Production studies of B and D mesons

ICHEP2020

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MOTIVATION FOR D AND B MESON PRODUCTION MEASUREMENTS

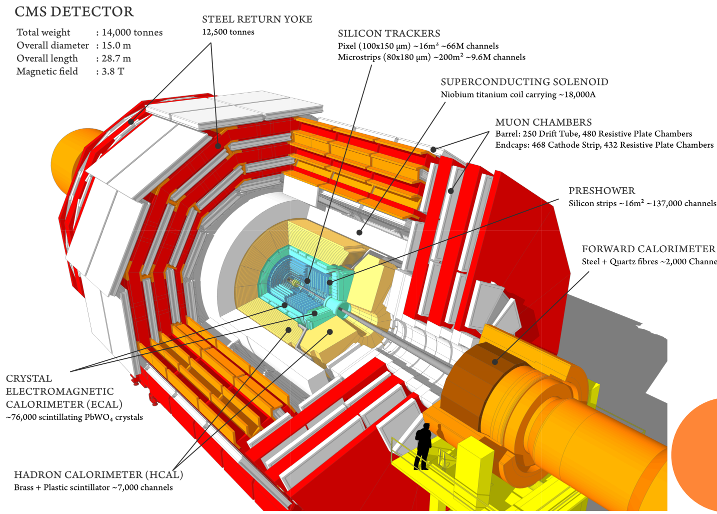
- Measurements and observations of heavy flavour production provide **important tests of QCD** and give insight into particle production at colliders

- **Hadronization challenging** to understand -> measurements needed

- Form **baseline or background** for other physics studies at the LHC

- LHC provides access to **wide kinematic range** with a **very high production cross section** if compared to ee colliders.

- I will show the **recent results on D and B meson production** obtained with the CMS experiment



D MESON PRODUCTION: OVERVIEW

CMS PAS BPH-18-003

We considered the states:

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

+ c.c.

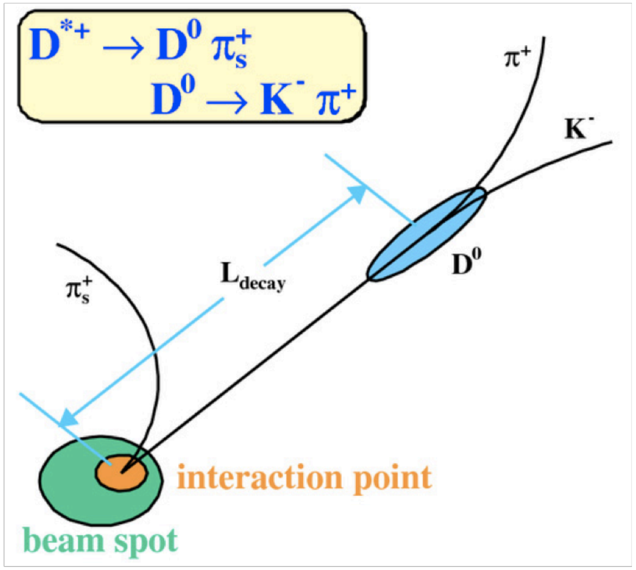
- Analysed data: pp collisions at $\sqrt{s}$ = 13 TeV collected in 2016
- Phase space: 4 < p_T (D) < 100 GeV && $|\eta|$ < 2.1
- ZeroBias trigger applied (the most inclusive one)

Differential cross section measurement in p_T and $|\eta|$ bins

The first measurement of the open charm production cross section in pp collisions for CMS!

D meson production: reconstruction strategy

- "prompt" produced mesons=> around the interaction point
- D^0 decay length: $c\tau \approx 10^{-2}$cm
- 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 length

D MESON PRODUCTION: RECONSTRUCTION STRATEGY

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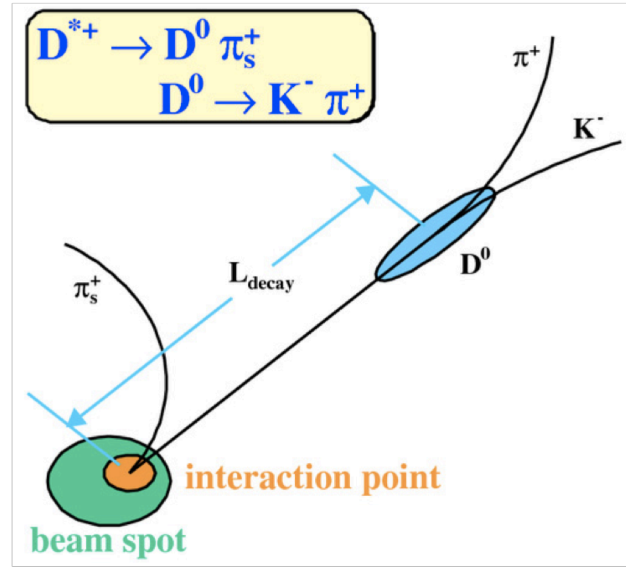

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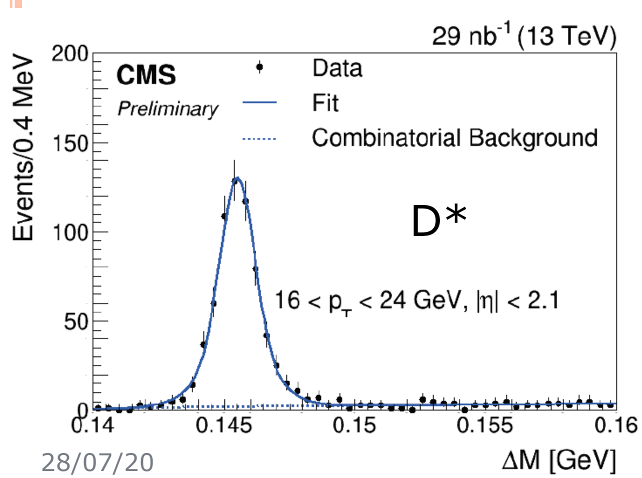
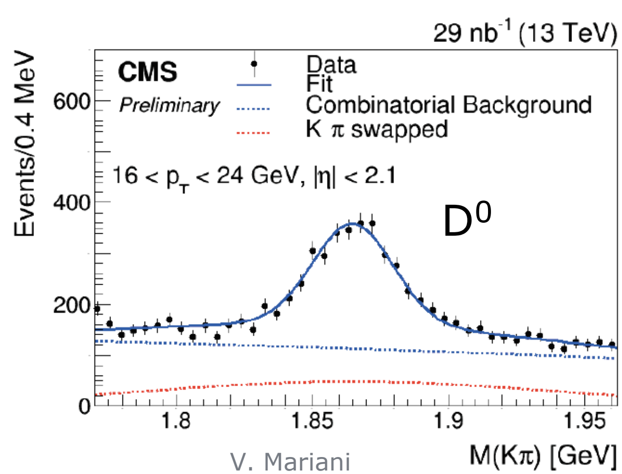
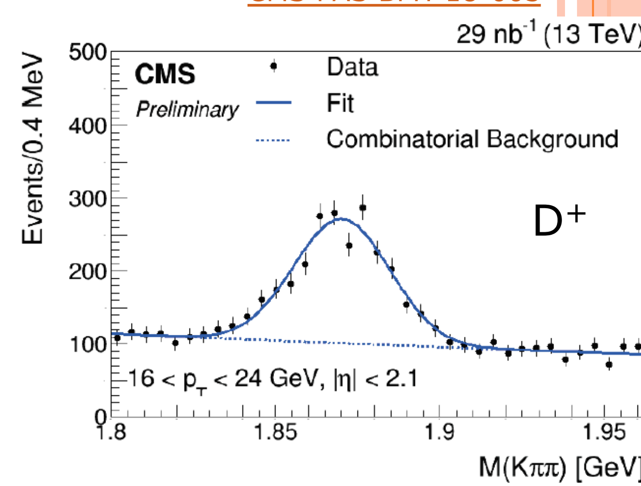
CMS PAS BPH-18-003

