Charged Higgs Probes of Dark Bosons

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Dark Interactions:
Perspectives from Theory and Experiment
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Charged Higgs + Zd

- Dark Z + 2HDM (type I)
- Charged Higgs: H+/H- (mW < mH+ < mtop)
- Neutral Higgses: h, H and A
- Dark Z: Zd of mass O(1-10) GeV (1, 2 and 5 GeV)

TRIUMF

Vector Portal Parameter: ϵ

- What are the physical effects of this mixing?

$$\mathcal{L} \supset -\frac{\epsilon}{2} X_{\mu\nu} \left(F^{\mu\nu} - t_W Z^{\mu\nu}\right)$$

- Two Cases:

1. Massive X vector: Dark Photon

1′. Massive X vector with extra mass mixing: Dark Z

2. Massless X vector: Paraphoton

TRIUMF

Case 1′: Extra Mass Mixing [Davoudiasl, Lee, Marciano 2012]

- Mass matrix with general mixing:

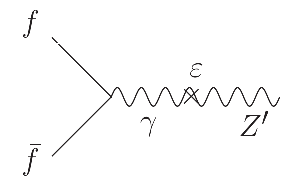
$$\mathcal{M}^2 = m_Z^2 \begin{pmatrix} m_x^2/m_Z^2 & -\epsilon_Z \\ -\epsilon_Z & 1 \end{pmatrix} \quad \text{with} \quad \epsilon_Z = \left(\frac{m_x}{m_Z}\right)\delta$$

- At low energies:

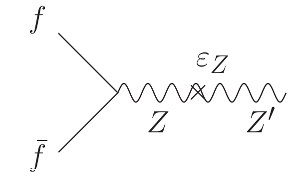
$$-\mathcal{L}_{eff} \supset \delta \frac{g_x g_Z}{m_x m_Z} j_x^\mu j_{Z\,\mu} + (1+\delta^2)\frac{g_Z^2}{m_Z^2} j_Z^\mu j_{Z\,\mu}$$

Much less suppression!

From David's talk



Types of Dark Force



It may interact with DM, but SM particles have zero charges

Both models commonly assume the kinetic mixing of $U(1)_Y$ and $U(1)_{dark}$.

[Holdom (1986)]

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$

(i) Popular Model: **"Dark Photon"** [Arkani-Hamed *et al* (2008); and others]
mass ≈ O(1) GeV
coupling = ε×(Photon coupling)
$\mathcal{L}_{\rm int} = -\varepsilon\, e J^\mu_{em} Z'_\mu$

(ii) New Model: **"Dark Z"** [Davoudiasl, LEE, Marciano (2012)]
mass ≈ O(1) GeV
coupling = ε×(Photon coupling) + ε_Z×(Z coupling)
$\mathcal{L}_{\rm int} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\,(g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$

inherits properties of Z boson (including the parity violation)

Higgs structure matters

Model-dependence in coupling comes from **how Z' gets mass** (or Higgs sector).
- Dark Photon: (Example) additional Higgs singlet gives mass to Z'
  coupling = ε×(Photon coupling)
- Dark Z: (Example) additional Higgs doublet (+ singlet) gives mass to Z'
  coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

(Example) Dark Photon case
: Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading order.

$$\mathcal{L}_{\rm int} \sim -eJ^\mu_{em}A_\mu - (g/2\cos\theta_W)J^\mu_{NC}Z_\mu$$

(Kinetic mixing diagonalization) $\rightarrow -eJ^\mu_{em}[A_\mu + \varepsilon Z'_\mu] - (g/2\cos\theta_W)J^\mu_{NC}[Z_\mu + O(\varepsilon)Z'_\mu]$

(Z-Z' mass matrix diagonalization) $\rightarrow -eJ^\mu_{em}[A_\mu + \varepsilon Z'_\mu] - (g/2\cos\theta_W)J^\mu_{NC}Z_\mu$

(depends on Higgs sector) *(for Higgs singlet)*

Dark Force couplings depend on "Higgs sector".

From Hye-Sung's talk

Dark Zprime (Zd)

- A gauge boson of a new dark U(1).
- Light Zd with weak couplings to SM may address various anomalies such as positron data, muon g-2 etc.

$$\begin{aligned}\mathcal{L}_{\text{dark } Z} &= -\left(\varepsilon e J^{\mu}_{em} + \varepsilon_Z g_Z J^{\mu}_{\text{NC}}\right) Z'_{\mu} \\ &= \bar{f}\left(g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5\right) f Z'_{\mu}\end{aligned}$$

- Zd has no direct couplings to SM. It couples to SM via kinetic mixing + extra mass mixing.

$$\begin{aligned}g_V &= -\varepsilon e Q_f - \varepsilon_Z g_Z \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right) \\ g_A &= -\varepsilon_Z g_Z \left(\frac{1}{2}T_{3f}\right),\end{aligned}$$

- Exact couplings depend on details of model, especially on higgs sector.

$$|\varepsilon| \lesssim 10^{-2} \qquad \varepsilon_Z \equiv \delta \, \frac{m_{Z'}}{m_Z}$$

$$|\delta| \lesssim 10^{-2}$$

- It opens up exotic Higgs decays and provides interesting collider signatures!

