The FASER experiment at the CERN LHC

From searches for weakly interacting particles to first measurements of collider neutrinos

Seminar at CP3, Louvain-La-Neuve
17 June 2020

Anna Sfyrla
University of Geneva
The landscape of new particles @ colliders
The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example

A plethora of searches (e.g. SUSY)

Exploration of H physics

Standard Model measurements
The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example

Searches for exotic H decays

**ATLAS Preliminary**

Run 1: $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
Run 2: $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

2HDM+S Type-II, \(\tan\beta = 2\)

Searches for Long-Lived Particles

**ATLAS Long-lived Particle Searches** - 95% CL Exclusion

**ATLAS Preliminary**

$|e\ell tt (18.4 - 36.1) \text{ fb}^{-1} \sqrt{s} = 8, 13$ TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>(L_c \ell tt) [fb$^{-1}$]</th>
<th>Lifetime limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow e\ell tt)</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(7.9 \times 10^{-11})</td>
<td>1904.09140</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow Z \ell \ell)</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(2.0 \times 10^{-10})</td>
<td>1904.09140</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow Z \ell \ell)</td>
<td>displaced dimuons</td>
<td>32.9</td>
<td>(2.0 \times 10^{-10})</td>
<td>1906.03087</td>
</tr>
<tr>
<td>CMSSM</td>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>(3.9 \times 10^{-10})</td>
<td>1403.05490</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1310.32675</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1712.02110</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1906.05932</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1811.15709</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1808.04995</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_1 \rightarrow \text{SPH} + \text{hadronic})</td>
<td>displaced leptons + jets</td>
<td>20.3</td>
<td>(3.9 \times 10^{-10})</td>
<td>1716.04881</td>
</tr>
</tbody>
</table>

*Only a selection of the available lifetime limits is shown.*
The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed

Known physics
- Strongly interacting heavy particles
  - LHC Physics
- Weakly interacting light particles
  - Intensity Frontier

MeV GeV TeV

Mass of new particle (m)

Coupling to known particles ($\epsilon$)

$10^{-6} \quad 10^{-3} \quad 1$
The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- Burning open questions remain!
The landscape of new particles @ colliders

- Simple mechanism for DM generation: “freeze out”

\[ \rho_X \propto \frac{m_X^2}{\epsilon_X^4} \]

- Surviving DM density:

<table>
<thead>
<tr>
<th>Coupling to known particles (ε)</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Too heavy to be good DM candidates
- Too light to be good DM candidates
- Good dark matter candidates

Feng, Kumar - PRL 101, 231301 (2008)
The landscape of new particles @ colliders

- **Lifetime**: A characteristic of weakly interacting light particles

- Distinct signatures, exploited in both general purpose and dedicated experiments

- Most general purpose searches still do target particles that decay promptly

- Opportunity for exploration!
  - Experiments under evaluation: MATHUSLA, milliQan, SHiP, LDMX, ...
  - Recently approved: FASER

Distance travelled by particles:

\[ L = v \tau \gamma \propto c \frac{1}{\epsilon^2 m} \frac{E}{m} \]

- Known physics
- Strongly interacting heavy particles
- Weakly interacting light particles

**ForwArd Search ExpeRiment at the LHC**

- Searches for new weakly interacting light particles produced in decays of light mesons (e.g. $\pi$, K)
- Such light particles are abundantly produced in p-p collisions, primarily in large pseudorapidity

**FASER acceptance:**
- 20 cm diameter, 480 m from ATLAS IP ($2 \times 10^{-6}$% solid angle)

- $\sim 10^{16}$ $\pi$ per year
- 2% within FASER acceptance

- $\pi^0$ - Spectrum [ab/bin]

- Coupling to known particles ($\epsilon$)
- Coupling to new particles

- Known physics
- Strongly interacting heavy particles
- Weakly interacting light particles
- Intensity Frontier
- LHC Physics

- Mass of new particle ($m$)

- Energy Frontier

**Coupling to known particles ($\epsilon$)**

- $10^{-6}$
- $10^{-3}$
- $10^{-1}$
- $10^{0}$
- $10^{1}$
- $10^{2}$
- $10^{3}$
- $10^{4}$
- $10^{5}$

