PSI/UZH Workshop:
Impact of $B \rightarrow \mu^+\mu^-$ on
New Physics Searches

18th-19th December 2017 at the Paul Scherrer Institute

Speakers: F. Bernlochner, A. Crivellin, I. de Medeiros Varzielas, S. Descotes-Genon, M. Fael, D. Ghosh, A. Greljo, M. Hoferichter, G. Isidori, U. Langenegger, M. Misiak, M. Mulder, U. Nierste, A. Papa, M. Rama, P. Reznicek and D. Straub

Abstract

In these mini-proceedings we review the results of the workshop “Impact of $B \rightarrow \mu^+\mu^-$ on New Physics Searches” that took place at the Paul Scherrer Institute (PSI) on the 18th-19th December 2017.

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1 Introduction

So far, the LHC has not directly observed any particle beyond the ones of the Standard Model (SM). However, in recent years interesting hints for New Physics (NP) have been accumulated in flavour physics.

These discrepancies with the SM predictions are most pronounced in semi-leptonic $B$ decays. Here, we have two classes of processes:

- $b \to c\tau\nu$: In these processes, mediated at tree-level in the SM, several measurements like
  \begin{align}
  R_\tau(X) &\equiv \frac{B(B \to X\tau\nu_\tau)}{B(B \to X\ell\nu_\ell)} \quad \text{with } X = D, D^* , \\
  R_\tau(J/\psi) &\equiv \frac{B(B_c \to J/\psi\tau\nu_\tau)}{B(B_c \to J/\psi\ell\nu_\ell)}
  \end{align}
  with $\ell = e, \mu$ point towards lepton flavour universality violation (LFUV) in $\tau - \mu, e$ at the $\approx 4\sigma$ level [1].

- $b \to s\ell^+\ell^-$: This flavour changing neutral current process is loop suppressed and is proportional to the CKM element $V_{ts}$. Here the measurements of $R_\mu(K)$ [2] and $R_\mu(K^*)$ [3], defined as
  \begin{align}
  R_\mu(X) &\equiv \frac{B(B \to X\mu^+\mu^-)}{B(B \to Xe^+e^-)}
  \end{align}
  are supported by other $b \to s\mu^+\mu^-$ observables (like $P_5^\mu \equiv P_5'$ as defined in [4]) which also show deviations from the SM predictions.

In the second class of processes, the decay $B_s \to \mu^+\mu^-$ is included. Currently, the measurements are in agreement with the SM. However, while the theory predictions are quite precise, the experimental errors are still as large as the effect one can expect from other $b \to s\mu^+\mu^-$ observables like $R_\mu(K^{(*)})$, $P_5'$, etc. Nonetheless, in the future we can expect significant progress in $B_s \to \mu^+\mu^-$ and this decay will play a key role in distinguishing among different NP scenarios. Furthermore, with increasing statistics, one can also improve the search for $b \to d\ell^+\ell^-$ transitions, closing in on the SM predictions and making $B_d \to \mu^+\mu^-$ a golden mode for a NP discovery.

In this workshop, we discussed the current experimental status of $b \to s\ell^+\ell^-$ transitions (with focus on $B \to \mu^+\mu^-$) as well as possible connections to $b \to c\tau\nu$, charged lepton flavour violation (LFV), and kaon physics.

2 Summary of presented talks

In the following sections we will summarise the talks presented during the workshop. The speakers’ slides are available on the conference web page indico.cern.ch/event/655338/.
2.1 $B \to \mu^+\mu^-$ at CMS

Speaker: Urs Langenegger
Paul Scherrer Institute

CMS searched for both $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ events in the Run-1 data, corresponding to 25 fb$^{-1}$. The current status of these measurements, using an unbinned maximum likelihood fit, is [5]

$$B(B_s \to \mu^+\mu^-)_{\text{CMS}} = (3.0^{+1.0}_{-0.9}) \times 10^{-9},$$
$$B(B_d \to \mu^+\mu^-)_{\text{CMS}} < 1.1 \times 10^{-9} \ (95\% \ C.L.).$$

The $B_s \to \mu^+\mu^-$ signal yield is incompatible with the background-only hypothesis at 4.3 $\sigma$. In addition, CMS also performed an analysis of $B \to K^*\mu^+\mu^-$ determining $P_1$ and $P_5$ [6]. Also here, the results are compatible with the SM predictions but still have quite large errors due to statistics.

By 2017 the integrated luminosity has been increased by a factor of three and the Run-2 analysis is pursued with high priority. An analysis with 300 fb$^{-1}$ will give a 12% accuracy in $B(B_s \to \mu^+\mu^-)$ and a 47% accuracy in $B(B_d \to \mu^+\mu^-)$ [7]. Furthermore, an analysis of $R_\mu(K)$, testing the current LHCb results, is forthcoming.

