Exploring Higgs Triplet Models via Vector Boson Scattering at the LHC

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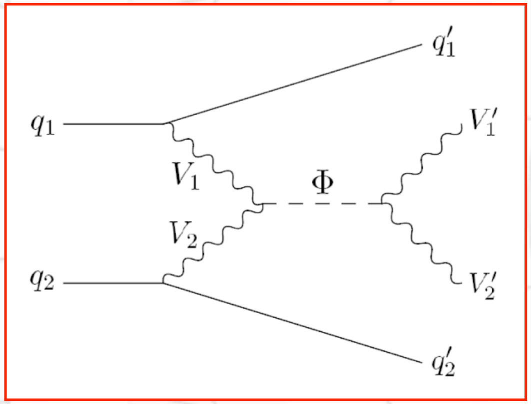
Introduction

- Need Physics beyond the SM (hierarchy, fine-tuning problems)
  $\Rightarrow$ Extended Higgs sectors

- TeV scale Higgs bosons can be produced at the LHC via vector boson scattering:
  $pp \rightarrow \Phi\, jj \rightarrow VV\, jj \quad (V = W^{\pm}, Z)$



- $\Phi^{\pm\pm}$ production via $W^{\pm}W^{\pm}$ scattering has been studied in Higgs Triplet Models G. Azuelos et al., hep-ph/0402037v1 & hep-ph/0503096v1

- Also need to study $\Phi^{\pm}$ production ($W^{\pm}Z$) and Φ^{0} production ($W^{+}W^{-}$ & ZZ)

- $W^{+}Z\Phi^{-}$ interaction not present in 2HDM (i.e. SUSY)
  $\therefore$ WZ scattering may provide evidence for Higgs triplets

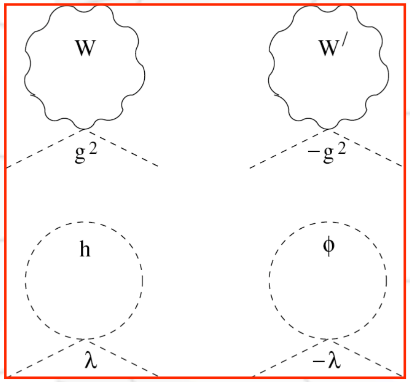
The Littlest Higgs Model

N. Arkani-Hamed et al. (2002) hep-ph/0206021

- Introduce new interactions at scale $\Lambda = 4\pi f \sim 10$ TeV with new particles at $f \sim 1$ TeV: heavy gauge bosons, heavy scalars, new heavy quarks.

- Quadratic divergences in ${M_H}^2$ are cancelled by the contributions of these new particles.

$$\boxed{\delta M_H^2 = \frac{G_F \Lambda^2}{4\sqrt{2}\pi^2}\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2\right) + \ldots}$$



- Scalar Sector:

$$\boxed{h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}}$$

Doublet

$$\boxed{\phi = \begin{pmatrix} \phi^{++} & \phi^+/\sqrt{2} \\ \phi^+/\sqrt{2} & \phi^0 \end{pmatrix}}$$

Triplet

The Littlest Higgs Model

N. Arkani-Hamed et al. (2002) hep-ph/0206021

- Higgs fields acquire vevs, triggering EWSB

$$\boxed{\langle h^0 \rangle = v/\sqrt{2}} \qquad \boxed{\langle i\phi^0 \rangle = v'}$$

$W^+_\mu W^-_\nu \Phi^0$	$-\frac{i}{2} g^2 (s_0 v - 2\sqrt{2} v') g_{\mu\nu} \simeq 0$
$Z_\mu Z_\nu \Phi^0$	$-\frac{i}{2} \frac{g^2}{c_W^2} (s_0 v - 4\sqrt{2} v') g_{\mu\nu} \simeq \sqrt{2} i \frac{g^2}{c_W^2} v' g_{\mu\nu}$
$W^+_\mu Z_\nu \Phi^-$	$-i \frac{g^2}{c_W} v' g_{\mu\nu}$
$W^+_\mu h \Phi^-$	$-i \frac{g}{2} (\sqrt{2} s_0 - s_+)(p_1 - p_2)_\mu \simeq -i g \frac{v'}{v} (p_1 - p_2)_\mu$
$W^+_\mu W^+_\nu \Phi^{--}$	$2 i g^2 v' g_{\mu\nu}$

- Couplings to vector bosons ~ v'

