Dark showers in ATLAS and CMS

- Introduction
- Emerging jets
- Displaced jets
  - From ZH production with H decays
  - From pair production of neutral scalars
- RECAST from displaced jets: dark-photon jets
- Summary/Outlook
The dark sector

- A very rich phenomenology, depending on the underlying model (symmetries), mediator, couplings, number of families, and masses
  - Lepton-jets, photons, new hadronic showers
  - Multiplicity may be very high or low
  - May have boosted signals, missing energy...

- Lifetime: considered a free parameter
  - Prompt: hadronic exotic searches (resonant & non-resonant)
  - Long lived: striking new signatures

- Challenging analyses
  - Often need complex trigger strategies
  - Novel final states that require dedicated reconstruction techniques
    ▪ New algorithms, taggers
  - Exciting challenges for experiments!

Aran Garcia-Bellido (Rochester)
Many different signatures

Semivisible jets

Soft unclustered energy

Emerging jets
CMS-EXO-18-001

Displaced Jets
ATL-EXO-17-05
ATL-EXO-17-25
CMS-EXO-19-021
CMS-EXO-20-015
LHCb-PAPER-16-065

SIMP
Trackless jets
CMS-EXO-17-010

Muons

Lepton-jets
ATL-EXO-14-09
LHCb-PAPER-2017-038

Higgs mediated DM
ATL-CONF-21-005
CMS EXO-20-003

Dark Photon jets
ATL-PUB-20-007
CMS: Emerging jets

- Pair produced bifundamental scalars ($X_d \rightarrow Q_d q$)
- Dark quarks $Q_d$ hadronize in hidden sector
  - Dark pions $\pi_d$ have lifetime and then decay to SM
  \[
  cT \approx 80 \, \text{mm} \left( \frac{1}{\kappa^4} \right) \left( \frac{2 \, \text{GeV}}{f_{\pi_d}} \right)^2 \left( \frac{100 \, \text{MeV}}{m_{\text{down}}} \right)^2 \left( \frac{2 \, \text{GeV}}{m_{\pi_d}} \right) \left( \frac{1 \, \text{TeV}}{m_{X_d}} \right)^4
  \]
  - Multiple secondary vertices within same jet
- Signature: 2 emerging jets + 2 prompt jets
- Selection: 4 AK4 jets, $|\eta|<2$ with $H_T > 900$ GeV
  - 7 signal regions based on:
    - Median of IP$_{2D}$ of tracks within jet
    - $p_T$ fraction of “prompt” tracks in jet $\alpha_{PV} = \frac{\sum_{trk \in PV} p_{trk}^T}{\sum p_T^{trk}}$

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CMS: Emerging jets background estimate

- Signal consists of tracks originating from several vertices at varying IP from PV
  - Sub-jet axes point out radially from PV
  - Heavy flavor jets could mimic the signature of short $\pi_d$ lifetime
- Multijet QCD (light and b-jets) is the main background
- Estimate fake rate in two $\gamma$+jets CRs in data, one with heavy flavor and one without
  - The b-jet fraction of each CR ($f_b$) is fitted to two MC templates (light and b jets)

\[
\begin{pmatrix}
\epsilon_{f1} \\
\epsilon_{f2}
\end{pmatrix}
= \begin{pmatrix}
f_{b1} & 1 - f_{b1} \\
f_{b2} & 1 - f_{b2}
\end{pmatrix}
\begin{pmatrix}
\epsilon_{fb} \\
\epsilon_{fl}
\end{pmatrix}

\begin{pmatrix}
\epsilon_{fb} \\
\epsilon_{fl}
\end{pmatrix}
= \begin{pmatrix}
\frac{1 - f_{b2}}{f_{b1} - f_{b2}} & \frac{1 - f_{b1}}{f_{b1} - f_{b2}} \\
\frac{1 - f_{b1}}{f_{b2} - f_{b1}} & \frac{1 - f_{b2}}{f_{b2} - f_{b1}}
\end{pmatrix}
\begin{pmatrix}
\epsilon_{fl} \\
\epsilon_{f2}
\end{pmatrix}

\epsilon_f = \epsilon_{fb} f_b + \epsilon_{fl} (1 - f_b)
\]

$P(EMJ) \propto \epsilon_f \epsilon_f (1 - \epsilon_f)(1 - \epsilon_f) + \ldots$

Validation in QCD-rich sample
Observed events in agreement with expected background in all 7 SR

