Feasibility study of a future accelerator neutrino experiment in China

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Abstract: We investigate prospects of building a future accelerator-based neutrino oscillation experiment in China, including site selection, beam optimization and tau neutrino physics. CP violation, non-unitary mixing and non-standard neutrino interactions are discussed. We simulate a muon-decay-based neutrino beam setup with a hybrid detector and compare the Chinese laboratory sites by their sensitivities. A case study on Super Proton-Proton Collider and China JinPing underground Physics Laboratory is also presented. At 90% confidence level, we show that this setup can measure the Dirac CP phase by about 5% precision, whereas non-unitarity can be probed down to $|\alpha_{ij}| \lesssim 0.37$ ($i \neq j = 1, 2, 3$) and non-standard interactions to $|\epsilon_{\mu\ell'}| \lesssim 0.11$ ($\ell \neq \ell' = e, \mu, \tau$), respectively.
1 Introduction

The near-future of neutrino oscillation physics will be highlighted by the precision measurements on the neutrino oscillation parameters. The missing pieces of the mechanism that governs the oscillations in the three-neutrino picture will be searched in a variety of neutrino oscillation experiments. The next generation of neutrino experiments, including the Jiangmen Underground Neutrino Observatory (JUNO) [1], Tokai-to-Hyper-Kamiokande (T2HK) [2] and Deep Underground Neutrino Experiment (DUNE) [3], will look for the remaining unknowns in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [4–8] and squared differences of the neutrino masses which parameterize the oscillations of three active neutrinos\(^1\). These experiments will furthermore improve the precision on the already measured neutrino oscillation parameters. Especially, it is important to conduct measurements on oscillations involving \(\nu_\tau\) in order to improve the precision of unitarity tests on the PMNS matrix [9]. Without answers are also the questions of absolute scale of neutrino

\(^1\)The main objectives are to determine whether neutrino masses follow normal ordering, \(m_1 < m_2 < m_3\), or inverted ordering, \(m_3 < m_1 < m_2\), and whether the Dirac CP phase \(\delta_{\text{CP}}\) is CP-conserving, \(\sin \delta_{\text{CP}} \neq 0\) or CP-violating, \(\sin \delta_{\text{CP}} \neq 0\). Also waiting to be measured is the octancy of \(\theta_{23}\), which may be either low, \(\theta_{23} < 45^\circ\), or high, \(\theta_{23} > 45^\circ\).
masses and whether neutrinos are of Dirac or Majorana nature, which are studied in neutrinoless double beta decay searches and cosmological probes as well as in direct neutrino mass experiments such as the Karlsruhe TRItium Neutrino experiment (KATRIN) [10].

China has been a major stage to reactor neutrino physics for many years. The most notable accomplishments were achieved in the Daya Bay reactor neutrino experiment, which contributed to the discovery of the non-zero reactor mixing angle $\theta_{13}$ [11]. In the next few years, the analysis of the reactor neutrino data will be continued in JUNO, with the main goal set in determining the neutrino mass ordering by at least 3 $\sigma$ confidence level (CL) [1]. At the same time, the discovery of dark matter is being sought in the China JinPing underground Laboratory (CJPL) [12] with PandaX [13] and CDEX [14]. While the near-future of Chinese underground experiments will mainly focus on addressing the questions of the neutrino mass ordering and the nature of dark matter, the era after the next-generation experiments will very likely see extensive studies on the physics beyond the Standard Model\textsuperscript{2}. There have also been a number of accelerator laboratories being constructed in China, which offer an opportunity to consider an accelerator-based experimental neutrino program. One promising example is the proposal of MuOn-decay MEedium-baseline neutrino facility (MOMENT) [22], which presents a novel concept of producing a high-intensity low-energy neutrino beam using muon decay as their source. The physics case of MOMENT has been established in both the CP-violation searches and in precision measurements of the standard neutrino oscillation parameters as well as in the searches for new physics [23–29]. On the other end of the national research planning in China are the next-generation collider experiments of the Circular Electron-Positron Collider (CEPC) and its high-energy upgrade Super Proton-Proton Collider (SPPC) [30–32]. Diverting a proton beam from such accelerators could be used in a neutrino physics program.

We investigate the prospects of building a future accelerator-based neutrino oscillation experiment in China by using the existing and planned research infrastructure as its foundation. The neutrino detector for example could be hosted in one of the two existing underground laboratories, which are JUNO and CJPL. The beamline needed for the neutrino beam could then be realized in an existing accelerator laboratory such as the China Spallation Neutron Source (CSNS) [33] and China initiative for Accelerator Driven System (CiADS) [34], or in a planned facility such as the one at the Institute of Modern Physics of the Chinese Academy of Sciences (CAS-IMP) [35] or at the Proton Linear Accelerator Institute in Nanjing University [36]. Another interesting option for a future neutrino experiment is to build a neutrino beam facility at the SPPC accelerator complex, where the proton beam required for neutrino production could be diverted from one of the accelerator rings in the injector chain. In the present work, we briefly review the available locations for the accelerator and detector facilities and analyse the physics prospects in establishing the conservation or violation of the CP symmetry, determining the value of the Dirac CP phase as well as other standard oscillation parameters, and running precision tests on Standard Model by searching for signs of non-standard interactions and non-unitary neutrino

\textsuperscript{2}The prospects of using future experiments as probes for new physics have been studied very extensively in the literature. Some good examples are presented in Refs. [15–21].
mixing. We study the experiment sensitivities for the available baselines by simulating a hypothetical accelerator neutrino experiment with GLoBES [37, 38]. We also present a case study on a specific configuration where an accelerator neutrino facility based on the neutrino factory design [39–43] is established at the SPPC injector chain whereas neutrino detector similar to magnetized iron and emulsion chamber technologies is established at CPJL, introducing a baseline length of 1736 km. Noting also the prospects of studying tau neutrinos in long-baseline neutrino experiments [18, 44–46], we place emphasis on \( \nu_\tau \) appearance. We call this setup PR{}ecisiOn Measurements and Physics with Tau neutrinos (PROMPT) and investigate its prospects as a future accelerator neutrino experiment.

The article is organized as follows: we define the physics scenarios to be considered in this work in section 2. In section 3, we present an overview on several accelerator and underground laboratories in China. In section 4 we discuss the potential experiment setups that can be established in the considered research infrastructure. We then compare their physics prospects in section 5. We summarize our findings in section 6.

2 Review of theoretical formalism

In this section, we briefly define the physics goals we wish to set for the future accelerator-based neutrino oscillation experiment. We specifically focus on experiment configurations with long baseline lengths. Hence, the general overview of neutrino oscillations relevant for long-baseline experiments is provided in this section. We begin with the standard scenario with the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and Mikheyev-Smirnov-Wolfenstein (MSW) effect in section 2.1, extend the discussion to non-unitary mixing in section 2.2 and non-standard interactions in section 2.3.

2.1 The standard paradigm

In the standard parameterization of neutrino oscillations, the mixing between the three active neutrinos \( \nu_e, \nu_\mu \) and \( \nu_\tau \) is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [4–8], which is a unitary \( 3 \times 3 \) matrix that decomposes into three parts:

\[
U_{\text{PMNS}} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta_{\text{CP}}} \\
0 & 1 & 0 \\
s_{13} e^{i \delta_{\text{CP}}} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix},
\]

where \( s_{ij} = \sin \theta_{ij} \) and \( c_{ij} = \cos \theta_{ij} \) are defined by the mixing angles \( \theta_{12}, \theta_{13} \) and \( \theta_{23} \), and \( \delta_{\text{CP}} \) is the Dirac CP phase. In addition to the PMNS matrix, the oscillation probabilities depend on the three neutrino mass states \( m_1, m_2 \) and \( m_3 \), which can be arranged in either normal ordering, \( m_3 > m_2 > m_1 \), or inverted ordering, \( m_2 > m_1 > m_3 \). The oscillation frequencies are defined by the mass-square differences \( \Delta m_{21}^2 \equiv m_2^2 - m_1^2 \) and \( \Delta m_{31}^2 \equiv m_3^2 - m_2^2 \). Together these parameters are known as the standard oscillation parameters.

Neutrino oscillations become subject to matter effects when neutrinos traverse in a medium. This phenomenon is known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect [47, 48]. The effective Hamiltonian responsible for the neutrino propagation in matter
can be written as:

\[ H = \frac{1}{2E_\nu} \left[ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + A_{CC} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right], \]

(2.2)

where \( E_\nu \) is the (anti)neutrino energy, \( U \) is the PMNS matrix and \( A_{CC} \) is the matter potential arising from exchanges of \( W \) and \( Z \) bosons with the medium. For neutrinos, the matter potential is defined as \( A_{CC} = \sqrt{2} G_F N_e \), with \( G_F \) denoting the Fermi constant and \( N_e \) the electron number density in the medium. For antineutrinos, the matter potential is obtained from the transformation \( A_{CC} \rightarrow -A_{CC} \).