- EW data indicate: 1 GeV $\lesssim v' \lesssim$ 4 GeV for $f = 2$ TeV

M.-C. Chen and S. Dawson (2004) hep-ph/0311032v3

The Left-Right Symmetric Model

R.N. Mohapatra and J.C. Pati, Phys. Rev. D **11**, 566 (1975)

$$\begin{aligned}\Delta_L &= \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \\ \Delta_R &= \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}\end{aligned}$$

$$\langle \Delta_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$$

- Triplet vevs break $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$

- Δ_R couples to W_R, Z_R (heavy gauge bosons) with couplings ~ v_R
- Δ_L couples to W_L, Z_L (SM gauge bosons) with couplings ~ v_L

$$\rho = 1.0004^{+0.0027}_{-0.0007} \text{ at } 2\sigma$$

C. Amsler et al. (PDG), Phys. Lett. B **667**, 1 (2008)

- Constraints on ρ parameter $\Rightarrow$

$$v' \equiv v_L/\sqrt{2} \lesssim 2 \text{ GeV}$$

The Georgi-Machacek Model

H. Georgi and M. Machacek, Nucl. Phys. B **262**, 463 (1985)

- Introduce scalar triplets:

$$\boxed{\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}}$$

$$\boxed{\langle \chi^0 \rangle = \langle \xi^0 \rangle = v'}$$

- Triplet mass eigenstates:
  - (H_3^+, H_3^0, H_3^-) couples to fermions
  - (H_5^{++}, H_5^+, H_5^0) couples to vector bosons with couplings $\sim s_H \sim v'$

$$\boxed{s_H{}^2 \equiv \frac{8v'^2}{v^2}}$$

- $\tan\theta_H \equiv s_H / c_H \lesssim 0.5, 1, 1.7$ for $M_{H3} = 0.1, 0.5, 1$ TeV (95% C.L. from $Zb\bar{b}$)

  H. Haber and H. Logan, Phys. Rev. D **62**, 015011 (2000)

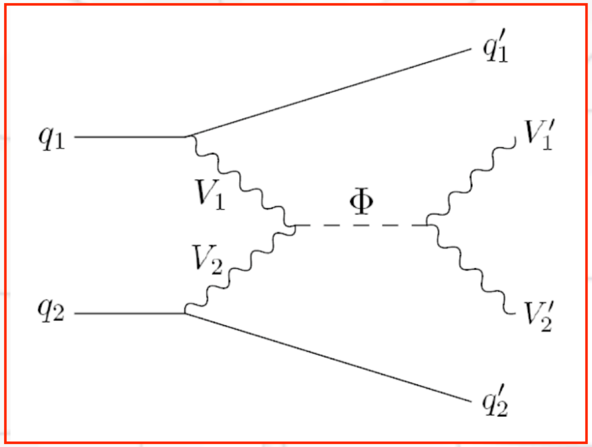
- In our calculations, we use $\tan\theta_H = 0.5 \quad \Rightarrow \quad v' = 39$ GeV

Vector Boson Scattering

$pp \rightarrow$ V V jj   (V = W$^{\pm}$, Z)

Consider “gold-plated” leptonic decay modes (smaller branching ratio, but lower QCD backgrounds than hadronic or semileptonic decays)

Decay mode $(\ell = e,\mu)$	B.R.
$W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\,\ell^{\pm}\nu$	0.047
$W^{\pm}Z \rightarrow \ell^{\pm}\nu\,\ell^{+}\ell^{-}$	0.015
$W^{+}W^{-} \rightarrow \ell^{+}\nu\,\ell^{-}\nu$	0.047
$Z\,Z \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	0.0045
$Z\,Z \rightarrow \ell^{+}\ell^{-}\nu\bar{\nu}$	0.019



Signal Characteristics:

- 2 energetic forward jets
- Low jet activity in central region
- Leptons at low rapidity
- $\sigma_{\rm sig} \sim v'^{2}$

Vector Boson Scattering

Backgrounds V. Barger et al. (1990) & J. Bagger et al. (1994, 1995)

- Irreducible EW background: $q_1 q_2 \rightarrow q_1' q_2' V V$ at $O(\alpha^4)$

$$\boxed{\sigma_{signal}(pp \rightarrow V_L V_L jj) \equiv \sigma_{total}(pp \rightarrow VVjj) - \sigma_{SM}(pp \rightarrow VVjj)}$$

- QCD background: $q_1 q_2 \rightarrow VV + QCD\ jets$ up to $O(\alpha^2 \alpha_s^2)$

- Top quark backgrounds (t →Wb):

