Looking forward to new physics with

FASER: ForwArd Search ExpeRiment at the LHC

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(FASER group see https://twiki.cern.ch/twiki/bin/viewauth/FASER/WebHome)

Email to the group: faser-all@cern.ch

arXiv:1708.09389;1710.09387;1801.08947;1806.02348 (PRD, with J.L.Feng, I.Galon, F.Kling)

arXiv:1811.12522 (physics case)
Akitaki Ariga,¹ Tomoko Ariga,¹,² Jamie Boyd,³ Franck Cadoux,⁴ David W. Casper,⁵ Yannick Favre,⁴ Jonathan L. Feng,⁵ Didier Ferrere,⁴ Iftah Galon,⁶ Sergio Gonzalez-Sevilla,⁴ Shih-Chieh Hsu,⁷ Giuseppe Iacobucci,⁴ Enrique Kajomovitz,⁸ Felix Kling,⁵ Susanne Kuehn,³ Lorne Levinson,⁹ Hidetoshi Otono,² Brian Petersen,³ Osamu Sato,¹⁰ Matthias Schott,¹¹ Anna Sfyrila,⁴ Jordan Smolinsky,⁵ Aaron M. Soffa,⁵ Yosuke Takubo,¹² Eric Torrence,¹³ Sebastian Trojanowski,¹⁴,¹⁵ and Gang Zhang¹⁶
Motivation behind the intensity frontier searches for light long-lived particles (LLPs)

FASER: ForwArd Search ExpeRiment at the LHC

Remarks about FASER physics program
-- dark photons,
-- axion-like particles,
-- possible measurements for SM neutrinos
-- ... and many other models

Background: simulations & in-situ measurements

Concluding remarks
MOTIVATION

Heavy and strongly-coupled new physics e.g. SUSY, extra dimensions, ...
here also missing energy searches for heavy WIMP DM

Light and very weakly coupled new physics:
-- requires large „luminosities“ (statistics)
-- new particles decay back to SM, but with highly displaced vertices
-- SM BG needs to be highly suppressed

Exciting physics:
-- cosmology
(dark matter, inflation, bariogenesis,...)
-- neutrino masses
(GeV-scale heavy neutral leptons)
-- (g-2)_\mu
-- ...

Generalized WIMP miracle: \( \Omega_{DM} h^2 \sim \frac{m^2}{g^4} \sim 0.1 \)
\( g \ll g_{\text{weak}} \Rightarrow m \ll m_{\text{weak}} \)
FASER - IDEA

FASER – newly proposed, small (~0.05 m³) and inexpensive (~1.5M$) detector to be placed few hundred meters downstream away from the ATLAS IP to harness large, currently „wasted” forward LHC cross section

$$\sigma_{\text{inel}} \sim 75 \text{ mb}, \text{ e.g., } N_{\pi} \sim 10^{17} \text{ at } 3 \text{ ab}^{-1}$$

(for comparison $$\sigma \sim \text{ fb} - \text{ pb}, \text{ e.g., } N_{\text{H}} \sim 10^7 \text{ at } 300 \text{ fb}^{-1}$$ in high-p_T searches)

FASER will complement ATLAS/CMS by searching for new Light Long-Lived Particles

(part of Physics Beyond Colliders Study Group at CERN)
• promising location in a side tunnel TI12 (former service tunnel connecting SPS to LEP)
• about $L \sim 480\text{m}$ away from the IP along the beam axis
• space for a few-meter-long detector
• precise position of the beam axis in the tunnel up to mm precision (CERN Engineering Dep).
• corrections due to beam crossing angle (for $300\mu\text{rad}$ the displacement is $\sim 7\text{ cm}$)
TUNNEL TI12

new physics (hidden in the dark)

main LHC tunnel
• cylindrical decay volume

• 2 stages of the project:

**FASER 1**: \( L = 1.5 \text{ m}, R = 10 \text{ cm}, V = 0.05 \text{ m}^3, 150 \text{ fb}^{-1} \) (Run 3)

**FASER 2**: \( L = 5 \text{ m}, R = 1 \text{ m}, V = 16 \text{ m}^3, 3 \text{ ab}^{-1} \) (HL-LHC)

Plans for recycling existing spare modules:
- ATLAS SCT modules (Tracker)
- LHCb ECAL modules (Calorimeter)
(save money & time)
SIGNAL DETECTION

Signal is a pair of oppositely charged high-energy particles e.g. $1 \text{ TeV} A' \rightarrow e^+ e^-$

In the following we assume 100% detection efficiency for a better comparison with other experiments.

