Outline

- Background & Motivation
- FASER construction & operation
- First direct observation of collider neutrinos
- First observation of $\nu_e$ at collider
- First FASER Dark Photon search
- Looking ahead to HL-LHC
Background and Motivation
LHC searches/experiments focus on heavy, strongly interacting particles

- Produced ~isotropically and at relatively low rates, especially in high $p_T$ regions
- $\sigma \sim \text{fb to pb} \rightarrow \text{In Run-3 } N \sim 10^2 - 10^5$
FASER Philosophy

- Could be misguided - Need to target light and weakly interacting particles.
- Lack of new physics in “traditional” searches.
- Scenarios that e.g. satisfy Dark Matter relic density.
- Exploit huge inelastic pp cross section $\rightarrow 10^{16}$ collisions in Run 3 $\rightarrow 10^{17} \pi, 10^{13} B$

**Light meson**: low $p_T \sim \Lambda_{QCD} \rightarrow$ particles are collimated:
- $\theta \sim \Lambda_{QCD}/E \sim \text{mrad}$
FASER Philosophy

- Could be misguided - Need to target light and weakly interacting particles
- Lack of new physics in “traditional” searches.
- Scenarios that e.g. satisfy Dark Matter relic density.
- Exploit huge inelastic pp cross section → $10^{16}$ collisions in Run 3 → $10^{17} \pi$, $10^{13}$ B

**Light meson**: low $p_T \sim \Lambda_{QCD}$ → particles are collimated:
  - $\theta \sim \Lambda_{QCD}/E \sim$mrad

- From only $10^{-8}$ of solid angle 1% of $\pi_0$s are in acceptance.

- Gain sensitivity to long-lived particles with very weak couplings and neutrinos
FASER Philosophy

- **FASER** is a new experiment designed to cover this scenario at the LHC.
FASER Overview

- Detector is 480m from ATLAS IP1
- In line with beam collision axis. Transverse size of 10cm → mrad regime (η>9.1)
- Neutrinos produced copiously in decays of forward hadrons
- Very weakly interacting LLPs could be produced in significant numbers
First concept in 2017 (Feng, Galon, Kling, Trojanowski)

- Approved by CERN in March 2019 (limited budget ~ $2M)
- The TI12 service tunnel happens to be in just the right place for FASER:
  - Old SPS → LEP tunnel
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds - Charged particles bent by LHC magnets
Concept and Location

A 27-kilometre ring!

Accelerator smashing speeded-up protons together!

Large Hadron Collider (LHC)
@ Geneva, Switzerland

Colliding protons accelerated to an incredible 99.9999999% the speed of light with a powerful 13.6 TeV smash

Where Protons Meet: The Collision Point

Produced many particles with the collision energy

Enlarge

Underground Rock

Only the elusive muons, neutrinos, and potential new particles can pass directly through bedrock to their point of collision.

μ
neutrino

υ
new particle

FASER

Forward Search Experiment
FASER Location

- Wider setting at the LHC
In relation to ATLAS at Point 1
FASER Location

- A closer look at the LHC infrastructure on the line-of-sight:
Making the case

14th June 2017

FASER: ForWard Search ExpeRiment at the LHC

Jonathan L. Feng,1, * Itah Galon,1, ∼ Felix Kling,1, ∼ and Sebastian Trojanowski1, ∼

1Department of Physics and Astronomy,
University of California, Irvine, CA 92697-4570 USA
2National Centre for Nuclear Research,
Hoza 69, 00-681 Warsaw, Poland

Abstract

New physics has traditionally been expected in the high-p_T region at high-energy collider experiments. If new particles are light and weakly-coupled, however, this focus may be completely misguided. Light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly-coupled particles may be produced in large numbers there. We propose a new experiment, ForWard Search ExpeRiment, or FASER, which would be placed upstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there. Two representative on-axis locations are studied: a far location, 400 m from the IP and just off the beam tunnel, and a near location, just 150 m from the IP and right behind the TAN neutral particle absorber. For each location, we examine leading neutrino- and beam-induced backgrounds. As a concrete example of light,
Making the case

14th June 2017

LETTER OF INTENT

FASTER
FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaka Ariga,1 Tomoko Ariga,1,2 Jamie Boyd,3,4 David W. Casper,4 Jonathan L. Feng,4,5 Ifah Galon,6 Shih-Chieh Hsu,6 Felix Kling,7 Hidetoshi Otono,7 Brian Petersen,3 Osama Sato,1 Aaron M. Soffa,1 Jeffrey R. Swanson,3 and Sebastian Trojanski8

1Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
2Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan
3CERN, CH-1211 Geneva 23, Switzerland
4Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA
5New High Energy Theory Center, Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854-4601, USA
6University of Washington, PO Box 351560, Seattle, WA 98195-1560, USA
7Nagoya University, Furo-cho, Chikusa-ku, Nagoya-shi 464-8602, Japan
8National Centre for Nuclear Research, Hoza 69, 00-681 Warsaw, Poland

18th July 2018
Making the case

Josh McFayden | Warwick | 19/10/2023

14th June 2017

LETTER OF INTENT

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaka Ariga,1 Tomoko Ariga,1, 2 Jamie Boyd,1 Ifah Galon,3 Shih-Chieh Hsu,4 Felix Kling1, 5 Osama Sato,1 Aaron M. Soffa,4 Jeffrey R. Wood1

1Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
2Kyushu University, Nishi-ku, Fukuoka, Japan
3CERN, CH-1211 Geneva 23, Switzerland
4Department of Physics, University of California, Irvine, CA 92697, USA
5New High Energy Theory Group, The State University of New Jersey, Piscataway, New Jersey
6University of Washington, Box 35
7Nagoya University, Fuku-cho, Chikusa-ku, Nagoya 464-8602, Japan
8National Centre for Nuclear Research, Warsaw, Poland

Submitted to the LHCC, 18 July 2018

TECHNICAL PROPOSAL

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaka Ariga,1 Tomoko Ariga,1, 2 Jamie Boyd,1 Ifah Galon,3 Shih-Chieh Hsu,4 Felix Kling1, 5 Osama Sato,1 Aaron M. Soffa,4 Jeffrey R. Wood1

1Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
2Kyushu University, Nishi-ku, Fukuoka, Japan
3CERN, CH-1211 Geneva 23, Switzerland
4Department of Physics, University of California, Irvine, CA 92697, USA
5New High Energy Theory Group, The State University of New Jersey, Piscataway, New Jersey

Submitted to the LHCC, 7 November 2018

18th July 2018

7th Nov 2018
Making the case

FASER: Forward Search Experiment at the LHC

Jonathan L. Feng, Itzhak Galon, Felix Kling

1Department of Physics at University of California, Irvine, 1
2National Centre for Nuclear Hawa 69, 00-681 Wars

Abstract

New physics has traditionally been expected in the experiments. If new particles are light and weakly-couple
light particles are typically highly concentrated
of searches with small detectors, and even
in large numbers there. We propose a new ex
search, which would be placed downstream of the
very forward region and operated concurrently the
are studies: a far location, 400 m from the IP and just
just 150 m from the IP and right behind the TAN
we examine leading neutrino- and beam-induced back

17th Nov 2018

[arXiv:1708.09389]

