Searches for Rare Decays at LHCb

Mathieu Perrin-Terrin,
on behalf of the LHCb Collaboration

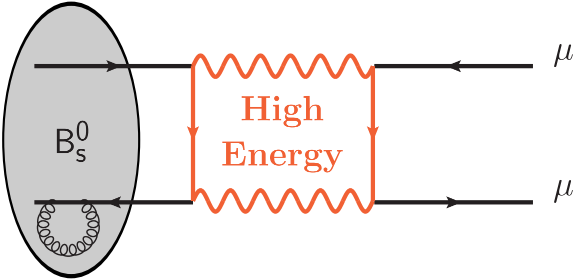
Centre de Physique des Particules de Marseille, France

August 16, 2013

**Meeting of the American Physical Society
Division of Particles and Fields
Santa Cruz, California**

Why Studying Rare Decays?

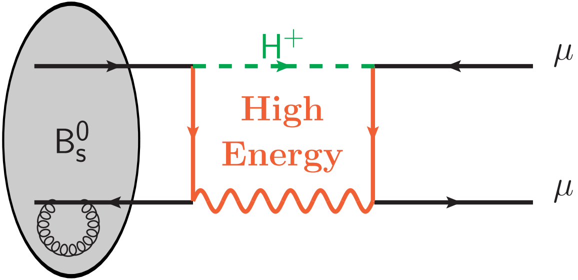
- SM: likely an effective low energy version of a more general theory
- New Physics (NP) could arise at high energy
- Access high energy phenomenology with heavy flavour meson decays:



- Why RARE decays?
  Look for channels where NP could drive the decay amplitude
  The smaller the SM contributions the more visible the NP effects!

Why Studying Rare Decays?

- SM: likely an effective low energy version of a more general theory
- New Physics (NP) could arise at high energy
- Access high energy phenomenology with heavy flavour meson decays:



- Why RARE decays?
  Look for channels where NP could drive the decay amplitude
  The smaller the SM contributions the more visible the NP effects!

The Tour of LHCb Rare Decays

1. $B^0_s \to \mu^+\mu^-$
2. $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
3. $B^0_{(s)} \to e^+\mu^-$
4. $D^0 \to \mu^+\mu^-$
5. $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_s \to \pi^-\mu^+\mu^+$
6. $\tau^- \to \mu^-\mu^-\mu^+$ and $\tau^- \to p\mu^-\mu^-$ (not presented here see [LHCb, 2013b])

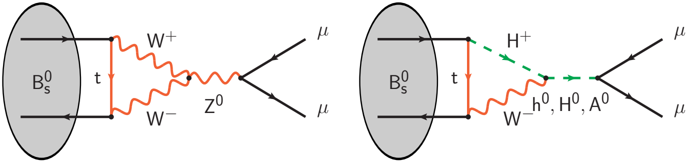
Outline

1. $B^0_s \to \mu^+\mu^-$
2. $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
3. $B^0_{(s)} \to e^+\mu^-$
4. $D^0 \to \mu^+\mu^-$
5. $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_s \to \pi^-\mu^+\mu^+$
6. $\tau^- \to \mu^-\mu^-\mu^+$ and $\tau^- \to p\mu^-\mu^-$ (not presented here see [LHCb, 2013b])

Reference: arXiv:1307.5024 to appear in Physical Review Letter

Motivations

- Rare in SM: FCNC process and helicity suppressed



$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) \propto \left(1 - \frac{4m_\mu^2}{m_B^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + 2\frac{m_\mu}{m_B^2}(C_{10} - C_{10}')\right|^2$$

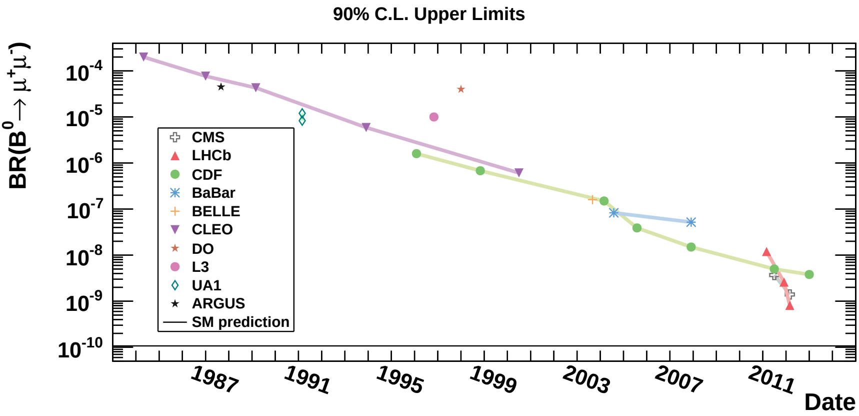
- Sensitive to scalar and pseudo-scalar NP contributions
- Precise predictions (purely leptonic final state)[Buras et al., 2012]:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)^1 \overset{\text{SM}}{=} (3.56 \pm 0.30) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \overset{\text{SM}}{=} (1.07 \pm 0.10) \times 10^{-10}$$

[1] Time integrated $\mathcal{B}$ obtained [Bruyn et al., 2012] with y_s and $\tau_{B_s^0}$ from [HFAG, 2012]

