What is the “Lee-Wick Standard Model”?

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Outline

- Foundations of Lee-Wick Electrodynamics:
  Unitarity & Causality
- The Lee-Wick Stadard Model:
  Motivations & Main Features
- Phenomenology:
  Signatures at Particle Colliders, Electroweak Precision tests, Flavor Physics, Neutrinos...
- Concluding Remarks

Lee-Wick Electrodynamics

T.D. Lee and G.C. Wick, Nucl. Phys. B **9**, 209 (1969)

T.D. Lee and G.C. Wick, Phys. Rev. D **2**, 1033 (1970)

The photon field is replaced by the combination:

$$\boxed{A_\mu \to A_\mu + iB_\mu}$$

The Lagrange density:

$$\mathcal{L} = \bar{\psi}(i\partial_\mu\gamma^\mu - m_0)\psi - \tfrac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu)$$
$$-\tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)(\partial^\mu B^\nu - \partial^\nu B^\mu) + \tfrac{1}{2}\mu_0^2 B_\mu B^\mu + e_0\bar{\psi}\gamma^\mu\psi(A_\mu + iB_\mu)$$

The propagador for the coherent mixture $A_\mu + iB_\mu$:

$$\frac{1}{k^2} - \frac{1}{k^2 - \mu_0^2} = \frac{-\mu_0^2}{k^2(k^2 - \mu_0^2)} \xrightarrow[k^2\to\infty]{} \frac{1}{k^4}$$

→ Finite electromagnetic mass differences between hadrons in a same isospin multiplet

Non-Hermitian Lagrangian ⇒ Non-Unitary *S*-matrix?

Lee-Wick Electrodynamics (Unitarity)

A different metric in Hilbert space:

$\boxed{\langle\, |\eta(-1)^{N_B}|\,\rangle > 0}$ In a particular basis: $\eta = (-1)^{N_B}$, $A_\mu(B_\mu)$ is of positive (negative) metric

$\boxed{\eta H^\dagger \eta = H}$ Self-adjoint Hamiltonian → real energy expectation values

However, *H* may have complex eigenvalues

$\boxed{S^\dagger \eta S = \eta}$ Pseudo-unitary condition for the *S*-matrix → not satisfactory

Lee and Wick show that *S* is unitary if *all* stable particles are of positive metric:

$\boxed{\langle \mathbf{r}|\eta|\mathbf{r}\rangle > 0}$ → for all eigenvectors of *H* with real eigenvalues

Is this condition satisfied?

Lee-Wick Electrodynamics (Unitarity)

The *S*-matrix is well defined in terms of the eigenvectors of *H* with real eigenvalues:

$$S_{r'r} = \langle r'^{in} | \eta | r^{out} \rangle$$

The *U*-operator in the interaction picture can be decomposed:

$$U(t,-t) = U^{reg}(t,-t) + \boxed{U^{exp}(t,-t)}$$

diverges exponentially as t → ∞

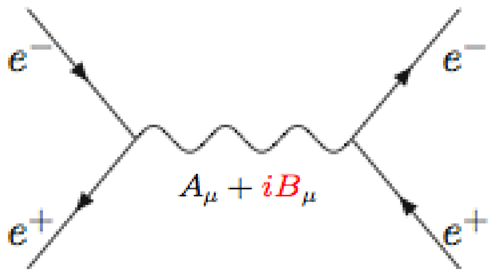
The usual relation between *U* and *S* does not hold, however:

$$\boxed{\lim_{t\to\infty} U^{reg}(t,-t) = S}$$

New Feynman rules in momentum space

Lee-Wick Electrodynamics (Unitarity)

Electron-positron scattering at lowest order:

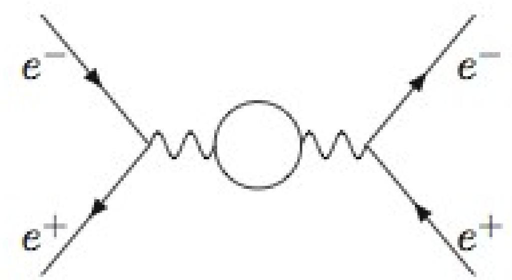


Unusual sign in the free propagator

$$D(k) = \frac{-\mu_0^2}{k^2(k^2-\mu_0^2)}$$

Im$(\mathcal{M}) < 0$ $\cancel{\checkmark}$

Adding corrections to the propagator:



The corrected propagator fixes the problem

$$D(k) = \frac{1}{k^2} + \int_{4m^2} \frac{\rho(a^2)da^2}{k^2-a^2} + \frac{\beta}{k^2-\mu_+^2} + \frac{\beta^*}{k^2-\mu_-^2}$$

$$\mu_\pm = \mu \pm \frac{i\gamma}{2}$$

Im$(\mathcal{M}) > 0$ $\checkmark$

Complex poles in unusual places → modified distribution of contours of integration

Lee-Wick Electrodynamics (Unitarity)

- T.D. Lee, in *Quanta*, Chicago U.P., 260 (1970):
  "Naive" prescription for integration paths in Feynman integrals (not relativisticaly invariant)

