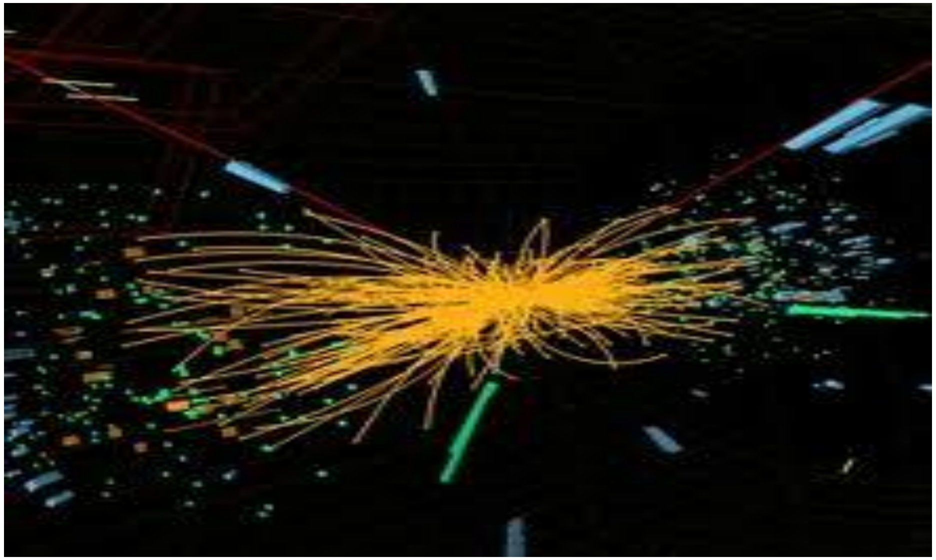
H$\longrightarrow\gamma\gamma$ in SU(5) GUT with 45_H



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SU(5) GUT

- **SU(5) GUT, proposed by Georgi and Glashow in 1974, is the simplest extension of the SM that provides a natural framework for the unification of fundamental interactions.**

- **SM quarks and leptons are combined into irreducible SU(5) representations: $\bar{5}$ and 10:**

$$\bar{5} \equiv \psi^i_L = \begin{pmatrix} d^c_{r(1)} \\ d^c_{g(2)} \\ d^c_{b(3)} \\ e^- \\ -\nu_e \end{pmatrix}_L \begin{matrix} \left.\right] \text{SU(3)c} \\ \left.\right\} \text{SU}_L(2) \end{matrix} ; 10 \equiv (\chi_{ij})_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u^c_3 & -u^c_2 & -u^1 & -d^1 \\ -u^c_3 & 0 & u^c_1 & -u^2 & -d^2 \\ u^c_2 & -u^c_1 & 0 & -u^3 & -d^3 \\ u^1 & u^2 & u^3 & 0 & -e^+ \\ d^1 & d^2 & u^3 & e^+ & 0 \end{pmatrix}_L$$

- **The Higgs sector in the minimal SU(5) contains adjoint 24_H and fundamental 5_H.**

$$SU(5) \rightarrow SU_C(3) \times SU_L(2) \times U_Y(1) \rightarrow SU_C(3) \times U_Q(1).$$

- **Minimal SU(5) is very predictive:**

  i. Predicts quantization of electric charge: $\mathrm{Tr}\,Q_{\bar{5}} = 0$, hence $Q(d) = 1/3\,Q(e^-)$.

  ii. Predicts $\sin^2\theta_W$ in a very good agreement with the current result.

  iii. Leads to $m_b/m_\tau \simeq 3$, which is consistent with the measured masses

- **Several drawbacks for minimal SU(5):**

  i. Predicts proton decay, $p \rightarrow e^+\pi^0$, with a life-time~10^{32} years, in a contradiction with the experimental bound $> 5 \times 10^{33}$

  ii. Leads to a wrong mass relation: $m_e/m_\mu = m_d/m_s$.

  iii. No right-handed neutrino and neutrinos are massless

  iv. Gauge couplings do not unify at all.

  v. Suffers from a naturalness problem due to the gauge hierarchy problem and a doublet-triplet splitting.

SU(5) with 45-plet

- **Under SU(5)**

$$5^* \times 10 = 5 + 45$$

$$10 \times 10 = 5^* + 45^* + 50$$

$$5^* \times 5^* = 10^* + 15^*$$

- **So the SU(5) invariant Yuakwa terms are:**

$$5^* \otimes 10 \otimes 5^*_H, \qquad 5^* \otimes 10 \otimes 45^*_H$$

$$10 \otimes 10 \otimes 5_H, \qquad 10 \otimes 10 \otimes 45_H$$

- **SU(5) Yukawa Lagrangian**

$$\mathcal{L}_{\rm Yuk} = Y_1 \bar{5}_\alpha 10^{\alpha\beta} (5^*_H)_\beta + Y_2 \bar{5}_\delta 10^{\alpha\beta} (45^*_H)^\delta_{\alpha\beta} + \epsilon_{\alpha\beta\gamma\delta\lambda} \left[Y_3 10^{\alpha\beta} 10^{\gamma\delta} 5^\lambda_H + Y_4 10^{\alpha\beta} 10^{\xi\gamma}_L (45_H)^{\delta\lambda}_\xi \right].$$

- **The 5_H and 45_H decomposition are**

$$5_H = (3,1)_{-1/3} \oplus (1,2)_{1/2}$$
$$45_H = (8,2)_{1/2} \oplus (1,2)_{1/2} \oplus (3,1)_{-1/3} \oplus (3,3)_{-1/3} \oplus (6^*,1){-1/3} \oplus (3^*,2)_{-7/6} \oplus (3^*,1)_{4/3}.$$

- **The 45_H satisfy the following conditions:**

$$45^{\alpha\beta}_{\gamma} = -45^{\beta\alpha}_{\gamma} \text{ and } \sum_{\alpha}^{5}(45)^{\alpha\beta}_{\alpha} = 0.$$

- **$SU(2)_L \times U(1)_Y$ is spontaneously broken into $U(1)_{em}$ through the non-vanishing vev of the doublets in 5_H and 45_H**

$$\langle 5_H \rangle = v_5,$$
$$\langle 45_H \rangle^{15}_1 = \langle 45_H \rangle^{25}_2 = \langle 45_H \rangle^{35}_3 = v_{45}, \quad \langle 45_H \rangle^{45}_4 = -3v_{45}.$$

- **In this case, the fermion masses are given by**

$$M_E = Y_1^T v_5^* - 6Y_2^T v_{45}^*,$$
$$M_D = Y_1 v_5^* + 2Y_2 v_{45}^*,$$
$$M_U = 4(Y_3 + Y_3^T)v_5 - 8(Y_4^T - Y_4)v_{45}$$

Higgs Sector

- **The 5_H doublet is defined as**

$$H \equiv (1,2)_{1/2} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix},$$

- **45_H doublet is given by**

$$D \equiv (1,2)_{1/2} = \begin{pmatrix} D_4^{54} & D_5^{54} \\ D_4^{45} & D_5^{45} \end{pmatrix} = \begin{pmatrix} -D_5^{45} \\ D_4^{45} \end{pmatrix} = \begin{pmatrix} -D^+ \\ D^0 \end{pmatrix}$$

- **45_H color octet scalars are given by**

$$S_j^{ia} \equiv (8,2)_{1/2} = (45_j^{ia})_H - \frac{1}{3}\delta_j^i (45_H)_m^{ma} = \begin{pmatrix} S^+ \\ S_R^0 + iS_I^0 \end{pmatrix} \equiv S^A T^A,$$

- **The SU(5) invariant potential is**

$$\begin{aligned} V(5_H, 45_H) = & -\mu_5^2\, 5_\alpha^* 5^\alpha + \lambda_1 \left(5_\alpha^* 5^\alpha\right)^2 - \mu_{45}^2\, 45_{\alpha\beta}^{\gamma *} 45_\gamma^{\alpha\beta} + \lambda_2 \left(45_{\alpha\beta}^{\gamma *} 45_\gamma^{\alpha\beta}\right)^2 + \lambda_3 \left(45_{\alpha\beta}^{\gamma *} 45_\gamma^{\alpha\beta}\right) 5_\delta^* 5^\delta \\ & + \lambda_4\, 45_{\alpha\beta}^{\gamma *}\, 5^\beta\, 5_\delta^*\, 45_\gamma^{\alpha\delta} + \frac{1}{2}\lambda_5 \left[5_\beta^*\, 45_\gamma^{\alpha\beta}\, 5_\delta^*\, 45_\alpha^{\gamma\delta} + 45_{\alpha\beta}^{\gamma *}\, 5^\beta\, 45_{\gamma\delta}^{\alpha}\, 5^\delta\right] + \lambda_6\, 45_\gamma^{\alpha\beta} 5^\gamma 5_\delta^* 45_{\alpha\beta}^{*\delta}. \end{aligned}$$

