A Left-Right Symmetric Model (LRSM) with doublets

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Flavorful ways to NP, Freudenstadt

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Breaking pattern

Motivation: Understand why and how parity or charge-conjugation are not good symmetries of the quantum world. Studied over the last 40 years [Pati, Salam, Mohapatra, Senjanovic '70s].

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow_{(\kappa_R)}$$
$$SU(2)_L \otimes U(1)_Y$$
$$\downarrow_{(\kappa_{1,2},\kappa_L)}$$
$$U(1)_{EM}$$

- $g_L,\ g_R,\ g'$
- $\kappa_R \gg$ EWSB ($\sim$ many TeV)
- New Gauge Bosons: $W'^{\pm},\ Z'$
- $\kappa \equiv \sqrt{\kappa_1^2 + \kappa_2^2 + \kappa_L^2}$ sets EWSB
- Known Gauge Bosons: $W^{\pm} \sim W^{\pm}_{L\,/\,SM}$ and $Z \sim Z_{SM}$
- Define $\epsilon_{SB} = \kappa/\kappa_R$

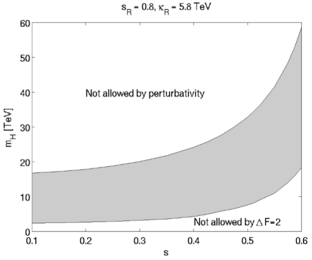
Generalities

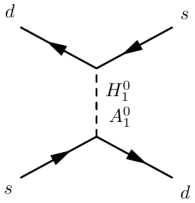
- **Quarks:** $Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$, and **leptons:** $L_{L,R} = \begin{pmatrix} \nu_{L,R} \\ \ell_{L,R} \end{pmatrix}$
- **Yukawa interactions:** $\overline{Q}_L Y \phi Q_R + \overline{Q}_L \tilde{Y} \tilde{\phi} Q_R + h.c.,$
  $\tilde{\phi} \equiv \sigma_2 \phi^* \sigma_2$.
  Bidoublet scalar field, $\phi \to U_L \phi U_R^\dagger$, **related to the SM Higgs**
  VEVs: $\langle \phi \rangle = \mathrm{diag}(\kappa_1, \kappa_2)$
- **Mass matrices:** $M_u = \kappa_1 Y + \kappa_2 \tilde{Y}$ and $M_d = \kappa_1 \tilde{Y} + \kappa_2 Y$.
  General combination of $Y, \tilde{Y} \Rightarrow$ **FCNC**
- **Mixing matrices:** $V_L \simeq V^{CKM}$ and V_R
- Special cases: Under $\mathcal{P}$ or $\mathcal{C}$, constrained V_R
- Additional sources of CPV (Higgs potential and VEVs)

Higgs content: Bidoublet+triplets

Triplets: $\langle \Delta_R^T \rangle = (0,\, 0,\, \kappa_R)$ and $\langle \Delta_L^T \rangle = (0,\, 0,\, \kappa_L)$

- 1 light Higgs + 5 H^0, 2 $H^\pm$, 1 $H^{\pm\pm}$
- **See-saw mechanism** $m_{\nu_L} \propto \kappa^2 / m_{\nu_R}$. However κ_R at TeV-ish and light m_{ν_L} requires **large fine-tuning or new symmetries** [Gunion et al. '91]
- $\rho = M_W^2 / (\cos^2(\theta_W) \cdot M_Z^2) \simeq 1 \Rightarrow \kappa_L = 0$
- FCNC: $\sim$ 10 TeV, for gen. V_R, $\frac{g_L}{g_R}$, $s \equiv \frac{\kappa_2}{\kappa}$ [Blanke, Buras, Gemmler, Heidsieck '11]

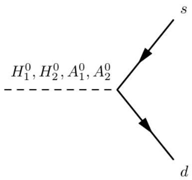




Higgs content: Bidoublet+doublets

Doublets: $\langle \chi_R^T \rangle = (0, \kappa_R)$ and $\langle \chi_L^T \rangle = (0, \kappa_L)$

- 1 light Higgs + 5 H^0, 2 $H^{\pm}$
- $\rho = 1$ at tree-level: The VEV κ_L needs to be probed
- No see-saw (neutrinos are Dirac particles in this minimal picture)



Coupling depends on κ_L
More Higgses participate

ElectroWeak Precision Tests

Observables: $\Gamma_{Z,W}$, σ_{had}, $R_{b,c}$, R_ℓ, $\mathcal{A}_{b,c,\ell}$, $A_{FB}(b,c,\ell)$, $Q_{weak}(Cs, Tl)$, M_W, direct searches for $M_{W'}$

SM

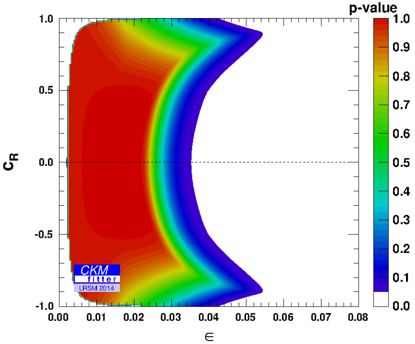
- Freitas '14 parameterizes under $S \equiv \{m_Z, m_{top}, m_{h-light}, \alpha_s, \Delta\alpha_{QED}\}$, EW @ two-loops
- `Zfitter`, semi-analytical program, to parameterize under S

