



Studies of rare B meson decays with the CMS detector

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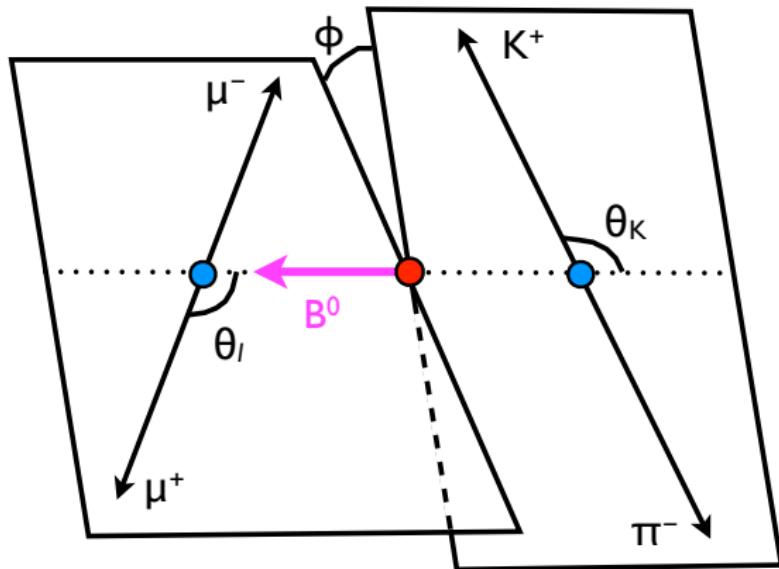
Rare B mesons decays are a crucial probe of physics Beyond the Standard Model

- FCNC, highly suppressed decays
- Virtual New Physics particles can contribute in loops
- Tiny effects so NP can be at the same level of SM
- High precision predictions of SM observables
- If observed, deviations from SM will be indirect evidence of NP
 - ▷ Rare B decays potential smoking gun for physics BSM

In this talk:

- Angular analysis and branching ratio measurement of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+ \mu^-$

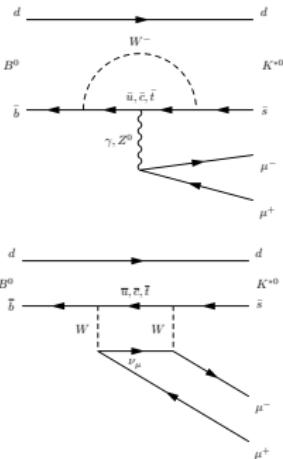
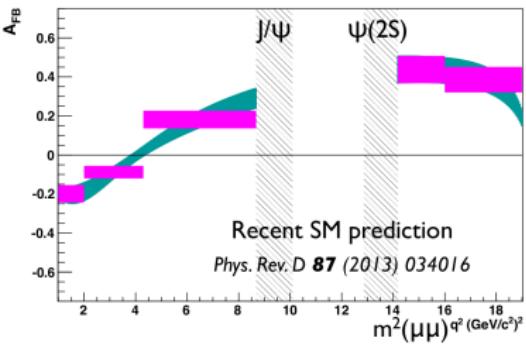
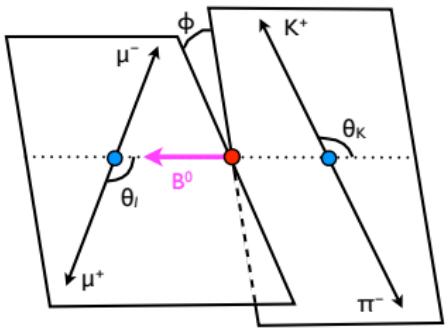
Angular analysis and branching ratio measurement of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$



CMS-PAS-BPH-11-009
arXiv:1308.3409
Submitted to PLB

The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

- $b \rightarrow s\ell^+\ell^-$ transition, suppressed in the standard model:
 - ▷ FCNC
 - ▶ Tree-level suppression
 - ▶ Box/penguin diagrams
 - ▷ Robust calculations, especially at low $q^2 = m_{\mu\mu}^2$
- Four-particles final states ($K\pi\mu\mu$) \rightarrow angular observables
 - ▷ Decay fully described by q^2 and three angles (θ_K, θ_L, ϕ)
- CMS measurements:
 - ▷ Differential branching fraction, $d\mathcal{B}/dq^2$
 - ▷ Dimuon forward-backward asymmetry, A_{FB}
 - ▷ Longitudinal K^{*0} polarization, F_L



- Full 2011 dataset: 5 fb^{-1} , $\sqrt{s} = 7 \text{ TeV}$
- Unbinned extended maximum likelihood fits in q^2 bins:
 - ▷ 6 signal q^2 bins ($1 - 19 \text{ GeV}^2$)
 - ▷ 1 normalization q^2 bin ($B^0 \rightarrow K^{*0} J/\psi$)
 - ▷ 1 control q^2 bin ($B^0 \rightarrow K^{*0} \psi'$)
 - ▶ Signal and control channels are selected/treated identically
- A_{FB} and F_L are extracted from fits to the two angular variables: $\cos \theta_K$, and $\cos \theta_L$.

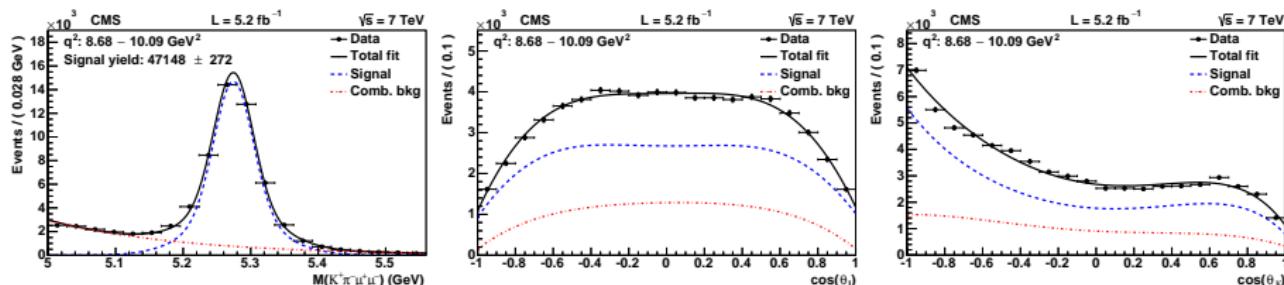
$$\frac{1}{\Gamma} \frac{d^3\Gamma}{d \cos \theta_K d \cos \theta_L dq^2} = \frac{9}{16} \left\{ \left[\frac{2}{3} F_S + \frac{4}{3} A_S \cos \theta_K \right] (1 - \cos^2 \theta_L) \right. \\ + (1 - F_L) \left[2F_L \cos^2 \theta_K (1 - \cos^2 \theta_L) \right. \\ + \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_L) \\ \left. \left. + \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_L \right] \right\}$$

