Constraining the Doublet Left-Right Model

Luiz Vale

Université Paris-Sud & CNRS
S. Descotes-Genon (LPT) and V. Bernard (IPN)
Rencontre de Physique des Particules, Paris

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The model

Framework where a symmetry relating left and right (e.g. $\mathcal{P}$) is broken spontaneously at high energies. Studied over the last 40 years [Pati, Salam, Mohapatra, Senjanovic '70s], **mainly its triplet version.**

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\downarrow_{(\langle\chi_R\rangle : \kappa_R)}$$

$$SU(2)_L \otimes U(1)_Y$$

$$\downarrow^{(\langle\phi\rangle : \kappa_{1,2}\,,}_{\langle\chi_L\rangle : \kappa_L)}$$

$$U(1)_{EM}$$

- g_L, g_R, g' couplings
- $\kappa_R \gg$ EWSB ($\kappa_R \gtrsim$ TeV scale)
- $\kappa \equiv \sqrt{\kappa_1^2 + \kappa_2^2 + \kappa_L^2}$ sets EWSB
- Then $\epsilon \equiv \kappa/\kappa_R \ll 1$
- Known Gauge Bosons: $\xi, \zeta = \mathcal{O}(\epsilon^2)$
  $W^\pm = W_L^\pm + \xi^* W_R^\pm$ and $Z = X + \zeta X'$
- New Gauge Bosons: $M = \mathcal{O}(\kappa_R)$
  $W'^\pm = W_R^\pm - \xi W_L^\pm$ and $Z' = X' - \zeta X$

Other aspects

- **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:** $\overline{Q}_L Y \phi Q_R + \overline{Q}_L \tilde{Y} \sigma_2 \phi^* \sigma_2 Q_R + h.c.$

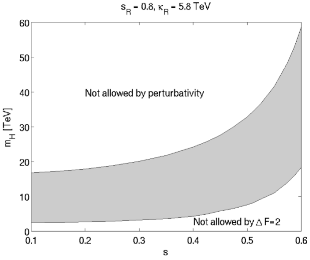
  Bidoublet scalar field, $\phi = \begin{pmatrix} \varphi_1^0 & \varphi_2^+ \\ \varphi_1^- & \varphi_2^0 \end{pmatrix}$, related to the SM Higgs

  VEVs: $\langle \phi \rangle = \mathrm{diag}(\kappa_1, \kappa_2)$
- **Mixing matrices:** V_L related to V^{CKM} and V_R

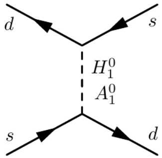
Higgs content in the case of triplets

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

- 1 light Higgs + 5 H^0, 2 $H^\pm$, 2 $H^{\pm\pm}$
- See-saw mechanism for the neutrinos. However κ_R at TeV-ish and light m_{ν_L} requires large fine-tuning or new symmetries [Gunion et al. '91]
- $\rho = M_W^2/(\cos^2(\theta_W)\cdot M_Z^2) \simeq 1 \Rightarrow \kappa_L/\sqrt{\kappa_1^2+\kappa_2^2} \ll 1$
- $K\overline{K}$ mixing: $m_{H,A} \gtrsim 2.4$ TeV, for gen. V_R, $\frac{g_L}{g_R}$, $s \equiv \frac{\kappa_2}{\sqrt{\kappa_1^2+\kappa_2^2}}$ [Blanke et al. '11]



FCNC:

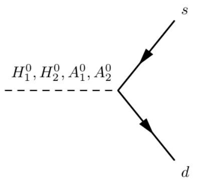


H_1^0, A_1^0 d.o.f. from the bi-doublet

Higgs content in the case of doublets

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

- 1 light Higgs + 5 H^0, 2 $H^\pm$
- $\rho = 1$ at tree-level: κ_L must be constrained by other means
- In this minimal picture, neutrinos are Dirac particles: no see-saw
- Other contributions to neutral meson mixing, modifying the constraint on $m_{H,A}$



Higgses	General FCNC
H_1^0, A_1^0	$h(\kappa_L) \sum_a m_u^a V_L^{as*} V_R^{ad}$
H_2^0, A_2^0	$f(\kappa_L) \sum_a m_u^a V_L^{as*} V_R^{ad}$

$h \to 1$ and $f \to 0$ when $\kappa_L \to 0$

Model considered and how to constraint it

Model w/ doublets, w/o additional sources of CPV (Higgs potential and VEVs), and w/o discrete symmetry $\mathcal{P}$ or $\mathcal{C}$. The case w/ a discrete symmetry can be analyzed as a special case.

