SUB-Millicharge ExperimenT (SUBMET) at J-PARC

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Abstract

The SUB-Millicharge ExperimenT (SUBMET) is designed to search for particles with minuscule electric charge, produced in proton fixed-target collisions at J-PARC. The detector, placed 280 meters from the target, has two layers of scintillator bars read out by photomultiplier tubes (PMTs). Its main background comes from accidental signals in both layers, mostly from PMT dark noise and environmental radiation. With an expected exposure of 5×10^{21} protons on target, SUBMET can search for such particles in the region where previous experiments could not reach. Installed in spring 2024, the detector collected beam data as well as auxiliary data for calibration studies. Using them, calibration of single photoelectrons and charge calibration using cosmic muons were performed. In addition, background prediction with beam-off data demonstrated robustness of the method and applicability to beam-on data.

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Introduction

SUB-Millicharge ExperimenT (SUBMET) [1] searches for millicharged particles (χs) using the 30 GeV proton fixed-target collisions at J-PARC. 10×8 plastic scintillator bars with dimensions 5 cm $\times$ 5 cm $\times$ 150 cm are stacked in two layers and are coupled to photomultiplier tubes. A combination of a bar and a PMT is called a module. The bars are aligned with the flux of χs such that they hit the two aligned modules in two layers in a short time interval. The detector was installed in the Neutrino Monitor Building in May 2024 and has taken data since then. Photo of the installed detector is shown in Figure 1.

Fig. 1: Installed SUBMET detector.

Figure 2 shows the exclusion limits from various experiments in the plan of mass and charge of χs [2–9]. SUBMET targets the phase space which is largely not covered by previous and existing searches. In particular, $m_\chi < 1.6$ GeV and $Q < 10^{-3}e$ is of main interest. The red solid line shows the expected reach of SUBMET with $N_{POT} = 10^{21}$, the amount of data we expect to accumulate by the end of detector operation. The blue dotted line corresponds to the reach with 0.5% N_{POT}, which corresponds to a fraction of data taken in 2024.

When the χs pass through a scintillator, photons are produced by ionization. Since the strength of ionization is proportional to Q^2, the average number of photons can be less than 1 in the target phase space ($Q < 10^{-3}e$). In this case, most χs leave no signal, but when they do, interactions typically yield a single photon. So, we detect χs by identifying single photoelectron (SPE) signals from the PMTs. The signature of χs is coincident

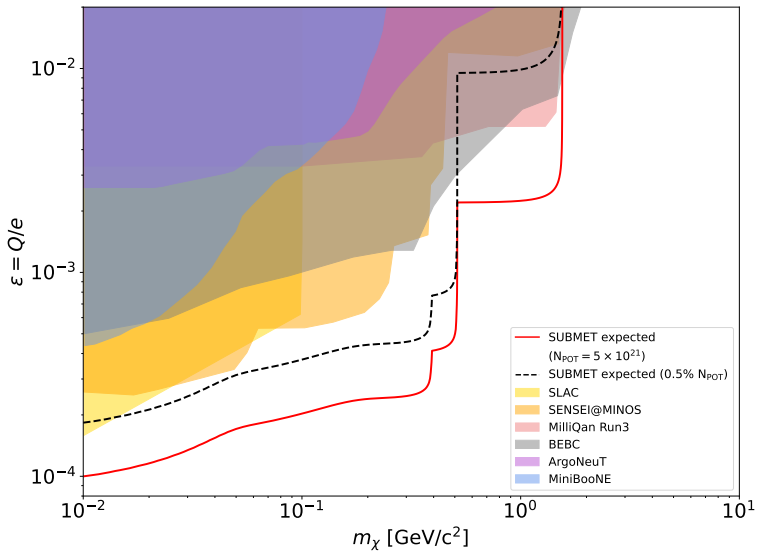

Fig. 2: Sensitivity of SUBMET with the target N_{POT} and 0.5% N_{POT} which corresponds to fraction of data taken in 2024.

($\Delta t < 20$ ns) SPE signals in two aligned modules.

