Towards a Simultaneous Explanation of the 750 GeV Diphoton Excess, $R_K^{\mu/e}$, and $R_{D^{(*)}}^{\tau/\ell}$

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Genova Seminario
11 febbraio 2016,
based on arXiv:1512.06976

Outline

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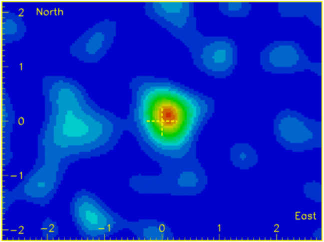
1. Diphoton Excess at the LHC
2. Anomalies in Semileptonic B-meson Decays
3. A Leptoquark Model for the Diphoton Excess and the B-decay Anomalies
4. Summary

A New Era for Particle Physics?

"Who Ordered That?" - I. Rabi

Muon



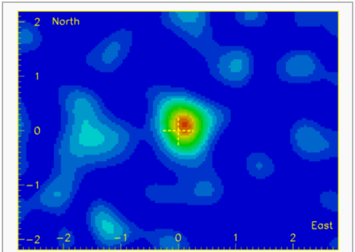
The Moon's cosmic ray shadow, as seen in secondary muons generated by cosmic rays in the atmosphere, and detected 700 meters below ground, at the Soudan II detector

From Wikipedia

A New Era for Particle Physics?

"Who Ordered That?" - I. Rabi

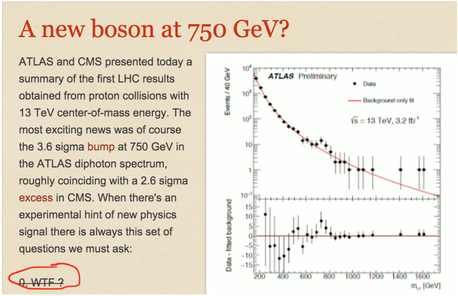
Muon



The Moon's cosmic ray shadow, as seen in secondary muons generated by cosmic rays in the atmosphere, and detected 700 meters below ground, at the Soudan II detector

From Wikipedia

"WTF?" - A. Falkowski



A new boson at 750 GeV?

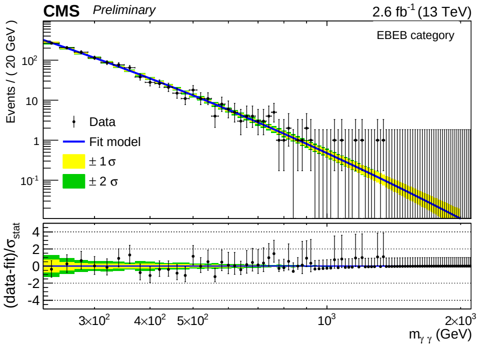
ATLAS and CMS presented today a summary of the first LHC results obtained from proton collisions with 13 TeV center-of-mass energy. The most exciting news was of course the 3.6 sigma bump at 750 GeV in the ATLAS diphoton spectrum, roughly coinciding with a 2.6 sigma excess in CMS. When there's an experimental hint of new physics signal there is always this set of questions we must ask:

0. WTF ?

From Résonaances

Diphoton Excess - CMS

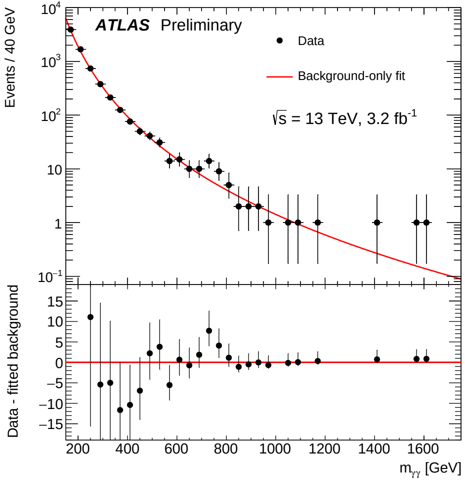
- $2.6\ \sigma$ local excess in Diphotons near $M_X \approx 760$ GeV
- $1.2\ \sigma$ global significance
- assumes narrow width



CMS-PAS-EXO-15-004

Diphoton Excess - ATLAS

- $(3.6 \div 3.9)\ \sigma$ local excess in Diphotons near $M_X \approx 750$ GeV
- $(2.0 \div 2.3)\ \sigma$ global significance
- significance width dependent: (NWA $\div\ \Gamma_X/M_X \approx 6\%$)



ATLAS-CONF-2015-081

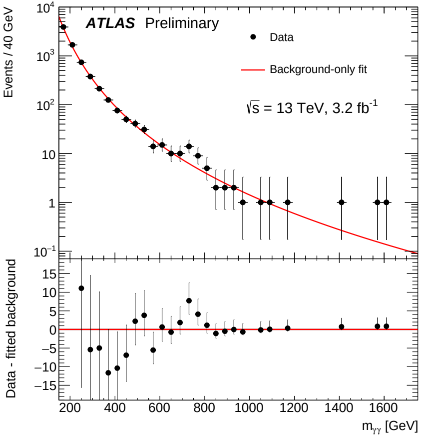
Diphoton Excess - ATLAS

SM Higgs boson w/ $M_h = 750$ GeV:

- $\sigma(pp \to h)\ \mathrm{Br}(h \to \gamma\gamma) = 1.55 \cdot 10^{-4}$ fb
- $\Gamma_h = 247$ GeV

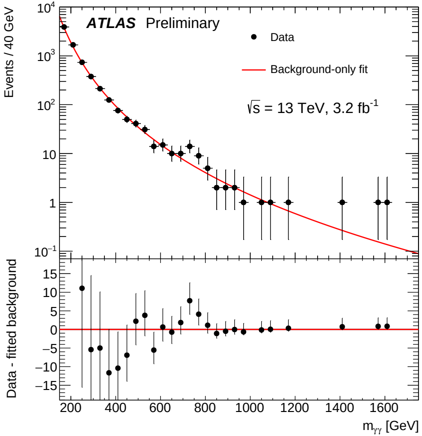
Depending on who you ask:

- $\sigma(pp \to X)\ \mathrm{Br}(X \to \gamma\gamma) = (1 \div 13)$ fb
- 6% width (45 GeV): very important or not important at all

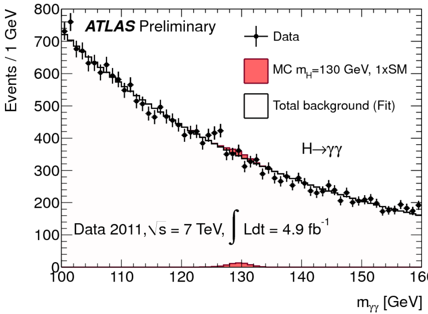


ATLAS-CONF-2015-081

Reminiscent of Another Excess in Diphotons



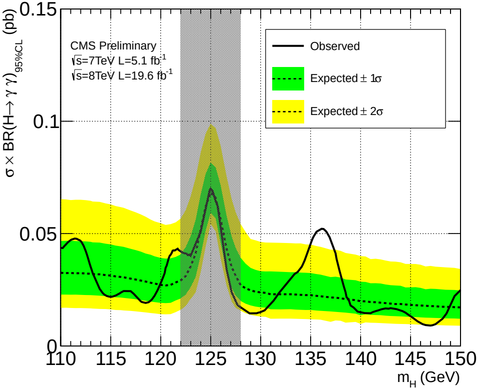
ATLAS-CONF-2015-081



ATLAS-CONF-2011-163

This Has Happened Before

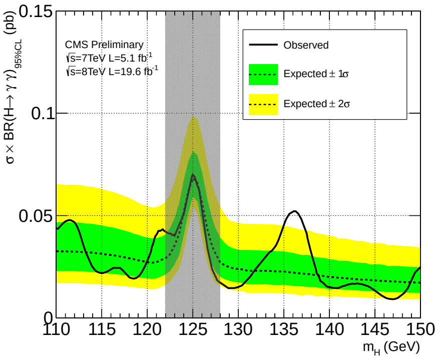
- $2.93\ \sigma$ excess in Diphotons w/ $m_{\gamma\gamma} \approx 136.5$ GeV
- preliminary analysis w/ full Run-1 dataset
- seen in both ggF and VBF
- 125 GeV Higgs boson included in background



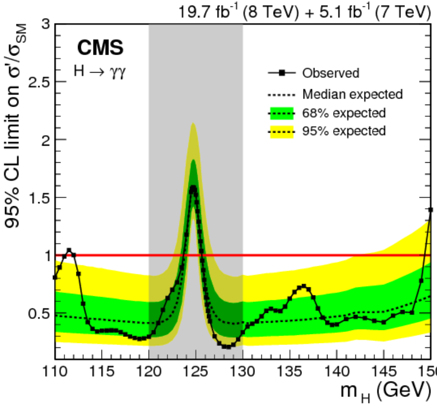
CMS-PAS-HIG-13-016

This Has Happened Before

Excess disappeared in final analysis (w/ same amount of data)!

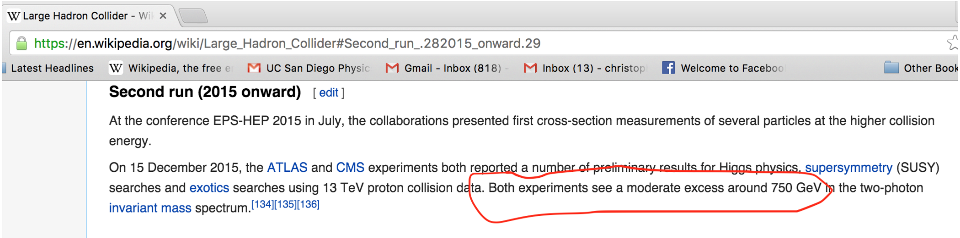


CMS-PAS-HIG-13-016



arXiv:1407.0558

750 GeV Diphoton Excess

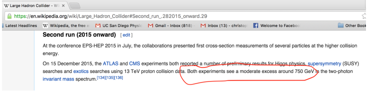


Second run (2015 onward) [edit]

At the conference EPS-HEP 2015 in July, the collaborations presented first cross-section measurements of several particles at the higher collision energy.

