

Notes on a Z'

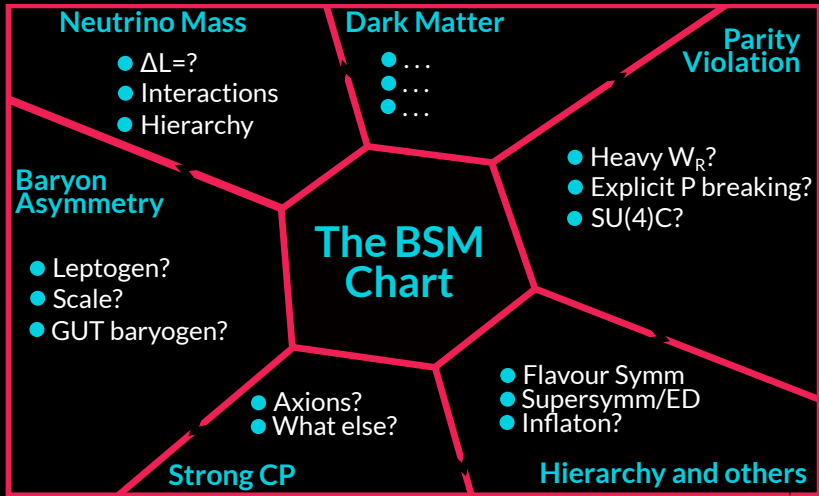
by

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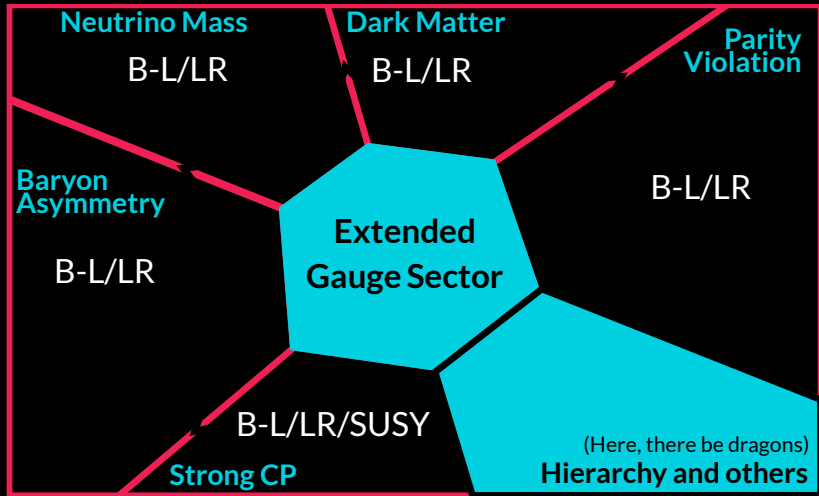