<table>
<thead>
<tr>
<th>Set number</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal</th>
<th>$m_X_{DK}$ [GeV]</th>
<th>$m_{\pi_{DK}}$ [GeV]</th>
<th>$c\tau_{\pi_{DK}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>168 ± 15 ± 5</td>
<td>131</td>
<td>36.7 ± 4.0</td>
<td>600</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>31.8 ± 5.0 ± 1.4</td>
<td>47</td>
<td>(14.6 ± 2.6) × 10²</td>
<td>400</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>19.4 ± 7.0 ± 5.5</td>
<td>20</td>
<td>15.6 ± 1.6</td>
<td>1250</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>22.5 ± 2.5 ± 1.5</td>
<td>16</td>
<td>15.1 ± 2.0</td>
<td>1000</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>13.9 ± 1.9 ± 0.6</td>
<td>14</td>
<td>35.3 ± 4.0</td>
<td>1000</td>
<td>2</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>9.4 ± 2.0 ± 0.3</td>
<td>11</td>
<td>20.7 ± 2.5</td>
<td>1000</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>4.40 ± 0.84 ± 0.28</td>
<td>2</td>
<td>5.61 ± 0.64</td>
<td>1250</td>
<td>5</td>
<td>225</td>
</tr>
</tbody>
</table>
Emerging jet candidate

- Event passes SR1 and SR5
- Jets 1 and 4 pass the EMJ criteria
ATLAS: Higgs to displaced jets

- New pseudoscalar boson $a$ decaying exclusively to $b\bar{b}$, $Z \rightarrow \ell\ell$ used for trigger (allows reach to low jet $p_T$)
  - Sensitive to $2 < c\tau_a < 20$ mm
  - $M_a \in [15, 55]$ GeV
- Extend std. reco. tracks to Large Radius Tracking
- Standard $b$-tag algos are ineffecient for long $c\tau$
- DisplacedVertex algorithm: $N_{DVjets} \geq 2$
  - Prune for displaced tracks
  - $N_{trk} > 2$, $m/\Delta R_{max} > 3$ GeV, $r/\sigma_r > 100$, $\max|d_0| > 3$ mm
- At least one central jet with $CHF < 0.045$ or $\alpha_{max} < 0.05$

$$CHF = \frac{\sum_{trk} p_T^{trk} |d_0| < 0.5 mm}{p_T^{jet}}$$

$$\alpha_{PV_i} = \frac{\sum_{trk \in PV_i} p_T^{trk}}{\sum p_T^{trk}}$$

- Bkg validation in orthogonal $\gamma$+jets sample
  - DV algo achieves similar efficiency as $b$-tagging DL1 algorithm
ATLAS: Higgs to displaced jets results

- Control regions defined based on $N_{\text{DVjets}}$
- Use CR to estimate bkgd in $n_{\text{DV}} \geq 2$

No observed events, expected: $1.30 \pm 0.08 \text{(stat)} \pm 0.27 \text{(sys)}$
Pair-production of long-lived neutral scalar $X$ with equal decays to $u,d,c,s,b$.

- Use displaced jet trigger ($H_T$ and track IP reqs)
- Dijet candidates from all possible pairs of jets (AK4)
- Adaptive vertex fitter (annealing) to find SV applied to each dijet candidate
- Preselection based on SV $\chi^2/\text{ndof}$, $m_{vtx}$, $p_T(vtx)$, second largest IP$_{\text{sig}}$, vtx track energy fraction in dijet, and $\zeta$

<table>
<thead>
<tr>
<th>Secondary-vertex/dijet variable</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex $\chi^2/\text{ndof}$</td>
<td>$&lt;5.0$</td>
</tr>
<tr>
<td>Vertex invariant mass</td>
<td>$&gt;4 \text{ GeV}$</td>
</tr>
<tr>
<td>Vertex transverse momentum</td>
<td>$&gt;8 \text{ GeV}$</td>
</tr>
<tr>
<td>Second largest two-dimensional IP significance</td>
<td>$&gt;15$</td>
</tr>
<tr>
<td>Vertex track energy fraction in the dijet</td>
<td>$&gt;0.15$</td>
</tr>
<tr>
<td>$\zeta$ (charged energy fraction associated with compatible primary vertices)</td>
<td>$&lt;0.20$</td>
</tr>
</tbody>
</table>

Build likelihood discriminant based on: vertex track multiplicity; vertex $L_{xy}$ significance; Cluster RMS

$$L_{xy}^{\exp} = \frac{IP_{2D}^{\text{track}}}{\sin(\phi_{\text{track}} - \phi_{\text{dijet}})} \left(1 - \frac{|IP_{2D}^{\text{track}}|}{R}\right)$$

$$RMS_{\text{cluster}} = \sqrt{\frac{1}{N_{\text{tracks}}} \sum_{i=0}^{N_{\text{tracks}}} \frac{(L_{xy}(i) - L_{xy})^2}{L_{xy}^2}}$$
CMS: $XX \rightarrow qq$ qq displaced jets Likelihood

