ヒッグスレス模型と余剰次元

実験理論共同研究会「*LHC* が切り拓く新しい物理」

東京大学 *(4* 月 *1* 日〜*3* 日*)*

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2009 年 *4* 月 *2* 日

Why do we need a 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*.

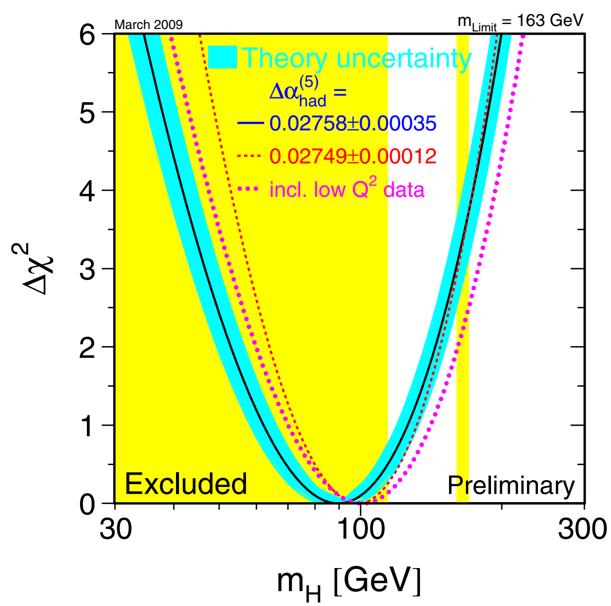
- Unitarity :

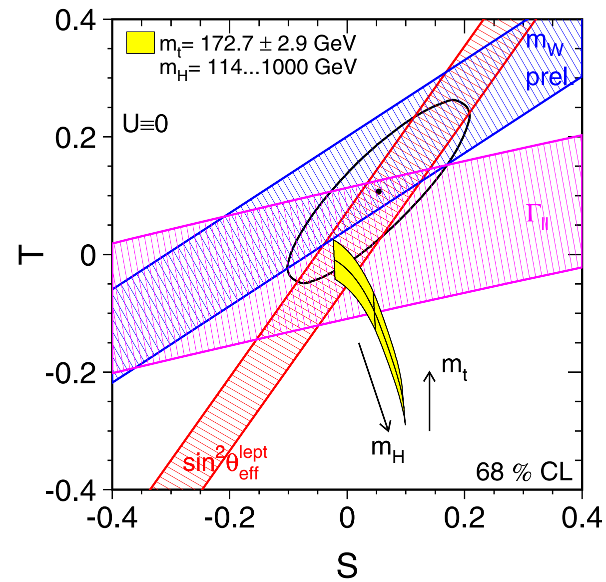
  The longitudinal W boson (W_L) scattering amplitude grows as the CM energy increases. If there is no Higgs boson, it eventually violates the unitarity.

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?



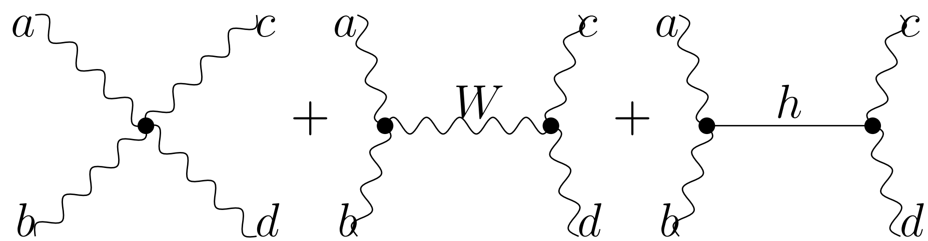


Unitarity:

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

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

$$i\mathcal{M}(W_L^aW_L^b \to W_L^cW_L^d) =$$



+crossed.

For $E \gg M_W$

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

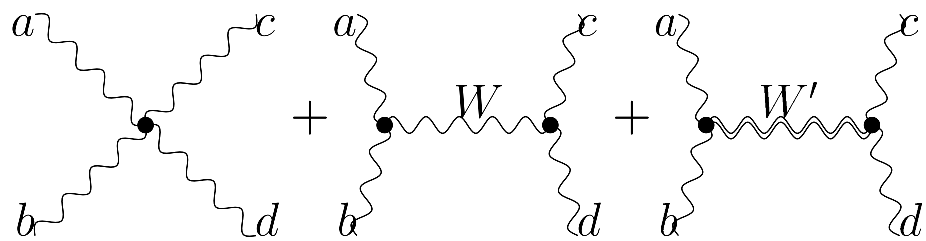
with

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

- W_LW_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?

