

Antielectron neutrinos at high-energy neutrino experiments: Identification strategies and physics potential

Felix Kling^{1,2}, Toni Mäkelä¹, and Josh McFayden³

¹*Department of Physics and Astronomy, University of California, Irvine, California 92697 USA*

²*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

³*Department of Physics and Astronomy, University of Sussex, Sussex House, Falmer, Brighton, BN1 9RH, United Kingdom*



(Received 2 July 2025; accepted 5 January 2026; published 27 January 2026)

Most existing and proposed high-energy neutrino experiments have excellent muon charge identification capabilities, enabling the distinction of ν_μ and $\bar{\nu}_\mu$ charged current interactions. In contrast, distinguishing electrons and positrons from ν_e and $\bar{\nu}_e$ interactions is typically impossible, as they quickly interact within the characteristically dense detector material and fail to reach the spectrometer. In this letter, we propose a compact and cost-effective plastic target, placed right before the spectrometer, to maximize the rate of electrons and positrons that reach the spectrometer before interacting. We demonstrate that, when installed at the FASER experiment, the Forward Physics Facility, or SHiP, this setup could enable the first separate measurement of ν_e and $\bar{\nu}_e$ cross sections at high energy. Additionally, this setup opens new opportunities to study forward particle production at collider neutrino experiments, such as constraining forward Λ hyperon production, and, by reducing flux uncertainties, significantly improve limits on nonstandard neutrino interactions in neutral currents.

DOI: [10.1103/9757-h3f6](https://doi.org/10.1103/9757-h3f6)

I. INTRODUCTION

For decades, high-energy neutrino interactions have served as a sensitive probe of fundamental physics, for example, to measure neutrino cross sections, constrain proton structure, and search for signs of new physics. In the past, such measurements were performed by accelerator-based neutrino experiments, such as CHARM [1] or NuTeV [2], which have probed neutrinos with energies up to several hundred GeV. This program will be continued by the planned SHiP experiment [3].

More recently, new experiments began probing neutrinos with up to multi-TeV energies produced at the Large Hadron Collider (LHC) [4]. In spring 2023, FASER Collaboration [5] reported the first observation of collider neutrino interactions, which was confirmed shortly after by SND@LHC Collaboration [6]. Since then, FASER has performed the first measurements of neutrino cross sections and fluxes [7,8], marking the beginning of a new field of collider neutrino physics. Both experiments plan to continue operations during LHC Run 4 with upgraded detectors [9,10]. Additional collider neutrino detectors with

significantly increased target mass have also been proposed in the context of the Forward Physics Facility (FPF) [11–14] as well as on the surface exit points of the LHC neutrino beam [15,16].

With several new and upgraded high-energy neutrino experiments set to begin operations in the 2030s, it is crucial to explore ways to maximize their physics potential. In this letter, we propose a small plastic target to be placed just before the spectrometer of the planned detectors, enabling the distinction of electron neutrino and antineutrino interactions. As we will demonstrate below, this addition will allow separate measurements of their cross sections at high energies for the first time, provide novel constraints in forward particle production, and enhance the sensitivity of searches for neutrino nonstandard interactions (NSIs).

II. DETECTOR CONCEPT

The existing FASER experiment [17–21] as well as the proposed FASER ν 2 and FLArE detectors at the FPF, and the neutrino detector at SHiP, are expected to see a large number of electron, muon, and tau neutrino charged current (CC) interactions. All these detectors have excellent charge identification capabilities for the muons from ν_μ and $\bar{\nu}_\mu$ CC interactions, passing through an empty magnetized spectrometer located behind the target volume. However, the distinction of electrons and positrons from ν_e and $\bar{\nu}_e$ CC

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

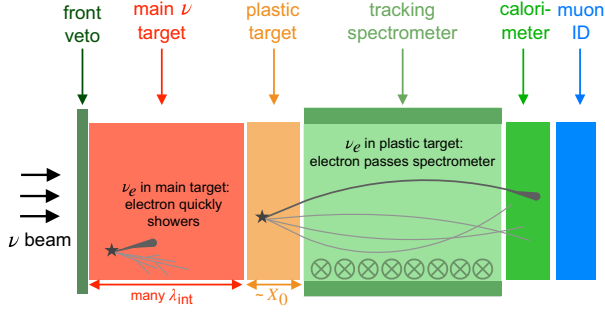


FIG. 1. Schematic of the setup, illustrating the position of the proposed plastic target and the path of the electrons and positrons through the experiment.

interactions is nearly impossible, as the $e^\pm$ interact very quickly within the dense target material, thereby evading charge identification in the spectrometer.

The exception are electron neutrinos interacting in the last radiation length X_0 of the target before the spectrometer—a feature that we aim to exploit by optimizing the corresponding target. The rate of such electron neutrino interactions with escaping electrons is proportional to $\rho X_0[1 - \exp(-L/X_0)]$, with the target's length L and density ρ . The product ρX_0 is maximized for materials with low atomic numbers Z . Restricting ourselves to solid and nonhazardous materials, the most suitable materials are graphite and plastic. We note that a plastic target has the additional advantage that it can be used as an active scintillator, providing additional information on the vertex position and deposited energy.

The term $1 - \exp(-L/X_0)$ is close to being maximized for $L \sim X_0$, corresponding to target lengths of 20 and 40 cm for graphite and plastic, respectively. This coincides with the space available at the current FASER location, without excessive compromise on the size of the main neutrino target. In the following, we therefore consider the addition of a 20-cm-thick plastic target in front of the existing FASER spectrometer. We also consider a 20-cm-thick target for FASER2 and SHiP. However, spatial constraints are significantly relaxed at these locations, allowing for the possibility of deeper detectors to increase event statistics. A schematic experimental setup is illustrated in Fig. 1 using the example of the FASER experiment. The information of the tracker and recently installed high-granularity pre-shower detector [22] and muon system then allow to reliably identify the electron track and measure its charge and momentum.

