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

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EPS HEP Grenoble
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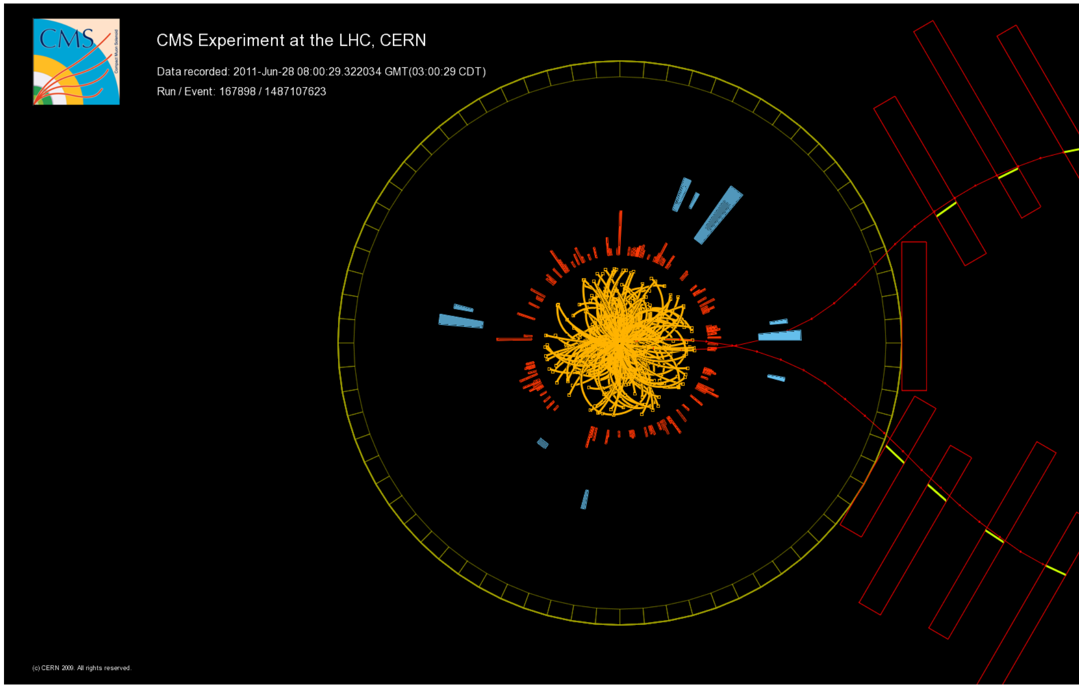
- Introduction
  - motivation and methodology
  - detector
- Analysis
  - signal and normalization
  - pileup is not an issue
- Results with $1.14\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$

Abstract #206

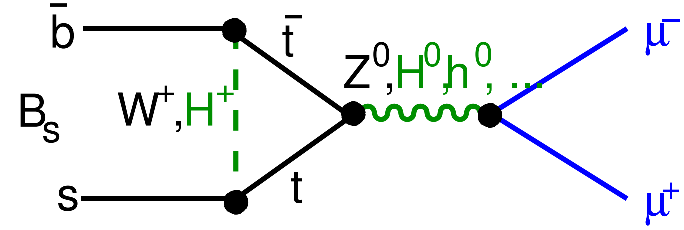


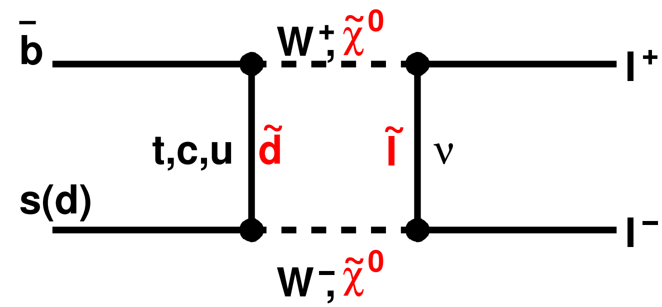
Motivation: search for new physics

- Decays highly suppressed in Standard Model
  - ▷ effective FCNC, helicity suppression
  - ▷ SM expectation:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

(Buras 2010)





  - ▷ Cabibbo-enhancement $(|V_{ts}| > |V_{td}|)$ of $B_s^0 \to \mu^+\mu^-$ over $B^0 \to \mu^+\mu^-$ only in MFV models

- Indirect sensitivity to new physics
  - ▷ 2HDM: $\mathcal{B} \propto (\tan\beta)^4, m_{H^+}$; MSSM: $\mathcal{B} \propto (\tan\beta)^6$
  - → sensitivity to extended Higgs boson sectors
  - → constraints on parameter regions

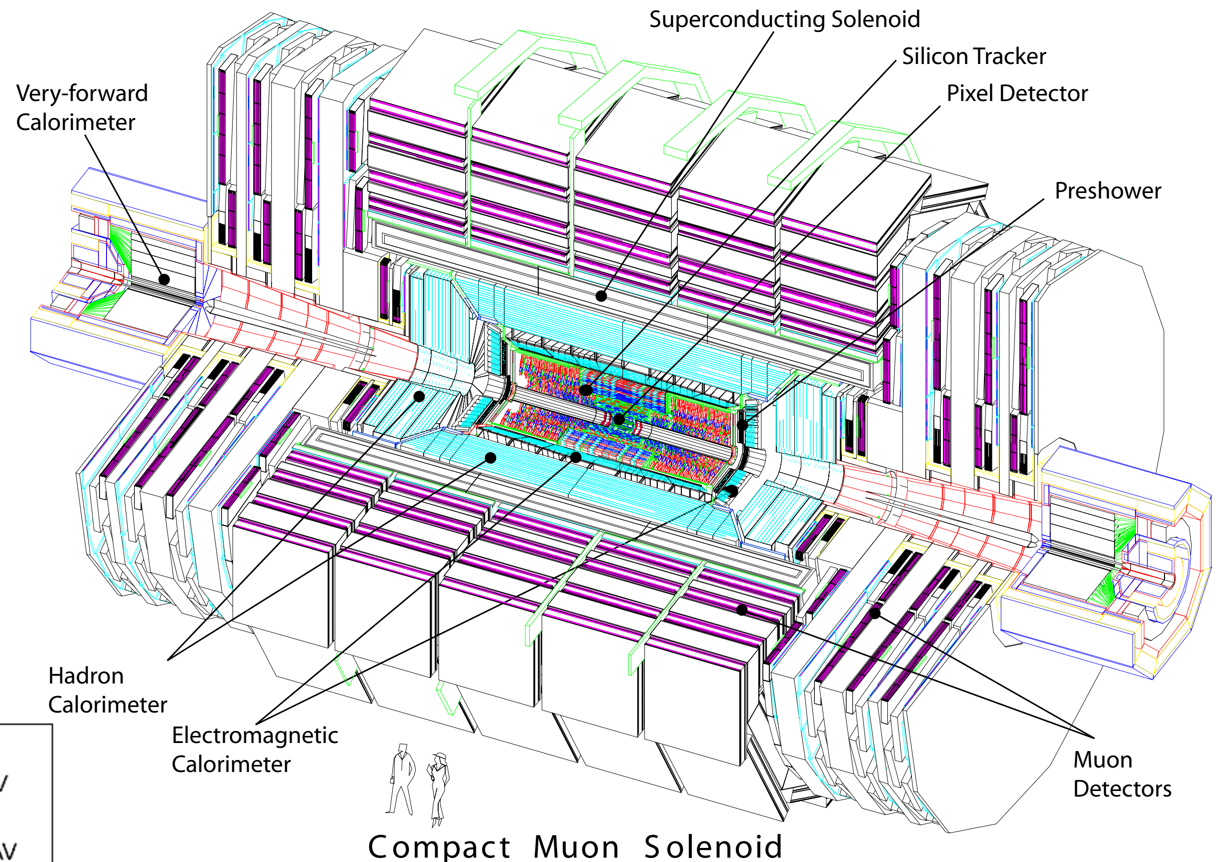
- $B_s^0 \to \mu^+\mu^-$ considered as golden channel
  - ▷ high sensitivity to new physics and small theoretical uncertainties
  - → especially in connection with $B^0 \to \mu^+\mu^-$

