A Spartan Model for the (disappearing?) Di-Photon Excess

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James Ingoldby, Maurizio Piai,
Jedidiah Thompson, Thomas Appelquist
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13 TeV ATLAS and CMS Hints:

750 GeV Di-photon Excess

Narrow (Sub-GeV) width? ***
Broader ($\rightarrow$ 50 GeV) width?

- Off-Topic

  No holography
  No conformality
  No Lattice (yet)
  No citations (yet)

- Disappearing-Ambulance chasing?

  "No real sign of a di-photon excess at 750 GeV in the 2016 data, but it is still early." "The data is pouring in at a wonderful rate."

  K. Baker, Yale-ATLAS

- Very Minimal "EFT"

Outline

The Model / (EFT ?)

SM: Φ (f), W_μ (g), SM-fermions

New Sector: Φ_V (f_V), V_μ (g_V), ….

Linkage: B_μ (g')

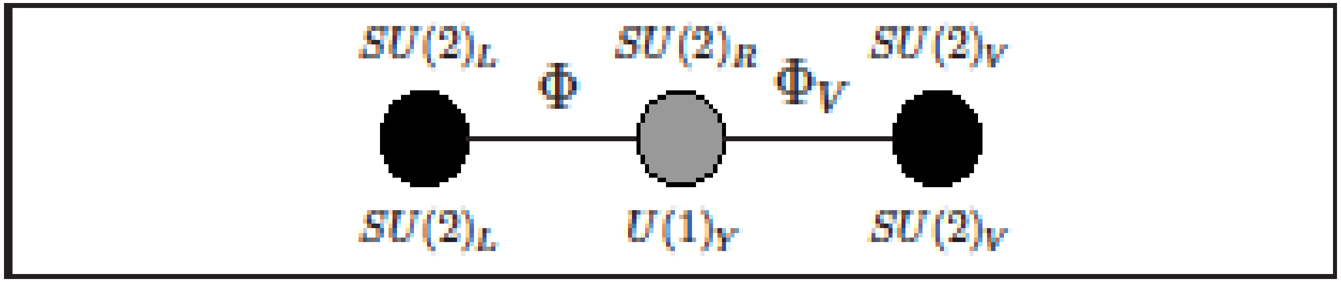
$$SU(2)_L \times U(1)_Y \times SU(2)_V$$

$W_\mu = W_\mu^a \, T_L^a$ $\quad$ $V_\mu = V_\mu^a \, T_V^a$

$$B_\mu = B_\mu^3 \, [\, T_R^3 + \tfrac{1}{2}(B-L)]$$

$Y = T_R^3 + \tfrac{1}{2}(B-L)$ $\quad$ $Q = T_L^3 + Y + T_R^3$

Field Content



Fields	$SU(2)_L$	$SU(2)_R$	$SU(2)_V$	$U(1)_{B-L}$	$U(1)_Y$
Φ	2	2	1	0	$\pm 1/2$
Φ_V	1	2	2	0	$\mp 1/2$
q_L	2	1	1	1/3	1/6
q_R	1	2	1	1/3	$1/6 \pm 1/2$
ℓ_L	2	1	1	-1	$-1/2$
ℓ_R	1	2	1	-1	$-1/2 \pm 1/2$
W_μ	3	1	1	0	0
V_μ	1	1	3	0	0
B_μ	1	*	1	0	0

Dimension-Four Lagrangian
$SU(2)_L \times U(1)_Y \times SU(2)_V$

$$\begin{aligned}\mathcal{L} \;=\;& +2g\mathrm{Tr}W^{\mu}J_{L\,\mu} - 2g'\mathrm{Tr}B^{\mu}J_{Y\,\mu} \\ & -\frac{1}{2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{2}\mathrm{Tr}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}\mathrm{Tr}B_{\mu\nu}B^{\mu\nu} \\ & +\frac{1}{4}\mathrm{Tr}|D\Phi|^2 + \frac{1}{4}\mathrm{Tr}|D\Phi_V|^2 - V(\Phi_i) \\ & -\frac{1}{\sqrt{2}}\bar{q}_L\Phi y_q q_R - \frac{1}{\sqrt{2}}\bar{\ell}_L\Phi y_\ell \ell_R\end{aligned}$$

$$V(\Phi_i) \;=\; +\frac{\lambda}{16}\left(\mathrm{Tr}\left[\Phi\Phi^\dagger - f^2\,\mathbb{1}_2\right]\right)^2 + \frac{\lambda_V}{16}\left(\mathrm{Tr}\left[\Phi_V\Phi_V^\dagger - f_V^2\,\mathbb{1}_2\right]\right)^2$$

$$D_\mu\Phi = \partial_\mu\Phi - i\,(g\,W_\mu\Phi - g'\,\Phi\,B_\mu)$$

$$D_\mu\Phi_V = \partial_\mu\Phi_V - i\,(g'\,B_\mu\,\Phi_V - g_V\,\Phi_V\,V_\mu)$$

- Unitary Gauge: $\Phi = (f + h)1_2$, $\Phi_V = (f_V + H)1_2$

- Omitted Dimension-Four Term:

$$\mathrm{Tr}\, \Phi\Phi^\dagger\ \mathrm{Tr}\, \Phi_V\Phi_V^\dagger = 2\, \mathrm{Tr}\, \Phi\Phi_V \Phi_V^\dagger \Phi^\dagger$$

Generated at loop level, but with a **small coefficient**.

