Proposal: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

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Abstract

We propose a new experiment searching for sub-millicharged particles (χs) using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs and is proposed to be installed 280 m from the target. The main background is a random coincidence between two layers due to dark counts in PMTs, which can be reduced to a negligible level using the timing of the proton beam. With $N_{\mathrm{POT}} = 5{\times}10^{21}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to χs with the charge down to $6 \times 10^{-5}e$ in $m_\chi < 0.2$ GeV/c^2 and $10^{-3}e$ in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by the previous experiments.

1 Motivation for the experiment

Electric charge quantization is a long-standing question in particle physics. While fractionally charged particles (millicharged particles hereafter) have typically been thought to preclude the possibility for Grand Unified Theories (GUTs), well-motivated dark-sector models have been proposed to predict the existence of millicharged particles while preserving the possibility for unification. Such models can contain a rich internal structure, providing candidate particles for dark matter. One well motivated mechanism that leads to millicharged particles is to introduce a new $U(1)$ in dark sector with a massless dark-photon (A') and a massive dark-fermion (χ) [1,2],

$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}\left(\not{\partial} + ie'\not{A}' + i\mathrm{m}_{\chi}\right)\chi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu} \tag{1}$$

where the last term shows that A' and B kinetically mix with the mixing parameter κ. After replacing $\not{A}'$ with $\not{A}'+\kappa B_{\mu}$, the coupling between the dark fermion and B becomes $\kappa e'$ ($\kappa e'\bar{\chi}\not{B}\chi$). The charge of χ varies by the size of mixing, so χ can be a millicharged particle. Hereafter, χ is used to denote millicharged particles.

A number of experiments have searched for millicharged particles, including an electron fixed-target experiment [3], proton-proton colliders [4–6], proton fixed-target experiment [7] and neutrino experiments [8,9]. A comprehensive review is in Reference [10]. In the parameter space of the charge (Q) and mass (m_{χ}), the region of $m_{\chi} > 0.1$ GeV/c^2 and $Q < 10^{-3}e$ is largely unexplored.

Proton fixed-target experiments provide a solid testing ground for χs. The particle flux is much larger than in collider experiments and they can reach a higher energy than electron fixed-target experiments. The sensitivity of such experiments to χs can reach beyond $Q \sim 10^{-3}e$ for a wide mass range from a few MeV/c^2 to a few GeV/c^2. We proposes a new experiment, SUBMET (SUB-Millicharge ExperimenT), which utilizes the 30 GeV proton beam at J-PARC to search for χs in this unexplored region. This proposal is largely based on the feasibility study in Reference [11].

2 Production of millicharged particles at J-PARC

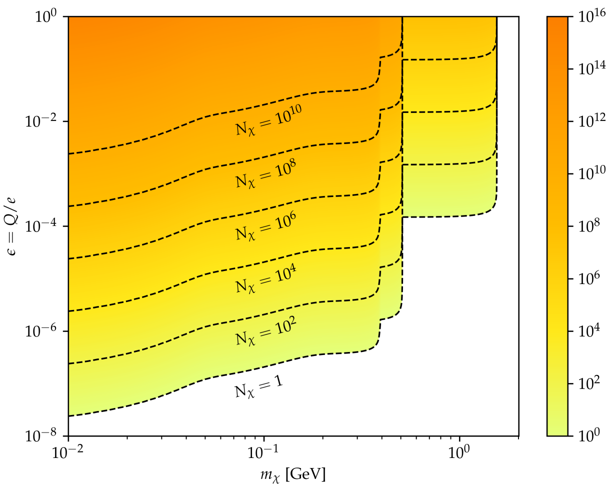

Figure 1: Expected number of χs that reach 0.25 m^2 detector area located at 280 m from the target. $N_{POT} = 5 \times 10^{21}$ is assumed.

