Studies of beauty-quark production, hadronisation and cold nuclear matter effects in pp and p–Pb collisions with ALICE

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Hard Probes 2024, Nagasaki

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ALICE

université PARIS-SACLAY

Laboratoire de Physique des 2 infinis Irène Joliot-Curie

Studying pQCD using heavy quarks

Heavy quarks are excellent probes to test perturbative QCD

- Produced **early in the collision** via hard scattering processes, they experience the **full evolution** of the medium
- Large masses ⟶ **Large squared momentum transfer**, Q^2, allowing us to use perturbative QCD

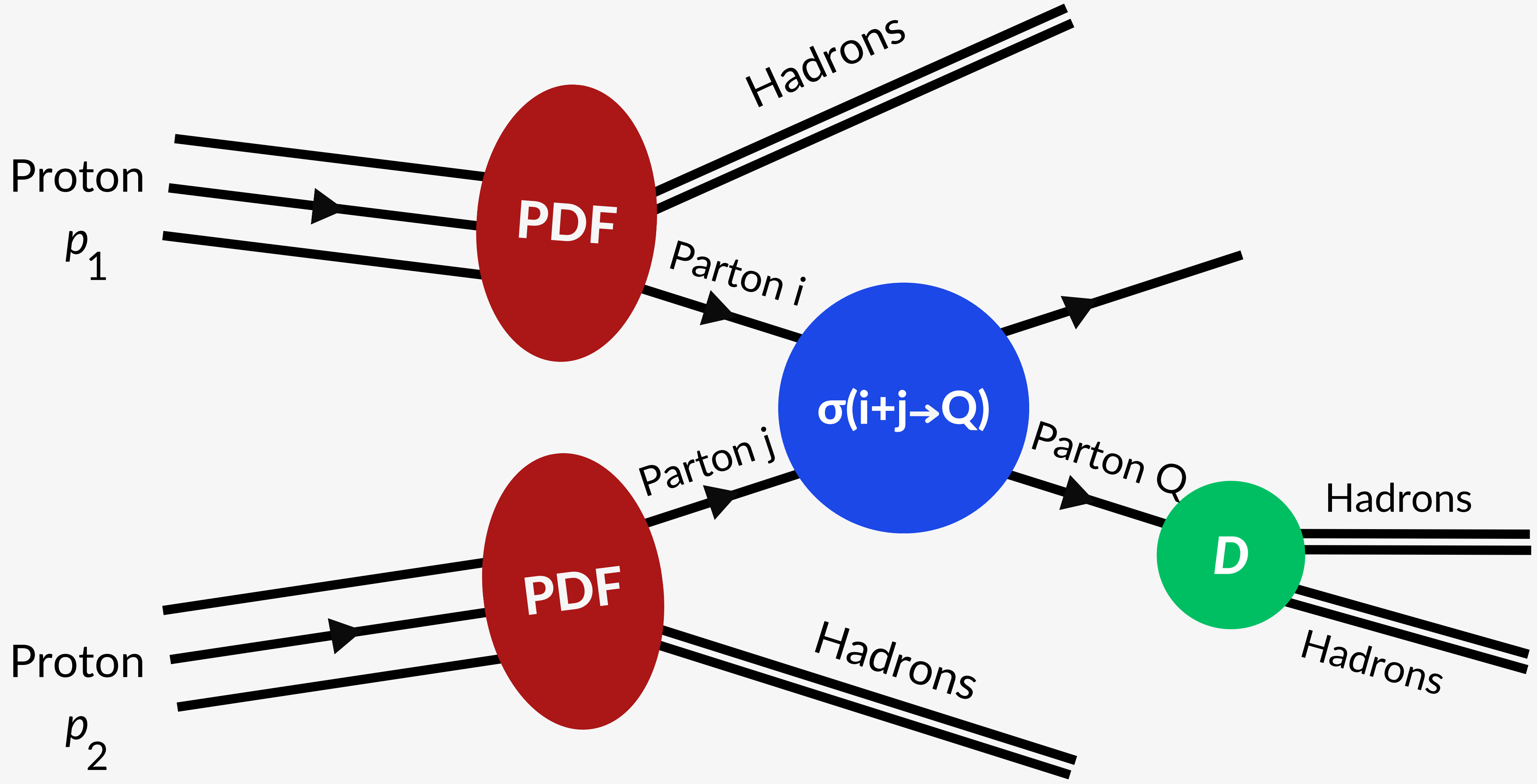
Factorisation approach in pQCD calculations:

$$\frac{d\sigma^{pp\to H_Q}}{dp_T} = f_i(x_i, \mu_f^2) f_j(x_j, \mu_f^2) \otimes \frac{d\sigma^{ij\to Q}}{dp_T} \otimes D_{Q\to H_Q}\left(z_Q = \frac{p_{H_Q}}{p_Q}, \mu_f^2\right)$$

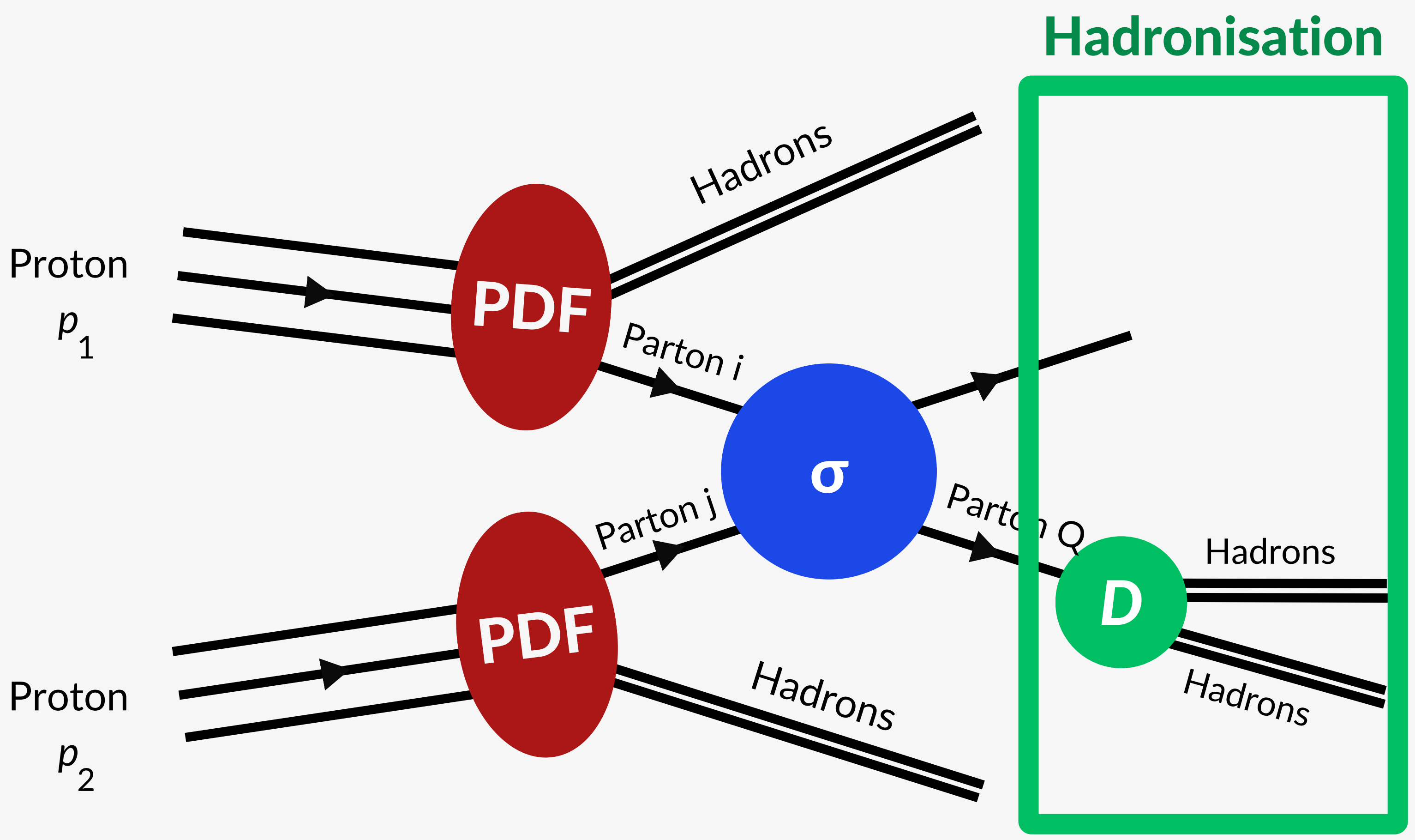
PDFs

Parton scattering cross section

Fragmentation function (Hadronisation)

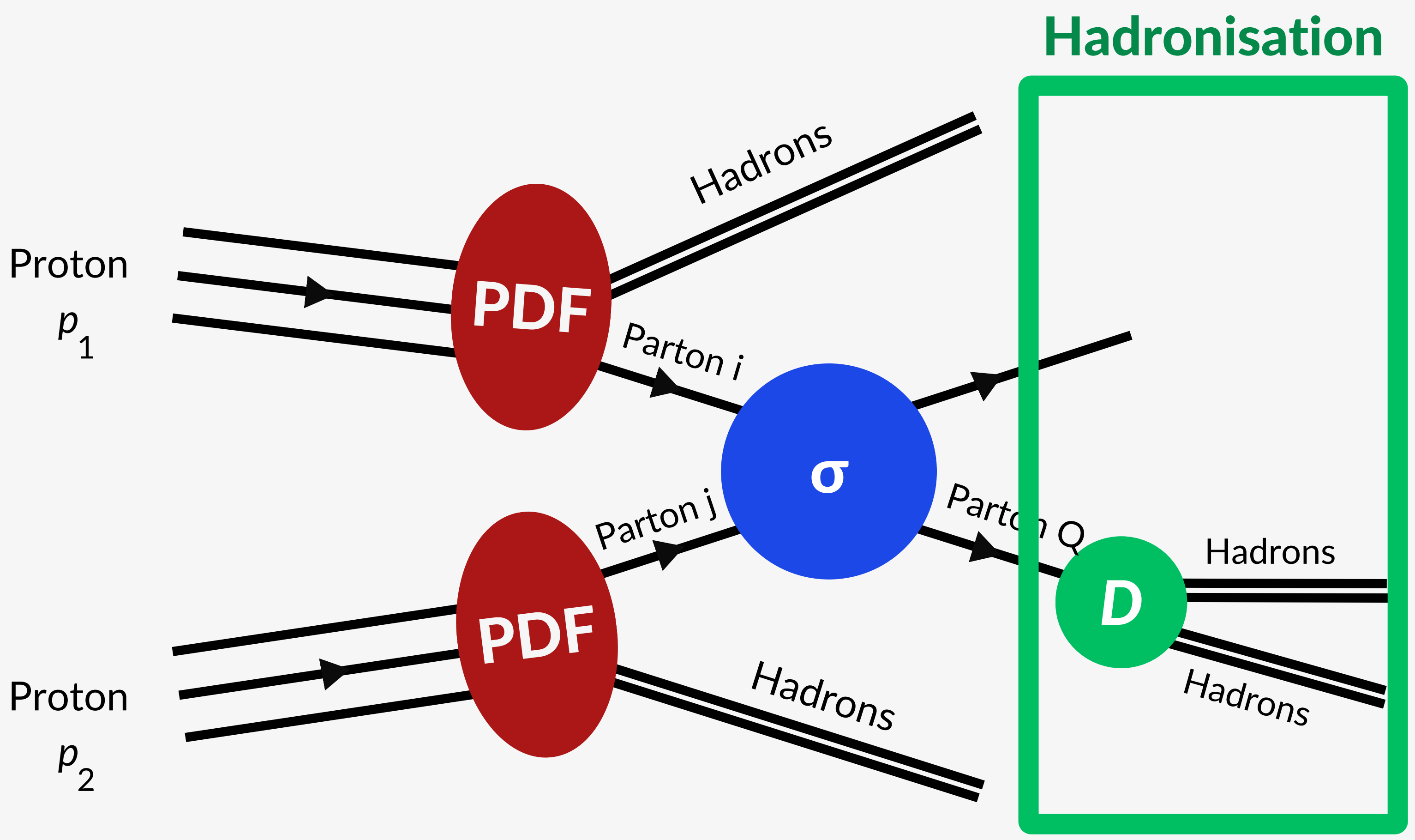


Heavy quarks and hadronisation



- Fragmentation functions are generally considered to be **universal across collision systems**
  - Extracted from e^+e^- and ep measurements
- One way to study hadronisation is through **particle yields and ratios:**
  - **Meson-to-meson:** measurements in pp and p—Pb are consistent with e^+e^- and ep
  - **Baryon-to-meson:** differences between e^+e^- and pp (or p—Pb)!

Heavy quarks and hadronisation



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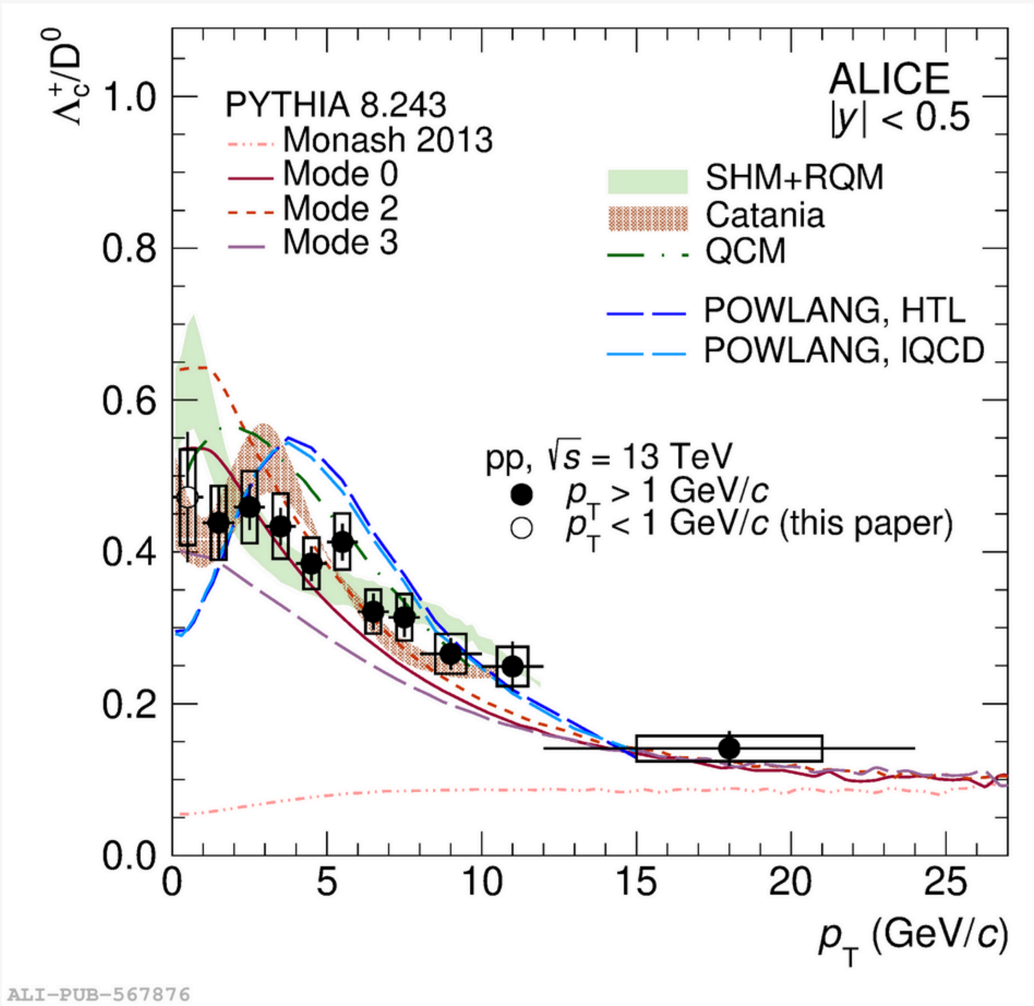
Heavy-flavour baryon-to-meson ratios show a **strong enhancement at low p_T**, even in pp. Some possible explanations include:

- Existence of unobserved **excited baryon states**
- **Colour reconnection** beyond leading colour approximation
- **Coalescence**