Letter of Intent

FORWARD SEARCH EXPERIMENT

Akitaka Ariga, Tomoko Ariga, Jamie Boyd, Itzhak Galon, Shih-Chieh Hsu, Felix Kling, Osama Sato, Aaron M. Soffa, Jeffrey R. Thoma

1Universität Bern, Sidlerstrasse
2Kyushu University, Nishi-ku,
3CERN, CH-1211 Gen
4Department of Physi
5University of California, It
6New High Energy The
7The State Univer
8University of Washington, PO Box 35
9Nagoya University, Furo-cho, Chiku
10National Centre for Nuclear Research, Wars

[arXiv:1811.10243]

Technical Proposal

FORWARD SEARCH EXPERIMENT

Akitaka Ariga, Tomoko Ariga, Jamie Boyd, Francesco Cerutti, Salvatore Danzea, Jonathan L. Feng, Didier Ferreire, Jo
gonzalez-Sevilla, Shih-Chieh Hsu, Giuseppe

1Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
2Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan
3CERN, CH-1211 Geneva 23, Switzerland
4Département de Physique Nucléaire et Corpusculaire, University of Geneva, CH-1211 Geneva 4, Switzerland
5Department of Physics and Astronomy,
Approved by CERN in March 2019
~18 months from theory paper to start of construction!
Making the case

Ready to take data for start of LHC Run3

Approved by CERN in March 2019
~18 months from theory paper to start of construction!
FASER: ForwArd Search ExpeRiment

“The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”
The **LHC experiments** are producing incredible results, searching in previously unexplored phase spaces and performing increasingly precise measurements.

But the lack of any observation of BSM physics (yet!) motivates **looking elsewhere** too.
The indirect observations of *dark matter* offers one of the most tangible indications of BSM physics and strongly motivates closer attention.
The indirect observations of dark matter offers one of the most tangible indications of BSM physics and strongly motivates closer attention.

Main region of interest is for new particles that satisfy DM relic density requirements.

Physics Motivation | BSM

$\frac{\Omega_X}{\epsilon} \propto \frac{m_X^2}{\epsilon_X^4}$

Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$
One of the defining characteristics of weakly interacting light particles is their long lifetime.

- Distinct signatures
- Opportunity for exploration!
Neutrinos produced copiously in decays of forward hadrons

Highly energetic (TeV scale) \(\rightarrow\) high interaction cross section

Extends FASER physics program into SM measurements

Targets measurement of highest energy human-made neutrinos

Energy range complementary to existing neutrino experiments
Physics Motivation | Neutrinos

- Neutrinos produced copiously in decays of forward hadrons
- Highly energetic (TeV scale) → high interaction cross section
- Extends FASER physics program into SM measurements
- Targets measurement of highest energy human-made neutrinos
- Energy range complementary to existing neutrino experiments
Detector Construction and Operation
Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:

- Detector that can be constructed and installed **quickly & cheaply**
- Have tried to re-use **existing detector components** where possible
- Aimed for a **simple, robust detector** (access difficult)
- Tried to **minimize the services** to simplify the installation and operations

**Rough dimensions**

- 10 cm radius, 1.5 m decay volume, ~7 m total length

**Many challenges of the large LHC experiments not there for FASER:**

- Trigger rate ~500Hz (mostly single muon events)
- Low radiation
- Low occupancy / event size
Installation

8/2018

8/2019

4/2020

11/2020

3/2021
Detector design

Small inexpensive design [2207.11427]

- Tracking spectrometer stations: 3 x 3 layers of ATLAS SCT strip modules
- Electromagnetic Calorimeter: 4 LHCb Outer ECAL modules
- Trigger / pre-shower scintillator system
- Magnets: 0.57 T Dipoles, 1.5 m decay volume

Front Scintillator veto system:
- 2 x 20 mm thick, 35 x 30 cm area

Decay volume

Scintillator veto system:
- 2 x 20 mm thick, 30 x 30 cm area

Interface Tracker (IFT)

Trigger / timing scintillator station:
- 10mm thick + dual PMT readout (σ = 400 ps)

FASERν emulsion detector:
- 730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)
Installation
Mika Vesterinen @MikaVesteri · Feb 25
I could never quite grasp the scale of @HyperKamiokande. I just needed to see it next to the @warwickuni physics building 😊
University of Warwick Physics building
(Photo by Ares Osborn)
Operations

- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered lumi.
  - DAQ dead-time of 1.3%
  - Couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after this exchange

Analyses presented use 27.0 fb⁻¹ or 35.4 fb⁻¹
Operations

- All detector components performing excellently
- More than 350M single-muon events recorded
- Example: muon leaving track passing through full detector - consistent with MIP
First observation of collider neutrinos
Neutrino analysis

- Neutrinos produced copiously in decays of forward hadrons
- Highly energetic (TeV scale) → high interaction cross section
- Extends FASER physics program into SM measurements
- Targets measurement of highest energy man-made neutrinos
- Energy range complementary to existing neutrino experiments

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main source</strong></td>
<td>Kaons</td>
<td>Pions</td>
<td>Charm</td>
</tr>
<tr>
<td># traversing FASER$\nu$</td>
<td>$\approx10^{10}$</td>
<td>$\approx10^{11}$</td>
<td>$\approx10^{8}$</td>
</tr>
<tr>
<td># interacting in FASER$\nu$</td>
<td>$\approx200$</td>
<td>$\approx1200$</td>
<td>$\approx4$</td>
</tr>
</tbody>
</table>

Study at colliders originally proposed by Rújula and Rückl in 1984!

[PRD 104, 113008]
Neutrino analysis | Selection

1. Collision event with good data quality
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos
4. Timing and preshower consistent with ≥1 MIP
5. Exactly 1 good fiducial (r < 95 mm) track
   - p > 100 GeV and θ < 25 mrad
   - Extrapolating to r < 120 mm in front veto
Neutrino analysis | Selection

- 1. Collision event with good data quality
- 2. No signal (<40 pc) in 2 front vetos
- 3. Signal (>40 pC) in other 3 vetos
- 4. Timing and preshower consistent with $\geq 1$ MIP
- 5. Exactly 1 good fiducial ($r < 95$ mm) track
  - $p > 100$ GeV and $\theta < 25$ mrad
  - Extrapolating to $r < 120$ mm in front veto
Neutrino analysis | Selection

First-ever observation of neutrinos from a collider like the LHC! Using the highest energy neutrinos ever created by humans, we’re diving deep into the nature of neutrinos and might even test physics beyond the standard model (BSM).

Muon neutrinos from proton collisions

Muons from outside are caught by the front detector and filtered out as background.

LHC-san @Geneva, Switzerland

Tungsten target (+ emulsion detector)

Dipole magnets

Silicon tracking detectors

Observing Muons through the Silicon Detector!