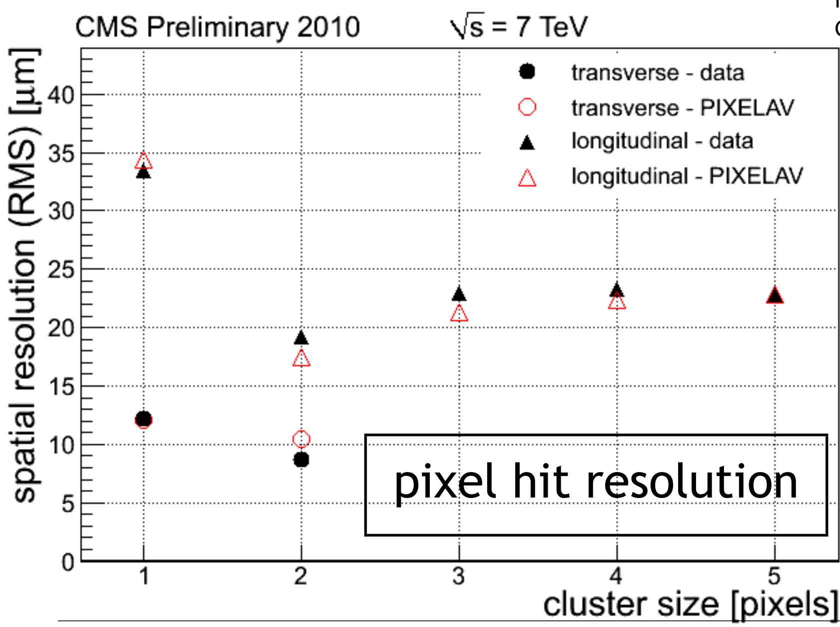
JINST 3, S08004 (2008)

The CMS detector

- Design prioritization
  - lepton ID
  - b/τ tagging
  - jets and $\not{E}_T$

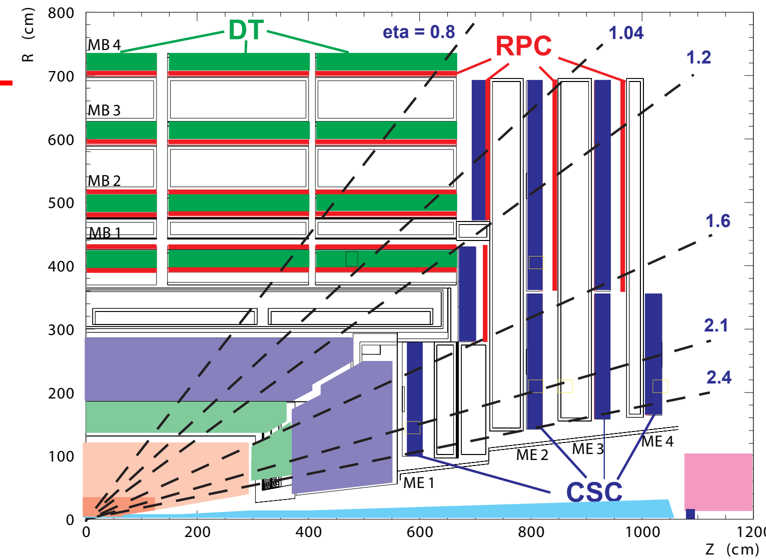
Weight	12'500 t
Length	21.6 m
Diameter	15 m
Magnetic field	3.8 T



