

Master Projects 26/27

Juan Rojo

VU Amsterdam & Theory group, Nikhef



ITFA & GRAPPA MSc Projects Bazaar

<https://juanrojo.com/talks-and-seminars/>

<https://juanrojo.com/scientific-software>

Master projects: common denominators

- 📍 Embedded in the Nikhef Theory group
- 📍 Collider phenomenology at the boundary between theory and experiment
- 📍 Strong computational and statistical / data analysis component, **with focus on ML & AI**
- 📍 Several recent MSc projects in the group have led to peer-reviewed publications

A first determination of the LHC neutrino fluxes from FASER data

Jukka John^a, Felix Kling^{b,c}, Jelle Koorn^a, Peter Krack^{a,d} and Juan Rojo^{a,d}

^aNikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands

^bDeutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

^cDepartment of Physics and Astronomy, University of California, Irvine, CA 92697-4575, U.S.A.

^dDepartment of Physics and Astronomy, Vrije Universiteit, NL-1081 HV Amsterdam, The Netherlands

E-mail: jjohn@nikhef.nl, felix.kling@desy.de, jkoorn@nikhef.nl, peter.krack@nikhef.nl, j.rojo@vu.nl

ABSTRACT: The detection of TeV neutrinos from the LHC by the far-forward detectors FASER and SND@LHC enables a plethora of novel physics opportunities. Among these, the measurement of the flavour, energy, and rapidity dependence of the LHC forward neutrino fluxes provides unique constraints on the theoretical predictions of forward particle production in hadronic collisions. We demonstrate that neutrino event yield measurements at FASER from Run 3 and at its HL-LHC upgrades enable a theory-agnostic extraction of the LHC forward neutrino fluxes. We exploit the equivalence of the problem with the determination of parton distributions from deep-inelastic structure functions to apply the NNPDF approach, based on machine learning regression and the Monte Carlo replica method, to LHC neutrino fluxes. The resulting NN ν flux methodology is validated through closure tests and applied to a first extraction of the LHC muon neutrino flux from the FASER 2024 data. We show how NN ν flux can discriminate between event generators of forward hadron production; scrutinize a possible intrinsic charm component in the proton; and constrain BSM scenarios with enhanced decays of neutral hadrons into neutrinos.

NNPDFPOL2.0: a global determination of polarised PDFs and their uncertainties at next-to-next-to-leading order

Juan Cruz-Martinez^a, Toon Hasenack^{b,c}, Felix Hekhorn^{d,e}, Giacomo Magni^{c,f}, Emanuele R. Nocera^g, Tanjona R. Rabemananjara^{c,f}, Juan Rojo^{c,f}, Tanishq Sharma^g and Gijs van Seeventer^{b,c}

^aCERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland

^bInstitute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, The Netherlands

^cNikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands

^dUniversity of Jyväskylä, Department of Physics, P.O. Box 35, FI-40014 University of Jyväskylä, Finland

^eHelsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland

^fDepartment of Physics and Astronomy, Vrije Universiteit, NL-1081 HV Amsterdam, The Netherlands

^gDipartimento di Fisica, Università degli Studi di Torino and INFN, Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy

E-mail: emanueleroberto.nocera@unito.it

ABSTRACT: We present NNPDFPOL2.0, a new set of collinear helicity parton distribution functions (PDFs) of the proton based on legacy measurements of structure functions in inclusive neutral-current longitudinally polarised deep-inelastic scattering (DIS), and of W -boson, single-inclusive, and di-jet production asymmetries in longitudinally polarised proton-proton collisions. The determination is accurate to next-to-next-to-leading order in the strong coupling, and includes heavy quark mass corrections in the analysis of DIS data. Uncertainties due to missing higher-order corrections are systematically incorporated by means of a covariance matrix determined by scale variations. NNPDFPOL2.0 is based on a machine learning methodology, that makes use of Monte Carlo sampling for the representation of uncertainties into PDFs, of a neural network for the parametrisation of PDFs, of stochastic gradient descent for the optimisation of PDF parameters, and of hyperoptimisation for the selection of the best fitting model. We study the impact on PDFs of higher-order corrections, of the positivity constraint, and of the data. We demonstrate two phenomenological applications