At proton fixed-target collisions at J-PARC, χs with charge Q can be produced from the decay of $\pi^0, \eta, \rho, \omega, \phi$ and J/ψ neutral mesons. The Υ production is not relevant because the center-of-mass energy is 7.5 GeV for the collisions between the 30 GeV proton beam and the fixed target. The lighter mesons ($\mathfrak{m} = \pi^0, \eta$) decay through photons ($\mathfrak{m} \to \gamma\chi\bar{\chi}$), while ρ, ω, ϕ, and J/ψ decay to a pair of χs directly ($\mathfrak{m} \to \chi\bar{\chi}$). In both cases, m_χ up to $m_\mathfrak{m}/2$ is kinematically allowed. The number of produced χs (N_χ) can be calculated by the equation in [12],

$$N_\chi \propto c_\mathfrak{m} \epsilon^2 N_{\mathrm{POT}} \times f\left(\frac{m_\chi^2}{m_\mathfrak{m}^2}\right) \tag{2}$$

where $c_\mathfrak{m}$ is the number of mesons produced per proton-on-target (POT), N_{POT} is the total number of POT, $\epsilon = Q/e$, and f is a phase space related integral. The $c_\mathfrak{m}$ of each meson is extracted using `PYTHIA8` [13] and the estimated values are $c_{\pi^0} = 1.9$, $c_\eta = 0.21$, $c_\rho = 0.24$, $c_\omega = 0.24$, $c_\phi = 4.9 \times 10^{-3}$, and $c_{J/\psi} = 2.5 \times 10^{-9}$. The result of the simulation is validated by comparing it with existing measurements. Particularly, the flux of muons passing through the beam dump [14] and the production rate of J/ψ [15] in simulation and measurements are found to be in good agreement. We assume $N_{\text{POT}} = 5 \times 10^{21}$ that corresponds to running the experiment for 3 years [16]. As Figure 1 shows, the expected number of χs that reach the detector is in the order of 10^{16} at $\epsilon = 1$ and 10^8 at $\epsilon = 10^{-4}$.

3 Site and detector concept

In J-PARC a 30 GeV proton beam is incident on a graphite target to produce hadrons that subsequently decay to a pair of muon and muon neutrino in the decay volume. The remaining hadrons are then dumped in the beam dump facility. Since they are Minimum Ionizing Particles, muons can penetrate the beam dump and be identified by the muon monitor located behind the beam dump facility. The on-axis near detector, Interactive Neutrino GRID (INGRID) [17], is inside the Neutrino Monitor (NM) building located 280 m from the target. The space between the muon monitor and INGRID is filled with sand. The experimental site is illustrated in Figure 2. The proton beam has a repetition rate of 1.16 s and each spill contains 8 bunches which are separated by 600 ns [18]. The beam timing is available at the site and this allows for substantial reduction of backgrounds by $O(10^{-6})$.

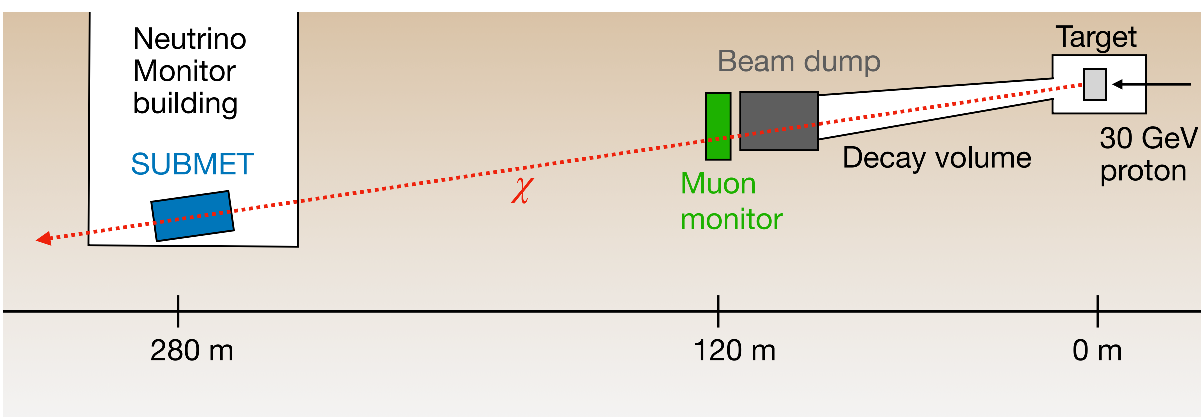

Figure 2: Illustration of the experimental site. χs are produced near the target and reach SUBMET after penetrating the beam dump, the muon monitor and the sand.

