Search for Very Rare Decays at LHCb

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Problems with the SM

“The beauty and clearness of the dynamical theory [...] is at present obscured by two clouds.”
– Lord Kelvin, 1901
New Physics Operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}}(A_a, \psi_i) + \mathcal{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$$\mathcal{L}_{\text{SM}} = \text{renormalizable part of } \mathcal{L}_{\text{eff}}$$

[ = all possible operators with $d \leq 4$ compatible with the gauge symmetry ]

operators of $d \geq 5$ containing SM fields only and compatible with the SM gauge symmetry

- **New Physics** expected to be small
  - If no flavour supp. in NP at tree level ($c_n \sim 1$): $\Lambda > 10^3 - 10^5$ TeV
  - NP also respects SM flavour structure? ($c_n << 1$)
  - Large SM $\rightarrow$ needs very high precision
  - **Suppressed SM $\rightarrow$ NP can compete**
  - Forbidden SM $\rightarrow$ NP smoking gun
Suppression Mechanisms

W. Altmannshofer
ACP Colloquium 2014

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \text{Green} \\ \text{Orange} \\ \text{Purple} \end{pmatrix} \]

No FCNC at tree level

Chiral weak interaction

www.nist.gov/pml/parity-whats-not-conserved
Luminosity

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018

- **Run 1**: 3 fb\(^{-1}\)
  - ~2.6x10\(^{11}\) bb
- **Run 2**: 5 fb\(^{-1}\)
  - ~7.6x10\(^{11}\) bb

Analysed data up to here
LHCb Performance

- $2 < \eta < 5$: ~25% of $b\bar{b}$ in acceptance
- Excellent **mass resolution**: 23 MeV for $B \to \mu\mu$
- Excellent IP resolution: ~20 μm at $p_T \sim 6$ GeV
- **Particle ID**: 1-3% misID, 97% eff. for muons
- **Trigger eff.**: ~90% for $\mu\mu$ channels
A Golden Channel

• FCNC: $b \rightarrow s, d$
• Helicity Suppressed
• Purely muonic final state:
  • Easiest to identify
  • High trigger efficiency
• 2-body decay: Excellent mass resolution
• Accurately predicted by SM*
  • $\mathcal{B}(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$
  • $\mathcal{B}(B_d \rightarrow \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

* PRL 112 (2014) 101801
New Physics Enhancement?

• Many possible new physics models could alter the decay rate

• E.g. some SUSY models can lift the helicity suppression
First Observation

- **Combined analysis** of LHCb and CMS
- The LHCb dataset (**Run I**):
  - 1 fb\(^{-1}\) at 7 TeV
  - 2 fb\(^{-1}\) at 8 TeV

- **First observation of the** \(B_s \rightarrow \mu\mu\) **decay mode** (6.2\(\sigma\))
- Evidence for \(B_d \rightarrow \mu\mu\) (3.2\(\sigma\))

- Mild tension with SM (2.2\(\sigma\))
- ATLAS also searched for these decays, but with less sensitivity
- Overall picture reasonably consistent
Updated results

• The dataset:
  • 1 fb$^{-1}$ at 7 TeV (\(\sim 0.7 \times 10^{11} \text{ b}\bar{b}\))
  • 2 fb$^{-1}$ at 8 TeV (\(\sim 1.7 \times 10^{11} \text{ b}\bar{b}\))
  • 1.4 fb$^{-1}$ at 13 TeV (\(\sim 2 \times 10^{11} \text{ b}\bar{b}\))
  • 80% more b\bar{b} accumulated

• Tighter PID and improved BDT significantly reduces $B^0 \to hh$ and combinatorial background

• Single experiment measurement of $B_s \to \mu\mu$ branching fraction (7.8\(\sigma\))
  • Significance of $B_d \to \mu\mu$ is reduced, improving agreement with SM (<1\(\sigma\))

• $\mathcal{B}(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
• $\mathcal{B}(B_d \to \mu\mu) < 3.4 \times 10^{-10}$ (95\% CL)

PRL 118, 191801 (2017)
Implications for SUSY

D. Straub, arXiv:1012.3893
Implications for SUSY

D. Straub, arXiv:1012.3893

* My superposition
What about lifetime?

- Non-scalar NP components may change effective lifetime while keeping BF almost unchanged
- Use tight window on $B_s$ mass to extract $B_s \rightarrow \mu\mu$ lifetime

  - $\tau(B_s \rightarrow \mu\mu) = (2.04 \pm 0.44 \pm 0.05)$ ps
  - SM: 1.62 ps
  - NP range: 1.41 – 1.62 ps

- Consistent with SM at 1$\sigma$
- Not strong enough to exclude NP: Consistent with $A_{\Delta\Gamma} = -1$ at 1.4$\sigma$
- Statistically limited

* Range between $B_{sH}$ and $B_{sL}$ (PDG 2018)
Can we add more muons?

