

Search for $B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ decays in CMS

BEACH 2012

Gemma Tinti on behalf of the CMS collaboration

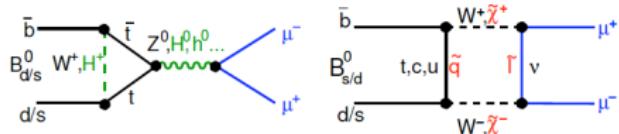
University of Kansas

07/26/2012



Motivation

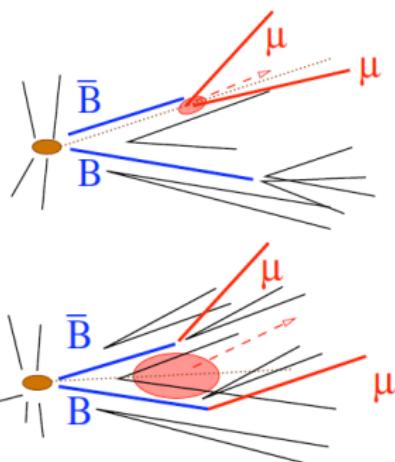
- ▶ Decay highly suppressed in Standard Model:
 - ▶ “effective” FCNC, possible only through box or penguin diagrams
 - ▶ helicity suppressed by a factor m_μ^2/m_B^2
 - ▶ internal quark annihilation within the B meson
 - ▶ SM expectations: $\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &= (3.2 \pm 0.2) \times 10^{-9} \\ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &= (1.0 \pm 0.1) \times 10^{-10} \end{aligned}$



- ▶ For New Physics, the branching fractions are modified:
 - ▶ 2HDM: $\mathcal{B} \propto (\tan^4 \beta)$, MSSM: $\mathcal{B} \propto (\tan^6 \beta)$
 - ▶ The BF can be also suppressed in some models

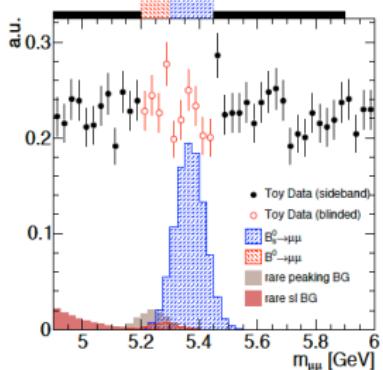
Signal and Backgrounds

- ▶ Event counting experiment in dimuon mass regions around $m_{B_s^0}$ and m_{B^0}
- ▶ Use data from 2011 from pp collisions at $\sqrt{s} = 7$ TeV. $\mathcal{L} = 5\text{fb}^{-1}$
- ▶ Blind analysis
- ▶ Signal:
 - ▶ two muons from one decay vertex
 - ▶ well reconstructed secondary vertex
 - ▶ invariant mass around $m_{B_s^0}$
 - ▶ momentum aligned with flight direction
 - ▶ isolation
- ▶ Background:
 - ▶ two semileptonic B decays
 - ▶ one semileptonic B decay and one misidentified hadron
 - ▶ rare single B decays with misidentified hadron:
 - ▶ e.g.: $B_s^0 \rightarrow K^+ K^-$ (peaking)
 - ▶ e.g.: $B_s^0 \rightarrow K^- \mu^+ \nu$ (non peaking)
 - ▶ not well reconstructed secondary vertex



Analysis strategy

- ▶ Analysis in two channels:
 - ▶ Barrel (both muons $|\eta| < 1.4$)
 - ▶ Endcap (at least one muon with $|\eta| \geq 1.4$)
- ▶ Background estimations:
 - ▶ MC for estimate of decays from real B mesons
 - ▶ Sideband data for combinatorial background
- ▶ Choose a well known channel: $B^\pm \rightarrow J/\psi K^\pm$ as a "normalization" channel (with $J/\psi \rightarrow \mu^+ \mu^-$)
- ▶ Measurement of $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ relative to "normalization" channel $\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$ to reduce uncertainties:



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \frac{N_{\text{obs}}^{B_s^0}}{N_{\text{obs}}^{B^\pm}} \times \frac{f_u}{f_s} \times \frac{\varepsilon_{\text{tot}}^{B^\pm}}{\varepsilon_{\text{tot}}^{B_s^0}} \times \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$$

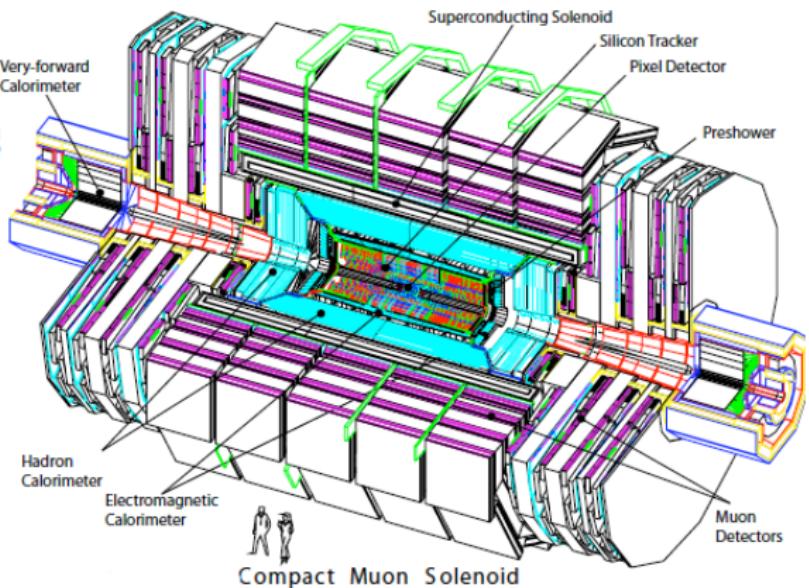
(where $f_s/f_u = 0.267 \pm 0.021$ from LHCb Phys. Rev. D 85 (2012) 032008)