$W^{\pm} t\bar{t}$ for $W^{\pm}W^{\pm}$ final state

$Z t\bar{t} + jet$ for $W^{\pm}Z$ final state

$t\bar{t} + jet$ for $W^{+}W^{-}$ final state

- Include $q_1 q_2 \rightarrow q_1' q_2' W^{\pm} Z \rightarrow \ell^{\pm} \ell^{\pm} + X$ as background to $W^{\pm}W^{\pm}$ channel

- MADGRAPH was used to simulate the signals and backgrounds $\left(\sqrt{s} = 14\ TeV\right)$

$\Phi^{\pm\pm}$ Production: $W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\,\ell^{\pm}\nu$

SM Backgrounds:

- EW Background:

$$pp \rightarrow W^{\pm}W^{\pm}jj,\ \mathcal{O}(\alpha^4)$$

- QCD Background:

$$pp \rightarrow W^{\pm}W^{\pm}jj,\ \mathcal{O}(\alpha^2\alpha_s^2)$$

- Top Quark Background:

$$\begin{aligned} pp &\rightarrow W^{\pm}t\bar{t}, \\ pp &\rightarrow W^{\pm}t\bar{t}j, \end{aligned}$$

with $t \rightarrow Wb$.

- $W^{\pm}Z$ Background:

$$pp \rightarrow W^{\pm}Z + nj$$

Cuts:

$$\begin{aligned} &3.0 < |y(j_{tag})| < 5.0 \\ &p_T(j_{tag}) > 40 \text{ GeV} \\ &E(j_{tag}) > 500 \text{ GeV} \\ &|y(j_{veto})| < 3.0 \\ &p_T(j_{veto}) > 100 \text{ GeV} \end{aligned}$$

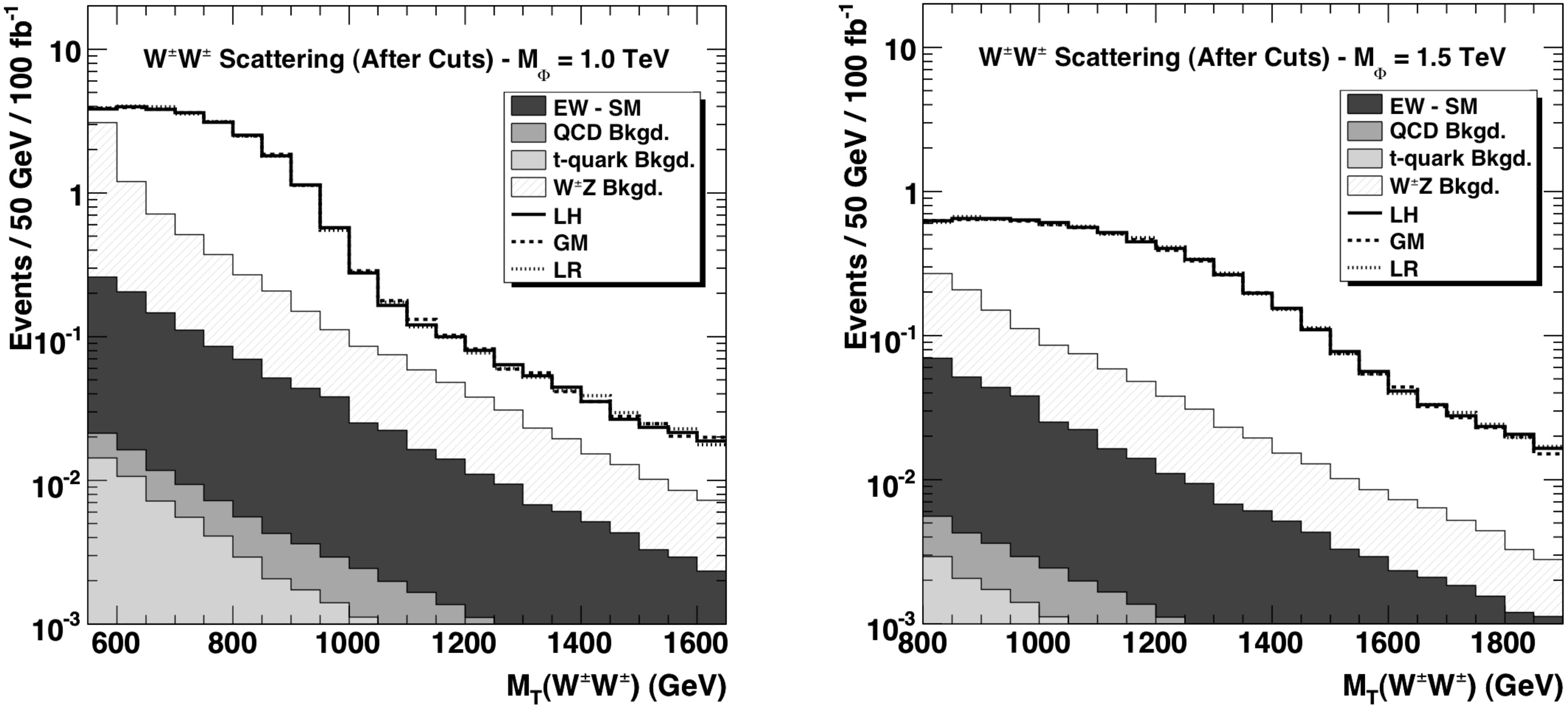
$$\begin{aligned} &|y(l)| < 2.5 \\ &p_T(l_1) > 200 \text{ GeV} \\ &p_T(l_2) > 50 \text{ GeV} \\ &\Delta p_T(ll) = |p_T(l_1) - p_T(l_2)| > 300 \text{ GeV} \\ &\Delta y(ll) = |y(l_1) - y(l_2)| < 3 \\ &M_T(WW) > 550\ (800) \text{ GeV} \\ &\quad \text{for } M_\Phi = 1.0\ (1.5) \text{ TeV} \end{aligned}$$