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



$+$crossed.

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

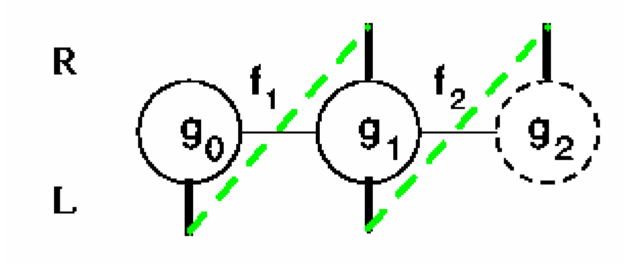
Gauge symmetry breaking through boundary conditions

Effective Theory

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).



- $SU(2)_0 \times SU(2)_1 \times U(1)_2$ のゲージ模型。"KK ゲージボソン" W', Z' を含む。
- The gauge sector is precisely that of the BESS model. Casalbuoni et al., PLB 155 95 (1985))
- 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 terms:

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

"KK クォーク", "KK レプトン" を含む。

Fermion mass matrix: (seesaw like)

$$\begin{pmatrix} m & 0 \\ M & m'_f \end{pmatrix}$$

Light fermion mass:

$$m_f \simeq \frac{m m'_f}{\sqrt{M^2 + m'^2_f}}$$

Heavy (KK) fermion mass:

$$M_{f,KK} \simeq \sqrt{M^2 + m'^2_f} \simeq M$$

S-parameter

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

vanishes in the *ideal delocalization* limit:

$$x_1 = \frac{g_0^2}{2g_1^2}$$

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

W' is almost fermiophobic:

$$g_{W'ff} = \frac{g_0^2}{2g_1}\left(-1 + \frac{2g_1^2}{g_0^2}x_1\right)$$

Hierarchy:

$$M_W, M_Z \ll M_{W'}, M_{Z'}, \quad (g_0 \ll g_1), \qquad W', Z' \text{ : KK gauge bosons}$$

$$m_t, m_b \ll M_T, M_B, \quad (m, m'_f \ll M), \qquad T, B \text{ : KK quarks}$$

$Z'WW$ and $W'WZ$ couplings are suppressed by $M_W/M_{W'}$:

$$g_{Z'WW} = -\frac{e}{2s}\frac{M_W}{M_{W'}}, \qquad g_{W'WZ} = -\frac{e}{2sc}\frac{M_W}{M_{W'}}$$

Triple gauge vertex (TGV):

$$\mathcal{L}_{\rm TGV} = -ie\frac{c}{s}(1+\Delta\kappa_Z)W_\mu^+ W_\nu^- Z^{\mu\nu}, \qquad \Delta\kappa_Z = \frac{1}{8c^2}\frac{g_0^2}{g_1^2}$$

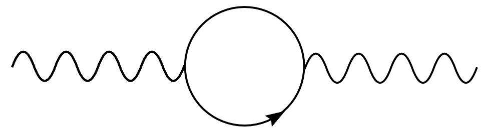
TGV bound from LEP2:

$$M_{W'} \gtrsim 380 \text{ GeV}$$

Tree level is not enough...

