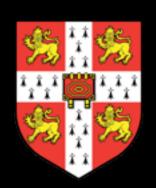
Diphoton Anomaly at the LHC

Marco Nardecchia

DAMTP and Cavendish Laboratory, University of Cambridge



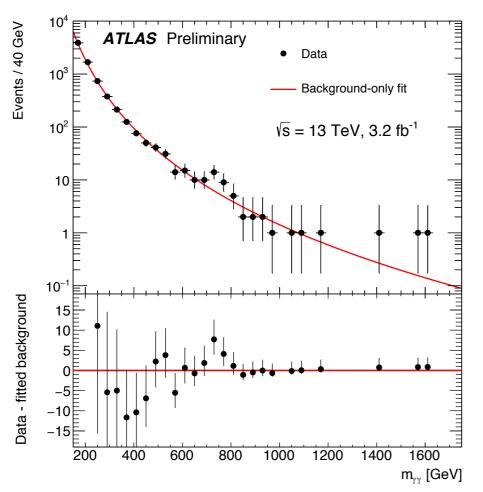


Outline

- General phenomenological aspects
- Weakly coupled extensions
- Strongly coupled extensions
- Conclusions

The Data

[ATLAS-CONF-2015-081] + talk by Christian Ohm

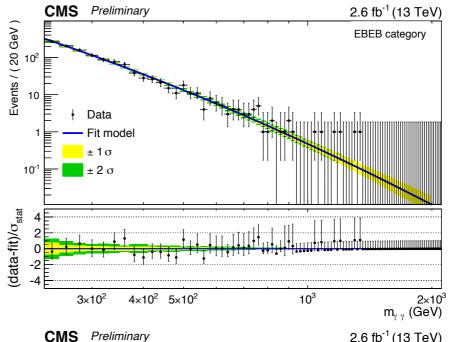


Bin[GeV]	650	690	730	770	810	850
$N_{ m events}$	10	10	14	9	5	2
$N_{ m background}$	11.0	8.2	6.3	5.0	3.9	3.1

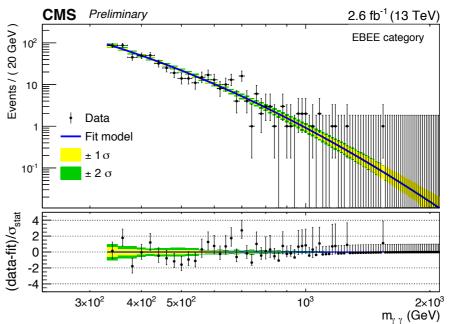
[1512.05777]

- ATLAS: local significance of 3.9σ
- ATLAS: best fit is obtained for $\alpha = \Gamma/M = 6\%$
- CMS: local significance of 2.6σ (narrow width)

[CMS-EXO-15-004] + talk by Raffaella Radogna



EBEB Barrel-Barrel



EBEE Barrel-Endcaps

Bin[GeV]	700	720	740	760	780	800
N_{events} (EBEB)	3	3	4	5	1	1
$N_{\text{background}}$ (EBEB)	2.7	2.5	2.1	1.9	1.6	1.5
$N_{\rm events}$ (EBEE)	16	4	1	6	2	3
$N_{\text{background}}$ (EBEE)	5.2	4.6	4.0	3.5	3.1	2.8

[1512.05777]

Warning



- We need more data, most likely just a statistical fluctuation
- However... more than 200 pre-prints on the arXiv
- I will try to give a (biased, partial and simplified) summary on possible interpretations of the anomaly in terms of New Physics, my apologies for the missing references/works/ideas

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- At this conference



Franceschini [1512.04933 1512.05330]



Marzocca [1512.04929 1603.00718]



McCullough [1512.04933]



Panci [1601.01571]



Sala [1512.05330]



Nardecchia [1512.08500]

- Focus on S-channel, 2-body decay, J=0
- •(J=1 forbidden, J=2 see backup)

