# Discovery Potentials of Light Higgs at LHC

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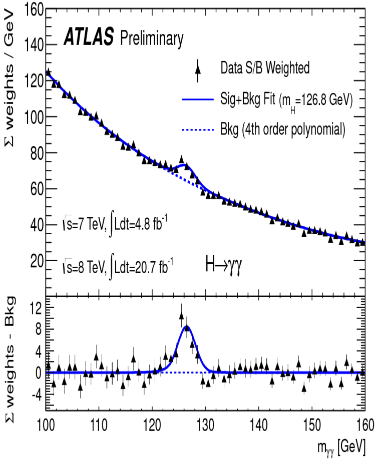
# Outline

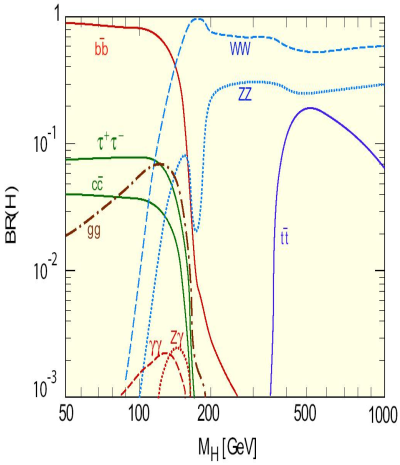
# What did we observe?




- On 4th of July 2012, Large Hadron Collider announced the discovery of a particle with mass 125 GeV.
- Is this 

?

# Higgs boson decay




Dominant decay to $b\bar{b}$ for $M_H < 130$ GeV.

- In the Standard model, Higgs couples to the gauge bosons via the Kinetic term i.e

$$D_\mu \Phi^\dagger D^\mu \Phi = \frac{M_V^2}{v} V^\mu V_\mu h$$

where

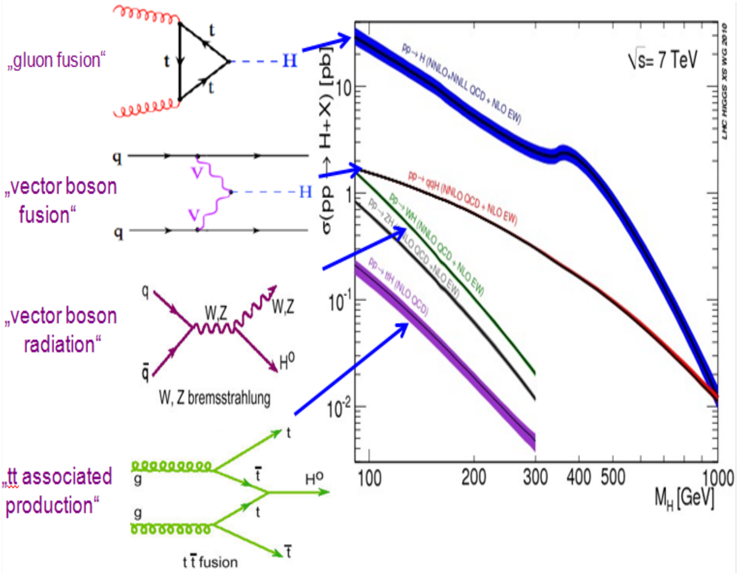
$$D^\mu \Phi = \partial_\mu + igTW_\mu + ig' B_\mu \begin{bmatrix} 0 \\ v+h \end{bmatrix}$$

- Higgs couples to the fermions via the Yukawa term

$$L_{yuk} = y_{ij} \bar{\Psi}^i \Phi \Psi^j = \frac{\sqrt{2} m_f}{v} \bar{\Psi} \Psi h$$

- Higgs couples to all particles via its mass

# Production at LHC



# Observing Higgs@LHC

- ggF $\to \gamma\gamma$
  - low branching ratio but clean environment
  - Possible to reconstruct the Higgs i.e photons 4-vectors are added to reconstruct the invariant mass of the intermediate particle.

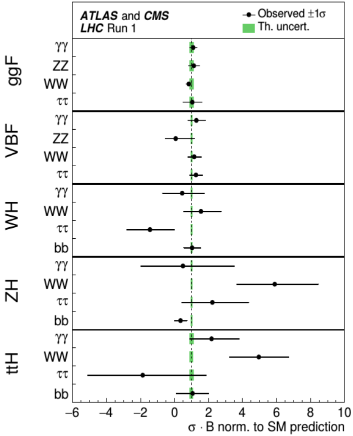
- ggF $\to ZZ^*$
  - Four lepton final states- clean environment and reconstruction

- ggF $\to WW^*$
  - due to the presence of neutrino, Higgs can not be reconstructed
  - probe electroweak symmetry breaking.

- VH $\to b\bar{b}$
  - clean signature compared to gluon fusion
  - leptons in the final state kills large multijet background
  - probing quark(down-type) coupling

- VBF/VH $\to \gamma\gamma, \tau\ \tau, WW^*, ZZ$ and $t\bar{t}h\ \to\ \gamma\gamma, b\bar{b}$ - can probe electroweak symmetry breaking and Yukawa structure

# Quantifying our observation




- Signal strength ($\mu$) defined as the ratio of the observed scalar rate to the SM expectation value i.e

$$\mu = \frac{\sigma(pp \to S \to ab)}{\sigma(pp \to h_{sm} \to ab)}$$

- The SM prediction lies close to the measured value of the signal strength for almost all channels -will improve with more events

- What does it mean?
  - No new physics- The scalar is our 'celebrated' Higgs and $\mu$ will become 1 with more precision.
  - It may belong to an enlarged scalar sector of a BSM scenario

# Where are the other scalars

- The BSM scenario will predict additional scalars along with the observed one.
- Till date, none of the searches at LHC has indicated any conclusive excess for additional scalars.
- In most of the analysis the scalars are assumed heavy and they are searched in $WW$, $ZZ$ and $hh$ decay mode.
- There might be a possibility that the scalars are light and till now, they are buried beneath huge SM backgrounds at the collider.
- The second phase of LHC is running with higher center of mass energy and with high luminosity- Is it possible to probe such scalars?

