Search for 2HDM high mass scalar bosons at 13 TeV by the ATLAS collaboration

THE UNIVERSITY *of* EDINBURGH

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on behalf of the ATLAS Collaboration

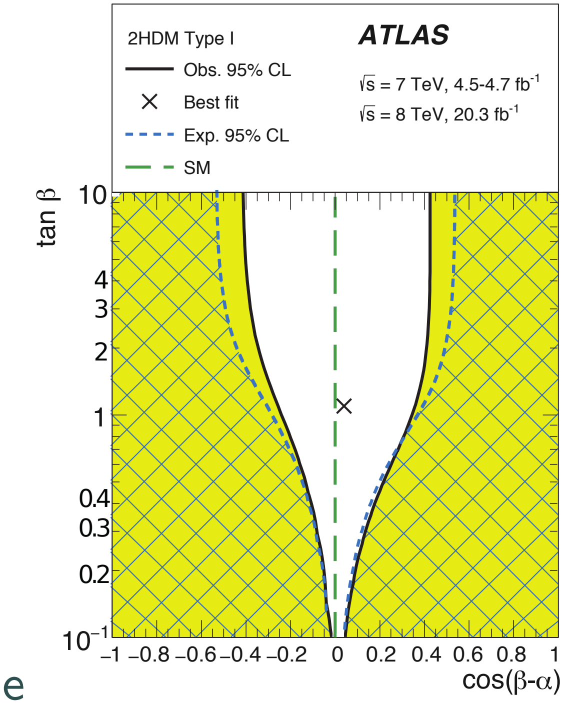
Overview

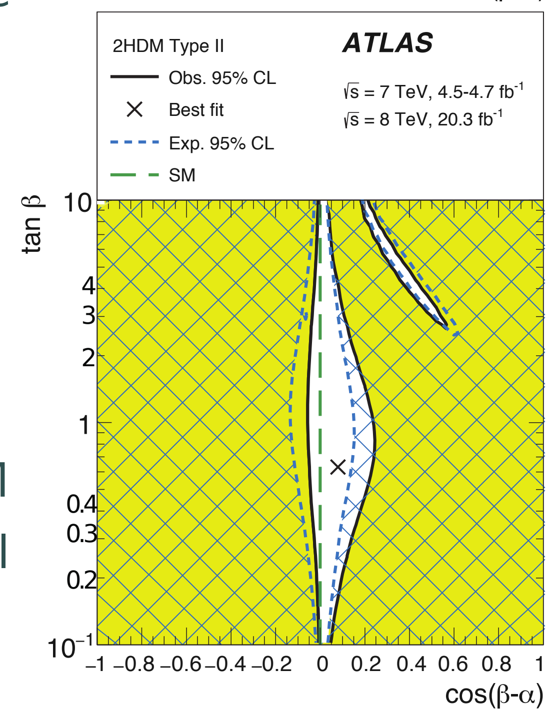
- Motivation
- 2HDM overview
- Experimental searches
  - Charged Higgs
  - Heavy scalar/pseudoscalar Higgs decay to $\tau\tau$
  - Heavy pseudoscalar Higgs decay to Zh

Motivation for 2HDM

- A Higgs boson was discovered in 2012 at 125 GeV, but... *is it the only one?*

- There is *no fundamental reason* to have only one Higgs boson.
- Why Two-Higgs-Doublet models (2HDM)?
  - Relatively simple extension to the SM
  - Baryon asymmetry
  - Dark matter
- Minimal Supersymmetric extension to the SM (MSSM) contains a Type II 2HDM with additional constraints





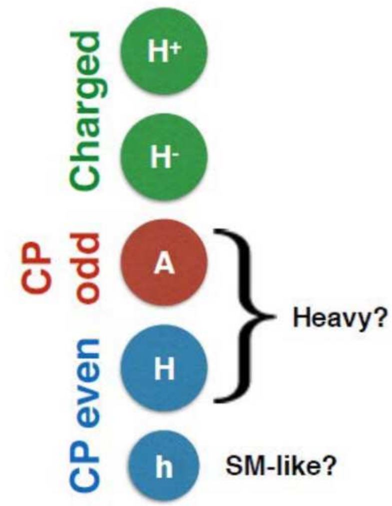
JHEP11(2015)206

The Two-Higgs-Doublet model

- Two complex doublet scalar fields → 8 degrees of freedom
- After electroweak symmetry breaking, $W^\pm$ and Z bosons acquire mass
- 5 Higgs particles remain: h, H, A and $H^\pm$
- Free parameters: masses of Higgs bosons, and two additional parameters (α and β)

