# Testing perturbative QCD calculations with beauty-meson production in proton–proton collisions with ALICE


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EPS HEP2025 MARSEILLE

# Heavy-flavour physics

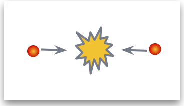
Charm and beauty quarks: $m_c \sim 1.3$ GeV/$c^2$ , $m_b \sim 4.2$ GeV/$c^2$

→ Significantly larger than $\Lambda_{QCD}$ (~200 MeV)

→ Produced in **hard-scattering processes** among partons

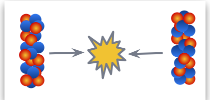
Marcello Di Costanzo
T04, Wed, 17:00

pp: test for pQCD-based models



→ Heavy-quark production
→ Hadronisation
→ Parton Distribution Functions (PDFs)
→ Reference for larger systems

Pb–Pb:



→ Energy loss in the QGP
→ Diffusion in the medium
→ Modification to hadronisation

In pp, the heavy-flavour hadron production cross section is calculated by factorisation approach:

$$\frac{d\sigma^{H_Q}}{dp_T}(p_T;\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\otimes \mathrm{PDF}(x_2,\mu_F) \otimes \frac{d\sigma^Q}{dp_T}(p_T;\mu_F,\mu_R) \otimes D_Q \to H_Q\left(z = p_{H_Q}/p_Q, \mu_F\right)$$

Parton distribution functions

Hard scattering cross section (pQCD)

Fragmentation functions (hadronisation)

Maja Karwowska
T05, Tue, 18:10

# ALICE in LHC Run 1 and Run 2

**Heavy-Flavour (HF) hadrons** are very short-lived:

**b-hadrons**: $c\tau \approx 500$ μm   **c-hadrons**: $c\tau \approx 45$–$300$ μm

Their reconstruction requires:

→ excellent spatial resolution for secondary-to-primary vertex separation

→ effective particle ID over wide $p_T$ region

**Prompt** $c \rightarrow H_c$   **Non-prompt** $b \rightarrow H_b \rightarrow H_c + X$

**Non-prompt charm hadrons** reconstructed by **ALICE**:

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow \pi^+ K^- \pi^+$

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^- K^+ \pi^+$

$H_b \rightarrow e^- + X$

$\Lambda_c^+ \rightarrow pK^- \pi^+$

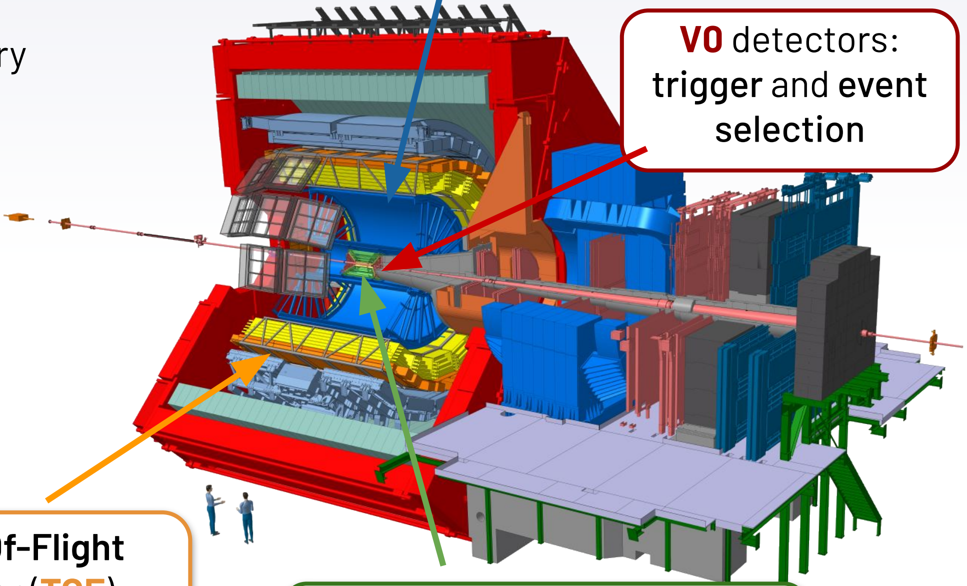
$\Lambda_c^+ \rightarrow pK_s^0$

$J/\psi \rightarrow e^+ e^-$

M. Zhang, mid-forward correlations Poster

**Time Projection Chamber (TPC)**: tracking and PID via d$E$/dx

**V0 detectors**: trigger and event selection



**Time-Of-Flight** Detector (**TOF**): PID via time of flight

**Inner Tracking System (ITS)**: tracking, vertexing

# Non–prompt D meson production cross section

**Non-prompt** $b \to H_b \to H_c + X$

Model description of non-prompt meson production consistent with data:

FONLL and GM-VFNS:

→ collinear factorisation

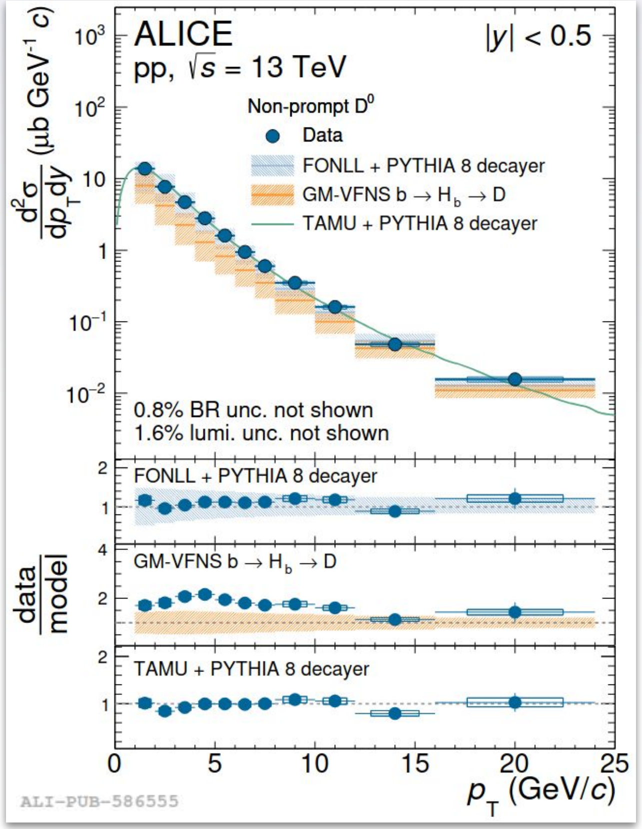
→ NLO + Next-to-Leading Logarithm (NLL) resummation

→ fragmentation functions $b \to H_b$ tuned on $e^+e^-$ collisions

TAMU:

