Studies of heavy-quark hadronisation in pp collisions with ALICE

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on behalf of the ALICE collaboration

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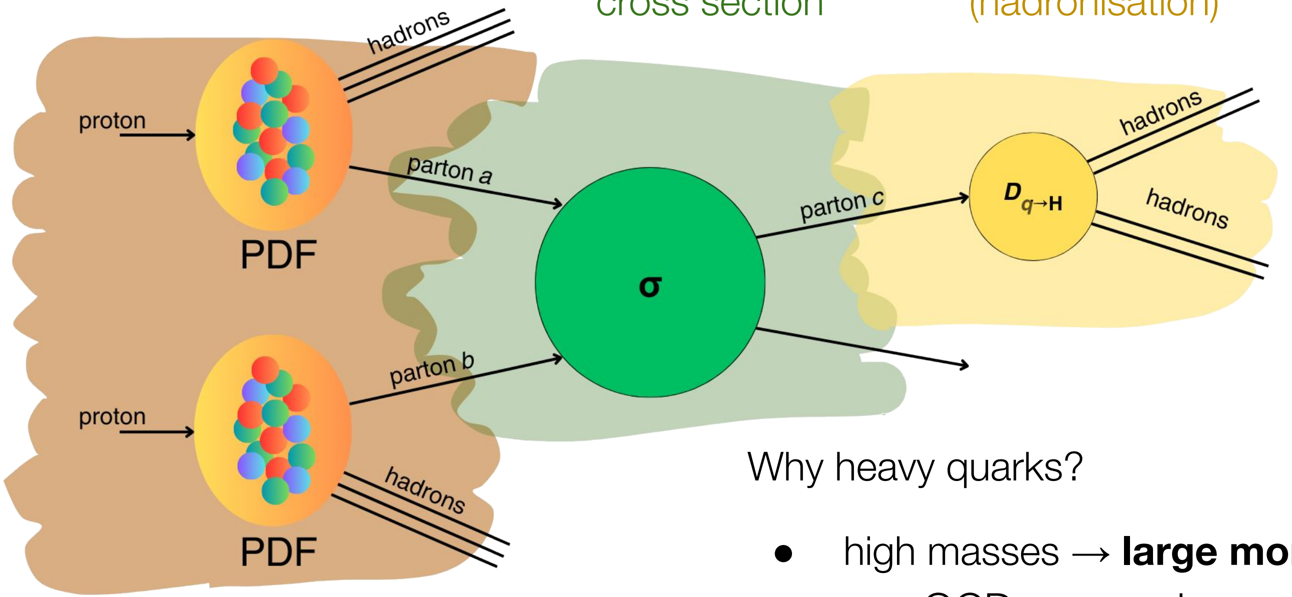
ALICE

Probing hadronisation in the pQCD scheme

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

parton distribution functions — hard scattering cross section — fragmentation function (hadronisation)

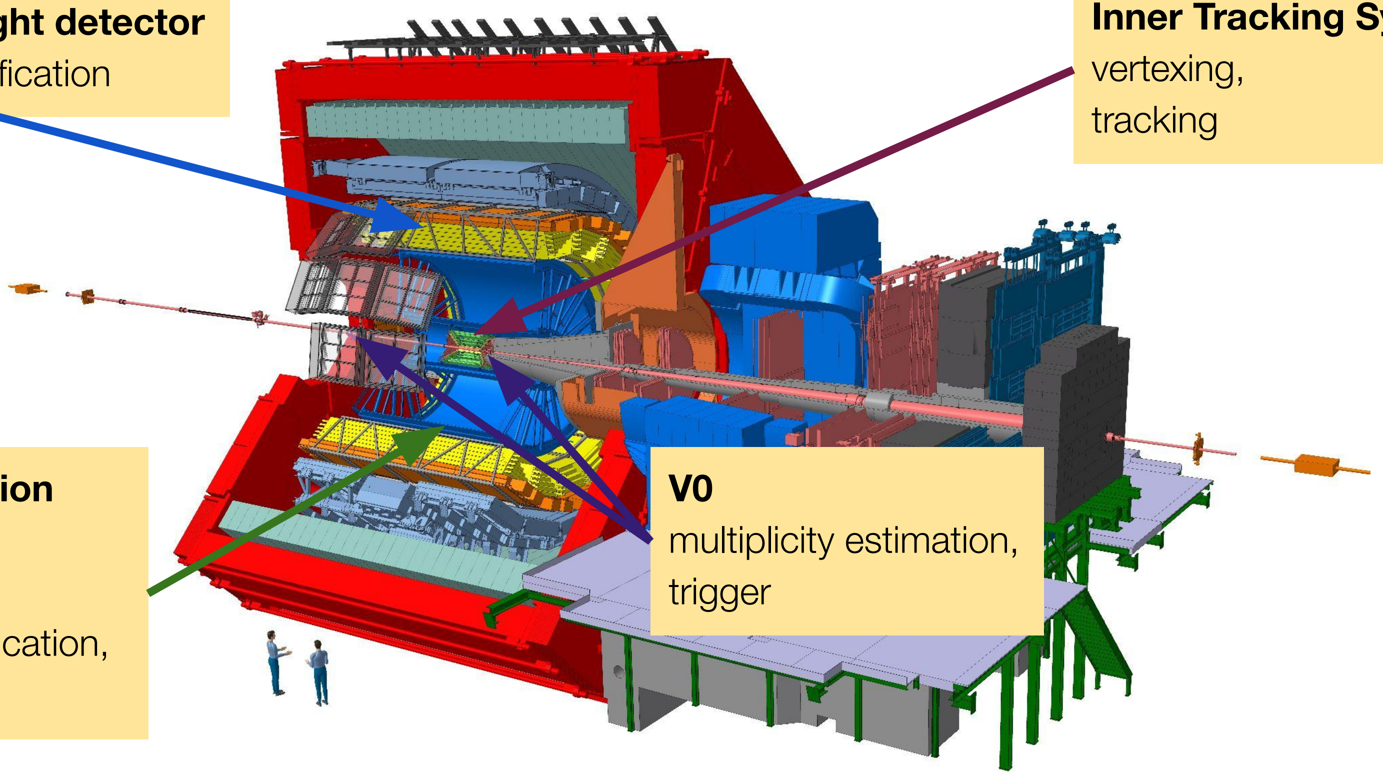


- perturbative approach not applicable
- assumed to be universal among collision systems

Why heavy quarks?

