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Testing the HyperCP anomaly at LHCb: evidence for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay

F Dettori ¹

Università degli Studi di Cagliari and INFN, Cagliari, Italy

E-mail: francesco.dettori@cern.ch

Abstract. A search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays with LHCb Run 1 data is presented, yielding an evidence for this decay and a measurement of a branching fraction compatible with the Standard Model. The HyperCP anomaly in the dimuon invariant mass distribution is not confirmed, and its branching fraction central value is excluded at 95% CL. Prospects for the future of this measurement in LHCb are also presented.

The $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay is a flavour changing neutral current, highly suppressed in the Standard Model. It gained attention when the HyperCP collaboration published an evidence for this decay [1], with a hint of a structure in the dimuon invariant mass distribution. This decay has been searched recently within the LHCb experiment [2]. This contribution will discuss this analysis with attention to clarify some points discussed at this conference while referring the reader to Ref. [2] for the rest of the detector and analysis details.

Within the Standard Model, the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay ² is dominated by the long-distance contributions for a predicted branching fraction of $1.2 \times 10^{-8} < \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) < 10.2 \times 10^{-8}$ [3,4], while the short distance contribution is well suppressed at the level of 10^{-13} . Given this large uncertainty, the primary physics interest in this decay comes from the mentioned experimental result from the HyperCP experiment. The branching fraction measured was $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6_{-5.4}^{+6.6} \pm 5.5) \cdot 10^{-8}$, well compatible with the SM predictions. However the HyperCP experiment observed that the three clean signal events had, within good accuracy, the same dimuon invariant mass value, rather than a phase-space distribution. This would point towards an unknown intermediate particle X^0 with mass with $m_{X^0} = 214.3 \pm 0.5$ MeV/ c^2 . The branching fraction, reinterpreted with such an intermediate state, would read $\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)) = (3.1_{-1.9}^{+2.4} \pm 5.5) \cdot 10^{-8}$. Albeit limited in statistical significance, this result attracted significant theoretical attention trying to explain this result [5–13]. A considerable experimental effort was put in order to search for this particle in other experiments and decays [14–25]. However no other search was done for the exact $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay prior to the LHCb one.

The LHCb search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays [2], is based on data samples corresponding to an integrated luminosity of 3 fb^{-1} , acquired in pp collisions at 7 and 8 TeV centre-of-mass energies in 2011 and 2012 (Run 1). The $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates are reconstructed in the LHCb detector from three charged tracks, with particle identification information consistent with one proton a

¹ On behalf of the LHCb collaboration

² The inclusion of the charge-conjugate modes is implied throughout this contribution.



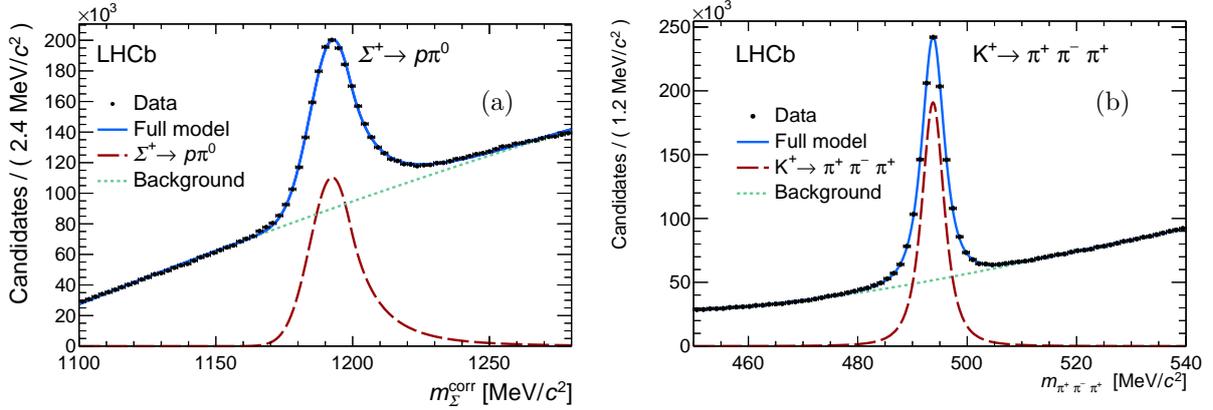


Figure 1. Invariant mass distribution for (a) $\Sigma^+ \rightarrow p\pi^0$ candidates in data, superimposed with the fit and (b) $K^+ \rightarrow \pi^+\pi^-\pi^+$ candidates in data (see text for details on the fits).