- **After SU(5) symmetry breaking**

$$V(H,D) = -\mu_H^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 - \mu_D^2 D^\dagger D + \lambda_2 (D^\dagger D)^2 + \lambda_3' (D^\dagger D)(H^\dagger H) + \frac{1}{2}\lambda_5 [(H^\dagger D)^2 + (D^\dagger H)^2] + \lambda_6' \left(\tilde{D}H\right)\left(\tilde{D}H\right)^\dagger,$$

- **The scalar potential of neutral Higgs bosons is given by**

$$V(H^0,D^0) = -\mu_H^2 H^{0*}H^0 + \lambda_1 (H^{0*}H^0)^2 - \mu_D^2 D^{0*}D^0 + \lambda_2 (D^{0*}D^0)^2 + \lambda_3' (D^{0*}D^0)(H^{0*}H^0) + \frac{1}{2}\lambda_5 [(H^{0*}D^0)^2 + (D^{0*}H^0)^2].$$

- **These neutral components develop vacuum expectations values: $\langle H^0 \rangle = v_1 \equiv v_5$ and $\langle D^0 \rangle = v_2 \equiv -3\, v_{45}$.**
- **In this case, he mass of the W-gauge bosons is given by $M_W = gv$, where $v = \sqrt{v_1^2 + v_2^2}$ and one defines $\tan\beta = v_2/v_1$.**
- **The minimization conditions are:**

$$-\mu_H^2 + 2\lambda_1\, v_1^2 + (\lambda_3' + \lambda_5) v_2^2 = 0,$$
$$-\mu_D^2 + 2\lambda_2\, v_2^2 + (\lambda_3' + \lambda_5) v_1^2 = 0.$$

CP-even Higgs bosons

- **Around the vacuum, H and D take the form:**

$$H = (H^+, H^0) = (H^+, v_5 + H_R^0 + iH_I^0),$$
$$D = (-D^+, D^0) = (-D^+, v_{45} + D_R^0 + iD_I^0),$$

- **The mass matrix of CP-even Higgs is given by**

$$M_R^2 = \begin{pmatrix} -\mu_H^2 + 6\lambda_1 v_1^2 + \lambda v_2^2 & \lambda v_1 v_2 \\ \lambda v_1 v_2 & -\mu_D^2 + 4\lambda_2 v_2^2 + \lambda v_1^2 \end{pmatrix} = \begin{pmatrix} 4\lambda_1 v_1^2 & \lambda v_1 v_2 \\ \lambda v_1 v_2 & 4\lambda_2 v_2^2 \end{pmatrix},$$

- **The mass eigenstates h and H are given by**

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_R^0 \\ D_R^0 \end{pmatrix},$$

- **The masses of the CP-even Higgs bosoes are**

$$M_{h,H}^2 = 2\lambda_1 v_1^2 + 2\lambda_2 v_2^2 \mp \sqrt{(2\lambda_1 v_1^2 - 2\lambda_2 v_2^2)^2 + \lambda^2 v_1^2 v_2^2}.$$

CP-odd & Charged Higgs bosons

- **The mass matrix of CP-even Higgs is given by**

$$M_I^2 = \begin{pmatrix} -\mu_H^2 + 2\lambda_1 v_1^2 + \lambda v_2^2 & 2\lambda_5 v_1 v_2 \\ 2\lambda_5 v_1 v_2 & -\mu_D^2 + 2\lambda_2 v_2^2 + \lambda v_1^2 \end{pmatrix} = \begin{pmatrix} -2\lambda_5 v_2^2 & 2\lambda_5 v_1 v_2 \\ 2\lambda_5 v_1 v_2 & -2\lambda_5 v_1^2 \end{pmatrix}.$$

- **The determinant of M_I^2 is zero. One eigenvalues vanishes, corresponds to the Goldstone boson. The other eigenvalue corresponds to the pseudoscalar Higgs A, with mass** $M_A^2 = 2\lambda_5(v_1^2 + v_2^2) = 2\lambda_5 v^2.$

- **The mass matrix of charged Higgs bosons**

$$M_{H^\pm}^2 = \begin{pmatrix} -\mu_H^2 + 2\lambda_1 v_1^2 + (\lambda_3' + \lambda_6')v_2^2 & (-\lambda_5 + \lambda_6')v_1 v_2 \\ (-\lambda_5 + \lambda_6')v_1 v_2 & -\mu_D^2 + 2\lambda_2 v_2^2 + (\lambda_3' + \lambda_6')v_1^2 \end{pmatrix} = \begin{pmatrix} (-\lambda_5 + \lambda_6')v_2^2 & (-\lambda_5 + \lambda_6')v_1 v_2 \\ (-\lambda_5 + \lambda_6')v_1 v_2 & (-\lambda_5 + \lambda_6')v_1^2 \end{pmatrix}.$$

- **One of the eigenvalues is zero and the other equal** $M_{H^\pm}^2 = (\lambda_6 - \lambda_5)v^2.$

Interactions with SM particles

- **The SM-like Higgs couplings to the SM fermions are:**

$$Y_{huu} = Y_3' \cos\alpha + Y_4' \sin\alpha = \frac{m_U}{v}\frac{\cos\alpha}{\cos\beta} + (\sin\alpha - \tan\beta\cos\alpha)Y_4',$$

$$Y_{hdd} = \left(\frac{3m_D + m_E.V_{CKM}}{4v_5}\right)\cos\alpha,$$

$$Y_{hee} = \left(\frac{3m_D V_{CKM}^\dagger + m_E}{4v_5}\right)\cos\alpha + \left(\frac{m_D V_{CKM}^\dagger - m_E}{4v_{45}}\right)\sin\alpha.$$

- **Here we assume flavor diagonal charged leptons and up-quarks, while down quark mass matrix is diagonalized by $V^d_L = V_{CKM}$ and $V^d_R = I$.**

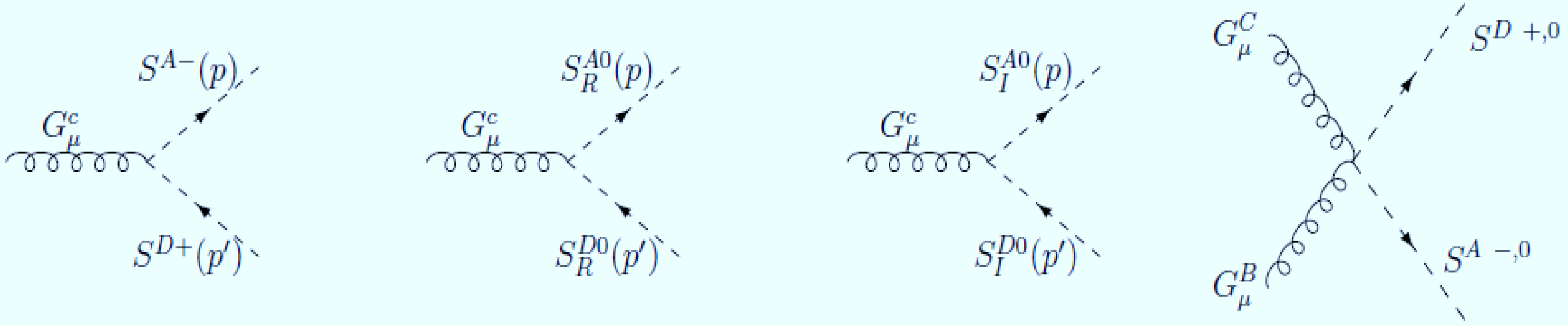
- **The couplings of h to W and Z are given by**

$$g_{hW_\mu^+W_\nu^-} \equiv gM_W \sin(\beta - \alpha)$$

$$g_{hZ_\mu Z_\nu} \equiv \frac{gM_z}{\cos\theta_W}\sin(\beta - \alpha),$$

Octet scalar Interactions with SM particles

- **Octet scalar interactions with the gluons:**



$-i/2g_s(p+p')^\mu \mathcal{F}^{ACD}$ $\quad$ $-i/2g_s(p+p')^\mu \mathcal{F}^{ACD}$ $\quad$ $-i/2g_s(p+p')^\mu \mathcal{F}^{ACD}$ $\quad$ $g^{\mu\nu} g_s^2 \mathcal{F}^{ABCD}$