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$$\sigma(pp \to \gamma \gamma) \approx \begin{cases} (0.5 \pm 0.6) \text{ fb} & \text{CMS [2]} \sqrt{s} = 8 \text{ TeV}, \\ (0.4 \pm 0.8) \text{ fb} & \text{ATLAS [3]} + \sqrt{s} = 8 \text{ TeV}, \\ (0.4 \pm 0.8) \text{ fb} & \text{ATLAS [3]} + \sqrt{s} = 8 \text{ TeV}, \\ (6 \pm 3) \text{ fb} & \text{CMSp[1]} = 3 \text{ TeV}, \\ (6 \pm 3) \text{ fb} & \text{CMSp[1]} = 3 \text{ TeV}, \\ (10 \pm 3) \text{ fb} & \text{ATLAS [1]} + \sqrt{s} = 4 \text{ TeV}, \\ (10 \pm 3) \text{ fb} & \text{ATLAS [1]} + \sqrt{s} = 4 \text{ TeV}, \\ \text{where } C_{\gamma \gamma} \text{ has a } 100\% \text{ uncertainty if extracted purely from data very standard at very standar$$

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 Consistency (at 20) with LHC8 Weighter answers to the questions in the title could just be "a st

 interesting to try to interpret the result as a manifestation of new assume that the signal is due to a prew resonance and reletermine the relating them to an effective description in terms of non-renormalization we present weakly-coupled renormalizable models that realise the Historian Tele Poter reignans (to tein closed ed phoro) con impidify the fing relative de unitated typical relative also Klas relatively da Kgo widt 20. of the specification characteristic but disclinitely compension and include specification of the specification of the specifical specification of the specif printesent bator lyayable cours at Inheesting 4 entrinterpass that signed ei

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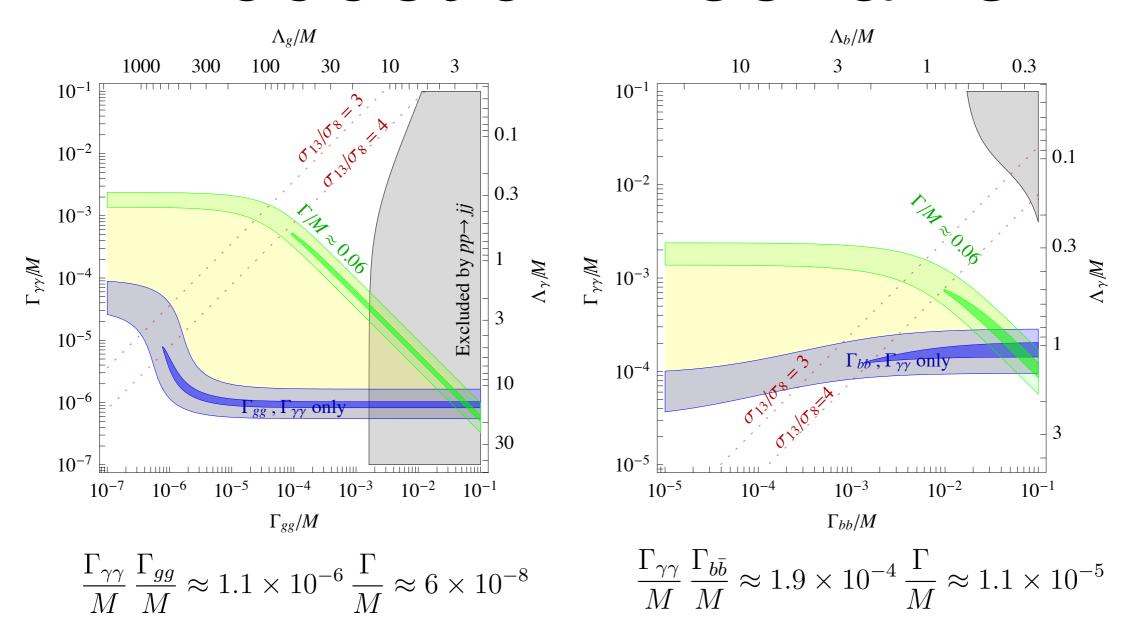
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- Focus on two cases: gluon-exploration bottom bott avethousider the ansinimum and Maakimum sedu
- Another option: change topology and kinematics to and proposence diffety, b

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Production mechanism



Large partial width in diphoton

$$\Gamma_{\gamma\gamma}/M\gtrsim 10^{-6}$$
 narrow width $\Gamma_{\gamma\gamma}/M\gtrsim 10^{-4}$ large width

$$\Gamma_{\gamma\gamma}/M\gtrsim 10^{-4}$$
 large width

[1512.04933

• In the gluon-gluon case, total width (if large) is dominated by decays into other channels

