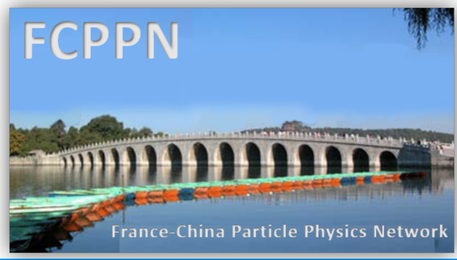

Measurement of associated production of open and hidden heavy-flavours in pp collisions with ALICE

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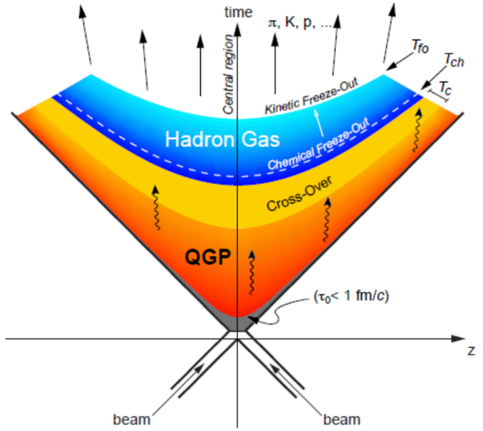
Laboratoire de Physique de Clermont Auvergne, Clermont-Fd, France

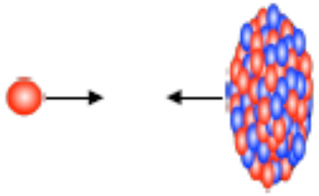
- Outline:
  - Recap of collaboration achievements
  - FCPPN/L at ALICE LHC Run 3
  - New outcomes
  - Conclusion

Qingdao, Shandong
21-25 July, 2025
16th France-China Particle Physics Network/Laboratory workshop

Physics motivation

- Heavy (charm and beauty) quarks: sensitive probes of the Quark-Gluon Plasma (QGP)
  - Produced in initial hard scatterings, prior to the formation of the QGP
    - $\tau_{c/b}$ ~ 0.01-0.1 fm/c < τ_{QGP} (~0.3 fm/c) [PRC 89 (2014) 034906]
  - Flavour conserved by the strong interaction
  - Experience the whole collision evolution
  - High momentum transfer: calculable within perturbative QCD (pQCD)
    - Excellent tool for studying the physics of strong interactions





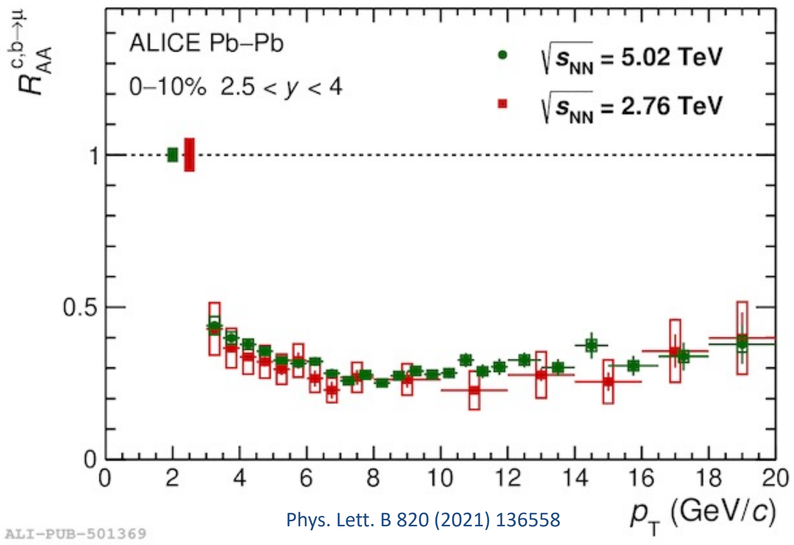
- Proton-proton (pp) collisions:
  - Test pQCD-based calculations
  - Production mechanisms
  - Reference for p-Pb and Pb-Pb collisions

- p-Pb collisions:
  - Cold nuclear matter effects
  - Flow-like phenomena in high-multiplicity collisions
  - Nuclear PDF
  - Reference for Pb-Pb collisions

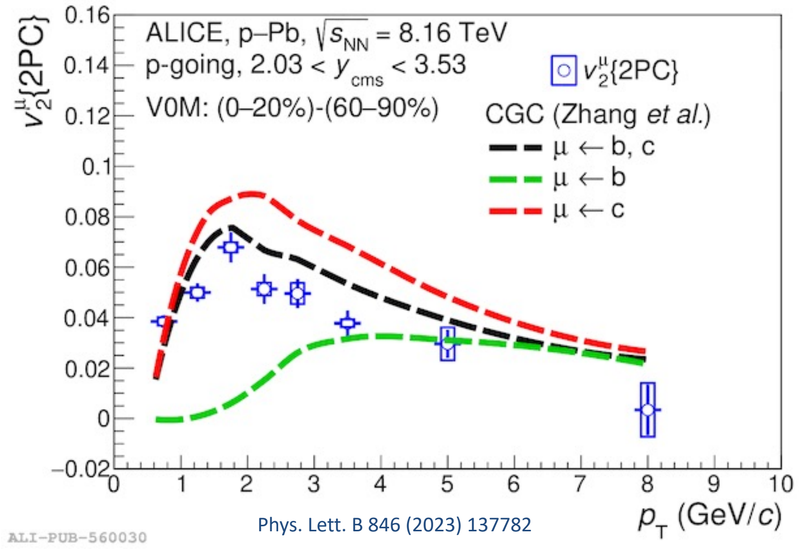
- Pb-Pb collisions:
  - Transport properties of the QGP
    - In-medium energy loss
    - Collective expansion
    - Thermal degree of freedom

Heavy-flavour measurements in Run 1 & 2

- Heavy-flavour measurements in different collision systems during Run 1 & 2 provided key insights into QGP properties and initial-state effects
  - Strong suppression of nuclear modification factor R_{AA} measured in Pb-Pb collisions due to hot nuclear matter effects
  - Positive muon elliptic flow v_2 measured in small systems, indicating the interplay of initial- and final-state effects



Phys. Lett. B 820 (2021) 136558



Phys. Lett. B 846 (2023) 137782

- R_{AA}: how particle production in heavy-ion collisions differs from that in pp collisions, indicating medium effects

$$R_{AA}(p_T, y) = \frac{1}{< T_{AA} >} \times \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy} = \frac{\text{QCD Medium}}{\text{QCD Vacuum}}$$

- v_2: second-order coefficient of the Fourier expansion of the azimuthal (ϕ) distribution w.r.t. to the reaction plane

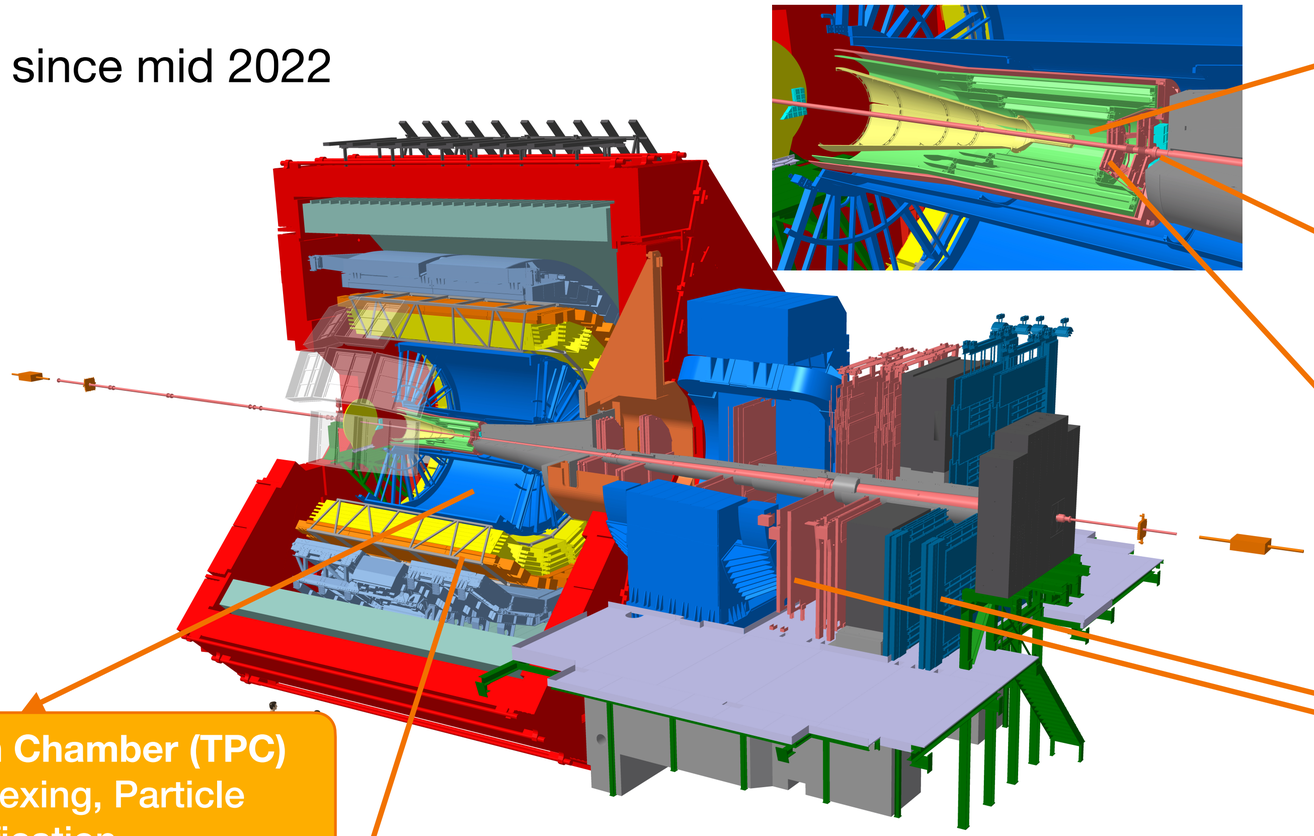
$$v_2 = < \cos\left[2\left(\varphi - \Psi_{RP}\right)\right] >$$

ALICE, PLB 708 (2012) 265
ALICE, PRL 109 (2012) 112301
ALICE, PLB 753 (2016) 41
ALICE, PLB 770 (2017) 459
ALICE, JHEP 09 (2019) 008
ALICE, PLB 819 (2021) 136637 &
CERN Courier Jan./Feb. 2021
ALICE, PLB 820 (2021) 136558

- Fruitful results achieved with support from the FCPPN/L framework
- ALICE Run 3 opens access to new Heavy-flavour correlation observables with improved precision and acceptance

ALICE detector in Run 3

- Major upgrades installed in 2019-2021
- In production since mid 2022



Inner Tracking System (ITS2)
Tracking, Primary and secondary vertexing

Fast interaction Trigger (FIT)
Triggering estimation, luminosity estimation

Muon Forward Tracker (MFT)
Vertexing at forward rapidity

Muon Spectrometer (-4 < η < -2.5)
Muon trigger, tracking

Time projection Chamber (TPC)
Tracking, vertexing, Particle identification

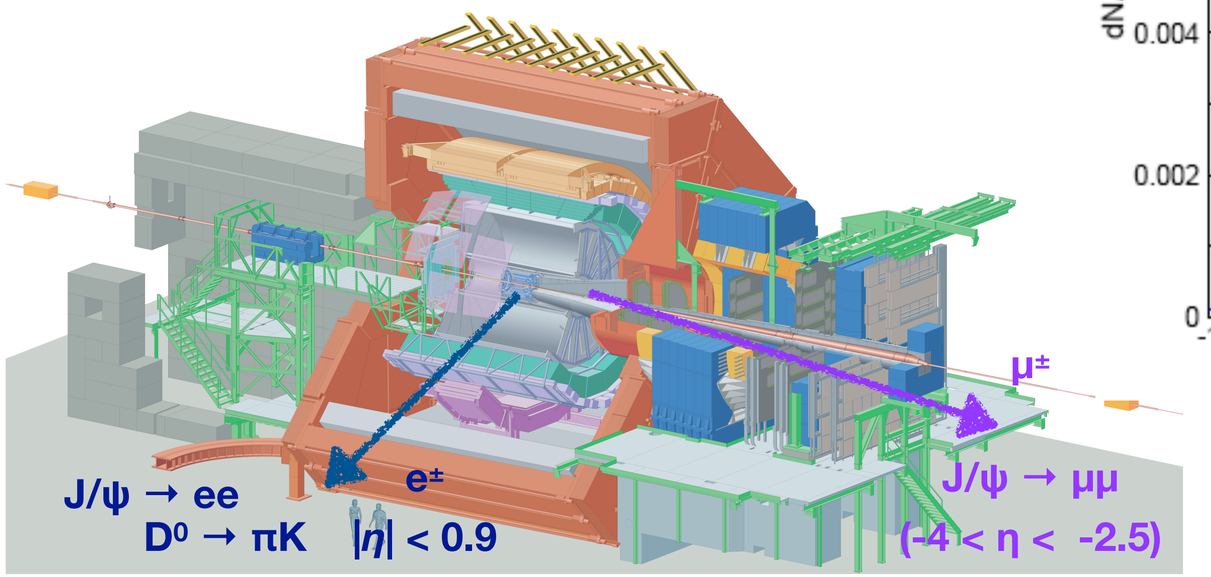
Time-Of-Flight detector (TOF)
Particle identification