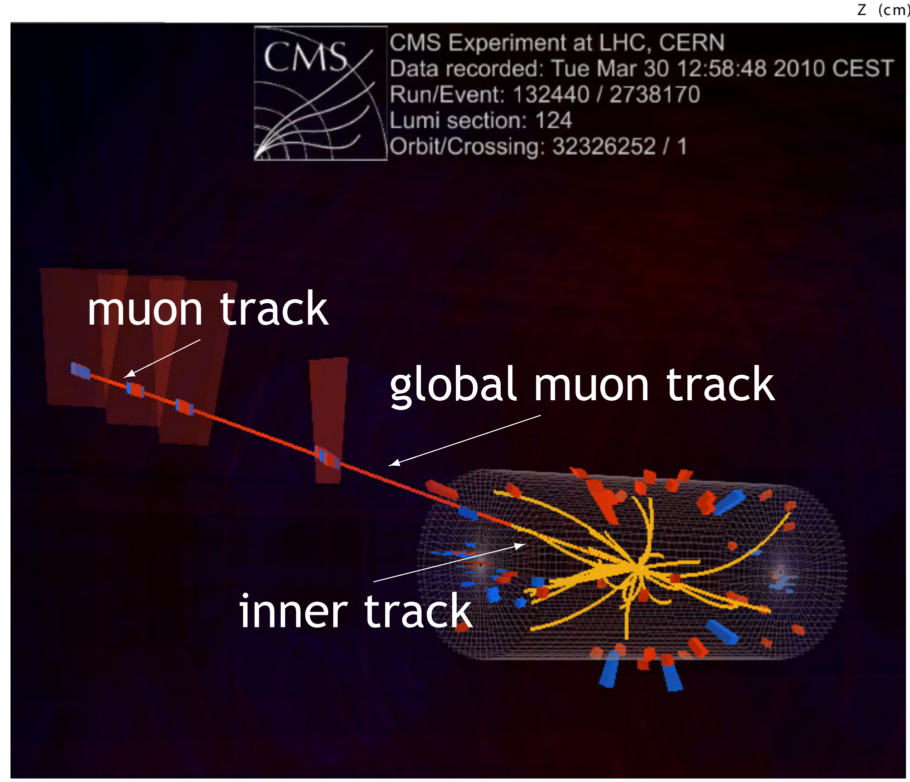


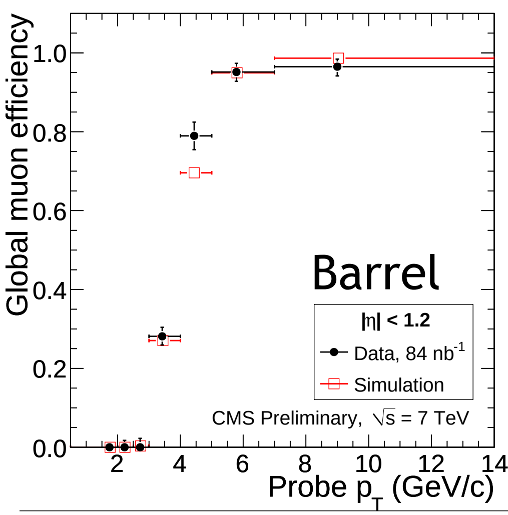
Component	Characteristics	resolutions
Pixel	3/2 Si layers	$\delta_z \approx 20\ \mu$m, $\delta_\phi \approx 10\ \mu$m
Tracker	10/12 Si strips	$\delta(p_\perp)/p_\perp \approx 1\%$
ECAL	$PbWO_4$	$\delta E/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
HCAL (B)	Brass/Sc, $> 7.2\lambda$	$\delta E/E \approx 100\sqrt{E}\%$
HCAL (F)	Fe/Quartz	$\delta(\not{E}_T) \approx 0.98\sqrt{\sum E_T}$
Magnet	3.8 T solenoid	
Muons	DT/CSC + RPC	$\delta(p_\perp)/p_\perp \approx 10\%$ (STA)

Muon reconstruction



- Large muon acceptance $|\eta| < 2.4$
  - ▷ drift tubes
  - ▷ cathode strip chambers
  - ▷ resistive plate chambers
- 3 muon reconstruction algorithms
  - ▷ standalone muon: reconstructed in muon system only
  - ▷ global muon ('GM'): outside-in standalone muon $\rightarrow$ to inner track
  - ▷ tracker muon ('TM'): inside-out inner track $\rightarrow$ muon detector





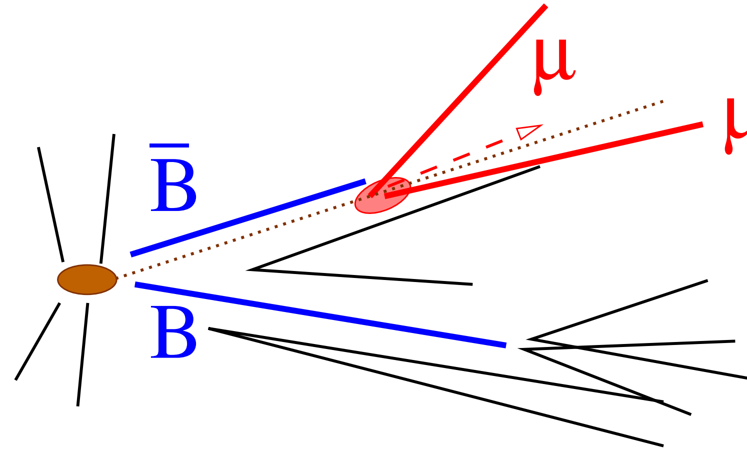
Muon misidentification

$$\varepsilon(\mu|\pi) \leq 0.3\%$$
$$\varepsilon(\mu|K) \leq 0.3\%$$
$$\varepsilon(\mu|p) \leq 0.05\%$$

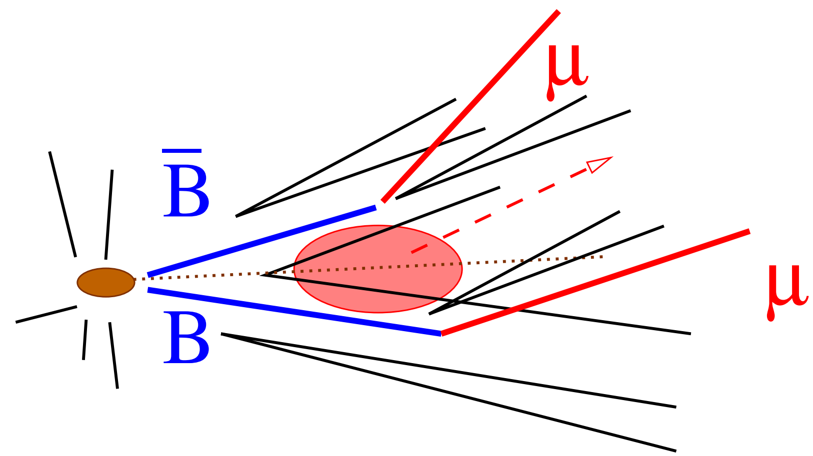
(measured in data and MC)

Analysis overview

- Signal $B_s^0 \to \mu^+\mu^-$
  - ▷ two muons from one decay vertex
    - mass around $m_{B_s^0}$
    - long-lived B
    - well reconstructed secondary vertex
    - momentum aligned with flight direction



- Background
  - ▷ two semileptonic (B) decays (gluon splitting)
  - ▷ one semileptonic (B) decay and one misidentified hadron
  - ▷ rare single B decays
    - peaking ($B_s^0 \to K^+K^-$)
    - non-peaking ($B_s^0 \to K^-\mu^+\nu$)
  - $\to$ mass resolution
  - $\to$ not well-reconstructed secondary vertex
  - $\to$ pointing angle



$\Rightarrow$ **High signal efficiency and high background reduction**

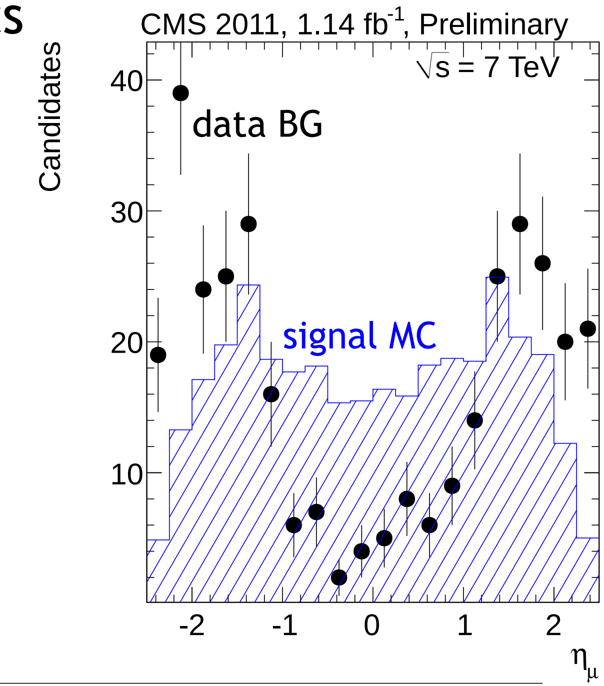
Methodology

- Measurement of $B_s^0 \to \mu^+\mu^-$ relative to normalization channel:
  - similar trigger and selection to reduce systematic uncertainties

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

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

- Calibration of MC with exclusively reconstructed decays
  - $B^\pm \to J/\psi\, K^\pm$: normalization with high statistics
  - $B_s^0 \to J/\psi\, \phi$: B_s^0 signal MC ($p_\perp$ and isolation)



