Higgs or Higgsless?
From a unitarity viewpoint

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Higgs sector of the standard model is known to be problematic.

Is it possible to construct models without Higgs?

The role of the Higgs boson in the SM:

- Renormalizability :

  W and Z are gauge bosons (universality of weak interaction).

  Explicit breaking of electroweak gauge symmetry makes the theory *non-renormalizable*. We need, at least, one Higgs boson so as to feed W and Z masses through *spontaneous breaking*.

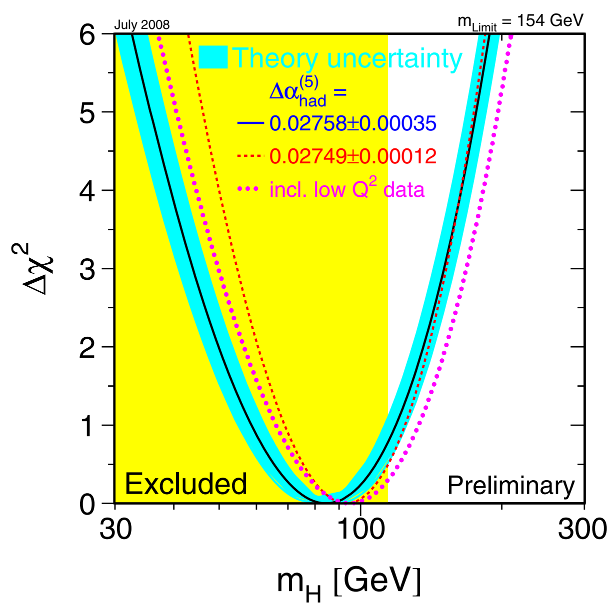
- Unitarity :

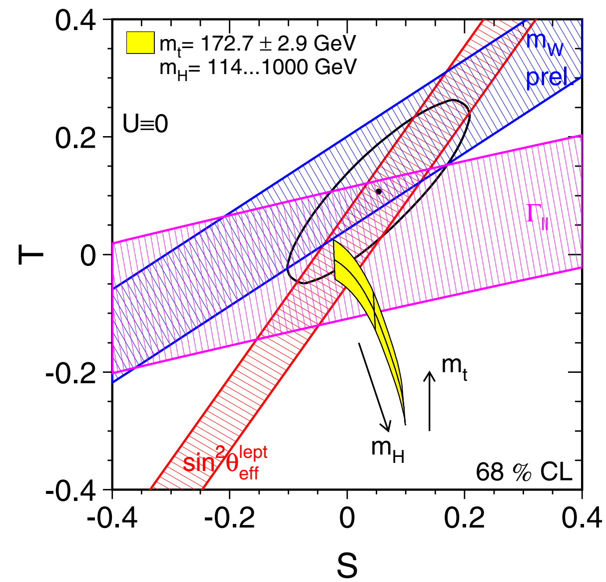
  The longitudinal W boson (W_L) scattering amplitude grows as the CM energy increases. If there is no Higgs boson, it eventually violates the unitarity.

Life without a Higgs

Renormalizability :

New physics (cutoff scale of SM) is believed to exist at TeV. In principle, renormalizability is not a primary issue in this sense. However, the lack of renormalizability usually implies a loss of robust predictability. How can we ensure the consistency with the existing precision electroweak measurements without introducing a Higgs boson then?



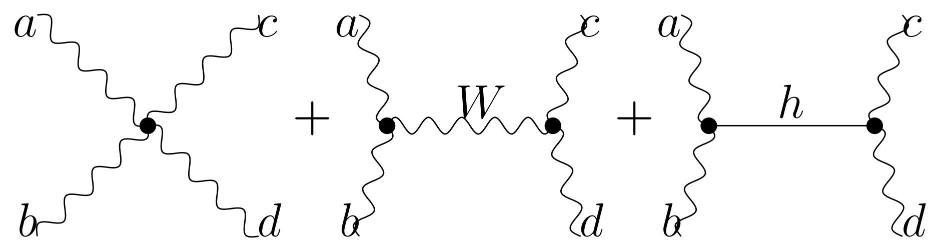


Unitarity:

B.W.Lee, C.Quigg, and H.B.Thacker

In the standard model, a Higgs boson (scalar resonance) *"unitarizes"* the $W_L W_L$ scattering amplitude:

$$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$$



$+$crossed.