Eur. Phys. J. C (2024) 84:1175
<https://doi.org/10.1140/epjc/s10052-024-13386-1>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article

Theoretical Physics

A phenomenological analysis of LHC neutrino scattering at NLO accuracy matched to parton showers

Melissa van Beekveld¹, Silvia Ferrario Ravasio², Eva Groenendijk¹, Peter Krack^{1,3,a}, Juan Rojo^{1,3}, Valentina Schütze Sánchez¹

¹Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands

²Theoretical Physics Department, CERN, Esplanade des Particules 1, Meyrin, Switzerland

³Department of Physics and Astronomy, Vrije Universiteit, 1081 HV Amsterdam, The Netherlands

Received: 22 July 2024 / Accepted: 16 September 2024 / Published online: 18 November 2024
© The Author(s) 2024

Abstract We perform a detailed phenomenological study of high-energy neutrino deep inelastic scattering (DIS) focused on LHC far-forward experiments such as FASER ν and SND@LHC. To this aim, we parametrise the neutrino fluxes reaching these LHC far-forward experiments in terms of ‘neutrino PDFs’ encoding their energy and rapidity dependence by means of the LHAPDF framework. We integrate these neutrino PDFs in the recently developed POWHEG-BOX-RES implementation of neutrino-induced DIS to produce predictions accurate at next-to-leading order (NLO) in the QCD coupling matched to parton showers (PS) with PYTHIA8. We present NLO+PS predictions for final-state distributions within the acceptance for FASER ν and SND@LHC as well as for two experiments of the proposed Forward Physics Facility (FPF), FASER ν 2 and FLArE. We quantify the impact of NLO QCD corrections, of the parton showering and hadronisation settings in PYTHIA8, of the QED shower, and of the incoming neutrino flavour for the description of these observables, and compare our predictions with the GENIE neutrino event generator. Our work demonstrates the relevance of modern higher-order event generators to achieve the key scientific targets of the LHC neutrino experiments.

