Searches for Higgs in 2HDM at the LHC

Workshop on Higgs and Beyond
Tohoku University, Sendai, Japan
5th – 9th, June, 2013

Simon Köhlmann on behalf of ATLAS and CMS collaborations

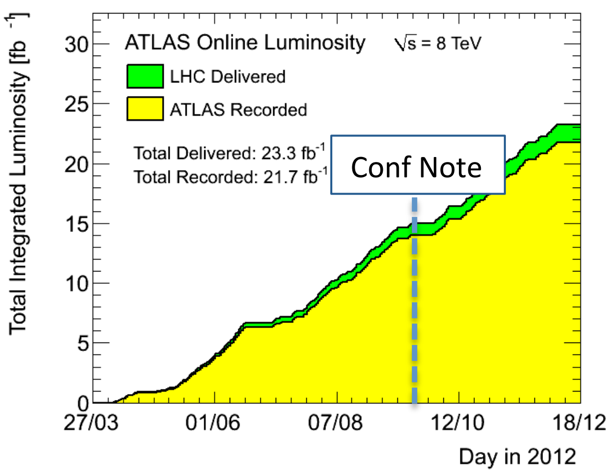
Outline

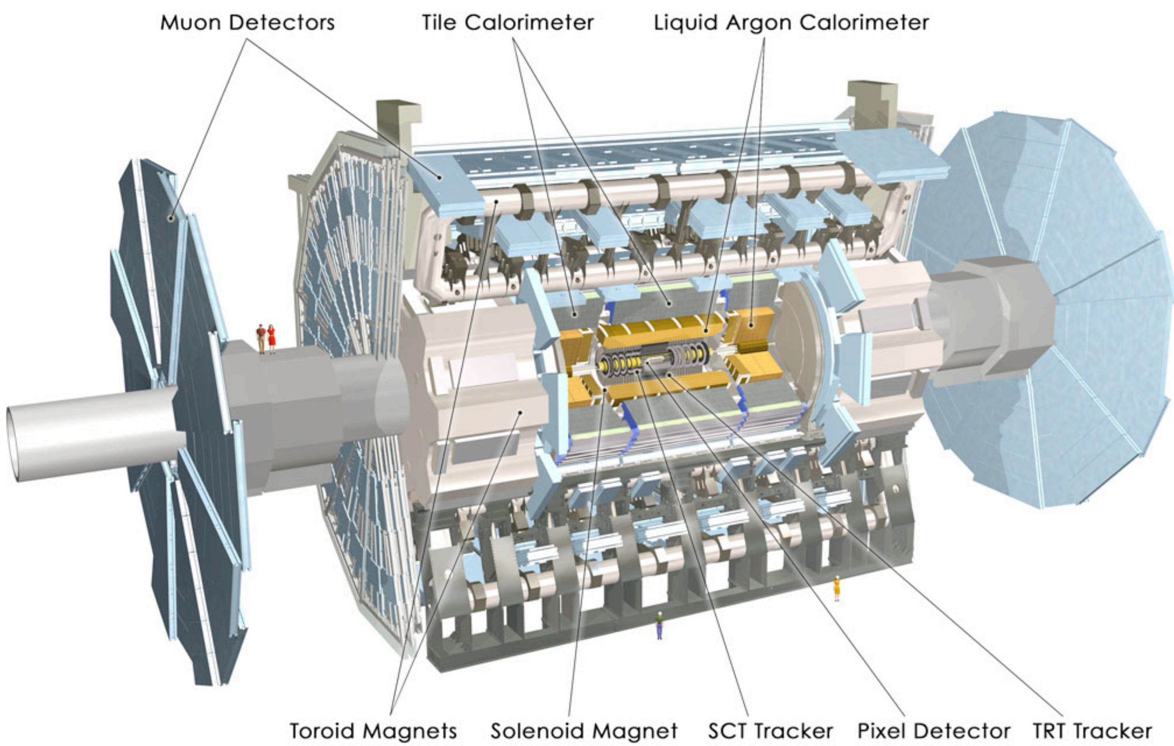
This talk will focus on the 2HDM $H \rightarrow WW \rightarrow e\nu\mu\nu$ results made public in March by ATLAS: https://cds.cern.ch/record/1525887

- Theory
  - Motivation
  - Phenomenology of the Two-Higgs-Doublet Model
  - Calculation of cross sections and branching ratios
- Event selection
- Usage of Neural Networks
- Results of the WW 2HDM analysis
- Charged Higgs searches and MSSM

ATLAS Detector

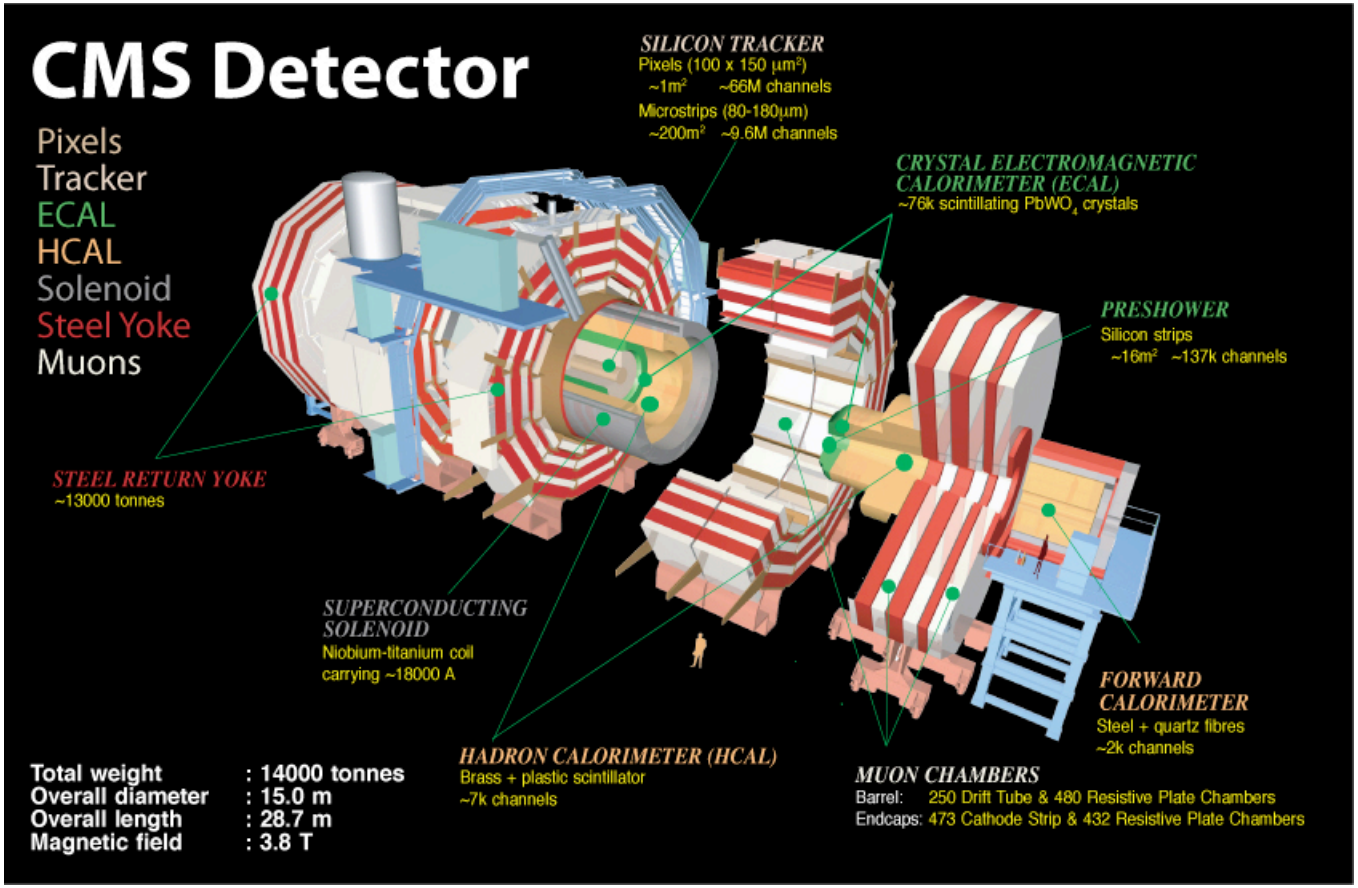
$\mathcal{L}$ = 13 fb^{-1} @ 8 TeV





> 93% recorded data good for physics

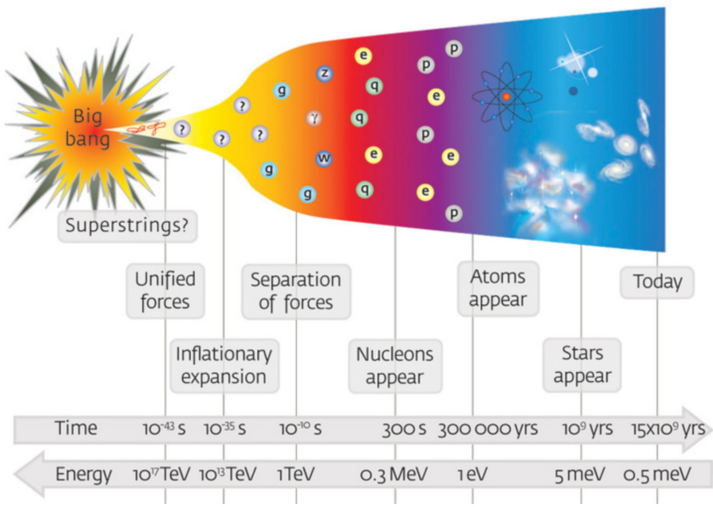
CMS Detector



Analysis Motivation
and
Theory of the 2HDM

Motivation for 2HDM

- Higgs-like boson discovered at m_h = 125 GeV, announced on July 4th, 2012
- Arising question: Is it the SM Higgs boson or is it part of a richer scalar sector?



CP-symmetry violation

- The amount of CP-violation in the CKM matrix is enough to explain the observed size of CP-violation in the B and K meson system.
- However, it is too small to generate the observable baryon asymmetry in the Universe.

→ Need additional source of CP violation

→ More degrees of freedom available for example in 2HDM

By adding a second Higgs doublet to the SM, the 2HDM is one of the easiest extension of the SM.

Parameters of 2HDMs

2HDM

neutral/CP-even scalars:

- h = light scalar
- H = heavy scalar

+ A, $H^{\pm}$

- The softly broken Z_2 symmetric 2HDM potential:

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \mathrm{h.c.} \right\}$$

- 2 parameters: mixing angles α and β

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

ψ_1, ψ_2: CP-even fields

χ_1, χ_2: CP-odd fields

$$\begin{pmatrix} A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1^\pm \\ \Phi_2^\pm \end{pmatrix}$$

- Exclusion limits on H depend on α, β and m_H

→ It makes sense to choose several values of tan β and plot exclusion limits in the cos α vs. m_H plane

Type I and Type II of the 2HDMs

- 2 models with natural flavour conservation: "type I" and "type II" 2HDM
  - In the type I 2HDM, all quarks couple to just one of the Higgs doublets
  - In the type II 2HDM, the Q = 2/3 right-handed quarks couple to one Higgs doublet and the Q = −1/3 right-handed quarks couple to the other.

Relevant couplings

Coupling	Type I	Type II
ξ_h^{V}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^{V}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Tree-level couplings of the neutral Higgs bosons to vector bosons, up- and down-type quarks in the type I and type II 2HDM models.

MSSM is a Type II 2HDM at tree level

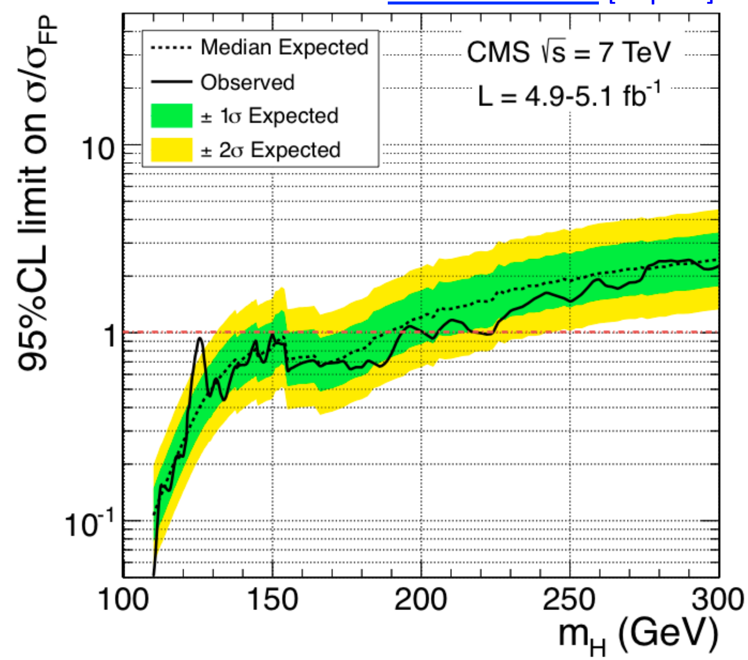
The Fermiophobic Higgs Model

Type I has a fermiophobic limit for $\cos(\alpha) = 0$ and $\cos(\beta) = 0$

Coupling	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

→ 0

arXiv:1207.1130 [hep-ex]



Exclusion: 110 GeV – 194 GeV

After the discovery of the Higgs-like boson the purely fermiophobic scenario is no longer realistic because the new particle couples most probably to fermions and bosons

More about the fermiophobic searches
→ Talk from Adrian Perieanu

Analysis Strategy

Analysis Strategy

<u>2HDM</u>

neutral/CP-even scalars:

- h = light scalar
- H = heavy scalar

+ A, $H^{\pm}$

- Search for H in the decay mode $H \rightarrow WW \rightarrow e\nu\mu\nu$
- Include h as a "measured"

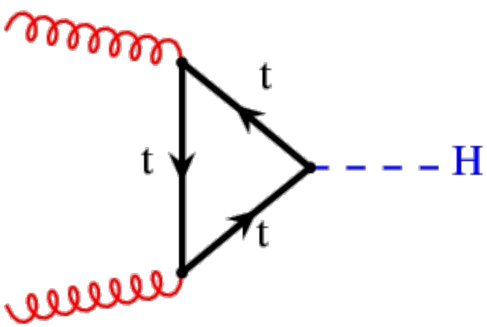
  part of the signal hypothesis
- Ensure consistent treatment of h and H in the model wrt the parameters of the model

For this analysis we assume:
The boson found at m_h = 125 GeV is the h of a 2HDM.

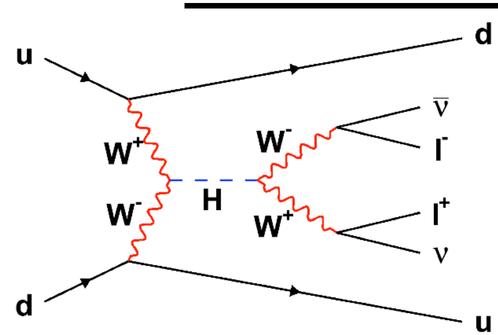
Experimental Channels

- In the general 2HDM scenario both production modes are relevant:

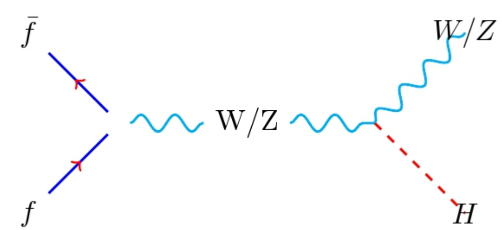
<u>gg-fusion</u>



<u>VBF + VH</u> (VH/VBF ≈ 2 %)



+



0 jet bin

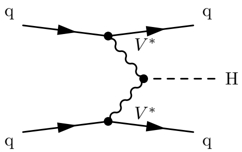
2 jet bin

➔ Analysis contains the 0 jet channel and the 2 jet channel.

