Custodial Isospin Violation in the Lee-Wick Standard Model

Arsham Farzinnia

Cargese 2010: Physics at TeV colliders - From Tevatron to LHC

July 22, 2010

Chivukula, Farzinnia, Foadi, Simmons
Phys. Rev. D 81, 095015 (2010)

Formalism: an example

* LW ϕ^4-theory

$$\mathcal{L}^{\mathrm{hd}}_{\phi^4} = \frac{1}{2}\partial_\mu \hat{\phi}\, \partial^\mu \hat{\phi} - \frac{1}{2M^2}(\partial^2 \hat{\phi})^2 - \frac{m^2}{2}\hat{\phi}^2 - \frac{\lambda}{4!}\hat{\phi}^4$$

(with M >> m)

→ tree-level propagator: $D_{\hat{\phi}}(q^2) = \dfrac{i}{q^2 - q^4/M^2 - m^2}$

TWO poles:

$$m_\phi = m(1 + \mathcal{O}(m^2/M^2))$$

$$M_{\tilde{\phi}} = M(1 + \mathcal{O}(m^2/M^2))$$

residue has the wrong sign!!

The "equivalent" formulation

In order to make the extra degree of freedom more manifest, introduce an auxiliary field, $\tilde{\phi}$

The higher derivative Lagrangian is then equivalent to:

$$\mathcal{L}_{\phi^4} = \frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi - \frac{1}{2}\partial_\mu \tilde{\phi} \, \partial^\mu \tilde{\phi} - \frac{m^2}{2}(\phi - \tilde{\phi})^2 + \frac{M^2}{2}\tilde{\phi}^2 - \frac{\lambda}{4!}(\phi - \tilde{\phi})^4$$

with no higher derivatives!!

$$\tilde{\phi} = \phi - \hat{\phi}$$

The "equivalent" formulation

In order to make ... extr... egree of freedom mor... ntr... duce an auxiliary field, $\tilde{\phi}$

The higher derivativ... angian is then equivalent to:

$$\mathcal{L}_{\phi^4} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}\partial_\mu\tilde{\phi}\,\partial^\mu\tilde{\phi} - \frac{m^2}{2}(\phi - \tilde{\phi})^2 + \frac{M^2}{2}\tilde{\phi}^2 - \frac{\lambda}{4!}(\phi - \tilde{\phi})^4$$

with no higher derivatives!!

$$\tilde{\phi} = \phi - \hat{\phi}$$

Lee-Wick Standard Model (LWSM)

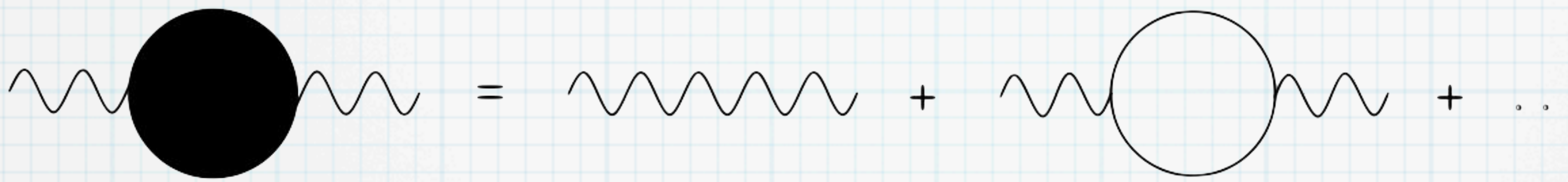
Grinstein, O'Connell, and Wise (2008)

Massive LW-"partner(s)" for EACH SM-field!!

→ Number of bosons is doubled

→ Number of fermions is tripled (to each helicity there corresponds a massive fermion, which is made of a left-handed and a right-handed field)

(Relevant) EW-Parameters



$= D^{-1}$

Π

$\left(\text{“ ' ”} \equiv \frac{d}{dq^2} \right)$

Barbieri, Pomarol, Rattazzi, and Strumia (2004)

Chivukula, Simmons, He, Kurachi, and Tanabashi (2004)

$$\hat{S} = g^2\, \Pi'_{\hat{W}^3 \hat{B}}(0)$$

$$\hat{T} = \frac{g^2}{m_W^2} \left(\Pi_{\hat{W}^3 \hat{W}^3}(0) - \Pi_{\hat{W}^+ \hat{W}^-}(0) \right)$$

$$Y = \frac{1}{2} g'^{\,2} m_W^2\, \Pi''_{\hat{B}\hat{B}}(0)$$

$$W = \frac{1}{2} g^{\,2} m_W^2\, \Pi''_{\hat{W}^3 \hat{W}^3}(0)$$

non-oblique!!

