The 750 GeV Resonance at LHC and HEP Christmas

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-
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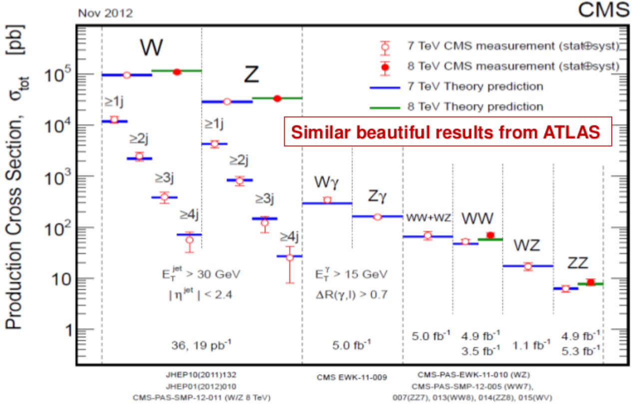
1. The winter of our "discontent"
2. Profile of the suspected 750 Resonance
3. Theory I (Models for all)
4. Theory II : (N+1) HDM with LFV Higgs, DM and 750 Resonance
5. Conclusions.

1.0 From the Higgs "extasis" ...

To the SM domain

A summary of Standard Model measurements

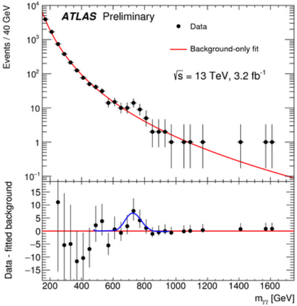


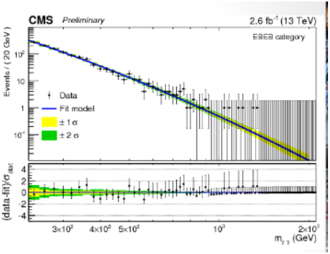
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

CERN, 20-Nov-2012
P Jenni (CERN) LHC experiments and results 72

And now a 750 GeV resonance shows up at LHC13 ?

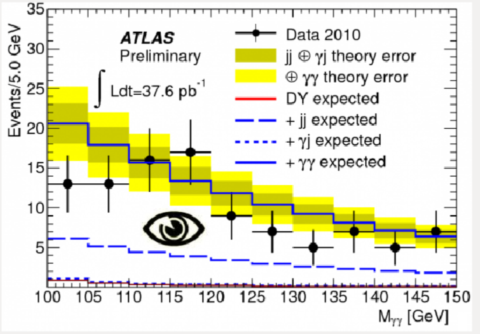
A possible new particle with mass $m_X = 750$ GeV has been reported both by CMS and ATLAS from run2 data (13 TeV) in the di-photon channel:

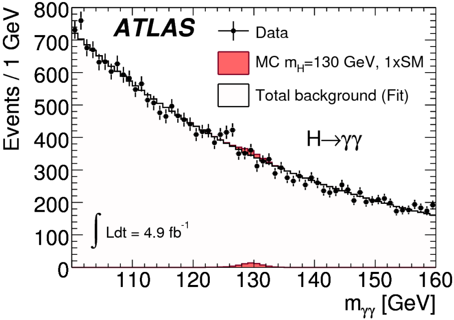




With 3.2 fb^1 ATLAS: 3.6σ (local) $\rightarrow$ 2.3σ (after LEE),
With 2.6 fb^1 CMS: 2.6σ (local) $\rightarrow$ 2.0σ (after LEE),

New physics or a statistical fluctuation?



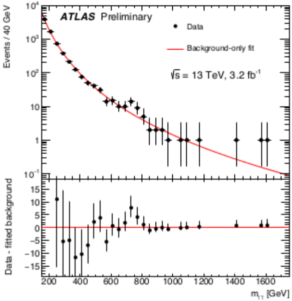


(Not to mention a 145 GeV Higgs signal from Atlas too)

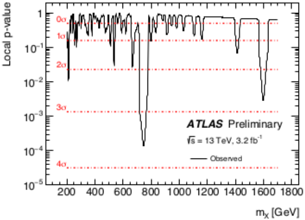
3.0 Profile of the suspected resonance - ATLAS

Search for a **Two Photons Resonance** (II)

Results: Events with mass in excess of 200 GeV are included in **unbinned fit**



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV
- Taking a LEE in a mass range (fixed before unblinding) **of 200 GeV to 2.0 TeV** the global significance of the excess is **2.0σ**



In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV
(Approx. 6% of the best fit mass of approximately 750 GeV)

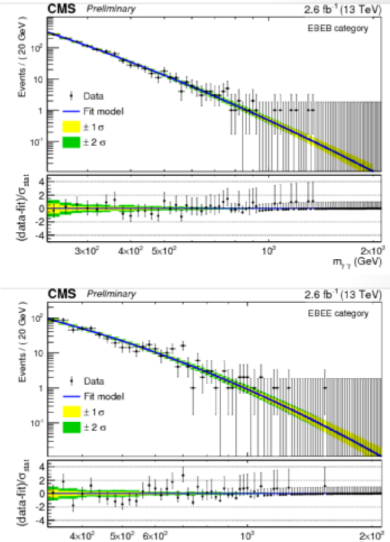
- As expected the local significance increases to **3.9σ**
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