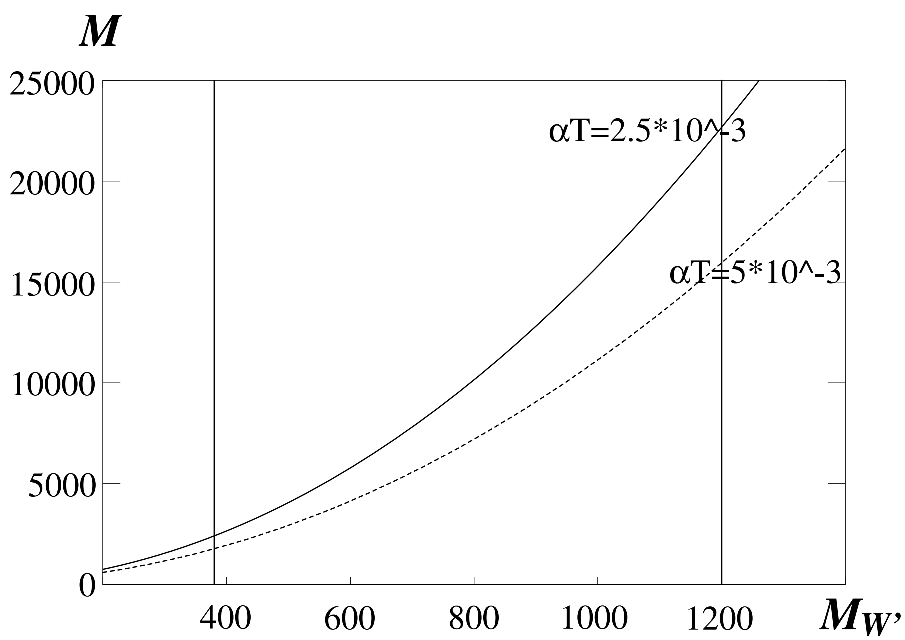
Fermionic one-loop corrections to T parameter

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



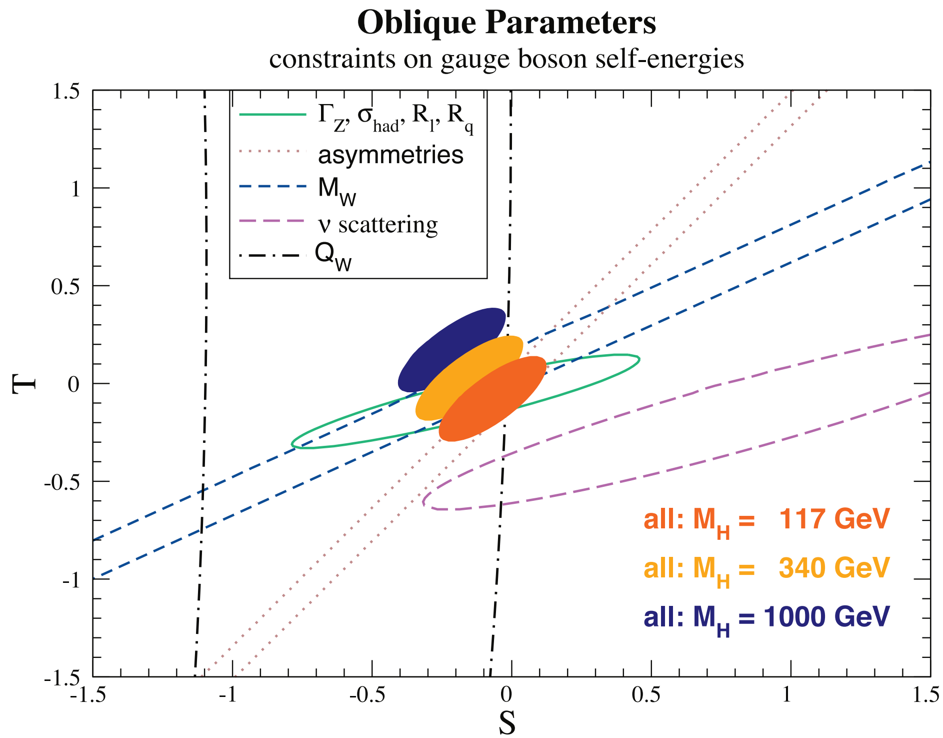
$$\alpha T \approx \frac{1}{16\pi^2}\frac{{m'_t}^4}{M^2 v^2} = \frac{1}{16\pi^2}\frac{\varepsilon_{tR}^4 M^2}{v^2} \; .$$