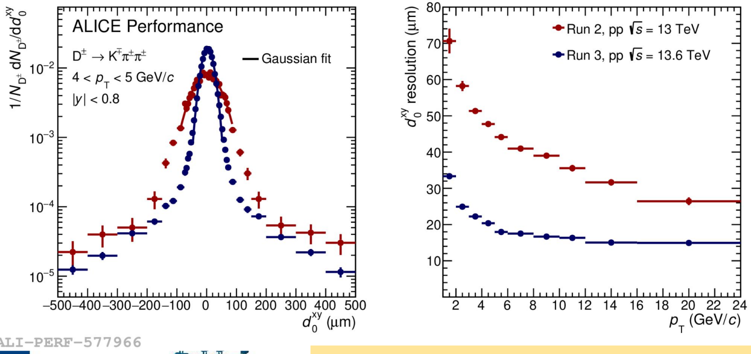
- high masses → **large momentum transfer**, Q^2 → pQCD approach can be used
- the fragmentation function for charm and beauty can be studied via **heavy-flavour particle ratios**

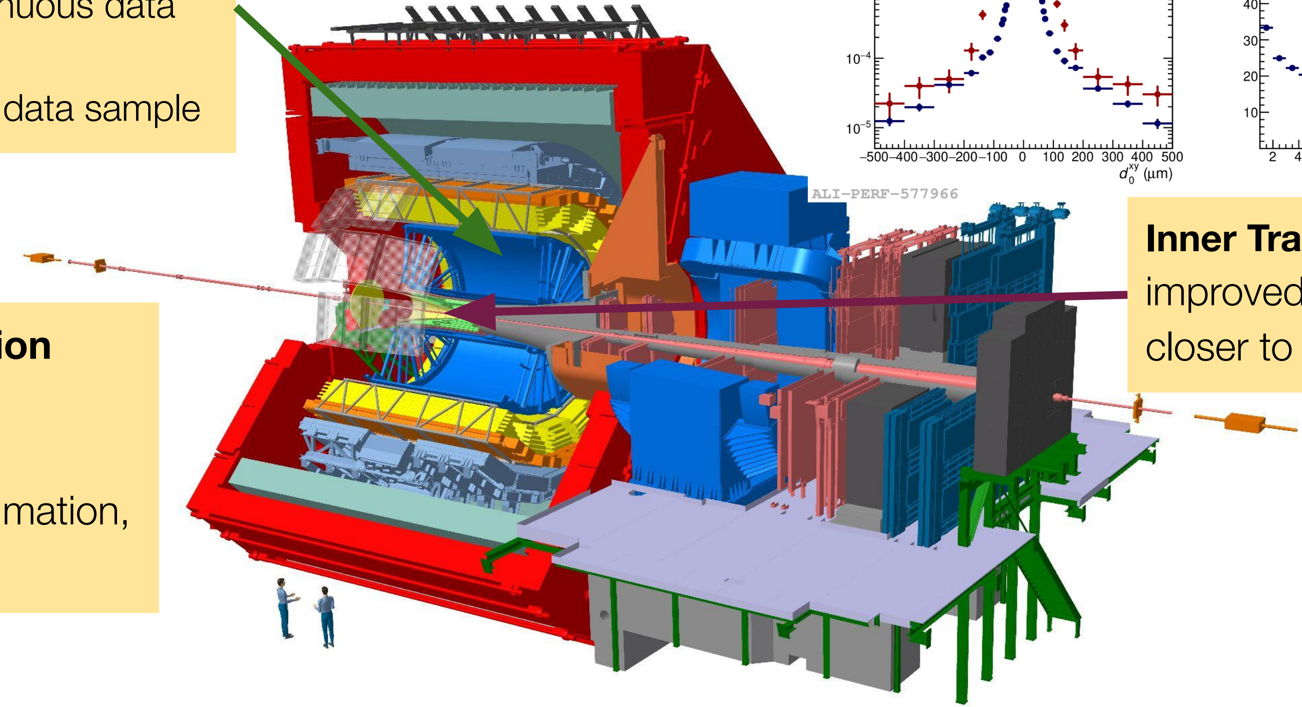
The ALICE experiment in Run 2



Upgraded ALICE in Run 3

Time Projection Chamber
new readout with GEM allows for continuous data stream
→ much larger data sample





Inner Tracking System
improved resolution, closer to the beam pipe

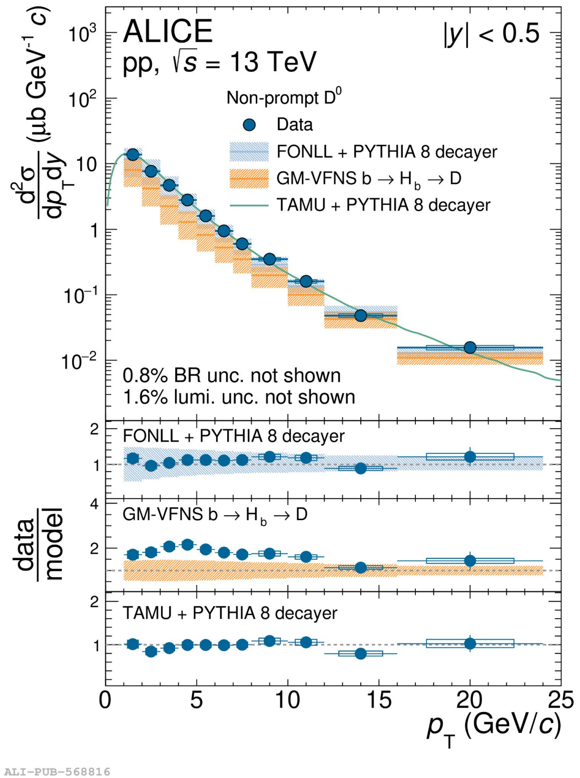
Fast Interaction Trigger
luminosity, multiplicity estimation, and trigger