More studies are needed



JHEP 12 (2023) 086

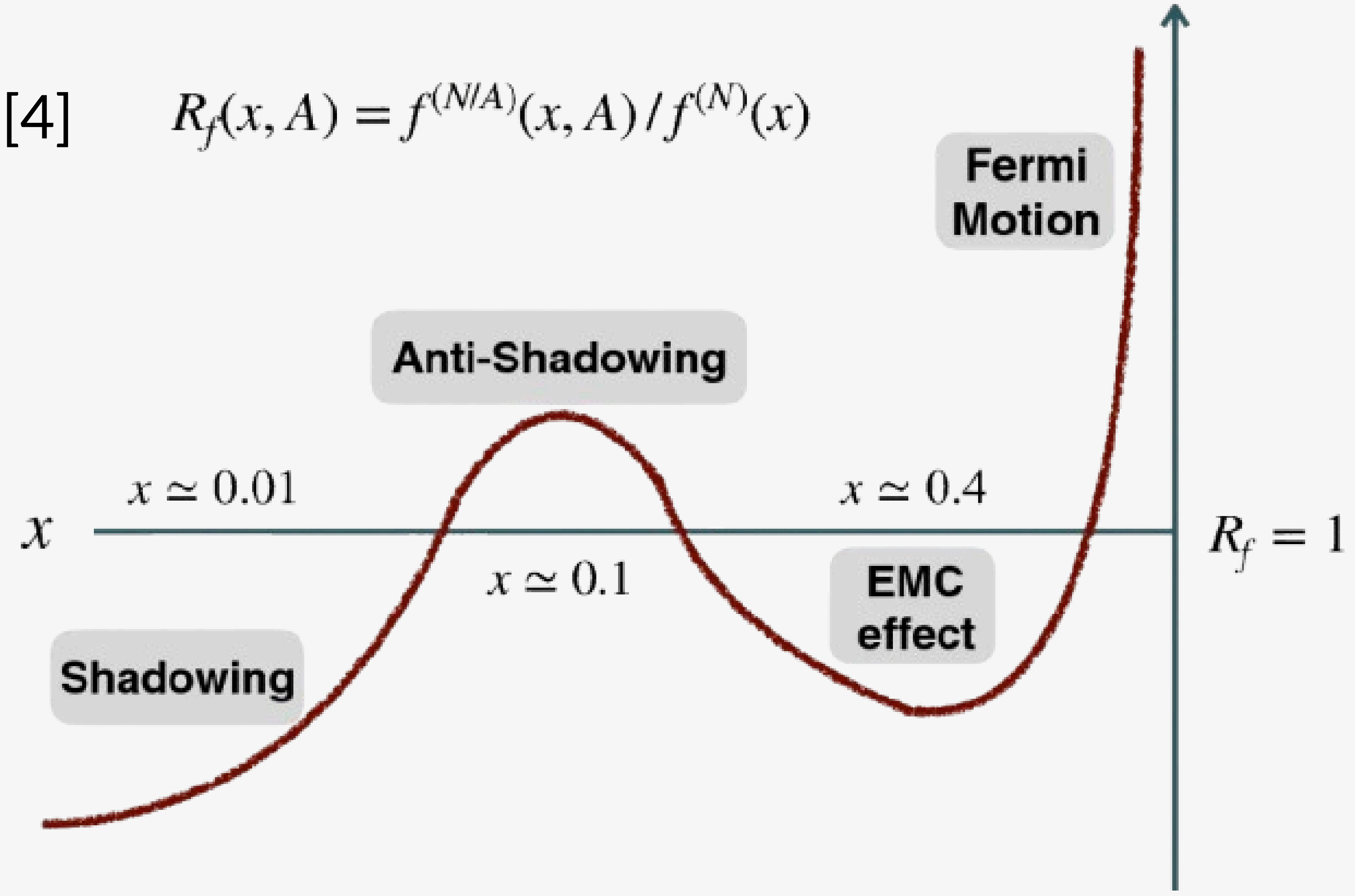
Cold nuclear matter (CNM) effects

Effects caused by the presence of nuclei in the colliding system

Initial-state effects

- PDFs are modified depending on *x*. These effects can be described by **nuclear PDFs** (nPDFs) [1]
  - **Gluon saturation** could cause this modification at low *x* [2]
- Enhanced initial-state radiation, leading to **energy loss** [3]
- Soft partonic collisions that cause **momentum broadening** [4]

$$R_f(x, A) = f^{(N/A)}(x, A) / f^{(N)}(x)$$



Final-state effects

- **Flow-like** effects from collective motion
- **Quark recombination** enhancement

[1] Khalek, R.A., Ethier, J.J. & Rojo, J. Eur. Phys. J. C 79, 471 (2019).
[2] *P. Tribedy, R. Venugopalan*, Phys.Lett.B 718 (2013) 1154
[3] *I. Vitev*, Phys.Rev.C75 (2007), 064906
[4] *X. Wang*, Phys.Rev.C 61 (2000), 064910

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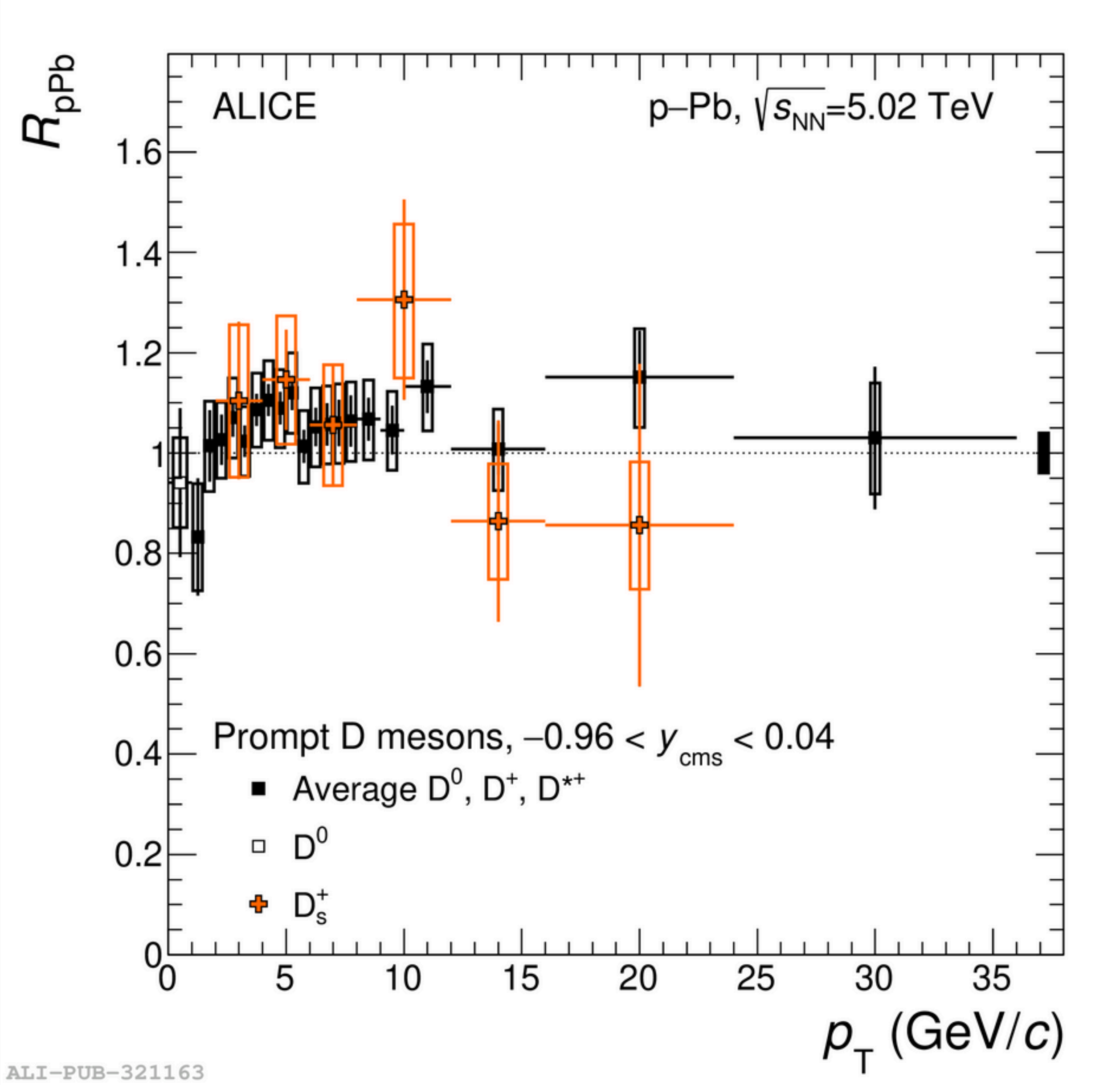
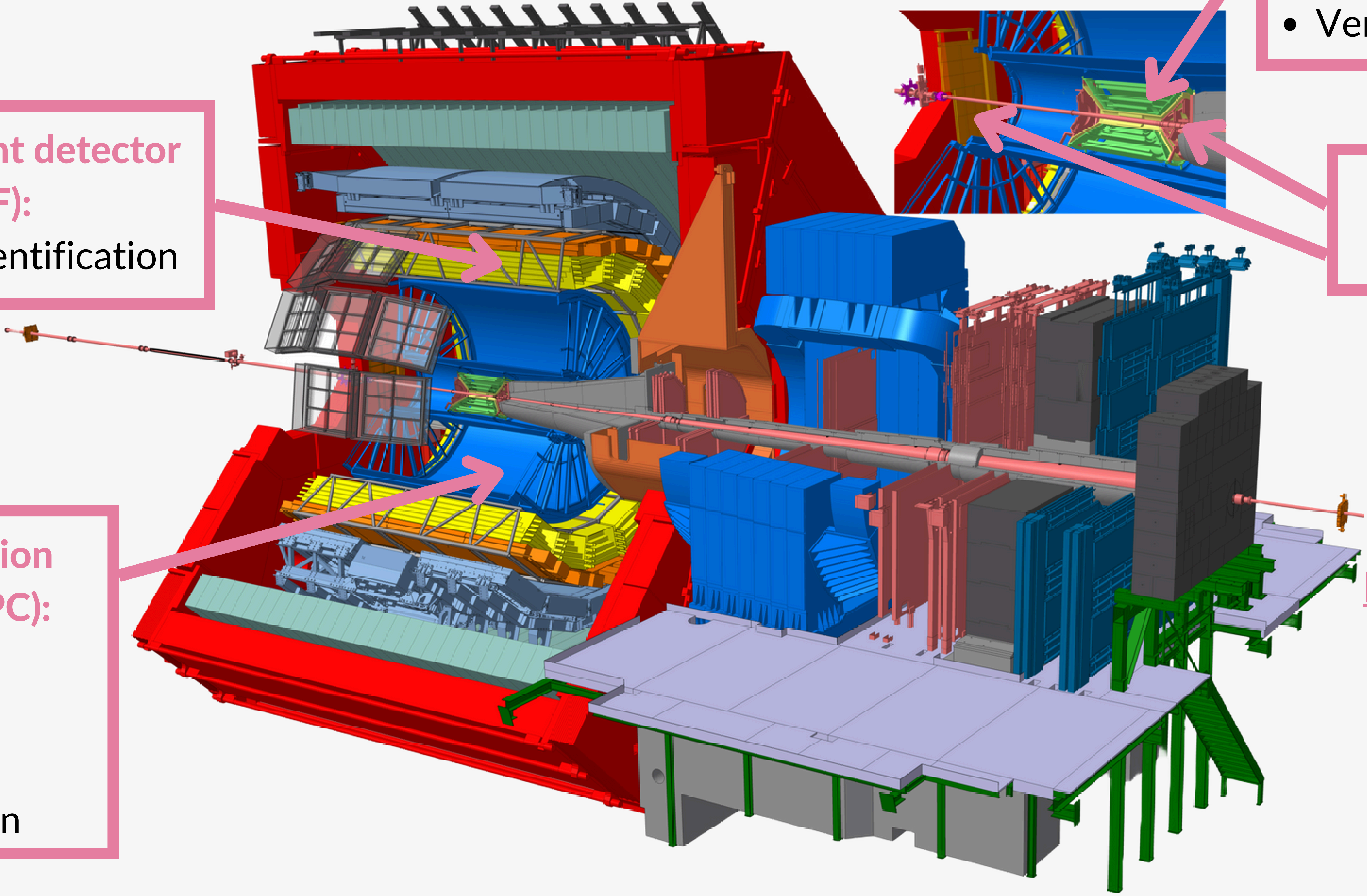
CNM effects can be investigated by studying the **nuclear modification factor**, R_{pPb} :

$$R_{\mathrm{pPb}} = \frac{1}{A_{\mathrm{Pb}}} \frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



JHEP 1912 (2019) 092

ALICE in Run 2



Inner Tracking System (ITS):
- Tracking
- Vertexing

Time-of-Flight detector (TOF):
- Particle identification

V0 detectors:
- Triggering

Time Projection Chamber (TPC):
- Tracking
- Vertexing
- Particle identification

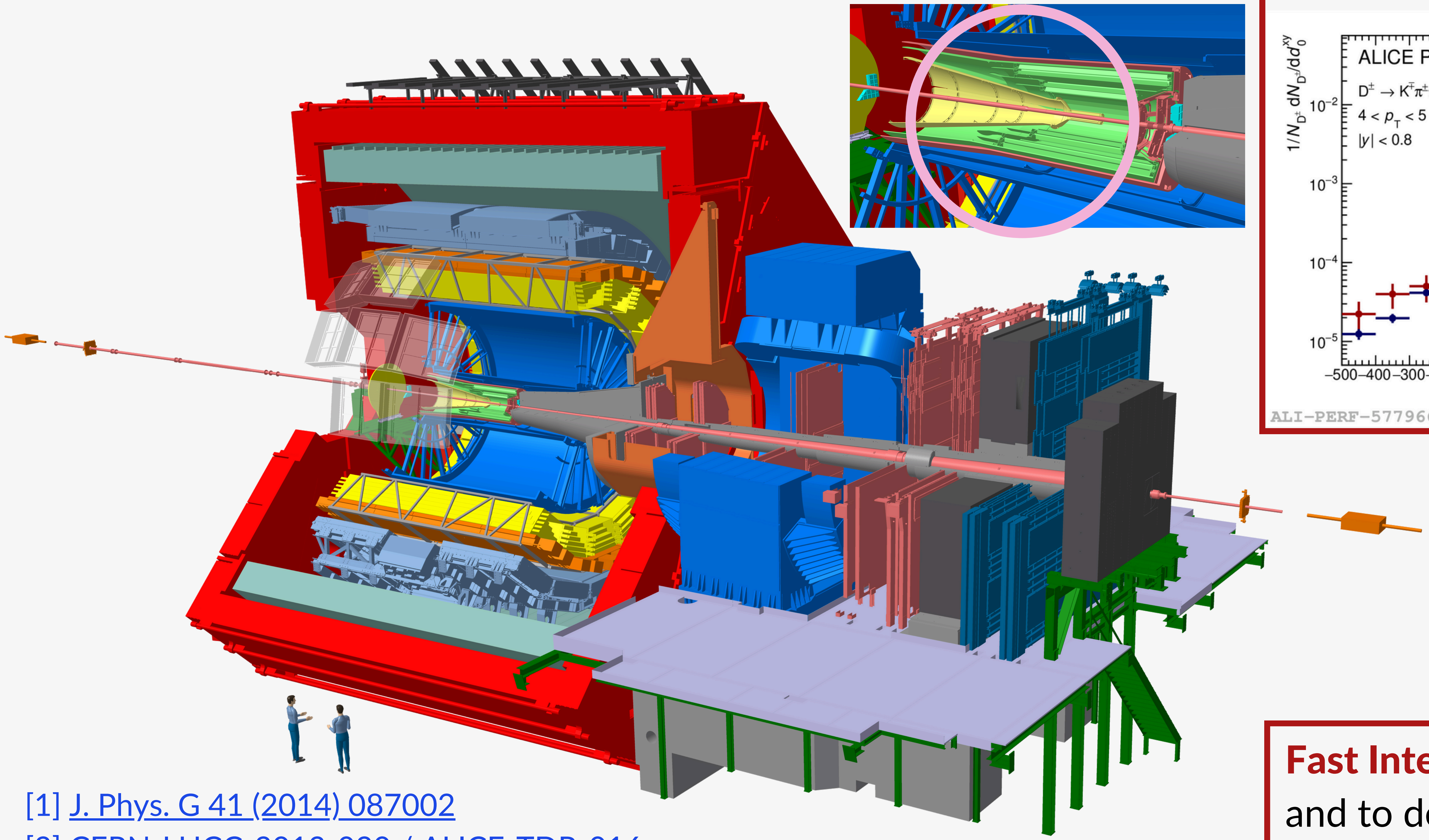
Charm hadrons are reconstructed using the **central barrel**

Rapidity coverage: **$|\eta| < 0.9$**

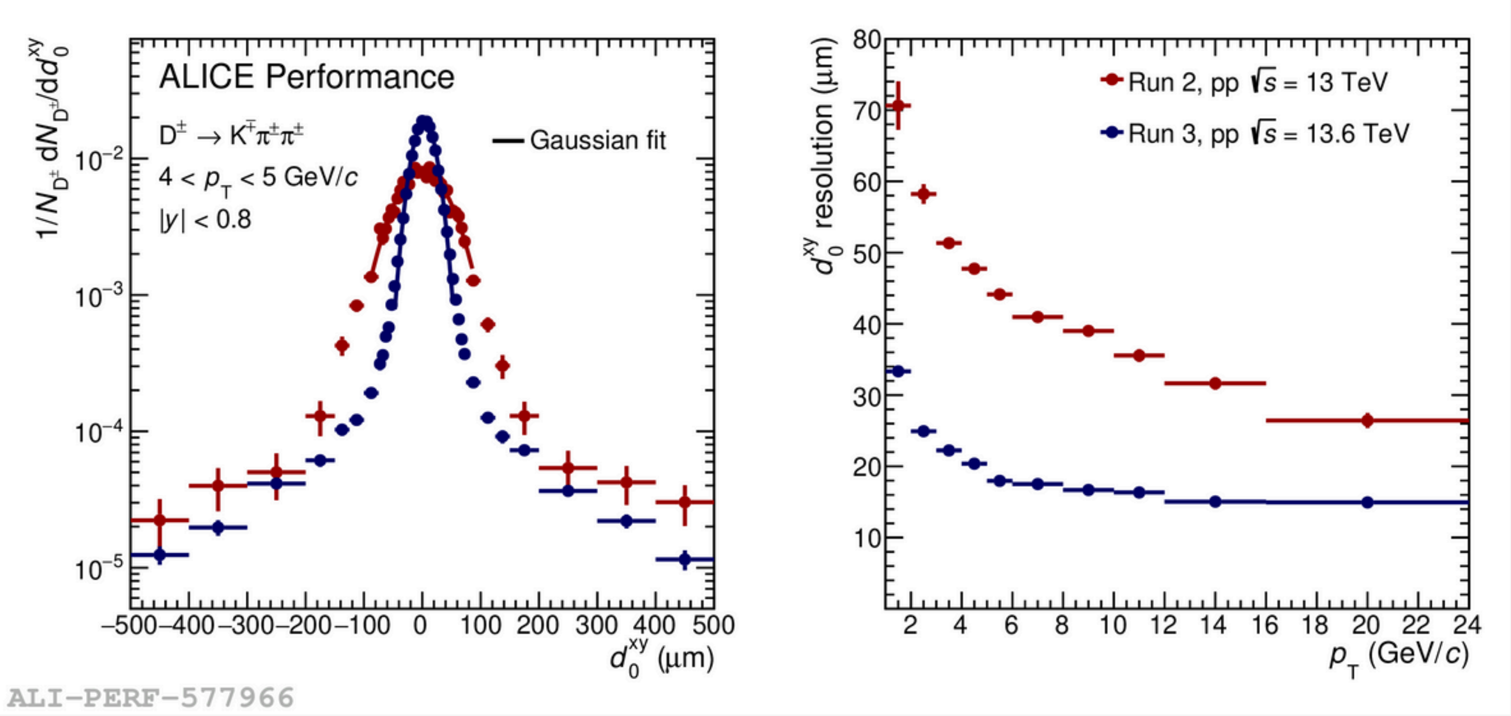
HF hadron reconstruction in this talk

- $D^0 \longrightarrow K^-\pi^+$
- $D^+ \longrightarrow K^-\pi^+\pi^+$
- $D_s^+ \longrightarrow \Phi\pi^+ \longrightarrow K^+K^-\pi^+$
- $\Lambda_c^+ \longrightarrow pK_s^0 \longrightarrow p\pi^+\pi^-$
- $\Lambda_c^+ \longrightarrow pK^-\pi^+$

