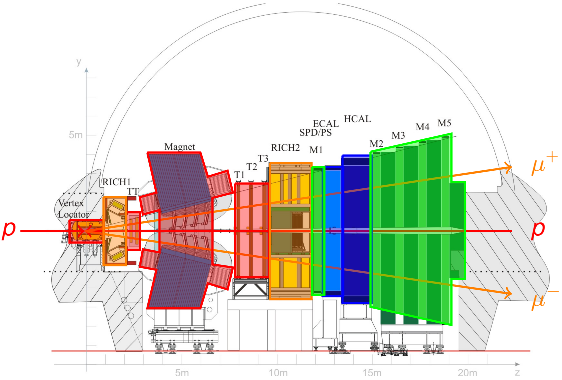
Rare *B* Decays at the LHCb Experiment

PhD Seminar 2012

Christian Elsasser

The LHCb Experiment

Experiment dedicated to the search for rare b decays and $\mathcal{CP}$ violation



Pseudorapidity:
$1.9 < \eta < 4.9$
$(\eta = -\log(\tan\theta/2))$

Tracking System
RICH
Calorimetry
Muon system

Theoretical Motivation for $B^0_{(s)} \rightarrow \mu^+\mu^-$

In the Standard Model (SM) the decays $B^0_{(s)} \rightarrow \mu^+\mu^-$ are only allowed via Penguin- and Box-diagrams and in addition helicity suppressed.

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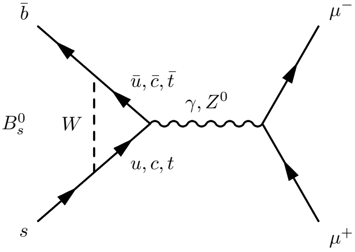

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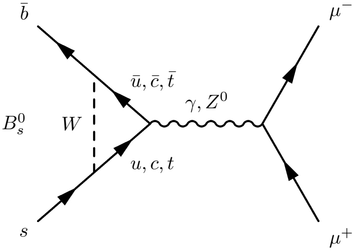

$\Rightarrow$ very small branching fractions predicted by SM

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \cdot 10^{-10}$$

arXiv:1208.0934v1 [hep-ph]

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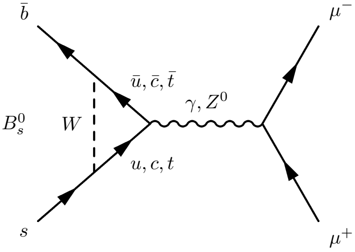

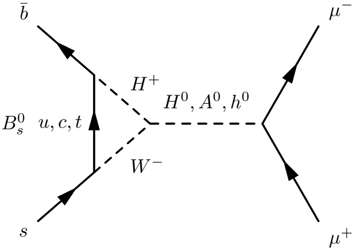

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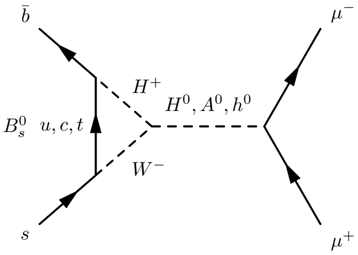
$\Rightarrow$ Measurement of $\mathcal{B}$ tests parameter space of New Physics models.

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) \quad \propto \quad \frac{\tan^6\beta}{M^4_{A^0}}$$



Pre-LHC Aera

CDF

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.3 \cdot 10^{-8} \text{ at 95\% CL with } 3.7\,\text{fb}^{-1}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.6 \cdot 10^{-9} \text{ at 95\% CL with } 3.7\,\text{fb}^{-1}$$

Public CDF note 9892 (2010)

D0

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.1 \cdot 10^{-8} \text{ at 95\% CL with } 6.1\,\text{fb}^{-1}$$

Phys. Lett B 693, 593 (2010)

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$\Rightarrow$ Significant amount of space left to see a larger branching fraction than predicted by the SM

Analysis Strategy at LHCb

Whole data sample collected in 2011 $\Rightarrow \sim 1\,\text{fb}^{-1}$

1. Loose pre-selection and blinding of signal region
2. Separation of signal and background by invariant Dimuon mass and a multivariate classifier
3. Normalization of the branching fraction to branching fractions of well-measured *B* decays
4. Extraction of the branching fraction (or its upper limit) by a binned CL_s method