$$\tan\beta = v_2/v_1$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$



Types of 2HDM models categorised by couplings

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

ATLAS BSM Higgs Searches at 13 TeV

2HDM or MSSM searches

Charged Higgs

$H^{\pm} \to \tau\nu$ - arXiv:1603.09203

Neutral Higgs

$H/A \to \tau\tau$ - ATLAS-CONF-2015-061

Higgs-to-Higgs

$A/H \to Zh(125)$ - ATLAS-CONF-2015-015

Not 2HDM or MSSM searches

Di-Higgs *(B. Kaplan, BSM Higgs II, Tue 2:45)*

$H \to hh \to b\bar{b}\gamma\gamma$ - ATLAS-CONF-2016-004

$H \to hh \to b\bar{b}b\bar{b}$ - ATLAS-CONF-2016-017

Dibosons *(B. Pearson, BSM II, Mon 5:30)*

$H \to ZZ \to 4\ell$ - ATLAS-CONF-2015-059

$H \to ZZ \to \ell\ell\nu\nu$ - ATLAS-CONF-2016-012

$H \to ZZ \to \ell\ell qq$ - ATLAS-CONF-2016-016

$H \to WW$ - ATLAS-CONF-2016-021

Boosted resonances - ATLAS-CONF-2015-068, ATLAS-CONF-2015-071, ATLAS-CONF-2015-075

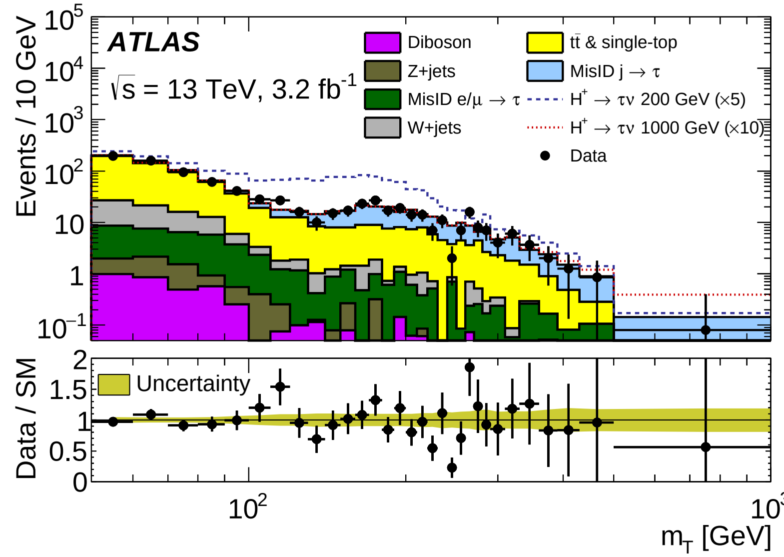
$X \to \gamma\gamma$ - ATLAS-CONF-2016-018

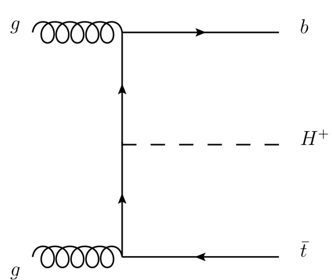
$X \to Z\gamma$ - ATLAS-CONF-2016-010

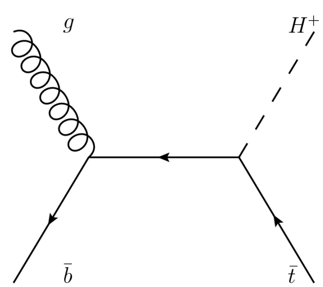
Search for $H^{\pm} \to \tau\nu$

- For $m_{H+} > m_t$, $H^{\pm}$ produced dominantly in association with top quark
- $H \to \tau\nu$ can have a substantial branching fraction (even in alignment limit)

$$m_T = \sqrt{2p_T^{\tau} E_T^{\text{miss}}(1 - \cos \Delta\phi_{\tau_{\text{had-vis}},\text{miss}})}$$







$$gg \to [\bar{t}b][H^+] \to [(q\bar{q}\bar{b})b][\tau^+_{\text{had-vis}} + \nu_\tau]$$

$$g\bar{b} \to [\bar{t}][H^+] \to [q\bar{q}\bar{b}][\tau^+_{\text{had-vis}} + \nu_\tau]$$

