The FASER experiment

A not-so-large LHC experiment in search for new physics in far corners

Claire Antel (University of Geneva)

Science coffee seminar, Lund University (Sweden)

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ForwArd Search ExpeRiment

In a nutshell

- An **LHC experiment** to search for **long-lived particles produced at or close to Interaction Point 1** (ATLAS) in Run 3 and beyond.

- **Concept** put forward in **2017** by UCI researchers Jonathan Feng, Iftah Galon, Felix Kling and Sebastian Trojanowski.

- **CERN-approved March 2019**, and to be **fully built & installed in current Long Shutdown**.

- 60 collaborators, 19 institutes, 8 countries.
Where is New Physics?

- Standard Model largely self-consistent but observations suggest so much more:
  - Dark matter? Neutrino oscillations? Baryon asymmetry?
  - At dawn of LHC, we had promising theories:
    - Supersymmetry
    - WIMP dark matter (thermal production).
From a Physics Perspective

Heavy and strongly coupled

- Focus at ATLAS & CMS: ~TeV scale particles with electroweak scale couplings

  Centrally produced where low SM inelastic background

  "Susy??"

- Measurably produced, as sizable coupling.

- No unambiguous signal observed so far. Where else to look?
Motivation for light and feebly coupled particles?
Light and feebly coupled

- Hidden sector physics
- New mediating particles, couplings to SM via mixing with SM “portal” operator
- Lowest dimensional renormalisable operators:

\[ \mathcal{L}_{\text{portal}} = \sum \mathcal{O}_{SM} \times \mathcal{O}_{HS} \]

<table>
<thead>
<tr>
<th>DM mediator candidate</th>
<th>DM candidate</th>
<th>Clue to baryogenesis, neutrino oscillations</th>
</tr>
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<tr>
<td>Portal</td>
<td>Coupling</td>
<td></td>
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<tr>
<td>Dark Photon, ( A_\mu )</td>
<td>( - \frac{e}{2 \cos \theta_W} F_{\mu\nu} B^{\mu\nu} )</td>
<td></td>
</tr>
<tr>
<td>Dark Higgs, ( S )</td>
<td>((\mu S + \lambda S^2) H^\dagger H )</td>
<td></td>
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<tr>
<td>Axion, ( a )</td>
<td>( \frac{a}{f_a} F_{\mu\nu} F^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu} G_{i}^{\mu\nu}, \frac{\partial_{\mu} a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi )</td>
<td></td>
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<tr>
<td>Sterile Neutrino, ( N )</td>
<td>( y_N L H N )</td>
<td></td>
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</tbody>
</table>

Ref: Physics Beyond Colliders Working Group Report
From a Physics Perspective

*Light and feebly coupled - current constraints*

Example: Dark photon to visible decays

Effective Lagrangian

\[
\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - ee \Sigma q_f \bar{f} A' f
\]

-> parameter space spanned by dark photon mass \( m_{A'} \) and kinetic mixing parameter \( \epsilon \).

Ref: Physics Beyond Colliders Working Group Report
From a Physics Perspective

*Light and feebly coupled*

- LHC *the* intensity and energy frontier. Where is all the energetic light physics being produced?
From a Physics Perspective

Light and feebly coupled

- LHC the intensity and energy frontier. Where is all the energetic light physics being produced?

Answer: Energetic SM inelastic cross-section in forward region.
From a Physics Perspective

**Light and feebly coupled**

- LHC the intensity and energy frontier. Where is all the energetic light physics being produced?

- Answer: Energetic SM inelastic cross-section in forward region.
From a Physics Perspective

Light and feebly coupled

~ $10^{16}$ inelastic scattering events/hemisphere in Run 3 (150 fb$^{-1}$) -> large light meson production rates.

$$\theta \sim \frac{m_{\pi^0}}{E} \sim \frac{\Lambda_{QCD}}{E}$$

-> Production rate at small $\theta$ to beam axis populated by $\pi^0$ of $>10$ GeV momenta (rate a magnitude less for $\eta$ mesons).

Ref: "Technical Proposal for FASER", FASER coll., 2018

MC event generator: EPOS-LHC

* Simulation of SM hadron spectra in forward region vastly improved in recent years. “LHC forward Physics” by LHC Forward Physics Working Group
Dark photon example

- Where there are pions there is potential new physics. Signal events/hemisphere in Run 3 (150fb⁻¹):

- Signal suppression roughly $\epsilon^2$ relative to SM: 1 in every $10^{10}$ neutral $\pi$ decay to $A'$.