On 15 December 2015, the ATLAS and CMS experiments both reported a number of preliminary results for Higgs physics, supersymmetry (SUSY) searches and exotics searches using 13 TeV proton collision data. Both experiments see a moderate excess around 750 GeV in the two-photon invariant mass spectrum.[134][135][136]

750 GeV Diphoton Excess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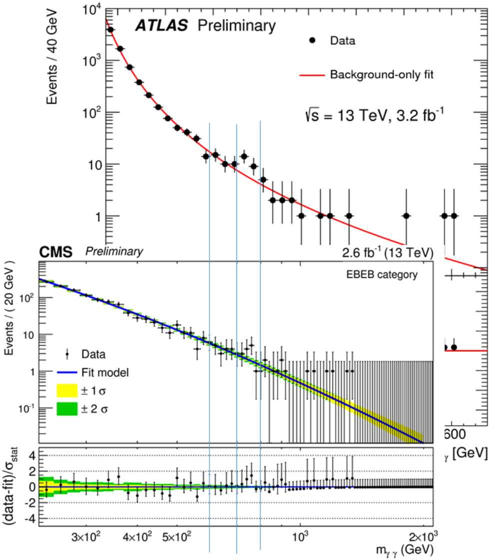
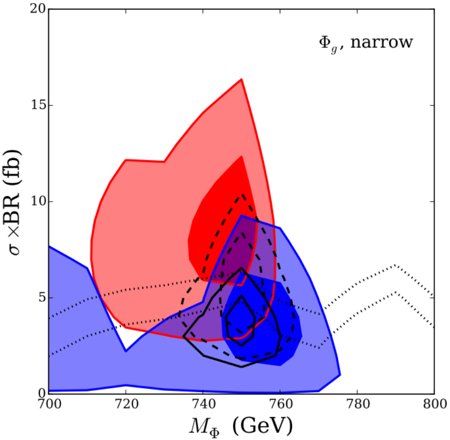
- Both experiments see a moderate excess around 750 GeV
- Figure by M. Strassler



Statistical Combination

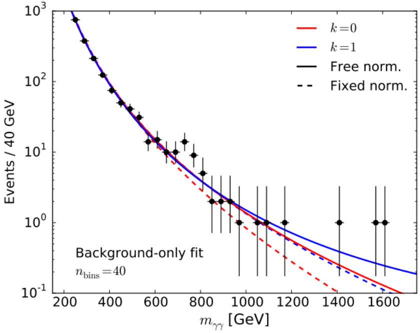
- Plot assumes spin-0, gluon fusion, narrow width
- Combination increases significance, 8 TeV data doesn't decrease significance
- No preference for spin-0 vs. spin-2, narrow vs. wide width



arXiv:1601.04751

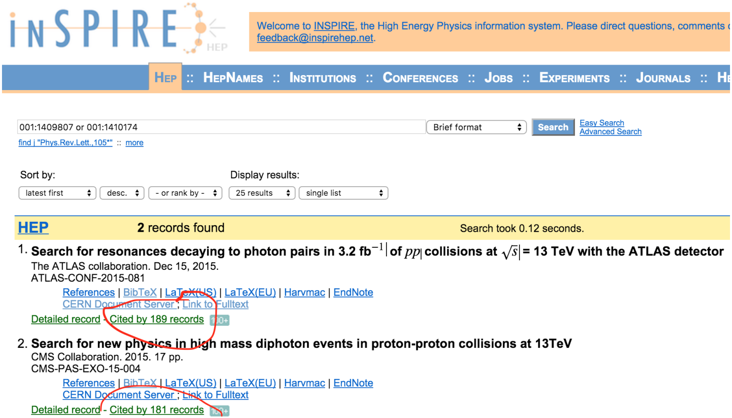
What About The Background?

arXiv:1601.07330:
significance of excess stable w.r.t. choice of background fit function



Background function	NWA	Free-width
Fixed normalisation		
$k=0$	4.2σ	4.9σ
$k=1$	3.4σ	3.7σ
$k=2$	3.4σ	3.7σ
Free normalisation		
$k=0^{\dagger}$	3.4σ	3.6σ
$k=1$	3.5σ	3.8σ
$k=2$	3.4σ	3.6σ
ATLAS reported	3.6σ	3.9σ

The Theoretical Community is Very Excited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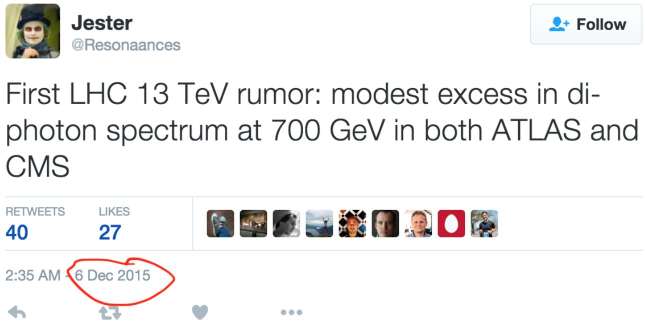
1. **Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector**
The ATLAS collaboration. Dec 15, 2015.
ATLAS-CONF-2015-081
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; Link to Fulltext
Detailed record - Cited by 189 records 100+

2. **Search for new physics in high mass diphoton events in proton-proton collisions at 13TeV**
CMS Collaboration. 2015. 17 pp.
CMS-PAS-EXO-15-004
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; Link to Fulltext
Detailed record - Cited by 181 records 100+

