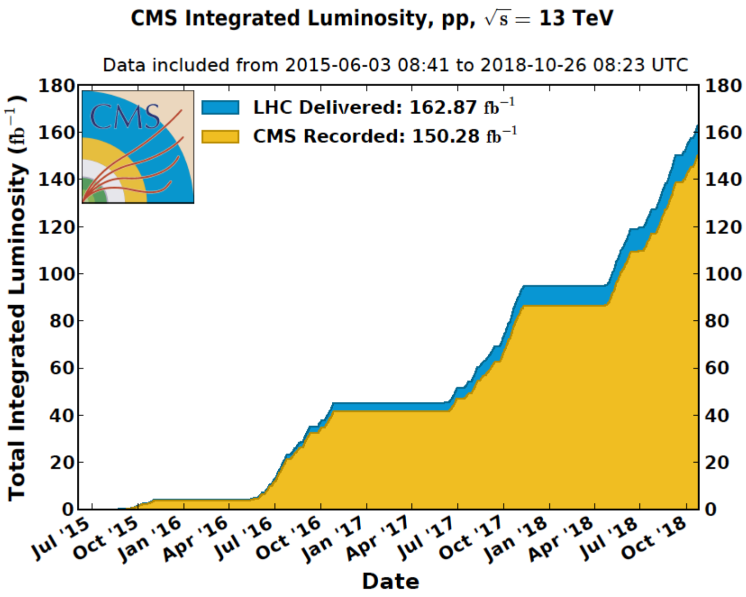
B physics in CMS
Highlights from Run2

V. Mariani on behalf of the CMS Collaboration

ICNFP 2019

INTRODUCTION

- LHC delivered large amount of collisions during Run 2 (~ 6 times Run 1)
- CMS detector had a very high efficiency in data collection (> 90%)
- Some analyses in B-physics suffer from the low statistic -> can benefit from the increasing amount of data.
- High luminosity also means new challenges:
  - New and smarter trigger algorithms
  - Sophisticated analysis techniques



INTRODUCTION AND OVERVIEW

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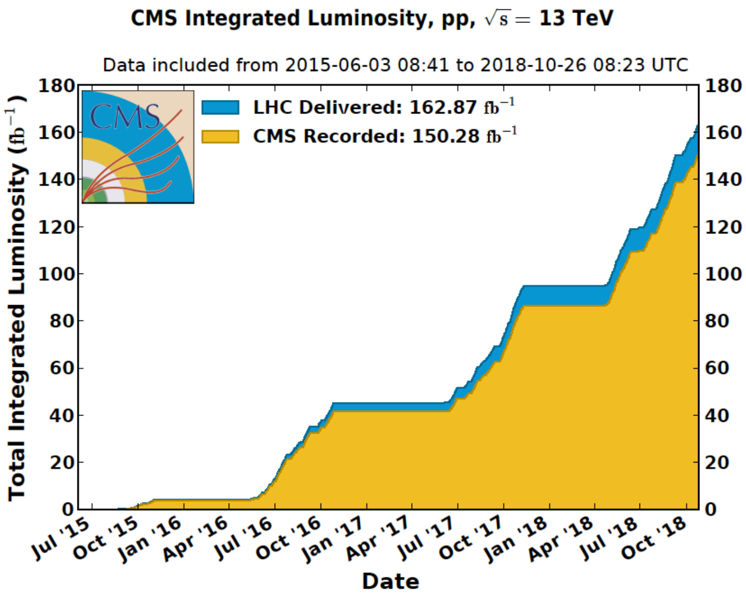


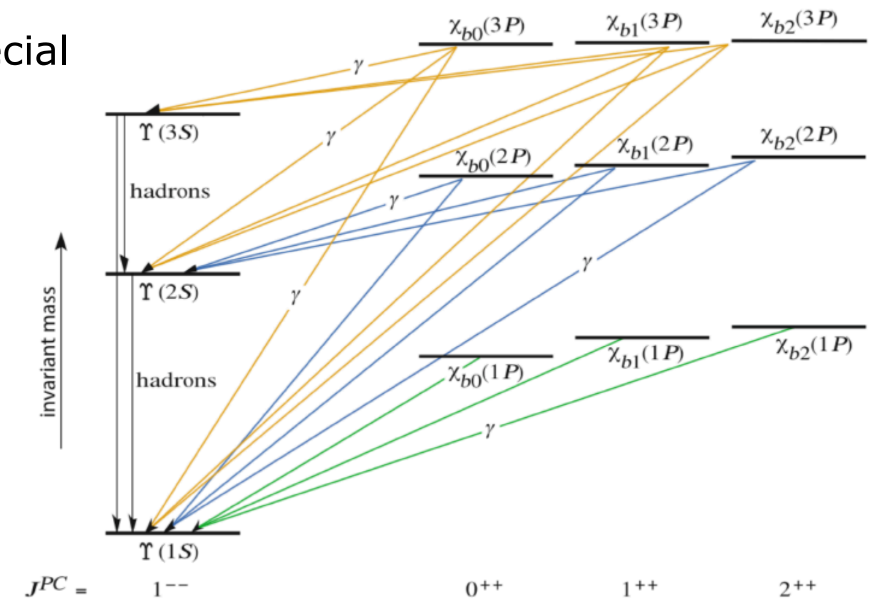
The latest results from B-physics will be discussed:

- Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states
- Observation of B_c^+ (2S) and B_c^{+*} (2S) states
- Search for $\tau \to 3\mu$
- Properties of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$ New
- Observation of $\Lambda_b \to J/\psi\Lambda\Phi$ decay New

Observation of the $\chi_{B1}(3P)$ and $\chi_{B2}(3P)$ states

PHYSICAL REVIEW LETTERS 121, 092002 (2018)

- The bottomonium family ($b\bar{b}$) plays a special role in understanding how the QCD binds quarks into hadrons
- The $\chi_b(3P)$ state is especially interesting since its properties could be affected by the proximity of the open-beauty threshold
- Unresolved $\chi_b(3P)$ state was observed by ATLAS[1], D0[2] and LHCb[3]



Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

- The $\chi_b(3P)$ state is reconstructed though the decay:

$$\chi_b \rightarrow \Upsilon(nS)\gamma \rightarrow 2\mu\gamma \qquad \text{where n = 1,2,3}$$

CMS performed the analysis using 2015, 2016, 2017 data (L = 80 fb^{-1}) and **observed for the first time the resolved states $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$**

[1] Phys. Rev. D **86**, 031103(R)
[2] Eur. Phys. J. C (2014) 74: 3092
[3] High Energ. Phys. (2014) 2014: 88

Observation of the $\chi_{B1}(3P)$ and $\chi_{B2}(3P)$ states

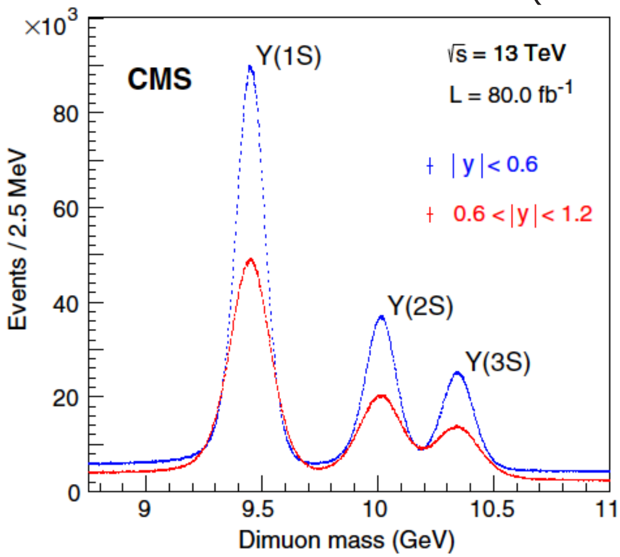
PHYSICAL REVIEW LETTERS 121, 092002 (2018)

Selection of $\Upsilon(nS)$ candidates

2 OS muons with inv mass in 8.5-11.5 GeV, common vertex

Υ **candidates** : pT > 14 GeV and |y| < 1.2

Dimuon mass resolution from 60 MeV (y=0) to 120 MeV (y=1.2)



Selection of $\chi_b(nP)$ candidates

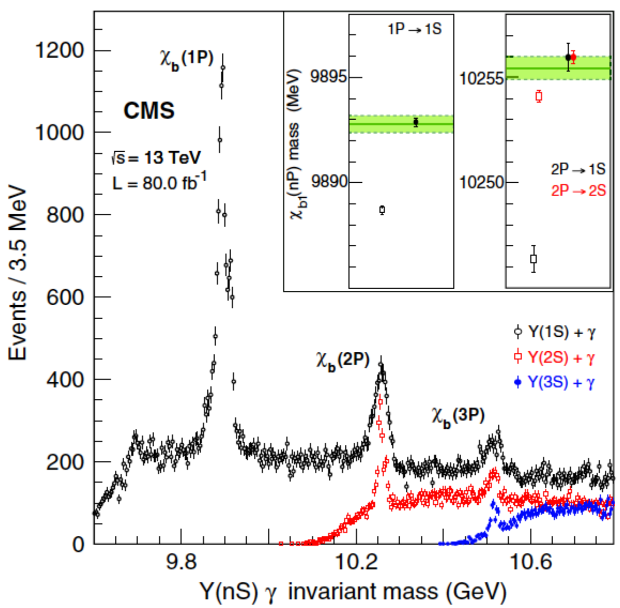
Photons reconstructed from the conversion $\gamma \to ee$

γ **candidates** : pT > 500 MeV and $|\eta|$ < 1.2

Photons energy scale calibrated in a control sample and applied event by event

Dimuon and photon are combined and constrained to have a common vertex with prob > 1%

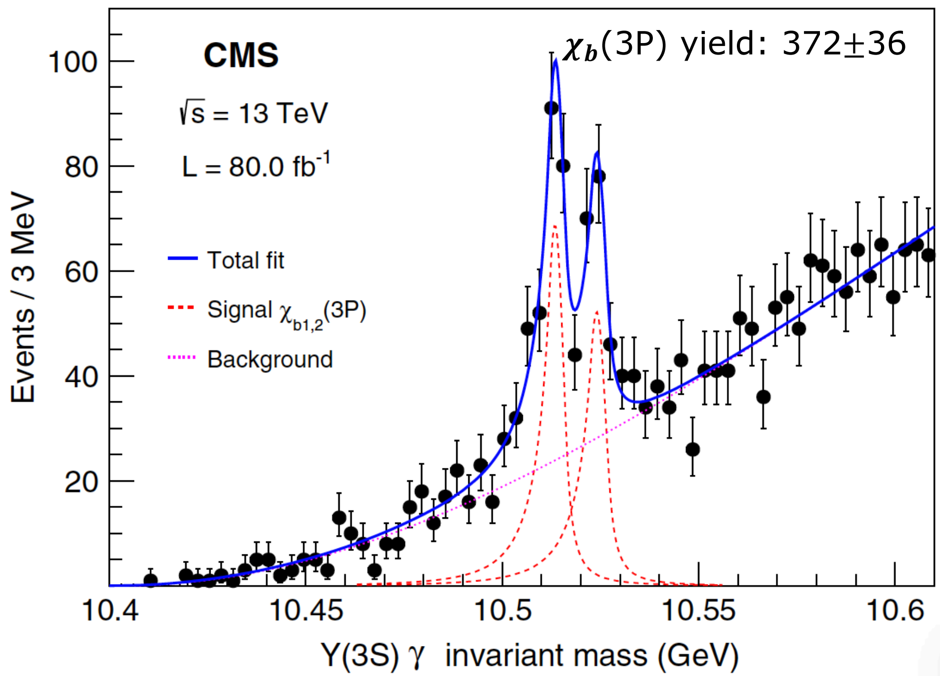
If multiple candidates -> best fit taken



OBSERVATION OF THE $\chi_{B1}(3P)$ AND $\chi_{B2}(3P)$ STATES

PHYSICAL REVIEW LETTERS 121, 092002 (2018)

- $\Upsilon(3S)\gamma$ invariant mass described by an unbinned maximum likelihood fit
- Mass resolution of 2.18 ± 0.32 MeV for the lower peak -> in agreement with the simulations
- Systematic uncertainty sources:
  - fit parameters fixed in signal and bkg (0.05 MeV)
  - Photon energy correction (0.16 - 0.17 MeV) -> dominant



OBSERVATION OF THE χ_{B1}(3P) AND χ_{B2}(3P) STATES

PHYSICAL REVIEW LETTERS 121, 092002 (2018)

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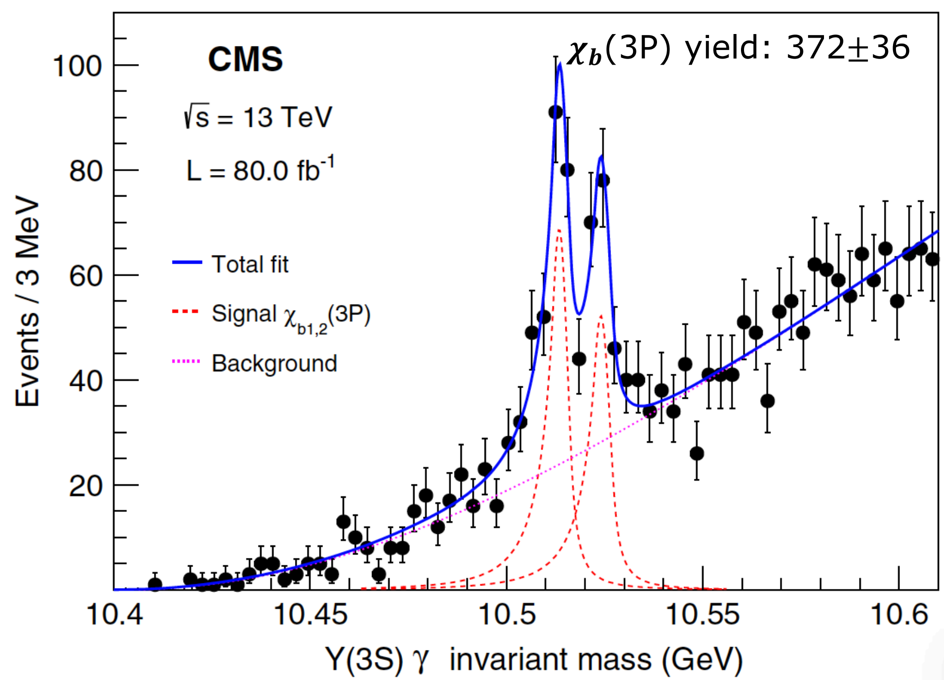


