DEEP-INELASTIC SCATTERING WITH COLLIDER NEUTRINOS AT THE LHC AND BEYOND*

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The proton–proton collisions at the LHC generate high-intensity collimated beams of forward neutrinos up to TeV energies. Their recent observations and the initiation of a novel LHC neutrino program motivate investigations of this previously unexploited beam. The kinematic region for neutrino deep-inelastic scattering measurements at the LHC overlaps with the Electron–Ion Collider. The effect of the LHC νDIS data on parton distribution functions (PDFs) is assessed by generating projections for the Run 3 LHC experiments and for selected proposed detectors at the HL-LHC. Estimating their impact in global (n)PDF analyses reveals a significant reduction of PDF uncertainties, particularly for strange and valence quarks. Furthermore, the effect of neutrino flux uncertainties is examined by parametrizing the correlations between a broad selection of neutrino production predictions in forward hadron decays. This allows determination of the highest achievable precision for neutrino observations, and constraining physics within and beyond the Standard Model, demonstrated by setting bounds on effective theory operators and projections for an experimental confirmation of the enhanced strangeness scenario proposed to resolve the cosmic ray muon puzzle, using LHC data. There is also promise for a first measurement of neutrino tridents with a statistical significance beyond 5σ.

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The first observations of neutrinos produced at the Large Hadron Collider (LHC) by the FASER [1] and SND@LHC [2] collaborations have started the era of accelerator-based neutrino research at the TeV scale. FASER has already performed the first measurement of ν_e and ν_μ interaction cross sections [3]. While the current experiments demonstrate great potential, both FASER [4] and SND@LHC [5, 6] will continue and upgrade their operations during the LHC Run 4. It is essential for maximizing the physics

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potential of the high-luminosity LHC run to continue expanding this program, and a purpose-built Forward Physics Facility (FPF) housing several larger experiments has been proposed [7–9] at the LHC. Similar experiments are considered also at the Future Circular Collider [10].

The neutrinos result from the weak decays of hadrons produced in the initial collisions at the LHC. Together with the potential forward long-lived particles, they are never observed in central experiments, but interact *e.g.* via deep inelastic scattering (DIS) in a forward fixed-target experiment. Various effects can affect the rates of both neutrino production and interactions in the detector. This work summarizes Refs. [11–13], showing how the LHC neutrinos probe physics within and beyond the Standard Model (SM).

The impact of the FPF data on global parton distribution functions (PDF) is estimated via a Hessian PDF profiling procedure [14–17], implemented in the xFitter open-source QCD analysis framework [18–21]. Figure 1 shows the results using the PDF4LHC21 [22] proton PDF, assuming an isoscalar-free nucleon target. Most improvement is observed for the valence and strange quarks. The improvement in the valence (strange) quark PDFs relies on the possibility of lepton charge identification (charm tagging). Similar improvement is also observed after accounting for nuclear corrections using the EPPS21 [23] set [11].

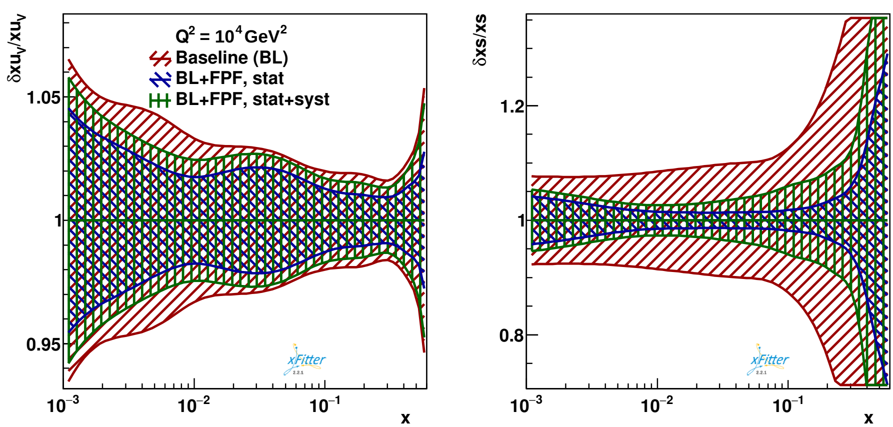

Fig. 1. Fractional uncertainties (68% C.L.) at $Q^2 = 10^4$ GeV^2 for the up valence (left) and strange (right) quarks in the PDF4LHC21 baseline (red), and the results of profiling with the FPF pseudodata. Projections accounting for estimated statistical(+systematic) uncertainties are shown in blue (green). Taken from Ref. [11].

