Search for neutral and charged BSM Higgs Bosons with the ATLAS detector

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on behalf of the ATLAS Collaboration

IFIC (CSIC - Universitat de València)

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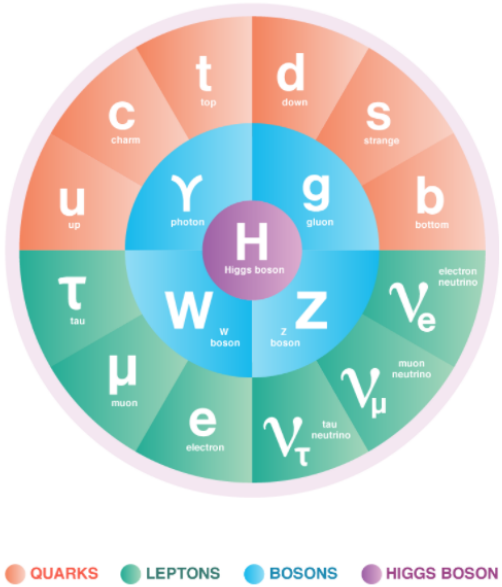
Introduction

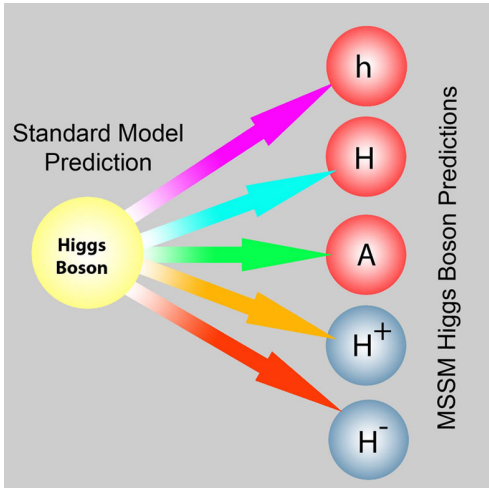
- The current Standard Model (SM) was completed with the discovery of the Higgs boson at $m_h = 125\,\text{GeV}$ in 2012

- However, the theory lacks explanation for several phenomena and shows *naturalness* issues (fine-tuning, hierarchy)

- Many models beyond the SM (BSM) have been proposed to cover these issues, which imply the inclusion of additional Higgs bosons:
  - Neutral (CP-even H and CP-odd A)
  - Charged (singly $H^{\pm}$ or doubly $H^{\pm\pm}$)

- Searches for these additional bosons are performed by looking for final states of their decays:
  - Fermionic, Bosonic, di-higgs





BSM Higgs Models

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Electroweak singlet

- Addition of real scalar field singlet S:
- Results in two mixing bosons: h and H

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Two-Higgs-Doublet Model **(2HDM)**

- Two Higgs doublets: ϕ_1, ϕ_2
- Five Higgs bosons: h, H, A, $H^{\pm}$
- Two parameters:
  - $\tan\beta \equiv v_1/v_2$, mixing angle α
- Several types, according to the coupling of doublets:

Type	Description	u-quarks	d-quarks	e-leptons
I	Fermiophobic	ϕ_2	ϕ_2	ϕ_2
II	MSSM-like	ϕ_2	ϕ_1	ϕ_1
X	Lepton-specific	ϕ_2	ϕ_2	ϕ_1
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Minimal Supersymmetric SM (MSSM)

- SUSY in its minimal form
- Implements Type-II 2HDM with five Higgs bosons: h, H, A, $H^{\pm}$
- At tree level, two parameters: $\tan\beta$ and m_A
- Higher-order corrections are fixed to scan phenomenological scenarios:
  - hMSSM, m_h^{max}, $m_h^{\text{mod}\pm}$, ...

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Higgs Triplet Model (HTM)

- Higgs triplet: $\vec{\phi} = (\phi^{++}, \phi^{+}, \phi^{0})$
- Seven Higgs bosons: h, H, A, $H^{\pm}$, $H^{\pm\pm}$

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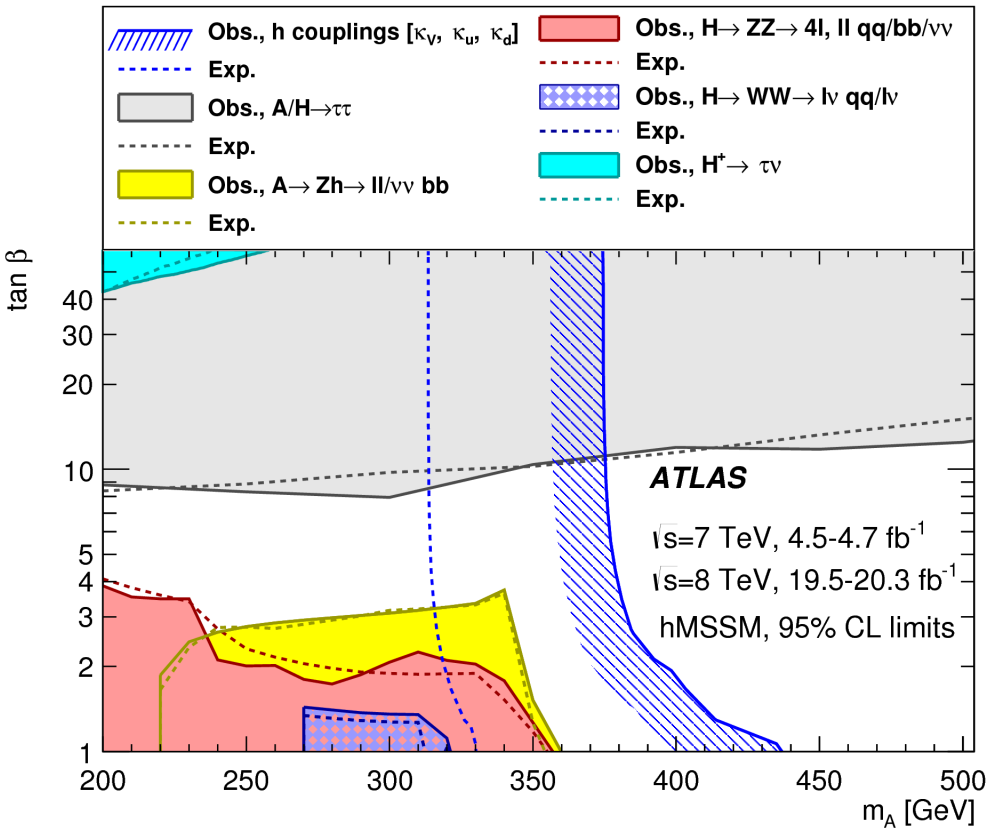
Other Models

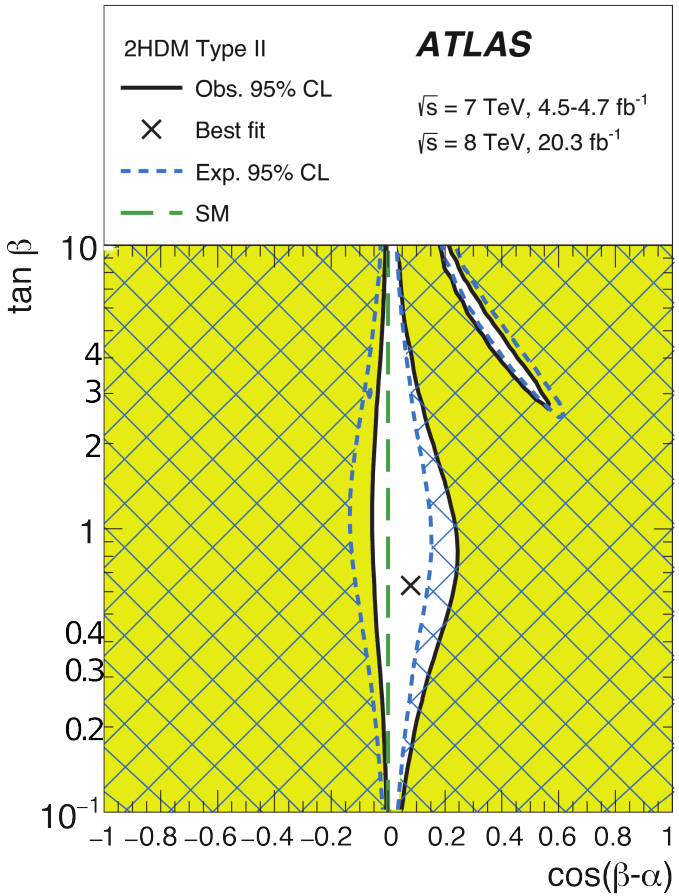
- **NMSSM**: h, H_1, H_2, A_1, A_2, $H^{\pm}$
- Left-Right symmetric models (**LSR**)

Introduction

- Many models beyond the SM (BSM) have been proposed to cover these issues:
  - 2HDM, MSSM, HTM, NMSSM, LRS
- Analysis of Run 1 data excluded regions of parameters from these models:



Exclusion limits for hMSSM scenario



Exclusion limits for Type-II 2HDM

Introduction

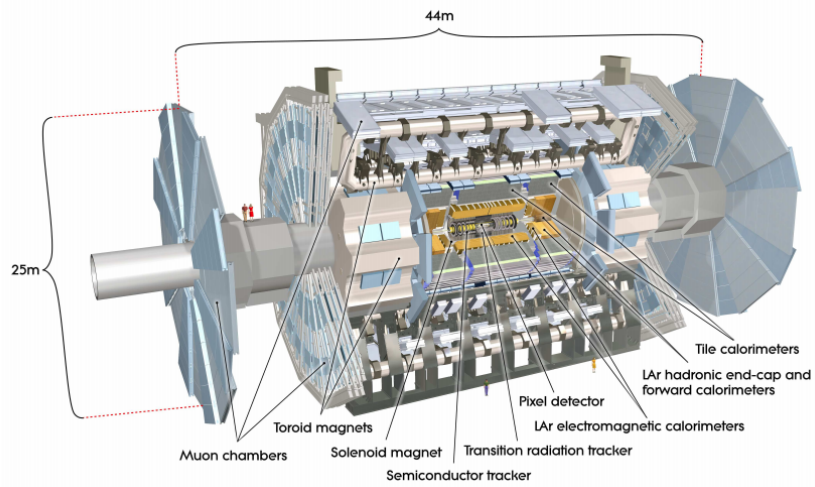
- Searches performed with the ATLAS detector

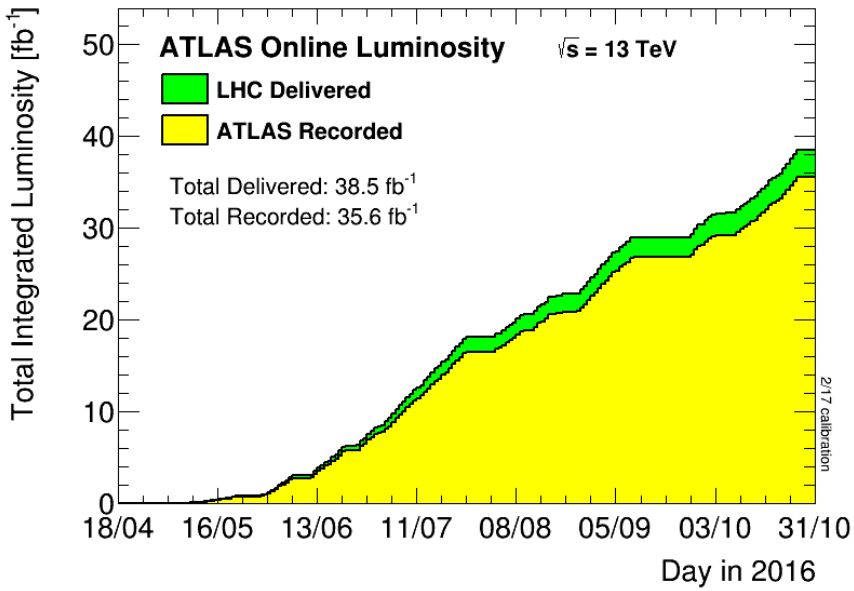
- Luminosity collected in Run 2 at $\sqrt{s} = 13\,\text{GeV}$
  - 2015: 3.2 fb^{-1}
  - 2016: 35.6 fb^{-1}

$\Rightarrow$ Most of results were published with part of 2016 data
  - Total analyzed: 3.2 fb^{-1} + [10-12] fb^{-1}

- Analysis with full 2016 data are in progress

- Last results will be covered here, in preparation for coming results!





