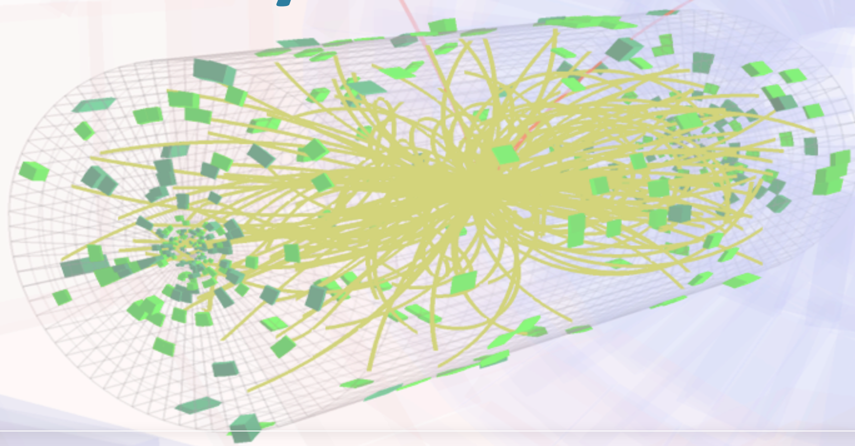
B Physics at CMS



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for the CMS collaboration

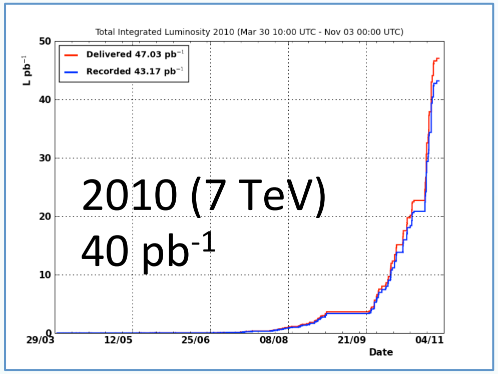
4th SuperB Collaboration Meeting
La Biodola (Isola d'Elba) Italy

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI PISA

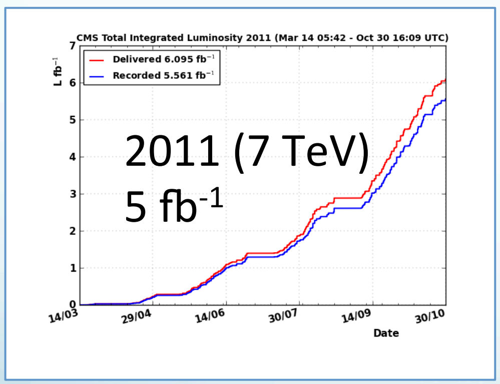
Summary

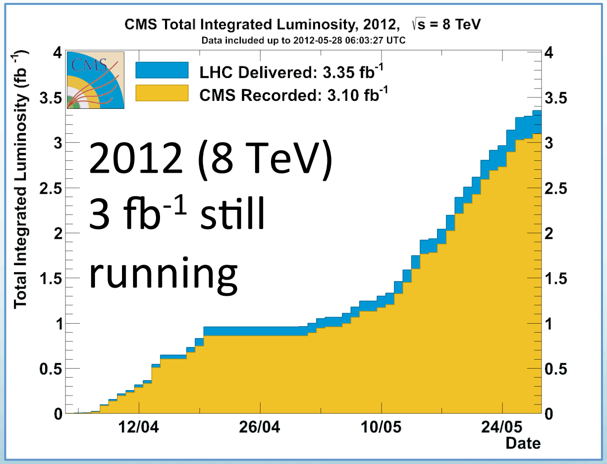
- The CMS experiment at the LHC
- Most recent published analyses
- A deeper look at the $B_s \rightarrow \mu^+\mu^-$ analysis
- Outlook

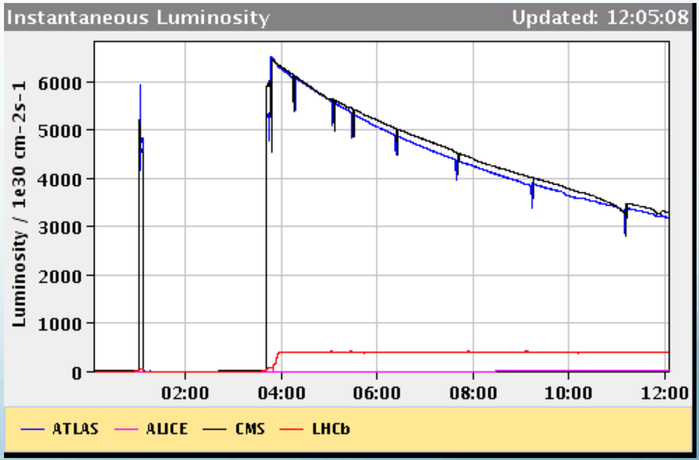
LHC Integrated Luminosity



- Great performance of the LHC machine since 2010
- Instantaneous luminosity now around 6 x 10^{33} cm^{-2} s^{-1}
- Expected 15-20 fb^{-1} at the end of 2012 (@ 8TeV)



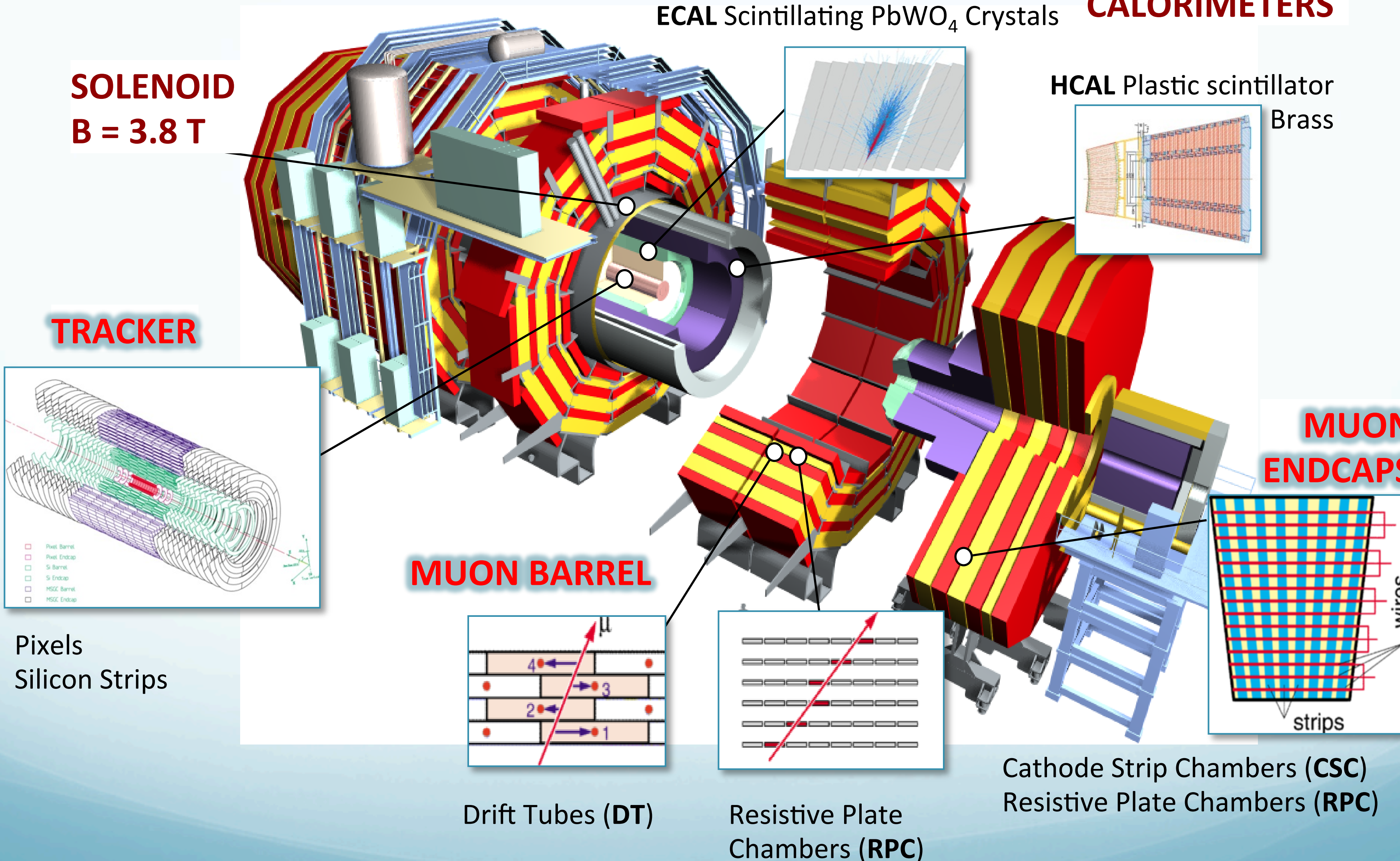




expected around 45 fb^{-1} in 2015, hundreds in 2020

The CMS detector

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

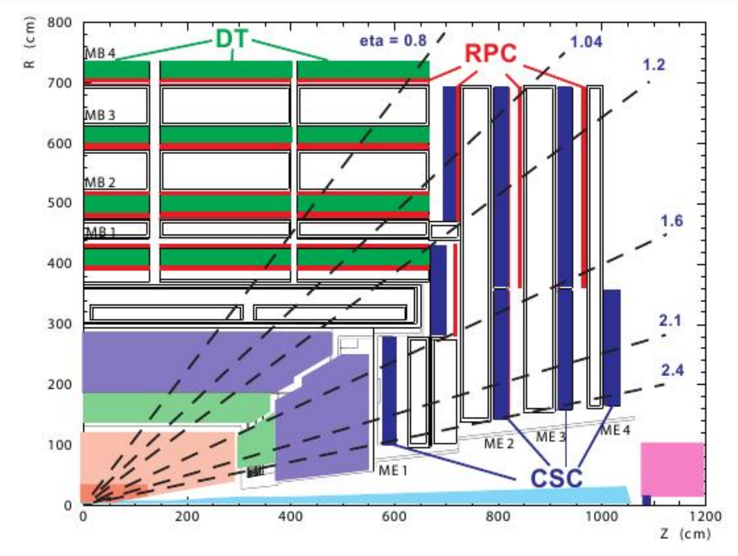


JINST 3, S08004 (2008)

