FASER: ForwArd Search ExpeRiment at the LHC

Sebastian Trojanowski
National Centre for Nuclear Research, Poland

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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)
OUTLINE

• Motivation and idea of the FASER experiment

• Location of the experiment

• Detector layout

• Models of new physics in FASER (connection to DM searches)
  -- dark photons,
  -- dark Higgs bosons
  -- axion-like particles,

• Background: simulations & in-situ measurements

• Conclusions
Traditionally, new physics has been searched for in the high-$p_T$ region. Focus on heavy and strongly-coupled particles, e.g., Higgs, SUSY, extra dim,...

$$\sigma \sim fb - pb, \text{ e.g., } N_H \sim 10^7 \text{ at } 300 \text{ fb}^{-1}$$

Energy frontier

Here also missing energy searches for heavy WIMP DM

Dark sectors with light mediators – rapidly emerging field!

SIDM (solving some problems of $\Lambda$CDM?), secluded annihilation, SIMP or ELDER DM, hidden valleys,…

(for reviews see 1311.0029, 1608.08632, 1707.04591)

also Monday plenary talk: S. Matsumto

More opportunities of considering light new physics particles:

viable models for $(g-2)_\mu$ & muonic hydrogen, other anomalies (Beryllium?), ...

However, light and weakly-coupled new particles typically escape detection in high-$p_T$ region, they can be produced e.g. in rare meson decays, and typically go in the far forward region

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

Intensity frontier

$$p_T \sim \Lambda_{QCD}, \theta \sim \Lambda_{QCD}/E \sim \text{ mrad}, \text{ new light particles are highly collimated along the beam-axis}$$
**FASER - IDEA**

**FASER** – newly proposed, small (~1 m³) and inexpensive (~1.5M$) detector to be placed few hundred meters downstream away from the ATLAS/CMS IP to harness large, currently „wasted” forward LHC cross section

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

In the context of DM, FASER will search for various possible light mediators.

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**LHCf, TOTEM, ALFA, CASTOR**
FASER LOCATION – TUNNEL TI18

• promising location in a side tunnel TI18 (former service tunnel connecting SPS to LEP)
• about L ~ 480m 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 300μrad the displacement is 7 ~ cm)

thanks to Mike Lamont
thanks to Mike Lamont

FASER LOCATION PHOTO (1)

New physics hidden in the dark...

beam pipe
thanks to Mike Lamont

...can be brought to light
• GEANT4 studies for optimization of:
  - length of decay volume,
  - number and placement of tracking layers,
  - strength and region of B field.

• cylindrical detector

• 2 stages of the project:

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

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

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

Practically zero BG search –
In the following we assume 100% detection efficiency for a better comparison with other exps
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 (pp$\rightarrow$pA'$\chi$)
– decays: dominantly into $e^+e^-$ and $\mu^+\mu^-$ up to $\sim 500$ MeV, then various hadronic decay modes

• typical decay length

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

for $\epsilon \sim 10^{-7}$-$10^{-3}$ and $m_{A'} \sim 10\text{MeV}$-$1\text{GeV}$ in the range of FASER

$A'$ as a DM-SM mediator

e.g. for $m_{A'} \sim m_\chi$ we obtain $<\sigma v> \sim \epsilon^2\alpha_\alpha_D / (m_{A'})^2$

requiring $<\sigma v> \sim \alpha^2_{\text{weak}} / m^2_{\text{weak}}$ and putting $\alpha\alpha_D \sim \alpha^2_{\text{weak}}$

one obtains $\epsilon \sim m_{A'}/m_{\text{weak}} \sim 10^{-3}$-$10^{-5}$ for $m_{A'} \sim 1$-$100$ MeV
DARK HIGGS BOSONS AT FASER

- 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, $h \to \phi \phi$,
- 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 \[ \mathcal{L} \supset - \frac{1}{2} \kappa \phi \bar{X} X \]

