

BEYOND THE STANDARD MODEL PHYSICS IN THE FAR-FORWARD REGION OF THE LARGE HADRON COLLIDER*

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*Received 30 April 2023, accepted 4 May 2023,
published online 6 September 2023*

A new physics program has been initiated as part of the ongoing LHC physics run in the far-forward region, where dedicated FASER and SND@LHC experiments are currently taking data. We discuss the possible discovery prospects of this program in the search for signatures of beyond the Standard Model physics. We focus on both the present period and the proposed future Forward Physics Facility (FPF) that will operate in the high luminosity LHC era.

DOI:10.5506/APhysPolBSupp.16.7-A17

1. Introduction

High-energy proton collisions at the Large Hadron Collider (LHC) have, without a doubt, brought us closer than ever to laboratory testing our understanding of very early periods in the evolution of the Universe. It has also been an excellent tool for a variety of studies complementing a theoretical picture of the Standard Model (SM), including measurements in its forward region [1]. However, the LHC experiments still need to achieve their maximum sensitivity. A large amount of data will be collected during Run 3 and in the future era of High-Luminosity LHC (HL-LHC). Up-to-date, the integrated luminosity delivered to the ATLAS and CMS experiments corresponds to only about 7.5% of the luminosity expected at the end of the HL-LHC era [2].

* Presented at the 29th Cracow Epiphany Conference on *Physics at the Electron-Ion Collider and Future Facilities*, Cracow, Poland, 16–19 January, 2023.

Given the expected long future operation of the LHC and the yet undetermined road ahead for next-generation colliders, it is also time to exploit the full discovery potential of the current machine. The far-forward region of the LHC has proven to be particularly fitting for such explorations. In particular, the new FASER [3–6] and SND@LHC [7, 8] experiments have recently started measuring high-energy neutrinos produced in pp collisions at the LHC. While this has long been discussed theoretically [9–13], a proof-of-principle experimental analysis by the FASER collaboration occurred only during the previous LHC Run 2 [14]. These capabilities have recently been confirmed using initial Run 3 data to report the first-ever observation of collider neutrinos with a statistical significance of 16 standard deviations [15]. By the end of the current operation, the ongoing experiments will measure $\mathcal{O}(10^4)$ high-energy neutrino events, including a few tens of tau neutrinos. Significantly, this relies on relatively small detectors with the active volume size of $\mathcal{O}(0.1\text{ m}^3)$. They allow detailed studies of neutrino interaction events at TeV energies at the precision level unattainable at large-scale neutrino facilities.

Measurements in the proposed Forward Physics Facility (FPF) to operate during the HL-LHC era would lead to increased event statistics of additional two orders of magnitude up to $\mathcal{O}(10^6)$ events. The FPF studies would have broad implications for our understanding of proton and nuclear structures and strong interactions, both via measuring the details of neutrino scatterings at different target nuclei and indirectly drawing conclusions about the forward production of parent mesons in pp collisions at the LHC [16, 17].

A broad experimental program in the LHC’s far-forward region also allows for studying physics beyond the Standard Model (BSM), *cf.* Fig. 1 for a schematic view. It includes searches for light new physics species with a

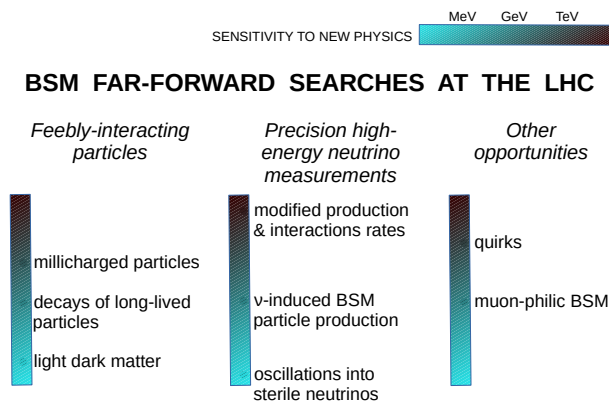


Fig. 1. A schematic view of the ongoing and proposed far-forward BSM physics searches at the LHC.

mass typically up to tens of GeV detected via their decays, scatterings, or ionization. Searches for even heavier BSM particles are possible in specific scenarios, while indirect probes reach a multi-TeV scale. In addition, the excellent capabilities of compact far-forward neutrino detectors introduce further opportunities to probe possible tiny deviations from pure SM interactions of neutrinos at energies up to a few TeV. The BSM physics can manifest itself in modified neutrino production rates and via oscillations. Below, we provide an overview of the BSM physics opportunities related to far-forward searches at the LHC, which summarizes a much more comprehensive discussion in Ref. [17] and mentions some of the most recent results.

