Running after Diphoton

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based on J. Gu and ZL, arXiv:1512.07624

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Why RUNNING?
RG running, QFT's beauty and tool to make connections to higher scale physics;
Run—excesses, good for physical strength/health; but bad if too much;
后知后觉slow on the uptake—need to catch up our theory friends/community.

Target diphoton rate at 13 TeV, a few (4~10) fb

$$\mathcal{L}^s \supset -c_g \frac{\alpha_s}{12\pi} \frac{s}{m_S} G_{\mu\nu} G^{\mu\nu} - c_\gamma \frac{\alpha}{6\pi} \frac{s}{m_S} F^{\mu\nu} F_{\mu\nu},$$

$$\mathcal{L}^a \supset \tilde{c}_g \frac{\alpha_s}{8\pi} \frac{a}{m_S} \epsilon_{\mu\nu\alpha\beta} G^{\mu\nu} G^{\alpha\beta} + \tilde{c}_\gamma \frac{\alpha}{4\pi} \frac{a}{m_S} \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}.$$

$$c_g,\ \tilde{c}_g = \sum_i y_i \frac{m_S}{M_i} \bar{A}_{1/2}(\tau_i)\,,$$

$$c_\gamma,\ \tilde{c}_\gamma = \sum_i y_i N_c Q_i^2 \frac{m_S}{M_i} \bar{A}_{1/2}(\tau_i)$$

normalization chosen that,
assuming vector-like quarks induces anomalous couplings, which is (one of) the **most common setup** for all these diphoton papers if they bother to talk about the origin of these couplings):

1) c_g basically the Yukawa coupling;
2) the needed Yukawa for given c_g scales as VLQ mass over 750 GeV;
3) loop functions differs for pseudo-scalar comparing to scalar; and provide finite corrections to the needed Yukawa;
4) more copies reduces the needed Yukawa;
5) if N_c Q^2 not too large (cg,cgamma same order), gluon pair dominant, diphoton Br (sub) percent level.

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$$\mathrm{Br}(S\to\gamma\gamma) = \frac{c_\gamma^2}{1.7\ c_\gamma^2 + 2c_g^2\frac{\alpha_s^2}{\alpha^2}(1+\frac{67}{4\pi}\alpha_s)}$$

factor of 1.7 comes from the sum of all diphoton, ZZ and Zgamma channel when VLQ is not SU(2)_L charged (for simplicity, and has no impact on the horizontal location).