- Analysis in two channels
  - barrel (both muons $|\eta| < 1.4$):
    better signal/background ratio $\to$ better sensitivity
    good mass resolution (36 MeV)
  - endcap (at least one muon with $|\eta| > 1.4$):
    add more statistics

$\Rightarrow$ Blind analysis

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

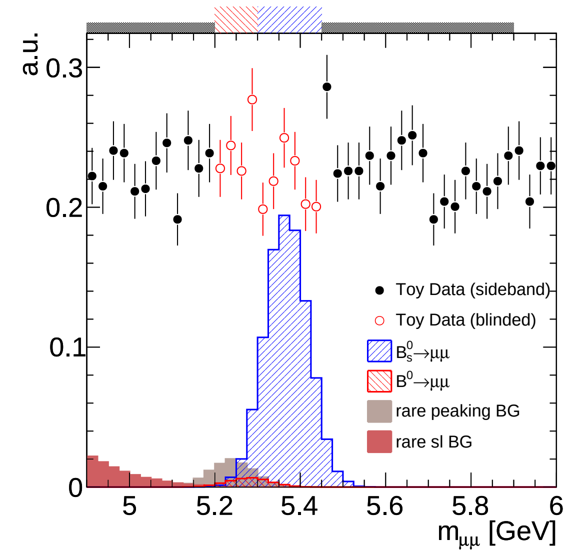
Determination
- ▷ MC simulation
- ▷ data

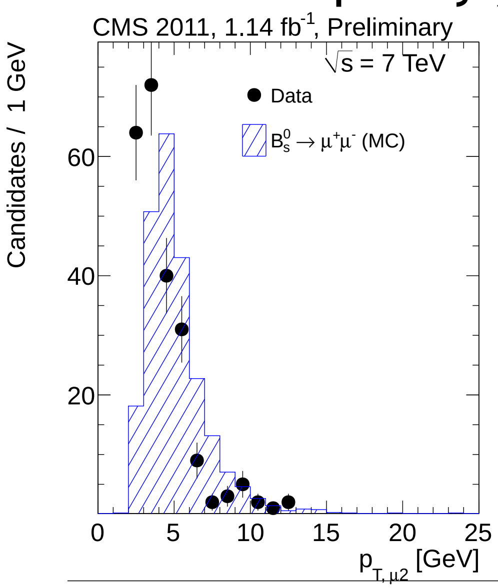
$\to$ systematics from difference

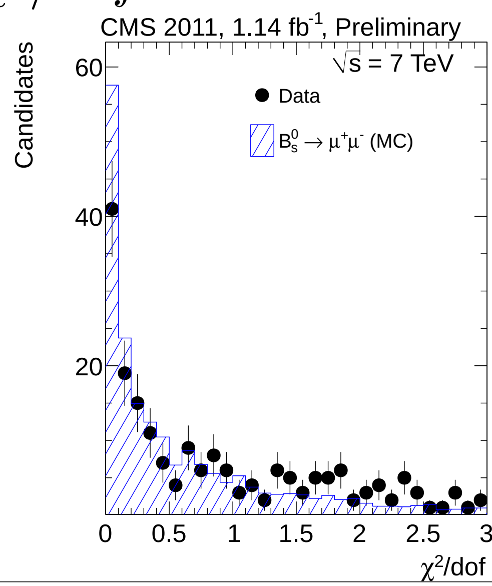
1.14 fb^{-1} at $\sqrt{s} = 7$ TeV taken in 2011

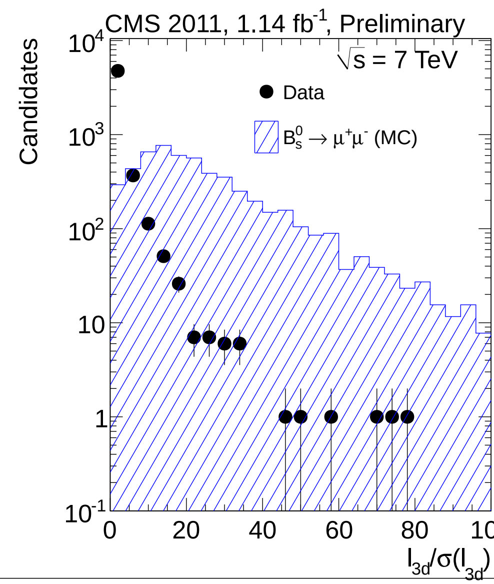
Signal selection

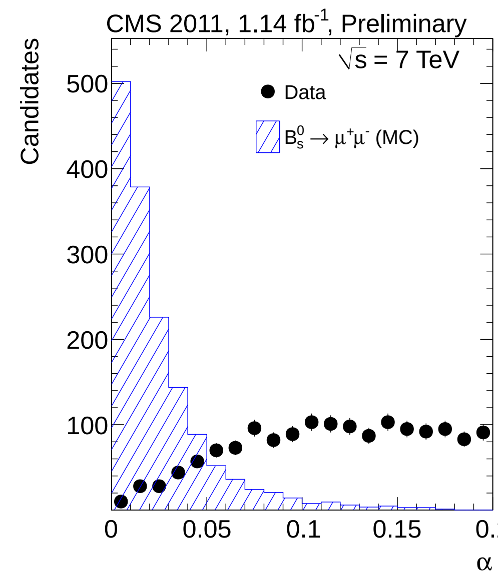
- Background in sidebands $(4.9 < m < 5.2\,\text{GeV and } 5.45 < m < 5.9\,\text{GeV})$
  - ▷ blinded region $5.2 < m < 5.45\,\text{GeV}$
- Optimized for best upper limit (grid search)
  - ▷ selection frozen before unblinding
- Discriminating variables
  - ▷ muon ID (GM and TM), muon and dimuon $p_\perp$
  - ▷ pointing angle α
  - ▷ flight length significance $\ell_{3d}/\sigma(\ell_{3d})$
  - ▷ fit quality χ^2/dof