With or without

- New, Global $U(1)_V$ Symmetry:

$$(\Phi_V(x) , V_\mu(x)) \rightarrow e^{i \beta T3} (\Phi_V(x) , V_\mu(x)) e^{-i \beta T3}$$

Stabilizes the charged $V_\mu^\pm$

Vector Spectrum

$$M_{\pm}^2 = \tfrac{1}{4} \begin{pmatrix} g^2 f^2 & 0 \\ 0 & g_V^2 f_V^2 \end{pmatrix}$$

W, V basis

$g = g_{SM} \approx 0.65$

$f = v_W = 246$ GeV

$g_V^2 f_V^2 >> g^2 f^2$

$$M_0^2 = \tfrac{1}{4} \begin{pmatrix} g^2 f^2 & -g\, g' f^2 & 0 \\ -g\, g' f^2 & g'^2 (f^2 + f_V^2) & -g' g_V f_V^2 \\ 0 & -g' g_V f_V^2 & g_V^2 f_V^2 \end{pmatrix}$$

W,B,V basis

Will see that $\Gamma(H \rightarrow \gamma\gamma) \sim 1/ f_V^2$, requiring

$f_V \lesssim f$

Thus $g_V^2 >> g^2 , g'^2$

In this limit

$$M_Z^2 = \frac{1}{4} (g^2+g'^2)f^2 - \frac{1}{4}(g'^4/g_V^2)f^2 + \cdots$$

$$M_{VO}^2 = \frac{1}{4} (g_V^2+g'^2)f_V^2 + \frac{1}{4}(g'^4/g_V^2)f^2 + \cdots$$

More Large-g_V Formulas

Mass Eigenstates:

$$A_\mu \approx \text{Usual} + [gg'/g_V(g^2 + g'^2)^{1/2}]V^3_\mu + \cdots$$

$$Z_\mu \approx \text{Usual} - [g'^2/g_V(g^2 + g'^2)^{1/2}]V^3_\mu + \cdots$$

$$V^0_\mu \approx V^3_\mu - [g'/g_V] B_\mu + \cdots$$

Other electroweak coupling:

$$g'_{SM} = g'(1 - g'^2/g_V^2 + \cdots) \approx 0.36$$

Masses and Coupling Strengths

Scalar:

$M_h^2 = 2\,\lambda\, f^2$

$m_h = 125$ GeV

$\lambda/4\pi^2 \approx 0.003$

$M_H^2 = 2\,\lambda_V\, f_V^2$

$m_H = 750$ GeV

$f_V \lesssim f$

$\lambda_V/4\pi^2 \gtrsim 0.11$

Vector:

$H \not\rightarrow V^0 Z^0$

$M_V \gtrsim 660$ GeV

$g_V^2/4\pi^2 \gtrsim 0.4$

Precision Electroweak and Higgs Physics

- Integrate out the new physics →

$$\mathrm{Tr}\ (\partial_\sigma B_{\mu\nu})\ (\partial^\sigma B^{\mu\nu}) + \ldots\ldots$$

- EW parameter:

$$Y = g'^2 g^2 f^2 / g_V^4 f_V^2 = g'^2 M_W^2 / g_V^2 M_V^2 < 0.0006\ (1\sigma)$$

Equivalently, $\Delta\rho$ Suppression Easy

- Higgs-ZZ coupling $a_{hZZ} \equiv (hZZ)\ /\ (hZZ)_{SM}$

$$a_{hZZ}^2 \approx 1 - 2\ g'^4 f^2 / g_V^4 f_V^2 > 0.6\ (1\sigma)$$

Real easy

Heavy Scalar Resonance

Decay: $H \not\to f\bar{f}$ $\not\to W^+W^-$

$$\Gamma(H\to ZZ)_{tree} \approx (g'^8 M_W^4 m_H^3) / (32\pi g^4 g_V^4 M_V^4 f_V^2)$$

Mixing Very small

(Comparable contribution from loop-level H-h mixing)

V_μ-Loop Induced Decay:

$$\Gamma(H\to\gamma\gamma) = (v_W/f_V)^2\,[G_F\alpha^2 m_H^3/128\sqrt{2}\,\pi^3\,]$$

$$\times\ |A_W(m_H^2/4M_V^2)|^2$$

Reliable?