Other decay channels

final	σ at	$\sqrt{s} = 8 \mathrm{Te}$	V	implied bound on
state f	observed	expected	ref.	$\Gamma(S \to f)/\Gamma(S \to \gamma \gamma)_{\rm obs}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[8, 9]	$< 0.8 \ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	$< 0.6 \ (r/5)$
$ au^+ au^-$	< 12 fb	< 15 fb	[11]	< 6 (r/5)
$Z\gamma$	< 11 fb	< 11 fb	[12]	< 6 (r/5)
ZZ	< 12 fb	< 20 fb	[13]	< 6 (r/5)
Zh	$< 19 \; {\rm fb}$	< 28 fb	[14]	$< 10 \ (r/5)$
hh	$< 39 \; {\rm fb}$	<42 fb	[15]	$< 20 \ (r/5)$
W^+W^-	< 40 fb	$<70~\mathrm{fb}$	[16, 17]	$< 20 \ (r/5)$
$t \overline{t}$	< 450 fb	< 600 fb	[18]	$< 300 \ (r/5)$
invisible	< 0.8 pb	-	[19]	$< 400 \ (r/5)$
$b\overline{b}$	$\lesssim 1 \mathrm{pb}$	$\lesssim 1\mathrm{pb}$	[20]	$< 500 \ (r/5)$
jj	$\lesssim 2.5 \text{ pb}$	-	[7]	$< 1300 \ (r/5)$

[1512.04933

 Electroweak gauge invariance suggests (forces) the presence of other decay channels accessible at the LHC

operator
$$\begin{vmatrix} \frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)} & \frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)} & \frac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)} \\ \hline WW \text{ only } & 2/\tan^2\theta_{\mathrm{W}} \approx 7 & 1/\tan^4\theta_{\mathrm{W}} \approx 12 & 2/\sin^4\theta_{\mathrm{W}} \approx 40 \\ BB \text{ only } & 2\tan^2\theta_{\mathrm{W}} \approx 0.6 & \tan^4\theta_{\mathrm{W}} \approx 0.08 & 0 \end{vmatrix}$$

$$g_1^2S \left(\frac{W_{\mu\nu}^2}{2\Lambda_W} + \frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W} \right)$$

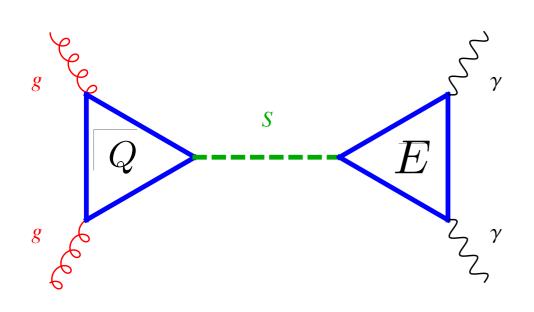
$$g_1^2S \left(\frac{B_{\mu\nu}^2}{2\Lambda_B} + \frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B} \right)$$

• An interesting possibility: S decays into a dark sector

$$-0.3 < \Lambda_B/\Lambda_W, \tilde{\Lambda}_B/\tilde{\Lambda}_W < 2.4$$

Weakly coupled models

• Let's focus on the gg production mechanism, a simple renormalizable picture is given by SM extensions with vector-like fermions



A simple toy model

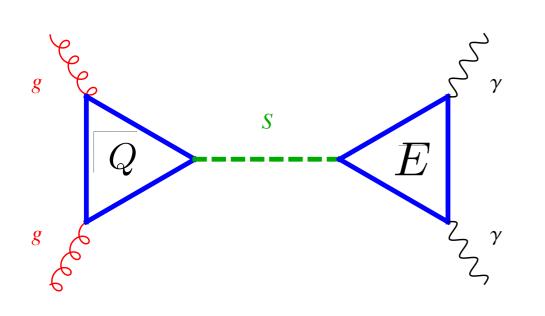
Goertz, Kamenik, Katz, MN 1512.08500 same mechanism in O(100) papers

$$S \sim (\mathbf{1}, \mathbf{1}, 0)$$
 $Q \sim (\mathbf{3}, \mathbf{1}, 0) \times N_Q$
 $E \sim (\mathbf{1}, \mathbf{1}, Y) \times N_E$

$$\mathcal{L} \supset iy_q S \, \overline{Q} \gamma^5 Q + iy_e S \, \overline{E} \gamma^5 E$$

