Institut
"Jožef Stefan"
Ljubljana, Slovenija

Colored Scalars and Vector-like Quarks in the light of recent Higgs data

Admir Greljo

"Jožef Stefan" Institute

In collaboration with:
Ilja Doršner, Svjetlana Fajfer, Ivana Mustać and Jernej Fesel Kamenik

"Higgs and Beyond the SM Physics at LHC",
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Outline

- Higgs data
- Fitting procedure
- Colored Scalars and Higgs phenomenology

  arXiv:1208.1266 (JHEP 2012:130) - I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik

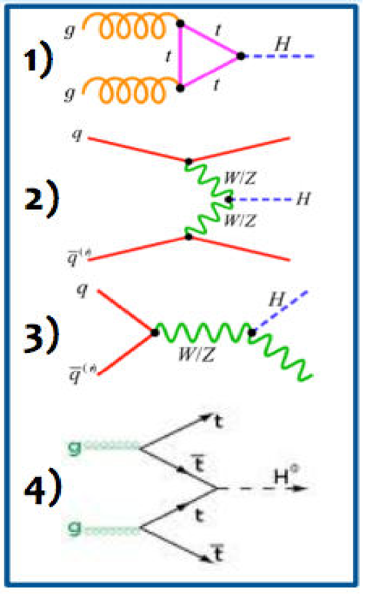
- Vector-like Quarks and Higgs phenomenology

  arXiv:1304.4219 (JHEP accepted) - S. Fajfer, A. Greljo, I. Mustać, J. F. Kamenik

- Conclusions

Higgs data so far...

- Decay channels:
  - h->bb (BR$_{SM}$=0.569)
  - h->WW* (BR$_{SM}$=0.224)
  - h->ττ (BR$_{SM}$=0.063)
  - h->ZZ* (BR$_{SM}$=0.028)
  - h->γγ (BR$_{SM}$=0.0023)
  - h->Zγ (BR$_{SM}$=0.0016)
  - h->μμ (BR$_{SM}$=0.0002)
  - h->invisible
- Production mechanisms:
  - Gluon-gluon fusion (ggF) (σ_{SM_8TeV}=19.4 pb)
  - Vector-boson fusion (VBF) (σ_{SM_8TeV}=1.55 pb)
  - Associated production with gauge bosons (VH) (σ_{SM_8TeV}=1.07 pb)
  - Associated production with top (ttH) (σ_{SM_8TeV}=0.13)