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 may introduce tree-level HWZprime coupling.
- For a light “dark” Z model (with mass < 10 GeV), charged Higgs may decay dominantly into W + Zd (for mass < mtop)
- 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.

Davoudiasl, Marciano, Ramos, Sher, 2014

Kong, Lee, Park, 2014

Production of H+/H-

- For tan(beta) ~10, single production cross section ($b\,g \;\rightarrow\; t\,H^-$) of charged Higgs (160 GeV) is ~ 20 (100) fb at 8 (14) TeV.

- DY provides another production. For 100 < MH < 175, DY cross section changes 50 fb to 5 fb at 8 TeV. At 14 TeV, cross sections are twice larger.

- Associated tH production is a factor of 4-10 larger than DY cross section for a similar mass. DY only becomes comparable for tan(beta) ~ 20 but it has negligible model dependence.

- H+H- production via top quark production is subdominant to DY over most of the relevant parameter space but single H+ (or H-) production from ttbar is quite dominant.

Davoudiasl, Marciano, Ramos, Sher, 2014

Charged Higgs (H+) decay

- For MH+ < mtop, dominant decays are into cs and tau-neutrino in usual 2HDM.
- 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. 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.

$$\Gamma(H^+ \to \nu\tau^+) \simeq \frac{m_{H^\pm}}{8\pi v^2}\frac{m_\tau^2}{\tan^2\beta}$$

$$\Gamma(H^\pm \to WZ') \simeq \frac{m_{H^\pm}^3}{16\pi v^2}(\sin\beta\cos\beta_d)^2\left(1-\frac{m_W^2}{m_{H^\pm}^2}\right)^3$$

$$\Gamma(H^\pm \to Wh) \simeq \frac{\sin^2\beta}{16\pi v^2}\frac{1}{m_{H^\pm}^3}\lambda^{3/2}(m_{H^\pm}^2, m_W^2, m_h^2)$$

$$Y \equiv \mathrm{BR}(H^\pm \to W + Z'\mathrm{s}),$$

(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).

Zd Production

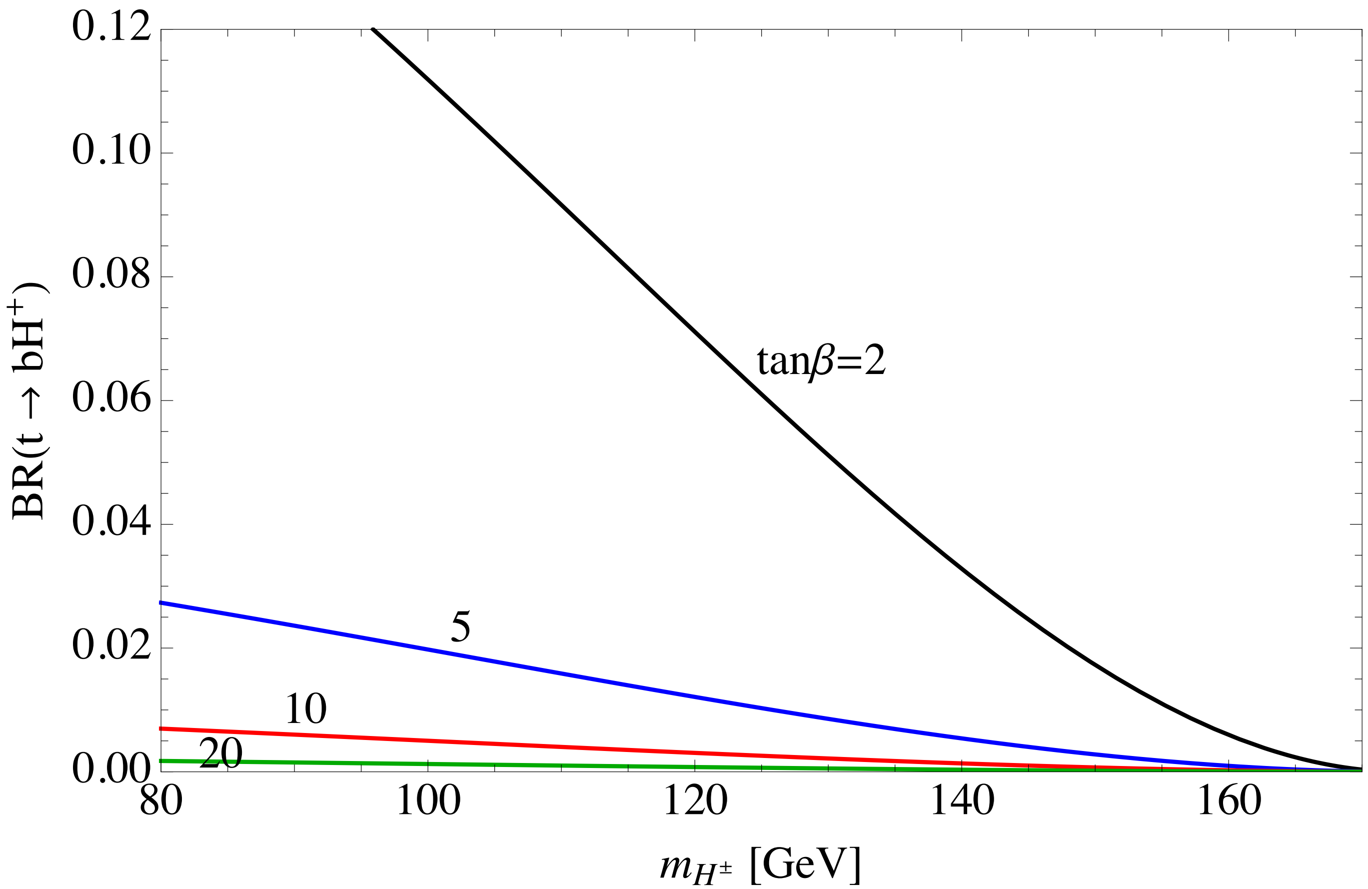
- For an invisibly decaying Zd, the search will likely be more challenging and depend on how well the missing energy signal can be separated from the background.