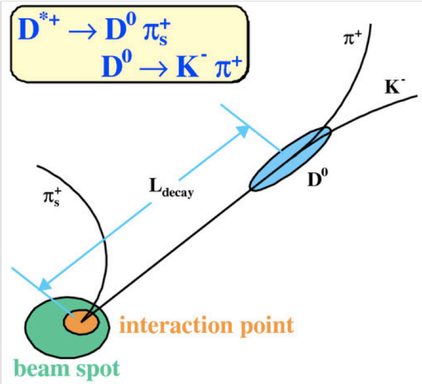






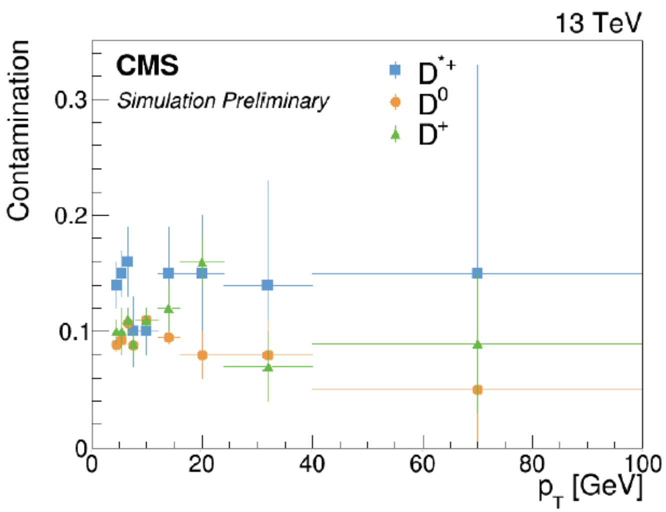
CONTRIBUTION FROM SECONDARY DECAY

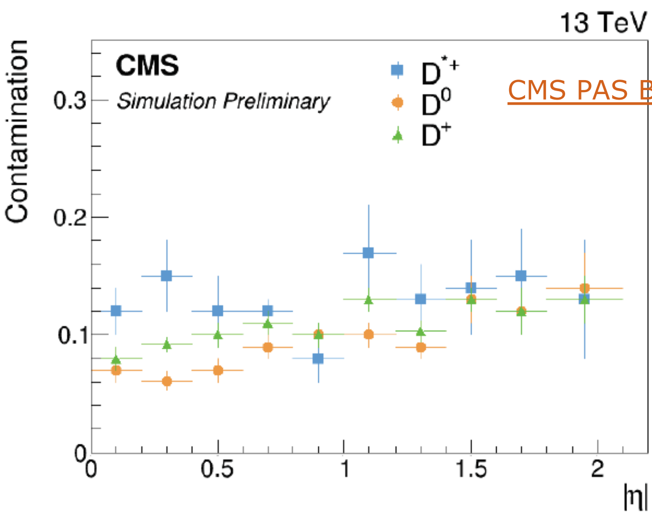
The aim of the analysis is to measure the prompt open-charm production cross section
-> prompt = coming from PV or charm excited states



Possible contamination: charm mesons coming from B meson decays

Contribution evaluated on MC as: $\boxed{contam = \frac{N_{sec}}{N_{prompt}+N_{sec}} \sim 10\text{-}15\%}$



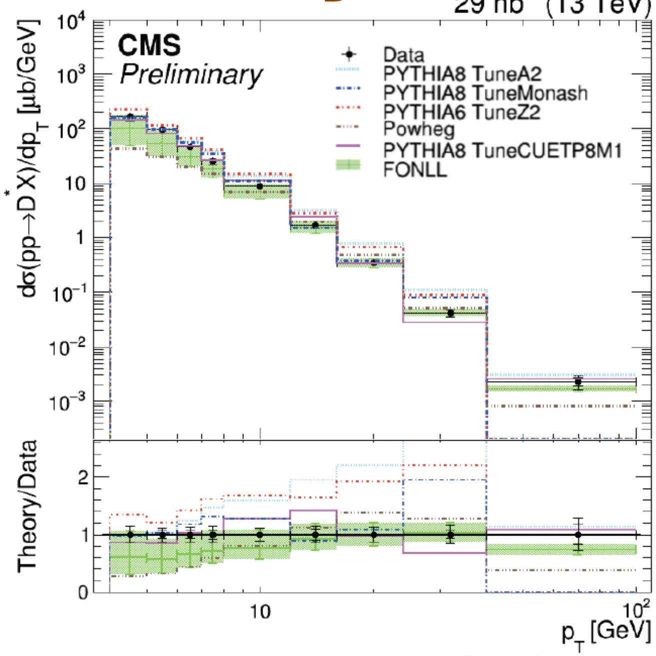


CMS PAS BPH-18-003

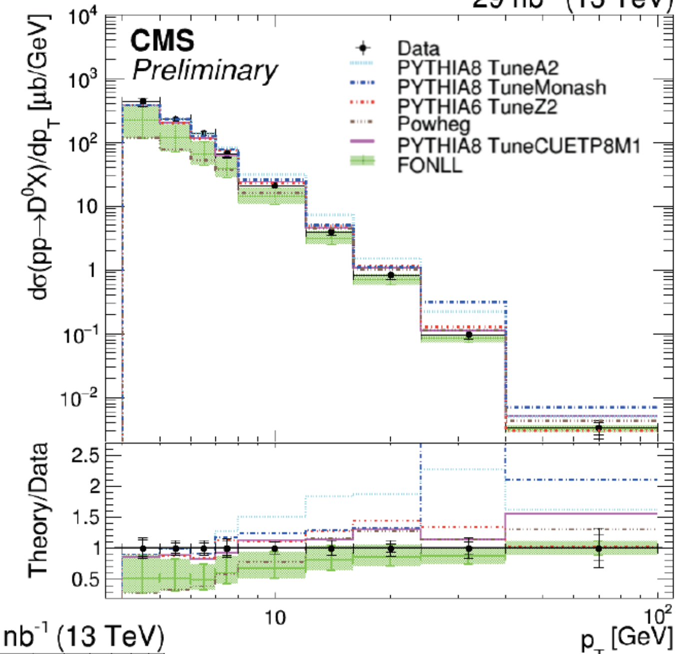
The visible cross section is corrected bin-by-bin for this contribution