Summary of the BSM Higgs Analysis

Neutral H to Bosons

- $\Rightarrow H \to \gamma\gamma$
- $\Rightarrow H \to WW \to \ell\nu\ell\nu$
- $\Rightarrow H \to WW \to l\nu qq$
- $\Rightarrow H \to ZZ \to 4\ell$
- $\Rightarrow H \to ZZ \to 2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$
- $\Rightarrow H \to ZZ \to \ell\ell qq'/\nu\nu qq'$
- $\Rightarrow H \to Z\gamma$
- $A \to Zh$

Neutral H to Fermions

- $\Rightarrow H/A \to \tau\tau$
- $\Rightarrow H/A \to tt$
- $H/A \to tt + jets$

Neutral H to SM di-higgs

- $\Rightarrow H \to hh \to WW\gamma\gamma$
- $\Rightarrow H \to hh \to bbbb$
- $\Rightarrow H \to hh \to bb\gamma\gamma$

Charged Higgs $H^{\pm}$, $H^{\pm\pm}$

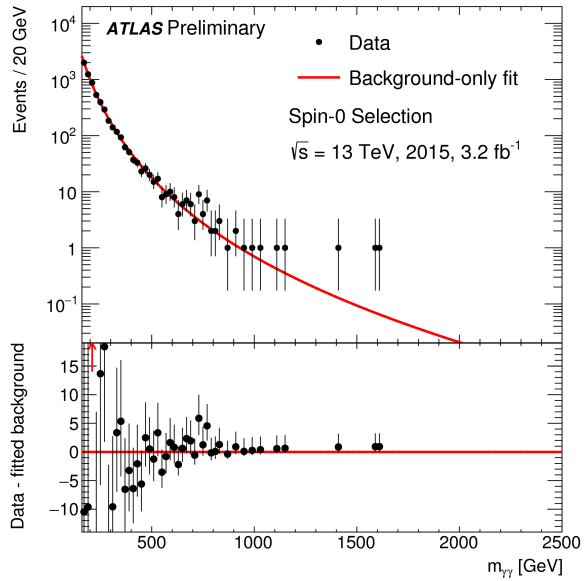
- $\Rightarrow H^{\pm} \to tb$
- $\Rightarrow H^{\pm} \to \tau\nu$
- $\Rightarrow H^{\pm\pm} \to e^{\pm}e^{\pm}$

Luminosity Legend

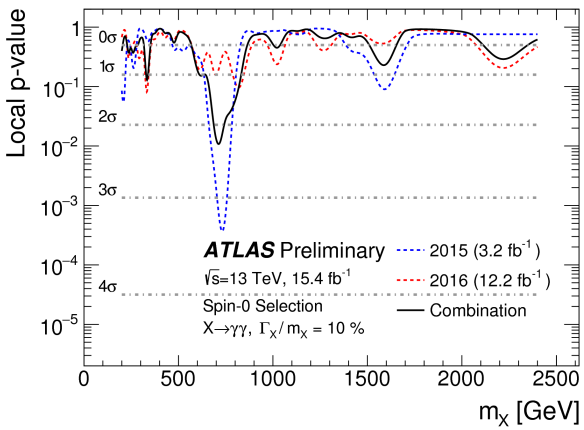
- Only 2015 $= 3.2\ \mathrm{fb}^{-1}$
- Partial 2016 $\sim 15\mathrm{fb}^{-1}$
- Full 2016 -

Neutral Higgs to Bosonic final states

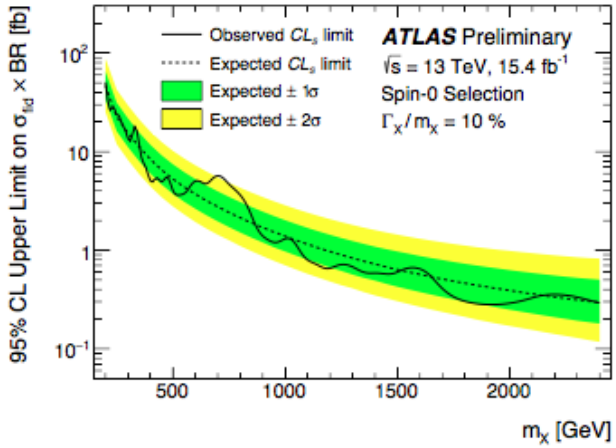
- In December 2015, ATLAS (and CMS) reported an excess or $\sim 4\sigma$ around 750 GeV with 3.2 fb^{-1}
- Latest ATLAS result with 15.4 fb^{-1} show no excess ($< 1\sigma$)
- Analysis limited to spin-0 resonance
- Event selection
  - 2 photons: $m_\gamma > (40\,\text{GeV}, 30\,\text{GeV})$
  - Decay products: $p_T^{\gamma 1} > 0.4\, m_{\gamma 1}$, $p_T^{\gamma 2} > 0.3\, m_{\gamma 2}$
  - Invariant mass $m_{\gamma\gamma} > 150\,\text{GeV}$



Data 2015: 3.2 fb^{-1}



$\Gamma_x/m_x = 10\%$



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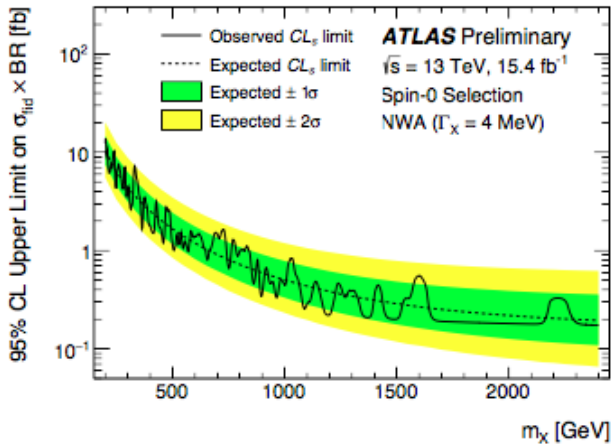

Narrow Width Approx (NWA)

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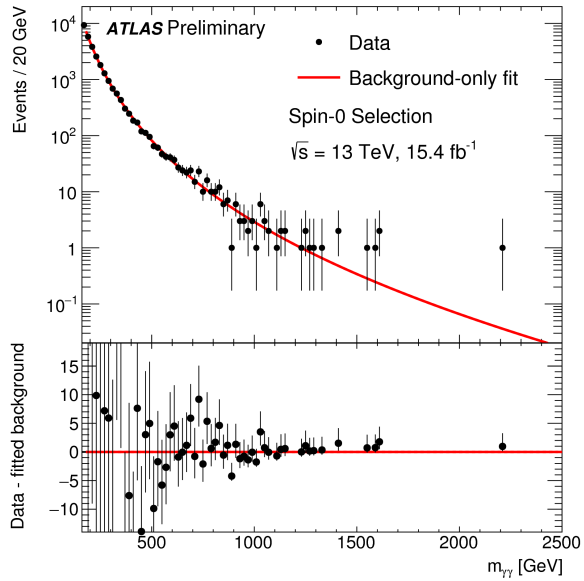
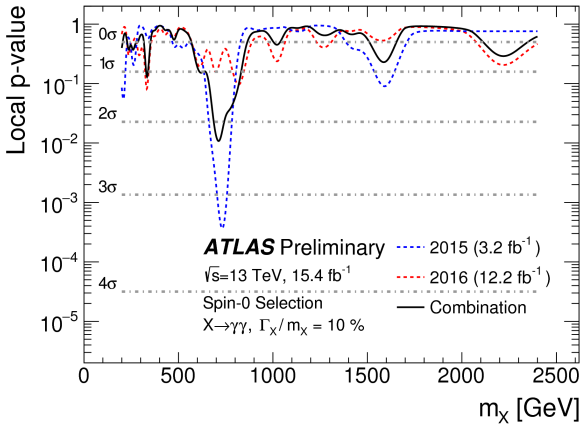


Data 2015+partial 2016: 15.4 fb^{-1}



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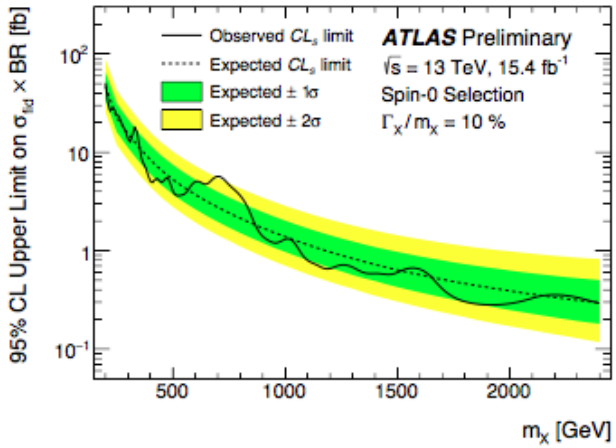

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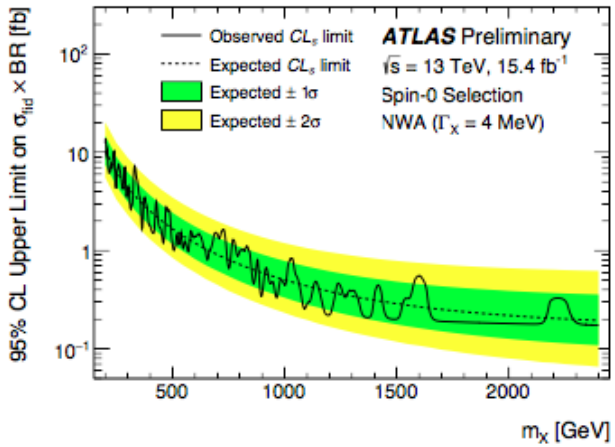


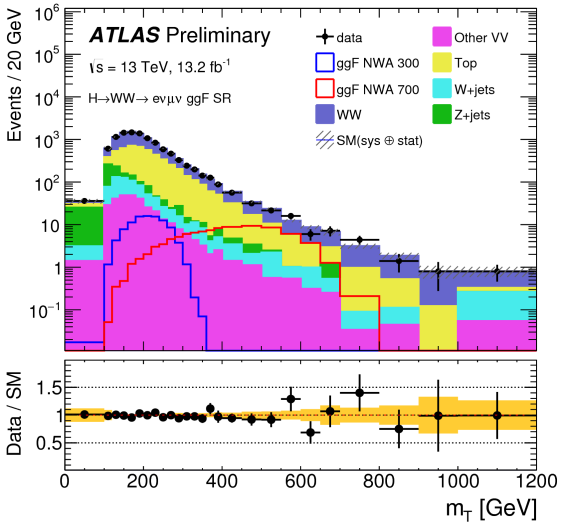
Narrow Width Approx (NWA)

