Search for the lepton-flavour violating decay $\tau^- \to \phi\mu^-$ at LHCb

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Summary. — Lepton flavour conservation is an approximate symmetry at the perturbative level in the Standard Model of Particle Physics, and neutrino oscillations represent the first and, so far, the only observed violation of this symmetry. Neutrino mixing implies that lepton flavour violation also occurs in charged decays, albeit with extremely low branching fractions of order $\mathcal{O}(10^{-50})$. The direct observation of charged lepton-flavour violating processes would be an indisputable sign of new physics beyond the Standard Model. The search for the $\tau^- \to \phi\mu^-$ decay allows to test several new physics scenarios, such as vector leptoquark models which predict values for the branching ratio up to 10^{-8}, close to current experimental limits. This contribution describes the search for the $\tau^- \to \phi\mu^-$ decay at the LHCb experiment at CERN, conducted for the first time in hadronic collisions. An expected upper limit of $\mathcal{B}(\tau^- \to \phi\mu^-) < 1.1 \times 10^{-6}$ at 90% of confidence level was achieved by performing a blind analysis using the full Run 2 data sample. A new analysis is ongoing with the goal of improving this limit, looking also at the Run 3 data being collected by the brand-new LHCb-Upgrade I detector.

1. – Introduction

The Standard Model (SM) of Particle Physics is currently our most complete and well-tested theory describing fundamental particles and their interactions. Within this framework, fundamental particles are classified into two groups: fermions, which are the building blocks of matter, and bosons, which mediate interactions. Fermions are divided into leptons and quarks, both of which occur in three generations with two particles each. Each lepton generation consists of an electrically charged lepton (e^-, μ^-, τ^-) paired with an uncharged neutrino (ν_e, ν_μ, ν_τ), and carries three *lepton flavours* that are accidentally conserved in all reactions. When the SM is extended to include mixing between neutrino flavour eigenstates, charged lepton-flavour violating (LFV) processes

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are permitted at higher order. However, these processes are suppressed at the order of $\mathcal{O}(10^{-50})$ due to the small neutrino masses [1, 2].

An example of an allowed LFV process occurring through neutrino oscillation is $\tau^- \to \phi\mu^-$ (1), as illustrated in Fig. 1.

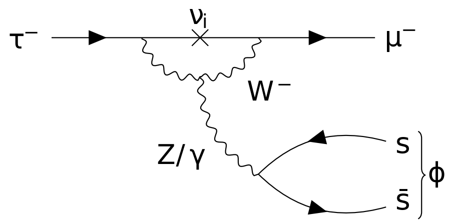

Fig. 1. – A possible Feynman diagram for the $\tau^- \to \phi\mu^-$ decay through neutrino oscillation.

Many new physics scenarios allow LFV decays at rates many orders of magnitude higher than those predicted by the SM extended with neutrino mixing. Among these theories, leptoquark models predict branching fractions for the $\tau^- \to \phi\mu^-$ decay up to 10^{-8} [3], which is close to the current experimental sensitivity. Additionally, unlike other potentially interesting decays, the final state of the $\tau^- \to \phi\mu^-$ decay includes only well-identifiable particles, minimising combinatorial background and allowing for the reconstruction of a clear and narrow mass peak, if it exists.

2. – State of the art of $\tau^- \to \phi\mu^-$ measurement

LFV tau decay searches are typically conducted at the B-factories, where the $e^+e^- \to \tau^+\tau^-$ production mechanism facilitates the nearly complete removal of all the background sources. The Belle collaboration currently sets the best experimental upper limit: $\mathcal{B}(\tau^- \to \phi\mu^-) < 2.3 \times 10^{-8}$ at 90% of credibility level, as reported in Table I along with the upper limits set by other e^+e^- experiments.

On the contrary, when the τ lepton is produced in pp collisions at the Large Hadron Collider, one can take advantage of a much larger production cross section, but with the presence of very abundant background sources that are extremely difficult to suppress. This fact presents a significant challenge that has so far prevented LHCb from being fully competitive in this class of measurements. Consequently, the LHCb collaboration has not yet measured this decay, and the ongoing analysis represents the first attempt to search for the $\tau^- \to \phi\mu^-$ decay at a hadron collider.

3. – τ lepton production at LHCb

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [9, 10]. Within its acceptance, τ leptons are primarily produced from the decays of D_s^-, D^- mesons and b-hadrons, as illustrated in Fig. 2. The dominant source is the leptonic decay $D_s^- \to \tau^-\bar{\nu}_\tau$, which contributes about 70% of the total τ production at LHCb. During the Run 2, approximately 10^{11} tau leptons were produced.

(1) Charge conjugate decay is implied in the following.