If χs are produced, they penetrate the space between the target and the detector without a significant energy loss because of their feeble interaction with matter. Therefore, they can be detected at the NM building if a detector sensitive to identifying such particles is installed. If the area behind the V-INGRID on B2 ($\sim$ 30 m underground) is available, it can be a potential detector site. The distance from the axis of the neutrino beam is $\sim$ 5 m. As described below, the signal acceptance is only slightly worse than the on-axis location.

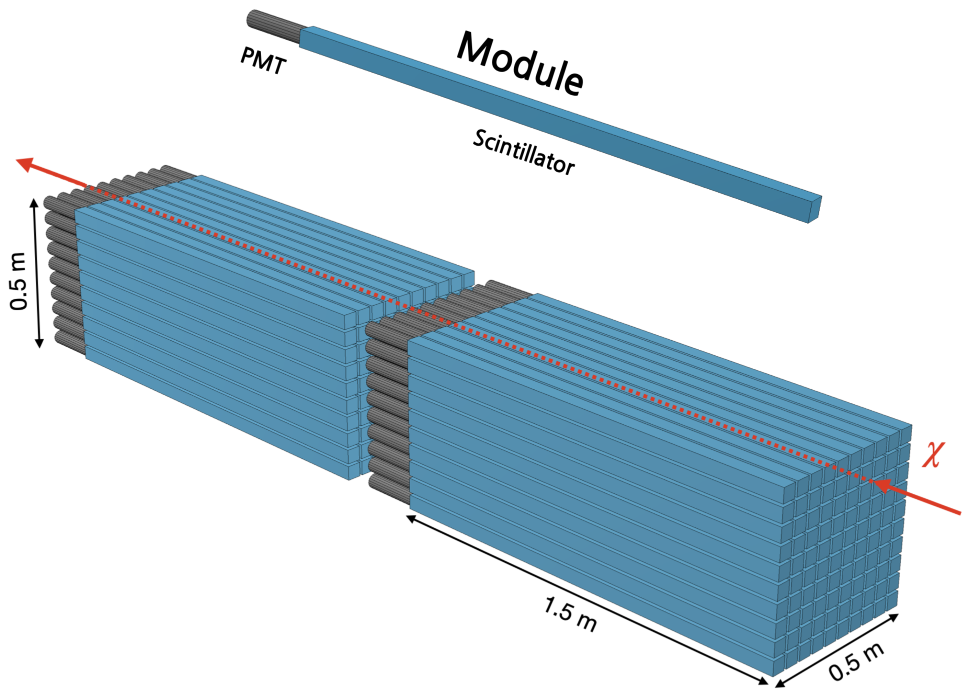

Figure 3: Demonstration of the SUBMET detector. A module is composed of a $5 \times 5 \times 150$ cm^3 scintillator bar (blue) and a PMT (grey). 10×10 modules are stacked together. Two layers of stacks are aligned such that a χ (red line) penetrates both layers in a narrow time window.

The detector concept proposed for this experiment is based on a similar proposal made in [19], sharing the idea to use a segmented detector with large scintillator bars. To be sensitive to charges below $10^{-3}e$, a thick sensitive volume is needed. It is advantageous to segment the large volume because it helps reducing backgrounds due to dark currents and shower particles from cosmogenic muons to a negligible level. It also allows for utilizing the directionality of the incident χs to further suppress non-pointing particles. The detector, as shown in Figure 3, is composed of 2 layers of stacked $5 \times 5 \times 150$ cm^3 BC-408 plastic scintillator bars [20]. They are aligned such that the produced χs pass through both layers in a narrow time window. In each layer there are 10×10 scintillator bars, so the area of the detector face is about 0.25 m^2.

A prototype of a detector with a similar design has been installed at the LHC, and shown robustness and sensitivity to χs [6].

At the end of each scintillator bar, a photodetector is attached to convert the photons to an electronic signal. Photomultipliers (PMTs) are suitable for this experiment because of their large area coverage, low cost, and low dark current. The total volume of the detector is approximately $0.5 \times 0.5 \times 4$ m^3 including the PMTs.

The signal acceptance rate, the fraction of χs that go into the detector area of 0.5 m^2 at 280 m from the target, is calculated as a function of distance from the beam axis to the detector. As shown in Figure 4, it is in the order of $O(10^{-5})$ and does not strongly depend on position, up to at least 10 meters from the axis, since the detector is located far from the target. This provides some flexibility in selecting the location of the detector. The effect of energy loss and multiple Coulomb scattering in the sand is estimated to be negligible for the charge range of interest, particularly below $10^{-3}e$, so they have a small impact on the sensitivity of the experiment.

