Single charm-hadron production and charm-hadron pairs production in pp collisions at 13.6 TeV

Maja Karwowska (WUT),
on behalf of the ALICE collaboration

2025 EPS-HEP, 7-11.07.2025

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

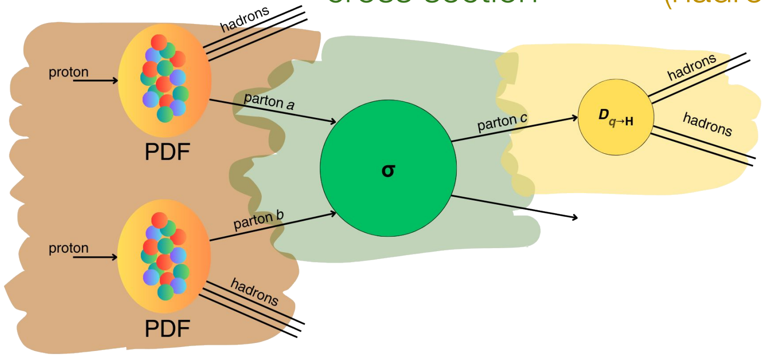
ALICE

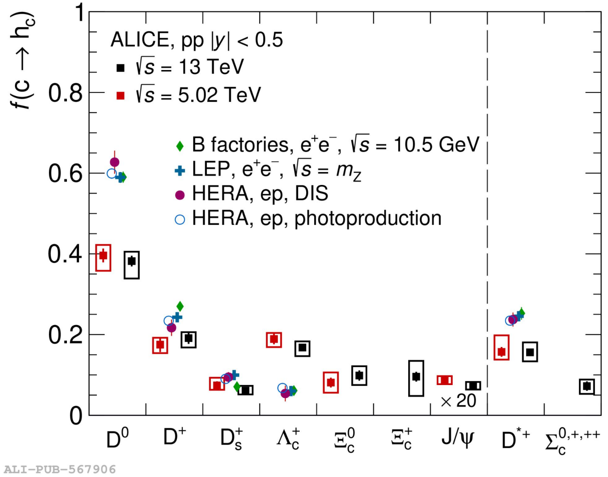
Probing hadronisation with charm hadrons

JHEP 12 (2023) 086

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

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



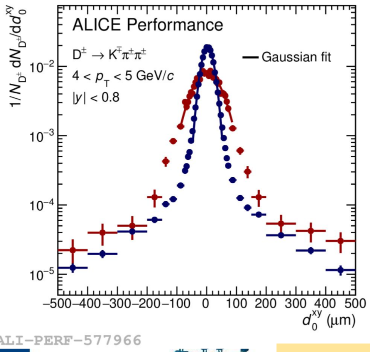


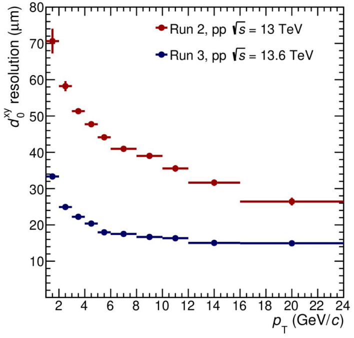
Why heavy quarks?

- high masses → **large momentum transfer**
  → perturbative Quantum Chromodynamics (pQCD) approach can be used
- **heavy-flavour particle yield ratios** are sensitive to charm fragmentation function
- **universality of fragmentation functions** across collision systems challenged by measurements of charm hadron production at LHC

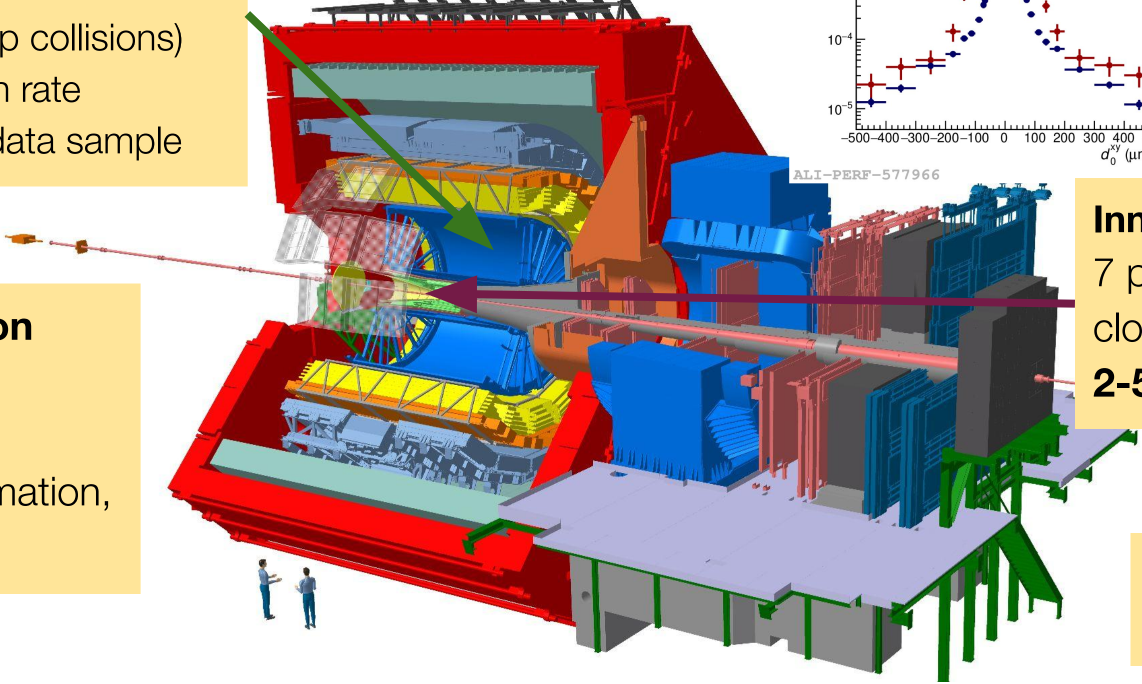
Upgraded ALICE in Run 3

More in Biao Zhang's talk
July 7th, 14:40





Time Projection Chamber
new readout with GEM allows for continuous data stream at **500-1000x** (pp collisions) higher interaction rate
→ much larger data sample



Inner Tracking System
7 pixel layers,
closer to the beam pipe,
2-5x improved resolution,

Fast Interaction Trigger
luminosity,
multiplicity estimation,
and trigger

Central barrel detectors
$|\eta| < 0.9$

Run 3 results

Strange-meson-to-meson ratio

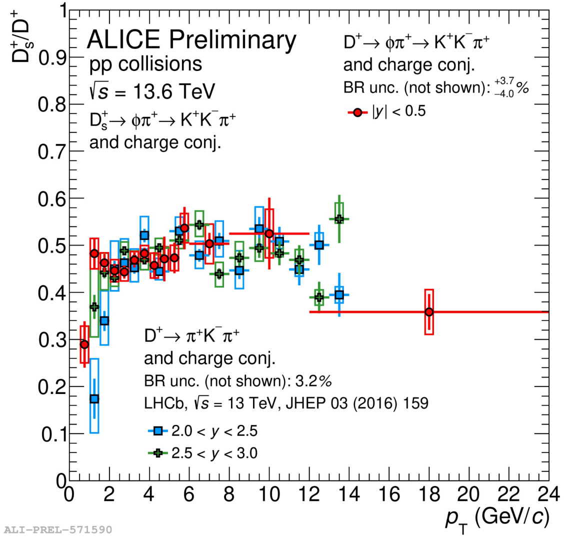
Results in general compatible at **different rapidities and centre-of-mass energies.**

PYTHIA 8 models generally **underestimate** the data.