- $\theta_\pi$
- $\rho_\pi$ [GeV]

- $10^{-5}$
- $10^{-4}$
- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
- $10^{0}$
- $10^{1}$
- $10^{2}$
- $10^{3}$
- $10^{4}$

- $10^{14}$
- $10^{15}$
- $10^{16}$
The FASER experiment
Location

SPS

Point 1

Point 1.8

Point 3.3

Point 4

Point 5

Point 6

Point 7

Point 8

Point 2

Point 3.2

ALICE

SPS

ATLAS

CMS

T12 before FASER
https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc
Drivers for choices: Tight timeline between experiment approval and installation & the limited budget.

- 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

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

- trigger rate O(500Hz) – mostly single muon events
- low radiation
- low occupancy / event size

Energy measurement
Tracking
Decay volume

Scintillator veto
A'
FASER Detector

- Magnets
- Tracker "backbone"
- Tracker stations
- Calorimeter
- Preshower and backsplash stopper
-Trigger / preshower station
- Trigger / timing station
- Veto station
- Magnets

Incoming LLPs

To ATLAS IP

Length: 5 m
Aperture: 20 cm
Decay volume: 1.5 m
An example physics case: Dark Photon $A'$

- New massive gauge boson in a dark sector with dark matter candidate $X$
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}=100$ MeV, $\epsilon \sim 10^{-5}$ and $E\sim$TeV, can travel long distance before decay

N.B.: FASER uses only lumi information from ATLAS!
An example physics case: Dark Photon $A'$

- New massive gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}=100$ MeV, $\epsilon \sim 10^{-5}$ and $E\sim$TeV, can travel long distance before decay

- Discovery contours assume at least 3 signal events, no background.

N.B.: FASER uses only lumi information from ATLAS!
Another example: Axion-like particles (ALPs)

- Photons from IP travel 140 m, collide with neutral particle absorber (TAN) and create ALPs

- Very challenging signature, esp. to distinguish the two close-by photons.
- FASER upgrade proposed to facilitate this.
FASER experiment construction and commissioning
Significant and challenging civil engineering work done by CERN SMB & contractors
Access tunnel and Infrastructure

Access to TI12 is over the LHC machine complicates the transport & safety

Next steps to install:
- Transport equipm’t
- Lights
- Racks
- Power
- Optical Fibers
- Compressed Air
- Cooling Unit
- Cable Trays
Magnets

• Field of 0.55 T; permanent dipole
• Halbach array design with fixed-field magnets
  • Maximizes field without need for too much support infrastructure
  • Allows for a compact design, reducing amount of digging

• Status:
  • Under construction by the CERN magnet group
  • Part of the first magnet successfully made, production process validated
  • Expecting magnetic block delivery to finalize production
• FASER uses ATLAS SCT spare modules
• 3 tracker stations x 3 tracker layers x 8 modules
  • 72 modules and $O(10^5)$ channels in total
• Mechanical stability by “backbone” fixed on magnets
• Read out with custom GPIO board

Tracker Stations

Mechanical stability by “backbone” fixed on magnets

Tracker “backbone”

SCT module
80 $\mu$m strip pitch / 40 mrad angle
17 $\mu$m / 580 $\mu$m track resolution

Tracker layer
Tracker

- SCT module ASICs, require ~ 5 W / module
- Detector cooling via water chiller operating at 10-15°C

Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

Low radiation in TI12 and much lower rates than ATLAS allow for simplifications in services and readout.
Tracker

SCT module ASICs, require ~ 5 W / module

Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

Tracker Station

FLEX cables
Tracker

SCT module ASICs, require ~ 5 W/module

FLEX cables

Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

Provides LV and HV

Wiener Power Supply
• Prototype layers produced and used for extensive testing (electrical, mechanical and thermal)
• Production planes in progress
• Commissioning started at CERN; well-defined procedure
• Gaining operational experience!