# Simplest extension - 2HDM

- The model has an additional $SU(2)_L$ doublet $\Phi_1$ along with SM fields.

- The Lagrangian is given by

$$\mathcal{L}_{\rm 2HDM} = (D_\mu \Phi_1)^\dagger D^\mu \Phi_1 + (D_\mu \Phi_2)^\dagger D^\mu \Phi_2 + \mathcal{L}_{\rm Yuk}(\Phi_1, \Phi_2) - V(\Phi_1, \Phi_2)$$

- $V(\Phi_1, \Phi_2)$ is the scalar potential,

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_{11}^2\, \Phi_1^\dagger \Phi_1 + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 \\ &\quad + m_{22}^2\, \Phi_2^\dagger \Phi_2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 - m_{12}^2 \Phi_1^\dagger \Phi_2 \\ &\quad + \lambda_3\, \Phi_1^\dagger \Phi_1\, \Phi_2^\dagger \Phi_2 + \lambda_4\, \Phi_1^\dagger \Phi_2\, \Phi_2^\dagger \Phi_1 \\ &\quad - \frac{1}{2} \lambda_5 \left( \Phi_1^\dagger \Phi_2 \right)^2 + h.c. \end{aligned}$$

# Types of 2HDM

- Most general Yukawa interaction is given by

$$\mathcal{L}_{\text{Yuk}} = \Sigma_{n=1,2}\overline{Q_L^i}\,\mathcal{Y}^d_{1\,ij}\Phi_n d_R^j + \overline{Q_L^i}\mathcal{Y}^u_{1\,ij}\Phi_n^c u_R^j + \overline{Q_L^i}\mathcal{Y}^e_{1\,ij}\Phi_n^c e_R^j + h.c.$$

- To suppress tree level FCNCs, the fermions should couple only to one doublet - A $Z_2$ symmetry is added

- Depending on which of the doublets couple to fermions, one can categorize 2HDM into four types:
  - Type 1 : $\Phi_2$ couples to fermions
  - Type 2: $\Phi_2$ couples to up-type quarks, $\Phi_1$ couples to down-type quarks and leptons
  - Lepton Specific (X) : $\Phi_2$ couples to quarks and $\Phi_1$ couples to leptons
  - Flipped (Y) : $\Phi_2$ couples to up-type quarks and leptons, $\Phi_1$ couples to down-type quarks

# Additional scalars

- Out of eight fields in $\Phi_n = \begin{pmatrix} \phi_n^+ \\ \frac{1}{\sqrt{2}}\left[\rho_n + i\eta_n + v_n\right] \end{pmatrix}$, three generates mass for $W, Z$ bosons and five physical scalars remains—h, H, A, $H^\pm$.

- The doublets can be expressed in terms of physical scalars and goldston bosons as

$$
\begin{aligned}
\Phi_1 &= \begin{pmatrix} G^+ \cos\beta + H^+ \sin\beta \\ \frac{1}{\sqrt{2}}\left[h \sin\alpha - H \cos\alpha + i\left(G \cos\beta + A \sin\beta\right) + v_1\right] \end{pmatrix} \\
\Phi_2 &= \begin{pmatrix} G^+ \sin\beta - H^+ \cos\beta \\ \frac{1}{\sqrt{2}}\left[-h \cos\alpha - H \sin\alpha + i\left(G \sin\beta - A \cos\beta\right) + v_2\right] \end{pmatrix}
\end{aligned}
$$

- $\alpha,\ \beta$ are the rotation angles that diagonalize the mass matrix of the scalars.

# Scalar Potential

- The potential is defined by eight parameters - $m_{11}$, $m_{22}$, $m_{12}$, $\lambda_i$'s.

- Masses of the scalars are given by,

$$m_A^2 = \left(\frac{m_{12}^2}{v_1 v_2} - 2\lambda_5\right) v^2 \ , \quad m_{H^\pm}^2 = m_A^2 + (\lambda_5 - \lambda_4) v^2 \ ,$$

$$\begin{pmatrix} m_h^2 \\ m_H^2 \end{pmatrix} = R^T M R \ \text{ where}$$

$$M = \begin{pmatrix} m_{12}^2 \tan^2\beta + \lambda_1 v_1^2 & -m_{12}^2 + (\lambda_3 + \lambda_4 + \lambda_5) v_1 v_2 \\ -m_{12}^2 + (\lambda_3 + \lambda_4 + \lambda_5) v_1 v_2 & m_{12}^2 \cot^2\beta + \lambda_2 v_2^2 \end{pmatrix}$$

and $\mathcal{R}$ is the rotation matrix, given by

$$\begin{pmatrix} \sin\alpha & -\cos\alpha \\ -\cos\alpha & -\sin\alpha \end{pmatrix}$$

# Trading Parameters

- Instead of using $\lambda_i$'s, the theory can be defined in terms of more 'physical' paramaters:
  - Masses of the scalars - $M_{H^\pm}, M_A, M_H, M_h$
  - Rotation angles - $\alpha$ and $\beta$
  - $m_{12}$- Softly broken $Z_2$ parameter- $m_H = 125$ GeV restricts the value of $m_{12}$. We have considered $m_{12}^2 = 1000$ GeV$^2$.