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$$\mathcal{L} \supset iy_q S \, \overline{Q} \gamma^5 Q + iy_e S \, \overline{E} \gamma^5 E$$

A large diphoton rate is required

$$\Gamma(S \to \gamma \gamma) = M \frac{\alpha^2}{16\pi^3} Y^4 N_E^2 y_e^2 \tau_E |\mathcal{P}(\tau_E)|^2$$

$$\tau_E = 4M_E^2/M^2$$

$$M_E \to 400 \text{ GeV}$$

$$T(S \to \gamma \gamma) = 1.1 \cdot 10^{-7} Y^4 y_e^2 N_E^2$$

 $Y^4 y_e^2 N_e^2 \approx 1.5$ for a top-like state

• Large Width $\Gamma_{\gamma\gamma}/M\gtrsim 10^{-4}$ \longrightarrow $Y^4y_e^2N_e^2\gtrsim 10^3$



Calculability in perturbative models

How large can the couplings and/or the number of states be?



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- Other possible issues
 - 1) Landau pole can be very close to the TeV scale
 - 2) Beta function changes very rapidly compared with the coupling itself

$$\mu \frac{d}{d\mu} y = \beta_y \qquad \qquad \mathcal{A} = y + \beta_y \log\left(\frac{\mu}{E}\right)$$
 Possible criterion
$$\left|\frac{\beta_y}{y}\right| < 1$$

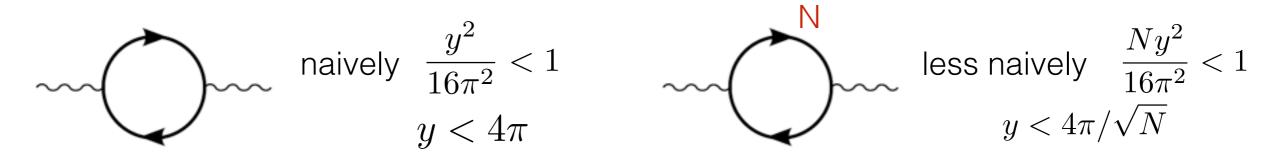
[1512.07624, 1512.08307, 1512.07889, 1512.08500, 1602.01460,,,

- 3) Vacuum stability, new interactions (and new scalars) can modify the scalar potential
- 4) Unitary implications from 2 —> 2 scatterings of mediators

[with L. Di Luzio and J. Kamenik, in preparation]

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 Strong constraints, a large width makes the interpretation of this anomaly in terms of weakly coupled models very challenging

If a single head south Stutypects

Most economical attempt at the renormalizable level: 2 Higgs Doublet Model

s is given by the pling strengths?" though som much duced through $b\bar{t}$ arger.

- Production: directly trough quarks at the tree level
- Decay into photons: trough loops of SM particles
- TREE level decays are available, for example

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{t\bar{t}}} \simeq \frac{2\alpha^2 m_t^2}{27\pi^2 M^2} \left[\pi^2 + 4\log^2(M/m_t)\right]^2 \simeq 10^{-5}$$