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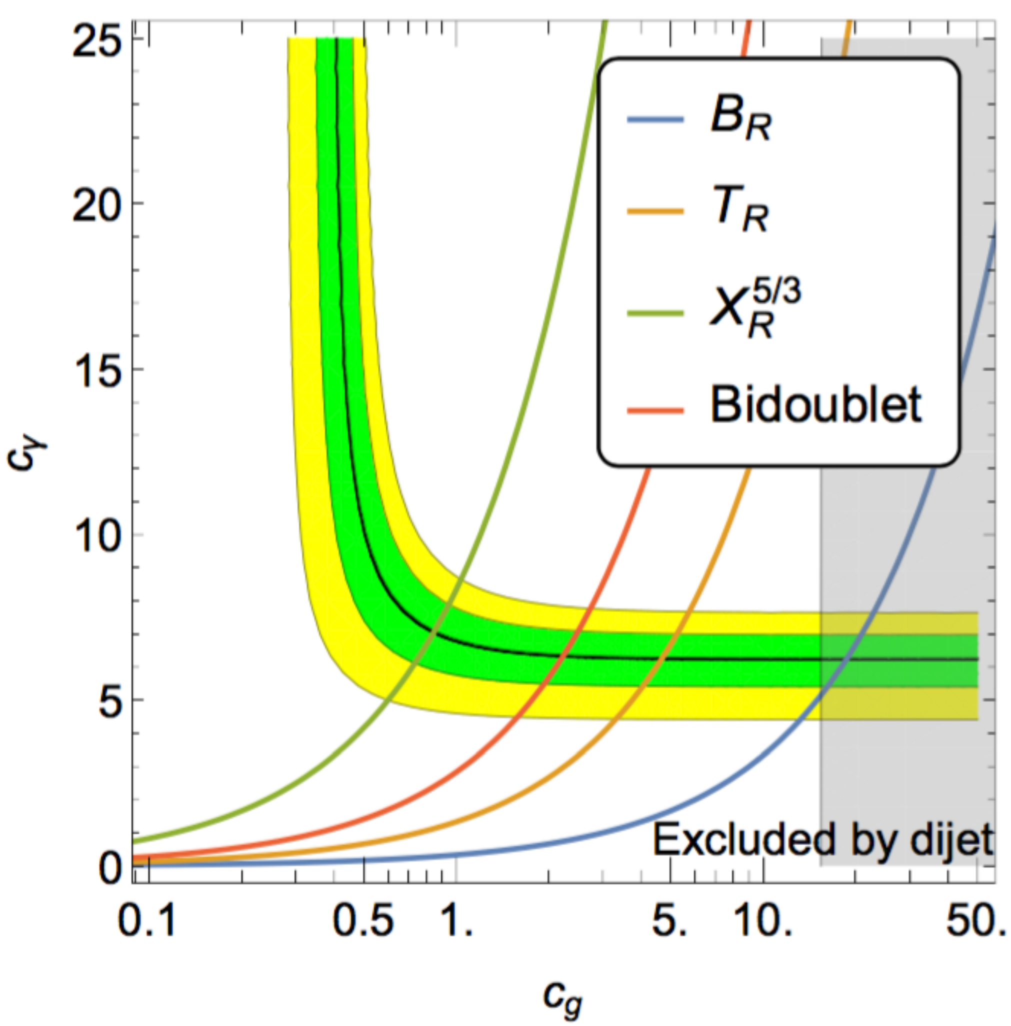