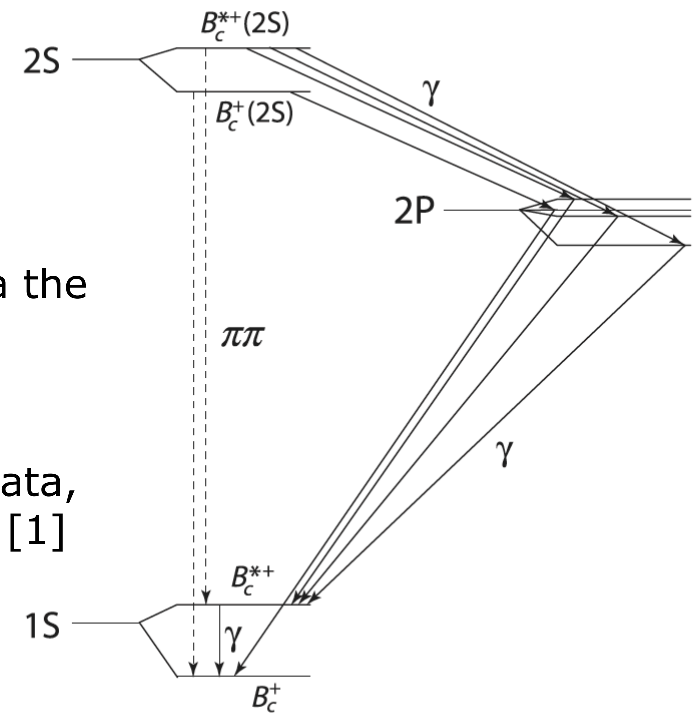
This is **the first observation of resolved χ_{b1}(3P) and χ_{b2}(3P) states** with masses:

$$M(\chi_{b1}(3P)) = 10513.42 \pm 0.41\ (\text{stat}) \pm 0.18\ (\text{syst}) \pm 0.5\ (\Upsilon(3S))\ \text{MeV}$$
$$M(\chi_{b2}(3P)) = 10524.02 \pm 0.57\ (\text{stat}) \pm 0.18\ (\text{syst}) \pm 0.5\ (\Upsilon(3S))\ \text{MeV}$$

$\Delta M = 10.60 \pm 0.64$ (stat) $\pm$ 0.17 (syst) MeV
compatible with the theoretical expectations

Observation of B_C^+ (2S) and B_C^{+*} (2S) states

PHYSICAL REVIEW LETTERS 122, 132001 (2019)



- The Bc mesons ($b\bar{c}$) family is predicted to be very populated but the spectroscopy and property studies are still scarces
- The $b\bar{c}$ exited states decay to the ground states via the cascade emission of γ and π pairs -> total width of O(100KeV) -> **hard to detect**
- ATLAS Collaboration observed a peak with Run 1 data, maybe the superimposition of $B_c^+(2S)$ and $B_c^{*+}(2S)$ [1]
- LHCb didn't confirm the observation with Run 1 data [2] but they saw the double peaks adding Run 2 data [3]

CMS performed the analysis using 2015, 2016, 2017, 2018 data (L = 143 fb^{-1}) and **observed for the first time the resolved states $B_c^+(2S)$ and $B_c^{*+}(2S)$**

[1] Phys. Rev. Lett. 113, 212004 (2014)
[2] J. High Energ. Phys. (2018) 2018: 138
[3] Phys. Rev. Lett. 122 (2019) 232001

Observation of B_c^+ (2S) and B_c^{+*} (2S) states

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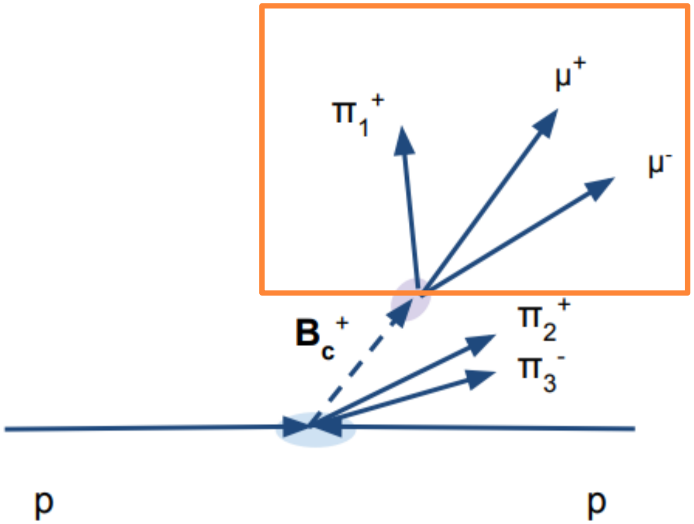


$B_c(2S) \rightarrow B_c\, \pi^+ \pi^-$

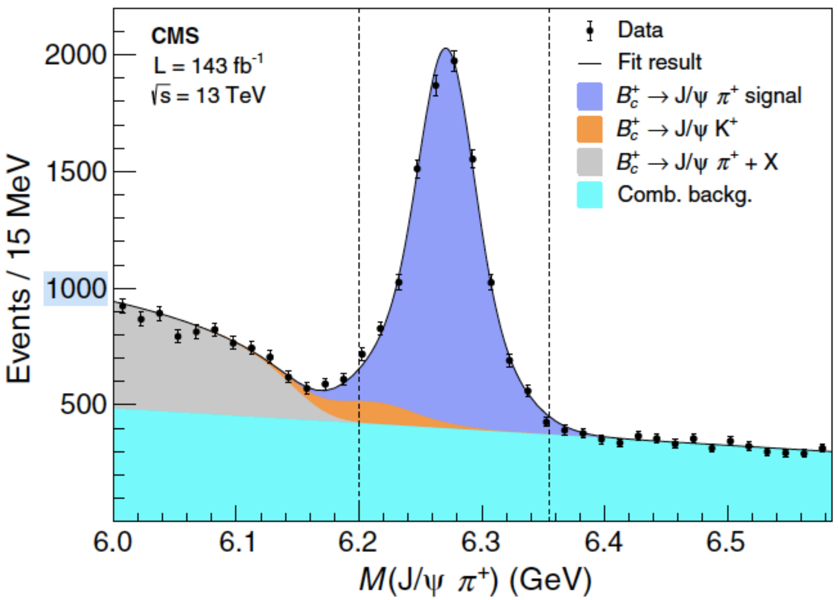
Selection of B_c^+ candidates

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

B_c^+ invariant mass fit

- Partially reconstructed bkg, $B_c^+ \rightarrow J/\psi + \pi + X$ -> ARGUS function
- Peaking bkg from $B_c^+ \rightarrow J/\psi + K$ –> shape from simulation
- Combinatorial bkg -> first-order Chebyshev polynomial
- Signal peak -> sum of 2 gaussians

B_c^+ yield: 7629 ± 225



B_c^+ mass = 6271.1 ± 0.5 MeV with a resolution of 33.5 ± 2.5 MeV

Observation of B_C^+ (2S) and B_C^{+*} (2S) states

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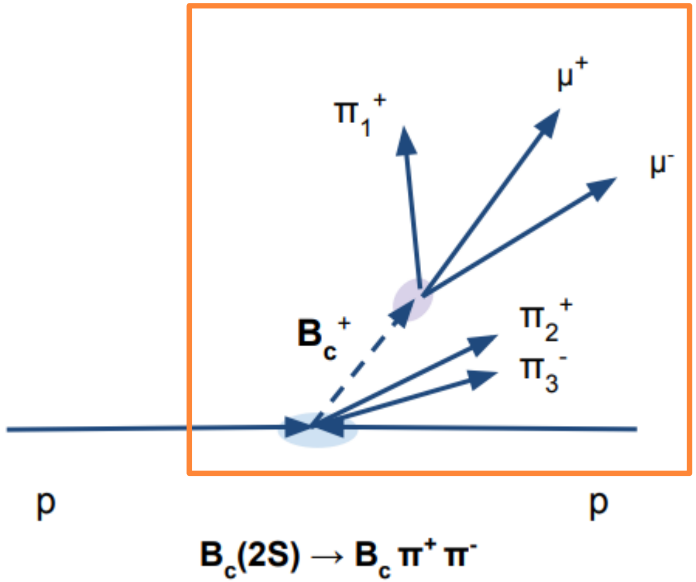


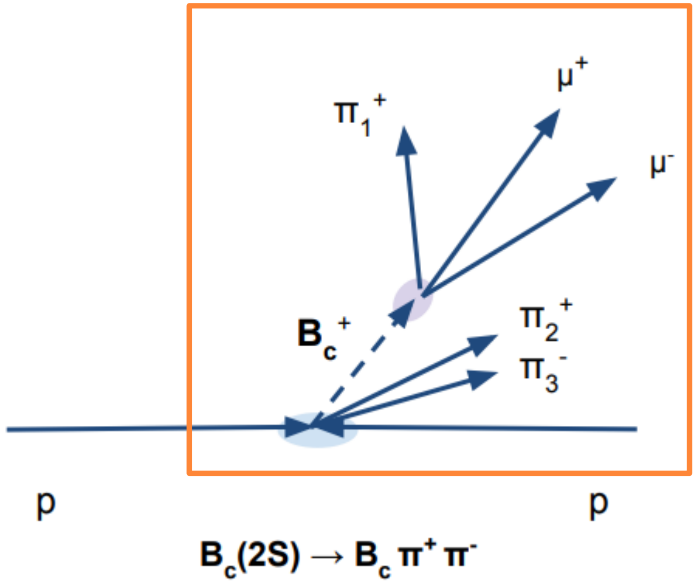
Selection of $B_c^+(2S)$ and $B_c^{+*}(2S)$ candidates

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

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

OBSERVATION OF B_C^+ (2S) AND B_C^{+*} (2S) STATES

PHYSICAL REVIEW LETTERS 122, 132001 (2019)



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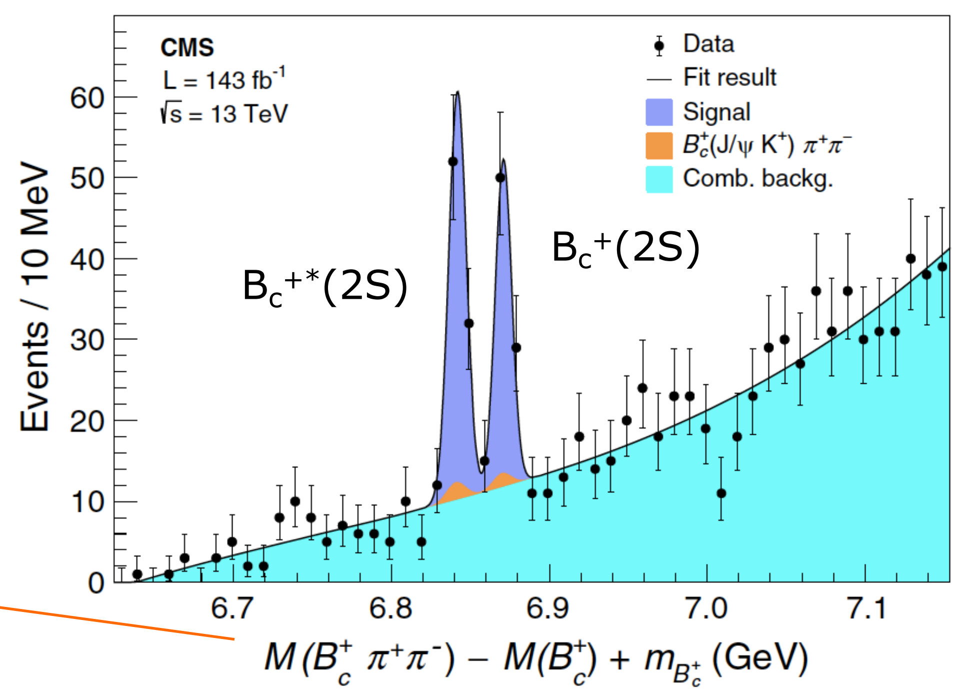
If more candidates found -> the one with highest pT is taken