- R. E. Cutkovsky, P.V. Landshoff, D.I. Olive and J.C. Polkinghorne, Nucl. Phys. B **12**, 281 (1969):
  Covariant prescription, "CLOP" (not derived from a Lagrangian formulation)

- N. Nakanishi, Phys. Rev. D **3,** 811 (1971):
  Lorentz invariance and a Lagrangian (non-perturbative) formulation seem to be not compatible

- T.D. Lee and G.C Wick, Phys. Rev. D **3**, 1046 (1971):
  Insist in a relativistic and unitary *S*-matrix in spite of the lack of a Lagragian formulation

- D.G. Boulware and D.J. Gross, Nucl. Phys. B **233**, 1 (1984):
  Functional integral for indefinite metric QFT; however, Lee-Wick theory can not be study non- pertubatively

- B.Grinstein, D.O'Connell, M.B.Wise, **arXiv**:0805.2156:
  Unitary and Lorentz invariant *S*-matrix in the Lee-Wick *O*(*N*) model

- A. van Tonder, **arXiv**:0810.1928:
  Lee-Wick electrodynamics is found to be unitary

Lee-Wick Electrodynamics (Causality)

S. Coleman, " Acausality", in *Erice 1969*, Academic Press, NY, 282 (1970)

Field operators obey the usual causality condition:

$$[\phi(x), \phi(y)] = 0 \longrightarrow \text{at space-like separations}$$

These operators not only create the usual states but also states with complex energy

The right asymptotic states are obatined by subtracting the complex-energy components

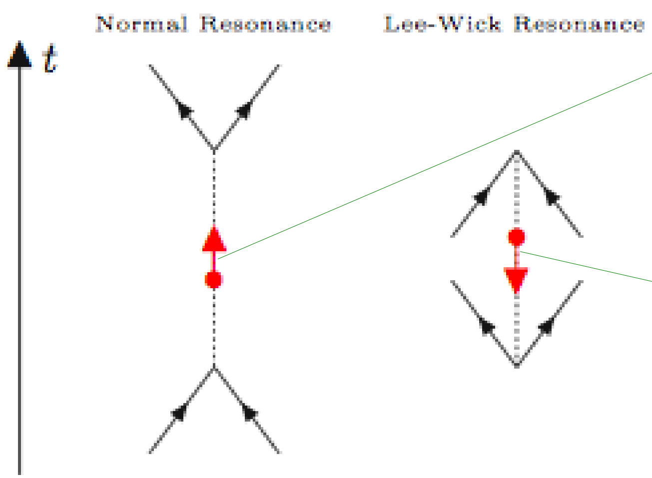
(*Prescriptions for contours of integration exclude outgoing exponentially growing modes*)

$$\downarrow$$

Violation of causality: reverse time order of physical processes

Lee-Wick Electrodynamics (Causality)

Complex-energy states show up as unusual resonances:



Usual unstable particles moving *forward* in time

"Antistable" particles moving *backwards* in time

A word on paradoxical behaviours:

What happens if the incoming particles are stopped before they collide?

Resolution(?): Well-defined *S*-matrix → natural limitations on the properties of stopping devices

The Lee-Wick Standard Model (LWSM)

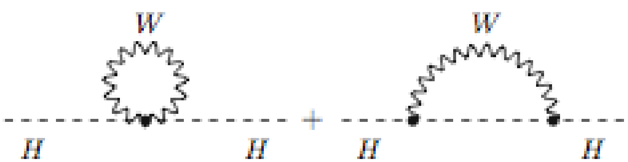
B. Grinstein, D. O'Connell and M. B. Wise, Phys. Rev. D **77**, 025012 (2008)

Hierarchy problem in the SM: Higgs mass corrections are quadratically sensitive to the cutoff

Tree-level Higgs mass:

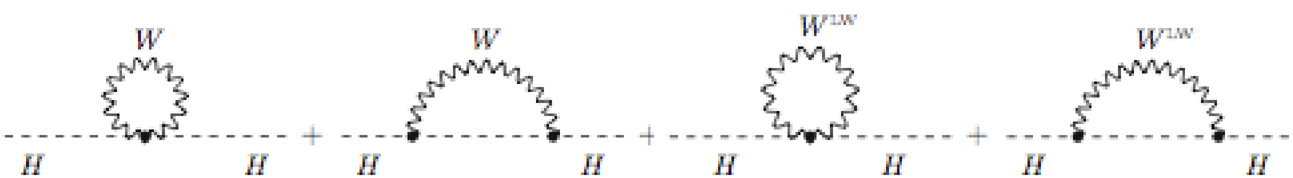
$$(m_h^2)_{bare} = 2\lambda\, v^2\,, \qquad \langle H \rangle = \frac{v}{\sqrt{2}}\,,\ v \sim 247\,\mathrm{GeV}$$

1-loop corrections from W bosons:



$$\longrightarrow \delta m_h^2 \sim \frac{g^2}{16\pi^2}\Lambda^2 \longrightarrow \text{If } \Lambda \sim M_{\rm PL} \Rightarrow \underbrace{\delta m_h^2 \sim (10^{18}\,\mathrm{GeV})^2}_{\text{fine tunning}}$$