- Residual contributions determined by the fit to the normalization sample $B^0 \rightarrow K^{*0} J/\psi$:
 - ▷ Spinless (S-wave) contribution to the $K\pi$ combination, F_S
 - ▷ S-wave/P-wave interference, A_S
- $d\mathcal{B}/dq^2$ is measured relative to the normalization channel $B^0 \rightarrow K^{*0} J/\psi$ from fit to the B^0 cand. invariant mass:

$$\frac{d\mathcal{B} (B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2} = \frac{Y_S}{Y_N} \frac{\epsilon_N}{\epsilon_S} \frac{\mathcal{B} (B^0 \rightarrow K^{*0} J/\psi)}{dq^2}$$

Fit on normalization channel

- Fit to the $B^0 \rightarrow K^{*0} J/\psi$ channel ($8.68 < q^2 < 10.09 \text{ GeV}^2$ bin)



- Vector (P-wave) and scalar (S-wave) contributions obtained from the fit
 - Direct estimation of the non-resonant $K\pi$ component from data

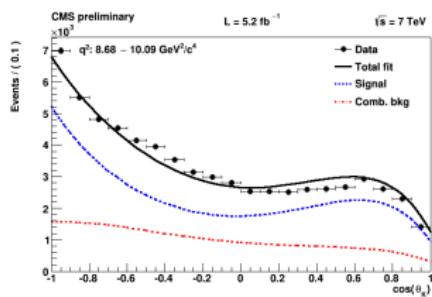
CMS results

- $F_L = 0.554 \pm 0.004$
- $A_{FB} = -0.004 \pm 0.004$

Expectations

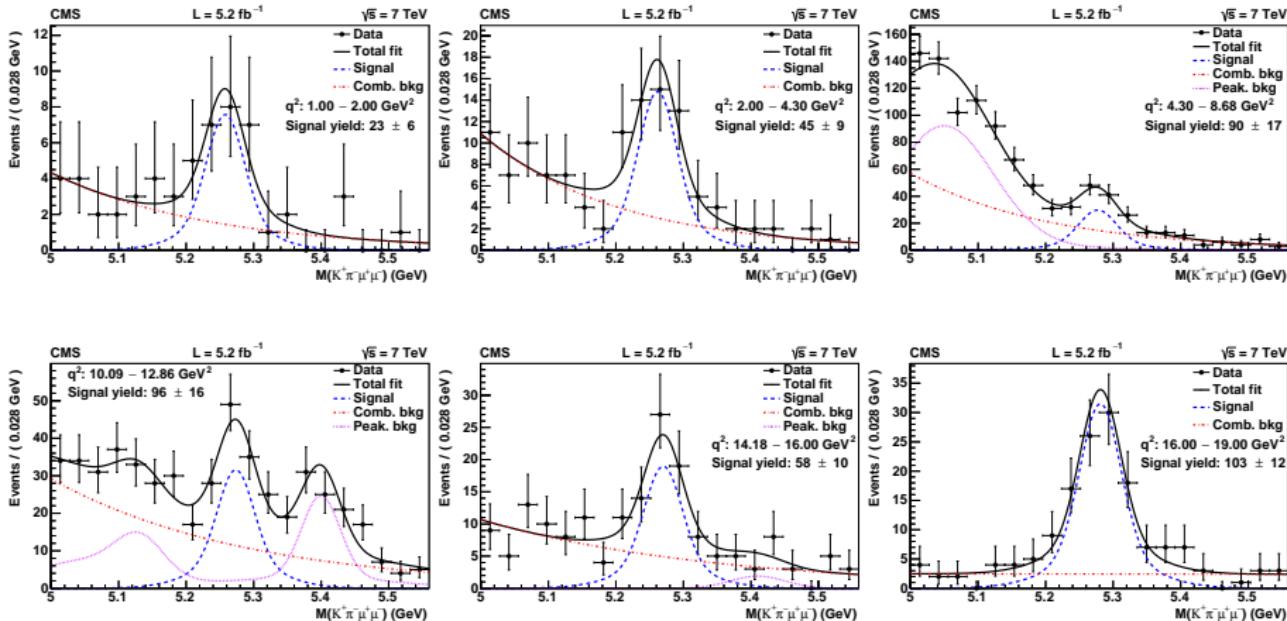
- $F_L = 0.570 \pm 0.008$ [PDG]
- A_{FB} compatible with zero

Fit performed neglecting the scalar $K\pi$ contributions (F_S, A_S)



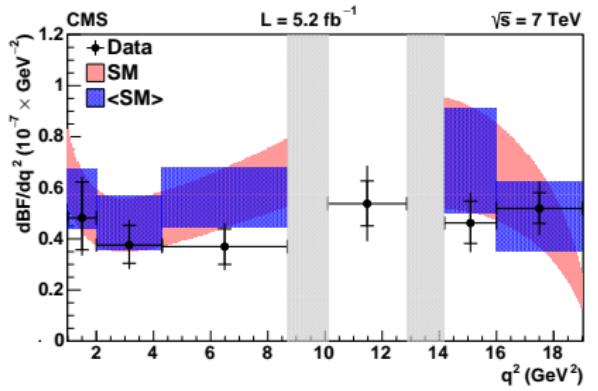
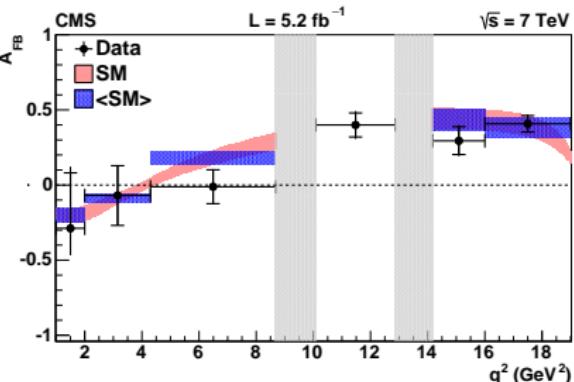
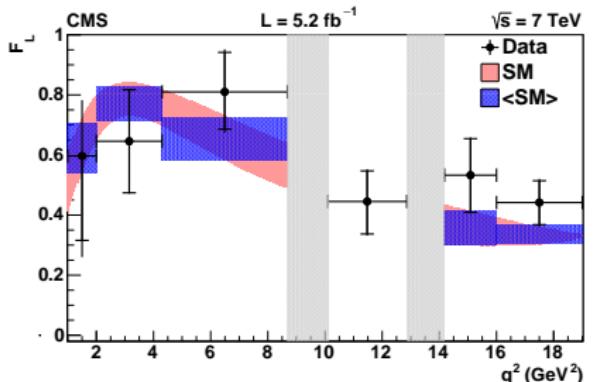
Fitting the signal

