Rare Decays at LHCb

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(on behalf of the LHCb collaboration)
LHCb searches for NP in **FCNC** with B (and D) decays, where new dynamics (particles) can enter in the loops and penguins and modify the SM predictions of some observables! An indirect search!

- Study **FCNC** processes with “precise” **SM prediction**
- Measure *Branching fractions, angular distributions, CP asymmetries*
- If no NP found, *models beyond SM are constrained*, or NP enters a higher energy scale!
- Also search for SM forbidden processes: **LFV** and **LNV**
Introduction

FCNC can be described by an effective Hamiltonian

\[
H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right] + \sum \frac{c}{\Lambda_{NP}^2} O_{NP}
\]

- Wilson coefficients \((C_i, \text{Left H}, C_i' \text{Right H})\) are related with observables
- Operators depends on hadronic form factors (theoretical uncertainties)

Rare B decays and its relevant terms:

- \(B_s \to \mu^+\mu^- (C_{10}, C_5, C_P \text{ Scalar and Pseudo-scalar})\)
- radiative decays \((C_7 \text{ photon penguin})\)
- \(b \to s \ell^+\ell^- (C_7 \text{ and } C_9, C_{10} \text{ EW penguin})\)
RD Analyses

- **Very rare decays**
  - $B_s \rightarrow \mu\mu$ [arXiv:1411.4413, Nature 552 (2015) 68]

- **Radiative decays**
  - $b \rightarrow s\gamma$, $\gamma$ polarization [1fb$^{-1}$/arXiv:1402.6852, PRL 112 (2014) 161801]

- $b \rightarrow sll$

- **Angular distributions $B \rightarrow K^*\mu\mu$** [LHCB-CONF-2015-002]

- **$B_s \rightarrow \phi\mu\mu$** [LHCB-PAPER-2015-023]

- **Angular distributions $B \rightarrow K^*\mu\mu$**

- **Lepton Universality**
  - $B^+ \rightarrow K^+\mu\mu$, $B^+ \rightarrow K^+ee$ [arXiv:1406.648, PRL 113 (2014) 151601]

- **“Forbidden” decays: LFV, LNV**
  - $\tau \rightarrow 3\mu$ [arXiv:1409.8548, JHEP 02 (2015) 121]

  - $B^- \rightarrow \pi^+\mu^-\mu^-$ [arXiv:1401.5361, PRL 112 (2014) 131802]
LHCb detector

- LHCb detector
  - single-arm spectrometer (2<\(\eta\)<5)
  - B, B\(_s\), B\(^+\), D, \(\Lambda\)\(_b\), ... produced at LHCb
  - trigger on \(\mu\), e, hadrons with “low” \(P_T\)
    - efficiency on dimuon channels \(\sim\)90%
  - precise vertex (IP \(\sim\)20 \(\mu\)m at high \(P_T\))
  - excellent momentum resolution \(\Delta p/p \approx 0.5\%\)
  - good particle ID (>97% \(\mu\)-eff, 1-3% mis-ID)

- LHCb operation
  - “beautifully”
  - operating @ 2 nominal luminosity
  - Integrated luminosity \(3\text{ fb}^{-1}\)
    (2 \(\text{fb}^{-1}\) 8 TeV, 1 \(\text{fb}^{-1}\) 7 TeV)
Lepton Universality $B^+ \rightarrow K^+ l^+ l^-$

- Ratio of $B^+ \rightarrow K^+ \mu^+ \mu^-$, $B^+ \rightarrow K^+ e^+ e^-$ as test of lepton universality

\[
R_K = \frac{\int q_{\text{max}}^2 dq^2 d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{\int q_{\text{min}}^2 dq^2 d\Gamma[B^+ \rightarrow K^+ e^+ e^-]},
\]

- uncertainties cancel on the ratio, $q^2 [1,6] \text{GeV}^2/c^4$
- in SM is almost one, deviations of $\mathcal{O}(10^{-3})$

- LHCb analysis:
  - relative measurement with respect $B^+ \rightarrow K^+ J/\psi(l^+ l^-)$
  - reconstruction of the e with bremsstrahlung photons

\[
R_K = \left(\frac{N_{K^+ \mu^+ \mu^-}}{N_{K^+ e^+ e^-}}\right) \left(\frac{N_{J/\psi(e^+ e^-)K^+}}{N_{J/\psi(\mu^+ \mu^-)K^+}}\right) \times \left(\frac{\epsilon_{K^+ e^+ e^-}}{\epsilon_{K^+ \mu^+ \mu^-}}\right) \left(\frac{\epsilon_{J/\psi(e^+ e^-)K^+}}{\epsilon_{J/\psi(\mu^+ \mu^-)K^+}}\right).
\]
Lepton Universality $B^+ \rightarrow K^+ l^+ l^-$

- Systematic dominated for the inv mass parameterization and trigger efficiencies

$$q^2 \text{ in } [1,6] \text{ GeV}^2/c^4$$

$$R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(syst)}.$$  

- Consistent with SM at 2.6 $\sigma$
  
  - A $Z'$ with different coupling with $e$ and $\mu$?
  
