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Search for the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb(*)

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Summary. — This contribution presents the two studies performed at LHCb to search for the rare $\Sigma^+ \to p\mu^+\mu^-$ decay using pp collision data recorded in 2011–2012 (2016–2018) at a centre-of-mass energy of $\sqrt{s} = 7$ and 8 TeV (13 TeV), corresponding to an integrated luminosity of 3 fb^{-1} (5.4 fb^{-1}). In the first analysis an excess of events is observed with respect to the background expectation with a signal significance of 4.1 standard deviations, in the second one the first observation of this mode is reported with a significance greater than 5 standard deviations. In both searches, no significant structure is observed in the dimuon invariant mass distribution, in contrast with a previous result from the HyperCP experiment.

1. – Introduction

The Standard Model of particle physics (SM) is a theoretical framework that describes the fundamental particles and their interactions through three fundamental known forces. While it has been extremely successful in predicting and explaining a wide range of experimental results in particle physics, it is also known that it is incomplete, as it does not incorporate gravity, it does not account for dark matter, it can not explain the baryon asymmetry and finally its original formulation did not foresee any mass term for the neutrinos, while non-zero neutrino masses are the direct result of the observed neutrino oscillations.

For these reasons, one of the main focuses of the particle physics community in the past years has been to search for possible signs of New Physics (NP) beyond the SM. The search for new particles usually happens along two complementary paths. The first approach relies on *direct searches*, aiming at the observation of new particles directly produced in high-energy collision. The second approach uses *indirect searches*, aiming at the observation of indirect effects of new particles in lower energy scales processes.

In the context of indirect searches, the study of rare and very rare decays and in particular the study of *flavour-changing neutral-currents* (FCNC) are sensitive tools able to probe NP effects. FCNC are forbidden at tree level making them ideal candidates to probe energy scales beyond the ones reachable by direct searches. Therefore, small deviation from the theory can be interpreted as contributions from NP.

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In this contribution a search for the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay ([1]) is presented with the Large Hadron Collider beauty (LHCb) experiment at CERN.

The LHCb detector [1, 2] is a single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks and more in general for the study of heavy flavour physics. The LHCb experiment has collected data corresponding to an integrated luminosity of 9 fb^{-1} in its first two data-taking periods, from 2010 until 2018. The upgraded detector, LHCb Upgrade I, started operating in 2022 and is planned to reach an integrated luminosity of ~ 50 fb^{-1} by the end of 2030 [3].

2. – Motivation

The rare hyperon $\Sigma^+ \to p\mu^+\mu^-$ decay is an $s \to d$ quark-flavour-changing neutral-current process, allowed only at loop level in the SM and thus highly suppressed. This process is dominated by long-distance contributions for a predicted branching fraction of $1.6 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)_{SM} < 9.1 \times 10^{-8}$ [4], while the short-distance ones are suppressed at a branching fraction of about 10^{-12}.

This decay gained attention in 2005 when the HyperCP collaboration at Fermilab reported the first evidence for this mode consisting of three events with the same dimuon invariant mass $m_{X^0} = 214.3 \pm 0.5$ MeV/c^2 [5], and a measured branching fraction of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)_{HyperCP} = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ [5], compatible with the SM. It was thought that, given the presence of this unexpected peak hint in the dimuon invariant mass distribution, the decay was mediated by an intermediate particle decaying into two muons, such that $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ with mass $m_{X^0} = 214.3 \pm 0.5$ MeV/c^2. Several theoretical efforts have been made to explain this result [6-16] as well as many experimental attempts to search for this particle in other experiments and decays modes without any success. [17-28].

A search for this particle in $\Sigma^+ \to p\mu^+\mu^-$ has been performed by the LHCb collaboration using pp collisions data recorded between 2011–2012 (Run 1) at a centre-of-mass energy of $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1} [29]. A new search has been recently presented at a conference ([2]) using 2016–2018 (Run 2) data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 5.4 fb^{-1} [30].

