1 Scientific goal of the project

The Standard Model of particle physics (SM) is the embodiment of our current understanding of the sub-atomic Universe. The SM describes all fundamental forces except gravity. Remarkably, this model successfully describes all current experimental data [1]. Despite its success, the SM has a few shortcomings. It fails to explain the scale of the observed matter-antimatter imbalance, the apparent dark-matter content of the Universe, and does not give the rationale behind the supposed non-zero neutrino masses [17].

These problems are at the core of particle physics research today, as even a minor deviation from the SM would be a breakthrough suggesting the existence of a more fundamental theory beyond the SM (BSM). Experimental tests of the fundamental symmetries underlying the SM, are one of the most promising areas of searching for BSM. Among symmetries being tested today, there is the symmetry corresponding to the invariance under CPT transformation, which is assumed to be strictly conserved in the SM. CPT symmetry is a combination of three operations, (C) transforming particles into antiparticles, (P) spacial reflection and (T) which is the time-reversal operation. In the PRELUDIUM project I will assess the viability of testing CPT symmetry in high luminosity experiments such as LHCb by studying neutral meson oscillations [6]. Neutral-meson oscillations are recurrent spontaneous transitions between the matter and anti-matter states of neutrally charged mesons. The sensitivity of CPT violation (CPTV) studies is linked to the number of events $N = L \cdot \sigma$ available in the chosen mode, where L and σ are the integrated luminosity (recorded at the experiment) and the cross-section respectively.

In this appeal, I propose a study of the possibility of achieving sensitivity to CPTV in the successive data-taking periods (runs) of the LHCb experiment by examining different theories incorporating CPTV. I shall focus on two popular frameworks for testing CPTV in neutral-meson oscillations. Namely, the complex phenomenological parametrisation (p, q, z) of CPTV (also known as the classical framework) and the Standard Model Extension framework (SME) [6, 8]. All SME CPTV analyses to date in neutral-meson oscillations have been performed using the minimal SME (mSME) [8]. In mSME the target coefficients are Δa_μ parameters which arise from the difference between the couplings of valence quarks with the Lorentz violating field (LV) [15]. The theoretical foundation of the SME is the observation that we can search for CPTV by looking at LV effects [8, 7]. In the classical framework the scale of CPTV is controlled by the ad-hoc complex parameter z [11, 6], which is also referred to as ζ.

I will examine the sensitivity to CPTV for data sets of size comparable to the statistics collected at subsequent LHCb runs, with special emphasis on Run 3 in $D^0 \to K^-\pi^+$ channel. For that, I am going to finish the implementation of my own Monte Carlo (MC) generator of neutral-meson oscillations written in C++/ROOT and use it to simulate neutral-meson oscillations for present and future LHCb high-luminosity runs.

The sensitivity to CPTV achieved for a MC generated sample using mSME and the classical framework is going to be determined based on two advanced statistical likelihood-based methods of testing new physics used in the discovery of Higgs boson (e.g. the CLs and asymptotic likelihood-based tests of new physics [4, 3], see methodology). Both approaches will be compared to each other and to the results of CPTV studies performed on the existing LHCb data set containing neutral D meson oscillations (Run 1 or Run 2). As a result of my analysis, I shall report the threshold values of CPTV parameters that can be statistically distinguished from the null-hypothesis of CPT invariance ($z = 0$, $\Delta a_\mu = 0$). Finally, I plan to test the results obtained based on the MC generated sample with the partial predictions of CPTV for LHCb data containing sample of neutral D meson oscillations from $D^0 \to K^+\pi^-$ mode.

2 Significance of the project

On the one hand, the results of the proposed analysis will indicate which theories and methods used for studies of CPT invariance in neutral-meson systems are the most promising. On the other hand, the developed tools are going to be so versatile that they will be helpful in sensitivity studies and CPTV searches in many different experiments irrespective of the oscillating meson species. Consequently, they might be used as reference for both CPTV searches using experimental data and future feasibility studies of CPTV measurement in high luminosity searches for BSM in neutral meson systems.

The LHCb experiment was designed to be very sensitive to the charm and beauty sectors. The current best limit on CPTV in the beauty sector was reported by LHCb [2]. The reported result is one order of magnitude more precise than that reported by the D0 experiment and 10^3 better than the result of the Babar experiment [10, 9](see, Figure.1).