For $E \gg M_W$

$$\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) = \frac{s}{v^2}\frac{M_H^2}{M_H^2 - s}\delta^{ab}\delta^{cd} + \frac{t}{v^2}\frac{M_H^2}{M_H^2 - t}\delta^{ac}\delta^{bd} + \frac{u}{v^2}\frac{M_H^2}{M_H^2 - u}\delta^{ad}\delta^{bc},$$

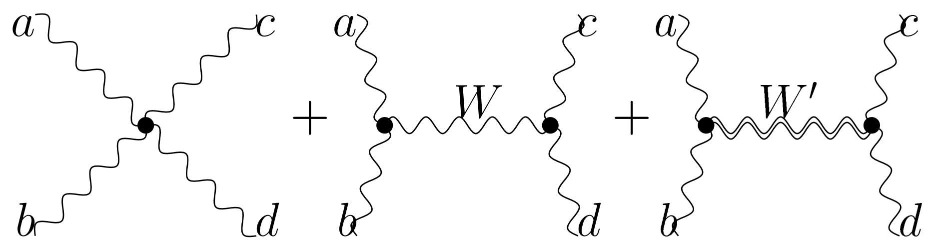
with

$$M_H^2 = \lambda v^2, \qquad v \simeq 250 \text{ GeV}.$$

- $W_L W_L$ scattering amplitude remains perturbative even at high energy scale $\sqrt{s} \gg 1$ TeV thanks to the light Higgs exchange.

Can a spin-1 resonance unitarize the $W_L W_L$ scattering amplitude?

$$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$$



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Answer: **Yes!** *if we suitably adjust WWW' coupling.*

$$\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) = \frac{1}{3v^2}\left((s-u)\frac{M_{W'}^2}{M_{W'}^2 - t} + (s-t)\frac{M_{W'}^2}{M_{W'}^2 - u}\right)\delta^{ab}\delta^{cd} + \cdots$$

Cancellation of bad high-energy behavior is achieved through *exchange of massive spin-1 particle W'*.

Note, however,

we need to introduce yet another massive vector particle W'' so as to unitarize the $W'_L W'_L \to W'_L W'_L$ amplitude ....

$$\Downarrow$$

A tower of massive vector particles:

$$W, \quad W', \quad W'', \quad W''', \cdots$$

This situation is naturally realized in gauge theory with an *extra dimension*

A tower of massive Kaluza-Klein modes

Chivukula, Dicus and He ; Csaki, Grojean, Murayama, Pilo and Terning

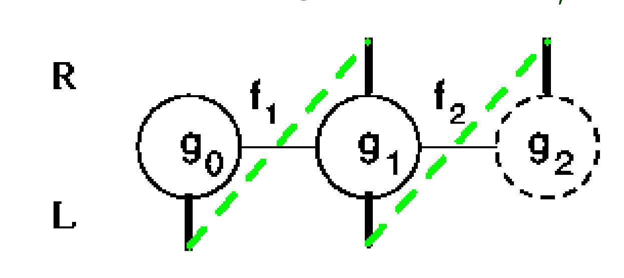
Gauge symmetry breaking through boundary conditions

Effective Theory in 4D

How can we ensure the consistency with the existing precision electroweak measurements?

A three-site Higgsless model

Chivukula, Coleppa, Di Chiara, Simmons, He, Kurachi and M.T., PRD72 075012 (2006);
See also Bando, Kugo, Yamawaki's HLS model Phys.Rep.164,217(1988).



$SU(2) \times SU(2) \times U(1)$ gauge theory

- The gauge sector is precisely that of the BESS model. Casalbuoni et al., PLB 155 95 (1985))
- Fermion mass terms:

$$\mathcal{L}_f = -\lambda f_1 \bar{\psi}_{L0} U_1 \psi_{R1} - M \bar{\psi}_{R1} \psi_{L1} - f_2 \bar{\psi}_{L1} U_2 \begin{pmatrix} \lambda'_u & \\ & \lambda'_d \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} + \text{h.c.}.$$

- For simplicity, we examine the case $f_1 = f_2 = \sqrt{2}v$ and work in the limit

$$\frac{g_0}{g_1} \ll 1, \quad \frac{g_2}{g_1} \ll 1, \qquad \text{and thus,} \quad g_W \simeq g_0, \quad g_Y \simeq g_1.$$