The measurement performed with Run 1 data is discussed in sect. **3**, while the latest update in sect. **4**.

3. – Run 1 analysis

The selection of the events consists of two steps: the online selection and the offline selection. The former is performed by the trigger, which first uses information from the calorimeter and muon systems in its hardware stage and then follows with two software stages, the first performing a preliminary event reconstruction based on partial information while the second performing a full event reconstruction.

([1]) The inclusion of charge conjugated processes is implied throughout this document.
([2]) Study presented at the 15th International Conference on Beauty, Charm, Hyperons in Hadronic Interactions (BEACH 2024), Charleston, South Carolina, United States, 3–7 June 2024

The analysis strategy is briefly summarised as follows: after the trigger, a loose selection is applied based on geometric and kinematic variables; candidates are selected using a multivariate selection based on a boosted decision tree algorithm (BDT) [31, 32]; the final sample is obtained by rejecting the background with a requirement on the BDT output and on particle identification variables; the signal yield is obtained from a fit to the $p\mu^+\mu^-$ invariant mass and is converted into a branching fraction by normalising to the $\Sigma^+ \to p\pi^0$ channel; a search for possible peaks in the dimuon invariant mass distribution is carried out, in order to discover the possible existence of new unknown particles.

The $\Sigma^+ \to p\mu^+\mu^-$ candidates are selected by combining one track with proton identification with two good quality oppositely charged tracks with muon identification. The three tracks are required to form a good quality secondary vertex (SV) displaced from the pp collision point (PV) and thus a measured Σ^+ lifetime greater than 6 ps is requested. Furthermore, for Σ^+ candidates, the following criteria are applied: a transverse momentum greater than 500 GeV/c, an impact parameter (IP) χ^2 less than 36, the cosine of the angle between the flight direction and the reconstructed momentum greater than 0.9, and an invariant mass $|m_{p\mu^+\mu^-} - m_{\Sigma^+}| < 500$ MeV/c^2, where m_{Σ^+} is the known mass of the Σ^+ particle [33].

The normalization $\Sigma^+ \to p\pi^0$ channel is reconstructed and selected combining a track identified as a proton with a π^0 reconstructed from two photon clusters in the electromagnetic calorimeter.

After the described selection, background to $\Sigma^+ \to p\mu^+\mu^-$ candidates is composed of combinatorial candidates and candidates where a $\Lambda^0 \to p\pi^-$ decay, with a pion misidentified as a muon, is combined with an additional muon of the same event. While the former is suppressed through a multivariate selection (BDT) based on geometric and kinematic variables and on isolation information, the latter is explicitly rejected by requiring the proton and muon of opposite sign to have a pair invariant mass under the $p\pi$ hypothesis, outside a window of 10 MeV/c^2 from the known Λ mass.

The BDT combines information from the following variables: the angle between the Σ^+ reconstructed momentum and the vector joining the PV to the SV, the flight distance significance of the Σ^+ candidate, the distance of closest approach between any pair of the three daughters, the transverse momenta of the final-state particles, the impact parameter χ^2 of the final-state particles and of the Σ^+ candidate, the χ^2 of the SV, and an isolation variable constructed from the number of tracks within an angular cone around each of the final-state particles. No BDT selection is applied to the normalisation channel.

The $\Sigma^+ \to p\mu^+\mu^-$ branching fraction is measured by normalising the decay candidates to those of the $\Sigma^+ \to p\pi^0$ decay, according to:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{N_{\Sigma^+\to p\mu^+\mu^-}}{N_{\Sigma^+\to p\pi^0}} \frac{\epsilon_{\Sigma^+\to p\pi^0}}{\epsilon_{\Sigma^+\to p\mu^+\mu^-}} \mathcal{B}(\Sigma^+ \to p\pi^0) \quad , \tag{1}$$

where $\mathcal{B}$, ϵ and N are respectively the branching fraction, efficiency and yield of the considered decays. The yield of $\Sigma^+ \to p\pi^0$ decays is obtained from a fit to the corrected invariant mass $m^{\Sigma}_{corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}$ distribution, where m_{π^0} and $m_{\gamma\gamma}$ are respectively the known mass of the π^0 meson and the invariant mass of the two photons [33]. The observed number of $\Sigma^+ \to p\pi^0$ candidates is $(1171 \pm 9) \times 10^3$. Selection and reconstruction efficiencies are evaluated in simulations with corrections extracted from data.

