CMS MEASUREMENT OF PROMPT OPEN CHARM PRODUCTION CROSS SECTIONS IN P-P COLLISIONS AT 13 TEV

FPCP2020: Conference on Flavour Physics and CP violation

Valentina Mariani for the CMS Collaboration
vmariani@cern.ch

Why is charm so charming?

Charm **decays** are particularly interesting:

-> c quark can only decay weakly, mediated by a W, in a strange or down quark

$$\bar{D}^0 \to K^+ + \pi^-$$

$$\bar{c}u \to u\bar{s} + \bar{u}d$$

weak interaction W^{*-}

$$\bar{D}^+ \to K^- + \pi^+ + \pi^+$$

$$c\bar{d} \to \bar{u}s + u\bar{d} + u\bar{d}$$

weak interaction W^{*+}

Open-charm particles are the only ones that allow to study the weak decay of an up-type quark in a bound state.

Charm is the third heaviest quark (m_c=1.3 GeV) -> theoretical predictions are hard in term of approximation but it **provides important insights into QCD from a different perspective**

Exited states of charmonium and open-charm particles are an excellent lab for the study of QCD

FROM AN EXPERIMENTAL POINT OF VIEW

Most of the charm results come from the **e^+e^- colliders** (discovery, mixing..)

- Clear initial state -> clean final state
  - Precision measurements
  - If asymmetric beams also time dependent measurement are accessible
  - But…the production cross section are rather small

FROM AN EXPERIMENTAL POINT OF VIEW

Most of the charm results come from the **e^+e^- colliders** (discovery, mixing..)

- Clear initial state -> clean final state
  - Precision measurements
  - If asymmetric beams also time dependent measurement are accessible
  - But…the production cross section are rather small

In the **hadronic colliders** LHCb is the ideal experiment to perform flavour physics -> charm is mostly produced in asymmetric collisions with a boost

- The cross section is ~6 order of magnitude larger than at e^+e^-
- We pay the price of having a complex initial state and high luminosity (PU)

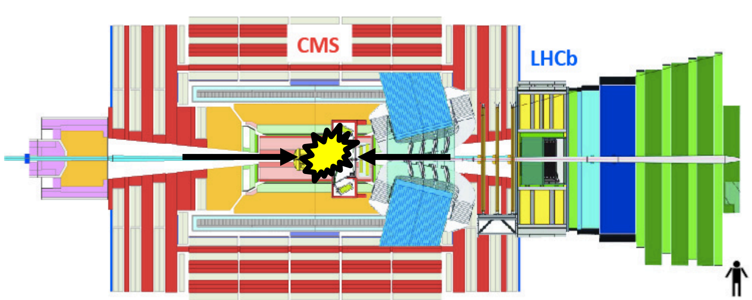
Most of the charm results come from the **e^+e^- colliders** (discovery, mixing..)

- Clear initial state -> clean final state
  - Precision measurements
  - If asymmetric beams also time dependent measurement are accessible
  - But…the production cross section are rather small

In the **hadronic colliders** LHCb is the ideal experiment to perform flavour physics -> charm is mostly produced in asymmetric collisions with a boost

- The cross section is ~6 order of magnitude larger than e^+e^-
- We pay the price of having a complex initial state and high luminosity (PU)

In addition…



Doing charm physics in CMS is more challenging => **this is the first result on charm production produced so far by CMS in pp collisions!**
Having a complementary acceptance w.r.t. LHCb can provide interesting results on how the cross section evolves with the kinematic

CMS-PAS-BPH-18-003

We considered the states:

- D^{*+}-> $D0\pi^+_{slow}$->$K^-\pi^+\pi^+_{slow}$
- D^0 -> $K^-\pi^+$
- D^+ -> $K^-\pi^+\pi^+$

+ c.c.

Production and decay chain	Branching fraction
$pp \to D^{*+}X \to D^0\pi^+_{slow}X \to K^-\pi^+\pi^+_{slow}X$	$BR = (2.67 \pm 0.03)\%$
$pp \to D^0X \to K^-\pi^+X$	$BR = (3.95 \pm 0.03)\%$
$pp \to D^+X \to K^-\pi^+\pi^+X$	$BR = (9.38 \pm 0.16)\%$

- Analysed data: pp collisions at $\sqrt{s}$ = 13 TeV collected in 2016
- Phase space: 4 < pT < 100 GeV && $|\eta|$ < 2.1
- ZeroBias trigger applied (the most inclusive one)

- **Differential cross section measurement in pt and $|\eta|$ bins:**

$$\frac{d\sigma(pp \to DX)}{dp_T} = \frac{N_i(D \to f)}{\Delta p_T \mathcal{B}(D \to f)\mathcal{L}\varepsilon_{i,tot}(D \to f)}$$

Signal yield bin by bin evaluated on data

Bin width

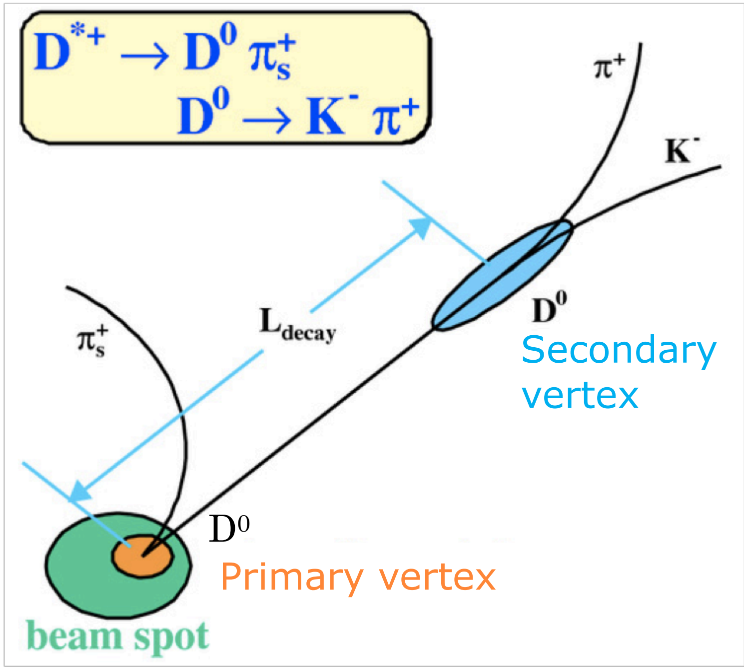
Branching ratio

Integrated luminosity

Total reconstruction efficiency bin by bin evaluated on MC

RECONSTRUCTION STRATEGY

- “prompt” produced mesons=> around the interaction point
- D^0 decay lenght: $c\tau \approx 10^{-4}$m
- Decay vertex of D^0 != generation vertex of D^0

