ForwArd Search ExpeRiment at the LHC

https://twiki.cern.ch/twiki/bin/view/FASER/
Technical Proposal: arXiv:1811.12522

Shih-Chieh Hsu
University of Washington
On behalf of the FASER Collaboration

Jan 23rd 2019, IAS HEP, HKUST
The Lamppost Landscape

- **Alcohol Discovered**
- **Strongly Interacting Heavy Particles**
- **Weakly Interacting Light Particles**
- **Impossible to Discover**

- **New Targets of Small Experiments**
- **Traditional Targets of Big Science**

Axes:
- Interaction Strength
- Mass

Scales:
- $10^{-6}$
- $10^{-3}$
- 1

Energy Scales:
- MeV
- GeV
- TeV

Courtesy Jonathan Feng
• New physics searches at the LHC have traditionally focused on high pT. This is appropriate for heavy, strongly-interacting particles
  \[ \sigma \sim \text{fb to pb} \rightarrow N_{\pi} \sim 10^3 - 10^6 \text{ in } 3 \text{ ab}^{-1} \text{ produced } \sim\text{isotropically} \]

• However, if new particles are light and weakly interacting, this may be completely misguided. Instead should exploit
  \[ \sigma_{\text{inel}} \sim 100 \text{ mb} \rightarrow N_{\pi} \sim 10^{17}, \theta_{\text{beam axis}} \sim \frac{m_\pi}{\text{TeV}} \sim 0.1 \text{ mrad} \]

• These light, weakly-interacting particles are long-lived and collimated. This motivates a small (~0.1 m³) and inexpensive (~1M CHF) experiment placed in the very forward region of ATLAS (480 m downstream).
ATLAS

Fit 5m long detector but less service supports.

FASER
FASER location

The view looking west

New Physics (Dark Sector)

LHC Beamline (Visible Sector)
Long-lived particles in FASER

LLP starts at IP, travels through Target Absorber Neutral (TAN) and other very forward infrastructure, then leaves the LHC tunnel, travels through 100 m of rock, decays to two highly energetic (~TeV) charged tracks in FASER.
• FASER will be placed on the beam collision axis ("on-axis") within mm accuracy. A little digging is required to lower the floor by 45 cm toward ATLAS.

• The beam crossing angle also matters: with 285 (590) μrad, the "on axis" location at FRASER shifts by 6 (12) cm.
Dark Photon Discovery Potential

- **FASER**
  - Collect data during Run 3 (150 fb$^{-1}$)
  - Decay volume: R=10 cm, L=1.5 m

- **FASER 2**
  - Collect data during HL-LHC (3 ab$^{-1}$)
  - Decay volume: R=1 m, L=5 m

FASER is complementary to other proposed experiments. FASER covers more parameter space for new particles produced in pion decays.
Axion-Like Particle and Dark Higgs

Similar to QCD axion

Dark Higgs-DM portal

Produced through Primakoff process ($\gamma N \rightarrow aN$)

Produced in B decay to probe $h-\phi$ mixing and $h\phi\phi$ trilinear coupling
Detector Layout

Particles from IP1

1.5 m Decay Volume

2 m Spectrometer

Scintillator/Pb Veto to veto incoming charged particles and protons

0.6 Tesla permanent dipole magnets with 20 cm aperture

Tracking stations
3 planes of silicon strip detector per station

1100.00 mm

5100.00 mm

Trigger/preshower scintillator station

Electromagnetic calorimeter (Lead/scintillator)
Detector Technology

CERN made permanent dipole magnet to minimize services

ATLAS SCT module
10% mom resolution @ 1TeV muon

LHCb ECAL module 25 X_0
1% energy resolution @ 1TeV electron

Scintillator/Pb Veto to veto incoming charged

Pitch 80 um

σ_E / E ≈ 10% / √E + 1%

Scintillator planes for trigger/timing

Pre-sampler (to be dropped)
• Muons coming from IP
  EPOS+theory with FLUKA simulation
  70 Hz (>100 GeV) at $L=2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

• Neutrino-induced events: low rate
  a few ~100 GeV events at 150 fb$^{-1}$

• The FLUKA study also finds that
  proton showers in dispersion suppressor and beam-gas background (from “beam 2”) are also negligible.

• The radiation level is low (<$10^{-2}$ Gy/year), which is encouraging for detector electronics.