• Module QA
• Three stations all providing triggering capability:
  • Very high efficiency veto station for incoming charged particles (x4 planes)
  • Timing station; precise timing (~ ns) wrt IP (x1 plane)
  • Preshower station; coincidence with timing station (x2 planes)
• Read out with PMTs and CAEN digitizer
**Scintillators Status**

- Scintillator planes produced at CERN
- PMTs purchased and studied
- Characterization with cosmics and LEDs
  - First results indicate good light yields (~ 400 photo-electrons/MIP) and high efficiency (> 99.8%)

Ongoing cosmic tests

---

FASER scintillators produced at CERN
FASER uses 4 LHCb spare outer ECAL modules
  • 25 radiation lengths long
  • Lead/scintillator calorimeter
• Energy resolution ~ 1% for TeV deposits
  • No longitudinal shower information
• Provides triggering capability
• Read out with PMTs and CAEN digitizer
Calorimeter Status

- Calorimeter modules tested; characterization ongoing
- First calibration and linearity measurements with cosmics
  - good agreement with LHCb pulses

Calo PMTs

FASER cosmic signal
LHCb shapes
~10 ns rise time
Trigger & Data acquisition

• Expected **trigger rate** about **500 Hz**, dominated by muons from the IP
  • L1A includes random and software triggers

• Expected **bandwidth** about **15 MB/s**, dominated by PMTs’ wide signal (~1 μs)

• All TDAQ electronics will be placed in TI12
Trigger & Data acquisition Status

- Electronics available and tested
  - Connected to rack & available online during CERN lockdown for continuing testing
  - Communication tests resumed last week!
- DAQ SW based on CERN’s “DAQling”, adapted for FASER
  - Initial implementations for all detectors in place
  - Includes online monitoring
- DCS follows CERN practices

Initial Run Control application, produced by summer intern
• Two base-plates made of aluminum
  • Align magnets to each other and LOS within mm
  • Allow detector to follow LOS movements

• An upper frame, segmented in sections
  • Align detectors within mm

• Tracker backbone fixed on magnets
  • ensures tracker alignment (<100 μm wrt frame)
FASER experiment construction and commissioning
**Commissioning**

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN’s Prevessin site (“ENH1”) for full-detector commissioning

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Where</th>
<th>When in 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual component commissioning</td>
<td>CERN labs</td>
<td>July</td>
</tr>
<tr>
<td>Detector commissioning</td>
<td>ENH1</td>
<td>September</td>
</tr>
<tr>
<td>Installation of magnets</td>
<td>ENH1</td>
<td>September</td>
</tr>
<tr>
<td>Complete dry assembly and testing</td>
<td>ENH1</td>
<td>October</td>
</tr>
<tr>
<td>Full detector installation</td>
<td>TI12</td>
<td>November</td>
</tr>
<tr>
<td>In-situ dry commissioning</td>
<td>TI12</td>
<td>December</td>
</tr>
</tbody>
</table>

At this point, still some uncertainties in these timescales
Backgrounds

- Major background from IP:
  - Muons and neutrinos directly from IP; muons that brems off another particle
  - Veto in scintillators (4 uncorrelated layers) renders this negligible

- Background from beam:
  - Beam-gas or diffractive proton losses are found to both be negligible
  - Simulation, validated by emulsion-based measurement (recorded ~ 13/fb of data). CERN beam monitoring also installed

- The radiation level is low (<10^{-2} Gy/year)

→ TI12 very quiet location!
Huge flux of high-energy neutrinos

• Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

Experiments to study collider neutrinos have been proposed since the 80s, e.g., A. De Rujula and R. Ruckl. “Neutrino and muon physics in the collider mode of future accelerators” Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, 1984.
Huge flux of high-energy neutrinos

• Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

• Expected event yields

<table>
<thead>
<tr>
<th>150/fb @14TeV</th>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main production source</td>
<td>kaon decay</td>
<td>pion decay</td>
<td>charm decay</td>
</tr>
<tr>
<td># traversing FASERnu 25cm x 25cm</td>
<td>$O(10^{11})$</td>
<td>$O(10^{12})$</td>
<td>$O(10^9)$</td>
</tr>
<tr>
<td># interacting in FASERnu (1.2tn Tungsten)</td>
<td>~1300</td>
<td>~20000</td>
<td>~20</td>
</tr>
</tbody>
</table>