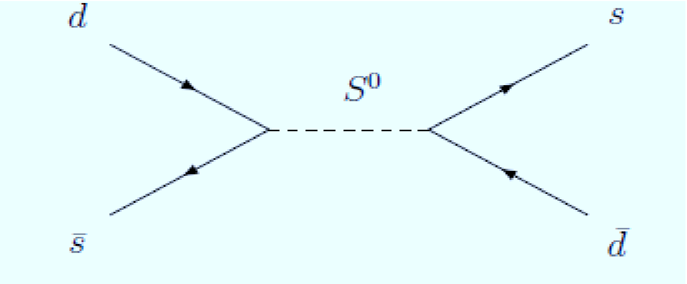
- **Octet scalar with lightest Higgs:**

$$hS^+S^- : -\lambda_3 v_5 \sin\alpha$$
$$hS_{0I}S_{0I} : -(\lambda_3+\lambda_4-\lambda_5)v_5 \sin\alpha$$
$$hS_{0R}S_{0R} : -(\lambda_3+\lambda_4+\lambda_5)v_5 \sin\alpha.$$

Constraints on octet scalar

- Constraints from $K^0 - \overline{K}^0$ & $B_q{}^0 - \overline{B_q}{}^0$

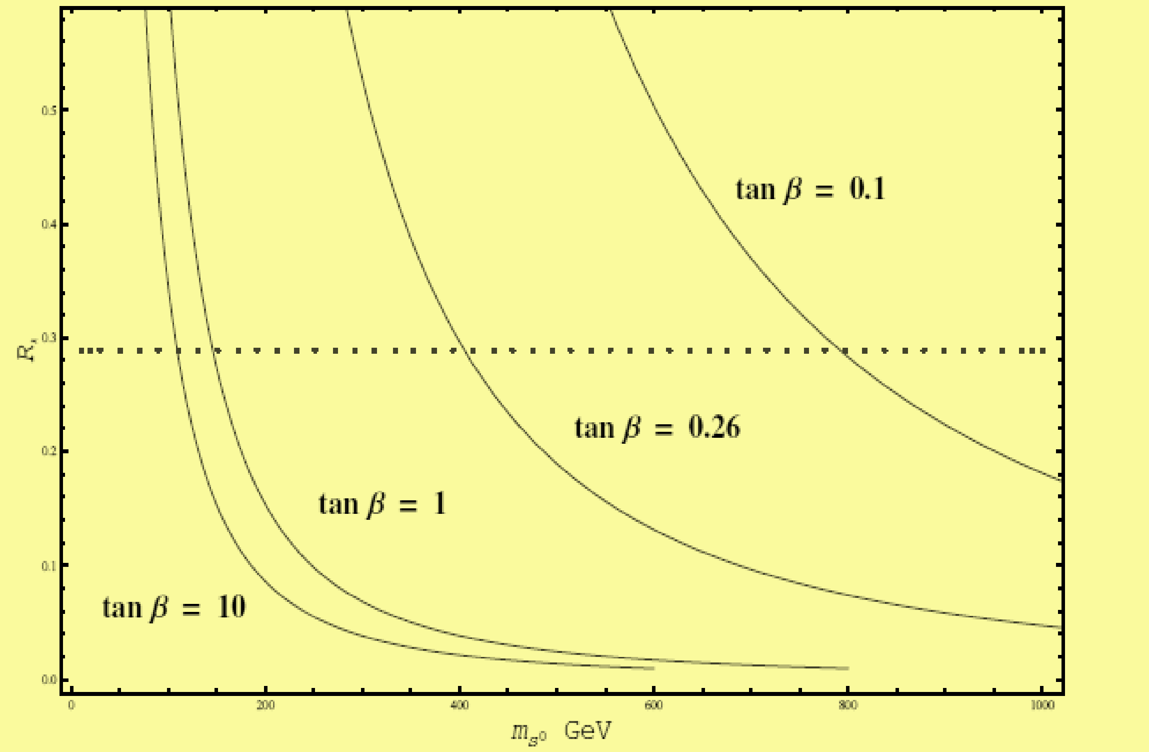
$$Y_{S^0 d_R d_L} = \frac{1}{4v_{45}} \left[M_D^{diag} - V_R^{d+}.M_E.V_L^d \right].$$



