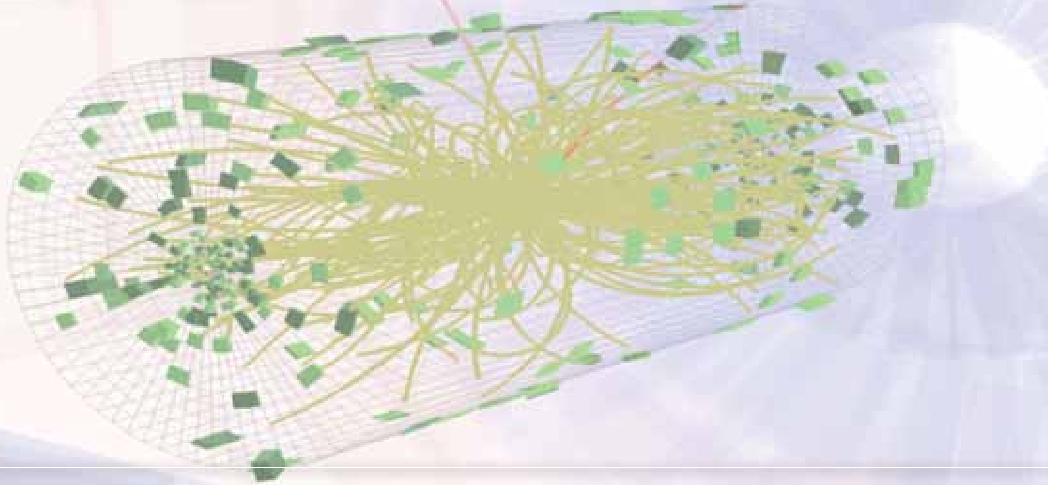
Search for the B_s and B^0 decays to dimuons with the CMS experiment



Luca Martini (INFN Pisa & Uni Siena)
for the CMS collaboration

Rencontres de Moriond on
"Electroweak Interactions and Unified Theories"
3-10 Mar 2012, La Thuile, AO (Italy)

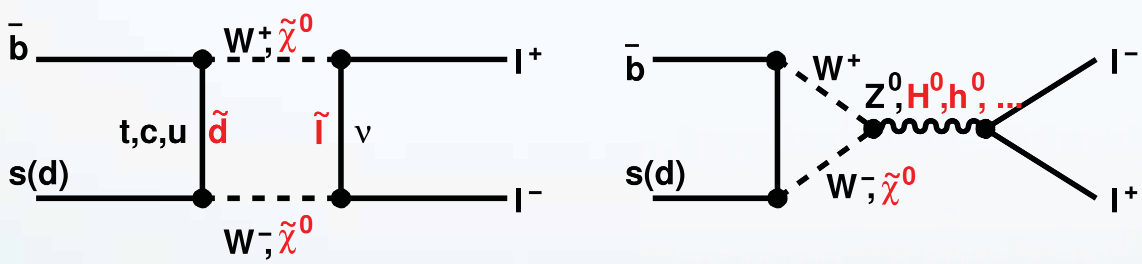
Motivation: search for new physics

In SM $B_s^0 \rightarrow \mu\mu$ and $B^0 \rightarrow \mu\mu$ have a highly suppressed rate:

1. **forbidden at tree level** and can only proceed through higher-order loop diagrams
2. **helicity suppressed** by factors of $(m_l/m_B)^2$, where m_l and m_B are the masses of the lepton and B meson
3. **require an internal quark annihilation** within the B meson

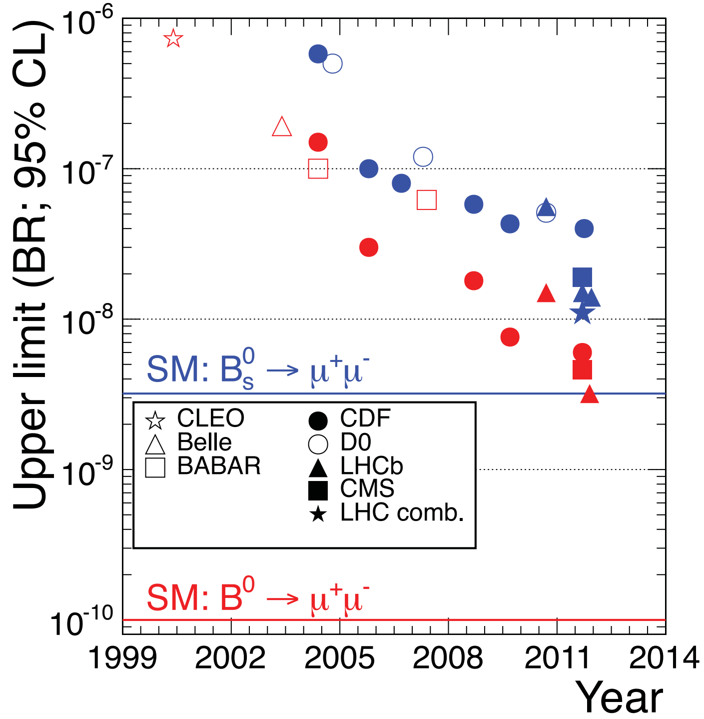
Decay channel	BF SM predictions*
$B_s^0 \rightarrow \mu^+\mu^-$	$(3.2 \pm 0.2) \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$(1.1 \pm 0.1) \times 10^{-10}$

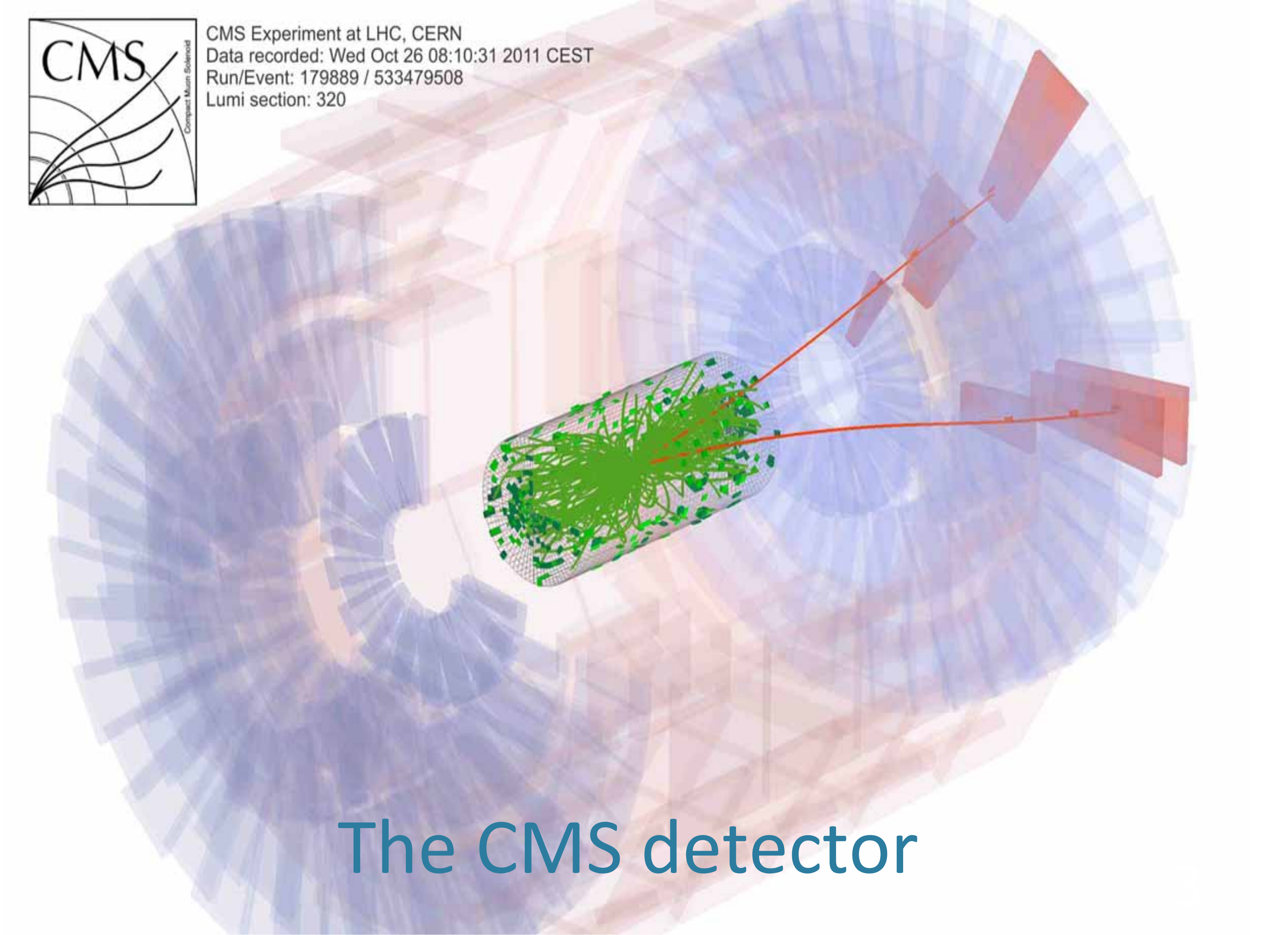
*Buras arXiv:1009.1303.



$BF(B_{(s)}^0 \rightarrow \mu\mu)$ are potentially sensitive probes for Physics Beyond SM:

- Sensitivity to extended Higgs boson sectors
- Constraints on SUSY parameter regions
- Small theoretical uncertainties