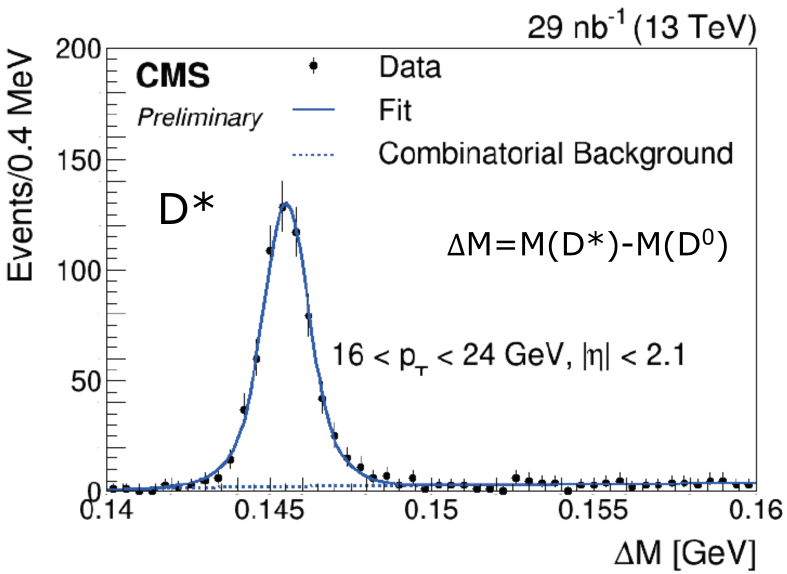


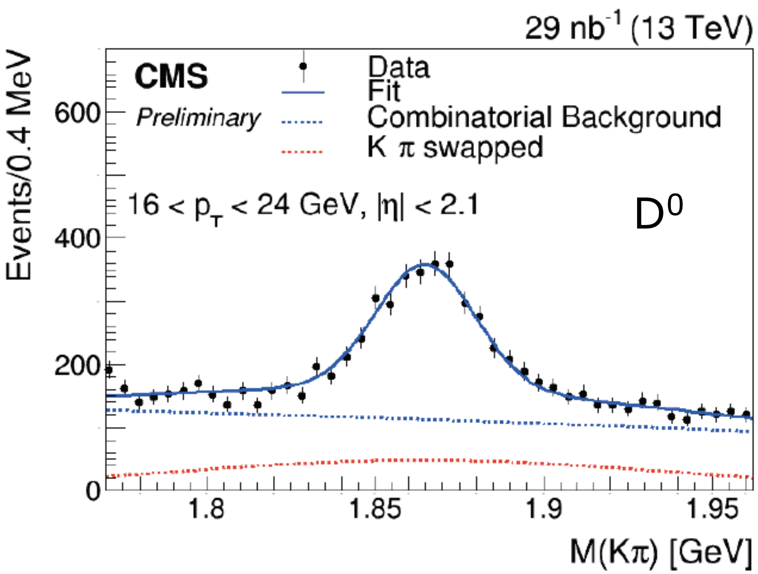
Selection applied:

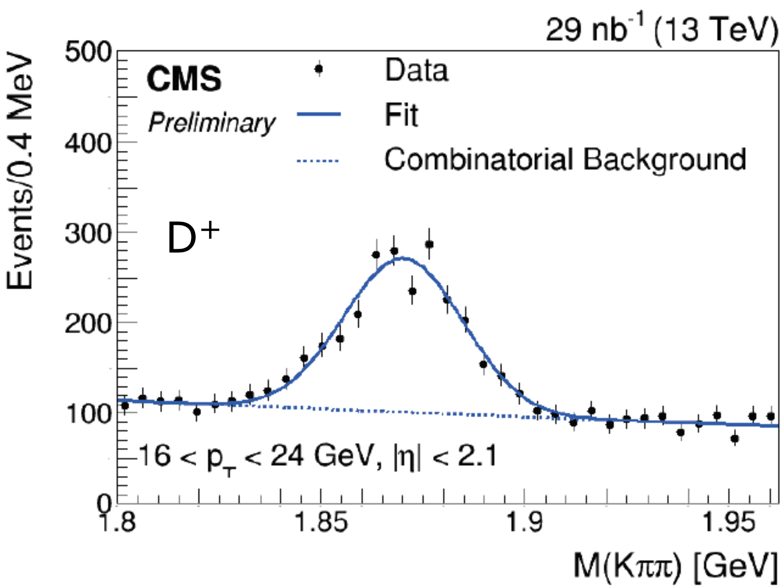
- Look for “high quality” tracks -> no PID in CMS
- Secondary reconstructed vertex with CL > 1%
- Parallel direction of the meson w.r.t. the PV-SV distance
- Cuts on the decay lenght

Details in backup

MESONS RECONSTRUCTION





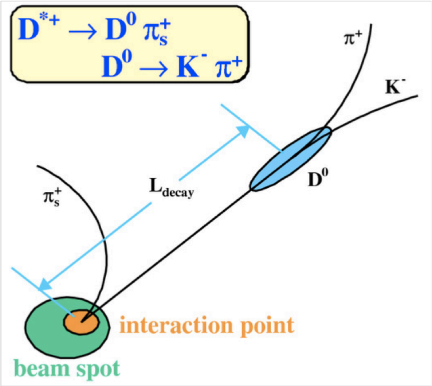


Signal component described by the sum of two gaussians with the same mean
Bkg component described by a 3-degree polynomial for D0 and D+ and a threshold function for the D*:

$$f = \left(1 - e^{-\frac{\Delta M - m_0}{p_0}}\right)\left(\frac{\Delta M}{m_0}\right)^{p_1} + p_2\left(\frac{\Delta M}{m_0} - 1\right)$$

CONTRIBUTION FROM SECONDARY DECAY

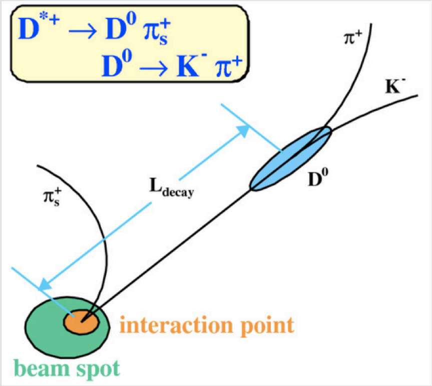
The aim of the analysis is to measure the prompt open-charm production cross section
-> prompt = coming from PV or charm excited states