- ▶ Analysis validation on "control" channel $B_s^0 \rightarrow J/\psi \phi$, where $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$

The CMS detector

JINST 3, S08004 (2008)

Weight	12500t
Length	21.6 m
Diameter	15 m
magnetic field	3.8 T

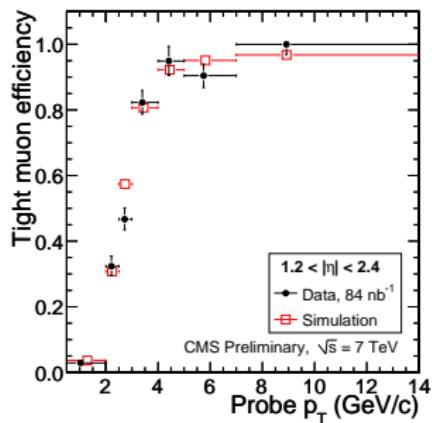
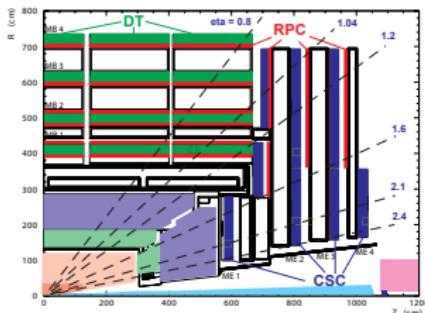


Component	Characteristics	Resolutions
Pixel Tracker	3/2 Si layers 10/12 Si strips	$\delta_z \approx 20 \mu\text{m}$, $\delta_\phi \approx 10 \mu\text{m}$ $\delta(p_\perp)/p_\perp \approx 1\%$
ECAL	PbWO ₄	$\delta E/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
HCAL (B)	Brass/Sc, $> 7.2\lambda$	$\delta E/E \approx 100\sqrt{E}\%$
HCAL (F)	Fe/Quartz	$\delta(E_T) \approx 0.98\sqrt{\sum E_T}$
Magnet	3.8 T solenoid	
Muons	DT/CSC + RPC	$\delta(p_\perp)/p_\perp \approx 10\%$ (STA)

Muon reconstruction

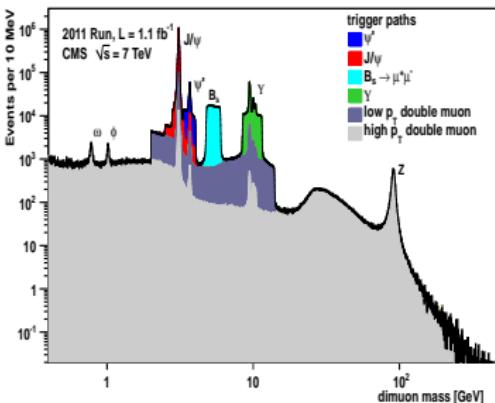
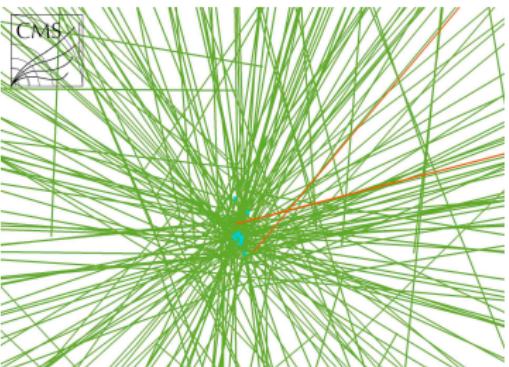
CMS-PAS-MUO-10-002

- ▶ p_T resolution 1%
- ▶ Tracking efficiency >99% for central muons
- ▶ Excellent vertex reconstruction and impact parameter resolution ($\approx 15 \mu\text{m}$)
- ▶ Muon candidate matched between muon segments and a silicon track
- ▶ Tight muons: High quality reco objects
- ▶ Muon misidentification evaluated from real data:
 - ▶ use $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$, $\Lambda^0 \rightarrow p\pi^-$
 - ▶ Misid rate: π and K < 0.10%
 - ▶ Misid rate: p < 0.05%
- ▶ Muon reco efficiencies vs p_T and η :
 - ▶ MC
 - ▶ Cross check with “Tag and Probe”



