Charged Higgs Probes of Dark Bosons

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BSM1 Discussion Questions

• 1) Is there a place that we are not covering well? Is it because of fashions, lack of triggers, or otherwise?
  – How to target the compressed region, or degeneracies (e.g. $m_{\text{stop}} \sim m_{\text{top}}$)
  – Inclusion of soft leptons from quasi-degenerate higgsino LSPs?

• 2) How confident are we in the modeling and performance of high $p_T$ / boosted objects at 14 TeV?
  – What if we see a resonance at mass not equal to $m_W$ or $m_{\text{top}} \rightarrow$ are we confident that it is real?
  – Modeling of accidental substructure leading to broad differences in mass distribution?
  – Extrapolation to high $p_T$ and high PU?

• 3) What blinding strategy should we pursue in the future? Should ATLAS and CMS agree on a common policy?

• 4) At 14 TeV, the spotlight will be on high masses $\rightarrow$ how much emphasis should the experiments place on lower masses?
• Exotic top decay with very small branching fraction.
  • top -> H+ b -> W+ b Zprime, with Zprime -> dilepton
  • Signal: ttbar + collimated dilepton
• We do not know much about a very light Zprime.
  • A light Zprime of O(1) GeV mass is well motivated and not ruled out.
• Existing analysis may miss such a signal.
Dark Z'prime (Zd)

- Zd: a gauge boson of a new dark U(1).
- Zd has no direct couplings to SM and couples to SM via kinetic mixing.
- Exact couplings depend on details of model.
- For a Zd with O(1) GeV mass, BR into leptons is large.
- At LHC, such a Zd can be boosted, and two leptons from Zd decay appear as a Lepton-Jet.
- Light Zd with weak couplings to SM may address various anomalies such as positron data, muon g-2 etc.

\[
\mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2\cos\theta_W} B_{\mu\nu} Z'_{\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z'^{\mu\nu}.
\]

\[
\mathcal{L}_{\text{dark} \ Z} = - (\varepsilon e J_{em}^{\mu} + \varepsilon Z g Z J_{NC}^{\mu}) Z_\mu' \\
= -f (g_V \gamma^\mu - g_A \gamma^\mu \gamma^5) f Z_\mu'
\]

\[
g_V = -\varepsilon e Q_f - \varepsilon Z g_Z \left(\frac{1}{2} T_{3f} - Q_f \sin^2 \theta_W\right)
\]

\[
g_A = -\varepsilon Z g_Z \left(\frac{1}{2} T_{3f}\right),
\]

\[
|\varepsilon| \lesssim 10^{-2} \quad |\delta| \lesssim 10^{-2} \quad \varepsilon_Z \equiv \delta \frac{m_{Z'}}{m_Z}
\]

Davoudiasl, Marciano, Ramos, Sher, 2014
Kong, Lee, Park, 2014
Higgs + Zd

- Exotic decay of Higgs
- Multi-leptons from \( h \rightarrow Z Zd \), \( h \rightarrow Zd Zd \)

The four leptons are divided into two same flavor opposite sign (SFOS) pairs: the pair closest to Z "Z1" and the other pair "Z2"

Setting bounds ZZ\( ^* \): present 9/13

Bounds coming from SM h \( \rightarrow ZZ^* \rightarrow 4l \) searches at the LHC

\( BR(h \rightarrow ZZ^* D) \approx 10^{-3} \) are already probed with the present (undedicated) 7+8 TeV LHC searches

Counting experiment: \( m_{Z^d}, m_{Z^2} \)

The Higgs bound is already approaching the bound coming from ~20 years of EWPTs!
Charged Higgs + Zd

- In 2HDM, FCNC constraints can be addressed by a new U(1), under which Higgs doublets carry different charges.

- Such a scenario implies tree-level HWZprime coupling.

- For a light “dark” Z model (Zprime=Zd with mass < 10 GeV), charged Higgs may decay dominantly into W + Zd (for mass < mtop),

- Dominant production of charged Higgs is via top decay.