Profile of the suspected resonance - CMS

EXO-15-004

Search for diphoton resonances

- Two categories: barrel-barrel (EBEB), barrel-endcap (EBEE)
- $p_T(\gamma) > 75$ GeV, $I_{ch} < 5$ GeV (in 0.3 cone around photon direction)
- Efficiency, scale and resolution calibrated on $Z \rightarrow ee$ and high-mass DY events
- Search for RS graviton with three assumptions on coupling: $\tilde{\kappa} = 0.01$ (narrow), 0.1, 0.2 (wide)
- **Blind analysis, no changes have been made to the analysis since unblinding data in the signal region**



Number of events for Atlas and CMS

ATLAS finds an excess of events with invariant mass of 750 GeV:

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

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_{events} (EBEE)	16	4	1	6	2	3
$N_{\text{background}}$ (EBEE)	5.2	4.6	4.0	3.5	3.1	2.8

while CMS events are peaked at 760 GeV[1].

[1] Tables from Jester arXive:1512.05777 [hep-ph]

Summary of 750 GeV resonance data [2]

- ATLAS excess of about 14 events (with selection efficiency 0.4) appear in at least two energy bins, suggesting a width of about 45 GeV (i.e. $\Gamma/M \simeq 0.06$),
- For CMS best fit has a narrow width, while assuming a large width ($\Gamma/M \simeq 0.06$), decreases the significance, which corresponds to a cross section of about 6 fb.
- The anomalous events are not accompanied by significant missing energy, nor leptons or jets. No resonances at invariant mass 750 GeV are seen in the new data in ZZ, W+ W- , or jj events.
- No $\gamma\gamma$ resonances were seen in Run 1 data at s = 8 TeV, altought both CMS and ATLAS data showed a mild upward fluctuation at $m_{\gamma\gamma} = 750$ GeV.
- The data at s = 8 and 13 TeV are compatible at 2σ if the signal cross section grows by at least a factor of 5.

[2] Giudice et al, arXive: 1512.05332 [hep-ph]

Production of S resonance at LHC

Resonant process $pp \to S \to \gamma\gamma$:

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{Ms\Gamma}[C_{gg}\Gamma(S \to gg) + C_{qq}\Gamma(S \to qq)]\Gamma(S \to \gamma\gamma)$$

- S is a new uncoloured boson with mass M , spin J, and total width Γ, coupled to partons in the proton, with proton c.of.m. energy s,
- Resonance S could be an scalar (spin=0) or tensor (spin=2),
- For a spin-0 resonance produced from gluon fusion and decays into two photons, the signal rate is reproduced for $\frac{\Gamma_{\gamma\gamma}\Gamma_{gg}}{MM} \simeq 1.1 \times 10^{-6}\frac{\Gamma}{M} \simeq 6 \times 10^{-8}$,
- When resonance S is produced from bottom quark annihilation, the signal is reproduced for $\frac{\Gamma_{\gamma\gamma}\Gamma_{bb}}{MM} \simeq 1.9 \times 10^{-4}\frac{\Gamma}{M} \simeq 1.1 \times 10^{-5}$,

Parton luminosity run1 $\to$ run2

Their numerical values, computed for a resonance at $M = 750\,\mathrm{GeV}$ using the MST
set of pdfs evaluated at the scale $\mu = M$, are:

$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

Thus, the gain factors $r = \sigma_{13\,\mathrm{TeV}}/\sigma_{8\,\mathrm{TeV}} = [C_{gg}/s]_{13\,\mathrm{TeV}}/[C_{gg}/s]_{8\,\mathrm{TeV}}$ from 8 to 13

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

A quick profile of the 750 resonance

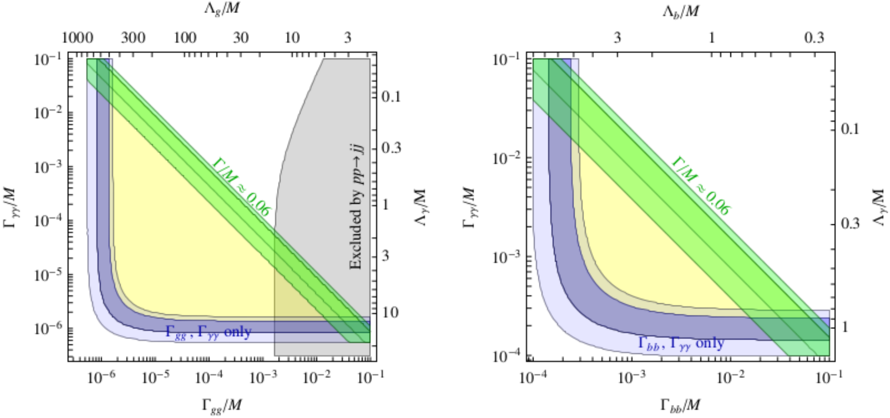
Assume the new particle S couples with photons, gluons and heavy quarks through the effective lagrangian:

$$\mathcal{L} = g_s^2(\frac{S}{2\Lambda_g}G^{a\mu\nu}G^a_{\mu\nu} + d.t.) + e^2(\frac{S}{2\Lambda_\gamma}F^{\mu\nu}F_{\mu\nu} + d.t.) + \frac{S}{\Lambda_b}Q_L^3 H D_R^3 \quad (1)$$

