A triplet gauge boson with hypercharge one

(W_1^μ with electroweak quantum numbers ~~(3,0)~~ (3,1))

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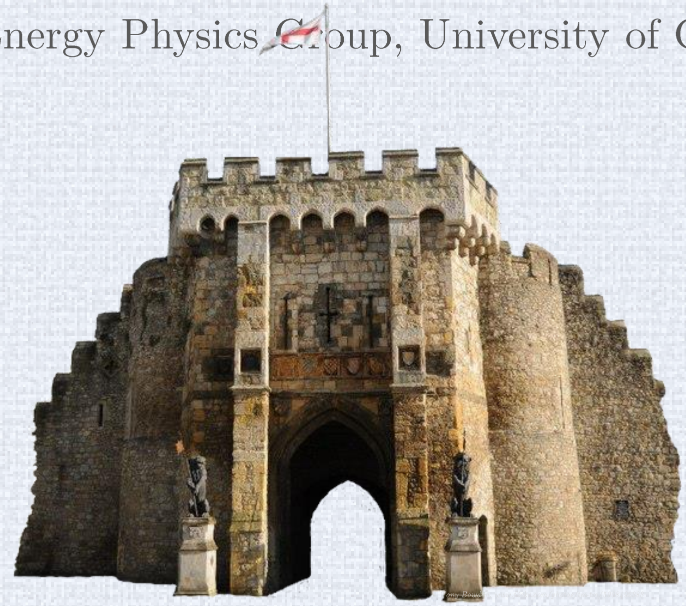


Talk based on RF, Phys.Rev.D 107 (2023) 9, 095007, 2205.12294 [hep-ph]

SUSY 2023, Southampton, July 2023

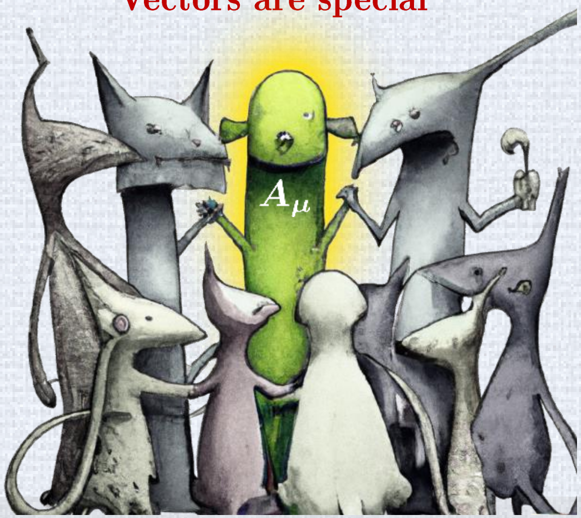
W_1^μ? Why?

Few fields can contribute to dim 6 SMEFT operators at tree level

Scalars and (vector-like) fermions are trivial to include in new models

That is not the case for vector fields which, if fundamental, should be gauge bosons of some extended group

Vectors are special



Scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

Fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

Vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

[Blas, Criado, Pérez-Victoria, Santiago 1711.10391]

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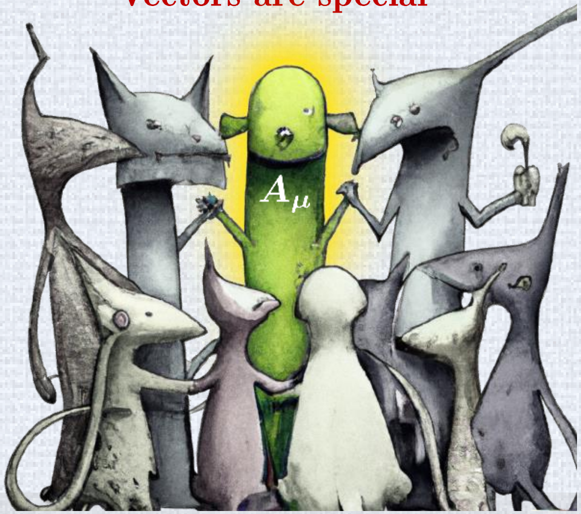

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
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Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

Vectors

this talk

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

[Blas, Criado, Pérez-Victoria, Santiago 1711.10391]

Fantastic Vector Bosons and Where to Find Them

Actual models where they can be found

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Model	$G_{SM}\times U(1)$	LR	$G_{SM}\times SU(2)$		$G_{SM}\times SU(3)$			$SU(3)_C\times SU(3)\times U(1)\equiv 331$

Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$
Model	331	Pati-Salam		$SU(5)$				