Assuming ideal delocalization of fermions, we find



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

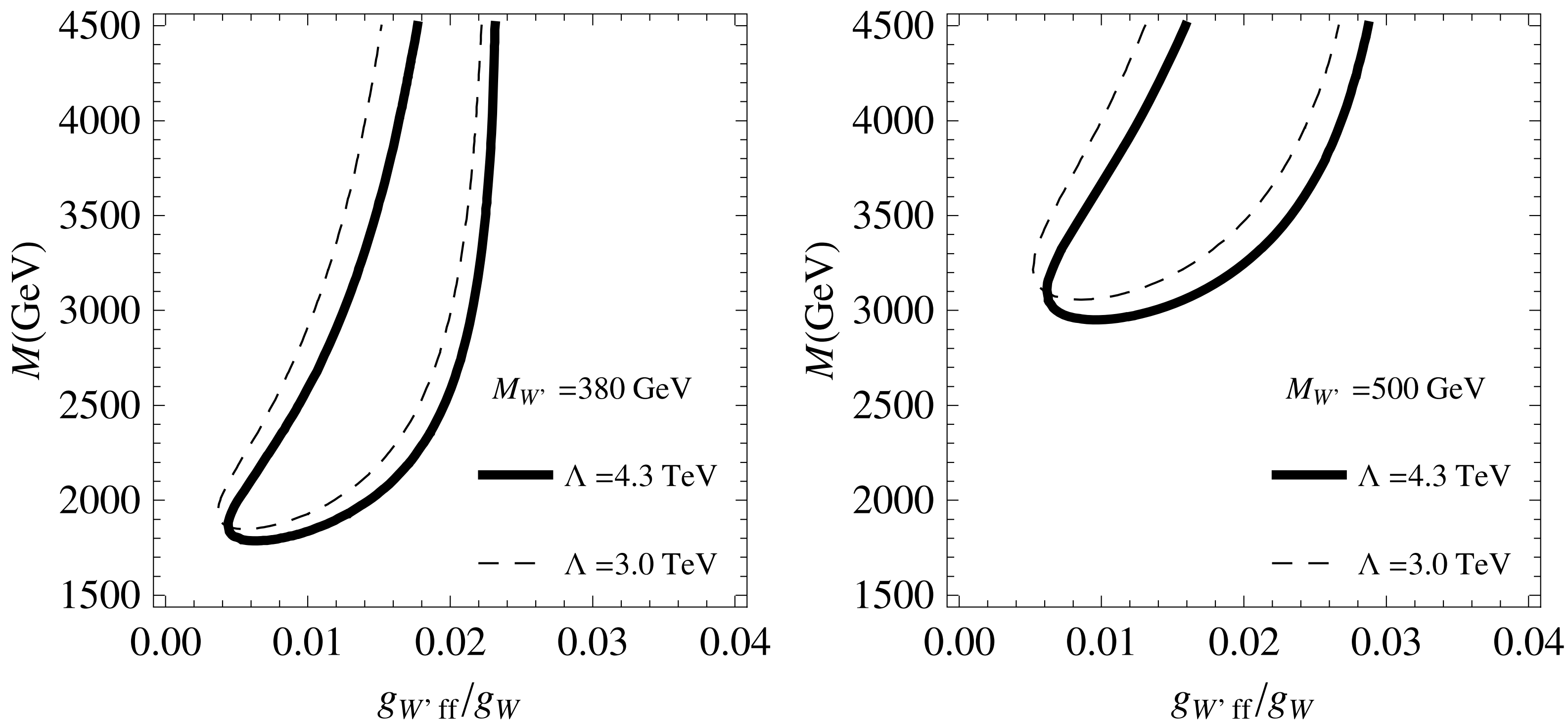
$$S \equiv S_{\mathrm{BSM}} - S_{\mathrm{SM}}(M_{H,\mathrm{ref}}), \qquad T \equiv T_{\mathrm{BSM}} - T_{\mathrm{SM}}(M_{H,\mathrm{ref}})$$



$\alpha T < 2.5 \times 10^{-3}$ (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.*