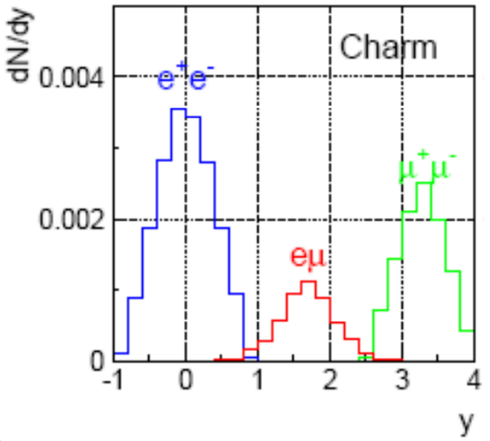
- New Inner Tracking System: better pointing resolution at mid-rapidity
- New Muon Forward Tracker: secondary vertexing at forward rapidity
- New TPC: readout based on Gas Electron Multipliers
- Continuous readout and increased luminosity: higher statistics

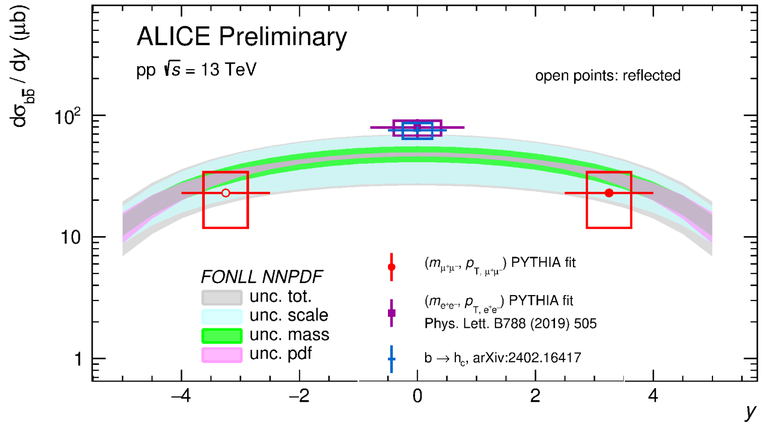
Associated heavy-flavour measurements in ALICE Run 3

Analysis Note by M.Pennisi

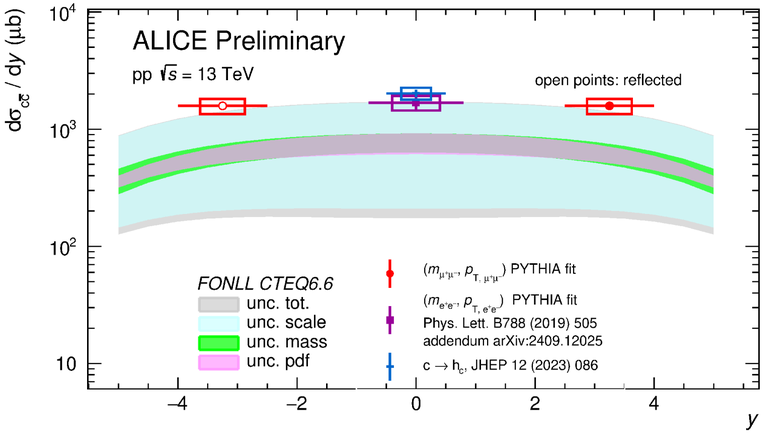
- ALICE in Run 3: more differential measurements with larger statistics
  - Long range correlations between mid- and forward-rapidities
  - Study the production mechanisms and the role of multi-parton interactions
- Associated heavy flavour production in ALICE Run 3:
  - Heavy-flavour e-μ correlations/coincidences
  - J/ψ-D^0 associated production
  - D^0-D^0 pair associated production







ALI-PREL-581594



ALI-PREL-581604

- Towards the measurement of the correlated charm/beauty production cross section in the rapidity region not covered by ALICE

Associated heavy-flavour measurements in ALICE Run 3

- ALICE in Run 3: more differential measurements with larger statistics
  - Long range correlations between mid- and forward-rapidities
  - Study the production mechanisms and the role of multi-parton interactions
- Associated heavy flavour production in ALICE Run 3:
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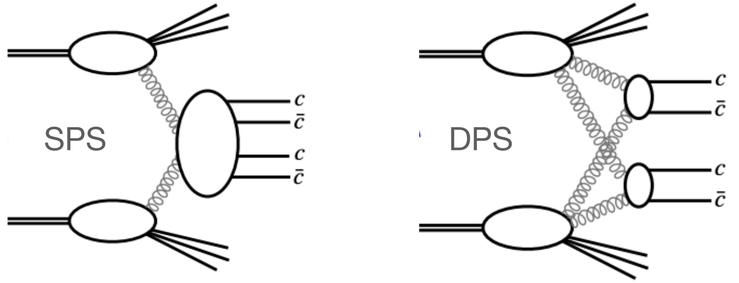
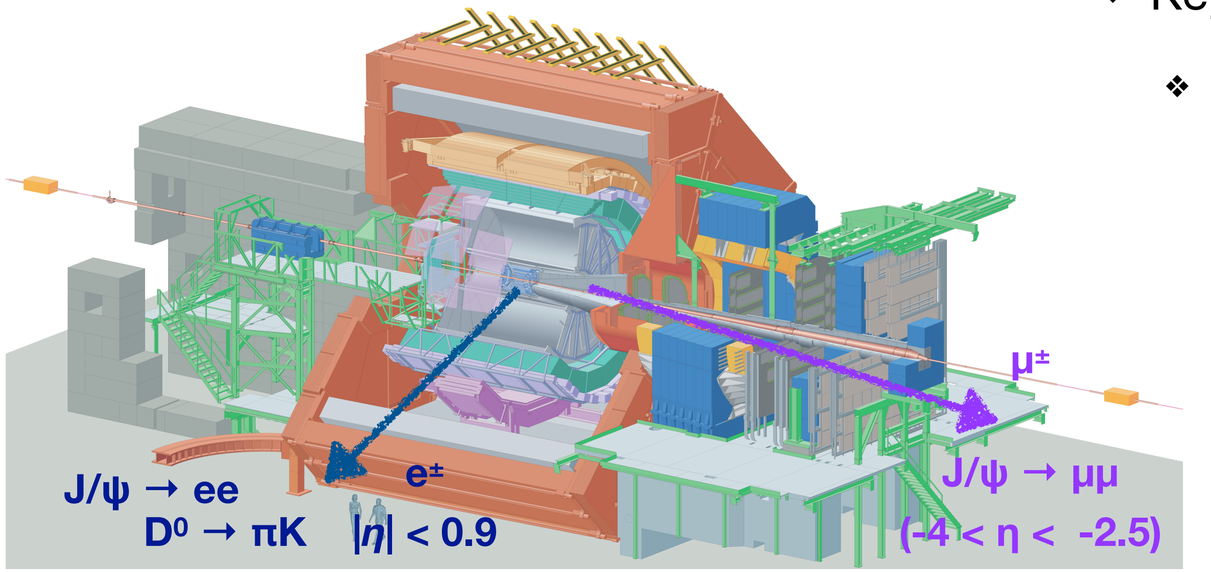
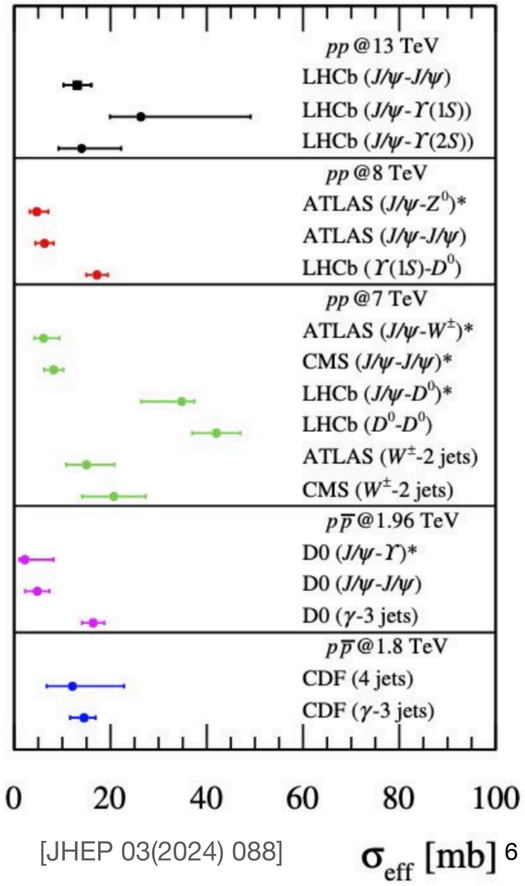




- Separation of Single Parton Scattering (SPS) and Double Parton Scattering (DPS) via $\Delta y(\Delta\phi)$
- Key observable for DPS studies:
  - effective cross section σ_{eff}

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

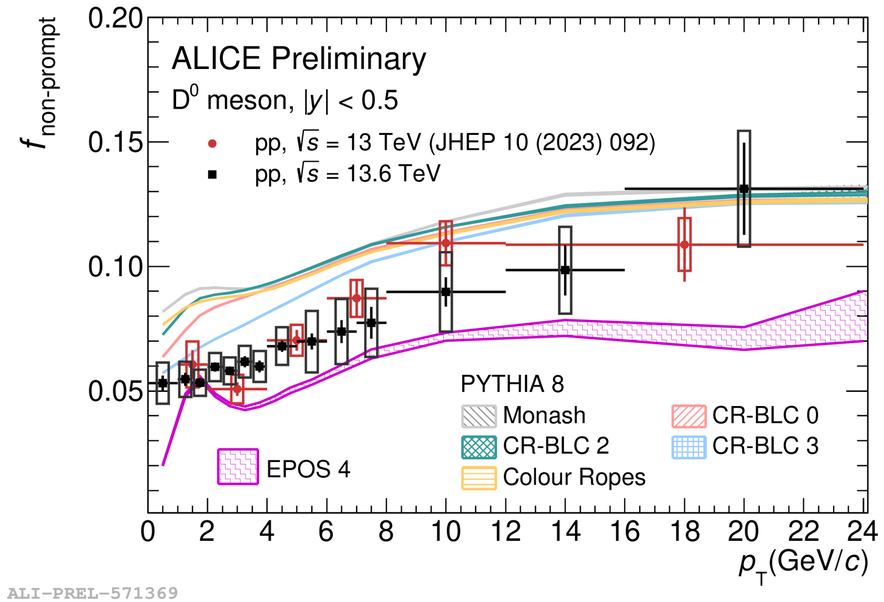
- Assumed to be independent w.r.t. $\sqrt{s}$