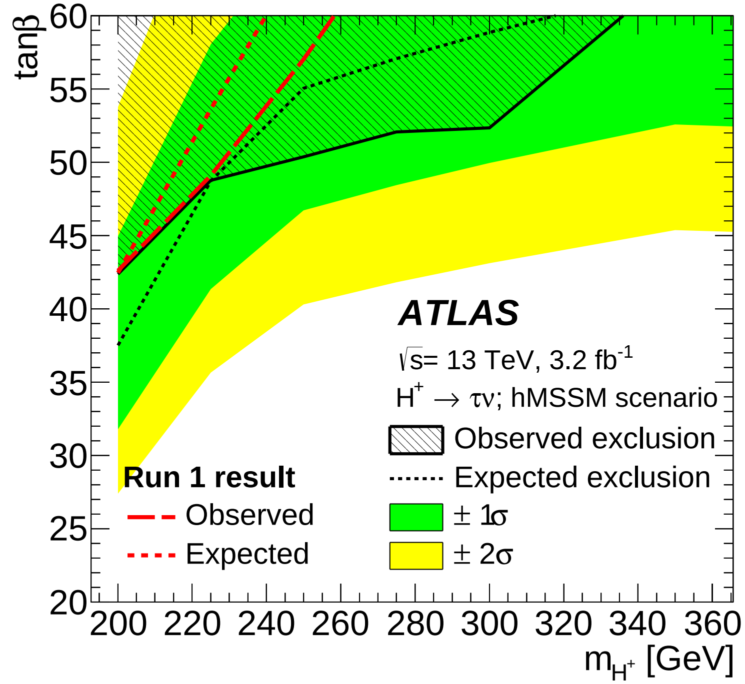
Event Selection:

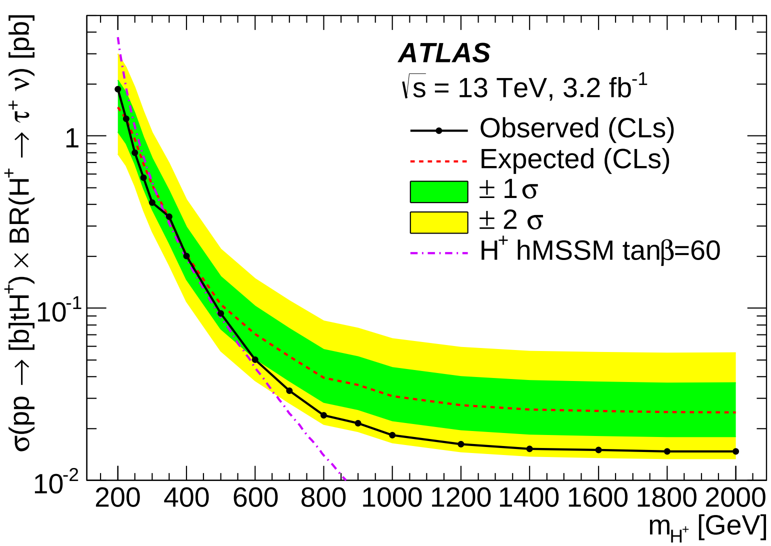
- At least 3 jets with $p_T > 25$ GeV including ≥ 1 b-tag
- One τ candidate, no e or μ
- $E_T^{\text{miss}} > 150$ GeV
- $m_T > 50$ GeV

Search for $H^{\pm} \to \tau\nu$

Background estimation

- True τ: $t\bar{t}$, W+jets from MC, validated in control region (CR)
- Fake τ:
  - From jets (QCD multijet): data-driven
  - From leptons (top, V+jets, di-bosons): shapes from MC, normalisation from data





13 TeV hMSSM results (3.2 fb^{-1})

- Values of $\tan\beta$ from 42-60 excluded for $m_{H\pm} = 200$ GeV
- At $\tan\beta = 60$, $200 < m_{H\pm} < 340$ GeV excluded