$B_c^+(2S)$ invariant mass fit

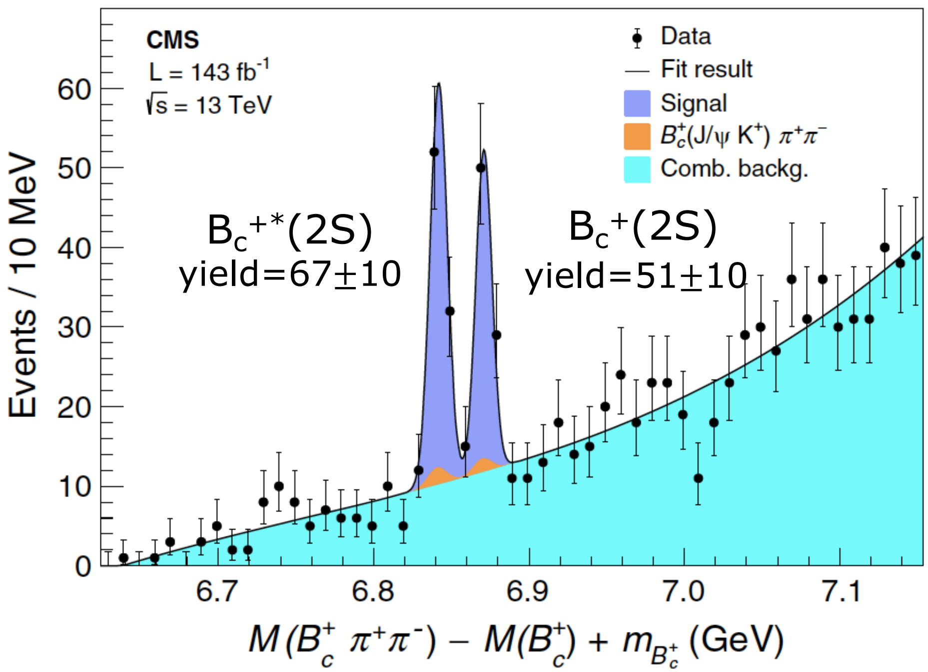
- Peaking bkg from $B_c^+(J/\psi + K)\pi\pi$ -> gaussian
- Combinatorial bkg -> 3-order Chebyshev polynomial
- Signal peak -> sum of 2 gaussians



$M(B_c\pi\pi)$ and $M(B_c)$ are reconstructed invariant masses of the $B_c\pi\pi$ and B_c candidates, and m_{Bc} is the world-average B_c mass

Observation of B_c^+ (2S) and B_c^{+*} (2S) states

PHYSICAL REVIEW LETTERS 122, 132001 (2019)



Emitted γ not detectable (effi < 1%) -> mass of B_c^{+*}(2S) not measured

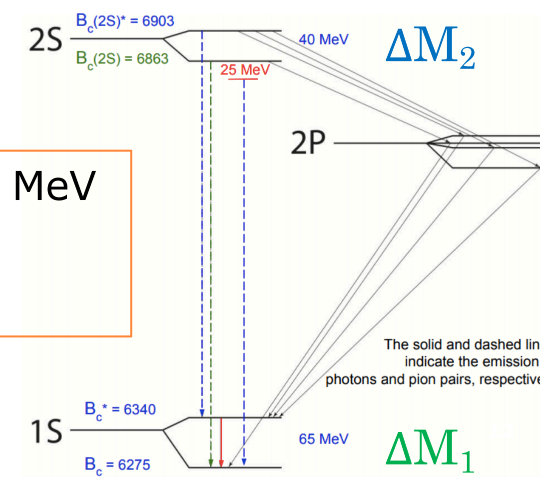
Main systematic source: peak modelling (0.7/0.8 MeV)

Significance of 2 peaks instead of 1 is 6.5 σ

First observation of two exited states

$M(B_c^+(2s))$ = 6871.0 ± 1.2 (stat) ± 0.8 (syst) ± 0.8 (B_c^+) MeV

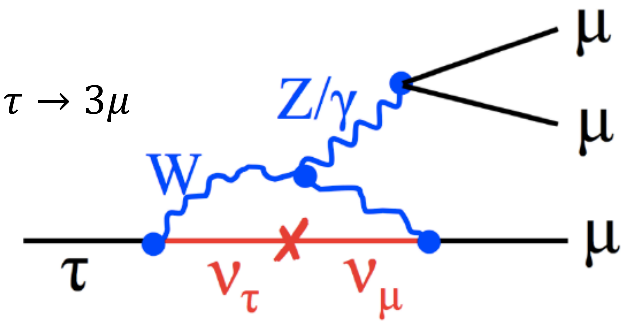
$\Delta M = \Delta M_1 - \Delta M_2$ = 29.1 ± 1.5 (stat) ± 0.7 (syst) MeV

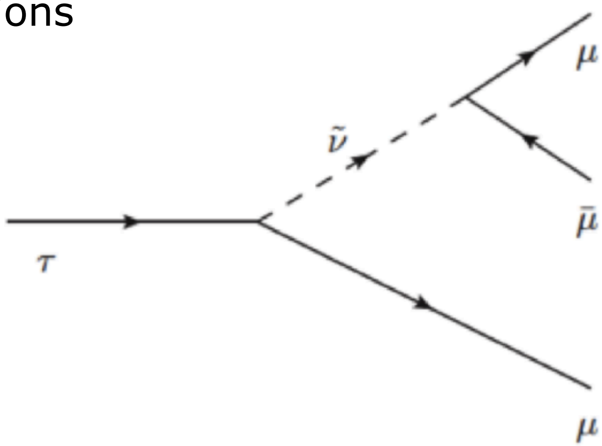


Search for $\tau \to 3\mu$, with τ coming from D and B mesons

CMS-PAS-BPH-17-004

- Search for lepton flavour violation (LFV) in the decay $\tau \to 3\mu$
  - Very clean final state for CMS
- Allowed by neutrino oscillation with very small BR
- Some NP models foresees appreciable branching fractions
- So far only upper limit set by Belle [1], BaBar [2], ATLAS [3], LHCb[4]
- The best limit comes from Belle: BR < $2.1 \cdot 10^{-8}$ (90% CL)





The CMS analysis searches for the $\tau \to 3\mu$ decay, with the τ produced in D and B hadron decays, using the data collected in 2016, corresponding to 33 fb^{-1}

[1] Phys. Lett. B 687 (2010) 139
[2] Phys. Rev. D 81 (2010) 111101
[3] JINST 3 (2008) S08005
[4] JINST 3 (2008) S08003

Search for $\tau \rightarrow 3\mu$, with τ coming from D and B mesons

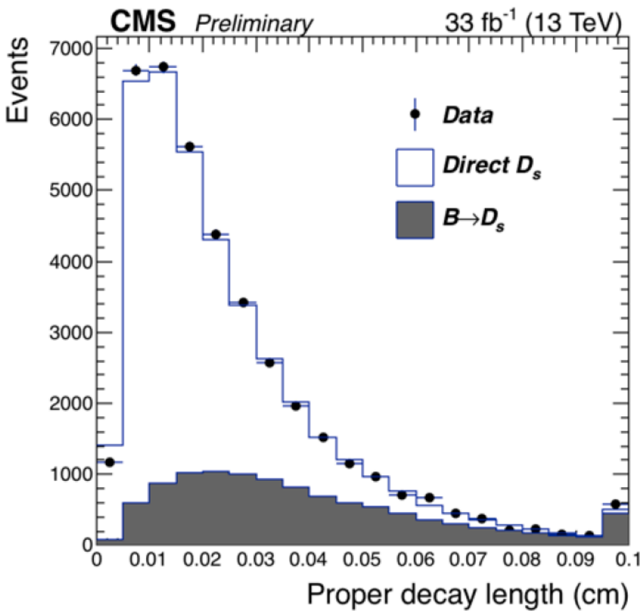
CMS-PAS-BPH-17-004

Selection of τ candidates

Muon pT > 2 GeV, muon $|\eta|$ < 2.4
Muons with a common displaced vertex
τ candidates: 3 muon with all the muon pairs with |ΔR| < 0.8 and |Δz| < 0.5 cm.
total charge ± 1
trimuon mass range [1.61 - 2] GeV

Normalisation sample

$D_S^{\pm} \rightarrow \phi\pi^{\pm} \rightarrow \mu^{+}\mu^{-}\pi^{\pm}$ decays used as normalisation channel
Events selected with the same signal trigger and momentum requests
Used to measure the production rate of D and B mesons in the kinematic phase space relevant for the search, directly from data



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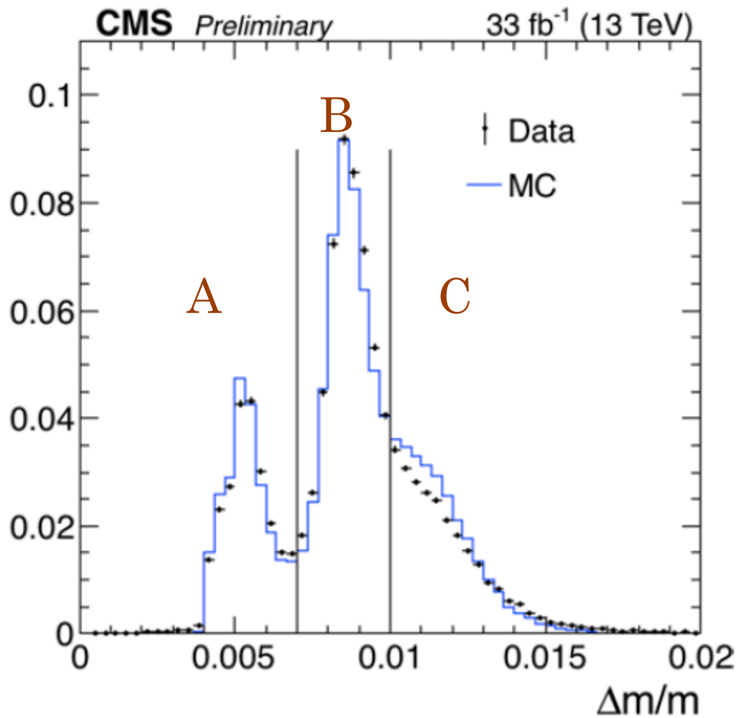
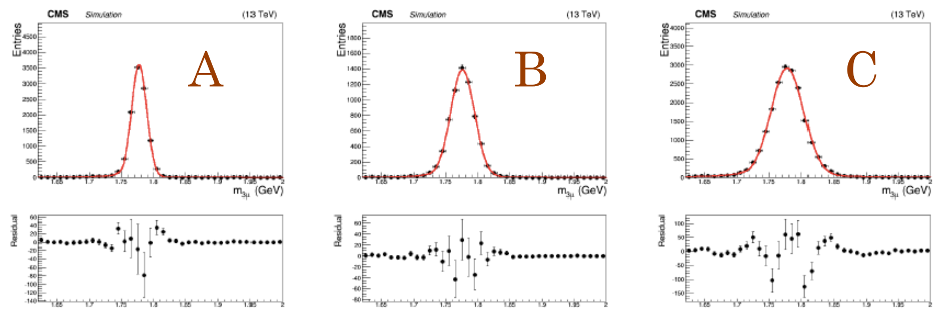
CMS-PAS-BPH-17-004

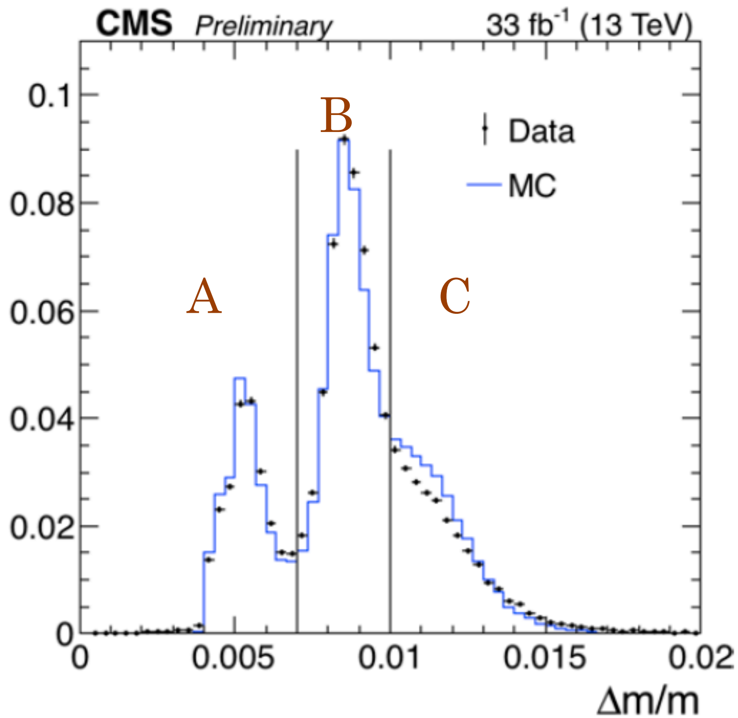


Mass resolution changes [0.4 – 1.5 %] according to the muon rapidity: 3 categories identified



SEARCH FOR $\tau \to 3\mu$, WITH τ COMING FROM D AND B MESONS

CMS-PAS-BPH-17-004



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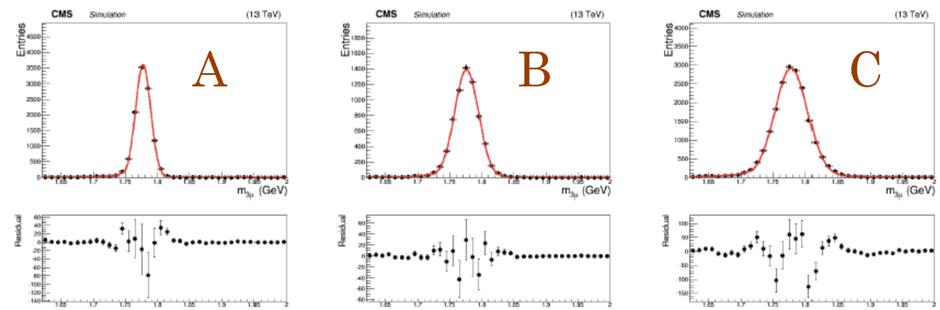
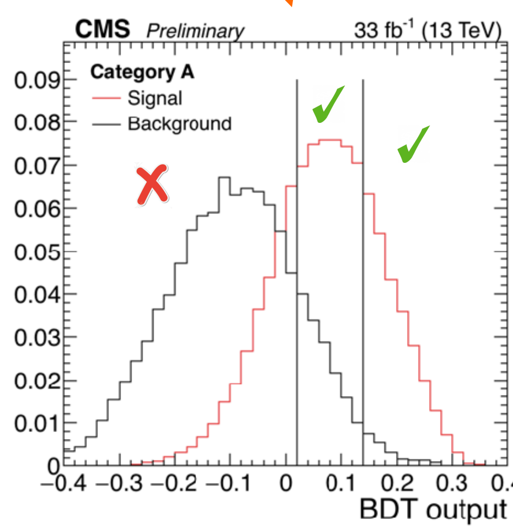
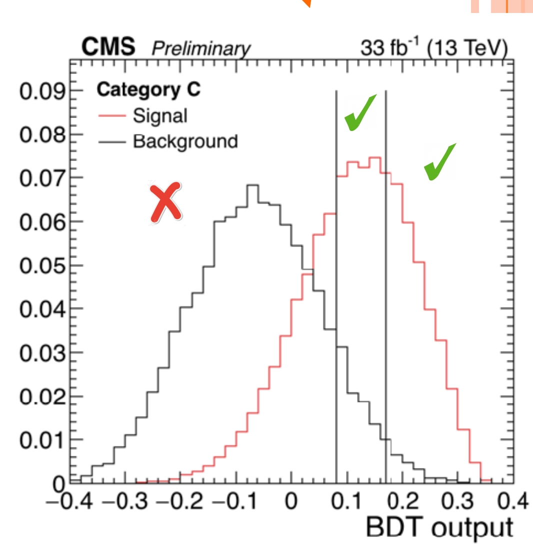


