New Light Vector Bosons

Electroweak Precision Measurements

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1. Explaining our goal

Theoretical Summary

- Additional U(1) symmetries are predicted in the most common extensions of the SM gauge group: $SO(10)$ and E_6 GUT groups, extra-dimensional models, and string theory;
- The gauge boson associated with an extra U(1) symmetry will be massive, neutral, colorless, and self-adjoint;
- If such gauge boson is weakly coupled, it can also be very light (within the eV-GeV mass range);
- Both kinetic and mass mixings with the SM photon and Z boson are allowed.

2. Extending the SM by a new $U(1)$ symmetry

	$SU(3)_C$	$SU(2)$	$U(1)_Y$	$U(1)_X$
Q^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	0
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	0
L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	0
ν_R^i	$\mathbf{1}$	$\mathbf{1}$	0	0
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	q_X
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	$-q_X$

Quantum numbers of the fields contained in our model. The index i runs over the three SM generations. The SM model field, now denoted by H_u, is uncharged under the new $U(1)$ symmetry.

THE NEW LAGRANGIAN

$$\mathcal{L}_{Kinetic} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + \\ + (D_\mu H_u)^\dagger (D^\mu H_u) + (D_\mu H_d)^\dagger (D^\mu H_d) + (D_\mu \phi)^* (D^\mu \phi),$$

$$\mathcal{L}_{Potential} = \mu_u^2 H_u^\dagger H_u - \lambda_u (H_u^\dagger H_u)^2 + \mu_d^2 H_d^\dagger H_d - \lambda_d (H_d^\dagger H_d)^2 + \\ + \mu_\phi^2 \phi^* \phi - \lambda_\phi (\phi^* \phi)^2 - \lambda_{ud}(H_u^\dagger H_u)(H_d^\dagger H_d) - \lambda'_{ud}(\tilde{H}_u^t H_d)(\tilde{H}_d^t H_u) - \\ - \lambda_{u\phi}(H_u^\dagger H_u)(\phi^*\phi) - \lambda_{d\phi}(H_d^\dagger H_d)(\phi^*\phi) + i\kappa H_u^t \sigma^2 H_d \phi,$$

$$\mathcal{L}_{Yukawa} = -Y_d^{ij}\bar{Q}^i \tilde{H}_d \phi^* d_R^j - Y_e^{ij}\bar{L}^i \tilde{H}_d \phi^* e_R^j - Y_u^{ij}\bar{Q}^i \tilde{H}_u u_R^j.$$

The scalar fields acquire a vev, such that the gauge Lagrangian takes the form $\mathcal{L} \supset -\frac{1}{4}\hat{\mathbf{V}}_{\mu\nu}^{T} K \hat{\mathbf{V}}_{\mu\nu} + \frac{1}{2}\hat{\mathbf{V}}_{\mu}^{T} M^2 \hat{\mathbf{V}}_{\mu}$, where

$$\hat{\mathbf{V}}^{T} \equiv \left(\hat{Z}\ \hat{A}\ \hat{X}\right),$$

$$K \equiv \begin{bmatrix} 1 & 0 & -\frac{g'}{\sqrt{g^2+g'^2}}\frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & 1 & \frac{g}{\sqrt{g^2+g'^2}}\frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{bmatrix},$$

$$M^2 = \begin{pmatrix} \frac{1}{4}(v_u^2+v_d^2)(g^2+g'^2) & 0 & -\frac{1}{2}\sqrt{g^2+g'^2}q_X g_X v_d^2 \\ 0 & 0 & 0 \\ -\frac{1}{2}\sqrt{g^2+g'^2}q_X g_X v_d^2 & 0 & q_X^2 g_X^2 (v_d^2+w^2) \end{pmatrix}.$$

Since $det\,(M^2) = 0$, we already know there will be a massless eigenstate in our model.

Eigensystem (Part I)

In order to determine the observable eigensystem:

- Diagonalize the kinetic matrix;
- Diagonalize the resulting mass matrix;
- Identify the parameters that "control" both kinetic and mass mixings,

$$\sinh(\xi) = \frac{\epsilon}{\sqrt{1-\epsilon^2}}, \quad \frac{v_u}{v_d} = \frac{1}{\tan(\beta)}, \quad \text{and} \quad \frac{w}{v_d} = \frac{1}{\tan(\eta)}.$$

Eigensystem (Part II)

Z Boson

$Z = \hat{Z} +$ small corrections in $\hat{Z}$ and $\hat{X}$
$M_Z = \hat{M}_Z +$ small corrections

Photon

$A = \hat{A} +$ small corrections in $\hat{A}$ and $\hat{X}$
$M_A = 0$

Z' Boson

$Z' = \hat{X} +$ small corrections in $\hat{Z}$ and $\hat{X}$
$M_{Z'} = \hat{M}_X +$ small corrections

What do we know so far?