### 2.2 Oscillations with a non-unitary mixing matrix

As the existence of the neutrino oscillations itself is a direct evidence of physics beyond the Standard Model, it is worthwhile to consider whether there could be non-standard physics also present in the neutrino mixing itself. One popular form of new physics manifests itself as non-unitarity in the neutrino mixing matrix, as is the case with theoretical models featuring Type-I and Type-III SeeSaw mechanism [49].

When one studies a model where the neutrino mixing matrix might not be unitary, the mixing between the active and sterile states can be presented in the block form [50]:

\[ U = \begin{pmatrix} N & V \\ S & T \end{pmatrix}, \]

(2.3)

where \( U \) is the unitary \( 3+n \times 3+n \) matrix describing the mixing between the three active neutrinos and \( n \) sterile neutrinos. The mixing between the active-active states is enclosed in \( N \), active-sterile and sterile-active in \( V \) and \( S \), and sterile-sterile in \( T \), respectively, which are all non-unitary \( 3 \times 3 \) matrices.

In this particular scenario the matrix \( N \) may not necessarily be unitary, which has several implications on the fit values of the standard oscillation parameters in the global neutrino oscillation data. In absence of \( \nu_\mu \rightarrow \nu_\tau \) oscillations in the conventional superbeam experiments, for example, the matrix element \( |U_{\tau 3}|^2 \) is only present as a sub-leading term in \( \nu_\mu \rightarrow \nu_\mu \) oscillations, whereas the information on \( |U_{\tau 1}|^2 \) and \( |U_{\tau 2}|^2 \) is lost. One therefore needs either excellent statistics from the \( \nu_\mu \rightarrow \nu_\mu \) channel or access to \( \nu_\mu \rightarrow \nu_\tau \) channel to recover the sensitivity.

The non-unitarity of the sub-matrix \( N \) describing the mixing between the three active neutrino states \( \nu_1, \nu_2 \) and \( \nu_3 \) alters the effective Hamiltonian, where the neutral currents can no longer be ignored:

\[ H = \frac{1}{2E_\nu} \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} + N^\dagger \begin{pmatrix} A_{CC} - A_{NC} & 0 & 0 \\ 0 & -A_{NC} & 0 \\ 0 & 0 & -A_{NC} \end{pmatrix} N. \]

(2.4)

There are multiple ways to parameterize the non-unitarity of the mixing between the three active neutrinos. The corresponding non-unitary matrix \( N \) can be decomposed into
unitary and non-unitary parts [51, 52]:

\[
N = \begin{pmatrix}
\alpha_{11} & 0 & 0 \\
\alpha_{21} & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix} U_{\text{PMNS}},
\]

(2.5)

where \(\alpha_{11}, \alpha_{22}, \) and \(\alpha_{33}\) are real parameters and retain values close to unity, while the off-diagonal parameters \(\alpha_{21}, \alpha_{31}, \) and \(\alpha_{32}\) are small and may attain complex values. Though the representation used in equation (2.5) is widely used, it is often convenient to parameterize the non-unitary part of the mixing matrix \(N\) with the alternate representation [53], where all new parameters are close to zero [54]:

\[
\alpha_{ii} \rightarrow 1 - \alpha_{\ell\ell} \quad \text{and} \quad \alpha_{ij} \rightarrow -\alpha_{\ell'\ell}, \quad \text{where} \quad i \neq j
\]

for the latter transformation and \(\ell, \ell' = e, \mu \) and \(\tau\). Note that \(U_{\text{PMNS}}\) stands for the PMNS matrix. The advantage of dividing the non-unitary mixing matrix \(N\) into two parts is that it allows to interpret the impact of the non-unitarity without the need to provide the fit results for the standard oscillation parameters in \(U_{\text{PMNS}}\) in the extended picture.

Let us now make a remark on the complementarity of the different oscillation channels in a multi-channel oscillation probability analysis. While the leading terms in the \(\nu_e \rightarrow \nu_e, \nu_\mu \rightarrow \nu_e\) and \(\nu_\mu \rightarrow \nu_\mu\) channels and their respective antineutrino channels allow direct measurement of the non-unitarity parameters in the first and second rows, the inclusion of the tau neutrino appearance in \(\nu_e \rightarrow \nu_\tau\) provides a hint of the elements in the bottom row. This is particularly noted to be true in near detectors [46]. While the diagonal term \(\alpha_{33}\) is expected the bear the lowest impact onto tau neutrino appearance, the off-diagonal parameters \(\alpha_{31}\) and \(\alpha_{32}\) can be very sensitive to neutrino channels featuring \(\nu_\tau\).

### 2.3 Non-standard neutrino interactions

In addition to the standard precision tests on three-neutrino mixing, future neutrino experiments are also able to look for new physics in neutrino interactions. In the quantum mechanical description of neutrino oscillations, this new physics is often described with the non-standard interaction (NSI) parameters which parameterize new interactions in terms of the Fermi coupling constant \(G_F\). The incoherent production and detection of neutrinos give rise to NSI in the source and detection, which are expressed by the source and detection NSI parameters \(\epsilon_s^{\ell\ell'}\) and \(\epsilon_d^{\ell\ell'}\), where \(\ell, \ell' = e, \mu \) and \(\tau\) stand for the neutrino flavour [55–57]:

\[
|\nu_s^\ell\rangle = \left(1 + \frac{(1 + \epsilon_s^{\ell\ell})\epsilon_a}{N_s^\ell}\right)|\nu_\alpha\rangle, \quad \langle\nu_d^{\ell'}| = \langle\nu_\alpha| \frac{(1 + \epsilon_d^{d\ell})\alpha_{\ell'}^\ell}{N_d^{d\ell'}}.
\]

(2.6)

In the expressions shown in equation (2.6), the flavour states representing the neutrino in the production and detection, \(|\nu_s^\ell\rangle\) and \(\langle\nu_d^{\ell'}|\) respectively, are related to the eigenstates via the source and detection NSI parameters with the normalization factors \(N_s^\ell = \sqrt{(1 + \epsilon_s^{\ell\ell})(1 + \epsilon_s^{\ell\ell})}\) and \(N_d^{d\ell} = \sqrt{(1 + \epsilon_d^{d\ell})(1 + \epsilon_d^{d\ell})}\). Neutrino oscillations are furthermore affected by the NSI turning up in the propagation. In the effective Hamiltonian, the

\footnote{Parameters \(\alpha_{ij}\) (\(i, j = 1, 2, 3\)) can also be expressed in terms of matrix elements: \(\alpha_{ii} = 1 - \frac{1}{2} \sum_k |U_{ki}|^2\) and \(\alpha_{ij} = \sum_k U_{ik} U_{jk}^\ast\). Here \(k\) runs over the matrix elements which are not included in \(N\).}
standard matter effects are complemented with matter NSI parameters $\epsilon_{\ell'\ell}'$ as follows:

$$H = \frac{1}{2 E_{\nu}} \left[ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 + \epsilon_{ee}' & \epsilon_{e\mu}' & \epsilon_{e\tau}' \\ \epsilon_{e\mu}' & \epsilon_{\mu\mu}' & \epsilon_{\mu\tau}' \\ \epsilon_{e\tau}' & \epsilon_{\mu\tau}' & \epsilon_{\tau\tau}' \end{pmatrix} \right] ,$$

(2.7)

where the diagonal elements of the $\epsilon^m$ matrix are real, whereas the off-diagonal parameters can be complex numbers. The probability for a neutrino of flavour $\ell$ to oscillate into a neutrino of flavour $\ell'$ is then given by $P_{\ell'\ell} = |\langle \nu^d_{\ell'} | e^{-i H L} | \nu^s_{\ell} \rangle|^2$.

Source and detection NSI parameters are strictly constrained by experimental data from short-baseline experiments [58], whereas bounds on matter NSI parameters are fairly loose [54]. Future experiments with long baseline lengths are most suitable to study NSI effects in neutrino propagation. Especially tau neutrino physics is known to be beneficial in the measurement of $\epsilon_{\ell'\ell}'$ parameters in the third row of equation (2.7) [40, 44].

3 Overview of the accelerator and underground laboratories in China

There are a number of large-scale experimental research laboratories that are currently underway in China. In this section, we present a survey on seven notable laboratories that could be considered as a candidate for a neutrino source or detector site.

3.1 Accelerator laboratories

At the moment, there are five different laboratories and institutes with the capability to host a proton accelerator center. Three of them, CSNS, CiADS and CAS-IMP, are already in operation and underway to reach their full potential. Two other laboratories, Nanjing University and SPPC, are going through the planning phase.