Fermion mass matrix: (seesaw like)

$$\begin{pmatrix} m & 0 \\ M & m'_f \end{pmatrix} \equiv \sqrt{2}\tilde{\lambda} v \begin{pmatrix} \varepsilon_L & 0 \\ 1 & \varepsilon_{fR} \end{pmatrix}, \qquad \varepsilon_L \equiv \frac{\lambda}{\tilde{\lambda}}, \quad \varepsilon_{fR} \equiv \frac{\lambda'_f}{\tilde{\lambda}}$$

Light fermion mass:

$$m_f \simeq \frac{m m'_f}{\sqrt{M^2 + m'^2_f}} = \frac{\sqrt{2}\tilde{\lambda} v \varepsilon_L \varepsilon_{fR}}{\sqrt{1 + \varepsilon_{fR}^2}}$$

and its eigenstate (or delocalization)

$$\psi_L^{f,\text{light}} \simeq -\left(1 - \frac{\varepsilon_L^2}{2}\right)\psi_{L0}^f + \varepsilon_L \psi_{L1}^f$$

where we assumed $\varepsilon_{fR} \ll 1$.

Heavy (KK) fermion mass:

$$M_{f,KK} \simeq \sqrt{M^2 + m'^2_f} = \sqrt{2}\tilde{\lambda} v \sqrt{1 + \varepsilon_{fR}^2}$$

For $M \gg v$, we can integrate out the heavy KK-fermion. The fermion delocalization effect can then be replaced by an operator

$$\mathcal{L}'_f = -x_1 \bar{\psi}_L (i \not{D} U_1 \cdot U_1^\dagger) \psi_L, \qquad x_1 \equiv \varepsilon_L^2, \quad \varepsilon_L = \frac{\sqrt{2}\lambda v}{M}$$

ψ_L is a left-hand fermion at site-0,

$$D_\mu \psi_L = \partial_\mu \psi_L - i g_0 W_{0\mu} \psi_L.$$

S-parameter

$$S = \frac{4\pi}{g_1^2}\left(1 - \frac{2g_1^2}{g_0^2} x_1\right)$$

vanishes in the ideal delocalization limit:

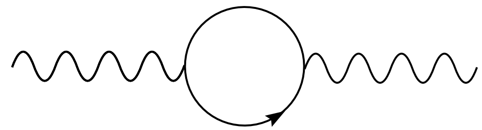
$$x_1 = \frac{g_0^2}{2g_1^2}, \qquad g_{W'ff} = 0.$$

c.f. Anichini, Casalbuoni, and De Curtis, PLB348 521 (1995).

Tree level is not enough...

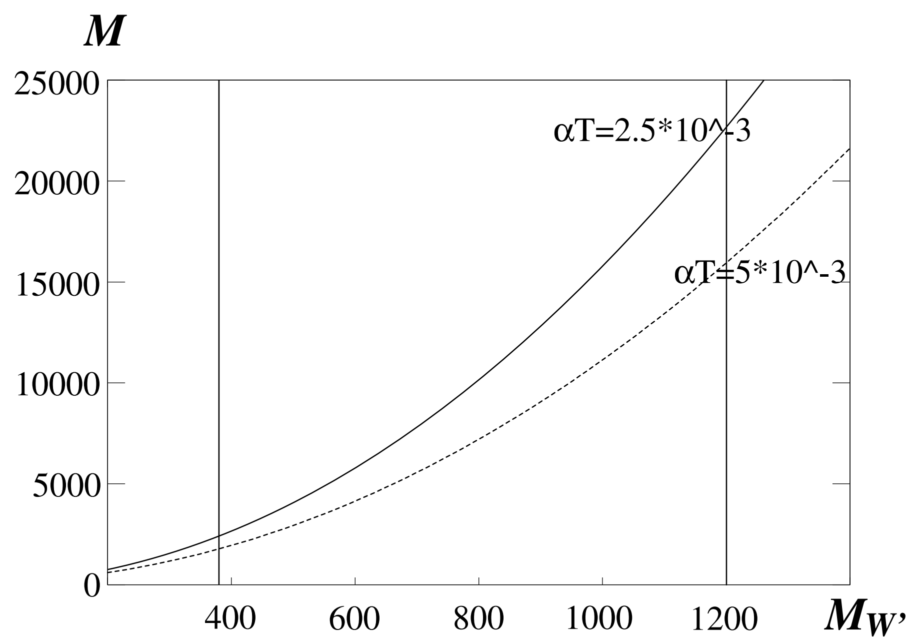
Fermionic one-loop corrections to T parameter

