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Custodial Isospin Violation in the Lee-Wick Standard Model

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PHENO 2010

May 11, 2010

Chivukula, Farzinnia, Foadi, Simmons
arXiv:1002.0343 [hep-ph]



Motivation

The Hierarchy Problem!!

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

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



Central Idea of the Talk

- * 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 ($M_1, M_2 \geq 2.4$ TeV)
- * Fermion sector contributes only to \hat{S} and \hat{T} (one-loop)
→ constrains the LW fermion masses ($M_t, M_q \geq 1.6$ TeV)



Gian-Carlo Wick (1909-1992)

Tsung-Dao Lee (1926-)

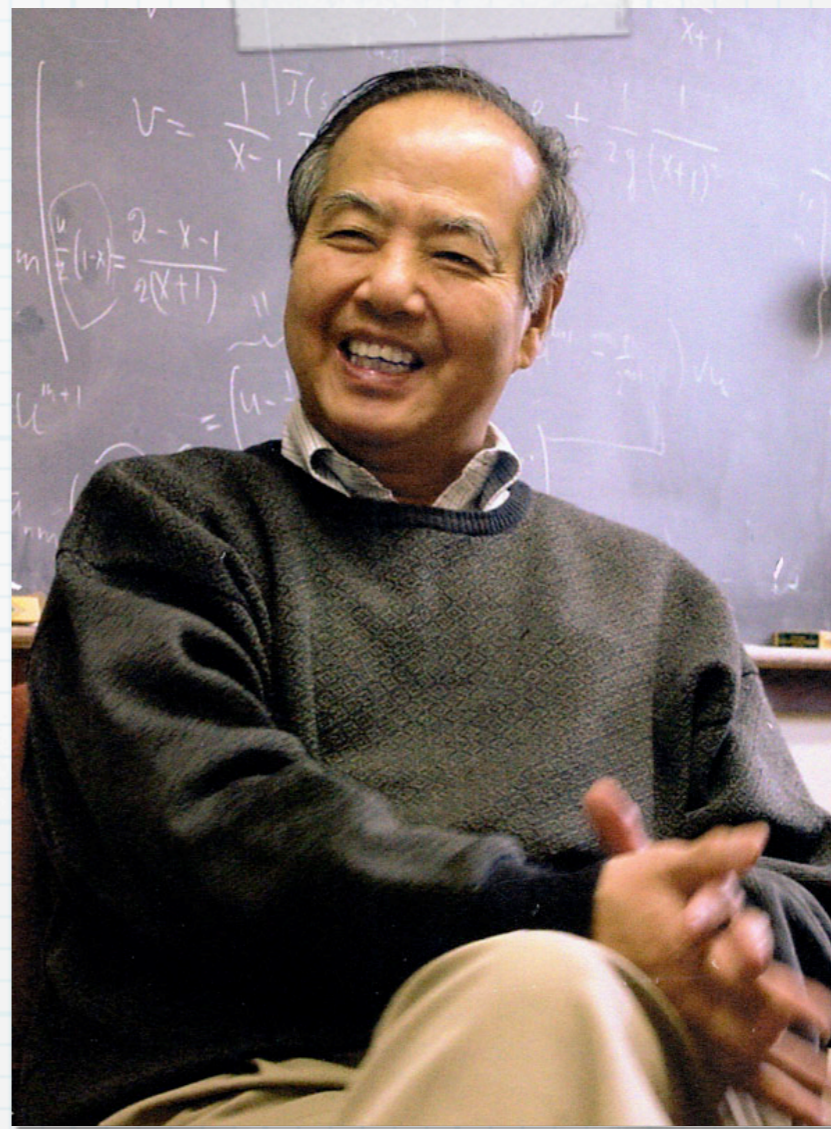
Regulator propagator in Pauli-Villars corresponds to an actual **PHYSICAL** degree of freedom

Lee & Wick
(1969, 1970)

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



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Formalism: an example

* LW ϕ^4 -theory

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

(with $M \gg m$)

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

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:

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

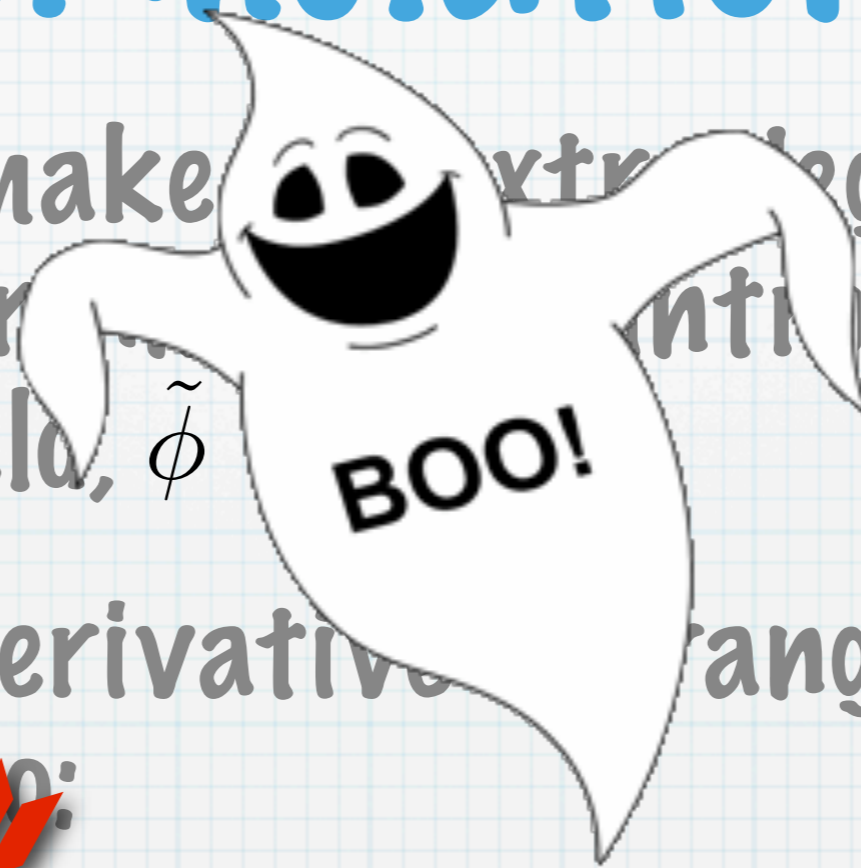
with no higher derivatives!!

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



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Lee-Wick Standard Model (LWSM)

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)

Grinstein,
O'Connell, and
Wise
(2008)



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



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

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

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

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

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

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

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

Grinstein,
O'Connell, and
Wise
(2008)



LWSM Formalism: Fermion and Yukawa Sector

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

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

non-standard sources of isospin breaking

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

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

Grinstein, O'Connell, and Wise (2008)



(Relevant) EW-Parameters



$$\begin{array}{c}
 \text{wavy line} \text{---} \text{black circle} \text{---} \text{wavy line} \\
 \Pi
 \end{array}
 = \text{wavy line} + \text{wavy line} \text{---} \text{white circle} \text{---} \text{wavy line} + \dots = D^{-1}$$

(“'” $\equiv \frac{d}{dq^2}$)

Barbieri,
Pomarol,
Rattazzi, and
Strumia
(2004)

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

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

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

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

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

non-oblique!!

Peskin &
Takeuchi
(1992)

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

oblique!!



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:

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



Contributions to the EW-Parameters: Tree-Level

Yellow exclusion-region
corresponds to a “light”
Higgs ($m_H = 115 \text{ GeV}$);
for a “heavy” Higgs
($m_H = 800 \text{ GeV}$) the
additional narrow pink
strip is also excluded