RESULTS

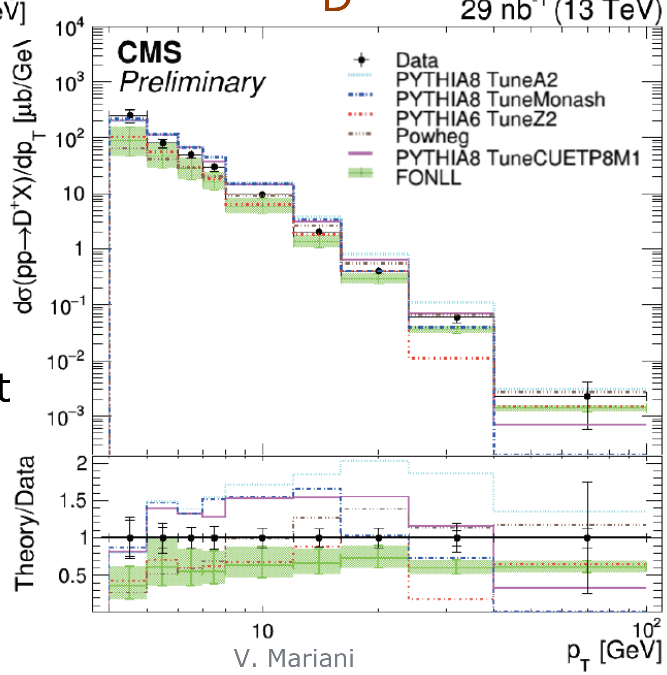
D*



D^0



D$^+$



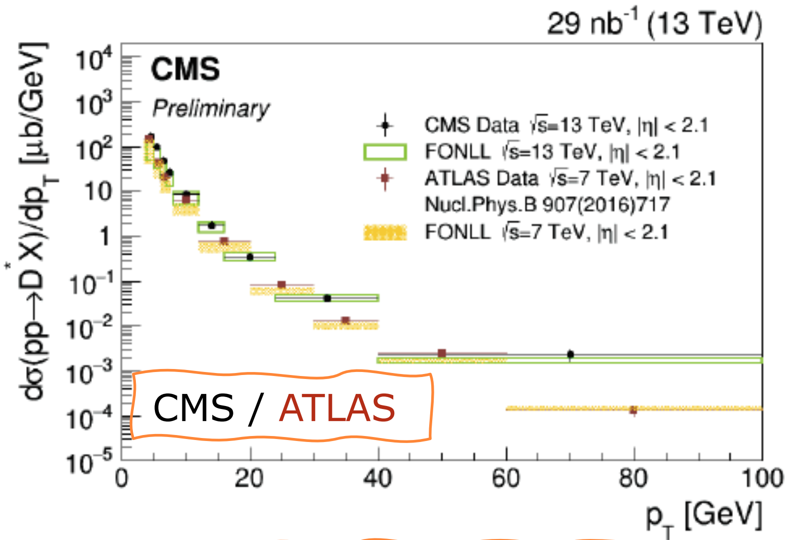
CMS PAS BPH-18-003

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

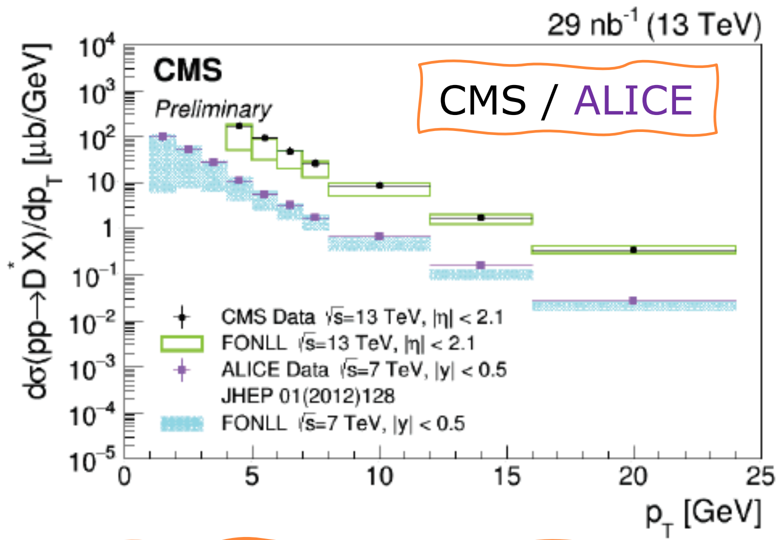
COMPARISON WITH THE PREVIOUS RESULTS

- Next slide shows the comparison of CMS data with the previous results obtained by the other 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 the previous results – D* only

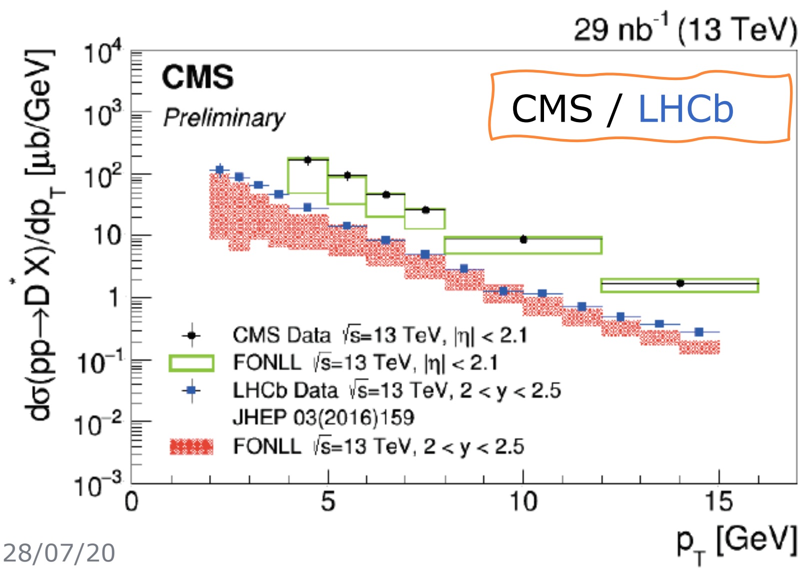


7 TeV



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

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



13 TeV

CMS PAS BPH-18-003

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

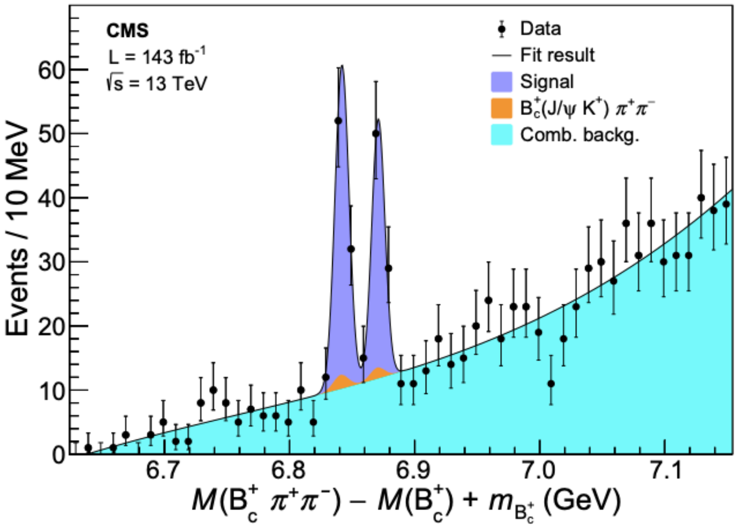
Full set of distributions in backup

CMS PAS BPH-19-001

The observation of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states have been recently published by CMS [1]

-> masses consistent with the theoretical predictions

[1] Phys. Rev. Lett. 122 (2019) 132001



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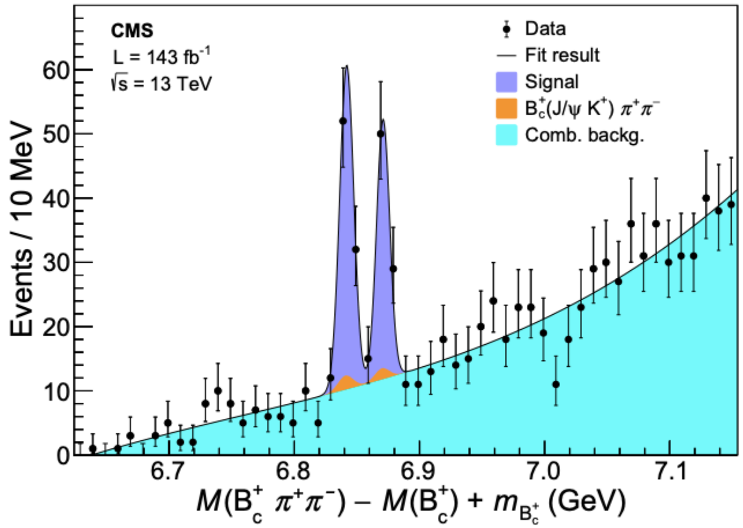
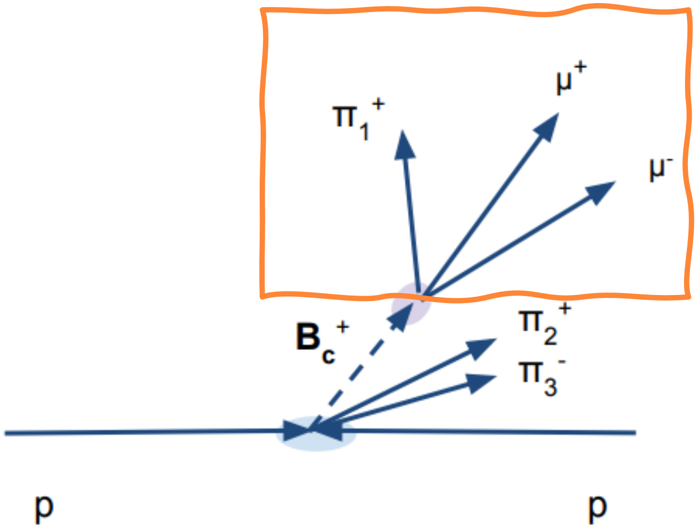