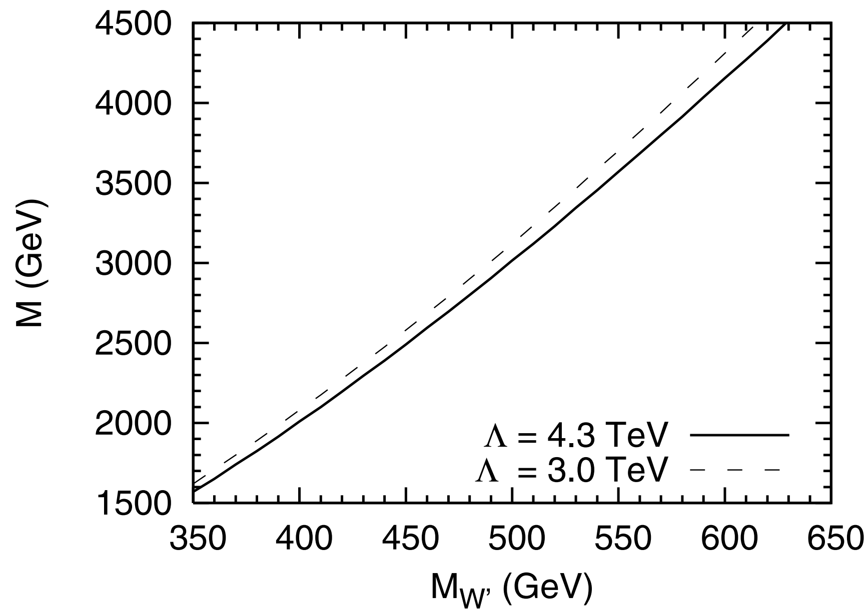
One loop constraint from precision electroweak measurements (95%CL):



