Very rare decays at LHCb

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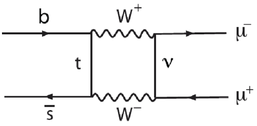
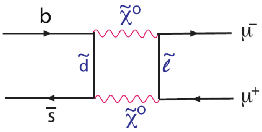
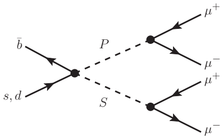
1. $B^0_{d,s} \to \mu^+\mu^-$
2. $D^0 \to \mu^+\mu^-$
3. $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$

Introduction

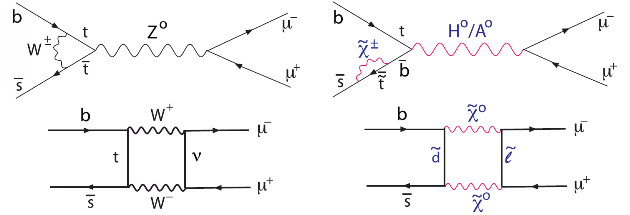






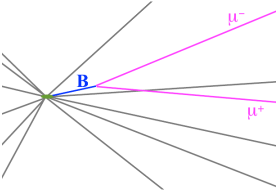
- $B^0_{d,s} \to \mu^+\mu^-, D^0 \to \mu^+\mu^-$ and $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$: Flavour Changing Neutral Current (FCNC) decays
- Forbidden at tree level in the SM $\to$ sensitive to New Physics (NP) diagrams
  - $B^0_{d,s} \to \mu^+\mu^-, D^0 \to \mu^+\mu^-$: Indirectly probe energy scales greater than $\sqrt{s}$ (due to new particles in loop diagrams)
  - $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$: Probes novel four-prong flavour-violating vertices
- Two approaches to interpret rare decay results:
  - Model dependent: Constrain specific models, such as SUSY
  - Model independent: Constrain generic coupling types via Wilson coefficients

$B^0_{d,s} \to \mu^+\mu^-$: Theoretical overview

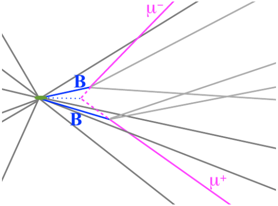


- Precise SM branching fractions (arXiv:1208.0934):
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$
- Sensitive to new scalar, pseudoscalar, axial-vector particles in loop
  - Sensitive to SUSY particles

Experimental overview



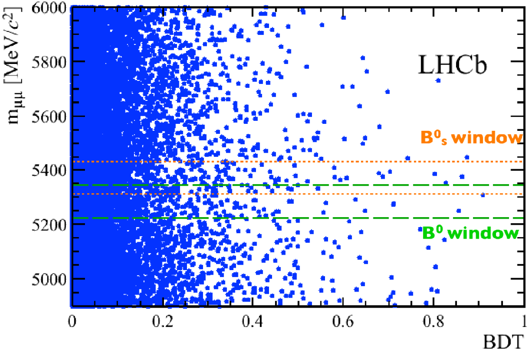
(a) $B^0_{d,s} \to \mu^+\mu^-$ signal



(b) $bb \to \mu^+\mu^- X$ background

- Use $\sim 2/3$ LHCb dataset: $1.0\ \mathrm{fb}^{-1}$ @ $7\ \mathrm{TeV}$ + $1.1\ \mathrm{fb}^{-1}$ @ $8\ \mathrm{TeV}$
- Select oppositely charged muon pair with decay vertex displaced from primary vertex (PV,) combined $p_{\mathrm{T}}(\mu^+\mu^-) > 0.5\ \mathrm{GeV}/c$
- Distinguish between signal and $bb \to \mu^+\mu^- X$ background with Boosted Decision Tree (BDT) classifier:
  - Train and optimise on simulated events
  - Input variables: $\tau(B)$, impact parameter (IP) of μ & B, isolation of μ & B, distance of closest approach for $\mu^+\mu^-$, $p_{\mathrm{T}}(\mu)$, $\cos P(\mu)$

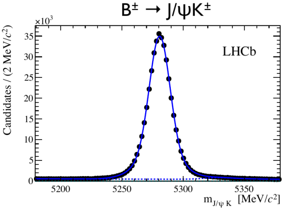
Experimental overview

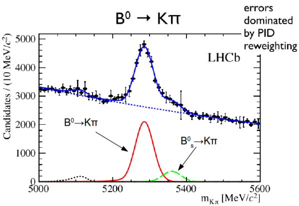


- Split dataset into 8(7) BDT bins for 7(8) TeV data, 15 bins in total
- Count signal events in mass windows around the B^0_s and B^0 masses

