LFV, lepton universality, and rare decay searches at the LHC

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On behalf of LHCb, with results from ATLAS and CMS

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- Rare decays of b-hadrons are flavour changing neutral current (FCNC) decays that take place only at loop level

\[ b \rightarrow W^- s, \quad Z^0, \gamma \rightarrow \ell^+ \ell^- \]

**SM**

- Sensitive to theories beyond the Standard Model (SM)

**Non-SM**

- Observable measurements => indirect search for non-SM effects
- Several recent results have hinted at departure from SM expectations => active area of investigation
Rare decays: $B_{(s)}^0 \rightarrow \ell^+\ell^-$

- $B_{(s)}^0 \rightarrow \ell^+\ell^-$, $\ell = e, \mu, \tau$ decays are helicity suppressed FCNC decays

$$\mathcal{B}(B_{s/l}^0 \rightarrow W^+Z^0) \frac{1}{B_{s/l}^0 \rightarrow W^-W^-}$$

$B^0$ mode more suppressed than $B_s^0$ as $|V_{td}| < |V_{ts}|$

Greater helicity suppression for $e$ than $\tau$ as $m_e < m_\tau$

- Purely leptonic final state $\implies$ precise SM predictions of branching fractions (BFs):
  - $\mathcal{B}(B_s^0 \rightarrow e^+e^-)/\mathcal{B}(B_s^0 \rightarrow e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}/(2.48 \pm 0.21) \times 10^{-15}$
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}/(1.06 \pm 0.09) \times 10^{-10}$
  - $\mathcal{B}(B_s^0 \rightarrow \tau^+\tau^-)/\mathcal{B}(B^0 \rightarrow \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}/(2.22 \pm 0.19) \times 10^{-8}$

[PRL 112 (2014) 101801]

- Muon mode measurements/searches made by ATLAS, CMS and LHCb
  - $B_s^0 \rightarrow \mu^+\mu^-$ seen [Nature (2015) 14474]
  - $B^0 \rightarrow \mu^+\mu^-$ no observation yet

- Tau mode searched for by LHCb — no evidence yet [PRL 118 (2017) 251802]

- Electron mode measurement at LHCb currently in progress
$B_{(s)}^0 \rightarrow \mu^+\mu^-$: LHCb

- Data collected in 2011-2012 (Run 1, 3 fb$^{-1}$), and 2015-2016 (Run 2, 1.4 fb$^{-1}$)

- Normalisation channels: $B^+ \rightarrow J/\psi K^+$ (similar trigger), and $B_{(s)}^0 \rightarrow K^+\pi^-$ (similar topology)

- Extract BF through simultaneous unbinned maximum likelihood (UML) fit to the dimuon invariant mass distributions in five boosted decision tree (BDT) score bins for Run 1 and 2

- Measured $\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2} \times 10^{-9})$ — first single experiment observation (7.8 $\sigma$)

- Previous evidence for $B^0$ mode not confirmed (1.6 $\sigma$): $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% C.L.
- Data collected in 2015-2016 (Run 2, 26.3 fb$^{-1}$)
- Single signal component for both $B^0_s$ and $B^0_s$ contributions due to limited resolution
- Extracted BF via simultaneous UML fit to four BDT score bins

- Measured (combined with Run 1) $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = 3.2^{+1.1}_{-1.0} \times 10^{-9}$ ($2.8^{+0.8}_{-0.7} \times 10^{-9}$)
- Determined (combined with Run 1) $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-10}$ ($2.1 \times 10^{-10}$) at 95% C.L.
- $B^0_s \rightarrow \mu^+\mu^-$ Run 1+2 significance: $4.6 \sigma$
- Preliminary results only
- Data collected in 2011, 2012 and 2016 (61 fb\(^{-1}\))
- Extracted BF via simultaneous UML fit to 14 subsamples (four data collection eras × two bins in pseudorapidity, each sample is split further, where possible, into two regions based on BDT score)
- UML fit to \(m_{\mu\mu}\), relative mass resolution (\(\sigma(m_{\mu^+\mu^-})/m_{\mu^+\mu^-}\)), and a binary distribution with 1 (-1) for muon tracks bending towards (away from) each other

\[
B_{(s)}^0 \rightarrow \mu^+\mu^- : \text{CMS}
\]

