Search for $B^0_{(s)} \rightarrow \mu^+\mu^-$ with CMS

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Motivation

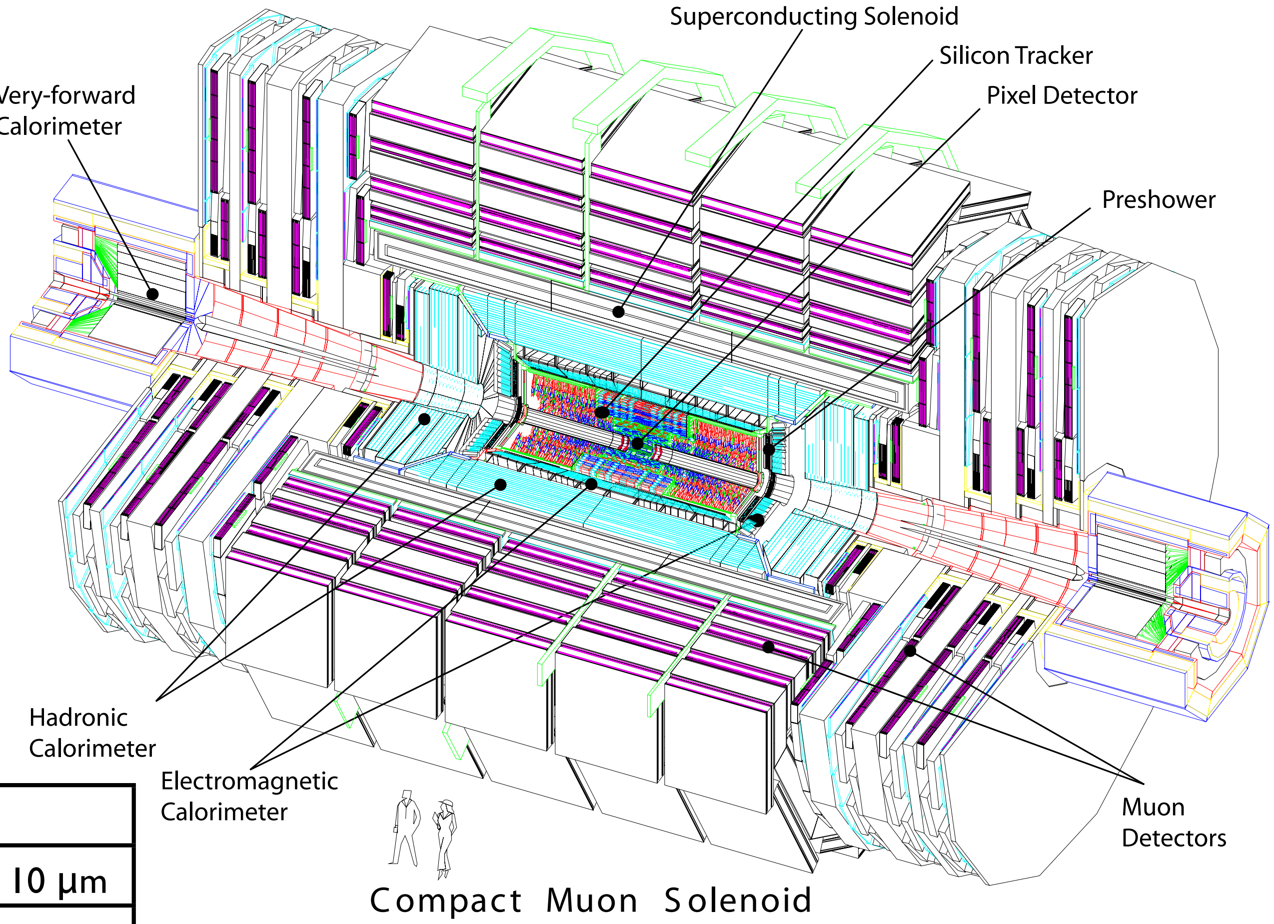
- Decays are highly suppressed in the Standard Model (SM)
  - Require a Flavor Changing Neutral Current (FCNC) transition
  - Helicity suppressed by factor of $(m_\mu/m_B)^2$
  - SM expectations are:
    - $Br(B_s^0 \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
    - $Br(B^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$

Buras 2010

- Decays make excellent probes for NP
  - MSSM enhancement of $Br \propto (\tan\beta)^6$
    - Constrains parameter regions
    - Indirect "measurement" of $\tan\beta$
- Time dependent physics program
  - Very early data: π, K events for muon misidentification rates
  - Early data: $B^+ \rightarrow J/\Psi K^+$, $B_s^0 \rightarrow J/\Psi \Phi$ for normalization/control sample
  - Current data: $Br(B^0_{(s)} \rightarrow \mu^+\mu^-)$ upper limit

The CMS Detector

- General details
  - Weight ~ 12500 tons
  - Length of 21.6 meters
  - Diameter of 15 meters
  - 4T Magnetic Field
- Sub-detectors used for this analysis
  - Silicon tracker
    - Si pixels and Si strips
  - Muon system