CSNS

China Spallation Neutrino Source (CSNS) is an accelerator-based neutron source commissioned to conduct experiments with neutrons [33]. It is one of the largest on-ground research facilities in China and its primary purpose is to develop novel methods for material characterization using neutron scattering techniques. CNSN is stationed in Dongguan, Guangdong, and includes linear proton accelerator, rapid circling synchrotron and a target station with three neutron instruments. The accelerator facility in CSNS is home to a 1.6 GeV proton driver with 100 kW beam power in its first stage (CSNS I), which will be upgraded to 500 kW for its second stage (CSNS II). The CSNS accelerator facility has ultimately the prospects to reach 4 MW beam power and 128 GeV proton energy, when a post-acceleration system is added (CSNS+). In addition to its primary goal of serving neutron science, the CSNS accelerator laboratory also provides opportunities to conduct fundamental research. Applications to use the post-accelerated protons of the CSNS+ phase have been studied in a neutrino superbeam experiment [59]. In such case, extracting only roughly 10% of the CSNS protons from the neutron source would allow to generate 4 MW proton beam of 128 GeV energy, which could be used to produce neutrinos via pion decay.
It is also possible to consider further prospects in producing neutrinos via muon beams, with the Experimental Muon Source (EMuS) currently in place in CSNS.

CSNS could make an attractive location for a future accelerator neutrino facility, with its location of 84 km from JUNO and 1329 km from CJPL. It could therefore be used in medium-baseline oscillation experiments as well as in long-baseline neutrino experiments.

**CiADS**

China initiative for Accelerator Driven System (CiADS) is a strategic plan to solve the nuclear waste and resource problems concerning the future nuclear power industry in China [34]. The initiative entails a long-term experimental program where an accelerator-driven sub-critical demonstration facility is built and operated over a staged 20-year plan. The first stage of the program involving a proton beam of 100 kW power and 1.5 GeV energy is presently operational. The facility delivers a 10 mA beam and runs entirely continuous-wave mode. The next stage upgrades the system to 500 kW beam power and is already funded. At the end its program, the facility is expected to reach proton beam energies as high as 15 MW in continuous-wave mode. The technology developed in the CiADS program and even the facility itself can be used in a neutrino physics program. The idea of building a neutrino experiment has previously been experiment in the MOMENT proposal [22].

Located in located within the city of Huizhou in Guangdong, approximately 146 km from the JUNO detector site and 1389 km from CJPL. Whereas the distance to JUNO is suitable for a low-energy neutrino beam facility like MOMENT, the longer baseline involved in the CJPL site is more suitable for higher neutrino energies, including the beam energies that are currently being planned for DUNE.

**CAS-IMP**

Institute of Modern Physics of the Chinese Academy of Sciences (CAS-IMP) is a major research institute located in the city of Lanzhou in central China. The institute was founded in 1957 and it has developed into the most important Chinese research center focusing on heavy ion physics. The institute has a long-running tradition in accelerator physics, hosting many experts in heavy ion physics while operating the Heavy Ion Research Facility in Lanzhou [35]. CAS-IMP is also in charge of establishing the next major Chinese heavy ion physics laboratory High Intensity Heavy-ion Accelerator [60] in the southern province of Guangdong, not far from the CiADS laboratory. Whereas the accelerator facility in Lanzhou is able to propel ions up to 1 GeV, the accelerator in Huizhou operates with proton energies up to 800 MeV.

The CAS-IMP site in Lanzhou is located approximately 894 km from CJPL and 1742 km from JUNO, making it a viable candidate for long-baseline neutrino oscillation physics. In this work, we consider CAS-IMP in Lanzhou as one of the potential sites for an accelerator neutrino facility in a future experiment.

**Nanjing**

Nanjing University is one of the major public universities in China. Several years ago, the university initiated a new technology development program in the field of high-energy
charged particle beam applications and fundamental sciences [36]. A key part of the program is the Proton Linear Accelerator Institute where plans to build a high-current proton linear accelerator were recently unveiled. The proton accelerator will serve for a variety of purposes, ranging from radio-isotopes and medical applications to nuclear physics and material sciences. The original plan for the accelerator aims at energy range of [10, 1000] MeV with a 26 mA current. The operation module may be chosen from either the continuous-wave (CW) or pulsed beam technique, with operation frequencies of 403 MHz and 806 MHz. In future upgrades the accelerator laboratory could potentially host additional programs dedicated to fundamental sciences. In this work we consider the accelerator laboratory at the Proton Linear Accelerator Institute of the Nanjing University as a potential location for a future accelerator-based neutrino production facility.

The Proton Linear Accelerator Institute of Nanjing University is suitable for an accelerator neutrino facility in a long-baseline oscillation experiment, being located roughly 1189 km from JUNO and 1693 km from CJPL.

**SPPC**

The Super Proton-Proton Collider (SPPC) is a future high-energy collider and the second stage of the China Electron-Positron Collider (CEPC) experiment currently being planned in China [31, 32]. The experimental program of SPPC includes the measurements on the Higgs couplings, with an aim to measure several rare decay processes and probing the Higgs self-coupling and $Htt$ coupling. Knowledge on these coupling strengths is considered to be crucial in understanding the form of the Higgs potential, and a direct measurement on the $HHH$ coupling could help to understand whether the electroweak phase transition is of the first or second order.

The SPPC accelerator complex consists of a large collider ring of 100 km circumference, with two interaction points and a nominal luminosity of $1.0 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ in each. The collider is expected to reach 75 TeV center of mass energy in its initial stage, with a prospect to ultimately reach 125–150 TeV. The accelerator also includes a four-stage injector chain, which consists of a proton linac and three synchrotron rings. The injector chain delivers 2.1 TeV proton beam to the SPPC ring. The duty cycle of the injector chain also allows to consider non-collider physics programs, with the potential to divert high-energy protons at 3.2 MW average beam power [31].

In the present work, we investigate the feasibility of realizing a future neutrino source in the SPPC accelerator facility near Beijing. The neutrino source would be located about 1736 km from CJPL and 1814 km from JUNO, respectively.

### 3.2 Underground laboratories

There are presently two underground laboratories of high importance. While CJPL is already in place and ready for extensions, the civil construction in JUNO is underway.

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4 High-luminosity upgrades and non-collider physics can also be considered for SPPC. In a recent study [61], for example, the SPPC accelerator was studied as a host for a lepton-proton collider.
CJPL

China Jinping Laboratory (CJPL) is one of the two underground laboratories currently in operation in China. Located under the Jinping mountain in Sichuan. Located more than 2400 meters underground, CJPL is currently the deepest underground laboratory in the world. It has relatively low cosmic muon flux and muon-induced background. The laboratory is also far from the major nuclear power plants, giving it low reactor neutrino background. CJPL is therefore an optimal location to study physics that requires low background, such as solar neutrinos, dark matter and supernova neutrinos. The laboratory currently hosts two dark matter experiments, PandaX and CDEX, and there are aspirations to build a neutrino detector to study low-energy astrophysical neutrinos.

JUNO

Jiangmen Underground Neutrino Observatory (JUNO) is a reactor neutrino experiment designed to study reactor neutrino flux from the Taishan and Yangjiang nuclear power plants in the province of Guangzhou in China. The experiment has a major goal of determining the neutrino mass ordering by at least $3\sigma$ confidence level of statistical significance. The experiment hosts an underground laboratory located 53 km from Taishan and Yangjiang in Jiangmen. The civil construction began in 2015 and the experiment is expected to be operational in 2023\textsuperscript{5}. The laboratory provides the facilities for a totally transparent liquid scintillator detector of 20 kton fiducial mass and it is planned to be operational for 6 years. The underground laboratory in JUNO is suitable for low-energy neutrino physics due to the relatively low background from the atmospheric neutrinos.

Choosing location for accelerator and detector facilities

The compatibility of the source and detector locations can be evaluated with the position on the oscillation maximum. Oscillation maximum defines the neutrino energy for which the conversion $\nu_\ell \rightarrow \nu_{\ell'}$, $\ell \neq \ell'$ occurs at its local maximum. Focusing the neutrino beam on one or more oscillation maxima is therefore preferred in an oscillation experiment. In accelerator neutrino experiments with medium and long baseline lengths, the oscillations in the channels $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$ reach their maximum when the following condition is satisfied:

$$\frac{L\Delta m^2_{31}}{4E_\nu} = \frac{n \cdot \pi}{2},$$  \hspace{1cm} (3.1)

where $n = 1$ for the first maximum and $n = 2$ for the second maximum\textsuperscript{6}. Using the geographical locations of the laboratories discussed in this section, we present the baseline lengths as well as the approximate neutrino energies for the first and second oscillation max-

\textsuperscript{5}Owing to several setbacks, it is not yet known when JUNO will begin to take data.