A BDT has been used to separate signal and bkg, using as input variables vertex-quality and muon-quality variables

- Signal is taken from simulation
- Bkg from data sb

BDT output used to identify 3 more subcategories. 2 used and 1 rejected





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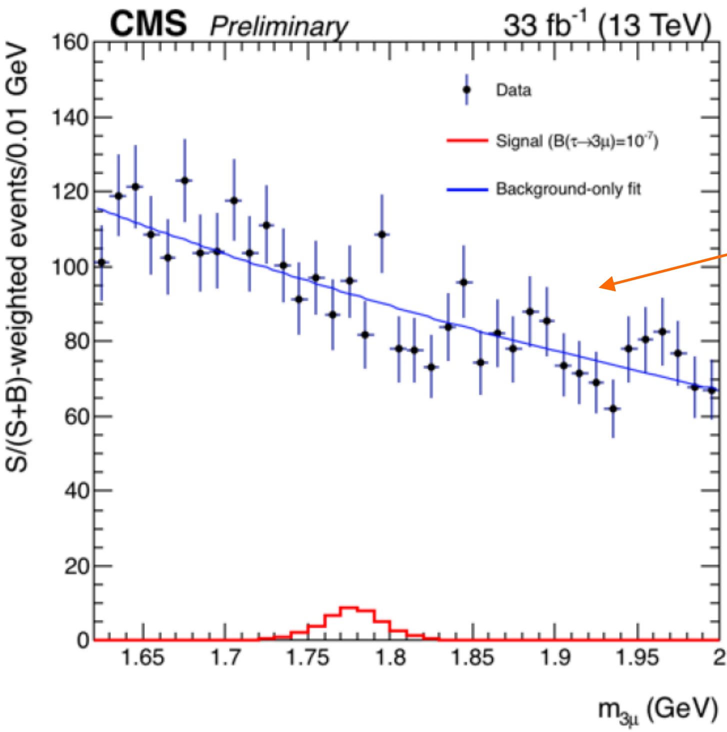


- Maximum likelihood fit performed on the six categories simultaneously (backup)
- The 6 categories are then combined with the appropriate weights
- Several systematic uncertainties considered: D_s normalization dominates (10%)
- No excess observed -> limit set

Expected limit 90% CL : BR $(\tau \to 3\mu)$ = $9.9 \cdot 10^{-8}$
Observed limit 90% CL : BR $(\tau \to 3\mu)$ = $8.8 \cdot 10^{-8}$

PROPERTIES OF $B_s^0 \to \mu^+\mu^-$ AND SEARCH FOR $B^0 \to \mu^+\mu^-$

New

CMS-PAS-BPH-16-004

- Leptonic B meson decays offer excellent opportunities to perform precision tests of the SM because there are minimal hadronic uncertainties.

- In the SM:
  BR($B_s^0 \to \mu^+\mu^-$) = (3.57 ± 0.17)*10^{-9} and BR($B^0 \to \mu^+\mu^-$) = (1.06 ± 0.09)*10^{-10}

- The BR($B_s^0 \to \mu^+\mu^-$) has been measured by CMS [1], LHCb [2] and ATLAS [3]
- The BR($B^0 \to \mu^+\mu^-$) has been only measured by CMS and LHCb combined [4]

- Results on **BR($B_s^0 \to \mu^+\mu^-$) and BR($B^0 \to \mu^+\mu^-$)** are reported together with the first measurement in CMS of the **$B_s^0 \to \mu^+\mu^-$ effective lifetime**

- Used data from 2011, 2012 and 2016 at 3 different center of mass enegies:
  7, 8, 13 TeV -> L= 5 + 20 + 36 fb^{-1}

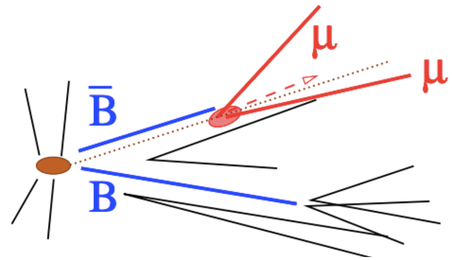
[1] Phys. Rev. Lett. 111 (2013) 101804
[2] Phys. Rev. Lett. 118 (2017) 191801
[3] JHEP 04 (2019)738 098
[4] Nature 522 (2015) 68

PROPERTIES OF $B_s^0 \to \mu^+\mu^-$ AND SEARCH FOR $B^0 \to \mu^+\mu^-$

CMS-PAS-BPH-16-004

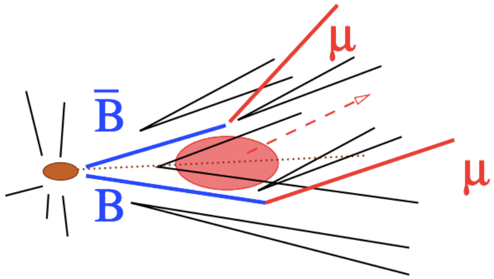
Signal

Two OS muons from a common vertex



Background

- Combinatorial
- Rare single B decay



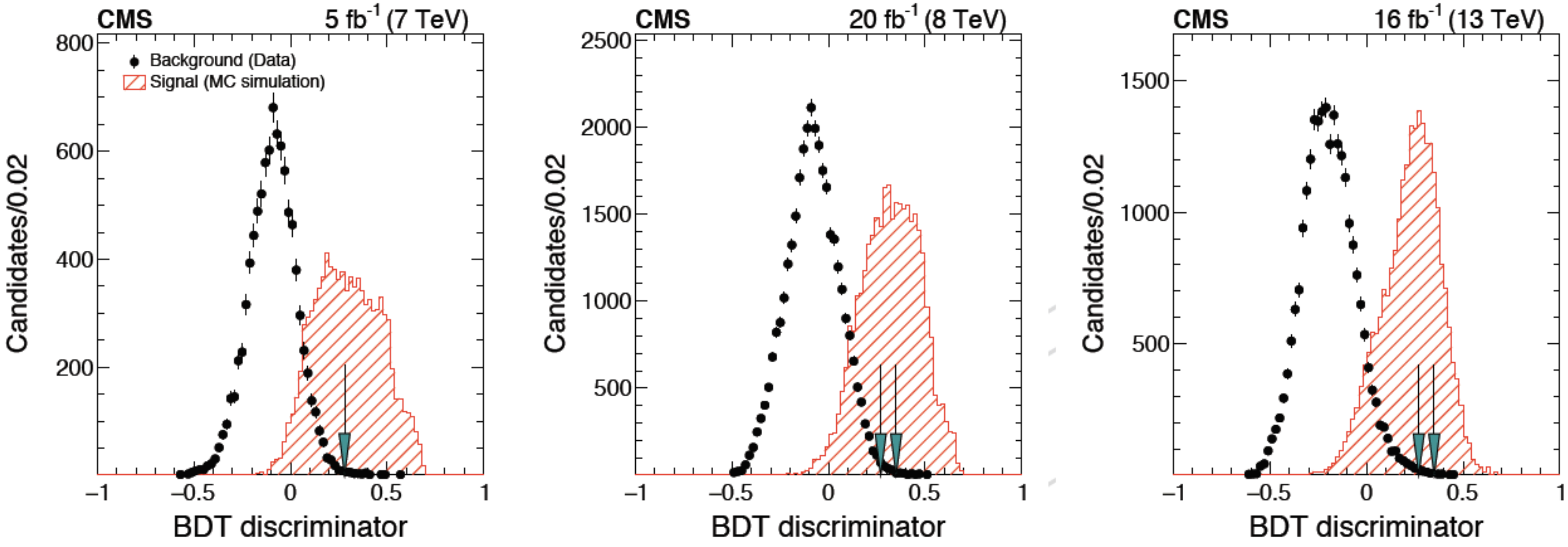
Main improvement from the Run1 analysis: better muon identification (via MVA) with a 5% improvement on muon efficiency and a misidentification rate about 10 times lower for global muons

Trigger: dedicated B^0_s trigger with 2 OS muons with $4.8 < |m_{\mu\mu}| < 6$ GeV

Several control sample used for the validation and for the BR calculation

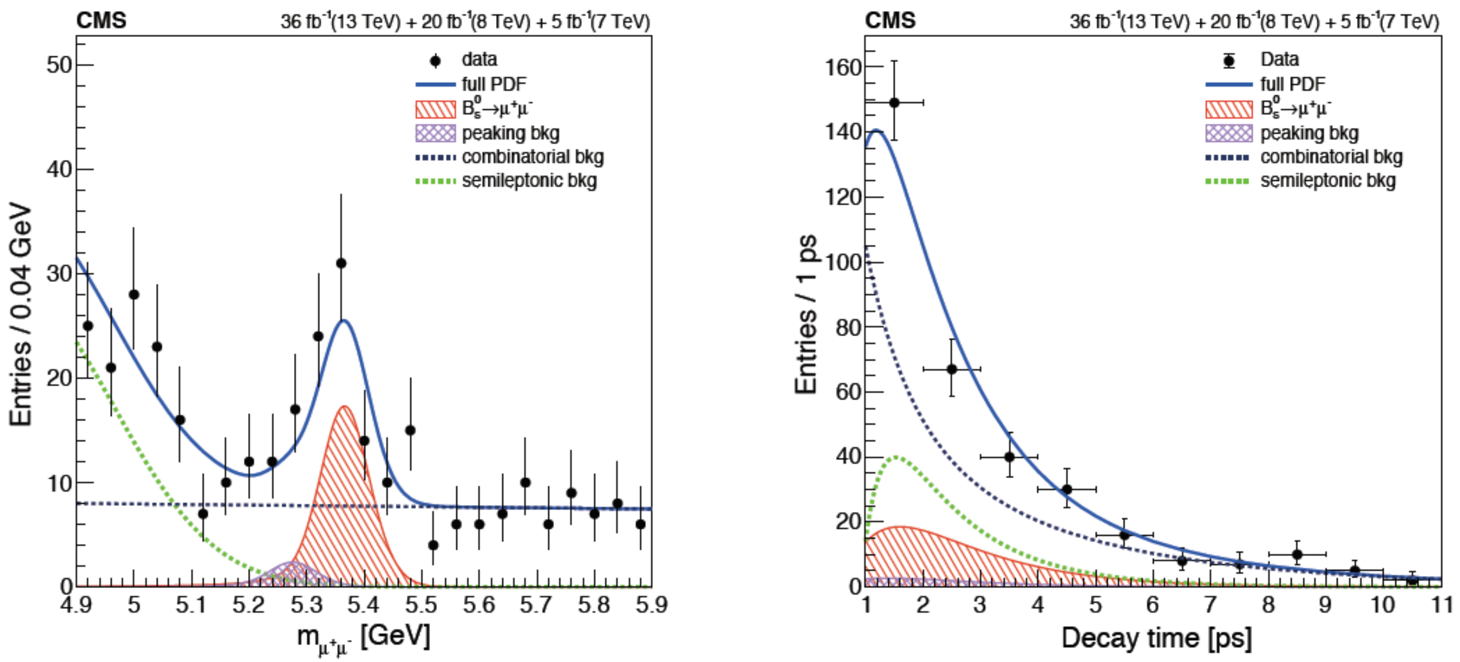
PROPERTIES OF $B_s^0 \rightarrow \mu^+\mu^-$ AND SEARCH FOR $B^0 \rightarrow \mu^+\mu^-$

- A BDT has been used for the signal – bkg separation
  - Same variables as run1 analysis: B candidates/tracks, vertexing and isolation
- Run1 data are analysed with the old BDT, run2 data with a new one