Chivukula, Coleppa, Di Chiara, Simmons, He, Kurachi and M.T., PRD72 075012 (2006)



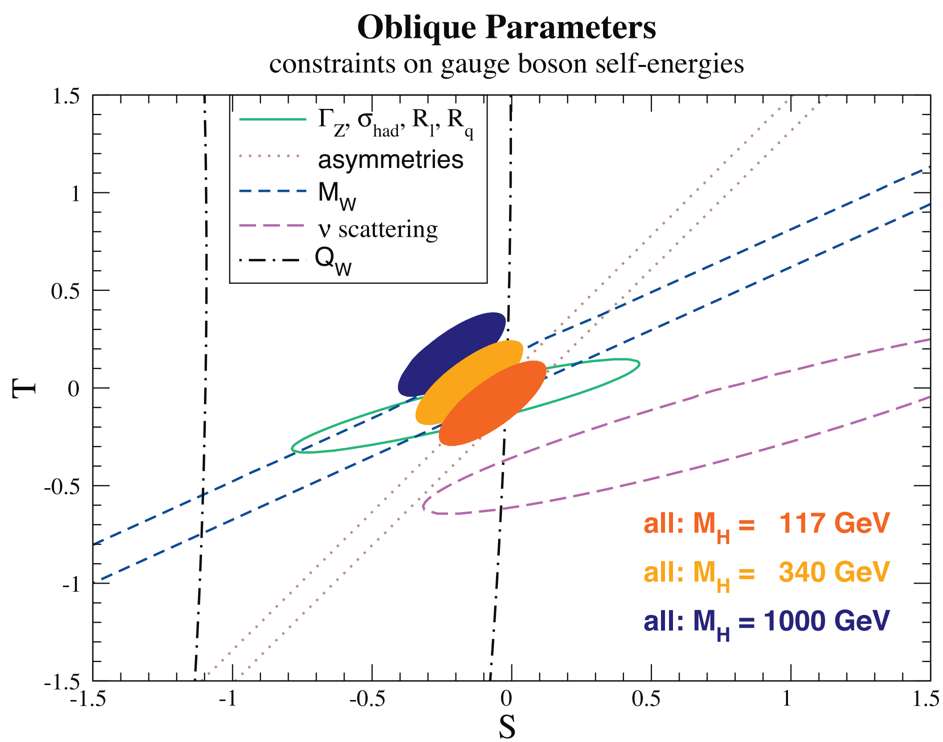
$$\alpha T \approx \frac{1}{16\pi^2}\frac{{m'_t}^4}{M^2 v^2} = \frac{1}{16\pi^2}\frac{\varepsilon_{tR}^4 M^2}{v^2} \ .$$

Assuming ideal delocalization of fermions, we find



Allowed region in S-T depends on the *"reference" Higgs mass* $M_{H,\mathrm{ref}}$.