Resolution in the LWSM: one LW partner with SM couplings for each SM particle



$$\longrightarrow \delta m_h^2 \sim \frac{g^2 M_{LW}^2}{16\pi^2} \ln \frac{\Lambda^2}{M_{LW}^2}$$

LWSM from a Higher Order Theory

In the LWSM every field in the SM has a higher derivative term → massive LW-particle

How does it work in a toy model?

$$\mathcal{L}_{\rm hd} = \tfrac{1}{2}\partial_\mu\hat{\phi}\partial^\mu\hat{\phi} - \tfrac{1}{2M^2}(\partial^2\hat{\phi})^2 - \tfrac{1}{2}m^2\hat{\phi}^2 - \tfrac{1}{4!}g\hat{\phi}^4, \qquad m >> M$$

$$\hat{D}(p) = \frac{i}{p^2 - p^4/M^2 - m^2} \longrightarrow \textbf{two poles}: p^2 = m, M$$

Defining an auxiliary field, $\tilde{\phi}$:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\hat{\phi}\partial^\mu\hat{\phi} - \frac{1}{2}m^2\hat{\phi}^2 - \tilde{\phi}\partial^2\hat{\phi} + \frac{1}{2}M^2\tilde{\phi}^2 - \frac{1}{4!}g\hat{\phi}^4$$

Eliminating $\tilde{\phi}$ in $\mathcal{L}$ using the equations of motion reproduces $\mathcal{L}_{\rm hd}$

Explicit particle content through the definition $\phi = \hat{\phi} + \tilde{\phi}$:

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

$$\longrightarrow \tilde{D}(p) = \frac{-i}{p^2 - M^2}$$

LWSM: Particle Content & Interactions (Basics)

LW-gauge bosons are massive and mix:

$$
\begin{aligned}
\mathcal{L}_{2g} = \quad & - \quad \frac{1}{2}\mathrm{Tr}\left(B_{\mu\nu}B^{\mu\nu} - \tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} - \tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right) \\
& - \quad \frac{1}{2}({M_1}^2\tilde{B}_\mu\tilde{B}^\mu + {M_2}^2\tilde{W}^a_\mu\tilde{W}^\mu_a) + \frac{g_2^2 v^2}{8}(W^{1,2}_\mu + \tilde{W}^{1,2}_\mu)^2 \\
& + \quad \frac{v^2}{8}(g_1 B_\mu + g_1\tilde{B}_\mu + g_2 W^3_\mu + g_2\tilde{W}^3_\mu)^2
\end{aligned}
$$

LW-fermions are vector-like and mix:

$$
\begin{aligned}
\mathcal{L}_{2\psi} \quad = \quad & \sum_{\psi=q_L,u_R,d_R} \bar{\psi} i \not{\partial}\psi - \sum_{\tilde{\psi}=q,u,d} \bar{\tilde{\psi}}(i\not{\partial} - M_\psi)\tilde{\psi} \\
& -m_u(\bar{u}_R - \bar{\tilde{u}}_R)(q^u_L - \tilde{q}^u_L) - m_d(\bar{d}_R - \bar{\tilde{d}}_R)(q^d_L - \tilde{q}^d_L) + \mathrm{h.c.}
\end{aligned}
$$

Interactions between gauge bosons and fermions:

$$
\begin{aligned}
\mathcal{L}_{int} = \quad & - \sum_{\psi=q_L,u_R,d_R} [g_1\bar{\psi}(\not{B} + \not{\tilde{B}})\psi + g_2\bar{\psi}(\not{W} + \not{\tilde{W}})\psi] \\
& + \sum_{\psi=q,u,d} \left[g_1\bar{\tilde{\psi}}(\not{B} + \not{\tilde{B}})\tilde{\psi} + g_2\bar{\tilde{\psi}}(\not{W} + \not{\tilde{W}})\tilde{\psi}\right].
\end{aligned}
$$

Experimental Signatures of LW Particles

T. G. Rizzo, JHEP **0706**, 070 (2007)
T. G. Rizzo, JHEP **0801**, 042 (2008)

- Rizzo consider the resonant production of LW-gauge bosons, $W_{\rm LW}^{\pm,0}$, $B_{\rm LW}$ and $g_{\rm LW}$ at the LHC and future e^-e^+ colliders, looking for a unique identification of the LWSM

- These processes have been analized: $pp \to (W_{\rm LW}^0, B_{\rm LW}) \to l^+l^- + X$, $pp \to W_{\rm LW}^\pm \to l^\pm E_T^{miss} + X$, $pp \to g_{\rm LW} \to jj + X$, $e^-e^+ \to (W_{\rm LW}^0, B_{\rm LW}) \to e^-e^+$