\textsuperscript{6}It should be noted that equation (3.1) defines oscillation maximum for $\Delta m^2_{31}$-driven neutrino oscillations. In a similar manner, one may derive the relation for $\Delta m^2_{21}$-driven oscillation mode. An important yet largely unexplored topic is the interference of $\Delta m^2_{21}$ and $\Delta m^2_{31}$-driven frequencies in neutrino oscillation experiments and their effect on the oscillation maximum.
### Table 1

| Accelerator facility | JUNO | | | CJPL | | |
|----------------------|------|---|---|---|---|---|
|                      | Baseline | 1st maximum | 2nd maximum | Baseline | 1st maximum | 2nd maximum |
| CAS-IMP              | 1742 km | 3.5 GeV | 1.2 GeV | 894 km | 2.7 GeV | 600 MeV |
| CiADS                | 146 km  | 300 MeV | 100 MeV | 1389 km | 1.8 GeV | 940 MeV |
| CSNS                 | 84 km   | 170 MeV | 60 MeV | 1329 km | 2.8 GeV | 900 MeV |
| Nanjing              | 1189 km | 2.4 GeV | 800 MeV | 1693 km | 3.4 GeV | 1.1 GeV |
| SPPC                 | 1814 km | 3.7 GeV | 1.2 GeV | 1736 km | 3.5 GeV | 1.2 GeV |

We find the laboratory setups discussed in this section to have the diversity and potential to provide foundation for an accelerator-based neutrino physics program. The existing accelerator and detector laboratories could therefore host neutrino programs between 84 km to 1814 km baseline lengths.

### 4 Description of the experimental configuration

In order to understand which of the available experimental sites provide favourable conditions for a future accelerator-based neutrino oscillation experiment, we perform a simulation study of hypothetical neutrino oscillation experiment utilizing the research infrastructure in China. In this section, we define key parameters of the experimental configuration simulated in our study. The general setup for the simulated neutrino experiment is discussed in section 4.1. Methods for the statistical analysis are summarized in section 4.2.

#### 4.1 General configuration for an accelerator neutrino experiment in China

As the numerical part of this work, we investigate the prospects of the neutrino experiment configurations that could be established using accelerator and underground laboratories in China. In this subsection, we briefly review the available neutrino beam and detector options which could be considered for such a neutrino oscillation experiment. We furthermore discuss what could be a concrete proposal for a future accelerator-based neutrino oscillation experiment based in China.

Accelerator neutrino experiments operating over long baseline lengths can be divided into three stages: neutrino production, propagation and detection. Each of these stages play an important role in determining the success of any future experiment. The neutrino configuration.
production method in such experiment could be based on technologies such as the conventional superbeam, neutrino factory or beta beam designs [62]. Neutrino detectors on the other hand could be developed using any of the presently established technologies, which include Water Cherenkov (W.C.), Magnetized Iron (M.I.) and Liquid Scintillator (L.Sc.) neutrino detector concepts. Hybrid detectors combining one or more detection methods could also be considered. There are also new types of detector technologies currently under investigation, the most notably example being the Liquid Argon Time Projection Chamber (LArTPC) [63] currently being developed for DUNE [64]. Emerging neutrino detector technologies are also under active R&D in various collaborations, including projects such as the W.C. and L.Sc. hybrid THEIA [65] and opaque detector concept LiquidO [66]. As the potential accelerator neutrino oscillation experiment in China would presumably take place in the not-so-near future, any of the beam and detector technologies mentioned above could be considered for its experimental setup.

One of the key questions in the development of future neutrino detectors is their capability to detect tau neutrinos. Tau neutrino appearance channels such as $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\tau$ are reported to have a notable potential to increase the sensitivity to many physics-driven goals, such as the precision measurements on standard oscillation parameters, testing unitarity of PMNS matrix as well as searching non-standard effects in neutrino interactions [46]. Prospects of using $\nu_\tau$ events to improve prospects to new physics have previously been studied in experiments like OPERA [45] and DUNE [18, 46]. The main challenges related to $\nu_\tau$ detection are the relatively high creation threshold, around 3.5 GeV, as well as short $\tau$ lifetime. These challenges must be addressed in future neutrino detectors to increase $\nu_\tau$ statistics. If technical difficulties can be mitigated, the inclusion of the silver channel $\nu_e \rightarrow \nu_\tau$ could lead to significant improvements in the sensitivity to new physics in neutrino experiments driven by muon decay [44].

In the present work, we consider the muon-decay-based neutrino beam technology which has been investigated in great detail in previous studies. The most general study on the prospects and limits of beam technologies based on high-energy muon decay are presented in the International Scope Study for the Neutrino Factory (ISS-NF) [42, 43]. Similar setups with lower muon beam energies have previously been considered for shorter baselines in $\nu$STORM and MOMENT proposals [22, 67]. In China, a promising candidate for neutrino beam facility using the muon decay technology is the injector chain of the SPPC accelerator complex [31], which is illustrated in figure 1. In the SPPC injector, protons are at first accelerated to 1.2 GeV energy in p-Linac and continue their way to p-RCS and MSS beamlines\(^8\) at 10 GeV and 180 GeV proton energies, respectively. The final stage before injecting to SPPC is the SS accelerator ring, where the protons reach 2.1 TeV energy. A neutrino beam facility could be built either adjacent to p-RCS or MSS rings, which both could divert a 3.2 MW proton beam for a non-collider physics program such as neutrino beams [31]. Once the collider is ready to take data, the SPPC accelerator facility will remain operational for at least 10 years. The p-RCS and MSS rings could also be used

\(^8\)The individual parts of SPPC injector are named as follows: proton linac (p-Linac), rapid cycling synchrotron (p-RCS), medium-stage synchrotron (MSS) and final stage synchrotron (SS) [32]. The option to use p-RCS and MSS in neutrino beams is first mentioned in Ref. [68].
Figure 1: A schematic illustration of the SPPC injector chain complemented with a neutrino production beamline. The injector chain consists of four stages, three of which could be used for proton extraction for a neutrino beam. The accelerated proton energies at the end of each stage is 1.2 GeV, 10 GeV, 180 GeV and 2.1 TeV, respectively. The MSS ring appears the most suitable for a neutrino program with its 180 GeV proton beam energy and opportunity to divert 3.2 MW to non-collider programs.

for non-collider physics several years prior to the launch of the collider program [31]. This gives an opportunity to consider various configurations for a potential neutrino beam.

The most favourable neutrino detector technology for neutrino factory is deemed to be M.I. detector, which provides excellent prospects to study $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations [39–41]. Such detector setup is often studied together with an emulsion could chamber (E.C.C.) detector, which provides the ability to reconstruct tau neutrinos from $\nu_e \rightarrow \nu_\tau$ oscillations [44]. One of the shortcomings of this technique is the relatively low statistics of $\nu_\tau$ owing to the low detector efficiency. In the present work, we consider a scenario where efficiency limits are at least partially mitigated, allowing a sizable $\nu_\tau$ sample.

In this work, we demonstrate the physics potential of an SPPC-based neutrino beamline in a hypothetical accelerator neutrino experiment. As the scope of this study is focused on the precision measurement of standard oscillation parameters and the search of non-unitary mixing and non-standard neutrino interactions, we call this configuration PROMPT (PRecisiOn Measurements and new Physics with Tau neutrinos). Following the discussion presented in section 3, we simulate a configuration where a neutrino detector is placed in CJPL, giving access to neutrino oscillations of 1736 km propagation\(^9\).

\(^9\)One could equivalently consider placing neutrino detector at the JUNO site instead of that of CJPL. In such case, the baseline length would become 1814 km whereas the physics prospects are similar to the
Table 2: Benchmark details of the simulated neutrino oscillation experiment. The configuration consists of a neutrino beam facility similar to neutrino factory and a neutrino detector based on a hybrid of magnetized iron and emulsion cloud chamber technologies.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Production method          | muon decay-in-flight   |
| Detection method           | hybrid detector        |
| Useful muon decays         | $2.5 \times 10^{20}$ year$^{-1}$ |
| Detector mass              | 50 kton                |
| Detection threshold        | 1 GeV                  |
| Energy resolution          | 15%/E$_{\nu}$          |
| Energy bins                | 45                     |
| Running time               | 5+5 years              |

The simulation study is carried out with General Long-Baseline Experiment Simulator \([37, 38]\) and its New Physics package \([69]\). We begin this study by analysing the prospects of all available baseline setups while considering muon energies between 5 and 50 GeV, which have previously been considered in Refs. \([39, 44, 70–72]\). We test the available beam configurations for 5, 15, 25 and 50 GeV. As for the neutrino detector, we adopt the M.I. and E.C.C. hybrid detector setup assuming 50 kton fiducial mass and 10 years of data taking. The operational time is divided evenly between the positively and negatively charged muon modes. The key details regarding the simulated configurations is summarized in table 2.

The channel composition of the considered neutrino beam setup is shown in table 3. Signal events in the appearance channels consist of neutrinos undergoing charged current (CC) interactions in the gold and silver channels $\nu_e \rightarrow \nu_e$, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ and $\nu_e \rightarrow \nu_\tau$. The efficiencies for these channels are 45%, 35% and 9.6%, respectively. The main backgrounds to the gold channels are neutral currents (NC) and charge mis-identifications (mis-id.), where acceptance rates are taken to be $5 \times 10^{-6}$ for each. The silver channel on the other hand acquires background from a number of CC and NC channels, the largest component being CC events from $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ with 0.1% acceptance. The disappearance channels $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ are analysed while no charge-identification is assumed\(^{10}\), increasing the efficiency to 90% in both channels. Disappearance channels gain backgrounds from NC events at $10^{-5}$ rate.