- A total of more than 400 signal events
- Clear yields from all the q^2 bins



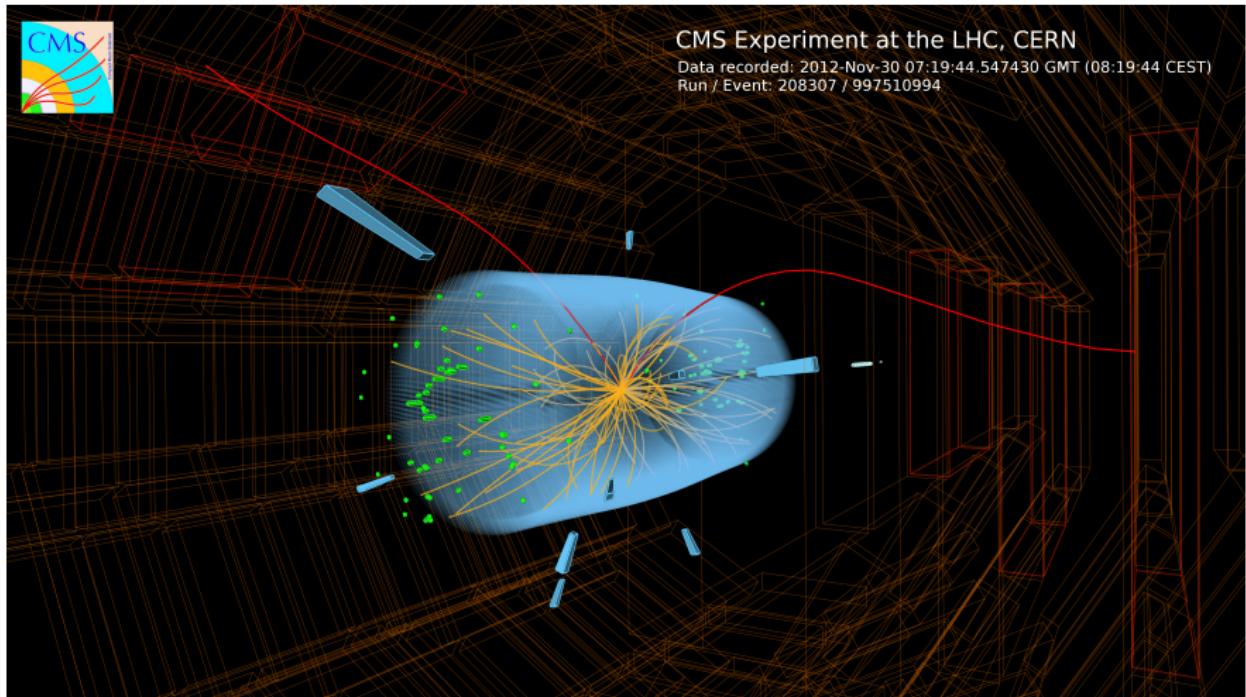
- Signal
- Combinatorial background: randomly associated hadron-muon pairs
- Peaking background: feed-through from dimuon resonant channels

Results – $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis



- Short error bars: statistical uncertainty
 - Long error bars: total uncertainty
 - Red band: standard model predictions
 - Blue boxes: SM predictions averaged over the q^2 bin
- [Bobeth et al. PRD 87, 034016]
- No deviations from the standard model are found
 - Results still dominated by the statistical uncertainty

Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+ \mu^-$

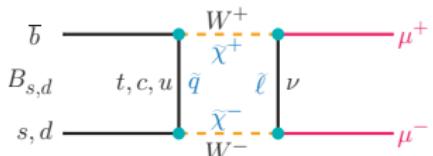
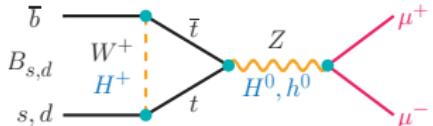


CMS-PAS-BPH-13-004
arXiv:1307.5025
Accepted by PRL

The B_s^0 (B^0) $\rightarrow \mu^+ \mu^-$ decay

- B_s^0 (B^0) $\rightarrow \mu^+ \mu^-$ decays highly suppressed in standard model:

- ▷ FCNC
 - ▶ Tree-level suppression
 - ▶ Box/penguin diagrams
- ▷ Elicity suppression (m_μ^2/m_B^2)
- ▷ Internal quark annihilation (f_B^2/m_B^2)



SM predictions (time-integrated)

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.57 \pm 0.30) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

[De Bruyn et al. PRL 109, 041801]

[A. Buras et al. arXiv:1303.3820]

- $\mathcal{B}(B_s^0$ (B^0) $\rightarrow \mu^+ \mu^-$) probe for physics BSM
 - ▷ $\mathcal{B} \sim (\tan \beta)^6$ in MSSM
 - ▷ $\mathcal{B} \sim (\tan \beta)^4$, m_{H^\pm} in 2HDM
- (Very) Small theoretical uncertainties
- High sensitivity to new physics
 - ▷ Comparable to $\mu \rightarrow e\gamma$, $B \rightarrow X\nu\nu$

- Complete re-analysis of entire 2011 (5 fb^{-1} , $\sqrt{s} = 7 \text{ TeV}$) + 2012 (20 fb^{-1} , $\sqrt{s} = 8 \text{ TeV}$) datasets
 - ▷ Blind analysis (2011 dataset re-blinded)
 - ▷ Better muonID and fake suppression (BDT based)
 - ▷ New (and improved) analysis variables
 - ▷ BDT based discriminant
 - ▷ Simultaneous maximum likelihood fit to dimuon mass in several BDT bins and two rapidity ranges

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

- $\mathcal{B}(B_s^0 (B^0) \rightarrow \mu^+ \mu^-)$ is measured relative to the $B^+ \rightarrow J/\psi K^+$ normalization channel
 - ▷ \mathcal{B} independent from the luminosity measurement
 - ▷ Avoid uncertainties related to b quark production cross section
 - ▷ Mitigate the effects of uncertainties in the efficiencies
- Control sample $B_s^0 \rightarrow J/\psi \phi(KK)$ to compare and validate B_s^0 mesons in data and MC simulations

MVA selection

- The events are selected by a Boosted Decision Tree (BDT)

- Signal: $B_s^0 \rightarrow \mu^+ \mu^-$ MC simulation
- Background: dimuon data mass sidebands
- Data randomly split in 3 subset:
 - Train on 1, test on 2, apply on 3
 - Avoid selection bias

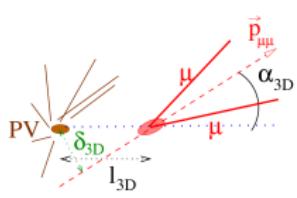
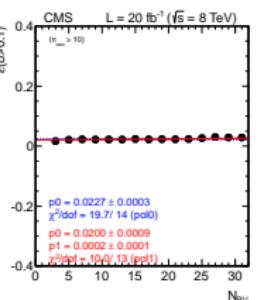
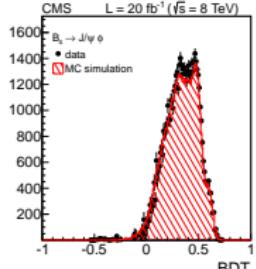
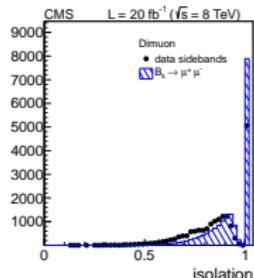
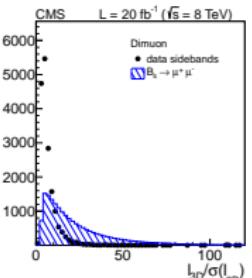
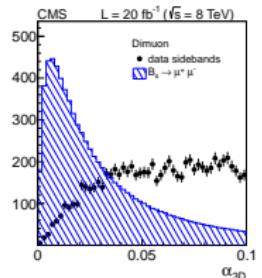
- Studies on BDT output:

- insensitive to invariant mass
- insensitive to pileup

- Use the same BDT for normalization and control samples

- differences between Data and MC BDT output as systematic uncertainties

- A (very short) selection of the most significant variables:



BR extraction

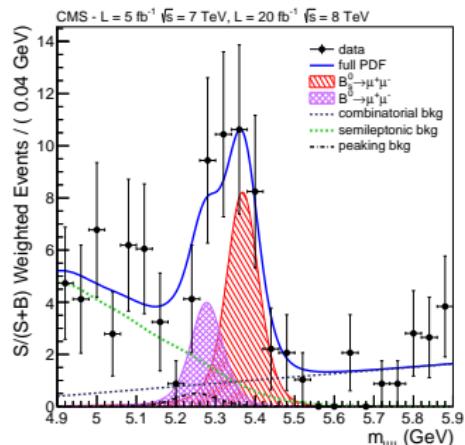
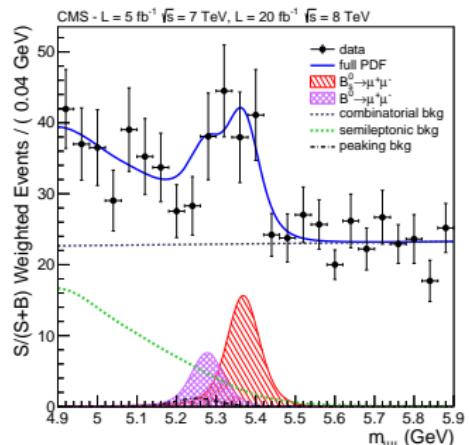
■ 2 approaches:

- ▷ Categorized-BDT to extract $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$
 - ▶ UML fit to 12 mass distributions in BDT bins split in Barrel/Endcap
 - ▶ BDT binning chosen to equalize the expected number of signal events

- ▷ 1D-BDT to extract CL_s limits on $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$
 - ▶ Optimized cut on BDT output and event counting in mass windows

min. bin edges	1	2	3	4
2011 barrel	0.10	0.31	-	-
2011 endcap	0.10	0.29	-	-
2012 barrel	0.10	0.23	0.33	0.44
2012 endcap	0.10	0.22	0.29	0.45

$b >$	barrel	endcap
2011	0.29	0.29
2012	0.38	0.39



Results – $B_s^0 (B^0) \rightarrow \mu^+ \mu^-$



- Observation of $B_s^0 \rightarrow \mu^+ \mu^-$ decay

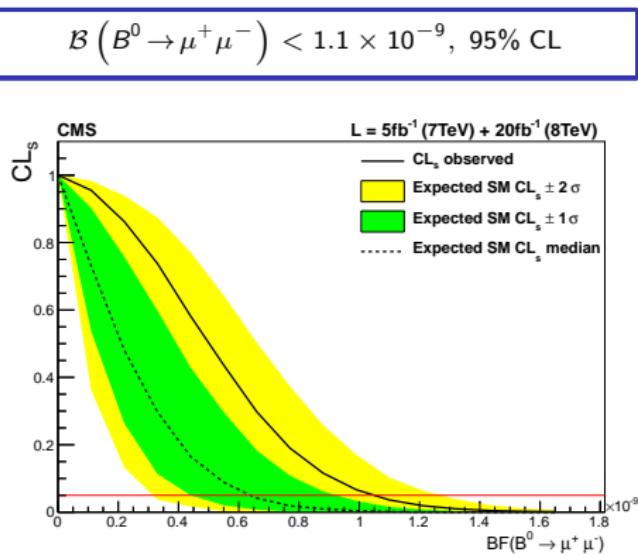
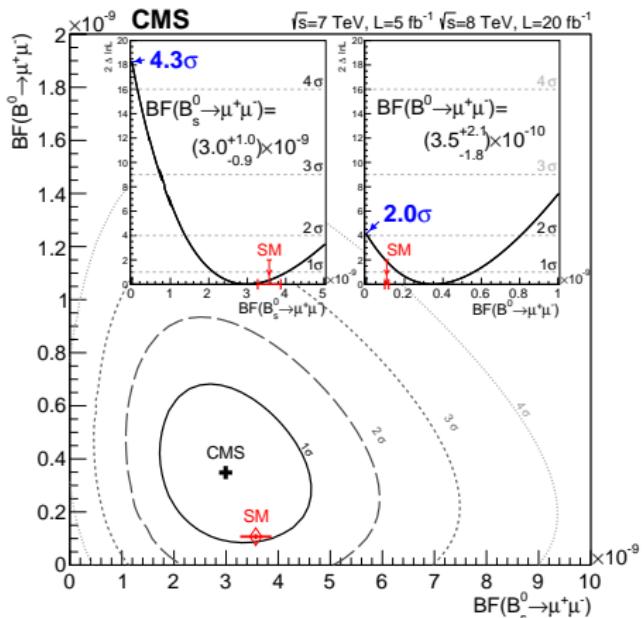
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

4.3σ significance (expected 4.8σ median)

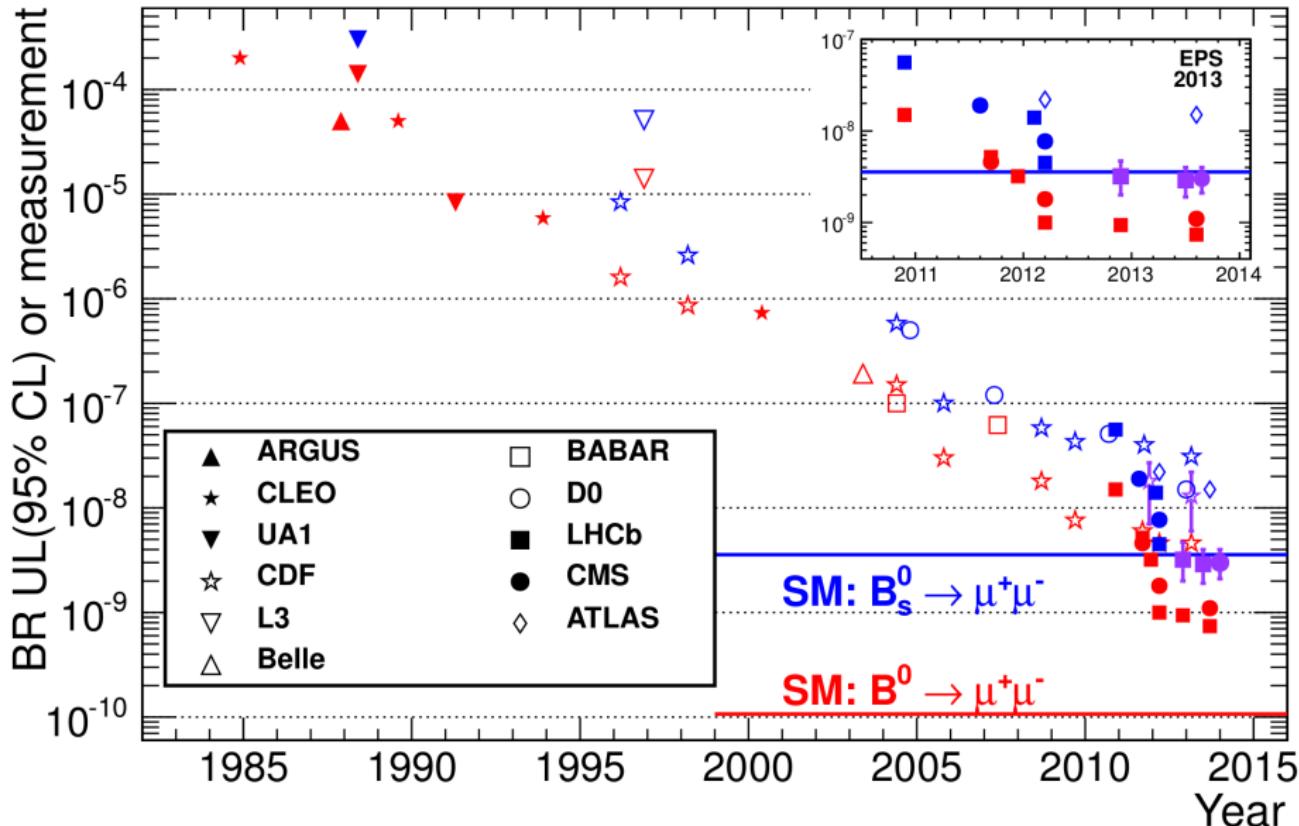
- No significant excess of $B^0 \rightarrow \mu^+ \mu^-$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

