Application for the START programme.

Exploring τ sector: nature of lepton flavour and new sources of CP violation

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Abstract

It is an experimental particle-physics project aimed at the world's most precise tests of the standard model through the study of properties of the tau lepton at Belle II experiment.

Wider research context Our understanding of nature at the microscopic level is framed into a quantum-field-theory, the standard model. For decades it predicts results of the high energy physics experiments. However, the model is known to be conceptually limited and fails to describe such phenomena as the predominance of matter over antimatter and the as-yet-unknown forms of matter and energy inferred from astrophysical observations. Moreover, the recent experiments start to show inconsistency with the SM predictions, especially in the sector of the lepton flavour.

Research questions The project aims to answer the following questions:

- Is the neutrino oscillation the only source of the lepton flavour violation?
- Do all three generations of lepton interact with the weak field identically?
- Are there new sources of CP violation?

Approach We will put the new constraints on the processes violating flavour of the charged leptons by searching for the $ee \to \tau l(\gamma)$ process in Belle II data. Alongside with the valuable result, this study will include the background study of the $ee \to \tau\tau$ processes which will be used to search for the new sources of CP violation in $\tau \to K_s^0 \pi\nu$ decays. Finally, based on the experience acquired in these two measurements, we will do the world's most precise measurement of the lifetime of the tau lepton, which is one of the limiting factors for the global tests for the universality of the lepton flavour.

Level of originality/innovation The proposed measurements will be done on the Belle II experiment. This is a new machine and project will require the creation of the novel bespoke approaches to describe the detector performance. The amount of data available for the proposed measurements makes them unique and, in case of the measurement of the tau lifetime, conceptually different from previous studies of this kind. Finally, the project features the innovative analysis techniques: the first search for the radiative lepton flavour violating production process and the novel interpretation of the obtained result; the new method of reducing the systematic uncertainty to the search for the new sources of the CP violation; the new approach for measuring the lifetime of tau lepton with high-statistics samples.

Primary researcher Ilya Komarov will be the principal investigator of the project leading the group of one postdoctoral researcher and three doctoral students.

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1. Research project

1.1 Aims and hypothesis of the research question

It is an experimental particle-physics project aimed at the study of properties of the τ lepton at Belle II experiment. The project is made of three parts offering the **new search for the lepton flavour violation**, **search for new sources of CP asymmetry**, and significant update of precision of the **test of the lepton flavour universality**. The project is built in a way to produce valuable results through its course continuously. The unprecedented size of the dataset, original ideas, and the new analysis techniques guarantee the relevance of the obtained results.

1.2 State of the research field

Introduction of Standard Model and its problems; limitation of direct searches; indirect probes.

Particle physics aims at understanding the fundamental constituents of matter and the interactions that govern them. The understanding of nature at the fundamentally microscopic level is framed into a quantum-field-theory, the standard model (SM), conceptually founded on invariance properties of the fields. Many open questions show that the SM is incomplete. While a picture of remarkable success emerged after almost 50 years of detailed scrutiny through thousands of precise, diverse, and redundant experimental tests, the SM still fails to describe gravity, the predominance of matter over antimatter in the universe, the mechanism that generates neutrino masses, and the as-yet-unknown forms of matter and energy inferred from astrophysical observations. Besides, the SM suffers from theoretical self-consistency limitations. The SM is believed to be an effective theory that reproduces observations in the energy regime probed thus far, but remains insufficient at higher energies, where additional dynamical degrees of freedom would complete it. Identifying the particles that provide such degrees of freedom is the chief goal of today's particle physics.

The premier strategy to discover new heavy particles has traditionally been to produce controlled particle collisions at the highest energies (E) technically achievable, and exploit the relationship $E = mc^2$ with the maximum achievable value of mass m for the produced particles. Such a *direct* approach is the core mission of the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN).

Today, an imminent discovery in direct searches seems more unlikely than before the LHC startup. Numerous direct searches performed thus far have yielded null results, which constrains the proposed possibilities of non-SM dynamics severely. Also, the peculiar value of the observed SM Higgs-boson mass loosens the technical upper bounds significantly on the masses of hypothetical non-SM particles. The standard model as we know it could reliably describe dynamics up to energies a million times higher than LHC's collision energies. Hence, perspectives of direct discovery in the current generation of colliders are toughly challenged.

Fortunately, powerful probes of non-SM physics exist that are not limited in reach by the collision energies available. The SM offers accurate predictions for many observables that are accessible experimentally in lower-energy processes and could involve exchanges of virtual non-SM particles. Such exchanges may influence the transition amplitudes, and therefore the values of measured quantities. Thus, opportune comparisons between measurements and predictions will either reveal *indirectly* the presence of potential particles with nearly arbitrarily high masses or provide stringent exclusion bounds.

1.2.1 Proposed project

Tau lepton; charged lepton flavour violation; lpeton flavour universality; ne sources of CP-asymmetry.

The project aims to answer, with the world-best precision, the following questions:

- Is the neutrino oscillation the only source of the lepton flavour violation?
- Do all three generations of lepton interact with the weak field identically?
- Are there new sources of CP violation?

Tau lepton (τ) is the heaviest known lepton discovered in 1975 [1]. Due to the conservation of the lepton flavour, the tau leptons can only decay to the final states containing neutrino that can't be detected in the current collider experiments. This peculiarity of the tau lepton challenges its experimental study.

While we don't have any evidence of violation of the flavour of the charged leptons (CLFV), the lepton flavour itself is not a conserved quantum number. By now, the only evidence of the violation of the lepton flavour comes from the the neutrino oscillations. Belle, BaBar, and LHCb experiments performed a broad search for CLFV τ decays [2] that limited the probability of such processes to be lower than one-per-million. However, the recent phenomenology developments ([3, 4, 5] and private communications) showed that there could be CLFV processes that would be more visible in *production* rather than in *decays*. Search for CLFV in production is currently done only on the small subset of BaBar data [6]. The new dataset collected by the Belle II experiment in the next few years will allow either to discover or to rule out the CLFV production mechanism processes with the ultimate precision.

Despite three orders of magnitude in mass difference, electron, muon, and tau lepton are believed to have the same interaction properties. That feature of the SM is known as the Lepton Flavour Universality (LFU). In recent year, it was questioned by the anomalies observed in decays of heavy mesons at LHCb [7, 8, 9, 10, 11], Belle [12, 13, 14, 15, 16, 17], and BaBar [18, 19, 20] experiments. To answer the question whether the charged weak current interaction has the same coupling for all lepton generations we need to combine several properties of leptons, such as decay branching fractions, lifetimes, and masses [2]. The current measurement that limits the precision of this test is the lifetime of the tau lepton. This measurement could be significantly improved with the full dataset collected by the Belle II experiment in the next six years.

