Minimal Composite Dynamics versus Axion Origin of the Diphoton Excess

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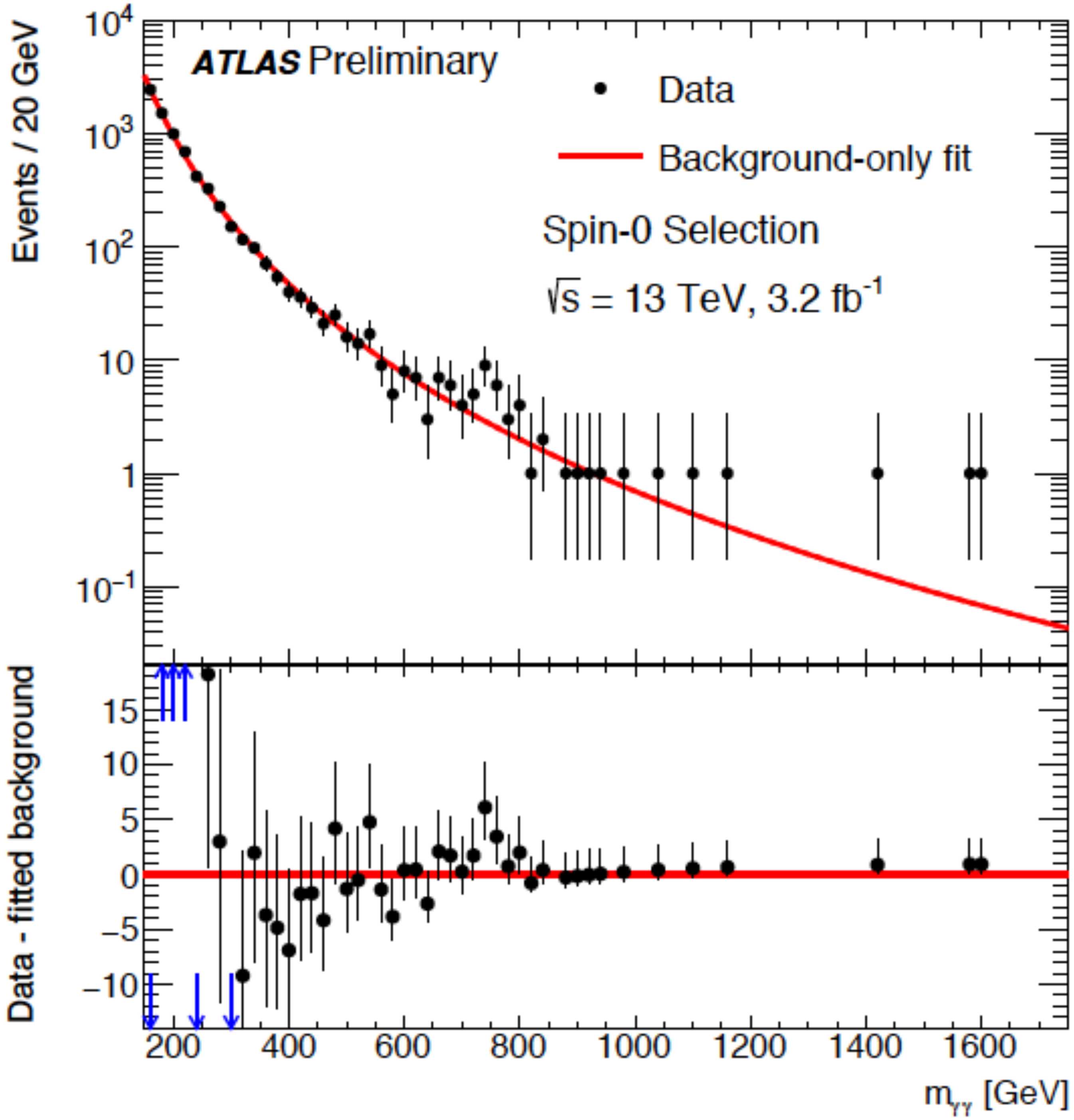
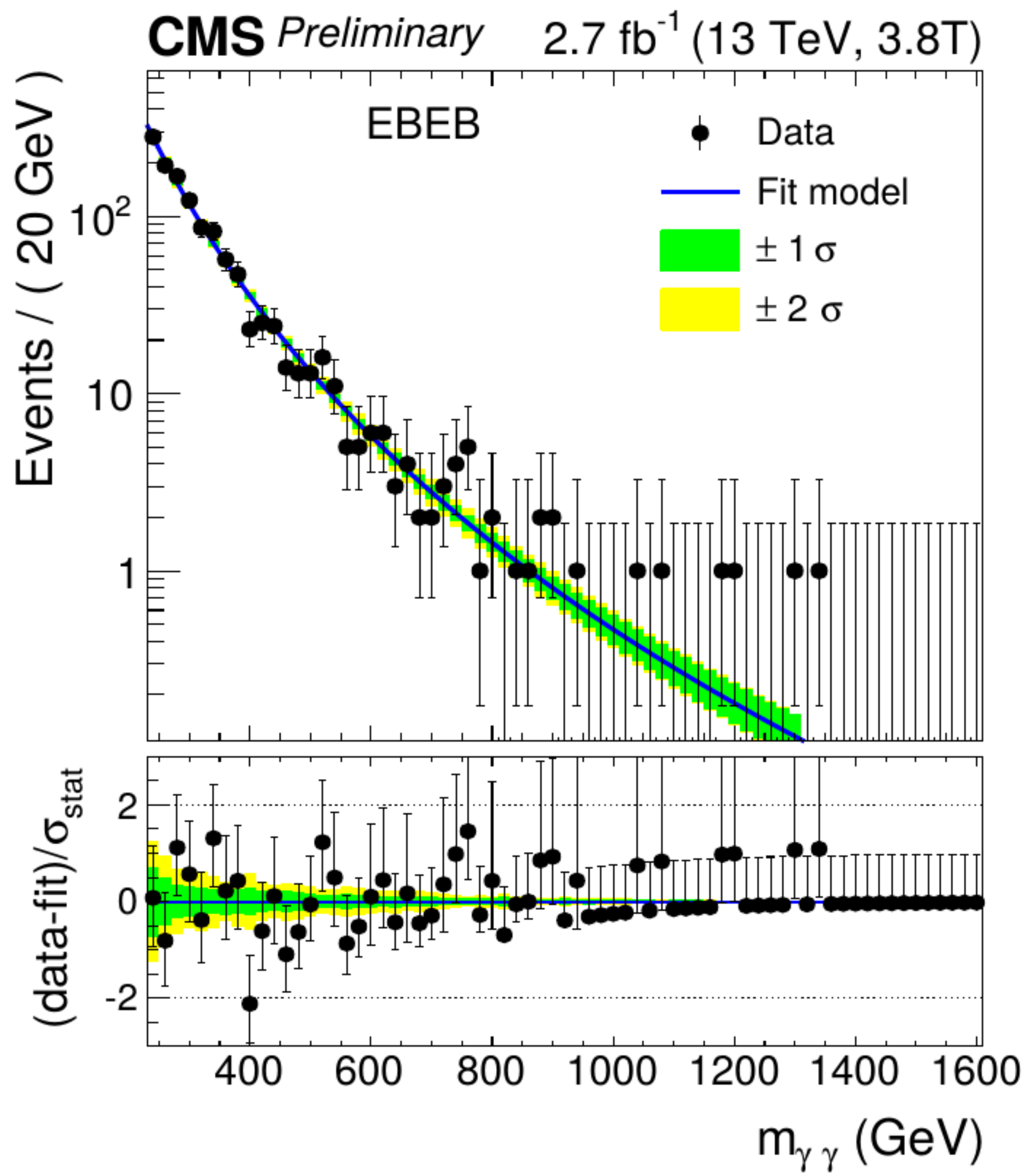
Diphoton invariant mass searches



