



Physics with TeV Neutrinos at the LHC

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The Dawn of the LHC Neutrino Era

Back to the Future

 In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-ofmass energy 30 GeV.



During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.

- "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
- "There was initially a broad belief that physics action would be in the forward directions at a hadron collider.... It is easy to say after the fact, still with regrets, that with an earlier availability of more complete... experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC ." – Lyn Evans and Peter Jenni, "Discovery Machines," CERN Courier (2021).

Bottom line: The collider was creating new forms of matter (charm), but the detectors focused on the forward region (along the beamline) and so missed them.

J. Feng, CERN Colloquium, June 2023

After the establishment of the SM and QCD in the early 70s, it became clear that the central/transverse (high- p_T) region is where new particles and phenomena were to be found

- The ATLAS and CMS detectors were designed with a focus on identifying particles with masses at the electroweak and TeV scale
- Due to kinematics, their decay products lie in the **central rapidity** acceptance region



Light particles (pions, kaons, protons, heavy flavour mesons) produced predominantly in the forward rapidity region, justifying e.g. the design of LHCb

for LHCb $2.0 \le \eta \le 4.5$

- Solution Sector Sect
- In addition, there are guaranteed physics targets to be reached should we instrument the forward region of the LHC, based on exploiting the most energetic, high-intensity neutrino beam ever produced in a laboratory



electron (tau) neutrinos mostly (entirely) from D-meson decays, muon neutrinos from pion/kaon decays



electron neutrinos mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays

muon neutrino flux dominated by pion & kaon decays

tau neutrinos entirely from D-meson decays





The dawn of the LHC neutrino era

Two far-forward experiments, FASER and SND@LHC, have been instrumenting the LHC farforward region since the begin of Run III and reported evidence for LHC neutrinos (March 2023)

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Editors' Suggestion Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of 35.4 fb⁻¹ using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

DOI: 10.1103/PhysRevLett.131.031801

153 neutrinos detected, 151±41 expected



PHYSICAL REVIEW LETTERS 131, 031802 (2023)

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb⁻¹. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_{μ} interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_{μ} signal.

DOI: 10.1103/PhysRevLett.131.031802

8 neutrinos detected, 4 expected



Now is the time to start exploiting their physics potential















Being able to detect and utilise the most energetic human-made neutrinos ever produced would open many exciting avenues in QCD, neutrino, and astroparticle physics



Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux



Searching for the invisible

These far-forward LHC detectors also operate as background-free to search for dark sector particles, feebly-interacting particles (FIPs), long-lived particles (LLP),



Unique blend of guaranteed deliverables and exploration potential

The Forward Physics Facility

A proposed new CERN facility to achieve the full potential of LHC far-forward physics



Complementary suite of far-forward experiments, operating concurrently with the HL-LHC
 Start civil engineering during LS3 or shortly thereafter, to maximise overlap with HL-LHC
 Positive outcome of ongoing site investigation studies (geological drill down to the cavern depth)

Physics with LHC neutrinos



unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours** anomalous neutrino couplings, **lepton-flavour universality** tests with neutrinos

Neutrino Interactions at the TeV

First measurement of muon neutrino and tau neutrino cross-sections at the TeV: test lepton flavour universality, search for anomalous interactions (*e.g.* in EFT framework)



LHC neutrinos cover unexplored gap in neutrino interactions

Indirect HERA constraints restricted to electron neutrinos, cross-sect measured at the 15% level at TeV energies

Largest sample of tau neutrinos, explore with exquisite precision worst known particle of the SM

	D	Detector	Number of CC Interactions			
Name	Mass	Coverage	Luminosity	$\nu_e + \bar{\nu}_e$	$ u_{\mu}\!\!+\!ar{ u}_{\mu}$	$\nu_{ au} + ar{ u}_{ au}$
$\mathrm{FASER}\nu$	1 ton	$\eta\gtrsim 8.5$	$150 { m fb^{-1}}$	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	$150 { m fb^{-1}}$	137 / 395	790 / 1.0k	7.6 / 18.6
$FASER\nu 2$	20 tons	$\eta\gtrsim 8.5$	$3 \mathrm{~ab^{-1}}$	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta\gtrsim7.5$	$3 \mathrm{~ab^{-1}}$	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Thousands of tau neutrino events expected, current world sample being O(10)