- But with large $\pi^0$ intensity, appreciable rate of high momentum signal in forward region. And once it decays…

Ref: "Technical Proposal for FASER", FASER coll., 2018
From a Physics Perspective

Dark photon signal processes

- A striking signature:

\[ \theta \sim \frac{\Lambda_{QCD}}{E} \]

- For dark photon at small angles to beam axis, decay signature is two highly collimated high E (~TeV scale) particles.

- Striking when there is no other background...
From a Physics Perspective

Light and feebly coupled

How to search for the hidden sector? A different set of challenges…

- Highest production rate in forward direction, where ATLAS not sensitive.
- Extremely weakly interacting: Rare, requires ~zero background.

But this offers an advantage: It is long-lived…

- Can travel considerable distance before decaying to SM,
  ... traversing any material, including rock.
From a Technical Perspective

The ideal detector location
New physics travels straight down beam axis, along with SM forward physics.
The ideal detector location

From a Technical Perspective

Charged particles deviated by LHC magnets

... neutral + charged particles absorbed by LHC absorbers, material and rock

ATLAS IP
The ideal detector location

Total distance from IP: 480 m (90 m of rock)
From a Technical Perspective

The ideal detector location

Well almost ideal: Just need a ~50 cm deep trench
Detector components:

- EM calorimeter
- 0.6 T permanent dipole magnets
- Trigger scintillator station
- Tracking stations
- Veto scintillator station
- Newly approved mystery component

Geometry:
- 5 m length total
- 20 cm aperture
- 1.5 m decay volume

Particles:
- $e^+/\mu^+$
- $e^-/\mu^-$
**Detector components**

**From a Technical Perspective**

- EM calorimeter
- 0.55 T permanent dipole magnets
- Trigger scintillator station
- Tracking stations
- Veto scintillator station
- Newly approved mystery component

**Small and inexpensive:**
- Low risk

**Geometry:**
- 5 m length total
- 20 cm aperture
- 1.5 m decay volume

**Spares from other LHC detectors**
Determining background rate

- FLUKA simulation, including
  - (i) Particles from IP or produced at IP and interact downstream, e.g. in target for neutral particles (TAN): Specifically, muons & neutrinos.
  - (ii) Particles from showers from off-momentum protons hitting beam pipe.
  - (iii) Particles produced in beam-gas interactions by beam passing FASER in ATLAS direction (no rock shielding).

- In-situ measurements
  - Emulsion detector installed in TI12 during 2018 running to verify FLUKA results.

Ref: "Technical Proposal for FASER", FASER coll., 2018
Determining background rate

**Faser Physics Reach**

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  - (i) Particles from IP or produced at IP and interact downstream, e.g. in target for neutral particles (TAN): Specifically, muons & neutrinos.
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  - (iii) Particles produced in beam-gas interactions by beam passing FASER in ATLAS direction (no rock shielding). **Negligible at high energies.**

- In-situ measurements
  - Emulsion detector installed in TI12 during 2018 running to verify FLUKA results.

Ref: *"Technical Proposal for FASER", FASER coll., 2018*
Determining background rate

- **Expected rate:**
  - Neutrino BG negligible due to low neutrino cross-section and different event kinematics.
  - FLUKA & insitu measurements: 0.4 cm\(^{-2}\) s\(^{-1}\) for > 10 GeV muons, roughly ~ 500 Hz event rate in FASER aperture.
  - 99.9999999999% should effectively be vetoed by first trigger station.
  - Can assume zero background to first order.

FLUKA simulation: Magnets very helpfully deflect muons away from beam axis.
Faser Physics Reach

Dark photon to visible decay sensitivity for zero background

Probability of long-lived particle decaying in detector volume:

\[ \mathcal{P}(p, \theta) = (e^{-(L-\Delta)/d} - e^{-L/d})\Theta(R - \tan\theta L) \]

\[ \approx \frac{\Delta}{d} e^{-L/d} \Theta(R - \theta L) \]

where \( d = c\tau\beta\gamma = c\tau p/m \)

L, \( \Delta \) and R are distance from production, decay volume length and aperture radius, respectively. \( d \) is decay length in lab frame.

FASER could already break new ground with 10 fb\(^{-1}\)...