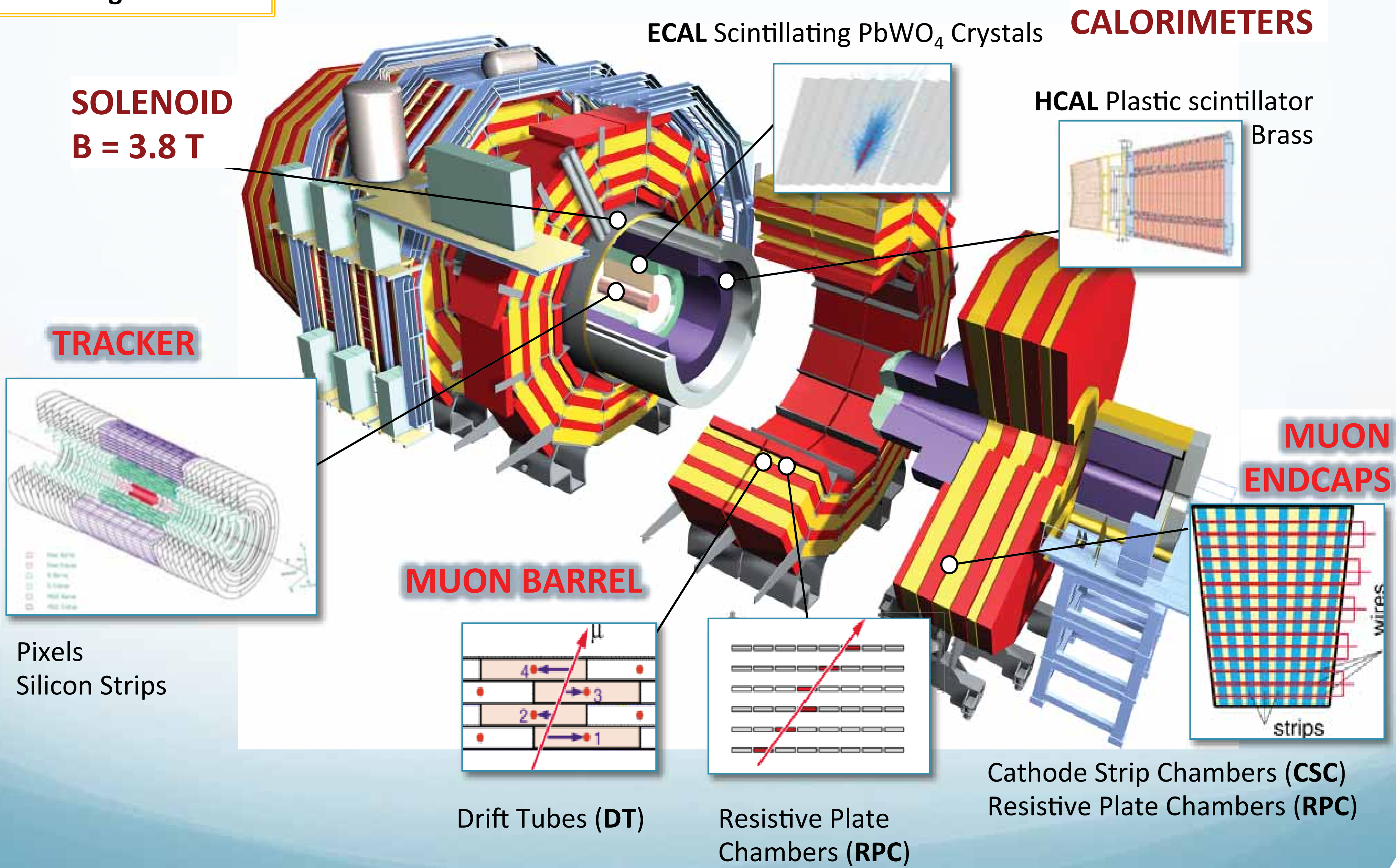




The CMS detector

The CMS detector

weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

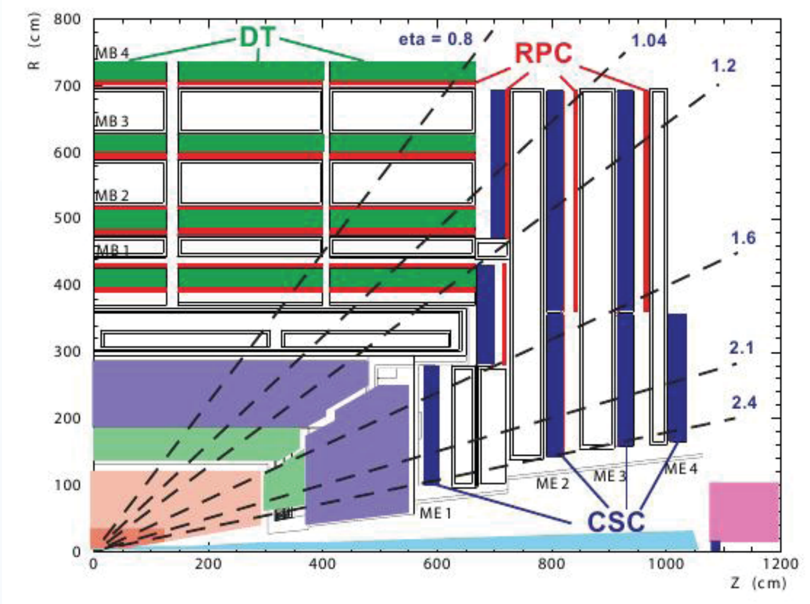


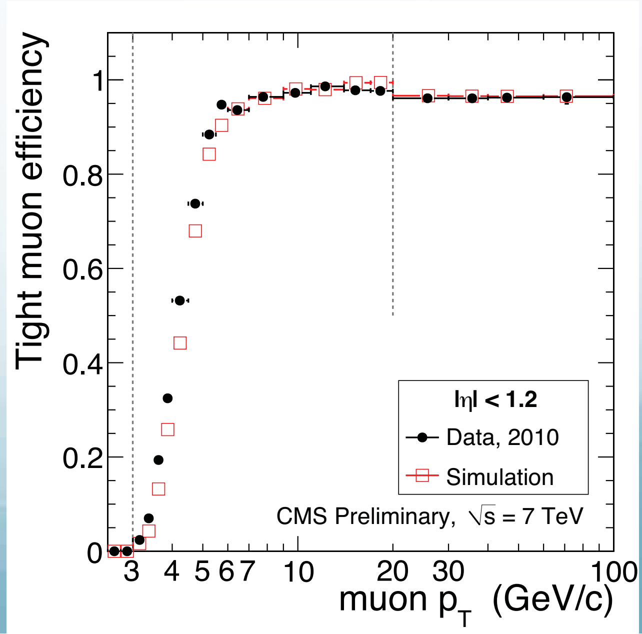
JINST 3, S08004 (2008)

Muon track reconstruction

CMS-PAS-MUO-10-002

- Tracks: Excellent p_T resolution ≈ 1%
- Tracking efficiency > 99% for central muons
- Excellent vertex reconstruction and impact parameter resolution (≈ 15 μm)
- Muon candidates: Match between muon segments and a silicon track
- Large pseudorapidity coverage: $|\eta| < 2.4$
- Muon and trigger efficiencies evaluated with
    1. MC methods
    2. Data-driven methods: Tag & Probe





Analysis overview

Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2} < 5.90$
blinding window	$5.20 < m_{\mu1\mu2} < 5.45$
$B^0 \to \mu^+\mu^-$ window	$5.20 < m_{\mu1\mu2} < 5.30$
$B_s^0 \to \mu^+\mu^-$ window	$5.30 < m_{\mu1\mu2} < 5.45$

- All the selections chosen with the signal regions ***blinded***
- Backgrounds estimated from the sidebands and from MC
- **Normalization sample** $B^\pm \to J/\psi K^\pm \to (\mu^+\mu^-) K^\pm$ to avoid
  - uncertainties of the $b\bar{b}$ production cross section
  - luminosity measurement
  - mitigate the efficiency effects

$$Br\left(B_s^0 \to \mu^+\mu^-\right) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} Br\left(B^+\right)$$

$f_s/f_u = 0.267 \pm 0.021$ [LHCb arxiv:1111.2357]
Br(B^+) from the PDG

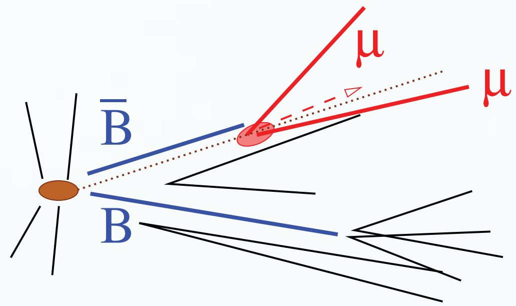
- **Control sample** $B_s^0 \to J/\psi\varphi \to (\mu^+\mu^-)(K^+K^-)$ to compare and validate B_s^0 mesons in data and MC simulations

- **We do not need the luminosity absolute value anywhere**

- Divided the sample in:
  - **barrel** (both muons with $|\eta|<1.4$) → better sensitivity, mass resolution ≈ 40 MeV
  - **endcap** (otherwise) → add statistics, mass resolution ≈ 60 MeV

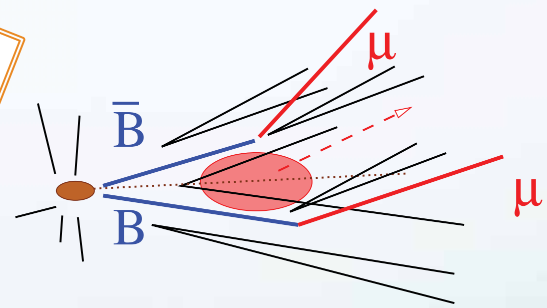
Signal versus Background

- Signal $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$:
  - two reconstructed muons
  - invariant mass around m($B_{(s)}^{0}$)
  - long lived B, with a well reconstructed secondary vertex and a momentum aligned with flight direction

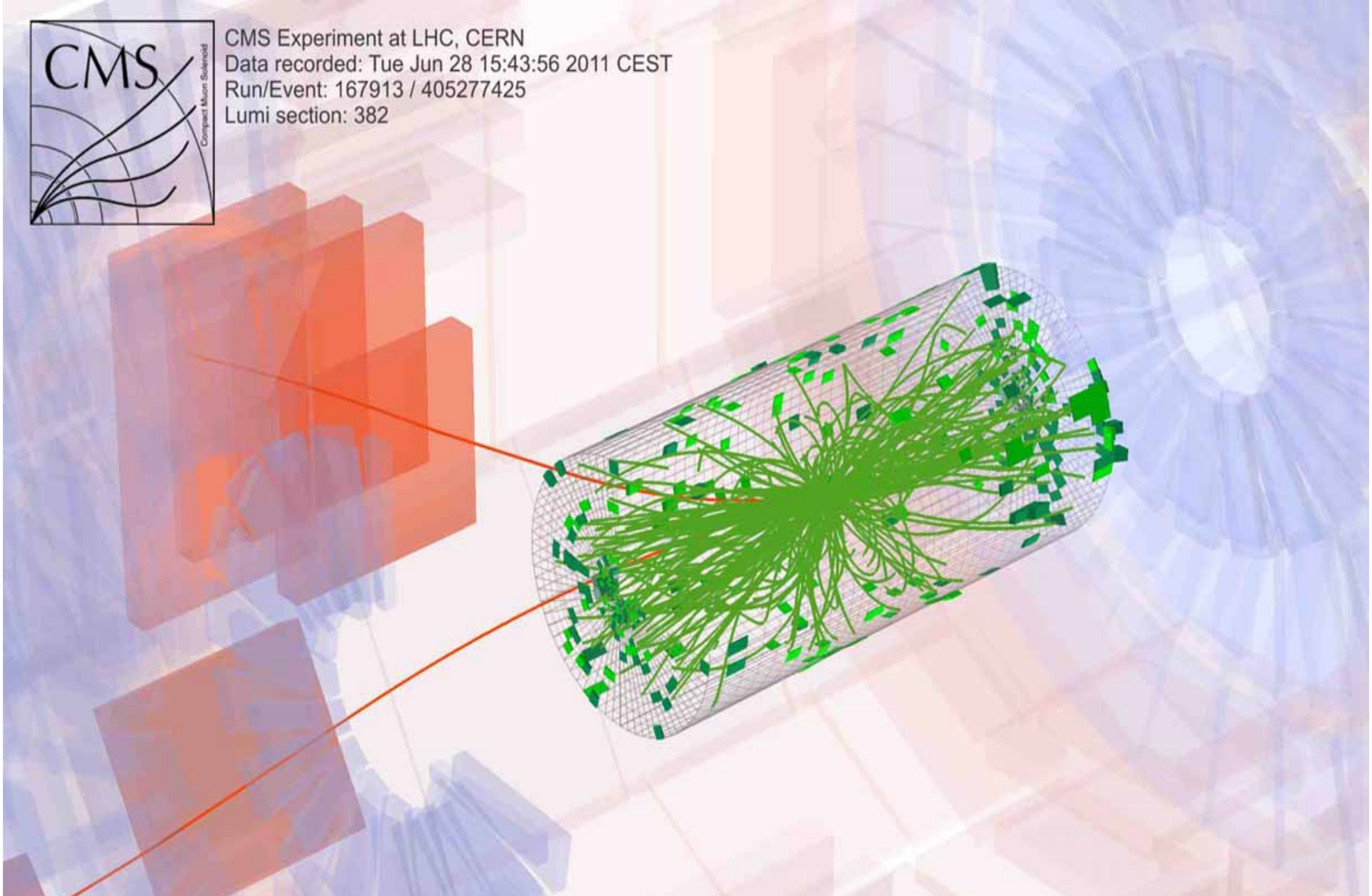


- Backgrounds
  - two semileptonic B decays
  - one semileptonic B decay and one misidentified hadron
  - single B decays
    - peaking ($B_s^0 \rightarrow K^- K^+$)
    - non peaking ($B_s^0 \rightarrow K^- \mu^+ \nu$)