Properties of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$

CMS-PAS-BPH-16-004



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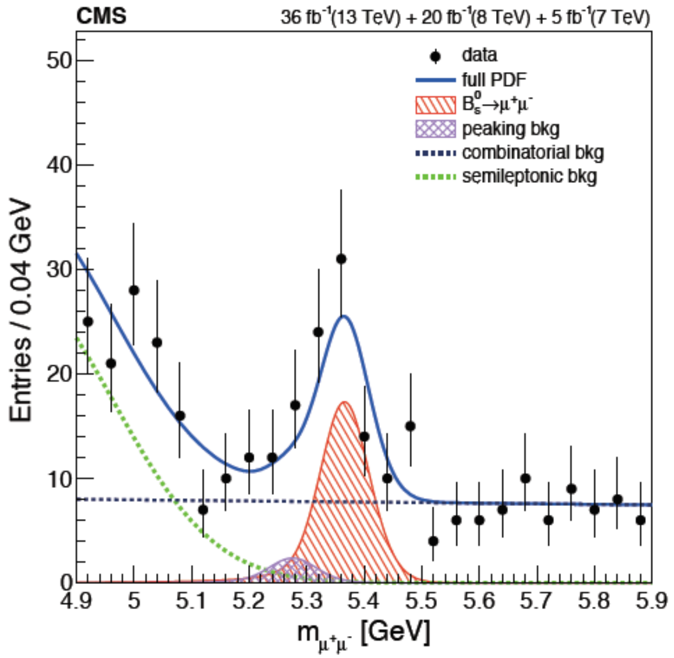
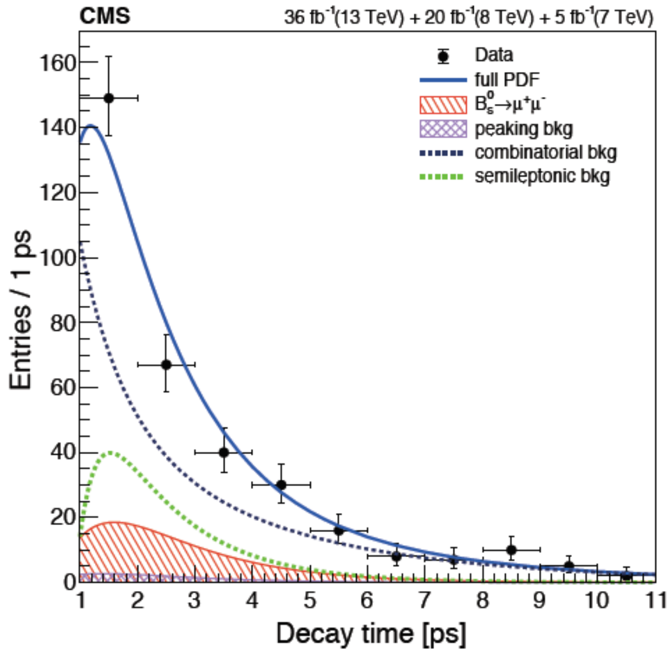




The B_s^0 **peak is clearly visible** with an observed significance of 5.6 σ

BR $(B_s^0 \to \mu^+\mu^-) = [2.9^{-0.7}_{-0.6} \pm 0.2(\frac{f_s}{f_u})] \cdot 10^{-9}$

No significant signal observed for the B^0

-> upper limit set on the BR

BR $(B^0 \to \mu^+\mu^-) < 3.6 \cdot 10^{-10}$ at 95% CL

The B_s^0 lifetime is evaluated with a 2D unbinned maximum likelihood fit

$\boldsymbol{\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0,44}}$ **ps**

OBSERVATION OF $\Lambda_b \rightarrow J/\psi\Lambda\Phi$ DECAY

New

CMS-PAS-BPH-19-002

- The study of b baryon decays is important to understand the dynamic of heavy flavour decay process

- Several studies have been carried out by ATLAS, CMS and LHCb on the Λ_b^0
  - mass measurement of ground [1] and exited [2] states, lifetime[3], polarization [4] mostly in $\Lambda_b^0 \rightarrow J/\psi\Lambda$
  - from the decay of the Λ_b^0 new pentaquarks states have been observed by LHCb [5]

- CMS performed **the first observation of the decay $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$** with the measurement of the branching ratio fraction as:

$$\frac{BR(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)}{BR(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)}{N(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} \frac{BR(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)}{BR(\phi \rightarrow K^-K^+)} \frac{\epsilon(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)}{\epsilon(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)}$$

2018 data collected at 13 TeV have been used-> L ~ 60 fb^{-1}

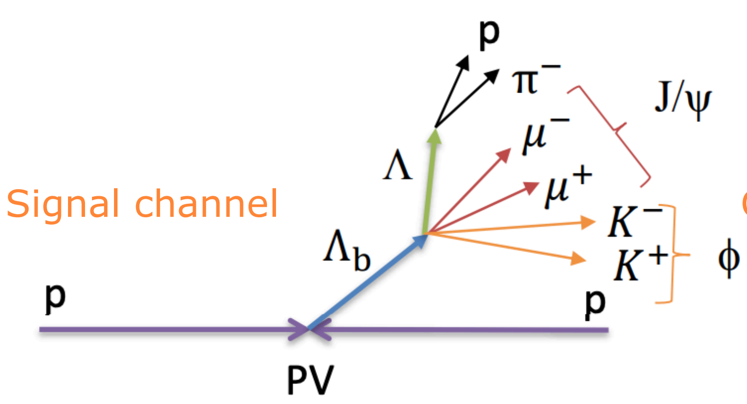
[1] Phys. Rev. Lett. 119 (2017) 062001
[2] Phys. Rev. Lett. 109 (2012) 172003
[3] Phys. Rev. D 87 (2013) 032002
[4] Phys. Rev. D 97 (2018) 072010
[5] Phys. Rev. Lett. 122 (2019) 222001

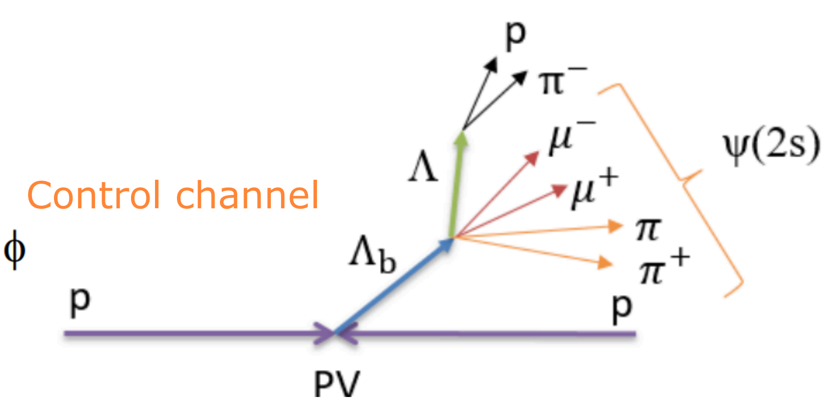
OBSERVATION OF $\Lambda_b \to J/\psi\Lambda\Phi$ DECAY

CMS-PAS-BPH-19-002

Object selection

Muon: pT(μ ±) > 4.0 GeV, |η(μ ±)| < 2.4
J/ψ: |mJ/ψ-3096.9 MeV|< 100 MeV, pT (J/ ψ) > 7.0 GeV, vtx prob(J/ψ) >10%, J/ψ L/σ > 3.0
Charged tracks: pT(tracks) > 0.8 GeV, $|m_{KK} - 1.02| < 0.03$ GeV for signal, $|m_{J/\psi\pi\pi}-m_{\psi(2S)}^{PDG}| < 15$ MeV for norm
Λ selection: pT Λ > 1 GeV, vtx prob(Λ)>1%, |mΛ − mV0|<7,5 MeV
Λ_b selection: pT Λ_b > 10 GeV, L/σ > 3, vtx prob(Λ_b)>1%, 1 candidate per event, $\cos_{PV}(\alpha)$ >0.99

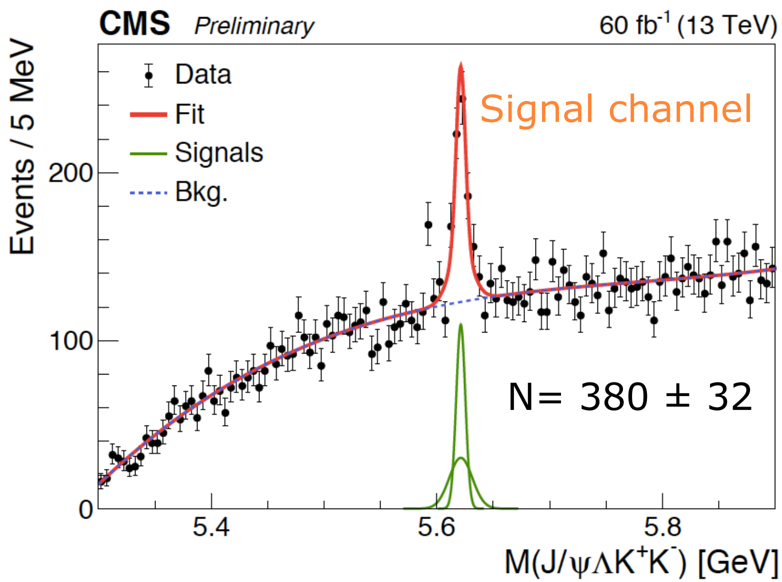


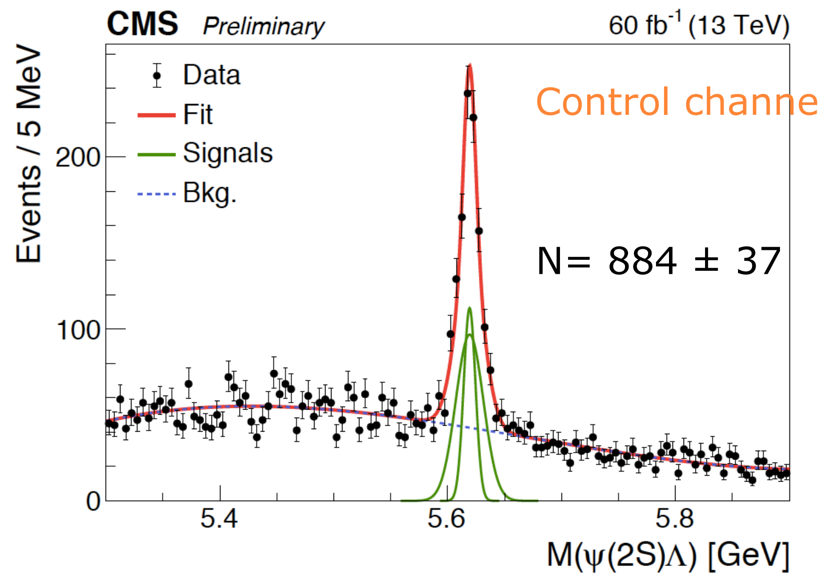


Observation of $\Lambda_b \to J/\psi\Lambda\Phi$ decay

CMS-PAS-BPH-19-002

Main syst uncertainties: data/simulation difference in Λ^0_b resolution for the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay (6.6%)





The first observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay

$$\frac{BR(\Lambda_b^0 \to J/\psi\Lambda\phi)}{BR(\Lambda_b^0 \to \psi(2S)\Lambda)} = 8.26 \pm 0.90(stat) \pm 0.68\,(syst) \pm 0.11\,(BR) \times 10^{-2}$$

SUMMARY

Very important results have been recently produced in the B-physics group in CMS:

- First observation of the resolved **χ_{b1}(3P) and χ_{b2}(3P) states**:
- First observation of the resolved **B_c^+ (2S) and B_c^{+*} (2S) states**:
- First results in CMS for the search for $\tau \to 3\mu$, with τ coming from D and B mesons;
- Properties of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$ superseding the old CMS results;
- First observation of $\Lambda_b \to J/\psi\Lambda\Phi$ **decay**:

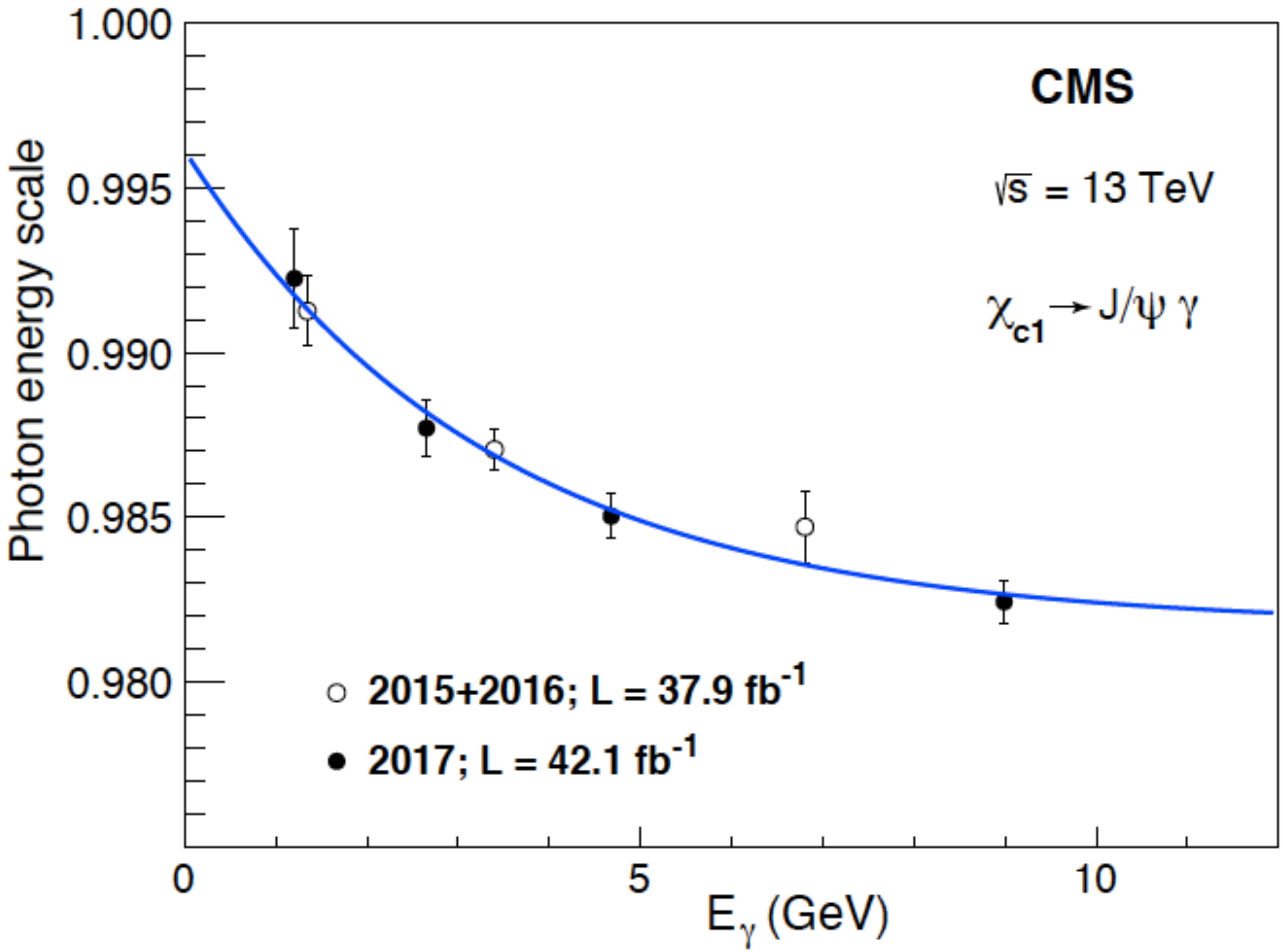
Interesting results from the B-physics -> **more has to come!**

