Research proposal

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MESON:
Muon Excess Study with Off-axis Neutrinos

- **Goal:** explain the long-standing excess of muons in cosmic-ray showers.
- **How:** measure neutrinos in the far-forward region of LHC collisions.

Ultra-high-energy cosmic rays (UHECRs) are protons or heavy nuclei produced by unknown astronomical sources. They arrive at Earth, where they interact with our atmosphere, producing extensive showers of particles. The Muon Puzzle describes the large, unexplained excess of muons from the most energetic showers. The muon excess is large ($\sim$50%) compared to hadronic interaction models, and has been reported by multiple experiments. Studying cosmic rays using muons could provide valuable information on the mass composition of UHECRs. However, this potential is limited by the modeling uncertainties following from the Muon Puzzle.

A leading explanation is *strangeness enhancement* (ζ) in the shower: an excess of kaons at the expense of pions. This would lead to a higher multiplicity of muons observed at ground level. Such an enhancement has precedent in observations from the ALICE and LHCb experiments, but it has not yet been linked to UHECR showers.

This proposal seeks to study pion and kaon production from LHC collisions using the far-forward neutrino flux produced by pion and kaon decays. A neutrino detector will cover the pseudorapidity where the meson energy flux is expected to peak ($6.7 < \eta < 8.8$). The proposed detector, made from repurposed existing subdetectors, will be installed in the LHC tunnel $\sim$490 m downstream of the ATLAS experiment. Three deliverables are proposed: a measurement of the differential neutrino flux ($d^2\Phi_\nu/dE_\nu d\eta_\nu$), a constraint on the pion/kaon ratio, and a search/measurement of ζ. This program will further our knowledge of the meson composition of UHECR showers and may shed light on the Muon Puzzle.

Part I of the Scientific Proposal

Ultra-high-energy cosmic rays (UHECRs) are protons or heavy nuclei produced by unidentified astronomical sources. They are characterized by two traits: their energy and their mean logarithmic atomic mass, $\langle \ln A \rangle$. Various sources, such as active galactic nuclei or hypernovae, are predicted to produce UHECRs of different $\langle \ln A \rangle$ at different energies [1]. Accurate measurements of $\langle \ln A \rangle$ would advance our knowledge of these sources, but this is complicated by our limited understanding of how UHECRs interact with our atmosphere. A large excess of muons in cosmic-ray showers, called the **Muon Puzzle**, adds systematic uncertainties on the measurement of $\langle \ln A \rangle$. This document proposes an experiment to measure neutrinos produced by HL-LHC collisions to study cosmic-ray shower composition and shed light on the Muon Puzzle.

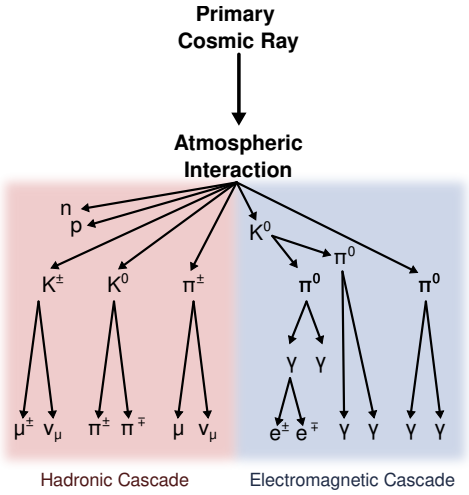


Fig. 1: Illustration of cosmic-ray shower and the hadronic (red) and electromagnetic (blue) cascades.

UHECRs arrive at Earth with incredible energies and collide with nuclei in our atmosphere. The collision of the primary cosmic ray creates bursts of energetic particles that interact or decay, leading to cosmic-ray showers. A shower evolves from an initial interaction into two semi-independent cascades of particles, as shown in Figure 1. The **electromagnetic cascade** is produced by mesons, especially π^0, decaying to photons. The **hadronic cascade** consists of long-lived hadrons: mesons (two-quark states) and baryons (three-quark states). Mesons like pions ($\pi^{\pm}$) and kaons ($K^{\pm}$, $K^0_{\mathrm{S/L}}$) often produce muons in their decay. These muons may be observed at ground level. Extensive ground-based observatories study UHECRs by observing such atmospheric showers.

Observatories like Pierre Auger (PAO) measure the energy of UHECRs with multiple independent methods. One method is the multiplicity of muons (N_μ) observed in the shower: higher energies or massive nuclei produce more muons. Alternative methods include imaging UV light emitted by the shower. Light nuclei deposit UV deeper in the atmosphere (X_{max}), and more energetic UHECRs deposit more UV overall. Both methods provide a prediction of the atomic mass of the UHECR. The Muon Puzzle arises as a discrepancy between estimates of atomic mass based on N_μ and other methods like X_{max}. PAO has reported that N_μ is 1.33-1.61 times larger than hadronic interaction models predict for a given atomic mass [2]. The discrepancy appears as an excess of muons from UHECRs beginning at $\sim 10^4$ TeV and becoming more pronounced at higher energies.

Observations of a muon excess relative to modeled expectations date back to HiRes-MIA in 2000 [3]. Since then, the muon excess has been replicated by multiple experiments. Observations from SUGAR show a N_μ excess of 1.7 times the expectation for 10^5 TeV proton primaries [4]. NEVOD-DECOR observed a 30% increase across a wide range of UHECR energies [5, 6]. The AGASA observatory measured an excess of 49–66% for UHECRs with energy above $10^{6.8}$ TeV [7]. Recently, the Jinping Neutrino Experiment reported a 44-51% excess of muons [8]. After decades of observation, the muon excess is significant (slope significance 8σ) [9], large ($\sim 30-60\%$) [10], and persistent.

On the theoretical side, it has proven difficult to simply retune the expected N_μ in showers. One study was unable to alter N_μ by more than $\sim 10\%$ without altering other observables including X_{max} [11].

The muons from UHECR showers can be observed both day and night, while optical methods require clear dark skies. The Muon Puzzle poses a significant limitation on their use to study UHECRs. Understanding the mechanism behind the Muon Puzzle would enable muon measurements to play a significant role in UHECR astronomy. An improved use of muons in UHECR showers is estimated to reduce the uncertainty on $\langle \ln A \rangle$ by a factor of 2.5-4 [10].

Explanation and models

The muon excess in showers suggests an enhancement of mesons that decay eventually to muons (especially $\pi^{\pm}$, $K^{\pm}$, $K^0_{S/L}$). A compelling explanation for this is an increase of kaon production at the expense of pions. Such a mechanism would shift energy that would enter the electromagnetic cascade (through $\pi^0 \to \gamma\gamma$) to the hadronic cascade. This has been labeled a **strangeness enhancement**, referring to the strange quark in kaons.