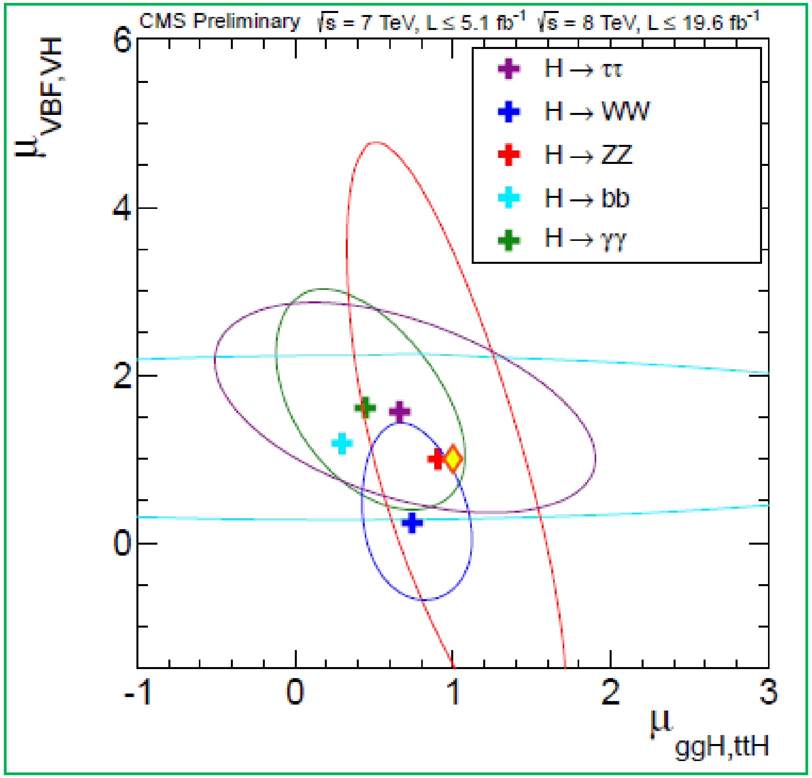


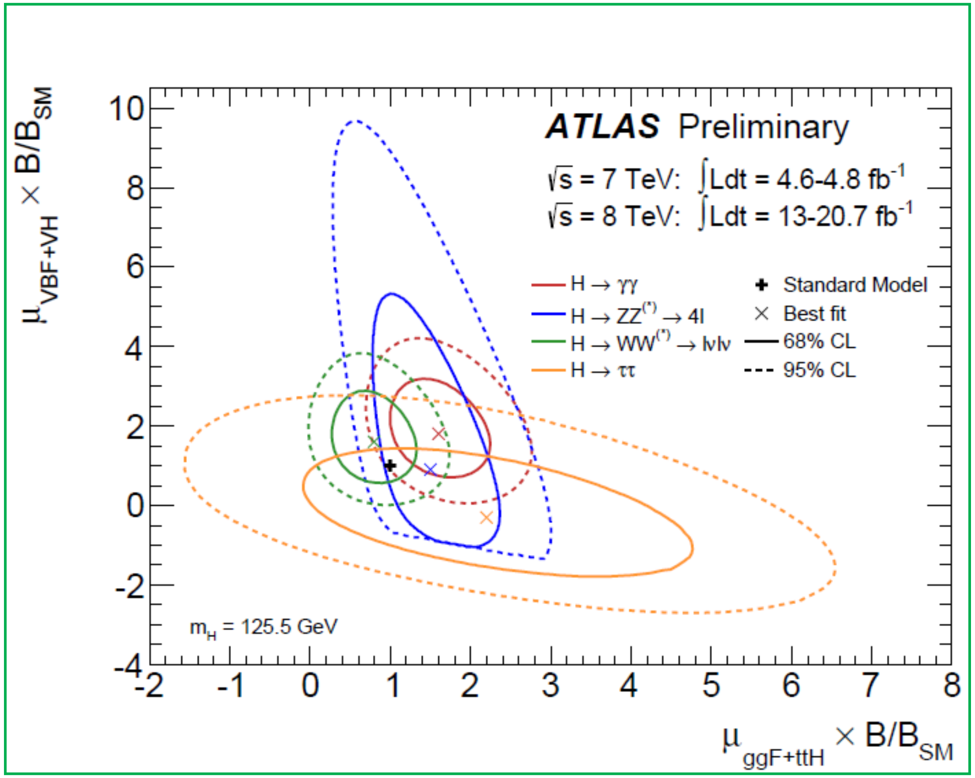
- Signal strengths (μ)
  - Number of signal events normalized to SM prediction

$$\mu_{A\to h}^{h\to B} = \frac{\sigma_{A\to h}}{\sigma_{A\to h}^{SM}} \frac{\mathcal{B}_{h\to B}}{\mathcal{B}_{h\to B}^{SM}}$$

- Several analysis categories for each decay channel
  - Generally target certain production mechanism
    - 0/1 – jets, VBF-tag, VH-tag, ttH-tag
  - Does not imply 100% purity

Decomposition into production mechanisms





- Parameterize likelihood with (G. Cacciapaglia et al, G. Belanger et al)

$$\chi_1^2 = \sum_i \left(\mu^i_{GF} - \hat{\mu}^i_{GF},\ \mu^i_{VF} - \hat{\mu}^i_{VF} \right) \begin{pmatrix} (\hat{\sigma}^i_{GF})^2 & \rho^i \hat{\sigma}^i_{GF}\hat{\sigma}^i_{VF} \\ \rho^i \hat{\sigma}^i_{GF}\hat{\sigma}^i_{VF} & (\hat{\sigma}^i_{VF})^2 \end{pmatrix}^{-1} \begin{pmatrix} \mu^i_{GF} - \hat{\mu}^i_{GF} \\ \mu^i_{VF} - \hat{\mu}^i_{VF} \end{pmatrix}$$

Higgs data summarized

(arXiv:1304.4219 - S. Fajfer, A. Greljo, I. Mustać, J. F. Kamenik)

Decay channel	Production mode	Signal strength	Comment
ATLAS			
$h \to ZZ^*$	Inclusive (87% ggF)	1.5 ± 0.4	[14, 21]
$h \to b\bar{b}$	VH	-0.4 ± 1.0	[14]
$h \to WW^*$	ggF+ttH	0.79 ± 0.35	Correlation $\rho = -0.3$, [14, 22]
	VBF+VH	1.6 ± 0.8	
$h \to \gamma\gamma$	ggF+ttH	1.60 ± 0.44	Correlation $\rho = -0.4$, [14, 23]
	VBF+VH	1.80 ± 0.87	
$h \to \tau\tau$	ggF+ttH	2.2 ± 1.6	Correlation $\rho = -0.5$, [14]
	VBF+VH	-0.3 ± 1.1	
CMS			
$h \to b\bar{b}$	VH	1.3 ± 0.7	[15]
$h \to WW^*$	0/1 jet (97% ggF)	0.76 ± 0.21	[24]
	VBF-tag (20% ggF)	0.0 ± 0.7	[15]
	VH	-0.3 ± 2.1	[15]
$h \to ZZ^*$	ggF+ttH	0.90 ± 0.45	Correlation $\rho = -0.7$, [25]
	VBF+VH	1.0 ± 2.3	
$h \to \gamma\gamma$	ggF+ttH	0.52 ± 0.40	Correlation, $\rho = -0.5$, [26]
	VBF+VH	1.5 ± 0.9	
$h \to \tau\tau$	0/1 jet (80% ggF)	0.73 ± 0.51	[27]
	VBF-tag (20% ggF)	1.37 ± 0.63	[27]
	VH	0.75 ± 1.5	[27]

Table I: LHC Higgs data used in the analysis.

Light colored scalars and Higgs phenomenology

arXiv:1208.1266 (JHEP 2012:130) - I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik

- Motivation (Grand Unified Theory)
  - Light colored scalars improve unification –
    - Correlation with observable partial proton decay lifetimes
  - We find viable unification scenarios for two SU(5) models
    - 5-, 45- scalar and 24- dimensional fermion – Perez (2007)
    - 5-, 15-, 45- scalar – Doršner and Perez (2006), Doršner and Mocioiu (2008)