Possible contamination: charm mesons coming from B meson decays

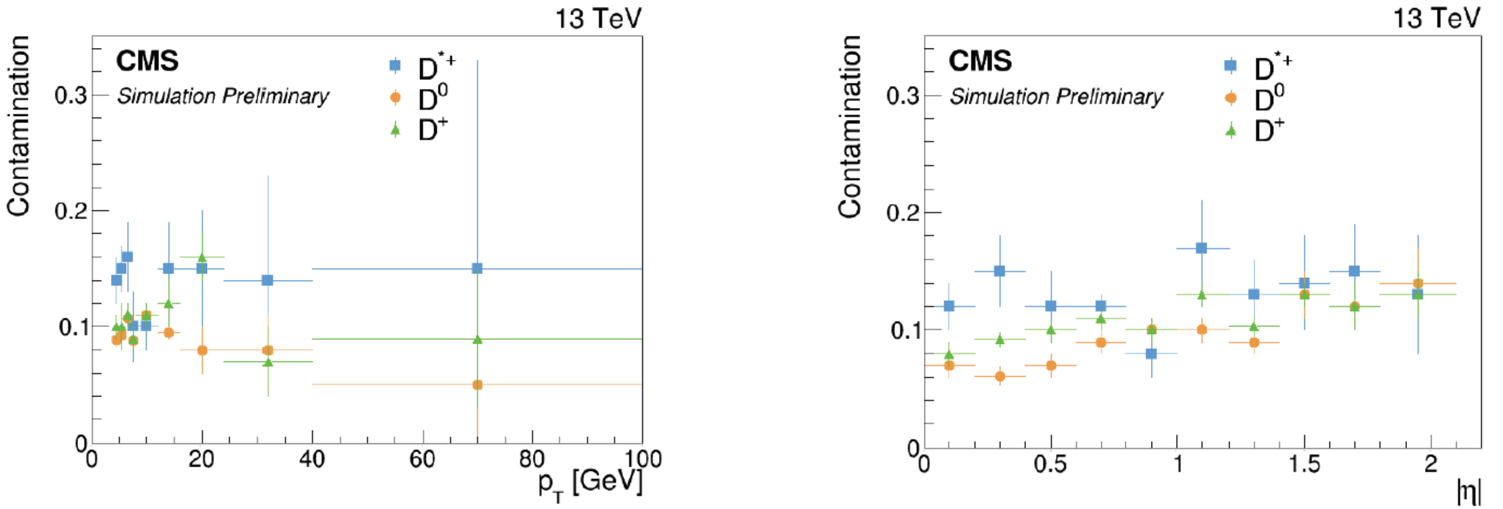
Contribution evaluated on MC as: $\boxed{contam = \frac{N_{sec}}{N_{prompt}+N_{sec}}}$

The aim of the analysis is to measure the prompt open-charm production cross section
-> prompt = coming from PV or charm excited states



Possible contamination: charm mesons coming from B meson decays

Contribution evaluated on MC as: $\boxed{contam = \frac{N_{sec}}{N_{prompt}+N_{sec}}}$



These values are subtracted bin by bin from the "visible" cross section

Systematic uncertainties

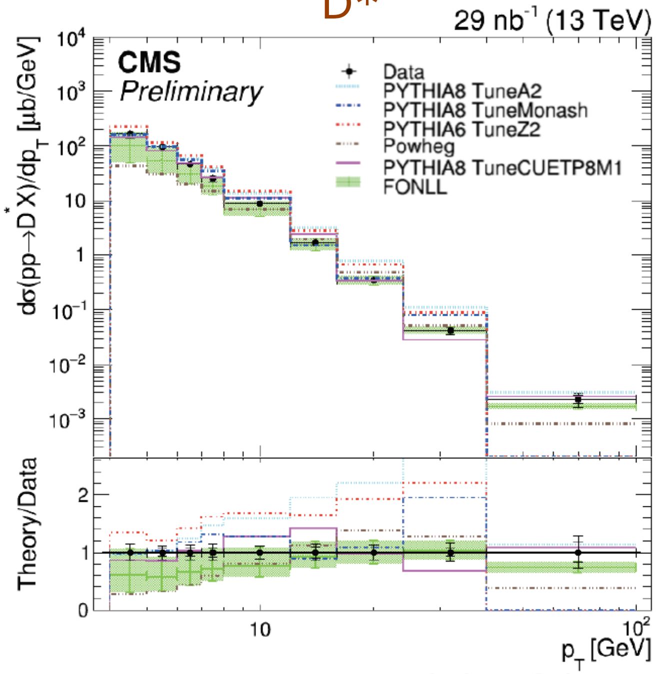
	Relative uncertainties (%)		
	D^{*+}	D^0	D^+
Signal efficiency calculation	0.3	0.3	3.5
Secondary decay contamination	2.9	0.8	1.4
PU reweighting	1.0	1.0	2.0
Branching fraction	1.1	0.8	1.7
Tracking efficiency	9.4	4.2	6.1
Signal modeling	3.6	5.0	4.2
Background modeling	1.2	4.8	8.0
Luminosity	2.5	2.5	2.5
Data taking instability	1.4	1.4	1.4
Total	11.0	8.7	12.2

The dominant ones are:
- Tracking efficiency
- Signal / bkg modelling

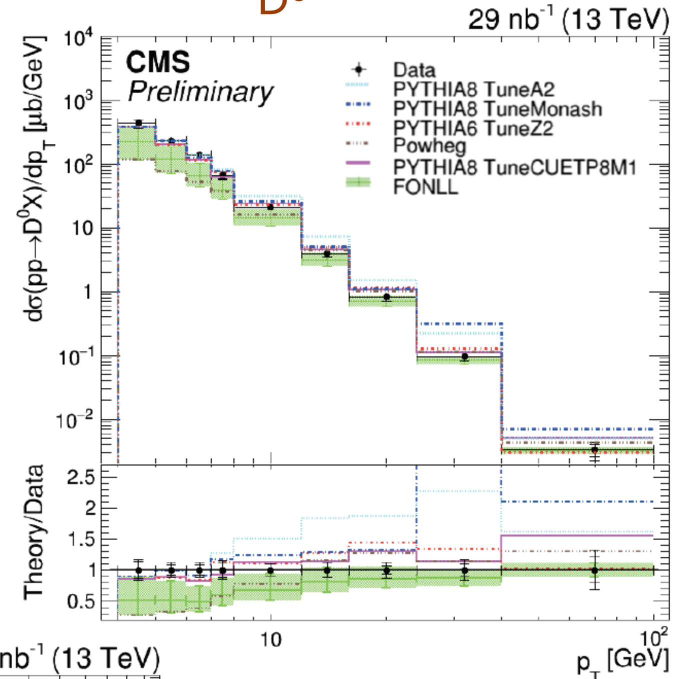
Data taking instability -> due to tracker inefficiency during the 2016 data taking