THANK YOU FOR THE ATTENTION

BACKUP

OBSERVATION OF THE $\chi_{B1}(3P)$ AND $\chi_{B2}(3P)$ STATES

Photon energy correction



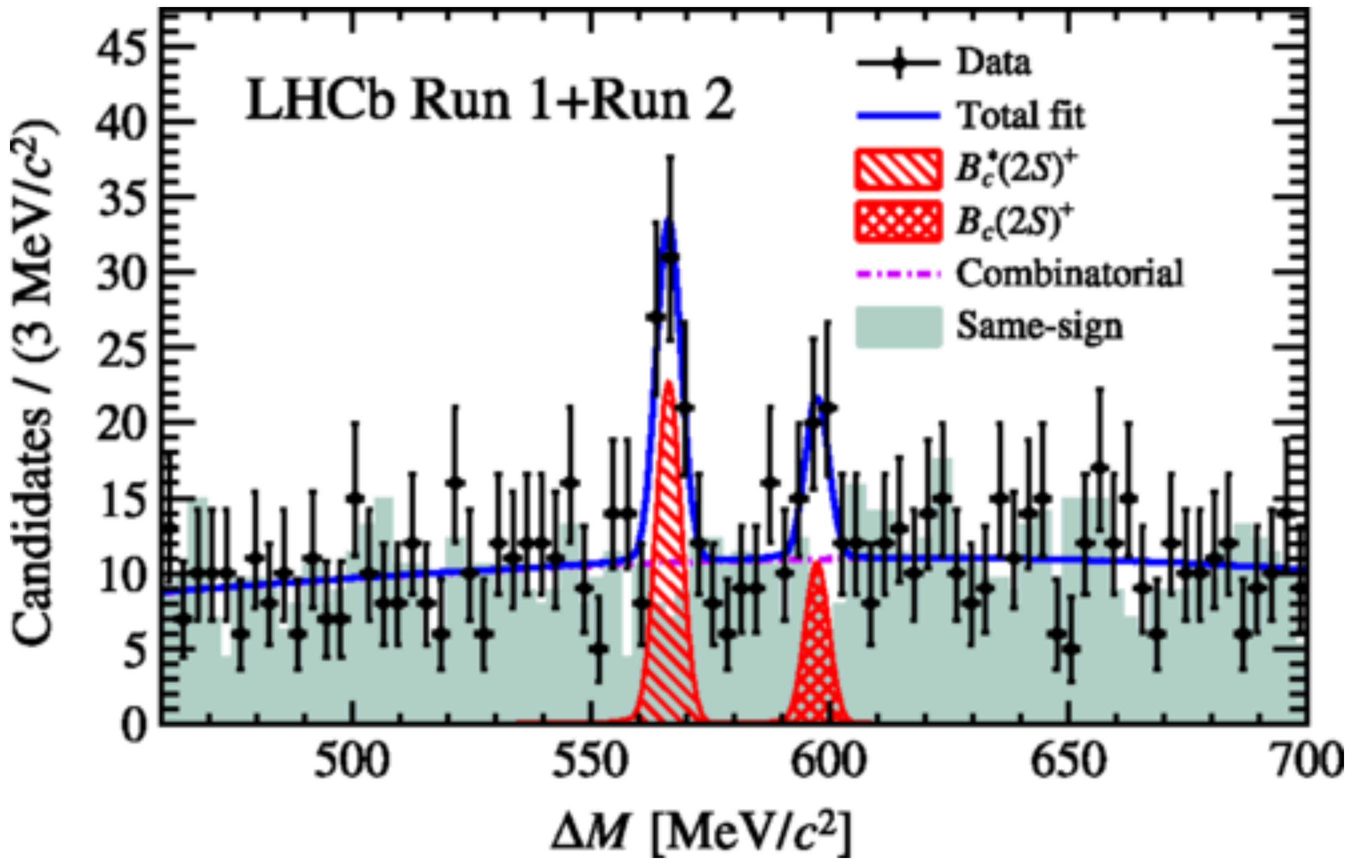
Observation of B^+_c (2S) and B^{+*}_c (2S) states

LHCb results:

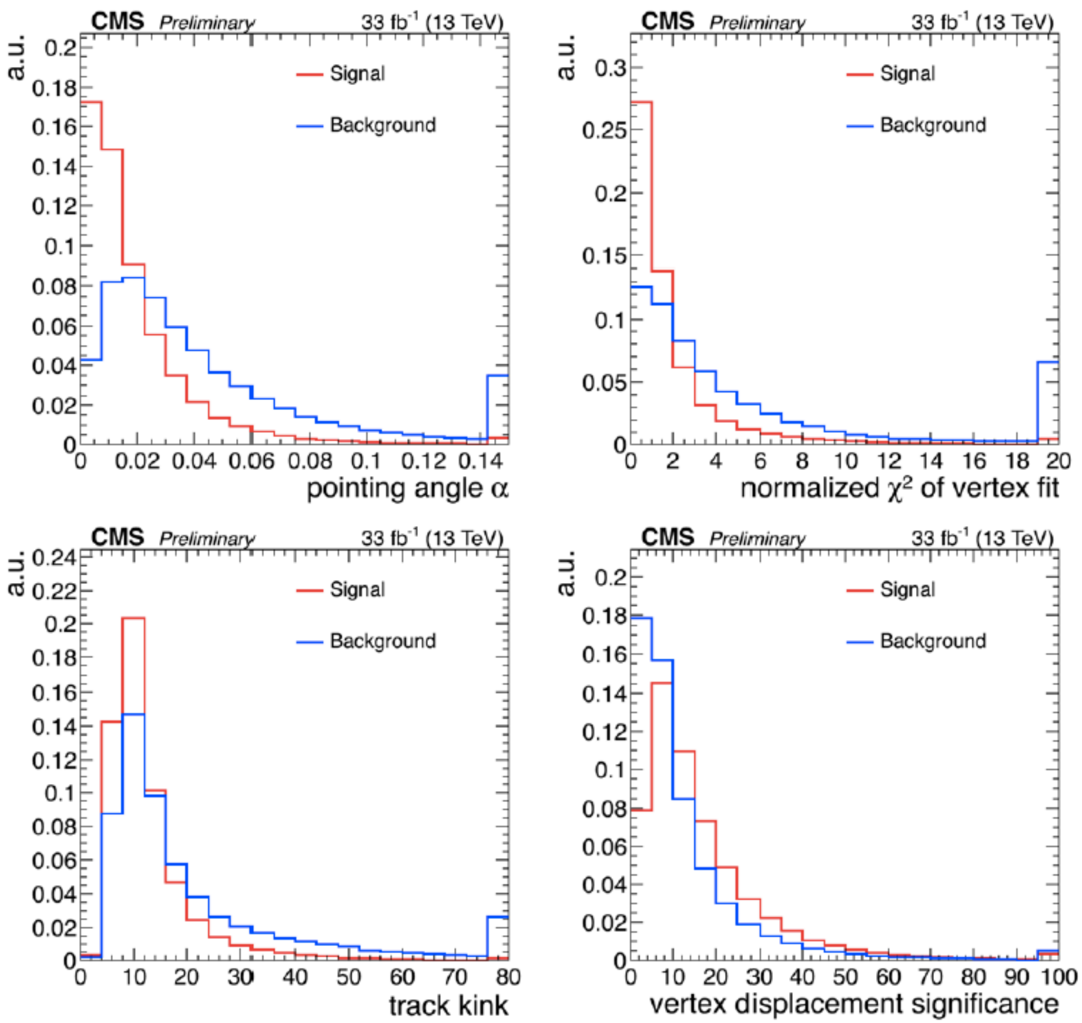
$\sqrt{s}$=7,8,13 TeV -> L = 8.5 fb^{-1}

First peak with mass 6841.2±0.6(stat)±0.1(syst)±0.8(B^+_c) MeV/c compatible with the B^{+*}_c (2S) state

Second peak with a global (local) statistical significance of 2.2σ (3.2σ) and mass of 6872.1±1.3(stat)±0.1(syst)±0.8(B+c) MeV/c^2, consistent with the B^+_c (2S) state



SEARCH FOR $\tau \rightarrow 3\mu$, WITH τ COMING FROM D AND B MESONS

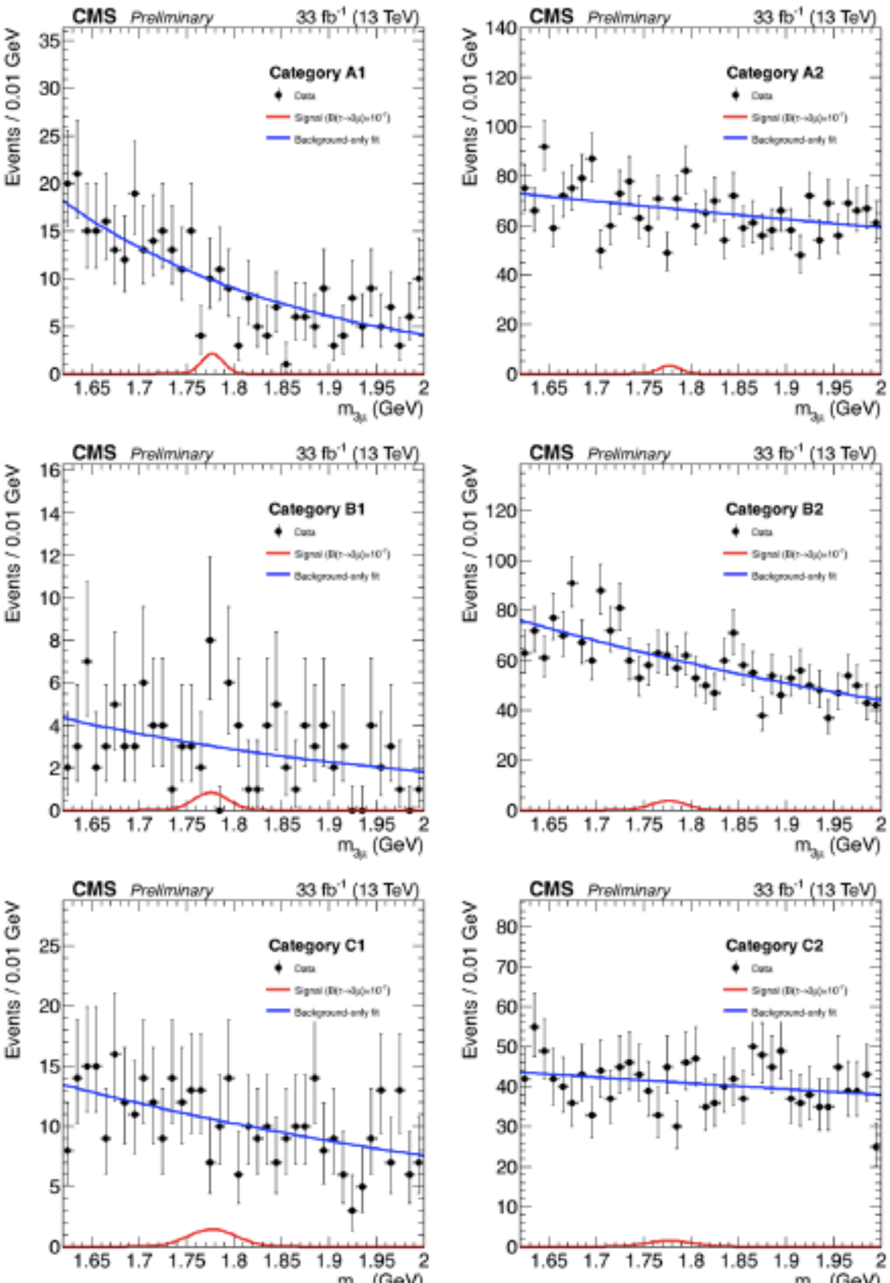


BDT training:
signal = signal simulation with mixed the D and B meson samples
background = data events from the trimuon mass sb.

10 variables divided in 2 groups:

- Signal with trimuon system from a common vertex displaced from the primary IP (better discriminating)
- Background dominated by muons coming from charged pion/kaon decays in flight or (semi-)random matching between hadron tracks in the tracker and track segments reconstructed in the muon system

Search for $\tau \to 3\mu$, with τ coming from D and B mesons



Search for $\tau \to 3\mu$, with τ coming from D and B mesons

Table 1: The expected inclusive number of τ leptons produced in D and B meson decays at LHC (13 TeV) for an integrated luminosity of 33 fb^{-1}. Numbers are from PYTHIA (without EVTGEN). Charge conjugated states are implied. For comparison, the number of τ leptons produced in W and Z boson decays is 8×10^8.