- Branching Ratio of $B^+ \rightarrow K^+ e^+ e^-$

$$[1.56^{+0.19}_{-0.15} \text{(stat)} +0.06_{-0.04} \text{(syst)}] \times 10^{-7}.$$  

- Consistent with SM predictions!
(Lepton Universality $B^+ \rightarrow D^{*+} l^- \nu$)

- Ratio of $B \rightarrow D^* \mu^- \nu$, $B \rightarrow D^* \tau^- \nu$ as test of lepton universality
  - Ratio affected for charged Higgs
  - BaBar published results on tension $2.7(2)$ $\sigma$ for $D^*(D)$ ratios [PRD 88 (2013) 072012], Belle preliminary (see this workshop)

- LHCb analysis:
  - trigger and selection without using $\mu$ to not bias kinematics
  - selecting: $\tau \rightarrow \mu^- \nu$, $D^{*+} \rightarrow D^0(K\pi)\pi^+$
  - required separation and isolation of vertices: $B$, $D^*$, $\tau$ using MVA
  - reconstruct kinematical variables: $p_{B,z} = p_{D^*,z} + p_{\mu,z}$, $M_{\text{mis}}^2 = (p_B-p_{D^*}-p_\mu)^2$
  - fit $M_{\text{mis}}^2$, $q^2$, $E_\mu$ using templates from simulation for signal and background but validated with data
(Lepton Universality $B^+ \rightarrow D^* + l^- \nu$)

- systematic dominated by size of simulated samples and “$\mu$-midid” efficiencies

\[ R(D^*) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst).} \]

- 2.1 $\sigma$ deviation with respect SM
Angular analysis \(B \rightarrow K^* e^+ e^-\) at low \(q^2\)

- Angular analysis of \(B \rightarrow K^* e^+ e^-\) at low \(q^2\)
  - \(q^2\) in [0.002, 1.120] GeV\(^2\)/c\(^4\), dominated by \(\gamma\) pole
  - sensible to \(C' \gamma\), photon polarization (\(b \rightarrow s \gamma\)) SM LH!

\[
\frac{1}{d\Gamma/dq^2} = \frac{3}{16\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{2}(1 - F_L)A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + \frac{1}{2}(1 - F_L)A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right].
\]

- LHCb analysis
  - Three angles \(\theta_K, \theta_\ell, \phi\). But \(\phi\) folded due to limited statistics
  - Four observables \(F_T, A_T^{(2)}, A_T^{(\text{Im})}, A_T^{(\text{Re})}\) related to Wilson Coefficients

\[
A_T^{(2)}(q^2 \rightarrow 0) = \frac{2R e(C_7C_7^*)}{|C_7|^2 + |C_7^*|^2} \quad \text{and} \quad A_T^{(\text{Im})}(q^2 \rightarrow 0) = \frac{2I m(C_7C_7^*)}{|C_7|^2 + |C_7^*|^2}.
\]
Angular analysis $B \rightarrow K^*e^+e^-$ at low $q^2$

$q^2$ distribution

$F_L = 0.16 \pm 0.06 \pm 0.03$

$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$

$A_T^{\text{Im}} = +0.14 \pm 0.22 \pm 0.05$

$A_T^{\text{Re}} = +0.10 \pm 0.18 \pm 0.05$,

- Consistent with SM!
- Ratio $C'_7/C_7$ is consistent with 0
- More precise than from radiative decays

- Systematic dominated by angular acceptance and the combinatorial background angular distribution modeling
Diff. Branching ratios $B \rightarrow K^{(*)} \mu^+ \mu^-$

- **Differential branching ratio $B \rightarrow K^{(*)} \mu^+ \mu^-$ vs $q^2$**

- uncertainties from form factors, normalized to $B \rightarrow J/\psi K^{(*)}$

4756 candidates

176 candidates

162 candidates

- In agreement with SM prediction but measurements systematically below expectations

Angular Analysis \( B \rightarrow K^* \mu^+ \mu^- \)