→ FONLL for beauty-quark production cross section

→ $H_b$ aboundances from statistical hadronisation model




JHEP 10 (2024) 110

Cacciari et al., JHEP05(1998)007

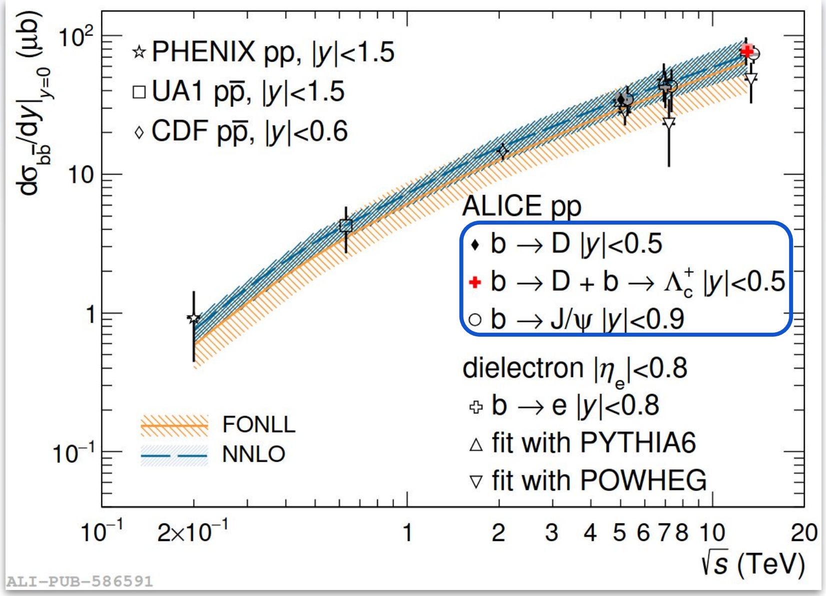
Benzke et al., EPJC 79, 814 (2019)

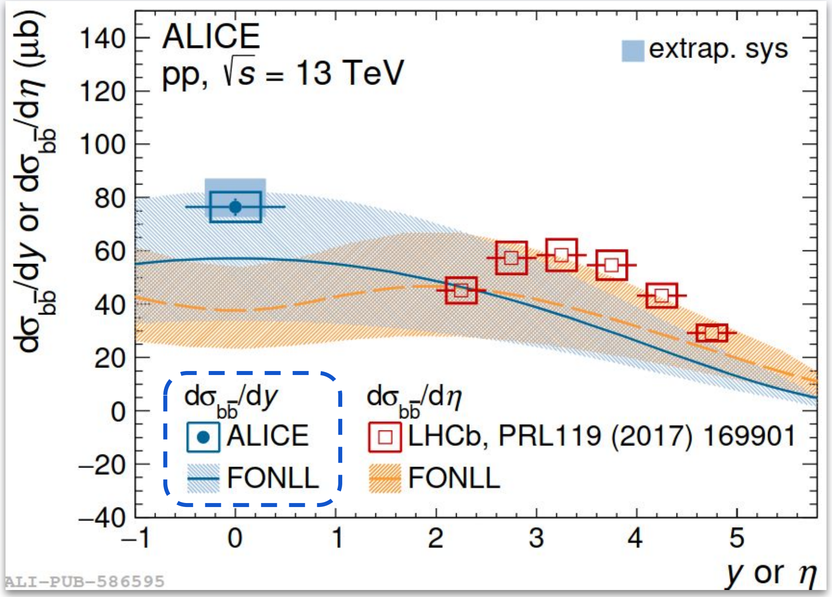
He et al., PRL 131 (2023) 1, 012301

# $b\bar{b}$ production cross section

The **beauty-quark** production cross section at midrapidity
is extrapolated from measurements of **non-prompt charm hadrons**

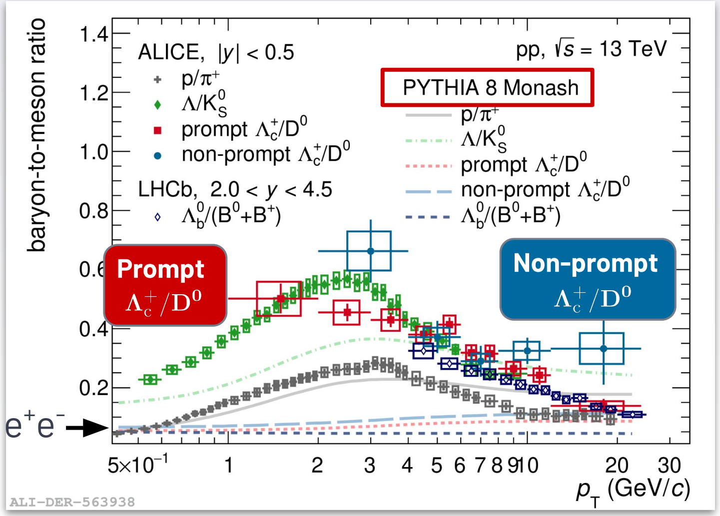
JHEP 10 (2024) 110



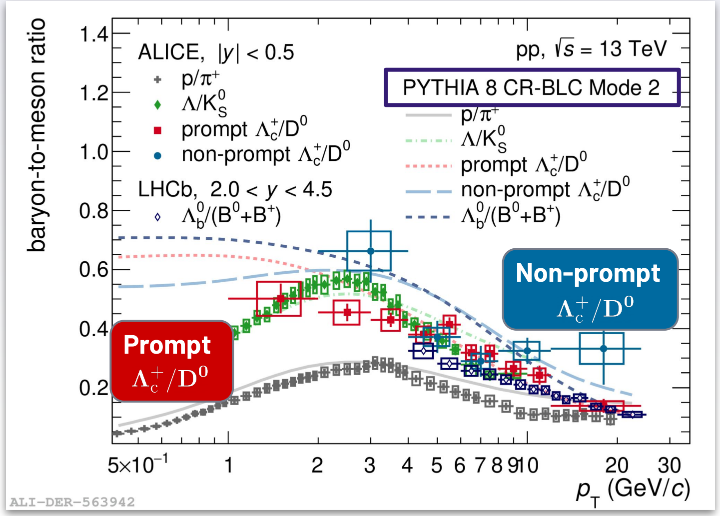




Cacciari et al., JHEP05(1998)007
Catani et al., JHEP 03 (2021) 029
UA1: Phys. Lett. B 256 (1991)
CDF: Phys. Rev. D 71 (2005) 032001
PHENIX: Phys. Rev. Lett, .103(2009) 082002