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

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

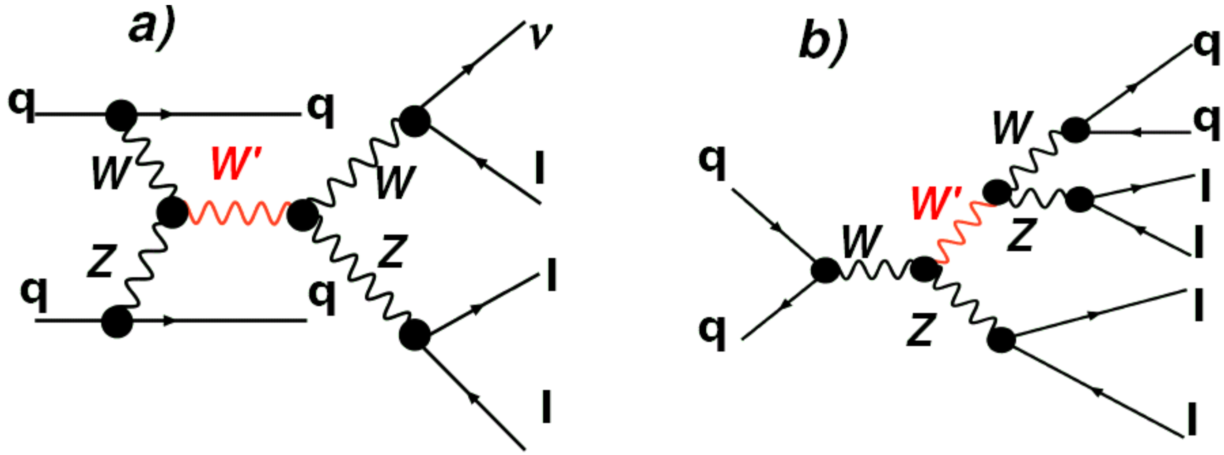
which implies

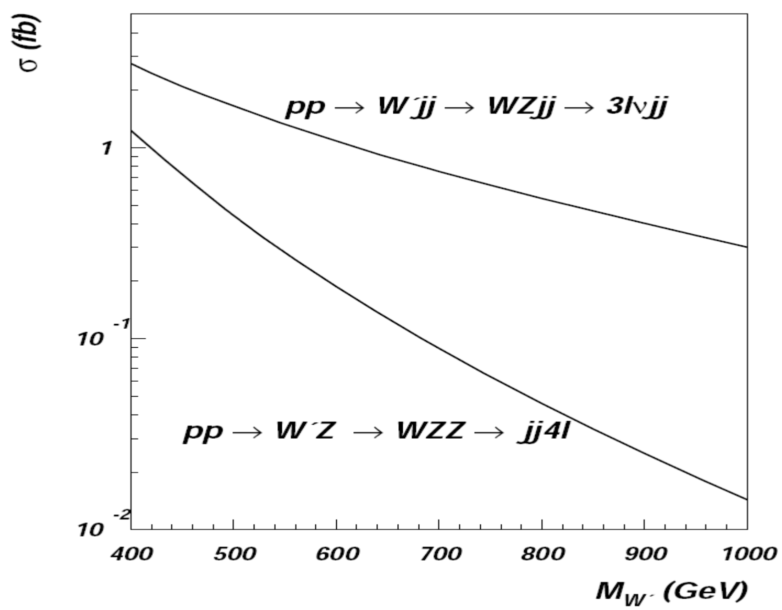
$$M_{W'} \lesssim 600\text{GeV}$$

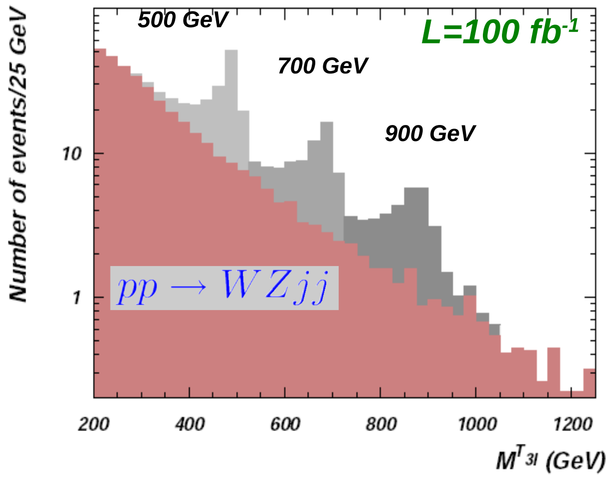
LHC phenomenology

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

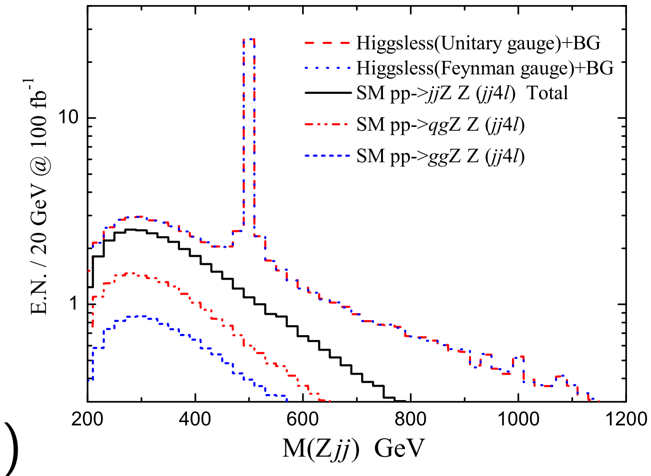
H.-J. He et al., arXiv:0708.2588





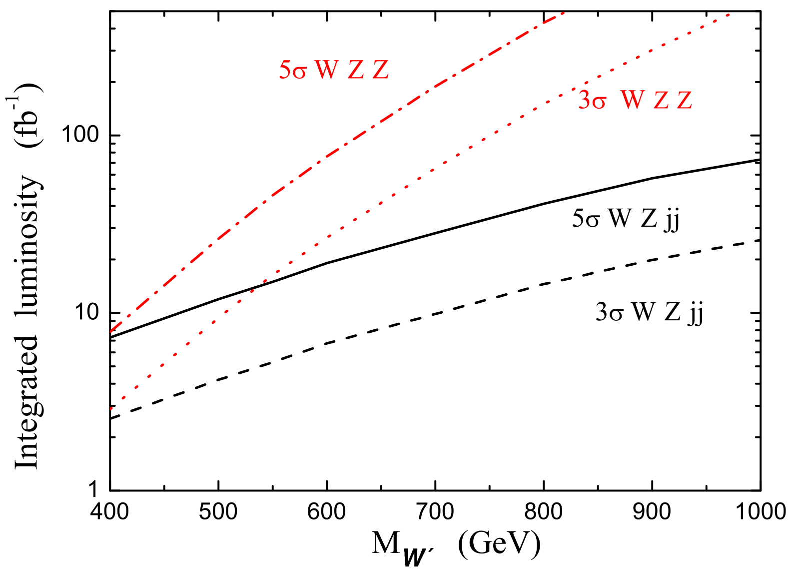


(a)



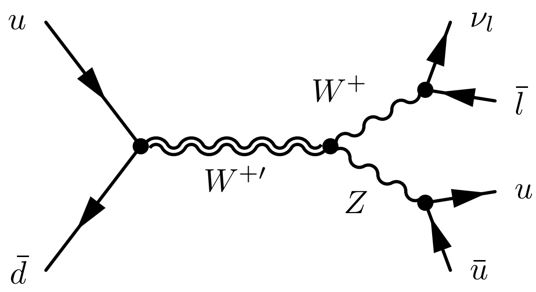
(b)