4 NLO+PS predictions for LHC far-forward neutrino experiments 10
5 Summary and outlook 19
References 19

1 Introduction

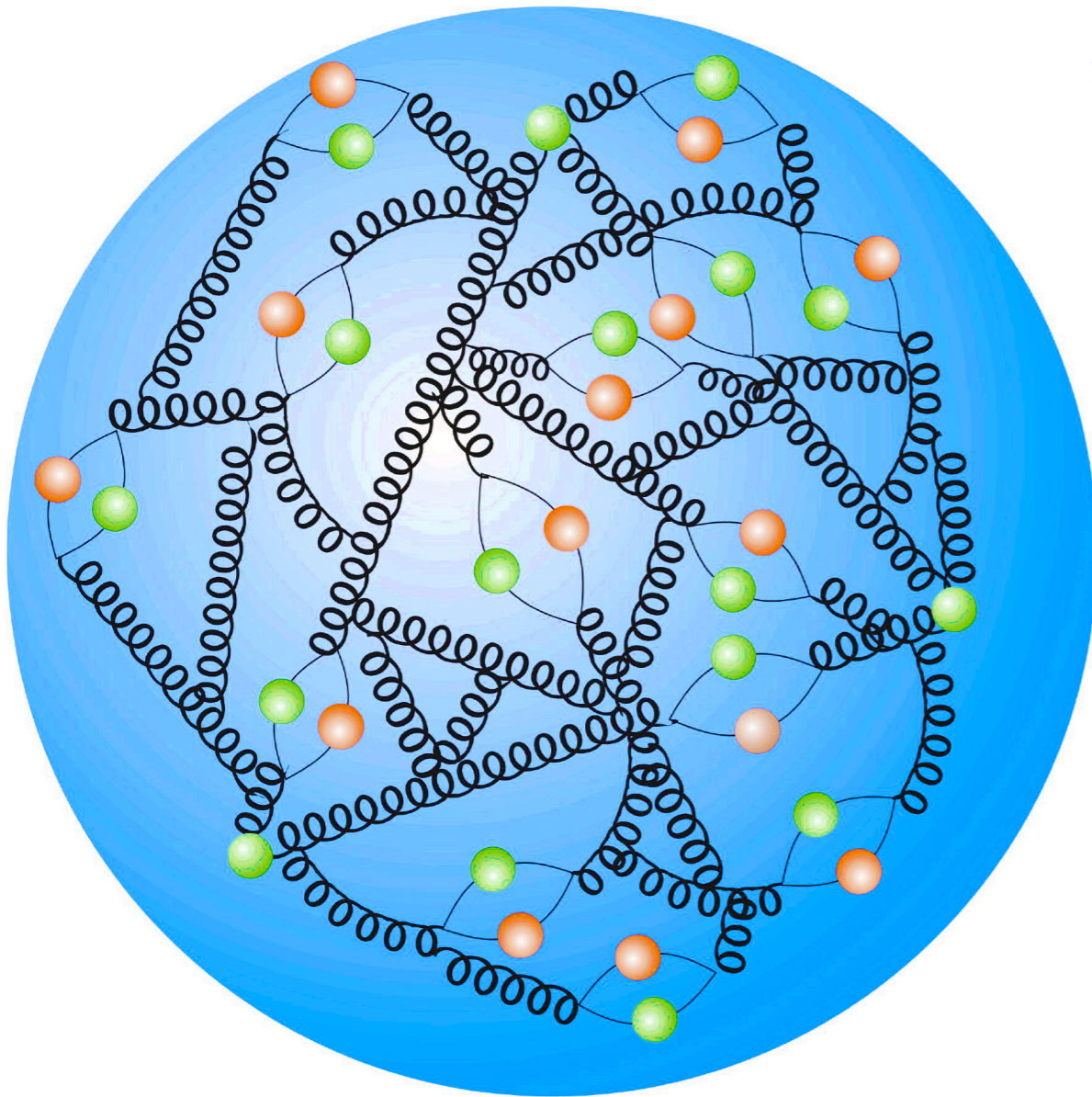
The recent groundbreaking observation of LHC neutrinos from the FASER [1] and SND@LHC [2] far-forward experiments, together with the first measurement of the neutrino interaction cross-section at TeV energies by FASER ν [3], herald the beginning of the collider neutrino era in particle physics. LHC neutrinos, characterised by the highest energies ever achieved in a laboratory experiment, provide unique information enabling novel opportunities in various areas of particle, hadronic, and astroparticle physics (see [4,5] for an overview).

Both FASER/FASER ν and SND@LHC will take data for the rest of Run-3, and FASER has also been approved to operate (albeit without the FASER ν module) during Run-4. An upgrade of FASER ν , dubbed FASER ν 2, together with new far-forward experiments, such as FLArE [6], may be installed in a proposed Forward Physics Facility (FPF) [4,5] operat-

Focus topics: proton structure with machine learning, searches for New Physics at the LHC and beyond using Effective Field Theories, high energy neutrinos at colliders and in the cosmos

The proton as a gateway to unravel QCD

QCD bound state of **quarks** and **gluons**



- ☑ **Valence quarks (up and down)** give the proton its quantum numbers (e.g. electric charge)

