Charm and beauty production at forward rapidity with ALICE

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on behalf of ALICE Collaboration
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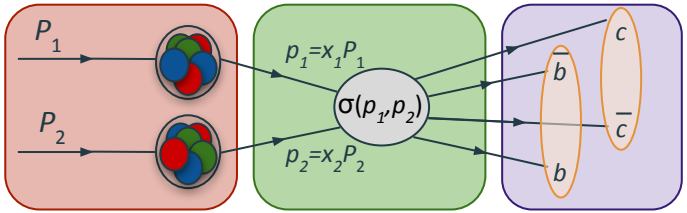
HP2024
NAGASAKI

HF production in pp collisions

- **In pp collisions:** description of open heavy-flavor (*i.e.* bound states of charm or beauty quark with a light quark) production mechanism represents a challenge for theory
- **Factorisation approach:** for calculating production cross section



$$\frac{d\sigma^{H_{c/b}}}{dp_T} = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c/b}}{dp_T^{c/b}}(x_1,x_2,\mu_R,\mu_F) \otimes H_{c/b\to H_{c,b}}\left(z = p_{H_{c/b}}/p_{c/b}\,,\mu_F\right)$$

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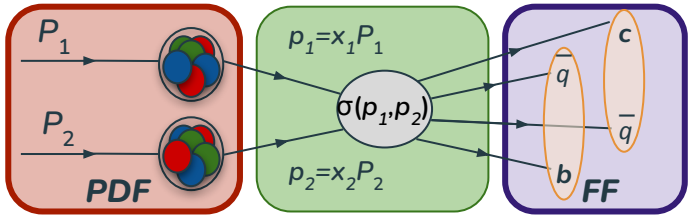

Non-perturbative problem, pQCD calculations not applicable !

- *Parton distributions functions:* from deep-inelastic scattering measurements
- *Fragmentation fraction:* parameterized on e^-e^+ data

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Parton distributions functions

Fragmentation functions

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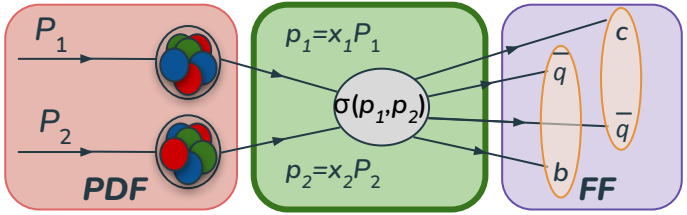

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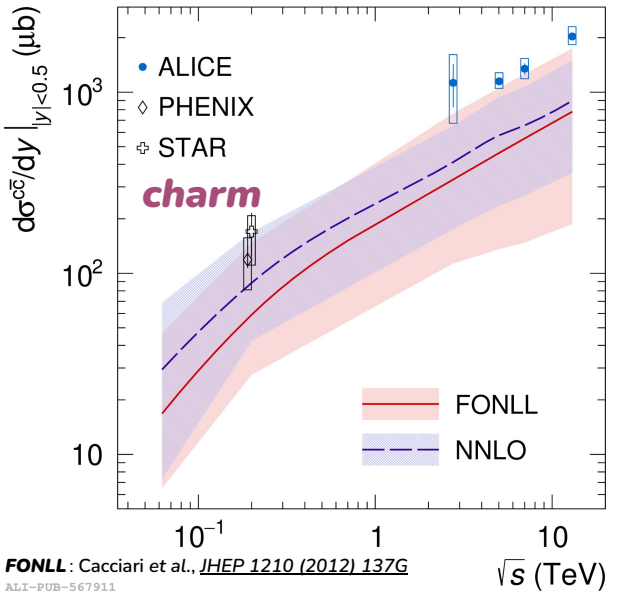
Parton distributions functions | **Partonic cross section** | **Fragmentation functions**

Perturbative regime (large quark masses), pQCD applicable!

Measurements of charm and beauty cross section

- Measurement of ***charm*** and ***beauty*** cross sections by reconstructing ***prompt*** and ***non–prompt*** charm particles hadronic decays at mid-rapidity (**|y| < 0.5**)

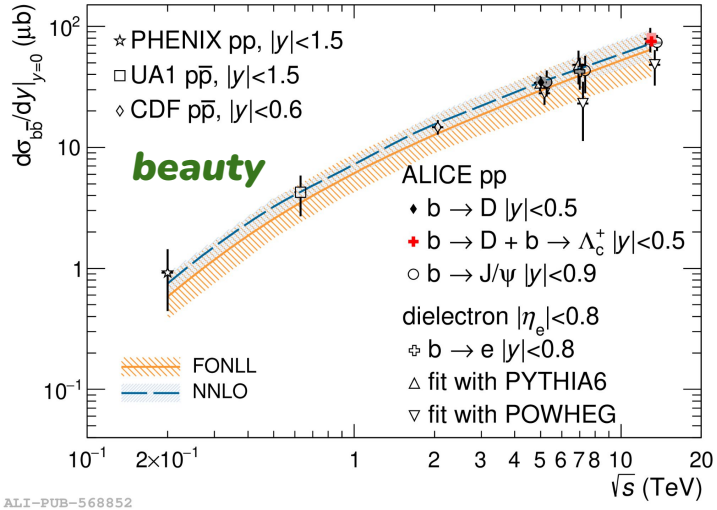
ALICE paper *JHEP 12 (2023) 086*



FONLL: Cacciari *et al.*, *JHEP 1210 (2012) 137G*

ALI-PUB-567911

ALICE paper : *arXiv:2402.16417*



ALI-PUB-568852

NNLO: d'Enterria *et al.*, *Phys. Rev. Lett. 118, 122001*

- ALICE results in agreement with FONLL and NNLO predictions

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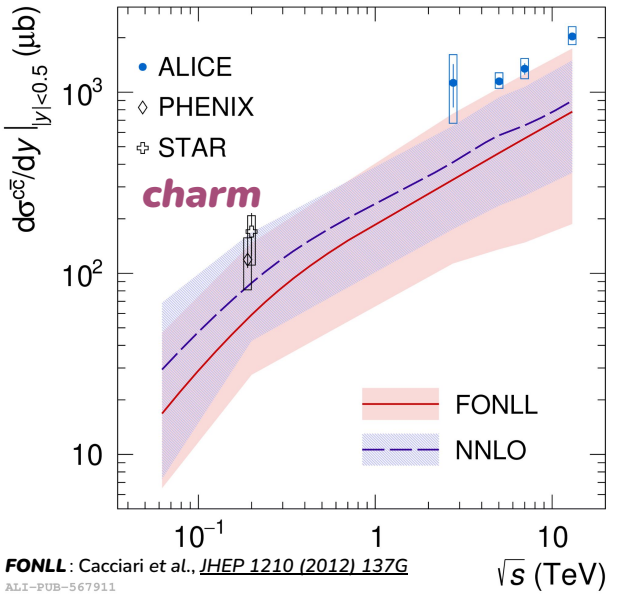

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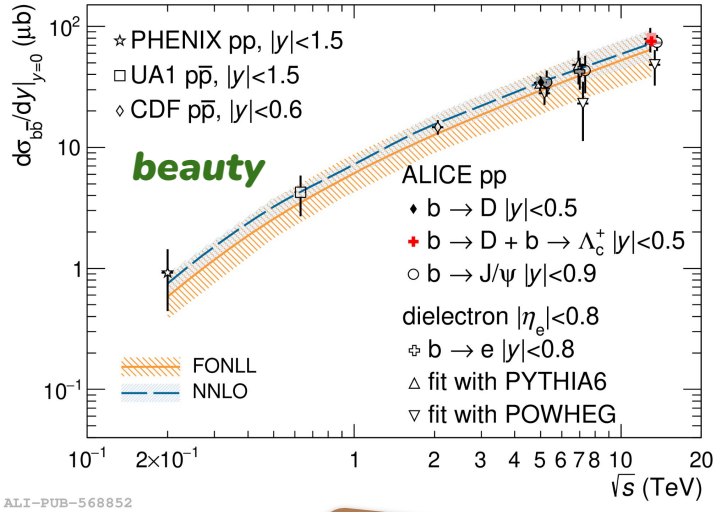

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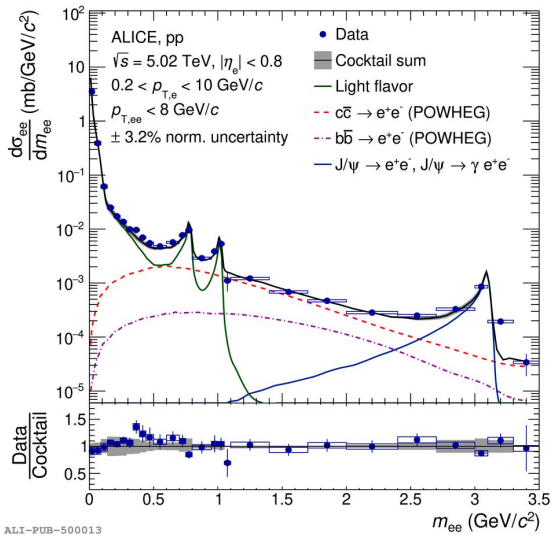
For more details give a look to Andrea Taviria Garcia talk (23/09 14:40)

- ALICE results in agreement with FONLL and NNLO predictions

Measurements of charm and beauty cross section

- Measurement of ***charm*** and ***beauty*** cross sections via a template fit to low-mass dielectron invariant mass distribution at mid-*y* (**|*y*|<0.8**)

ALICE paper *Phys.Lett.B* 788 (2019) 505-518



PYTHIA : EPJC 74 (2014) 8

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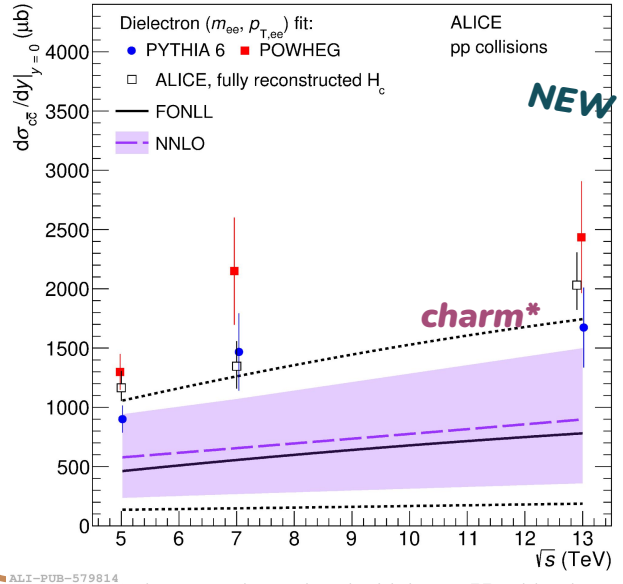

