Open heavy-flavour production from the high-mass dilepton spectrum in pp collisions with ALICE

Sesto Incontro Nazionale di Fisica Nucleare (INFN2024)

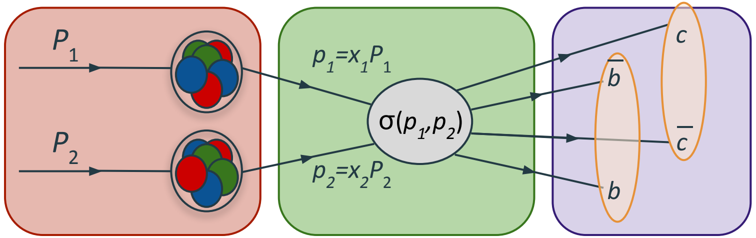
Trento 26/02/2024

Michele Pennisi

for the ALICE Collaboration

Physics Motivations

- Heavy quarks are produced in initial hard-scattering processes in hadronic 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*



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

Parton distributions functions **(non perturbative)**	Partonic cross section **(perturbative)**	Fragmentation functions **(non perturbative)**

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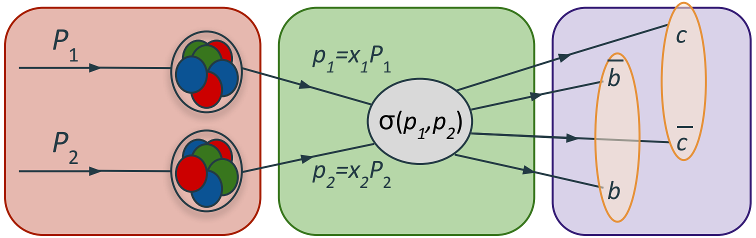

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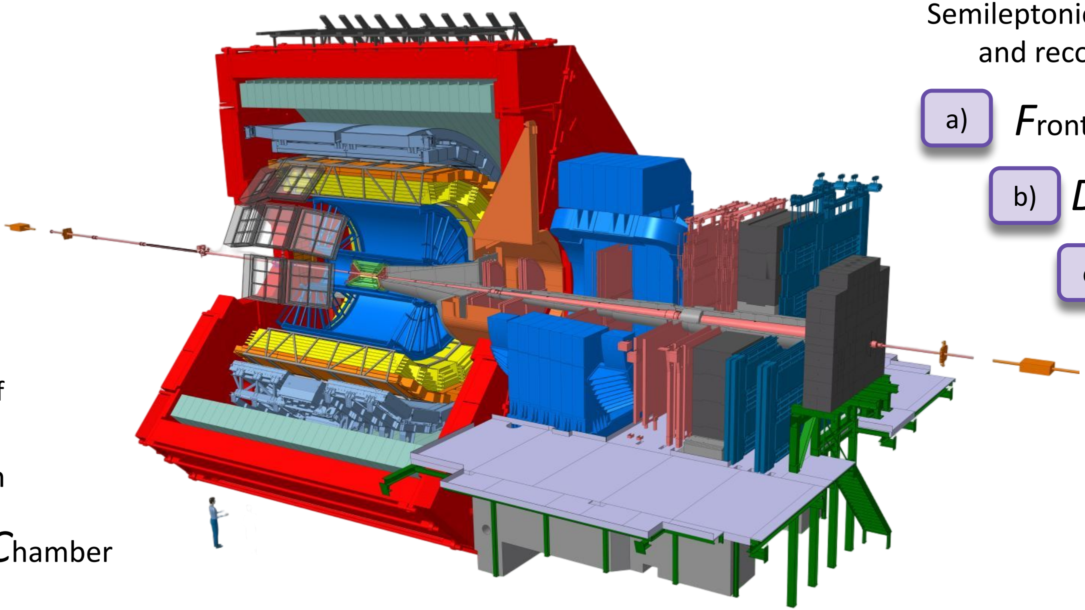
Parton distributions functions **(non perturbative)**	Partonic cross section **(perturbative)**	Fragmentation functions **(non perturbative)**

With this analysis, the first measurement of charm and beauty quark pair production at forward rapidity at LHC energies is provided

A Large Ion Collider Experiment (*Run2*)



Central Barrel

Reconstruct hadronic decays of HF particles

a) *I*nner *T*racking *S*ystem

b) *T*ime *P*rojection *C*hamber

c) *T*ime *O*f *F*light

d) *V0*

Muon spectrometer (MS)

Semileptonic decay of HF particles and reconstruct quarkonia

a) *F*ront absorber

b) *D*ipole magnet

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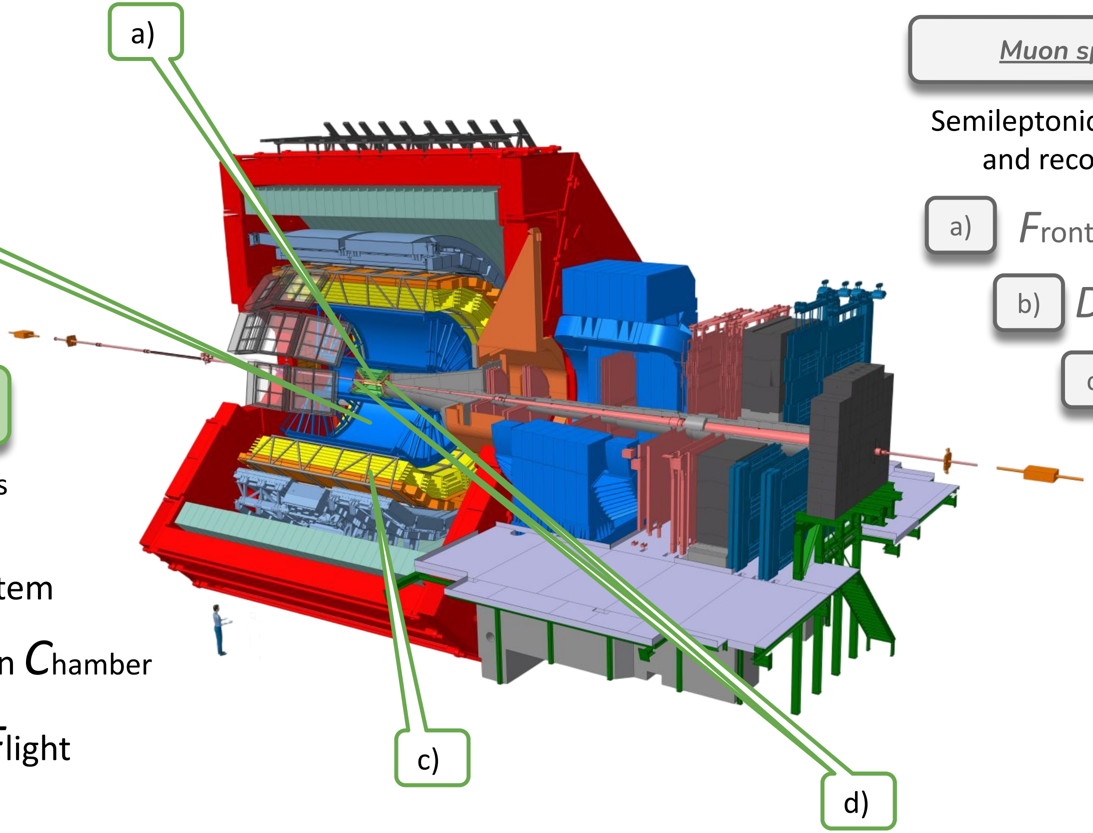

Central Barrel

Reconstruct hadronic decays of HF particles

- a) *Inner Tracking System*
- b) *Time Projection Chamber*
- c) *Time Of Flight*
- d) *V0*

Muon spectrometer (MS)

Semileptonic decay of HF particles and reconstruct quarkonia

- a) *Front absorber*
- b) *Dipole magnet*
- c) *Tracking System*
- d) *Trigger system*

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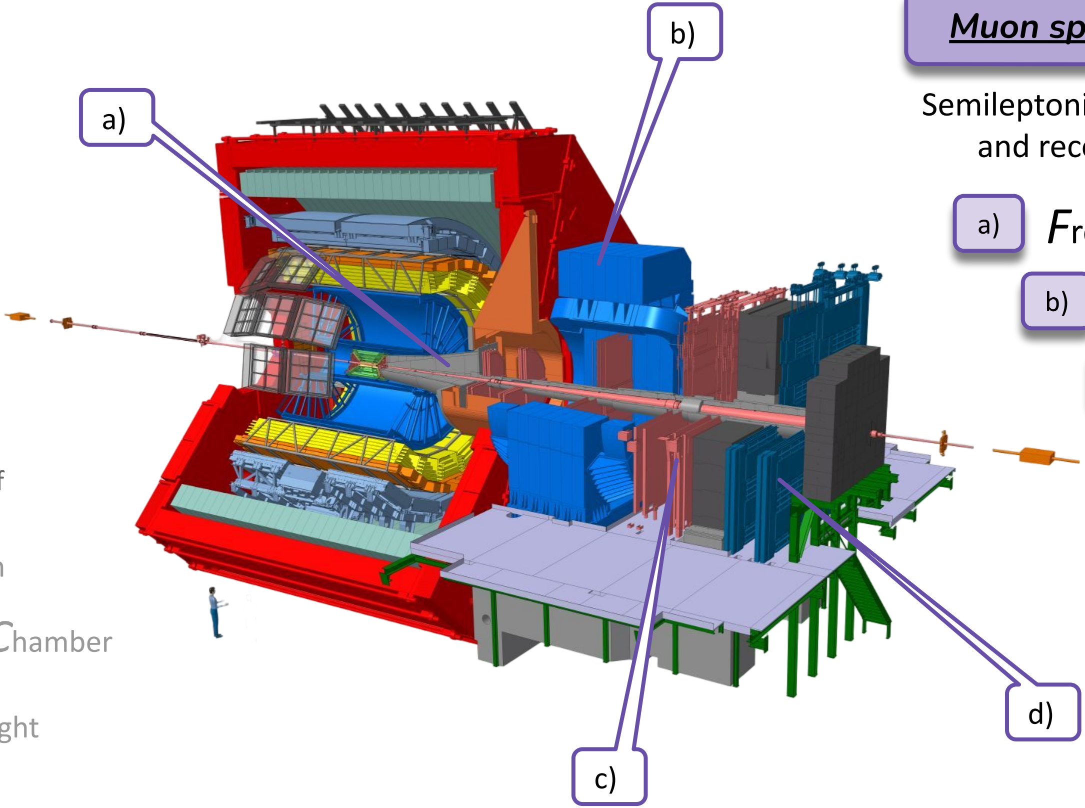

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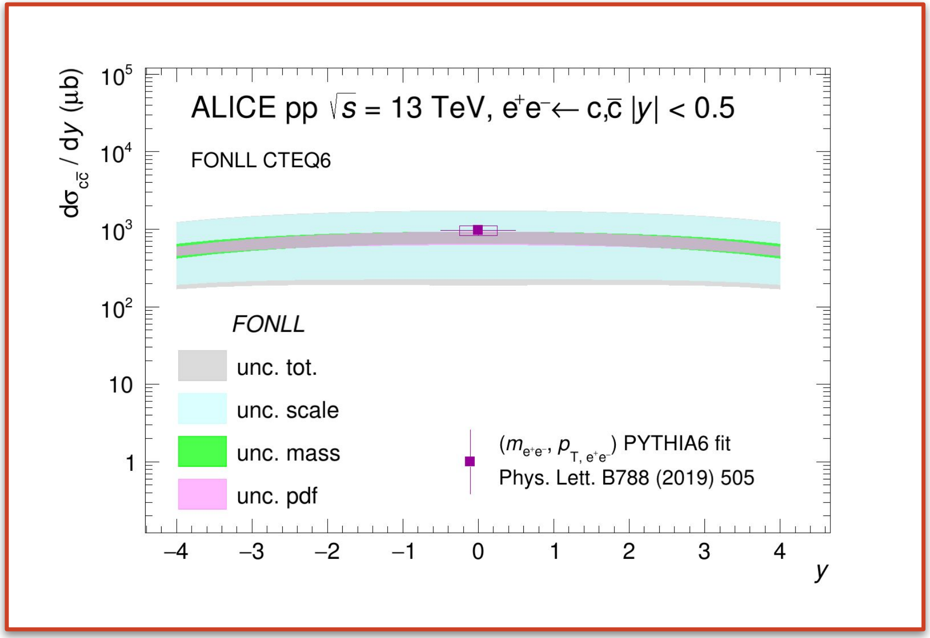
Previous heavy-flavor measurements with dileptons in pp