The trigger

- ▶ Trigger requirements raised following the increasing instantaneous luminosity
- ▶ $B_s^0 \rightarrow \mu^+ \mu^-$:
 - ▶ each muon $p_T > 4$ GeV, dimuon $p_T > 3.9$ (5.9) GeV in barrel (endcap)
 - ▶ $4.8 < m_{\mu\mu} < 6$ GeV
 - ▶ dimuon vertex $\chi^2/\text{dof} > 0.5\%$
 - ▶ distance of closest approach between muons $d_{\text{ca}} < 0.5$ cm
- ▶ $B^\pm \rightarrow J/\psi K^\pm$ and $B_s^0 \rightarrow J/\psi \phi$:
 - ▶ single muon $p_T > 4$ GeV, dimuon $p_T > 6.9$ GeV
 - ▶ muons $d_{\text{ca}} < 0.5$ cm
 - ▶ $2.9 < m_{\mu\mu} < 3.3$ GeV
 - ▶ $\cos(\text{pointing angle}) > 0.9$, dimuon vertex $\chi^2/\text{dof} > 15\%$
 - ▶ displaced J/ψ : flight length significance $|l/\sigma(l)| > 3$
- ▶ Trigger efficiencies vs p_T and η :
 - ▶ MC
 - ▶ Cross check with ‘Tag and Probe’

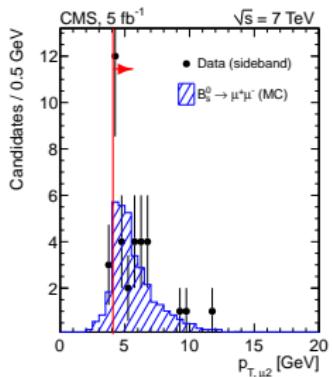
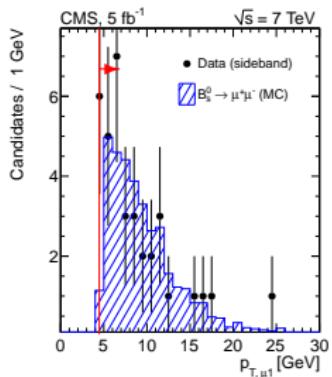


Signal selection: muon kinematic

- Two opposite charged muons with invariant mass:

overall window	$4.9 < m_{\mu\mu} < 5.9 \text{ GeV}$
blinding window	$5.2 < m_{\mu\mu} < 5.45 \text{ GeV}$
$B^0 \rightarrow \mu^+ \mu^-$ window	$5.2 < m_{\mu\mu} < 5.3 \text{ GeV}$
$B_s^0 \rightarrow \mu^+ \mu^-$ window	$5.3 < m_{\mu\mu} < 5.45 \text{ GeV}$

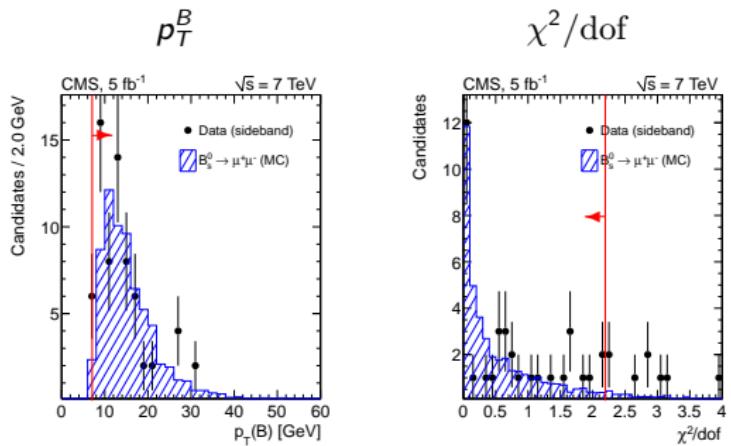
- Require muons to be originated from a common vertex
- Cuts have been optimized to the best expected upper limit
- All other cuts applied in following plots



$$p_T^{\mu_1} > 4.5 \text{ GeV B/E} \quad p_T^{\mu_2} > 4(4.2) \text{ GeV B(E)}$$

Signal selection: secondary vertex

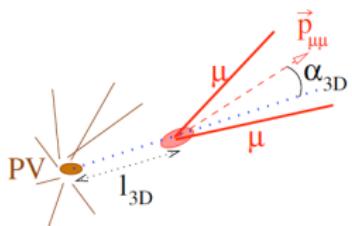
- ▶ The common vertex of the two muons is fit (B candidate decay vertex)
- ▶ Look at goodness of the fit



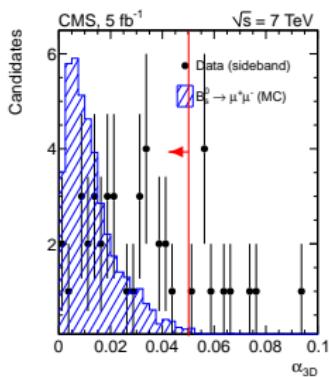
$$p_T^B > 6.5(8.5) \text{ GeV } B(E) \quad \chi^2/\text{dof} < 2.2(1.8) \text{ } B(E)$$