- An approximate bound on this mode can be inferred from ATLAS/CMS bounds on stop production followed by stop decay to top + neutralino of mass ~50 GeV, LHC bounds are ~ 2pb for a stop mass 250 GeV, which may constrain only a lower mass of H+. More detailed analysis or data from run II will constrain the parameter space.

- We will consider Zd decay into dilepton.

Davoudiasl, Marciano, Ramos, Sher, 2014

Top decay into Zd via H+



- For numerical analysis, we focus on

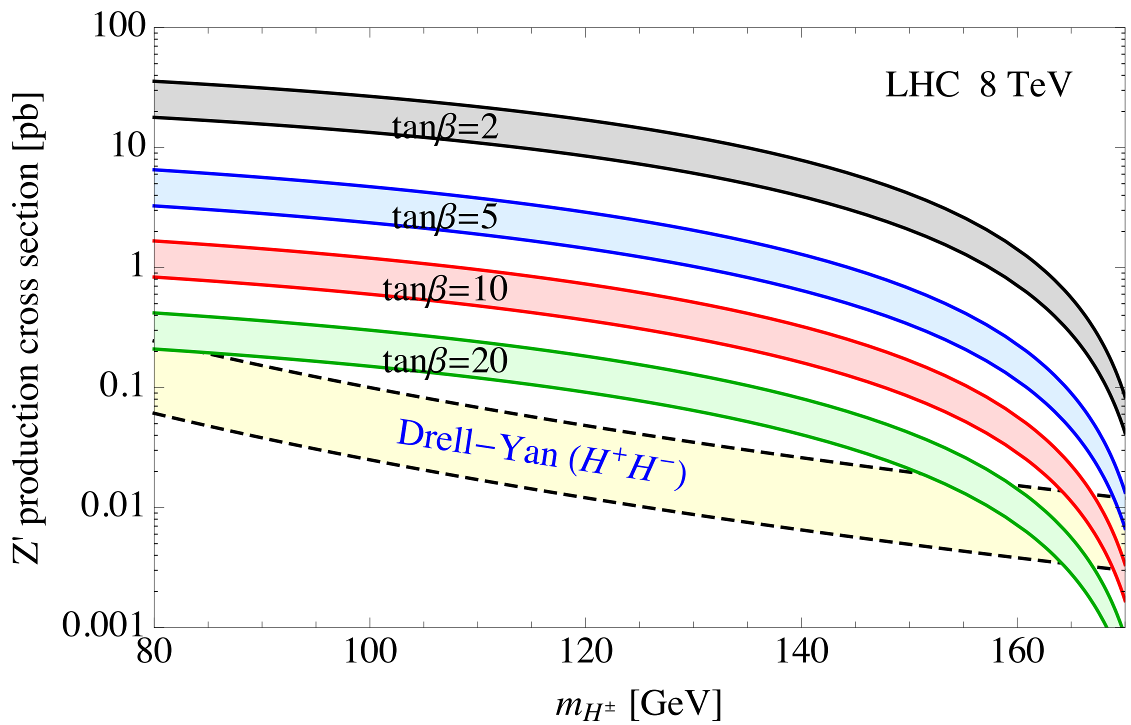
  (i) $t \to bH^+ \to bW + Z'$
  (through $H^\pm W^\mp Z'$ coupling)