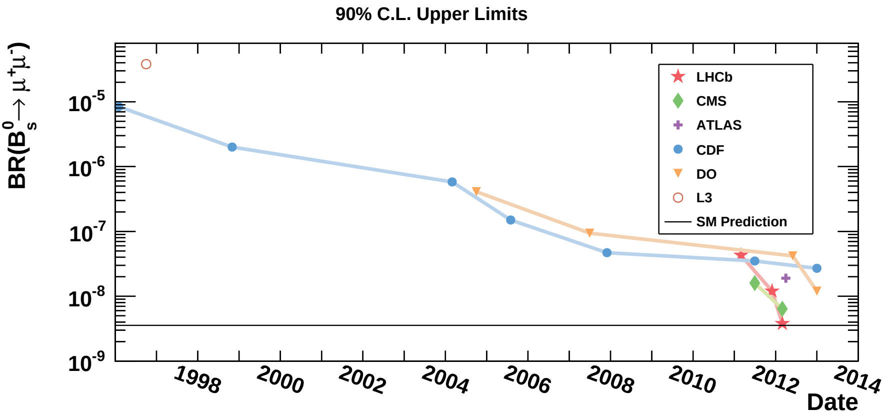
History

- $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to NP has motivated searches since 1984!
- $\mathcal{B}(B^0 \to \mu^+\mu^-)$ upper limit approaching SM prediction



History

- $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to NP has motivated searches since 1984!
- First evidence of $B_s^0 \to \mu^+\mu^-$, significance of 3.5σ [LHCb, 2013a] $(2.0\,\mathrm{fb}^{-1})$



History

- $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to NP has motivated searches since 1984!
- Recent updates by CMS and LHCb ($3.0\,\mathrm{fb}^{-1}$) [LHCb, 2013c, CMS, 2013]

BBC

NEWS SCIENCE & ENVIRONMENT

24 July 2013 Last updated at 13:50 GMT

Ultra-rare decay confirmed in LHC

By Melissa Hogenboom
Science reporter, BBC News

LHCb Analysis Strategy – Overview and Normalisation

Data Set

- $3\,\mathrm{fb}^{-1}$ of integrated luminosity
- Reconstruction improved wrt previous analysis ($2\,\mathrm{fb}^{-1}$ [LHCb, 2013a])
- Analysis designed prior to looking at data in signal mass region

The Goal $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \dfrac{N_{B^0_{(s)}\to\mu^+\mu^-}}{N_{B^0_{(s)}}}$

Normalise to $B^0 \to K^+\pi^-$ **and** $B^+ \to J/\psi K^+$**:**

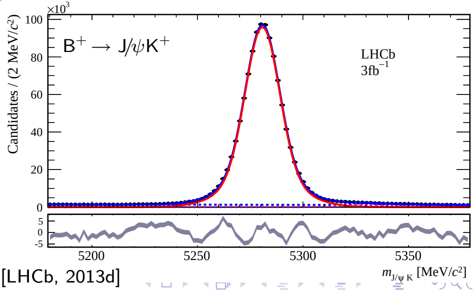
$$N_{B^0_{(s)}} = \frac{N_{cc}}{\mathcal{B}_{cc}} \times \frac{1}{\epsilon_{cc}} \times \frac{f_s}{f_{cc}}$$

$f_s/f_{d,u} = N_{B^0_s}/N_{B^{0(+)}}$:

main analysis systematics

new $\mathcal{B}(D_s^- \to K^+K^-\pi^-)$ and $\tau_{B^0_s}$

$f_s/f_{d,u}$ error reduced from 7.8% to 5.8% [LHCb, 2013d]



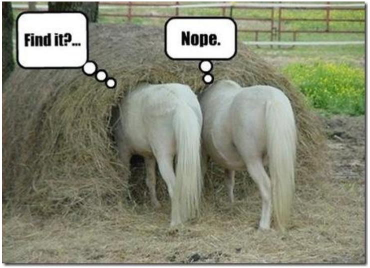
LHCb Analysis Strategy

$N_{B^0_{(s)}\to\mu^+\mu^-}$: A Needle in a Haystack

- $\sim 40\ B_s^0 \to \mu^+\mu^-$ evts (SM)
- Huge Combinatorial background
- Partially reconstructed and mis-id:

$B^0_{(s)} \to h^+h'^-$ $\quad B_s^0 \to K^-\mu^+\nu_\mu$ $\quad B^{0,+} \to \pi^{0,+}\mu^+\mu^-$

$\Lambda_b \to p\mu^-\nu_\mu$ $\quad B^0 \to \pi^-\mu^+\nu_\mu$ $\quad B_c^+ \to J/\psi(\mu\mu)\mu^+\nu_\mu$



Extract Signal From Background

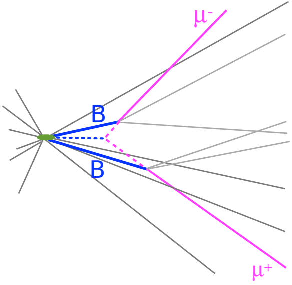
- Loose event selection then classification in the plane: $m_{\mu\mu}$ $\times$ Boosted Decision Tree✠ based on geometry and kinematics
- Both classifier PDFs obtained with data driven methods (Bkg PDF✠)

Upper Limits: $\mathrm{CL_s}$

$\mathcal{B}$ Measurements: Simultaneous Fit to $m_{\mu\mu}$ in all BDT Ranges

LHCb Analysis Strategy

$N_{B^0_{(s)}\to\mu^+\mu^-}$: A Needle in a Haystack



- $\sim 40\ B_s^0 \to \mu^+\mu^-$ evts (SM)
- Huge Combinatorial background
- Partially reconstructed and mis-id:

$B^0_{(s)} \to h^+h'^-$	$B_s^0 \to K^-\mu^+\nu_\mu$	$B^{0,+} \to \pi^{0,+}\mu^+\mu^-$
$\Lambda_b \to p\mu^-\nu_\mu$	$B^0 \to \pi^-\mu^+\nu_\mu$	$B_c^+ \to J/\psi(\mu\mu)\mu^+\nu_\mu$

Extract Signal From Background

- Loose event selection then classification in the plane:
  $m_{\mu\mu}$ × Boosted Decision Tree✠ based on geometry and kinematics
- Both classifier PDFs obtained with data driven methods (Bkg PDF✠)