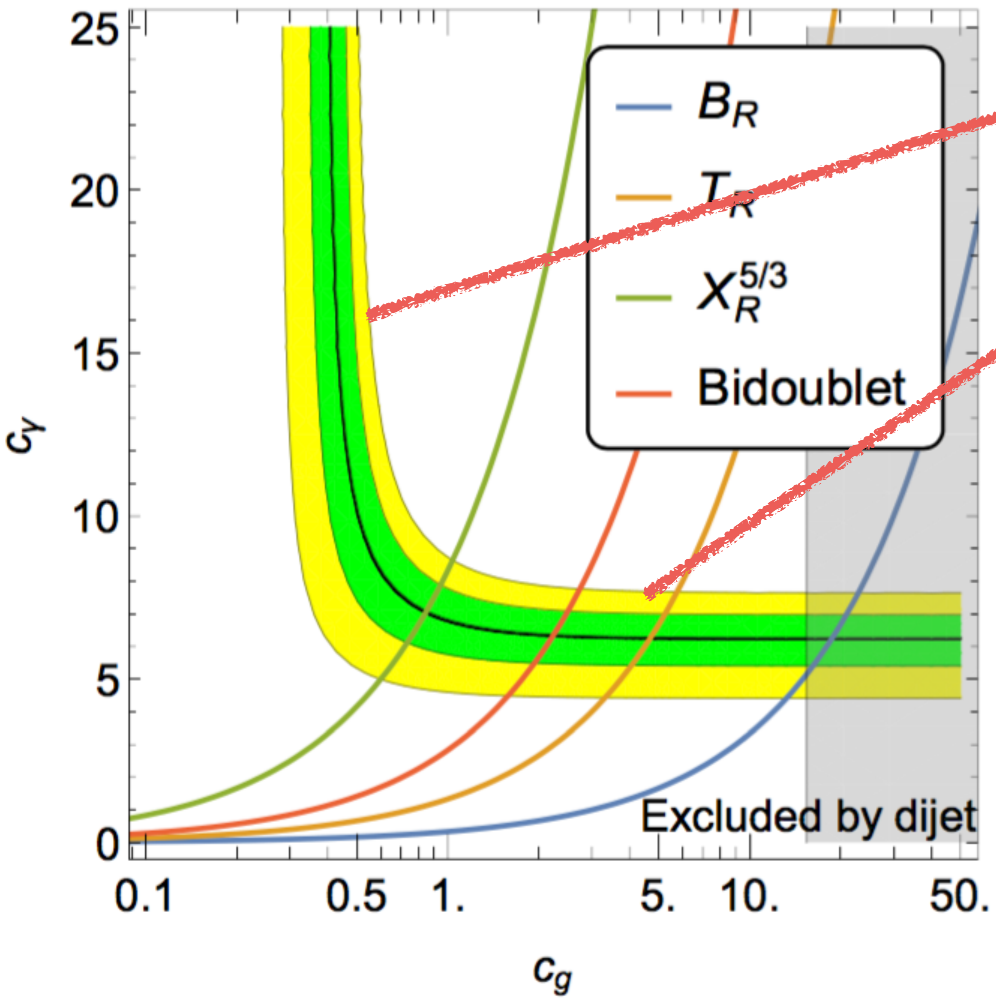
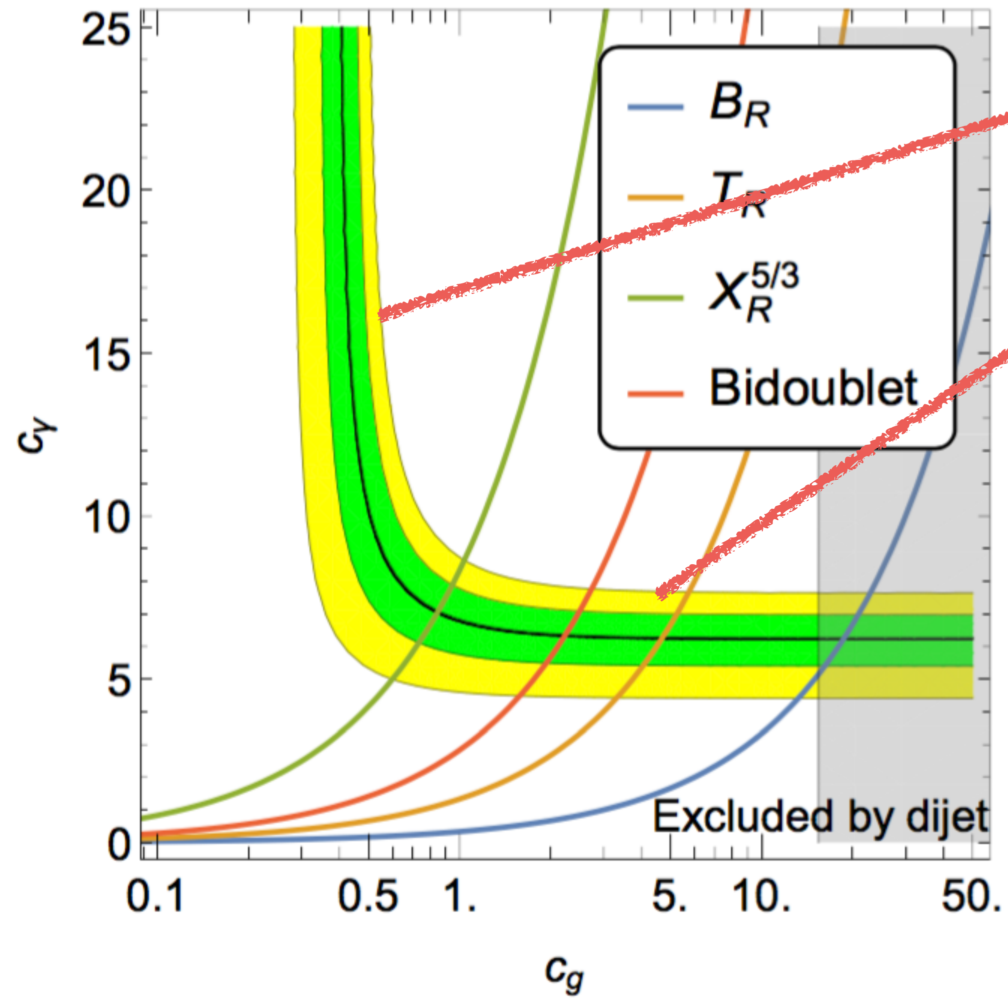