# Beauty baryon-to-meson ratio




Phys. Rev. D 108, 112003 (2023) EPJC 74 3024 (2014)

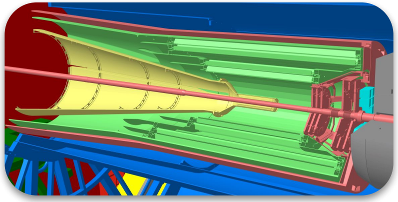



Phys. Rev. D 108, 112003 (2023) JHEP 1508 (2015) 003

- Similar trend for charm, beauty, and strange-hadrons
- Models using FF tuned on $e^+e^-$ significantly underestimate the HF baryon-to-meson ratios
- PYTHIA 8, CR-BLC tune shows a good agreement for charm and strange hadrons, slightly worse for beauty

Samuele Cattaruzzi, T05, Thu, 19:10

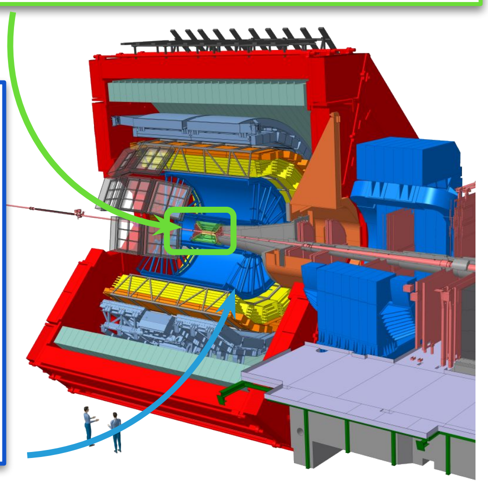
# ALICE upgrades for LHC Run 3



## New ITS ( ITS2 )

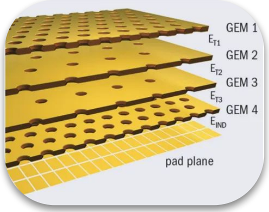
→ $1^{st}$ layer closer to IP
→ reduced material budget
→ 7 layers of pixel sensors

*J. Phys. G 41 (2014) 087002*



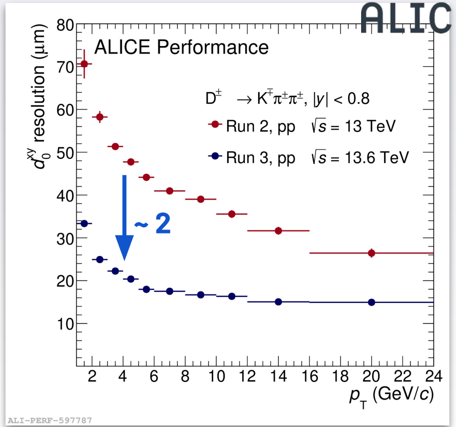
## TPC upgrade

From MWPC to GEM-based readout




## Improved spatial resolution

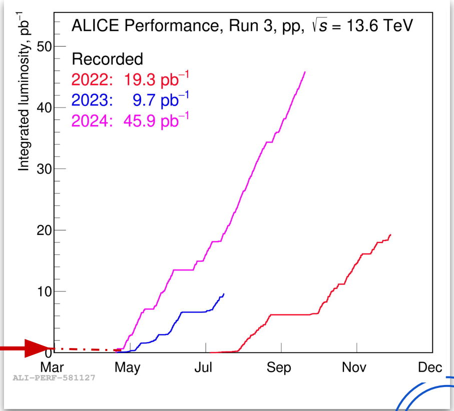
→ better background and prompt-to-feed-down separation




## Continuous readout

+ higher interaction rate
(pp ~600 kHz, Pb–Pb 50 kHz)

Run 2: $\mathscr{L}_{int}$ (MB pp, 13 TeV) = 32 $nb^{-1}$



# Offline Trigger Selections

Data collection in continuous readout at high interaction rate produces an **extremely large** volume of data

→ necessary to minimize the amount of data stored permanently on disk

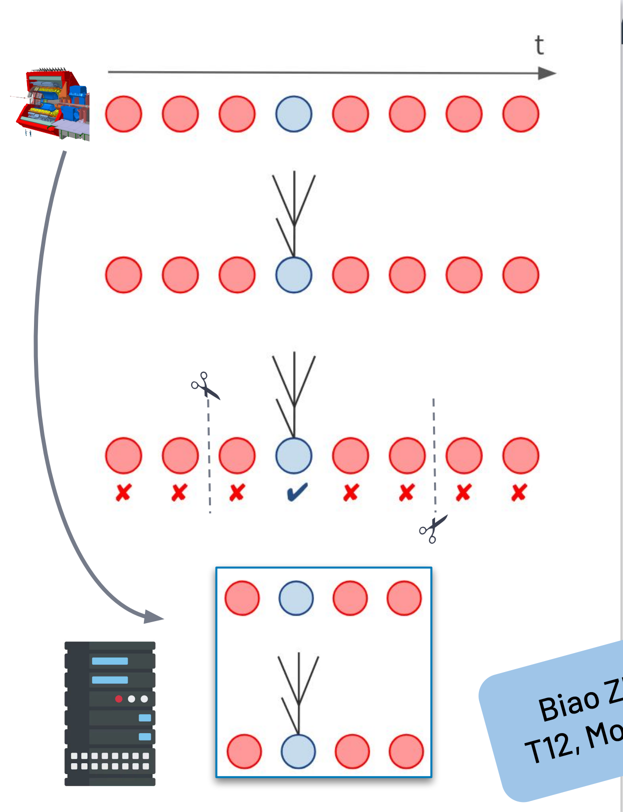
→ **Offline Trigger Selections (OTS)**

**Software-based** event selection process:

1) complete **reconstruction** and **calibration** of the full dataset
2) **identification** of events of interest (**OTS**)
3) **data skimming:**

   → Keep **only** raw data in Δt window ($^{+125}_{-25}\,\mu s$ )

4) Final reconstruction




Credits: F. Chinu

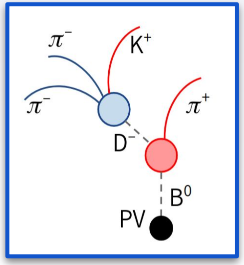
Biao Zhang, T12, Mon, 14:40

ALICE-PUBLIC-2020-005

# OTS for beauty-hadron reconstruction

Example of beauty hadron reconstruction:

$$B^0 \to D^-\pi^+ \text{ (BR} = 0.25\%)$$
$$\hookrightarrow \pi^-K^+\pi^- \text{ (BR} = 9.38\%)$$