Process	Number of τ leptons (33 fb^{-1})
$pp \to c\,\bar{c} + ...$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^\pm$)
$pp \to b\overline{b} + ...$	
$B \to \tau\nu + ...$	1.5×10^{12} (44% $B^\pm$, 45% B^0, 11% B^0_s, 0% $B^\pm_c$)
$B \to D(\tau\nu) + ...$	6.3×10^{11} (98% D_s, 2% $D^\pm$)

Table 2: D and B meson decay branching fractions (and their uncertainties) used in this analysis.

Process	Branching ratio	Reference
$D_s \to \tau\nu$	$5.48 \pm 0.23\%$	PDG [13]
$B^+ \to \tau + \nu + D^{0(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^+ \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^0 \to \tau + \nu + D^{+(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^0 \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^+ \to D_s + X$	$9.0 \pm 1.5\%$	PDG [13]
$B^0 \to D_s + X$	$10.3 \pm 2.1\%$	PDG [13]
$D_s \to \phi(\mu\mu)\pi$	$1.3(\pm 0.1) \times 10^{-5}$	PDG [13]

SEARCH FOR $\tau \rightarrow 3\mu$, WITH τ COMING FROM D AND B MESONS

Table 3: Number of expected signal events, assuming $\mathcal{B}(\tau \rightarrow 3\mu) = 10^{-7}$, and the number of observed events in data at each step of the event selection. Events are counted in the trimuon mass range 1.62–2.00 GeV.

	Signal		Data
	$D_s \rightarrow \tau\nu$	$B^{\pm}/B^0 \rightarrow \tau...$	
Produced in pp collisions	4.4×10^5	1.5×10^5	
(with three muons in fiducial volume)	(6.6×10^3)	(2.3×10^3)	
L1/HLT trigger	214	114	
At least 3 global muons ($p_T > 2$ GeV)	88	47	1.0×10^7
Trimuon candidate selection	64	29	1.0×10^5

Table 4: Sources of systematic uncertainties affecting the signal modeling, and their impacts on the expected signal event yield and trimuon mass distribution shape.

Source of uncertainty	Yield	Shape
Uncertainty on D_s normalization [10%]	10%	
Relative uncertainty in $\mathcal{B}(D_s \rightarrow \tau\nu)$ [4%]	3%	
Relative uncertainty in $\mathcal{B}(D_s \rightarrow \phi\pi \rightarrow \mu\mu\pi)$ [8%]	8%	
Relative uncertainty in $\mathcal{B}(B \rightarrow D_s + ...)$ [16%]	5%	
Relative uncertainty in $\mathcal{B}(B \rightarrow \tau + ...)$ [11%]	3%	
Uncertainty in f (B/D ratio) [11%]	3%	
Uncertainty on D^+ as a source of τ [100%]	3%	
Uncertainty on B_s as a source of τ [100%]	4%	
Uncertainty in number of events triggered by trimuon trigger [8%]	2%	
Uncertainty in the ratio of acceptances $\mathcal{A}_{sig}/\mathcal{A}_{2\mu\pi}$ [1%]	1%	
Muon reconstruction efficiency [1.5%]	1.5%	
Charged pion reconstruction efficiency [2.3%]	2.3%	
BDT cut efficiency [5%]	5%	
Mass scale uncertainty [0.07%]	–	yes
Mass resolution uncertainty [2.5%]	–	yes

Table 5: Signal and data yields for the six event categories in the mass range 1.62–2.00 GeV. The signal yields are shown for $\mathcal{B}(\tau \rightarrow 3\mu) = 10^{-7}$. The data yields inside parentheses are in the mass ranges of 1.78 GeV $\pm 2\sigma$, where σ is the mass resolution (12 MeV, 19 MeV, and 25 MeV for the category A, B, and C respectively).

	Signal		Data	
	sub-category 1	sub-category 2	sub-category 1	sub-category 2
Category A	6.3	10.3	360(44)	2502(319)
Category B	3.9	18.5	110(27)	2229(449)
Category C	9.4	9.6	389(107)	1549(400)

Signal from D_s

$$N_{sig(D)} = N \frac{\mathcal{B}(D_s \rightarrow \tau\nu)}{\mathcal{B}(D_s \rightarrow \phi\pi \rightarrow \mu\mu\pi)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{2\mu\pi}} \frac{\epsilon_{reco}^{3\mu}}{\epsilon_{reco}^{2\mu\pi}} \frac{\epsilon_{trig,sig}^{2\mu}}{\epsilon_{trig(\mu\mu\pi)}^{2\mu}} \mathcal{B}(\tau \rightarrow 3\mu)$$

Signal from B

$$N_{sig(B)} = f \frac{\mathcal{B}(B \rightarrow \tau + \cdots)}{\mathcal{B}(B \rightarrow Ds + \cdots)\mathcal{B}(D_s \rightarrow \tau\nu)} \frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{3\mu(D)}} N_{sign(D)}$$

Search for $\tau \to 3\mu$, with τ coming from D and B mesons

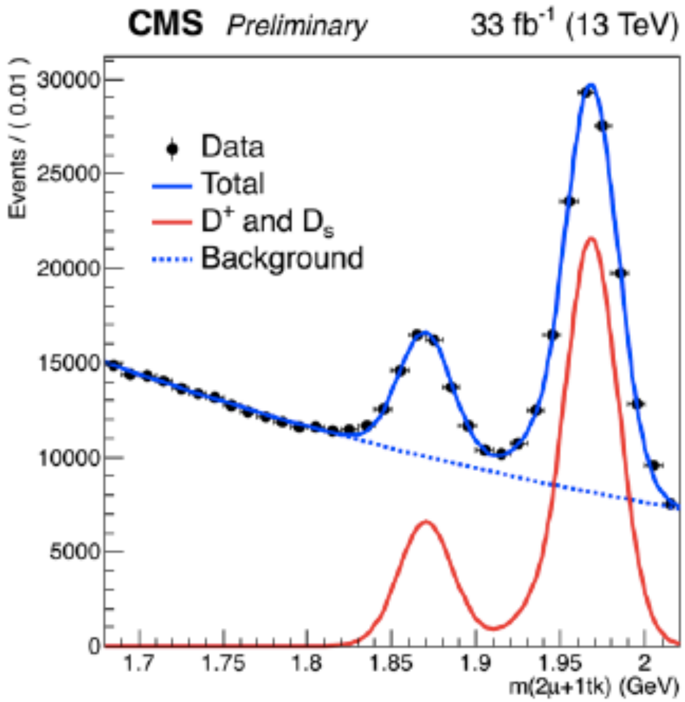


Figure 6: The invariant mass distribution for two muons and a pion after applying signal-like kinematic cuts on two muons and a pion, and after requiring that the two muons have opposite signs and their invariant mass is consistent the ϕ meson mass. The two peaks are associated with D_s (1.97 GeV) and D^+ (1.87 GeV) decays, and modelled with Crystal-Ball functions, while the background is fitted with an exponential function.

PROPERTIES OF $B_s^0 \to \mu^+\mu^-$ AND SEARCH FOR $B^0 \to \mu^+\mu^-$

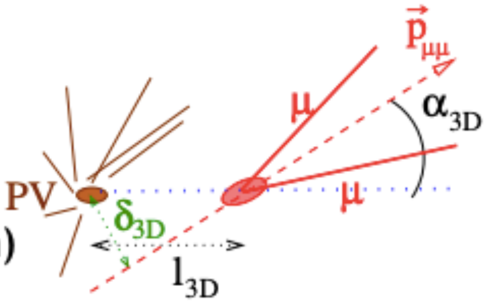
$$\mathcal{B}_{\mathrm{SM}}(B_s^0 \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9}$$
$$\mathcal{B}_{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{n^{\mathrm{obs}}_{B_s^0}}{N(B^+ \to J/\psi\, K^+)} \frac{A_{B^+}}{A_{B_s^0}} \frac{\varepsilon^{ana}_{B^+}}{\varepsilon^{ana}_{B_s^0}} \frac{\varepsilon^{\mu}_{B^+}}{\varepsilon^{\mu}_{B_s^0}} \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B_s^0}} \frac{f_u}{f_s} \mathcal{B}(B^+ \to J/\psi\,[\mu^+\mu^-]K^+)$$

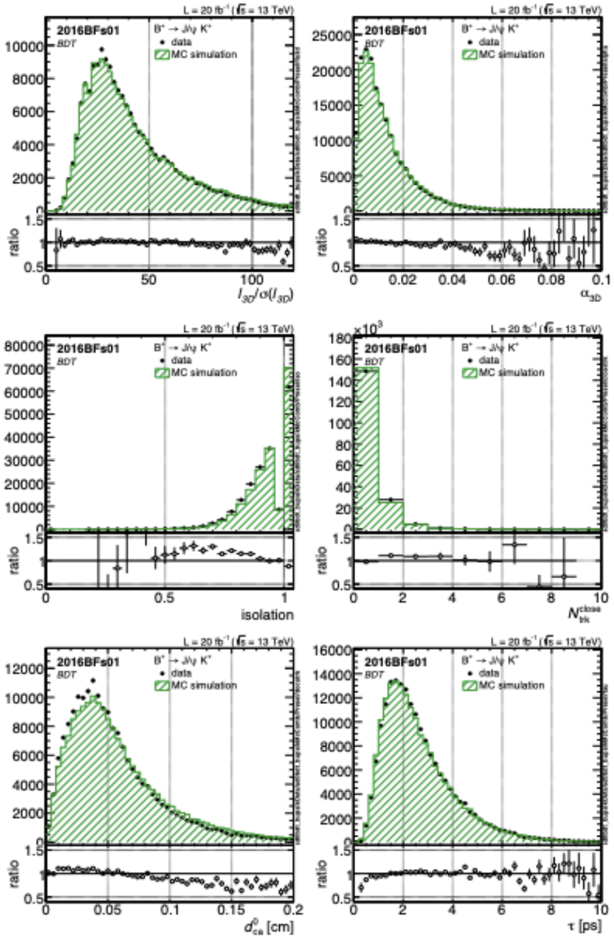
$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t) \to \mu^+\mu^-)\,dt}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)\,dt} = \frac{\tau_{B_s^0}}{1 - y_s^2} \left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s} \right)$$

LHCb: $\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05$ **ps,** $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$

- Variables unchanged compared to Bmm3
- B Candidate/tracks
  - $p_\perp$ and η
  - η_f of 'most-forward' muon ('channel' definition)
  - d_{ca}^{max}: maximum d_{ca} between B tracks



- Vertexing (of B-SV)
  - PV chosen based on minimum $|\ell_z|$ (not pointing angle)
  - α_{3D}, ℓ_{3D}, $\ell_{3D}/\sigma(\ell_{3D})$, δ_{3D}, $\delta_{3D}/\sigma(\delta_{3D})$: in 3D, PV refitted w/o B tracks
  - χ^2/dof: for dimuon vertex (also for $B \to J/\psi X$, refitted for this purpose)
- Isolation
  - $\sum_{trk}$ w/ tracks from B-PV or no other PV, but passing d_{ca} requirement
  - $I \equiv p_{\perp B}/(p_{\perp B} + \sum_{trk} p_\perp)$: $p_\perp > 0.9, \Delta R < 0.7, d_{ca} < 0.05$ cm
  - $I_\mu \equiv p_{\perp\mu}/(p_{\perp\mu} + \sum_{trk} p_\perp)$: $p_\perp > 0.5, \Delta R < 0.5, d_{ca} < 0.1$ cm
  - N_{trk}^{close}: count tracks with $p_\perp > 0.5$ GeV and $d_{ca} < 0.03$ cm
  - d_{ca}^0: minimum d_{ca} of these tracks to B-SV

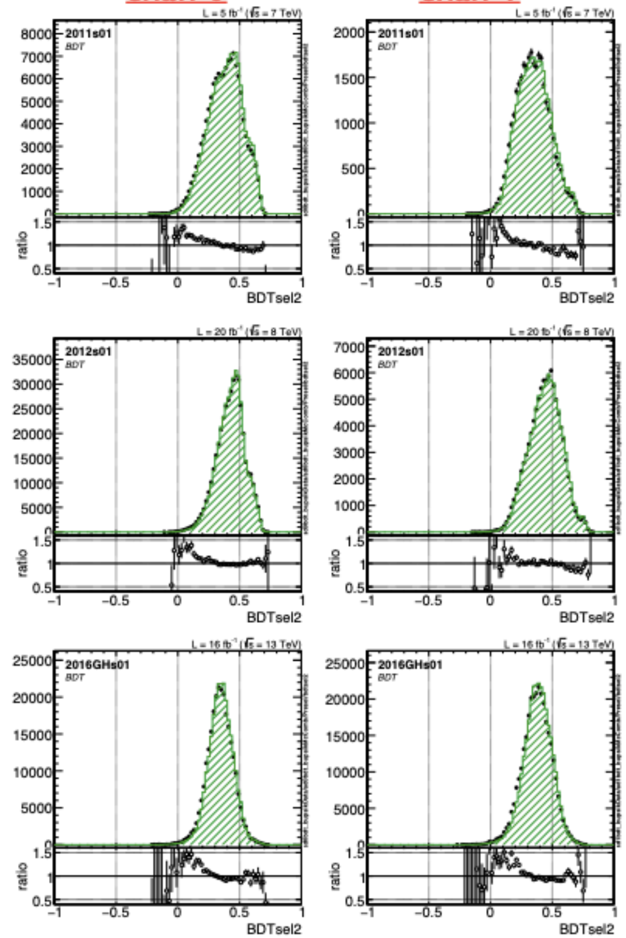


Variables from 2016BF/chan0

BDT response distributions (chan0 and chan1)

chan 0

chan 1



PROPERTIES OF $B_s^0 \to \mu^+ \mu^-$ AND SEARCH FOR $B^0 \to \mu^+ \mu^-$

Source	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [%]	$\tau_{\mu^+\mu^-}$ [ps]	
		2D UML	*sPlot*
Kaon tracking	2.3–4	—	—
Normalization yield	4	—	—
Background yields	1	0.03	(*)
Production process	3	—	—
Muon identification	3	—	—
Trigger	3	—	—
Efficiency (data/MC simulation)	5–10	—	(*)
Efficiency (functional form)	—	0.01	0.04
Efficiency lifetime dependence	1–3	(*)	(*)
Era dependence	5–6	0.07	0.07
BDT discriminator threshold	—	0.02	0.02
Silicon tracker alignment	—	0.02	—
Finite size of MC sample	—	0.03	—
Fit bias	—	—	0.09
$\mathcal{C}$-correction	—	0.01	0.01
Total systematic uncertainty	$(^{+0.3}_{-0.2}) \times 10^{-9}$	0.09	0.12
Total uncertainty	$(^{+0.7}_{-0.6}) \times 10^{-9}$	$^{+0.61}_{-0.44}$	$^{+0.52}_{-0.33}$