WW Cluster Transverse Mass:

$$M_T^2(WW) = \left[\sqrt{M^2(ll) + p_T^2(ll)} + |\not{\mathbf{p}}_T|\right]^2 - \left[\mathbf{p}_T(ll) + \not{\mathbf{p}}_T\right]^2$$

$\Phi^{\pm\pm}$ Production: $W^{\pm} W^{\pm} \to \ell^{\pm} \nu \, \ell^{\pm} \nu$

$v' = 39\ GeV$



- Identical signals in all 3 models (same $W^+W^+\Phi^{--}$ vertices)
- $\sigma_{sig} = 0.245\ (0.0848)$ fb & $\sigma_{back} = 0.0798\ (0.0204)$ fb for $M_\Phi = 1.0\ (1.5)$ TeV

$\Phi^\pm$ Production: $W^\pm Z \rightarrow \ell^\pm \nu \ell^+ \ell^-$

SM Backgrounds:

- EW Background:

$$pp \rightarrow W^\pm Zjj,\ \mathcal{O}(\alpha^4)$$

- QCD Background:

$$\begin{aligned} pp &\rightarrow W^\pm Zj,\ \mathcal{O}(\alpha^2\alpha_s) \\ pp &\rightarrow W^\pm Zjj,\ \mathcal{O}(\alpha^2\alpha_s^2) \end{aligned}$$

- Top Quark Background:

$$\begin{aligned} pp &\rightarrow Zt\bar{t}, \\ pp &\rightarrow Zt\bar{t}j, \end{aligned}$$

with $t \rightarrow Wb$.

Cuts:

$|y(l)| < 2.5$
$p_T(l_1) > 150$ GeV
$p_T(l_2) > 50$ GeV
$p_T(l_3) > 50$ GeV
$\not{p}_T > 50$ GeV
$M_T(WZ) > 900\ (1250)$ GeV
for $M_\Phi = 1.0\ (1.5)$ TeV

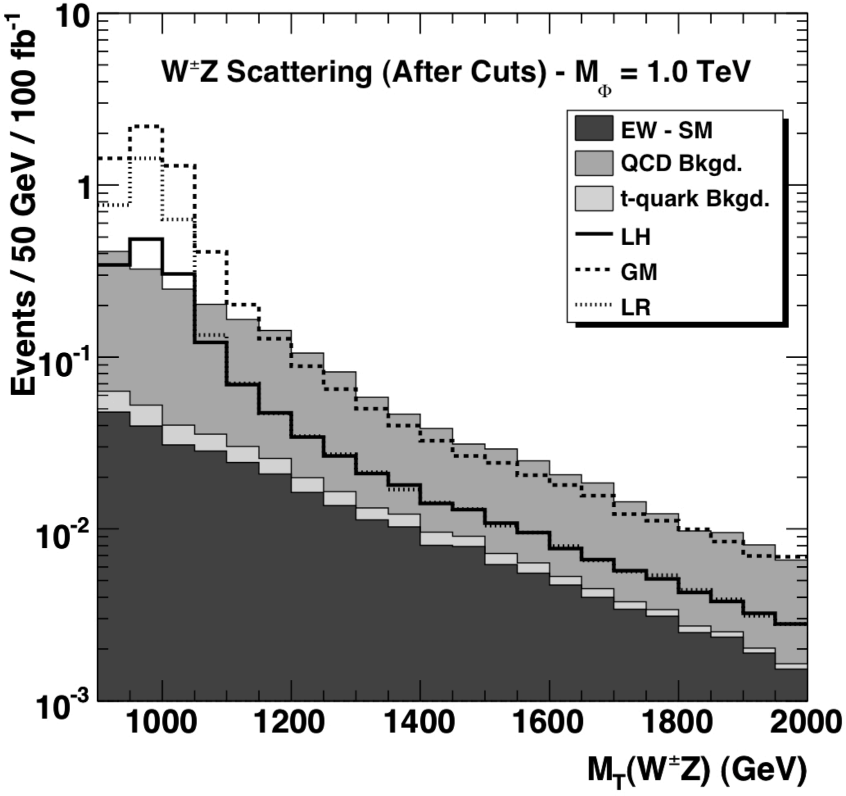
$3.0 < |y(j_{tag})| < 5.0$
$p_T(j_{tag}) > 40$ GeV
$E(j_{tag}) > 500$ GeV
$|y(j_{veto})| < 3.0$
$p_T(j_{veto}) > 100$ GeV

