Looking forward to new physics with
FASER: ForwArd Search ExpeRiment at the LHC

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University of Sheffield

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arXiv:1708.09389;1710.09387;1801.08947;1806.02348 (PRD,with J.L.Feng,I.Galon,F.Kling)
arXiv:1811.12522 physics case
arXiv:1901.04468 input to the European Particle Physics Strategy
FASER COLLABORATION

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

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• Motivation behind the intensity frontier searches for light long-lived particles (LLPs)

• FASER: ForwArd Search ExpeRiment at the LHC (idea, basic detector design)

• Remarks about FASER physics program
  -- dark photons,
  -- axion-like particles,
  -- dark Higgs bosons,
  -- 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:
\[ \Omega_{\text{DM}} h^2 \sim \frac{m^2}{g^4} \sim 0.1 \quad g \ll g_{\text{weak}} \Rightarrow m \ll m_{\text{weak}} \]
**FASER - IDEA**

**FASER** – newly proposed, small (~0.05 m$^3$) and inexpensive (~2M$\$$) experiment 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} \text{ in high-} p_T \text{ searches})$

**FASER** will complement ATLAS/CMS by searching for highly-displaced decays of new Light Long-Lived Particles

(part of Physics Beyond Colliders Study Group at CERN)
FASER LOCATION – TUNNEL TI12

- Location in a side tunnel TI12 (former service tunnel connecting SPS to LEP)
- $L \sim 485\text{m}$ away from the IP along the beam axis
- Space for a 5-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 $\sim 300\mu\text{rad}$ the displacement is $\sim 7-8\text{ cm}$)
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) (above layout)

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

Thank you !!!

Recycling existing spare modules:
- ATLAS SCT modules (Tracker)
- LHCb ECAL modules (Calorimeter)
• 0.6T permanent dipole magnets based on the Halbach array design
  — LOS to pass through the magnet center
  — minimum digging to the floor in TI12
  — minimized needed services (power, cooling)
• manufacture: CERN magnet group
• stray field around scintillator PMTs ~5mT shielding (mu-metal)
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!
- 72 SCT modules needed for the full tracker
- 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:

- measuring the EM energy in the event (up to 1% accuracy in energy ~1 TeV)

- Will use 4 spare LHCb outer ECAL modules
  - Many thanks to LHCb Collaboration for allowing us to use these!
  - 66 layers of lead/scintillator (2mm lead, 4mm plastic scintillator)
    - 25 radiation lengths long
    - no longitudinal shower information
    - Resolution will degrade at higher energy due to not containing full shower in calorimeter
  - Scintillators used for vetoing charged particles entering the decay volume, for triggering and as a preshower
    - To be produced at CERN scintillator lab
    - Vetoing: achievable extremely efficient charged particle veto (eff>99.99%)
    - Trigger: also timing the signal with respect to timing of the $pp$ interactions
    - Preshower: thin radiator in front, photon showering (disentangling from $\nu$ interactions in ECAL)
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

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

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

$\theta_{\pi}$

EPOS-LHC

$p_\pi$ [GeV]

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

LLPs produced from B mesons in FASER 2

$p_\pi \sim m_B$ larger angular spread target for FASER 2

at FASER energies: $N_B/N_\pi \sim 10^{-2}$

(10^{-7} for typical beam dumps)
DARK PHOTON

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

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

- 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

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

$A'$ as a DM-SM mediator

FASER 2 comparable to proposed large SHiP detector

$$N_{\text{sig}} \propto \mathcal{L}^{\text{int}} \epsilon^2 \epsilon^{-L_{\text{min}}/\bar{d}} \quad \text{for} \quad \bar{d} \ll L_{\text{min}}$$

$$\bar{d} \sim \epsilon^{-2}$$

no of events grows exponentially with a small shift in $\epsilon$
Almost imperceptible differences in reach for various MC tools

$$N_{\text{sig}} \propto \mathcal{L}^{\text{int}} \epsilon^2 e^{-L_{\text{min}}/\bar{d}} \quad \text{for} \quad \bar{d} \ll L_{\text{min}}$$

no of events grows exponentially with a small shift in $\epsilon$

FASER reach unaffected by a small offset as long as the beam collision axis goes through the detector
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 \( (1/\Lambda)aV^{\mu\nu}\bar{V}_{\mu\nu} \),
– dim-5 couplings to fermions also allowed \( (\partial_\mu a/\Lambda)f\gamma_\mu\gamma_5 f \),
– 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
DARK HIGGS BOSONS