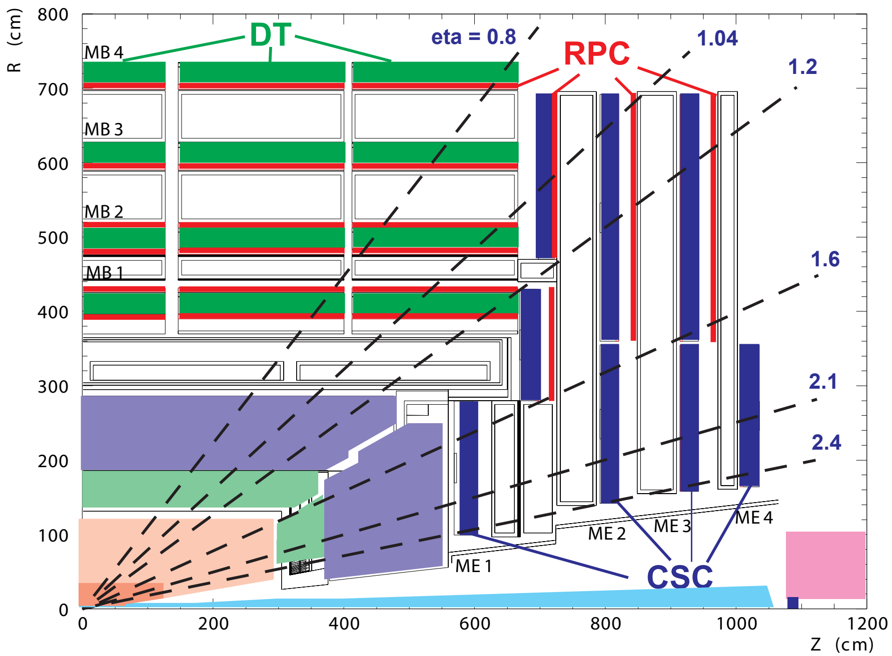


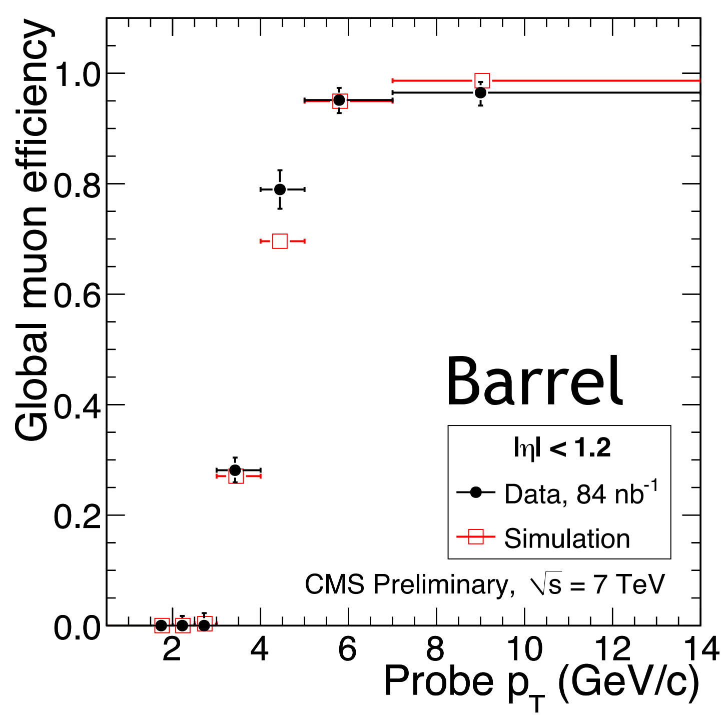
Component	Details	Resolution
Pixel B(F)	3(2) Si Layers(Disks)	$\delta_z \approx 20\ \mu m, \delta_\phi \approx 10\ \mu m$
Tracker B(F)	10(12) Si Strips	$\delta(p_T)/p_T \approx 1\%$
ECal	$PbWO_4$	$\delta E/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
HCal (B)	Bras/Sc, > 7.2λ	$\delta E/E \approx 100\ \sqrt{E}\%$
HCal (F)	Fe/Quartz	$\delta(ME_T) \approx 0.98\sqrt{(\sum E_T)}$
Magnet	3.8T Solenoid	
Muon	DT/SCS and RPC	$\delta(p_T)/p_T \approx 10\%$ (sta)

Muon Reconstruction

- Large Acceptance |η| < 2.4
  - Drift tubes (DT), cathode drift chambers (CDC), restive plate chambers (RPC)
- Analysis uses two muon reconstruction algorithms
  - Global muon (GM): reconstructed outside-in,
    - Standalone muon → inner track
  - Tracker muon (TM): reconstructed inside-out
    - Inner track → muon detector
- Muon misidentification
  - $\varepsilon(\mu|\pi) \leq 0.3\%$
  - $\varepsilon(\mu|K) \leq 0.3\%$
  - $\varepsilon(\mu|p) \leq 0.05\%$
  - Measured in data and MC

