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Request to run FASER in Run 4

FASER Collaboration

Roshan Mammen Abraham[1] **John Anders**[2] **Claire Antel**[3] **Akitaka Ariga**[4,5] **Tomoko Ariga**[6] **Jeremy Atkinson**[4] **Florian U. Bernlochner**[7] **Tobias Boeckh**[7] **Jamie Boyd**[2] **Lydia Brenner**[8] **Franck Cadoux**[3] **Roberto Cardella**[3] **David W. Casper**[1] **Charlotte Cavanagh**[9] **Xin Chen**[10] **Andrea Coccaro**[11] **Monica D'Onofrio**[9] **Stephane Débieux**[3] **Ansh Desai**[12] **Sergey Dmitrievsky**[13] **Yannick Favre**[3] **Deion Fellers**[12] **Jonathan L. Feng**[1] **Carlo Alberto Fenoglio**[3] **Didier Ferrere**[3] **Max Fieg**[1] **Stephen Gibson**[14] **Sergio Gonzalez-Sevilla**[3] **Yuri Gornushkin**[13] **Carl Gwilliam**[9] **Daiki Hayakawa**[5] **Shih-Chieh Hsu**[15] **Zhen Hu**[10] **Giuseppe Iacobucci**[3] **Tomohiro Inada**[10] **Luca Iodice**[3] **Sune Jakobsen**[2] **Hans Joos**[2,16] **Enrique Kajomovitz**[17] **Hiroaki Kawahara**[6] **Alex Keyken**[14] **Felix Kling**[18] **Daniela Köck**[12] **Pantelis Kontaxakis**[2] **Umut Kose**[19] **Rafaella Kotitsa**[2] **Susanne Kuehn**[2] **Thanushan Kugathasan**[2] **Lorne Levinson**[20] **Ke Li**[15] **Jinfeng Liu**[10] **Jack MacDonald**[21] **Chiara Magliocca**[3] **Josh McFayden**[22] **Andrea Pizarro Medina**[3] **Matteo Milanesio**[3] **Théo Moretti**[3] **Mitsuhiro Nakamura**[23] **Toshiyuki Nakano**[23] **Laurie Nevay**[2,14] **Ken Ohashi**[4] **Hidetoshi Otono**[6] **Hao Pang**[10] **Lorenzo Paolozzi**[2,3] **Brian Petersen**[2] **Markus Prim**[7] **Michaela Queitsch-Maitland**[24] **Hiroki Rokujo**[23] **Andre Rubbia**[19] **Jorge Sabater-Iglesias**[3] **Osamu Sato**[23] **Paola Scampoli**[4,25] **Kristof Schmieden**[21] **Matthias Schott**[21] **Anna Sfyrla**[3] **Savannah Shively**[1] **Yosuke Takubo**[26] **Noshin Tarannum**[3] **Ondrej Theiner**[3] **Eric Torrence**[12] **Svetlana Vasina**[13] **Benedikt Vormwald**[2] **Di Wang**[10] **Eli Welch**[1] **Samuel Zahorec**[2,27] **Stefano Zambito**[3]

[1]*Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA*
[2]*CERN, CH-1211 Geneva 23, Switzerland*
[3]*Département de Physique Nucléaire et Corpusculaire, University of Geneva,CH-1211,Geneva 4, Switzerland*
[4]*Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[5]*Department of Physics, Chiba University, 1-33 Yayoi-cho Inage-ku, 263-8522 Chiba, Japan*
[6]*Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan*
[7]*Universität Bonn, Regina-Pacis-Weg 3, D-53113 Bonn, Germany*
[8]*Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands*
[9]*University of Liverpool, Liverpool L69 3BX, United Kingdom*
[10]*Department of Physics, Tsinghua University, Beijing, China*
[11]*INFN Sezione di Genova, Via Dodecaneso, 33–16146, Genova, Italy*
[12]*University of Oregon, Eugene, OR 97403, USA*
[13]*Affiliated with an international laboratory covered by a cooperation agreement with CERN.*

[14]*Royal Holloway, University of London, Egham, TW20 0EX, United Kingdom*
[15]*Department of Physics, University of Washington, PO Box 351560, Seattle, WA 98195-1460, USA*
[16]*II. Physikalisches Institut, Universität Göttingen, Göttingen, Germany*
[17]*Department of Physics and Astronomy, Technion—Israel Institute of Technology, Haifa 32000, Israel*
[18]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[19]*ETH Zurich, Institute for Particle physics and Astrophysics, CH-8093 Zurich, Switzerland*
[20]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*
[21]*Institut für Physik, Universität Mainz, Mainz, Germany*
[22]*Department of Physics & Astronomy, University of Sussex, Sussex House, Falmer, Brighton, BN1 9RH, United Kingdom*
[23]*Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan*
[24]*University of Manchester, School of Physics and Astronomy, Schuster Building, Oxford Rd, Manchester M13 9PL, United Kingdom*
[25]*Dipartimento di Fisica "Ettore Pancini", Università di Napoli Federico II, Complesso Universitario di Monte S. Angelo, I-80126, Napoli, Italy*
[26]*Institute of Particle and Nuclear Studies, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan*
[27]*Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*