# Interactions

- The Yukawa interactions of the scalars is given by,

$$
\begin{aligned}
\mathcal{L}_{\rm Yuk} = \Sigma_k \quad & \overline{Q^i_L}\,\mathcal{Y}^d_{1\,ij}\Phi_k d^j_R + \overline{Q^i_L}\mathcal{Y}^u_{1\,ij}\Phi^c_k u^j_R + \overline{Q^i_L}\mathcal{Y}^e_{1\,ij}\Phi^c_k e^j_R + h.c.\ , \\
= \quad & -\sum_{f=u,d,\ell}\frac{m_f}{v}\left(\xi^f_h\overline{f}f\,h + \xi^f_H\overline{f}f\,H - i\xi^f_A\overline{f}\gamma_5 f\,A\right) \\
& -\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi^u_A P_L + m_d\xi^d_A P_R\right) - \frac{\sqrt{2}}{v}\xi^\ell_A\overline{\nu_L}\ell_R H^+ + h.c.\ .
\end{aligned}
$$

- Gauge interaction

$$
\begin{aligned}
\mathcal{L}_{\rm V-H} \quad &= \frac{m_Z^2}{v}\xi^V_h Z_\mu Z^\mu h + \frac{m_Z^2}{v}\xi^V_H Z_\mu Z^\mu H + 2\frac{m_W^2}{v}\xi^V_H W_\mu W^\mu H \\
& + + 2\frac{m_W^2}{v}\xi^V_h W_\mu W^\mu h + \frac{g\xi^V_H}{2\cos\theta_W}(p^\mu_h + p^\mu_A)Z_\mu A\,h \\
& -\frac{i\,g\cos 2\theta_W}{2\cos\theta_W}(p^\mu_{H^+} + p^\mu_{H^-})Z_\mu H^+H^- - i\,e\,(p^\mu_{H^+} + p^\mu_{H^-})A_\mu H^+H^- \\
& -\frac{g\xi^V_h}{2\cos\theta_W}(p^\mu_H + p^\mu_A)Z_\mu A\,H
\end{aligned}
$$

# Interactions

| | Type I | Type II | Lepton-specific | Flipped |
|---|---|---|---|---|
| $\xi_h^u$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $\xi_h^d$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $\xi_h^\ell$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |
| $\xi_H^u$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $\xi_H^d$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $\xi_H^\ell$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ |
| $\xi_A^u$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $\xi_A^d$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\tan\beta$ |
| $\xi_A^\ell$ | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ |

$$\xi_h^V = \sin(\beta-\alpha) \quad , \quad \xi_H^V = \cos(\beta-\alpha)\,.$$

## $\gamma\gamma$ and $gg$

$$
\begin{aligned}
\mathcal{L}_{\gamma\gamma(\mathrm{gg})-\mathrm{H}} &= \frac{\alpha_s}{8\pi v} G^a_{\mu\nu} G^{a\mu\nu} \left( \xi^f_h F_{1/2}(\tau_f) h + \xi^f_H F_{1/2}(\tau_f) H \right) \\
&+ \frac{\alpha_e}{8\pi v} F_{\mu\nu} F^{\mu\nu} \left( \xi^f_h \frac{4}{3} F_{1/2}(\tau_f) + \xi^V_h F_1(\tau_W) \right) h \\
&+ \frac{\alpha_e}{8\pi v} F_{\mu\nu} F^{\mu\nu} \left( \xi^f_H \frac{4}{3} F_{1/2}(\tau_f) + \xi^V_H F_1(\tau_W) \right) H \\
&+ \frac{\alpha_e}{4\pi v} F_{\mu\nu} \tilde{F}^{\mu\nu} \left( \xi^f_A \frac{4}{3} F_{1/2}(\tau_f) \right) A \\
&+ \frac{\alpha_s}{4\pi v} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} \left( \xi^f_A F_{1/2}(\tau_f) A \right)
\end{aligned}
$$

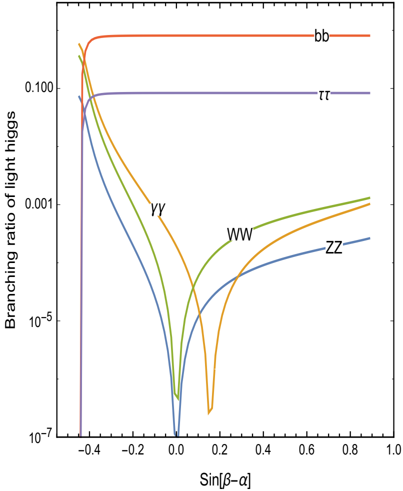
$$
\xi^\gamma_h = \xi^f_h \frac{4}{3} F_{1/2}(\tau_f) + \xi^V_h F_1(\tau_W) \text{ and } \xi^\gamma_H = \xi^f_H \frac{4}{3} F_{1/2}(\tau_f) + \xi^V_H F_1(\tau_W) \,,
$$

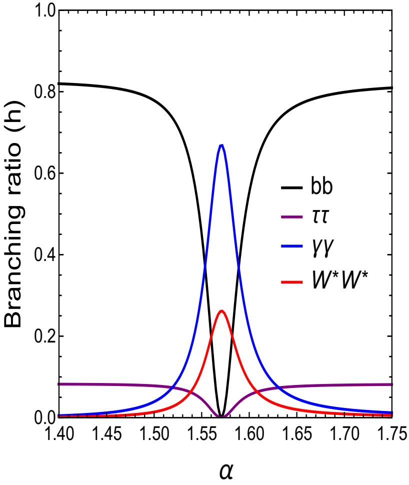
# Working Plan

- We consider H as the observed scalar i.e $m_H = 125$ GeV.
- Where is the lighter scalar i.e $h$?
  - Can be lighter than $m_h/2$ : $H \to hh$ is possible and there will be exotic signatures such as $4\mu, 4\gamma$, $2b2\mu$, $2\mu 2\tau$ etc.
  - $m_h > 65$ GeV: Single production will be same as that of SM Higgs with its decay to $\gamma\gamma$, $b\bar{b}$, $\tau\tau$ and $VV^*$ - Higgs searches of Run-1 can be used to look for it.