The matter and antimatter were produced in equal quantities during the Big Bang. In coarse of the evolution of the Universe, matter starts to prevail. This happened due to the subtle differences in the properties of particles and anti-particles. However, current experimental evidence of such differences fails to explain the scale of the asymmetry. From the theory side, despite making successful predictions, the SM mechanism of the CP violation proposed by Makoto Kobayashi and Toshihide Maskawa [21] can not be solely responsible for the matter-antimatter inequality [22]. This motivates searches for the new sources of CP violation.

The SM predicts small, but non-negligible asymmetry in decay rates of τ leptons to $K_s^0\pi\nu$ final state: the decay rate of positively-charged τ leptons to this mode is expected to be $\sim 0.7\%$ higher than that of negatively-charged. In 2012, BaBar collaboration published their measurement of CPviolation in the same channel [23] and they found that positively-charged τ leptons decay to that final state at $(0.7 \pm 0.5)\%$ **rarer** than negatively-charged, *i.e.* the observation contradicts to the SM expectation and is 2.8σ away from it. Such perplexing discrepancy triggered a discussion about its source within the theory community [24, 25, 26]. While the conclusion on the mechanism for the anomalous CP violation in hadronic τ decays is not currently reached, all papers stress the necessity of the new experimental study of this subject that could be done on data collected by the Belle II experiment in the next four years.

Period	Luminosity	Analysis	Expected result
now - 2022	1 ab^{-1}	Search for CLFV production $e^+e^- \to l\tau(\gamma)$	Best limit on CLFV production cross-section.
2023 - 2024	5 ab^{-1}	Search for CP violation in τ decays	Factor of 3.5 improvement in precision of the current world-best result.
2025 - 2028	20 ab^{-1}	Measurement of the τ lifetime	Factor of 2 improvement in precision of all LFU probes in τ sector.

Table 1 – Milestones of the research programme.

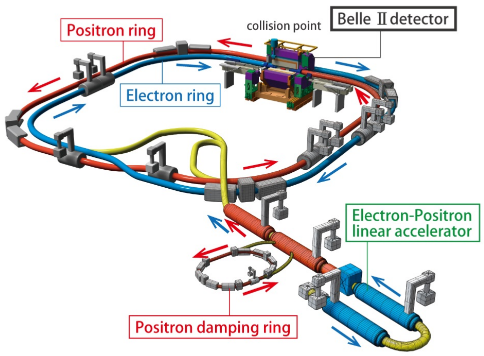
In the next seven years, the Belle II experiment will gather the world's most extensive collection of τ leptons. I aim for a comprehensive analysis of this data aimed at the novel search for the LFV processes in e^+e^- collisions, the discovery of CP asymmetry in τ decays and exhaustive tests of the lepton flavour universality of the Standard Model. The milestones of my program (with my expectations of the acquired luminosity) are summarised in Table 1. This project has several attractive features:

- The measurements are ordered in a way that will allow to continuously provide the important results, alongside with increase of the collected data;
- The anticipated size of the collected data and the new methods of the analysis will guarantee the production of world-best results at all stages;
- The performance studies made for early stages of the project will be used by the later once. Hence there is a synergy between the measurements;
- The proposed search naturally completes the studies of the dark sector and the lepton flavour phenomena held by HEPHY Belle II group.

1.3 The Belle II experiment

Belle II experiment; plans for data taking; three phases of the project.

The Belle II detector operates at the SuperKEKB electron-positron collider [27], located at the KEK laboratory in Tsukuba, Japan. Schematic layout of the SuperKEKB collider and Belle II experiment are shown in the Figure 1. The energies of the electron and positron beams are 7 GeV and 4 GeV, respectively, resulting in a boost of $\beta\gamma = 0.28$ and the centre-of-mass energy of $\sqrt{s} = 10.58$ GeV. The Belle II detector has a cylindrical



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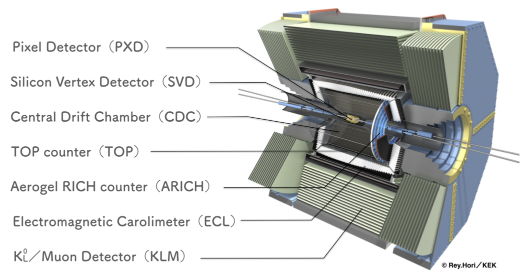

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Figure 1 – Layout of SuperKEKB facility (left) and schematic overview of Belle II experiment (right).

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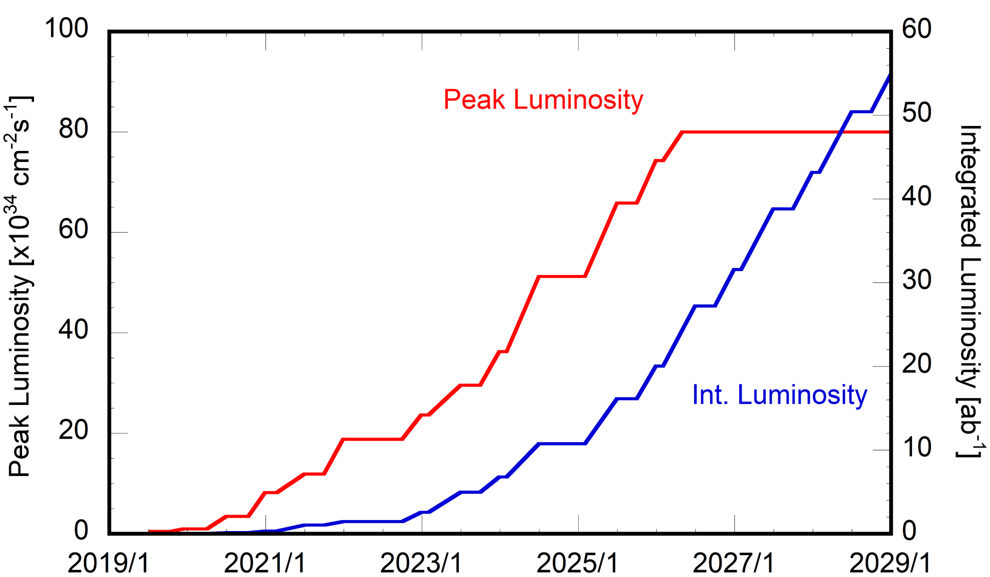


Figure 2 – Luminosity projection for Belle II experiment.