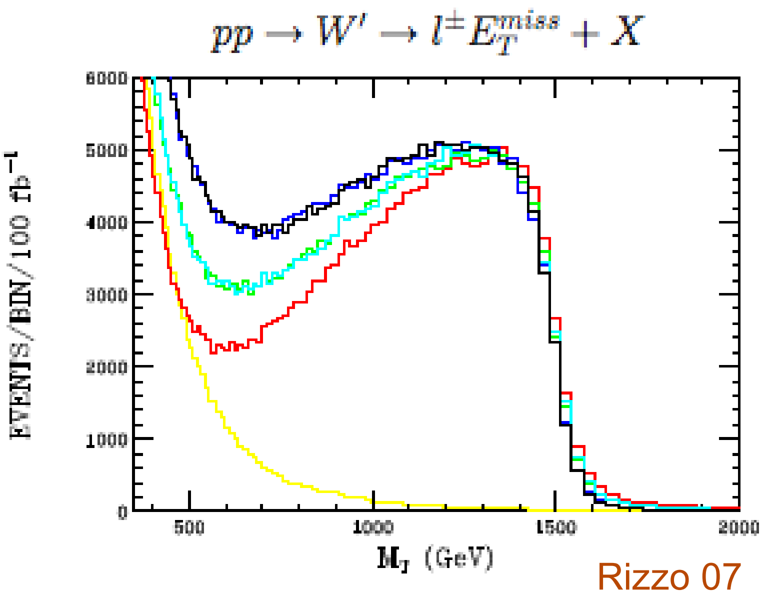
  - Tree-level amplitudes contain the exchange of both SM and LW-gauge bosons:

$$A \sim \frac{i}{p^2 - M_{\rm SM}^2 + iM_{\rm SM}\Gamma_{\rm SM}} - \frac{i}{p^2 - M_{\rm LW}^2 + iM_{\rm LW}\Gamma_{\rm LW}}$$

- Tree-level trilinear couplings between one LW- and two SM- gauges fileds are absent. LW-gluons can not be produced in gluon-gluon collisions

- The analysis of single production of LW fermions is desfavored by SM backgrounds. Pair production seem to be the dominant mechanism for LW fermions

Experimental Signatures of LW Particles (cont'd)



Transverse mass distribution for a W' of 1.5 TeV at the LHC

Black: Lee-Wick Standard Model. **Blue**: Extra dimension models

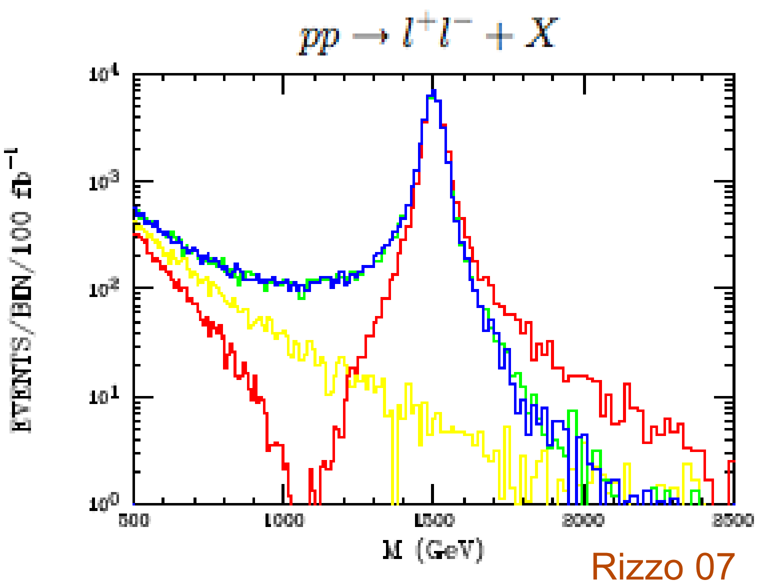
Red: Conventional W' models (SSM). **Green**: Left Right Sym. Model

Cyan: General extra dimensional models. **Yellow**: SM background

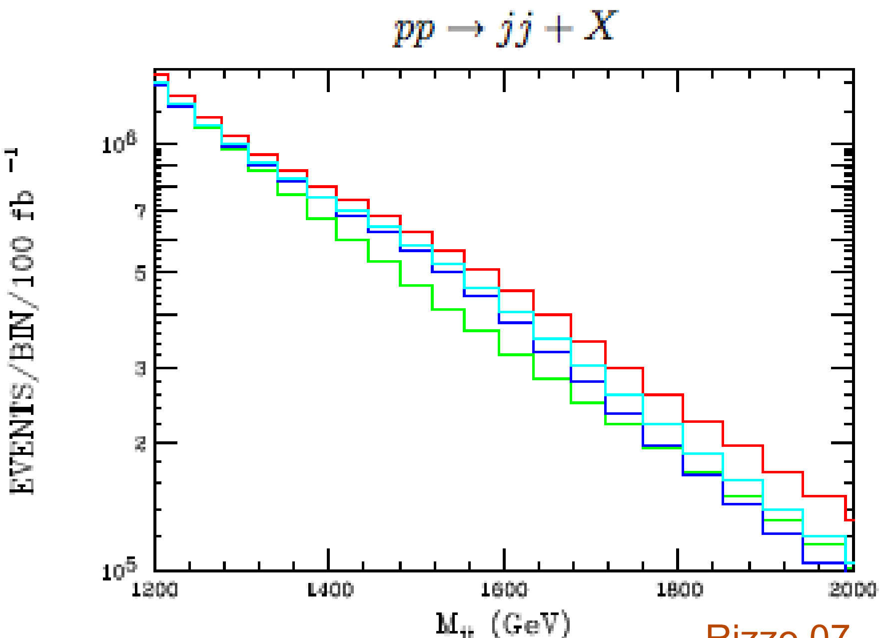
Dilepton pair mass distribution at the LHC for resonances of 1.5 TeV