- Next important step is the measurement of relative cross sections of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states with respect to the B_c^+:

  - $B_c^+(2S)$ to B_c^+ and $B_c^{*+}(2S)$ to B_c^+ cross section ratios
  - $B_c^{*+}(2S)$ to $B_c^+(2S)$ cross section ratio

- Analysed data: pp collisions at $\sqrt{s}$ = 13 TeV collected in 2015-2018 $\rightarrow$ L = 143/fb
- Phase space: $p_T(B_c^+) > 15$ GeV and $|y| < 2.4$

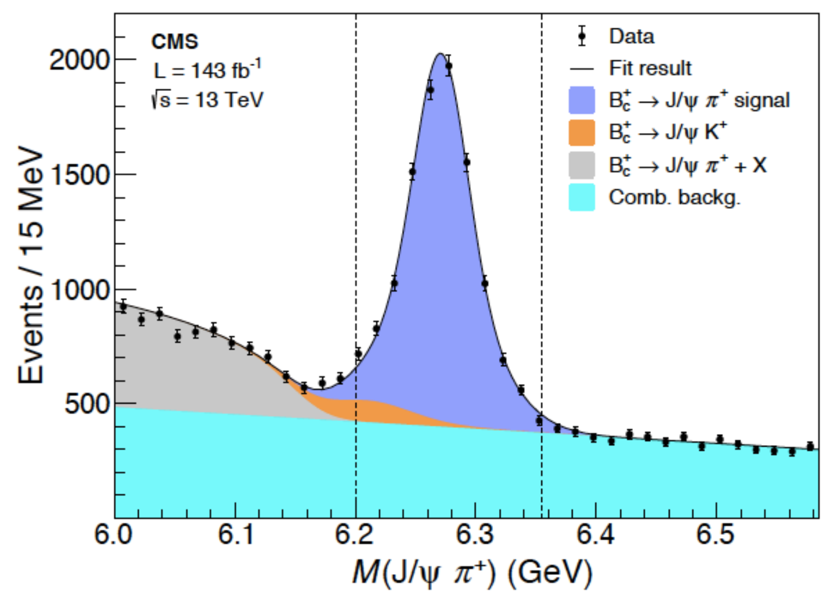
B_C MESON PRODUCTION: RECONSTRUCTION STRATEGY



$B_c(2S) \rightarrow B_c \pi^+ \pi^-$

2 OS muons with inv mass within 2.9-3.3 GeV, p_T > 4 GeV, + a track with p_T > 3.5 GeV
Common displaiced (> 100 μm) vertex
B_c^+ **candidates** with p_T > 15 GeV, |y| < 2.4

CMS PAS BPH-19-001

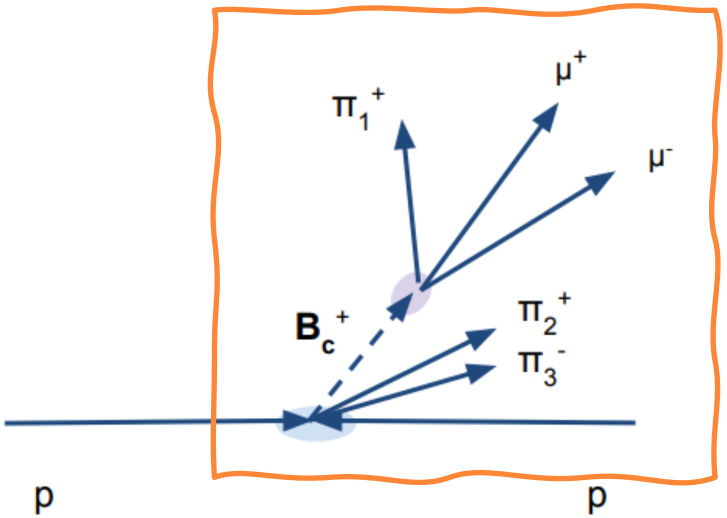


Fit functions

- signal: sum of 2 gaussians with common mean and different widths
- backgrounds: sum of 3 contributions
  - Uncorrelated j/psi – track combination (first order polynomial)
  - Partially reconstructed $B_c^+ \rightarrow J/\psi\pi^+$ X (ARGUS function)
  - $B_c^+ \rightarrow J/\psi K^+$ contribution (shape fixed from simulation)

B_c^+ signal yield: 7629 $\pm$ 225 events

B_C MESON PRODUCTION: RECONSTRUCTION STRATEGY

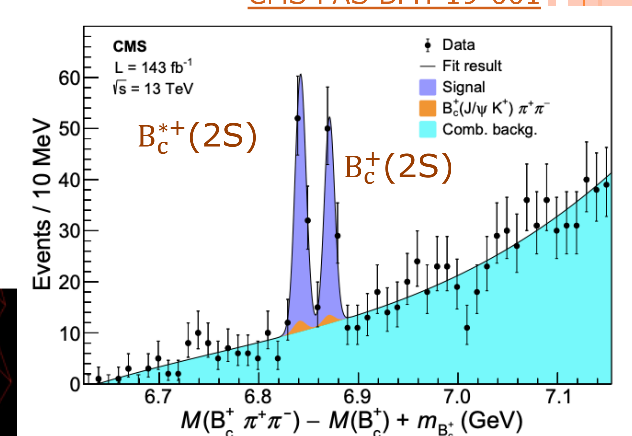


$B_c(2S) \rightarrow B_c \pi^+ \pi^-$

Combine the two OS charged tracks with the B_c^+ candidate (range 6.2 – 6.335 GeV)
Pion with p_T > 0.6 and 0.8 GeV
Common vertex between B_c^+ and $\pi\pi$

If more candidates found -> the one with highest p_T is taken

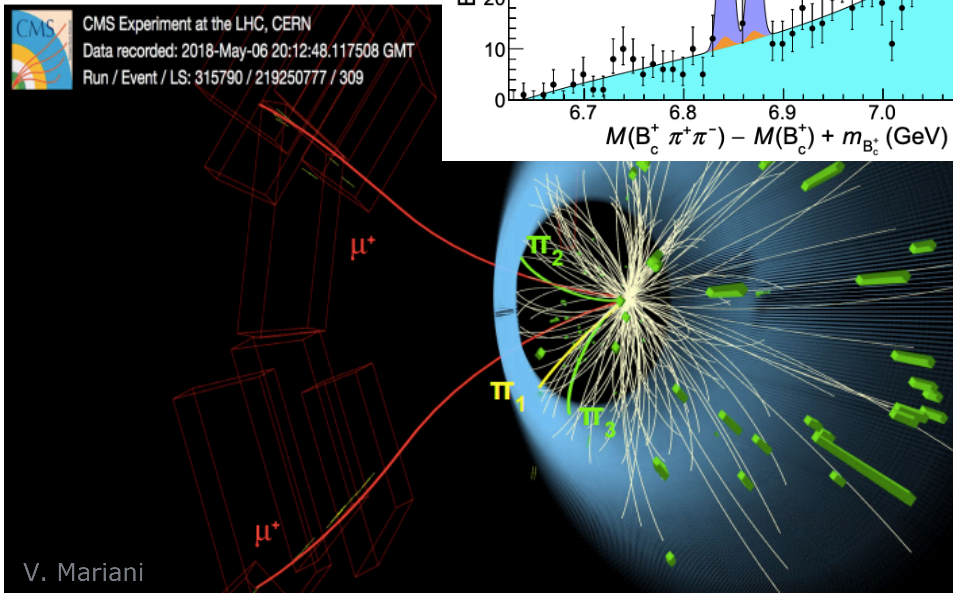
CMS PAS BPH-19-001



Fit functions:
- signal: 2 independent gaussians, (1 for each peak)
- backgrounds:
  - Chebyshev polynomial for the continuum bkg
  - 2 small contributions from the $B_c^+ \rightarrow J/\psi K^+$ (same shape than signal)

$B_c^{*+}(2S)$ signal yield: 67 $\pm$ 10 events
$B_c^+(2S)$ signal yield: 51 $\pm$ 10 events