- **Angular Analysis \( B \rightarrow K^* \mu^+ \mu^- \)**
  - Forward backward muon asymmetry, SM \( q^2_0 \sim 4 \text{ GeV}^2/c^4 \)
  - Full angular distribution, observables sensible to \( C^{(7)}, C^{(9)}, C^{(10)} \) and form factors.

\[
\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^3(\Gamma + \Gamma)}{d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.
\]

\[
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l
\]

\[
- F_L \cos^2 \theta_K \cos 2\theta_l + S_i \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi
\]

\[
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin 2\theta_l \sin \phi
\]

\[
+ \frac{2}{9} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi
\]

\[
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \bigg].
\]

- Depends on \( F_L, A_{FB}, S_i \), observables, that are sensible to \( C^{(7)}, C^{(9)}, C^{(10)} \) and form factors.
- Additional “optimized” observables, with cancellation of leading form-factor uncertainties

\[
P_5' = \frac{S_5}{\sqrt{F_L (1 - F_L)}}
\]

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**References:**

- JHEP 08 (2013) 131
- JHEP 01 (2013) 048
Angular Analysis $B \to K^* \mu^+ \mu^-$

- Control channel $B \to J/\psi (\mu^+ \mu^-) K^*$, remove $J/\psi$, $\psi(2S)$ resonances
  - veto peaking background due to mis-id: $\Lambda_b \to p K^- \mu^+ \mu^-$, $B_s \to \phi (K^+ K^-) \mu^+ \mu^-$
- Full fit in $q^2$ angles, mass and also $K^*$ mass and S-wave contribution
  - angular acceptance parameterized with Legendre polynomials, check with control channel
  - events are weighted according with acceptance
  - background angular distribution parameterized using Chebychev Polynomials (2nd degree)
Angular Analysis $B \rightarrow K^* \mu^+ \mu^-$

$1.1 < q^2 < 6 \text{ GeV}^2/\text{c}^2$

Fig. 4 shows the projections of the fitted probability density function on the angular and mass distributions for the $1.1 < q^2 < 6 \text{ GeV}^2/\text{c}^2$ bin. Good agreement of the fitted function with the data is observed. Projections for the other $q^2$ bins are provided in Appendix B.
Angular Analysis $B \rightarrow K^* \mu^+ \mu^-$

- LHCb has clarified the $A_{FB}$ picture
- zero-crossing point of $A_{FB}$ in agreement with SM
  \[(3.7^{+0.8}_{-1.1}) \text{ GeV}^2/c^4,\]
- but mild tension in $A_{FB}$ with respect SM ($\sim 1\sigma$)

Angular Analysis $B \rightarrow K^* \mu^+ \mu^-$

**Good agreement with SM**

**But tension on $S_5$**
Angular Analysis $B \to K^* \mu^+ \mu^-$

◆ Wilson coefficients global fit from $b \to s \mu^+ \mu^-$

- Including results from LHCb but also ATLAS, CMS
- Preferred solution: $C^{NP}_9 \sim -1.1$!

Several interpretations

- A possible $Z'$ at 7 TeV with FV coupling.
- If different coupling to $e, \mu$; it could explain $R_K$

JHEP 1401 (2014) 069, JHEP 1402 (2014) 111,
PRD 89 (2014) 095033

Altmannshofer and Straub arXiv:1503.06199
Branching ratio and Angular Analysis $B_s \rightarrow \phi(K^+K^-) \mu^+\mu^-$

- **Branching ratio and angular analysis**
  - Similar to $B \rightarrow K^* \mu^+\mu^-$, but production suppressed and not flavour specific final state

- Most precise measurement
- 3 $\sigma$ tension in $1 < q^2 < 6$ GeV$^2$/c$^2$

$$\frac{B(B^0_s \rightarrow \phi \mu^+\mu^-)}{B(B^0_s \rightarrow J/\psi \phi)} = (7.40^{+0.42}_{-0.40} \pm 0.16 \pm 0.21) \times 10^{-4},$$

$$B(B^0_s \rightarrow \phi \mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.18 \pm 0.23 \pm 0.60) \times 10^{-7}$$
Branching ratio and Angular Analysis $B_s \rightarrow \phi(K^+K^-) \mu^+\mu^-$

\[
\frac{1}{d\Gamma/dq^2} \frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K \right. \\
+ \frac{1}{2}(1 - F_L) \sin^2\theta_K \cos 2\theta_l - F_L \cos^2\theta_K \cos 2\theta_l \\
+ S_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi \\
+ A_5 \sin 2\theta_K \sin \theta_l \cos \phi + A_6^s \sin^2\theta_K \cos \theta_l \\
+ S_7 \sin 2\theta_K \sin \theta_l \sin \phi + A_8 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ A_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \right].
\]