Davoudiasl, Marciano, Ramos, Sher, 2014
Kong, Lee, Park, 2014
Top decay into Zd via H+

- Possible scenarios to search for Zd in connection to the top quark are
  (i) $t \to bH^+ \to bW + Z'$
    (through $H^\pm W^\mp Z'$ coupling),
  (ii) $t \to bH^+ \to bW + h \to bW + Z'Z'$
    (with a light non-SM Higgs boson $h$),
  (iii) $t \to bW^* \to bW + Z'$
    (through $Z'WW$ coupling),
  (iv) $t \to bW^* \to bW + h \to bW + Z'Z'$
    (through $hWW$ coupling).

- We focus on (i) and (ii).
- We assume: $m_W < m_{H^+} < m_{t\text{top}}$

- Whether (i) or (ii) dominates depends on the mass of Higgs boson, especially mass of non-SM Higgs.

- In principle, $t \to qZ'$ (with $q = u, c$) is possible.
Charged Higgs (H+) decay

- We assume Type I-2HDM.

- For MH+ < mtop, dominant decays are into cs and tau-neutrino.

- For (i), the lighter Higgs boson is SM-like. H+W-Zd coupling is small but H+ Br to WZd can be large.

- For (ii), the charged Higgs can decay to the lighter Higgs. In the decoupling limit (alpha=pi/2 or -pi/2), the heavier Higgs is SM-like.

- Br(h -> Zd Zd) ~ 1, since h does not couple to SM fermions. (Type I)

- In both (i) and (ii), over much of parameter space, Y~1.

- We take Y=0.5-1.

\[ \Gamma(H^+ \rightarrow \nu \tau^+) \approx \frac{m_{H^+}}{8\pi v^2} \frac{m_{\tau}^2}{\tan^2 \beta} \]

\[ \Gamma(H^\pm \rightarrow WZ') \approx \frac{m_{H^\pm}^3}{16\pi v^2} (\sin \beta \cos \beta_d)^2 \left( 1 - \frac{m_W^2}{m_{H^\pm}^2} \right)^3 \]

\[ \Gamma(H^\pm \rightarrow Wh) \approx \frac{\sin^2 \beta}{16\pi v^2} \frac{1}{m_{H^\pm}^3} \lambda^{3/2}(m_{H^\pm}^2, m_W^2, m_h^2) \]

\[ Y \equiv \text{BR}(H^\pm \rightarrow W + Z's), \]

(i) \( t \rightarrow bH^+ \rightarrow bW + Z' \)

(through \( H^\pm W^\mp Z' \) coupling).

(ii) \( t \rightarrow bH^+ \rightarrow bW + h \rightarrow bW + Z'Z' \)

(with a light non-SM Higgs boson h),
Top decay into $Zd$ via $H^+$

- For numerical analysis, we focus on
  
  (i) $t \to bH^+ \to bW + Z'$
  (through $H^\pm W^\mp Z'$ coupling).

- Higher BR for lower tan(beta).

- Current limit allows $O(1\%)$ branching fraction.

$$
\text{BR}(t \to bH^+) \approx \frac{\Gamma_{t \to bH^+}}{\Gamma_{t \to bW} + \Gamma_{t \to bH^+}} \approx \left(\frac{m_t^2 - m_{H^\pm}^2}{m_t^2 - m_W^2}\right)^2 \frac{1}{1 + 2m_W^2/m_t^2} \frac{1}{\tan^2 \beta}
$$
Production of Zd

- Zd production in DY (\( pp \rightarrow H^+ H^- \rightarrow WW + Z'Z' \)) and top pair production,

\[
\sigma(pp \rightarrow bW \bar{b}W + Z's) \simeq \sigma_{tt} 2X \quad X = BR(t \rightarrow bH^+) Y
\]

- The band indicates BR(H+ \rightarrow W Zd)=0.5-1 range. \( Y = BR(H^\pm \rightarrow WZ') = 0.5 - 1 \)

- Cross section at 14 TeV is about 4 times larger than that at 8 TeV.