2.2 $B \to \ell^+\ell^-$ at LHCb

Speaker: Matteo Rama
INFN Pisa

A new LHCb branching fraction measurement in 2017 uses an improved analysis as well as more data. The results are [8]

$$B(B_s \to \mu^+\mu^-)_{\text{LHCb}} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9},$$
$$B(B_d \to \mu^+\mu^-)_{\text{LHCb}} = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10}$$
$$< 3.4 \times 10^{-10} \ (95\% \ C.L.).$$

The latter branching ratio disfavours the background-only hypothesis at 1.6 $\sigma$. Both results are compatible with the SM predictions.

In addition, the $B_s \to \mu^+\mu^-$ effective lifetime was measured for the first time [8]:

$$\tau (B_s \to \mu^+\mu^-)_{\text{LHCb}} = (2.04 \pm 0.44 \pm 0.05) \text{ps}.$$ (5)

This is consistent with the lifetime asymmetry $A^\mu_\Delta = 1(-1)$ hypothesis at 1.0(1.4) $\sigma$.

In addition, LHCb also searched for $B_q \to \tau^+\tau^-$ decays, which are experimentally very challenging. The $B_s$ and $B_d$ decays cannot be separated and hence, assumptions on one decay are needed to extract the limit on the other one. LHCb obtains [9]

$$B(B_s \to \tau^+\tau^-)_{\text{LHCb}} < 5.2(6.8) \times 10^{-3} \ (90(95)\% \ C.L.),$$
$$B(B_d \to \tau^+\tau^-)_{\text{LHCb}} < 1.6(2.1) \times 10^{-3} \ (90(95)\% \ C.L.).$$ (6a) (6b)
There is also a recent update on the LFV decays $B \to e^\pm \mu^\mp$ \cite{10}:

\begin{align}
    B(B_s \to e^\pm \mu^\mp)_{\text{LHCb}} &< 5.4(6.3) \times 10^{-9} \quad (90(95)\% \text{ C.L.}), \\
    B(B_d \to e^\pm \mu^\mp)_{\text{LHCb}} &< 1.0(1.3) \times 10^{-9} \quad (90(95)\% \text{ C.L.}),
\end{align}

which is a factor 2-3 more precise than the previous LHCb measurements.

### 2.3 $b \to s\ell^+\ell^-$ at LHCb

**Speaker: Mick Mulder**

Nikhef

The most significant deviations from the SM predictions in $b \to s\ell^+\ell^-$ processes were found by the LHCb collaboration. In 2013, using the 1 fb$^{-1}$ dataset, the LHCb experiment measured the optimised observables of \cite{11} for $B \to K^*\mu^+\mu^-$ \cite{12}, observing a sizeable 3.7$\sigma$ discrepancy in one bin of $P_5^\ell$. This was later confirmed by the analysis of the 3 fb$^{-1}$ dataset, finding 3$\sigma$ deviations in each of two adjacent bins at large $K^*$ recoil \cite{4}. Furthermore, LHCb also measured the branching ratios of several semi-leptonic $B$ decays \cite{13,14} observing a systematic deficit with respect to SM predictions.

A conceptually new element arose when the ratios $R_{\mu}(K)$ \cite{2} and $R_{\mu}(K^*)$ \cite{3} were measured and found to be significantly below the SM predictions which are very close to one (see Figure 1).

Currently, many more tests of LFUV, such as $R_{\mu}(\phi)$, $R_{\mu}(\Lambda)$ or $P_5^{\mu} - P_5^{e}$, are under investigation at LHCb and significant improvements on LFV decays like $B \to K\mu^\pm e^\mp$ or $\Lambda_b^0 \to \Lambda^0\mu^\pm e^\mp$ are expected.

![Figure 1: Measurements and SM predictions of $R_{\mu}(K)$ and $R_{\mu}(K^*)$. Figure taken from \cite{2,3}.](image-url)
2.4 $b \to s \ell^+ \ell^-$ at ATLAS

Speaker: Pavel Reznicek
Charles University

The ATLAS experiment performed measurements of $B \to \mu^+ \mu^-$ [15] and an angular analysis of $B_d \to K^{*0} \mu^+ \mu^-$ [16].

The $B \to \mu^+ \mu^-$ analysis was done using the full Run-1 dataset of $(4.9 + 20) \text{fb}^{-1}$ at 7 and 8 TeV respectively with a muon threshold of $p_T(\mu) > 4 \text{ GeV}$. The branching ratio measurement is normalised to $B_s \to J/\psi (\mu^+ \mu^-)K^{\pm}$ and corrected by Monte Carlo to account for the different production cross sections and the different detector acceptances and efficiencies. To discriminate signal from background, a boosted decision tree (BDT) was trained on Monte Carlo data and tested on the data side bands. The result is compatible with the SM at 2.0σ

$$B(B_s \to \mu^+ \mu^-)_{\text{ATLAS}} = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9},$$

$$B(B_d \to \mu^+ \mu^-)_{\text{ATLAS}} < 4.2 \times 10^{-10} \text{ (95\% C.L.)} \ .$$

In the most recent analysis of $B_d \to K^{*0} \mu^+ \mu^-$ using 20.3 fb$^{-1}$ of 8 TeV data the decay angles were fitted in the most general parametrisation allowed by the process. The analysis, which was done up to $q^2 = m_{\ell^+ \ell^-}^2 < 6 \text{ GeV}$, suffers mostly from its low statistics but allows one to cancel large hadronic uncertainties from the form factors by defining the $P_i^{(t)}$ variables. The results are roughly compatible with the SM predictions, with the largest deviation of 2.5σ in $P_5^t$ which is compatible with the LHCb measurement.