Physics with LHC neutrinos



Probe **small-x QCD** (e.g. non-linear dynamics) in uncharged regions

- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for BSM searches e.g. via sterile neutrino oscillations

The LHC as a Neutrinolon Collider

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela, T. Rabemananjara, and J. Rojo, *arXiv:2309.09581*



Parton Distributions

 $u(x, Q^2)$

Probability of finding an up quark inside a proton, carrying a fraction *x* of the proton momentum, when probed with energy *Q* **Energy** of hard-scattering reaction: inverse of resolution length

x: fraction of proton momentum carried by gluon

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

$$u(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \dots)$$

constrain from global fit to high-p_T data

Dependence on *Q* fixed by perturbative QCD dynamics: computed up to aN³LO

$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

Parton Distributions

credit: visualising the proton, Arts at MIT (https://arts.mit.edu/visualizing-the-proton/)

Bjorken-x: fraction of the proton energy carried by a quark or gluon

Seutrino deep-inelastic scattering is a powerful probe of the quark/gluon structure of hadrons

Double-differential measurements provide direct access to different flavour combinations

$$\frac{d^2 \sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2} \left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$
$$y = Q^2/(2xm_n E_\nu)$$

Cross-section expressed in terms of LO structure functions:

$$\begin{array}{lll} F_{2}^{\nu p}(x,Q^{2}) &=& 2x\left(f_{\bar{u}}+f_{d}+f_{s}+f_{\bar{c}}\right)\left(x,Q^{2}\right), \\ F_{2}^{\bar{\nu}p}(x,Q^{2}) &=& 2x\left(f_{u}+f_{\bar{d}}+f_{\bar{s}}+f_{c}\right)\left(x,Q^{2}\right), \\ xF_{3}^{\nu p}(x,Q^{2}) &=& 2x\left(-f_{\bar{u}}+f_{d}+f_{s}-f_{\bar{c}}\right)\left(x,Q^{2}\right), \\ xF_{3}^{\bar{\nu}p}(x,Q^{2}) &=& 2x\left(f_{u}-f_{\bar{d}}-f_{\bar{s}}+f_{c}\right)\left(x,Q^{2}\right). \end{array}$$

Goal: quantify the impact of **ongoing and future LHC neutrino experiments** on the proton PDFs, and assess their implications for the (**HL)-LHC precision physics program**

Generate **DIS pseudo-data** at current and 10^{4} proposed LHC neutrino experiments Fully differential calculation based on state- 10^{3} of-the-art QCD calculations

Binning

- Model systematic errors based on the expected performance of the experiments
- Consider both inclusive and charmproduction DIS

Events per bin

Geometry



cross-section

number of DIS events per bin

 10^{5}

Model detector performance based on most updated design

acceptance)



x: momentum fraction of quarks/gluons in the proton

Q²: momentum transfer from incoming lepton

Continue highly succesful program of neutrino DIS experiments @ CERN

- **Expand kinematic coverage** of available experiments by an order of magnitude in x and Q^2
- Subscription of the Electron-Ion Collider covering same region of phase space

Integrated event rates for DIS kinematics for inclusive (charm-tagged) production

Detector	$N_{ u_e}$	$N_{ar{ u}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	$N_{ u_{\mu}}$	$N_{ar{ u}_{\mu}}$	$N_{ u_{\mu}} + N_{ar{ u}_{\mu}}$
$FASER\nu$	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190(25)	700 (83)
$FASER\nu 2$	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	133k (23k)	510k (76k)
AdvSND-far	12k (1.5k)	5.5k (0.82k)	18k (2.3k)	40k (4.8k)	16k (2.2k)	56k (7k)
FLArE10	44k (5.5k)	20k (3.0k)	64k (8.5k)	76k (10k)	38k (5.0k)	110k (15k)
FLArE100	290k (35k)	130k (19k)	420k (54k)	440k (60k)	232k (30k)	670k (90k)