Peskin & Takeuchi (1992)

$$S = \frac{4 s_W^2}{\alpha} \left(\hat{S} - Y - W \right) \qquad T = \frac{1}{\alpha} \left(\hat{T} - \frac{s_W^2}{c_W^2} Y \right)$$

oblique!!

Contributions to the EW-Parameters: Tree-Level

Yellow exclusion-region corresponds to a "light" Higgs (m_H = 115 GeV); for a "heavy" Higgs (m_H = 800 GeV) the additional narrow pink strip is also excluded

Barbieri, Pomarol, Rattazzi, and Strumia (2004)

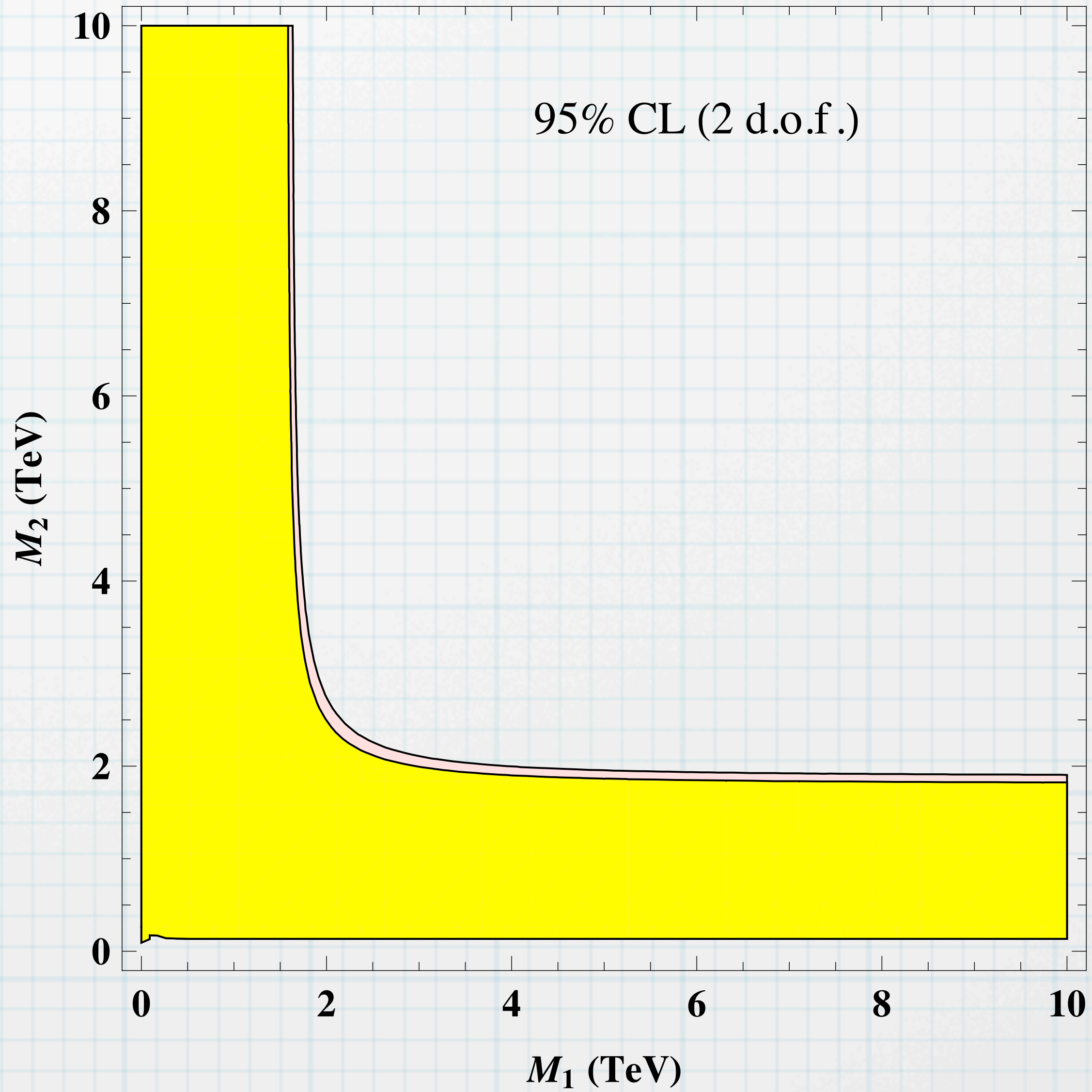
→ M_1, $M_2 \gtrsim 2.4$ TeV

Underwood & Zwicky (2009)