RESULTS

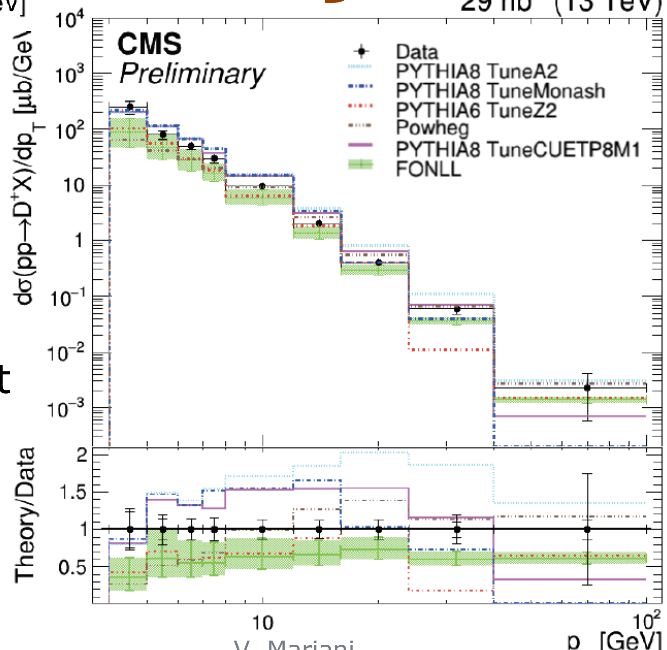
D*



D^0



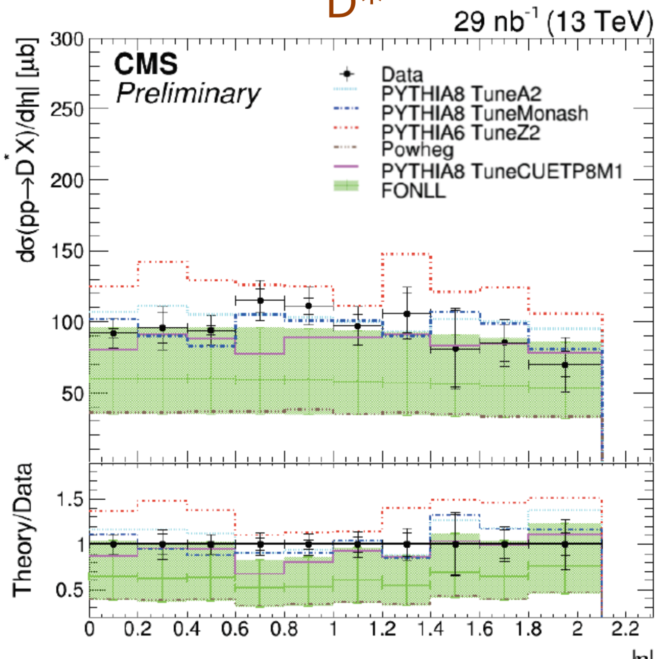
D$^+$



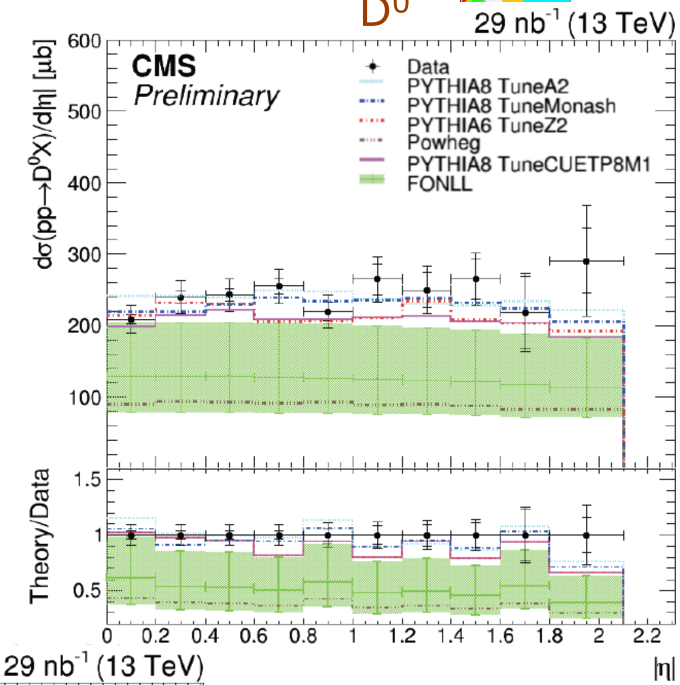
Data are compared to different MC and FONLL predictions (fixed-order next-to-leading-logarithm)

RESULTS

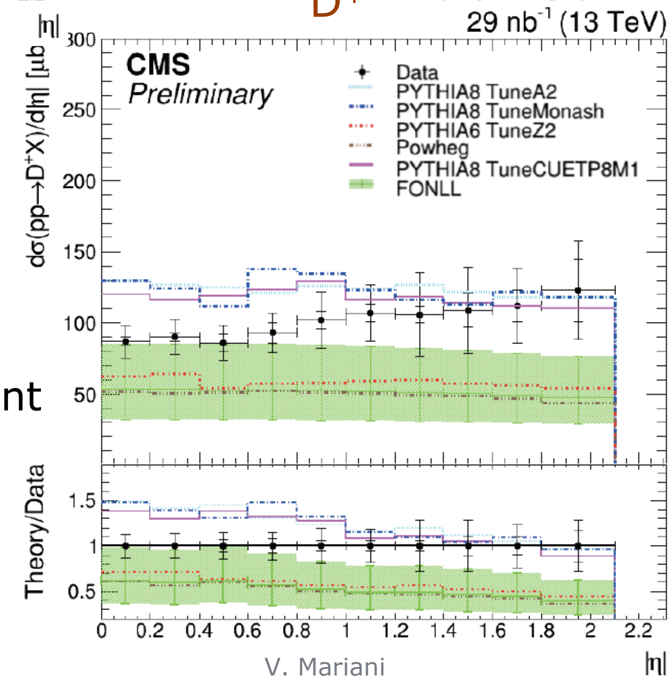
D*



D^0



D$^+$



Data are compared to different MC and FONLL predictions (fixed-order next-to-leading-logarithm)