- Dark Higgs boson: additional hidden real scalar field $\phi$,
- often adopted phenomenological parametrization:

$$ \mathcal{L} \supset -m_{\phi}^2 \phi^2 - \sin \theta \frac{m_t}{v} \phi \bar{f}f - \lambda v h \phi $$
- Higgs-like couplings suppressed by $\theta^2$,
- production: $B$ and $K$ decays, $h \rightarrow \phi \phi$,
- decays: into the heaviest kinematically allowed states: $\mu^+ \mu^-, \pi \pi, KK, \ldots$

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

Dark Higgs-DM portal

$$ \langle \sigma v \rangle \sim \kappa^4 \rightarrow \kappa \text{ fixed by relic density} $$

complementarity between FASER and other proposed experiments (large boost, probing lower $\tau$)
# MORE MODELS OF NEW PHYSICS

*table refers to the benchmark scenarios of the Physics Beyond Colliders CERN study group*

<table>
<thead>
<tr>
<th>Benchmark Model</th>
<th>Label</th>
<th>Section</th>
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<td>VII C</td>
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Other models & FASER sensitivity studies e.g.:
- RPV SUSY (D. Drecks, J. de Vries, H.K. Dreiner, Z.S. Wang, 1810.03617)
- Inelastic dark matter (A. Berlin, F. Kling, 1810.01879)
SM NEUTRINOS IN FASER

General idea:
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 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 ideas are also explored e.g. measurements of $\nu_\tau$ employing emulsion detectors


(further work in progress)
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.

• Neutrino-induced events: low rate

• 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

  Expected trigger rate ~650 Hz

Other particles: detailed simulations, highly reduced rate (shielding + LHC magnets)

study by the members of the CERN FLUKA team:

<table>
<thead>
<tr>
<th>Part. type</th>
<th>Cut T &gt; 100 GeV</th>
<th>Cut T &gt; 500 GeV</th>
<th>Cut T &gt; 1 TeV</th>
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<tr>
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<td>fluence rate (cm² s⁻¹)</td>
<td>fluence per bunch crossing per cm²</td>
<td>fluence rate (cm² s⁻¹)</td>
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<td>μ⁺</td>
<td>0.18</td>
<td>6.1·10⁹</td>
<td>0.02</td>
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<td>μ⁻</td>
<td>0.40</td>
<td>1.3·10⁸</td>
<td>0.22</td>
</tr>
<tr>
<td>π⁺</td>
<td>~10⁻⁷</td>
<td>~10⁻³⁴</td>
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</tr>
<tr>
<td>π⁻</td>
<td>~10⁻⁵</td>
<td>~10⁻³²</td>
<td>~10⁻⁷</td>
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<table>
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<th>Process</th>
<th>Expected Number of Events</th>
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<td>μ</td>
<td>540M</td>
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<tr>
<td>μ + γ_{brem}</td>
<td></td>
</tr>
<tr>
<td>[μ + (γ_{brem} → e⁺e⁻)]</td>
<td>41K</td>
</tr>
<tr>
<td>μ + EM shower</td>
<td>22K</td>
</tr>
<tr>
<td>μ + hadronic shower</td>
<td>21K</td>
</tr>
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</table>
Cross section of the tunnel containing FASER

At FASER location:
muon flux reduced along the beam collision axis (helpful role of the LHC magnets)
BACKGROUNDs – IN-SITU MEASUREMENTS

- Emulsion detectors – focusing on a small region around the beam axis (FASER location)
- TimePix Beam Lumi Monitors
- BatMons (battery-operated radiation monitors)

Analyses show that results are consistent with FLUKA simulations

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

PRACTICALLY ZERO BG SEARCH
FASER – GROWING COLLABORATION


...within ~1.5 year FASER grew to an international collaboration recognized at CERN

Currently: ~30 active members from ~15 institutions in ~8 countries (growing),

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

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

Dec 2018: Technical Proposal recommended by the LHC Committee for a full approval

Dec 2018/Jan 2019: fundings granted for the detector (Heisig-Simons and Simons foundations)