Run 3 vs. Run 2



ITS2 [1]: improved resolution and faster readout

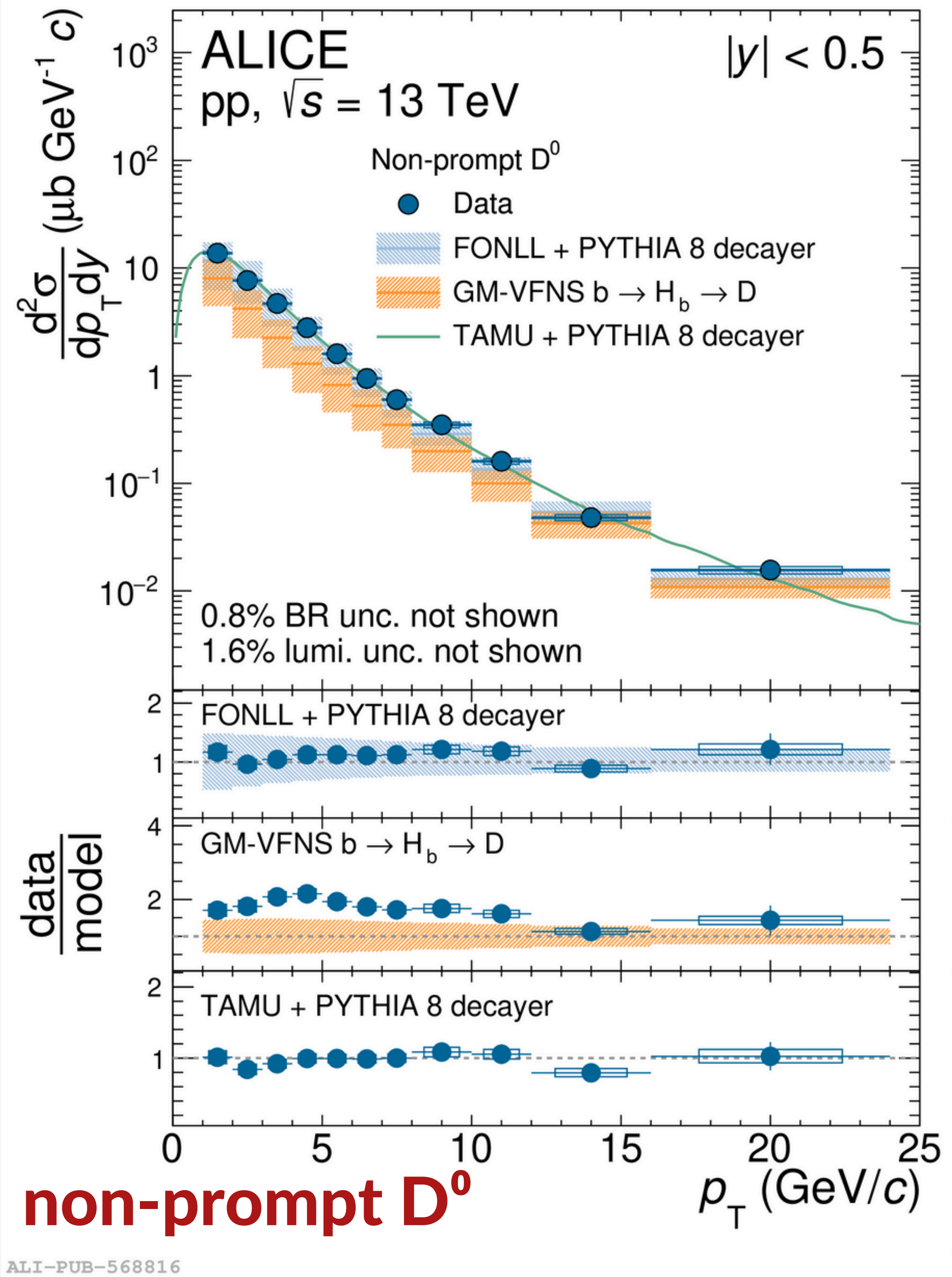


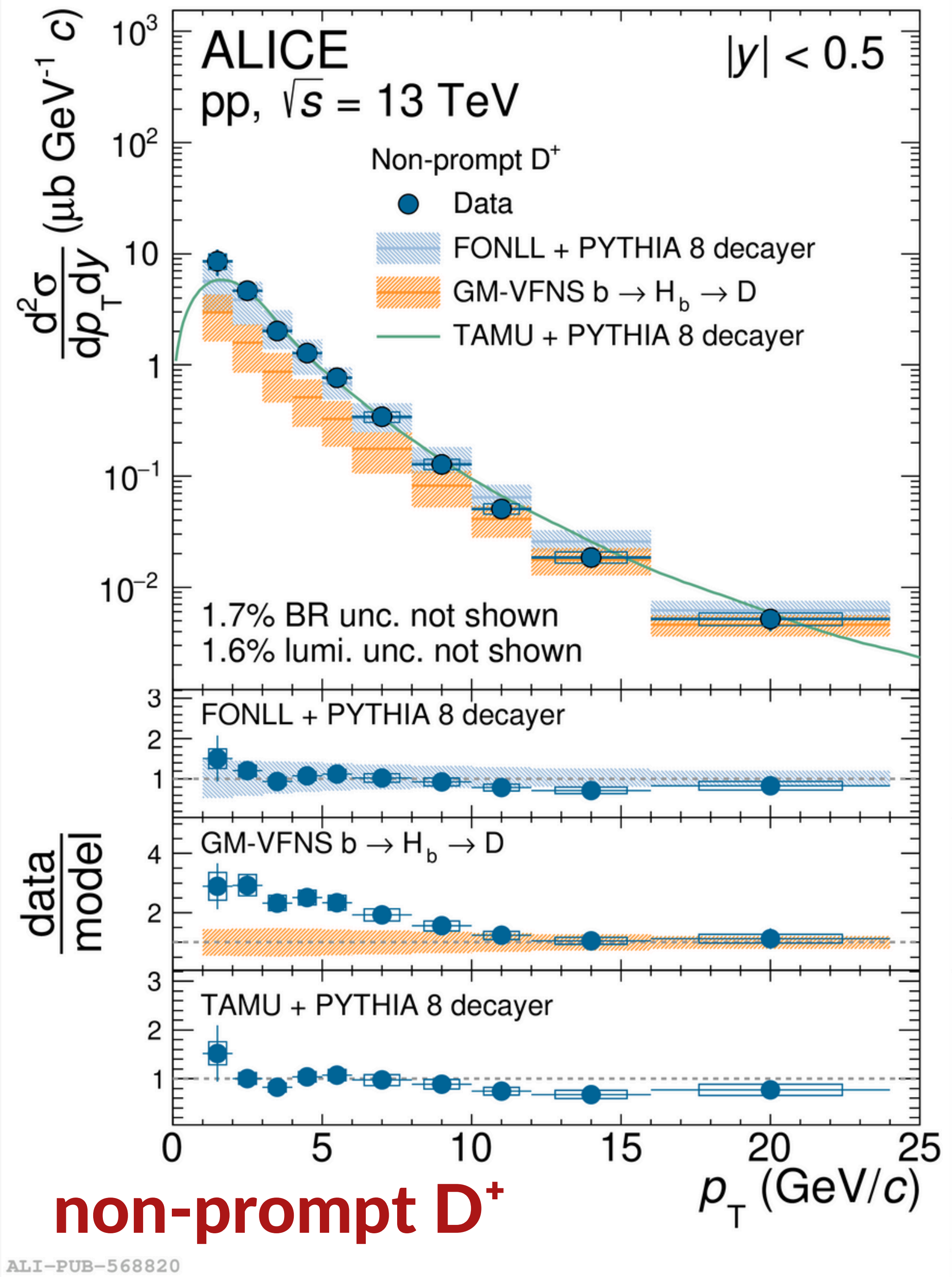
New TPC readout [2]: allows for continuous readout, granting **much larger datasets** than in Run 2

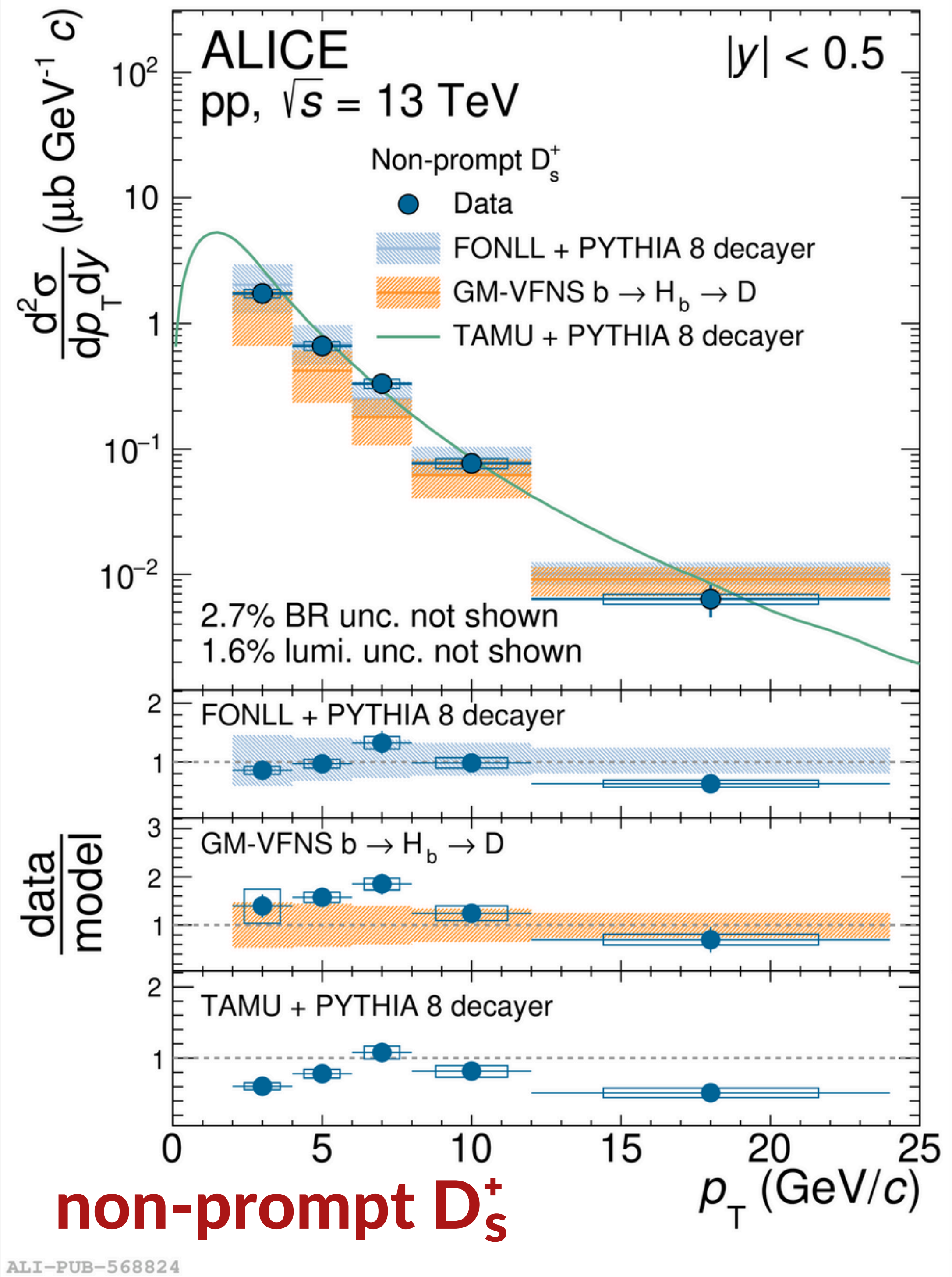
Fast Interaction Trigger (FIT) [3]: used to trigger and to determine luminosity and multiplicity

[1] J. Phys. G 41 (2014) 087002
[2] CERN-LHCC-2013-020 / ALICE-TDR-016
[3] EPJ Web Conf. 204 (2019) 11003

Non-prompt D-meson cross sections (pp)







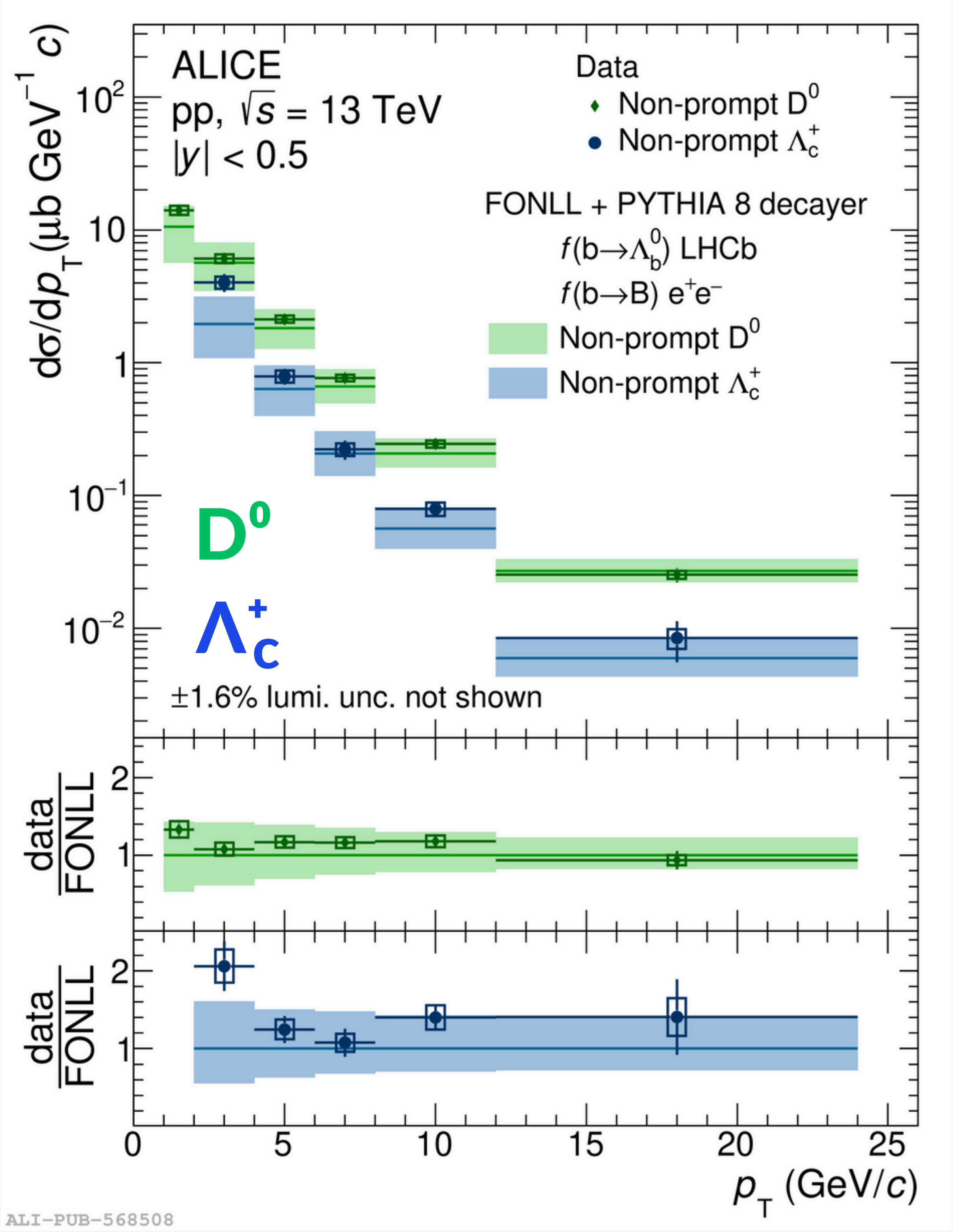
arXiv:2402.16417

- **FONLL + PYTHIA 8 decayer** is consistent with the data for all D-mesons
- **GM-VFNS** underestimates the measurements at low p_T
- **TAMU + PYTHIA 8** agrees with the data for D^0 and D^+, but overestimates the data for D_s^+