- Update of extended search of the leptonic decay of WW analysis to high-mass region ($m_{WW} > 300$ GeV) for NWA and LWA
- Three orthogonal categories: 0-jet (ggF oriented), 1 jet and ≥ 2 jets (both VBF oriented)
- Discriminating variable: transverse mass (m_T)

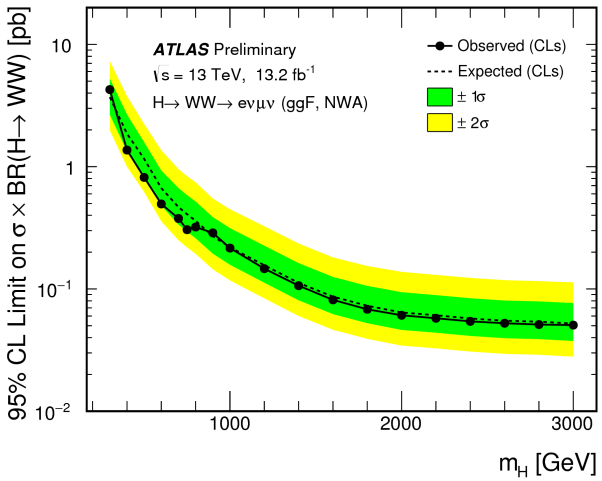
$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(p_T^{\ell\ell} + E_T^{\text{miss}}\right)^2}$$

- Main event selection
  - Two Opposite Sign (OS) Different Flavour (DF) leptons, with $p_T > (45\,\text{GeV}, 30\,\text{GeV})$
  - Invariant mass $m_{\ell\ell} > 55$ GeV
  - b-veto, $\Delta\eta_{\ell\ell} < 1.8$, $m_T^W > 50$ GeV

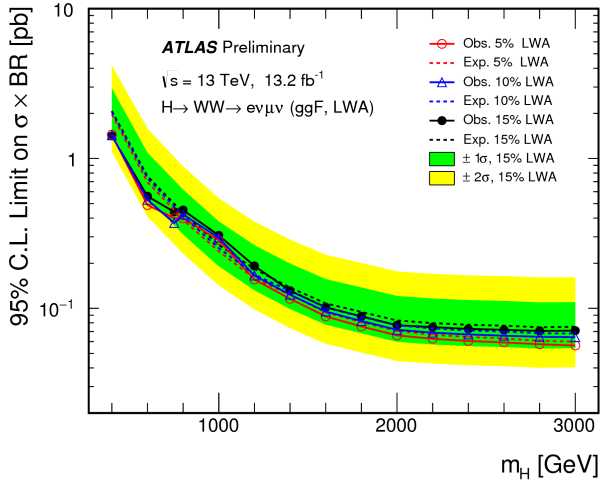
$$m_T^W = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} (1 - \cos(\phi_\ell - \phi(E_T^{\text{miss}})))}$$



SR ggF

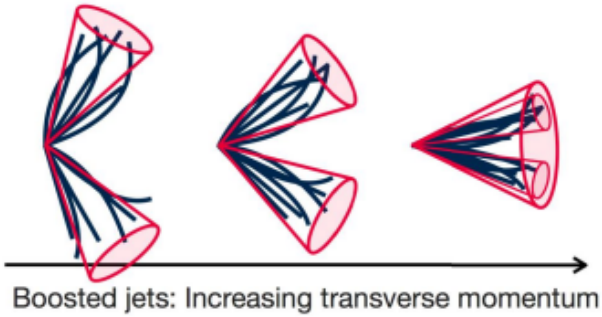


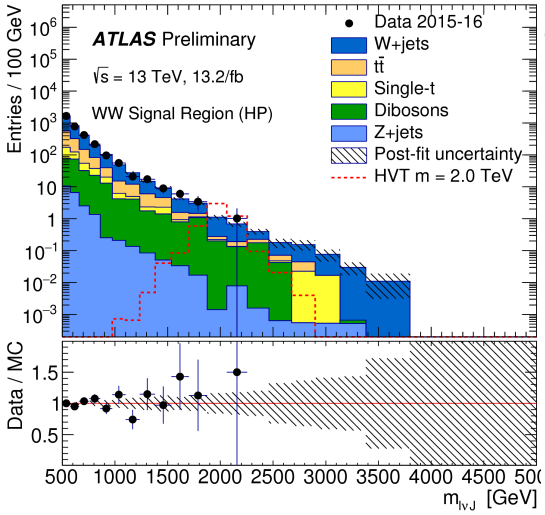
ggF NWA



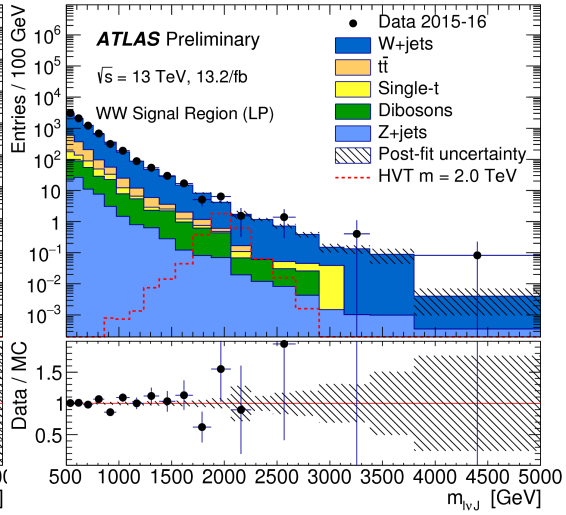
ggF LWA

- Diboson resonance (WW) in the NWA with mass width of 4 GeV
- One W decays leptonically (e or μ plus neutrino) and the other hadronically
- The two jets are boosted and can be reconstructed as a single jet (J)
- Main event selection:
  - W_{lep}: One lepton, Missing $E_{\text{T}} > 100$ GeV, $p_{\text{T}}(\ell\nu) > 200$ GeV
  - p_{T}^{J} and $p_{\text{T}}^{\ell\nu} > 0.4 m_{J,\ell\nu}$, Invariant mass $m_J \sim 15$ GeV of m_W
  - b-jet veto, sub-jet structure checks, which defines two categories: high-purity and low-purity

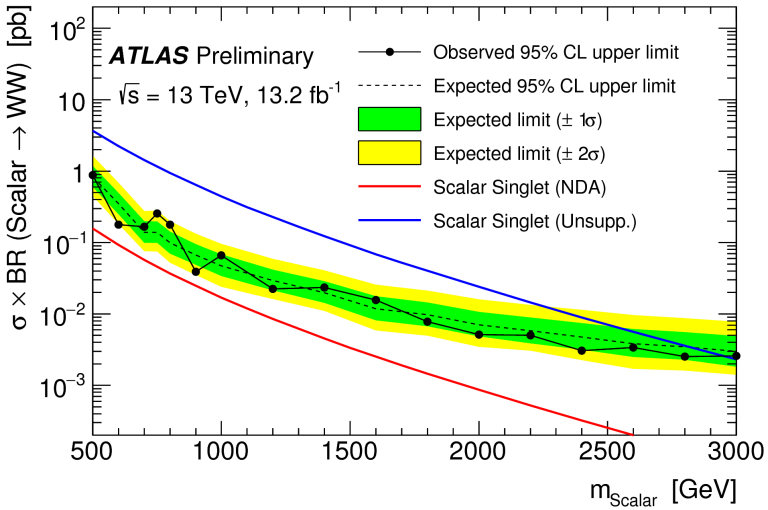




WW SR, High-Purity

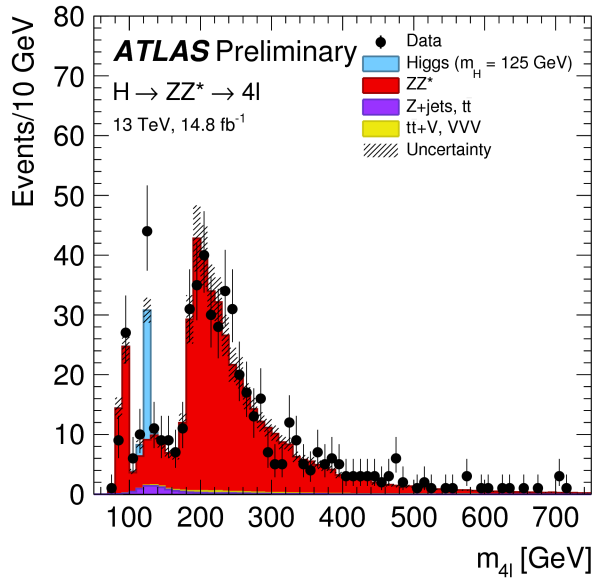


WW SR, Low-Purity

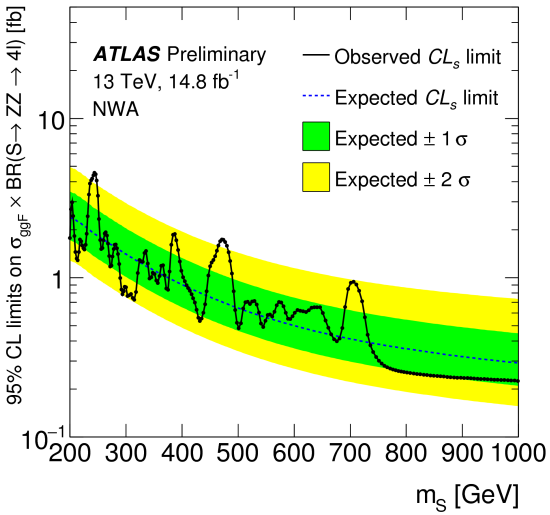


Exclusion limit for heavy Higgs in NWA

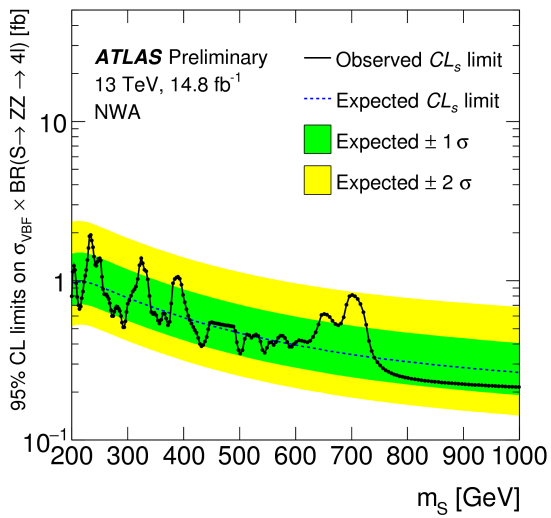
- Extended search of ZZ analysis to high-mass region ($m_{4\ell} > 140$ GeV) in NWA and LWA
- In NWA, two categories:
  - VBF: 2 jets, $m_{jj} > 400$ GeV, $\Delta\eta_{jj} > 3.3$
  - ggF: rest
- Main event selection
  - Two pairs of OS SF leptons with p_T >(20 GeV,15 GeV,10 GeV,reco)
  - Leading pair inv. mass: 50 GeV $< m_{12} <$ 106 GeV
  - Sub-Leading pair inv. mass: 12 GeV $< m_{34} <$ 115 GeV



