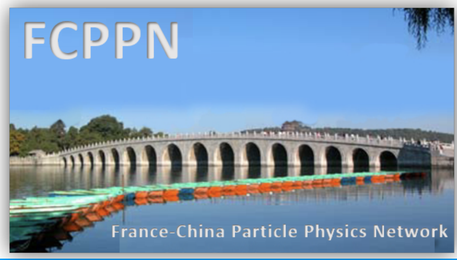

Open heavy-flavour measurement in pp collisions with ALICE in the LHC Run 3

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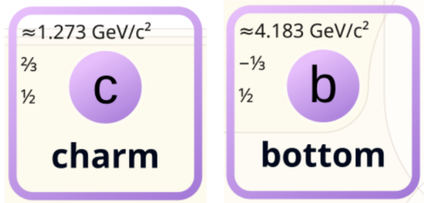
Laboratoire de Physique de Clermont Auvergne, Clermont-Fd, France

- Outline:
  - Motivation
  - ALICE detector in Run 3
  - Open heavy-flavour production
  - Associated production

Lyon, France
29 June - 3 July, 2026
17th France-China Particle Physics Network/Laboratory workshop

Physics motivation (1)

- Heavy quarks (charm and beauty): $m_c \approx 1.3$ GeV/c^2 $m_b \approx 4.2$ GeV/c^2
  - $m_Q \gg \Lambda_{QCD}$ (~ 200 MeV)
  - Produced in hard scattering processes, with large transferred momentum Q^2
  - Excellent probes of pQCD (perturbative QCD)
  - In pp, the heavy-flavour hadron production cross section is calculated by factorisation approach

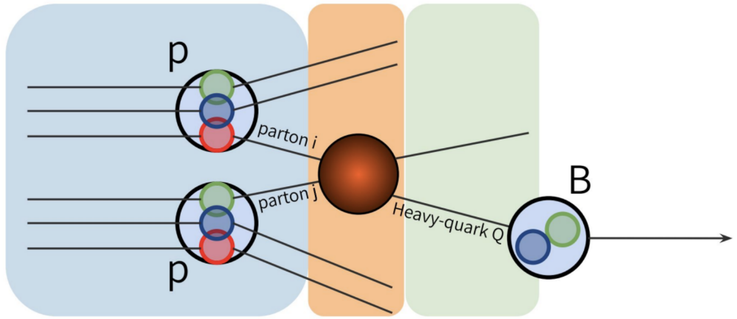


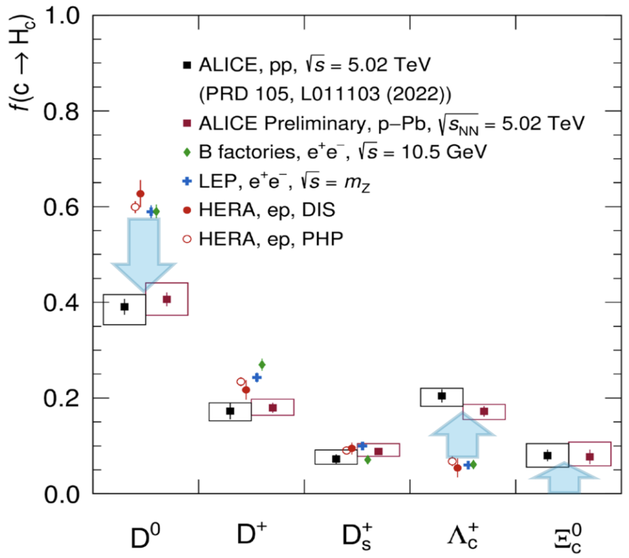
$$\frac{d\sigma^{H_q}}{dp_T{}^{H_q}}(p_T, \mu_F, \mu_R) = PDF(x_a, \mu_F) \otimes PDF(x_b, \mu_F) \otimes \frac{d\sigma^q}{dp_T{}^q}(x_a, x_b, \mu_F, \mu_R) \otimes D_{q\to H_q}(z = p_{H_q} p_q, \mu_F)$$

Parton distribution functions (initial-state hadronic structure)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization, assumed universal across collision system)





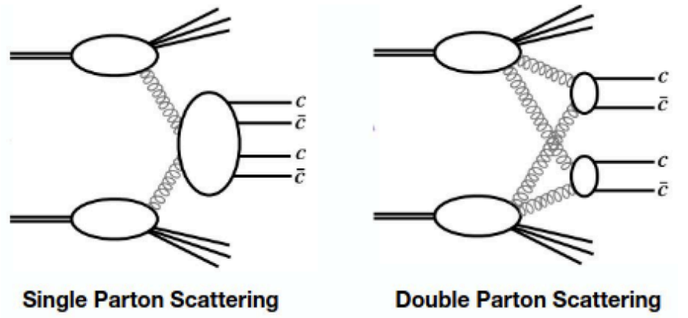
Higher order effects/Coalescence in pp collisions?

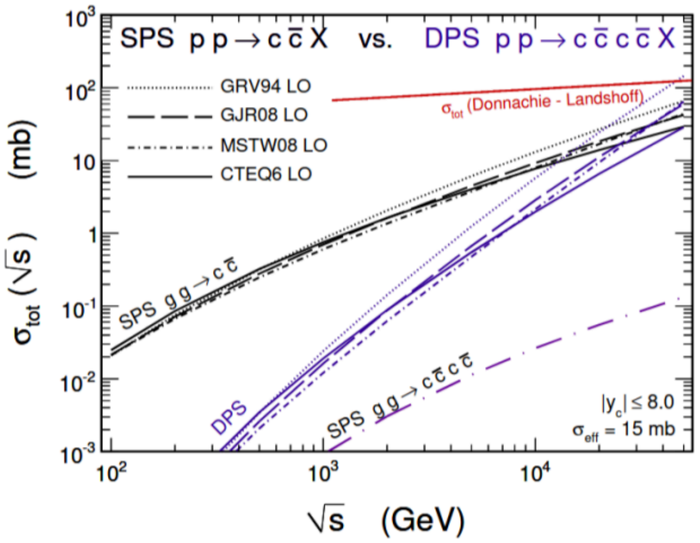
- Investigate hadronisation mechanisms
- Reference for heavy-ion studies

ALI-PREL-541012

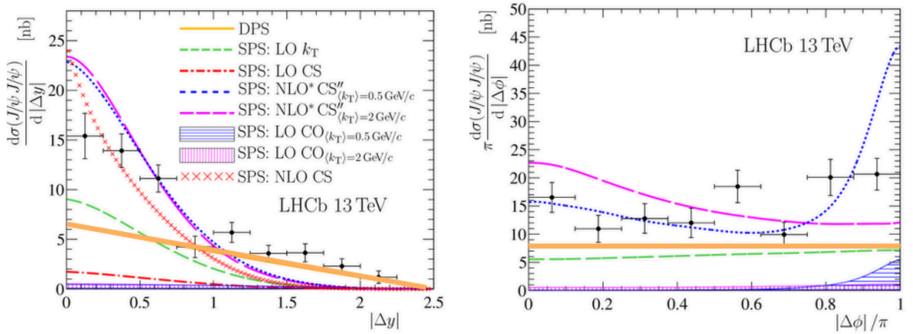
Physics motivation (2)

- Multiple parton interactions (MPI)
  - Investigate non-perturbative hadronsation mechanisms (color reconnection, etc)
  - Probe the spatial structure of the proton
- Double parton scattering (DPS): simplest form of MPI
- DPS cross section increases faster than Single Parton Scattering (SPS) with collision energy





[A.Szczurek, R.Maciuła AIP Conf. Proc. 1523, 255–259 (2013)]

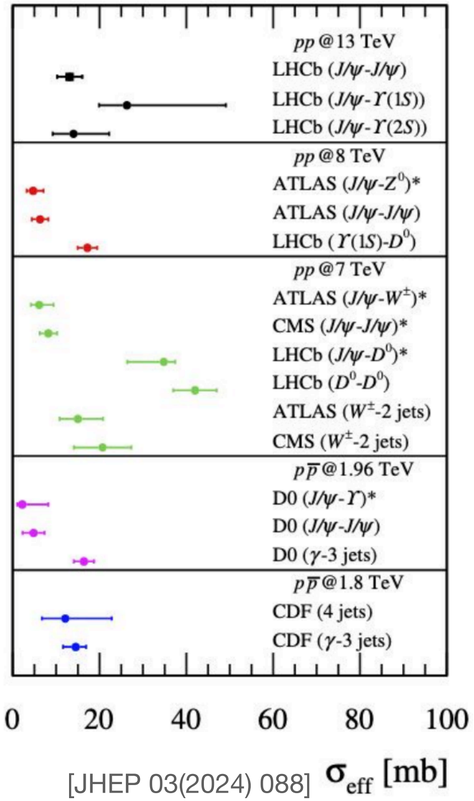


[LHCb Collaboration, JHEP (2017) 2017 : 68]

- Separation of SPS and DPS via Δy and $\Delta\phi$
- Key observable for DPS studies:
  - effective cross section σ_{eff}
  - Assumed to be independent w.r.t. process and $\sqrt{s}$