The considered target masses of the experiment's main detector and the proposed plastic targets, along with the expected number of electron neutrino interactions for all detectors, are summarized in Table I. This estimate is based on the flux predictions presented in Refs. [23–25] for the LHC and in Refs. [3,26] for SHiP. As we will see below, selection cuts are not expected to significantly reduce the observable event rate.

TABLE I. Target mass and expected number of electron neutrino interactions in FASER with 680 fb^{-1} , the FPF with 3 ab^{-1} , and SHiP with 6×10^{20} protons on target.

	Main detector		Plastic target		
	Mass (ton)	$\nu_e + \bar{\nu}_e$	Mass (kg)	ν_e	$\bar{\nu}_e$
FASER	1.2	4.9k	6.5	21	11
FPF	20	210k	600	1120	525
SHiP	3	3.3M	33	30k	6.6k

III. SIGNAL IDENTIFICATION

To illustrate the feasibility of separate ν_e and $\bar{\nu}_e$ measurements with the proposed detector design, we perform a simulation to study signal identification and background rejection. For concreteness, we consider a 20-cm-thick plastic target at the FPF, but note that the same arguments also apply for FASER and SHiP.

In order to consider the efficiency of identifying the ν_e CC signal from the background ν_μ CC and neutral current (NC) events at FASER2, a sample containing ν_e CC and $\bar{\nu}_e$ CC signal events and ν_μ CC and NC background events is generated using PYTHIA8 [27]. To simulate the electromagnetic (EM) showers in the plastic detector, the photons and $e^\pm$ in the generated sample are subjected to a showering algorithm accounting for $\gamma \rightarrow e^+e^-$ pair production following Ref. [28], while the generation of additional photons in $e^\pm \rightarrow e^\pm + \gamma$ bremsstrahlung is implemented following Refs. [29,30], accounting for the Landau-Migdal-Pomeranchuk effect [31–33] and avoiding the $x=0$ singularity of the bremsstrahlung cross section in Ref. [28]. The algorithm is recursively applied on the additional photons and $e^\pm$, until the energy of the produced particles becomes negligible or the shower reaches the end of the detector volume. The implementation of the procession of the EM shower through the detector is inspired by Ref. [34].¹ The inverse of the mean free path (MFP) for a particle of energy E , interacting via a process with a differential cross section $d\sigma/dx$, reads

$$\lambda^{-1}(E) = \frac{1}{X_0} \int_0^1 \frac{d\sigma(E)}{dx} dx. \quad (1)$$

For pair production, this yields $\lambda \approx 9/7X_0$, as expected. For bremsstrahlung, however, the MFP is significantly below X_0 . This determines the length scale required in sampling a longitudinal step size from the exponential distribution. Transverse smearing is added by sampling a squared

¹Reference [34] uses a different integration variable W , covering all energies from a low- E cutoff to the energy of the radiated photon. Here, dx is used instead of dW , but any factors introduced by the change of variables cancel, while the integration limits become from 0 to 1, and the normalization is taken to be the radiation length.

TABLE II. Event statistics after simple physics-motivated cuts that could be used for a cut and count analysis to distinguish the signal ν_e CC events from the background ν_μ CC and NC events. The numbers of events of each category classified as signal events in the BDT analysis are shown for comparison. The BDT preserves the signal well across all energies, at the expense of retaining more NC events than the final cuts in the cut and count analysis, which also remove signal events. See the text for details.

Cut	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	NC
No cuts	1120	525	8298	243
$E_\mu < 20$ GeV	1111	520	34	235
$E_{\text{EM}}/E_{\text{Tot}} > 40\%$	984	490	22	144
$E_{e^\pm}/E_{\text{EM}} > 25\%$	856	434	15	73
$E_{e^\pm} > 100$ GeV	612	332	1	19
BDT	1075	515	13	112

transverse momentum for the produced particles according to $p_T^2 = b((1 + p_{T,\text{max}}^2/b)^u - 1)$, which essentially inverts the cumulative distribution function of $1/(p_T^2 + b)$. Here, $u \in \text{Uniform}[0, 1]$, $p_{T,\text{max}} = xE\theta_{\text{max}}$, and $b = x^2 m_e^2$ ($b = m_e^2$) for bremsstrahlung (pair production), with $\theta_{\text{max}} = 0.1$ based on the small angle approximation being good for angles below 0.1 rad.

We assume that the detector has good capabilities for measuring the EM energy E_{EM} arising from photons and $e^\pm$, the energy of all visible particles E_{Tot} , as well as the energies of the most energetic muons and electrons, E_μ and $E_{e^\pm}$, respectively, as well as their charge. To contribute to these observables, charged particles are required to have energies above 20 GeV in order to pass through the whole spectrometer.

Using the above observables and the simple physics-motivated cuts listed in Table II allows a good separation of the signal and SM backgrounds already in a cut and count analysis. Over 99% of all ν_μ CC backgrounds are removed with minimal effect to the signal by demanding that there are no muons with energies above 20 GeV. After this, it remains to distinguish ν_e CC events from NC events producing electrons. Demanding that the E_{EM} in the event is above 40% of the energy of all visible particles in the event removes 40% of NC events. Requiring the highest electron or positron energies to be above 25% of the EM energy removes another 50% of the remaining NC event, particularly those occurring in the back of the detector. The majority of the remaining backgrounds are removed by restricting to events with an electron or positron of at least 100 GeV, which, however, also annuls all signal events in the $\mathcal{O}(10 \text{ GeV})$ range.