Upper Limits: $\mathrm{CL_s}$

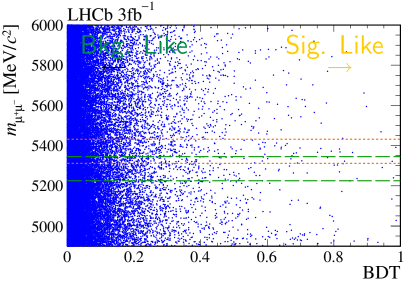
$\mathcal{B}$ Measurements: Simultaneous Fit to $m_{\mu\mu}$ in all BDT Ranges

LHCb Analysis Strategy

$N_{B^0_{(s)}\to\mu^+\mu^-}$: A Needle in a Haystack

- $\sim 40\ B_s^0 \to \mu^+\mu^-$ evts (SM)
- Huge Combinatorial background
- Partially reconstructed and mis-id:

$B^0_{(s)} \to h^+h'^-$	$B_s^0 \to K^-\mu^+\nu_\mu$	$B^{0,+} \to \pi^{0,+}\mu^+\mu^-$
$\Lambda_b \to p\mu^-\nu_\mu$	$B^0 \to \pi^-\mu^+\nu_\mu$	$B_c^+ \to J/\psi(\mu\mu)\mu^+\nu_\mu$



Extract Signal From Background

- Loose event selection then classification in the plane: $m_{\mu\mu}\ \times$ **B**oosted **D**ecision **T**ree✠ based on geometry and kinematics
- Both classifier PDFs obtained with data driven methods (Bkg PDF✠)

Upper Limits: $\mathrm{CL_s}$

$\mathcal{B}$ Measurements: Simultaneous Fit to $m_{\mu\mu}$ in all BDT Ranges

Results

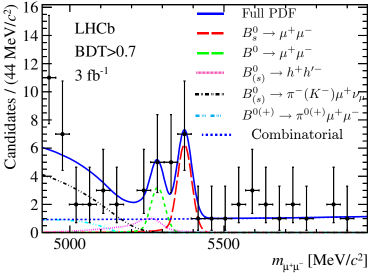
$\mathcal{B}$ measurements

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0} st\ ^{+0.3}_{-0.1} sy) \times 10^{-9}$$

Significance : 4.0 (*Expected* 5.0)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1} st\ ^{+0.6}_{-0.4} sy) \times 10^{-10}$$

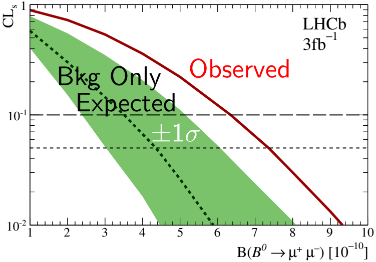
Significance : 2.0



Upper Limit

No compelling $B^0 \to \mu^+\mu^-$ signal hint

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95%C.L.



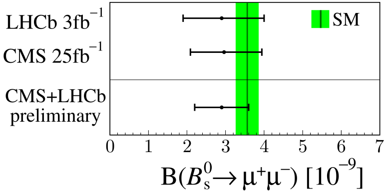
LHC Wide [CMS and LHCb, 2013]

New Results by CMS [CMS, 2013]

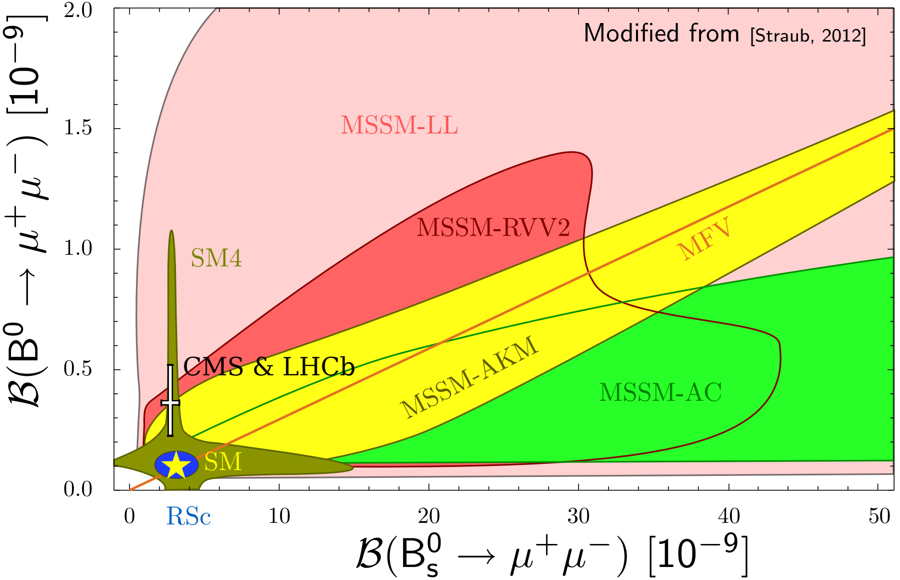
- $25\,\mathrm{fb}^{-1}$ of integrated luminosity
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ Significance $= 4.3\sigma$ (4.8 Expected)
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ Significance $= 2.0\sigma$

Weighed B Average (not Likelihood Combination)

			Significance
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\overset{\mathrm{LHC}}{=}$	$(2.9 \pm 0.7) \times 10^{-9}$	$> 5\sigma$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	$\overset{\mathrm{LHC}}{=}$	$(3.6^{+1.6}_{-1.4}) \times 10^{-10}$	$> 3\sigma$



Implications



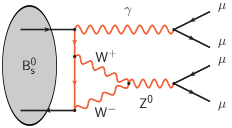
Outline

1. $B^0_s \to \mu^+\mu^-$
2. $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
3. $B^0_{(s)} \to e^+\mu^-$
4. $D^0 \to \mu^+\mu^-$
5. $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_s \to \pi^-\mu^+\mu^+$
6. $\tau^- \to \mu^-\mu^-\mu^+$ and $\tau^- \to p\mu^-\mu^-$ (not presented here see [LHCb, 2013b])