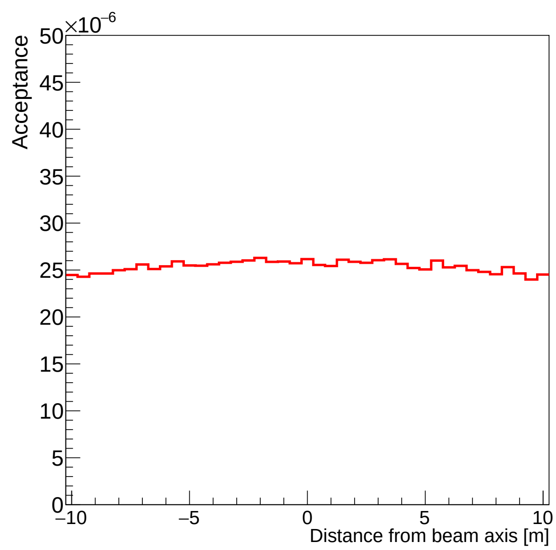

Figure 4: Signal acceptance rate at 280 m from the target as a function of distance from the beam axis to the detector location. One bin corresponds to the width of the detector 0.5 m.

4 Background sources

χs that reach the detector will go through both layers within a ~ 10 ns time window producing a coincidence signal. In this section, the background sources that can mimic this coincidence signal are discussed. They can be divided into three categories; random coincidence, beam-induced, and cosmic-induced backgrounds.

In PMTs, spurious current pulses can be produced by thermal electrons liberated from the photocathode. Therefore, a random coincidence of such pulses in different layers can be identified as a millicharge signal. The typical size of the pulses is very small and this makes random coincidence the major background source in $Q < 10^{-3}e$ regime. The rate of random coincidence can be large depending on the rate of the spurious pulses (dark count rate, DCR) even if the time window for the coincidence signal is 10 ns. The random coincidence rate is $nN^n\tau^{n-1}$ where n is the number of layers, N is the DCR, and τ is the coincidence time window. Using a typical PMT DCR of 500 Hz at room temperature, $n = 2$, and $\tau = 10$ ns, the random coincidence rate of two bars is 0.15 per year. There can be $10 \times 10 = 100$ such coincidence signals, so the total coincidence rate is 15 per year. The liberation of electrons is a thermal activity, which can be reduced by cooling the cathodes. With $N = 100$ Hz, the random coincidence background is reduced to < 1 events per year.

Muons are produced from pion decays in the decay volume together with neutrinos. The density of quartz, which typically takes up the largest fraction of sand, is 2.65 g/cm^3 and $dE/dx = 1.699$ MeVcm^2/g [21], so the energy loss of a MIP in > 100 m of sand is much larger than 30 GeV. Therefore, such beam-induced muons can't reach the detector. Although the muons from pion decays can't reach the detector, neutrinos can and may interact with the scintillator material to produce small signals. The number of neutrino interaction events in INGRID is $\sim 8 \times 10^7$ for $N_{\mathrm{POT}} = 5 \times 10^{21}$ [22]. Since a large fraction of INGRID material is iron, the rate of neutrino interaction in INGRID can be used as an upper bound for SUBMET. One layer of SUBMET is approximately 60 times smaller, so the rate is $\sim 10^6$ for $N_{\mathrm{POT}} = 5 \times 10^{21}$ in one layer of SUBMET. Requiring coincidence in two layers, the expected number of events from this background source becomes negligible. The interaction of the neutrinos and the material of the wall of the NM building in front of the detector can produce muons that go through the detector. These muons can be identified and rejected by installing scintillator plates between the wall and the detector or by using the very large scintillation yield of a muon that can be separated from the millicharge signal.