combinatorial
flat shape



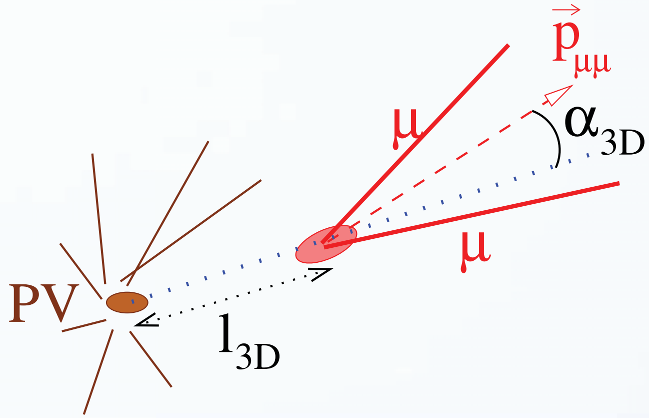
rare
shape from MC



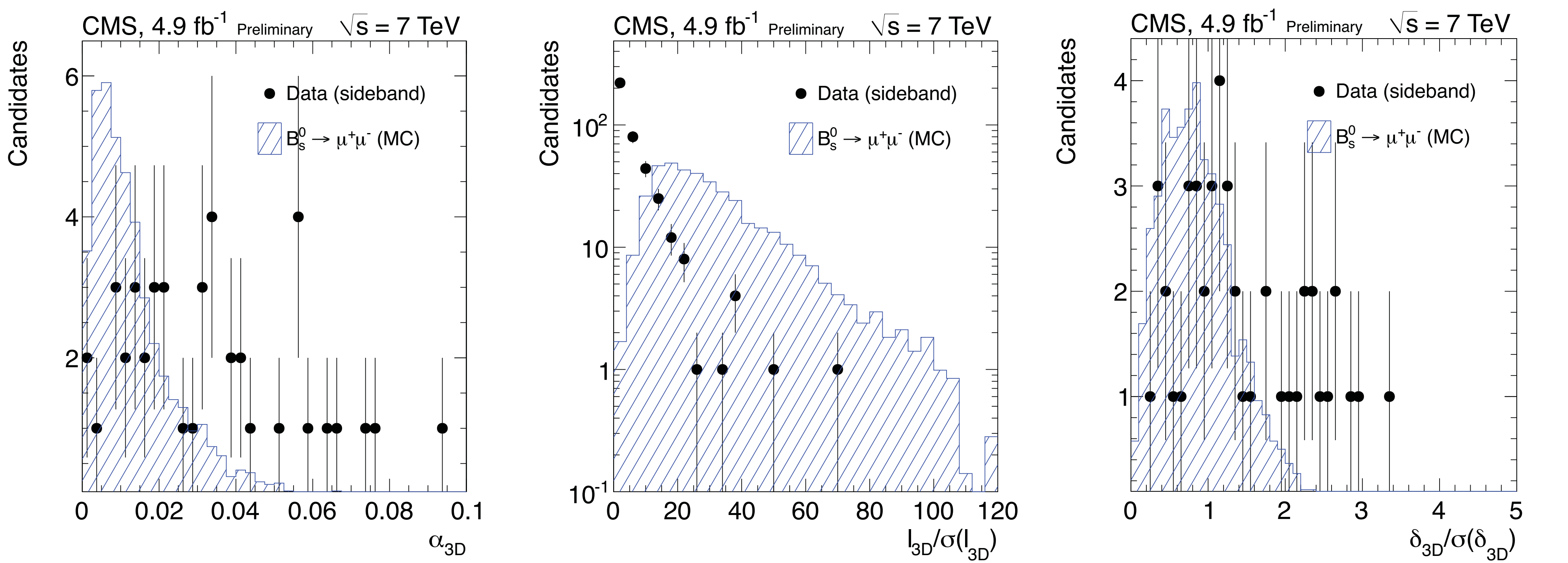
Candidate selection

Signal selection: most discriminating variables

- Pointing angle α_{3D}
- Flight length significance $l_{3D}/\sigma(l_{3D})$
- Impact parameter significance $\delta_{3D}/\sigma(\delta_{3D})$
- Selections optimized (random grid search) for best upper limit



Data side-bands vs signal MC:

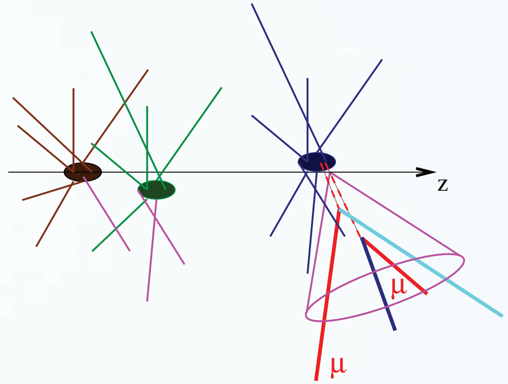


Isolation

- **Isolation cone around the Primary vertex:**

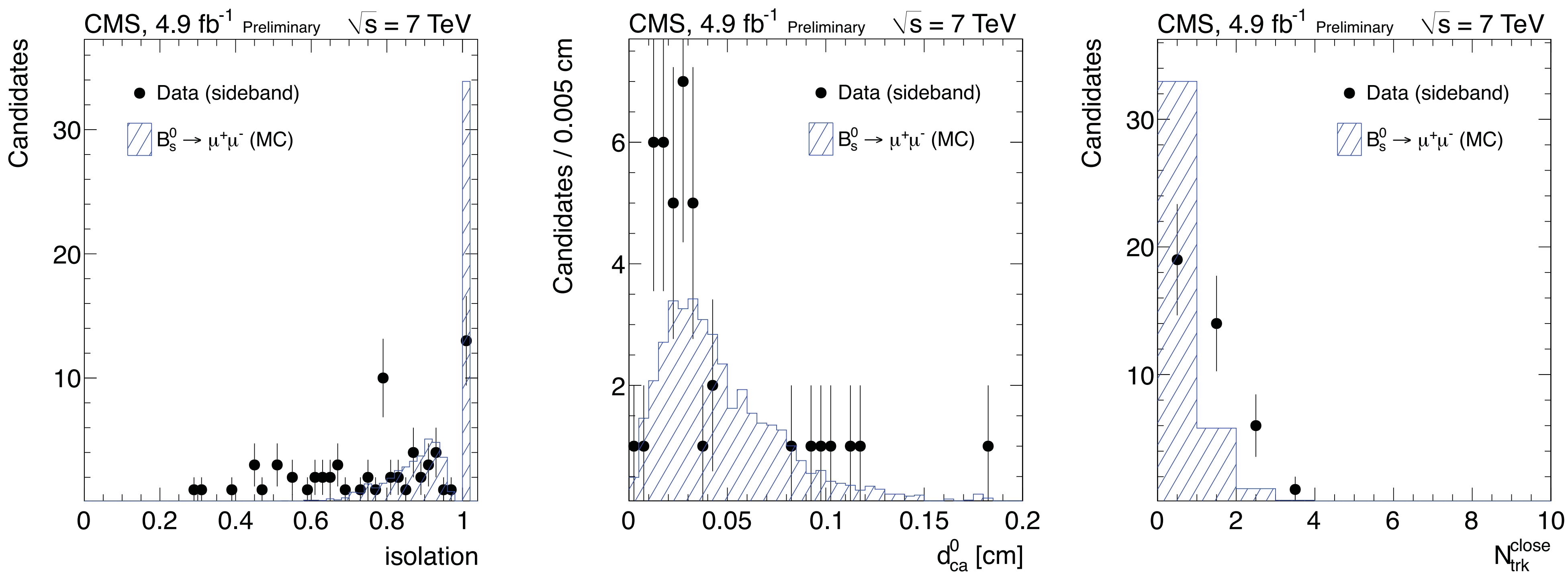
$$I = \frac{p_{\perp}(B)}{p_{\perp}(B) + \sum_{trk} |p_{\perp}|}$$

  - Tuned to minimize MC/data discrepancies and maximize bkg rejection



- **Isolation on the Secondary vertex:**
  - Distance of the closest track to SV (d_{ca}^{0})
  - Number of close tracks in $d_{ca} < 0.3$ mm and $p_T > 0.5$ GeV

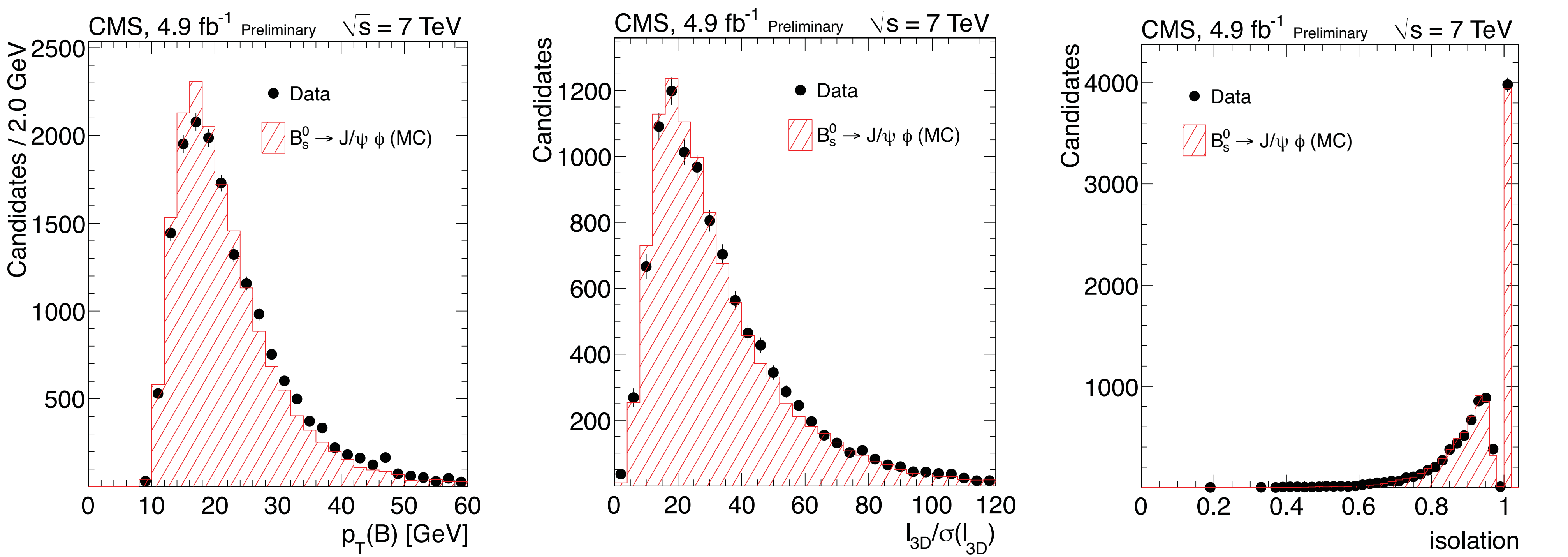
Data side-bands vs signal MC:



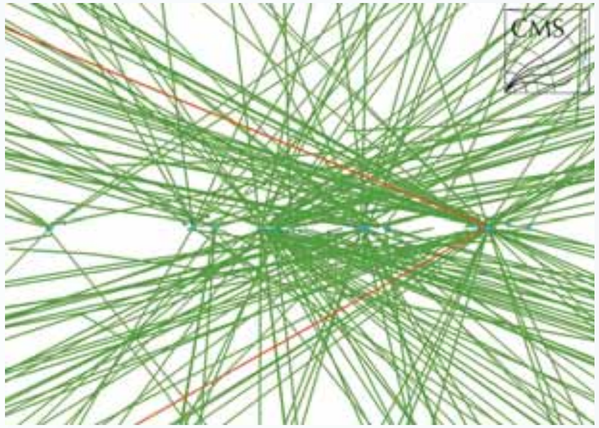
Data - Simulation comparison

- **Needed to validate signal (through the control sample) and normalization samples**
- Differences data – MC taken as systematics uncertainties:
  - *On* $B^{\pm} \rightarrow J/\psi K^{\pm}$, max diff = 2.5% (isolation) tot = 4%
  - *On* $B_s^0 \rightarrow J/\psi\varphi$, max diff = 1.6% (secondary vertex χ^2/ndof) tot = 3%
- Excellent MC – data comparison

Side-bands subtracted data vs control MC:

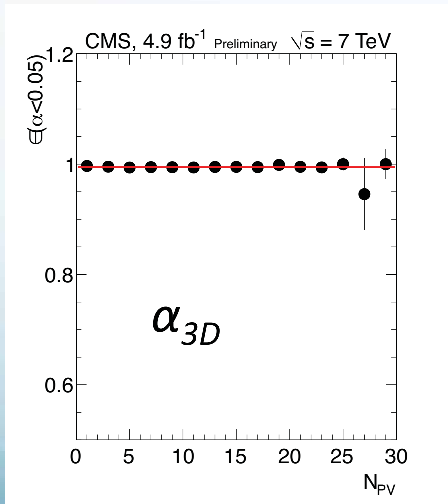


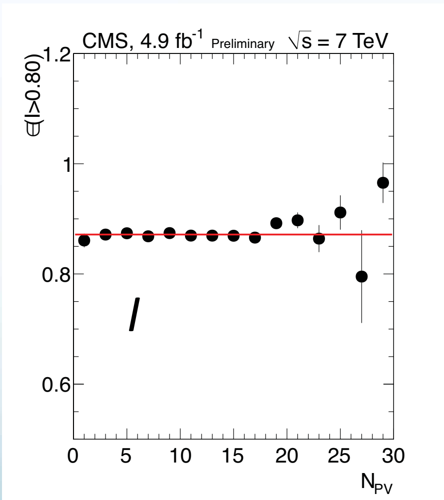
Pile-up



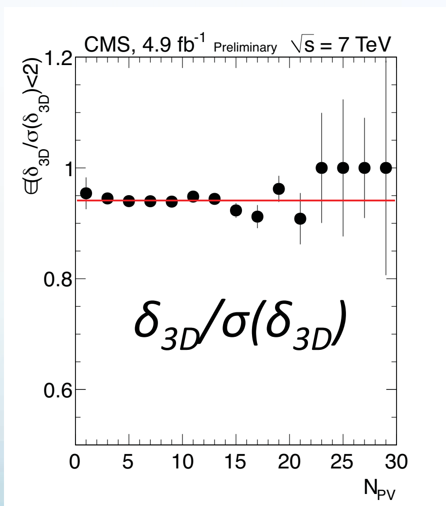
- in 2011: $\langle N_{PV} \rangle = 8$, RMS(z) = 5.6 cm
- Selections have been tuned to be pile-up independent
  - e.g. isolation searches only for tracks coming from the same primary vertex or not associated to any
- Efficiencies of all selection criteria have been evaluated versus the number of reconstructed primary vertices
- **All selections are compatible with a constant at least until 30 PV**

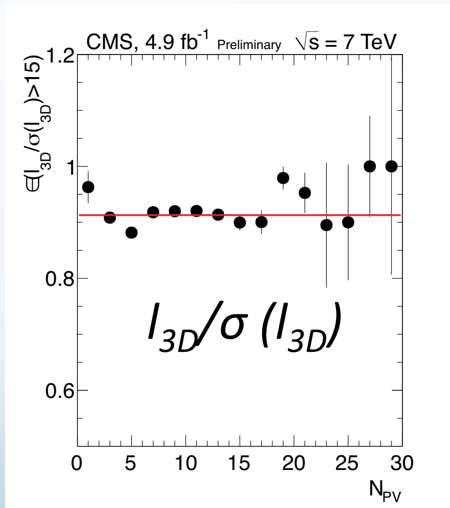
Normalization sample





Control sample



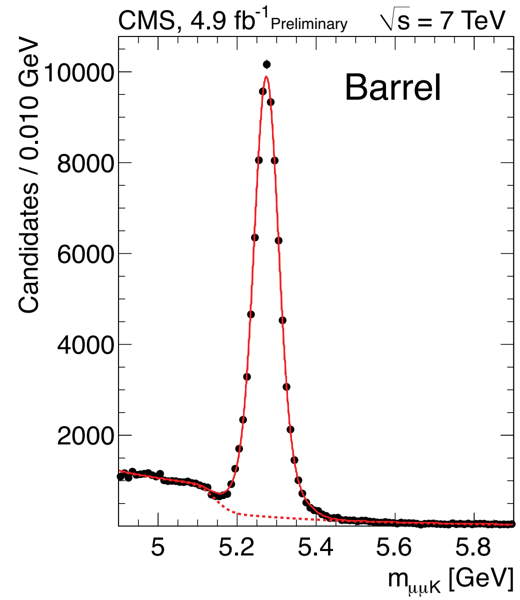


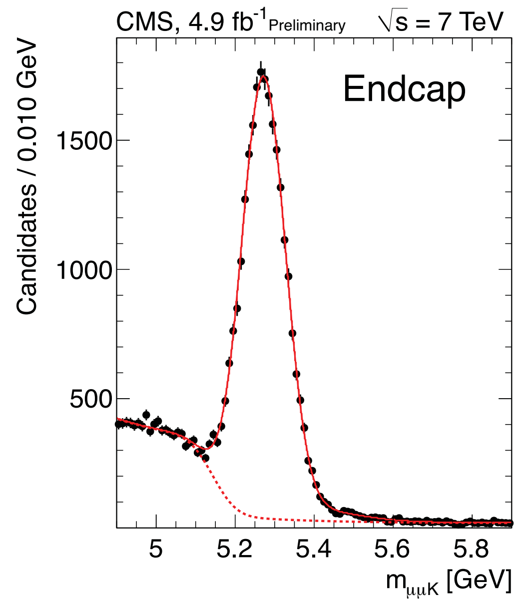
- The same conclusion is also obtained from MC simulations, looking at samples with low (<6) or high (>10) PU events

Normalization Channel: *$B^{\pm} \rightarrow J/\psi\ K^{\pm}$*

- Needed for the extraction of the branching fraction
- Same selections as for signal, plus
  - $3.0 < m(\mu\mu) < 3.2$ GeV
  - $pT(\mu\mu) > 7$ GeV
  - $pT(K) > 0.5$ GeV
  - all tracks used in vertexing
- Fit pdf:
  - signal: double Gaussian
  - bkg: exponential + error function at 5.145 GeV for
    - $B^0 \rightarrow J/\psi\ K^* \rightarrow \mu^+\mu^-K^-(\pi^+)$ decays
  - estimated sys error on the event yield: 5%
    - varying bkg, signal pdf
    - mass-constraining dimuons 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





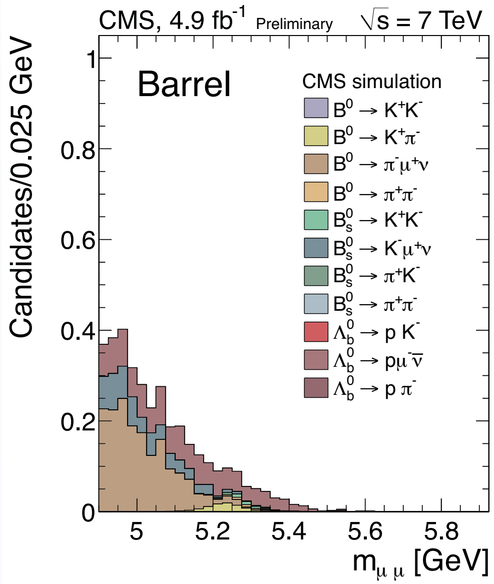
Rare Backgrounds

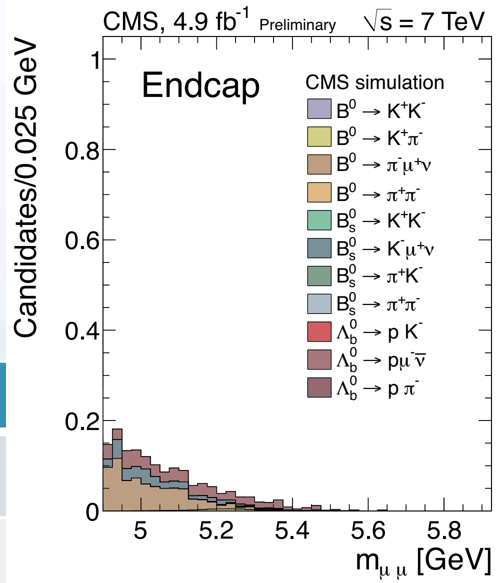
- CKM-suppressed semileptonic decays
  - e.g. $B_s^0 \to K^- \mu^+ \nu$, with one fake muon (continuous shape)
- Peaking hadronic decays
  - e.g. $B_s^0 \to K^- K^+$, with two fake muons (shifted to left due to muon mass assignment)
- Each channel normalized to $B^\pm$ in data:

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

- weighted with muon-misid evaluated from data:
  $D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$, $\Lambda \to p \pi^-$
  - $r \leq 0.10$ % both for pions and kaons
  - $r \leq 0.05$ % for protons
- sys errors: branching fractions and f_s/f_u
- Expected events:

Channel	low sideband	B^0 window	B_s^0 window	high sideband
Barrel	3.01 ± 0.63	0.332 ± 0.070	0.182 ± 0.057	0.02 ± 0.00
Endcap	1.26 ± 0.24	0.149 ± 0.028	0.082 ± 0.023	0.02 ± 0.00