The coverage of charged-current (CC) interactions at the FPF in the x, Q^2 kinematic plane overlaps with the neutral-current (NC) interactions at the Electron–Ion Collider (EIC) [24], thus, providing complementary information [11]. Although PDF4LHC21 includes previous neutrino DIS data, the FPF is shown to provide even further constraints. The LHC Run 3 statistics are however determined insufficient for constraining PDFs, further motivating the FPF and EIC. The improved PDF uncertainties will increase the precision of SM cross sections relevant to key measurements, *e.g.* inclusive Drell–Yan, W mass, and the Weinberg angle [11]. Similar work in the context of the FCC has indicated great potential for studying *e.g.* polarized PDFs and cold nuclear matter in pPb collisions. This relies on a perturbative charm production description and tying forward neutrino data to events at the central experiment, probing nuclear PDFs at $x \sim 10^{-9}$ [10].

As the experiments probe a previously unexplored kinematic region, there are large discrepancies between neutrino flux predictions due to assuming different phenomenological models, affecting the shape and magnitude of the ν spectra. The prediction envelope is very large, and it is crucial to ensure that sought-after physics effects are not obscured by uncertainties. Via a Fisher information approach, Ref. [12] presents a framework for obtaining the smallest uncertainty achievable in a measurement by parametrizing the correlations in the energy and radial distributions, as well as the neutrino flavor and parent hadron composition between multiple predictions.

This allows for investigating the most stringent exclusion bounds at the existing and proposed detectors. The LHC is demonstrated to *e.g.* help solve the cosmic ray muon puzzle, a deficit of high-energy muons in air shower simulations compared to measurements first observed by the Pierre Auger Observatory [25–27]. The issue may be due to mismodeling the distribution of secondary particles, and the enhanced strangeness hypothesis suggests increasing the number of muons by enhanced s production, leading to less pions and more kaons at the LHC. A phenomenological model reweighing the counts of neutrinos from pions by a factor of $(1-f_s)$ and from kaons by $(1+Ff_s)$, with F a factor accounting for the π/K production rate difference, could explain the muon puzzle if $f_s = 0.5$ [28]. Figure 2 shows that such values have been constrained by FASERν already during Run 3. If f_s has lower values at LHC energies, such cases can be probed at the FPF.

It is also possible to constrain non-standard interactions and extend the SM by dimension-6 effective operators, connecting a u and d quark to a ν_τ and a muon or to a ν_e and a τ [29]. The former modifies pion decays, affecting the rate of incoming neutrinos, while the latter affects the rates of interactions at the detector. The projected FPF limits are observed to improve on contemporary constraints already with just 10% of the expected data, while the full result can improve the bounds on specific operators by an order of magnitude [12].

Observing neutrino tridents, the production of three-lepton final states in neutrino scattering off a nucleus through photon exchange, is a notoriously difficult task. CHARM-II [30] and CCFR [31] have claimed detections, while

