Notes on a Z'

by

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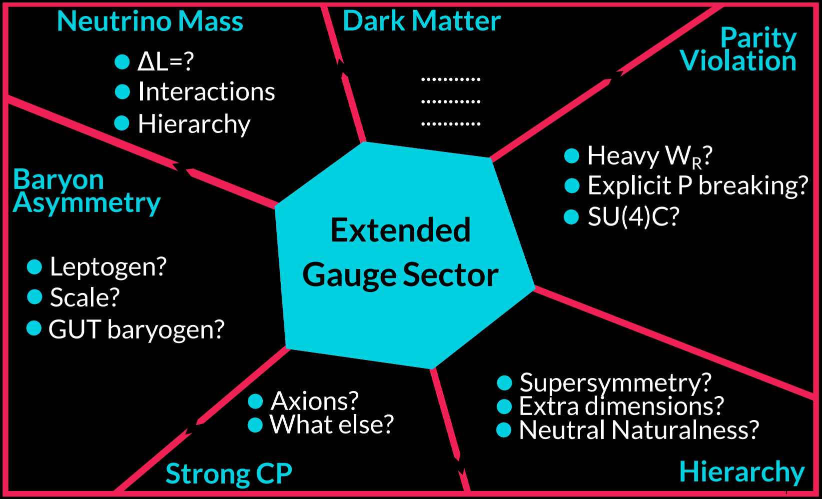
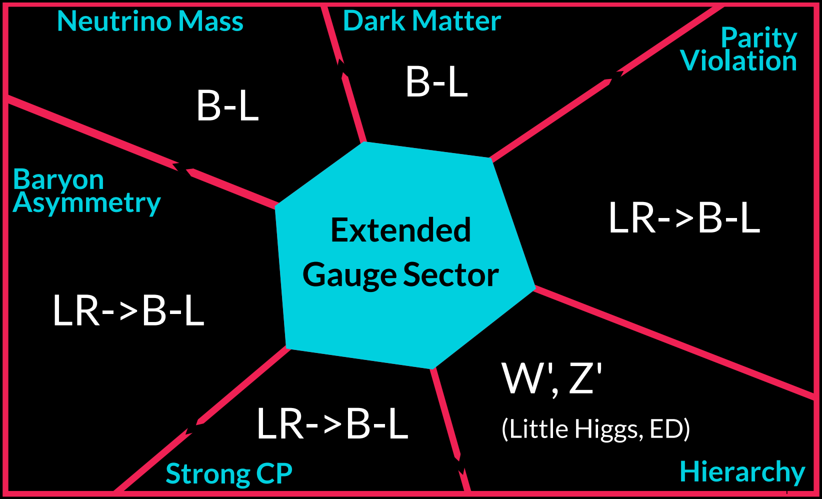
Compass beyond the SM



Compass beyond the SM



Compass beyond the SM

Neutrino Mass

Dark Matter

Baryon Asymmetry

Z'

(Like it or not)

(I don't)

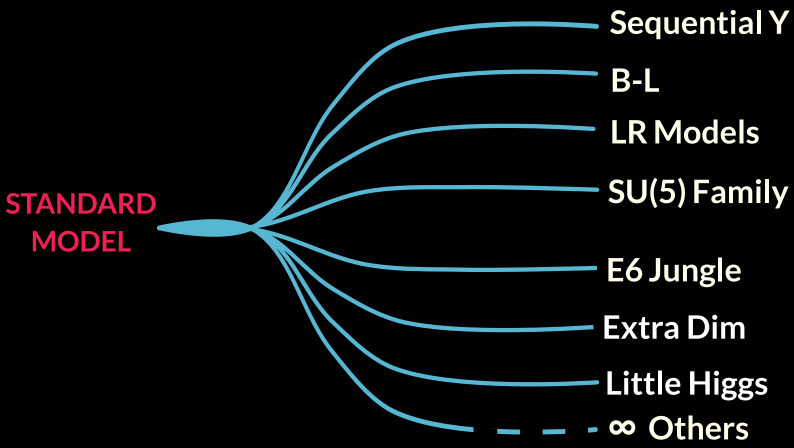
(For the record)