The best result in the charm sector was published by the FOCUS collaboration [16]. They reported the accuracy of measurement of z of $O(1)$ order and concluded that uncertainties of Δa_μ are about $3 \cdot 10^{-13}$ GeV (see, [13, 16] for review). The fact that the LHCb experiment has proven to be more efficient in the beauty sector compared to earlier measurements gives us hope that this will also be the case in the charm sector. In Run 2 and 3, we have access to 10^4 and 10^5 times greater statistics than that of FOCUS. Another advantage of the LHCb experiment is its high effective decay-time resolution of 45fs, which results in sensitivity to small differences in decay time between matter and antimatter. These two facts speak to the viability of CPTV searches in LHCb. I expect to be able to show that CPTV measurements in high luminosity experiments, such as LHCb will yield far better results than the most precise measurement of CPTV in the charm sector published by FOCUS [16, 14] (around 170 times better accuracy in LHCb Run 3 compared to FOCUS).

The unique thing about the proposed project is that it will be one of very few, if not the single most detailed analysis of the feasibility of measurement of CPTV in the charm sector. Whereas most authors extrapolate the sensitivity of future experiments based on simple scaling of uncertainties from earlier experiments, I am going to employ advanced statistical machinery used in the discovery of Higgs boson (e.g. the CLs and asymptotic likelihood-based tests [3, 4], see section 4). My approach does not require any prior knowledge of CPTV parameter uncertainties from fits of CPTV parametrisation models to experimental data, but it is based on MC generated psuedo-experiments. The mSME and the classical model are the most popular CPTV testing frameworks, which makes my project relevant to the current research [14, 8, 6]. Studies in this project are a part of the group activity in the LHCb internal project on simulations for upgraded LHCb detector at high-intensity LHC (G.Corti et al., LHCb-INT-2021-001).

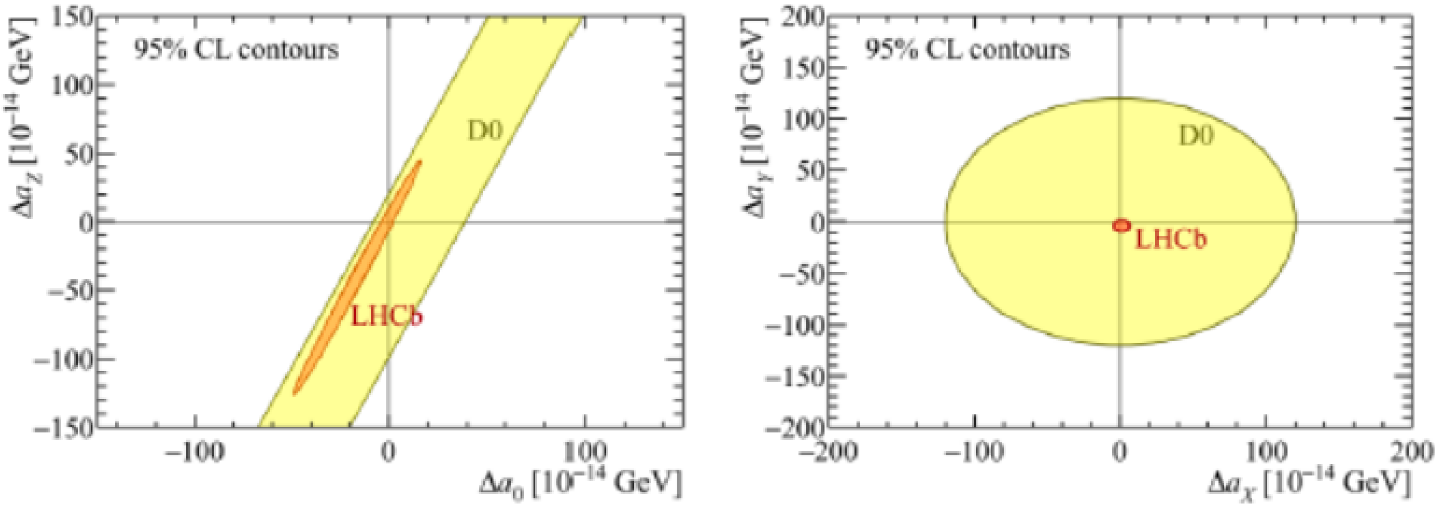

Figure 1 – Values of CPTV coefficients Δa_μ with 95% CL contours measured by the LHCb experiment in B_d^0 mixing [2] compared to the formerly best measurements from D0 [9]. Images taken from the presentation entitled: Violation of CPT and Lorentz symmetry in neutral-mesons, Séminaire de Physique des Hautes Energies IPHC Strasbourg, Jeroen van Tilburg (LHCb).