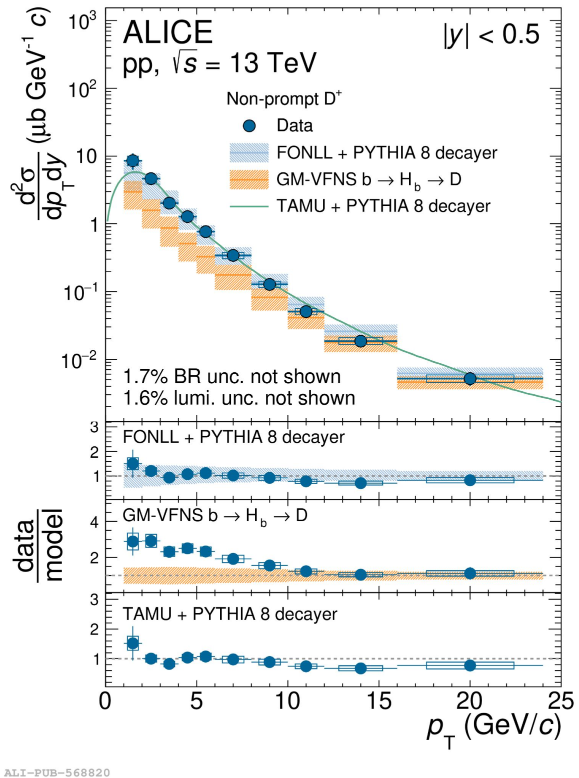
Non-prompt D-meson cross sections

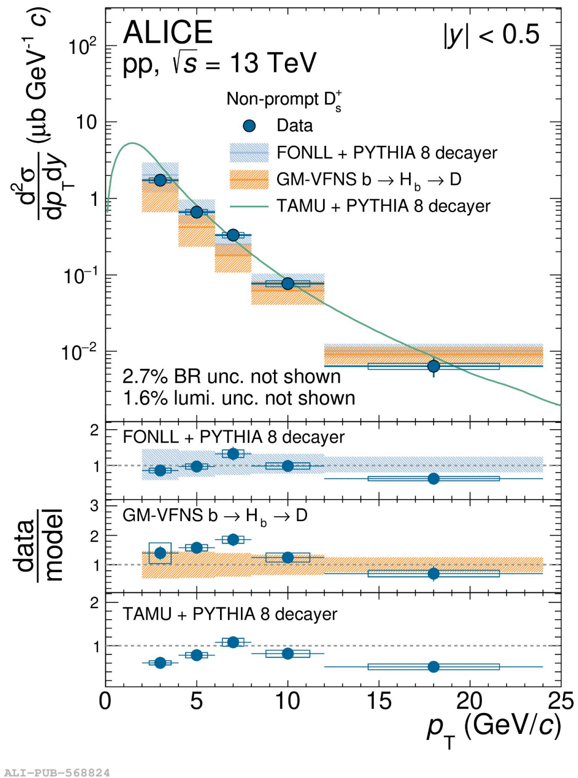
arXiv:2402.16417 (2024)

GM-VFNS **underestimates** data at low p_T, and TAMU + PYTHIA 8 tends to **overestimate D_s^+**

FONLL + PYTHIA 8 **agrees** with data





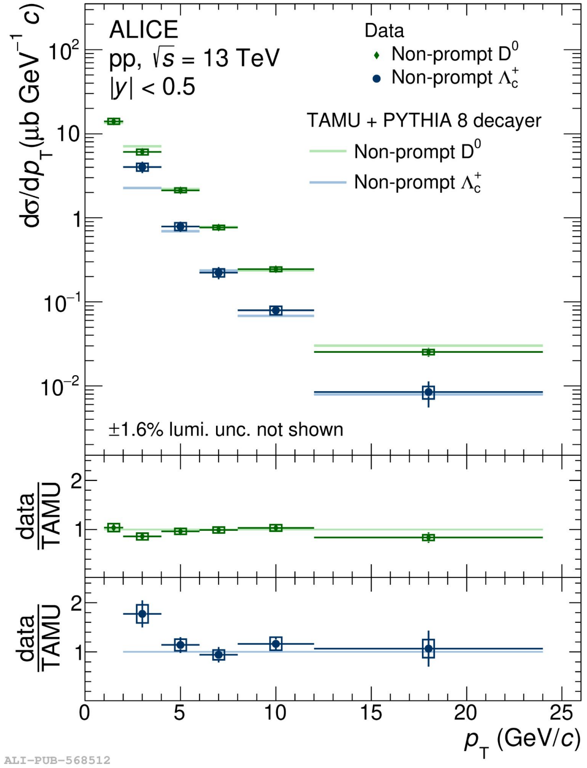


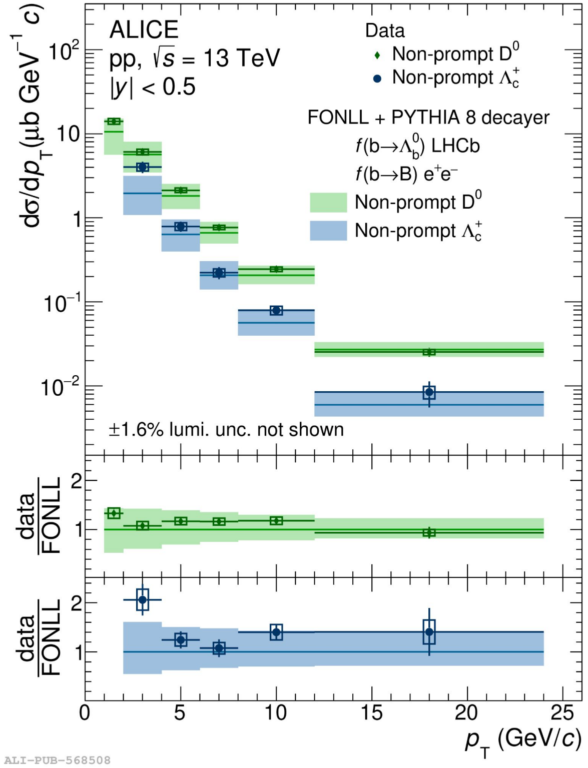
GM-VFNS: Kniehl et al., Phys. Rev. D 71 (2005a) 014018
TAMU: He et al., Phys. Lett. B 795 (2019) 117
FONLL: Cacciari et al., JHEP05 (1998) 007
Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159