local significance of 3.6σ
wide width preferred Γ_a/m_a ~ 0.06
$\sigma(pp \to \gamma\gamma) = (10 \pm 3)$ fb

local significance of 3.4σ
narrow width preferred
$\sigma(pp \to \gamma\gamma) = (6 \pm 3)$ fb



Effective Lagrangian for $J^p = 0^-$

New **elementary** axion-like or **composite** η'-like state with a mass of 750 GeV

$$\mathcal{L}_{\rm eff} = -\frac{c_{GG}}{8f_a} a\,\mathrm{Tr}\left[G^{\mu\nu}\tilde{G}_{\mu\nu}\right] - \frac{c_{AA}}{8f_a} a\, A^{\mu\nu}\tilde{A}_{\mu\nu} - \frac{c_{AZ}}{4f_a} a\, A^{\mu\nu}\tilde{Z}_{\mu\nu} - \frac{c_{WW}}{4f_a} a\, W^{+\mu\nu}\tilde{W}^{-}_{\mu\nu} - \frac{c_{ZZ}}{8f_a} a\, Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

with $\tilde{V}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$

Effective coupling to a vector-like quark T with $m_T > m_a/2$:

$$i\overline{T}\gamma_\mu D^\mu T - m_T \overline{T} T + \Delta^{\rm mix}_{t-T} - i y_T \frac{m_T}{f_a} a\, \bar{T}\gamma_5 T$$

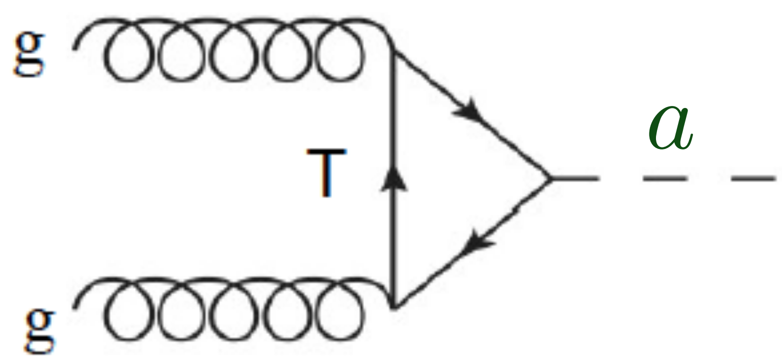
which induces/affects c_{GG} and c_{AA} .