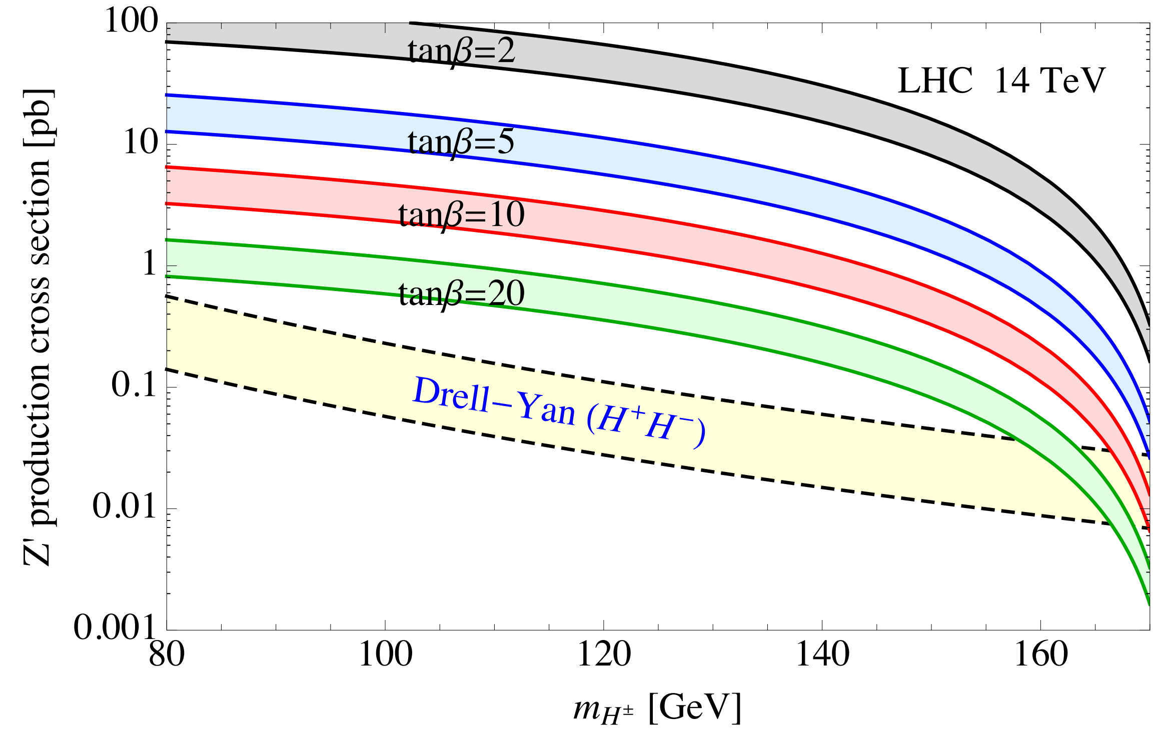
- Higher BR for lower tan(beta).

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

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

Production of Zd





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

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

- The band indicates BR(H+ -> W Zd)=0.5-1 range. $Y = \text{BR}(H^\pm \to WZ') = 0.5 - 1$
- 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.
- $\Delta R \simeq \Delta\eta$ since $\Delta\phi$ is peaked at 0.

$$\begin{aligned} m^2_{\ell^+\ell^-} &= 2P_{T_1}P_{T_2}\left(\cosh\Delta\eta - 1\right) \\ &\simeq 2P_{T_1}P_{T_2}\left(\cosh\Delta R - 1\right) \end{aligned}$$

- For a moderate lepton tagging efficiency, most analysis require

$$P^{\min}_{T(e)} = 10 \text{ GeV}, \quad P^{\min}_{T(\mu)} = 5 \text{ GeV}.$$

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

$$m_{ee} > \sqrt{2P^{\min}_{T(e)}P^{\min}_{T(e)}(\cosh(0.3) - 1)} \simeq 3 \text{ GeV},$$

$$m_{\mu\mu} > \sqrt{2P^{\min}_{T(\mu)}P^{\min}_{T(\mu)}(\cosh(0.3) - 1)} \simeq 1.5 \text{ GeV}.$$