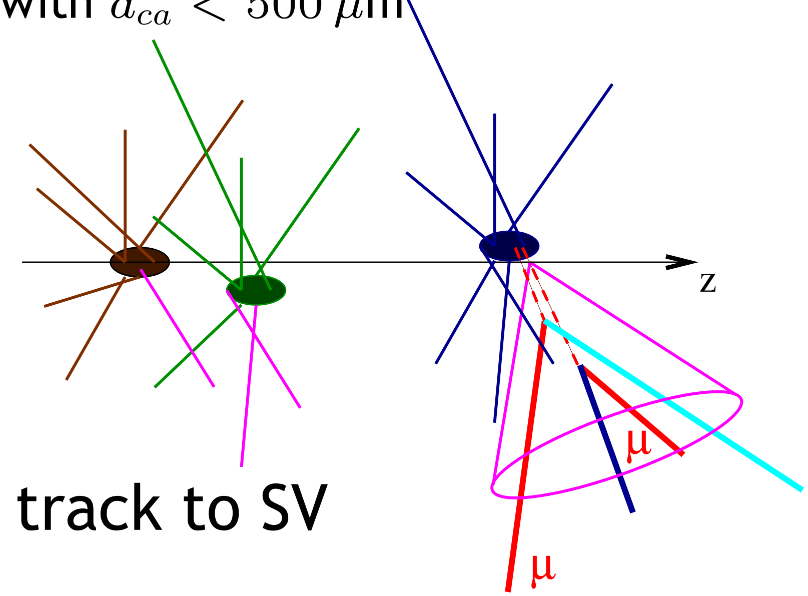


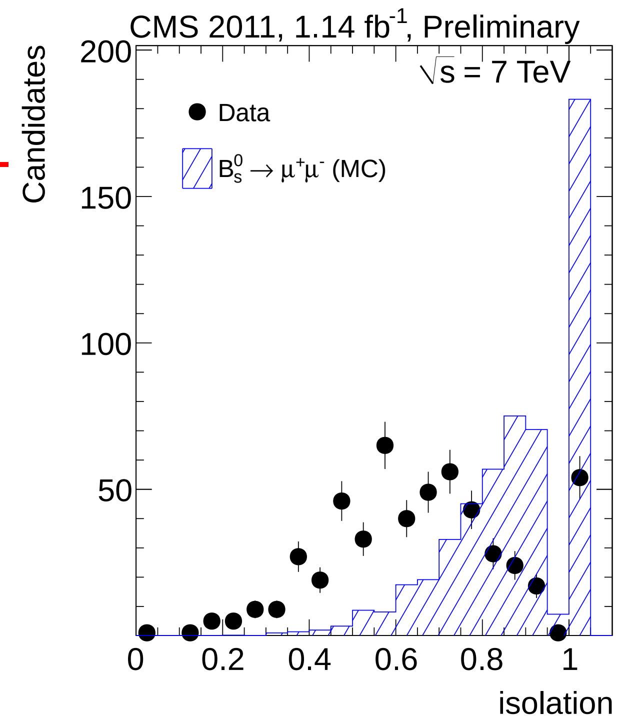
Isolation

- Relative isolation of dimuon

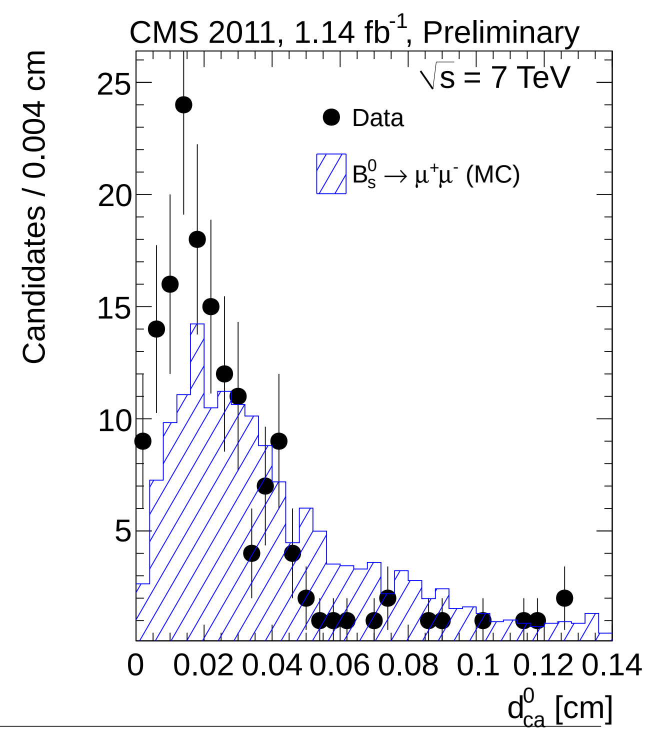
$$I = \frac{p_\perp(\mu^+\mu^-)}{p_\perp(\mu^+\mu^-) + \sum_{\Delta R<1} p_\perp}$$

  - ▷ in cone around dimuon momentum
  - ▷ for tracks in cone with $\Delta R < 1$
    - with $p_\perp > 0.9$ GeV
    - either associated to same PV as candidate
    - or with $d_{ca} < 500\,\mu$m