structure arranged around the beam pipe. It consists of several subdetectors placed in a 1.5 T magnetic field provided by a superconducting solenoid. The full description of the Belle II detector is given in [28, 29]. The interaction point is surrounded by six layers of semiconductor detectors for precise measurement of the position of the origin of the charged particle. Vertex detector and the central drift chamber (CDC) represent the tracking system of the Belle II experiment. CDC signals are also used by the trigger system to decide whether the event should be stored for future analysis or discarded. The particles identification system is made of the Time-Of-Propagation counter (TOP) placed in the barrel region and the Aerogel Ring Imaging Cherenkov detector (ARICH) placed in the forward end-cap region, Electromagnetic Calorimeter (ECL), and K_L and μ detector (KLM) made of Resistive Plate Chamber (RPC) and scintillators layers. ARICH and TOP detectors are mainly responsible for K/π separation; ECL gives the main contribution to the electron identification, and its signal is also used by the trigger system, and KLM signal is the most important for the muon identification.

Belle II started data taking in 2018, and it has collected $\mathcal{O}(70)$ fb^{-1} so far. It plans to reach 40$\mathbf{ab}^{-1}$ by 2028, according to the plan shown in Figure 2. While the exact schedule of the data taking depends on the progress of SuperKEKB in achieving goal peak luminosity for respective run periods, it is still possible to highlight several important periods in the data taking:

- **Early phase** of the data taking has started in 2018 and will continue until the end of 2022. It will conclude with the start of the long shutdown during which the second layer of silicon pixels will be installed. During this period, Belle II will collect 1-2 ab^{-1}, which compatible to the integrated luminosity collected by BaBar or Belle.
- **Middle phase** will start after the long shutdown, in spring 2023 and ends in 2025. During this phase, the experiment will collect up to 10 ab^{-1} of data, that will allow to compete and outperform combined results of BaBar and Belle.
- **Late phase** will start in 2025 and will last until the end of the experiment.

The plan of measurements are built around this schedule. However, as it is discussed later in Section 3, there is a margin of safety for each step which demolish any chances to end up empty-handed.

1.4 Search for the lepton flavour violation

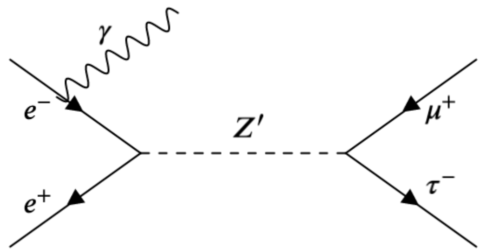
- **Goals**
  - Set the world-best constraints on the CLFV cross-section of $ee \to l\tau(\gamma)$ process.
  - Understand the performance of Belle II detector for studies of $ee \to \tau\tau$ events.
- **Deliverables**
  - Analysis note describing performance of the Belle 2 detector for $ee \to \tau\tau$ events.
  - Paper in high-profile journal reporting our results on CLFV cross-section.
- **Timescale** By the end of 2023.

Due to the limited statistics available in the first few years of the data taking, it's rather challenging to compete with measurements that were performed at the full Belle or BaBar luminosities. However, it is the best time to exploit the new ideas, especially if they largely coincide with the performance studies for future analyses. The right candidate for the early phase analysis is a search for the lepton flavour violating process $e^+e^- \to l\tau(\gamma)$. Similar search has been performed at early BaBar data at 211 fb^{-1}, where they search for the LFV production process $e^+e^- \to l\tau$ [6]. Having 1 ab^{-1} by the end of 2022, we aim to improve BaBar's precision be the factor of 2.

Most of the production mechanisms that would be able to contribute to this process are largely suppressed from LFV τ decays, but some might survive, such as production through the on-shell LFV mediator or anomalous dimension operator (see Figure 3).

Due to the simple kinematics of the signal process, it is possible to perform the analysis in a model-independent manner. I propose to search for the $e^+e^- \to l\tau(\gamma)$ process, considering two modes for decays of tau lepton: to three and to one charged hadrons. To discriminate signal $e^+e^- \to l\tau(\gamma)$ events from the SM backgrounds we will look at the distribution of the *missing mass*, that is invariant mass of the system recoiling against reconstructed particles. In signal events, the only missing particle is the neutrino, and hence the values of the missing mass form a narrow peak around zero.

The main background in this analysis will be the taupair production, $e^+e^- \to \tau\tau$ with one τ decaying leptonically $\tau \to l\nu\bar{\nu}$ (so-called $1-prong$ decay), and another to three or to one charged hadrons ($3-prong$ or $1-prong$ decays accordingly). These events will have at least three neutrinos in the final state, and hence they will form a broad structure in the missing mass distribution, away from the signal region. Nevertheless, it is vital to study those events thoroughly, to control background levels and validate the detector performance.



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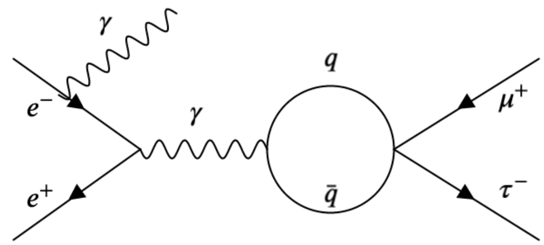

(b)

Figure 3 – Example of Feynman production mechanisms of $e^+e^- \to l\tau(\gamma)$ that could allow surviving constraints coming form limits on the rate of $\tau \to e^+e^-l$ decay: production through the new on-shell mediator (left) or the high dimension operator (right)

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The detector performance is described by the efficiency of the online selection, track finding, and particle identification efficiency. We have already done these performance estimates for very early Bell II data:

- Together with HEPHY colleagues, we have developed the method to measure the efficiency of the trigger selection directly from the data [30][1]. We have successfully used it in the Z' search [31] and in other studies [32, 33]. Our study of the performance of the trigger system [34] shows that the efficiency of the CDC trigger for this analysis will be close to 100%.
- Information of the number of tracks and their momentum comes from the tracking system, mainly from the CDC. Our early estimates show the high track reconstruction efficiency that is well described by simulations [35].
- Identification of the electrons will be made mostly by the electromagnetic calorimeter. Electron is the only charged particle produced in the detector that deposits all its energy in the ECL, which makes electron identification very reliable. The efficiency of the electron identification is already controlled on data [36, 37, 38].
- The main subsystem to identify muons is the K-Long and Muon detector. Opposite to electrons, muons have the highest penetrating ability among all charged particles produced in the detector, and their long trace in the KLM identifies them. The recent performance studies show good performance of the KLM for the muon selection [36, 37].
- Pion/kaon separation is done mostly by the CDC, ARICH and TOP detectors. It's performance, as well as misidentification fake rates, are monitored on data [39, 40].