- **Vertex track multiplicity**
  - Events/1.0 vs. Vertex track multiplicity
  - Data vs. Jet-Jet model with settings $m_R = 300$ GeV, $c_t = 3$ mm

- **Vertex $L_{xy}$ significance**
  - Events/20.0 vs. Vertex $L_{xy}$ significance
  - Data vs. Jet-Jet model with settings $m_R = 300$ GeV, $c_t = 3$ mm

- **Cluster RMS**
  - Events/0.1 vs. Cluster RMS
  - Data vs. Jet-Jet model with settings $m_R = 300$ GeV, $c_t = 3$ mm

- **Likelihood discriminant**
  - Events/0.04 vs. Likelihood discriminant
  - Data vs. Jet-Jet model with settings $m_R = 300$ GeV, $c_t = 3$ mm
Final selection also requires:
- For jet1: $N(3D \text{ prompt tracks}) \leq 1$, $\text{CPEF} < 0.15$
- For jet2: $N(3D \text{ prompt tracks}) \leq 1$, $\text{CPEF} < 0.13$
- $L\text{hood} > 0.9993 \rightarrow N_{\text{obs}} = 1; N_{\text{exp}} = 1.0 \pm 0.2$

$\sigma_{XX} > 0.2 \text{ fb}$ are excluded for $m_X > 1 \text{ TeV}$ for $c\tau_0 \in [3, 130] \text{ mm}$

The lowest $\sigma_{XX}$ excluded is $0.13 \text{ fb}$, at $c\tau_0 = 30 \text{ mm}$ and $m_X > 1 \text{ TeV}$

Charged prompt energy fraction:

$$CPEF = \frac{\sum E_{\text{trk}, |d_0| < 0.5\text{mm}}}{\sum E_{\text{trk}}}$$
ATLAS: Displaced jets with RECAST

- Based on CalRatio displaced jets (decay in HCAL)
  - With dedicated CalRatio triggers for jets with high values of $E_H/E_{EM}$
    - Includes L1 topological selection $\rightarrow$ low $m_\Phi$
  - Train NN with $L_{xy}$, $L_z$, $E_H/E_{EM}$ to get $L_{xy}$, $L_z$ for each jet
  - Then use BDT to classify each jet as LLP signal, SM multi-jet or Beam-Induced-Background

- Recast into Higgs mediator/dark photon production
  - Dark photons are boosted, decay into quarks
  - Validated with signal from original analysis
  - Powerful use of Analysis Preservation tools
ATLAS: Dark-photon jets results

\( m_H = 125 \text{ GeV} \) (new limit in this region)

\( m_H = 800 \text{ GeV} \)
Exciting new signatures with dark shower phenomenology

- No excess in the data so far
- Investigating regions of parameter space for BSM previously unexplored at colliders
- Still room for new searches in ATLAS and CMS
- But stay tuned, several new analyses in the works!

Strong collaboration with theorists to tune models, implement signal MC tools...

Overlap with LLP searches can shed light on some models/final states

Need to develop new triggers, reconstruction techniques, algorithms for jet tagging, and background estimation

Detector upgrades will bring new trigger capabilities, better pointing calorimeters, more timing information...

**Summary/Outlook**

**ATLAS Preliminary**

- **H → ss**
  - ID/MS vtx, low EMF/trk jets: 36.1
  - s lifetime: 3.6-62 mm

- **VH with H → ss → bbbb**
  - 2l + 2 displaced vertices: 139
  - 2 e, μ- jets: 20.3

- **FRVZ H → 2γ + X**
  - 2 μ- jets: 36.1

- **FRVZ H → 4γ + X**
  - 2 μ- jets: 36.1

- **H → Z0Z0**
  - displaced dimuon: 32.9

- **H → ZZ0**
  - 2 e, μ + low-EMF trackless jet: 36.1

**CMS Preliminary**

- **H→XX(10%), X→ee, m_X = 125 GeV, m_e = 20 GeV**
  - X

- **H→XX(10%), X→μμ, m_μ = 125 GeV, m_μ = 20 GeV**
  - X

- **H→XX(10%), X→bb, m_b = 125 GeV, m_b = 40 GeV**
  - X

- **H→XX(10%), X→bb, m_b = 125 GeV, m_b = 40 GeV**
  - X

- **H→XX(10%), X→bb, m_b = 125 GeV, m_b = 40 GeV**
  - X

- **H→XX(10%), X→bb, m_b = 125 GeV, m_b = 40 GeV**
  - X

- **H→XX(10%), X→bb, m_b = 125 GeV, m_b = 40 GeV**
  - X

**RHIC/ALICE**

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.
Extra material

Z(ℓℓ)H, Higgs to displaced jets

Zoomed view of secondary vertices
Complementarity of H decay searches

**ATLAS** Preliminary

\( \sqrt{s} = 13 \text{ TeV} \)