Well determined observables to constrain the model:

Class	Observables	Main parameters to constraint
EWPO	Z pole, etc.	VEVs, $M_{W'}$, $\frac{g_L}{g_R}$
$K\overline{K}$, $B\overline{B}$	ϵ_K, $\Delta m_{d,s}$	VEVs, $M_{W'}$, $\frac{g_L}{g_R}$, V_L, V_R, $m_{Higgses}$, Higgs potential
tree-level processes	(semi-)leptonic decays	V_L, V_R
rare decays	$b \to s\gamma$	$M_{W'}$, $m_{Higgses}$

ElectroWeak Precision Tests

Γ_Z, σ^0_{had}, $R_{b,c}$, $R_{e,\mu,\tau}$, $\mathcal{A}_{b,c,\ell}$, $A_{FB}(b,c,\ell)$, $Q_{weak}(Cs, Tl)$, M_W, Γ_W

SM

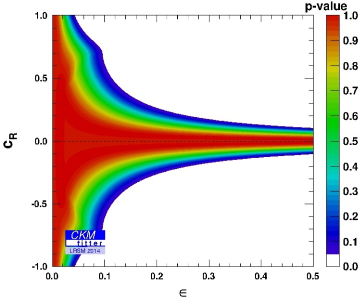
- Analytical: Freitas '14 parameterizes under $\mathcal{S} \equiv \{M_Z, m_{top}, m_h, \alpha_s, \Delta\alpha_{QED}\}$, includes two-loop 'fermionic' EW corrections
- Semi-analytical: `Zfitter`, to parameterize under $\mathcal{S}$
  (A_{LR} and A_{FB} include 2nd order ISR, APV incl. 1-loop EW,
  M_W incl. two-loop 'fermionic' EW, etc.)

LRM

- Corrections: $\mathcal{O}(\epsilon^2)$. Example: $M_Z^{LR} = M_Z \cdot [1 + f_{M_Z}(c_R^2, w, r) \cdot \epsilon^2]$
- **Parameters:** $\mathcal{S} + \{c_R^2 \equiv f(\frac{g_L}{g_R}),\ \epsilon \equiv \frac{\kappa}{\kappa_R},\ r \equiv \frac{\kappa_2}{\kappa_1},\ w \equiv \frac{\kappa_L}{\kappa_1}\}$

Global fit of EWPO

- CKMfitter
- $\chi^2_{min,SM} = 22.24$, $\chi^2_{min,LR} = 22.19$
- $g^2_{R,B-L} < 4\pi$ implies $0.1 \lesssim |c_R| < 1$
- Direct searches for W'



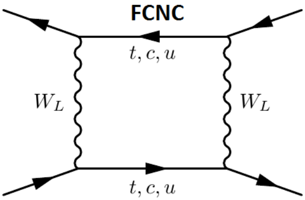
	SM pull	LRM pull
m_{top}	0.08	0.11
$m_h,\ \alpha_s,\ M_Z$	0.	0.
Γ_Z	-0.12*	-0.22*
σ^0_{had}	-1.49*	-1.32*
R_b	-0.80	-0.81
R_c	0.05	0.06
R_e	-1.19	-1.24
R_μ	-1.23	-1.30
R_τ	0.61*	0.56*
$A_{FB}(b)$	2.77	2.81
$A_{FB}(c)$	0.97	0.97
$A_{FB}(e)$	0.76	0.76
$A_{FB}(\mu)$	-0.39	-0.38
$A_{FB}(\tau)$	-1.42	-1.41
A_b	0.58	0.58
A_c	-0.07	-0.07
A_e^{SLD}	-1.81	-1.76
$A_e(P_\tau)$	-0.41	-0.39
A_μ^{SLD}	0.39	0.39
A_τ^{SLD}	0.79	0.79
$A_\tau(P_\tau)$	0.91	0.93
M_W	-0.77*	-0.83*
Γ_W	0.16	0.15
$Q_W(Cs)$	0.69*	0.74*
$Q_W(Tl)$	-0.02	-0.01

Effect of $w \equiv \frac{\kappa_L}{\kappa_1}$

Fixed $M_{W'} = 1.5$ TeV

w	ϵ^2	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

- $w \neq 0$ preferred
- Moreover, $g_X^2 < 4\pi \Rightarrow g_X < 3.54$, what disfavors $w = 0$
- The chi-squared does not change a lot: need to include other processes to eliminate flat directions of the fit



EFT

$$H^{|\Delta F|=2} = \sum_i C_i^{q_1 q_2}(\mu)\eta_i^{q_1 q_2}\langle O_i(\mu)\rangle,$$

($\eta = 1$ w/o QCD)