$$\sigma(gg \to S) = \frac{\sigma(gg \to H^{\rm SM}_{750\,\rm GeV})}{\frac{m_H^2}{v^2}|\bar{A}(\frac{m_H^2}{4M_{\rm top}^2})|^2} \times c_g^2,\ \frac{9}{4}\tilde{c}_g^2 = 55c_g^2,\ 125\tilde{c}_g^2\ \text{fb},$$



1) diphoton decay dominance—rate controlled by coupling to gluons, production rate
2) gluon decay dominance—rate controlled by coupling to diphoton

***usual models will fall some lines between these benchmarks, unless it has some very exotic large electric charge, or huge scale separation between mass scales of lepton partners and quark partners.**



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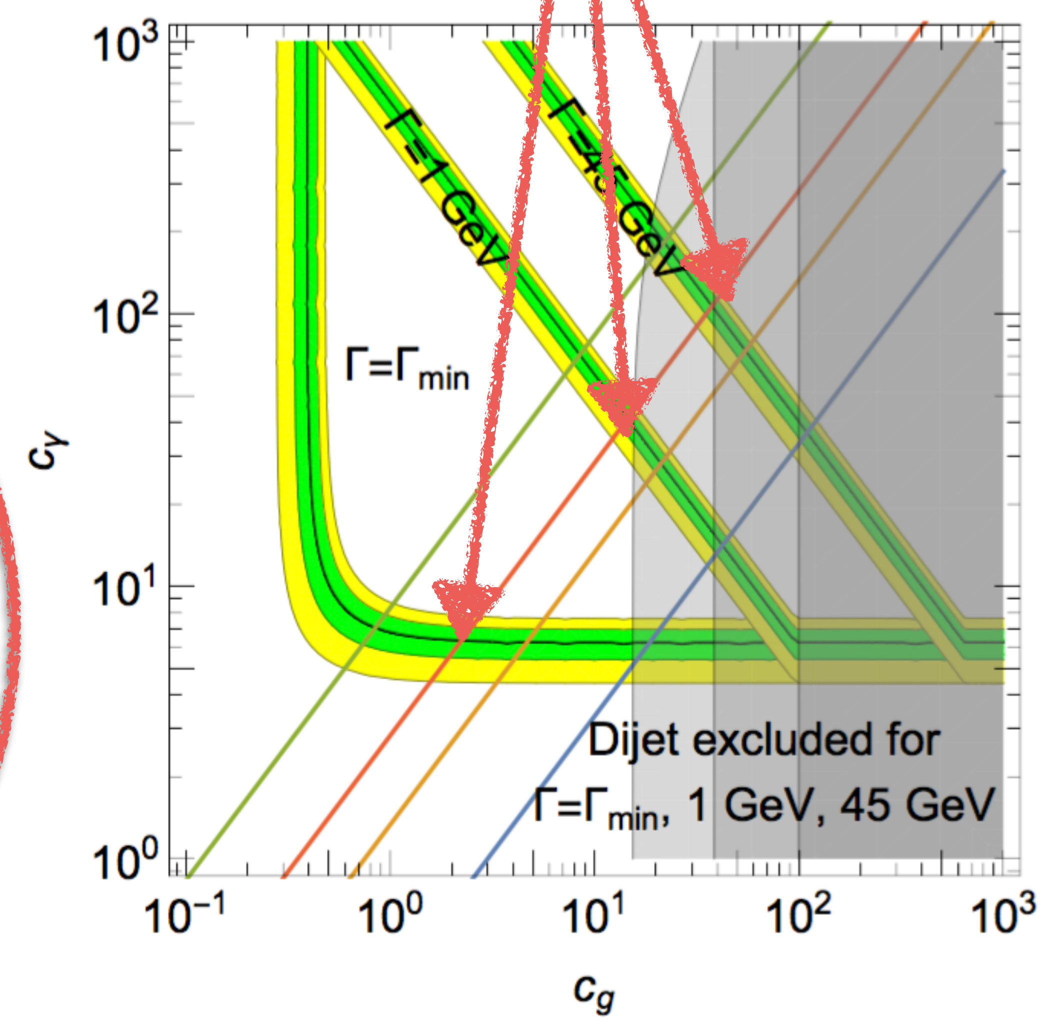
Larger width requires much large couplings

Name	$Q_{\rm em}$ states	$\sigma_{\gamma\gamma}$ Fits with various Γ			
		$\Gamma_{\rm min}$, only gg, $\gamma\gamma$		1 GeV	45 GeV
		c_g	c_γ	c_g	c_g
B_R	$-\frac{1}{3}$	$18.7^{+2.2}_{-2.5}$	$6.24^{+0.74}_{-0.84}$	$42.5^{+2.4}_{-2.9}$	110^{+6}_{-8}
T_R	$\frac{2}{3}$	$4.70^{+0.55}_{-0.63}$	$6.26^{+0.74}_{-0.84}$	$21.2^{+1.2}_{-1.5}$	$55.0^{+3.2}_{-3.8}$
$X_R^{5/3}$	$\frac{5}{3}$	$0.85^{+0.10}_{-0.11}$	$7.06^{+0.83}_{-0.95}$	$8.50^{+0.49}_{-0.59}$	$22.0^{+1.3}_{-1.5}$
Bidoublet	$-\frac{1}{3}+\frac{2}{3}+\frac{2}{3}+\frac{5}{3}$	$2.24^{+0.26}_{-0.30}$	$6.34^{+0.75}_{-0.85}$	$14.6^{+0.8}_{-1.0}$	$37.7^{+2.2}_{-2.6}$
Name	$Q_{\rm em}$ states	$\tilde{c}_g$	$\tilde{c}_\gamma$	$\tilde{c}_g$	$\tilde{c}_g$
B_R	$-\frac{1}{3}$	$12.3^{+1.5}_{-1.6}$	$4.09^{+0.48}_{-0.55}$	$28.1^{+1.6}_{-2.0}$	$72.8^{+4.2}_{-5.1}$
T_R	$\frac{2}{3}$	$3.08^{+0.36}_{-0.41}$	$4.11^{+0.49}_{-0.55}$	$14.1^{+0.8}_{-1.0}$	$36.4^{+2.1}_{-2.5}$
$X_R^{5/3}$	$\frac{5}{3}$	$0.56^{+0.07}_{-0.08}$	$4.63^{+0.55}_{-0.62}$	$5.62^{+0.32}_{-0.39}$	$14.6^{+0.8}_{-1.0}$
Bidoublet	$-\frac{1}{3}+\frac{2}{3}+\frac{2}{3}+\frac{5}{3}$	$1.47^{+0.17}_{-0.20}$	$4.16^{+0.49}_{-0.56}$	$9.64^{+0.55}_{-0.67}$	$25.0^{+1.4}_{-1.}$ [illegible]