## Decay of h

- Branching ratio of h in Type-I ($m_h = 80$ GeV and $\tan\beta = 2$)



# Special points

- At $\alpha \to \pi/2$, $\xi_h^f$ vanishes and $h$ behaves as fermiophobic- $h$ decays dominantly to diphoton.
- $\alpha \sim \beta$, the coupling of H is exactly same as SM Higgs - termed as alignment limit and $h$ becomes fermiophillic.
- The aim of the analysis to probe the parameter space robustly using interplay of various channels
  - ggF/tth $\to \gamma\gamma$
  - $Wh/VBF \to \gamma\gamma$
  - $Wh/VBF \to f\bar{f}$
  - $tth \to tt\bar{f}f$

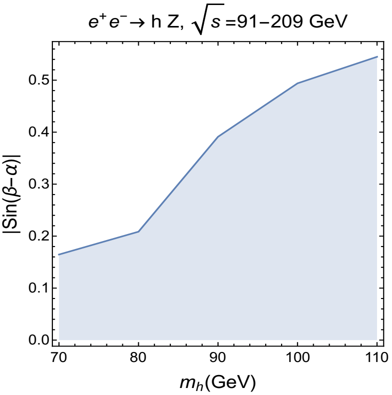
# Constraints

- We considered the region consistent with
  - Perturbative bounds - The quartic Higgs coupling $C_{H_i H_j H_k H_l} < 4\pi$ -Large masses of scalars are not allowed.
  - The potential should have a stable minima i.e .

$$\lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq \sqrt{\lambda_1 \lambda_2} \text{ and } |\lambda_3 + \lambda_4 - |\lambda_5|| > -\sqrt{\lambda_1 \lambda_2}$$

  - The scattering amplitude of longitudinal gauge bosons with Higgs should follow perturbative unitarity.
  - The T parameter forces $m_A \sim m_{H^\pm}$ for $m_{H^\pm} > 200$ GeV. For $m_{H^\pm} < 200$ GeV, $m_A$ is unconstrained.
  - The charged Higgs contributes to processes such as $B_s \to s\gamma, B_s \to \mu^+\mu^-$. For Type-I scenario, the couplings are suppressed by $\tan\beta$ and hence, the parameter space is not constrained for $\tan\beta > 2$

# LEP constraints




- LEP has extensively searched for light Higgs in $e^+e^- \to Zh$ channel in $b\bar{b}$ and $\tau\tau$ channel.
- Null observation of excess over SM background put a stronger limit on $\xi_h^V$ i.e $\sin(\beta - \alpha)$
- LEP has also searched for fermiophobic Higgs in $e^+e^- \to Z \to hA \to b\bar{b}\gamma\gamma$. No signal implies that the fermiophobic limit $(\alpha \sim \pi/2)$ is ruled out for $m_h + m_A < 189$ GeV. We consider $m_A = m_{H^\pm} = 500$ GeV.

# LHC observables

- H is the scalar at 125 GeV - Signal strength measurement will constraint couplings of $H$ i.e $\xi_H^V, \xi_H^f, \xi_H^\gamma$

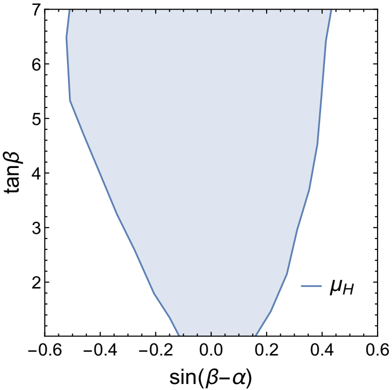
- We parametrize

$$\mu_j^i = \mu^i \mu_j, \quad \mu^i = \frac{\sigma(i \to H)}{\sigma(i \to H_{\rm SM})}, \quad \mu_j = \frac{{\rm BR}(H \to j)}{{\rm BR}(H_{\rm SM} \to j)}$$

| | $f\bar{f}$ | $VV^*$ | $\gamma\gamma$ |
|---|---|---|---|
| ggF/ttH | $(\xi_H^f)^4$ | $(\xi_H^f)^2(\xi_H^V)^2$ | $(\xi_H^f)^2(\xi_H^\gamma)^2$ |
| VBF/VH | $(\xi_H^V)^2(\xi_H^f)^2$ | $(\xi_H^V)^4$ | $(\xi_H^V)^2(\xi_H^\gamma)^2$ |

Table : The $ij^{\rm th}$ element is defined as $\mu_j^i \times \Sigma_k (\xi_H^k)^2\ {\rm BR}(H_{\rm SM}^{125} \to k)$. The summation is over $k$ where $k$ denotes all possible decay modes of H.

# LHC constraints




- Negative region of $\sin(\beta - \alpha)$ is ruled out by $\mu_{125}^{\gamma\gamma}$ due to large destructive interference of top and W loop.

- Positive $\sin(\beta - \alpha)$ is ruled out from $\mu_{125}^{ggF}$. With increase in $\sin(\beta)$, $\mu_H^{ggF}$ decreases.

- With increase in $\tan\beta$ amount of destructive interference decreases and $\mu_H^{\gamma\gamma}$ approaches 1 - Negative region is slightly favored for large $\tan\beta$.

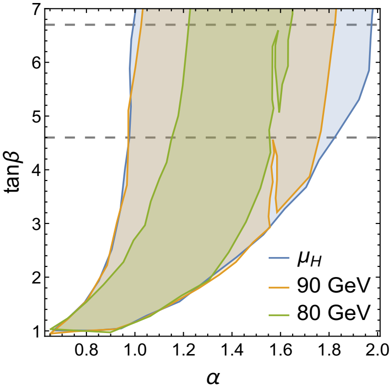
## LHC observables

- The effective scaling factor of total cross section for $h$ where it has been produced in $i^{th}$ channel and it decays to $j^{th}$ channel is given by the

| | $f\bar{f}$ | $VV^*$ | $\gamma\gamma$ |
|---|---|---|---|
| ggF/tth | $(\xi_h^f)^4$ | $(\xi_h^f)^2(\xi_h^V)^2$ | $(\xi_h^f)^2(\xi_h^\gamma)^2$ |
| VBF/Vh | $(\xi_h^V)^2(\xi_h^f)^2$ | $(\xi_h^V)^4$ | $(\xi_h^V)^2(\xi_h^\gamma)^2$ |

Table : The ij$^{\rm th}$ element of the table is defined as $\sigma_j^{h\ i} \times \Sigma_k (\xi_h^k)^2$ BR$(h_{\rm SM} \to k)$. $\sigma_j^{h\ i}$ represents the production cross section of SM-like Higgs (with mass $m_h$) in $i^{th}$ channel times its branching ratio in $j^{th}$ channel. The summation is over $k$ where $k$ denotes all possible decay modes of h.