Green: LW Standard Model. **Blue**: SSM (opposite quark couplings)

Red: Sequential Standard Model (SSM). **Yellow**: SM background



Experimental Signatures of LW Particles (cont'd)



Rizzo 07

Dijet pair mass distribution at the LHC for resonances of 1.5 TeV

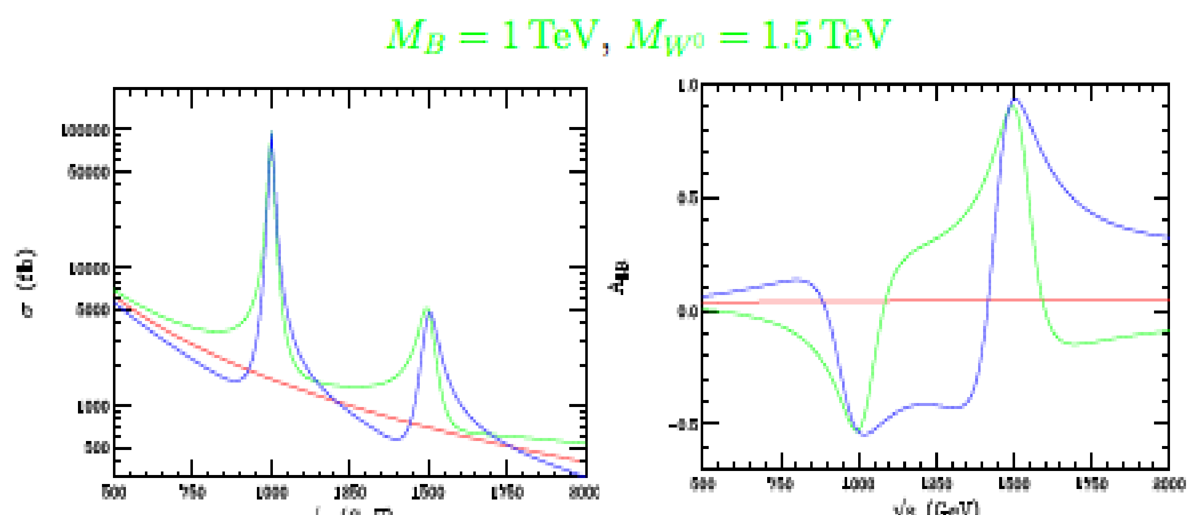
Blue: LW Standard Model. **Red**: KK-like copy of the SM

Cyan: Axigluon Model. **Green**: SM background

Cross section for $e^-e^+ \to e^-e^+$ & LR Asymmetry

Green: Lee-Wick Standard Model

Blue: Heavier SM copies. **Red**: SM prediction



Rizzo 08

Constrains from Electroweak Precision Tests

E. Álvarez, L. Da Rold, C. Schat and A.S. , JHEP **0804**, 026 (2008)

- We compute the oblique parameters S and T at 1-loop level

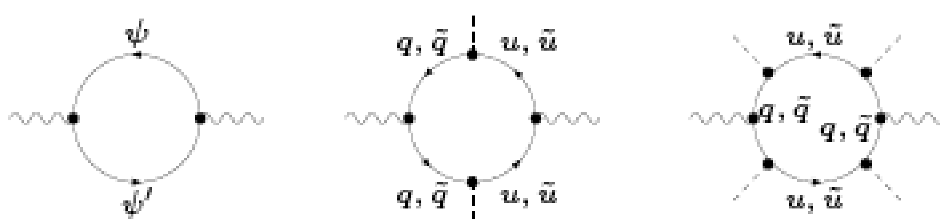
  - We integrate out the LW fields and obtain an effective Lagrangian after a field redefinition:

$$\mathcal{L}_{eff} = -\frac{1}{2}\Pi'_{3B}(0)\mathbf{W}^{\mu\nu}_{\mathrm{SM}}\mathbf{B}^{\mathrm{SM}}_{\mu\nu} + \frac{1}{2}g_2^2\Pi_{33}(0)(\mathbf{W}^3_{\mathrm{SM}})^2 + \frac{1}{2}g_2^2\Pi_{11}(0)(\mathbf{W}^1_{\mathrm{SM}})^2 + \ldots$$

  - Using the definitions of S and T: $S = \frac{16\pi}{g_1 g_2}\Pi'_{3B}(0)\ , \ T = \frac{4\pi}{s^2c^2m_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)]$