Non-prompt Λ_c^+ cross sections

Phys. Rev. D 108, 112003 (2023)

Both **TAMU** and **FONLL underestimate** Λ_c^+ cross section at low p_T





Λ_c^+: weighted average of the results from $\Lambda_c^+ \to pK^0 \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^-\pi^+$

TAMU: He et al., Phys. Lett. B 795 (2019) 117
FONLL: Cacciari et al., JHEP05 (1998) 007

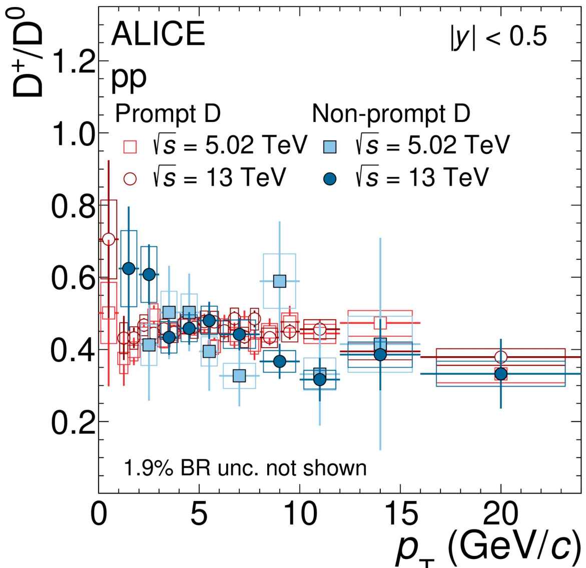
Meson-to-meson ratio

[arxiv:2402.16417 (2024)](arxiv:2402.16417)

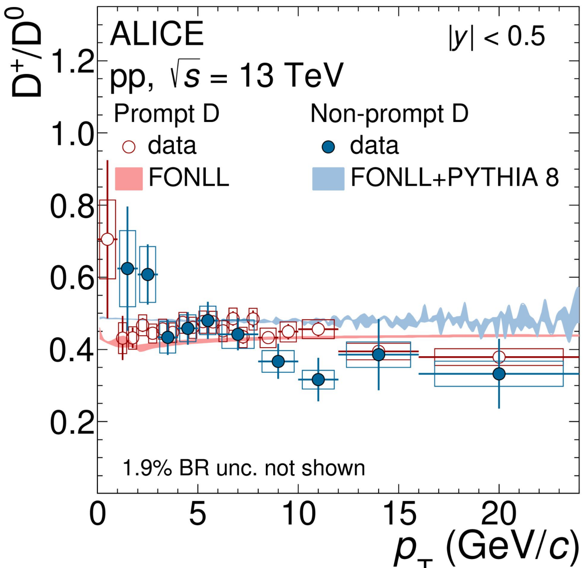
Similar fractions for **prompt and non-prompt** D mesons.

FONLL uses fragmentation functions based on e^+e^- measurements, and it describes the data
→ **fragmentation universality preserved in the meson sector.**

Results compatible for **different centre-of-mass energies**.



ALI-PUB-568828



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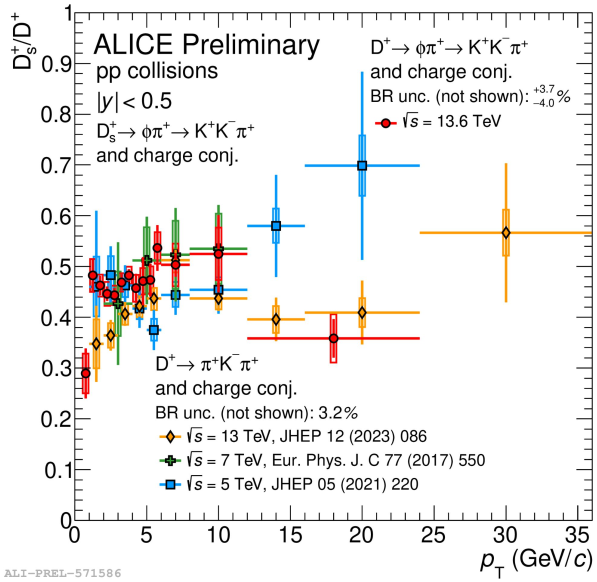
FONLL: Cacciari et al., JHEP05 (1998) 007
Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159

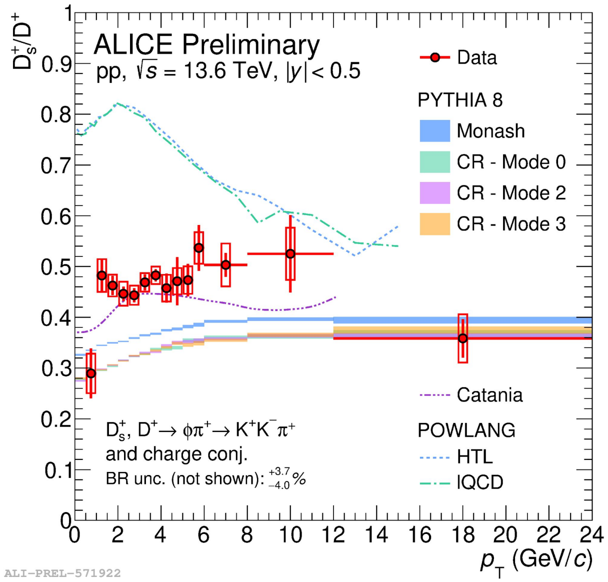
Strange-meson-to-meson ratio

New Run 3 results

Results in general compatible across **different centre-of-mass energies**.

PYTHIA 8 models generally **underestimate** the data.
POWLANG models **overestimate** the data.
Catania is compatible with the data in a **limited p_T range**.