ABSTRACT: The FASER experiment was approved by the CERN Research Board in March 2019 to run through LHC Run 3. The operation of the detector during 2022 and 2023 LHC running has been very smooth with 97% of the delivered data recorded with good data quality. The release of first physics results in March 2023 demonstrated the excellent detector performance and that backgrounds are under control for physics analysis. The FASER Collaboration requests to continue to operate the experiment in LHC Run 4. This document summarizes the improvement in physics sensitivity expected by adding the Run 4 FASER data, increasing the total expected luminosity for physics from 250 fb^{-1} to 930 fb^{-1}. In addition, the ability of the detector to collect high quality data with the HL-LHC beams in Run 4, and the needed resources to continue operations, are presented.

Contents

1 Introduction

The ForwArd Search ExpeRiment (FASER) [1–3] at the LHC is designed to search for light and weakly interacting particles and to study high-energy neutrino interactions. The experiment was approved by the CERN Research Board in March 2019 for operation during LHC Run 3. The FASER detector [4] has operated flawlessly during 2022 and 2023 LHC operations, collecting 97% of the luminosity delivered to IP1. First physics results based on the 2022 dataset were released for the Moriond conference in March 2023, setting new constraints on dark photon parameter space in a region motivated by dark matter [5, 6] and observing for the first time interactions from collider neutrinos [7]. The speed at which these results were released and the quality of the results, where in both cases an almost background-free analysis was achieved, highlight the excellent detector performance, as well as the quality of the offline reconstruction, simulation, and analysis chain. Based on this and the strong physics case, the FASER Collaboration decided at the Collaboration Board meeting in June 2023 to request to continue to operate the experiment during LHC Run 4 (currently scheduled for four years, from 2029 to the end of 2032). The extension of FASER operations in Run 4 will significantly increase the physics output from the experiment with little additional resource needs, and it will allow further exploitation of the investment made in the construction of the detector and its upgrades and the development of the associated software tools.

A large fraction of the FASER Collaboration are actively working on the Forward Physics Facility (FPF) proposal [8], including the proposed FASER2 and FASERν2 experiments. Being significantly larger, these experiments will greatly improve the physics reach beyond FASER. For example, FASER will detect around 1000 ν_μ interactions in Run 3 and 2800 in Run 4, while detectors at the FPF will detect roughly 1000 *per day*. Therefore, extending the operation of FASER into Run 4 does not diminish the physics case for FASER2 or the FPF, but will rather bridge the gap between Run 3 FASER running and the start of FPF physics towards the end of Run 4 (assuming the FPF project goes ahead).

The baseline operational scenario presented in this note is that FASER would operate without the dedicated FASERν emulsion/tungsten neutrino detector in Run 4. This is because the higher muon background rate would require frequent FASERν exchanges. The option of installing a FASERν box for one exposure of about a month per year during Run 4 is being explored. However, for all FASER running during Run 4, we plan to install the 1.1-tonne tungsten target without emulsion film, since this would allow muon neutrino studies with the electronic components of the FASER detector, as was done in Ref. [7].

This document outlines the physics motivation for continued FASER running in Run 4 (Section 2), as well as the technical feasibility for detector operations in Run 4 (Section 3) and the implications in terms of resources (Section 4).

2 Physics Motivations

2.1 Assumptions for physics projections

The physics motivation for continuing to operate FASER in Run 4 is quantified for several scenarios in this section. For the projections shown, a number of assumptions are used, which are related to the expected beam and detector conditions.

A relevant parameter effecting the detector acceptance is the distance from the collision axis line-of-sight (LOS) to the centre of the FASER detector in the transverse plane. This depends on the (half) crossing angle magnitude and the crossing angle direction, as well as the detector alignment with the nominal LOS. The magnitude of the half crossing angle for Run 3 (Run 4) is assumed to be 160 μrad (250 μrad), which moves the LOS 7.5 cm (12 cm) at the FASER location. The values used for the projections are shown in Table 1. For 2022 and 2023 running, the values in Table 1 reflect the actual situation, whereas the values for 2024 and 2025 follow discussion with the LHC Programme Coordinators. The crossing angle values for Run 4 are taken from Ref. [9], and the expected luminosity from Ref. [10]. Figure 1 shows the projected integrated luminosity during Run 4 and is taken from Ref. [10].