\( m_H = 125 \text{ GeV} \)

**Prompt**

- \( m_a = 15 \text{ GeV} \)
- \( m_a = 35 \text{ GeV} \)
- \( m_a = 55 \text{ GeV} \)

CR+(MS1+MS2)

- \( m_a = 5 \text{ GeV} \)
- \( m_a = 8 \text{ GeV} \)
- \( m_a = 15 \text{ GeV} \)
- \( m_a = 25 \text{ GeV} \)
- \( m_a = 40 \text{ GeV} \)

\( m_3 = 40 \text{ GeV} \)
By assuming the flight direction of the SV is aligned with the dijet direction, we can estimate the position of the SV using track parameters:

- Vertex $L_{xy}$ can be estimated based on the track IP$_{2D}$, track curvature R and the dijet direction:

$$L_{xy}^{\text{exp}} = \frac{IP_{2D}^{\text{track}}}{\sin(\phi_{\text{track}} - \phi_{\text{dijet}})} \left( 1 - \frac{|IP_{2D}^{\text{track}}|}{R} \right)$$

- Then tracks are clustered based on the similarity in $L_{xy}^{\text{exp}}$ using hierarchical agglomerative clustering algorithm.

- The cluster that is closest to the reconstructed vertex (i.e. AVF vertex) is chosen.
CMS: Higgs to displaced jets

- **Backgrounds:**
  - 90% Z → ℓℓ+jets: estimated in low Z p_T CR
  - 10% tt: estimated in eμ+jets CR

- **Tagging variables for DV algorithm:**
  - Track IP_{sig} in xy ; α_{max}
  - Track angle Θ_{2D}: between ray from PV to track innermost hit and jet direction
  - Jets are DV: log(IP_{sig})>1.25, log(Θ_{2D})>-1.5, α_{max}<0.45
CMS: Higgs to displaced jets results

- Global fit to CR(tt)+CR(Z+jets)+SR: get bkgs with scale factors
  - Largest systematic uncertainty assigned to SFs
- 7 validation regions defined by inverting one or more tag vars.
  - Perform fit in VRs as well
  - Fit closes within uncertainty for all validation samples
- Results also include $S \rightarrow d \bar{d}$ search

![Graph of CMS Preliminary data]

$N_{\text{obs}} = 3$

$N_{\text{bkg}} = 3.5 \pm 1.8$
CMS: Strongly Interacting massive particles

- **Signature:** pair of narrow neutral jets (neutron-like)
  - Large $\chi$ cross-section yields early showers in ECAL
  - Small $\chi$ cross-section yields punch-through and MET

- **Selection:**
  - $N_{jets} = 2$, $p_T > 550$ GeV, $\Delta\phi(j_1,j_2)>2$
  - Photon & conversion veto, MET filters
  - $N_{vtx} \geq 2$, $\text{ChF}_{j_1,j_2} < 0.05$
  - Use data CR to estimate $\text{ChF}(p_T,\eta)$

- **SIMP-nucleon interactions are uncertain for $m_{\chi}>100$ GeV**

<table>
<thead>
<tr>
<th>ChF selection criterion</th>
<th>Background prediction from data</th>
<th>Obs.</th>
<th>SIMP signal $[m_{\chi}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 GeV</td>
<td>100 GeV</td>
<td>1000 GeV</td>
</tr>
<tr>
<td>&lt; 0.20</td>
<td>$898 \pm 30$ (stat) $\pm 33$ (syst)</td>
<td>969</td>
<td>1300 $\pm 58$</td>
</tr>
<tr>
<td>&lt; 0.15</td>
<td>$209 \pm 10$ (stat) $\pm 17$ (syst)</td>
<td>229</td>
<td>1269 $\pm 57$</td>
</tr>
<tr>
<td>&lt; 0.10</td>
<td>$26.6 \pm 2.2$ (stat) $\pm 9.3$ (syst)</td>
<td>30</td>
<td>1197 $\pm 56$</td>
</tr>
<tr>
<td>&lt; 0.07</td>
<td>$5.1 \pm 0.6$ (stat) $\pm 4.1$ (syst)</td>
<td>4</td>
<td>1153 $\pm 55$</td>
</tr>
<tr>
<td>&lt; 0.05</td>
<td>$1.27 \pm 0.22$ (stat) $\pm 3.40$ (syst)</td>
<td>0</td>
<td>1101 $\pm 53$</td>
</tr>
</tbody>
</table>

*16.1 fb$^{-1}$ (13 TeV)*