3 Concept and work plan

Up until this point, I implemented a MC generator of neutral-meson decays enabling studies of sensitivity to CPTV in neutral-meson systems based on the classical model and tested it for moderate statistics $< 6.5 \cdot 10^7$ (this was my master's project). As expected, the results of my preliminary research suggest that the fit error of parameter z describing CPTV obtained from the fit of the classical model to MC generated data is proportional to $\frac{1}{\sqrt{N}}$, where N is the number of decays generated per pseudo-experiment, which is in line with the MC scaling law. This result is consistent with the theoretical predictions and suggests that LHCb Run 3 should have $\sqrt{\frac{N_{FOCUS}}{N_{LHCb}}} = 170$ times better precision than FOCUS, where N_{FOCUS} marks the sample size used for the analysis by FOCUS and N_{LHCb} is the size of statistics that will be collected in Run 3. For the same reason, we expect 40 times better accuracy in Run 1 (2010-2012), and 60 times better accuracy in Run 2 (2015-2019) compared to FOCUS.

In this project, the MC generator will be extended by the addition of full kinematic and dynamic models of decays related to the oscillating neutral-mesons, for which we make SME predictions, as well as, the optimisation of memory usage and processing time of the programme. The latter is necessary because of the need of achieving high numerical accuracy and the requirement of generating large MC samples, corresponding to the size of expected statistics.

In mSME, Δa_μ coefficients depend on the mesons' momenta, which makes it is insufficient to generate just the decay-times. Now, we need to generate mesons' momenta taking into account full kinematics and dynamics of decays related to the simulated oscillations. This process will require the inclusion of relevant form factors. In the classical model we use only the decay-time acceptance function to account for detector efficiency, as opposed to the mSME frameworkmk where the effective distribution of mesons' momenta will require the introduction of the momentum-dependent acceptance correction.

Finally, the statistical methods used to study the sensitivity of CPTV measurement in LHCb used in my master's thesis were far more simplistic than those which I plan to apply now (such as the CLs and asymptotic likelihood-based tests of new physics [3, 4], see methodology).

The general work plan can be summed up in the following steps:

1. Model design and implementation using Wolfram Mathematica. The plan is to thoroughly examine the phenomenological and mSME frameworks. (2 months)
2. Introduction of the description of experimental uncertainties connected with detector effects (time and momentum-dependent acceptance functions). (3 months)
3. Implementation of the examined models in C++ using RooFit framework. The implemented models will be used for MC generation of decays. (3 months)
4. MC simulations of neutral-meson oscillations in the classical framework. (4 months)
5. MC simulations of neutral-meson oscillations based on the mSME framework. (5 months)
6. Estimation of sensitivity to CPTV for MC generated data using advanced statistical methods, such as the CLs and asymptotic likelihood-based tests of new physics [4, 3]. (4 months)
7. Cross-checks of MC sample with real data acquired by the LHCb (Run 2 or Run 1). Comparison of the distribution of kinematic variables, systematic uncertainties. (3 months)

Upon finishing the project and publishing the results, I plan to publish the code of my generator online with a technical note so that other people can use it for research.

The project will be carried out by me under supervision of my PhD supervisor. To my mind, the main risk factors of the proposed analysis are that the tested methods might turn out to be ineffective. In case of the neutral D meson system in the classical framework this risk is not particularly high owing to my previous experience with similar MC simulations. The analysis in mSME might prove to be more challenging, as it will require the development of the necessary know-how on my side.

For that purposes of MC simulations, I will take advantage of my unpaid access to Centrum Informatyczne Świerk (CIŚ) infrastructure, which enables parallelization of processes and plenty of storage space. My assessment of the time required to simulate all of the necessary pseudo-experiments was based on my prior experience in simulating neutral D meson oscillations for my master's thesis using CIŚ infrastructure. As a member of the LHCb collaboration I will have an easy access to experimental data collected at LHCb.