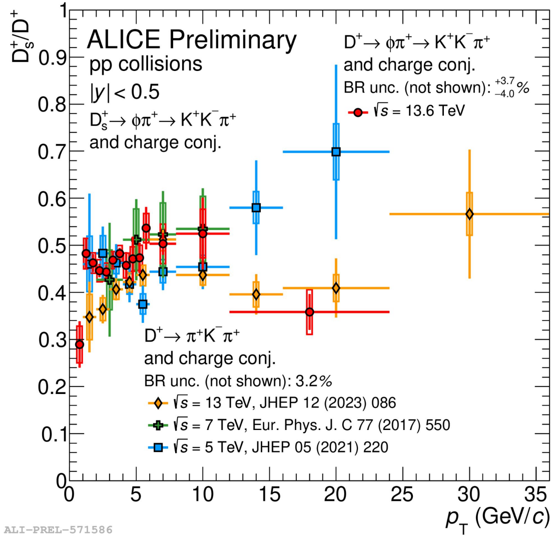
POWLANG models **overestimate** the data.

Catania describes the data better.

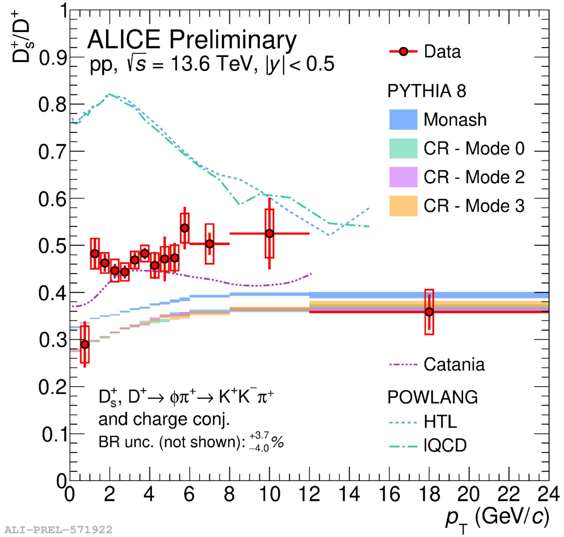
Different rapidities



Different centre-of-mass energies



Data vs. models



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

Strange-meson-to-meson ratio vs multiplicity

New Run 3 results

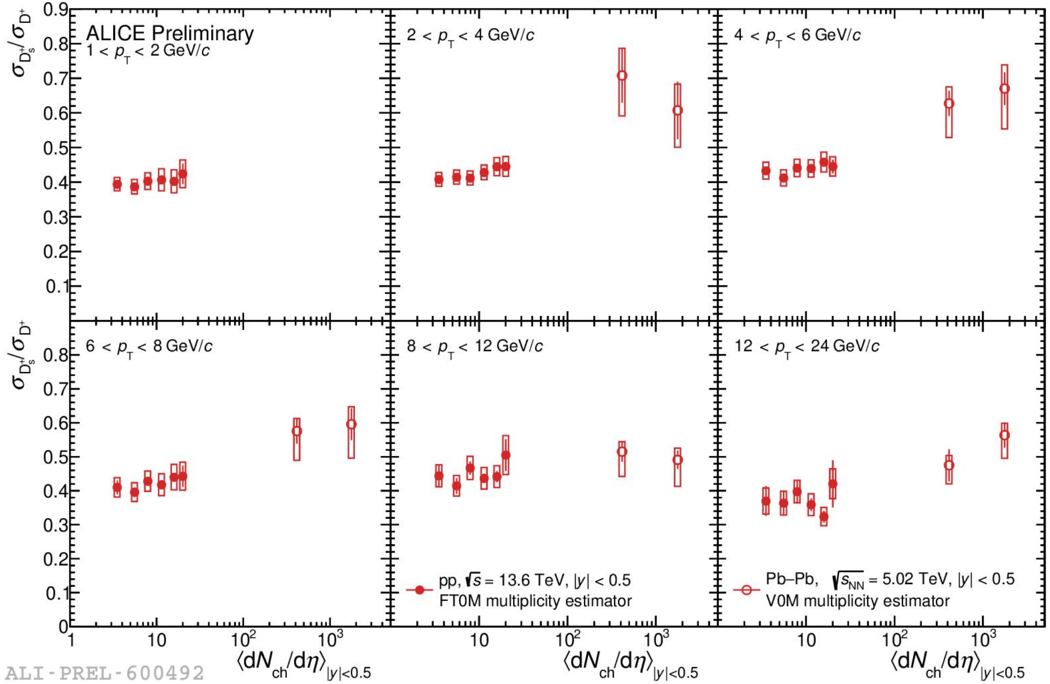
No p_T and multiplicity dependence in pp collisions.

Results in pp collisions compatible with measurements in e^+e^- collisions.

LEP average: 0.408 +/- 0.040 (Lisovyi et al. EPJC 76 (2016) 397)

Pb–Pb collisions:
PLB 827, 136986 (2022)

Significantly higher ratio in Pb–Pb collisions at low and intermediate p_T.
→ **Recombination of charm quarks with strange quarks.**



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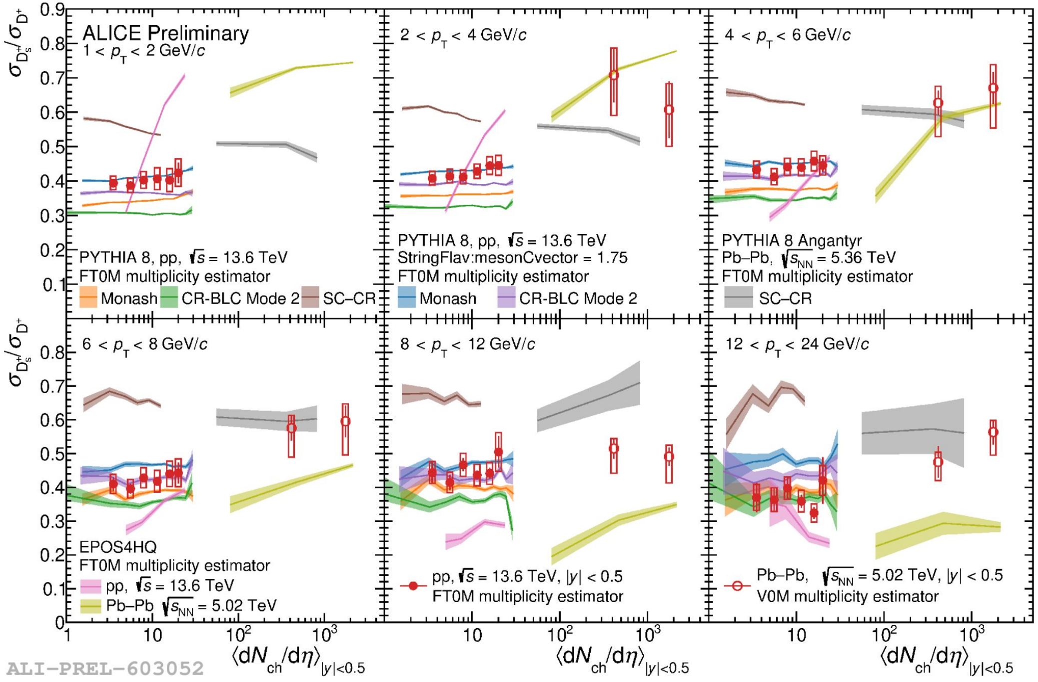
Pb–Pb collisions:
PLB 827, 136986 (2022)

Significantly higher ratio in Pb–Pb collisions at low and intermediate p_T.
→ **Recombination of charm quarks with strange quarks.**

Results in pp compatible with PYTHIA 8 Monash and CR BLC with tuned **feed-down from vector mesons (D^*).**

Pb–Pb results described by PYTHIA Angantyr and EPOS4HQ.