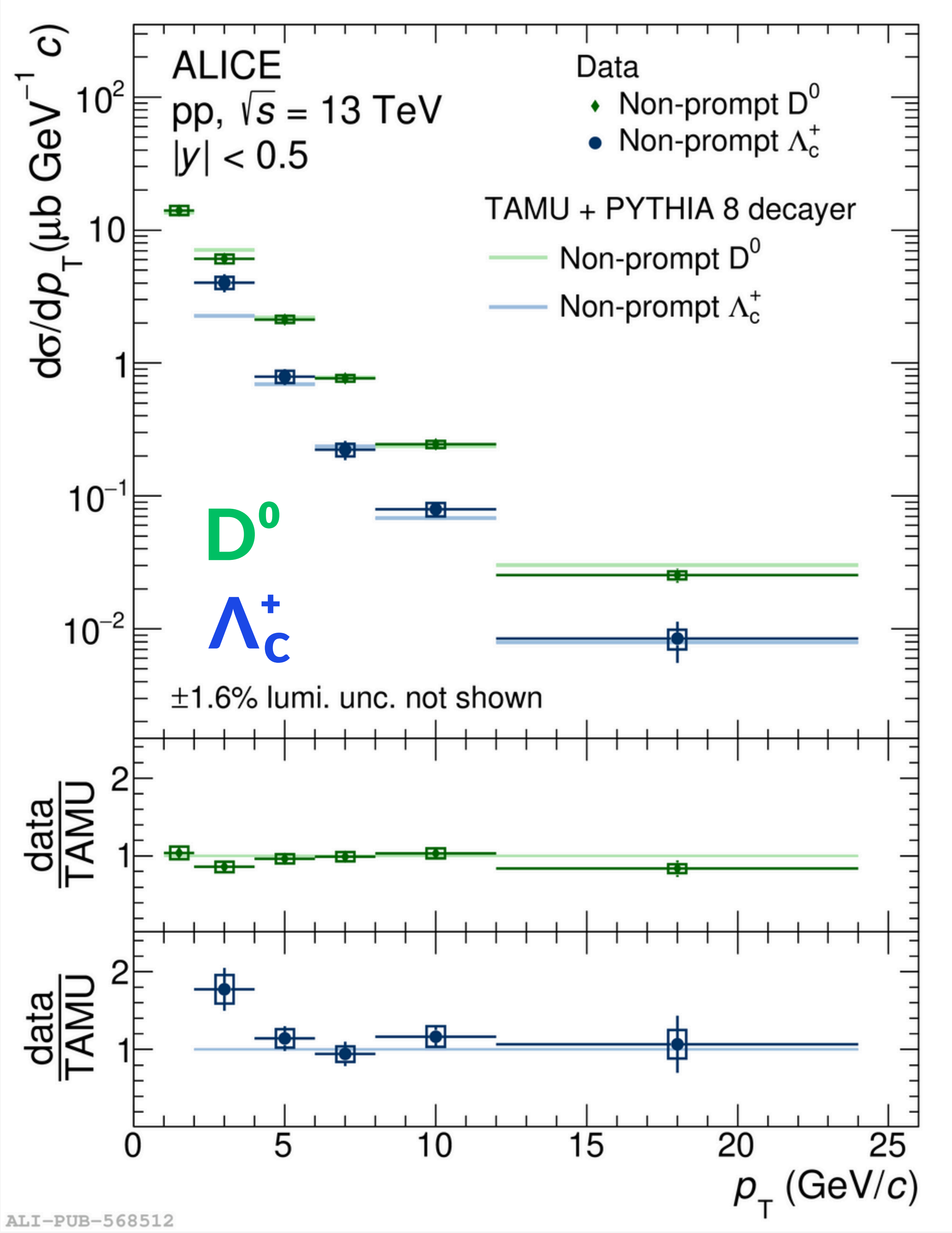
Non-prompt Λ_c^+ cross-section

pp

Comparison with FONLL



Comparison with TAMU

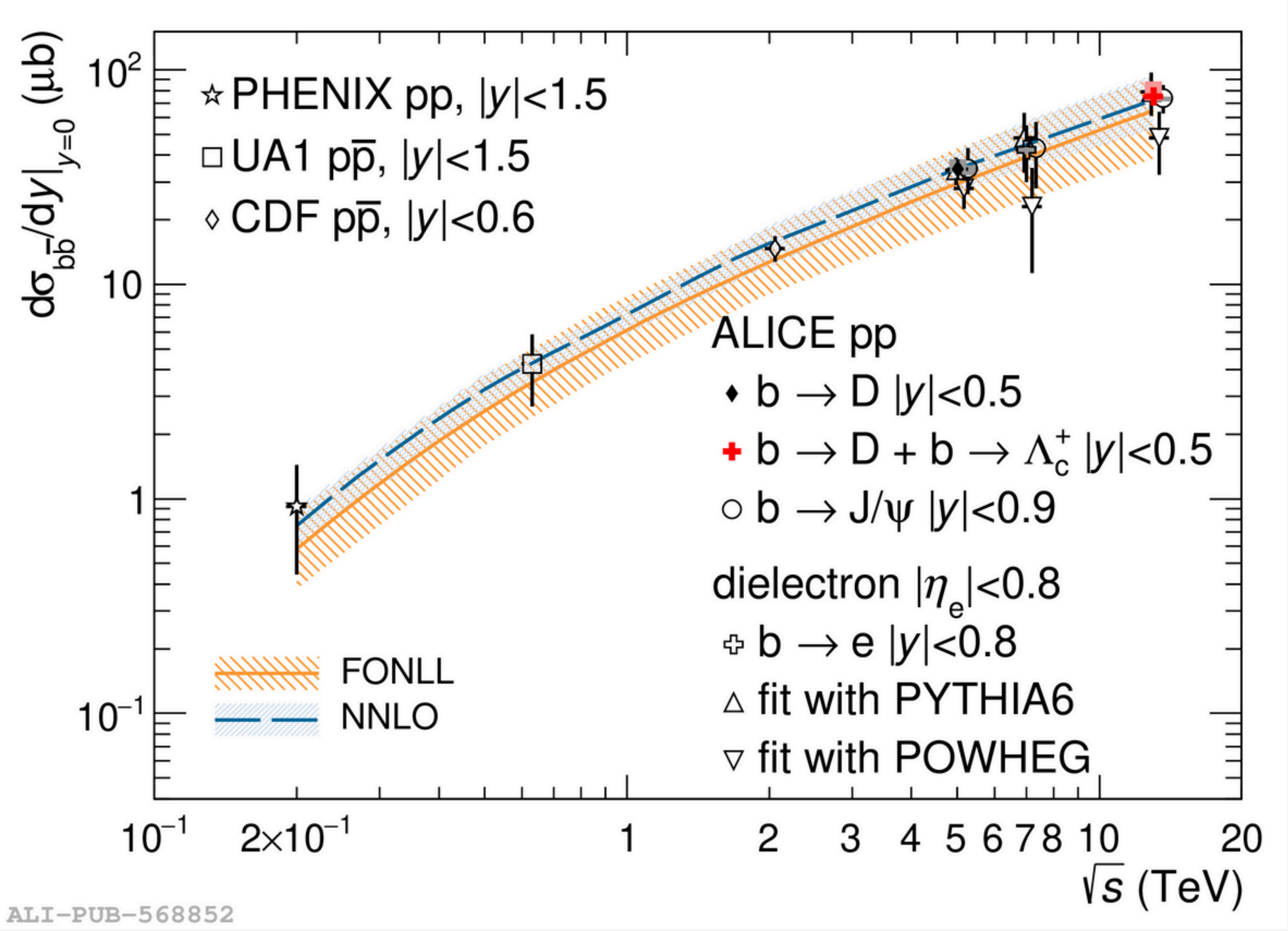


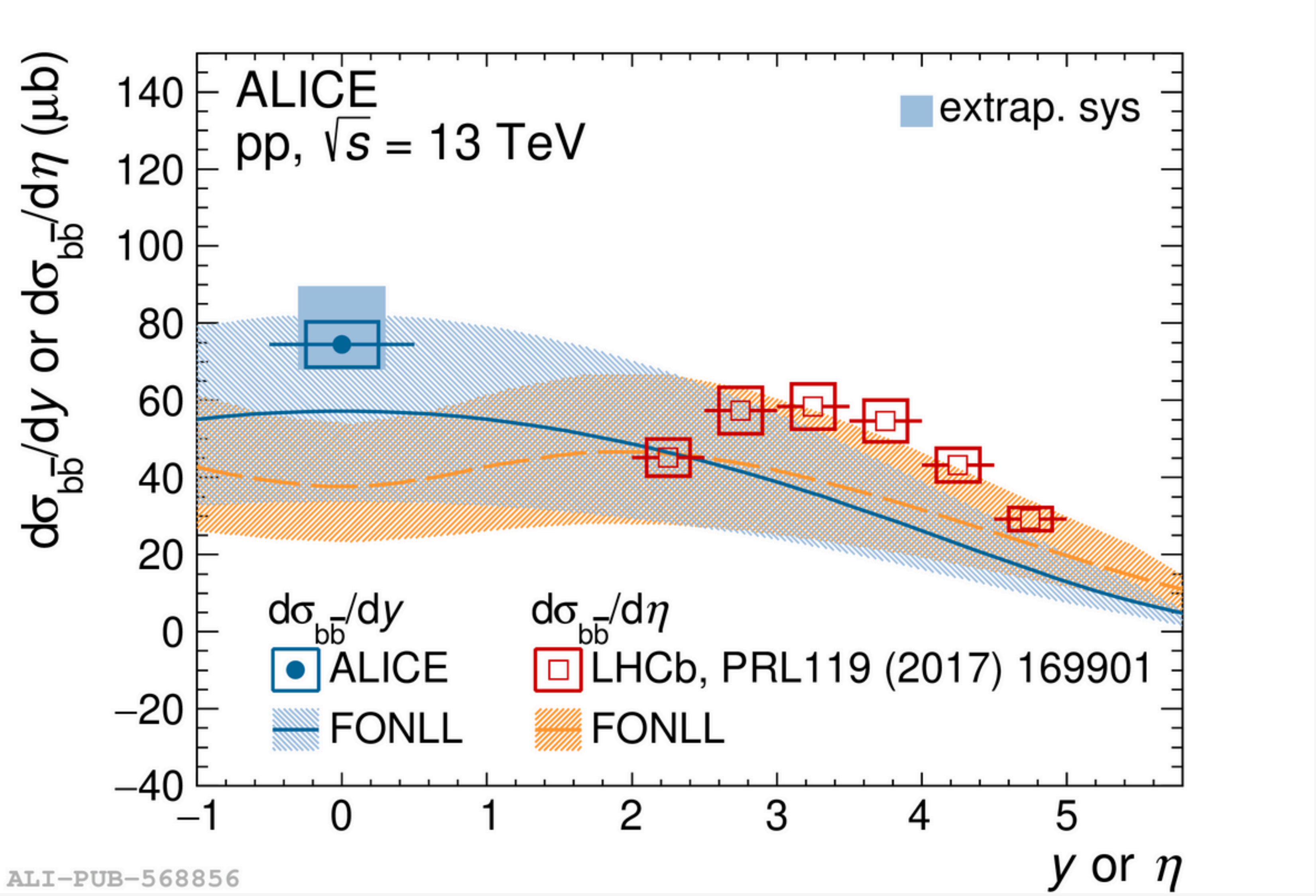
- Weighted average of the results from $\Lambda_c^+ \rightarrow pK_S^0 \rightarrow p\pi^+\pi^-$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$
- Results compared to FONLL + PYTHIA 8 and TAMU + PYTHIA 8
  - Both tend to underestimate the data in the $2 < p_T < 4$ GeV/c interval

FONLL: *M. Cacciari, M. Greco, P. Nason,* JHEP 9805 (1998) 007
GM-VFNS: *P. Bolzoni, G. Kramer,* Nucl. Phys. B 872, 253 (2013)
TAMU: M. *He and R. Rapp,* Phys. Rev. Lett. 131 (2023) 012301

Phys. Rev. D 108, 112003 (2023)

$b\bar{b}$ production cross section





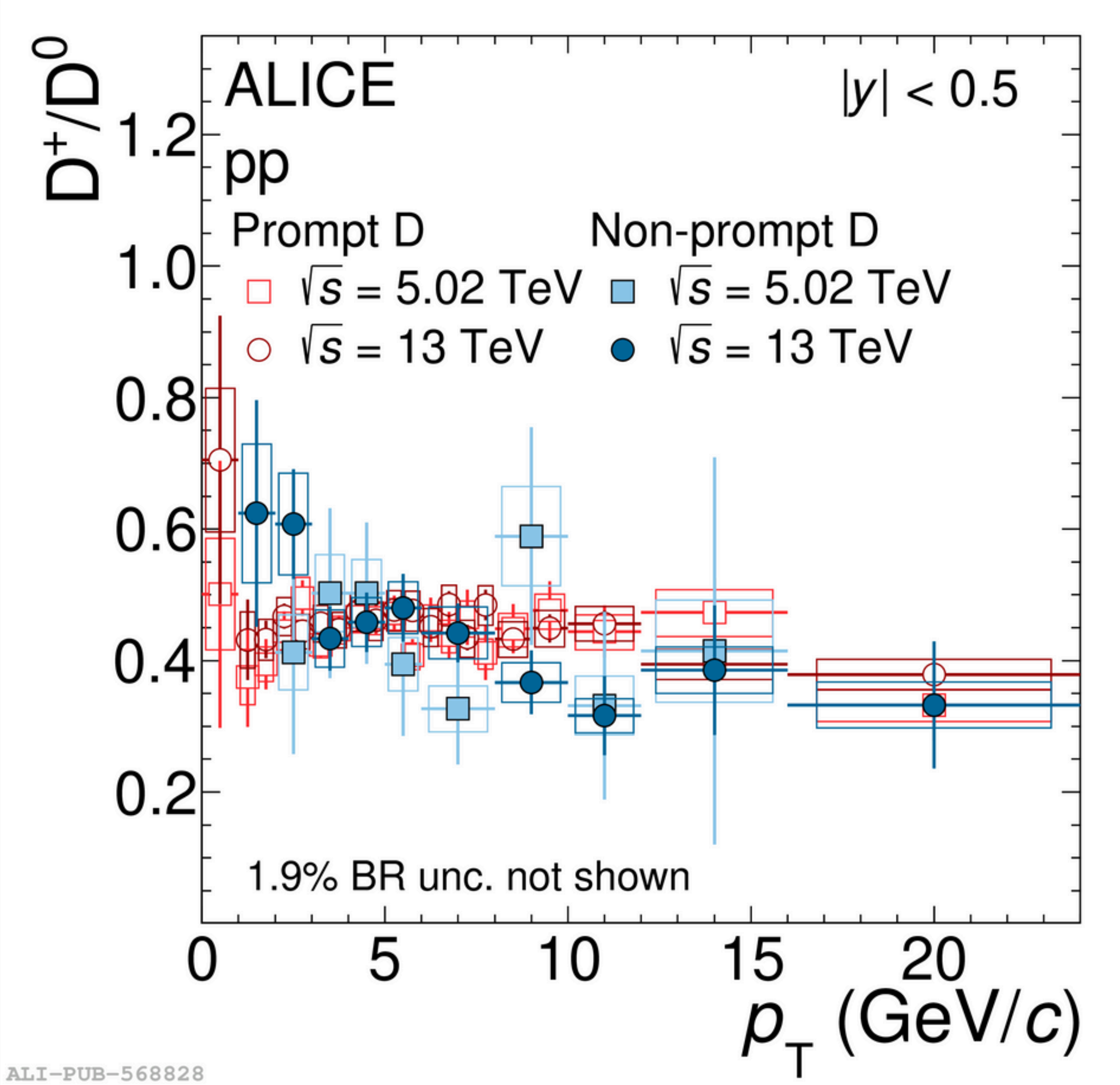
p_T-integrated measurement at midrapidity based on the production cross sections of D^0, D^+, D_s^+ and Λ_c^+

NEW on ArXiv!

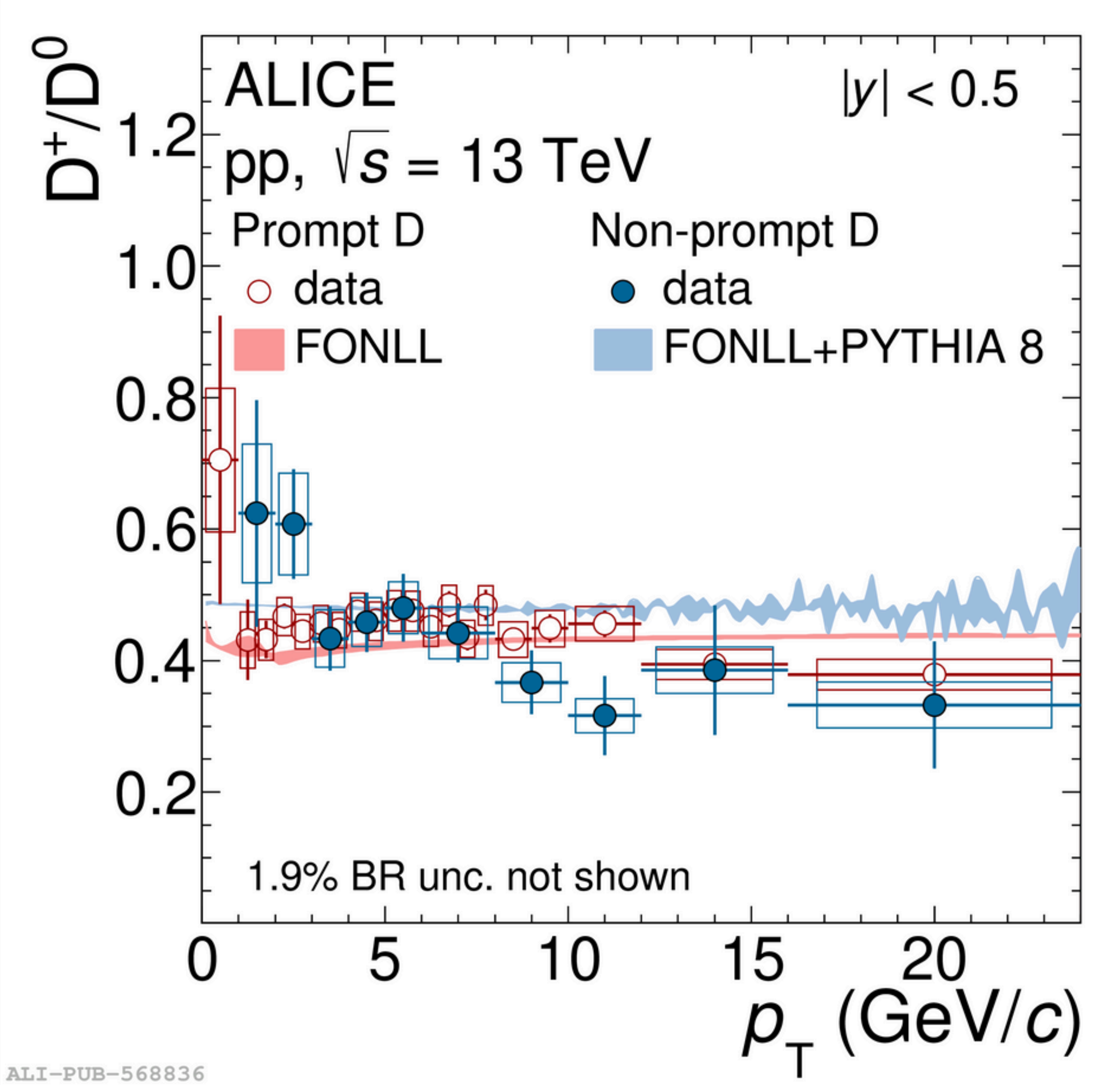
- The **cross section vs. centre-of-mass energy is well described** by pQCD, especially NNLO
- **Results** are compatible with pQCD but tend to lie **close to the upper boundary** of the uncertainty bands