There are viable, known models based on these groups and with these fields

Fantastic Vector Bosons and Where to Find Them

Actual models where they can be found

	$G_{SM}\times U(1)$	LR	$G_{SM}\times SU(2)$	???	$G_{SM}\times SU(3)$			$SU(3)_C\times SU(3)\times U(1)\equiv 331$
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$
	331	Pati-Salam		$SU(5)$				

There are viable, known models based on these groups and with these fields

No model for W_1

(that I know of)

Fantastic Vector Bosons and Where to Find Them

As a purely group theoretical analysis, here are more possibilities:

Vector	Model
$\mathcal{B}_\mu$	$U(1)'$, Extra Dimensions
$\mathcal{B}^1_\mu$	$SU(2)_R \otimes U(1)_X \to U(1)_Y$
$\mathcal{W}_\mu$	$SU(2)_1 \otimes SU(2)_2 \to SU(2)_D \equiv SU(2)_L$, Extra Dimensions
$\mathcal{W}^1_\mu$	$SU(4) \to U(1) \otimes (SU(3) \to SU(2))$
$\mathcal{G}_\mu$	$SU(3)_1 \otimes SU(3)_2 \to SU(3)_D \equiv SU(3)_c$, Extra Dimensions
$\mathcal{G}^1_\mu$	$SO(12) \to (SO(8) \to SU(3)) \otimes (SU(2) \otimes SU(2) \to SU(2)_D \to U(1)_Y)$
$\mathcal{H}_\mu$	$SU(6) \to SU(3) \otimes SU(2)$
$\mathcal{L}_\mu$	$G_2 \to SU(2) \otimes (SU(2) \to U(1)_Y)$
$\mathcal{U}^2_\mu$, $\mathcal{U}^5_\mu$	$SU(4) \to SU(3) \otimes U(1)$
$\mathcal{Q}^1_\mu$, $\mathcal{Q}^5_\mu$	$SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
$\mathcal{X}_\mu$	$SU(6) \to U(1) \otimes SU(3) \otimes (SU(3) \to SU(2))$
$\mathcal{Y}^1_\mu$, $\mathcal{Y}^5_\mu$	$F_4 \to SU(3) \otimes (SU(3) \to SU(2) \otimes U(1))$

[del Aguila, Blas, Pérez-Victoria, Santiago 1005.3998]

For W1

The suggestion here is the full group would be $SU(3)_C \times SU(4)$

Note:

Examples given in this paper are not necessarily minimal nor phenomenologically viable

What can W_1 do?

As mentioned previously, this is one of a rather small list of fields with SM-SM-BSM interactions

$$\frac{\kappa}{2} W_1^{\mu,a*} H^T \left(i\sigma_2\sigma_a\right) D_\mu H$$

Note: It's *HH*, not *H*H*

This generates a dimension 6 operator ...

$$-\frac{|\kappa|^2}{4m_{W_1}^2}\left[(D^\mu H)^\dagger (D_\mu H)(H^\dagger H)+\left|H^\dagger (D^\mu H)\right|^2\right]$$

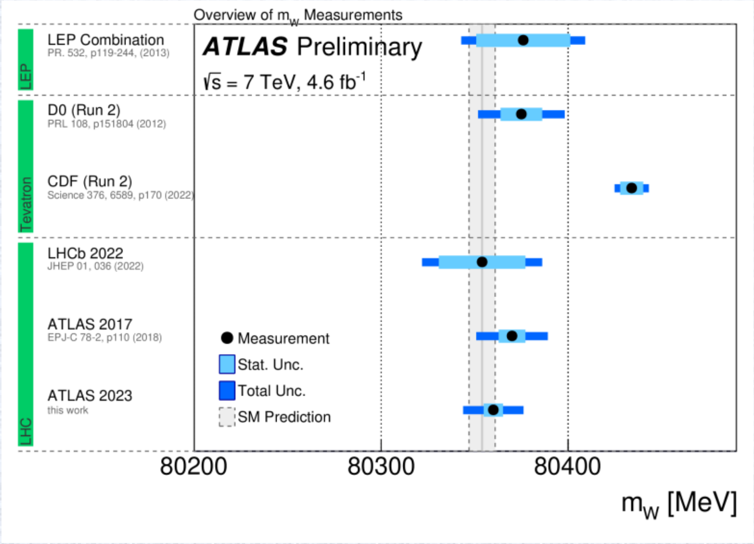
... which affects the T parameter

$$\widehat{T}\equiv\frac{\Pi_{W^3W^3}(0)-\Pi_{W^+W^-}(0)}{m_W^2}=\frac{|\kappa|^2}{4}\frac{v^2}{m_{W_1}^2}$$

Collider searches

W_1 is **hard to produce**. It is colorless and fermionfobic.
Single production via Drell-Yan/vector-boson fusion is not possible.
Mass limits are likely well below 1 TeV.