- Measured \(\mathcal{B}(B_{s}^0 \rightarrow \mu^+\mu^-) = (2.9^{+0.7}_{-0.6} \text{(exp)} \pm 0.2 \text{(frag)}) \times 10^{-9}\) with 5.6 \(\sigma\) significance
- No significant excess observed for \(B^0\) decay, \(\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10}\) at 95% C.L.
- Likelihood contours (and combination) of the most recent ATLAS, LHCb and CMS (preliminary) results:

- Good agreement with SM in general, but starting to become interesting…
$B_s^0 \rightarrow \mu^+\mu^-$ effective lifetime measurements

- Measurement of $B_s^0 \rightarrow \mu^+\mu^-$ lifetime provides a complementary test of SM
- The effective lifetime (without distinguishing $B_s^0/\overline{B_s^0}$) can be expressed as:

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2} \left( 1 + 2A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2 \right)$$

$$\tau_{B_s^0} = 1.510 \pm 0.005 \text{ ps}$$

$$y_s \equiv \tau_{B_s^0} \Delta \Gamma / 2 = 0.062 \pm 0.006$$

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{\Gamma(B_s^H \rightarrow \mu^+\mu^-) - \Gamma(B_s^L \rightarrow \mu^+\mu^-)}{\Gamma(B_s^H \rightarrow \mu^+\mu^-) + \Gamma(B_s^L \rightarrow \mu^+\mu^-)}$$

- In the SM, $A_{\Delta\Gamma}^{\mu^+\mu^-} = 1$, but in beyond SM theories it may be anywhere in the range of [-1, 1]
- Both LHCb and CMS measured $\tau_{\mu^+\mu^-}$, yielding:
  - $2.04 \pm 0.44 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ ps (LHCb)}$
  - $1.70^{+0.61}_{-0.44} \text{ ps (CMS preliminary)}$
- Results are in agreement with SM

[PDF]

[CMS PAS BPH-16-004]

[CMS PAS BPH-16-004]

[ CMS Preliminary 36 fb^{-1}(13 TeV) + 20 fb^{-1}(8 TeV) + 5 fb^{-1}(7 TeV) ]

[PRL 118 (2017) 191801]
**B_{(s)}^{0} → ℓ^{+}ℓ^{-} decays: the future**

- LHCb, ATLAS and CMS produced estimations of total uncertainties/BF limits for future runs/upgrades:  
  [LHCB-PUB-2018-009] [ATL-PHYS-PUB-2018-005] [CMS PAS FTR-14-013/-015]

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<th>Large Hadron Collider (LHC)</th>
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Rare decays: $b \rightarrow s \ell^+ \ell^-$ processes

- Another group of rare $b$-hadron FCNC decays feature the underlying $b \rightarrow s \ell^+ \ell^-$ transition

- Measurements of observables of these decays have shown some interesting (albeit inconclusive) tensions with the SM

- Of particular interest are ‘clean’ observables with precise SM predictions, in particular ratios of branching fractions ($R_{K(*)}$),

$$ R_{K(*)} = \frac{\int_{q_{\text{max}}^2}^{q_{\text{min}}^2} dq^2 \frac{d\Gamma(B \rightarrow K^{(*)}\mu^+\mu^-)}{dq^2}}{\int_{q_{\text{max}}^2}^{q_{\text{min}}^2} dq^2 \frac{d\Gamma(B \rightarrow K^{(*)}e^+e^-)}{dq^2}} $$  

[PRD 69 (2003) 074020]

- Lepton flavour universality (LFU): electroweak couplings are identical for all lepton flavours, and differences between decay modes are due only to their mass differences

Lepton flavour universality test: $R_K$

- $R_K = 1 \pm \mathcal{O}(10^{-2})$, $1.1 < q^2 < 6.0 \text{ GeV}^2/\text{c}^4$ (SM) [EPJC 10 (2016) 1140]