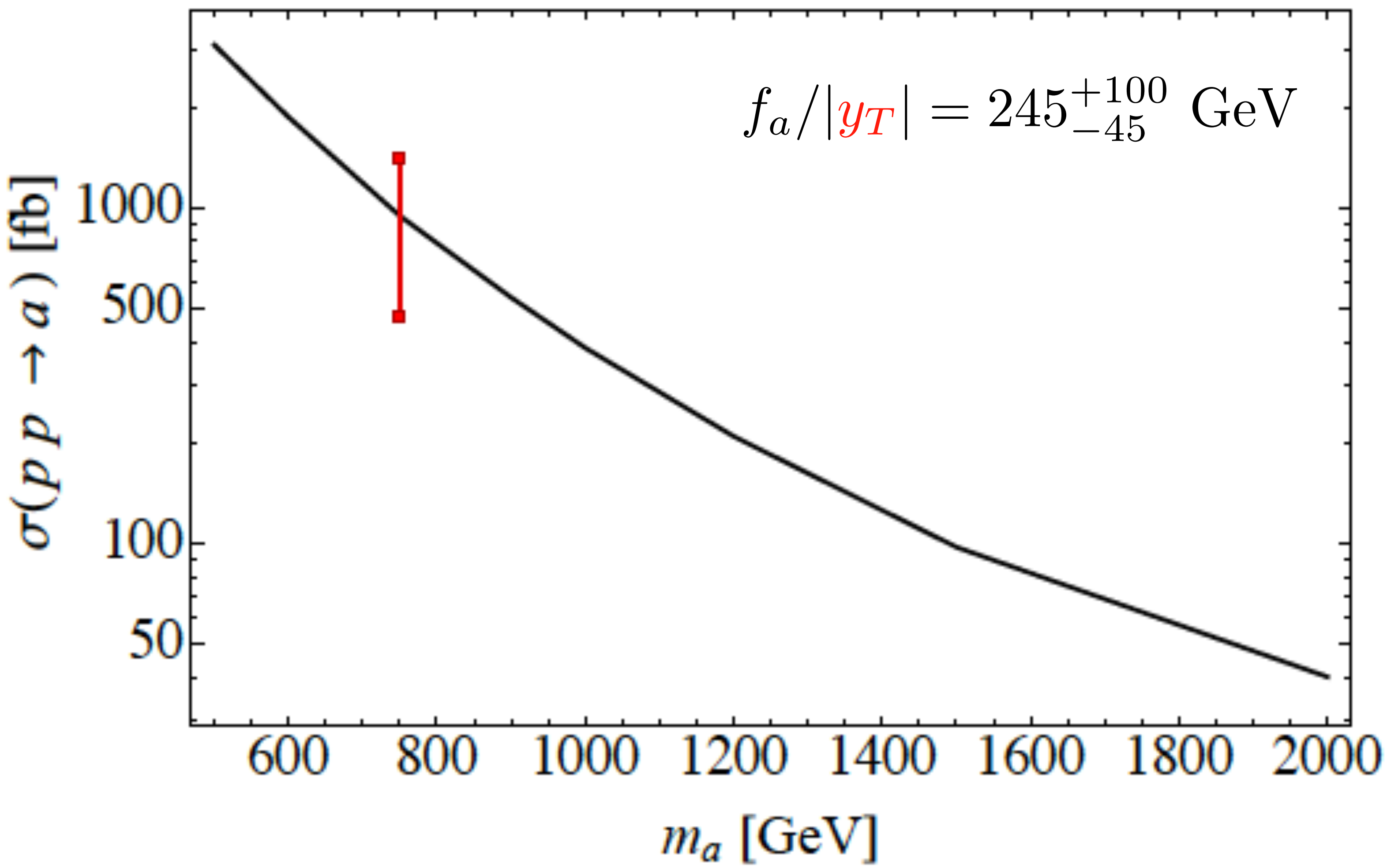
It is possible to derive distinctive signatures aimed at disentangling the **composite** nature from the **elementary** one.