(Experimentalists not so much)

Apparently I Should Get a Twitter Account



An S-Channel Resonance

$$\sigma(pp \to X \to \gamma\gamma) = \frac{2J+1}{M_X s}\left[\sum_i C_{i\bar{i}}\,\Gamma(X \to i\bar{i})\right]\,\mathrm{Br}(X \to \gamma\gamma)$$

$$C_{gg} = \frac{\pi^2}{8}\int_y^1 \frac{dx}{x} g(x) g\left(\frac{y}{x}\right), \quad y = \frac{M_X^2}{s},$$

$$C_{q\bar{q}} = \frac{4\pi^2}{9}\int_y^1 \frac{dx}{x}\,\left[q(x)\bar{q}\left(\frac{y}{x}\right) + \bar{q}(x) q\left(\frac{y}{x}\right)\right]$$

$\sqrt{s}$/ TeV	$C_{\gamma\gamma}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
13	54	15.3	36	83	627	1054	2137
8	11	1.1	2.7	7.2	89	158	174

see e.g. arXiv:1512.06799

An S-Channel Resonance

$$\sigma(pp \to X \to \gamma\gamma) = \frac{2J+1}{M_X s} \left[\sum_i C_{i\bar{i}} \, \Gamma(X \to i\bar{i}) \right] \, \mathrm{Br}(X \to \gamma\gamma)$$

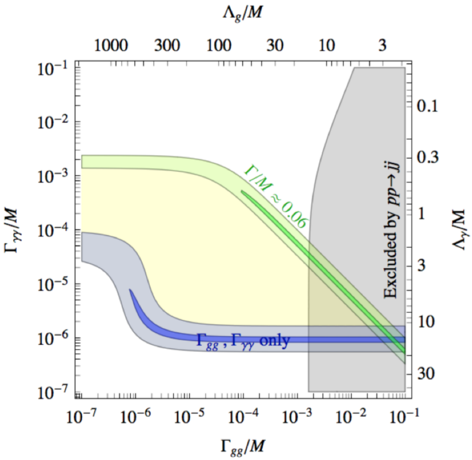
Exotic Possibilities:

- Spin-2 Resonance: $J = 2$
- Multiple Resonances: $\sigma(pp \to \gamma\gamma) = \sum_j \sigma(pp \to X_j \to \gamma\gamma)$

Production through Gluon Fusion

Assume $\sigma(pp \to X \to \gamma\gamma) \approx 8$ fb

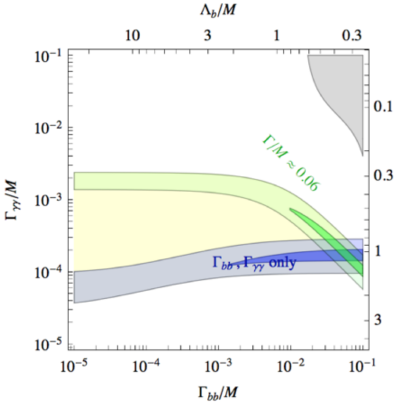
- Gluon Production:
  $\frac{\Gamma_{\gamma\gamma}}{M_X}\frac{\Gamma_{gg}}{M_X} \approx 1.1 \times 10^{-6}\frac{\Gamma_{total}}{M_X}$
- Small Width:
  $\frac{\Gamma(X\to\gamma\gamma)}{M_X} > 10^{-6}$
- 45 GeV Width:
  $\frac{\Gamma(X\to\gamma\gamma)}{M_X} > 10^{-4}$



arXiv:1512.04933

b Production:

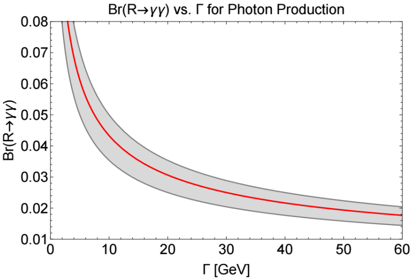
$$\frac{\Gamma_{\gamma\gamma}}{M_X}\frac{\Gamma_{b\bar{b}}}{M_X} \approx 1.9\times10^{-4}\frac{\Gamma_{total}}{M_X}$$



arXiv:1512.04933

γ Production:

$$\sigma(pp\to X\to\gamma\gamma)\approx$$
$$10.8\text{ pb }\left(\frac{\Gamma_{total}}{45\text{ GeV}}\right)\text{ Br}^2(X\to\gamma\gamma)$$



arXiv:1601.00638

What About Other Channels?