- **Higgs portal!** $\Phi^\dagger \Phi H^\dagger H$

- Loop induced Higgs decays
  - Sensitive to colored and/or charged massive particles

  a) $h \to \gamma\gamma$, $h \to Z\gamma$

  b) $gg \to h$

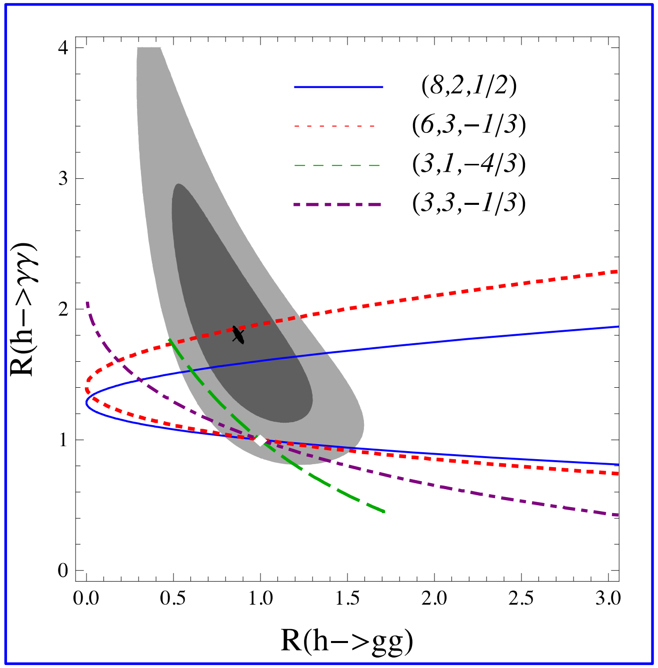
- Higgs signal strengths analysis:
  - Fitting parameters: $R_{gg}=\sigma_{ggF}/\sigma_{ggF}^{SM}$ and $R_{\gamma\gamma}=\Gamma_{h\to\gamma\gamma}/\Gamma_{h\to\gamma\gamma}^{SM}$

Light colored scalars and Higgs phenomenology: Results

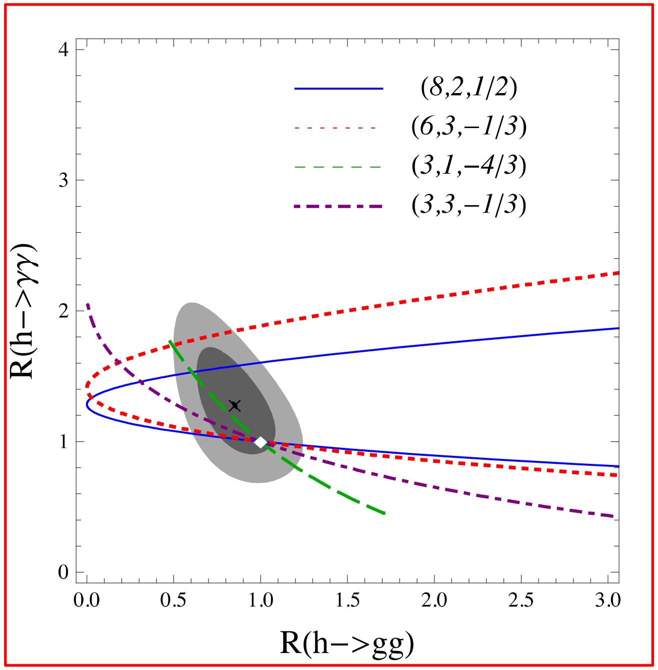
- Correlation between h→γγ and gg→h
  - Dimension and Index of color rep. - d_ϕ and C_ϕ
  - Electric charge Q_ϕ
- Single parameter $\lambda v^2/m_\phi^2$
  - Do one-dimensional χ^2, find allowed parameter region

$$\frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}} = \left|1 - 0.026\sum_\phi \frac{\lambda v^2}{m_\phi^2} d_\phi Q_\phi^2\right|^2$$

$$\frac{\sigma_{ggF}}{\sigma^{SM}_{ggF}} = \left|1 + 0.26\sum_\phi \frac{\lambda v^2}{m_\phi^2} C_\phi\right|^2$$



August 2012.



April 2013.

$SU(3)\times SU(2)\times U(1)$	$\lambda v^2/m_\phi^2$
$(\bar{\mathbf{3}},\mathbf{1},1/3)$	-0.3 ± 0.5
$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	-0.4 ± 0.6
$(\mathbf{3},\mathbf{1},-4/3)$	-0.7 ± 0.6
$(\mathbf{3},\mathbf{2},1/6)$	-0.2 ± 0.3
$(\mathbf{3},\mathbf{2},7/6)$	-0.3 ± 0.3
$(\mathbf{3},\mathbf{3},-1/3)$	-0.2 ± 0.2
$(\bar{\mathbf{6}},\mathbf{1},-1/3)$	-0.06 ± 0.12
$(\bar{\mathbf{6}},\mathbf{1},2/3)$	-0.07 ± 0.12
$(\bar{\mathbf{6}},\mathbf{1},-4/3)$	-0.09 ± 0.12
$(\bar{\mathbf{6}},\mathbf{3},-1/3)$	-0.02 ± 0.04
	$-1.0<x<0.9$
$(\mathbf{8},\mathbf{2},1/2)$	-0.03 ± 0.05
	-1.22 ± 0.04