Signal selection: primary vertex

- ▶ Choose one primary vertex (minimal separation in z)
 - ▶ refit without signal tracks
 - ▶ Dimuon momentum aligned with B candidate flight direction
 - ▶ longitudinal impact parameter

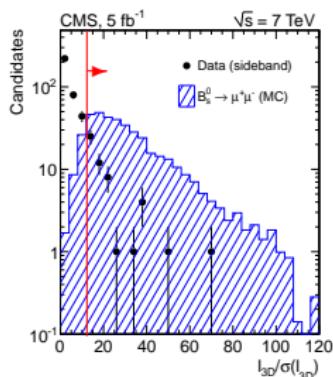


pointing angle



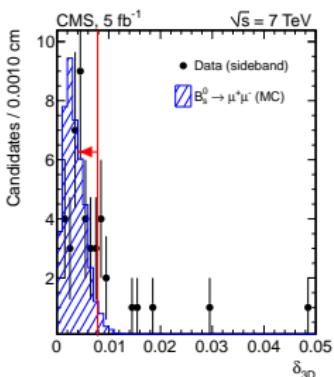
$$\alpha < 0.05(0.3) \text{ rad } B(E)$$

flight length significance



$$l_{3D} / \sigma(l_{3D}) > 13(15) \text{ B}(E)$$

3D impact parameter



$$\delta_{3D} < 0.008 \text{ cm } B/E$$

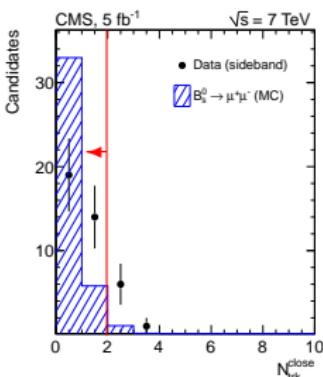
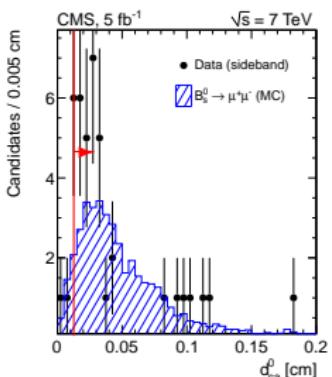
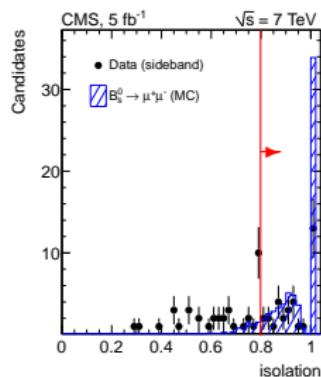
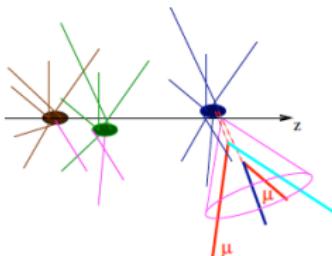
Signal selection: isolation

- ▶ Isolation of the primary B vertex

$$I = \frac{p_T(B)}{p_T(B) + \sum_{\text{trk}, \Delta R < 0.7, p_T > 0.9} p_T}$$

tracks must not be associated to $\neq \text{PV}$

- ▶ distance of closest track to B vertex
- ▶ number of close tracks ($d_{\text{ca}}^0 < 300 \mu\text{m}$, $p_T > 0.5 \text{ GeV}$)



$$I > 0.80 \text{ B/E}$$

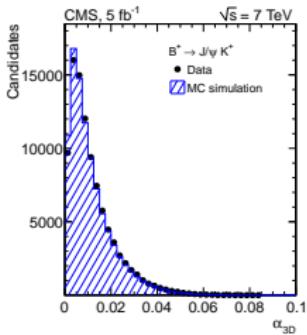
$$d_{\text{ca}}^0 > 0.015 \text{ cm B/E}$$

$$N_{\text{trk}}^{\text{close}} < 2 \text{ B/E}$$

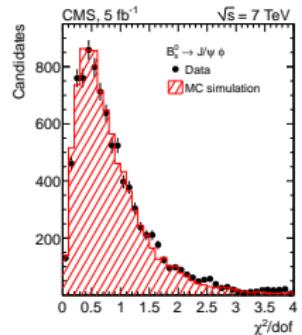
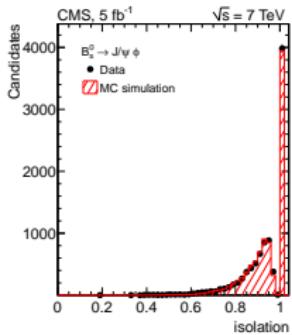
Normalization and control sample