$\nabla M_K = \nabla M_K{}^{SM}$ $(1+R_K)$

$R_K = M_{12}(K)/M_{12}{}^{SM}(K)$

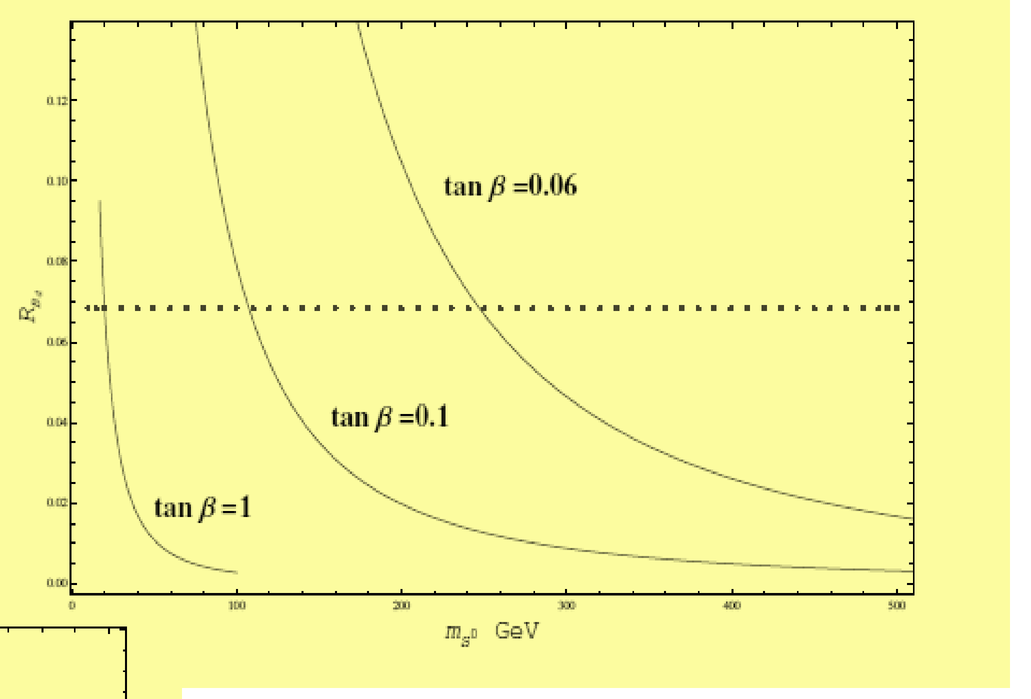
$R_K \leq 0.2891$

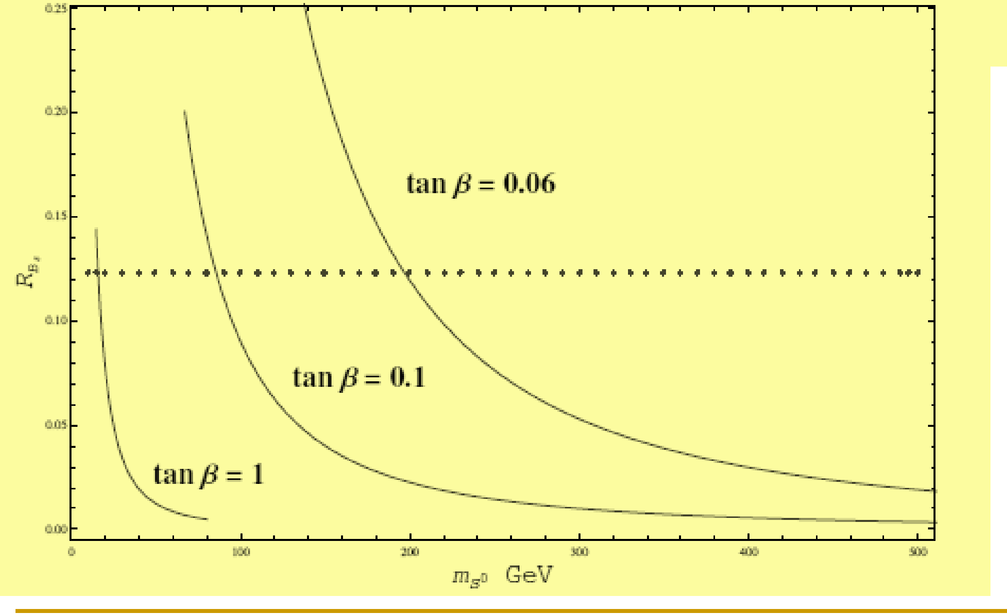


$B_d^0 - \overline{B_d}^0$ Constraints

$R_{Bd} = M_{12}(B_d)/M_{12}^{SM}(B_d)$

$R_{Bd} \leq 0.0683$





$B_s^0 - \overline{B_s}^0$ Constraints

$R_{Bs} = M_{12}(B_s)/M_{12}^{SM}(B_s)$

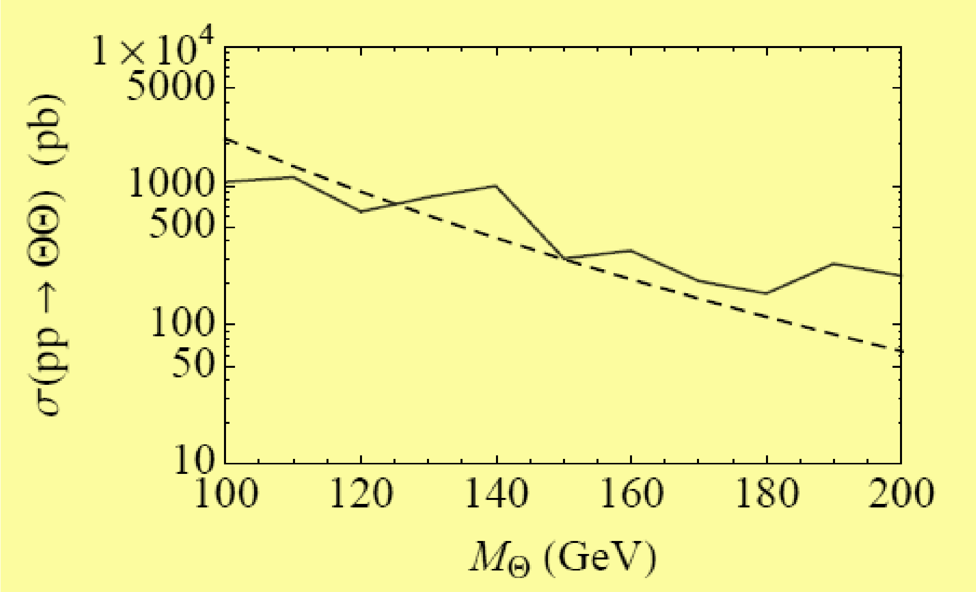
$R_{Bs} \leq 0.1220$

Direct Searches constraint

- The octet scalar can be pair produced copiously at the LHC:

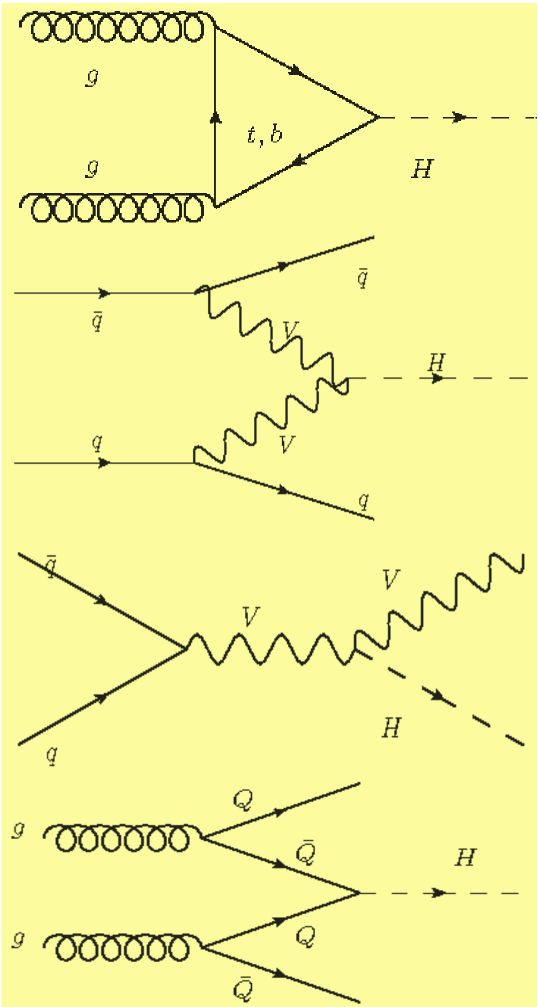
  $gg \to S^0 S^0$ or $gg \to S^+ S^-$
- The octet scalars decay to the SM quarks without missing energy.
- The associated signature is a pair of dijet resonances, with enormous QCD multi-jets background.

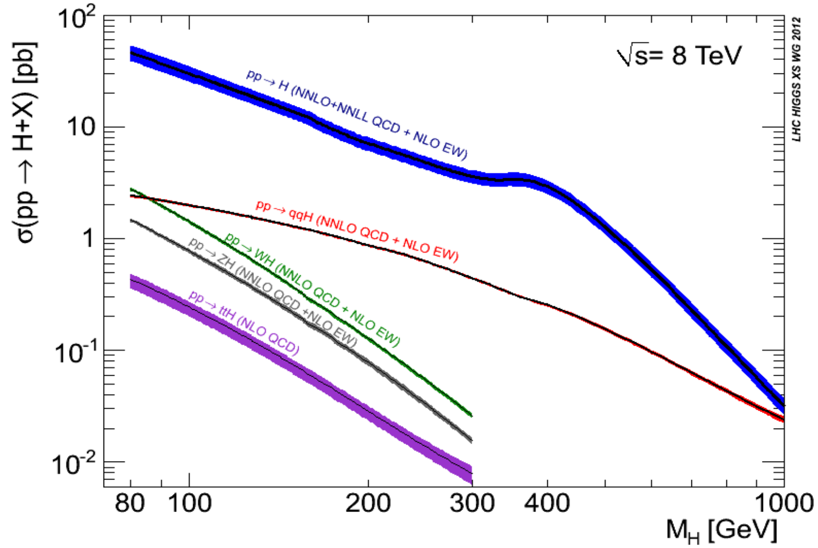
The latest result with $\sqrt{s} = 7$ Tev ruled out octet scalar masses less than 150 GeV at 90% CL limit.



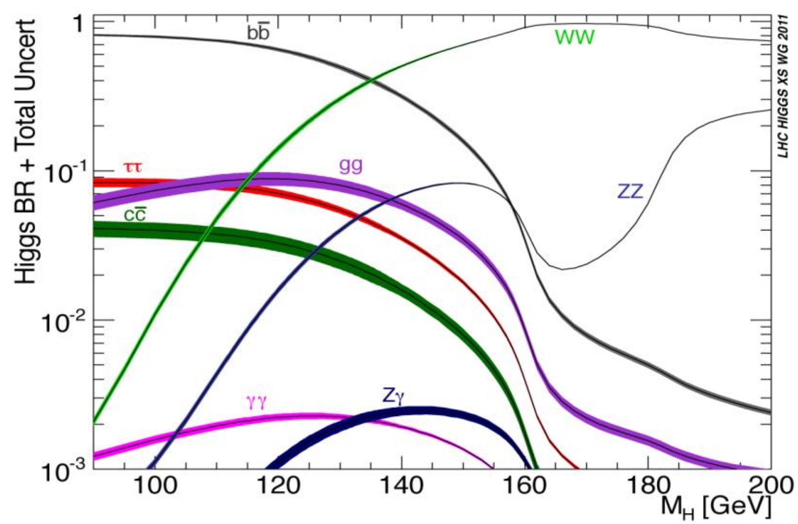
Limit on the production cross section for a pair of dijet resonances from ATLAS (solid line), and the leading- order theoretical cross section (dashed line) for pair production of a color-octet real scalar at the 7 TeV LHC.