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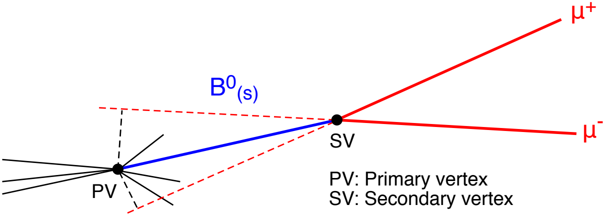
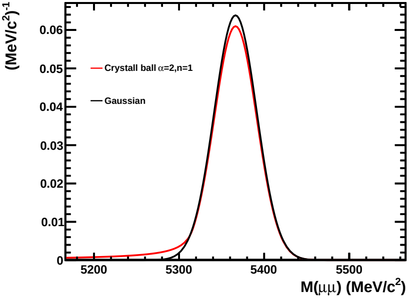
1. Loose Pre-selection and Blinding



- Muon candidates:
  - Track reconstruction quality
  - Impact parameter
  - Closest approach of the two muons
  - p and p_T
  - Particle identification
- $B^0_{(s)}$ candidates:
  - Impact parameter
  - Flight direction
  - Decay vertex quality
  - $\tau_{B^0_{(s)}}$, Flight distance significance
  - Blinding window: $|m_{\mu\mu} - m_{B^0_{(s)}}| < 60\,\mathrm{MeV/c^2}$

2. Signal-Background Separation: Invariant Mass

Distribution of signal described by a Crystal Ball function



Distribution of background described by an exponential function

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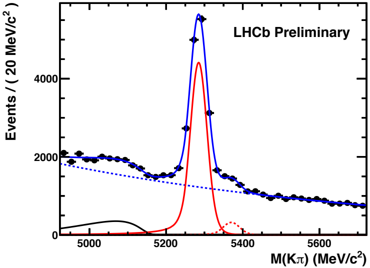
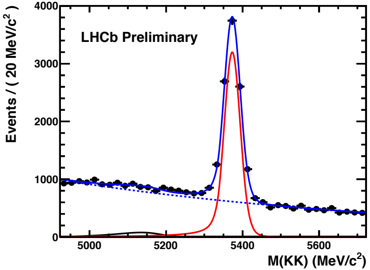


$B^0_{(s)} \to K^+\pi^-$



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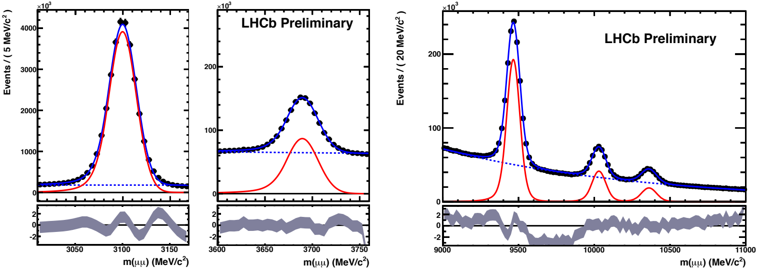

$(J)/\psi(nS) \to \mu^+\mu^-$ $\Upsilon(nS) \to \mu^+\mu^-$

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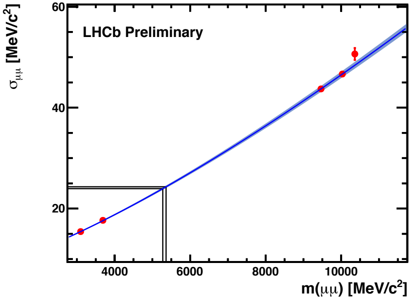

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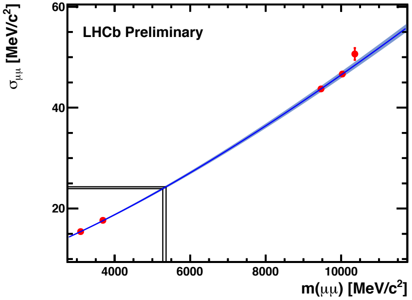
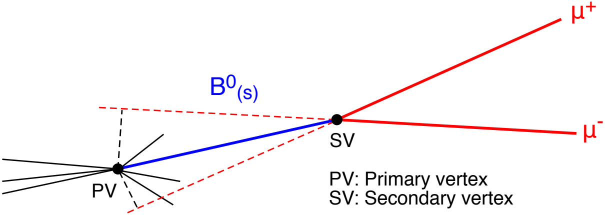