Meson-to-meson ratios

D^+/D^0 at different centre-of-mass energies



D^+/D^0 vs. theoretical predictions



Compatible results at different collision energies

Similar ratios for prompt and non-prompt contributions

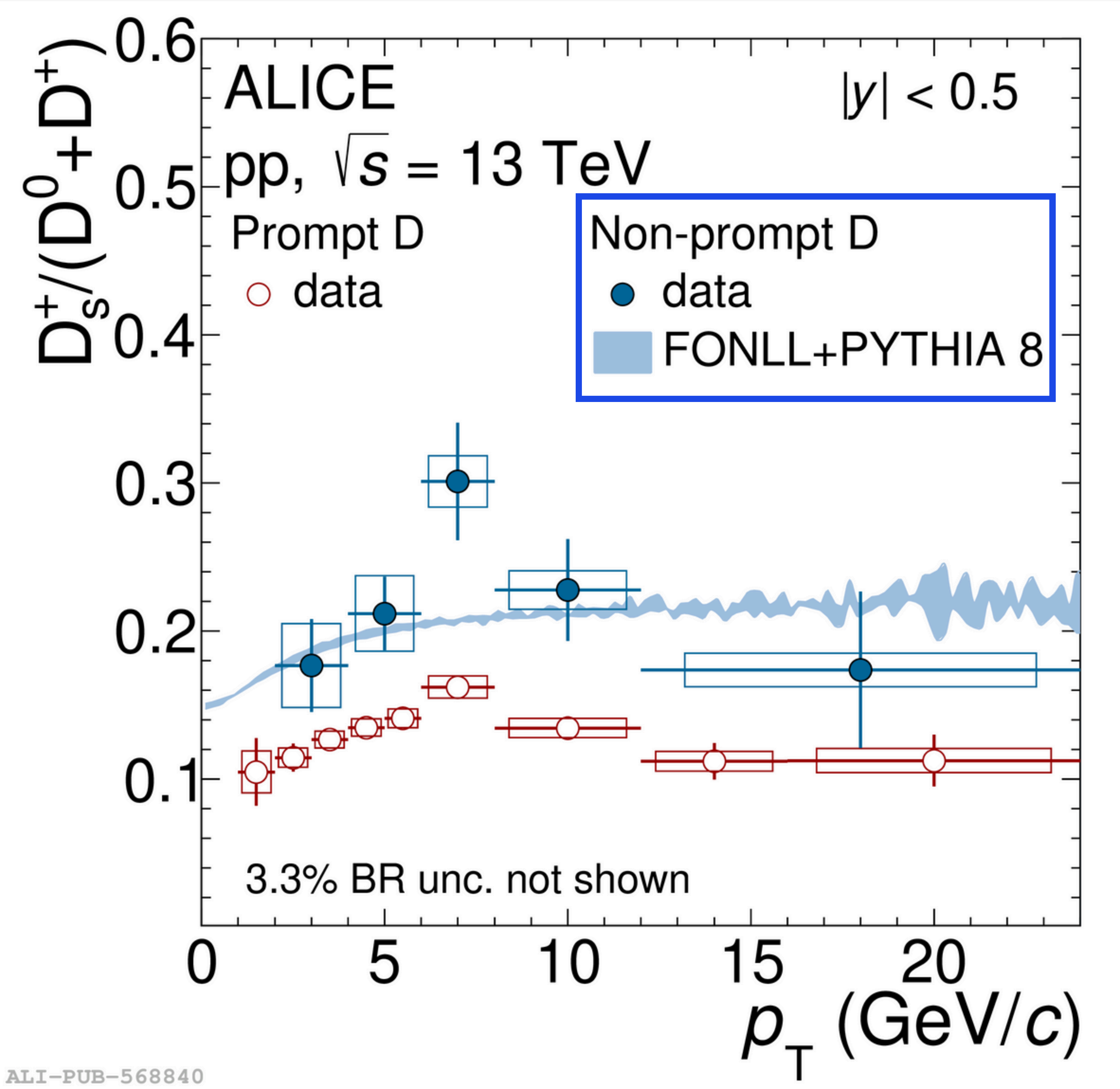
Results are well described by FONLL + PYTHIA 8

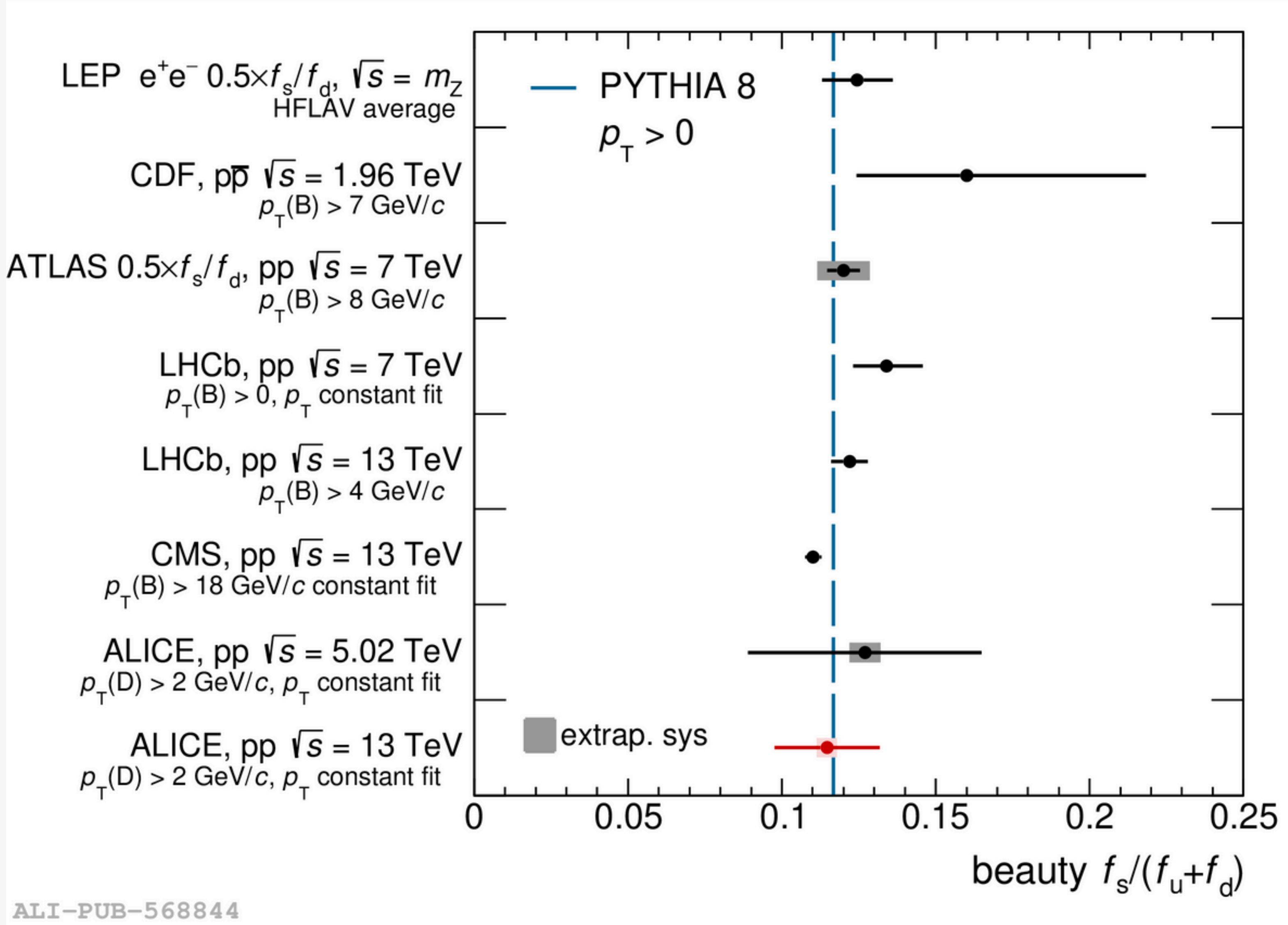
NEW on ArXiv!

arXiv:2402.16417

Strange meson-to-meson ratio

prompt vs. non-prompt $D_s^+/(D^0+D^+)$





Beauty $f_s/(f_d+f_u)$

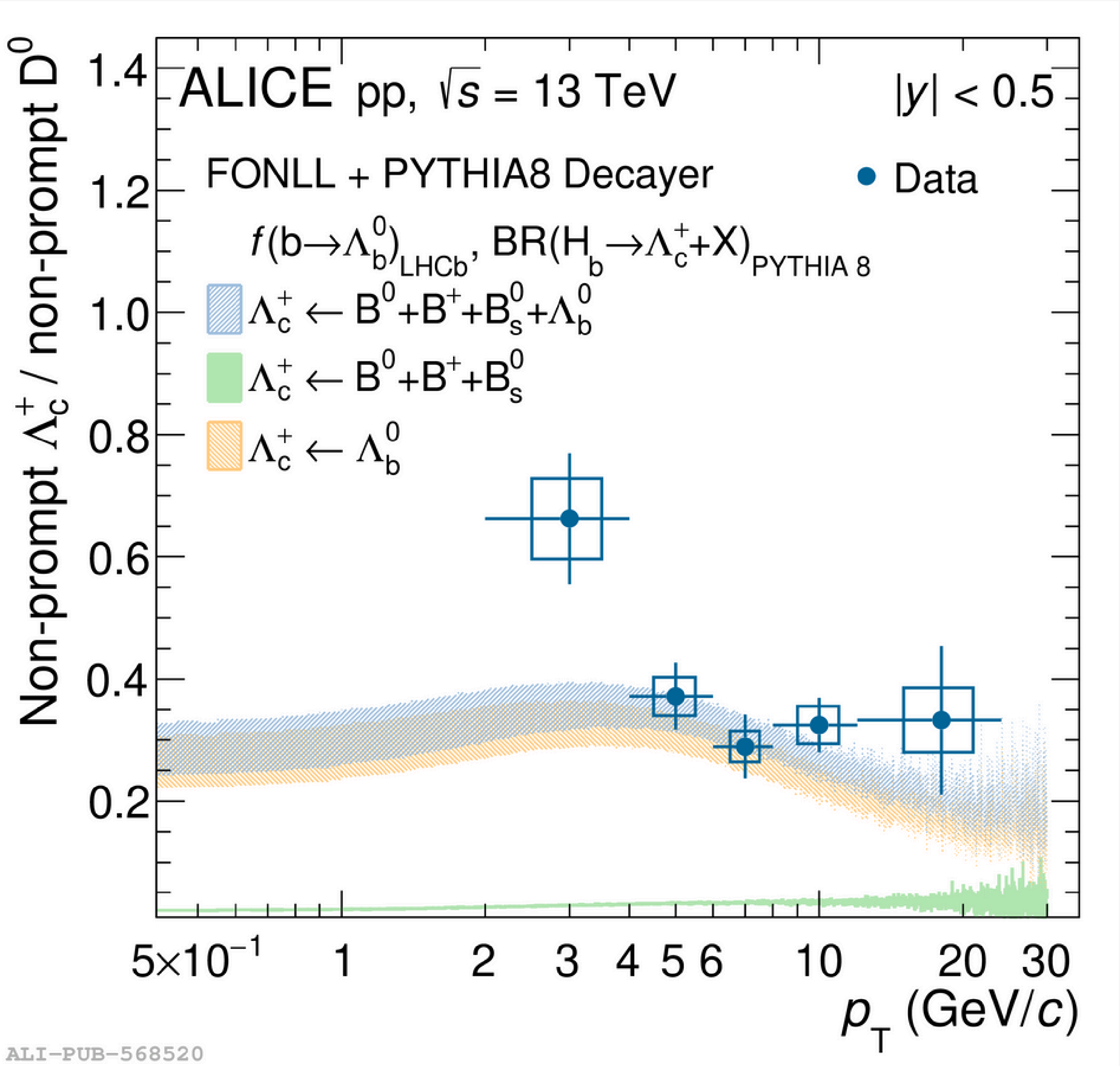
- Access to **fragmentation fraction ratio of beauty quarks into strange (f_s) and non-strange (f_u, f_d) B** mesons
- **Compatible** with previous results and PYTHIA 8

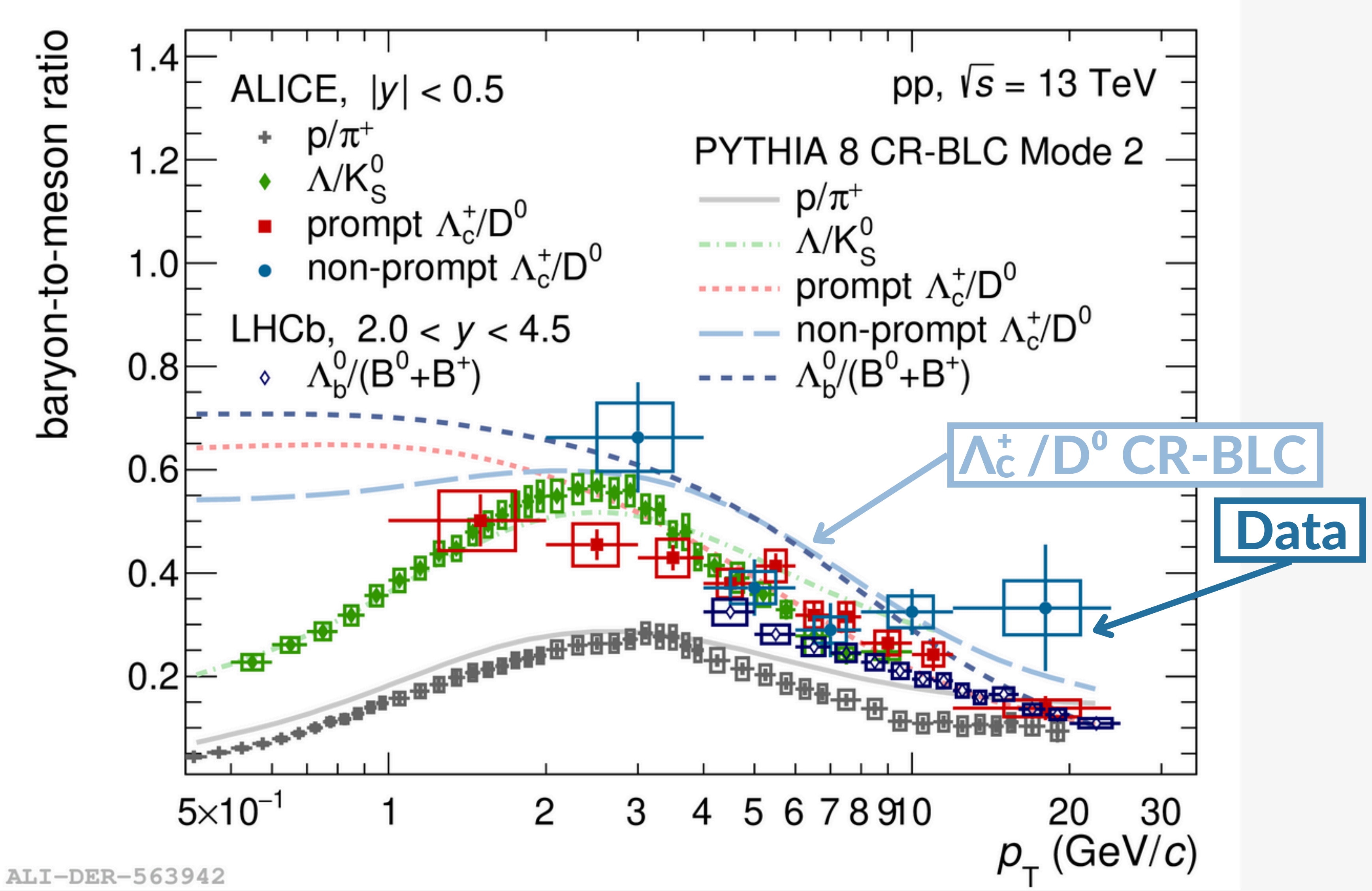
NEW on ArXiv!

arXiv:2402.16417

Baryon-to-meson ratio

Non-prompt Λ_c^+/ non-prompt D^0 ratio vs. theoretical predictions

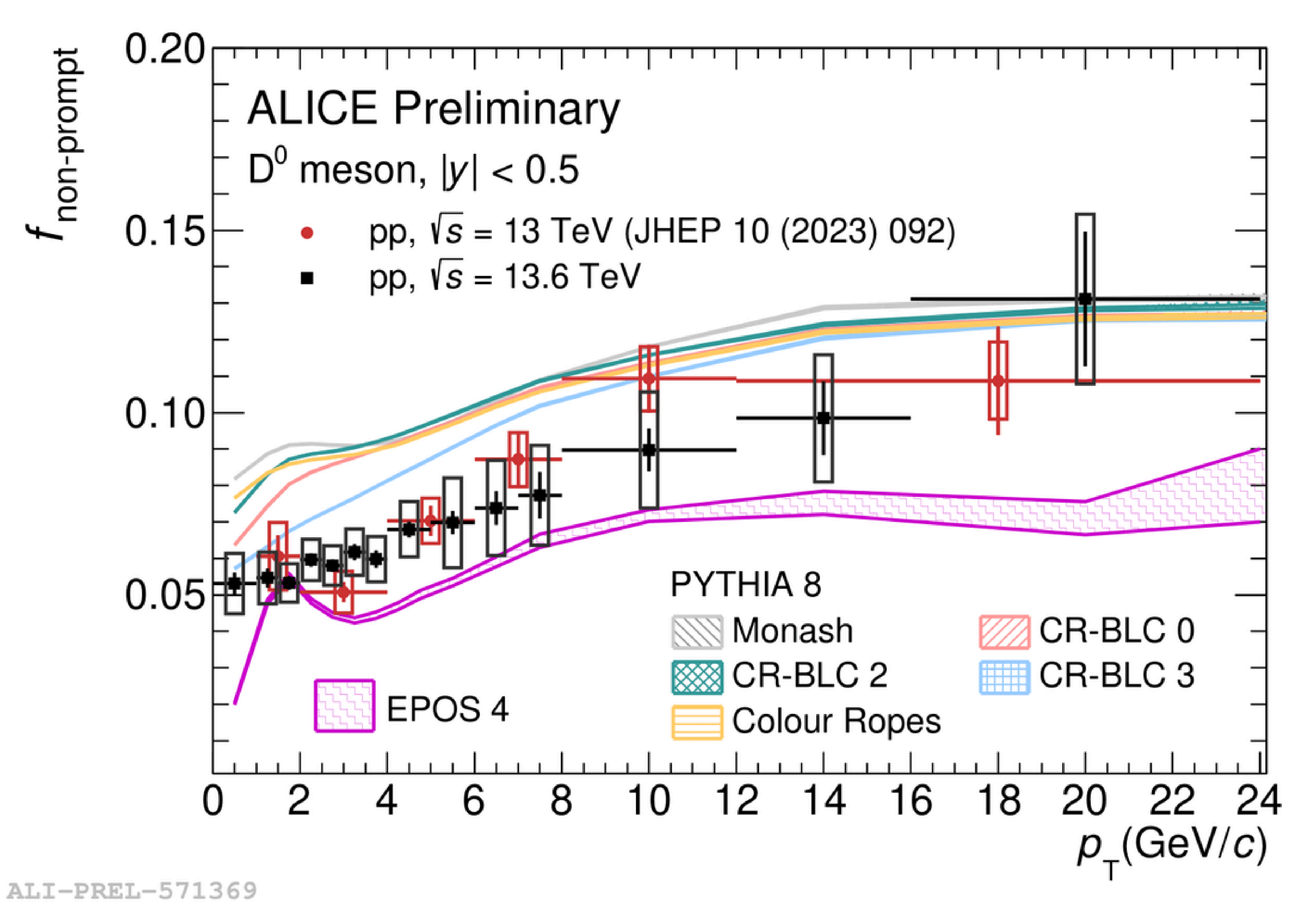




- Most non-prompt Λ_c^+ **baryons come from** Λ_b^0 , rather than B mesons
- **FONLL + PYTHIA 8** provides a good description at $p_T > 4$ GeV/c
- **PYTHIA 8 CR-BLC** accurately describes the data