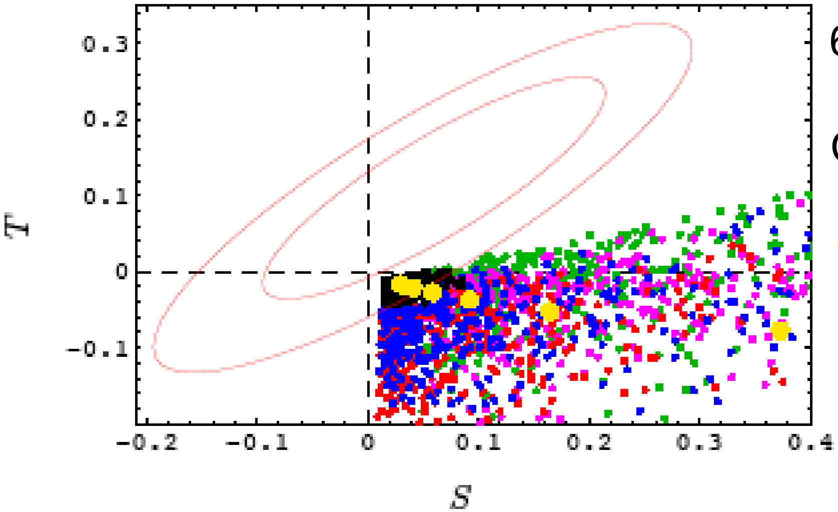
We obtain the tree-level contributions: $\boxed{S = 4\pi v^2\left(\frac{1}{M_1^2}+\frac{1}{M_2^2}\right) + \mathcal{O}\left(\frac{v^4}{M_i^4}\right)\ , \quad T = \pi\frac{g_1^2+g_2^2}{g_2^2}\frac{v^2}{M_1^2}}$

  - At 1-loop level the dominant contribution comes from quarks:



Constrains from Electroweak Precision Tests (cont'd)

- We scan the parameter space of the model and obtain bounds on the masses of LW particles



68% and 95% Confidence Level Contours in the (S, T) plane

Colored dots indicate which mass M_1, M_2, M_q, M_u is less than 4 TeV

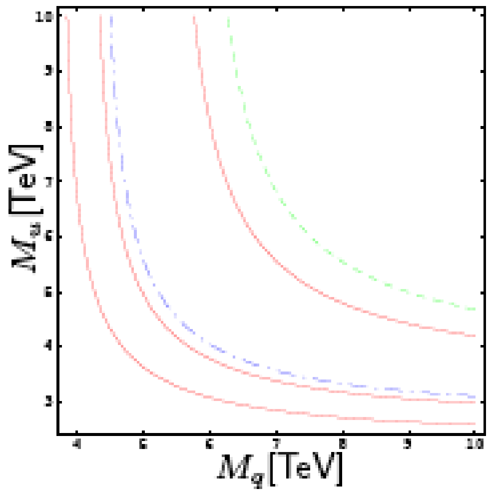
Yellow dots from the left t right, all masses equal to 7, 6, 5, 4... TeV

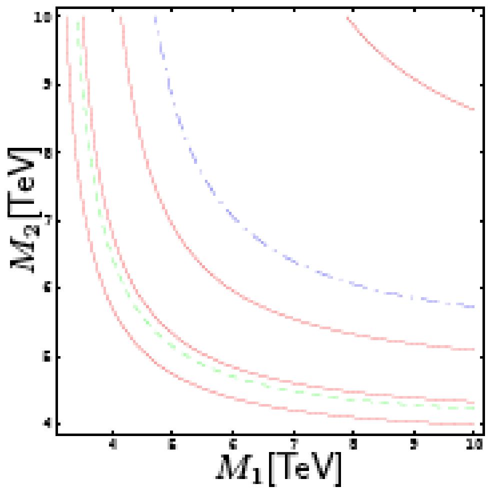
Black dots indicate that all M_1, M_2, M_q, M_u are larger than 4 TeV

Region above the curves is allowed @ 95% CL

Left: red curves (from left to right), $M_1 = M_2 = 7, 6, 5$ TeV

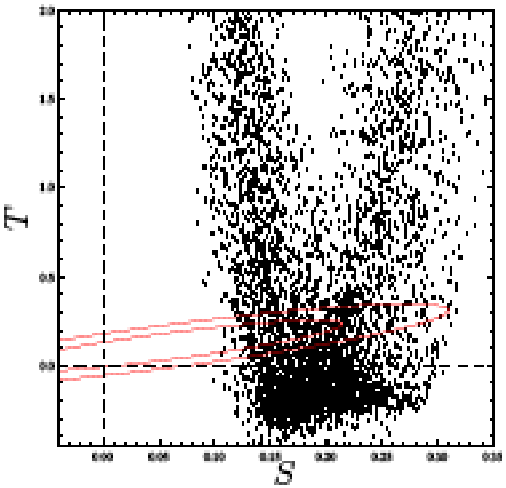
Right: red curves (from left to right), $M_q = M_u = 7, 6, 5, 4$

