Topologies for X+Displaced Signals

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Triggering on New Physics @ LH-LHC, PCTS, Jan 16, 2018
Theoretical motivation for DV searches
(an incomplete list)

Higgs hierarchy problem

Small scale structure puzzles of the universe

Connection to indirect detection signal?

Matter/anti-matter asymmetry
DV + DV + ... from *Neutral Naturalness* models
Example: Twin Higgs model

Chacko, Goh, Harnik 05’ (see Daniel’s talk)

A solution to the little hierarchy problem without colored partners

\[ \delta m_h^2 \approx \frac{3\Lambda^2}{4\pi^2} (y_t^2 - \hat{y}_t^2) \]
<table>
<thead>
<tr>
<th>SM</th>
<th>Twin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{Y}_t$</td>
<td>$\mathcal{Y}_t^\hat{}$</td>
</tr>
<tr>
<td>SU(3) x SU(2) gauge couplings</td>
<td>SU(3) x SU(2) gauge couplings</td>
</tr>
<tr>
<td>EWSB scale $\mathcal{U}$</td>
<td>EWSB scale $f$</td>
</tr>
<tr>
<td>Other Yukawa couplings</td>
<td>Other Yukawa couplings</td>
</tr>
<tr>
<td>$U(1)_Y$ coupling</td>
<td>$U(1)_{Y^\prime}$ coupling</td>
</tr>
</tbody>
</table>
Displaced jet signal in Fraternal TH

Scalar glueballs can be the lightest twin hadron

Displaced decay into jets

Lifetime $\sim$ mm to km

$\sim$ 2-4 hadrons from Higgs

$\sim$ 15 - 30 GeV $b$'s

displaced decay via Higgs portal

Craig, Katz, Strassler, Sundrum (15')
Curtin, Verhaaren (15')
Chacko, Curtin, Verhaaren (15')

Can also come from associate Higgs productions

=> additional $W/Z$, forward jets
Displaced lepton signal in Fraternal TH

Light vector twin-b mesons (twin Upsilon)

Vector meson decays via Twin/SM photon mixing

DV into muons
Lifetime: depending on the photon mixing
~ 2-4 hadrons from Higgs
~ 15 - 30 GeV muons

Cheng, Jung, Salvioni, YT (15’
Exotic Higgs decay in Fraternal Twin Higgs

e.g. CMS displaced di-muon search (1411.6977)

Trigger: 2 muons, decay inside tracker, each muon pT > 26 GeV

Mediation scale of photon mixing

Cheng, Jung, Salvioni, YT (15')

8 TeV

13 TeV

300 fb^{-1}

cτ_{\tilde{\gamma}} > 30 cm

cτ_{\tilde{\gamma}} < 0.1 mm: h \rightarrow prompt ?
With lighter generation twin-qurks

Twin \( (b, c, s) \), twin hadrons \( \sim O(1) \) GeV, multiplicity \( \sim 6 - 8 \)

Several DVs with muons < 10 GeV
LHCb search, Higgs decays into dark showers

\[ h \rightarrow N_{\omega_v} \times \omega_v + N_{\eta_v} \times \eta_v \quad \omega_v \rightarrow \mu^+ \mu^- \quad \langle N_{\omega_v} \rangle / \langle N_{\eta_v} \rangle = 3 \]

Twin Higgs \( y_b = y_b \quad f / v = 4 \)

\[ h \rightarrow \hat{b} \hat{b} \rightarrow 2 \text{ GeV twin-hadrons} \]

\[ m_{\omega_v} = 2 \text{ GeV} \]

\[ m_{\omega_v} = 6 \text{ GeV} \]

LHCb 15/fb, 95% C.L.