NUFACT, WG5, Virginia Tech
August 16, 2018

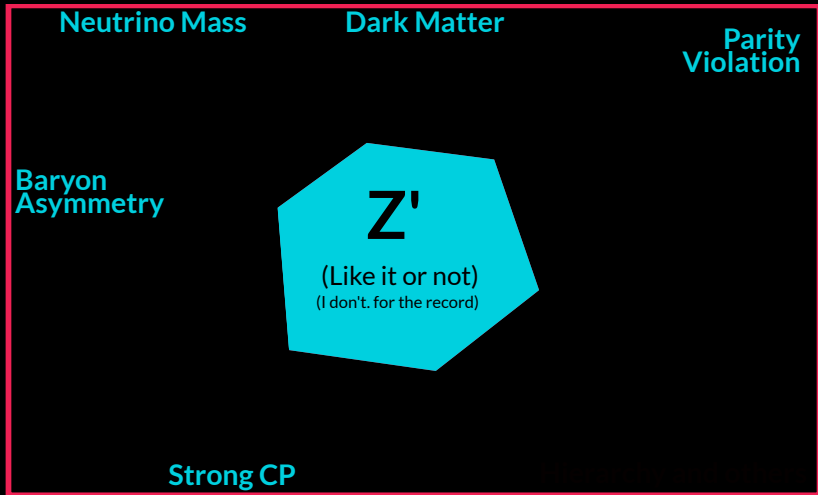
Compass beyond the SM



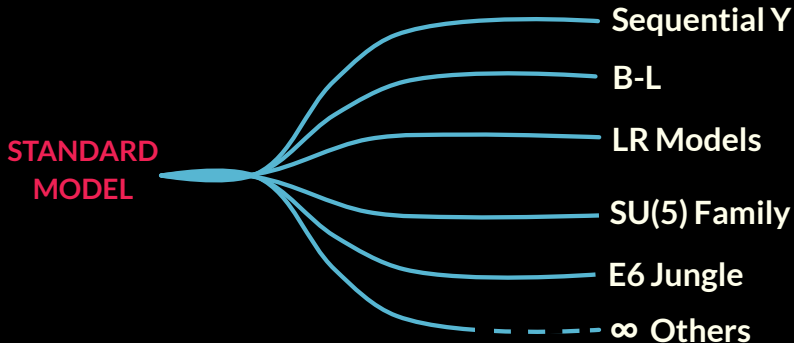
Compass beyond the SM



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Gauge Extension \rightarrow Rank



Formalism

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:

$$❖ S \sim \left(0(Y), \frac{1}{2}(X) \right) \text{ (Charge normalisation)}$$

❖ 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

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

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

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

- ❖ 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

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

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

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

...

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

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

Charges \rightarrow Anomaly

Anomaly Cancellation

$$[SU(2)_L]^2 U(1)_X \Rightarrow 3x_q + x_l = 0$$

$$[SU(3)_C]^2 U(1)_X \Rightarrow 2x_q = x_d + x_u$$

$$\text{Gauge Gravity} \Rightarrow 6x_q + 2x_l = 3(x_u + x_d) + (x_e + x_N)$$

$$[U(1)_Y]^2 U(1)_X \Rightarrow 2x_q + 6x_l = 16x_u + 4x_d + 12x_e$$

- Five charges, Four equations \rightarrow One parameter $\sim \kappa_x$

Fermion Masses

- Dirac mass

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

- Majorana Mass

$$x_N = -1/4 \quad (x_S = 1/2)$$

- x'_ϕ not free parameter \therefore neither is $\kappa_x!$ \implies In the $(M_{Z'}, \alpha_z, \tan \theta_x)$ formalism there is no model dependence

Charge parametrisation

Q_L	3	2	1/6	$\kappa_x/3$
U_R	3	1	2/3	$4\kappa_x/3 - 1/4$
d_R	3	1	-1/3	$-2\kappa_x/3 + 1/4$
L_L	1	2	-1/2	$-\kappa_x$
e_R	1	1	-1	$-2\kappa_x + 1/4$
N_R	1	1	0	$-1/4$
Φ	1	2	1/2	$\kappa_x - 1/4$
S	1	1	0	$1/2$

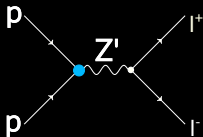
Models

$U(1)_{B-L}$	$U(1)_R$	$U(1)_X$	$U(1)_R \times U(1)_{B-L}$
$\frac{(B-L)}{4}$	$-\frac{T_{3R}}{2}$	$-Q_X/\sqrt{10}$	$\frac{1}{5} \left[(B-L) - \frac{1}{2} T_{3R} \right]$
$\frac{1}{4}$	0	$\frac{3}{20}$	$\frac{1}{5}$

Exclusions

Direct Detection

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

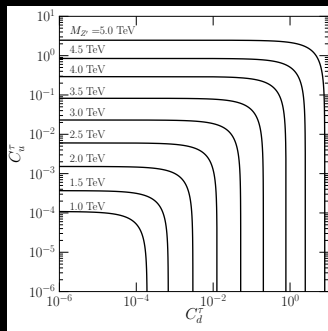
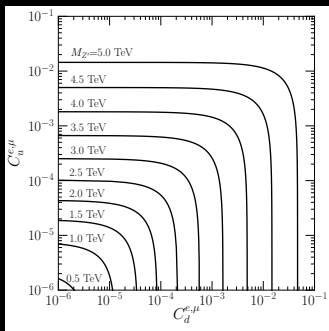