Search for $H/A \to \tau\tau$

- Decays of H/A to τ-leptons enhanced in MSSM for large values of $\tan\beta$

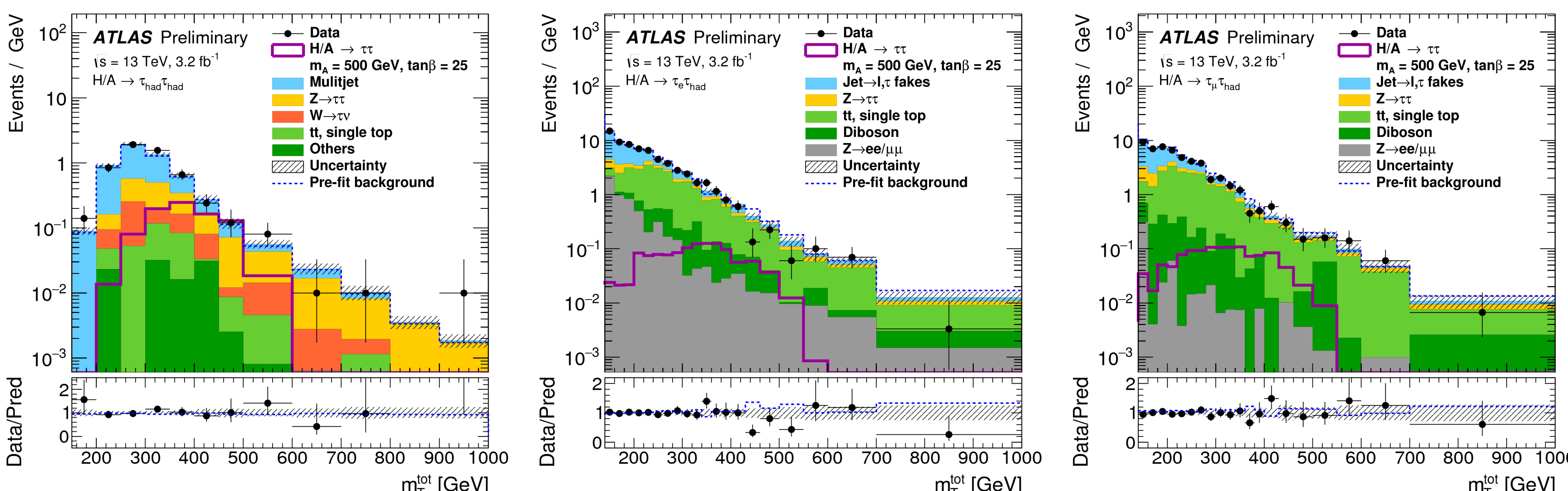
$\tau_{\rm lep}\tau_{\rm had}$ event selection

- 1 τ with $p_T > 20$ GeV, 1 OS e or μ with $p_T > 30$ GeV
- $\Delta\Phi(\tau, \ell) > 2.4$, $\ell = e, \mu$
- W and Z vetos:
  - $40 < m_T(\ell, E_T^{\rm miss}) < 150$ GeV
  - $80 < m_{\rm vis} < 110$ GeV (e channel only)

$\tau_{\rm had}\tau_{\rm had}$ selection

- 2 OS τ candidates ($p_T > 135$, 55 GeV)
- No e or μ
- $\Delta\Phi(\tau_1, \tau_2) > 2.7$

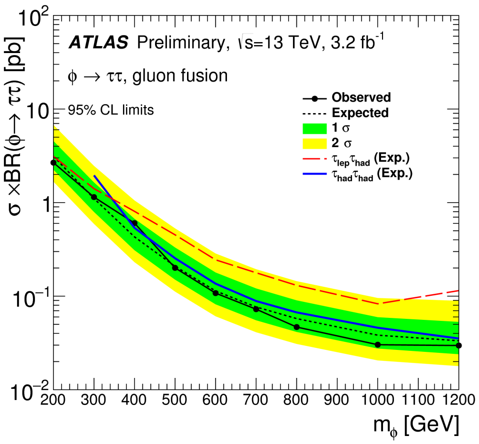
$$(m_T^{\rm tot})^2 = m_T^2(E_T^{\rm miss}, \tau_1) + m_T^2(E_T^{\rm miss}, \tau_2) + m_T^2(\tau_1, \tau_2)$$