In the future, detector upgrades and new trigger strategies will help to cope with the higher luminosity. Further, the feasibility of measuring final states including electrons is under investigation.

2.5 $B \to \mu^+ \mu^-$ theory status

Speaker: Mikolaj Misiak
University of Warsaw

The average time-integrated branching ratios for $B_q \to \ell^+ \ell^-$ within the SM are known very precisely. They are given by [17]

$$\mathcal{B}_{q\ell} = \left| V_{tb} V_{tq}^{*} \right|^2 G_F^2 m_{\ell^+}^3 m_{B_q} f_{B_q}^2 \sqrt{1 - \frac{4m_{\ell^-}^2}{m_{B_q}^2} \eta_{\text{QED}}} |C_A(\mu_b)|^2 \ ,$$

where all the masses are assumed to be renormalised on shell, and $\Gamma_H^q$ is the decay width of the heavier eigenstate in the $B_q\bar{B}_q$ system. Perturbative calculations of the Wilson coefficient $C_A$, including the three-loop QCD [18] and two-loop electroweak corrections [19], give $C_A(\mu_b) \simeq 0.4690 (M_t/173.1 \text{ GeV})^{1.53} (\alpha_s(m_Z)/0.1184)^{-0.09}$ at $\mu_b = 5 \text{ GeV}$ [17]. In the global $b \to s \ell^+ \ell^-$ fits, $C_{10} = -2C_A / \sin^2 \theta_W$ can be used instead, after carefully adjusting the renormalization scheme for $\sin^2 \theta_W$.

All the non-perturbative inputs in Eq. (9) that come from theoretical calculations are encoded in the $B_q$-meson decay constants $f_{B_q}$ (that can reliably be calculated using lattice...
Table 2: Input parameters used in evaluating the SM predictions for $B_s\mu\mu$ and $B_d\mu\mu$.

| parameter | value | source |
|-----------|-------|--------|
| $M_t[GeV]$ | $174.30(65)$ | [23] |
| $\alpha_s(m_Z)$ | $0.1182(12)$ | [24] |
| $f_{B_s}[GeV]$ | $0.2240(50)$ | [25, 26] |
| $f_{B_d}[GeV]$ | $0.1860(40)$ | [25, 26] |
| $|V_{cb}|$ | $0.04200(64)$ | [22] |
| $|V_{cb}^*V_{ts}|/|V_{cb}|$ | $0.9819(4)$ | derived from [27] |
| $|V_{td}^*V_{tb}|/|V_{cb}|$ | $0.0087(2)$ | derived from [27] |
| $1/\Gamma_h^s[ps]$ | $1.619(9)$ | [1] |
| $1/\Gamma_f^d[ps]$ | $1.518(4)$ | [1] |

QCD) as well as in the QED correction factor $\eta_{QED}$. The latter factor stands for QED effects emerging below the scale $\mu_b$, and depending on several Wilson coefficients. A recent calculation [20] of power-enhanced QED effects gives $\eta_{QED} = 0.993 \pm 0.004$.

Using the inputs from Table 2, we obtain the SM predictions $\overline{B}_{s\mu} = (3.54 \pm 0.21) \times 10^{-9}$ and $\overline{B}_{d\mu} = (1.00 \pm 0.07) \times 10^{-10}$. Apart from the parametric uncertainties, an additional uncertainty of 1.5% has been included in the above predictions, following the estimate in [17].

The largest uncertainty at the moment is parametric, coming mainly from the decay constants $f_{B_q}$ and CKM elements $V_{tq}$. In the $B_s \rightarrow \ell^+\ell^-$ case, the element $V_{ts}$ is linked via unitarity to $V_{cb}$. However, the determination of $V_{cb}$ suffers from tensions between the inclusive and exclusive calculations. Since these tensions cannot be attributed to NP [21], it is very important to improve on the determinations of $V_{cb}$ to reduce the uncertainty in $\overline{B}_{s\ell}$. Here, only the inclusive determination [22] of $V_{cb}$ has been used.

### 2.6 $b \rightarrow s\mu^+\mu^-$ global analysis

**Speaker: Sébastien Descotes-Genon**

Laboratoire de Physique Théorique d’Orsay, CNRS

A global six-dimensional fit to all available $b \rightarrow s\ell^+\ell^-$ data for the Wilson coefficients $C_7^{(7)}$, $C_9^{(9)}$, $C_{10}^{(10)}$ confirms the need for a large contribution to $C_9$, with a SM pull reaching $5.0 \sigma$ once the $R_\mu(K^*)$ measurement is included [28]. Hadronic uncertainties conform to theoretical expectations [29] and unexpectedly large effects (power corrections to form factors, charm-loop contributions) are disfavoured by the significant amount of LFUV observed.