[1] HEPHY contribution to the low-multiplicity performance studies is partly funded by the standalone project FWF P31361, *Searches for dark matter and dark forces at Belle II*

We will update these studies with the full luminosity available by the end of 2022 and convert them to the measurement of the LFV cross-section at Belle II.

The background study for this analysis will also be used, with minimal changes, in the second measurement of this project. This is due to the fact that $e^+e^- \to \tau(\to l\nu\bar{\nu})\tau(\to hhh\nu)$ is a major background for both measurements.

1.5 Search for the new sources of CP asymmetry

- **Goals**
  - Test, with unprecedented precision, the existence of the new sources of CP violation in decays of τ lepton.
- **Deliverables**
  - Analysis note describing charge asymmetry of Belle II detector.
  - Paper in high-profile journal reporting our results.
- **Timescale** By the end of 2024.

The middle phase of the project is devoted to the measurement of the asymmetry in $\tau \to K_s^0\pi\nu$ decay rate

$$A_Q = \frac{\Gamma(\tau^+ \to K_s^0\pi^+\nu) - \Gamma(\tau^- \to K_s^0\pi^-\nu)}{\Gamma(\tau^+ \to K_s^0\pi^+\nu) + \Gamma(\tau^- \to K_s^0\pi^-\nu)}. \tag{1}$$

with per mille precision using the data collected in e^+e^- collisions at Belle II experiment containing 4.5 billion of τ lepton pairs (5 ab^{-1}). BaBar collaboration measured this quantity to be $A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$ using 437 million τ lepton pairs [23]. The Standard Model expectations are $A_Q^{\mathrm{SM}} = (0.33 \pm 0.01)\%$ [41]. Using the larger available statistics and new approaches for constraining the detector-induced asymmetries (that are crucial for this measurement), we aim to reach 0.06% statistical and negligible systematical uncertainties.

In this section, the *signal* taupair events are those with one τ lepton decaying to $K_s^0\pi(\geq 0\pi^0)\nu$ final state, and another - to the final state with one charged track t (electron, muon or pion) and any number of neutral pions ($\tau \to t(\geq 0\pi^0)\nu(\bar{\nu})$). The main background for this analysis comes from similar taupair events, where one of the τ decays not to the $K_s^0\pi\nu$, but to the $\pi\pi\pi\nu$ final state. While taupair background is irreducible, we can constrain its contribution in a data-driven manner using the information about the quality of displaced K_s^0 vertex.

To suppress candidates formed not in $ee \to \tau\tau$ events, we will limit the event thrust, momentum of the tag side objects, and constrain the kinematics of the probe side as we did in previous studies [32, 33]. To further suppress background events, we will train multivariate classifiers that will use the information on the kinematics of the tag and probe sides, K_s^0 vertex, and quality of particle identification of prompt tracks.

The primary source of the systematical uncertainty in this study are the detector-induced asymmetries: for example if the detector reconstructs 99 out of 100 positively-charged tracks and 98 out of 100 negatively-charged tracks, and if we don't account for this in the simulations, the observed value of A_Q will be driven by the detector asymmetry and the contribution of the real decay rate asymmetry will be negligible.

One of the ways to control the detector-induced asymmetries is to measure A_Q in the *control* sample. The control sample is the sample with the high statistics made of events that are similar to the signal ones. In their paper [23], BaBar collaboration used $\tau \to hhh(\geq 0\pi^0)\nu$ channel as the control sample, and the experimental uncertainty of the A_Q^{control} measurement became the dominant component of the systematic uncertainty of A_Q. The systematic uncertainty estimated in this way depends on the size of $\tau \to hhh(\geq 0\pi^0)\nu$ sample, so it will decrease as a square root of the luminosity - in the same way as the statistical uncertainty: even having 1 ab^{-1} of data available for this study, we will reduce the systematic uncertainty estimated in this way by 30% with respect to the current world-best result.

It is possible, however, to further suppress systematic uncertainty coming from this source. I suggest the unique novel technique to control the detector-induced asymmetries by **using hadronic decays of D mesons**. They are perfect for control studies since the invariant mass of charm meson is close to that of the τ lepton, and one can fully reconstruct D meson decayed hadronically. Besides, the hadronic decays of D mesons having K_s^0 in the final state will allow accounting for the dependence of the K_s^0 reconstruction efficiency from the K_s^0 lifetime and its momentum, which can not be tackled with $\tau \to hhh\nu$ sample. The production rate of charm mesons at Belle II is close to that of taupairs, and charm mesons mostly decay to hadronic final states. Hereby, combining several decay modes (*e.g.* $D \to K_s^0\pi$ and $D_s \to \phi\pi$) we will get a control sample compatible to $\tau \to hhh(\geq 0\pi^0)\nu$. Combination of the traditional and the novel approaches will allow to increase the overall size of the control sample by the factor of 2, which yields to $\sim 40\%$ reduction of the systematic uncertainty caused by the detector-induced asymmetries per unit integrated luminosity.

The analysis aims at the measurement of the decay rate asymmetry for $\tau \to K_s^0\pi(\geq 0\pi^0)\nu$ process with the data set collected by the Belle II experiment corresponding to the integrated luminosity of 5 ab^{-1}. Assuming the similar detection efficiency of Belle II and BaBar experiments, we expect to have the statistical uncertainty of the measurement to be at the level of 0.06%. The default approach for evaluation of the systematic uncertainty will give 0.03%, and the novel approach will make the systematic uncertainty negligible ($\sim 0.02\%$). This measurement will be sensitive enough for SM-predicted decay rate asymmetry of 0.3%

with 5σ confidence level.

1.6 Testing the lepton flavour universality

- **Goals**
  - Measure the lifetime of τ lepton with better than per mille precision.
  - Make the world's most precise test of lepton flavour universality.
- **Deliverables**
  - Analysis note describing alignment of Belle II vertex detector.
  - Paper in high-profile journal reporting our measurement of the τ lifetime.
  - Paper in high-profile journal reporting the new limits of LFU test of the Standard Model.
- **Timescale** By the end of 2028.

