Testing non-standard couplings of fermions to Z

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V. Bernard, M.O., E. Passemar, J.Stern, Phys. Lett. B 638 (2006) 480
V. Bernard, M.O., E. Passemar, J.Stern, arXiv:0707.4194 [hep-ph]

Theoretical framework to classify non-standard EW effects

- High energies: larger symmetry $\longrightarrow$ observable effects at low energies?
- "Bottom-up" approach: low energy effective theory framework does not depend on particular model at high energies
- Decoupling scenario: new physics operators suppressed by energy scale Λ
- "Not quite decoupling" effective theory (valid for $p \ll \Lambda \sim 3TeV$) fulfilling
  - Equipped with a systematic infrared power counting ($p \to p\lambda$ in the limit $\lambda \to 0$)

$$\mathcal{L}_{eff} = \sum_{d\geq 2} \mathcal{L}_d \quad d = n_p + n_g + \frac{n_\psi}{2}$$

  - Renormalisation order by order in the expansion scheme
  - Assuming naturality (all operators allowed by the symmetries at a given order appear with "natural" strength)
  - Observed phenomenology, i.e., at lowest order the higgsless vertices of the SM should be recovered and nothing else
  - (Light) particle content (below $\sim$ 3 TeV), here all observed particle of the SM, i.e., gauge bosons W, Z, γ + quarks + leptons
  - Appropriate symmetry (partially non-linearly realised at low energies) to garantuee these conditions

Constructing the minimal not quite decoupling LEET

- Most simple LEET based on $SU_L(2) \times U_Y(1)$ (chiral electroweak Lagrangian) gives rise to unwanted operators (e.g. lowest order contributions to the parameters S, T)
- Solution: larger symmetry $S_{nat} \supset SU_L(2) \times U_Y(1)$ survives at low energy and becomes non-linearly realised:
  S_{nat} constrains the interactions at low energy
- Minimal solution to get at lowest order the higgsless vertices of the SM: symmetry $S_{nat} = [SU(2)]^4 \times U(1)_{B-L}$ (Hirn&Stern '04,'06)
- Reduction of $S_{nat} \to S_{\mathrm{EW}}$ via spurions $\mathcal{X}, \mathcal{Y}, \mathcal{Z}$ populating the coset space S_{nat}/S_{EW} with $D_\mu \mathcal{X} = D_\mu \mathcal{Y} = D_\mu \mathcal{Z} = 0$
- Power counting in terms of momenta and spurion parameters (in the standard gauge $\mathcal{X} = \xi \Omega_L, \mathcal{Y} = \eta \Omega_R$ with $\Omega_L, \Omega_R \in SU(2)$)
- Counting $\xi, \eta \sim \mathcal{O}(p^{1/2})$ $(m_{\mathrm{Dirac}} \sim \mathcal{O}(\xi\eta))$: $\kappa = \frac{k+l}{2}$ for $\mathcal{O}(\xi^k \eta^l)$

Next-to leading order

- Momentum and spurion (κ) power counting :

$$\mathcal{L}_{\text{eff}} = \sum_{d^* \geq 2} \mathcal{L}_{d^*} \quad d^* = d + \kappa = 2 + 2L + \sum_v (d_v^* - 2)$$

- Leading order ($d^* = 2$): SM without Higgs

$$\begin{array}{rl} \mathcal{O}(p^2\kappa^0): & \frac{f^2}{4}\langle D_\mu \Sigma^\dagger D^\mu \Sigma \rangle + \ldots \\ \mathcal{O}(p^1\kappa^1): & \text{fermion mass terms} \end{array}$$

- Two operators at NLO ($\mathcal{O}(p^2\kappa^1)$)

$$\mathcal{O}_L = \bar{\Psi}_L \mathcal{X}^\dagger \Sigma \gamma^\mu D_\mu \Sigma^\dagger \mathcal{X} \Psi_L \qquad \mathcal{O}_R^{a,b} = \bar{\Psi}_R \mathcal{Y}_a^\dagger \Sigma^\dagger \gamma^\mu D_\mu \Sigma \mathcal{Y}_b \Psi_R$$