- For a low tan(beta), top quark production is important.
Lepton Pair from Zd decay

- Light Zd cannot be reconstructed with the usual lepton tagging.
- $\Delta R \approx \Delta \eta$ since $\Delta \phi$ is peaked at 0.

\[
m_{\ell^+\ell^-} = 2P_{T_1}P_{T_2} (\cosh \Delta \eta - 1) \\
\approx 2P_{T_1}P_{T_2} (\cosh \Delta R - 1)
\]

- For a moderate lepton tagging efficiency, most analysis require

\[
P_{T(e)}^{\text{min}} = 10 \text{ GeV}, \quad P_{T(\mu)}^{\text{min}} = 5 \text{ GeV}.
\]

- With an isolation requirement of $\Delta R > 0.3$,

\[
m_{ee} > \sqrt{2P_{T(e)}^{\text{min}}P_{T(e)}^{\text{min}}(\cosh(0.3) - 1)} \approx 3 \text{ GeV},
\]

\[
m_{\mu\mu} > \sqrt{2P_{T(\mu)}^{\text{min}}P_{T(\mu)}^{\text{min}}(\cosh(0.3) - 1)} \approx 1.5 \text{ GeV}.
\]

- Conventional analysis would miss Zd lighter than 3 (1.5) GeV in the dielectron (dimuon) channel.
Lepton Pair from Zd decay

- Light Zd cannot be reconstructed with the usual lepton tagging.

\[ \Delta R(\text{peak}) \sim \cosh^{-1}\left( \frac{2m_{Z'}^2}{(E_\ell^{(\text{cusp})})^2} + 1 \right) \]

\[ \eta_{H\pm} = \cosh^{-1}\left( \frac{m_e^2 + m_{H\pm}^2 - m_\ell^2}{2m_\ell m_{H\pm}} \right), \]

\[ \eta_{Z'} = \cosh^{-1}\left( \frac{m_{Z'}^2 + m_{Z'}^2 - m_{W'}^2}{2m_{Z'} m_{W'}} \right). \]

\[ E_\ell^{(\text{max})} = \frac{m_{Z'}}{2} e^{(\eta_{Z'} + \eta_{H\pm})} \]

\[ P_T = \frac{1}{2} E_\ell^{(\text{cusp})}. \]
Improved Lepton Selection

1. At least two same flavor leptons with $P_T > 10$ GeV (electron), 5 GeV (muon) and in a cone of $\Delta R < 0.1$.

2. Isolation: Hadronic and leptonic isolation of $\sum P_T < 3$ GeV in $0.1 < \Delta R < 0.4$.

3. Invariant mass cut on lepton-jet: $|m_{LJ} - m_{Z'}| < 0.2 \times m_{Z'}$.

   • We make minor changes in the Delphes module to include the non-zero muon mass in the original routine.

   • We add the lepton-jet class in the Delphes, following above definitions.

   • Use anti-kt with DeltaR < 0.5. Require at least one b-tagged jet and above LJ conditions.

   • For numerical study, we use $X = 0.001$ and $\text{BR}(Z' \rightarrow \ell^+\ell^-) = 0.2$

   $$\sigma(pp \rightarrow bW \bar{b}W + Z's) \simeq \sigma_{tt} 2X \quad X = \text{BR}(t \rightarrow bH^+)Y$$

• For our study, we use FeynRules, MG4, PYTHIA, and Delphes.

• 60%-75% of b-tagging efficiency, depending on PT and ETA, following CMS CSVM tagging.
Signal and Backgrounds

- Dilepton channel
  - $pt < 20 \text{ GeV, } \eta < 2.5$ for electron and $pt > 20 \text{ GeV, } \eta < 2.1$ for muon
  - veto OSSF with $m_{ll} < 20 \text{ GeV}$ and $|M_{Zd} - m_{ll}| < 15 \text{ GeV}$, $met > 40 \text{ GeV}$
  - at least two jets with $pt > 30 \text{ GeV, } \eta < 2.5$

- Semileptonic channel
  - $pt > 30 \text{ GeV, } \eta < 2.5$ for electron and $pt > 26 \text{ GeV, } \eta < 2.1$ for muon
  - at least four jets with $pt_1, pt_2 > 45 \text{ GeV, } pt_3, pt_4 > 35 \text{ GeV}$.