Lepton flavour universality assumes that all leptons have the same coupling to the weak force, *i.e.* $g_l/g_{l'} \equiv 1$ for every two lepton flavours l and l'. Experimental probes of this universality depend on several observables (only τ-related components are written explicitly) [2]:

$$\frac{g_\tau}{g_l} \sim \frac{\mathcal{B}(\tau \to l'\nu_\tau\bar{\nu}_{l'})}{t_\tau M_\tau^5} \tag{2}$$

$$(\frac{g_\mu}{g_e})^2 \sim \frac{\mathcal{B}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e)} \tag{3}$$

$$(\frac{g_\tau}{g_\mu})^2 \sim \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)}\frac{1}{M_\tau^3 t_\tau} \tag{4}$$

With this, the overall precision of the experimental LFU tests is driven by the following observables:

- **Mass of τ**. This quantity is known up to 0.007%, which is much more precise than other component entering the global LFU tests.
- **Branching fractions**. Branching fractions of $\tau \to l\nu\bar{\nu}$ and $\tau \to h\nu$ decays are known up to 0.2% precision from the combination of branching fractions of exclusive channels by HFLAV group. Currently, this is one of the limiting factors for the global precision

of LFU tests. HEPHY Belle II group aims to measure them with below per mille precision[2].

- **Lifetime of τ.** This is the bottleneck of the global LFU tests. The lifetime of τ lepton is measured up to 0.17% precision. In this project I aim to reach below per mille precision for this quantity using the full Belle II data set.

The current best measurement of τ lifetime is done at the full Belle sample [42]. The Belle authors reconstruct both τ leptons decaying to 3-hadron states, and, using kinematic and topological constraints, define their production point and their lifetimes. The measurement is statistically limited, and the main systematic uncertainty comes from the detector alignment.

While the performance of the Belle II detector for this measurement is not studied yet in details, one could expect having similar vertex resolution thanks to the improved vertex detector that would compensate for the smaller boost. This means that it is possible to estimate the Belle II sensitivity by scaling the luminosity:

- Statistical uncertainty will scale down as a square root of the integrated luminosity.
- Main systematical uncertainty coming from an understanding of the detector alignment is also statistically limited. Bigger control samples will allow reducing this uncertainty, so this uncertainty scales in the same manner with the statistical uncertainty.

Hereby, having ~ 5 ab^{-1}, it will be possible to reach the per mille precision in τ lifetime using Belle technique. For higher luminosities, new sources of the systematic uncertainty might start to prevail so that the further improvements will require more detailed systematic studies.

The key to the success of this study is in the thorough scrutiny of decays of τ lepton to the 3-hadron final state, which we will do during the previous stages of the project. Having selection, reconstruction, and detector performance under control, we will be able to focus on the detector alignment and the improvement of the analysis procedure. Thus, we aim to investigate whether other typologies of taupair events could improve the sensitivity of the experiment per unit integrated luminosity. Such, 5-prong tau decays look particularly promising: they offer better decay vertex resolution for the price of lower rate, which may be a good deal for the high-statistics samples.

Once the measurement is accomplished, we will make the final test of the Lepton Flavour Universality combining of our results with those obtained by HEPHY group in branching fractions of τ decays.

1.7 Innovative aspects

The project is built around the original idea of detailed scrutiny of properties of τ lepton aimed to answer fundamental questions that were previously addressed by different groups.

[2] ERC StG 947006 *InterLeptons*

While each part of the project address well-established problem, they all have own innovative approach for the solution.

The early stage of the project offers the new search for the lepton flavour violation, that has never been considered at Belle II experiment. Close contact with the world-leading theory group will allow us to transform our finding to stringent constraints of the new physics, which was not done for the previous studies of this kind. Proposed search for the new sources of the CP asymmetry benefits from the new approach for dealing with the detector-induced asymmetry that allows reducing the systematic uncertainty of the analysis by 40% per unit integrated luminosity compared to the existing approach of BaBar collaboration [23]. The final part of the project, the measurement of the lifetime of τ leptons, will be done with the unprecedented amount of data and require an understanding of the performance of the detector at the below-per-mile level. We will have to develop the novel approaches to estimate and fight the systematic uncertainties of this measurement. I also propose the new method of the measurement of the lifetime of τ meson that could be more sensitive for high-statistics samples.

2. Project schedule

The first part of the project aims at the novel search for the lepton flavour violation and detailed study of $ee \to \tau\tau$ events where one lepton decays to three charged particles and another to one. The milestones of this step are the analysis note describing the background study and the publication of Belle II limits for LFV production cross-section. This paper is referred as *Publication* 1 in Figure 4.

The second part of the project aims at the most precise measurement of CP asymmetry in hadronic τ decays. The milestones are the analysis note describing detector-induced asymmetry and publication of Belle II measurement of the asymmetry. This paper is referred as *Publication* 2 in Figure 4.

The final part of the project aims at the most precise test of the lepton flavour universality. To achieve this goal, we need to achieve two intermediate milestones: we will have to provide the detailed study of the Belle II alignment and to measure the lifetime of the τ lepton (*Publication* 3 in Figure 4). Once these steps are done, we will combine results of the τ lifetime with results on branching fractions of τ decays achieved by HEPHY group and publish the world-best limits on conservation of the lepton flavour universality within the Standard Model. This paper is referred as *Publication* 4 in Figure 4.

3. Risk assessment

3.1 Acquired luminosity

The **baseline scenario** of this project assumes that Belle II will collect data with approximately twice lower rate than is currently anticipated. The high margin of safety that is grounded into this assumption means that we might have up to a factor of 2 more data, that will increase the precision of the measurements. This is an **optimistic scenario**.

In **pessimistic scenario**, Belle II will have some major break down that would take up to a year to fix. The action plan to cope with it depends on the time of such malfunction:

- The malfunction happens at the beginning of the project, and Belle II fails to collect 1 ab^{-1} by the end of 2022. In this case, we will Belle data using the `b2bii` framework [43] that allows using of Belle II software for this purpose.
- The malfunction happens in the middle phase of the project, and Belle II fails to collect 5 ab^{-1} by the end of 2024. In these unlikely circumstances, we will move the target timeline for publication of the results of the search for CPviolation in τ for one year and start working on Belle II alignment in parallel.
- The malfunction happens in the late phase of the project. This will not jeopardise our goals of going below per mille precision in the measurement of τ lifetime, since we will achieve it even with the fraction of the total luminosity results.