Table 1: The assumed relevant LHC running conditions for the projected sensitivity shown in this Section. For the cases with horizontal crossing angle, we assume the detector is moved 5 cm sideways.

Year	Collision Energy	Luminosity	Half crossing angle magnitude, direction	Detector position	Distance from LOS
2022	13.6 TeV	40 fb^{-1}	160 μrad, $\downarrow$	1.2 cm $\downarrow$	6.3 cm
2023	13.6 TeV	30 fb^{-1}	160 μrad, $\downarrow$	1.2 cm $\downarrow$	6.3 cm
2024	13.6 TeV	90 fb^{-1}	160 μrad, $\uparrow$	1.2 cm $\downarrow$	8.7 cm
2025	13.6 TeV	90 fb^{-1}	160 μrad, $\rightarrow$	1.2 cm $\downarrow$ / 5 cm $\rightarrow$	2.8 cm
Run 3	13.6 TeV	250 fb^{-1}	–	–	ave.: 5.9 cm
Run 4	14.0 TeV	680 fb^{-1}	250 μrad, $\rightarrow$	1.2 cm $\downarrow$ / 5 cm $\rightarrow$	7.1 cm

2.2 Beyond Standard Model searches

In this subsection the projected FASER sensitivity for several beyond-the-standard-model (BSM) models are shown for the case where FASER only takes data in Run 3, or in Run 3 + Run 4. For simplicity, the projections shown assume a selection efficiency of 100% and no background. The first FASER dark photon search [6] demonstrated that a background-free analysis is feasible for such searches at FASER. In that analysis a typical signal selection efficiency of 50% was achieved. Assuming 100% efficiency for the projections does not have a significant affect on the sensitivity curves, especially when comparing the Run 3 and Run 3 + Run 4 results.

In the case of BSM scenarios leading to a signature with closely-spaced high-energy photons in FASER, such as axion-like particles (ALPs), the current FASER detector will not be able to achieve a background-free search, because of an irreducible background from high-energy neutrino interactions in the calorimeter. The installation of the high granularity tungsten/silicon preshower

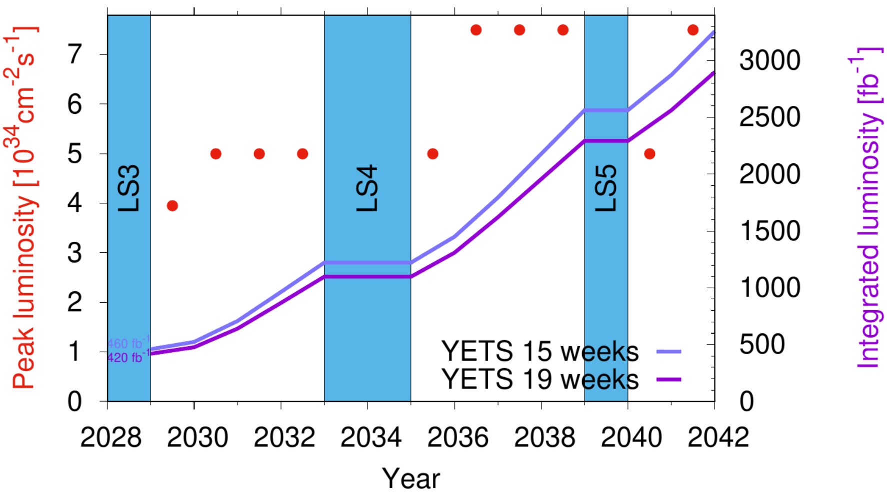

Figure 1: The projected luminosity production during LHC Run 4 taken from Ref. [10]. The blue and purple curves show the expected integrated luminosity based on different assumptions on the lengths of the year-end technical stops (YETS), where the more conservative 19-week YETS is assumed to give the total Run 4 luminosity of 680 fb^{-1}used in this document.

system [11] before 2025 data taking will allow a background-free analysis in this channel. For the projections of ALP sensitivity, we therefore present the expected reach with the 2025 data (90 fb^{-1}), compared to the full 2025 + Run 4 dataset (770 fb^{-1}).

Figure 2 shows the projected FASER sensitivity for dark photons in the dark photon mass ($m_{A'}$) and coupling (ϵ) plane for the Run 3 dataset and the combined Run 3 + Run 4 dataset. The sensitivity improves significantly with the addition of the Run 4 data, extending the region of parameter space probed up to masses of 200 MeV.

