Snowmass 2021 Letter of Interest:
Neutrino physics with muon-decay medium-baseline neutrino beam facility (MOMENT)

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MOMENT is a novel neutrino production facility concept where a low-energy high-flux beam of neutrinos and antineutrinos is conceived via muon decay. As a medium-baseline accelerator neutrino facility with low beam-related backgrounds and an unprecedentedly intense neutrino flux, MOMENT is suitable for the precision measurement of the *CP* violating Dirac phase as well as to look for hints of new physics in three-neutrino oscillations. To fully realize the potential of MOMENT and its neutrino physics program, we present this Letter of Interest to Snowmass 2021.

Keywords: Neutrino beam, accelerator neutrinos, CP violation, physics beyond the standard model

I. MOTIVATION

Neutrino oscillation experiments provide an important tool to address the questions that relate to the neutrino masses and mixing. Precision measurements on the standard oscillation parameters defining the Pontecorvo-Maki-Nakagawa-Sakata matrix [1–3] are therefore of fundamental importance. The next-generation neutrino oscillation experiments are expected to provide decisive evidence of the ordering the neutrino masses and establish either the violation or conservation of the *CP* symmetry in the lepton sector. As the precision on the standard neutrino oscillation parameters increases, measurements in the next-generation experiments will give an opportunity to seek residues of flavour symmetries in the structure of the neutrino mass matrix. Observation of such pattern could hint the origin of the neutrino mixing. Furthermore, the mounting data from neutrino oscillation experiments of various kinds will also allow to search for deviations from the well-established standard three-neutrino oscillations. Neutrino oscillations will provide a valuable tool to check for existence of physics beyond the Standard Model and look for signatures of specific models.

The U.S. particle physics community has held a long tradition in planning and facilitating neutrino oscillation experiments. The U.S. institutions have a crucial role in the planning and realization of the next-generation long-baseline experiment DUNE [4]. There is also a solid representation in the similar experiment T2HK in Japan [5] and in the next-generation reactor neutrino experiment JUNO in China [6].

In this Letter, we draw attention to the next-generation medium-baseline muon-decay neutrino facility MOMENT [7]. MOMENT presents a novel neutrino beam concept where an intensive low-energy beam of neutrinos and antineutrinos is produced via muon decays. The beam facility is envisioned to operate with 15 MW continuous-wave proton beam which will deliver a high-flux beam of neutrinos and antineutrinos from $\mu^+ \to \bar{\nu}_\mu \nu_e e^+$ and $\mu^- \to \nu_\mu \bar{\nu}_e e^-$. The result is a neutrino/antineutrino beam which will peak between 100 MeV and 300 MeV energies, with relatively easy prospects to change the beam polarity. For this kind of beam, a baseline of approximately 150 km length is suitable for performing precision measurements on the neutrino oscillation parameters. Previously, a Water Cherenkov detector of 500 kton fiducial mass with gadolinium doping has been considered for MOMENT. Although the relatively low cross-sections in the relevant beam energies must be compensated with a very-large detector mass, the Water Cherenkov technology is thought to be the most suitable due to its excellent performance at low energies [7].

As the search for new physics calls for measurements of higher precision and various methods, the nearly background-free accelerator facilities based on muon decays are needed to complement the existing technologies. The medium-baseline experiment facility MOMENT provides an excellent opportunity to look for new physics in a new experimental setup, where the low exposure to matter effects combined with the nearly background-free muon-decay beam facility. MOMENT could therefore complement the measurements of the future long-baseline experiments T2HK and DUNE, and the reactor neutrino experiment JUNO, which generate neutrinos from pion decays and beta decay, respectively.

II. PRECISION MEASUREMENT ON THE *CP* VIOLATING PHASE

The efficacy of MOMENT has recently been examined for the physics prospects of measuring the Dirac *CP* phase δ_{CP} [8, 9]. The present world data from neutrino oscillation experiments prefer a CP-violating phase with the allowed values $\delta_{CP} \simeq 123°$–$369°$ within $3\,\sigma$ confidence level for normal ordering and 193°–352° for inverted ordering [10]. A significantly higher precision is needed to establish *CP* violation in neutrino oscillations, however. Whether or not this milestone can be reached in MOMENT will depend on the experimental configuration [8] as well as on the true value of δ_{CP}, though it has been shown that an overall precision as good as 12° can be accomplished [9].