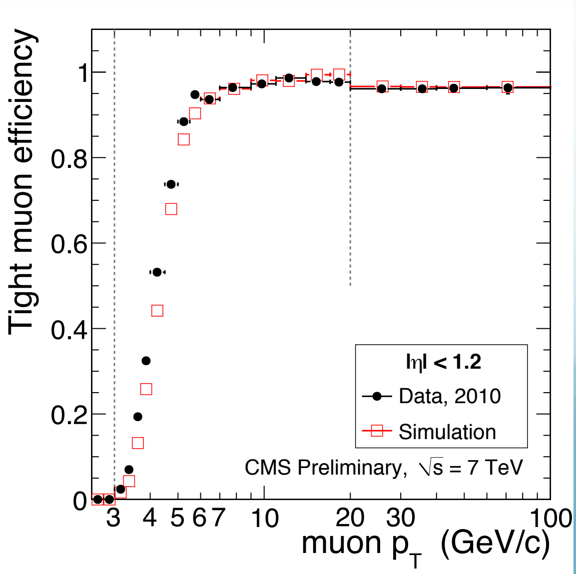
Muon track reconstruction

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: $|\eta| < 2.4$



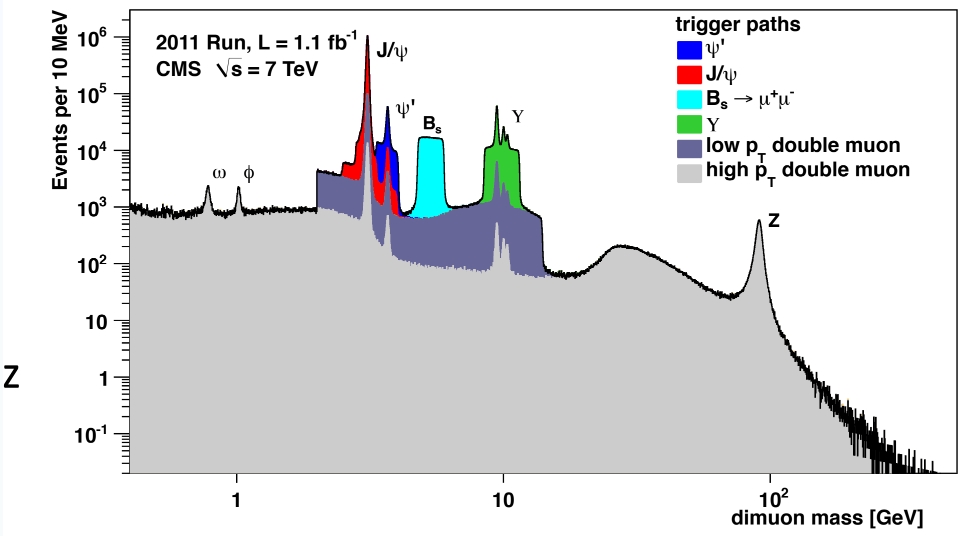
- Muon efficiencies evaluated with
  1. MC methods
  2. Data-driven methods: Tag & Probe

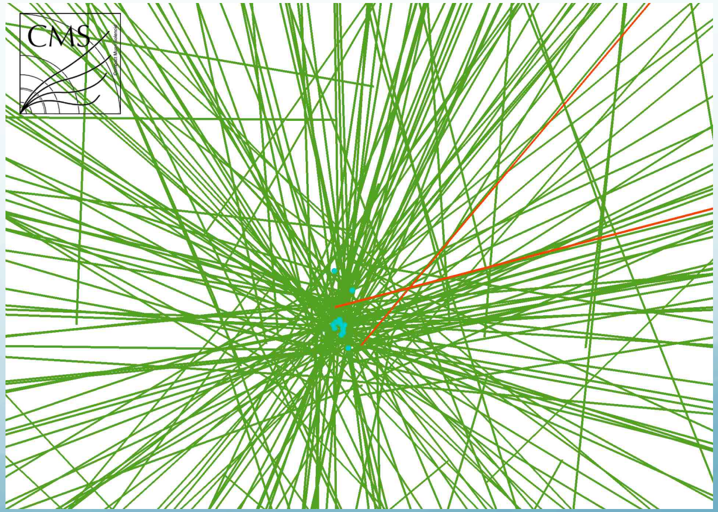


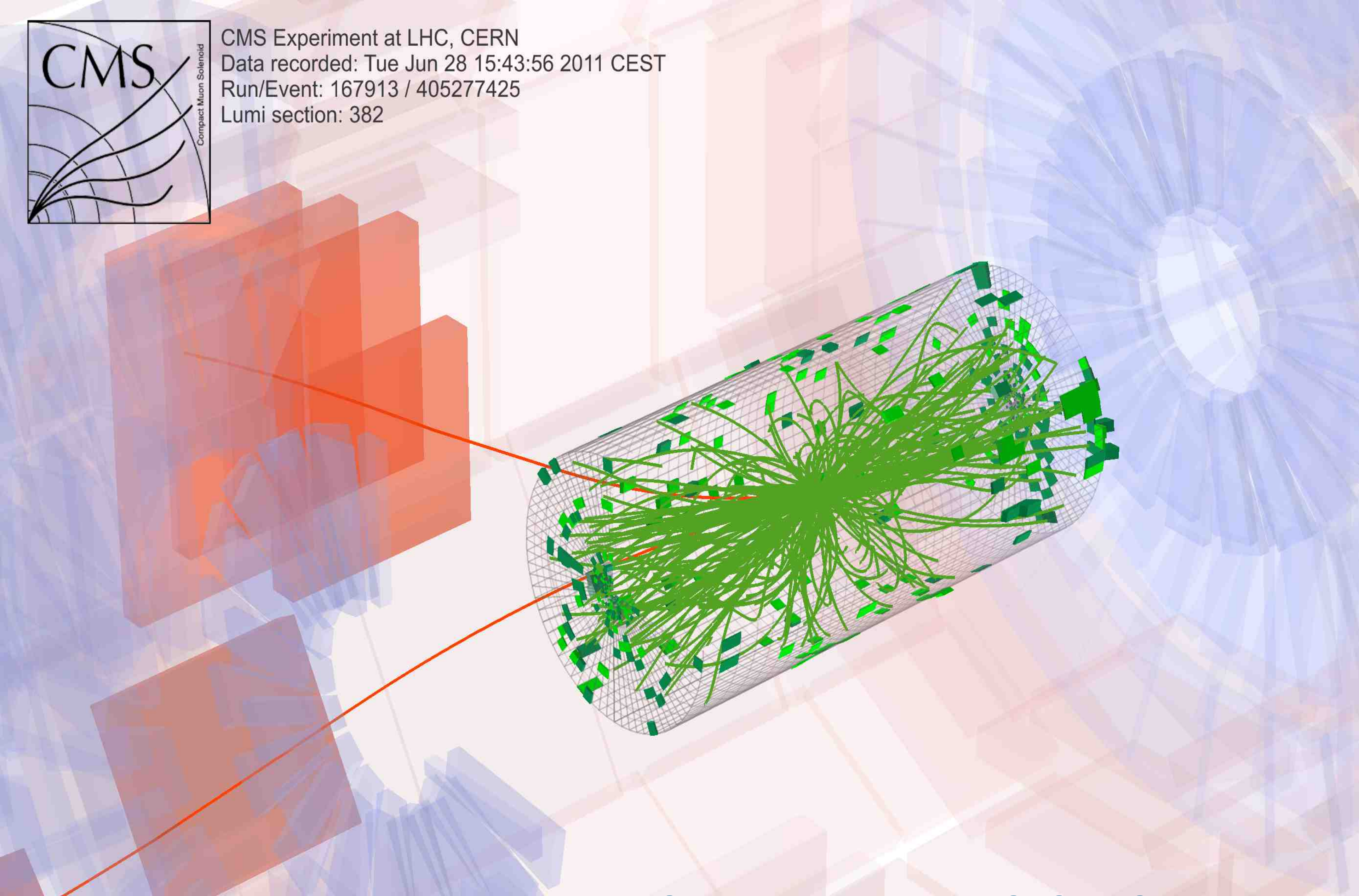
BPhysics Triggers

- BPhysics at CMS relies on dimuon triggers
- Trigger requirements tightening, following the increasing instantaneous luminosity
- Rates of few Hertz
  - the total CMS rate is few hundreds Hz
- Trigger selections based on:
  - p_T and $|\eta|$ of (di)muons
  - dimuon invariant mass
  - secondary vertex probability
  - impact parameters
  - flight length
  - pointing angle
- Trigger efficiencies evaluated with
  1. MC methods
  2. Data-driven methods: Tag & Probe