$$\rightarrow M_1, M_2 \geq 2.4 \text{ TeV}$$

Barbieri,
Pomarol,
Rattazzi, and
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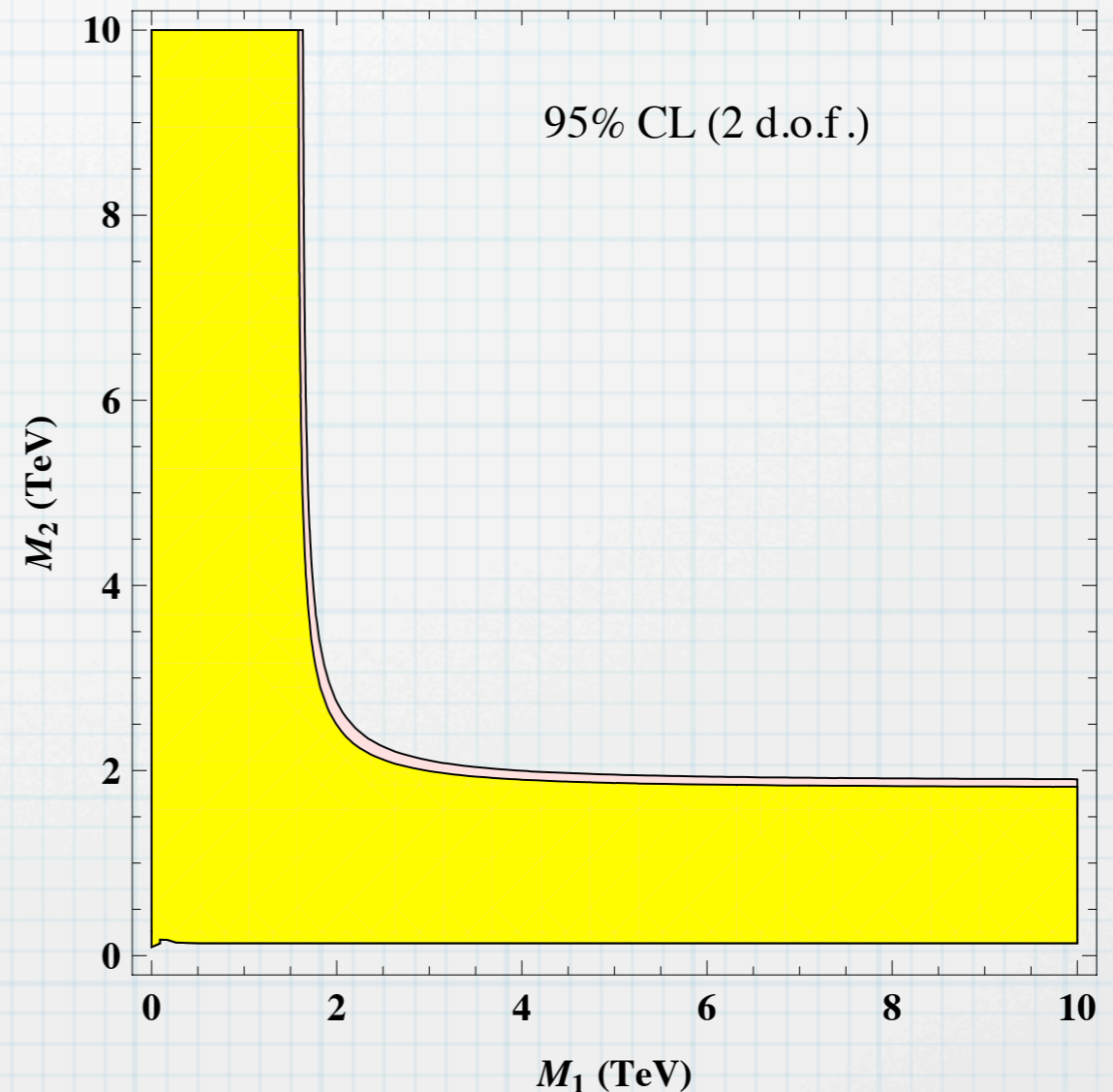
Underwood &
Zwicky
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Barbieri, Pomarol, Rattazzi, and Strumia (2004)

Underwood & Zwicky (2009)



Contributions to the EW-Parameters: One-Loop

$$\Pi_{\hat{W}^+ \hat{W}^-}^f(q^2) = \sum_{ij} 3 \left[\begin{array}{c} \hat{W}^+ \xrightarrow{q} \begin{array}{c} \text{---} \text{---} \\ \text{---} \text{---} \\ \text{---} \text{---} \end{array} \hat{W}^- \end{array} \right]$$

$$\Pi_{\hat{W}^3 \hat{W}^3}^f(q^2) = \sum_{ij} 3 \left[\begin{array}{c} \hat{W}^3 \xrightarrow{q} \begin{array}{c} \text{---} \text{---} \\ \text{---} \text{---} \\ \text{---} \text{---} \end{array} \hat{W}^3 + \hat{W}^3 \xrightarrow{q} \begin{array}{c} \text{---} \text{---} \\ \text{---} \text{---} \\ \text{---} \text{---} \end{array} \hat{W}^3 \end{array} \right]$$

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



Contributions to the EW-Parameters: One-Loop

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

(non-degenerate
case)

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

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

(loop corrections to Y and W are negligible)



Contributions to the EW-Parameters: One-Loop

Yellow exclusion-region
corresponds to a “light”
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($m_H = 800 \text{ GeV}$) there’s
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excluded)!!