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
Pythia Angantyr: Bierlich et al. JHEP (2018), 134
EPOS4HQ: Zhao et al. PRC 110, (2024) 024909

Excited charm-strange state cross section

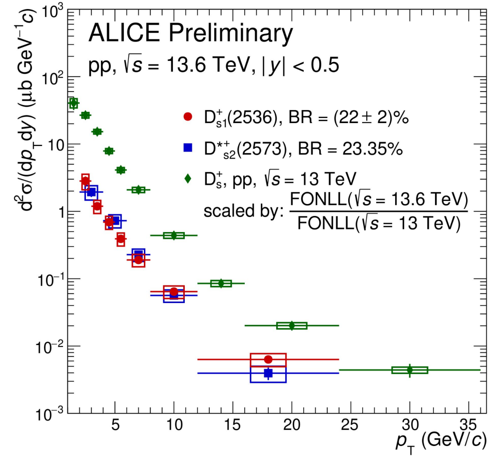
New Run 3 results

ALICE

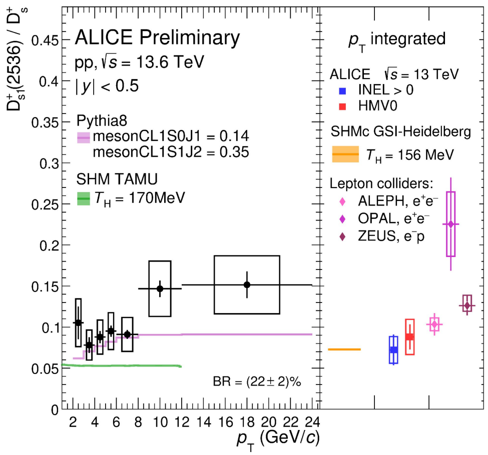
$D^{+}_{S1}(2536)$ and $D^{*+}_{S2}(2573)$ contribute to the ground-state D-meson yields.
First p_T-differential measurements relative to the ground state.

ALICE measurements **consistent** with p_T-integrated Run 2 results, SHM+TAMU, SHMc, and **e^+e^- and e^-p**.

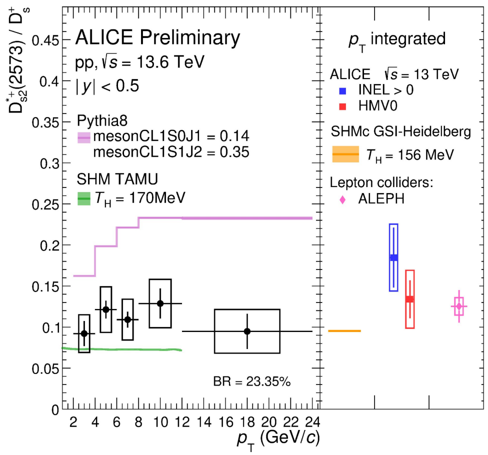
PYTHIA is tuned on ALICE Run 2 results and overestimates $D^{*+}_{S2}(2573)$ production yield.



ALI-PREL-595833



ALI-PREL-595839



ALI-PREL-595844

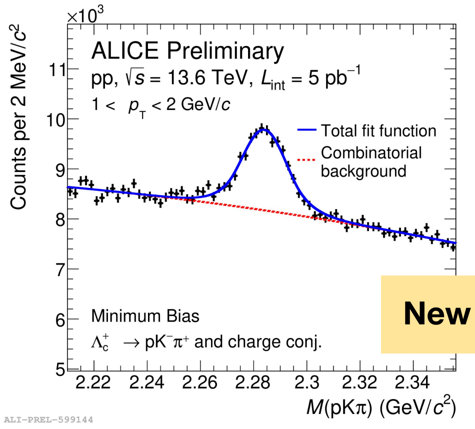
PYTHIA: Sjöstrand et al., JHEP 05 (2006) 026; CPC 191 (2015) 159
SHM + RQM: He et al., PLB 795 (2019) 117-121
TAMU: He et al., Phys. Lett. B 795 (2019) 117
SHMc: Andronic et al., PLB 797 (2019) 134836

Baryon-to-meson cross-section ratio

JHEP 12 (2023) 086

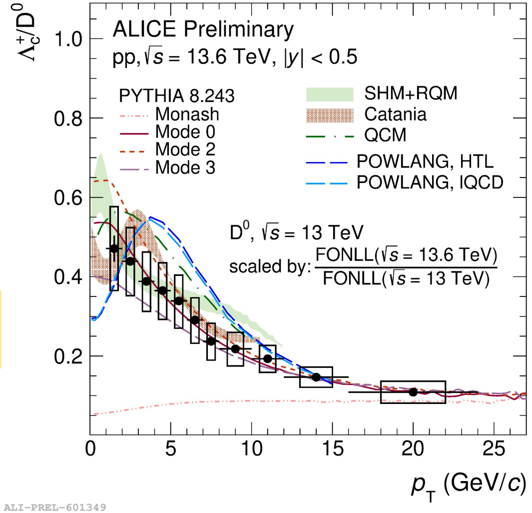
Depends on p_T: larger ratio at low-intermediate p_T compared to high p_T.
PYTHIA 8 with Monash tune (tuned to e^+e^- measurements) largely **underestimates** the data.
Other models, implementing modified hadronisation, are closer to the data.
Strange-charm baryons: all models tend to **underestimate** the data larger enhancement than for non-strange charm?

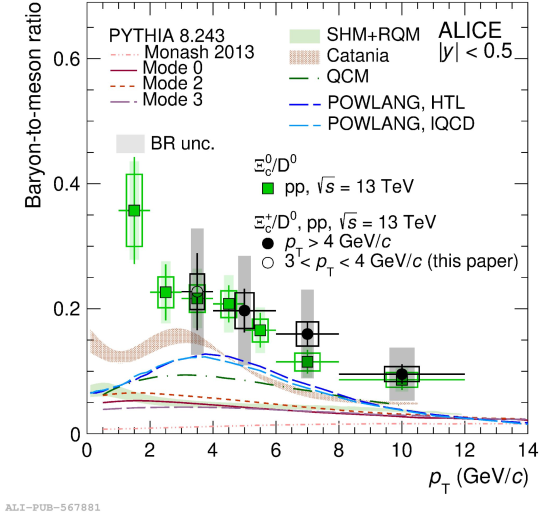
Modified mechanisms of **charm-quark hadronization** in pp collisions compared to e^+e^- collisions (in-vacuum fragmentation).



New Run 3 result

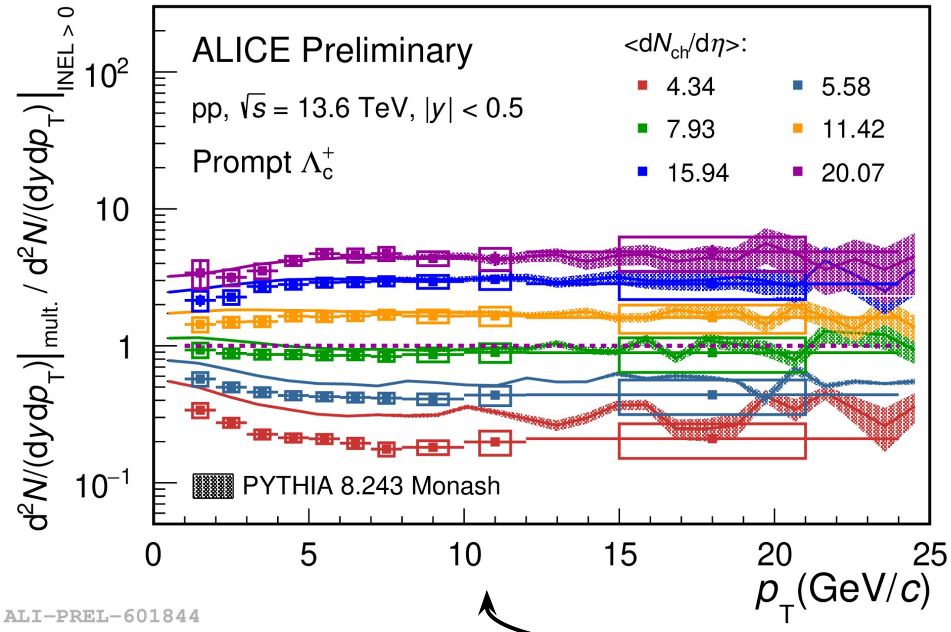
150x larger min. bias sample w.r.t. Run 2