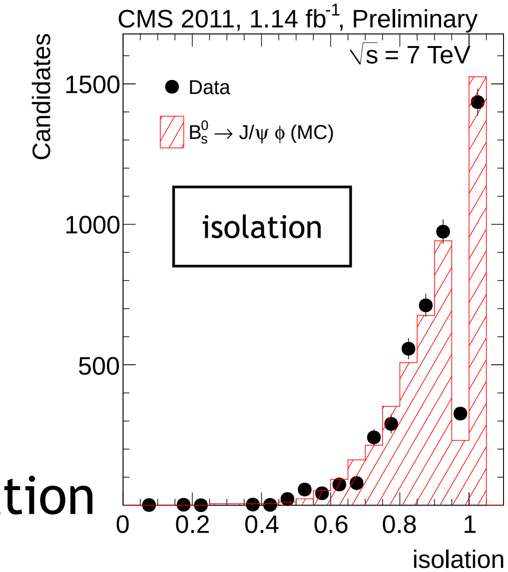
- Closest track to SV
  - ▷ d_{ca}^0

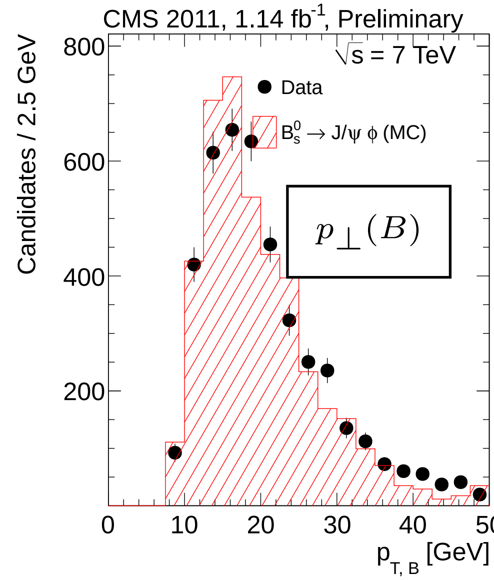


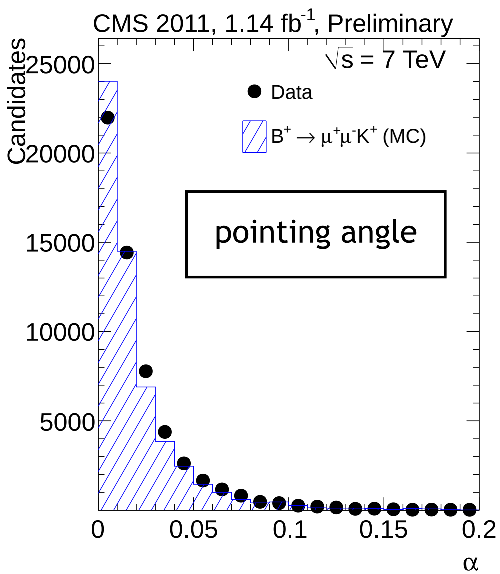
MC simulation vs. data

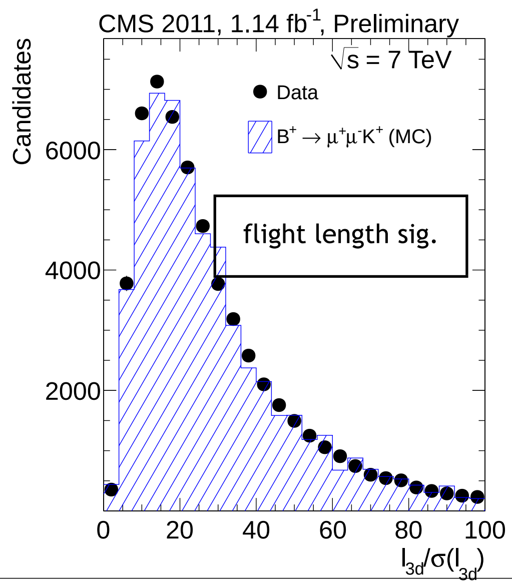
- Comparison of sideband-subtracted distributions
  - ▷ In general good agreement
- Differences $\rightarrow$ systematics
  - ▷ single requirement efficiencies (incl. statistical component)
  - ▷ $B^0_s \rightarrow J/\psi\,\phi$: 7.9%
  - ▷ $B^\pm \rightarrow J/\psi\,K^\pm$: 4.0%

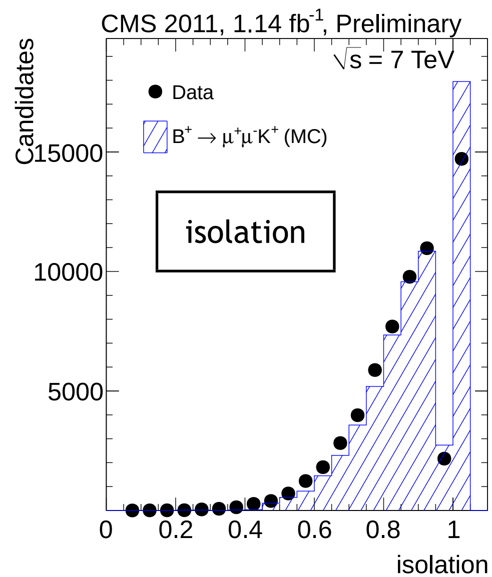
$\rightarrow$ $B^0_s \rightarrow J/\psi\,\phi$ used as B^0_s MC validation

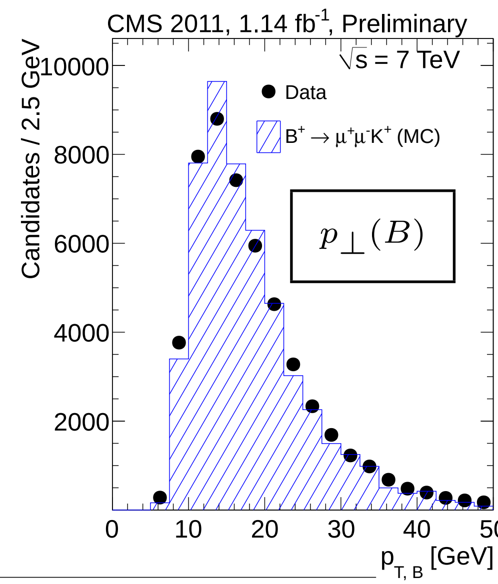








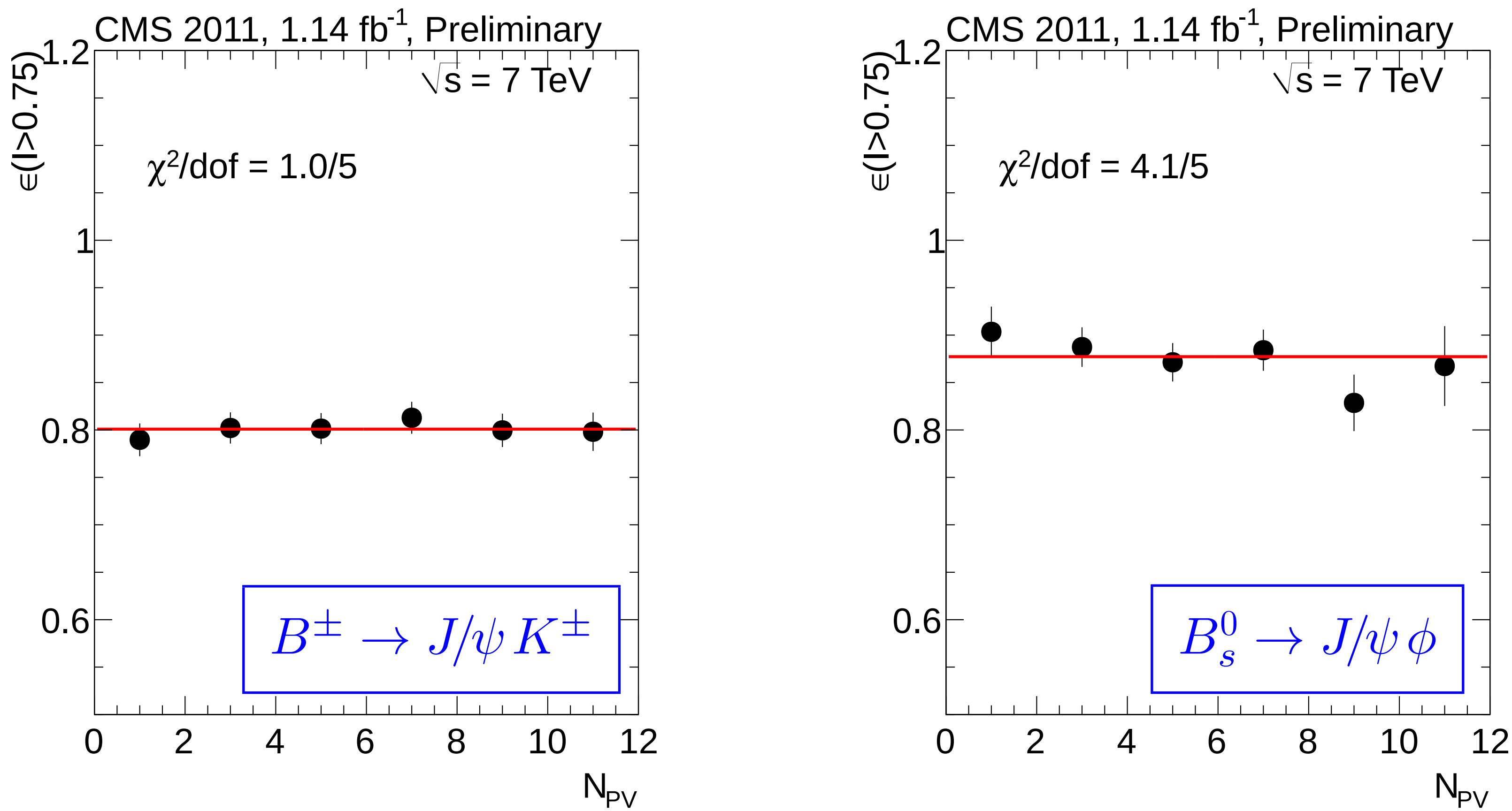




Pileup independence

- Pileup independence checked
  - ▷ Signal MC event samples with pileup
  - ▷ Data: efficiency of selection vs. number of primary vertices
    - isolation
    - flight length significance