- ▶ Need to validate signal selection on control and normalization sample
- ▶ Compare data sideband subtracted distributions to MC
- ▶ Differences are taken as systematic uncertainties:
 - ▶ $B^\pm \rightarrow J/\psi K^\pm$: max diff 2.5% (I) $\rightarrow 4\%$ tot
 - ▶ $B_s^0 \rightarrow J/\psi \phi$: max diff 1.6% (χ^2/dof) $\rightarrow 3\%$ tot

$$B^\pm \rightarrow J/\psi K^\pm$$

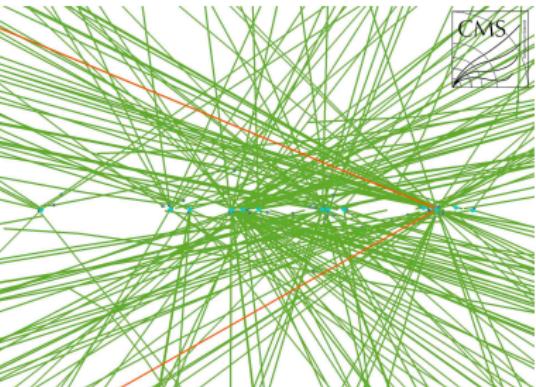


$$B_s^0 \rightarrow J/\psi \phi$$

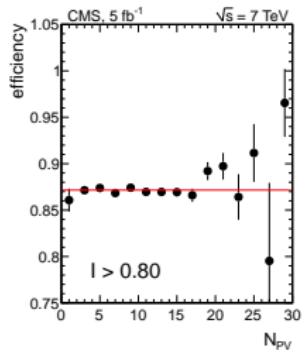
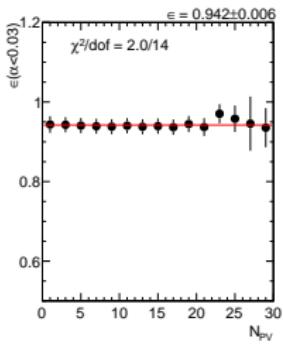


Pileup independence

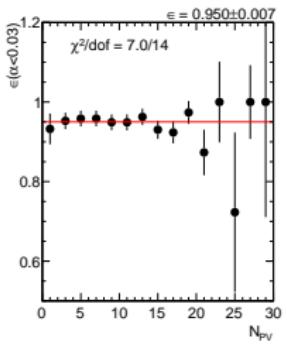
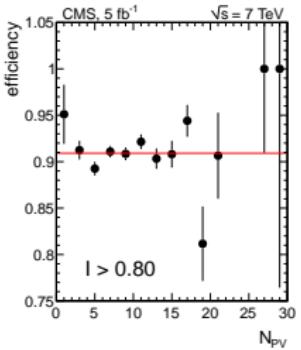
- ▶ In 2011: $\langle N_{PV} \rangle \approx 8$, RMS (z) ≈ 5.6 cm
- ▶ The selection is very robust against pileup
 - ▶ I searches only for tracks coming from the same PV



$$B^\pm \rightarrow J/\psi K^\pm$$



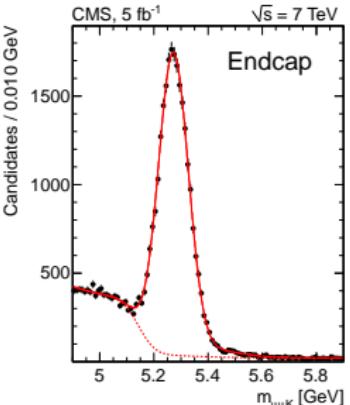
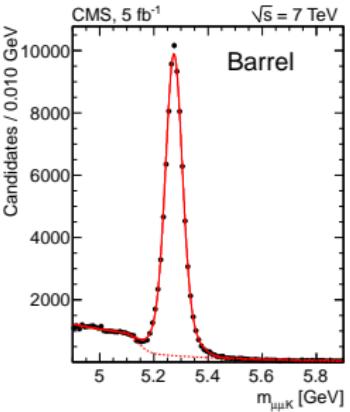
$$B_s^0 \rightarrow J/\psi \phi$$



Measurement of $B^\pm \rightarrow J/\psi K^\pm$

- ▶ Use same selection as signal, plus:
 - ▶ $3.0 < m(\mu\mu) < 3.2 \text{ GeV}$
 - ▶ $p_\perp(\mu\mu) > 7 \text{ GeV}, p_\perp(K) > 0.5 \text{ GeV}$
 - ▶ all tracks used in vertexing
- ▶ Fit:
 - ▶ Signal: double Gaussian
 - ▶ Background: exponential + error function (at 5.145 GeV for $B^0 \rightarrow J/\psi K^* \rightarrow \mu^+ \mu^- K^- (\pi^+)$)
- ▶ Systematic uncertainty on yield: 5% (varying signal and bkg pdf, constraining dimuon mass to J/ψ)

	barrel	endcap
acceptance	0.162 ± 0.006	0.111 ± 0.006
ε_{tot}	0.00110 ± 0.00009	0.00032 ± 0.00004
N_{obs}	82712 ± 4146	23809 ± 1203