Comparison with the previous results

- We compared our data with the previous results obtains within the LHC collaborations

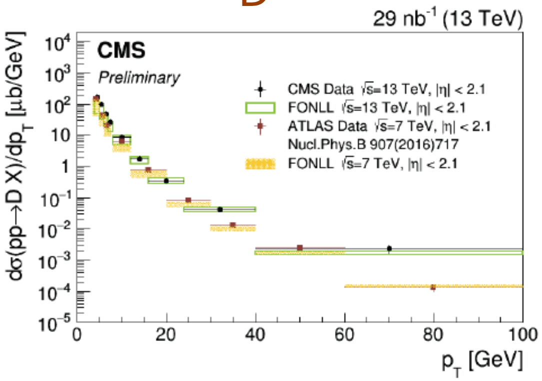
- We study how the cross section evolves with the center of mass energy and w.r.t. the different kinematic region analysed

- We used the **FONLL predictions** for this comparison
  - NLO + fragmentation fraction
  - FONLL calculations are developed to obtain stable and reliable predictions in the conditions $p_{T,Q} \approx m_Q$

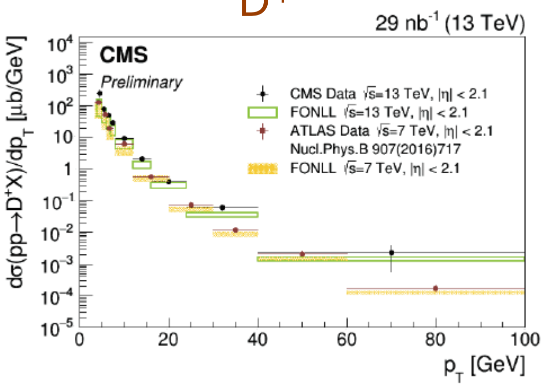
COMPARISON WITH MEASUREMENTS DONE AT 7 TEV

- ATLAS

D*



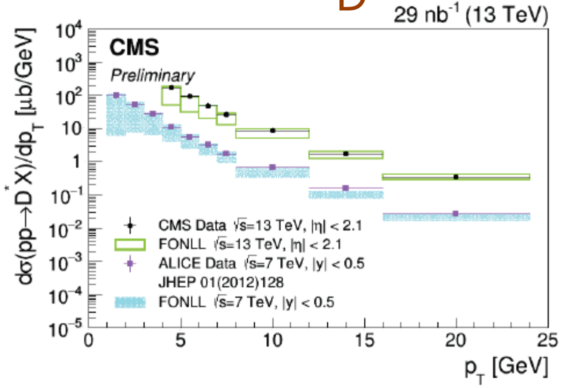
D+



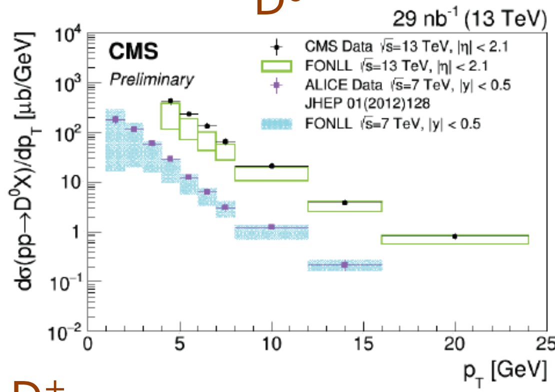
Same kinematic range but different binning
We can directly see how the cross section scales with the center of mass energy

- ALICE

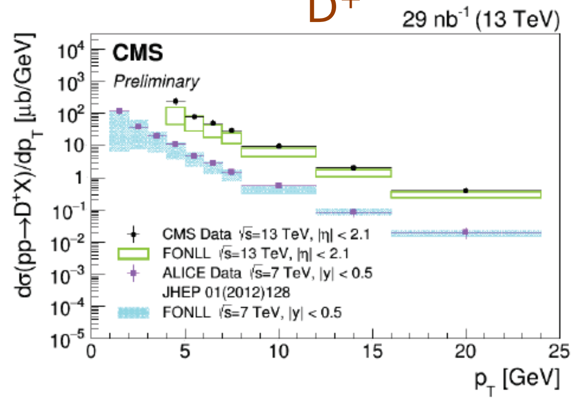
D*



D0



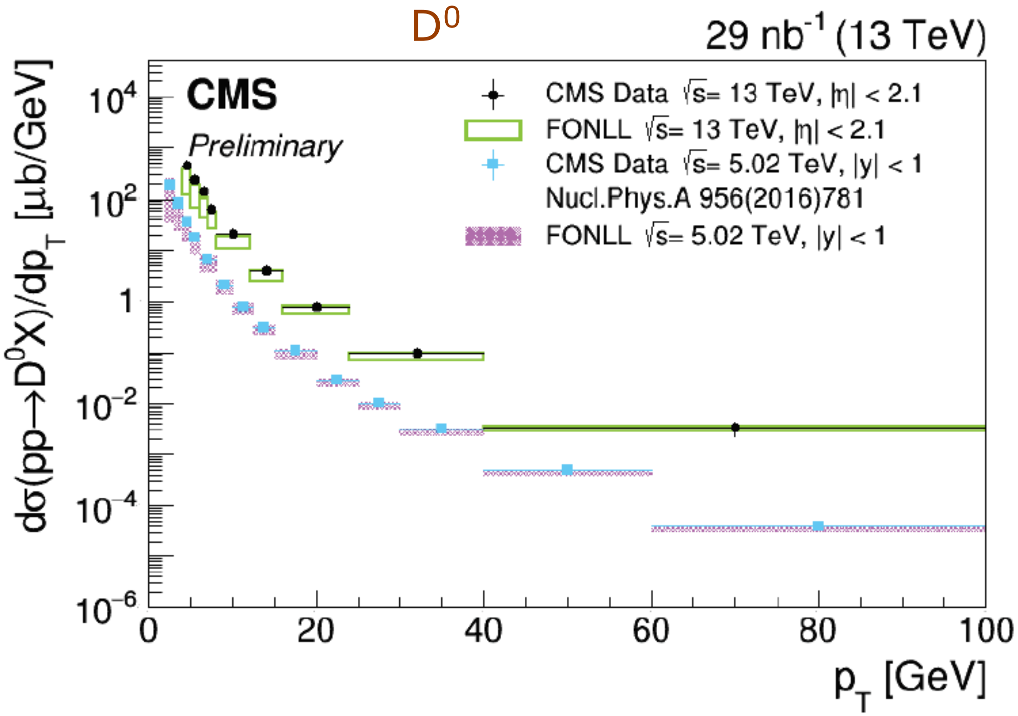
D+



Different kinematic range
CMS data shown only for pT < 24 GeV
Factor 2 since the cc are not included in ALICE