- [Cacciari et al, JHEP 10 (2012) 137](#) (FONLL)

Previous measurements for **charm** cross-section with dileptons in pp collisions:

- **ALICE**: low-mass dielectrons at midrapidity:
  - @13 TeV: [*Phys.Lett.B* 788 (2019) 505-518](#)
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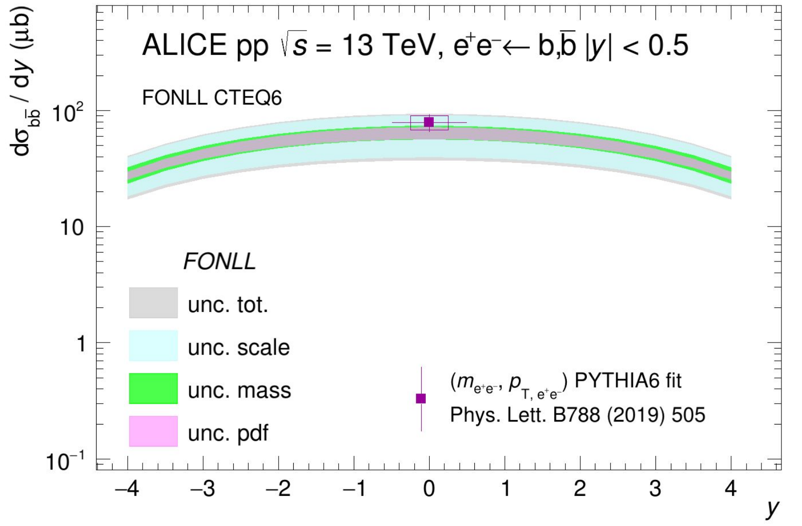

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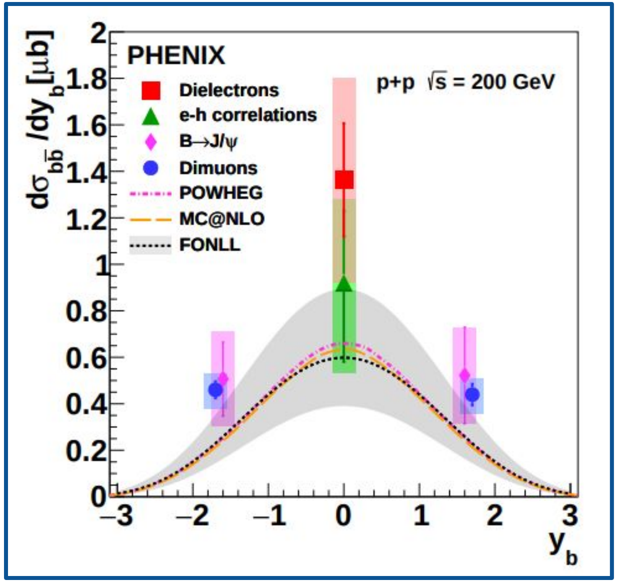

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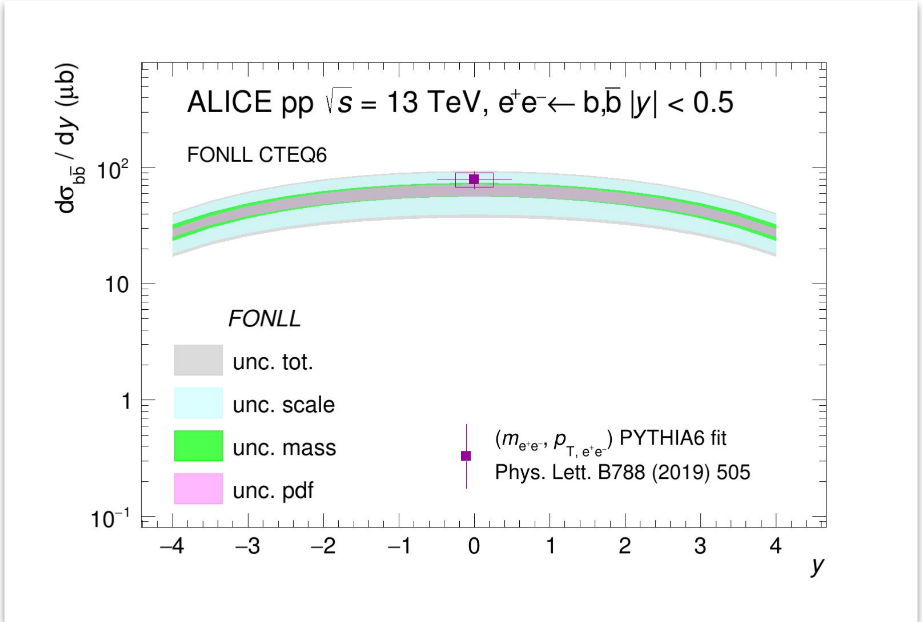
- **PHENIX**: low-mass dimuons $1.2<|\eta|<2.2$:
  - @200 GeV: *Phys.Rev.D 99 (2019)*

Previous heavy-flavor measurements with dileptons in pp

All the measurement are compatible with Fixed-Order-Next-Leading-Logarithm (FONLL) predictions, which represent the theoretical standard in open heavy-flavor calculations



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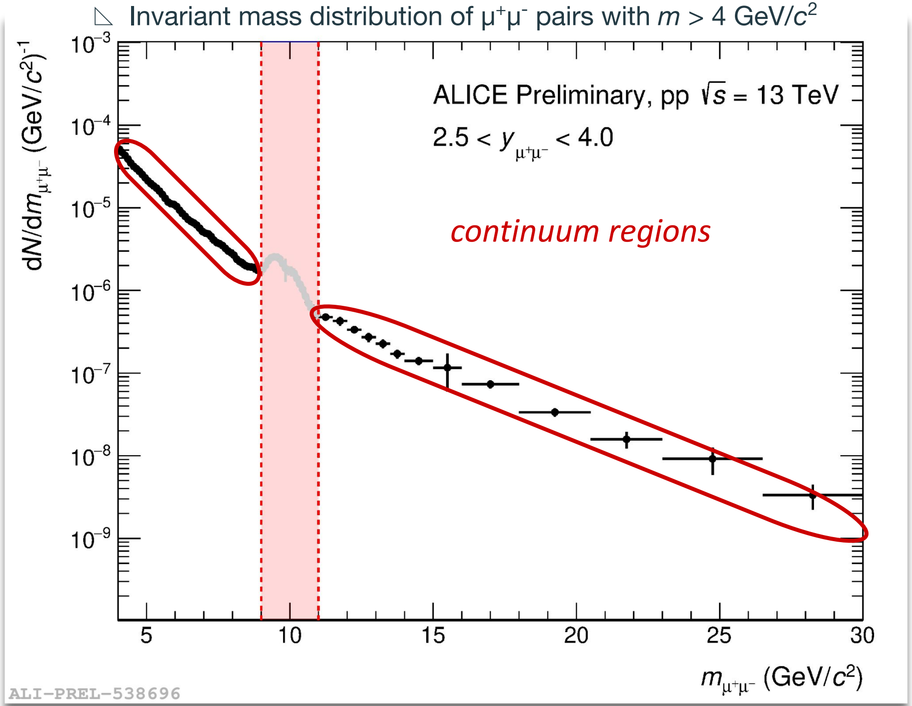
Analysis technique



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

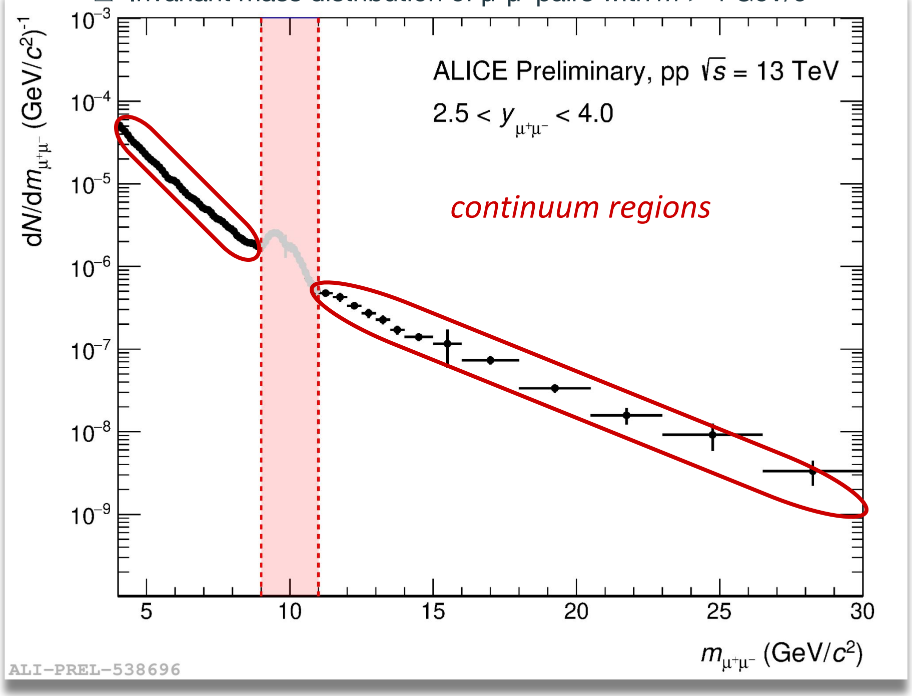
Semileptonic decays of pairs of open heavy-flavor (HF) hadrons

Combinatorial bkg. from light-flavor (LF) hadrons

Drell-Yan mechanism

Analysis technique

Invariant mass distribution of $\mu^+\mu^-$ pairs with $m > 4$ GeV/c^2



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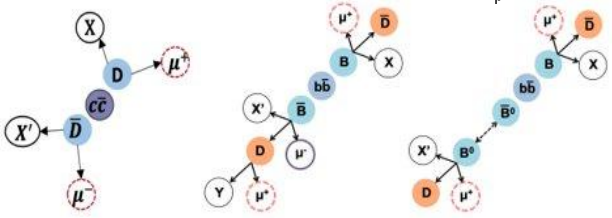
from the hadronization of cc and bb pairs

c -> D -> $\mu + \nu_\mu$ + cc.
b -> B -> $\mu + \nu_\mu$ + cc.
b -> B -> D -> $\mu + \nu_\mu$ + cc.



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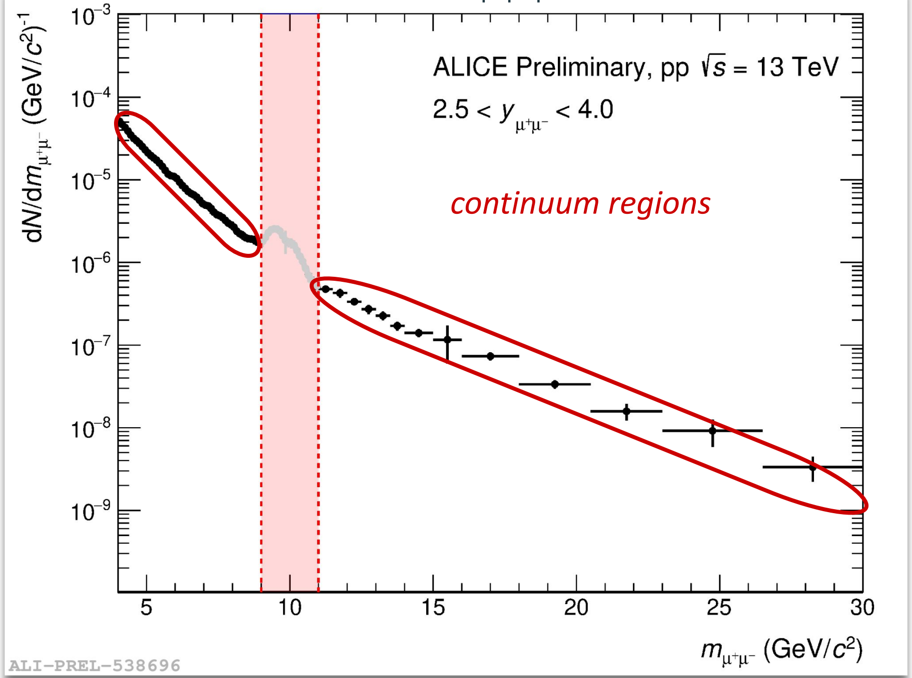