SM Higgs at the LHC



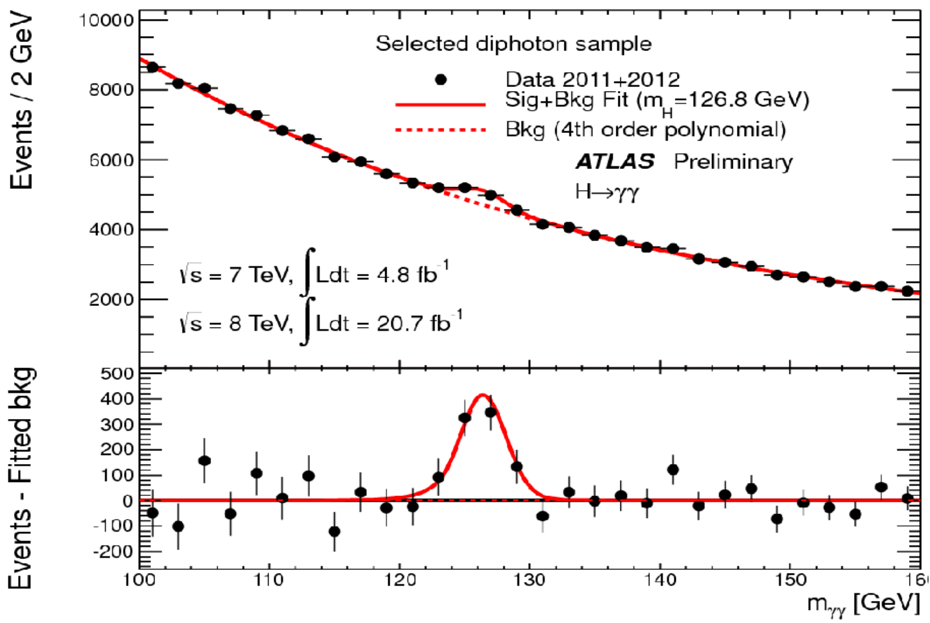


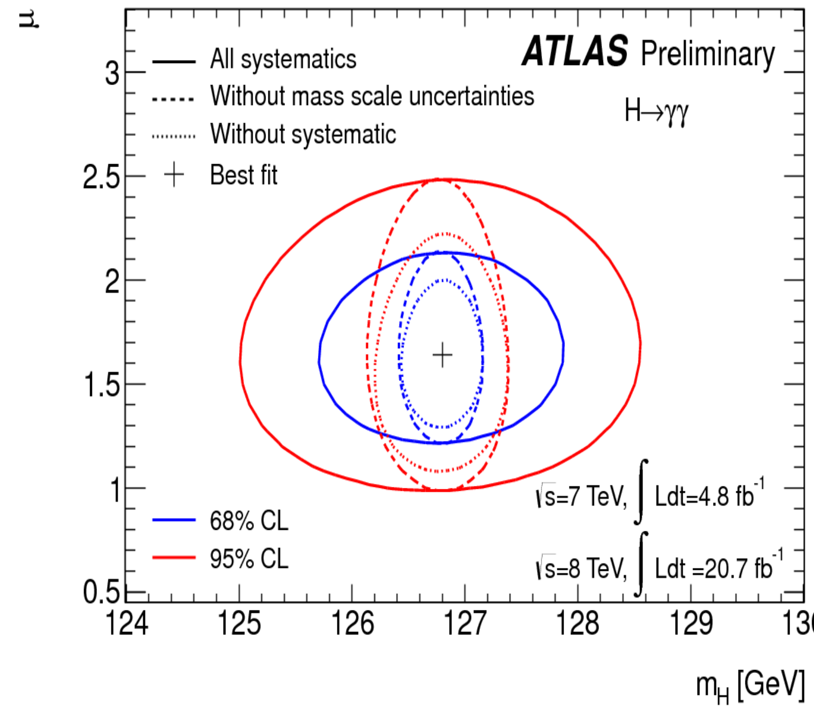
19.5 pb ggF
1.6 pb VBF
1.1 pb VH
0.1 pb ttH
@ mH=125 GeV



21.5 % WW
2.6 % ZZ
0.23 % γγ
0.15 % Zγ
@ mH=125 GeV

H→γγ: ATLAS results

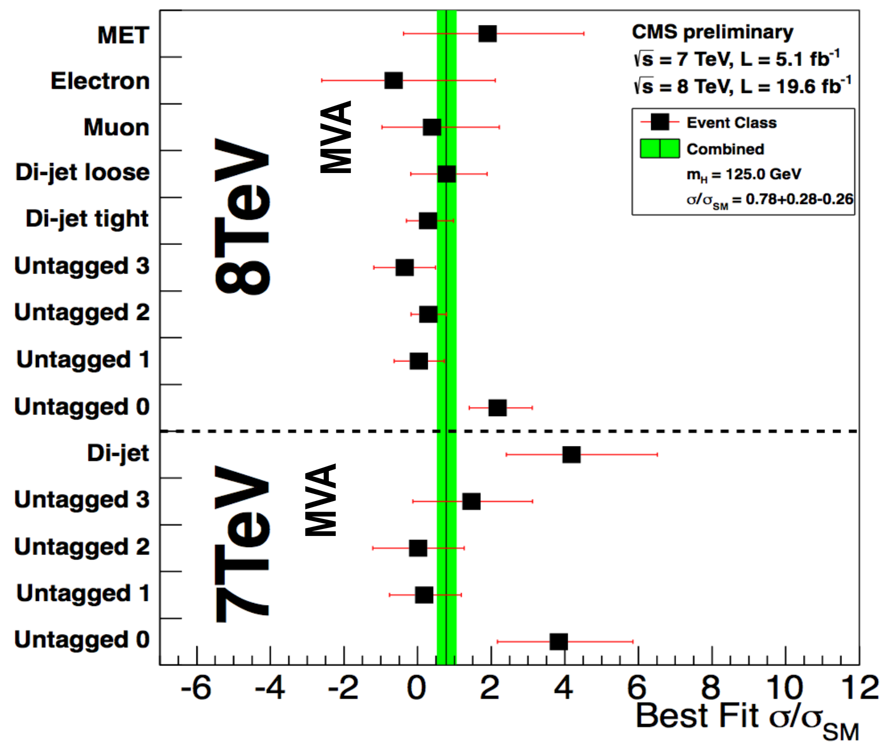




- Best fit mass:
- **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
- Signal strength:
- **1.65 ± 0.24 (stat)+0.25 -0.18(syst)**
- Dominant systematics contribution from theory, luminosity, γ energy scale

H→γγ: CMS Results

MVA mass-factorized

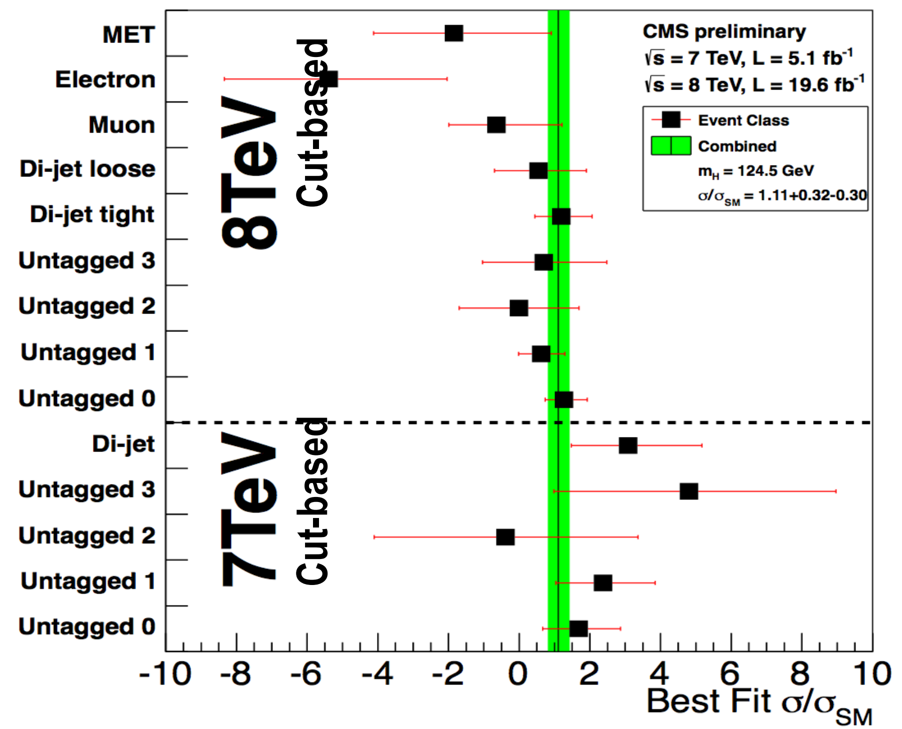


$7+8$ TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$

Cut-based



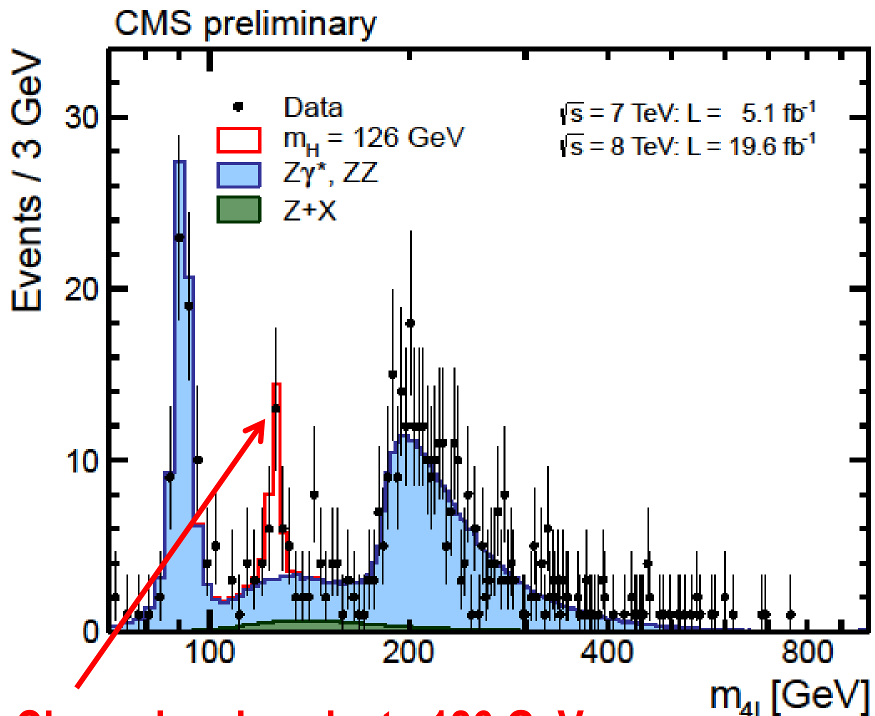
$7+8$ TeV: σ/σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$

