Dark Higgs and Exotic Higgs Decay Searches at Colliders

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Dark Sectors Workshop
SLAC
April 28-30, 2016

https://indico.cern.ch/event/507783/
BaBar Dark Higgs Search

- New possible channel with dark Higgs and dark photons
  \[ e^+e^- \rightarrow A'h', h' \rightarrow A'A' \]
- \( A' \) decays to lepton pairs, pion pairs, or other (less pure)
- Backgrounds determined from same-sign data
- 6 events observed, consistent with backgrounds
  (3 possible pairings of \( h' \rightarrow A'A' \) per event)
BaBar Dark Higgs Search

- New possible channel with dark Higgs and dark photons
  \[ e^+e^- \rightarrow A'h', h' \rightarrow A'A' \]
- \( A' \) decays to lepton pairs, pion pairs, or other (less pure)
- Set limits on the dark gauge couplings, vs. \( h', A' \) masses
LHC era is just starting!

- 7 TeV in 2010/11, ~5/fb ... 8 TeV in 2012, ~21/fb
- 13 TeV in 2015, ~3/fb ... 2016, just restarted data taking
LHC: The intense energy frontier

Billions of Z bosons per year
Millions of H bosons per year

40 million p-p collisions / second!

1000 Hz of jets, pT>100 GeV

2 Hz of Z->ee or µµ

1 Higgs / minute

1 Higgs->ZZ->eeµµ / week!
Higgs, finally!

Combination of ATLAS+CMS mass measurements in
- $H \rightarrow \gamma\gamma$
- $H \rightarrow 4l$

Aim to be agnostic to the signal yields: 3 signal strength parameter $\mu$ for
- $gg \rightarrow H \rightarrow \gamma\gamma$
- VBF $H \rightarrow \gamma\gamma$
- $H \rightarrow 4l$

simultaneously determined from data (profiled)
H → Z_{(d)} Z_{d} → 4l (ATLAS)

Higgs as a portal to the hidden/dark sector

Light exotic gauge boson \( Z_{d} \): \( m_{Z_{d}} < m_{Z} \)

Based on SM Higgs to 4l analysis
Model independent analysis

115 GeV < \( m_{4l} \) < 130 GeV

Look for excess in \( m_{34} \)
\( m_{12} \) closest to \( m_{Z} \)

Look for excess in \( m_{ll} \)
\( |m_{12} - m_{34}| = \text{min} \)

ATLAS (8 TeV)
arXiv:1505.07645
Submitted to PRD

\[ n(H \to 4\ell) = n(4\ell) - n(ZZ^*) - n(tt) - n(Z + \text{jets}). \]

BGs: \( H \to ZZ^* \to 4l \) determined from data, \( ZZ^* \) (MC), \( tt \), \( Z + \text{jets} \) (DD)

BGs: \( \text{(MC)} \) \( H \to ZZ^* \to 4l \), \( ZZ^* \to 4l \)
\( m_{Z_{d}} - m_{ll} < 5/3/4.5 \text{ GeV} - 4e/4\mu/2e2\mu \)
**H\rightarrow Z_{(d)} Z_{d} \rightarrow 4l** (ATLAS)

**Observed data well described by SM expectation**

**Upper limits set**

- **H\rightarrow ZZ_{d} \rightarrow 4l**

  \[ R_{B} = \frac{BR(H \rightarrow ZZ_{d} \rightarrow 4\ell)}{BR(H \rightarrow 4\ell)} \]

  \[ m_{Z_{d}} [GeV] \]

  - 95% CL limits: \( R_{B} < 0.4 \ (0.2) \)

- **H\rightarrow Z_{d} Z_{d} \rightarrow 4l**

  \[ \mu_{d} = \frac{\sigma \times BR(H \rightarrow Z_{d} Z_{d} \rightarrow 4\ell)}{[\sigma \times BR(H \rightarrow ZZ^{*} \rightarrow 4\ell)]_{SM}} \]

  \[ m_{Z_{d}} [GeV] \]