While a sizeable effect in $C_9$ with muons is required ($\mathcal{O}(25\%)$ of the SM contribution), an effect in $C_{10}$, including even $C_9 = -C_{10}$, is possible. Even though $R_\mu(K)$ and $R_\mu(K^*)$ can already tell us about NP effects in $C_9$, $B_s \rightarrow \mu^+\mu^-$ is crucial for determining if $C_{10}$ is SM-like or not. Therefore, if $C_9 = -C_{10}$ is realised in nature, one expects a significant reduction of $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ compared to the SM.
Figure 3: Predictions of the branching ratios of the $b \to s\tau^+\tau^-$ processes (including uncertainties) as a function of $R_\tau(X)/R_\tau(X)^{\text{SM}}$. Figure taken from [30].

Another possibility to establish the presence of NP in $b \to s\ell^+\ell^-$ transitions is looking at $b \to s\tau^+\tau^-$ processes. Here, $R_\tau(D)$, $R_\tau(D^*)$ and $R_\tau(J/\psi)$ suggest that $b \to s\tau^+\tau^-$ processes can be enhanced by up to three orders of magnitude compared to the SM [30], (see Figure 3).

2.7 $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ in the SM EFT

Speaker: Matteo Fael
University of Siegen

In order to evaluate the predictions of the SM effective field theory (EFT), realised above the EW breaking scale, the matching of the gauge invariant dimension-six operators on the $B$ physics Hamiltonian (including LFV operators) integrating out the top, $W$, $Z$ and the Higgs has to be performed [31]. Here, operators within the SMEFT involving top quarks are of special interest since they do not contribute to $b \to s$ processes at the tree level, because the top is not a dynamical degree of freedom of the $B$ physics Hamiltonian. Therefore, all operators involving right-handed top quarks can give numerically important contributions at the one loop-level [32]:

1. 4-fermion operators to 4-fermion operators ($\Delta B = \Delta S = 1$)
2. 4-fermion operators to 4-fermion operators ($\Delta B = \Delta S = 2$)
3. 4-fermion operators to $O_7$ and $O_8$
4. Right-handed $Z$ couplings to $O_9$, $O_{10}$ and $O_{10}^q$
5. Right-handed $W$ couplings to $O_7$ and $O_8$
6. Magnetic operators to $O_7, O_8, O_9, O_{10}$ and $O_4^q$

In fact, for a vector operator with right-handed top quarks and left-handed muons, this effect can be used to explain the anomalies in $b \to s\mu^+\mu^-$ in UV complete models, either with a $Z'$ [33] or with leptoquarks (LQ) [34].

### 2.8 Impact of future $B \to \mu^+\mu^-$

**Speaker: David Straub**

TU Munich

The $B_s \to \mu^+\mu^-$ decay is particularly sensitive to scalar NP contributions that can be parametrised in a model-independent way by means of two complex parameters $S$ and $P$ [35]:

$$B(B_s \to \mu^+\mu^-) = \frac{G_F \alpha^2}{16\pi^3} |V_{tb}|^2 f_{B_s} m_{B_s} m_{\mu}^2 \sqrt{1 - \frac{4m_{\mu}^2}{m_{B_s}^2}} |C_{10}^{\text{SM}}|^2 \left( |P|^2 + |S|^2 \right). \quad (10)$$

Within an EFT approach, the effective operators giving rise to $S$ and $P$ are

$$O_{10}^{(t)} = (\bar{s}_L(R)\gamma_\rho b_L(R)) (\bar{\mu} \gamma^\rho \gamma^5 \mu),$$
$$O_S^{(t)} = m_b (\bar{s}_L(R)\gamma_\rho b_R(L)) (\bar{\mu} \mu),$$
$$O_P^{(t)} = m_b (\bar{s}_L(R)\gamma_\rho b_R(L)) (\bar{\mu} \gamma^5 \mu). \quad (11)$$

The pseudoscalar contribution $P$ can be expressed in terms of the Wilson coefficient combinations $C_{10} - C_{10}'$ and $C_P - C_P'$, while the scalar contribution $S$ is proportional to $C_{S} - C_{S}'$. This leads to a degeneracy in the parameter space that can be broken by the measurement of the lifetime asymmetry $A_{\Delta f}^{\mu^+\mu^-}$ (up to a two-fold ambiguity)

$$A_{\Delta f}^{\mu^+\mu^-} = \frac{|P|^2 \cos (2\varphi_P - \varphi_s^{\text{NP}}) - |S|^2 \cos (2\varphi_S - \varphi_s^{\text{NP}})}{|P|^2 + |S|^2}. \quad (12)$$

Large effects in the coefficients $C_{S,P}$ arise at tree level mediated by a neutral scalar $\varphi \sim (1, 2, -1)$ or vector LQ in the representations $U_1 \sim (3, 1, -4/3)$ or $V_2 \sim (3, 2, -5/3)$. In other contexts, like the MFV MSSM, these contributions arise at the loop level. In Figure 4 the current constraints on the Wilson coefficients $C_S$ and $C_S'$ are shown, together with the expected constraints at the future run 5.