Scaling of Cross-Sections and Branching Ratios

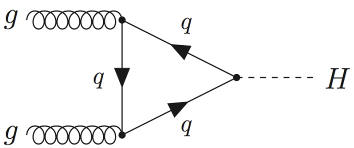
We need to calculate the expected event yields as a function of the couplings for both Higgs bosons h and H.

xs for VBF in 2HDM: $\sigma_{h/H}(VV \to h/H) = \sigma_{SM}(VV \to h/H) \times (\xi^{V}_{h/H})^2$



xs for ggF in 2HDM:

Using SusHi where 2HDM option is available
Robert Harlander et al. arXiv:1212.3249



Decay:

$$\mathrm{BR}_{h/H}(\mathrm{H} \to \mathrm{WW}) = \frac{\Gamma(\mathrm{H} \to WW)}{\Gamma_{\mathrm{total}}}$$

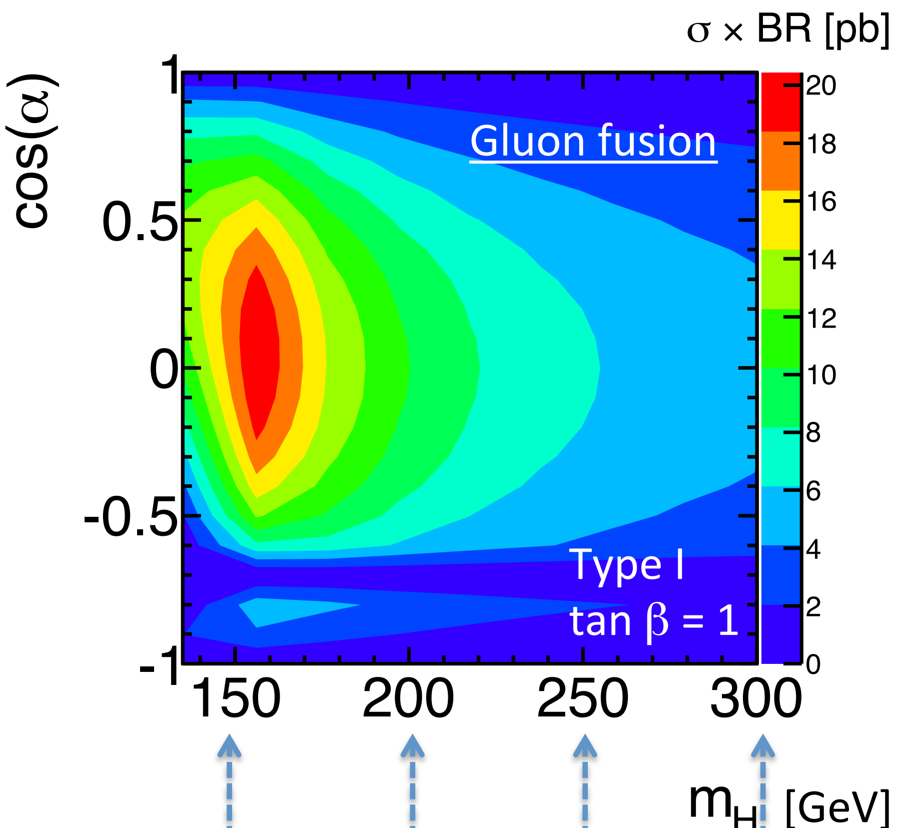
$$= \frac{\Gamma_{\mathrm{SM}}(\mathrm{H} \to \mathrm{WW})(\xi^{v}_{h/H})^2}{\Gamma_{\mathrm{SM}}(\mathrm{H} \to VV) \times (\xi^{v}_{h/H})^2 + \Gamma_{\mathrm{SM}}(\mathrm{H} \to bb) \times (\xi^{d}_{h/H})^2}$$

$$= \frac{\mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \mathrm{WW})(\xi^{v}_{h/H})^2}{\mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to VV) \times (\xi^{v}_{h/H})^2 + \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to bb) \times (\xi^{d}_{h/H})^2}$$

σ x BR for the heavy Higgs boson H

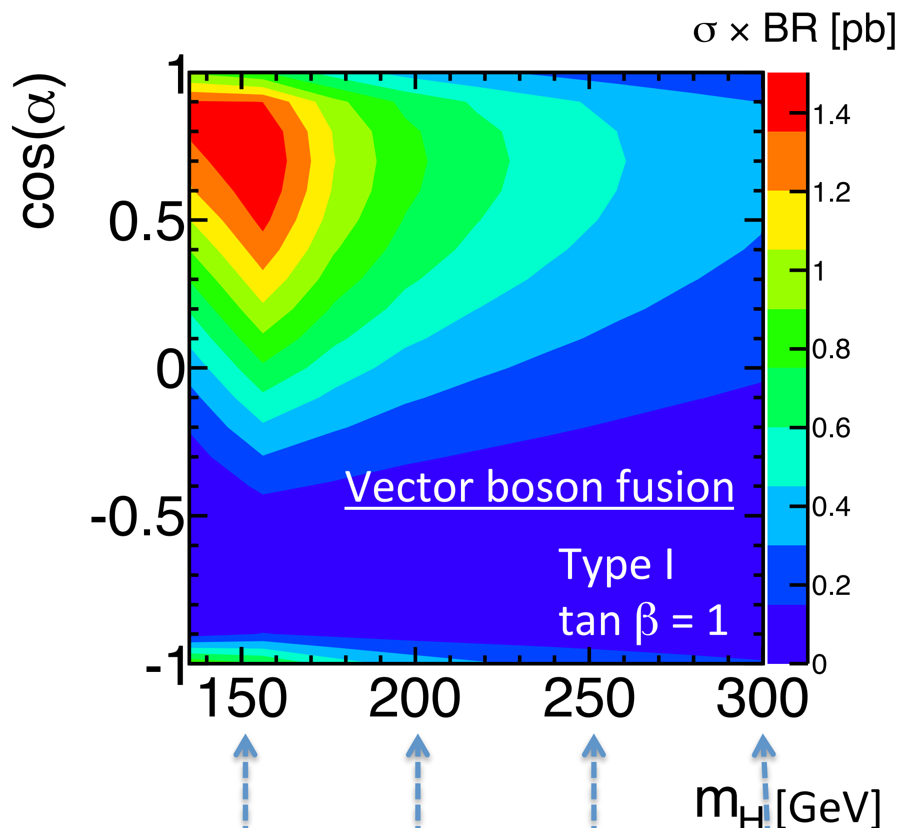
Parameter fixed at
Type I and tan β = 1

$\sigma_H(ggF \to H) \times \mathrm{BR}_H(H \to WW)$



SM: 9.5 5.3 3.4 2.5

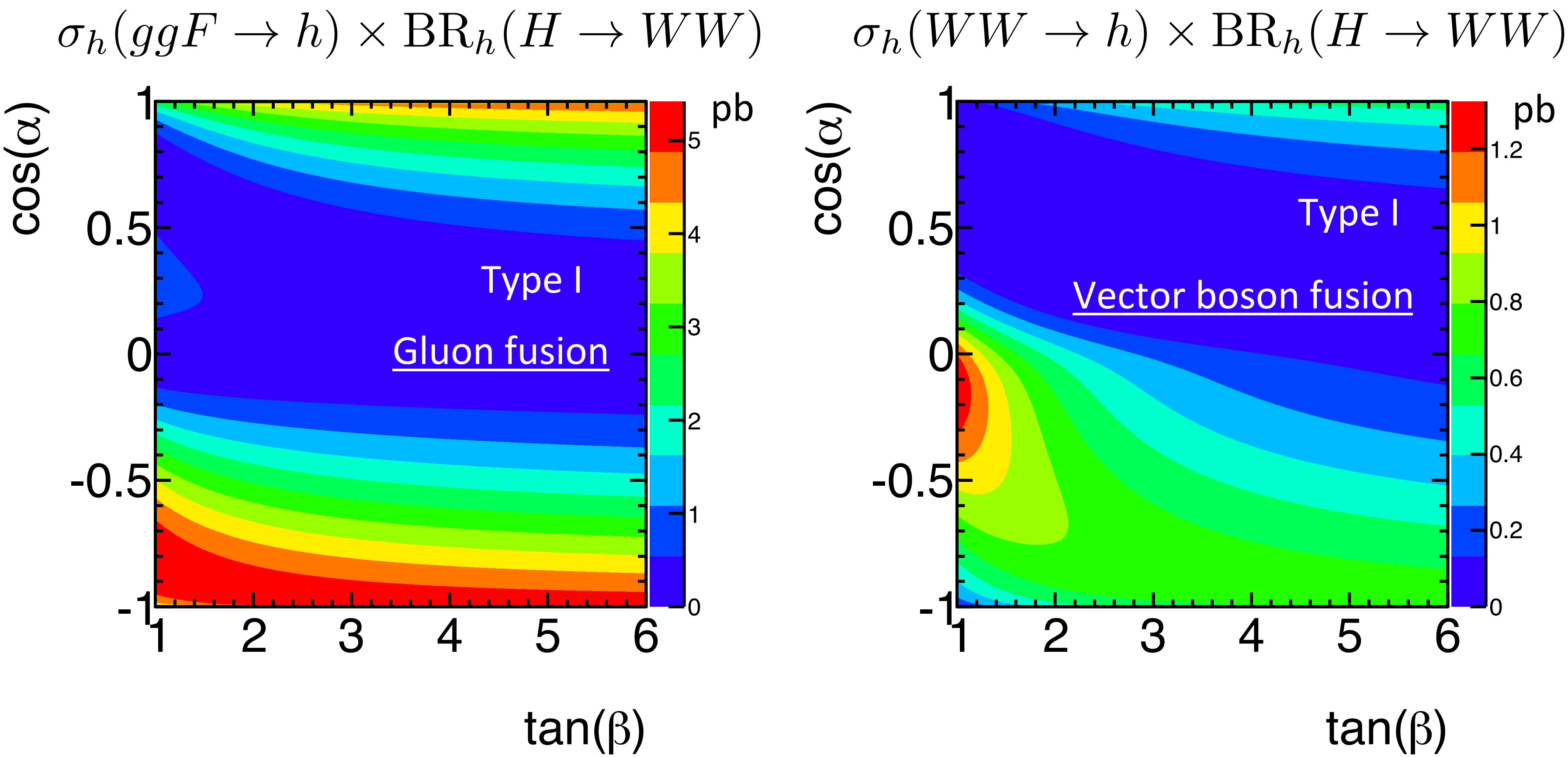
$\sigma_H(WW \to H) \times \mathrm{BR}_H(H \to WW)$



SM: 0.9 0.6 0.4 0.3

σ x BR for the light Higgs boson h

Parameter fixed at
Type I and m_h = 125 GeV



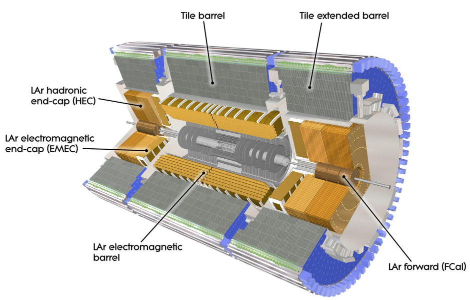
Event Selection

Object definition

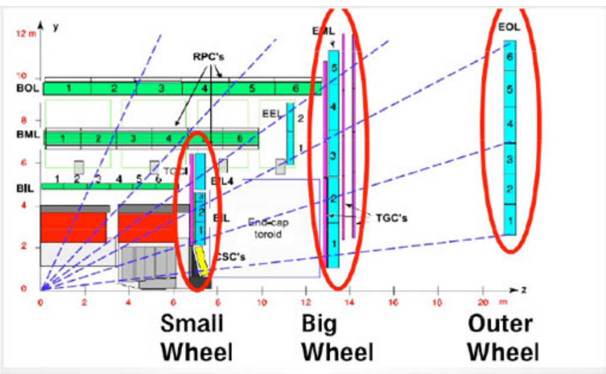
Using $\mathcal{L}$ = 13 fb^{-1} of 8 TeV pp data from ATLAS

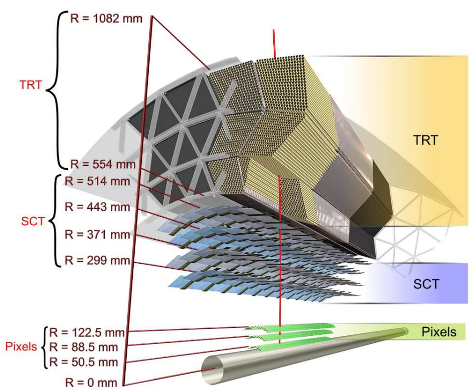
Electron Selection
Calorimeter clusters matched to tracks
Track must match primary vertex and must be isolated

Muon Selection
Matched tracks from Inner Detector and Muon Spectrometer
Energy from ID must agree with MS
Tracks must be isolated



Energy taken from the calorimeter clusters





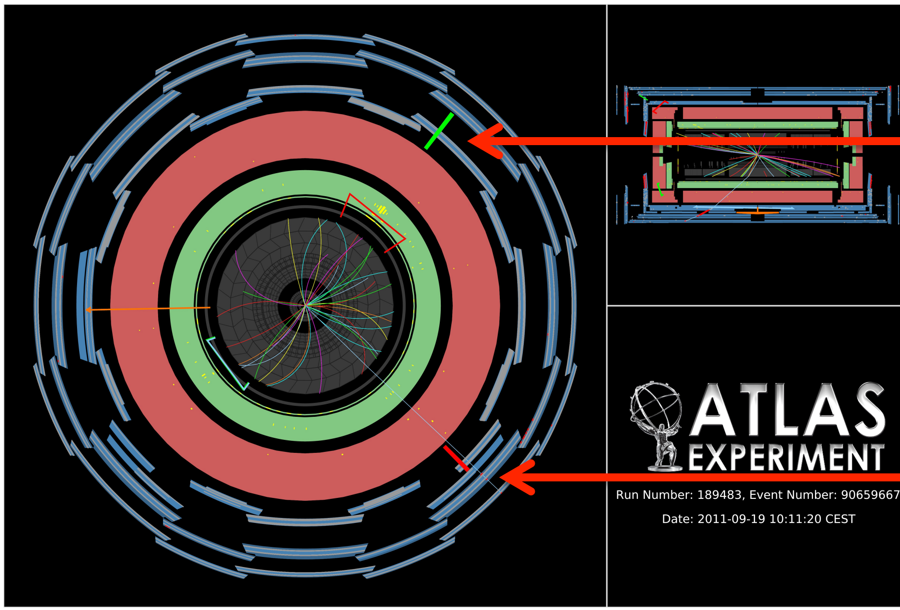
Position taken from the track

Jet Selection
Anti-kt algorithm with R = 0.4
Jets must have highest p_T tracks associated to Primary Vertex

Preselection

Preselection cuts are in common with SM H→ WW.

These cuts remove large amount of background before moving to Neural Networks.