8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

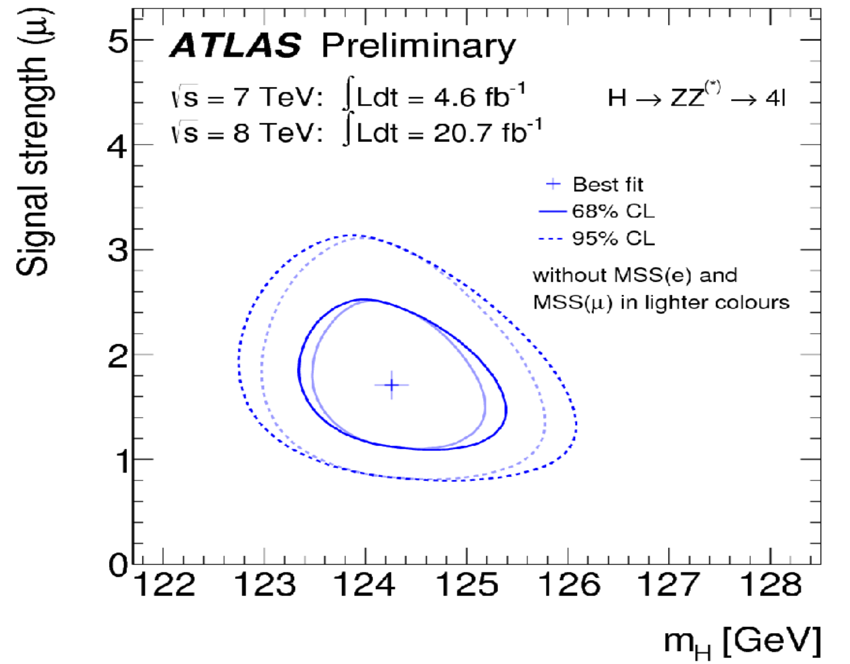
- Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent

H→ZZ*→4l: mass/signal stength



Clean signal peak at ~126 GeV

σ/σ_{SM} @ 125.8 GeV = $0.91^{+0.30}_{-0.24}$



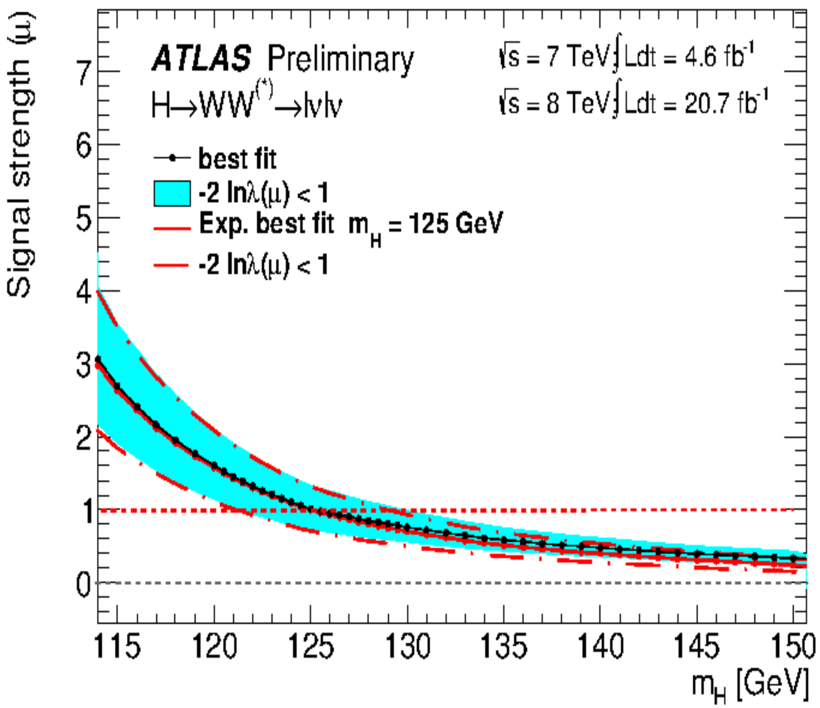
Best fit mass:

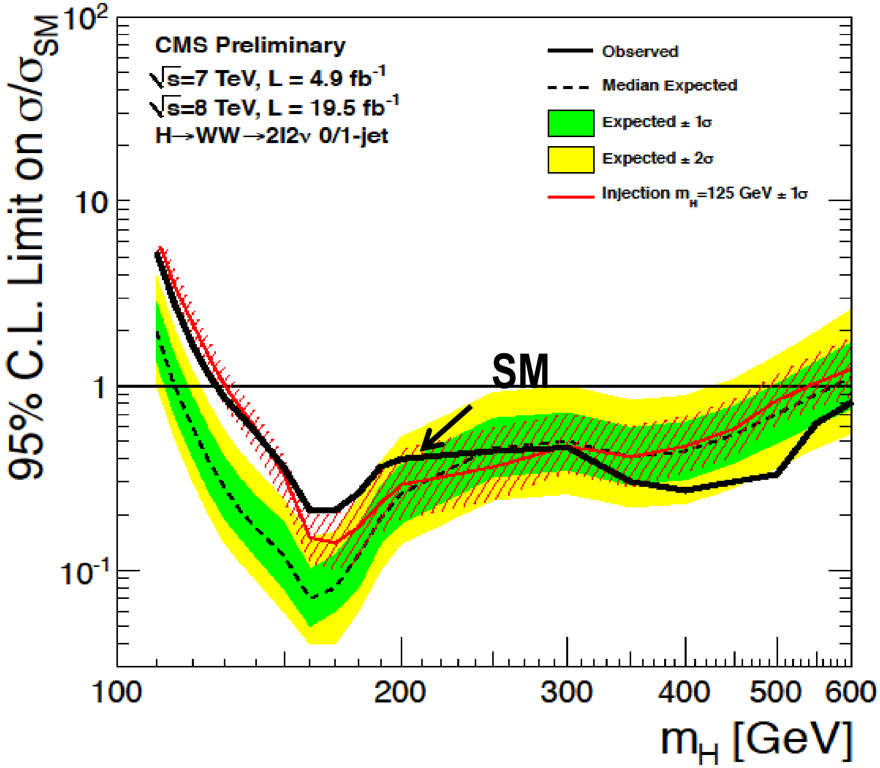
124.3 +0.6 -0.5(stat) +0.5 -0.3(syst) GeV

Signal strength:

1.7 +0.5 -0.4, for **mH=124.3 GeV [1.5 ± 0.4**, for **mH=125.5 GeV**

H →WW→2l2ν



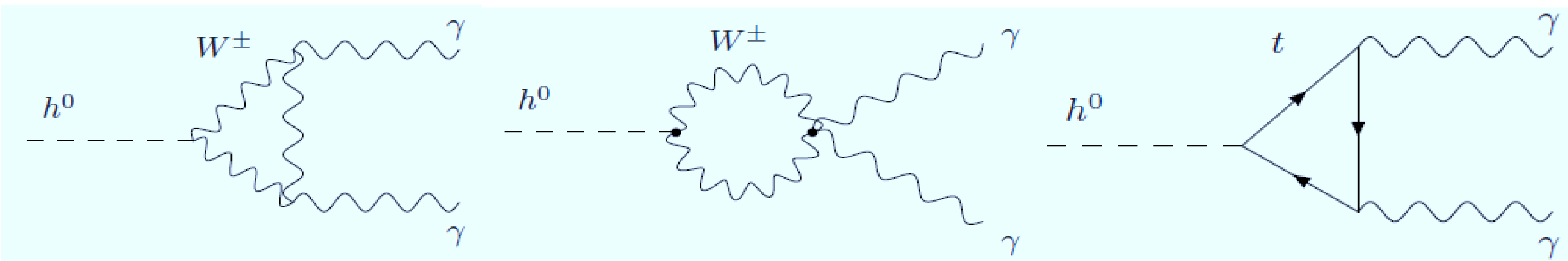


Signal strength at 125 GeV:
1.01±0.21(stat)±0.19(th)±0.12(syst)±0.04 (lumi)

