Beyond-the-Standard Model Higgs physics using the ATLAS experiment
PANIC 2014 – Hamburg

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Fachbereich C - Physik

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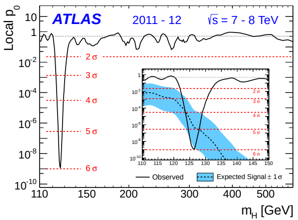
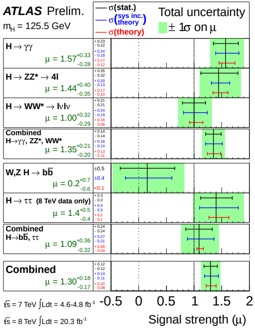
Why ask for more?

- On 4th July 2012 a new particle was found.
- **Today:** It's pretty much SM-Higgs like.
- But that does not explain. . .
- . . . Dark matter/ dark energy.
- . . . Matter/ antimatter asymmetry.
- . . . The hierarchy problem.



http://arxiv.org/abs/1207.7214



https://cds.cern.ch/record/1670012

Popular SM extensions

- In the **2HDM** one has two, complex scalar $SU(2)$ doublets $\Phi_i = (\Phi_i^{\pm}, \Phi_i^0)^T$
- Assuming no FCNC and lepton flavour violation this leads to...

5 2HDM particles

$\mathcal{CP}$ even: **h**, **H**

$\mathcal{CP}$ odd : **A**

Charged : $\mathbf{H}^{\pm}$

6 parameters

$m_{\mathbf{h}}$, $m_{\mathbf{H}}$: $\mathcal{CP}$ even masses
$m_{\mathbf{A}}$: $\mathcal{CP}$ odd masses
$m_{\mathbf{H}^{\pm}}$: Charged masses
α : Mixing angle
$\tan\beta$: Ratio of vev's

- The Higgs sector of the **MSSM** is equivalent to the 2HDM, but is constraint.
- ...and it has of course SUSY particles.

MSSM constraints

$$-\frac{\pi}{2} \leq \alpha \leq 0$$

$$m^2_{\mathbf{h},\mathbf{H}} = \frac{1}{2}(m^2_{\mathbf{A}} + m^2_Z \mp \sqrt{\Delta})$$

$$m_{\mathbf{H}^{\pm}} = m^2_{\mathbf{A}} + m^2_W, \text{ with}$$

$$\Delta = (m^2_{\mathbf{A}} + m^2_Z)^2 - 4m^2_{\mathbf{A}} m^2_Z \cos^2(2\beta)$$

Generic Model Searches

- **Intuitive idea**: look for another, (heavier) Higgs boson.
- The **search range** varies between:
- 65 GeV – 600 GeV for $X \to \gamma\gamma$
- 200 GeV – 900 GeV for $\mathbf{H} \to ZZ \to 4\ell$
- 260 GeV – 1000 GeV for $\mathbf{H} \to WW \to \mu\nu e\nu$
- Similar **analysis strategies** have been applied.

Search channels:

$X \to \gamma\gamma$	arXiv:1407.6583
$\mathbf{H} \to WW \to \mu\nu e\nu$	ATLAS-CONF-2013-067
$\mathbf{H} \to ZZ \to 4\ell$	ATLAS-CONF-2013-013

Analysis strategies:

$X \to \gamma\gamma$	cut based, $m_{\gamma\gamma}$ fits
$\mathbf{H} \to WW \to \mu\nu e\nu$	cut based, m_T fit
$\mathbf{H} \to ZZ \to 4\ell$	cut based, $m_{4\ell}$ fit

The X $\rightarrow \gamma\gamma$ search

Mass range:

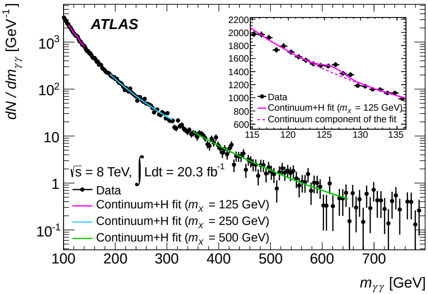
Low mass region:
65 GeV $< m_X <$ 110 GeV
High mass region
110 GeV $< m_X <$ 600 GeV

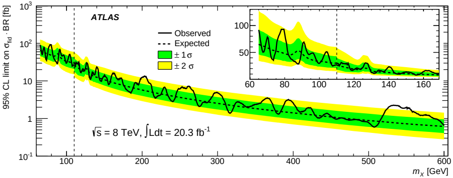
Backgrounds:

Irreducible: $q\bar{q}/gg \rightarrow \gamma\gamma$
Reducible: DY prod. of e^+e^- pairs
γ+jets and jet-jet events

Selection:

- Two γ's with high p_T
- Strong isolation criteria for γ's
- Low mass: Three photon categories
- High mass: Relative cuts on $\frac{E_T^{\gamma 1/2}}{m_{\gamma\gamma}}$





No evidence for an **additional** scalar diphoton resonance can be seen!

