# Search for Additional Higgs Bosons via Higgs Cascades

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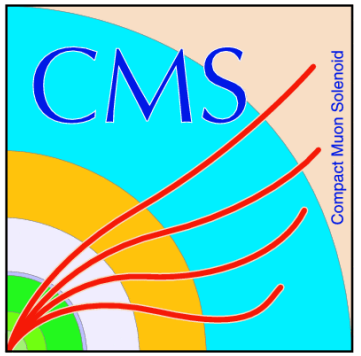
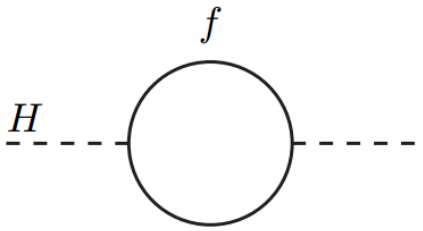


# Motivation

- Standard Model
  - Higgs boson discovery
  - problem of naturalness of the standard model




$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \dots.$$

- New Physics?
  - Extensions of the standard model generally require an *extension of the Higgs sector*.
  - *the simplified models* with the minimum degrees of freedom are useful tools for generating signal events and interpreting the result of the searches.
  - *Two Higgs Doublet model* is the simplest models.

# The two-Higgs-doublet model (2HDM)

- Many parameters in 2HDM, few of them are the most important for phenomenology.
  - the ratio of the VEVs of the two Higgs doublets, conventionally parameterized by $tan\beta = \frac{v_2}{v_1}$, with $v = \sqrt{v_1^2 + v_2^2} = 246\ GeV$.
  - mixing angle $\alpha$ that defines the mass eigenstates of the neutral CP even scalar states.

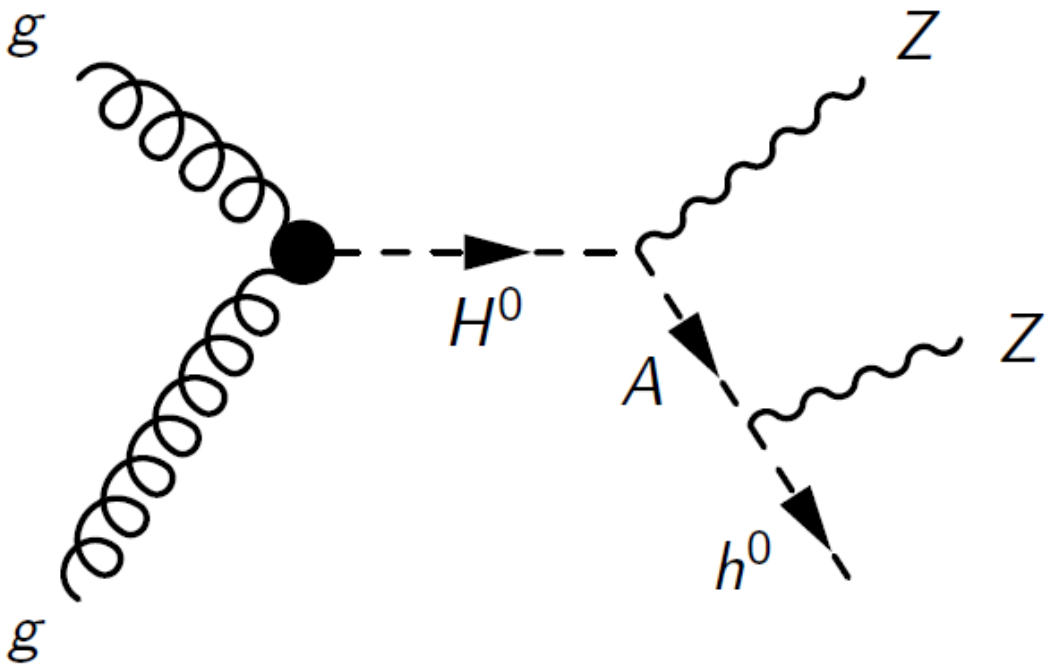
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

  - Coupling of Higgs bosons to vector bosons determined by $\beta - \alpha$.

- Additional physical states: $A$, $H^{\pm}$, $H^0$.

- Type I: one doublet couples to all fermions

# Cascade : ZZh final states

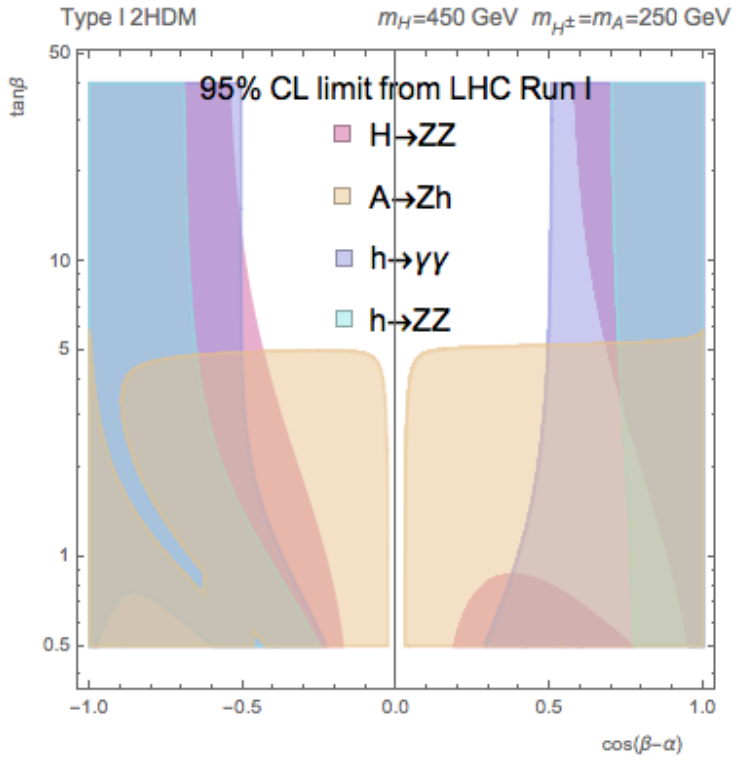



$A \to t\bar{t}$ closed
$H \to ZA$ and $A \to Zh$ open.

Benchmark:
$m_H = 450\ GeV$
$m_A = m_{H^\pm} = 250\ GeV$

# Status of Type I 2HDM after LHC Run I

- Most constraint result from run I searches (8 TeV)
  - h-> γγ and h->ZZ/WW give the most constraint results to both type I and type II 2HDM. 95% C.L. limit is $0.68 < \mu(h\to\gamma\gamma) < 1.66$
  - 2HDM search A->Zh.
    95% C.L. limit $\sigma > 0.3$ pb at 8 TeV.
  - 2HDM search H->ZZ. 95% C.L. limit
    $\sigma >$ 0.05 pb.



