FASER
FORWARD SEARCH EXPERIMENT
AT THE LHC

Carleton University

Jonathan Feng, UC Irvine

Based on 1708.09389 and 1710.09387
with Iftah Galon, Felix Kling, Sebastian Trojanowski

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SUMMARY

• New physics searches at the LHC focus on high $p_T$. This is appropriate for heavy, strongly coupled particles
  $\sigma \sim \text{fb to pb} \rightarrow N \sim 10^3 - 10^6$, produced $\sim$isotropically

• However, if new particles are light and weakly coupled, this may be completely misguided. Instead should exploit
  $\sigma_{\text{inel}} \sim 100 \text{ mb} \rightarrow N \sim 10^{17}$, $\theta \sim \Lambda_{\text{QCD}} / E \sim 250 \text{ MeV} / \text{TeV} \sim \text{mrad}$

• We propose a small, inexpensive experiment, FASER, to be placed in the very forward region of ATLAS/CMS, a few 100m downstream of the IP, and analyze its discovery potential
This field is generating worldwide interest. At CERN: LHCb, NA62, SHiP, MATHUSLA, MilliQan, Codex-b, ...

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

• Very Forward Region Infrastructure
• New Physics Example: Dark Photons
• Signal
• Backgrounds
• Results
• New Physics Example: Dark Higgs Bosons
• Summary and Outlook
LHC ring consists of 8 straight 545 m intersections and 8 curved arcs. The infrastructure common to IP1 and IP5 (also have ALFA, CASTOR, LHCf, TOTEM, etc.):

TAS: front quadrupole absorbers ($\theta > 0.85$ mrad)  
D1: dipole magnet, splits beams, deflects $\mu, p, ...$

TAN: neutral target absorbers ($n, \gamma$)

Note the extreme difference in longitudinal and transverse scales
FASER LOCATIONS

- We want to place FASER along the beam \textit{collision} axis
  - Far location: 400 m from IP, after beams curve, 2.6 m from the beams
  - Near location: 150 m, after TAN, between the beams

- ATLAS/CMS beams cross at 285 $\mu$rad in vertical/horizontal plane $\rightarrow$ shifts far (near) location by 5.7 (2.1) cm

- HL-LHC: 285$\rightarrow$590 $\mu$rad, TAN$\rightarrow$TAXN moves forward 10 m,...

We assume current parameters, FASER is exactly on-axis
• Dark matter is our most solid evidence for new particles. In recent years, the idea of dark matter has been generalized to dark sectors.

• Dark sectors motivate light, weakly coupled particles (WIMPless miracle, SIMP miracle, small-scale structure, ..)

• A prominent example: vector portal, leading to dark photons.

\[ \epsilon F_{\mu \nu} F_{\text{hidden}}^{\mu \nu} \]

• The resulting theory contains a new gauge boson \( A' \) with mass \( m_{A'} \) and \( \epsilon Q_f \) couplings to SM fermions \( f \).
DARK PHOTON PROPERTIES

• Produced in meson decays, e.g.,

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

and also through dark bremsstrahlung \( pp \rightarrow p A' X \) and direct QCD processes \( qq \rightarrow A' X \) (requires pdfs at low \( Q^2, x \))

• Travels long distances through matter without interacting, decays mainly to \( e^+e^- \) (and \( \mu^+\mu^- \) for \( m_{A'} > 2 m_\mu \))

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

• The essential tension: low \( \varepsilon \) \( \rightarrow \) low event rate, high \( \varepsilon \) \( \rightarrow \) decays too fast. Is there a happy middle ground?
DARK PHOTON STATUS

- Lots of unconstrained parameter space with
  \[ m_{A'} > 10 \text{ MeV} \]
  \[ \varepsilon \sim 10^{-6} - 10^{-3} \]
- 2 representative model points: \((m_{A'}, \varepsilon) = \)
  
  (20 MeV, 10^{-4})
  
  (100 MeV, 10^{-5})
PION PRODUCTION AT THE LHC

- Forward particle production simulations and models have been greatly constrained by LHC data
- EPOS-LHC, SIBYLL 2.3, QGSJETII-04 agree very well
- Enormous event rates ($\sigma_{\text{inel}} \sim 70\, \text{mb}, N_{\text{inel}} \sim 10^{17}$), production is peaked at $p_T \sim \Lambda_{\text{QCD}}$, but with significant width
DARK PHOTON PRODUCTION

- Consider $\pi^0$ decay, $\eta$ decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\text{ MeV}, 10^{-4})$

- From $\pi^0 \rightarrow \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after $\varepsilon^2$ suppression, $N_{A'} \sim 10^8$: LHC is a dark photon factory!
Now require dark photons to decay in the far detector: consider cylindrical detector with volume $\sim 1 \text{ m}^2$

- Only the highest energy A's survive, but there are still many of them, and they are highly collimated
**SIGNAL DEPENDENCE ON DETECTOR SPECS**

- For dark photons, moving the detector closer helps.
- At the far location, \( R = 20 \text{ cm} \) captures almost all the \( A' \).

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**Distance between detector and IP**

- \( \pi^0 \rightarrow \gamma A' \)
- \( \eta \rightarrow \gamma A' \)
- Bremsstrahlung

- \( \varepsilon: 10^{-4} \)
- \( m_{A'}: 20 \text{ MeV} \quad 100 \text{ MeV} \)

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**Detector Radius: far location**

- \( L_{\text{max}} = 400 \text{ m}, \Delta = 10 \text{ m} \)
- \( E_{A'} > 100 \text{ GeV} \)
DARK PHOTONS IN THE NEAR DETECTOR

• Now require dark photons to decay in the near detector: detector volume only $\sim 0.1 \text{ m}^2$!