$\longrightarrow$ non-standard couplings of fermions to W and Z ($\{a, b\} \in \{U, D\}$)

- NLO Lagrangian with $\mathcal{O}(1)$ prefactors $\rho_L, \lambda_L, \rho_R^{a,b}, \lambda_R^{a,b}$

$$\mathcal{L}_{\text{NLO}} = \rho_L \mathcal{O}_L(l) + \lambda_L \mathcal{O}_L(q) + \sum_{a,b} \rho_R^{a,b} \mathcal{O}_R^{a,b}(l) + \sum_{a,b} \lambda_R^{a,b} \mathcal{O}_R^{a,b}(q)$$

- Oblique corrections and loop corrections at NNLO ($d^* \geq 4$)
- What are the constraints on these non-standard couplings?

Structure of couplings to W at NLO

- Lepton sector:
  - Universal modification of left-handed couplings $\longrightarrow$ redefinition of G_F
  - Additional Z_2 symmetry ($\nu_R \to -\nu_R$)
    $\longrightarrow$ suppresses Dirac mass for neutrinos
    $\longrightarrow$ no right-handed charged lepton current
- Effective quark charged current interaction, $\delta = (\rho_L - \lambda_L)\xi^2$, $\epsilon = \eta^2 \lambda_R^{u,d}$

$$W_\mu^+ \Big((1+\delta)\, \bar{U}_L \, \gamma^\mu \, V^L \, D_L \; + \; \epsilon \, \bar{U}_R \, \gamma^\mu \, V^R \, D_R \Big) + h.c.$$

- V^L and V^R: two a priori independent unitary mixing matrices
- $\epsilon \neq 0$: direct coupling of right-handed quarks to W
- Experimental tests for light quarks at NLO: $K^L_{\mu 3}$ decays ($\to$ KLOE talk this afternoon), hadronic tau decays, hadronic width of W, $\pi^0 \to 2\gamma$
  (V. Bernard et al, arXiv:0707.4194)
- Many possible tests beyond NLO (e.g. FCNC processes)

Structure of couplings to Z at NLO

- Effective neutral current interaction (universal non-standard effects)

$$Z_\mu \left(\sum_f g_L^f \bar{\psi}^f{}_L \, \gamma^\mu \, \psi_L^f + \sum_f g_R^f \bar{\psi}^f{}_R \, \gamma^\mu \, \psi_R^f \right)$$

- Effective couplings of left-handed fermions to Z ($\tilde{s}_w^2 = s^2/(1-\xi^2\rho_L)$)

$$g_L^u = \frac{1+\delta}{2} - \frac{2}{3}\tilde{s}_w^2 \qquad g_L^d = -\frac{1+\delta}{2} + \frac{1}{3}\tilde{s}_w^2 \qquad g_L^e = -\frac{1}{2} + \tilde{s}_w^2 \qquad g_L^\nu = \frac{1}{2}$$

- Effective couplings of right-handed fermions to Z:

$$g_R^u = -\frac{2}{3}\tilde{s}_w^2 + \frac{1}{2}\epsilon^u \qquad g_R^d = \frac{1}{3}\tilde{s}_w^2 - \frac{1}{2}\epsilon^d \qquad g_R^e = \tilde{s}_w^2 - \frac{1}{2}\epsilon^e \qquad g_R^\nu = \frac{1}{2}\epsilon^\nu$$

- Parameter $\delta = (\rho_L - \lambda_L)\xi^2$, the same as for the coupling of left-handed quarks to W
- Parameter $\epsilon^i = \eta^2 \rho_R^i$ proportional to η^2 as for ϵ (W)
- Coupling of right-handed neutrinos enters only quadratically the Z width $\longrightarrow$ no NLO effect

Remarks on G_F and the W mass

- Relate fundamental couplings of the theory (g, g') to α and muon life time

$$\alpha(0) = e^2/(4\pi), \qquad \frac{G_F}{\sqrt{2}} = \frac{4\pi\alpha(0)}{8m_Z^2 c^2 s^2 (1-\Delta r)}(1-\xi^2\rho_L)^2$$