see also 1512.04921 1512.05332

1512.05623 1512.06587

1512.07497 1512.07616

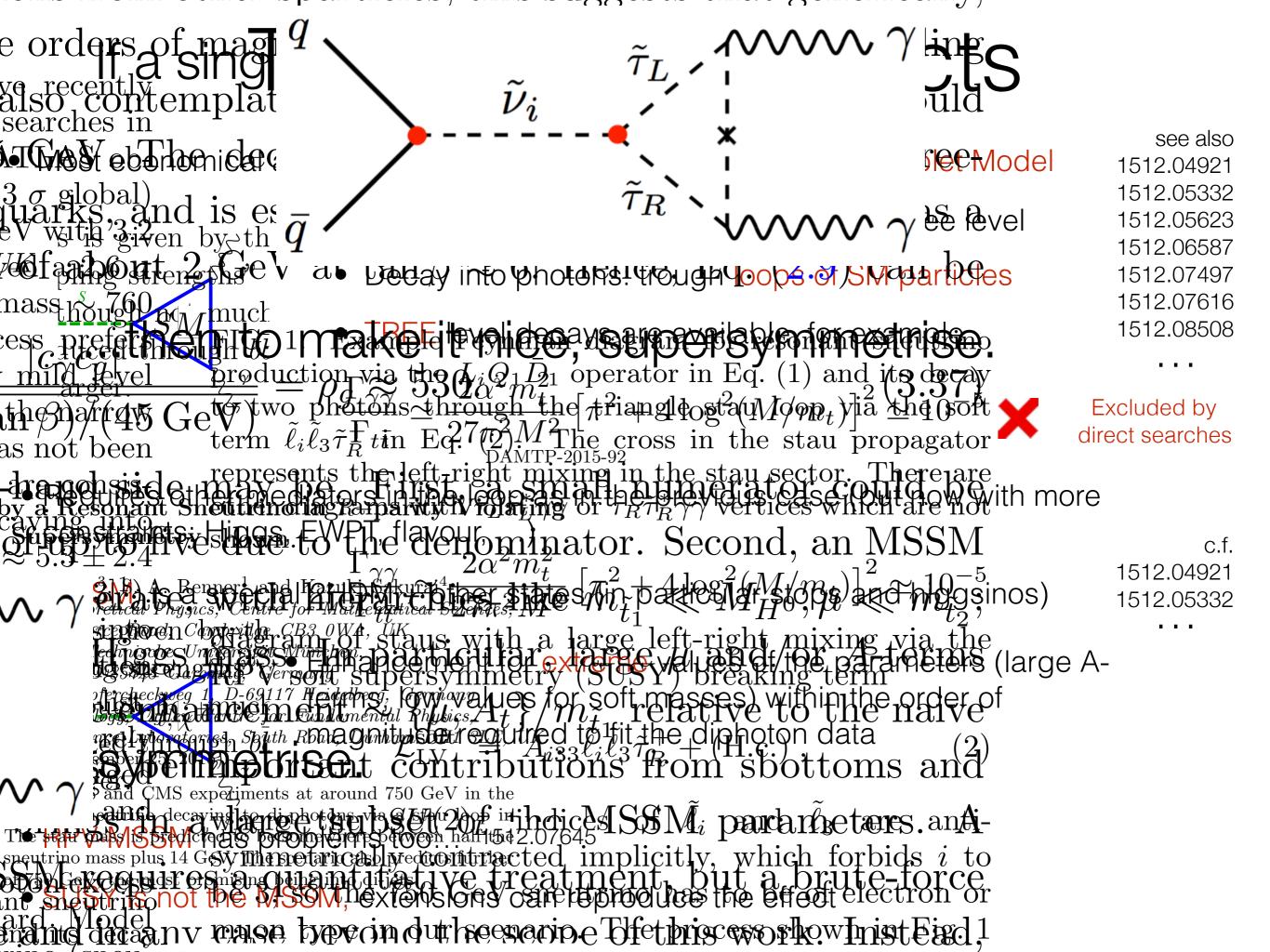
1512.08508

. . .

Excluded by direct searches

 Requires other mediators in the loop as in the previous case (but now with more constraints: Higgs, EWPT, flavour, ...)

constraints: Higgs, EWPT, flavour, ...)
$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{t\bar{t}}}\simeq\frac{2\alpha^2m_t^2}{27\pi^2M^2}\left[\pi^2+4\log^2(M/m_t)\right]^2\simeq 10^{-5}$$



- The 750 GeV state is a composite state of a strongly coupled sector
- Simplest idea: vector-like confinement (not direct connection with the EW breaking)

	$G_H = SU(N)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Ψ_D			1	1/3
Ψ_L		1		-1/2
$ar{\Psi}_D$			1	-1/3
$ar{\Psi}_L$		1		1/2

[From 1602.01092, see also 1512.04850, 1512.04933 1602.07297

SU(N) gauge dynamics similar to QCD

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	$G_H = SU(N)$	$SU(3)_C$	$SU(2)_L$	$U(1)_{Y}$	[From 1602 01002
Ψ_D			1	1/3	[From 1602.01092, see also
Ψ_L		1		-1/2	1512.04850, 1512.04933
$ar{\Psi}_D$			1	-1/3	1602.07297
$ar{\Psi}_L$		1		1/2	J