- The Z boson mass and coupling are modified;
- The Z' boson couples to both SM neutral currents J_Z and J_{EM};
- A mixing between the neutral gauge bosons can have important consequences on the EW precision measurements;

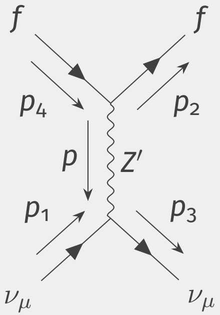
3. The Z' boson phenomenology

EW Observables at the Z Resonance (LEP 1)

- Class of observables measured in e^+e^- collisions;
- Z boson partial and total widths, left-right asymmetries for Z production, forward-backward asymmetries for $e^+e^- \to \bar{f}f$;
- The existence of a Z' boson can affect these quantities;
- We must make use of the precision program:
  - Choose the best-measured observables to describe all the other EW observables;
  - The new gauge boson changes the relation between the theoretical parameters and the reference observables;
  - Sufficient to compute contributions only at tree-level.

Neutrino-Electron Scattering

We can extend our analysis by including low-energy scattering of muon neutrinos with electrons. These types of scattering are mediated by the exchange of a virtual Z boson in the SM. However, in the presence of new physics such process can also be mediated by the exchange of a virtual Z' boson:



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Neglecting the scalar sector, we can re-express the interaction Lagrangians in terms of the standard parameters $\alpha_e(M_Z^2)$, s, and c:

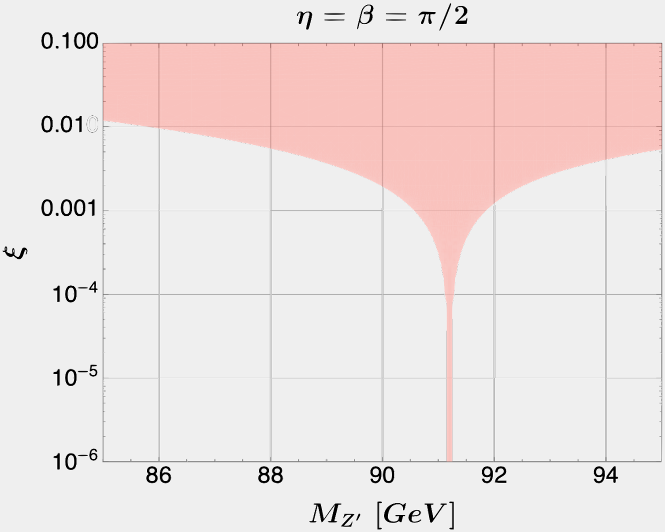
$$\mathcal{L}_{int}^{Z} = \frac{\sqrt{4\pi\alpha_e(M_Z^2)}}{sc} Z_\mu \bar{\psi}\gamma^\mu \left[\left(g_L^{\psi,SM} + \delta g_L^{\psi} \right) P_L + \left(g_R^{\psi,SM} + \delta g_R^{\psi} \right) P_R \right] \psi,$$

$$\mathcal{L}_{int}^{A} = \sqrt{4\pi\alpha_e(M_Z^2)} A_\mu \bar{\psi}\gamma^\mu \left[\left(1 - \frac{\delta\alpha_e}{2} \right) Q \right] \psi,$$

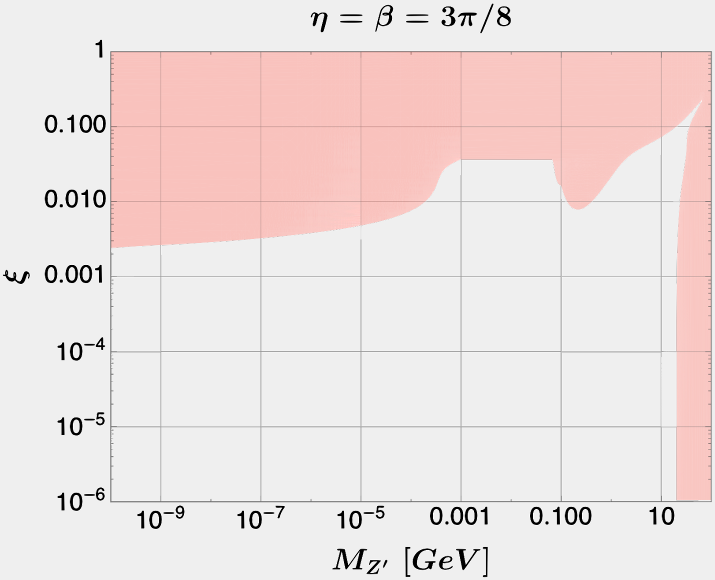
$$\mathcal{L}_{int}^{Z'} = \frac{\sqrt{4\pi\alpha_e(M_Z^2)}}{sc} Z'_\mu \bar{\psi}\gamma^\mu \left[\left(\delta\tilde{g}_L^{\psi} \right) P_L + \left(\delta\tilde{g}_R^{\psi} \right) P_R \right] \psi,$$

From these Lagrangians, we can calculate all the EW observables in the presence of a Z' boson.

Global Fit – Kinetic Mixing



Global Fit – Both Kinetic and Mass Mixings



4. Final Conclusions

What does the future hold?

- For our purposes, the relevant LEP2 observables are the cross sections of $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \sum_q \bar{q}q$ at energies around 200 GeV;
- In the presence of new physics, these scattering processes can also occur by the exchange of Z';
- We have encountered some difficulties when calculating the cross section in the regime of very light Z' bosons (choosing the gauge, Goldstone bosons, SSB in the limit of $M_{Z'} \to 0$).

Thank you!