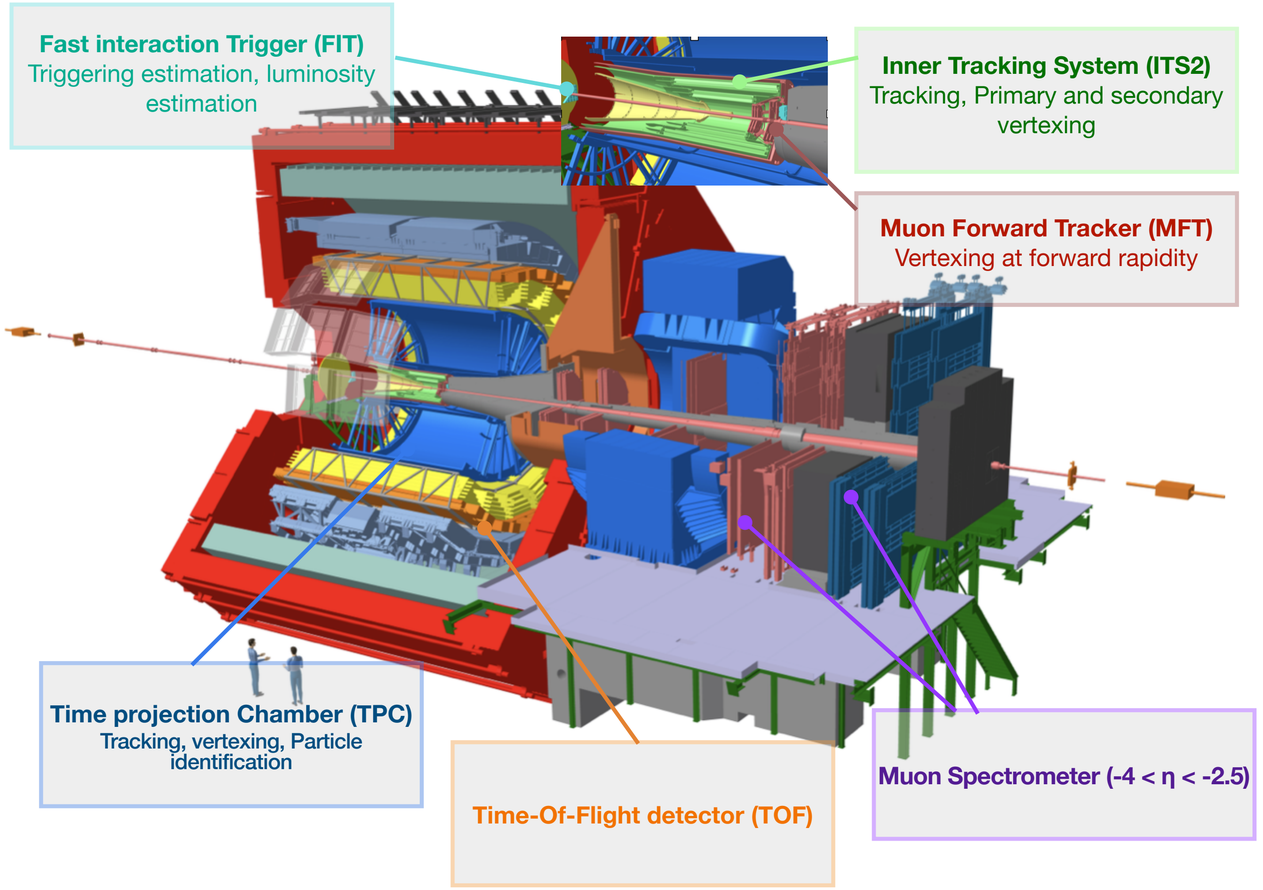
$$\sigma_{eff} = \frac{1}{1+\delta_{AB}}\frac{\sigma_A \sigma_B}{\sigma_{A,B}^{DPS}}$$

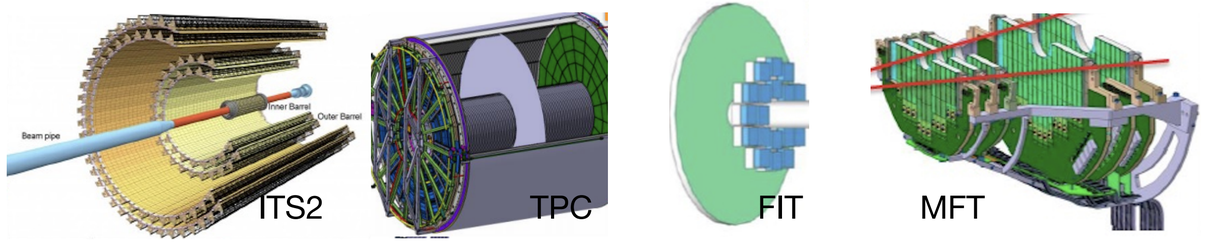
$$\delta_{AB} = \begin{cases} 1, & A = B \\ 0, & A \neq B \end{cases}$$



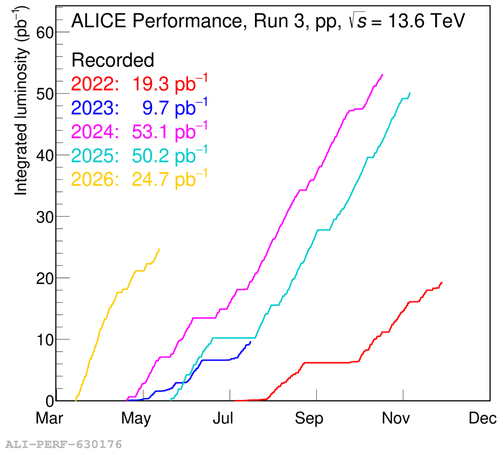
[JHEP 03(2024) 088]

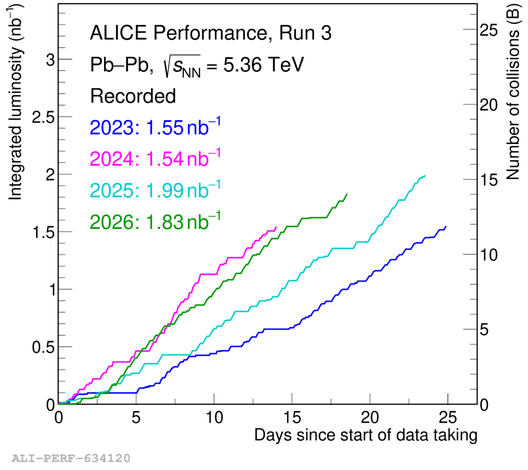
ALICE detector in Run 3





- New Inner Tracking System: better pointing resolution at mid-rapidity
- New TPC: readout based on Gas Electron Multipliers
- New MFT: vertexing capabilities at forward rapidity
- New FIT: forward multiplicity and continuous readout





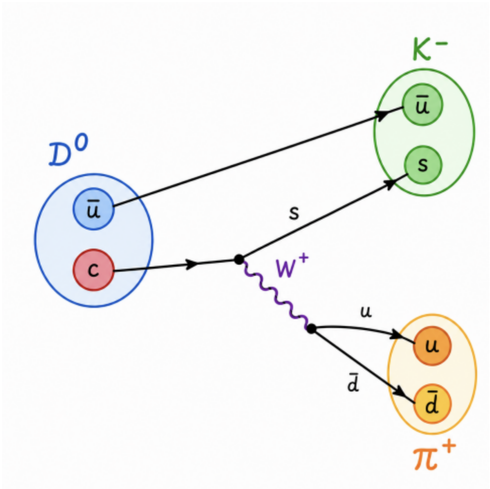
- Large data sample collected:
  - Higher interaction rates (up to 750 kHz in pp, 50 kHz in Pb–Pb)
  - Data taking in continuous readout mode

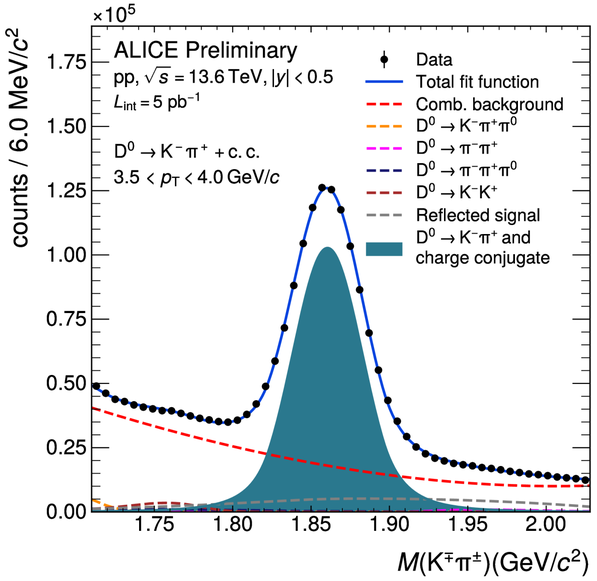
~ 8×10^{12} minimum bias (MB) pp events
× 10^3 more MB than Run 1+2