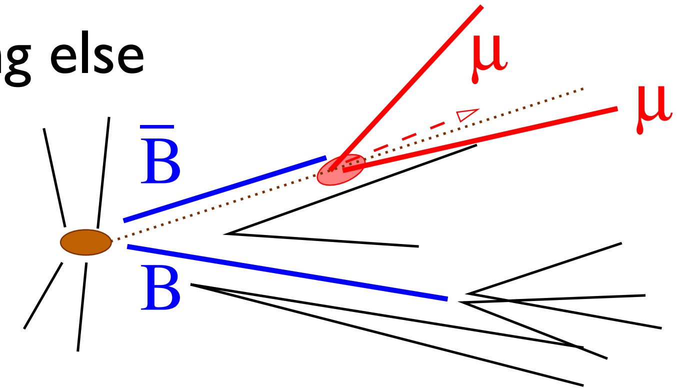
CMS-PAS-MUO-10-002





Analysis Overview

- Blind analysis
  - Simultaneous search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
- Signal signature
  - Two muons from one decay vertex and nothing else
  - Well reconstructed secondary vertex
    - Well separated from primary vertex
  - Di-muon mass around m_{Bs}
    - Di-muon momentum well aligned with flight direction



- Backgrounds
  - Two independent semileptonic B decays
    - Mostly from gluon splitting
  - One semileptonic (B) decay with one misidentified hadron
  - Rare single B decays
    - Peaking and non-peaking

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Methodology

Measurement of the branching fraction...

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-; 95\%\text{C.L.}) = \frac{N(n_{obs}, n_B, n_S; 95\%C.L.)}{\varepsilon_{B_s^0} N_{B_s^0}} = \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{B_s^0} \mathcal{L}\, \sigma(pp \to B_s^0)}$$

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

Where

n_B, n_S	expected number of background, signal events
$n_{obs} = n_B + n_S$	expected number of observed events
$N(n_{obs}, n_B, n_S)$	number of signal candidates at 95% CL
f_u, f_s	fragmentation probability for $b \to B^+$ and $b \to B_s^0$
A_x, ε_x^{ana}, ε_x^{μ}, ε_x^{trig}	acceptance and efficiencies for *x* channel

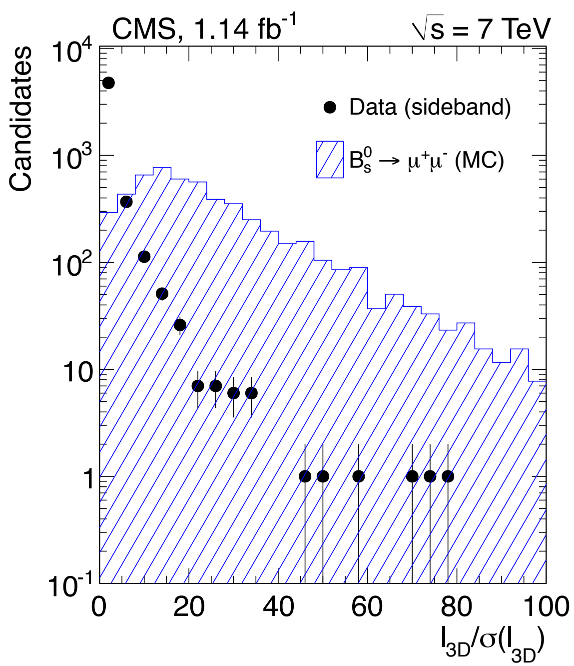
$B^+ \to J/\Psi K^+$ sample used as normalization channel

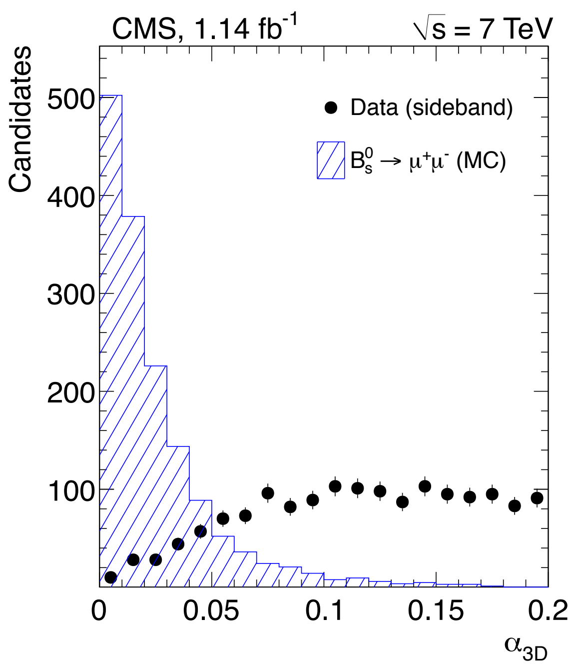
$B_s^0 \to J/\Psi\Phi$ sample used to extract efficiency of isolation cut and to validate the signal MC