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

Lepton Pair from Zd decay

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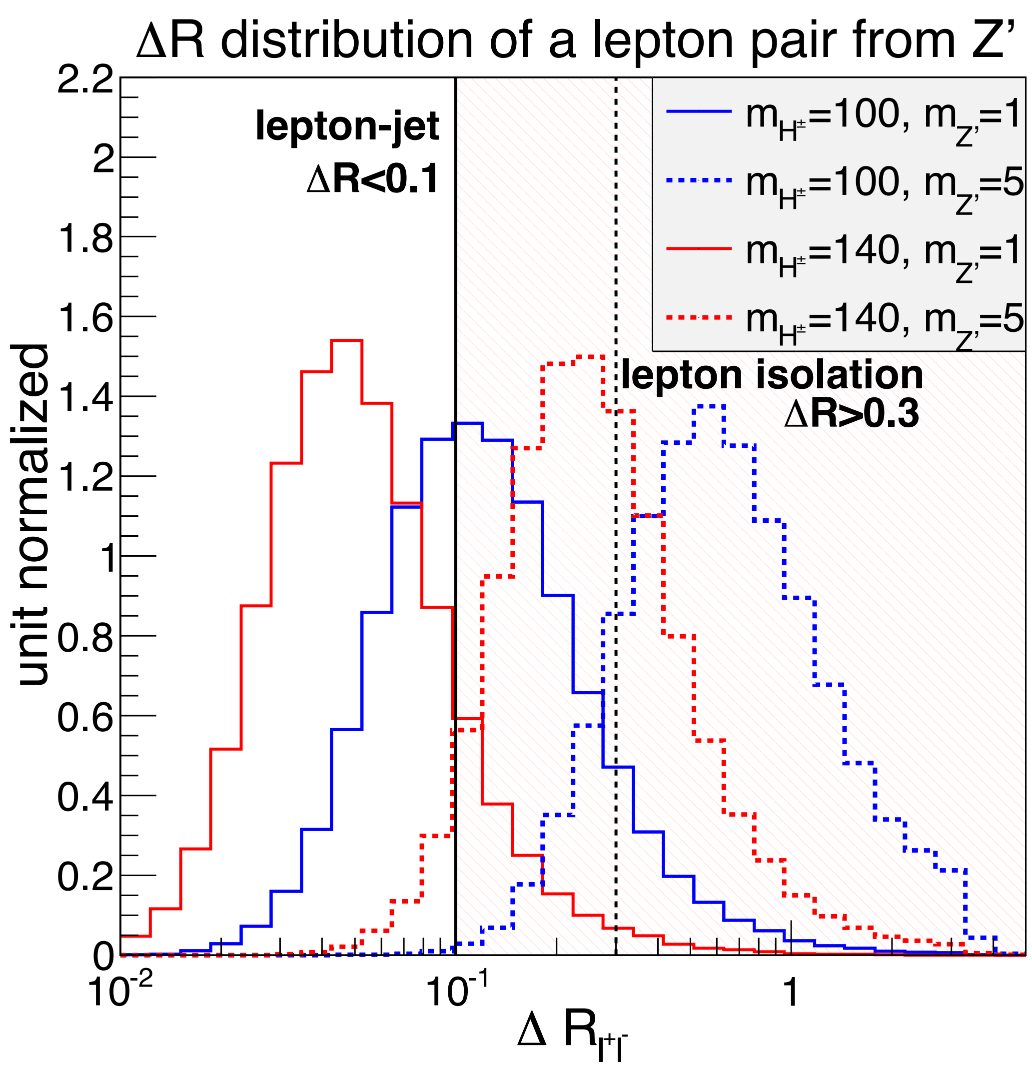

