Snowmass2021 - Letter of Interest

The EMPHATIC Table-Top Spectrometer: Enabling Hadron Scattering and Production Measurements for Improved Beam Simulations

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors
■ (EF05) QCD and strong interactions:Precision QCD
■ (EF06) QCD and strong interactions:Hadronic structure and forward QCD
■ (RF3) Fundamental Physics in Small Experiments
■ (RF7) Hadron Spectroscopy
■ (IF9) Cross Cutting and Systems Integration

Contact Information:
Name (Institution) [email]: Jonathan Paley (Fermilab) [jpaley@fnal.gov]

Authors: Jonathan Paley (Fermilab), Laura Fields (Fermilab), Mathew Muether (Wichita State University), Akira Konaka (TRIUMF)

Abstract: The EMPHATIC detector is a table-top sized spectrometer located at the Fermilab Test Beam Facility. The EMPHATIC collaboration plans a series of upgrades that will ultimately provide particle identification capabilities up to 15 GeV/c, allowing measurements of hadron scattering and production that will reduce accelerator-based neutrino beam flux uncertainties by a factor of two, to approximately 5%. In this LOI, we outline possible extensions of the EMPHATIC concept that would enable hadron scattering and production measurements that would further reduce neutrino flux uncertainties, improve our understanding of rates of Standard Model processes that are backgrounds to searches for rare processes, and make beamline designs more precise and robust.

Run	Momenta	Targets	Goals
1 (small acceptance config.)	4, 8, 12, 20, 31, 60, 120	C, Al, Fe	Elastic and quasi-elastic scattering, low-acceptance hadron production
2 (large acceptance config.)	4, 8, 12, 20, 31, 60, 120	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	Full-acceptance hadron production with PID up to 8 GeV/c
3 (large acceptance config.)	4, 8, 12, 20 31, 60, 120	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	Full-acceptance hadron production with PID up to 15 GeV/c
4 (NuMI Spectrometer)	120	NuMI Target + Horn	Hadron spectra downstream of horn

Table 1: The proposed phases of the EMPHATIC run plan. Each phase will have a data collection duration of 3-4 weeks at the FTBF.

Hadron scattering and production uncertainties are often among the dominant systematic uncertainties in particle physics experiments with characteristic energies below a few hundred GeV. First principle calculations with QCD are difficult since perturbation theory is not viable in these systems, and thus phenomenological models driven by data are required. Unlike nuclear structure or neutron scattering which have rich and organized modern data-sets, the hadron interaction data is sparse and often very old, even for basic quantities like elastic and quasi-elastic scattering on nuclei.

This lack of precise hadron scattering and production cross sections across a broad range of energies and nuclei results in simulated accelerator-based neutrino flux uncertainties of up to 30%. Over the past decade, a targeted global effort to collect hadron production data relevant to neutrino oscillation experiments has reduced the uncertainty in the predicted neutrino flux from greater than 20% to less than 10%. However, new precision measurements will be required to reduce the uncertainties below 5%.

EMPHATIC[1] is a low-cost, table-top-sized, hadron production experiment located at the Fermilab Test Beam Facility (FTBF) that will measure hadron interactions with careful evaluation of the systematic uncertainties. The spectrometer is based on a compact permanent dipole Halbach-array magnet and modern particle detector and data acquisition technologies. High statistics data will be collected using a minimum bias trigger, enabling measurements of both interacting and non-interacting cross sections. FTBF provides hadron beam with momenta between 1-120 GeV/c and the spectrometer has a 400 mrad solid angle acceptance for out-going hadrons. These energies and angles are very relevant for accelerator-based and atmospheric neutrino fluxes, but also for other experiments.

Table 1 shows the planned data collection runs for EMPHATIC. In the coming years, the new thin-target data collected by EMPHATIC and publication of the associated systematic covariances can reduce the neutrino flux uncertainty to 5% or below. The combination of EMPHATIC thin-target measurements with new mock- or actual neutrino production target measurements will further reduce neutrino flux uncertainties due to hadron production uncertainties to a couple of percent for NuMI and LBNF to a couple percent. We will then be in a new era where the dominant neutrino flux uncertainty arises from modeling the focusing system downstream of the production target, at the level of 4-5%. Although designed for thin-target hadron production measurements, the EMPHATIC spectrometer will also be used in 2023-2024 for a novel measurement of hadrons downstream of a neutrino focusing horn, depicted in Figure 1. The spectrometer will be moved to the MCenter beamline at Fermilab and used in conjunction with a replica NuMI target and spare NuMI focusing horn. A motion table will be used to move EMPHATIC across the downstream face of the horn. Measuring not only hadron production in the target but also reinteractions in the horn and unmodeled effects such as fringe fields and imperfections in conductor shapes, this will offer an new method of validating neutrino flux predictions. If successful, this measurement could be repeated with LBNF horns in the DUNE