  - 2 \((4e, 4\mu)\) observed events with significance 1.7 \(\sigma\)

- 95% CL limits: \( BR(H \rightarrow ZZ_{d} \rightarrow 4\ell) < (1-9) \times 10^{-5} \)

- 95% CL limits \( BR(H \rightarrow Z_{d} Z_{d} \rightarrow 4\ell) : (2-3) \times 10^{-5} \)
CMS search for $H \rightarrow \text{muon-jets}$

- Select 4-muon events
- Look for di-muon invariant mass bump at low mass in *isolated* muon pairs

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12012
CMS search for $H \rightarrow \muon$-jets

- Look for two mu+ mu- pairs to have the same mass
- Exclude SM H decays with <1% BR to muon-jets

**Dark SUSY 95% CL Limit:**
- $m_{\gamma_D} = 0.4 \text{ GeV}/c^2$
- Prediction with $\sigma(pp \rightarrow h) = \sigma_{\text{SM}}$

$B(h \rightarrow 2\nu_l) = 1\%$, $B(n_1 \rightarrow \gamma_D + n_D) = 50\%$
and $B(\gamma_D \rightarrow 2\mu) = 45\%$

**Sensitive to decays ~40 cm displaced!**
CMS search for $H \rightarrow \text{dimuon-jets}$

- **Recently updated with 8 TeV dataset!**
  - NMSSM Higgs sector: 3 CP-even neutral Higgs bosons $h_{1,2,3}$, 2 CP-odd neutral Higgs bosons $\alpha$ and a pair of charged Higgs bosons $h^\pm$
  - $h_{1,2} \rightarrow 2\alpha_1$, $h_1$ or $h_2$ can be the boson observed at 125 GeV
  - $\alpha_1 \rightarrow 2\mu$, 2 pairs of isolated muons (di-muons), $m_{1\mu\mu} \approx m_{2\mu\mu}$ within detector resolution

Light boson masses in the range $2m_\mu < m_\alpha < 2m_\tau$ (0.25-3.55 GeV)

*1 event obs. 2.2±0.7 SM exp.*

BGs dominated by $b\bar{b}$ and $J/\psi$ pair production

- 95% CL upper limits for NMSSM on
  - $\sigma(pp \rightarrow h_{1/2} \rightarrow 2\alpha_1) B^2(\alpha_1 \rightarrow 2\mu)$ as a function of
    - $m_{h_1}$ ($86 < m_{h_1} < 125$ GeV) and
    - $m_{h_2}$ ($m_{h_2} > 125$ GeV)
  - Limits compared to predicted rate (solid curve), with simplified scenario
    - $\sigma(pp \rightarrow h_i \rightarrow 2\alpha_1) = 0.008 \sigma_{SM}$
ATLAS Search for $H \rightarrow \text{ditau-jets}$

NMSSM CP-odd scalar assumed to be light

$H \rightarrow a_1 a_1 \rightarrow 2\mu 2\tau$ offers advantages wrt $4\tau$
despite the smaller BR

use $m_{\mu\mu}$ as final observable

$\tau_{\text{lep}}$ decay

Boosted $a_1$ decays: special $\tau_{\text{had}}$ ID

search performed in range $2m_\tau < m_{a_1} < 50$ GeV

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ATLAS Preliminary

![Graphs and diagrams showing experimental results and theoretical predictions for $H \rightarrow \text{ditau-jets}$]
Other LHC Rich Hidden Sector Searches

- Rich dark sector with long-lived dark-pions ... **Emerging Jets**

What are emerging jets?

A novel LHC signature where dark or hidden sector quarks decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object. Pair-produced dark quarks then give rise to neither prompt jets nor a pair of displaced jets pointing to the same displaced vertex, but to **emerging jets**.