$$|\Psi\rangle \approx |uud\rangle$$

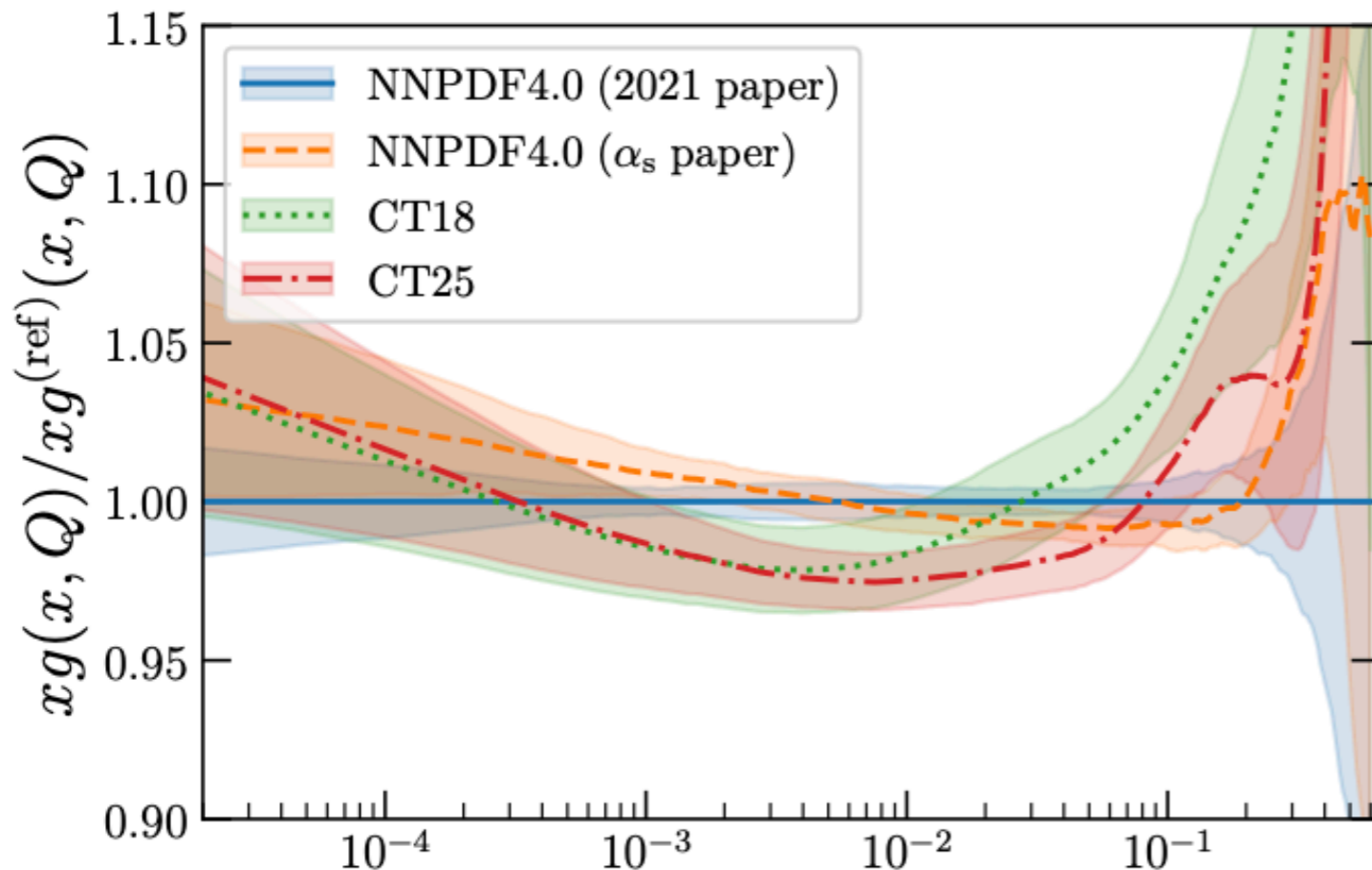
$$Q_p = +1 \quad \begin{array}{l} Q_u = +2/3 \\ Q_d = -1/3 \end{array}$$

- ☑ **Sea quarks (antiup, antidown, strange, ...)** arise from quantum fluctuations
- ☑ Tightly held together by **gluons**, can only be broken in extremely energetic collisions

The proton as a gateway to unravel QCD

Project goals:

- Use AI methods (**neural simulation based inference**) to design novel observables with optimal sensitivity to proton structure
- Implement the new pipeline in the NNPDF global analysis framework to study open questions in QCD, such as the heavy quark content of the proton or the gluon PDF
- Assess the implications for Higgs and BSM analyses at the (High-Luminosity) LHC