Constraints from the $B_s \to \mu^+\mu^-$ branching ratio and the lifetime asymmetry are shown to be complementary to direct searches in probing NP.
Figure 4: Present and future constraints on the real parts of the Wilson coefficients $C_S$ and $C'_S$ (1 $\sigma$ and 2 $\sigma$ contours). Figure taken from [35].

2.9 Colloquium: Precision studies in flavour physics: a gateway to new laws of nature

Speaker: Ulrich Nierste
Karlsruhe Institute of Technology

Even though not directly related to the hints for LFUV, there are also interesting hints for NP in $\epsilon'/\epsilon$ at the 3 $\sigma$ level [36]. While neither the tensions in $b \to s\mu^+\mu^-$ [37] nor in $b \to c\tau\nu$ [38] can be explained by the most common models of NP, the plain MSSM can account for $\epsilon'/\epsilon$ [39]. This is possible due to cancellations between crossed and uncrossed box-diagram contributions to kaon mixing [40]. In this case, interesting correlations with $K \to \pi\nu\bar{\nu}$ arise [41] which can be tested at NA62.

2.10 Experimental overview on $R_{\tau}(D)$ and $R_{\tau}(D^*)$

Speaker: Florian Bernlochner
Karlsruhe Institute of Technology

The SM predictions for the ratio $R_{\tau}(D)$ are $R_{\tau}(D)_{\text{SM}} = 0.299 \pm 0.003$ and $R_{\tau}(D^*)_{\text{SM}} = 0.257 \pm 0.003$ [42]. The experimental results are summarised in Figure 5, where the current world average is shown, as well as the SM predictions. The BaBar measurements of $R_{\tau}(D)$ and $R_{\tau}(D^*)$ [43, 44] using hadronic and leptonic tags for the tau decays show the biggest deviations from the SM predictions of 2 $\sigma$ and 2.7 $\sigma$, respectively. The Belle measurements of $R_{\tau}(D^{(*)})$ [45, 46, 47] are performed with various techniques: with the $\tau$ decaying to $e\nu\bar{\nu}$ or $\mu\nu\bar{\nu}$ and a hadronic and semileptonic tag. The deviations from the SM are less pronounced, i.e. below the 2 $\sigma$ level, but consistent with the values provided by BaBar. Furthermore, [46, 47] contain the first polarisation measurements in this context.

LHCb measures $R_{\tau}(D^*)$ from two different decay channels. In $B_d \to D^*\tau^-\bar{\nu}$ with the subsequent decay $\tau \to \mu\nu\bar{\nu}$ [48], finding compatibility with BaBar and Belle and a 2.1 $\sigma$
deviation from SM. In $B_d \to D^{*-}\tau^+\bar{\nu}$ with the subsequent decay $\tau \to \pi\pi\pi(\pi^0)\nu$ [49] the result is only slightly higher than the SM value.

Recently, LHCb has also performed an analysis of the ratio $R_\tau(J/\psi)$ [50], obtaining the result

$$R_\tau(J/\psi) = 0.71 \pm 0.17 \pm 0.18,$$

which is significantly above the SM prediction of [0.25, 0.28], but the errors are still large.

Looking into the future, the expected precision for $R_\tau(D^{(*)})$ with a luminosity of 10 fb$^{-1}$ is 4%, and will improve further to 2% with a luminosity of 22 fb$^{-1}$. The expected precision for $R_\tau(D)$ ($R_\tau(D^*)$) at Belle II is 5.6% (3.9%) with 5 ab$^{-1}$ and 3.2% (2.2%) with 40 ab$^{-1}$.

### 2.11 $R_\tau(D)$ and $R_\tau(D^*)$ EFT analysis

*Speaker: Diptimoy Ghosh
ICTP Trieste*

The combined significance for NP in $b \to c\tau\nu$ processes is at the 4$\sigma$ level. In an effective field theoretical approach, one can examine which operators are capable of explaining $R_\tau(D)$ and $R_\tau(D^*)$ without violating bounds from other observables [51]. Here, three classes of operators are possible at the dimension-6 level: vector, scalar and tensor operators. While scalar operators cannot explain $R_\tau(D)$ and $R_\tau(D^*)$ at the same time without violating bounds from the $B_c$ lifetime [52, 53, 54, 55] and $q^2$ distributions [56, 53, 57], vector operators provide a good fit to data. In particular, purely left-handed operators are interesting possibilities. They simply rescale the SM contributions, leaving $q^2$ distributions unchanged, and predict $R_\tau(X)/R_\tau(X)_{SM}$ for $X \in \{D, D^*, J/\psi\}$. However, also tensor operators [58] (possibly in combination with scalar ones) are capable of addressing $b \to c\tau\nu$ data coherently.
2.12 Anomalies in $B$ decays: high-$p_T$ frontier