(if no band: SM prediction is zero)

- In agreement with SM
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9} \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10} \]

**LHCb B\( (s)\rightarrow\mu\mu\) search**

- Very rare decay, SM helicity suppressed
- Very sensible to presence of new scalar \((C_{10}, C_s, C_P)\)
- Precise SM prediction

![Diagram](image)

**LHCb B\( (s)\rightarrow\mu\mu\) search**

- Great invariant mass resolution \(~23\) MeV
- separation signal/background with a BDT
- calibrated with data B\( (s)\rightarrow hh\)
- Normalized to B\(^+\rightarrow J/\psi(\mu^+\mu^-)K^+\)

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**Figure 2:** C. Linn (CERN) | EW penguin decays

**Figure 3:** Plots illustrating the combination of all categories used in the categorized-BDT method (left) and the 1D-BDT method (right). For these plots, the individual categories are

- LHCb
- Signal
- Background

**PDF**

\[ \text{PDF} \]

**BDT**

- LHCb
- BDT>0.7
- 3 fb\(^ {-1}\)

**Candidates / (14 MeV/c\(^ 2\))**

- LHCb
- BDT>0.7
- 3 fb\(^ {-1}\)

\[ m_{\mu\mu} \text{ [MeV/c}^2\text{]} \]

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**PRL 112 (2014) 101801**

**Combined LHCb and CMS search**

- simultaneous analysis, shared signal and nuisance parameters

![Graph showing CMS and LHCb data](image)

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.8 \pm 0.7 \right) \times 10^{-9} \text{ and } \\
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = \left(3.9 \pm 1.6 \right) \times 10^{-10},
\]

- \(B_s \rightarrow \mu\mu\) first observation (6.2 \(\sigma\)) and \(B \rightarrow \mu\mu\) with 3\(\sigma\) significance!
- In agreement with SM!, stringent constraint for BSM!
$B(s) \rightarrow \mu\mu$

- **likelihood scan**
  - Figure 2 provides an improved measurement of its branching fraction. This concludes a search that establishes conclusively the existence of the $S$ (see Extended Data Fig. 5).
  - The combined analysis of data from CMS and LHCb, taking advantage of their full statistical power, is denoted with the vertical (red) band. The (black) cross on panel (a) shows the result of the fit in a single dimuon invariant mass spectrum, the mass distribution for the six categories with the highest $S$ is overlaid. An alternative representation of the fit to the dimuon invariant mass likelihood scans for both decay modes are displayed in the same figure. In addition to contours for $B(\bar{B}_s^0 \rightarrow \mu^+ \mu^-)$, the (black) cross on panel (b) shows the measured value of $R (\text{theory}) = 0.0295 \pm 0.0028$.

- **Determination of the BR ratio**
  - The measured value of $R$ is $0.0295^{+0.0028}_{-0.0025}$. Associated likelihood contours and one-dimensional distributions of all categories, weighted according to values of $S$, as well as displays of events with high probability to be genuine signal decays, are shown in that category, are added together and shown in Fig. 2. The result of the simultaneous fit is overlaid. An alternative representation of the fit to the dimuon invariant mass is shown in Fig. 4, which provides an improved measurement of its branching fraction. This concludes a search that establishes conclusively the existence of the $S$ (see Extended Data Fig. 5).
  - The combined fit leads to the measurements $B(\bar{B}_s^0 \rightarrow \mu^+ \mu^-) = 9.39^{+0.67}_{-0.52}$ and $B(\bar{B}_s^0 \rightarrow \mu^+ \mu^-) = 6.2^{+0.6}_{-0.5}$.

- **SM ratio prediction**
  - PRL 112 (2014) 101801
  - $0.0295^{+0.0028}_{-0.0025}$

- **Measured for first time**
  - $R = \frac{B(\bar{B}_s^0 \rightarrow \mu\mu)}{B(\bar{B}_s^0 \rightarrow \mu\mu) \times \text{SM ratio prediction}} = 0.14^{+0.08}_{-0.06}$

- **Compatible with SM at 2.3 $\sigma$**

- **SM ratio prediction**
  - PRL 112 (2014) 101801
  - $0.0295^{+0.0028}_{-0.0025}$

- **Measured for first time**
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- **Compatible with SM at 2.3 $\sigma$**
BR is sensitive to:

\[ BR(B_s \to \mu^+\mu^-) \propto m_{\mu}^2 \left( \left| (C_{10}^{SM} + C_{10}^{NP} - C_{10}^{s}) - \frac{m_{B_s}}{2m_{\mu}} (C_{SP} + C_{SP}^{'}) \right|^2 + \left| \frac{m_{B_s}}{2m_{\mu}} (C_{SP} - C_{SP}^{'}) \right|^2 \right) \]