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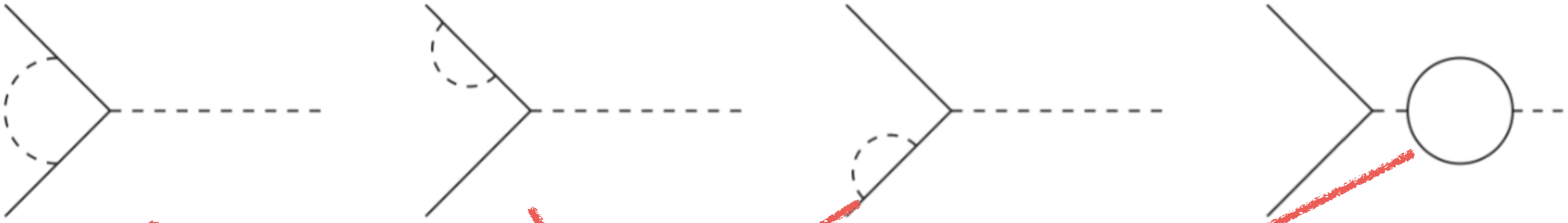


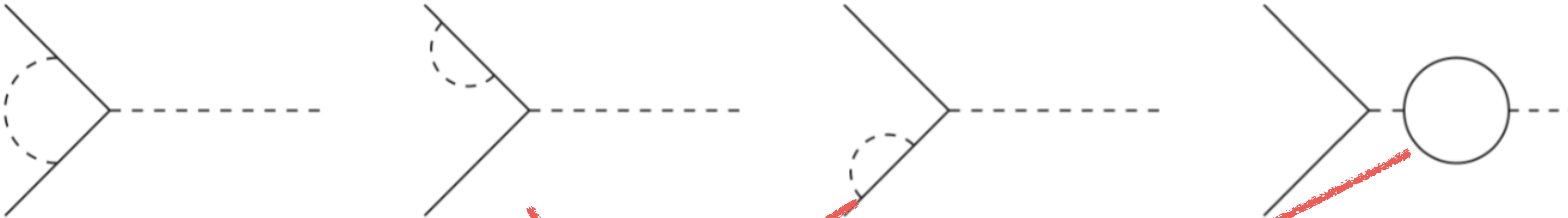
$$16\pi^2 \frac{dy}{dt} = (3 + 6N_f)\, y^3$$

$$c_g = A\, y_0\, N_f \frac{m_S}{M}$$

To explain the excess, sizable value of c_g (and Yukawa) is needed; Increase the number of species (N_f) reduces the Yukawa coupling at 750 GeV needed.

1) Yukawa runs really fast and still can hit the Landau pole quickly;
2) The running will then be N_f enhanced from the scalar self-energy diagram—the running is faster;
3) The perturbativity/unitarity violation coupling strength is \sqrt N_f suppressed, making the criteria harder (NLO corrections like the scalar self-energy, sees all the species; amplitudes goes to all species as well).—the ceiling is closer;