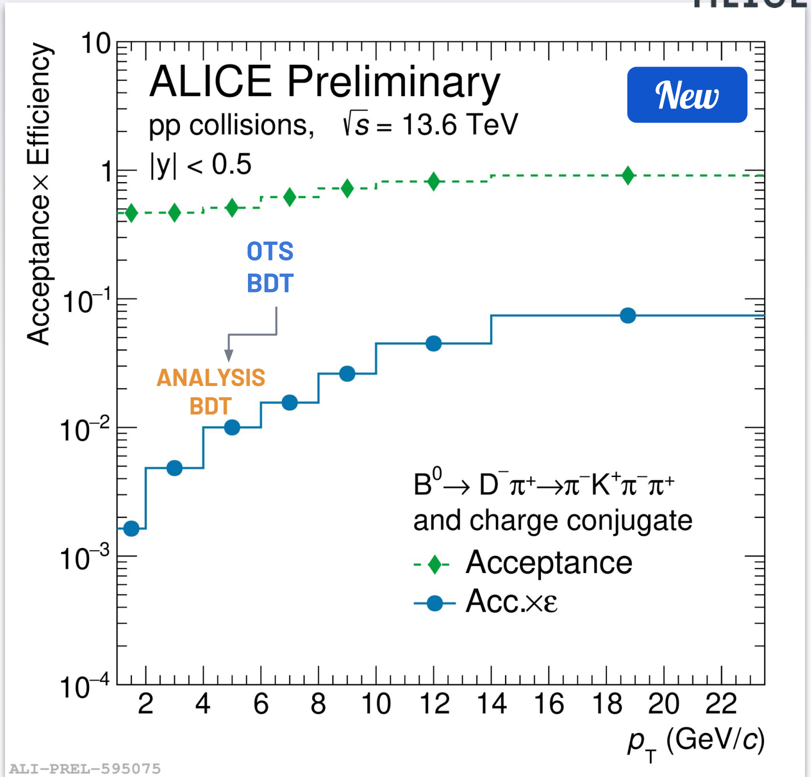



**D⁻ candidates:**

- Built from **triplets of tracks** with correct charge hyp.
- **OTS selection**: Boosted Decision Tree (BDT)
  - → Enhanced **non-prompt D-meson** selections

**B⁰ candidates:**

- OTS-selected D meson combined with a displaced track
- BDT for signal and background separation

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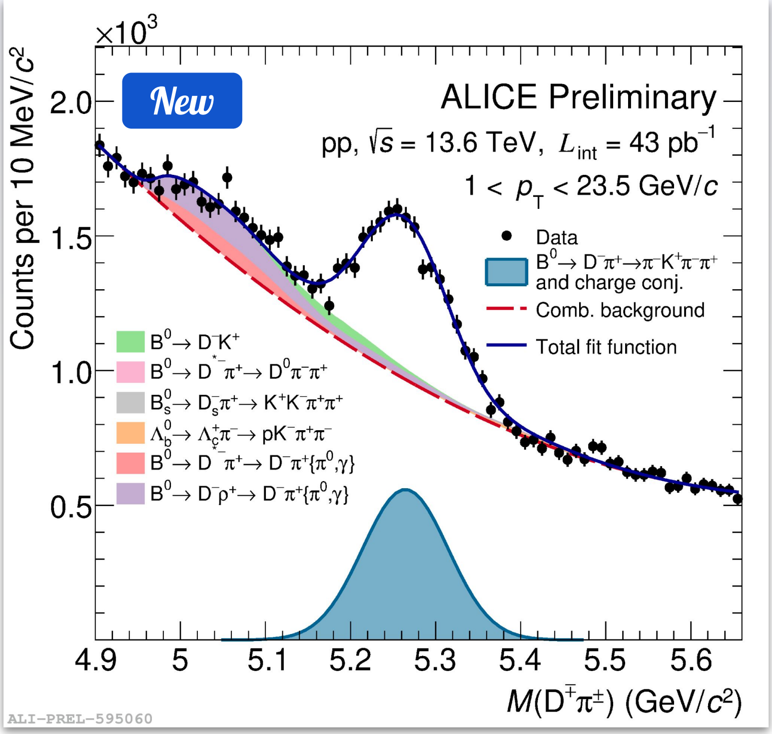
# $B^0$-meson invariant mass distribution




ALICE-PUBLIC-2025-004

Invariant mass peak of fully reconstructed $B^0$ mesons with ALICE

**$B^0$** candidates reconstructed in $1 < p_T < 23.5$ GeV/$c$

**Raw yields** extracted via unbinned maximum likelihood fits:

→ **$B^0$ signal peak**: gaussian

→ **combinatorial background**: $2^{nd}$-order polynomial

→ **correlated background**: templates from Monte Carlo simulations

(partially/mis-reconstructed beauty hadrons)

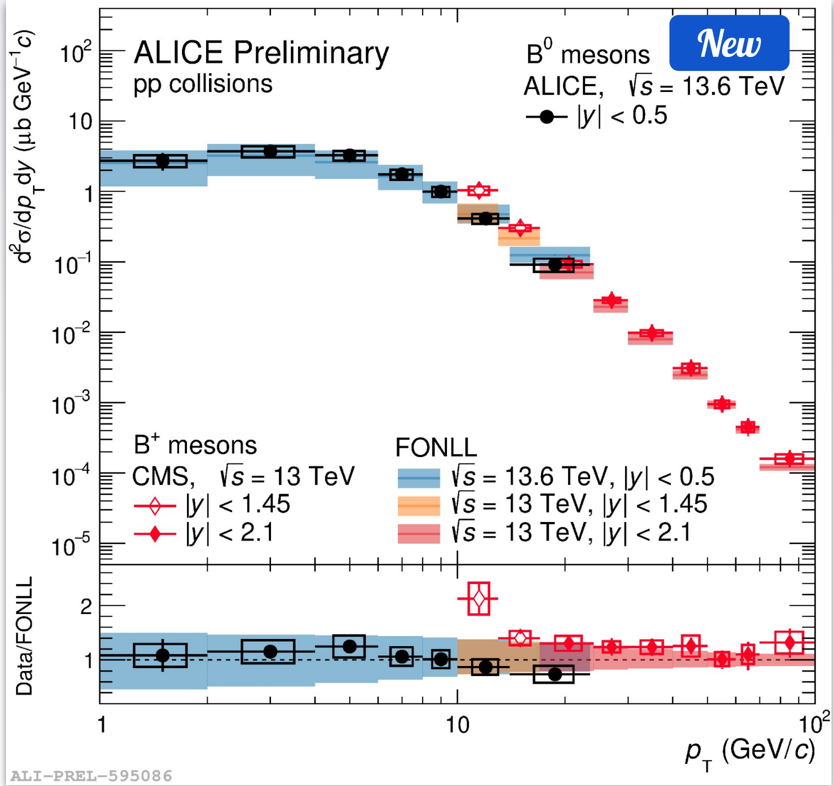
# $B^0$ production cross section

From the $p_T$-differential analysis the **first measurement** at **ALICE** of **$p_T$-dependent beauty-hadron production cross section** was obtained.

