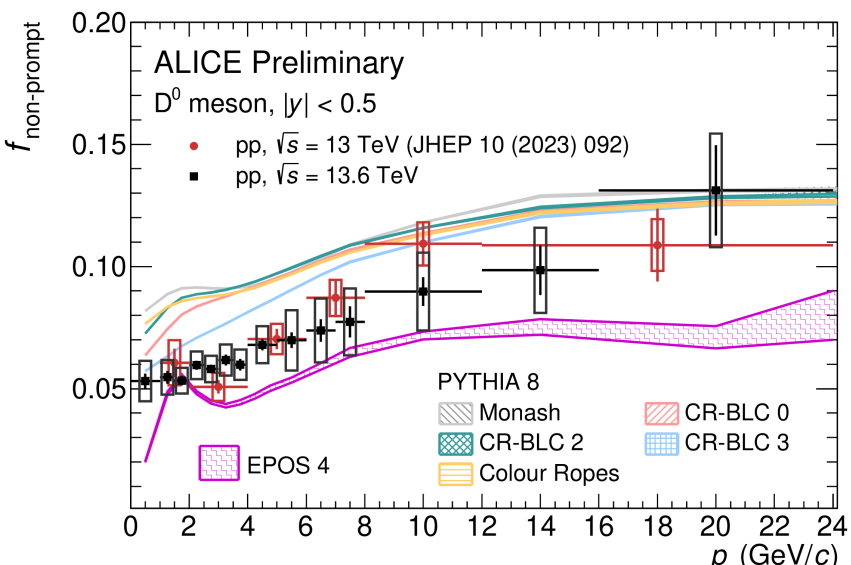


Non-prompt fractions

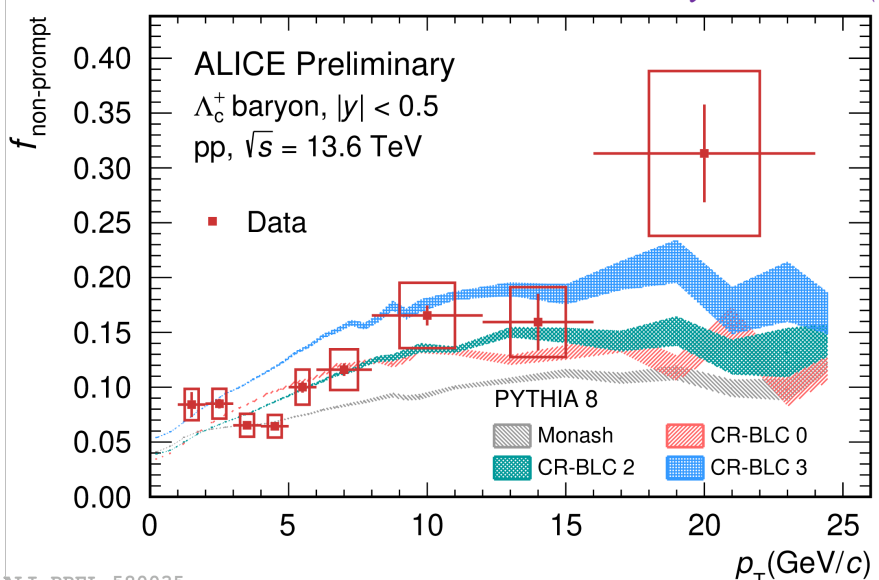
- Constraints generators differing in MPI, fragmentation and hadronization:
- All PYTHIA 8 tunes tend to overestimate the D^0 non-prompt fraction, while EPOS 4 tends to underestimate it
- PYTHIA 8 Monash tune underestimates the Λ_c^+ non-prompt fraction, while PYTHIA 8 CR-BLC tunes have better agreement

Run 3 Result

PYTHIA 8 Monash: Eur. Phys. J. C 74 (2014) 3024
PYTHIA 8 CR-BLC: J. High Energ. Phys. 08 (2015) 003
PYTHIA 8 Colour Ropes: J. High Energ. Phys. 03 (2015) 148
EPOS 4: Phys. Rev. C. 108 (2023) 064903