- If excess due to BSM physics, can't just be one new particle!
- Size of coupling to SM particles needed would have already been seen in another channel

Final State	95% CL U.L. on $\sigma \times$ BR [fb]	lim. normalized to $\sigma_{\gamma\gamma} = 5 \div 10\,$fb
WW (gluon fusion)	174	$17.4 \div 34.8$
WW (VBF)	70	$7 \div 14$
ZZ (gg prod.)	89	$9 \div 18$
ZZ (VBF prod.)	40	$4 \div 8$
$Z\gamma$	42	$4.2 \div 8.4$
Zh	572	$57 \div 114$
hh	209	$21 \div 42$
bb	10^4	$1 \div 2 \times 10^3$
tt	4.04×10^3	$404 \div 807$
$\tau\tau$ (gg prod.)	56	$6 \div 11$
$\tau\tau$ (assoc. b production)	54	$5.4 \div 10.8$
qq	10^4	$1 \div 2 \times 10^3$
$\ell\ell$	3.5	$0.35 \div 0.7$

arXiv:1512.04928

A Simple Model

Most plausible candidate: scalar resonance coupled to photons and gluons

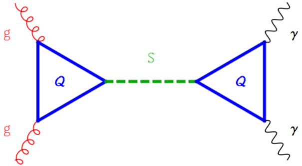


Figure from arXiv:1512.04933

$$\mathcal{L} \supset g_3^2 X \frac{G_{\mu\nu}^2}{2\Lambda_g} + e^2 X \frac{F_{\mu\nu}^2}{2\Lambda_\gamma}$$

$$\Gamma(X \to \gamma\gamma) = \pi\alpha^2 \frac{M_X^3}{\Lambda_\gamma^2}, \quad \Gamma(X \to gg) = 8\pi\alpha_3^2 \frac{M_X^3}{\Lambda_g^2}$$

(analogous formulas for psuedoscalar coupled to $F\tilde{F}$)

$$\frac{M_X}{\Lambda_\gamma}\frac{M_X}{\Lambda_g} \approx 0.037\sqrt{\frac{\Gamma_{total}}{45\text{ GeV}}}$$

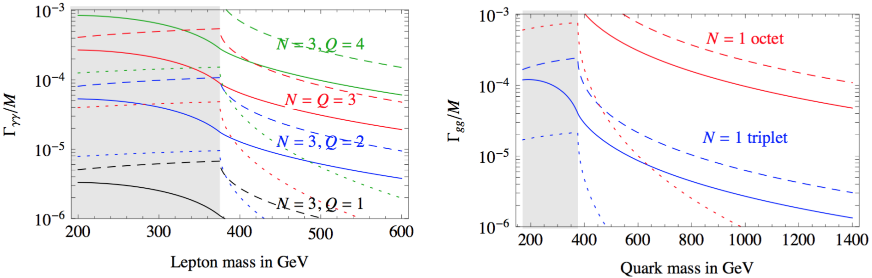
Simple Models

Scalar resonance + vector-like fermions

- $\mathcal{L} \supset -X\bar{f}(y_f + iy_5\gamma_5)f$
- Easy to reproduce signal

$$\frac{\Gamma(X\to\gamma\gamma)}{M_X} \approx 5.4\times10^{-8}\left|\sum d_{r_f} Q_f^2 y_f \frac{M_X}{2m_f}\right|^2,$$

$$\frac{\Gamma(X\to gg)}{M_X} \approx 7.2\times10^{-5}\left|\sum I_{r_f} y_f \frac{M_X}{2m_f}\right|^2$$



arXiv:1512.04933

Models

Compilation by S. Knapen

EW singlets

Buttazzo et. al. 1512.04929
Falkowski et. al. 1512.05777
Raidal et. al. 1512.04939
Gupta et. al. 1512.05332
Craig et. al. 1512.07733
Knapen et. al. 1512.04928
Francescini et. al. : 1512.04933

Falkowski. et. al. 1512.05777
Aloni et. al. : 1512.05778
Trott et. al. 1512.06799
McDermott et. al.1512.05326
Ellis et al. 1512.05327
Benbrik et. al.1512.06028
Low et. al. 1512.05328
...

2HDM's

Altmannshofer et. al. 1512.07616
Becirevic et. al. 1512.05623
Bertuzzo et. al. 1601.07508
Badziak et. al. 1512.07497
Chakrabortty et. al. 1512.05767
Gupta et. al. 1512.05332

Bizot et. al. 1512.08508

Models

Compilation by S. Knapen

Photon fusion

Harland–Lang, et. al: 1601.07187
Martina et. al: 1601.07774
Csaki et. al. :1601.00638
Csaki et. al. :1512.05776

Fichet et. al. : 1512.05751
Fichet et. al. : 1601.01712

Dark matter

Backovic et al. 1512.07992
Bi et al. 1512.06787
Han et al. 1512.04917
Park et al. 1512.08117
D'eramo et al. 1601.01571
Bhattacharya et al. 1601.01569
Huang et al. 1512.08992
Dev et al. 1512.07243
+ many others

Flavor anomalies

Bauer et. al. 1512.06828
Murphy 1512.06976
Bizot et. al 1512.08508

What It Can't Be: Hypercharge Neutral

$SU(2) \times U(1)$ invariant Lagrangian:

$$\mathcal{L} \supset g_3^2 X \frac{G_{\mu\nu}^2}{2\Lambda_g} + g_2^2 X \frac{W_{\mu\nu}^2}{2\Lambda_W} + g_1^2 X \frac{B_{\mu\nu}^2}{2\Lambda_B} + \ldots$$