Pierce, Shakya, YT, Zhao (17')
Search of light/soft DVs (Zp model, muons)

\[ \omega_v \rightarrow \mu^+ \mu^- \] ATLAS/CMS (300/fb) vs LHCb (15/fb), 95% CL

\[ \sigma(Z_p) \times BR(Z_p \rightarrow q\bar{q}v, \omega_v \rightarrow \mu^+ \mu^-) \text{ [fb]} \]

\[ m_{Z_p} = 200 \text{ GeV} \quad m_{\omega_v, \eta_v} = 0.3 \text{ GeV} \]

Pierce, Shakya, YT, Zhao (17')
Search of light/soft DVs (Zp model, bb or cc)

\[ Z_p \rightarrow N_{\omega_v} \times \omega_v \quad \omega_v \rightarrow c\bar{c} \quad m_{\omega_v} = 6 \text{ GeV} \quad m_{Z_p} = 200 \text{ GeV} \quad \langle N_{\omega_v} \rangle = 8 \]

Pierce, Shakya, YT, Zhao (17')
**DV signals from Neutral Naturalness models**

<table>
<thead>
<tr>
<th>Signal / Neutral Naturalness Models:</th>
<th>Paper</th>
<th>LLP Mass</th>
<th>LLP Multiplicity</th>
<th>ctau</th>
<th>SM contents</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin Higgs (TH), Fraternal TH (FTH), Folded-SUSY (FSUSY), Quirky Little Higgs (QLH) Exotic Higgs Decay, Heavy Resonance Decay, Pair Production &amp; Decay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h &gt; glueball (FTH, FSUSY), signal: DV bb</td>
<td>1501.05310, 1506.06141</td>
<td>10-60 GeV</td>
<td>2-4</td>
<td>micro m - km</td>
<td>DV bb, tau-tau</td>
<td></td>
</tr>
<tr>
<td>h &gt; twin bottomonia (FTH), signal: DV bb or mumu</td>
<td>1501.05310, 1512.02647</td>
<td>10-60 GeV</td>
<td>2-4</td>
<td>~&lt; m (twist upilon, assume heavy twin photon &amp; cosmo bound), 0.01mm - 1m (twitn chi, SM/5 &lt; twin yb &lt; SM)</td>
<td>DV bb, tau-tau, mumu</td>
<td></td>
</tr>
<tr>
<td>h &gt; lighter twin hadrons (~MTH), signal: DV mumu, cc, tau-tau</td>
<td>1708.05389</td>
<td>1-10 GeV</td>
<td>2-8</td>
<td>~&lt; m (twist omega, assume heavy twin photon &amp; cosmo bound), Higgs portal too slow</td>
<td>DV cc, tau-tau, mumu</td>
<td></td>
</tr>
</tbody>
</table>

| Exotic fermion bound state > SM W + twin glueball (FTH), DV to bb | 1612.03176, 1710.06437 | 10-60 GeV | 1-2 (T=0.3-0.5 TeV) | micro m - km | DV bb, tau-tau, prompt lepton |
| Quirky bound state > glueball (FSUSY), signal: DV bb | 1512.05782 | 10-60 GeV | 2-8 (T=0.5-1 TeV) | micro m - km | DV bb, tau-tau |
| Quirky bound state > glueball (QLH), signal: DV bb | 1512.05782 | 10-60 GeV | 2-8 (T=0.5-1 TeV) | micro m - km | DV bb, tau-tau |
| Heavy Higgs > glueball (FTH), signal: DV bb | 1711.03107 | 10-60 GeV | 20-30 (H=1-2.5 TeV) | micro m - km | DV bb, tau-tau |

Lots of assumptions in the mass/multiplicity/lifetime estimation
See the reference for details
DV + prompt SM object

From Neutral Naturalness models
Probing the UV structure: exotic-quarks @ LHC

DV into $b\bar{b}$ or muons + lepton ($p_T > 100$)

Cheng, Jung, Salvioni, YT (15’)

Different curves in the same style:
different assumptions of g-ball multiplicities
DV from a decay of EW-charged bound state

Resonance decays into SM + DV

EW-charged bound state from twin QCD binding force
(can produce more than one $G_0$'s)

Trigger using the hard lepton

95% CL exclusion on the UV-extended FTH

Exotic fermions decay

- $Y_X \rightarrow W + (bb)_D$ (300 fb$^{-1}$)
- $Y_X \rightarrow \ell \nu$ (300 fb$^{-1}$)
- $Y_X \rightarrow \ell \nu$ (36 fb$^{-1}$)

Li, Salvioni, YT, Zheng (17')
From Self Interacting Dark Matter

$DV + DV$

$\not{p}$

$DV$

$DV$

From Self Interacting Dark Matter
Self-Interacting DM (SIDM) provides solutions to small scale structure puzzles

e.g., Core/Cusp problem, Diversity Problem

Strong self-interaction helps to thermalize DM in the inner part of the halo, thus explains the star motion we see