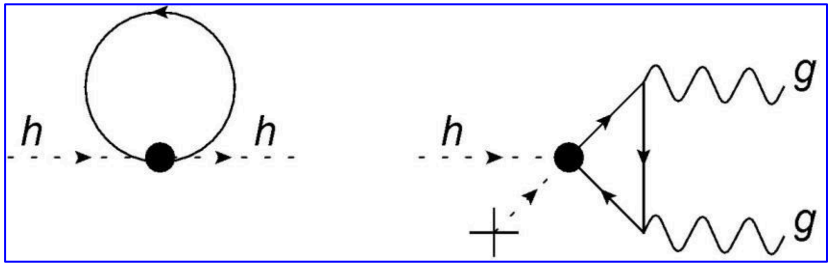
Light Vector-like Quarks and Higgs Phenomenology

arXiv:1304.4219 (JHEP accepted) - S. Fajfer, A. Greljo, I. Mustać, J. F. Kamenik

- Set-up
  - Assume new lightest degree of freedom - Vector-like Quark (VLQ)
  - Consider weak representation of SM chiral quarks – mixing!
    - Singlet Up-type VLQ, Singlet Down-type VLQ, Doublet VLQ
  - Study leading dimension five operators (5DO)

$$H^\dagger H \overline{q}_i Q, \;\; H^\dagger H \overline{Q} Q$$

- Motivation
  - Models addressing EW hierarchy problem with Higgs and VLQ being lightest composite remnants of strong TeV dynamics
- Higgs data: Probe of Naturalness



- Renormalizable models with VLQ
  - Mass terms in weak (chiral) eigenbasis

$$-\mathcal{L}_{\text{mass}} = \bar{u}^i_L \mathcal{M}^{ij}_u u^j_R + \bar{d}^i_L \mathcal{M}^{ij}_d d^j_R + \text{h.c.}$$

  - Bi-unitary rotations

$$\mathcal{M}_{u,d,\text{diag}} = U^{u,d}_L \mathcal{M}_{u,d} U^{u,d\dagger}_R$$

  - Interaction terms in mass eigenbasis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}(V^L_{ij}\bar{u}^i\gamma^\mu P_L d^j + V^R_{ij}\bar{u}^i\gamma^\mu P_R d^j)W^+_\mu + \text{h.c.}\,,$$

$$\mathcal{L}_Z = -\frac{g}{2c_W}\left(X^u_{ij}\bar{u}^i\gamma^\mu P_L u^j - X^d_{ij}\bar{d}^i\gamma^\mu P_L d^j + Y^u_{ij}\bar{u}^i\gamma^\mu P_R u^j - Y^d_{ij}\bar{d}^i\gamma^\mu P_R d^j - 2s^2_W J^\mu_{\text{EM}}\right) Z_\mu\,,$$

$$\mathcal{L}^{(0)}_h = -(X^u_{ij} - Y^u_{ij})\frac{m_j}{v}\bar{u}^i P_R u^j h - (X^d_{ij} - Y^d_{ij})\frac{m_j}{v}\bar{d}^i P_R d^j h + \text{h.c.}\,,$$

  - Flavour matrices

$$V^L_{ij} \equiv (U^d_L)^*_{jk}(U^u_L)_{ik} \qquad X^u \equiv V^L V^{L\dagger},\ X^d \equiv V^{L\dagger}V^L$$

- Higgs interactions fixed by neutral current interactions!

- Summarized constraints on flavor matrices (Renormalizable models with VLQ)

Coupling	Constraint	Reference
$\lvert X^u_{cu}\rvert, \lvert Y^u_{cu}\rvert$	$< 2.1 \times 10^{-4}$	[12, 58]
$\lvert X^u_{tu,tc}\rvert, \lvert Y^u_{tu,tc}\rvert$	< 0.14	Appendix A
$\lvert X^d_{ds}\rvert, \lvert Y^d_{ds}\rvert$	$< 1.4 \times 10^{-5}$	Appendix B
$\lvert X^d_{db}\rvert, \lvert Y^d_{db}\rvert$	$< 4 \times 10^{-4}$	
$\lvert X^d_{sb}\rvert, \lvert Y^d_{sb}\rvert$	$< 1 \times 10^{-3}$	
δX^u_{uu}	$-0.0001(6)$	[9]
δX^u_{cc}	$-0.0020(13)$	Appendix C
δX^d_{dd}	$-0.0031(20)$	Appendix C
δX^d_{ss}	$-0.002(3)$	
δX^d_{bb}	$0.0027(15)$	
δY^u_{uu}	$0.035(40)$	Appendix C
δY^u_{cc}	$-0.003(9)$	
δY^d_{dd}	$0.030(35)$	
δY^d_{ss}	$-0.05^{+0.08}_{-0.06}$	
δY^d_{bb}	$-0.018(6)$	

- Lesson for Higgs: Hard to distinguish from SM!

- Including dimension five operators
  - Manifestly preserve mass diagonalization! - ($v^2/2-|H|^2$)
- The main consequences of dim-5 operators