Contributions to the EW-Parameters: Tree-Level

Yellow exclusion-region corresponds to a "light" Higgs (m_H = 115 GeV); for a "heavy" Higgs (m_H = 800 GeV) the additional narrow pink strip is also excluded

→ M_1, $M_2 \gtrsim 2.4$ TeV



Barbieri, Pomarol, Rattazzi, and Strumia (2004)

Underwood & Zwicky (2009)

Contributions to the EW-Parameters: One-Loop

Yellow exclusion-region corresponds to a "light" Higgs (m_H = 115 GeV); for a "heavy" Higgs (m_H = 800 GeV) there's no agreement (the whole region is excluded)!!

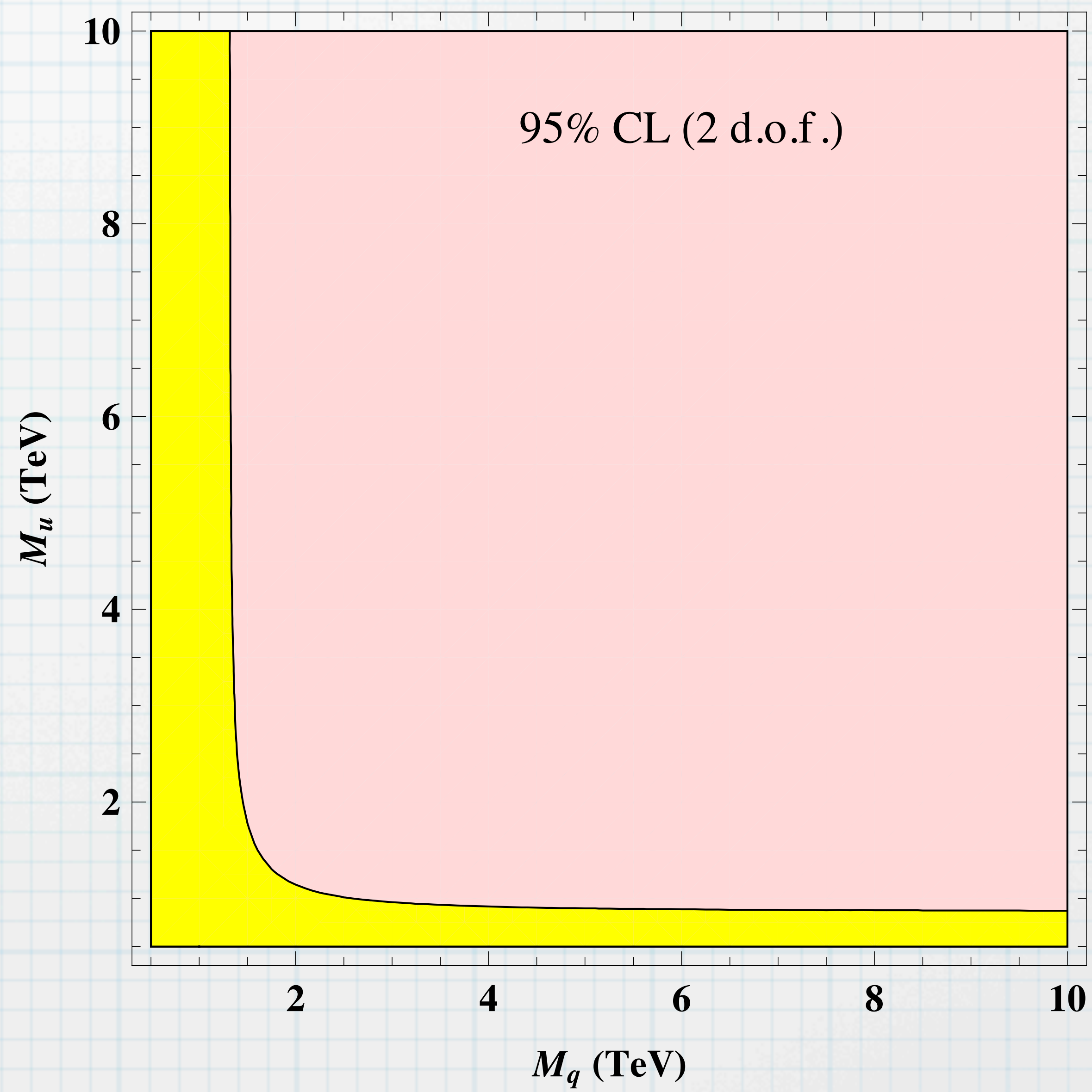
→ M_t, $M_Q \gtrsim$ 1.6 TeV for the light Higgs