Cosmic muons that penetrate the cavern or the materials above the detector can produce a shower of particles that is large enough to hit both layers simultaneously. In such events, the hits in multiple layers can be within the coincidence time window and will look like a signal event. The particles in the shower generate more photons than χs, so the signals from cosmic muon showers can be rejected by vetoing large pulses. As done to tag the muons produced in the wall of the NM building in front of the detector, scintillator plates can be installed covering the whole detector to tag any ordinary-charged particles or photons incident from top and sides of the detector. These auxiliary components were proven to be effective in rejecting events with such particles [6]. In addition, the cosmic shower penetrates the detector sideways, leaving hits in multiple bars in the same layer, while χs will cause a smaller number of hits. A cosmic shower and signals from radioactive decays overlapping with dark current can be another source of background. Since the rate of this background depends on the environment strongly, a precise measurement can be performed *in situ* only.

To estimate the sensitivity of the experiment, we assume that the total background ($N_{\rm bkg}$) over three years of running is 5 events for DCR=100 Hz and 50 events for DCR=500 Hz.

5 Sensitivity

The probability of detecting a χ in a detector with n layers is given by Poisson distribution $P = (1 - e^{-N_{\rm PE}})^n$ where $N_{\rm PE}$ is the number of photoelectrons. $N_{\rm PE}$ is proportional to the quantum efficiency (QE) of PMT, ϵ^2, and the number of photons that reach the end of the scintillator (N_γ). The ϵ^2 term comes from the fact that the energy loss of a charged particle in matter is proportional to Q^2. In order to calculate N_γ a `GEANT4` [23] simulation is performed. Using a $5 \times 5 \times 150$ cm^3 BC-408 scintillator with a surface reflectivity of 98%, N_γ is 8.3×10^5. Taking QE into account, $N_{\rm PE}$ is $2.5 \times 10^5 \epsilon^2$. Once we have $N_{\rm PE}$ and P, the total number of

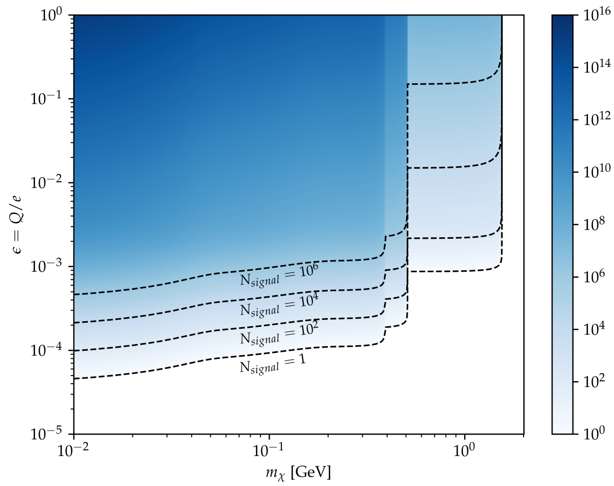

Figure 5: Number of signal events N_{signal} observed by the SUBMET detector for $N_{\mathrm{POT}} = 5 \times 10^{21}$. Dashed lines indicate $N_{signal} = 1, 10^2, 10^4$, and 10^6.

signal events measured by the detector can be calculated as $s = N_\chi P$. The number of signal events is shown in Figure 5. Due to small P, we expect < 1 events to be detected for ϵ below $\sim 5 \times 10^{-5}$.

Figure 6 shows the 95% CL exclusion curve for $N_{\mathrm{POT}} = 5 \times 10^{21}$. SUBMET provides the exclusion down to $\epsilon = 6 \times 10^{-5}$ in $m_\chi < 0.2$ GeV/c^2 and $\epsilon = 10^{-3}$ in $m_\chi < 1.6$ GeV/c^2. Systematic uncertainty on b is not considered because it does not have a significant impact on the exclusion limit [11]. The sudden degradation of sensitivity at $m_\chi = 0.2$ GeV/c^2 is because of the small production rate of J/ψ with the 30 GeV proton beam.

As shown in Fig 5, the number of signal events recorded by the detector drops rapidly in $\epsilon < 10^{-3}$ due to small $\mathrm{N_{PE}}$. Therefore, one can expect that increasing $\mathrm{N_{PE}}$ or N_χ would not have a large impact on the sensitivity.