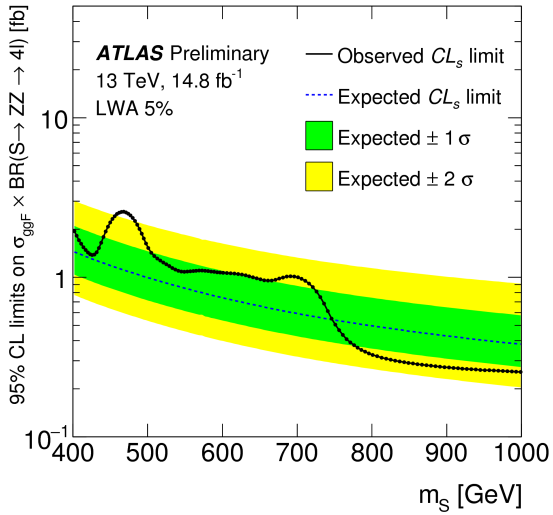
Signal Region



NWA ggF



NWA VBF



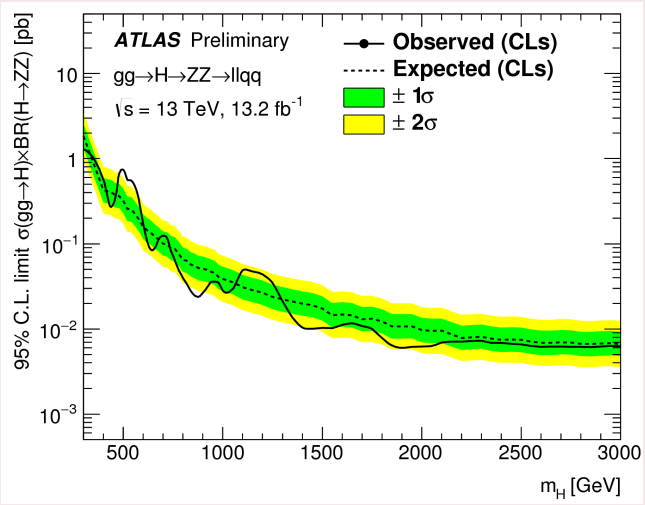
LWA VBF width 5% m_H

Other bosonic channels

$H \to ZV$

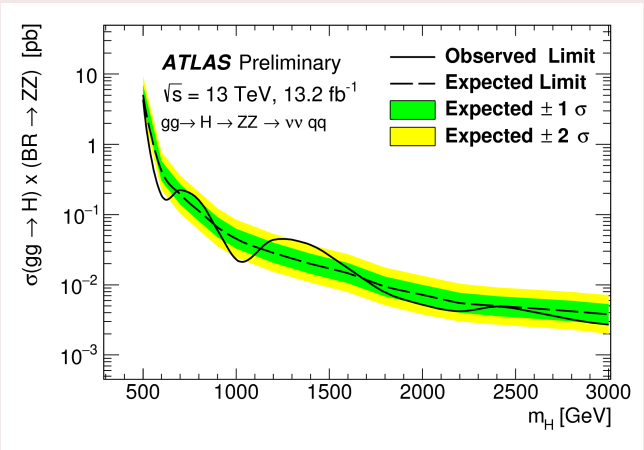
$\ell\ell qq$

- Boosted and Resolved analysis
- Invariant mass of system (m_{ZV})



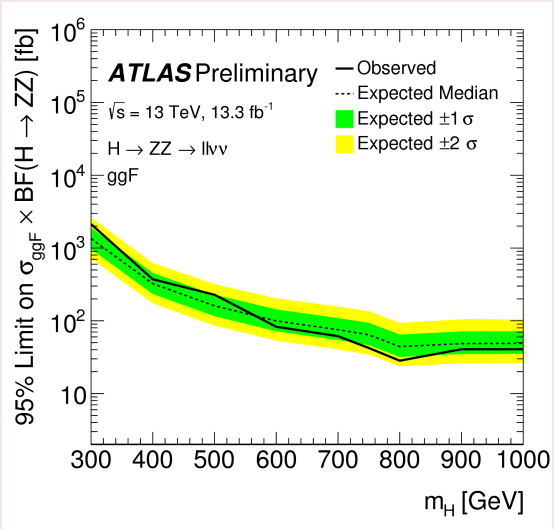
$\nu\nu qq$

- Only Boosted analysis
- Transverse mass of system (m_T)



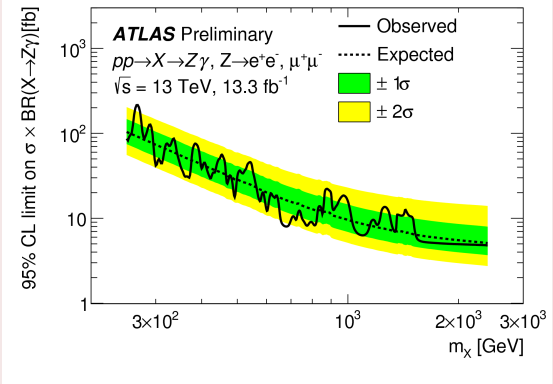
$H \to Z(\ell\ell) + E_T^{miss}$

- Two OS SF leptons and high E_T^{miss}
- Mass range 300-1000 GeV



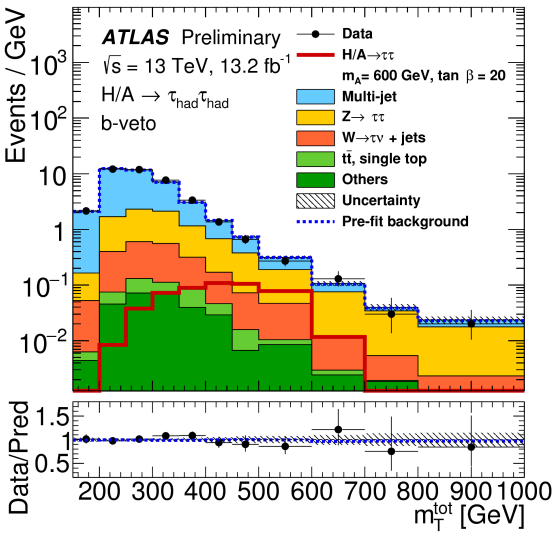
$H \to Z\gamma$

- $Z\gamma$ in 250-2400 GeV
- Leptonic decay of Z (e, μ)

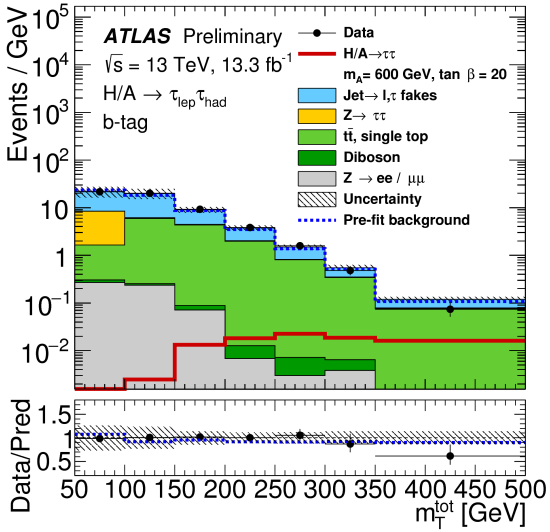


Neutral Scalars to Fermionic final states

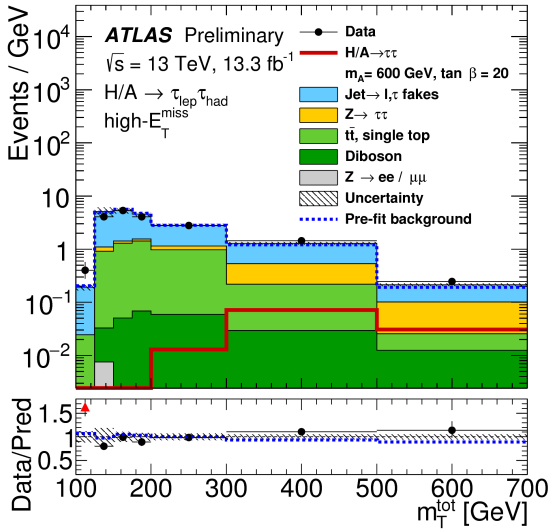
- Searching for heavy resonance in di-τ events in mass range between 200 and 1200 GeV
- Results interpreted in different MSSM scenarios
- In MSSM, large tan β enhances coupling of H with *down* fermions: τ and b
- Two main categories: b-tagged (bbH oriented) and b-veto (ggF)
- Two final states
  - Fully hadronic: two hadronic τ with trigger and p_T variable requirements
  - Semi-leptonic: combination of single-lepton and E_T^{miss} triggers, adds high-E_T^{miss} category



$\tau_{had}\tau_{had}$ b-veto

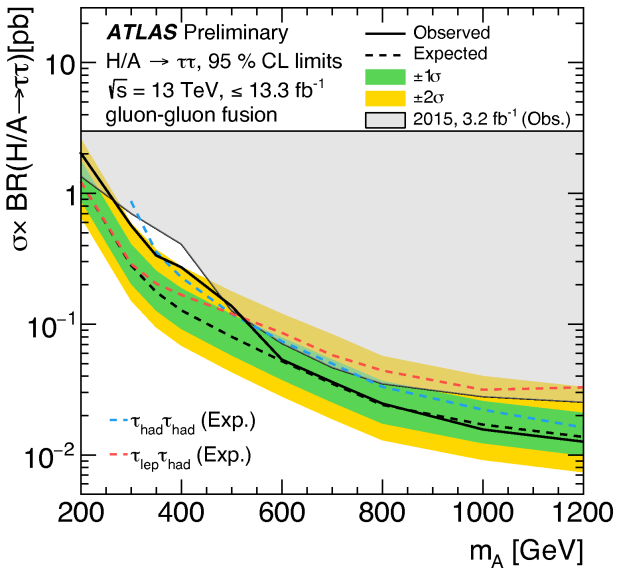


$\tau_{lep}\tau_{had}$ b-tag

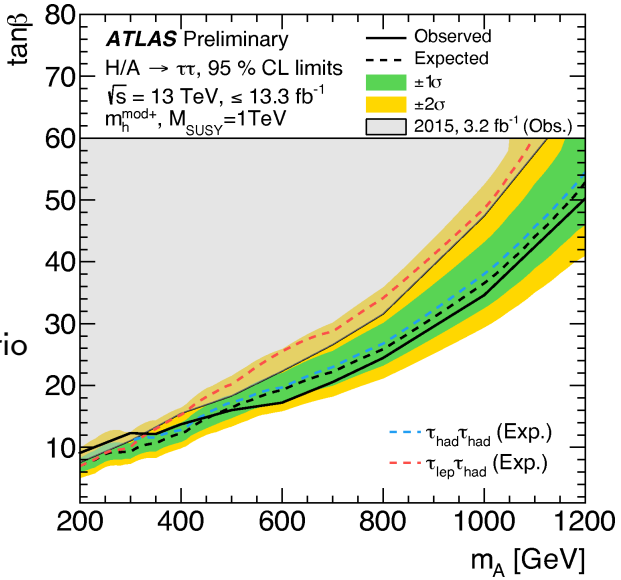


$\tau_{lep}\tau_{had}$ high-E_T^{miss}

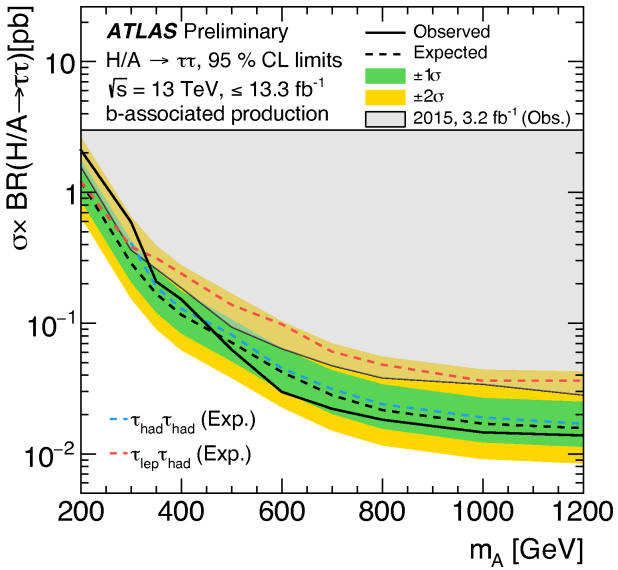
Excl. limits on production $\sigma \times BR$ for model-independent (ggF,bbH) and model-dependent ($m_h^{\text{mod+}}$, hMSSM)