Outside of UHECR observations, strangeness enhancements have been observed at particle colliders. Collider measurements are relevant to UHECRs because a 10^5 TeV ray striking a stationary atmospheric nucleus is kinematically similar to a $\sqrt{s} = 14$ TeV collision at the LHC [10]. The forward region, along the collision axis, is particularly relevant. Air-shower studies show that more energetic mesons are more impactful to the evolution of the hadronic cascade than their less energetic counterparts [12]. It follows that the most relevant collisions are those with far-forward showers produced nearly along the collision axis, where hadrons carry a substantial fraction of the collision energy. The forwardness is described by pseudorapidity (η) which goes from $\eta = 0$ perpendicular to the collision axis to $\eta \to \infty$ along the collision axis.

The ALICE, LHCb, and FASER experiments have made measurements that help build a picture of forward strangeness.

The ALICE experiment has reported that strange-hadron production relative to pions increases with event multiplicity. This rise is observed in $K^0_S/\pi^{\pm}$, and is stronger for hadrons that contain more strange quarks, especially in the ratio $\Omega^{\pm}/\pi^{\pm}$ [13]. This is a clue, but the measurement is restricted to rapidity $|y| < 0.5$, which is outside the region most relevant to the Muon Puzzle [10].

The LHCb experiment also has a measurement of strangeness enhancement in the ratio D_s^+/D^+ in high-multiplicity proton-lead collisions [14]. Although D mesons are too rare in atmospheric showers to alter N_μ, this result reached $\eta < 5$ and suggests that strangeness enhancement continues into the forward region.

The picture is complicated by a recent FASER measurement of neutrino (ν) flux in the far-forward region $\eta > 8.8$ [15]. This found a deficit (p-value 5.9%) in the number of νs from kaons relative to pions - the opposite of what would be expected from strangeness enhancement.

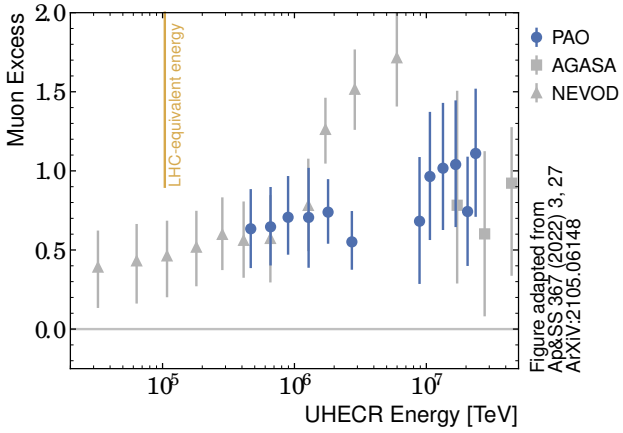


Fig. 2: Excess muons in showers compared to the EPOS-LHC model, highlighting PAO. The excess grows with UHECR energy in a *puzzling* way.

The results from ALICE and LHCb are suggestive, while the results from FASER indicate the picture is somewhat complicated in the far-forward region. A definitive search for strangeness enhancement in the intermediate pseudorapidity range is needed to resolve this tension.

In what region of phase-space would this strangeness enhancement have to appear in order to provide an explanation for the Muon Puzzle? The observations shown in Figure 2 give two known quantities: the magnitude of the enhancement and the energy scale at which it appears, the turn-on. Following [12], I parameterize strangeness enhancement with a modification factor ζ to the coefficients of pion production, $c_{\pi^{\pm 0}}$, and kaon production, $c_{K^{\pm 0}}$, in a shower. (These coefficients are inputs to step-by-step shower simulations, determining the probability of producing particular mesons.) ζ reduces $c_{\pi^{\pm 0}}$ and correspondingly increases $c_{K^{\pm 0}}$:

$$c^{\text{mod}}_{\pi^{\pm 0}} = (1-\zeta)c_{\pi^{\pm 0}}$$
$$c^{\text{mod}}_{K^{\pm 0}} = c_{K^{\pm 0}} + \zeta c_{\pi^{\pm 0}}.$$

As Figure 2 shows, the enhancement grows with energy, but the functional form is model dependent.

Phenomenological studies have suggested ζ could have a step turn-on [16] or a smooth growth [12, 17, 18]. At a collider it is convenient to use x_{thr} where x is the meson momentum fraction $x = p_{\text{meson}}/p_{\text{beam}}$. This defines a $\zeta - x_{\text{thr}}$ plane in which to search.

A number of mechanisms for strangeness enhancement have been proposed. Sibyll*, a set of tunes of the Sibyll hadronization model, alters hadron production and increases N_μ without significantly changing X_{max} [18]. One study suggests that deconfined quarks and gluons can lead to an enhancement of strange quark production [19, 20]. Another study proposes that showers consist of a dense core and rarefied corona, with a strangeness enhancement in the core [21]. These mechanisms can be differentiated by the energy and angular dependence of the enhancement. A precise measurement of ζ therefore helps both to reduce uncertainties on UHECR mass and may further identify the mechanism responsible for the excess muons.

The study [12] identifies the region of $\zeta - x_{\text{thr}}$ that is compatible with the muon excess observed by PAO. Most of this region is bound by $\zeta > 0.375$ and $x_{\text{thr}} < 0.1$, however this assumes a specific energy dependence for ζ. While useful as a guide, the paper notes that 8.4% uncertainty in the kaon/pion ratio is required to achieve the projected coverage. In reality, this is a challenging measurement and projecting FASER's recent measurement [15] to Run 3 luminosity suggests a $\sim 30\%$ statistical uncertainty. A dedicated measurement is necessary to better cover the $\zeta - x_{\text{thr}}$ plane.

Proposed measurement

One of the challenges in studying UHECR showers is the unknown initial conditions of particles arriving from space. Fortunately, collisions in the LHC produce similar showers in a controlled environment.

This proposal takes advantage of such collisions inside the ATLAS experiment. These collisions produce showers of pions, kaons, and charm-hadrons (H_c) that travel along the collision axis. Many of these mesons and baryons decay before being absorbed by materials. A beam of neutrinos produced by these decays travels along the collision axis from ATLAS through hundreds of meters of rock, while the LHC tunnel curves away. The νs emerge from the rock in the UJ12 utility tunnel as shown in Figure 3. Here, the flux is large enough that they can be studied via their rare interactions in target material. This principle was recently established by FASER and SND@LHC with the first measurement of collider neutrinos [22]. By measuring the ν flux in UJ12, it is possible to determine the meson composition of the original shower.