\(^{10}\) An alternative to the joint analysis is to introduce charge identification. In such case, efficiencies to $\nu_\mu$ and $\bar{\nu}_\mu$ events drop to 45% and 35%, respectively.
Table 3: The full composition of the signal and background channels studied in this work. The simulated configuration is adapted from the neutrino factory setup described in [39–41].

| Appearance channels | Disappearance channels |
|---------------------|------------------------|
| **Signal:**         | **Signal:**            |
| $\nu_e \rightarrow \nu_\mu$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\nu_e \rightarrow \nu_\mu$ |
| $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\nu_e \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\nu_e \rightarrow \nu_\tau$ |
| $\nu_e \rightarrow \nu_\tau$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\nu_e \rightarrow \nu_\mu$ |
| **Background:**     | **Background:**        |
| $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\nu_e \rightarrow \nu_\mu$ |
| \(\nu_\mu \rightarrow \nu_\mu\) and \(\bar{\nu}_e \rightarrow \bar{\nu}_\mu\) | \(\nu_\mu \rightarrow \nu_\mu\) and \(\bar{\nu}_e \rightarrow \bar{\nu}_\mu\) |

4.2 Simulation methods

In this subsection, we describe the simulation and analysis methods of the neutrino oscillation data produced in the experimental configurations studied in this work. All of the experimental setups studied in this work have very high statistics. The simulated neutrino data is therefore analysed with the following $\chi^2$ function, which is characterized by two types of systematic uncertainties:

$$
\chi^2 = \sum_i 2 \left[ T_i - O_i \left( 1 + \log \frac{O_i}{T_i} \right) \right] + \frac{\zeta_{\text{sg}}^2}{\sigma_{\zeta_{\text{sg}}}^2} + \frac{\zeta_{\text{bg}}^2}{\sigma_{\zeta_{\text{bg}}}^2} + \text{priors},
$$

(4.1)

where $O_i$ and $T_i$ are the predicted events for the reference and test data in $i^{th}$ energy bin, computed from the true and test values respectively. The systematic uncertainties are taken into account with the pull method [73] with the pull parameters $\zeta_{\text{sg}}$ and $\zeta_{\text{bg}}$, which describe the uncorrelated systematic uncertainties in the signal and background events. In our simulation of the neutrino beam facility, the systematic uncertainty treatment follows that of the neutrino factory setup with silver channel [39–41]: Whereas muon appearance channels $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ are characterised with 2.5% normalization uncertainty on the signal events, 15% uncertainty is assumed for the tau neutrino appearance signal $\nu_e \rightarrow \nu_\tau$. An overall 20% uncertainty is adopted for the analysis of background events.

In the analysis of the simulated data, we make use of the neutrino oscillation data that has been obtained in previous experiments. We adopt priors from the global three-neutrino best-fit values presented by the NuFit group [74]. The approximate values for the best fits (central values) and relative errors at 1 $\sigma$ and 3 $\sigma$ confidence levels (CL) are shown in table 4. In our analysis, we adopt the prior values as Gaussian distributions defined by the
Table 4: The best-fit values of the standard oscillation parameters presented with 1 $\sigma$ and 3 $\sigma$ C.L. relative errors [74, 75]. The values are shown for normal mass ordering.

| Parameter | Central value | Relative error (1 $\sigma$) | Relative error (3 $\sigma$) |
|-----------|---------------|-----------------------------|-----------------------------|
| $\theta_{12}$ ($^\circ$) | 33.4 | 2.3% | 13.7% |
| $\theta_{13}$ ($^\circ$) | 8.6 | 1.4% | 8.5% |
| $\theta_{23}$ ($^\circ$) | 49.2 | 2.1% | 25.3% |
| $\delta_{CP}$ ($^\circ$) | 197.0 | 12.9% | unconstrained |
| $\Delta m_{21}^2$ ($10^{-5}$ eV$^2$) | 7.4 | 2.8% | 16.4% |
| $\Delta m_{31}^2$ ($10^{-3}$ eV$^2$) | 2.5 | 1.1% | 6.5% |

central values and 1 $\sigma$ CL errors as given in the table. Without loss of generality, we carry out our analysis assuming normally ordered neutrino masses, that is, $m_3 \gg m_2 > m_1$.

The simulated data is analysed in the $CP$ violation search, precision measurements of $\theta_{23}$, $\delta_{CP}$ and $\Delta m_{31}^2$ as well as sensitivities to non-unitarity parameters $\alpha_{ij}$ and NSI parameters $\epsilon_{\ell\ell'}$. In each case, $\Delta \chi^2 = \chi^2_{\text{test}} - \chi^2_{\text{true}}$ distributions are calculated for the test and true hypotheses. Standard oscillation probabilities are calculated numerically with GLoBES, while the non-unitarity and NSI effects are evaluated with self-developed probability code and New Physics package, respectively. It is also useful to compare the expected prospects in PROMPT and other simulated configurations with those of T2HK and DUNE. For this reason, we simulate DUNE and T2HK by following configurations and techniques described in Refs. [2, 16, 76].

5 Physics prospects

In this section, we investigate the physics prospects of an accelerator neutrino experiment in China. We begin this study in section 5.1 by calculating the potential to discover $CP$ violation and measure the standard oscillation parameters $\theta_{23}$, $\delta_{CP}$ and $\Delta m_{31}^2$ at various baselines and beam energies. We also examine the prospects to study potential non-unitarity in neutrino mixing and non-standard interactions of neutrinos. We continue the study in section 5.2 where projections are presented for PROMPT.

5.1 Optimization of the muon beam and baseline

We consider the accelerator and detector laboratories described in section 3 and experiment configurations in section 4. The first step in our study is to investigate the physics prospects in each of the considered experiment configurations. We then determine the most favourable configurations for a future accelerator neutrino experiment using existing research infrastructure in China.

In order to determine the most suitable muon beam energy, we consider each setup with four different beam energies: 5 GeV, 15 GeV, 25 GeV and 50 GeV. In figure 2, the expected
sensitivities to $CP$ violation (top left), $\delta_{CP}$ precision (top right), $\theta_{23}$ precision (bottom left) and $\Delta m^2_{31}$ precision (bottom right) are shown as function of baseline lengths within [200, 2000] km range. The $CP$ violation discovery potential is expressed as a fraction of theoretically allowed $\delta_{CP}$ values for which discovery could be reached by 3$\sigma$ or higher confidence level. The precision on $\delta_{CP}$, $\theta_{23}$ and $\Delta m^2_{31}$ on the other hand is shown as the relative error at 1$\sigma$ C.L. with respect to corresponding best-fit result from the global fit [75].

The available baseline length that could be considered in the accelerator-detector laboratory pairs outlined in section 3 are represented by the shaded rectangles. The laboratory pairs considered in this work can be divided into two general categories. The medium-baseline region at the center of the parameter space constitutes the laboratories with baseline lengths 894 km...1389 km. This region encloses four configurations: CAS-IMP→CJPL, Nanjing→JUNO CSNS→CJPL and CiADS→CJPL. The other group visible in the considered parameter space is the long-baseline region 1693 km...1814 km, which are located on the right-hand side in each panel. The long-baseline region includes configurations Nanjing→CJPL, SPPC→CJPL, CAS-IMP→JUNO and SPPC→JUNO respectively. The medium-baseline group is the more interesting in the precision measurements of the standard oscillation parameters $\delta_{CP}$, $\theta_{23}$ and $\Delta m^2_{31}$, as the turning point of each sensitivity curve occurs within this region. Increments in baseline length after this region yields relatively small improvements to the overall precision. The $CP$ violation discovery potential on the other hand is generally achieved for larger portions of $\delta_{CP}$ values in the long-baseline group. Of the four muon beam energies, the energies of 15 GeV and 25 GeV yield the highest sensitivities, with 15 GeV dominating before the turning point and 25 GeV after it. It is noteworthy that the low-energy option of 5 GeV shows a local maximum in the medium-baseline region in $CP$ violation discovery potential and presents comparable sensitivities to the higher beam energies at longer baseline lengths. In the long-baseline group, the best sensitivities are achieved with 25 GeV muon parent energy.