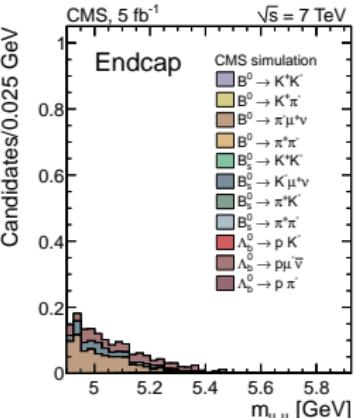
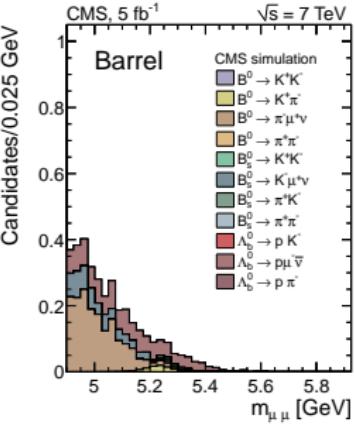


Rare backgrounds

- ▶ CKM-suppressed semileptonic decays:
 - ▶ e.g.: $B_s^0 \rightarrow K^- \mu^+ \nu$ with one fake muon
 - ▶ continuous spectrum on low side of the mass spectrum
- ▶ Peaking hadronic decays:
 - ▶ e.g.: $B_s^0 \rightarrow K^+ K^-$ with two fake muons
- ▶ Normalization to B^+ yield in data:

$$N(X) = \frac{\mathcal{B}(Y \rightarrow X)}{\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)} \frac{f_Y}{f_u} \frac{\varepsilon_{\text{tot}}^X}{\varepsilon_{\text{tot}}^{B^+}} N_{\text{obs}}(B^+)$$

- ▶ weighted with the hadron fake probability from data ($D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$, $\Lambda^0 \rightarrow p \pi^-$)



Systematic uncertainties

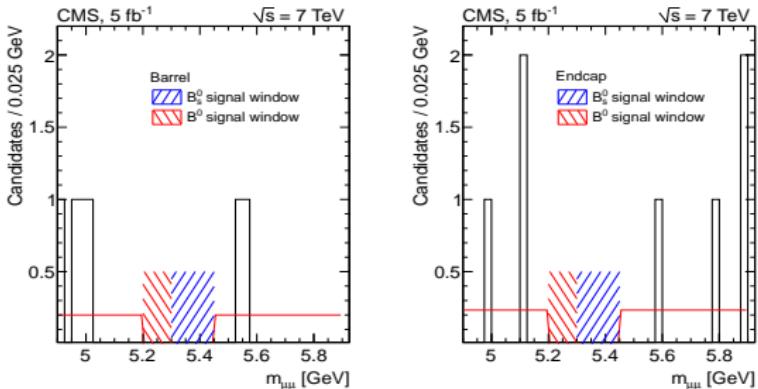
- ▶ Uncertainties on input variables:

Category	Uncertainty	Barrel	Endcap
f_s/f_u	production ratio of u and s quarks	8.0	8.0
acceptance	production processes	3.5	5.0
P_{ij}^B	mass scale and resolution	3.0	3.0
efficiency (signal)	discrepancies data/MC simulation	3.0	3.0
efficiency (normalization)	discrepancies data/MC simulation	4.0	4.0
efficiency (normalization)	kaon track efficiency	4.0	4.0
efficiency	trigger	3.0	6.0
efficiency	muon identification	4.0	8.0
normalization	fit pdf	5.0	5.0
background	shape of combinatorial background	4.0	4.0
background	rare decays	20.0	20.0

- ▶ Total efficiency \times acceptance for $B_s^0 \rightarrow \mu^+ \mu^-$:

barrel	endcap
0.0029 ± 0.0002	0.0016 ± 0.0002

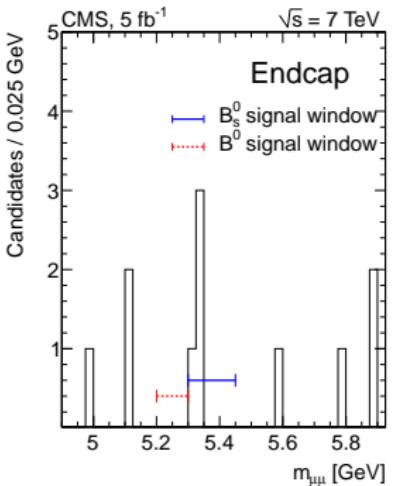
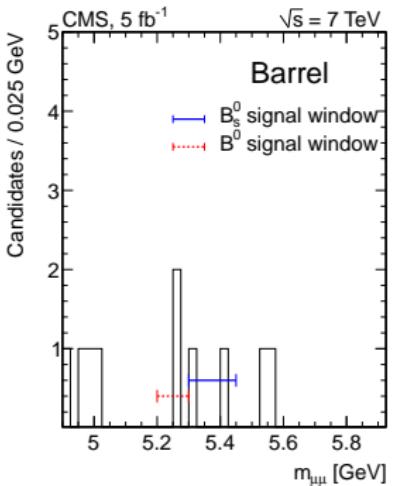
Dimuon mass distribution (blinded)



- ▶ Combinatorial (continuous) + rare (MC shape)
- ▶ Expected non peaking background in signal window:
 - ▶ Subtract the rare background events from lower sideband
 - ▶ Scale remaining sideband events for mass region