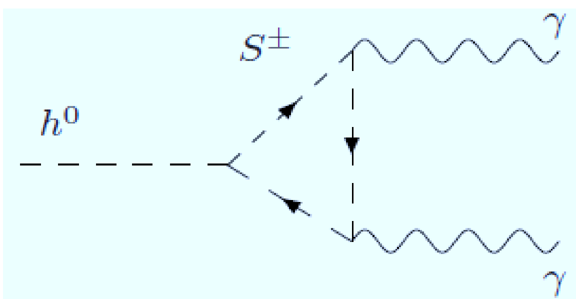
σ/σ_{SM} @ 125 GeV = 0.76 ± 0.21

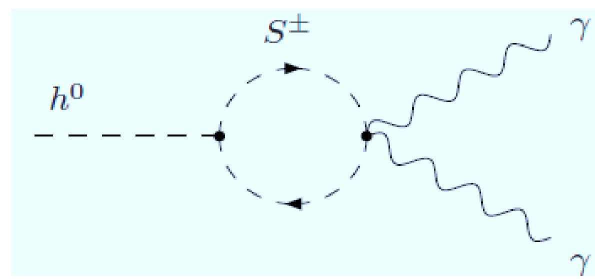
Color-octet contributions H→γγ

- **In SM H→γγ is generated via the one loop:**



- **In SU(5) effective model, we have new contributions:**





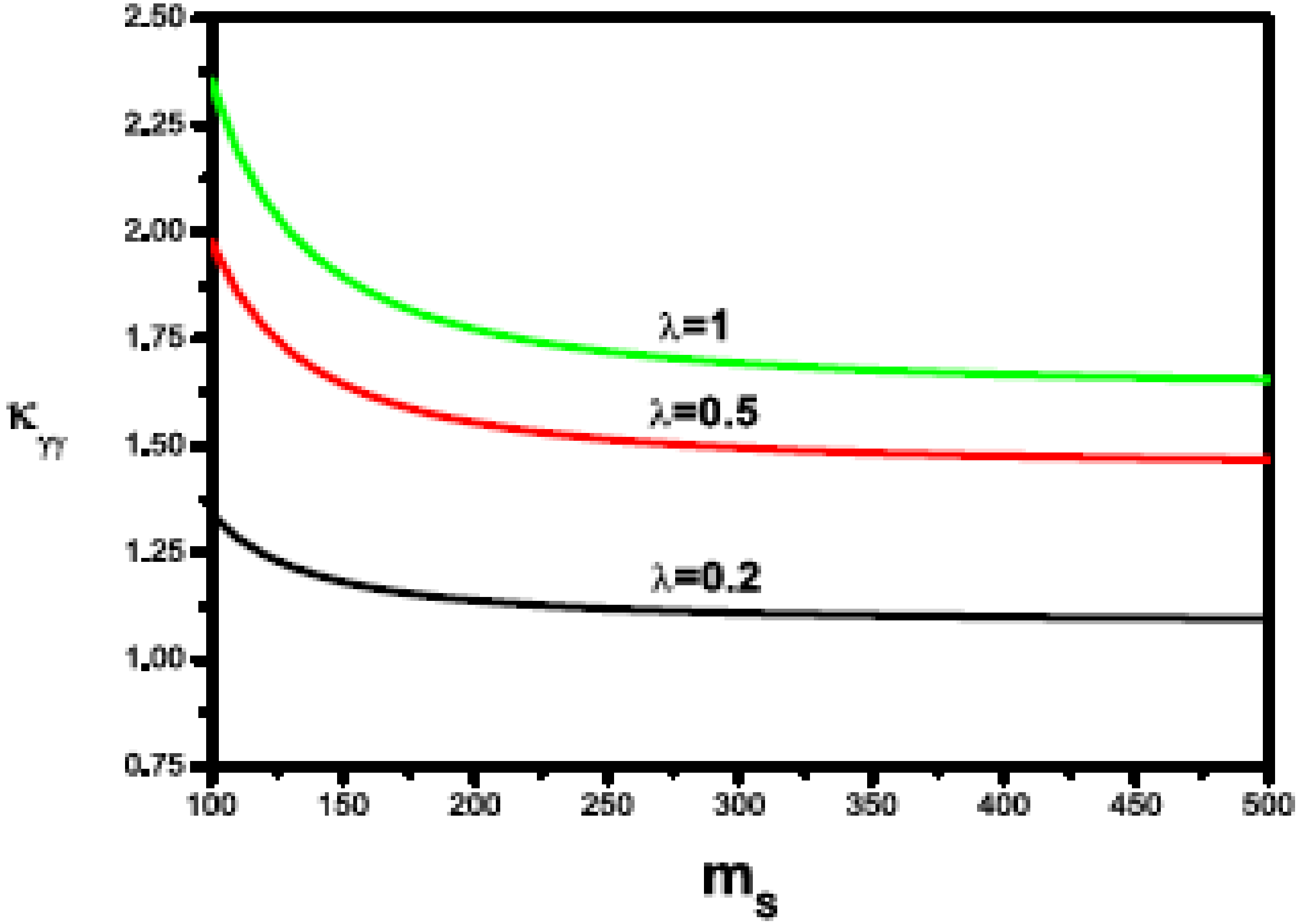
- **The di-photon partial decay width in SU(5) is given by**

$$\Gamma(h \to \gamma\gamma)_U = \frac{\alpha^2 m_h^3}{1024\pi^3}\left|\frac{g_{hWW}^U}{m_W^2} Q_W^2 A_1(\tau_W) + \frac{2Y_{ht\bar{t}}^U}{m_t} N_{c,t} Q_t^2 A_{1/2}(\tau_t) + N_{c,S} Q_S^2 \frac{g_{hS^{\pm}S^{\mp}}}{m_{S^{\pm}}^2} A_0(\tau_{S^{\pm}})\right|^2.$$

- For m_h =125 GeV, $A_1(\tau_W) \cong -8.32$ and $A_{1/2}(\tau_W) \cong +1.38$
- In order to enhance $\Gamma(h \to \gamma\gamma)$, we show have:
  - Constructive interference between S and W contributions: $g_{hS^+S^-} < 0$ since $A_0(\tau_S) > 0$.
  - Suppress the top contribution: $Y_t^{SU(5)} < Y_t^{SM}$.
- Usually, any enhancement to $\Gamma(h \to \gamma\gamma)$, leads to reduction in $\Gamma(h \to gg)$,

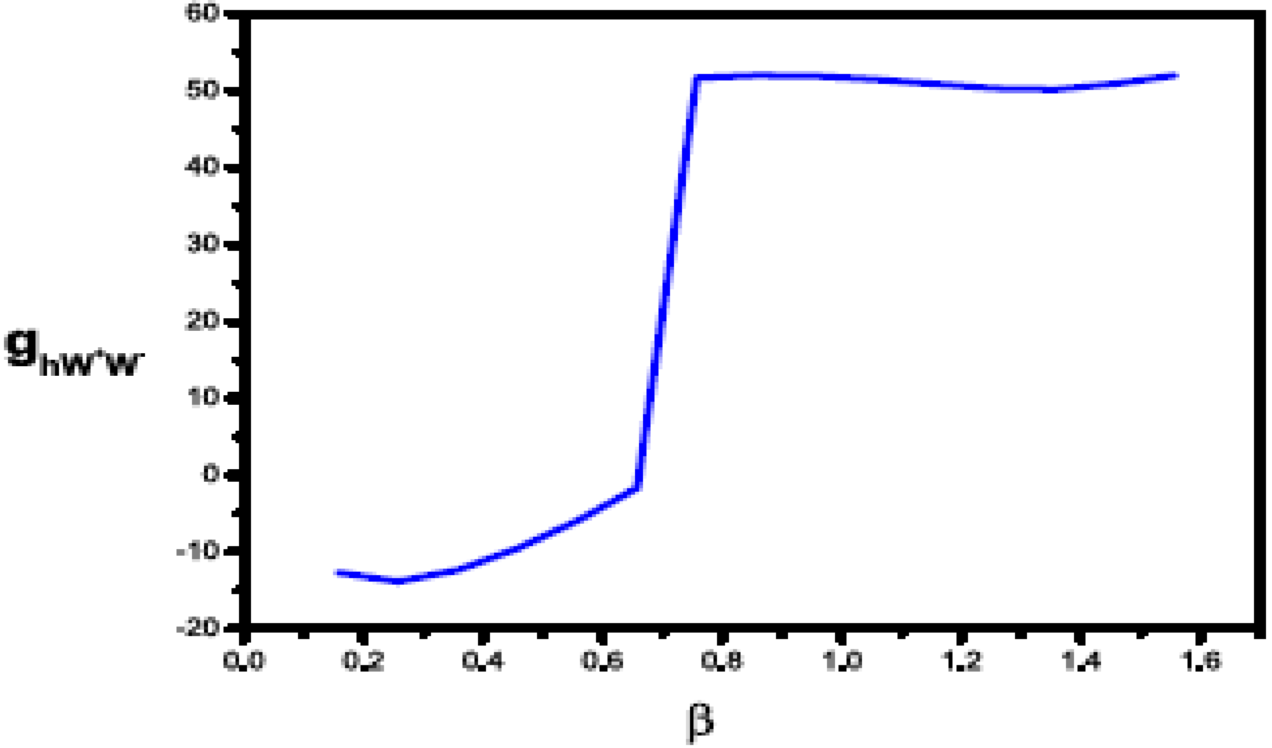
$$R_{\gamma\gamma} = \frac{\Gamma(h \to gg)^{SU(5)}}{\Gamma(h \to gg)^{SM}} \frac{\Gamma_{tot}^{SM}}{\Gamma_{tot}^{SU(5)}} \frac{\Gamma(h \to \gamma\gamma)^{SU(5)}}{\Gamma(h \to \gamma\gamma)^{SM}}.$$

- $g_{hSS} = -\lambda_3 v_5 \sin\alpha$ & $\sin\alpha < 0 \to \lambda_3 \cong O(-1)$.



