Strong constraints on the $K_S^0 \to \mu^+\mu^−$ branching fraction

LHCb collaboration†

Abstract

A search for the decay $K_S^0 \to \mu^+\mu^−$ is performed using proton-proton collision data, corresponding to an integrated luminosity of $5.6\,\text{fb}^{-1}$ and collected with the LHCb experiment during 2016, 2017 and 2018 at a center-of-mass energy of $13\,\text{TeV}$. The observed signal yield is consistent with zero, yielding an upper limit of $\mathcal{B}(K_S^0 \to \mu^+\mu^−) < 2.2 \times 10^{-10}$ at 90% CL. The limit reduces to $\mathcal{B}(K_S^0 \to \mu^+\mu^−) < 2.1 \times 10^{-10}$ at 90% CL once combined with the result from data taken in 2011 and 2012.

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The decay \( K_S^0 \rightarrow \mu^+\mu^- \) is a Flavor-Changing Neutral Current (FCNC) process which has not been observed yet. In the Standard Model (SM), this decay is highly suppressed \(^1\(^2\), with an expected branching fraction \( B(K_S^0 \rightarrow \mu^+\mu^-)_{\text{SM}} = (5.18 \pm 1.50_{\text{LD}} \pm 0.02_{\text{SD}}) \times 10^{-12} \(^3\). The uncertainties with subscripts LD and SD relate to long-distance and short-distance effects, respectively. The main contributions to the \( K_S^0 \rightarrow \mu^+\mu^- \) decay amplitude are illustrated in Fig. 1. The related channel \( K_L^0 \rightarrow \mu^+\mu^- \) is predicted in the SM to occur with a branching fraction \( B(K_L^0 \rightarrow \mu^+\mu^-)_{\text{SM}} = (6.85 \pm 1.49_{\text{LD}} \pm 0.13_{\text{SD}}) \times 10^{-9} \) for an (unknown) positive or a negative relative sign of the \( K_L^0 \rightarrow \gamma\gamma \) amplitude \(^4\), respectively. These predictions are in good agreement with the experimental world average \( B(K_L^0 \rightarrow \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9} \) \(^5\), based on Refs. \(^6\)\(^8\). Both the \( K_S^0 \) and the \( K_L^0 \) decay amplitudes are dominated by LD contributions in the SM. The large difference between the two branching fractions is due to the S-wave component, which is charge-parity (CP) violating and CP conserving for the \( K_S^0 \) and \( K_L^0 \) modes, respectively. In the \( K_S^0 \) case, the CP-conserving long-distance contribution can only proceed through P-wave, and the CP-violating short distance component in the SM is even more suppressed.

Due to the strong suppression of the SM decay amplitude, dynamics beyond the Standard Model (BSM) can induce large deviations of \( B(K_S^0 \rightarrow \mu^+\mu^-) \) with respect to the SM prediction. This has been shown to be the case in SUSY scenarios \(^9\) as well as in leptoquark models \(^10\)\(^11\). The current best limit, \( B(K_S^0 \rightarrow \mu^+\mu^-) < 0.8 \times 10^{-9} \) at 90% confidence level (CL), was set by LHCb \(^12\) with the data collected during Run 1 (2011–2012).

In this letter, a significantly improved limit is presented. Results are based on proton-proton \((pp)\) collision data collected with the LHCb detector at a center-of-mass energy of 13 TeV during 2016, 2017, and 2018 (Run 2), corresponding to an integrated luminosity of 5.6 fb\(^{-1}\). This measurement benefits from the huge \( K_S^0 \) production cross section at the LHC of approximately 0.6 barn at a center-of-mass energy of 13 TeV \(^13\), and from the forward geometry of the vertex detector of LHCb since \( K_S^0 \) mesons are predominantly produced at low angles with respect to the beam pipe. A major improvement with respect to the previous analysis is achieved by employing dedicated software triggers that were

![Figure 1: Diagrams representing SM contributions to the \( K_S^0 \rightarrow \mu^+\mu^- \) decay amplitude: (top) long-distance contribution, generated by two intermediate photons, and (bottom) short-distance contributions.](image-url)
not present in Run 1. These new triggers were included from the start of 2016 data taking, so data from 2015 is not used, due to a lower trigger efficiency and integrated luminosity. While the analysis strategy closely follows what was done for Run 1, the event reconstruction and selection have been improved.