SPE calibration

Since identifying SPEs is crucial, we performed a dedicated SPE calibration procedure using a weak LED light as a single-photon source. In each scintillator, an LED is attached to the other end of the PMT side so that SPE calibration can be done in situ. The LEDs are turned on periodically such that it barely emits a single photon.

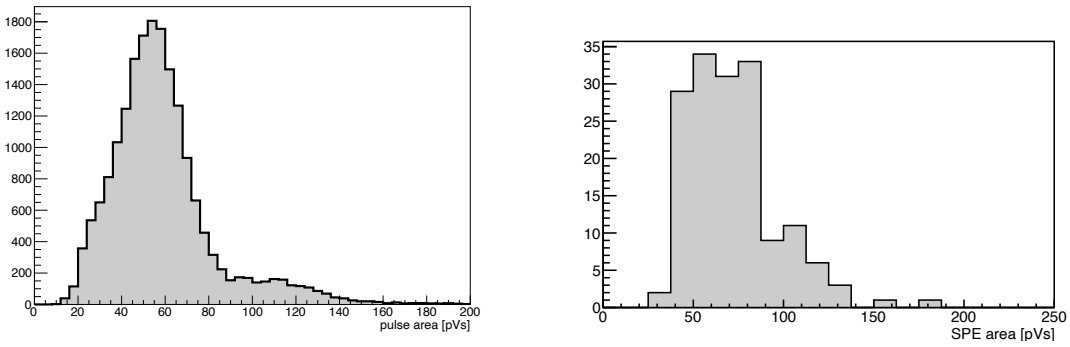

Fig. 3: Distribution of pulse area of a module (left) and distribution of mean of SPE peak of all modules (right).

Figure 3 (left) shows the pulse area distribution of a module. One can clearly observe that the SPE peak around the mean is 55 pVs with width 30% of the mean. Around 110 pVs, double Photoelectron (DPE) peak is also visible. We performed the same measurement for all 160 modules, and the distribution of mean of SPE area is shown in Figure 3 (right).

Charge calibration

It is also important to know the average number of photoelectrons (N_{PE}s) for a given energy for each module because then we can extrapolate it to lower charge by ϵ^2. Higher N_{PE} per energy means better sensitivity to lower charge. We measured N_{PE} per energy in situ by using cosmic muons in combination with the SPE calibration results. N_{PE} produced by a cosmic muon is calculated by dividing its pulse area by that of SPE. Since we can calculate the energy loss by a cosmic muon in the scintillator, we know how much ionization energy the N_{PE} corresponds to.