$$y \sim \frac{4\pi}{\sqrt{N_c N_f}}$$



$$16\pi^2 \frac{dy}{dt} = (3 + 6N_f)\, y^3 - 8g_3^2\, y,$$

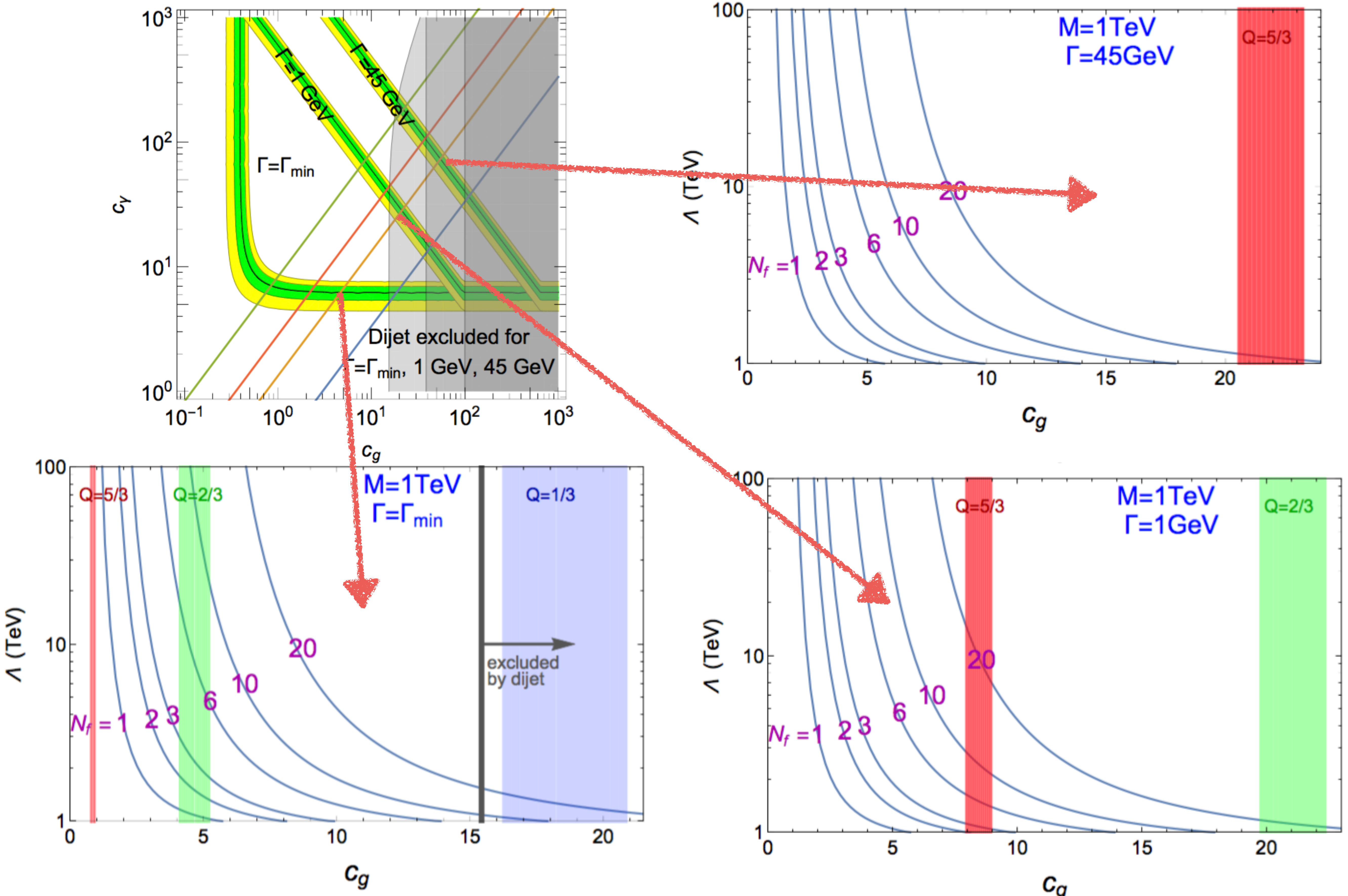
Fermion self-energy from gauge interactions (replace the scalar with gluons, other gauge interactions ignored for simplicity)

$$c_g = A\, y_0\, N_f \frac{m_S}{M}$$

$$y \sim \frac{4\pi}{\sqrt{N_c N_f}}$$

If the initial values of y reduced enough, the model could be perturbative up to very high scale due to possible cancellation in the RG equation, may even approaching approximate fix point, providing different view angle about the origin of this excess.

Around which scale you need new ingredients than the scalar and the VLQs?