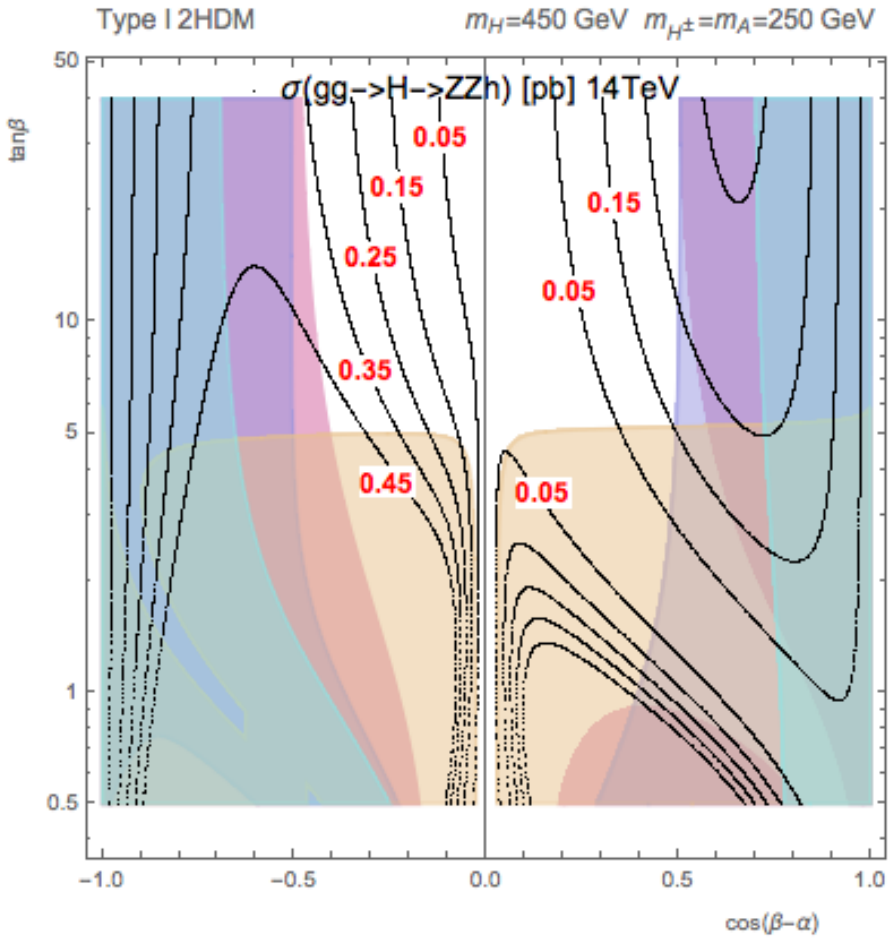

- CMS new search in Run II: H->ZA

# Searching for ZZh final states

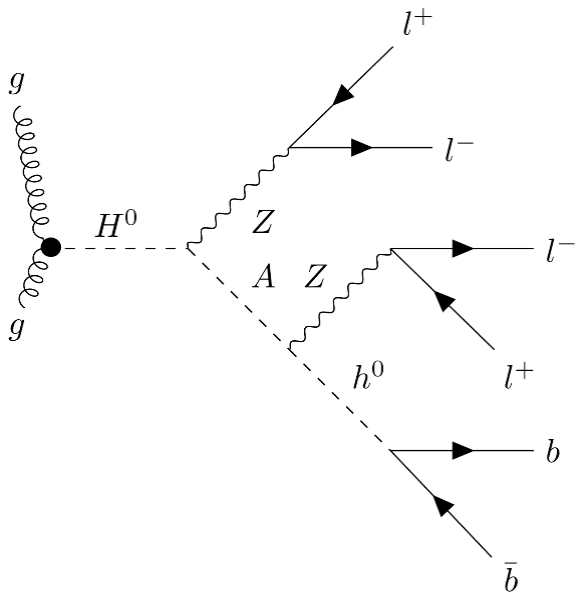
- LHC Run I constrains along with the contour line of $\sigma(gg \to H \to ZZh)$ in the 2HDM type I.

- Cross section benchmark : the optimal cross section.

  $\sigma_{opt}(gg \to H \to ZZh) = 0.45$ pb



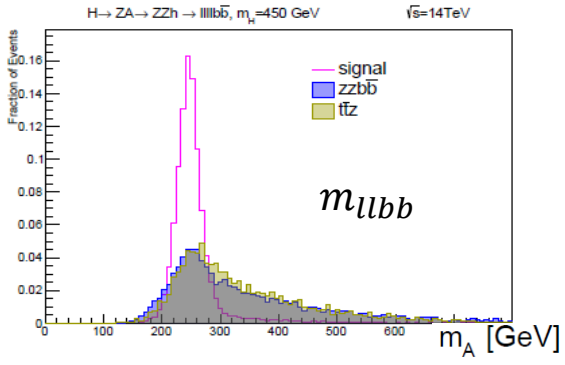
# Golden Channel: Z → ll, Z → ll, h → bb

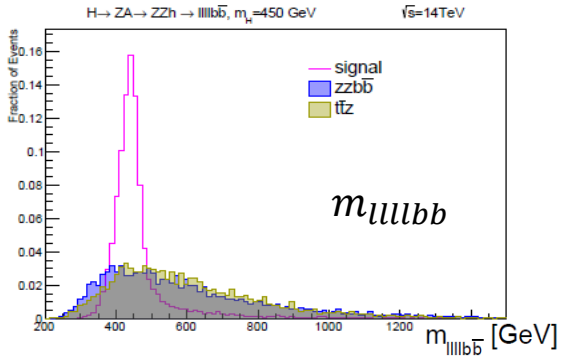


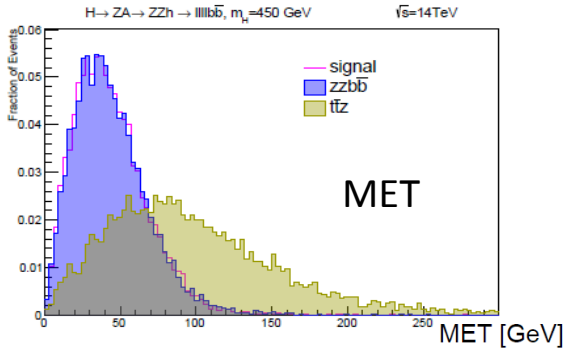

- Selection:
  - 2 b-tagged jets with $p_T > 20$ GeV
  - 2 opposite sign same flavor (OSSF) isolated lepton pairs
  - $p_T(l_1) > 20$ GeV, $p_T(l_2) > 15$ GeV, $p_T(l_{3/4}) > 10$ GeV
- Main SM backgrounds:
  - $ZZ + b\bar{b}$
  - $t\bar{t} + Z$
- Background rejection:
  - Mass resonance of lepton pairs, bottom pairs.
  - Missing ET / Missing transverse energy
  - Reconstructed mass of pseudoscalar A and heavy higgs H

# Golden Channel: Z → ll, Z → ll, h → bb

- MC truth level generated by MadGraph5
- Shower, hadronization simulated by pythia8
- CMS detector response simulated by Delphes
- Kinematics comparison: in good agreement with CMSSW generated MC

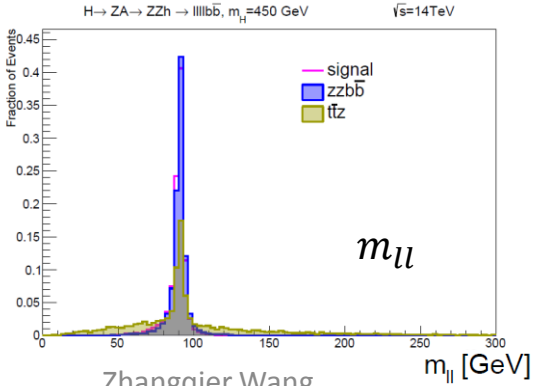


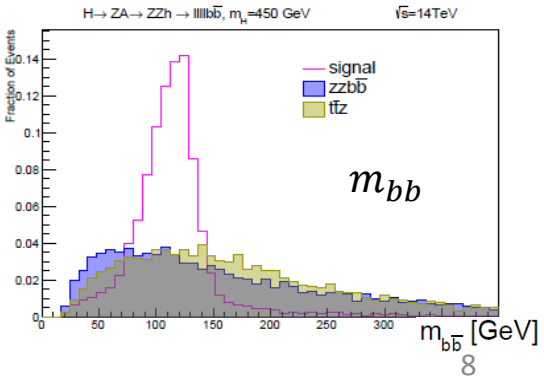




**Optimized Cuts:**

- $MET < 80\ GeV$
- $|m(ll) - m_Z| < 20\ GeV$
- $m(b\bar{b}) \in [70,160]\ GeV$
- $|m(llb\bar{b}) - m_A| < 40\ GeV$
- $|m(llllb\bar{b}) - m_H| < 50\ GeV$



# Golden Channel: Z → ll, Z → ll, h → bb

- Results

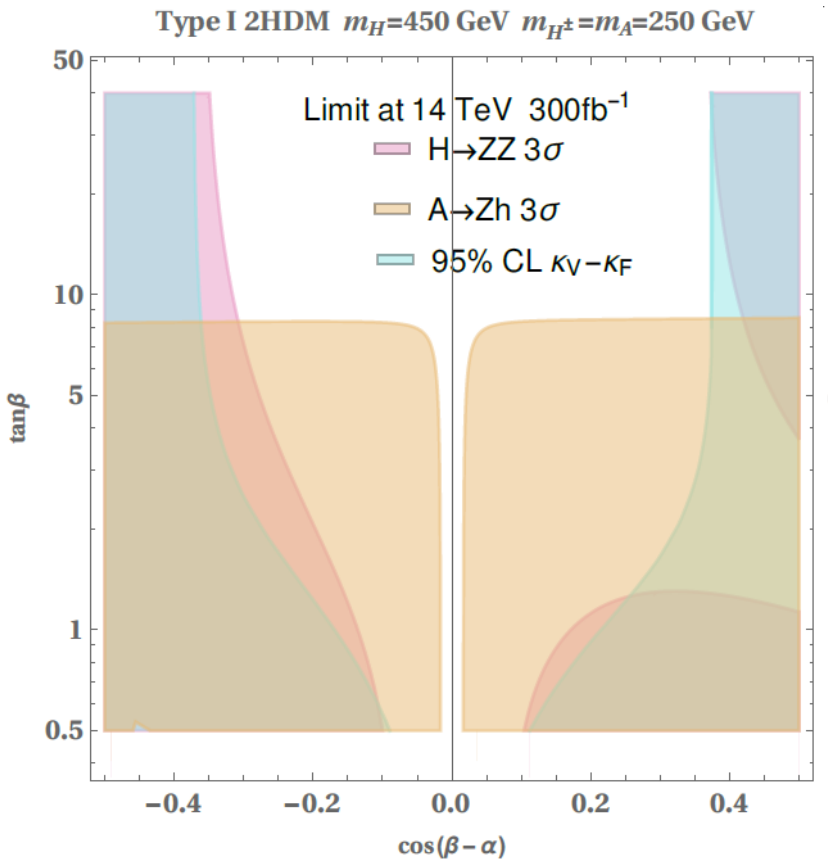
| # Selection[GeV] | 0 Initial | 1 $\ell^-\ell^+\ell^-\ell^+b\bar{b}$ | 2 $70 < m_{b\bar{b}} < 160$ | 3 $\lvert m_{\ell^+\ell^-} - m_Z \rvert < 20$ | 4 $\not{E}_T < 80$ | 5 $\lvert m_{\ell\ell b\bar{b}} - m_A \rvert < 40$ | 6 $\lvert m_{\ell\ell\ell\ell b\bar{b}} - m_H \rvert < 50$ |
|---|---|---|---|---|---|---|---|
| Signal | 353 | 39.5 | 33.6 | 31.8 | 29.5 | 28.4 | 23.9 |
| $ttZ$ | 643 | 37.5 | 14.3 | 3.77 | 1.51 | 1.20 | 0.53 |
| $ZZb\bar{b}$ | 81.6 | 6.09 | 2.18 | 2.06 | 1.70 | 1.16 | 0.43 |
| Total background | 725 | 43.6 | 16.5 | 5.83 | 3.21 | 2.35 | 0.96 |