Ref: “FASER’s Physics Reach…”, FASER coll., 2018
- 3 tracker stations: each 3 planes of semiconductor strip modules.
  - Spare SCT modules donated by ATLAS!
  - Each module two pairs of silicon strip detectors, glued back-to-back: 768 read-out channels/side
  - Oriented modules for precision in bending and non-bending plane.

24 cm x 24 cm of active area
**FASER in detail**

**Tracking system performance requirements**

- 300 μm conservative estimate for required separation to create isolated SCT clusters.
- By 2nd tracking station, good track separation achieved across large range in energies.

**Track separation**

- Do not expect to reconstruct particle masses but still aim for as good as possible to e.g. eliminate low energy (<100 GeV) background.
- Simulations show ~ 3% σ(p)/p for 100 GeV muon tracks.
FASER in detail

Scintillator trigger stations

- Including lead block absorber of 20 radiation length to absorb/shower photons radiated by nearby muons.
- And preshower layer of 2 radiation length lead to convert photons and distinguish from deep-inelastic scattering of neutrinos in calorimeter.

Produced in CERN scintillator lab
Calorimeters

- 4 Calorimeter modules
- 4 spare outer electromagnetic calorimeter modules donated by LHCb!
- 66 layers of lead/scintillator, 25 radiation lengths.
- Read-out via PMT, no longitudinal segmentation.
- 1% energy resolution for 1 TeV electron, degradation due to leakage of extremely high energy signals expected but tolerable.
Triggering and data acquisition

**FASER in detail**

9 X TRACKER READOUT BOARDS

X 4 calo pulses

X 10 scint pulses

DIGITIZER

DAQ SERVER

TRIGGER LOGIC BOARD

above surface

x 8 digitizer “signal above threshold” inputs
FASER in detail

Triggering and data acquisition

DAQ SERVER

above surface

Readout via ethernet

9 X TRACKER READOUT BOARDS

L1 Accept

TRIGGER Logic BOARD

Yes!

Combines 8 digit signals into "Do we have Coincidence", "Coincidence+Veto", "Calo only"...

x 8 digitizer "signal above threshold" inputs

DIGITIZER
FASER in detail

Triggering and data acquisition

**DAQ SERVER**

**LHC CLOCK AND ORBIT**

Also applies prescales, deadtime vetos, rate limitations, LHC clock distribution, bunch crossing reset distribution,…

**9 X TRACKER READOUT BOARDS**

**TRIGGER LOGIC BOARD**

**DIGITIZER**
**FASER in detail**

**Triggering and data acquisition**

- **Digitizer**: CAEN digitizer card

- **Flat cable delivers 8 inputs from digitizer to TLB**

- **Trigger Logic Board (TLB)**: GPIO board housing an FPGA with complete trigger functionality.

- **Tracker Readout Board (TRB)**: GPIO board housing an FPGA for simple data processing & error handling.
**FASER in detail**

**Triggering and data acquisition**

- **FASER DAQ framework** relies on **DAQling**, DAQ core framework for small experiments, developed by CERN Detector Technologies - Detector Interface group (we’re one of their first clients!).

- **Software** entirely C++ with python for distribution of commands, configs

**EventBuilder:** Combines data fragments from same event. No object reconstruction or event selection
Triggering and data acquisition

FASER in detail
FASERν

FASER neutrino detector (the newly approved mystery component)

- FASERν
  - Approved in December 2019. Recent publication: “Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC”
  - FASER to extend detector to measure SM collider neutrinos for the first time!
  - Extension is a 25 cm x 25 cm x 1.35 m emulsion detector in front of FASER.

FASERν to set neutrino-nucleon cross-section constraints at whole new neutrino energies. Plots assume 150 fb⁻¹ of pp collisions at 14 TeV.
FASERν

FASER neutrino detector (the newly approved mystery component)

- **FASERν detector**
  - 25 cm x 25 cm x 1.35 m emulsion detector with 1000 emulsion layers interleaved with tungsten plates.
  - Tungsten target mass 1.2 tons.
  - Spatial resolution of 50 nm, but no time resolution.
    - Analysis possible for up to $10^6$ tracks/cm$^2$.
    - Thus emulsion films to be replaced every 10-50 fb$^{-1}$ (during LHC technical stops).
FASER Commissioning

Timeline

- At the whim of LHC schedule.
- FASER civil engineering works happening in tunnel now - April.
- FASER installation of base plate during May.
- FASER **full installation and commissioning mid-July-end October** (barring LHC electric tests in-between)
- Window defined by LHC cool-down and when LHC handed over to LHC operations.
- Data taking to commence in Run 3, 2021.
FASER Commissioning

Civil engineering

TI12 tunnel before and after!