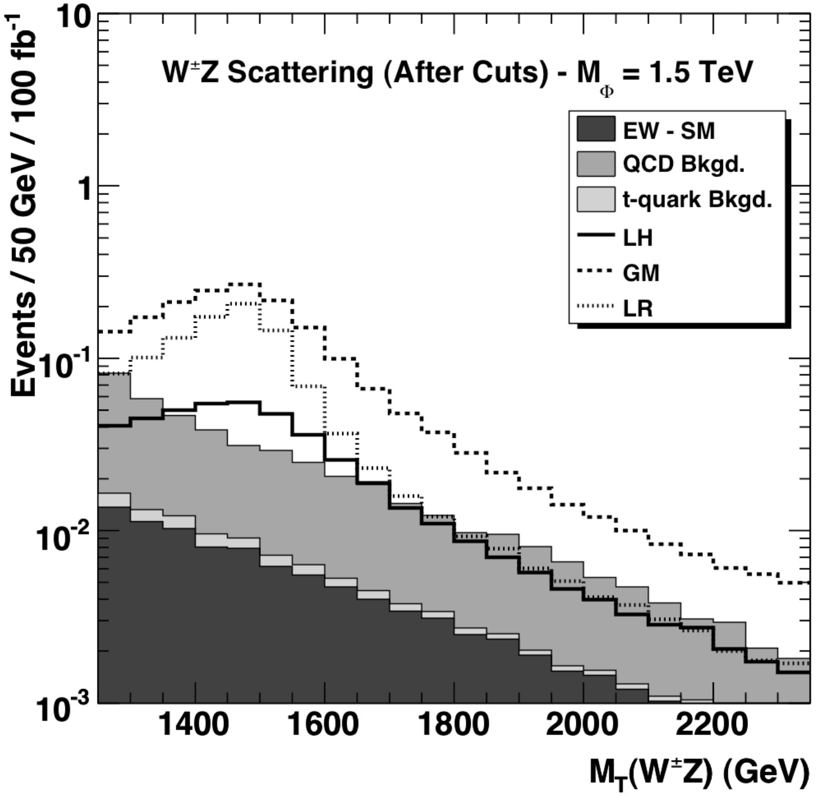
WZ Cluster Transverse Mass:

$$M_T^2(WZ) = \left[\sqrt{M^2(lll) + p_T^2(lll)} + |\not{\mathbf{p}}_T|\right]^2 - \left[\mathbf{p}_T(lll) + \not{\mathbf{p}}_T\right]^2$$

$\Phi^{\pm}$ Production: $W^{\pm}Z \to \ell^{\pm}\nu\,\ell^{+}\ell^{-}$

$v' = 39\ GeV$





Φ^0 Production: $W^+W^- \to \ell^+\nu\,\ell^-\bar{\nu}$

SM Backgrounds:

- EW Background:

$$pp \to W^+W^-jj,\ \mathcal{O}(\alpha^4)$$

- QCD Background:

$$\begin{aligned} pp &\to W^+W^-j,\ \mathcal{O}(\alpha^2\alpha_s) \\ pp &\to W^+W^-jj,\ \mathcal{O}(\alpha^2\alpha_s^2) \end{aligned}$$

- Top Quark Background:

$$\begin{aligned} pp &\to t\bar{t}, \\ pp &\to t\bar{t}j, \end{aligned}$$

with $t \to Wb$.