- Weak loop corrections at NNLO $\longrightarrow\ \Delta r = \Delta\alpha$
- Spurion contribution and loop corrections modify LO result in the same way
- Writing charged current observables in terms of G_F: $\xi^2\rho_L$ not accesible
- Couplings to Z: $\xi^2\rho_L$ enters independently via $\tilde{s}_w^2 \longrightarrow$ express $\xi^2\rho_L$ and m_W in terms of $\tilde{s}_w^2$, G_F (and α, m_Z)

$$\frac{m_W^2}{m_Z^2} = \frac{h}{h+\tilde{s}^4}, \qquad 1-\xi^2\rho_L = \frac{\tilde{s}_w^2}{h+\tilde{s}^4} \qquad \left(h = \frac{\pi\alpha(0)}{\sqrt{2}G_F m_Z^2(1-\Delta r)}\right)$$

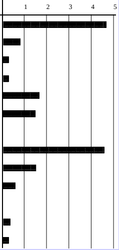
- Note: no direct modification of m_W at NLO

Experimental information: couplings to Z

1. Data near the Z resonance: (LEP/SLD compilation Phys. Rep. '06)

- Perform a fit to Z-pole data
- Include leptonic branching fraction of W (sensitive to δ)
- Take EM/QCD radiative corrections into account
- Simultaneous determination of α_s and spurion parameters difficult
- $\alpha_s(m_Z) = 0.1190$ for the presented result
- For comparison, first LO result
- At LO, no variable parameter ($\alpha_s(m_Z)$ fixed for better comparison with NLO result

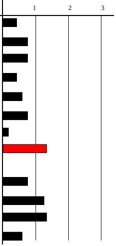
	Measurement	Fit	$\frac{(\lvert O^{meas} - O^{fit}\rvert)}{\sigma^{meas}}$
Γ_Z [GeV]	2.4952(23)	2.4842	
σ_{had} [nb]	41.540(37)	41.507	
R_e	20.767(25)	20.770	
A^l_{FB}	0.0171(10)	0.0173	
$\mathcal{A}_l(P_\tau)$	0.1465(32)	0.1519	
R_b	0.21629(66)	0.2173	
R_c	0.1721(30)	0.1719	
A^b_{FB}	0.0992(16)	0.1066	
A^c_{FB}	0.0707(35)	0.0763	
$\mathcal{A}_b$	0.923(20)	0.936	
$\mathcal{A}_c$	0.670(27)	0.670	
$\mathcal{A}_l$(SLD)	0.1513(21)	0.1519	
$Br(W \to l\nu)$	0.1084(9)	0.1082	



Z pole data, NLO result

- Good quality of the NLO fit ($\chi^2/dof = 8.5/8$)
- Again: $\alpha_s(m_Z) = 0.1190$ for the presented result
- "A^b_{FB} puzzle" can be solved with universal modification of couplings important point: non-standard couplings of right-handed quarks

	Measurement	Fit	$\frac{(\lvert O^{meas} - O^{fit}\rvert)}{\sigma^{meas}}$
Γ_Z [GeV]	2.4952(23)	2.4943	
σ_{had} [nb]	41.540(37)	41.569	
R_e	20.767(25)	20.785	
A^l_{FB}	0.0171(10)	0.0165	
$\mathcal{A}_l(P_\tau)$	0.1465(32)	0.1485	
R_b	0.21629(66)	0.21685	
R_c	0.1721(30)	0.1725	
A^b_{FB}	0.0992(16)	0.1012	
A^c_{FB}	0.0707(35)	0.0707	
$\mathcal{A}_b$	0.923(20)	0.910	
$\mathcal{A}_c$	0.670(27)	0.636	
$\mathcal{A}_l$(SLD)	0.1513(21)	0.1485	
$Br(W \to l\nu)$	0.1084(9)	0.1089	



- Values for the parameters coherent with the LEET:

$$(\epsilon^e)_{\rm NLO} = -0.0024(5) \quad (\epsilon^u)_{\rm NLO} = -0.02(1) \quad (\epsilon^d)_{\rm NLO} = -0.03(1)$$
$$(\tilde{s}^2_w)_{\rm NLO} = 0.2307(2) \quad (\delta)_{\rm NLO} = -0.004(2)$$