Then:

$$\begin{aligned} \Gamma(S \to gg) &= \pi\alpha^2 M(\frac{M^2}{\Lambda_\gamma} + d.t.) \\ \Gamma(S \to \gamma\gamma) &= 8\pi{\alpha_s}^2 M(\frac{M^2}{\Lambda_g} + d.t.) \\ \Gamma(S \to bb) &= \frac{3M}{8\pi}(\frac{v^2}{\Lambda_b}) \end{aligned}$$

A quick profile of the 750 resonance



Model Classification

- General Approach / Effective Lagrangian,
- Multi-particle models (2HDM, SUSY, extra fermions, LR, etc),
- Composite Higgs models,
- Exotics (Axions, KK gravitons, dilaton, low unification, etc)

General Approach / Effective Lagrangian

A. Djouadi, J. Ellis, R. Godbole and J. Quevillon, "Future Collider Signatures of the Possible 750 GeV State," arXiv:1601.03696 [hep-ph]. J.H. Davis, M. Fairbairn, J. Heal and P. Tunney, "The Significance of the 750 GeV Fluctuation in the ATLAS Run 2 Diphoton Data," arXiv:1601.03153 [hep-ph]. M. Fabbrichesi and A.Urbano, "The breaking of the $SU(2)_L \times U(1)_Y$ symmetry: The 750 GeV resonance at the LHC and perturbative unitarity," arXiv:1601.02447 [hep-ph].
....
R.S.Gupta, S.Jager, Y.Kats, G.Perez and E.Stamou,"Interpreting a 750 GeV Diphoton Resonance," arXiv:1512.05332 [hep-ph]. [134 citas] J.Ellis, S.A.R. Ellis, J.Quevillon, V.Sanz and T.You,"On the Interpretation of a Possible ~ 750 GeV Particle Decaying into $\gamma\gamma$," arXiv:1512.05327 [hep-ph]. [135 citas] R.Franceschini *et al.*, "What is the gamma gamma resonance at 750 GeV?," arXiv:1512.04933 [hep-ph]. [158 citas]

Multi-particle models (2HDM, SUSY, extra fermions, LR, etc),

Bertuzzo, P. Machado and M.Taoso, "Di-Photon excess in the 2HDM: hasting towards the instability and the non-perturbative regime," arXiv:1601.07508 [hep-ph]. T.Nomura and H.Okada,"Generalized Zee-Babu model with 750 GeV Diphoton Resonance," arXiv:1601.07339 [hep-ph]. J. Kawamura and Y. Omura, "Diphoton excess at 750 GeV and LHC constraints in models with vector-like particles," arXiv:1601.07396 [hep-ph]. S.F. King and R.Nevzorov,"750 GeV Diphoton Resonance from Singlets in an Exceptional Supersymmetric Standard Model," arXiv:1601.07242 [hep-ph]. C.W.Chiang and A.L.Kuo,"750-GeV Diphoton Resonance as the Singlet of Custodial Higgs Triplet Model," arXiv:1601.06394 [hep-ph]. Q.H.Cao, Y.Q.Gong, X.Wang, B.Yan and L.L.Yang,"One Bump or Two Peaks? The 750 GeV Diphoton Excess and Dark Matter with a Complex Mediator," arXiv:1601.06374 [hep-ph]. H. Okada and K. Yagyu, "Renormalizable Model for Neutrino Mass, Dark Matter, Muon $g-2$ and 750 GeV Diphoton Excess," arXiv:1601.05038 [hep-ph]. X.F. Han, L. Wang and J.M. Yang, "An extension of two-Higgs-doublet model and the excesses of 750 GeV diphoton, muon g-2 and $h \to \mu\tau$," arXiv:1601.04954 [hep-ph]. W. Chao, "The Diphoton Excess Inspired Electroweak Baryogenesis," arXiv:1601.04678 [hep-ph] T. Nomura and H. Okada,"Four-loop Radiative Seesaw Model with 750 GeV Diphoton Resonance," arXiv:1601.04516 [hep-ph]. A.E. Faraggi and J.Rizos, "The 750 GeV diphoton LHC excess and Extra Z's in Heterotic-String Derived Models," arXiv:1601.03604 [hep-ph]. I. Dorsner, S. Fajfer and N. Kosnik,"Is symmetry breaking of SU(5) theory responsible for the diphoton excess?," arXiv:1601.03267 [hep-ph]. C. Hati, "Explaining the diphoton excess in Alternative Left-Right Symmetric Model," arXiv:1601.02457 [hep-ph].