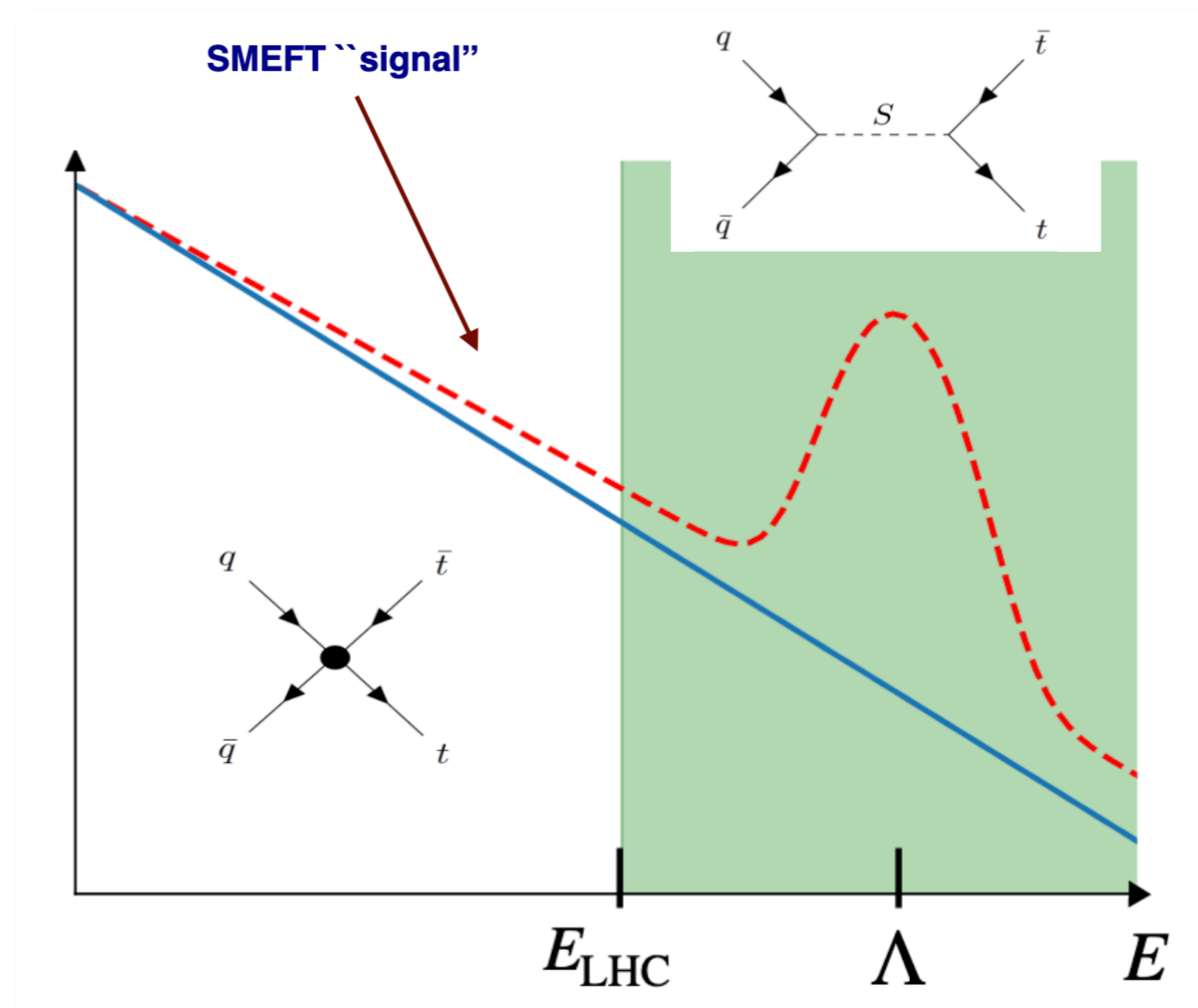


Which of the many available models of proton structure describe best the data, when using AI-boosted observables?

The Standard Model as an EFT

The Standard Model EFT is defined by:

- **Particle (matter) content:** quarks and leptons
- **Gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly-realized SU(2)_L EWSB
- **Validity only up to certain energy scale Λ**



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^2} \mathcal{O}_j^{(8)} + \dots$$