The enhanced precision on the standard oscillation parameters also gives an opportunity to test unitarity of the PMNS mixing matrix. In this work, we parameterize deviations from unitarity paradigm with parameters $\alpha_{ij}$ ($i, j = 1, 2, 3$) introduced in section 2.2. Non-observation of unitarity breaking allows to derive constraints on the parameter region related to each parameter describing strength of non-unitarity. In the experiment configurations considered in this work, the constraints on magnitude of off-diagonal parameters $\alpha_{21}$, $\alpha_{31}$ and $\alpha_{32}$ are presented in figure 3. Without loss of generality, these three parameters are taken to be real. In each panel, the sensitivity to designated $\alpha_{ij}$ parameter is studied while keeping other non-unitarity parameters fixed at the value that corresponds to the unitarity paradigm. In this regard, we do not consider the diagonal parameters. Sensitivities in figure 3 are therefore obtained for $\alpha_{21}$, $\alpha_{31}$ and $\alpha_{32}$, which are presented in left, center and right panels, respectively. All projected sensitivities are shown at 90% C.L.

The projected sensitivities obtained for $\alpha_{21}$, $\alpha_{31}$ and $\alpha_{32}$ show both medium-baseline and long-baseline groups to have good prospects to study unitarity in three-neutrino oscillations. The turning point occurs for parameters $\alpha_{21}$ and $\alpha_{31}$ at baseline lengths 300 km...500 km for muon beam energies 15 GeV, 25 GeV and 50 GeV and about 1300 km...1500 km for 5 GeV. The medium-baseline group offers two options in the vicinity of this turning point:
Figure 2: Sensitivities to $CP$ violation and precision on the mixing parameters $\theta_{23}$, $\Delta m^2_{32}$ and $\delta_{CP}$ in the considered neutrino factory setup with baseline lengths 100 km...2000 km. Muon beam energies 5 GeV, 15 GeV, 25 GeV and 50 GeV are considered in a hybrid detector based on magnetized iron and emulsion chamber technologies and 50 kton active mass.

CSNS→CJPL at 1329 km and CiADS→CJPL at 1389 km. The situation is fundamentally different for $\alpha_{32}$, where turning point occurs clearly at longer baseline lengths. For 5 GeV muon beam energy, the most favorable sensitivity is achieved approximately at 1500 km baseline length, whereas other beam options provide more stringent constraints.
Figure 3: Sensitivities to the non-unitarity parameters $\alpha_{ij}$ ($i, j' = 1, 2, 3$) in the considered neutrino factory setup with baselines between 100 km and 2000 km. Projections are based on a hybrid detector based on the magnetized iron and emulsion chamber technologies and 50 kton active mass. Muon beam energies of 5, 15, 25 and 50 GeV are considered.

for configurations in the long-baseline group. The most ideal setups to study non-unitarity parameter $\alpha_{31}$ are therefore found in Nanjing→CJPL, SPPC→CJPL, CAS-IMP→JUNO and SPPC→JUNO with baseline lengths 1693 km, 1736 km, 1742 km and 1814 km, respectively. The off-diagonal parameters $\alpha_{21}$ and $\alpha_{31}$ can be probed to about $O(10^{-2}–10^{-1})$ and $\alpha_{32}$ to $O(10^{-3}–10^{-2})$, where higher beam energies provide more stringent constraints.

The final physics topic to be discussed in this work is the search for non-standard interactions in the neutrino sector. In the considered laboratory pairs options, the most relevant form of neutrino NSI is formed in the propagation. For this purpose, we leave out potential neutrino NSI attributed to the neutrino production and detection, and focus on the constraining ability to matter NSI parameters $\epsilon_{m\ell\ell'} = |\epsilon_{m\ell\ell'}^m|\exp^{-i\phi_{m\ell\ell'}}$ where $\ell, \ell' = e, \mu$ and $\tau$. The sensitivities to the off-diagonal matter NSI parameters $\epsilon_{e\mu}, \epsilon_{e\tau}$ and $\epsilon_{m\mu\tau}$ are presented in figure 4, where the upper constraints on each NSI parameter are derived assuming other NSI parameters to be zero. Similarly to the non-unitarity study presented above, we assume all NSI parameters to be real and focus on the general effect on the magnitude of each NSI parameter.

Sensitivity projections in figure 4 display the effect of the muon beam energy in search for matter NSI in neutrino propagation. The highest sensitivities are reached for $\epsilon_{e\mu}$ where the parameter space can be probed to as low as $O(10^{-3})$ for muon beam energies 15 GeV, 25 GeV and 50 GeV. The sensitivity reach saturates before 500 km distance, leaving the medium-baseline and long-baseline groups with similar sensitivities. For the low-energy
Figure 4: Sensitivities to the non-standard interaction parameters $\epsilon_{\mu\ell'}^m$, where $\ell, \ell' = e, \mu, \tau$ in the neutrino factory setup with baselines between 100 km and 2000 km. Muon beam energies are shown for 5, 15, 25 and 50 GeV, respectively. Neutrino detector is based on a hybrid model utilizing magnetized iron and emulsion chamber technologies. We consider 50 kton active mass.

Option of 5 GeV, the preferred baseline length is approximately 1700 km, which matches closely with Nanjing→CJPL and SPPC→CJPL setups. For parameter $\epsilon_{e\tau}^m$, sensitivities are about an order of magnitude weaker for the considered beam energies and turning point for 5 GeV is reached at much longer baseline lengths. Sensitivities of similar magnitude are also achieved for $\epsilon_{\mu\tau}^m$, but the exclusion limits continue to improve to the end of the considered range of baseline lengths and the low-energy beam option of 5 GeV reaches its best sensitivity at about 1600 km...1700 km. Accelerator-detector laboratory pairs in the long-baseline group therefore offer the more optimal sensitivities to prove the off-diagonal matter NSI parameters. Constraining power of each configuration in this region scales up as function of muon beam energy.

We finally comment on the accelerator-detector laboratory pairs investigated in figures 2–4. Basing on the sensitivities that were obtained for each configuration in the physics goals related to standard three-neutrino oscillations we find setups both the medium-baseline and long-baseline groups offering competitive choices for a future accelerator-based neutrino beam experiment in China. However, probing non-unitarity parameter $\alpha_{32}$ and matter NSI parameter $\epsilon_{\mu\tau}^m$ generally benefits from using longer baseline lengths than what are included in the medium-baseline group. Regarding muon beam energies, it is found that muon beam energies of 15 GeV and 25 GeV lead to the highest sensitivities in medium-baseline and long-baseline groups respectively, when precision on the standard oscillation
parameters are studied. When sensitivities to non-unitarity and matter NSI parameter are also examined, baseline configurations achieve better results with higher muon beam energies. Based on these observations, we remark that setups in the long-baseline group with 25 GeV muon beam energies provide the most promising results both in the standard neutrino oscillation physics and in the search for physics beyond the Standard Model. Baseline lengths in the medium-baseline group might also offer adequate conditions to study neutrino oscillations at high sensitivity. It is noteworthy that projections obtained in this work offer a promising landscape for future accelerator neutrino physics programs in China. Accelerator and detector laboratories considered in this work offer multiple choices to study neutrino oscillations in both medium-baseline and long-baseline categories.

5.2 Sensitivities in PROMPT

In this section, we present a case study on PROMPT, where a neutrino beam facility similar to neutrino factory is proposed to the SPPC injector chain and hybrid detector based on magnetized iron and emulsion cloud chamber techniques to the CJPL site. Based on the results obtained from the comparative study in the previous subsection, we simulate the PROMPT setup with 25 GeV muon beam energies at SPPC→CJPL baseline. In the following, we study the physics prospects of PROMPT in the precision measurement of $\delta_{\text{CP}}$, $\theta_{23}$ and $\Delta m_{31}^2$ under normal hierarchy, and the sensitivity to non-unitarity parameters $\alpha_{ij}$ and non-standard interaction parameters $\epsilon_{\ell\ell'}^m$, where $i, j = 1, 2, 3$ and $\ell, \ell' = e, \mu, \tau$.

**Precision measurements on standard oscillation parameters**

We begin by simulating PROMPT in the precision measurement of standard oscillation parameters. Discovery potential to CP violation and expected precision on parameters $\delta_{\text{CP}}$, $\theta_{23}$ and $\Delta m_{31}^2$ are presented for the 25 GeV muon beam setup in figure 5. Top left panel encloses the CP violation discovery potential within theoretically allowed $\delta_{\text{CP}}$ values, whereas other panels show the relative precision on parameters $\delta_{\text{CP}}$ (top right), $\theta_{23}$ (bottom left) and $\Delta m_{31}^2$ (bottom right), all of which have sizeable experimental uncertainties. In each panel, sensitivities are shown for DUNE, T2HK and PROMPT configurations as well as for their combination. We also show discovery potential for the setup where sensitivity to $\nu_\tau$ in PROMPT is turned off. Finally, we show the experimentally allowed values at $1\sigma$ C.L. from the recent global fit [75]. The allowed values are indicated with the shaded regions, whereas the vertical grey line represents the current best-fit.