The signal identification performance is assessed by considering the sample purity P , defined as the ratio of $\nu_e + \bar{\nu}_e$ signal events to all signal and background events, the charge identification success rate C , defined as the ratio of neutrino- and antineutrino-induced events labeled correctly as ν_e CC or $\bar{\nu}_e$ CC events vs all signal events surviving

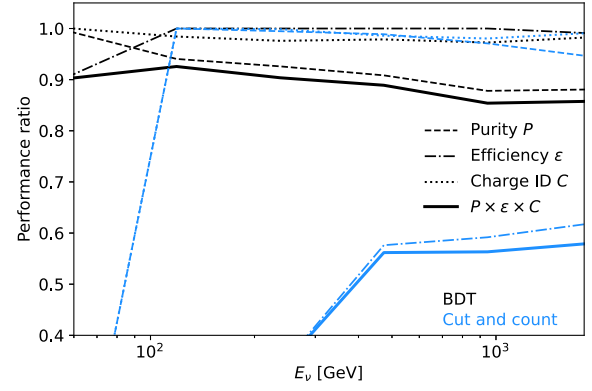


FIG. 2. The energy dependence of the detector performance metrics for a 20 cm detector. The result of the BDT analysis (black) is contrasted with the result of a simple cut and count analysis (blue).

the cuts, and efficiency ϵ , defined as the fraction of signal events after and before the cuts. In the cut and count analysis, events are classified as originating from ν_e or $\bar{\nu}_e$ depending on the sign of the most energetic $e^\pm$, and a sample purity above 90% and near-perfect charge identification can be achieved, retaining more than 50% of the signal events with E_ν above a few hundred GeV, as illustrated in Fig. 2.

The signal acceptance and background rejection can be improved further by an optimized multivariate analysis considering additional correlations between the observables. To this end, the observables listed above are passed as features to the boosted decision tree (BDT) implemented in the SCIKIT-LEARN package [35], tasked with classifying events in the generated sample into ν_e CC, $\bar{\nu}_e$ CC, ν_μ CC, and NC categories. Besides the observables utilized in the cut and count analysis, the BDT is passed with the following additional features: the neutrino interaction vertex position achievable via a longitudinally segmented plastic target, the energy of all charged tracks E_{Ch} , the total charge of $e^\pm$ with energies above 100 GeV, the leading $e^\pm$ angle with respect to the line of sight, as well as the standard deviation and maximum of the angles of all EM tracks from the leading $e^\pm$, characterizing the spread of the EM shower. This results in an excellent performance, with the product of the sample purity, charge identification rate, and efficiency, $P \times C \times \epsilon$ around 90% in the $E_\nu \sim \mathcal{O}(100 \text{ GeV})$ range, as shown in Fig. 2.

If additional space is available, a deeper plastic target can be considered for increasing event statistics. In the following, we consider the performance metrics in terms of the longitudinal vertex location to estimate an optimal target depth. Figure 3 illustrates the number of events passing the BDT selection cuts and the associated BDT charge identification success rate as a function of the vertex z position. While increasing the detector depth will in general increase statistics, the performance metrics decrease with increasing

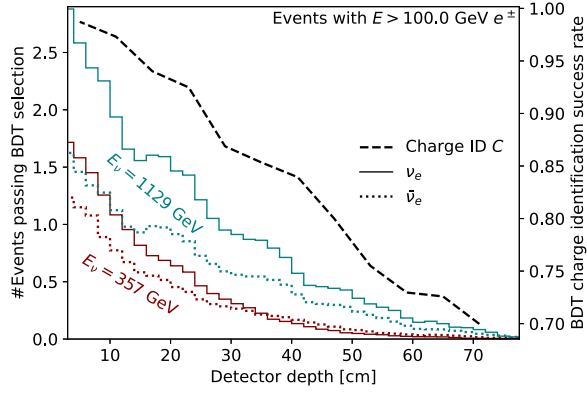


FIG. 3. The events passing the BDT selection criteria and containing an electron of $E_e > 100$ GeV, originating at a given depth in the detector, for neutrino energies of 357 GeV (brown) and 1129 GeV (teal). The solid (dashed) lines correspond to ν_e CC ($\bar{\nu}_e$ CC) events, and the numbers of events originating at a given depth are given on the left vertical axis. Detectors deeper than 50 cm add no significant contributions to the number of signal events with a high-energy electron. The black dashed line indicates the BDT charge identification success rate, with values given on the right vertical axis.

z such that detector depths exceeding about 50 cm bring no significant additions to the signal. Therefore, if space and longitudinal segmentation are available, a detector depth corresponding to X_0 could be considered for increasing statistics, but deeper targets will provide diminishing returns.

Finally, neutrino energy resolution is estimated by performing a regression BDT analysis, using the same observables as features as in the BDT analysis discussed above. This time, the BDT is trained to reconstruct the incoming neutrino energies in events classified as ν_e CC or $\bar{\nu}_e$ CC. As a result, a linear dependence between the reconstructed and true E_ν is observed, with a relative standard error of $\delta E_\nu/E_\nu < 30\%$ for the reconstruction.

IV. NEUTRINO CROSS SECTIONS

Although the number of total events in this plastic target is far below that of the main neutrino targets, it offers several novel measurement opportunities. This includes the separate measurement of the ν_e and $\bar{\nu}_e$ interaction cross section as well as their fluxes. We note that this detector alone will only constrain a combination of neutrino flux and the interaction cross section. However, this degeneracy can be broken using external input: prior knowledge on one quantity allows us to interpret the data in terms of the other.