Properties of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$

Category	$N(B_s^0)$	$N(B^0)$	N_{comb}	$N_{\text{obs}}^{B^+}/100$	$\langle p_T(B_s^0)\rangle$ [GeV]	$\varepsilon_{\text{tot}}/\varepsilon_{\text{tot}}^{B^+}$
2011/central/high	$3.6^{+0.9}_{-0.8}$	$0.4^{+0.7}_{-0.6}$	8.4 ± 3.8	750 ± 30	16.4	3.9 ± 0.5
2011/forward/high	$2.0^{+0.5}_{-0.4}$	$0.2^{+0.4}_{-0.3}$	3.2 ± 2.2	220 ± 12	14.9	7.5 ± 0.8
2012/central/low	$3.7^{+0.9}_{-0.8}$	$0.4^{+0.6}_{-0.6}$	115.8 ± 11.3	790 ± 32	16.1	3.8 ± 0.5
2012/central/high	$9.3^{+2.3}_{-2.1}$	$1.0^{+1.7}_{-1.6}$	30.2 ± 7.3	2360 ± 95	17.3	3.2 ± 0.4
2012/forward/low	$1.7^{+0.4}_{-0.4}$	$0.2^{+0.3}_{-0.3}$	116.7 ± 11.0	190 ± 9	14.3	7.3 ± 1.0
2012/forward/high	$4.7^{+1.2}_{-1.1}$	$0.5^{+0.9}_{-0.8}$	31.0 ± 6.5	660 ± 27	15.5	5.9 ± 0.8
2016A/central/low	$2.2^{+0.5}_{-0.5}$	$0.2^{+0.4}_{-0.4}$	43.0 ± 7.1	580 ± 23	17.5	3.1 ± 0.4
2016A/central/high	$4.0^{+1.0}_{-0.9}$	$0.4^{+0.8}_{-0.7}$	13.3 ± 4.7	1290 ± 57	19.3	2.5 ± 0.3
2016A/forward/low	$3.7^{+0.9}_{-0.8}$	$0.4^{+0.7}_{-0.7}$	168.8 ± 13.5	780 ± 31	15.8	3.9 ± 0.5
2016A/forward/high	$8.1^{+2.0}_{-1.8}$	$0.8^{+1.5}_{-1.4}$	64.2 ± 9.7	1920 ± 78	17.5	3.4 ± 0.4
2016B/central/low	$4.1^{+1.0}_{-0.9}$	$0.4^{+0.8}_{-0.7}$	128.8 ± 12.0	1020 ± 44	17.2	3.3 ± 0.4
2016B/central/high	$3.6^{+0.9}_{-0.8}$	$0.4^{+0.7}_{-0.6}$	7.8 ± 3.6	1320 ± 54	20.8	2.2 ± 0.2
2016B/forward/low	$6.1^{+1.5}_{-1.4}$	$0.6^{+1.1}_{-1.0}$	133.4 ± 12.5	1260 ± 51	16.2	3.9 ± 0.4
2016B/forward/high	$3.9^{+1.0}_{-0.9}$	$0.4^{+0.8}_{-0.7}$	14.1 ± 4.6	1180 ± 49	19.5	2.7 ± 0.3

	2011		2012		2016A		2016B	
Channel	Central	Forward	Central	Forward	Central	Forward	Central	Forward
BDT	0.22	0.19	0.32	0.32	0.22	0.30	0.22	0.29

Properties of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$

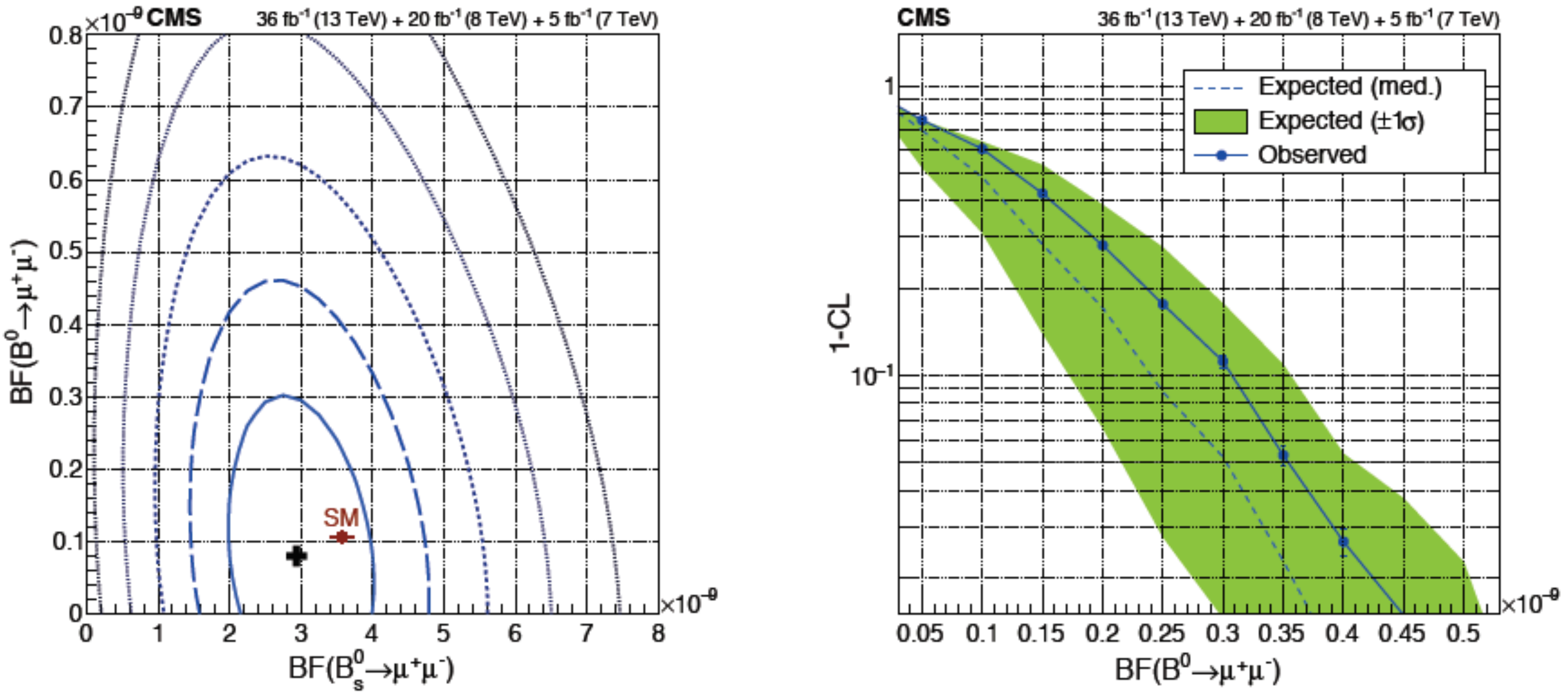


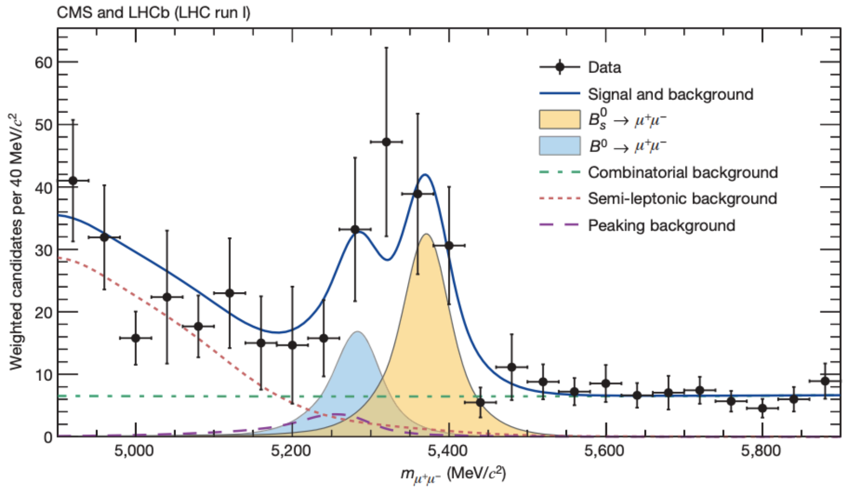
Figure 6: (Left) Likelihood contours for the fit to the branching fractions $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$, together with the SM expectation. The contours correspond to regions with 1–5 standard deviation coverage. (Right) The quantity $1 - \mathrm{CL}$ as a function of the assumed $B^0 \to \mu^+\mu^-$ branching fraction. The dashed curve shows the median expected value for the background-only hypothesis while the solid line is the observed value. The green region indicates the 1 standard deviation uncertainty band.

From Run1 analysis:

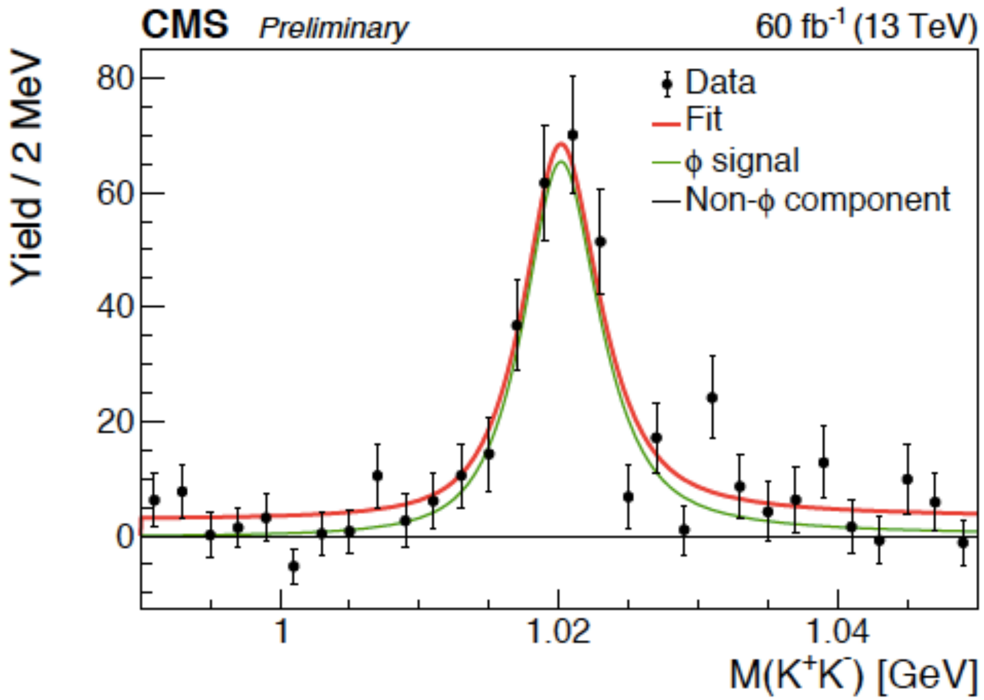
BR(Bs to mu+ mu-) = (3 +1.0/-0.9)E-9.
An excess of B(s) to mu+ mu- events with respect to background is observed with a significance of 4.3 standard deviations.

For the decay B0 to mu+ mu- an upper limit of
BR(B0 to mu+ mu-) < 1.1E-9 at the 95% confidence level is determin

CMS + LHC measured BR(B0 to mu+ mu-) = $3.9^{+1.6}_{-1.4} * 10^{-10}$ and
BR(Bs to mu+ mu-) = $2.8^{+0.7}_{-0.6} * 10^{-9}$



OBSERVATION OF $\Lambda_b \to J/\psi\Lambda\Phi$ DECAY



To extract the yield of $\Lambda^0{}_b \to J/\psi\Lambda\Phi$ decay the background-subtracted distribution of M(K^+K^-) is fitted with the convolution of a Gaussian and a relativistic Breit–Wigner functions for the Φ signal and with a first-order Bernstein polynomial for the non-Φ background.
The natural width of the Φ meson is fixed to the world-average value since it is measured with a good precision

OBSERVATION OF $\Lambda_b \rightarrow J/\psi\Lambda\Phi$ DECAY

Table 1: Summary of the relative systematic uncertainties in $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)$.

Source	Relative uncertainty (%)
Data/simulation difference in the η and two-body mass distributions	0.2
Background model in $M(J/\psi\Lambda K^+K^-)$ distribution	0.6
Background model in $M(\psi(2S)\Lambda)$ distribution	0.8
Background model in $M(K^+K^-)$ distribution	0.8
Signal model in $M(J/\psi\Lambda K^+K^-)$ distribution	0.8
Signal model in $M(\psi(2S)\Lambda)$ distribution	1.1
Signal model in $M(K^+K^-)$ distribution	0.5
Data/simulation difference in Λ_b^0 resolution for the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ decay	6.6
Data/simulation difference in Λ_b^0 resolution for the $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ decay	3.1
Data/simulation difference in ϕ resolution	1.4
Simulation sample size	2.9
Total systematic uncertainty	8.2