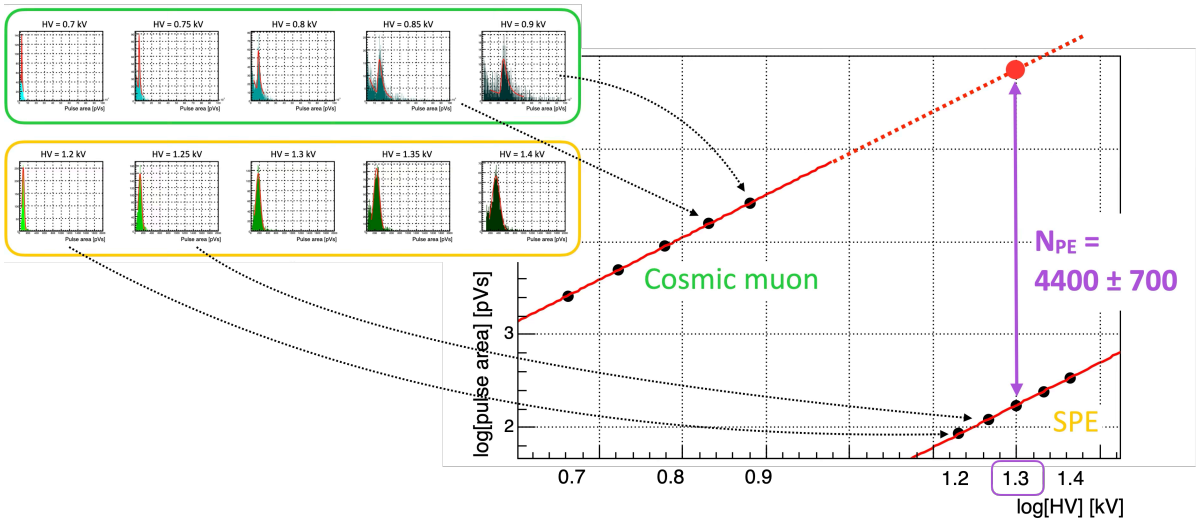

Fig. 4: Distributions of pulse area due to cosmic muons and SPEs at 5 different HVs and relation between log HV and log pulse area. Linear fit is performed and shown as red lines.

But, the challenge is that at HV = 1.3 kV, which is the operation voltage of PMTs, cosmic muon signals are saturated in DAQ. We used the linear relation between log HV and log gain (log pulse area), and extrapolated the cosmic muon measurements to 1.3 kV. Figure 4 shows measurement of cosmic muon and SPE pulse areas at 5 different HVs for each, and the result of linear fit. For this particular module, the ratio of the extrapolated cosmic muon area to the SPE area is 4400 ± 700. The same measurement has been perform with all modules and the mean N_{PE} is about 4000. This corresponds to $0.4 N_{PE}/keV$, which is consistent with the measurements using Cd-109 source.

Beam-off backgrounds

We studied beam-off backgrounds to understand the size of its contribution and to validate the background prediction method. Data with 12M events was taken by a random trigger in the absence of beam. The prediction was done using to uncorrelated variables - directionality and coincidence. Directionality is 1 if two modules with hits are at the same horizontal and vertical positions in the each layer. Coincidence is 1 if Δt between two hits in two layers is less than 20 ns. Then, the ABCD method is used for the prediction in the region where two hits have both directionality and coincidence 1. The prediction 10.2 ± 1.2 is consistent with the observation 11.

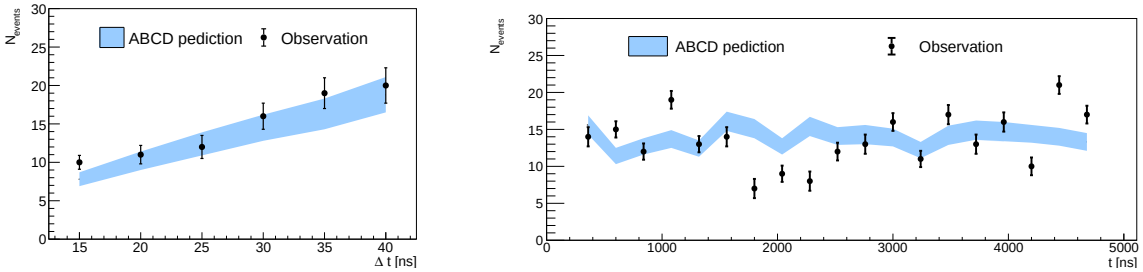

Fig. 5: Comparison of prediction and observation with a different size of coincidence window (left) and with different locations of readout window (right).

The method was tested further by varying the size of coincidence window and the location of readout window. Figure 5 (left) shows the comparison between prediction and observation by varying Δt from 15 to 40 ns. Good agreement indicates that beam-off backgrounds are mostly random coincidence. Figure 5 (right) shows the prediction and observation with only a particular readout window of size 240 ns. They agree in all regions of readout window. These two additional tests demonstrates robustness of the background prediction method.

Summary

The SUB-Millicharge ExperimenT (SUBMET) aims to detect particles with extremely small electric charges produced in proton fixed-target collisions at J-PARC. With a planned exposure of 5×10^{21} protons on target, SUBMET will probe regions of parameter space previously inaccessible to earlier experiments. Installed in the spring of 2024, the detector has collected beam data and auxiliary calibration data, which were used to perform single-photoelectron calibration and charge calibration with cosmic muons. Background prediction method used for beam-off data further demonstrated the robustness of the analysis strategy and its applicability to beam-on data.

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