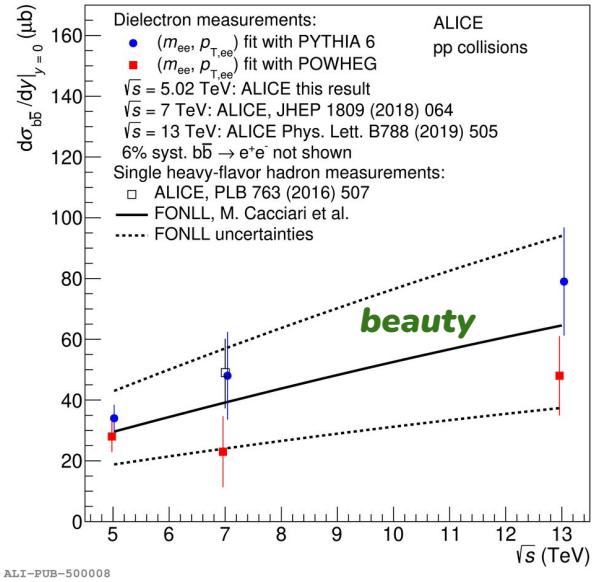

* charm results updated with latest FF, addendum close to be published

- ***Difference w.r.t. results with hadronic decays***: template contains complementary information about the initial correlation of charm quarks, i. e. the underlying production mechanism, not accessible in conventional single HF measurements. This is strictly correlated with MC generator employed (*i.e.* PYTHIA and POWHEG)

Measurements of charm and beauty cross section

- Measurement of ***charm*** and ***beauty*** cross sections via a template fit to low-mass dielectron invariant mass distribution at mid-*y* (**|*y*|<0.8**)

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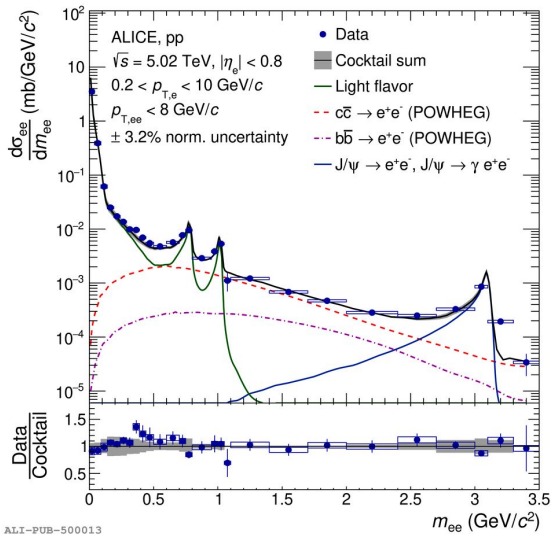

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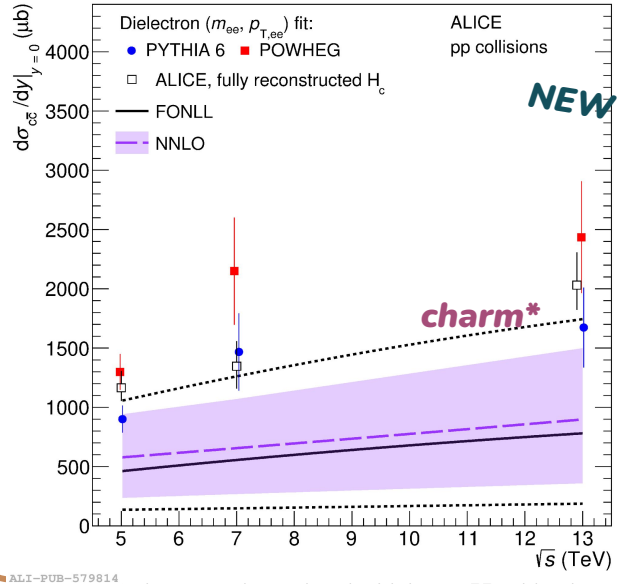
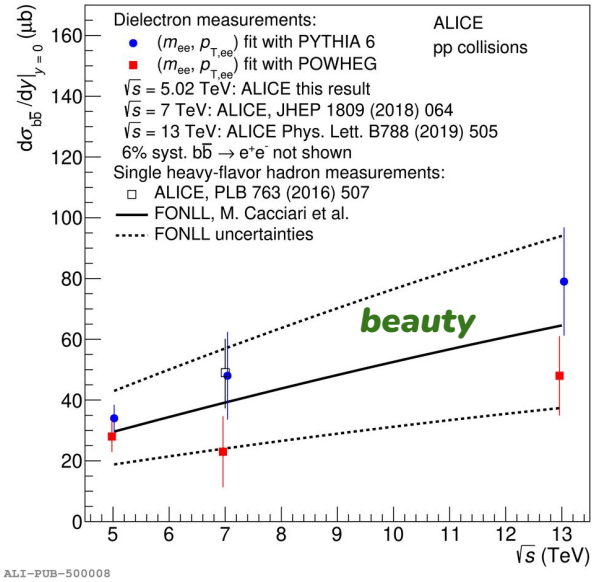




* charm results updated with latest FF, addendum close to be published

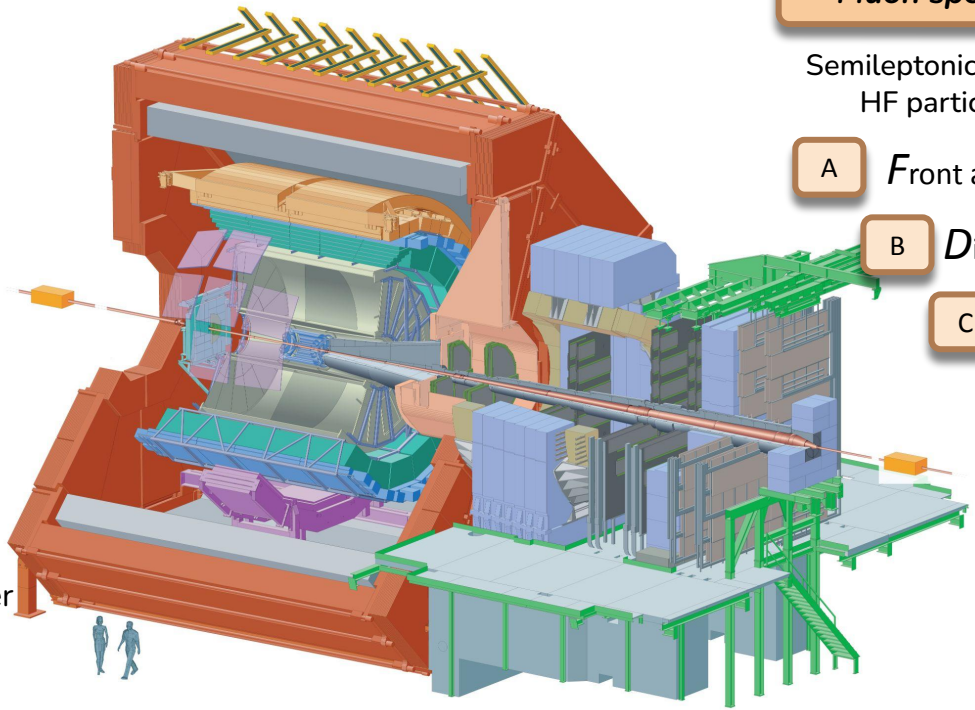
- ALICE results in agreement with FONLL and NNLO predictions. For ***charm*** both PYTHIA and POWHEG results lie on the upper edge of FONLL and NNLO predictions. For ***beauty*** , PYTHIA agrees with th. predictions, while POWHEG stays in the lower edge

A Large Ion Collider Experiment (Run 2)

Central Barrel

Semileptonic (**electrons**) decay of HF particles + quarkonia + hadronic decays of HF particles

- A — Inner Tracking System
- B — Time Projection Chamber
- C — Time Of Flight
- D — V0

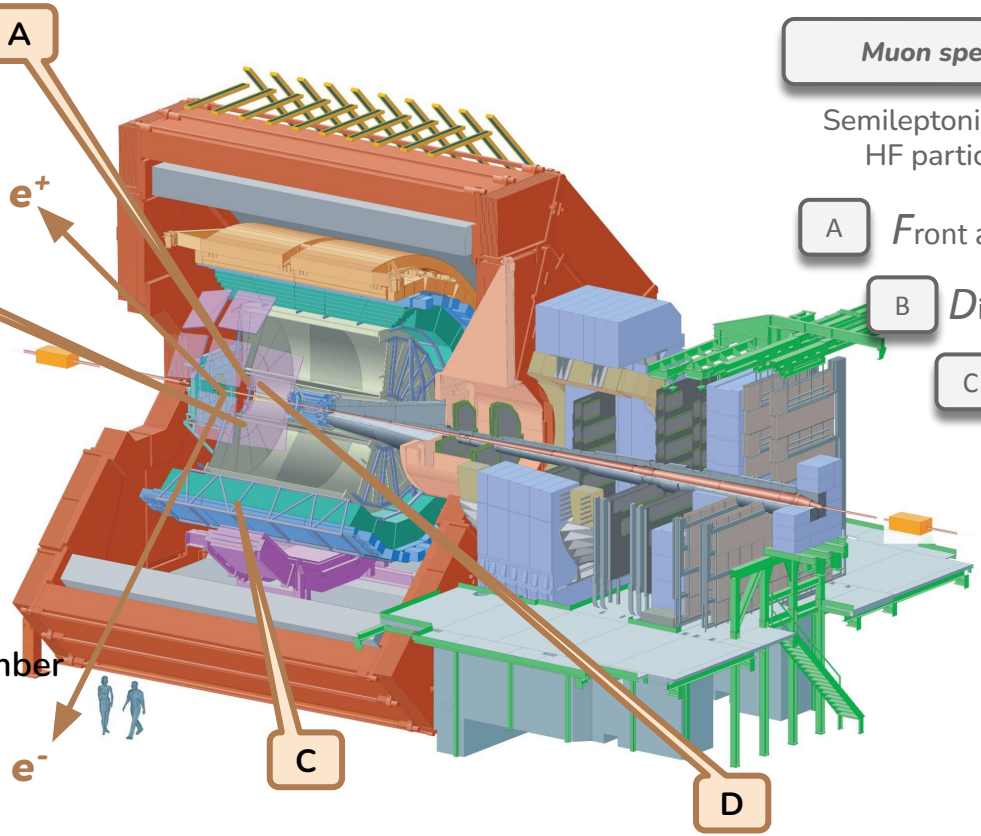


Muon spectrometer (MS)

Semileptonic (**muons**) decay of HF particles + quarkonia

- A — Front absorber
- B — Dipole magnet
- C — Tracking System
- D — Trigger system

A Large Ion Collider Experiment (Run 2)



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Semileptonic (**electrons**) decay of HF particles + quarkonia + hadronic decays of HF particles