Reference: Physical Review Letter 110 (2013) 211801

Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ with $\int \mathcal{L} = 1.0\,\mathrm{fb}^{-1}$

Motivations



- Resonant SM mode $\mathcal{B}(B^0_s \to J/\psi\phi) = (2.3 \pm 0.8) \times 10^{-8}$
- Non-resonant SM mode $\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 10^{-10}$
- Could be enhanced by physics beyond SM
  c.f. HyperCP anomaly [HyperCP, 2005], MSSM [Demidov and Gorbunov, 2012]

Strategy: a Cut and Count Analysis

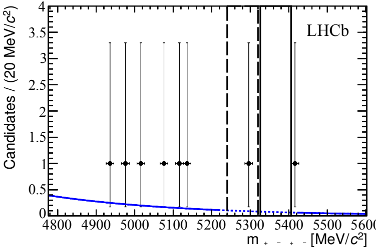
- Selection optimised on resonant candidates
- Normalisation to $B^0_s \to J/\psi K^{*0}$

Upper Limits ($\mathrm{CL_s}$)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 1.6 \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6 \times 10^{-9}$$

World Best!

Observed Data

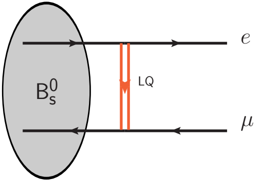


Outline

1. $B^0_s \to \mu^+\mu^-$
2. $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
3. $B^0_{(s)} \to e^+\mu^-$
4. $D^0 \to \mu^+\mu^-$
5. $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_s \to \pi^-\mu^+\mu^+$
6. $\tau^- \to \mu^-\mu^-\mu^+$ and $\tau^- \to p\mu^-\mu^-$ (not presented here see [LHCb, 2013b])

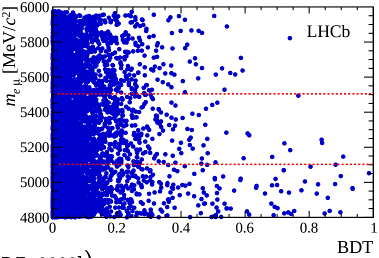
Reference: arXiv:1307.4889 submitted to Physical Review Letter

Searches for $B^0_{(s)} \to e^+\mu^-$ with $\int \mathcal{L} = 1.0\,\mathrm{fb}^{-1}$



Motivations

- Lepton Flavour Violation forbidden in SM
- Possible in SM extensions:
  Pati-Salam leptoqarks [Pati and Salam, 1974],
  SUSY [Diaz et al., 2005]
  Heavy singlet Dirac neutrino [Ilakovac, 2000]



Analysis based on $B^0_s \to \mu^+\mu^-$

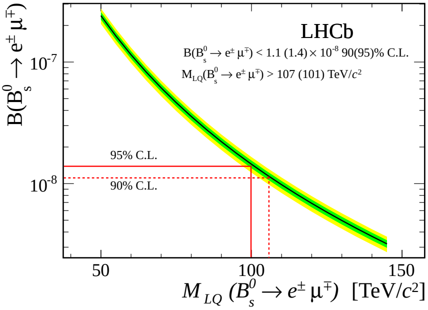
$m_{e\mu} \times$BDT classification
Normalisation $B^0 \to K^+\pi^-$

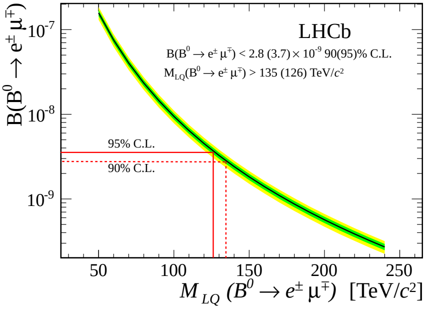
Results: 95% C.L. upper limits

		LHCb	Current ([CDF, 2009])
$\mathcal{B}(B^0_s \to e^+\mu^-)$	$<$	14×10^{-9}	206×10^{-9}
$\mathcal{B}(B^0 \to e^+\mu^-)$	$<$	3.7×10^{-9}	79×10^{-9}

Implications: Leptoquarks Mass Lower Bounds

Convert upper limits into lepto-quark (LQ) mass bounds with formula by [Valencia and Willenbrock, 1994]





		LHCb	Current ([CDF, 2009])
$m_{LQ}(B^0_s \to e^+\mu^-)$	$>$	101 TeV	44.9 TeV
$m_{LQ}(B^0 \to e^+\mu^-)$	$>$	126 TeV	53.6 TeV

Outline

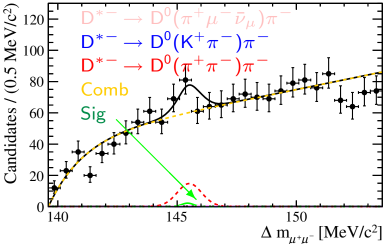
1. $B_s^0 \to \mu^+\mu^-$
2. $B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$
3. $B_{(s)}^0 \to e^+\mu^-$
4. $D^0 \to \mu^+\mu^-$
5. $D_{(s)}^+ \to \pi^+\mu^+\mu^-$ and $D_s^+ \to \pi^-\mu^+\mu^+$
6. $\tau^- \to \mu^-\mu^-\mu^+$ and $\tau^- \to p\mu^-\mu^-$ (not presented here see [LHCb, 2013b])