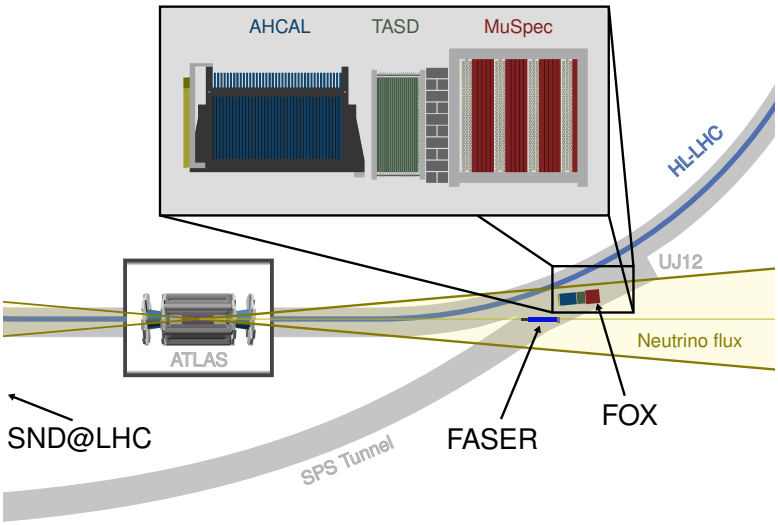


Fig. 3: Location of the FOX detector in the UJ12 tunnel (not to scale). The neutrino beam is produced inside ATLAS before reaching UJ12. The LHC curves away from the collision axis, allowing this space to be instrumented. FOX is placed off-axis, adjacent to the FASER experiment.

The optimal location to make this measurement depends on meson production. UJ12 covers a very interesting pseudorapidity for this purpose. The proposed measurement covers $6.7 < \eta < 8.8$: this is above LHCb ($\eta < 5$) and SND@LHC ($6.9 < \eta < 7.7$ in Run 4 [23]), and below FASER ($\eta > 8.8$). This range is important because according to simulations with the Sibyll [24] model and CRMC [25], the maximum for ν interactions from mesons falls in the pseudorapidity range $7.5 < \eta < 8.8$, as shown in Figure 4. The main background, neutrinos from H_c decays, peaks at lower pseudorapidity. The proposed measurement therefore covers both the region with maximum signal, while providing a constraint on the H_c background.

A detector built in UJ12 can make three important measurements:

- The **first measurement**: ν-flux. This is the differential flux measurement $d^2\Phi_\nu/dE_\nu d\eta_\nu$ in terms of neutrino pseudorapidity (η_ν) and energy (E_ν) for both electron-neutrinos (ν_e) and muon-neutrinos (ν_μ). The proposed measurement covers a region of pseudorapidity, much of which has never been instrumented for νs, and helps complete the global picture of forward ν-flux from SND@LHC and FASER.

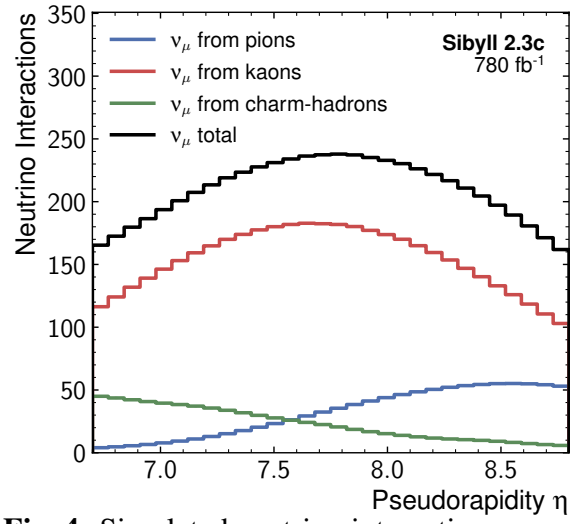


Fig. 4: Simulated neutrino interactions (> 200 GeV) in the proposed detector of muon-neutrinos produced by kaon (red), pion (blue), and H_c (green) decays. The proposed $6.7 < \eta < 8.8$ coverage helps to distinguish sources, isolating the H_c background.

- The **second measurement**: derive kaon/pion production. This uses the ratio of neutrino flavors, $R_\nu = N_{\nu_e}/N_{\nu_\mu}$. This is useful because ν_e are produced primarily by kaons and H_c decays, while ν_μ are additionally produced by $\pi^\pm$. For $E_\nu < 1$ TeV, the H_c contribution is small and the approximation $R_\nu \approx R_{\text{meson}} = N_K/(N_K + N_\pi)$ can be used [12]. However, the proposed measurement will extend to higher E_ν by taking advantage of the low-η_ν region to constrain H_c production in a combined fit of kaon, pion, and H_c for both ν flavors. This measurement is important to reconcile the different strangeness enhancements seen by ALICE, LHCb, and FASER. R_{meson} is also useful to constrain models of hadronic interactions for atmospheric-ν flux predictions, which are a background for ν observatories like IceCube [26].

- The **third measurement**: interpretation for ζ. This will either measure ζ, or exclude strangeness enhancement in the region most compatible with the muon excess. First, a strangeness enhancement can be searched for across the E_ν spectra in bins of energy. Next, if a non-zero ζ is measured, the location in the $\zeta - x_{\text{thr}}$ plane helps to support or exclude different mechanisms. A null result for ζ is also interesting: this would exclude a promising class of explanations for the Muon Puzzle, and raise a tension with the ALICE and LHCb results.

The final connection to the Muon Puzzle is the connection between ζ and the observed muon multiplicity N_μ. The MCEq air-shower simulation [27] is provided with the meson coefficients, modified by ζ. MCEq evolves the electromagnetic and hadronic cascades, relating ζ to the number of muons observed at ground level.

Together, these measurements form a unique physics program that has no equivalent at the LHC.

Experiment

A Forward Off-axis eXperiment (FOX) designed for these measurements has two requirements. First, it must reconstruct the energy of the showers from the ν interactions in the target material. This task is performed by calorimeters. Second, it must measure the momentum of the muon produced by ν_μ interactions. The muon is measured by a muon spectrometer which determines the momentum from the muon's deflection in a magnetic field. This proposal describes how FOX can be assembled on a short time scale, by adapting existing detectors that have been donated for this measurement.

FOX consists of three subdetectors, which I have the relevant experience to commission and operate.

- The hadronic calorimeter (AHCAL) is a pixelated sampling calorimeter that provides a target mass. As the project leader for AHCAL, I led the successful installation and data-taking in 2026, where we recorded data from 32.8 fb^{-1} of integrated luminosity.

- The electromagnetic calorimeter (TASD) was built in 2013 by AIDA [28], and has been donated to this project. It helps improve the energy resolution of electromagnetic showers originating in AHCAL.

- The muon spectrometer (MuSpec) will be built from single-wire proportional chambers (MDTs) that have been donated by the ATLAS experiment. I have worked extensively on the ATLAS Muon Spectrometer, including building a cosmic ray telescope with MDT chambers.

The arrangement of these subdetectors in FOX, and their location it the LHC tunnel, are shown in Figure 3 inset.

The planned data taking will begin in 2030, when the upgraded HL-LHC returns for its Run 4. In the first 2.5 years, an expected 390 fb^{-1} of integrated luminosity will be delivered from ATLAS collisions. This partial Run 4 dataset will provide sensitivity covering the region most preferred by the PAO observation shown in [12]. Subsequent measurements with the whole Run 4 dataset will extend below $\zeta = 0.1$.