Parity Violation

Strong CP

Hierarchy

Gauge Extension → Rank



Unified parametrisation

- Symmetry breaking
  - $U(1)_1 \times U(1)_2 \sim U(1)_Y \times U(1)_X \xrightarrow[v_s]{S} U(1)_Y$
- Scalar Charge:
  - $S \sim \left(0(Y), \frac{1}{2}(X)\right)$ (Charge normalisation)
- Gauge Kinetic Lagrangian ($U(1)$)
  - $-\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu}$
- Transformations:
  - Go to Canonical Kinetic basis (O_{GKM})
  - Go to $U(1)_Y \times U(1)_X$ basis ($O_{U(1)}$)
  - Go to mass basis (O_{mas})
- $V_{Phys} = (O_{mas} \times O_{U(1)} \times O_{GKM}) \cdot V_{gauge}$

Theoretical Constraints

$$M_{11}^2 \equiv M_Z^2 \cos^2\alpha_z + {M_{Z'}}^2 \sin^2\alpha_z = \frac{M_W^2}{\cos^2\theta_W}$$

$$\left({M_{Z'}}^2 \cos^2\alpha_z + M_Z^2 \sin^2\alpha_z\right)/\tan^2\theta_x = M_W^2\left(r^2 + {x'_\Phi}^2\right)$$

$$\left({M_{Z'}}^2 - M_Z^2\right)\sin 2\alpha_z/\tan\theta_x = \frac{2x'_\Phi M_W^2}{\cos\theta_W}$$

- No assumption of the smallness of α_Z,χ
- Careful parametrisation
- g_x not an observable, g'_x is
- X'_Φ goes away from anomaly cancellation

$$\tan\theta_W = \frac{g_Y}{g}$$

$$\tan\theta_x = \frac{g'_x}{g}$$

$$r = \frac{v_S}{v}$$

$$\cdots$$

$$g'_x = g_x \sec\chi$$

$$x'_\Phi = x_\Phi - \frac{g_Y}{g_x}\sin\chi$$

Charges $\to$ Anomaly

(i) $[SU(2)_L]^2U(1)_X$ (ii) $[SU(3)_C]^2U(1)_X$ (iii) Gravity (iV) $[U(1)_Y]^2U(1)_X$

(i) Q_L (ii) u_R (iii) d_R (iv) ℓ_L (v) e_R (vi) N_R

Majorana Mass: $N \sim -1/4$ $(S \sim 1/2)$

5 charges, **4** equations $\to$ One parameter $\sim \kappa_x$

Fermion Masses

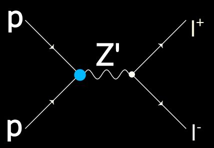
- $x_d - x_q = x_q - x_u = x_\ell - x_N = x_e - x_\ell = -x_\phi/2$

x'_Φ not free parameter $\therefore$ neither is κ_x!

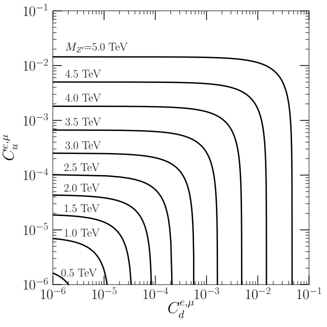
$\Longrightarrow$ In the $(M_{Z'}, \alpha_z, \tan\theta_x)$ formalism no model dependence

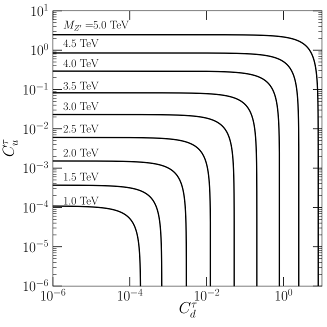
Direct Detection

$pp \to Z' \to l^+ l^-$



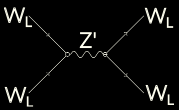
- Can be factorised:
  - $\sigma\left(pp \to Z' \to \ell^+\ell^-\right) \approx \frac{\pi}{6s}\left[C_u^\ell w_u\left(s, M_{Z'}^2\right) + C_d^\ell w_d\left(s, M_{Z'}^2\right)\right]$
  - $C_q^\ell = \left[\left(g_L^q\right)^2 + \left(g_R^q\right)^2\right] \mathrm{BR}(Z' \to \ell^+\ell^-)$
  - $w_u, w_d \to$ PDF folding (NLO)