The observed number of signal $\Sigma^+ \to p\mu^+\mu^-$ decays is obtained with a fit to the $p\mu^+\mu^-$ invariant mass distribution in the range $1149.6 < m_{p\mu^+\mu^-} < 1409.6$ MeV/c^2;

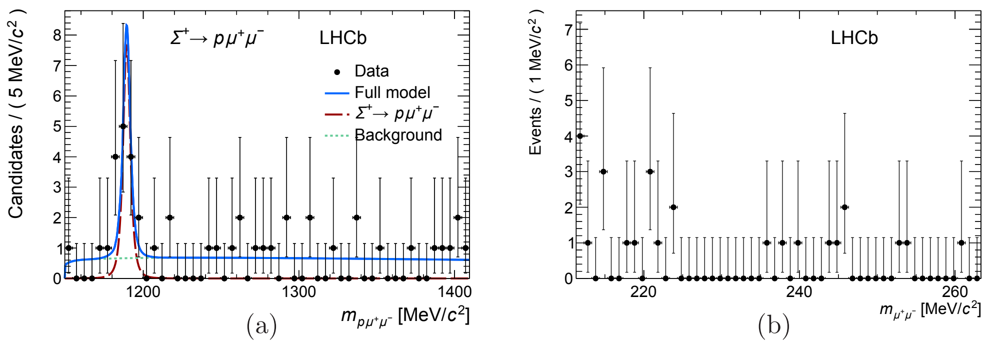

Fig. 1. – (a) Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ candidates in Run 1 data; (b) Distribution of the dimuon invariant mass for $\Sigma^+ \to p\mu^+\mu^-$ candidates [29].

this distribution, shown in fig. 1(a), is described by a modified ARGUS function for the background and an Hypatia function for the signal [34, 35]. An excess of events with respect to the background-only hypothesis is found with a significance of 4.1σ. A signal yield of $10.2\,^{+3.9}_{-3.5}$ is observed, which corresponds to a branching fraction of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2\,^{+0.9}_{-0.8}\,^{+1.5}_{-1.1})\times 10^{-8}$, where the first uncertainty is statistical and the second systematic; the measured branching fraction is compatible with the SM prediction.

A scan for a possible peak in the dimuon invariant mass is performed selecting candidates in a region within two times the resolution in the $p\mu^+\mu^-$ invariant mass around the known Σ^+ mass. The distribution of these candidates is shown in fig. 1(b) and no significant structure is found.

4. – Run 2 analysis

As mentioned before, after the IFAE held in April 2024, a search for the $\Sigma^+ \to p\mu^+\mu^-$ decay was published using Run 2 data to be then presented at a conference in June 2024 [30].

A great effort has been done to improve the trigger selection for strange hadron physics during the Run 2 data taking [36]. A mixture of inclusive and exclusive trigger selection have been implemented at the software level allowing to increase the selection efficiency for $\Sigma^+ \to p\mu^+\mu^-$ decay by a factor 10 compared to the Run 1 analysis, which has also to be combined with the increase in statistics due to the larger data sample in Run 2 by roughly a factor 4.

The Run 2 analysis follows a similar strategy to that one performed using Run 1, and thus it will not be described in detail again in this report. As for the Run 1 analysis, a multivariate operator based on a BDT is used to reduce the background combining the following variables: the impact parameter χ^2 of the Σ^+ and of the final-state particles tracks with respect to the best PV; the maximum distance of closest approach between any pair of the three daughter tracks; the flight distance of the Σ^+ from the PV divided by its uncertainty; the angle between the Σ^+ momentum and the lines joining the PV and the SV; the χ^2 of the Σ^+ vertex fit; the transverse momentum of the final-state particles tracks; an isolation variable depending on the transverse momentum of charged particles.