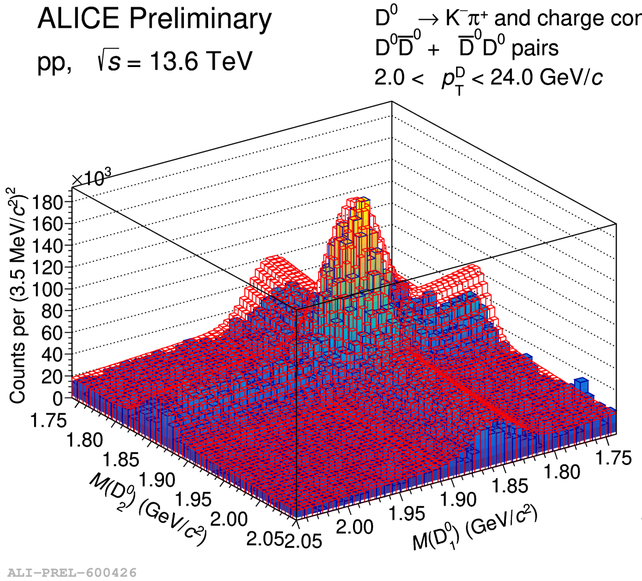


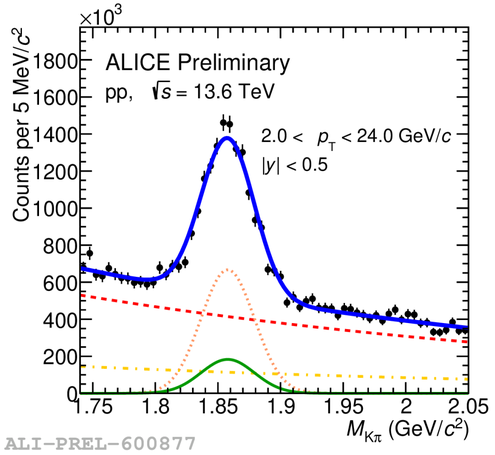
[JHEP 03(2024) 088]

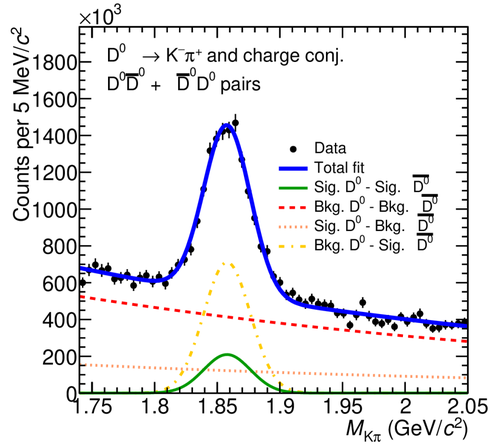
Associated production of D^0-D^0 pairs in pp collisions

- D^0-D^0 pairs measured at $|y| < 0.5$, with D^0 candidate preselection and prompt fraction f_{prompt} extraction using data-driven method
- Unbinned-likelihood fit to the 2D invariant mass of the D^0 to extract the raw yields N_{raw}









Example of opposite sign (OS) D^0 pairs

Analysis note by A. Tavira Gacia

Associated production of D^0-D^0 pairs in pp collisions

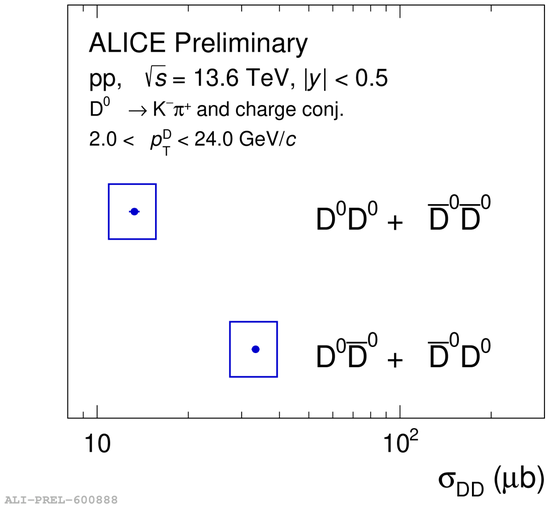
- The D^0-D^0 integrated cross section and cross section ratio of single D^0 to D^0-D^0 pairs calculated as

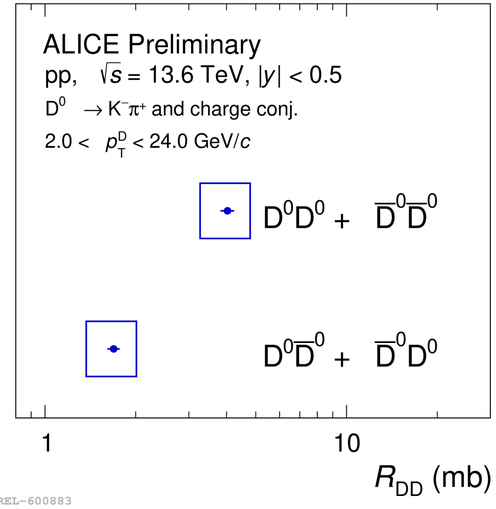
$$\sigma_{DD}^{prompt} = \frac{N_{raw} \cdot f_{prompt}^2}{(Acc \times \epsilon) \cdot BR^2(D^0 \to K^+\pi^-) \cdot L_{int}}$$

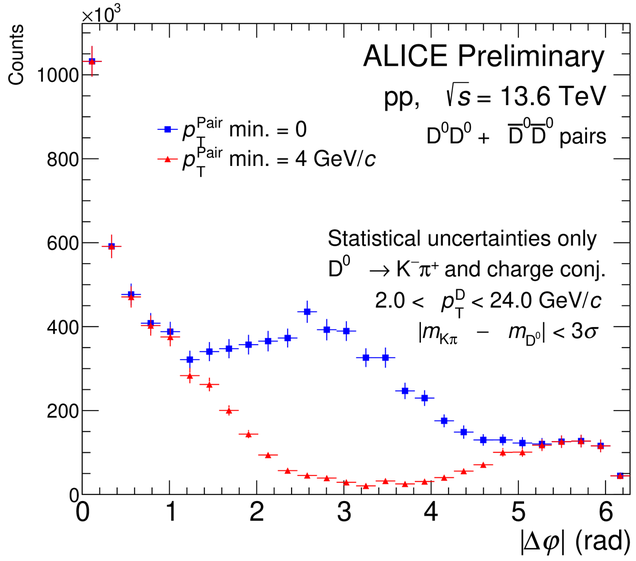
$$R_{DD} = \alpha \frac{\sigma_D \sigma_D}{\sigma_{DD}}$$

α = 1/4: both particles are identical and non-self-conjugate

Single D cross section σ_D taken from Run 2 data [JHEP 2023, 86(2023)]



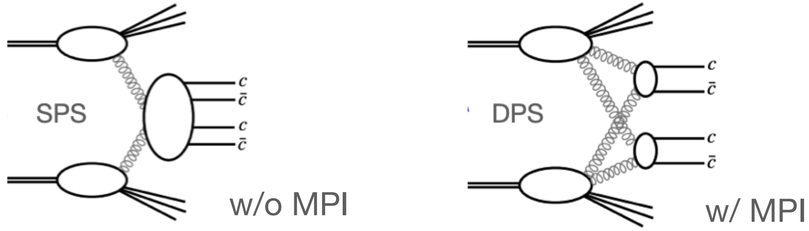




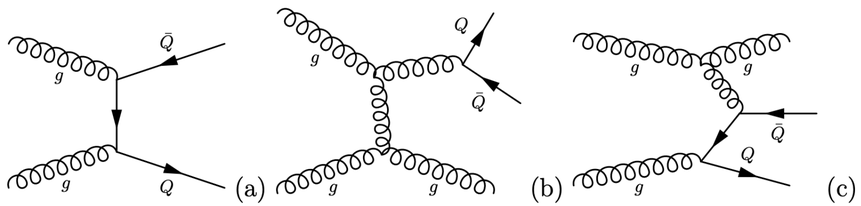
- Cross section ratio R_{DD} is of the same order of magnitude as the effective cross section, promising for the measurement of DPS
- Ongoing:
  - Separate the SPS and DPS components with $\Delta\phi$ distribution in the D^0D^0 measurement to extract the real effective cross section

Heavy-flavour electron-muon pairs with PYTHIA

- PYTHIA 8 simulation for a better understanding of the e-μ pair production
  - The effect of Multi-Parton Interactions (MPI)
    - MPI used as an approximation of DPS



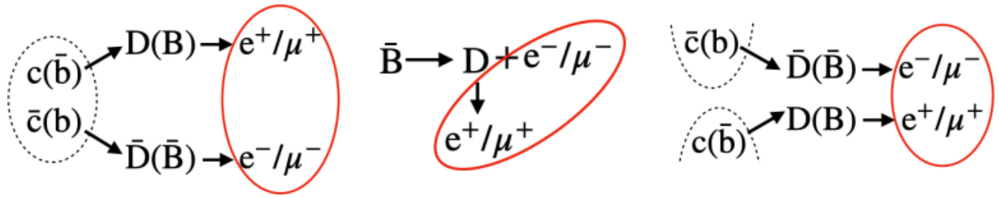
Correlated pairs:



Pair production **Gluon splitting** **Flavour excitation**

- Correlated pairs tagged according to the their heavy-quark production mechanism
  - Different processes such as pair production, gluon splitting and flavour excitation used to reproduce the NLO production

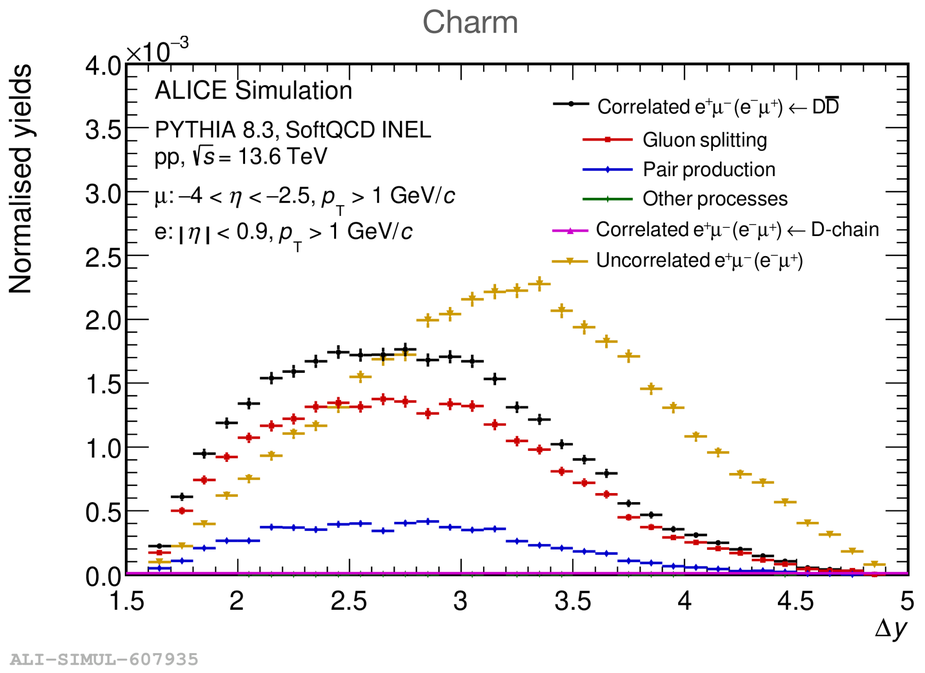
- The contributions of the chain decays and uncorrelated pairs are included as well