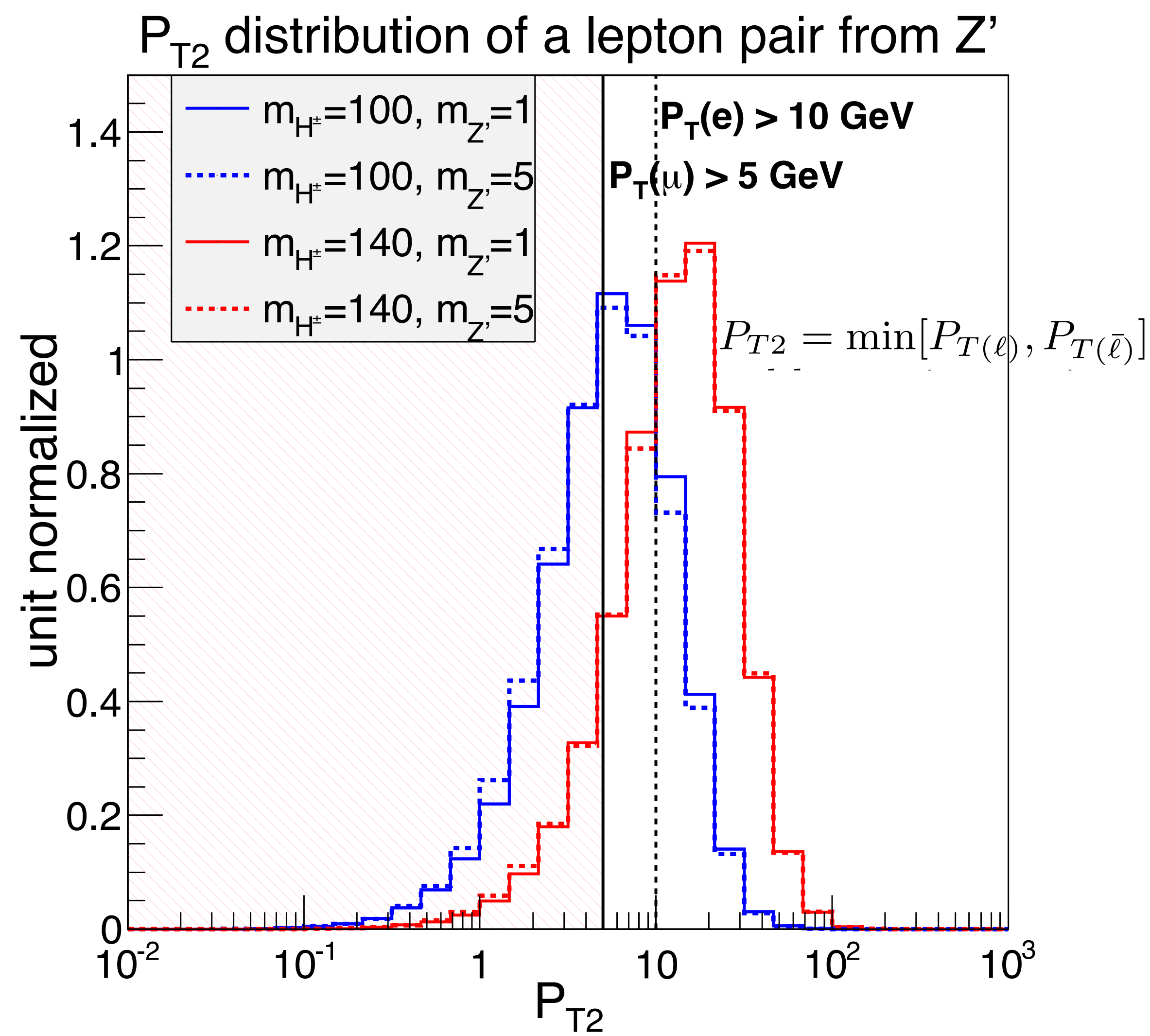

$$\Delta R^{(\text{peak})} \sim \cosh^{-1}\left(\frac{2m_{Z'}^2}{(E_\ell^{(\text{cusp})})^2}+1\right)$$

$$\eta_{H^\pm} = \cosh^{-1}\left(\frac{m_t^2 + m_{H^\pm}^2 - m_b^2}{2m_t m_{H^\pm}}\right),$$

$$\eta_{Z'} = \cosh^{-1}\left(\frac{m_{H^\pm}^2 + m_{Z'}^2 - m_W^2}{2m_{Z'} m_{H^\pm}}\right).$$

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

$$E_\ell^{(\text{cusp})} \equiv \frac{m_{Z'}}{2} e^{|\eta_{Z'}-\eta_{H^\pm}|}$$

$$P_T^{\text{peak}} \equiv \frac{1}{2} E_\ell^{(\text{cusp})}$$

Kong, Lee, Park, 2014

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: $|m_{\rm LJ} - m_{Z'}| < 0.2 \times m_{Z'}$.

- 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.

- 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 $\mathrm{BR}(Z' \to \ell^+\ell^-) = 0.2$

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

Signal and Backgrounds

- Dilepton channel
  - pt < 20 GeV, eta < 2.5 for electron   and   pt > 20 GeV, eta < 2.1 for muon
  - veto OSSF with mll < 20 GeV and | MZd - mll | < 15 GeV,   met > 40 GeV
  - at least two jets with pt > 30 GeV, eta < 2.5
- Semileptonic channel
  - pt > 30 GeV, eta < 2.5 for electron   and   pt > 26 GeV, eta < 2.1 for muon
  - at least four jets with pt1, pt2 > 45 GeV, pt3, pt4 > 35 GeV.
- Hadronic channel
  - at least 6 jets, pt > 30 GeV, eta < 2.4.
  - CMS requires pt1, pt2, pt3, pt4 > 60 GeV, pt5 > 50 GeV, pt6 > 30 GeV, and additional constrains for two b-tagged jets and a kinematic for mass reconstruction of tops and W.
- Backgrounds: ttbar + dilepton   with Kbknd=2. (Ksig=1.74 (1.84) at 8 (14) TeV.)

LJ Tagging Efficiencies

LHC [TeV]	$m_{Z'}$ [GeV]	$\epsilon_{\rm LJ}(\epsilon_{\rm (LJ+CMS)})$ [%] for signal $m_{H^\pm} = 100$ GeV	$m_{H^\pm} = 140$ GeV	$m_{H^\pm} = 160$ GeV	Mass range of $m_{\ell^+\ell^-}$ [GeV]	$\sigma^{\rm LO}_{\rm bkg}$ [pb]	$\epsilon_{\rm LJ}(\epsilon_{\rm (LJ+CMS)})$ [%] for background
8	1	16.37 (4.18/2.07)	46.77 (10.96/4.51)	52.04 (9.40/3.04)	$0.5 - 1.5$	0.617	2.05 (0.61/0.28)
	2	3.07 (0.92/0.43)	31.01 (7.64/3.13)	40.74 (7.57/2.50)	$1.0 - 3.0$	0.157	0.53 (0.19/0.08)
	5	0.02 (0.00/0.00)	2.24 (0.64/0.26)	5.55 (1.25/0.48)	$3.0 - 5.0$	0.0175	0.32 (0.10/0.04)
14	1	16.38 (4.28/2.02)	44.28 (10.73/4.37)	50.54 (9.44/3.13)	$0.5 - 1.5$	2.536	2.18 (0.60/0.30)
	2	3.33 (1.11/0.49)	29.73 (7.52/3.13)	39.31 (7.64/2.51)	$1.0 - 3.0$	0.640	0.57 (0.23/0.11)
	5	0.03 (0.01/0.00)	2.57 (0.76/0.28)	5.90 (1.40/0.47)	$3.0 - 5.0$	0.0706	0.34 (0.15/0.08)

TABLE III: Lepton-jet tagging efficiency $\epsilon_{\rm LJ}$ (%) in $pp \to bW\bar{b}W + \ell^+\ell^-$ 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 ($\epsilon_{\rm (LJ+CMS[1b])}/\epsilon_{\rm (LJ+CMS[2b])}$) are the efficiencies when we require additional selection cuts, requiring one b-tagged or two b-tagged jets as described in Appendix A 2. 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.