As one can see from the obtained results, PROMPT compares relatively well with the sensitivities projected for the future long-baseline neutrino experiments T2HK and DUNE. Figure 5 reveals CP violation can be discovered at the T2HK experiment with remarkable $6.2\sigma$ C.L. sensitivity should the experimental program discussed in Refs. [2, 16] be carried out and true value $\delta_{\text{CP}} \simeq 282^\circ$. Similar discovery reach can be achieved in PROMPT for $\delta_{\text{CP}} \simeq 248^\circ$. The lowest sensitivity is obtained from DUNE at $4.9\sigma$ C.L., which is also very remarkable. In the precision measurement of $\delta_{\text{CP}}$, most stringent constraint is achieved in PROMPT where $1\sigma$ C.L. precision is confined within $4.9\%$ relative uncertainty, while $7.0\%$ and $9.2\%$ are the uncertainties achievable at T2HK and DUNE respectively. Here we focus on the region $180^\circ \lesssim \delta_{\text{CP}} \lesssim 360^\circ$, which is presently favoured by the experimental data [75].
Figure 5: Expected sensitivities to $CP$ violation (top left) and precision on $\delta_{CP}$ (top right), $\theta_{23}$ (bottom left) and $\Delta m^2_{31}$ (bottom right). Also shown are the expected sensitivities for the configuration without $\nu_\tau$ appearance as well as for DUNE and T2HK setups. The sensitivities are given at 90% C.L. while the global fit result with 1 $\sigma$ C.L. uncertainties are indicated by the shaded regions.

In the case of $\theta_{23}$ and $\Delta m^2_{31}$ measurements, relative uncertainties 1.6%, 2.2% and 2.6% can be accomplished for $\theta_{23}$ and 0.43%, 0.18% and 0.40% for $\Delta m^2_{31}$ in PROMPT, T2HK and DUNE, respectively. The effect of $\nu_\tau$ sample in PROMPT is evident in all measurements.
except that of $\Delta m^2_{31}$, though the effect is relatively small.

True potential of PROMPT appears when sensitivities of PROMPT are obtained together with those extracted for T2HK and DUNE. In figure 5, combined sensitivities are highlighted with the solid red curves. In precision measurement of $\delta_{CP}$, the combined run of PROMPT, T2HK and DUNE results in 3.8% relative precision, which amounts to about 10° precision at $\delta_{CP} \approx 280°$. Such precision would be a major achievement in the measurement of $\delta_{CP}$. Other significant milestones include taking the precision of $\theta_{23}$ to sub-percent level and $\Delta m^2_{31}$ to 0.1% level, respectively.

In summary, we find the baseline setup and configuration considered for PROMPT altogether very promising for the measurement of standard oscillation parameters $\delta_{CP}$, $\theta_{23}$ and $\Delta m^2_{31}$. Sensitivities to these parameters are improved from T2HK and DUNE, whilst the combined sensitivities in these configurations lead to several important milestones. The most significant contributors in PROMPT are the golden channels $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_\mu$, whereas the silver channel $\nu_e \rightarrow \nu_\tau$ has limited but noticeable effect.

Non-unitarity of the neutrino mixing matrix

Precision tests on the unitarity of three-neutrino mixing matrix can be studied in future neutrino oscillation experiments with the parameterization introduced in section 2.2. Deviations from the unitarity paradigm can be studied with parameters $\alpha_{ij} = |\alpha_{ij}| \exp(-i\varphi_{ij})$, where $i, j = 1, 2 \text{ and } 3$. Diagonal parameters $\alpha_{11}$, $\alpha_{22}$ and $\alpha_{33}$ are real and attain unity when the mixing matrix is unitary. Off-diagonal parameters on the other hand are complex and are set to zero to recover unitary mixing. The non-unitarity parameters are furthermore strictly constrained by previous experimental searches. Comparative surveys of present constraints can by found in Refs. [52, 54], for example. In the following, we discuss the prospects of constraining non-unitarity of the neutrino mixing matrix in PROMPT.

The exclusion limits for the non-unitarity parameters are presented in figure 6. The top row represents the expected sensitivities to constrain the parameter space for off-diagonal parameters $\alpha_{21}$, $\alpha_{31}$ and $\alpha_{32}$. The sensitivities are obtained for PROMPT, T2HK and DUNE setups as well as for the case where $\nu_\tau$ are disregarded in PROMPT. The bottom row on the other hand discloses the corresponding sensitivities to diagonal parameters $\alpha_{11}$, $\alpha_{22}$ and $\alpha_{33}$. In off-diagonal parameters, the most favourable sensitivities are provided PROMPT, PROMPT without $\nu_\tau$, DUNE and T2HK, respectively. Silver channel events lead to small improvements in measurements of $\alpha_{31}$ and $\alpha_{32}$, where $\nu_\tau$ sample tightens the constraints near the maximally $CP$-violating values $\varphi_{31}$, $\varphi_{32} \approx \pm 90°$. Differences between the projections for PROMPT, DUNE and T2HK are notable for off-diagonal parameters, which can be attributed to the baseline length. In case of diagonal parameters, differences between the four configurations are negligible and each parameter can be measured to few-percent level at 1 σ C.L.

We find PROMPT to be able to improve the constraints on all three off-diagonal parameters significantly from those predicted for T2HK and DUNE. The inclusion of $\nu_\tau$ sample in PROMPT is also visible in the exclusion limits obtained for $\alpha_{31}$ and $\alpha_{32}$. The effect is hindered by the relatively small statistics of $\nu_\tau$ in PROMPT, which derives from the limited efficiency to reconstruct $\nu_\tau$ events in the neutrino detector.
Figure 6: The sensitivity to the non-unitarity parameters $\alpha_{ij} = |\alpha_{ij}| e^{-i\phi_{ij}}$ ($i, j = 1, 2$ and $3$) in PROMPT. The projections of PROMPT are presented both for the baseline setup (dashed curve) and without sensitivity to tau neutrinos (dot-dashed). The expected sensitivities for the T2HK (dotted) and DUNE (solid) are also shown. Sensitivities to off-diagonal parameters are presented at 90% C.L.

Non-standard neutrino interactions

Non-standard neutrino interactions (NSI) in medium can be efficiently probed in experiments with very long baseline lengths. In the present work, we discuss the sensitivities to matter NSI parameters $\epsilon_{\alpha \beta}$ as described in section 2.3. In order to give a consistent comparison of the prospects in T2HK, DUNE and PROMPT, we ignore the sub-leading effects coming from the source and detection NSI parameters and consider one matter NSI parameter at a time. We derive constraints to off-diagonal parameters $\epsilon_{\ell \ell'} = |\epsilon_{\ell \ell'}| \exp(-i\phi)$ at 90% C.L. ($\ell \neq \ell'$) and to diagonal parameters $\epsilon_{\ell \ell}$ in terms of $\Delta \chi^2$ (1 d.o.f.).

Sensitivities to the NSI parameters are presented in figure 7. The top three panels represent the exclusion limits for the off-diagonal parameters $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ and $\epsilon_{\mu\tau}$, while the two bottom panels show the sensitivities to $\epsilon_{e\mu} - \epsilon_{\mu\mu}$ and $\epsilon_{e\tau} - \epsilon_{\mu\mu}$. In case of $\epsilon_{e\mu}$, PROMPT has clear advantage over T2HK and DUNE setups in the discovery of new physics. As is indicated in the top left panel, parameter space of $|\epsilon_{e\mu}|$ is constrained below 0.02 in PROMPT setup and PROMPT (w/o $\nu_{\tau}$) setup, indicating the sensitivity to arise entirely from the golden channels. DUNE and T2HK setups yield sensitivities 0.04 and 0.16, respectively. In

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11It is safe to ignore source and detection NSI effects in long-baseline neutrino experiments up to the point where sensitivity to matter NSI becomes comparable with source and detection NSI parameters, which are currently constrained to percent level [59]. Beyond this point, correlations with source and detection NSI parameters must be taken into account to attain a more realistic estimate on sensitivities, as was done in e.g. [54].
Figure 7: The sensitivities to the matter NSI parameters $\epsilon_m^{\alpha\beta}$ ($\alpha, \beta = e, \mu, \tau$) as function of the magnitude and phase. The sensitivities to the diagonal elements are shown for $(\epsilon_m^{ee} - \epsilon_m^{\tau\tau})$ and $(\epsilon_m^{\mu\mu} - \epsilon_m^{\tau\tau})$. The projections are presented for PROMPT with the baseline setup (dashed curve), without sensitivity to tau neutrinos (dot-dashed), DUNE (solid) and T2HK (dotted), respectively. All sensitivities are presented at 90% CL statistical significance.

Regarding the other matter NSI parameters, $\nu_\tau$ sample plays no observable role. Searches for new physics with parameter $\epsilon_m^{\mu\tau}$ yields identical constraints to the parameter space in both PROMPT setups, which are able to probe the parameter down to 0.11. Corresponding projections for DUNE and T2HK setups in this case 0.17 and 0.53, respectively.