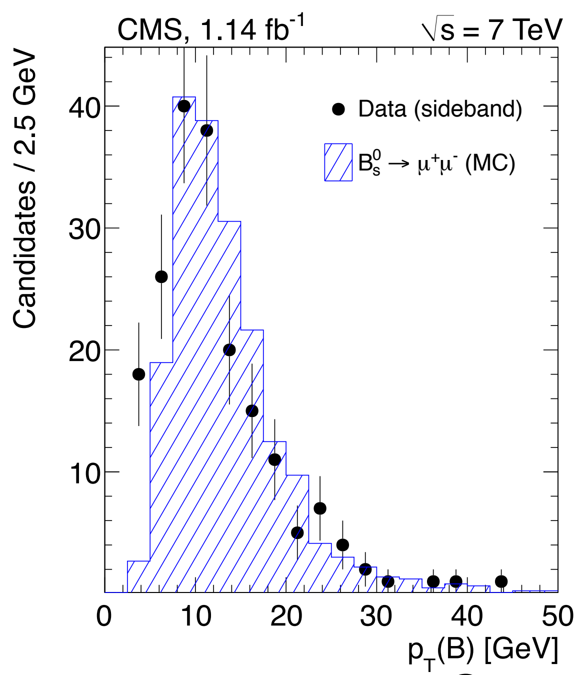
Analysis divided into barrel and encaps

Data Selection: Signal

- Background taken from sidebands
  - Defined as
    - $4.9 < m_{\mu1\mu2} < 5.2$ GeV and
    - $5.45 < m_{\mu1\mu2} < 5.9$ GeV
  - Blinded region $5.2 < m_{\mu1\mu2} < 5.45$ GeV
- Optimized for best upper limit
  - Done in a "grid search"
- Selection frozen before unblinding
- Discriminating variables
  - Fit quality χ^2/dof
  - Flight length significance $l_{3d}/\sigma(l_{3d})$
  - Pointing angle α
- Muon ID (both GM and TM)
  - Muon and dimuon p_T





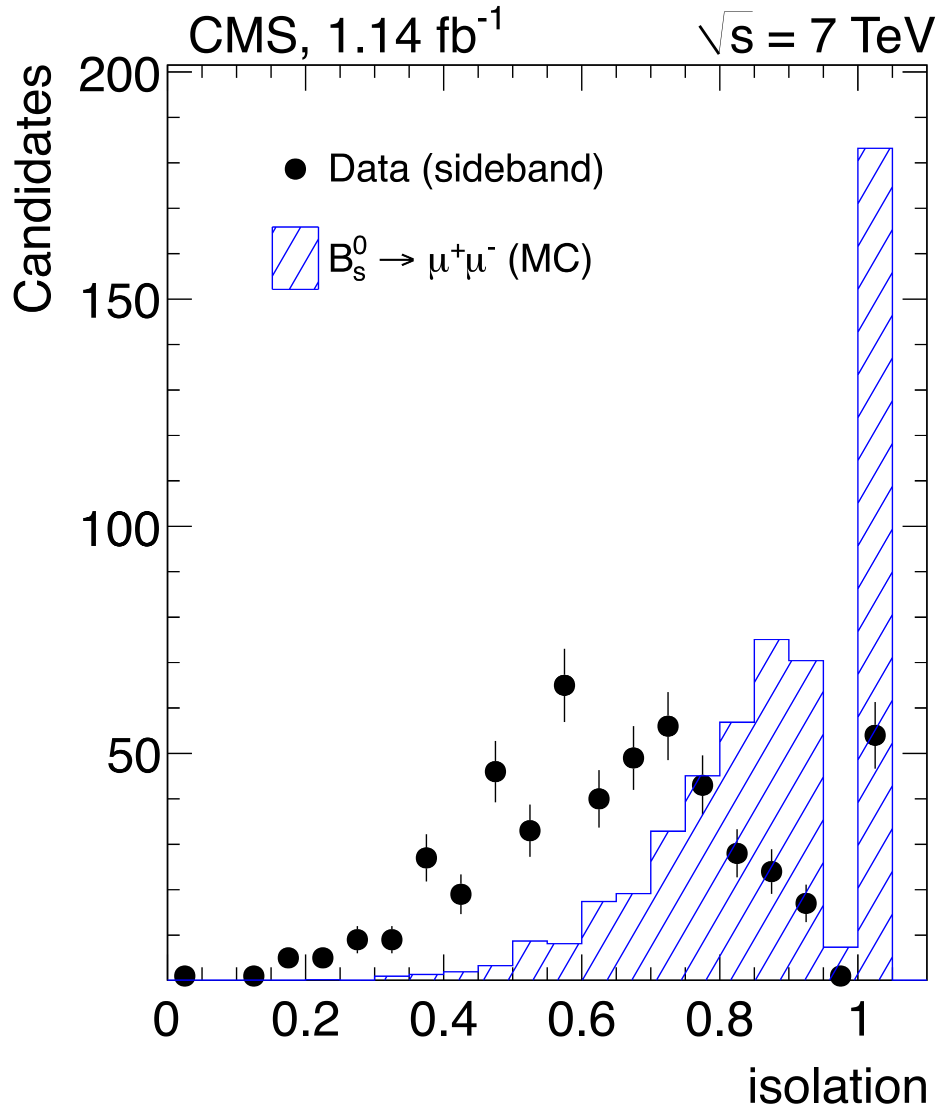


Isolation

The definition is given by:

$$I = \frac{p_T(B_{\text{cand}})}{p_T(B_{\text{cand}}) + \sum_{\text{track } t} p_T(t)}$$