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Signal and Backgrounds

$m_{Z'}$ [GeV]	$m_{H^\pm}$ 100 GeV	140 GeV	160 GeV	BKG
1	40.0	86.2	58.1	69.6
2	8.2	59.9	47.8	5.0
5	0.1	5.0	9.1	0.3

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 $\mathrm{BR}(Z' \to \ell^-\ell^+) = 0.2$. Signal events were obtained with high order $\sigma_{t\bar{t}}$ with branching ratio, and the background events were obtained with tree-level simulation with $K_{\rm bkg} = 2$.

$m_{Z'}$ [GeV]	$m_{H^\pm}$ 100 GeV	140 GeV	160 GeV
1	$7.8\,\mathrm{fb}^{-1}$	$1.9\,\mathrm{fb}^{-1}$	$3.4\,\mathrm{fb}^{-1}$
2	$14.5\,\mathrm{fb}^{-1}$	$0.7\,\mathrm{fb}^{-1}$	$1.0\,\mathrm{fb}^{-1}$
5	-	$7.3\,\mathrm{fb}^{-1}$	$3.5\,\mathrm{fb}^{-1}$

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

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

$$N_{\rm sig} = \sigma_{t\bar{t}}\, 2X\, \mathrm{BR}(Z' \to \ell^+\ell^-)\, \epsilon_{\rm sig}\, L \approx 60$$

$$N_{\rm bkg} = \sigma_{\rm bkg}\, \epsilon_{\rm bkg}\, L \approx 5$$

$$N_{\rm obs} = N_{\rm sig} + N_{\rm bkg}$$

$$S_{\rm cL} = \sqrt{2N_{\rm obs}\log\left(1 + N_{\rm sig}/N_{\rm bkg}\right) - 2N_{\rm sig}} \simeq 14.6$$

- Conventional search gives Nsig~ 4 with eff=0.71%, and signal is buried in background uncertainty, which is 591.
- $N_{\rm bkg} \simeq 1.7 \times 10^4$ results in ScL=0.03.
- Good sensitivity for LHC Run II.