The LHCb detector [14,15] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/$c$. The minimum distance of a track to a proton-proton collision vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu$m, where $p_T$ is the component of the momentum transverse to the beam axis, in GeV/$c$. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. In addition, information from the tracking system, the calorimeter system and the RICH detectors is used to further improve the muon identification.

Events are first required to pass a hardware-trigger selection [16], based on information from the calorimeter and the muon system, relying on high-$p_T$ signatures. Subsequently, a full event reconstruction is applied in a two-step software selection. In the previous analysis, the search was limited by a muon $p_T$ threshold of approximately 1.8 GeV/$c$. In Run 2, a new tracking method was included, in order to improve the reconstruction of muons with low transverse momentum. By using the information from the muon chambers at early stages in the reconstruction chain, a drastic reduction of the number of tracks to be processed by the most time-consuming reconstruction algorithms is achieved. This new reconstruction method allowed to reduce the $p_T$ muon threshold to 80 MeV/$c$. In addition, a dedicated software trigger selection was developed, using the aforementioned reconstruction method, fully covering the dimuon invariant mass spectra of many strange decays, including $K^0_S \to \mu^+\mu^-$. This translates into an increase of the trigger efficiency for $K^0_S \to \mu^+\mu^-$ of about an order of magnitude with respect to Run 1 [17]. After the upgrade of the LHCb detector [18], the hardware trigger will no longer be present, allowing for further efficiency improvements.

The measurement of the $K^0_S \to \mu^+\mu^-$ branching fraction requires the normalization to the $K^0_S$ meson production rate, which is done using $K^0_S \to \pi^+\pi^-$ decays, given its abundance, its similar topology to $K^0_S \to \mu^+\mu^-$ and its well-known branching fraction [5]. Common offline preselection criteria are applied to $K^0_S \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$ candidates in order to reduce many systematic effects in the efficiency ratio. Candidate $K^0_S \to \mu^+\mu^-$ ($K^0_S \to \pi^+\pi^-$) decays are obtained from two tracks with opposite charge identified as muons (pions), forming a secondary vertex (SV) and with an invariant mass in the range 400–600 MeV/$c^2$. Kaon candidates are required to decay inside the VELO, where the best $K^0_S$ invariant mass resolution is achieved. Approximately 22% of $K^0_S$ mesons produced at the $pp$ interaction point decay within the acceptance of the VELO.
The $K_S^0$ candidate origin must be compatible with a PV, while its decay products should be inconsistent with originating from any PV. The SV must be well detached from the PV by requiring the $K_S^0$ candidate decay time to be larger than 6% of the known $K_S^0$ lifetime. Decays of $Λ$ baryons to $pπ^−$, and the charge-conjugate counterpart are suppressed by removing candidates close to the expected elliptical kinematic regions in the Armenteros–Podolanski plane. The corresponding loss in signal efficiency is negligible. Muon tracks are required to have associated hits in the muon system, while pions from $K_S^0 → π^+π^−$ decays are required to be within the muon system acceptance. The main background sources are random combinations of tracks, inelastic interactions with the detector material, and $K_S^0 → π^+π^−$ decays, where the two pions are misidentified as muons. In doubly misidentified $K_S^0 → π^+π^−$ decays, the invariant mass of the kaon candidate is underestimated on average by $40\,\text{MeV}/c^2$, corresponding to ten times the dimuon invariant mass resolution in this energy regime.