→ Measured down to very **low $p_T$ ($\geq 1$ GeV/$c$)**

→ **Extension** of the kinematic reach **beyond** existing mid-rapidity measurements

→ Compatible with **FONLL** predictions within uncertainties



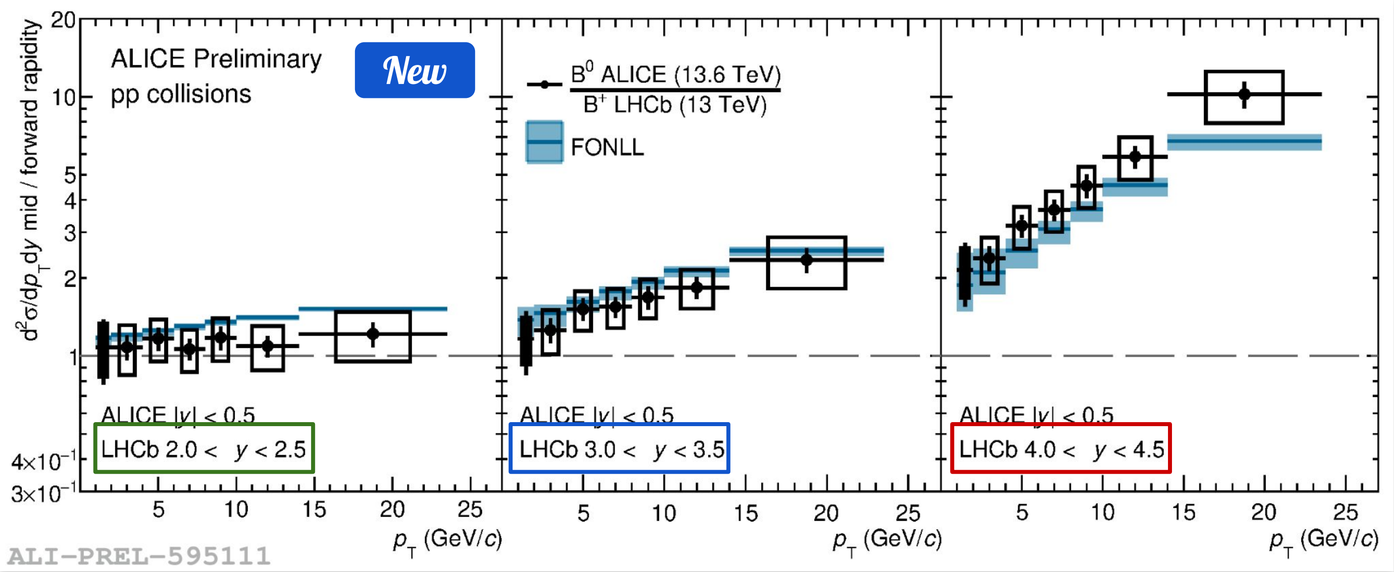

ALICE-PUBLIC-2025-004

CMS, Phys. Lett. B 771 (2017) 435

Cacciari et al., JHEP05(1998)007

# Mid-to-forward rapidity ratio: beauty mesons

Investigating **rapidity dependence** of B-meson production:




ALICE-PUBLIC-2025-004

LHCb, JHEP 12 (2017) 026

Cacciari et al., JHEP05(1998) 007

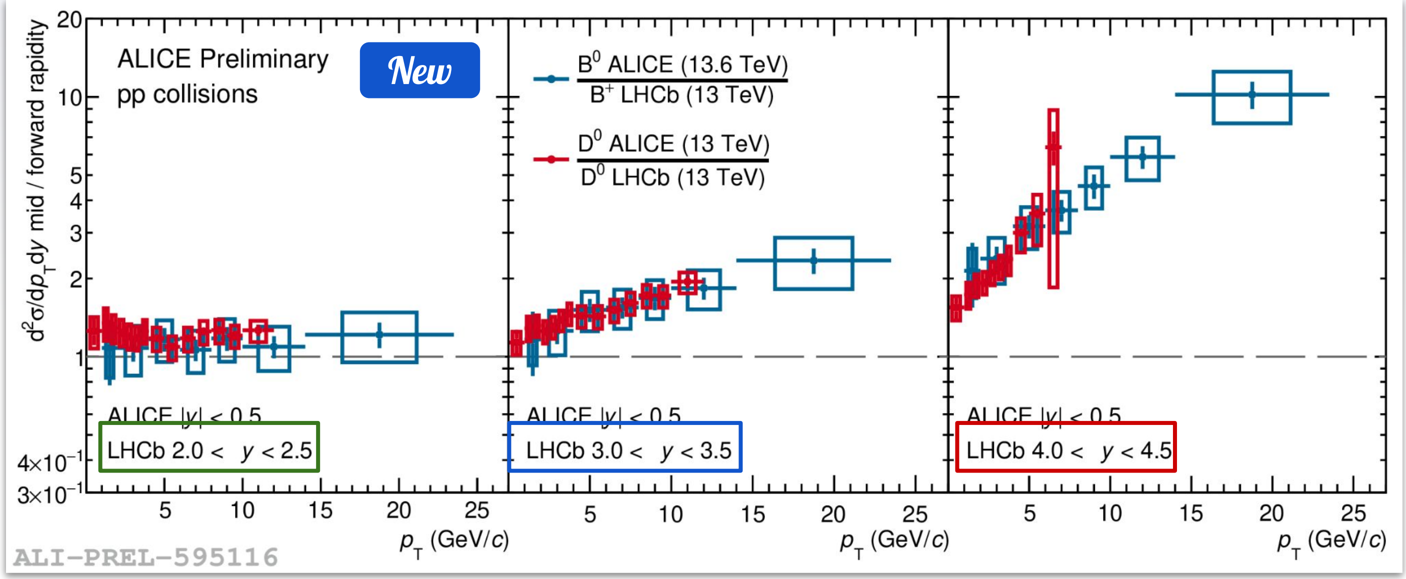
Comparison with **FONLL** predictions:

→ good agreement with data

→ hint of different $p_T$-slopes ?

# Mid-to-forward rapidity ratio: beauty & charm mesons

What about the charm?