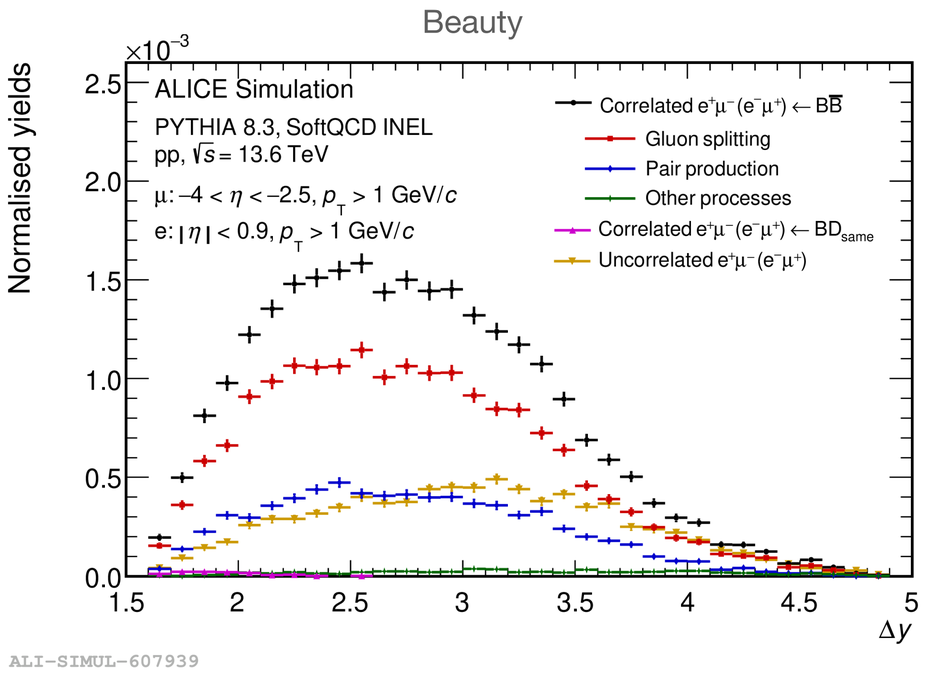


Correlated decays **Chain decay (BD_{same})** **Uncorrelated pairs**

[T. Sjöstrand et al., Comput. Phys. Commun. 191 (2015) 159-177]

Electron-muon pairs from heavy-flavour decays with PYTHIA

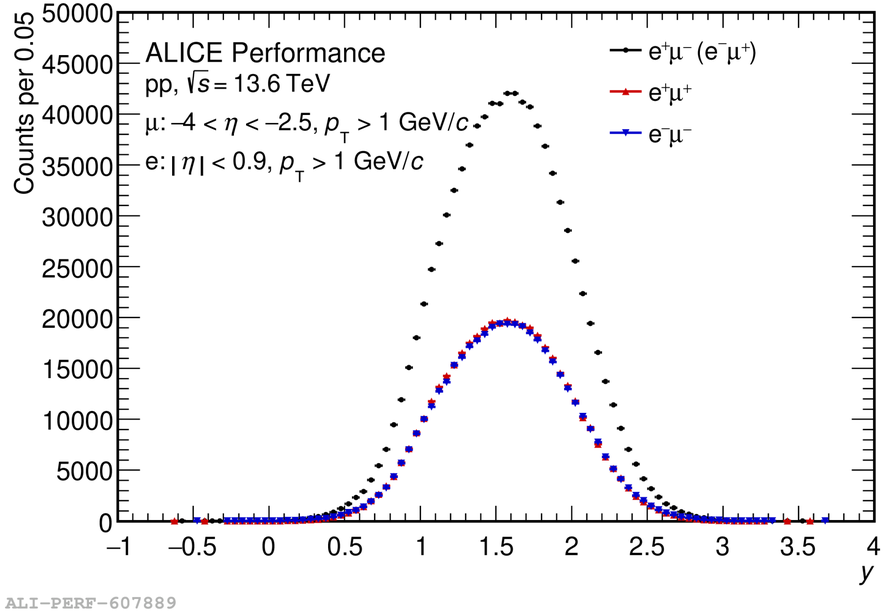


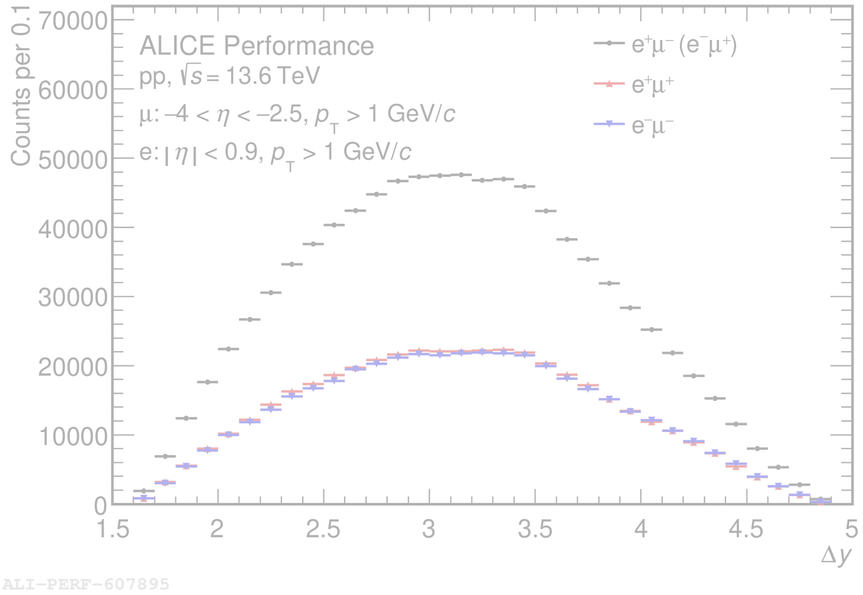


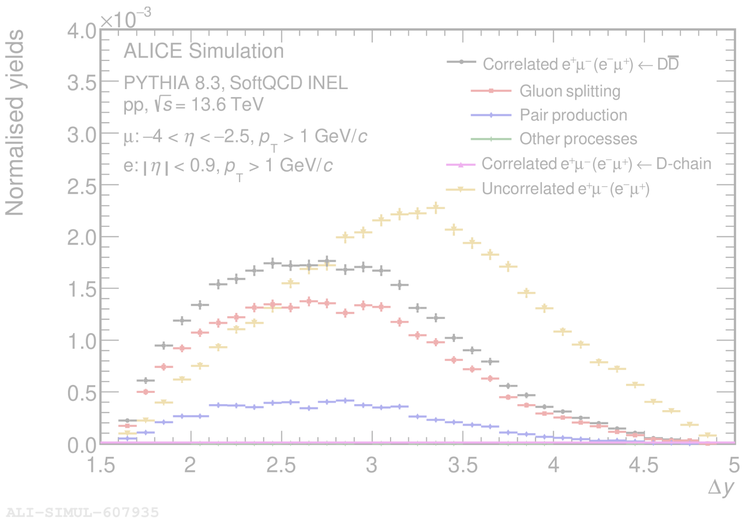
- Non-negligible uncorrelated pairs coming from MPI (~80%): illustrating DPS contributions
  - Uncorrelated pairs from B-hadron decays is less pronounced compared to D-hadron decays
  - Difference in Δy: approach of SPS/DPS separation
- Chain decay contributions (D-chain & BD_{same}) suppressed by the acceptance selection

Heavy flavour electron-muon pairs in pp collisions

- First look of e-μ correlation distributions in ALICE





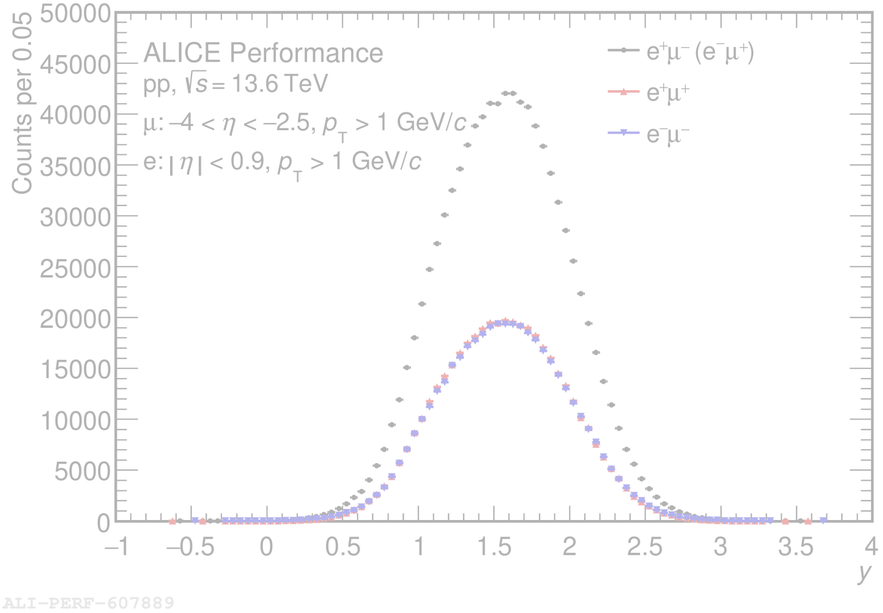


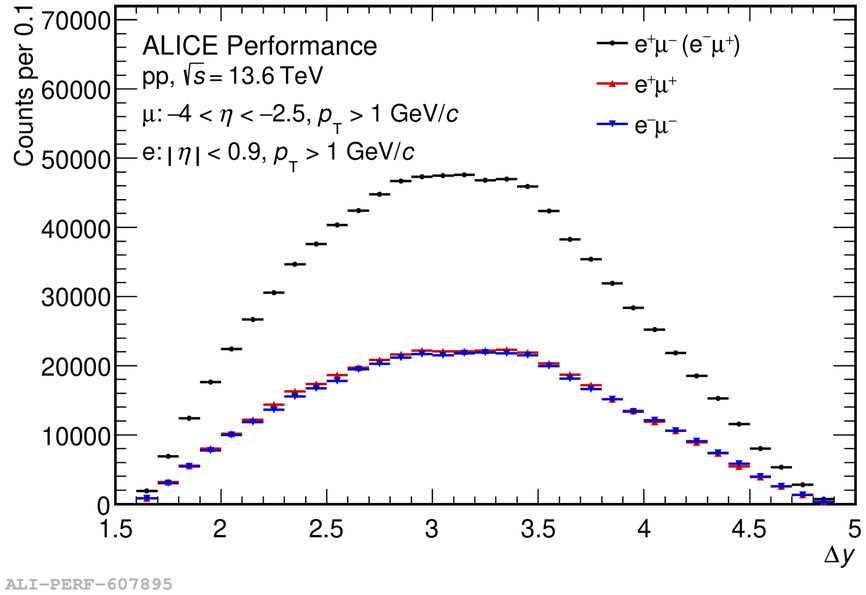
(background to be subtracted)

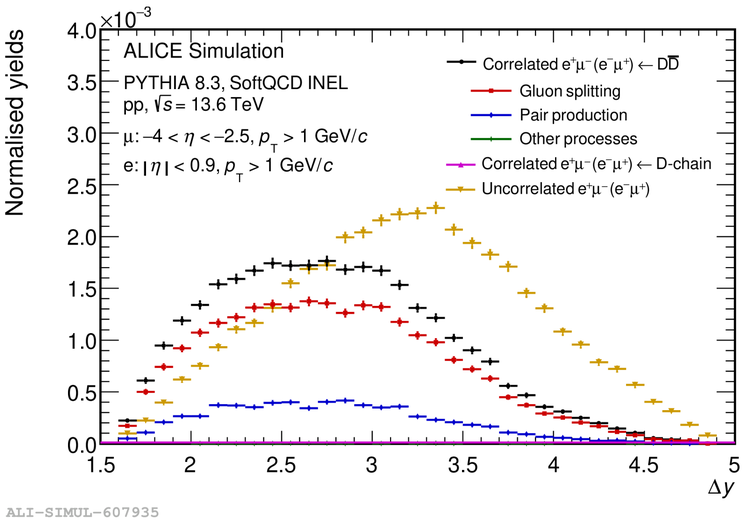
- e-μ pairs measured in an interesting pair y region, between central barrel and muon arm of the ALICE detector
  - Complementary to existing mid-rapidity and forward rapidity measurements

Heavy flavour electron-muon pairs in pp collisions

- First look of e-μ correlation distributions in ALICE





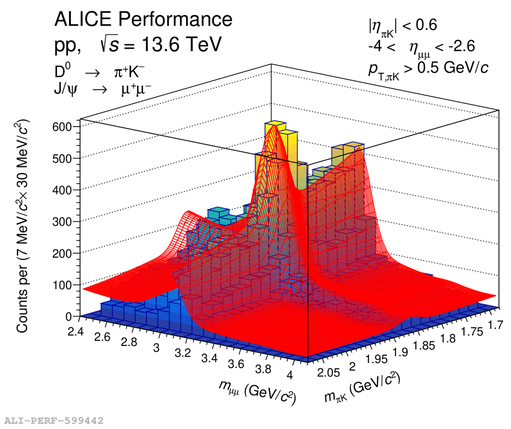


(background to be subtracted)