Eventually…
FASER Commissioning
Civil engineering

Gangway, hoist and protection needed to transport across LHC cryogenics distribution line

Digging of trench has just begun.
FASER Commissioning

Lab status

Cosmics run using 2 scintillator layers and calo module.

Connection test: TLB-> TRB -> Tracker modules

Connection test: TLB-> Digitizer
Lab status

FASER Commissioning

Scintillator production

Testing of tracker module, temperature and humidity interlock, cooling, low voltage breaks...

Tracker frames production
Summary

What you now know...

- Not all LHC experiments are **big** and **expensive**.

- Further reading:
  
  "Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report"

- A lot of **LHC luminosity** has formerly remained unexploited -> **Untapped resource** to potential new physics and SM physics at new energies (neutrinos).

- FASER will probe new phase space at **extremely weak couplings** and **light particle masses** for dark photons and axions, dark Higgs and sterile neutrinos…

- FASER still on schedule for data taking beginning of Run 3 and beyond, with exciting upgrades planned.
**Outlook**

**FASER beyond Run 3**

- **FASER2**: Bigger and better. Expanding the aperture of FASER will vastly increase sensitivity to new physics (exact geometry to be decided).

Dark Higgs produced mainly in rare decays of B-mesons. Larger spread in $p_T$ for B meson production, thus larger angular acceptance of FASER 2 boosts dark Higgs sensitivity.

FASER: 150 fb$^{-1}$, FASER 2: 3 ab$^{-1}$, with assumed dimensions: $R=1$ m, $\Delta=5$ m
Thank you for listening!

The FASER collaboration

Jonathan L. Feng & Jamie Boyd
(FASER co-spokespeople)

We owe many thanks to:

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Bonus slides ...
Standard Model neutrino measurements
The "WIMP Miracle":

New 0.1-1 TeV DM particle with weak-scale interaction would naturally be thermally produced in early universe resulting in correct DM density to fit today’s observations.

SUSY readily predicts particles at this mass scale.

References:

- “WIMP dark matter candidates and searches…”, L. Roszkowski, E.M. Sessolo, 2018
- “The WIMPless Miracle:…”, Feng J., Kumar J., 2008
The “WIMPless Miracle”:
But it is the ratio $m_\chi/g_\chi^2$ that matters in obtaining the right DM relic density …

$$m_\chi/g_\chi^2 \sim m_{\text{weak}}/g_{\text{weak}}^2$$

… So that a larger range in $g_\chi$ and $m_\chi$ is in fact relevant:

$$10^{-3} \lesssim g_\chi \lesssim 3$$

$$10 \text{ MeV} \lesssim m_\chi \lesssim 10 \text{ TeV}$$

Bounded by perturbativity limitations and requirement for DM to be non-relativistic at time of freeze-out.

References:
• “WIMP dark matter candidates and searches…”, L. Roszkowski, E.M. Sessolo, 2018
• “The WIMPless Miracle:…”, Feng J., Kumar J., 2008
~ $10^{16}$ inelastic events/hemisphere in Run 3 (150 fb$^{-1}$) -> large meson production rates.

| Production rate for $\pi^0$ at measurable momenta (>10 GeV) at small $\theta$ to beam axis (rate a magnitude less for $\eta$ mesons).
| Smaller production rates for heavier mesons.

Ref: "Technical Proposal for FASER", FASER coll., 2018
More physics

Dark photon production rate

- Total number of photons produced in one hemisphere for 300 ifb 13 TeV pp collisions for various production modes (no detector decay volume limitation).
Assumptions by other experiments in sensitivity plots:

- **NA62** assumes $10^{18}$ protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3; **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; the proposed beam dump experiment **SHiP** assumes $\approx 2 \times 10^{20}$ POT collected in 5 years of operation; the proposed electron fixed-target experiment **LDMX** during Phase II with a beam energy of 8 GeV and $10^{16}$ electrons on target (EOT); **Belle-II** and **LHCb** assume the full expected integrated luminosity of $50 \text{ ab}^{-1}$ and $15 \text{ fb}^{-1}$, respectively; **HPS** assumes 4 weeks of data at JLab at each of several different beam energies; **NA64** corresponds to $5 \times 10^{12}$ EOT with 100 GeV energy; and **AWAKE** 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 $O(50 \text{ GeV})$.