The H $\rightarrow WW \rightarrow \mu\nu e\nu$ search

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Mass range:

260 GeV – 1000 GeV

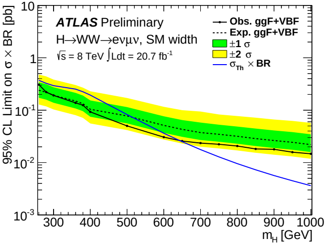
Backgrounds:

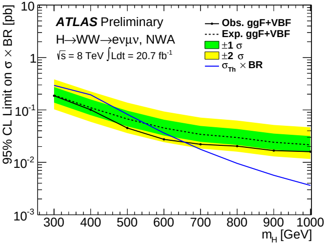
Dominant: WW and $t\bar{t}/Wt$
$Z/\gamma^* \rightarrow \tau\tau \rightarrow \mu\nu e\nu$
W+jets

Minor: $W\gamma^{(*)}$, $WZ^{(*)}$

Selection:

- Only $\mu\nu e\nu$ channel is used
- Two opp. sign high p_{T} leptons
- Large $E_{\mathrm{T}}^{\mathrm{miss.}}$
- b-jet veto in 1 and 2 jet channels





A SM-like heavy Higgs can be **excluded** up to 642 GeV!

The H $\rightarrow ZZ \rightarrow 4\ell$ search

Mass range:

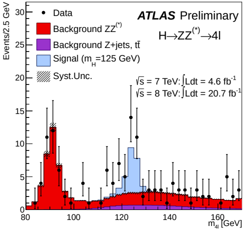
Light Higgs:
80 GeV – 170 GeV
Heavy Higgs:
170 GeV – 900 GeV

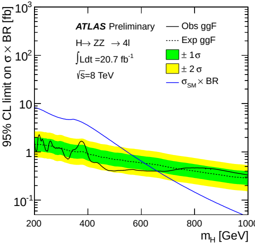
Backgrounds:

Irreducible: $q\bar{q}/gg \rightarrow ZZ$
Reducible: DY$/Z$+jets
$t\bar{t}$

Selection:

- Two opp. sign high p_T lepton pairs with same flavour
- One lepton pair: $m_{\ell\ell} \sim m_Z$
- Small impact parameter





A SM-like heavy Higgs can be **excluded** up to $\sim$ 650 GeV!

Dedicated BSM searches

- **Different approach**: Exploit the properties of BSM models
- Goal: Find something or exclude parameter spaces
- **MSSM**: Search for a neutral Higgs boson in the mass range: 90 GeV – 1000 GeV
- **2HDM**: Search for a neutral $\mathcal{CP}$ even Higgs boson in the mass range: 135 GeV – 300 GeV

Search channels:

$\Phi \rightarrow \tau\tau$	ATLAS-CONF-2014-049
$\mathbf{H} \rightarrow WW \rightarrow \mu\nu e\nu$	ATLAS-CONF-2013-027

Advantages of dedicated searches

- The 125 GeV Higgs can be included into the model.
- Higgs states might not be independent of each other
- Coupling ratio is fixed in a generic analysis, but might be different in BSM models

MSSM: $\Phi \rightarrow \tau\tau$ search

Mass range:

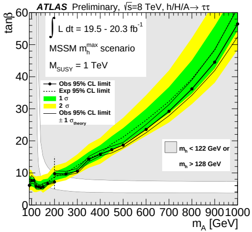
Low mass region:
90 GeV – 200 GeV
High mass region:
200 GeV – 1000 GeV

Backgrounds:

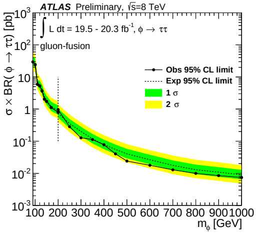
Dominant: $Z/\gamma^* \rightarrow \tau\tau$
$t\bar{t}$, multijets
DY/Z+jets