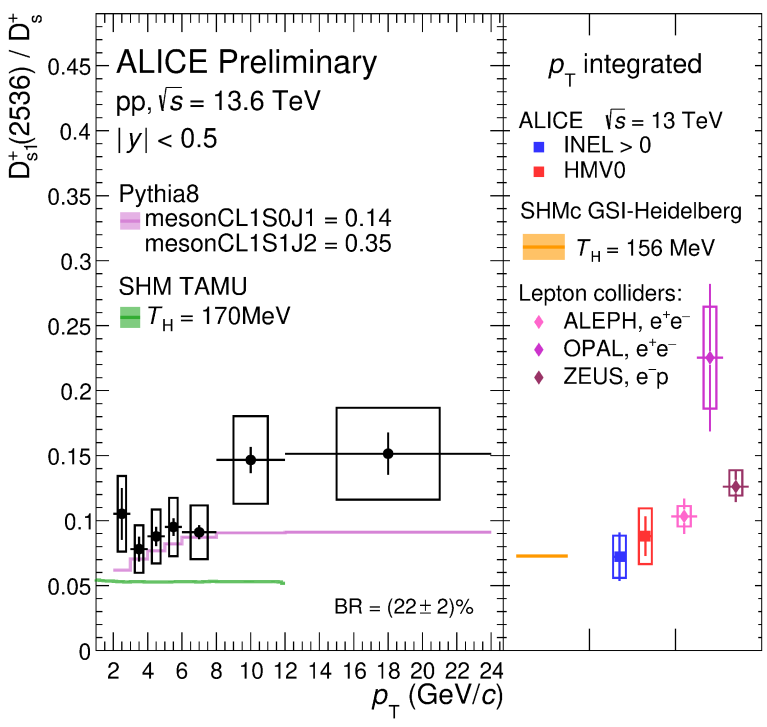
ALI-PREL-571369

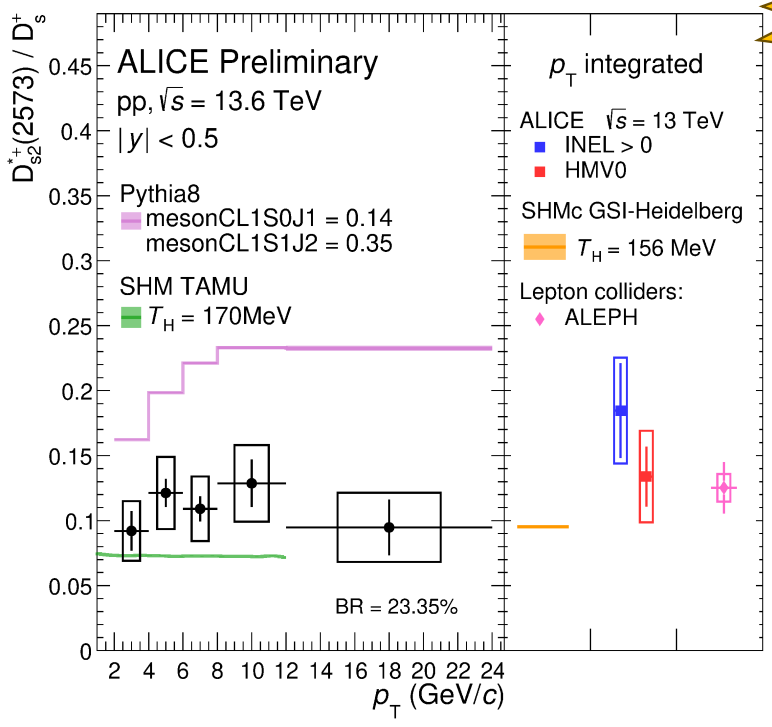


ALI-PREL-580035

Excited D_s mesons in pp collisions

- Measurement of orbitally excited D_s mesons in Run 3
- Result compatible with p_T integrated results from Run 2 and lepton colliders





Run 3 Result

Λ_c^+ measurement in Pb–Pb collisions

CMS, JHEP 01 (2024) 128
ALICE, Phys. Lett. B 839 (2023) 137796

- The R_{AA} shows a suppression for central collisions, with a maximal suppression around $p_T \approx 14$ GeV/c
- Comparison with ALICE values show a good agreement in the overlapping p_T range
- ALICE and CMS combined results show that the **suppression is larger at intermediate p_T values**, similar to what was observed for D^0 mesons