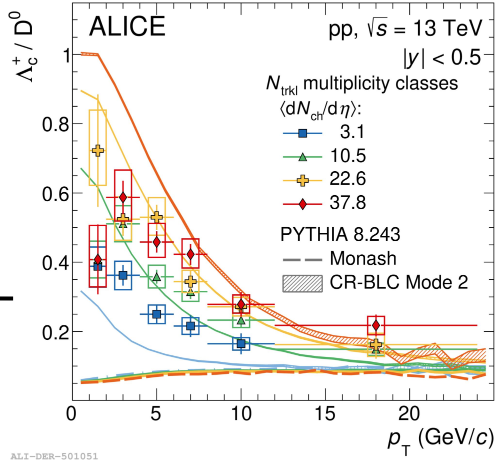


Λ_c^+ production vs. multiplicity

New Run 3 results



- p_T-differential yield **increases** from the lowest to the highest **multiplicity class**
- PYTHIA 8 Monash describes the multiplicity dependence of the p_T-spectra, except for **low multiplicity** classes of events



significantly more precise and more differential in p_T and multiplicity compared to Run 2

PYTHIA: Sjöstrand et al., JHEP 05 (2006) 026; CPC 191 (2015) 159
Monash: Skands et al., EPJ C 74 (2014) 3024

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

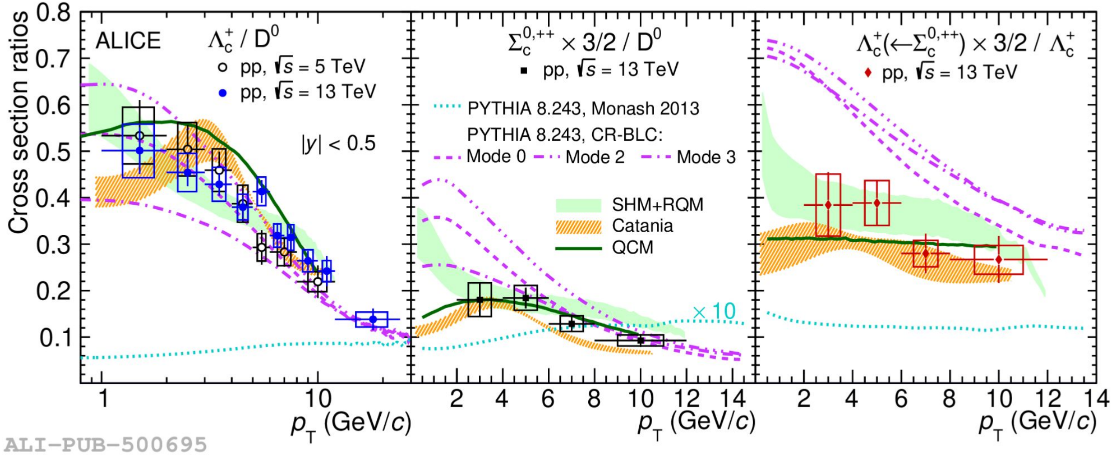
Phys. Rev. Lett. 128, 012001 (2022)

ALICE

Compatible Λ_c^+/D^0 ratios at different center-of-mass energies.

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

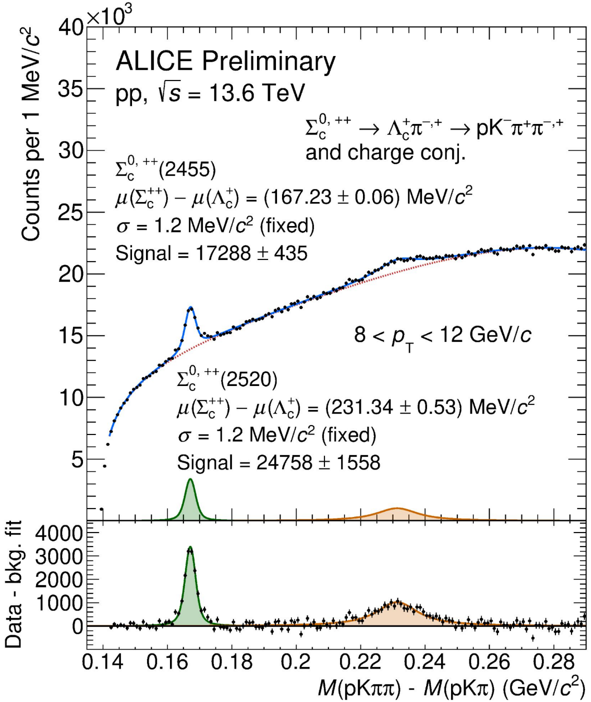
SHM + RQM is close to data for $\Lambda_c^+(\leftarrow\Sigma_c^{0,++}(2455))/\Lambda_c^+$.
PYTHIA Mode 2 describes results for Λ_c^+/D^0, but fails to describe $\Lambda_c^+(\leftarrow\Sigma_c^{0,++}(2455))/\Lambda_c^+$.



PYTHIA: Sjöstrand et al., 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
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

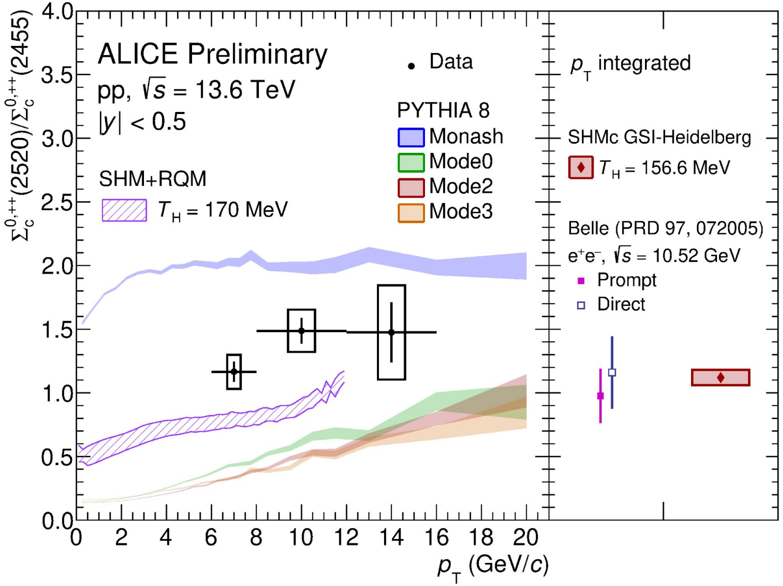
$\Sigma_c^{0,++}$ ratios

First measurement of relative production 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., 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
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

Run 3 results

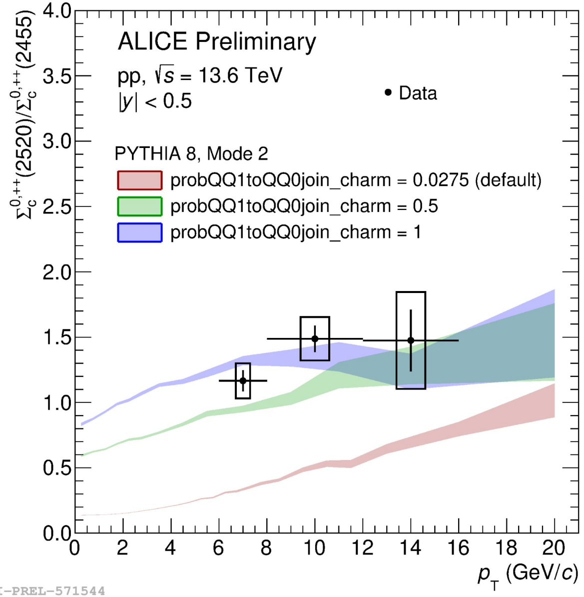
Altmann et al., EPJ C 85, 16 (2025)

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

PYTHIA 8 Mode 2 parameter `probQQ1toQQ0join_charm` controls **the probability of diquarks having spin 1.**

- The larger the parameter is, the larger **$\Sigma_c^{0,++}$(2520) and Λ_c^+($\leftarrow\Sigma_c^{0,++}$(2520)) production** and the smaller **Λ_c^+($\leftarrow\Sigma_c^{0,++}$(2455))/$\Lambda_c^+$ feeddown fraction.**
- Measurement important to understand the role of **spin-1 charm diquarks** for **charm-baryon hadronisation.**

Σ_c measurements essential for tuning the model.