Background from material interactions and random combinations of tracks is suppressed using an Adaptive Boosted Decision Tree (BDT) algorithm, based on the XGBoost library. Simulated $K_S^0 → μ^+μ^−$ decays are used as a proxy for signal, and $K_S^0 → μ^+μ^−$ candidates from data in the dimuon invariant mass region above $520\,\text{MeV}/c^2$ as a proxy for background. Data from the left sideband is not considered since it is dominated by doubly misidentified $K_S^0 → π^+π^−$ decays. Before the BDT training, the simulated $K_S^0 → μ^+μ^−$ candidates are weighted using a Gradient Boost algorithm trained with $K_S^0 → π^+π^−$ candidates in simulation and data, to take into account small differences between data and simulation. Since the background candidates used in the training are part of the fitted sample, the $k$-folding approach is applied to avoid overtraining. The BDT is trained independently in two mutually exclusive categories. In the first category, referred to as exclusively triggered-on-signal (xTOS), events are triggered at the hardware stage exclusively by the signal candidate decay products. The second category, referred to as triggered-independent-of-signal (TIS), consists of events triggered at the hardware stage independently of the trigger decision on the decay products of the signal candidate. Both categories are required to fulfill the same software trigger requirements. The BDT input variables are: the kaon candidate decay time and IP significance ($χ^2_{IP}$), defined as the increase of the $χ^2$ of the PV when considering the kaon candidate in the vertex fit; the $χ^2_{IP}$ and the track-fit $χ^2$ of each of the two tracks; the distance of closest approach between the two tracks; the cosine of the helicity angle; the $χ^2$ of the SV fit; two SV isolation variables, defined as the difference in the $χ^2$ in the vertex fit with only the two final-state tracks and that obtained when adding the one or two nearest tracks; and a VELO material veto variable. The VELO material veto variable efficiently suppresses background originating from inelastic interactions with the VELO stations and RF foil which separates the VELO modules from the beam vacuum. See Appendix A for more information about the material veto and the interactions with the VELO material. A selection requirement is placed on the BDT, rejecting 99% of the background with a signal efficiency of approximately 63% for both trigger categories.

Another significant background source is $K_L^0 → μ^+μ^−$ decays, for which the LHCb detector has the efficiency suppressed by a factor of approximately $2.3 \times 10^{-3}$ relative to $K_S^0 → μ^+μ^−$ decays due to its longer lifetime. Interference between $K_S^0$ and $K_L^0$ mesons is neglected since $K^0$ and $\bar{K}^0$ mesons are expected to be produced in equal amounts.

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1The inclusion of charge-conjugate processes is implied throughout this paper, unless otherwise noted.
at the LHC. Contributions from other background sources, such as $K^0 \rightarrow \mu^+ \mu^- \gamma(\gamma)$, $\Sigma^+ \rightarrow p\mu^+\mu^-$, $K^{0,\ast+} \rightarrow \pi^0\mu^+\mu^-$, $\Lambda \rightarrow p\pi^-, \omega \rightarrow \pi^0\mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-\gamma$, as well as from $K^0_L \rightarrow \pi^0\mu^+\nu_\mu$ and $K^0_S \rightarrow \pi^0\mu^+\nu_\mu$ decays, the latter recently discovered by the KLOE-2 collaboration [28], are found to be negligible.

Candidates satisfying the preselection criteria are divided into twenty subsets: ten bins of the BDT response for each of the two trigger categories. The BDT bins are chosen to have the same fraction of simulated signal candidates in each bin. A dedicated muon identification Boosted Decision Tree ($\mu$BDT) is used to suppress $K^0_S \rightarrow \pi^+\pi^-$ decays, whose performance can be consulted in Ref. [12]. The selection criterion on the $\mu$BDT is optimized and applied independently for each of the twenty categories.

The $K^0_S \rightarrow \mu^+\mu^-$ branching fraction is determined in an unbinned maximum-likelihood fit to the kaon candidate invariant mass in the range 480–595 MeV/$c^2$. Taking into account the ratio of detection efficiencies, the signal yield is normalized to $K^0_S \rightarrow \pi^+\pi^-$ decays to cancel uncertainties due to the $K^0_S$ cross-section, luminosity, reconstruction, and partially due to selection criteria including the BDT binning. The fit is performed simultaneously in the twenty data categories. The contributions considered are: $K^0_S \rightarrow \mu^+\mu^-$ signal, modelled with a Hypathia distribution [29]; background from material interactions and random combination of tracks, described by an exponential function; the $K^0_S \rightarrow \pi^+\pi^-$ background, modelled with a power law distribution; and $K^0_L \rightarrow \mu^+\mu^-$, described with the same probability density function as the $K^0_S \rightarrow \mu^+\mu^-$ decay. All yields are free to vary in the fit. A Gaussian constraint is applied to the yield of the $K^0_S \rightarrow \mu^+\mu^-$ component, based on its known branching fraction [5] and on the efficiency ratios between $K^0_L \rightarrow \mu^+\mu^-$ and $K^0_S \rightarrow \mu^+\mu^-$. Additional Gaussian constraints are applied to the efficiency ratios between $K^0_S \rightarrow \mu^+\mu^-$ and $K^0_S \rightarrow \pi^+\pi^-$, accounting for the systematic uncertainties. An independent sample of $K^0_S \rightarrow \pi^+\pi^-$ decays obtained from a trigger-unbiased sample is used to calibrate the $K^0_S$ invariant mass peak position and resolution parameters (see Fig. 2). It is also used to correct the simulation to obtain the efficiencies of the signal and the normalization channel.