- Parameter values susceptible to be modified at NNLO (remind: only loop corrections + counter terms meaningful within the LEET), but hardly imaginable that the nice agreement with data is spoiled

Couplings to Z, data at low momentum transfer

2. Data at low momentum transfer:

- Atomic parity violation experiments : test the weak charge

$$
\begin{aligned}
Q_W &= 4g_A^e\Big(Z\,(2g_V^u + g_V^d) + N\,(g_V^u + 2g_V^d)\Big) \\
Q_W(NLO) &= (1-\epsilon^e)\Big(Z(1-4\tilde{s}_w^2 + \delta - \epsilon^d + 2\,\epsilon^u) - N(1+\delta+2\,\epsilon^d - \epsilon^u)\Big)
\end{aligned}
$$

- Take the value from the fit to Z pole data: $(Q_W(^{133}\mathrm{Cs}))_{\mathrm{NLO}} = -70.72 \pm 4.19$ in agreement with the experimental value, $Q_W(^{133}\mathrm{Cs}) = -72.71(49)$ (Guena et al '05)
- QWEAK experiment will measure Q_W of the proton
  NLO result very small ($Q_W^p = 0.062(22)$) because $1 - 4\tilde{s}_w^2 \ll 1$
  $\longrightarrow$ enhanced sensitivity to higher orders
- The same for weak charge of electrons (Møller scattering):

$$Q_W^e = 1 - 4\,\tilde{s}_w^2\,(1-\epsilon^e)$$

with $(Q_W^e)_{\mathrm{NLO}} = 0.074(1)$ compared with measurement $Q_W^e = 0.041(5)$
again $(1 - 4\tilde{s}_w^2 \ll 1)$: higher order corrections probably important

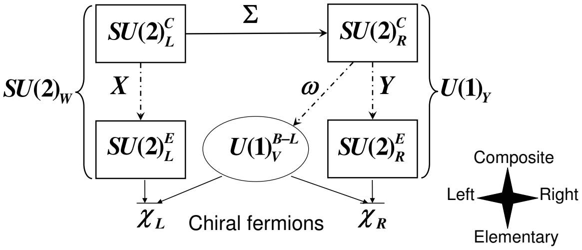
Summary and outlook

- Summary:
  - Minimal (not quite decoupling) effective theory: first effects beyond the SM are non-standard couplings of fermions to W and Z
  - Determination of EW and QCD parameters correlated
  - Most spectacular effect: direct coupling of right-handed quarks to W (stringent test in $K^L_{\mu 3}$ decays, (V. Bernard et al, PLB '06), see also KLOE talk kaon WG)
  - Here: couplings to Z
    - Z-pole data can be nicely reproduced at NLO (in particular A^b_{FB})
    - Nice agreement with atomic parity violation data
    - No inconsistencies with the systematics of the effective theory

- Outlook:
  - Heavy quark sector (couplings to W)
  - Loop effects (CP violation, FCNC,....)

Structure of the minimal effective theory

- Minimal solution to get at lowest order the higgsless vertices of the SM: symmetry $S_{nat} = [SU(2)]^4 \times U(1)_{B-L}$ (Hirn&Stern '04,'06)



- GB Σ : link $L \longleftrightarrow R$
- Spurions X, Y, ω : link $C \longleftrightarrow E$
- Covariant constraints reducing the symmetry and the physical dof to

$$SU(2) \otimes U(1)_Y \Leftrightarrow \boxed{D_\mu X = D_\mu Y = D_\mu \omega = 0}$$

- $X \sim \xi \quad Y \sim \eta \quad \omega \sim \varsigma$ small expansion parameters.

- Counting $\xi, \eta \sim \mathcal{O}(p^{1/2}) \quad (m_{\mathrm{Dirac}} \sim \mathcal{O}(\xi\eta))$: $\kappa = \frac{k+l}{2}$ for $\mathcal{O}(\xi^k \eta^l)$