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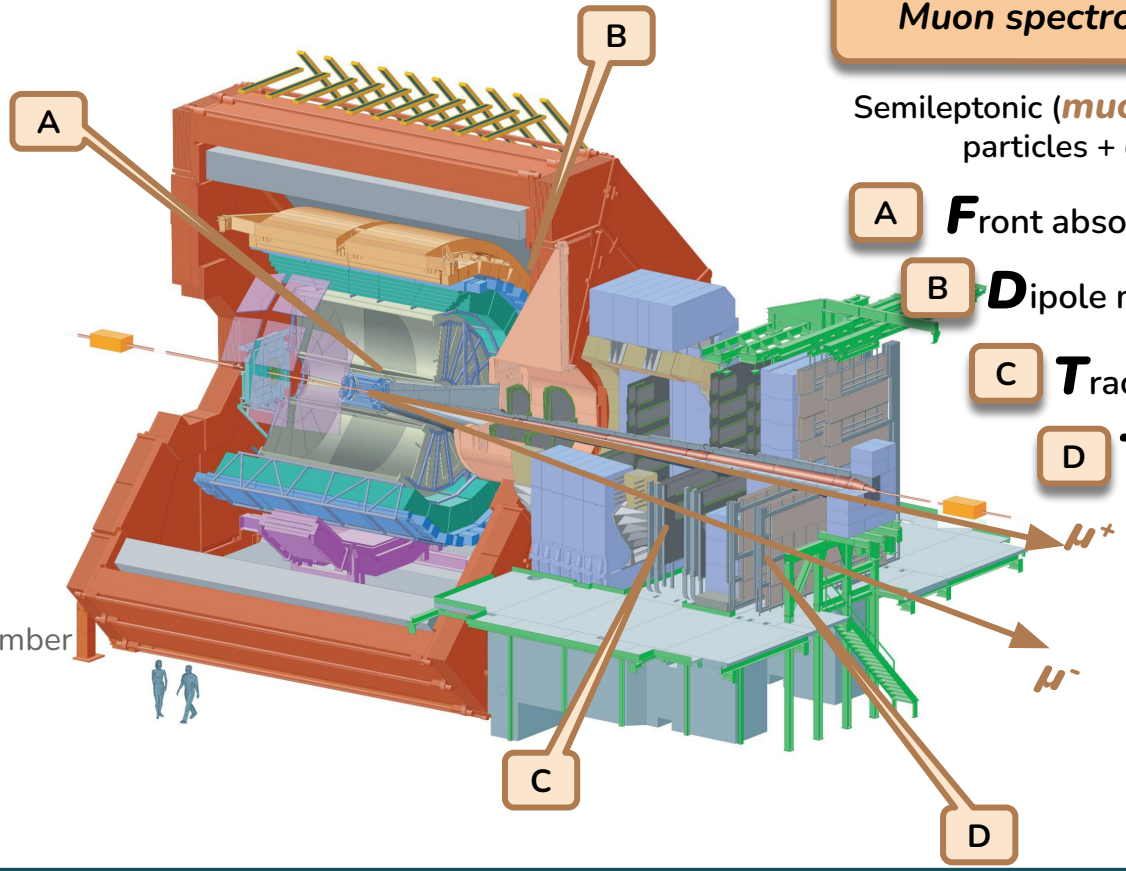

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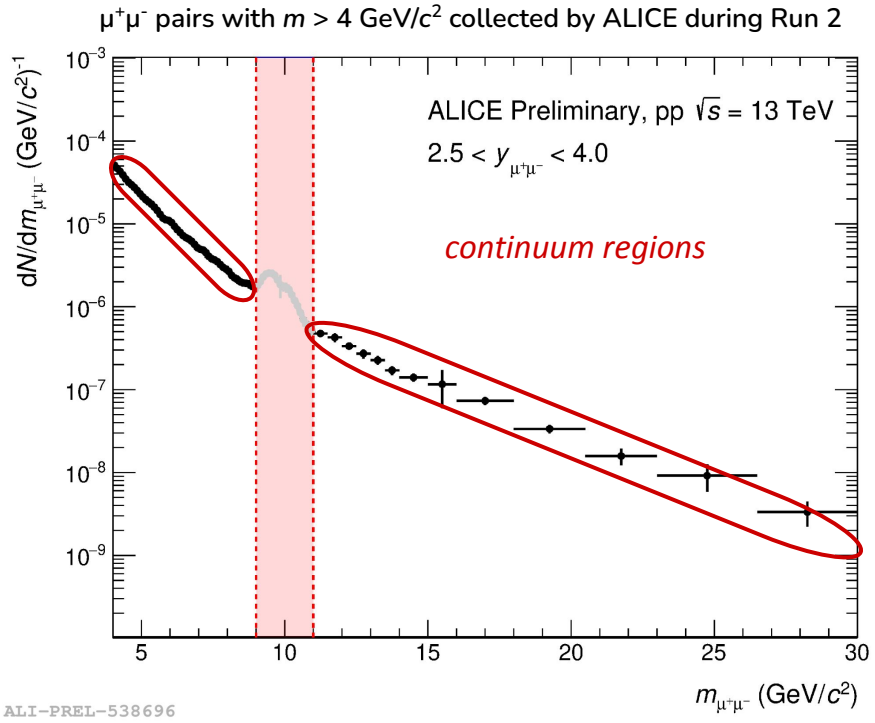
High-mass dimuon measurements with ALICE

Continuum regions of the dimuon mass spectrum



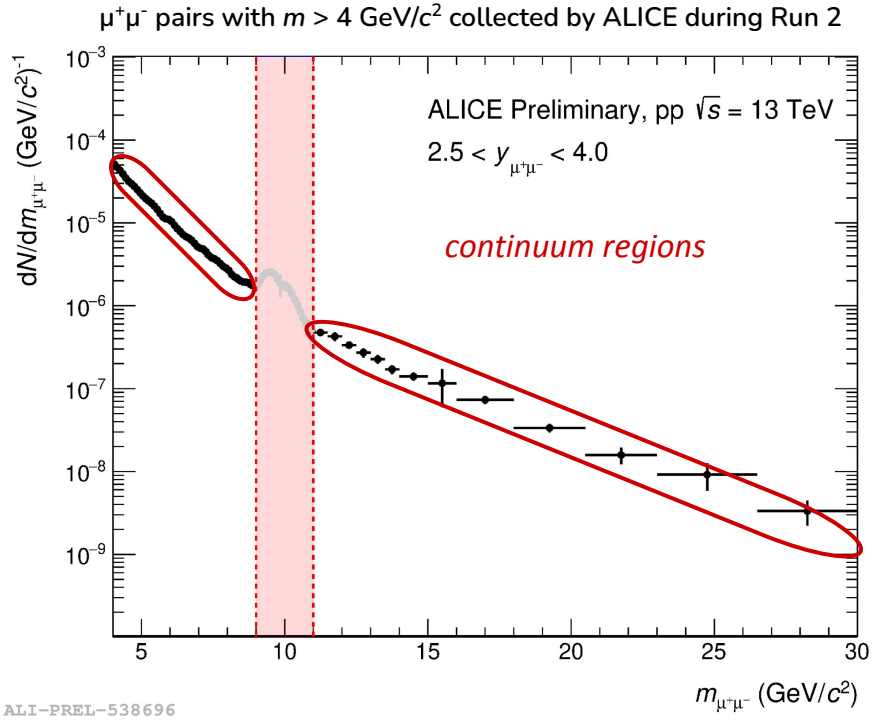
Continuum regions (above $m_{\mu\mu} = 4$ GeV/c^2) are mainly populated by:

Semileptonic decays of pairs of open heavy-flavor (HF) hadrons

Drell-Yan mechanism

Combinatorial bkg. from light-flavor (LF) hadrons

Continuum regions of the dimuon mass spectrum



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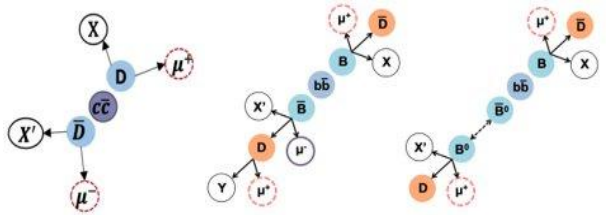
from the hadronization of cc and bb pairs

c -> D -> μ + ν_μ + cc.
b -> B -> μ + ν_μ + cc.
b -> B -> D -> μ + ν_μ + cc.



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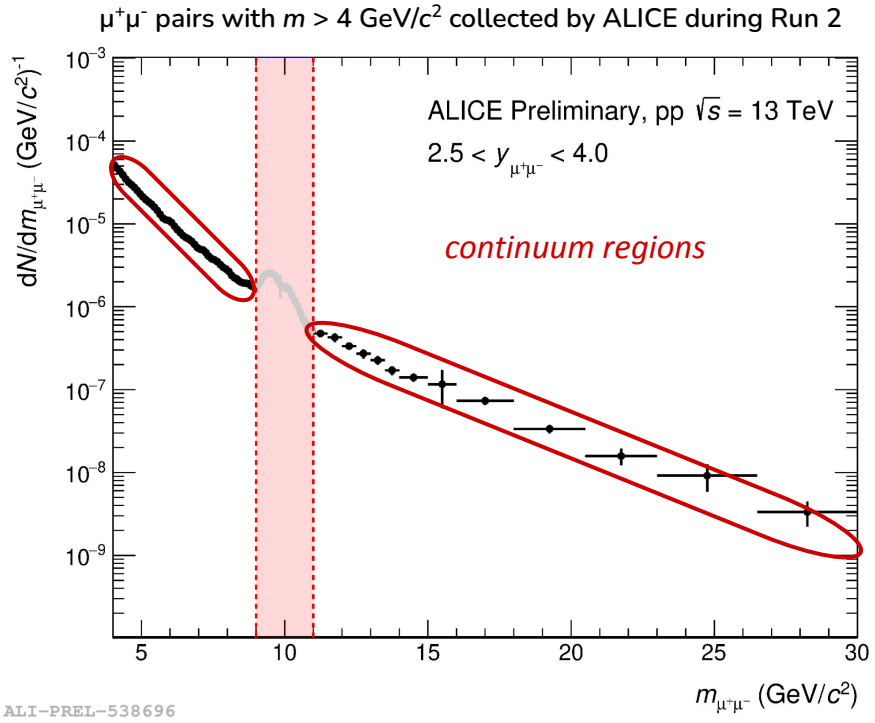