- Experimentally, electron and muon reconstruction are very different
  
  => higher efficiency

- Muons are relatively easy to trigger on and reconstruct

- Electrons undergo significant bremsstrahlung emission
  
  => reduced trigger/reconstruction efficiency and resolution

- To mitigate experiment-related electron-muon differences, the $R_K$ measurement is made using a double ratio, which makes use of the normalisation mode $B^0 \to KJ/\psi$:

\[
R(K) = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))} \times \frac{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to Ke^+e^-)},
\]

\[
= \frac{N_{B^+ \to K\mu\mu}}{\epsilon_{B^+ \to K\mu\mu}} \times \frac{N_{B^+ \to Ke^+e^-}}{\epsilon_{B^+ \to Ke^+e^-}} \times \frac{\epsilon_{B^+ \to KJ/\psi(\mu\mu)}}{N_{B^+ \to KJ/\psi(\mu\mu)}} \times \frac{\epsilon_{B^+ \to KJ/\psi(ee)}}{N_{B^+ \to KJ/\psi(ee))}
\]
Lepton flavour universality test: $R_K$

- Several cross-checks to validate the analysis strategy:
  - Measured $r_{J/\psi}$ single ratio:
    \[
    r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+ \mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))} = 1.014 \pm 0.035 \]
  - Measured $R_K^{\psi(2S)}$ double ratio:
    \[
    R_K^{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+ \mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+ \mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.986 \pm 0.013
    \]

- The most recent $R_K$ result is consistent with the previous measurement, and show slight tension at $\sim 2.5\sigma$ with SM:
  \[
  R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}
  \]
Lepton flavour universality test: $R_{D^*}$

- LFU-test involving another group of decays — processes featuring the underlying tree-level b-hadron decays ($b \rightarrow c\ell\nu$), show notable tension with SM.

- Most recent measurement of this set ($R_{D^*}$) performed by LHCb using data from 2011-2012 (Run 1, 3 fb$^{-1}$):

$$R_{D^*} \equiv \frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)} \left\{ D^{*-} \rightarrow \bar{D}^0(\rightarrow K^+\pi^-)\pi^- \right\} \tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

- Strategy: measure $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ normalised to $B^0 \rightarrow D^{*-}3\pi$:

$$K_{D^{*-}} \equiv \frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi)} \quad R_{D^{*-}} \equiv K_{D^{*-}} \times \frac{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi)_{\text{ext}}}{\mathcal{B}(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)_{\text{ext}}}.$$ 

- Suppress backgrounds from $B \rightarrow D^{*}3\pi X$ by imposing that the $3\pi$ vertex is downstream of, and significantly detached from, the $B^0$ vertex.

- Background from double-charm (e.g. $B^0 \rightarrow D^{*-}D^{+}(X)$) decays suppressed using BDT.

- Extract signal yield via 3d binned maximum likelihood fit to $\tau$ decay time, $q^2$ and BDT output distributions.

- Final result is compatible with SM (within 1$\sigma$):

$$R_{D^*} = 0.291 \pm 0.019\,\text{(stat)} \pm 0.026\,\text{(syst)} \pm 0.013\,\text{(ext)}$$
Current LFU-tests at the LHCb involving $b \rightarrow s\ell^+\ell^-$ ($R_{K^{(*)}}$) and $b \rightarrow c\ell\nu$ ($R_{D^{(*)}}, R_{J/\psi}$) decays show tensions with SM predictions [see also Backup slide A].

More statistics and additional measurements from LHCb and other collaborations (e.g. Belle-II) will help to clarify the picture.