If self-interaction comes from a dark photon, need \( O(10) \) GeV DM, sub-GeV photon mass with \( O(1) \) coupling

Tulin, Yu, Zurek (15’)
Kaplinghat, Tulin, Yu (13’)
For a review: Tulin, Yu (17’
SIDM bound state at collider

One of the final decays can be prompt, displaced, MET

DM annihilation at the LHC

Two displaced lepton-jets

Dark photon can be quite boosted

e.g. ATLAS displaced lepton-jets
(ATLAS-CONF-2016-042)

Narrow-Scan trigger for muon signals / Tri-muon MS only trigger

YT, Wang, Zhao (15’)

\[
p \rightarrow m_q(\bar{q} \gamma^5 q)(\bar{\chi} \gamma^5 \chi) / v M^2 \\
\overline{p} \rightarrow \text{displaced lepton-jet}
\]
Estimate the bound on SIDM production

Due to the low center of mass energy (=2x DM mass), the EFT description works fine in the study.

Dark photon with boost >~ 1000 can be hard to see
Relation to Indirect Detection Signals

$DV + DV + \ldots$

$p$

$p$
Example: galactic center gamma ray (?)

Freytesis, Robinson, YT (14’) and Freytesis, Knapen, Robinson, YT (16’)

Dark showers can provide a reasonable spectrum for the galactic center gamma-ray excess, while avoiding constraints from other cosmic-ray searches (positron, anti-proton)

Calore, Cholis, Weniger (14’)
Softer photons/higher multiplicity

GMSB model

\[ g \rightarrow \tilde{g} \rightarrow q^{(*)} \rightarrow X_1^0 \rightarrow \gamma \]
\[ g \rightarrow \tilde{g}^{(*)} \rightarrow X_1^0 \rightarrow \gamma \]
\[ \text{jet} \rightarrow \text{jet} \rightarrow \tilde{G} \]

\[ q \rightarrow \bar{q} \rightarrow Z' \rightarrow \eta' \rightarrow \gamma \]
\[ \eta' \rightarrow \gamma \]
\[ \Delta_v \rightarrow \gamma \]

\[ q \rightarrow \bar{q} \rightarrow Z' \text{Hidden Valley} \]

E.g., for Zp = 200 GeV, meson = 20 GeV, multiplicity \( \sim 4 \), time to ECAL \( \sim 0.3 \) ns

Trigger? HT > 350 GeV (too high), di-photon trigger (22, 16 GeV), single photon > 31 GeV, get from Cristina’s slides
DV + DV

From WIMP Baryogenesis
WIMP Baryogenesis

Cui, Sundrum (12’)

Where does matter/anti-matter asymmetry come from?
Why does baryon have similar relic density to DM?

WIMP like mother particle decays into baryon (but not anti-baryon)

$\chi_{BG}$  mother particle freeze out  mother particle decay with CPV

Decay needs to happen AFTER freeze out $\Rightarrow$ lifetime $>$ meter scale
DV from WIMP Baryogenesis

Cui, Shuve (15’)

When the mother particle is heavier than the EW scale, they decay into jets/leptons with proper length $\sim \mathcal{O}(10) \text{ cm}$

Two sets of displaced jets

e.g. ATLAS displaced di-jets (CMS-PAS-EXO-12-038)

Trigger: total jet HT $> 300$ GeV, 2 displaced jets, each $p_T > 60$ GeV
When the mother particle mass is below the EW scale, they decay into jets with proper length $\sim O(10)$ cm. If both decays inside detector, 6 displaced jets, each has $p_T < 30$ GeV. Two sets of displaced jets.

Still not easy.

e.g. ATLAS multi-track DV (1504.05162)
Trigger: (4, 5, 6) jets with $p_T > (80, 55, 45)$ GeV.
Summary and outlook

- Displaced vertices can be accompanied by many different objects
- Connect to deep understanding of new physics
- $DV + X = \text{tops, leptons, jets, } W/Z, \text{ MET, additional } DV(\text{'s})$
- Need better trigger/search for soft displaced objects