[Diagram of emerging jets]

ArXiv:1502.05409

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Other LHC Rich Hidden Sector Searches

Tracks
- Red: Truth
- Blue: Reconstructed

Clearly some challenges by-eye: “Where” is the emerging jet? Is some measure of “emergingness” of a standard jet possible if the displaced vertices are so broadly distributed?

Event-level quantity possibly more manageable and powerful enough (TBD — still running)

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Hidden Sector

- $\gamma_d$ accompanied by zoo of other “hidden” particles?
- $G_{dark}$ bigger than $U'(1)$?

A Conceptual Diagram

- Production of multiple boosted $\gamma_d$ from long decay chains $\rightarrow$ multiple displaced LJs

[D. Ventura, ATLAS]
Run 1 Results: ATLAS

Targets $\gamma_d$ decays beyond pixel detector, up to muon spectrometer

- Muon pairs: have only spectrometer information
- Electron / pion pairs: appear as jets in calorimeters

- LJ categorization:

  - LJ TYPE0: only muons
  - LJ TYPE1: muons + jets
  - LJ TYPE2: only jets

[arXiv:1409.0746]
New Displaced Dark Photon Searches

Run 1 Results: ATLAS

Events (+/- stat. +/- sys.)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Cosmic rays</th>
<th>Multi-jets (ABCD)</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>119</td>
<td>40 ± 11 ± 9</td>
<td>70 ± 58 ± 11</td>
<td>110 ± 59 ± 14</td>
</tr>
</tbody>
</table>

FRVZ benchmark model (with gg fusion):

<table>
<thead>
<tr>
<th>FRVZ model</th>
<th>Excluded cτ [mm] BR(10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → 2γ_d + X</td>
<td>14 ≤ cτ ≤ 140</td>
</tr>
<tr>
<td>H → 4γ_d + X</td>
<td>15 ≤ cτ ≤ 260</td>
</tr>
</tbody>
</table>

[arXiv:1409.0746]
**Run 1 Results: CMS**

**Targets** $\gamma_d$ decays within the pixel detector, into muon LJs only

- **Trigger:** dimuon, $p_T > 17$ GeV (leading), $p_T > 8$ GeV (subleading)
- **Selection criteria:**

**Model-independent 95% CL:**

$$\sigma(pp \rightarrow 2a + X) B^2(a \rightarrow 2\mu) \alpha_{gen} \leq 0.24 + 0.09 \exp\left(-\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2}\right) = \frac{N(m_{\mu\mu})}{(L\bar{r})}$$

**Dark SUSY benchmark model (with gg fusion):**

\begin{align*}
\alpha &= \text{kinematic} \& \text{geometrical acceptance} \\
\varepsilon &= \text{selection efficiency} \\
\Gamma &= \varepsilon_{\text{data}} / \alpha_{\text{gen}}
\end{align*}

<table>
<thead>
<tr>
<th>$m_{\gamma_D}$ [GeV]</th>
<th>$c\tau_{\gamma_D}$ [mm]</th>
<th>0</th>
<th>0.25</th>
<th>0.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{sim}}$ [%]</td>
<td>8.85 $\pm$ 0.12</td>
<td>1.76 $\pm$ 0.05</td>
<td>0.23 $\pm$ 0.03</td>
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<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>14.32 $\pm$ 0.14</td>
<td>2.7 $\pm$ 0.06</td>
<td>0.31 $\pm$ 0.03</td>
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<td></td>
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<tr>
<td>$\varepsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.62 $\pm$ 0.01</td>
<td>0.65 $\pm$ 0.02</td>
<td>0.74 $\pm$ 0.13</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{\gamma_D}$ [GeV]</th>
<th>$c\tau_{\gamma_D}$ [mm]</th>
<th>0</th>
<th>1.0</th>
<th>0.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{sim}}$ [%]</td>
<td>6.13 $\pm$ 0.23</td>
<td>4.73 $\pm$ 0.07</td>
<td>1.15 $\pm$ 0.04</td>
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<td>$\alpha_{\text{gen}}$ [%]</td>
<td>8.89 $\pm$ 0.28</td>
<td>6.98 $\pm$ 0.09</td>
<td>1.68 $\pm$ 0.05</td>
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<tr>
<td>$\varepsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.69 $\pm$ 0.03</td>
<td>0.68 $\pm$ 0.01</td>
<td>0.68 $\pm$ 0.03</td>
<td></td>
<td></td>
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</tbody>
</table>