ALI-PREL-571544

PYTHIA: Sjöstrand et al., JHEP 05 (2006) 026; CPC 191 (2015) 159
CR-BLC: Christiansen et al., JHEP 08 (2015) 003

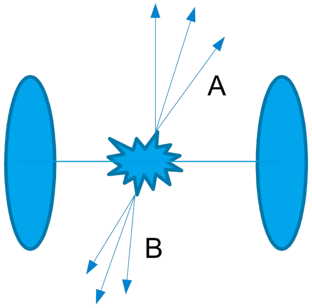
Production of D^0 pairs

New Run 3 results

Multi-Parton Interactions

Single Parton Scattering (SPS)

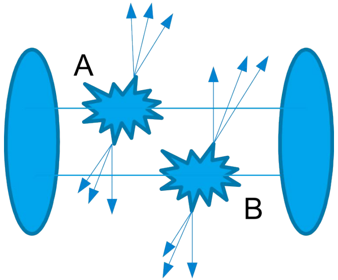
mostly unlike-sign meson pairs

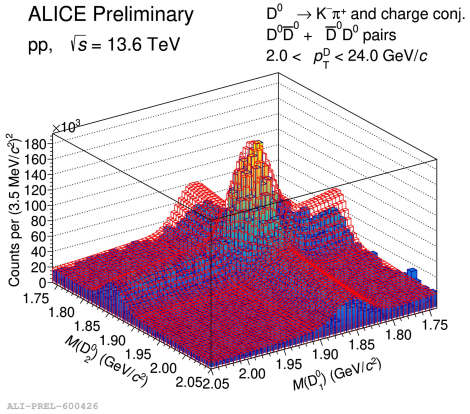


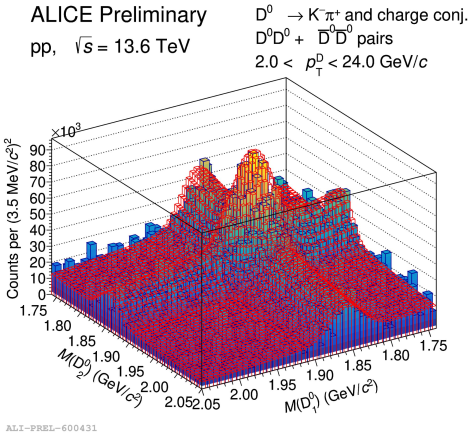
Double Parton Scattering (DPS)

like- and unlike-sign meson pairs

2 independent, simultaneous scatterings







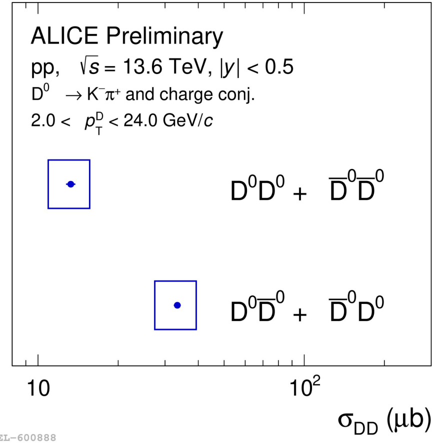
Images: J. Gaunt, Multiparton Interactions – Theory, SM@LHC 2015

Production of D^0 pairs

New Run 3 results

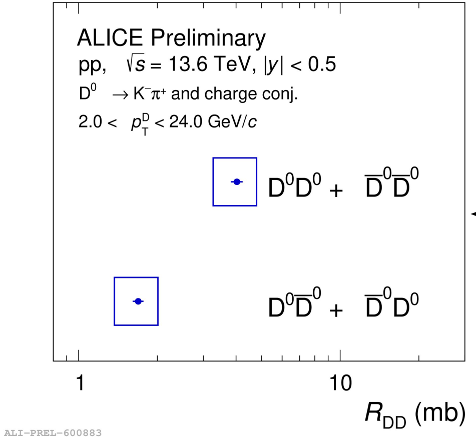
Multi-Parton Interactions → $R_{H_1H_2} = \frac{m}{2}\frac{\sigma_{H_1}\sigma_{H_2}}{\sigma_{H_1H_2}}$

Unlike-sign D^0 pairs have double the integrated yield of **same-sign** pairs: contribution from SPS within acceptance.



Next steps:

- compare with the models that include MPI
- study Δφ, Δη distributions to separate SPS and MPI contributions.

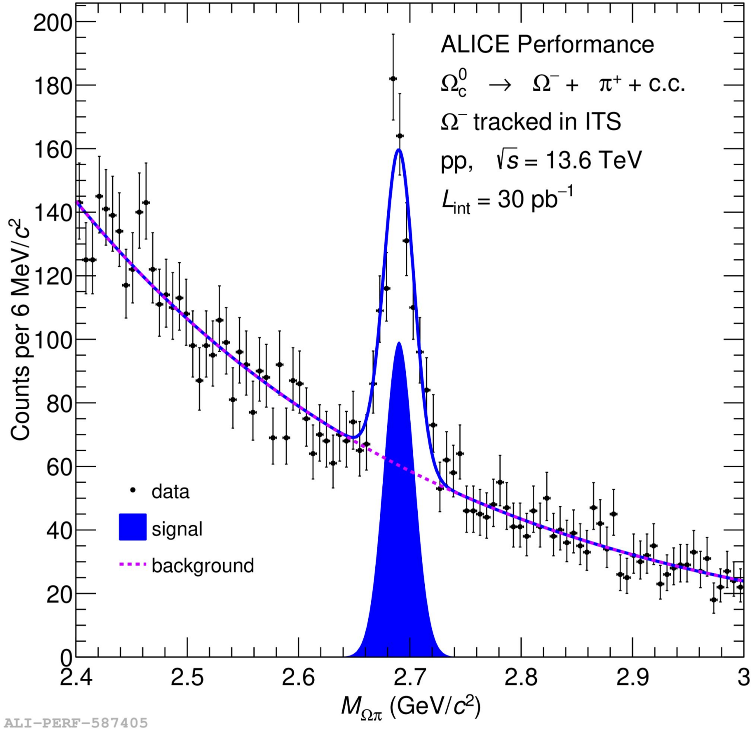


Ratio of single D^0 yield at 13 TeV over the pairs yield

More Run 3 results to come!