Figure 3 shows the projected FASER sensitivity in the ALP mass (m_a) and coupling (g_{aWW}) plane for the 2025 dataset and the combined 2025 + Run 4 dataset. In the model considered [12, 13], the ALP couples to gauge bosons and is predominantly produced in the decay of B mesons and decays to two photons. The sensitivity improves significantly with the addition of the Run 4 data, extending the reach in mass from 500 MeV to 900 MeV, and improving the lowest probed coupling value from $g_{aWW} = 6 \times 10^{-6}$ to less than $g_{aWW} = 2 \times 10^{-6}$.

Finally, Figure 4 shows the projected FASER sensitivity for a dark Higgs boson model. In the relevant region of parameter space the dark Higgs boson (ϕ) decays to either $\pi^+\pi^-$ or $\pi^0\pi^0$. For the projections shown, we calculate the signal yields assuming the full Run 3 luminosity for the charged pion final state, but only the 2025 luminosity for the neutral pion final state, since the preshower is needed to ensure a background-free analysis, and sum these to give the overall Run 3 sensitivity. In Run 3 alone, FASER can hardly probe new parameter space in this model, but adding the Run 4 data gives new sensitivity to masses from 300 MeV to 600 MeV and mixing parameters $\theta > 2 \times 10^{-4}$.

FASER has sensitivity in many other BSM scenarios, as discussed in Ref. [14]. The addition of the Run 4 data will improve the sensitivity to all models considered in this paper. Assuming essentially background-free searches, as has been realized in searches so far [6], it is possible that no BSM signal is found in Run 3, but 3 or more events are seen in Run 4, producing a 5σ signal.

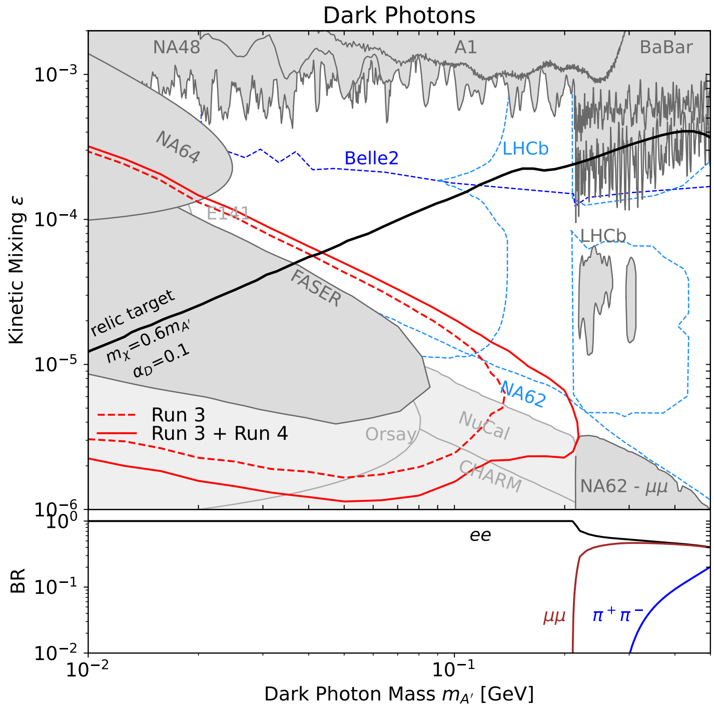

Figure 2: The projected sensitivity for dark photons for the Run 3 and Run 3 + Run 4 datasets. The bottom panel shows the branching fraction to the different final states as a function of the dark photon mass.