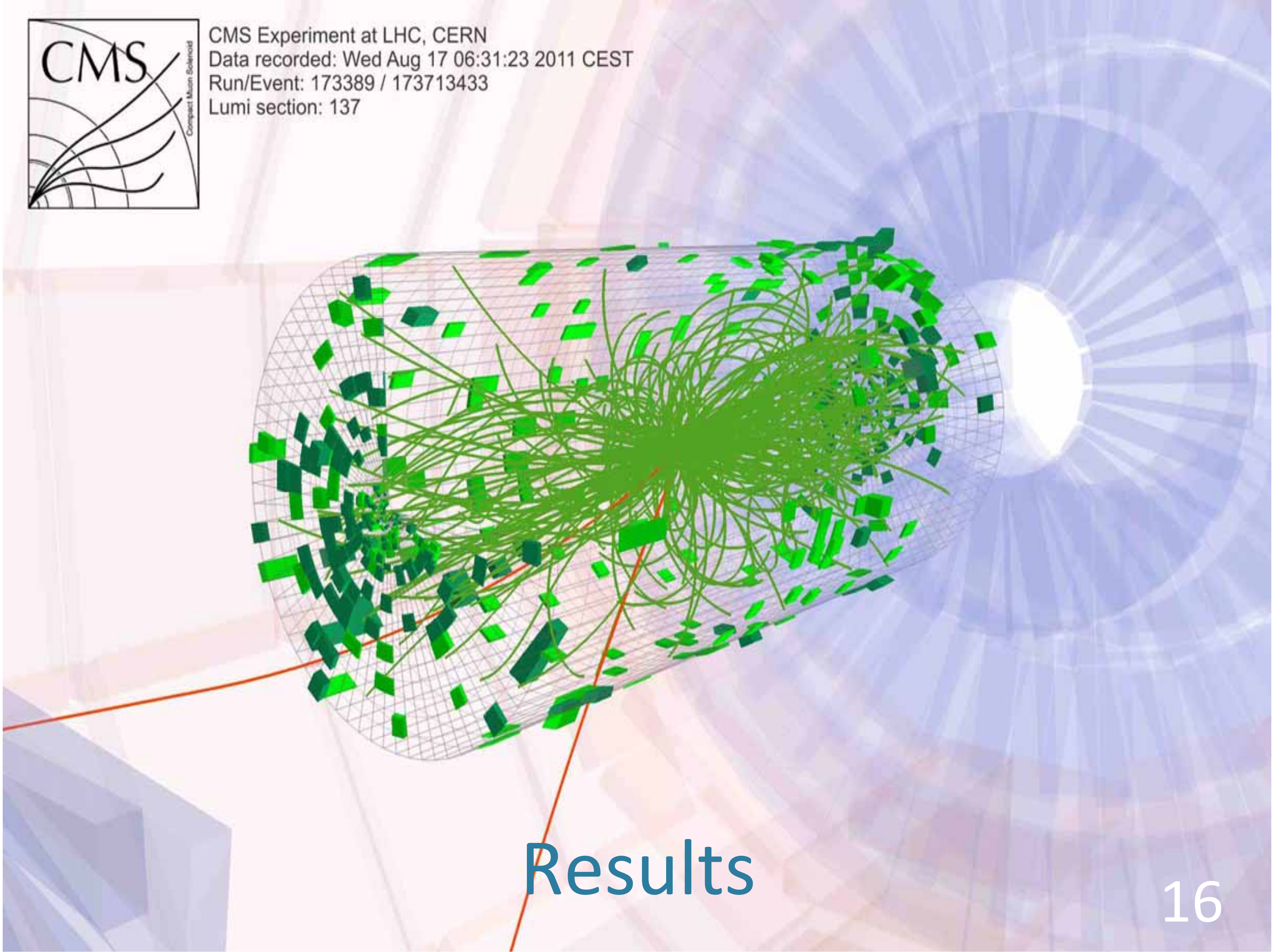


Systematics & cross-checks

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^B_{ij}	*	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

Cross Checks:

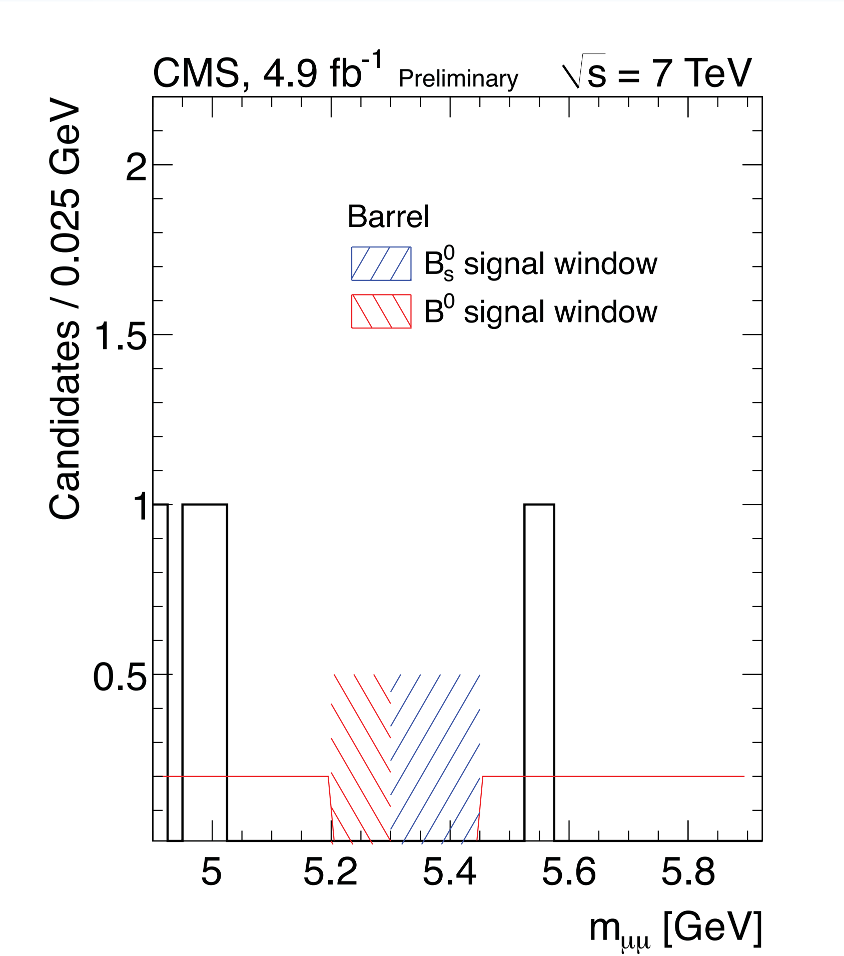
- **Background estimate with inverted isolation (I<0.7, not blinded)**
- **Branching fraction of $B^0_s \rightarrow J/\psi\varphi$**
  - cross-check for consistency
- **Stability of the event yield ratios during 2011**

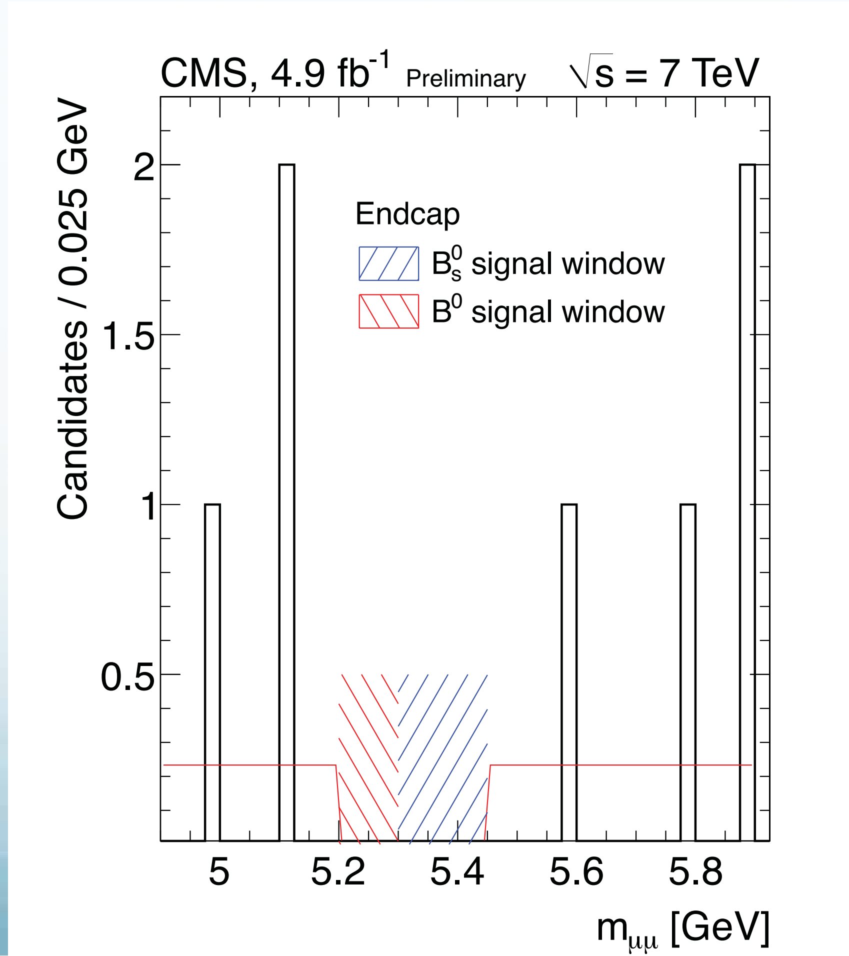

CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Aug 17 06:31:23 2011 CEST
Run/Event: 173389 / 173713433
Lumi section: 137

Results

Before unblinding…

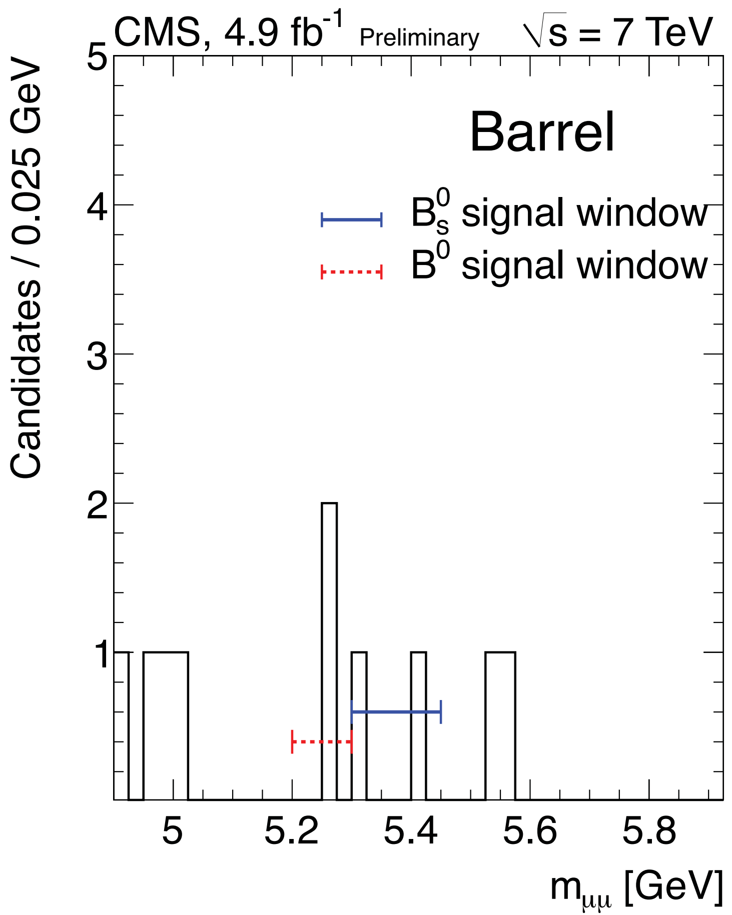
- **Background** = **combinatorial** (constant shape) + **rare** (MC shape)
- **Combinatorial** events in **signal windows**:
  - subtract rare events from sidebands
  - scale remaining events to the different widths of the regions