The response of the muon identification is calibrated using $J/\psi \rightarrow \mu^+\mu^-$ decays, complemented with the use of $K^0 \rightarrow \pi^-\mu^+\nu_\mu$ decays due to the lower transverse momentum of the decay products. The yield of $K^0 \rightarrow \pi^-\mu^+\nu_\mu$ decays as a function of the data taking period is also used to evaluate the variation of the total efficiency with time, mostly caused by changes in the thresholds of the hardware trigger. The obtained single-event sensitivity is $(3.0 \pm 0.6) \times 10^{-12}$, meaning that approximately two $K^0_S \rightarrow \mu^+\mu^-$ and five $K^0_L \rightarrow \mu^+\mu^-$ signal decays are expected to be present in the data set, using the SM prediction for the branching fractions, and also taking into account the $K^0_L \rightarrow \mu^+\mu^-$ detection suppression of $2.3 \times 10^{-3}$.

Various sources of systematic uncertainty are taken into account. The main sources are: the determination of the trigger efficiency, yielding a systematic uncertainty of 11% for the hardware trigger and 13% for the software trigger; data-simulation differences in the muon identification, with systematic uncertainties varying between 4% and 12%, depending on the trigger category and BDT bin; and the correction applied on simulation, evaluated to be 6%. Other sources include the efficiency ratio between the signal and normalization modes, the BDT response due to changes in the experimental conditions, and the uncertainty on the $K^0_S \rightarrow \pi^+\pi^-$ branching fraction. The total systematic uncertainty is between 19% and 23%, depending on the trigger category and the BDT bin. It tends to be lower in the TIS trigger category and higher in lower BDT bins, which have lower
Figure 2: Invariant-mass distribution of $K^0_S \rightarrow \pi^+\pi^-$ candidates in 2016 trigger-unbiased data (points with error-bars) and corrected simulation (solid histogram). The histogram of simulated candidates is normalized to data.

signal-to-background ratio, due to the stronger muon identification requirements for the lower bins and the bigger systematic uncertainty for the xTOS trigger efficiency. The systematic uncertainties are taken into account as Gaussian constraints in the fit to the data.

The fit shows no evidence for $K^0_S \rightarrow \mu^+\mu^-$ decays (see Fig. 3), with a yield of $34 \pm 23$ signal candidates. The significance with respect to the background-only hypothesis is $1.5\sigma$ ($1.4\sigma$ when combined with Run 1 data). An upper limit on the branching fraction is obtained by integrating the profile likelihood multiplied by a flat prior in the positive branching fraction domain, yielding $2.2 \times 10^{-10}$ at 90 (95)% CL. The likelihood is combined with the Run 1 result, obtaining a limit of $2.1 \times 10^{-10}$ at 90 (95)% CL. A log-likelihood interval of one standard deviation ($-2\Delta \log L = 1$) from the Run 2 data set yields $\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) = 1.0^{+0.8}_{-0.7} \times 10^{-10}$. Combined with Run 1 it yields $\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) = 0.9^{+0.7}_{-0.6} \times 10^{-10}$. The profile likelihoods are shown in Fig. 4.