Selection:

- Three channels: $\tau_e\tau_\mu$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$
- Two categories: b-tag and b-veto
- Mass reconstruction with MMC algorithm



Grey area: Incompatible with a 125 GeV Higgs



Excluded range: $\sigma \times \text{BR} > 29$ pb to $\sigma \times \text{BR} > 7.4$ fb

2HDM: **H** $\rightarrow WW \rightarrow \mu\nu e\nu$ search

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Mass range:

135 GeV – 300 GeV

Backgrounds:

0 jets: $WW/WZ/ZZ/W\gamma^{(*)}$
W+jets

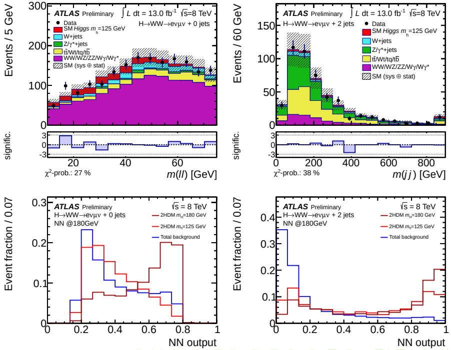
2 jets: $t\bar{t}/Wt/tq/t\bar{b}$
DY/Z+jets

Selection:

- Two high p_T DF leptons
- Large $E_T^{miss.}$
- Two VBF tagging jets
- Reject b-tagged jets
- Usage of artificial neural networks

Artificial Neural Networks

- Networks are trained at three mass points
- with 6/9 input variables in 0/2 jet channel



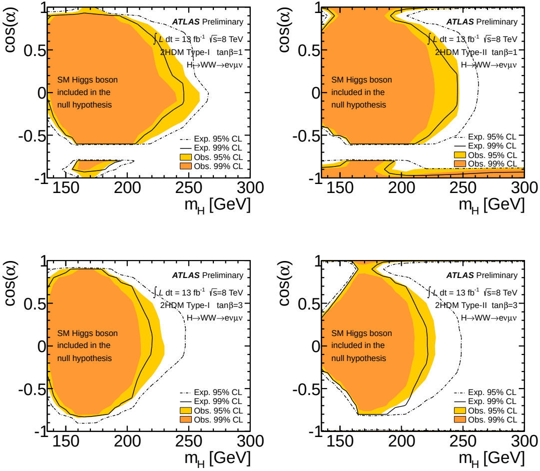
2HDM: $\mathbf{H} \to WW \to \mu\nu e\nu$ details

Exclusion limits

- Limits are calculated for type I and type II 2HDM

	Type I	Type II
$\xi_{\mathbf{H}}^{V}$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
$\xi_{\mathbf{H}}^{u}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
$\xi_{\mathbf{H}}^{d}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
$\xi_{\mathbf{H}}^{l}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$

- Confidence level is calculated for each $(\tan\beta, \cos\alpha, m_{\mathbf{H}})$-triplet
- **Null hypothesis**: SM with light Higgs



No evidence for a heavy Higgs boson is found. Large parts of parameter space can be excluded.

Conclusion

- A variety of searches for BSM Higgs bosons were performed by ATLAS.
- Many decay channels have been considered:
  - **Generic model searches**: $X \to \gamma\gamma$, $\mathbf{H} \to WW \to \mu\nu e\nu$, $\mathbf{H} \to ZZ \to 4\ell$
  - **Dedicated searches**: $\Phi \to \tau\tau$, $\mathbf{H} \to WW \to \mu\nu e\nu$
- Still, **no deviation** from the SM could be found…
- …but:
  - Limits on **cross sections** and **branching ratios** could be set
  - The **parameter space** of BSM models could be constraint
  - Look forward to Constraints on new phenomena through Higgs coupling measurements with the ATLAS detector
- ATLAS will continue its search for BSM physics in 2015 with the new 13–14 TeV data.

Stay tuned!