Our first example is the separate measurement of the ν_e and $\bar{\nu}_e$ interaction cross section. While separate cross section measurements have been performed for muon neutrinos and antineutrinos by a large number of experiments, mainly combined measurements are available for

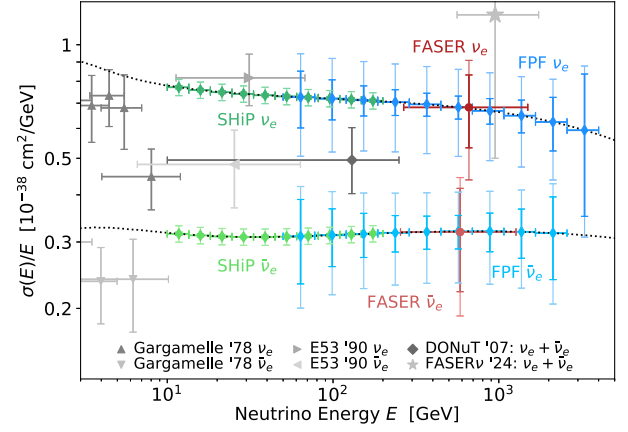


FIG. 4. Predicted precision of the neutrino-nucleon cross sections for ν_e and $\bar{\nu}_e$, normalized to the neutrino energy, using a plastic target at FASER, the FPF, and SHiP. We also show previous measurements performed at Gargamelle [37], E53 [38], DONuT [36], and FASERν [8]. The dotted line shows the predicted cross section obtained using the Bodek-Yang model [42], as implemented in GENIE [43,44]. See the text for details.

high-energy electron neutrinos and antineutrinos, as performed by DONuT [36] and FASERν [8]. Separate measurements at low energies have been performed using the bubble chamber experiments Gargamelle [37] and E53 [38], partially using separate neutrino- and antineutrino-dominated beams.

In Fig. 4, we present the projected sensitivity to separately measure the ν_e and $\bar{\nu}_e$ cross sections using a plastic target at FASER, the FPF, and SHiP. The inner (thicker) error bars indicate the expected statistical precision, corresponding to uncertainties of approximately 25%, 10%, and 1% per bin at FASER, the FPF, and SHiP, respectively. The outer (thinner) error bars include an approximate estimate of the flux uncertainties. At SHiP, the neutrino flux is predominantly produced in the decays of charmed hadrons. Their production rate has been constrained by the NA27 experiment with a precision of about 20% [39], and the ongoing NA65 experiment is expected to further reduce this uncertainty to a few percent [40]. For illustration, we therefore assume a 5% flux uncertainty for SHiP in Fig. 4. At the LHC, the neutrino flux uncertainty is primarily driven by the modeling of forward hadron production in hadronic interaction models at collider energies. Current state-of-the-art frameworks, such as EPOS, QGSJET, and SIBYLL, still exhibit sizable differences at the level of about 25% [25]. A comparable uncertainty was also obtained from tuning variations in Pythia in Ref. [41]. A concerted community effort to improve hadronic interaction modeling is ongoing and is expected to further reduce these uncertainties by the time such measurements are performed.

V. FORWARD HYPERON PRODUCTION

The LHC neutrino beam is mainly generated via the decays of forward charged pions, kaons, charm hadrons, and hyperons. The production of these particles in the forward region at LHC energies has not been measured before. Thus, collider neutrino flux measurements offer unique constraints on forward particle production, complementing measurements of π^0 , η , and neutron production by the LHCf [45–47]. These data are crucial for improving and validating hadronic interaction models, which are particularly important in astroparticle physics to model particle production in extreme astrophysical environments and describe cosmic ray interactions in the Earth’s atmosphere.

At the highest rapidities, electron neutrinos and anti-neutrinos primarily originate from kaons and hyperons at energies $E_\nu < \text{TeV}$, as well as charm hadrons at higher energies. As discussed in Ref. [23], the fluxes of ν_e and $\bar{\nu}_e$ are not equal, which is a consequence of the net charge and baryon number of the proton-proton collision system. This leads, for example, to a strongly enhanced production of forward Λ baryons compared to a negligible rate of $\bar{\Lambda}$ antibaryons, and hence induces an enhancement of $\bar{\nu}_e$ neutrino flux via the decay $\Lambda \rightarrow p e^- \bar{\nu}_e$.

This feature enables a novel measurement of forward Λ production. First, note that the production of charged kaons, and the resulting ν_e and $\bar{\nu}_e$ flux from their decays, can be tightly constrained using ν_μ and $\bar{\nu}_\mu$ flux measurements at the main target of the collider neutrino experiment. The remaining, unconstrained component of the flux then primarily originates from K^0 and Λ decays. Since K^0 decays produce ν_e and $\bar{\nu}_e$ symmetrically, while Λ decays yield only $\bar{\nu}_e$, any $\bar{\nu}_e - \nu_e$ flux asymmetry observed using the plastic target can be attributed to Λ decays.

This is illustrated in Fig. 5, which shows the ν_e and $\bar{\nu}_e$ fluxes, along with their sum and difference, at FASER and the FPF, as estimated using SIBYLL 2.3d [48] and POWHEG+Pythia [24]. At the FPF, we only consider the rapidity region $\eta > 8.7$, since the Λ component decreases for lower rapidities. We can see that the $\bar{\nu}_e - \nu_e$ flux difference (black dashed) is indeed a good estimator of the flux of neutrinos from Λ decays (red solid), hence confirming the conceptual argument. The estimated precision at which the neutrino flux from Λ decays is shown via the error bars. Here, we assume SM neutrino scattering cross sections which are constrained at the few percent level, with the uncertainties arising predominantly from the parton distribution functions. While a first measurement, statistically limited, is possible at FASER in Run 4, a differential analysis becomes feasible at the FPF.