Cuts:

$3.0 < |y(j_{tag})| < 5.0$
$p_T(j_{tag}) > 40$ GeV
$E(j_{tag}) > 800$ GeV
$|y(j_{veto})| < 3.0$
$p_T(j_{veto}) > 60$ GeV

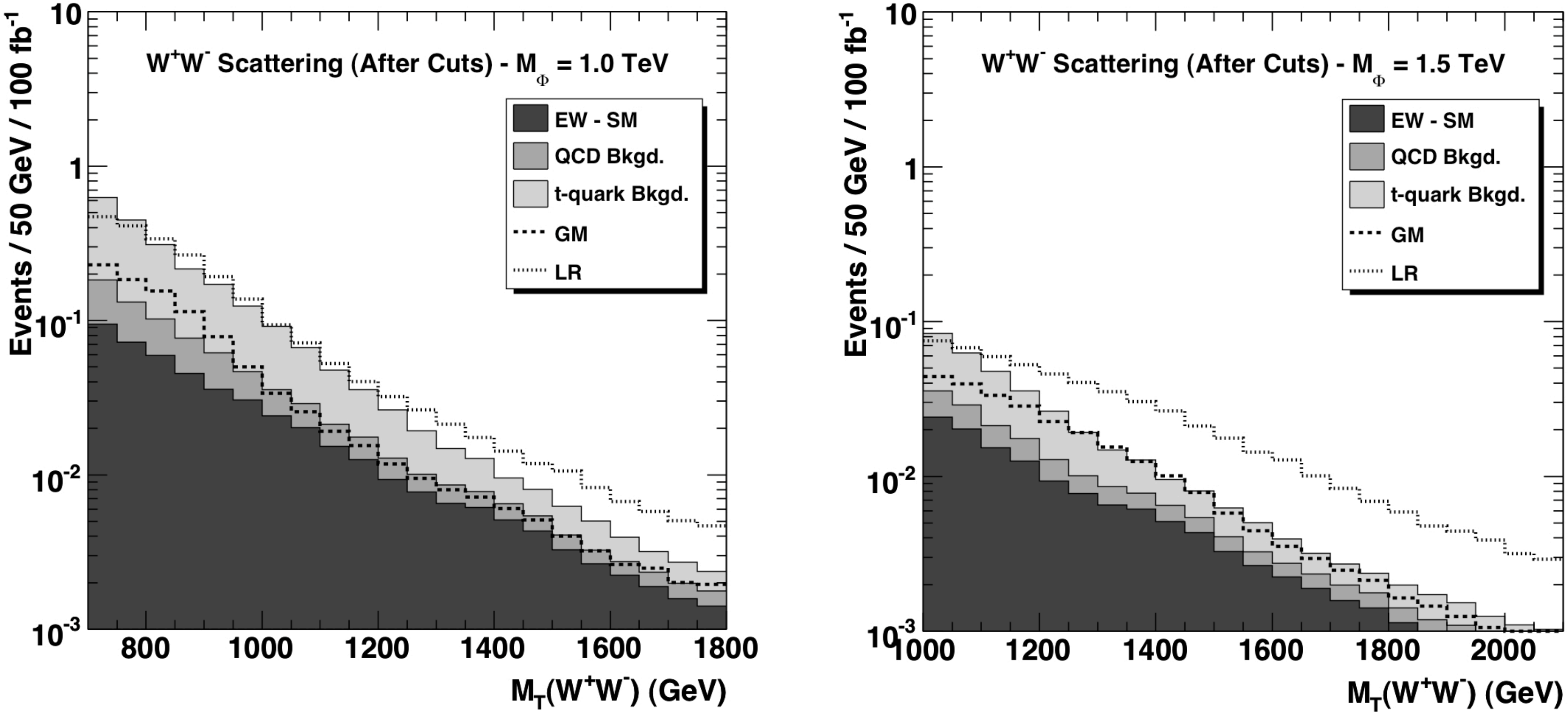
$|y(l)| < 2.5$
$p_T(l_1) > 300$ GeV
$p_T(l_2) > 150$ GeV
$\Delta p_T(ll) = |p_T(l_1) - p_T(l_2)| > 500$ GeV
$\Delta y(ll) = |y(l_1) - y(l_2)| < 3$
$M_T(WW) > 700\ (1000)$ GeV
for $M_\Phi = 1.0\ (1.5)$ TeV

WW Cluster Transverse Mass:

$$M_T^2(WW) = \left[\sqrt{M^2(ll) + p_T^2(ll)} + |\not{\mathbf{p}}_T|\right]^2 - \left[\mathbf{p}_T(ll) + \not{\mathbf{p}}_T\right]^2$$