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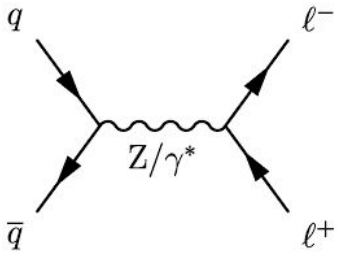
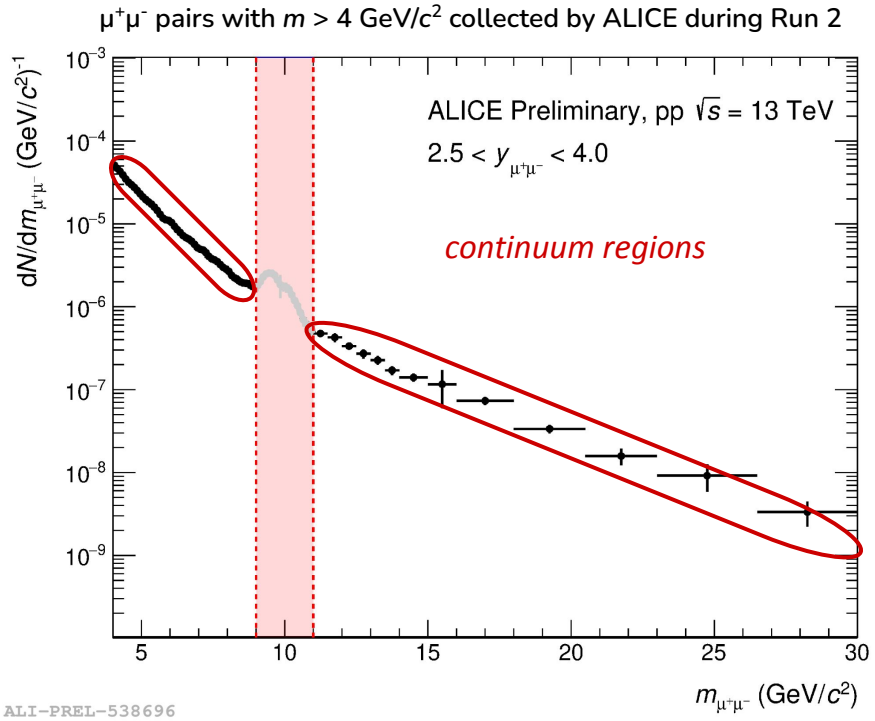


Access to Drell-Yan process at fwd-y for the first time at LHC energies (studies in progress)

Combinatorial bkg. from light-flavor (LF) hadrons

Continuum regions of the dimuon mass spectrum



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Semileptonic decays of pairs of open heavy-flavor (HF) hadrons

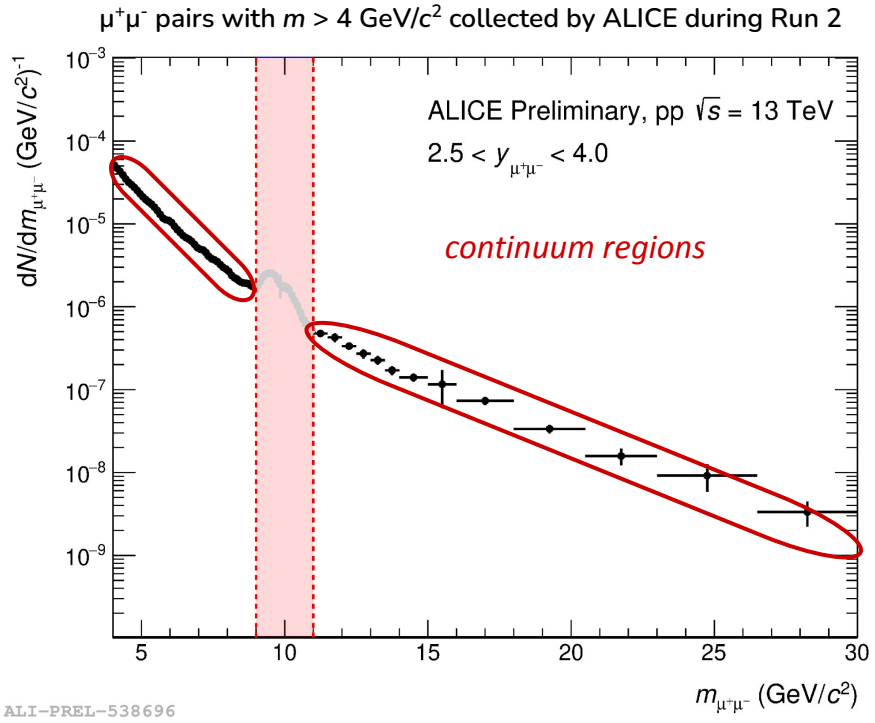
Drell-Yan mechanism

Combinatorial bkg. from light-flavor (LF) hadrons

Two possible bkg. sources:

- $\mu^+\mu^-$ <- LF : both μ produced by LF hadron decay
- $\mu^+\mu^-$ <- LF,HF : one μ from HF, the other μ from LF

Continuum regions of the dimuon mass spectrum

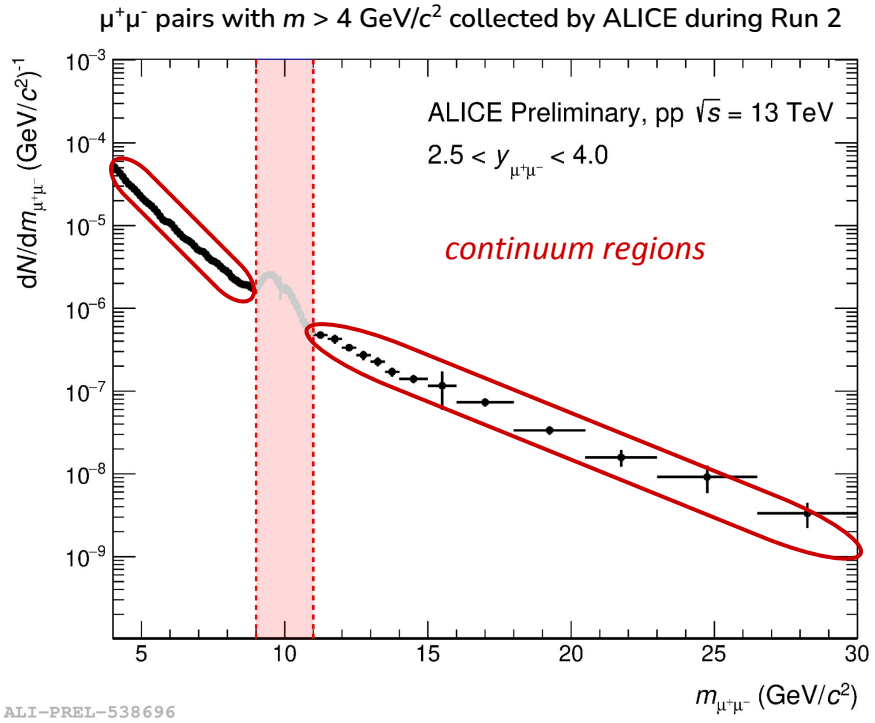


ALICE explores the continuum of the $\mu^+\mu^-$ mass spectrum to make the first-ever measurement of charm and beauty quark pair production at forward rapidity in LHC collisions.

Extension of previous ALICE measurements at mid-rapidity ($|y| < 0.5$ for HF and $|y| < 0.8$ for dielectrons).

Analysis technique

Analysis steps

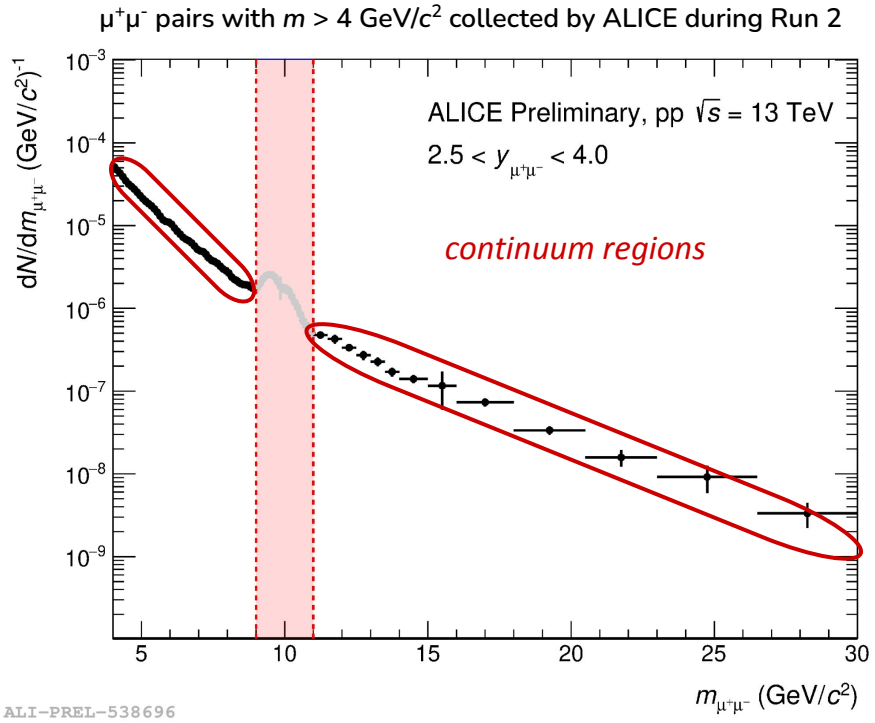


Dedicated Monte Carlo simulations (PYTHIA 8) to study the different μ⁺μ⁻ sources above $m_{\mu\mu}$ = 4 GeV/c^2

Template fit with the shapes of the main μ⁺μ⁻ sources in the continuum region, extracted from PYTHIA simulations

Cross section calculation and results

Analysis steps



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- **LF hadrons** (combinatorial background):
  - Minimum bias MC to study the contamination of LF ➜ $\mu^+\mu^-$ and LF,HF ➜ $\mu^+\mu^-$
- **HF hadrons** :
  - HF-enriched* MC to study the different HF components

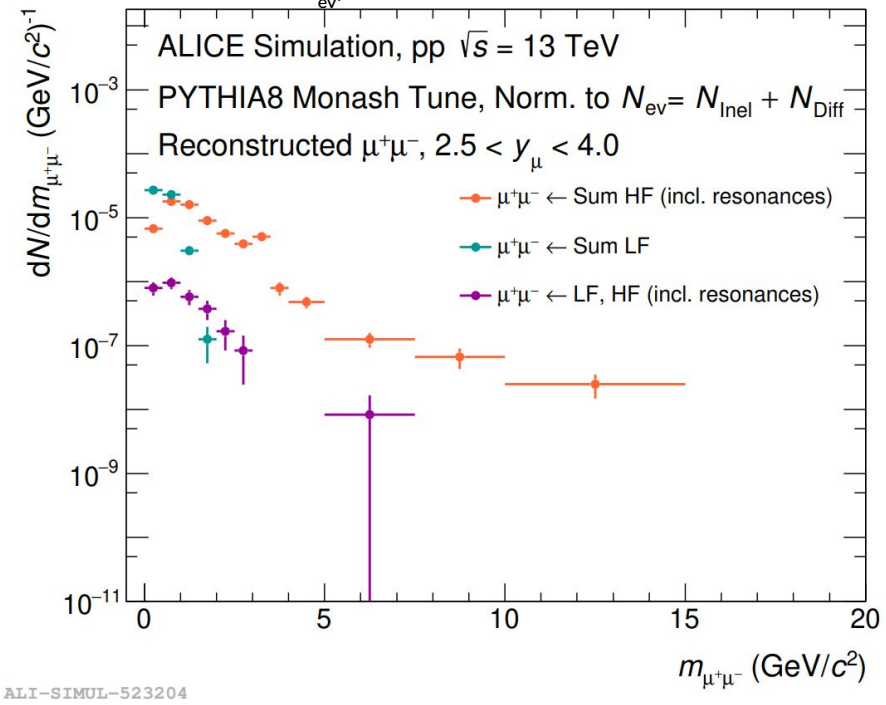
  * required the presence of cc/bb pair in the event + a μ <- HF at fwd. rapidity to increase the HF ➜ $\mu^+\mu^-$ above $m_{\mu\mu}$ = 4 GeV/c^2