- Muon-neutrinos: larger event rates, smaller production uncertainties
- Current experiments limited by statistics, FPF by systematics
- Ultimate reach achieved by combining all experiments



PDF constraints from LHC neutrinos



- Impact on proton PDFs quantified by the Hessian profiling of PDF4LHC21 (xFitter) and by direct inclusion in the global NNPDF4.0 fit
- Most impact on up and down valence quarks as well as in strangeness, ultimately limited by systematics
- Uncertainties in incoming neutrino fluxes subdominant, once constrained *in-situ* at FASER & FPF



Impact at the HL-LHC





Impact on core HL-LHC processes i.e. single and double weak boson production and Higgs production (VH, VBF)

Also relevant for BSM searches at large-mass (via large-x PDFs)

e.g. high-mass dilepton resonances

Fully independent constraints on proton structure, crucial to disentangle possible BSM signatures in high p_T data

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**



common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up**, **down**, **strange (anti-)quarks** but **no intrinsic charm quarks**

It does not need to be so! An intrinsic charm component predicted in many models



Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudcc Fock component. The interesting consequences of such a hypothesis are explored.

within global PDF fit:

 $c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{(\text{pert})}(x,Q) + c^{(n_f=4)}_{(\text{intr})}(x,Q)$

Extracted from data

from QCD radiation and matching from intrinsic component



The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**



- No reason why intrinsic charm should be symmetric (it is not in most models)
 i.e. up, down, and strange quark PDFs are asymmetric
- Extend the NNPDF4.0 analysis with an separate determination of charm and anti-charm PDFs
- PDF uncertainties are large, but preference for a non-zero, positive IC asymmetry around x=0.3

A non-zero valence charm PDF is the ultimate smoking gun for IC, since no perturbative mechanism can generate it

R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn,
K. Kudashkin, G. Magni & J. Rojo, *Nature* 608 (2022) 7923, 483-487
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn,
E. R. Nocera, G. Magni, J. Rojo & R. Stegeman, *arXiv:2311.00743*





Probing Ultra-Small-x QCD

LHC neutrinos and small-x QCD



LHC neutrinos and small-x QCD



Spread of PDF predictions (e.g. small-x gluon) modifies predicted fluxes up to factor 2

- Focus on electron and tau neutrinos, with the largest contribution from charm production where QCD factorisation can be applied
- Seconstruct tailored observables where QCD uncertainties (partially) cancel out

$$R_{\tau/e}(E_{\nu}) \equiv \frac{N(\nu_{\tau} + \bar{\nu}_{\tau}; E_{\nu})}{N(\nu_{e} + \bar{\nu}_{e}; E_{\nu})}, \qquad R_{\exp}^{\nu_{e}}(E_{\nu}) = \frac{N_{\text{FASER}\nu}(\nu_{e} + \bar{\nu}_{e}E_{\nu})}{N_{\text{SND}@LHC}(\nu_{e} + \bar{\nu}_{e}; E_{\nu})}$$

Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

Proxy for 2D xsec differential in (energy, rapidity)

LHC neutrinos and small-x QCD



Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment

- Fhese initial projections are now being extended to full-fledged simulations with state-of-the-art QCD
- Quantify impact for UHE neutrinos and for cross-sections at a 100 TeV proton collider

Implications for FCC-pp



- FCC-pp would be a small-x machine, even Higgs and EWK sensitive to small-x QCD
- LHC neutrinos: laboratory to test small-x QCD for dedicated FCC-pp physics and simulations
- Current projections show a marked PDF error reduction on FCC-pp cross-sections thanks to constraints from LHC neutrinos



QCD, Neutrino, and BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider

Roshan Abraham, Jyotismita Adhikary, Jonathan Feng, Max Fieg, Felix Kling, Juan Rojo, and Sebastian Trojanowski, **WIP**