→ no concern at least until $N_{PV} \leq 12$ (currently: $\langle N_{PV} \rangle \approx 5.5$)



Final selection: normalization sample

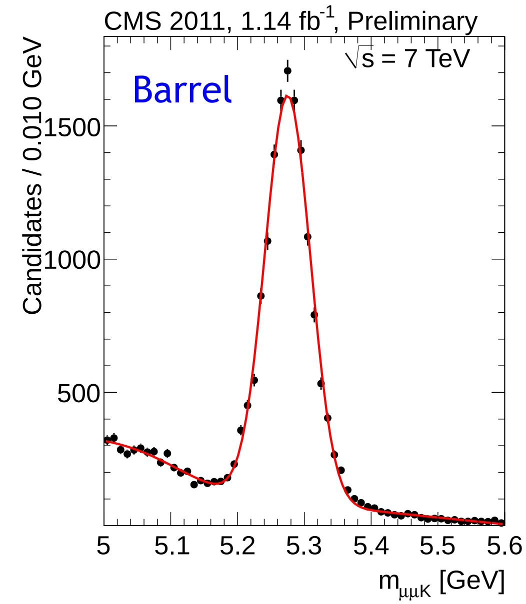
- same selection as for signal
  - ▷ differences between barrel and endcap

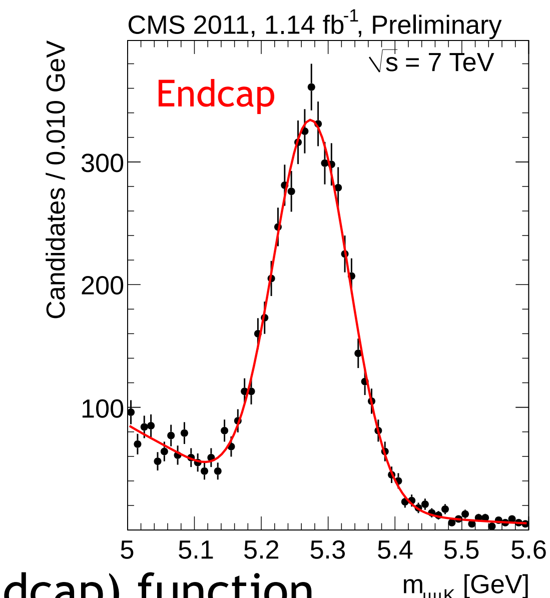
Variable		Barrel	Endcap	units
$p_{\perp \mu_1}$	$>$	4.5	4.5	GeV
$p_{\perp \mu_2}$	$>$	4.0	4.0	GeV
$p_{\perp B}$	$>$	6.5	6.5	GeV
χ^2/dof	$<$	1.6	1.6	
α	$<$	0.050	0.025	rad
$\ell_{3d}/\sigma(\ell_{3d})$	$>$	15.0	20.0	
I	$>$	0.75	0.75	
d^0_{ca}	$>$	n/a	0.015	cm

  - ▷ for normalization additionally require
    two muons bending away from each other

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

  - ▷ Systematics (5%) dominated by background pdf
    error function plus linear (barrel) or exponential (endcap) function



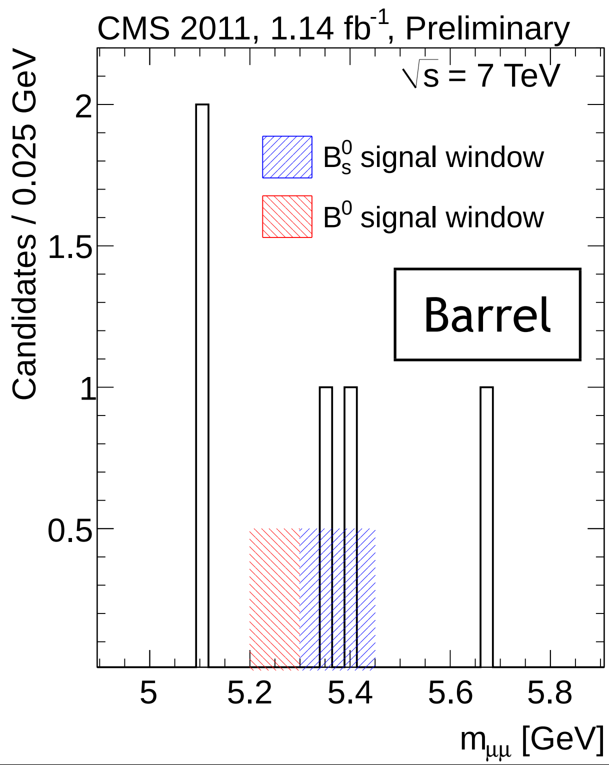


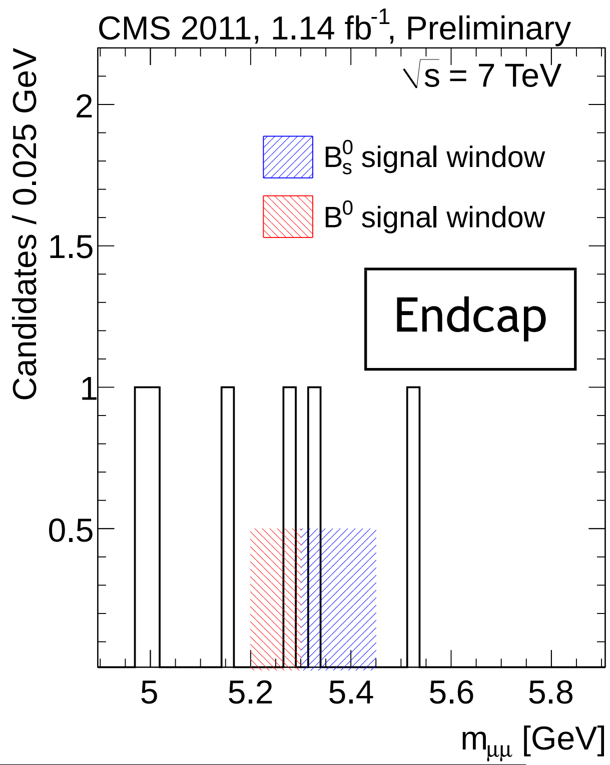
Expectations and observation

	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

- As expected
  - ▷ based on sidebands
  - ▷ studied with $I < 0.7$
  - → no evidence for anomalous signal
- Expected UL (median)