We finally studied the sensitivities to diagonal parameters $\epsilon_m^{ee}$, $\epsilon_m^{\mu\mu}$ and $\epsilon_m^{\tau\tau}$. Since one may subtract any number from the diagonal parameters without affecting the oscillation probabilities, it is only possible to probe the diagonal parameters through their relative differences. In this work, we parameterize matter NSI effects in terms of $(\epsilon_m^{ee} - \epsilon_m^{\tau\tau})$ and $(\epsilon_m^{\mu\mu} - \epsilon_m^{\tau\tau})$, which are both real and relatively unconstrained [54, 58]. Within 1 σ C.L. interval, T2HK setup yields the least constraining sensitivity to $\epsilon_m^{ee} - \epsilon_m^{\tau\tau}$ while searches with PROMPT and DUNE configurations return similar sensitivities. Constraints on $\epsilon_m^{ee} - \epsilon_m^{\tau\tau}$ are found to be [-2.21, 2.29], [-0.29, 0.26] and [-0.34, 0.27] at 90% C.L. for T2HK, PROMPT and DUNE, respectively. In case of $\epsilon_m^{\mu\mu} - \epsilon_m^{\tau\tau}$, the most stringent constraint is obtained from DUNE while PROMPT and T2HK respectively bring next-best sensitivities with [-}
0.11, 0.12], [-0.19, 0.16] and [-0.34, 0.27]. The \( \nu_\tau \) sample collected in PROMPT bears no significant effect on the sensitivities to \( \epsilon^m_{\mu\tau} - \epsilon^m_{\tau\tau} \) or \( \epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau} \).

We find altogether very promising prospects for PROMPT setup in the search for NSI effects in neutrino propagation. The inclusion of tau neutrinos in the statistical analysis of PROMPT allows to reach notably higher sensitivity to matter NSI parameter \( \epsilon^m_{\mu\tau} \) compared to the alternative where \( \nu_\tau \) events were not studied. Sensitivity to \( \epsilon^m_{\mu\tau} \) could furthermore be elevated by increasing the \( \nu_\tau \) statistics, though this is limited by the relatively low efficiency in \( \nu_\tau \) reconstruction in known detector technologies.

6 Summary

In this work, we investigate the feasibility of building a next-generation accelerator-based neutrino beam experiment in China. We presented a survey of five accelerator laboratories and two underground laboratories capable of hosting neutrino beam and detector facilities. The suitability of the considered facilities were studied by their geological location in long-baseline neutrino oscillation physics. The study presented in this work focuses on three aspects of neutrino oscillations: (1) CP violation and precision measurement of Dirac \( CP \) phase, (2) precision measurement of the oscillation parameters \( \theta_{23} \) and \( \Delta m^2_{31} \), (3) unitarity of the Pontecorvo-Maki-Nakagawa-Sakata matrix and (4) sensitivity to non-standard interactions (NSIs) in neutrino sector.

In the center of our work is the design of future accelerator neutrino experiment that could be realized in China. Focusing on long-baseline neutrino oscillations, we presented a comparative study of the available baseline lengths. For the neutrino beam, we studied the well-established neutrino factory design where intense beams of neutrinos and antineutrinos are produced via muon decay. We considered neutrino beams with various parent muon energies and baseline lengths. Our results show configurations with baseline lengths 1000–1400 km provide favourable conditions for nearly all measurement goals. Three of the considered laboratory pairs (Nanjing\( \rightarrow \)JUNO, CiADS\( \rightarrow \)CJPL and CSNS\( \rightarrow \)CJPL) fall into this category. Exceptions are found with the non-unitarity parameter \( \alpha_{32} \) and non-standard interaction parameter \( \epsilon^m_{\mu\tau} \) where baseline length 1500–1800 km are more favourable. Three configurations (Nanjing\( \rightarrow \)CJPL, SPPC\( \rightarrow \)CJPL and CAS-IMP\( \rightarrow \)JUNO) belong to the latter category.

As a concrete example of what could be a future accelerator neutrino experiment in China, we present case study on a configuration where a neutrino beam is generated at the SPPC injector and received at a neutrino detector facility in CJPL. The baseline length of this configuration is 1736 km\(^{12} \). In the accelerator, we study a muon-decay-based neutrino beam similar to neutrino factory with parent energy 25 GeV. For the neutrino detector, we consider a hybrid detector based on magnetized iron and emulsion cloud chamber technologies with 50 kt fiducial mass. A comparison of projections are presented for PROMPT and the next-generation superbeam experiments T2HK and DUNE in table 5, which shows notable improvements in PROMPT both in precision measurement of standard oscillation

\(^{12}\)The exact location of the CEPC and SPPC facilities is still under active consideration. In the present work, we assume the accelerator complex to be located in the wider Beijing area.
Table 5: The allowed values of the non-unitarity parameters $\alpha_{ij}$ and matter NSI parameters $\epsilon_{m}^{\ell\ell'}$ in the DUNE, T2HK and PROMPT configurations. Also shown is the precision on standard oscillation parameters $\delta_{CP}$, $\theta_{23}$ and $\Delta m_{31}^2$. All sensitivities are provided at 90% confidence level assuming normally ordered neutrino masses. Beam powers are expressed as annual protons on target (POT) for pion-decay and useful muon decays for muon-decay beams.

| Parameter                  | DUNE   | T2HK   | PROMPT |
|----------------------------|--------|--------|--------|
| $\theta_{23}$ precision    | 2.6%   | 2.2%   | 1.6%   |
| $\delta_{CP}$ precision    | 9.2%   | 7.0%   | 4.9%   |
| $\Delta m_{31}^2$ precision| 0.40%  | 0.18%  | 0.43%  |
| $\alpha_{11}$              | [0.96, 1.04] | [0.96, 1.04] | [0.96, 1.04] |
| $\alpha_{22}$              | [0.98, 1.02] | [0.98, 1.02] | [0.98, 1.02] |
| $\alpha_{33}$              | [0.98, 1.02] | [0.98, 1.02] | [0.98, 1.02] |
| $|\alpha_{21}|$             | [0.00, 0.62] | [0.00, 0.62] | [0.00, 0.31] |
| $|\alpha_{31}|$             | [0.00, 0.62] | [0.00, 0.62] | [0.00, 0.37] |
| $|\alpha_{32}|$             | [0.00, 0.029] | [0.00, 0.029] | [0.00, 0.07] |
| $\epsilon_{ee}^{m} - \epsilon_{\tau\tau}^{m}$ | [-0.34, 0.27] | [-2.21, 2.29] | [-0.29, 0.26] |
| $\epsilon_{\mu\mu}^{m} - \epsilon_{\tau\tau}^{m}$ | [-0.11, 0.12] | [-0.35, 0.35] | [-0.19, 0.16] |
| $|\epsilon_{\tau\mu}|$    | [0, 0.04]  | [0, 0.16]  | [0, 0.02]  |
| $|\epsilon_{\tau\tau}|$   | [0, 0.10]  | [0, 0.40]  | [0, 0.03]  |
| $|\epsilon_{\mu\tau}|$    | [0, 0.17]  | [0, 0.053] | [0, 0.11]  |
| Production method           | pion decay | pion decay | muon decay |
| Beam power [year$^{-1}$]    | $8.82 \times 10^{21}$ POT | $2.7 \times 10^{22}$ POT | $2.5 \times 10^{20}$ $\mu$ decays |
| Energy range [GeV]          | 0.5–8    | 0.1–1.2 | 1–25 |
| Baseline length [km]        | 1300     | 295     | 1736 |
| Target material             | liquid argon | ultra-pure water | magnetized iron and emulsion hybrid |
| Detector size [kton]        | 40       | 187(374) | 50   |
| Reference                   | Ref. [18] | Ref. [16] | this work |

parameters and in sensitivities to new physics parameters. We note that the sensitivity to tau neutrino appearance channel $\nu_e \to \nu_\tau$ in PROMPT results in an enhanced sensitivity to $\epsilon_{ee}^{m}$, $\alpha_{31}$ and $\alpha_{32}$ but its effect is negligible in other measurements. The inclusion of $\nu_\tau$ sample has good prospects in new physics searches, though the improvement is limited.
by the relatively low statistics. It is necessary for neutrino detectors beyond the current
generation to increase efficiency of $\nu_\tau$ identification in order to reach higher sensitivities.

We have studied the prospects and requirements of a future accelerator neutrino ex-
periment in China. Our survey reveals a very promising landscape for future neutrino
beam and detector facilities thanks to the growing research infrastructure. Our case study
on PROMPT serves as a concrete example of the prospects of a future accelerator-driven
neutrino beam experiment.

Acknowledgments

SV thanks Pedro Pasquini for helpful discussions on non-unitary neutrino mixing. The au-
thors were supported supported in part by National Natural Science Foundation of China
under Grant No. 12075326 and No. 11881240247, by Guangdong Basic and Applied Basic
Research Foundation under Grant No. 2019A1515012216. SV was also supported by
China Postdoctoral Science Foundation under Grant No.2020M672930. JT acknowledges
the support from the CAS Center for Excellence in Particle Physics (CCEPP).

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