Distribution of background described by an exponential function

2. Signal-Background Separation: MV Classifier

Boosted Decision Tree (BDT) based on topological and kinematical variables and uncorrelated to the invariant mass



Training on $b\bar{b} \to \mu^+\mu^- X$ MC for background and $B^0_{(s)} \to \mu^+\mu^-$ MC for signal

Calibration of signal on $B^0_{(s)} \to h^+h'^-$ events ($h = \pi, K$)

Calibration of background simultaneous with calibration of invariant mass on data side-bands

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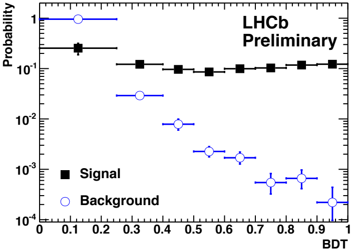

Calibration of signal on $B^0_{(s)} \rightarrow h^+ h'^-$ events ($h = \pi, K$)
Calibration of background simultaneous with calibration of invariant mass on data side-bands

3. Normalization of the Branching Fraction

Three normalization channels:

– $B^{\pm} \to J/\psi(1S)(\to \mu^{+}\mu^{-})K^{\pm}$
– $B_s^0 \to J/\psi(1S)(\to \mu^{+}\mu^{-})\phi(\to K^{+}K^{-})$
– $B^0 \to K^{\pm}\pi^{\mp}$

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$$\alpha_{B^0_{(s)}} = \frac{\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)}{N_{B^0_{(s)}\to\mu^+\mu^-}} = \frac{f_{\text{calib}}}{f_{\text{sig}}} \cdot \frac{\varepsilon^{\text{tot}}_{\text{calib}}}{\varepsilon^{\text{tot}}_{\text{sig}}} \cdot \frac{A_{\text{calib}}}{A_{\text{sig}}} \cdot \frac{\mathcal{B}_{\text{calib}}}{N_{\text{calib}}}$$

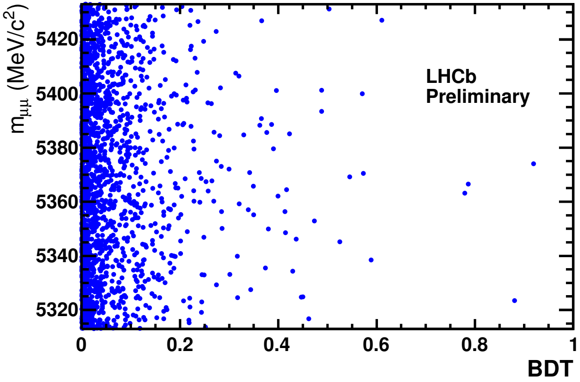
- $f_s/f_{d,u} = 0.268 \pm 0.008$ (stat.) ${}^{+0.022}_{-0.020}$ (syst.)
  Phys. Rev. D **85** (2012) 032008

- ε^{tot}: Combined reconstruction, selection and trigger efficiency

Result: $\alpha_{B_s^0} = (3.19 \pm 0.28) \cdot 10^{-10}$, $\alpha_{B^0} = (8.38 \pm 0.39) \cdot 10^{-11}$

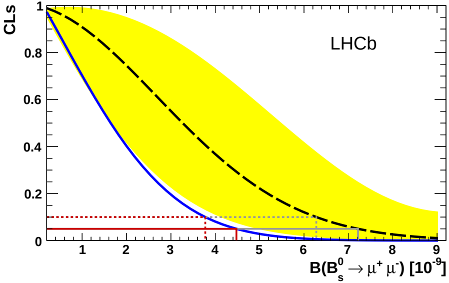
4. Extraction of the Branching Fraction

Invariant Dimuon mass vs BDT of events in B_s^0 mass window



About 10 signal events are expected over the whole BDT range.