μ: renormalization scale

Alternative method

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

$C(\mu)$ (Wilson coefficients) and η

- Short distance QCD
- Perturbative calculation
- NLO ([Herrlich, Nierste]) and NNLO ([Gorbahn and Brod])

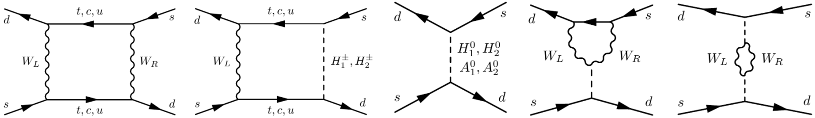
$\langle O(\mu)\rangle$

- Long distance QCD
- No expansion on α_s: Lattice QCD

[ETMC]: SM operators (and LR as well)

SM: $K\overline{K}$, LO	η_{tt}	η_{cc}	η_{ct}
EFT [Buras et al. '96]	0.612	1.12	0.35
Vysostskii's method	0.60	0.92	0.34

Short distance corrections to LRM, preliminary results



Calculations employing EFT are only partially available for the LR operators. We then employ [Vysotskii '80], [Ecker, Grimus '85]

LRM: LO	$\eta_{tt}^{K\overline{K}}$	$\eta_{cc}^{K\overline{K}}$	$\eta_{ct}^{K\overline{K}}$	$\eta_{tt}^{B\overline{B}}$
$W^{\pm}W'^{\pm}$, $W^{\pm}H^{\pm}$	2.89	0.78	1.50	2.19
$G^{\pm}W'^{\pm}$	2.89	0.92	1.50	2.19
$G^{\pm}H^{\pm}$	2.89	0.31	0.41	2.18
tree-level FCNC	2.15	0.58	1.12	1.63

N_f thresholds included, $\mu_{\text{had}}^{K\overline{K}} = 2$ GeV, $\mu_{\text{had}}^{B\overline{B}} = 4$ GeV

Context

- Model studied mainly in its triplet version, where FCNC puts rather strong constraints in its Higgs sector
- A different Higgs content implying different couplings may lead to less stringent constraints

Summary

- EWPO: $w \equiv \kappa_L/\kappa_1 \neq 0$ is possible in principle
- Meson-mixing: short-distance corrections estimated, analysis under way (to constrain w, Higgs masses, V_R, etc.)

Next steps

- Meson-mixing: estimate short-distance corrections at NLO
- Include other constraints to verify the viability of Doublet LRM: Leptonic and semi-leptonic processes, etc. and combine them using CKMfitter
- Analyze compatibility w/ a discrete symmetry between L and R sectors (e.g. $\mathcal{P}$ or $\mathcal{C}$)

Thank you for the attention

Example: Usual method for η_{cc}

$\mu \sim m_c \ll M_W \Rightarrow$ large corrections from large logs

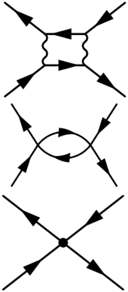
Matching at a scale μ_t, μ_W into $O_\pm$

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

Matching at an intermediate scale μ_c into $(\bar{d}\gamma_\mu P_L s)(\bar{s}\gamma^\mu P_L d)$

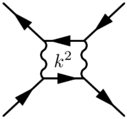
$\downarrow_{\Delta F=2}$, **running**

hadronization scale (2 GeV $\rightarrow K\overline{K}$, $m_b \rightarrow B\overline{B}$):
Matching at Lattice [ETMC]



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

- Fix k^2, then put gluons in all possible ways
- Running: $\mu_W \to k^2 \to \mu$
- $\alpha_s^{\gamma}(k^2)$, γ from anomalous dimensions [Buras et al. '00]
- Determine relevant interval of momenta for k^2
  $\eta_{tt,ct}^{K\overline{K}}$: $k^2 \to m_t^2$, $\eta_{cc}^{K\overline{K}}$: $k^2 \to [m_c^2, M_W^2]$



Parameters

- Doublets only
- EWSB energy scale κ_1, κ_2, and $\kappa_L \neq 0$
- High energy scale κ_R or $\epsilon \equiv \kappa_1/\kappa_R$
- 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 $\mathcal{P}$: $V_L = S_u V_R S_d$

Example of parameterization

Define: $L_H \equiv \log\left(\frac{m_h}{125.7}\right)$, $\Delta_t \equiv \left(\frac{m_{top}}{173.2}\right)^2 - 1$, $\Delta_{\alpha_s} = \frac{\alpha_s(M_Z)}{0.1184} - 1$, $\Delta_\alpha \equiv \frac{\Delta\alpha}{0.059} - 1$, and $\Delta_Z \equiv \frac{M_Z}{91.1876} - 1$.