Ref: “FASER’s Physics Reach…”, FASER coll., 2018
Beside production in inelastic events, ALPs may be produced via the Primakoff process at the TAN*.

~ $10^{16}$ photon-TAN interactions in Run 3.

... Giving FASER sensitivity to ALPS with coupling to photons.

Ref: “FASER’s Physics Reach…”, FASER coll., 2018
Physics predicted exclusion limits

Axion interactions

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_s^2}{8} g_{a g g} a G^A_{\mu\nu} \tilde{G}^{A\mu\nu} - i \sum_f g_{a f} \frac{m_f}{v} a \tilde{f} \gamma_5 f$$

largest B.R.: $a \rightarrow \gamma \gamma$

largest B.R.: $a \rightarrow \gamma \gamma$

largest B.R.: $a \rightarrow f \bar{f}$

$\mathcal{L}_{SM}$: Standard Model Lagrangian

$\mathcal{L}_{DS}$: Dark Sector Lagrangian

$g_{a\gamma}$: Axion-photon coupling

$g_{a g g}$: Axion-gluon coupling

$g_{a f}$: Axion-quark coupling

$m_a$: Axion mass

$v$: Higgs vacuum expectation value

$F_{\mu\nu}$: Electromagnetic field tensor

$G^A_{\mu\nu}$: Axionic field tensor

$\tilde{F}^{\mu\nu}$: Dual electromagnetic field tensor

$\tilde{G}^{A\mu\nu}$: Dual axionic field tensor

$\gamma_5$: Dirac gamma matrix

$\bar{f}$: antiquark
Physics predicted exclusion limits

Dark Higgs

- Sensitivity to dark Higgs without and with trilinear couplings

Effective Lagrangian

\[ \mathcal{L} = -m_\phi^2 \phi^2 - \sin \theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi \phi + \ldots \]

trilinear couplings \( \lambda = 0.0046, 0.0015 \) (10\% ,1\% B. R.)
Overview

- Based on selection of specific models.
Physics predicted exclusion limits

Dark photon to visible decay

- 5 year timescale
- 10-15 year timescale
Physics predicted exclusion limits

Dark photon to invisible decay

- NA64: 5 year timescale
- LDMX, KLEVER: 10-15 year timescale

Ref: Physics Beyond Colliders Working Group Report
Physics predicted exclusion limits

Heavy Neutral Lepton Current and Future Bounds

- Projected limits on 5 year time scale.

- Projected limits on 10-15 year time scale.

Ref: Physics Beyond Colliders Working Group Report
<table>
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<tr>
<th>Benchmark Model</th>
<th>FASER 1</th>
<th>FASER 2</th>
<th>References</th>
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<tr>
<td>BC1: Dark Photon</td>
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<td>BC2: Invisible Dark Photon</td>
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<td>BC3: Milli-Charged Particle</td>
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<td>BC4: Dark Higgs Boson</td>
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<td>BC5: Dark Higgs with hSS</td>
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<td>BC10: ALP with fermion</td>
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<td>1811.12522</td>
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<tr>
<td>BC11: ALP with gluon</td>
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</tr>
</tbody>
</table>
FASER effects on sensitivity

Offset dependence

- LHC crossing angle of 160 $\mu$rad, corresponds to shift of collision axis of 7.2 cm.

- Dark photon

- ALP (fermion dominance)
FASER effects on sensitivity

Energy threshold dependence

- Dark photon
- Axion, fermion dominance
FASER effects on sensitivity

Signal efficiency

- Signal $\varepsilon$ as function of dark photon energy and decay’s longitudinal position for $mA'=100$ MeV, $\varepsilon = 10^{-5}$, track separation $> 300 \, \mu\text{m}$ for 2nd & 3rd tracker stations.

- More accurate signal $\varepsilon$ studies with GEANT simulation ongoing.