two muons of opposite sign. A standard reconstruction is employed, in particular only *long* tracks are used, *i.e.* tracks with hits also in the VELO detector. This limits the reconstruction length to decay vertices within about one meter from the primary interaction (PV). In the future, other analyses based on different tracking reconstruction could enlarge this to about 2 meters, albeit with worse invariant mass resolution. The selection of the $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates is based on standard kinematic and geometric variables. In addition, the normalisation $\Sigma^+ \rightarrow p\pi^0$ decay is selected from a track consistent with proton particle identification, and a π^0 reconstructed from two photon clusters in the electromagnetic calorimeter.

Data used to search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates does not have any special trigger requirement: all events saved in the considered data set are used in order to maximise the statistics. Instead, in order to ease the trigger efficiency evaluation, events used for the normalisation decay are required to belong to events triggered by particles independent of the $\Sigma^+ \rightarrow p\pi^0$ decay. After the mentioned selection, background to $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates is composed of combinatorial candidates and candidates where a $\Lambda \rightarrow p\pi^-$ decay, with a pion misidentified as a muon, is combined with an additional muon of the same event. Combinatorial background is suppressed through a multivariate selection based on geometric and kinematic variables and on isolation information. This is trained with a simulated signal sample and a $\Sigma^+ \rightarrow \bar{p}\mu^+\mu^+$ (wrong-sign) sample from data to mimic background. The $\Lambda \rightarrow p\pi^-$ background is explicitly vetoed 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 from the known Λ mass. In addition to this, stringent particle identification criteria are used to suppressed both background sources.

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

$$\begin{aligned} \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) &= \frac{\varepsilon_{\Sigma^+ \rightarrow p\pi^0}}{\varepsilon_{\Sigma^+ \rightarrow p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)}{N_{\Sigma^+ \rightarrow p\pi^0}} N_{\Sigma^+ \rightarrow p\mu^+\mu^-} \\ &= \alpha N_{\Sigma^+ \rightarrow p\mu^+\mu^-} \end{aligned}$$

where \mathcal{B} , ε and N are respectively the branching fraction, efficiency and yield of the considered decays. The yield of $\Sigma^+ \rightarrow p\pi^0$ decays is obtained from a fit to the corrected invariant mass $m_{\Sigma}^{\text{corr}} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}$ distribution, shown in Fig. 1. The $\Sigma^+ \rightarrow p\pi^0$ distribution is described as a Gaussian function with a power tail on the right side, while the background is described by a modified ARGUS function [26]. While the reconstruction and selection of $\Sigma^+ \rightarrow p\pi^0$ decays is difficult in LHCb, lacking a secondary vertex reconstruction, given the very large Σ^+