Template fit with the shapes of the main $\mu^+\mu^-$ sources in the continuum region

Cross section calculation and results

Analysis steps: study LF contamination

Invariant mass distribution per pp collision of $\mu^+\mu^-$ pairs, normalized to N_{ev}, from minimum bias PYTHIA 8 simulation



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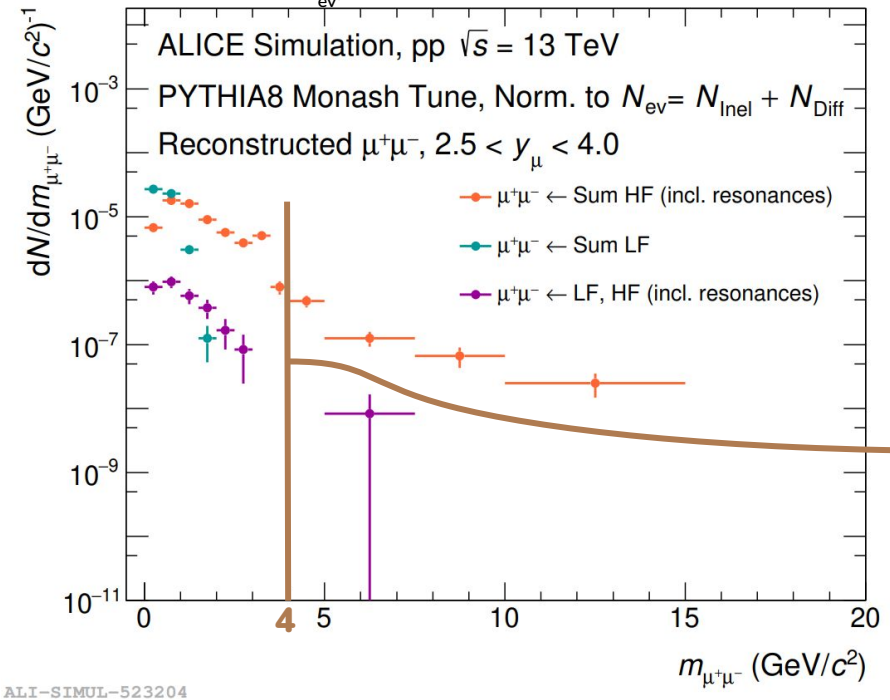

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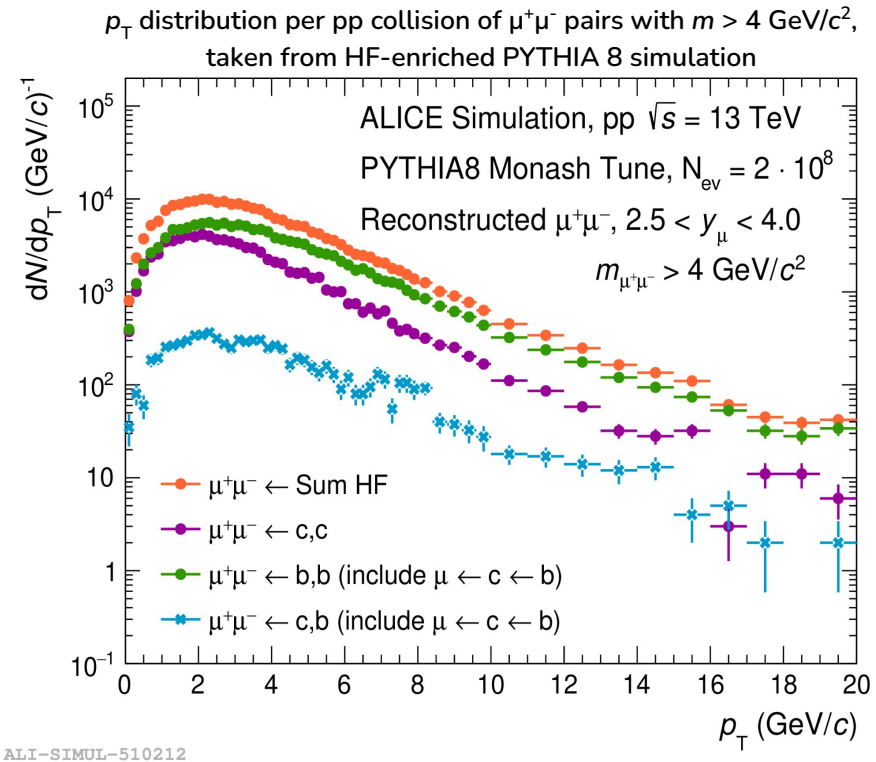
↪ Different contributions above $m_{\mu\mu}$ = 4 GeV/c^2:

- $\mu^+\mu^-$ <- HF : both μ produced by HF decay
- $\mu^+\mu^-$ <- LF : both μ produced by LF decay
- $\mu^+\mu^-$ <- LF,HF : one μ from HF, the other mu from LF

↪ The $\mu^+\mu^-$ <- LF contribution is negligible for $m_{\mu\mu}$ = 4 GeV/c^2:

↪ Almost negligible contribution of the **mixed LF-HF** component, further studies needed to precisely quantify the effect

Analysis steps: study HF components



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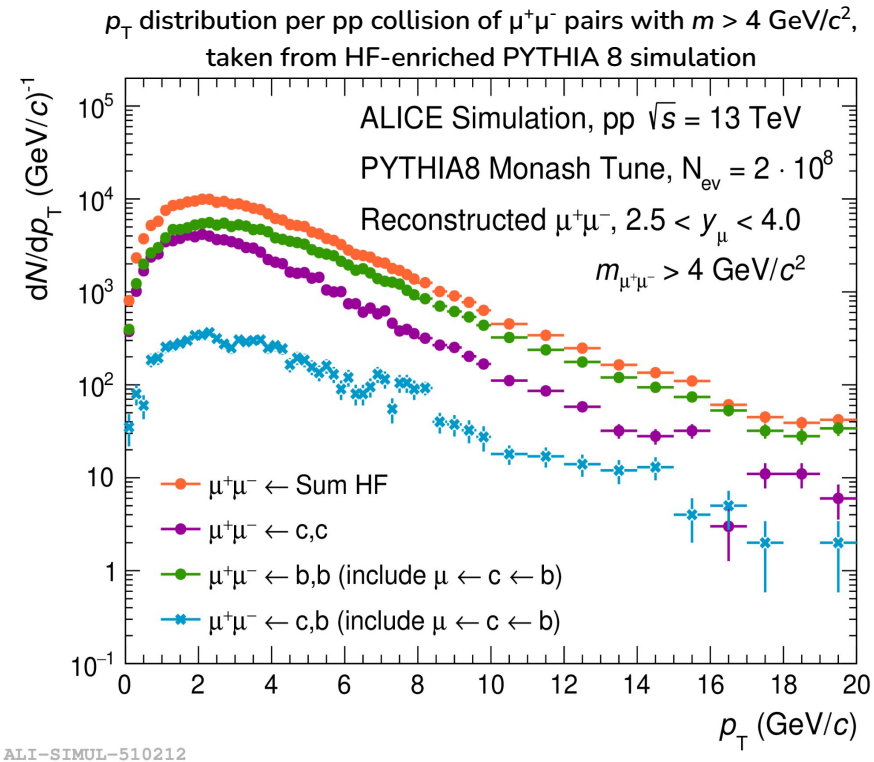

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    * required the presence of cc/bb pair in the event + a μ <- HF at fwd. rapidity to increase the HF ➜ $\mu^+\mu^-$ above $m_{\mu\mu}$ = 4 GeV/c^2

↪ Different contributions **$\mu^+\mu^-$ <- Sum HF** above **$m_{\mu\mu}$ = 4 GeV/c^2**:

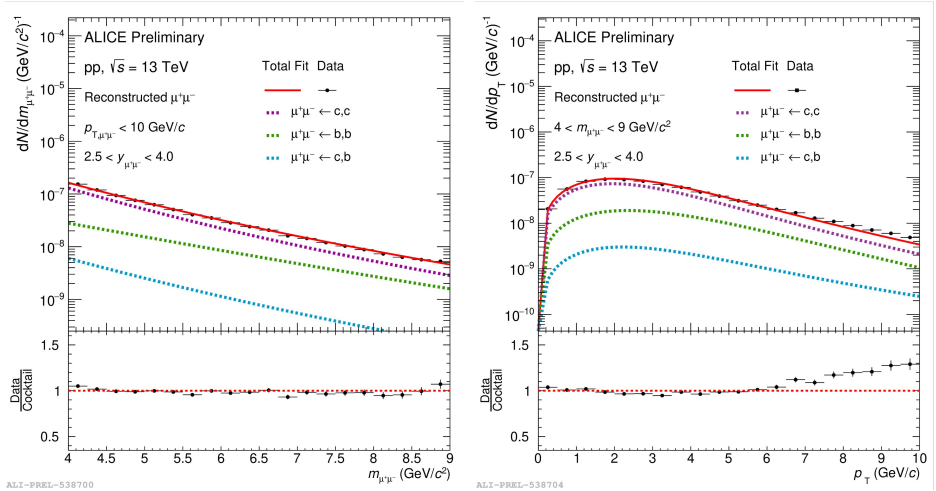
↪ **$\mu^+\mu^-$<- c,c** : both μ produced by prompt charm particle decays

↪ **$\mu^+\mu^-$<- b,b** : both μ produced by beauty particle decays (include the non prompt charm component)

↪ **$\mu^+\mu^-$ <- c,b** : one μ from prompt charm particle, the other μ from beauty particle

Analysis steps: template fit

Mass and p_T components of the template fit to the data, using a HF cocktail with PYTHIA



Dedicated Monte Carlo simulations (PYTHIA 8) to study the different $\mu^+\mu^-$ sources above $m_{\mu\mu}$ = 4 GeV/c^2

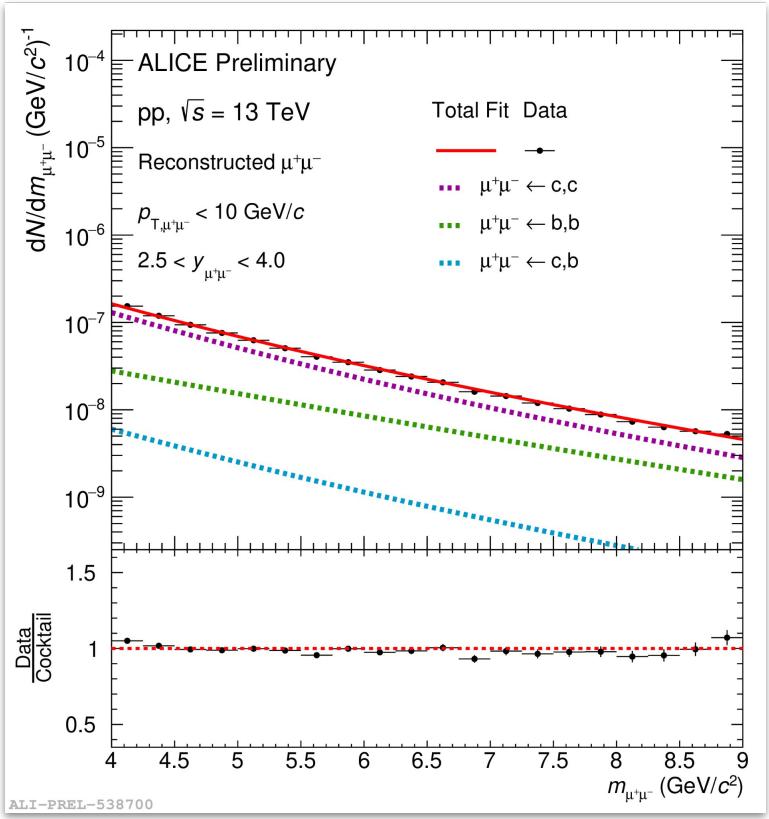
Template fit with the shapes of the main $\mu^+\mu^-$ sources in the continuum region, extracted from PYTHIA simulations