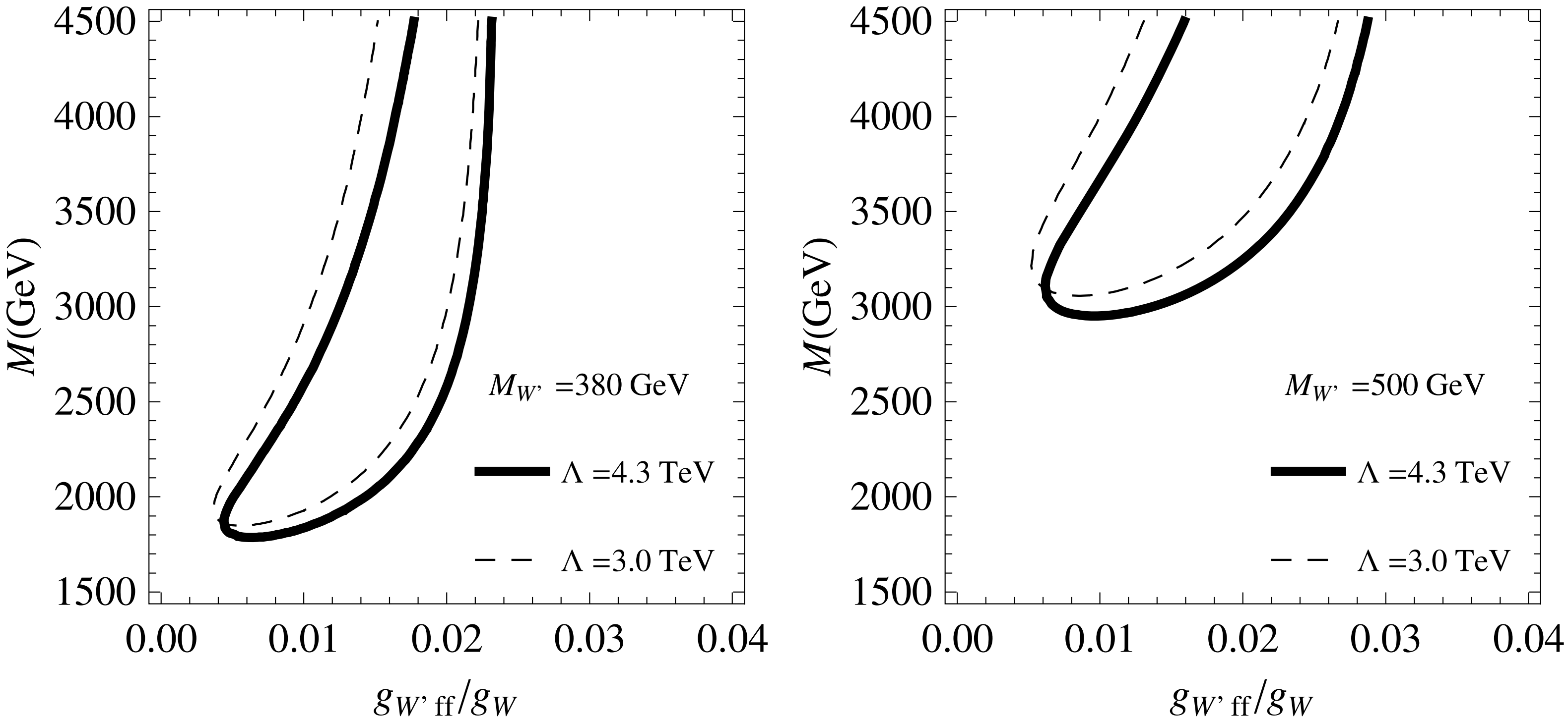
$$S \equiv S_{\mathrm{BSM}} - S_{\mathrm{SM}}(M_{H,\mathrm{ref}}), \qquad T \equiv T_{\mathrm{BSM}} - T_{\mathrm{SM}}(M_{H,\mathrm{ref}})$$



$\alpha T < 2.5 \times 10^{-3}$ (5×10^{-3}) for $M_{H,\mathrm{ref}} = 340$GeV $(1000$GeV$)$.

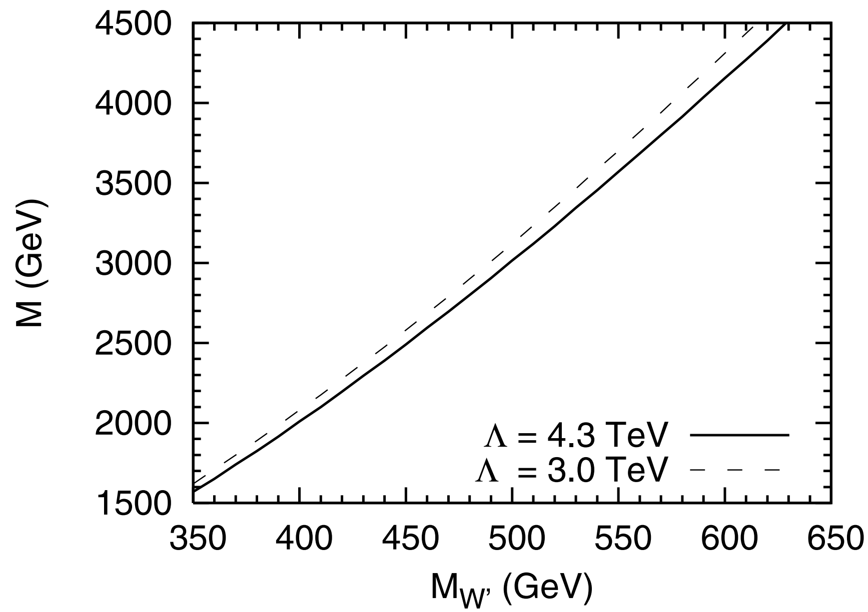
Which $M_{H,\mathrm{ref}}$ should we use? *We need to evaluate bosonic one-loop diagrams in order to get more precise bounds.*

One loop constraint from precision electroweak measurements (95%CL):



T. Abe, S. Matsuzaki, and M.T., PRD78, 055020 (2008)

The cutoff dependence is small.
Tiny (but non-zero) $W'ff$ coupling.