Experiments to study collider neutrinos have been proposed since the 80s, e.g.: A. De Rujula and R. Ruckl, “Neutrino and muon physics in the collider mode of future accelerators” Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 57–596, 1984.
Huge flux of high-energy neutrinos

- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

- Expected spectra: complementary to existing experiments

- Expected cross section reach: extends current measurements already with 150/fb

- Uncertainty from neutrino production important

- Neutrino energy with 30% resolution (simu)
• Emulsion film detector with tungsten plates; well known neutrino detector technology
• Track position resolution $O(50\text{nm})$, and angular resolution $O(0.35\text{mrad})$. No timing resolution
• Replace every 20-50/fb to maintain manageable track density
• Challenge: replace the 1-ton-scale detector about 3 times/year

• Status:
  • Testing samples of tungsten planes for detector assembly

N.B.: Interface tracker for charge ID and improved measurements to be added at a longer timescale
Pilot run in 2018

• A 30 kg detector at TL18

• Collected ~ 13/fb

• About 30 neutrino interactions expected to have occurred

• Data reconstruction and analysis ongoing
  • a testbed for physics data

Reconstructed neutral vertices in the prototype dataset
FASER Timeline
FASER proposed by Feng, Galon, Kling, Trojanowski

FASER approved by CERN Research Board, construction started

FASER$\nu$ approved by CERN Research Board

FASER surface commissioning started

FASER commissioned on surface

FASER commissioned in TI12

Physics data taking

FASER$\nu$ installed in TI12

FASER commissioned in TI12

FASER commissioning with beams

FASER Letter of Intent

FASER Technical proposal

FASER installed in TI12

08/2017

08/2018

03/2019

12/2019

01/2020

11/2020

12/2020

09/2020

06/2021

2022

2022 -

today
Global timeline

- 08/2017: FASER proposed by Feng, Galon, Kling, Trojanowski
- 11/2018: FASER Letter of Intent
- 03/2019: FASER Technical proposal
- 12/2019: FASER approved by CERN Research Board, construction started
- 01/2020: FASER surface commissioning started
- 09/2020: FASER commissioned on surface
- 11/2020: FASER installed in TI12
- 12/2020: FASER commissioned in TI12
- 06/2021: FASERv installed in TI12
- 2022: FASER commissioning with beams
- 2022 - : Physics data taking

(*) FASERν approved by CERN Research Board

08/2017: FASER Letter of Intent
03/2019: FASER Technical proposal
12/2019: FASER approved by CERN Research Board, construction started
01/2020: FASER surface commissioning started
09/2020: FASER commissioned on surface
11/2020: FASER installed in TI12
12/2020: FASER commissioned in TI12
06/2021: FASERv installed in TI12
2022: FASER commissioning with beams
2022 -: Physics data taking
### Beyond FASER

**Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity**

---

**Table: Benchmark Models**

<table>
<thead>
<tr>
<th>Benchmark model</th>
<th>Label</th>
<th>Section</th>
<th>PBC</th>
<th>Refs.</th>
<th>FASER</th>
<th>FASER 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark photons</td>
<td>V1</td>
<td>IV A</td>
<td>BC1</td>
<td>[7]</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$B-L$ gauge bosons</td>
<td>V2</td>
<td>IV B</td>
<td></td>
<td>[30]</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$L_i-L_j$ gauge bosons</td>
<td>V3</td>
<td>IV C</td>
<td></td>
<td>[30]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark Higgs bosons</td>
<td>S1</td>
<td>V A</td>
<td>BC4</td>
<td>[26,27]</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Dark Higgs bosons with $hSS$</td>
<td>S2</td>
<td>V B</td>
<td>BC5</td>
<td>[26]</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>HNLs with $e$</td>
<td>F1</td>
<td>VI</td>
<td>BC6</td>
<td>[28,29]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HNLs with $\mu$</td>
<td>F2</td>
<td>VI</td>
<td>BC7</td>
<td>[28,29]</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>HNLs with $\tau$</td>
<td>F3</td>
<td>VI</td>
<td>BC8</td>
<td>[28,29]</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>ALPs with photon</td>
<td>A1</td>
<td>VII A</td>
<td>BC9</td>
<td>[32]</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ALPs with fermion</td>
<td>A2</td>
<td>VII B</td>
<td>BC10</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>ALPs with gluon</td>
<td>A3</td>
<td>VII C</td>
<td>BC11</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Dark pseudoscalars</td>
<td>P1</td>
<td>VIII</td>
<td></td>
<td>[36]</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