# Direct Detection bounds




- LHC has searched for a lighter Higgs in diphoton channel in ggF as well as associated gauge boson production mode.
- Excluded region corresponds to $\alpha \sim \pi/2$ i.e fermiophobic limit.
- With increase in $\tan\beta$, $\sin(\beta - \alpha)$ decreases and $Wh$ production rate decreases -Wedge-like structure
- As mass increases $Wh$ production rate decreases and the search does not rule out any additional parameter space.

# Outline

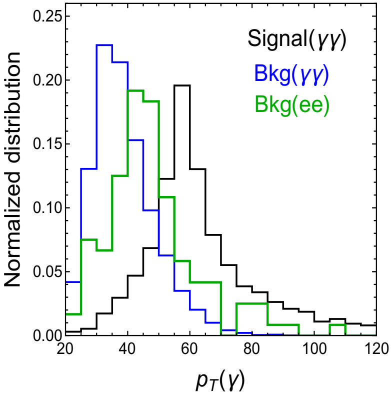
# Channels to explore

- We consider the following channel:
  - $pp \to \gamma\gamma$
  - $pp \to Wh \to l\nu\gamma\gamma$
  - $pp \to Wh \to l\nu b\bar{b}$
  - $pp \to tth \to ttb\bar{b}$.

# Channel 1: $pp \to \gamma\gamma$

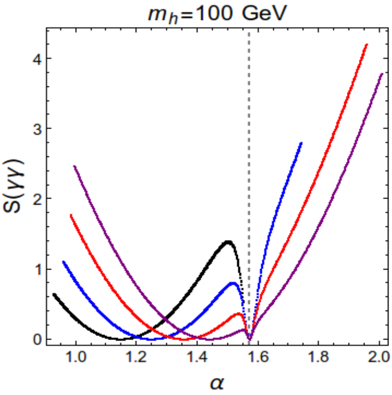
- Our signal topology is two isolated photons.
- SM backgrounds mimicking two isolated photons are
    - $\gamma\gamma$ : quark-quark annihilation and gluon box process produces two isolated photons
    - $j\gamma$: $\pi^0 \to \gamma\gamma$ conversion produces two collimated photons that gets detected as a single photon at detector.
    - Drell Yan ($Z \to e^+e^-$): Electron can fake a photon due to track mismeasurement and we consider 5% probability. Near Z-pole, the background is comparabble to $\gamma\gamma$.

# Selection Criteria




- Inspite of large cross section for $j\gamma$ process, the background can be suppressed by demanding tight isolation criteria.
- $p_T$ of photons arising from signal peak near $m_h/2$ -We applied a hard $p_T$ cut that suppresses irreducible $\gamma\gamma$ background.
- Finally, owing to clean reconstruction of diphoton invariant mass, we select events with $m_{\gamma\gamma}$ around 5 GeV bin of $m_h$ i.e. $|m_h - m_{\gamma\gamma}| < 2.5$ GeV.

# Significance




Black($\tan\beta = 3$), Blue ($\tan\beta = 4$), Red ($\tan\beta = 6$), Purple ($\tan\beta = 10$)

- The channel can probe large $\alpha$ region i.e $\sin(\beta - \alpha) < 0$ -constructive interference between top and W loop.
- The dip in significance corresponds to $\xi_h^f \to 0$ and $\xi_h^\gamma \to 0$ -Channel is insensitive for probing fermiophobic limit.
- With increase in $\tan\beta$, gluon fusion production rate decreases ($\xi_h^f$) and hence, significance decreases.
- For lower mass (till $m_h = 90$) GeV, the significance is low even with $3000 fb^{-1}$.

# Channel 2: $pp \to Wh \to l\nu\gamma\gamma$

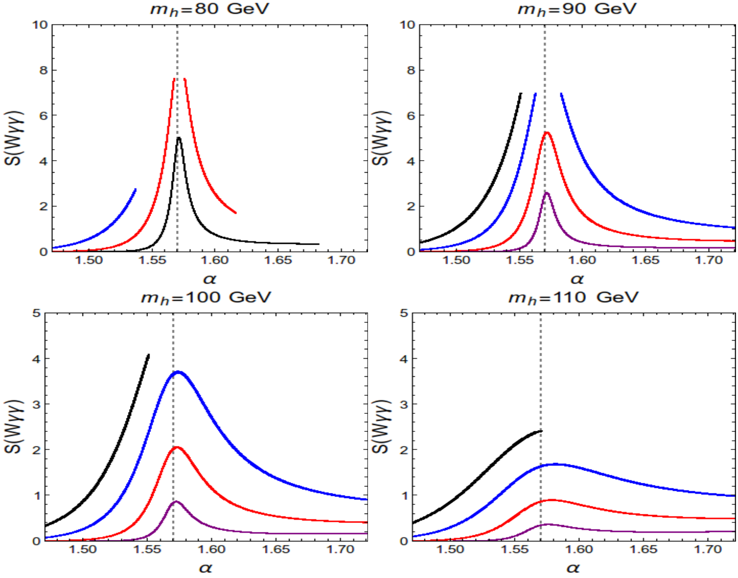
- Signal : an isolated lepton, two isolated photons and $E_T^{miss} > 30$ GeV.

- The channel is relatively cleaner with the following SM backgrounds:
  - hard photon emitted from $pp \to W\gamma$ and $Wj$ processes.
  - $pp \to WZ$ where $Z \to e^+e^-$.