- LHCb+CMS measurements eliminates NP on \( C_{10}^{NP} - C_{10}^{'}, \) and constrain \( C_s-C_s' \)

arXiv:1407.7044
LNV: $B^- \rightarrow \pi^+ \mu^- \mu^-$

- **Search for Majorana neutrinos using $B^- \rightarrow \pi^+ \mu^- \mu^-$**
  - 250-5000 MeV and lifetimes $<1000$ ps
  - categories: detached or not ($< 1ps$): BR limit vs mass, lifetime

\[
\begin{array}{lll}
\tau < 1 \text{ ps} & 19 \text{ (17.8 bkg) candidates} & 60 \text{ (54.5 bkg) candidates} \\
\tau > 1 \text{ ps} & 1 < \tau < 1000 \text{ ps} &
\end{array}
\]

\[\mathcal{B}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9} \] @ 95% C.L.

- $\tau < 1$ ps

\[\text{Upper limit} \times 10^{6} \]

\[\text{Neutrino mass [MeV]} \]

- $\tau > 1$ ps

\[\text{Upper limit} \times 10^{6} \]

\[\text{Neutrino mass [MeV]} \]
Conclusions

- Rare hadron b decays allow us to explore *indirectly NP*

- Stringent constraints for BSM due to the LHCb+CMS observation of $B_s \rightarrow \mu \mu$ and the evidence of $B \rightarrow \mu \mu$ in agreement with SM

- LHCb rare B decays are largely in agreement with SM

- But there are some tantalizing tensions:
  - In the lepton universality ratio from $B^+ \rightarrow K^+ l^+ l^-$
  - In one observable, $P'_5$, of the angular distributions of $B \rightarrow K^* \mu^+ \mu^-$, there is a local discrepancy with SM at $\sim 3.7 \sigma$
  - They can be accommodated in a global fit of Wilson Coefficients, with preferred solution: $C_{NP9} \sim -1.1$

- LHCb is running again!
  - $B_{(s)} \rightarrow \mu \mu$ analysis will enter in a different era!
  - Expectation about updates on the angular distribution of $b \rightarrow s \mu \mu$ processes
  - And pay attention to the checks of the lepton universality
backup!!!!!!!!!!!!!!!!!!!!!!!!!!!
Angular Analysis $B \rightarrow K^* \mu^+ \mu^-$

- Control channel $B \rightarrow J/\psi(\mu^+ \mu^-) K^*$
- consistent with current measurements

Figure 7: Angular and mass distribution of $B_0 \rightarrow J/\psi K^*$ candidates in data. A small signal component is also included in the fit to account for $B_0 \rightarrow J/\psi K^*$ decays. Overlaid are the projections of the total fitted distribution (black line) and its different components. The signal is shown by the blue component and the background is shown by the red hatched component.
**LFV: \( \tau \rightarrow 3\mu \)**

- **Search for LFV with \( \tau \rightarrow 3\mu \)**
  - Large inclusive production from b,c
  - Separation using two discriminants (geometric, 3 body, and PID) and \( \tau \) mass
  - Normalization and control channel \( D_s^- \rightarrow \phi(\mu\mu)\pi^- \)

\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 4.6 (5.6) \times 10^{-8}. \]

@ 90 (95)% C.L.

- Approaching current best 90% C.L. limits from Babar, 3.3 \( 10^{-8} \) and Belle, 2.1 \( 10^{-8} \)
Lepton Universality $B^+ \rightarrow K^+ l^+ l^-$

- **Ratio of $B^+ \rightarrow K^+ \mu^+ \mu^-$, $B^+ \rightarrow K^+ e^+ e^-$ as test of lepton universality**

$$R_K = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B^+ \rightarrow K^+ e^+ e^-]} \frac{dq^2}{dq^2},$$

- uncertainties cancel on the rations
- in SM is almost one $\theta(10^{-3})$
- **LHCb analysis**
  - relative measurement with respect $B^+ \rightarrow K + J/\psi(l^+l^-)$
  - reconstruction of the $e$ with bremsstrahlung photons
  - in different trigger categories (e,h,other)
  - efficiencies from simulation, corrected with data
  - range $q^2 [1, 6] \text{ GeV}^2$
  - systematic dominated by the $B^+ \rightarrow J/\psi(ee)K^+$ mass parameterization and the trigger

$$R_K = 0.745^{+0.099}_{-0.074}\text{ (stat)} \pm 0.036\text{ (syst)}. $$