---

Outlook

• The collaboration is working feverishly to construct, commission and install the detector over the current Long Shutdown

• CERN teams work on civil engineering, services, magnets, ...

• Remarkable progress in all fronts

• Goal: get ready for data taking with the start of Run3!

• Enormous potential to:
  • either make a new discovery or constrain parts of phase-space which no current experiment has access to
  • make the first collider-originated neutrino measurements

• We have started thinking about FASER2!

Stay in touch:
🌐 [https://faser.web.cern.ch/](https://faser.web.cern.ch/)
🐦 @FASERexperiment
References

FASER collaboration:

• Letter of Intent  arXiv:1811.10243
• Technical Proposal arXiv:1812.09139
• FASER's Physics Reach for Long-Lived arXiv:1811.12522
• Input to the European Strategy for Particle Physics Update arXiv:1901.04468
• Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC arXiv:1908.02310

Plus several theory papers

More information:  https://faser.web.cern.ch/physics/publications
Thanks!

• Many thanks to my collaborators for providing material & great pictures from component testing!

• And to the Heising-Simons foundation, Simons foundation and CERN for their financial support

FASER Collaboration: 8 countries, 20 institutes, about 60 members
LLP production at ATLAS IP
• Adapt open source ATLAS Athena ("Calypso")
• First versions of detector description, Geant4 simulation and event display working
• Track reconstruction with “ACTS” under development
Accessing TI12

Preparation of TI12

Before FASER

Q2 2019

02/2020
Accessing TI12
Extremely simplified TDAQ system
**SIGNALS: DARK PHOTONS**

- **Pions at the IP**
  - Enormous event rates: $N_{\pi} \sim 10^{15}$ per bin
  - Production is peaked at low transverse momentum $\sim 250$ MeV

- **$A'$ at the IP**
  - Rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
  - But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

- **$A'$ decay in FASER**
  - Rates suppressed again, but still $N_{A'} \sim 100$ signal events
  - Signal is $E \sim \text{TeV}$ $A'$s within 20 cm of the line of sight

---

Slide from J. Feng
An example physics case: Dark Photon $A'$

- New massive gauge boson in a dark sector with dark matter candidate $X$
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}=100 \text{ MeV}$, $\epsilon \sim 10^{-5}$ and $E\sim\text{TeV}$, can travel long distance before decay

• Discovery contours assume at least 3 signal events, no background.

N.B.: FASER uses only lumi information from ATLAS!
Assumptions in sensitivity plots

**Results:** The projected dark photon sensitivity reaches for FASER at LHC Run 3 with 150 fb\(^{-1}\) and FASER 2 at HL-LHC with 3 ab\(^{-1}\) are shown in the right panel of Fig. 6. The gray-shaded regions are excluded by current bounds; see Refs. [30, 37] and references therein. For comparison we also show the projected sensitivities of other experiments: NA62 assumes 10\(^{18}\) protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3 [17]; SeaQuest assumes 1.44 \times 10^{18} POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter [19]; the proposed beam dump experiment SHiP assumes \sim 2 \times 10^{20} POT collected in 5 years of operation [20]; the proposed electron fixed-target experiment LDMX during Phase II with a beam energy of 8 GeV and 10\(^{16}\) electrons on target (EOT) [25]; Belle-II and LHCb assume the full expected integrated luminosity of 50 ab\(^{-1}\) [14] and 15 fb\(^{-1}\) [15, 16], respectively; HPS assumes 4 weeks of data at JLab at each of several different beam energies [1, 55]; NA64 [56] corresponds to 5 \times 10^{12} EOT with 100 GeV energy; and AWAKE [57] is assumed to be working as a fixed-target experiment with a 10-m-long decay volume and 10\(^{16}\) EOT accelerated in a 50 – 100 m long plasma cell to the energy \mathcal{O}(50 \text{ GeV}).
Scintillators – Veto stations