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Combinatorial bkg. from light-flavor (LF) hadrons

especially pions and kaons

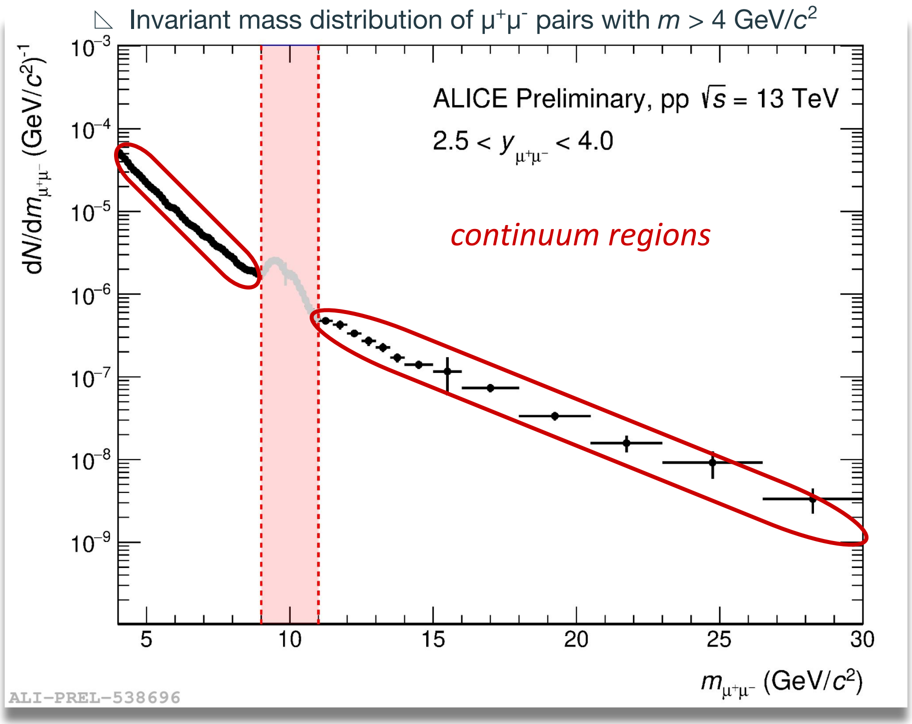
$\pi \to \mu + \nu_\mu$ + cc.
$K \to \mu + \nu_\mu$ + cc.

two possible bkg. sources:

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

Drell-Yan mechanism

Analysis technique



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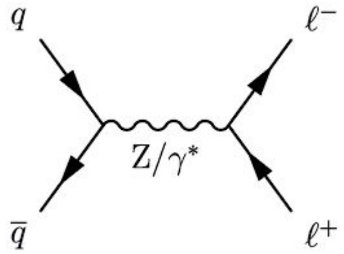
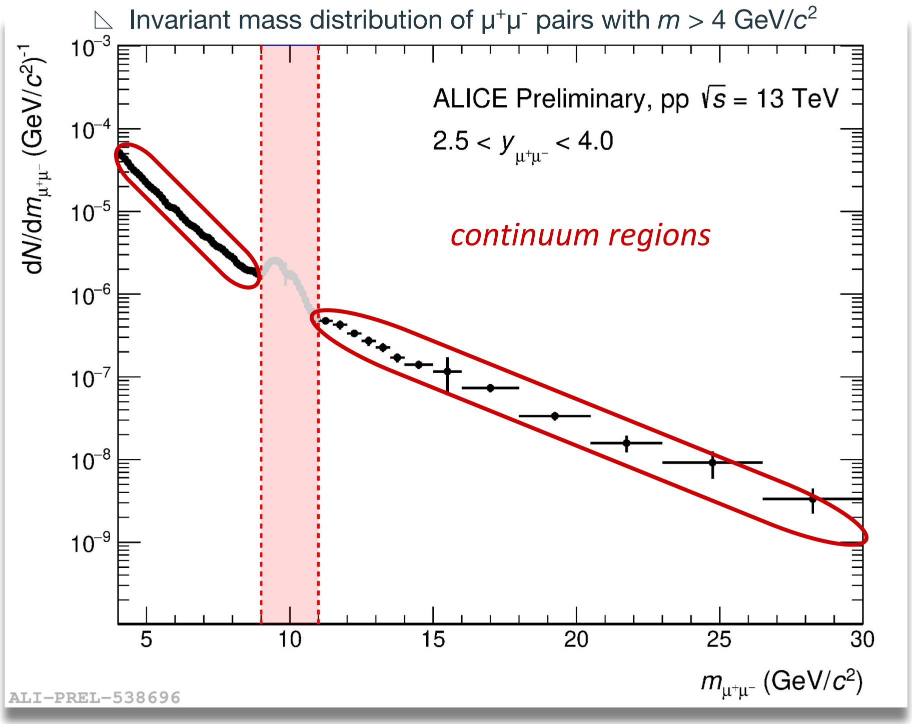
Drell-Yan mechanism



At high mass, Drell-Yan contribution might become sizeable (under investigation)

Analysis technique



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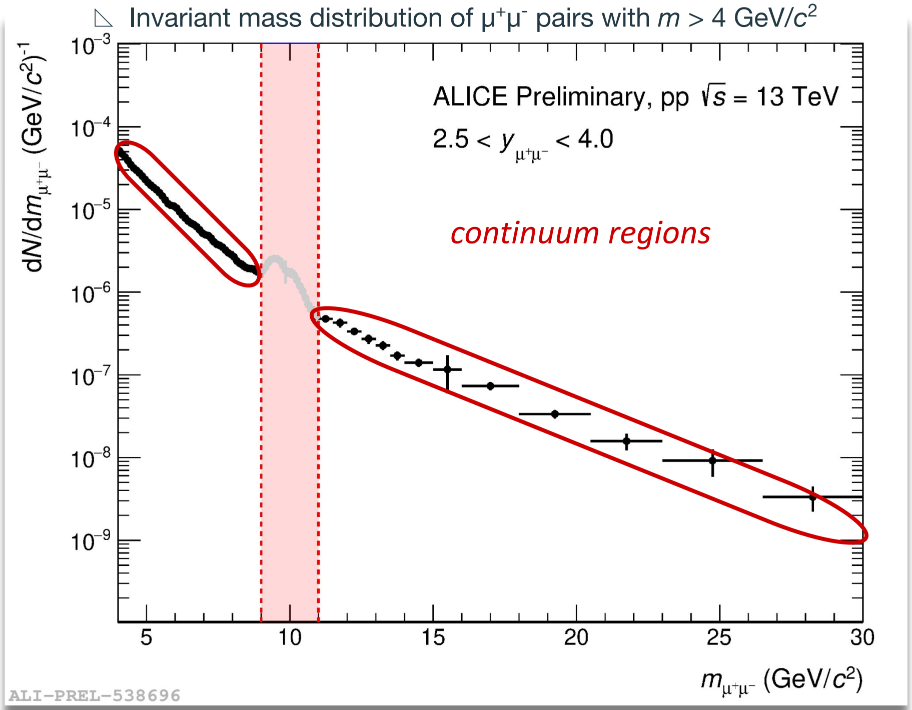
Drell-Yan mechanism

LF background dominates at low masses, its role becomes quickly negligible at high mass, allowing to study the HF quark production in almost not contaminated environment

Analysis outline



Dedicated Monte Carlo simulations (PYTHIA8) 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 preliminary results

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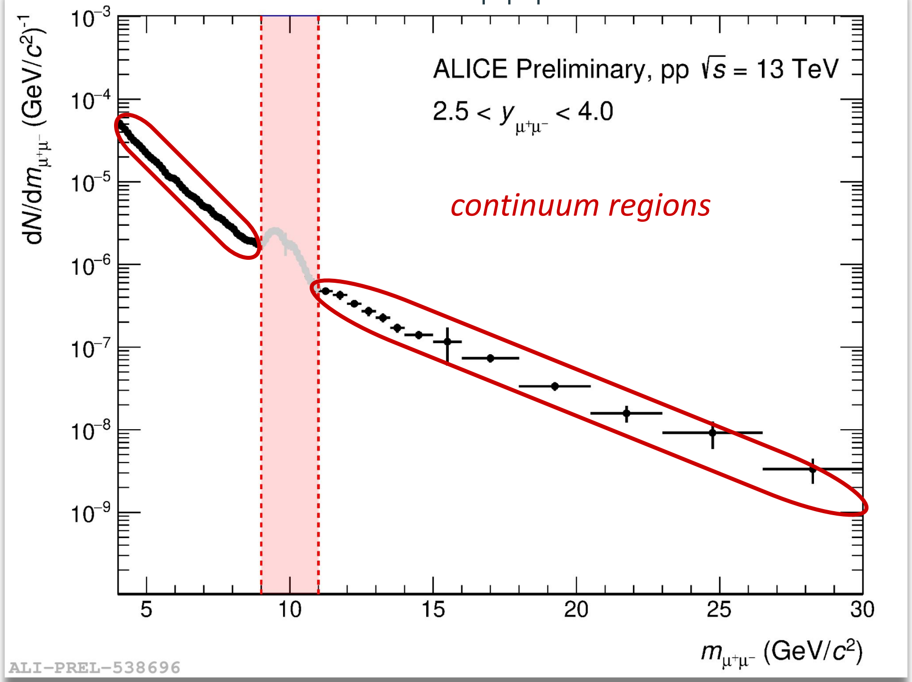
Invariant mass distribution of $\mu^+\mu^-$ pairs with m > 4 GeV/c^2



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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

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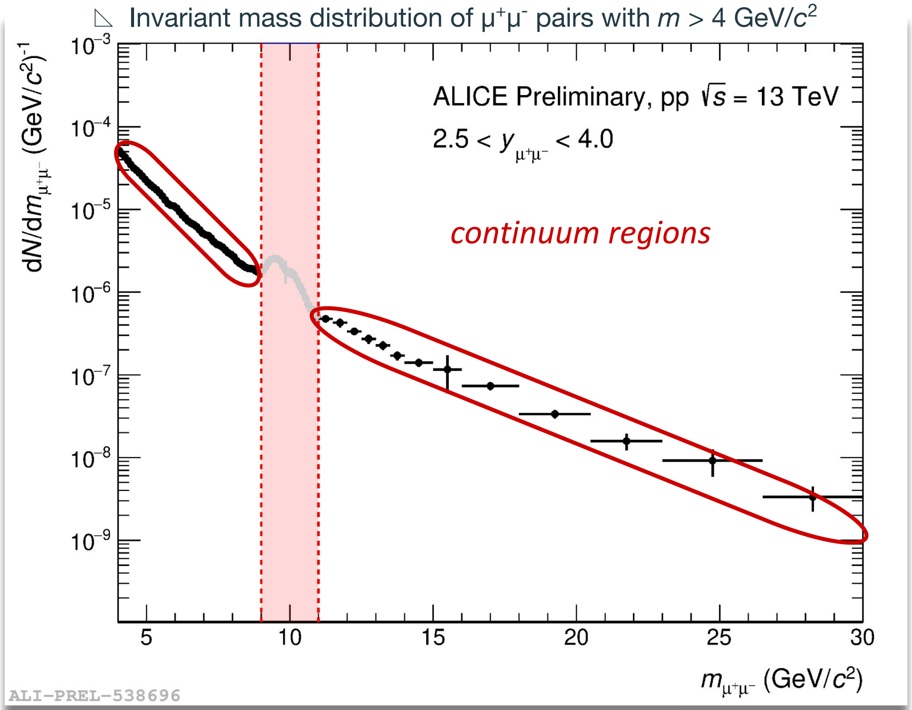

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- ➢ Extraction of the charm and beauty probability density functions (PDFs) from HF-enriched MC
- ➢ Closure test with a toy MC to verify the goodness of the procedure
- ➢ Simultaneous unbinned p_T and m fit of data with the cocktail of the signals from HF-enriched MC