Mar 2019: possible full approval by the CERN Research Board

PLANS:
– Final detector design, manufacture, installation and commissioning during Long Shutdown 2 (ongoing work)

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

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

related article
CONCLUSIONS

• Light Long-lived Particles (LLPs) – 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 to complement the existing experimental programs at the LHC, as well as other proposed experiments,

• FASER & LHC Committee: Letter of Intent accepted, Technical Proposal recommended for a full approval by the CERN Res Board

• 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,
  - Measurements of SM neutrinos

• Possible timeline:
  
  Install FASER 1 in LS2 (2019-20) for Run 3 (150 fb⁻¹)
  – R = 10 cm, L = 1.5 m, Target dark photons, B-L gauge bosons, ALPs...
  
  Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab⁻¹)
  – R = 1 m, L = 5 m, Full physics program: dark vectors, ALPs, dark Higgs, HNLs...
BACKUP
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 $TeV $p_T/E \sim 0.1$ mrad
  • even $\sim 10^{15}$ pions per $(\theta, p)$ bin

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

• only highly boosted $A'$s survive until FASER $E_{A'} \sim $TeV
  • further suppression from decay in volume probability
  • still up to $N_{A'} \sim 100$ events in FASER, mostly within $r<20cm$
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
DPMJET 3.06
QGSJET II, SIBYLL lower estimates

THESE DISCREPANCIES HAVE VERY LITTLE IMPACT ON FASER SENSITIVITY
(see next slides)
Almost impreceptible differences in reach for various MC tools

\[ N_{\text{sig}} \propto \mathcal{L}^{\text{int}} \epsilon^2 e^{-L_{\text{min}}/\overline{d}} \quad \text{for } \overline{d} \ll L_{\text{min}} \]

no of events grows exponentially with a small shift in \( \epsilon \)

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

\[ \overline{d} \sim \epsilon^{-2} \]
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 \( B(h \rightarrow \phi \phi) \sim 0.1 \)

• up to \( \sim 100 \)s of events
HEAVY NEUTRAL LEPTONS

- seesaw mechanism, e.g., for type-I seesaw

\[ \mathcal{L} = \mathcal{L}_{SM} + i \tilde{N}_I \phi \tilde{N}_I - F_{\alpha I} \bar{L}_\alpha \tilde{N}_I \tilde{\Phi} - \frac{1}{2} \tilde{N}_I M_I \tilde{N}_I + h.c. \]

- 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 \( \Rightarrow \) signatu

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

possible 2 charged tracks
HEAVY NEUTRAL LEPTONS AT FASER

Typical simplified approach:

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

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

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

$$D^0, \pm \rightarrow N e^\pm \ K^{\mp,0},(*) \quad D_s^\pm \rightarrow N e^\pm, \ldots$$

$$B^0, \pm \rightarrow N e^\pm \ D^{\mp,0},(*) \quad B^\pm \rightarrow N e^\pm, \quad B_c^\pm \rightarrow N e^\pm, \ldots$$

Decay modes:

$BR(N \rightarrow 3\nu) \sim 10\% - 20\%$ invisible

$BR(N \rightarrow \nu l_1^+ l_2^-) \sim 20\%$ ($BR(N \rightarrow \nu e^+ e^-) \sim \text{few percent}$)

$BR(N \rightarrow \text{hadrons}) \sim 60\% - 70\%$, various final states

FASER 2

$\Rightarrow$ up to $\sim 10^3$ events for $m_N \gtrsim m_D$

$\Rightarrow$ for $m_N \lesssim m_D$ possible $\sim 10^1$-$10^2$ events
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

~480m away from the IP
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></th>
<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>
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<td>TI18</td>
<td>2.86</td>
<td>18407</td>
<td>0.25</td>
<td>$(2.6 \pm 0.7) \times 10^4$</td>
<td>$(1.2 \pm 0.4) \times 10^4$</td>
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<tr>
<td>TI12</td>
<td>7.07</td>
<td>174208</td>
<td>0.80</td>
<td>$(3.0 \pm 0.3) \times 10^4$</td>
<td>$(1.9 \pm 0.2) \times 10^4$</td>
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<td>FLUKA simulation, $E&gt;100$ GeV</td>
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<td>$1 \times 10^4$</td>
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