→ -7

$$\approx 3\text{ MeV }(v_W/f_V)^2$$

$$\Gamma^{tot} \approx 1.7\,\Gamma(H\to\gamma\gamma)\ ,\ \ BR_{\gamma\gamma} \approx 2/3$$

γγ, γZ, ZZ

H Production By Photon Fusion:

$$\sigma(pp \to H \to \gamma\gamma) = (BR_{\gamma\gamma} / M_H\, s)\, C_{\gamma\gamma}\, \Gamma(H \to \gamma\gamma)$$

↑ Photon-parton luminosity ≈ 54 ± ? NNPDF

$$\approx 0.5 \text{ fb } (v_W/f_V)^2\, BR_{\gamma\gamma}$$

CMS ≈ 4.8 ± 2.1 fb
ATLAS ≈ 5.5 ± 1.5 fb

Strumia 1605.090401
& references therein

- Is this model a bonafide EFT ?

    1. Relevant degrees of freedom identified?

    2. Reliable approximate calculations over some energy range?

- Maybe. If not, only (O of M) estimates.

Vector Resonances

Neutral:

$pp \rightarrow V^0 \rightarrow e^+e^- + \mu^+\mu^-$

$$\Gamma(V^0 \rightarrow \text{SM fermions}) = (5/12\pi)\,(g'^4/g_V{}^2)\,M_{V0}$$

$$\Gamma(V^0 \rightarrow \text{SM bosons}) = (1/96\pi)\,(g'^4/g_V{}^2)\,M_{V0}$$

$BR_{e+e-} = 1/8$

$$\sigma(pp \to V^0 \to X) = (3/M_{V0}\,\Gamma_{V0}^{tot}\, s) \times \left[\sum_{ij} C_{ij}\,\Gamma(V^0 \to ij)\right] \Gamma(V^0 \to ij)$$

For $M_{V0} \approx 700$ GeV: $\Gamma_{V0}^{tot} \approx 10$ MeV

$$\sigma\,(pp \to V^0 \to l^+l^-)_{8TeV} \approx 21000 \text{ fb } (g'^4/g_V^2) \gtrsim 7 \text{ fb}$$

$$\sigma\,(pp \to V^0 \to l^+l^-)_{13TeV} \approx 53000 \text{ fb } (g'^4/g_V^2) \gtrsim 20 \text{ fb}$$

$g_V^2 \lesssim 4\pi^2$

Current upper bounds:

~ 2 fb $_{8TeV}$

~ 7 fb $_{13TeV}$

Charged Vectors:

Pair production via virtual γ, Z, V^0

Must break $U(1)_V$ via higher-dimension operators to allow decay

Dimension-six Example: $(1/\Lambda_V^2)\ \mathrm{Tr}\ (D_\mu \Phi)\, \Phi_V\, (D_\mu \Phi_V)^\dagger\, \Phi^\dagger$

$\rightarrow$ $V^\pm \rightarrow W^\pm\, h$

Λ_V: (1) Large enough to satisfy precision constraints
(2) Small enough to insure rapid enough decay.

$10 \text{ TeV} \lesssim \Lambda_V \lesssim 1000 \text{ TeV}$

- Production suppressed relative to V^0
- Final states more difficult to re-construct

Symmetry and Fine Tuning

$SU(2)^4 \;\longrightarrow\; SU(2)_L \times U(1)_Y \times SU(2)_V$

All dimension-four terms

gauging

+ accidental global $U(1)_V$ symmetry including all dimension-four operators

broken by higher-dimension operators

$\lambda_V,\; g_V^2 >> g^2, g'^2$

One-loop Effective Potential

$$V_1 = \frac{3\Lambda^2}{256\pi^2}\left[(3g^2 + g'^2)\,\mathrm{Tr}\Phi^\dagger\Phi + (g'^2 + 3g_V^2)\,\mathrm{Tr}\Phi_V^\dagger\Phi_V \right] +$$

+ λ, y_t^2 terms + λ_V term

$$+\frac{3}{4096\pi^2}\Big[(3g^4 + 2g^2g'^2 + g'^4)\,(\mathrm{Tr}\Phi^\dagger\Phi)^2 + 2g'^4(\mathrm{Tr}\Phi^\dagger\Phi)(\mathrm{Tr}\Phi_V\Phi_V^\dagger) + (g'^4 + 2g'^2g_V^2 + 3g_V^4)\,(\mathrm{Tr}\Phi_V\Phi_V^\dagger)^2\Big]\ln\frac{\mu^2}{\Lambda^2} + \cdots$$

+ λ^2, λ_V^2, y_t^4 terms

Λ^2 terms: "Acceptable" fine tuning if $\Lambda <$ few TeV

ln Λ terms: Mixing term ~ g'^4 →small h-H mixing
$U(1)_V$ preservation

Summary

1. Simple model accommodating the 750 excess

2. Photon fusion production

3. Three heavy vectors M < 1 TeV

4. Precision constraints OK

5. Testable via V^0 production

6. An EFT? Yes for $f_V \to f = v_W$.
   $\lambda_V, g_V^2 < 4\pi^2$

Outlook

If the H signals are confirmed
and hints of the V_μ^0 emerge:

1. Explore the phenomenology of the $V_\mu^\pm$

2. Develop the (nearby) UV completion

"Right now it's only a notion, but I think I
can get the money to make it into a
concept, and later turn it into an idea.“

“Annie Hall” 1976 ,
Woody Allen