Sabate-Gilarte, Cerutti, Tsinganis (2018)
In-situ background measurements in TI18

- First measurements already performed
  - Emulsion detectors
  - BatMon (Battery-operated radiation monitor)
- First results promising - consistent with FLUKA
- Data analysis and TI12 measurements on-going
The FASER Collaboration

The FASER collaboration: 27 collaborators, 17 institutions, 8 countries

Akitaka Ariga,¹ Tomoko Ariga,¹,² Jamie Boyd,³,* Franck Cadoux,⁴ David W. Casper,⁵ Francesco Cerutti,³ Salvatore Danzeca,³ Liam Dougherty,³ Yannick Favre,⁴ Jonathan L. Feng,⁵,† Didier Ferrere,⁴ Jonathan Gall,³ Itah Galon,⁶ Sergio Gonzalez-Sevilla,⁴ Shih-Chieh Hsu,⁷ Giuseppe Iacobucci,⁴ Enrique Kajornovitz,⁸ Felix Kling,⁵ Susanne Kuehn,³ Mike Lamont,³ Lorne Levinson,⁹ Hidetoshi Otono,² John Osborne,³ Brian Petersen,³ Osamu Sato,¹⁰ Marta Sabaté-Gilarte,³,¹¹ Matthias Schott,¹² Anna Sfyrila,⁴ Jordan Smolinsky,⁵ Aaron M. Sofia,⁵ Yosuke Takubo,¹³ Pierre Thonet,³ Eric Torrence,¹⁴ Sebastian Trojanowski,¹⁵,¹⁶ and Gang Zhang¹⁷
We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER gratefully acknowledges invaluable assistance from many people, including the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; Rhodri Jones, James Storey, Swann Levasseur, Christos Zamantzas, Tom Levens, Enrico Bravin (beam instrumentation); Dominique Missiaen, Pierre Valentin, Tobias Dobers (survey); Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport); Andrea Tsinganis (FLUKA simulation and background characterization); Attilio Milanese, Davide Tommasini, Luca Bottura (magnets); Burkhard Schmitt, Christian Joram, Raphael Dumps, Sune Jacobsen (scintillators); Dave Robinson, Steve McMahon (ATLAS SCT); Yuri Guz (LHCb calorimeters); Stephane Fartoukh, Jorg Wenninger (LHC optics), Michaela Schumann (LHC vibrations); Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Thomas Otto, Markus Brugger (LHC access and schedule); Simon Marsh, Marco Andreini, Olga Beltramello (safety); Stephen Wotton, Floris Keizer (SCT QA system and SCT readout); Yannic Body, Olivier Crespo-Lopez (cooling/ventilation); Yann Maurer (power); Marc Collignon, Mohssen Souayah (networking); Gianluca Canale, Jeremy Blanc, Maria Papamichali (readout signals); Bernd Panzer-Steindel (computing infrastructure); and Fido Dittus, Andreas Hoecker, Andy Lankford, Giovanna Lehmann, Ludovico Pontecorvo, Michel Raymond, Christoph Rembser, Stefan Schlenker (useful discussions).
First proposal:
J. Feng, I. Galon, F. Kling, S. Trojanowski

Letter of Intent
https://arxiv.org/abs/1811.10243

Technical Proposal
https://arxiv.org/abs/1811.12522

Physics White paper
https://arxiv.org/abs/1811.12522

European Strategy
https://arxiv.org/abs/1901.04468
Timeline

- Currently Approval Process
  - LOI July 2018 supported by LHCC
  - TP Nov 2018 recommended by LHCC
  - CERN research board approval in Jan 2019
  - Pursuing full approval by LS2 schedule committee by March
  - Magnet construction started soon
  - Procurement, Finalization of Engineering Design, Construction by Spring 2020
  - Installation, Commission starting from Aut 2020
  - Data taking in April 2021 - ready for Run III

- Funding from Simons and Heinsing-Simones
  - 1M CHF from each
  - 420k CHF for Magnet construction
  - 300k CHF for the rest of detectors
  - 300k CHF for Civil Engineering, Transportation, Powering
  - The rest is to support students
FASER is an opportunity for a small and inexpensive experiment to search for a full range of light and weakly-interacting particles, complementing other experiments.

If successful, a possible timeline and plan is

- Install FASER in LS2 (2019-20) for Run 3 (150 fb\(^{-1}\))
  - Decay volume \( R = 10 \text{ cm}, L = 1.5 \text{ m}, \text{ requires lowering floor by 50cm} \)
  - Target dark photons, ALPs, etc.
- Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab\(^{-1}\))
  - Decay volume \( R = 1 \text{ m}, L = 5 \text{ m}, \text{ requires some extension of existing tunnel} \)
  - Full physics program: dark photons, B-L gauge boson, ALPs, dark Higgs, HNLs, etc.
DARK MATTER @ LHC 2019

13~16 August
University of Washington
Seattle

https://indico.cern.ch/event/dmlhc2019
Backup
FASER Tracker

- The FASER tracker is composed of spare SCT modules from ATLAS. About 350 spares were prepared. They were not needed, and the ATLAS SCT collaboration has now kindly allowed us to use 80 of them.

- 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations.
The FASER ECAL will consist of spare LHCb outer ECAL modules, which the LHCb Collaboration has kindly allowed us to use.