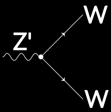
Unitarity

$$\mathcal{M}(W_L^+ W_L^- \to W_L^+ W_L^-)|_{l=0}$$



$$\frac{8}{3}\frac{g^2 \cos^2\theta_W E^4}{M_W^4}\sin^2\alpha_z < 8\pi$$

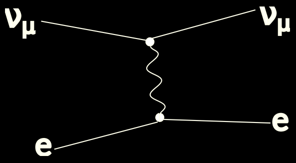
$$\Gamma(Z' \to W^+ W^-)/M_{Z'}$$



$$\frac{1}{64\pi}\frac{g^2\cos^2\theta_W \sin^2\alpha_z}{3}\left(\frac{M_{Z'}}{M_W}\right)^4$$

$$\frac{M_{Z'}^4 \sin^2\alpha_z}{\left(M_Z^2\cos^2\alpha_z + M_{Z'}^2\sin^2\alpha_z\right)} < 48\pi \times \frac{1}{\sqrt{2}G_F}$$

ν_μ-e scattering or g_V, g_A



- Purely NC
- Ancient (Gargamelle)
- Of course, LEP

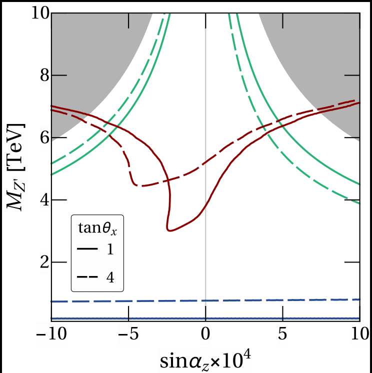
$$\mathcal{L}_{FF} = -\frac{G_F}{\sqrt{2}} \left[\bar{\nu}\gamma^\mu \left(1-\gamma^5\right)\nu\right] \left[\bar{e}\gamma_\mu \left(g_V^{\nu e} - g_A^{\nu e}\gamma^5\right) e\right]$$

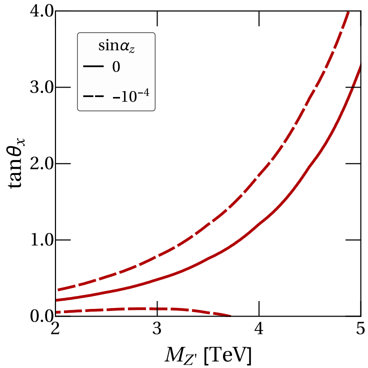
$$(g_V^{\nu e})^{SM} \equiv (g_V^e)^{SM} = -\frac{1}{2} + 2\sin^2\theta_W\,, \quad (g_A^{\nu e})^{SM} \equiv (g_A^e)^{SM} = -\frac{1}{2}$$

$$\left(g_{(V,A)}^{\nu e}\right)^{BSM} = M_{11}^2 \left(\frac{\kappa_Z g_{(V,A)}^e}{M_Z^2} + \frac{\kappa_{Z'} g'^e_{(V,A)}}{M_{Z'}^2}\right)$$

$$g_V^{\nu e} = -0.040 \pm 0.015\,, \qquad g_A^{\nu e} = -0.507 \pm 0.014\,,$$

2σ Exclusions





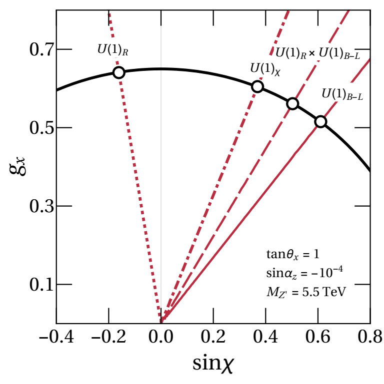
$t_x = 4$	$M_{Z'}$ exclusion at $\alpha_z = 0$	5.1 TeV
	Lowest possible value of $M_{Z'}$	4.4 TeV
$t_x = 1$	$M_{Z'}$ exclusion at $\alpha_z = 0$	3.8 TeV
	Lowest possible value of $M_{Z'}$	3.0 TeV

