Asymptotically Safe QCD

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based on work with

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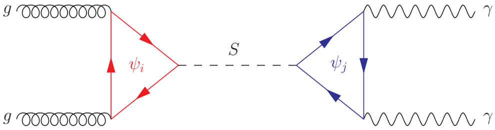
Overview

750 GeV diphoton excess

The excess in $m_{\gamma\gamma}$ distribution measured by ATLAS and CMS.

$$m_{\gamma\gamma} \simeq 750 \text{ GeV}$$

$$\begin{aligned} \Gamma_S/M_S &\sim 6\%, \qquad \sigma_{LW} \in [3-13] \text{ fb} \\ \Gamma_S/M_S &\lesssim 1\%, \qquad \sigma_{NW} \in [3-7] \text{ fb} \end{aligned}$$



$$\mathcal{L} \sim -M_\psi \bar{\psi}_i \psi_i + y S \bar{\psi}_i \psi_i$$

D.Buttazzo et al.(arXiv:1512.04929), S.Di Chiara et al.(arXiv:1512.04939), A.Angelescu et al.(arXiv:1512.04921),

S.D.McDermott et al.(arXiv:1512.05326), R.Benbrik et al.(arXiv:1512.06028),...

Phenomenology

If ψ transforms as $\psi = (R_3, R_2, Y_\psi)$, then

$$\Gamma_{\gamma\gamma} = \frac{\alpha_{em}^2 m_S^3}{256\pi^3}\Big|\sum_{i=1}^{n_f}\frac{d(R_3)(S_2(R_2)+d(R_2)Y_\psi^2)y}{M_\psi}A_{1/2}(x)\Big|^2,$$

$$\Gamma_{gg} = \frac{\alpha_s^2 m_S^3}{32\pi^3}\Big|\sum_{i=1}^{n_f}\frac{yd(R_2)S_2(R_3)}{M_\psi}A_{1/2}(x)\Big|^2$$

$$\sigma(pp\to S\to\gamma\gamma) = \sigma(pp\to S)\mathrm{BR}(S\to\gamma\gamma) = \frac{\pi^2}{8m_S^3\Gamma_S}I_{\mathrm{pdf}}\Gamma_{\gamma\gamma}\Gamma_{gg}$$

Requires: large y, large n_f, large Y_ψ

Constraints

Perturbativity

B.Bellazzini et al.(arXiv:1512.05330), R.Franceschini et al.(arXiv:1512.04933), M.Dhuria et al.(arXiv:1512.06782), J.Gu et al.(arXiv:1512.07624), J.Zhang et al.(arXiv:1512.07889), A.Salvio et al.(arXiv:1512.08184), M.Son et al. (arXiv:1512.08307),...

Large n_f, y, $Y_\psi \rightarrow$ Landau Poles in g_1, y, g_3

$$\beta_{g_3}^{(1)} = g_3^3 \left(-7 + \frac{4}{3} n_f S(R_3)\right),$$

$$\beta_{g_1}^{(1)} = g_1^3 \left(\frac{41}{10} + \frac{4}{5} n_f d(R_3) Y_\psi^2\right),$$

$$\beta_{y}^{(1)} = y \left(y^2(1 + n_f d(R_3)) - 6C_2(R_3) g_3^2 - \frac{18}{5} Y_\psi^2 g_1^2\right)$$

Dijet bound

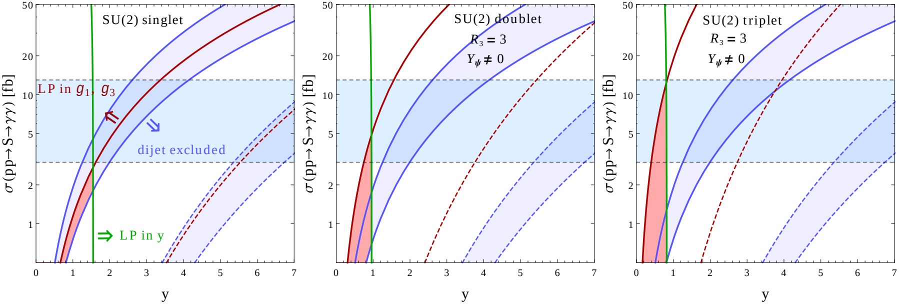
13 TeV ATLAS June 2016:

$$\sigma_{jj} \times A \times BR < 1.3\,\mathrm{pb} \quad \text{for narrow width}$$

$$\sigma_{jj} \times A \times BR < 1.9\,\mathrm{pb} \quad \text{for wide width}$$

$$\Gamma_{gg}/\Gamma_{\gamma\gamma} = \frac{8\alpha_s^2}{\alpha_{em}^2} \left(\frac{d(R_2) S_2(R_3)}{d(R_3)\left(S_2(R_2) + d(R_2) Y_\psi^2\right)}\right)^2$$

Constraints



Status:

- There are solutions perturbative up to M_{PL} in the NW case
- LW implies Landau Poles much below M_{PL}
- The dijet bound favors higher reps. of $SU(2)_L$