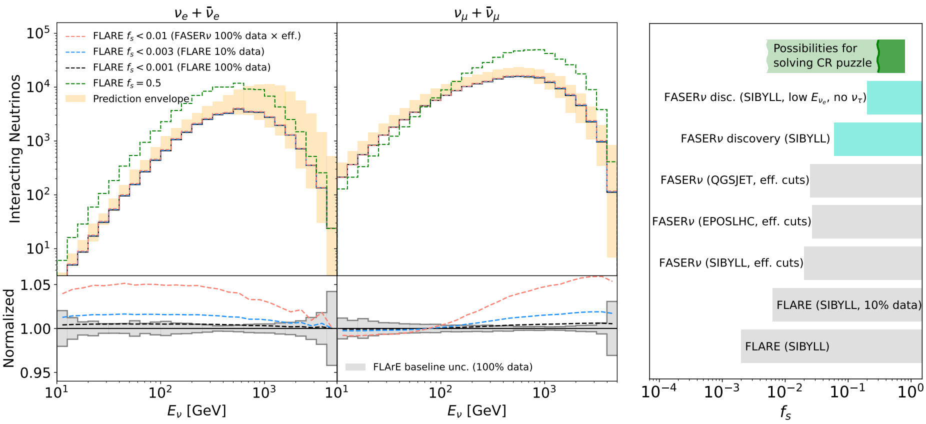

Fig. 2. Left: The ν_e and ν_μ CC rates at FLArE, with no s enhancement (solid black). The dashed orange (blue, black) correspond to the 1σ exclusion bounds for FASERν and FLARE with 10% or 100% of the expected data, respectively. The $f_s = 0.5$ case, possibly solving the muon puzzle, is shown in green. The yellow band indicates the initial spread of the predictions entering the analysis yielding the ultimate uncertainty band (gray). Right: The 2σ constrained values (gray) for f_s at FLARE and FASERν, compared to the FASERν discovery potential (turquoise), with and without information on ν_τ and high-energy contributions to the ν_e spectrum. All bounds cover the $f_s \in [0.3, 0.8]$ region (dark green) favored by the enhanced strangeness solution to the CR muon puzzle, although the effect may manifest in more subtle ways at the LHC (light green). Taken from Ref. [12].

NuTeV [32] identified diffractive charm production as a previously neglected background, claiming no observation. The main task of trident studies is thus assessing the prospects for resolving the signal from backgrounds, the two main ones at FASERν2 being single pion and charm production.

An example of a trident diagram is given in Fig. 3 (left); the signal is characterized by two long muon tracks in the emulsion coming from the same vertex. The signal muons are required to travel through the FASERν2 interface tracker, veto station, spectrometer, electromagnetic calorimeter, and an iron block to be identified as muons. In contrast, the background events contain at least one charged hadron track. For pions, this can be long, but typically ends in a hadronic interaction in the tungsten, lead, or iron and is discarded. However, a charmed hadron may have a short track and decay into a second muon, mimicking the trident signature. Figure 3 (right) illustrates the near-perfect background rejection achievable at FASERν2 with minimal effect on the signal. The event analysis relies on reverse tracking between the interface tracker and the emulsion, and restricting the angle between two outgoing muons to $\theta < 0.1$ rad, parent meson decay length to $d < 2$ mm, and the number of charged tracks $N_{\rm ch}$ with momentum $p > 300$ MeV to exactly two. With these, FASERν2 has potential for a definitive observation of neutrino tridents with dimuon final states [13].

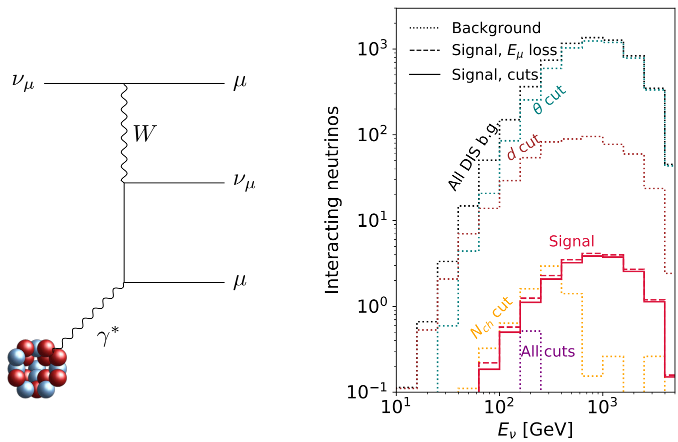

Fig. 3. Left: Example of trident dimuon production. Right: The signal events permitting reverse tracking of both muons (surviving energy losses in the detector), shown in dashed red (solid red) before (after) the cuts to reject the background. The dotted lines show the backgrounds after each cut. Taken from Ref. [13].

The first measurements of neutrino interaction cross sections by the FASER Collaboration mark the beginning of the era of using the LHC neutrinos for physics. To maximize the physics potential of the LHC and future colliders, it is important to consider the possibilities of an expanded forward neutrino program. Proposed forward experiments at the LHC have good prospects for *e.g.* solving the cosmic ray muon excess, probing proton and nuclear PDFs, as well as constraining non-standard and 4-Fermi interactions. Additionally, FASERν2 has great potential for a conclusive observation of neutrino tridents, probing physics at the EW scale and below. Moreover, synergies can be expected between measurements at the EIC and the FPF, and forward neutrino experiments at the FCC could probe proton and nuclear structure at even lower x than currently possible.

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