ΔM: 29.1 $\pm$ 1.5 MeV



Bc meson production: results

$$R^{+} \equiv \frac{\sigma(\mathrm{B}_c^+(2S))}{\sigma(\mathrm{B}_c^+)} \cdot \mathcal{B}(\mathrm{B}_c^+(2S) \to \mathrm{B}_c^+ \pi^+\pi^-) = \frac{N(\mathrm{B}_c^+(2S))}{N(\mathrm{B}_c^+)} \frac{\epsilon(\mathrm{B}_c^+)}{\epsilon(\mathrm{B}_c^+(2S))},$$

$$R^{*+} \equiv \frac{\sigma(\mathrm{B}_c^{*+}(2S))}{\sigma(\mathrm{B}_c^+)} \cdot \mathcal{B}(\mathrm{B}_c^{*+}(2S) \to \mathrm{B}_c^+ \pi^+\pi^-) = \frac{N(\mathrm{B}_c^{*+}(2S))}{N(\mathrm{B}_c^+)} \frac{\epsilon(\mathrm{B}_c^+)}{\epsilon(\mathrm{B}_c^{*+}(2S))},$$

$$R^{*+}/R^{+} = \frac{\sigma(\mathrm{B}_c^{*+}(2S))}{\sigma(\mathrm{B}_c^+(2S))} \cdot \frac{\mathcal{B}(\mathrm{B}_c^{*+}(2S) \to \mathrm{B}_c^+ \pi^+\pi^-)}{\mathcal{B}(\mathrm{B}_c^+(2S) \to \mathrm{B}_c^+ \pi^+\pi^-)} = \frac{N(\mathrm{B}_c^{*+}(2S))}{N(\mathrm{B}_c^+(2S))} \frac{\epsilon(\mathrm{B}_c^+(2S))}{\epsilon(\mathrm{B}_c^{*+}(2S))}.$$

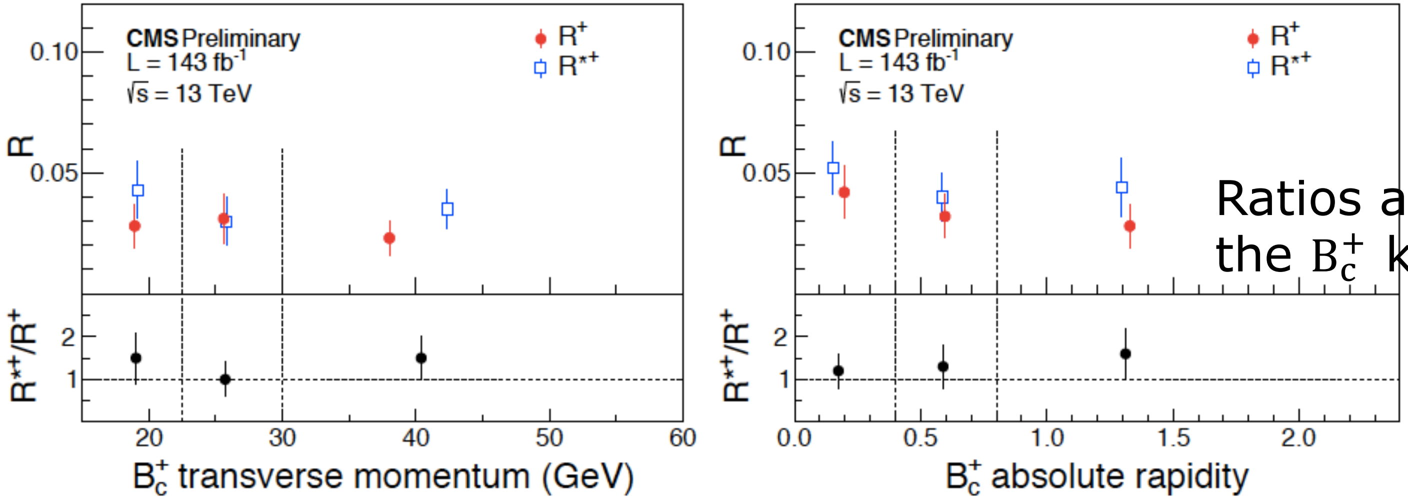
N.B. the BR do not reflect the B_c^{*+} -> $\mathrm{B}_c^{+}\gamma$ since the γ is too soft to be detected. BR taken as 100%.

$$R^{+} = 3.57 \pm 0.69\,(\text{stat}) \pm 0.32\,(\text{syst})\,\%,$$

$$R^{*+} = 4.91 \pm 0.69\,(\text{stat}) \pm 0.57\,(\text{syst})\,\%,$$

$$R^{*+}/R^{+} = 1.39 \pm 0.35\,(\text{stat}) \pm 0.09\,(\text{syst}),$$

CMS PAS BPH-19-001



Ratios are stable w.r.t. the B_c^+ kinematics

CONCLUSION

- The results on the **first measurement of the open-charm production cross section in pp collision in CMS**, using 2016 data, have been presented here.

- **CMS measurements show a good agreement with the previous ones within LHC**, considering the evolution in the center of mass energy scale and the kinematic dependences, as described by the theory predictions.

- The latest results about the B_c mesons have been also presented: **$B_c^+(2S)$ to B_c^+, $B_c^{*+}(2S)$ to B_c^+, and $B_c^{*+}(2S)$ to $B_c^+(2S)$ cross section ratios.**

- **No significant dependences on the p_T or |y|** of the B_c^+ mesons have been observed.
- **Important experimental information** to improve the theoretical understanding of the bc heavy quarkonium states and their production.

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 $\lvert M(K\pi\pi)$ - $M^{PDG}(D^+) \rvert$

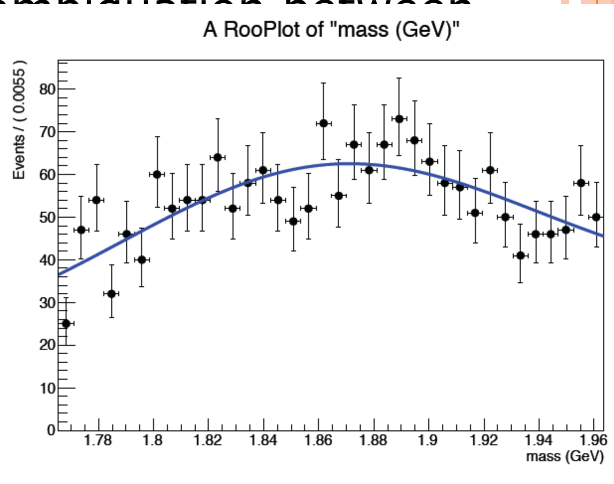
K/PI SWAP TREATMENT IN THE D0 RECONSTRUCTION

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 evaluate
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:

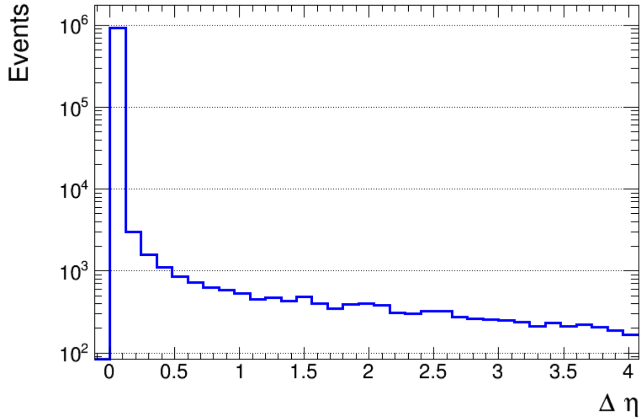
- Width obtained bin by bin from MC
- Normalization defined w.r.t. to the other two gaussians in data, so that for every bin the integral for the two contributions (wide and thin) is the same.