2.0 σ significance



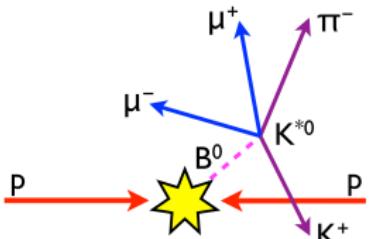
- First CMS angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, using 2011 dataset (5 fb^{-1})
 - ▷ More than 400 signal decays
 - ▷ No deviations from the SM predictions are found
 - ▷ Results with 2011 data are statistically limited
 - ▶ Analysis of the 2012 data is starting
- $\mathcal{B}(B_s^0 (B^0) \rightarrow \mu^+ \mu^-)$ analysis, using 2011+2012 datasets (25 fb^{-1})
 - ▷ Substantial improvements to previous analysis
 - ▶ Muon identification with BDT
 - ▶ Analysis selection with BDT
 - ▶ UML fit to mass distributions
 - ▷ 4.3 σ significance of $B_s^0 \rightarrow \mu^+ \mu^-$ observation
 - ▶ Consistent with SM predictions
 - ▷ No significant excess is observed for $B^0 \rightarrow \mu^+ \mu^-$ decay
 - ▶ Upper limit using CLs method
 - ▷ Future plans
 - ▶ Looking forward for LHC Run2
- All public BPH results from the CMS collaboration
 - ▷ <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH>



BACKUP

Signal:

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - ▷ Two well reconstructed/identified muons with invariant mass far from the J/ψ and ψ' (q^2 bins)
 - ▷ $K^{*0}(892)$ reconstructed through the decay in $K\pi$ (both tracks must fail muonID)
 - ▷ 4-track vertex candidate identified as B^0 (\bar{B}^0) if $K^+\pi^- (K^-\pi^+)$ is the closest to the nominal K^{*0} mass

Background:

- Peaking
 - ▷ Feed-through from $B^0 \rightarrow K^{*0} J/\psi$ and $B^0 \rightarrow K^{*0} \psi'$ decays not removed by the q^2 cut
 - ▷ Dimuon mass reconstructed far from the true $J/\psi (\psi')$ mass $\rightarrow K\pi\mu\mu$ mass shifted from the true B^0 mass
 - ▷ Shape obtained from simulation.
- Combinatorial
 - ▷ Unavoidable fraction of mis-reconstructed B^0 from randomly associated muons to hadrons
 - ▷ Shape described by a single exponential in mass, and by polynomials for the angular variables.

Muon selection

- events recorded with dimuon low-mass, vertex displaced trigger
- $\mu^+ \mu^-$ vertex transverse flight length significance cut (in trigger)
- $1 < m_{\mu\mu} < 4.8$ GeV (in trigger)
- $p_T(\mu) > 3, 4, 4.5, 5$ GeV (depending on trigger)

Hadron selection

- hadron must fail muon ID
- $p_T(h) > 0.75$ GeV
- cut on transverse distance of closest approach
- $|m(K\pi) - m_{PDG}(K^{*0})| < 80$ MeV

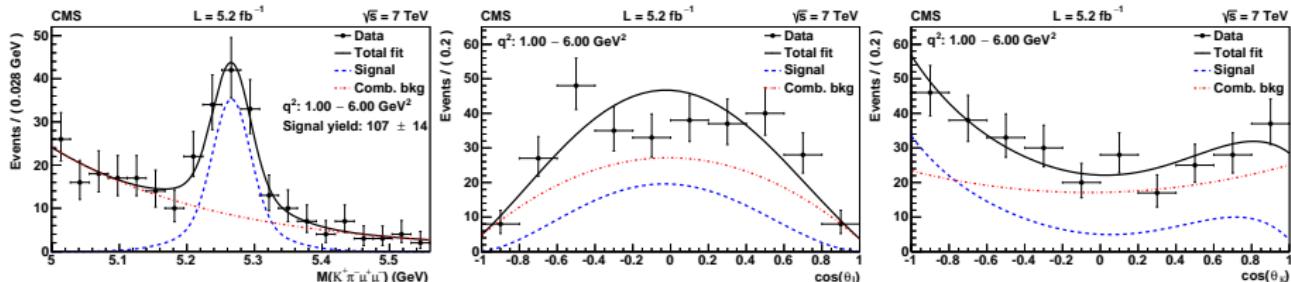
 B^0 selection

- B^0 vertex CL $> 9\%$
- B^0 vertex transverse flight length significance cut
- $\cos(\alpha) > 0.9994$, α being the angle in transverse plane between B^0 momentum and line-of-flight

CP state assignment

- tag the CP state based on closest distance from K^{*0} PDG mass
- reject event if both K^{*0} and $\overline{K^{*0}}$ masses are within 50MeV of PDG mass ($\sim 1\Gamma$)
- mistag rate : 8% on MC; 10% on data

