FORWARD SEARCH EXPERIMENT (FASER) AT THE LHC

Ke Li
04/06/2021
Seminar at Shanghai Jiao Tong University
The new particle landscape

Mass

Strongly Interacting Heavy Particles

Weakly Interacting Light Particles

Already Discovered

Impossible to Discover

New Targets of Small Experiments

Traditional Targets of Big Science

Interaction Strength

MeV

GeV

TeV

$10^{-6}$

$10^{-3}$
The new particle landscape

Mass

MeV  GeV  TeV

Interaction Strength

Weakly Interacting Light Particles  Impossible to Discover

Strongly Interacting Heavy Particles

Already Discovered

ATLAS&CMS

FASER

10^{-6}

10^{-3}

Particle Colliders
Outline

- Introduction of LHC and FASER
- Detector concept and construction
- Offline software framework
- Sensitivity study
- FASER\(\nu\) extension
- Status and summary
Large Hadron Collider (LHC)

- Largest collider so far.
  - 27 circumstance
  - 13 TeV center-of-mass energy, will be 14 TeV
  - Starts from 2012
  - Four experiments
    - ATLAS
    - CMS
    - LHCb
    - ALICE

- Preparing for upgrade
FASER: the idea

- **FASER** (twiki) is a proposed experiment designed to cover this scenario at the LHC to search for the long lived particle (LLP).

- Detector to be placed 480m from IP1 directly on the beam collision axis line of sight (LOS) with transverse radius of only 10cm covering the mrad regime.

Arxiv:1811.12522
History

- August 2017: Idea paper by Feng, Galon, Kling, Trojanowski
- Fall 2017: Geant4 detector simulations validate concept
- Winter 2018: Experimental collaboration forms
- July 2018: Letter of Intent
- December 2018: Technical Proposal, funding commitment
- March 2019: Approved by CERN Research Board!
- Tracker installed at March 2021!

Season 11, Episode 9, “The Bitcoin Entanglement” (November 2017)
Recent activities

> Previous plan: data taking at 2021
> Then COVID pandemic ...
> But we are making amazing progress
  • Tracker installation is done (a little bit ahead of schedule)

FASER tracker arriving on the surface at point-1 and then transported down to the LHC (87m) by crane
Tracker removed from transport box to be carried over the LHC in UJ12
Tracker attached to crane for final installation onto detector
Tracker installed onto detector
FASER location
FASER will be situated along the beam *collision* axis line of sight (LOS)
- ~480 m from IP
- after beams start to bend

TI12 unused tunnel, that intersects LOS 480m from IP1
FASER location

> The unused TI-12 tunnel offers a near-ideal place for such a search
  > Along collision axis line-of-sight
  > Beam has started to bend away
  > Only a few meters from beamline
    > Easy access
    > All necessary services available

> Shielded from IP by ~100 m of rock and concrete along line of sight
  > Only muons and long-lived, weakly-interacting neutrals from IP can reach
  > Very low radiation levels confirmed by *in-situ* measurements
  > Good sensitivity for discovery
FASER collaboration

- 70 members from 19 institutions from 8 countries

- Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Franck Cadoux (Geneva), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Monica D’Onofrio (Liverpool), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Carl Gwilliam (Liverpool), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Tomohiro Inada (Tsinghua), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (CERN), Sam Meehan (CERN), Dimitar Mladenov (CERN), Mitsuo Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Laurie Nevay (Royal Holloway), Hidetoshi Otono (Kyushu), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Johanna Price (UC Irvine), Markus Prim (Bonn), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Hiroki Rokujo (Nagoya), Jakob Salzfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), John Spencer (Washington), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Serhan Tufanli (CERN), Benedikt Vormwald (CERN), Di Wang (Tsinghua), Gang Zhang (Tsinghua)

Collaborators on reconstruction
Latest FASER (in-person) collaboration meeting

Part of the FASER Collaboration at the Collaboration dinner in October 2019.
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An example: Dark photon

- Produced in meson decays, e.g.,

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

and also through other processes

- Travels long distances through matter without interacting, decays to $e^+e^-, m^+m^-$ for $m_{A'} > 2 m_m$, other charged pairs
- TeV energies at the LHC $\Rightarrow$ huge boost, decay lengths of $\sim 100$ m are possible for viable and interesting parameters
Production at LHC

FASER takes advantage of the huge number of light mesons ($\pi^0, \eta, ...$) that are produced at the LHC, predominantly in the very forward direction.

For example for $E(\pi^0) \geq 10$ GeV,

- 2% of $\pi^0$s fall in FASER acceptance;
- whereas the FASER acceptance covers just $(2 \times 10^{-6})\%$ of the solid angle.

Run-3 (0.15/ab) will produce a huge number of $\pi^0$s in FASER angular acceptance. Even with large suppression ($e^2 \sim 10^{-8} − 10^{-10}$ for relevant region of phase space) can still have very large number of dark photons produced.