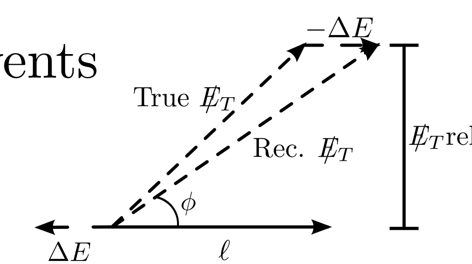
$p_T(l_2)$>15GeV, $|\eta_e|$<2.47

Invariant mass of the two leptons: $m(ll)$>10GeV

$p_T(l_1)$>25GeV, $|\eta_\mu|$<2.4

$E^{\mathrm{miss}}_{\mathrm{T,rel}} > 25$ GeV to supress QCD, Z+jets, Drell-Yan $\tau\tau$ events

$$E^{\mathrm{miss}}_{\mathrm{T,rel}} = \begin{cases} E^{\mathrm{miss}}_{\mathrm{T}} \sin(\Delta\phi_{\mathrm{min}}) & \text{if } \Delta\phi_{\mathrm{min}} < \pi/2 \\ E^{\mathrm{miss}}_{\mathrm{T}} & \text{if } \Delta\phi_{\mathrm{min}} \geq \pi/2 \end{cases}$$



$\Delta\phi_{\mathrm{min}}$ is the min angle between $E_{T,\mathrm{miss}}$ and a lepton or jet

Analysis channels

0 jet bin

- Additional cuts after the preselection(→ common selection for all jet bins as in WW SM analysis) :
  - 0 jets
  - | $\Delta\phi(l_1,l_2)$ | < 2.4
  - m(ll) < 75 GeV
- 6 Input variables

  Choice of variables was optimised according to exclusion power
- Evaluate Neural Network in
  - WW control regions
  - Signal regions

2 jet bin

- Additional cuts after the preselection (→ common selection for all jet bins as in WW SM analysis):
  - 2 jets
  - Btag veto
  - Opp. Hemispheres
  - m_T < 180 GeV
  - m(*ll*) < 80 GeV
- 9 Input variables

  Choice of variables was optimised according to exclusion power
- Evaluate Neural Network in
  - Top control regions
  - Signal regions

Input variables

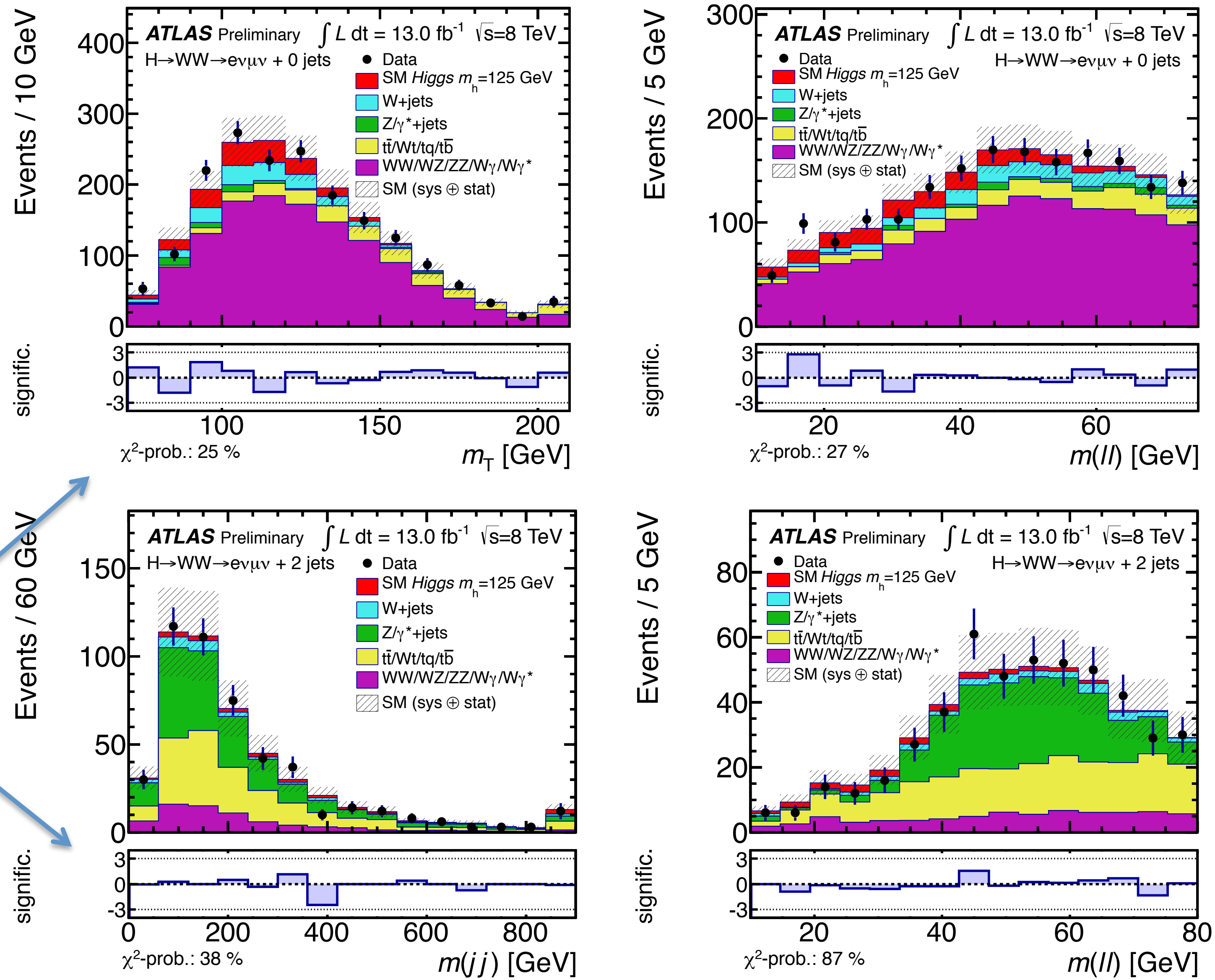
Signal processes for training (here for $\tan\beta = 3$, $\alpha = \pi/2$)

Background processes for training

Process	0 jet	2 jet	Top control region	WW control region
Signal (m_h = 125 GeV)	2.55 ± 0.50	5.52 ± 0.71	1.35 ± 0.19	0.76 ± 0.13
Signal (m_H = 150 GeV)	470 ± 140	76 ± 19	20.9 ± 5.7	16.1 ± 3.9
$WW/WZ/ZZ/W\gamma/W\gamma*$	1140 ± 290	63 ± 18	22.1 ± 6.2	1170 ± 310
Z/γ^* + jets	41 ± 15	194 ± 72	84 ± 31	15.7 ± 6.4
W+jets	135 ± 58	23.4 ± 9.7	18.3 ± 7.6	78 ± 32
$t\bar{t}/tW/tb/tqb$	175 ± 49	168 ± 77	1760 ± 440	313 ± 97
Total background	1490 ± 420	450 ± 180	1890 ± 480	1580 ± 450
S/B	0.31	0.18	–	–
Observed	1815	483	1986	1725

- We trained the 2HDM signal, which is the light Higgs boson plus the heavy Higgs boson in the case of the 2HDM, against the background processes. The SM signal did not go into the training and the limit calculation.
- The SM signal with a mass of 125 GeV was only used in the distributions of the input variables and the NN output to illustrate the modeling and comparing with the SM WW analysis.
    - We fitted the processes with the SM signal included separately. The SM signal fit value is
    - $\hat{\mu} = 1.58 \pm 0.75$ in the 0 jet channel (SM WW analysis = 1.5 ± 0.6)
    - $\hat{\mu} = 1.30 \pm 1.12$ in the 2 jet channel

Input variables in SR with SM signal normalised to fit value



<u>0 jet channel:</u>

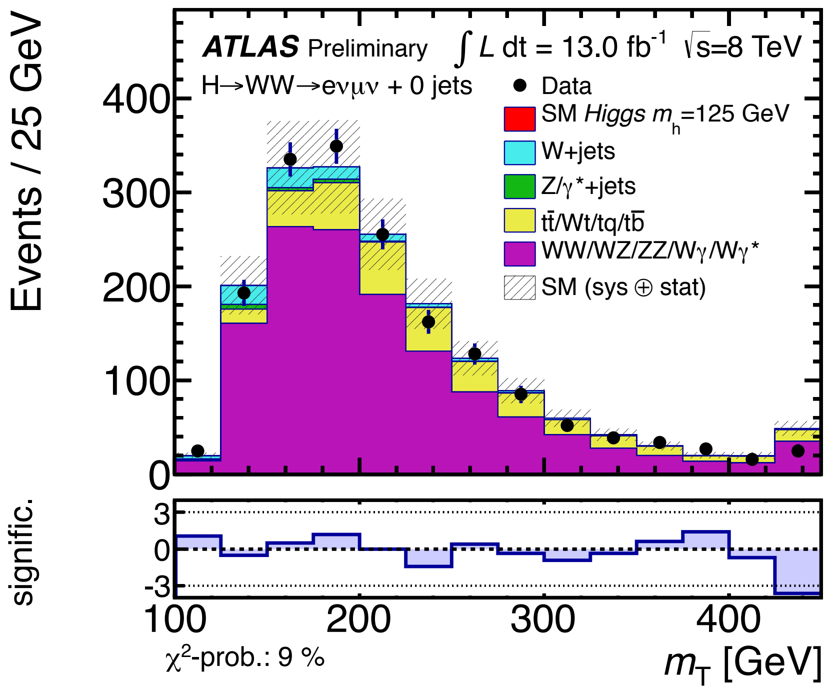
<u>2 jet channel:</u>

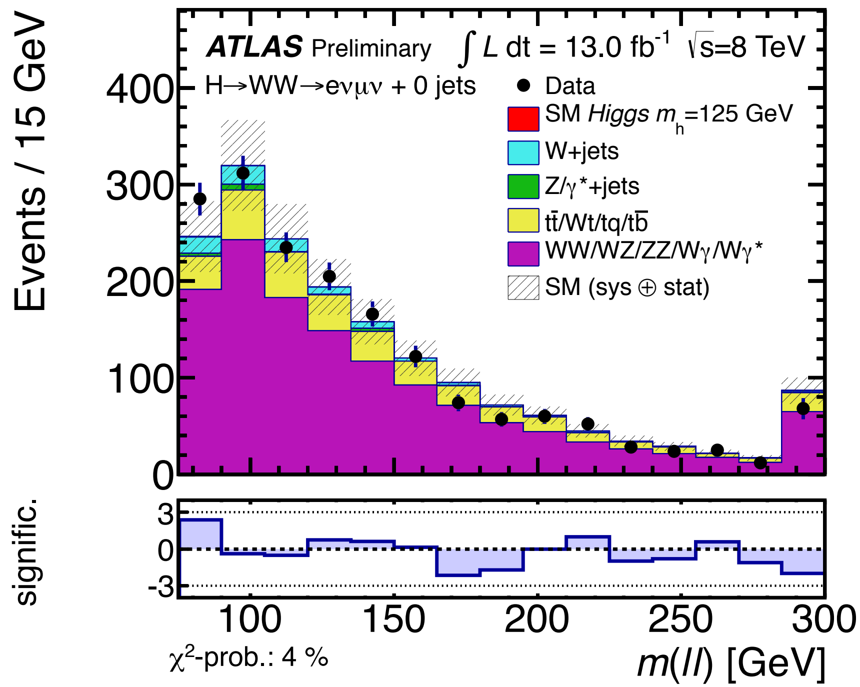
Significance of difference between data and expectation

Following the advice of the statistics forum: http://arxiv.org/abs/1111.2062

Diboson CR with SM signal (0 jet bin)

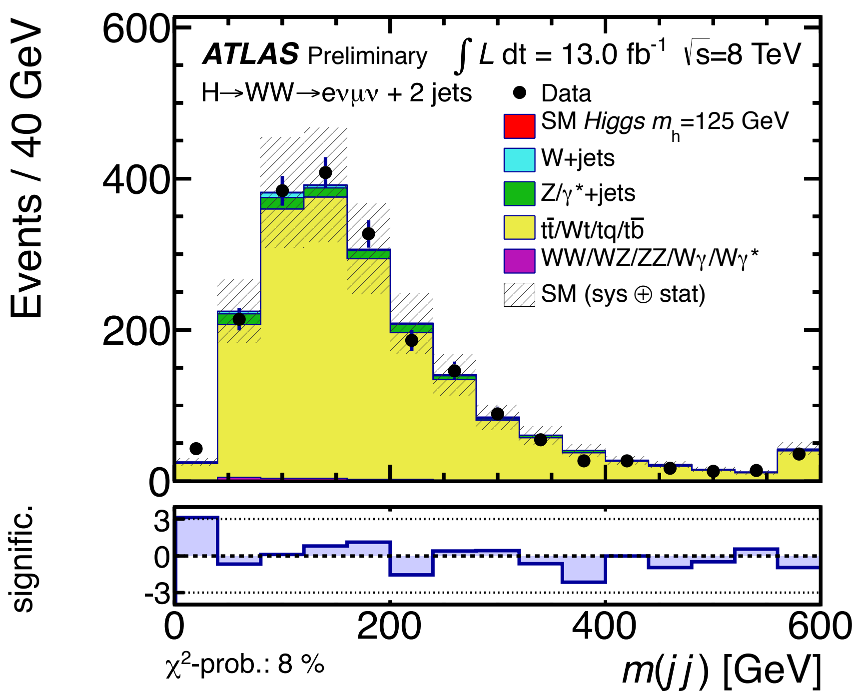
- The WW control region is defined through all events passing the full selection but we require: m(ll) > 80
- To reduce Z+jets an addition cut has been required: P_T(ll) > 30 GeV

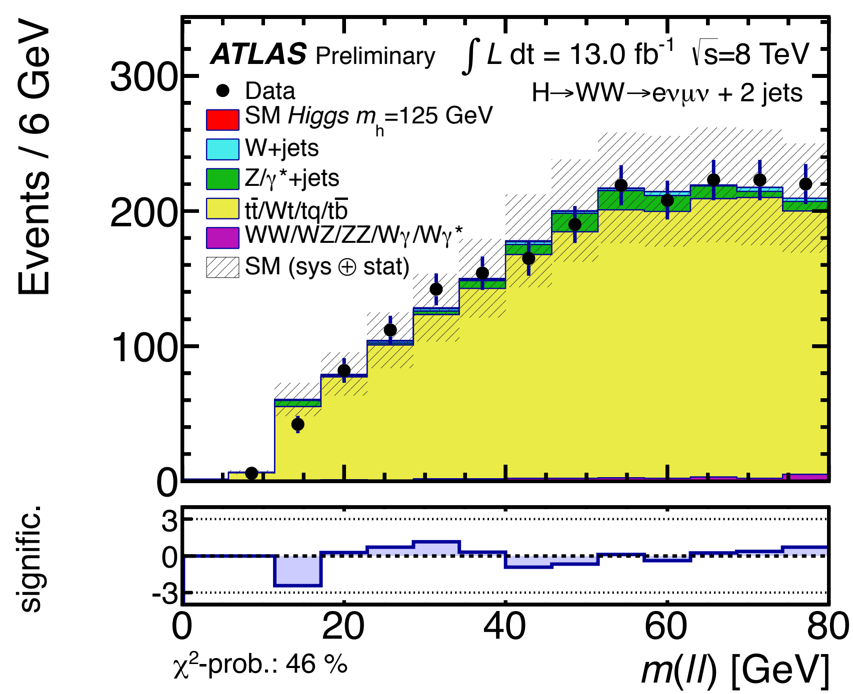




Top control region with SM signal (2 jet bin)

- The top control region is defined through all events passing the full selection but instead of the b-jet veto, at least 1 b-tagged jet is required.
- Using top CR to fit the top MC simultaneously during the limit calculation.