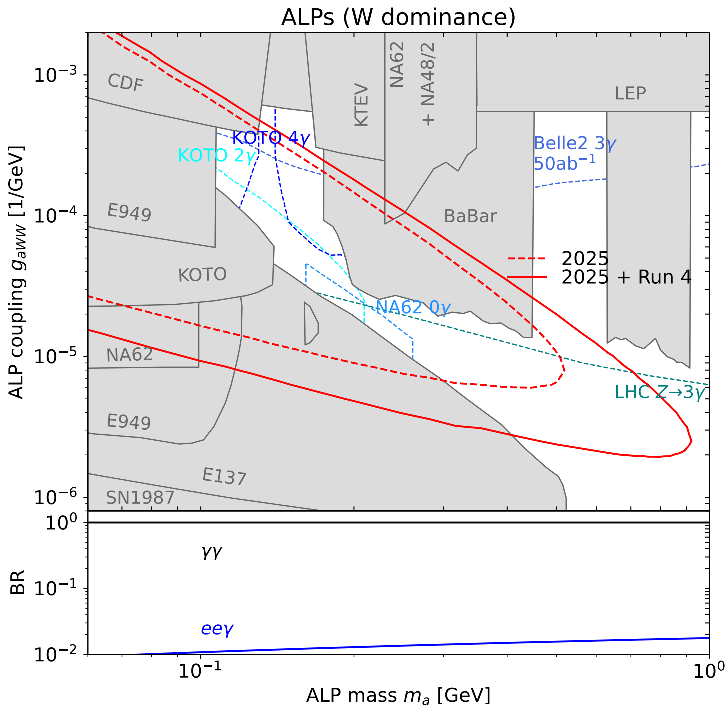

Figure 3: The projected sensitivity for ALPs with W couplings for the 2025 and 2025 + Run 4 datasets. The bottom panel shows the branching fraction to the different final states as a function of the ALP mass.

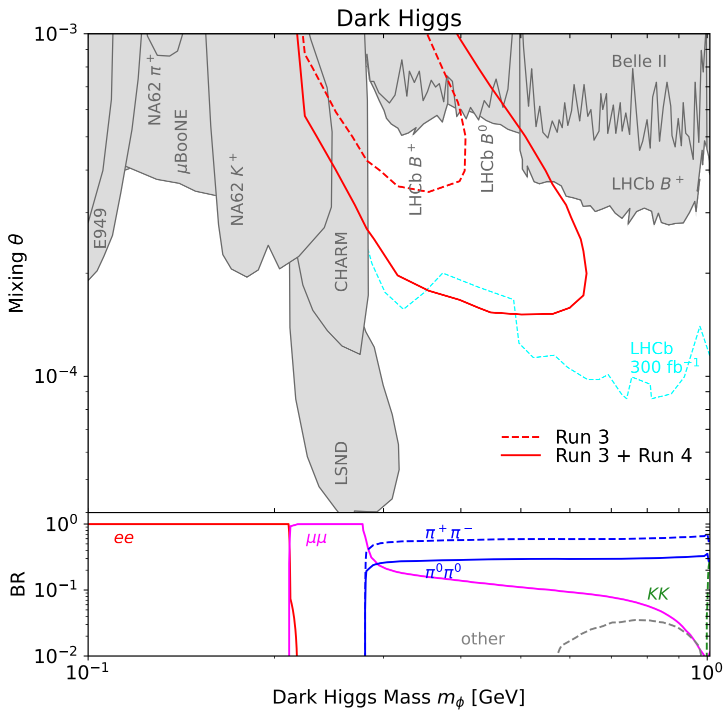

Figure 4: The projected sensitivity for dark Higgs bosons for the Run 3 and Run 3 + Run 4 datasets. The bottom panel shows the branching fraction to the different final states as a function of the dark Higgs boson mass.

2.3 Neutrino physics

The FASER study of muon neutrino charged-current (CC) interactions using the electronic detector components with the 2022 dataset [7] observed 153 neutrino candidates in 37.5 fb^{-1}. The same analysis running over the full 250 fb^{-1} of Run 3 data would yield around 1000 muon neutrino CC candidates, and in Run 4 an additional 2800 candidates would be available. The increase in the number of events would allow the statistical uncertainty on the inclusive yield to decrease from the 10% level to around 2%.

Figure 5 shows the projected statistical uncertainties from the 2022 + 2023, full Run 3, and Run 3 + Run 4 datasets for FASER muon neutrino CC cross section measurements.[1] As evident from the figure, FASER is sensitive to neutrino interactions in the window of energies between other accelerator and astroparticle experiments, where there is currently little data. In addition, FASER will be able to separately identify neutrino and anti-neutrino interactions for neutrino energies below 1 TeV.

The improved statistics from including Run 4 data will have important physics implications. For example, assuming the SM neutrino interaction cross section, which is relatively well known, neutrino measurements at FASER can be used to constrain the neutrino fluxes. This is shown in Figure 6, which shows the expected rate of detected CC muon neutrino interaction events for different bins of neutrino energy and flavour. The statistical uncertainty is shown for the 2022 + 2023 dataset, as well as for the full Run 3 and Run 3 + Run 4 datasets, showing a substantial increase in precision across all bins.

In addition, Figure 6 shows the flux composition of neutrinos arising from different hadron decays. The neutrino flux measurement will indirectly constrain the forward production of hadrons, in particular charged pions, kaons, and charm, which have not been measured before in the forward direction. This measurement will probe QCD in novel kinematic regimes (e.g., forward strangeness and charm, low-x QCD) and will provide useful input for astroparticle physics (e.g., the cosmic ray muon puzzle, prompt atmospheric neutrinos) [8, 15].