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



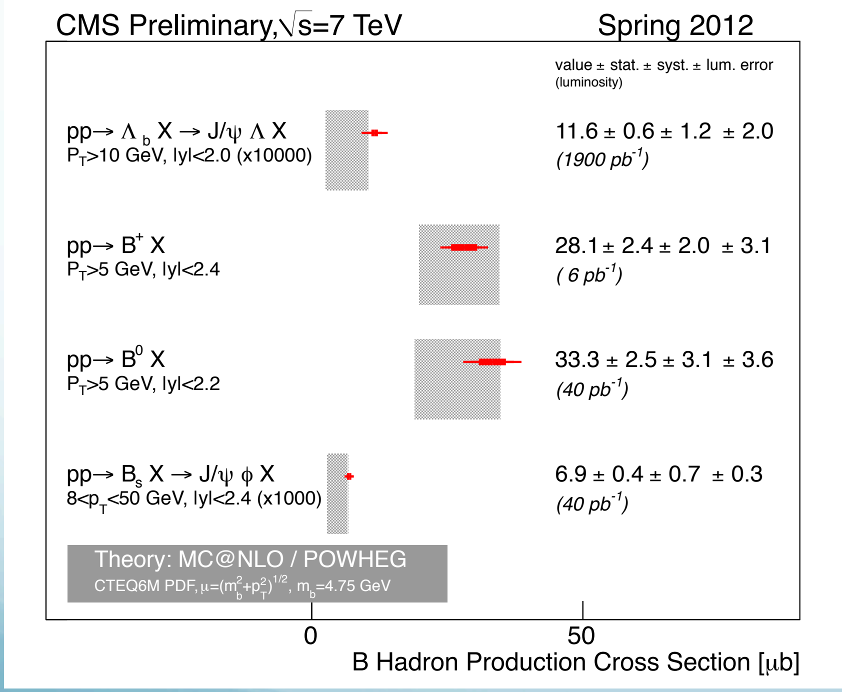


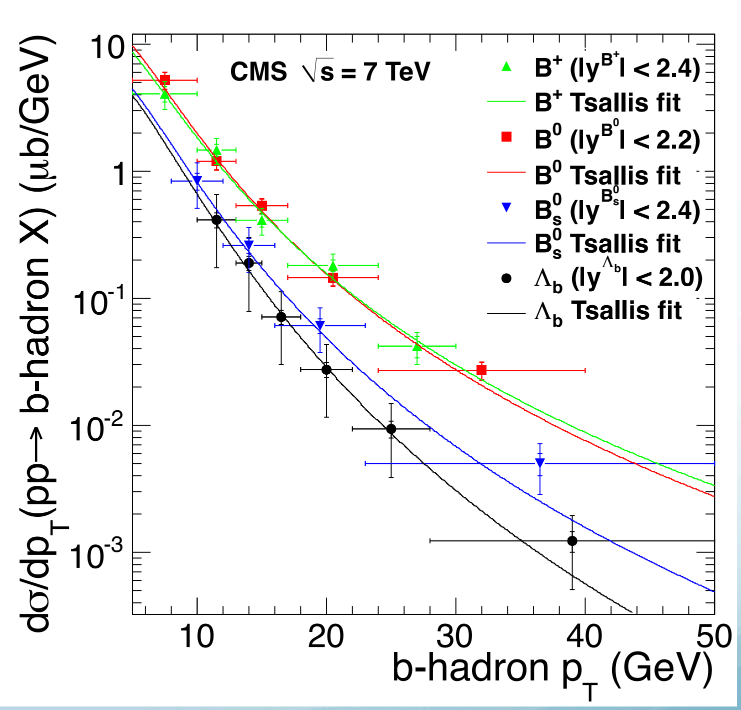


Recent CMS BPhysics Highlights

B-hadrons cross-sections

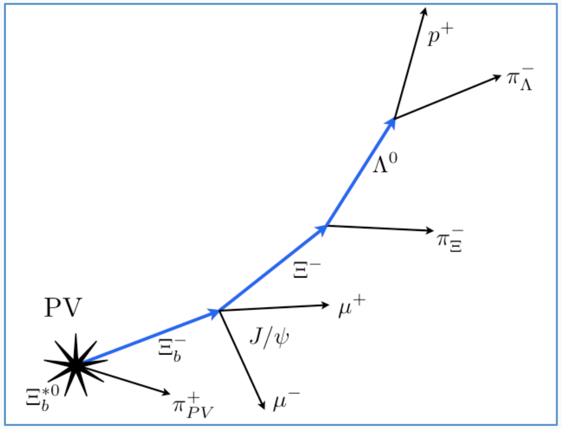
- Integrated and double differential cross sections published:
  - Phys.Rev.Lett.106:112001,2011 (B^+), Phys. Rev. Lett. 106, 252001 (2011) (B_d), Phys.Rev. D 84, 052008 (2011) (B_s), arXiv:1205.0594 (Λ_b)



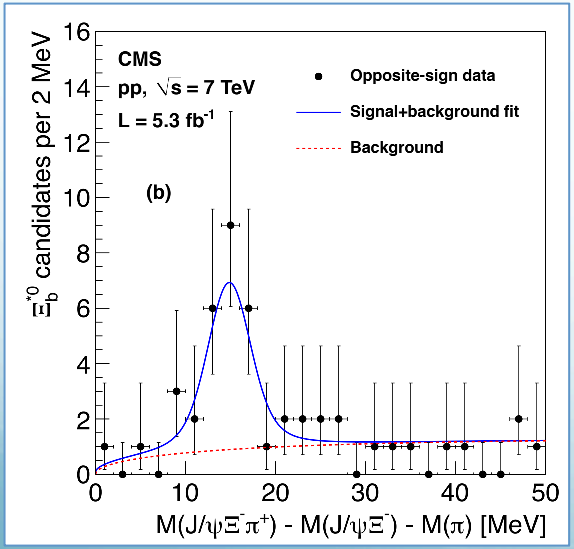


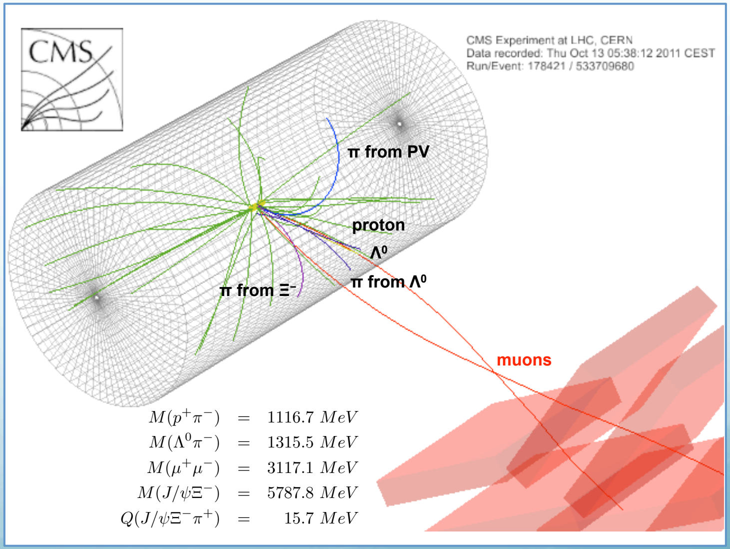
First observation of the Ξ_b^{*0} hadron

- Through the decay chain:
  - $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$
  - $\Xi_b^- \rightarrow J/\psi\ (\mu^+\mu^-)\ \Xi^-$
  - $\Xi^- \rightarrow \Lambda^0 \pi^-$
  - $\Lambda^0 \rightarrow p^+ \pi^-$