Barbieri, Pomarol, Rattazzi, and Strumia (2004)

Contributions to the EW-Parameters: One-Loop

Yellow exclusion-region corresponds to a "light" Higgs (m_H = 115 GeV); for a "heavy" Higgs (m_H = 800 GeV) there's no agreement (the whole region is excluded)!!

→ M_t, $M_Q \gtrsim 1.6$ TeV for the light Higgs



Barbieri, Pomarol, Rattazzi, and Strumia (2004)

Conclusion

* LW's strangeness: Sizable contributions to Y and W, while small contributions to $\hat{S}$ and $\hat{T}$
* Tension between Naturalness (Higgs) and Isospin Violation (electroweak precision data)
* Gauge sector contributes only to Y and W (tree level) → constrains the LW gauge masses (M_1, $M_2 \gtrsim 2.4$ TeV)
* Fermion sector contributes only to $\hat{S}$ and $\hat{T}$ (one-loop) → constrains the LW fermion masses (M_t, $M_Q \gtrsim 1.6$ TeV)

✔

Thank you..

Backups..

Motivation

The Hierarchy Problem!!

The quadratic divergences destabilizing the Higgs mass require extreme fine-tuning in the SM → extensions beyond the SM (SUSY, etc.)

One possible extension is the Lee-Wick theory (LW)

Gian-Carlo Wick (1909-1992)

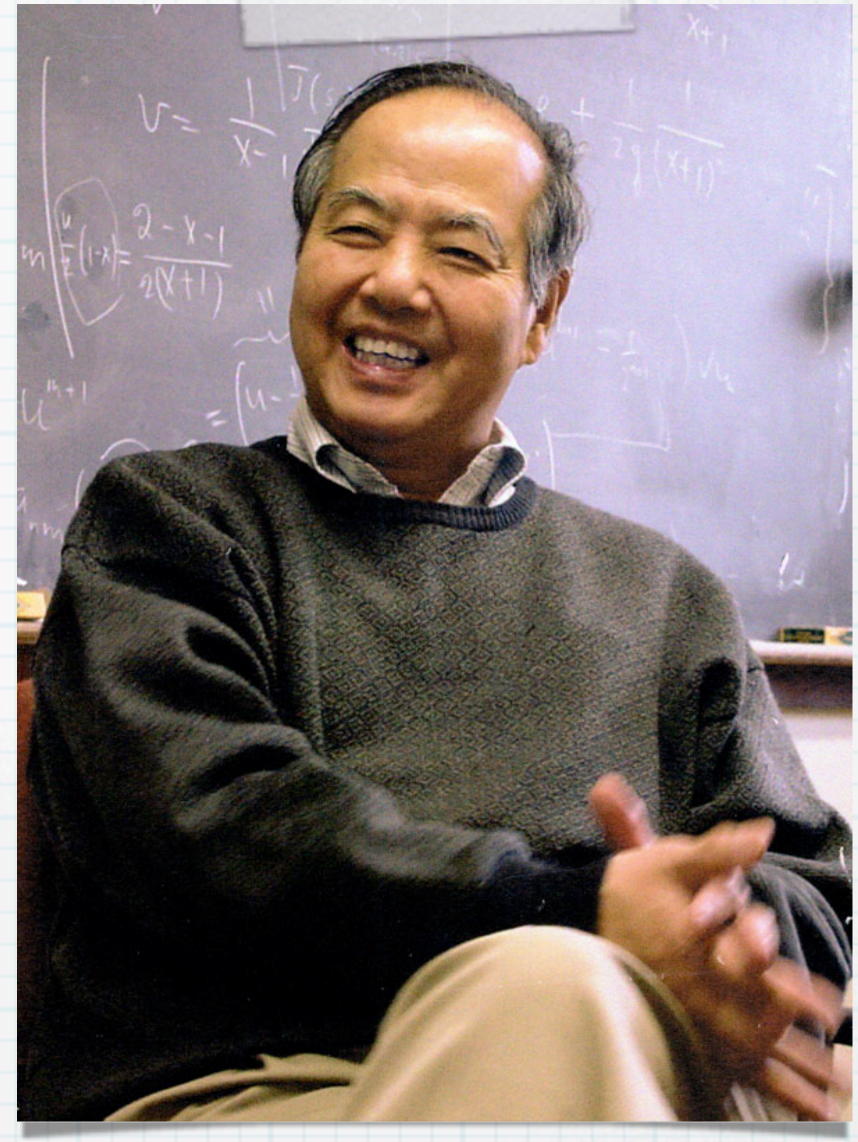
Tsung-Dao Lee (1926-)