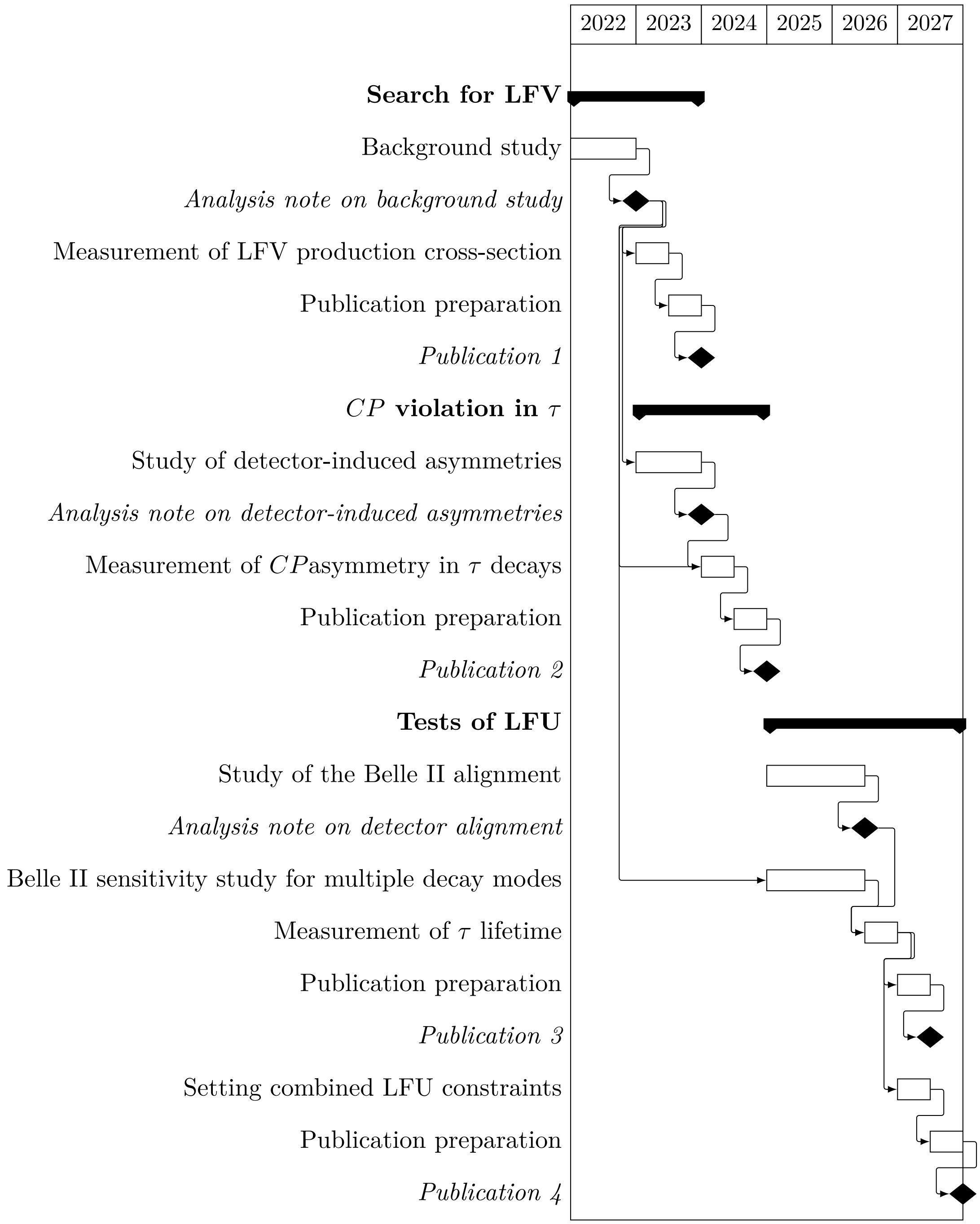

Figure 4 – Schedule of the project

3.2 On travel availability

While I aim to use the data collected by the experiment located in Japan, it is possible to fully carry the project without a physical presence on-site in case of the extraordinary circumstances. Soon after the travel restrictions took place worldwide, Belle II collaboration adapted to the new conditions by making most of the meeting virtual and allowing for remote experimental shifts. These measures allowed to continue the data taking at the planned pace, and they will enable to fully satisfy the collaboration agreements (e.g. taking shifts and performing service task) under the travel restrictions. Hereby, the travel bans (caused by COVID-19 or any other major disaster) may not jeopardise the success of the project.

While the Belle II has proven it's sustainability in the world with severe travel restriction, as soon as the travel restrictions are lifted, the experiment will return to the normal operation mode. This implies the renewal of the regular collaboration meetings in Japan and the presence of the on-site shifters from all involved institutes. The travel budget of the project is designed assuming no travels for 2022.

4. Ethical, safety-related and regulatory aspects

The project does not rise any ethical, safety-related, or regulatory issues.

5. Sex-specific and gender-related aspects

5.1 Sex-specific and gender-related findings

The project will not produce any gender-related findings.

5.2 Diversity and inclusion statement

The last few decades brought a diversity revolution to the STEM community. The joint research of people of different cultures and unique talents was proven to be exceptionally fruitful by many international collaborations. We recognized inclusion as a critical component of the success of research in a diverse team. We made a significant step in the right direction, and we should not lose our pace.

As a coordinator of the training efforts of Belle II collaboration, I acknowledged the importance of the inclusion. At this role, I organized workshops for the newly-joined colleagues to teach them the basics of data analysis at our experiment. Students of various cultural, language and educational backgrounds attended these events, and it was my job to prevent those differences from becoming barriers. During the classes, we created an atmosphere where every student receives individual guidance and assistance.

I will keep this attitude within the group. I value the diversity and believe that it is one of the keys to scientific excellence. To keep my commitments toward the spread and foresting of inclusion culture in STEM, and to build a successful research group, I will work on creating a healthy environment based on principles of inclusion, diversity and equity.

6. Human resources

6.1 Academic qualification of the researchers involved

I plan to work closely with ERC group of Dr Gianluca Inguglia with whom we are collaborating already. We published the search for the Z' particles in Belle II detector [31] and made performance studies of the trigger system [30, 34]. In 2019, I was supervising Mr Paul Feichtinger, who is currently a member of the group of Dr Inguglia, during his summer program at DESY. Together with Mr Feichtinger, we studied the particle identification performance for τ decays at Belle II [44].

These days the group of Dr Inguglia is working on searches for non-SM phenomena in low-multiplicity events at Belle II with a strong focus on τ physics and dark sector. Many detector studies required for their work are overlapping with those for my project. Finally, one of the goals of Dr Inguglia's research programme is the measurement of the branching fraction of τ decays. Result of this measurement, combined with the lifetime measurement of τ lepton, will allow making the world's most stringent test of the lepton flavour universality in the Standard Model. Close work with Dr Inguglia will allow for the knowledge transfer and speed up our researches.