ALICE-PUBLIC-2025-004

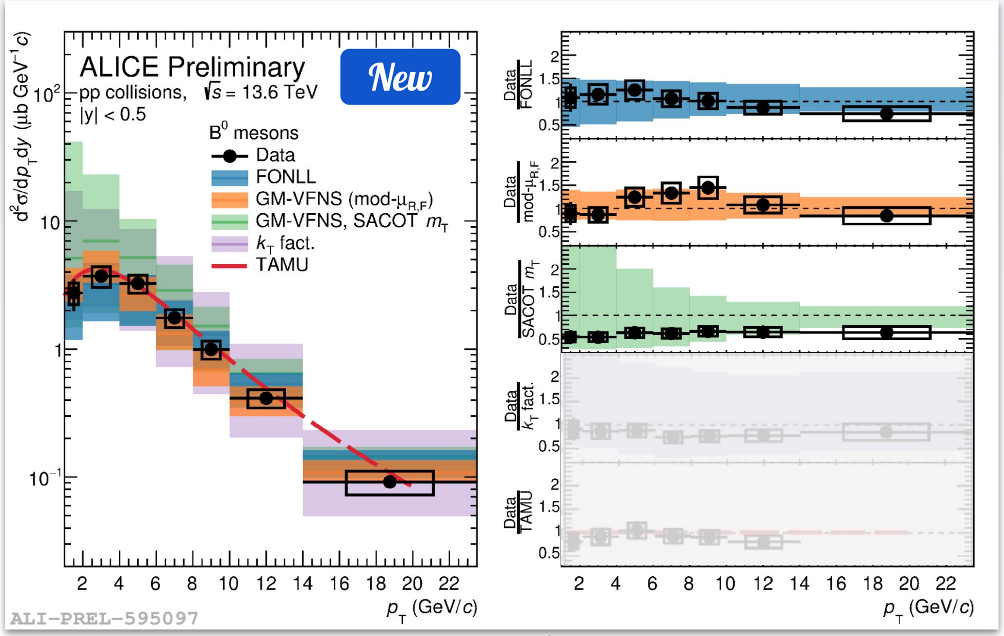
ALICE, JHEP 12 (2023) 086

LHCb, JHEP 12 (2017) 026

→ **Similar dependence** on **rapidity** for **charm** and **beauty** mesons

# Comparisons with theoretical predictions

The measurement is compatible with all the predictions based on **pQCD calculations**:

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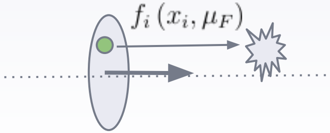
FONLL, GM-VFNS(mod-$\mu_{R,F}$), GM-VFNS (SACOT-$m_T$)

- collinear factorisation
- NLO + NLL resum.





Cacciari et al., JHEP 05 (1998) 007
Benzke et al., EPJC 79, 814 (2019)
Helenius et al., JHEP 07 (2023) 054
Barattini et al., JHEP 05 (2025) 115
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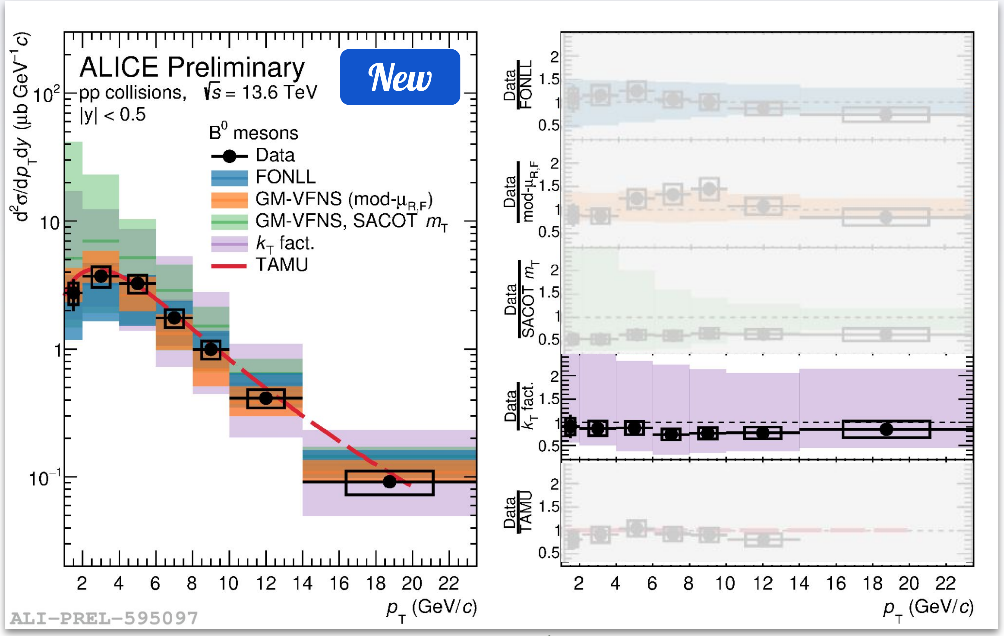


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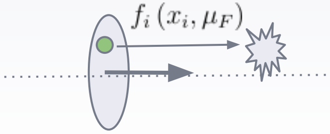
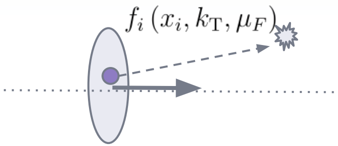



$k_T$ factorisation:

- NLO + NLL resum.




ALICE-PUBLIC-2025-004


Cacciari et al., JHEP 05 (1998) 007
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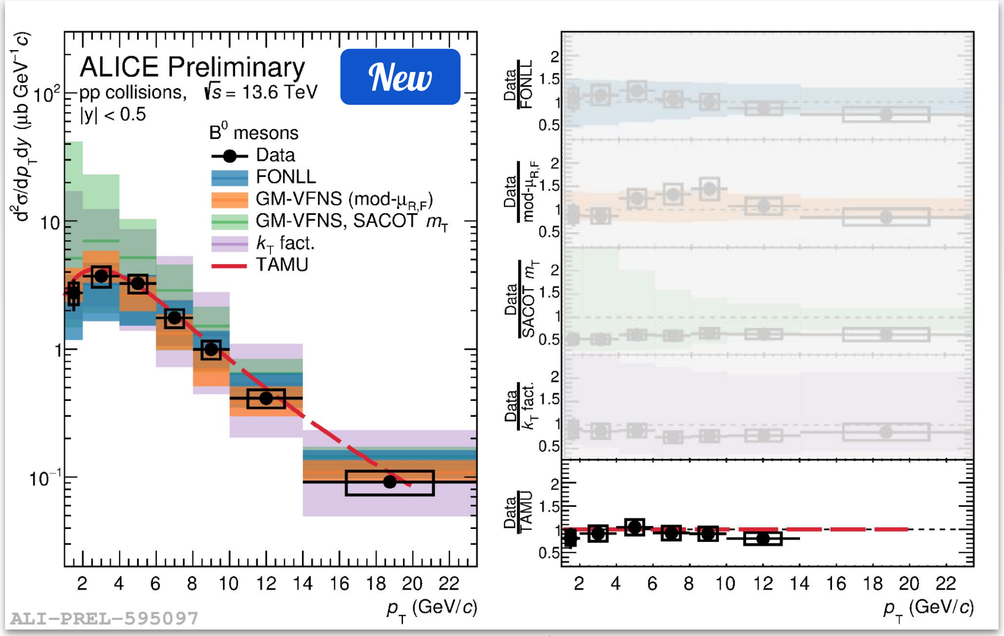