- To suppress SM backgrounds, we selected events with

$$p^{\gamma}_{T_{\rm lead}} > \frac{m_h}{2} - 10 \text{ GeV} \;, p^{\gamma}_{T_{\rm sub}} > \frac{m_h}{2} - 15 \text{ GeV} \;, |m^{\gamma\gamma}_{\rm inv} - m_h| < 2.5 \text{ GeV} \;.$$

## Significance

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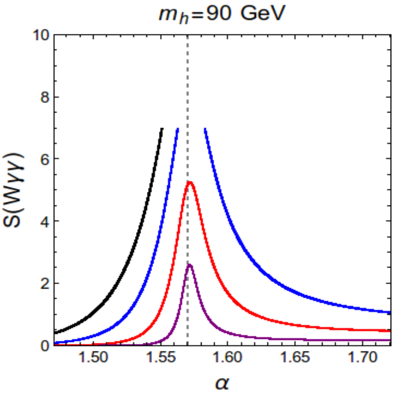
# Significance




- The channel has outstanding performance near fermiophobic limit i.e $\alpha \sim \pi/2$ for moderate values of $\tan\beta$.
- With increase in mass, production rate of $Wh$ decreases and hence, significance decreases.
- For lower $\tan\beta$, $\alpha \sim \pi/2$ is already ruled out by LHC signal strength measurements.
- With increase in $\tan\beta$, $\sin(\beta - \alpha)$ i.e $\xi_h^V$ decreases.

## Channel 3: $pp \to Wh \to l\nu b\bar{b}$

- Signal is two b-tagged jets, an isolated leptons and $E_T^{miss} > 30$ GeV.

- The channel accompanies huge SM backgrounds -
  - $WZ$ - Z decaying to $b\bar{b}$ - Maximum cross section around $Z - pole$.
  - $t\bar{t}$ - If one of the W escapes detection, $\sigma_{tt}^{14TeV} = 900$ pb.
  - $W$+jets: jets fake b jets.

- The value of $\xi_h^V$ is constrained for $m_h \leq 90$ GeV and hence, the $Wh$ production cross section is really small.

- It is nearly impossible to observe any excess using conventional approaches.

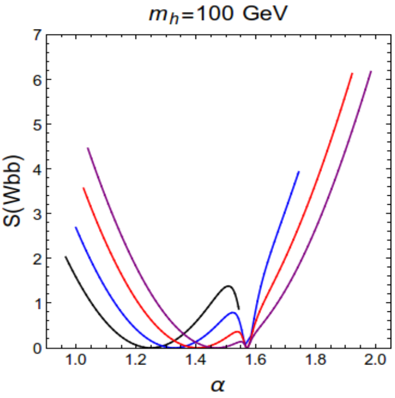
# Way out...

- Instead of looking into two b-jets, consider the kinematic region where $p_T^h > 2m_h$ - Small fraction of events are present

- The two b's are collimated and can be encompassed with a fat jet of $R > 2m_h/p_T^h$ - We consider $R_J = 0.8$.

- We employed BDRS technique that hinges on massdrop criteria:
  - Split the fat jet into two subjets ($j_1$ and $j_2$) such that $m_{j_1} > m_{j_2}$ and $m_{j_1} < 0.67 m_J$.
  - Keep two subjets and check whether the subjets have b inside it.
  - Finally, select only those events having jet mass close to $m_h$ i.e $|m_J - m_h| < 5$ GeV.

# Significance




- The dip in significance corresponds to $\xi_h^f \rightarrow 0$ and $\xi_h^V \rightarrow 0$ - Channel is insensitive for probing fermiophobic limit.
- The channel can probe large $\xi_h^V$ region i.e $\alpha$ away from $\beta$.
- $\alpha > \beta$ is slightly favored over $\alpha < \beta$ as LHC signal strength measurements favors negative $\sin(\beta - \alpha)$ more.
- For lower mass (till $m_h = 90$) GeV, the significance is low even with $3000 fb^{-1}$.

## Channel 4: $pp \to tth \to tt b\bar{b}$

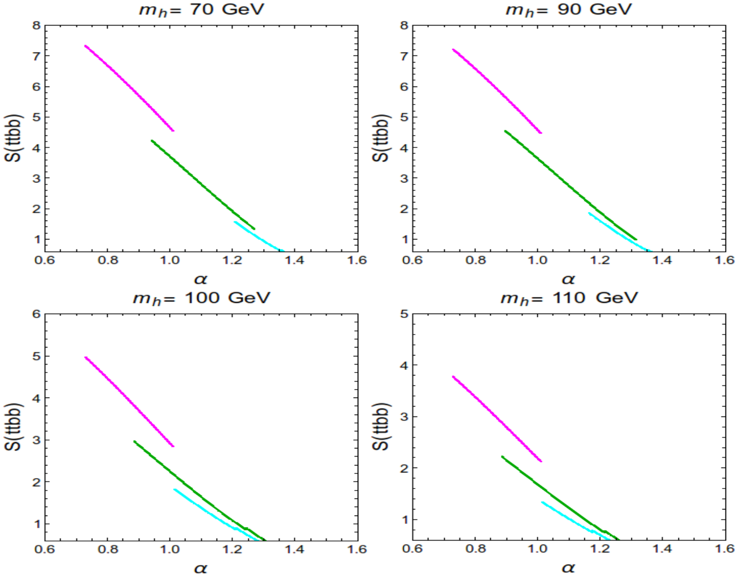
- We considered semi leptonic decay of top pairs. Signal is characterized by 4 b jets - suffers large combinatorics.
- Instead of looking into four b-jets, we consider two fat jets.
- Out of these two jets, we tag one of them as top-jet (three subjets) using HEPTOPTAGER and the other as Higgs.
- To suppress $ttjj$ background, we demand another b-jet outside the Higgs as well as top.
- Thus, we consider

$$p_T^{\ell} > 30 \text{ GeV}, \ \mathrm{E_T^{miss}} > 30 \text{ GeV}, \ \mathrm{p_T^J} > 125 \text{ GeV and } \mathrm{R_J} = 1.2,$$

$$p_T^{top} > 250 \, \text{GeV}, \ 150\text{GeV} < m_J^{top} < 200\text{GeV and } |m_J^{\text{Higgs}} - m_h| < 5.$$