6 Summary and discussion

We propose a new experiment, SUBMET, sensitive to millicharged particles produced at the 30 GeV proton fixed-target collisions at J-PARC. The detector, inspired by the milliQan experi-

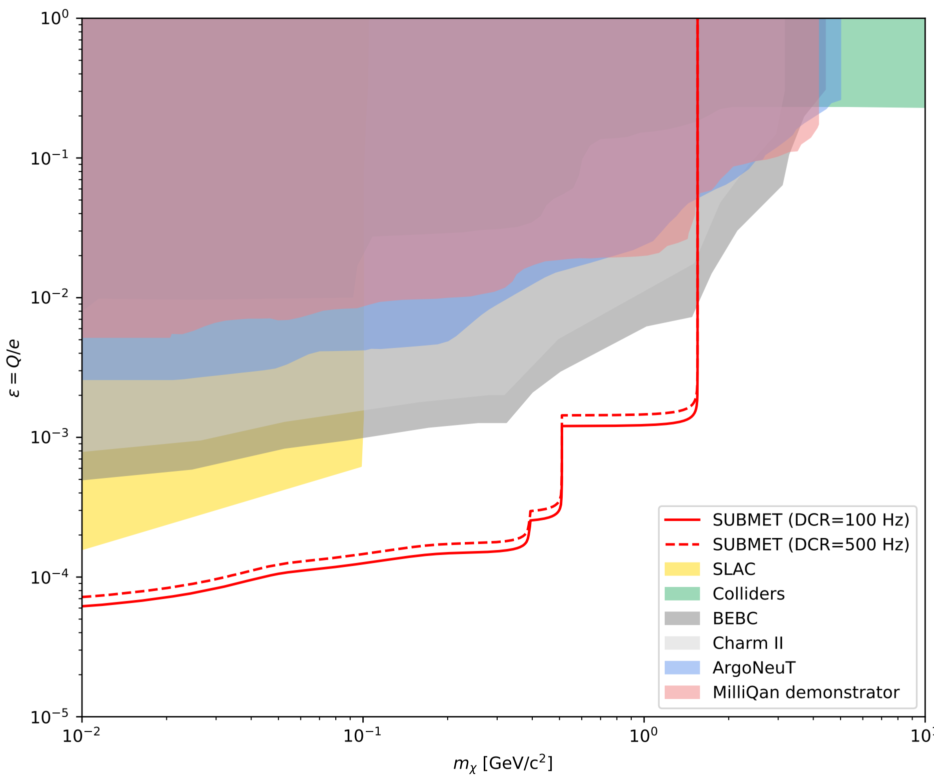

Figure 6: Exclusion at 95% CL for $N_{\mathrm{POT}} = 5 \times 10^{21}$. Two DCR scenarios are shown, DCR=100 Hz and DCR=500 Hz. The constraints from previous experiments are shown as shaded areas. The expected sensitivity of FerMINI [12] is drawn in the gray dotted line. There are other proposed experiments [19, 24], but only FerMINI with the NuMI beam and NA64μ [25] are included because they are in a similar time scale of SUBMET (within next 5 years).

ment, is based on long scintillators and is located in the Neutrino Monitor building 280 m from the target. With 5×10^{21} protons on target, the experiment is sensitive to particles with electric charge $6 \times 10^{-5}\, e$ for mass less than 0.2 GeV/c^2 and $10^{-3}\, e$ for mass less than 1.6 GeV/c^2.

SUMBET would place the best limit in low mass region $m_\chi < 0.2$ GeV/c^2 among existing and proposed experiments. In this regime, the N_{PE} is very small so the probability to observe a photon produced by millicharged particles per layer ($P_{\mathrm{layer}} = (1 - e^{-N_{\mathrm{PE}}})$) is extremely small. Since the total probability is a power of P_{layer} by the number of layers, using two layers significantly enhances the probability compared to the detector designs with 3 or 4 layers.

In the single-photoelectron regime, contributions from cosmic and radioactive backgrounds are expected to be suppressed because of the large number of photoelectrons they produce and the effective data-taking time (< 100 s for 3 years) due to correlation with the presence of beam. In the end, they are sensitive to the environment the detector is in, so they need to be measured in situ.

Note that this experiment is complementary to the existing proposals [12, 19, 26] since the main interest is in the low mass region. The center of mass energy of the proton-target collisions is 7.5 GeV and this limits the mass reach of the experiment to below $m_{J/\psi}/2$ while other proposals can cover higher mass regions. Compared to the FerMINI experiment, the production rate of J/ψ is much smaller due to lower beam energy. So, the sensitivity to the χs from J/ψ decay is slightly worse though it is still competitive.