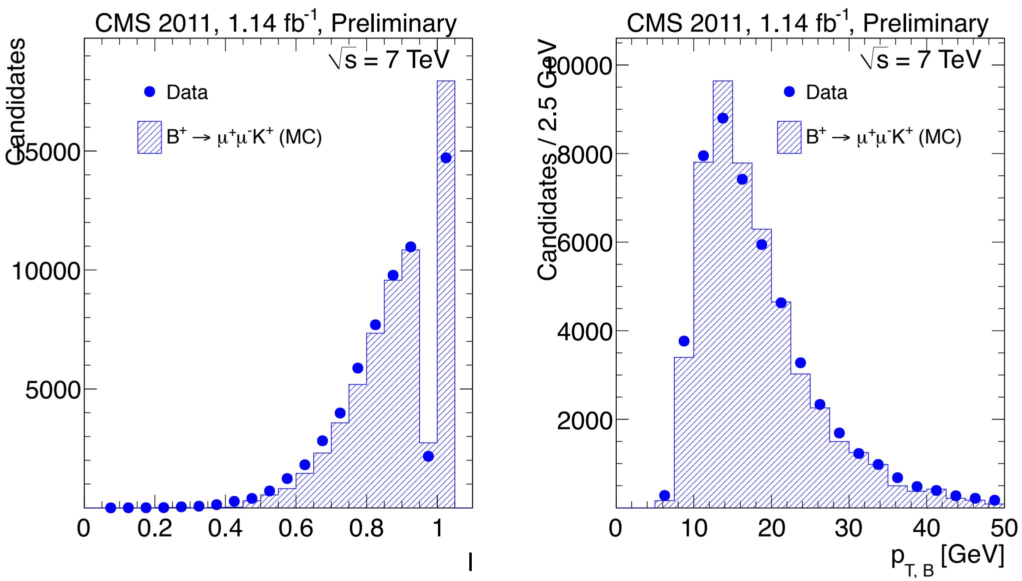
- Defined in cone around dimuon momentum with $\Delta R < 1$
- Sum includes tracks with
  - $p_T > 0.9$ GeV
  - Not be part of the B candidate
  - Associated with same PV as the B candidate
  - Or with distance of closest approach (d_{ca}) < 500 μm with respect to the B vertex
- Closest track to SV
  - $d^0_{ca} > 150$ μm (endcap only)



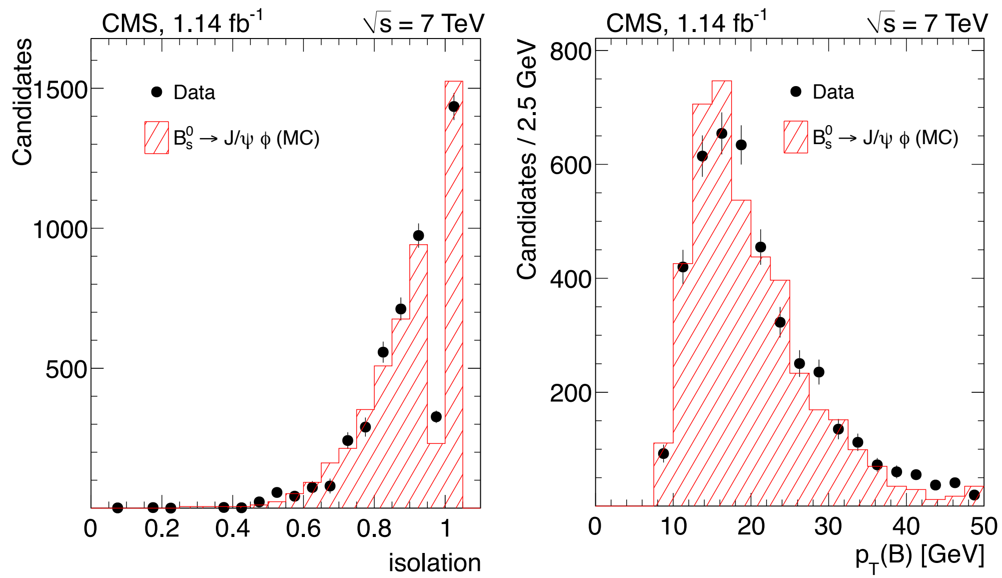
Data and MC Comparison

- Comparison of sideband-subtracted distributions
  - Generally in good agreement
- Differences are taken to be due to systematic uncertainties
  - Single requirement efficiencies including statistical components
    - values shown above figures
- $B_s^0 \rightarrow J/\Psi\Phi$ used as B_s^0 MC validation