Training of the Neural Network

Neural Network

Implementation with NeuroBayes

- The contribution of VBF is very low in the 0 jet bin

→ Signal production mainly through ggH
- Adding 2 jet bin to include the VBF production and gain sensitivity.

<u>0 jet bin</u>

$\mathrm{m_T}$

$\mathrm{m}(ll)$

$p_\mathrm{T}(ll)$

$|\Delta\mathrm{Y}(ll)|$

$\mathrm{E^{miss}_{T,rel}}$

$|\eta(l_1)|$

<u>2 jet bin</u>

$\mathrm{m}(jj)$

$\mathrm{m}(ll)$

$\mathrm{m_T}$

$p_\mathrm{T}^\mathrm{tot}$

$p_\mathrm{T}(l_2)$

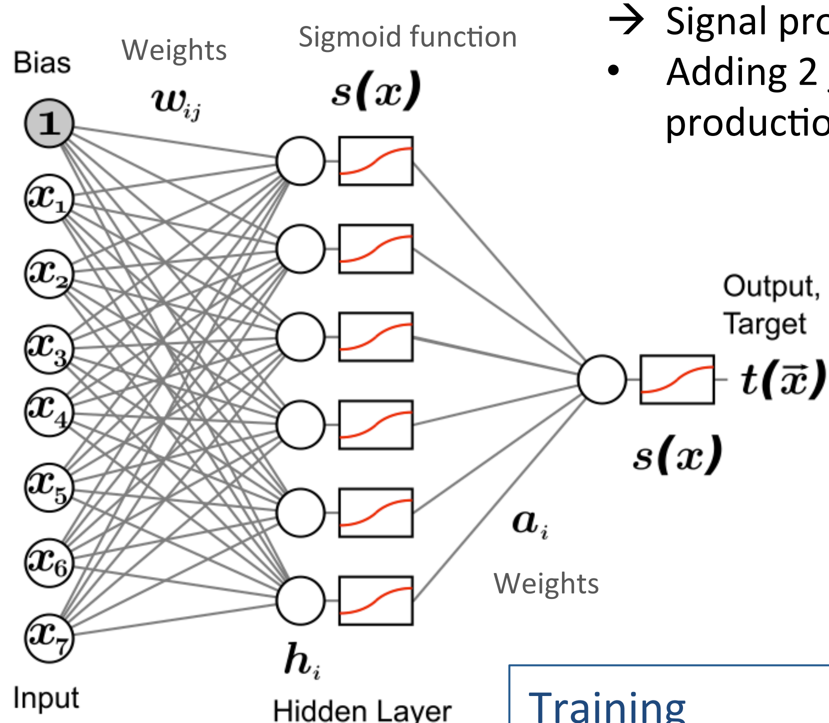
$|\eta(l_1)|$

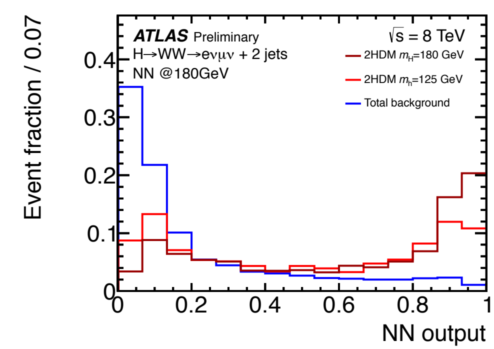
$p_\mathrm{T}(j_1)$

$\mathrm{m}(j_1)$

$\cos\theta(l_1, l_2)$

6 hidden nodes





<u>Training</u>
<u>in 0 jet bin:</u>
ggH as signal
VBF not included

<u>Training</u>
<u>in 2 jet bin:</u>
VBF as signal
ggH not included

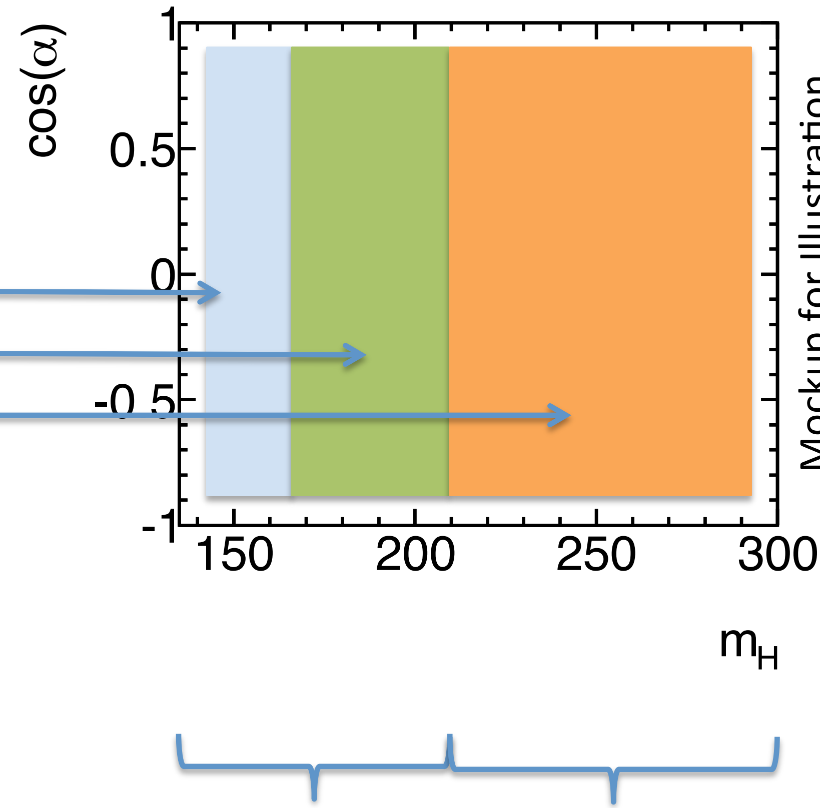
$$p_\mathrm{T}^\mathrm{tot} = |\mathbf{p}_\mathrm{T}^\mathrm{tot}| = |\mathbf{p}_\mathrm{T}^{\ell 1} + \mathbf{p}_\mathrm{T}^{\ell 2} + \mathbf{p}_\mathrm{T}^{j1} + \mathbf{p}_\mathrm{T}^{j2} + \mathbf{p}_\mathrm{T}^\mathrm{miss}|$$

$$m_\mathrm{T} = \sqrt{(E_\mathrm{T}(\ell\ell) + E_\mathrm{T}(\nu\nu))^2 - (\mathbf{p}_\mathrm{T}(\ell\ell) + \mathbf{p}_\mathrm{T}^\mathrm{miss})^2} \quad \text{with} \quad E_\mathrm{T}(\ell\ell) = \sqrt{\mathbf{p}_\mathrm{T}^2(\ell\ell) + m^2(\ell\ell)}$$

Using three networks

Three neural networks have been used for the 0 and 2 jet bin respectively

- NN @ 150 GeV: 135 GeV – 160 GeV
- NN @ 180 GeV: 165 GeV – 200 GeV
- NN @ 240 GeV: 220 GeV – 300 GeV



The mass resolution in the $WW \to e\nu\mu\nu$ decay channel is very limited.
The combination of three networks is sufficient to cover the whole mass range without loosing sensitivity (~ 1%).