- Extraction of the charm and beauty probability density functions (PDFs) from HF-enriched MC
- Simultaneous unbinned p_T and m fit of data with the cocktail of the signals from HF-enriched MC

Cross section calculation and results

Analysis steps: template fit (mass component)

***mass* component** of the template fit to the data, using a HF cocktail with PYTHIA

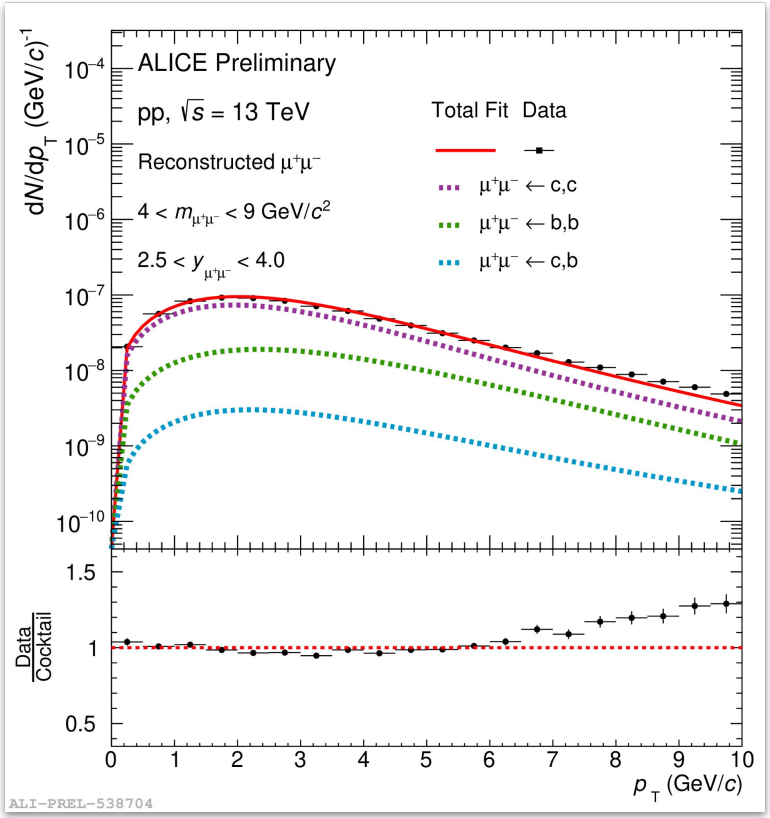


Template fit with the shapes of the main $\mu^+\mu^-$ sources in the continuum region, extracted from PYTHIA simulations

- Extraction of the charm and beauty probability density functions (PDFs) from HF-enriched MC
- Simultaneous unbinned fit to m and p_T data distributions with **cocktail of HF sources** from the HF-enriched PYTHIA 8 simulation
- **Good agreement** between the fit and the data in the mass region under study

Analysis steps: template fit (p_T component)

p_T component of the template fit to the data, using a HF cocktail with PYTHIA



Template fit with the shapes of the main $\mu^+\mu^-$ sources in the continuum region, extracted from PYTHIA simulations

- Extraction of the charm and beauty probability density functions (PDFs) from HF-enriched MC
- Simultaneous unbinned fit to m and p_T data distributions with **cocktail of HF sources** from the HF-enriched PYTHIA 8 simulation
- **Good agreement** between the fit and the data in the mass region under study
- **Stringent test** of Monte Carlo generators (PYTHIA) predictions:
  - ↪ Results show that measured m and p_T yields are well reproduced by a superposition of known sources within a 20% discrepancy in very broad m and p_T ranges

Analysis steps: results

Dedicated Monte Carlo simulations (PYTHIA 8) to study the different $\mu^+\mu^-$ sources above $m_{\mu\mu} = 4$ GeV/c^2

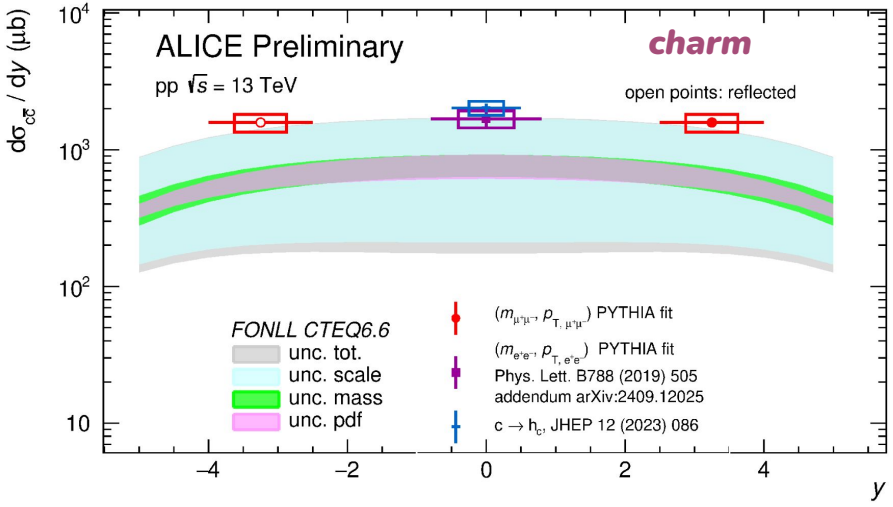
Template fit with the shapes of the main $\mu^+\mu^-$ sources in the continuum region

Cross section calculation and results

- By using the $\mu^+\mu^-$ <- c,c and $\mu^+\mu^-$ <- b,b yields, calculate the charm and beauty cross section
- **First measurement of charm and beauty cross section at forward rapidity ($2.5 < y < 4$) at LHC energies**

Analysis steps: charm cross section

New ALICE ***charm*** cross section results at fwd–*y* (***high-mass dimuons***) compared previous measurements at mid–*y* (low-mass dielectrons* and ***via hadronic decays***)



ALI-PREL-581604

* charm results updated with latest FF, addendum close to be published

Cross section calculation and results

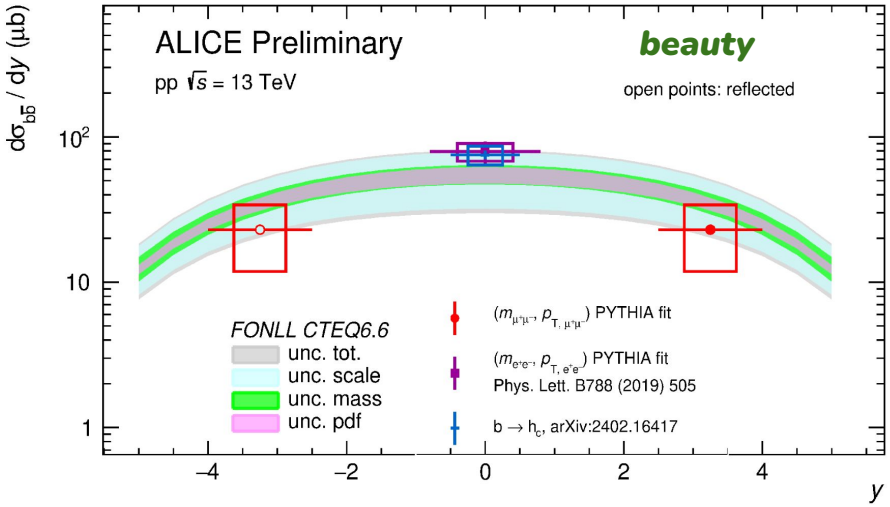
- Stringent test of Monte Carlo generators (PYTHIA) predictions:
  - ↪ Results show that measured *m* and p_T yields are well reproduced by a superposition of known sources within a 20% discrepancy in very broad *m* and p_T ranges

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

- Results compatible with other mid-*y* measurements
- Testing ***FONLL*** predictions rapidity coverage:
  - ↪ ***Charm*** cross section value lie on the ***upper*** edge

Analysis steps: beauty cross section

New ALICE ***beauty*** cross section results at fwd–*y* (***high-mass dimuons***) compared previous measurements at mid–*y* (low-mass dielectrons and ***via hadronic decays***)



ALI-PREL-581599

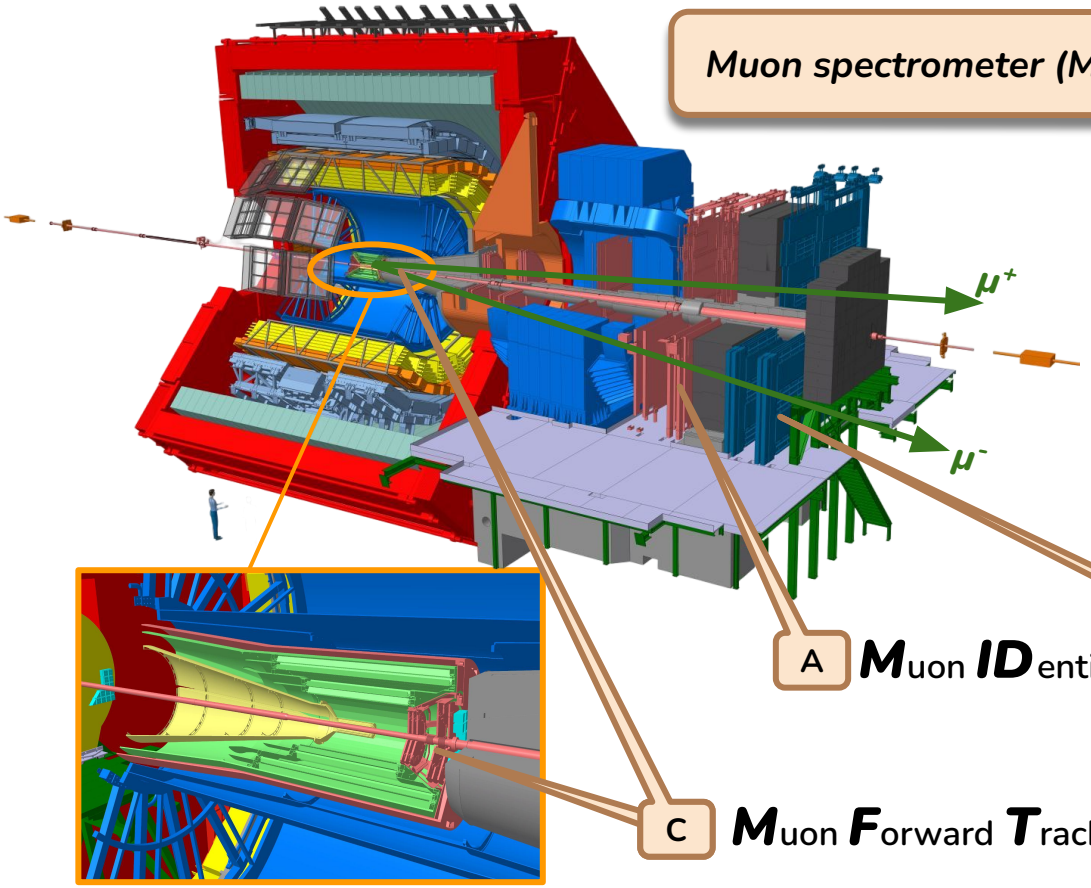
Cross section calculation and results

- Stringent test of Monte Carlo generators (PYTHIA) predictions:
  - ↪ Results show that measured *m* and p_T yields are well reproduced by a superposition of known sources within a 20% discrepancy in very broad *m* and p_T ranges