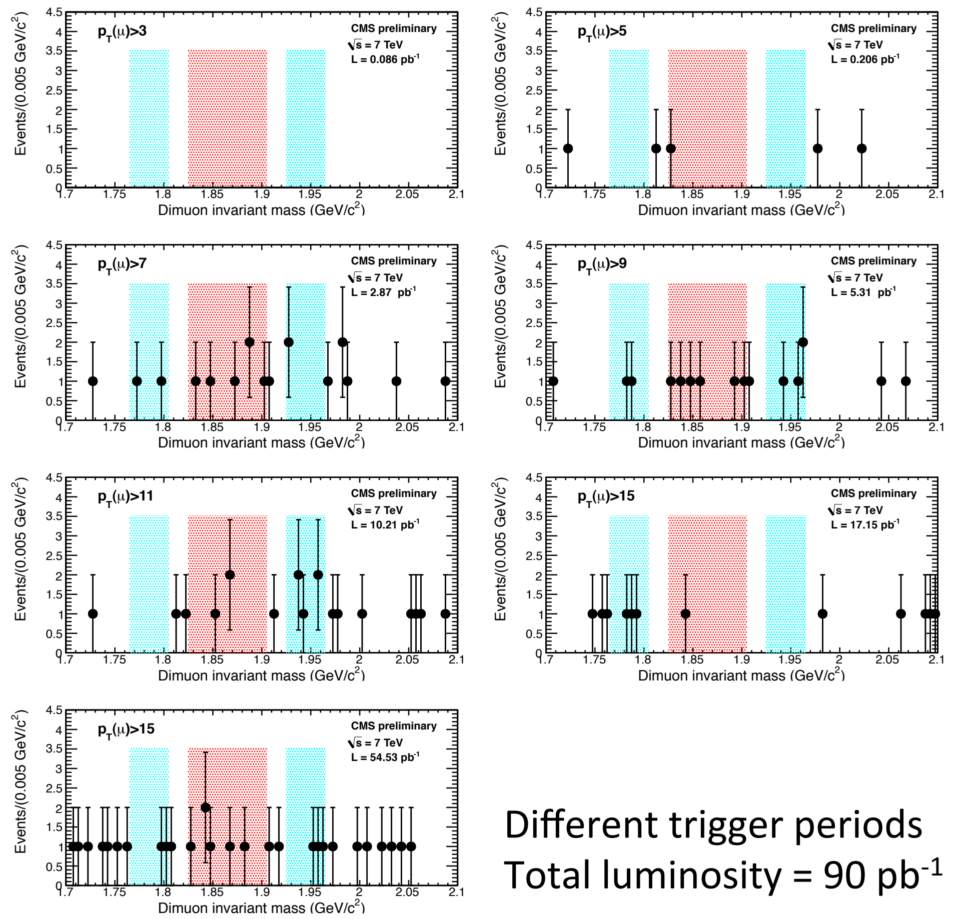
- Significance = 6.9 σ





arXiv:1204.5955

Search for $D^0 \to \mu^+\mu^-$



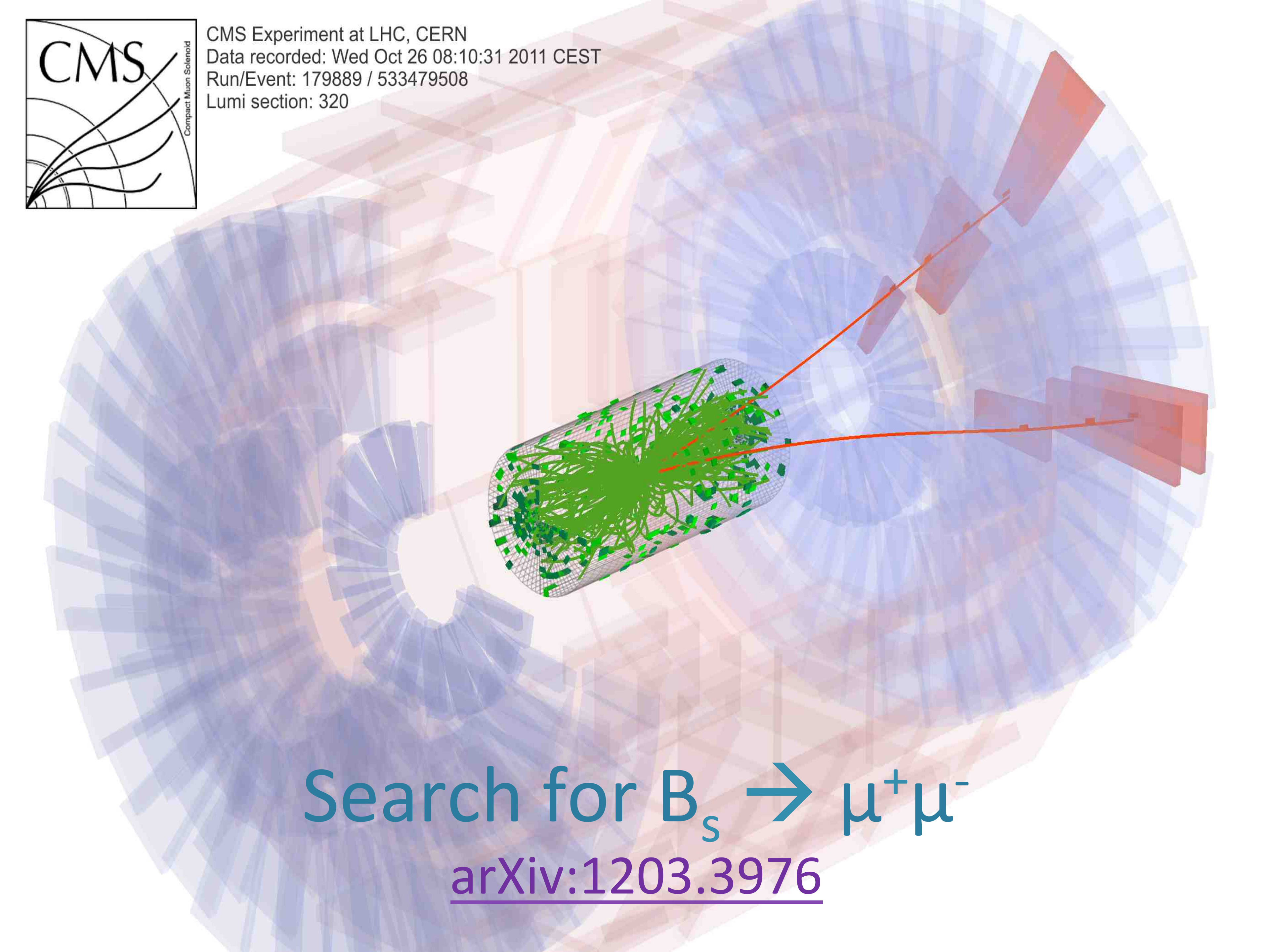
Different trigger periods
Total luminosity = 90 pb^{-1}

Normalization mode: $D^0 \to K^-\mu^+\nu$ to minimize differences at trigger level (single mu trigger)

No evidence of $D^0 \to \mu^+\mu^-$ from D^{*+}:

BR($D^0 \to \mu^+\mu^-$) ≤ **5.4 x 10^{-7}** (at 90% CL)

CMS-PAS-BPH-11-017



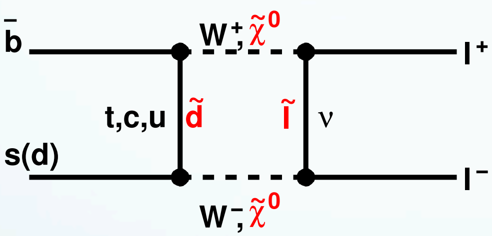
Search for $B_s \rightarrow \mu^+\mu^-$

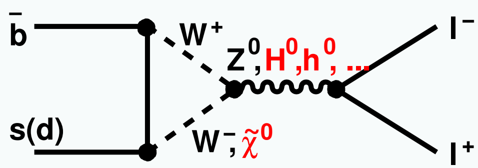
arXiv:1203.3976

Motivation:
search for new physics

In SM $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ 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





Most recent results from other experiments:

95% CL upper limit*	CDF	ATLAS	LHCb
BR ($\times 10^{-9}$)	0.8< BR <34	< 22	< 4.5

Decay channel	BF SM predictions*
$B^0 \to \mu^+\mu^-$	$(1.1 \pm 0.1) \times 10^{-10}$ (Buras)
$B_s^0 \to \mu^+\mu^-$	$(3.2 \pm 0.2) \times 10^{-9}$ (Buras)
$B_s^0 \to \mu^+\mu^-$	$(3.6\,^{+0.2}_{-0.3}) \times 10^{-9}$ (CKM fitter)

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

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

- Buras arXiv:1009.1303
- CKM fitter: http://hep.ustc.edu.cn/indico/getFile.py/access?contribId=46&sessionId=18&resId=0&materialId=slides&confId=7
- LHCb: arXiv:1203.4493
- Atlas: arXiv:1204.0735
- CDF: http://agenda.infn.it/getFile.py/access?contribId=32&sessionId=5&resId=0&materialId=slides&confId=4116

Analysis overview

- Data corresponds to full 2011 run
- All the selections chosen with the signal regions ***blinded***
- Backgrounds estimated from the sidebands and from MC

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	$5.30 < m_{\mu1\mu2} < 5.45$

- **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
  - and to mitigate the efficiency effects

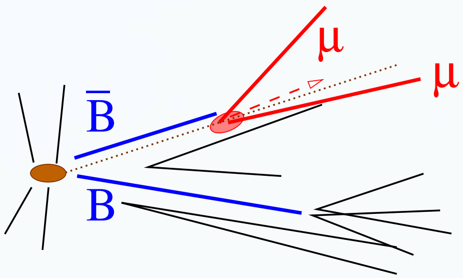
$$Br\left(B_s^0 \to \mu^+\mu^-\right) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} Br\left(B^+\right)$$

$f_s / f_u = 0.267 \pm 0.021$ [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

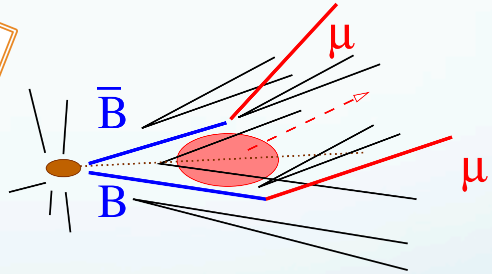
Signal versus Background

- 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

combinatorial
flat shape

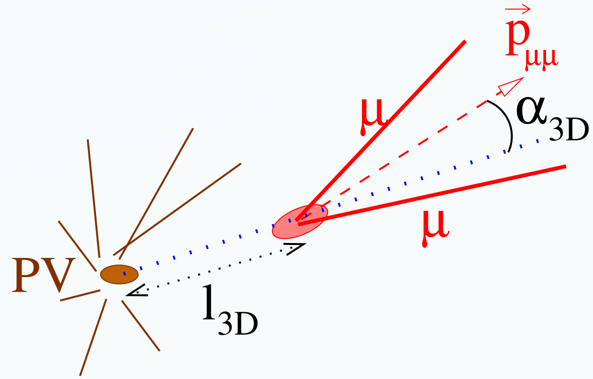


  - single B decays
    - peaking ($B_s^0 \rightarrow K^- K^+$)
    - non peaking ($B_s^0 \rightarrow K^- \mu^+ \nu$)

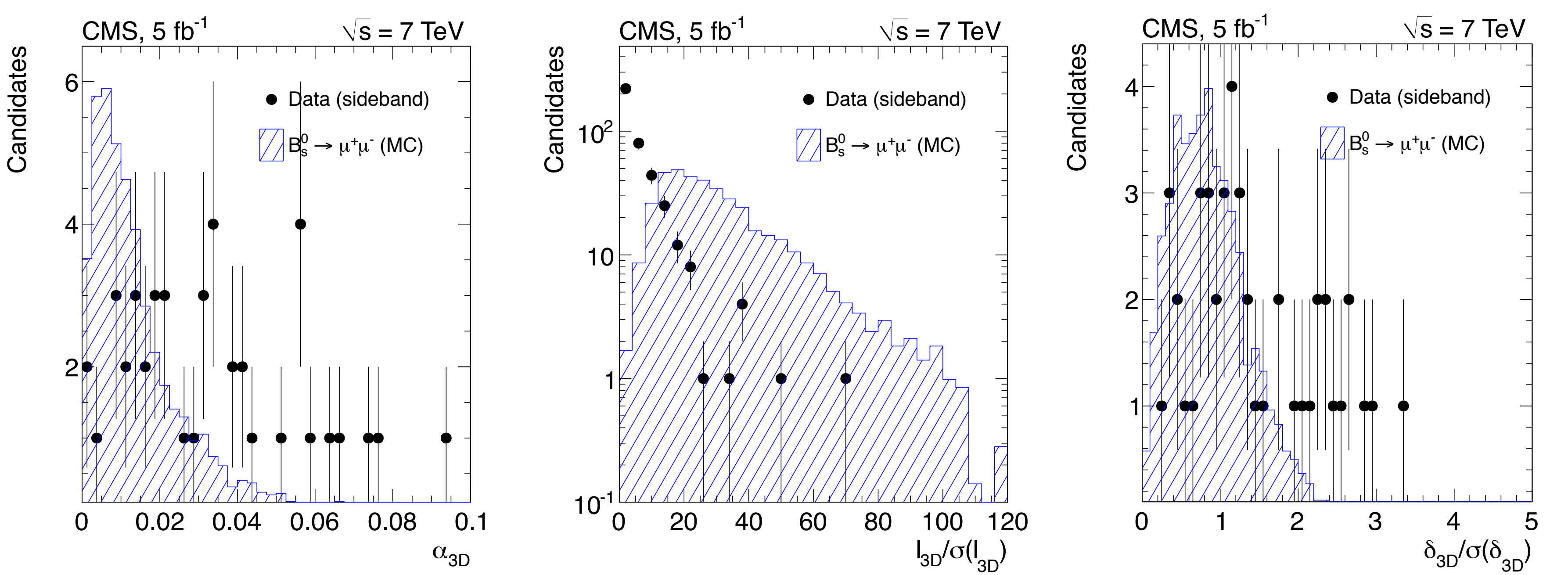
rare
shape from MC

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:

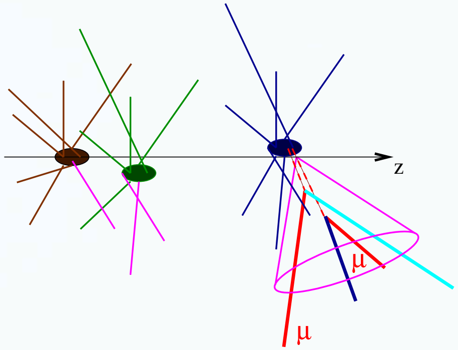


Isolation

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

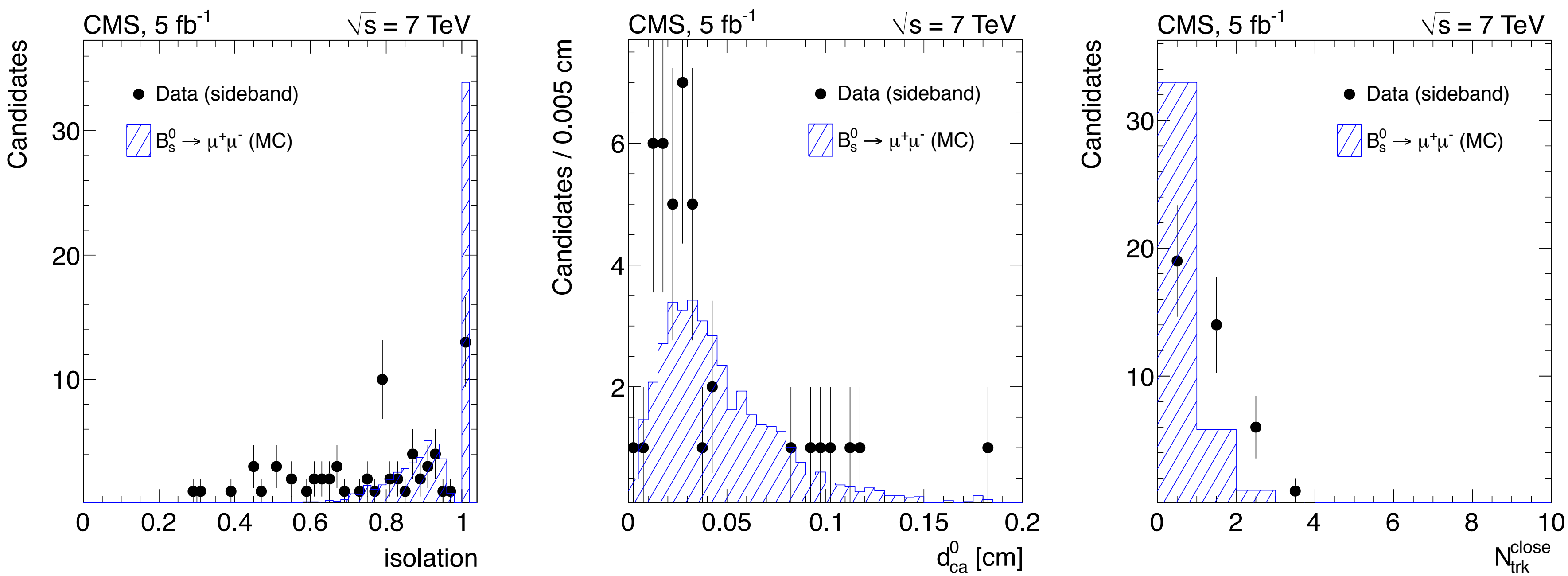
$$I = \frac{p_\perp(B)}{p_\perp(B) + \sum_{trk} |p_\perp|}$$

  - 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:



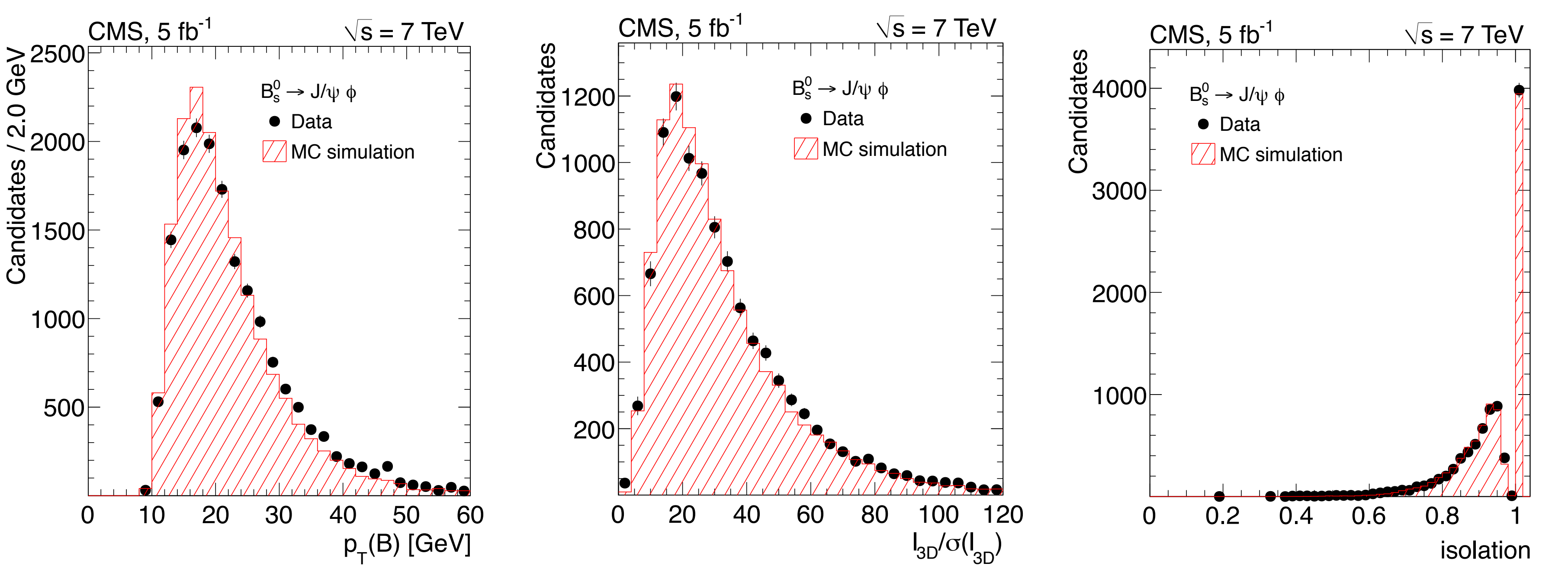
Data - Simulation comparison

- **Needed to validate signal (through the control sample) and normalization samples**

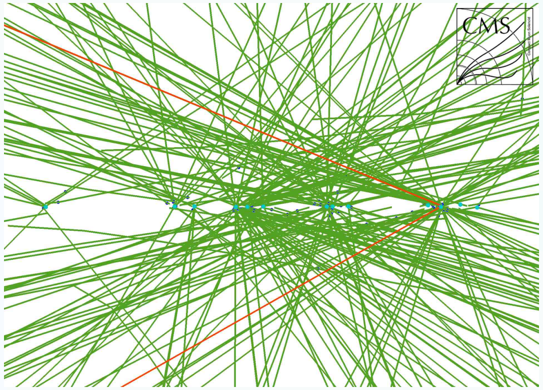
- Differences data – MC taken as systematics uncertainties:
  - *On $B^{\pm} \rightarrow J/\psi K^{\pm}$*, max diff = 2.5% (isolation) tot = 4%
  - *On $B_s^0 \rightarrow J/\psi\varphi$*, max diff = 1.6% (secondary vertex χ^2/ndof) tot = 3%

- Excellent MC – data comparison

Side-bands subtracted data vs control MC:

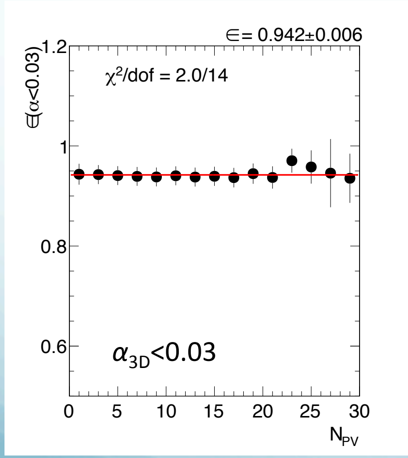


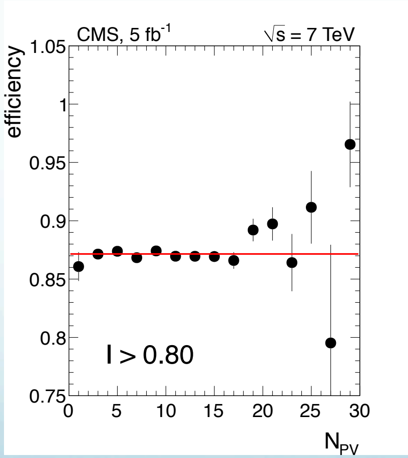
Pile-up



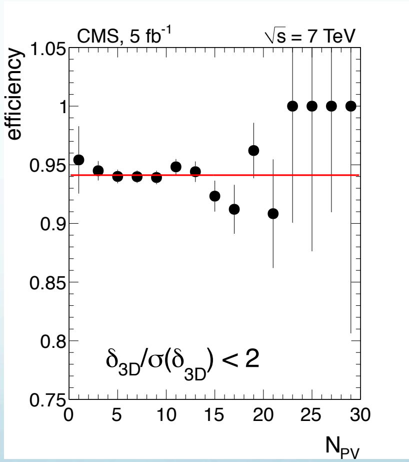
- in 2011: $\langle N_{PV} \rangle = 8$, RMS(z) = 5.6 cm
- Selections have been tuned to be pile-up independent
  - e.g. isolation searches only for tracks coming from the same primary vertex or not associated to any
- Efficiencies of all selection criteria have been evaluated versus the number of reconstructed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