Maximum $|\sin\alpha_z| \sim 10^{-3}$ (Conservative)

Model parameters

$$\tan\chi = \left(2\kappa_x - \frac{1}{2}\right)\tan\theta_x \cot\theta_W - \frac{\mathcal{F}(M_{Z'}, \alpha_Z)}{\sin\theta_W}\,, \qquad (1)$$

- $M_Z' = 5.5$ TeV
- $\tan\theta_x = 1$
- $\sin\alpha_z = -10^{-4}$



Endnote

Summary

- $(M_{Z'}, \alpha_Z, \tan\theta_x)$ parametrisation absorbs model dpndnc
- Bounds from different sides on the Z' parameter space
- DY bound strongest, situational merits for unitarity and low energy bounds
- For a Z' coupling as strongly as the SM W, $M_{Z'} \gtrsim 4.5$ TeV, $|\alpha_Z| < 0.001$ at 95% CL.

Acknowledgements

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  - G. Bhattacharyya, D. Das, A. Raychaudhuri (1803.07989)

Thank You

Questions/Input/Critique?

Suppl 1

$$w_q\left(s, M_{Z'}^2\right) = \int_0^1 dx \int_0^1 dy \int_0^1 dz\, \delta\left(\frac{M_{Z'}^2}{s} - xyz\right) \times \left\{F_{qq}\left(x,y,M_{Z'}^2\right) \Delta_{qq}\left(z, M_{Z'}^2\right) + F_{gq}\left(x,y,M_{Z'}^2\right) \Delta_{gq}\left(z, M_{Z'}^2\right)\right\}, \quad (2)$$

$$F_{qq}\left(x,y,M_{Z'}^2\right) = f_{q\leftarrow P}\left(x, M_{Z'}^2\right) f_{\bar{q}\leftarrow P}\left(y, M_{Z'}^2\right) + (x \leftrightarrow y)\,, \quad (3a)$$

$$F_{gq}\left(x,y,M_{Z'}^2\right) = f_{g\leftarrow P}\left(x, M_{Z'}^2\right) \left[f_{q\leftarrow P}\left(y, M_{Z'}^2\right) + f_{\bar{q}\leftarrow P}\left(y, M_{Z'}^2\right)\right] + (x \leftrightarrow y)\,, \quad (3b)$$

$$\Delta_{qq}\left(z, M_{Z'}^2\right) = \delta(1-z) + \frac{\alpha_s(M_{Z'}^2)}{\pi} C_F \left[\left(\frac{\pi^2}{3} - 4\right)\delta(1-z) - \frac{1+z^2}{1-z}\ln(z) - 2(1+z)\ln(1-z) + 4(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+\right], \quad (4a)$$

$$\Delta_{gq}\left(z, M_{Z'}^2\right) = \frac{\alpha_s(M_{Z'}^2)}{2\pi} T_F \left[(1-2z+2z^2)\ln\frac{(1-z)^2}{z} + \frac{1}{2} + 3z - \frac{7}{2}z^2\right], \quad (4b)$$

where $C_F = 4/3$ and $T_F = 1/2$

$$\int_0^1 dx\, f(x)\, g(x)_+ = \int_0^1 dx\, [f(x) - f(1)]\, g(x)\,. \quad (5)$$

Suppl 2

$$\begin{pmatrix} B'_\mu \\ W^3_\mu \\ X'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W\cos\alpha_z & \sin\theta_W\sin\alpha_z \\ \sin\theta_W & \cos\theta_W\cos\alpha_z & -\cos\theta_W\sin\alpha_z \\ 0 & \sin\alpha_z & \cos\alpha_z \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}. \quad (6)$$