If c_{GG} and c_{AA} are generated only by triangle diagrams with the SM top, it is not possible to explain the diphoton resonance

Elementary axion-like scenario

Production via gluon fusion mediated by a new vector-like quark T





From T-loop contribution:

$$c^T_{GG} = y_T \frac{\alpha_S}{2\pi} F\left(\frac{m_a^2}{4m_T^2}\right)$$

$$c^T_{AA} = y_T \frac{4}{3}\frac{\alpha_{em}}{\pi} F\left(\frac{m_a^2}{4m_T^2}\right)$$

SU(2)$_L$ invariance implies:

$$c^T_{AZ} = \tan(\theta_W)\, c^T_{AA}$$
$$c^T_{ZZ} = \tan^2(\theta_W)\, c^T_{AA}$$

$$B(a \to \gamma\gamma) \approx 0.0063$$
$$B(a \to \gamma Z) \approx 0.0037$$
$$B(a \to ZZ) \approx 0.00055$$

non-perturbative coupling for $m_T \gtrsim 1$ TeV

observation of $Z\gamma$ ($Z \to ll$) with ~100 fb^{-1}

σ($a \to jj$) ~ 7 fb

Minimal composite model at the EW scale

New strongly coupled sector engaging a SU(N_T) gauge interaction

The theory dynamically explains the breaking of the electroweak symmetry

Minimal model with $N_F = 2$ techniquarks (SM colour singlets)

$$Q_L \equiv (U_L, D_L) \qquad\qquad U_R,\ D_R$$

New leptons cancel gauge anomalies (needed for non-zero Q_L hypercharge)

$$L_L \equiv (N_L,\ E_L) \qquad\qquad N_R,\ E_R$$

Hypercharge assignments:

$$Y(Q_L) = \frac{y}{2}\,, \qquad Y(U_R/D_R) = \frac{y \pm 1}{2}$$

$$Y(L_L) = -d(R)\,\frac{y}{2} \qquad Y(N_R/E_R)\ \frac{-d(R)\,y \pm 1}{2}$$

y: real parameter

$d(R)$: dimension of the representation R of the techniquarks under SU(N_T)

η'-like diphoton resonance

The new strong gauge sector generates chiral and EW symmetry breaking with confining scale Λ_T and technipion decay constant F_T

$$\mathcal{U} = e^{i\Phi/F_T} = \exp\left[\frac{i}{F_T}(a + \tau\cdot\mathbf{\Pi})\right]$$

Under a chiral transformation:

$$\mathcal{U} \to u_L\,\mathcal{U}\,u_R^\dagger$$

Pseudoscalar state associated with $U(1)_A$ anomaly, analogous to the QCD η'

technipions provide the longitudinal components of W and Z

EW interactions are a subgroup of $SU(2)_L \times SU(2)_R \times U(1)_V$

$$\langle 0|\overline{U}U + \overline{D}D|0\rangle \neq 0 \quad \Rightarrow$$

$$m_W^2 = \frac{1}{2}g_W\,F_T^2 \qquad m_Z^2 = \frac{1}{2}\sqrt{g_W^2 + g_Y^2}\,F_T^2$$

$$F_T = 246\ \mathrm{GeV}$$

η'-like diphoton resonance

Below the composite scale Λ_T the low energy physics is described by an effective Lagrangian satisfying all the symmetries of the underlying theory

$$\mathcal{L}_{\rm eff} = \frac{1}{4} F_T^2 \, {\rm Tr} \left[\left(\mathcal{D}^\mu \mathcal{U} \right)^\dagger \, \mathcal{D}_\mu \mathcal{U} \right] + \mathcal{L}_{m_a} + \mathcal{L}_{\rm WZW} + \ldots$$

η'-like diphoton resonance

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$$\mathcal{L}_{m_a} = \frac{1}{32} m_a^2 \, F_T^2 \, {\rm Tr}\left[\ln \mathcal{U} - \ln \mathcal{U}^\dagger \right]^2$$

For massless techniquarks in the fundamental representation, ***d(R)*=*N*$_T$**, we have in the large N_T limit the Witten-Veneziano relation:

$$m_a = \sqrt{\frac{2}{3}} \frac{F_T}{f_\pi} \frac{3}{N_T} m_{\eta_0} \approx \frac{6}{N_T} \, {\rm TeV}$$

$$m_{\eta_0}^2 = m_{\eta'}^2 + m_\eta^2 - 2\, m_K^2 \approx 850 \ {\rm GeV}$$

a natural candidate for the 750 GeV state

η'-like diphoton resonance

Below the composite scale Λ_T the low energy physics is described by an effective Lagrangian satisfying all the symmetries of the underlying theory

$$\mathcal{L}_{\rm eff} = \frac{1}{4} F_T^2 \, {\rm Tr}\left[\left(\mathcal{D}^\mu \mathcal{U}\right)^\dagger \mathcal{D}_\mu \mathcal{U} \right] + \mathcal{L}_{m_a} + \mathcal{L}_{\rm WZW} + \ldots$$