VI. NEUTRINO NONSTANDARD INTERACTIONS

The ability of ν_e and $\bar{\nu}_e$ separation via the plastic target will also contribute to reducing systematic uncertainties in measurements performed with the main targets of collider

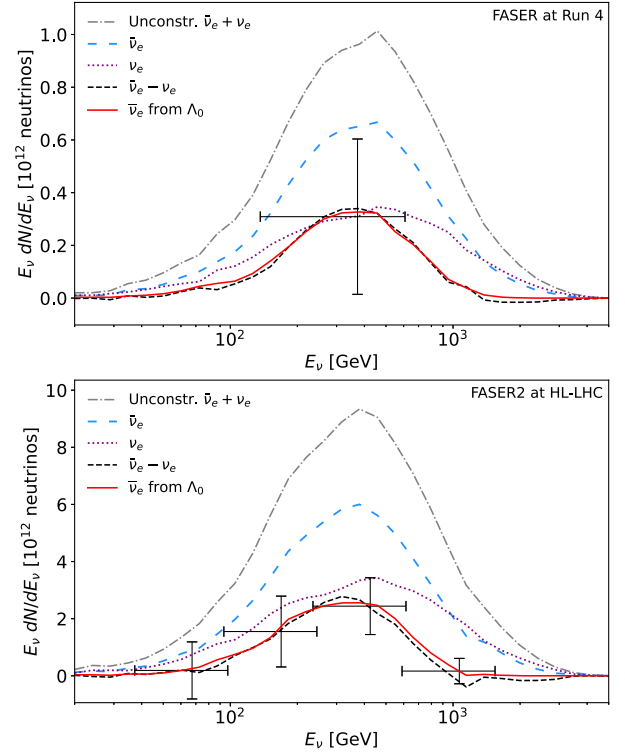


FIG. 5. Flux of ν_e , $\bar{\nu}_e$, their sum, and their difference, originating from the unconstrained K^0 , Λ , and charm hadrons passing through the plastic target at FASER and the FPF. The neutrino flux from Λ decays is shown for comparison. The error bars depict the expected precision of its measurement, as inferred from the statistical uncertainties in the number of ν_e and $\bar{\nu}_e$ CC interaction events in the plastic target.

neutrino detectors. We demonstrate this by considering a measurement of neutrino NSIs, which are parametrized by dimension-6 effective field theory operators

$$\mathcal{L} = -\sqrt{2}G_F[\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta][\epsilon_{\alpha\beta}^{qV}\bar{q}\gamma_\mu q + \epsilon_{\alpha\beta}^{qA}\bar{q}\gamma_\mu\gamma^5 q].$$

Here, G_F is the Fermi constant and $\epsilon_{\alpha\beta}^{q,V/A}$ are Wilson coefficients for operators modifying the (axial) vector coupling between neutrinos and a quark q . Alternatively, one can consider the operators affecting the left- and right-handed couplings by writing the $\epsilon_{\alpha\beta}^{qV/A}$ in terms of $\epsilon_{\alpha\beta}^{qL/R}$.

The presence of such NSIs modify the rate of NC interactions, which can be measured with high statistics in the main targets. Conceptually, one can use the CC interaction rate measurement to constrain the incoming neutrino flux and then search for deviations in the NC interaction rate due to NSIs. For illustration, we focus on NSIs affecting muon neutrinos, which are most abundant at colliders and whose flux will be well constrained. However, since neutrino flavors are indistinguishable in NC events, uncertainties in the ν_e and $\bar{\nu}_e$ fluxes will propagate into the NC rate measurement and weaken the sensitivity to NSIs.

To quantify this effect, we use simulated data to derive projected 95% confidence level bounds on the NSI Wilson coefficients. We perform a binned χ^2 analysis based on the reconstructed neutrino energy distribution, incorporating both statistical and systematic uncertainties in each energy bin, added in quadrature. As a validation step, we reproduce the results of Ref. [49], which assumed only statistical uncertainties and included only muon (anti)neutrinos in the incoming flux. Our analysis generalizes this by accounting for all neutrino flavors contributing to the observed NC interactions and by including flux uncertainties.

The systematic uncertainties for the electron neutrino contribution are estimated for scenarios with and without input from a plastic target. While the total rate of $\nu_e + \bar{\nu}_e$ CC interactions is well constrained using measurements at the main target, the relative contributions from ν_e and $\bar{\nu}_e$ remain unconstrained. To conservatively parametrize the resulting flux uncertainty in the absence of a plastic target, we assume that the unconstrained part of the electron neutrino spectrum could originate entirely from either K^0 or Λ decays. The resulting variation on the predicted number of NC interactions defines the systematic uncertainty. If a plastic target is integrated into the experiment, the uncertainties of the electron neutrino flux and NC interaction rate can be reduced. We obtain an estimate by constraining the hyperon fraction to be consistent with the projected measurement, as discussed in the previous section.

The projected bounds on two Wilson coefficients, $\epsilon_{\mu\mu}^{dV}$ and $\epsilon_{\mu\mu}^{dA}$, are shown in Fig. 6, with all other NSI parameters assumed to vanish. Existing constraints were derived from a global fit to neutrino oscillation and COHERENT data [50], and from neutrino scattering measurements at the CHARM experiment [51] and the NuTeV experiment [52,53]. While the neutrino oscillation and COHERENT data are only sensitive to the vector coupling, but not axial counterparts, high-energy neutrino scattering experiments can probe the NSI regardless of the underlying spin structure. The constraints from NuTeV are particularly stringent due to the ability to perform separate ν and $\bar{\nu}$ measurements.

Even without the plastic target, measurements at the main targets already provide complementary constraints to the constraints from CHARM as well as neutrino oscillations and COHERENT. Incorporating the plastic target significantly improves sensitivity by reducing flux-related systematics. We note that the measurement remains limited by flux systematics, as demonstrated by the comparison to the contour assuming only statistical uncertainties. The same conclusions hold for measurements at the FPF.