Composite Higgs models,

D.B.Franzosi and M.T.Frandsen, "Symmetries and composite dynamics for the 750 GeV diphoton excess," arXiv:1601.05357 [hep-ph].

.....

R.Franceschini *et al.*, "What is the gamma gamma resonance at 750 GeV?," arXiv:1512.04933 [hep-ph]. [158 citas]

Exotics (Axions, KK gravitons, dilaton, low unification, etc)

Ben-Dayan and R. Brustein, “Hypercharge Axion and the Diphoton 750 GeV Resonance,” arXiv:1601.07564 [hep-ph]. C.Q.Geng and D. Huang, “Note on Spin-2 Particle Interpretation of the 750 GeV Diphoton Excess,” arXiv:1601.07385 [hep-ph]. S. Abel and V. V. Khoze, “Photo-production of a 750 GeV di-photon resonance mediated by Kaluza-Klein leptons in the loop,” arXiv:1601.07167 [hep-ph]. U. Aydemir and T. Mandal, “Interpretation of the 750 GeV diphoton excess with colored scalars in $SO(10)$ grand unification,” arXiv:1601.06761 [hep-ph]. A.Martini, K.Mawatari and D.Sengupta,“Diphoton excess in phenomenological spin-2 resonance scenarios,” arXiv:1601.05729 [hep-ph]. A.Ghoshal, “On Electroweak Phase Transition and Di-photon Excess with a 750 GeV Scalar Resonance,” arXiv:1601.04291 [hep-ph]. J. H. Yu, “Hidden Gauged U(1) Model: Unifying Scotogenic Neutrino and Flavor Dark Matter,” arXiv:1601.02609 [hep-ph]. ....
M.Backovic, A.Mariotti and D.Redigolo,“Di-photon excess illuminates Dark Matter,” arXiv:1512.04917 [hep-ph]. [132 citas]

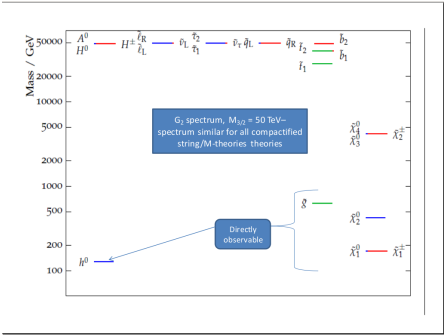
The 750 resonance in weakly coupled models

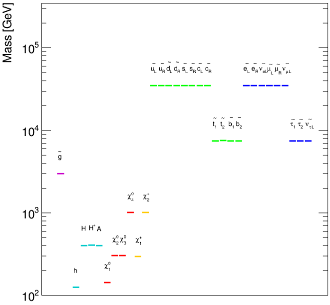
- Extended the SM by adding one (or more) scalar S and extra vector-like fermions Q f (or scalars) with mass M_f , hypercharge Y_f , charge Q_f and in the colour representation r_f , with the Yukawa coupling Y_f,
- Then the partial widths should lie in the neighbourhood of $\Gamma(S \to \gamma\gamma)/M \simeq 10^{-6}$ and $\Gamma(S \to gg)/M \simeq 10^{-3} - 10^{-6}$.
- Such widths can be easily achieved with with order one electric charges and conventional colour reps. For example, a heavy quark triplet with charge Q gives $\Gamma(S \to gg)/\Gamma(S \to \gamma\gamma) \simeq 36/Q^4$, which equals $\simeq 3000$ for Q $= 1/3$.
- Any ratio of $\Gamma(S \to gg)/\Gamma(S \to \gamma\gamma)$ can be obtained by including the appropriate content of heavy leptons and quarks with different masses.
- $Q > 5/3$ are strongly constrained by same-sign dilepton searches and the lower limit on their mass is of order 1 TeV, depending on Q.

The 750 resonance in weakly coupled models

- These weakly-coupled models can reproduce easily the event rates, however they face a challenge to reproduce the total width,
- The typical expression for a tree-level decay width is $\Gamma/M \simeq y^2/4\pi$; so the relatively large total width can be reproduced through a tree-level decay if the relevant coupling y is of order one (beyond pert.?).
- Other solution with many more states gets too barroque...
- one possibility; work within 2HDM ($\rightarrow h, H, A, H^+$), then it is possible that $m_H \simeq m_A$, and the large width is because there are two particles being produced,
- The data can not be reproduced with the simplest 2HDM,
- The data can no be reproduced within the minimal MSSM, but it does in extensions with extra quarks or NMSSM,

What about predictions for Heavy Higgses?





Heavy Higgses with $M \leq$ O(TeV) were "predicted" in Slim SUSY (Diaz-Cruz et al)

BSM with Multi-Higgs models

- The lack of understanding for the SM structure (Parameters, gauge unification, DM, BAU, etc) have motivated the search for extensions of the SM where such problmes could be adressed,
- We know now that nature likes scalars, so may be more will be detected at LHC or future colliders,
- In particular, models with an extended Higgs sector have been studied considerably for several reasons (Hierarchy problem, SUSY, Composite Higgs, Flavor, DM)
- Here, we would like to explore model with extended Higgs sector that includes:

  - N active Higgs doublets + 1 inert-type Higgs doublet + 1 singlet of FN type
- And would like to see if such model can accomodate: LFV Higgs anomaly, Dark matter constraints and the heavy resonance with $m_h = 750$ GeV observed recently at LHC,

The answer is yes ...