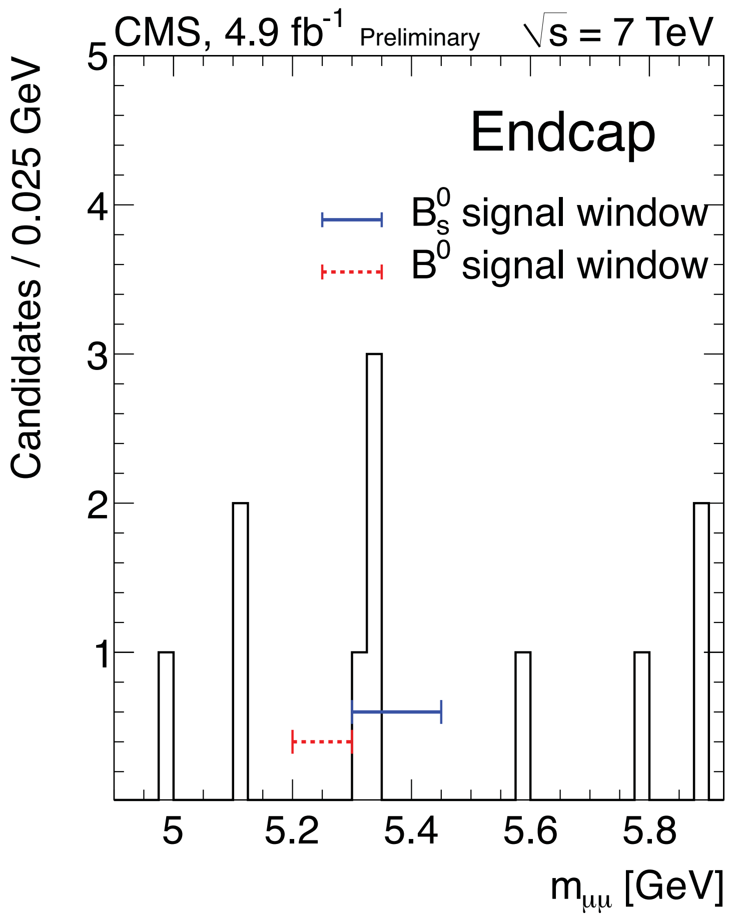




…Unblinded

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



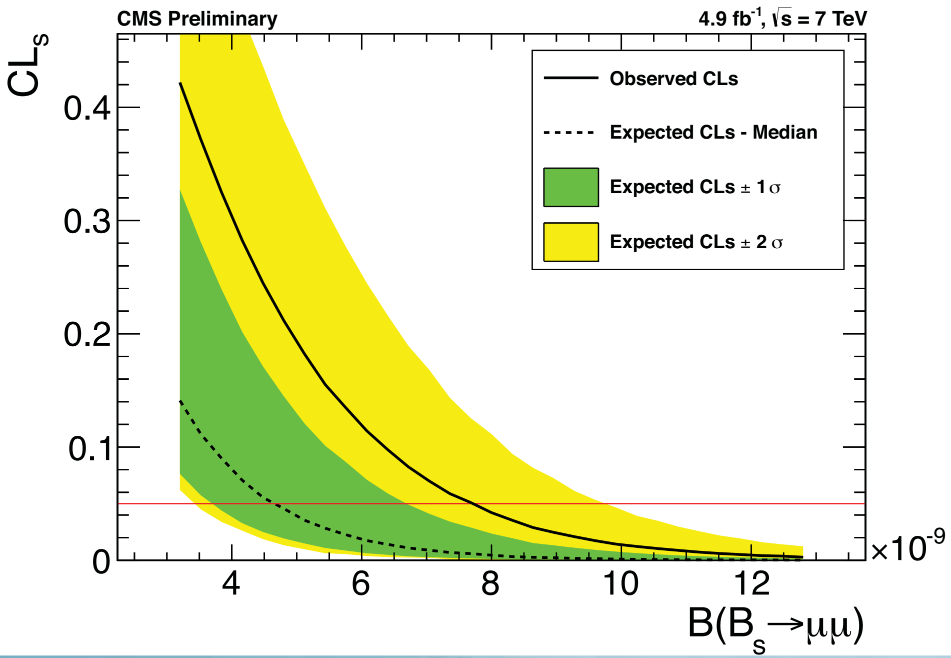


Results on the upper limits

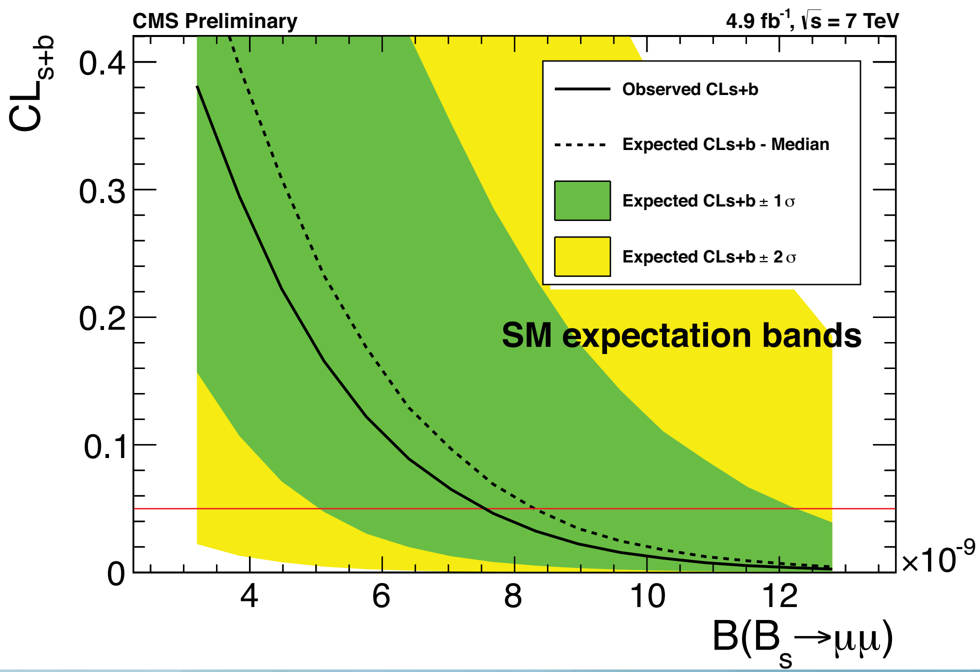
With CLs at 95%CL:

	observed	median expected
BR($B_s^0 \rightarrow \mu\mu$)	**7.7 x 10^{-9}**	**8.4 x 10^{-9}**
BR($B^0 \rightarrow \mu\mu$)	**1.8 x 10^{-9}**	**1.6 x 10^{-9}**

Bkg only hypothesis



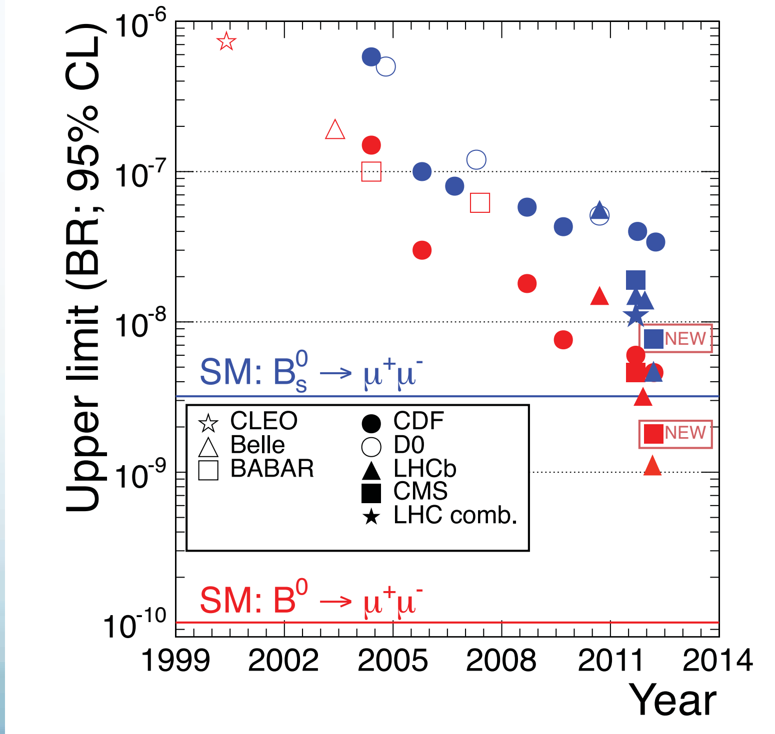
Bkg + SM hypothesis



Conclusions

- A blind analysis searching for the rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ has been performed by CMS in *pp* collisions at √(s) = 7 TeV
- The data sample corresponds to the integrated luminosity of all 2011 run (4.9 fb^{-1})
- This result supersedes our previous measurement (BR($B_s^0 \rightarrow \mu^+\mu^-$) < 19 x 10^{-9})
  - Stricter selection requirements are applied resulting in a better sensitivity and a higher signal to background ratio

Channel	CMS new upper limits (95%CL)
BR($B_s^0 \rightarrow \mu\mu$)	7.7 x 10^{-9}
BR($B^0 \rightarrow \mu\mu$)	1.8 x 10^{-9}

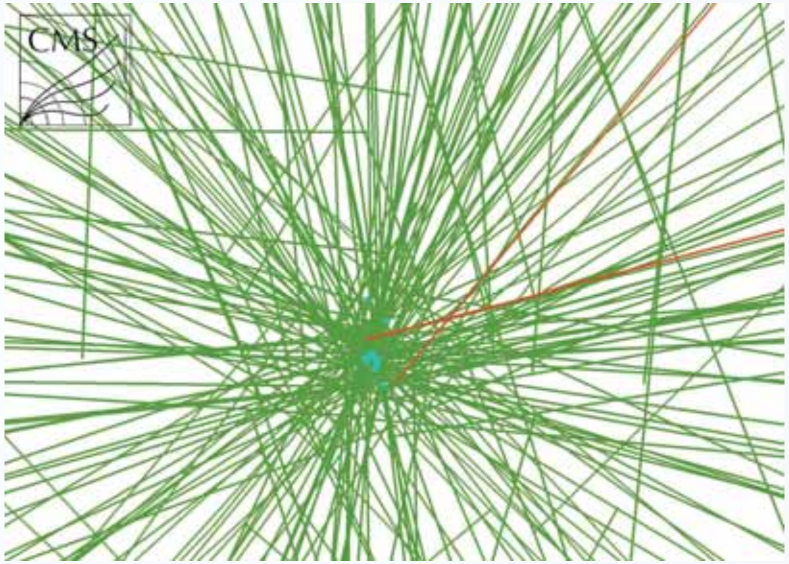


Backup

A new and improved analysis

- The data analyzed here includes the data set used to obtain the earlier result
  - 1.14 fb^{-1} have been “reblinded”
- Significant analysis improvements
  - Muon identification algorithm moved to a tighter selection
    - decreases the muon misidentification rate by 3x
  - Isolation variables:
    - primary vertex isolation *modified*
    - distance of closest track *modified*
    - track counting *added*
  - Added 3D impact parameter
  - non-monotonous changes
- **Analysis improved with**
  - **higher sensitivity**
  - **pile-up insensitive up to ~30 primary vertexes**
  - **larger S/B**