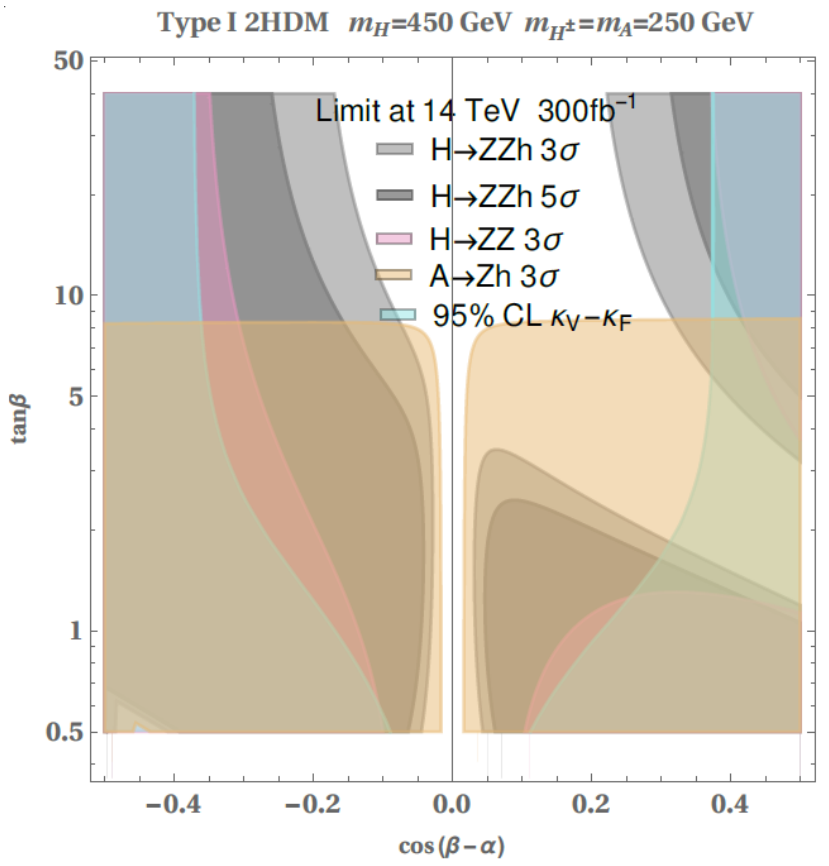
Table: Cut flows after each selection for llllbb channel. The signal and background yields are estimated for a luminosity of 300 $fb^{-1}$.

- For final results, $S \approx 23.9$ $B \approx 0.96$. The significance is more than 10 $\sigma$.
- Reaches to $3\sigma$ at 32 $fb^{-1}$( $5\sigma$ at 66 $fb^{-1}$).

# Results of the Benchmark Study (Type I)

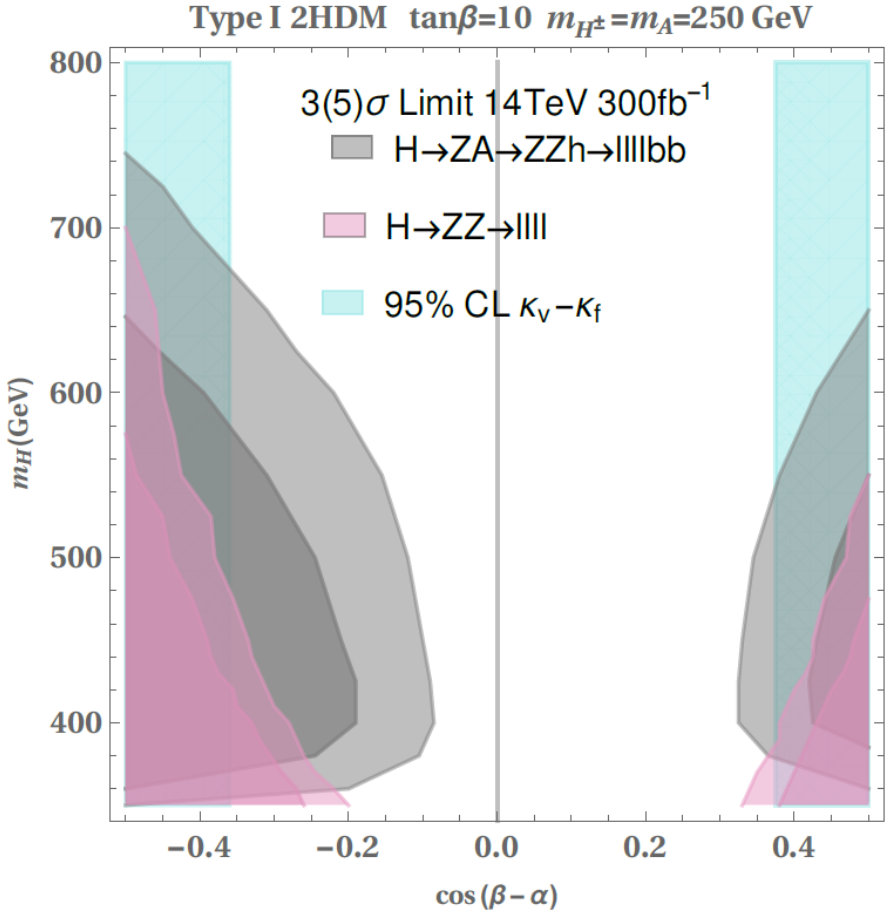
- 14 TeV projected bounds and $3\sigma$ $(5\sigma)$ cascade search



# Mass Scan of Heavy Higgs Boson

- How does our search perform for different mass of heavy higgs?
- Fix $\tan\beta = 10$ and consider $350\ GeV < m_H < 800\ GeV$




**More sensitivity: Heavy Higgs Mass up to 650 GeV**

# Conclusion

- The search $gg \rightarrow H \rightarrow ZA \rightarrow ZZh$ could be the discovery mode for additional Higgs boson at LHC Run-II.
- For the benchmark with $m_H = 450\ GeV$ and $m_A = 250\ GeV$, channel llllbb performs best, with $11\sigma$ significance for $300\ fb^{-1}$ at 14 TeV.
- The search can be the most sensitive probe of 2HDM type I at high $tan\beta$ ($\geq 8$). The reach persists for values of $m_H$ up to 650 GeV.
- The searches for ZZh final states are highly motivated at LHC Run-II.
- Search Continues: use real data soon, now we have luminosity ~$37\ fb^{-1}$

**Thanks!**

# Backup Slides

# The two-Higgs-doublet model (2HDM)

- Yukawa Term

$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$
$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u \xi_A^u \mathrm{P}_L + m_d \xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v}\,\overline{\nu_L}\ell_R H^+ + \mathrm{H.c.}\right\}$$

| Model | $u_R^i$ | $d_R^i$ | $e_R^i$ |
|---|---|---|---|
| Type I | $H_2$ | $H_2$ | $H_2$ |
| Type II | $H_2$ | $H_1$ | $H_1$ |

Type I:

$$AhZ \propto \cos(\beta-\alpha), \qquad AHZ \propto \sin(\beta-\alpha),$$
$$hZZ \propto \sin(\beta-\alpha), \qquad HZZ \propto \cos(\beta-\alpha).$$

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

# Analysis Method

- Simulated events for both signal and SM backgrounds were generated by MadGraph5, with showering and hadronization simulated by Pythia8 and the detector response simulated by Delphes3

| $ZZh$ decay modes | Comments | Significance |
|---|---|---|
| $(\ell^+\ell^-)(\ell^+\ell^-)(b\bar{b})$ | clean, ideal for reconstruction | $11\sigma$ |
| $(\ell^+\ell^-)(jj)(b\bar{b})$ | large signal and background | $3.6\sigma$ |
| $(\ell^+\ell^-)(\nu\nu)(b\bar{b})$ | overwhelmed by $t\bar{t}$ background | small |
| $(\ell^+\ell^-)(jj)(\tau_h\tau_h)$ | overwhelmed by jet-faked $\tau$ background | $0.7\sigma$ |
| $(\ell^+\ell^-)(\nu\nu)(\tau_h\tau_h)$ | not enough signal yield | small |
| $(\ell^+\ell^-)(jj)(\gamma\gamma)$ | relatively clean, small signal cross section | $1.7\sigma$ |
| $(\nu\nu)(jj)(\gamma\gamma)$ | hard to reconstruct | $0.5\sigma$ |
| $(\ell^+\ell^-)(\nu\nu)(\gamma\gamma)$ | clean but very small cross section | $2.8\sigma$ |
| $\ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}$ | relatively clean after hard $\not{E}_{\mathrm{T}}$ cut | $2.1\sigma$ |

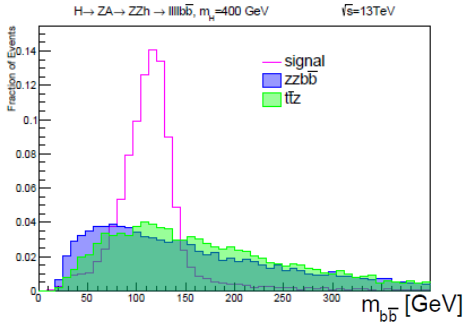
Table: All the channels that have been considered in the search, with decay mode, comments and signal significance at LHC 14 TeV with luminosity 300 $fb^{-1}$.