~ 5×10^{10} MB Pb–Pb events
× 160 more MB than Run 1+2

Prompt D^0-meson production in Run 3

- Prompt D^0-meson production measured with high precision down to $p_T = 0$





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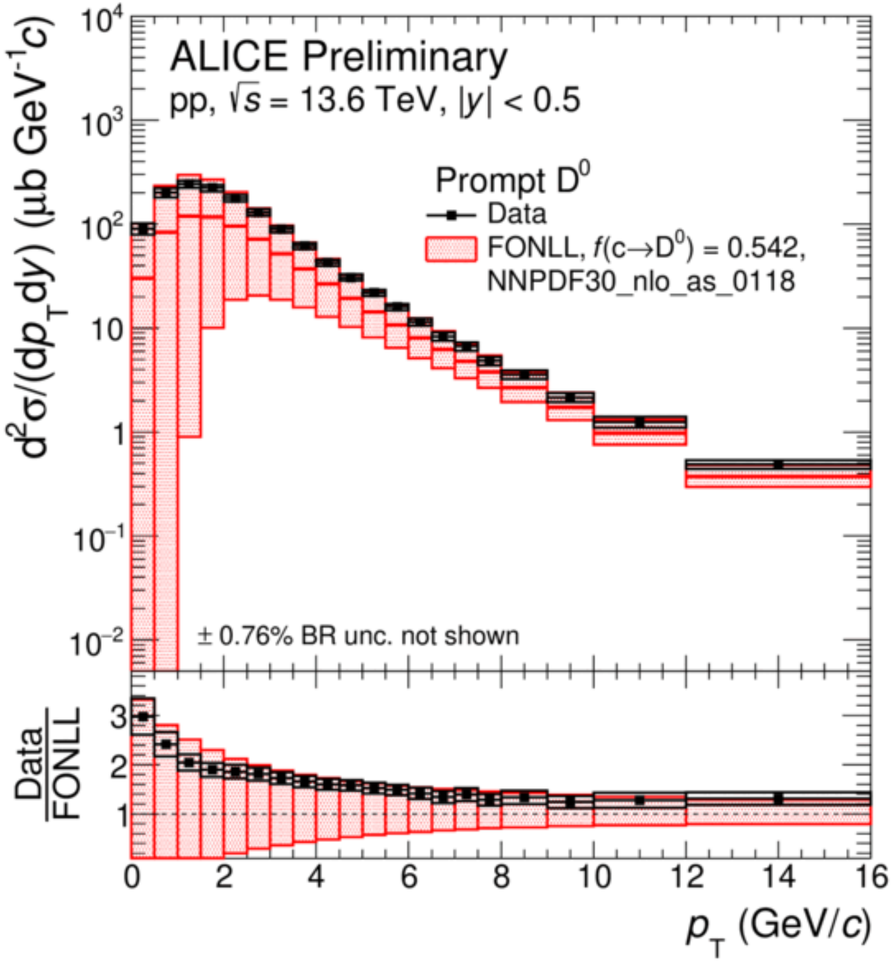


ALI-PREL-623534

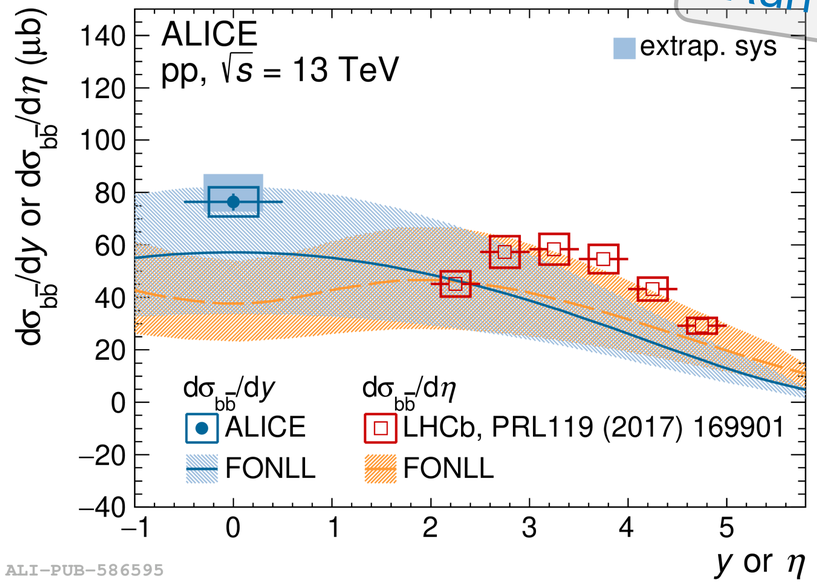
- $D^0 \rightarrow K\pi$ at midrapidity ($|y|<0.5$)
- Signal selection performed via BDT (boosted decision tree)
- Model predictions based on FONLL calculations compatible with the measurement within the uncertainties
- High precision measurement thanks to the large statistics
- Benefit for the associated heavy-flavour measurements

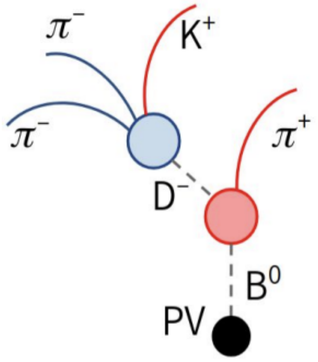
FONLL: [M. Cacciari et al., JHEP05(1998)007]
NNPDF30nlo_as0118: [R. D. Ball et al., Nuclear Physics B 855 (2012) 153]

Beauty production measurements in Run 2 and Run 3

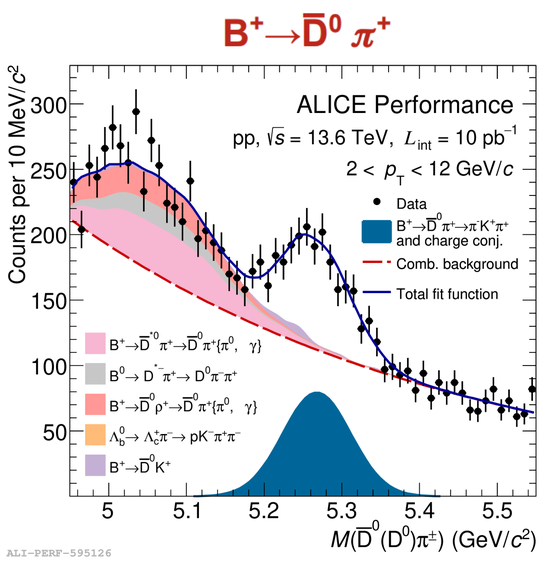
- During Run 2, ALICE measured the beauty cross section at midrapidity indirectly, via non-prompt charm hadrons
  - Limited constraint on beauty hadronisation models
- Run 3: direct reconstructed beauty hadrons accessible in various channels