Gauged Wess-Zumino-Witten topological term associated with global axial-vector currents anomalies:

$$\begin{aligned} \mathcal{L}_{\rm WZW} \;=\; & -\frac{d(R)}{48\pi^2 F_T} \epsilon_{\mu\nu\rho\sigma} {\rm Tr}\left[\Phi\left(\partial^\mu A_L^\nu \partial^\rho A_L^\sigma + \partial^\mu A_R^\nu \partial^\rho A_R^\sigma + \partial^\mu \left(A_L^\nu + A_R^\nu\right) \partial^\rho \left(A_L^\sigma + A_R^\sigma\right)\right)\right] \\ & -\frac{i\, d(R)}{48\pi^2 F_T^3} \epsilon_{\mu\nu\rho\sigma} {\rm Tr}\left[\partial^\mu \Phi \partial^\nu \Phi \partial^\rho \Phi \left(A_L^\sigma + A_R^\sigma\right)\right] + \ldots \end{aligned}$$

$$\Phi = a + \tau \cdot \mathbf{\Pi} \qquad A_L^\mu = g_Y \left(Q - \frac{1}{2}\tau_3\right) B^\mu + \frac{1}{2} g_W \, \boldsymbol{\tau} \cdot \boldsymbol{W}^\mu \,, \qquad A_R^\mu = g_Y \, Q \, B^\mu$$

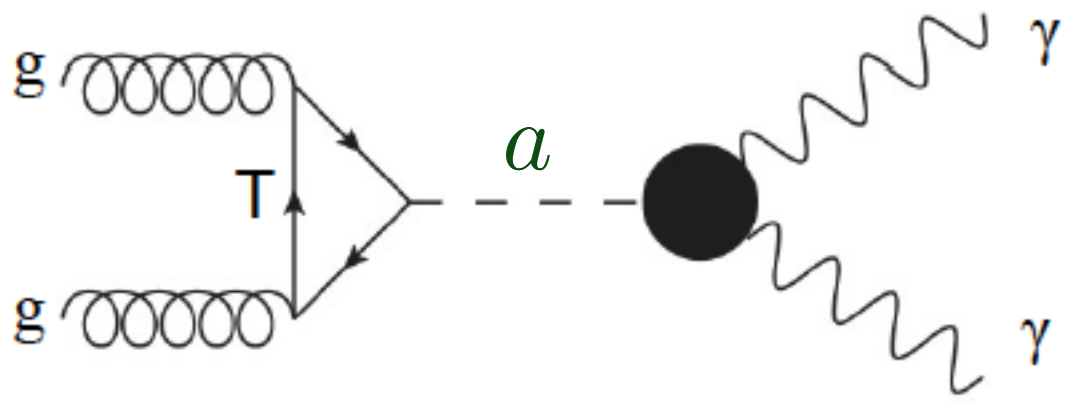
three-body decays $a \to 3\Pi$ (relevant only for $m_a \gtrsim 2$ TeV)

topological sector predicts a decay rates:

$$a \to \gamma\gamma,\, \gamma Z,\, ZZ,\, W^+W^-$$

η'-like diphoton resonance

Production via gluon fusion mediated by a new vector-like quark T



$$c_{VV} = c^T_{VV} + c^{\rm comp}_{VV}$$

$$f_a \equiv F_T = 246 \ \mathrm{GeV}$$

From T-loop contribution:

$$c^T_{GG} = y_T \frac{\alpha_S}{2\pi} F\left(\frac{m_a^2}{4m_T^2}\right)$$

$$c^T_{AA} = y_T \frac{4}{3}\frac{\alpha_{\rm em}}{\pi} F\left(\frac{m_a^2}{4m_T^2}\right)$$

SU(2)$_L$ invariance implies:

$$c^T_{AZ} = \tan(\theta_W)\, c^T_{AA} \qquad c^T_{WW} = 0$$

$$c^T_{ZZ} = \tan^2(\theta_W)\, c^T_{AA}$$

From gauged WZW term:

$$c^{\rm comp}_{AA} = \left(1+y^2\right)\frac{e^2 d(R)}{8\,\pi^2}$$

$$c^{\rm comp}_{AZ} = \frac{1-2(1+y^2)s^2_W}{2\,c_W\,s_W}\frac{e^2 d(R)}{8\,\pi^2}$$