Phys. Rev. D 108, 112003 (2023)

D^0 non-prompt fraction (Run 3)

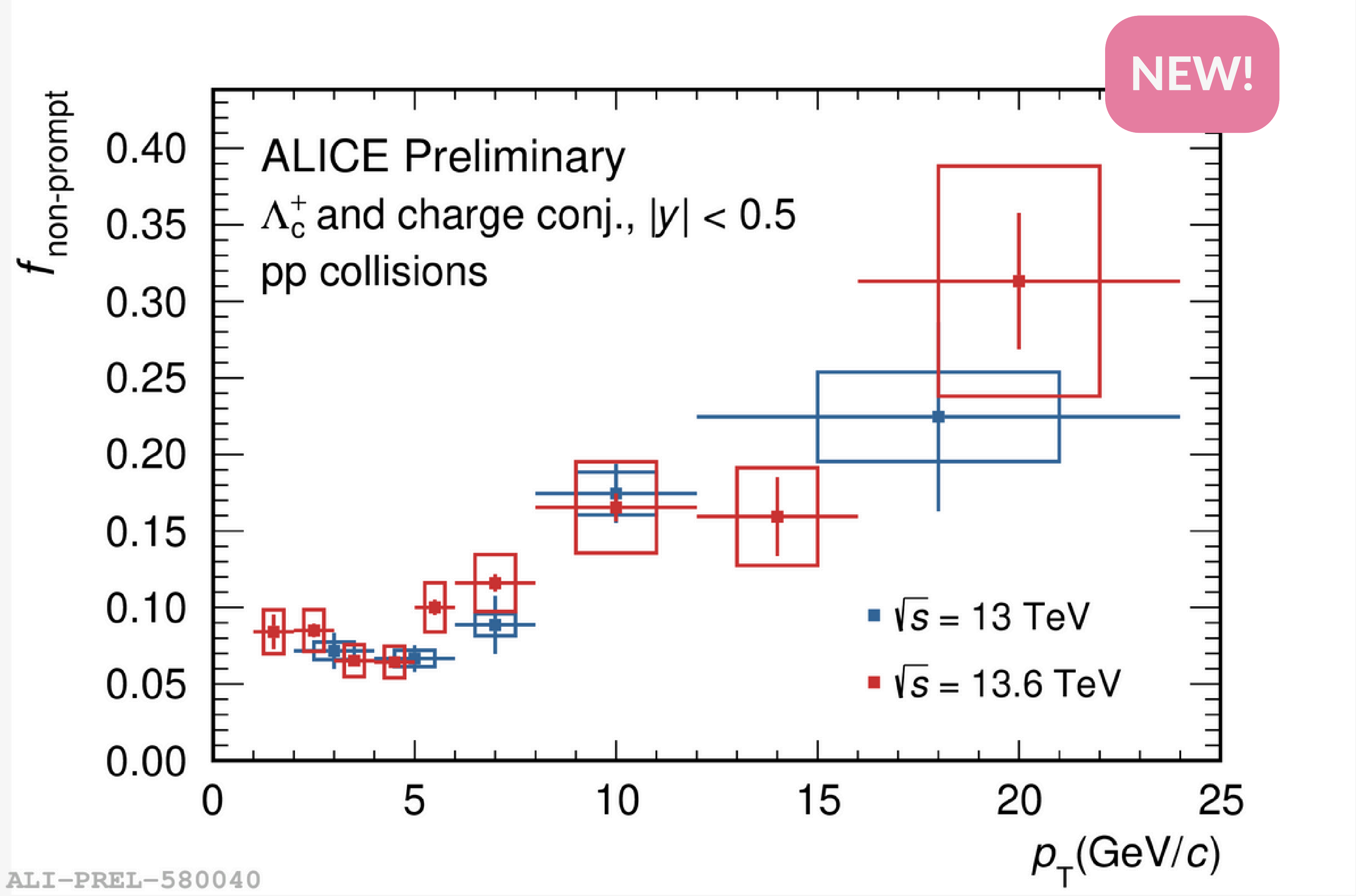


- **Increased precision** compared to Run 2
- **More granular results** are achieved, with an extension down to $p_T = 0$
- **Tighter constraints** to hadronisation models:
  - Overall, PYTHIA tunes seem to overestimate the data
  - EPOS 4 tends to underestimate the data

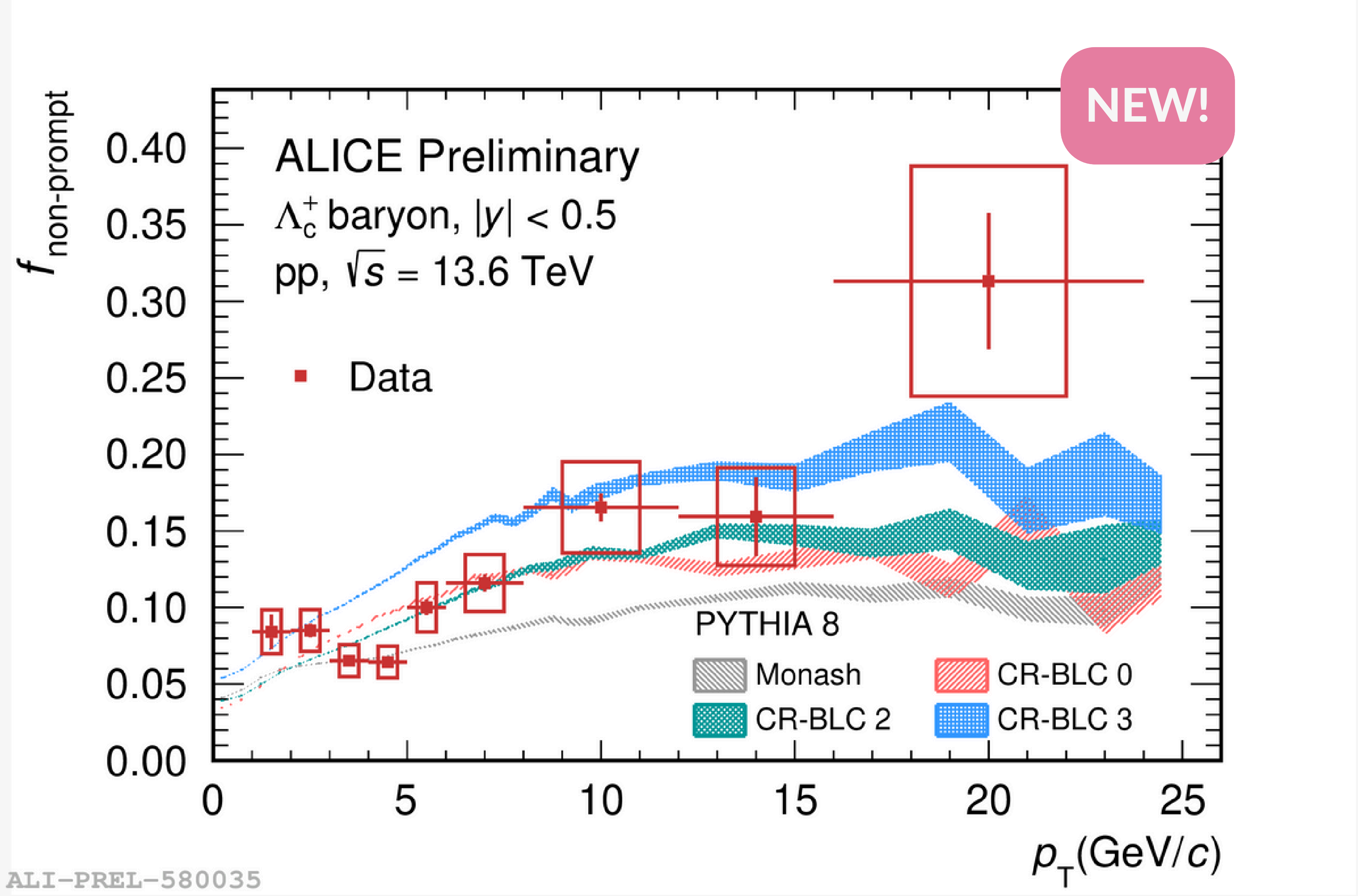
Non-prompt Λ_c^+ fraction (Run 3)

pp

Λ_c^+ non-prompt fraction Run 3 vs. Run 2



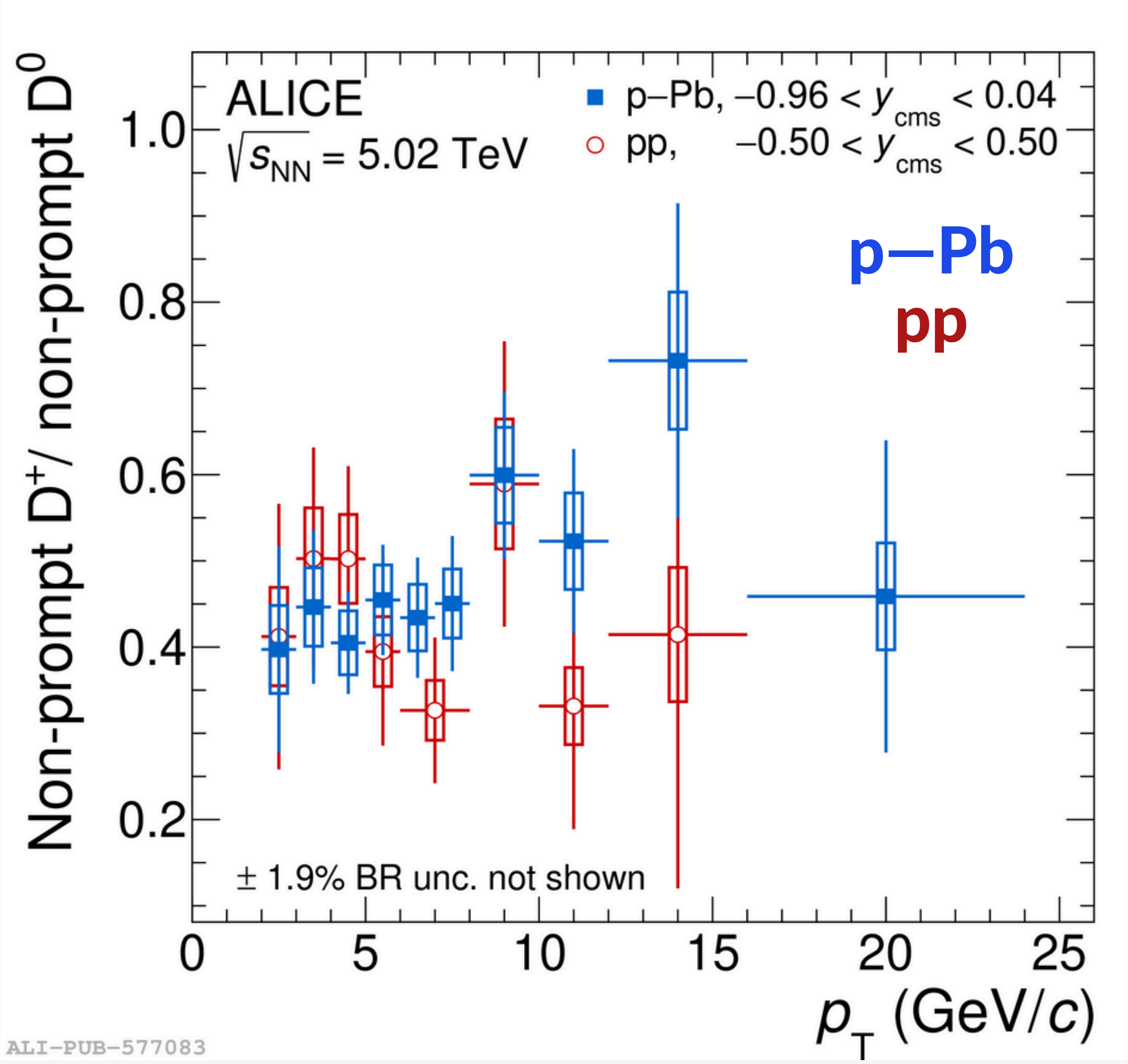
Λ_c^+ non-prompt fraction vs. theoretical predictions



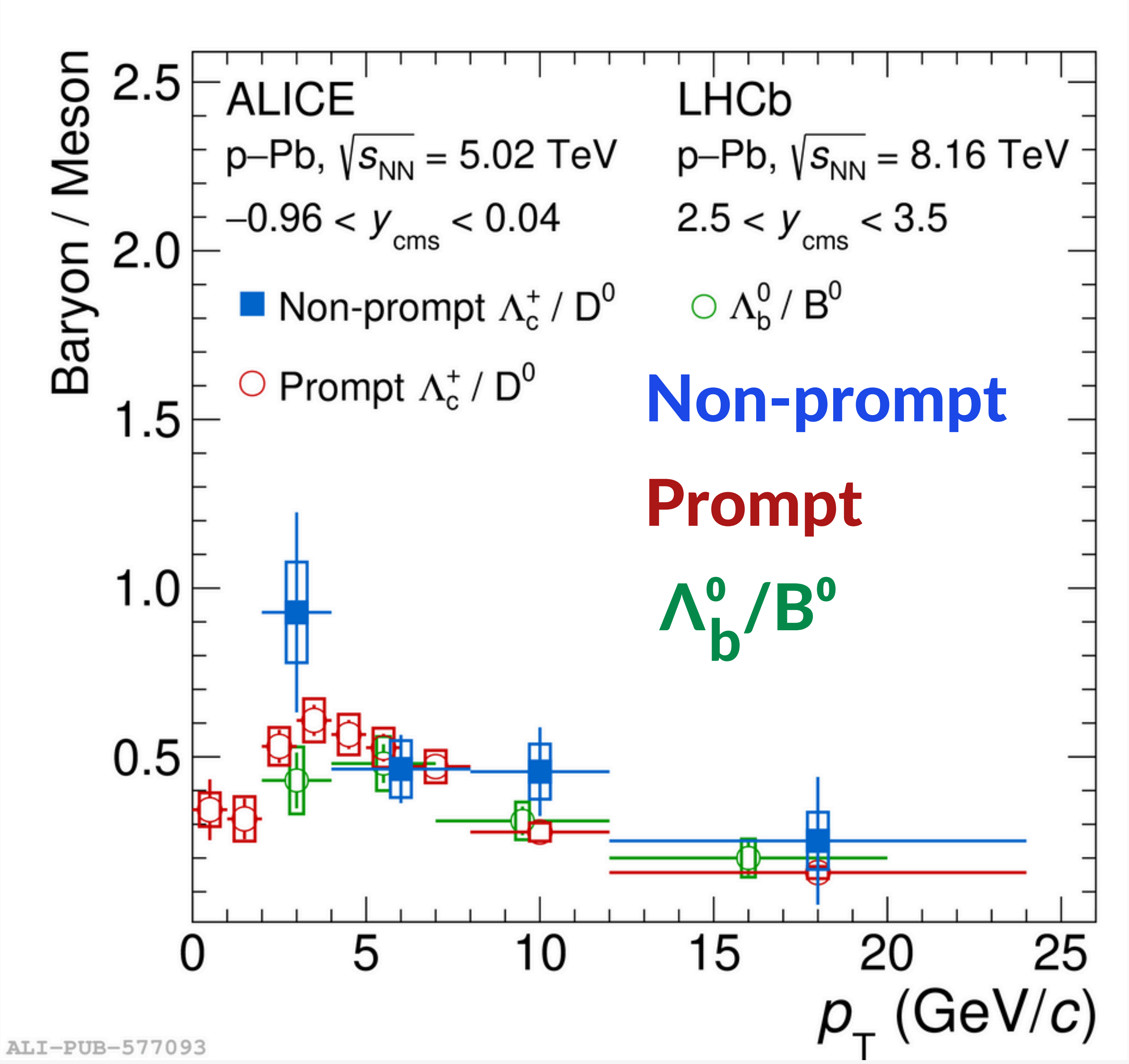
- **Run 3 results are more granular** and provide lower p_T reach
- **PYTHIA Monash** tends to underestimate the data
- **PYTHIA CR-BLC modes** provide a better description of the data compared to the Monash tune

Particle ratios

Non-prompt D^+/ Non-prompt D^0 pp vs. p—Pb



Λ_c^+/D^0 prompt vs. non-prompt



NEW on ArXiv!