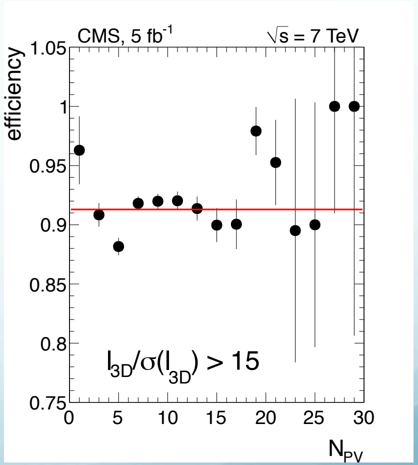
Normalization sample





Control sample



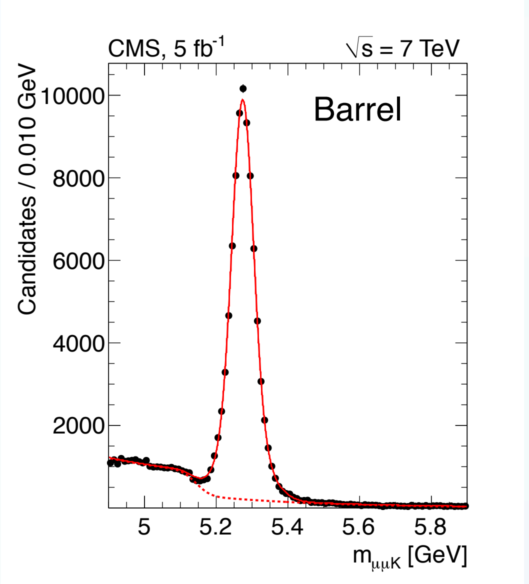


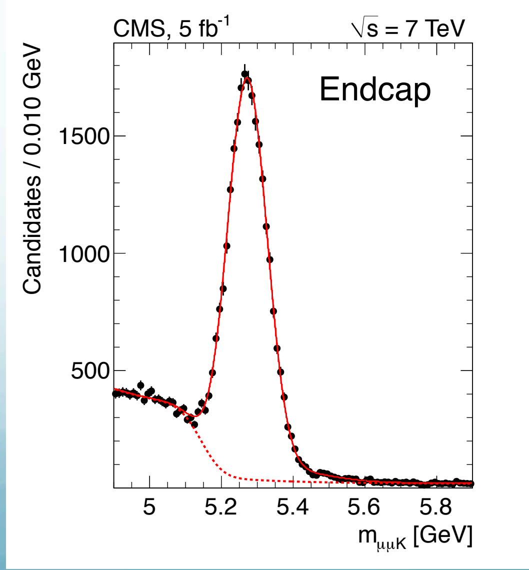
- The same conclusion is also obtained from MC simulations, looking at samples with low (<6) or high (>10) PU events

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





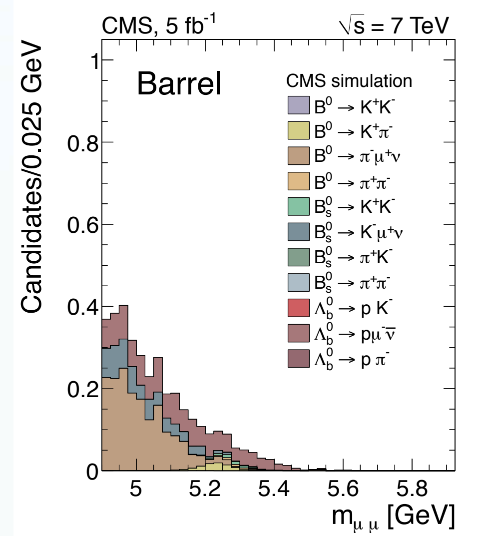
Rare Backgrounds

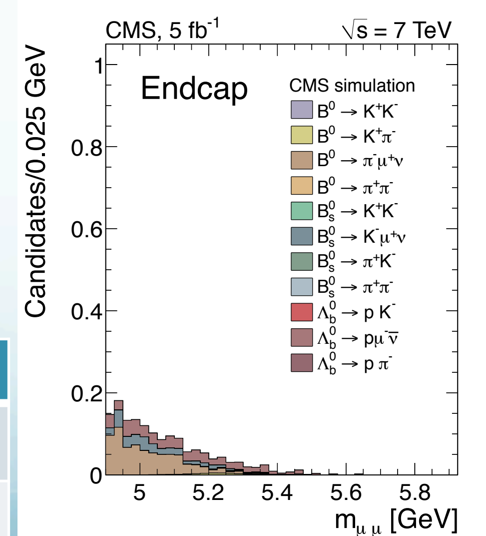
- CKM-suppressed semileptonic decays
  - e.g. $B_s^0 \rightarrow K^- \mu^+ \nu$, with one fake muon (continuous shape)
- Peaking hadronic decays
  - e.g. $B_s^0 \rightarrow K^- K^+$, with two fake muons (shifted to left due to muon mass assignment)
- Each channel normalized to $B^{\pm}$ in data:

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

- weighted with muon-misid evaluated from data:
  $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+, \quad \Lambda \rightarrow p\pi^-$
  - $r \leq 0.10$ % 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

- Uncertainties on the estimations of the single **sources**:

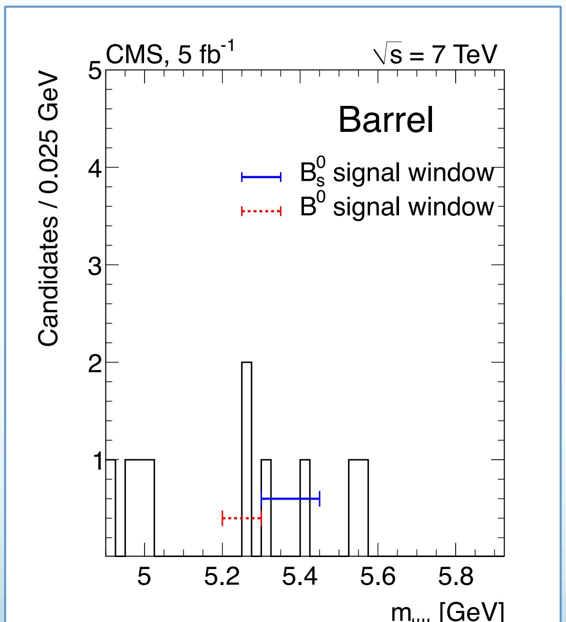
Category	Uncertainty	Barrel	Endcap
f_s/f_u	production ratio of u and s quarks	8.0	8.0
acceptance	production processes	3.5	5.0
P_{ij}^{B} *	mass scale and resolution	3.0	3.0
efficiency (signal)	discrepancies data/MC simulation	3.0	3.0
efficiency (normalization)	discrepancies data/MC simulation	4.0	4.0
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

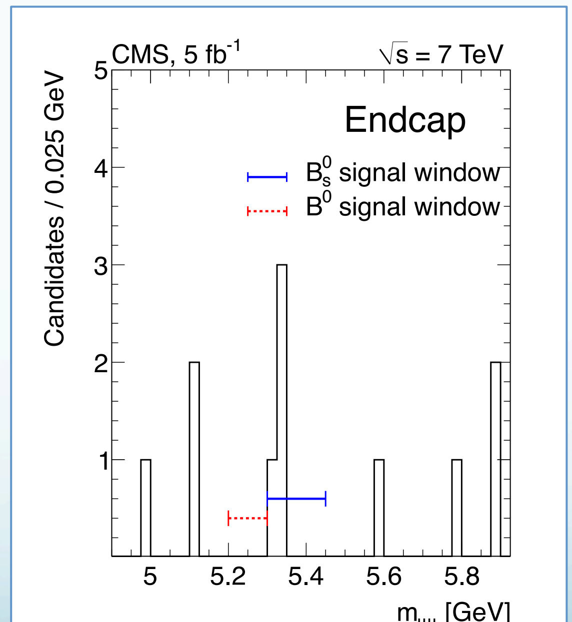
Cross Checks:

- **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**

…unblinding

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**





Estimated combinatorial events in **signal windows**:

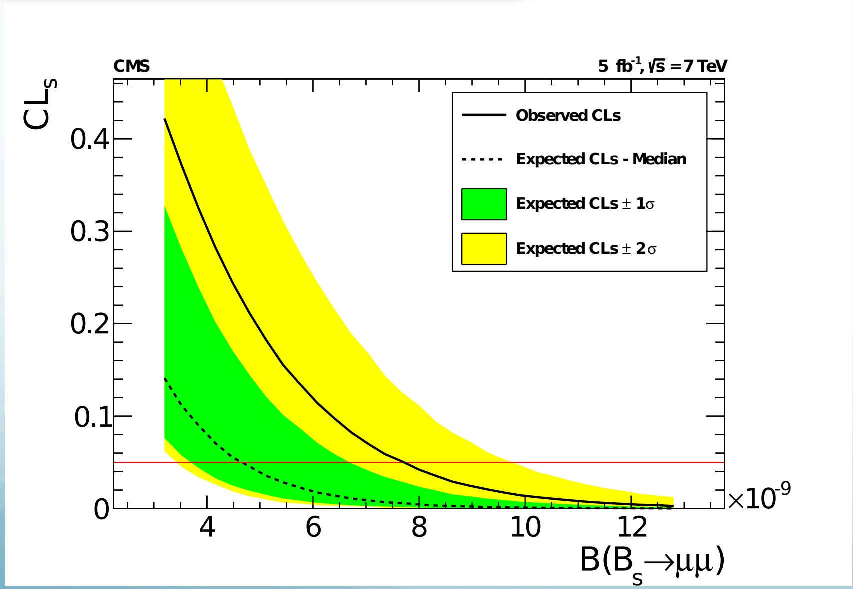
1. subtract rare events from sidebands
2. scale remaining events to the different widths of the regions

Results on the upper limits

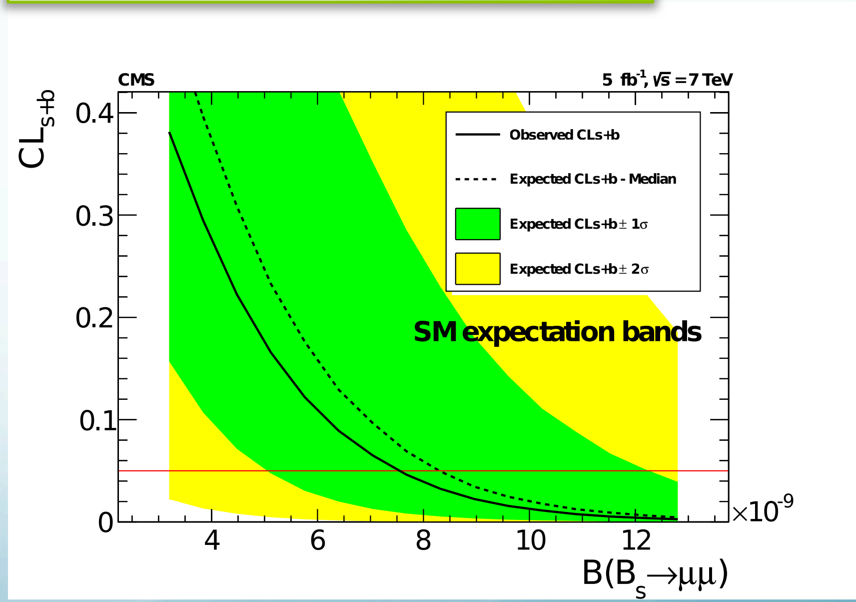
With CLs at 95%CL:

	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}**

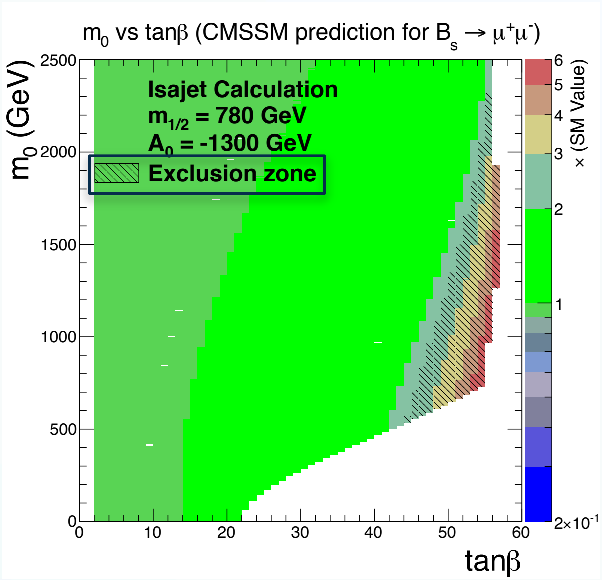
Bkg only hypothesis:

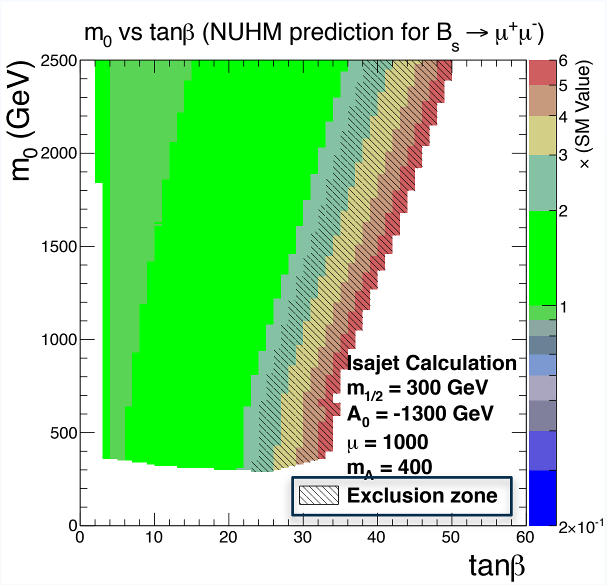


Bkg + SM signal hypothesis:



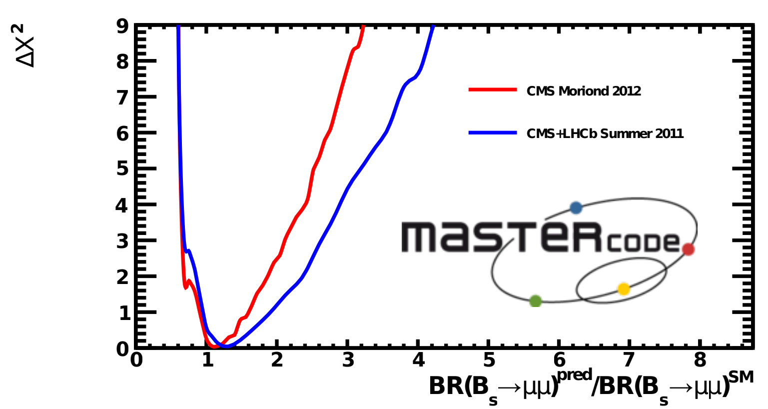
Few SUSY interpretations: CMSSM and NUHM1 models



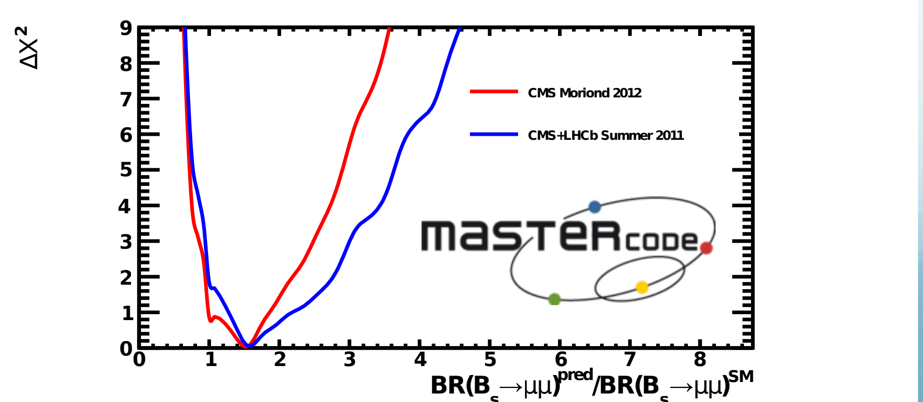


- White regions due to previous upper limit results
- Biggest impact for high tan(β)

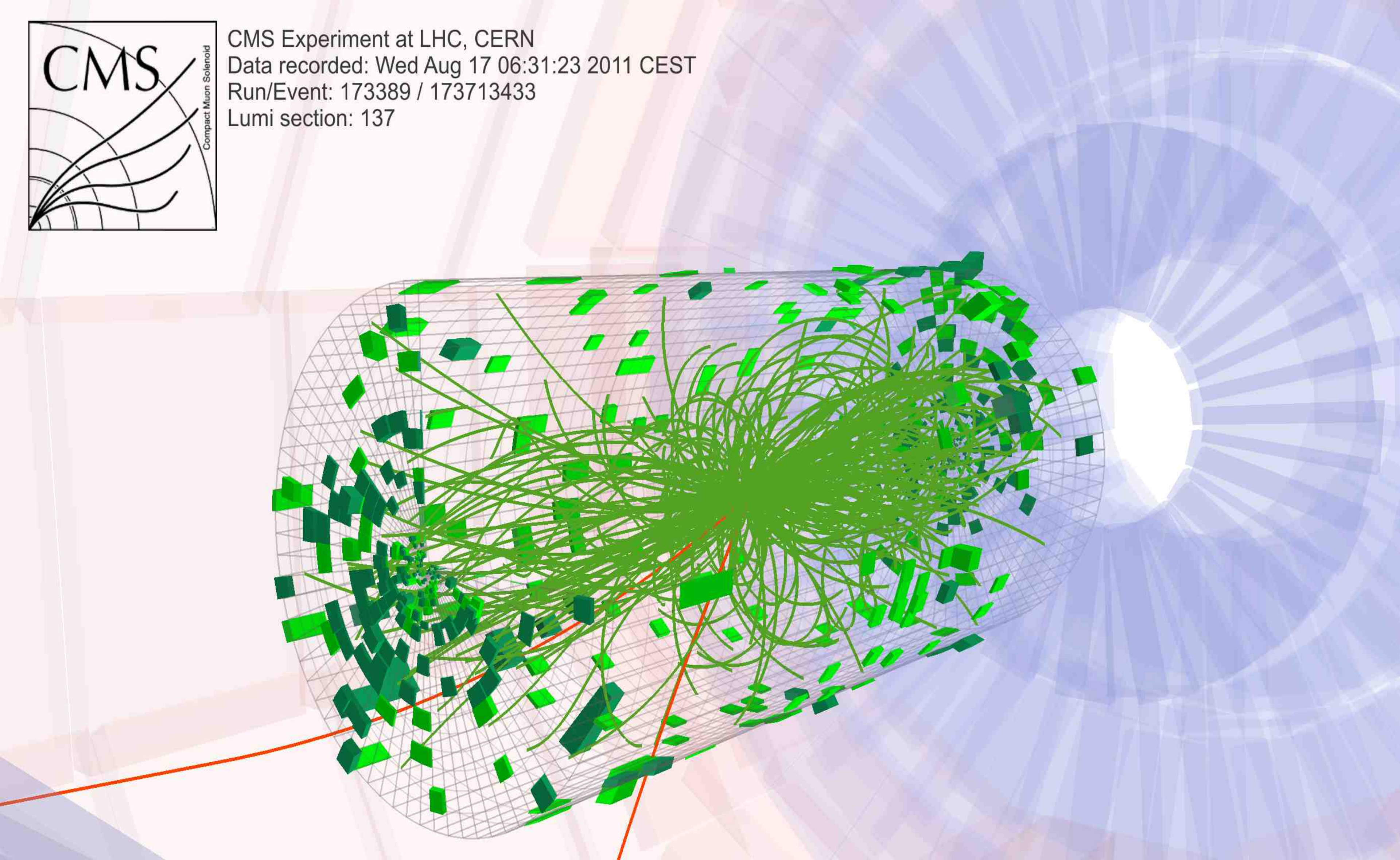
CMSSM



NUHM1



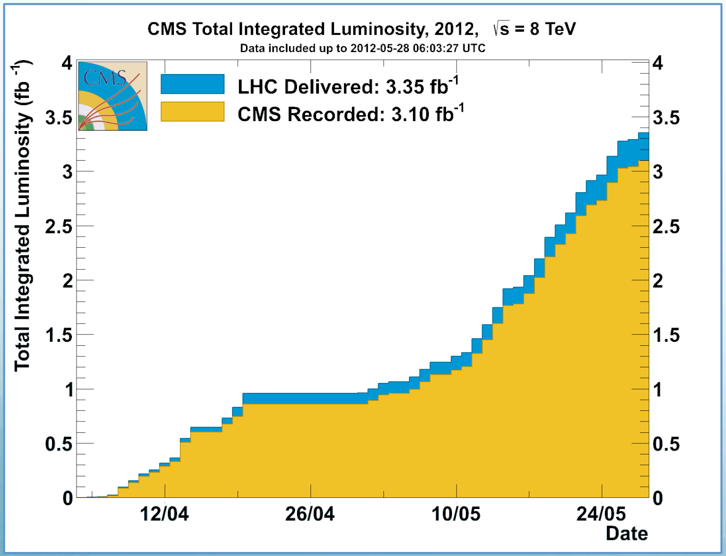
SuperIso V3.1 (CPC, 180, 1579)
MasterCode (arXiv:1112.3564)


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

Forecasts

Outlook for 2012 data taking and more

- **CMS BPhysics programme is on and looking forward the LHC integrated luminosity**
- **Main limitation is the trigger bandwidth**
- **Focus is the significant scientific interest and competitiveness with other experiments**



Year	Int Lumi (1/fb)
2011	5
2012	15
2015	45
2017	95
> 2019	few hundred

Conclusions

- After the first two years of LHC running, CMS has shown its strength in heavy flavor physics:
  - Comprehensive set of open B and Quarkonium cross sections
  - Discovery of a new beauty baryon
  - Upper limits on rare B and D decays
- Flexible trigger, efficient muon reconstruction, good mass resolution and accurate vertexing have been the the main factors facilitating the successful CMS programme
- The increasing instantaneous luminosity will impose constraints on this programme through the CMS bandwidth assigned to BPhysics.
- **Expect great analysis improvements for $B_s \rightarrow \mu^+\mu^-$ search in 2012:**
  - MVA techniques under study
  - 2012 trigger is looser than in 2011
  - About 15 fb^{-1} expected to be added to 2011 data
- Looking forward new exciting physics at CMS!