Summary

The significant excess of muons in UHECR showers is a longstanding question in particle physics. This proposal describes how measurements of forward neutrino production can illuminate the meson composition of these showers, and possibly resolve the Muon Puzzle. Three unique measurements are proposed in the off-axis region $6.7 < \eta < 8.8$, much of which has never been covered. First, the differential measurements of neutrino flux $d^2\Phi_{\nu_e}/dE_{\nu_e}d\eta_{\nu_e}$ and $d^2\Phi_{\nu_\mu}/dE_{\nu_\mu}d\eta_{\nu_\mu}$, along with the flavor ratio R_ν, are useful inputs to simulate forward hadronization. Second, the ratio of mesons, R_{meson}, will help constrain the composition of UHECR showers. Third, the search and possible measurement of a strangeness enhancement ζ will eliminate many explanations for the Muon Puzzle, and hopefully identify the mechanism behind the muon enhancement. Figure 5 shows how the expected reach of the measurement in the $\zeta - x_{\text{thr}}$ plane compares to the level of strangeness enhancement best fit to PAO data.

The main challenge in making such a measurement is the detector. On this front, two coincidences align to make a measurement possible. First, the utility tunnel UJ12 happens to be located in the region of maximum meson flux from ATLAS. Second, several suitable subdetectors (AHCAL, TASD, MDTs) are available that fit the physics (and space!) requirements of this project.

The measurement is proposed to take place during the first half of the HL-LHC Run 4. The expected integrated luminosity from this partial dataset will provide sensitivity reaching $\zeta = 0.11$, below the preferred value $\zeta = 0.375$. Constructing and commissioning a detector would usually be beyond the scope of a small project. Re-using reliable subdetectors reduces the normal risk of detector development. This in turn allows a comprehensive program of integration to ensure the performance meets the requirements of the measurement. The FOX detector will be ready for data-taking by the start of Run 4 in 2030.

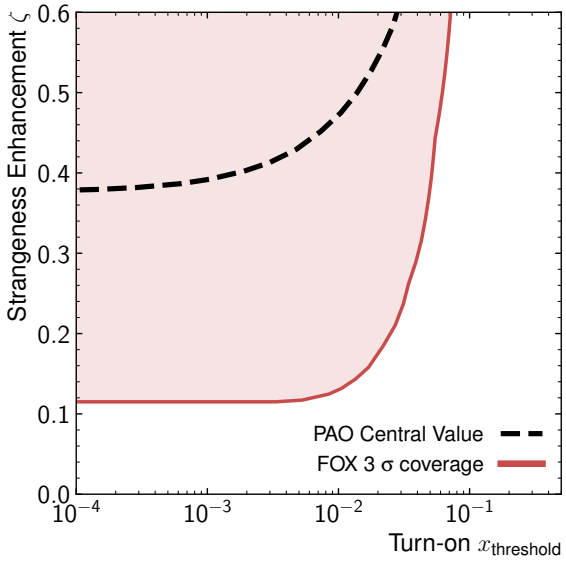


Fig. 5: Expected 3σ reach of the proposed measurement using the partial Run 4 dataset in the $\zeta - x_{\text{thr}}$ plane compared to the best fit to PAO data [12].

The Muon Puzzle is a decades-long mystery, and has limited the utility of muons as a source of information about UHECRs. This proposal shows how measurements of forward neutrinos at the LHC will offer unique and valuable information on the muon excess.

Part II of the Scientific Proposal

This document describes the opportunity to address the **Muon Puzzle** using the far-forward neutrino flux at CERN's LHC[1]. Next, it describes the methodology of how neutrino measurements can constrain the composition of UHECRs. To realize this, a new Forward Off-axis eXperiment (FOX) is defined to make this measurement during Run 4 of the HL-LHC. The FOX detector allows the physics reach of the measurement to cover the relevant phase space with the precision needed to address the Muon Puzzle. The final sections present the workplan, description of roles, and risk analysis.

The deliverables are the measurements: **D1** differential measurements of ν_e and ν_μ fluxes in a unique pseudorapidity (η), **D2** measurement of forward pion/kaon production, and **D3** a measurement or exclusion of strangeness enhancement as an explanation for the Muon Puzzle.

Measuring Forward Neutrinos

Collisions in ATLAS produce a large flux of light hadrons in the far forward region. Of interest are pions ($\pi^{\pm}$, π^0), kaons ($K^{\pm}$, $K^0_{S/L}$), and charmed mesons (H_c) that travel down the beampipe along the line-of-sight (LOS). Many long-lived charged mesons are swept away by the magnets of the LHC. Others decay promptly or happen to decay before being deflected, producing a flux of ν_e and ν_μ. These neutrinos travel hundreds of meters through rock, before reaching the location for the proposed measurement: the UJ12 service tunnel.

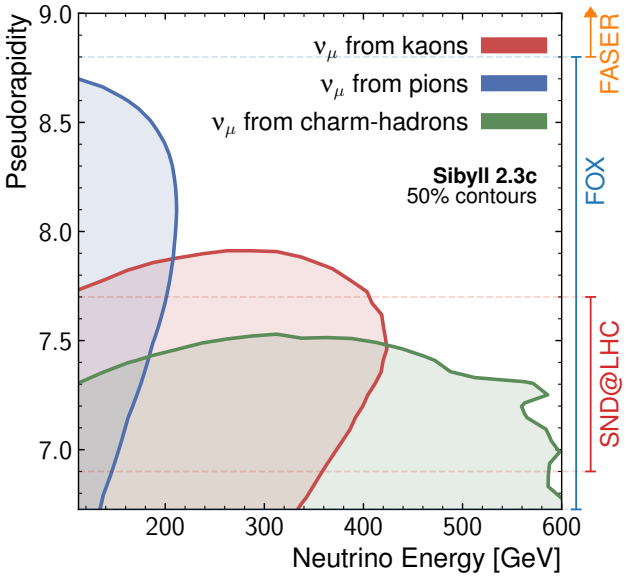


Fig. 6: Contours containing 50% of ν_μ from pion (blue) kaon (red) and H_c (green) sources. Highlights separation of sources. The η coverage of experiments is shown on the right axis.

Different production mechanisms (pion, kaon, H_c) can be separated by three observables: neutrino energy (E_ν), pseudorapidity (η_ν), and flavor. As separating these productions is central to the proposed measurement, it is helpful to develop a heuristic for their production. Figure 6 shows how the production mechanisms are separated on the $\eta_\nu - \mathrm{E}_\nu$ plane. Pion decays typically produce ν_μ with higher η_ν, while kaons populate lower η_ν. Pion decays generally have a softer energy spectrum than kaons. Charm-hadrons decay with a harder spectrum and produce lower η_ν. Neutrino flavor provides further separation, because while kaons contribute to both ν_e and ν_μ fluxes, charged pions preferentially decay to ν_μ. This separation in the $\eta_\nu - \mathrm{E}_\nu$ plane makes it possible to constrain each production mechanism.