The constraints from the NuTeV measurement [52] were, however, originally presented in terms of the left- and right-handed coefficients and varying both u and d quark coefficients simultaneously in Ref. [53]. The projected bounds for $\epsilon_{\mu\mu}^{dL}$ and $\epsilon_{\mu\mu}^{uL}$ at the FPF are shown in Fig. 7 and

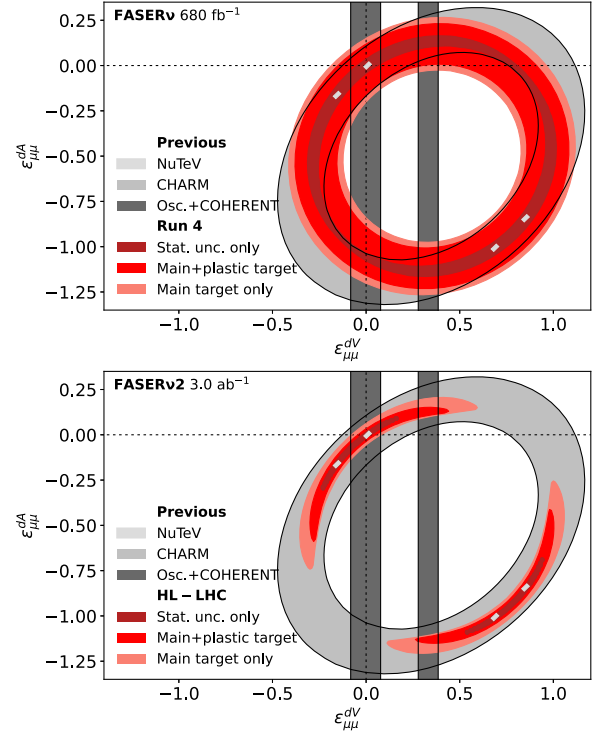


FIG. 6. The 95% CL bounds on the Wilson coefficients $\epsilon_{\mu\mu}^{dV}$ and $\epsilon_{\mu\mu}^{dA}$ at FASER (top) and at FASER2 (bottom) assuming flux uncertainties constrained by the main target (light red) as well as the main and plastic targets (red). The sensitivity considering only statistical uncertainties is shown for comparison (dark red). Previous constraints are shown in gray [50–53]. The intersection of the black dotted lines indicates the standard model point.

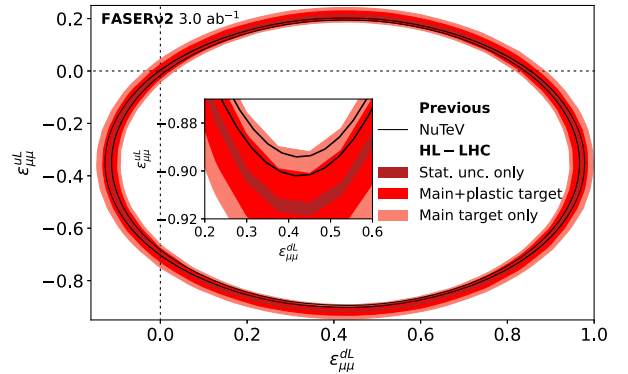


FIG. 7. The 95% CL bounds on the Wilson coefficients $\epsilon_{\mu\mu}^{dL}$ and $\epsilon_{\mu\mu}^{uL}$ at FASER2 assuming flux uncertainties constrained by the main target (light red) as well as the main and plastic targets (red). The sensitivity considering only statistical uncertainties is shown for comparison (dark red). The area between black ellipses is allowed by previous constraints from NuTeV [52,53]. The insert indicates a region where FASER2 can complement the stringent NuTeV results, if the plastic target is included. The black dotted lines intersect at the standard model point.

compared to the constraints from NuTeV. In this parameter space, there is a region where the FPF, with the proposed plastic scintillator included, may complement the NuTeV constraints due to the mildly different shapes of the elliptical constraint bands due to differences in the numbers of neutrons and protons in the target nuclei of the two experiments.

VII. CONCLUSIONS

The recently initiated forward neutrino program at the LHC has begun to provide the first observations and measurements, and the future is promising: both FASER and SND@LHC Collaborations will continue operations during the LHC Run 4, the SHiP experiment has been approved, and the proposed FPF is projected to yield an abundance of precision results for physics both within and beyond the standard model. In order to make the best use of this unique direction of LHC physics, it is important to consider how to develop the detection capabilities of these experiments even further.

In the present work, a small plastic target placed just before the spectrometer of the planned detectors is proposed, allowing the distinction of ν_e and $\bar{\nu}_e$ interactions. It would yield the first separate measurements of their cross sections at high energies, and help reduce the electron neutrino flux uncertainty. Furthermore, as the contribution of hyperons to the forward hadron flux can be understood through a measurement of the difference of the $\bar{\nu}_e$ and ν_e spectra, this allows constraining forward strangeness in the baryon sector, providing results that are useful also for the astrophysics community.

When installed at FASER or at the proposed FPF, the considered detector is demonstrated to reduce the

uncertainties in the electron neutrino flux and the spectrum of NC interactions, leading to enhanced sensitivity for neutrino NSIs in NC interactions. Hence, despite its simple and cost-effective design, the proposed detector can increase the physics potential of existing and proposed forward neutrino experiments at the LHC, SHiP, and potential future detectors at the LHC and beyond [54,55].

ACKNOWLEDGMENTS

We thank Jamie Boyd, Sebastian Trojanowski, and Max Fieg for useful discussions. We are grateful to the authors and maintainers of many open-source software packages, including RIVET [56,57], SCIKIT-HEP [58], and SCIKIT-LEARN [35]. The work of F.K. is supported in part by the Heising-Simons Foundation Grant 2020-1840, by the U.S. National Science Foundation Grants PHY-2210283 and PHY-2514888, and by the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy—EXC 2121 Quantum Universe—390833306. The work of T.M. is supported in part by U.S. National Science Foundation Grants PHY-2111427 and PHY-2210283 and the Heising-Simons Foundation Grant 2020-1840, and by the National Science Centre, Poland, Research Grant No. 2021/42/E/ST2/00031. The work of J.M. was supported by the Royal Society Grant URF/R1\201519 and STFC Grant ST/W000512/1.

DATA AVAILABILITY

The data that support the findings of this article are openly available [59].