One of the challenges embedded in the physics potential of MOMENT is finding the suitable detector technology.

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The relatively low average energy of the neutrino/antineutrino beam asks for a scalable detector technology that can perform well at low energies [7]. One of the applicable choices is the conventional Water Cherenkov vessel with a sufficient level of gadolinium doping. It was suggested that a detector of about 500 kt fiducial mass would be required to compensate for the low cross-sections that emerge at the MOMENT energies with this technology. However, this is seen to introduce new difficulties in limiting the backgrounds [8]. It was found that the precision on δ_{CP} could be brought down to 12° within 3 σ confidence level when a joint-analysis is done with MOMENT, DUNE and T2HK [9].

Mitigation of the conventional bottlenecks in the neutrino detector can also be sought by considering alternative detector technologies in MOMENT. One recently completed study [11] focused on the applications of the opaque detectors. The study focused on a specific kind of liquid scintillator where the medium is loaded opaque with heavy elements, such as lead or gadolinium [12–14]. It was found in Ref. [11] that this technology could potentially improve the sensitivity to *CP* violation search in MOMENT, though a more detailed study in detector responses is needed.

III. SEARCHES FOR PHYSICS BEYOND THE STANDARD MODEL

Besides the precision measurements on the standard neutrino oscillation parameters, MOMENT may also complement the on-going search for physics beyond the Standard Model. There are several anomalies that lead to believe the Standard Model does not give the complete picture. In the neutrino sector, the so-called short-baseline [15] and reactor neutrino anomalies [16] give reasons to consider whether there are physics beyond the Standard Model that could potentially influence the on-going neutrino oscillation experiments.

There are also theoretical motivations to look for physics beyond the standard three-neutrino oscillation pattern. In many extensions to the Standard Model, the vanishing mass of the three active neutrinos is explained with the presence of one or more sterile neutrinos, which may influence the oscillations between the the active neutrino states. The existence of such neutrinos may not only enable the search for new physics in the neutrino oscillation experiments, but their effect may also smear the on-going measurements of the standard oscillation parameters [17].

To understand the nature of new physics, it is useful to observe the phenomena predicted by the same new-physics model using different technologies and methods. To this extent, MOMENT will complement the experimental runs of the future long-baseline experiments T2HK and DUNE, as well as the medium-baseline reactor experiment JUNO.

The sensitivity to new physics in MOMENT has been studied on several occasions. The sensitivity to the light sterile neutrino was investigated with both the Water Cherenkov and the opaque detector technologies [11], finding moderate sensitivities for the fourth neutrino mass around $\Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq 1$ eV^2. The littlest seesaw was also studied in MOMENT [18] using the so-called tri-direct approach in model building [19]. If the additional neutrino states are sufficiently heavy, the decay into lighter neutrino states could occur [20]. The efficiency of using MOMENT in constraining the neutrino decay scenario was studied in the case of invisible neutrino decay [21].

One manifestation of new physics that could be of particular interest in MOMENT is the charged-current non-standard neutrino interactions (CC-NSI) [22]. The sensitivity to the CC-NSI was studied in near and far detectors of MOMENT assuming two identical Water Cherenkov vessels [22]. In contrast to the long-baseline experiments DUNE and T2HK, the comparatively shorter baseline length in MOMENT makes the measurement of CC-NSI nearly free of neutral current non-standard interactions (NC-NSI), as was noted in Refs. [23] and [24]. Analysing the MOMENT data in conjunction with those from NOνA and T2K will help to disentangle the *CP* phase and octancy measurements from the matter NSI effects [23].

Altogether, MOMENT could provide valuable information about the nature of new physics as alternative technology to the currently planned long-baseline experiments T2HK and DUNE and the medium-baseline reactor experiment JUNO.

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