The latest results in the searches for rare decays at LHCb are presented. The photon polarization in $b \to s\gamma$ transitions is observed with a 5.2σ significance. World’s best limits are set on the branching fractions of the lepton number violating decay $B^-\to \pi^+\mu^-\mu^-$, which could be mediated by a Majorana neutrino, and the flavour changing neutral current decay $D^0\to \pi^+\pi^-\mu^+\mu^-$. The angular distribution of $B^0\to K^{(*)}\mu^+\mu^-$ decays hint at small discrepancies from the Standard Model.

1 Photon polarization in $b \to s\gamma$ transitions

Photons from the electroweak penguin loop in $b \to s\gamma$ transitions are predominantly left-handed in the Standard Model (SM), due to the left-handed coupling of the $s$ quark and the $W$ boson. A number of New Physics (NP) models\textsuperscript{1} enable the photon to acquire a right-handed component, such as via the exchange of a heavy fermion in the loop\textsuperscript{2}.

In the LHCb analysis of $B^+\to K^+\pi^-\pi^+\gamma$ decays\textsuperscript{3}, the photon polarization is probed via the up-down asymmetry, $A_{ud}$, which is determined using 3.0 fb\textsuperscript{-1} of data collected at 7 and 8 TeV. Here $A_{ud}$ is defined as the asymmetry between the number of photons emitted either side of the plane defined by the momenta of the $K^+\pi^-\pi^+$ in their centre-of-mass frame, as shown in Fig. 1 (left). A non-zero value of $A_{ud}$ would indicate that the photon is polarised.

The distribution of the cosine of the angle, $\cos\theta$, between the direction opposite to the photon momentum and the normal $\vec{p}_{\pi,slow} \times \vec{p}_{\pi,fast}$ to the plane is calculated in four $K^+\pi^-\pi^+$ mass bins. The distribution is fitted with a fourth-order polynomial function, where $A_{ud}$ is proportional to the values of the first and third coefficients. The combined $\chi^2$ of the values of $A_{ud}$ in all four $K^+\pi^-\pi^+$ mass bins, shown in Fig. 1 (right), corresponds to a 5.2σ significance for

![Figure 1](image-url)
Figure 2 – Left: Upper limit on the branching fraction of the $B^- \rightarrow \pi^+ \mu^- \mu^-$ decay as a function of the mass and the lifetime of the Majorana neutrino. Right: Upper limit on the coupling of a fourth-generation Majorana neutrino to muons as a function of the neutrino mass.

a non-zero up-down asymmetry. This is the first observation of a non-zero photon polarisation in $b \rightarrow s \gamma$ transitions. As $A_{ud}$ depends on both the photon polarisation and on the different resonant contributions to the $K^+\pi^-\pi^+$ final state, a limited knowledge of the structure of the $K^+\pi^-\pi^+$ mass spectrum currently prevents the determination of the corresponding value for the photon polarisation. However, if theoretical predictions become available, it would be possible to determine the value of the photon polarisation for the first time.

2 Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$

The lepton number violating decay $B^- \rightarrow \pi^+ \mu^- \mu^-$ is forbidden in the SM, but can proceed via an on-shell or virtual Majorana neutrino of any mass. The LHCb analysis uses 3.0 fb$^{-1}$ of data collected at 7 and 8 TeV to search for neutrinos in the mass range 250 – 5000 MeV and with lifetimes between 0 and 1000 ps, with two different selection criteria, depending on the lifetime of the neutrino. The search is normalised to the $B^- \rightarrow J/\psi K^-$ channel, and backgrounds from $B$ decays to charmonium are estimated using fully reconstructed $J/\psi K^-(\pi^-)$ and $\psi(2S) K^-(\pi^-)$ events in data.

No significant signals are observed, and the CLs method is used to set the world’s best upper limits on the branching fraction of the $B^- \rightarrow \pi^+ \mu^- \mu^-$ decay as a function of the mass and the lifetime of the Majorana neutrino, as shown in Fig. 2 (left). For neutrino lifetimes shorter than 1 ps an upper limit of $B(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9}$ is obtained at 95% confidence level. The result significantly improves the limits on the branching fraction, and extends the lifetime range of the search for Majorana neutrinos by LHCb. The branching fraction limits can be converted into model dependent upper limits on the coupling of a fourth-generation Majorana neutrino to muons, as shown in Fig. 2 (right).

3 Search for the FCNC decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

The expected branching fraction for the flavour changing neutral current (FCNC) decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ is in the range $(1–3) \times 10^{-9}$ in the SM, as it can only occur at the loop level and is GIM suppressed. However, the branching fraction can be enhanced by NP, such that it can be several orders of magnitude larger.