Result for $B_s^0 \to \mu^+\mu^-$



Observed CL_s
Expected CL_s
$\pm 1\sigma$ region

	at 90% CL	at 95% CL
Observed limit	$3.8 \cdot 10^{-9}$	$4.5 \cdot 10^{-9}$
Expected limit: Bkg+SM	$6.3 \cdot 10^{-9}$	$7.3 \cdot 10^{-9}$
Expected limit: Bkg only	$2.8 \cdot 10^{-9}$	$3.4 \cdot 10^{-9}$

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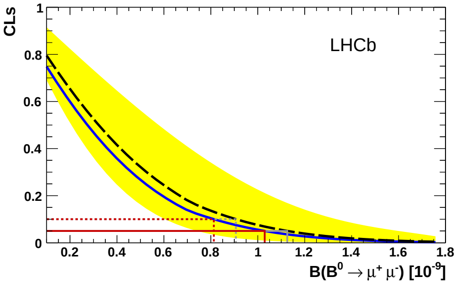

Observed CL_s
Expected CL_s
$\pm 1\sigma$ region

	at 90% CL	at 95% CL
Observed limit	$0.81 \cdot 10^{-9}$	$1.0 \cdot 10^{-9}$
Expected limit: Bkg only	$0.91 \cdot 10^{-9}$	$1.1 \cdot 10^{-9}$

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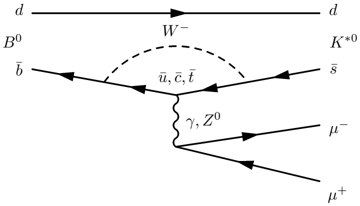

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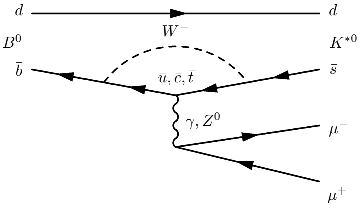

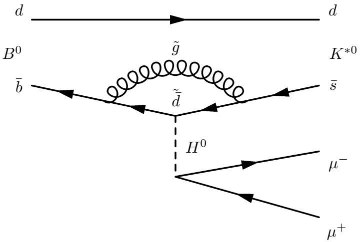

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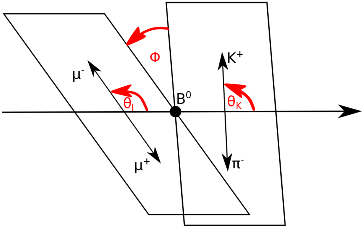

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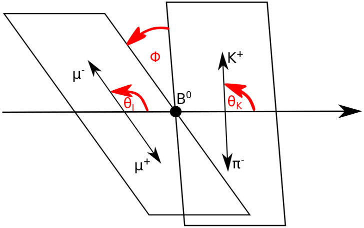

$$q^2 = m^2_{\mu\mu}$$

$$A_{FB}(q^2) = 1 \Big/ \frac{d(\Gamma+\bar{\Gamma})}{dq^2} \left(\int_0^1 d\cos\theta_l \frac{d^2(\Gamma+\bar{\Gamma})}{d\cos\theta_l dq^2} - \int_{-1}^0 d\cos\theta_l \frac{d^2(\Gamma+\bar{\Gamma})}{d\cos\theta_l dq^2} \right)$$

Zero-crossing-point:

q_0^2 s.t. $A_{FB}(q_0^2) = 0$

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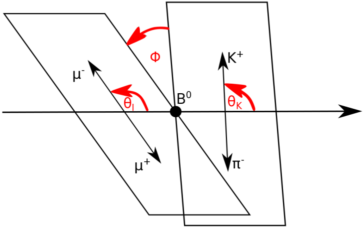

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Zero-crossing-point:

$$q_0^2 \text{ s.t. } A_{FB}(q_0^2) = 0$$

$$q^2_{0,\mathrm{SM}} = (3.97 \pm 0.03(\mathrm{F.F.}) \pm 0.09(\mathrm{S.L.})^{+0.29}_{-0.27}(\mathrm{S.D.}))\ \mathrm{GeV}^2/c^4$$

10.1007 JHEP01(2012) 107

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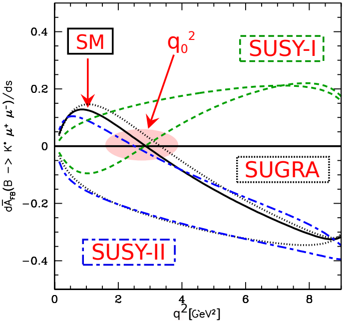