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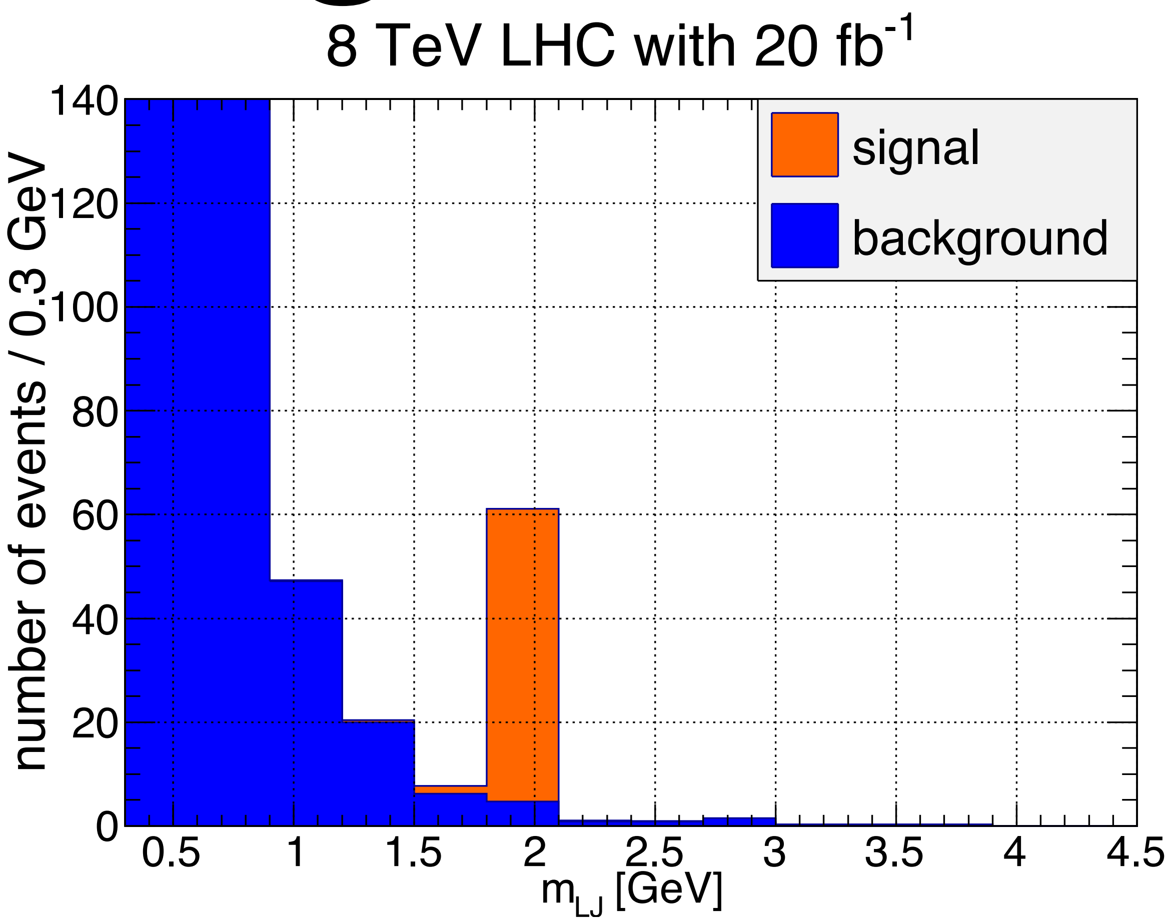
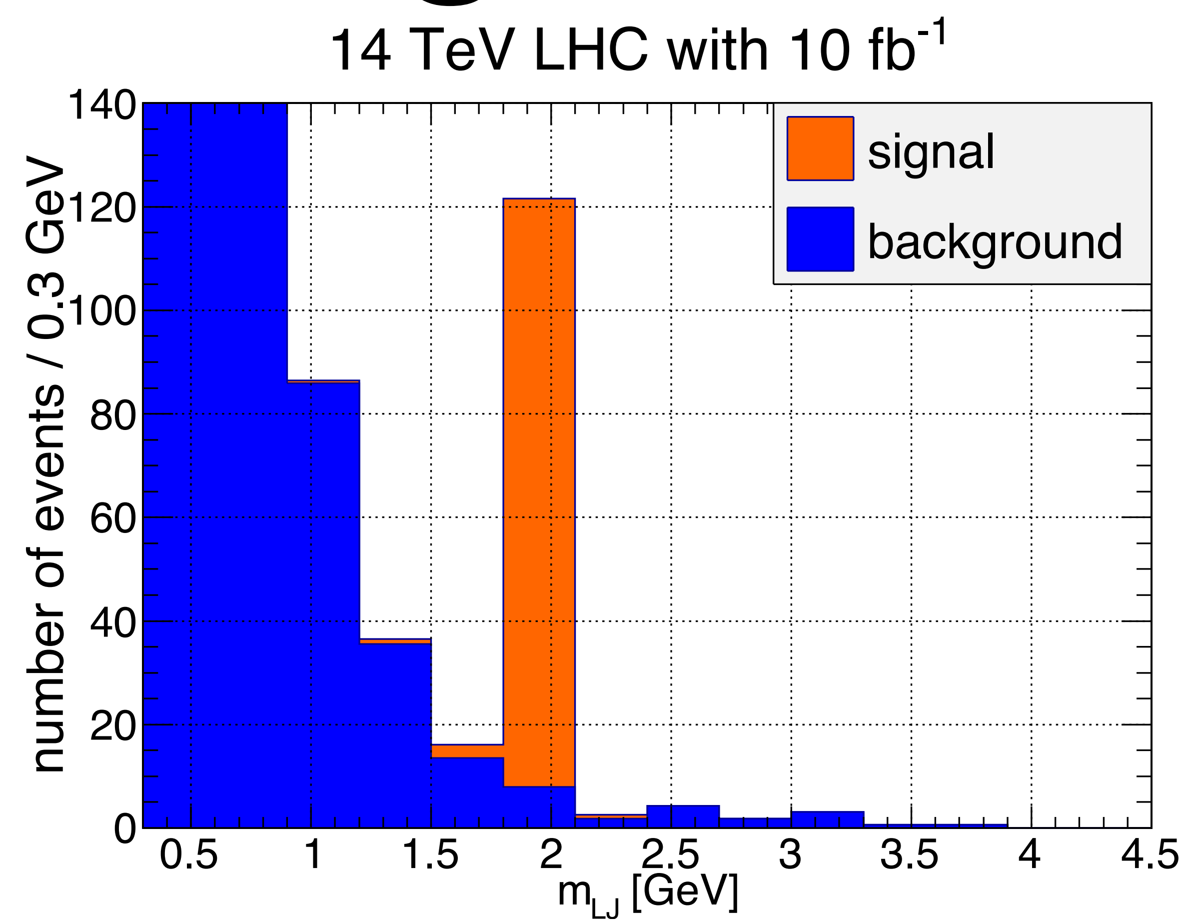
Signal and Backgrounds





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Summary

- A light Zprime (Zd) is well motivated and its search is very active at low energy experimental facilities.
- It also provides interesting collider signatures.
- We considered the production of light Zd via charged Higgs with Zd decays to a collimated lepton pair, which may be missed by conventional searches.
- 8 TeV already rules out some parameter space.
- Exciting opportunity at LHC run II.