Searches at the LHC including FASER

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Outline

1. Introduction to dark sectors
2. Long lived particles at the LHC
3. Dark photons at LHCb
4. FASER
5. Conclusion/Outlook (inc. future projects)
So far at the LHC we have only seen (what looks like) the SM Higgs (and some tantalising anomalies).

The existence of something like dark matter seems all but confirmed, but WIMPs have eluded us so far.

The next energy scale could be at the Planck scale.

→ Maybe the answers lie at lower energies $\lesssim \mathcal{O}(10\text{ GeV})$, hidden by feeble interactions?
Searching for dark sectors

While the dark sector may be very rich, there are a finite number of portal terms which can link it to the SM:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{DS}} \]

The CERN Physics Beyond Collider BSM working group defined several benchmark models for each portal to compare current and future experiments: [CERN-PBC-REPORT-2018-007]

› BC1-3: **Vector portal** (visible, invisible, milli-charged particles)
› BC4-5: **Scalar portal** (dark Higgs, +quartic coupling)
› BC6-8: **Neutrino/fermion portal** (\(e, \mu, \tau\))
› BC9-11: **Axion-like particle portal** (photons, fermions, gluons)
Dark photons

Kinetic mixing with SM photon with suppression factor $\epsilon$:

$$\epsilon e A'_\mu J^\mu_{EM}$$

- Production identical to $\gamma^* \to$ QCD, light meson decays, Drell-Yan
- Decay to visible particles if decay to dark matter not dominant/allowed ($m(A') < 2m(\chi)$)
- Mostly forward for light dark photons: LHCb and FASER ideally placed
- Well motivated as carrier of a new force and candidate for a mediator of dark matter
Active and growing community studying long lived particles at the LHC
  › Regular workshops
  › Bringing together experimentalists and theorists across (current and future) experiments

http://cern.ch/longlivedparticles
Dark sector signatures at ATLAS and CMS

- Dark sectors can result in a variety of signatures
- Many are free of SM background, but may require some creativity to reconstruct
- Focus on signatures reduces model-dependence
- Can benefit from upgrades:
  - CMS timing layer [CERN-LHCC-2017-027]
  - ATLAS ITk [ATLAS-TDR-030]

Fig: Heather Russel, 2017
Selected LHC results

Pair produced dark photons

Prompt

Displaced

[PLB 796 (2019) 131-154]

And many more: ATLAS and CMS world-leading for higher-$p_T$ LLP searches, see e.g. [arXiv:1903.04497]

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[arXiv:1909.01246]
 › Less luminosity, **but unique capabilities**
 › Forward coverage favouring light particles: 
   \[ 2 < \eta < 5 \]
 › Specialised detector:
   › Very good muon efficiency and momentum resolution
   › Very good primary and secondary vertex separation resolution
   › Good particle ID
   › Can trigger low-\(p_T\) muons: 1.5 GeV
 › Velo upgrade and Real Time Analysis (RTA) will build on these strengths in run 3
LHCb: Search for $A' \rightarrow \mu \mu$

- Update of [PRL 120 (2018) 061801], proposed in [PRL 116, 251803 (2016)]
- Two searches: prompt + displaced ('long-lived')
- Using full run 2 sample: 5.5 fb$^{-1}$
- Fully data-driven using $\gamma^* \rightarrow \mu \mu$ as reference
- Assuming only visible decays, limits can be reinterpreted for combination of visible+invisible decays (or dark scalars) [JHEP 1806 (2018) 004]
A’ indistinguishable from γ* in production and decay: can exploit this to cancel efficiencies and systematics

- Scan mass range between dimuon threshold up to 70 GeV for A’ signal, vetoing SM resonances
- Fit the \( \min[\chi^2_{IP}(\mu)] \)-distribution to distinguish between prompt-\( \mu\mu \) and background
- No excess found: set 90% CL limits
LHCb: Search for $A' \rightarrow \mu\mu$ (long-lived)

- Select dimuon pairs inconsistent with originating from any primary vertex
- Scan $m(A')$ and $\tau(A')[m(A'), \epsilon^2]$
- Background from photon conversion controlled using decay kinematics and a high-precision 3D material map of the VELO
- No excess found: set 90% CL limits

90% CL upper limit on $n^X_{ob}[m(A'), \epsilon^2] / n^X_{ex}[m(A'), \epsilon^2]$
LHCb: Search for $A' \rightarrow \mu\mu$

- Prompt search places most-stringent constraints on dark photons with $214 < m(A') < 740$ MeV and $10.6 < m(A') \lesssim 30$ GeV
- Long-lived search covers unique region between collider and beam-dump experiments inaccessible elsewhere
- $+15$ fb$^{-1}$ expected in run 3 with upgraded detector and trigger will significantly extend the reach of the search
- Could be complemented by a search for $D^* \rightarrow D^0 A' (\rightarrow ee)$ [PRD 92, 115017 (2015)] to reach lower masses

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8th LHC experiment: funded and approved for run 3

- 480 m from ATLAS interaction point in TI12
- Charged particles are deflected by LHC magnets, neutral particles absorbed by rock
- Despite angular acceptance of 0.2 mrad, large yield of very boosted light mesons
› Look for displaced vertex of two oppositely charged tracks: e.g. $A' \rightarrow ee$

› Extremely boosted signal leading to nearly collinear decay products

› Scintillator/Pb veto for charged particles and photons produced upstream of the detector

› Fine-grained trackers for vertexing

› ECAL can measure energy and reconstruct photons
FASER sensitivities: Dark Photon and ALP

the FASER sensitivities: Dark Photon and ALP

these and other models: [PRD 99, 095011]

Run 3: 150 fb⁻¹

Estimate zero background based on FLUKA, in situ measurements → 3 events for discovery

Assume 100% detector/reconstruction efficiency

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Proposed upgrade of FASER for the HL-LHC

<table>
<thead>
<tr>
<th></th>
<th>FASER</th>
<th>FASER2</th>
</tr>
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<tbody>
<tr>
<td>decay volume length/metre</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>radius/metre</td>
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<td>1</td>
</tr>
<tr>
<td>angular acceptance/mrad</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>$\int \mathcal{L} dt/fb^{-1}$</td>
<td>150</td>
<td>3000</td>
</tr>
</tbody>
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There is also a proposed emulsion detector for neutrino physics upstream of FASER: FASER$\nu$

[arXiv:1908.02310]
Future experiments

› MilliQan [arXiv:1607.04669] is designed to look for milli-charged particles (BC3) produced at the CMS interaction point, data taken with prototype in 2018
› SND@LHC [info soon] combines nuclear emulsions and active detectors to search for scattering of neutral particles, allowing study of neutrinos and light dark matter
Conclusion & Outlook

- Dark sector and long lived particles under active study at the LHC
- Reach complementary to beam dumps and non-accelerator searches
- Run 3 and HL-LHC will significantly push sensitivity of current searches—particularly for background-free searches
- New search ideas and new experiments for run 3 and beyond: a lot to look forward to!