Cross section calculation and preliminary results

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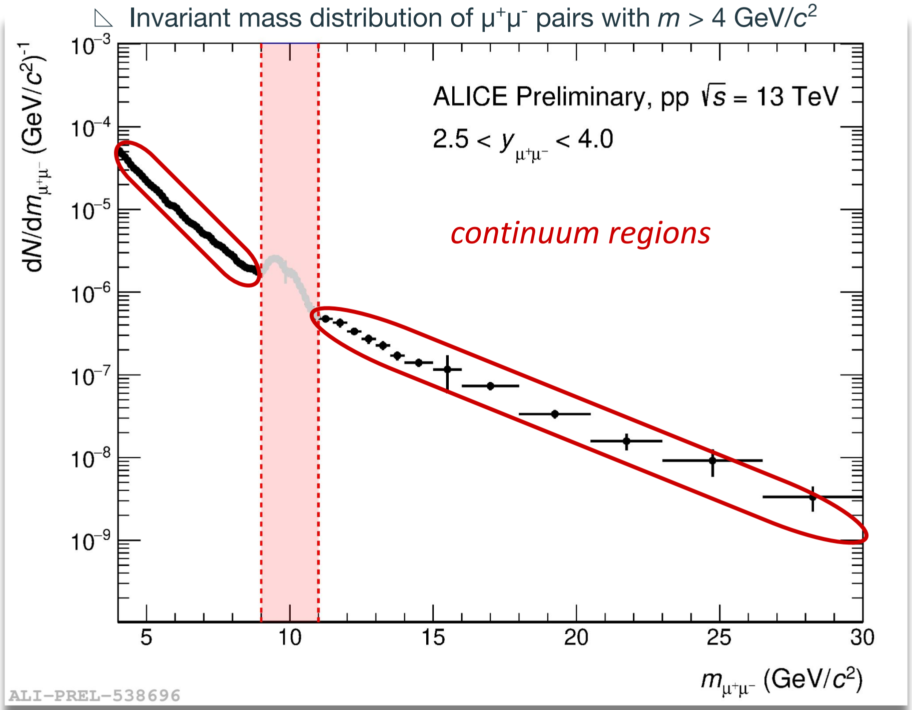

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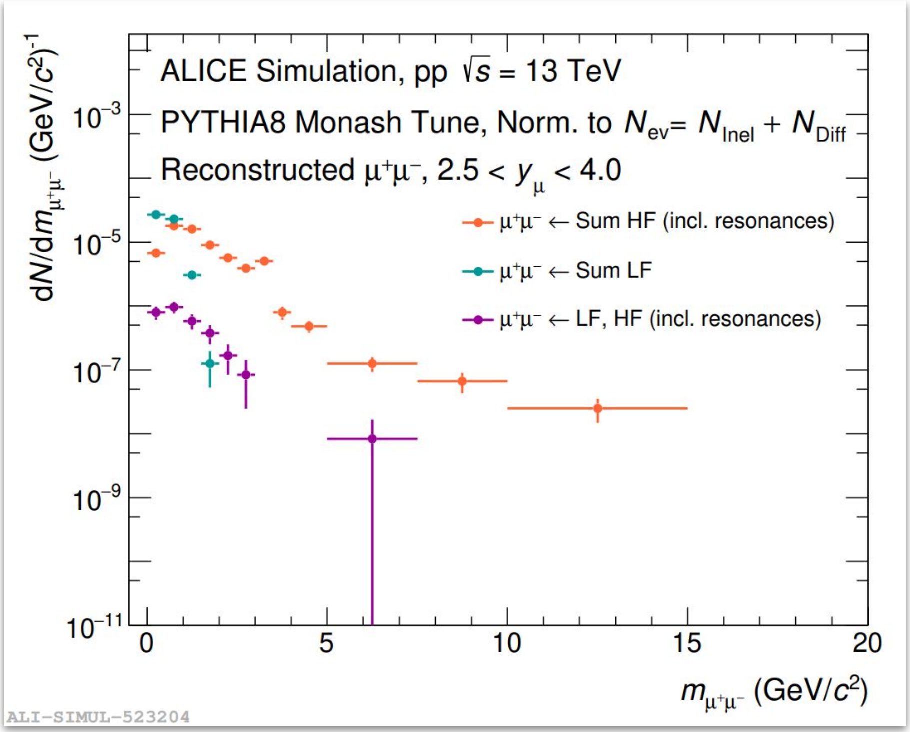
- By using the $\mu^+\mu^-$ <- c,c and $\mu^+\mu^-$ <- b,b yields, calculate the charm and beauty cross section
- First measurement of charm and beauty cross at forward rapidity (2.5 < y < 4) at the LHC energies

Study of the contamination from LF hadrons

◺ Invariant mass distribution per pp collision of $\mu^+\mu^-$ pairs, normalized to N_{ev}



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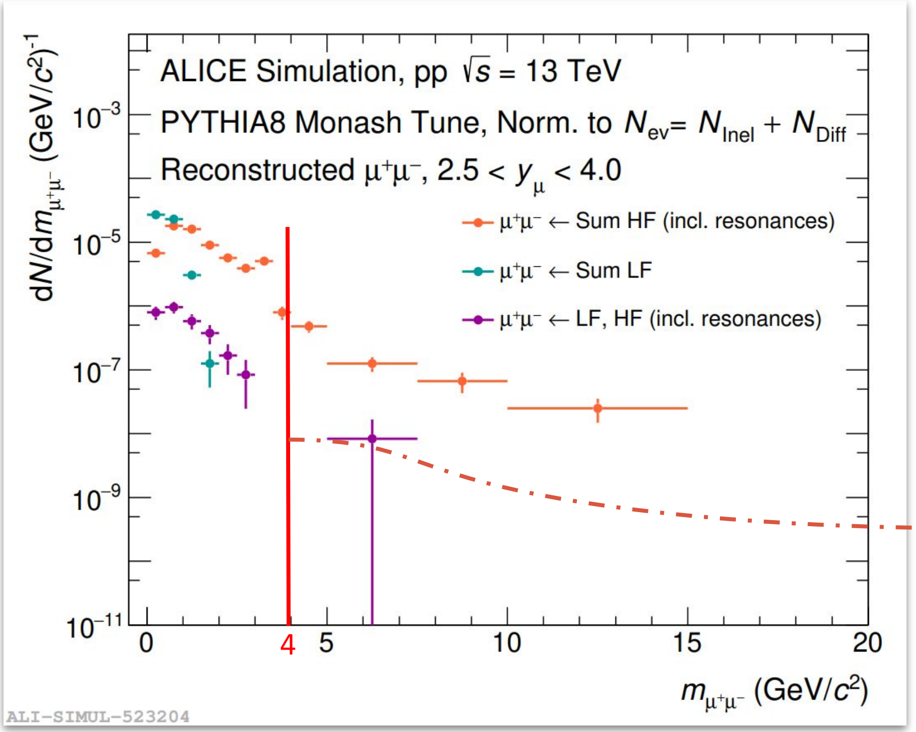

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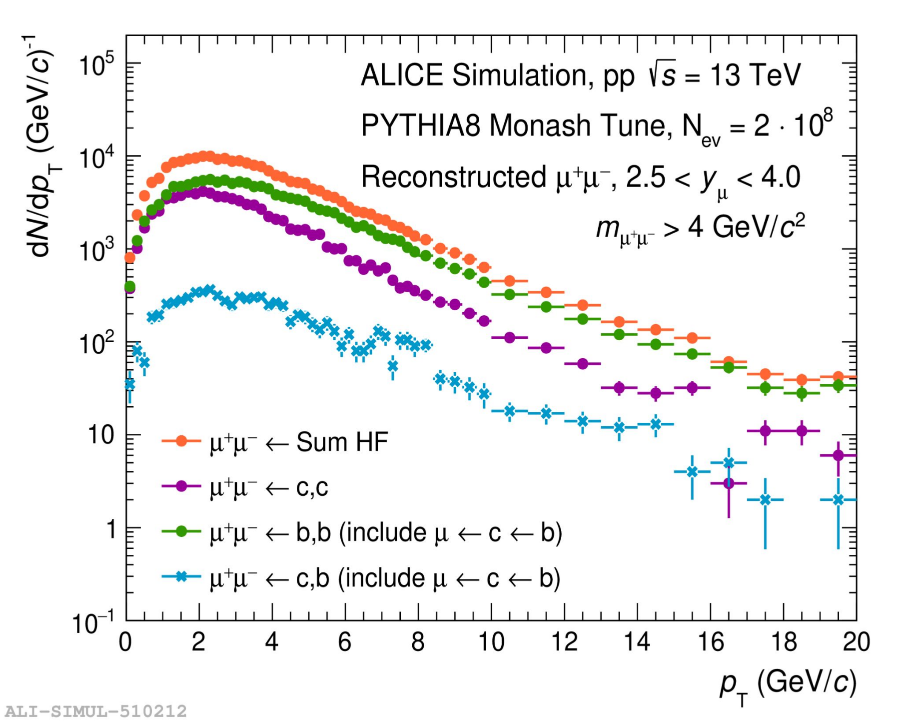
- Different contributions to the dimuon yield above ***$m_{\mu\mu}$* = 4 GeV/*c*²**:
  - ○ **$\mu^+\mu^-$ <- HF** : both μ produced by HF decay
  - ○ **$\mu^+\mu^-$ <- LF** : both μ produced by LF decay
  - ○ **$\mu^+\mu^-$ <- LF,HF** : one μ from HF, the other mu from LF
- The **$\mu^+\mu^-$ <- LF** contribution is negligible
- Almost negligible contribution of the **mixed LF-HF** component, further studies needed to precisely quantify the effect

Investigate the different HF-> $\mu^+\mu^-$ components

- p_T distribution per pp collision of $\mu^+\mu^-$ pairs with m > 4 GeV/c^2, normalized to N_{ev}, taken from HF-enriched PYTHIA8 simulation



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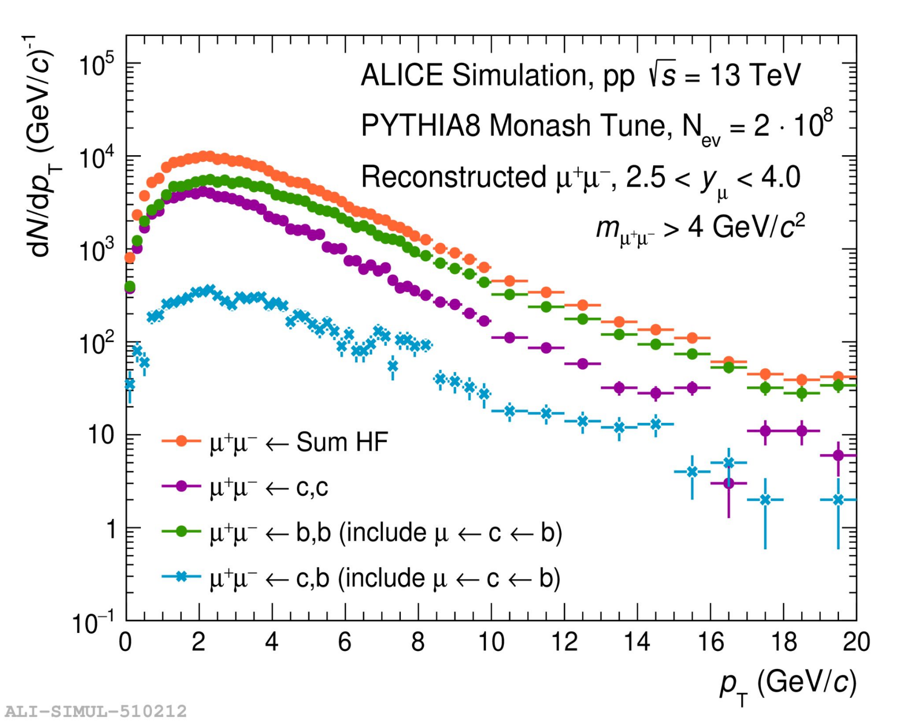

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↪ Different contributions **$\mu^+\mu^-$ <- Sum HF** above $m_{\mu\mu}$= 4 GeV/c^2:

- ↪ **$\mu^+\mu^-$<- 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

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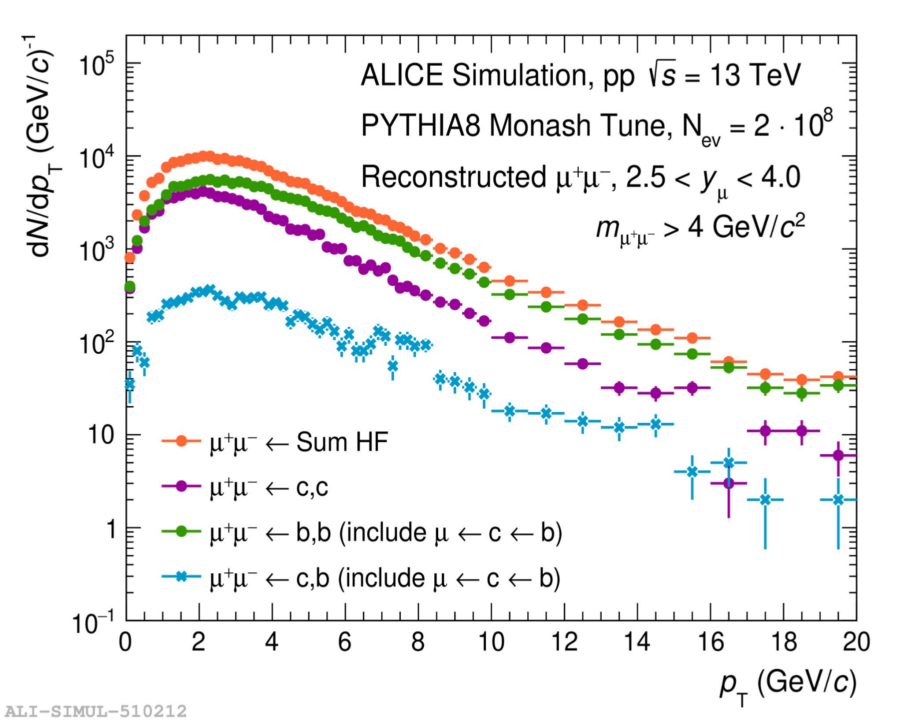