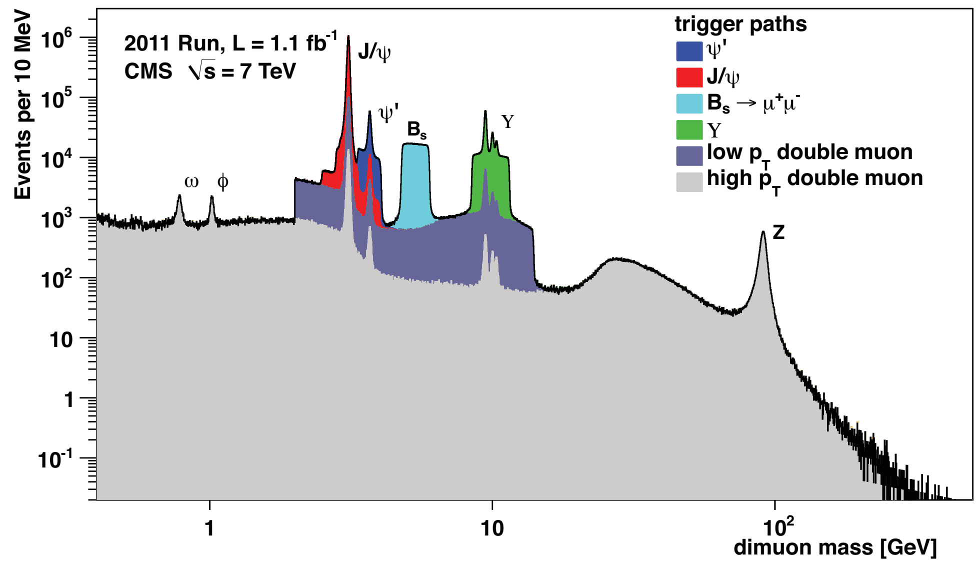
Trigger



- **Trigger requirements tightened during the 2011 data-taking, following the increasing instantaneous luminosity**
- **Signal (eff 74-84%)**
  - dimuon *pT* > 3.9 GeV (5.9 GeV in the endcap)
  - muon *pT* > 4 GeV,
  - invariant mass 4.8 < $m_{\mu\mu}$ < 6.0 GeV,
  - distance of closest approach to each other < 5 mm
  - dimuon vertex fit *χ2/dof* > 0.5%
- **Normalization and control samples (eff 77-60%)**
  - dimuon *pT* > 6.9 GeV
  - muon *pT* > 4 GeV, |η| < 2.2
  - invariant mass 2.9 < $m_{\mu\mu}$ < 3.3 GeV
  - distance of closest approach to each other < 5mm
  - dimuon vertex fit *χ2/dof* > 15%

  - **+ "displacement"**:
  - pointing angle cos α_{xy} > 0.9
  - flight distance significance $l_{xy}/\sigma(l_{xy}) > 3$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH



Trigger efficiencies evaluated vs p_T and η with

1. MC methods
2. Data-driven methods: Tag & Probe

The defining regions

For the signal: B Mass = 5.28 GeV, B_s Mass = 5.37 GeV

Region definitions	Invariant mass (GeV)	Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2} < 5.90$	$B^0 \to \mu^+\mu^-$ window	$5.20 < m_{\mu1\mu2} < 5.30$
blinding window	$5.20 < m_{\mu1\mu2} < 5.45$	$B_s^0 \to \mu^+\mu^-$ window	$5.30 < m_{\mu1\mu2} < 5.45$

For the normalization: (Jpsi mass in [3.0, 3.2])

Region definitions	Invariant mass (GeV)	Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2K} < 5.90$	signal region	$5.20 < m_{\mu1\mu2K} < 5.35$
low sideband	$5.05 < m_{\mu1\mu2K} < 5.15$	high sideband	$5.40 < m_{\mu1\mu2K} < 5.50$

For the control: (Jpsi mass in [3.0, 3.2], Phi mass in [0.995, 1.045] and ΔR_{kk}<0.25)

Region definitions	Invariant mass (GeV)	Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2KK} < 5.90$	signal region	$5.27 < m_{\mu1\mu2KK} < 5.47$
low sideband	$5.10 < m_{\mu1\mu2KK} < 5.20$	high sideband	$5.50 < m_{\mu1\mu2KK} < 5.60$

Candidate Selection: optimization

- Optimization of the selections made with a random grid search with 1.4 x 10^6 runs
- Uses Bkg side-band and signal MC
- figure of merit: best upper limit

Variable	Barrel	Endcap	units
$p_{T\mu,1} >$	4.5	4.5	GeV
$p_{T\mu,2} >$	4.0	4.2	GeV
$p_{TB} >$	6.5	8.5	GeV
$\delta_{3D} <$	0.008	0.008	cm
$\delta_{3D}/\sigma(\delta_{3D}) <$	2.000	2.000	
$\alpha <$	0.050	0.030	rad
$\chi^2/dof <$	2.2	1.8	
$\ell_{3d}/\sigma(\ell_{3d}) >$	13.0	15.0	
$I >$	0.80	0.80	
$d^0_{ca} >$	0.015	0.015	cm
$N^{close}_{trk} <$	2	2	tracks

Combinatorial bkg evaluation

- Dimuon background = rare + combinatorial background
- The combinatorial bkg is assumed to have a constant shape
  - checked with inverted isolation sample (syst 4%)
  - The rare bkg is subtracted from the sidebands
  - scale the remaining event counts proportionally τ:

$$\tau_{s,d} = \frac{\Delta m_{s,d}}{5.9 - 4.9 - 0.25} = \frac{\text{width of the signal window}}{\text{width of the side-bands}}$$

Upper limit extraction

$$N_s^B \sim \text{Pois}(\tau_s^B \nu_b^B + \nu_{s,\text{rare}}^B + P_{ss}^B \mu_s \nu_s^B + P_{sd}^B \mu_d \nu_d^B)$$
$$N_d^B \sim \text{Pois}(\tau_d^B \nu_b^B + \nu_{d,\text{rare}}^B + P_{ds}^B \mu_s \nu_s^B + P_{dd}^B \mu_d \nu_d^B)$$

with $(i = s, d)$

τ_i^B	Ratio of $(B_i^0 \to \mu\mu)$-signal window size to size of background window
$\nu_{i,\text{rare}}^B$	Expected number of rare background in $(B_i^0 \to \mu\mu)$-signal window.
ν_i^B	Expected number of reconstructed $(B_i^0 \to \mu\mu)$ decays in barrel region assuming the SM
P_{ij}^B	Probability for a reconstructed $B_j^0 \to \mu\mu$ decay to be in $(B_i^0 \to \mu\mu)$-signal window.
μ_i	Signal strength of $B_i^0 \to \mu\mu$, that is the ratio of true branching ratio to SM branching ratio.

The expected number of reconstructed decays assuming SM is

$$\nu_i = \frac{\mathcal{B}^{\text{SM}}(B_i^0 \to \mu\mu)}{\mathcal{B}(B^\pm \to J/\psi K^\pm)} \frac{f_s}{f_u} \frac{A_{B_s^0}}{A_{B^\pm}} \frac{\varepsilon_{\text{trig}}^{B_s^0}}{\varepsilon_{\text{trig}}^{B+}} \frac{\varepsilon_{\mu}^{B_s^0}}{\varepsilon_{\mu}^{B+}} \frac{\varepsilon_{\text{analysis}}^{B_s^0}}{\varepsilon_{\text{analysis}}^{B+}} N^{\text{obs}}(B^\pm \to J/\psi K^\pm)$$

in each "channel" (B_s, B_d in barrel, endcap)

The total model is 6 poissonian observables (N_s^E, N_s^B, N_d^E, N_d^B, N_b^E, N_b^B) , 2 nuisance parameters for background (ν_b^E, ν_b^B) and additional nuisance parameters for systematic uncertainties.

Results on the upper limits: p-values

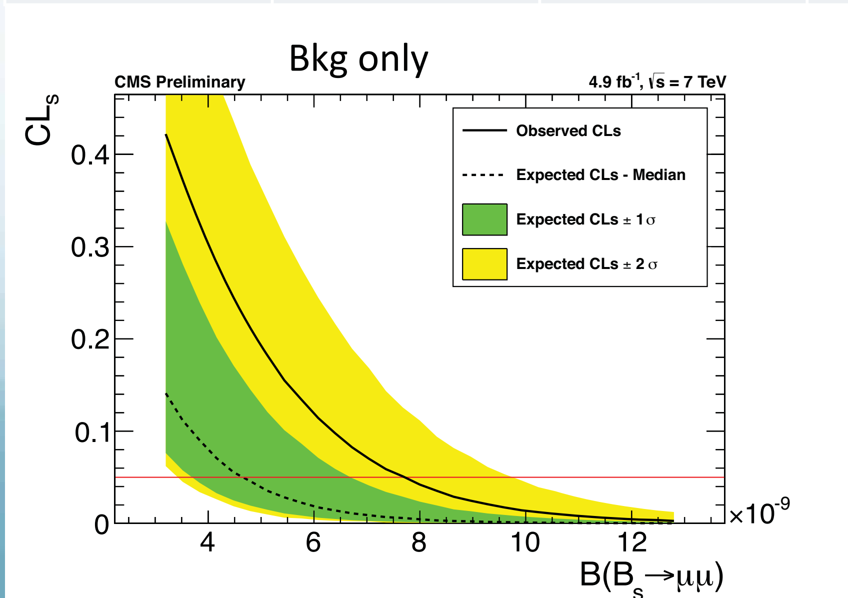
- With CLs at 95%CL

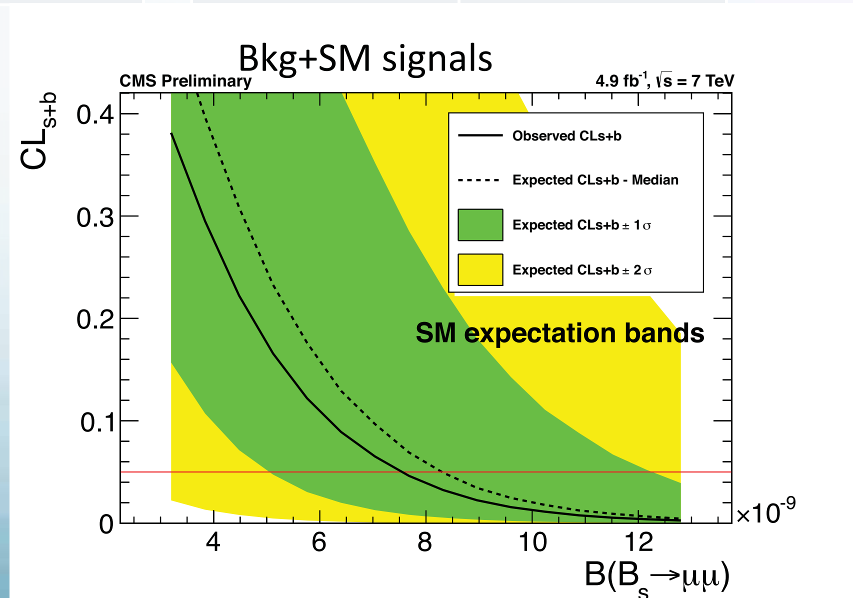
	observed	median expected
BR($B_s^0 \rightarrow \mu\mu$)	**7.7 x 10^{-9}**	**8.4 x 10^{-9}**
BR($B^0 \rightarrow \mu\mu$)	**1.8 x 10^{-9}**	**1.6 x 10^{-9}**

	w/o cross feed	w/ SM cross feed	floating cross feed
BR($B_s^0 \rightarrow \mu\mu$)	0.06 (1.5σ)	0.07 (1.5σ)	0.11 (1.2σ)
BR($B^0 \rightarrow \mu\mu$)	0.11 (1.2σ)	0.29 (0.6σ)	0.24 (0.7σ)