2.0 SM Higgs Review

- SSB occurs in the SM through a Higgs doublet (Minimal SM) i.e. $\Phi = (\phi^+, \phi^0)$,
- The neutral scalar component gets a v.e.v.: $\phi^0 \to <\phi^0> = v$, which leads to : $SU(2)_L \times U(1)_Y \to U(1)_{em}$,
- Gauge bosons masses are generated, $M_V = \frac{1}{4} g^2 v^2$,
- Fermion masses also arise from SSB:

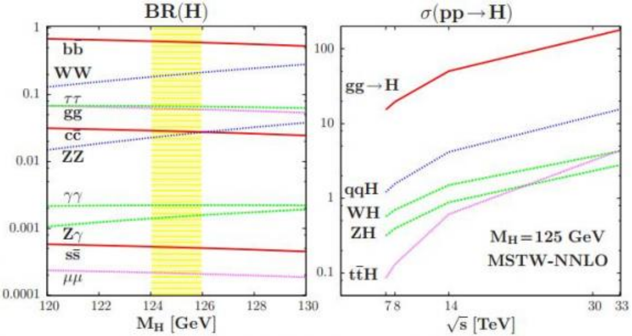
$$m_f = v\, y_f \ , \qquad g_{hff} = y_f$$

- The essential feature of the SM Higgs is that it couples proportional to the masses of the particles,

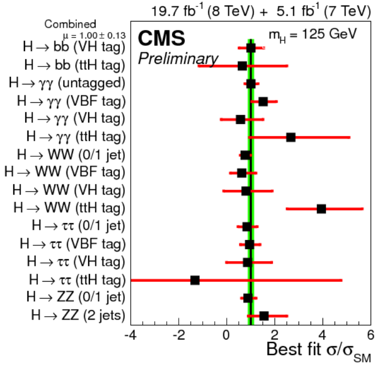
$$(hVV): \quad \frac{2m_V^2}{v}, \qquad\qquad (hff): \quad \frac{m_f}{v}$$

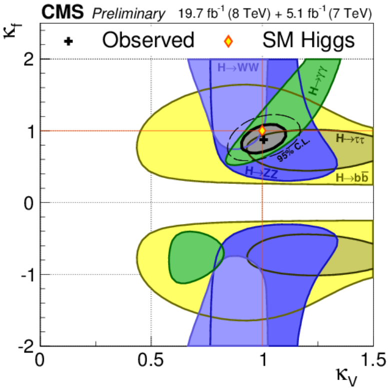
$$(hhh): \quad \frac{3}{2}\lambda v, \qquad\qquad (hhhh): \quad \frac{3}{2}\lambda$$

SM Higgs Decays and production



2.1 Higgs couplings from LHC

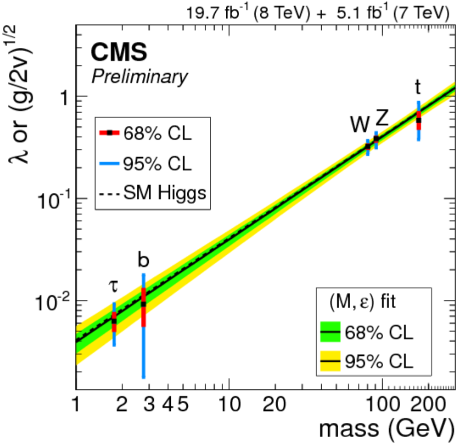


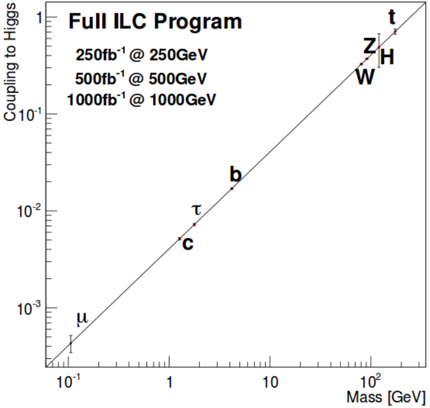


$$g_{hVV} = \kappa_V g_{hVV}^{sm}, \quad g_{hff} = \kappa_F g_{hff}^{sm},$$

The Higgs identity from LHC:

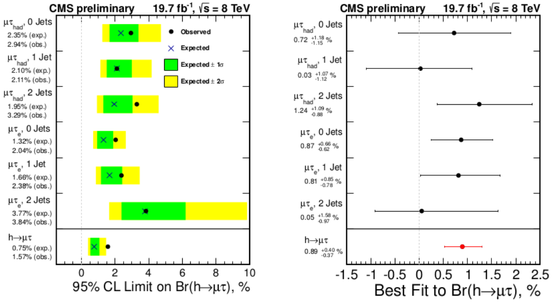
The couplings of the Higgs with particles, as a function of the mass, lays on a single line, which as been tested at LHC, i.e.