[arXiv:1506.00424] $m_{n_1} = 10$ GeV, $m_{n_D} = 1$ GeV
New Displaced Dark Photon Searches

Run 1 Results: ATLAS + CMS

Combined results for $\gamma_d$ interpretation:

- Complementary coverage in $\gamma_d$ parameter space
- In regions other experiments were unable to reach!
  - ATLAS & CMS limits have extra parameter (BR for $h \to$ hidden)

$\text{CMS (95\% CL)}$

$\text{ATLAS (90\% CL)}$

$\text{pp} \to h \to n_1 n_1 \to \gamma_D Y_D n_D n_D$

$\mathcal{B}(h \to \gamma_D Y_D + X) = 0.1 - 40\%$

[arXiv:1506.00424]
New LHC Experiment: MilliQan

- Milli-charged particles → massive, with electric charge $\sim 10^{-3}\ e$
- Easy to add to SM: “dark U(1)” (with massless dark photon) kinetic mixing → dark fermion milli-charged under SM
- Currently weak direct limits for fermion mass $> 100\ \text{MeV}$
- $\sim 1$ photo-electron observed per 1m long scintillator
- Require triple-incidence in time window
- Moving forward in CMS “drainage gallery”
750 Pound Elephant in the Room

- Let's not forget the $\sim 3\sigma$ diphoton excess at both ATLAS and CMS
- We'll have enough data by $\sim$July to either confirm or refute
- What if it is real?
- Rich dark sector connections? Analyses we should plan?
Lepton jets

• Dark photons are *boosted*

Create “lepton jets”: pairs of collinear electrons or muons

![Diagram of lepton jets](image)

Probably prompt decays, but maybe not...

\[
\tau_{2\text{-body}} \sim \frac{1}{\alpha^2 m_{\gamma'}} = 2.7 \times 10^{-6} \text{ cm} \left( \frac{\text{GeV}}{m_{\gamma'}} \right) \left( \frac{10^{-3}}{\epsilon} \right)^2
\]
SUSY lepton jets

- LSP decays to dark sector?! \[ \text{BR} = 1! \]

- Changes signature of SUSY
  - Less MET
  - Two *dark* photons (lepton jets)

\[ \tau_{\text{LSP} \rightarrow h + \bar{h}} \sim \left( \frac{\alpha_y^{\text{dark}} f_B^2 e^2 M_{\text{LSP}}}{\epsilon} \right)^{-1} \]

\[ = 7 \times 10^{-19} \text{s} \left( \frac{100 \text{ GeV}}{M_{\text{LSP}}} \right)^2 \left( \frac{0.01}{\alpha_y^{\text{dark}}} \right) \left( \frac{1.0}{f_B} \right)^2 \left( \frac{10^{-3}}{\epsilon} \right)^2 \]

Electroweak production is small but still observable

Possibly large production rate for colored SUSY particles...
SUSY lepton jets at ATLAS

Simulated muon-jet SUSY signal event
SUSY lepton jets at ATLAS

- Search for events with:
  - 2 prompt muon lepton-jets
  - 2 prompt electron lepton-jets
  - 1 prompt 4-muon lepton-jet
- Custom lepton-jet identification to separate from QCD jets
- Backgrounds measured in control regions
- Dark photon also could give peak at dark photon mass
- No excess observed