Lepton flavour universality tests: the future

- A number of rare b-hadron decay $R_X$ analyses are currently in progress, including updates to $R_{K^{(*)}}$ using full Run 2 (up to 2018) statistics, $R_\phi$, $R_{pK}$ and $R_\pi$

- $R_X$ measurements involving tree-level b-hadron decays are also ongoing, with interesting prospects

CMS started to gather data (B-parking) for LFU tests, including the potential measurement of $R_{K^{(*)}}$
Lepton flavour violation

- Lepton flavour violation (LFV), e.g. $\mu \rightarrow e\gamma$, is forbidden in the SM
- Observations of neutrino oscillations suggest LFV occurs for neutral leptons
- However, no evidence for LFV involving charged leptons has ever been found

Recent hints of LFU violation motivate the search for LFV in the decays of $b$-hadrons, as beyond-SM models capable of accommodating for LFU generally predict charged LFV with measurable BFs

- LHCb is the main experiment involved in the searches for LFV decays of $b$-hadrons
- Recent developments in this area include searches (at LHCb) for:
  - $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$
  - $B^+ \rightarrow K^+ \mu^\pm e^\mp$

$\mathcal{B}(\mu \rightarrow e\gamma)_{SM} < 10^{-50}$
Lepton flavour violation search: $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$

- Analysis performed by LHCb using data collected in 2011-2012 (Run 1, 3 fb$^{-1}$)
- Reconstruct $\tau$ from the decay chain $\tau^- \rightarrow a_1^-(1260)\nu_\tau$, $a_1^-(1260) \rightarrow \rho^0(770)( \rightarrow \pi^+\pi^-)\pi^-$
- Normalisation mode: $B^0 \rightarrow D^- (\rightarrow K^+\pi^-\pi^-)\pi^+$
- Reduce backgrounds with cut based selection, e.g. $\tau$ decay time and masses of pion combinations
- Use two BDTs to further reduce backgrounds

- Use a final classifier to split sample into four bins to further enhance signal-background separation
- Extract BF by performing UML fit to $m_{\tau\mu}$ (from analytical reconstruction) in the four bins, taking the expected signal fraction per bin into account
- Obtained BF limits at 95% CL of
  - $\mathcal{B}(B^0_s \rightarrow \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}$
  - $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 1.4 \times 10^{-5}$

BF can be as large as $O(10^{-5})$ in some models with $Z'$/leptoquarks e.g. [JHEP 11 (2016) 035]
Lepton flavour violation search: $B^+ \to K^+ \mu^\pm e^\mp$

- Search performed by LHCb using data taken in 2011-2012 (Run 1, 3 fb$^{-1}$)
- Different lepton charge combinations studied separately
- One multivariate classifier to reduce combinatorial background, another to reduce background from partially reconstructed b-hadron decays
- Classifier output cuts optimised for best expected BF upper limit
- Found 1 (2) candidates in signal region
- Upper limits at 95% CL determined to be:
  - $\mathcal{B}(B^+ \to K^+ \mu^- e^+) < 9.5 \times 10^{-9}$
  - $\mathcal{B}(B^+ \to K^+ \mu^+ e^-) < 8.8 \times 10^{-9}$

BF up to $\mathcal{O}(10^{-8})$ in some leptoquark models

e.g. [JHEP 06 (2015) 072]
Lepton flavour violation search - the future

- LHCb has produced some limit estimations for the future:

<table>
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<tr>
<th>Year</th>
<th>Run 1 (Current)</th>
<th>Upgrade I</th>
<th>Upgrade II</th>
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<tbody>
<tr>
<td>2021</td>
<td>$B^0 \to e^\pm \mu^\mp$</td>
<td>$&lt; 1.3 \times 10^{-9}$</td>
<td>$&lt; 2 \times 10^{-10}$</td>
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<td>2022</td>
<td>$B_s^0 \to e^\pm \mu^\mp$</td>
<td>$&lt; 6.3 \times 10^{-9}$</td>
<td>$&lt; 8 \times 10^{-10}$</td>
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<td>2023</td>
<td>$B^0 \to \tau^\pm \mu^\mp$</td>
<td>$&lt; 1.4 \times 10^{-5}$</td>
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[LFHCB-PUB-2018-009]

- Searches for other LFV decays of b-hadrons at LHCb, such as $B^0 \to K^{*0} \tau^\pm \mu^\mp$, $B^+ \to K^+ \tau^\pm \mu^\mp$ and $\Lambda^0_b \to \Lambda e^\pm \mu^\mp$, are in progress.