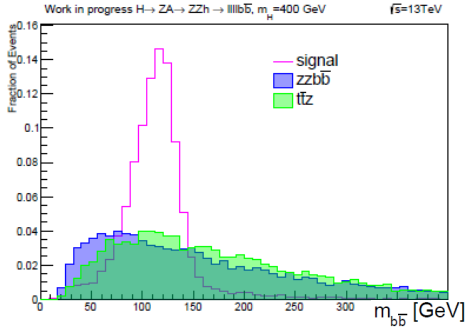
# Delphes Simulation vs. CMSSW Simulation

- Delphes simulation performance
  - Based on same lhe file (channel llllbb, m_H=400 GeV @ 13 TeV)

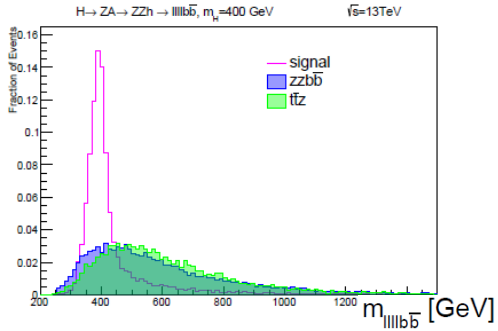
•Delphes simulation vs •CMSSW simulation

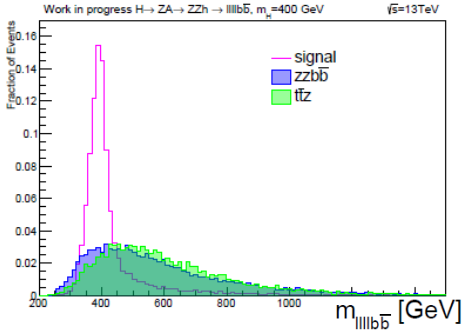
reco h



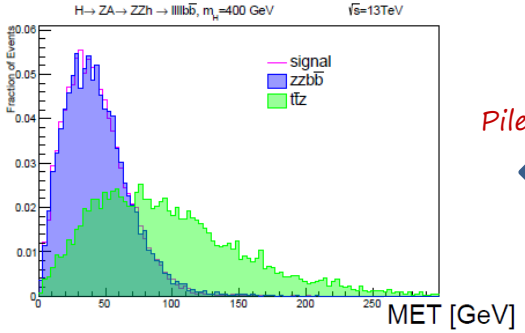




reco H

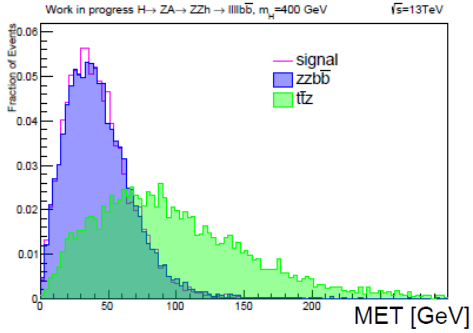



met




Pile-up: smearing MET




Consistent!

# Status of Type II 2HDM after LHC Run I

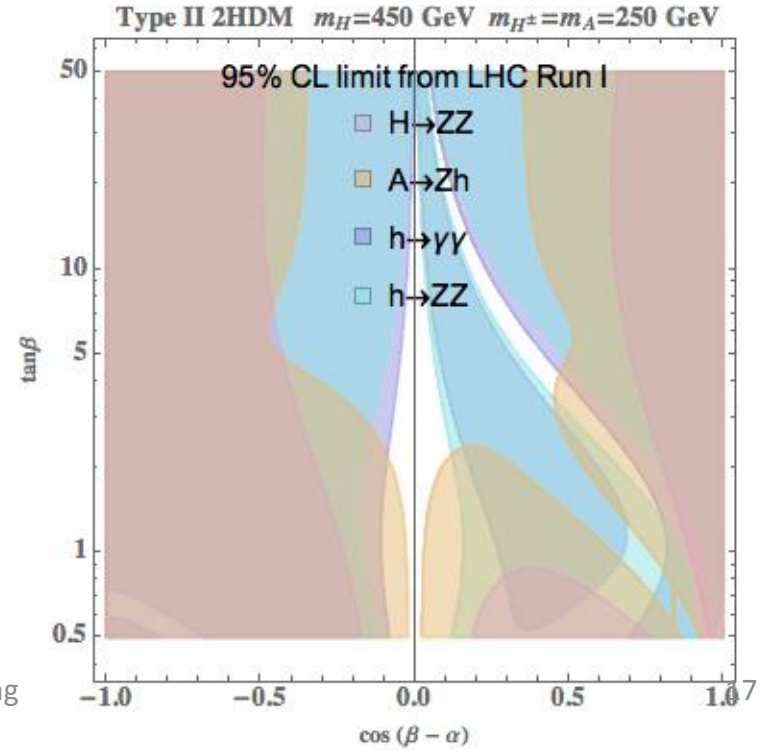
- Most constraint result from run I searches (8 TeV)
  - Among all the SM higgs search, h-> γγ and h->VV give the most constraint results to both type I and type II 2HDM. 95% C.L. limit is $0.68 < \mu(h\to\gamma\gamma) < 1.66$

$$\frac{\sigma \times \mathrm{Br}(gg \to h^0 \to XX)}{\mathrm{SM}} = \frac{\sigma(gg \to h^0)}{\sigma_{\mathrm{SM}}} \times \frac{\mathrm{Br}(h^0 \to XX)}{\mathrm{Br}(h_{\mathrm{SM}} \to XX)},$$

  - 2HDM search A->Zh.

    95% C.L. limit $\sigma > 0.3$ pb at 8 TeV.
  - 2HDM search H->ZZ. 95% C.L. limit

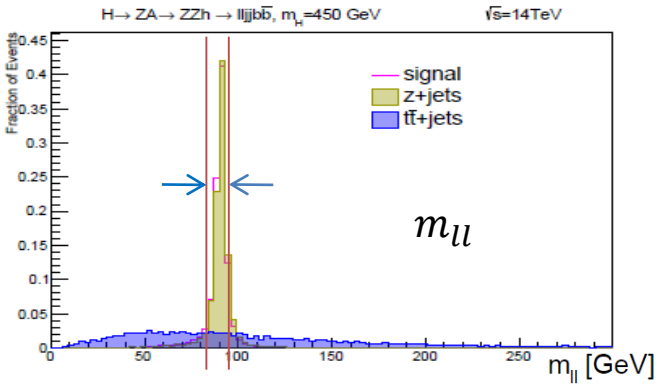
    $\sigma >$ 0.05 pb.