Speaker: Admir Greljo
JGU Mainz

Anomalies in $B$ meson decays point to a new mass scale potentially interesting for the ongoing experiments at the high-$p_T$ frontier (ATLAS and CMS). More precisely, the charged current anomaly ($b \rightarrow c \tau \nu$) implies the effective scale of $\mathcal{O}(1 \text{ TeV})$, while the neutral current anomaly ($b \rightarrow s \mu \mu$) implies the effective scale of $\mathcal{O}(30 \text{ TeV})$ [60]. This scale corresponds roughly to the mediator mass with $\mathcal{O}(1)$ couplings when the effect is tree-level generated. However, some explicit models exhibit parametric suppression (e.g. from flavour), or dynamical suppression (e.g. loop-generated), lowering the new mass scale towards the interesting range for the LHC.

All tree-level models have either colour-neutral vectors ($W'$ and $Z'$) or colour-triplet scalar or vector LQ, or a combination of those. The expected high-$p_T$ signatures of $Z'$ models are dilepton resonances or non-resonant deviations in the tails (see e.g. [61, 59]). Interestingly enough, even if the $Z'$ boson mass is beyond the kinematical reach for on-shell production, a correlated signal in the tails could be observed. As shown in Figure 6, the present dimuon LHC data already sets stringent limits on the $Z'$ models with minimal flavour violation (MFV) explaining $b \rightarrow s \mu \mu$ [59].

The $B$ physics anomalies inspired LQ searches at the LHC exhibit interesting interplay between three production mechanisms: LQ pair production, single LQ production in association with the lepton, and di-lepton production (see e.g. [62] for a recent discussion). In particular, as shown in [61], the present ditau LHC data sets stringent limits on most models for $b \rightarrow c \tau \nu$ with exclusive coupling to the third family. Sizeable bottom-strange flavour violation can partially relax these constraints [63, 64, 65], introducing potentially dangerous flavour changing neutral currents in the down quark sector.

The combined explanation of $B$ anomalies singles out the $U_1$ vector leptoquark representation as a viable single mediator model [63]. As shown in [63], going beyond LHC...
Figure 7: Outline of the model $PS_1 \times PS_2 \times PS_3 \rightarrow SM$, that provides an explanation for both flavour anomalies and Yukawa hierarchies. The high scale $PS_1$ breaking lies at $\Lambda_1 \sim 10^3$ TeV, while SM$_{1+2} \times PS_3 \rightarrow SM$ occurs in two steps at lower energies ($\Lambda_{23} \sim 20$ TeV and $\Lambda_3 \sim 1$ TeV). Figure taken from [67].

is required to fully explore the relevant parameter space. However, when considering an explicit ultraviolet completion of this simplified model (e.g. [66, 67, 68, 69]), a coloron decaying to dijet is predicted to be around the corner at the LHC.

2.13 Simultaneous explanations of $R_\tau(D)$, $R_\tau(D^*)$ and $b \rightarrow s \mu^+\mu^-$ data

Speaker: Gino Isidori
University of Zurich

The anomalies are only seen in semi-leptonic processes and indicate non-vanishing coefficients of left-handed vector operators. In order to explain $R_\tau(D)$, NP of $O(10\%)$ of the tree-level SM contribution is required. This is in contrast to $b \rightarrow s \mu^+\mu^-$ which is a loop- and CKM-suppressed process in the SM and therefore NP of approximately 25% of this (suppressed) contribution is required.

From the phenomenological point of view, this indicates NP with $O(1)$ couplings to third generation, moderate couplings to the second generation and small or vanishing couplings to the first generation, i.e. a structure similar to the one appearing in the SM Yukawa couplings.

One can follow two approaches to explain both anomalies simultaneously. First, using an EFT approach, it can be shown that both anomalies can be explained simultaneously without any fine tuning [63]. The corresponding EFT solution is not unique, but its main features are stable once we require a fit to both anomalies. In particular, left-handed four-fermion operators with almost equal strength for singlet and triplet terms are needed.
Second, one can try to derive these effective operators using simplified dynamical models. Among the possible options, the vector LQ singlet $U_1$ with quantum numbers $U_1 \sim (\bar{3}, 1, -4/3)$ gives a particularly good fit to data (with no fine tuning) [70]. However, the introduction of a massive vector LQ requires a Higgs sector in order to achieve an UV complete model. Recently, several models that use an $SU(4)$ Pati-Salam symmetry and give renormalisable massive vector LQ were proposed [66, 71, 67, 68, 72]. In [67] a model in which at high energies the three families are charged under three different gauge groups $PS_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i$ is introduced (see Figure 7). The interest of this model is that it offers not only a solution to the anomalies, but also an explanation for the observed hierarchies in the Yukawa couplings of quarks and leptons.