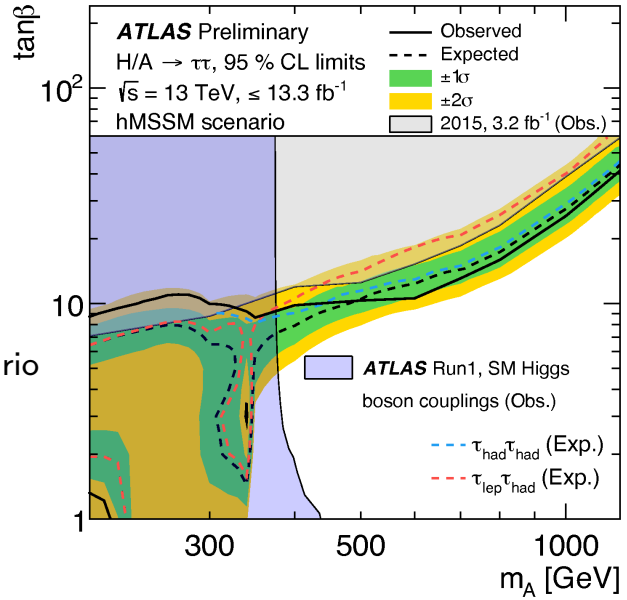
ggF



$m_h^{\text{mod+}}$ scenario



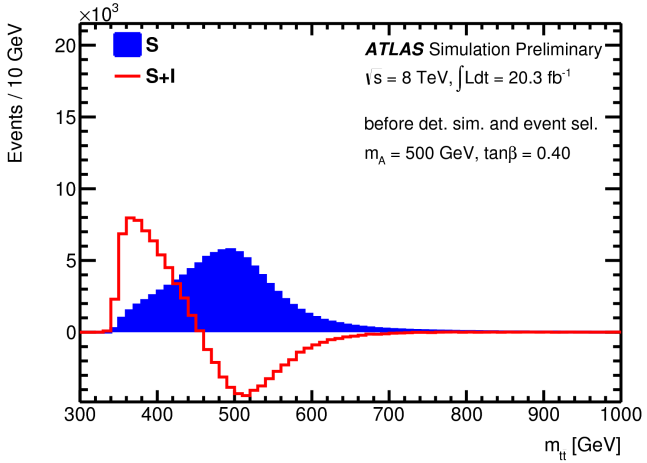
bbH



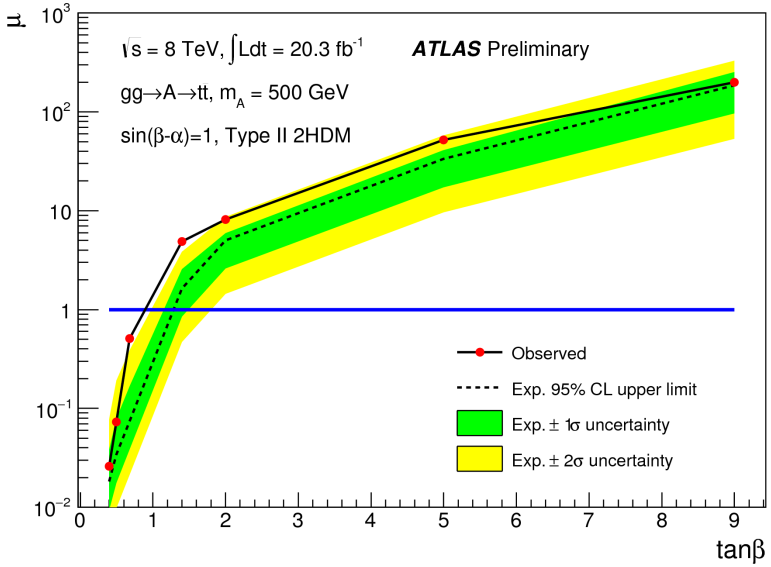
hMSSM scenario

$A/H \to t\bar{t}$ - Run 1: 20.3 fb^{-1} at $\sqrt{s} = 8$ GeV ATLAS-CONF-2016-073

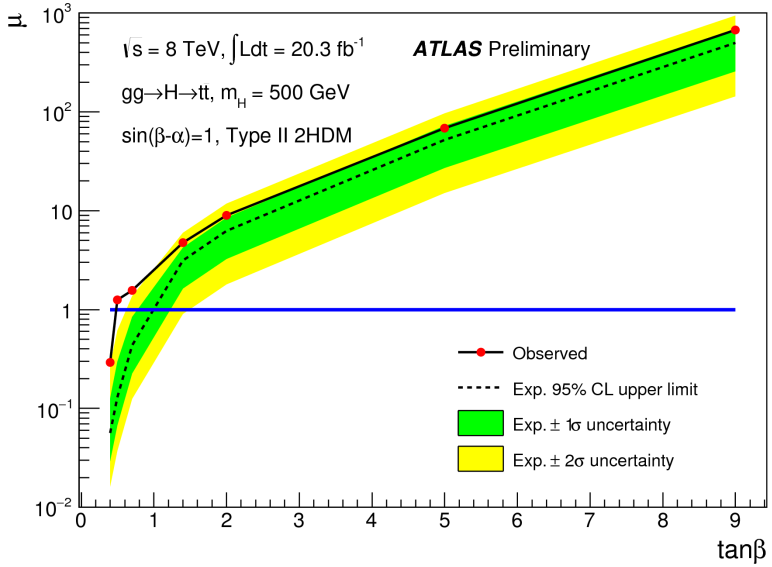
- Update of analysis adding inference of signal with SM $t\bar{t}$ background in mass range 400-800 GeV
- Signal: $A/H \to t\bar{t} \to b\bar{b}W(\to q\bar{q})W(\to \ell\nu)$
- Aimed for resolved topology (top quark with low p_T and thus, separated jets)
- Main event selection
  - 2 leptons with p_T >25 GeV, E_T^{miss} >20 GeV, $E_T^{miss} + m_T^W > 60$ GeV
  - Four jets, at least one b-tagged $\to$ three categories



Signal interference for m_A =500 GeV, tan β =0.4



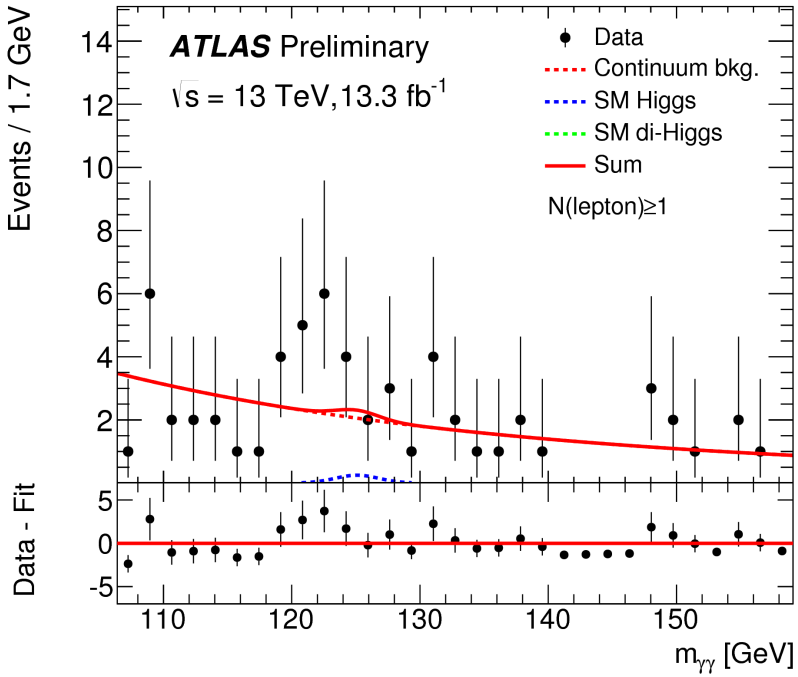
Excl. limit on signal strength μ for m_A =500 GeV in type-II 2HDM



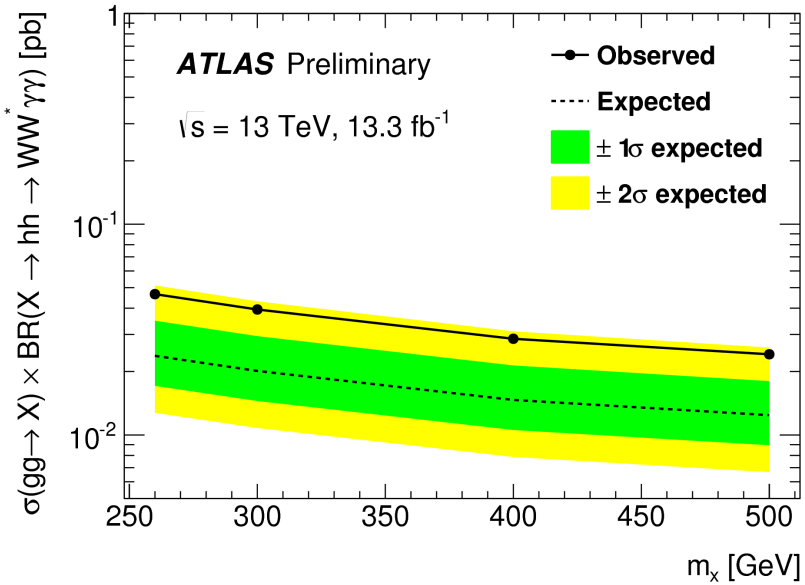
Excl. limit on signal strength μ for m_H =500 GeV in type-II 2HDM

Di-Higgs production

- Semileptonic decay of WW and two photons
- Large BR of WW and clean signature of $\gamma\gamma$ and one lepton
- Low BR of $\gamma\gamma$ at high mass so range: 260-500 GeV
- Main event selection
  - 2 γ with $p_T > (35\,\text{GeV}, 25\,\text{GeV})$ and $m_{\gamma\gamma}$ between 105-160 GeV
  - Two jets with b-veto
  - Two categories: 1-lepton (SR) and 0-leptons (CR)
  - SR: $|m_{\gamma\gamma} - m_H| < 2\sigma_{\gamma\gamma}$