We only consider the production of χs from the primary meson decays, but they can be produced from the electromagnetic component of the hadronic shower in the beam dump. The fact that its contribution is sensitive to both the geometry and material of the surrounding environment makes the estimation complicated.

A few detector designs to achieve an optimal sensitivity were considered in Reference [11]. We found that the configuration of the detector generally does not affect the sensitivity. In addition, the operation of the upgraded proton beam at J-PARC will start in 2022 [18]. These indicate that it is very important to install the detector as early as possible to fully exploit the upgraded power of the beam.

The principle of the experiment has been validated by the milliQan demonstrator [6]. With a sophisticated detector simulation and comparison with data, various background sources have been understood. This proposal is based on this experience. Some key members of the milliQan demonstrator group are included in this proposal and SUBMET can take advantage of the successful experience.

7 Schedule and cost estimate

Schedule

A tentative schedule of the experiment is shown in Table 7, assuming that the experiment is approved by summer 2022. It will be adjusted depending on the progress of the review process. The modules will be assembled in Korea and will be sent to J-PARC. Due to the availability of funding, the detector will be constructed in stages; 2/3 will be built in 2022 and the rest 1/3 will be added in 2023. Some of the collaborators are involved in the upgrade of the milliQan demonstrator [6], but its major work is expected to be finished by the end of 2021. Therefore, no conflict of resources is foreseen.

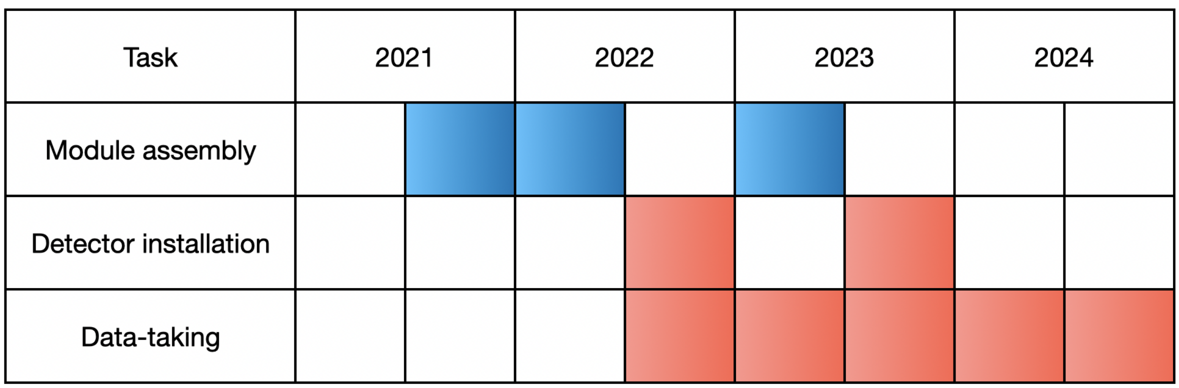

Figure 7: Schedule of the experiment. Tasks to be done in Korea are in blue and the ones to be done in J-PARC are in red.

Cost estimate and funding availability

Cost estimate is summarized in Table 1. The experiment already has funding from the National Research Foundation of Korea (NRF).

8 Requests

Network

JLAN network connection is needed for a computer that controls the DAQ system by a remote operator.

Item	Cost [JPY]	Funding source
Scintillator	15M	NRF
PMT	20M	NRF
Readout	10M	NRF
High Voltage Supply	10M	NRF
Service	10M	NRF
Total	65M	NRF

Table 1: Cost estimate for this proposal. Service includes cables, potential PMT cooling, etc. The experiment is fully supported by NRF.

Beam timing information

It is crucial to receive the signal related to the timing of the proton beam in order to suppress random coincidence backgrounds. We request the pre-beam trigger, beam trigger, and spill number which are already available in the Neutrino Monitor building.

Space for the experiment

Detector volume is $1 \times 1 \times 4$ m^3, so an area of 1×4 m^2 is needed for the detector itself. Additional space of 1×1 m^2 is needed for a rack that hosts readout electronics and HV supply. In total, an area of 1×5 m^2 is needed. One should note that if the detector is located behind the V-INGRID detector, we don't expect any interference with the measurements of the neutrino beam properties and the operation of the INGRID detector.

Beam time

No dedicated beam time will be requested by this experiment because it can be run in the shadow of the operation of the T2K experiment.

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