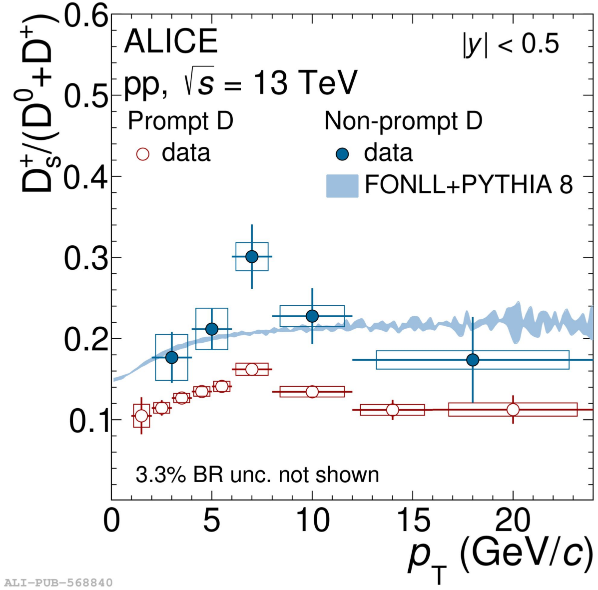
Pythia: Sjöstrand et al., JHEP 05 (2006) 026; CPC 191 (2015) 159
Monash: Skands et al., EPJ C 74 (2014) 3024
CR-BLC: Christiansen et al., JHEP 08 (2015) 003
Powlang: Beraudo et al., arXiv:2306.02152
Catania: Greco et al., PLB 821 (2021) 136622

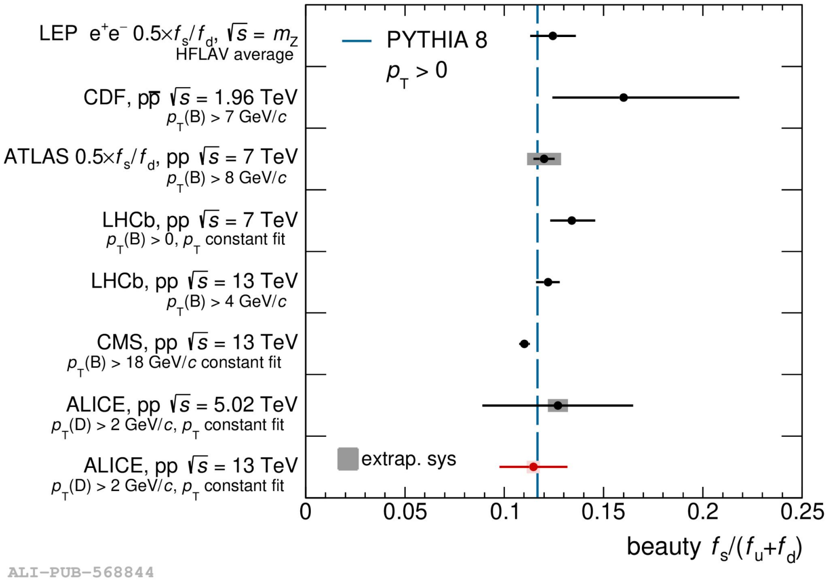
Beauty fragmentation fraction ratio

arxiv:2402.16417 (2024)

Non-prompt $D_S^+/(D^0+D^+)$: main ingredient to evaluate the **fragmentation fraction ratio** of **beauty quarks** into strange-to-non-strange **B mesons**.

Result **consistent** with FONLL + PYTHIA 8 and previous results, including **e⁺e⁻ collisions**





FONLL: Cacciari et al., JHEP05 (1998) 007
Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159

Baryon-to-meson ratio

JHEP 12 (2023) 086,
Phys. Rev. D 108, 112003 (2023)

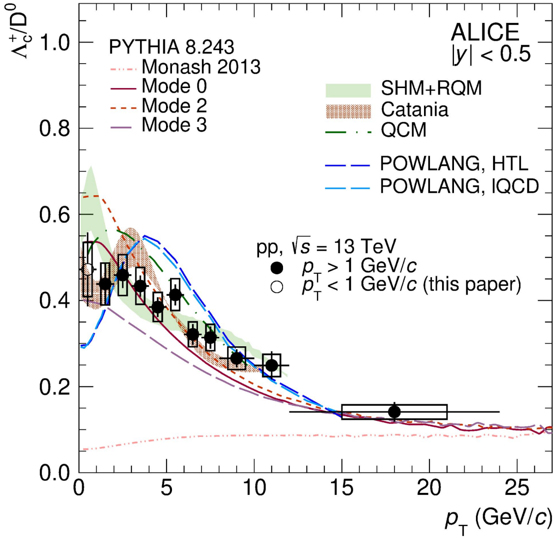
Depends on p_T: larger ratio at lower p_T.

PYTHIA 8 with Monash tune (tuned to e^-e^+ measurements) largely **underestimates** the data.

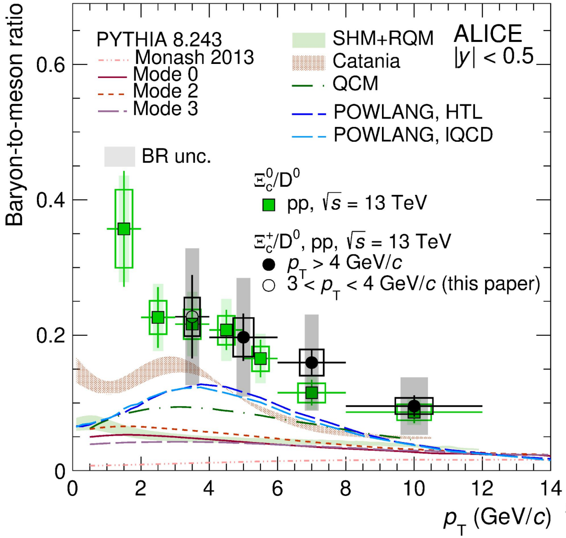
Other models, implementing modified hadronisation, are closer to the data.

Strange charm baryons: all models tend to **underestimate** the data larger enhancement than for non-strange charm?