One-lepton region $m_{\gamma\gamma}$ continuum

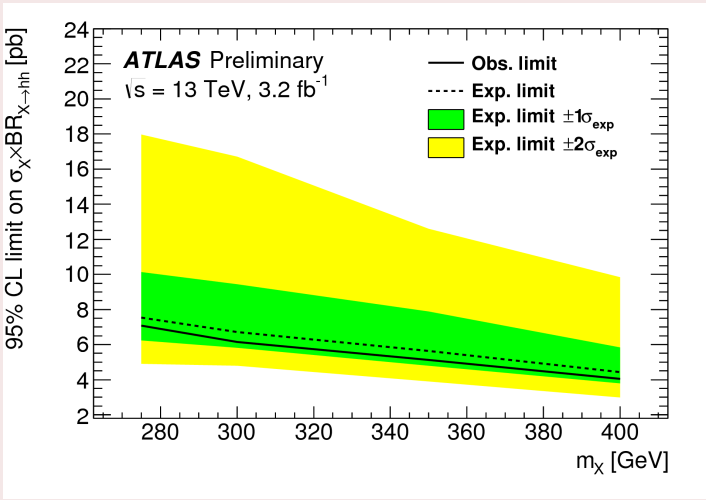


Excl. limit on $\sigma(gg \to X) \times BR(X \to hh \to WW\gamma\gamma)$

Other di-higgs analysis

$H \to bb\gamma\gamma$ - 3.2fb^{-1}

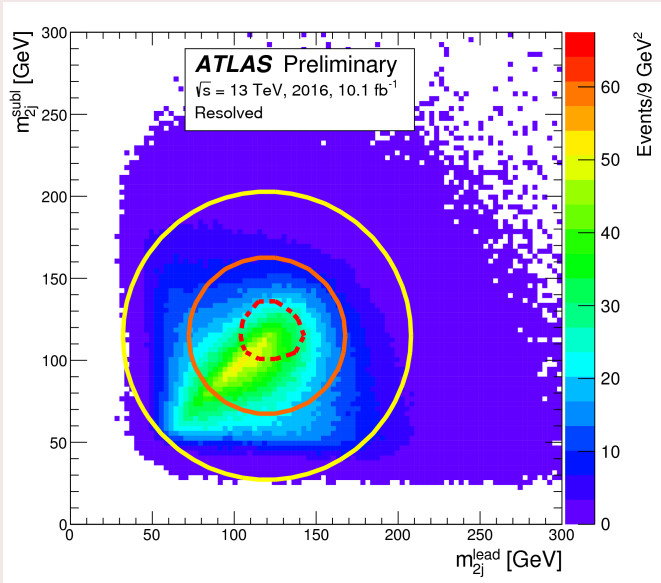
- Benefit from large bb BR and clean $\gamma\gamma$
- Limited mass range: 300-1000 GeV
- Two γ, b-jets, $m_{\gamma\gamma}$: 105-160 GeV



Excl. limit as a function of m_X on $\sigma_X \times BR(x \to hh)$ for NWA

$H \to bbbb$ - 13.2fb^{-1}

- Resolved analysis
  - Two h-candidates with $m_{bb} \sim m_H$
  - Mass range between 300-1200 GeV
- Boosted analysis:
  - Two large-R jets
  - p_T^J¿(450 GeV, 250 GeV), $|\eta| < 2.0$ and $m_J > 50$ GeV

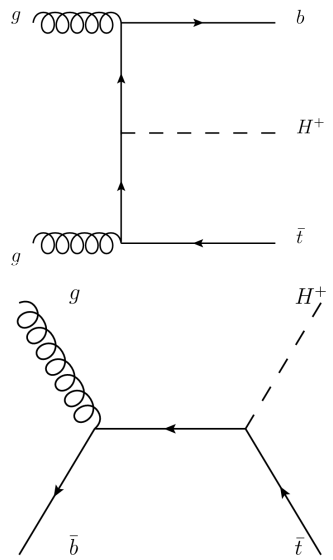


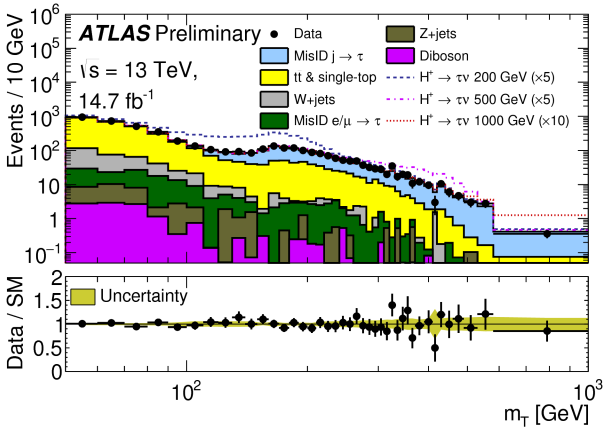
Resolved SR (red) and CR (yellow)

Charged Higgs boson

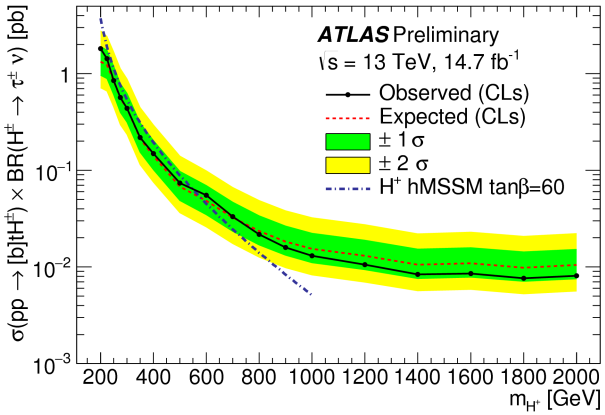
$H^{\pm} \to \tau\nu$ - 13.2 fb^{-1} ATLAS-CONF-2016-088

- Searching $H^{\pm}$ in final states with one τ, $E_{\mathrm{T}}^{\mathrm{miss}}$ and a top quark in mass range of 200-2000 GeV
- Signal coming from $tbH^{\pm}$ and $tH^{\pm}$ modes 4/5 FS
- Analysis uses fully hadronic decays of τ and top quark
- Interpretation of result in hMSSM $m_h^{\text{mod-}}$ scenarios
- Main event selection
  - One hadronic τ with p_{T} >40 GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - Three jets with at least one of them being b-tagged
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ >150 GeV and m_{T} >50 GeV

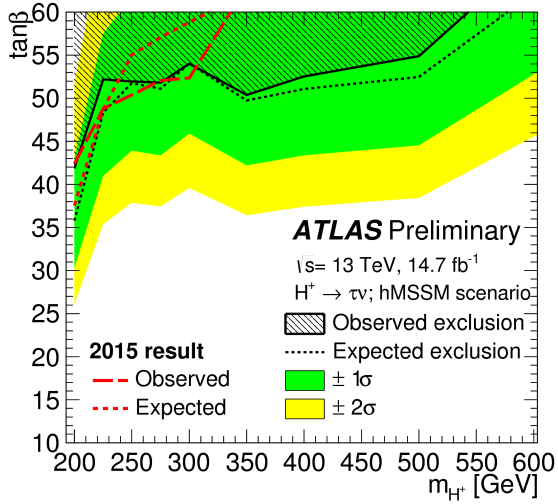




Distribution of m_{T} after full event selection and a fit to the data

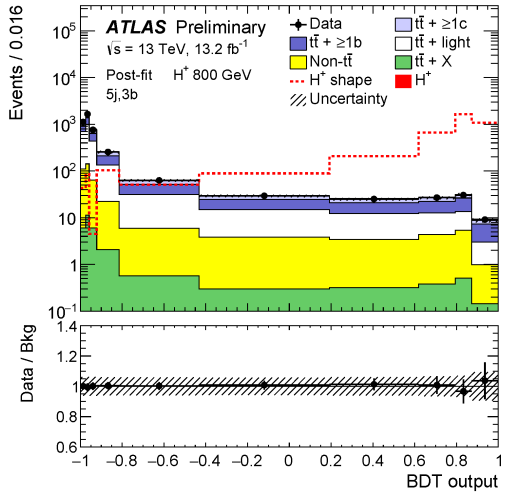


Limit on $\sigma(pp \to [b]tH^{\pm}) \times BR(H^{\pm} \to \tau\nu)$

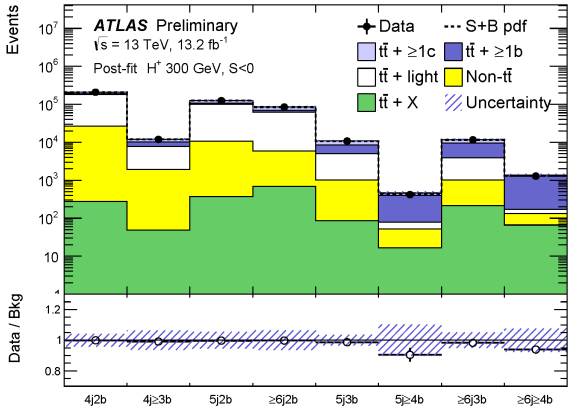


Limit on tan β-$mH^{\pm}$ in the m_h^{mod+} scenario

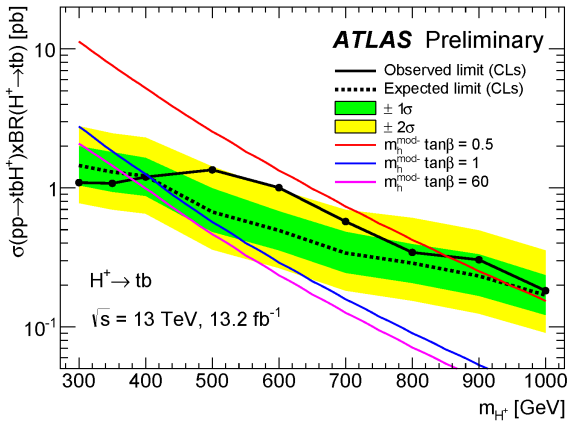
- Searching $H^{\pm}$ in final states with one lepton + (b) jets
- Production of $H^{\pm}$ in association with tb is explored in mass range 300 to 1000 GeV
- Analysis uses MVA technique: BDT
- Interpretation of result in $m_h^{\text{mod-}}$ scenario of MSSM
- Main event selection
  - One lepton (e or μ) with p_T >25 GeV
  - Four jets with at least two of them b-tagged
  - Four SR and CR are defined, according to the distribution of jets and b-jets



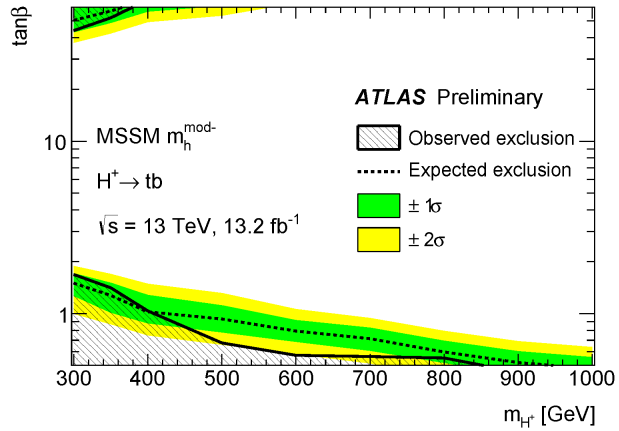
BDT output for the SR: 5j-3b cat



Post-fit distribution of predicted and observed events in the four CR (left) and the four SR (right)

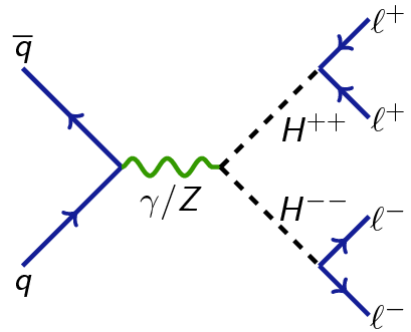


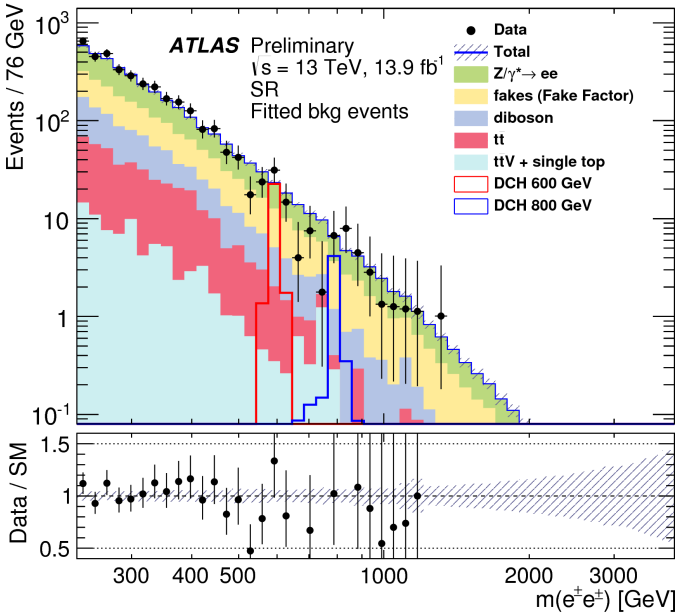
Limit on $\sigma(pp \to tbH^{\pm}) \times BR(H^{\pm} \to tb)$ with three models of $m_h^{\text{mod-}}$ scenario