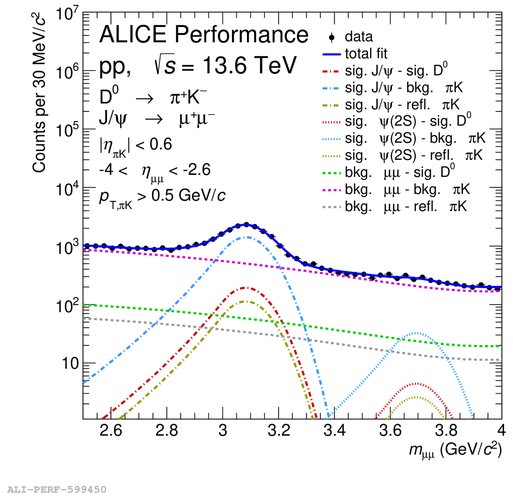
- Unique rapidity gap at LHC provided by ALICE, up to about 5 units
  - Advanced in SPS/DPS separation: DPS more pronounced at larger Δy
- Similar distributions in PYTHIA simulation and data: promising new measurement with ALICE in Run 3

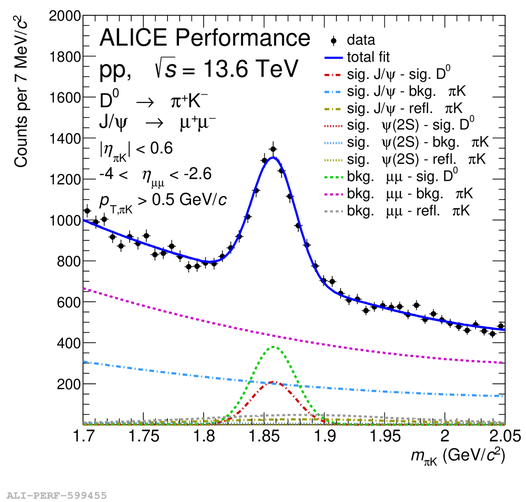
Associated production of quarkonia and open heavy-flavour hadrons in pp collisions

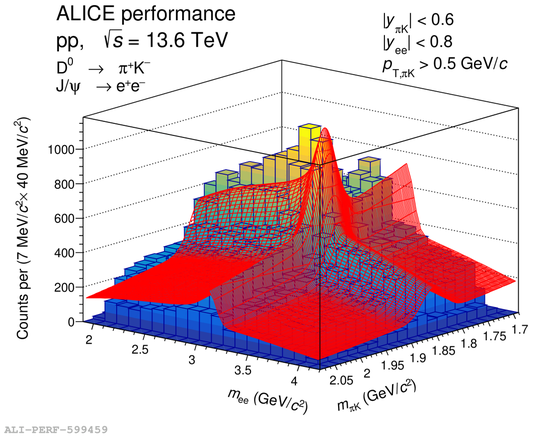
- J/ψ-D^0 associated production measured in two channels, covered rapidity gap from 0 to 4.6



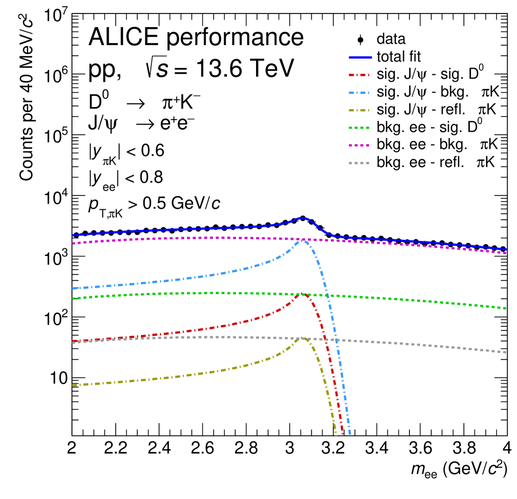
- $J/\psi \rightarrow \mu\mu$ at $-4 < \eta < -2.5$
- $D^0 \rightarrow K\pi$ at $|\eta| < 0.6$

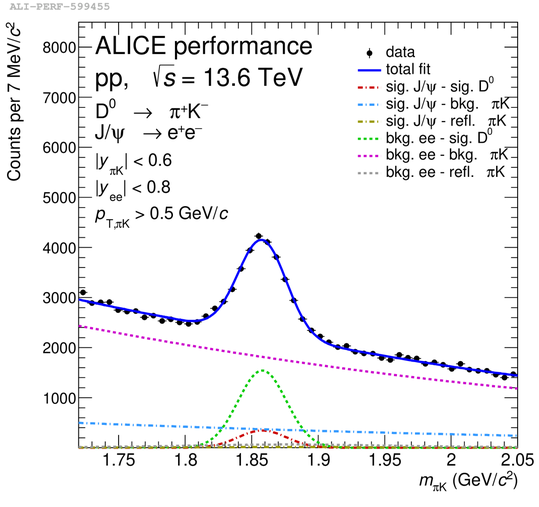






- $J/\psi \rightarrow ee$ at $|\eta| < 0.9$
- $D^0 \rightarrow K\pi$ at $|\eta| < 0.6$





- 2D fits to the invariant mass of the D^0 and the J/ψ to extract the signal
- A notable J/ψ-D^0 signal can be observed in both channels

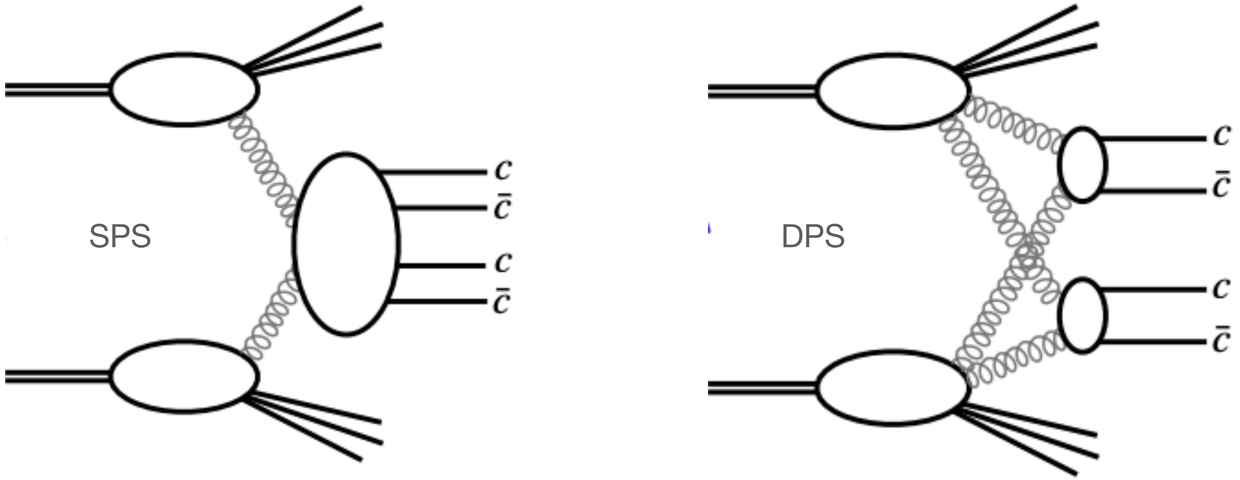
Summary

- Detector upgrades and large Run 3 data samples enable new measurements in ALICE
  - 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 wide-range correlations
- Associated e–μ production from heavy-flavour decays, J/ψ–D^0 and D^0–D^0 associated production measured in pp collisions at $\sqrt{s}$ = 13.6 TeV
  - Access to charm/beauty correlation cross sections in a novel rapidity configuration
  - Open opportunities to disentangle SPS and DPS contributions in the heavy-flavour sector
- These measurements will provide new insights into charm/beauty production mechanisms and the role of multi-parton interactions in proton-proton collisions

Thank you for your attention
Merci pour votre attention
感谢聆听

Backup

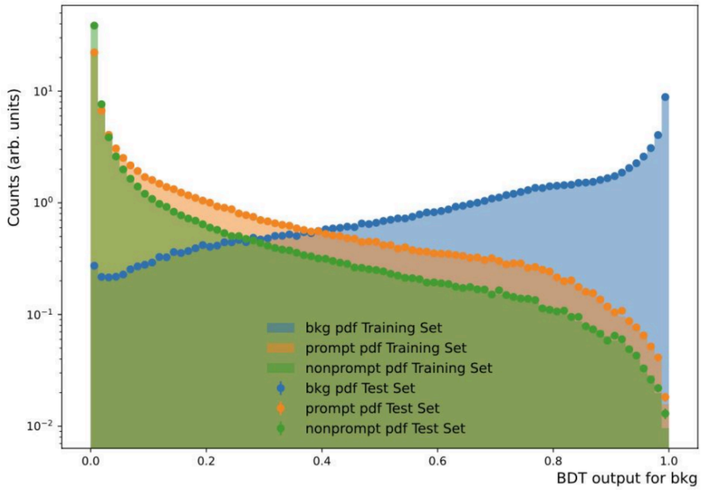
SPS/DPS

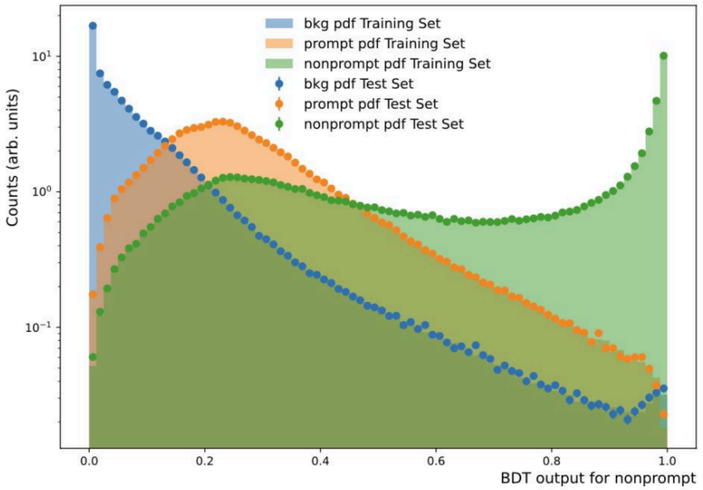


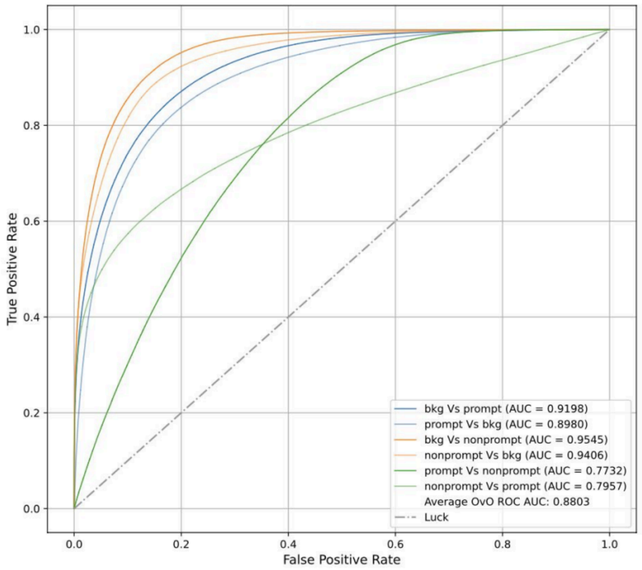
- SPS: Access the internal dynamics of protons
  - Study the transverse-momentum dependent distributions of gluons
  - investigate the puzzle surrounding the quarkonium production mechanism
- DPS: Study the parton transverse profile and correlations
  - Improve our understanding of the background (, etc.) in searches for new physics