### 2.14 Experimental status and prospects for $\mu \rightarrow e$ experiments

**Speaker: Angela Papa**  
Paul Scherrer Institute

Some of the most severe bounds of LFV come from $\mu \rightarrow e$ experiments because these processes are practically zero in the SM. For example, the neutrino oscillation induced $\mu^+ \rightarrow e^+\gamma$ branching ratio lies with $10^{-54}$ far below the experimental reach. The other ‘golden channels’ for $\mu \rightarrow e$ flavour violation are $\mu \rightarrow eee$ and $\mu N \rightarrow eN$. A summary of the current and expected future bounds for these processes is shown in Table 8.

Because $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ are coincidence experiments, they benefit from a continuous (DC) muon beam like the one at PSI with an intensity of $O(10^8)\mu/s$. On the other hand, non-coincidence experiments measuring $\mu - e$ conversion need a pulsed beam that reaches $O(10^{11})\mu/s$. Because the future MEG II and Mu3e experiments have similar beam requirements (high intensity DC-beam at low momentum) they will share the PiE5 beam line of the HIPA accelerator at PSI. There are efforts ongoing to increase the intensity by two more orders of magnitude by 2025.

The clean back-to-back signature of $\mu \rightarrow e\gamma$ in MEG can be separated from the radiative muon decay $\mu \rightarrow \nu\bar{\nu}e\gamma$ or accidental backgrounds $\mu + \gamma \rightarrow \nu\bar{\nu}e + \gamma$. MEG II will double the resolution and use twice the beam intensity of MEG to further push the bound. MEG II will conduct a full engineering run in 2018.

For Mu3e the signature is more complicated and requires a very good energy resolution to fully reconstruct $\sum E_i = m_\mu$. This controls the background from the rare muon decay $\mu \rightarrow \nu\bar{\nu}eee$. To control accidental backgrounds, high timing and position resolution is necessary. To that end, the pixel layers’ thickness does not exceed 0.1% of the radiation lengths. In contrast to MEG, Mu3e will use the full rate of $10^8\mu/s$. A pre-engineering run

| Process         | Current upper limit  | Future sensitivity                                      |
|-----------------|----------------------|--------------------------------------------------------|
| $\mu \rightarrow e\gamma$ | $4.2 \times 10^{-13}$ [73] | $4 \times 10^{-14}$ (MEG II [74, 75])                   |
| $\mu \rightarrow eee$       | $1.0 \times 10^{-12}$ [76] | $1 \times 10^{-16}$ (Mu3e [77, 78, 79])                 |
| $\mu N \rightarrow eN$      | $7.0 \times 10^{-13}$ [80] | $\leq 10^{-16}$ (Mu2e [81, 82] and COMET [83])         |

Table 8: Current and future bounds for $\mu \rightarrow e$ processes
is expected in 2020.

$\mu - e$ conversion experiments such as Mu2e and COMET search for a single mono-
energetic electron. For that, they require a very large number of stopped muons $\mathcal{O}(10^{18})$. Both experiments need a good energy resolution to reject backgrounds from a muon decay
in orbit. Further, an extinction factor of the beam of $\mathcal{O}(10^{-10})$ and precise timing is
required to handle beam related backgrounds. This is further aided by having the stopping
target and the production target well separated. The third major background are cosmic
rays that may fake a high energy electron in the detector. The first phase of the COMET
experiment is expected to have a full engineering run 2018 while Mu2e is still under
construction.

### 2.15 Connections between $R_\mu(K)$, $R_\mu(K^*)$ and $\mu \to e$ processes

**Speaker:** Ivo de Medeiros Varzielas

Instituto Superior Técnico

An explanation of $R_\mu(K)$ and $R_\mu(K^*)$ requires new physics couplings to muons and/or
electrons. Among the possible extensions of the SM such as $Z'$ models, compositeness
or SUSY, this talk focuses on LQ. As shown in a model independent analysis, LQ can
provide a solution to these anomalies $[84, 85, 86]$. Based on $[87]$ the impact of LQ on the
LFV processes $B \to K\ell\ell$, $B \to \ell\ell$ and $\ell \to \ell'\gamma$ has been analysed, explaining $R_\mu(K)$
and $R_\mu(K^*)$. The focus of this analysis were the scalar triplet with quantum numbers
$\Delta \sim (3, 3, -2/3)$ and scalar doublet the $\Delta \sim (3, 2, -1/3)$. Experimental limits such as
$\mu \to e\gamma$, $B_s - \bar{B}_s$-mixing and $B \to K\mu e$ give constraints on the parameter space and a
combined analysis leads to an upper limit of the LQ mass of 50 TeV, which could be within
the reach of future colliders. The constraints will become more stringent in the coming
years, see Table 8.

Experimental data favour a Yukawa-like hierarchical structure of the LQ couplings.
From the theoretical point of view this can be achieved in a natural way e.g. introducing
an additional SU(3)$_F$ symmetry for SM fermions which is then broken by the vacuum
expectation value of the so-called familon. This way, one can either have or avoid LQ
coupling to electrons and hence, have models that may be tested in the future through
important constraints, e.g. $\mu \to e\gamma$ $[88]$.