LHC can be a dark photon factory!
Production at LHC

- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_{\pi} \sim 10^{15}$ per bin

- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

- Only highly boosted $\sim$TeV $A'$ decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ signal events, and almost all are within 20 cm of “on axis”

Note this is an old slide, and FASER volume $R=10$cm now!
Detector concept

FASER is:

- A 1.5-meter magnetized decay volume
- A 2-meter magnetic spectrometer with three tracking stations
- An electromagnetic calorimeter
- Three scintillator stations for triggering, veto and precise timing

Signal signature

1. No signal in the veto scintillator;
2. Two high energy oppositely charged tracks, consistent with originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP;
3. For A’->ee decay: Large EM energy in calorimeter. EM showers too close to be resolved.
The FASER detector

- Scintillator/Pb Veto to veto incoming charged particles and protons
- Tracking stations: 3 planes of silicon strip detector per station
- 1100.00 mm
- 5100.00 mm
- Decoy Volume
- 0.6 Tesla permanent dipole magnets with 20 cm aperture
- Trigger/timing scintillator station
- Trigger/preshower scintillator station
- Electromagnetic calorimeter (Lead/scintillator)
Magnets

> Halbach array permanent dipoles designed by CERN magnet group
  
  • Provides strong, uniform field (0.55 T) with no infrastructure required
  
  • 1.5 meter decay volume
  
  • Two 1.0 meter for spectrometer
The FASER Tracker will be made up of 3 tracking stations:
- Each containing 3 layers of double sided silicon micro-strip detectors:
  - Spare ATLAS SCT modules will be used:
    - 80µm strip pitch, 40mrad stereo angle
    - 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:
  - $10^5$ channels in total
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Electromagnetic calorimeter

- **FASER EM calorimeter for:**
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- **Will use 4 spare LHCb outer ECAL modules**
  - 66 layers of lead/scintillator, light out by wavelength shifting fibers
    - 25 radiation lengths long
  - Readout by PMT (no longitudinal shower information)
  - dimensions: 12cmx12cm – 75cm long (including PMT)
  - Provides ~1% energy resolution for 1 TeV electrons
    - Resolution will degrade at higher energy due to not containing full shower in calorimeter
- **Testing of calorimeter modules** at CERN in March showed expected response in all modules tested.
Scintillator

- **Three scintillator stations:**
  - **Veto (upstream)**
    - 4 high-efficiency planes to tag entering charged particles
    - 20 radiation lengths of lead to convert entering gammas
    - Trigger anti-coincidence
  - **Trigger/timing (central)**
    - Precision timing and charged particle trigger signal
  - **Trigger/preshower (downstream)**
    - Coincidence trigger logic with central station
    - Lead preshower layers to convert (and tag) entering photons
Trigger and DAQ

- Trigger rate expected to be ~600 Hz dominated by muons from IP.
- Trigger will be an OR of triggers from scintillators and from the ECAL.
- No signals shared with ATLAS, need LHC orbit and clock signals, and for offline analysis ATLAS luminosity.
- Readout and trigger logic needs to be in TI12 tunnel, as not sufficient time to send signals to surface and back. Event builder on surface (in SR1)

All hardware and firmware implemented and tested

Interlock and monitoring board
From Tsinghua group.
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Offline software framework

> **Our detector is physically (and logically) small**
  - Tracker has only about 2% of ATLAS SCT channels
  - Calorimeter is 0.07% of LHCb Ecal channels
  - Designed and constructed rapidly and inexpensively
    > Thanks to hardware donated by ATLAS and LHCb

> **Collaboration is also small, and most have other commitments**
  - Fewer than 10 developers actively working (most part-time) on FASER offline software!
  - Unfortunately, the offline software system does not scale to the size, cost or construction time of the experiment, or the size of the collaboration
  - Our offline software must do most of the things a much larger experiment’s would
  - We have fewer subdetectors but the same requirements for them
Main components

> Core framework
> Detector description
> Alignment/calibration/conditions
> Event data model and persistency
> Data preparation
> Data quality validation and monitoring
> Detector simulation
> Electronics simulation (“digitization”)
> Event display
> Event generation
> Track reconstruction

Based on ATLAS’s framework, i.e. Athena

Our main contribution
Offline software framework

- Calypso (adapt open source ATLAS Athena) framework for offline
  - First versions of detector description, Geant4 simulation and event display working
- Track reconstruction with ACTS
Data flow in Calypso

- Use similar event data model with ATLAS (Athena)

- Recorded data rate ~15 MB/s

- In ATLAS:
  - raw data object -> event summary data -> analysis object data

- In FASER, we can put all the objects into analysis object since the event size is acceptable.
Tracking in Calypso with ACTS

- A Common Tracking Software (ACTS) ([ATL-SOFT-SLIDE-2016-746](ATL-SOFT-SLIDE-2016-746))
- ACTS is designed for all the HEP tracking
  - ATLAS will use it for phase II upgrade
  - CEPC and FCC are working on the migration of ACTS
  - Belle II shows interest to use it
  - ...