We first briefly recap experimental aspects of the ongoing and proposed future research program in the far-forward region of the LHC. By far-forward experiments, we mean here detectors placed along the beam collision axis at substantial distances from the pp Interaction Point (IP) such that they remain well-shielded from most SM backgrounds related to proton interactions at the LHC. This shielding requires placing the detectors outside the main LHC tunnel after it curves away from the beam collision axis.

Two such experiments have been installed to take data during the ongoing LHC Run 3: FASER [3, 4] and SND@LHC [7, 8]. They are placed on both sides of the ATLAS IP at a distance about $L \simeq 480$ m away from it. The FASER detector is devoted to searching for postulated BSM light long-lived particles (LLPs) that decay visibly in an empty detector volume, as initially proposed in Refs. [13, 18–20], *cf.* also Ref. [21]. The charged particles (*e.g.*, e^+e^- pairs) produced in such decays travel through the FASER spectrometer and calorimeter for their measurement and identification. The FASER ν emulsion subdetector [5, 6] studies interactions of high-energy neutrinos. The emulsion detector technology and additional electronic components are also used in the SND@LHC experiment [7, 8]. The FASER detector is placed along the beam collision axis covering the pseudorapidity region of $\eta \gtrsim 9.1$ in the neutrino measurements, while the sensitivity of the SND@LHC experiment corresponds to $7.2 \lesssim \eta \lesssim 8.4$.

An extension of this experimental program has been proposed for the HL-LHC era. A purpose-built Forward Physics Facility [16, 17] could host successors of the current experiments: FASER2, FASER ν 2, and Advanced SND@LHC that will significantly improve the sensitivity of the BSM and SM far-forward physics searches. In addition, two other experiments have been proposed to operate in the FPF: liquid-argon time projection chamber (LArTPC) detector, dubbed FLArE, to study neutrino interactions and search for light dark matter (DM) species [22], and a milliQan-type detector FORMOSA targeting new postulated millicharged particles (mCPs) [23]. The location of the new underground facility would allow for placing the experiments on the beam collision axis at a distance of $L \gtrsim 620$ m away from

the ATLAS IP. The detectors would be shielded from the IP by more than 200 m of rock and concrete. An important source of backgrounds is remnant muons produced at the IP that are not deflected away by the LHC magnets. The ongoing far-forward experiments, however, have already demonstrated excellent capabilities in rejecting muon-induced events [4, 8, 24].

2. Far-forward new physics searches

2.1. Feebly-interacting particles

Driven by both theoretical appeal and the history of past discoveries in particle physics, the primary focus of the BSM physics program at the LHC has been on heavy new species and high- p_T searches. While this program is continued and expanded, the importance of going beyond this paradigm has also been realized, particularly in connection to searches for light and feebly interacting particles [25]. Such new physics species with the mass $m \lesssim \mathcal{O}(10 \text{ GeV})$ can preferentially be produced with low transverse momentum $p_T \sim m$ and travel along the beam collision axis, $p_T/p \ll 1$ for $p \sim \text{TeV}$. Based on various experimental signatures, the far-forward experiments at the LHC can probe LLP particles with masses up to a few tens of GeV.

Essential for the current LHC Run 3 are searches for very light species with $m \lesssim m_\pi$ that can come from rare pions and other mesons decays. One expects even a few $\times 10^{17}$ pions to be produced in this period of the LHC operation [21]. Nearly 2% of such pions with $E_\pi \gtrsim 10 \text{ GeV}$ travel forward towards the FASER experiment, even though the angular size of this detector is very small, of the order of 10^{-8} part of the forward hemisphere. Hence, new light species produced in rare decays of pions and other light mesons can form a highly collimated flux of particles going through the far-forward experiments.