Φ^0 Production: $W^+W^- \to \ell^+\nu\,\ell^-\overline{\nu}$

$v' = 39\ GeV$



Note: $W^+W^-\Phi^0 \approx 0$ in Littlest Higgs Model

W^+W^- final state suffers from large QCD & t-quark backgrounds

Φ^0 Production: $ZZ \to \ell^+\ell^-\ell^+\ell^-$

SM Backgrounds:

- EW Background:

$$pp \to ZZjj,\ \mathcal{O}(\alpha^4)$$

- QCD Background:

$$\begin{aligned} pp &\to ZZj,\ \mathcal{O}(\alpha^2\alpha_s) \\ pp &\to ZZjj,\ \mathcal{O}(\alpha^2\alpha_s^2) \end{aligned}$$

Cuts:

$$\begin{aligned} &3.0 < |y(j_{tag})| < 5.0 \\ &p_T(j_{tag}) > 40 \text{ GeV} \\ &E(j_{tag}) > 500 \text{ GeV} \\ &\text{no jet veto} \end{aligned}$$

$$\begin{aligned} &|y(l)| < 2.5 \\ &p_T(l) > 70 \text{ GeV} \\ &M(ZZ) > 900\ (1250) \text{ GeV} \\ &\qquad \text{for } M_\Phi = 1.0\ (1.5) \text{ TeV} \end{aligned}$$

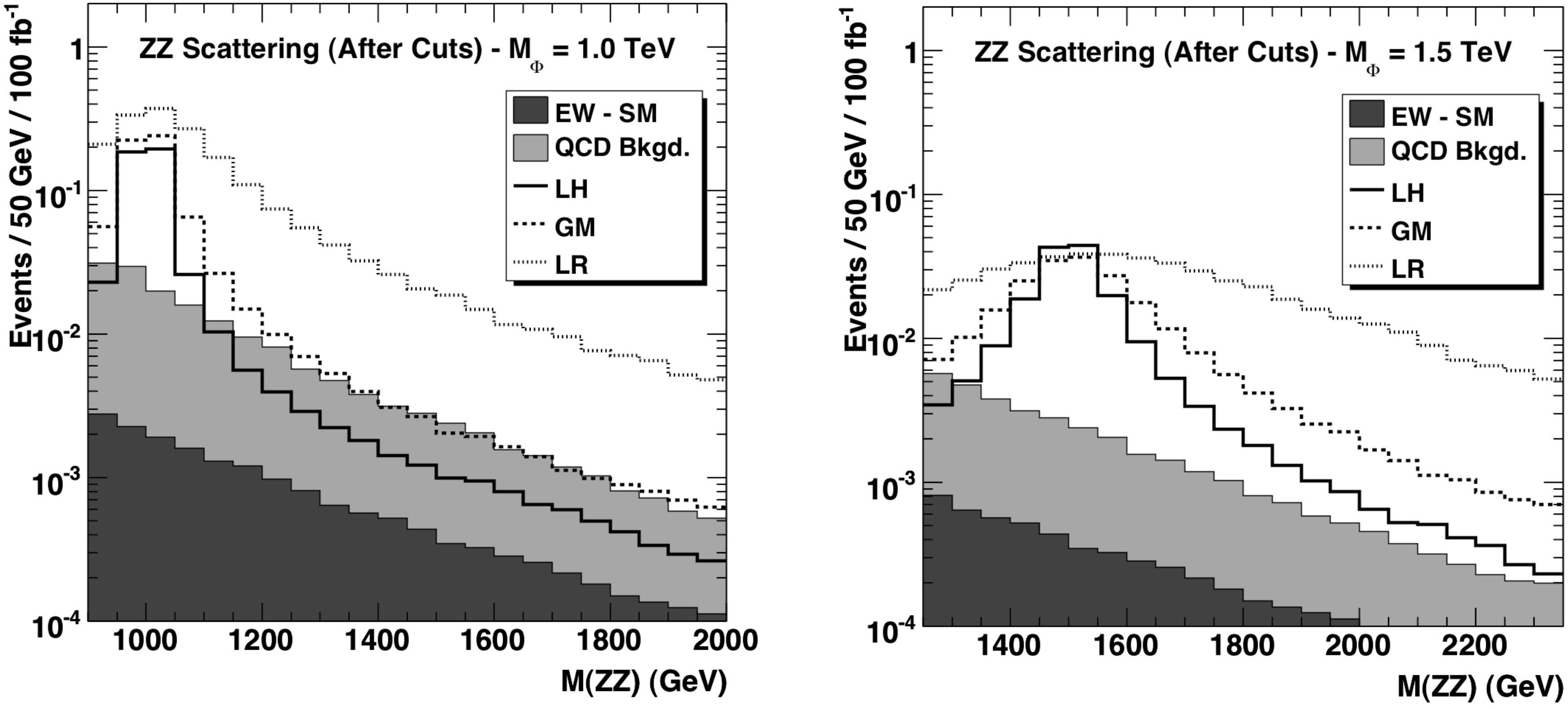
No t-quark backgrounds

Jet veto not used, as this further reduces the already small number of signal events