< 500 GeV: drop in $\varepsilon$ due to magnet bending.

at larger $z$: decay to close to first tracking station for enough track separation.
FASER effects on sensitivity

Dependence on signal selection

 mA' = 100 MeV
**FASER in detail**

**Triggering and data acquisition**

- Expected trigger rate:
  - Veto scintillator: 360 Hz
  - Timing scintillators: 640 Hz
  - Preshower scintillators: 360 Hz
  - Calorimeter (E>100 GeV): < 5 Hz
  - Random trigger: ~10 Hz

Largely overlapping
FLUKA simulation: Magnets very helpfully deflect muons away from beam axis.

Development of studies with accurate LHC, material and detector simulations ongoing for more accurate determination of background rate.
Faser Physics Reach

Determining background rate

Fluence rate (GeV\(^{-1}\) cm\(^2\) s\(^{-1}\)) for muons: 10 GeV threshold

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

Tracking system performance requirements

Track momentum resolution

- Idealised momentum resolution: 8 tracking layers good compromise between resolution and costs. For low momenta, expect good resolution.
FASER expected performance

Track separation

Preliminary two-track separation efficiency based on isolated space-points in the first tracker plane, for a dark photon of mass M and energy E (simulation)

References:
• “FASER Technical Proposal”, FASER coll., 2018

Space point resolutions for simulated dark photon decay
FASER in detail

Triggering and data acquisition
Triggering and data acquisition
**FASER in detail**

*Tracking system*

- Read out not big challenge, ~650 Hz rate, roughly 200 bytes/plane:
- Read-out on custom made flex cables, delivering data to single tracker read-out board/plane.
- TRB a general purpose (GPIO) board with one FPGA:
- Simple data processing & error handling.
Installation

Backbone for insertion of stations into permanent magnets

Water cooling for tracker modules.

Trench needed to keep detector aligned with collision axis line-of-sight
Core testing
FASER magnet
Design and installation

Magnetic vertical field along the center of the magnet and beyond; red line is the end of the magnet. Closest PMT is at 350 mm.

Halbach array design, 0.6 T. Neodymium
FASER $$$

(more or less up to date)

### Tracker costs (readout in TDAQ):

<table>
<thead>
<tr>
<th>Item</th>
<th>TP</th>
<th>Current</th>
<th>Comments</th>
</tr>
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<tr>
<td>Module frame</td>
<td>66 kCHF</td>
<td>~46 kCHF</td>
<td>Dropped outer box. Support not incl.</td>
</tr>
<tr>
<td>Flex+patch panel</td>
<td>18 kCHF</td>
<td>38 kCHF</td>
<td>5k covered by Kyushu university</td>
</tr>
<tr>
<td>Chiller system</td>
<td>15 kCHF</td>
<td>20 kCHF</td>
<td>Chillers alone were 8 kCHF</td>
</tr>
<tr>
<td>Power supplies</td>
<td>77 kCHF</td>
<td>83 kCHF</td>
<td>Better HV PSs</td>
</tr>
<tr>
<td>TIM</td>
<td>10 kCHF</td>
<td>20 kCHF</td>
<td>Covered by Tsinghua university</td>
</tr>
<tr>
<td>Cables</td>
<td>7 kCHF</td>
<td>25 kCHF</td>
<td>Cables are 19 kCHF, added splitter etc.</td>
</tr>
<tr>
<td>Total</td>
<td>193 kCHF</td>
<td>232 kCHF</td>
<td></td>
</tr>
</tbody>
</table>

### Calo/Scintillator costs (readout in TDAQ):

<table>
<thead>
<tr>
<th>Item</th>
<th>TP</th>
<th>Current</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillators</td>
<td>17 kCHF</td>
<td>~17 kCHF</td>
<td>Only 3kCHF for plates confirmed</td>
</tr>
<tr>
<td>PMTs (and filters)</td>
<td>32 kCHF</td>
<td>11 kCHF</td>
<td>Calo PMTs donated by LHCb, others half price</td>
</tr>
<tr>
<td>HV PS</td>
<td>16 kCHF</td>
<td>9.1 kCHF</td>
<td>Ordered</td>
</tr>
<tr>
<td>Cables</td>
<td>3 kCHF</td>
<td>5 kCHF</td>
<td>Use 15m low-loss coax signal cables</td>
</tr>
<tr>
<td>Shielding</td>
<td>6.7 kCHF</td>
<td>~5 kCHF</td>
<td>Still to be ordered</td>
</tr>
<tr>
<td>LED calib. system</td>
<td>Not incl.</td>
<td>~1 kCHF</td>
<td>Under development</td>
</tr>
<tr>
<td>Total</td>
<td>74.7 kCHF</td>
<td>48.1 kCHF</td>
<td></td>
</tr>
</tbody>
</table>