A vanilla example of such a model is a secluded dark photon A' which couples to the SM via kinetic mixing [26, 27]. Light dark photons mostly come from rare pions and eta mesons decays, $(\pi/\eta) \rightarrow \gamma A'$. For the kinetic mixing parameter in the range of $\epsilon \sim (10^{-6} - 10^{-4})$, this yields up to $\mathcal{O}(10^8)$ high-energy A' s produced in the forward region of the LHC [13]. Boosted with characteristic LHC energies, they travel sizable distances until they decay into an energetic e^+e^- or $\mu^+\mu^-$ pair. Null results of the search for such decays inside the FASER detector provide the leading bounds on dark photons in this $(m_{A'}, \epsilon)$ range based on initial Run 3 data [24]. Probing larger masses of the dark photon in the far-forward region of the LHC relies on other production modes, *e.g.*, proton bremsstrahlung, *cf.* Refs. [13, 28–30]. The FASER(2) sensitivity to light dark vector bosons that arise from gauging various global SM symmetries has been studied in Refs. [21, 31–35].

Decays of heavier mesons can also lead to large fluxes of LLPs in the far-forward region of the LHC. A prime example is the search for a dark Higgs boson that couples to the SM via mixing with the SM Higgs boson. The light BSM scalar ϕ with Yukawa-like couplings to the SM fermions is dominantly produced in rare decays of B mesons. The latter are abundantly produced in high-energy pp collisions at the LHC, *e.g.*, one expects about $N_B \sim 10^{15}$ of B mesons during the HL-LHC era. The corresponding sensitivity reach of the FASER2 experiment proposed for the FPF is shown in Fig. 2 in the (m_ϕ, θ) plane where θ is the ϕ - h mixing angle [18, 21, 36]. As shown in the plot, the FASER2 reach can be further enhanced by invisible decays of the SM Higgs bosons into lighter scalars, $h^* \rightarrow \phi\phi$, with the assumed 5% branching fraction. These can be probed indirectly via additional contributions to B -meson decays with the off-shell h^* . The similar far-forward experimental programs at future hadron colliders could also probe direct $h \rightarrow \phi\phi$ decays of on-shell SM Higgs bosons [36]. Cosmological implications of light dark scalar searches in FASER and beyond have been studied, *i.a.*, in Refs. [37–39]. The FASER(2) sensitivity can also be interpreted in terms of Type-I Two Higgs Doublet Model (2HDM) [40], flavor-philic scalar couplings [41], or a supersymmetric sgoldstino [42].

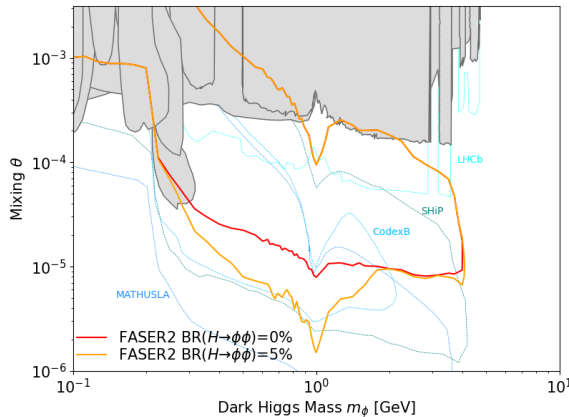


Fig. 2. Sensitivity of FASER2 (HL-LHC) in the search for dark Higgs bosons. The plot obtained with FORESEE [36].