LFV Higgs decays

Very recently CMS (LHC) have found an small B.R. for LFV Higgs decay, with $B.R.(h \to \tau\mu) \simeq 10^{-2}$,



- LFV Higgs decays $h \to l_i l_j$ were first studied by Pilaftsis (PLB92),
- Diaz-Cruz and Toscano (PRD2000) focus on $h \to \tau\mu$ within eff. Lagr. , 2HDM (with $B.R.(h \to \tau\mu) \simeq 10^{-2} - 10^{-3}$),
- For SUSY (MSSM): $B.R.(h \to \tau\mu) \simeq 10^{-5}$ (Diaz-Cruz, JHEP2003),

A 3+1 Higgs doublets model with LFV, DM and 750 resonance

So, I want to build a model where:

1. up-, down- and lepton masses como from a different doublet,
2. Flavor violation is allowed at consistent rates with FCNC phenomenology,
3. It includes a dark matter candidate (IDM),
4. And it also reproduce the 750 GeV resonance,

Could it be done? I think so....

Construction of a 3+1 Higgs doublets model

- To study possible deviations from the SM Higgs couplings, we shall work with a 3+1 - Higgs doublet model (Φ_1, Φ_2, Φ_3 and Φ_0)
- The Higgs doublets only couple to one fermion type each, and thus do not induce FCNC,

  $\Phi_1 \to$ up-, $\Phi_2 \to$ down- and $\Phi_3 \to$ l,
- The model also includes one Froggart-Nielsen singlet (S) , which works to reproduce the fermion masses and CKM,
- Through Higgs-Flavon mixing, it is possible to induce Flavor Violating interactions for the Higgs boson(s),
- Φ_0 is odd under a discrete symmetry, and therefore its ligthest state is stable and a possible DM candidate,

The FN Mechanism I

- Under Abelian Flavor symmetry ($U(1)_F$), charges of LH-fermion doublet F_i, RH- fermion singlets f_j, and the Higgs doublets Φ_a, add to $n_{ij} \neq 0$, thus Yukawa couplings are forbidden,
- Flavon field S is assumed to have flavor charge equal to -1,
- Thus, Model includes non-renormalizable operators of the type:

$$\mathcal{L}_{eff} = \alpha^a_{ij}(\frac{S}{M_F})^{n_{ij}} \bar{F}_i f_j \tilde{\Phi}_a + h.c. \qquad (2)$$

which is $U(1)_F$-invariant.

- Then, Yukawa matrices arise after the spontaneous breaking of the flavor symmetry, i.e. with vev $< S >= u$,
- The entries of Yukawa mattrices are given by $Y^f_{ij} \simeq (\frac{u}{M_F})^{n^f_{ij}}$.
- The scale M_F represents the mass of heavy fields that transmit such symmetry breaking to the quarks and leptons.

FN Mechanism- II

- Thus, the Yukawa matrices are given as: $Y^f_{ij} = \rho^f_{ij}(\lambda_F)^{n^f_{ij}}$,
- One fixes: $\lambda_F = \frac{u}{\sqrt{2}\Lambda_F} = \lambda \simeq 0.22$, which is of the order of the Cabibbo angle.
- For up-type quarks we shall consider abelian charges that give:

$$Y^u = \begin{pmatrix} \rho^u_{11}\lambda^4 & \rho^u_{12}\lambda^4 & \rho^u_{13}\lambda^4 \\ \rho^u_{21}\lambda^4 & \rho^u_{22}\lambda^2 & \rho^u_{23}\lambda^2 \\ \rho^u_{13}\lambda^4 & \rho^u_{23}\lambda^2 & \rho^u_{33} \end{pmatrix} \tag{3}$$

- Notice that $(Y^u)_{33}$ does not have a power of λ, i.e. FN mechanism does not explain top Yukawa ($\rightarrow$ Yukawa-Gauge-Higgs unification?)
- This will imply that Flavon coupling with the top quark will be suppressed (in mass-eigen basis); coud be of order of charm-Higgs coupling or FV Higgs coupling htc,
- But $(Y^d)_{33}$ (and $(Y^l)_{33}$) could depend on λ,

Higgs-Flavon Mixing

- The Flavon field is written in terms of vev, real and imaginary components, as:
  $S = \frac{1}{\sqrt{2}}(u + s_1 + is_2)$,
- Then, one expands powers of Flavon field to linear order, as follows:

$$(\frac{S}{\Lambda_F})^{n_{ij}} = \lambda_F^{n_{ij}}(1 + \frac{n_{ij}}{u}(s_1 + is_2)) \tag{4}$$

- The Flavon interactions with fermions are described by the matrix:

$$Z_{ij}^f = \rho_{ij}^f n_{ij}^f (\lambda_F)^{n_{ij}^f} \tag{5}$$

- We still need to go to quark/lepton mass eigenstate basis, and take proper care of CKM matrix.