In concrete models generated by matter w/ SM charges:

operator	$\frac{\Gamma(X \to Z\gamma)}{\Gamma(X \to \gamma\gamma)}$	$\frac{\Gamma(X \to ZZ)}{\Gamma(X \to \gamma\gamma)}$	$\frac{\Gamma(X \to WW)}{\Gamma(X \to \gamma\gamma)}$
WW only	$2/\tan^2\theta_W \approx 7$	$1/\tan^4\theta_W \approx 12$	$2/\sin^4\theta_W \approx 40$
BB only	$2\tan^2\theta_W \approx 0.6$	$\tan^4\theta_W \approx 0.08$	0

see e.g. arXiv:1512.04929, arXiv:1512.04933

What It Can't Be: 2HDM and similar

Claim: any model where all the BSM particles are scalars, and the scalar interactions are all generated by dimension-4 operators, cannot explain the size of the diphoton excess

Ex. 2HDM:

$$\frac{\Gamma(h\to WW)}{\Gamma(h\to WW)_{SM}} = \sin^2(\beta-\alpha), \quad \frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \approx \frac{\cos^2\alpha}{\sin^2\beta}, \quad \frac{\Gamma(h\to b\bar{b})}{\Gamma(h\to b\bar{b})_{SM}} = \frac{\sin^2\alpha}{\cos^2\beta}$$

Alignment limit, $\beta-\alpha \sim \pi/2$, experimentally preferred

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$$g_{HH^+H^-} = -v[Z_3\cos(\beta-\alpha) - Z_7\sin(\beta-\alpha)]$$
$$|Z_7| \leq 8\pi$$

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Theoretical Constraints on Weakly Coupled Models

- Perturbative Unitarity: $|a_0| < 1$, $|\text{Re}(a_0)| < 1/2$,

$$a_0 = \frac{1}{16\pi s} \int_{-s}^{0} dt \, \mathcal{A}(s,t)$$

- BSM theory of scalars, $\mathcal{L} \supset -mX\phi^{Q+}\phi^{Q-} - \lambda(\phi^{Q+}\phi^{Q-})^2$,

$$\mathcal{A}(\phi^{Q+}\phi^{Q+} \to \phi^{Q+}\phi^{Q+}) = -\lambda - m^2 \left(\frac{1}{t - M_X^2} + \frac{1}{u - M_X^2} \right),$$

$$16\pi a_0 = \begin{cases} -\lambda & s \gg M_{X,Q} \\ \frac{2m^2}{M_X^2} \frac{M_X^2 + 2M_Q^2}{M_X^2 + 4M_Q^2} - \lambda & s \to 4M_Q^2 \end{cases}$$

$|m| < (6.2 \div 7.3)$ TeV or $(4.4 \div 5.1)$ TeV

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- BSM theory of scalars, $\mathcal{L} \supset -mX\phi^{Q+}\phi^{Q-} - \lambda(\phi^{Q+}\phi^{Q-})^2$,

$$\mathcal{A}(\phi^{Q+}\phi^{Q+} \to \phi^{Q+}\phi^{Q+}) = -\lambda - m^2\left(\frac{1}{t - M_X^2} + \frac{1}{u - M_X^2}\right),$$

$$16\pi a_0 = \begin{cases} -\lambda & s \gg M_{X,Q} \\ \frac{2m^2}{M_X^2}\frac{M_X^2 + 2M_Q^2}{M_X^2 + 4M_Q^2} - \lambda & s \to 4M_Q^2 \end{cases}$$

$|m| < (6.2 \div 7.3)$ TeV or $(4.4 \div 5.1)$ TeV

Theoretical Constraints on Weakly Coupled Models

- Perturbative Unitarity: $|a_0| < 1$, $|\text{Re}(a_0)| < 1/2$,

$$a_0 = \frac{1}{16\pi s} \int_{-s}^{0} dt\, \mathcal{A}(s,t)$$

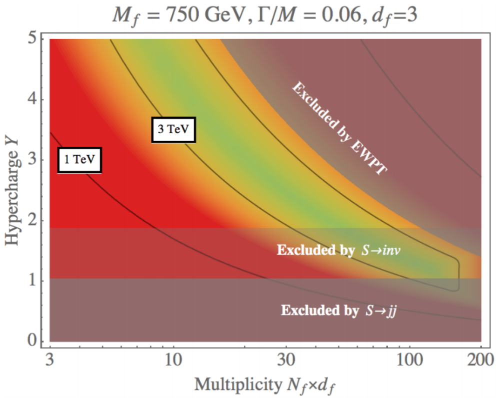
- Scalar and Vectors: $\mathcal{L} \supset \kappa \frac{2M_V^2}{v} X V_\mu^\dagger V^\mu$,

$$\mathcal{A}(V_L V_L \to V_L V_L) \sim \left(\frac{\sqrt{s}}{M_V}\right)^4 \left(\frac{\kappa M_V^2}{v}\right)^2 \frac{1}{s},$$