The LHCb analysis uses $D^0$ mesons from $D^{*+} \rightarrow D^0 \pi^+$ decays to reduce the large combinatorial background. Four dimuon mass ranges are studied, such that the contribution of resonant dimuon final states is excluded. Fig. 3 shows the signal yield in the low and high dimuon mass ranges (away from the $\eta$, $\rho^0$ and $\phi$ resonances) which is normalised to the yield of $D^0 \rightarrow \pi^+ \pi^- \phi(\mu^+ \mu^-)$ decays in 1.0 fb$^{-1}$ of data collected at 7 TeV. The number of events is consistent with the background-only expectation, and a world’s best upper limit of $B(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) < 5.5 \times 10^{-7}$ is obtained at 90% confidence level, assuming the value of
Figure 3 – Distributions of $m(\pi^+ \pi^- \mu^+ \mu^-)$ in the low (left) and high (right) dimuon mass ranges. The blue line indicates the combined fit, whilst the black line, the green line and the red line indicate the signal, the $D^0 \to \pi^+ \pi^- \pi^- \pi^-$ background and the combinatorial background respectively.

$B(D^0 \to \pi^+ \pi^- \phi(\mu^+ \mu^-))$ estimated in Ref. 9. The result is the most stringent to date, with a factor of 50 improvement in sensitivity compared to the previous world’s best measurement.

4 Angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$

The angular distribution of the FCNC decay $B^0 \to K^{*0} \mu^+ \mu^-$, where the $K^*(892)^0$ decays to $K^+ \pi^-$, depends on three angles and the dimuon invariant mass squared, $q^2$. The $q^2$ dependence can be parameterised in terms of Wilson coefficients and form-factors, where the Wilson coefficients are sensitive to modifications from NP models. The form-factors have large theoretical uncertainties, prompting the study of the variables $P'_{i}$, in which the dominant form-factor uncertainties can be cancelled at low $q^2$ values.

The LHCb analysis uses 1.0 fb$^{-1}$ of data collected at 7 TeV to measure each observable in six $q^2$ bins, in the range $0.1 < q^2 < 19.0$ GeV$^2$, giving 24 measurements. Peaking backgrounds from charmonium decays are removed by vetoing several ranges of dimuon mass. Backgrounds from $B^0_s \to \phi(K^+ K^-)\mu^+ \mu^-$ decays are removed by assigning the kaon mass hypothesis to the pion candidate and rejecting events for which the resulting $K^+ K^-$ mass is consistent with the $\phi$ mass. A similar procedure is applied to remove $B^0 \to J/\psi K^{*0}$ and $\Lambda_b^0 \to \Lambda(pK^-)\mu^+ \mu^-$ events. Detector acceptance effects are determined from simulation and verified using the $B^0 \to J/\psi K^{*0}$ control channel in data.

A local 3.7 σ deviation from the SM is found in the $4.3 < q^2 < 8.68$ GeV$^2$ bin of $P'_5$, as shown in Fig. 4, with the SM values given in light blue. There is a 0.5% probability to observe such a discrepancy if the measurements are considered independent. Whilst this can be interpreted as a NP contribution to the Wilson coefficient $C_9$, SM predictions with different assumptions
about the cancellation of form-factor uncertainties\textsuperscript{13} give reduced tension with the data, as shown in dark blue on Fig. 4. An upcoming update using 3.0 fb\textsuperscript{−1} of LHCb data may help to resolve the situation.

5 Other $B \to K\mu^+\mu^−$ decays

The discrepancy in the angular observables of $B^0 \to K^{∗0}\mu^+\mu^−$ decays motivates the study of other $B \to K\mu^+\mu^−$ decays.

The isospin asymmetry, $A_I$, and partial branching fractions are measured as a function of $q^2$ in the LHCb analysis of $B \to K(\ast)\mu^+\mu^−$ decays\textsuperscript{14}, whilst the forward-backward asymmetry, $A_{FB}$ and the flat parameter, $F_H$, are measured in the LHCb analysis of $B^+ \to K^+\mu^+\mu^−$ and $B^0 \to K^{∗0}\mu^+\mu^−$ decays\textsuperscript{15}. Both analyses use 3.0 fb\textsuperscript{−1} of data collected at 7 and 8 TeV.

All measurements, such as $A_I$ for $B \to K\mu^+\mu^−$ decays, shown in Fig. 5 (left), are found to be consistent with the SM. However, the branching fraction measurements, while individually consistent, all have lower values than the SM predictions, as shown in Fig. 5 (right) for $B^0 \to K^{∗0}\mu^+\mu^−$ decays. The large deviation in the value of $A_I$ from the SM prediction seen in the analysis of 1.0 fb\textsuperscript{−1} of LHCb data\textsuperscript{16} is not supported by the increased dataset.

References

4. A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 05, 030 (2009).