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

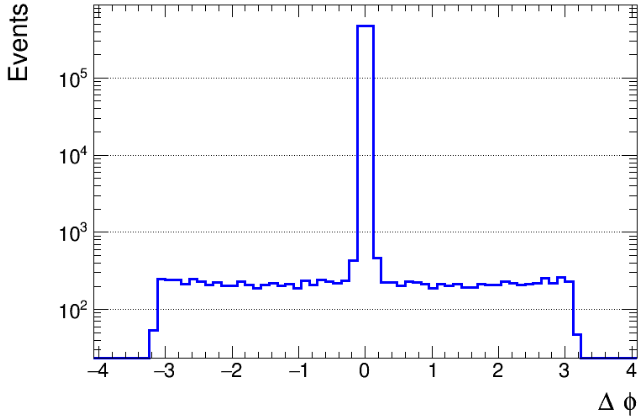
Efficiency calculation

- 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.

$\Delta\eta$



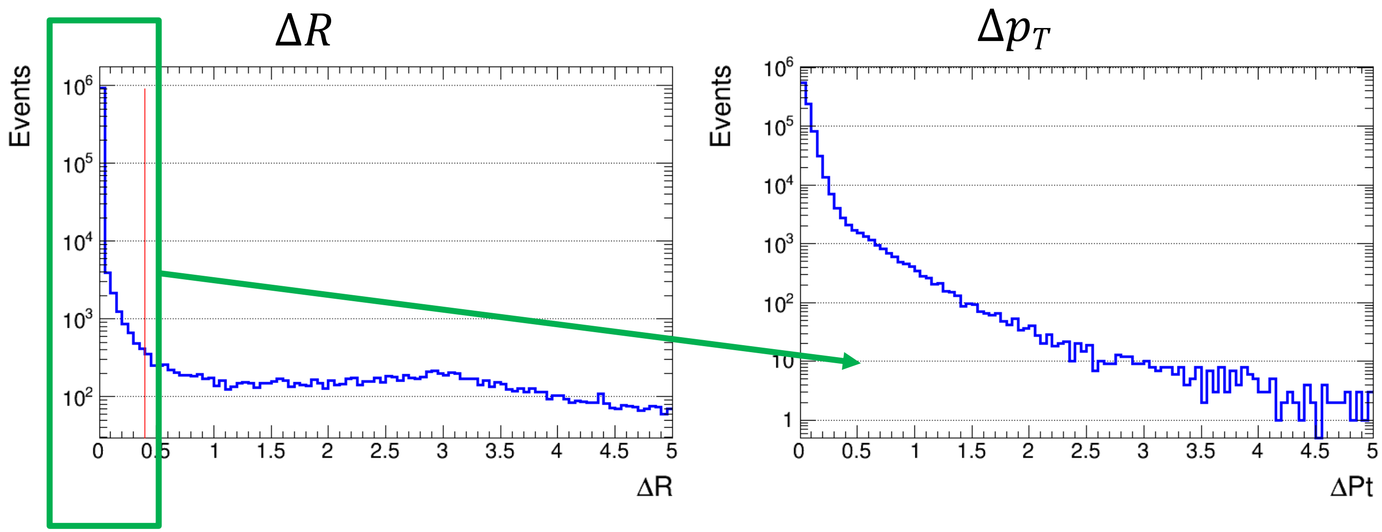
$\Delta\phi$



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

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

SYSTEMATIC UNCERTAINTIES

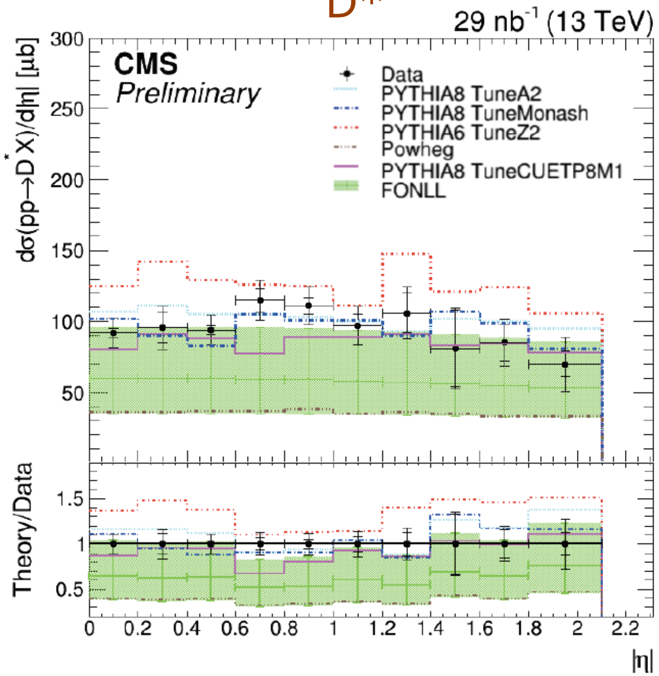
	Relative uncertainties (%)		
	D^{*+}	D^0	D^+
Signal efficiency calculation	0.3	0.3	3.5
Secondary decay contamination	2.9	0.8	1.4
PU reweighting	1.0	1.0	2.0
Branching fraction	1.1	0.8	1.7
Tracking efficiency	9.4	4.2	6.1
Signal modeling	3.6	5.0	4.2
Background modeling	1.2	4.8	8.0
Luminosity	2.5	2.5	2.5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

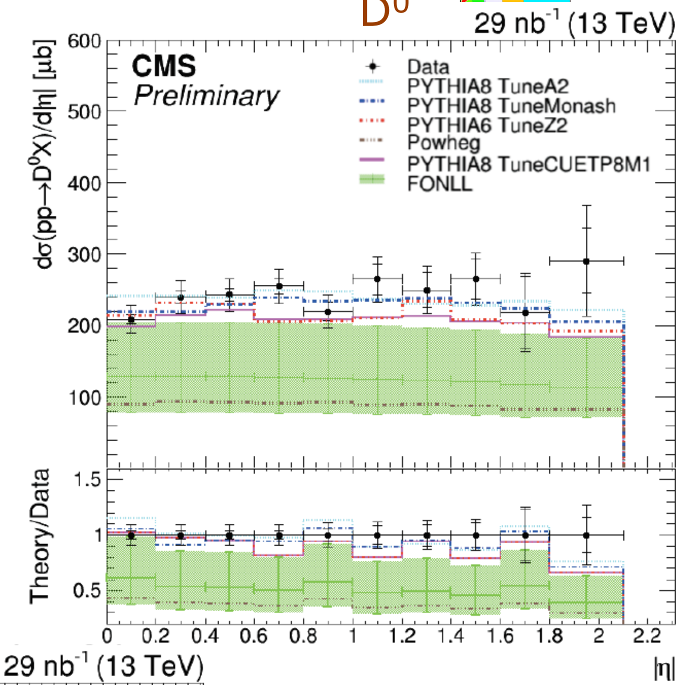
Data taking instability -> due to tracker inefficiency during the 2016 data taking

