FASTER AND OTHER OUTPOSTS ON THE LIFETIME FRONTIER

New Probes for Physics Beyond the Standard Model, KITP, Santa Barbara

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Based on 1708.09389 and 1710.09387 with

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LAMPPOST LANDSCAPE

Strongly Interacting
Heavy Particles

Weakly Interacting
Light Particles

Impossible to
Discover

1

10^{-3}

10^{-6}

MeV  GeV  TeV

Coupling Strength

Mass
STRONGLY INTERACTING, HEAVY PARTICLES

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

• Motivations: WIMP miracle, gauge hierarchy, anomalies (muon g-2, ...)

Hagiwara et al. (2017)
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 existing anomalies, open new possibilities for experimental detection
FASER: 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 \(~\text{isotropically}\)

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

• 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

• Very popular, many interesting experiments: LHCb, Belle-II, NA62, SHiP, SeaQuest, MilliQan, MATHUSLA, Codex-b, and many others

• FASER: ForwArd Search ExpeRiment. “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 and Backgrounds

• Event Rates and Reach

• New Physics Example: Dark Higgs Bosons

• Recent Progress

• Summary and Outlook
FASER LOCATION

- We want to place FASER along the beam collision axis
  - Far location: ~400 m from IP, after beams curve, ~3 m from the beams
  - Near location: 150 m, after TAN, between the beams

- Here, focus on far location, assume FASER is exactly on-axis

- If ATLAS/CMS beams cross at 285 (590) μrad in vertical/horizontal plane, far location shifts by 6 (12) cm
SERVICE TUNNEL TI18

SPS

Point 1

Point 1.8

FASER

ATLAS
• 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

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

• 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 to \( e^+e^- \), \( \mu^+\mu^- \) for \( m_{A'} > 2 m_\mu \), other charged pairs

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

• TeV energies at the LHC \( \rightarrow \) huge boost, decay lengths of \( \sim 100 \text{ m} \) are possible for viable and interesting parameters
DARK PHOTON STATUS

• Low $\varepsilon \rightarrow$ fixed target constraints, high $\varepsilon \rightarrow$ collider, precision constraints

• But still lots of open parameter space with $m_{A'} > 10$ MeV
  $\varepsilon \sim 10^{-6} - 10^{-3}$

• E.g., 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 $p_T \sim \Lambda_{\text{QCD}}$
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 $\pi^0 \to \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
  • But note rates: even after $\varepsilon^2$ suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!
DARK PHOTONS IN FASER

• Now require dark photons to decay in FASER: 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, $R = 20$ cm captures almost all the $A'$.
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 \(\rightarrow\) a tracker-based technology.

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

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

Many backgrounds are eliminated simply by virtue of FASER’s location. Particles from IP must pass through \(\sim 50\) m of matter to get to FASER. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet.

Leading backgrounds: neutrino-induced backgrounds and beam-induced backgrounds.
BACKGROUNDs

• If $\pi^+ \to \mu \nu$ before D1 magnet, neutrinos can propagate into FASER, produce charged tracks through CC interactions

$$\nu_\ell N \to \ell X$$

$$\nu N \to \mu^\pm \pi^\mp X$$

• Coincident single tracks that fake double tracks are negligible; second process eliminated by requiring no other activity, tracks start in the detector and have high and symmetric energies

• Beam-induced backgrounds currently being investigated by CERN FLUKA study
• Up to $10^5$ dark photons decay in FASER in 300 fb$^{-1}$ in parameter regions with $m_{A'} \sim 10 - 500$ MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$

• Note that at upper $\varepsilon$ boundary, rates are extremely sensitive to $\varepsilon$ and the reach is quite insensitive to background, provided it is known
DARK HIGGS BOSONS

• Another renormalizable coupling: Higgs portal

\[ h^\dagger h \phi_h^\dagger \phi_h \]

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

\[ \mathcal{L} = -m_\phi^2 \phi^2 - \sin \theta \frac{m_f}{v} \phi \bar{f} f - \lambda vh\phi\phi + \ldots \]
DARK HIGGS PROPERTIES

• Dark Higgs couples to mass, so favors decays to heaviest possible states

\[ B(B \rightarrow \phi) \gg B(K \rightarrow \phi) \gg B(\eta, \pi \rightarrow \phi) \]

• In contrast to fixed target experiments, lots of COM energy to produce \( \sim 10^{15} \) B mesons, excellent probe of new physics that couples to 3\(^{rd}\) generation

• 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

• 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 + beam
Alekhin et al. (2015)

MATHUSLA

~200,000 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)
RECENT PROGRESS

• Theory: see also studies of flavor-specific scalar mediators (Batell, Freitas, Ismail, McKeen, 1712.10022), HNLs (heavy neutral leptons, sterile neutrinos) (Kling, Trojanowski, 1801.08947; Helo, Hirsch, Wang, 1803.02212), other gauge bosons (Bauer, Foldenauer, Jaeckel, 1803.05466), ALPs (axion-like particles) and other models in progress

• Experiment: FASER, MATHUSLA, CODEX-b, MilliQan have joined the CERN Physics Beyond Collider study. A few examples of recent progress follow. Thanks to Jamie Boyd, Dave Casper, Francesco Cerrutti and FLUKA team, Paolo Fessia, Shih-Chieh Hsu, and Mike Lamont.
FASER: LOCATION

FASER

ATLAS
FASER: LOCATION
FASER: GEANT STUDY UNDERWAY

- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.
Plot from F. Cerutti’s talk at Chamonix 2018.
Comparing FLUKA and BLM data for 2015 fill (reasonable agreement).
FASER location close to Q12 – lucky low background from collision debris, background peaks at Q11/Q13 due to dispersion at these points (these are +/-~50m along ring from FASER location). (In theory this depends on the optics, but should also be valid for HL-LHC)
SUMMARY AND OUTLOOK

• The LHC has seen no new physics. Adding supplementary detectors to improve discovery prospects is a good idea, and there are many proposals targeting the lifetime frontier.

• FASER targets light, weakly-coupled new particles at low $p_T$, runs simultaneously with ATLAS/CMS, is small, fast, and cheap.

• FASER has significant discovery potential for dark photons, dark Higgs bosons, heavy neutral leptons (sterile neutrinos), ALPs, other gauge bosons, and many other new particles.

• Possible timeline: install prototype in LS2 (2019-20) for Run 3 (150-300 fb$^{-1}$), install full detector in LS3 (2023-25) for HL-LHC (3 ab$^{-1}$).