Figure 6 also illustrates the η coverage of the proposed experiment compared to FASER and SND@LHC. The proposed coverage ($6.7 < \eta < 8.8$) has two advantages. First, it extends low enough to constrain the H_c background. Second, it extends high enough to isolate ν_μ produced by pions. The UJ12 cavern, which is located ~ 1 m off the LOS, provides the ideal location to cover this η.

This project presents three related physics deliverables.

The **first deliverable** is the measurement of forward neutrino flux. This is based on the very rare charged-current (CC) interactions of an incident ν upon a nucleon N_1 in a target mass: $\nu_\ell + N_1 \to N_2 + \ell^{\pm}$. The nucleon in the final state N_2 recoils and produces a hadronic shower. For $\ell^{\pm} = e^{\pm}$, this can produce an electromagnetic shower. For $\ell^{\pm} = \mu^{\pm}$, this produces a track in a detector. By measuring the hadronic shower, electromagnetic shower, and charged tracks, it is possible to reconstruct the incident neutrino energy, E_ν and pseudorapidity, η_ν. A preliminary study using only AHCAL shows

[1] This activity takes place outside of the EU, in Switzerland. It follows all CERN ethical, safety, and scientific integrity requirements. No additional ethical issues are identified.

promising CC flavor identification efficiencies: 81%(56%) for ν_μ (ν_e) using a simple neural network, with 17%(21%) neutral-current (NC) contamination. The rejection of NC events will improve with the addition of the MuSpec and TASD to tag muons and electrons respectively. This is the basis for measuring the differential flux, $d^2\Phi_\nu/dE_\nu d\eta_\nu$, in bins of η_ν and E_ν. It also provides the ν-flavor ratio, $R_\nu = N_{\nu_e}/N_{\nu_\mu}$, which is a model-independent measurement useful for comparison between experiments.

The **second deliverable** is the measurement of the meson ratio $R_{\text{meson}} = N_K/(N_K + N_\pi)$. This is based on fitting simulated templates for pion, kaon, and H_c in the $\eta_\nu - \mathrm{E}_\nu$ plane for both ν_e and ν_μ. Figure 6 shows how η_ν and E_ν separate the three production mechanisms, providing a good constraint on each. The production templates used for the fits are model-dependent, so this will be repeated with templates from the leading generators (EPOS-LHC [29], Sibyll 2.3c [24], QGSJetII-04 [30]). The good separation of the underlying distributions means this measurement can be made in several bins of η_ν. The highest bin, ending at $\eta = 8.8$, is contiguous with FASER acceptance, and will offer an interesting comparison with the observed kaon deficit in that region [31].

The **third deliverable** is the search for strangeness enhancement. This is parameterized by a modification ζ to the coefficients of pion production, $c_{\pi^{\pm 0}}$, and kaon production, $c_{K^{\pm 0}}$, in a shower. ζ reduces $c_{\pi^{\pm 0}}$ and correspondingly increases $c_{K^{\pm 0}}$:

$$c^{\text{mod}}_{\pi^{\pm 0}} = (1-\zeta)c_{\pi^{\pm 0}}$$
$$c^{\text{mod}}_{K^{\pm 0}} = c_{K^{\pm 0}} + \zeta c_{\pi^{\pm 0}}.$$

The first test is for a global non-zero ζ across the E_ν spectra. Afterward, different models propose different behavior for ζ: minimum turn-on energy, energy evolution, and momentum fraction x_{thr} are all model specific. Each relevant model can in turn be tested against the measured ζ.

Sensitivity Comparison

It is helpful to look at the importance of η coverage on ζ-sensitivity using a phenomenological study. The results shown here use ν production simulated by Sibyll 2.3c and CRMC [25]. The simulation covers kaon, pion, and H_c production in the forward region, but not the background from NC events. Charged mesons are required to decay before reaching the LHC magnet, while long-lived neutral mesons must decay before reaching material. Events are weighted by the probability of parent meson's decay before reaching its maximum travel. Neutrinos have a very small interaction cross section in matter that scales with their energy, so only a small fraction of ν interact with the proposed detector. Events are weighted by the interaction probability within a fiducial volume of the AHCAL.

Reconstructing neutrino interactions will use a dedicated algorithm, but the performance can be approximated with measurements and simulation. The energy resolution of AHCAL has been measured in test beams at CERN as $0.6/\sqrt{E\text{GeV}}$. This measurement dominates the reconstruction of ν_e, while the MuSpec measurement of muon momentum accounts for 80% of ν_μ energy resolution. The MuSpec was simulated in FATRAS [32] and hits were reconstructed into tracks using ACTS [33]. The FATRAS simulation does not account for punch-through of the hadronic shower from the calorimeter into the MuSpec, which can saturate the measurement from the first station. Punch-through is simulated in GEANT4 [34] in order to determine that 10 cm lead absorber adequately shields the MuSpec. The simulated MuSpec resolution grows with muon momentum from 19% (p_μ =150 GeV) to 25% (p_μ =1 TeV), including multiple scattering effects. For the results shown here, parameterized detector performance is used to smear reconstructed E_ν.

The $\eta_\nu - \mathrm{E}_\nu$ planes from kaon, pion, and H_c production are fit to an Asimov dataset, across both neutrino flavors. Detector resolution is modeled by smearing the event kinematics based on the expected resolution. R_{meson} and the enhancement ζ are extracted with fits, along with their uncertainties.

The procedure is repeated for Asimov datasets corresponding to different degrees of ζ and an enhancement with a small x_{thr}. The resulting significance of the measured ζ relative to the injected ζ is shown in Figure 7. The 3σ reach extends down to $\zeta = 0.11$ for the partial Run 4 integrated

luminosity, and $\zeta = 0.08$ with the full luminosity. Changing the hadronization model to EPOS-LHC has a negligible impact on these results.

This study also highlights the importance of the position of the detector, compared to other experiments. The same study is repeated assuming similar detector performance and $\eta - \phi$ acceptance matching SND@LHC, with the interaction cross-section scaled up by SND's larger target depth. This comparison shows how different η coverage impacts sensitivity to ζ, but this is a simplistic model and doesn't fully represent the performance of SND. It should also be noted that strangeness enhancement is not the primary physics focus of SND, and its location is optimized for a H_c/flavor physics focus. Constraints on charm production by SND will provide a valuable constraint for the proposed measurement.

Another useful combination would be with the on-axis FASER measurement. Combining with this would yield a 12% improvement in sensitivity, compared to the off-axis measurement on its own.

The lowest ζ allowed is somewhat model dependent. In a more realistic phenomenological model proposed by [12] the strangeness enhancement appears for mesons carrying a momentum fraction above x_{thr}. Following this model, the toy analysis is expanded to cover two dimensions, as shown in Figure 8. These plots show the 3σ and 5σ sensitivity in the $\zeta - x_{\text{thr}}$ plane. Figure 8a and Figure 8b highlight the coverage with respect to the preferred values to explain the PAO observation. Comparing Figure 8a and Figure 8b highlights the strength in x_{thr} of the on-axis FASER vs the strength in ζ of the off-axis FOX. Figure 8c shows the impact of luminosity and the combination of FASER+FOX for maximal sensitivity.