- Dimensions: 12cm x 12cm – 75cm long (including PMT)
- 66 layers of lead/scintillator, light out by wavelength shifting fibres, and readout by PMT (no longitudinal shower information)
- 25 radiation lengths long
- Provides ~1% energy resolution for 1 TeV electrons

Scintillators used for vetoing charged particles entering the decay volume and for triggering, to be produced by the CERN scintillator lab
FASER Tracker Performance

**Left Panel:** 
- *x-space points - x-truth hits [mm]*
- **Mean = 0 µm**
- **RMS = 14 µm**

**Right Panel:** 
- *y-space points - y-truth hits [mm]*
- **Mean = 6 µm**
- **RMS = 506 µm**

**Bottom Left Panel:** 
- *Separation efficiency vs. E(A0) [GeV]*
- **M(A0) = 20 MeV**
- **M(A0) = 100 MeV**

**Bottom Right Panel:** 
- *q(p)/p vs. p(µ) [GeV]*
- **Predicted**
- **Simulation**
FASER has a full physics program: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (g, f, g); and many other examples.

| Benchmark Model                  | FASER | FASER 2 | References                                            |
|----------------------------------|-------|---------|-------------------------------------------------------|
| BC1: Dark Photon                 | √     | √       | Feng, Galon, Kling, Trojanowski, 1708.09389           |
| BC1’: U(1)_{B-L} Gauge Boson     | √     | √       | Bauer, Foldenauer, Jaeckel, 1803.05466                |
|                                  |       |         | FASER Collaboration, 1811.12522                       |
| BC2: Invisible Dark Photon       | –     | –       | –                                                     |
| BC3: Milli-Charged Particle      | –     | –       | –                                                     |
| BC4: Dark Higgs Boson            | –     | √       | Feng, Galon, Kling, Trojanowski, 1710.09387           |
|                                  |       |         | Batell, Freitas, Ismail, McKeen, 1712.10022           |
| BC5: Dark Higgs with hSS         | –     | √       | Feng, Galon, Kling, Trojanowski, 1710.09387           |
| BC6: HNL with e                  | –     | √       | Kling, Trojanowski, 1801.08947                        |
|                                  |       |         | Helo, Hirsch, Wang, 1803.02212                        |
| BC7: HNL with μ                  | –     | √       | Kling, Trojanowski, 1801.08947                        |
|                                  |       |         | Helo, Hirsch, Wang, 1803.02212                        |
| BC8: HNL with τ                  | √     | √       | Kling, Trojanowski, 1801.08947                        |
|                                  |       |         | Helo, Hirsch, Wang, 1803.02212                        |
| BC9: ALP with photon             | √     | √       | Feng, Galon, Kling, Trojanowski, 1806.02348           |
| BC10: ALP with fermion           | √     | √       | FASER Collaboration, 1811.12522                       |
| BC11: ALP with gluon             | √     | √       | FASER Collaboration, 1811.12522                       |
proton showers in dispersion suppressor and beam-gas background (from “beam 2”) are also negligible. The radiation level is low (<$10^{-2}$ Gy/year), which is encouraging for ddetector electronics.

- For HL-LHC conditions
  - Luminosity: $5\times10^{34}$ cm$^{-2}$s$^{-1}$
  - Cross section p-p collision: 85 mb
  - Pile-up: 140 events/bunch crossing

- A high-energy muon that brems off a photon or an EM or hadronic jet is a leading background if the incoming muon is not vetoed.
The FASER magnets are 0.6T permanent dipole magnets based on the Halbach array design:
- Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in T112
- Minimizes needed services (power, cooling etc.)

To be constructed by the CERN magnet group

- Permanent magnet block (NdFeB)
- Magnetic yoke (low carbon steel)
- Non magnetic internal ring (stainless steel)
- Non magnetic frame (extruded Cu or Al)
- Non magnetic shim (stainless steel)
- Epoxy resin

| Parameter                  | Value  | Unit |
|----------------------------|--------|------|
| Magnetic material          | NdFeB  |      |
| Central Field              | 0.6    | T    |
| Aperture                   | 200    | mm   |
| Outer diameter             | 430    | mm   |
| Field homogeneity          | ±2     | %    |
| Temperature dependence     | -0.12  | %/K  |
| Weight / meter             | ≈1000  | kg/m |
Tracking Spectrum

Signal Efficiency
loose selection

Track Energy Spectrum

\( E_A [\text{TeV}] \)

\( z [\text{m}] \)

\( \text{event rate [ab/bin]} \)

\( E_{e^0} [\text{TeV}] \)

\( \varepsilon = 2 \times 10^{-5} \)

\( \varepsilon = 10^{-5} \)

\( \varepsilon = 7 \times 10^{-6} \)
A conservative estimate of the separation required to FASER’s choice create isolated clusters in a silicon strip detector.
FASER Emulsion

|          | Energy cutoff   | Flux / 14 fb⁻¹ |
|----------|-----------------|----------------|
| Emulsion | $E > 0.5$ GeV   | $1.8 \times 10^5$ /cm² |
| FLUKA    | $E > 100$ GeV   | $1.4 \times 10^5$ /cm² |
40MHz synchronous to LHC

Event size 25 kB

650 Hz Trigger Rate (dominant by high energy muon) at $L = 2 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}$

| Source                        | Rate [Hz] |
|-------------------------------|-----------|
| Veto scintillators            | 360       |
| Timing scintillators          | 640       |
| Preshower scintillators       | 360       |
| Calorimeter ($E > 100 \text{GeV}$) | < 5 Hz   |
| Random trigger                | 10        |
| **Total**                     | **650**   |