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Helenius et al., JHEP 07 (2023) 054

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He et al., PRL 131 (2023) 1, 012301

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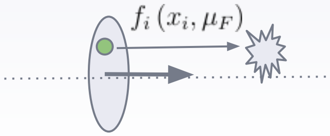


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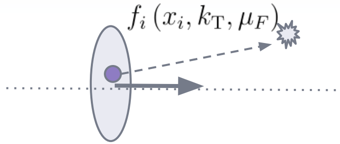



and **models**:

TAMU:

- FONLL for beauty-quark production cross section
- b → $H_b$ from statistical hadronisation model

# Summary

First measurement of fully reconstructed decays of beauty mesons with **ALICE**:

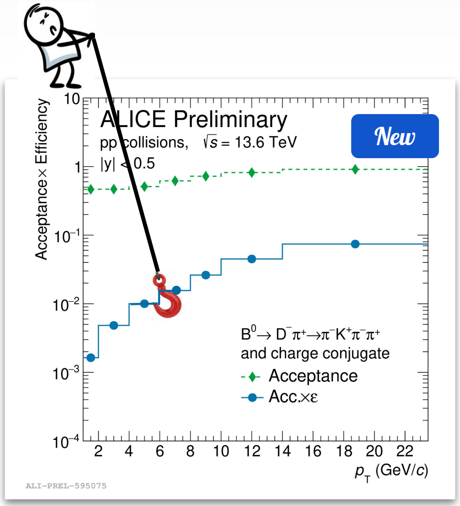
→ theoretical predictions successfully describe experimental results

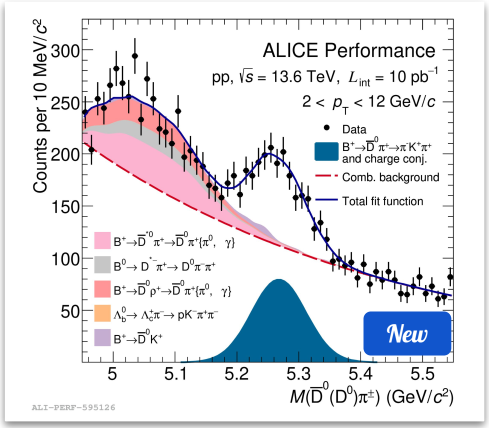
## Future perspectives:

- Improvement of OTS for 2025 data taking
- Other beauty mesons are on the way

- Huge amount of **Pb–Pb** collision data collected in Run 3:

→ Possibility of studying the QGP with beauty hadrons without dilution of physics effects from decay kinematics

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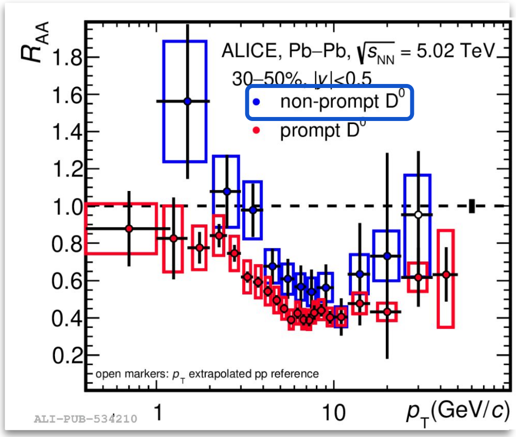
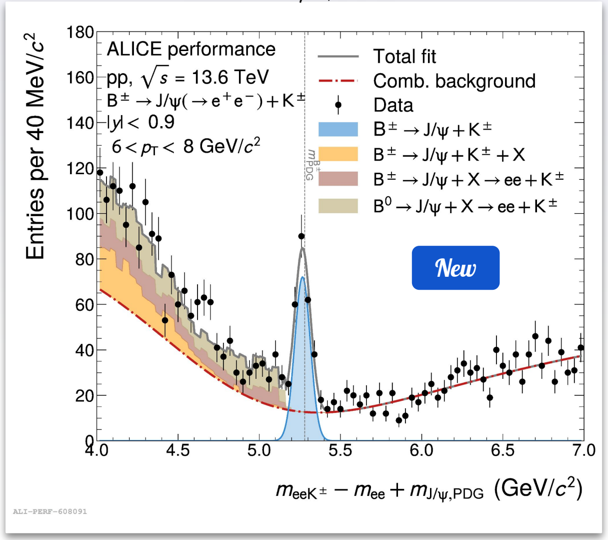