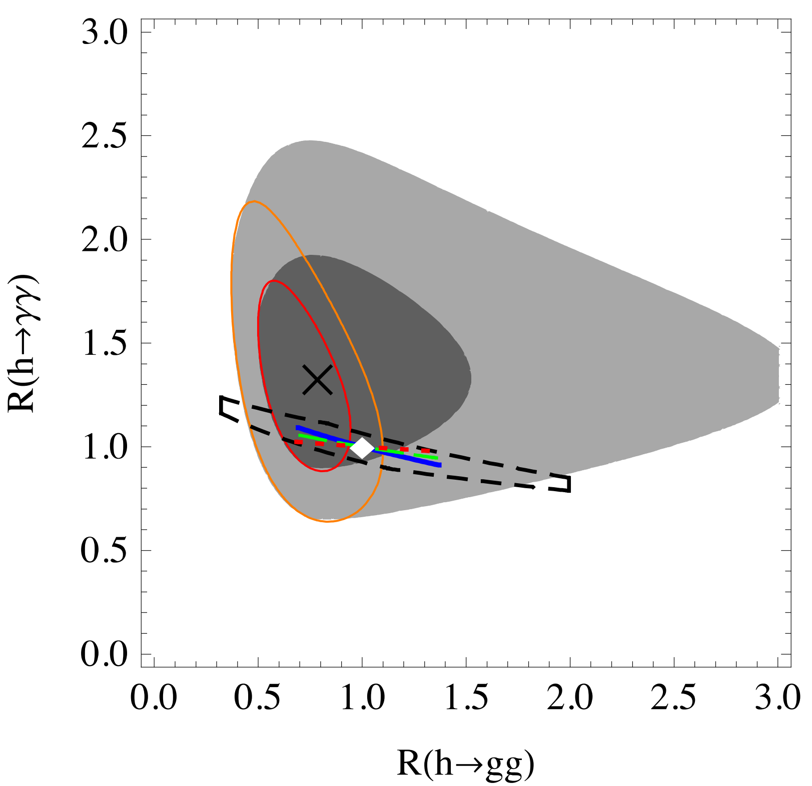
$$\mathcal{L}_h^{(1)} = \left(\frac{X_{ij}^{u\prime}}{\Lambda} \bar{u}_L^i u_R^j + \frac{X_{ij}^{d\prime}}{\Lambda} \bar{d}_L^i d_R^j \right) \left[vh + \frac{h^2}{2} \right] + \text{h.c.}$$

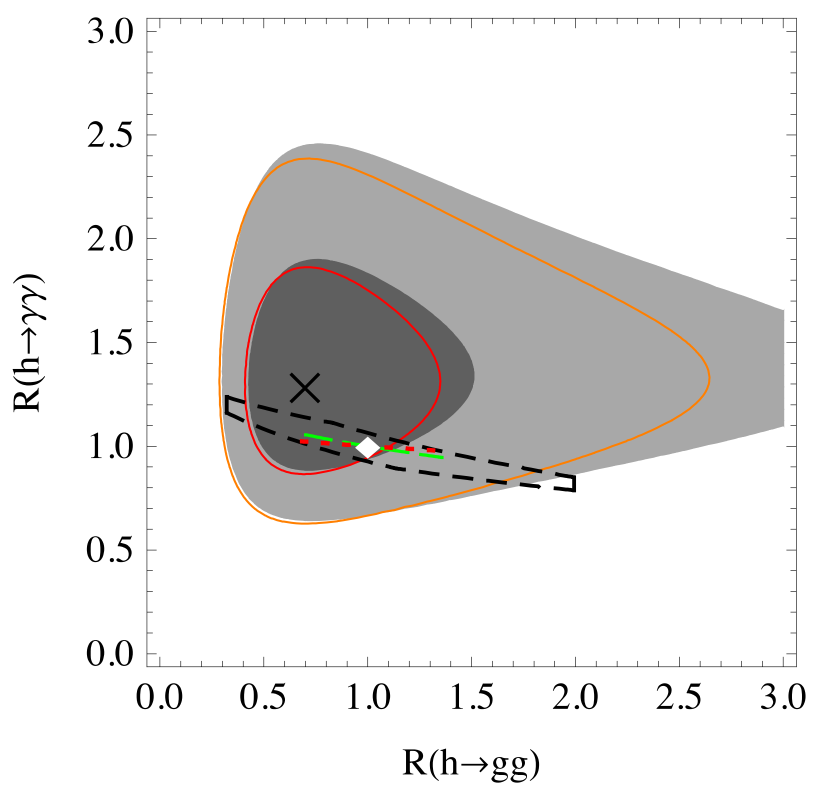
  - Direct di-Higgs coupling
  - Modification of single Higgs - quark coupling
    - not related to weak currents!
- Possible effects:
  - Large flavour diagonal Higgs couplings to light quarks
    - Additional Higgs decay width
    - h->bb
  - Modification of loop induced decays
    - New heavy quarks in the loops

- Higgs data fit
  - Fitting parameters – R_{gg}, $R_{\gamma\gamma}$, R_{bb}, $\Delta\gamma$
  - Four scenarios

$$\hat{\Gamma} \equiv \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}} = 0.569R_{bb} + 0.317 + 0.085R_{gg} + \Delta\gamma$$

$$\mu_{GF}^{h\to\gamma\gamma} = \frac{R_{gg}}{\hat{\Gamma}}R_{\gamma\gamma}\,, \quad \mu_{GF}^{h\to ZZ,WW,\tau\tau} = \frac{R_{gg}}{\hat{\Gamma}}\,, \quad \mu_{VF}^{h\to\gamma\gamma} = \frac{R_{\gamma\gamma}}{\hat{\Gamma}} \quad \mu_{VF}^{h\to ZZ,WW,\tau\tau} = \frac{1}{\hat{\Gamma}}\,, \quad \mu_{VH}^{h\to\bar{b}b} = \frac{R_{bb}}{\hat{\Gamma}}.$$

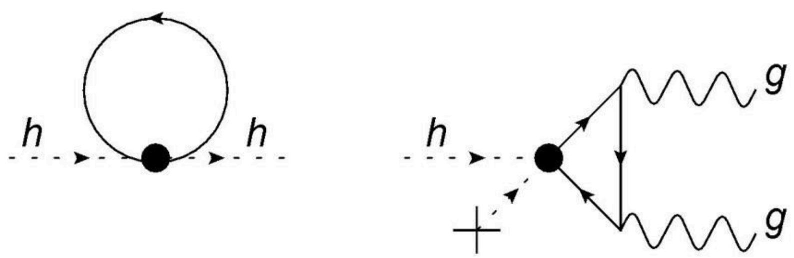




- Ex: Singlet up-like VLQ
  - Correlation

$$R_{gg} = \frac{|0.68 r_y - 0.040|^2 + 0.057^2}{0.65^2} \qquad R_{\gamma\gamma} = \frac{|-8.3 + 1.8 r_y|^2}{|-6.5|^2}$$

  - Naturalness criteria $r_y = 1 - \frac{m_t^2}{m_{u'}^2}$



- From the Higgs fit: $r_y^t = 0.87 \pm 0.08$
- Indirect constraint on top partner's mass:
  - $m_{u'} > 360$ GeV @ 95% C.L.
- Complementary probe to direct searches
- More statistics needed!