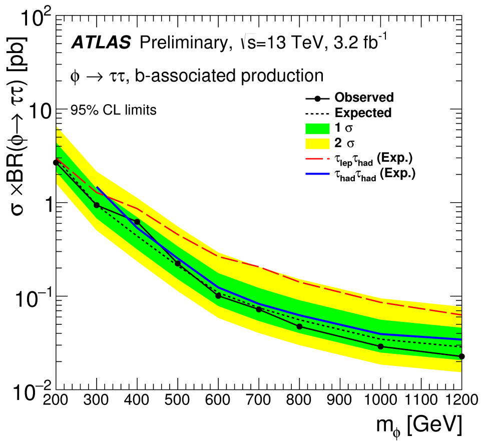


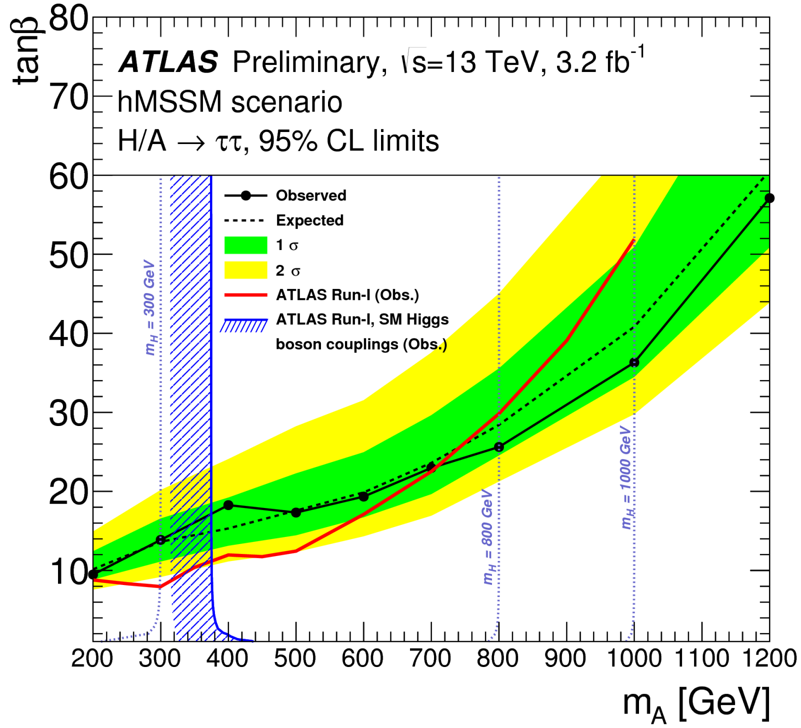
Search for $H/A \to \tau\tau$

Background estimation

- True τ: $t\bar{t}$, Z/γ from MC
- Fake τ from jets: W+jets, multijet from data-driven method







13 TeV hMSSM results (3.2 fb^{-1})

- $\tan\beta > 10$ excluded for $m_A = 200$ GeV (95% CL)
- At $\tan\beta = 60$, $200 < m_A < 1200$ GeV excluded

Search for $A \to Zh$, $h \to b\bar{b}$

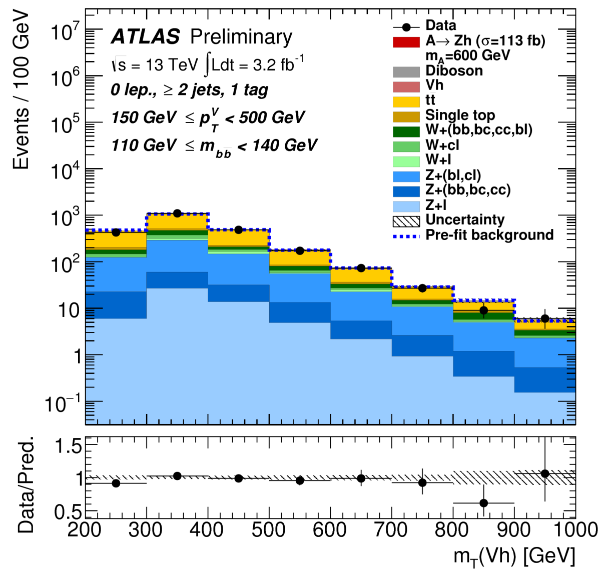
- Resonant production of heavy pseudoscalar decaying to Z and 125 GeV Higgs
- Light higgs (h) decays to two b quarks
- Considering Z decays to $\nu\nu$ and $\ell\ell$ ($\ell = e, \mu$)
- Categories used to separate decay channels and to improve analysis sensitivity

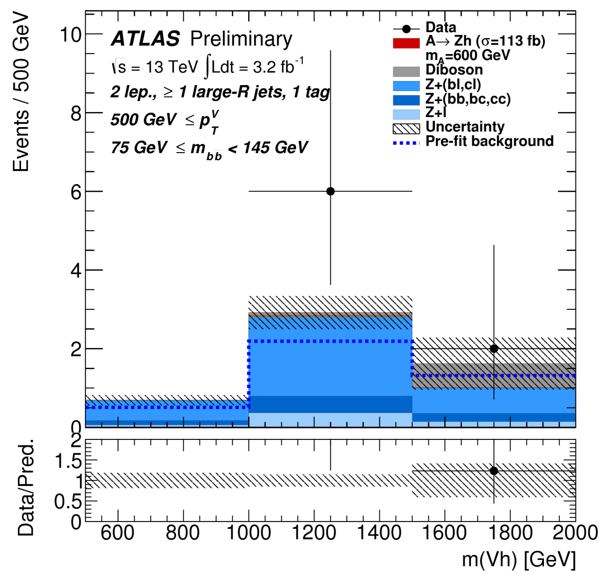
Categories

- 0- and 2-leptons
- non-boosted and boosted Z ($p_T^Z > 500$ GeV uses large radius jets)
- 1- and 2-b-tagged jets