- SU(N) gauge dynamics similar to QCD
- S is a pseudo-Goldstone boson associated to the breaking of the global symmetry

$$SU(5)_L \times SU(5)_R \to SU(5)_V$$

Extra colored and charged "pions" are predicted

$$\pi \sim (\mathbf{8}, \mathbf{1}, 0) \oplus (\mathbf{3}, \mathbf{2}, -5/6) \oplus (\overline{\mathbf{3}}, \mathbf{2}, +5/6) \oplus (\mathbf{1}, \mathbf{3}, 0) \oplus (\mathbf{1}, \mathbf{1}, 0)$$

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Extra colored and charged "pions" are predicted

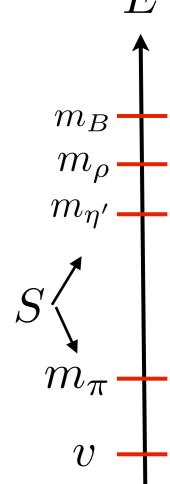
$$\pi \sim (\mathbf{8}, \mathbf{1}, 0) \oplus (\mathbf{3}, \mathbf{2}, -5/6) \oplus (\overline{\mathbf{3}}, \mathbf{2}, +5/6) \oplus (\mathbf{1}, \mathbf{3}, 0) \oplus \oplus (\mathbf{1}, \mathbf{1}, 0)$$

Di-gluon and Di-photon couplings are generated by WZW terms

$$\frac{Ng_3^2}{32\sqrt{15}\pi^2 f} \phi \, \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} - \frac{3Ng_2^2}{64\sqrt{15}\pi^2 f} \phi \, \epsilon^{\mu\nu\rho\sigma} W^{\alpha}_{\mu\nu} W^{\alpha}_{\rho\sigma} - \frac{Ng_1^2}{64\sqrt{15}\pi^2 f} \phi \, \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}$$

ullet Same as in QCD $\pi^0 o \gamma \gamma$

- Other phenomenological aspects of this class of theories:
 - 1) Large coset space contains coloured pseudo-goldstone
 - 2) $f \gtrsim v$, other strongly coupled resonances accessible at the LHC
 - 3) These models are automatically MFV (Minimally Flavour Violating) because of the gauge symmetry
 - 4) Other options can be explored (for example S is associated with an anomalous current like the eta' in QCD) [in particular see 1602.07297]
 - 5) Possible dark matter candidate(s) because of extra symmetries



he TeV scale are mainly motivated One them hickarly consequence of partial compositeness is that nat the Higgs is a composite state. The assemble for the bie and the charge in the call of the SM togangery the first of the weak scale the new distributions and photons is thus an unavoidable section of the control of the same of the otential analyzading sertions and option seems, more likely to descend that minimal technically to describe an aspacts directors in the contraction of the contracti gluons.
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Conclusions

- Experimental situation needs to be clarified, we need more data
- Information on the width is crucial for model building
- We expect to see more decays channels at the LHC, in particular decays into EW gauge bosons
- It is very plausible to have more states at or below the TeV
- Which is the role of S in connection with other open issues of the SM? (Naturalness problem and origin of the EW scale, DM, flavour,)

Backup

Spin 2

A motived candidate: KK graviton from a warped extra-dimension

$$\mathcal{L} \sim \frac{1}{M_{\rm Planck}} T^{\mu\nu} h_{\mu\nu}^{(0)} + \frac{1}{M_{\rm Planck} e^{-kb}} T^{\mu\nu} \sum h_{\mu\nu}^{(m)}$$

- Massless graviton is Plank suppressed, while the KK modes can have a TeV strength
- Couplings are universal, in particular $\Gamma(h_{\mu\nu}^{(1)} \to \gamma\gamma) = \frac{1}{8}\Gamma(h_{\mu\nu}^{(1)} \to gg)$
- Diphoton anomaly can be reproduced but now we have also another prediction

$$\Gamma(h_{\mu\nu}^{(1)} \to \gamma\gamma) = 2\Gamma(h_{\mu\nu}^{(1)} \to \ell^+\ell^-)$$

• At the moment, absence of peaks in di-leptons in Run 2 data

$$\sigma(pp o S o \ell^+\ell^-) < 5 ext{ fb}$$
 [ATLAS-CONF-2015-081] $\sigma(pp o S o \ell^+\ell^-) \lesssim 3 ext{ fb}$ [CMS-EXO-15-004]

- Another candidate: a resonance from a strongly interacting theory, however difficult to motivate the absence of detection of states with lower spin
- Also, away from the energy-tensor limit, scatterings have very bad UV behaviour