- “Special” bin → very precise theoretical predictions



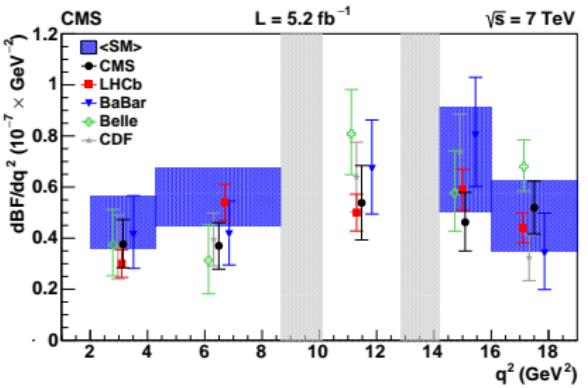
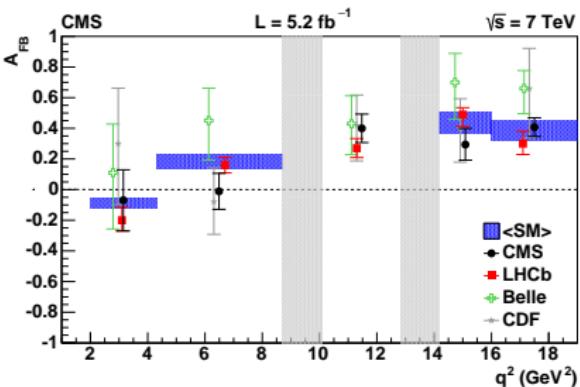
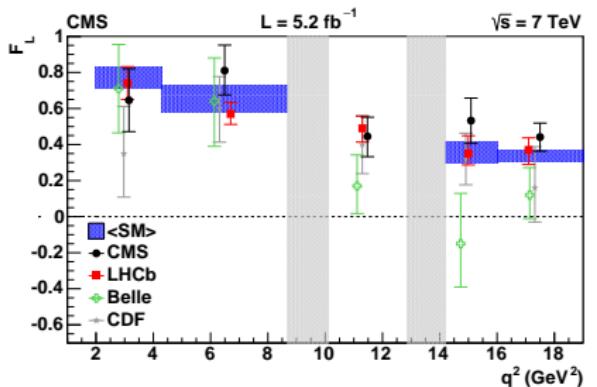
CMS results

- $F_L = 0.68 \pm 0.10 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$
- $A_{FB} = -0.07 \pm 0.12 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$
- $d\mathcal{B}/dq^2 = (4.4 \pm 0.6 \text{ (stat.)} \pm 0.7 \text{ (syst.)}) \times 10^{-8} \text{ GeV}^{-2}$

SM predictions (Bobeth et al. PRD 87 034016)

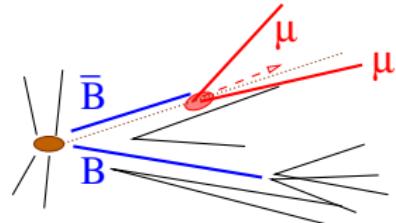
- $F_L = 0.74^{+0.06}_{-0.07}$
- $A_{FB} = -0.04 \pm 0.03$
- $d\mathcal{B}/dq^2 = (4.9^{+1.0}_{-1.1}) \times 10^{-8} \text{ GeV}^{-2}$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ – Comparison with other experiments



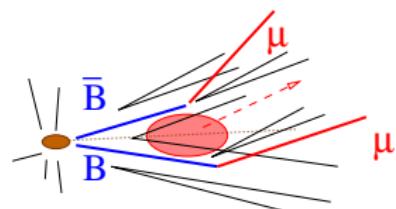
Signal

- Two muons from one decay (secondary) vertex
 - ▷ Well reconstructed secondary vertex
 - ▷ Dimuon momentum aligned with SV flight direction
 - ▷ $m_{\mu\mu}$ close to the nominal $m_{B_s^0(B^0)}$ value
 - ▷ PV/SV/muon isolation



Background

- Combinatorial (estimated from sidebands)
 - ▷ One semileptonic B decay and one hadron (K/π) misidentified as a muon
 - ▷ Two semileptonic B decays
- Rare single B decays (estimated from MC simulation)
 - ▷ Peaking: $B_s^0 \rightarrow K\pi$, $B_s^0 \rightarrow KK$, $B^0 \rightarrow \pi\pi$, ...
 - ▷ Non-peaking: $B_s^0 \rightarrow K\mu\nu$, $\Lambda_b \rightarrow p\mu\nu$, ...



Crucial aspects of the analysis

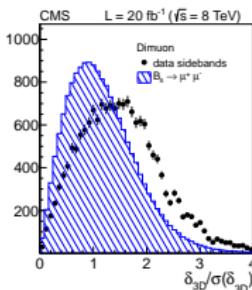
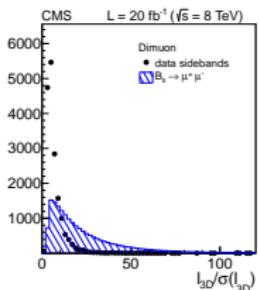
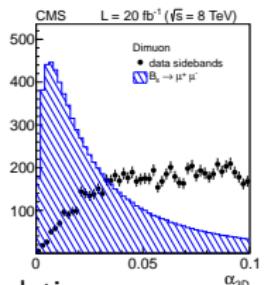
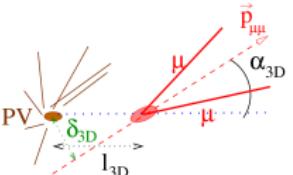
- muonID and $h \rightarrow \mu$ suppression
- vertexing variables
- isolation variables

- Improved muon identification to cope with peaking and semileptonic backgrounds
 - ▷ Use a MVA based on Silicon Tracker and Muon Detector information
 - ▶ distribution of hits in the tracker as compared to expected
 - ▶ kink identification
 - ▶ muon segment compatibility
 - ▶ χ^2/ndof
 - ▶ muon p_T and η
 - ▷ Muon MC efficiency validated with Tag&Probe methods in data
 - ▷ Muon fake rate reduced by a factor of ~ 2 compared to previous analysis, at the expenses of $\sim 10\%$ muon efficiency reduction
 - ▶ $\varepsilon(\mu|\pi) < 0.15\%$
 - ▶ $\varepsilon(\mu|K) < 0.20\%$
 - ▶ $\varepsilon(\mu|p) < 0.10\%$
 - ▷ Analysis uses MC p_T -dependent fake rate, validated with data (50% uncertainty)
 - ▶ $D^{*0} \rightarrow D^0 \pi$, $K_s \rightarrow \pi\pi$, $\Lambda \rightarrow p\pi$

$B_s^0 (B^0) \rightarrow \mu^+ \mu^-$ – Most discriminating variables

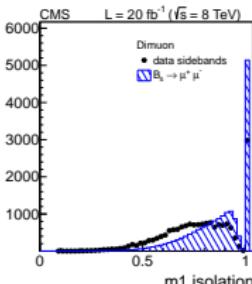
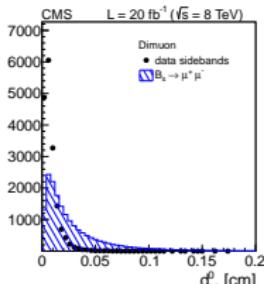
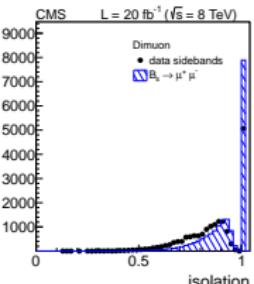
■ Vertexing:

- ▷ Angle between PV ad SV
- ▷ SV flight length significance
- ▷ Dimuon impact parameter significance