Final discriminant:

$$m_{T,Zh} = \sqrt{(E_T^h + E_T^{\text{miss}})^2 - (\vec{p}_T^{\,h} + \vec{E}_T^{\text{miss}})^2}$$

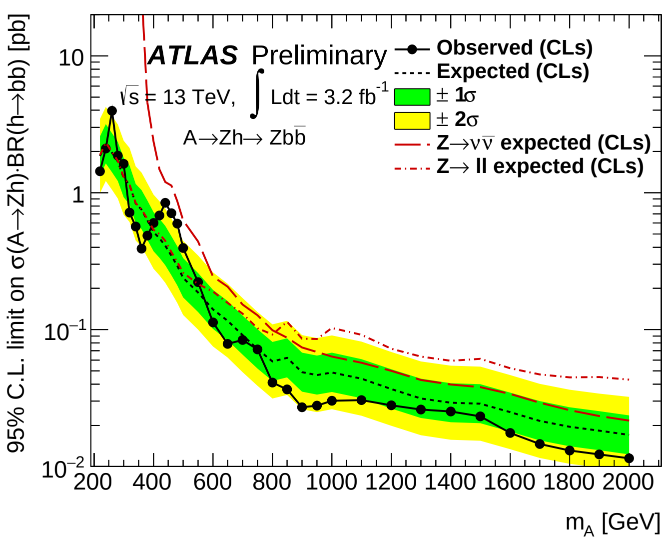




Search for $A \to Zh$, $h \to b\bar{b}$

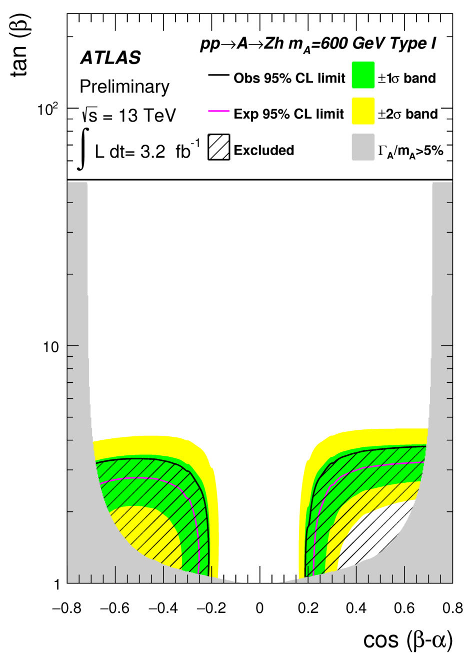
Background estimation

- W/Z+jets, $t\bar{t}$ shapes from MC, normalisations from CR
- Several "W/Z+jets" CR defined based on number of leptons and b-tags
- Additional $t\bar{t}$ CR defined with e and μ
- Diboson and single top from MC

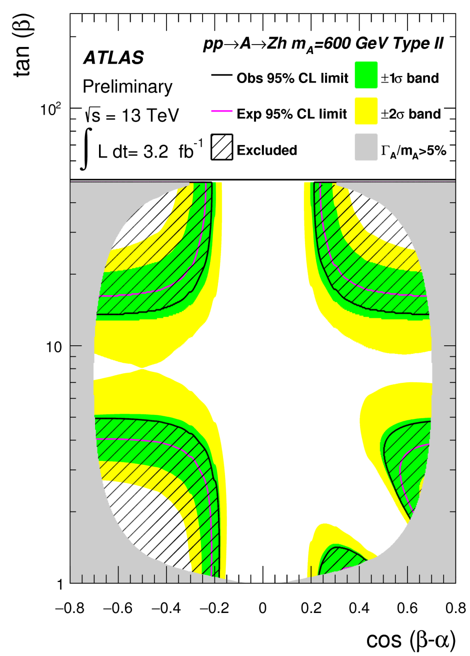


(Limit assumes 100% gluon fusion)