Comparison with measurement done at 5.02 TeV

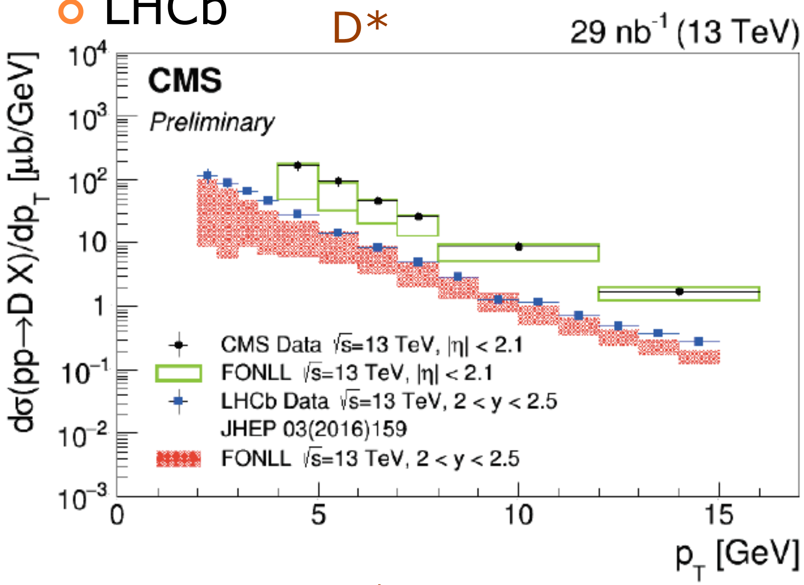
- CMS group performed a Pb-Pb measurement at 5.02 TeV and used the pp cross section to normalise

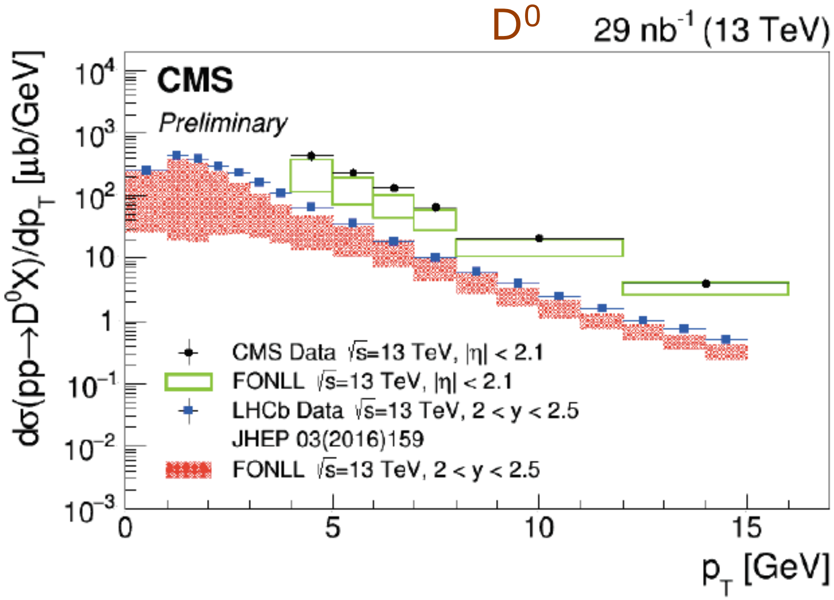


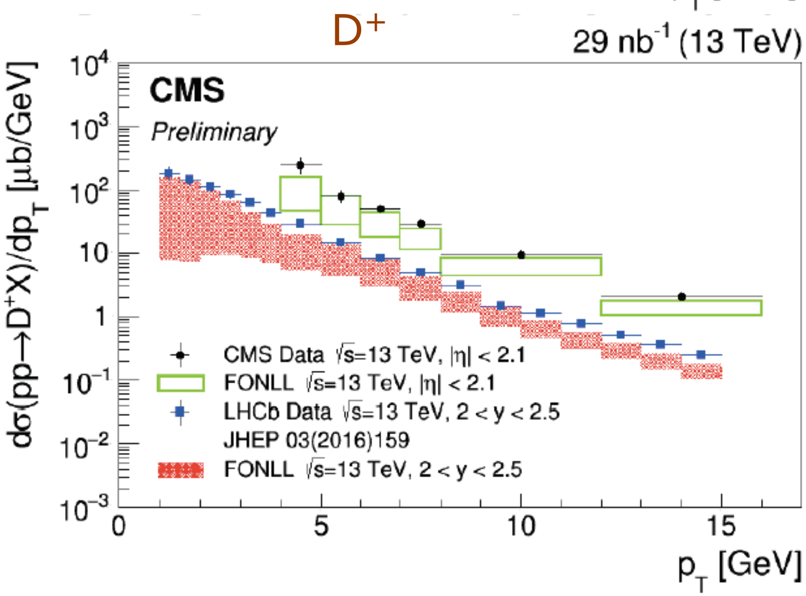
Different kinematic range and binning
Evolution (theory / data) in good agreement

Comparison with measurement done at 13 TeV

- LHCb







Complementary acceptance for the two experiments
Only the first y bin is shown for LHCb
CMS data are reported only for pT < 16 GeV to have a better comparison.

-> **Good agreement in the scale for the three mesons.**

CONCLUSION

- I presented the results on the **first measurement of the open-charm production cross section in pp collision in CMS**, using 2016 data

- We developed a reconstruction strategy to identify these mesons with a clear significance even in a not ideal environment as LHC is for such states

- Results have been compared to different MC predictions and theory models

- Among them, we used FONLL prediction to compare CMS measurements with the previous results already published within LHC. **CMS measurements show a good agreement with the others**, considering the evolution in the center of mass energy scale and the kinematic dependences, as described by the theory predictions.