- $B_s \rightarrow \mu\mu\mu\mu$ lifts the helicity suppression, but higher order diagrams

- SM $\mathcal{B}(B_s \rightarrow \mu\mu\mu\mu) \sim 3.5 \times 10^{-11}$ *

- May have NP contributions, e.g. MSSM:
  - $B^0 \rightarrow (S \rightarrow \mu\mu)(P \rightarrow \mu\mu)$

- No signal observed
- At 95% CL
  - $\mathcal{B}(B_s \rightarrow \mu\mu\mu\mu) < 2.5 \times 10^{-9}$
  - $\mathcal{B}(B_d \rightarrow \mu\mu\mu\mu) < 6.9 \times 10^{-10}$

- The dataset (Run I):
  - 1 fb$^{-1}$ at 7 TeV
  - 2 fb$^{-1}$ at 8 TeV

* PLB 556 (2003) 169
Maybe $\tau$ is the answer?

- In $B^0 \rightarrow D(\ast)\ell\nu$ decays, $\tau$ BF seems boosted w.r.t. $\mu$ BF
- Maybe $B^0 \rightarrow \tau\tau$ also boosted?

- SM predictions: *
  - $\mathcal{B}(B_s \rightarrow \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$
  - $\mathcal{B}(B_d \rightarrow \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$

- Less helicity suppressed, but...
- **Much more challenging** experimentally
- Rely on $\tau \rightarrow 3\pi \nu$ decays
- Exploit characteristic resonances
- Missing two $\nu$'s: No distinct mass peak
- Fit to NN output variable

* PRL 112 (2014) 101801

14 Sep 2018 J. Coelho - LISHEP

PRL 118, 251802 (2017)
Maybe $\tau$ is the answer?

- No signal observed
  - $\mathcal{B}(B_s \rightarrow \tau\tau) < 6.8 \times 10^{-3}$ (95% CL)
  - $\mathcal{B}(B_d \rightarrow \tau\tau) < 2.1 \times 10^{-3}$ (95% CL)

- First limits on $B_s \rightarrow \tau\tau$
- Best limits on $B_d \rightarrow \tau\tau$
- Still very far from SM prediction
- The dataset: 3 fb$^{-1}$ (Run I)

PRL 118, 251802 (2017)
If LFUV, then LFV?

- LFV nearly forbidden in the SM*
- Many theories explaining LFUV hints would also predict large LFV

- Easiest mode: $B^0 \rightarrow e\mu$
- Somewhat more challenging than the $B^0 \rightarrow \mu\mu$ mode due to worse electron momentum resolution (bremsstrahlung)

- **Best limits to date:**
  - $\mathcal{B}(B_d \rightarrow e\mu) < 1.3 \times 10^{-9}$ (95% CL)
  - $\mathcal{B}(B_s \rightarrow e\mu) < 6.3 \times 10^{-9}$ (95% CL)

- The dataset: 3 fb$^{-1}$ (Run I)

* Allowed with neutrino mass, BF < 10$^{-40}$
Many more searches

\[ B^0 \rightarrow pp \]

\[ K_{S}^0 \rightarrow \mu\mu \]

\[ D^0 \rightarrow \mu\mu \]

\[ \Sigma \rightarrow p\mu\mu \]

\[ B \rightarrow D_s \phi \]

\[ D^0 \rightarrow e\mu \]

\[ \Lambda_c \rightarrow p\mu\mu \]

\[ \tau \rightarrow \mu\mu\mu \]

\[ \mu^- \]

\[ \pi^+ \]

\[ \pi^- \]

\[ K^+ \]

\[ B^+ \]

\[ e^+ \]

\[ \mu^- \]
Looking into the future

- Two planned upgrades:
  - 50 fb$^{-1}$ by 2030
  - 300 fb$^{-1}$ by 2037
- Reach:
  - $\sigma[B_d/B_s \rightarrow \mu\mu] \sim 10\%$
  - $\sigma[\tau(B_s \rightarrow \mu\mu)] \sim 2\%$
  - $\mathcal{B}(B_d \rightarrow e\mu) < 9 \times 10^{-11}$

arXiv:1808.08865 [hep-ex]
Summary

- **Very rare decays** allow us to **probe new physics** scenarios at much higher energy scales indirectly

- Large number of possible NP scenarios rejected so far

- Further studies of already observed decays will give access to new observables sensitive to complementary new physics scenarios (e.g. effective $B_s \rightarrow \mu\mu$ lifetime)

- Observing the $B_d \rightarrow \mu\mu$ is one of LHCb’s priorities in the near future

- **Searches for LFV**, also very interesting given current anomalies in LFU*. Extremely rare in the SM

- Much more data to come. **Stay tuned!**

* See talk by B.G. Plana on Tuesday afternoon
Thank you!
Backup Sides
Analysis Comparison

2013 Analysis

- Sig $B_s$ / Comb. ~ 6
- Sig $B_s$ / $hh$ ~ 6

2017 Analysis

- Sig $B_s$ / Comb. ~ 10
- Sig $B_s$ / $hh$ ~ 14

LHCb

BDT > 0.7

3 fb$^{-1}$

BDT > 0.5

Candidates / (44 MeV/c$^2$)

Candidates / (50 MeV/c$^2$)
Normalisation Channels

$B^0 \rightarrow \mu\mu$

$B^0 \rightarrow e\mu$

$B^0 \rightarrow \mu\mu\mu\mu$

$B^0 \rightarrow \tau\tau$