Dark sector searches with the ATLAS and CMS experiments

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On behalf of the ATLAS and CMS collaborations

8th annual conference on Large Hadron Collider Physics
25-30th May 2020

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Image: https://www.symmetrymagazine.org/article/voyage-into-the-dark-sector
The hidden sector…

• The “dark sector” consists of particles that do not couple to known SM fields, but interact through a mediator:
  • Dark photons (vector portal), dark scalars (Higgs portal), ALPs (axion), sterile neutrinos…
  • Mediators can provide “portal” to DM candidates or be candidates themselves.

• This talk:
  • Searches for dark photons
  • Collider constraints on scalar dark energy
  • See other talks for dark sector searches with more “unconventional signatures” e.g. dark QCD sector (emerging jets), dark scalars (displaced jets).
Dark photons, $A'$

Add a $U(1)_D$ where massive dark gauge boson ($A'/Z_D/\gamma_D$) kinetically mix with SM photon

**Parameters:** kinetic mixing term, $\epsilon$, and $m_{A'}$

Search strategies

- **Prompt, resolved decay** products: $Z_DZ_D/Z_DZ^*$
- **Prompt, collimated decay**:
  - "lepton jets" (LJ)
  - Displaced muons
- **Medium lifetime**,
  - resolved decays:
  - Displaced muons
- **Medium lifetime**, collimated decays:
  - Displaced LJ
- **ATLAS/CMS detector stable lifetimes:**
  - MET signature

<table>
<thead>
<tr>
<th>Mass</th>
<th>Lifetime (depends on $m_{A'}$ and $\epsilon$)</th>
<th>$\gamma_d$ Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prompt, resolved decay products: $Z_DZ_D/Z_DZ^*$</td>
<td>$\gamma_d$ Mass [GeV]</td>
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<td>Prompt, collimated decay: &quot;lepton jets&quot; (LJ)</td>
<td>$e^+e^-$</td>
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<td>Medium lifetime, resolved decays: Displaced muons</td>
<td>$\mu^+\mu^-$</td>
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<tr>
<td></td>
<td>Medium lifetime, collimated decays: Displaced LJ</td>
<td>Hadrons</td>
</tr>
</tbody>
</table>

arXiv:1002.2952
Lepton jets

- Search for collimated production of leptons: “lepton jets”.
- Benchmark model(s): Higgs portal production and vector portal decay (FRVZ model).
- Dark fermions ($f_{d2}$) produced in $H$ decays, which decay to $\gamma_D$ (via dark scalar, $s_d$) and HLSP.

Model 1

Model 2

- Different experimental signatures depending on lifetime of dark photon.
- Mean lifetime,

$$\tau \propto \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{\gamma_D}} \right)$$

- Prompt and displaced lepton jet signatures

HLSP = hidden lightest stable particle (fermion)
Lepton jets

- Interpreted in terms of limits on the kinetic mixing parameter, $\epsilon$, and $m_{A'}$.
- Limits are shown for $B(h \rightarrow 2\gamma_D + X)$ in range 1–20%.

For details see talk on LLPs by M. Saito
Dark photons in ZH decays

- Search for $Z(\rightarrow \ell\ell)H(\rightarrow \gamma\gamma_D)$ production, where $\ell = e, \mu$.
- Massless dark photon, $m(\gamma_D) = 0$, couples to Higgs boson through charged dark sector.
- Dominant backgrounds normalised in control regions.

| $m_\ell - m_Z$ | < 15 GeV

\[ E_T^{\text{miss}} > 110 \text{ GeV} \]

$D$istinguish signal from background with $m_T$ (endpoint at $m_T \sim m_H$ for signal)

\[ m_T = \sqrt{2p_T^{\text{miss}} E_T^{\gamma} [1 - \cos(\Delta \phi_{p_T^{\text{miss}}, E_T^{\gamma}})]} \]
Dark photons in ZH decays

- Binned maximum-likelihood fit to $m_T$ in signal and control regions.
- Interpret in terms of limit on Higgs branching fraction: $B(H \rightarrow \text{inv. } + \gamma)$
- Assuming SM ZH production, upper limit on $B$ of 4.6%.
Higgs to light BSM bosons

- Search for \( H \to ZZ_D / Z_D Z_D \to 4\ell \)
- \( 2e, 2e2\mu, 4\mu \) for \( 15 < m_{Z_D} < 62.5 \text{ GeV} \)
- \( 4\mu \) for \( 1 < m_{Z_D} < 15 \text{ GeV} \)
- Dark vector bosons produced via hypercharge / Higgs (S) portal models
- Reconstruct \( Z/Z_0 \) bosons from lepton quadruplets, with veto on quarkonia resonances.
- Signal region defined by:
  \[ m_{4\ell} \in [115,130] \text{ GeV} \]
Higgs to light BSM bosons

- Results interpreted in terms of upper limits on H branching fraction for benchmark models.
- **Higgs portal model**: related to Higgs mixing parameter, $\kappa$
- **Hypercharge portal**: related to kinetic mixing, $\epsilon$, and mass-mixing, $\delta$, parameters
Higgs to light BSM bosons

- Search for $H \rightarrow 4\mu + X$ with dark SUSY benchmark model:
  - $n_1 =$ lightest non-dark neutralino, and $n_D =$ a dark neutralino that is undetected.