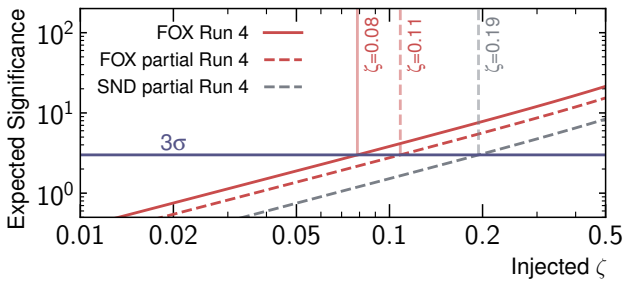
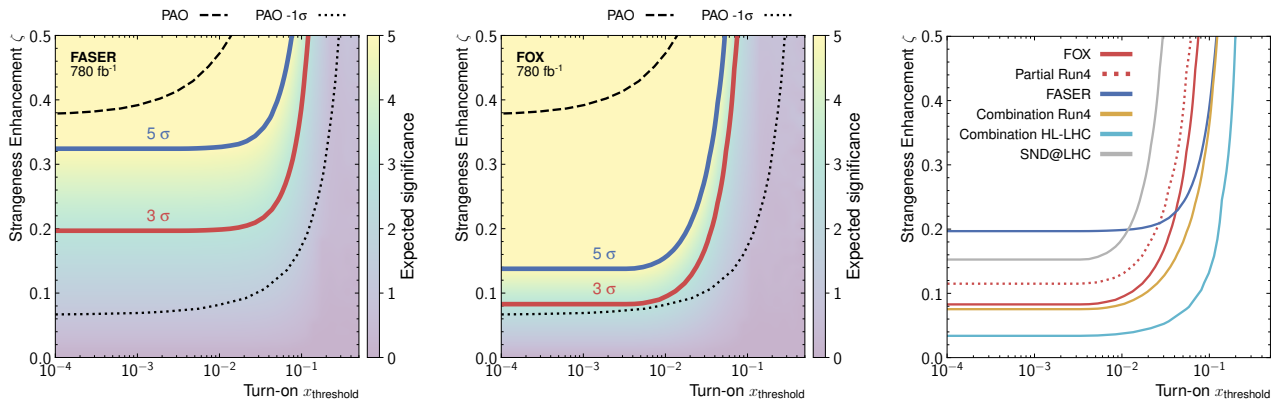


Fig. 7: Expected significance for different sizes of strangeness enhancement ζ. The lowest ζ with sensitivity above 3σ is marked.



(a) FASER **(b)** FOX **(c)** 3σ comparison

Fig. 8: Contours showing 3σ and 5σ sensitivity on the $\zeta - x_{\text{thr}}$ plane. The curve most compatible with the PAO observation [12] is shown as a dotted line in (a) and (b). (c) compares sensitivity of FOX with the full and partial Run 4 dataset (red), FASER (blue), and a FASER+FOX combination (yellow). A comparison of FOX vs SND@LHC/FASER illustrates benefit of the $6.7 < \eta < 8.8$ range for this measurement.

This study shows that FOX covers a significant region of phase space preferred by the PAO observation. Despite this, some regions within 1σ of the preferred region are inaccessible in this model. Although improvements in the analysis strategy are anticipated to improve sensitivity, it remains possible that no strangeness enhancement will be measured. A null result for strangeness enhancement will focus searches on the remaining phase space. A longer exposure and full HL-LHC luminosity (3000 fb^{-1}) will also enable sensitivity down to $\zeta = 0.035$ for low x_{thr}. Regardless of the ζ result, the flux and R_{meson} measurements will be valuable contributions to our knowledge of forward ν production.

Building the Detector

This section describes the experiment required to make these measurements. The three detector subsystems are shown in Figure 9: 1) the Analog Hadronic Calorimeter (AHCAL), 2) the Totally Active Scintillating Detector (TASD) calorimeter, and 3) a Muon Spectrometer (MuSpec).

Of the enormous number of neutrinos produced in ATLAS, several thousand will interact with the steel target of AHCAL. The neutrinos recoil off of a nucleon in the target (charged current), producing a hadronic shower and a charged lepton. The TASD electromagnetic calorimeter improves the energy reconstruction for electrons. In the case of muons, their momentum is measured by their deflection in the muon spectrometer.

This proposal is made feasible by reusing existing detectors and electronics kindly donated by their previous owners (ATLAS, USTC, AIDA). In this section, workpackage steps (WP) and milestones (M) corresponding to Figure 10 are highlighted.

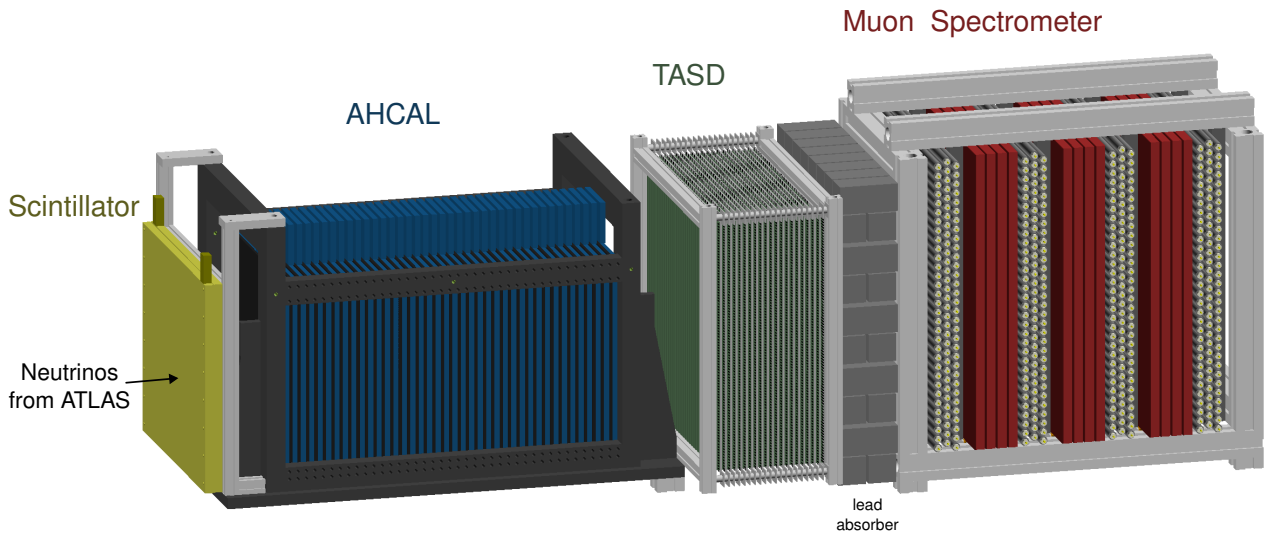


Fig. 9: Illustration of the detector system, consisting of muon veto scintillators (yellow) followed by the AHCAL calorimeter (blue), the TASD used as an electromagnetic calorimeter (green) and the muon spectrometer consisting of MDT chambers (beige) and magnet stations (red). Neutrinos produced in ATLAS collisions enter the detector from the left and interact inside AHCAL.