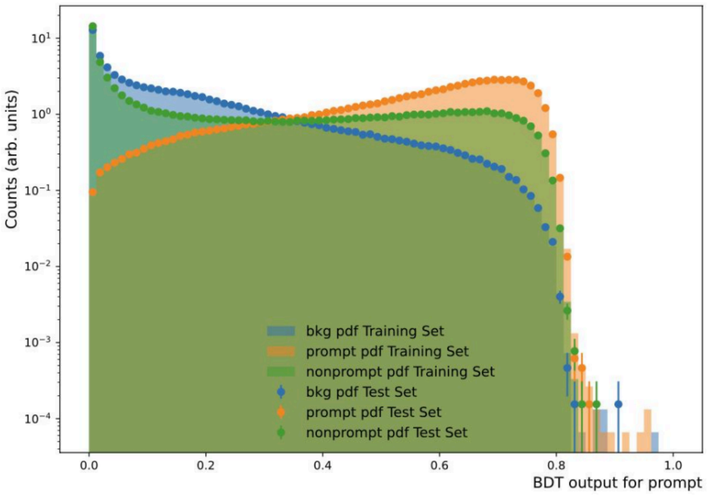
D0 selections

$1 < p_T < 2$ GeV/c





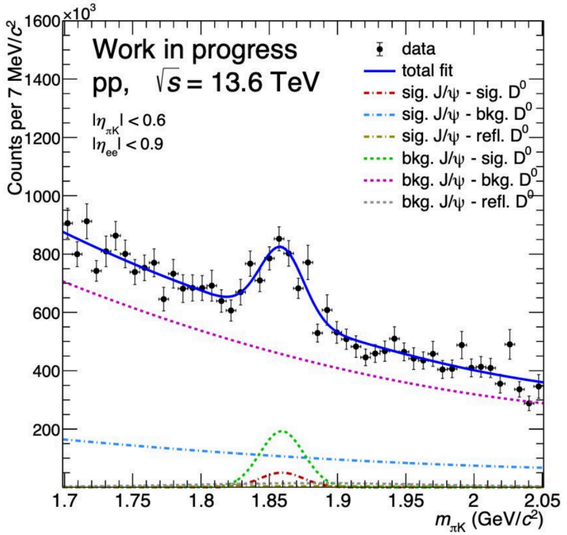


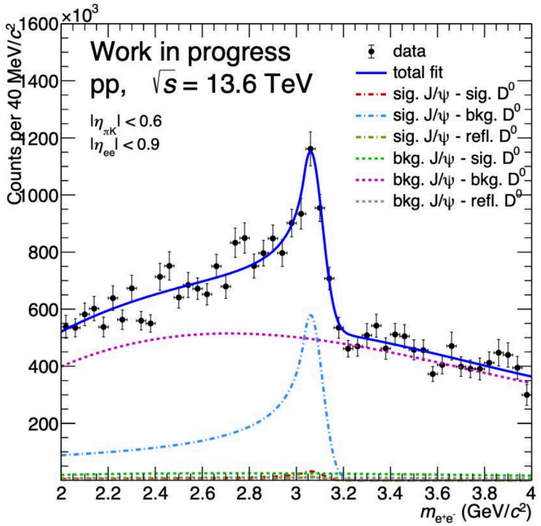


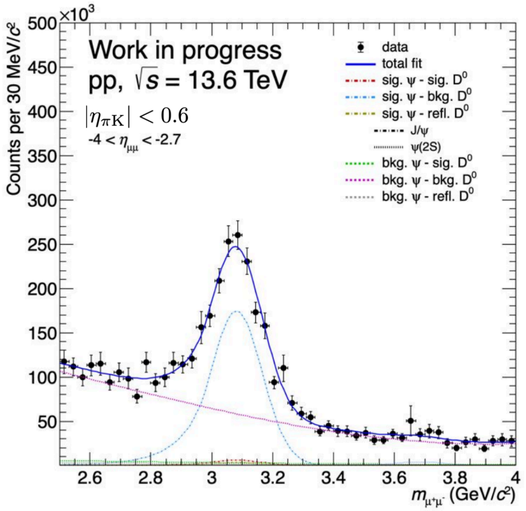
- Only selection to the BDT output score related to the probability to be background
  - A cut on the BDT score for prompt/non-prompt to be considered to reduce contamination from beauty decays

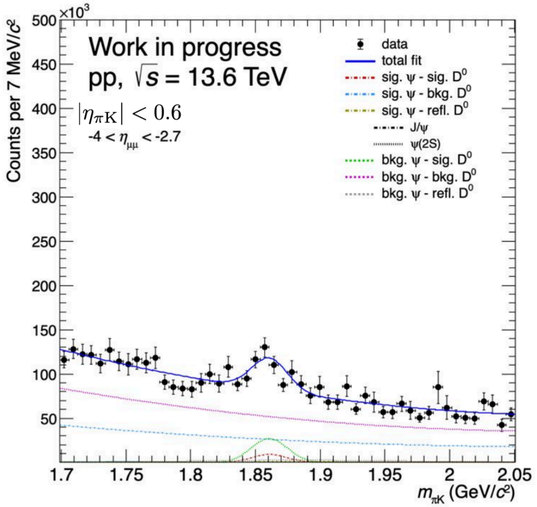
p_T (GeV/c)	[0, 1]	[1, 3]	[3, 4]	[4, 8]	[8, 50]
BDT(bkg)	< 0.05	< 0.1	< 0.2	< 0.3	< 0.5

- Axe corrected results of Jpsi-D0

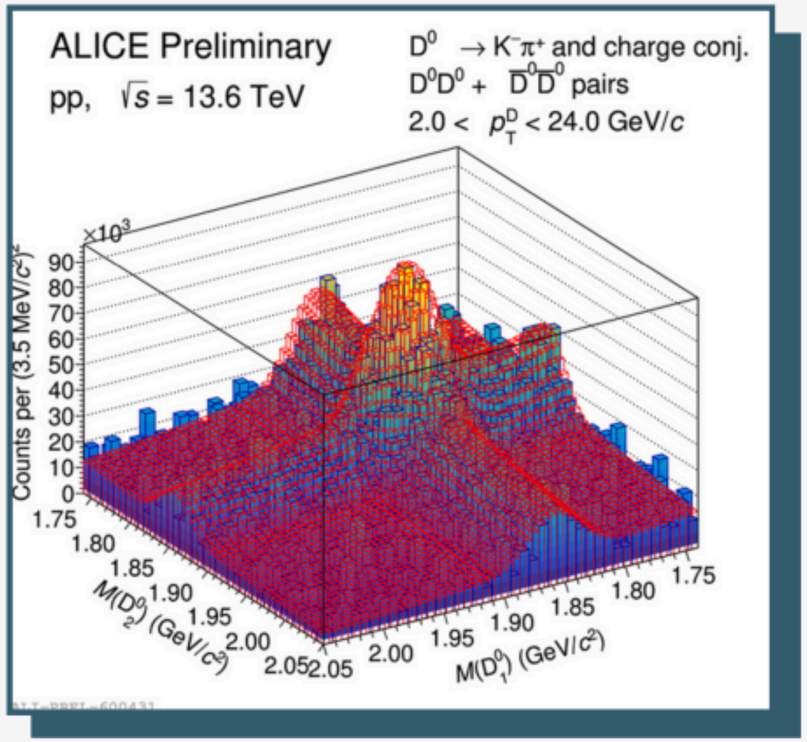


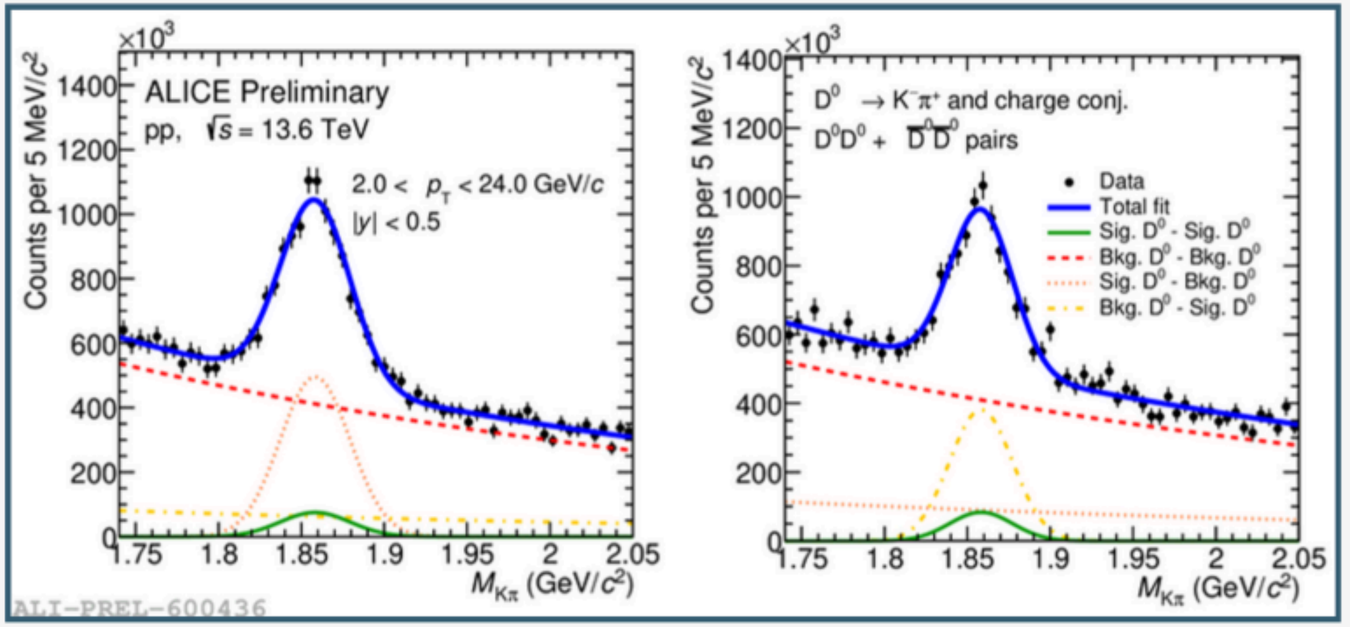






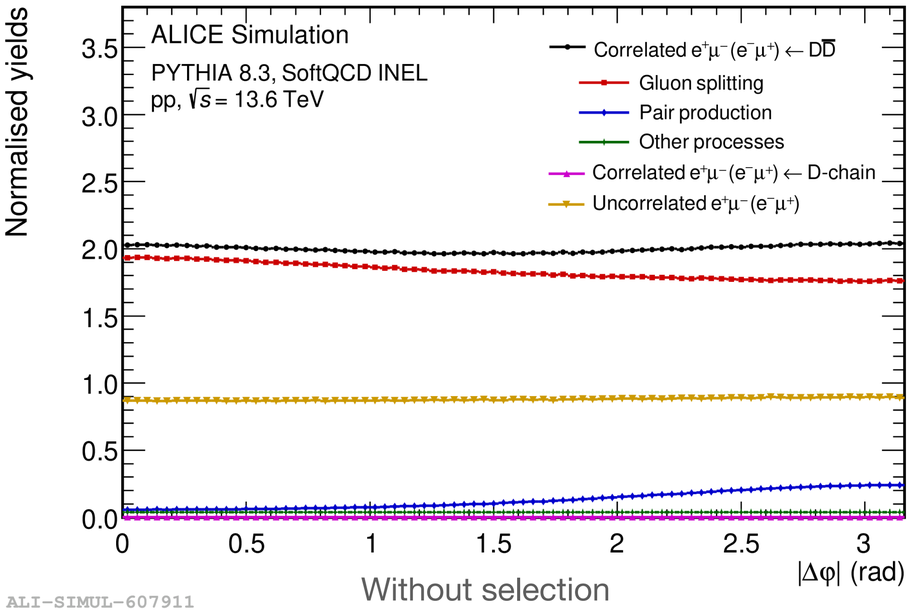
- Like-sign N_{raw} of D^0 pairs

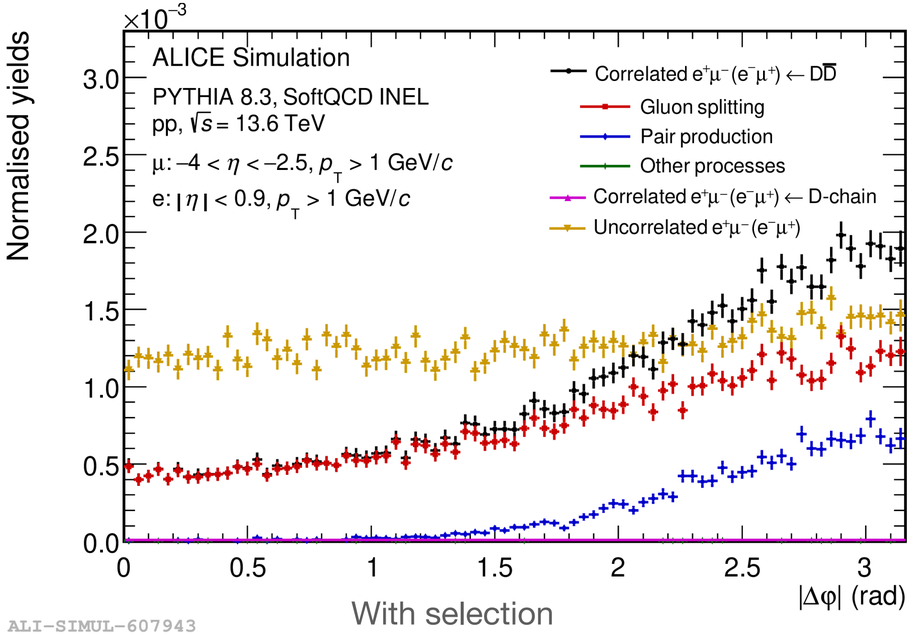




Unbinned-likelihood fit to the 2D invariant mass distribution to extract the raw yield N_{raw}.