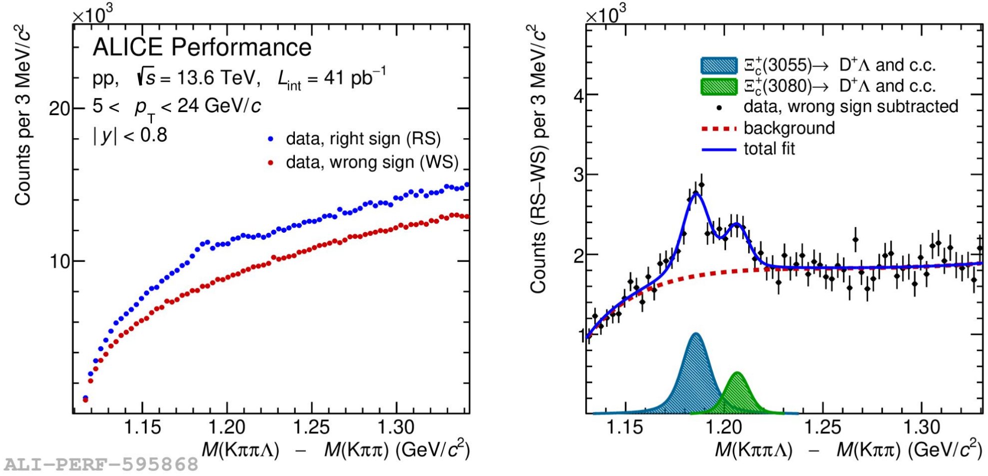
New Run 3 results

Charmed Ω baryon with strangeness tracking



Software triggers allow us to integrate **more luminosity** and look for **rarer signals**
→ check Biao Zhang's talk July 7th, 14:40

Studies of Ξ_c resonances



Summary

pQCD-based calculations do not describe well **strange-to-non-strange meson** and **baryon-to-meson ratios**

- no universal description of strange-to-non-strange meson ratios across collision systems
- **large baryon enhancement** at **low and intermediate p_T** compared to e^+e^- collisions
- 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 into the role of **spin-1 diquarks**.

More insight into Multi-Parton Interactions via first Run 3 measurements of charm-hadron pairs

- opposite-sign D^0 pairs produced at twice the yield of same-sign pairs within acceptance selections

More results to come from Run 3

- **more precise and differential** measurements in p_T and multiplicity
- first production measurements of higher mass hadrons possible

Thank you for your attention!

Backup

Hadronization mechanisms in models

Pythia 8 CR BLC

Junction string topologies beyond leading color enhance baryon production

SHM + RQM

Statistical hadronization with feed-down from enhanced set of charm baryons predicted by Relativistic Quark model

Catania

Coalescence (Wigner Functions) + 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.

Multi-Parton Interactions (MPI)

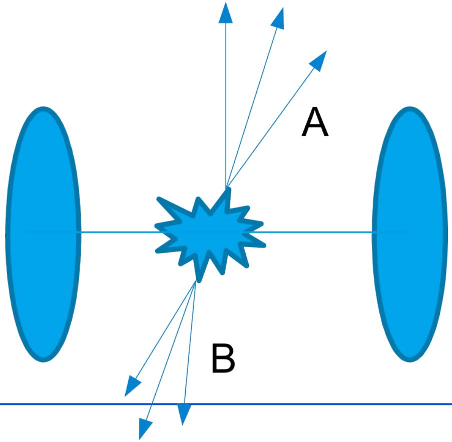
$$\sigma_{ABCD\to H1H2} = \frac{m}{2} \Sigma_{a,b,c,d} \int F_q^{ac}(x_a,x_c,r;Q_{H1}Q_{H2}) F_q^{bd}(x_b,x_d,r;Q_{H1}Q_{H2}) \times \sigma_{ab\to H1}(x_a,x_b)\sigma_{cd\to H2}(x_c,x_d)\, dx_a dx_b dx_c dx_d dr^2$$

symmetry factor   collinear double parton distribution   parton-level cross sections

assuming no correlation between *x* and *r*: $\sigma_{ABCD\to H_1H_2} = \frac{m}{2}\frac{\sigma_{AB\to H_1}\sigma_{CD\to H_2}}{\sigma_{eff}}$

Single Parton Scattering (SPS)

mostly unlike-sign meson pairs



Double Parton Scattering (DPS)

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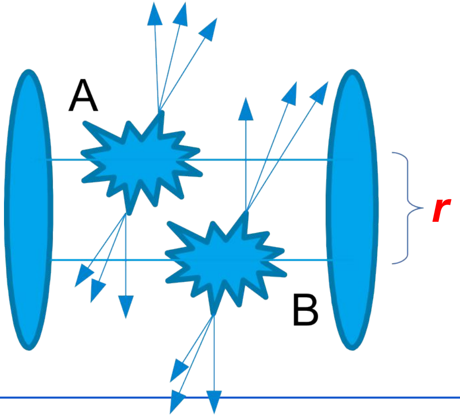


studied via production of **charm-hadron pairs →** investigation of **double charm** production

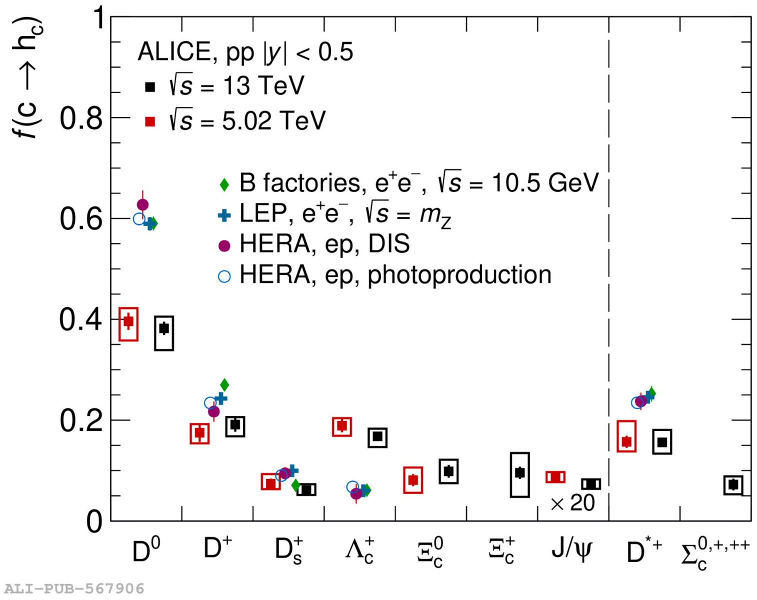
Image source: Jonathan Gaunt, Multiparton Interactions – Theory, SM@LHC 2015, Florence, Italy, 23rd April 2015