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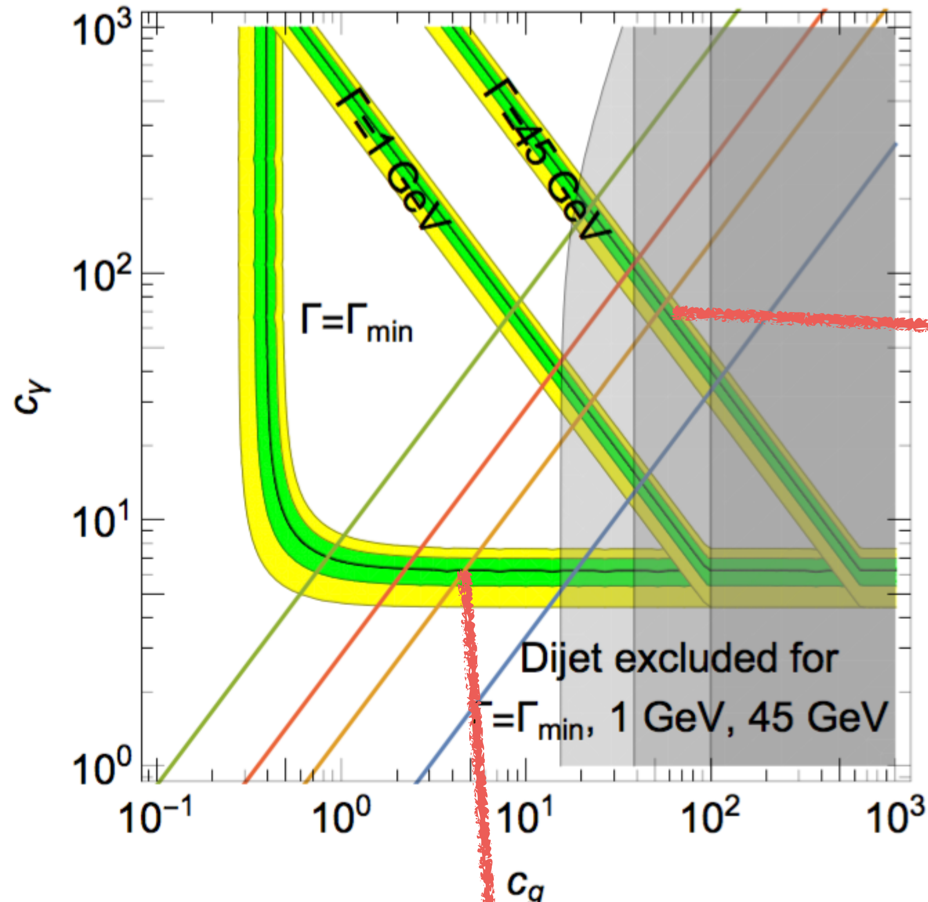