Phys. Rev. D **61** (2000) 074024

Unbinned Counting Method

Selection of signal event with a BDT and veto of decays
$B^0 \to J/\psi(1S)/\psi(2S)K^{*0}$

$$
\begin{aligned}
A_{\mathrm{FB}}(q^2) \quad &= \quad \frac{N_F \cdot PDF_F(q^2) - N_B \cdot PDF_B(q^2)}{N_F \cdot PDF_F(q^2) + N_B \cdot PDF_B(q^2)} \\
N_F : \quad & \quad \text{Number of events with } \cos\theta_l > 0 \\
N_B : \quad & \quad \text{Number of events with } \cos\theta_l < 0 \\
PDF_F : \quad & \quad \text{Distribution of forward events in } q^2 \\
PDF_B : \quad & \quad \text{Distribution of backward events in } q^2
\end{aligned}
$$

Signal PDF in q^2 is a third order Chebychev polynomial.
Background PDF in q^2 is a second order Chebychev polynomial.

Forward Fit

Simultaneous fit to the B^0 candidate mass and q^2 to disentangle residual background and signal for events with $\cos\theta_l > 0$

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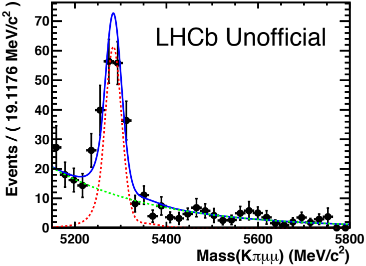

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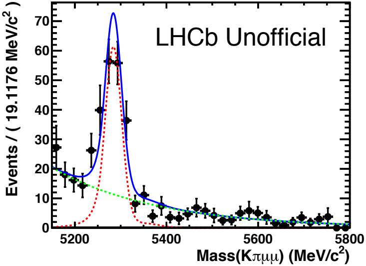

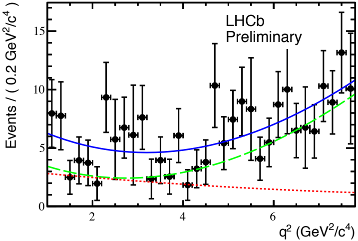

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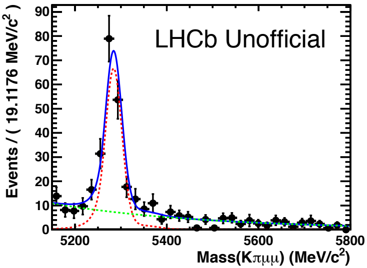

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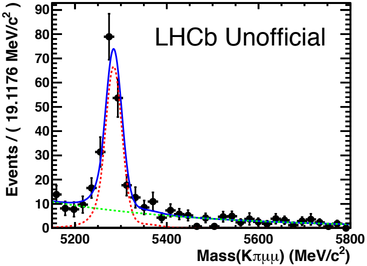
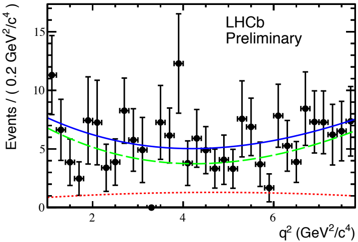
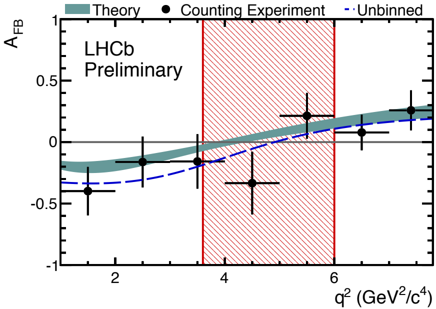




Zero Crossing Point



$$q_0^2 = (4.9^{+1.1}_{-1.3})\,\mathrm{GeV}^2/c^4$$

$$q_{0,\mathrm{SM}}^2 = (3.97 \pm 0.03(\mathrm{F.F.}) \pm 0.09(\mathrm{S.L.})^{+0.29}_{-0.27}(\mathrm{S.D.}))\,\mathrm{GeV}^2/c^4$$

Error is only statistical (determined with Bootstrapping method)

Summary

- Upper limit on $B_s^0 \to \mu^+\mu^-$ which is very close to the Standard Model prediction $\Rightarrow$ not much space left to see signs of New Physics by an enhanced branching fraction
- First measurement of the Zero Crossing Point for $B^0 \to K^{*0}\mu^+\mu^- \Rightarrow$ compatible with Standard Model