  $B_s^0 \to \mu^+\mu^- : 1.8 \times 10^{-9}$





Results

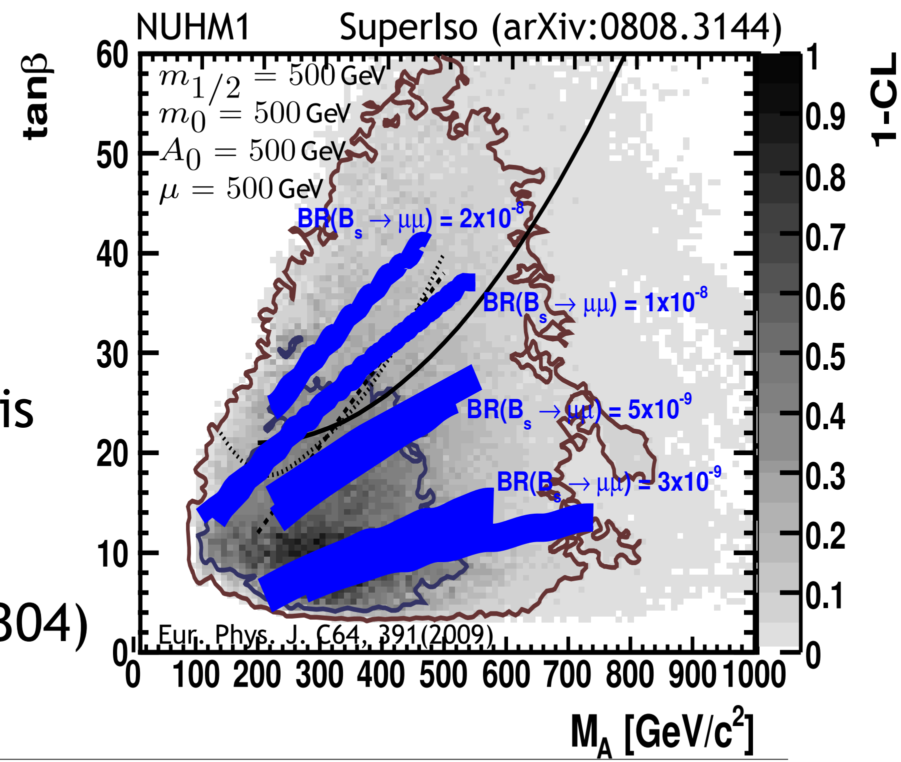
- Upper limits and significance for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  - $\mathrm{CL_s}$ and $\mathrm{CL_b}$
  - Input from PDG

$$\begin{aligned} f_u &= 0.401 \pm 0.013 \\ f_s &= 0.113 \pm 0.013 \\ \mathcal{B}(B^+) &= (6.0 \pm 0.2) \times 10^{-5} \end{aligned}$$

- Upper limits

$$\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 1.9 \times 10^{-8} \quad (95\%\ \mathrm{C.L.}) \\ \mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 1.6 \times 10^{-8} \quad (90\%\ \mathrm{C.L.}) \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &< 4.6 \times 10^{-9} \quad (95\%\ \mathrm{C.L.}) \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &< 3.7 \times 10^{-9} \quad (90\%\ \mathrm{C.L.}) \end{aligned}$$

  - p values for background-only hypothesis
    - $B_s^0 \to \mu^+\mu^-$: 0.11
    - $B^0 \to \mu^+\mu^-$: 0.40
  - p value for $5.6 \times \mathrm{SM}$ (cf. arXiv:1107.2304)
    - $B_s^0 \to \mu^+\mu^-$: 0.053



Systematics and cross checks

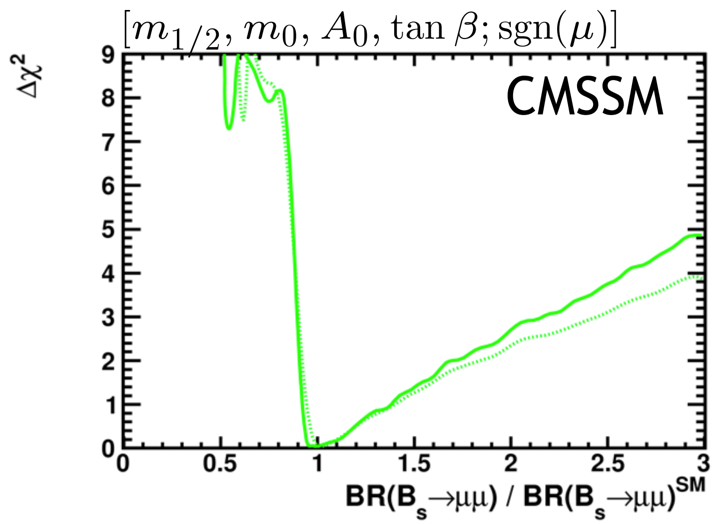
- Background, studied from — 4%
  inverted isolation sample: loosened selection
- Signal
  - ▷ acceptance: difference between production processes — 4%
  - ▷ analysis efficiency: comparison of data and MC — 7.9%
  - ▷ mass scale (resolution) from J/ψ and $\Upsilon(1S)$ — 3%
- Normalization
  - ▷ analysis efficiency: comparison of data and MC — 4%
  - ▷ kaon tracking efficiency — 3.9%
  - ▷ yield fitting — 5%
- Muon identification and trigger
  - ▷ estimated through difference of MC and data-driven methods
  - ▷ muon identification efficiency ratio — 5%
  - ▷ trigger efficiency ratio — 3%
- Cross checks performed
  sample yield vs time, $\mathcal{B}(B_s^0 \to J/\psi\,\phi)$, inverted isolation yield

Conclusions and outlook

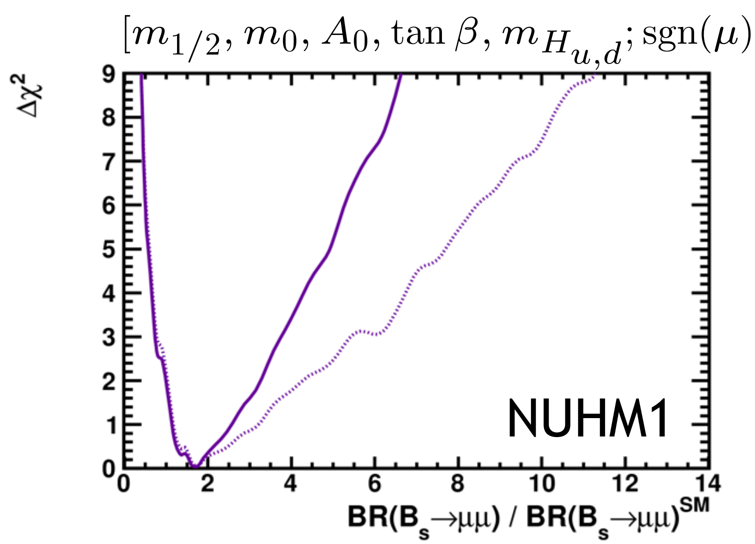
- Search for $B^0_{s(d)} \to \mu^+\mu^-$ with $1.14\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$
  - ▷ no signal found beyond SM expectation
  - ▷ determine upper limits

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) < 1.9 \times 10^{-8} \quad (95\%\,\text{C.L.})$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9} \quad (95\%\,\text{C.L.})$$

  - ▷ impact on new physics models



- Bright prospects
  - ▷ background events not irreducible
  - ▷ upgrade to multi-variate analysis
  - → looking forward to LHC's increasing luminosity



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