Lee & Wick
(1969, 1970)

Regulator propagator in Pauli-Villars corresponds to an actual PHYSICAL degree of freedom

$$\frac{1}{k^2 + i\varepsilon} - \frac{1}{k^2 - \Lambda^2 + i\varepsilon}$$

Gian-Carlo Wick (1909-1992)



Tsung-Dao Lee (1926-)

Regulator propagator in Pauli-Villars corresponds to an actual PHYSICAL degree of freedom

Lee & Wick (1969, 1970)

$$\frac{1}{k^2 + i\varepsilon} - \frac{1}{k^2 - \Lambda^2 + i\varepsilon}$$

LWSM

* No QUADRATIC divergences in LWSM!!

  LW-poles cancel the quadratic divergences in the Higgs propagator; the sum of the corrections to the Higgs mass from both poles is proportional to M^2

Grinstein, O'Connell, and Wise (2008)

$$\delta m_h^2 = \frac{3\lambda_t^2}{8\pi^2} M_q^2 \log \frac{\Lambda^2}{M_q^2}$$

Top-Yukawa sector, with degenerate LW Top masses

LWSM Formalism: Gauge Sector

$$\mathcal{L}^{\text{hd}}_{\text{gauge}} = -\frac{1}{4g_1^2}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{2g_2^2}\text{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] + \frac{1}{2g_1^2 M_1^2}\partial^\mu \hat{B}_{\mu\nu}\partial_\lambda \hat{B}^{\lambda\nu} + \frac{1}{g_2^2 M_2^2}\text{Tr}\left[D^\mu \hat{W}_{\mu\nu} D_\lambda \hat{W}^{\lambda\nu}\right]$$

$$\hat{D}_\mu = \partial_\mu - i\hat{W}^a_\mu t^a - i\hat{B}_\mu Y$$

$$\hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu$$

$$\hat{W}_\mu = \hat{W}^a_\mu t^a$$

(M_1 and M_2 masses of the LW-gauge bosons)

$$\mathcal{L}^{\text{hd}}_{\text{Higgs}} = |\hat{D}_\mu \hat{\phi}|^2 - \lambda\left(\hat{\phi}^\dagger\hat{\phi} - \frac{v^2}{2}\right)^2 - \frac{1}{M_h^2}|\hat{D}^2\hat{\phi}|^2$$

$$\hat{\phi} = \frac{1}{\sqrt{2}}\begin{pmatrix} i\sqrt{2}\hat{\phi}^+ \\ v + \hat{h} - i\hat{\phi}^0 \end{pmatrix}$$

Grinstein, O'Connell, and Wise (2008)

LWSM Formalism: Fermion and Yukawa Sector

$$
\begin{aligned}
\mathcal{L}^{\text{hd}}_{\text{quark}} &= \bar{\hat{q}}\, i\hat{\not{D}} P_L \hat{q} + \frac{1}{M_Q^2}\bar{\hat{q}}\, i\hat{\not{D}}^3 P_L \hat{q} \\
&+ \bar{\hat{t}}'\, i\hat{\not{D}} P_R \hat{t}' + \frac{1}{M_t^2}\bar{\hat{t}}'\, i\hat{\not{D}}^3 P_R \hat{t}' \\
&+ \bar{\hat{b}}'\, i\hat{\not{D}} P_R \hat{b}' + \frac{1}{M_b^2}\bar{\hat{b}}'\, i\hat{\not{D}}^3 P_R \hat{b}'
\end{aligned}
$$

$$
\left(\hat{q} = \begin{pmatrix} \hat{t} \\ \hat{b} \end{pmatrix} \quad , \qquad P_{L,R} \equiv \frac{1}{2}\left(1 \mp \gamma_5\right) \right)
$$