Hadronic Calorimeter (AHCAL)

AHCAL [35] is a pixelated sampling calorimeter based on the CALICE design [36]. It consists of 40 layers featuring 4×4 cm^2 plastic scintillating tiles. It was built in 2022 as a prototype, and returned to CERN to be installed next to FASER in 2026. As project leader, I oversaw the collection of 32.8 fb^{-1} of data with AHCAL. With 39 steel absorber plates (2 cm thick), AHCAL will also provide the 3.2 ton target mass for neutrino interactions in the forward section of the calorimeter.

Several minor upgrades to improve performance are necessary. The main readout board is limited in bandwidth and will be replaced with commercial FPGA boards WP-A1. Minor repairs are needed on the front-end electronics WP-A2. Aside from this work, AHCAL is suitable for data taking in Run 4. AHCAL with the new readout board will be assembled in the EHN1 lab and tested with the CERN muon beam M1.

Electromagnetic Calorimeter (TASD)

The AIDA project built TASD, a segmented plastic-scintillator detector consisting of layers of scintillating bars monitored by SiPMs [37]. The 1 cm pitch of the bars is finer than AHCAL's pixels, providing a more granular measurement of an electromagnetic shower. The major work for TASD is the replacement of its readout chain with a modern system WP-A3. This will be nearly identical to the readout designed for another FASER Run 4 upgrade project, FORTVNE. The only difference is that due to the different geometry of the scintillators, the SiPMs will need to be mounted on their

own specialized PCB. The testing for the TASD electronics involves validating 3600 SiPMs and 360 carrier PCBs. This procedure will follow a similar validation procedure designed for FORTVNE: boards will be attached to scintillators, and their output digitized on a test bench in order to build a calibration database WP-A4. At this point, data acquisition (DAQ) software will be developed WP-A5. Otherwise, the readout electronics are identical, simplifying development and integration. Additionally, lead absorbers will be inserted between the scintillating layers to optimize the capture of electromagnetic showers. Once ready, the TASD will be assembled in the EHN1 lab and tested with the muon beam M2.

Muon Spectrometer

The MuSpec is the core detector development in this proposal. MuSpec is based on Monitored Drift Tubes (MDTs), the gas-filled single-wire proportional chambers used in the ATLAS Muon Spectrometer. Many MDT chambers will be removed from ATLAS as part of its upgrade for HL-LHC. Eight of these (BIS480) will be arranged into four stations separated by three magnet stations. The main work is the production of the magnets, an adapter card, and a gas system.

The design of the electromagnets is based on similar magnets built for the BabyMIND detector [38]. These consist of ARMCO steel-core plates machined with slots. Conductors are wrapped through the slots, providing a uniform 1.5 T field contained in the steel. The magnets will be built by the Magnet Group at CERN WP-B1.

The legacy front-end electronics will digitize the output from the MDTs. An adapter board will serve as a communication interface to the front-end carrying data, configuration, and timing. This system will be built mostly with commercial components, with the advantage that it can be shared by other recipients of the MDTs WP-B2. The adapter board will require firmware to communicate with DAQling software [39] via an Ethernet connection WP-B3.

The gas system must supply the MDT chambers with a hydrated mixture of 93% Ar and 7% CO_2 gas at 3 bar. The gas is continuously replaced to remove contaminants. The radiation environment in UJ12 is less severe than in the ATLAS cavern; a lower gas replacement rate will be suitable. The outflow from the chambers will be tested for contaminants during the commissioning phase to determine the minimum flow rate WP-B4. Depending on the flow rate, the system will require a recirculation pump, safety systems, and three 50L cylinders to operate for eight months WP-B5.

Testing, integration and commissioning

In order to ensure smooth data collection during operation, it is essential to test every component individually before installation. The system will be commissioned on the surface using the test beam available in EHN1. Testing falls into three categories: new constructions, reused electronics, and detectors.

Power supplies are required: LV for the front-end, HV (3kV) for the MuSpec chambers, and high-amperage for the magnet system. These need to be integrated with the DCS system WP-C1. Simultaneously the mechanical structure for TASD and MuSpec will be prepared WP-C2. The combined DAQ and event building from each subdetector will be integrated WP-C3. Data quality monitoring will be developed consisting of online monitoring during data taking, and offline monitoring once runs are completed WP-C4.

The trigger system will be based on the current AHCAL trigger. Four layers of AHCAL will provide fast trigger signals to detect a coincidence between layers. The forward scintillators are used to veto muons entering FOX from ATLAS. This will be controlled by a FASER trigger logic board, and will be adapted for FOX WP-C5.

As soon as possible, the subdetectors will be tested in combined runs in EHN1 WP-C6. A full integration of the trigger and DAQ readout chain defines M4. An integration program is essential to ensure that everything works together before installation: event reconstruction, DCS, data quality monitoring, and trigger will be confirmed to work together before installation in UJ12.

Operation and data taking

Preparation for operation begins in UJ12 a year before the start of HL-LHC in 2030. The installation of the gas system and power cables requires flexibility to accommodate the Engineering Department's schedule **WP-D1**. Each magnet layer weighs 800 kg, so they must be transported to UJ12 separately before being assembled into the three magnet stations on-site **WP-D2**. At this point, the three subdetectors will be transported to UJ12 **WP-D3**, and start combined data taking in the tunnel **M5**. DCS monitoring will be enabled at each stage (gas installation, services, power-up) **WP-D4**.

Physics collisions are expected to begin in the second half of 2030. FOX will begin continuous calibrations **WP-D5** once each subdetector is running. The muon spectrometer requires periodic alignment with the magnets off to provide straight muon tracks **WP-D6**. Physics data taking will begin and continue throughout Run 4, with maintenance work and gas replacement during yearly technical stops **WP-D7**. The anticipated data volume is 0.1 TB/fb^{-1}, or 39 TB in total, to be stored on CERN's EOS and a backup machine. Online data quality will be integrated into the DAQling software framework. Continuous data monitoring for each run will be performed when data is synchronized to EOS. Environmental monitoring, ADC peaks, and pedestals will also be logged.

The HL-LHC Run 4 is expected to provide an integrated luminosity of 780 fb^{-1}. This proposal covers operations for the first 2.5 years, with an expected integrated luminosity sufficient to shed light on the Muon Puzzle **M6**. Continued operation throughout Run 4 is anticipated with future funding.