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

- Results compatible with other mid-*y* measurements
- Testing ***FONLL*** predictions rapidity coverage:
  - ↪ ***Beauty*** cross section value lie on the ***lower*** edge, compatible with other measurements at mid-*y*

Quarkonia and HF performances in Run 3



Muon spectrometer (MS)

MFT – Muon Forward Tracker [CERN-LHCC-2015-001]

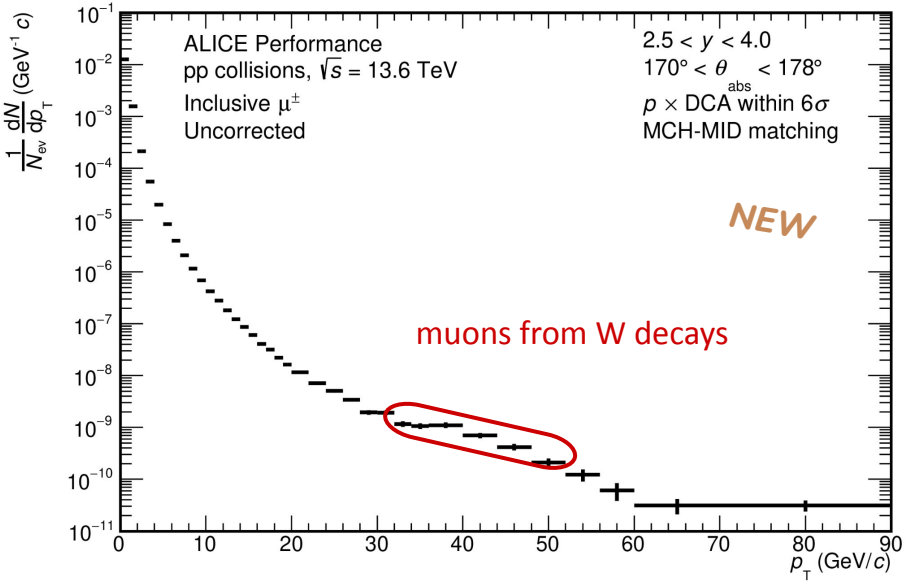
Providing vertexing capabilities at forward rapidity, allowing prompt/non-prompt separation for HF hadrons

A **M**uon **ID**entifier

B **M**uon **CH**amber

C **M**uon **F**orward **T**racker

Prompt/non-prompt separation at fwd

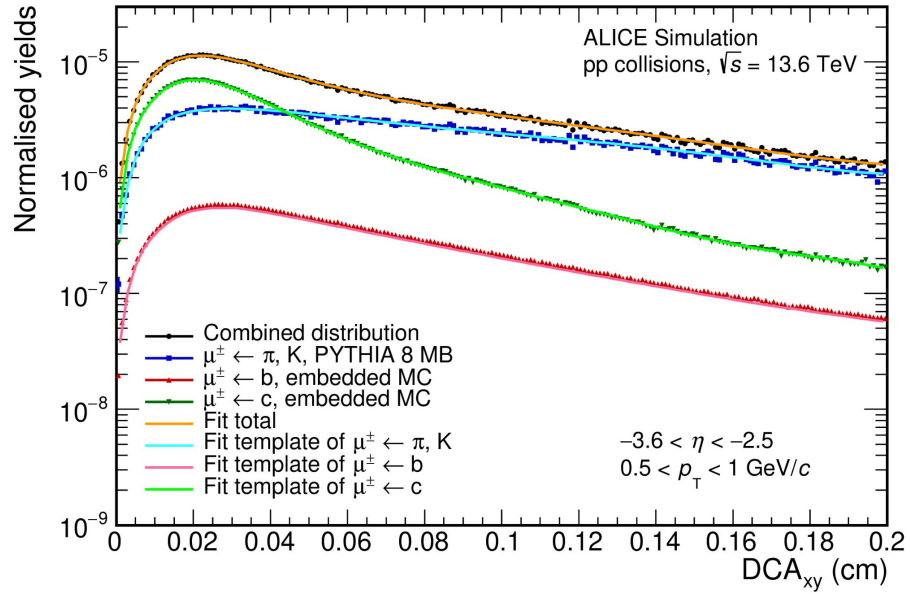


ALI-PERF-571756

A lot of statistics in Run 3!

- High-p_T region measurements feasible even with a fraction of the 2022-2023 pp sample at 13.6 TeV
- Muons from W-boson decays clearly observed at p_T ~ 40 GeV/c
- Multi-differential measurements of open heavy flavours in the semi-muonic channel with high precision can be performed

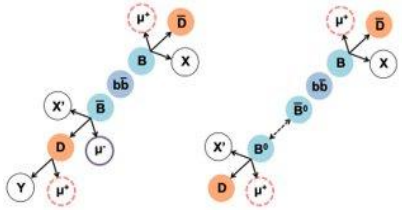
Prompt/non-prompt separation at fwd



ALI-SIMUL-547324

Prompt/non prompt charm muons separation

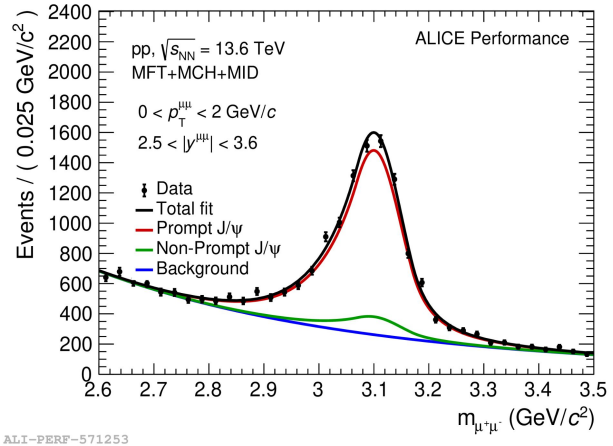
- Multi-differential measurements of open heavy flavours in the semi-muonic channel with high precision can be performed

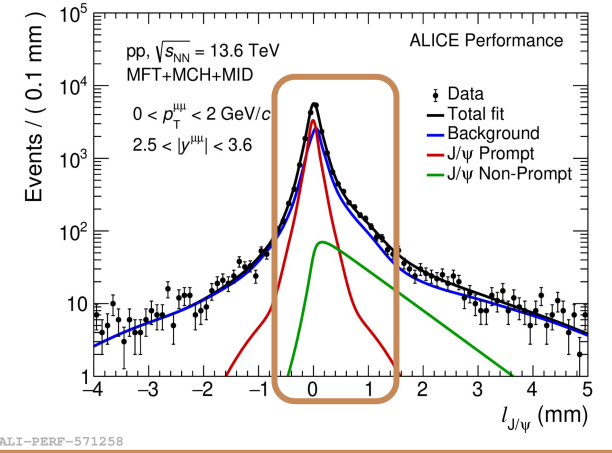


<u>beauty sector more complicated</u> producing muons also through charm hadrons

- Observable: **DCA_{xy}** (Distance of Closest Approach to the primary vertex in the transverse plane) of heavy-flavour decay muons

Prompt/non-prompt separation at fwd





Prompt/non prompt J/ ψ separation

- Performance in pp with MFT+MCH+MID muon tracks
- Boost at forward rapidity allows non-prompt fraction measurement down to $p_T = 0$

z-position of the primary (PV) and secondary vertex

J/ψ pseudo-proper decay length

$$l_{J/\psi} = c \cdot \frac{(z_{PV} - z_{SV}) \cdot m_{J/\psi}}{p_z}$$

z-component of J/ψ momentum

- Different decay **pseudo-proper length** for prompt and non–prompt J/ψ observed
- Simultaneous 2D fit to J/ψ mass and pseudo-proper decay length distributions to extract non-prompt fraction at fwd rapidity for the first time in ALICE

Conclusions

- **Charm and beauty measurements via high-mass dimuons:**
  - Opposite sign dimuons, already employed for quarkonium analyses in ALICE, can be used to study heavy-flavour production at fwd-y
    - ⇒ *Extension of ALICE HF cross section measurements to fwd rapidity*
  - ***First measurement*** of charm and beauty cross section at fwd-y with ALICE
  - ***First measurement*** of charm cross section at fwd-y at LHC energies
    - ⇒ *Charm and beauty cross section values lie on the upper and lower edges of FONLL predictions, respectively*

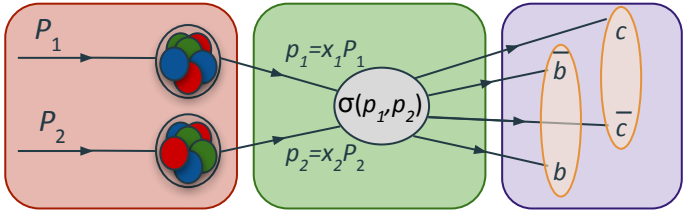
- **Run 3 perspectives:**
  - Thanks to the MFT, ALICE has now vertexing capabilities also at fwd-*y*
  - First performances of prompt/non–prompt charm muons separation show potential for directly accessing the beauty sector also at fwd-*y*


Thanks for your attention!
HP2024
NAGASAKI

What can we study with HF in pp?

Given their large masses (m_c=1.3 GeV/ c^2, m_b=4.2 GeV/ c^2), heavy quarks are generated predominantly during the initial stages of collisions.