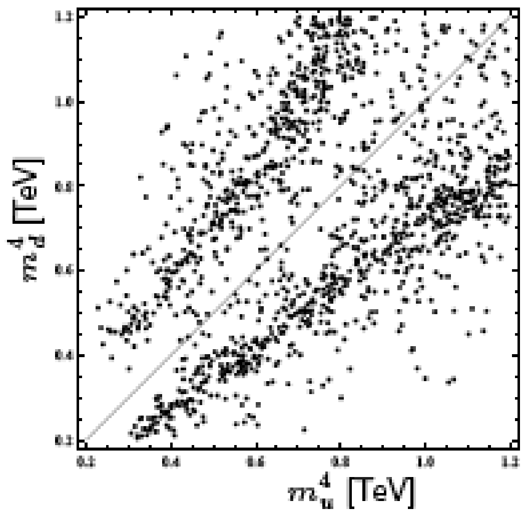




Constrains from Electroweak Precision Tests (cont'd)

- We consider an extension of the LWSM including a fourth generation of fermions and find new bounds on the LW masses





Left: 68% and 95% CL Contours in the (S, T) plane

Fermionic LW masses, values in the range 0.2 - 1.5 TeV

Isospin violation in the fourth generation is about a **30%**

Bounds on masses in the LWSM	Bounds on masses in the 4th-generation scenario
LW fermions > 2.4 – 3.5 TeV	LW fermions > 0.4 – 1.5 TeV
LW-gauge bosons > 5 – 8 TeV	LW-gauge bosons > 3 TeV

Other articles on electroweak constrains: T.E J. Underwood and R. Zwicky, Phys. Rev. D **79**, 035016 (2009)
C.D. Carone and R.F. Lebed, Phys. Lett. B **668**, 221 (2008)

Comments on the LWSM Flavor Structure

T.R. Dulaney and M.B. Wise, Phys. Lett. B **658**, 230 (2008)

- The higher derivative kinetic terms contain the new flavor structure:

$$\mathcal{L}_{\rm hd}^{(\rm kin)} = \overline{\hat{Q}^i}_L i\hat{\not{D}}\hat{Q}^i_L + r_Q^{ij}\overline{\hat{Q}^i}_L i\hat{\not{D}}\hat{\not{D}}\hat{\not{D}}\hat{Q}^j_L + \overline{\hat{L}^i}_L i\hat{\not{D}}\hat{L}^i_L + r_L^{ij}\overline{\hat{L}^i}_L i\hat{\not{D}}\hat{\not{D}}\hat{\not{D}}\hat{L}^j_L + \overline{\hat{u}^i}_R i\hat{\not{D}}\hat{u}^i_R$$
$$+ r_U^{ij}\overline{\hat{u}^i}_R i\hat{\not{D}}\hat{\not{D}}\hat{\not{D}}\hat{u}^j_R + \overline{\hat{d}^i}_R i\hat{\not{D}}\hat{d}^i_R + r_D^{ij}\overline{\hat{d}^i}_R i\hat{\not{D}}\hat{\not{D}}\hat{\not{D}}\hat{d}^j_R + \overline{\hat{e}^i}_R i\hat{\not{D}}\hat{e}^i_R + r_E^{ij}\overline{\hat{e}^i}_R i\hat{\not{D}}\hat{\not{D}}\hat{\not{D}}\hat{e}^j_R$$

- The authors integrate out the LW fermions finding flavor changing *Z* couplings:

$$\Delta\mathcal{L}_Z = \sqrt{g_1^2+g_2^2}Z_\mu\left[\overline{u}_R m_u^{\rm diag}\left(\mathcal{U}(u,L)^\dagger \boxed{r_Q}\,\mathcal{U}(u,L)\right)m_u^{\rm diag}\gamma^\mu u_R\right.$$
$$+\overline{d}_R m_d^{\rm diag}\left(\mathcal{U}(d,L)^\dagger \boxed{r_Q}\,\mathcal{U}(d,L)\right)m_d^{\rm diag}\gamma^\mu d_R + \overline{e}_R m_e^{\rm diag}\left(\mathcal{U}(e,L)^\dagger \boxed{r_L}\,\mathcal{U}(e,L)\right)m_e^{\rm diag}\gamma^\mu e_R$$
$$+\overline{u}_L m_u^{\rm diag}\left(\mathcal{U}(u,R)^\dagger \boxed{r_U}\,\mathcal{U}(u,R)\right)m_u^{\rm diag}\gamma^\mu u_L + \overline{d}_L m_d^{\rm diag}\left(\mathcal{U}(d,R)^\dagger \boxed{r_D}\,\mathcal{U}(d,R)\right)m_d^{\rm diag}\gamma^\mu d_L$$
$$\left.+\,\overline{e}_L m_e^{\rm diag}\left(\mathcal{U}(e,R)^\dagger \boxed{r_E}\,\mathcal{U}(e,R)\right)m_e^{\rm diag}\gamma^\mu e_L\right]$$