Final design could be more vertical PMT position
Will have port for LED signal

Light-guides, PMT-holders and assembly to be done at CERN

Interlocking lead bricks
- ~150x300x300mm³
- exact bricks TBD
- shower/stops photons from upstream muons

Hamamatsu H6410 PMTs
- large diameter (46mm)
- large gain $10^6$-$10^8$

Two independent scintillator layers per station
- 20x300x300mm³
- EJ-200 from Eljen Tech.

- expect ~200 photo-electrons per MIP
Scintillators – Trigger / Timing

Scintillator layer split in two
- 10X200x400mm³
- split reduces vertical time-walk and eases construction
- will have small offset and overlap to avoid gap
- again EJ-200 scintillator
- double sided readout:
  1. allows correction for horizontal time-walk
  2. can reduce noise triggers by requiring coincidence
- expect ~80 photo-electrons per MIP
- timing resolution still to be determined (~ns)

Same H6410 PMTs

Large area to catch muons coming at angle generating showers only seen in last layer/calorimeter, a dominant(?) background for photons-only signal
Scintillators – Trigger / Preshower

Trigger/Preshower station has same scintillator design as veto stations

Carbon fiber (low-Z) blocks between tracker and calorimeter to reduce backsplash from calorimeter
  • exact thickness will depend available space after support is designed should be three ~5cm thick blocks

Embed/glue in two 1 radiation length (~5mm) lead plates in front of scintillator layers to start EM shower
  • allows to discriminate between incoming di-photon signal and neutrino interactions in calorimeter
Calorimeter

Using 4 LHCb spare outer ECAL modules for calorimeter (have 8)

Theoretical energy resolution ~1%, but we will be limited by how well we can calibrate and by punch-through

7 R7899-20 Hamamatsu PMT provided by LHCb
  • tubes are almost new (from 2018)

Prototype

Had to make our own HV base
  • done by Friedemann

Have new base with non-solder connection

Divider to be shortened to fit in calorimeter tube – waiting for final tests of proto-type
Interface detector

- Possibility to connect FASER$_\nu$ with rest of FASER for:
  - Charge identification, Improved energy resolution, Better background rejection
- Would require interface detector in front of FASER
  - Precision tracker to link FASER$_\nu$ and FASER tracks
  - Most likely a fourth station of spare ATLAS SCT modules
- To not jeopardize FASER schedule, this would be installed in 2021/22 YETS
  - Most data anyway expected after that
Read-out & Analysis

In Japan
Emulsion film production

Detector assembling

Exposure

Disassembling

Development

In Japan
Full area Readout

At CERN

Off-line analysis

Kinematic analysis

Search for tau/charm decays

μ / e ID

Vertex reconstruction

Track reconstruction

Alignment
Module structure

vacuum packed module
20 emulsion films +
20 tungsten plates

≈ 2 cm
holding edge

atmospheric pressure
≈ 1 Bar
≈ 6250 N / 625 cm²

25 cm

Teflon plate 2 mm

≈ 0.3 mm

micro-dot glue
(silicone dots)

FASERν box

≈ 6250 N

x50 modules
Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).
Neutrino production

<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^+ \rightarrow \mu\nu )</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>Kaons</td>
<td>( K^+, K_S, K_L )</td>
<td>( K^+ \rightarrow \mu\nu, K \rightarrow \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 \rightarrow 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 \rightarrow K\ell\nu, D_s \rightarrow \tau\nu, \Lambda_c \rightarrow \Lambda\ell\nu )</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bottom</td>
<td>( B^+, B^0, B_s, \Lambda_b, \ldots )</td>
<td>( B \rightarrow D\ell\nu, \Lambda_b \rightarrow \Lambda_c\ell\nu )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
</tbody>
</table>