Problem: perturbativity

Gauge-Yukawa model

$$
\begin{aligned}
\mathcal{L} \sim \quad & - \quad y\bar{\psi}_i S_{ij}\psi_j - M_\psi \bar{\psi}_i \psi_i \\
& - \quad \lambda_h (H^\dagger H)^2 - \lambda_{hs} H^\dagger H \mathrm{Tr}(S^\dagger S) - \lambda_u \mathrm{Tr}\left[(S^\dagger S)^2\right] - \lambda_v \left[\mathrm{Tr}(S^\dagger S)\right]^2
\end{aligned}
$$

- ψ_i in fundamental of $SU(N_c)$
- S is a $N_f \times N_f$ complex matrix

Asymptotic Safety

Litim, Sannino, JHEP 1412, 178 (2014) (arXiv:1406.2337)

The set of RGEs for gauge ($SU(N_c)$) and Yukawa couplings:

$$\beta_{\alpha_3} = \frac{d\alpha_3}{d\ln\mu} = \alpha_3^2(-B + C\alpha_3 - D\alpha_y),$$
$$\beta_{\alpha_y} = \frac{d\alpha_y}{d\ln\mu} = \alpha_y(E\alpha_y - F\alpha_3)$$

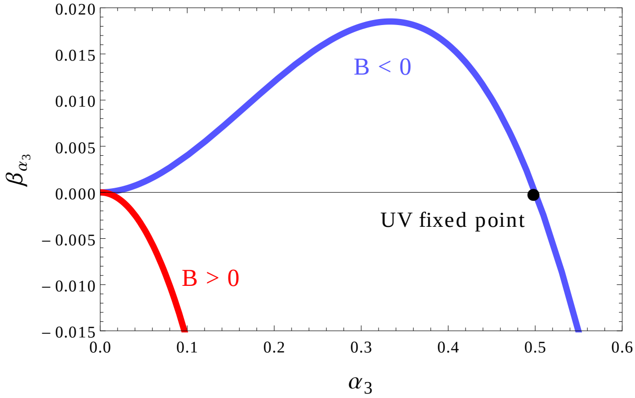
(where $\alpha_3 = \frac{g_3^2}{(4\pi)^2}$, $\alpha_y = \frac{y^2}{(4\pi)^2}$, $C, D, E, F > 0$)

can develop an interacting UV fixed point:

$$(\alpha_3^*, \alpha_y^*) = \left(\frac{BE}{CE - DF}, \frac{BF}{CE - DF},\right)$$

- Cancellation between 1-loop and 2-loop contributions,
- No asymptotic freedom for $SU(N_c)$ ($B < 0$),
- Small $\epsilon = N_f/N_c - 11/2$ (Veneziano limit: $N_f, N_c \to \infty$).

Asymptotic Safety

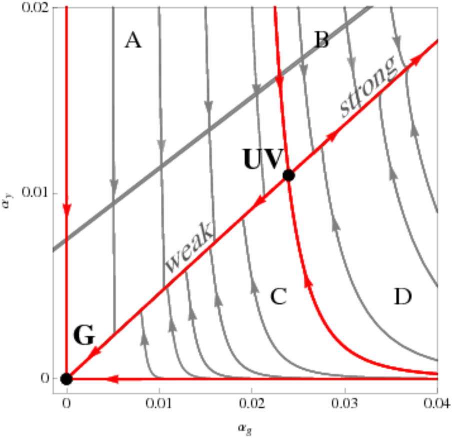


The couplings can be stabilized in UV with non-vanishing values.

Critical directions

The UV fixed point can be reached only along a critical direction.

Litim, Sannino, arXiv:1406.2337



Additional relation between gauge and Yukawa couplings.

Asymptotically safe QCD?

In QCD:

$$B_3 = 14 - \frac{8n_f}{3} S_2(R_3) d(R_2)$$

Asymptotic freedom lost ($B_3 < 0$);

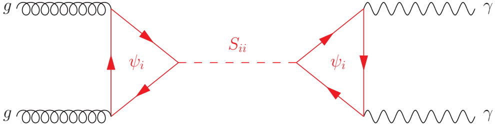
$$n_f \geq \frac{21}{4 S_2(R_3) d(R_2)}$$

$R_3 = d(R_3)$	$S_2(R_3)$	$n_{AF}(1)$	$n_{AS}(1)$	$n_{AF}(2)$	$n_{AS}(2)$	$n_{AF}(3)$	$n_{AS}(3)$
3	1/2	11	-	6	-	4	-
6	5/2	3	37	1	77	-	116
8	3	2	95	-	198	-	299
10	15/2	1	17	-	34	-	51
15	10	-	30	-	60	-	90
$15'$	35/2	-	17	-	33	-	50

AS for $SU(3)$ representations with dimension > 3

Large number of new fermions needed.