THANK YOU FOR THE ATTENTION

BACKUP

DATASETS AND EVENT SELECTION

- We analysed all the 2016 ZeroBias samples:
  - /ZeroBias/Run2016(B-G)-23Sep2016-v*/AOD
  - /ZeroBias/Run2016H-PromptReco-v*/AOD
  - ~ 233 Million events

- The MonteCarlo used for the efficiency calculation:
  - /DStarToD0Pi D0KPi DStarFilter TuneCUEP8M1 13TeV-pythia8-evtgen/RunIIFall15DR76-PU25nsData2015v1 76X mcRun2 asymptotic v12-v1/AODSIM =>(58 M events)
    - Generated with Pythia6 TuneCUEP8M1 and filter in D*->D0 pi_{slow}->K pi pi_{slow} applied at gen level
    - 2015 scenario -> PU reweighting needed
    - not enriched in D^+ -> small bias cured

- Trigger used: HLT_ZeroBias_v* -> Effective luminosity analysed: $29*10^3\ \mu b^{-1}$
  - The most inclusive trigger
  - Chosen because the kinematic of the objects is particularly soft.

- Vertex selection: we select the first good vertex as PV
  - first = highest $\sum p_T$
  - good = valid, not fake, ndof > 4, $|z_{PV} - z_{BS}| < 10$ cm

SELECTION

Variables	D^{*+}	D^0	D^+
PV selection:	largest $\sum p_T^2$	largest $\sum p_T^2$	largest $\sum p_T^2$
Tracks: $p_{T min}$ [GeV]	0.5 (0.3 for the π_s)	0.8	0.7
Tracks: reduced χ^2	< 2.5 (3 for the π_s)	< 2.5	< 2.5
Tracks: N Tracker Hits	≥ 5 (> 2 for the π_s)	≥ 5	≥ 5
Tracks: N Pixel Hits	≥ 2 (none for the π_s)	≥ 2	≥ 2
Tracks: IP_{xy} [cm]	< 0.1 (sig. < 3 for π_s)	< 0.1	< 0.1
Tracks: IP_z [cm]	< 1 (sig. < 3 for π_s)	< 1	< 1
$\lvert M_{cand} - M_{PDG} \rvert$ [GeV]	< 0.023	< 0.10	< 0.10
SV fit CL	$> 1\%$	$> 1\%$	$> 1\%$
Pointing, $cos\Phi$	> 0.99	> 0.99	> 0.99
L significance:	> 3	> 5	> 10
Arbitration	min ΔM	min $\lvert M(K\pi) - M^{PDG}(D^0) \rvert$	min $\lvert M(K\pi\pi) - M^{PDG}(D^+) \rvert$

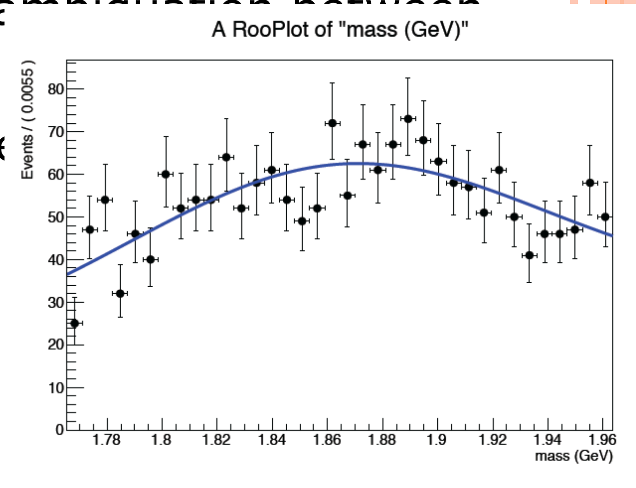
K/PI SWAP TREATMENT IN THE D0 RECONSTRUCTION

Since CMS has not a PID we have an ambiguation in the $K^+\pi^-$ and $K^-\pi^+$ states.

We manually assign the mass hypothesis to the tracks according to the charge, but since the D^0 is a neutral particle the disa… D^0 and $\overline{D^0}$ has to be explicitly done.

Contribution of the wrong mass assignment evaluat… in a MB MC sample using the gen level info as truth

Gaussian contribution (σ =0.075 +/- 0.007 GeV) to be considered as signal component.



-> A third wide gaussian has been added in the signal shape modelling in data:

- Width obtained bin by bin from MC
- Normalization defined w.r.t. to the other two gaussians in data, so that for every bin the integral for the two contributions (wide and thin) is the same.

Signal yield taken from the thin contribution to avoid double counting.

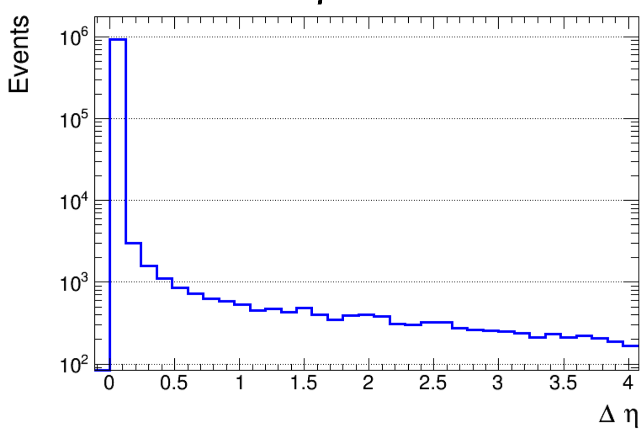
EFFICIENCY CALCULATION

- The efficiency measurements have been performend on the enriched MC

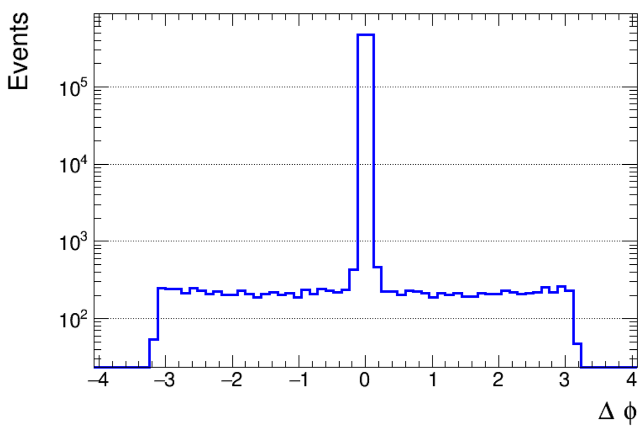
- We selected at gen level the events containing the requested decay chains and then we applied the reconstruction strategy and the acceptance cuts on this sub-sample.