- Hadronic channel
  - at least 6 jets, $pt > 30 \text{ GeV, } \eta < 2.4$.
  - CMS requires $pt_1, pt_2, pt_3, pt_4 > 60 \text{ GeV, } pt_5 > 50 \text{ GeV, } pt_6 > 30 \text{ GeV}$, and additional constrains for two b-tagged jets and a kinematic for mass reconstruction of tops and W.

- Backgrounds: $ttbar + \text{dilepton}$ with $K_{bkdnd}=2$. ($K_{sig}=1.74 \ (1.84)$ at 8 \ (14) TeV.)
LJ Tagging Efficiencies

<table>
<thead>
<tr>
<th>LHC [TeV]</th>
<th>m_{Z'} [GeV]</th>
<th>\epsilon_{\text{LJ}}(\epsilon_{\text{LJ+CMS}}) [%] for signal</th>
<th>Mass range of m_{\ell^+\ell^-} [GeV]</th>
<th>\sigma_{\text{bkg}} [pb]</th>
<th>\epsilon_{\text{LJ}}(\epsilon_{\text{LJ+CMS}}) [%] for background</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>16.37 (4.18/2.07)</td>
<td>m_{H^\pm} = 100 GeV</td>
<td>m_{H^\pm} = 140 GeV</td>
<td>m_{H^\pm} = 160 GeV</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.07 (0.92/0.43)</td>
<td>46.77 (10.96/4.51)</td>
<td>52.04 (9.40/3.04)</td>
<td>0.5 – 1.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.02 (0.00/0.00)</td>
<td>2.24 (0.64/0.26)</td>
<td>5.55 (1.25/0.48)</td>
<td>0.32 (0.10/0.04)</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>16.38 (4.28/2.02)</td>
<td>44.28 (10.73/4.37)</td>
<td>50.54 (9.44/3.13)</td>
<td>0.5 – 1.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.33 (1.11/0.49)</td>
<td>29.73 (7.52/3.13)</td>
<td>39.31 (7.64/2.51)</td>
<td>1.0 – 3.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.03 (0.01/0.00)</td>
<td>2.57 (0.76/0.28)</td>
<td>5.90 (1.40/0.47)</td>
<td>3.0 – 5.0</td>
</tr>
</tbody>
</table>

TABLE III: Lepton-jet tagging efficiency \( \epsilon_{\text{LJ}} \) (\%) in \( pp \rightarrow bWbW + \ell^+\ell^- \) for signal (for given \( m_{H^\pm} \) and \( m_{Z'} \)) and background (from virtual photon and virtual \( Z \) boson) at the 8 and 14 TeV LHC. The numbers in parentheses \( \epsilon_{\text{LJ+CMS}[1b]/\epsilon_{\text{LJ+CMS}[2b]} \) are the efficiencies when we require additional selection cuts, requiring one \( b \)-tagged or two \( b \)-tagged jets as described in Appendix A2. Coupling structure of \( Z' \) to the lepton does not give a significant effect on the tagging efficiency. In the above table, we take axial coupling as an example. For backgrounds, we set the trigger of a \( m_{\ell^+\ell^-} \) mass window as in the table to enlarge statistics.
## Signal and Backgrounds

### Table I: Expected number of events in each lepton-jet bin

<table>
<thead>
<tr>
<th>$m_{Z'}$ [GeV]</th>
<th>$m_{H^-}$ 100 GeV</th>
<th>$m_{H^-}$ 140 GeV</th>
<th>$m_{H^-}$ 160 GeV</th>
<th>BKG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.0</td>
<td>86.2</td>
<td>58.1</td>
<td>69.6</td>
</tr>
<tr>
<td>2</td>
<td>8.2</td>
<td>59.9</td>
<td>47.8</td>
<td>5.0</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>5.0</td>
<td>9.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

TABLE I: Expected number of events in each lepton-jet bin (20% window of the $Z'$ mass) with two $b$-tagging in 8 TeV LHC 20 fb$^{-1}$. We set $X = 0.001$ and BR($Z' \rightarrow \ell^- \ell^+$) = 0.2. Signal events were obtained with high order $\sigma_{tt}$ with branching ratio, and the background events were obtained with tree-level simulation with $K_{bkg} = 2$.