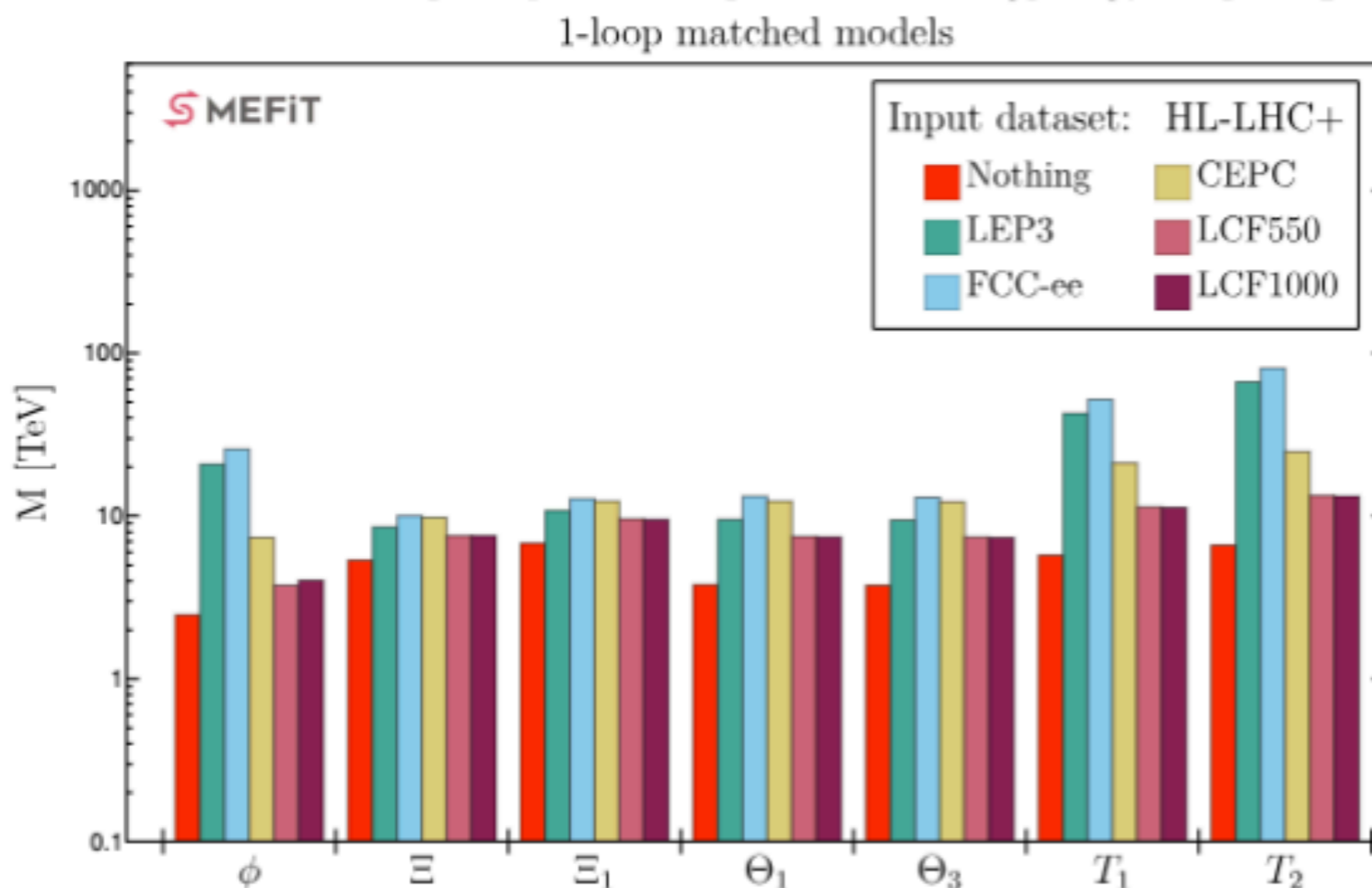
All possible operators of **mass-dimension 6** consistent with above requirements

Powerful, model independent framework to identify New Physics

The Standard Model as an EFT

Project goals:

- 🔧 Develop a new framework to search for New Physics at the LHC based on the EFT approach
- 🔧 Implement the new pipeline in the SMEFiT global analysis framework, matched to general models of New Physics, and extended to the latest data constraints from LHC.
- 🔧 Compare the **reach of the EFT approach** with that of direct searches.



Will EFT identify a New Physics signals at the LHC or future colliders?