Grinstein, O'Connell, and Wise (2008)

$$
\mathcal{L}_{\text{Yukawa}} = -y_t\; \bar{\hat{q}}\; \hat{\varphi}\; P_R \hat{t}' \;+\; \text{h.c.}
$$

non-standard sources of isospin breaking

$$
\left(\hat{\varphi} \equiv i\sigma^2 \hat{\phi}^* \right)
$$

Contributions to the EW-Parameters: Tree-Level

$$\Pi_{\hat{W}^+\hat{W}^-}(q^2) = \Pi_{\hat{W}^3\hat{W}^3}(q^2) = \frac{q^2}{g_2^2} - \frac{q^4}{g_2^2\ M_2^2} - \frac{v^2}{4}$$

$$\Pi_{\hat{W}^3\hat{B}}(q^2) = \frac{v^2}{4}$$

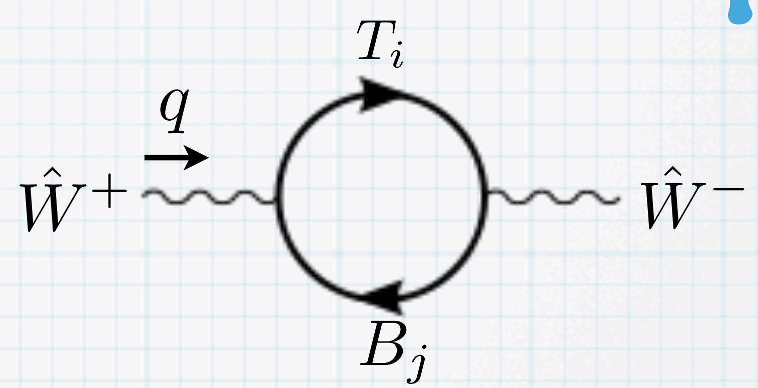
$$\Pi_{\hat{B}\hat{B}}(q^2) = \frac{q^2}{g_1^2} - \frac{q^4}{g_1^2\ M_1^2} - \frac{v^2}{4}$$

These imply at tree-level:

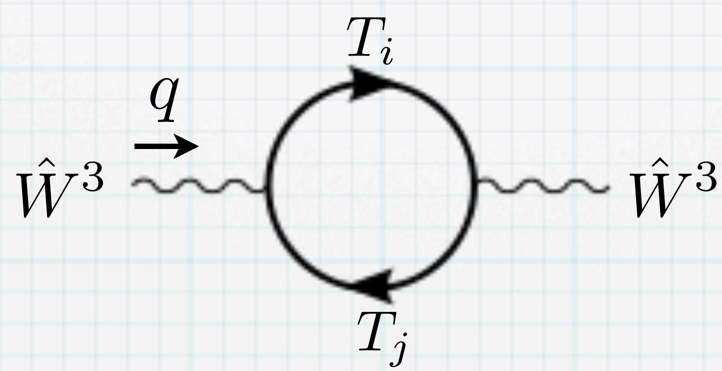
$$\hat{S} = \hat{T} = 0 \qquad Y = -\frac{m_W^2}{M_1^2} \qquad W = -\frac{m_W^2}{M_2^2}$$

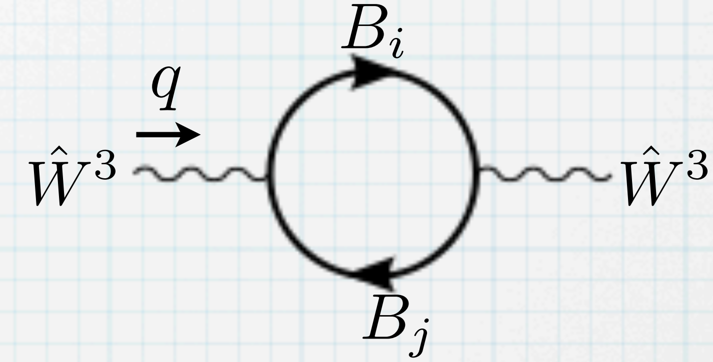
Contributions to the EW-Parameters: One-Loop