Can be factorised:

$$\sigma(pp \rightarrow Z' \rightarrow l^+ l^-) \approx \frac{\pi}{6s} [C_u^\ell w_u(s, M_{Z'}^2) + C_d^\ell w_d(s, M_{Z'}^2)]$$

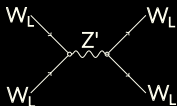
$$C_q^\ell = [(g_L^q)^2 + (g_R^q)^2] \text{BR}(Z' \rightarrow l^+ l^-)$$

$w_u, w_d \rightarrow$ PDF folding (NLO)



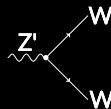
Unitarity

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



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

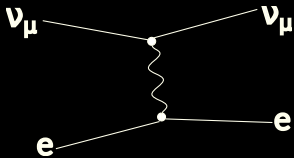
$$\Gamma(Z' \rightarrow W^+ W^-) / M_{Z'}$$



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

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

ν_μ -e scattering or g_V, g_A



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

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

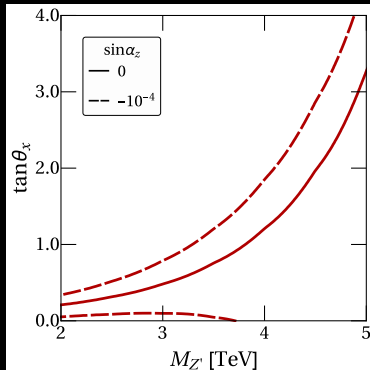
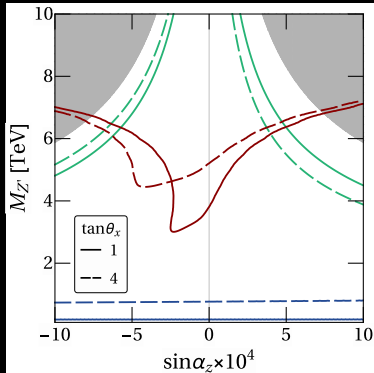
$$(g_V^{\nu e})^{SM} \equiv (g_V^e)^{SM} = -\frac{1}{2} + 2 \sin^2 \theta_w, \quad (g_A^{\nu e})^{SM} \equiv (g_A^e)^{SM} = -\frac{1}{2}$$

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

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

Results

2σ Exclusions



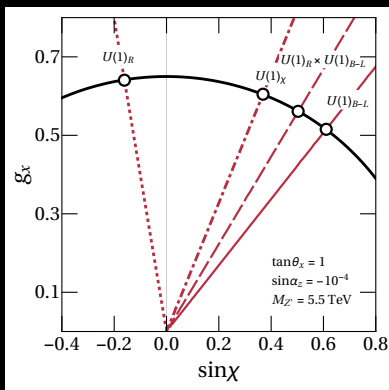
$t_x = 4$	$M_{Z'}$ exclusion at $\alpha_z = 0$	5.1 TeV
	Lowest possible value of $M_{Z'}$	4.4 TeV
$t_x = 1$	$M_{Z'}$ exclusion at $\alpha_z = 0$	3.8 TeV
	Lowest possible value of $M_{Z'}$	3.0 TeV

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

Model parameters

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

- ❖ $M_{Z'} = 5.5 \text{ TeV}$
- ❖ $\tan \theta_X = 1$
- ❖ $\sin \alpha_Z = -10^{-4}$



Endnote

Summary

- ❖ $(M_{Z'}, \alpha_Z, \tan \theta_x)$ parametrisation absorbs model dependence
- ❖ 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.

Directions

- ❖ Low mass Z' (Dent, Kim)
- ❖ Loops
- ❖ E_6

Acknowledgements

❖ In collaboration with:

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

Thank You

Questions/Input/Critique?

Suppl 1

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

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

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

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

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

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

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