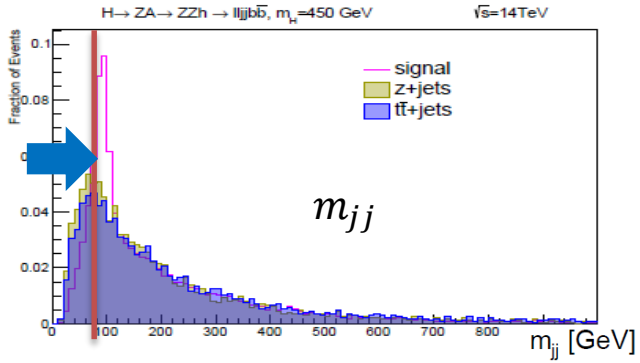


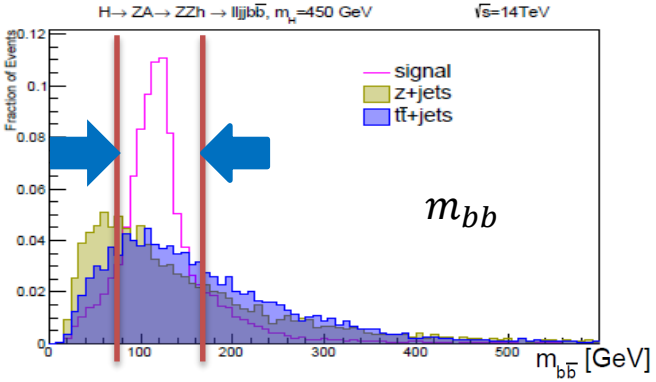
# lljjbb channel

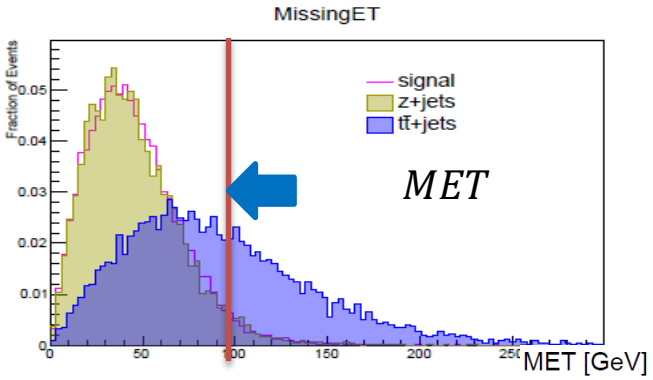
- Z → ll, Z → jj, h → bb channel
  - Larger branching ratio
  - Main backgrounds: $Z + jets$, $t\bar{t} + jets$
  - Requirements:
    - One OSSF lepton pair, 2 non-tagged jets and 2 b-tagged jets.
    - $p_T(l_1) > 30\ GeV, p_T(l_2) > 10\ GeV$
  - Kinematics
    - Mass resonance of lepton, jet and bottom pair.
    - Boosted? Pt of particles ( X )
    - Angles or delta R (delta Phi) between particles. ( X )

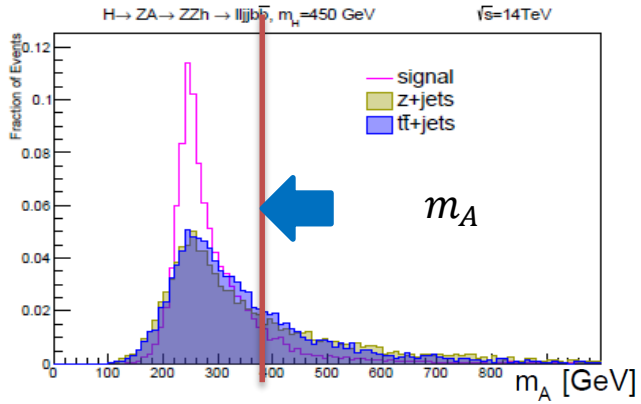
# lljjbb channel

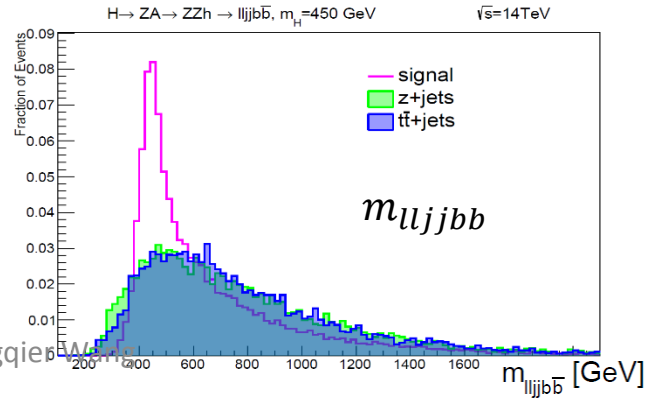


# lljjbb channel

- Optimized Cuts:

**Optimized Cuts:**

- $MET < 120\ GeV$
- $m(b\bar{b}) \in [85,160]\ GeV$
- $|m(ll) - m_Z| < 10\ GeV$
- $m(jj) > 60\ GeV$
- $m(llb\bar{b}\ or\ jjb\bar{b}) < 390\ GeV$

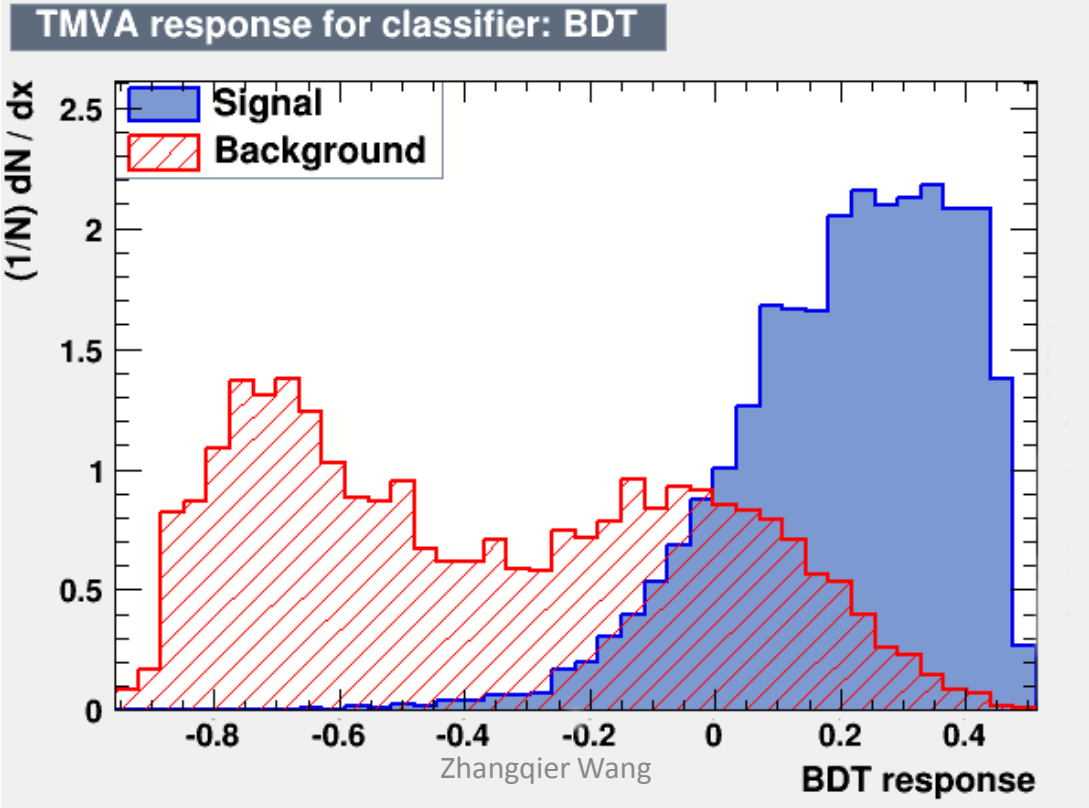
| # Selection | 0 Initial | 1 $\ell^+\ell^- jjb\bar{b}$ | 2 $m_{b\bar{b}}$ | 3 $m_{\ell^+\ell^-}$ | 4 $m_{jj}$ | 5 $\not{E}_{\mathrm{T}}$ | 6 $m_A$ |
|---|---|---|---|---|---|---|---|
| Signal | 5660 | 916 | 606 | 560 | 526 | 510 | 495 |
| $Z$ + jets | $7.1 \times 10^6$ | $8.8 \times 10^4$ | $2.3 \times 10^4$ | $2.2 \times 10^4$ | $1.8 \times 10^4$ | $1.7 \times 10^4$ | $1.4 \times 10^4$ |
| $t\bar{t}jj$ | $2.7 \times 10^7$ | $2.5 \times 10^5$ | $7.3 \times 10^4$ | $1.0 \times 10^4$ | $8.5 \times 10^3$ | $5.9 \times 10^3$ | $5.7 \times 10^3$ |
| Total background | $3.4 \times 10^7$ | $3.4 \times 10^5$ | $9.6 \times 10^4$ | $3.2 \times 10^4$ | $2.6 \times 10^4$ | $2.3 \times 10^4$ | $1.9 \times 10^4$ |

$S \approx 495, B \approx 19000$. Significance 3.6 $\sigma$

# lljjbb channel

- More information used
  - Distribution shape: all kinematics distributions
  - Distribution at all region

Multivariate Analysis (MVA): Boosted Decision Tree(BDT)