Conclusions

- Higgs data fitting procedure reviewed
- Constraints on Higgs interactions with light colored scalars
- Higgs phenomenology in presence of dynamical VLQ and dimension five operators
- Higgs precision physics – New indirect probe of New Physics

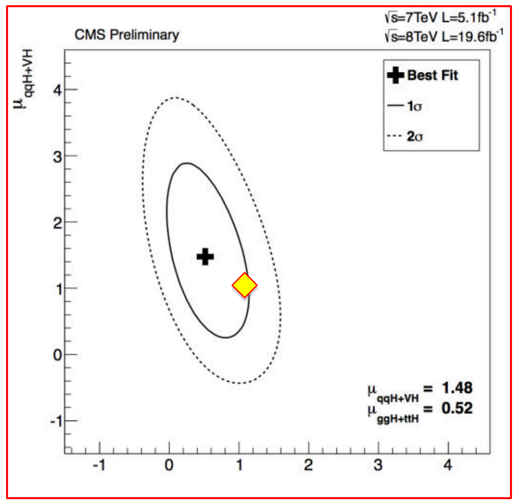
Back up

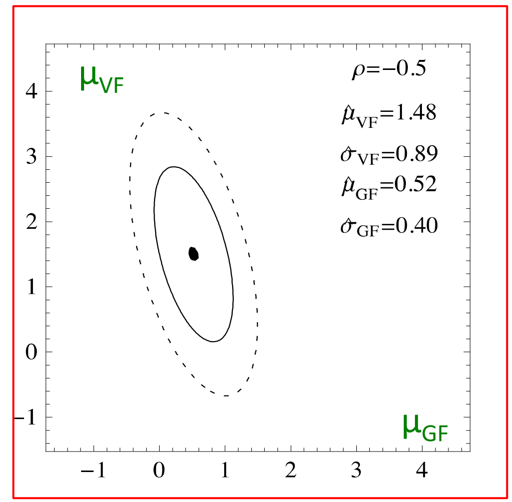
Higgs data and fitting procedure

- Improved χ^2 method
- Separation into GF=(ggF+tth) and VF=(VBF+VH)
  - Parameterize likelihood with

$$\chi_1^2 = \sum_i \left(\mu_{GF}^i - \hat{\mu}_{GF}^i,\ \mu_{VF}^i - \hat{\mu}_{VF}^i \right) \begin{pmatrix} (\hat{\sigma}_{GF}^i)^2 & \rho^i \hat{\sigma}_{GF}^i \hat{\sigma}_{VF}^i \\ \rho^i \hat{\sigma}_{GF}^i \hat{\sigma}_{VF}^i & (\hat{\sigma}_{VF}^i)^2 \end{pmatrix}^{-1} \begin{pmatrix} \mu_{GF}^i - \hat{\mu}_{GF}^i \\ \mu_{VF}^i - \hat{\mu}_{VF}^i \end{pmatrix}$$

  - Example:
    CMS h->γγ decay channel





- If the separation is not provided, use search categories
  - Estimate contribution from each production mode

$$\frac{\sigma_{A\to h}}{\sigma_{A\to h}^{SM}} = \xi_{ggF} \frac{\sigma_{ggF}}{\sigma_{ggF}^{SM}} + \xi_{VBF} \frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} + \xi_{VH} \frac{\sigma_{VH}}{\sigma_{VH}^{SM}} + \xi_{ttH} \frac{\sigma_{ttH}}{\sigma_{ttH}^{SM}}$$

  - Parameterize with likelihood

$$\chi_2^2 = \sum_j \left(\frac{\mu_j - \hat{\mu}_j}{\hat{\sigma}_j} \right)^2$$

- Total $\chi^2(\mu_i)=\chi_1^2+\chi_2^2$

$$\mu_{A\to h}^{h\to B} = \frac{\sigma_{A\to h}}{\sigma_{A\to h}^{SM}} \frac{\mathcal{B}_{h\to B}}{\mathcal{B}_{h\to B}^{SM}}$$

Renormalizable Adjoint SU(5) (P. Fileviez Perez, Phys. Lett. B 654, 189 (2007))

- Standard Model matter fields $\boxed{\bar{5} \oplus 10}$

$$\bar{5} \to \left(\bar{3}, 1, \frac{1}{3}\right) \oplus \left(1, 2, -\frac{1}{2}\right) \qquad 10 \to \left(3, 2, \frac{1}{6}\right) \oplus \left(\bar{3}, 1, -\frac{2}{3}\right) \oplus (1,1,1)$$

$$\bar{5} \equiv \begin{bmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{bmatrix} \qquad 10 \equiv \begin{bmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{bmatrix}$$