Figure from *CERN CDS 1493613, Nov 2012*

Branching fraction meausrement



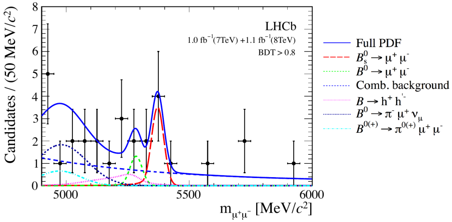


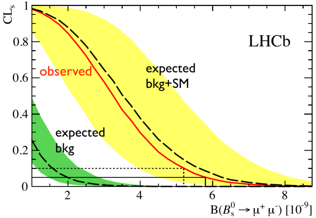
$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \mathcal{B}_{norm} \times \frac{\epsilon_{norm}}{\epsilon_{B^0_{d,s}\to\mu^+\mu^-}} \times \frac{f_{norm}}{f_{d,s}} \times \frac{N_{B^0_{d,s}\to\mu^+\mu^-}}{N_{norm}}$$

- Normalise to well measured decay modes $B^+ \to J/\psi K^+$ and $B^0 \to K\pi$
- ϵ: efficiency of reconstructing, selecting and triggering the decay
  - Determined from simulation, cross-checked on normalisation channels
- f: Probability of b quark hadronising into a given meson
  - Ratio measured at LHCb: Arxiv:1301.5286
- N_{norm}: Normalisation channel yield, taken from mass-fits
- $N_{B^0_{d,s}\to\mu^+\mu^-}$: No. of signal events, counted in mass window around $B^0_{d,s}$ mass

Figures from CERN CDS 1493613, Nov 2012

Results

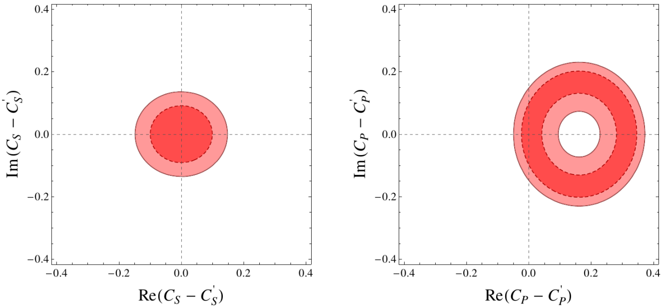




- Compatibility with background only hypothesis (1-$\mathrm{CL_b}$):
  - $B^0 \to \mu^+\mu^-$: 0.11
  - $B^0_s \to \mu^+\mu^-$: $5.3 \times 10^{-4} \to 3.5\sigma$, evidence of decay!
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ (at 95 % CL)
  - Set using the $\mathrm{CL_s}$ method
- $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
  - Profile likelihood scan of $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ by simultaneously fitting $m_{\mu^+\mu^-}$ across all BDT bins for 7 & 8 TeV datasets

Figures from CERN CDS 1493613, Nov 2012

Implications: model independent



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| C_{10}^{SM} + C_{10}^{NP} - C'_{10}) + \frac{m_{B_s}}{2m_\mu}(C_P - C'_P) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C'_S) \right|^2 \right)$$

- $B^0_{d,s} \to \mu^+\mu^-$ sensitive to scalar (C_S), pseudoscalar (C_P) and vector-axial (C_{10}) Wilson coefficients (C_{10} can have SM contribution)

Figure from Arxiv:1306.0022

Implications: model independent

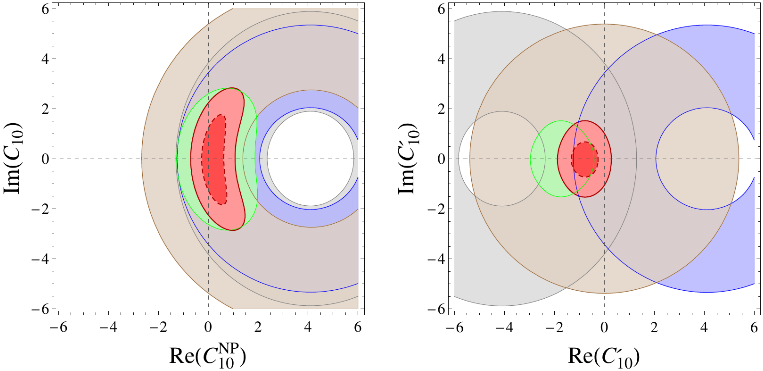


Figure: Constraints on C_{10}, $B^0_s \to \mu^+\mu^-$ contribution in grey, combined 1,2 σ constraints in red.