Ongoing work on full detector simulations.

CHARGED TRACK SEPARATION EFFICIENCY

1st tracking station

2nd/3rd tracking station (separation $> 0.3\text{mm}$)
EXAMPLE OF LHC/FASER KINEMATICS
LLP FROM PION PRODUCTION AT THE IP

Soft pions going towards high-$p_T$ detectors:
- produced LLPs would be too soft for triggers
- large SM backgrounds

Hard pions highly collimated along the beam axis since their $p_T \sim \Lambda_{QCD}$ e.g. for $E_{\pi^0} \geq 10$ GeV
$\sim 1.7\%$ of $\pi^0$s go towards FASER
$\sim 24\%$ of $\pi^0$s go towards FASER 2

This can be compared to the angular size of both detectors with respect to the total solid angle of the forward hemisphere ($2\pi$):
$\sim (2 \times 10^{-6})\%$ for FASER
$\sim (2 \times 10^{-4})\%$ for FASER 2

LLPs produced from $B$ mesons in FASER 2
$p_T \sim m_B$ larger angular spread target for FASER 2
at FASER energies: $N_B/N_\pi \sim 10^{-2}$
($10^{-7}$ for typical beam dumps)
COMPARISON – VARIOUS MC TOOLS

CRUCIAL CONTRIBUTION FROM LHC FORWARD PHYSICS AND DIFFRACTION WG

Overall agreement between MC and data

For large $p_z$: EPOS-LHC gives some overestimate

QGSJET II, SIBYLL lower estimates

THESE DISCREPANCIES HAVE VERY LITTLE IMPACT ON FASER SENSITIVITY (see next slides)
DARK PHOTON

- (broken) dark $U(1)$ gauge group,
- kinetic mixing with the SM photon: $\epsilon F^{\mu\nu} F'^{\mu\nu}$,
- after field redefinition:

$$\mathcal{L} \supset -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^\mu A'^\mu + \sum f (i \bar{\phi} - \epsilon e q_f A') f$$

- production: $\pi^0$ and $\eta$ decays, bremsstrahlung,
  direct production in $q\bar{q}$ scatterings
- decays: dominantly into $e^+e^-$ and $\mu^+\mu^-$ up to $\sim 500$ MeV,
  then various hadronic decay modes

$$d = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80 \text{ m}) B_e \left[ \frac{10^{-5}}{\epsilon} \right]^2 \left[ \frac{E_{A'}}{\text{TeV}} \right] \left[ \frac{100 \text{ MeV}}{m_{A'}} \right]^2$$

$A'$ as a DM-SM mediator

FASER 2 comparable to proposed large SHiP detector

Other models include e.g.:
-- B-L gauge bosons
-- dark Higgs boson  J. L. Feng, I. Galon, F. Kling, ST, 1710.0938
-- heavy neutral leptons  F. Kling, ST, 1801.08947
-- ALPs  J. L. Feng, I. Galon, F. Kling, ST, 1806.02348
-- inelastic DM  A. Berlin, F. Kling, 1810.01879
-- RPV SUSY  D. Dercks, J. de Vries, H. K. Dreiner, Z. S. Wang  1810.03617

Physics case: 1811.12522
Almost imperceptible differences in reach for various MC tools

FASER reach unaffected by a small offset as long as the beam collision axis goes through the detector

\[ N_{\text{sig}} \propto L_{\text{int}} \epsilon^2 e^{-L_{\min}/\bar{d}} \text{ for } \bar{d} \ll L_{\min} \]
ALPS AT FASER –

LHC AS A PHOTON BEAM DUMP

– similarly to the QCD axion, they can appear as pseudo-Nambu-Goldstone bosons in theories with broken global symmetries

– suppressed dim-5 couplings to gauge bosons \((1/\Lambda)aV_{\mu\nu}\vec{V}_{\mu\nu}\),

– dim-5 couplings to fermions also allowed \((\partial_\mu a/\Lambda)\bar{f}\gamma_\mu\gamma_5f\),