The work on the project will be done within τ working group of the Belle II experiment, which is convened by Dr Armine Rostomyan from DESY. We are already working together with Dr Rostomyan on performance studies of the Belle II detector for τ physics, and I have coordinated the proposed research program with her. Her interest in the proposed project will allow benefiting from her rich experience and knowledge of the field.

Prof Alexey Petrov from Wayne State University is interested in the search for the lepton flavour violating cross-sections at Belle II. For some time already, we are analysing the possible impact of this measurement. Cooperation with prof Petrov will allow translating measured upper limit on the LFV cross-section to the constraints that could be probed in other experiments .

If the Belle II experiment is unable to collect at least 1 ab^{-1} of data by the end of 2022, we will use the data set collected by Belle experiment and analyse it with the Belle II software framework. Dr Michel Hernandez Villanueva from the University of Mississippi is currently working on the conversion of the low-multiplicity Belle data to Belle II format, and he has unique experience in this area. Together with Dr Villanueva, we have already done some preliminary work on the search for the LFV cross-section, and his expertise will help us to deliver the results for the first phase o the project even in the worst-case scenario.

We are developing the new method for measuring the detector asymmetries using decays of D meson together with Dr Angelo Di Canto from the Brookhaven National Laboratory. Dr Di Canto is the world-leading expert in charm physics, and we have already worked with him studying the CPasymmetry in D decays at LHCb experiment [2].

6.2 Career development of the applicant

Since the inception of my tertiary studies, I have been interested in pursuing a research career in academia. The interest for fundamental science aimed at unravelling the underlying mechanisms of nature stronger and stronger as I advanced in my studies; and the enriching, exciting interactions with professors and researchers I have had the privilege to work with along the way strengthened my perception of an academic job as my ideal long-term career goal.

During my career, I had the opportunity to discover and absorb different styles and methods to do research and to learn from bright scientists from all around the world. I had a chance to move to different counties and discover its fascinating traditions and culture. Being awarded Early.Mobility postdoc fellowship by the Swiss National Science Foundation, I had an experience of managing the research funds. I also had an experience of pursuing independent research under that fellowship and during my current position of DESY postdoctoral fellow.

The START programme will allow me to continue along this trajectory, thus enriching my scientific background by joining a high-profile research institute. START programme will significantly extend my experience of pursuing independent research. Through this programme, I will build my own group, manage the group's budget, and follow the long-term research plan.

If I enrol to the programme, I plan to continue my engagement with HEPHY to extend and supplement the scientific goals stated in my research plan by fully exploiting the opportunities offered by the Belle II experiment. I would also like to benefit from the association of HEPHY with the Vienna University of Technology by getting an opportunity to teach students. This will allow me to get the essential teaching experience and, eventually, to invite master students to work on my projects. I also aim to acquire the habilitation which is necessary for professorship position.

Getting the prestigious START fellowship and handling teaching responsibilities will make me a natural candidate for a faculty position in Austria, which is my ambitious goal. Austrian institutes are among the most appealing for the attractive combination of vast scientific opportunities, lively and dynamic research environment, and, in general, high quality of life.

A. Research institution and financial aspects

A.1 Research institution

The Institute of High Energy Physics (HEPHY) is Austria's largest centre for experimental and theoretical particle physics. It has gained a well-established reputation in the worldwide HEP community with prominent roles in a variety of collider-physics experiments, in developing novel detector technologies and in contributing to advances in theory and phenomenology. The HEPHY group plays a leading role in the Belle-II collaboration with critical responsibilities in the construction of the vertex detector and the physics analysis.

The Belle II HEPHY group led by Dr Christoph Schwanda consists of 16 physicists and engineers working on data analysis and detector development. The group is rapidly growing and has a constant influx of the PhD and master students joining the pursued research. In particular, the project will be done in close cooperation with the subgroup of Dr Gianluca Inguglia focused on experimental studies of the low multiplicity physics at Belle II.

The project does not require specific infrastructure except the workplaces for the group. To locate 2-4 people simultaneously working on the project, we will need two rooms with two workplaces in each. This infrastructure will be provided by HEPHY.

A.2 Requested funding

The overall requested budget of the project is listed in the Table 2 and yields 1199890 euro. This money will be spent as follows:

- Salaries of the principal investigator, the postdoc and three PhD students amount 1084390 euro, which is $\sim 90\%$ of the budget.
- Travel expenses yield 85500 euro, which is $\sim 7\%$ of the overall budget. These money will be spent on attendance of conferences, collaboration meetings, and pursuing service work in Japan.
- The final 3% of the budget (30000 euro) will fulfil the common funds of the HEPHY Belle II group. This money will be spent to cover the Belle II membership fee of the senior group members and infrastructure expenses. The common funds are calculated, assuming 3000 euro per senior group member per year.

A.2.1 Detailed travel budget

The travel expenses can be split into three categories:

- Major international conference. Senior group members are expected to attend one such conference in two years, while the doctoral students are expected to attend one major international conference through their contract. The estimated cost of

	2022	2023	2024	2025	2026	2027	Total
Principal Investigator							
Salary	75890	75890	75890	75890	75890	75890	455340
Common funds	3000	3000	3000	3000	3000	3000	18000
Postdoctoral researcher							
Salary			69040	69040	69040	69040	276160
Common funds			3000	3000	3000	3000	12000
Doctoral student							
Salary	39210	39210	39210				117630
Doctoral student							
Salary		39210	39210	39210			117630
Doctoral student							
Salary				39210	39210	39210	117630
Travel budget							
	0	17500	17500	19500	15500	15500	85500
						Total:	1199890

Table 2 – Budget of the research project. All numbers are in euro.

attendance of such event is 2000 euro which will cover tickets, accommodation, and registration fees.

- Collaboration meetings. Belle II is international collaboration whose members are scattered all over the world. Three times a year, collaboration meets in Japan. All group members are expected to attend two of such meetings per year (doctoral students will attend only one meeting during their final year since they will focus on writing their thesis). The estimated cost of participation at the collaboration meeting is 2000 euro.

- Service work in Japan. Once the current travel restrictions are lifted, the oversea groups will have to fulfil their quotas on on-site shifts. To match these requirements, I reserve a budget of 1500 euro per year to extend the stay of the group members in Japan. This should be enough to cover the presence of the group members at KEK for two extra weeks per year. This will allow to fulfill shifting responsibilities of the group without the overlap with the tight schedule of the group meetings.