Reference: Physics Letter B725 (2013) 15-24

Search for $D^0 \to \mu^+\mu^-$ with $\int \mathcal{L} = 0.9\,\text{fb}^{-1}$

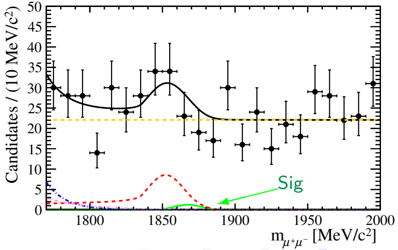
Motivations

- FCNC helicity suppressed in SM: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-13}$ [Burdman et al., 2002]
- Possible enhancement in SM extensions [Burdman and Shipsey, 2003, Paul et al., 2012]
- Probe u-type dynamics: complementary to B and K rare decays



Analysis:

- D^0 from $D^{*-} \to D^0\pi^-$
- Bkg: combinatorial + misidentified
- Normalise to $D^{*-} \to D^0(\pi^+\pi^-)\pi^-$
- Fit to $\Delta m = m_{D^{*-}} - m_{D^0}$ and $m_{\mu\mu}$



Results: 95% C.L. Upper Limit

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

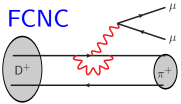
Outline

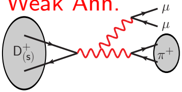
Reference: Physics Letter B724 (2013) 203-212

Searches for $D^+_{(s)} \to \pi^+\mu^+\mu^\mp$ with $\int \mathcal{L} = 1.0\,\mathrm{fb}^{-1}$

Four Decay Modes to Look for NP

- Same Sign μ: $D^+ \to \pi^-\mu^+\mu^+$ and $D^+_s \to \pi^-\mu^+\mu^+$
  - Lepton Number Violation
  - Forbidden in SM, possible in NP (e.g. Majorana ν)
- Opposite Sign μ: $D^+ \to \pi^+\mu^+\mu^-$ and $D^+_s \to \pi^+\mu^+\mu^-$
  - in SM through resonances $(\eta, \rho/\omega, \phi)$
  - and FCNC and Weak Annihilation $\mathcal{B} \sim 10^{-9}$

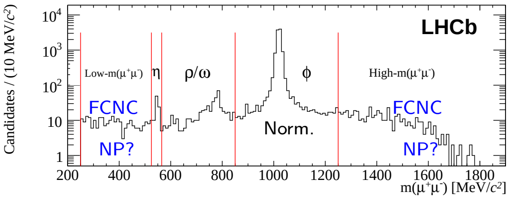




Analysis Strategy

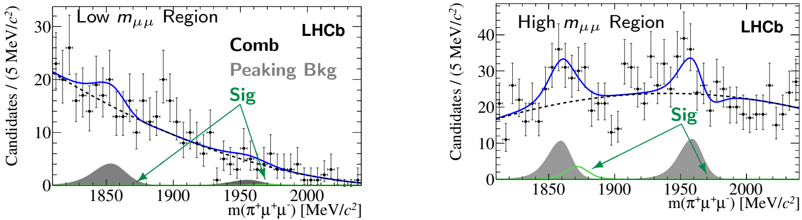
- MVA Selection
- SS: Fit $m_{\pi\mu\mu}$ in $m_{\mu\pi}$ ranges
  OS: Fit $m_{\pi\mu\mu}$ in $m_{\mu\mu}$ ranges
- Normalisation:
  $D^+_{(s)} \to \pi^+\phi(\mu\mu)$

$m_{\mu\mu}$ ranges (OS)



Results: 95% C.L. upper limits

Opposite Sign μ



$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 8.3 \times 10^{-8}$$

$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.8 \times 10^{-7}$$

Same Sign μ

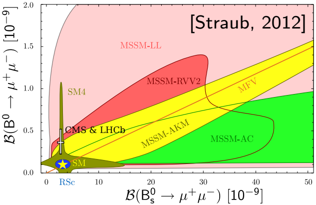
$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 2.5 \times 10^{-8}$$

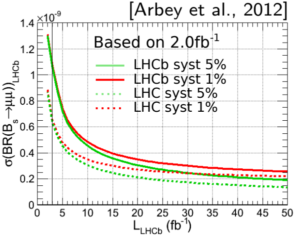
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 1.4 \times 10^{-7}$$

Previous limits [BaBar, 2011] divided by 50!

Conclusions and Prospects

- LHCb (and CMS) confirmed the first evidence of $B^0_s \to \mu^+\mu^-$
- Stringent constraints on $B^0 \to \mu^+\mu^-$





Prospects:

- Combined Likelihood: $B^0_s \to \mu^+\mu^-$ $(> 5\sigma)$, $B^0 \to \mu^+\mu^-(> 3\sigma)$
- New Observables: $\mathcal{B}(B^0_s \to \mu^+\mu^-)/\mathcal{B}(B^0 \to \mu^+\mu^-)$, $\mathcal{A}_{\Delta\Gamma}$ [Buras et al., 2013]
- More statistics in 2015

- World best upper limits on: $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$, $D^0 \to \mu^+\mu^-$, $D^+_{(s)} \to \pi^+\mu^+\mu^-$

Prospects: More data ready to be analysed ($3\,\text{fb}^{-1}$ in total)

$B_s^0 \to \mu^+\mu^-$ in New Physics [Straub, 2012]

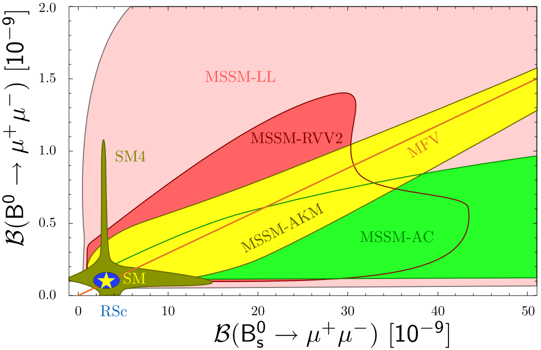


Figure: Prediction for the branching fractions of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in Minimal Flavour Violation models (MFV), the SM with a fourth generation (SM4), the Randall-Sundrum model (RSc) with custodial protection [Blanke et al., 2009], and four Minimal SUSY favour models (MSSM), Agashe and Carone (AC) [Agashe and Carone, 2003], Ross, Velasco-Sevilla and Vives (RVV2) [Ross et al., 2004], Antusch, King and Malinsky (AKM10) [Antusch et al., 2008] and a model with left-handed currents only (LL11) [Hall and Murayama, 1995].