Normalization sample systematics = 4.0%

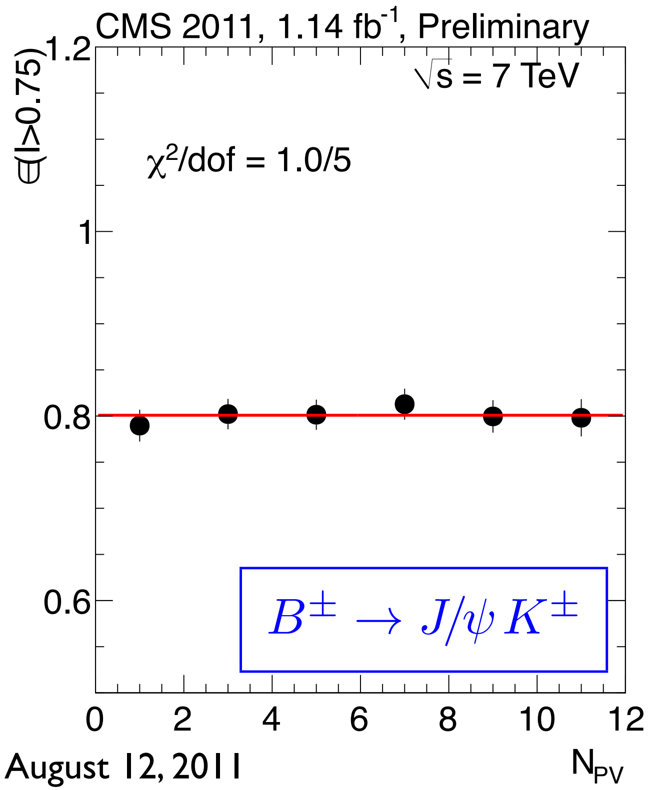


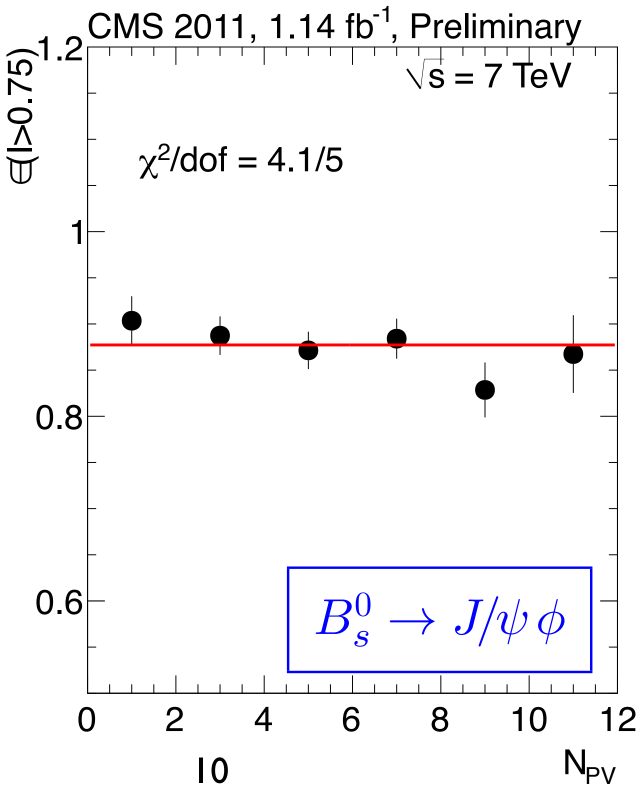
Control sample systematics = 7.9%



Pileup Study

- Isolation depends on number of tracks
  - May be sensitive to pileup
- Flight length significance also sensitive to pileup
  - To much lesser extent
- Used signal MC sample with pileup to study effects
- Data used for efficiency of selection vs number of primary vertices





Study done for N_{PV} < 12

In data for this analysis: $\langle N_{PV} \rangle \approx 5.5$

No problems seen for the current data

Final Selection

Same selection as used for signal

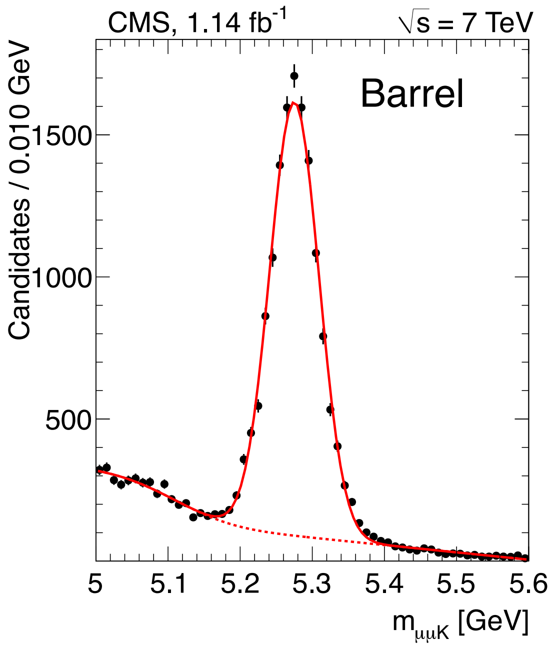
Differences between barrel and endcaps

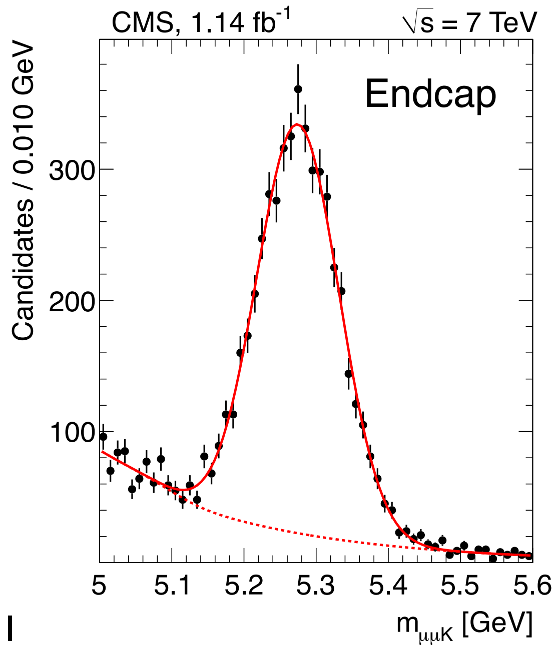
Variable	Barrel	Endcap	Units
$p_T(\mu_1)$ >	4.5	4.5	GeV
$p_T(\mu_2)$ >	4.0	4.0	GeV
$p_T(B)$ >	6.5	6.5	GeV
χ^2/dof <	1.6	1.6	
α <	0.050	0.025	rad
$l_{3d}/\sigma(l_{3d})$ >	15.0	20.0	
l >	0.75	0.75	
d^0_{ca} >	n/a	0.015	cm