RESULTS

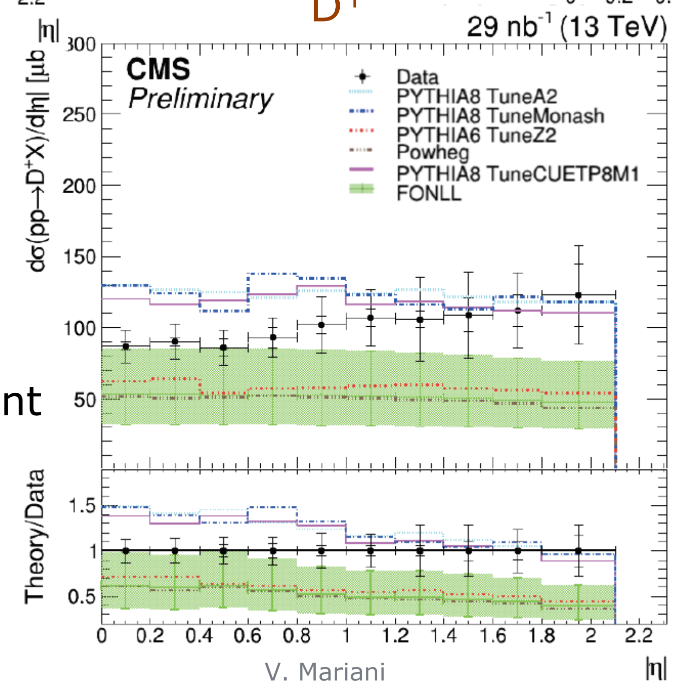
D*



D^0



D^+



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

MC AND THEORY MODELS USED TO COMPARE DATA

The cross-section values are compared to

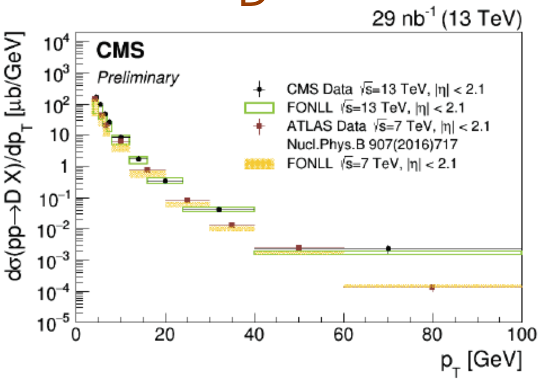
- FONLL predictions [1] shown as boxes representing the upper and lower limit for a given bin
  - Central values: mb = 4.75 GeV for bottom, mc = 1.5 GeV for charm, μR = μF = μ0 = sqrt(m2 + pT2)
    Scales uncertainties: μ0/2 < μR, μF < 2μ0 with 1/2 < μR/μF < 2.
    Mass uncertainties: mb = 4.5, 5.0 GeV 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

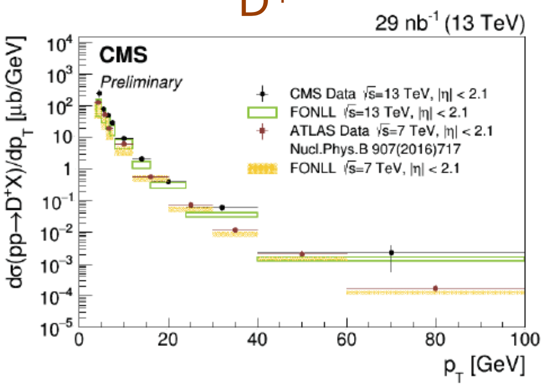
Comparison with measurements done at 7 TeV

- ATLAS

D*

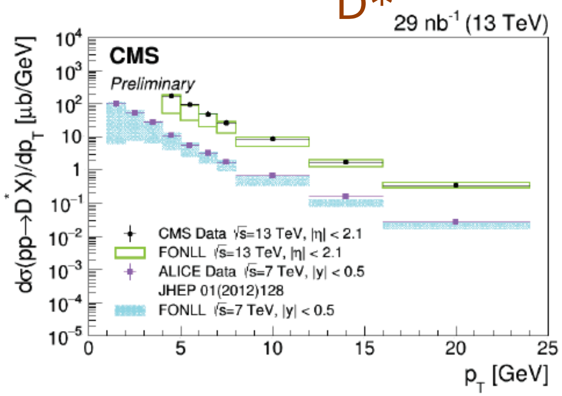


D+

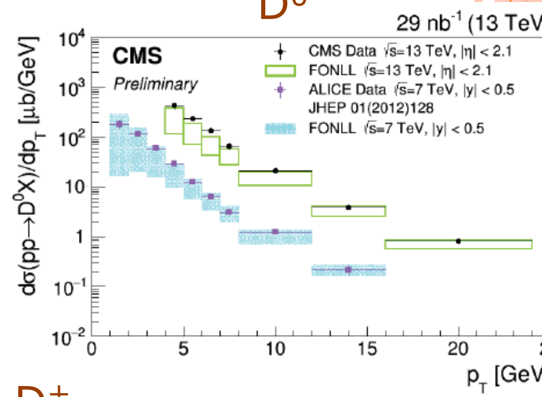


- ALICE

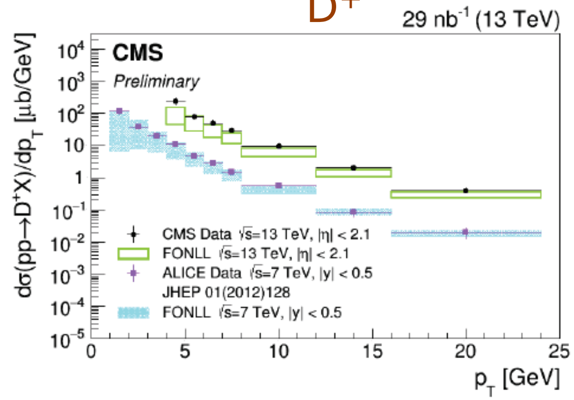
D*



D0



D+

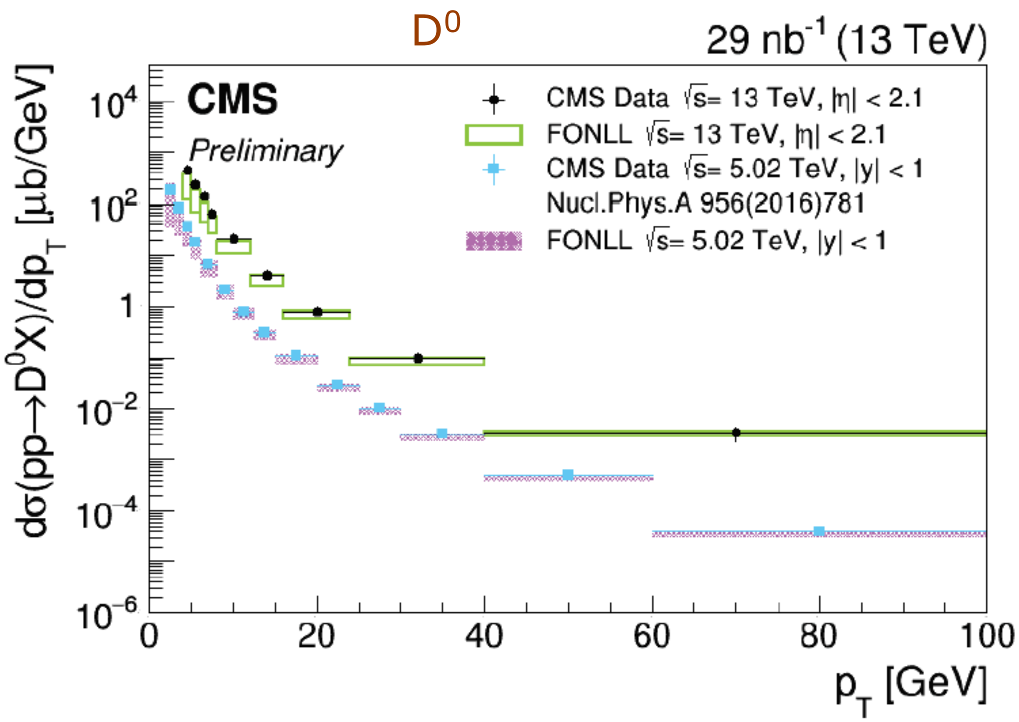


Same kinematic range but different binning
We can directly see how the cross section scales with the center of mass energy

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

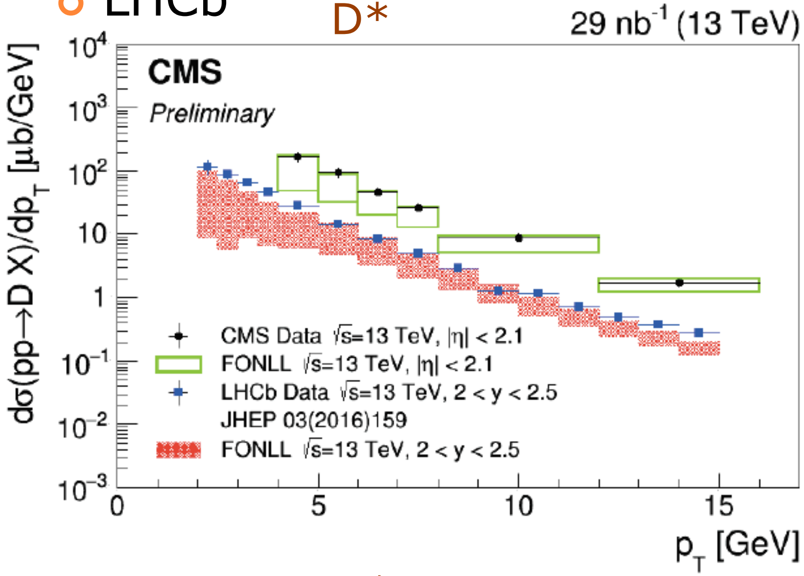


Different kinematic range and binning
Evolution (theory / data) in good agreement