The increased statistics provided by the Run 4 dataset will also allow analyses of double differential flux measurements in terms of both neutrino energy and neutrino pseudorapidity. This will provide additional information that can be used to constrain the neutrino production mechanisms.

[1] This does not include the expected results using the FASERν emulsion detector in Run 3, which will have similar statistical power to the “electronic” neutrino analysis, but cannot distinguish neutrinos from anti-neutrinos. FASERν will also measure the electron and tau neutrino cross sections, which will not be possible with the pure electronic components of the detector.

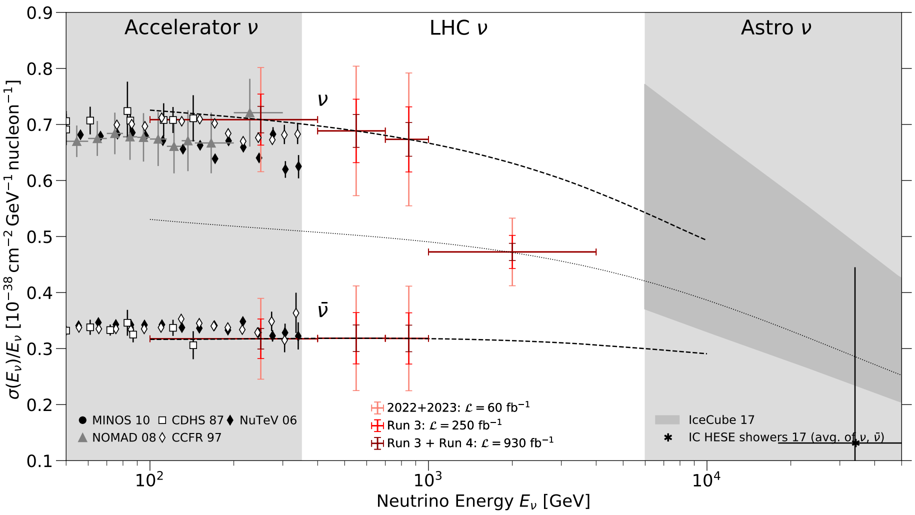

Figure 5: The projected statistical uncertainties from the 2022 + 2023, full Run 3, and Run 3 + Run 4 datasets for FASER muon neutrino CC cross section measurements. For energies less than 1 TeV the projections are shown separately for neutrinos and anti-neutrinos, whereas above 1 TeV it is assumed these cannot be experimentally differentiated. The digitized cross sections and plotting script from Ref. [16] were used to make this figure.

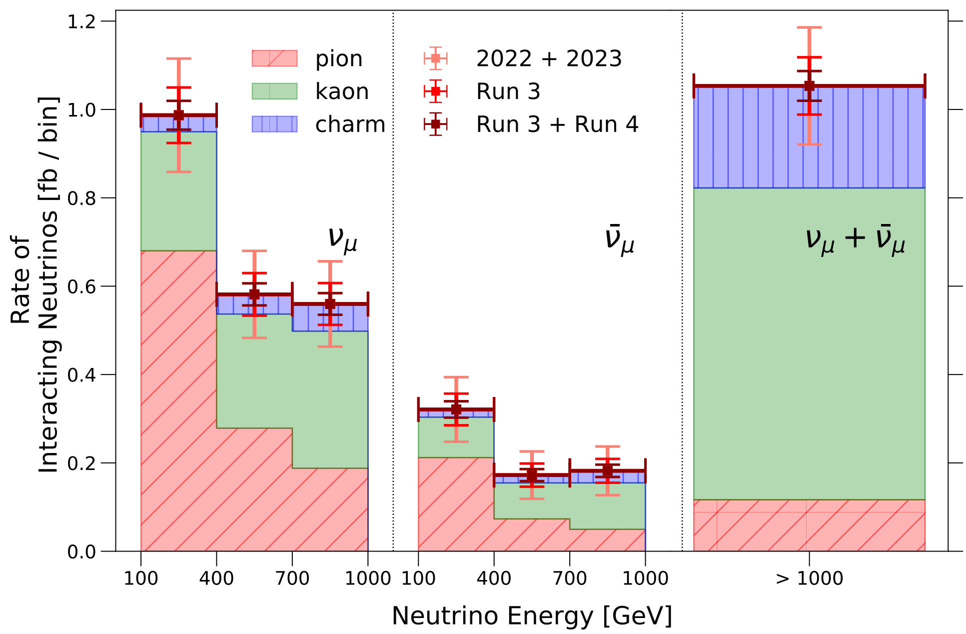

Figure 6: The projected number of muon neutrino CC interactions detected by FASER per fb^{-1} using the Run 3 and Run 3 + Run 4 datasets, as a function of the neutrino energy. For energies less than 1 TeV, the projections are shown separately for neutrinos and anti-neutrinos, whereas above 1 TeV it is assumed these cannot be experimentally differentiated. For each bin shown, the composition of the neutrino production (in terms of production from pion decay, kaon decay, or charm hadron decay) is shown.