BACKUP SLIDES

$X \to \gamma\gamma$: Selection details and samples

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Selection details:

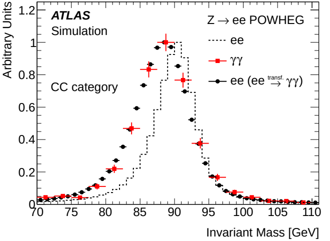
- Two photons with $E_{\mathrm{T}} > 22$ GeV and $|\eta| < 2.37$
- Jets reduction: $E_{\mathrm{T}}^{\mathrm{iso.}} < 6$ GeV, where $E_{\mathrm{T}}^{\mathrm{iso.}}$ is defined as the sum of transverse energies within a cone of $\Delta R = 0.4$.
- High mass category: $E_{\mathrm{T}}^{\gamma_1/\gamma_2}/m_{\gamma\gamma} > 0.4/0.3$
- $m_{\gamma\gamma}$ uses both photon energies, the azimuthal angle $\Delta\phi$ and the pseudorapidity $\Delta\eta$.
- Dominant background: $\gamma\gamma$, γ-jet, jet-jet events and DY production

Data samples:

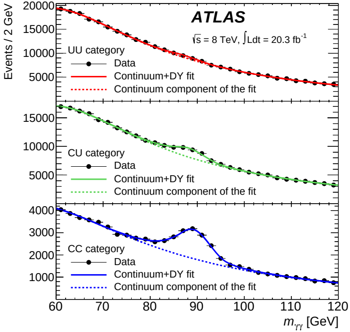
ggF	Powheg+Pythia8
VBF	Powheg+Pythia8
$Z \to ee$	Powheg+Pythia8

$X \to \gamma\gamma$: Photon categories

- The invariant mass distribution of the Z boson reconstructed as a photon pair is wider and shifted to lower masses by up to 2 GeV with respect to the Z boson mass reconstructed as an electron pair.



- The solid lines show the sum of the Drell–Yan and the continuum background components. The dashed lines show the continuum background component only.



H $\to WW \to \mu\nu e\nu$: Selection and samples

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- DF only is used to reduce DY bkg from pile up
- $p_{\mathrm{T}}(\ell_i) > 40$ GeV
- $E_{\mathrm{T,rel}}^{\mathrm{miss.}} > 25/20$ GeV
- Reject DY events: $p_{\mathrm{T}}(\ell\ell) > 30$ GeV
- Events compatible with a $Z \to \tau\tau$ decay are rejected by requiring $|m_{\tau\tau} - m_Z| \geq 25$ GeV

Data samples:

Background	MC generator
Higgs	Powheg+Pythia8
$q\bar{q}/gq \to WW$	Powheg+Pythia6
$gg \to WW$	GG2WW+Herwig
$t\bar{t}$	MC@NLO+Herwig
$tW,\ tb$	MC@NLO+Herwig
tqb	AcerMC+Pythia6
Z/γ^*	Alpgen+Herwig
$WZ/W\gamma^*$	Powheg+Pythia8
$W\gamma^*$	MadGraph+Pythia6
$W\gamma$	Alpgen+Herwig

H $\to WW \to \mu\nu e\nu$: Statistics

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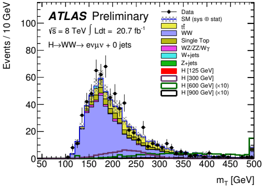
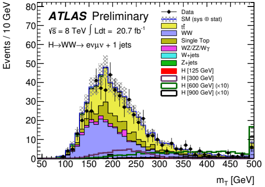
- Define likelihood function using m_{T} distribution.
- Use bins of variable width o have the same number of expected background events in each bin.
- Use q_μ as test statistic:

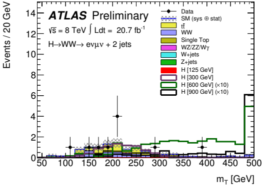
$$q_\mu = -2ln\left(\frac{\mathcal{L}(\mu;\hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu};\hat{\theta})}\right)$$

$\hat{\mu},\hat{\theta}$: unconditionally maximise $\mathcal{L}$
$\mu;\hat{\theta}_\mu$: maximise $\mathcal{L}$ for a given μ

- Each systematic is parametrised by a corresponding nuisance parameter θ, constrained by a Gaussian function.







