Very rare decays at LHC

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Why look for very rare decays?

**Rare decays**
- Small Standard Model (SM) branching fractions $\rightarrow$ relatively large hypothetical **new physics** (NP) contributions
- Sensitive to higher energy than direct searches due to virtual contributions
- Often Flavour Changing Neutral Currents (FCNCs), which are not possible at tree level in SM
- **Anomalies** seen in $b \rightarrow s \ell^+ \ell^-$ FCNCs
  - See e.g. F. Dettori's and C. Langenbruch's talks for $b \rightarrow s \ell^+ \ell^-$

**Forbidden decays**
- If you see SM forbidden decays, obviously new physics

*Note: will only discuss a selection of recent results*
$B_{(s)}^0 \to \mu^+ \mu^-$: the flagship of very rare decays

**Standard Model**

- $b \to s \ell^+ \ell^-$ and $b \to d \ell^+ \ell^-$ like FCNC
- Both loop diagrams and helicity suppression, so **heavily suppressed**
  - In SM: $\mathcal{B}(B_{s}^0 \to \mu^+ \mu^-) \approx 4 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+ \mu^-) \approx 1 \times 10^{-10}$
- **Theoretically clean** and experimentally favourable

**New physics scenarios**

- New particles in loops
- Sensitive to (pseudo)scalars
  (no helicity suppression)
- Specific: e.g. certain SUSY models, multiple Higgs models

First observation of $B^0_s \rightarrow \mu^+ \mu^-$ with CMS+LHCb combined analysis from full LHC Run 1 dataset published in 2015

First evidence of $B^0 \rightarrow \mu^+ \mu^-$ (slight enhancement from SM)

Although compatible with SM

\[
\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}
\]
$B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-} : \ \text{ATLAS}$, [Eur.Phys.J. C76 (2016) no.9, 513]

- Data from full Run 1 dataset
- No significant signal, but \textbf{consistent} with SM with 2.0\sigma
- Result in \textbf{agreement} with CMS+LHCb results

\[ B(B^{0}_{s} \rightarrow \mu^{+}\mu^{-}) = 0.9^{+1.1}_{-0.8} \times 10^{-9} \]

\[ B(B^{0} \rightarrow \mu^{+}\mu^{-}) < 4.2 \times 10^{-10} \ [95\% \ CL] \]

\textbf{High BDT}\textsuperscript{1} \textbf{region}

\textbf{Limits}

\textsuperscript{1}[Multivariate classifier (Boosted Decision Tree)]
$B_{(s)}^0 \rightarrow \mu^+ \mu^-$: LHCb, update [Phys. Rev. Lett. 118, 191801 (2017)]

Updated $B$ measurement
- Run 1 + part Run 2 (2015/2016; 1.4 fb$^{-1}$) data
- Improved BDT and $B \rightarrow h^+ h^-$ rejection
- Result **compatible** with SM
- $B^0 \rightarrow \mu^+ \mu^-$ fluctuated down

**Effective lifetime measurement**
- Possible **NP orthogonal to $B$** contribution in effective lifetime
- Disentangle CP-odd versus CP-even contribution
- First measurement, as proof of principle, compatible with SM

**High BDT region**

**Decay time distribution**

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10}$ [95% CL]

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$B_{(s)}^0 \rightarrow \tau^+ \tau^-$

- **Lepton Flavour Universality tensions** hint to new physics with $\tau$’s
- Similar to $B_{(s)}^0 \rightarrow \mu^+ \mu^-$, but **less helicity suppressed**
  - In SM\(^1\): $\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) \approx 8 \times 10^{-7}$ and $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) \approx 2 \times 10^{-8}$
- Experimentally much more **difficult**
  - Neutrinos in final state

**Previous limit** from BaBar [Phys. Rev. Lett. 96, 241802 (2006)]

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3} \ [90\% \ CL]$$

\(^1\)[Phys. Rev. Lett. 112, 101801 (2014)]
$B^0_{(s)} \to \tau^+ \tau^-$: LHCb, [Phys. Rev. Lett. 118, 251802 (2017)]

- Run 1 data
- $\tau$ reconstruction with $\tau^+ \to \pi^+ \pi^- \pi^+ \nu$
- No clear mass peak due to neutrinos, **fit neural net output**
- Different Dalitz regions of $\tau$ decay and control decay channels to determine/verify neural net response

### Neural net for signal region

![Neural network output graph]

- **New best limits**
  - $\mathcal{B}(B^0 \to \tau^+ \tau^-) < 2.1 \times 10^{-3}$ [95% CL]
  - $\mathcal{B}(B^0_s \to \tau^+ \tau^-) < 6.8 \times 10^{-3}$ [95% CL]

[a] [Neural net used as multivariate classifier]
\( B_{(s)}^0 \rightarrow e^\pm \mu^\mp \): forbidden lepton flavour violating decays

Lepton flavour violation linked to lepton universality\(^2\)

- SM has no charged lepton flavour violation
- For example leptoquark model could explain seen tensions
- Opens up possibilities for lepton flavour violation (like \( B_{(s)}^0 \rightarrow e^\pm \mu^\mp \))
- Previous limits for \( B_{(s)}^0 \rightarrow e^\pm \mu^\mp \) at about \( 10^{-8} \) to \( 10^{-9} \)

\[
B_{s}^0 \rightarrow \ell'^+ \ell'^- \quad (\text{like } B_{(s)}^0 \rightarrow e^\pm \mu^\mp)
\]