$$\Pi^f_{\hat{W}^+\hat{W}^-}(q^2) = \sum_{ij} 3 \Big[\quad \Big]$$

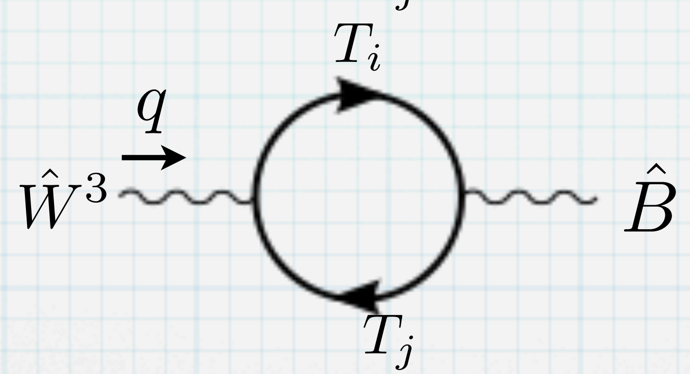


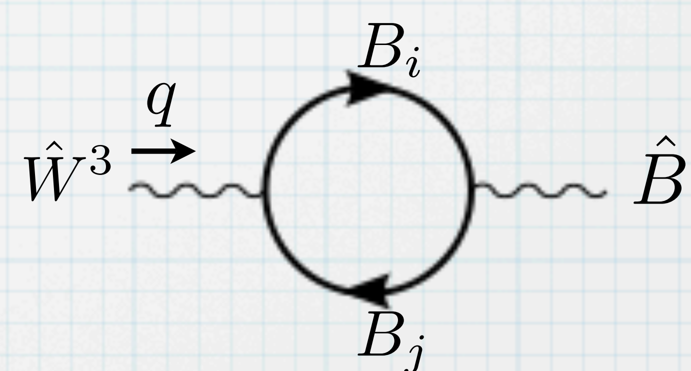
$$\Pi^f_{\hat{W}^3\hat{W}^3}(q^2) = \sum_{ij} 3 \Big[\quad + \quad \Big]$$



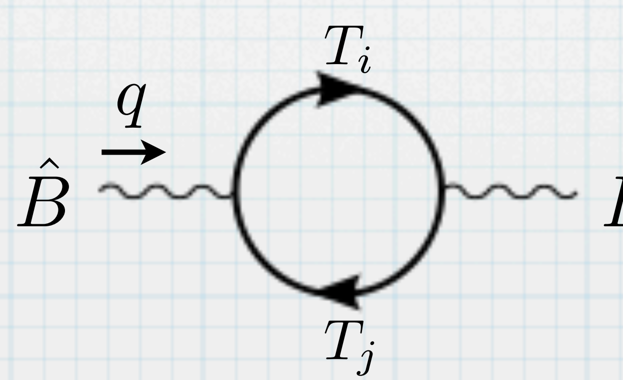


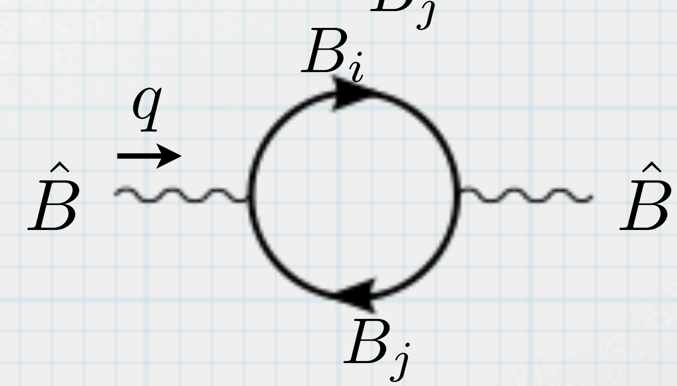
$$\Pi^f_{\hat{W}^3\hat{B}}(q^2) = \sum_{ij} 3 \Big[\quad + \quad \Big]$$





$$\Pi^f_{\hat{B}\hat{B}}(q^2) = \sum_{ij} 3 \Big[\quad + \quad \Big]$$





Note: for each LW-field in the loop, a negative sign should be included!!