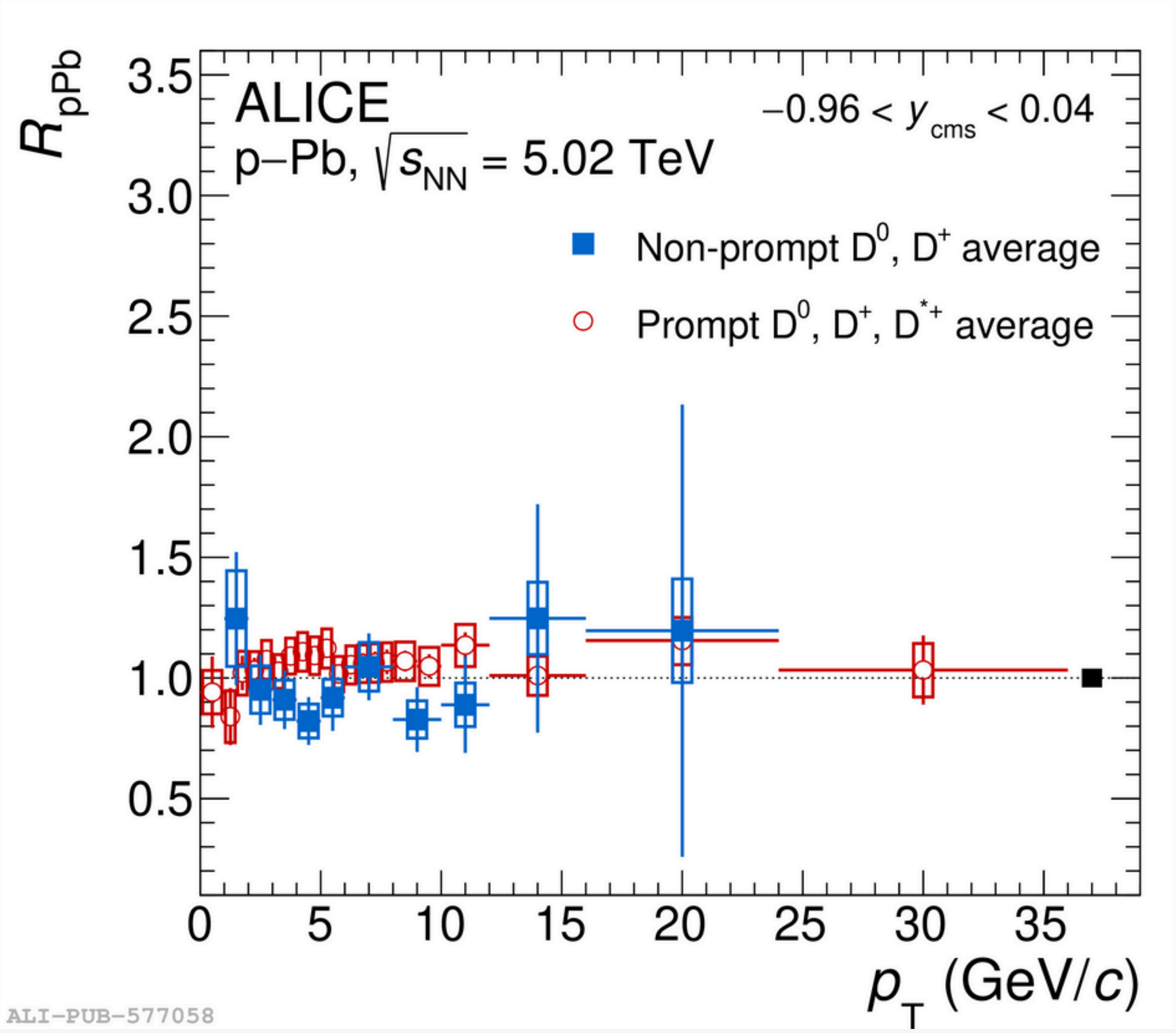
- **Lack of models for p—Pb**
- Non-prompt D^+ / non-prompt D^0 production yield ratio is **compatible with pp** results
- **Compatible results for prompt and non-prompt Λ_c^+/D^0**

Similar hadronisation modifications for charm and beauty?

arXiv:2407.10593

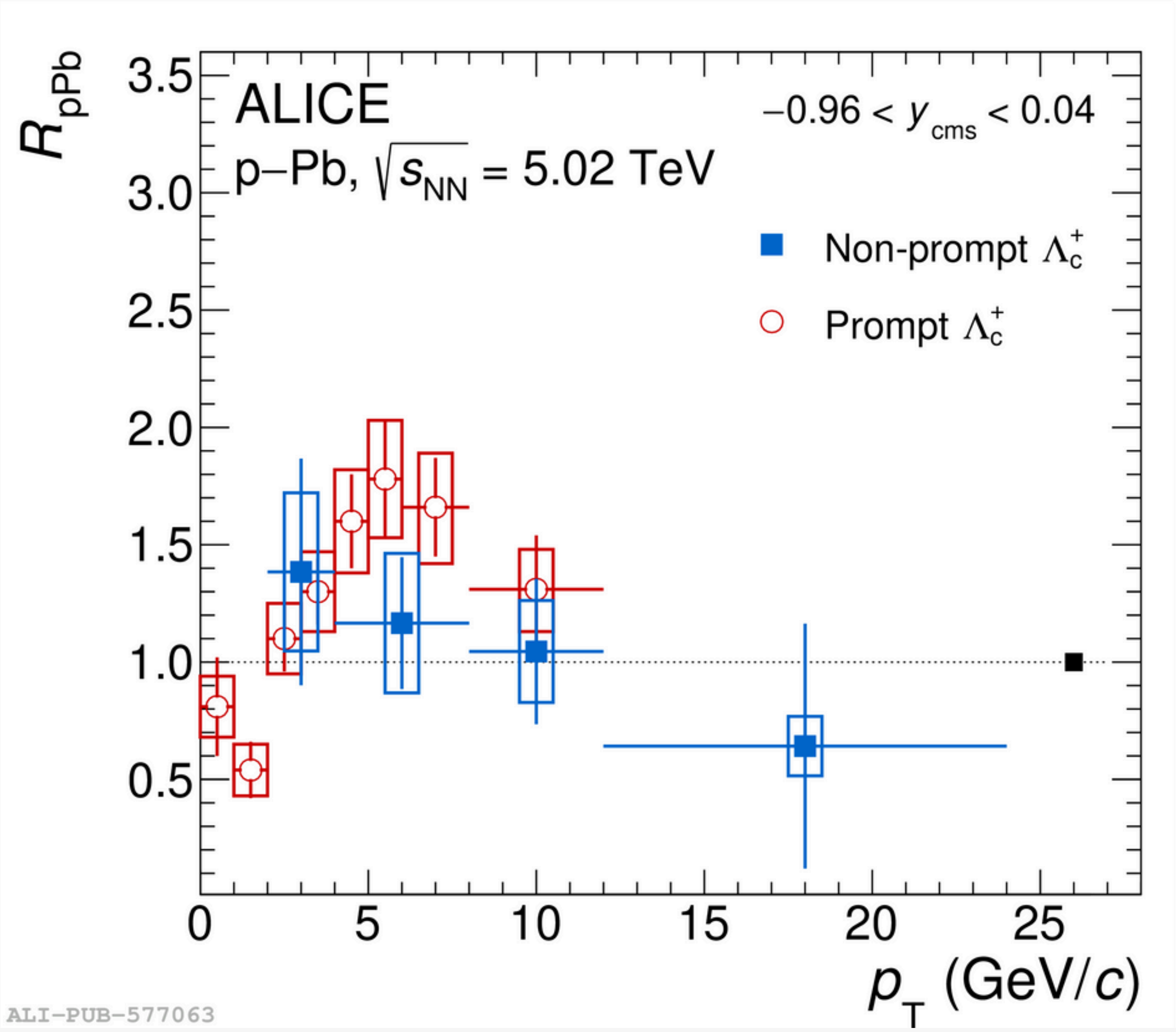
Nuclear modification factor

R_{pPb} of D-mesons



Compatible with unity for both prompt and non-prompt

R_{pPb} of Λ_c^+



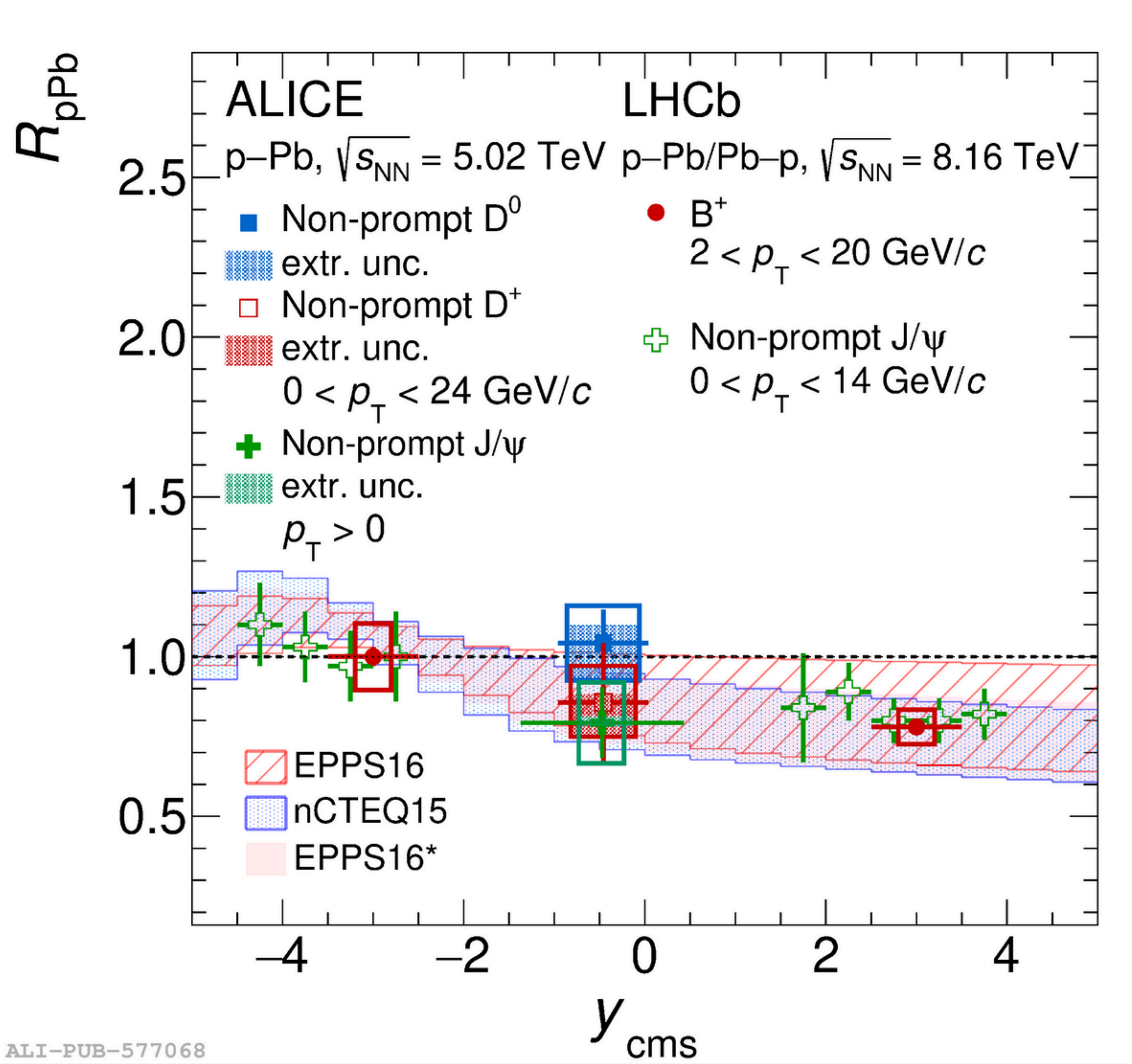
- **Prompt Λ_c^+** shows deviation from unity ⟶ Effects beyond nPDFs (hadronisation? expanding medium?)
- **Non-prompt Λ_c^+**'s uncertainties are too large to draw a conclusion

NEW on ArXiv!

arXiv:2407.10593

Nuclear modification factor

p_T integrated R_{pPb} of D-mesons and J/Ψ vs. rapidity



- Results are **compared to B^+ calculations** using HELAC-onia with different sets of PDFs
  - They all provide **good descriptions** of the data
- All data points for the considered particles are **consistent with each other and aligned with unity**

The effects of CNM in non-prompt charm particles, if any, are small

HELAC-onia: *H.-S. Shao*, Comput. Phys. Commun. 184 (2013) 2562–2570
EPPS16: *K. J. Eskola, P. Paakkinen, et al.*, Eur. Phys. J. C 77 (2017) 163
nCTEQ15: *K. Kovarik et al.*, Phys. Rev. D 93 (2016) 085037
EPPS16*: *A. Kusina, J.-P. Lansberg et al.*, Phys. Rev. Lett. 121 (2018) 052004

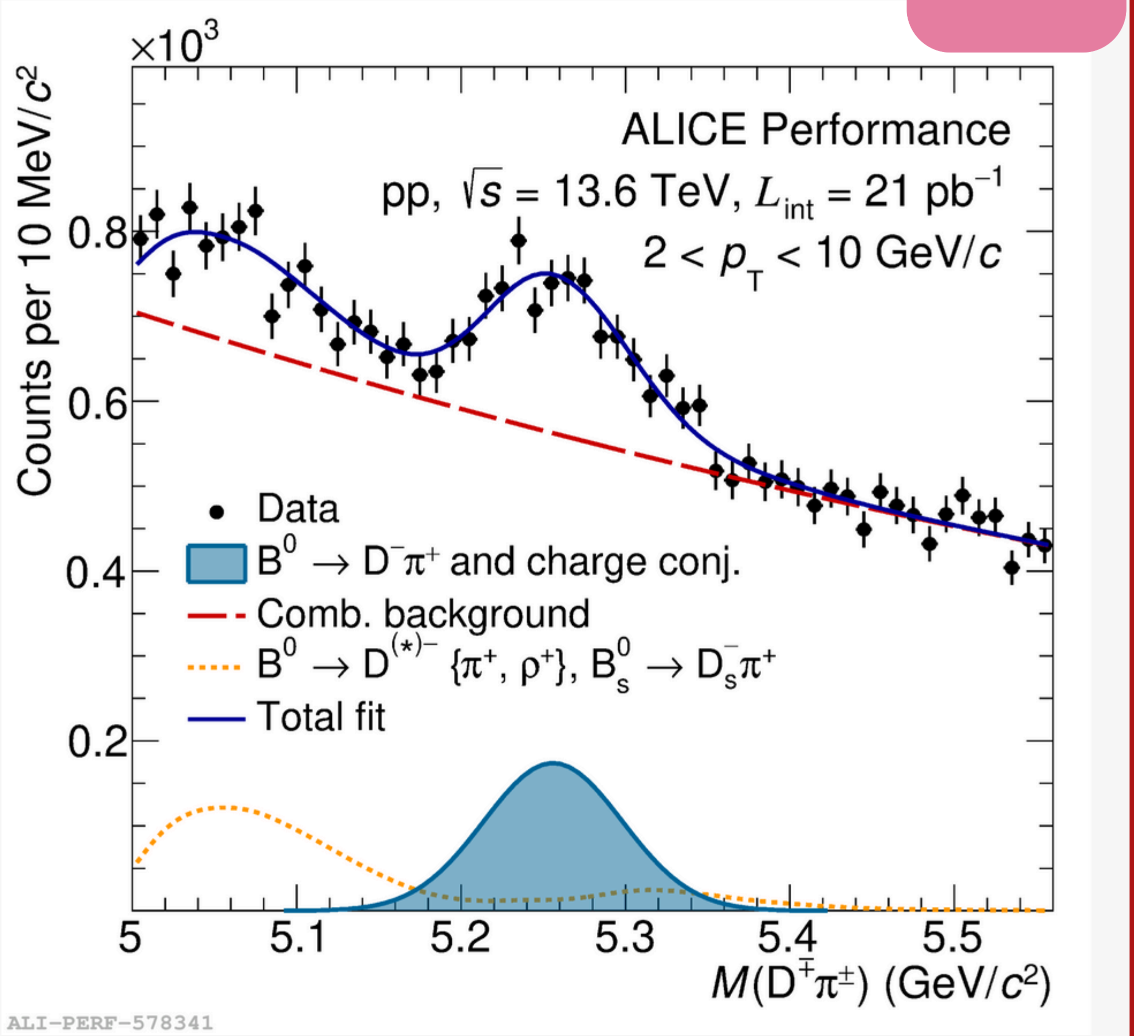
NEW on ArXiv!

arXiv:2407.10593

Summary

First direct measurement of B^0 meson in ALICE!

NEW!