The scalar spectrum in a 3+1 Higgs doublets model

- For CPC HP 4 Real d. of f. $\rightarrow$ 4 CP-even Higgs bosons,
- To go from weak to mass-eigenstates: $\phi^0_a = O^T_{ab} h_b$ (a,b=1,4)
  O_{ab} = diagonalizing matrix, it depends on form of Higgs potential,
- Imaginary components could be light, but let us focus on CP-even Higgs sector,
- Lightest state $(h_1) \simeq$ SM higgs boson, with $m_h \simeq 125$ GeV,
- Three possibilities for the spectrum are:

(See S. Davidson et al, arXive:1512.08508 ; JM Yan et al, arXive: 1601.04954)

Conclusions.

- Mild evidence for new resonance with $M = 750$ GeV,
- Possible to interprete it with weakly coupled theories, but issue of large width remmains open,
- More narural to interprete it with strongly interacting theories,
- Another signal of new physics provided by $h \to \tau\mu$,
- Our (N+1)HDM seems promising to explain them all,

SM Higgs interactions

In the SM a Higgs doublet can work (Minimal)
SM lagrangian for a Higgs doublet $\Phi = (\phi^+, \phi^0)$ includes:

- Gauge ints. $\rightarrow$ Gauge boson masses,

  i.e. $\mathcal{L}_{HV} = (D^\mu \Phi)^\dagger (D_\mu \Phi)$

- Yukawa sector $\rightarrow$ fermion masses,

  i.e. $\mathcal{L}_Y = Y_u Q_L \Phi u_R$, etc.

- Higgs potential $V(\Phi) \rightarrow$ SSB and Higgs mass,

  i.e. $V(\Phi) = \lambda(|\Phi|^2 - v^2)^2$,

- One unknown parameter λ,
  - it determines Higgs mass: $m_h \simeq \lambda v$

Higgs vevs in spherical coordinates

- The vevs: $< \phi_a^0 >= \frac{v_a}{\sqrt{2}}$ (a=1,3) and $< S >= \frac{u}{\sqrt{2}}$
- $v^2 = v_1^2 + v_2^2 + v_3^2 = (246GeV)^2$
- In spherical coord.:
  $v_1 = v\cos\beta_1, \quad v_2 = v\sin\beta_1\cos\beta_2$ and $v_3 = v\sin\beta_1\sin\beta_2.$

Yukawa Lagrangian for 3+1-HDM

The lagrangian for the fermion couplings of the light Higgs boson is,

$$\mathcal{L}_Y = [\frac{\eta^u}{v}\bar{U}M_uU + \frac{\eta^d}{v}\bar{D}M_dD + \frac{\eta^l}{v}\bar{L}M_lL + \kappa^u\bar{U}_i\tilde{Z}^uU_j + \kappa^d\bar{D}_i\tilde{Z}^dD_j + \kappa^l\bar{L}_i\tilde{Z}^lL_j]h^0 \tag{6}$$

For FC Higgs couplings:

$\eta^u = O^T_{11}/\cos\theta, \quad \eta^d = O^T_{21}/\sin\theta\cos\phi, \quad \eta^l = O^T_{31}/\sin\theta\sin\phi,$

For FV Higgs couplings:

$\kappa^u = \frac{v}{u}O^T_{41}\cos\theta, \quad \kappa^d = \frac{v}{u}O^T_{41}\sin\theta\cos\phi, \quad \kappa^l = \frac{v}{u}O^T_{41}\cos\theta\sin\phi.$

A 3+1 HDM - Gauge interactions

- The Higgs couplings of the lightest Higgs state ($h^0 = h_1^0$) with vector bosons are written as $g_{hVV} = g_{hVV}^{sm} \chi_V$, with χ_V:

$$\begin{aligned} \chi_V &= \frac{v_1}{v} O_{11}^T + \frac{v_2}{v} O_{21}^T + \frac{v_3}{v} O_{31}^T \\ &= \cos\beta_1\, O_{11}^T + \sin\beta_1 \cos\beta_2\, O_{21}^T + \sin\beta_1 \sin\beta_2\, O_{31}^T \end{aligned} \tag{7}$$

- Sum rule for light Higgs couplings:

$$\chi_V = \cos^2\beta_1\, \eta^u + \sin^2\beta_1 \cos^2\beta_2\, \eta^d + \sin^2\beta_1 \sin^2\beta_2\, \eta^l \tag{8}$$

- To compare with LHC limits one needs to choose a pattern for v_i and O_{ab},
- For instance, we can choose: $v_1 >> v_2 = v_3$ i.e. $\beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta >> 1$ in 2HDM)
- Another possibility is to assume equal vevs i.e. $\beta_1 = \beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta = 1$ in 2HDM)

Higgs rotation

- We shall consider the special case when the light Higgs only mixes with the Flavon, i.e. the rotation matrix is written as: $O = \hat{O}\tilde{O}$,

$$\tilde{O} = \begin{pmatrix} c_4 & 0 & 0 & s_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_4 & 0 & 0 & c_4 \end{pmatrix} \tag{9}$$

- $\hat{O}$ diagonalizes the $3x3$ subsystem of heavy Higges-flavon:

$$\hat{O} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_1c_2 & s_1c_2 & s_2 \\ 0 & R_{21} & R_{22} & c_2s_3 \\ 0 & R_{31} & R_{32} & c_2c_3 \end{pmatrix} \tag{10}$$

where: $R_{21} = -c_1s_2s_3 - s_1c_3$, $R_{22} = c_1c_3 - s_1s_2s_3$, $R_{31} = s_1s_3 - c_1s_2c_3$, $R_{32} = -c_1s_3 - s_1s_2c_3$, and $s_i = \sin\alpha_i$, $c_i = \cos\alpha_i$.