- At 8 TeV, top pair production cross section $\sim 239$ pb.
- For $mH^+ = 140$ GeV, $MZd=2$ GeV,

  $$N_{\text{sig}} = \sigma_{tt} 2X \text{BR}(Z' \rightarrow \ell^+ \ell^-) \epsilon_{\text{sig}} L \approx 60.$$  

  $$N_{\text{bkg}} = \sigma_{\text{bkg}} \epsilon_{\text{bkg}} L \approx 5.$$  

  $$N_{\text{obs}} = N_{\text{sig}} + N_{\text{bkg}}.$$  

  $$S_{CL} = \sqrt{2N_{\text{obs}} \log (1 + N_{\text{sig}}/N_{\text{bkg}}) - 2N_{\text{sig}}} \approx 14.6.$$  

### Table II: Required luminosity for 14 TeV LHC to see the likelihood ratio $S_{CL} = 5$ (corresponding to $5\sigma$ discovery). Basically the same method as Table I is used.

<table>
<thead>
<tr>
<th>$m_{Z'}$ [GeV]</th>
<th>$m_{H^-}$ 100 GeV</th>
<th>$m_{H^-}$ 140 GeV</th>
<th>$m_{H^-}$ 160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.8 fb$^{-1}$</td>
<td>1.9 fb$^{-1}$</td>
<td>3.4 fb$^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>14.5 fb$^{-1}$</td>
<td>0.7 fb$^{-1}$</td>
<td>1.0 fb$^{-1}$</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>7.3 fb$^{-1}$</td>
<td>3.5 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- Conventional search gives $N_{\text{sig}} \sim 4$ with eff=0.71%, and signal is buried in background uncertainty, which is 591.
  - $N_{\text{bkg}} \approx 1.7 \times 10^4$ results in $S_{CL}=0.03$.
- Good sensitivity for LHC Run II.
Summary

• A light Zprime (Zd) is well motivated.

• Its search is very active at low energy experimental facilities and dedicated study on the LHC sensitivity is needed.

• Dark Z opens up exotic Higgs decays.

• We considered the production of light Zd through the top quark decay, with Zd decays to the collimated lepton pair, which may be missed by conventional searches.

• 8 TeV already rules out some parameter space.

• Exciting opportunity at LHC run II.
BSM2 Discussion Questions

• 1) The standard question: is there a place that we are not covering well? Is it because of fashions, lack of triggers, or otherwise?

• 2) If the galactic center signal is the DM annihilating, what is the best way of looking for it at colliders?
  – And what is the best way to put constraints on the mediator?

• 3) How applicable is EFT when extrapolating collider results to limits in the DM $\sigma$ vs. $M$ plane?
  – How should we treat this in the future (e.g., simplified models)?
  – Do different models require different search strategies/selections?

• 4) What range of neutralino DM masses is NOT excluded by our current results, and how do we target these holes?
FIG. 1: Various constraints on dark matter annihilation cross section as a function of dark matter mass in the final states with (a) $b\bar{b}$ and (b) $\ell\bar{\ell}$. We consider limits coming from anti-proton flux (in red), diffuse radio emission (in blue), CMB (in black), positron data (in magenta), and colliders (in light blue and in yellow-shaded region). Current bounds are shown in solid (or dashed) curves while the projected sensitivities are denoted by the dotted. Two reference cross sections marked as ‘square’ are fitted results in Ref. [25]. A rescaling factor of $1/3$ is taken into account for democratic annihilations into leptons as shown in (b). Therefore the same cross section is applied to each leptonic final state. We also show the 3$\sigma$-contour in (a) from Ref. [24].

**DM couplings to third generation may be important.**

Kong, Park, PLB 2014