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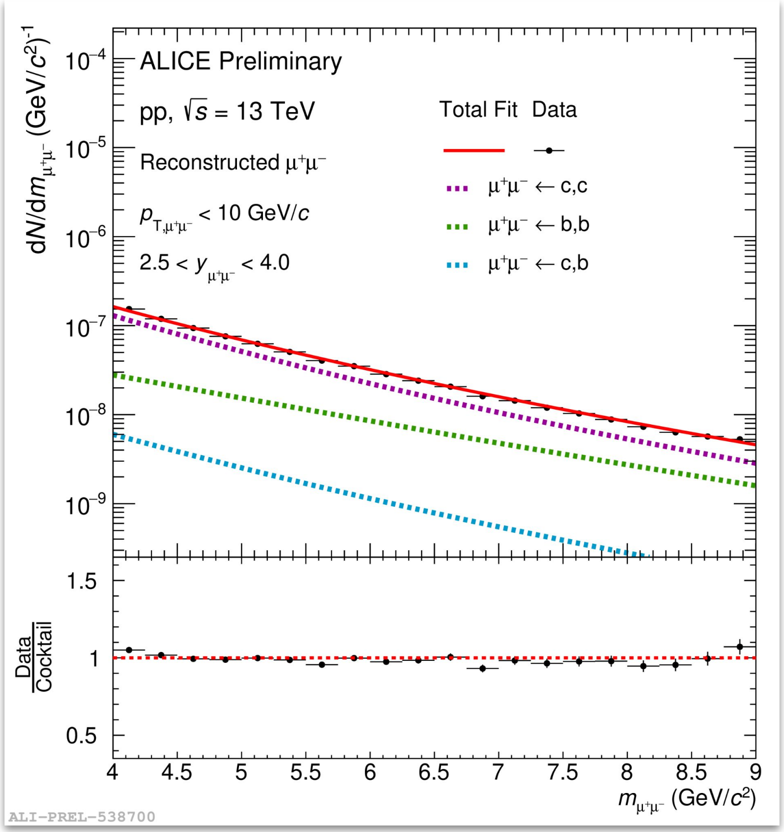
↪ PYTHIA predicts the following weights

$\mu^+\mu^-$ <- c,c	$\mu^+\mu^-$<- b,b	$\mu^+\mu^-$ <- c,b
35.9%	60.5%	3.6%

↪ OS muon pairs mainly produced by beauty particles decays

Estimation of charm and beauty yields from data



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

- Simultaneous unbinned fit to m and p_T data distributions with **cocktail of HF sources** from the HF-enriched PYTHIA8 simulation

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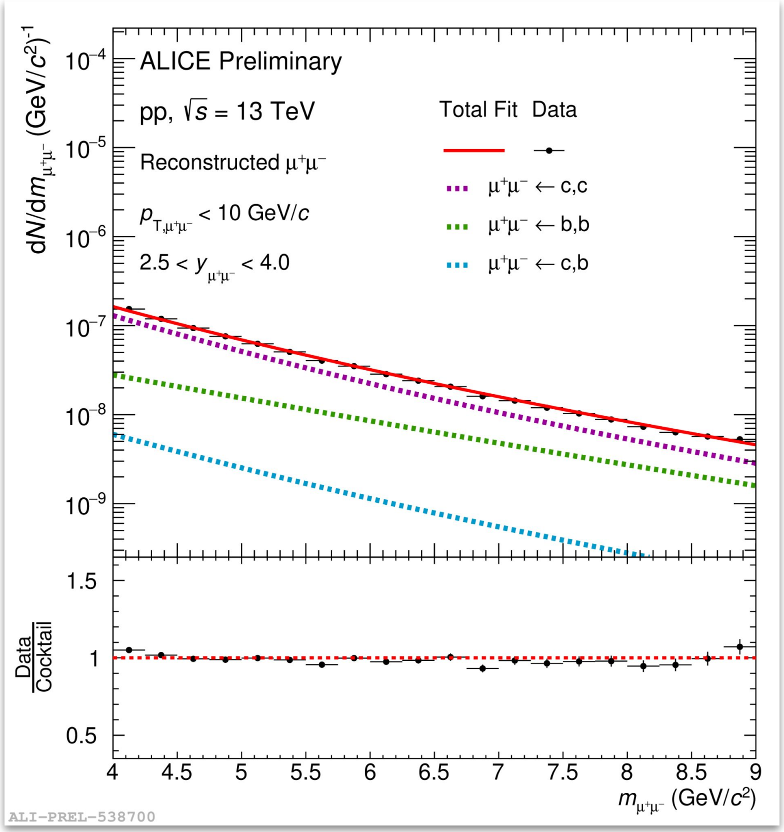

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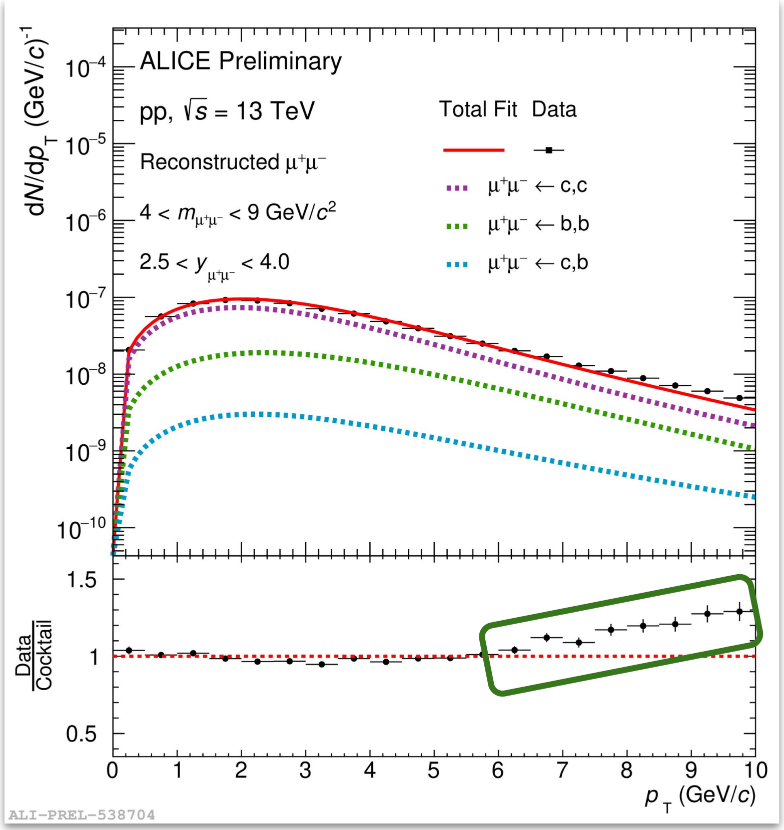
- ➢ Simultaneous unbinned fit to m and p_T data distributions with **cocktail of HF sources** from the HF-enriched PYTHIA8 simulation
- ➢ **Good agreement** between the fit and the data in the mass region studied

Estimation of charm and beauty yields from data



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

- Simultaneous unbinned fit to m and p_T data distributions with **cocktail of HF sources** from the HF-enriched PYTHIA8 simulation
- **Good agreement** between the fit and the data in the *mass* region studied
- **Slight underestimation** at high-p_T ($6 < p_T < 10$ GeV/c) due to a possible contribution from ***Drell-Yan*** (ongoing studies)

Few ingredients for estimating the cross section

How the cross section is computed:

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

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$N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}$ $N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}$ are the **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

Few ingredients for estimating the cross section

How the cross section is computed:

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

$N^{c\bar{c}/b\bar{b}}_{\mu\mu,data}$ $N^{c\bar{c}/b\bar{b}}_{\mu\mu,MC}$ are the **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

$\boxed{d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy}$ are the **charm** and **beauty** quark pair cross sections in PYTHIA simulation, estimated as:

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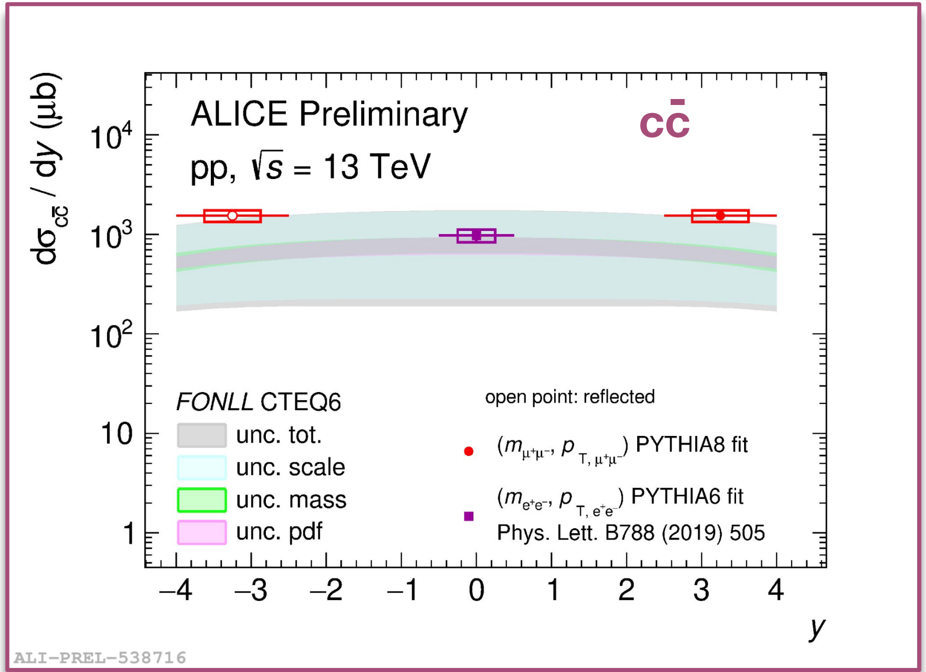
$d\sigma^{c\bar{c}/b\bar{b}}_{MC}/dy$ are the **charm** and **beauty** quark pair cross sections in PYTHIA simulation, estimated as:

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

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

PYTHIA8 cross section of a inelastic pp collision

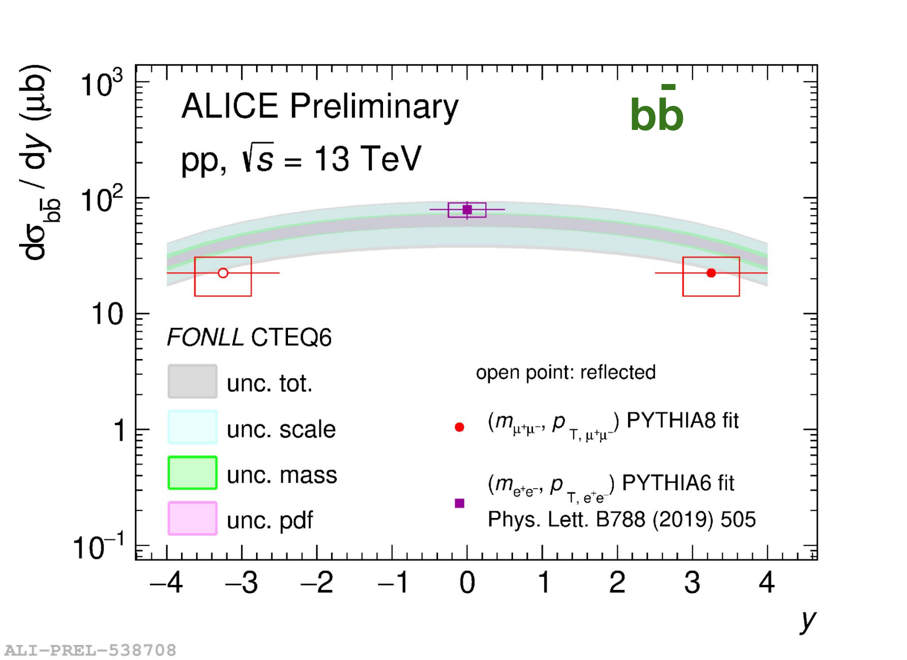
Results



Cross section calculation and preliminary results

➢ First preliminary measurement of **charm** quark pairs cross-section at ***forward rapidity*** compared with previous ALICE measurement at ***midrapidity***