- Limits for $B^+ \to K^+ \tau^\pm \mu^\mp$ and $B^0 \to K^{*0} \tau^\pm \mu^\mp$ using Upgrade II data are expected to provide strong constraints on beyond-SM models.
Summary

- Observables of rare b-hadron FCNC decays are ideal for the indirect search for beyond-SM effects
- Leptonic B decay searches/BF measurements carried out for the muon (and tau modes), producing results consistent with SM predictions
- Multiple LFU tests involving b-hadron decays, such as $R_{K^{(*)}}$ (rare $b \rightarrow s\ell^+\ell^-$ processes) and $R_{D^{(*)}}$ (tree-level $b \rightarrow c\ell\nu$), show slight tension with SM
- LFV searches produced limits that are starting to encroach upon beyond-SM theory predictions in some cases
- Upcoming LFU tests with full Run 2 statistics and beyond will help clarify the current situation
- Significant improvements to more challenging rare decays/LFV searches require larger statistics from Run 3 (end of 2023) onwards
Backup
Other lepton flavour universality tests

- Other tests of LFU at the LHCb include:

\[ b \to s \ell\ell \]

\[ R_{K^*} = \frac{\mathcal{B}(B \to K^{*}\mu\mu)}{\mathcal{B}(B \to K^{*}ee)} = \frac{0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)}}{1.1 < q^2 < 6.0 \text{ GeV}^2/c^4} \]

Compatibility with SM (1 ± \mathcal{O}(10^{-2})): 2.4 − 2.5σ \[ \text{JHEP 08 (2017) 055} \]

- Tree level decays with large BF (few percent), and precise SM predictions

\[ b \to c \ell\nu \]

\[ R_{D^{(*)}} \equiv \frac{\mathcal{B}(B^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \]

\[ \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau \quad \text{: } 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)} \]

\[ \tau^- \to \pi^+\pi^-\pi^-\nu_\tau \quad \text{: } 0.291 \pm 0.019 \text{ (stat)} \pm 0.026 \text{ (syst)} \pm 0.013 \text{ (ext)} \]

Compatibility with SM (0.252 ± 0.003): \sim 2.1σ \[ \text{PRD 85 (2012) 094025} \]


\[ R_{J/\psi} \equiv \frac{\mathcal{B}(B_{c} \to J/\psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_{c} \to J/\psi\mu\bar{\nu}_\mu)} = \frac{0.71 \pm 0.17 \text{ (stat)} \pm 0.18 \text{ (syst)}}{\text{PRL 120 (2018) 121801}} \]

Compatibility with SM (0.25-0.28)*: \sim 2σ

*\[ \text{PLB 452 (1999) 129136} \quad \text{PRD 74 (2006) 074008} \quad \text{hep-ph/0211021} \quad \text{PRD 73 (2006) 054024} \]
In the determination of $B_{(s)}^0 \rightarrow \mu^+\mu^-$ BF, LHCb, ATLAS and CMS all* use the normalisation mode of $B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+$ involving a $B^\pm$ [bu]:

$$\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+\mu^-) = \frac{\mathcal{B}_{\text{norm}}\epsilon_{\text{norm}}}{N_{\text{norm}}\epsilon_{\text{sig}}} \frac{f_{\text{norm}}}{f_{d(s)}} N_{B_{(s)}^0 \rightarrow \mu^+\mu^-} = \alpha_{B_{(s)}^0 \rightarrow \mu^+\mu^-}^\text{norm} N_{B_{(s)}^0 \rightarrow \mu^+\mu^-}$$

This necessitates the value for $f_s/f_d$, which has the (latest) LHC-average of $0.252 \pm 0.012$ (assuming $f_u/f_d = 1$) [PDG]

However $f_s/f_d$ will vary depending on e.g. centre-of-mass energy and PT

Some evidence of variation with PT has been seen by LHCb

CMS added extra uncertainty for most recent measurement ($\pm 0.015$)