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

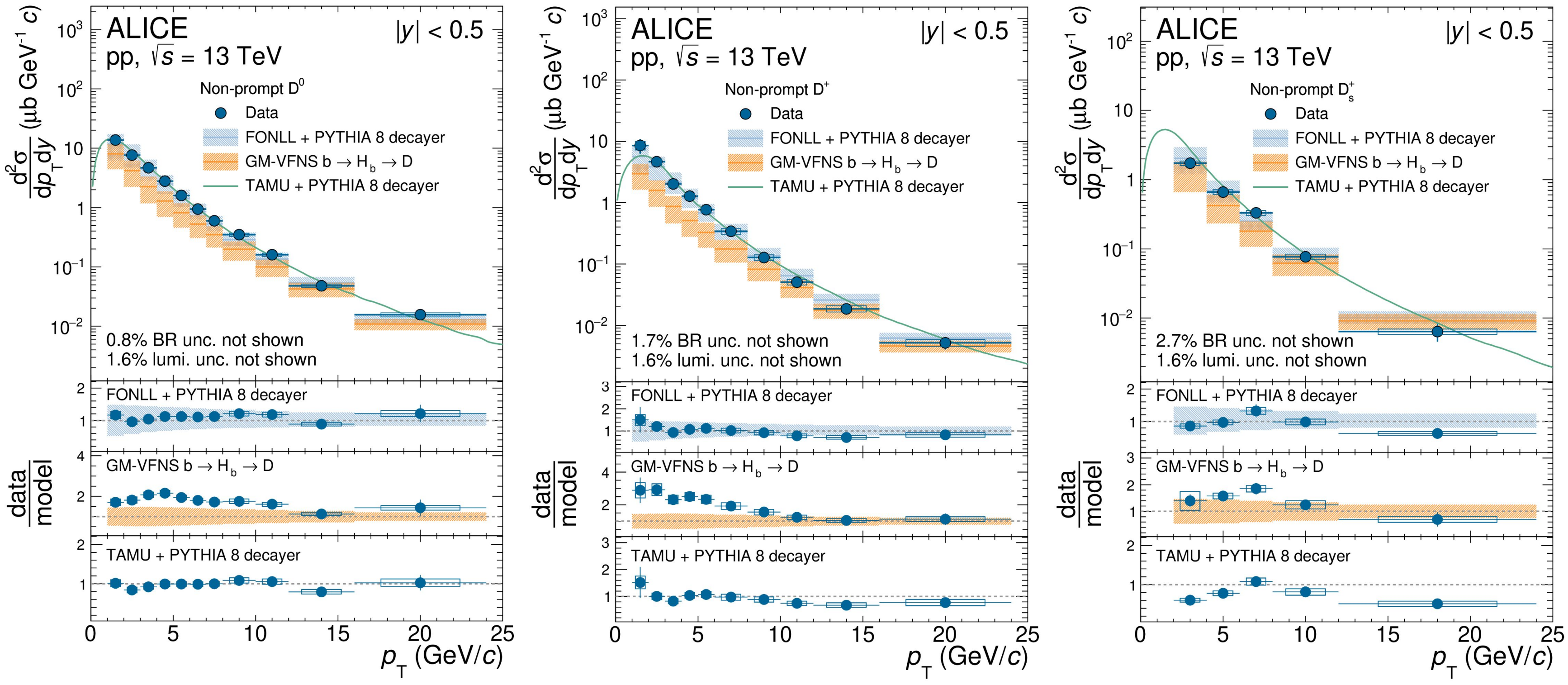


Non-prompt D-meson cross sections

arXiv:2402.16417 (2024)

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

FONLL + PYTHIA 8 **agrees** with data



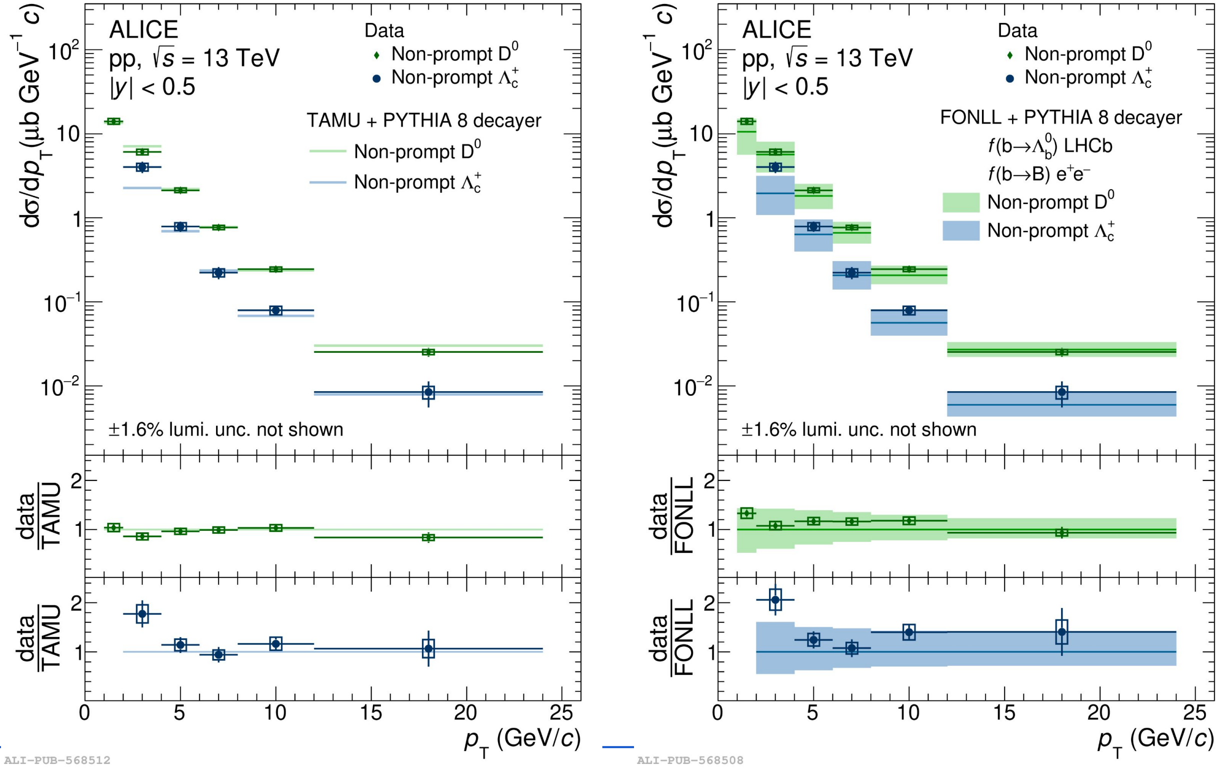
ALI-PUB-568816 ALI-PUB-568820 ALI-PUB-568824

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

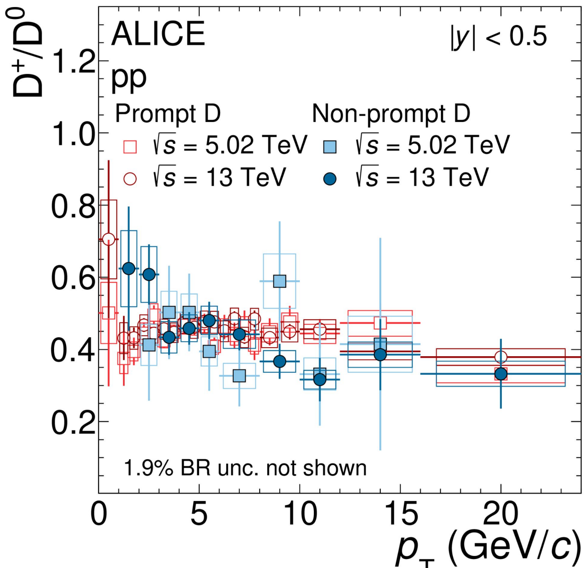
Meson-to-meson ratio

arxiv:2402.16417 (2024)

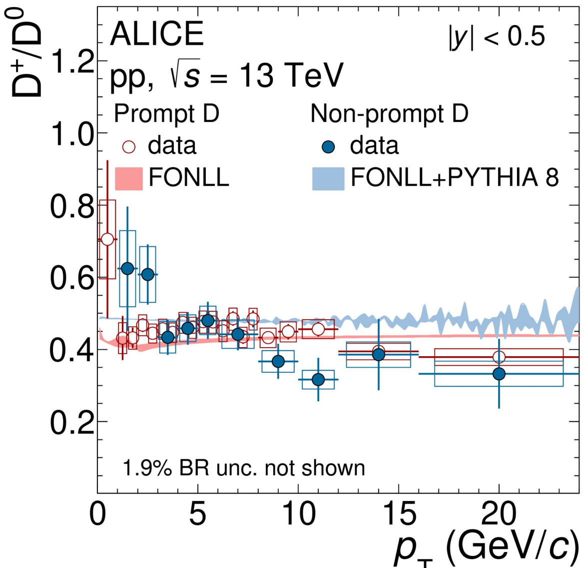
Similar fractions for **prompt and non-prompt** D mesons.

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**.