Higgs Couplings - For special case $v_2 = v_3$ $(\phi = \frac{\pi}{4})$

The Higgs coupling with gauge bosons is:

$$\chi_V = \cos\theta\, O^T_{11} + \frac{\sin\theta}{\sqrt{2}} \left[O^T_{21} + O^T_{31}\right] \tag{11}$$

The FC and FV Higgs-fermion couplings factors are:

$$\begin{aligned} \eta^u &= \frac{O^T_{11}}{\cos\theta} \\ \eta^d &= \frac{\sqrt{2}}{\sin\theta} O^T_{21} \\ \eta^l &= \frac{\sqrt{2}}{\sin\theta} O^T_{31} \end{aligned} \tag{12}$$

$$\begin{aligned} \kappa^u &= \frac{v}{u} O^T_{41} \cos\theta \\ \kappa^d &= \frac{v}{u} O^T_{41} \frac{\sin\theta}{\sqrt{2}} \\ \kappa^l &= \frac{v}{u} O^T_{41} \frac{\sin\theta}{\sqrt{2}} \end{aligned} \tag{13}$$

Higgs Couplings - special cases

- In this case: $O^T_{11} = c_4$, $O^T_{21} = s_4 R_{31}$, $O^T_{31} = s_4 R_{32}$ and $O^T_{41} = s_4 c_2 c_3$.
- When we also assume: $\theta_2 = -\theta_1$, we have: $R_{31} = s_1 s_3 + c_1 s_1 c_3$, $R_{32} = -c_1 s_3 + s_1^2 c_3$,
- Further, when also $\theta_3 = 0$, which means that the heavy higgses do not mix with the flavon, we get: $O^T_{11} = c_4$, $O^T_{21} = s_1 c_1 s_4$, $O^T_{31} = s_1^2 s_4$ and $O^T_{41} = c_1 s_4$.

The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{14}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ $(\epsilon_W = -0.15 \pm 0.14)$,
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

Parameter scenarios in 3+1 HDM

- We will work in the 2-family limit for yukawa couplings, i.e. $V_{cb} \simeq s_{23} = s_{23}^d - s_{23}^u \simeq 0.04$
- With $s_{23}^u = r_2^u(1 + r_1^u)$, where: $r_1^u \simeq r_u$, $r_u = m_c/m_t$ and:

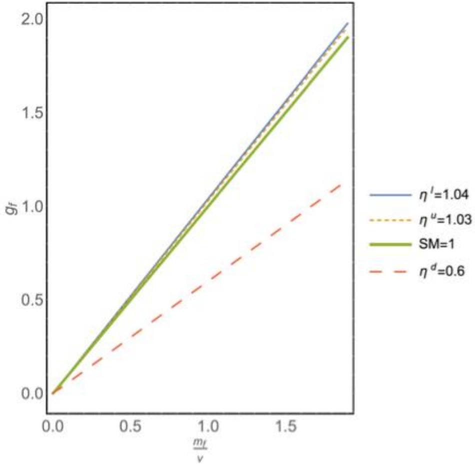
$$r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{15}$$

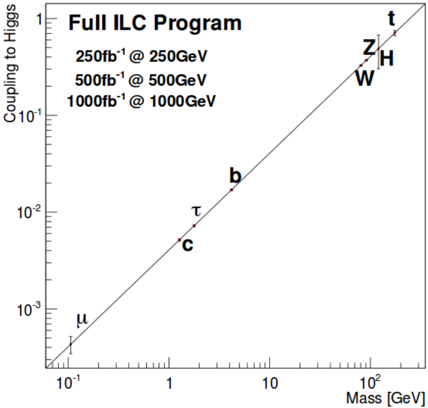
- For up quarks the $\tilde{Z}$-matrix is given by:

$$\tilde{Z}^u = \begin{pmatrix} Y_{22}^u & Y_{23}^u \\ Y_{23}^u & 2s_u Y_{23}^u \end{pmatrix} \tag{16}$$

- $Y_{22}^u = r_1^u Y_{33}^u, \quad Y_{23}^u = r_2^u Y_{33}^u \quad \text{and} \quad Y_{33}^u \simeq \tilde{Y}_{33}^u = \sqrt{2} m_t / v,$
- For vevs: $\cos\theta \simeq 1$ and $\sin\theta \simeq \epsilon$
- For Higgs rotation: $\alpha_1 = -\alpha_2$ and $\alpha_3 = 0$

Higgs couplings in 3+1 HDM





Work on flavon-Higgs phenomenology

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