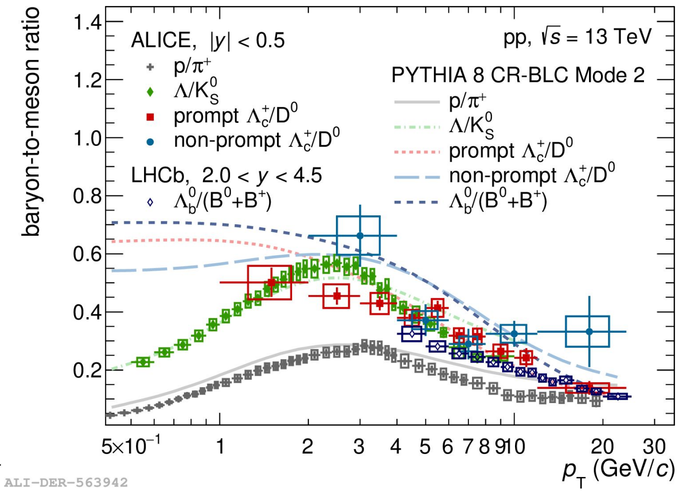
Modified mechanisms of **charm- and beauty-quark hadronization** in pp collisions compared to e^+e^- collisions (in-vacuum fragmentation).



ALI-PUB-567876



ALI-PUB-567881



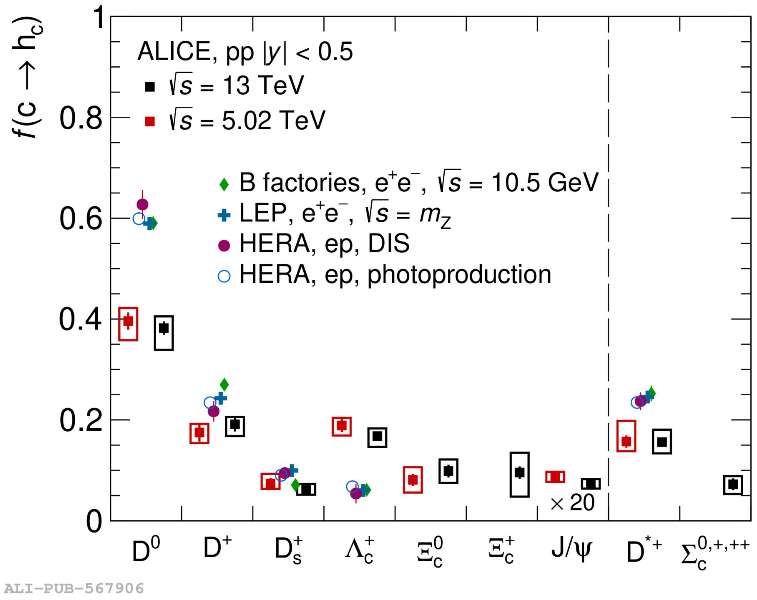
ALI-DER-563942

Charm fragmentation fractions

JHEP 12 (2023) 086

- assumed **universality of fragmentation functions**
- ALICE: significantly **larger fraction** of heavy quarks hadronising into **baryons** in **pp collisions** compared to leptonic collisions with a corresponding **decrease** of **non-strange D mesons**.
- compatible results at **different centre-of-mass-energies.**

~x3 enhancement of Λ_c^+ fraction
~x1.2-1.5 decrease for charm mesons



Λ_c^+ from $\Sigma_c^{0,++}$(2455) decay

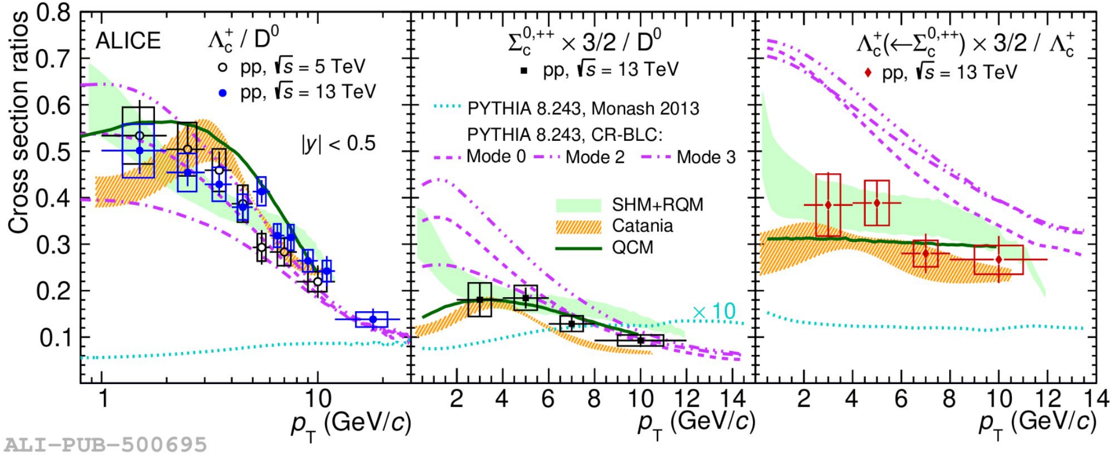
Phys. Rev. Lett. 128, 012001 (2022)

Λ_c^+/D^0 ratio is compatible at different center-of-mass energies.

Around 40% of Λ_c^+ comes from $\Sigma_c^{0,++}$(2455) decay → increased non-prompt Λ_c^+ production partially contributes to increase in overall Λ_c^+/D^0 ratio.

SHM + RQM is close to data for $\Lambda_c^+(\leftarrow\Sigma_c^{0,++}(2455))/\Lambda_c^+$.

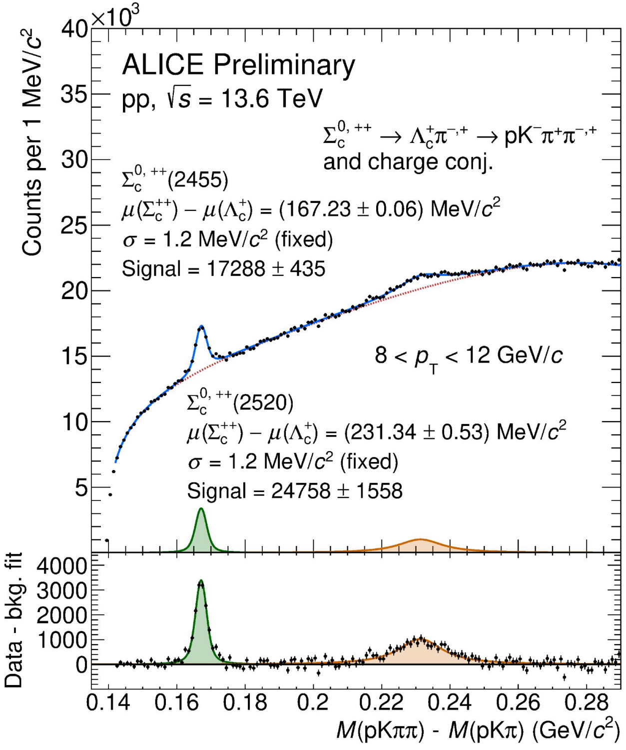
PYTHIA Mode 2 describes results for Λ_c^+/D^0, but fails to describe $\Lambda_c^+(\leftarrow\Sigma_c^{0,++}(2455))/\Lambda_c^+$.



Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159
Monash: Skands et al., EPJ C 74 (2014) 3024
CR-BLC: Christiansen et al., JHEP 08 (2015) 003
SHM + RQM: He et al., PLB 795 (2019) 117-121
QCM: Song et al., EPJ C 78 (2018) 344
Catania: Greco et al., PLB 821 (2021) 136622

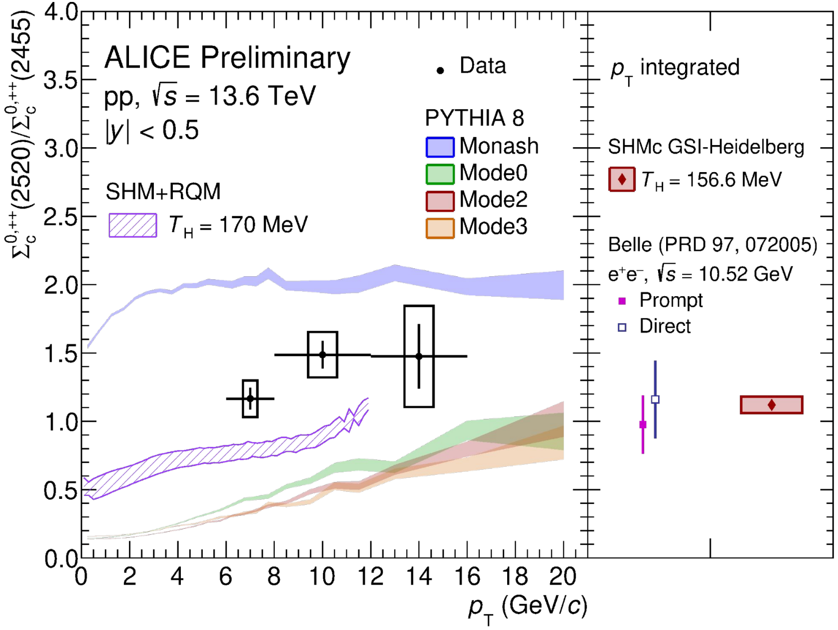
$\Sigma_c^{0,++}$ ratios

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



ALI-PREL-571534

ALICE measurement **compatible with e⁺e⁻** (p_T-integrated) and SHM+RQM.
PYTHIA 8 Monash **overestimates** the data, **CR-BLC** tunes **underestimate** them.



ALI-PREL-574270

Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159
Monash: Skands et al., EPJ C 74 (2014) 3024
CR-BLC: Christiansen et al., JHEP 08 (2015) 003
SHM + RQM: He et al., PLB 795 (2019) 117-121
SHMc: Andronic et al., PLB 797 (2019) 134836
Belle: Belle, Phys. Rev. D 97 (2018) 072005

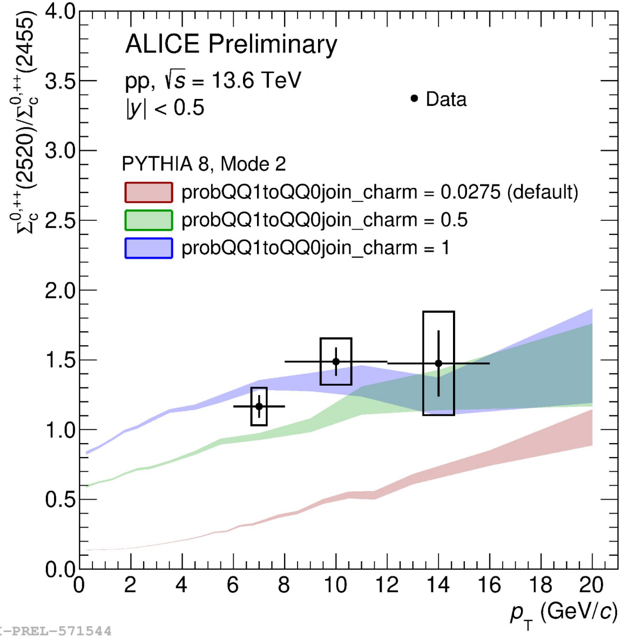
$\Sigma_c^{0,++}$ ratios – different PYTHIA 8 settings

PYTHIA 8 Mode {0,2,3} underestimates the data.

PYTHIA 8 Mode 2 parameter `probQQ1toQQ0join_charm` controls the amount of **the suppression of Σ_c production relative to Λ_c**.

- $\Sigma_c^{0,++}$(2520) more likely to decay to Λ_c^+ than $\Sigma_c^{0,++}$(2455) → amount of **$\Sigma_c^{0,++}$(2520) production** modifies the **Λ_c^+(←$\Sigma_c^{0,++}$(2455))/Λ_c^+ feeddown fraction**.
- Measurement important to understand the role of **spin-1 diquarks** for **charm-baryon hadronisation**.

Σ_c measurements essential for tuning the model.