3 FASER Operations in Run 4

3.1 FASER trigger rate

The most important change for detector operations in Run 4 is the increase in the flux of background particles (muons) traversing the detector initiated by the collisions in IP1. To assess the muon flux at the HL-LHC, FLUKA simulation [17, 18] studies were carried out in the context of the Forward Physics Facility (FPF) [8]. These studies [19] show an expected muon rate of 0.6 Hz cm^{-2} close to the LOS for an instantaneous luminosity of $L = 5 \times 10^{34}$ cm^{-2} s^{-1}, the maximum luminosity expected in LHC Run 4. Figure 7 shows the estimated muon flux from these simulations, in the transverse plane, where (0, 0) represents the nominal LOS.

The estimated flux is significantly lower than what would be expected by scaling the predicted rate at FASER in Run 3 (for $L = 2 \times 10^{34}$ cm^{-2} s^{-1}) by the increase in luminosity. This is because a large fraction of the LHC infrastructure between IP1 and FASER will be upgraded for the HL-LHC, with larger aperture magnets, stronger field separation/recombination dipole magnets (D1 and D2), and updated absorbers and collimators which are fully modelled in the HL-LHC FLUKA model. It should be noted that the FLUKA estimates of the muon background rates for LHC Run 3 have been validated at the 30% level by FASER [20] and SND@LHC [21] measurements, giving confidence that the simulations for the HL-LHC configuration will be reliable.

During 2022/2023 operations, the maximum FASER trigger rate was 1.5 kHz, dominated by triggers in the timing scintillator station. The rate is larger than that expected by muons traversing the detector systems due to a component from low energy particles firing the timing scintillators.[2] The observed maximum trigger rate is 130% higher than that expected from only muons traversing the detector (1.5 kHz versus 640 Hz), where this fraction does not scale purely with luminosity; it is higher at the start of physics fills and drops off as the fill progresses (likely related to beam losses from tails in the beam profile, which reduce during the fill). If we assume the same fraction of triggers from this source for Run 4, we would expect an overall FASER trigger rate in Run 4 of 2.2 kHz. The FASER TDAQ system [22] has been tested with optimized settings for high rate running. At a trigger rate of 2.5 kHz, a deadtime of <3% can be achieved. The specifications of the readout for the preshower upgrade require a deadtime of <5% at a trigger rate of 2.2 kHz. It is therefore expected that the current FASER experiment can efficiently take data in Run 4.

In the case that the trigger rate is higher than expected (for example, due to more beam background with the higher bunch intensities that will be used in Run 4), the FASER trigger menu can be adapted to significantly reduce the rate. Triggers from the timing scintillators can be prescaled or even removed, which can reduce the rate by more than a factor of two at the cost of some trigger redundancy.

3.2 Detector spares and maintenance

FASER was constructed in 2020 with sufficient spare components for the experiment to run throughout Run 3. There are at least one spare for every electronics board, power supply card, electronics

[2] These scintillators only require a signal in a single scintillator to fire, whereas other scintillator triggers require coincidence in signals between two adjacent scintillators, ensuring the incident particle to be energetic enough to traverse the two scintillators.