Moving the detector closer $\rightarrow$ more dark photons decay in the detector, even though the after-TAN location is crowded.

$\text{on-axis: } L = 150 \text{ m}$

$\Delta = 5 \text{ m}$

Outer radius $R_{\text{out}} = 4 \text{ cm}$

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BACKGROUNDs

- The signal is two simultaneous, opposite-sign, highly-energetic (E > 500 GeV) charged particles that start in the detector at a vertex and point back to IP → a tracker-based technology.

- The opening angle is \( \theta_{ee} \sim m_A / E \sim 10 \, \mu\text{rad} \). After traveling ~1 m, this leads to 10 \( \mu \text{m} \) separation, too small to resolve, so we need a small magnetic field:

\[
h_B \approx \frac{ecl^2}{E} B = 3 \, \text{mm} \left[ \frac{1 \, \text{TeV}}{E} \right] \left[ \frac{\ell}{10 \, \text{m}} \right]^2 \left[ \frac{B}{0.1 \, \text{T}} \right]
\]

- Many backgrounds are eliminated simply by virtue of FASER’s location. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet.

- Leading backgrounds originate at the IP: neutrino-induced and beam-induced backgrounds.
NEUTRINO-INDUCED BACKGROUND

- If $\pi^+ \rightarrow \mu \nu$ before D1 magnet, resulting neutrinos can propagate into FASER, interact through

$$\nu_\ell N \rightarrow \ell X \quad \text{and} \quad \nu N \rightarrow \mu^\pm \pi^{\mp} X$$

- Coincident single tracks that fake double tracks: negligible

- Second process eliminated by requiring no other activity, tracks start in the detector and have high and symmetric energies

- $\nu \rightarrow K_{S,L} \rightarrow 2$ charged tracks also negligible with same cuts
BEAM-INDUCED Backgrounds: Far Location

- Particles from IP must pass through ~50 m of matter. Hadrons, electrons are stopped, only muons are relevant.

- Muon background from 2011 ATLAS study can be used to determine muon background at far location. Requiring $E_\mu > 100$ GeV, the flux is

$$\Phi \sim 10^{-3} \ \text{Hz cm}^{-2}$$

- The muon arrival times correspond to bunch crossings. Accounting for the bunch structure and assuming a timing resolution of 100 (10) ps, get ~0.1 (~0.01) coincident $\mu^+\mu^-$ pairs in 1 LHC year.

- No significant backgrounds identified for far location.
BEAM-INDUCED BACKGROUND: NEAR LOCATION

• Far more challenging environment

• Dedicated simulation using MARS/FLUKA/etc. should be used, but we can use published results to get an estimate
  Mokhov, Rakhno, Kerby, Strait (2003)

• Hadrons and electrons absorbed in the TAN

• Coincident muon background $\sim 10^8$ per LHC year. Can be greatly suppressed by requiring tracks to start in the detector and reconstruct a vertex, and requiring high and symmetric energies

• Electron background greatly reduced if electrons can be distinguished from muons
DARK PHOTON EVENT RATES

- Up to $10^5$ dark photons arrive in FASER in 300 fb$^{-1}$ in currently unconstrained regions of dark photon parameter space

\[ pp \rightarrow A' X \, , \, A' \text{ travels} \sim \mathcal{O}(100) \text{ m} \, , \, A' \rightarrow e^+e^-, \mu^+\mu^- \]
• Assuming negligible background, FASER may probe parameter space with $m_{A'} \sim 10 - 500$ MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$

• SHiP much more sensitive at very low $\varepsilon$, but much of this is excluded already. SHiP reach at high $m_{A'}$ is from direct QCD production, which we have neglected
DARK HIGGS BOSONS

• Another renormalizable coupling: Higgs portal

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

• The resulting theory contains a new scalar boson $\phi$ with mass $m_\phi$, Higgs-like couplings suppressed by $\sin \theta$, and a trilinear coupling $\lambda$
DARK HIGGS PROPERTIES

- $N_B << N_K \sim N_\pi$, but dark Higgs couples to mass, so

$$B(B \to \phi) \gg B(K \to \phi) \gg B(\eta, \pi \to \phi)$$

Turns out B and K are similar and the dominant sources of dark Higgses

- Decays to heaviest possible states
• In B decays, $p_T \sim m_B$, dark Higgs bosons are less collimated than dark photons
FASER probes a large swath of new parameter space and is complementary to other current and proposed experiments.
TRILINEAR COUPLINGS REACH

• FASER can also probe the trilinear couplings through

\[ V_{tb} \rightarrow h \rightarrow \phi \phi \] (invisible)

• This competes with

• Can get 100s of events from “double dark Higgs” production
COMPLEMENTARY PROPOSED EXPERIMENTS

SHiP

~1000 m$^3$, ~100M CHF
Alekhin et al. (2015)

MATHUSLA

~2 $10^5$ m$^3$ ~ 1 IKEA, ~$50M$
Chou, Curtin, Lubatti (2016)

CODEX-b

~1000 m$^3$
Gligorov, Knapen, Papucci, Robinson (2017)

FASER

~1 m$^3$ ~ 5 µIKEAs
Feng, Galon, Kling, Trojanowski (2017)
SUMMARY AND OUTLOOK

• The LHC has seen no new physics. Adding inexpensive, small detectors to improve discovery prospects is a good idea.

• FASER: targets light, weakly-coupled new particles at low $p_T$, runs simultaneously with the LHC program, and is small and inexpensive.

• No significant backgrounds identified for the far location; near location requires much more study.

• FASER will probe significant new regions of dark photon and dark Higgs parameter space. Other models?

• Much work to do. Hope to install prototype in LS2, install full detector in LS3 in time for the HL-LHC era.