- Many other interesting analysis
  - $B_s^0 \to \phi\mu^+\mu^-$
  - $B^\pm \to K^\pm/\pi^\pm\mu^+\mu^-$
  - $B^0 \to K^{*0}\gamma$
  - $B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$

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  - $B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$

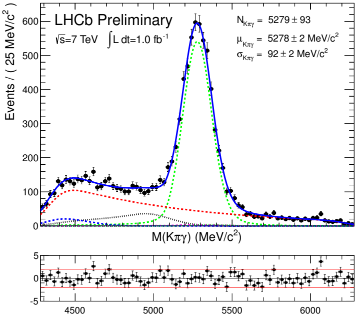
Backup

Backup: Radiative B decays

$$\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^0 \to K^{*0}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^0 \to K^{*0}\gamma)}$$

$$\mathcal{A}_{\mathrm{CP,SM}} = (-6.1 \pm 4.3) \cdot 10^{-3}$$

Phys. Rev. D **72** (2005) 014013



Large enhancement in physics beyond the SM through additional CP violating couplings arXiv:0710.3819 [hep-ph]

Correction of detection asymmetry using $B^0/\bar{B}^0 \to K^{\pm}\pi^{\mp}$ and production asymmetry using $B^0 \to J/\psi K^{*0}$

$$\mathcal{A}_{\mathrm{CP}} = (0.008 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst}))$$

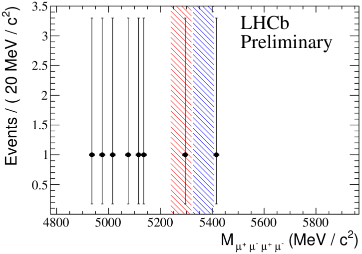
Backup: $B^0_{(s)} \to \mu^+\mu^+\mu^-\mu^-$

$$\mathcal{B}_{\text{SM,non-reso}} \sim 10^{-11} - 10^{-10}$$

Phys. Rev. D **70**, 114028, (2004)

$$\mathcal{B}_{\text{SM,reso}} = (2.3 \pm 0.9) \cdot 10^{-8}$$

$$B^0_s \to J/\psi(\mu\mu)\phi(\mu\mu)$$



Enhancement in physics beyond the SM, especially models including sgoldstinos arXiv:1112.5230 [hep-ph]

Cut based analysis with normalization to $B^0 \to J/\psi K^{*0}$

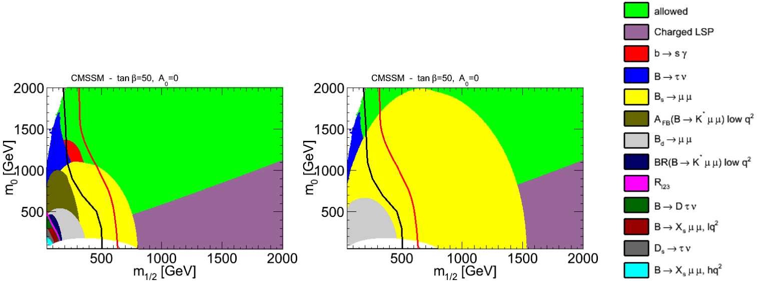
$$\mathcal{B}_{\text{non-reso}}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 1.28 \cdot 10^{-8} \text{ @ 95\% C.L.}$$

$$\mathcal{B}_{\text{non-reso}}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 0.54 \cdot 10^{-8} \text{ @ 95\% C.L.}$$

Backup: Theory Prediction

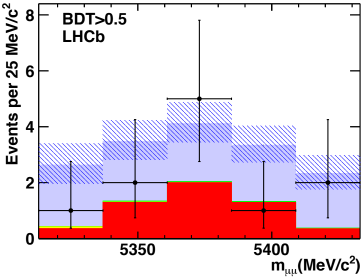
A. Buras & G. Isidori	$(3.23 \pm 0.27) \cdot 10^{-9}$	arXiv:1208.0934v1 [hep-ph]
A. Buras	$(3.2 \pm 0.2) \cdot 10^{-9}$	arXiv:1012.1447v2 [hep-ph]
E. Golowich et al.	$(3.31 \pm 0.21) \cdot 10^{-9}$	arXiv:1102.0009v2 [hep-ph]
K. De Bruyn et al.	$(3.5 \pm 0.2) \cdot 10^{-9}$	arXiv:1204.1737 [hep-ph]
F. Mahmoudi et al.	$(3.53 \pm 0.38) \cdot 10^{-9}$	arXiv:1205.1845v1 [hep-ph]
CKMfitter	$(3.64^{+0.21}_{-0.32}) \cdot 10^{-9}$	ckmfitter.in2p3.fr
UTfit	$(3.54 \pm 0.28) \cdot 10^{-9}$	www.utfit.org