Comparison with measurement done at 13 TeV

- LHCb

D*



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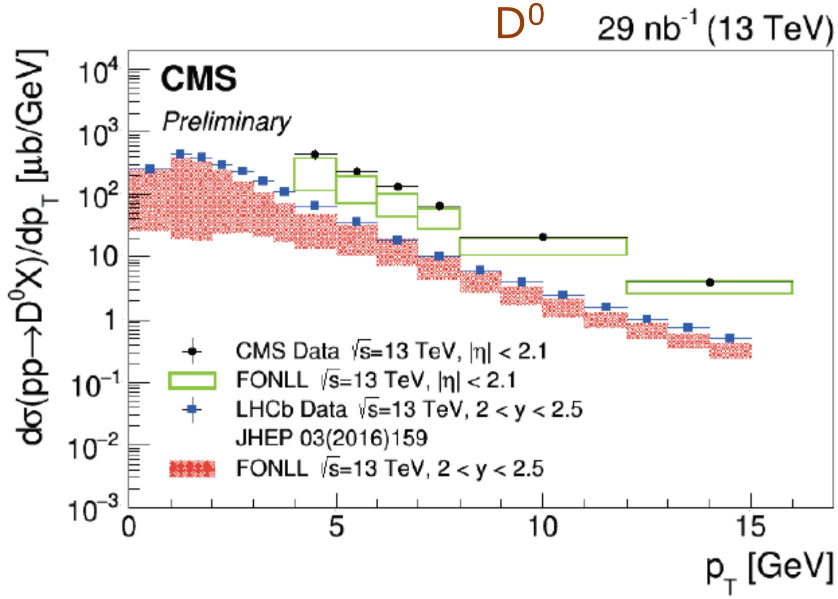
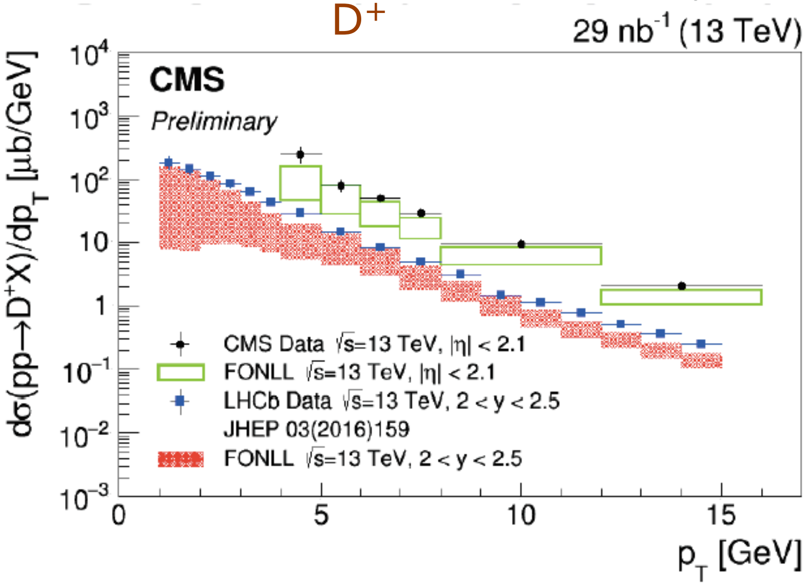


D+



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.**

Trigger requirements

- HLT
  - 2 OS muon with invariant mass 2.9 – 3.3 GeV
  - dimuon vertex fit probability > 10%
  - distance of closest approach between muons < 0.5 cm
  - distance between the dimuon vertex and the beam axis > 3σ
  - muon p_T > 4 GeV and |eta| < 2.5
  - dimuon p_T aligned with the transverse displacement vector, cosθ > 0.9
  - third track produced in the dimuon vertex

Offline reconstruction

- 2OS muons matching the HLT ones
- |eta| < 2.4
- cosθ > 0.98
- high-purity tracks
- soft muon identification
- muon close in angular space ΔR < 1.2

B meson production – cross section ratio

$$R^+ \equiv \frac{\sigma(B_c^+(2S))}{\sigma(B_c^+)} \cdot \mathcal{B}(B_c^+(2S) \to B_c^+ \pi^+\pi^-) = \frac{N(B_c^+(2S))}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^+(2S))},$$

$$R^{*+} \equiv \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+)} \cdot \mathcal{B}(B_c^{*+}(2S) \to B_c^+ \pi^+\pi^-) = \frac{N(B_c^{*+}(2S))}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^{*+}(2S))},$$

$$R^{*+}/R^+ = \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+(2S))} \cdot \frac{\mathcal{B}(B_c^{*+}(2S) \to B_c^+ \pi^+\pi^-)}{\mathcal{B}(B_c^+(2S) \to B_c^+ \pi^+\pi^-)} = \frac{N(B_c^{*+}(2S))}{N(B_c^+(2S))} \frac{\epsilon(B_c^+(2S))}{\epsilon(B_c^{*+}(2S))}.$$

- N -> signal yield measured by fitting the mass distribution with
- epsilon -> reconstruction efficiency for the 3 states evaluated on MC (independently for the 4 years are reweighted for the integrated lumi)
  - $\varepsilon(B_c^+)$ = 1.313 %
  - $\varepsilon(B_c^+(2S))$ = 0.256 %
  - $\varepsilon(B_c^{*+}(2S))$ = 0.244 % -> slightly smaller because of the missing low energy gamma

	central	stat.	disp.	pions
$\epsilon(B_c^+(2S))/\epsilon(B_c^+)$	0.1874	1.1%	1.8%	4.2%
$\epsilon(B_c^{*+}(2S))/\epsilon(B_c^+)$	0.1789	1.0%	1.6%	4.2%
$\epsilon(B_c^{*+}(2S))/\epsilon(B_c^+(2S))$	0.955	1.4%	0.9%	–

stat -> statistical uncertainty
disp -> covers potential mismatch between the 4 data taking periods
pions -> reconstruction efficiency for the 2 pions

Systematic uncertainties

- Signal modelling – B_c^+: 1 gaussian replaced with a Crystal ball. 1 additional parameter that improves the fit -> 2.7 % for R^+ and R^{*+}, cancel for R^{*+}/R^+
- Signal modelling – Bc(2S): each peak described by 2 gauss instead of 1 / fitting the signal-free mass sidebands with the background function evaluating the signal yields counting events in each peak mass window and subtracting the background yields. Both made with a 3rd order Chebyschev pol -> 5.9% for R^+, 2.9% for R^{*+} and R^{*+}/R^+
- Bkg modelling – B_c^+: exponential function instead of a first degree polynomial -> 3.5 % for R^+ and R^{*+}, cancel for R^{*+}/R^+
- Reconstruction efficiency: stat + dispersion + pion tracks
- Decay kinematic: MC reweighting considering the possibility that the dipion decay distribution could reflect the existence of intermediate state -> 1.5 %, 6.9 % and 4.2% for R^+, R^{*+} and R^{*+}/R^+
- Helicity angle: MC reweighting considering the possibility that the dipion decay distribution could be dependent on the different spin of $B_c^+(2S)$ – $B_c^{*+}(2S)$ states) (helicity angle is made by the positive pion with the B_c^+ meson in the frame where the dipion system is at rest) -> 1%, 6%, 3.5% for R^+, R^{*+} and R^{*+}/R^+

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\ \pi^+$ fit model	4.4	4.4	–
$B_c^+\ \pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: dispersion among years	1.8	1.6	0.9
Efficiencies: dipion tracking	4.2	4.2	–
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total systematic uncertainty	8.9	11.5	6.4

Invariant mass distributions of the dipions emitted in the $B_c^+\pi^+\pi^-$ decays of the two $B_c^+(2S)$ states.