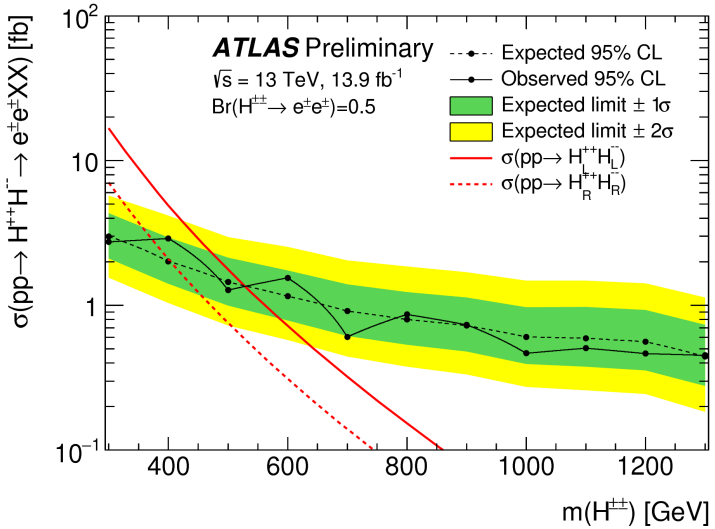
Limit on tan β-$mH^{\pm}$ in the $m_h^{\text{mod-}}$ scenario

- Doubly-charged Higgs bosons arise in some BSM: LRSM, HTM,...
- Pairs of high-p_T isolated SS $e^{\pm}$ can be enhanced
- Main event selection
  - 4 regions: Signal Region (SR), Validation Region (VR) and 2 Control Region (CR)
  - SR: At least one SS pair of e with $m_{ee} > 300$ GeV
  - OS CR for deriving scaling factors for Drell-Yan and $t\bar{t}$ backgrounds
  - Diboson CR for deriving respective factor: OS electron pair in Z mass window and additional SS pair with $m_{ee} > 200$ GeV
  - SS VR: Same selection than SR but for $m_{ee} < 200$ GeV





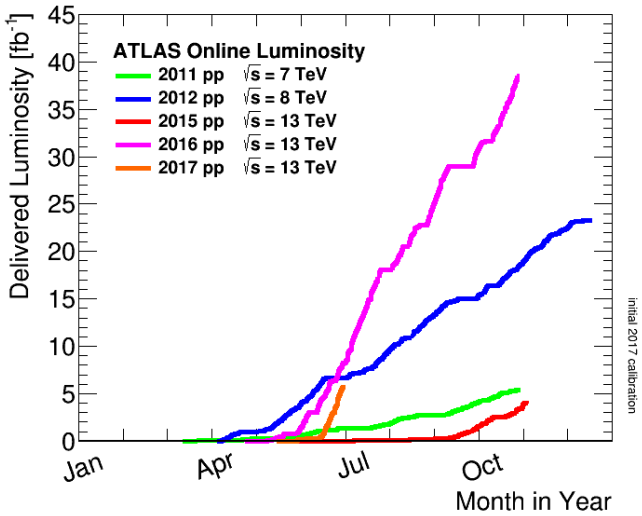
Distribution of m_{ee} after full event selection and a fit to the data

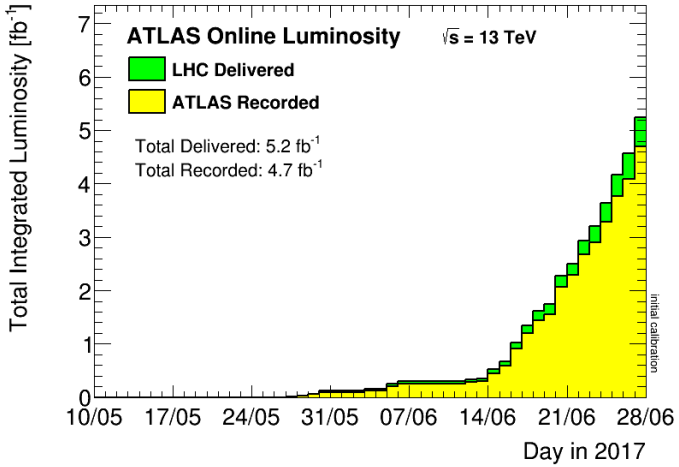


Limit on $\sigma(pp \to H^{\pm\pm}H^{\pm\pm} \to eeee)$ with the assumption $BR(H^{\pm\pm} \to ee) = 50\%$

Conclusions

- Current status of the heavy Higgs searches have been reviewed
- Most of the analysis have been published with half of luminosity collected in 2016 ($< 16\,\text{fb}^{-1}$)
- ATLAS has many more results in heavy searches!
  - ATLAS heavy Higgs results
- No excesses over SM have been found, we need to wait :)
- Analysis with full 2016 data are in process
  - Get ready for updates in next months!
- Also, data-taking of 2017 have started, ATLAS have collected almost $5\,\text{fb}^{-1}$ already!





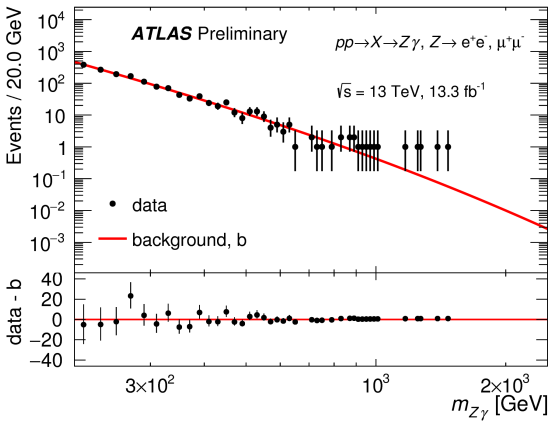
Conclusions

Decay	Analysis	Code	L (fb^{-1})	Date
Bosonic	$A \to Zh$	ATLAS-CONF-2016-015	3.2	16/03/2016
	$H \to WWto\ell\nu qq$	ATLAS-CONF-2016-062	13.2	03/08/2016
	$H \to Z\gamma$	ATLAS-CONF-2016-044	13.3	03/08/2016
	$H \to Z\ell\ell + et$	ATLAS-CONF-2016-056	13.3	03/08/2016
	$H \to WW \to \ell\nu\ell\nu$	ATLAS-CONF-2016-074	13.2	04/08/2016
	$H \to ZV \to \ell\ell qq/\nu\nu qq$	ATLAS-CONF-2016-082	13.2	04/08/2016
	$H \to ZZ \to 4\ell$	ATLAS-CONF-2016-079	15.8	04/08/2016
	$H \to \gamma\gamma$	ATLAS-CONF-2016-059	15.4	05/08/2016
Fermionic	$A/H \to tt$	ATLAS-CONF-2016-073	20.3*	03/08/2016
	$A/H \to \tau\tau$	ATLAS-CONF-2016-085	13.3	04/08/2016
	$A/H \to \tau\nu$	ATLAS-CONF-2016-104	13.2	28/09/2016
Charged	$H^{\pm} \to \tau\nu$	ATLAS-CONF-2016-088	13.2	04/08/2016
	$H^{\pm} \to tb$	ATLAS-CONF-2016-089	13.2	09/08/2016
	$H^{\pm\pm} \to ee$	ATLAS-CONF-2016-051	13.9	03/08/2016
Di-higgs	$H \to hh \to bb\gamma\gamma$	ATLAS-CONF-2016-004	3.2	14/03/2016
	$H \to hh \to bbbb$	ATLAS-CONF-2016-049	13.2	03/08/2016
	$H \to hh \to WW\gamma\gamma$	ATLAS-CONF-2016-071	13.3	04/08/2016

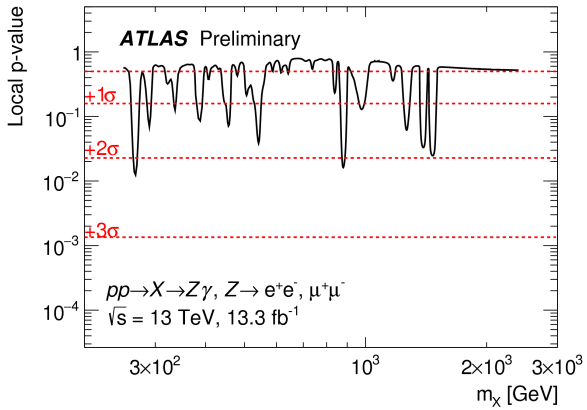
$*$ taken in Run 1 at $\sqrt{s} = 8$ GeV

Backup

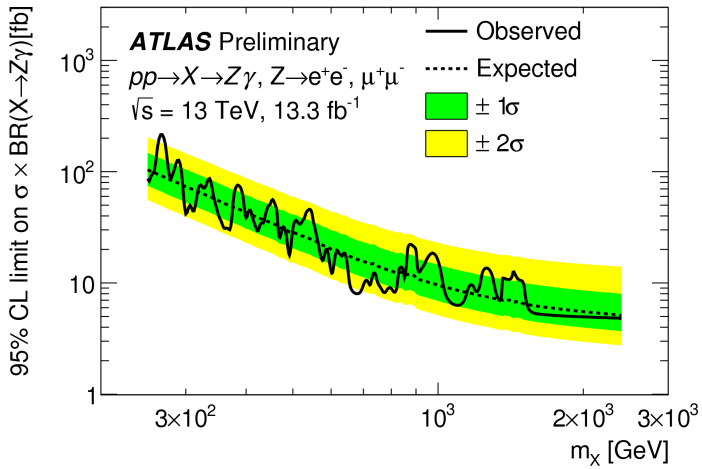
- $Z\gamma$ decay in 250-2400 GeV
- Z decays leptonically (e or μ) and a photon, due to easy measurement in low background
- The two jets are boosted, so they can be reconstructed as a single jet (J)
- Main event selection:
  - Z candidate with two OS leptons and $m_{\ell\ell} \sim 15\% m_Z$
  - $p_T^\gamma > 30\% m_{Z\gamma}$
  - Two categories according to lepton flavour