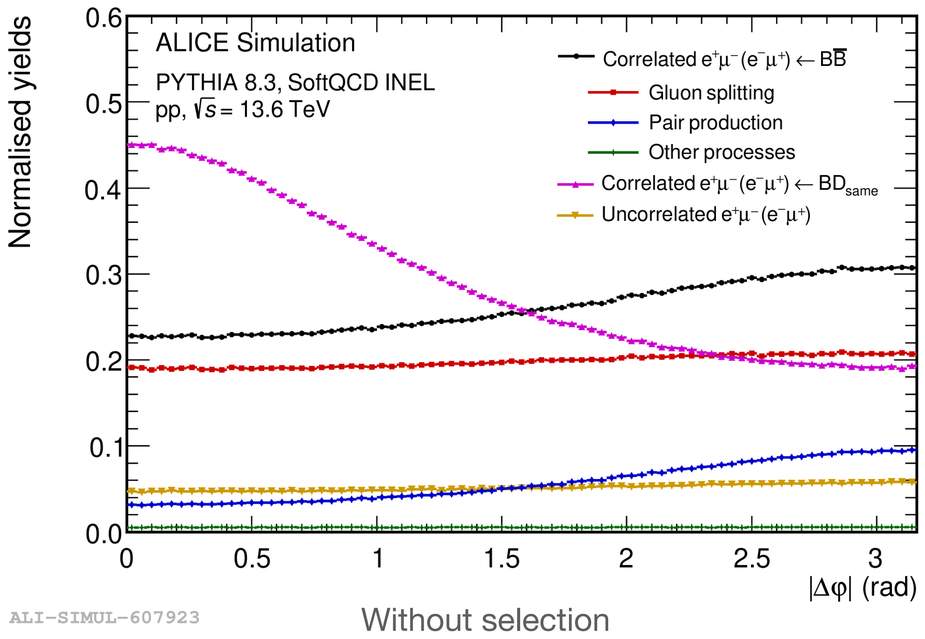
Electron-muon pairs from charm decays with PYTHIA



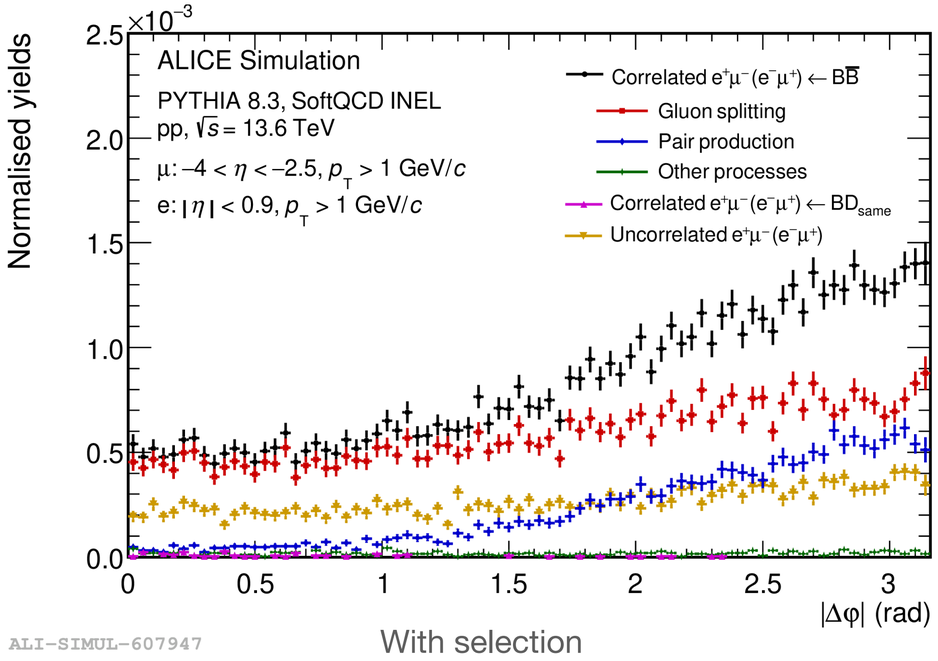


- Non-negligible uncorrelated pairs coming from MPI (~80%) observed within the heavy flavour signals
- Correlated e-μ pairs from D-hadron decays dominated by gluon splitting process
  - Maximum at $\Delta\phi$ = 180° with selection condition due to the acceptance asymmetry
- Chain decay contributions (D-chain & BD_{same}) negligible with selection condition

Electron-muon pairs from beauty decays with PYTHIA



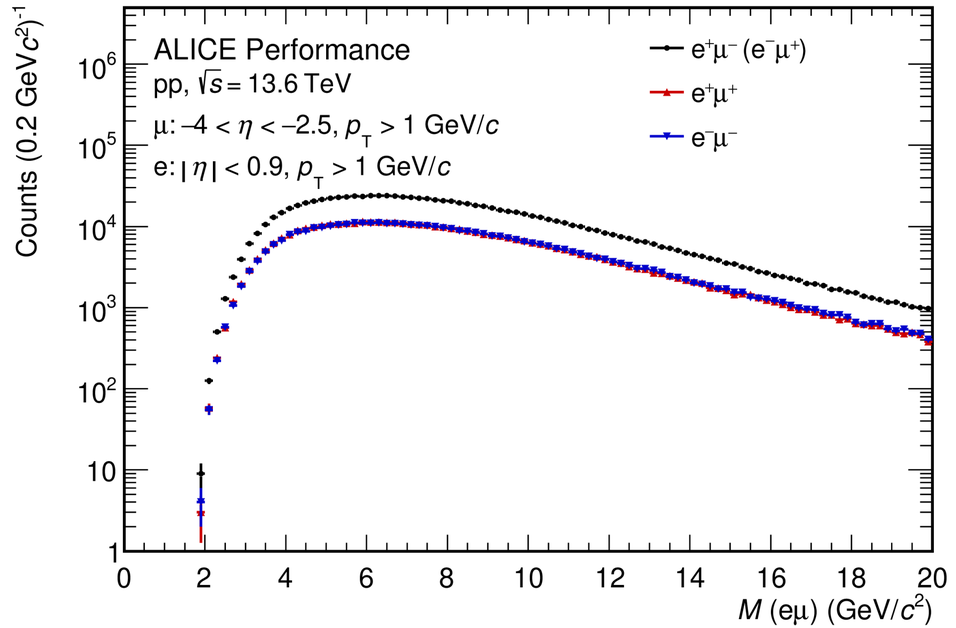
Without selection

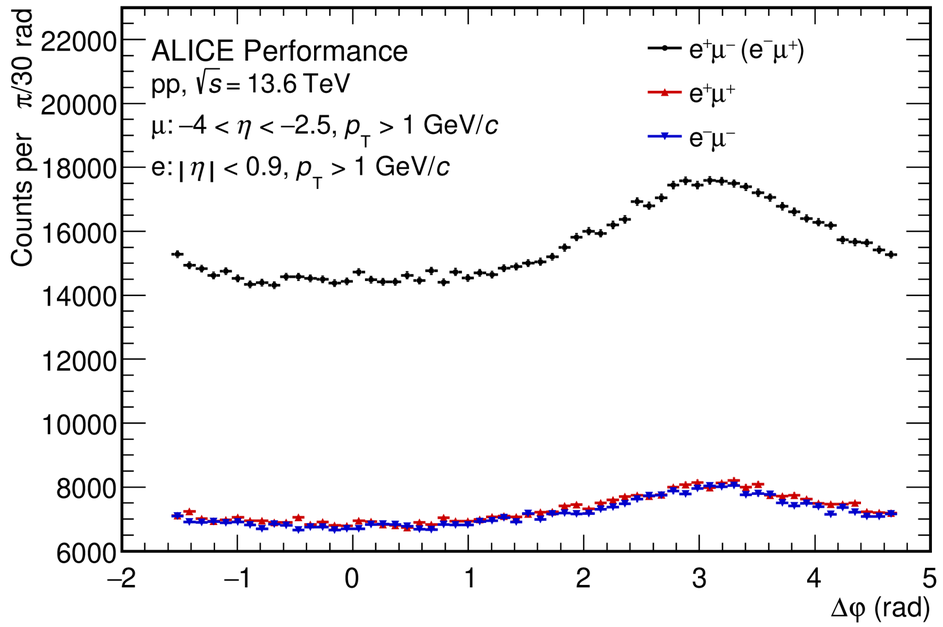


With selection

- Significant chain decay contributions (BD_{same}) observed and maximum at small $\Delta\phi = 0$
  - Successfully suppressed by applying η and p_T selections
- Uncorrelated e-μ pairs from B-hadron decays is less pronounced compared to D-hadron decays
  - Negligible compared to the correlated signal

Heavy flavour electron-muon pairs in pp collisions





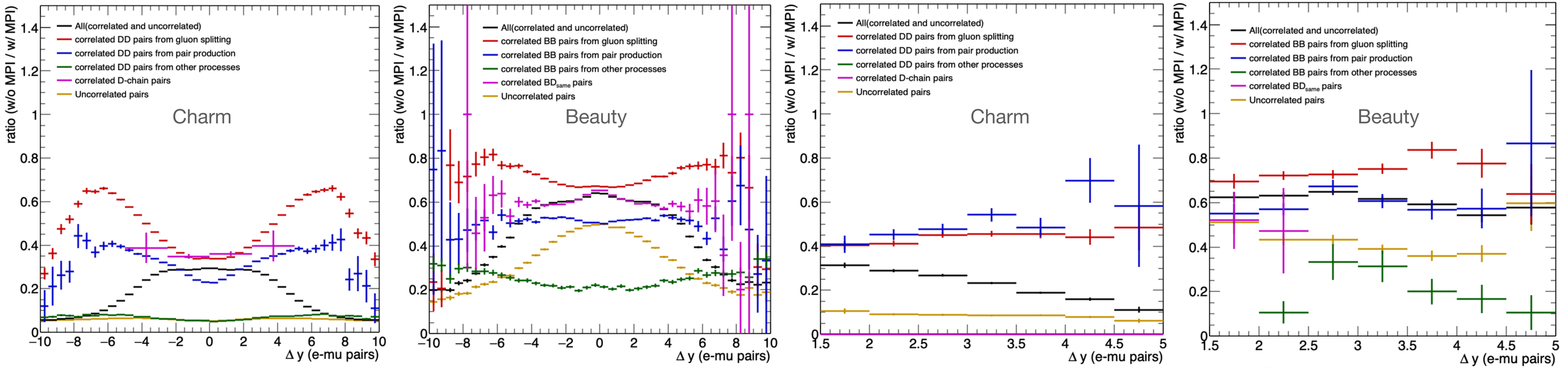
(background to be subtracted)

- **Pair $M_{e\mu}$ spreads over several GeV/c^2 without structure: challenging for background estimation**
- **Pair $\Delta\phi$ maximum at 180° as observed in PYTHIA**