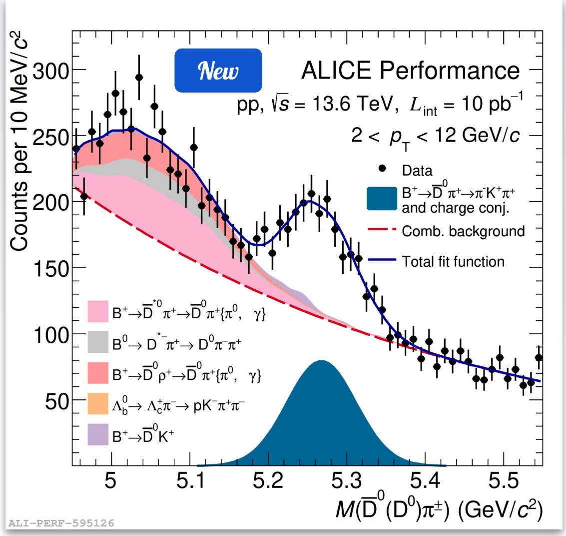

JHEP 12 (2022) 126

# What's cooking?

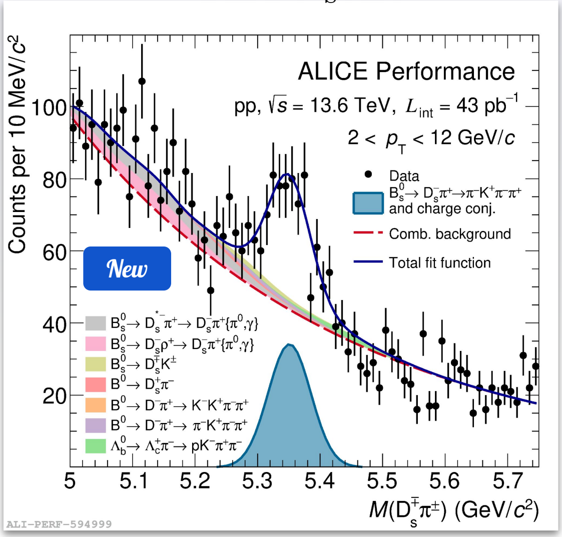
$B^+ \rightarrow J/\psi\, K^+$




$B^+ \rightarrow \overline{D}^0 \pi^+$




$B_s \rightarrow D_s^- \pi^+$

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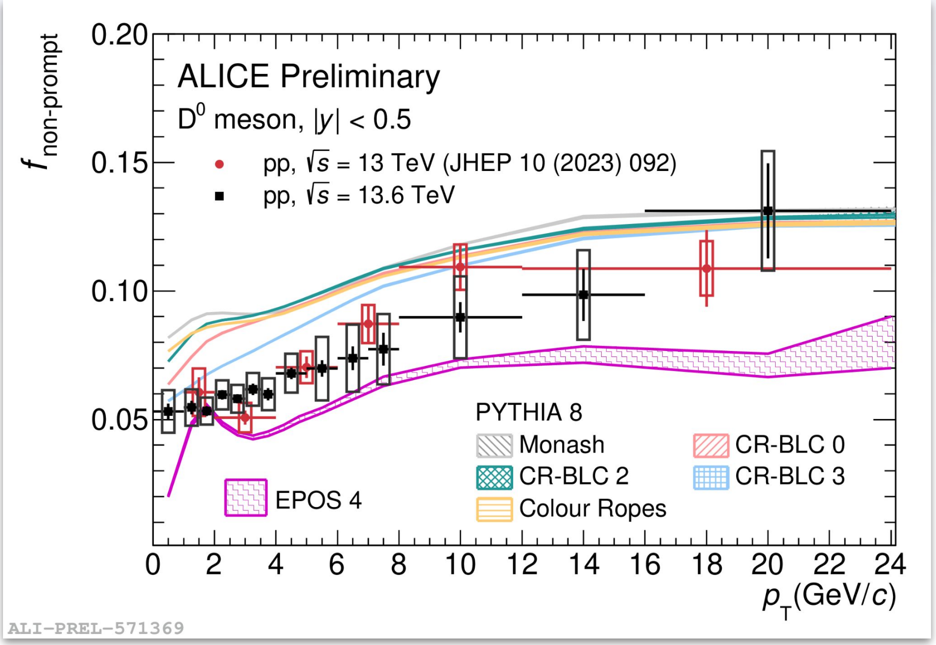
**Thanks for the attention!**

# Additional Material

# $D^0$ meson non-prompt fraction in Run 3




Monash: EPJC 74 3024 (2014)

CR-BLC: JHEP 1508 (2015) 003

EPOS: PRC 108, 064903 (2023)

**$D^0$ non-prompt fraction** as a function of $p_T$

MB pp collisions at $\sqrt{s}$=13.6 TeV: $\mathcal{L}_{int} = 7\ pb^{-1}$

→ good agreement with Run 2 data

→ Extension of $p_T$ reach down to 0 GeV/$c$

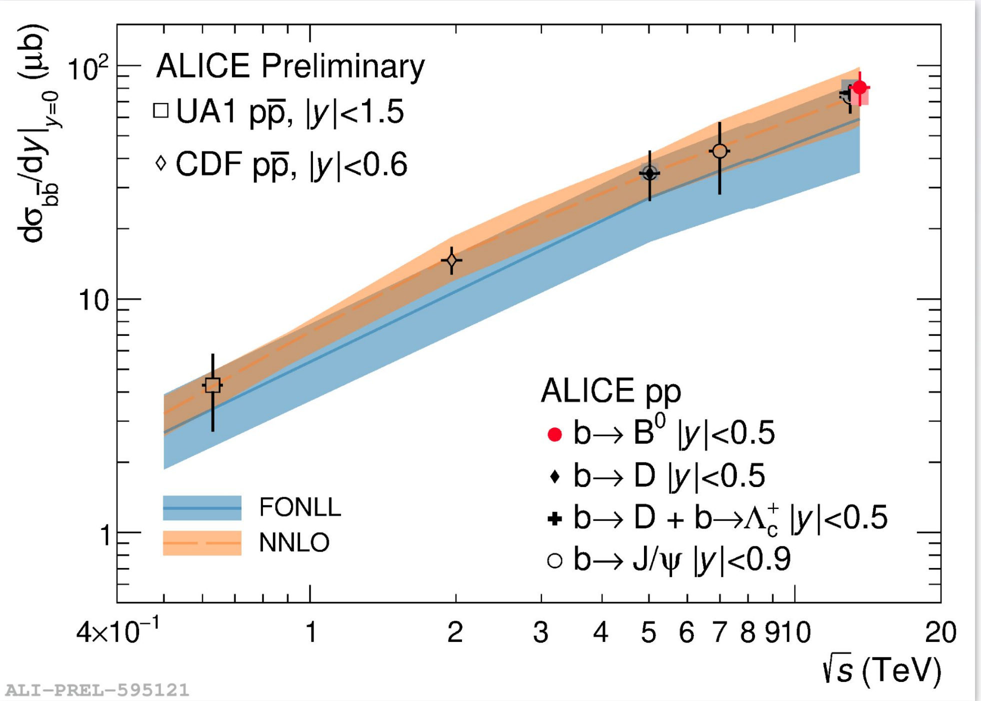
→ Increased granularity

Comparison with models:

→ **PYTHIA 8 tunes** catch the trend but overpredincts the full $p_T$ range;

→ **EPOS** tends to underpredict the high-$p_T$ region.

# $p_T$-integrated beauty quark cross section




Extrapolated **beauty-quark** production cross section at midrapidity from $B^0$ production measurements

→ Values and collision-energy dependence reproduced by **FONLL** and **NNLO**


FONLL: Cacciari et al., JHEP05(1998)007
NNLL: Catani et al., JHEP 03 (2021) 029
UA1: Phys. Lett. B 256 (1991)
CDF: Phys. Rev. D 71 (2005) 032001