Asymptotically Safe 750 GeV excess



Different flavor structure:

- Modified cross-section (max. interference)

$$\sigma(pp \to S_{1,\ldots,n_f} \to \gamma\gamma) = n_f^2 \sigma(pp \to S_i)\mathrm{BR}(S_i \to \gamma\gamma) = \frac{n_f^2 \pi^2}{8 m_S^3 \Gamma_S^i} I_{\mathrm{pdf}} \Gamma_{\gamma\gamma}^{i(1)} \Gamma_{gg}^{i(1)}$$

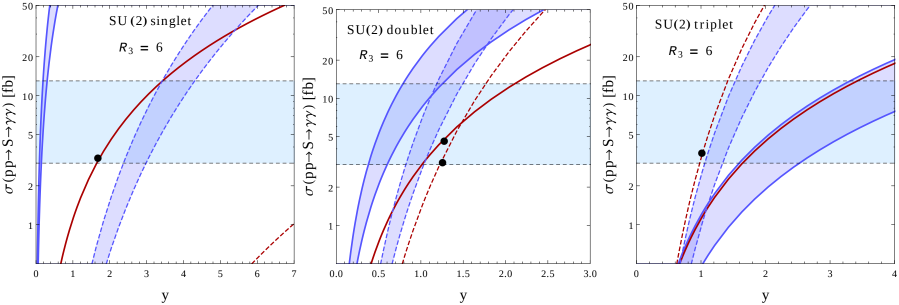
- Modified RGEs

$$\beta_y^{(1)} = y \left(y^2 (n_f + d(R_3)) - 6 C_2(R_3) g_3^2 - \frac{18}{5} Y_\psi^2 g_1^2 \right)$$

Asymptotically Safe 750 GeV excess

Strategy:

- We keep $U(1)_Y$ perturbative up to M_{PL} (low values $Y_\psi \to$ tension with the dijet bound, larger $SU(2)$ reps. needed),
- Strong and Yukawa couplings AS - no Landau Pole problem.



Dijet bound not satisfied! Dijet bound ok!

Asymptotically Safe 750 GeV excess

Some benchmark models...

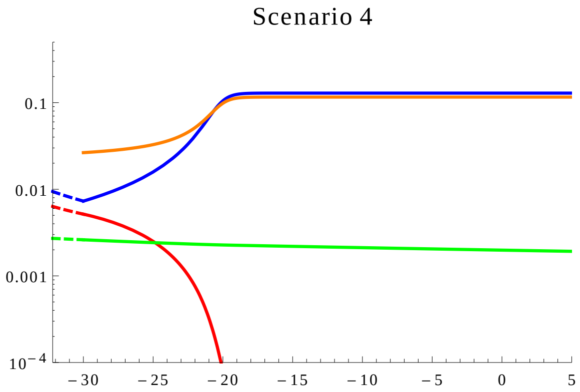
$R_3, 2$	n_f	g_3^*	y^*	y_{m_S}	σ_{NW}	M_ψ	σ_{LW}	M_ψ	$\frac{\Gamma_{jj}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}}$
6	80	11.7	5.5	1.23	4.6 fb	25 TeV	3.0 fb	1.5 TeV	3.3×10^3	6.7	11	37.4
8	200	12.4	3.6	0.78	3.6 fb	60 TeV	3.8 fb	1.8 TeV	2.7×10^3	6.7	11	37.4
10	35	10.6	8.6	1.91	3.0 fb	35 TeV	3.5 fb	3.3 TeV	1.1×10^4	6.7	11	37.4
15	65	9.2	5.3	1.39	3.6 fb	55 TeV	3.6 fb	4.6 TeV	8.5×10^3	6.7	11	37.4
15′	35	8.4	7.8	1.95	3.5 fb	50 TeV	3.7 fb	6.2 TeV	2.6×10^4	6.7	11	37.4

$R_3, 3$	n_f	g_3^*	y^*	y_{m_S}	σ_{NW}	M_ψ	σ_{LW}	M_ψ	$\frac{\Gamma_{jj}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}}$	$\frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}}$
6	115	12.8	5.0	1.03	3.5 fb	140 TeV	3.6 fb	3.5 TeV	436	6.5	10.9	37
8	300	12.5	2.9	0.64	3.1 fb	320 TeV	3.4 fb	4.5 TeV	378	6.6	11	37.3
10	52	11.2	7.4	1.56	3.5 fb	160 TeV	3.5 fb	8 TeV	1493	6.5	10.9	36.8
15	90	12.5	6.1	1.18	3.8 fb	300 TeV	3.9 fb	11 TeV	1192	6.6	11	37.2
15′	50	11.3	8.7	1.64	3.3 fb	250 TeV	3.1 fb	16 TeV	3633	6.6	10.9	37

- $SU(2)$ triplets favored by the dijet bound,
- Smaller (**6**, **8**) reps. of $SU(3)$ favored,
- Very large numbers of n_f needed.

Summary - open issues

1. Asymptotic safety - new venue for model building.
2. AS QCD can be constructed with reps. other than fundamental.
3. Large number of new (heavy) fermions needed.
4. Offers perturbative solutions to 750 GeV in the large width case.
5. Higher order effects need to be quantified (work in progress...).


Scenario 4
0.1
0.01
0.001
10^{-4}
−30
−25
−20
−15
−10
−5
0
5