-
- [1] A. N. Diddens *et al.* (CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration), A detector for neutral current interactions of high-energy neutrinos, *Nucl. Instrum. Methods* **178**, 27 (1980).
 - [2] T. Bolton, M. H. Shaevitz, S. R. Mishra, P. C. Rowson, W. G. Seligman, R. H. Bernstein, M. Lamm, M. Lamm, and F. Taylor (NuTeV Collaboration), Precision measurements of neutrino neutral current interactions using a sign-selected beam, Report No. FERMILAB-PROPOSAL-0815, 1990.
 - [3] C. Ahdida *et al.*, Post-LS3 experimental options in ECN3, *arXiv:2310.17726*.
 - [4] A. Ariga, J. Boyd, F. Kling, and A. De Roeck, Neutrino experiments at the large hadron collider, *Annu. Rev. Nucl. Part. Sci.* **75**, 57 (2025).
 - [5] H. Abreu *et al.* (FASER Collaboration), First direct observation of collider neutrinos with FASER at the LHC, *Phys. Rev. Lett.* **131**, 031801 (2023).
 - [6] R. Albanese *et al.* (SND@LHC Collaboration), Observation of collider muon neutrinos with the SND@LHC experiment, *Phys. Rev. Lett.* **131**, 031802 (2023).
 - [7] R. Mammen Abraham *et al.* (FASER Collaboration), First measurement of νe and $\nu\mu$ interaction cross sections at the LHC with FASER's emulsion detector, *Phys. Rev. Lett.* **133**, 021802 (2024).
 - [8] R. Mammen Abraham *et al.* (FASER Collaboration), First measurement of the muon neutrino interaction cross section and flux as a function of energy at the LHC with FASER, *Phys. Rev. Lett.* **134**, 211801 (2025).
 - [9] R. Mammen Abraham *et al.* (FASER Collaboration), Prospects and opportunities with an upgraded FASER neutrino detector during the HL-LHC era: Input to the EPPSU, *arXiv:2503.19775*.
 - [10] D. Abbaneo *et al.* (SND@LHC Collaboration), SND@HL-LHC, scattering and neutrino detector in run 4 of the LHC,

- Technical Reports No. CERN-LHCC-2025-004, No. LHCC-P-026, CERN, Geneva, 2025, <https://cds.cern.ch/record/2926288>.
- [11] L. A. Anchordoqui *et al.*, The forward physics facility: Sites, experiments, and physics potential, *Phys. Rep.* **968**, 1 (2022).
- [12] J. L. Feng *et al.*, The forward physics facility at the high-luminosity LHC, *J. Phys. G* **50**, 030501 (2023).
- [13] J. Adhikary *et al.*, Scientific program for the Forward Physics Facility, *Eur. Phys. J. C* **85**, 430 (2025).
- [14] L. A. Anchordoqui *et al.* (FPF Collaboration), Letter of intent: The forward physics facility, *arXiv:2510.26260*.
- [15] A. Ariga, S. Barwick, J. Boyd, M. Fieg, F. Kling, T. Mäkelä, C. Vendeuvre, and B. Weyer, Detecting LHC neutrinos at surface level, *J. High Energy Phys.* **07** (2025) 270.
- [16] N. W. Kamp, C. A. Argüelles, A. Karle, J. Thomas, and T. Yuan, Lake- and surface-based detectors for forward neutrino physics, *arXiv:2501.08278*.
- [17] A. Ariga *et al.* (FASER Collaboration), Letter of intent for FASER: Forward search experiment at the LHC, *arXiv:1811.10243*.
- [18] A. Ariga *et al.* (FASER Collaboration), Technical proposal for FASER: Forward search experiment at the LHC, *arXiv:1812.09139*.
- [19] H. Abreu *et al.* (FASER Collaboration), Detecting and studying high-energy collider neutrinos with FASER at the LHC, *Eur. Phys. J. C* **80**, 61 (2020).
- [20] H. Abreu *et al.* (FASER Collaboration), Technical proposal: FASERnu, *arXiv:2001.03073*.
- [21] H. Abreu *et al.* (FASER Collaboration), The FASER detector, *J. Instrum.* **19**, P05066 (2024).
- [22] J. Boyd, The FASER W-Si high precision preshower technical proposal, Technical Reports No. CERN-LHCC-2022-006, No. LHCC-P-023, CERN, Geneva, 2022, <https://cds.cern.ch/record/2803084>.
- [23] F. Kling and L. J. Nevay, Forward neutrino fluxes at the LHC, *Phys. Rev. D* **104**, 113008 (2021).
- [24] L. Buonocore, F. Kling, L. Rottoli, and J. Sominka, Predictions for neutrinos and new physics from forward heavy hadron production at the LHC, *Eur. Phys. J. C* **84**, 363 (2024).
- [25] R. Mammen Abraham *et al.* (FASER Collaboration), Neutrino rate predictions for FASER, *Phys. Rev. D* **110**, 012009 (2024).
- [26] R. Albanese *et al.* (SHiP Collaboration), BDF/SHiP at the ECN3 high-intensity beam facility, Technical Reports No. CERN-SPSC-2023-033, No. SPSC-P-369, CERN, Geneva, 2023, <https://cds.cern.ch/record/2878604>.
- [27] C. Bierlich *et al.*, A comprehensive guide to the physics and usage of Pythia 8.3, *SciPost Phys. Codebases* **2022**, 8 (2022).
- [28] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [29] S. Klein, Suppression of Bremsstrahlung and pair production due to environmental factors, *Rev. Mod. Phys.* **71**, 1501 (1999).
- [30] T. Stanev, C. Vankov, R. E. Streitmatter, R. W. Ellsworth, and T. Bowen, Development of ultrahigh-energy electromagnetic cascades in water and lead including the Landau-Pomeranchuk-Migdal effect, *Phys. Rev. D* **25**, 1291 (1982).
- [31] L. D. Landau and I. Pomeranchuk, The limits of applicability of the theory of Bremsstrahlung by electrons and of the creation of pairs at large energies, *Dokl. Akad. Nauk SSSR* **92**, 586 (1953).
- [32] L. D. Landau and I. Pomeranchuk, Electron cascade process at very high-energies, *Dokl. Akad. Nauk Ser. Fiz.* **92**, 735 (1953).
- [33] A. B. Migdal, Bremsstrahlung and pair production in condensed media at high energies, *Phys. Rev.* **103**, 1811 (1956).
- [34] F. Salvat, *PENELOPE 2018: A Code System for Monte Carlo Simulation of Electron and Photon Transport* (OECD Publishing, Paris, 2019), https://www.oecd.org/en/publications/penelope-2018-a-code-system-for-monte-carlo-simulation-of-electron-and-photon-transport_32da5043-en.html.
- [35] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg *et al.*, Scikit-learn: Machine learning in Python, *J. Mach. Learn. Res.* **12**, 2825 (2011).
- [36] K. Kodama *et al.* (DONuT Collaboration), Final tau-neutrino results from the DONuT experiment, *Phys. Rev. D* **78**, 052002 (2008).
- [37] J. Blietschau *et al.* (Gargamelle Collaboration), Total cross-sections for electron-neutrino and anti-electron-neutrino interactions and search for neutrino oscillations and decay, *Nucl. Phys. B* **133**, 205 (1978).
- [38] C. Baltay *et al.* (E53 Collaboration), $\nu_\mu - \nu_e$ universality in charged current neutrino interactions, *Phys. Rev. D* **41**, 2653 (1990).
- [39] M. Aguilar-Benitez *et al.* (LEBC-EHS Collaboration), Charm hadron properties in 400-GeV/c p p interactions, *Z. Phys. C* **40**, 321 (1988).
- [40] S. Aoki *et al.* (DsTau Collaboration), DsTau: Study of tau neutrino production with 400 GeV protons from the CERN-SPS, *J. High Energy Phys.* **01** (2020) 033.
- [41] M. Fieg, F. Kling, H. Schulz, and T. Sjöstrand, Tuning Pythia for forward physics experiments, *Phys. Rev. D* **109**, 016010 (2024).
- [42] A. Bodek and U. K. Yang, Modeling deep inelastic cross-sections in the few GeV region, *Nucl. Phys. B, Proc. Suppl.* **112**, 70 (2002).
- [43] C. Andreopoulos *et al.*, The GENIE neutrino Monte Carlo generator, *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 87 (2010).
- [44] L. Alvarez-Ruso *et al.* (GENIE Collaboration), Recent highlights from GENIE v3, *Eur. Phys. J. Spec. Top.* **230**, 4449 (2021).
- [45] O. Adriani *et al.* (LHCf Collaboration), Measurement of forward photon production cross-section in proton-proton collisions at $\sqrt{s} = 13$ TeV with the LHCf detector, *Phys. Lett. B* **780**, 233 (2018).
- [46] O. Adriani *et al.* (LHCf Collaboration), Measurement of inclusive forward neutron production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV with the LHCf Arm2 detector, *J. High Energy Phys.* **11** (2018) 073.
- [47] G. Piparo *et al.*, Measurement of the forward η meson production rate in p-p collisions at $\sqrt{s} = 13$ TeV with the LHCf-Arm2 detector, *J. High Energy Phys.* **10** (2023) 169.