Combined SR

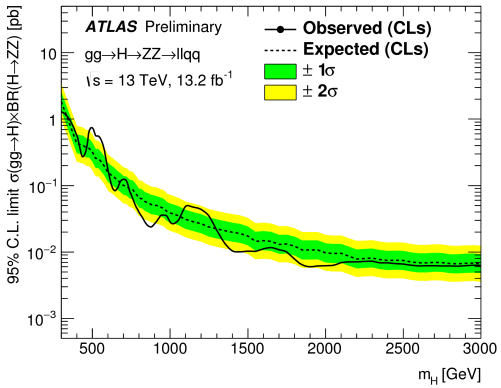


p-value plot

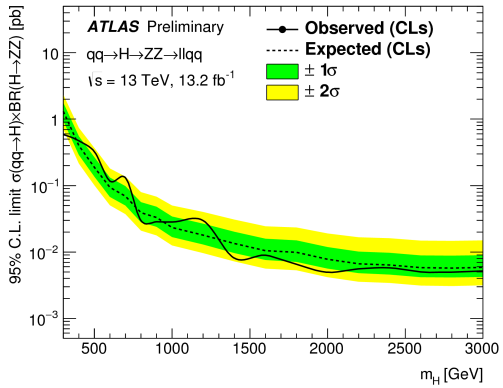


Exclusion limit on $\sigma \times BR(X \to Z\gamma)$

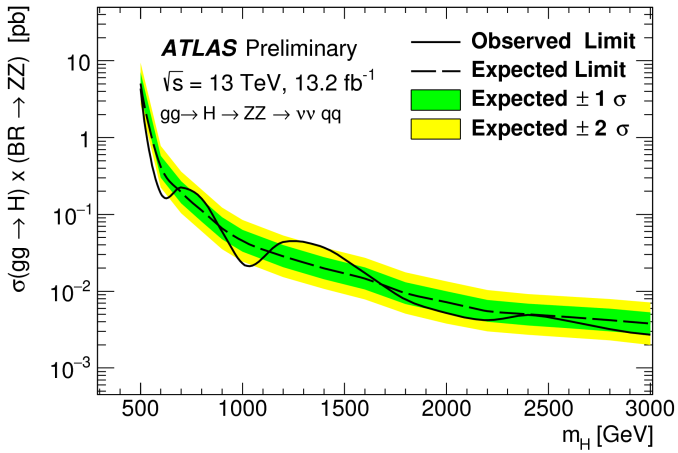
- Decays of ZZ and ZW resonances in $\ell\ell qq$ and $\nu\nu qq'$ final states
- $ZV \to \ell\ell qq$
  - Uses both boosted and resolved V decay
  - Final discriminant is the invariant mass
- $ZV \to \nu\nu qq$
  - Uses only resolved reconstruction of V decay
  - Final discriminant is the transverse mass (m_T)



$H \to ZV \to \ell\ell qq$ ggF



$H \to ZV \to \ell\ell qq$ VBF

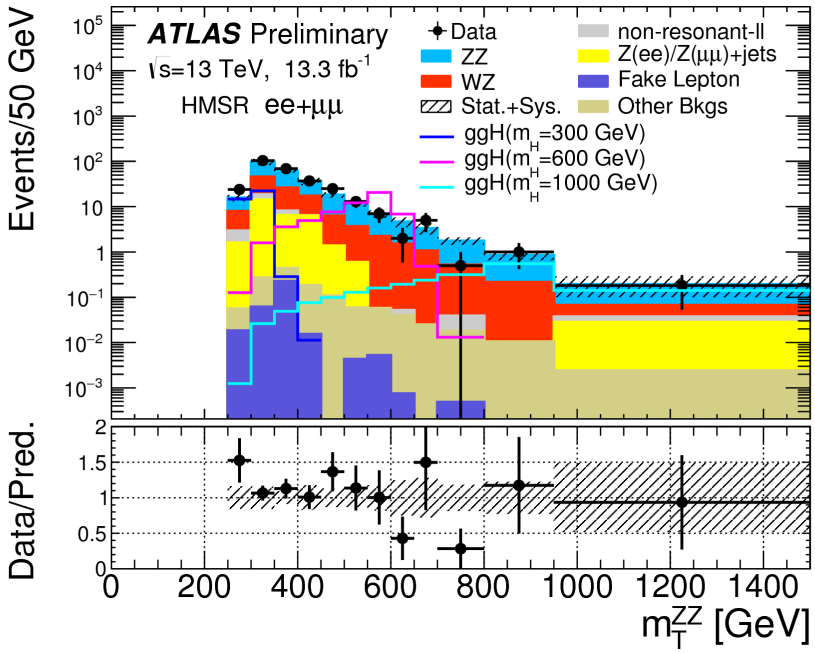


$H \to ZV \to \nu\nu qq$

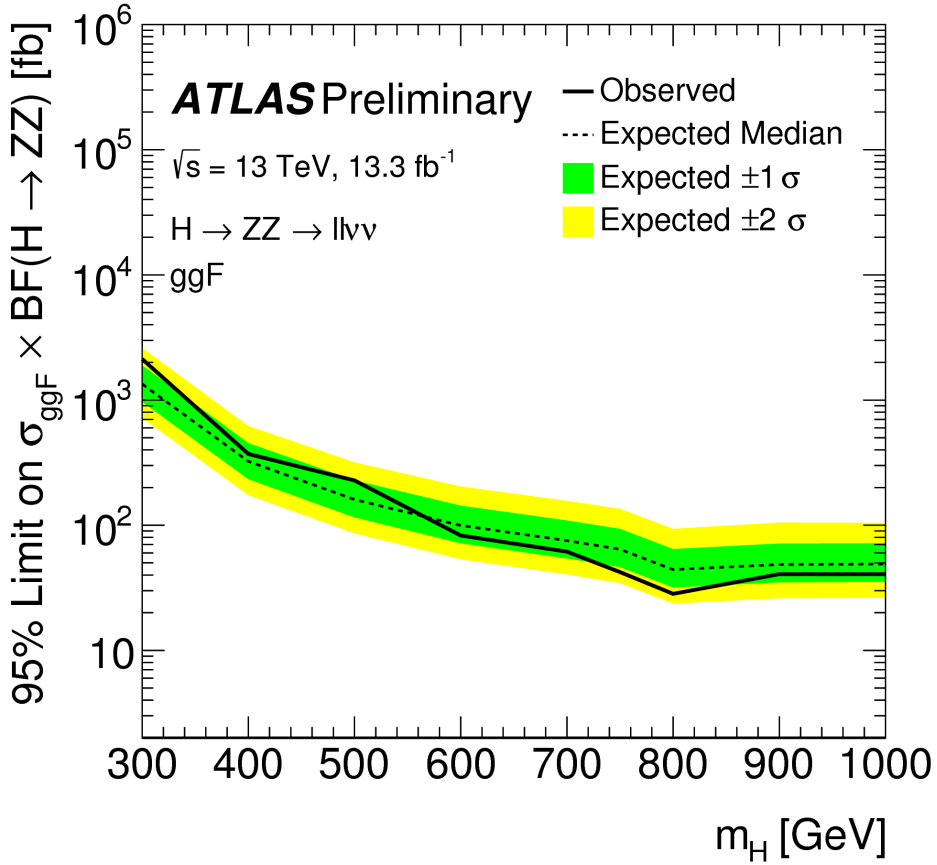
$H \to Z(to\ell\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$ - 13.3 fb^{-1} ATLAS-CONF-2016-056

- $H \to Z(\to \ell\ell)Z(\to \nu\nu)$ in mass range 300-1000 GeV
- Discriminant m_T^{ZZ}, defined as:
- Main event selection:
  - Two OS SF leptons and $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV
  - $\Delta R_{\ell\ell} < 1.8$, $\Delta\phi(Z, E_{\mathrm{T}}^{\mathrm{miss}}) < 2.7$
  - Cuts in transverse variables of $E_{\mathrm{T}}^{\mathrm{miss}}$-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$-Z systems

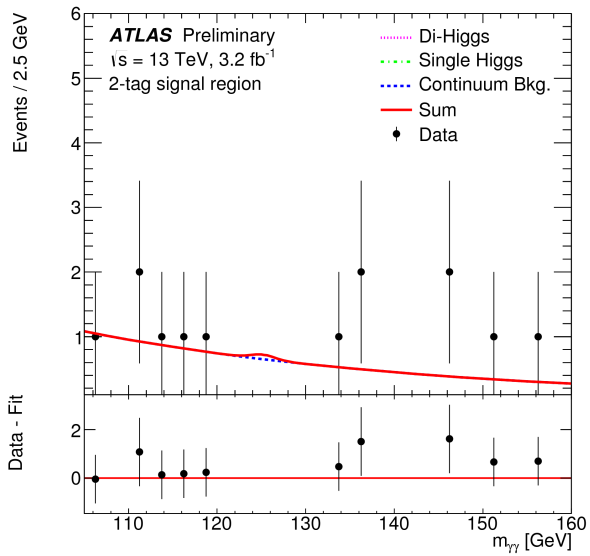
$$m_T^{ZZ} \equiv \left(\sqrt{m_Z^2 + \left|p_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|E_{\mathrm{T}}^{\mathrm{miss}}\right|^2}\right)^2 - \left|p_{\mathrm{T}}^{\vec{\ell\ell}} + E_{\mathrm{T}}^{\vec{\mathrm{miss}}}\right|$$



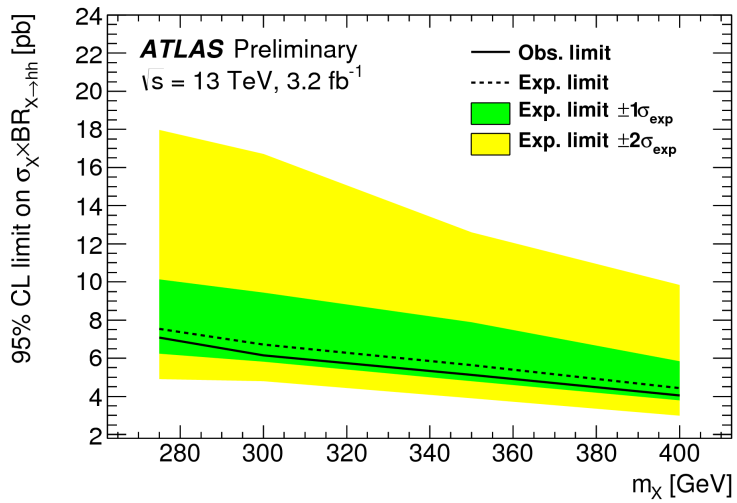
Combined SR



- $bb\gamma\gamma$ final state benefits from large BR from bb pair and clean diphoton signal
- However, because of the BR of $\gamma\gamma$ the mass range is limited from 275-400 GeV
- Main event selection
  - Two isolated photons with $m_{\gamma\gamma}$ in range 105-160 GeV, two b-jets with m_{bb} in range 95-135 GeV
  - CR: Two non-b-tagged jets to estimate continuum background
  - Additional criteria: Crystal Ball fit to $m_{\gamma\gamma}$ to constrain $m_{\gamma\gamma}$ range and linear parametrization to account for resonances not simulated



Distribution of $m_{\gamma\gamma}$
after full event selection and a fit to the data



Excl. limit as a function of m_X on $\sigma_X \times BR(x \to hh)$
for a narrow resonance

Not enough statistics to exclude the modest excess in Run 1: 3.0σ local (2.1σ global) at 300 GeV

- Search for heavy Higgs decaying to pair of SM Higgs via $H \to hh$ and final state $bbbb$
- Two strategies: resolved and boosted
- Resolved analysis: Two h candidates with low p_T: separated decay objects
  - Two pairs of two b-jets, $m_{bb} \sim h$
  - Angular conditions on the pairing of b-jets to form h candidates
  - Mass range between 300 and 1200 GeV
- Boosted analysis: h candidates with high p_T: decay objects merged in large jet
  - Two large-R jets (anti-k_t with $R = 1$)
  - Candidates: $p_T >$(450 GeV,250 GeV), $|\eta| < 2.0$ and $m_J > 50$ GeV
  - Central jets: $|\Delta\eta_{hh}| < 1.7$
  - Each large-R jet needs at least one b-tagged $R = 0.2$ track jet.