CMS is considering other options, e.g. $B_s \rightarrow J/\psi\phi$ (need to be careful about BF uncertainty)

*LHCb uses $B_{(s)}^0 \rightarrow K^+\pi^-$ in addition, but contribution to average ($\alpha_{B_{(s)}^0 \rightarrow \mu^+\mu^-}^\text{norm}$) dominated by $B^+$ mode with more events
$B_{(s)}^0 \rightarrow \tau^+\tau^-$: LHCb

- Data collected in 2011 and 2012 (3 fb$^{-1}$)
- Reconstruct $\tau$ from the decay chain $\tau^- \rightarrow a_1^- (1260) \nu_\tau$, $a_1^- (1260) \rightarrow \rho^0 (770) (\rightarrow \pi^+\pi^-)\pi^-$
- Normalisation channel: $B^0 \rightarrow D^- (\rightarrow K^+\pi^-\pi^-)D_s^+ (\rightarrow K^-K^+\pi^+)$
- Larger BF (less helicity suppressed), but analysis complicated by undetected neutrinos: $m_{\tau\tau}$ allows for only weak signal-background separation, $B^0/B_s^0$ not resolved $\Rightarrow$ optimise for $B_s^0$
- Use two neural networks (NN) following cut-based selection
- Perform 1d histogram fit to second NN output distribution

- No evidence (yet), BR limits at 95% CL:
  - $\mathcal{B}(B_s^0 \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3}$
  - $\mathcal{B}(B^0 \rightarrow \tau^+\tau^+) < 2.1 \times 10^{-3}$ (assuming no $B_s^0$ contribution)
Lepton flavour violation search: $B^{0}_{(s)} \rightarrow e^{\pm}\mu^{\mp}$

- Analysis performed by LHCb using data collected in 2011-2012 (Run 1, 3fb-1)
- Combinatorial BDT trained using simulated $B^{0}_{(s)} \rightarrow e^{\pm}\mu^{-}$ (signal) and same sign $B^{0}_{(s)} \rightarrow e^{\pm}\mu^{\mp}$ data (background)
- Extract BF via simultaneous UML fit to seven BDT output bins and two bremsstrahlung categories
- No excesses observed, upper limits at 95% CL are found to be:
  - $\mathcal{B}(B^{0}_{s} \rightarrow e^{\pm}\mu^{\mp}) < 6.3(7.2) \times 10^{-9}$ for heavy (light) mass eigenstate
  - $\mathcal{B}(B^{0} \rightarrow e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-9}$
Search for $K_S^0 \rightarrow \mu^+ \mu^-$

- $K_S^0 \rightarrow \mu^+ \mu^-$ is a rare, as-of-yet unobserved FCNC decay that is highly suppressed in the SM, with 
  \[ \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-)_{SM} = (5.18 \pm 1.5_{LD} \pm 0.02_{SD}) \times 10^{-12} \]
- Feynman diagrams showing long distance (LD) and short distance (SD) SM contributions:

- Beyond-SM theories, including some leptoquark models, predict deviations in $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-)$
- Recently LHCb reported the (preliminary) result of a search that uses data collected in 2016, 2017 and 2018 (Run 2, 5.6 fb$^{-1}$)
Search for $K_S^0 \rightarrow \mu^+ \mu^-$

- Normalisation mode (similar topology): $K_S^0 \rightarrow \pi^+ \pi^-$
- Simultaneous UML fit to $m_{\mu^+\mu^-}$ of twenty subsamples (two trigger categories $\times$ ten combinatorial BDT bins)
- $K_S^0 \rightarrow \pi^+ \pi^-$ background suppressed via dedicated muon identification BDT, $K_L^0 \rightarrow \mu^+ \mu^-$ constrained using well-known BF and $K_S^0/K_L^0$ efficiency ratio from corrected simulation

- Determined (combined with Run 1) $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 2.4 \times 10^{-10} (2.3 \times 10^{-10})$ at 95% C.L.
- $B_S^0 \rightarrow \mu^+ \mu^-$ Run 1(+2) significance: 1.5(1.4)$\sigma$