$\mathbf{H} \to ZZ \to 4\ell$: Selection and samples

- Two same-flavour, opp. sign lepton pairs
- $p_{\mathrm{T}}(\ell_{1/2/3}) > 20/15/10$ GeV
- SF: $\Delta R > 0.1$, DF: $\Delta R > 0.2$
- Leading di-lepton mass: $50\ \mathrm{GeV} < m_{12} < 106\ \mathrm{GeV}$
- Subleading di-lepton mass: $m_{\mathrm{min}} < m_{34} < 115$ GeV, with $m_{\mathrm{min}} \in [12, 50]$ GeV
- Reduce Z+jets and $t\bar{t}$: Impact parameter significance $\frac{d_0}{\sigma_{d_0}} < 3.5(6.5)$

Data samples:

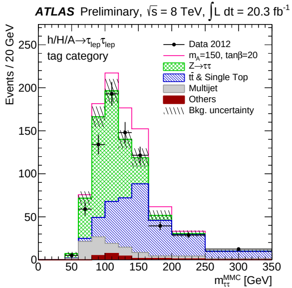
Background	MC generator
ggF/VBF	Powheg+Pythia8+Photos
$WH/ZH/ttH$	Pythia
$q\bar{q}/gq \to ZZ$	Powheg+Pythia6
$gg \to WW$	gg2ZZ+Herwig
$ZZ^{*}qq'$	Sherpa

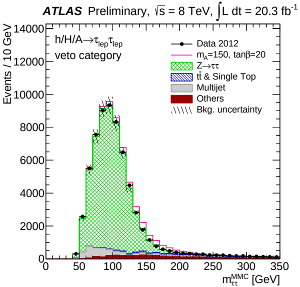
MSSM: $\Phi \to \tau\tau$: MMC details

- The MMC algorithm assumes that the missing transverse momentum is due entirely to the neutrinos, and performs a scan over the angles between the neutrinos and the visible τ decay products.

- The MMC mass, $m_{\tau\tau}^{\mathrm{MMC}}$, is defined as the most likely value chosen by weighting each solution according to probability density functions that are derived from simulated τ lepton decays.

- **Left plots:** Reconstructed MMC mass for the low mass region in the tag and veto categories with a hypothetical MSSM signal with $m_{\mathbf{h}} = 150$ GeV, $\tan\beta = 20$





2HDM: **H** $\rightarrow WW \rightarrow \mu\nu e\nu$: Selection and samples

- DF only is used to reduce DY bkg from pile up
- $p_{\mathrm{T}}(\ell_{1/2}) > 25/15$ GeV
- $m(\ell\ell) > 10$ GeV
- $E_{\mathrm{T,rel}}^{\mathrm{miss.}} > 25$ GeV
- 0 jets: $|\Delta\phi(\ell_1, \ell_2)| < 2.4$, $m(\ell\ell) < 75$ GeV
- 2 jets: b-veto, $m_{\mathrm{T}} < 180$ GeV, $m(\ell\ell) < 80$ GeV

Data samples:

Background	MC generator
ggF	Powheg+Pythia8
VBF	Powheg+Pythia8
WH/ZH	Pythia8
$q\bar{q}/gq \rightarrow WW$	Powheg+Pythia6
$gg \rightarrow WW$	GG2WW+Herwig
$t\bar{t}$	MC@NLO+Herwig
tW, tb	MC@NLO+Herwig
tqb	AcerMC+Pythia6
Inclusive W	Alpgen+Herwig
Inclusive Z/γ^*	Alpgen+Herwig
$Z^{(*)}Z^{(*)} \rightarrow 4\ell$	Powheg+Pythia8
$WZ/W\gamma^*$	Powheg+Pythia8
$W\gamma^*$	MadGraph+Pythia6
$W\gamma$	Alpgen+Herwig

2HDM: H $\to WW \to \mu\nu e\nu$: Neural networks

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Input variables of the Neural Networks