Calorimeter

Evidence of Neutrino Detection!
Neutral hadrons

- Estimated from 2-step simulation
- Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
- Most accompanied by μ but conservatively assume missed
- Estimate fraction of these passing event selection
- Most are absorbed in tungsten with no high-momentum track
- Predict N = 0.11 ± 0.06 events
Scattered muons

- Estimated from data sideband
- Take events w/o front veto radius requirement and single track segment in first tracker station with $90 < r < 95$ mm
- Fit to extrapolate to higher momentum
- Scale by # events with front veto cut
- Use MC to extrapolate to signal region
- Predict $N = 0.08 \pm 1.83$ events
- Uncertainty from varying selection

**Neutrino analysis | Backgrounds**

![Scattered muons in FASERv emulsion detector](image)
Neutrino analysis | Backgrounds

- Veto inefficiency
  - Estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Final negligible background due to very high veto efficiency

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
<th>Expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>4</td>
<td>$n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$</td>
</tr>
<tr>
<td>$n_{10}$</td>
<td>6</td>
<td>$n_b \cdot (1 - p_1) \cdot p_2$</td>
</tr>
<tr>
<td>$n_{01}$</td>
<td></td>
<td>$n_b \cdot p_1 \cdot (1 - p_2)$</td>
</tr>
<tr>
<td>$n_2$</td>
<td>64014695</td>
<td>$n_b \cdot (1 - p_1) \cdot (1 - p_2)$</td>
</tr>
</tbody>
</table>
FASER

Josh McFayden   |  Warwick  |  19/10/2023

Unblinded to find 153 events with no veto signal

Just 10 events with one veto signal

First direct detection of collider neutrinos!

With signal significance of $16\sigma$

Expected $151 \pm 41$ events from GENIE simulation

Unblinded to find 153 events with no veto signal

Just 10 events with one veto signal

First direct detection of collider neutrinos!

With signal significance of $16\sigma$

Expected $151 \pm 41$ events from GENIE simulation

With signal significance of $16\sigma$

Expected $151 \pm 41$ events from GENIE simulation

Extrapolated $r_{\nu_{\text{veto}}}$ vs $p_{\mu}$

Extrapolated $x_{\nu_{\text{veto}}}$ vs $y_{\nu_{\text{veto}}}$
Neutrino analysis | Results

- Candidate neutrino events match expectation from signal
- High occupancy in front tracker station
- Most events have high $\mu$ momentum
- More $\nu_\mu$ than anti-$\nu_\mu$
- High occupancy in front tracker station
- Large angle $\theta$ with respect to LOS

NB: no acceptance corrections nor any systematic uncertainties in these plots
Emulsion detector with 1.1T tungsten target

- 730 1.1mm thick tungsten plates interleaved with emulsion film
- Well understood neutrino detector technology
- Replace every 20-50 fb\(^{-1}\) to maintain track density low

Challenges:
- Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
- Procedure well developed for production and offline analysis

New analysis!
FASER

First analysis includes 150 of 730 plates
- 68kg target mass for this analysis (24 x 9 x 16.5 cm)
- \(9.5 \text{ fb}^{-1}\) of LHC proton collision data

- Expect \(29.4 \pm 5.0 (\nu_\mu)\) and \(11.8 \pm 7.5 (\nu_e)\) charged current (CC) neutrino interactions before selection
- Select vertices with associated lepton candidate (e or \(\mu\)) and E>200 GeV

Backgrounds
- Neutral hadron background; low-momentum signal
- Neutral-current neutrino interactions
Emulsion analysis | Results

- Preliminary results: CERN-FASER-CONF-2023-002
- Expected 0.6–5.2 ($\nu_e$ CC) and 3.0–8.6 ($\nu_\mu$ CC) passing selection
- Observed 3 $\nu_e$ vertices (5$\sigma$), and 4 $\nu_\mu$ vertices (2.5$\sigma$) - Candidates with E ~ 1TeV!

First direct observation of collider electron neutrinos!
Preliminary results: CERN-FASER-CONF-2023-002

- Expected 0.6–5.2 ($\nu_e$ CC) and 3.0–8.6 ($\nu_\mu$ CC) passing selection
- Observed 3 $\nu_e$ vertices (5$\sigma$), and 4 $\nu_\mu$ vertices (2.5$\sigma$) - Candidates with $E \sim 1$TeV!

First direct observation of collider electron neutrinos!
Emulsion analysis | Results

- Preliminary results: CERN-FASER-CONF-2023-002
- Expected 0.6–5.2 ($\nu_e$ CC) and 3.0–8.6 ($\nu_\mu$ CC) passing selection
- Observed 3 $\nu_e$ vertices (5$\sigma$), and 4 $\nu_\mu$ vertices (2.5$\sigma$) - Candidates with $E \sim 1$TeV!

- First direct observation of collider electron neutrinos!
Emulsion analysis | Results

- Preliminary results: CERN-FASER-CONF-2023-002
- Expected $0.6–5.2$ ($\nu_e$ CC) and $3.0–8.6$ ($\nu_\mu$ CC) passing selection
- Observed $3 \nu_e$ vertices ($5 \sigma$), and $4 \nu_\mu$ vertices ($2.5 \sigma$) - Candidates with $E \sim 1$TeV!

- First direct observation of collider electron neutrinos!
Dark Photon Search
Dark Photon Search

- Dark photon a common feature of hidden sector models

\[ \mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon e \sum_f q_f \bar{f} A' f \]

- MeV A’s produced mainly in meson decays at LHC

\[ B(\pi^0 \rightarrow A'\gamma) = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \rightarrow \gamma\gamma) \]

- FASER targets small \(\varepsilon\), where A’ has long decay length

\[ L = c\beta\tau\gamma \approx (80 \text{ m}) \left[ \frac{10^{-5}}{\varepsilon} \right]^2 \left[ \frac{E_{A'}}{\text{TeV}} \right] \left[ \frac{100 \text{ MeV}}{m_{A'}} \right]^2 \]

- Below 2\(m_\mu\), A’ has 100% decay to e+e- pair

* arXiv:2105.07077

- \(A' \rightarrow e^+e^-\) simulated with FORESEE*
  - \(\pi^0\) and \(\eta\) via EPOS-LHC generator
  - Subdominant dark brem. via FWW

- Generator uncertainty dominates
  - Difference to QGSJET/SIBYLL
  - Parameterised based on A’ energy
**Dark Photon Search | Selection**

- Simple and robust $A' \rightarrow e^+e^-$ selection
  - Blind events with no veto signal and $E(\text{calo}) > 100 \text{ GeV}$
- Selection
  1. Collision event with good data quality
  2. No signal ($< 40 \text{ pc}$) in any veto scintillator
  3. Timing and preshower consistent with $\geq 2 \text{ MIPs}$
  4. Exactly 2 good fiducial tracks
    - $p > 20 \text{ GeV}$ and $r < 95 \text{ mm}$ & Extrapolating to $r < 95 \text{ mm}$ at vetos
  5. Calo $E > 500 \text{ GeV}$

**Efficiency of $\sim 40\%$ across sensitive region**

![Diagram of Dark Photon Search setup](image_url)
Dark Photon Search | Selection

- Simple and robust $A' \rightarrow e^+e^-$ selection
  - Blind events with no veto signal and E(calo) > 100 GeV

- Selection
  1. Collision event with good data quality
  2. No signal (< 40 pc) in any veto scintillator
  3. Timing and preshower consistent with $\geq$2 MIPs
  4. Exactly 2 good fiducial tracks
    - $p > 20$ GeV and $r < 95$ mm && Extrapolating to $r < 95$ mm at vetos
  5. Calo E > 500 GeV

Efficiency of ~40% across sensitive region

$arXiv:2308.05587$
Dark Photon | Backgrounds

- **Veto inefficiency**
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. $10^8$ muons to negligible level (even before cuts) (<$10^{-20}$ inefficiency)

- **Non-collision backgrounds**
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with $\geq 1$ track or $E_{\text{calo}} > 500$ GeV individually

[arXiv:2308.05587]
Main background is from Neutrino interactions
- Primarily coming from vicinity of timing detector
- Estimated from GENIE simulation (300 ab-1)
- Uncertainties from neutrino flux & mismodelling
- Predicted events with E(calo) > 500 GeV
  \[ N = (1.5 \pm 2.0) \times 10^{-3} \]

Neutral hadrons (e.g. Ks) from upstream muons interacting in rock in front of FASER
- Heavily suppressed since:
  - muon nearly always continues after interaction
  - has to pass through 8 interaction lengths (FASERν)
  - decay products have to leave E(calo) > 500 GeV
- Estimated from lower energy events with 2/3 tracks and different veto conditions
  \[ N = (0.8 \pm 1.2) \times 10^{-3} \]

[arXiv:2308.05587]
- No events in unblinded signal region
- Not even any with ≥1 fiducial track

- Expected background
  - $0.0023 \pm 0.0023$

[arXiv:2308.05587]
After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.

