PhD Project

# Search for dark matter mediators in rare decays at NA62 Kaon factory

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The presence of several anomalies in muon physics might hint at new particles beyond the Standard Model (SM). The long standing $\sim 3.5\sigma$ discrepancy between the observed and the SM predicted value of the muon anomalous magnetic moment, $a_\mu = (g-2)_\mu/2$, has been recently scrutinized by the Fermilab National Accelerator Laboratory *Muon g-2* experiment [1]. For past measurements, it is not clear if the observed tension results from experimental errors or theoretical errors or a combination of the two. The new measure of the $(g-2)_\mu$ anomaly, combined with the previous measurement of the Brookhaven National Laboratory (BNL) experiment E821, has been compared with the improved SM calculation performed by the *Muon g-2 Theory Initiative* group [2] and the tension increased to $4.2\sigma$.

The exchange of a light dark matter (DM) mediator ($X$), both a gauge boson vector or a CP-even scalar, with mass $\lesssim 1$ $GeV$, neutral with respect to the SM interactions and coupling preferentially to muons, could compensate the observed theoretical deficit of the $a_\mu$ with New Physics below the electroweak scale [3]; muonic forces could also justify the elusive nature of the Dark Matter (DM) in direct detection experiments. Light muonic forces could be emitted in rare lepton flavour preserving processes involving initial or final state muons so, for example, kaon decays could be excellent probes of them: in the $K^+ \to \mu^+\nu_\mu$ decay, $X$ could be radiated from the muon via the $\mu - X$ coupling, if the $X$ mass is lower than $m_K - m_\mu$, making $K^+ \to \mu^+\nu_\mu X$ a rare decay channel for X search.

The NA62 fixed target experiment at the CERN Super Proton Synchrotron [4] aims to measure with 10% statistical precision the branching ratio (BR) of the ultra rare decay $K^+ \to \pi^+\nu\bar{\nu}$, whose very precise SM prediction is $(0.84\pm0.10)\times10^{-10}$. To this extent, NA62 is currently producing an unprecedented number of kaons, so it could also have unprecedented sensitivity to the dark muonic forces production through $K^+ \to \mu^+\nu_\mu X$, for both invisible and visible $X$ decay scenarios. A theoretical study [5] of the $X$ invisibly decaying into neutrino or DM pairs using NA62 results showed that, in both of this two channels, NA62 could probe, with the full kaon luminosity and for some choices of parameters, the region of the $X - \mu$ coupling explaining the $(g-2)_\mu$ anomaly. Concerning the $X$ visibly decaying scenario, for scalar mediators, $X \to \gamma\gamma$ can be assumed as the main $X$ decay channel for $m_X < 2m_\mu$, in the absence of other interactions. If $X$ decays into $\mu^+\mu^-$, NA62 could improve the coverage for both scalar and vector forces in the region for $m_K - m_\mu > m_X > 2m_\mu$.

## Master thesis achievements

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In my master thesis I preliminary studied the NA62 sensitivity to the process $K^+ \to \mu^+\nu_\mu X$, $X \to \gamma\gamma$. I analysed the full dataset collected by NA62 during 2017B data taking period, considering Monte Carlo samples simulating both the $K^+ \to \mu^+\nu_\mu X$, $X \to \gamma\gamma$ signal in the range of $X$ mass hypotheses between 20 $MeV$ and 360 $MeV$ and the main background sources with respect to the signal. Assuming the $X \to \gamma\gamma$ decay occurs inside the $K^+$ fiducial decay volume of the NA62 detector, I chose the two photons invariant mass ($m_{\gamma\gamma}$) as the main discriminating variable for signal search and determined a preliminary meaningful set of signal selection criteria, refined to suppress the main backgrounds. I was able to identify two sensitive signal regions in the $X$ mass range considered, R1: $m_{\gamma\gamma} < 110$ $MeV$ and R2: $m_{\gamma\gamma} > 160$ $MeV$. In a conservative approach, I used only the data sample for background estimate and I considered the $X$ search, for fixed values of $m_X$, as a counting experiment with a single observation channel. I quoted the expected upper limit at 90% CL on the signal yield through the $CL_s$ method and used it to estimate the expected BR sensitivity. The best sensitivity, of order $10^{-7}$, with the current dataset and preliminary selection criteria I used, was achieved for $m_X$ included in the range $m_{\gamma\gamma} > 160\ MeV$.

## Research project

My PhD project is a continuation of the my master thesis, an experimental work of data analysis concerning the search of new scalar dark muon-philic mediators radiated in the $K^+ \to \mu^+ \nu_\mu X$ decay, mainly considering the $X \to \gamma\gamma$ decay but also other $X$ decay channels, such as $X \to \mu^+\mu^-$ or the invisible $X \to \nu\bar{\nu}$.

My first aim is to get an expected experimental BR sensitivity to $K^+ \to \mu^+ \nu_\mu X$, $X \to \gamma\gamma$ having a theoretical relevance. A gain of O($10^2$) is needed with respect to my current result to achieve the best possible sensitivity obtainable assuming the full NA62 luminosity and the search to be statistic dominated. I expect to improve the sensitivity enlarging the dataset, so I will include the full NA62 collected statistics (2016, 2017 and 2018 samples) and the data that will be collected in future Runs restarting from 2021, to which I will participate actively. In order to fully exploit the probing power of NA62, I will better study accidentals to be able to relax some tight conditions required at the time being to select an event. I will also study possibilities to enlarge signal regions R1 and R2 and refine the signal selection to further suppress backgrounds. Moreover, it may be possible to search for a $X \to \gamma\gamma$ resonance if the $X$ decay occurs inside the detector fiducial decay volume, so I will perform a shape analysis on the $m_{\gamma\gamma}$ distribution, this approach being different from and complementary to the one I used in my master thesis analysis. I also plan to use this machinery to optimize current selection criteria rejecting the main backgrounds.

Concerning, $X \to \mu^+\mu^-$ decay, a di-muon resonance search in $K^+ \to \mu^+ \nu_\mu X$, $X \to \mu^+\mu^-$ with opposite sign muons can be performed and for a scalar mediator, NA62 could substantially improve the existing bounds on muonic forces.

For the $X$ invisible decays analysis, with respect to the theoretical study, which used 2015 data, an experimental study will profit from the significant increase of the statistics, the crucial improvement of the kinematic resolution due to the fully functionality of the beam spectrometer in 2016-2018 and future data taking periods, and the deeper knowledge of the backgrounds that has been achieved.

To improve the analysis for the $K^+ \to \mu^+ \nu_\mu X$ decay it would also be possible to assess the feasibility of dedicated triggers in the future data taking, in particular for the $K^+ \to \mu^+ +$ *invisible* decay.

## References

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[3] R. Essig *et al.*, in *Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013): Minneapolis, 2013*, *Dark Sectors and New, Light, Weakly-Coupled Particles*, arXiv:1311.0029 [hep-ph].

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