- $M_{W'} \gtrsim 380$MeV is required by the ZWW measurement at LEP2.
- The cutoff Λ should satisfy

$$\Lambda \lesssim 4\pi f_1 = 4\pi f_2 = 4.3\text{TeV},$$

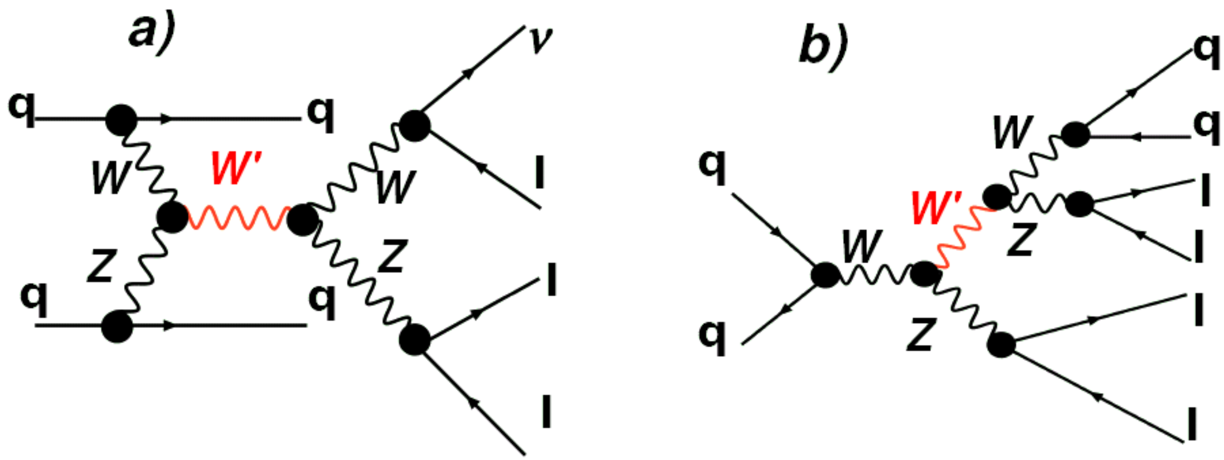
which implies

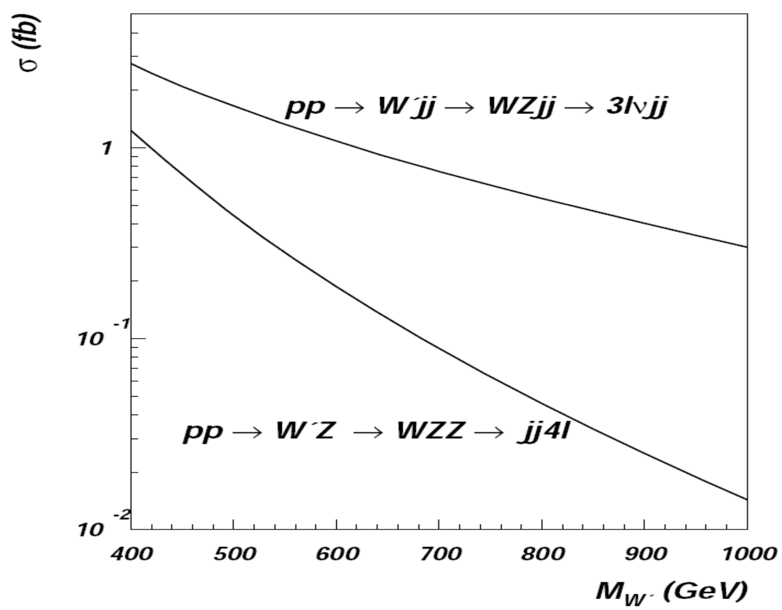