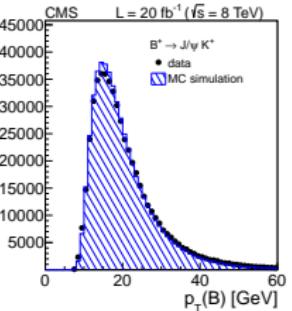
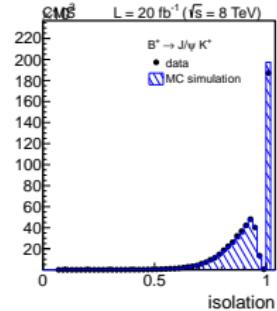
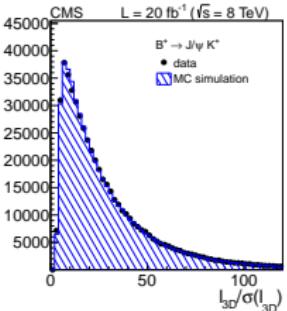
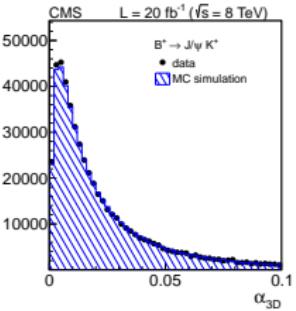
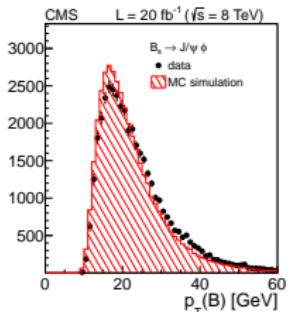
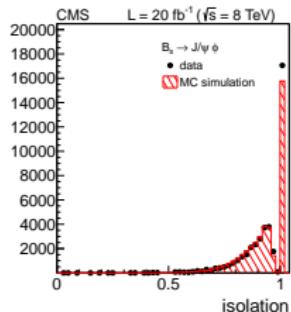
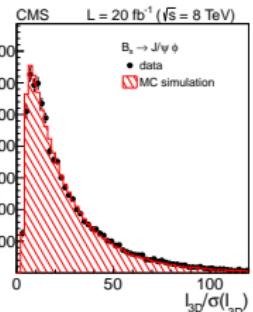
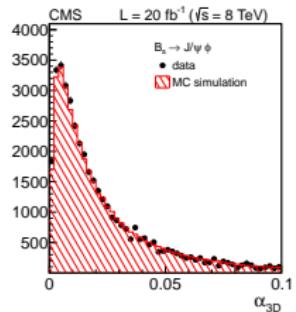


■ Isolation:

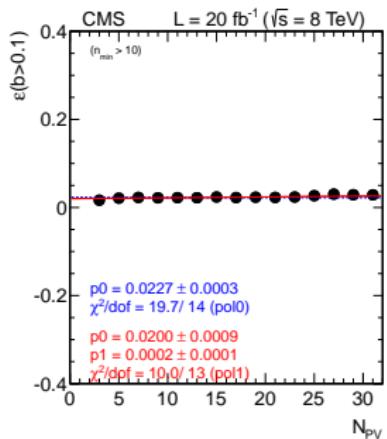
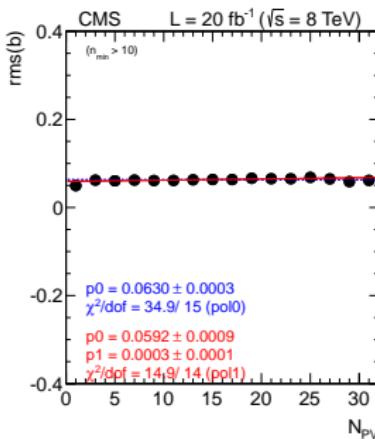
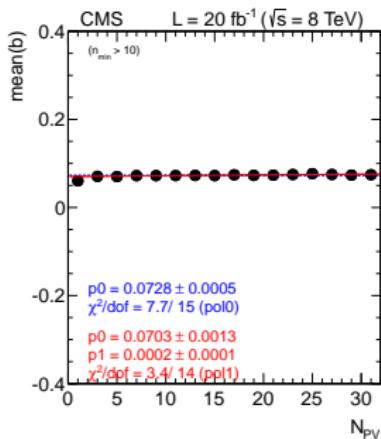
- ▷ Primary Vertex isolation (dimuon isolation)
- ▷ Secondary Vertex isolation (B-cand. isolation)
- ▷ Muon isolation



- Comparison of sidebands subtracted distributions
 - Good agreement

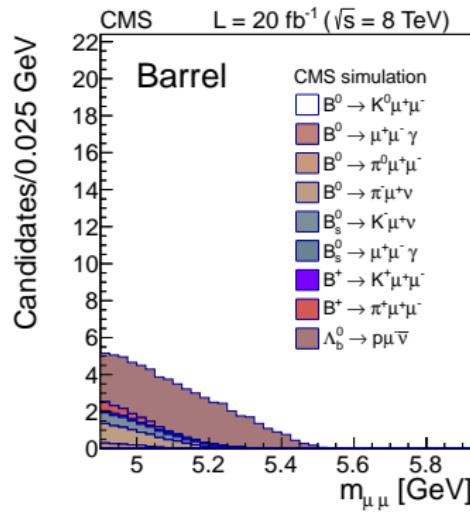
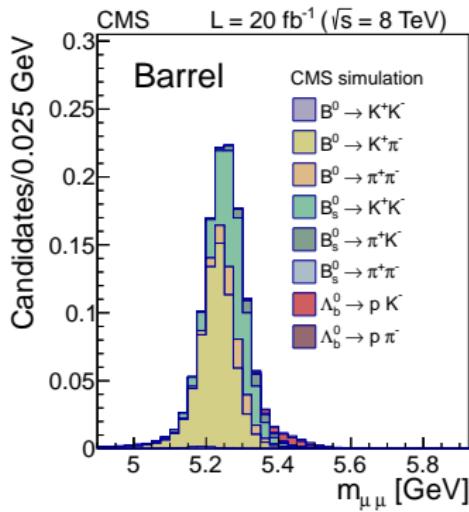


- Average number of interactions per bunch crossing
 - ▷ 2011: ≈ 9
 - ▷ 2012: ≈ 21
- Pileup independence checked
 - ▷ Signal MC event samples with pileup
 - ▶ every single variable used in BDT is shown to be pileup independent
 - ▷ Data studies with BDT output distribution vs. N_{PV}
 - ▶ mean and RMS, efficiency of BDT requirement
- No significant pileup dependence observed