### TDAQ costs:

<table>
<thead>
<tr>
<th>Item</th>
<th>TP</th>
<th>Current</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger boards</td>
<td>5 kCHF</td>
<td>~5 kCHF</td>
<td></td>
</tr>
<tr>
<td>Readout boards</td>
<td>43 kCHF</td>
<td>~52 kCHF</td>
<td>Digitizer, tracker board, minicrate, cables</td>
</tr>
<tr>
<td>VME crates</td>
<td>10 kCHF</td>
<td>14 kCHF</td>
<td>Use LHC standard VME crate</td>
</tr>
<tr>
<td>PCs</td>
<td>12 kCHF</td>
<td>~12 kCHF</td>
<td>To be ordered with CERN IT etc.</td>
</tr>
<tr>
<td>Switches</td>
<td>8.5 kCHF</td>
<td>~11 kCHF</td>
<td>Add switch to split DAQ and DCS</td>
</tr>
<tr>
<td>DCS components</td>
<td>~2 kCHF</td>
<td>PDUs, environment monitoring</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>78.5 kCHF</td>
<td>96 kCHF</td>
<td></td>
</tr>
</tbody>
</table>

### Detector support cost (least mature at the moment):

<table>
<thead>
<tr>
<th>Item</th>
<th>TP</th>
<th>Current</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base plate</td>
<td>30 kCHF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper frame</td>
<td>5 kCHF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustable magnet feet</td>
<td>25 kCHF</td>
<td>0?</td>
<td>Included in magnet support now</td>
</tr>
<tr>
<td>Total</td>
<td>60 kCHF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component</td>
<td>Cost estimation (CHF)</td>
<td>Actual cost (CHF)</td>
<td>Status</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-----------------------</td>
<td>--------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Permanent magnet blocks</td>
<td>210000</td>
<td>240000</td>
<td>Ordered (CN)</td>
</tr>
<tr>
<td>Machining of yoke cylinders</td>
<td>50000</td>
<td>27000</td>
<td>Ordered (NOR)</td>
</tr>
<tr>
<td>Production of aluminum guiding profiles</td>
<td>30000</td>
<td>16000 (extruded)</td>
<td>Ordered (NL and SP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25000 (machined)</td>
<td></td>
</tr>
<tr>
<td>Measurement and assembly tooling</td>
<td>30000</td>
<td>6000</td>
<td>Partially ordered (FR)</td>
</tr>
<tr>
<td>Contingency</td>
<td>30000</td>
<td></td>
<td>Not yet used</td>
</tr>
<tr>
<td><strong>TOTAL COST (1 dipole 1.5 m long + 2 dipoles 1 m long)</strong></td>
<td><strong>350000 CHF</strong></td>
<td><strong>314000 CHF</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(October 2019)</td>
</tr>
</tbody>
</table>
### TABLE VIII. Cost estimate for the tungsten/emulsion detector.

<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>

### TABLE IX. Cost estimate for the interface detector.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost [kCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCT modules</td>
<td>0</td>
</tr>
<tr>
<td>Tracker mechanics</td>
<td>20</td>
</tr>
<tr>
<td>Chiller</td>
<td>0</td>
</tr>
<tr>
<td>Connection to EN-CV</td>
<td>2</td>
</tr>
<tr>
<td>Tracker Readout Board</td>
<td>5</td>
</tr>
<tr>
<td>Powersupplies</td>
<td>31</td>
</tr>
<tr>
<td>Cables</td>
<td>11</td>
</tr>
<tr>
<td>Flex cable</td>
<td>10</td>
</tr>
<tr>
<td>Patch panel</td>
<td>10</td>
</tr>
<tr>
<td>Tracker Interlock and Monitoring Board</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>92</strong></td>
</tr>
</tbody>
</table>

### TABLE X. The host lab costs.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost [kCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport infrastructure</td>
<td>20</td>
</tr>
<tr>
<td>Chemical disposal</td>
<td>20</td>
</tr>
<tr>
<td>Computing storage (EOS disk space)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70</strong></td>
</tr>
</tbody>
</table>
Until installation in July, FASER components to be assembled and tested in test hall on CERN’s Prevessin site.