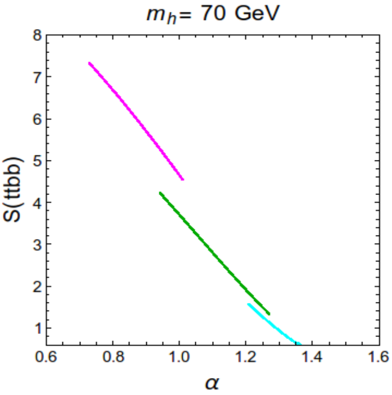
GeV

# Significance




Magenta($\tan\beta = 1.2$), ($\tan\beta = 2$) and Cyan($\tan\beta = 5$)

# Significance




- The channel is sensitive for low values of $\tan\beta$ as the scaling is $(\xi_h^f)^4$
- With increase in mass, production rate of $tth$ decreases and hence, significance decreases.
- With increase in $\alpha$, $\xi_h^f$ decreases and significance decreases.

# Summary

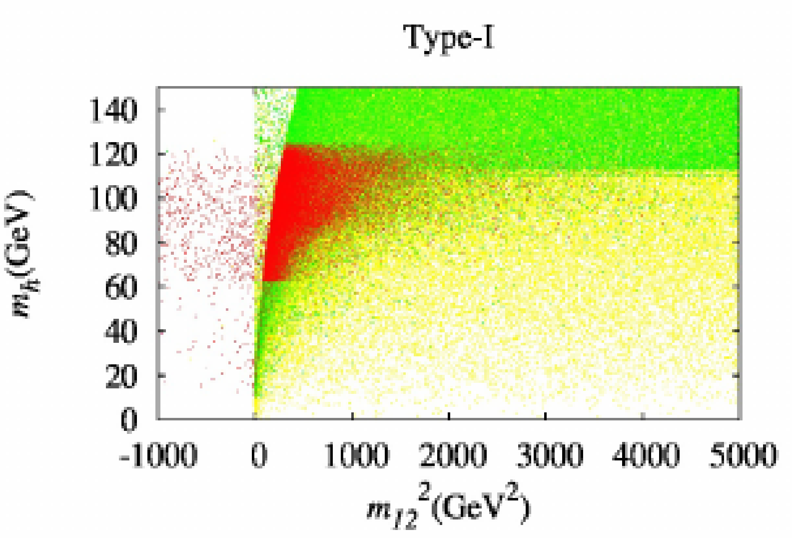
| $m_h$ (GeV) | $\tan\beta$ | $\alpha^{\text{excluded}}$ LEP + $\mu_{125}$ | $\alpha^{\text{excluded}}$ $\gamma\gamma$ | Future Prospect $\alpha$ | Future Prospect Channel | Future Prospect $\mathcal{L}$ fb$^{-1}$ (ECM) |
|---|---|---|---|---|---|---|
| 70 | 1.2 | $\alpha < 0.8$, $\alpha > 1.2$ | – | 0.8 – 0.9 | ttbb | 1000 (14) |
| | 2.0 | $\alpha < 0.9$, $\alpha > 1.3$ | – | 1.0 – 1.1 | ttbb | 3000 (14) |
| 80 | 1.2 | $\alpha < 0.7$, $\alpha > 1.1$ | – | 0.7 – 1.0 | ttbb | 1000 (14) |
| | 2.0 | $\alpha < 0.9$, $\alpha > 1.32$ | – | 1.0 – 1.1 | ttbb | 3000 (14) |
| | 6.0 | $\alpha < 1.2$, $\alpha > 1.61$ | $\pi/2$ | $\lvert\pi/2 - \alpha\rvert < 0.01$ | $\ell\nu\gamma\gamma$ | 50 (13) |
| 90 | 3.0 | $\alpha < 0.92$, $\alpha > 1.55$ | $\pi/2$ | $> 1.54$ | $\ell\nu\gamma\gamma$ | 50 (13) |
| | 6.0 | $\alpha < 1.0$, $\alpha > 1.8$ | – | $\lvert\pi/2 - \alpha\rvert < 0.01$ | $\ell\nu\gamma\gamma$ | 50 (13) |
| 100 | 1.2 | $\alpha < 0.7$, $\alpha > 1.0$ | – | 0.8 – 1.0 | ttbb | 3000 (14) |
| | 4.0 | $\alpha < 0.95$, $\alpha > 1.75$ | – | $1.565 < \alpha < 1.584$ | $\ell\nu\gamma\gamma$ | 100 (13) |
| | 6.0 | $\alpha < 0.97$, $\alpha > 1.96$ | – | $> 1.8$ | $\ell\nu b\bar{b}$ | 1000 (14) |
| 110 | 1.2 | $\alpha < 0.7$, $\alpha > 1.0$ | – | 0.7 – 0.9 | ttbb | 3000 (14) |
| | 4.0 | $\alpha < 0.95$, $\alpha > 1.75$ | – | $1.563 < \alpha < 1.60$ | $\ell\nu\gamma\gamma$ | 500 (14) |
| | 6.0 | $\alpha < 0.97$, $\alpha > 1.96$ | – | $> 1.9$ | $\gamma\gamma$ | 1000 (14) |

# Conclusion

- The null observation of any new physics scenario has provoked us to probe higher energy scale.
- We demonstrate an alternate scenario where a light particle is buried beneath huge SM backgrounds
- Detailed signal background analysis can probe the scalar in future run of LHC.
- Some of the region is testable with current luminosity.