→ $M_t, M_q \geq 1.6 \text{ TeV}$
for the light Higgs

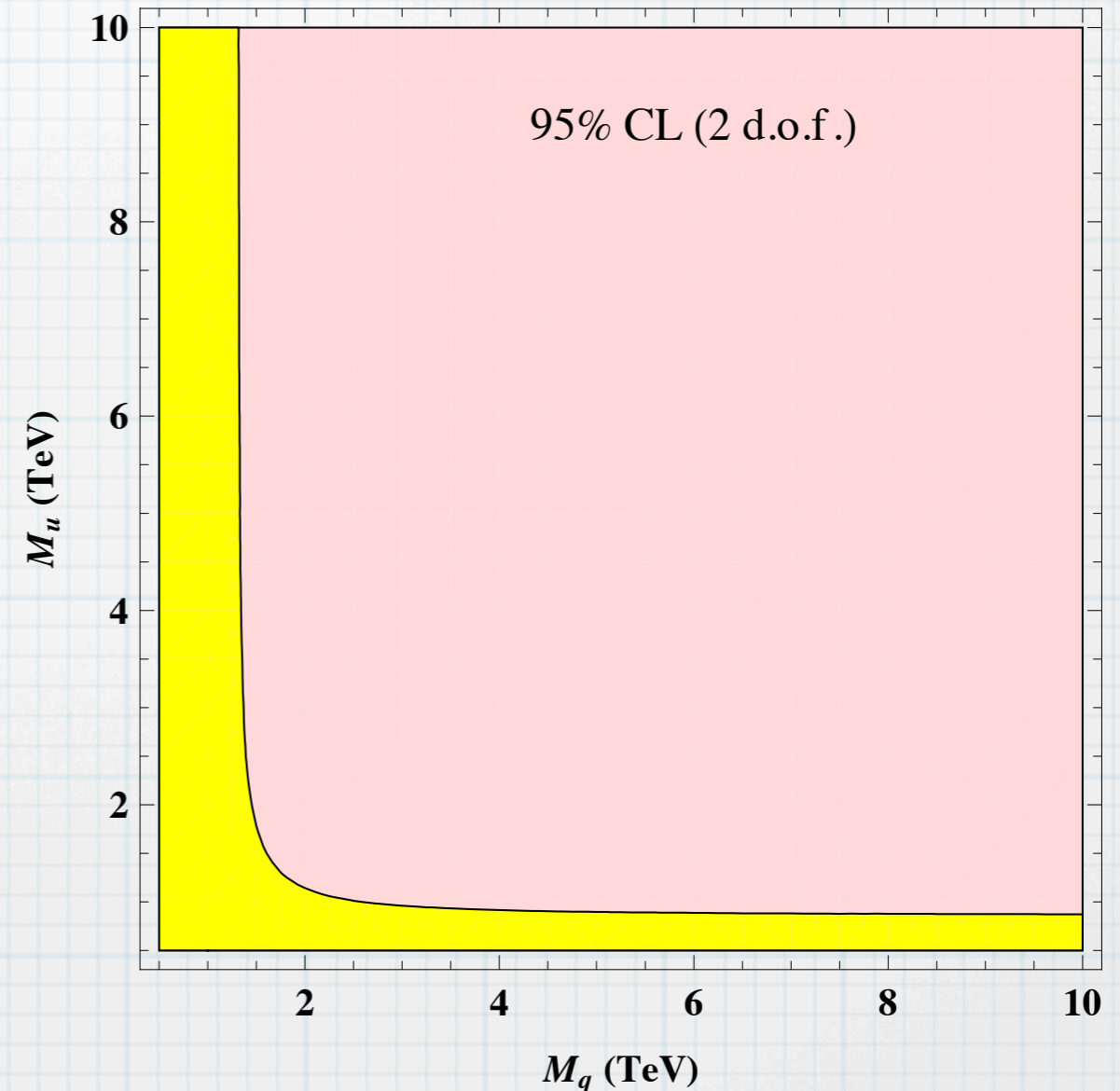
Barbieri,
Pomarol,
Rattazzi, and
Strumia
(2004)



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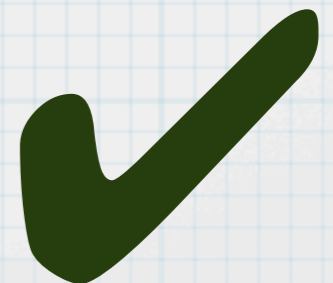


Barbieri,
Pomarol,
Rattazzi, and
Strumia
(2004)



Conclusion

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- * Tension between Naturalness (Higgs) and Isospin Violation (electroweak precision data)
- * Gauge sector contributes only to Y and W (tree level)
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Thank you..





Backups..



EW-Parameters

Following (non-canonical) normalizations:

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

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

Barbieri,
Pomarol,
Rattazzi, and
Strumia
(2004)

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:

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

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

$$T^\pm \equiv T^1 \mp iT^2$$



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

receives no correction from the loops!!

$$\begin{aligned} W &= \frac{1}{2} g^2 m_W^2 \Pi''_{\hat{W}^3\hat{W}^3}(0) \\ &= -\frac{m_W^2}{M_2^2} + \frac{g^2 m_W^2}{640\pi^2 M_q^2} \left[-7 + \frac{3}{r_b^2} - \frac{9}{r_t^2} \right] \end{aligned}$$

receives negligible corrections from the loops!!