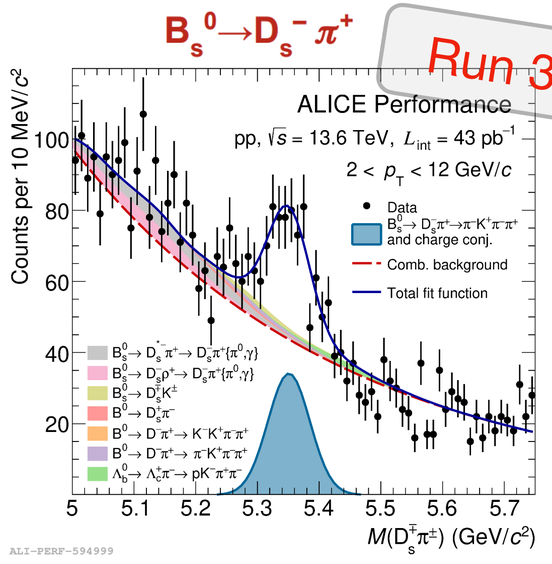
Run 2

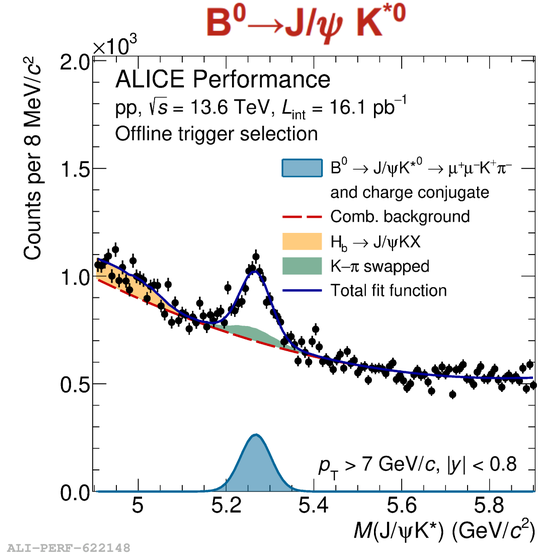


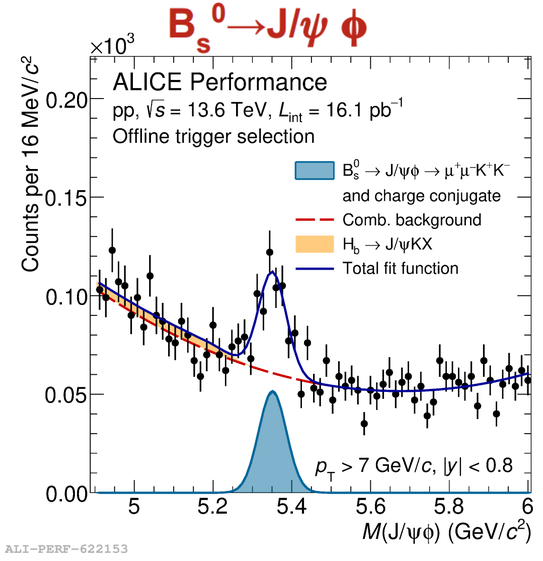


Run 3



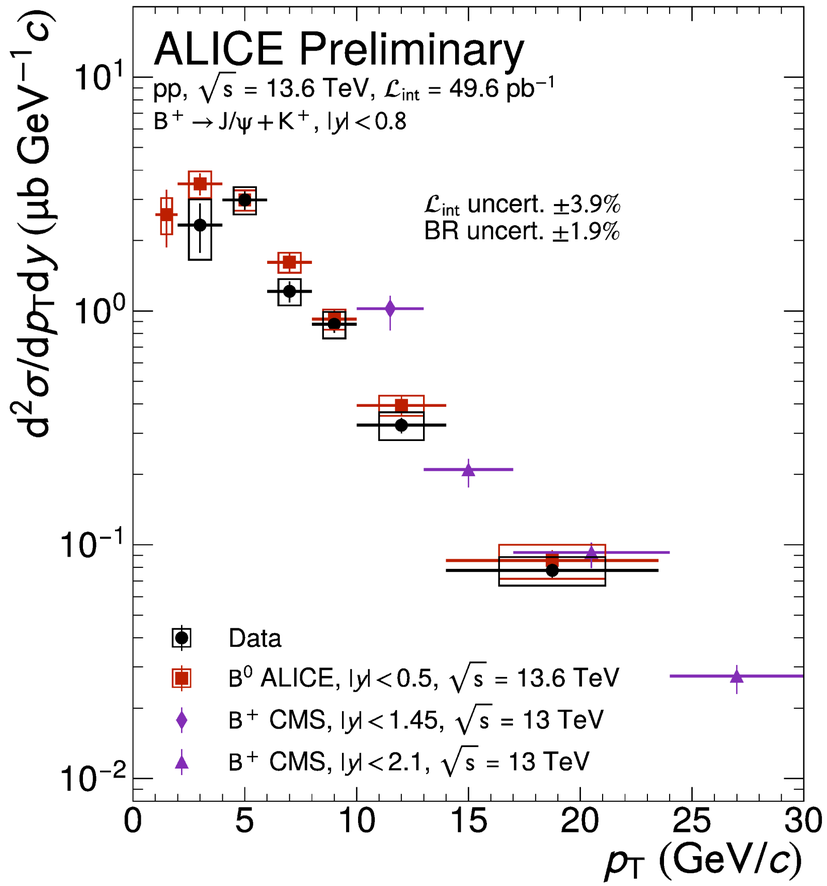


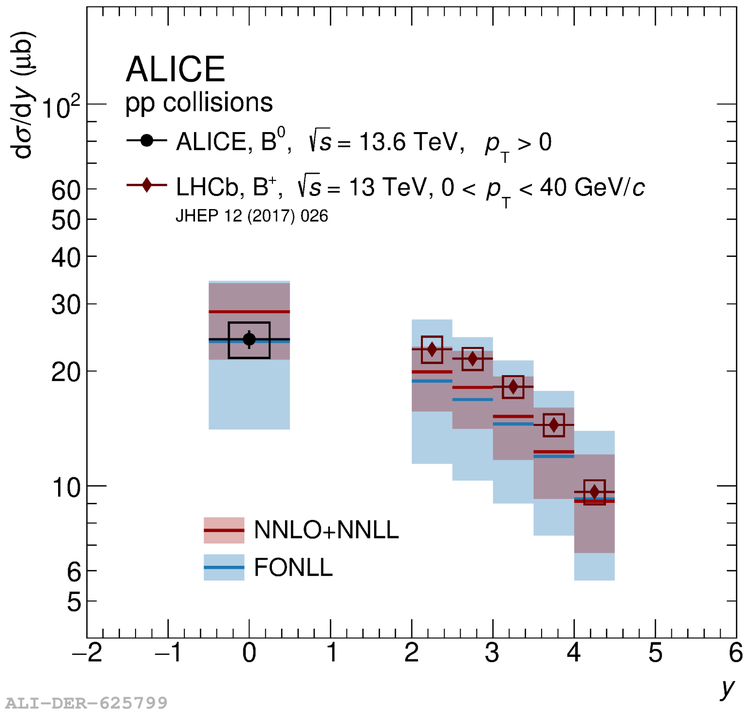




Exclusive beauty hadron reconstruction in Run 3

- First exclusive reconstruction of open-beauty hadrons by the ALICE Collaboration
  - Using offline software triggers
  - Direct access to the beauty sector
- B^0 and B^+ production cross sections measured down to low p_T
  - Complementary to CMS and LHCb results
- Results compatible with FONLL and NNLO+NNLL predictions within uncertainties





LHCb, [JHEP 12 (2017) 026]

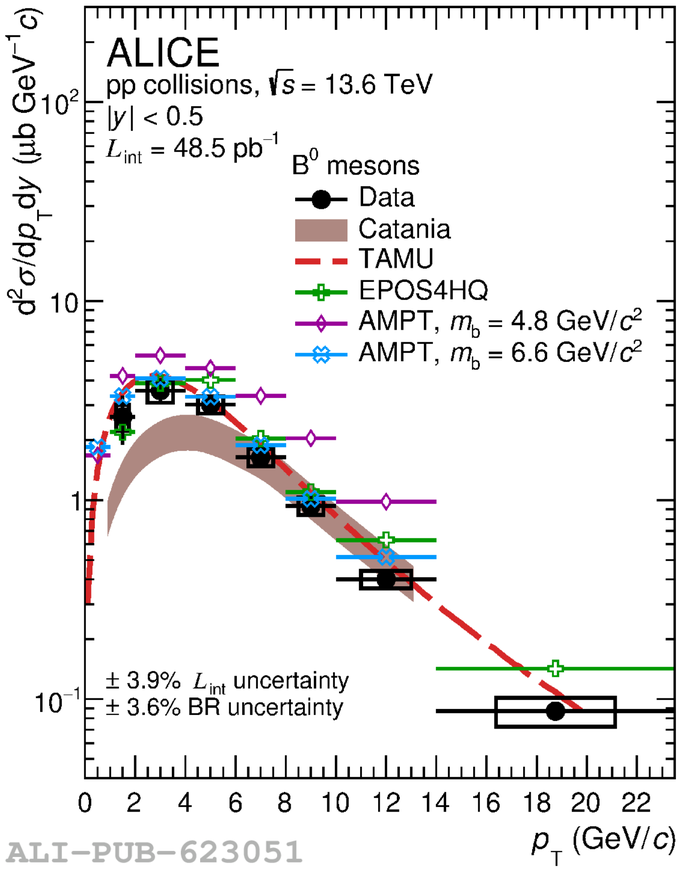
CMS: [PLB 771 (2017) 435-456]

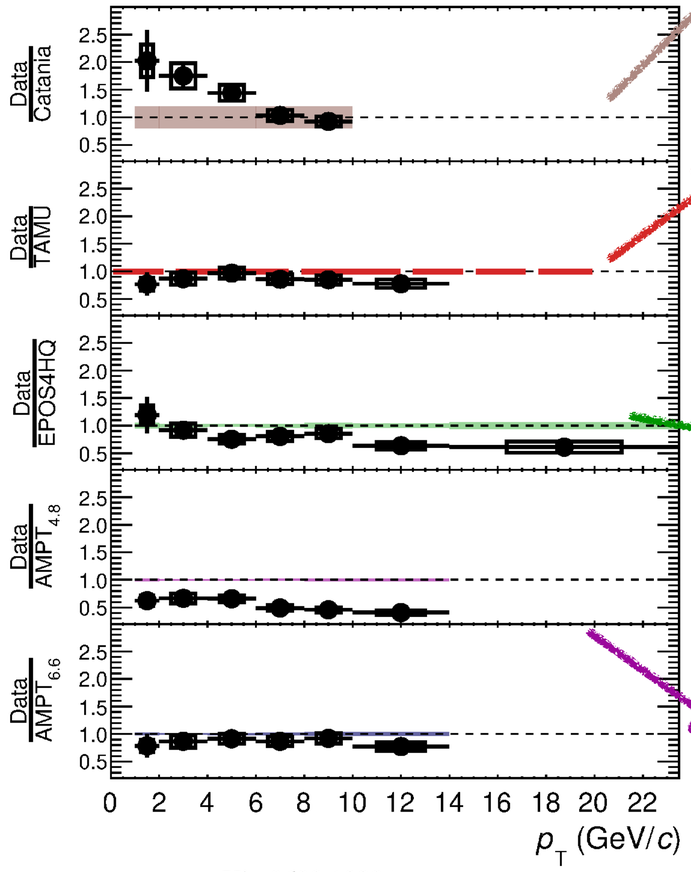
arXiv:2603.18904

FONLL: [Cacciari et al., JHEP 9805:007,1998] NNLO+NNLL: [Czakon et al. PRL 135 (2025) 16, 161903]

B^0 production cross section

- Production cross section compared with transport models



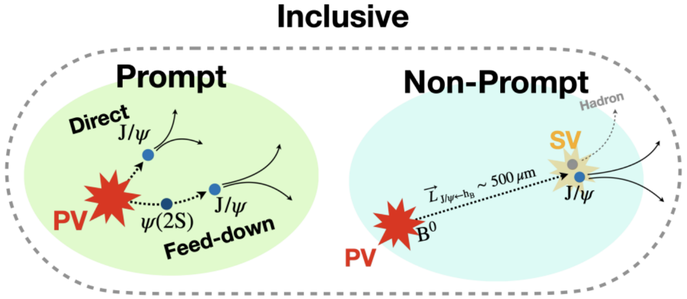


arXiv:2603.18904

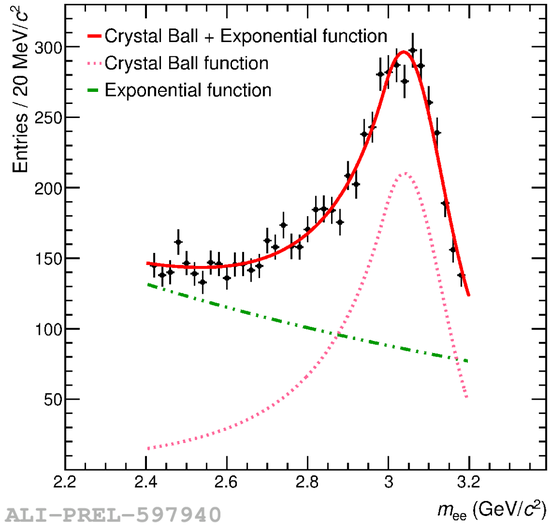
- Catania [V. Minnisale et al., PLB 2021 136622]
  - FONNL b-quark spectra
  - Hadronisation via fragmentation and coalescence
  - Underestimates the data at low p_T
- TAMU [He et al., PRL 131 (2023) 1, 012301]
  - LHCb $b\bar{b}$ + FONLL b-quark p_T spectra
  - b → H_b from statistical hadronisation model
  - Better describes data
- EPOS4HQ [Zhao et al., PRC 110 024909]
  - Hydrodynamic evolution with heavy quark propagation
  - Hadronisation via fragmentation and coalescence
  - Describes data well up to 10 GeV/c only
- AMPT [He et al., JHEP 07(2021) 035]
  - Multi-phase partonic and hadronic interactions
  - Hadronisation via fragmentation and coalescence
  - Overestimates data for m_b = 4.8 GeV/c^2