- [48] F. Riehn, R. Engel, A. Fedynitch, T.K. Gaisser, and T. Stanev, Hadronic interaction model Sibyll 2.3d and extensive air showers, *Phys. Rev. D* **102**, 063002 (2020).
- [49] A. Ismail, R. Mammen Abraham, and F. Kling, Neutral current neutrino interactions at FASER ν , *Phys. Rev. D* **103**, 056014 (2021).
- [50] P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, and M. Maltoni, Improved global fit to non-standard neutrino interactions using COHERENT energy and timing data, *J. High Energy Phys.* **02** (2020) 023; **12** (2020) 071(A).
- [51] J. V. Allaby *et al.* (CHARM Collaboration), A precise determination of the electroweak mixing angle from semileptonic neutrino scattering, *Z. Phys. C* **36**, 611 (1987).
- [52] G. P. Zeller *et al.* (NuTeV Collaboration), A precise determination of electroweak parameters in neutrino nucleon scattering, *Phys. Rev. Lett.* **88**, 091802 (2002); **90**, 239902(E) (2003).
- [53] S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria, Present and future bounds on nonstandard neutrino interactions, *J. High Energy Phys.* **03** (2003) 011.
- [54] R. Mammen Abraham, J. Adhikary, J. L. Feng, M. Fieg, F. Kling, J. Li, J. Pei, T. R. Rabemananjara, J. Rojo, and S. Trojanowski, FPF@FCC: Neutrino, QCD, and BSM physics opportunities with far-forward experiments at a 100 TeV proton collider, *J. High Energy Phys.* **01** (2025) 094.
- [55] C. Accettura *et al.* (International Muon Collider Collaboration), The muon collider, [arXiv:2504.21417](https://arxiv.org/abs/2504.21417).
- [56] A. Buckley, J. Butterworth, D. Grellscheid, H. Hoeth, L. Lonnblad, J. Monk, H. Schulz, and F. Siegert, Rivet user manual, *Comput. Phys. Commun.* **184**, 2803 (2013).
- [57] C. Bierlich *et al.*, Robust independent validation of experiment and theory: Rivet version 3, *SciPost Phys.* **8**, 026 (2020).
- [58] E. Rodrigues *et al.*, The Scikit HEP project—overview and prospects, *EPJ Web Conf.* **245**, 06028 (2020).
- [59] Toni Mäkelä and Felix Kling, Forward ν flux fit (2025), <https://github.com/makelat/forward-nu-flux-fit>.