FPF@FCC

- An FPF-like suite of far-forward experiments could be integrated in FCC design from day one
- Benefit from i) higher CoM energy, ii) higher luminosity, iii) larger/better detectors & technology



Event rates



Access neutrino cross-sections at multi-TeV energies, test Lepton Flavour Universality for the three neutrino generations, and search for anomalous interactions with permille precision

Proton Structure & Small-x QCD



Access proton structure and ultra-small-x
QCD in uncharted regimes

input for UHE astroparticle physics

Improved understanding of small-x BFKL QCD (& even non-linear QCD!) will be instrumental for core FCC-pp program PDF via v-scattering: x ~ 1/Ev



Large statistics & extended kinematic coverage enable multi-differential measurements (e.g. proton 3D structure)

Which novel features of proton 3D structure can be revealed by a neutrino probe?

Would need dedicated ``general-purpose'' detector to extract all physics potential

hermeticity, particle ID, jet reconstruction

New SM Opportunities

Polarised DIS with neutrinos: spin mapping

RM3-TH/00-20

Polarized Parton Distributions from Charged–Current Deep-Inelastic Scattering and Future Neutrino Factories

Stefano Forte †

14 Mar 2001

arXiv:hep-ph/0101192v2

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Abstract

We discuss the determination of polarized parton distributions from chargedcurrent deep-inelastic scattering experiments. We summarize the next-to-leading order treatment of charged-current polarized structure functions, their relation to polarized parton distributions and scale dependence, and discuss their description by means of a next-to-leading order evolution code. We discuss current theoretical expectations and positivity constraints on the unmeasured C-odd combinations $\Delta q - \Delta \bar{q}$ of polarized quark distributions, and their determination in chargedcurrent deep-inelastic scattering experiments. We give estimates of the expected errors on charged-current structure functions at a future neutrino factory, and perform a study of the accuracy in the determination of polarized parton distributions that would be possible at such a facility. We show that these measurements have the potential to distinguish between different theoretical scenarios for the proton spin structure.

- Realise first neutrino DIS experiment on polarised target: CC analog of polarized EIC collisions
- Assuming a COMPASS-like ⁶LiD polarised target, FPF@HL-LHC would record O(10 events)



New SM Opportunities

Polarised DIS with neutrinos: **spin mapping**

Novel probe to scrutinize proton spin and 3D structure!



- Realise first neutrino DIS experiment on polarised target: CC analog of polarized EIC collisions
- Assuming a COMPASS-like ⁶LiD polarised target, FPF@HL-LHC would record O(10 events)
- FPF@FPF: O(200K) muon neutrino events with COMPASS-like target, increases to O(10⁷) events if FASERv2-like geometry can be polarised





New SM Opportunities



Neutrinos from proton-ion collisions

FPF@HL-LHC:
$$\sqrt{s_{NN}} = 8.16 \text{ TeV}$$
, $L_{pPb} = 1 \text{ pb}^{-1}$



FPF@FCC $\sqrt{s_{NN}} = 63 \text{ TeV}$, $L_{pPb} = 29 \text{ pb}^{-1}/\text{month}$

- x100 from higher √s_{NN}, x150 higher L_{pPb} (6m)
- O(30K) muon neutrinos from p-Pb scattering
- Unique probe of **ultra-dense gluonic matter**
- Different ions: map nuclear dependence

Summary and outlook

- LHC neutrinos realise an exciting program in a broad range of topics from BSM and long-lived particles to neutrinos, QCD and hadron structure, and astroparticle physics
- Measurements of neutrino DIS structure functions at the LHC open a new probe to proton and nuclear structure with a charged-current counterpart of the Electron Ion Collider
- They provide a unique perspective on quark flavour separation, enhance theory predictions for HL-LHC observables, and scrutinise the charm content of the proton
- Measurements of electron and tau neutrino event rates at the LHC constrain the small-x gluon and large-x charm in unexplored regions by using dedicated observables
- Far-forward neutrino experiments integrated in a 100 TeV pp collider would collect a massive sample of O(1B) muon neutrinos and up to O(50M) tau neutrinos with multi-TeV energies