- SU(5) spontaneously broken down to Standard Model gauge group at GUT scale by $\mathbf{24_H}$ (adjoint) Higgs representation

$$\mathbf{24} \equiv (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\bar{3},2)}, \Sigma_{24}) = (\mathbf{8}, \mathbf{1}, 0) \oplus (\mathbf{1}, \mathbf{3}, 0) \oplus (\mathbf{3}, \mathbf{2}, -5/6) \oplus (\bar{\mathbf{3}}, \mathbf{2}, 5/6) \oplus (\mathbf{1}, \mathbf{1}, 0)$$

$$\mathbf{24}_H = \begin{bmatrix} (\Sigma_8)_{3\times3} & (\Sigma_{(3,2)})_{3\times2} \\ (\Sigma_{(\bar{3},2)})_{2\times3} & (\Sigma_3)_{2\times2} \end{bmatrix}_{5\times5} + \left(1 + \frac{\Sigma_{24}}{v}\right) \langle \mathbf{24}_H \rangle \qquad \langle 24_H \rangle = \frac{v}{\sqrt{30}} \begin{pmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & -3 & 0 \\ 0 & 0 & 0 & 0 & -3 \end{pmatrix}$$

- Scalar fields

$$\mathbf{5} \equiv (\Psi_D, \Psi_T) = (\mathbf{1}, \mathbf{2}, 1/2) \oplus (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\mathbf{45} \equiv (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$
$$= (\mathbf{8}, \mathbf{2}, 1/2) \oplus (\bar{\mathbf{6}}, \mathbf{1}, -1/3) \oplus (\mathbf{3}, \mathbf{3}, -1/3) \oplus (\bar{\mathbf{3}}, \mathbf{2}, -7/6) \oplus (\mathbf{3}, \mathbf{1}, -1/3) \oplus (\bar{\mathbf{3}}, \mathbf{1}, 4/3) \oplus (\mathbf{1}, \mathbf{2}, 1/2)$$

- Extra fermion representation $\mathbf{24_F}$ (adjoint) (B. Bajc and G. Senjanovic, JHEP 0708, 014 (2007))

$$\mathbf{24}_F \equiv (\rho_8, \rho_3, \rho_{(3,2)}, \rho_{(\bar{3},2)}, \rho_{24}) = (\mathbf{8}, \mathbf{1}, 0) \oplus (\mathbf{1}, \mathbf{3}, 0) \oplus (\mathbf{3}, \mathbf{2}, -5/6) \oplus (\bar{\mathbf{3}}, \mathbf{2}, 5/6) \oplus (\mathbf{1}, \mathbf{1}, 0)$$

Viable unification for Renormalizable Adjoint SU(5)

- Mass spliting constraints - from the potential $V_{24} = m\, Tr(24^2) + \lambda\, Tr(24^2 24_H)$

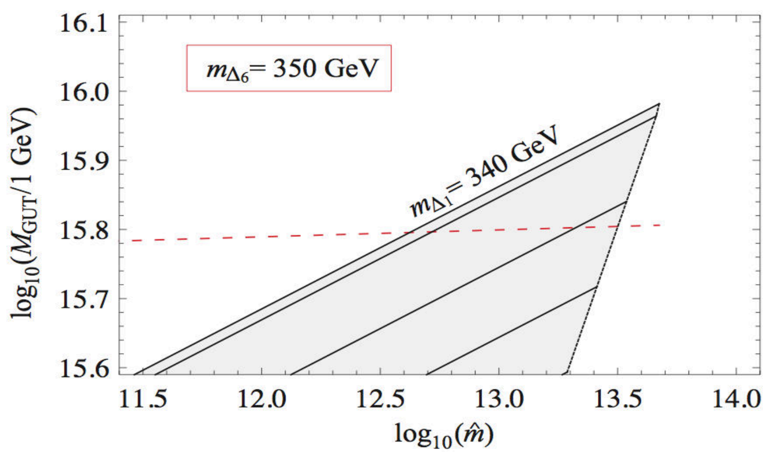
$$m_{\rho_8} = \hat{m} m_{\rho_3}, \qquad m_{\rho_{(3,2)}} = m_{\rho_{(\bar{3},2)}} = \frac{(m_{\rho_3} + m_{\rho_8})}{2}$$

- We present a viable unification in a $\hat{m}$ vs. M_{GUT} plane, where M_{GUT} represents the scale of gauge coupling unification.
  - M_{GUT} is maximized through numerical procedure that varies scalar and fermion masses, in accordance with mass splitting constraints, in the following ranges:

$$200\, GeV \le m_{\Sigma_3}, m_{\Delta_1}, m_{\Delta_2}, m_{\Delta_4}, m_{\Delta_7}, m_{\rho_3}, m_{\rho_8}, m_{\rho_{(3,2)}}, m_{\rho_{(\bar{3},2)}} \le M_{\rm GUT}$$

$$10^{12}\, GeV \le m_{\Psi_T}, m_{\Delta_3}, m_{\Delta_5} \le M_{\rm GUT} \quad 10^5\, GeV \le m_{\Sigma_8} \le M_{\rm GUT}$$

- All unification scenarios below the dashed line in figure are excluded by experimental limits on $p \rightarrow \pi^0 e^+$. A lower bound on proton decay mediating scalar masses imposed.