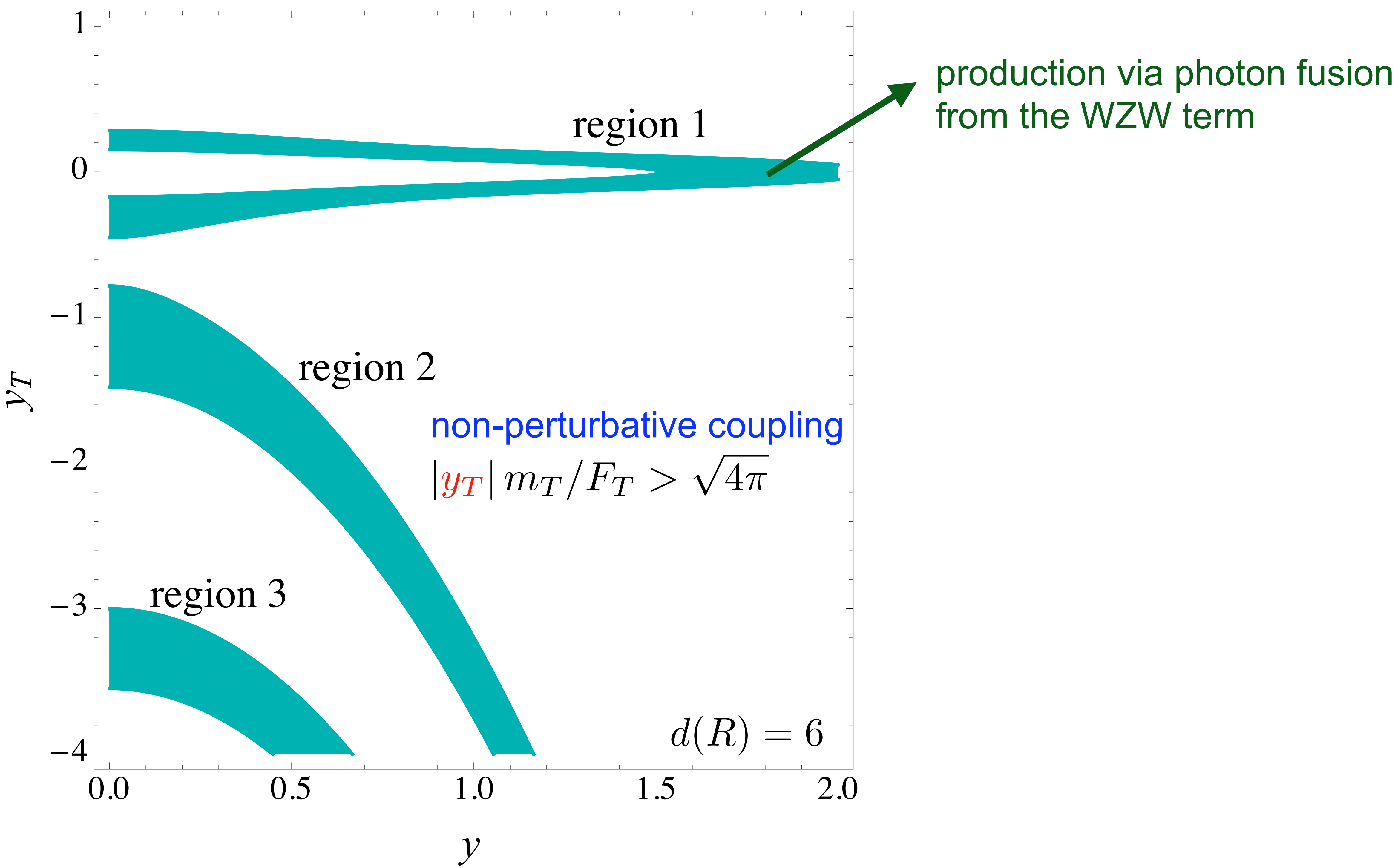
$$c^{\rm comp}_{ZZ} = \frac{1-3s^2_W+3(1+y^2)s^4_W}{3\,c^2_W\,s^2_W}\frac{e^2 d(R)}{8\,\pi^2}$$