- p-values for SM + bkg

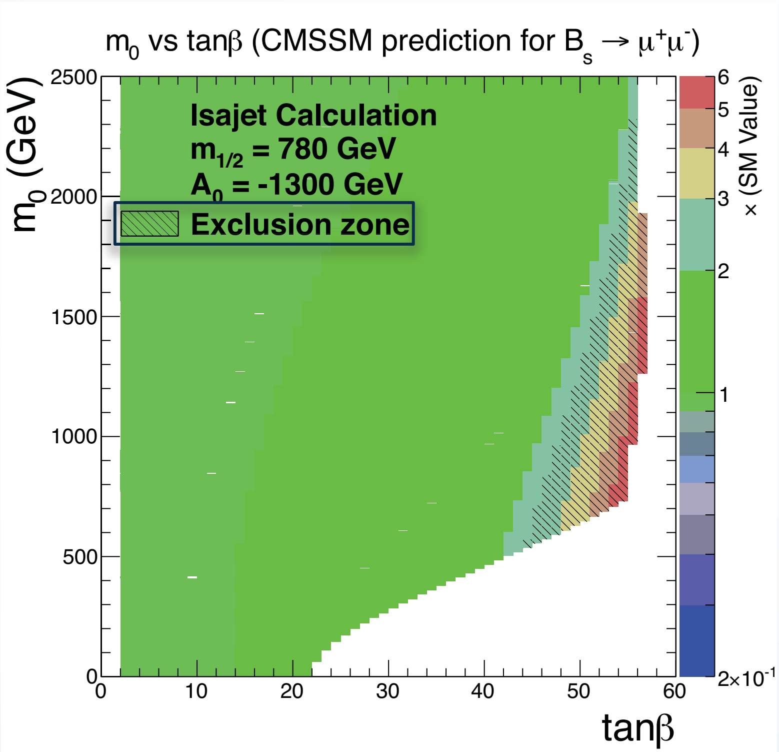
	w/ SM cross feed
BR($B_s^0 \rightarrow \mu\mu$)	0.71
BR($B^0 \rightarrow \mu\mu$)	0.86

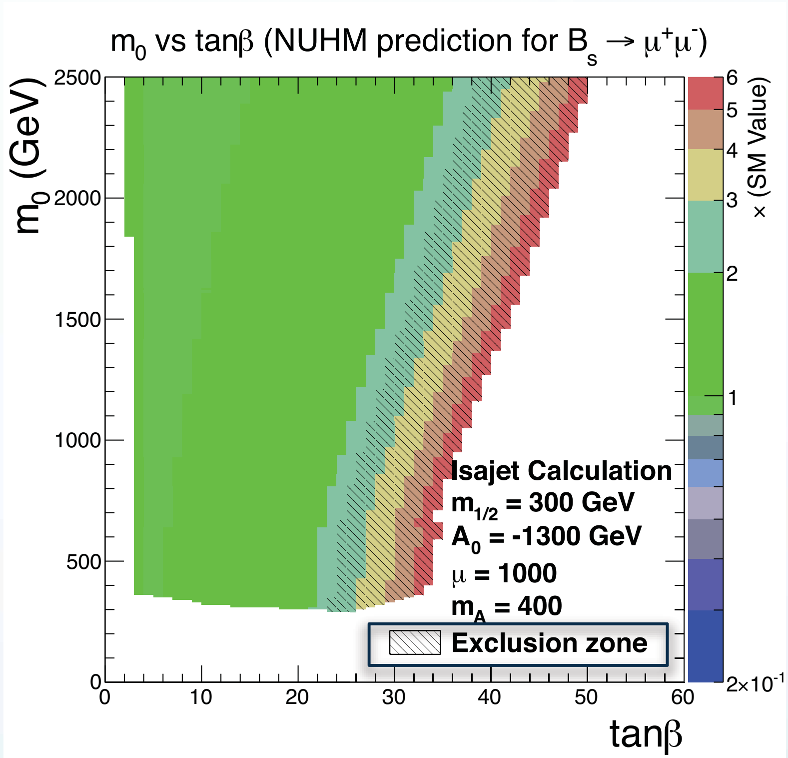




SuperIso V3.1 (CPC, 180, 1579)

Few interpretation examples, IsaJet calculations





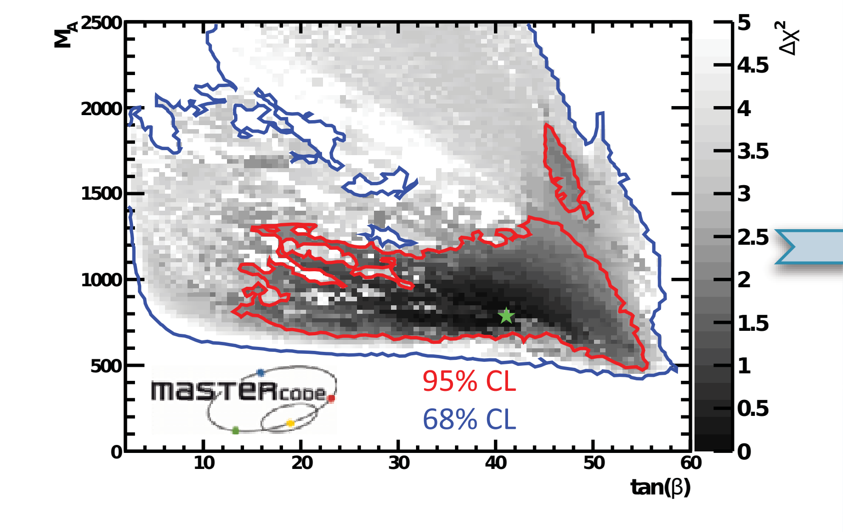
White regions due to previous upper limit results

Biggest impact for high tan(β)

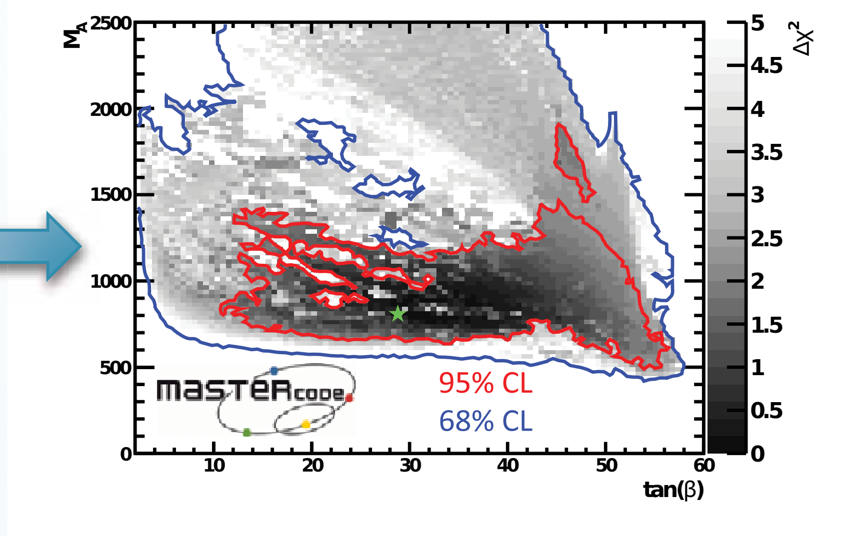
MasterCode

Best fit for CMSSM

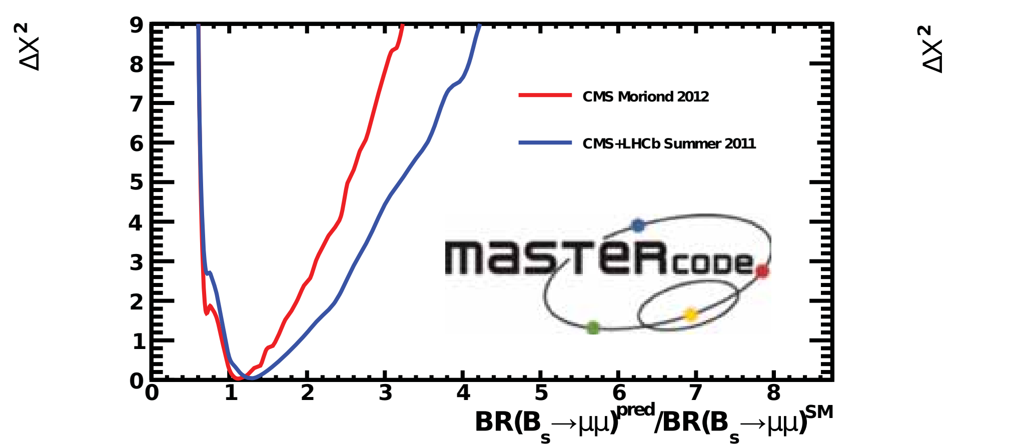
With summer 2011 result



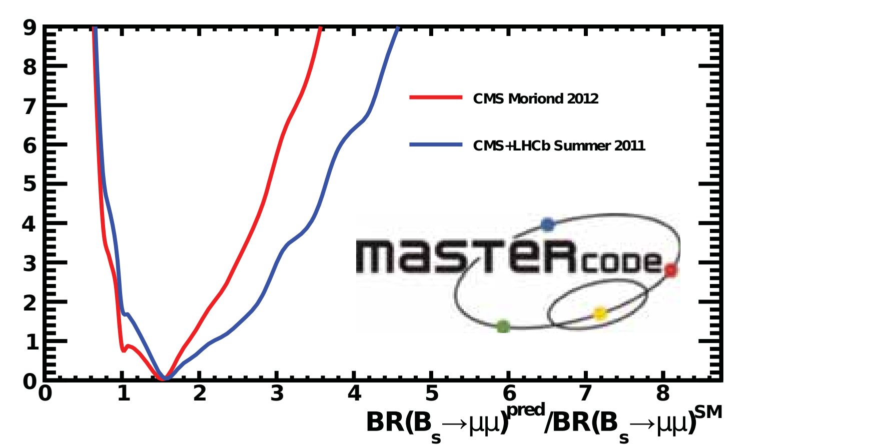
With this new result



CMSSM



NUHM1



- In the process of precision determination of the luminosity collected by CMS in 2011, a slight time-dependent calibration drift was found in the calorimeter used as a luminometer
- To remedy this, we developed an independent luminosity determination using stable and precise pixel tracker
- Preliminary result presented at the LHC Luminosity Days suggests an upward change in the estimated luminosity for 2011 by ~6%, i.e. slightly outside the 1σ-band of our original estimate of the luminosity uncertainty
  - The corresponding change for the low-luminosity part of the run (2011A), which is the basis of our new and published precision measurements, is ~3.5%, well within the quoted systematics
- We are finalizing determination of the new luminosity measurement, with significantly better precision
- The anticipated change has a very minor effect on our preliminary results and no visible change in published limits
- Instability does not affect the 2010 luminosity determination, as it only affects high-luminosity running