LRSM

- Corrections at tree-level: $\mathcal{O}(\epsilon_{SB}^2)$
- **Parameters:** $S + \{c_R^2 \equiv 1 - \frac{s_w^2}{1-s_w^2}(g_L/g_R)^2,\ \epsilon_{SB} \equiv \kappa/v_R,\ r_{bidoublet} \equiv \kappa_2/\kappa_1,\ w_{LRD} \equiv \kappa_L/\kappa_1\}$
- `CKMfitter`: Frequentist framework for stat. analyses

Preliminary fit: EWPO and direct M_{W_R}

	SM pull	LRSM pull
σ^0_{had}	-1.49	-1.32
R_e	-1.19	-1.24
R_μ	-1.23	-1.30
$A_{FB}(b)$	2.77	2.81
$A_{FB}(\tau)$	-1.42	-1.41
A_e^{SLD}	-1.81	-1.76
M_W	-0.77	-0.83
$Q_W(Cs)$	0.69	0.74
...	...	...



- pull $\equiv (O_{exp} - O_{fit}|_{w/o\ input})/\sigma_{exp}$
- SM and LRSM similar results: $\chi^2_{min,SM} = 22.24$, $\chi^2_{min,LR} = 22.19$
- $r_{bidoublet}$, w_{LRD} and c_R are not much constrained by the fit
- Under assumptions, $M_{W'} \gtrsim 2$ TeV [CMS and ATLAS]

Effect of w

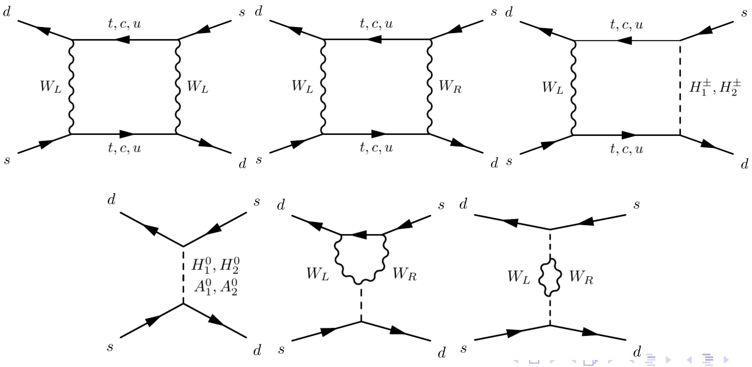
Fixed $M_{W'} = 1.5$ TeV

w_{LRD}	ϵ^2_{SB}	c_R	g_L	g_R	g_X	$M_{Z'}$[TeV]	χ^2_{min}
0	0.88	0.11	0.65	0.36	3.57	13.1	26.12
1	1.04	0.40	0.65	0.39	0.90	3.8	25.14
2	1.43	0.63	0.65	0.46	0.56	2.4	24.06

- $w_{LRD} \neq 0$ preferred
- But the chi-squared does not change a lot
- Need to include other processes

Meson oscillations, $\Delta F = 2$

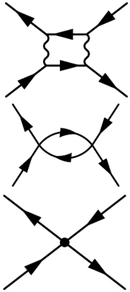
- SM: WW, WG, GG boxes (G=Goldstone)
- LRSM: boxes WW', GW' + charged Higgs boxes + FCNC + vertex and self-energy corrections (gauge invariance [Pal et al. '85])
- $w_{LRD} \neq 0$: New charged Higgs boxes and other FCNC



QCD corrections

Estimate η, i.e. running and matching effects ($\eta = 1$ w/o QCD)

$$C_i(\mu_0) = \eta_{ij}(\mu_0, \mu) C_j(\mu)$$



Matching at a scale $\mu_{W'}$, μ_W (small α_s)

$\downarrow_{\Delta F=1}$, **running**

Matching at an intermediate scale

$\downarrow_{\Delta F=2}$, **running**

hadronization scale (2 GeV): **Matching** at Lattice

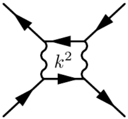
N_f thresholds can be included

[Buras, Misiak, Urban '00], [Buras, Jager, Urban '01]

Approximate method [Vysotskii '80], [Ecker, Grimus '85]

Two-loop integral → dominant momenta of the one-loop process

- Fix k^2, then put gluons in all possible ways: $\alpha_s^\gamma(k^2)$
- If $\int d^4k \cdot f(k^2) \sim (m^2)^c$, certain c, then $\int d^4k \cdot f(k^2)\alpha_s^\gamma(k^2) \sim (m^2)^c \alpha_s^\gamma(m^2)$
- If $\int d^4k \cdot f(k^2) \sim \log\left(\frac{m_2}{m_1}\right)$, then $\int_{m_1^2}^{m_2^2} \frac{dk^2}{k^2}[\alpha_s(k^2)]^\gamma$