In summary, a search for the rare decay $K^0_S \rightarrow \mu^+\mu^-$ has been performed on a LHCb data set of about 8.6 fb$^{-1}$. The obtained results supersede those of our previous publications [12,30]. The data are consistent both with the background-only hypothesis and the combined background and SM signal expectation at the 1.4$\sigma$ and 1.3$\sigma$ level, respectively. The most stringent upper limit on the $K^0_S \rightarrow \mu^+\mu^-$ branching fraction to date of $2.1 \times 10^{-10}$ at 90 (95)% confidence level is set, improving the previous best limit by a factor of four. This result imposes constraints on MSSM and leptoquark models.

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Figure 3: Projection of the fit to the dimuon invariant mass distribution for (top) two TIS and (bottom) two xTOS BDT bins. These bins correspond to the BDT response with the biggest signal-to-background ratio (increasing from left to right). The dashed orange line shows the signal contribution, the dotted green line the $K^0_S \rightarrow \mu^+\mu^-$ contribution, the dash dotted red line the $K^0_S \rightarrow \pi^+\pi^-$ contribution, the loosely dotted brown line the background from random combination of tracks and material interactions, and the solid blue line the total p.d.f.

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Figure 4: Evaluation of $-2\Delta \log \mathcal{L}$, where $\mathcal{L}$ is the likelihood of the fit model, as a function of $\mathcal{B}(K_0^S \to \mu^+\mu^-)$. The dotted orange line corresponds to the Run 1 result, the dashed blue line to the Run 2 result, and the solid green line shows the combination. The two vertical lines show the location of the upper limit of the combined result at 90% and 95% confidence level.
A Supplemental material

In the right sideband of the dimuon invariant mass spectrum, candidates originated from material interactions with the detector dominate, as can be seen in Fig. 5. In order to reduce this contribution, a tool profiting from the parametrization of the VELO using proton-gas events, described in detail in Ref. [31], is used. This algorithm defines an uncertainty-weighted distance to the material

\[ D = \sqrt{\left(\frac{x - SV_x}{\sigma_x}\right)^2 + \left(\frac{y - SV_y}{\sigma_y}\right)^2 + \left(\frac{z - SV_z}{\sigma_z}\right)^2}, \]

where \( SV_{x,y,z} \) denote the position of the reconstructed secondary vertex in the three coordinates, and \( \sigma_{x,y,z} \) the associated uncertainty. This quantity gives information about how likely a vertex arises from an inelastic material interaction.

PRL justification

Justification for PRL: This letter contains the world best upper limit on the very rare decay \( K^0_S \rightarrow \mu^+\mu^- \), overtaking the previous limit by a factor of four, and reaching a precision below the \( 10^{-10} \) range, unprecedented in branching fraction measurements at the LHC. The result imposes severe constraints in certain types of leptoquark models that have been suggested as an explanation for the \( \varepsilon'/\varepsilon \) experimental value when interpreted as an anomaly. It also excludes fine-tuned regions of the MSSM parameter space previously allowed.

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References

[1] G. Ecker and A. Pich, *The longitudinal muon polarization in \( K_L \to \mu^+\mu^- \)*, Nucl. Phys. B366 (1991) 189.

[2] G. Isidori and R. Unterdorfer, *On the short distance constraints from \( K_{LS} \to \mu^+\mu^- \)*, JHEP 01 (2004) 009, arXiv:hep-ph/0311084.

[3] G. D’Ambrosio and T. Kitahara, *Direct CP violation in \( K \to \mu^+\mu^- \)*, Phys. Rev. Lett 119 (2017) 201802, arXiv:1707.06999.

[4] G. D’Ambrosio, G. Ecker, G. Isidori, and H. Neufeld, *Radiative nonleptonic kaon decays*, in 2nd DAPHNE Physics Handbook, 265, 1994, arXiv:hep-ph/9411439.

[5] Particle Data Group, M. Tanabashi et al., *Review of particle physics*, Phys. Rev. D98 (2018) 030001.

[6] E871 collaboration, D. Ambrose et al., *Improved branching ratio measurement for the decay \( K^0_L \to \mu^+\mu^- \)*, Phys. Rev. Lett. 84 (2000) 1389.

[7] E137 collaboration, T. Akagi et al., *Experimental study of the rare decays \( K^0_L \to \mu e \), \( K^0_L \to e e \), \( K^0_L \to \mu \mu \) and \( K^0_L \to e e e \)*, Phys. Rev. D51 (1995) 2061.