### 2.16 Correlations with kaon physics

**Speaker:** Martin Hoferichter

University of Washington

The flavour anomalies discussed so far suggest to search for LFV and LFUV in the kaon
sector $[89]$. Here the decays $K \to \pi\ell^+\ell^-$ and $K \to \ell^+\ell^-$ are especially interesting but
also very challenging: long-distance contributions from the SM need to be separated from
the interesting short-distance effects, both of which enter in poorly known low-energy
constants of the expansion in chiral perturbation theory. However, in the context of
LFUV, this complication is absent if the difference between electron and muon parameters
is considered. This simplification is due to the fact that in the SM all interactions (except for the Higgs boson Yukawa couplings) are LFU conserving. Since the Higgs corrections are negligible, it follows that the SM decays of kaons to muons or electrons differ only by phase-space factors. Thus, any deviation from the SM predictions must be related to LFUV NP which is necessarily short-distance once the new particles are assumed to be heavy. Assuming MFV, the derived limits from kaon decays would need to be improved by at least an order of magnitude in order to probe the parameter space relevant for the explanation of the $B$ meson anomalies and thereby test those anomalies within the MFV hypothesis. However, it is well possible that NP does not respect MFV, so that effects in kaon decays could be observed earlier, or, if not, non-MFV models that predict so would be excluded.

Another anomaly that could in principle be related to $b \to s \mu^+ \mu^-$ and $b \to c \tau \nu$ is the $CP$ asymmetry in $\tau \to K_s \pi \nu$ which, as measured by the BaBar collaboration, differs from the SM prediction by $2.8\sigma$ [90]. Most non-standard interactions do not allow for the required strong phase needed to produce a non-vanishing $CP$ asymmetry, leaving only new tensor interactions as a possible mechanism [91, 92]. However, contrary to previous assumptions in the literature, the crucial interference between vector and tensor phases is suppressed by at least two orders of magnitude due to Watson’s final-state-interaction theorem [93]. Furthermore, the strength of the relevant $CP$-violating tensor interaction is strongly constrained by bounds from the neutron electric dipole moment [94] and $D$–$\bar{D}$ mixing. These observations together imply that it is extremely difficult to explain the current $\tau \to K_s \pi \nu$ measurement in terms of physics beyond the SM originating in the ultraviolet regime [95].

2.17 Summary and outlook

Speaker: Andreas Crivellin
Paul Scherrer Institute

The experimental hints for lepton flavour universality violation are convincing since they form a consistent picture: large effects related to tau leptons, moderate effects related to muons while electron channels seem to be SM-like. Confirming these hints would probably be the biggest breakthrough in particle physics since the discovery of parity violation in 1956. Accounting for LFUV would require some radical NP, providing us with a convincing physics case for a future collider, and would lead us to a golden age for particle physics. On the other hand, if these hints for NP disappeared, it would be well possible that we are ahead of a desert ranging over many orders of magnitude in energy. However, if one believes in statistics and that the experimental analysis as well as the theory predictions were done correctly, the first option is fortunately much more likely.

3 Conclusion

In recent years we accumulated intriguing hints for physics beyond the SM in $b \to c \tau \nu$ and $b \to s \mu^+ \mu^-$ processes. These signs of NP are accompanied by more hints for NP whose common pattern is the violation of lepton flavour universality (see Figure 9).

In this workshop we first considered the experimental and theoretical status of $b \to$
Figure 9: Deviations from the SM predictions pointing at the violation of lepton flavour universality. In addition to the hints discussed in this workshop, we included the anomalous magnetic moment of the muon (see e.g. [96]) and $V_{us}$ extracted from tau decays [97].

$s\mu^+\mu^-$ transitions with focus on $B_s \rightarrow \ell^+\ell^-$. Currently, the deviations from the SM predictions are dominated by the measurements of $R_{\mu}(K^{(*)})$ and $P'_5$. However, because of its theoretical cleanliness, in the future $B_s \rightarrow \mu^+\mu^-$ will play a crucial role distinguishing various NP scenarios, i.e. confirming or disproving whether NP couples also axial-vectorially (in addition to vectorial couplings) to muons or not.

The second day of the workshop began with the study of the anomalies in $b \rightarrow c\tau\nu$ processes and its connections to $b \rightarrow s\ell^+\ell^-$ transitions. While a common origin of the two anomalies seems plausible, simultaneous explanations are challenging and further data will decide whether the discrepancies in $b \rightarrow c\tau\nu$ persist. Finally, we discussed the implications of $R_{\mu}(K^{(*)})$ for experiments searching for $\mu \rightarrow e$ flavour violation and LFV in kaon decays.

Furthermore, (even though we did not discuss it in detail in this workshop) the anomalous magnetic moment of the muon can be linked to the hints for LFUV in $B$ decays as well and $\tau$ decays provide additional interesting tests of the SM.

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