Signal samples are available in steps of M_H = 5 GeV 20 GeV

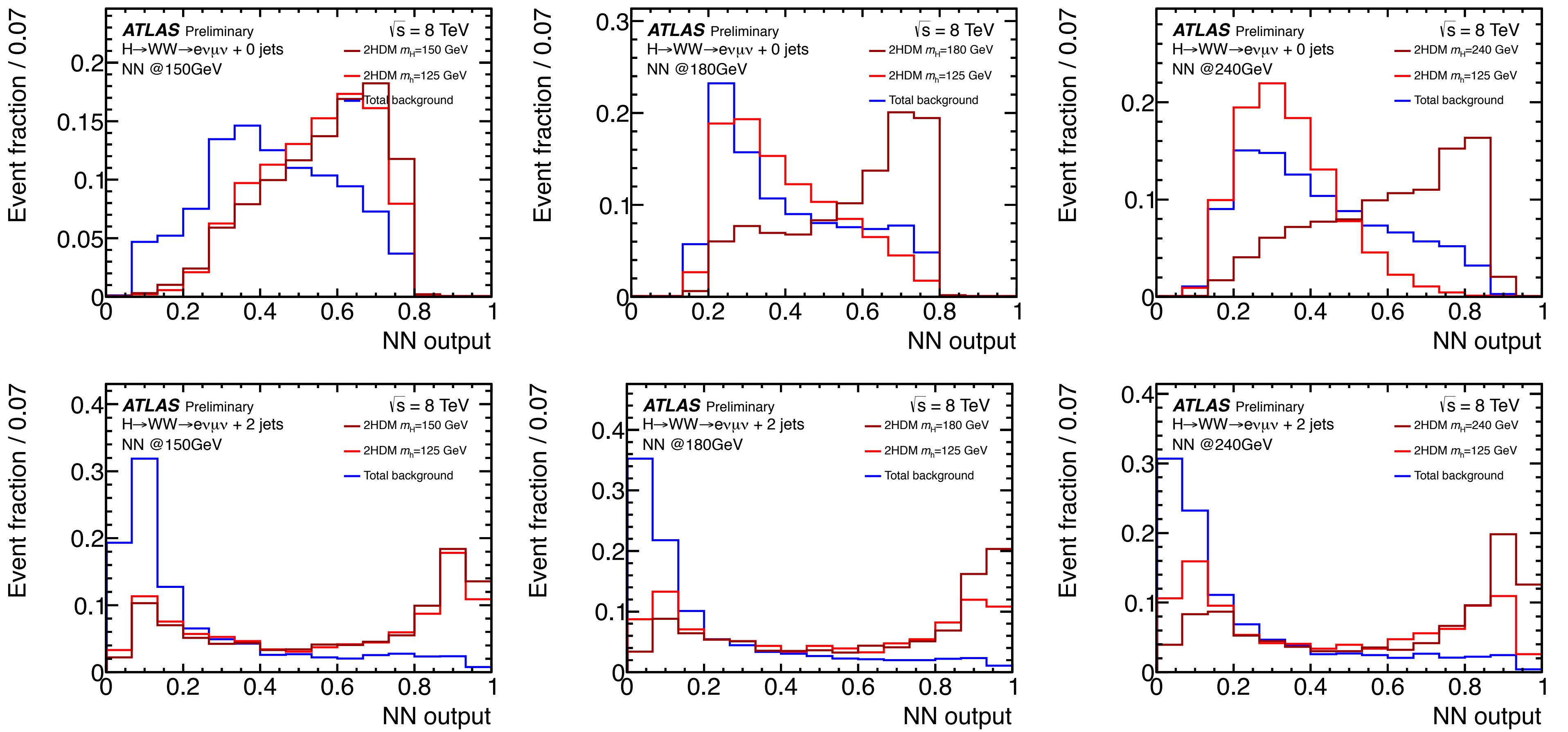
Templates of the NN Output Distribution

Legend: Heavy Higgs Light Higgs Total background

NN trained @ m_H = 150 GeV

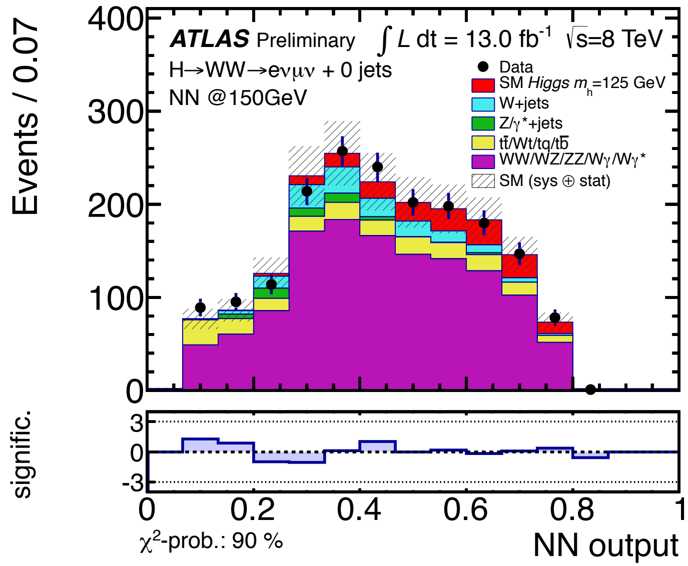
NN trained @ m_H = 180 GeV

NN trained @ m_H = 240 GeV

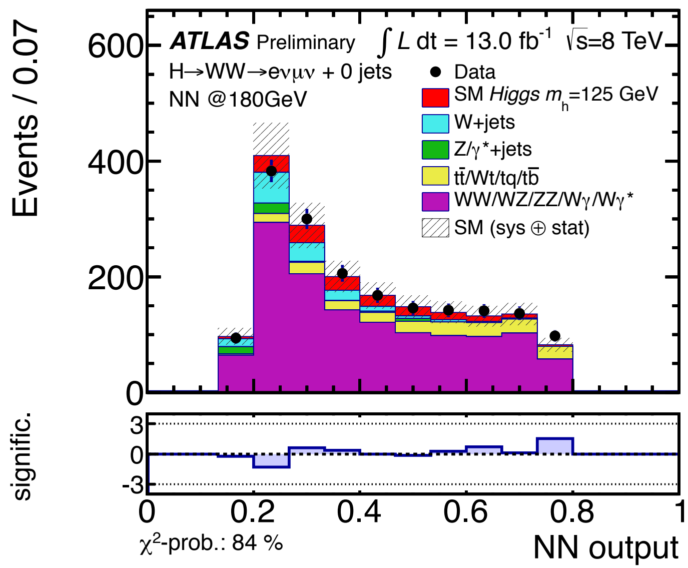


NN Output in the 0-Jet Channel

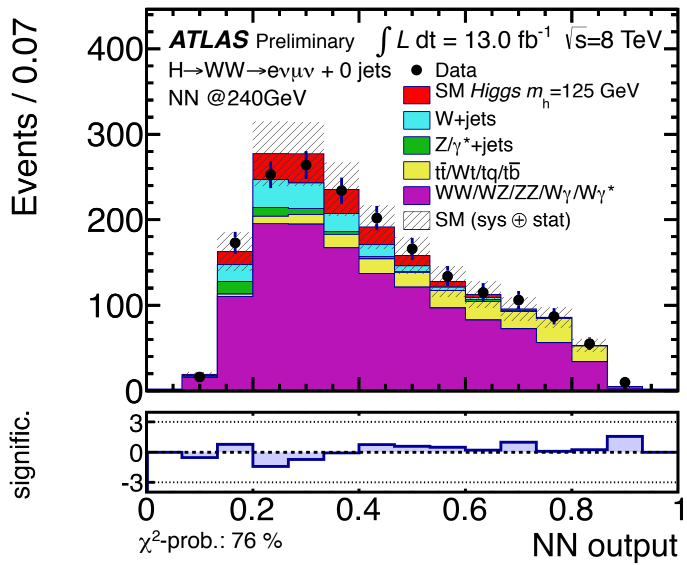
NN trained @ m_H = 150 GeV



NN trained @ m_H = 180 GeV

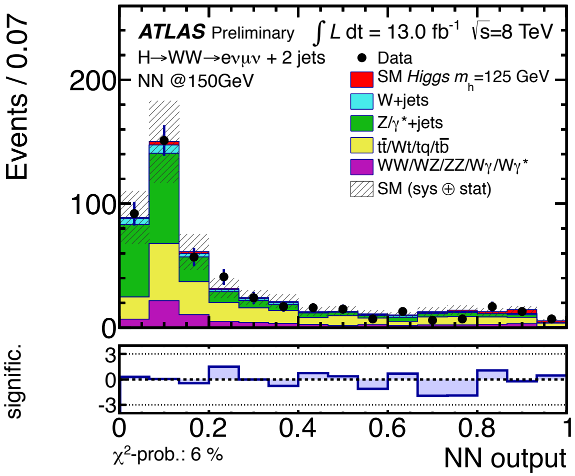


NN trained @ m_H = 240 GeV

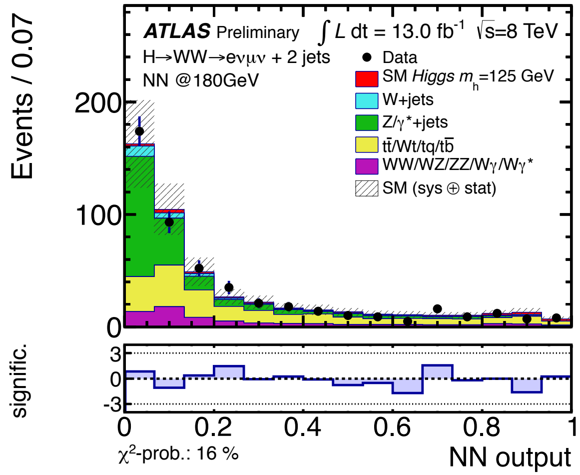


NN Output in the 2-Jet Channel

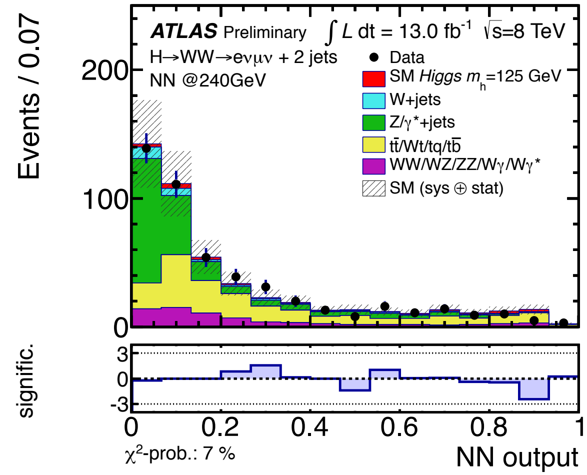
NN trained @ m_H = 150 GeV



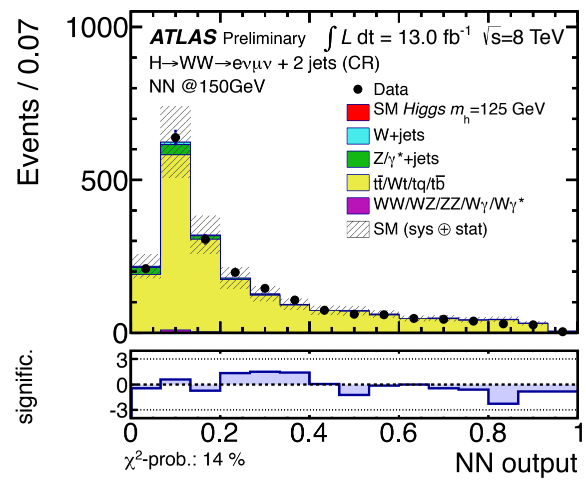
NN trained @ m_H = 180 GeV



NN trained @ m_H = 240 GeV

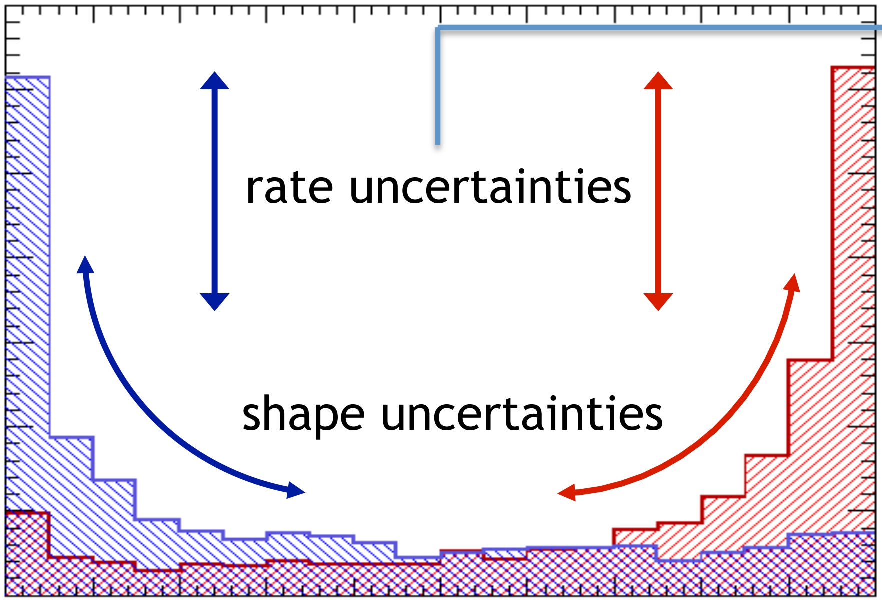


Evaluate NN for the 2 jet bin in Top control region



Systematics
and
Exclusion limits in the 2HDM

Rate and shape systematics



Rate systematics

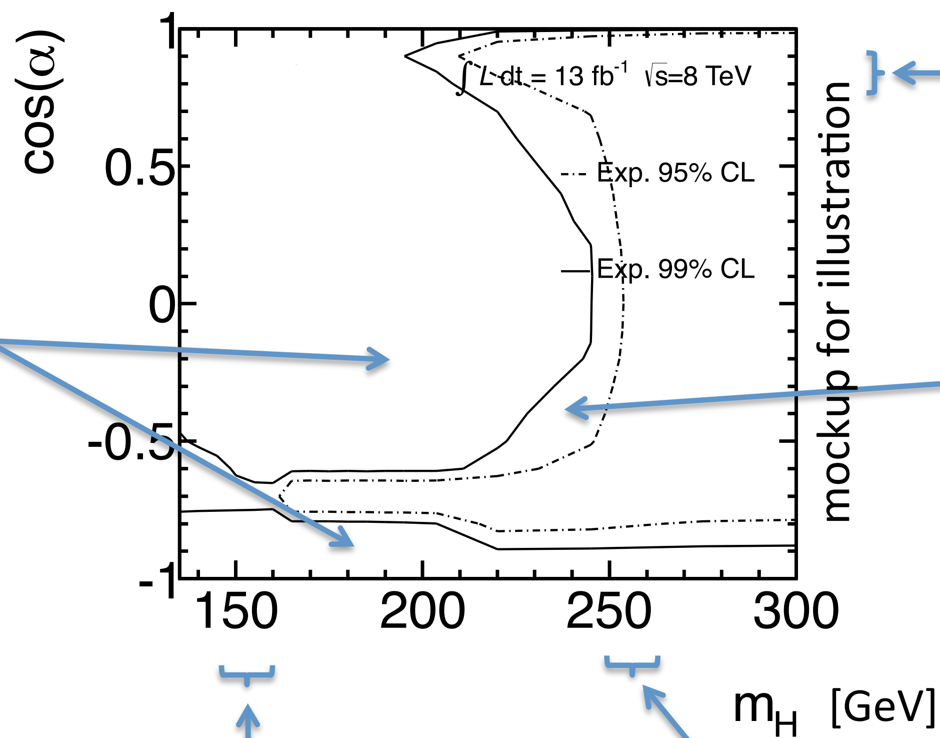
Process		$WW/WZ/ZZ/W\gamma/W\gamma^*$	$t\bar{t}/Wt/tq/t\bar{b}$	DY/Z+jets
Jet modelling	0-jet bin	3%	14%	10%
	2-jet bin	11%	37%	12%
Lepton modelling	0-jet bin	2%	2%	6%
	2-jet bin	2%	2%	2%
Lumi	0-jet bin	4%	4%	4%
	2-jet bin	4%	4%	4%
PDF	0-jet bin	6%	6%	6%
	2-jet bin	5%	7%	5%
Generator	0-jet bin	1%	3%	–
	2-jet bin	2%	22%	–
Pile-up modelling	0-jet bin	2%	1%	2%
	2-jet bin	1%	1%	1%
Parton Shower	0-jet bin	–	7%	–
	2-jet bin	–	13%	–
Total	0-jet bin	8%	18%	14%
	2-jet bin	13%	46%	14%
Cross section		25%	22%	34%

- Rate systematics give histogram templates freedom to move vertically only. All bins move in a synchronous, proportional way.
- Shape systematics allow templates to 'slide horizontally' (bin by bin). → distortion

Exclusion limit in the cos α vs. m_H plane

- Use CL_s method to compute confidence level for each triplet (tan β, cos α, m_H)
- Plot exclusion contours in the cos α vs. m_H plane

Only expected



y bin width = 0.1

Expected exclusion limit of 99%

Expected exclusion limit of 95%

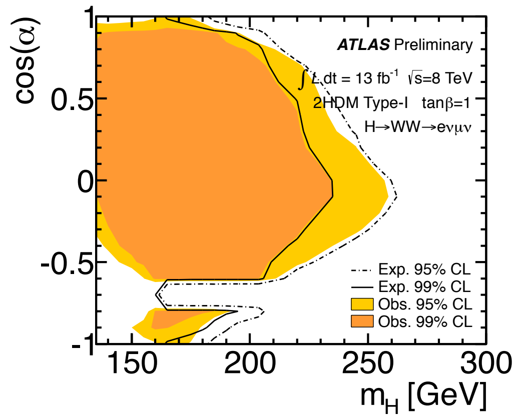
x bin width = 5 GeV

x bin width = 20 GeV

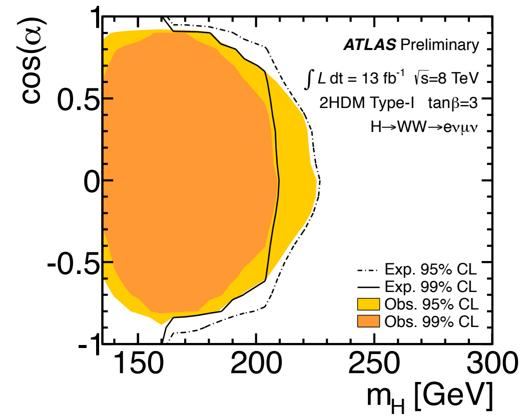
Exclusion limit for 2HDM (Type I)

$y_{2\mathrm{HDM}}/y_{\mathrm{SM}}$	Type I	Type II
ξ_h^{v}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^{u}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^{d}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^{v}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^{u}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^{d}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

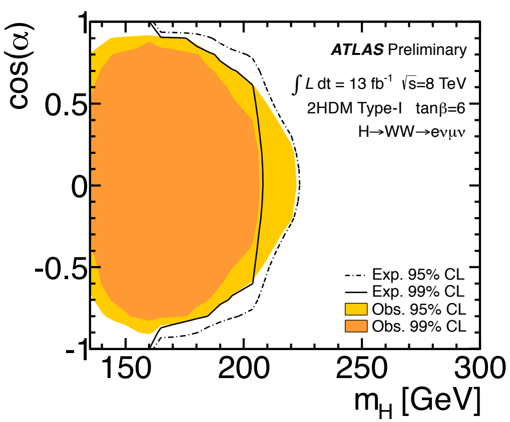
tan β = 1



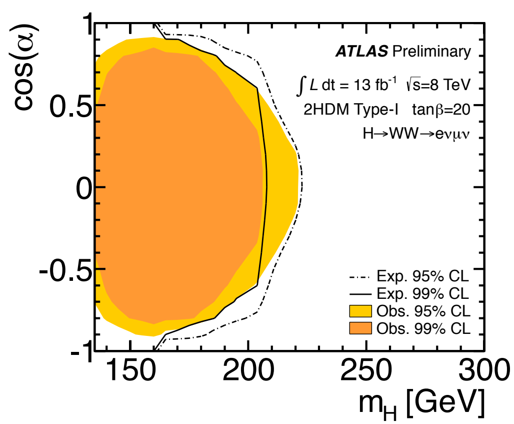
tan β = 3



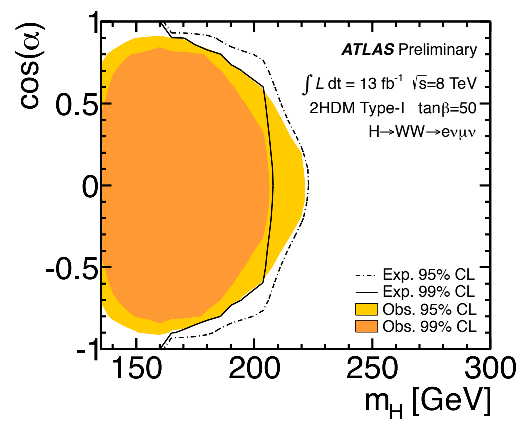
tan β = 6



tan β = 20



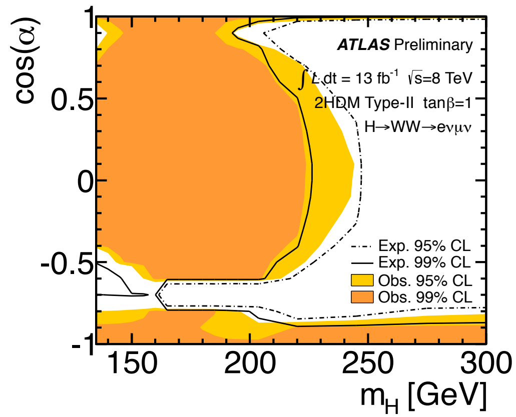
tan β = 50



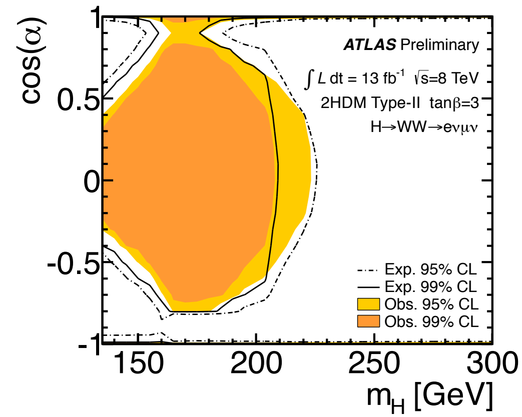
Exclusion limit for 2HDM (Type II)

$y_{\mathrm{2HDM}}/y_{\mathrm{SM}}$	Type I	Type II
ξ_h^{v}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^{u}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^{d}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^{v}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^{u}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^{d}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