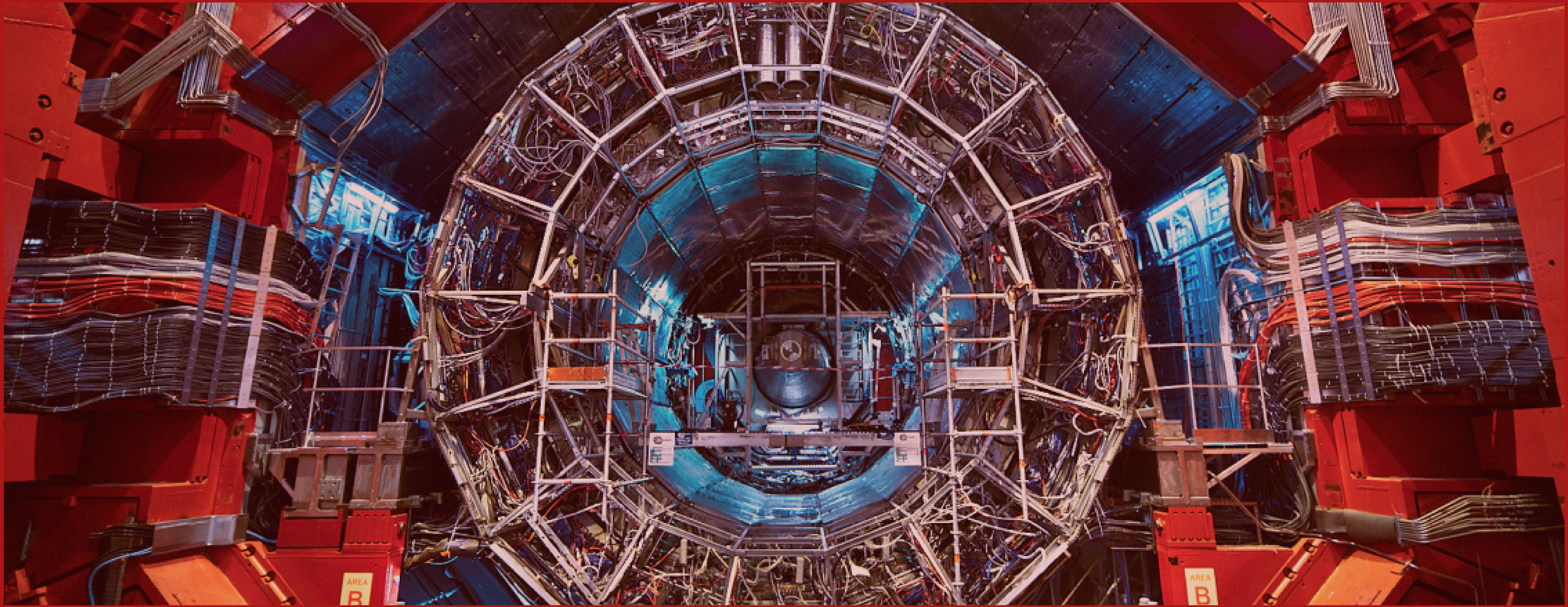


01 **pQCD calculations** can adequately describe non-prompt **D-meson cross sections** and **meson-to-meson** ratios in pp, but do not properly describe **baryon cross sections** and **baryon-to-meson** ratios in pp in all p_T ranges

02 **Similar hadronisation effects** are observed in **pp** and **p—Pb** collisions. Dedicated model calculations are needed for p—Pb

03 Studies on the nuclear modification factor show that the **effects of CNM on non-prompt charm hadrons are small**

04 **More results to come from Run 3 data samples,** allowing for better constraints on theoretical models

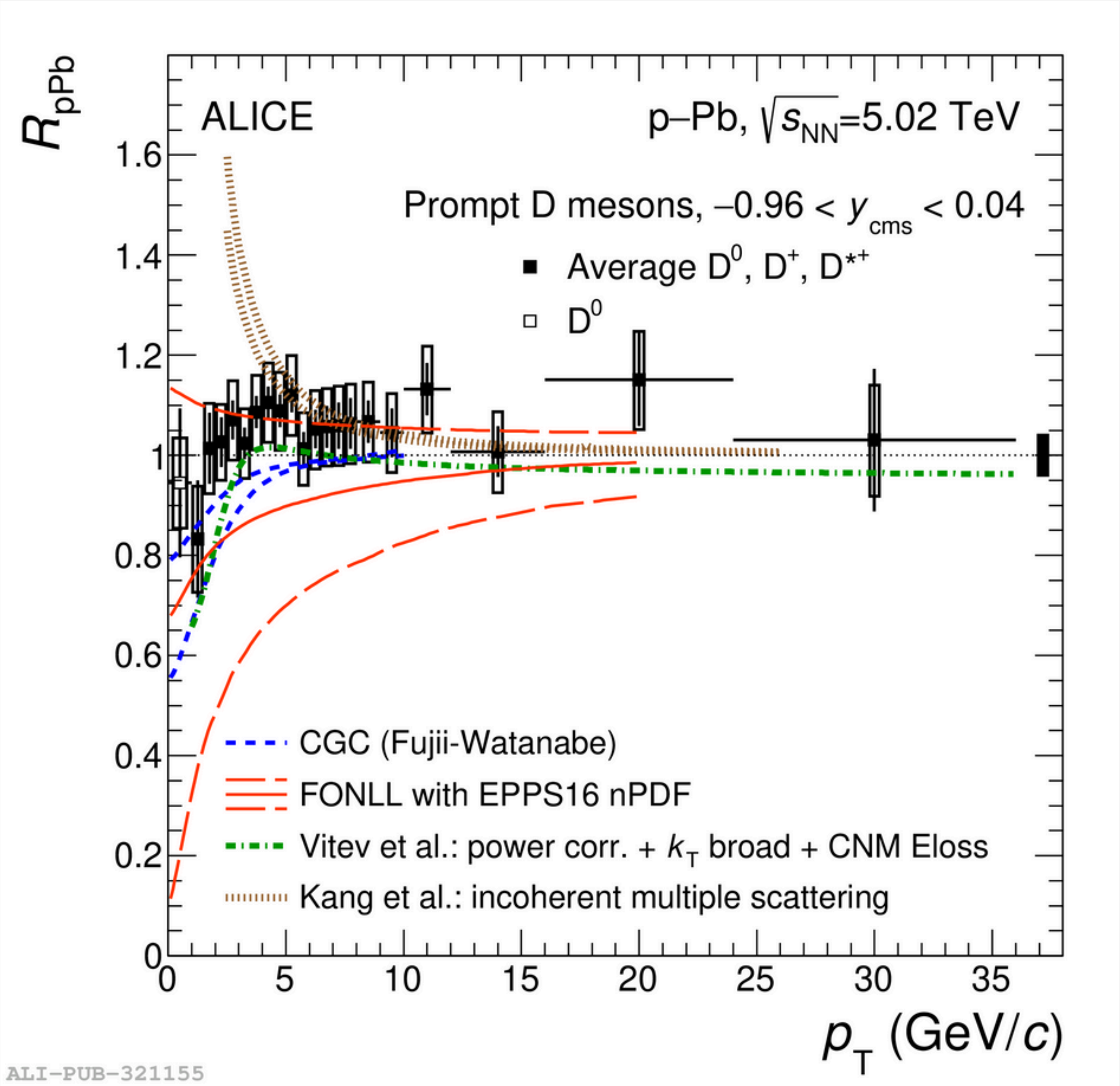


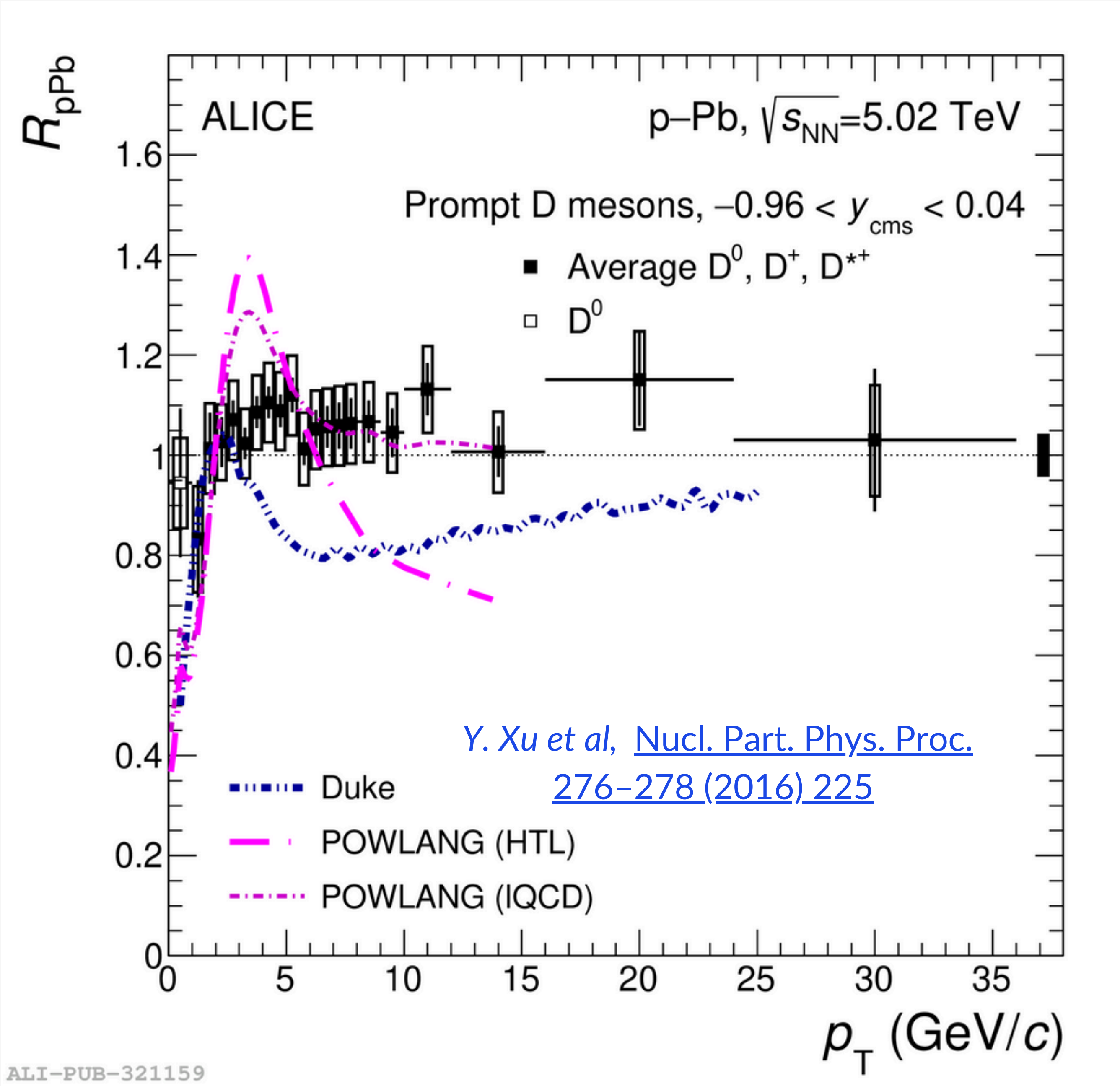
Thank you, ありがとう!

Any questions?

Nuclear modification factor vs. models

p–Pb





Models that only include CNM effects

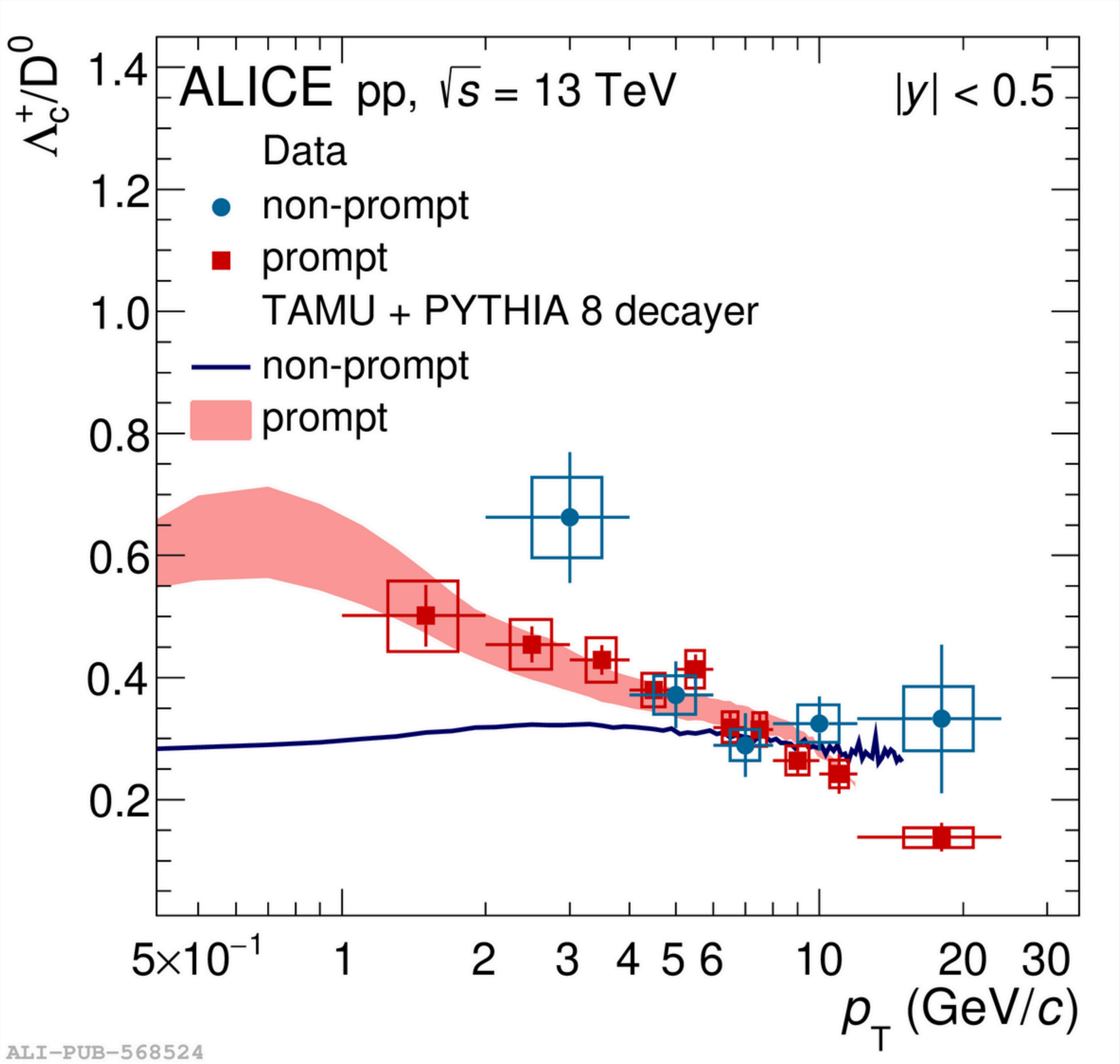
- **FONLL**, ***Vitev et al.***, and **CGC** follow the same trend as the data
- ***Kang et al***. is excluded by the data for p_T< 4 GeV/c

Transport models

Models suggest the existence of a **peak at low p_T** which is not visible in data

Baryon-to-meson ratio

pp



Λ_c^+/ D^0 ratio vs. theoretical predictions

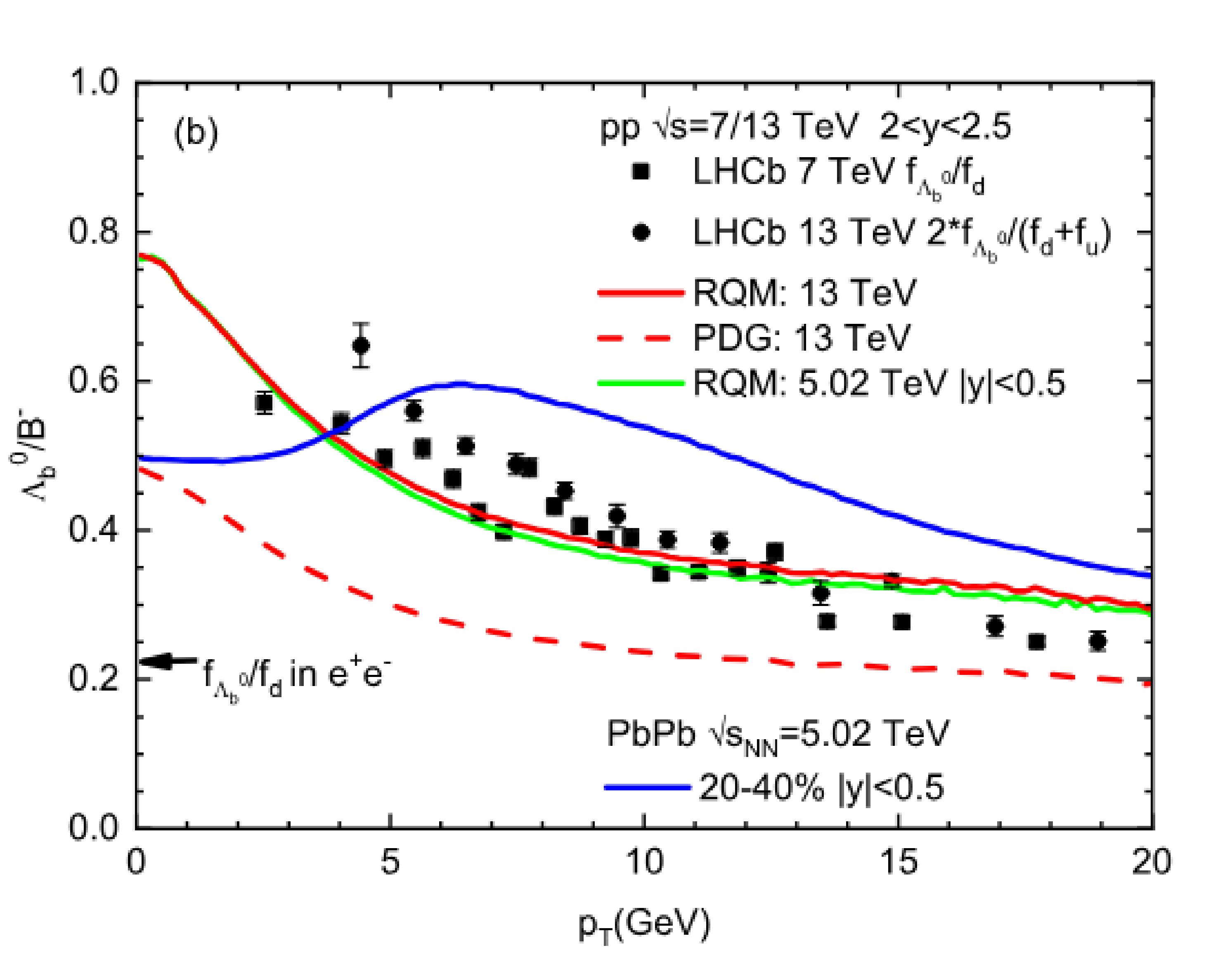
- Data is compared with TAMU + PYTHIA 8 calculations
- Prompt Λ_c^+ are well described by the model, but that is not the case for non-prompt Λ_c^+

Phys. Rev. D 108, 112003 (2023)

About the TAMU model

M. He and R. Rapp,
Phys. Rev. Lett. 131 (2023) 012301

It employs a statistical hadronisation model (SHM) using a relativistic quark model (RQM) input



RQM provides a set of **unobserved b-hadron states** beyond the ones currently present in the PDG, which are needed to describe the data

Beauty fragmentation functions are calculated using t**hermal densities**

Relative abundances of beauty-hadrons depend on their masses and a universal hadronisation temperature