Jet prob bkgd method: $14.55^{+0.23}_{-0.04}$, 2.2 ± 0.9 events
SUSY lepton jets at ATLAS

- Cross-sections excluded for various dark-photon masses and radiation parameters $< \sim 0.02 - 0.1$ pb

- Constrains strong-production up to $\sim$TeV and even weak-production up to $\sim$400 GeV (assuming LSP $\rightarrow$ lepton-jet)

- Update to 2012 data

- Study *long-lived* decays to electron (or muon?) lepton-jets in the tracker ($\sim 0.1 - 10$ cm)

Cross-section limits for various decays

<table>
<thead>
<tr>
<th>Signal Parameters</th>
<th>Electron LJ</th>
<th>1 Muon LJ</th>
<th>2 Muon LJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_d$</td>
<td>$m_{rD}$[MeV]</td>
<td>Obs (Exp) pb</td>
<td>Obs (Exp) pb</td>
</tr>
<tr>
<td>0.0</td>
<td>150</td>
<td>0.082 (0.082)</td>
<td>-</td>
</tr>
<tr>
<td>0.0</td>
<td>300</td>
<td>0.11 (0.11)</td>
<td>0.060 (0.035)</td>
</tr>
<tr>
<td>0.0</td>
<td>500</td>
<td>0.20 (0.21)</td>
<td>0.15 (0.090)</td>
</tr>
<tr>
<td>0.10</td>
<td>150</td>
<td>0.096 (0.10)</td>
<td>-</td>
</tr>
<tr>
<td>0.10</td>
<td>300</td>
<td>0.37 (0.37)</td>
<td>0.064 (0.036)</td>
</tr>
<tr>
<td>0.10</td>
<td>500</td>
<td>0.39 (0.39)</td>
<td>0.053 (0.035)</td>
</tr>
<tr>
<td>0.30</td>
<td>150</td>
<td>0.11 (0.11)</td>
<td>0.099 (0.055)</td>
</tr>
<tr>
<td>0.30</td>
<td>300</td>
<td>0.40 (0.40)</td>
<td>0.066 (0.043)</td>
</tr>
<tr>
<td>0.30</td>
<td>500</td>
<td>1.2 (1.2)</td>
<td>-</td>
</tr>
</tbody>
</table>

ATLAS Search for WH → prompt electron-jets

- Electron lepton-jets would have:
  - Large EM energy fraction
  - Large charged particle pT fraction
  - Large number of tracks

- Separate signal from other backgrounds with QCD jets
ATLAS Search for WH → prompt electron-jets

- No excess observed with 2 electron-jets
- $\text{BR}(h \rightarrow \text{electron-jets}) < \sim 50\%$

http://arxiv.org/abs/1302.4403

Backgrounds are small:
$20 \text{ fb}^{-1}$ at 8 TeV $\rightarrow \text{BR} < \sim 5\%$!
Dark-photon production

- **Jet + dark-photon**

*New, kinetically coupled U(1)*

\[
\mathcal{L}_{\text{gauge mix}} = -\frac{1}{2} \epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2} \epsilon_2 b_{\mu\nu} Z^{\mu\nu}
\]

\[\Psi_{\text{dark matter}} \xrightarrow{\epsilon} G_{\text{dark}} \supset U(1)_y \xrightarrow{\epsilon} (\text{MS})\text{SM}\]

\[\sigma \approx (\alpha_{\text{EM}} \epsilon)^2\]

Large jet background

\[\sigma \approx (\alpha_s)^2\]
Rare Z decays

- Z decays to dark sector

\[
\text{BR}(Z^0 \rightarrow d_i d_i) = \frac{c_{d_i} \epsilon^2 g_y^2 y_{d_i}^2 \sin^2 \theta_W}{\Gamma_Z^0} \frac{1}{48\pi} M_{Z^0}
\]

Factor \(\sim 200\) smaller cross-section

But *two* dark-things in each event

Much less background from jets