– interesting pheno scenario – dominant \(a\gamma\gamma\) coupling

B. Döbrich et al, JHEP 1602 (2016) 018

Photon beam dump (also „light shining through a wall")

ALPs produced in the Primakoff process

1806.02348, PRD 98 (2018) no.5, 055021
Few cm thick lead plate will be put between several front veto layers (in front of FASER)

Incoming neutrinos can CC interact inside the lead plate producing muon $\mu$, with no counterpart in layers in front of the plate

Potentially hundreds of events in FASER

Measurement of the neutrino CC scattering cross section for $E_\nu \sim \text{TeV}$

Further possibilities are also explored e.g. measurements of $\nu_\tau$ employing emulsion detectors

A. Ariga, T. Ariga, O. Sato
Spectacular signal:
-- two opposite-sign, high energy (few hundred GeV) charged tracks,
-- that originate from a common vertex inside the decay volume,
-- and point back to the IP (+no associated signal in a veto layer in front of FASER),
-- and are consistent with bunch crossing timing.

Other particles: detailed simulations,
highly reduced rate (shielding + LHC magnets)
study by the members of the CERN FLUKA team:

- Neutrino-induced events: low rate + highly asymmetric momentum distribution
- Very small activity close to FASER from diffractive proton losses
- The radiation level in TI18 is low (<$10^{-2}$ Gy/year), encouraging for detector electronics.
- Proton showers in a nearby Disperssion Suppresor lead to negligible BG after ~90m of rocks in front of FASER
- Muons coming from the IP – front veto layers

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>540M</td>
</tr>
<tr>
<td>$\mu + \gamma_{\text{brem}}$ $[\mu + (\gamma_{\text{brem}} \rightarrow e^+e^-)]$</td>
<td>41K [7.4K]</td>
</tr>
<tr>
<td>$\mu + \text{EM shower}$</td>
<td>22K</td>
</tr>
<tr>
<td>$\mu + \text{hadronic shower}$</td>
<td>21K</td>
</tr>
</tbody>
</table>
Cross section of the tunnel containing FASER

Muon flux reduced at FASER location (helpful role of the LHC magnets)
BACKGROUNDS – IN-SITU MEASUREMENTS

- Emulsion detectors – focusing on a small region around the beam axis (FASER location)

- BatMons (battery-operated radiation monitors)

First analyses show that given uncertainties results are consistent with FLUKA simulations

More work ongoing to refine simulations and analyse in-situ measurements

PRACTICALLY ZERO BG SEARCH
**FASER – GROWING COLLABORATION**

**Sep 2017:** First paper, J. Feng, I. Galon, F. Kling, ST, PRD 97 035001 (2018)

...within ~year FASER grew to an international collaboration recognized at CERN

**Currently:** 27 active members from 15 institutions in 8 countries,

**Spokespersons:** Jonathan L. Feng (UC Irvine), Jamie Boyd (CERN)

During LHC Run 2 (2018): detailed BG simulations (CERN Eng Dep) + in-situ measurements

**Sep 2018:** FASER Letter of Intent – accepted by the LHC Committee

**Currently:** longer Technical Proposal submitted to the LHC Committee

very important and positive feedback possible approval: March 2019

CERN Research Board

**PLAN:**

-- Install detector during Long Shutdown 2 (work beginning in early 2019)

-- Data taking during LHC Run 3 (2021-23)

– FASER 2 (major upgrade for HL-LHC)
FASER IN POPULAR CULTURE

related article
CONCLUSIONS

• Intensity frontier searches – exciting new physics !!!

• **FASER** is a newly proposed, small and inexpensive experiment to be placed at the LHC to search for Light Long-lived Particles (LLPs) to complement the existing experimental programs at the LHC, as well as other proposed experiments,

• FASER & LHC Committee: Letter of Intent accepted, Technical Proposal submitted

• **FASER** would not affect any of the existing LHC programs and do not have to compete with them for the beam time etc.

• Rich physics prospects:
  - popular LLP models (dark photon, dark Higgs boson, GeV-scale HNLs, ALPs...),
  - Many connections to DM and cosmology
  - Invisible decays of the SM Higgs,
  - Measurments of SM neutrinos
• Possible timeline:

  Install FASER 1 in LS2 (2019-20) for Run 3 (150 fb⁻¹)
  – \( R = 10 \text{ cm}, L = 1.5 \text{ m} \), Target dark photons, B-L gauge bosons, ALPs...

  Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab⁻¹)
  – \( R = 1 \text{ m}, L = 5 \text{ m} \), Full physics program: dark vectors, ALPs, dark Higgs, HNLs...

New physics reach even after first 10fb⁻¹ (end of 2021?)
INELASTIC P-P COLLISIONS

EPOS-LHC
DARK PHOTONS AT FASER – KINEMATICS

- Monte Carlo fitted to experimental data (LHCf, ALFA)
- typically $p_T \sim \Lambda_{QCD}$
- for $E \sim \text{TeV}$ $p_T/E \sim 0.1$ mrad
- even $\sim 10^{15}$ pions per $(\theta, p)$ bin

- $\pi^0 \rightarrow A' \gamma$
- high-energy $\pi^0$
  - collimated A’s
- $\varepsilon^2 \sim 10^{-10}$ suppression but still up to $10^5$ A’s per bin

- only highly boosted A’s survive until FASER $E_{A'} \sim \text{TeV}$
- further suppression from decay in volume probability
- still up to $N_{A'} \sim 100$ events in FASER, mostly within $r<20\text{cm}$
DARK HIGGS BOSONS

- Dark Higgs boson: additional hidden real scalar field $\phi$,
- often adopted phenomenological parametrization:
  \[ \mathcal{L} \supset -m_\phi^2 \phi^2 - \sin \theta \frac{m_f}{v} \phi \bar{f}f - \lambda v h \phi \phi \]
- Higgs-like couplings suppressed by $\theta^2$,
- production: $B$ and $K$ decays, $h \rightarrow \phi \phi$,
- decays: into the heaviest kinematically allowed states: $\mu^+ \mu^-$, $\pi \pi$, $KK$, ...

- at FASER energies: $N_B/N_\pi \sim 10^{-2}$ (10^{-7} for typical beam+dumps)
- Typical $p_T \sim m_B$ \rightarrow improved reach for FASER 2 (R=1m)

**Dark Higgs-DM portal**

\[ <\sigma v> \sim \kappa^4 \rightarrow \kappa \text{ fixed by relic density} \]

complementarity between FASER and other proposed experiments
(large boost, probing lower $\tau$)
PROBING INVISIBLE DECAYS OF THE SM HIGGS

\[ \mathcal{L} \supset - \lambda \nu h \phi \phi \]

- trilinear coupling
  - invisible Higgs decays \( h \rightarrow \phi \phi \)

- far-forward region: efficient production via off-shell Higgs, \( B \rightarrow X_s h^* (\rightarrow \phi \phi) \)

- can extend the reach in \( \theta \) up to \( 10^{-6} \)
  - for \( B(h \rightarrow \phi \phi) \approx 0.1 \)

- up to \( \sim 100 \) events
HEAVY NEUTRAL LEPTONS

- seesaw mechanism, e.g., for type-I seesaw
  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + i \tilde{N}_I \phi \tilde{N}_I - F_{\alpha I} \bar{L}_\alpha \tilde{N}_I \tilde{\phi} - \frac{1}{2} \tilde{N}_I M_I \tilde{N}_I + \text{h.c.} \]

- popular model: $\nu$MSM with the lightest $N_1$ being a DM candidate possibly consistent with 3.5 keV excess and two heavier HNLs, $N_{2,3}$, detectable in LLP searches,

- typically considered in searches for LLPs, possibly a primary motivation to build SHiP

- they mix with the SM (active) neutrinos,

- phenomenologically they behave like heavy or sterile neutrinos with masses $m_{N_I}$ and mixing angles $U_{eI}$, $U_{\mu I}$, $U_{\tau I}$

- HNLs can decay into lighter SM particles $\Rightarrow$ signatures

  \[ N_i \rightarrow Z \rightarrow l_j^+ l_j^- , \nu_j \bar{\nu}_j , q\bar{q} \]

  possible 2 charged tracks
Typical simplified approach:

- we focus on only one HNL leaving a signature in FASER
- we vary as free parameters

$$m_N, \ U_{eN}, \ U_{\mu N}, \ U_{\tau N}, \ \text{where only one } U_{\ell N} \neq 0 \ \text{at a time.}$$