TABLE I. – *Current status of upper limits on the branching ratio of the* $\tau^- \to \phi\mu^-$ *decay. The* CL *stands for confidence level estimates with a statistical frequentist approach, except for* $(*)$ *where* CL *means credibility level estimates with a Bayesian method.*

Experiment	Upper limit @ 90% CL	Year	Integrated luminosity	Reference
CLEO	7.0×10^{-6}	1998	4.79 fb^{-1}	[4]
BaBar	1.9×10^{-7}	2009	451 fb^{-1}	[5]
Belle	8.4×10^{-8}	2011	854 fb^{-1}	[6]
Belle	$2.3 \times 10^{-8}(*)$	2023	980 fb^{-1}	[7]
Belle II	9.7×10^{-8}	2023	190 fb^{-1}	[8]

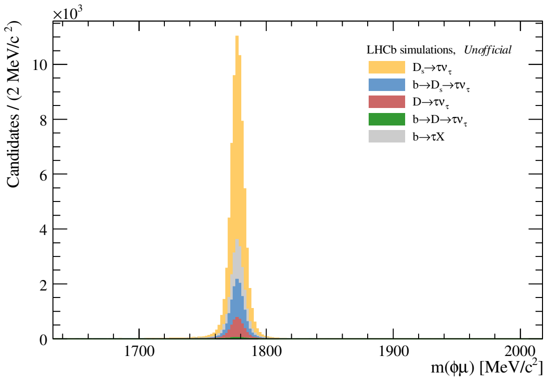

Fig. 2. – Monte Carlo simulations representing the main production channels of τ leptons within the LHCb detector acceptance. The relative contributions from different components are computed using the LHCb cross-section measurements of D, D_s and B mesons, taking into account also the efficiencies of the analysis selections.

4. – Analysis strategy

The analysis is conducted by reconstructing $\phi\mu$ candidates, with $\phi \to K^+K^-$, in the mass region $[1632, 2020]\,\text{MeV/c}^2$ and blinding a signal region of $\pm\,20\,\text{MeV/c}^2$ around the known τ mass [11], corresponding to about four times the expected mass resolution. The sideband regions, defined as $[1632, 1755]\,\text{MeV/c}^2$ and $[1795, 2020]\,\text{MeV/c}^2$, are used to study the background sources. The most relevant background, which is continuum and non-peaking, is the $D_s^- \to \phi\mu^-\bar{\nu}_\mu$ decay, where the neutrino is not detected, and the $\phi\mu$ pair originates from the same decay vertex. Figure 3 shows the reconstructed $\phi\mu$ mass distributions for the main background channels and their respective shapes. Two peaks are presented in the right sideband region due to the $D^- \to \phi\pi^-$ and $D_s^- \to \phi\pi^-$ decays, where the pion in the final state is misidentified as a muon. These two channels are used to extract the production rate of $D_{(s)}^-$ mesons directly from data and also serve as control channels for the multivariate analysis (MVA) performed to reduce the background in the signal region. Two binary classifiers are developed to disentangle the combinatorial and the physical backgrounds from the signal using MC samples and real data for training and testing. Finally, the signal yield is determined by performing a simultaneous fit of

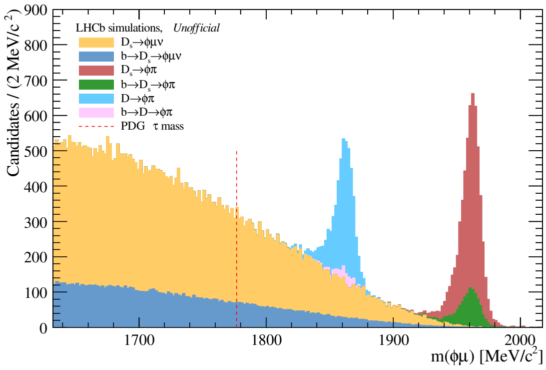

Fig. 3. – Monte Carlo simulations illustrating the main background channels and their shapes after the analysis selections.

the $\phi\mu$ mass distribution in different MVA output bins.

5. – Preliminary results and future prospects

An expected upper limit of $\mathcal{B}(\tau^- \to \phi\mu^-) < 1.1 \times 10^{-6}$ at 90% of confidence level was achieved by performing a blind analysis using the full Run 2 (2016-2018) dataset [12]. This result is the starting point of the ongoing analysis which implements new methodologies to address experimental challenges at hadron colliders. The Run 3 (2024) data from the brand-new LHCb Upgrade I detector presents a significant opportunity to further lower the upper limit that will be found with Run 2 data.

In conclusion, the search for $\tau^- \to \phi\mu^-$ at LHCb, alongside other processes such as $\tau^- \to \mu^+\mu^-\mu^-$, aims to complement the results from e^+e^- experiments, demonstrating the accessibility of LFV studies in the challenging and crowded hadronic environment.

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