# Outline

## $m_{12}$ with $m_H$



Type-I
$m_h$(GeV)
140
120
100
80
60
40
20
0
-1000
0
1000
2000
3000
4000
5000
$m_{12}^2$(GeV$^2$)

## S matrix unitarity

$$a_\pm = \frac{3}{2}(\lambda_1 + \lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2},$$

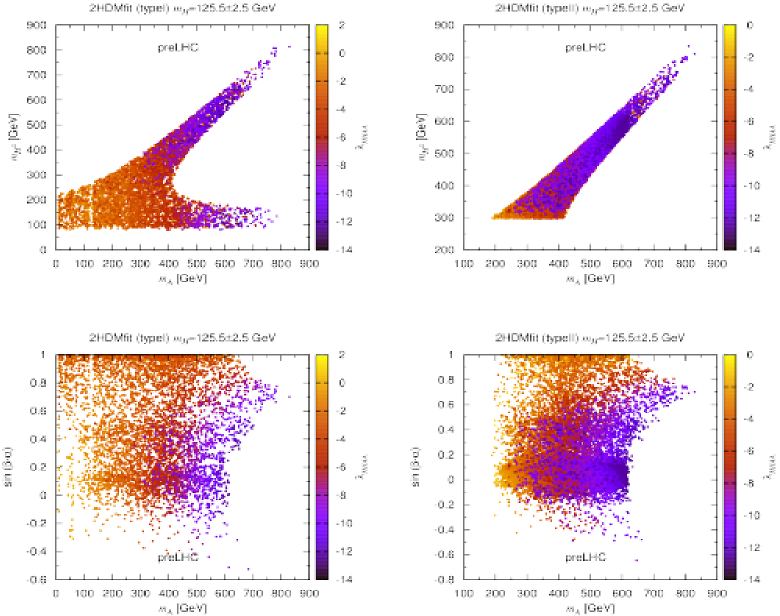
$$b_\pm = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right),$$

$$c_\pm = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right),$$

$$f_+ = \lambda_3 + 2\lambda_4 + 3\lambda_5, \quad f_- = \lambda_3 + \lambda_5, \quad f_1 = \lambda_3 + \lambda_4,$$

$$e_1 = \lambda_3 + 2\lambda_4 - 3\lambda_5, \quad e_2 = \lambda_3 - \lambda_5, \quad p_1 = \lambda_3 - \lambda_4.$$

# quartic coupling

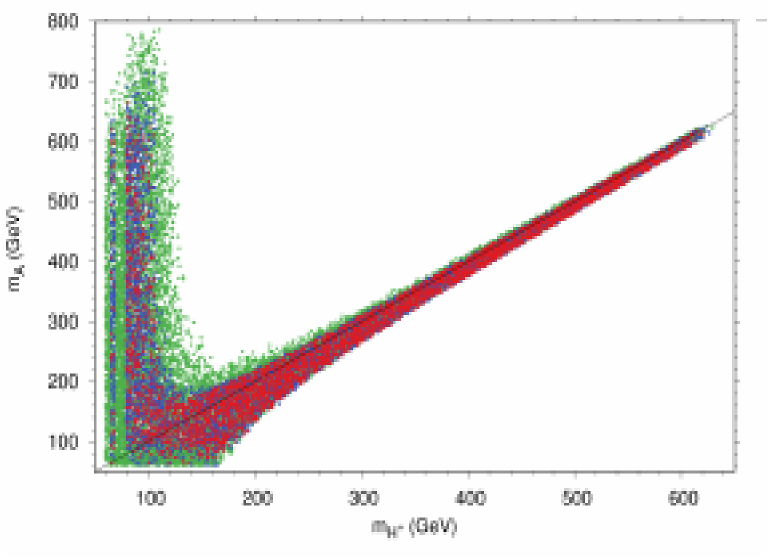


# T

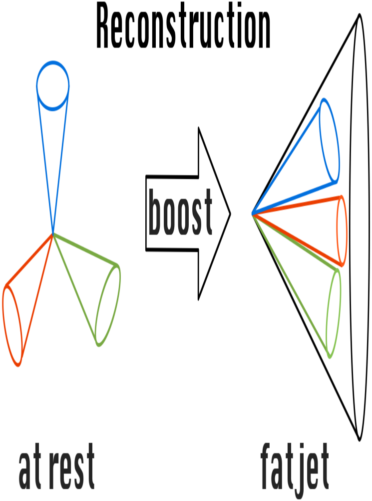
$$A^{HH}_{WW}(0) - \cos^2\theta_W A^{HH}_{ZZ}(0) = \frac{g^2}{64\pi^2}\Big[F_{\Delta\rho}(m^2_{H+}, m^2_{A^0})$$
$$+ F_{\Delta\rho}(m^2_{H+}, m^2_{H^0})\sin^2(\beta-\alpha) + F_{\Delta\rho}(m^2_{H+}, m^2_{h^0})\cos^2(\beta-\alpha)$$
$$- F_{\Delta\rho}(m^2_{A^0}, m^2_{H^0})\sin^2(\beta-\alpha) - F_{\Delta\rho}(m^2_{A^0}, m^2_{h^0})\cos^2(\beta-\alpha)\Big],$$

$$F_{\Delta\rho}(m_1^2, m_2^2) \equiv \frac{1}{2}(m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\frac{m_1^2}{m_2^2}.$$

# T parameter


800
700
600
500
400
300
200
100
$m_A$ (GeV)
100
200
300
400
500
600
$m_{H^\pm}$ (GeV)

# Tagging Boosted Tops




- Instead of considering 3 resolved ($\Delta R = 0.4$) jets, consider a fat jets with ($\Delta R = 1.2$).
- Look for the decay product inside the jet: Find hard substructure by undoing the last clustering, if $m_{daughter} > 0.2 * m_{parent}$ keep the daughters. We need at least three hard substructures.
- Filter the jets and select those jets whose mass is close to the $m_t$. The subjets are then made to satisfy top decay kinematics.