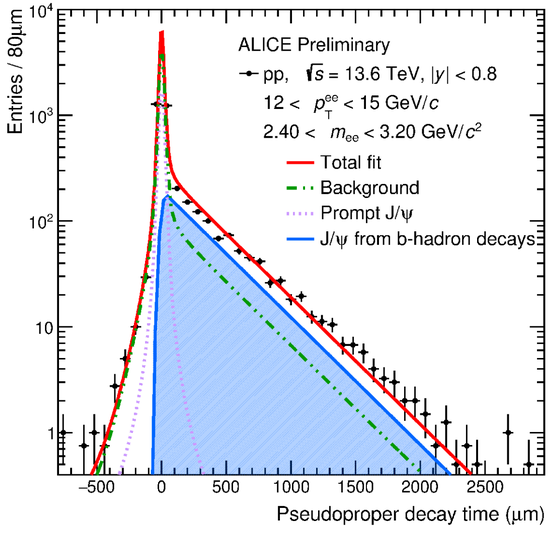
Beauty production measurement via quarkonia

- J/ψ and ψ(2S): bound states of charm and anti-charm pairs
- Non-prompt J/ψ and ψ(2S): produced by B-hadron decays

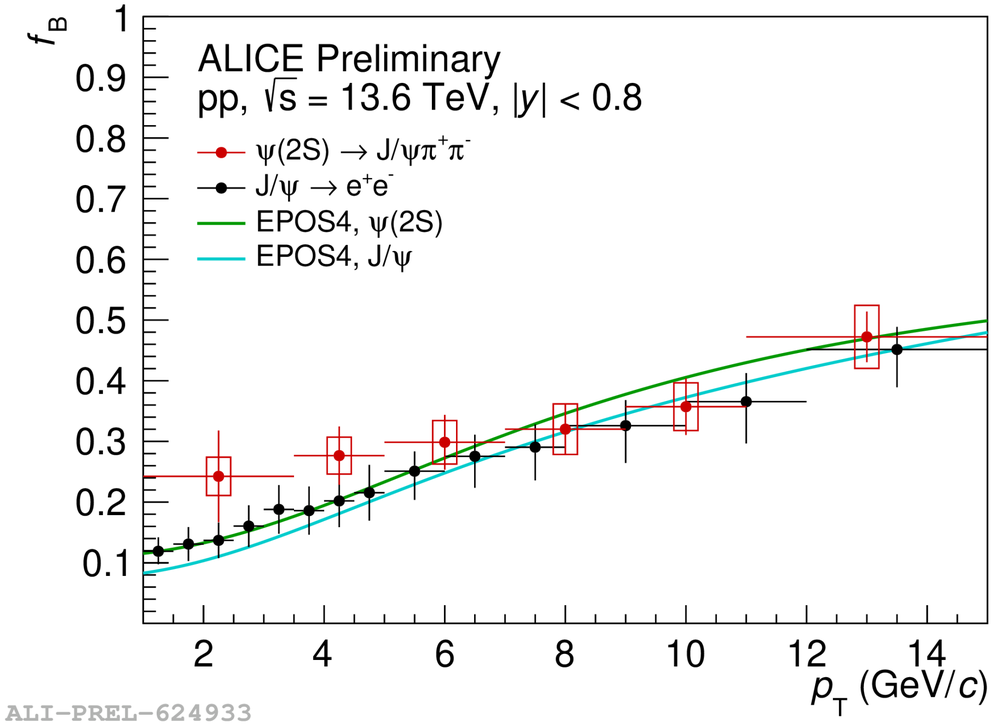


- The non-prompt fraction of quarkonia f_B is extracted through a simultaneous fit of:
  - The pseudo-proper decay time τ
  - The dilepton invariant-mass distribution m_{ee}





ALI-PREL-597940

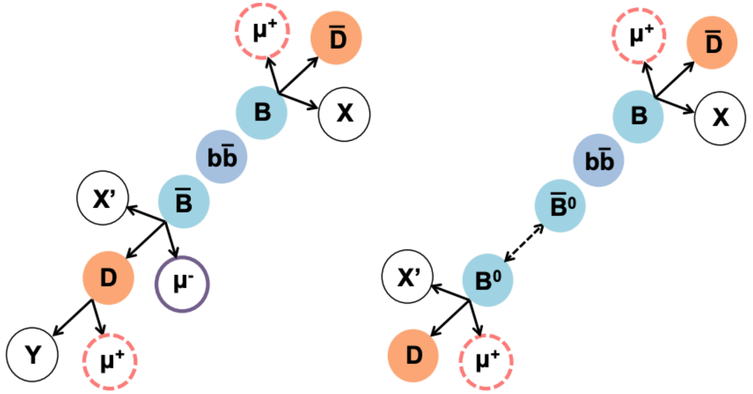


ALI-PREL-624933

- First measurement of the fraction of ψ(2S) originating from B-hadron decays at midrapidity in the low-p_T region
- Hint of a larger f_B(ψ(2S)) than f_B(J/ψ) at low p_T
- Comparison with EPOS4 predictions:
  - Good description of f_B(J/ψ) for p_T > 4 GeV/c
  - A slightly larger predicted f_B(ψ(2S)) compared to f_B(J/ψ)

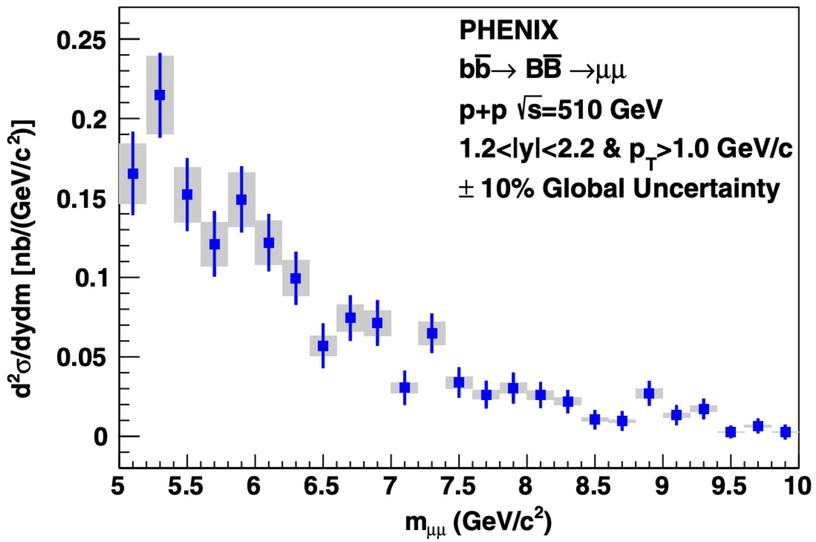
Beauty production measurement via like-sign muons

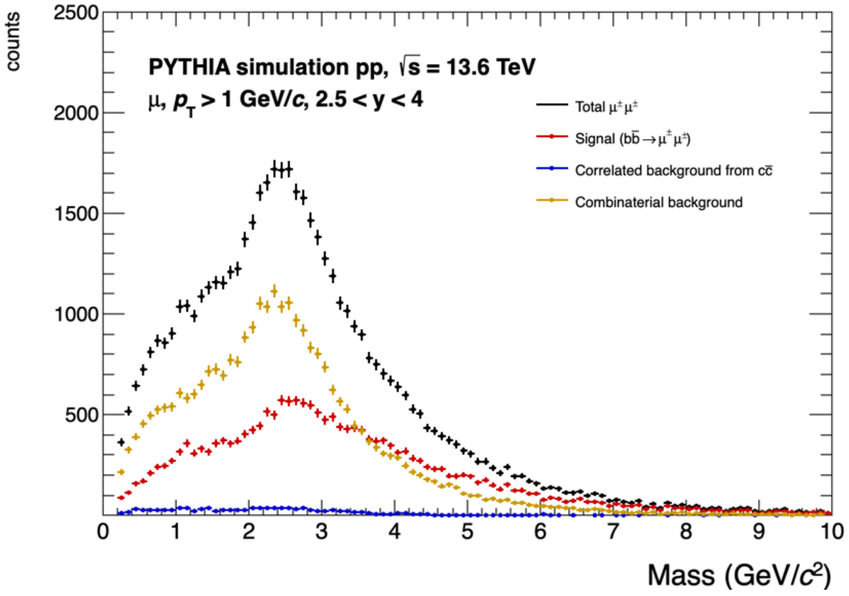
- Beauty production cross section can be measured at forward rapidity via muons with ALICE detector
  - Like-sign dimuons: a clean signal channel free from quarkonia and Drell-Yan contaminations
  - Similar measurement performed in PHENIX: can be extended to the LHC energy regime



Like-sign dimuons

[PHENIX: PhysRevD.102.092002]