Variable	$B^0 \rightarrow \mu^+ \mu^-$ Barrel	$B_s^0 \rightarrow \mu^+ \mu^-$ Barrel	$B^0 \rightarrow \mu^+ \mu^-$ Endcap	$B_s^0 \rightarrow \mu^+ \mu^-$ Endcap
ε_{tot}	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
$N_{\text{signal}}^{\text{exp}}$	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
$N_{\text{peak}}^{\text{exp}}$	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
$N_{\text{comb}}^{\text{exp}}$	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
$N_{\text{total}}^{\text{exp}}$	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56

Dimuon mass distribution: unblinded results



Variable	$B^0 \rightarrow \mu^+ \mu^-$ Barrel	$B_s^0 \rightarrow \mu^+ \mu^-$ Barrel	$B^0 \rightarrow \mu^+ \mu^-$ Endcap	$B_s^0 \rightarrow \mu^+ \mu^-$ Endcap
ϵ_{tot}	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
$N_{\text{signal}}^{\text{exp}}$	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
$N_{\text{peak}}^{\text{exp}}$	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
$N_{\text{comb}}^{\text{exp}}$	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
$N_{\text{total}}^{\text{exp}}$	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4

Results: upper limits

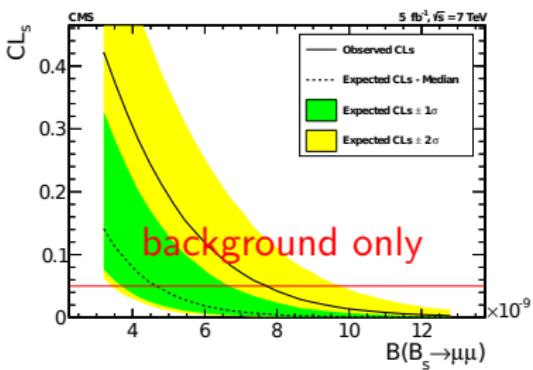
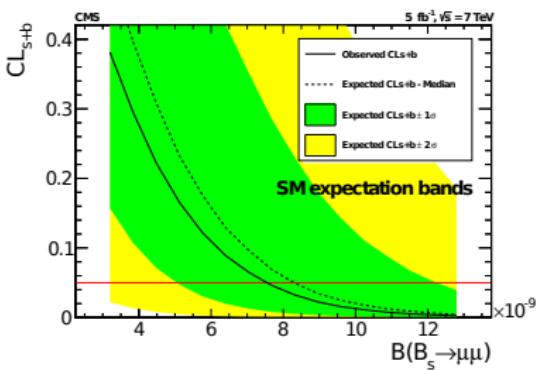
JHEP 04(2012) 033

- Upper limit on $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$

upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	1.8×10^{-9}	1.6×10^{-9}

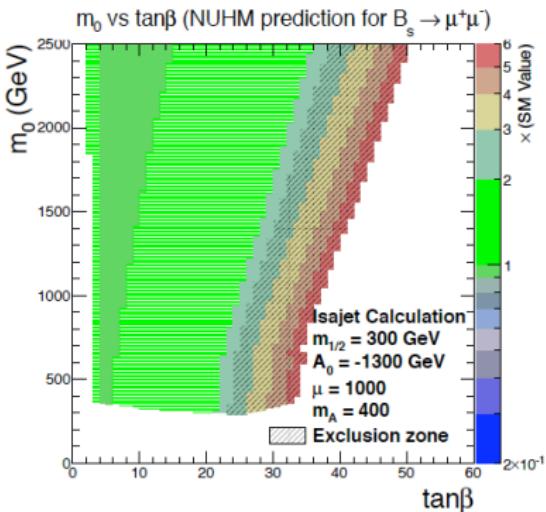
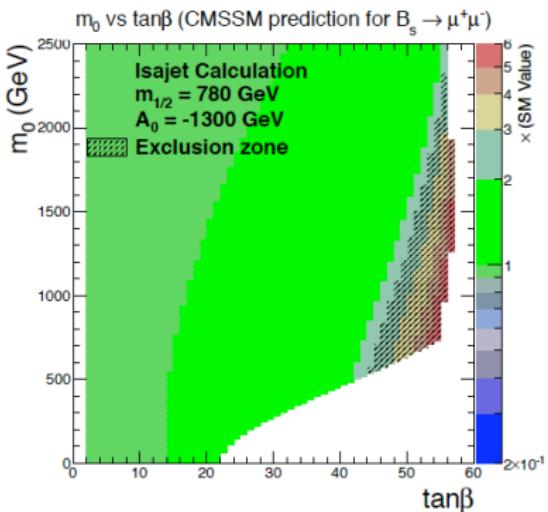
- p -values for background only hypotheses:

p -values	background only	SM cross feed	floating cross feed
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	0.06 (1.5 σ)	0.07 (1.5 σ)	0.11 (1.2 σ)
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	0.11 (1.2 σ)	0.29 (0.6 σ)	0.24 (0.7 σ)



Interpretation

- ▶ Some examples (SuperIso V3.2, CPC, 18-, 1579)
- ▶ Empty region due to previous upper limit on other published data
- ▶ Exclusion of some portion of the phase space at large $\tan\beta$



Recent results of other LHC experiments

► LHCb:

- ▶ $\mathcal{L} = 1.0 \text{ fb}^{-1}$, pp collisions at $\sqrt{s} = 7 \text{ TeV}$:
 - ▶ $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$ at 95% CL
 - ▶ $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 10 \times 10^{-10}$ at 95% CL
- ▶ Previous measurement, on independent dataset of 0.037 fb^{-1} in pp collisions at $\sqrt{s} = 7 \text{ TeV}$:
 - ▶ $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 56 \times 10^{-9}$ at 95% CL
 - ▶ $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 150 \times 10^{-10}$ at 95% CL

► ATLAS:

- ▶ $\mathcal{L} = 2.4 \text{ fb}^{-1}$, pp collisions at $\sqrt{s} = 7 \text{ TeV}$:
 - ▶ $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 22 \times 10^{-9}$ at 95% CL

► CMS: different limit estimator (fully consistent results)

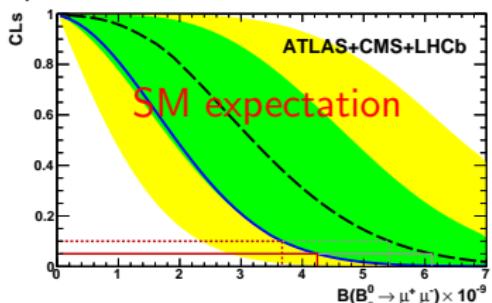
- ▶ $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 7.2 \times 10^{-9}$ at 95% CL
- ▶ $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.6 \times 10^{-9}$ at 95% CL

LHC Combination

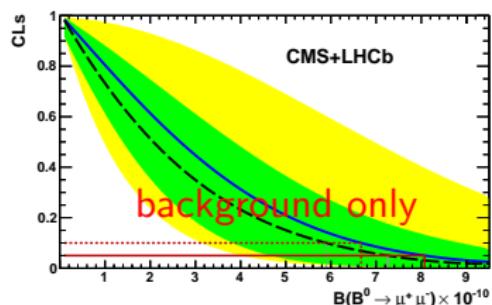
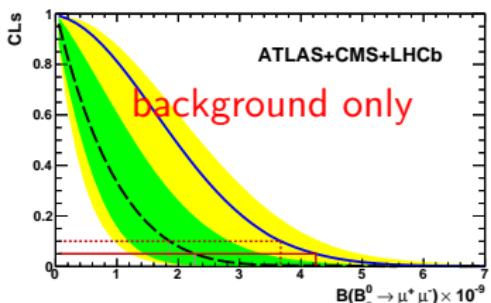
CMS-PAS-BPH-12-009

$B_s^0 \rightarrow \mu^+ \mu^-$:

Mode	limit	Combined result
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) (10^{-9})$	Bkg only	2.3
	Bkg + SM	6.1
	Obs	4.2
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) (10^{-10})$	Bkg only	7.3
	Obs	8.1

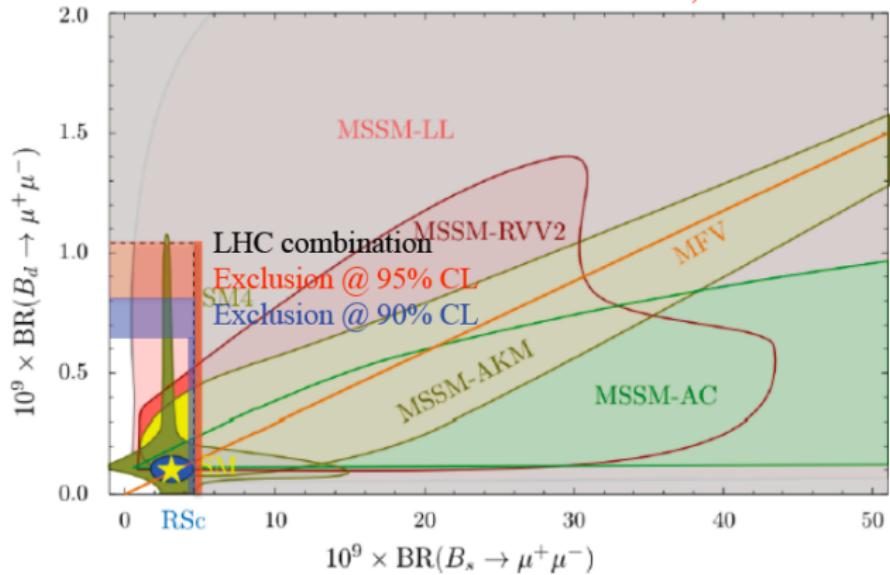


$B^0 \rightarrow \mu^+ \mu^-$:



LHC combination

D. Straub, arXiv 1205.6094



- Grey area ruled out before LHC combination
- Red area ruled out by LHC combination at 95% CL

Conclusions

- ▶ Search for $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ in 2011 dataset in CMS:

upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	1.8×10^{-9}	1.6×10^{-9}

- ▶ The combination with ATLAS and LHCb results further improves limits:

Upper limit (95%CL)	observed	expected
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	4.2×10^{-9}	6.1×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	8.1×10^{-10}	7.3×10^{-10}

- ▶ Now working on a multivariate analysis on 2011 dataset and the 8 TeV dataset
→ stay tuned!