Collaborate with ACTS and Tsinghua group.
Overview of tracking in calypso

Cluster Making
group strips with hits as clusters

Space point formation
combine clusters to space points

Track finding
simple track finding to estimate initial parameters

Combinatorial Kalman Filter
combine track finding and track fitting
Tracking with KalmanFilter

Task: find state vector \( \hat{x} = (x, y, \theta, \phi, q/p) \)
- start with initial state vector \( \hat{x}_0 \)
- extrapolate state vector \( \hat{x}_{i-1} \) and covariance matrix \( C_{i-1} \)
- update extrapolated state \( x_i \) with measurements \( m_i \)
- \( \chi^2 \) value gives compatibility of extrapolated parameters and measurement

But: requires list of space points
Combinatorial KalmanFilter

combine track finding and track fitting:

- create new trajectory for each possible hit
- beat combinatorics: cut on max. $\chi^2$ value, #trajectories
- final selection: trajectory with least $\chi^2$ value
Single muon

Secondary particle from interaction with material

Incident muon

Fired-strip

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Expected performance - tracking

- Main backgrounds radiative processes associated with high energy muons entering the detector from the IP
  - All can be vetoed by scintillator at front of detector
- Potential small backgrounds from neutrino interactions inside the detector
  - Very low rate, and give different detector signature allowing to reject events
- Efficiency for separating very closely spaced tracks important for very high energy signals
Benchmark Sensitivity Studies for FASER 1 and 2

Reference scenarios

<table>
<thead>
<tr>
<th></th>
<th>Radius [cm]</th>
<th>Length [m]</th>
<th>Luminosity [$fb^{-1}$]</th>
<th>TimeScale</th>
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<tbody>
<tr>
<td>FASER 1</td>
<td>10</td>
<td>1.5</td>
<td>150</td>
<td>LHC Run3 2021-2023</td>
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<tr>
<td>FASER 2</td>
<td>100</td>
<td>5.0</td>
<td>3000</td>
<td>HL-LHC 2026-2035</td>
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</tbody>
</table>

FASER 1 is approved and being built
FASER 2 is a speculative extension for the HL-LHC

Benchmark sensitivity assumptions:

- Efficiency 100%
  - Results very insensitive to O(1) changes in efficiency
- Analysis threshold: 100 GeV
- No high-energy background
PBC BENCHMARK SUMMARY

- 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 examples that are not PBC benchmarks.

<table>
<thead>
<tr>
<th>Benchmark Model</th>
<th>FASER 1</th>
<th>FASER 2</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1: Dark Photon</td>
<td>✓</td>
<td>✓</td>
<td>Feng, Galon, Kling, Trojanowski, 1708.09389</td>
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<tr>
<td>BC1': U(1)$_{B-L}$ Gauge Boson</td>
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<td>✓</td>
<td>Bauer, Foldenauer, Jaeckel, 1803.05466; 1811.12522</td>
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<tr>
<td>BC2: Invisible Dark Photon</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>BC3: Milli-Charged Particle</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>BC4: Dark Higgs Boson</td>
<td>–</td>
<td>✓</td>
<td>Feng, Galon, Kling, Trojanowski, 1710.09387; Batell, Freitas, Ismail, McKeen, 1712.10022</td>
</tr>
<tr>
<td>BC5: Dark Higgs with hSS</td>
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<td>Feng, Galon, Kling, Trojanowski, 1710.09387</td>
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<tr>
<td>BC6: HNL with e</td>
<td>–</td>
<td>✓</td>
<td>Kling, Trojanowski, 1801.08947; Helo, Hirsch, Wang, 1803.02212</td>
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<td>BC7: HNL with μ</td>
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<td>Kling, Trojanowski, 1801.08947; Helo, Hirsch, Wang, 1803.02212</td>
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<td>BC8: HNL with τ</td>
<td>✓</td>
<td>✓</td>
<td>Kling, Trojanowski, 1801.08947; Helo, Hirsch, Wang, 1803.02212</td>
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<td>BC9: ALP with photon</td>
<td>✓</td>
<td>✓</td>
<td>Feng, Galon, Kling, Trojanowski, 1806.02348</td>
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<tr>
<td>BC10: ALP with fermion</td>
<td>✓</td>
<td>✓</td>
<td>1811.12522</td>
</tr>
<tr>
<td>BC11: ALP with gluon</td>
<td>✓</td>
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<td>1811.12522</td>
</tr>
</tbody>
</table>
Expected sensitivity for dark photon

FASER (150/fb) and FASER 2 (3/ab) benchmark sensitivities

• Production: mainly through decays of light mesons, $\pi, \eta \rightarrow \gamma A_0$ and through dark bremsstrahlung.