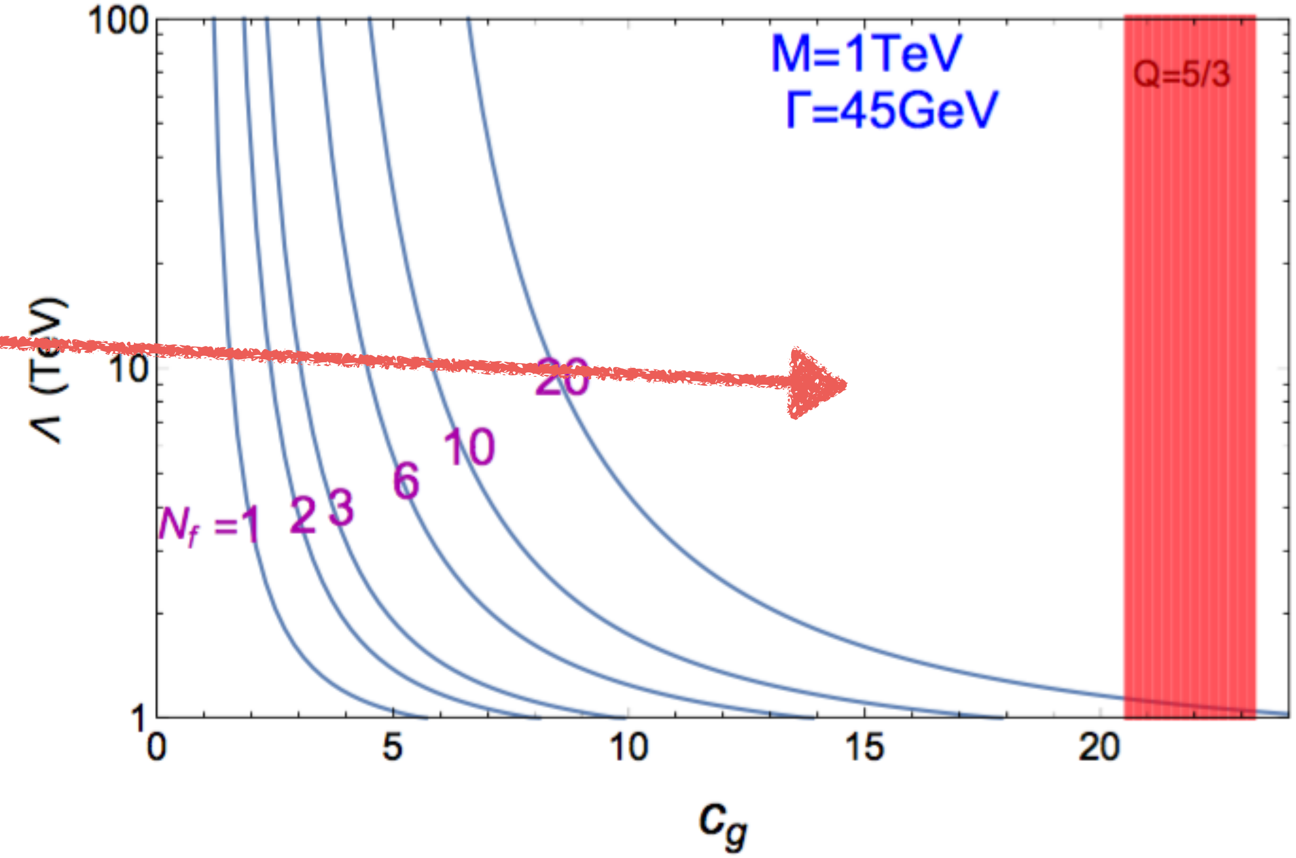

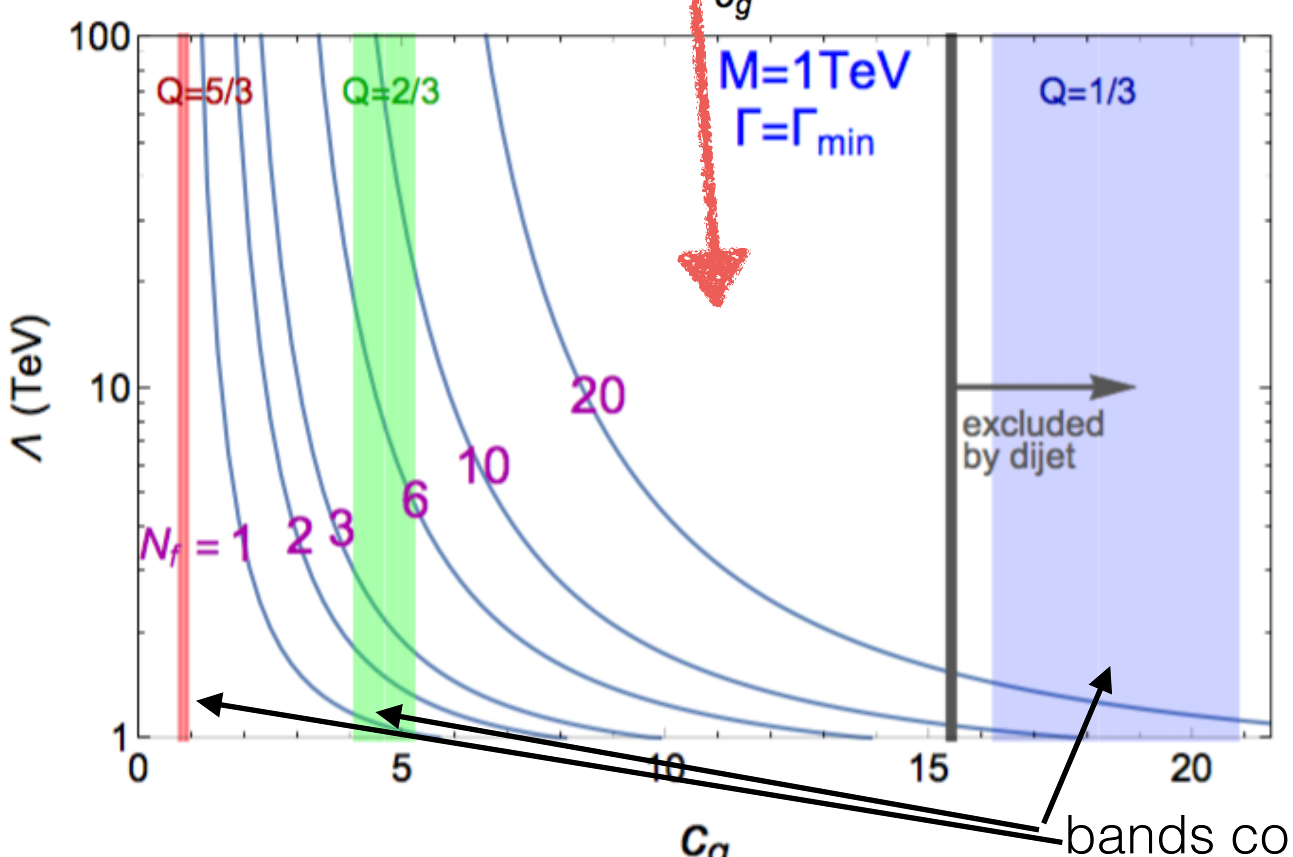

For minimal width case, a single TeV scale charge 5/3 VLQ is enough to bridge this 750 singlet scalar to be observed, the theory will be valid up to very high scale; but for charge 2/3 or 1/3 VLQ, one needs many copies.

For 45 GeV width, even 20 copies of the charge 5/3 VLQ at 1 1 TeV still hits the Landau pole before 2 TeV.

Similar practice could be done for bosonic insertions.

bands corresponds to the viable parameter region for given model.