theory break down around $\sqrt{s} \sim 4\sqrt{\pi} v/|\kappa|$

Theoretical Constraints on Weakly Coupled Models

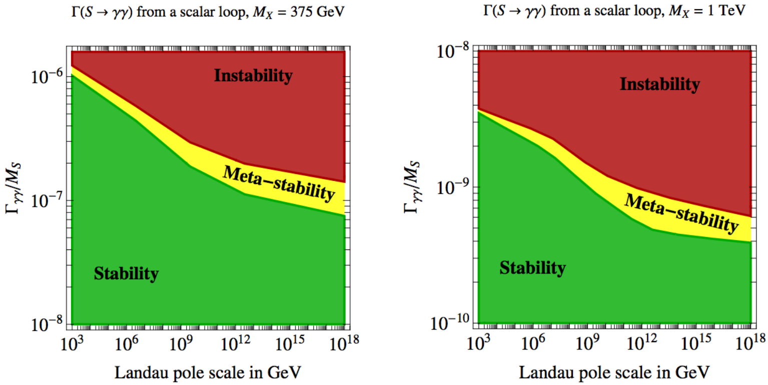
Quartic coupling, large width → large multiplicities, large charges, or large couplings → Landau poles



arXiv:1512.04933

Theoretical Constraints on Weakly Coupled Models

Cubic coupling, if large enough, could destabilize Higgs vacuum

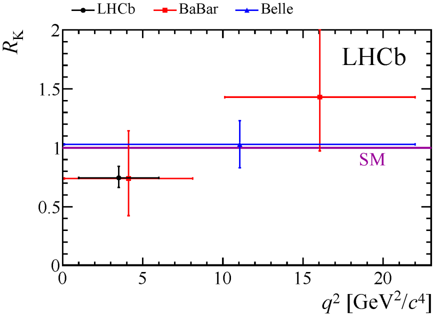


arXiv:1602.01460

Outline

Violations of Lepton Flavor Universality

LHCb: $2.6\ \sigma$ deviation from SM - Experimentally Clean

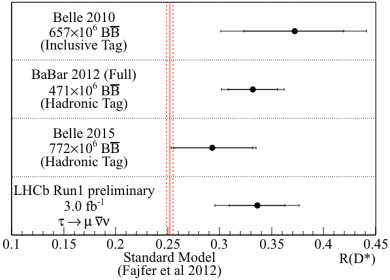


http://lhcb-public.web.cern.ch/lhcb-public/

$$R_K^{\mu/e} = \frac{\mathrm{Br}(B \to K\mu^+\mu^-)}{\mathrm{Br}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Violations of Lepton Flavor Universality

BaBar, Belle, LHCb: combined $3.9\ \sigma$ deviation from SM



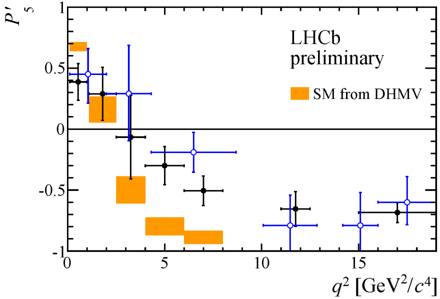
http://lhcb-public.web.cern.ch/lhcb-public/

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\text{Br}(\bar{B} \to D^{(*)}\tau\bar{\nu})/\text{Br}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{SM}}{\text{Br}(\bar{B} \to D^{(*)}\ell\bar{\nu})/\text{Br}(\bar{B} \to D^{(*)}\ell\bar{\nu})_{SM}},$$

$$R^{\tau/\ell}_{D} = 1.37 \pm 0.17,\ R^{\tau/\ell}_{D^*} = 1.28 \pm 0.08$$

Angular Analysis of $B^0 \to K^* \mu^+ \mu^-$

- LHCb: deviation from SM in S_5 and P_5' at low q^2
- Hadronic Uncertainties Important
  - depending on who you ask: $(2 \div 4)\ \sigma$ anomaly
  - LHCb: global fit yields $3.4\ \sigma$ deviation from SM

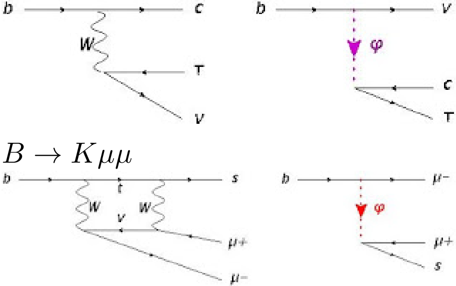


http://lhcb-public.web.cern.ch/lhcb-public/

- Leptoquarks: charged, colored, spin-0 or spin-1 bosons
- (Z' also proposed)
- See e.g. arXiv:1505.05164, arXiv:1506.01705, arXiv:1512.01560
- Symmetry arguments lead to Minimal Flavor Violation

$B \to D\tau\nu$

$B \to K\mu\mu$



Figures by A. Falkowski

$$\mathcal{L}_V = (V^{\mu}_{-2/3})^{\dagger}(D^2 + M_V^2)(V_{-2/3})_{\mu} + (g_{\ell q}\bar{\ell}_L\gamma_{\mu}q_L + g_{ed}\bar{e}_R\gamma_{\mu}d_R)V^{\mu}_{-2/3} + \text{h.c}$$

Outline

The Model

Model: SM + Scalar Singlet (ϕ) + Vector Leptoquarks (V_μ)

- Minimal extension of model for B-decay anomalies, no new fermions
- $\mathcal{L} \supset \kappa \frac{2M_V^2}{v} \phi V_\mu^\dagger V^\mu$, $\kappa \sim 0.1 \div 0.3$, $M_V \sim 1$ TeV
- Scalar leptoquarks and diphoton excess: arXiv:1512.06828, arXiv:1601.02457, arXiv:1601.03267