- They also show that new flavor changing charged currents are induced:

$$\Delta\mathcal{L}_W = \frac{g_2}{\sqrt{2}}W_\mu^-\left[\overline{d}_R m_d^{\rm diag}\left(\mathcal{U}(d,L)^\dagger \boxed{r_Q}\,\mathcal{U}(u,L)\right)m_u^{\rm diag}\gamma^\mu u_R + \frac{1}{2}\overline{d}_L V^\dagger m_u^{\rm diag}\left(\mathcal{U}(u,R)^\dagger \boxed{r_U}\,\mathcal{U}(u,R)\right)m_u^{\rm diag}\gamma^\mu u_L\right.$$
$$\left.+\frac{1}{2}\overline{d}_L m_d^{\rm diag}\left(\mathcal{U}(d,R)^\dagger \boxed{r_D}\,\mathcal{U}(d,R)\right)m_d^{\rm diag}\gamma^\mu V^\dagger u_L + \frac{1}{2}\overline{e}_L m_e^{\rm diag}\left(\mathcal{U}(e,R)^\dagger \boxed{r_E}\,\mathcal{U}(e,R)\right)m_e^{\rm diag}\gamma^\mu \nu_L\right] + \text{h.c.}$$

Comments on the LWSM Flavor Structure (cont'd)

- All the FCNC and the new FCCC couplings are suppressed by r_Q , r_L , r_U , r_D and r_E :

$$r_I = Y(\tilde{I}_L)\boxed{\left(\frac{1}{M_I^{(\mathrm{diag})}}\right)^2} Y^\dagger(\tilde{I}_L)\,, \quad I = Q, L \qquad r_J = Y(\tilde{J}_R)\boxed{\left(\frac{1}{M_J^{(\mathrm{diag})}}\right)^2} Y^\dagger(\tilde{J}_R)\,, \quad J = U, D, E$$

- Neutral lepton-familly violating processes are even suppressed by the SM lepton masses:

$$\boxed{\frac{\Gamma(\mu \to 3e)}{\Gamma(\mu \to e\bar{\nu}_e\nu_\mu)} \sim \left(\frac{m_e m_\mu}{1\mathrm{TeV}^2}\right)^2 \sim 10^{-21}}$$

- The effects can be larger if the LW and SM contributions interfere:

$$\boxed{\frac{\Delta\Gamma(b \to s\nu\bar{\nu})}{\Gamma(b \to s\nu\bar{\nu})} \sim \left(\frac{m_b m_s}{1\mathrm{TeV}^2}\right) \sim 10^{-6}}$$

- Corrections to the CKM matrix are small too:

$$\boxed{\Delta V_{cb} \sim \frac{m_c m_t}{(1TeV)^2} \sim 10^{-4}}$$

Mixings from FCCC and FCNC are suppressed in non-MFV scenarios if the LW scale if ≳ 1 TeV

Neutrino masses in the LWSM

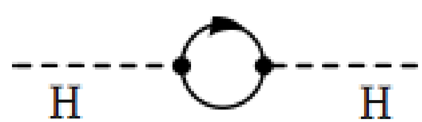
J.R. Espinosa, B. Grinstein, D. O'Connell and M.B. Wise,
Phys. Rev. D **77**, 085002 (2008)

- Does the coupling of LW states to very heavy particles preserve the stability of the weak scale?

  - Seesaw mechanism explains the smallness of the observed neutrino masses:

$$m_\nu \sim \frac{v^2}{m_R} \qquad m_R\uparrow \quad m_\nu\downarrow \qquad m_R \gtrsim 10^{11}\ \mathrm{TeV}$$

  - 1-loop right handed neutrino correction to the Higgs mass:



SM

$$\delta m_H^2 \simeq -\frac{g_Y^2}{8\pi^2} m_R^2 \log(m_R^2/\mu^2)$$

LWSM

$$\delta m_{\hat{H}}^2 = -\frac{g_Y^2}{8\pi^2} M_L^2 \log\left(\frac{m_R^2+\Lambda^2}{m_R^2}\right)$$

If $m_R \gtrsim 10^4\ \mathrm{TeV}$ corrections are too large

If $g_Y M_L \lesssim 10\ \mathrm{TeV}$ corrections are small enough

Other works on the LWSM

- F. Wu and M. Zhong, Phys. Lett. B **659**, 694 (2008); F. Wu and M. Zhong, Phys. Rev. D **78**, 085010 (2008):
  LW higher derivative terms are induced by gravitational radiative corrections

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and more...

Conclusions

- The Lee-Wick Standard Model cures the hierarchy problem by adding one degree of freedom for each SM field
- The LW partners have the same spin-statistics as the SM fields but quadratic terms with opposite signs
- The presence of negative-norm states anticipated conflicts with unitarity. Contours of integration have to be redefined. It appears that this can be done perturbatively in a way that preserves unitarity
- The theory is not causal at short time scales
- Unique experimental signals seem to be clearer at electron-positron colliders than at the LHC
- Electroweak precision tests contrain LW particles to be $\gtrsim 2.5$ TeV
- FCNC and FCCC are induced in the theory but their effecs are small
- Right-handed neutrinos with Majorana masses coupled to the LW fields do not destabilize the electroweak scale