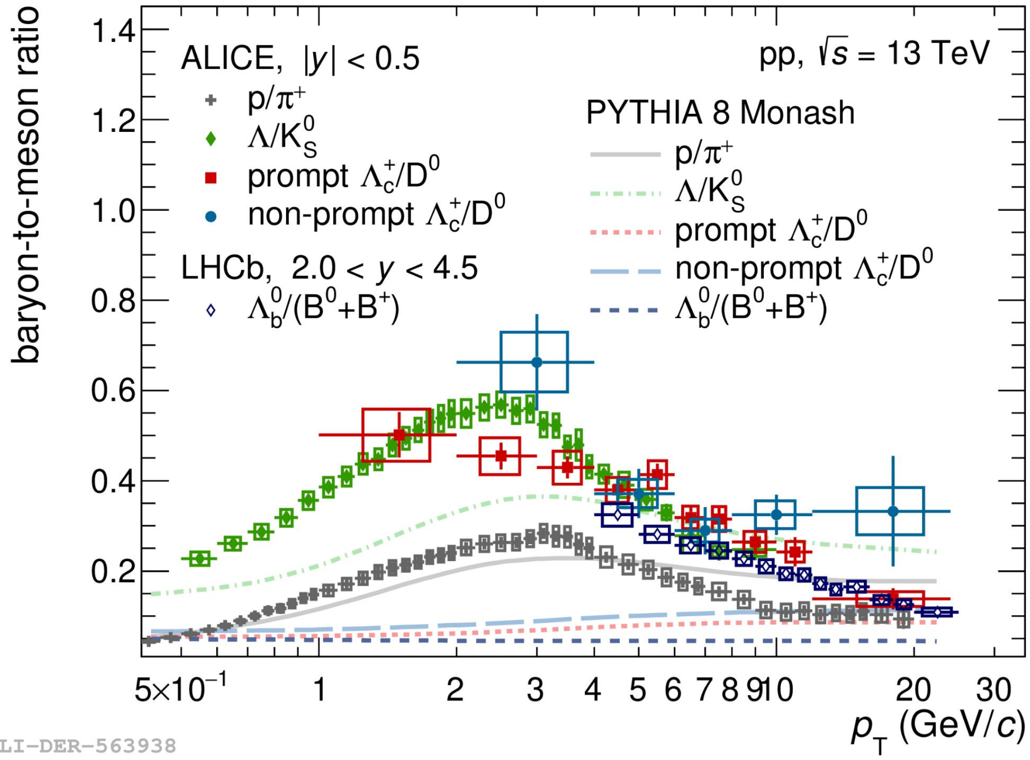
ALI-PUB-568828



ALI-PUB-568836

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

Beauty baryon-to-meson ratio vs PYTHIA 8 Monash



ALI-DER-563938

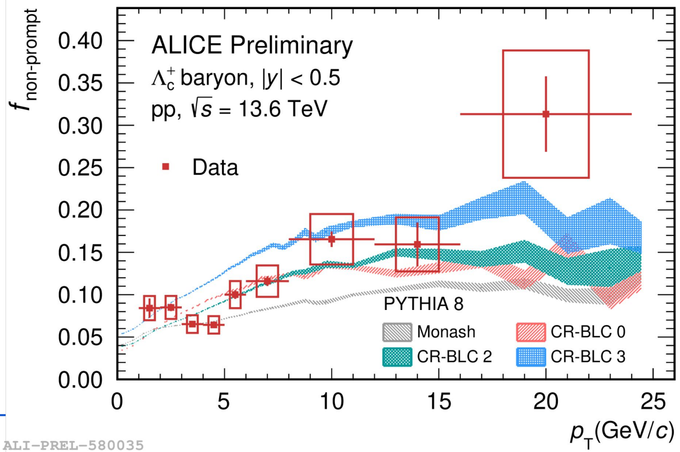
Non-prompt fractions in Run 3

New Run 3 results

- **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



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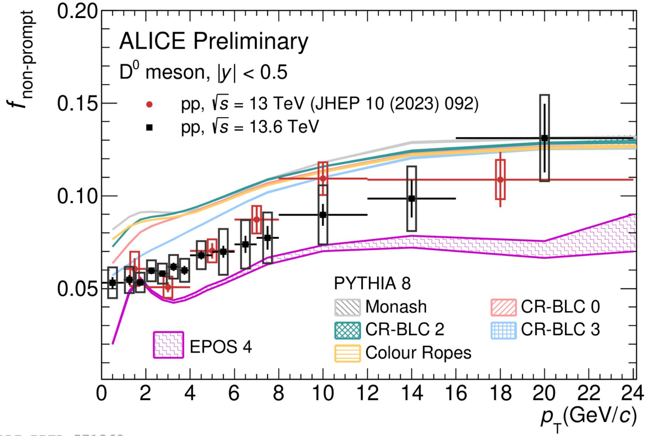
D^0 non-prompt fraction in Run 3

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



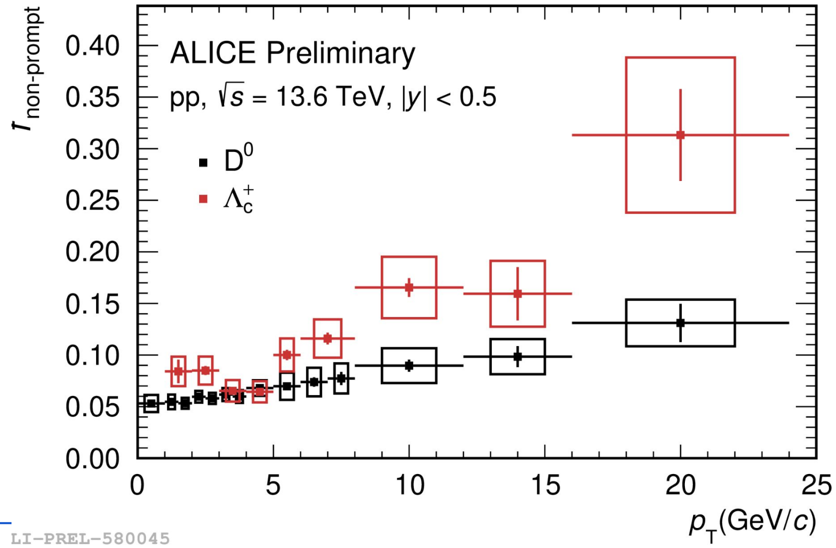
ALI-PREL-571369

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

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



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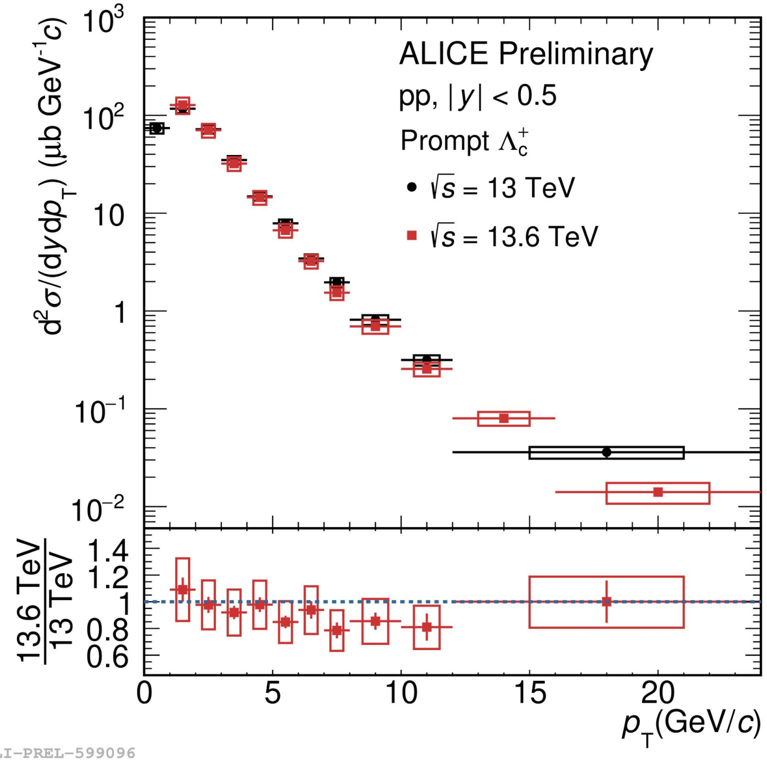
Λ_c^+ production in Run 3

Compatible with Run 2 measurements



ALI-PREL-599096