	η_{tt}	η_{cc}	η_{ct}
dominant k^2	m_t^2	m_c^2	$m_c^2 - M_W^2$
reviews, LO	0.612	1.12	0.35
approx., LO	0.57	0.92	0.34

For the LRSM, some estimates already done
NLO: errors, from running (20%)

Context

- Model studied mainly in its triplet version, where it is strongly constrained in its Higgs sector
- A different Higgs content may imply less stringent constraints

Summary

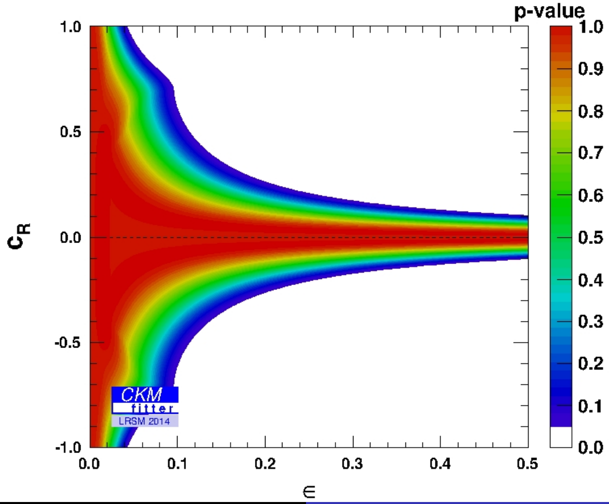
- EWPO: fixes mainly ϵ_{SB} and $w_{LRD} \neq 0$ is possible in principle
- Estimate corrections to the LR operators
- Include meson oscillations to constrain w_{LRD}, Higgs masses, V^R, etc.

Future

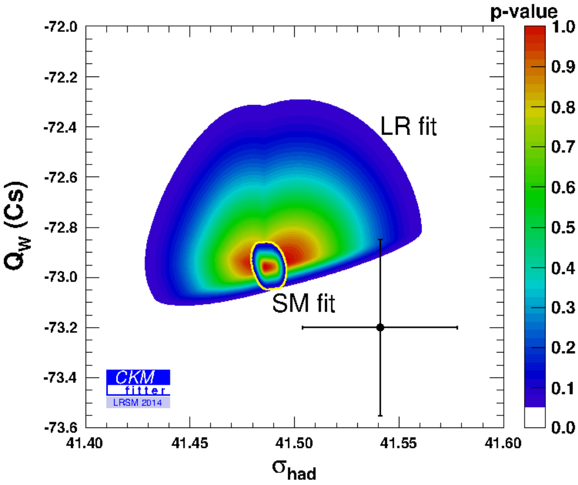
- Include other constraints: Lept., semi-lept. processes, fermionic spectrum, etc.
- Analyse $\mathcal{P}$ and $\mathcal{C}$

Thank you for the attention

Preliminary fit: correlation w/o M_{W_R} as input



Preliminary fit: correlation $\sigma^0_{had} - Q_W(Cs)$



Yukawa Couplings [Soni 0205082]

- The mass spectrum and the mixing matrices are inter-related through the Yukawas
  1. $M_u = \kappa_1 Y + \kappa_2 \tilde{Y}$ and $M_d = \kappa_2 Y + \kappa_1 \tilde{Y}$ (10 d.o.f. from $Y, \tilde{Y}$)
  2. Diagonalize them $(U_L^{u,d})^\dagger M_{u,d} U_R^{u,d} = m_{u,d}$
  3. and define $V_{L,R} \equiv (U^u_{L,R})^\dagger U^d_{L,R}$
- Same can be done for leptons. For neutrinos, set their masses to zero

Parameterization

First define: $L_H \equiv \log\left(\frac{m_{h-SM}}{125.7}\right)$, $\Delta_t \equiv \left(\frac{m_{top}}{173.2}\right)^2 - 1$,
$\Delta_{\alpha_s} = \frac{\alpha_s(M_Z)}{0.1184} - 1$, $\Delta_\alpha \equiv \frac{\Delta\alpha}{0.059} - 1$, and $\Delta_Z \equiv \frac{M_Z}{91.1876} - 1$.
Then calculate the coefficients in $O =$
$X_0 + c_1 \cdot L_H + c_2 \cdot \Delta_t + c_3 \cdot \Delta_{\alpha_s} + c_4 \cdot \Delta_\alpha^2 + c_5 \cdot \Delta_{\alpha_s}\Delta_t + c_6 \cdot \Delta_\alpha + c_7 \cdot \Delta_Z$.

Parameters

- Doublets only
- EWSB energy scale κ_1, κ_2, and $\kappa_L \neq 0$
- High energy scale κ_R or $\epsilon_{SB} \equiv \kappa_1/\kappa_R$
- For simplicity, no additional CPV (Higgs potential and VEVs: additional sources of CPV)
- Coupling constants g_R, g_L, g_{B-L}
- Mixing matrices V_L, V_R under $\mathcal{P}$: $V_L = S_u V_R S_d$