$$c^{\rm comp}_{WW} = \frac{e^2}{s^2_W}\frac{d(R)}{24\,\pi^2}$$

Di Vecchia, Veneziano, 1980

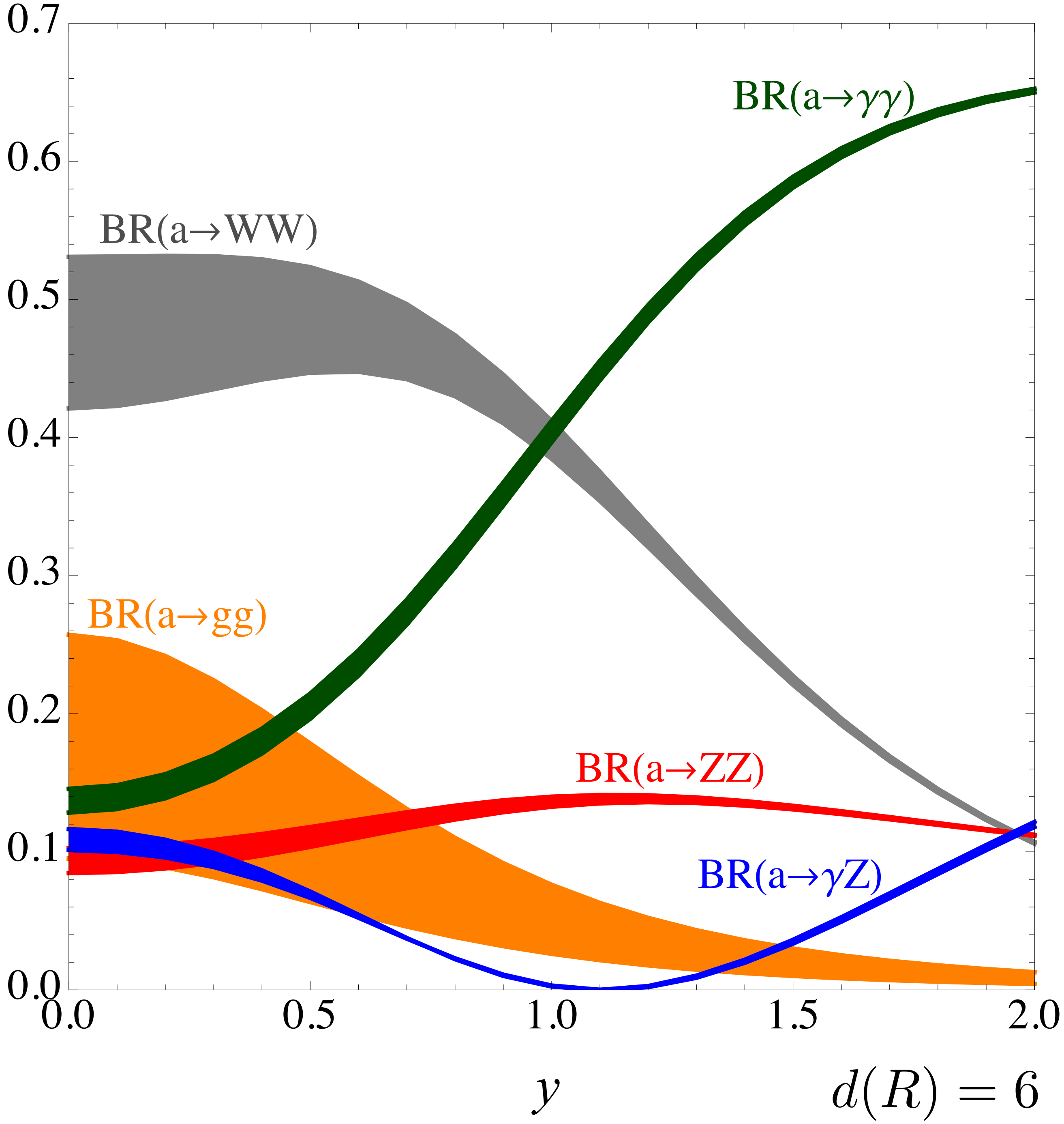
η'-like diphoton resonance

Parameter space reproducing the diphoton excess within 1σ



η'-like diphoton resonance

Predictions for the branching ratios for region 1 and $y_T \geq 0$



WW
enhanced compared to $\gamma\gamma$ for y<1
(absent in the axion-like case)

Zγ, ZZ
comparable with $\gamma\gamma$ for small y,
suppressed for y>1

gg
always subdominant

η'-like diphoton resonance

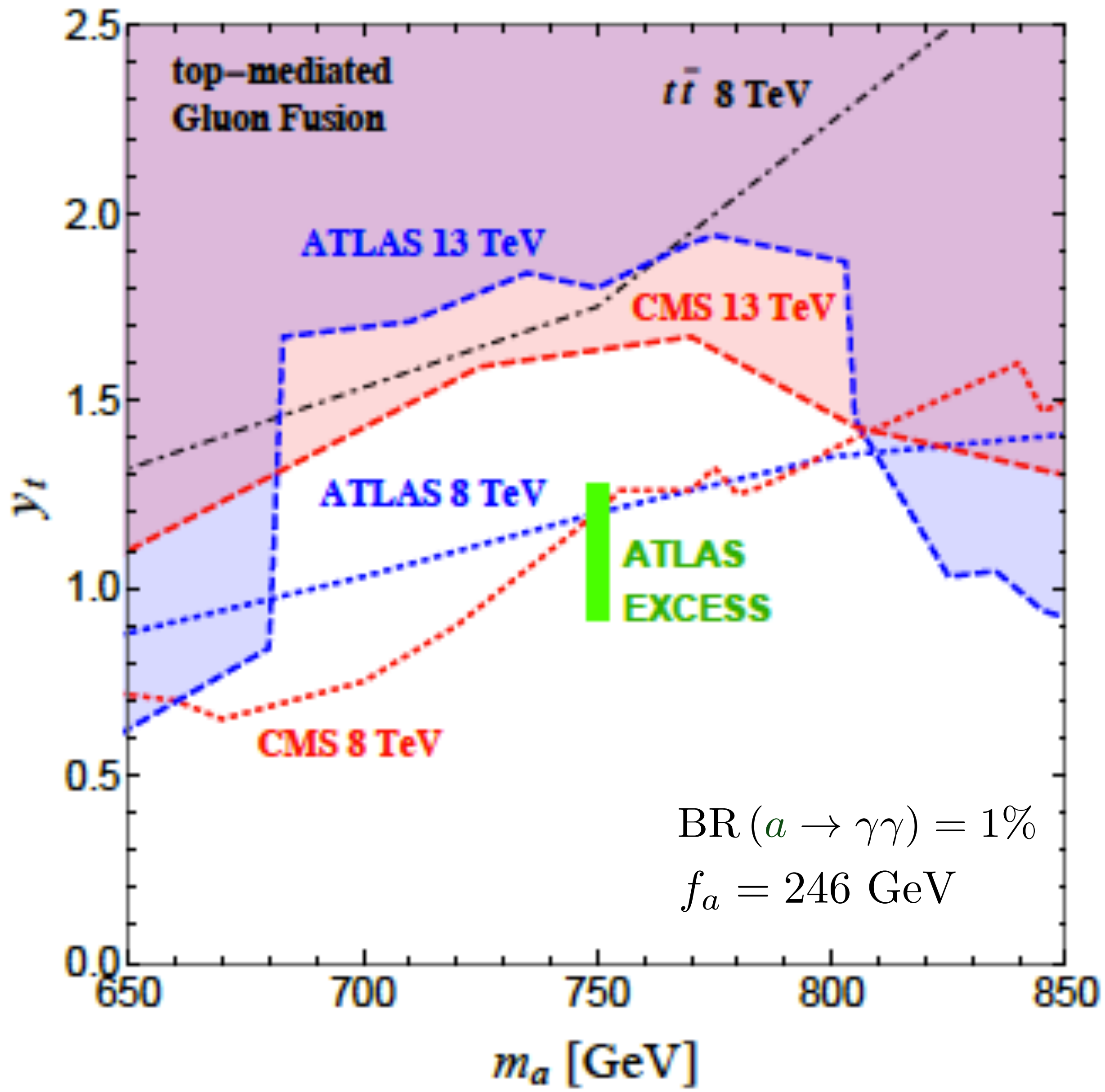
The composite diphoton resonance passes all the LHC constraints