First incursion (with NA62) into thermal relic region from low $\varepsilon$ since 1990’s.

Background-free analysis bodes well for future sensitivity.

Expect $\sim 10 \text{fb}^{-1}$ luminosity in Run 3 from 2023-25.
The region probed is cosmologically relevant

- Assuming a dark matter particle with mass $\frac{1}{2}m(A'_B-L)-m(A'_B-L)$ & very large $Q(B-L)$, limit includes region favoured by thermal freeze-out
- As B–L model includes 3 sterile neutrinos, that could be produced through freeze-in mechanism, resulting relic density may be significant in excluded region.
Next for FASER
FASER short-term future

- Preshower Upgrade
  - More transverse information
  - Beneficial for 2-photon signals, such as ALP searches
  - Installation planned for YETS 24/25
    - Technical proposal

- Run 3 and Beyond
  - Expect to collect 10x more data in Run 3
  - Excellent performance so far therefore...
  - Begun request process to continue operations after LS3
  - Potentially succeeded by FASER2/FASERν2 in the planned Forward Physics Facility (FPF) during the HL-LHC era
Forward Physics Facility
FASER, FASERv, and other proposed detectors are currently highly constrained by tunnels and infrastructure that was never designed to support experiments.

At the same time, it is becoming clear that there is a rich physics program in the far-forward region, spanning long-lived particle searches, neutrinos, QCD, dark matter, dark sector, cosmic rays, and cosmic neutrinos.

Strongly motivates to create a dedicated facility to house several far-forward experiments.
The FPF is well aligned with the recommendations of recent community studies in Europe and abroad:

- **2020 European Strategy Update:**
  - “The full physics potential of the LHC and the HL-LHC...should be exploited”
  - “The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through ... searches for axions, dark sector candidates and feebly interacting particles. ...A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported”

- **Snowmass 2021 Energy Frontier Report:**
  - “Our highest immediate priority accelerator and project is the HL-LHC,...including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades”
The FPF is well aligned with the recommendations of recent community studies in Europe and abroad:

- **2020 European Strategy Update:**
  - "The full physics potential of the LHC and the HL-LHC...should be exploited"
  - "The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through … searches for axions, dark sector candidates and feebly interacting particles. …A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported".

- **Snowmass 2021 Energy Frontier Report:**
  - "Our highest immediate priority accelerator and project is the HL-LHC,...including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades".
FPF Papers:

Hot off the press!

- FASER2
- FASERν2/AdvSND
- FORMOSA
- FLArE
Proof of principle now exists from FASER

Slightly different design philosophy limited by large aperture magnet technologies

Program for BSM and SM physics (main spectrometer to neutrino exps.)

Currently considering, SciFi tracker and dual-readout calorimetry.
**Veto**
- Plastic scintillator-based veto system
- Expected to reject muon rates of ~ 20kHz

**Tracker**
- Silicon photomultiplier and scintillating fiber tracker technology
- Based on LHCb’s SciFi® tracker
- Spatial resolution of ~ 100 μm
- Each station consists of vertical and horizontal SciFi modules

**Magnet**
- Rectangular aperture: 1 m in height, 3 m in width, 4 m depth
- Superconducting magnet technology
- Based on SAMURAI® experiment magnet
- BField 4 Tm bending power for particle separation, momentum resolution, and charge ID

**EM Calorimeter**
- Dual-readout calorimetry technology
- Spatial resolution for particle identification at ~ 1-10 mm separation
- Particle identification capabilities
Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.
Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.

FASER2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:

- \( \frac{N_B}{N_{\pi}} \sim 10^{-2} \) (~10\(^{-7}\) at beam dump expts)
FASER2 (R = 1 m, L = 5-20 m) can discover
- All candidates with renormalizable couplings (dark photon, dark Higgs, HNL)
- ALPs with all types of couplings (γ, f, g)
- and many other particles.

Among the PBC benchmark scenarios, FASER2’s discovery potential extends to all benchmark scenarios
- Except BC2 and BC3.

<table>
<thead>
<tr>
<th>Benchmark Model</th>
<th>FASER</th>
<th>FASER 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1: Dark Photon</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BC1’: U(1)$_{B-L}$ Gauge Boson</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BC2: Invisible Dark Photon</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BC3: Milli-Charged Particle</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BC4: Dark Higgs Boson</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>BC5: Dark Higgs with hSS</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>BC6: HNL with $e$</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>BC7: HNL with $\mu$</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>BC8: HNL with $\tau$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BC9: ALP with photon</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BC10: ALP with fermion</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BC11: ALP with gluon</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Neutrino physics

- Study neutrino interactions at high energy
- Search for BSM physics in neutrino production, propagation and interaction
- Study PDFs by DIS of neutrino in the target (fixed target 75 GeV CoM E)
- Study forward hadron production via neutrino flux measurements
The FPF experiments will see $10^5 \nu_e$, $10^6 \nu_\mu$ and $10^4 \nu_\tau$ interactions at E~TeV where there is currently no data.
Neutrinos are produced by forward hadron production: $\pi$, $K$, $D$... Energy spectra will inform:

- Astroparticle physics: muon puzzle, ...
- QCD: pdfs at $x \sim 10^{-1}$, $x \sim 10^{-7}$, intrinsic charm, small-x gluon saturation, ...
- Neutrino properties: short-baseline neutrino experiment. Sensitive to sterile neutrinos
Neutrinos are produced by forward hadron production: $\pi$, $K$, $D$...

- A neutrino-ion collider!

Energy spectra will inform:

- Astroparticle physics: muon puzzle, ...
- QCD: pdfs at $x \sim 10^{-1}$, $x \sim 10^{-7}$, intrinsic charm, small-$x$ gluon saturation, ...
- Neutrino properties: short-baseline neutrino experiment. Sensitive to sterile neutrinos

Fully differential neutrino DIS scatteringXS will improve constraints on pdfs

- arXiv:2309.09581
Significant input from UK institutes in FPF R&D
- Emphasis on FASER2, beam sim. and theory so far.

Existing experiments, providing proof-of-principle for FPF, running successfully with UK involvement and leadership.

