FASER:
FORWARD SEARCH EXPERIMENT AT THE LHC

UCLA
Jonathan Feng, UC Irvine
Based on 1708.09389 and 1710.09387 with

Iftah Galon  Felix Kling  Sebastian Trojanowski

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LAMPPOST LANDSCAPE

Already Discovered

Weakly Interacting Light Particles

Strongly Interacting Heavy Particles

Impossible to Discover

Coupling Strength

10^{-3}

10^{-6}

MeV

GeV

TeV

Mass

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STRONGLY INTERACTING, HEAVY PARTICLES

- The traditional target for new physics searches: the high energy frontier

- Motivations: WIMP miracle, gauge hierarchy, anomalies (muon g-2, ...)
WEAKLY INTERACTING, LIGHT PARTICLES

• A new target for new physics searches

• Similar motivations: WIMPless miracle, anomalies (muon g-2, \(^{8}\)Be, ...)

Weakly interacting, light particles can be thermal relic dark matter, resolve anomalies, open new possibilities for experimental detection
THE IDEA

• New physics searches at the LHC focus on high $p_T$. This is appropriate for heavy, strongly interacting 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 interacting, 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
THE LIFETIME FRONTIER

Increasing worldwide interest. At CERN: LHCb, NA62, SHiP, MilliQan, MATHUSLA, 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 CASTOR, LHCf, ALFA, 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 *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
SERVICE TUNNEL TI18

SPS

Point 1

Point 1.8

ATLAS
DARK PHOTONS

• 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.,
  \[ B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma), \]
  and also through dark bremsstrahlung \( pp \to p A' X \) and direct QCD processes \( qq \to A' X \) (requires pdfs at low \( Q^2, x \))

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

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

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

• Lots of unconstrained parameter space with
  \[ m_{A'} > 10 \text{ MeV} \]
  \[ \varepsilon \sim 10^{-6} - 10^{-3} \]

• E.g., 2 representative model points: \((m_{A'}, \varepsilon) =\)
  
  \((20 \text{ MeV}, 10^{-4})\)
  \((100 \text{ MeV}, 10^{-5})\)

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: $(m_{A'}, \epsilon) = (20 \text{ MeV}, 10^{-4})$

• From $\pi^0 \rightarrow \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)

• But note rates: even after $\epsilon^2$ suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!
DARK PHOTONS IN THE FAR DETECTOR

• Now require dark photons to decay in the far detector: consider cylindrical detector with volume ~1 m²

\[ \text{on-axis: } L=400 \text{m} \]

\[ \Delta = 10 \text{ m} \]

outer radius \( R_{\text{out}} = 20 \text{ cm} \)

• 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, $R = 20$ cm captures almost all the $A'$
DARK PHOTONS IN THE NEAR DETECTOR

• Now require dark photons to decay in the near detector: detector volume only ~0.1 m²! on-axis: $L = 150\text{m}$

- Moving the detector closer $\rightarrow$ more dark photons decay in the detector, even though the near detector is much smaller

$\Delta = 5\text{m}$

outer radius $R_{out} = 4\text{cm}$
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 $\theta_{ee} \sim m_{A'} / E \sim 10 \mu$rad. After traveling ~1 m, this leads to 10 $\mu$m separation, too small to resolve, so we need a small magnetic field

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

- 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: neutrino-induced backgrounds 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

- Depends on exact configuration. At 400m, line of sight is 2.6 m from beam, outside tunnel. With sufficient shielding, hadrons, electrons are stopped, only muons are relevant.

- A 2013 ATLAS study based on 2011 data 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 $\sim 0.1$ ($\sim 0.01$) coincident $\mu^+\mu^-$ pairs in 1 LHC year.

- No significant backgrounds identified for far location.
BEAM-INDUCED BACKGROUNDs: 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

$$pp \rightarrow A' X, \quad A' \text{ travels } \sim \mathcal{O}(100) \ m, \quad A' \rightarrow e^+ e^-, \mu^+ \mu^-$$
DARK PHOTON REACH

• 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

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

• 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

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

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

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

\[ V_{tb} \xrightarrow{\phi} W^+ \xrightarrow{h} V_{ts} \xrightarrow{\phi} \bar{s} \]

• This competes with \( h \rightarrow \phi \phi \) (invisible)

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

SHiP

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

FASER

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

MATHUSLA

~200,000 m$^3$ ~ 1 IKEA, ~$50$M
Chou, Curtin, Lubatti (2016)

CODEX-b

~1 m$^3$ ~ 5 $\mu$IKEAs
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 ATLAS/CMS, and is small and inexpensive.

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

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

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