# Results of the Benchmark Study

- Summary of the most sensitive channels

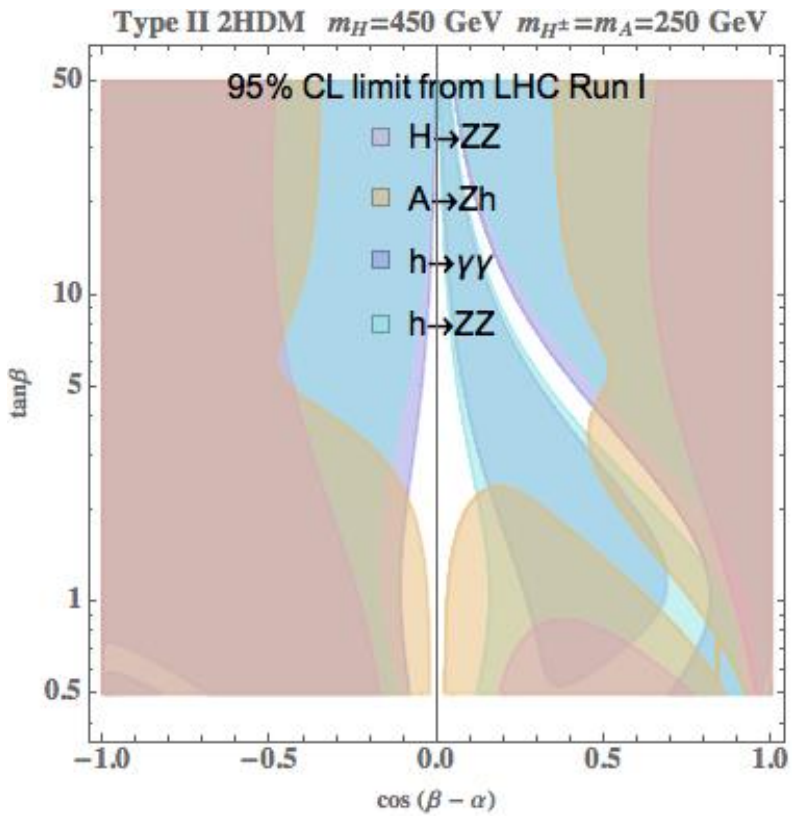
| Channel | 14 TeV 300fb$^{-1}$ | | | 14 TeV 3000fb$^{-1}$ | | |
|---|---|---|---|---|---|---|
| | Sig Yields | Bkg Yields | Significance | Sig Yields | Bkg Yields | Significance |
| $\ell^+\ell^-\ell^+\ell^-b\bar{b}$ | 24 | 0.96 | 11 $\sigma$ | 240 | 9.6 | 34 $\sigma$ |
| $\ell^+\ell^-jjb\bar{b}$ | 495 | $1.9\times10^4$ | 3.6 $\sigma$ | 4950 | $1.9\times10^5$ | 11 $\sigma$ |
| $\ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}$ | 9.7 | 18 | 2.1 $\sigma$ | 97 | 180 | 6.6 $\sigma$ |
| $\ell^+\ell^-\nu\nu\gamma\gamma$ | 2.1 | 0.14 | 2.8 $\sigma$ | 21 | 1.4 | 9.1 $\sigma$ |
| $\ell^+\ell^-jj\gamma\gamma$ | 5.7 | 9.6 | 1.7 $\sigma$ | 57 | 96 | 5.3 $\sigma$ |

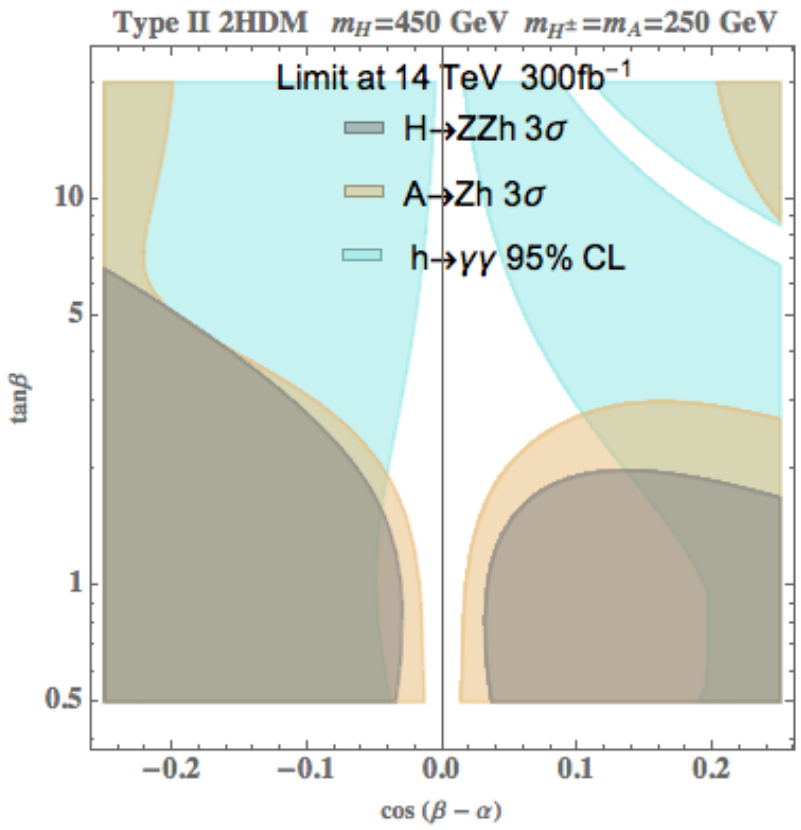
Table: Summary of the most sensitive channels of the $H \to ZA, A \to Zh$ cascade search for benchmark $m_H = 450\ GeV$, $m_A = m_{H^\pm} = 250\ GeV$, assuming the ZZh production cross section is 0.45 pb for the signal.

Combining channels will give $3\sigma$ $(5\sigma)$ significance at luminosity of about $20\ fb^{-1}$ ( $54\ fb^{-1}$).

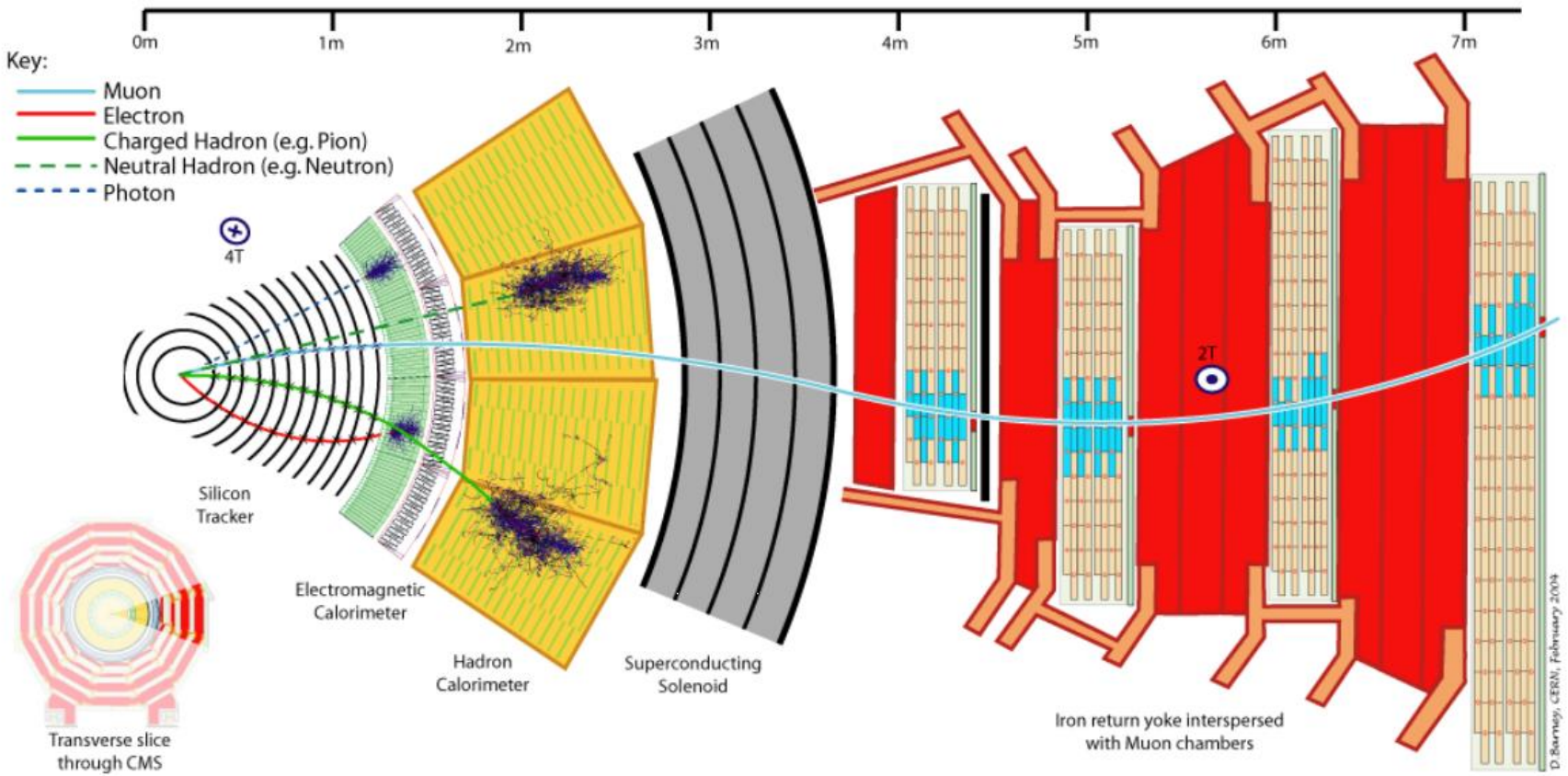
# Results of the Benchmark Study (Type II)

- Type II



# Compact Muon Solenoid (CMS)



# The two-Higgs-doublet model (2HDM)

- 2HDM
  - The most general scalar potential for 2 doublets with hpyercharge +1

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

$$
\langle\Phi_1\rangle_0 = \begin{pmatrix} 0 \\ \dfrac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \begin{pmatrix} 0 \\ \dfrac{v_2}{\sqrt{2}} \end{pmatrix}
$$

$$
\Phi_a = \begin{pmatrix} \phi_a^+ \\ \left(v_a + \rho_a + i\eta_a\right)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2.
$$