Above the B -meson mass, the primary production mode for LLPs is via a Drell–Yan process. This can lead to a sizeable number of dark photons with a mass up to tens of GeV that can travel along the beam collision axis, although they remain less collimated than lighter LLPs. Prompt and invisible decays of such A' s into a secondary flux of dark matter (DM) particles can have significant phenomenological consequences. In particular, unstable inelastic DM (iDM) species produced this way can be probed via their semi-

visible decays inside FASER(2), $\chi_2 \rightarrow \chi_1 e^+ e^-$, leading to the bounds for the DM mass inaccessible in experiments at lower energies [43]. For smaller masses, large boost factors of decaying iDM particles allow for probing very compressed spectra between χ_1 and χ_2 that produce visible signals that are too soft to be detected at lower energies [44]. See also Refs. [45, 46] for further discussion about probing iDM scenarios in FASER. produce visible signals that are too soft to be detected at lower energies

Light, sub-GeV DM species can also be probed directly in the FPF by searching for their electron scatterings in the FLArE detector [22]. Additional nuclear scattering signatures can also be employed [47] to probe, *e.g.*, hadrophilic DM scenarios [34], *cf.* also Ref. [48] for a discussion about the (Advanced) SND@LHC experiment. Neutrino-induced backgrounds need to be suppressed in this search. Given the typical high energy of far-forward neutrinos, $E_\nu \gtrsim 100$ GeV, this becomes more straightforward for small energy depositions in the detector characteristic for the BSM interactions mediated by light (sub-GeV) new particles. The electron scattering signature can equally well probe BSM interactions of high-energy neutrinos, *e.g.*, in a dipole or Z' portal model to heavy neutral leptons (HNLs) [49, 50] or for dark vector mediators coupled to the lepton number [51]. Unstable but extremely long-lived species can also be detected, *e.g.*, via scattering processes $Ne \rightarrow Ne$, where N is a right-handed neutrino [49].

Instead, postulated light new physics species with a fractional electric charge Q_χ would leave ionization signatures in the detectors. The LHC in its far-forward region is a factory of such mCPs with a mass up to tens of GeV. The search for them in the FORMOSA experiment, to operate in the FPF, is expected to deliver leading bounds on mCPs in the mass range up to $m \lesssim 100$ GeV and probe mCPs with electric charge as small as $Q_\chi \lesssim 10^{-3} e$ [23]. Additional constraints on such particles can result from the search for their expected electron scatterings in the FLArE detector [52]. The expected sensitivity reach in this search is shown in Fig. 3.

Besides the pp collisions, forward-going LLPs can also be produced in other parts of the LHC tunnel and beyond, in the material in front of the detector. For example, the production of axion-like particles (ALPs) coupled to photons in the Primakoff process in high-energy photon interactions determines FASER(2) sensitivity to this scenario [20], *cf.* also Ref. [53] for a discussion about FASER working as a light shining through a wall experiment. This secondary production of LLPs can also occur close to the detector or inside, leading to enhanced sensitivity in a low LLP lifetime regime [54], *cf.* also Refs. [49, 55, 56] for further discussion including BSM-induced high-energy photon and multi-muon signatures.

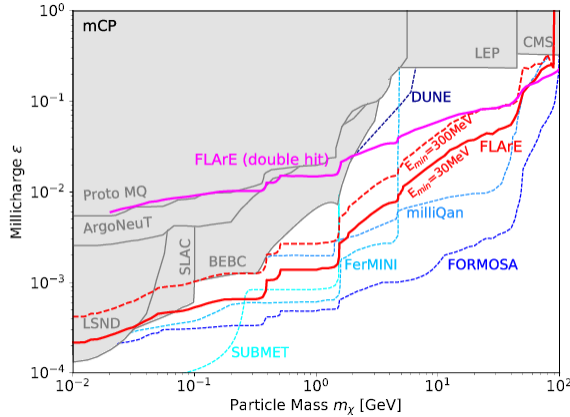


Fig. 3. Sensitivity of the FORMOSA and FLArE experiments in the search for millicharged particles. From Ref. [52].

Phenomenological studies related to LLP searches in FASER and FPF experiments can be significantly simplified with a dedicated simulation package FORESEE [36]. The tool allows one to run the entire analysis to obtain sensitivity reach plots for a growing library of the BSM models and extract valuable data for external simulations, *e.g.*, forward hadron spectra. In FORESEE, detector geometries, positions, and experimental cuts are free to vary by the user, which can be used likewise to study other ideas related to the forward region of the LHC [57]. The package additionally allows for testing the LLP model sensitivity of potential future far-forward experimental programs in hadronic colliders at 27 and 100 TeV energies.