$$O = X_0 + c_1 \cdot L_H + c_2 \cdot \Delta_t + c_3 \cdot \Delta_{\alpha_s} + c_4 \cdot \Delta_\alpha^2 + c_5 \cdot \Delta_{\alpha_s} \Delta_t + c_6 \cdot \Delta_\alpha + c_7 \cdot \Delta_Z$$

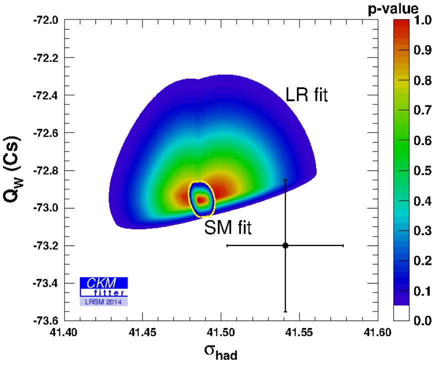
$\Gamma_Z[MeV]$	1	L_H	Δ_t	Δ_{α_s}	Δ_α^2	$\Delta_{\alpha_s}\Delta_t$	Δ_α	Δ_Z
Zfitter	2495.22	-2.4	20.1	63.48	-3.2	-1.8	-54.4	9225
Freitas	2494.24	-2.0	19.7	58.60	-4.0	8.0	-55.9	9267

ElectroWeak Precision Tests

References for inputs

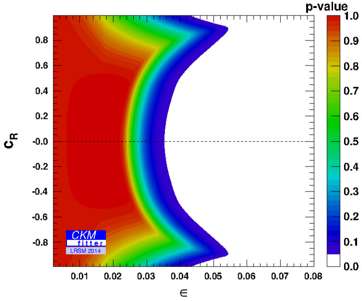
observable	reference	free in fit
m_{top}	[Tevatron, LHC]	yes
m_h	[CMS, ATLAS]	yes
α_s	[PDG] τ-decays, Lattice, DIS, e^+e^-, Z pole	yes
M_Z	[LEP, SLC]	yes
$\Delta\alpha^{(5)}_{had}$	–	yes
Γ_Z, σ^0_{had}, $R_{b,c}$, $R_{e,\mu,\tau}$, $\mathcal{A}_{b,c,\ell}$, $A_{FB}(b,c,\ell)$	[LEP, SLC]	–
$Q_{weak}(Cs)$	[Boulder and Paris groups]	–
$Q_{weak}(Tl)$	[Oxford and Seattle groups]	–
M_W	[Tevatron]	–
Γ_W	[LEP, SLC, Tevatron]	–
$M_{W'}$	[CMS, ATLAS]	–

Extra plot

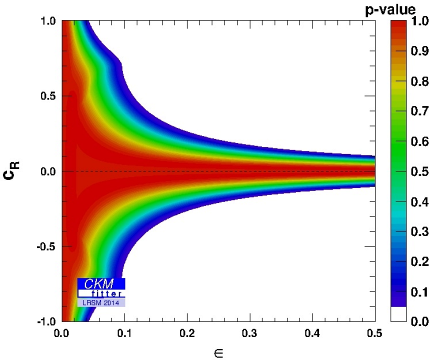

p-value
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-72.0
-72.2
-72.4
-72.6
-72.8
-73.0
-73.2
-73.4
-73.6
41.40
41.45
41.50
41.55
41.60
Q_W (Cs)
σ_{had}
LR fit
SM fit
CKM fitter
LRSM 2014

Direct $M_{W'} \simeq g_R \kappa_R / 2$

W/ $M_{W'}$ input



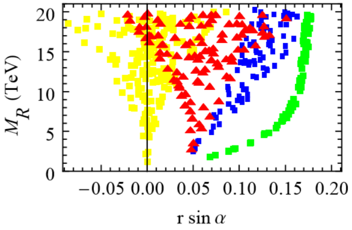
W/O $M_{W'}$ input

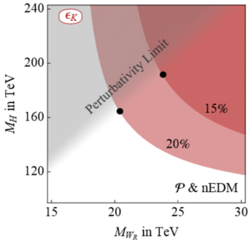


Under the assumptions $g_L = g_R$ and manifest V_R, $M_{W'} \gtrsim 2$ TeV [CMS and ATLAS]

Obs: r, w and c_R are not much constrained by the fit

Effect of discrete symmetry





Left: [Mohapatra et al. '07]; yellow corresponds to nEDM, while red $m_{Higgs} = \infty$, blue $m_{Higgs} = 75$ TeV and green $m_{Higgs} = 20$ TeV correspond to indirect CP violation in Kaon decay. Right: [Maiezza et al. '14]. Both references show strong constraints on m_{Higgs} under the case of a discrete symmetry.