Type I 2HDM, $m_A = 600$ GeV



Type II 2HDM, $m_A = 600$ GeV



Summary

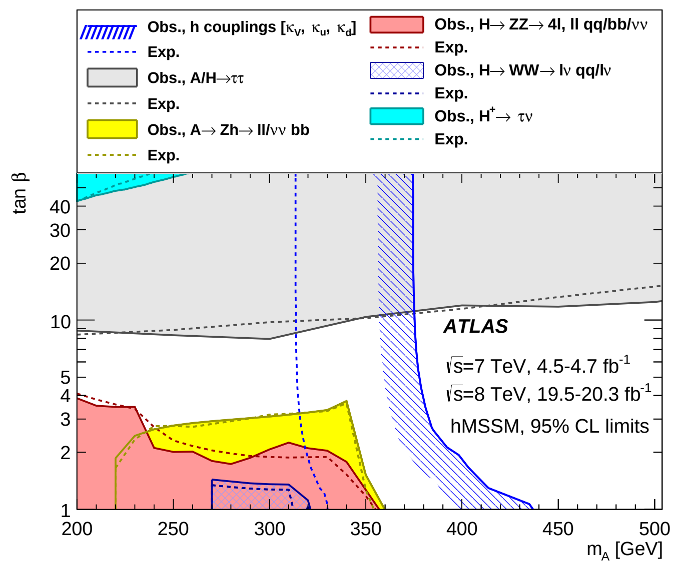
- ATLAS has a rich program of searches for BSM Higgs
- Results presented here cover searches for charged Higgs, CP-even and CP-odd neutral Higgs decaying directly to leptons and quarks at 13 TeV
- This is just the beginning… 2016 will be an exciting year for BSM searches!
- See Ben Kaplan's talk (Tuesday, 2:45 pm in BSM Higgs II) for $H \to hh$ and other interesting Higgs decays
- See Ben Pearson's talk (Monday, 5:30 pm in BSM II) for $H \to$ dibosons