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

- $B_{s,L}^0$ and $B_{s,H}^0$ have different decay widths [HFAG, 2012]:

$$y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} \overset{\text{meas.}}{=} 0.0615 \pm 0.0085$$

- Time dependent decay rate in the mass eigenstates basis:

$$\begin{aligned}\Gamma\left(B_s(t) \to \mu^+\mu^-\right) &= R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t} \\ &= (R_H + R_L) e^{-\Gamma_s t}\left[\cosh \frac{y_s t}{\tau_{B_s^0}} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{y_s t}{\tau_{B_s^0}}\right]\end{aligned}$$

- Decay rate is model dependent, parametrised by $\mathcal{A}_{\Delta\Gamma}$:

$$\mathcal{A}_{\Delta\Gamma} = \frac{R_H - R_L}{R_H + R_L} \overset{\text{SM}}{=} 1.0.$$

Time Integrated and CP average $\mathcal{B}$

Prediction: Inital CP average branching ratio, $\mathcal{B}^0$

$$\mathcal{B}^0(\mathrm{B_s^0} \to \mu^+\mu^-) = \frac{\tau_{\mathrm{B_s^0}}}{2}\Gamma\left(\mathrm{B_s(t)} \to \mu^+\mu^-\right)|_{t=0}$$

$$\overset{\mathrm{SM}}{=} (3.35 \pm 0.28) \times 10^{-9}$$

[Buras et al., 2012] update with $\tau_{\mathrm{B_s^0}}$ from [HFAG, 2012]

Measurement: Time Integrated branching ratio: $\langle\mathcal{B}\rangle$

$$\langle\mathcal{B}(\mathrm{B_s} \to \mu^+\mu^-)\rangle = \frac{1}{2}\int_0^\infty \Gamma\left(\mathrm{B_s(t)} \to \mu^+\mu^-\right)\mathrm{d}t$$

$$= \mathcal{B}^0(\mathrm{B_s} \to \mu^+\mu^-) \times \frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}$$

$$\overset{\mathrm{SM}}{=} \frac{\mathcal{B}^0(\mathrm{B_s} \to \mu^+\mu^-)}{1 - y_s} = (3.56 \pm 0.30) \times 10^{-9}$$

with y_s and $\tau_{\mathrm{B_s^0}}$ from [HFAG, 2012] and accounting for their experimental correlation

New Observable: $\mathcal{A}_{\Delta\Gamma}$

- Time-integrated $\mathcal{B}$ is model dep.:

$$\mathcal{B} = \mathcal{B}^0(B_s \to \mu^+\mu^-) \times \frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}$$

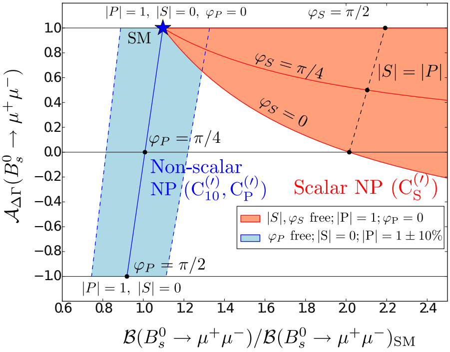
- Measuring $\mathcal{B}$ is not sufficient
- $\mathcal{A}_{\Delta\Gamma}$ is also needed!
- Effective $B_s^0 \to \mu^+\mu^-$ lifetime,

$$\tau_f = \frac{\int < \Gamma(B(t) \to f) > t\,dt}{\int < \Gamma(B(t) \to f) > dt}$$

allows to solve the $\mathcal{A}_{\Delta\Gamma}$ dependency:

$$\mathcal{B} \quad = \quad \mathcal{B}^0(B_s \to \mu^+\mu^-) \times \left(2 - (1 - y_s^2)\frac{\tau_f}{\tau_{B_s^0}}\right) \qquad (1)$$

[Bruyn et al., 2012] see also [Buras et al., 2013]



Solving the $\mathcal{A}_{\Delta\Gamma}$ Dependency

Measuring $\mathcal{A}_{\Delta\Gamma}$

- $B_s^0 \to K^+K^-$ effective lifetime measured in LHCb with 522 signal evt with an 7% precision [LHCb, 2012]
- accessible for $B_s^0 \to \mu^+\mu^-$ only at the upgrade or needs clever idea

A more complex situation: experimental results are model dependent

- BDT and selection depends on the lifetime
- hence time integrated efficiencies,

$$\epsilon = \frac{\int_0^\infty \Gamma(B_s^0(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\epsilon(t)\mathrm{d}t}{\int_0^\infty \Gamma(B_s^0(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\mathrm{d}t}$$

  and BDT PDF depend on $\mathcal{A}_{\Delta\Gamma}$!
- near future, provide $\mathcal{B}$ as a functin of $\mathcal{A}_{\Delta\Gamma}$

New Observable: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)/\mathcal{B}(B^0 \to \mu^+\mu^-)$

Sensitivity to New Physics

- Precise prediction in SM, MFV, and U(2)^3 flavour sym. [Buras, 2003]:

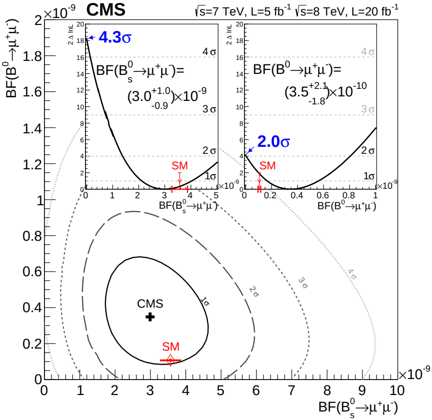
$$\frac{\mathcal{B}(B^0 \to \ell^+\ell^-)}{\mathcal{B}(B_s^0 \to \ell^+\ell^-)} = \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{m_{B^0}}{m_{B_s^0}} \frac{F_{B^0}}{F_{B_s^0}} \left| \frac{V_{td}}{V_{ts}} \right|^2$$

- Cannot be deduced by simply taking the ratio of:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \stackrel{\text{LHCb}}{=} (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\text{LHCb}}{=} (3.7^{+2.5}_{-2.1}) \times 10^{-10}$$

as these two measurements are correlated!

- Ratio will be provided by LHCb.



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

- BDT training and optimisation/variable choice done with simulated data
- MC signal and MC $b\bar{b} \to \mu\mu X$ (equivalent to 5.5 fb^{-1})
- 12 variables used (9 in previous analysis):

B variables:

- proper time
- impact parameter (IP)
- transverse momentum
- isolation [CDF, 2005]: $\frac{p_{T,B}}{p_{T,B}+\sum_{track} p_T}$
- angle between p_B and p_{thurst} ✠
- angle between p_{μ^+} and p_{thurst} in in B rest frame✠

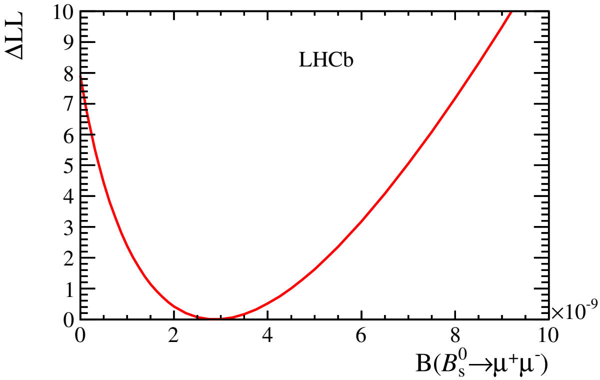
μ variables:

- min. IP significance
- distance of closest approach
- isolation
- polarisation angle[2]
- $|\eta_{\mu^+} - \eta_{\mu^-}|$ ✠
- $|\varphi_{\mu^+} - \varphi_{\mu^-}|$ ✠

p_{thurst} is the sum of momenta of all the long tracks coming from the B PV and excluding those coming from long lived particle

[2] angle between the muon momentum in the B rest frame and the vector perpendicular to the B momentum and the beam axis

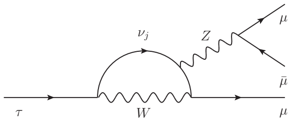
$B^0_{(s)} \to \mu^+\mu^-$ Profile Likelihood



Motivation and Strategy

Motivation

- Lepton Flavour Violation
- $\tau^- \to \mu^-\mu^-\mu^+$ is very suppressed in SM
- Could be enhanced by physics beyond SM



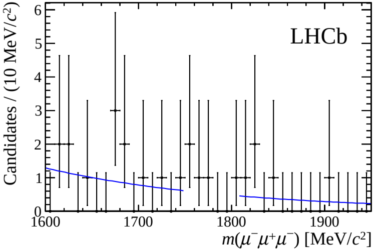
Strategy very similar to $B_s^0 \to \mu^+\mu^-$

- Loose selection
- Event classification in a **3D space**:
  - Invariant mass $m_{\mu\mu\mu}$
  - Topological MVA
  - Particle identification (PID) MVA
- Background: Combinatorial only
  $D^+ \to K^-\pi^+\pi^+$: remove by PID
  $D_s^+ \to \eta(\mu\mu\gamma)\mu^+\nu_\mu^+$: remove by mass resolution
- Normalisation to $D_s^- \to \phi(\mu^+\mu^-)\pi^-$

Results

- Upper limits 95 (90)% C.L.extracted using the $\mathrm{CL_s}$ method

$$\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+) < 8.3\ (10.2) \times 10^{-8}$$



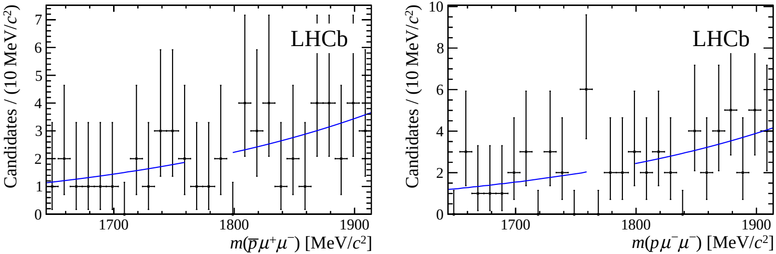
- Results comparable with Belle [Belle, 2010]
$\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+) < 2.1 \times 10^{-8}$ at 90% C.L.

$\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \overline{p}\mu^-\mu^+$

- NP enter differently in each mode
- Analysis similar to $\tau^- \to \mu^-\mu^-\mu^+$
- World first results (95% C.L. upper limits):

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 5.4 \times 10^{-7}$$

$$\mathcal{B}(\tau^- \to \overline{p}\mu^-\mu^+) < 4.6 \times 10^{-7}$$



[Agashe and Carone, 2003] Agashe, K. and Carone, C. D. (2003).
Supersymmetric flavor models and the $B \to \phi K^0_S$ anomaly.
Physical Review, D68:035017.