- Mixing angles

$$
\tan\beta \equiv \frac{v_2}{v_1}.
$$

physical pseudoscalar A and scalars h, H.

$$
\begin{aligned}
A &= \eta_1 \sin\beta - \eta_2 \cos\beta. \\
h &= \rho_1 \sin\alpha - \rho_2 \cos\alpha, \\
H &= -\rho_1 \cos\alpha - \rho_2 \sin\alpha.
\end{aligned}
$$

# The two-Higgs-doublet model (2HDM)

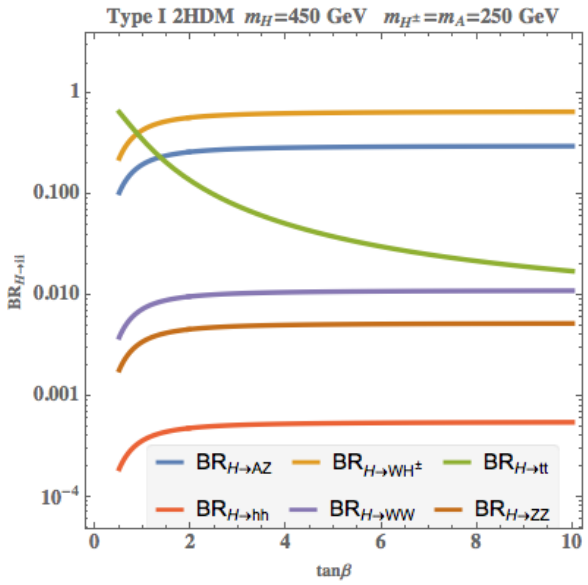
- Yukawa Term

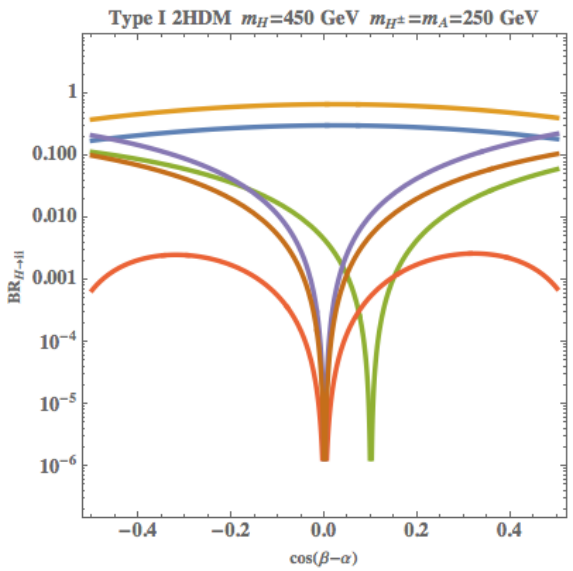
$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$
$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u \xi_A^u \mathrm{P}_L + m_d \xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v}\,\overline{\nu_L}\ell_R H^+ + \text{H.c.}\right\}$$

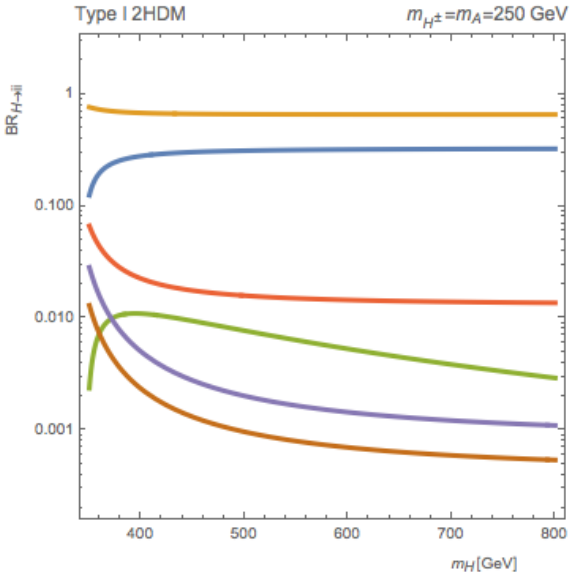
| Model | $u_R^i$ | $d_R^i$ | $e_R^i$ |
|---|---|---|---|
| Type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| Type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ |
| Lepton-specific | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ |
| Flipped | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ |

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

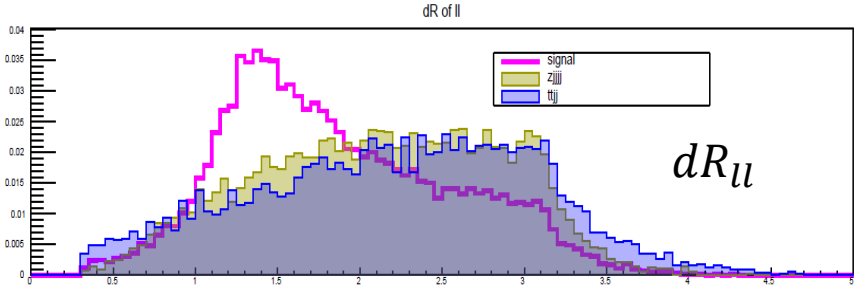
# The Branching Ratio

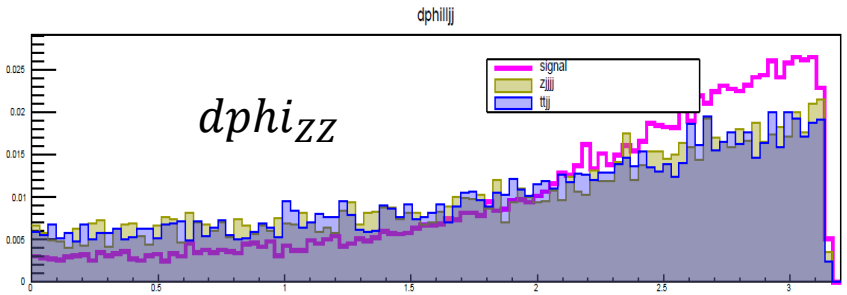


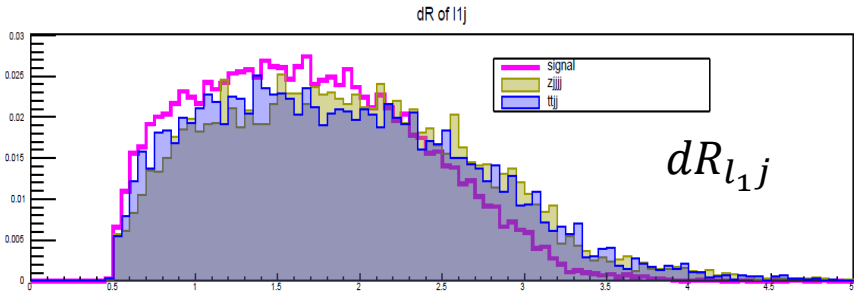



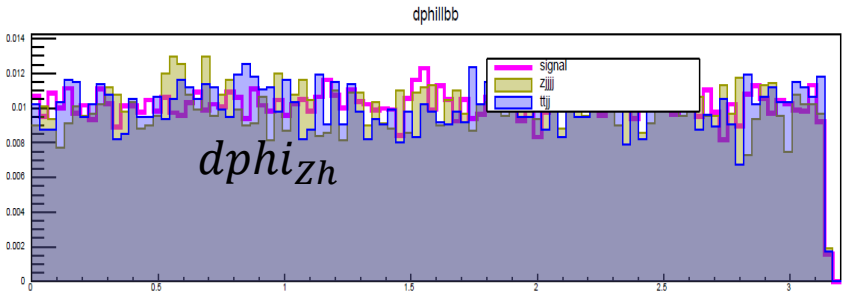



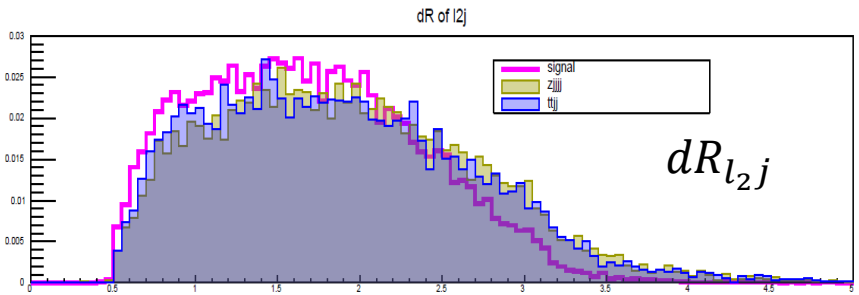
# lljjbb channel

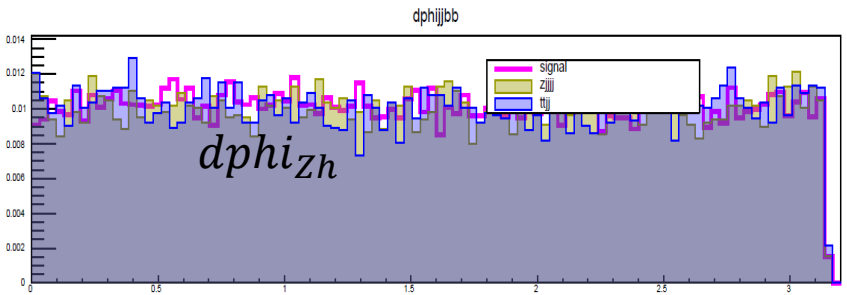


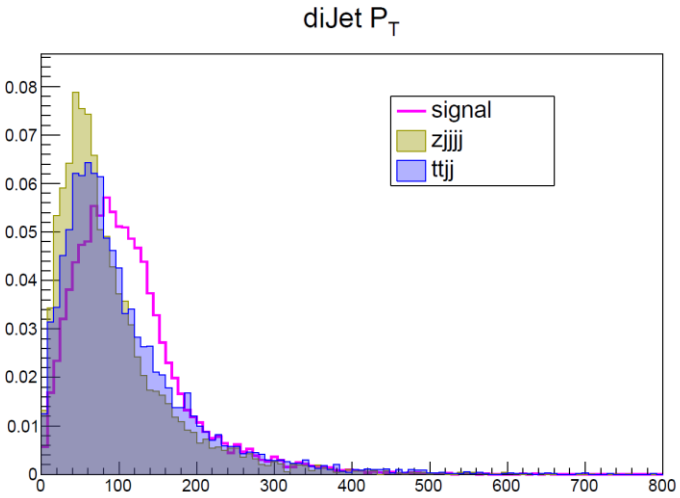



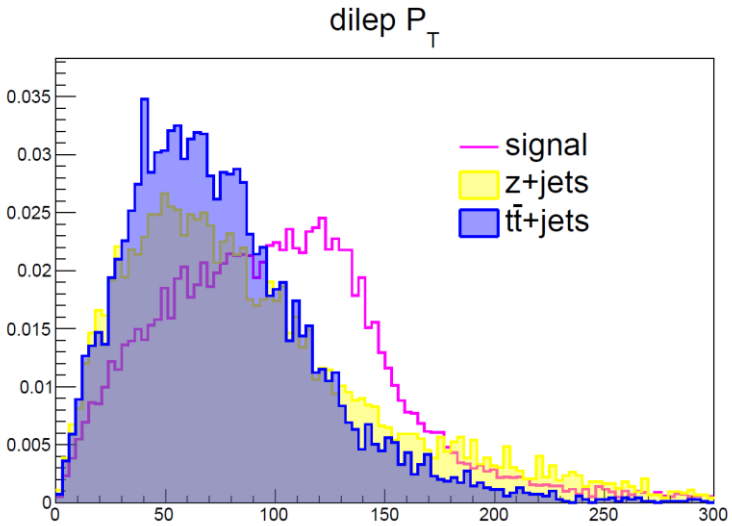



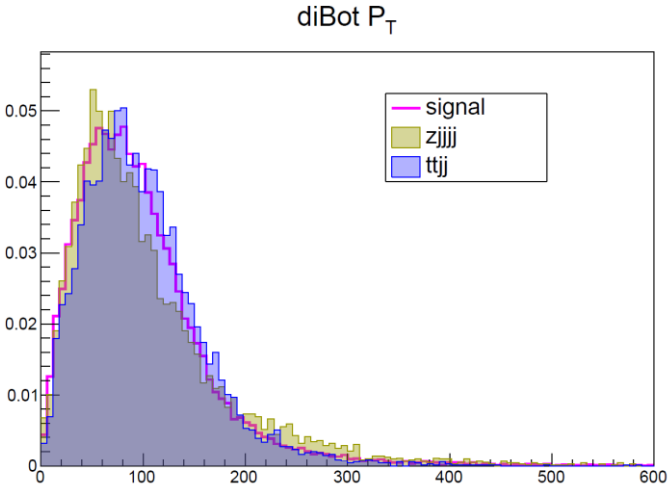



# lljjbb channel



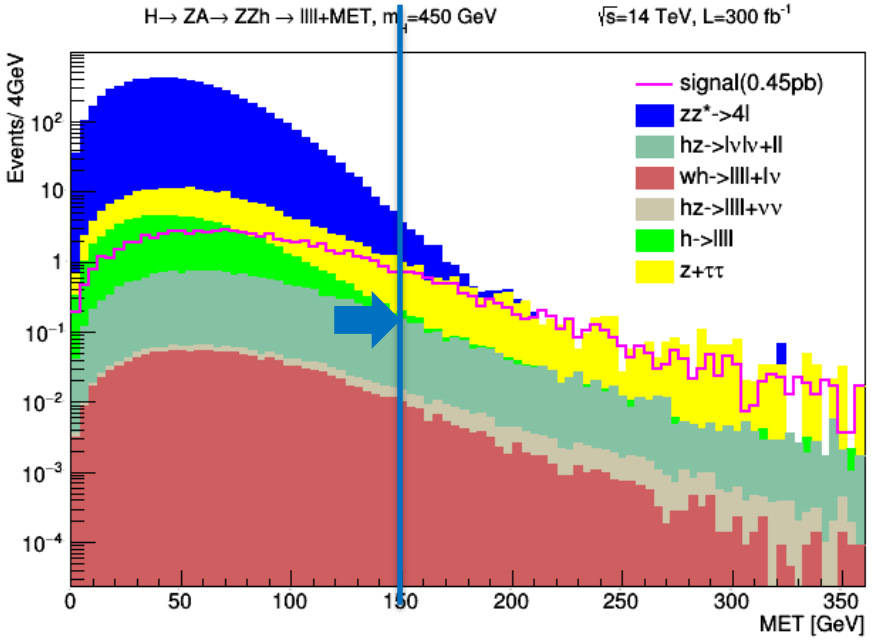

Not enough to suppress the background.

# 4l+met

- ZZh → llll+met channel
  - $Z \to ll, Z \to all, h \to WW \ or \ \tau_l\tau_l$
  - Event selection:
    - Four leptons, one OSSF pair with $|m_{ll} - m_Z| < 10\ GeV$.
    - Results( MET > 150 GeV):

| | Initial | Final Yields |
|---|---|---|
| Signal | 1600 | 9.7 |
| $ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$ | $1.5 \times 10^4$ | 8.2 |
| $ZZ \to (\tau^+\tau^-)(\ell^+\ell^-)$ | 7700 | 8.4 |
| $h \to \ell^+\ell^-\ell^+\ell^-$ | 240 | 0.16 |
| $Zh \to (\ell^+\ell^-)(\ell^+\ell^-\nu\nu)$ | 41 | 1.3 |
| $Zh \to (\nu\nu)(\ell^+\ell^-\ell^+\ell^-)$ | 1.3 | 0.08 |
| $Wh \to (\ell\nu)(\ell^+\ell^-\nu\nu)$ | 2.3 | 0.09 |
| Total background | $2.3 \times 10^4$ | 18 |

2.1 σ significance



| $m_H$ | $\ell\ell\ell\ell bb$ reco-efficiency | $m_A$ cut | $m_H$ cut |
|---|---|---|---|
| 360 GeV | 10.2% | $\pm 50$ | useless |
| 380 GeV | 10.4% | $\pm 50$ | useless |
| 400 GeV | 10.7% | $\pm 50$ | $\pm 60$ |
| 425 GeV | 11.1% | $\pm 50$ | $\pm 55$ |
| 450 GeV | 11.2% | $\pm 40$ | $\pm 50$ |
| 500 GeV | 11.8% | $\pm 35$ | $\pm 50$ |
| 550 GeV | 11.8% | $\pm 60$ | $\pm 60$ |
| 600 GeV | 11.8% | $\pm 60$ | $\pm 95$ |
| 625 GeV | 11.7% | $\pm 60$ | $\pm 110$ |
| 650 GeV | 11.7% | $\pm 60$ | $\pm 130$ |
| 700 GeV | 11.5% | $\pm 70$ | $\pm 160$ |
| 725 GeV | 11.9% | $\pm 70$ | $\pm 185$ |
| 745 GeV | 11.9% | $\pm 75$ | $\pm 200$ |
| 750 GeV | 11.5% | $\pm 80$ | $\pm 200$ |

| $m_H$ | $5\sigma$ crossx(after) | $3\sigma$ crossx(after) |
|---|---|---|
| 360 GeV | $0.211pb$ | $0.112pb$ |
| 380 GeV | $0.205pb$ | $0.109pb$ |
| 400 GeV | $0.183pb$ | $0.095pb$ |
| 425 GeV | $0.174pb$ | $0.090pb$ |
| 450 GeV | $0.164pb$ | $0.084pb$ |
| 500 GeV | $0.138pb$ | $0.069pb$ |
| 550 GeV | $0.125pb$ | $0.062pb$ |
| 600 GeV | $0.116pb$ | $0.058pb$ |
| 625 GeV | $0.116pb$ | $0.058pb$ |
| 650 GeV | $0.115pb$ | $0.057pb$ |
| 700 GeV | $0.117pb$ | $0.058pb$ |
| 725 GeV | $0.113pb$ | $0.057pb$ |
| 745 GeV | $0.115pb$ | $0.058pb$ |
| 750 GeV | $0.119pb$ | $0.060pb$ |