Additional requirement for normalization

Variable	Barrel	Endcap
Acceptance	$(16.14 \pm 0.65) \times 10^{-2}$	$(11.12 \pm 0.45) \times 10^{-2}$
$\varepsilon_{analysis}$	$(0.68 \pm 0.03) \times 10^{-2}$	$(0.34 \pm 0.02) \times 10^{-2}$
ε_{total}	$(0.77 \pm 0.08) \times 10^{-3}$	$(0.27 \pm 0.03) \times 10^{-3}$
N_{obs}	13045 ± 663	4450 ± 244

Background sum of linear and error function in barrel





Background sum of exponential and error function in endcaps

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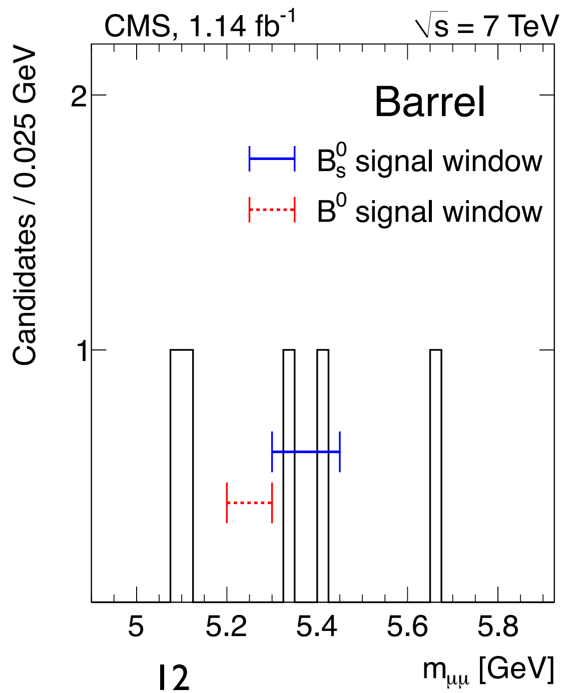
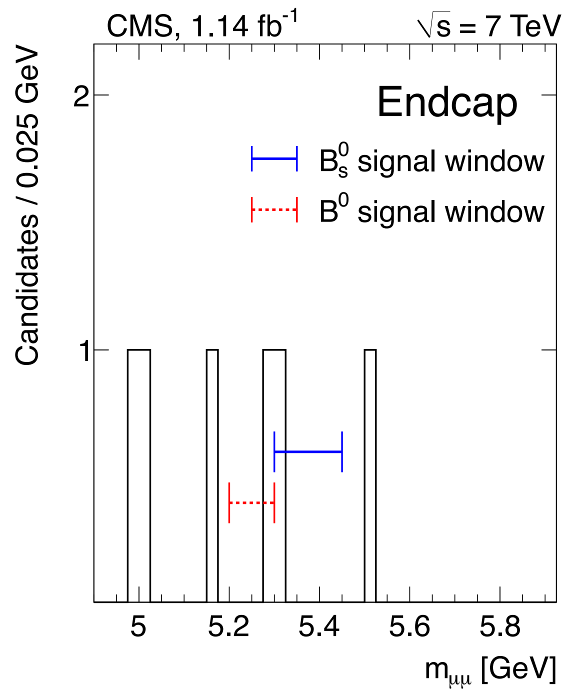
Expectations and Observation

	Barrel		Endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
Acceptance	$(24.62 \pm 0.99) \times 10^{-2}$	$(24.72 \pm 0.99) \times 10^{-2}$	$(22.61 \pm 0.91) \times 10^{-2}$	$(23.14 \pm 0.93) \times 10^{-2}$
$\varepsilon_{\text{analysis}}$	$(2.23 \pm 0.19) \times 10^{-2}$	$(2.22 \pm 0.19) \times 10^{-2}$	$(1.16 \pm 0.10) \times 10^{-2}$	$(1.24 \pm 0.11) \times 10^{-2}$
ε_{tot}	$(0.36 \pm 0.04) \times 10^{-2}$	$(0.36 \pm 0.04) \times 10^{-2}$	$(0.21 \pm 0.02) \times 10^{-2}$	$(0.21 \pm 0.02) \times 10^{-2}$
$N_{\text{signal}}^{\text{exp}}$	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
$N_{\text{bg}}^{\text{exp}}$	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
$N_{\text{peak}}^{\text{exp}}$	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01
N_{obs}	0	2	1	1

- Expected SM signal larger than background in barrel
- Expected peaking background for $B_s^0 \to \mu^+\mu^-$

- According to expectations
  - Based on sidebands
  - Studied with *I* < 0.7
    - No evidence for anomalous signal





Results

- Upper limits and significance for $B_s^0 \rightarrow \mu^+\mu^-$ and $B_d^0 \rightarrow \mu^+\mu^-$
  - Determined with CL_s approach
  - Input from PDG
    - fu = 0.401 ± 0.013
    - fs = 0.113 ± 0.013
    - $Br(B^+) = (6.0 \pm 0.2) \times 10^{-5}$
- Upper limits:
  - $Br(B_s^0 \rightarrow \mu^+\mu^-) = 1.9 \times 10^{-8}$ at 95% C.L.
  - $Br(B_s^0 \rightarrow \mu^+\mu^-) = 1.6 \times 10^{-8}$ at 90% C.L.
  - $Br(B^0 \rightarrow \mu^+\mu^-) = 4.6 \times 10^{-9}$ at 95% C.L.
  - $Br(B^0 \rightarrow \mu^+\mu^-) = 3.7 \times 10^{-9}$ at 90% C.L.
- Assuming background only, *p* values are
  - 0.11 for $B_s^0 \rightarrow \mu^+\mu^-$
  - 0.40 for $B^0 \rightarrow \mu^+\mu^-$