$$M_{W'} \lesssim 600\text{GeV}$$

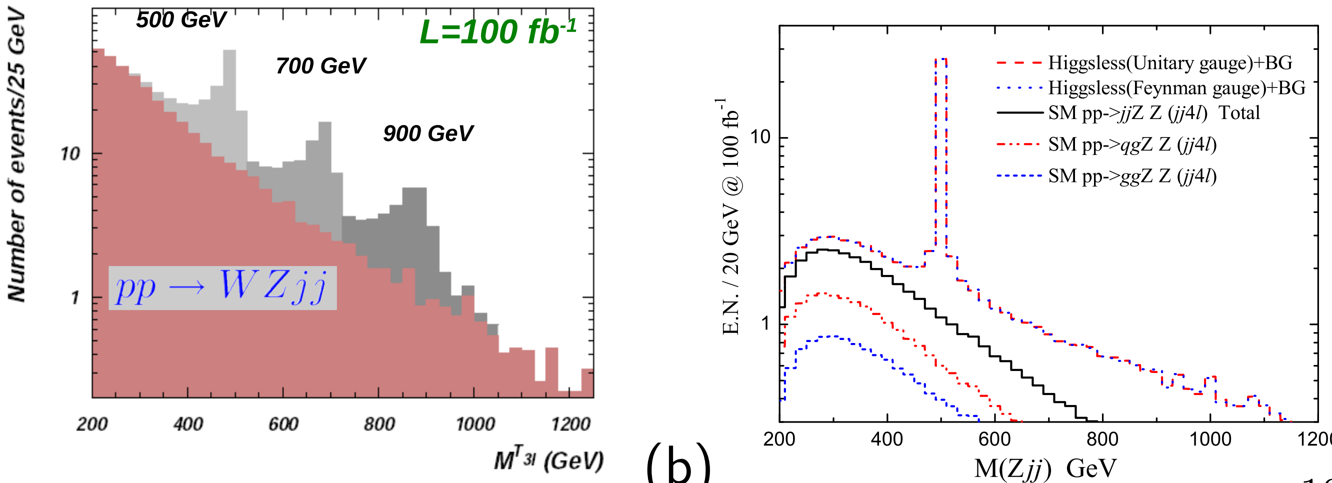
LHC phenomenology of W'

W' production cross sections through $W'WZ$ vertex:

H.-J. He et al., arXiv:0708.2588

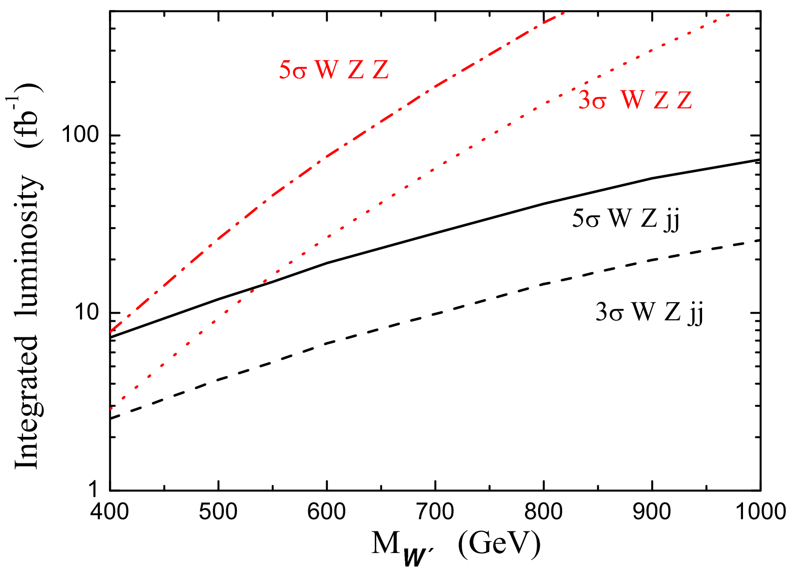






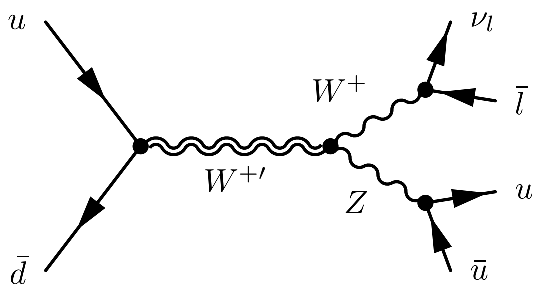
(a) (b)