- In order to ensure the reco D meson corresponds to the generated one a gen-reco matching is applyied.

$\Delta\eta$



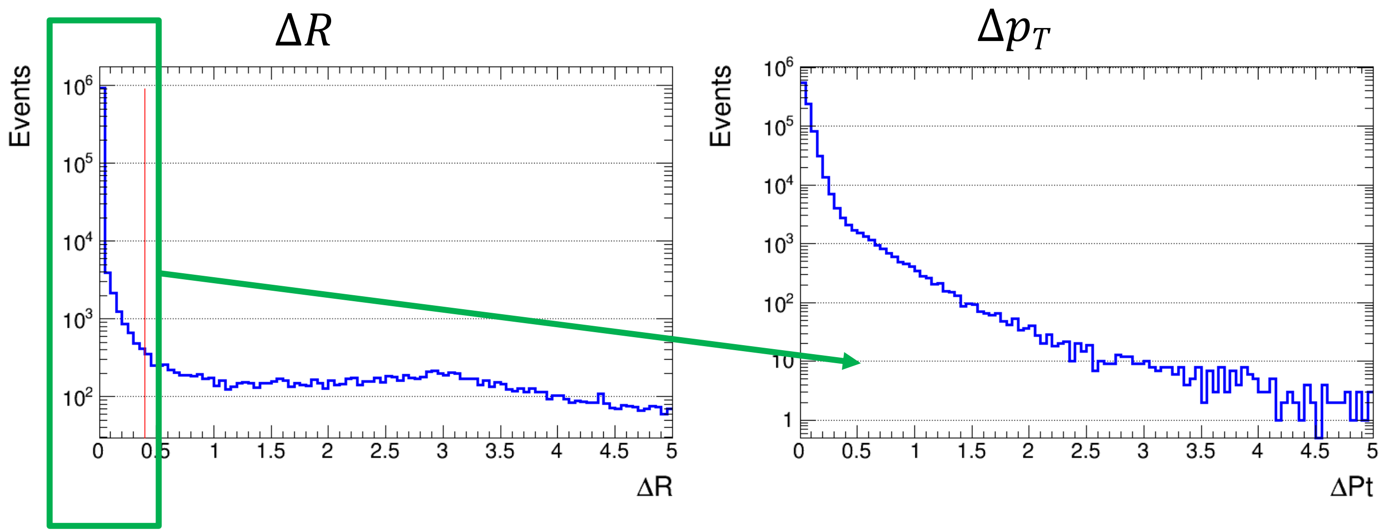
$\Delta\phi$



$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Efficiency calculation

Matching is satisfied if $\Delta R < 0.4$



Once the ΔR cut is applied most of the events have a $\Delta p_T < 0.5$ GeV -> no additional cut on the Δp_T are applied

The efficiency was thus calculated for each p_T and η bin and both the charged states as:

$$\boxed{\varepsilon_i = \frac{N_{rec_i}(D \to f)}{TOT_i(D \to f)}}$$

SYSTEMATIC UNCERTAINTIES

- **Luminosity** – measured by CMS for 2016 => 2.5%
- **BR** – uncertainties taken from the latest PDG edition
- **Tracking** - 2.3% per track
  - For the D* an additional 5.2 % has been introduced for the slow pion
- **Slow pion pT cut** - affect only the fit D* pt bin
- **MC statistics** - the statistical error from the enriched MC
- **Contamination** - the statistical error from the MinBias MC
- **Signal yield instability** - due to the dynamic inefficiency in the tracking during the 2016 data taking -> evaluated including the different PU scenario for each run
- **PU reweighting** - Bin by bin the statistical error related to the weight w=data/MC has been evaluated. The cross section is calculated using the upper and lower values.
- **L/sigmaL cut** - several studies done to check for possible bias of the cut -> we conclude that it is not possible to isolate and directly quantify the L/sigma systematic, since it can't be disentangled by the fit method effects.
- **Fit modelling** – Signal and background alternative models:
  - Signal: a single gaussian, a 3gaussian sum and a crystal ball function were used for the signal description. The biggest deviation between the three is taken as syst.
  - Background: a fourth degree polynomial was used for the bkg description
  - In addition to that has been found that the peaking background has a no negligible contribution for the D+ meson, while it is flat for the other two particles

The cross-section values are compared to

- FONLL predictions [1] shown as boxes representing the upper and lower limit for a given bin
  - Central values: mb = 4.75 GeV for bottom, mc = 1.5 GeV for charm, μR = μF = μ0 = sqrt(m2 + pT2)
    Scales uncertainties: μ0/2 < μR, μF < 2μ0 with 1/2 < μR/μF < 2.
    Mass uncertainties: mb = 4.5, 5.0 GeV for bottom, mc = 1.3, 1.7 GeV for charm, summed in quadrature to scales uncertainties.
    PDFs uncertainties: calculated according to the individual PDF set recipe, and summed in quadrature to scales and mass uncertainties.
    No fragmentation fractions (unless specified above) are included for the heavy quark -> heavy hadron fragmentation. This means that all heavy quarks are hadronised as if they fragmented into the chosen heavy hadron. To construct the proper mixing, the correct fragmentation fraction (FF) must be provided and the results summed separately. The D0 and D+ already include feedown from D*. The correct branching ratios (BR) for decays into leptons and other hadrons are instead provided by default.
- Pythia 6 [2]
- Pythia 8 (several tunes) [3]
- Powheg [4]

[1] The pT spectrum in heavy-flavour hadroproduction, M.Cacciari, S.Frixione, P.Nason, JHEP (9805) (1998) 007
[2] PYTHIA 6.4 Physics and Manual, T. Sjostrand, S.Mrenna P.Skands, JHEP 0605:026,2006
[3] A Brief Introduction to PYTHIA 8.1, T. Sjostrand, S.Mrenna P.Skands, arXiv:0710.3820
[4] Jet pair production in POWHEG, S. Alioli, K. Hamilton, P. Nason, C. Oleari, E. Re, JHEP 1104 (2011) 081