- **In pp collisions:** description of open heavy-flavor (*i.e.* bound states of charm or beauty quark with a light quark) production mechanism represents a challenge for theory
  - ↪ *Test both the perturbative and non-perturbative regimes of QCD*
  - ↪ *Fragmentation fraction: phenomenological functions parameterized on e^-e^+ data*



$$\frac{d\sigma^{H_{c/b}}}{dp_T} = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c/b}}{dp_T^{c/b}}(x_1,x_2,\mu_R,\mu_F) \otimes H_{c/b\to H_{c,b}}\left(z = p_{H_{c/b}}/p_{c/b}\,,\mu_F\right)$$

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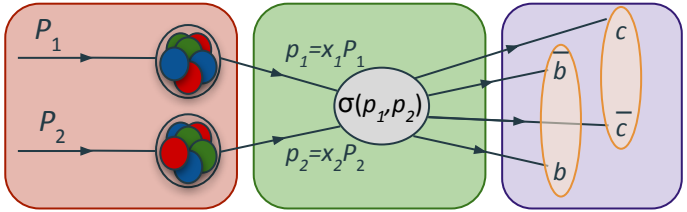

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  - cold nuclear matter effects (CNM), in particular PDFs modification
  - disentangle medium-induced effects in Pb–Pb

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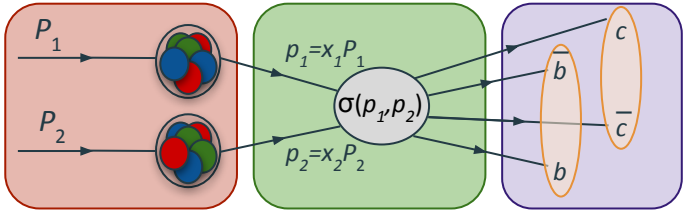

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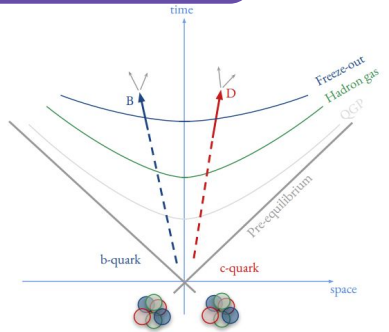
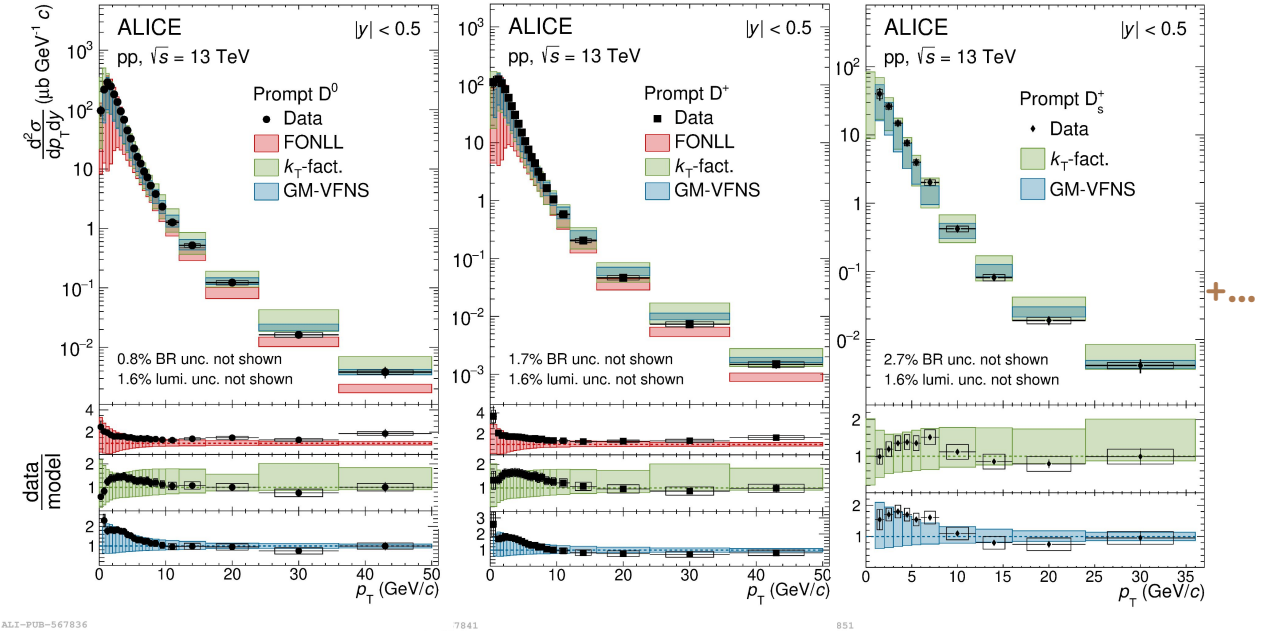


- **In Pb–Pb collisions** , HF are important to study:
  - QGP-induced effects of HF hadrons distributions
  - in particular using HF: quarkonium suppression, energy loss, azimuthal anisotropies

Measurements of charm cross section

- Measurement of *charm* cross section by reconstructing the prompt charm particles hadronic decays at mid-rapidity (|y|<0.5) D^0, D^+, D_s, Λ_c, and Ξ_c



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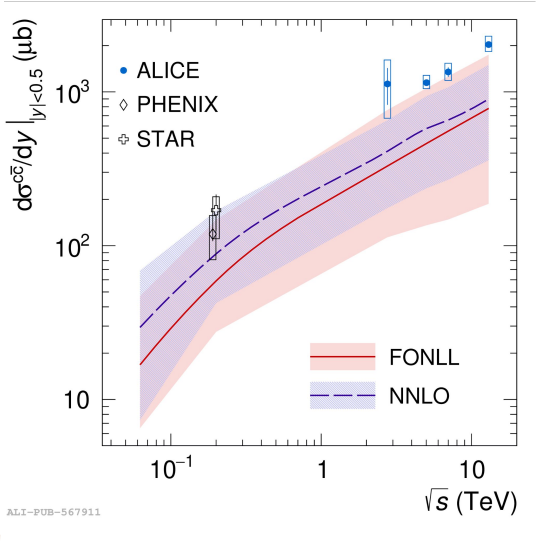
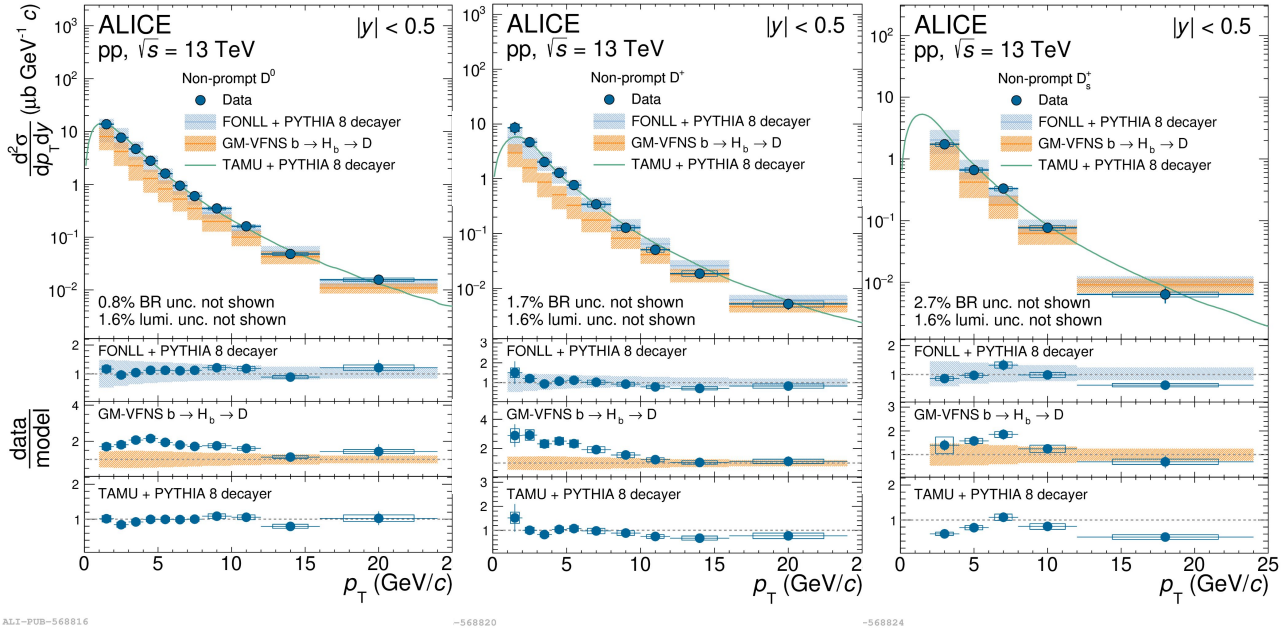
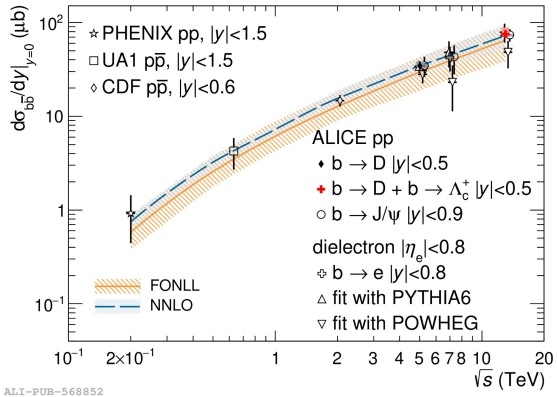


- ALICE lie on the upper edge of FONLL and NNLO predictions

Measurements of beauty cross section

- Measurement of ***beauty*** cross section by reconstructing the ***non–prompt*** charm particles hadronic decays at mid-rapidity D^0, D^+, D_s and extrapolating the cross section using FONLL





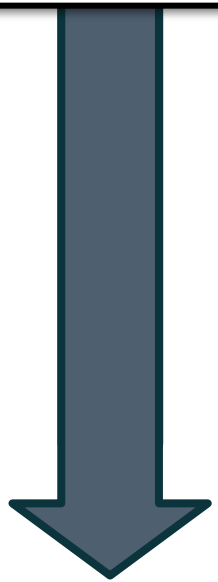
- ALICE results in agreement with FONLL and NNLO predictions

Analysis steps

How the cross section is computed:

Cross section calculation and results

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$



Analysis steps

How the cross section is computed:

charm and **beauty** dimuon yields extracted from the fit and from the HF-enriched simulation, normalized to the number of equivalent MB events in data and MC, respectively

Cross section calculation and results

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

$$N^{c\bar{c}/b\bar{b}}_{\mu\mu,data} \quad N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}$$

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charm and **beauty** dimuon yields extracted from the fit and from the HF-enriched simulation, normalized to the number of equivalent MB events in data and MC, respectively

charm and beauty quark pair cross sections in PYTHIA simulation, estimated as:

Cross section calculation and results

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

$$\frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}}$$

$$d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

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charm and **beauty** quark pair cross sections in PYTHIA simulation, estimated as:

charm and beauty quarks pairs produced at forward rapidity (2.5 < y < 4) x event

PYTHIA cross section of a inelastic pp collision

Cross section calculation and results

$$d\sigma^{c\bar{c}/b\bar{b}}_{data}/dy = \frac{N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}}{N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}} \times d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$$

$$N^{c\bar{c}/b\bar{b}}_{\mu\mu,data} \quad N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}$$

$$d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy \propto N^{c\bar{c}/b\bar{b}}_{2.5<y<4} \times \sigma^{PYTHIA}_{pp}$$