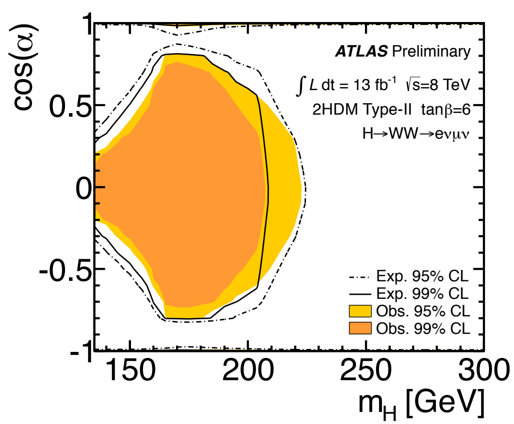
tan β = 1



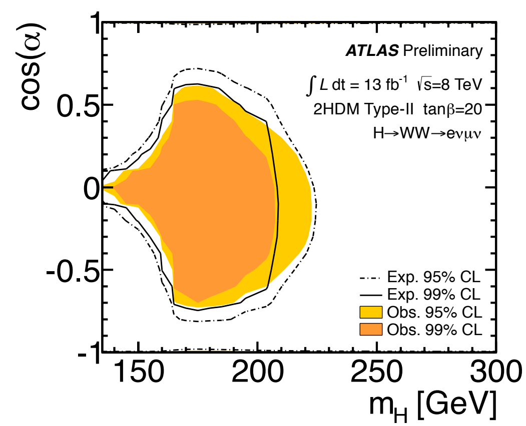
tan β = 3



tan β = 6

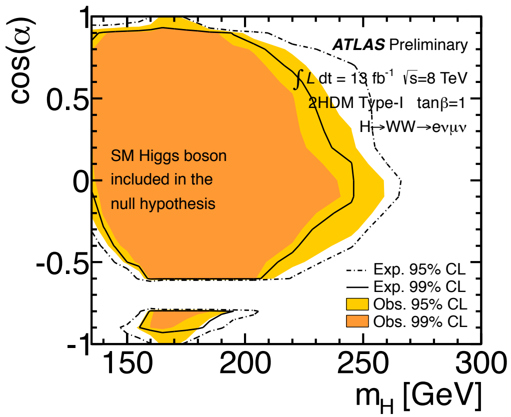


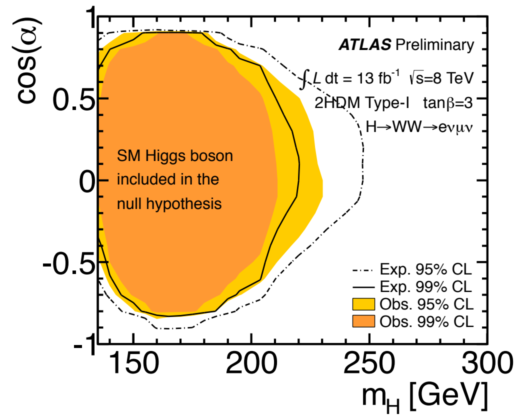
tan β = 20

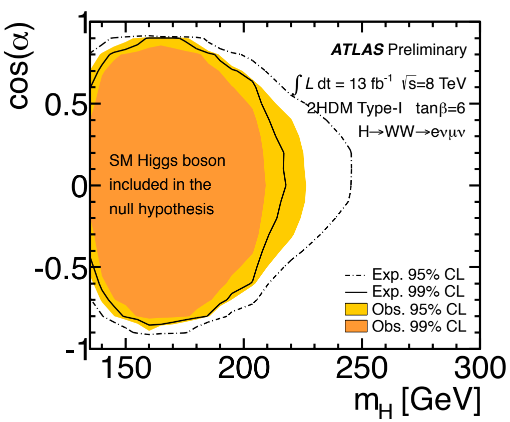


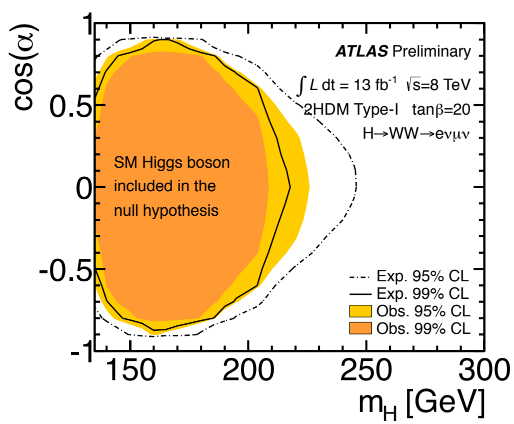
Exclusion limit for 2HDM (Type I)

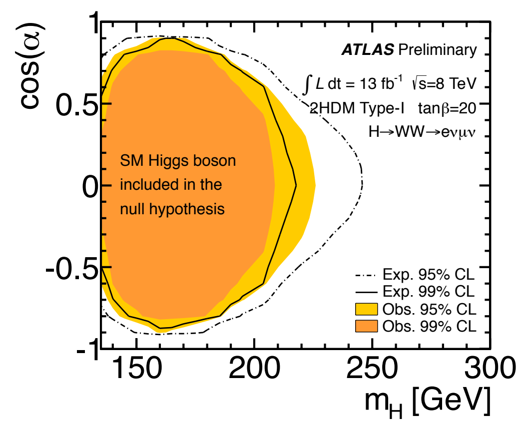
y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$











- Charged Higgs
- High-mass Higgs
- MSSM

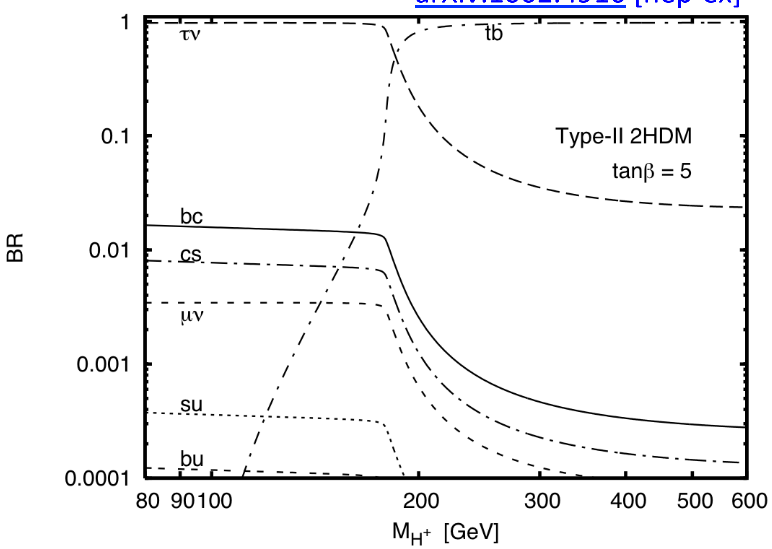
Charged Higgs

Searches for charged Higgs bosons can also provide limits on 2HDM's.

- W bosons decay equally to the 3 lepton generations
- H^+ may predominantly decay into $\tau\nu$
- Ratios between $e+\tau_{had}$ and $e+\mu$, as well as between $\mu+\tau_{had}$ and $\mu+e$ final states are measured

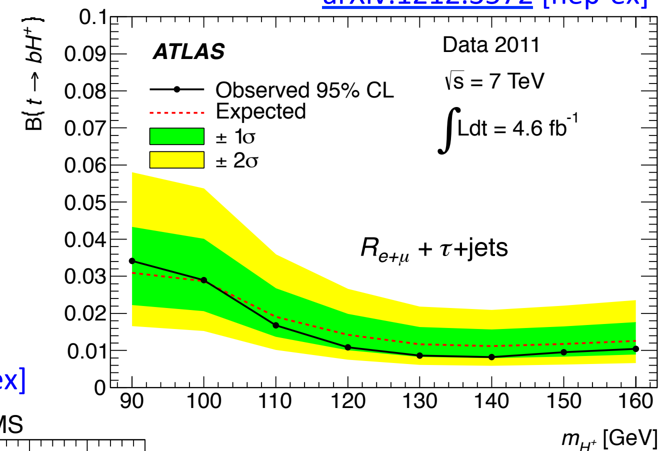
Branching ratios for various decay modes of the charged Higgs boson H^+ in the Type II 2HDM.

arXiv:1002.4916 [hep-ex]

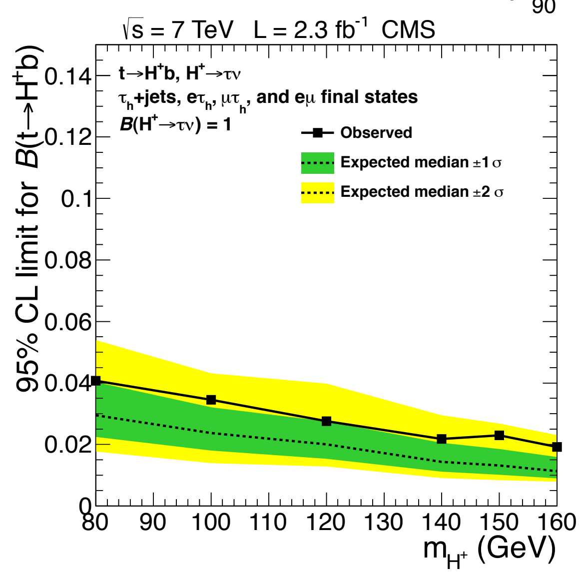


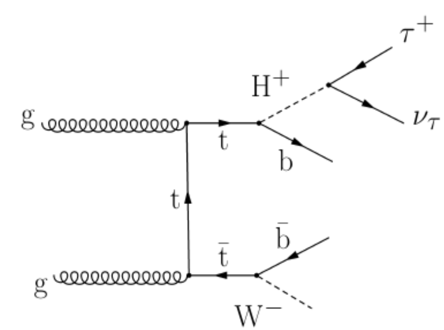
$H^+ \rightarrow \tau\nu$

arXiv:1212.3572 [hep-ex]



arXiv:1205.5736 [hep-ex]



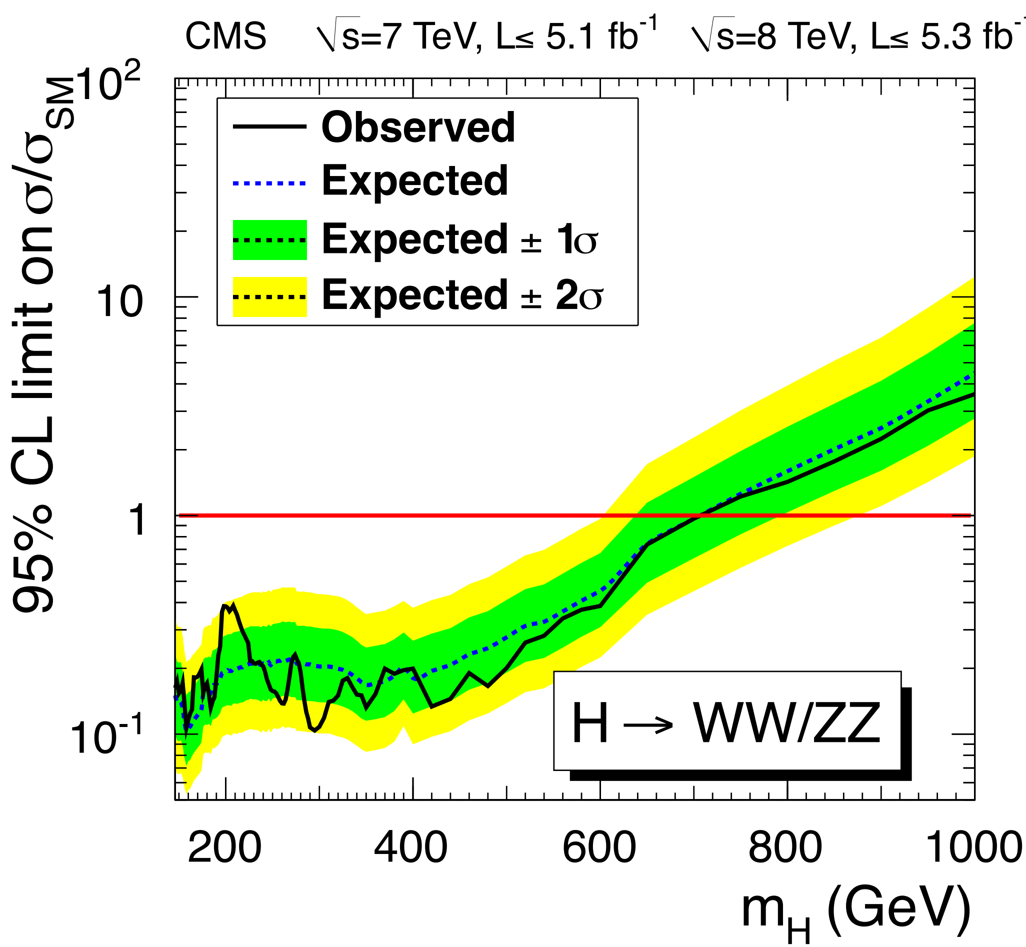


High-mass Higgs searches

The 2HDM as well as singlet model predicts the existence of additional resonances at high mass

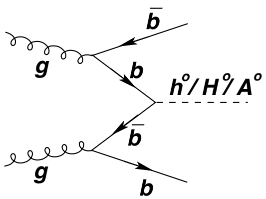
- For special parameters the heavy Higgs boson is SM-like.
- Decay channels: H→WW & H→ZZ
- Exclusion range: $145 < m_H < 710$ GeV

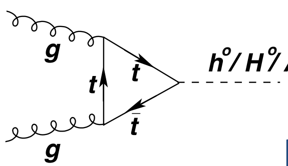
arXiv:1304.0213 [hep-ex]



MSSM

- Type II 2HDM describes the Higgs sector of the MSSM.
- Unlike the 2HDM, the MSSM predicts a partner for every SM particle.
- In the MSSM the Higgs sector is defined by 2 parameters: tanβ and m_A