In order to avoid getting stuck on technical programming issues, I will frequently consult my progress with my supervisor Prof. Dr hab. Wojciech Wiślicki (mentor) and auxiliary supervisor Dr inż. Wojciech Krzemień (Co-Investigator). My auxiliary supervisor is personally involved in the searches of CPTV in neutral meson oscillations based on Run 1 and Run 2 LHCb data in the frame of the LHCb collaboration. He will help me with preprocessing of the LHCb sample which will be used for cross-checks of my generator with experimental data. Furthermore, the project will be conducted in cooperation with Dr Gloria Corti (LHCb Simuation Cooridnator).

4 Research methodology

The hamiltonian governing time evolution of a flavoured neutral-meson system is a sum of the strong, electromagnetic and weak hamiltonians (H_{wk}). For time intervals much larger than the typical strong interaction scale, the ket of the neutral-meson system obeys the Schrödinger equation in a simplified WWA[1] formalism [5]. Let us denote the arbitrary neutral meson by M^0 and the arbitrary multi-particle final state by f. In this formalism the evolution of states is governed by the

[1] Weisskopf–Wigner approximation

effective hamiltonian (H_{eff}). We can express the eigenvectors of the effective Hamiltonian (mass states $|M_L\rangle$, $|M_H\rangle$) in terms of the strong interaction eigenstates (flavour states $\left|M^0\right\rangle$, $\left|\bar{M}^0\right\rangle$). The eigenstates of the effective Hamiltonian have well-defined masses $m_{H,L}$ and decay widths $\Gamma_{H,L}$. In this formalism, there is an elegant phenomenological CPV/CPTV complex parametrisation (q, p, z) [6, 11]:

$$|M_L\rangle = p\sqrt{1-z}\left|M^0\right\rangle + q\sqrt{1+z}\left|\bar{M}^0\right\rangle, \qquad |M_H\rangle = p\sqrt{1+z}\left|M^0\right\rangle - q\sqrt{1-z}\left|\bar{M}^0\right\rangle. \tag{1}$$

In this formalism, T conservation yields $\left|\frac{q}{p}\right| = 1$. CPT invariance induces $z = 0$ and CP requires that both of these conditions are fulfilled. The aforementioned parametrisation leads to phenomenological formulas for the following decay rates:

$$\frac{d\Gamma_{M^0\to f}(t)}{dt} = \left|\langle f|\, H_{wk}\left|M^0(t)\right\rangle\right|^2, \qquad \frac{d\Gamma_{\bar{M}^0\to \bar{f}}(t)}{dt} = \left|\langle \bar{f}|\, H_{wk}\left|\bar{M}^0(t)\right\rangle\right|^2. \tag{2}$$

Alongside the scale of discrete symmetries violation (characterised by p, q, z), different neutral mesons can be specified by setting their decay and oscillation properties ($\Delta\Gamma/\Gamma$ and $\Delta m/\Gamma$ respectively). We can also chose the type of the final state (e.g. CP-eigenstate or flavour-specific state[2]) by setting the decay amplitudes.

In order to account for technical time performance of the LHCb detector we need to multiply decay probability densities by decay-time acceptance function. The effect of non-zero finite decay-time measurement resolution 45fs (in LHCb $D^0 \to K\pi^+$ mode), can be simulated by a numerical convolution of the probability density distributions with gaussian.

Using the CPTV parametrisation model presented above we can generate two sets of N decays corresponding to N meson and N to antimeson decays. Next, we can construct the time-dependent asymmetry by dividing the difference of N events drawn from $\frac{d\Gamma_{M^0\to f}}{dt}$ and $\frac{d\Gamma_{\bar{M}^0\to \bar{f}}}{dt}$ distributions by their sum.

We can repeat this scheme many times creating a large set of MC generated pseudo-experiments. Now, let us notice that if we fit the right-sign asymmetry model[3] to the newly created asymmetry data sets we will be able to extract the values of CPTV parameter z and assess the quality of performed fits. The obtained fit-quality measures will be then used for hypothesis testing.