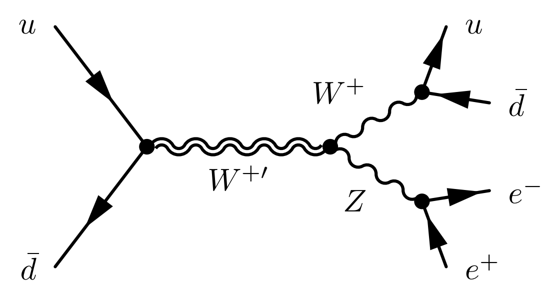
100fb^{-1}

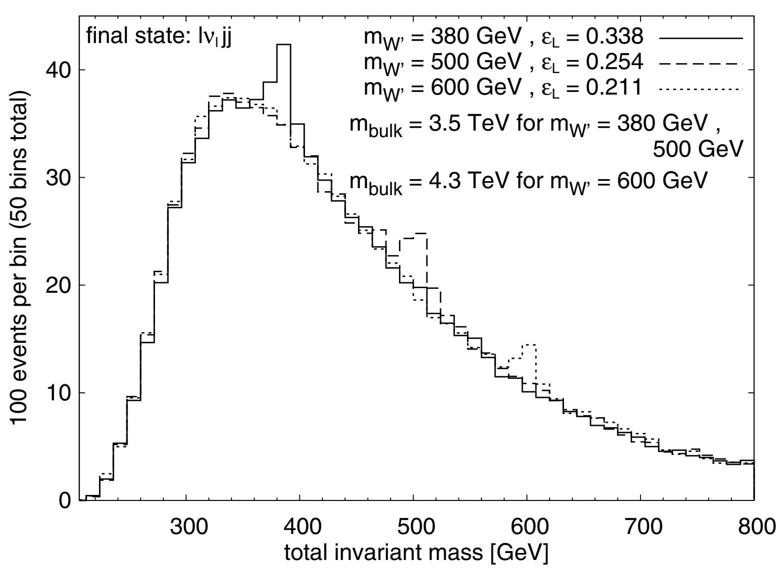


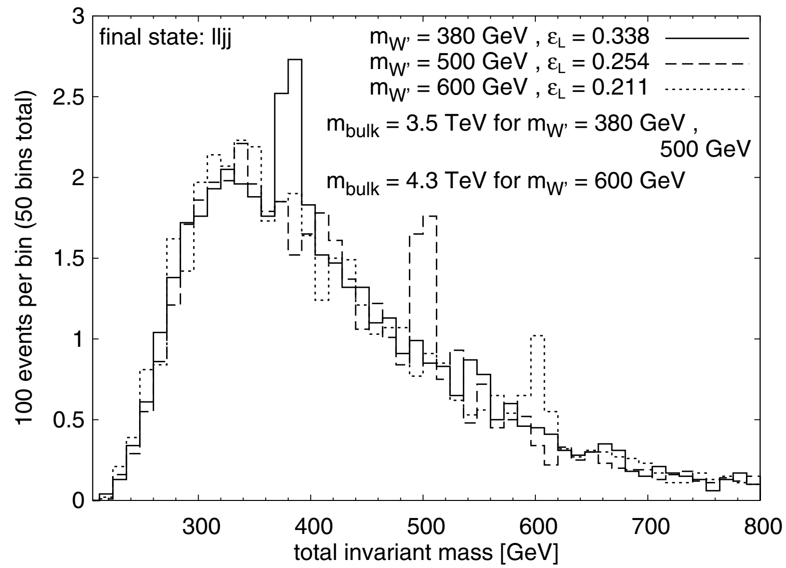
W' production cross sections through $W'ff$ vertex:

T. Ohl and C. Speckner, arXiv:0809.0023









100fb^{-1}

Summary

- Higgsless theory is an interesting alternative to the standard model Higgs, achieving tree level unitarity at 1TeV.
- We analyzed an effective theory (three site Higgsless model) at one-loop level and found the model is consistent with the available precicion electroweak measurements. The allow ranges of the KK gauge boson coupling $g_{W'ff}$, the KK gauge boson mass $M_{W'}$, and the KK quark/lepton masses M are severely constrained, however.
- The KK gauge boson W' will be discovered at LHC with $\int \mathcal{L} = 20 \sim 30$ fb^{-1}.
- Although, in the case of flavor universal KK-fermion mass, FCNC is protected by GIM mechanism, more study on the flavor physics should be done in the Higgsless theory.