Can reconstruct ZZ invariant mass

Φ^0 Production: $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$

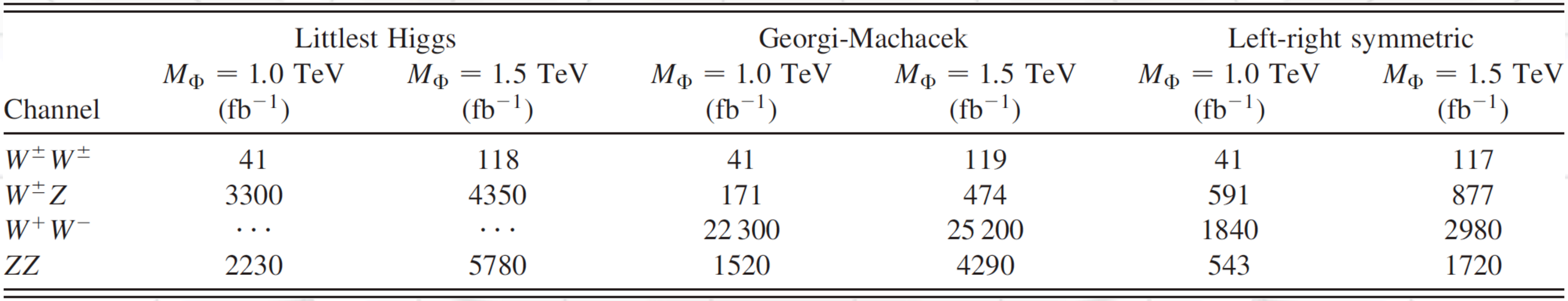
$v' = 39\ GeV$



- Low event rate in ZZ → 4 lepton channel
- $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ mode may improve Φ^0 discovery potential

Discovery Potential

Integrated luminosity required for at least 10 signal events and $S/\sqrt{B} \geq 5$



Channel	Littlest Higgs $M_\Phi = 1.0$ TeV (fb^{-1})	 $M_\Phi = 1.5$ TeV (fb^{-1})	Georgi-Machacek $M_\Phi = 1.0$ TeV (fb^{-1})	 $M_\Phi = 1.5$ TeV (fb^{-1})	Left-right symmetric $M_\Phi = 1.0$ TeV (fb^{-1})	 $M_\Phi = 1.5$ TeV (fb^{-1})
$W^\pm W^\pm$	41	118	41	119	41	117
$W^\pm Z$	3300	4350	171	474	591	877
$W^+ W^-$	⋯	⋯	22 300	25 200	1840	2980
ZZ	2230	5780	1520	4290	543	1720

- Unlikely to observe triplet during early years of LHC running (~ 10 fb^{-1} / year)
- Doubly charged (and possibly singly charged) Higgs in GM model may be observed once design luminosity (~ 100 fb^{-1} / year) is achieved

- Note: These results assume $v' = 39$ GeV, and $\sigma_{sig} \sim v'^2$

- Discovery in LH model (assuming $v' = 4$ GeV) and in L-R model (assuming $v' = 2$ GeV) would require several ab^{-1}

Conclusions

- Cross sections for Higgs triplet production depend quadratically on v'
- Discovery in the Georgi-Machacek model is more promising than in the Littlest Higgs or L-R Symmetric models (due to larger upper bound on v')

- $W^\pm W^\pm$ channel is most promising for discovery at the LHC
- $W^\pm Z$ scattering signal may be discovered for certain regions of parameter space
  $\Rightarrow$ smoking gun for Higgs triplet
- Ratio of rates in $W^\pm W^\pm$ & $W^\pm Z$ channel allows to distinguish models

- Discovery not very promising for W^+W^- final state (large QCD & t-quark backgrounds) or for $ZZ \rightarrow$ 4 leptons (small signal cross section)
- $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ mode may improve Φ^0 discovery potential
- Semi-leptonic decay modes may improve discovery potential
- High luminosity is required for some channels/models. Need to wait for SLHC.