A similar task can be performed in the mSME framework where the equations above remain valid, but now z depends on the 4-velocity β^μ in the observers frame, an so the target coefficients are determined in the fixed stars (sidereal) reference frame [13]. The experimental observables (Δa_μ) depend on the location of the laboratory on the Earth's surface [8]. Thanks to CERN's location the sidereal variation in the LHCb is close to being maximal.

FOCUS collaboration has reported the best constraint on CPTV in the charm sector [13]. They constructed a highly simplified asymmetry model based on the small statistics and taking advantage of slow oscillations in D^0 system.

At LHCb, we have access to far more decays ($6.5 \cdot 10^7$ decays (Run 1), $1.5 \cdot 10^8$ decays (Run 2) and 10^9 (Run 3)), which forces us to take double Cabibbo-supressed decays into account. These statistics where calculated based on luminositites in LHCb runs: 3fb^{-1} (Run 1), 8fb^{-1}(Run 2), 25fb^{-1} (Run 3) [18] (see, Figure.2). The other factor that we should consider in LHCb are production and detection asymmetries. Fortunately, they are bound to be independent of D^0 decay time, and add only to the constant term of asymmetry.

For hypothesis testing, I will use at least two likelihood based tests of discovery. The most standard one is the CLs method [3, 4]. In this method we create a histogram of the likelihood ratio for pseudo-experiments with pure background ($z, \Delta a_\mu = 0$) and a separate histogram of likelihood ratios for pseudo-experiments with both background and signal. Next, we need to calculate 95% left-sided p-values for both signal+background (CL_{s+b}) and pure background (CL_b) χ^2 histograms over the ensemble of pseudo-experiments. For $CL_s = \frac{CL_{s+b}}{CL_b} < 0.05$ the probability of falsely excluding signal is less than 5%. The signal in our case will be CPTV. Another method that I am going to use are asymptotic tests of new physics, which do not require time consuming MC simulations and can help you to obtain the upper limit on discovery within the matter of minutes instead of days. I plan to test both methods and compare them in the context of CPTV based tests of new physics.

[2] The final state of the same flavour as the initial state.

[3] $A_{CPT} = \dfrac{\frac{d\Gamma_{M^0\to f}}{dt} - \frac{d\Gamma_{\bar{M}^0\to \bar{f}}}{dt}}{\frac{d\Gamma_{M^0\to f}}{dt} + \frac{d\Gamma_{\bar{M}^0\to \bar{f}}}{dt}} + C$, where C is a real normalisation constant.

CIŚ (Centrum Informatyczne Świerk) infrastructure will be used in this project as it allows its users to store large sets of data and enables parallelization of jobs. By the way of example, If I run five MC simulations of Run 2 one after another I will need to wait 5 hours for the simulation to complete. When I run them simultaniously, in different processes on CIŚ, the waiting time shrinks to an hour. For implementation of MC simulations I will use RooFit package of ROOT.

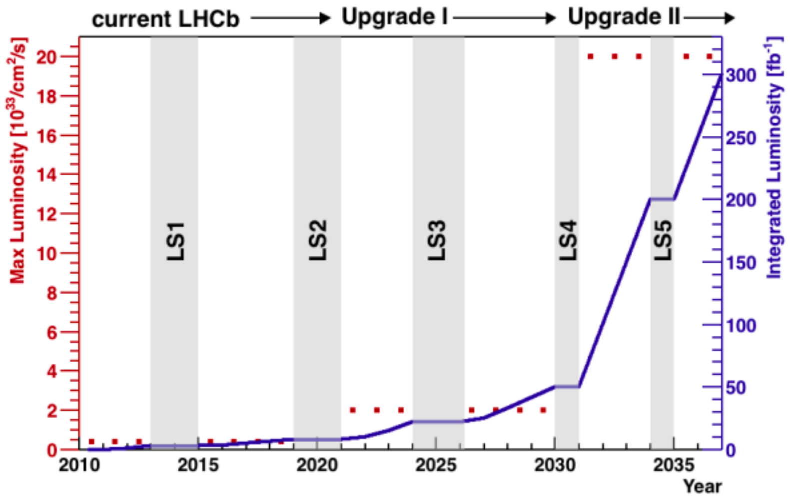

Figure 2 – Current and projected luminosity in LHCb experiment [18]

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