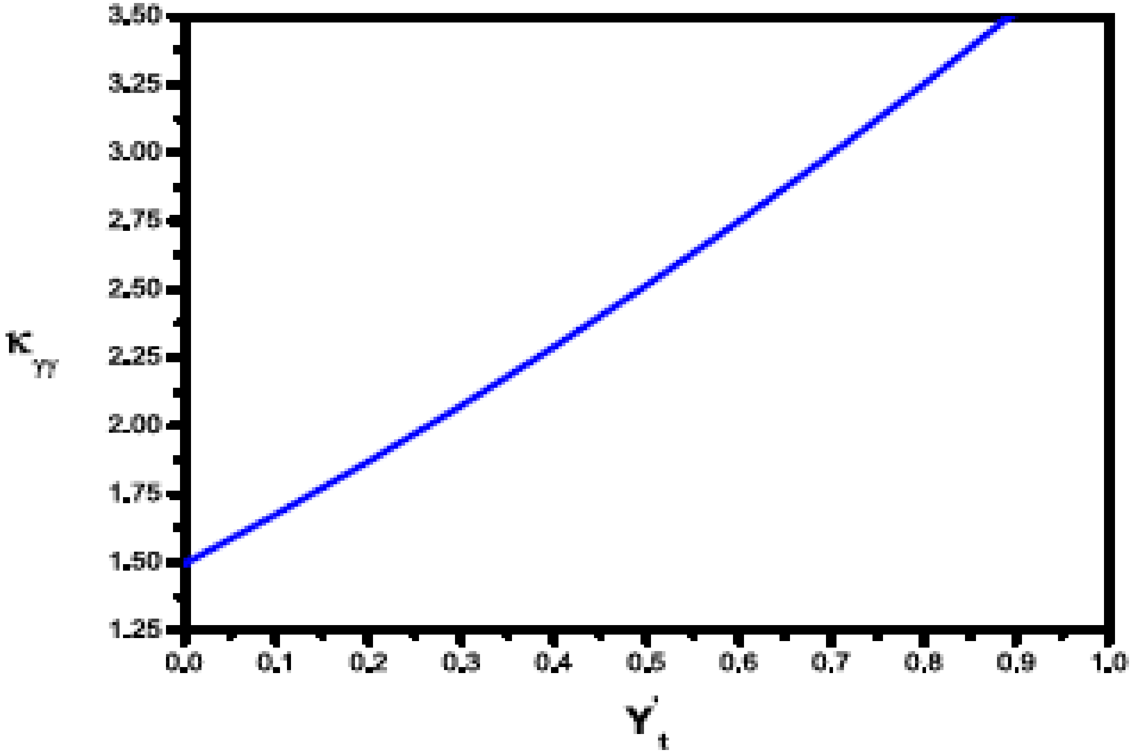
- $\kappa_{\gamma\gamma} = \dfrac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)^{SM}}$ **as a function of m_S for $\beta = \pi/4$, $\lambda_3 = -1$ & $Y'_t = Y_4 = 0.3$**

Constraint on tanβ from $g_{hW^+W^-}$



$$g_{hW^+W^-} = g\, M_W \sin(\beta - \alpha)$$

Modifying the top Contribution

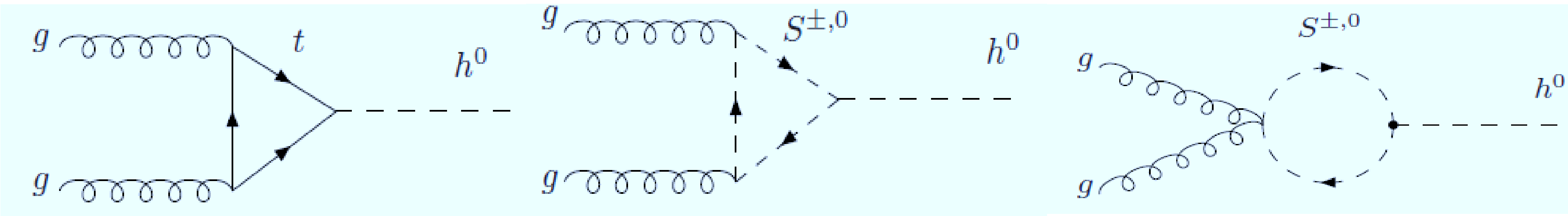


- **In SU(5) Y_{htt} can be easily reduced or even becomes negative**

$$Y_{htt} = \frac{m_t \cos\alpha}{v\cos\beta} + 4Y_4 \sin\alpha$$

$$m_t = 4(Y_3 + Y_3^T) v \cos\beta, with Y_4 = Y_4^T$$

Octet scalar & Higgs production



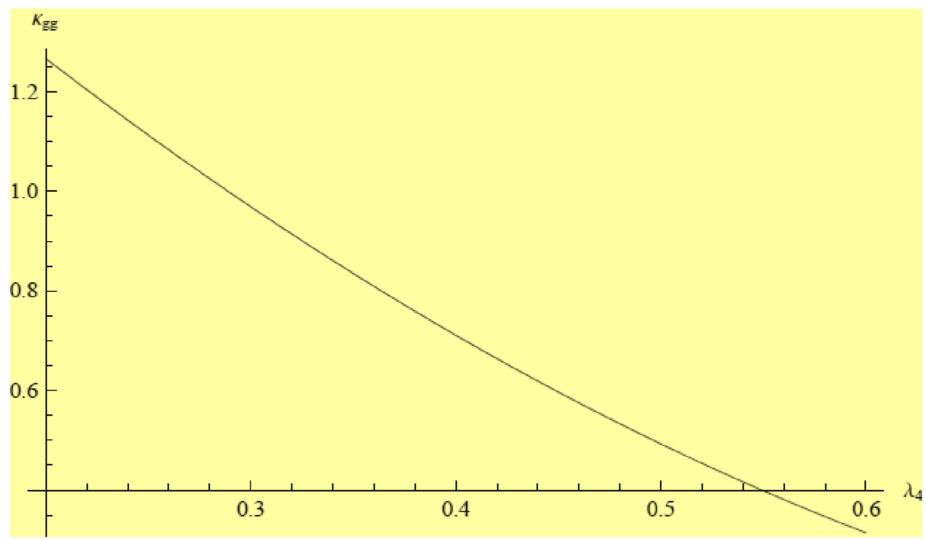
$$\Gamma(h\to gg)_U = \frac{\alpha_s^2 m_h^3}{128\pi^3}\left|C(r_t)\frac{2Y^U_{ht\bar t}}{m_t}A_{1/2}(\tau_t)+C(r_S)\frac{g_{hS^\pm S^\mp}}{m^2_{S^\pm}}A_0(\tau_{S^\pm})+C(r_S)\frac{g_{hSR^0SR^0}}{m^2_{S^0}}A_0(\tau_{S^0})+C(r_S)\frac{g_{hSI^0SI^0}}{m^2_{S^0}}A_0(\tau_{S^0})\right|^2.$$

Where

$C(r_t)=1/2$, $C(r_S)=3$

$$g_{hS^\pm S^\mp} = \frac{1}{2}(\lambda_3 + 2\lambda_4 + 2\lambda_5)$$

$$g_{hS^0S^0} = -\frac{1}{2}(\lambda_3 + 2\lambda_4 - 2\lambda_5)$$



Conclusions

- The LHC discovery of 125 GeV SM-like Higgs boson has been confirmed.

- Mass measurement: $H \to \gamma\gamma / H \to 4l$
- The observed signal strength: within ~2σ from SM expectation

- We investigated the capability of the effective SM derived from SU(5) with 45_H to explain the Higgs data.

- This model extends the SM by charged/neutral color-octet scalars and another Higgs doublet.

- These scalars are free from favor changing constraints and can be light.

- Charged and neutral octet scalars that contribute to $H \to \gamma\gamma$ and $H \to gg$.

- Reducing the top contribution and even the possibility of flipping its sign is a remarkable feature in this class of model

Thank you