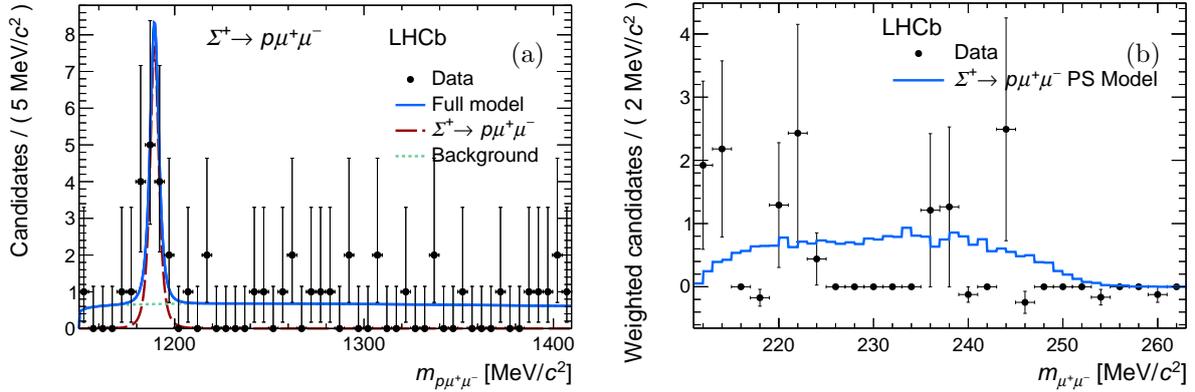


Figure 2. (a) Invariant mass distribution for $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates in data, superimposed with the fit (see text). (b) Background subtracted dimuon invariant mass distribution for candidates in the $\Sigma^+ \rightarrow p\mu^+\mu^-$ final sample, the continuous sky-blue line represents the expected distribution for a phase space decay.

production and the large branching fraction ($\sim 50\%$) a good signal can be seen. A total of $(1171 \pm 9) \times 10^3$ $\Sigma^+ \rightarrow p\pi^0$ decays are fitted, corresponding to an order of 10^{14} Σ^+ particles in LHCb. Selection and reconstruction efficiencies are evaluated in simulations with corrections extracted from data. In particular, particle identification efficiencies and trigger efficiencies bring large systematic uncertainties from their calibration on data. This is due to samples and techniques being developed in LHCb for higher transverse momentum signals. Several of the reconstruction and selection properties are cross-checked with the $K^+ \rightarrow \pi^+\pi^-\pi^+$ decay reconstructed with a similar selection in data (Fig 1(b)). This will be improved strongly in the future with dedicated samples and tools. A single event sensitivity $(2.2 \pm 1.2) \times 10^{-9}$ is obtained for this analysis, meaning that about 23 ± 20 $\Sigma^+ \rightarrow p\mu^+\mu^-$ events are expected in the final sample considering a typical SM branching fraction of $(5 \pm 4) \times 10^{-8}$. Considering the HyperCP phase-space branching fraction, this would correspond to about 40 events. En passant, we underline, as mentioned earlier, that both Σ^+ and $\bar{\Sigma}^-$ are searched for in this analysis and that the final sample is composed of about 48% $\bar{\Sigma}^-$ anti-baryon candidates.

The final search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays is performed looking for an excess in the $m_{p\mu^+\mu^-}$ invariant mass distribution. After the full selection the $\Lambda \rightarrow p\pi^-$ background is negligible and the only remaining background is of combinatorial nature. The invariant mass distribution, shown in Fig. 2(a), is described by a modified Argus function for the background and an Hypatia function [27] for the signal. An excess of events with respect to the background-only hypothesis is found with a significance of 4.1σ .

The fitted signal branching fraction is $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$, where the first uncertainty is statistical and the second systematic. This corresponds to $10.2^{+3.9}_{-3.5}$ $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays. The measured branching fraction is compatible with the lower range of the SM prediction.

The background subtracted dimuon invariant mass distribution for events in the final sample is shown in Figure 2(b). This is compared to the distribution from a $\Sigma^+ \rightarrow p\mu^+\mu^-$ phase space decay. It has to be noted that a phase-space distribution or a full amplitude calculation distribution [4] are very similar. Incidentally, an HyperCP-like signal would show up as a single peak at 214 MeV/c^2 , with a width of about 0.5 MeV/c^2 coming from the detector resolution.