- Ongoing: background subtraction, dedicated e-μ software trigger for 2025 data

Comparison of the distributions w/o and w/ MPI

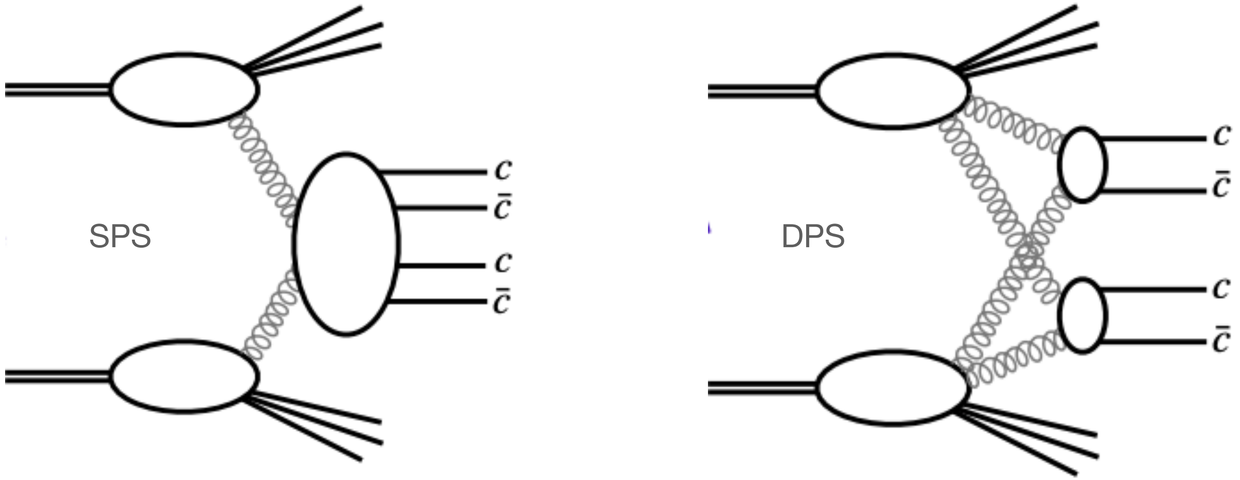
- The MPI contributes to ~80% of the e-mu pairs from D hadron decays and ~40% pairs from B hadron decays
  - Dominates at large Δy
  - The uncorrelated pairs and other processes pairs from D hadron decays mainly come from MPI (90%)
  - No significant difference between low and high p_T regions



No cuts applied

With acceptance and pT cuts

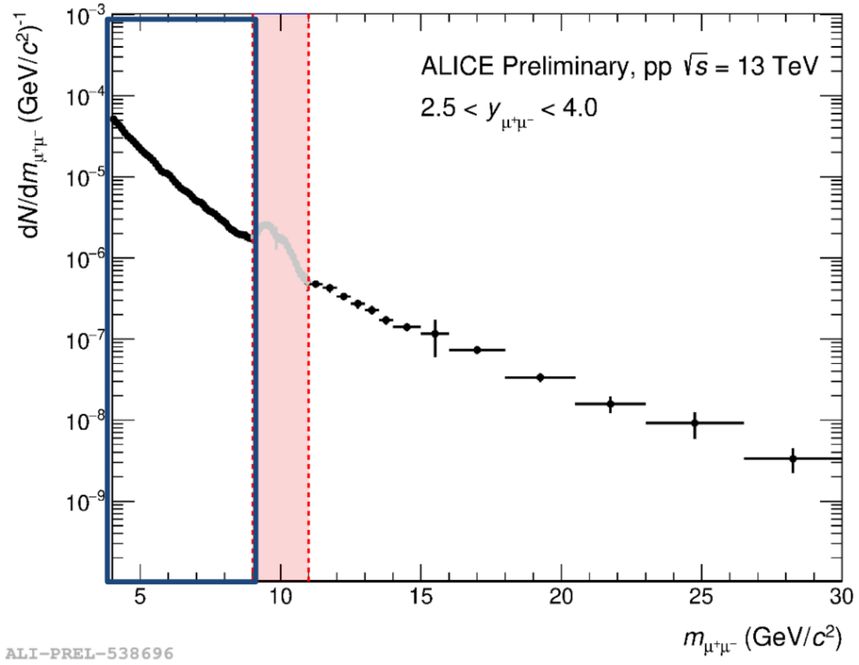
SPS/DPS

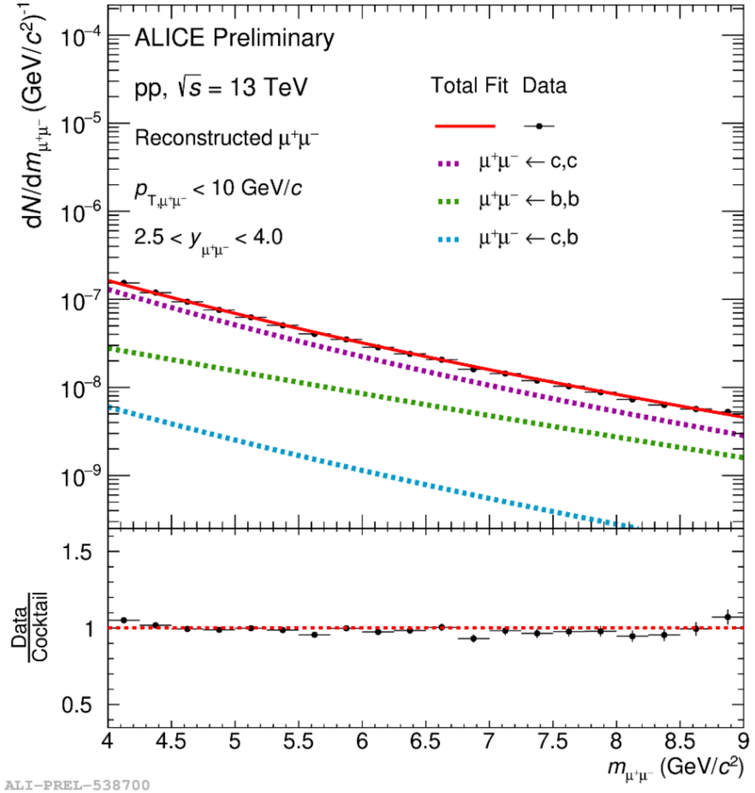


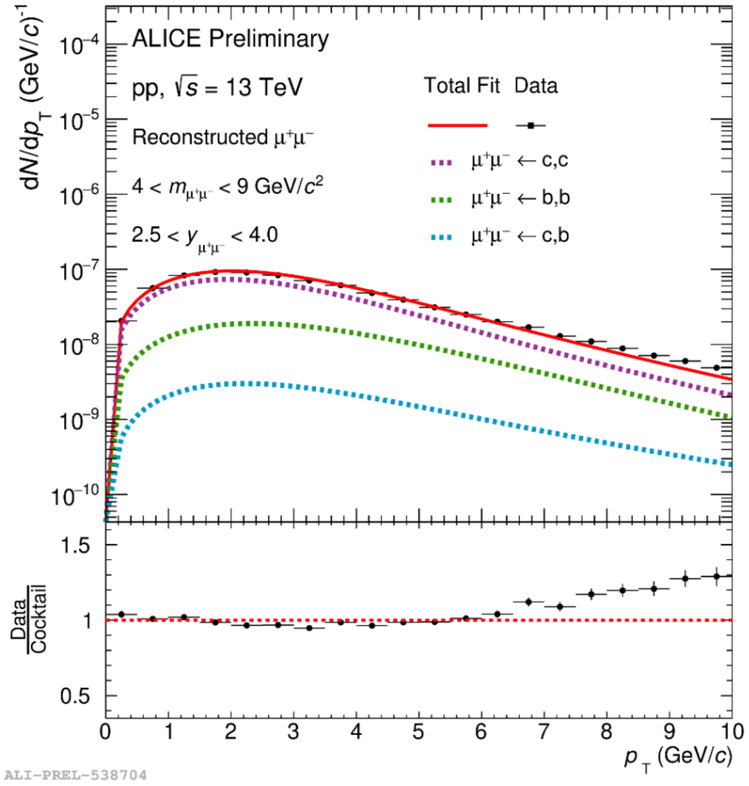
- SPS: Access the internal dynamics of protons
  - Study the transverse-momentum dependent distributions of gluons
  - investigate the puzzle surrounding the quarkonium production mechanism
- DPS: Study the parton transverse profile and correlations
  - Improve our understanding of the background in searches for new physics

Heavy-flavour production in pp collisions at forward y via dimuons

- Charm and beauty production measured at $2.5 < y < 4.0$ in pp collisions at $\sqrt{s}$ = 13 TeV, exploiting the dimuon high-mass continuum dominated by the semimuonic decays of heavy-flavour hadrons
- Simultaneous fit of the mass and p_T distributions with a combined template of the main sources in the continuum
  - Templates extracted from the heavy-flavour enriched PYTHIA 8 simulation



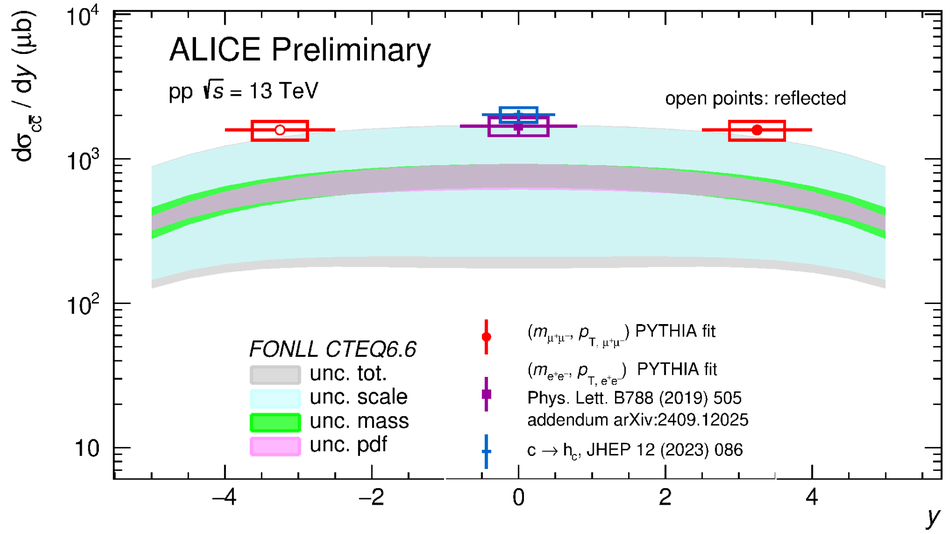




Analysis Note by M.Pennisi

Charm and beauty production cross sections at forward y in pp collisions at $\sqrt{s}$ = 13 TeV

Charm



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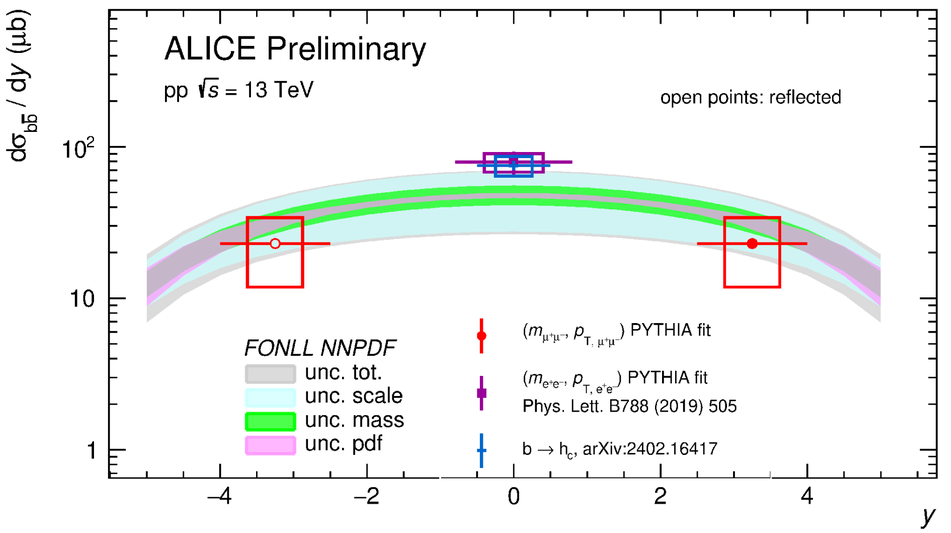
Beauty



ALI-PREL-581594

- Charm and beauty production cross sections measured separately at forward rapidity via the dimuon continuum
- Results in agreement with FONLL predictions within uncertainties, although they lie at the upper and lower limit of the calculations for charm and beauty production cross section, respectively
- Complement the previously published results at midrapidity in the dielectron channel [ALICE, Phys. Lett. B, 788 (2019) 505]