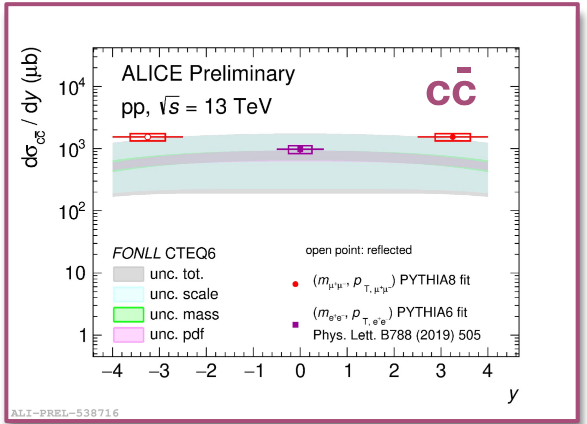
Results

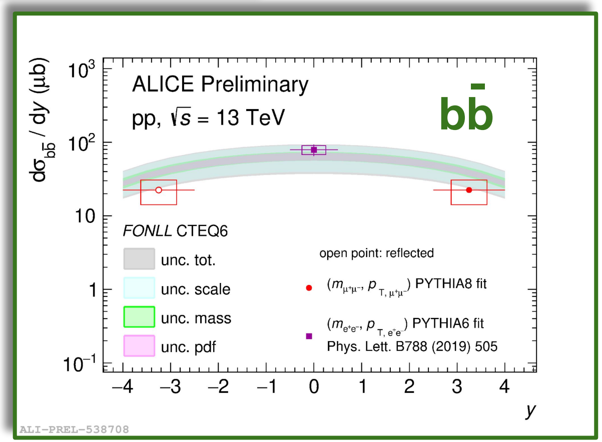


Cross section calculation and preliminary results

- ➢ First preliminary measurement of ***beauty*** quark pairs cross-section at ***forward rapidity*** compared with previous ALICE measurement at ***midrapidity***

Results



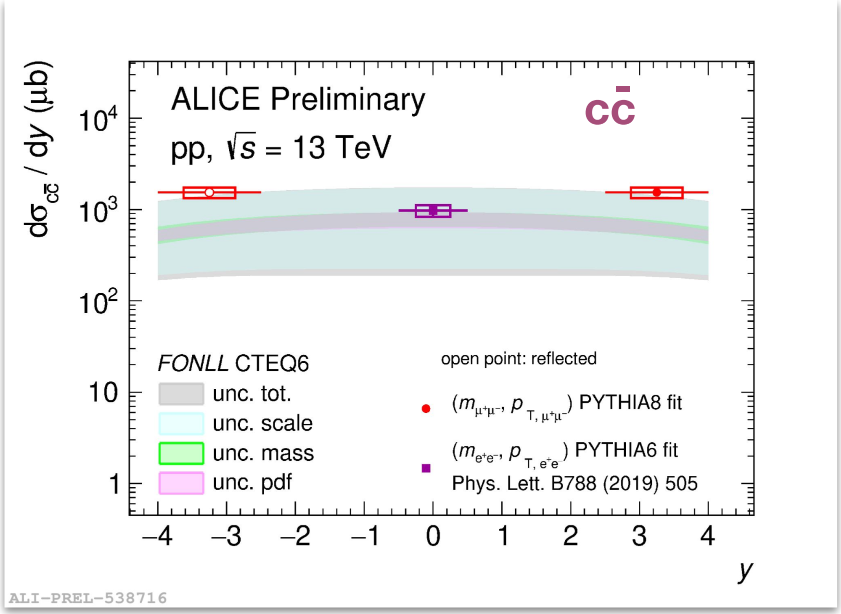


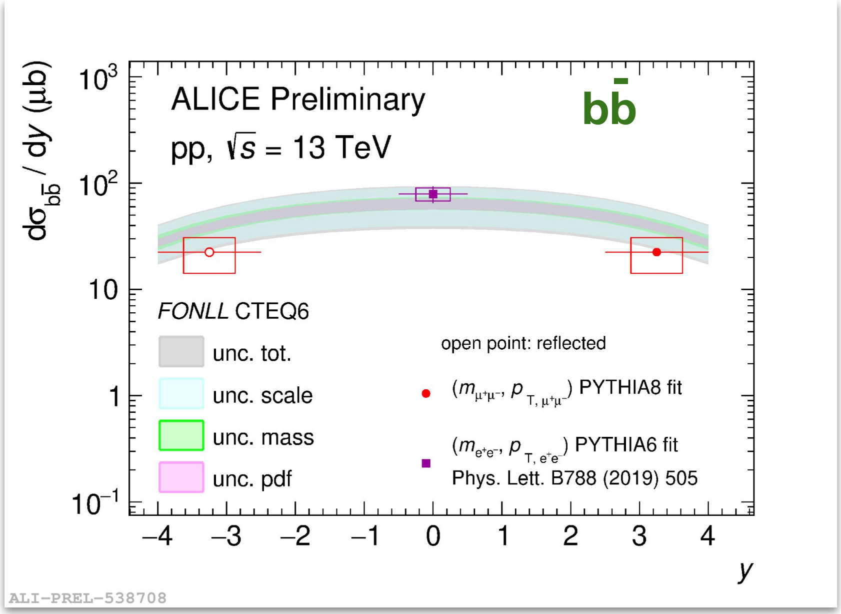
Cross section calculation and preliminary results

- First preliminary measurement of ***charm*** and ***beauty*** quark pairs cross-sections at ***forward rapidity*** compared with previous ALICE measurements at ***midrapidity***
- Both ALICE measurements are in fair agreement with FONLL predictions within uncertainties

Conclusions and outlook

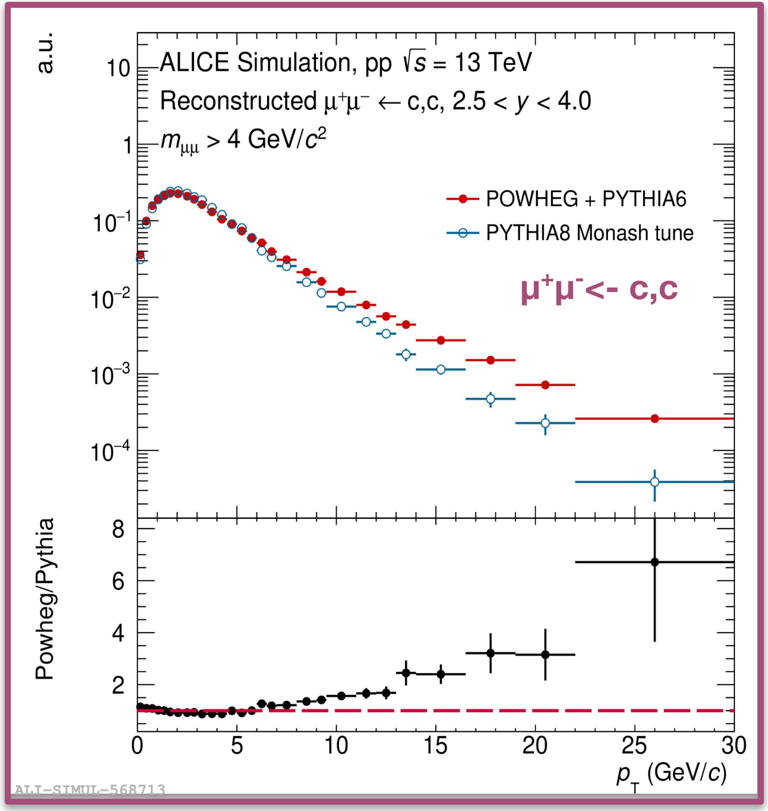
- Studying open heavy-flavor represents a fascinating challenge for theory, allowing to test different regimes of QCD
- ALICE unique experimental set-up provides the possibility of study HF in a broad rapidity interval
- First **charm** and **beauty** quark pairs cross section measurement at forward rapidity at the LHC energies
- Both forward and midrapidity results are in fair agreement with FONLL predictions





What next?

- comparison between **POWHEG** (full circles) and **PYTHIA8** (open circles) p_T shapes for ***charm*** dimuons



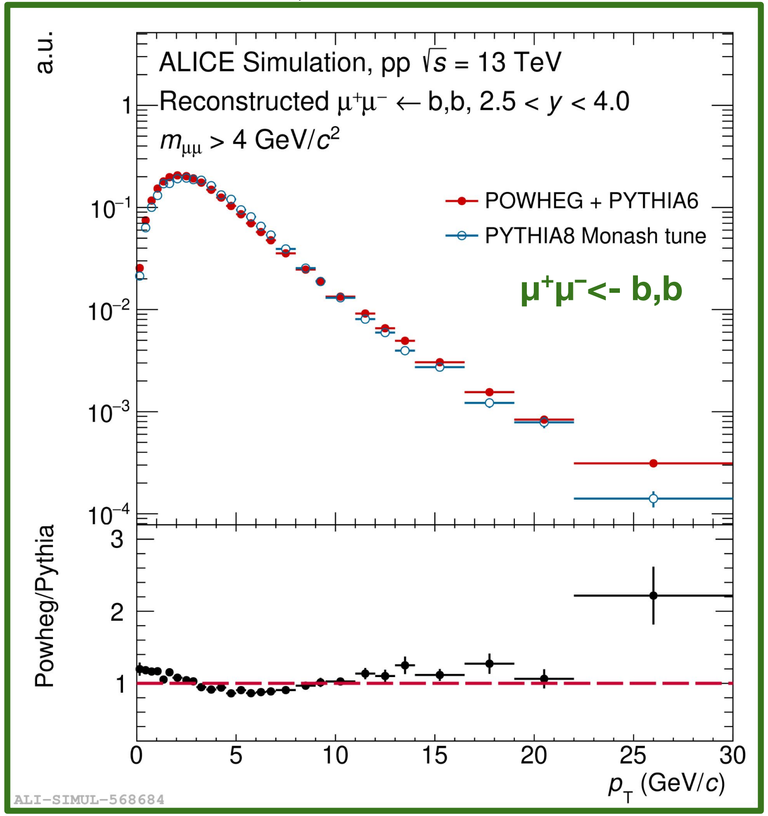
HF-cocktail using a Next-to-Leading-Order (NLO) calculation

- NLO generator such as **Powheg**, paired with parton shower generator (*i.e.* PYTHIA) will be used to build new HF templates
- POWHEG spectra are harder than **PYTHIA8**'s due to the introduction of NLO calculations

Introducing Drell-Yan contributions

What next?

- comparison between **POWHEG** (full circles) and **PYTHIA8** (open circles) p_T shapes for ***beauty*** dimuons



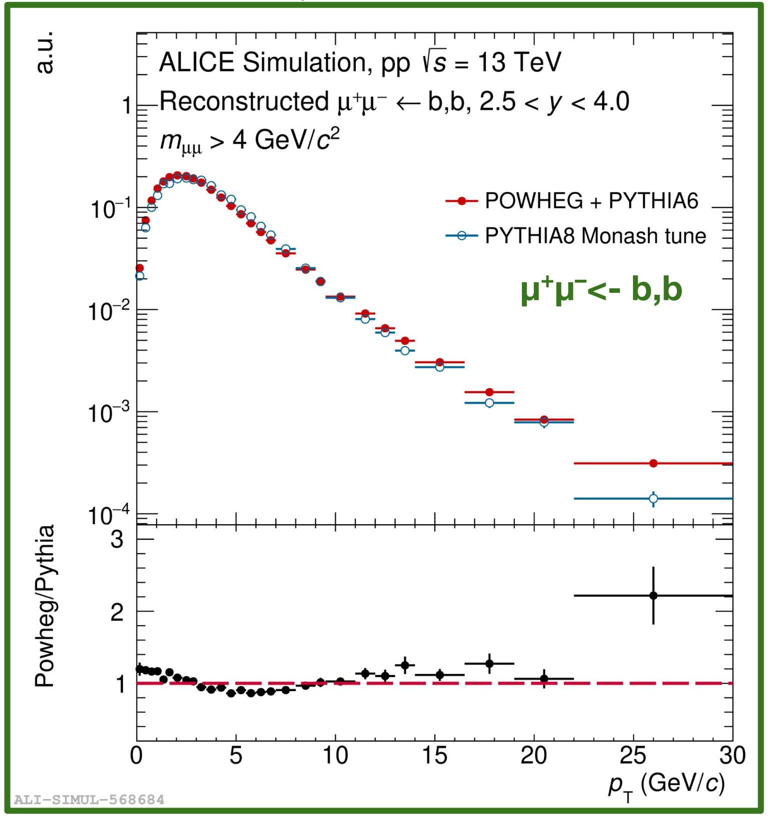
HF-cocktail using a Next-to-Leading-Order (NLO) calculation

- NLO generator such as **Powheg**, paired with parton shower generator (*i.e.* PYTHIA) will be used to build new HF templates
- POWHEG spectra are harder than **PYTHIA8**'s due to the introduction of NLO calculations (the effect is *weaker* for **beauty**)

Introducing Drell-Yan contributions

What next?