	LHC-13		η'-like state
WW	σ < 250 fb	[ATLAS-CONF-2015-075]	σ < 20 fb
$Z\gamma$	σ < 30 fb	[ATLAS-CONF-2016-010]	σ < 4 fb
ZZ	σ < 250 fb	[ATLAS-CONF-2015-071]	σ < 4 fb

	LHC-8		
WW	σ < 40 fb	[ATLAS arXiv:1509.00389]	σ < 4 fb
$Z\gamma$	σ < 4 fb	[ATLAS arXiv:1407.8150]	σ < 1 fb
ZZ	σ < 10 fb	[ATLAS arXiv:1507.05930]	σ < 1 fb

Top-mediated gluon fusion

$$\mathcal{L}_{\rm eff} \supset -i y_t \frac{m_t}{f_a}\, a\, \bar{t}\gamma_5 t + \ldots$$



$$\Gamma_a \approx \Gamma(a \to t\bar{t}) \approx 45 \text{ GeV}$$

$$\sigma(pp \to a \to \gamma\gamma) \simeq c_{AA}^2 \frac{\alpha_S^2 |F(m_a^2/4m_t^2)|^2}{6144\,\pi} \frac{m_a^4}{m_t^2 v^2} \frac{d\mathcal{L}^{gg}}{dm_a^2}$$

Top-mediated gluon fusion and WZW decay

Assume a direct coupling of ***a*** to SM fermions generated by the same EGD responsible for fermion masses:

SM third generation: $Q_3 \equiv (t,b)^T$

$$\mathcal{L}_{\rm ferm} = i\,\overline{Q}_{3L}\gamma_\mu\,(\partial^\mu - iA^\mu_L)\,Q_{3L} + i\,\overline{Q}_{3R}\gamma_\mu\,(\partial^\mu - iA^\mu_R)\,Q_{3R} - Y_1\,F_T\,f_1(h)\,\left(\overline{Q}_{3L}\mathcal{U}Q_{3R} + \overline{Q}_{3R}\mathcal{U}^\dagger Q_{3L}\right) - Y_2\,F_T\,f_2(h)\,\left(\overline{Q}_{3L}\mathcal{U}\tau_3\,Q_{3R} + \overline{Q}_{3R}\tau_3\,\mathcal{U}^\dagger Q_{3L}\right) + \ldots$$

Higgs effective couplings: $f_{1,2}(h) = 1 + c_{1,2}\,\frac{h}{F_T} + \ldots$

top and bottom masses: $m_t = (Y_1 + Y_2)\,F_T \qquad m_b = (Y_1 - Y_2)\,F_T$

effective couplings of ***a***: $\mathcal{L}_{\rm ferm} \supset -\frac{m_t}{F_T}\,i\,a\,\bar{t}\,\gamma_5\,t - \frac{m_b}{F_T}\,i\,a\,\bar{b}\,\gamma_5\,b \qquad y_t = 1$

If SM top mass is generated via four-fermion operators, the coupling of a to the top naturally gives a wide width resonance: $\Gamma_a/m_a \sim 0.06$

The ATLAS diphoton excess is explained for $y \gtrsim 3$

Summary

- **ATLAS and CMS find local excesses respectively of 3.6σ and 3.4σ for a spin-0 diphoton resonance with invariant mass around 750 GeV**
- **The new resonance can be explained by a new elementary axion-like or a composite η'-like state**
- **Searching for new decay channels will allow to discriminate between the two realisations**
- **A composite η'-like state coupled to the SM top naturally explains the ATLAS wide-width resonance fit**
- **Diphoton searches will be instrumental for testing minimal composite models of dynamical electroweak symmetry breaking**