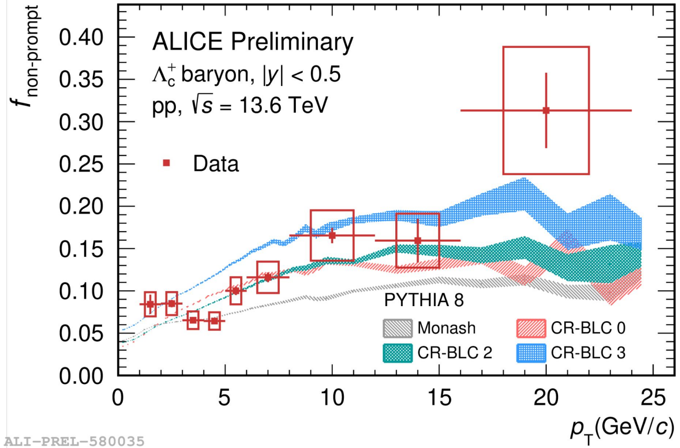
Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159
CR-BLC: Christiansen et al., JHEP 08 (2015) 003

Non-prompt fractions in Run 3

- **p_T range extended** to $0 < p_T < 24$ GeV/c for D^0 and $1 < p_T < 24$ GeV/c for Λ_c.
- **more granular results** compared to Run 2

Λ_c^+ non-prompt fraction in Run 3

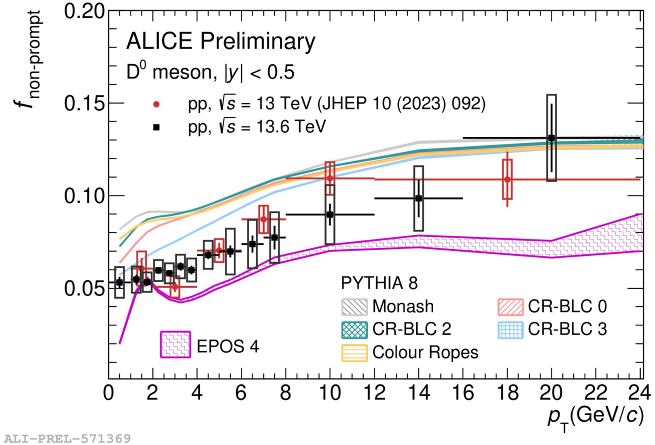
- Pythia Monash **underestimates** the data
- **Pythia with CR-BLC closer to the data** over the full p_T range



ALI-PREL-580035

D^0 non-prompt fraction in Run 3

- the data points tend to be **overestimated** by all **Pythia** models
- the data are slightly **underestimated** by EPOS 4



ALI-PREL-571369

Pythia: Sjöstrand et al., JHEP05 (2006) 026; CPC 191 (2015) 159
Monash: Skands et al., EPJ C 74 (2014) 3024
CR-BLC: Christiansen et al., JHEP 08 (2015) 003
Colour Ropes: Andersson et al., Nucl.Phys. B 355 (1991) 82–105
EPOS 4: Pierog et al., Phys. Rev. C 92 (2015) 034906

Summary

D-mesons cross sections and **meson-to-meson ratios** described well by existing models based on fragmentation functions evaluated from **e^+e^- and ep measurements**.

pQCD calculations do not describe well **baryon cross sections** and **baryon-to-meson ratios**

- **large enhancement** at **low and intermediate p_T**
- possibly **larger enhancement** for **strange charm baryons**

Charm-quark hadronization in pp collisions could occur via **additional mechanisms** compared to leptonic collisions.

Further **$\Sigma_c^{0,++}$ measurements essential** to constrain **model parameters** and get insight on the role of **spin-1 diquarks**.

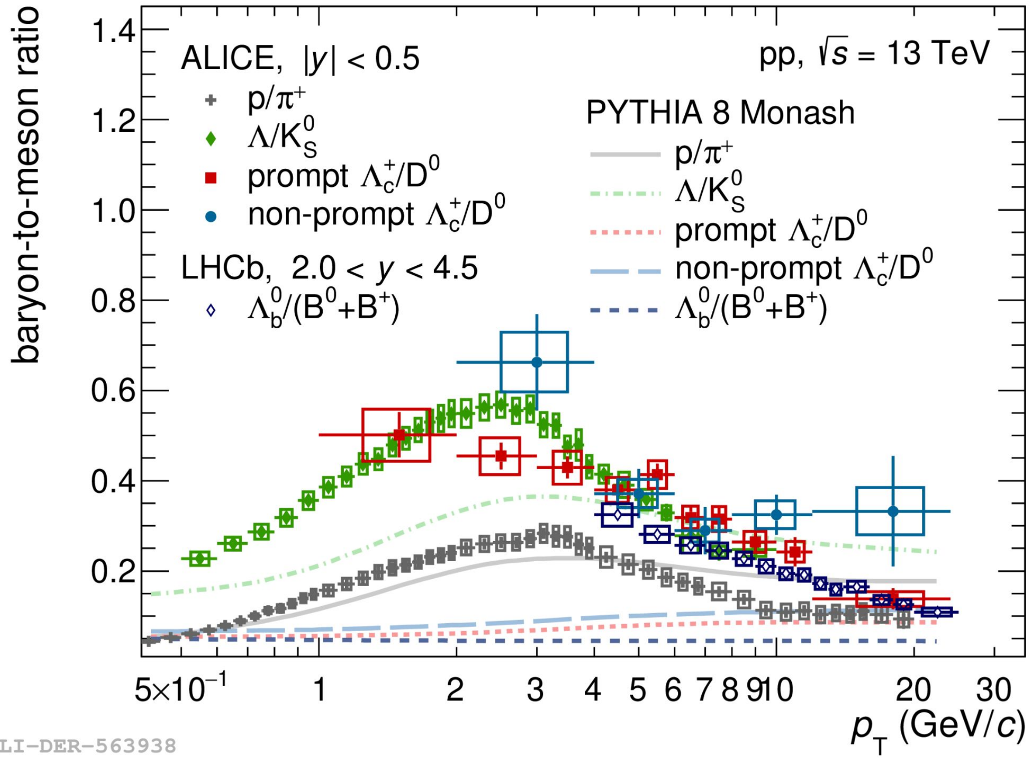
Some tension for the models in the description of the **non-prompt D_s fraction** and **charm-strange baryon enhancement**.

More results to come from Run 3.

Thank you for your attention!

Backup

Beauty baryon-to-meson ratio vs PYTHIA 8 Monash



Non-prompt fractions in Run 3

Λ_c^+ vs D^0 non-prompt fraction in Run 3

- Λ_c^+ non-prompt fraction tends to be larger than D^0 non-prompt fraction