*B and D meson decays* – we consider about $\sim 20$ production channels, dominant ones dictated by the CKM suppression, kinematics and fragmentation fractions

$$D^{0,\pm} \rightarrow N \ e^{\pm} \ K^{\mp,0,\ast}, \ D_s^{\pm} \rightarrow N \ e^{\pm}, \ldots$$

$$B^{0,\pm} \rightarrow N \ e^{\pm} \ D^{\mp,0,\ast}, \ B^\pm \rightarrow N \ e^{\pm}, \ B_c^\pm \rightarrow N \ e^{\pm}, \ldots$$

Decay modes:

- $\text{BR}(N \rightarrow 3\nu) \sim 10\% - 20\%$ invisible
- $\text{BR}(N \rightarrow \nu_1 l_1^{+} l_2^{-}) \sim 20\%$ (BR($N \rightarrow \nu_1 e^+ e^-$) $\sim$ few percent)
- $\text{BR}(N \rightarrow \text{hadrons}) \sim 60\% - 70\%$, various final states

FASER 2

⇒ up to $\sim 10^3$ events for $m_N \gtrsim m_D$
⇒ for $m_N \lesssim m_D$ possible $\sim 10^1 - 10^2$ events
POSSIBLE LOCATIONS (TI12 vs TI18)

- When designing the detector 2 main possible locations were considered: tunnels TI12 and TI18 on two sides of the ATLAS IP (~480m away from the IP)
- Both are former service tunnels connecting SPS and the main LHC tunnel
- Both are currently unused
- Both slope steeply upwards when leaving the main LHC tunnel (SPS is shallower than LHC)
- In both cases the line-of-sight (along the beam collision axis) is below the tunnel floor as it enters the tunnel, and then emerges from the floor
- Lowering of the floor up to 460mm is possible to maximize the detector length
  (CERN survey team)

- The tunnels do have identical geometry:
  about 5m long detector can be fit in tunnel TI12
  about 3m long detector can be fit in tunnel TI18
- Based on this the preferred location is the tunnel TI12
- BG measurements have been performed in both locations (below fluxes within 10 mrad)

<table>
<thead>
<tr>
<th>beam [fb⁻¹]</th>
<th>observed tracks [cm⁻²]</th>
<th>efficiency</th>
<th>normalized flux, all [fb cm⁻²]</th>
<th>normalized flux, main peak [fb cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI18</td>
<td>2.86</td>
<td>18407</td>
<td>(2.6 ± 0.7) × 10⁴</td>
<td>(1.2 ± 0.4) × 10⁴</td>
</tr>
<tr>
<td>TI12</td>
<td>7.07</td>
<td>174208</td>
<td>(3.0 ± 0.3) × 10⁴</td>
<td>(1.9 ± 0.2) × 10⁴</td>
</tr>
<tr>
<td>FLUKA simulation, E&gt;100 GeV</td>
<td></td>
<td></td>
<td>1 × 10⁴</td>
<td></td>
</tr>
</tbody>
</table>
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 TI12
- Minimized needed services (power, cooling etc.)

To be constructed by the CERN magnet group:
- Cost 450kCHF
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
  - $80\mu$m strip pitch, $40\text{mrad}$ 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
- Due to the low radiation in TI12 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)
FASER will have an ECAL for:

- measuring the EM energy in the event
- electron/photon identification
- triggering

Will use 4 spare LHCb outer ECAL modules

- Many thanks to LHCb for allowing us to use these!
- 66 layers of lead/scintillator, light out by wavelength shifting fibres, and readout by PMT (no longitudinal shower information)
  - 25 radiation lengths long
- dimensions: 12cm x 12cm – 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

Scintillators used for vetoing charged particles entering the decay volume, and for triggering

- To be produced at CERN scintillator lab
- Require extremely efficient charged particle veto (eff > 99.99%) – achievable with the current design
MORE ABOUT TRACK SEPARATION

GEANT 4
FASER AND SURROUNDING LHC INFRASTRUCTURE

ATLAS Interaction Point (IP)

Strong LHC dipole magnets

TAN Neutral Particle Absorber ~140m away from the IP

FASER location tunnel TI12 ~480m away from the IP