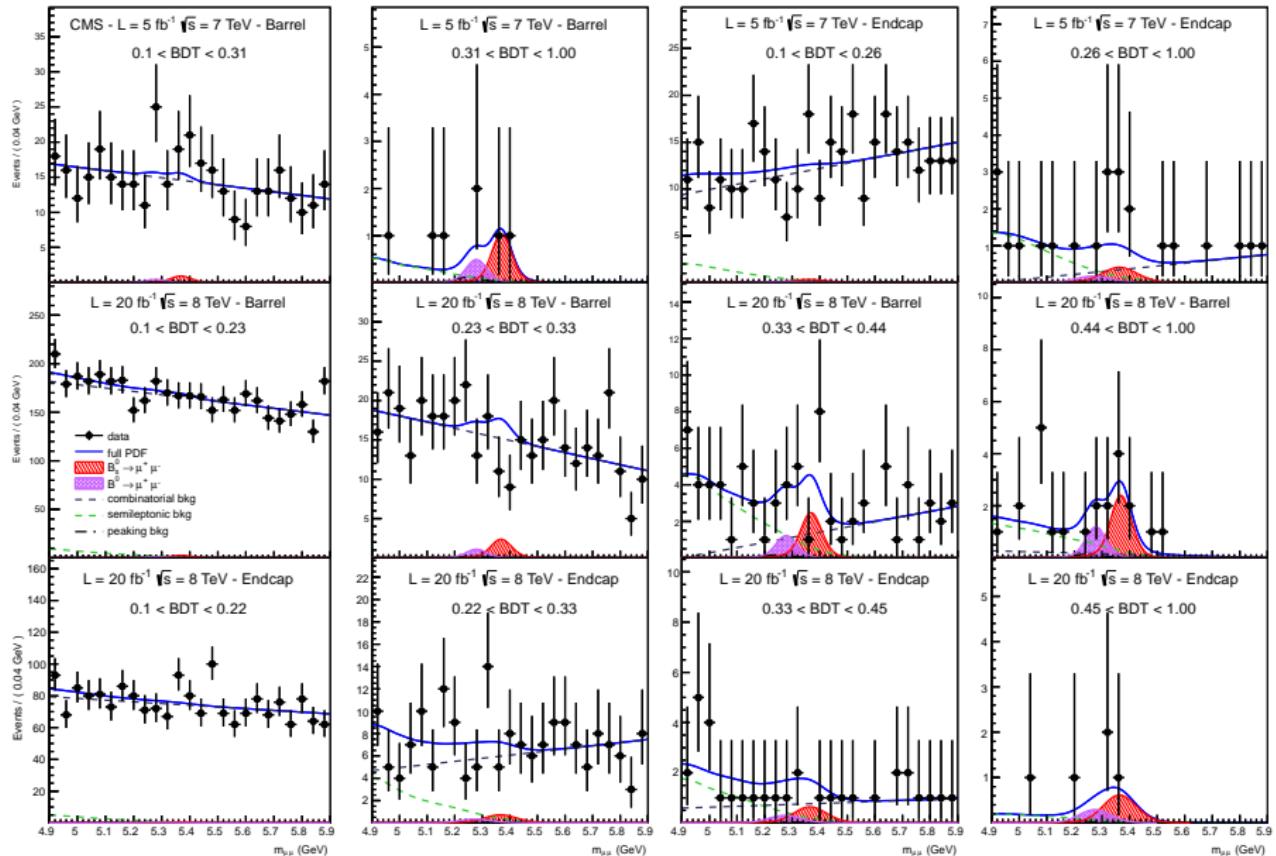


- Normalized to $B^+ \rightarrow J/\psi K^+$ yield in data

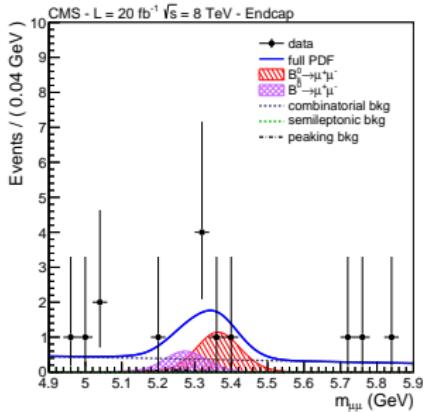
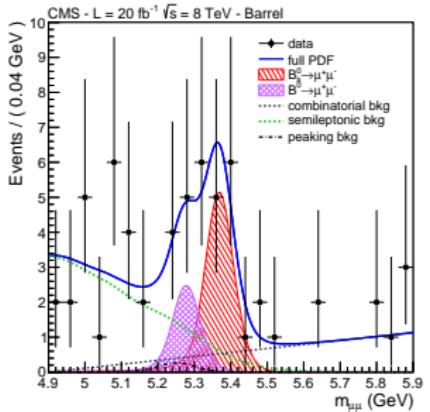
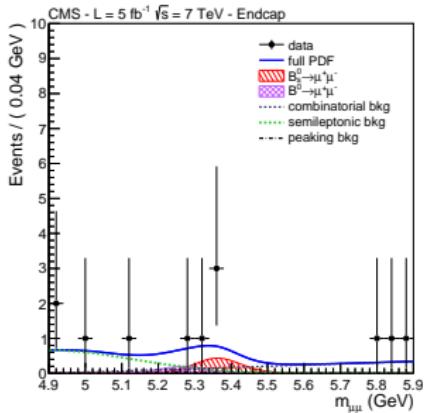
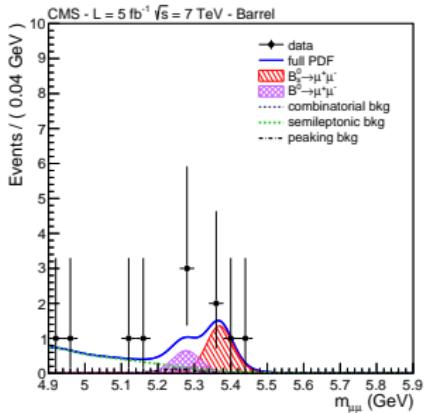
$$N(X) = \frac{\mathcal{B}(Y \rightarrow X)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} \frac{f_Y}{f_u} \frac{\varepsilon_{tot}^X}{\varepsilon_{tot}^{B^+}} N_{obs}(B^+)$$



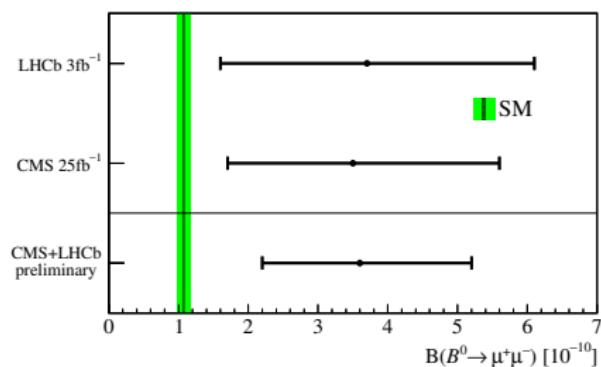
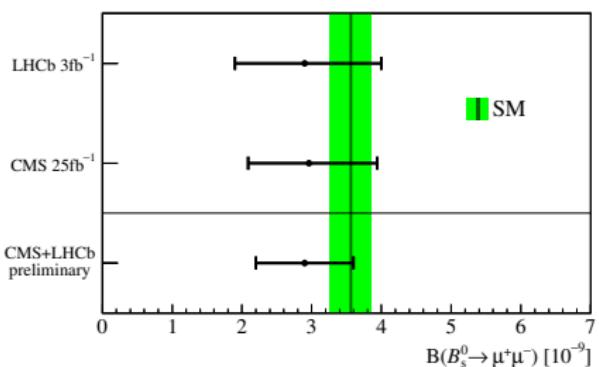
$B_s^0 (B^0) \rightarrow \mu^+ \mu^-$ – Categorized BDT fits



$B_s^0 (B^0) \rightarrow \mu^+ \mu^-$ – 1D-BDT fits



- CMS-PAS-BPH-13-007
- CERN-LHCb-CONF-2013-012



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$