The discovery prospects of FASER(2) in the search for light and feebly interacting particles are broader than the scenarios outlined above. Far-forward experiments are sensitive to popular GeV-scale heavy neutral leptons (HNLs) that couple to SM neutrinos via mass mixing [19, 58] or higher-dimensional operators [59, 60]. Similarly, light R-parity violating supersymmetric neutralinos can be probed via their predicted highly-displaced decays [61, 62]. The far-forward experiments can also constrain higher dimensional couplings between dark and visible fermions [63]. The FASER(2) sensitivity in the search for axion-like particles has also been extensively analyzed for various interaction terms. Besides the ALP-photon coupling mentioned above [20], phenomenological consequences of ALP interaction with SM fermions and gluons [21], $SU(2)_L$ gauge bosons [64], or flavor-specific couplings to up-type quarks [65] have been studied. A comprehensive review of these and other LLP searches at the FPF can be found in Ref. [17].

2.2. Neutrino BSM interactions

As mentioned above, precision high-energy neutrino physics is fundamental to far-forward searches at the LHC. Besides the rich SM experimental program, it can also be used for probing possible neutrino BSM interactions. These can affect neutrino production, propagation, and final detection through neutrino scatterings.

While electron and muon neutrinos are abundantly produced in decays of light mesons, and, therefore, there is little room to probe them via modified production rates in pp collisions at the LHC, this is not the case for tau neutrinos. These come predominantly from D meson and subsequent tau-lepton decays, which results in up to three orders of magnitude lower expected flux of ν_τ s than the dominant ν_μ flux [66]. If tau neutrinos can be additionally produced, *e.g.*, in rare BSM-induced pion decays, new physics can manifest itself as an excess of ν_τ charged current (CC) scattering events in FASER ν 2 [33], *cf.* also Refs. [34, 67, 68] for further illustration. This search requires carefully treating far-forward tau-neutrino flux uncertainties and potentially exploiting full neutrino scattering events' energy and position information to reduce them in the search for BSM phenomena, *cf.* Ref. [17] and references therein for further discussion about these uncertainties. Forward neutrino production rates can also be modified in the presence of lepton flavor non-universality [69].

Neutrino BSM couplings to charged leptons and quarks can, generally, affect both their production and detection process. At the effective field theory (EFT) level, this has been comprehensively studied in Ref. [70]. As shown therein, the lack of predicted deviations from SM neutrino interaction rates can lead to FASER ν bounds up to even a multi-TeV scale of new physics already during the ongoing LHC Run 3. These results can then be translated into specific BSM frameworks, *e.g.*, models predicting heavy lepto-quarks [17], *cf.* also Refs. [71, 72] for further discussion about probing heavy BSM species via neutrino interactions in the FPF.

The presence of high-energy neutrinos in the FPF additionally opens up the possibility of their upscattering into dark species with the mass $m \sim 1$ GeV. While kinematically inaccessible in low-energy experiments, the BSM effects of this type are also challenging to probe in atmospheric neutrino interactions in large-scale neutrino telescopes. These remain insensitive to subtle details of neutrino scattering events that could distinguish new physics contributions. Examples of such studies concern the FPF searches for effects of neutrino upscatterings driven by neutrino dipole portal coupling to HNLs [49, 50, 73]. The BSM species can also be produced in neutrino CC scatterings leading to anomalous patterns in the transverse momentum distribution of the outgoing charged particles, as illustrated for a popular model with a neutrino portal to DM in Ref. [74].

Measuring neutral current (NC) scatterings in the ongoing and future far-forward searches at the LHC remains more challenging, given the significant missing energy in the final state carried out by a final-state neutrino. The corresponding potential for NC event identification and neutrino energy measurement has been studied, however, with full event information available from precise emulsion detectors and by employing deep neural networks [75]. This analysis allows also for probing non-standard interactions (NSI) of neutrinos by determining the NC/CC ratio. Anomalous NC nuclear or electron scattering rates could further indicate new physics effects related to non-vanishing neutrino electromagnetic moments. In particular, the FPF can deliver leading bounds on charge-radius contributions of this type for electron neutrinos [76].