◺ comparison between POWHEG (full circles) and PYTHIA8 (open circles) p_T shapes for ***charm*** dimuons



HF-cocktail using a Next-to-Leading-Order (NLO) calculation

Introducing Drell-Yan contributions

- ➢ The contribution of Drell-Yan is currently investigated
- ➢ Preliminary studies at generator level using PYTHIA8 with Monash tune show promising possibilities of measuring DY cross-section by searching above m = 20 GeV/c^2
- ➢ Add the DY contribution to the POWHEG template

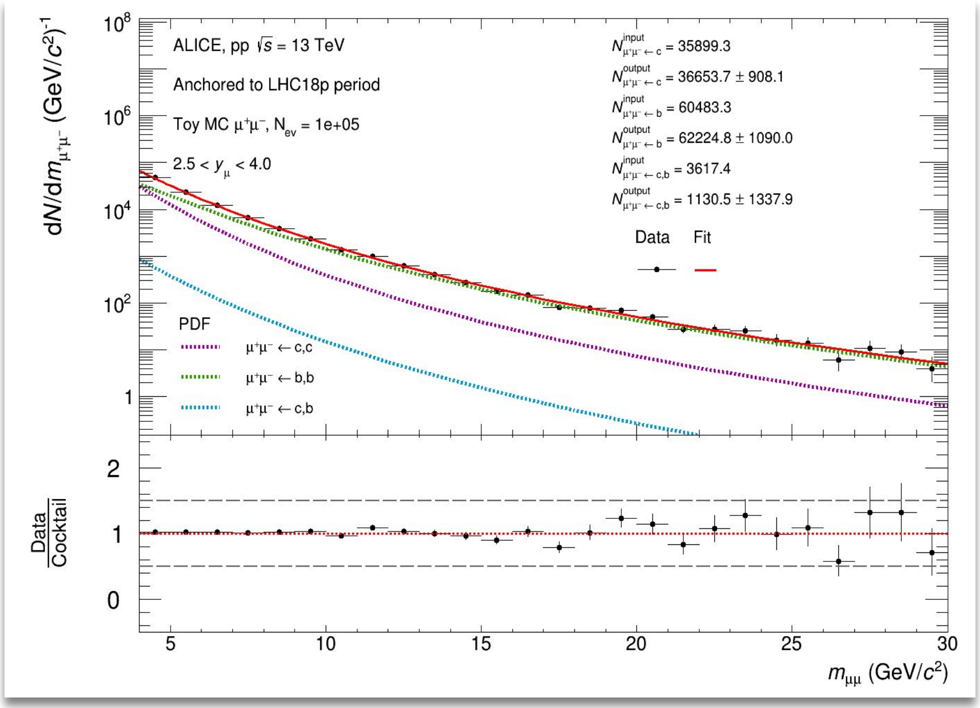
DY cross section has never been measured at forward rapidity at LHC energies!

Additional Material

Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI TORINO

Analysis steps: cocktail closure test



- Closure test with a toy MC
  - verify the goodness of the extraction procedure
  - test the fit procedure foreseen for real data

- Procedure:
  - ToyMC created with 100k dimuons using the fraction from PYTHIA HF enriched simulation
  - Unbinned fit (p_t and m simultaneously) to the TOY with the three shapes from MC (as done for data)
  - Useful to check the goodness of the pdf extraction and fit procedure foreseen for real data

The number of charm and beauty dimuons obtained as the output of the fit compatible with the input given within the uncertainty

Systematic uncertainties

- The following systematic uncertainties have been evaluated:

	uncertainty on N° $\mu\mu$ <- c,c	uncertainty on N° $\mu\mu$ <- b,b
signal extraction	9%	28%
HF mixed fraction	0.7%	5.4%
trigger response	0.06%	0.04%
pythia tune (mode2)	8.7%	23%

	Common uncertainties
f_{Norm}	2.9%
MCH efficiency	2%
MTR efficiency	2%
Matching efficiency	1%

Signal extraction systematic: some details

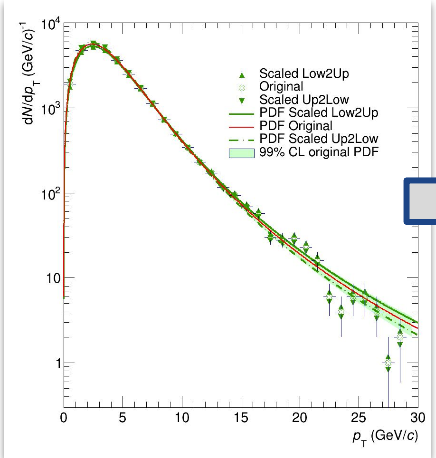
- ***Idea***: modification the beauty and charm distributions to see the impact on the fit result
- ***How***:
  - generate a linear deviation contained in the 99% CL band of the PDF extraction fit
  - weight the MC distributions with the 2 linear deviations and extract 2 new sets of PDF
- ***Simultaneous unbinned fit in p_t and m with the 2 sets of modified PDFs***
  (HF-mixed component PDF kept fixed to the original)

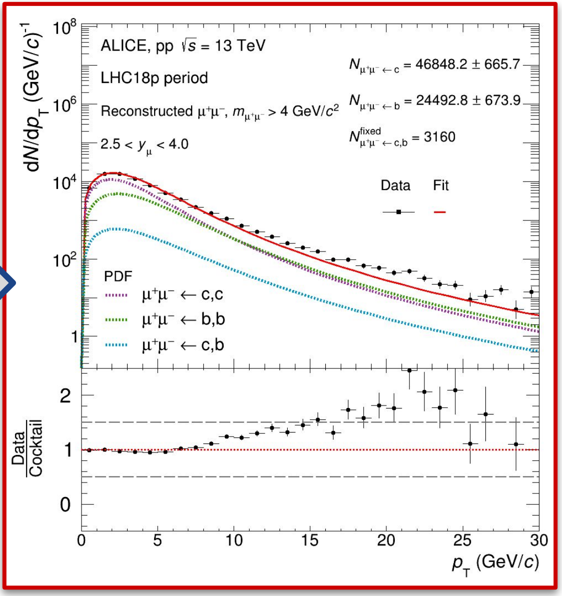
Up2Low

- → Variation on charm yield: 10.1%
- → Variation on beauty yield: 27.1%

Low2Up

- → Variation on charm yield: 10.9%
- → Variation on beauty yield: 30.1%





****for m distribution and charm see in the back-up***

Signal extraction systematic: some details

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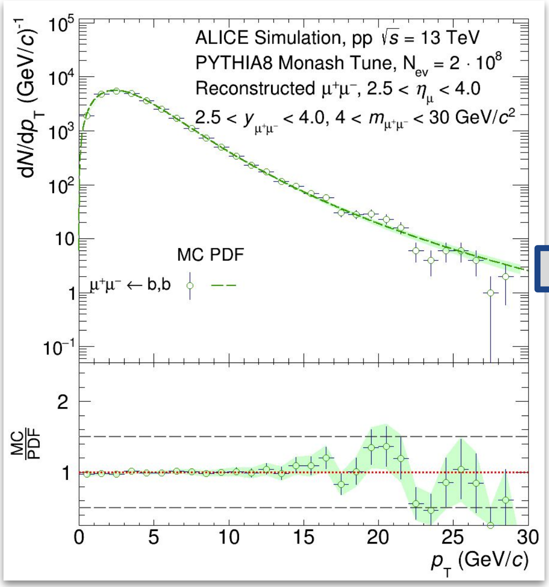

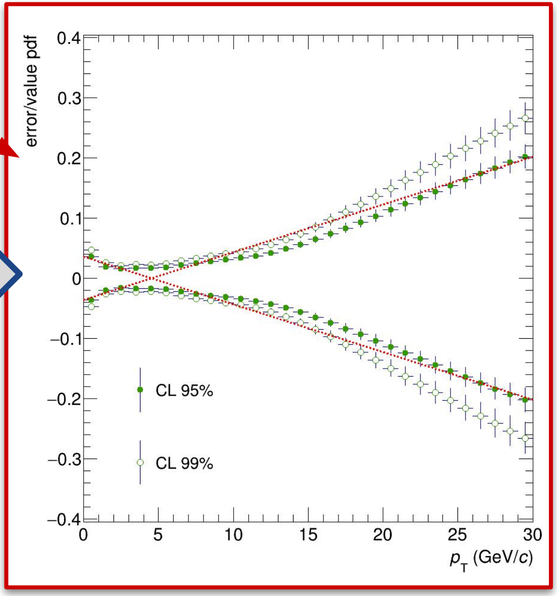

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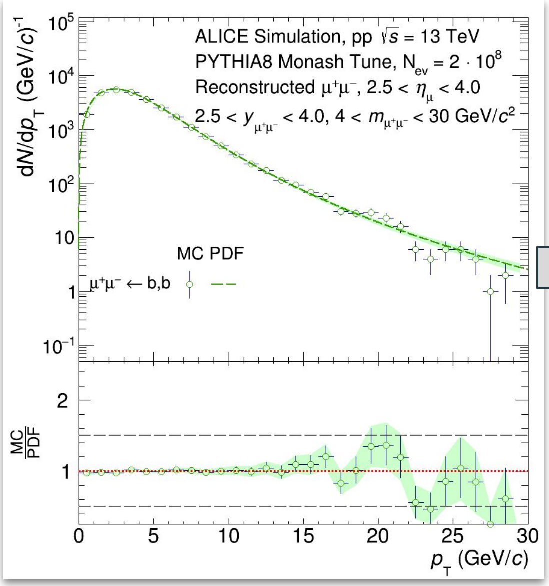
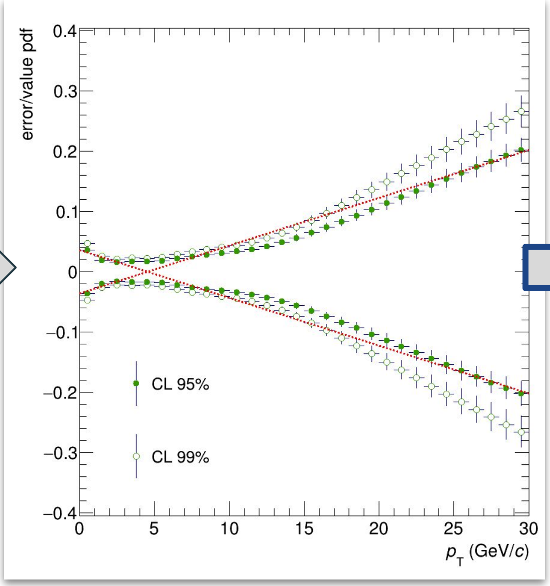
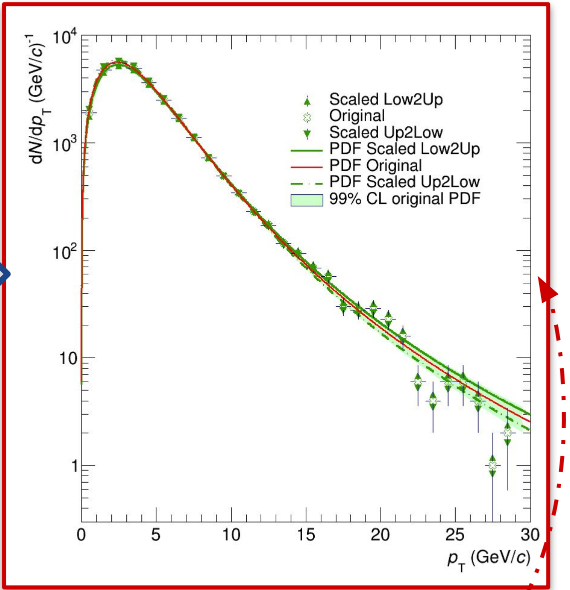