Figure from Arxiv:1305.5704

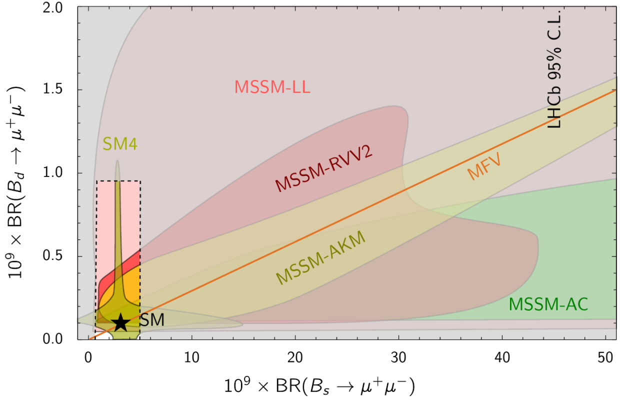
Implications: model independent

Operator		Λ [TeV] for $\lvert c_i \rvert = 1$				$\lvert c_i \rvert$ for $\Lambda = 1$ TeV			
		$+$	$-$	$+i$	$-i$	$+$	$-$	$+i$	$-i$
$\mathcal{O}_{10} =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$	43	33	23	23	$5.4 \cdot 10^{-4}$	$9.2 \cdot 10^{-4}$	$1.9 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
$\mathcal{O}'_{10} =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$	25	89	24	23	$1.7 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
$\mathcal{O}^{(\prime)}_S =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$	93	93	98	98	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
$\mathcal{O}_P =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)$	173	58	93	93	$3.3 \cdot 10^{-5}$	$3.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
$\mathcal{O}'_P =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)$	58	173	93	93	$3.0 \cdot 10^{-4}$	$3.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$

- Constraints from C_S, C_P) and C_{10} set minimum NP energy scale to 20-170 TeV (assuming no NP flavour suppression)
- Alternately, if NP scale is 1 TeV, very strong NP flavour suppression implied

Table from Arxiv:1206.0273

Implications: model dependent



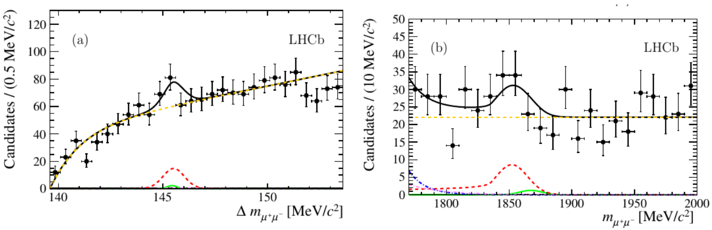
- Strong constraints on some SUSY models
  - Large *tan*β, pseudoscalar light Higgs SUSY models disfavoured
- Any model that violates flavour via (pseudo)scalar particles is constrained by $B^0_s \to \mu^+\mu^-$

Figure from Arxiv:1205.6094

$D^0 \to \mu^+\mu^-$: Experimental Overview

- SM prediction: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11}$
- Search for $D^{*+} \to (D^0 \to \mu^+\mu^-)\pi^+$
  - Two fit variables: $m_{\mu^+\mu^-}$ and $\Delta m_{\mu^+\mu^-} = m_{\mu^+\mu^-\pi} - m_{\mu^+\mu^-}$
- Dataset: $\sim 0.9\ \text{fb}^{-1}$ @ $7\ \mathrm{TeV}$
  - $80\ \text{pb}^{-1}$ used to train a BDT
- Normalise to $D^0 \to \pi^+\pi^-$
- Main background: mis-identified $D^0 \to \pi^+\pi^-$
  - misID rates obtained from data

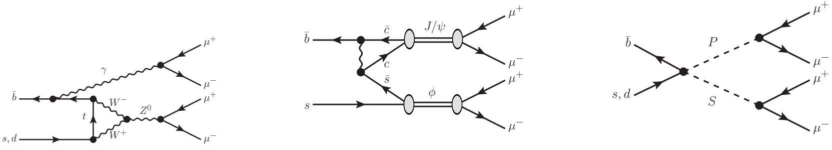
$D^0 \to \mu^+\mu^-$ results



- 2-dimensional fit to $m_{\mu^+\mu^-}$ (a) and $\Delta m_{\mu^+\mu^-}$ (b)
  - yellow: combinatorial background, red: mis-identified $D^{*+} \to (D^0 \to \pi^+\pi^-)\,\pi^+$, green: expected SM signal
- No signal observed, set limits using $\mathrm{CL_s}$ method:
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$ at 95% CL
  - $\times 20$ improvement on previous worlds best constraint! (BELLE, Arxiv:1003.2345)
- Paper to be published in Phys. Lett. B, preprint at Arxiv:1305.5059
- No model (in)dependent constraints extracted yet (very recent result!)