- Signal region defined by $m(\mu\mu)_1 \sim m(\mu\mu)_2$:
  $$|m(\mu\mu)_1 - m(\mu\mu)_2| < 5\sigma(m_{\mu\mu})$$

- Low background contributions from:
  - $b\bar{b}$ (decays to low-mass quarkonia resonances), double $J/\psi$ decays and electroweak processes.
Higgs to light BSM bosons

- Upper limits set on product of H production cross section and BR of Higgs boson (cascade) decay to a pair of dark photons:
  \[ \sigma(pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D) \times B(\gamma_D \rightarrow 2\mu) \]

- Interpreted in terms of limits on the kinetic mixing parameter, \( \epsilon \), and \( m_{A'} \).

- Limits are shown for \( B(h \rightarrow 2\gamma_D + X) \) in the range 0.1–40\%.
Search for narrow $\mu^+\mu^-\pm$ resonance

- Sliding window bump-hunt in $m_{\mu\mu}$ spectrum.
- Dedicated *data scouting* triggers:
  - Record data at a higher rate with a reduced amount of trigger-level information.
  - Increases acceptance below $m_{\mu\mu} < 45$ GeV
- Events categorised based on $m_{\mu\mu}$ resolution:
  - $\sim1\%$ in barrel $|\eta| < 0.9$
  - $\sim3\%$ in endcaps $|\eta| > 1.2$

![Graph showing data from CMS and simulated dark photon signal](image)
Search for narrow $\mu^\pm \mu'^\mp$ resonance

- Model-independent upper limits and dark photon interpretation with upper limits on $e^2$ as a function of $m_{A'}$ for $11.5 < m_{A'} < 200$ GeV.
Dark energy

- Dark energy = potential solution to accelerating expansion of the universe.
- Typically studied through cosmological observations and laboratory experiments searching for additional gravitational forces.

- Studied for the first time at a collider with EFT implementation the **Horndeski theories**
- Introduce a dark energy scalar, which if stable on collider scales would have experimental signature of MET.
Dark energy

- Set limits on least suppressed operators:
  - $\mathcal{L}_1 =$ coupling proportional to mass of fermion, $t\bar{t} + E_T^{\text{miss}}$
  - $\mathcal{L}_2 =$ coupling scales with momentum transfer, $j + E_T^{\text{miss}}$

- Constraints on suppression scale, $M$.
- EFT valid for $Q_{tr} < g_* M$, where $g_* =$ effective coupling related to UV completion of EFT ($g_* < 4\pi$).
Summary

• Many ongoing searches for dark sectors with ATLAS and CMS.
• Variety of experimental signatures requires broad experimental program.
• Full 2015-2018 data still being analysed, expect many new results in the coming year!

See other related talks/posters:
• Talk: Searches for unconventional signatures and long-lived particles (Bhawna Gomber)
• Talks: Searches for Dark Matter in ATLAS (Jon Burr), Searches for Dark Matter in CMS (Varun Sharma)
• Talk: DM interpretations of heavy resonances and BSM-Higgs searches in ATLAS and CMS (Mariia Savina)
• Talks: Searches for long-lived particles in CMS (Allison Reinsvold Hall), Searches for long-lived particles in ATLAS (Masahiko Saito)
• Poster: Searches for dark photon with the ATLAS detector at the LHC (Hassnae El Jarrari)
Backup
Dark photon collider search reach

- Dark photon collider search reach
- EW precision
- $e^+e^-$ colliders, B factories
- Accessible at hadron colliders
- Beam-dumps
- Supernova cooling
Higgs to scalars

- Search for pair-production of long-lived neutral particle produced by a Higgs boson or a heavy scalar.
- Signatures of displaced jets in:
  - The muon spectrometer
  - The inner detector + muon spectrometer
  - The hadronic calorimeter
- Limits placed on $\sigma \times B$ vs. $c\tau$.  

\[
\begin{align*}
\text{ATLAS} & \\
\text{Obs.} & \\
\text{Exp.} & \\
\text{ID} & \text{[33.0 fb}^{-1}] \\
\text{CR} & \text{[10.8 fb}^{-1}] + \text{MS2 [36.1 fb}^{-1}] \\
\text{ID+CR+MS2} & \\
\end{align*}
\]