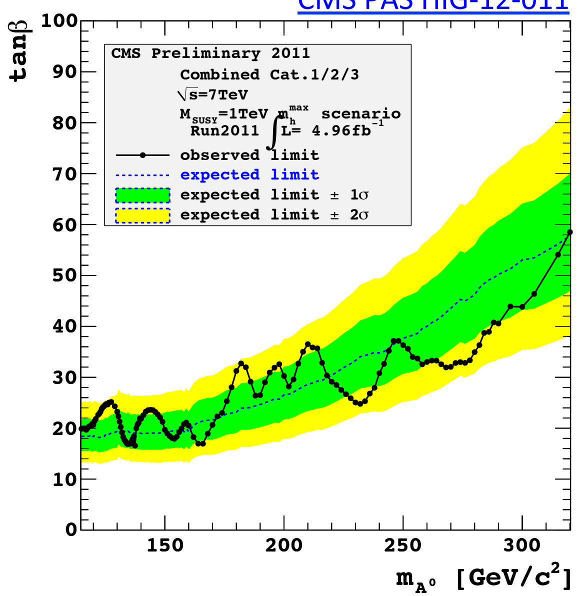




Exclusion limits in the MSSM parameter space of M_A and tanβ

h/H/A → $\mu\mu$

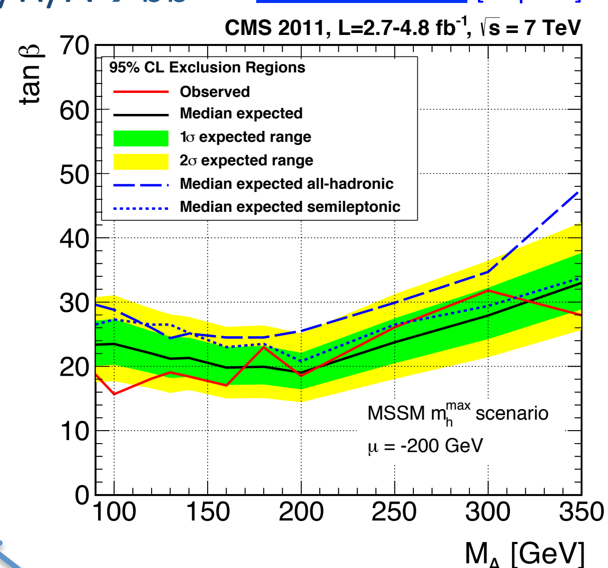
CMS PAS HIG-12-011



pp→bH+X

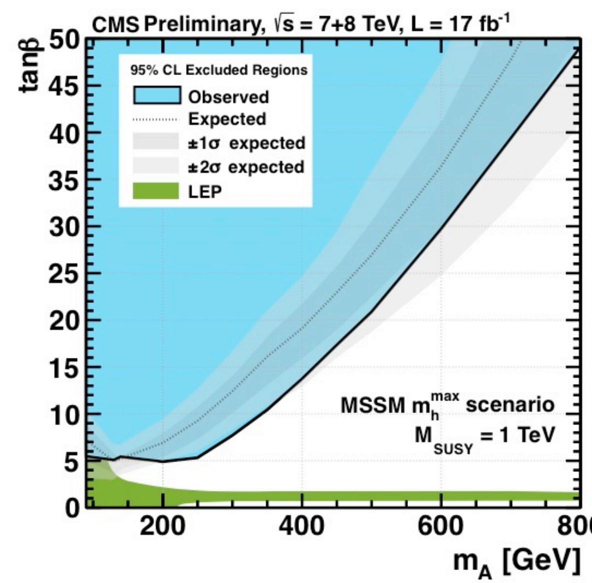
h/H/A→$b\bar{b}$

arXiv:1302.2892 [hep-ex]



h/H/A → $\tau\tau$

CMS PAS HIG-12-050



Excludes 16 < tanβ < 26 for
Higgs masses from 115 to 175 GeV

Summary

- First dedicated 2HDM analysis at LHC (ATLAS-CONF-2013-027
  - Analysis with 13 fb^{-1}
  - Calculated exclusion limits in the cos α vs. m_H plane for different values of tanβ
  - → Can exclude large parameter range for the Type I and Type II 2HDM

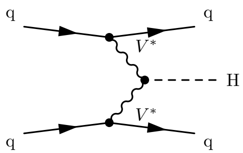
- Constraints of the BR of the charged Higgs boson H^+
- High-mass Higgs searches → Exclude SM-like resonances
- Exclusion limits of the MSSM in the tanβ vs m_A plane.

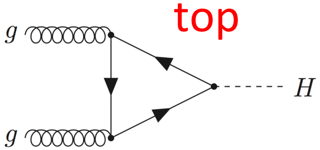
Backup

Scaling of Cross-Sections and Branching Ratios

- We need to calculate the expected event yields as a function of the couplings for both Higgs bosons h and H.
- Signal is simulated by rescaling the cross sections and branching ratios of the SM Higgs according to the three 2HDM parameters: α, β, m_H.

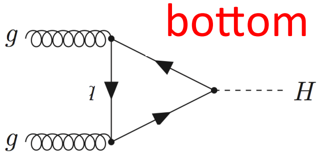
xs for VBF in 2HDM: $\sigma_{h/H}(VV \to h/H) = \sigma_{SM}(VV \to h/H) \times (\xi^V_{h/H})^2$





xs for ggF in 2HDM:

$$\sigma_{h/H}(ggF \to h/H) = \sigma_{SM}(ggF \to h/H) \times \{w_t(\xi^u_{h/H})^2 + w_b(\xi^d_{h/H})^2 + w_{tb}\xi^u_{h/H}\xi^d_{h/H}\}$$



Decay:

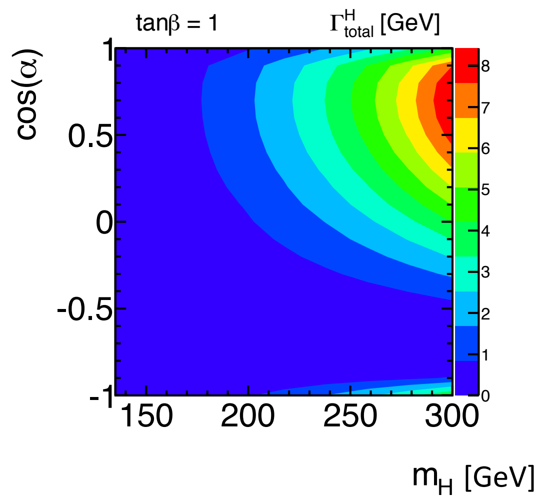
$$\mathrm{BR}_{h/H}(\mathrm{H} \to \mathrm{WW}) = \frac{\Gamma(\mathrm{H} \to WW)}{\Gamma_{\mathrm{total}}}$$

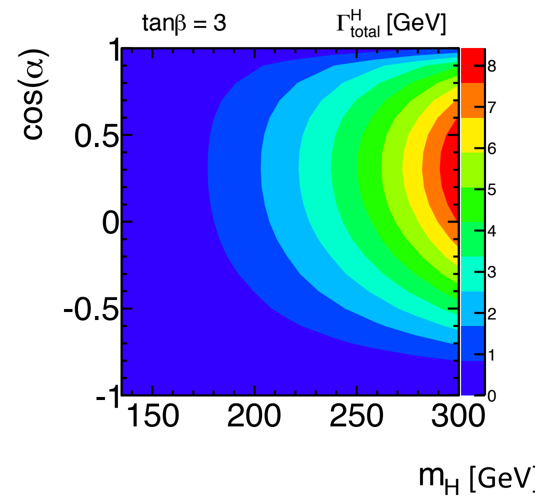
$$= \frac{\Gamma_{\mathrm{SM}}(\mathrm{H} \to \mathrm{WW})(\xi^v_{h/H})^2}{\Gamma_{\mathrm{SM}}(\mathrm{H} \to VV) \times (\xi^v_{h/H})^2 + \Gamma_{\mathrm{SM}}(\mathrm{H} \to bb) \times (\xi^d_{h/H})^2}$$

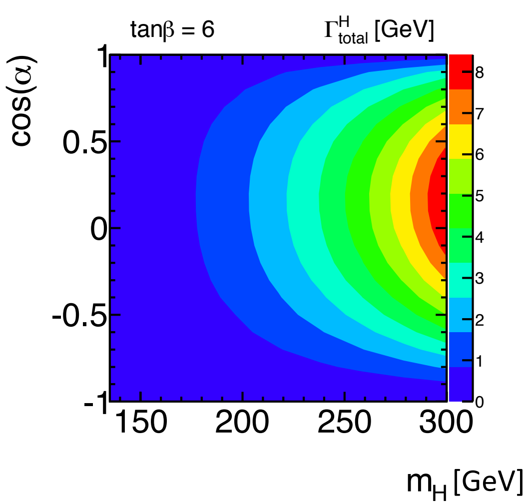
$$= \frac{\mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \mathrm{WW})(\xi^v_{h/H})^2}{\mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to VV) \times (\xi^v_{h/H})^2 + \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to bb) \times (\xi^d_{h/H})^2}$$

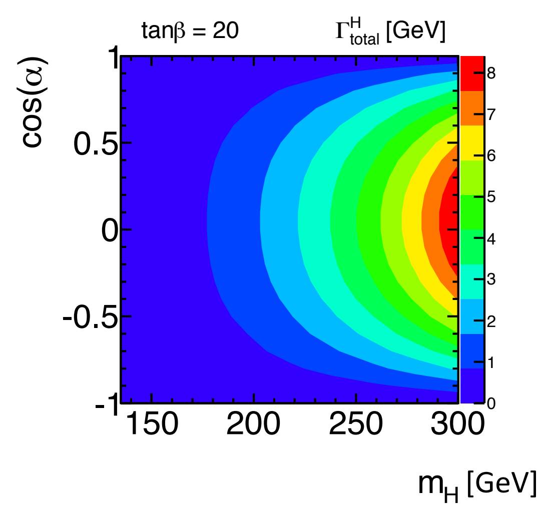
Decay width for 2HDM (Type I) heavy Higgs boson

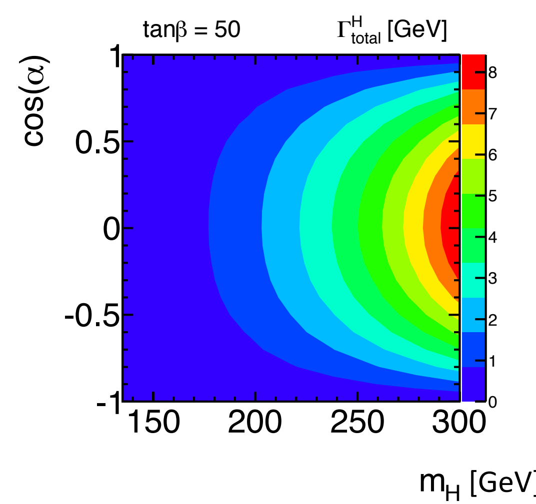
In the Type I 2HDM the decay width remains below 8 GeV.





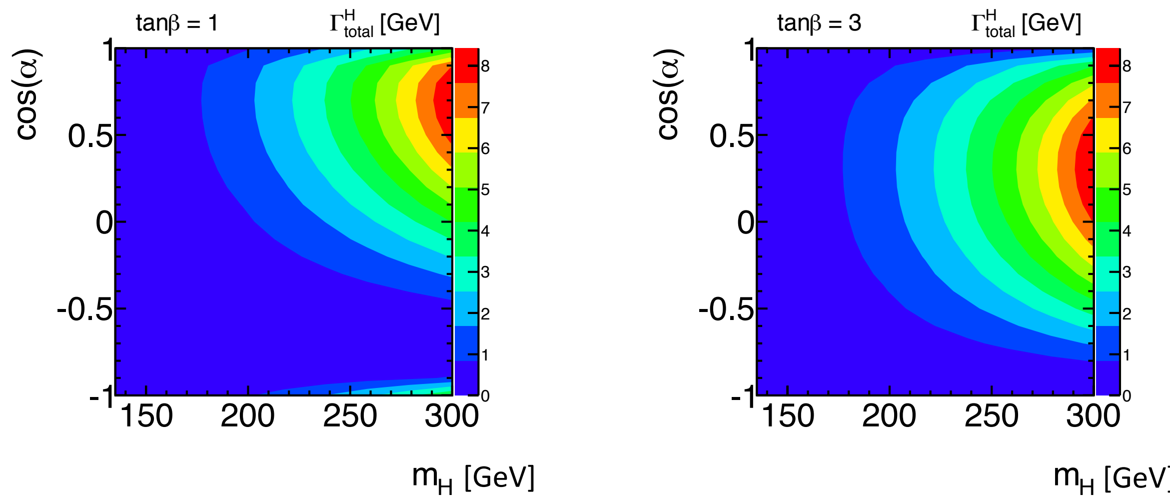


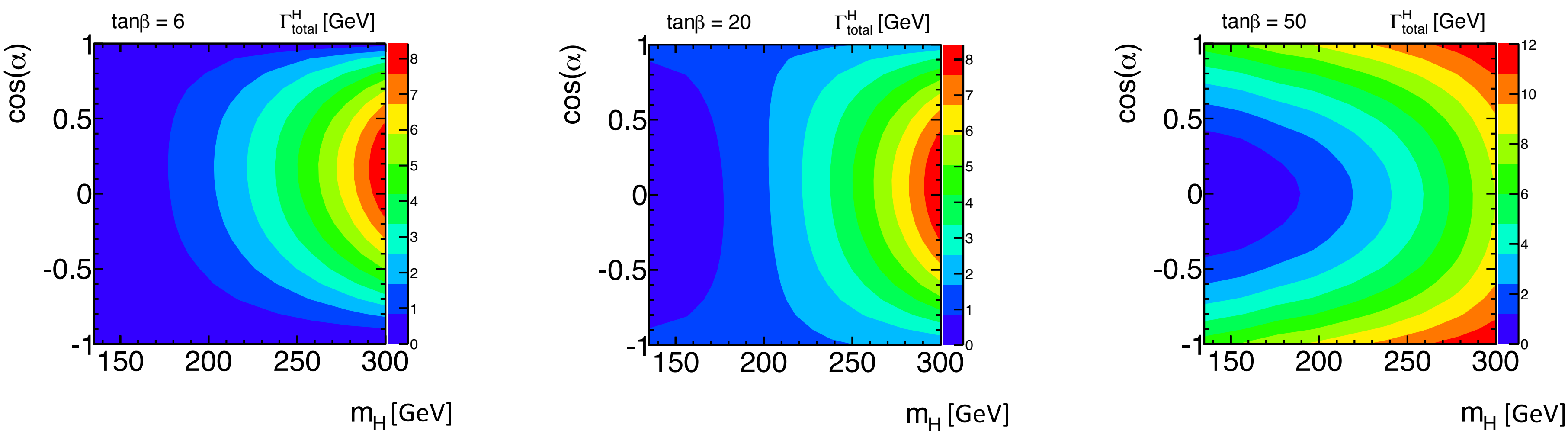




Decay width for 2HDM (Type II)
heavy Higgs boson

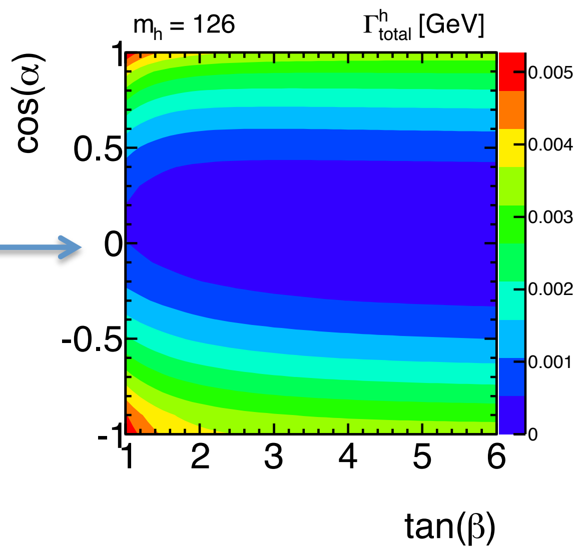
In the Type II 2HDM the decay width remains below 12 GeV.