$B^0_{(s)} \rightarrow e^{\pm} \mu^{\mp}$: LHCb, [LHCb-PAPER-2017-031] (accepted by JHEP)

- **New limits** factor 2 to 3 improvement on limit

**High BDT region**

![Graph showing candidates vs. m_{e^\pm\mu^\mp} (MeV/c^2)]

**Improvements**
- Increased BDT performance
- Higher trigger efficiency
- Full Run 1 dataset

**Limits**

$\mathcal{B}(B^0 \rightarrow e^{\pm} \mu^{\mp}) < 1.3 \times 10^{-9}$ [95% CL]

$\mathcal{B}(B^0_s \rightarrow e^{\pm} \mu^{\mp}) < 6.3 \times 10^{-9}$ [95% CL]
$K^0_{S} \rightarrow \mu^+ \mu^-$

- Similar to $B^0_{(s)} \rightarrow \mu^+ \mu^-$: also a FCNC, but $s \rightarrow d \ell^+ \ell^-$
- $K^0_{S} \rightarrow \mu^+ \mu^-$ requires $CP$ violation for s-wave SM component, which is small, so more suppressed, at level $5 \times 10^{-12}$ in SM
- Model-independent bounds on $CP$ violation phase of $s \rightarrow d \ell^+ \ell^-$

$K^0_{L} \rightarrow \mu^+ \mu^-$

- Observed: $(6.84 \pm 0.11) \times 10^{-9}$
  [PDG 2017]
- Excellent agreement with SM:
  $(6.85 \pm 0.32) \times 10^{-9}$

**Example of New Physics range**
[arXiv:1711.11030]
$K^0_S \rightarrow \mu^+ \mu^-$: LHCb, Eur. Phys. J. C, 77 10 (2017) 678

- Challenge for LHCb: high backgrounds and low trigger efficiencies
- **Improved trigger** and more data: full Run 1
- Main background: $K^0_S \rightarrow \pi^+ \pi^-$
- Specific BDTs for muon ID and against combinatorial

\[ K^0_S \rightarrow \pi^+ \pi^- \]

Part signal region (high BDT bin)

\[ \mathcal{B}(K^0_S \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-9} \,[95\% \, CL] \]

- **Improvement of factor 11** from previous result on limit
\[ \Sigma^+ \rightarrow p\mu^+\mu^- \]

- Similar \( s \rightarrow d\ell^+\ell^- \) transition as \( K^0_S \rightarrow \mu^+\mu^- \)
- SM \( B \) prediction higher, due to long-distance contributions, at \( 10^{-8} \) to \( 10^{-7} \)
- Non-resonant SM \( B \) at about \( 10^{-12} \)

**HyperCP**

- All 3 events at dimuon mass of \( \approx 214 \text{ MeV}/c^2 \)

\[
\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}
\]
$$\Sigma^+ \to p\mu^+\mu^-$$: LHCb, [LHCb-PAPER-2017-049] (submitted to PRL)

- Full Run 1 dataset
- **Evidence** for the decay! (4.0σ)
- Consistent with SM
- **No visible structure** in dimuon mass

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = 2.1^{+1.6}_{-1.2} \times 10^{-8}$$

**Limit on resonance at 214 MeV/c^2**

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.2 \times 10^{-8} \ [95\% \ CL]$$

**Dimuon mass**

**Sigma mass**

Limit on resonance at 214 MeV/c^2

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.2 \times 10^{-8} \ [95\% \ CL]$$

**Normalisation**
$\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ and $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

- $c \rightarrow u \ell^+ \ell^-$ FCNC
- Both $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ and $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ have this transition
- SM predicts both at around $10^{-9}$ for non-resonant contribution
$\Lambda_c^+ \rightarrow p\mu^+\mu^-$: LHCb, [LHCb-PAPER-2017-039] (submitted to PRL)

$\Lambda_c^+ \rightarrow p\phi(\rightarrow \mu^+\mu^-)$

- Previous limit at about $4 \times 10^{-5}$ [90% CL] from BaBar

This analysis

- Full Run 1 dataset
- Contributions seen from $\phi$ and $\omega$
- No signal seen in non-resonant region
- Near $10^3$ improvement in limit!

Limit on non-resonant contribution

$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 9.6 \times 10^{-8}$ [95% CL]
$D^0 \rightarrow h^+ h^- \mu^+ \mu^-$: LHCb, [Phys. Rev. Lett. 119, 181805 (2017)]

- Part Run 1 (2012, 2 fb$^{-1}$) dataset
- **First observation!** of both decays
- Rarest charm decay so far!
- Both in agreement with SM (long-distance contributions)

\[ D^0 \rightarrow K^+ K^- \mu^+ \mu^- \]

\[ B(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (9.64 \pm 0.48 \text{(stat.)} \pm 0.51 \text{(syst.)} \pm 0.97 \text{(norm.)}) \times 10^{-7} \]

\[ B(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (1.54 \pm 0.27 \text{(stat.)} \pm 0.09 \text{(syst.)} \pm 0.16 \text{(norm.)}) \times 10^{-7} \]
Summary

- Very rare decays **good probe for new physics**
- Rich field, many results not shown
- Many improved limits and observations of decays with suppressed FCNC $b \to s \ell^+ \ell^-$, $b \to d \ell^+ \ell^-$, $s \to d \ell^+ \ell^-$ and $c \to u \ell^+ \ell^-$ transitions
- Improved limits on lepton flavour violating channels
- Help to **constrain possible new physics in B-anomalies**
- Stay tuned for (Run 2) updates and new analyses!