The exact travel plan for each participant of the project is shown in Table 3. The funds secured for pursuing service work will be distributed each year depending on situation. The most of thiese mon

	2022	2023	2024	2025	2026	2027	Total
Principal Investigator							
Collaboration meetings	0	2×2000	2×2000	2×2000	2×2000	2×2000	20000
Conferences	0	2000	0	2000	0	2000	6000
Postdoctoral researcher							
Collaboration meetings			2×2000	2×2000	2×2000	2×2000	16000
Conferences			0	2000	0	2000	4000
Doctoral student							
Collaboration meetings	0	2×2000	2000				6000
Conferences	0	2000	0				2000
Doctoral student							
Collaboration meetings		2×2000	2×2000	2000			10000
Conferences		0	2000	0			2000
Doctoral student							
Collaboration meetings				2×2000	2×2000	2000	10000
Conferences				0	2000	0	2000
Service work							
Secured funds	0	1500	1500	1500	1500	1500	7500
						Total:	85500

Table 3 – Travel budget of the project. All numbers are in euro.

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C. Curriculim vitae

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I am an experienced researcher with extensive background in high energy physics proficient in **data analysis** and **statistics**. I gave primary direct contributions to **four high-impact papers** published within the LHCb and Belle II experiments. I made significant contributions to the experiments by creating innovative **software** and **hardware** solutions and by taking **leadership positions**.

Professional experience	
01/01/2018-current	Postdoctoral researcher at German Electron Synchrotron DESY
01/08/2016-31/12/2017	Postdoctoral researcher at Istituto Nazionale Di Fisica Nucleare (INFN) Trieste
01/06/2012-31/07/2016	Doctoral researcher at Swiss Federal Institute of Technology Lausanne (EPFL)
Education	
01/06/2012-31/07/2016	Doctoral student at Swiss Federal Institute of Technology Lausanne (EPFL)
01/09/2006-21/01/2012	Specialist in physics (equal to Master, **diploma with honours**) in Lomonosov Moscow State University (MSU)

The most important publications

1. I. Adachi *et al.* [Belle-II], "Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States," Phys. Rev. Lett. **124** (2020) no.14, 141801 [arXiv:1912.11276 [hep-ex]].

   I played a leading role in the first physics results of Belle II collaboration. I proposed the extension of the analysis to the lepton flavour violating scenario, established effective collaboration between co-authors, coordinated and performed detector studies necessary for the analysis, performed statistical interpretation of the results and participated in preparation of the publication itself.

2. R. Aaij *et al.* [LHCb], "Updated determination of D^0-$\overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays," Phys. Rev. D **97** (2018) no.3, 031101

[arXiv:1712.03220 [hep-ex]].

I developed the data-driven procedure to precisely account for biases coming from the decay-time evolution of signal candidates originating from b-hadron decays. This allowed to reduce the leading systematics uncerainty and make the most precise measurement of the charm mixing parameters in the world.

3. R. Aaij *et al.* [LHCb], "Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV," JHEP **10** (2015), 172 [arXiv:1509.00771 [hep-ex]].

   I was part of LHCb Run2 task force pioneering usage of the new paradigm for the data processing. Working in close cooperation with many LHCb stakeholders, the task force managed to provide the results on J/ψ production cross-section in just few weeks after the start of data-taking.

4. R. Aaij *et al.* [LHCb], "Study of the rare B_s^0 and B^0 decays into the $\pi^+\pi^-\mu^+\mu^-$ final state," Phys. Lett. B **743** (2015), 46-55 [arXiv:1412.6433 [hep-ex]].

   As the main contributor of this analysis, I worked on all steps of this study, from the sample selection to the preparation of the publication. I developed a sophisticated selection procedure based on multivariate algorithms, developed novel data-driven technique to control backgrounds and pursued solid data-driven validation studies.

Additional research achievements

- I founded and led a team of 30 people devoted to software training and knowledge transfer within the Belle II collaboration. I suggested the format and organised the collaboration-wide training events twice per year in Japan, as well as regional events in Germany, Korea, and US. I coordinated the transformation of the analysis software documentation from the archaic wiki pages to the modern system composed of in-code documentation (based on Sphinx), question-and-answer server (based on Askbot), collection of technical notes, all covered by a dedicated search engine. This work led me to the chair of the Collaboration, Education, Training and Outreach track of **CHEP 2019** conference.

- I founded and maintain the **fstate project** (`http://fstate.org/`). It finds all intermediate decays leading to the user-defined final state, which is crucial in evaluating backgrounds for any HEP analysis. It is based on an original recursive algorithm and built using industry-standard technologies (MongoDB, Flask).

- I built the hardware **interlock system for the vertex detector** of the Belle II experiment. My task was to understand the interlock conditions for different subsystems developed in institutes in Austria, Japan, Germany, and Italy, develop a logic that would account for all of the conditions, and communicate it to all stakeholders of the project. To facilitate the communication process, I created a bespoke online visualisation tool that demonstrates the design of the system.

- In 2016, I was **awarded an Early Mobility Postdoc fellowship** by Swiss National Grant Foundation in the amount of 87.000 Swiss francs to pursue research at INFN Trieste.
- I developed a system for interactive performance monitoring of the LHCb Silicon Tracker detector.
- I supervised 4 students at DESY summer school in 2018 and 2019. All of them have successfully finished their projects and continued their careers within Belle II experiment. I am currently supervising 4 master students working on Computer Science projects.

Talks, conferences, and invited seminars

- **DESY**, 2020: "Search for an invisibly decaying Z' boson at Belle II in $ee \to \mu\mu(e\mu)$ plus missing energy final states"
- **CHEP**, 2019: "Documentation and training at Belle II experiment"
- **INFN Trieste**, 2019: "Fun with tau: biased view on Belle II tau programme"
- **ICNFP**, 2019: "Dark sector physics with Belle II"
- **Rencontres de Moriond QCD**, 2018, Status and prospects of Belle II at SuperKEKB"
- **EPS conference on High Energy Physics**, 2017: "Prospects of CKM parameter measurements at Belle II"
- **INFN Trieste**, 2017: "Rare or medium rare: grilling new physics at LHCb"
- **Rencontres de Blois**, 2016: "First LHCb results in 13 TeV proton-proton collisions”
- **EPS conference on High Energy Physics**, 2015: "First LHCb results from the 13 TeV LHC data"

Outreach activities

- Public talk: “Career and science. Colliding views.”, Moscow 2020
- Public talk: “Searching for the Dark Matter”, Moscow 2019
- Public talk: “On irreversibility of time and Einstein’s theory”, Moscow 2015
- Interview “On the nature of the Universe” at “Mayak” national radio, Moscow 2015