Contributions to the EW-Parameters: One-Loop

$$\hat{S} = -\frac{g^2 m_t^2}{48\pi^2 M_Q^2}\left[\left(2+\frac{1}{r_t^2}\right)\log\frac{M_Q^2}{m_t^2} + \frac{1-3r_t^2+6r_t^4-r_t^6+3r_t^8}{r_t^2(1-r_t^2)^5}\log r_t^2 - \frac{5-17r_t^2+4r_t^4+12r_t^6-23r_t^8+7r_t^{10}}{2r_t^2(1-r_t^2)^4}\right]$$

(non-degenerate case)

$$\hat{T} = -\frac{3g^2 m_t^4}{32\pi^2 m_W^2 M_Q^2}\left[\left(2+\frac{1}{r_t^2}\right)\log\frac{M_Q^2}{m_t^2} + \frac{1-3r_t^2+6r_t^6}{r_t^2(1-r_t^2)^5}\log r_t^2 - \frac{9-12r_t^2-21r_t^4+46r_t^6-68r_t^8+22r_t^{10}}{6r_t^2(1-r_t^2)^4}\right]$$

$$\left(r_t \equiv \frac{M_t}{M_Q}\right)$$

(loop corrections to Y and W are negligible)

EW-Parameters

Following (non-canonical) normalizations:

Barbieri, Pomarol, Rattazzi, and Strumia (2004)

$$v^2 = \frac{1}{\sqrt{2}G_F} = -4\,\Pi_{\hat{W}^+\hat{W}^-}(0)$$

$$\frac{1}{g^2} = \Pi'_{\hat{W}^+\hat{W}^-}(0) \qquad \frac{1}{g'^{\,2}} = \Pi'_{\hat{B}\hat{B}}(0)$$

allow for a clean separation of the gauge tree-level contribution, and fermion loop contributions!

Contributions to the EW-Parameters: One-Loop

Diagonalize perturbatively using Symplectic rotation to get the mass eigenstates:

$$
\begin{aligned}
\mathcal{L}_{int} &= \frac{1}{\sqrt{2}}\, \bar{T}_i\, \not{\hat{W}}^{+} T^{-} \left(C_L^{ij} P_L + C_R^{ij} P_R \right) B_j + \text{h.c.} \\
&+ \sum_{f=T,B} \bar{f}_i\, \not{\hat{W}}^{3} T_f^3 \left(N_{fL}^{ij} P_L + N_{fR}^{ij} P_R \right) f_j \\
&+ \sum_{f=T,B} \bar{f}_i\, \not{\hat{B}} \left[\left(Y_q\, N_{fL}^{ij} + Y_f\, N_{fL}^{\prime ij} \right) P_L + \left(Y_q\, N_{fR}^{ij} + Y_f\, N_{fR}^{\prime ij} \right) P_R \right] f_j
\end{aligned}
$$

$$
\begin{aligned}
C_L^{ij} &\equiv L_t^{1i} L_b^{1j} - L_t^{3i} L_b^{3j} \quad , \quad C_R^{ij} \equiv -R_t^{3i} R_b^{3j} \\
N_{fL}^{ij} &\equiv L_f^{1i} L_f^{1j} - L_f^{3i} L_f^{3i} \quad , \quad N_{fR}^{ij} \equiv -R_f^{3i} R_f^{3j} \\
N_{fL}^{\prime ij} &\equiv -L_f^{2i} L_f^{2j} \quad , \quad N_{fR}^{\prime ij} \equiv R_f^{1i} R_f^{1j} - R_f^{2i} R_f^{2j}
\end{aligned}
$$

$$T^{\pm} \equiv T^1 \mp i T^2$$

$$Y = \frac{1}{2} g'^{\,2} m_W^2 \, \Pi''_{\hat{B}\hat{B}}(0) = -\frac{m_W^2}{M_1^2}$$

receives no correction from the loops!!

$$W = \frac{1}{2} g^{\,2} m_W^2 \, \Pi''_{\hat{W}^3\hat{W}^3}(0)$$

$$= -\frac{m_W^2}{M_2^2} + \frac{g^2 m_W^2}{640\pi^2 M_q^2}\left[-7 + \frac{3}{r_b^2} - \frac{9}{r_t^2} \right]$$

receives negligible corrections from the loops!!