The W mass



ATLAS-CONF-2023-004

Last year the CDF collaboration reported a surprisingly large W mass

[Science 376 (2022) 6589]

It is in tension with the SM and all other direct W mass measurements

Therefore a (large) amount of skepticism about this result is warranted

Nevertheless, it has been pointed out that $\widehat{T} \approx (8.8 \pm 1.4) \times 10^{-4}$ fits well the data

[Strumia 2204.04191, Asadi et al. 2204.05283]

$\to m(W_1)/\kappa \sim 3$ TeV

The single-field extension that gives the best fit, W_1, is an isospin triplet vector boson with non-zero hypercharge, which is not a common feature of unified gauge theories. The

0 cases (to my knowledge)

[Bagnaschi, Ellis, Madigan, Mimasu, Sanz, You 2204.05260]
See also [Luzio, Gröber, Paradisi 2204.05284]

Let's change that

(by building a minimal model with a W_1)

... but before doing so you should know that a $W_1^{\mu *} H D_\mu H$ interaction cannot be generated in a Yang-Mills theory

!

No $W_1^{\mu*} H D_\mu H$ (even if there is a W_1)

How could we get this interaction in a gauge theory?

Since there is no conjugation in either of the Higgs fields there would have to be a H_u=(2,1/2) and a H_d=(2,−1/2) in some multiplet Ω of some gauge group. Then

Write in G_{SM} components

Mass basis

$$\underbrace{\left(D^\mu\Omega\right)^\dagger\left(D_\mu\Omega\right)}_{\text{Kinetic term for }\Omega} \propto \cdots + \left(W_1^{\mu*} H_d^* D_\mu H_u + \text{h.c.}\right) \propto \cdots + \left(\underline{W_1^{\mu*} H D_\mu H} + \text{h.c.}\right)$$

But the prefactor of this term =0 always

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$$\underbrace{\left(D^\mu\Omega\right)^\dagger\left(D_\mu\Omega\right)}_{\text{Kinetic term for }\Omega} \overset{\text{Write in } G_{SM} \text{ components}}{\propto} \cdots + \left(W_1^{\mu *} H_d^* D_\mu H_u + \text{h.c.}\right) \overset{\text{Mass basis}}{\propto} \cdots + \left(\underline{W_1^{\mu *} H D_\mu H} + \text{h.c.}\right)$$

But the prefactor of this term =0 always

More generally: Write scalars as real fields and put then in a multiplet $\Phi\ (=\Phi^*)$

$$\Phi^T\left(igT_a\mathcal{A}_a^\mu\right)\left(D_\mu\Phi\right)$$

where the generators are anti-symmetric matrices: $T_a = T_a^\dagger = -T_a^*$

No matter what rotation we do on the scalars, in any basis we have

$$\mathcal{A}_a^\mu\left[\phi^T X_a\left(D_\mu\phi\right)\right] \quad \text{with } X_a = -X_a^T$$

For $\phi = H$ and $\mathcal{A} = B_1 = (1,1)$ there is no problem (two doublets contract anti-symmetrically to form a singlet)

However, $\phi = H$ and $\mathcal{A} = W_1 = (3,1)$ is no good: two doublet and a triplet contract symmetrically

see RF 2205.12294 for a longer discussion

Minimal model

SO(5) is the smallest group with a W_1

(Spinor) $\overset{SO(5)}{4} \to \overbrace{(2,1/2)+(2,-1/2)}^{SU(2)\times U(1)}$

(Adjoint) $10 \to (1,0)+(3,0)+\underbrace{(3,1)+(3,-1)}_{W_1}$

However, the EW group cannot be this $SU(2)\times U(1)$ [fermions are the problem]

$$SO(5)\times SU(2)\times U(1) \to \underbrace{SU(2)'\times SU(2)}_{\supset SU(2)_L}\times\underbrace{U(1)'\times U(1)}_{\supset U(1)_Y}$$

This works!