On their way to forward experiments at the LHC, neutrinos are negligibly affected by oscillations, given their typical energy and the distance to the detectors. Significant signs of such oscillations could then be indicative of new physics. These could, *e.g.*, manifest as suppression of events in specific energy bins, *cf.* Ref. [5], where such a ν_μ disappearance effect has been discussed for oscillations into sterile neutrinos with $\Delta m_{41}^2 \sim 2000 \text{ eV}^2$. Further analysis shows that this channel could provide leading bounds down to mixing angles $U_{\mu 4}^2 < 10^{-2}$ for $\Delta m_{41}^2 \sim (100\text{--}1000) \text{ eV}^2$ [17]. Neutrino spectrum shape uncertainties must be considered to estimate the impact of BSM oscillations correctly [77].

Last but not least, the far-forward LHC neutrino physics program can also be used to study predicted SM phenomena that could not have been better measured before or completely avoided detection up-to-date. A prime example of the former event type is ν_τ CC scatterings. Ultimately, the FPF would measure $\mathcal{O}(10^3)$ such interactions, dramatically increasing the available statistics of such events that have ever been available. These statistics could be further enhanced, *e.g.*, in the presence of intrinsic charm contribution to the ν_τ flux from excess production of charm mesons in the far-forward region of the LHC [78]. Finally, extremely rare SM events that require high scattering energy might become available for measurements in the FPF, *e.g.*, $\bar{\nu}_e e^- \rightarrow \rho^- \rightarrow \pi^- \pi^0$ process [79].

2.3. Other BSM physics opportunities

Far-forward searches at the LHC can also directly probe heavy new particles with masses up to $\mathcal{O}(1 \text{ TeV})$ if they are abundantly produced along the beam collision axis. A notable example is the proposed FASER(2) search for quirks charged under the SM and a hidden confining gauge group [80]. Quirks can be effectively pair-produced in pp collisions at the LHC with a

low combined transverse momentum of the pair. They then travel forward and could leave non-trivial and unique signatures in the detectors, complementing quirk searches in experiments operating at higher p_{T} s.

Additional opportunities for precision SM measurements and BSM searches could be related to a large flux of high-energy muons traveling through the far-forward experiments. While strong LHC magnets deflect away most of the muons produced at ATLAS IP, one still expects $\mathcal{O}(10^9)$ to reach FASER during LHC Run 3 [3, 5]. This number further grows for the FPF in the HL-LHC era. In particular, characteristic TeV energies of LHC muons could allow for probing heavier muon-philic LLPs produced in BSM muon interactions in the forward detector [81]. The full potential of such a possible muon physics program at the LHC remains to be studied in detail.

3. Summary

A new experimental program at the LHC has started during LHC Run 3 in its far-forward region with dedicated FASER and SND@LHC experiments. It focuses on precise high-energy neutrino measurements and related QCD studies and searches for new physics. The BSM physics program of the currently running experiments and the future proposed Forward Physics Facility is rich. It is devoted primarily to searches for postulated light feebly interacting particles and probing possible BSM neutrino interactions, although it is not limited to these topics. Various new physics scenarios have already been discussed in this context, and they connect to essential open questions in contemporary particle physics [17].

Besides the proposed experiments, the FPF could offer further opportunities for new searches and measurements to explore the LHC physics potential in its far-forward region fully. New ideas of this type are constantly discussed in the FPF community, which remains open to contributions from researchers at all stages of their careers. An essential aspect of the FPF studies is an interplay between the SM and BSM physics programs. The latter will significantly benefit from the ongoing and future neutrino measurements and constraints imposed on forward hadron production obtained this way.

S.T. would like to thank Brian Batell, Jonathan Feng, and Felix Kling for useful discussions. This work is supported by the grant “AstroCeNT: Particle Astrophysics Science and Technology Centre” carried out within the International Research Agendas programme of the Foundation for Polish Science financed by the European Union under the European Regional Development Fund and by the National Science Centre (NCN), Poland, research grant No. 2021/42/E/ST2/00031.

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