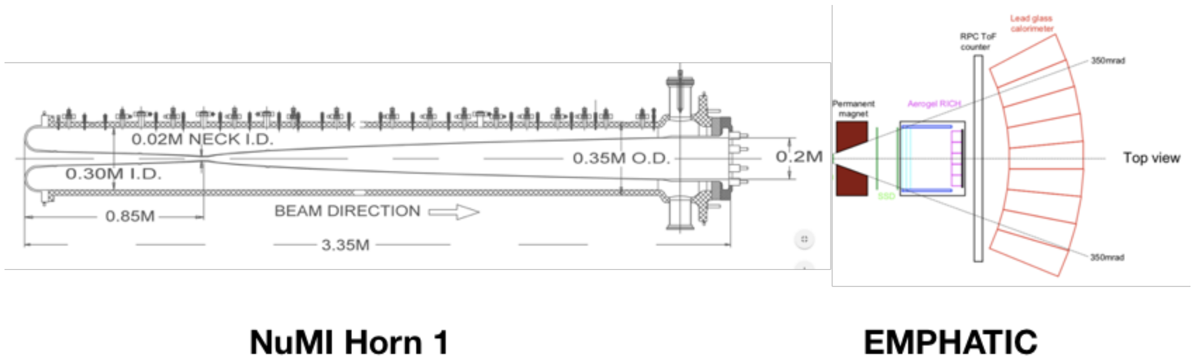

Figure 1: Caption

era.

The compact size of the EMPHATIC spectrometer is potentially game-changing, as small, relatively inexpensive spectrometers can be placed on movable platforms to conduct a myriad of measurements. Higher angle scattering measurements are possible by placing the spectrometer off-axis from the primary beam. Alternatively, 3D radiographs of smaller targets of nearly any geometry could be achieved by placing the target itself on a motion table. In either case, precision measurements covering $\sim 4\pi$ angular coverage are possible. Such data would make beamline designs more robust, simulations more accurate, and have possible medical or security applications.

The particle identification in the EMPHATIC proposal is achieved using a hybrid aerogel and heavy gas RICH detector and time-of-flight detector systems to separate particle types up to approximately 15 GeV/c. Higher momentum PID can be achieved using Cerenkov detectors with radiators of lower indices of refraction.

Hadron interaction data with systematic uncertainty covariance estimation is important for neutrino flux predictions and other applications where precise simulations and uncertainties on predictions are needed. As more and more hadron interaction data are compiled, we can rely less on the assumed empirical models. Machine Learning could become an ideal tool to digest hadron interaction data to develop a model interpolation once we have enough coverage of the phase space of hadron production.

With experiments like EMPHATIC, data for specific measurements can be collected on short time scales. These short setup and data-collection periods allow students and postdocs to gain rare hands-on experience of a project from the design, construction, operation and analysis. Such training is absolutely critical for the next generation of particle physicists.

In summary, the EMPHATIC table-top spectrometer concept is a cost-effective approach to enabling a large number and variety of measurements that will be extremely useful to the HEP community and beyond. EMPHATIC is a great example of how investments in relatively small experiments can have a out-sized impact on the field. The spectrometer can be used as-is for new measurements that will benefit currently and soon-to-be operational experiments. But because of it's compact size, it can also easily be expanded upon to meet the needs of a broad range of other kinds of measurements.

References

[1] T. Akaishi, et al, *EMPHATIC: A proposed experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions*, https://arxiv.org/abs/1912.08841

Additional Authors:
T. Akaishi (Osaka U.), L. Aliaga-Soplin (Fermilab), H. Asano (RIKEN), A. Aurisano (U. Cincinnati), M. Barbi(U. Regina), L. Bellantoni (Fermilab), S. Bhadra (York U.), W-C. Chang (York U.), A. Fiorentini (SDSMT), M. Friend (KEK), T. Fukuda (Nagoya U.), D. Harris (Fermilab/York U.), M. Hartz (IPMU, TRIUMF), Y. He (Fermilab), R. Honda (Tohoku U.), T. Ishikawa (Tohoku U.), B. Jamieson (U. Winnipeg), E. Kearns (Boston U.), M. Kordosky (College of William and Mary), N. Kolev (U. Regina), M. Komatsu (Nagoya U.), Y. Komatsu (KEK), K. Lang (U. Texas Austin), P. Lebrun (Fermilab), T. Lindner (U. Winnipeg, TRIUMF), Y. Ma (RIKEN), D. A. Martinez Caicedo (SDSMT), N. Naganawa (Nagoya U.), M. Naruki (Kyoto U.), E. Niner (Fermilab), H. Noumi (RCNP), K. Ozawa (KEK), M. Pavin (TRIUMF), P. de Perio (TRIUMF), M. Proga (U. Texas Austin), F. Sakuma (RIKEN), G. Santucci (York U.), T. Sawada (Osaka City U.), O. Sato (Nagoya U.), T. Sekiguchi (KEK), K. Shirotori (RCNP), A. Suzuki (Kobe U.), M. Tabata (Chiba U.), T. Takahashi (RCNP), N. Tomida (RCNP), R. Wendell (Kyoto U.), T. Yamaga (RIKEN), R. Zwaska (Fermilab)