[Antusch et al., 2008] Antusch, S., King, S. F., and Malinsky, M. (2008).
Solving the SUSY Flavour and CP Problems with SU(3) Family Symmetry.
Journal of High Energy Physics, 0806:068.

[Arbey et al., 2012] Arbey, A., Battaglia, M., Mahmoudi, F., and Santos, D. M. (2012).
Supersymmetry confronts $B^0_s \to \mu^+\mu^-$: Present and future status.

[BaBar, 2011] BaBar(2011).
Searches for Rare or Forbidden Semileptonic Charm Decays.
Physical Review, D84:072006.

[Belle, 2010] Belle(2010).
Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced $\tau^+\tau^-$ Pairs.
Physics Letter, B687:139–143.

[Blanke et al., 2009] Blanke, M., Buras, A. J., Duling, B., Gemmler, K., and Gori, S. (2009).

[LHCb, 2013b])

Rare K and B Decays in a Warped Extra Dimension with Custodial Protection.
Journal of High Energy Physics, 0903:108.

[Bruyn et al., 2012] Bruyn, K. D., Fleischer, R., Knegjens, R., Koppenburg, P., Merk, M., et al. (2012).
Probing New Physics via the $B_s^0 \to \mu^+\mu^-$ Effective Lifetime.
Physical Review Letter, 109:041801.

[Buras et al., 2012] Buras, A., Girrbach, J., Guadagnoli, D., and Isidori, G. (2012).
On the Standard Model prediction for $B_s^0 \to \mu^+\mu^-$.
European Physical Journal, C72:2172.

[Buras, 2003] Buras, A. J. (2003).
Minimal flavor violation.
Acta Physica Polonica, B34:5615–5668.

[Buras et al., 2013] Buras, A. J., Fleischer, R., Girrbach, J., and Knegjens, R. (2013).
Probing New Physics with the $B_s^0 \to \mu^+\mu^-$ Time-Dependent Rate.
Journal of High Energy Physics, 1307:77.

[LHCb, 2013b])

[Burdman et al., 2002] Burdman, G., Golowich, E., Hewett, J. L., and Pakvasa, S. (2002).
Rare charm decays in the standard model and beyond.
Physical Review, D66:014009.

[Burdman and Shipsey, 2003] Burdman, G. and Shipsey, I. (2003).
D^0-$\overline{D}^0$mixing and rare charm decays.
Annual Review of Nuclear and Particle Science, pages 431–499.

[CDF, 2005] CDF(2005).
Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays in $p\bar{p}$ collisions with CDF II.
Physical Review Letter, 95:221805.

[CDF, 2009] CDF(2009).
Search for the Decays $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ in CDF Run II.
Physical Review Letter, 102:201801.

[CMS, 2013] CMS(2013).
Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ with the CMS Experiment.

[CMS and LHCb, 2013] CMS and LHCb(2013).

[LHCb, 2013b])
Combination of results on the rare decays $B^0_{(s)} \to \mu^+\mu^-$ from the CMS and LHCb experiments.
Technical Report CERN-LHCb-CONF-2013-012, CERN, Geneva.

[Demidov and Gorbunov, 2012] Demidov, S. and Gorbunov, D. (2012).
Flavor violating processes with sgoldstino pair production.
Physical Review, D85:077701.

[Diaz et al., 2005] Diaz, R. A., Martinez, R., and Sandoval, C. E. (2005).
Flavor changing neutral currents from lepton and B decays in the two Higgs doublet model.
European Physical Journal, C41:305–310.

[Hall and Murayama, 1995] Hall, L. J. and Murayama, H. (1995).
A Geometry of the generations.
Physical Review Letter, 75:3985–3988.

[HFAG, 2012] HFAG(2012).
Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012.

[HyperCP, 2005] HyperCP(2005).
Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$.
Physical Review Letter, 94(2):021801.

[Ilakovac, 2000] Ilakovac, A. (2000).
Lepton flavor violation in the standard model extended by heavy singlet Dirac neutrinos.
Physical Review, D62:036010.

[LHCb, 2012] LHCb(2012).
Measurement of the effective $B_s^0 \to K^+K^-$ lifetime.
Physics Letter, B707:349–356.

[LHCb, 2013a] LHCb(2013a).
First evidence for the decay $B_s^0 \to \mu^+\mu^-$.
Physical Review Letter, 110:021801.

[LHCb, 2013b] LHCb(2013b).
Searches for violation of lepton flavour and baryon number in tau lepton decays at LHCb.
Physics Letter, B724:36–45.

[LHCb, 2013c] LHCb(2013c).
Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ decays at the LHCb experiment.

[LHCb, 2013d] LHCb(2013d).

Updated average f_s/f_d b-hadron production fraction ratio for 7 TeV pp collisions.
Technical Report LHCb-CONF-2013-011, CERN, Geneva.

[Pati and Salam, 1974] Pati, J. C. and Salam, A. (1974).
Lepton Number as the Fourth Color.
Physical Review, D10:275–289.

[Paul et al., 2012] Paul, A., de La Puente, A., and Bigi, I. I. (2012).
Manifestations of Warped Extra Dimension in Rare Charm Decays and Asymmetries.

[Ross et al., 2004] Ross, G. G., Velasco-Sevilla, L., and Vives, O. (2004).
Spontaneous CP violation and nonAbelian family symmetry in SUSY.
Nuclear Physics, B692:50–82.

[Straub, 2012] Straub, D. M. (2012).
Overview of Constraints on New Physics in Rare B Decays.

[Valencia and Willenbrock, 1994] Valencia, G. and Willenbrock, S. (1994).
Quark - lepton unification and rare meson decays.
Physical Review, D50:6843–6848.