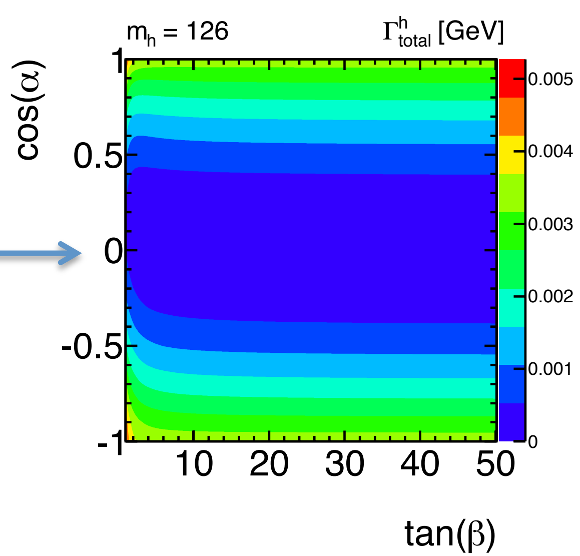




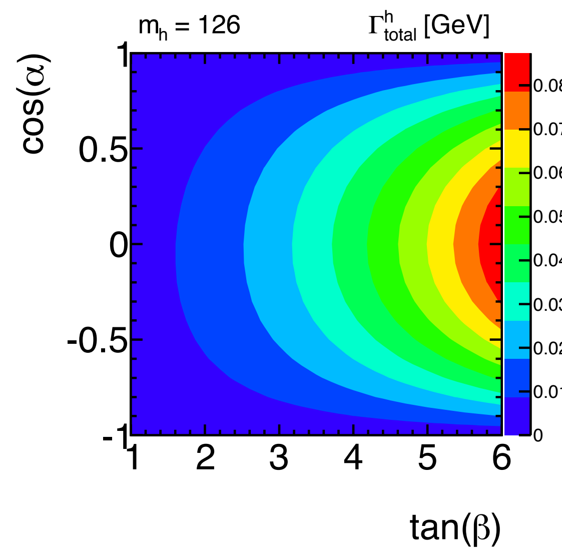
Decay width for 2HDM
light Higgs boson

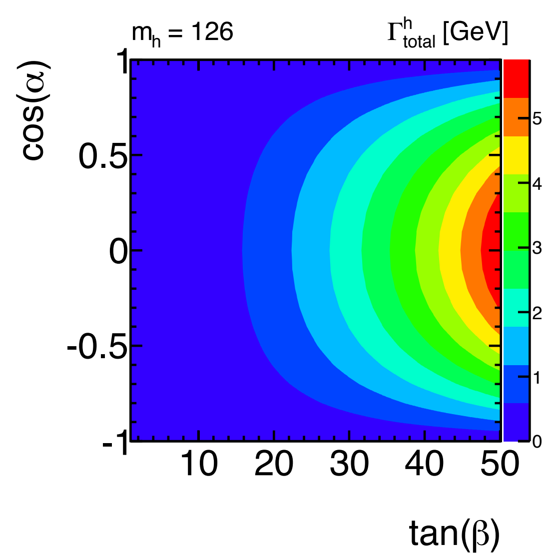
Type I



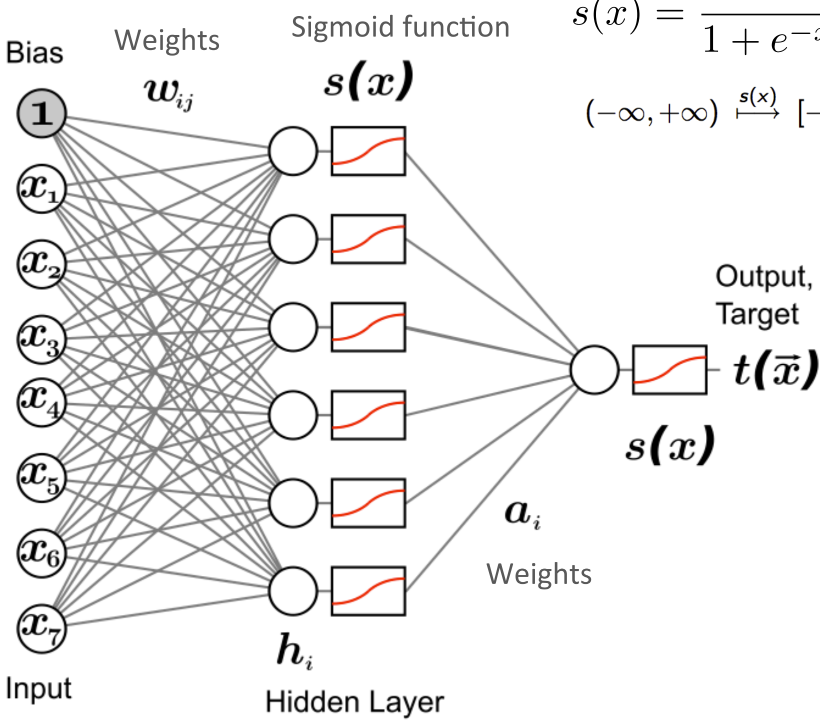


Type II



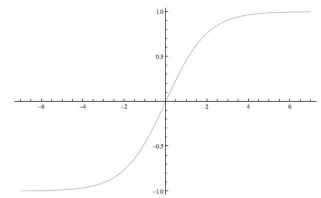


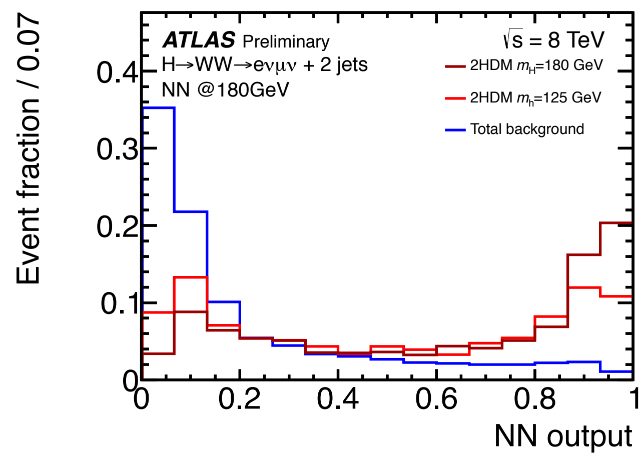
Using Neural Networks to improve sensitivity



$$s(x) = \frac{2}{1+e^{-x}} - 1$$

$$(-\infty, +\infty) \xrightarrow{s(x)} [-1, +1]$$





6 hidden nodes

Minimising the quadratic loss function

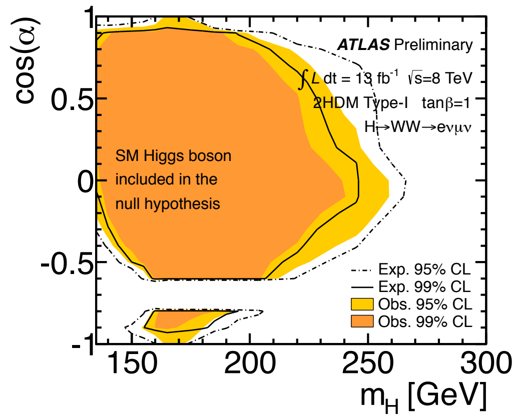
$$E = \frac{1}{2}\sum_i (t(\vec{x}_i) - T_i)^2$$

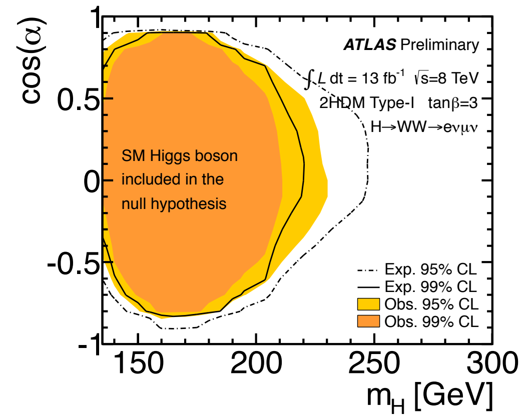
Known targets

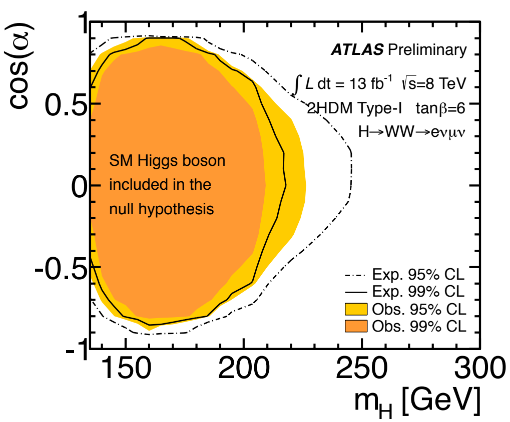
<phi-t>® *Implementation with NeuroBayes*

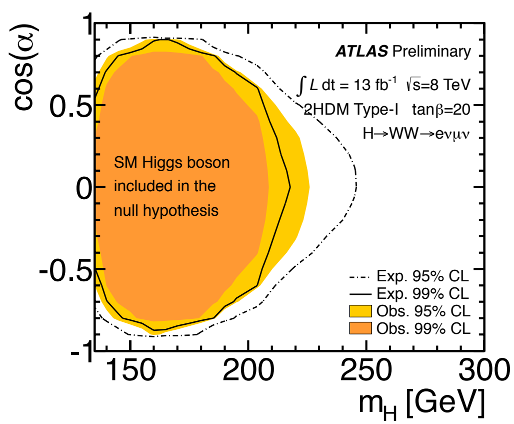
Exclusion limit for 2HDM (Type I)

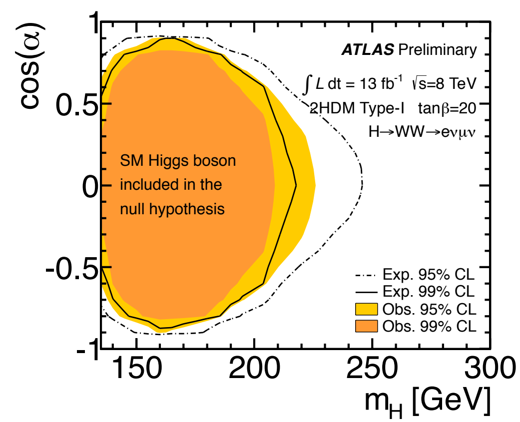
y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$





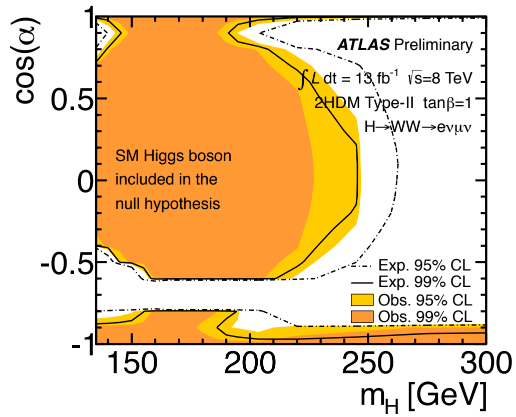


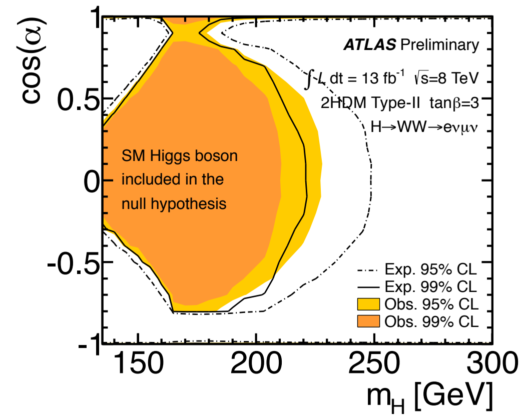


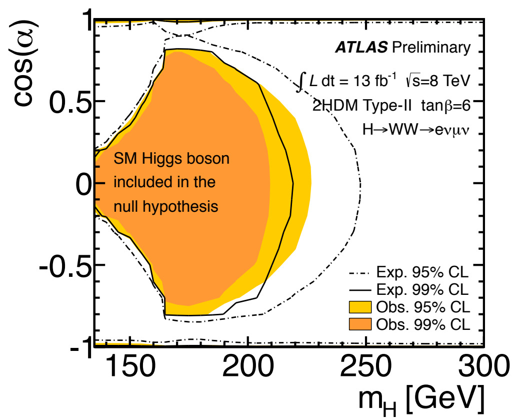


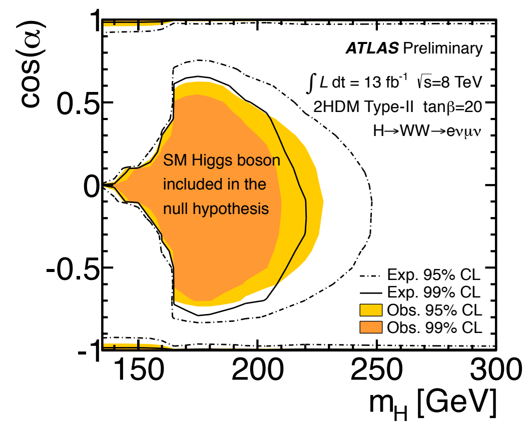
Exclusion limit for 2HDM (Type II)

$y_{\rm 2HDM}/y_{\rm SM}$	Type I	Type II
$\xi_h^{\rm v}$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^{u}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^{d}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
$\xi_H^{\rm v}$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^{u}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^{d}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

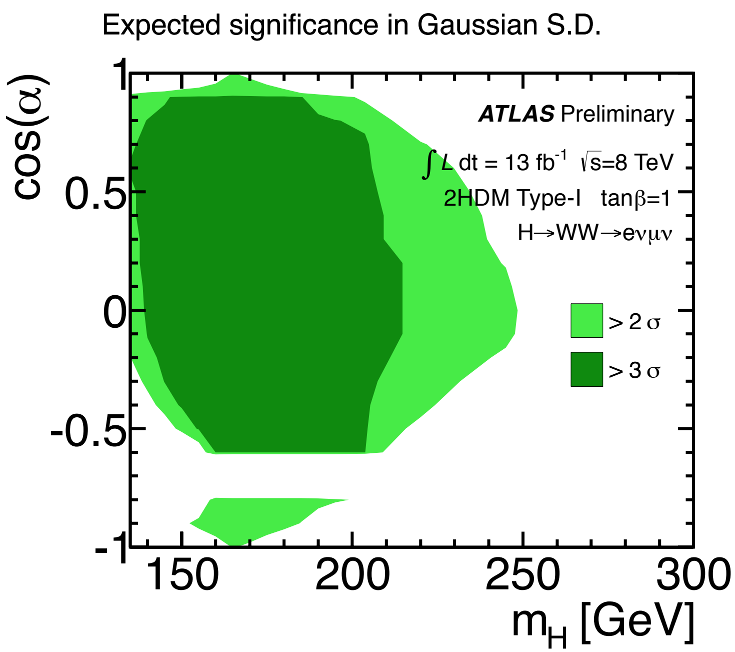


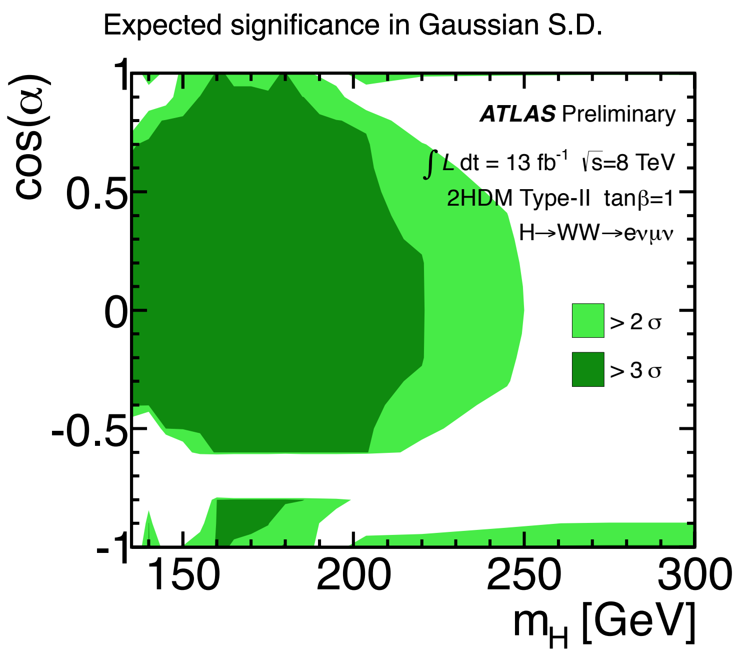






Expected significance in Gaussian S.D





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