Timescale for FPF LoI to CERN in early 2025 is not too far away
- Next step is to formalise, and ideally increase, UK participation.
- Involving Visions and then SoI submissions to STFC.
Summary
Summary

- First direct observation of collider neutrinos
  - Opens a new field: neutrino physics at the LHC
  - Published in PRL [2303.14185]
- First Dark Photon search
  - First limit in thermal relic region from low coupling for 30 yrs
  - Submitted to [arXiv:2308.05587]
- High-energy $\nu_e$ interactions in emulsion detector
  - [CERN-FASER-CONF-2023-002]
- More neutrino studies and BSM searches to come
  - Including searches for ALPs, light gauge bosons, ...
- Strongly motivates FPF & FASER2 for HL-LHC era
Summary

First direct observation of collider neutrinos

Opens a new field: neutrino physics at the LHC

First Dark Photon search

First limit in thermal relic region from low coupling for 30 yrs

Published in PRL [2303.14185]

Submitted to arXiv:2308.05587

High-energy νe interactions in emulsion detector

[CERN-FASER-CONF-2023-002]

More neutrino studies and BSM searches to come

Including searches for ALPs, light gauge bosons, …

Strongly motivates FPF & FASER2 for HL-LHC era
Acknowledgements

- FASER is supported by:

- And would additionally like to thank
  - LHC for the excellent performance in 2022
  - ATLAS for providing luminosity information
  - ATLAS for use of ATHENA s/w framework
  - ATLAS SCT for spare tracker modules
  - LHCb for spare ECAL modules
  - CERN FLUKA team for background sim
  - CERN PBC and technical infrastructure groups for excellent support during design construction and installation
Collaboration

- 87 members
- 24 institutions
- 10 countries

International laboratory covered by a cooperation agreement with CERN
Back-ups
Detector Performance: Trigger + DAQ

- DAQ running smoothly up to 1.3 kHz with deadtime only 1.3%
- Total trigger rate falls off faster than luminosity during run (higher beam-induced backgrounds) but coincidence trigger rate flat with respect to luminosity
The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments.

Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb⁻¹).

Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:

![Normalized Neutrino Interaction Rate vs. Displacement from Beam Axis](image)
# Neutrino analysis

[arXiv:1908.02310]

<table>
<thead>
<tr>
<th>Type</th>
<th>Particles</th>
<th>Main Decays</th>
<th>E</th>
<th>Q</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pions</td>
<td>$\pi^+$</td>
<td>$\pi^+ \to \mu\nu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>Kaons</td>
<td>$K^+, \bar{K}_S, K_L$</td>
<td>$K^+ \to \mu\nu, K \to \pi\ell\nu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>Hyperons</td>
<td>$\Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^{-}, \Omega^-$</td>
<td>$\Lambda \to p\ell\nu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>Charm</td>
<td>$D^+, D^0, D_s, \Lambda_c, \Xi^0_c, \Xi^+_c$</td>
<td>$D \to K\ell\nu, D_s \to \tau\nu, \Lambda_c \to \Lambda\ell\nu$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
</tr>
<tr>
<td>Bottom</td>
<td>$B^+, B^0, B_s, A_b, \ldots$</td>
<td>$B \to D\ell\nu, \Lambda_b \to \Lambda_c\ell\nu$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
</tr>
</tbody>
</table>

![pion decay](image1.png)

![kaon decay](image2.png)

![hyperon decay](image3.png)
Neutrino analysis

[PRD 104, 113008]
Emulsion analysis | Results

![Graph showing emulsion analysis results with markers for LoS, $\nu_e$ CC cand, and $\nu_\mu$ CC cand.](image)
<table>
<thead>
<tr>
<th>Selection</th>
<th>Quantity</th>
<th>$K_L$</th>
<th>$n$</th>
<th>$\Lambda$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ selection $E &gt; 50$ GeV</td>
<td>Raw MC events</td>
<td>77</td>
<td>71</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Scaled to analysis</td>
<td>1</td>
<td>0.07</td>
<td>0.16</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>dataset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ selection $E &gt; 50$ GeV</td>
<td>Raw MC events</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Scaled to analysis</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>dataset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ selection $E &gt; 200$ GeV</td>
<td>Raw MC events</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Scaled to analysis</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>dataset</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_e$ CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral-hadron interactions</td>
<td>$0.32 \pm 0.15$ (stat.)</td>
<td>$0.002 \pm 0.002$ (stat.)</td>
</tr>
<tr>
<td>NC neutrino interactions</td>
<td>$0.19 \pm 0.15$</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>$0.51 \pm 0.27$</td>
<td>$0.002 \pm 0.003$</td>
</tr>
</tbody>
</table>
Emulsion analysis | Performance

25% for EM energies at 200 GeV. Between 25-40% for higher energies.
Emulsion analysis | HTS

- Hyper Track Selector: [arXiv:1704.06814]
The track reconstruction algorithm is based on that of the NA65/DsTau experiment and is described in [http://arxiv.org/abs/1906.03487](http://arxiv.org/abs/1906.03487).

- Vertex: Convergence of >4 tracks, >3 tracks with \(\tan(\theta)<0.1\)
- Charged vertex: Looser track selection, tracks within 10 films before vertex, with 3 track hits, \(d0<=5<\mu m\), min. distance to 3 vertex tracks of \(<=3\mu m\).
Emulsion film made up of ~80μm emulsion layer on either side of 200μm plastic

- Emulsion gel active unit silver bromide crystals (dia. 200nm)
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~50nm, and angular resolution ~0.35mrad
- But no time resolution!
FASERv | Neutrino flux estimates

- Checking three simulations:
  - FLUKA (by F. Cerruti's group)
  - BDSIM (by H. Lefebvre, L. Nevay)
  - RIVET-module (by F. Kling)

- **Differences between generators** have been checked with the same propagation model (RIVET-module)

- $\nu_e$ mainly from kaon and charm decays
- $\nu_\mu$ mainly from pion and kaon decays
- $\nu_\tau$ mainly from $D_s$ and subsequent $\tau$ decays
Atmospheric muon puzzle

- Predictions show significant deficit compared to data in high energy muon rates from cosmic rays
- Cannot be tuned away with current MCs
- Strangeness enhancement could solve the issue
- Testable at FPF

Paper
BSM physics
- New light weakly coupled gauge boson ($\rightarrow \nu_\tau$) could enhance $\nu_\tau$ flux.
- Sterile neutrinos with mass $\sim 40$ eV can cause oscillations at FASER

QCD
- FASER’s neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
- Neutrinos from charm decay could allow to test transition to small-$x$ factorisation, constrain low-$x$ gluon PDF and probe intrinsic charm

Cosmic rays and neutrinos
- IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
- Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes
Dark Photon | Signal

- Acceptance $10^{-6}$
- Decay volume $10^{-8}$ solid angle
- $P(\text{decay in FASER}) = 10^{-3}$

$$L = c\beta\tau\gamma \approx (80 \text{ m}) \left[ \frac{10^{-5}}{\epsilon} \right]^2 \left[ \frac{E_{A'}}{\text{TeV}} \right] \left[ \frac{100 \text{ MeV}}{m_{A'}} \right]^2$$
# Dark Photon | Selection