[8] E791 collaboration, A. Heinson et al., *Measurement of the branching ratio for the rare decay \( K^0_L \to \mu^+\mu^- \)*, Phys. Rev. D51 (1995) 985.

[9] V. Chobanova et al., *Probing SUSY effects in \( K^0_S \to \mu^+\mu^- \)*, JHEP 05 (2018) 024, arXiv:1711.11030.

[10] I. Dorˇsner et al., *Limits on scalar leptoquark interactions and consequences for GUTs*, JHEP 11 (2011) 002, arXiv:1107.5393.

[11] C. Bobeth and A. J. Buras, *Leptoquarks meet \( \epsilon'/\epsilon \) and rare kaon processes*, JHEP 02 (2018) 101, arXiv:1712.01295.

[12] LHCb collaboration, R. Aaij et al., *Improved limit on the branching fraction of the rare decay \( K^0_S \to \mu^+\mu^- \)*, Eur. Phys. J. C77 (2017) 678, arXiv:1706.00758.

[13] A. A. Alves Jr. et al., *Prospects for measurements with strange hadrons at LHCb*, JHEP 05 (2019) 048, arXiv:1808.03477.

[14] A. A. Alves Jr. et al., *Performance of the LHCb muon system*, JINST 8 (2013) P02022, arXiv:1211.1346.

[15] LHCb collaboration, R. Aaij et al., *LHCb detector performance*, Int. J. Mod. Phys A30 (2015) 1530022, arXiv:1412.6352.

[16] R. Aaij et al., *The LHCb trigger and its performance in 2011*, JINST 8 (2013) P04022, arXiv:1211.3055.

[17] F. Dettori, D. Martínez Santos, and J. Prisciandaro, *Low-\( p_T \) dimuon triggers at LHCb in Run 2*, LHCb-PUB-2017-023, 2017.
[18] LHCb collaboration, *Computing Model of the Upgrade LHCb experiment*, CERN-LHCC-2018-014, 2018.

[19] J. Podolanski and R. Armenteros, *Analysis of V-events*, Phil. Mag. 45 (1954) 13.

[20] F. Archilli et al., *Performance of the muon identification at LHCb*, JINST 8 (2013) P10020, arXiv:1306.0249.

[21] Y. Freund and R. E. Schapire, *A decision-theoretic generalization of on-line learning and an application to boosting*, J. Comput. Syst. Sci. 55 (1997) 119.

[22] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.

[23] T. Chen and C. Guestrin, *XGBoost: A scalable tree boosting system*, in *Proceedings of the 22Nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD ’16, (New York, NY, USA), 785–794, ACM, 2016, arXiv:1603.02754.

[24] A. Rogozhnikov, *Reweighting with Boosted Decision Trees*, J. Phys. Conf. Ser. 762 (2016), arXiv:1608.05806, https://github.com/arogozhnikov/hep_ml.

[25] F. Pedregosa et al., *Scikit-learn: Machine learning in Python*, Journal of Machine Learning Research 12 (2011) 2825, see also http://scikit-learn.org.

[26] J. A. Hernando Morata et al., *Measurement of trigger efficiencies and biases*, LHCb-2008-073, 2010.

[27] M. Alexander et al., *Mapping the material in the LHCb vertex locator using secondary hadronic interactions*, JINST 13 (2018) P06008, arXiv:1803.07466.

[28] KLOE-2 collaboration, D. Babusci et al., *Measurement of the branching fraction for the decay $K_S \rightarrow \pi \mu \nu$ with the KLOE detector*, arXiv:1912.05990.

[29] D. Martínez Santos and F. Dupertuis, *Mass distributions marginalized over per-event errors*, Nucl. Instrum. Meth. A764 (2014) 150, arXiv:1312.5000.

[30] LHCb collaboration, R. Aaij et al., *Search for the rare decay $K_L^0 \rightarrow \mu^+ \mu^-$*, JHEP 01 (2013) 090, arXiv:1209.4029.

[31] M. Alexander et al., *Mapping the material in the LHCb vertex locator using secondary hadronic interactions*, JINST 13 (2018) P06008.
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