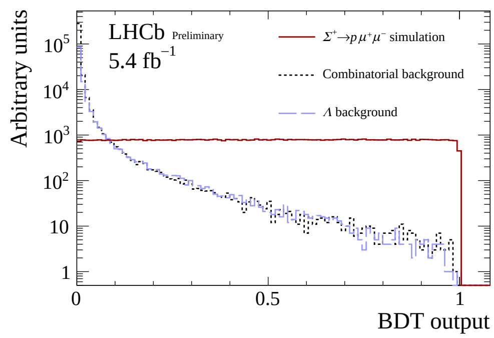

Fig. 2. – Distribution of the BDT output variable for simulated signal (red-solid line) and data divided into combinatorial background (black-dashed line) and Λ background (blue-long-dashed line).

The BDT output ranges from zero, for background-like candidates, to one, for signal-like candidates; the distribution of the BDT output for signal simulation and data is shown in fig. 2.

The final selection is based on: the BDT output, the muon and proton particle-identification variables [37] and the width of the Λ veto window.

The $m_{p\mu^+\mu^-}$ distribution for candidates satisfying the final selection criteria is shown in fig. 3(a). A clear peak at the Σ^+ mass is observed, with a small residual background; the fit results in a signal yield of $N_{\Sigma^+\to p\mu^+\mu^-} = 279 \pm 19$ where the uncertainty is statistical only. This result represents the first observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay with a significance greater than 5 standard deviations.

The distribution of the dimuon invariant mass for $\Sigma^+ \to p\mu^+\mu^-$ candidates in data is shown in fig. 3(b): as in the Run 1 analysis, no structure is observed and the result is compatible with expectations from the SM.

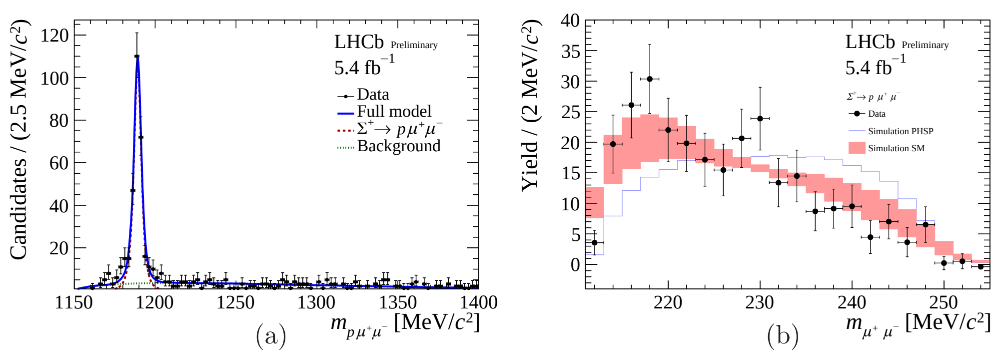

Fig. 3. – (a) Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ candidates in Run 2 data; (b) Distribution of the dimuon invariant mass for $\Sigma^+ \to p\mu^+\mu^-$ candidates in data compared with simulation. LHCb phase space and SM prediction [4] are respectively reported as a blue line and a red band.

5. – Conclusions and outlook

In summary, the two studies performed at LHCb to search for the rare $\Sigma^+ \to p\mu^+\mu^-$ decay have seen an excess of events with a signal significance of 4.1σ when using data recorded in Run 1 [29] and the first observation ever of this mode with high significance when using Run 2 data [30]. This is the rarest hyperon decay ever observed. In both searches, no significant structure is observed in the dimuon invariant mass distribution, in contrast with the previous result from HyperCP. With future publications using Run 2 data, a precise determination of the branching fraction will be presented, in addition to a measurement of the differential branching fraction, the Charge-Parity (CP) symmetry violation and forward-backward asymmetries.

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