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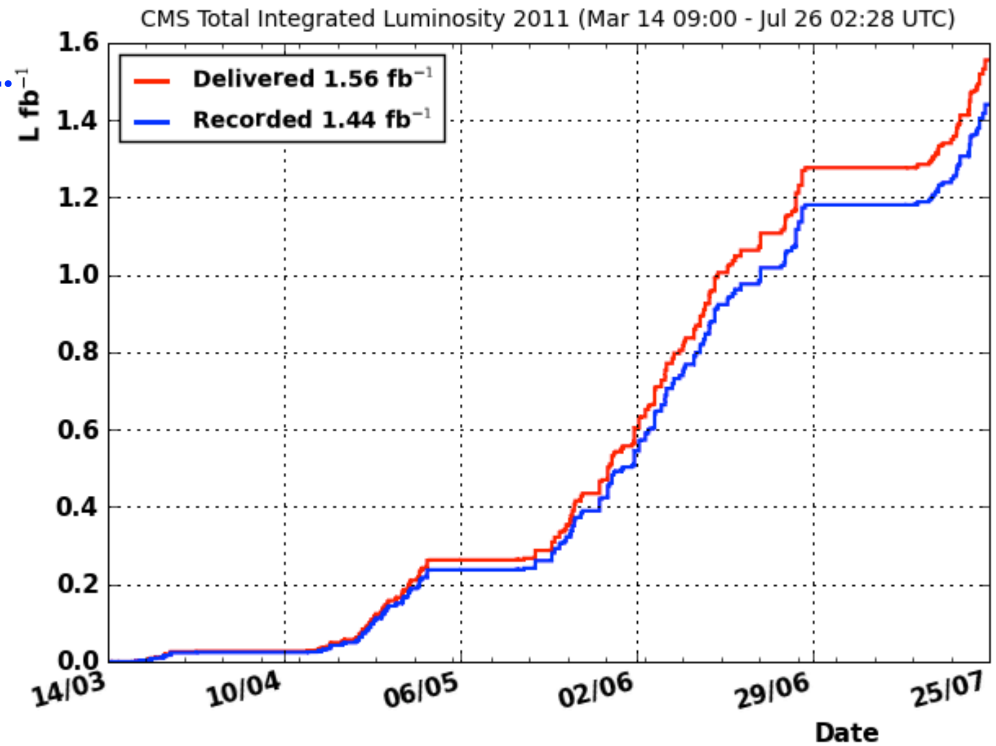
Summary

- Performed a search for $B^0_{s(d)} \rightarrow \mu^+\mu^-$ with 1.14 fb^{-1} at $\sqrt{s}$ = 7 TeV
    - Did not find signal beyond SM expectations
    - Determine upper limits
        - $Br(B_s^0 \rightarrow \mu^+\mu^-) = 1.9 \times 10^{-8}$ at 95% C.L.
        - $Br(B^0 \rightarrow \mu^+\mu^-) = 4.6 \times 10^{-9}$ at 95% C.L.



- Outlook
    - Upgrade to multi-variable analysis
    - Looking forward to LHC's increasing luminosity

References

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  - A. J. Buras, "Flavour Theory and the LHC Era", arXiv:1009.1303
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  - D. Kotlinski, A. Starodumov, C. Naegeli, L. Martini, and F. Palla

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Backup Slides

Trigger: $B_s^0 \to \mu^+\mu^-$ and $B^\pm \to J/\psi\, K^\pm$

- Dimuon trigger
  - ▷ L1 (hardware) trigger
    a few kHz at current peak luminosities
  - ▷ High-level trigger
    full tracking and vertexing
- HLT $B_s^0 \to \mu^+\mu^-$
  - ▷ two muons with opposite charge
  - ▷ inv. mass $4.8 < m_{\mu\mu} < 6.0$ GeV
  - ▷ distance of closest approach $d_{ca} < 0.5$ cm
  - ▷ single muon $p_\perp > 2$ GeV, dimuon $p_\perp > 4$ GeV
- HLT $B^\pm \to J/\psi\, K^\pm$ and $B_s^0 \to J/\psi\, \phi$
  - ▷ two muons with opposite charge, $2.9 < m_{\mu\mu} < 3.3$ GeV
  - ▷ distance of closest approach $d_{ca} < 0.5$ cm
  - ▷ single muon $p_\perp > 3$ GeV, dimuon $p_\perp > 6.9$ GeV
  - ▷ $\cos\alpha > 0.9$, $\mathcal{P}(\chi^2/dof) > 0.5\%$
  - $\to$ 'displaced' J/ψ

Trigger efficiency $\approx 80\%$
- ▷ after analysis selection
- ▷ constant over time

Determination
- ▷ MC simulation
- ▷ data
- $\to$ systematics from difference

1.14 fb^{-1} at $\sqrt{s} = 7$ TeV taken in 2011