Backup: Restriction on Parameter Space

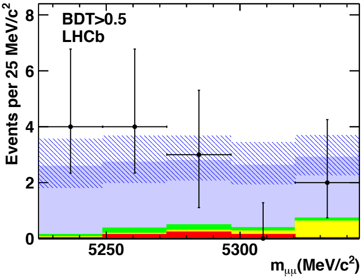


Constraints on m_0 and $m_{1/2}$ at $A_0 = 0$ and $\tan\beta = 50$ by different channels.
Left: data upto 2010; Right: data upto 2011; Yellow: $B_s^0 \to \mu^+\mu^-$,
Black line: CMS exclusion with 1.1 fb^{-1}, Red line: CMS exclusion with 4.4 fb^{-1}
arXiv:1205.3099 [hep-ph]

Backup: Distribution of Signal-like Events



$B_s^0 \to \mu^+\mu^-$



$B^0 \to \mu^+\mu^-$

Signal (SM)

Combinatorial background $b\bar{b} \to \mu^+\mu^- X$ semileptonic

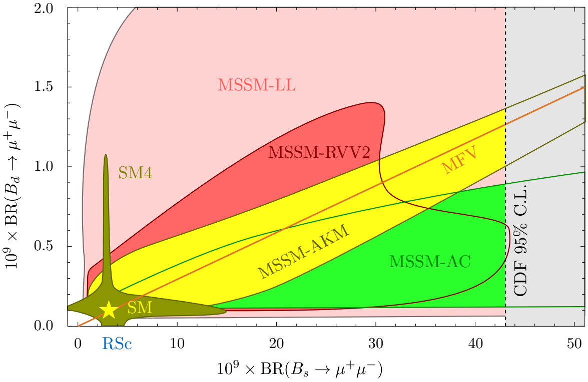
Misidentification from $B^0_{(s)} \to h^+h'^-$

Cross-feed

Hatched area: the uncertainty on the sum of the expected contributions

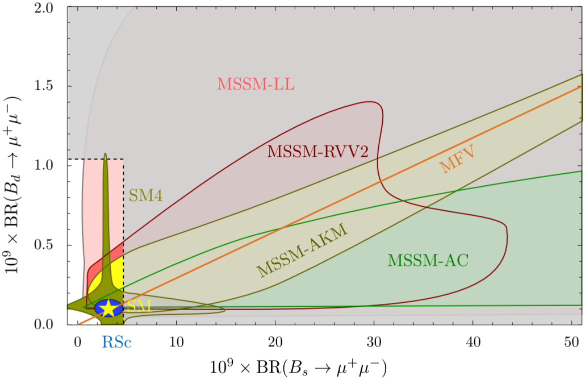
Backup: Implications for Theory 2010

arXiv:1107.0266v1 [hep-ph]



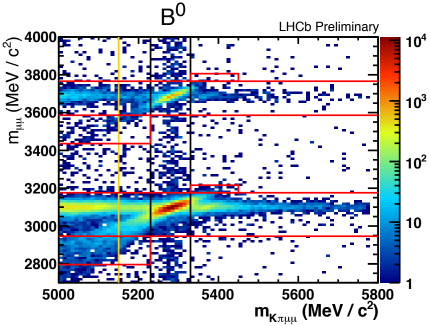
Backup: Implications for Theory 2011

arXiv:1205.6094v1 [hep-ph]



Backup: Event Selection for $B^0 \to K^{*0}\mu^+\mu^-$

After a loose pre-selection a BDT selection based on kinematical, topological and particle-identification variables (trained on $B^0 \to J/\psi K^{*0}$ for signal and side-bands for background) is applied.
(Results based on data sample of 2011 $\to \sim 1\ \mathrm{fb}^{-1}$)



The vetos on charmonium states $J/\psi(1S)$ and $\psi(2S)$ are shown in red.