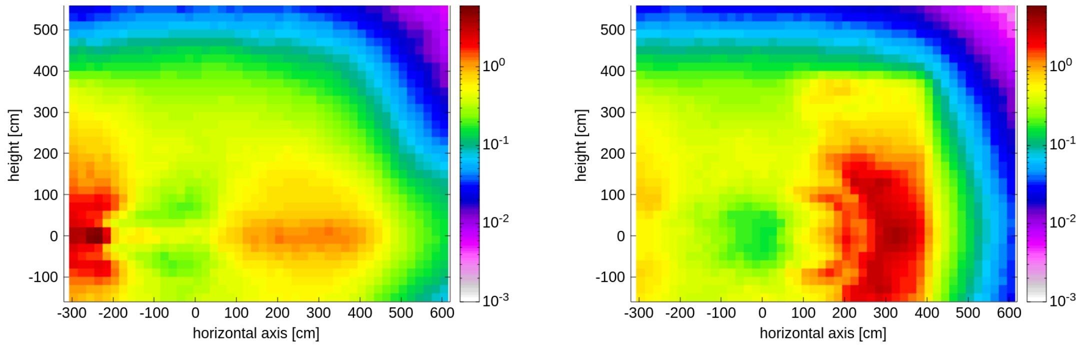

Figure 7: The FLUKA estimate of the muon fluence at the FASER location for the nominal luminosity of the HL-LHC of $5{\times}10^{34}$ cm^{-2}s^{-1} for negative muons (left) and positive muons (right). The fluence, in units of Hz/cm^2, is shown as a function of location in the transverse plane, where the origin $(0,0)$ represents the position of the LOS.

crate, and chiller, with more spares when there are many of the same component in the system. Therefore, to continue operating the experiment in Run 4, the existing number of spares is mostly sufficient. However, in some cases we have considered increasing the pool of spares or replacing components for running in Run 4, as discussed below:

- The FASER tracker readout boards (TRBs) and the trigger logic board (TLB) use the same GPIO FPGA board developed at the University of Geneva. Since the components for this board are starting to become unavailable, we plan to increase the set of spares for this by producing six additional boards.

- The FASER DAQ and DCS servers will be out of warranty at the end of Run 3, and we are considering to replace some or all of these with new machines for Run 4. (Given that the DCS machines only use a small fraction of their capacity, these may be kept with their hard-drives replaced.) The dedicated FASER switches in TI12 and on the surface (SR1) will also likely be replaced by CERN IT.

- FASER uses a custom electronics card from the CERN Beam Instrumentation (BI) group (the BOBR card) to access the LHC clock and orbit signals in the FASER DAQ system. These cards will stop being used by the BI group for Run 4, although discussions with BI experts suggest that they will likely still be supported in Run 4. If not, FASER should be able to move to the new WREN card that will be used by BI for Run 4 and beyond.

4 Resource Implications

To continue to operate the experiment in Run 4 and to produce physics results, there must be sufficient human resources working on FASER. The FASER operations model used in 2022 and 20023 running requires two shifters for detector operations, with each shift running for a week and generally taking up less than 10% of the time in that week. We also need to keep enough experts in the detector systems (including DAQ), as well as offline software (reconstruction and simulation).

All institutes currently working on FASER have indicated that they would continue to work on the experiment during Run 4, and that this would leave sufficient effort for additional work on the proposed FPF experiments. We therefore expect that there will be sufficient person power for covering operations shifts, as well as expert coverage to operate and maintain the experiment. We also expect to continue to be able to apply for funding for graduate students to work on FASER, which will make it possible to continue physics exploitation with the Run 4 data.

Resources will also be required to pay for the additional spares discussed in Section 3 and to support repairs and maintenance costs. Based on the considerations of detector spare parts discussed above, we have already reserved sufficient funds to support the expected hardware maintenance and operations costs of FASER through Run 4.

Extending FASER running in LHC Run 4 will not require significant additional resources from CERN as host laboratory. Computing resources provided by CERN would need to be increased to take into account the larger dataset, the increase in event size when including the preshower upgrade, and the need for storing Monte Carlo simulation and reprocessed data. Table 2 shows the requested resources for Run 3 and an estimate of the needs for Run 4. These requested resources are extremely small compared to the large LHC experiments.

Table 2: Requested computing resources in Run 3 and the expected needs for Run 4. Tape space to store raw data needs to include both the Run 3 and Run 4 data, whereas disk space and CPU needs are not cumulative in this way.

Year	Disk space (TB)	Tape space (TB)	CPU (HS06)
Run 3 (250 fb^{-1})	250	500	1000
Run 4 (680 fb^{-1})	700	1300	2000
Run 3 + Run 4 (930 fb^{-1})	700	1800	–

5 Conclusions

FASER requests to continue operations during LHC Run 4, increasing the expected luminosity from 250 fb^{-1} to 930 fb^{-1}. As shown in Section 2, this will lead to a significant increase in physics sensitivity. Given the expected increase in trigger rate and background levels for Run 4 conditions, the current FASER detector will be able to continue to efficiently collect physics data. If trigger rates are significantly higher than expected, mitigation strategies can be implemented to ensure continued operations.

Given that no significant changes to the detector are needed for Run 4 operations, only modest resources are needed to ensure sufficient spares and to replace some components. Discussions indicate that the Collaboration is committed to ensure that there will be the required person-power available to continue detector operations and fully mine the enhanced dataset for its SM and BSM physics implications.

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