- Feasibility study with PYTHIA shows significant signal and negligible correlated charm background, main background from combinatorial pairs

PYTHIA: [P. Skands et al., Eur. Phys. J. C (2014) 74:3024]

Beauty production measurement via like-sign muons

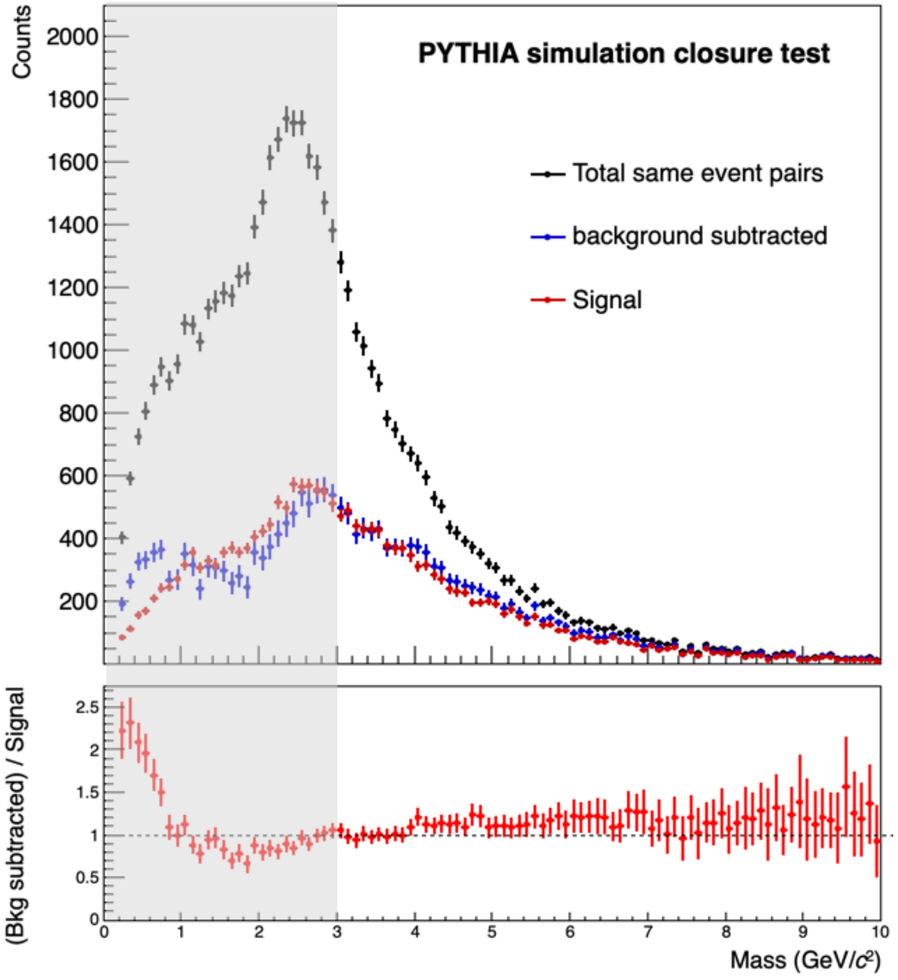
- Combinatorial background subtracted via the event-mixing technique:

$$N_{signal} = N^{SE}_{\pm\pm} - R \times N^{ME}_{\pm\pm} \quad where\ R = \frac{\sqrt{N^{SE}_{++} \times N^{SE}_{--}}}{\sqrt{N^{ME}_{++} \times N^{ME}_{--}}}$$

- Mixed events normalised by an iterative method:
  - The MC signal Sig is used to correct the overestimated normalisation factor R until it converges

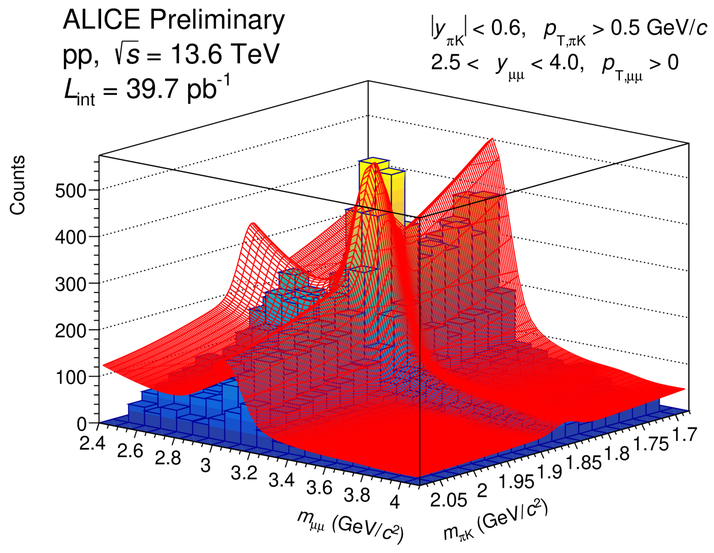
$$R^{i+1} = \sqrt{\frac{(N^{SE}_{++} - Sig^{i}_{++}) \times (N^{SE}_{--} - Sig^{i}_{--})}{N^{ME}_{++} \times N^{ME}_{--}}}$$

- Closure test with PYTHIA shows promising results in signal region 3-10 GeV/c^2
- Method validated, being applied to pp data

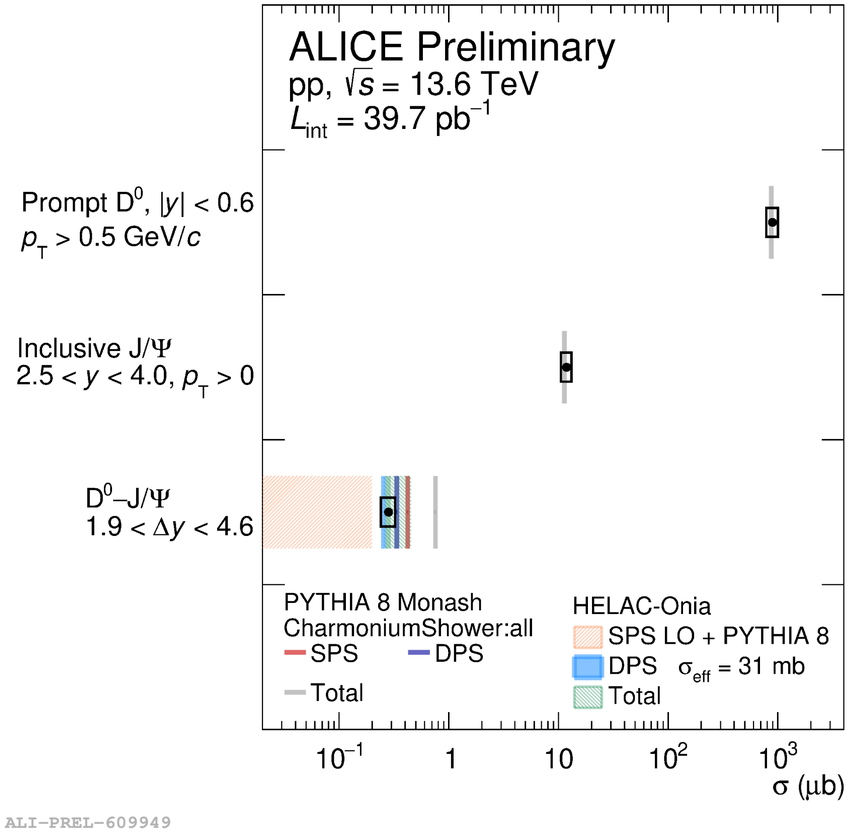


Associated production of prompt D^0 and J/ψ

- J/ψ-D^0 associated production cross section measured in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE detector
  - J/ψ reconstructed at forward rapidity via dimuons using offline trigger selection
  - 2D fits to the invariant mass of the D^0 and the J/ψ to extract the signal



- PYTHIA 8 simulations:
  - Monash tune + CharmoniumShower:all
  - Single prompt D^0 and inclusive J/ψ cross sections: **compatible** with data
  - J/ψ-D^0 cross section: **overestimate** data
- HELAC-onia:
  - DPS component is based on a σ_{eff} value (31 mb) which is extracted from a fit to the data
  - Reproduces the J/ψ-D^0 cross section
  - Large uncertainty on the SPS LO + PYTHIA 8 component: to be improved using NLO calculations



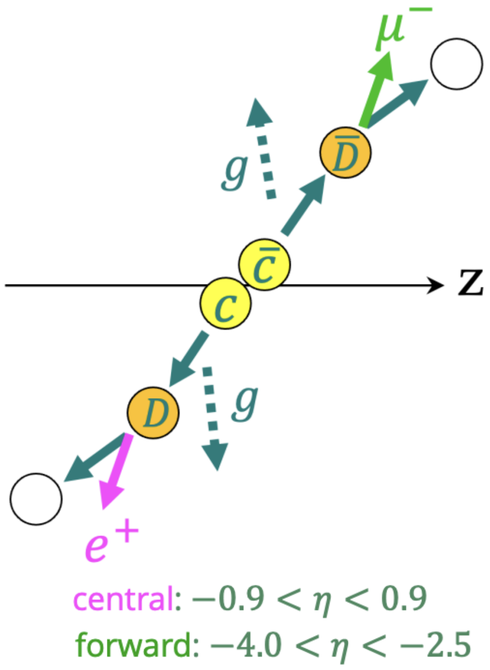
- A clear J/ψ-D^0 signal can be observed