Figures from Arxiv:1305.5059

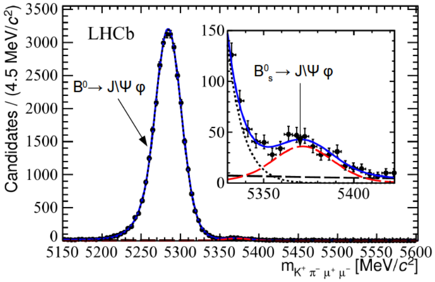
$B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$: Theoretical overview



(a) (b) (c)

- SM process very similar to $B^0_{d,s} \to \mu^+\mu^-$ (a)
  - Helicity supression removed $\mathcal{B}(\uparrow)$, two additional couplings $\mathcal{B}(\downarrow)$
  - SM $\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-) < 10^{-10}$ (Arxiv: 0410146)
  - resonant SM decay via J/ψ and ϕ (b) is vetoed in the search
- Sensitive to NP processes not probed by $B^0_{d,s} \to \mu^+\mu^-$:
  - SUSY sGoldstino particles (c) S (scalar) and P (pseudoscalar) (Arxiv: 1112.5230), $\mathcal{B}$ sensitive to scale of SUSY breaking
    - ★ HyperCP saw hints of 214.3 MeV/c^2 particle with properties consistent with P (Arxiv:0501014)
  - Hidden sector models (PRD 83, 054005 (2011))

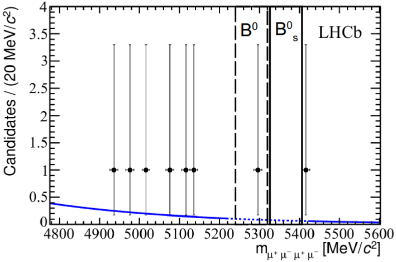
$B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$: Experimental Overview



- Dataset: 1.0 fb^{-1} @ 7 TeV
- Simple cut based selection on: IP of $B^0_{d,s}$ and μ, quality of $B^0_{d,s}$ vertex and flight distance, muon PID
  - trained and optimised on data $B^0_s \to J/\psi\,(\to \mu^+\mu^-)\,\phi\,(\to \mu^+\mu^-)$ decays
- Measure $\mathcal{B}$ in same way as for $B^0_{d,s} \to \mu^+\mu^-$, use $B^0 \to J/\psi K^{*0}$ as normalisation channel

Figure from PRL 110, 211801 (2013)

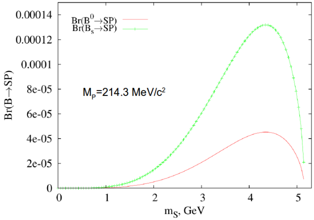
$B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$ results



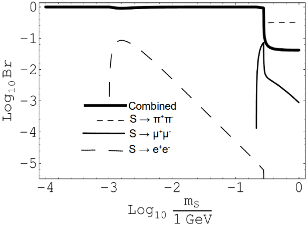
- See one event in B^0 mass window, none in B^0_s window
  - Consistent with background expectations
- Set 95% CL limits on generic phase-space models using CL_s :
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 1.6 \times 10^{-8}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6 \times 10^{-9}$
- Also limits on the sGoldstino models ($m_P = 214.3\,\mathrm{MeV}/c^2$, $m_S = 2.5\,\mathrm{GeV}/c^2$):
  - $\mathcal{B}(B^0_s \to SP) < 1.6 \times 10^{-8}$
  - $\mathcal{B}(B^0 \to SP) < 6.3 \times 10^{-9}$
- Paper published in PRL: PRL 110, 211801 (2013)

Figure from PRL 110, 211801 (2013)

Interpreting $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$ results



(d) $\mathcal{B}(B^0_{d,s} \to SP)$ vs m_S



(e) $\mathcal{B}(S \to \mu^+\mu^-)$ vs m_S

- Lots of free parameters in $B^0_{d,s} \to SP$ decays
- $m_S > 1\,\mathrm{GeV}/c^2$ and $\mathcal{B}(S,P) \to \mu^+\mu^- > 10\%$ models disfavoured
  - Phenomenologists can map out phase space, work out limits on SUSY breaking scale
- Future: extract model independent constraints?

Figure (c) from Arxiv:1112.5230, figure (d) from Arxiv:0007325

Conclusions

- Evidence of $B^0_s \to \mu^+\mu^-$ has set stringent constraints on NP
  - Model independent: flavour violating NP either strongly suppressed or at energies greater than LHC energy
  - Model dependent: large $tan\beta$, pseudoscalar light Higgs SUSY models disfavoured
- Stringent limits also set on $B^0 \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$
- Search for $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$ has started to probe the phase space of NP models with four-prong flavour violating vertices
- These searches will be updated with the full 2011+2012 LHCb dataset
- With more data, these constraints will get much stronger
  - LHCb upgrade: aim to collect $\sim 50\ \text{fb}^{-1}$!
  - Maybe see hints of the structure of NP?