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-selecton</td>
<td></td>
</tr>
<tr>
<td>Time consistent with a colliding bunch identifier</td>
<td></td>
</tr>
<tr>
<td>Timing scintillator trigger</td>
<td></td>
</tr>
<tr>
<td>Scintillator</td>
<td></td>
</tr>
<tr>
<td>Timing station:</td>
<td></td>
</tr>
<tr>
<td>Top or Bottom Scintillator charge</td>
<td>&gt; 70 pC</td>
</tr>
<tr>
<td>OR Top and Bottom charge</td>
<td>&gt; 30 pC</td>
</tr>
<tr>
<td>Each Preshower scintillator charge</td>
<td>&gt; 2.5 pC</td>
</tr>
<tr>
<td>Each Veto scintillator charge</td>
<td>&lt; 40 pC</td>
</tr>
<tr>
<td>Tracking</td>
<td></td>
</tr>
<tr>
<td>Exactly 2 Good Tracks</td>
<td></td>
</tr>
<tr>
<td>Momentum</td>
<td>&gt; 20 GeV</td>
</tr>
<tr>
<td>$\chi^2$/NDF</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>Number of tracker layers on track</td>
<td>&gt;= 7</td>
</tr>
<tr>
<td>Number of tracker hits on track</td>
<td>&gt;= 12</td>
</tr>
<tr>
<td>Fiducial selection</td>
<td></td>
</tr>
<tr>
<td>Track extrapolated to all scintillators and tracking stations</td>
<td>&lt; 95mm</td>
</tr>
<tr>
<td>Calorimeter</td>
<td></td>
</tr>
<tr>
<td>Calorimeter energy (sum of four channels)</td>
<td>&gt; 500 GeV</td>
</tr>
</tbody>
</table>

TABLE I. Summary of selection requirements.

![Graph](image1.png)

**Selection Criteria**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good collision event</td>
<td>99.7%</td>
</tr>
<tr>
<td>No Veto Signal</td>
<td>98.4%</td>
</tr>
<tr>
<td>Timing/Preshower Signal</td>
<td>97.3%</td>
</tr>
<tr>
<td>≥ 1 good track</td>
<td>89.2%</td>
</tr>
<tr>
<td>= 2 good tracks</td>
<td>44.5% *</td>
</tr>
<tr>
<td>Track radius &lt; 95 mm</td>
<td>42.3% *</td>
</tr>
<tr>
<td>Calo energy &gt; 500 GeV</td>
<td>41.6% *</td>
</tr>
</tbody>
</table>

$\epsilon = 3 \times 10^{-5}$ $m_A = 25.1$ MeV
<table>
<thead>
<tr>
<th>Selection</th>
<th>Nevents $E&lt;100$ GeV</th>
<th>Nevents $E&gt;500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 tracks (VetoNu signal)</td>
<td>544.7</td>
<td>11.0</td>
</tr>
<tr>
<td>2 tracks (No VetoNu signal)</td>
<td>1</td>
<td>Predicted: 0.02</td>
</tr>
</tbody>
</table>
Dark Photon | Scintillator efficiencies

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NuVeto-0</td>
<td>0.9999805(5)</td>
</tr>
<tr>
<td>NuVeto-1</td>
<td>0.9999810(5)</td>
</tr>
<tr>
<td>Veto-0</td>
<td>0.9999985(1)</td>
</tr>
<tr>
<td>Veto-1</td>
<td>0.9999984(1)</td>
</tr>
<tr>
<td>Veto-2</td>
<td>0.9999986(1)</td>
</tr>
</tbody>
</table>

Veto Nu Station 0
MIP efficiency = 99.99805(5) %

Veto Station 2, plane 2
MIP efficiency = 99.99986(1) %
Dark Photon | Performance

![Graph showing overlay efficiency and probability](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Effect on signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Generator</td>
<td>$\frac{0.15+(E_A'/4\text{TeV})^3}{1+(E_A'/4\text{TeV})^3}$</td>
<td>15-65% (15-45%)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>MC Statistics</td>
<td>$\sqrt{\sum W^2}$</td>
<td>1-3% (1-2%)</td>
</tr>
<tr>
<td>Track Momentum Scale</td>
<td>5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Track Momentum Resolution</td>
<td>5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Single Track Efficiency</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Two-track Efficiency</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>Calo E scale</td>
<td>6%</td>
<td>0-8% (&lt; 1%)</td>
</tr>
</tbody>
</table>

*Image showing photon conversion candidates with data points and curves.*
FPF Papers:

FPF Papers:

ECN3 | Reach comparison

- FPF
- HIKE+SHADOWS
- SHiP
  - CDS record
- FPF
- HIKE+SHADOWS
- SHiP
  - CDS record
ECN3 | Reach comparison

- FPF
- HIKE+SHADOWS
- SHiP
  - CDS record

![Graph showing reach comparison between different experiments.](image)

$\alpha_D = 0.1$
$m_{\chi} = 3m_{\chi}$
Figure 6: Schematic layout of the SHADOWS spectrometer.
FASER Location

- A closer look at the LHC infrastructure on the line-of-sight:
The FASER magnets are 0.55T permanent dipole magnets based on the Halbach array design.

- Thin enough to allow the LOS to pass through the magnet centre with minimum digging to the floor in TI12
- Minimize needed services (power, cooling etc.)
- Designed and constructed by magnet group at CERN
Magnets | Construction and testing

- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN.
- Measured field quality well within specifications.
Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN.

Measured field quality well within specifications.

All magnets now installed underground!
Spare ATLAS SCT modules are used

- 80μm strip pitch, 40mrad stereo angle (17μm / 580μm resolution)
- precision measurement in bending (vertical) plane
- Many thanks to the ATLAS SCT collaboration!
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) → 72 SCT modules needed for the full tracker
- Low radiation levels in TI12 allows silicon to be operated at room temp.
- But the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)
Overground testing

- Have space at CERN Prevesin site (same building as Neutrino Platform)
- Used for dry run above ground
- Assembly took place in Feb-April 2020
  - Test mechanical assembly
- Commissioning from March 2020
  - Detector installation
  - Alignment procedures
  - Cabling
  - Cooling
  - TDAQ
- Cosmics runs

<table>
<thead>
<tr>
<th>Date</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prepare ENH1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install Det. Support</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install Calo/Scin &amp; TDAQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Partial) System Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overground testing | Tracker

- Cosmic data taking with station on its side, and a scintillator on top/btm.
- Use full FASER TDAQ system to take data.
- Operational experience
- Tracker efficiency, resolution and alignment studies
- Offline s/w debugging
Overground testing | Tracker

- Straight track candidate along with event display:
- Also have partial detector combined run
- All scintillators and calorimeters with one tracker station
Also have partial detector combined run

- All scintillators and calorimeters with one tracker station

In just one week before disassembly started:

- Common clock provided by Technion clock card (40.08 MHz)
- Triggering on cosmic showers/random triggers
- Reading out full detector
- Tracker readout-timed in with respect to trigger signals
- Ran with FASER DAQ system, run control GUI and monitoring
- Data recorded to local disk and copied to EOS
The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments.

Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb⁻¹):

- Uncertainty from neutrino production important. $E_\nu$ reco resolution $\sim$30% (sim).

The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments.

Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb⁻¹):

- Uncertainty from neutrino production important. $E_\nu$ reco resolution $\sim$30% (sim).
The energy spectrum expected at FASERv is rather complementary to existing neutrino experiments.

Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb⁻¹).

Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:
Emulsion detector with tungsten target

- 1000 1mm thick tungsten plates interleaved with emulsion film
- Well understood neutrino detector technology
- Replace every 20-50 fb$^{-1}$ to maintain track density low

Challenges:

- Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
- Benefit from transport infrastructure installed in UJ12 and TI12 to install FASER detector
- Procedure well developed for production and offline analysis:
A 30 kg detector was installed in TI18 in 2018

- 12.5 fb\(^{-1}\) of data was collected
- ~30 neutrino interactions in the detector expected to have occurred
- Emulsion data developed, reconstructed and analysis ongoing
- Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
- Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons
A 30 kg detector was installed in TI18 in 2018

- 12.5 fb$^{-1}$ of data was collected
- ~30 neutrino interactions in the detector expected to have occurred
- Emulsion data developed, reconstructed and analysis ongoing
- Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
  - Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons
A 30 kg detector was installed in TI18 in 2018

- 12.5 fb$^{-1}$ of data was collected
- ~30 neutrino interactions in the detector expected to have occurred
- Emulsion data developed, reconstructed and analysis ongoing
- Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
  - Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons
FASERv | Rich neutrino physics program

- BSM physics
  - New light weakly coupled gauge boson ($\rightarrow \nu_\tau$) could enhance $\nu_\tau$ flux.
  - Sterile neutrinos with mass $\sim 40$ eV can cause oscillations at FASER

- QCD
  - FASER’s neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
  - Neutrinos from charm decay could allow to test transition to small-$x$ factorisation, constrain low-$x$ gluon PDF and probe intrinsic charm

- Cosmic rays and neutrinos
  - IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
  - Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes
Foresee is a numerical package for the FORward Experiment SEnsitivity Estimator (FORESEE), which can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. The simulations can be performed for 14 TeV collision energy characteristic for the LHC, as well as for larger energies: 27 and 100 TeV. In the package, a comprehensive list of validated forward spectra of various SM species is included. The capabilities of FORESEE are illustrated for the popular dark photon and dark Higgs boson models, as well as for the search for light up-hilic scalars. For the dark photon portal, we also comment on the complementarity between such searches and dark matter direct detection bounds. Additionally, for the first time, we discuss the prospects for the LLP searches in the proposed future hadron colliders: High-Energy LHC (HE-LHC), Super proton-proton Collider (SppC), and Future Circular Collider (FCC-hh).
Physics Motivation | Dark photons

- Dark photons are particularly interesting for FASER as we have fast sensitivity to new regions of phase space.
- There is a vast and largely unexplored parameter space.
- "Bump hunts" exclude larger $\varepsilon$.
- Mostly fixed target experiments exclude the gray region.
- Astrophysics (supernova, BBN, CMB) exclude at very low $\varepsilon$.
- Overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.
- Dark Sector models don’t give us too much guidance on expected mass or coupling strengths.
- Some other intriguing observations…
- Focusing on the mass scale
- Dark Sector Candidates
- Anomalies
- Search Techniques

We see some interesting things in the ~MeV range
The 3.7\(\sigma\) discrepancy between the SM and experiment can be resolved by MeV-GeV particles with \(\varepsilon \sim 10^{-3}\).

The dark photon is no longer a viable solution.

But other particles with similar masses and couplings are.
Physics Motivation | He/Be nuclei

- 2016: A 7σ anomaly in the decays of excited $^8$Be nuclei can be explained by a new particle with mass 17 MeV and couplings $\sim 10^{-3}$ to $10^{-4}$.

- 2019: A new 7σ anomaly in the decays of excited $^4$He nuclei can be explained by the same new particle...

Krasznahorkay et al. (2015, 2019)  
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)  
Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)  
See also Zhang, Miller (2020)
Physics Motivation | Self-interacting DM

- There are indications from small-scale structure that dark matter may be strongly self-interacting.
- For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted by standard cold dark matter.

This can be explained by a characteristic **dark sector mass scale of ~ 10-100 MeV.**

\[
\frac{\sigma}{m} \sim \text{cm}^2 \text{g}^{-1} \sim \text{barn GeV}^{-1} \sim (100 \text{ MeV})^{-3}
\]
FASER is probing a very interesting region of phase space

New sensitivity in this region will come even with only a small fraction of Run 3 data.
Hidden sector physics:

- New mediating particles, couplings to SM via mixing with SM “portal” operator
- Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations...
- Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)

Typically long-lived particles (LLPs) that travel macroscopic distances before decaying to SM particles

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

<table>
<thead>
<tr>
<th>Particle</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Photon, $A_\mu$</td>
<td>$-\frac{e}{2\cos\theta_W} F_{\mu\nu}' B_{\mu\nu}'$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}<em>{i,\mu\nu}$, $\partial</em>\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>
To connect muon tracks from $\nu\mu$ interactions for charge identification etc.

- Interface tracker (IFT) with 3 layers of silicon strip detector. A copy of FASER tracker station.
- Veto station consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle coming from upstream of FASER.
- Construction of the IFT will start in January 2021. Installation at FASER site is planned in fall 2021.
FLUKA simulations and *in situ* measurements used to assess expected backgrounds.

- IP1 collisions (shielded by 100m rock)
- Off-orbit protons hitting beam pipe aperture near TI12
- Beam-gas interactions
- Low particle flux along beam axis due to LHC optics.

### Conditions | Beam backgrounds

**Fluence rate spectra at FASER (above 10 GeV) for the LHC**

**Muon charge asymmetry due to LHC magnets**

**HL-LHC: Muon- distribution at FASER**

<table>
<thead>
<tr>
<th>Muons (@L=2x10⁻¹⁵ cm⁻² s⁻¹)</th>
<th>Energy threshold [GeV]</th>
<th>Charged Particle Flux [cm⁻² s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>
• *In situ* measurements using emulsion detectors and TimePix BLM in TI12 in 2018 confirm expected particle flux, and correlation with IP1 luminosity.
The FLUKA simulation tracks particle production, deflection, and energy loss with a detailed model of the geometry of the LHC tunnels, including the LHC material map and magnetic field layout. The simulation includes three potential sources of background at the FASER location:

- Particles produced in the $pp$ collisions at the IP or by particles produced at the IP that interact further downstream, e.g., in the TAN neutral particle absorber.

- Particles from showers initiated by off-momentum (and therefore off-orbit) protons hitting the beam pipe in the dispersion suppressor region close to FASER.

- Particles produced in beam-gas interactions by the beam passing FASER in the ATLAS direction (for which there is no rock shielding).

Always co-linear with accompanying muons

- $10^5 \rightarrow 10$ with veto
Radiation level predicted to be very low in T12 due to dispersion function of LHC at T12.

Measurements using BatMon radiation monitor in 2018 confirm FLUKA expectations:

- less than $5 \times 10^{-3}$ Gy/year
- less than $5 \times 10^{7}$ 1 MeV neutron equivalent fluence/year

**FASER detector does not need radiation hard electronics**
Overview | Dark photons

- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT\sim \Lambda_{QCD}
- enormous event rates N \sim 10^{15} per bin

- production peaks at pT\sim \Lambda_{QCD}
- rates highly suppressed by \varepsilon^2 \sim 10^{-10}
- still rates N\sim 10^5 per bin: LHC could be dark a photon factory

- only highly boosted \sim TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N\sim 100 signal events within 20cm of beam collision axis

Josh McFayden | Warwick | 19/10/2023
FASER

Overview | LLP production modes

\[ \pi^0 \rightarrow A' \]

\[ p \rightarrow \gamma^* \rightarrow p \]

\[ p \rightarrow A' \]

\[ g \rightarrow u \rightarrow A' \]

\[ N \rightarrow \gamma^* \rightarrow a \]
Overview | Dark photon reach

![Diagram of dark photon mass and kinetic mixing](image-url)
For lower lifetime the number of signal events becomes exponentially suppressed once the $A'$ decay length drops below the distance to the detector.