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

complementarity between FASER and other proposed experiments (large boost, probing lower $\tau$)
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 \( \frac{1}{\Lambda} a V^{\mu\nu} \overline{V}^{\mu\nu} \),
- dim-5 couplings to fermions also allowed \( (\partial_\mu a/\Lambda) \overline{f} \gamma_\mu \gamma_5 f \),
- interesting pheno scenario – dominant \( a\gamma\gamma \) coupling

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

“\( a\gamma\gamma \)” coupling – dominant production mode for FASER is the Primakoff process \( (\gamma N \rightarrow aN) \)
Spectacular signal:
-- two opposite-sign, high energy (E > 500 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 + 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

study by the members of the CERN FLUKA team: Marta Sabate-Gilarte, Francesco Cerutti, Andrea Tsinganis
- First measurements already performed

- Emulsion detectors
  A. Ariga, T. Ariga (Kyushu, BERN), O. Seto (Nagoya)

- BatMon (battery-operated radiation monitor)

  First results promising (consistent with FLUKA)

  Currently: ongoing thorough data analysis
August/September 2017 - first paper ~1 year ago (1708.09389), since then 3 more papers from the FASER group + increasing interest outside the group
Batell, Freitas, Ismail, McKeen, 1712.10022; Bauer, Foldenauer, Jaeckel, 1803.05466; Helo, Hirsch, Wang, 1803.02212

November 2017 – join the Physics Beyond Colliders (PBC) working group at CERN,
May 2018 – first results of detailed BG simulations,
June 2018 – first BG in-situ measurements,
Currently > 10 active members (mostly experimentalists) from ~8 institutions in 4 countries,
Akitaka Ariga (Bern, experimentalist)
Tomoko Ariga (Kyushu/Bern, experimentalist)
Jamie Boyd (CERN, experimentalist) (contact with PBC accelerator CERN working group)
Dave Casper (UCI, experimentalist)
Jonathan Feng (UCI, theorist) (contact with PBC BSM CERN working group)
Iftah Galon (Rutgers, theorist)
Shih-Chieh Hsu (Washington, experimentalist)
Felix Kling (UCI, theorist)
Hidetoshi Otono (Kyushu, experimentalist)
Brian Petersen (CERN, experimentalist)
Osamu Sato (Nagoya, experimentalist)
Aaron Soffa (UCI, experimentalist)
Jeffrey Swaney (UC Irvine, experimentalist)
Sebastian Trojanowski (National Center for Nuclear Research, theorist)
+ additional input from CERN Engineering Dep (e.g., BG simulations)
FASER IN POPULAR CULTURE

related article
CONCLUSIONS

• **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,
• proposed location is ~480m away from the ATLAS IP in a side tunnel,
• significant progress in BG understanding (simulations, in-situ measurements)...
• ...and in studies on detector design (Geant 4),
• **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,
  - LHC as a photon beam-dump (aγγ coupling),
  - ... (place for an input from you !!!)
• Currently pursuing funding options and seeking CERN approval. If successful, a possible timeline and plan is

Install FASER 1 in LS2 (2019-20) for Run 3 (150 fb⁻¹)
  - R = 10 cm, L = 1.5 m, requires lowering floor by 50cm in existing tunnel
  - Target dark photons, B-L gauge bosons, ALPs, etc.

Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab⁻¹)
  - R = 1 m, L = 5 m, requires some extension of the existing tunnel
  - Full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, etc.
BACKUP
LHC INFRASTRUCTURE AROUND

LLP – Light Long-lived Particle

- LLPs produced at the IP
- TAN absorber for neutral particles
- Some LLPs decay in FASER two (~TeV) charged tracks e.g. e⁺e⁻

- LHC magnets effectively deflect charged particles (reduced μ BG)
- Other LHC infrastructure + ~90m of rocks (shielding from the IP)
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 $\pi^0$ 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 $E_{A'} \sim TeV$
- further suppression from decay in volume probability
- still up to $N_{A'} \sim 100$ events in FASER, mostly within $r<20cm$
• both FASER 1 and FASER 2 can have world-leading sensitivity at the time of operation,
• in FASER 2 the reach extends to $m_{A'} > 1$GeV for $\epsilon \sim 10^{-7}$-$10^{-6}$,
• for $\epsilon \sim 10^{-4}$-$10^{-6}$ contours with $N_{A'} =$ const are very densely spaced
  (exponential suppression for decay length $\ll L \sim 480$ m)
• the reach is then similar for FASER and much larger experiments,
• also reach there is very mildly sensitive to the exact number of BG events, detector efficiency etc.
PROBING INVISIBLE DECAYS OF THE SM HIGGS