Renormalizable SU(5) with **5**, **45** and **15** Higgs

- Standard Model matter fields $\boxed{\overline{5} \oplus 10}$

$$\overline{5} \to \left(\overline{3}, 1, \frac{1}{3}\right) \oplus \left(1, 2, -\frac{1}{2}\right) \qquad 10 \to \left(3, 2, \frac{1}{6}\right) \oplus \left(\overline{3}, 1, -\frac{2}{3}\right) \oplus (1, 1, 1)$$

$$\overline{5} \equiv \begin{bmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{bmatrix} \qquad 10 \equiv \begin{bmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{bmatrix}$$

- SU(5) spontaneously broken down to Standard Model gauge group at GUT scale by **24_H** (adjoint) Higgs representation

$$\mathbf{24} \equiv (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\overline{3},2)}, \Sigma_{24}) = (\mathbf{8}, \mathbf{1}, 0) \oplus (\mathbf{1}, \mathbf{3}, 0) \oplus (\mathbf{3}, \mathbf{2}, -5/6) \oplus (\overline{\mathbf{3}}, \mathbf{2}, 5/6) \oplus (\mathbf{1}, \mathbf{1}, 0)$$

$$\mathbf{24}_H = \begin{bmatrix} (\Sigma_8)_{3\times3} & \left(\Sigma_{(3,2)}\right)_{3\times2} \\ \left(\Sigma_{(\overline{3},2)}\right)_{2\times3} & (\Sigma_3)_{2\times2} \end{bmatrix}_{5\times5} + \left(1 + \frac{\Sigma_{24}}{v}\right)\langle \mathbf{24}_H \rangle \qquad \langle 24_H \rangle = \frac{v}{\sqrt{30}} \begin{pmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & -3 & 0 \\ 0 & 0 & 0 & 0 & -3 \end{pmatrix}$$

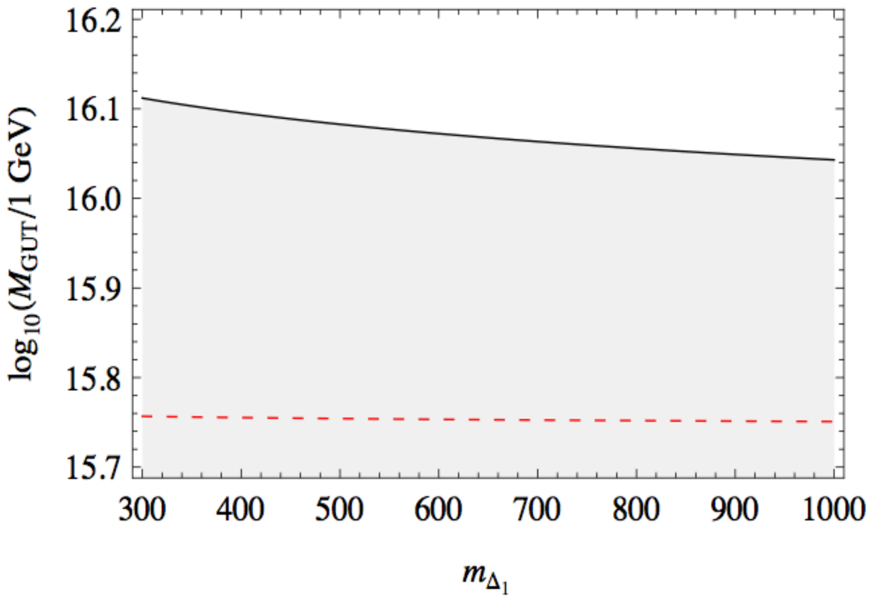
- Scalar fields

$$\mathbf{5} \equiv (\Psi_D, \Psi_T) = (\mathbf{1}, \mathbf{2}, 1/2) \oplus (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\mathbf{45} \equiv (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$
$$= (\mathbf{8}, \mathbf{2}, 1/2) \oplus (\overline{\mathbf{6}}, \mathbf{1}, -1/3) \oplus (\mathbf{3}, \mathbf{3}, -1/3) \oplus (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \oplus (\mathbf{3}, \mathbf{1}, -1/3) \oplus (\overline{\mathbf{3}}, \mathbf{1}, 4/3) \oplus (\mathbf{1}, \mathbf{2}, 1/2)$$

$$\mathbf{15} = (\Phi_a, \Phi_b, \Phi_c) = (\mathbf{1}, \mathbf{3}, 1) \oplus (\mathbf{3}, \mathbf{2}, 1/6) \oplus (\mathbf{6}, \mathbf{1}, -2/3)$$

Viable unification for Renormalizable SU(5) with **5**, **45** and **15** Higgs



- We present a viable unification in a $m_{\Delta 1}$ vs. M_{GUT} plane
  - M_{GUT} is maximized through numerical procedure that varies scalar masses in the following ranges:

$$200\,\text{GeV} \leq m_{\Sigma_3}, m_{\Delta_1}, m_{\Delta_2}, m_{\Delta_4}, m_{\Delta_6}, m_{\Delta_7}, m_{\rho_{(3,2)}}, m_{\rho_{(\bar{3},2)}}, m_{\Phi_a}, m_{\Phi_c} \leq M_{\text{GUT}}$$

$$10^{12}\,\text{GeV} \leq m_{\Psi_T}, m_{\Delta_3}, m_{\Delta_5}, m_{\Phi_b} \leq M_{\text{GUT}} \quad 10^5\,\text{GeV} \leq m_{\Sigma_8} \leq M_{\text{GUT}}$$

- A lower bound on proton decay mediating scalar masses imposed.
- In both models, the relevant coupling of the octet to the Higgs field originates from the following SU(5) contraction:

$$\boxed{\lambda_1 \mathbf{5}^*_\alpha \mathbf{5}^\alpha \mathbf{45}^{\beta\gamma}_\delta \mathbf{45}^{*\,\delta}_{\beta\gamma}}$$