Combining dependence in both production rate and decay width, total number of signal events in the detector scales as $\epsilon^4$. 
Target scenarios | Dark Photon

\[ B(A' \rightarrow XX) \sim 10^{-3} \]

\[ m_{A'} \text{ [GeV]} \]

\[ m_{A'} \text{ [GeV]} \]

\[ \epsilon^{-2} \sim 10^{-6} \]

\[ \epsilon \sim 10^{-3} \]

\[ 10^{-5} \]

\[ 10^{-7} \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ \text{Dark Photon} \]

\[ \text{NA64} \]

\[ \text{AWAKE} \]

\[ \text{LHCb} \]

\[ \text{Belle-II} \]

\[ \text{FASER} \]

\[ \text{FASER 2} \]

\[ \text{MATHUSLA} \]

\[ \text{SeaQuest} \]

\[ \text{NA63} \]
Target scenarios | Dark Higgs

- Dark Higgs scenarios
- FASER 2
- NA62
- SeaQuest
- LHCb
- CODEx-b
- MATHUSLA
- KLEVER
- SHiP

Diagram showing $B(\psi \to XX)$ vs. $m_{\psi}$ [GeV] with different decay modes (e.e, KK, cc, $\tau\tau$, $\mu\mu$, gg, ss) and $\theta^2 \cdot c_\ell \phi$.
Target scenarios | Dark Higgs

- Dark Higgs
- FASER 2
- MATHUSLA
- CODEX-b

Diagram showing $B(\phi \rightarrow XX)$ vs. $m_\phi$ [GeV] and $\theta^2 \cdot c_\tau \phi$ vs. $m_\phi$ [GeV].

- Target scenarios include $ee$, $ KK $, $ \tau \tau $, $ gg $, and $ ss $.
- $\theta^2 \cdot c_\tau \phi$ ranges from $10^{-3}$ to $10^6$.
- $B(\phi \rightarrow XX)$ ranges from $10^{-2}$ to $10^1$.

Josh McFayden | Warwick | 19/10/2023
Target scenarios | ALP

\[
B(\alpha \to XX) \propto (g_{\alpha V} \cdot \text{GeV})^2 \cdot c \tau_a \quad [\text{nm}]
\]

with $m_a$ in [GeV].

For $\gamma \gamma$: $B(\alpha \to \gamma \gamma) \\ee \gamma 

$g_{\alpha V} = 1/f_{\gamma}$ in [GeV$^{-1}$]

ALP – Photon Dominance

FASER, LDMX, NA62, Belle-II, \textit{etc.}
Target scenarios | ALP

![Graph of $g_{a\mu}^{2}cT_{a}$ vs $m_{a}$]  

- $B(a\rightarrow XX)$  
- $m_{a}$ [GeV]

- ALP - Fermion Dominance

- KLEVER
- FASER
- FASER 2
- CODEX-b
- SHIP
- MATHUSLA

![Graph of $g_{a\mu}=2v/\lambda_{a}$ vs $m_{a}$]  

- $m_{a}$ [GeV]
Civil Engineering in TI12

- Trench
  - To be aligned with the line-of-sight (LOS) in the vertical direction a shallow (<50cm deep) trench was needed in TI12.
  - Drain shallower than shown on historical drawings
    - Provided opportunity to increase trench depth - parallel to LOS.
  - Plan area increased to allow more space for FASERv.

- Trench strengthening
  - Improved rock characteristics enabled removal of steel frame.
  - Less complex site works and better ground conditions enabled increased depth.

Trench: ~7m x 1.5m x 0.5m
Modelling uncertainties

- Dark Photon

- FASER

- FASER 2

- Meson-Decay:
  - EPOS-LHC
  - QGSJET
  - SIBYLL

- Bremsstrahlung:
  - $p_T<10$ GeV
  - $p_T<1$ GeV

- $m_A^*$ [GeV]

- $\varepsilon$

- $10^{-7}$

- $10^{-6}$

- $10^{-5}$

- $10^{-4}$

- $10^{-3}$

- ALP – Fermion Dominance

- $m_a$ [GeV]

- $10^{-1}$

- $10^{-2}$

- $10^{-3}$

- $10^{-4}$

- $10^{-5}$

- CTEQ 6.6

- CTEQ 14 LO

- CTEQ 14 NLO

- NNPDF31 LO

- NNPDF31 NLO
Energy threshold
FASER2 | Magnet

- Rectangular magnet 3 x 0.5 x 2m
- 2 T bending in horizontal direction
Circular magnet 1m radius, 0.5m high
- More bending power in centre - highest energy
- Less stored energy
- 2 T bending in horizontal direction

Hide Otono
# FASER2 | Magnet

Cost estimation from TOSHIBA

Roughly 10 MCHF based on their experience on SAMURAI

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td></td>
<td>Dipole magnet</td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td>T</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Magnetic path length</td>
<td>T·m</td>
<td>4.7</td>
<td>Rough estimation from SAMURAI</td>
</tr>
<tr>
<td>Stored energy</td>
<td>MJ</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Magnetic pole gap distance</td>
<td>mm</td>
<td>880</td>
<td>same as SAMURAI</td>
</tr>
<tr>
<td>Magnetic pole radius</td>
<td>mm</td>
<td>2000</td>
<td>circular poles</td>
</tr>
<tr>
<td>Coil</td>
<td></td>
<td>Solenoid</td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>ton</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

SAMURAI (Superconducting Analyzer for Multi-particles from Radioisotope beams)
RI beam at RIKEN, Japan
Based on SciFi detector installed in LHCb in LS2.

- SiPM+scintillating fibre design
- Fibres 250um diameter => 80um resolution.
- Each module consists of a mat of 4 fibres, with >99% efficiency.
- Costing done by scaling LHCb detector to the FASER2 design, and includes readout.
- Cost could be reduced by re-using tooling from LHCb if relevant institutes were involved.
The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.

Cost: ~3.8M CHF
Existing dual-readout prototypes for Higgs factory detectors

- EM prototype exists, construction of hadronic-size prototype ongoing
- Costing based on HiDRa “hadronic size” prototype - INFN
- 65x65x250 cm (presentation)
- Aiming for 2023 construction and test beam
FASER2 | Calorimeter design

- Fully segmented design
- Perpendicular crossing of EM layers
- Don’t need dual readout - no Cherenkov fibres

Costing Option
- 3-5M Euros
- Depending on readout and granularity
Possibility to reuse old LHCb Preshower and Scintillating Pad Detector for FASER2 Calo

- Active part is made up of scintillator pads with wavelength shifter embedded.
- Pad size depends on the location and are 12 cm x 12 cm, 6 cm x 6 cm and 4 cm x 4 cm.
- Pads are supported on “super modules” with an active area of about 1 m x 5.8 m.