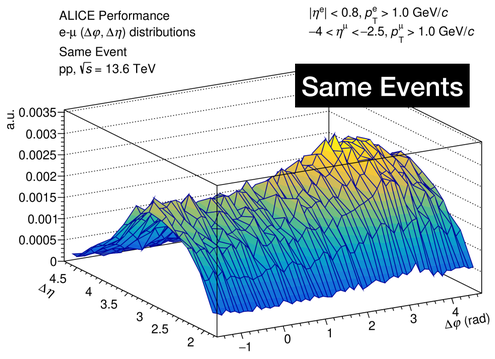
PYTHIA: [P. Skands et al., Eur. Phys. J. C (2014) 74:3024]

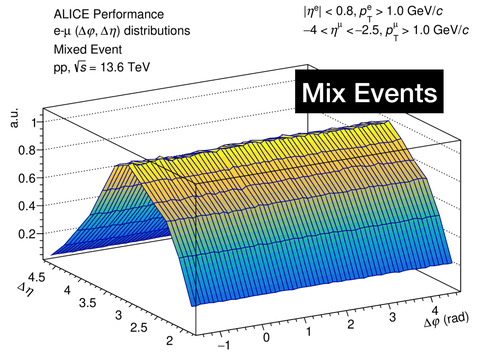
HELAC-Onia: [Hua-Sheng et al., Comput.Phys.Commun. 184 (2013) 2562-2570]

Associated production of heavy flavour e-μ pairs

- Heavy-flavour e-μ association production and angular correlation measured in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE
  - Mid-forward correlation: unique rapidity coverage
  - Opposite-flavour lepton pairs: clean signal free from resonance decays, thermal radiation, or Drell–Yan processes
  - Dedicated e-μ software trigger enables the measurement with pp data collected in the Run 3

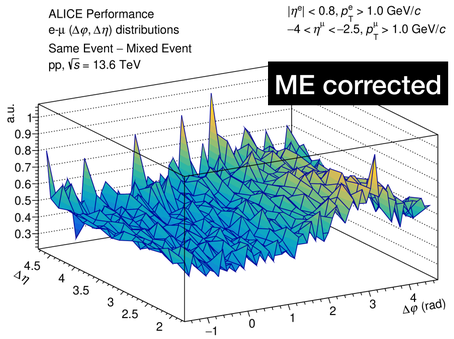




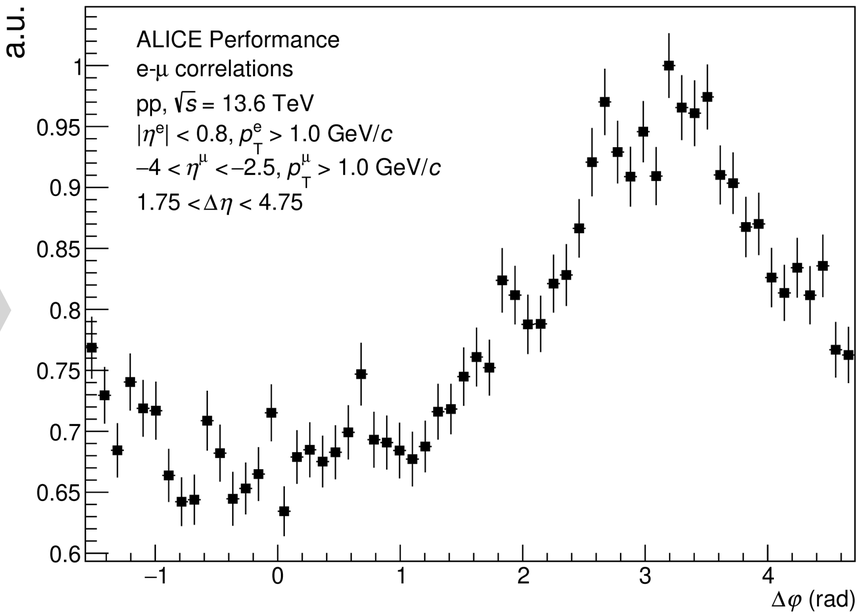


ALI-PERF-635577

$$C(\Delta\varphi, \Delta\eta) = \frac{SE(\Delta\varphi, \Delta\eta)}{ME(\Delta\varphi, \Delta\eta)}$$



ALI-PERF-635609



ALI-PERF-635634

- First performance estimation of ME-corrected e-μ azimuthal correlations
- Clear back-to-back away-side peak observed

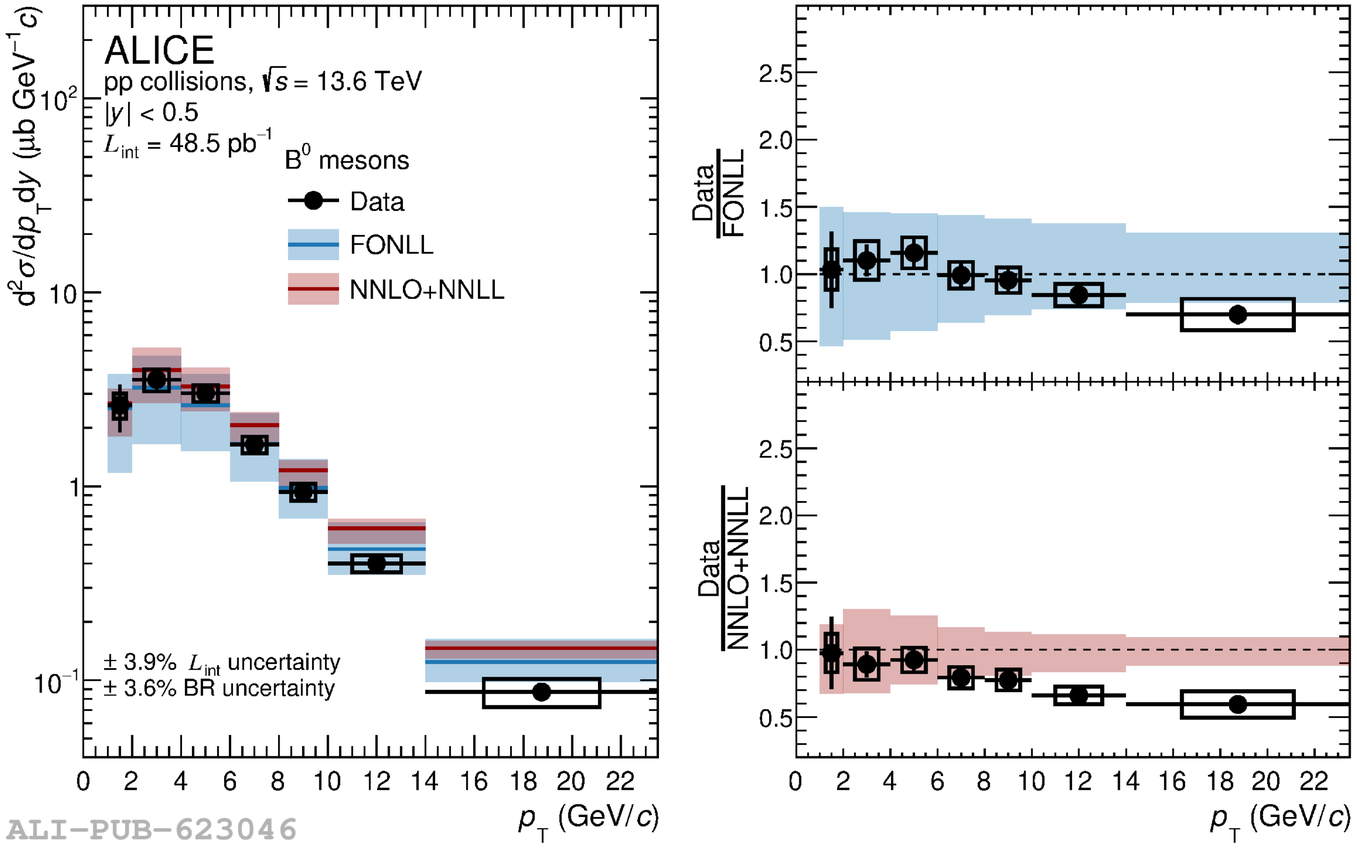
Summary

- LHC Run 3 opens the door to new physics channels for pQCD and QGP investigations with the ALICE detector
- The production of prompt D-meson and B-meson production measured in pp collisions at $\sqrt{s}$ = 13.6 TeV by ALICE
  - First measurement of full reconstruction of B mesons, set new constrains on model calculations
- New like-sign dimuon channel provides a new opportunity for exploring beauty physics at forward rapidity with the ALICE detector
- Double Parton Scattering studied by measuring associated production of J/ψ-D^0 and heavy flavour e-μ
  - Associated measurements between the central barrel and muon spectrometer now feasible in pp, and promising in Pb–Pb collisions
  - Rapidity gap coverage extended up to $|\Delta y| \approx 5$, allowing exploration of long-range correlations


Thank you for your attention
Merci pour votre attention
谢谢大家，敬请斧正！

Backup

B^0 meson production



- B^0-meson production cross section is well described by both NNLO+NNLL and FONLL predictions within uncertainties at $p_T < 10$ GeV/c