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

- trilinear coupling
  
  \[ \text{invisible Higgs decays } h \rightarrow \phi \phi \]

- 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
- high-energy $\gamma$s produced at the IP,
- $\gamma$s hit the neutral absorber TA(X)N $\sim 130$ m away from the IP,
- ALP production mainly in the Primakoff process,
- also exotic $\pi^0$ and $\eta$ decays,
- ALPs decay into 2 photons in FASER

- signal = 2 high-energy photons ($\gamma\gamma$),
- need of calorimeter;
existing technology e.g. LHCf calorimeter:
  -- 23cm long,
  -- 5% energy resolution for $E>100$GeV
    (used also for a few TeV energies)
  -- 2 photons reconstructed with 90% efficiency
    if they are \textbf{1mm} away from each other

$E_a \sim$ few hundred GeV,
for $m_a \sim 100$MeV \( \gamma_{\text{Lor}} = E_a/m_a \sim \text{few } \times 10^3 \)
typical opening angle $\theta_{\gamma\gamma} \sim 2/\gamma_{\text{Lor}} < 1$ mrad
after $>1$ m both photons are separated $\sim 1$mm
  (more details see 1806.02348)
- possible conversions in the tracker layers ($\gamma e^+ e^-$)
HEAVY NEUTRAL LEPTONS

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

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

- 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 $\Rightarrow$ signature

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

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 $m_N, \ U_{eN}, \ U_{\mu N}, \ U_{\tau N}$, where only one $U_{\ell N} \neq 0$ 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

$D^{0,\pm} \rightarrow N \ e^{\pm} K^{\pm,0}, D_s^\pm \rightarrow N \ e^\pm, \ldots$
$B^{0,\pm} \rightarrow N \ e^{\pm} D^{\pm,0}, B^\pm \rightarrow N \ e^\pm,$
$B_c^\pm \rightarrow N \ e^\pm, \ldots$

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

$\Rightarrow$ 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
INELASTIC DARK MATTER AT FASER

For more details see: A. Berlin, F. Kling, 1806.xxxxx
(also MATHUSLA, Codex-b, LHC)

Pseudo-Dirac pair $\chi_1$ and $\chi_2$ nearly degenerate in mass

$$-\mathcal{L} \supset m_D \eta \xi + \frac{1}{2} \delta_\eta \eta^2 + \frac{1}{2} \delta_\xi \xi^2 + \text{h.c.},$$

small mass splitting

$$\chi_1 \simeq \frac{i}{\sqrt{2}} (\eta - \xi),$$
$$\chi_2 \simeq \frac{1}{\sqrt{2}} (\eta + \xi),$$
$$\Delta \equiv \frac{m_2 - m_1}{m_1} \simeq \frac{\delta_\eta + \delta_\xi}{m_D} \ll 1$$

$\Lambda'$-portal, dominant off-diagonal coupling to $\Lambda'$

$$\mathcal{L} \supset i e_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2 + \mathcal{O}(\delta_\eta, \delta_\xi/m_D)$$

Production $pp \rightarrow \Lambda' \rightarrow \chi_1 \chi_2$ goes through $\Lambda'/Z$:
- meson decays,
- dark Bremstrahlung,
- Drell-Yan

$\chi_2$ decays are delayed by adjusting $\Delta$:

$$\Gamma(\chi_2 \rightarrow \chi_1 \ell^+ \ell^-) \simeq \frac{4 e^2 \alpha_{em} \alpha_D \Delta^5 m_1^5}{15 \pi m_A^4},$$

up to 100s of events in FASER
reach can go up to $m_A = 3 m_1 > 30 \text{GeV}$!
The rate of neutrino induced events
Helpful role of the LHC magnets

At the entrance of the DS (~90m before FASER)