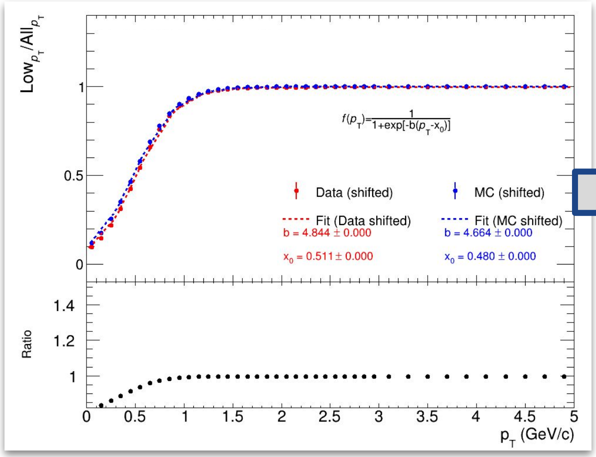


****for m distribution and charm see in the back-up***

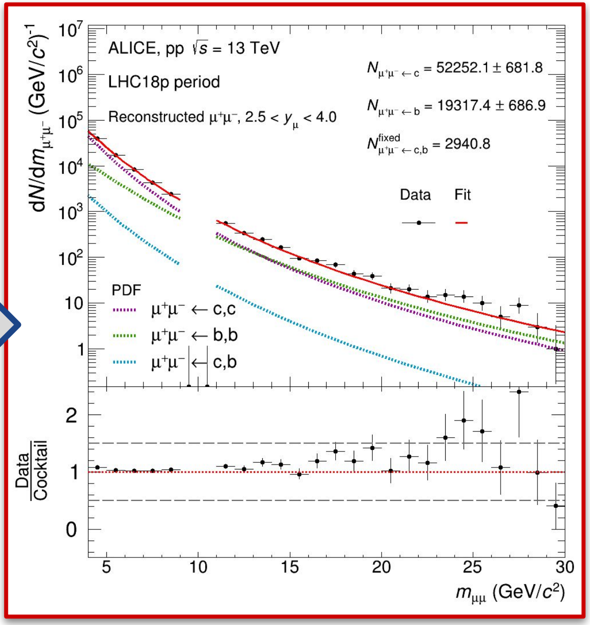
- ➢ weight the MC distributions with the 2 linear deviations and extract 2 new sets of PDF

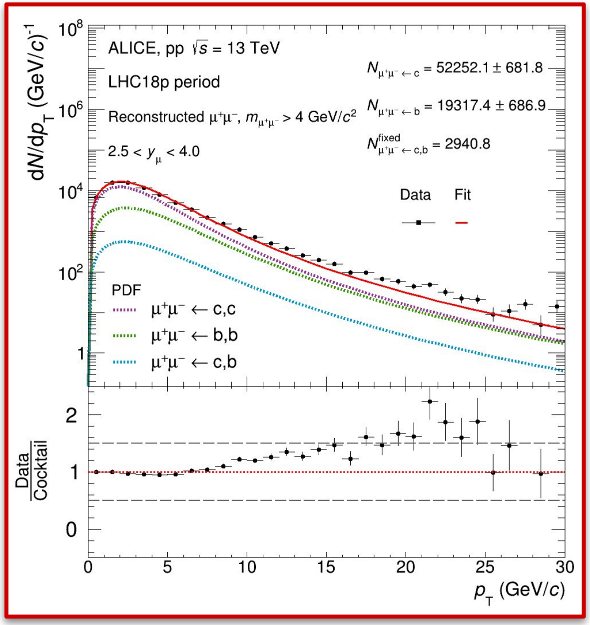
Trigger efficiency systematic: some details

- ❖ ***Procedure***: weight beauty and charm distributions with product of single muons efficiency



→ the new weighted mass and pt dimuon distributions used to re-evaluate the charm and beauty yields





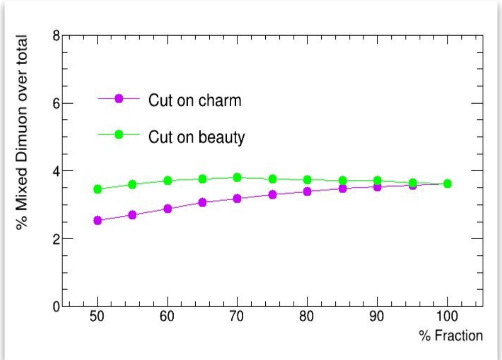
****single muon efficiency studied in 5 eta bins***
****LHC18p low-pt =1 GeV/c***
see in the back-up for more details

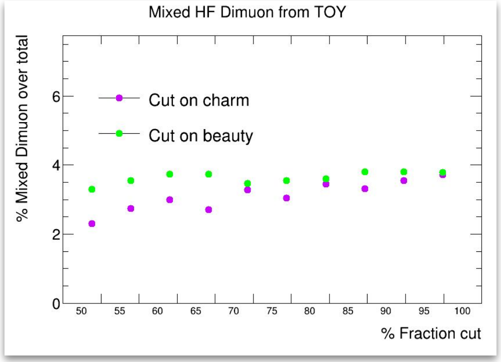
→ Variation on charm yield: 0.06%

→ Variation on beauty yield: 0.04%

HF mixed systematic: some details

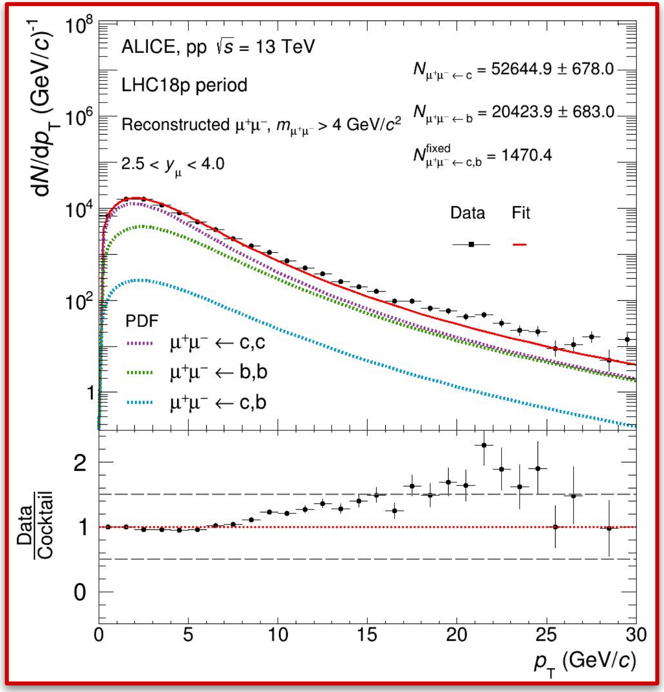
- ***Idea***: HF-mixed component is purely combinatorial
  Creation of only-statistical toy-MC, not containing any information about the physics
- ***How*** : Varying the fraction of charm/beauty muons the % of HF mixed over total changes between 2 and 4% in the toy and in the MC either
- ***Then*** : normalization of HF mixed can be kept fixed when fitting the data





- ***Systematic*** : charm and beauty yield obtained using different values of HF-mixed fraction

HF-mixed at 2%



→ Variation on charm yield: 0.7%

→ Variation on beauty yield: 5.4%

DY cross section: CMS measurement

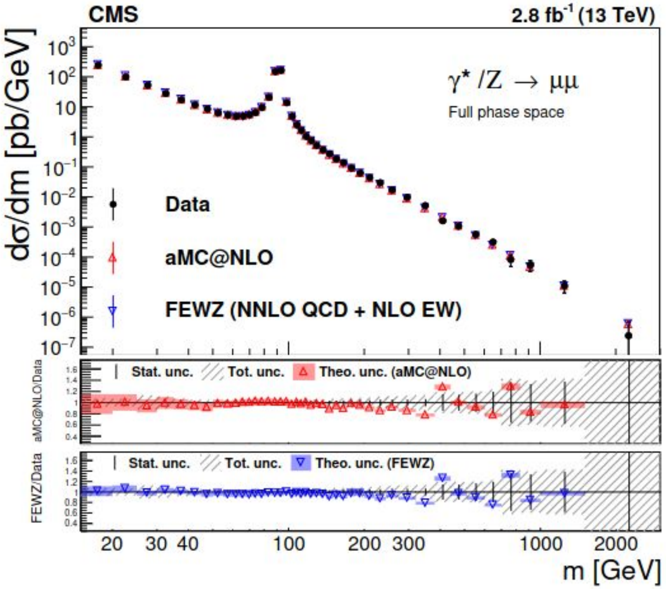
[Measurement of the differential Drell-Yan cross section in proton-proton collisions at √s= 13 TeV with CMS]

Table 3: Summary of the measured values of $d\sigma/dm$ (pb/GeV) in the dimuon channel with the statistical (δ_{stat}), experimental (δ_{exp}) and theoretical (δ_{theo}) uncertainties, respectively. Here, δ_{tot} is the quadratic sum of the three components.

m(GeV)	$\frac{d\sigma}{dm}$ (pb/GeV)	δ_{stat}	δ_{exp}	δ_{theo}	δ_{tot}
15–20	2.5×10^2	2.4×10^0	1.1×10^1	1.4×10^1	1.8×10^1

$\sigma_{DY\rightarrow\mu\mu}$ (15<m< 20 GeV) = 0.25 x 5 = 1.25 nb

→ to be compared with 0.99 nb from PYTHIA



Ingredients for estimating the cross section

- How the cross section is computed:

$$\frac{N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}}{N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ PYTHIA}} = \frac{d\sigma^{meas}_{c\bar{c}/b\bar{b}}/dy}{d\sigma^{PYTHIA}_{c\bar{c}/b\bar{b}}/dy} \Rightarrow d\sigma^{meas}_{c\bar{c}/b\bar{b}}/dy = \frac{N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}}{N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ PYTHIA}} \times d\sigma^{PYTHIA}_{c\bar{c}/b\bar{b}}/dy$$

$N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}$ → Is the **charm**/**beauty** yield extracted from the fit, normalized to number of equivalent minimum bias events

$N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ data}$ → Is the number of **charm**/**beauty** dimuons in HF-enriched MC, normalized to the number of equivalent MB events in the simulation

- These two quantities have been calculated by using:

$$\begin{cases} N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data} \Rightarrow \dfrac{N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu}}{N^{MB\ data}_{ev}} \quad with\ \ N^{MB\ data}_{ev} = N^{CMUL}_{ev} \times f_{norm} \\ N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ data} \Rightarrow \dfrac{N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu}}{N^{MB\ PYTHIA}_{ev}} \quad with\ \ N^{MB\ PYTHIA}_{ev} = N^{Sim}_{ev} \times Pythia_{eq} \end{cases}$$

Cross section ingredients

- How the cross section is computed:

$$\frac{N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}}{N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ PYTHIA}} = \frac{d\sigma^{meas}_{c\bar{c}/b\bar{b}}/dy}{d\sigma^{PYTHIA}_{c\bar{c}/b\bar{b}}/dy} \Rightarrow d\sigma^{meas}_{c\bar{c}/b\bar{b}}/dy = \frac{N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}}{N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ PYTHIA}} \times d\sigma^{PYTHIA}_{c\bar{c}/b\bar{b}}/dy$$

$N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu\ ,\ MB\ data}$ → Is the charm and beauty yield extracted from the fit, normalized to number of equivalent minimum bias events

$N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu\ ,\ MB\ data}$ → Is the number of charm and beauty dimuons in HF-enriched MC, normalized to the bumber of equivalent MB events in the simulation

- Obtaining:

	$N^{c\bar{c}/b\bar{b}\ PYTHIA}_{\mu\mu}$	$N^{c\bar{c}/b\bar{b}\ fit}_{\mu\mu}$	$d\sigma^{meas}_{c\bar{c}/b\bar{b}}/dy_{\ 2.5<y<4}$
charm	1.682e+04	5.228e+04 ± 0.068e+04(stat.)	1.55 ± 0.02 (stat.) ± 0.17(syst.) mb
beauty	2.836e+04	1.928e+04 ± 0.068e+04(stat.)	24.6 ± 0.9(stat.) ± 7.5(syst.) μb