<table>
<tr><th>0 jets</th><th>2 jets</th></tr>
<tr><td colspan="2">$|\eta(\ell_1)|$</td></tr>
<tr><td colspan="2">m_{T}</td></tr>
<tr><td colspan="2">$m(\ell_1\ell_2)$</td></tr>
<tr><td>$p_{\mathrm{T}}(\ell_1\ell_2)$</td><td>$p_{\mathrm{T}}(\ell_2)$</td></tr>
<tr><td>$E_{\mathrm{T,rel}}^{\mathrm{miss}}$</td><td>$p_{\mathrm{T}}(j_1)$</td></tr>
<tr><td>$|\Delta Y(\ell_1\ell_2)|$</td><td>$m(j_1)$</td></tr>
<tr><td></td><td>$\cos\theta(\ell_1,\ell_2)$</td></tr>
<tr><td></td><td>$m(j_1j_2)$</td></tr>
<tr><td></td><td>$p_{\mathrm{T}}^{\mathrm{tot}}$</td></tr>
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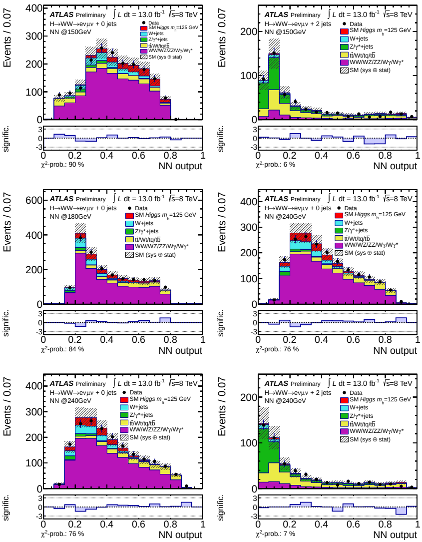
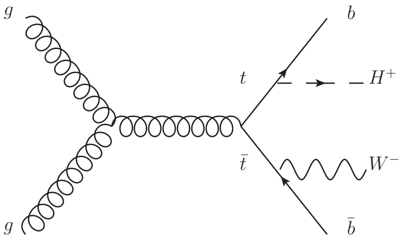


Charged Higgs Boson Searches

Charged Higgs in $t\bar{t}$ decays

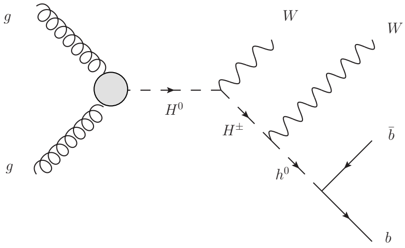
- arXiv:1302.3694
- Mass range: 90 GeV – 150 GeV



- The decay $\mathbf{H}^+ \to c\bar{s}$ is investigated

2HDM Cascade

- arXiv:1312.1956
- Mass range: 225 GeV – 925 GeV



- **Boosted decision trees** are used for the separation from $t\bar{t}$

Charged Higgs in $t\bar{t}$ decays

Mass range:

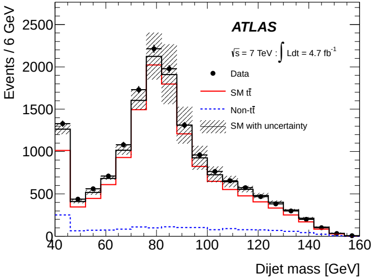
90 GeV – 150 GeV

Backgrounds:

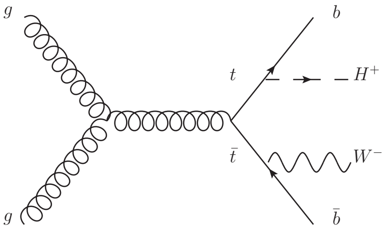
Dominant: $t\bar{t}$
single top
$WW/WZ/ZZ/W\gamma^{(*)}$
DY/Z+jets

Selection:

- One high p_T lepton
- Large $E_T^{miss.}$
- Two light jets with $m_{jj} \approx m_{H^+}$
- **Kinematic fitter**: Reco of the $t\bar{t}$ system



No significant deviation from SM!



2HDM Cascade

Mass range:

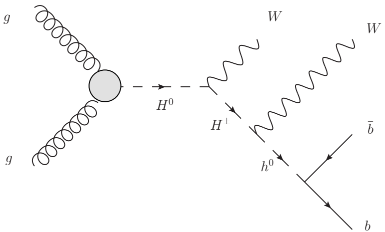
225 GeV – 925 GeV

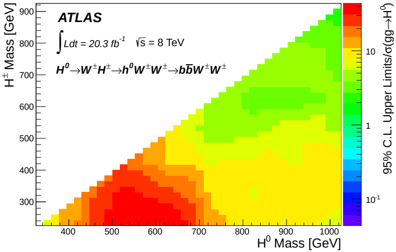
Backgrounds:

Dominant: $t\bar{t}$
Minor: single top
$WW/WZ/ZZ/W\gamma^{(*)}$
DY/Z+jets

Selection:

- One high p_{T} lepton
- Large $E_{\mathrm{T}}^{\text{miss.}}$
- Four high p_{T} jets (two b-tagged)
- BDT is trained with seven variables
  $\Rightarrow$ optimised for cross-section limits





Consistent with SM predictions!