• Decays: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
Expected sensitivity for Axion Like Particles (ALPs)

- Axion-like particles coupling primarily to photons could yield significant rate, but $a \rightarrow \gamma \gamma$ would not be resolvable as two photons
  - Possible high-energy calorimeter-only signal with no charged tracks
  - Background from neutrino interactions in calorimeter not yet studied quantitatively
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Extension: FASERν

- Detect the neutrinos from collider
  - Huge flux of neutrinos through FASER
  - With 150/fb at 14 TeV, $2 \times 10^{11} \nu_e$, $6 \times 10^{12} \nu_\mu$, and $4 \times 10^9 \nu_\tau$

- Probe neutrino interactions in the TeV energy range

![Produced neutrinos spectrum](image1)

![Interaction spectrum](image2)
FASERν sub-detector

- 1000 Emulsion films interleaves with 1mm tungsten plate (~2ton).
- Hit resolution 0.4 um
- Able to identify different flavor neutrinos
- No time resolution
- Replace 2/3 times in one year
With 150/fb data at 14 TeV, expect

- Guaranteed physics output for FASER
- Expected sensitivity significant extends current measurements
- \(~20000\ \nu_\mu\) interactions
- \(~1300\ \nu_e\) interactions
- \(~20\ \nu_\tau\) interactions
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Current status

- Experiment formally approved by CERN at the Research Board on March 5th 2019
- Detector designed to be affordable and fast to construct and install
  - Utilizing spare modules from existing experiments
  - Minimizing services needed where possible
  - Total detector cost <1MCHF (including contingency)
  - Host-Lab costs to be borne by CERN (civil engineering, transport, services)
- Funding for detector construction/operation secured from Simons Foundation and Heising-Simons Foundation
  - In commissioning
- LHC Run3 schedule is delayed due to COVID 19 pandemic

Milestone for construction:
- Cosmic ray tests on surface: July – November 2020
- Tracker installed at March 2021
- FASER’s hardware should be ready when collisions begin!
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Summary and outlook

- FASER is a proposed small, fast and cheap experiment to be installed in the LHC during LS2, to take data in Run 3
  - Taking advantage of already existing tunnel infrastructure and using spare detector parts from existing experiments

- It targets light, weakly-coupled new particles at low $p_T$, runs simultaneously with, and is complementary to, ATLAS/CMS, allowing to fill a possible hole in the current LHC new physics search program.
  - FASER has significant discovery potential for dark photons and other light, weakly coupled, new physics particles

- A possible upgrade FASER 2, with a bigger detector (radius = 1m) in LS3 would allow sensitivity to additional scenarios, including new particles produced in heavy meson decays
Back-up
FASER: the idea

> New physics searches at the LHC focus on high $p_T$. This is appropriate for heavy, strongly interacting particles
  • $s \sim \text{fb to pb} \rightarrow \text{In Run-3 N} \sim 10^2 - 10^5$, produced $\sim$ isotropically

> However, if new particles are light and weakly interacting, this may be completely misguided. Instead can exploit
  • $s_{\text{inel}} \sim 100 \text{ mb} \rightarrow \text{In Run-3 N} \sim 10^{16}$, $q \sim L_{\text{QCD}} / E \sim 250 \text{ MeV / TeV} \sim \text{mrad}$

> FASER is a proposed experiment designed to cover this scenario at the LHC to search for the long lived particle (LLP)

> Detector to be placed 480m from IP1 directly on the beam collision axis line of sight (LOS) with transverse radius of only 10cm covering the mrad regime

Arxiv:1811.12522
FORWARD SEARCH EXPERIMENT

• “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”

Feng, Galon, Kling, Trojanowski (2017)
BEAM BACKGROUND

- FLUKA simulations and *in situ* measurements have been used to assess the backgrounds expected in FASER.
- FLUKA simulations studied particles entering FASER from:
  - IP1 collisions (shielded by 100m of rock)
  - Off-orbit protons hitting beam pipe aperture in dispersion suppressor (close to FASER) (following diffractive interactions in IP1)
  - Beam-gas interactions
- Expect a flux of high energy muons ($E>10$ GeV) of $0.4\text{cm}^{-2}\text{s}^{-1}$ at FASER for $2\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ luminosity from IP1 collisions
  - Confirmed by *in situ* measurements in 2018 running (emulsion detector and TimePix BLM)
Cosmic data taking

Cosmic data taking with a tracker station on its side, with a scintillator above/below for triggering. Uses full FASER TDAQ chain. Extremely useful commissioning exercise.
Cosmic data taking

Event display from offline software reconstruction of a cosmic event. Very useful for debugging offline workflow.