$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	J_μ
$\bar{3}$	1	$-2/3$	$\bar{\ell}_L \gamma_\mu q_L$, $\bar{e}_R \gamma_\mu d_R$
$\bar{3}$	3	$-2/3$	$\bar{\ell}_L \gamma_\mu q_L$
$\bar{3}$	2	$5/6$	$\bar{\ell}_L^c \gamma_\mu d_R$, $\bar{e}_R^c \gamma_\mu q_L$
$\bar{3}$	1	$-5/3$	$\bar{e}_R \gamma_\mu u_R$
$\bar{3}$	2	$-1/6$	$\bar{\ell}_L^c \gamma_\mu u_R$

The Model

- Mixing with the Higgs,

$$\begin{pmatrix} \phi \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} X \\ h \end{pmatrix},$$

- leads to tree level decay rates,

$$\frac{\Gamma(X \to f\bar{f}, VV)}{\Gamma(X \to f\bar{f}, VV)_{SM}} = \sin^2\alpha, \quad \frac{\Gamma(h \to f\bar{f}, VV)}{\Gamma(h \to f\bar{f}, VV)_{SM}} = \cos^2\alpha.$$

The Model

- Interaction with leptoquarks,

$$\mathcal{L} \supset \cos\alpha\kappa\frac{2M_V^2}{v}XV_\mu^\dagger V^\mu,$$

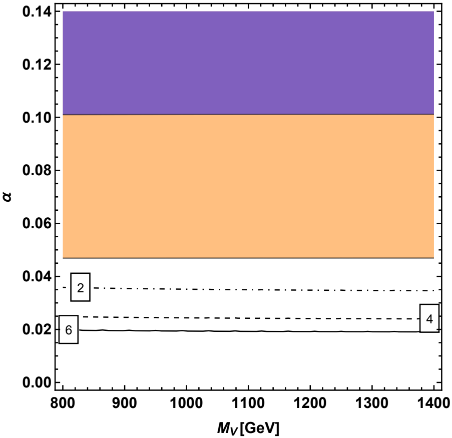
- leads to loop level decay rates,

$$\frac{\Gamma(X\to gg)}{\Gamma(X\to gg)_{SM}} = \left|\sin\alpha + \cos\alpha\frac{\kappa A_1(\tau_V)}{A_{1/2}(\tau_t)+A_{1/2}(\tau_b)}\right|^2,$$

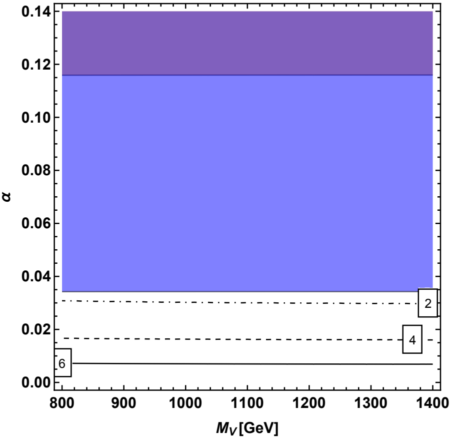
$$\frac{\Gamma(X\to \gamma\gamma)}{\Gamma(X\to \gamma\gamma)_{SM}} = \left|\sin\alpha + \cos\alpha\frac{N_{CV}Q_V^2\kappa A_1(\tau_V)}{\sum_f N_{Cf}Q_f^2 A_{1/2}(\tau_f)+A_1(\tau_W)}\right|^2.$$

Viable Parameter Space

Measurements of the 125 GeV Higgs boson



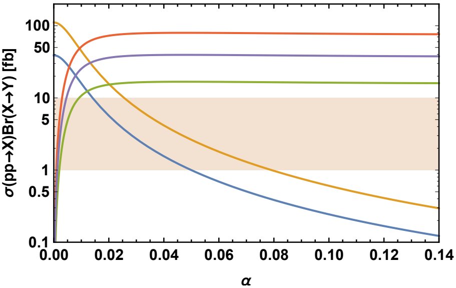
$V \sim (\bar{3}, 3)_{-2/3}$, $\kappa = 0.10$



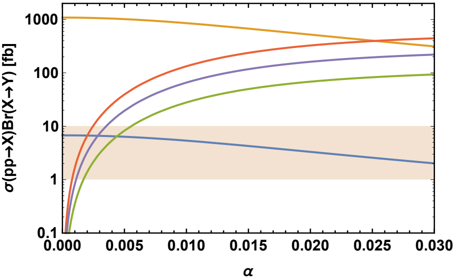
$V \sim (\bar{3}, 1)_{-2/3}$, $\kappa = 0.27$

Viable Parameter Space

Searches for resonances in other final states



$V \sim (\bar{3}, 3)_{-2/3}$, $\kappa = 0.10$



$V \sim (\bar{3}, 1)_{-2/3}$, $\kappa = 0.27$

Outline

Summary

- More data is needed, but the Diphoton Excess would be an amazing discovery if comfirmed
- First step towards a unified explanation of Diphoton Excess and B-decay Anomalies
- Found parameter space that gives the correct cross section for 750 GeV resonance decaying to photons, consistent with
  - unitarity
  - measurements of the 125 GeV Higgs boson
  - direct searches for resonances in other channels