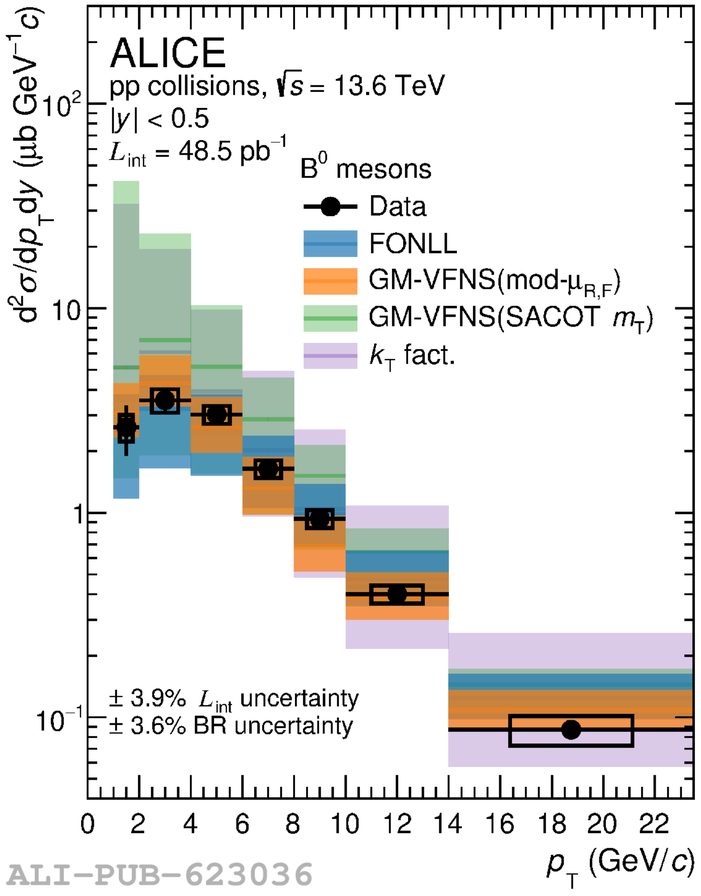
- NNLO+NNLL
  - Improved theoretical precision
  - Reduced scale dependence
  - Predictions located at the upper part of FONLL uncertainty band

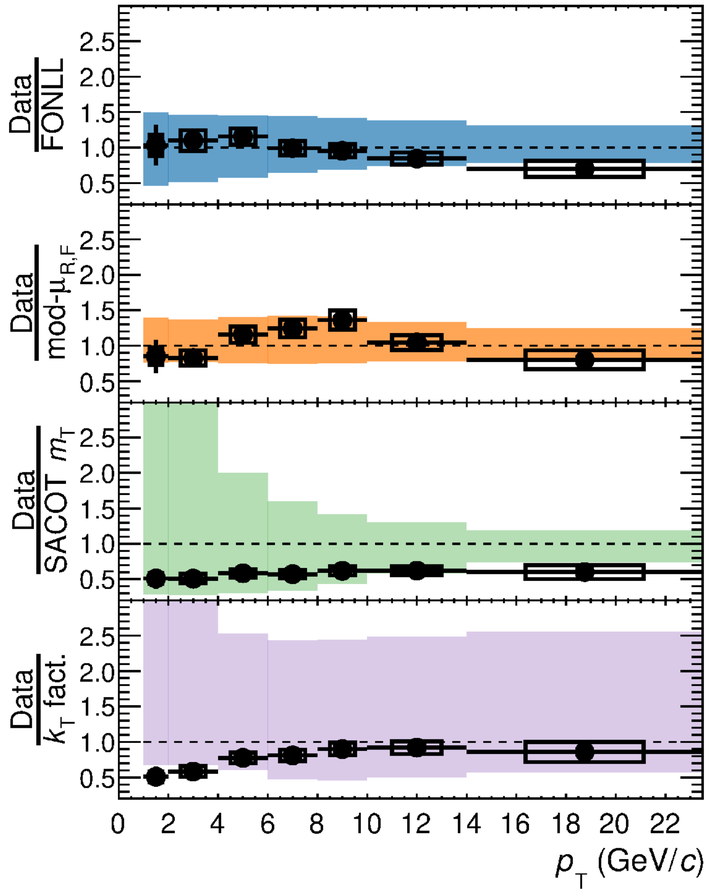
FONLL: [Cacciari et al., JHEP 9805:007,1998] NNLO+NNLL: [Czakon et al. PRL 135 (2025) 16, 161903]

ALICE, arXiv:2603.18904

B^0 meson production

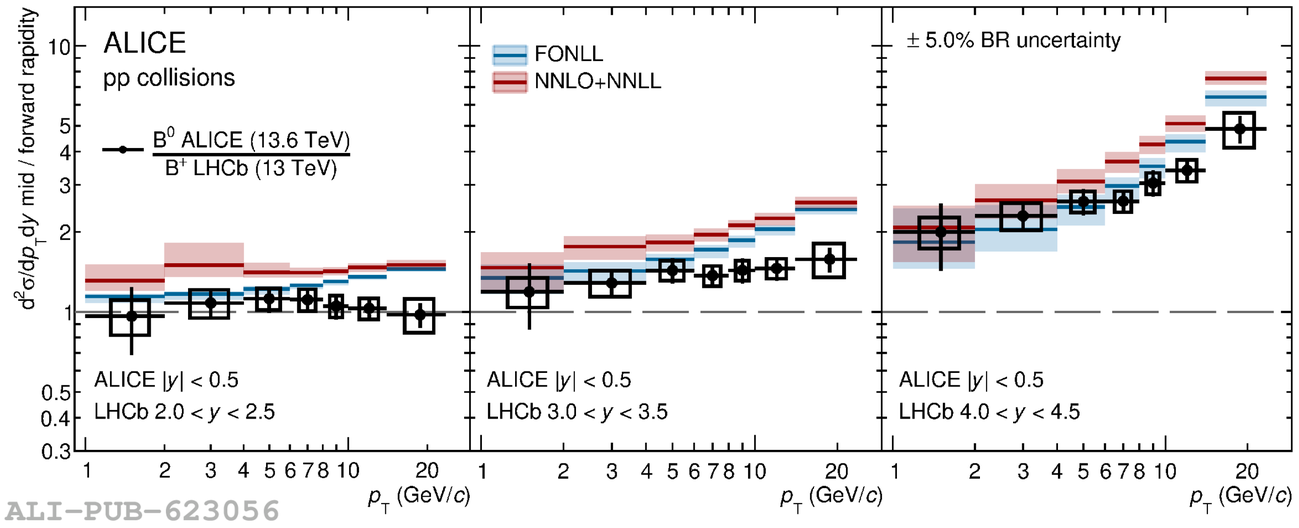
- First measurement of B^0-meson production at midrapidity down to low p_T = 1 GeV/c in pp collisions at 13.6 TeV by ALICE
- B^0-meson production cross section in agreement with various pQCD calculations



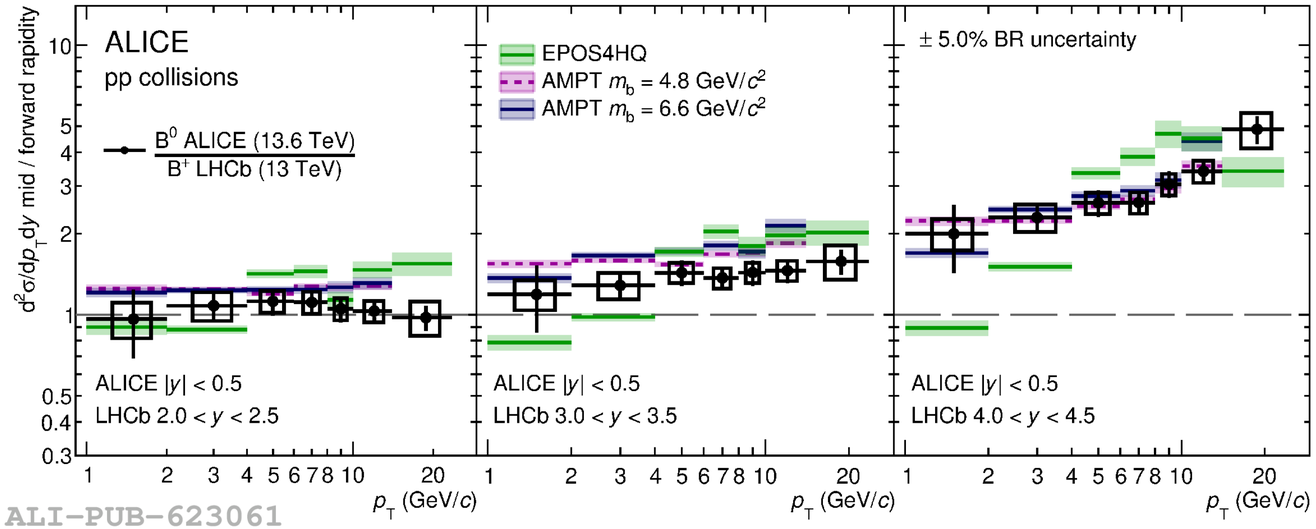


- FONLL, GM-VFNS (mod-$\mu_{R,F}$):
  - NLO + NLL calculations with collinear factorisation
  - Provide the best agreement over the full-p_T range
- GM-VFNS (SACOT m_T):
  - tends to overestimate the data, though still compatible within statistical uncertainties
- k_T factorisation:
  - NLO + NLL calculations with transverse momentum factorisation
  - Calculations provide on average larger values of the production cross section

B mesons mid-to-forward-rapidity ratio with models



ALI-PUB-623056



ALI-PUB-623061

- Harder p_T-spectrum and larger production towards midrapidty
- Comparison with models:
  - FONLL and NNLO+NNLL qualitatively describe the data, with NNLO+NNLL calculations systematically higher than FONLL
  - EPOS4HQ underestimates the ratio at low p_T
  - AMPT with two hypotheses for beauty-quark mass describes data

FONLL: [Cacciari et al., JHEP 9805:007,1998]

NNLO+NNLL: [Czakon et al. PRL 135 (2025) 16, 161903]

EPOS4HQ: [Zhao et al., PRC 110 024909]

AMPT: [He et al., JHEP 07(2021) 035]

arXiv:2603.18904