In order to search explicitly for an HyperCP-like signal, the fit to the $p\mu^+\mu^-$ invariant mass is repeated restricting to events within 1.5 times the resolution from the putative

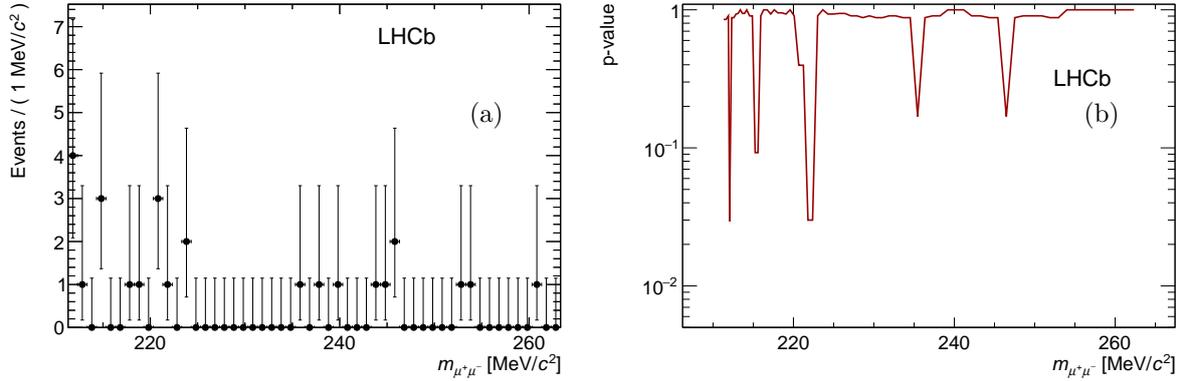


Figure 3. (a) Dimuon invariant mass distribution for $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidates in data (not background subtracted, see text). (b) Local p-value in the search for a structure in the dimuon invariant mass distribution.

particle ($m_{\mu^+\mu^-} \in [214.3 \pm 0.75] \text{ MeV}/c^2$). Since no significant signal is found an upper limit on the branching fraction of the resonant decay is set with the CL_s method [28] at $\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) < 1.4 \times 10^{-8}$ (1.7×10^{-8}) at 90% (95%) confidence level. This excludes the central value of the HyperCP result in the X^0 hypothesis reported above, although not the full range yet given the large uncertainties.

A more general search for structures in the dimuon invariant mass structure is also done by exploiting all the candidates within two times the resolution in the $p\mu^+\mu^-$ invariant mass around the known Σ^+ mass. The distribution of these candidates (not background subtracted) is shown in Fig. 3(a). In this case it is possible to apply the method developed in Ref. [29] for a generic search, to which we refer the reader for details. A scan is therefore performed and for each step the putative signal is estimated in a window of $\pm 1.5 \times \sigma(m_{\mu^+\mu^-})$ around the considered particle mass, while the background is estimated from the lower and upper sidebands. The obtained local p-value of the background-only hypothesis as a function of the dimuon mass is shown in Fig. 3(b) and no significant signal is found.

The results presented here only analyse Run 1 data of the LHCb experiment. During this period no dedicated trigger in any of the LHCb trigger levels was present for this kind of signals. Therefore this search is affected by very low trigger efficiencies, and is possible owing to the large hyperon production at LHC. However for the Run 2 data-taking (2015-2018) different inclusive and exclusive lines have been implemented at the first and second software level of the trigger [30]. This will guarantee about an order of magnitude increase in trigger efficiency according to simulations from about 0.8% to about 11% with respect to offline selected signal candidates; this together with another factor ten of increase in statistics from luminosity and cross-section in Run 2 allows to foresee a hundred-fold larger dataset for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay already collected and soon to be analysed. This dataset will ensure not only a high significance observation of this decay, given the current branching fraction, but also a precision measurement of this branching fraction. This will also be possible thanks to the lower trigger systematic uncertainty that will accompany the dedicated triggers, with respect to the current inclusive strategy. In addition, it will be possible to study the branching fraction separately for Σ^+ and $\bar{\Sigma}^-$, allowing a search for CP violation in these decays. Finally, further observables such as the forward backward asymmetry [4] will start to be in reach. In view of the Upgraded LHCb detector, this will start to become a precision field, not only for this particular decay but also for other hyperons at LHCb [31, 32].

In conclusion, the search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays at LHCb sees an evidence for this decay in

a SM configuration, not confirming the HyperCP anomaly, and measures its branching fraction. Prospects for the future highlight this analysis just as a starting step of hyperon physics at LHCb.

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