TABLE I. Decays considered for the estimate of forward neutrino production. For each type in the first column, we list the considered particles in the second column and the main decay modes contributing to neutrino production in the third column. In the last four columns we show which generators were used to obtain the meson spectra: EPOS-LHC (E) [59], QGSJET-II-04 (Q) [60], SIBYLL 2.3C (S) [61–64], and PYTHIA 8 (P) [66, 67], using both the MONASH-tune [68] and the minimum bias A2-tune [69].
Neutrino fluxes

The energy spectrum of neutrinos with CC interactions in a 1-ton tungsten detector with dimensions 25 cm × 25 cm × 1 m centered on the beam collision axis at the FASER location at the 14 TeV LHC with 150 fb–1

The neutrino interaction rate per unit area normalized to the prediction at the beam collision axis for a detector with large radius.
Possibility of probing tau neutrino production from the decay of light gauge bosons

![Diagram showing kinematic distributions and experimental setups](image)

**TABLE I.** Types of anomaly free gauge groups and corresponding fermion charges $q_i$. 

<table>
<thead>
<tr>
<th>Gauge Group</th>
<th>$q_e$</th>
<th>$q_\mu$</th>
<th>$q_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_e L_e + x_\mu L_\mu - (x_e + x_\mu) L_\tau$</td>
<td>0</td>
<td>$x_e$</td>
<td>$-x_e - x_\mu$</td>
</tr>
<tr>
<td>$B + x_e L_e + x_\mu L_\mu - (3 + x_e + x_\mu) L_\tau$</td>
<td>1/3</td>
<td>$x_e$</td>
<td>$-3x_e - x_\mu$</td>
</tr>
<tr>
<td>$B - L$</td>
<td>$1/3$</td>
<td>$-1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$B - L_\mu - 2 L_\tau$</td>
<td>$1/3$</td>
<td>0</td>
<td>$-2$</td>
</tr>
<tr>
<td>$B - L_\mu - 2 L_\tau$</td>
<td>$1/3$</td>
<td>0</td>
<td>$-2$</td>
</tr>
<tr>
<td>$B - 3 L_\tau$</td>
<td>$1/3$</td>
<td>0</td>
<td>$-3$</td>
</tr>
</tbody>
</table>

**Experimental Setup**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Status</th>
<th>$N_{POT}$</th>
<th>$A_{det}$</th>
<th>$A_{det}$</th>
<th>Ref.</th>
<th>$N_{vent}$</th>
<th>$E_{vent}$</th>
<th>$N_{vent}$</th>
<th>$E_{vent}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DONuT</td>
<td>completed</td>
<td>$3 \times 10^{17}$</td>
<td>$0.26 t$</td>
<td>$50 \times 50 \text{ cm}^2$</td>
<td>$0.2$</td>
<td>$10 \pm 4.6$</td>
<td>112 GeV</td>
<td>12</td>
<td>84 GeV</td>
</tr>
<tr>
<td>FASERν</td>
<td>approved</td>
<td>$150 \text{ fb}^{-1}$</td>
<td>$1.2 t$</td>
<td>$25 \times 25 \text{ cm}^2$</td>
<td>$0.52$</td>
<td>$11.6 \pm 5.1$</td>
<td>965 GeV</td>
<td>96</td>
<td>928 GeV</td>
</tr>
<tr>
<td>SND@LHC</td>
<td>proposed</td>
<td>$150 \text{ fb}^{-1}$</td>
<td>$0.85 t$</td>
<td>$40 \times 40 \text{ cm}^2$</td>
<td>$0.5$</td>
<td>$4.3 \pm 2.5$</td>
<td>720 GeV</td>
<td>3.5</td>
<td>382 GeV</td>
</tr>
<tr>
<td>SND@SHIP</td>
<td>proposed</td>
<td>$2 \times 10^{20}$</td>
<td>$8 t$</td>
<td>$80 \times 80 \text{ cm}^2$</td>
<td>$0.22$</td>
<td>$(10.9 \pm 3.6) \times 10^{3}$</td>
<td>52 GeV</td>
<td>$2 \times 10^{4}$</td>
<td>54 GeV</td>
</tr>
</tbody>
</table>