Backup

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	$4.90 < m_{\mu1\mu2} < 5.90$	$B^0 \rightarrow \mu^+\mu^-$ window	$5.20 < m_{\mu1\mu2} < 5.30$
blinding window	$5.20 < m_{\mu1\mu2} < 5.45$	$B_s^0 \rightarrow \mu^+\mu^-$ 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 $\Delta R_{kk}<0.25$)

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
$p_{T_B} >$	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

Upper limit extraction

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

with $(i = s, d)$

τ_i^B	Ratio of $(B_i^0 \to \mu\mu)$-signal window size to size of background window
$\nu_{i,\mathrm{rare}}^B$	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

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

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

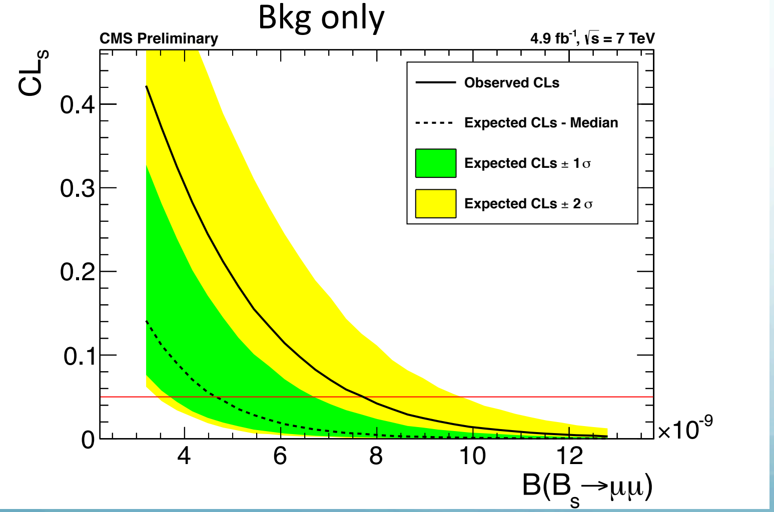
	observed	median expected
BR($B_s^0 \rightarrow \mu\mu$)	**7.7×10^{-9}**	**8.4×10^{-9}**
BR($B^0 \rightarrow \mu\mu$)	**1.8×10^{-9}**	**1.6×10^{-9}**

	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)

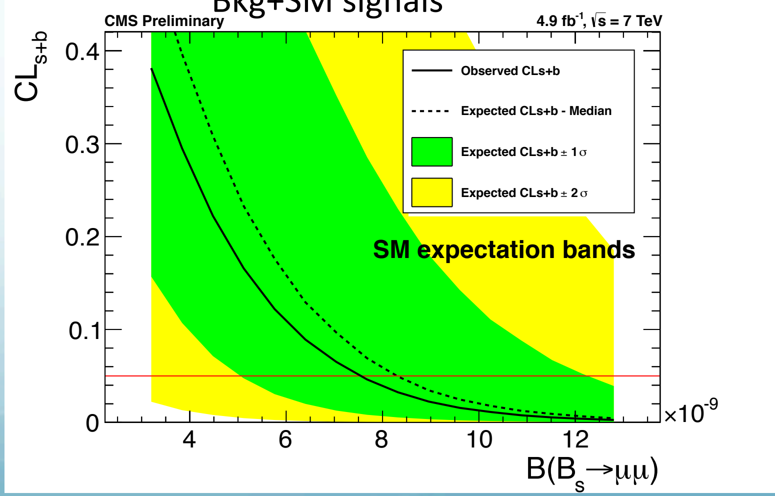
- p-values for SM + bkg

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

Bkg only



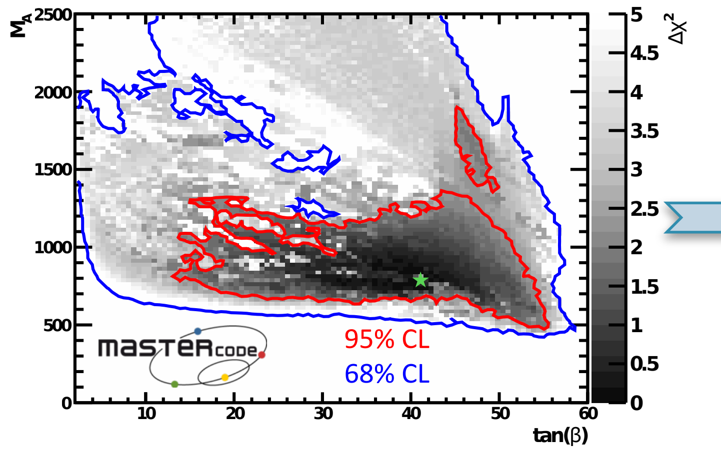
Bkg+SM signals



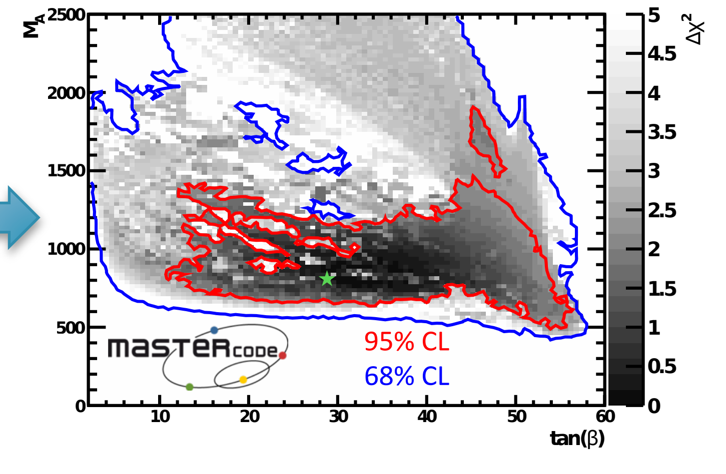
MasterCode

Best fit for CMSSM

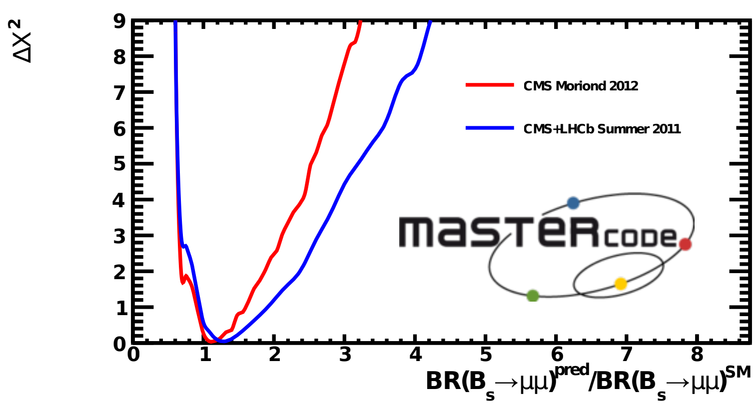
With summer 2011 result



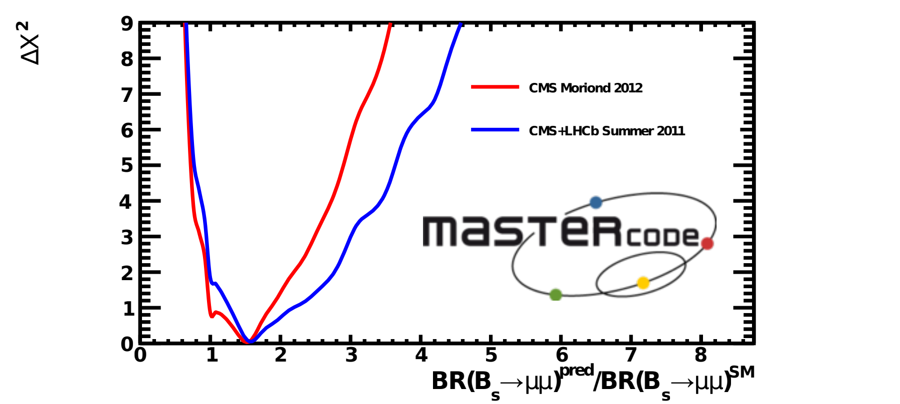
With this new result



CMSSM



NUHM1



Hot Topics

- **CP-violation phase ϕ_s through $B_s \rightarrow J/\psi\ \phi$ decay:**
  - roadmap: cross section (done) → lifetime difference $\Delta\Gamma$ → CP violating phase ϕ_s
  - flavor tagging
  - $B \rightarrow J/\psi\ f_0(980)$ can complement the measure
- **$\tau \rightarrow \mu\mu\mu$: Lepton Flavour Violation (Best limit: Belle 2.1 10^{-8} @90% CL)**
  - Collecting data with a 2 muons + 1 track trigger
  - Expected competitive UL with 10 fb^{-1} and total efficiency > 10%

Channel	CMS physics target
$B_s \rightarrow \mu^+\mu^-$	Measure the branching fraction
$B^0 \rightarrow \mu^+\mu^-$	Upper limit for the branching fraction
$B^0 \rightarrow \mu^+\mu^- K^{*0}$	Consistency with the SM
$B_s \rightarrow J/\psi\varphi$ ($B_s \rightarrow J/\psi f_0$)	Measure ϕ_s
$\tau^- \rightarrow \mu^-\mu^+\mu^-$	Improved upper limit for the branching fraction
$D^0 \rightarrow \mu^+\mu^-$	Improved upper limit for the branching fraction
Exotic quarkonium states	Discovery of new states