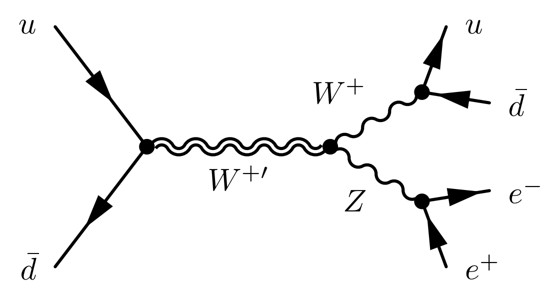
100fb^{-1}

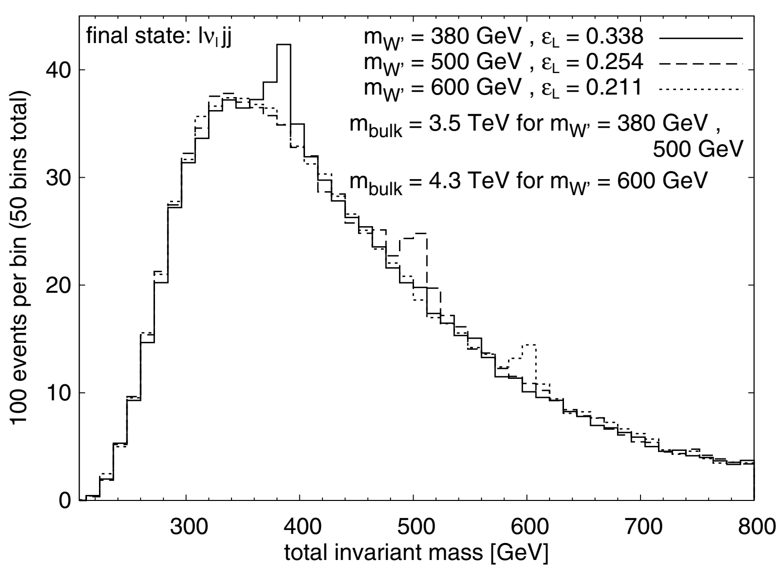


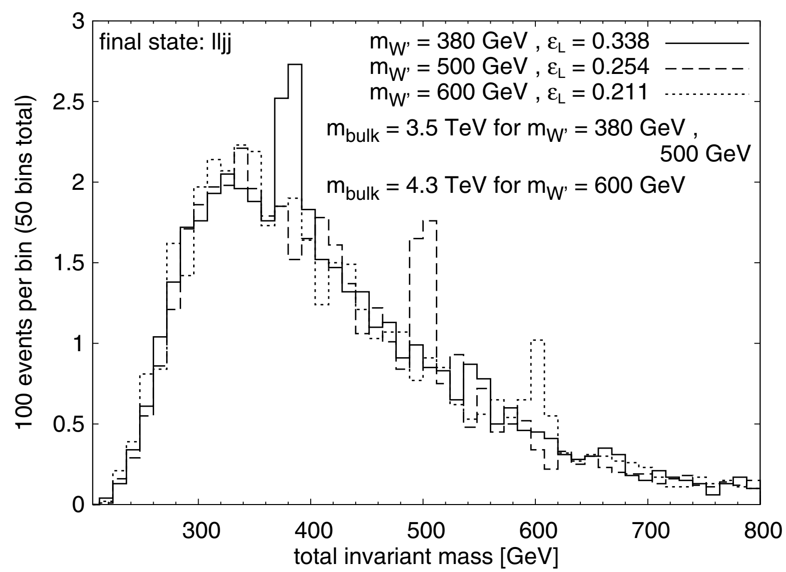
W' production cross sections through $W'ff$ vertex:

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. The KK gauge boson coupling $g_{W'ff}$, the KK gauge boson mass $M_{W'}$, and the KK quark/lepton masses M are constrained by the LEP/SLC precision measurements.
- The KK gauge boson W' will be discovered at LHC with $\int \mathcal{L} =$ a few $\times$ 10fb^{-1}.