Fermions are charged only under $SU(2)\times U(1)$; they are $SO(5)$ singlets

$W^*_{1,\mu} H_d^* D^\mu H_u$

Yukawa interactions

Break to $SU(2)_L\times U(1)_Y$

Scalar	$SO(5)\times SU(2)\times U(1)$	$SU(2)_L\times U(1)_Y$ decomposition
Ω	$(\mathbf{4},\mathbf{1},0)$	$(\mathbf{2},-\frac{1}{2})+(\mathbf{2},\frac{1}{2})$
$\widehat{H}$	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{2},\frac{1}{2})$
χ	$(\mathbf{4},\mathbf{2},\frac{1}{2})$	$(\mathbf{1},0)+(\mathbf{1},1)+(\mathbf{3},0)+(\mathbf{3},1)$

Minimal model

Symmetry breaking

$$D_\mu \chi_{jk} = \partial_\mu \chi_{jk} + i g_A A_\mu^{a,SO(5)} T^a_{jj'} \chi_{j'k} + \frac{i}{2} g_B A_\mu^{b,SU(2)} \sigma^b_{kk'} \chi_{jk'} + \frac{1}{2} g_C A_\mu^{U(1)} \chi_{jk}$$

$$\langle \chi \rangle \propto \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & -1 \\ 1 & 0 \end{pmatrix}$$

This a VEV breaks $SO(5) \times SU(2) \times U(1)$ to the EW group

Gauge boson masses

$$\boxed{\begin{aligned} g^{-2} &= g_A^{-2} + g_B^{-2} \\ (g')^{-2} &= g_A^{-2} + g_C^{-2} \end{aligned}}$$

$$\boxed{\begin{aligned} m_{W_1}^2 &= g_A^2 \langle \chi \rangle^2 \\ m_{W'}^2 &= \left(g_A^2 + g_B^2\right) \langle \chi \rangle^2 \\ m_{Z'}^2 &= \left(g_A^2 + g_C^2\right) \langle \chi \rangle^2 \end{aligned}}$$

$$\frac{m_{W_1}^2}{m_{Z'}^2} \left(\frac{m_{W'}^2}{m_{Z'}^2} - \tan^2\theta_w \right) = \left(1 - \tan^2\theta_w\right) \frac{m_{W'}^2}{m_{Z'}^2}$$

$$m_{W_1} < m_{Z'} < m_{W'}$$

W1 must be the lightest

The *Z'* can be, at most, ~19% heavier

$W_1 H H'$ interaction

$$\frac{g_A}{\sqrt{2}} W_1^{\mu,a*} \left[H_d^\dagger \sigma_a \left(D_\mu H_u\right) - \left(D_\mu H_d\right)^\dagger \sigma_a H_u \right] + h.c.$$

$$\kappa_{HH'} W_1^{\mu,a*} \left[H^T \left(i\sigma_2 \sigma_a\right) D_\mu H' - H'^T \left(i\sigma_2\sigma_a\right) D_\mu H \right]$$

As expected, no $W_1 H H$ interaction

A variation

Making fermions interact W_1

In the model we just saw, fermions are uncharged under *SO(5)*, therefore they do not interact with W_1

One can build a model where fermions do interact with the new gauge bosons, while still reproducing the low mass particles of the SM

Field	Spin	$SU(3)_C \times SO(5) \times SU(2) \times U(1)$
$F = Q, u^c, d^c, L, e^c$	$1/2$	As in the SM; $\mathbf{1}$ under $SO(5)$
$\mathbb{F} = \mathbb{Q}, \mathbb{u}^c, \mathbb{d}^c, \mathbb{L}, \mathbb{e}^c$	$1/2$	As in the SM; $\mathbf{4}$ under $SO(5)$
$\overline{\mathbb{F}} = \overline{\mathbb{Q}}, \overline{\mathbb{u}^c}, \overline{\mathbb{d}^c}, \overline{\mathbb{L}}, \overline{\mathbb{e}^c}$	$1/2$	Complex conjugate of $\mathbb{F}$
Ω	0	$(\mathbf{4}, \mathbf{1}, 0)$
χ	0	$\left(\mathbf{4}, \mathbf{2}, \frac{1}{2}\right)$

I will however not provide further details here **(see RF 2205.12294)**

Summary

Credit: Guilhem Vellut (https://www.flickr.com/photos/o_0/33725509613/)

Summary

The vector field $W_1 = (\mathbf{3},1)$ is quite unique. It's quantum numbers allow a $\boldsymbol{W_1^{\mu *} H D_\mu H}$ renormalizable coupling.

Due to this fact, W_1 has been pointed as one of the most promising explanations for the CDF W-mass measurement.

I have highlighted that in a Yang-Mills theory this interaction is <u>never</u> generated.

Even so, I've presented a minimal setup with a W_1 heavy gauge boson, based on the SO(5) group. There is also a Z' and a W', with W_1 being the lightest.

Thank you