Program and Planning

Workpackage	Scope	Outcome/Milestones
A - Calorimeters	Prepare AHCAL and TASD for individual operation, including electronics development.	M1: AHCAL data taking M2: TASD data taking
B - MuSpec	Construct MuSpec, adapter card, magnets, and gas system.	M3: MuSpec data taking
C - Integration	Mechanical structures, DAQ development, data quality, and combined data taking with beam test.	M4: Combined data taking M5: Installation in UJ12
D - Operation	Installation in UJ12, physics data taking, monitoring, calibrations/alignment.	Performance measured by data quality.
E - Analysis	Simulation, background studies, reconstruction, and measurement deliverables D1, D2, D3.	M6: Analysis complete for publication.

Roles and Responsibilities

This proposal supports three roles: a PI, a CERN Research Fellow (GRAF) and a CERN-associated doctoral student (DOCT). The PI is responsible throughout the project for each workpackage. During the intense period of commissioning and integration, a GRAF and later a DOCT student join. The former will focus on readout and the latter on testing - but the whole team will work closely on all aspects of the project. The DOCT program supports an external PhD candidate to be at CERN for one year; afterwards they are supported by their home institution continue the analysis.

Role	Responsibility	Workpackage Period
PI (funded)	All workpackages; coordination	Throughout
GRAF (funded)	Readout, integration, commissioning	Integration
DOCT (funded)	Testing, commissioning, analysis	Later integration; analysis
FASER students	DCS, monitoring, calibration, analysis	As needed
FASER engineers	Electronics, mechanics	Early design
FASER other	Installation, DAQ, shifts, facilities	Integration; operation

All critical components of this project are supported by this proposal, but person-power will be augmented by FASER collaborators. First, collaborator Hiroaki Menjo will provide two students to help with tasks like DCS, calibrations, and analysis. Second, collaborator Enrique Must will support an engineer to help with board design, and FASER's mechanical engineer will help with the mechanical structures. Third, certain aspects of the installation (person-power), operations (DAQ infrastructure, shifts) and facilities (lab space) will be supported by the FASER collaboration.

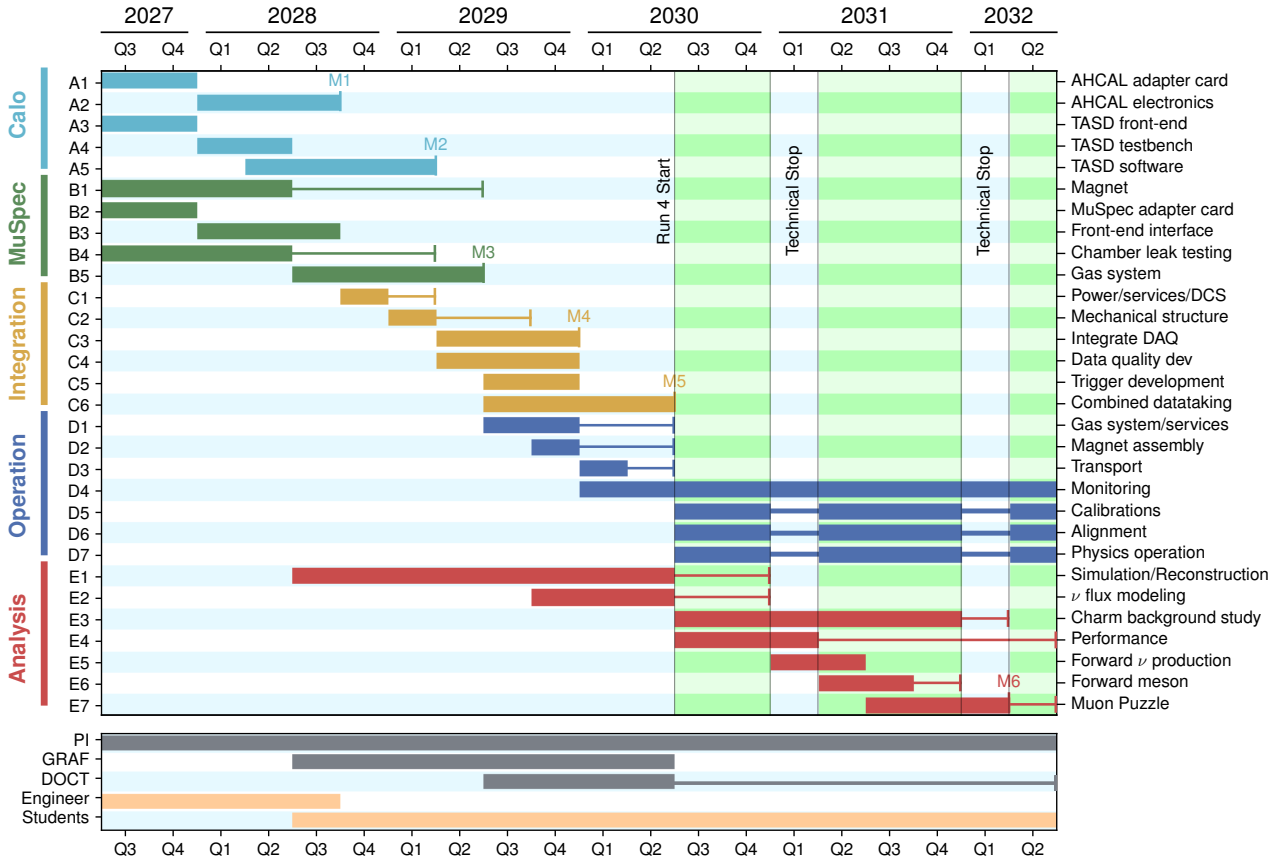


Fig. 10: The project is divided into two phases: before data taking begins and after. Periods with planned HL-LHC data taking are highlighted in green, while detector maintenance is planned during the technical stops. Important milestones are labeled at the end of tasks. The staging of person-power is shown in the lower section. These roles cover the critical work (grey), but person-power contributions from FASER collaborators are expected (orange).

Risks

Risk	Impact	Mitigation
HL-LHC start delayed	High	External constraint; loss of first year reduces partial Run 4 sensitivity to ζ by 15%.
LHCC approval delayed or modifications required	Medium	Begin preparatory work before final approval; retain design flexibility.
Electronics board issues	Low	Produce boards early to allow revisions.
TASD readout development delayed	Medium	Consider alternative systems, including AHCAL-based readout.
Gas and magnet production delayed	Medium	Submit production requests to CERN groups as early as possible.
Insufficient flavor/CC identification efficiency	Medium	Begin ML reconstruction studies two years before data taking to allow optimization.

Scope extensions. The measurement prospects shown here include only the components of FOX supported by this proposal. However extensions are possible with the help of my collaborators. Collaborator André Rubbia has proposed producing 3DCal[40] modules for Run 4. These can be placed off-axis in front of FOX, enhancing the target mass and significantly expanding the possible measurements. Collaborators Hidetoshi Otono and Zhen Hu are requesting funding to upgrade the readout ASIC for AHCAL, which would reduce dead time and increase ν yields by $\sim 25\%$. Collaborator Enrique Must will construct a precision thin gap chamber (TGC) to provide transverse muon measurements, which will help localize muons to hadronic showers.

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