**ArXiv**: 2005.03594
Extending the trench for FASERv
To avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle

- The half crossing angle is ~150μrad, which moves the collision axis by ~7.5cm at the FASER location
- Such a change reduces the signal acceptance in FASER by ~25%
- Leads to very small changes in physics sensitivity
ALP-$\gamma\gamma$ performance

- For ALP-$\gamma\gamma$ decay, magnetic field does not help separate closely spaced decay products.
- We investigated calorimeter / pre-shower to allow to be able to resolve closely spaced (~1mm) high energy photons (>500 GeV) - seems very challenging.
- Preliminary studies suggest that events with no tracks and a large amount of EM energy in the calorimeter would be ~background free => an ALP signal would be detectable without the need to resolve the 2 photons.
- Further studies show an interesting background would be high energy neutrino’s interacting in the calorimeter to give large EM showers.
- In longer term investigating installing a fine granularity silicon pre-shower to be able to separate close-by photons.
Cost (estimates from TP)

### FASER

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Cost [kCHF]</th>
<th>Detailed Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>420</td>
<td>Table V</td>
</tr>
<tr>
<td>Tracker Mechanics</td>
<td>66</td>
<td>Table VI</td>
</tr>
<tr>
<td>Tracker Services</td>
<td>105</td>
<td>Table VII</td>
</tr>
<tr>
<td>Scintillator Trigger &amp; Veto</td>
<td>52</td>
<td>Table VIII</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>13</td>
<td>Table IX</td>
</tr>
<tr>
<td>Support structure</td>
<td>60</td>
<td>Table X</td>
</tr>
<tr>
<td>Trigger &amp; Data Acquisition</td>
<td>52</td>
<td>Table XIV</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>768</strong></td>
<td></td>
</tr>
<tr>
<td>Spares</td>
<td>56</td>
<td></td>
</tr>
</tbody>
</table>

Biggest single costs:
- Magnet
- Power Supplies (~100kCHF)

### FASERν

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost [kCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion gel for 440 m²</td>
<td>315</td>
</tr>
<tr>
<td>Emulsion film production cost for 440 m²</td>
<td>32</td>
</tr>
<tr>
<td>Tungsten plates, 1200 kg (first set)</td>
<td>173</td>
</tr>
<tr>
<td>Tungsten plates, 1200 kg (second set)</td>
<td>173</td>
</tr>
<tr>
<td>Packing materials</td>
<td>5</td>
</tr>
<tr>
<td>Support structure</td>
<td>12</td>
</tr>
<tr>
<td>Chemicals for emulsion development</td>
<td>20</td>
</tr>
<tr>
<td>Tools for emulsion development</td>
<td>5</td>
</tr>
<tr>
<td>Racks for emulsion film storage</td>
<td>5</td>
</tr>
<tr>
<td>Computing server</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>750</strong></td>
</tr>
<tr>
<td>[Emulsion gel for 2024 running]</td>
<td>[135]</td>
</tr>
<tr>
<td>[Additional consumables for 2024 running]</td>
<td>[23]</td>
</tr>
<tr>
<td><strong>[Total including 2024 running]</strong></td>
<td><strong>[908]</strong></td>
</tr>
</tbody>
</table>

Biggest single costs:
- Tungsten plates (~350kCHF)
- Emulsion Gel (~300kCHF)

### Infrastructure

<table>
<thead>
<tr>
<th>Work</th>
<th>Cost [kCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil Engineering</td>
<td>160**</td>
</tr>
<tr>
<td>Transport</td>
<td>95**</td>
</tr>
<tr>
<td>Optical Fiber &amp; Network Connection</td>
<td>10*</td>
</tr>
<tr>
<td>Power Connection</td>
<td>10</td>
</tr>
<tr>
<td>Compressed Air Connection</td>
<td>6</td>
</tr>
<tr>
<td>Preparation of T112</td>
<td>10*</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>291</strong></td>
</tr>
</tbody>
</table>