13 TeV 2HDM Searches

$H^{\pm} \to \tau\nu$ - arXiv:1603.09203

$H/A \to \tau\tau$ - ATLAS-CONF-2015-061

$A/H \to Zh(125)$ - ATLAS-CONF-2015-015



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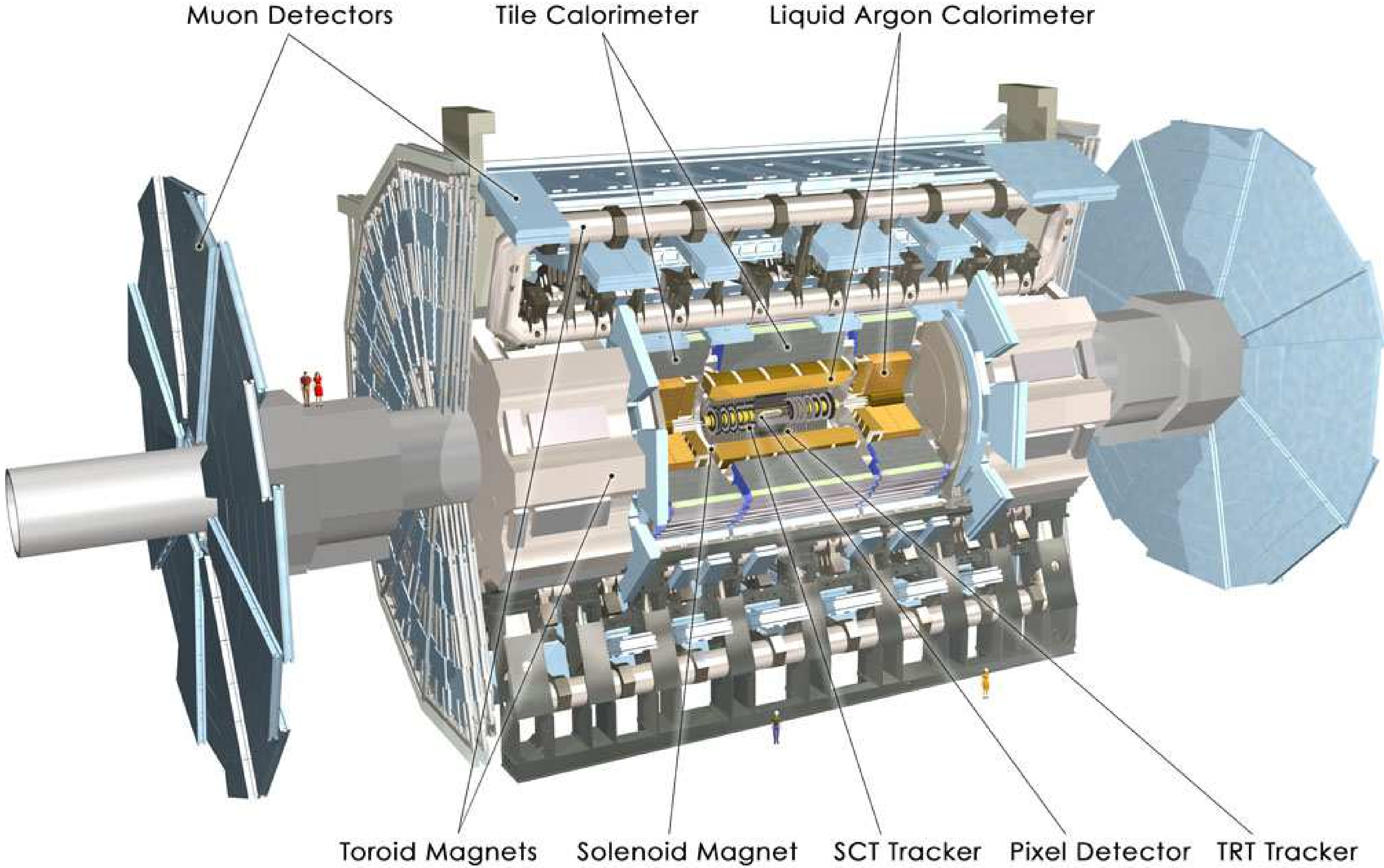
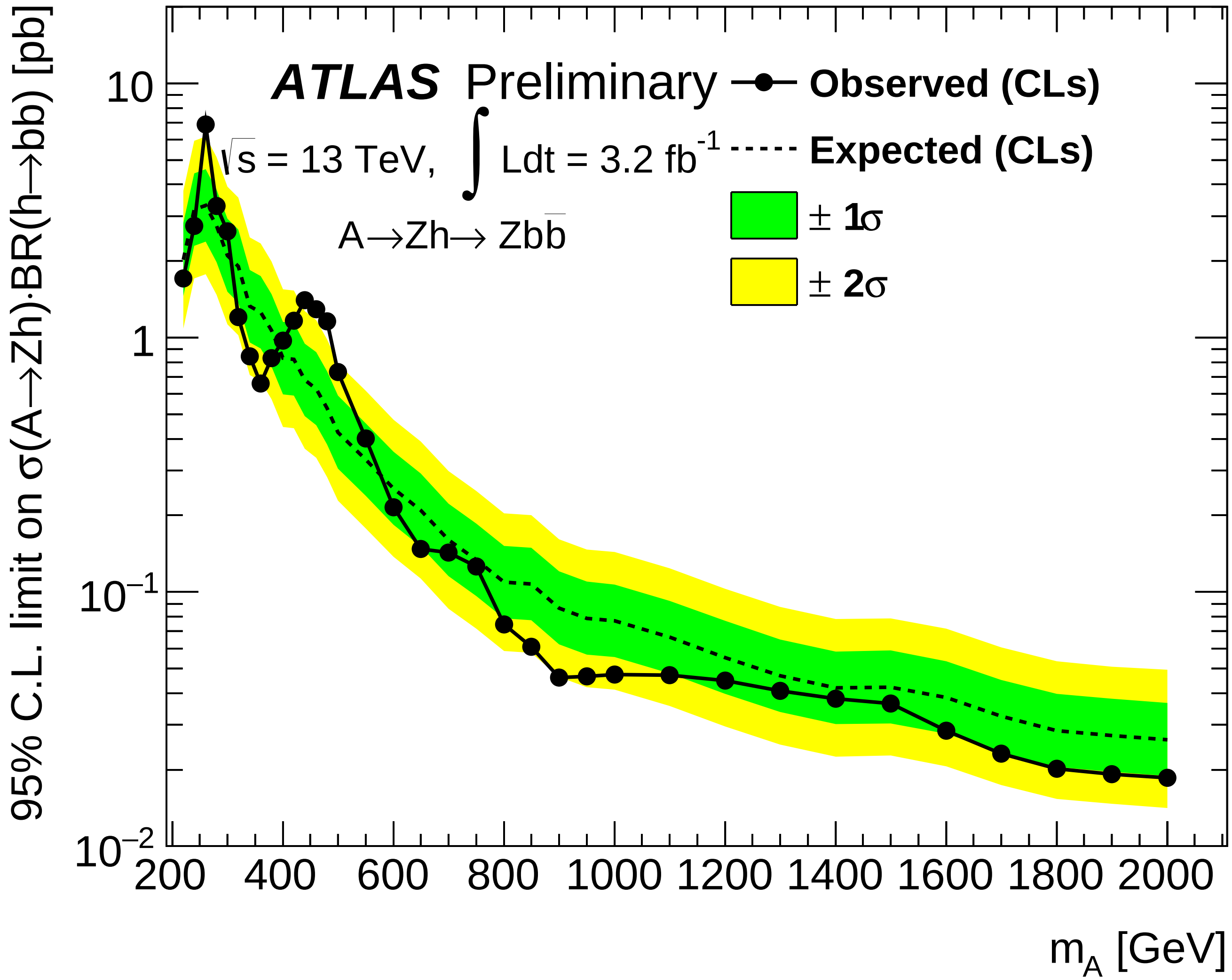
Backup Slides

ATLAS detector



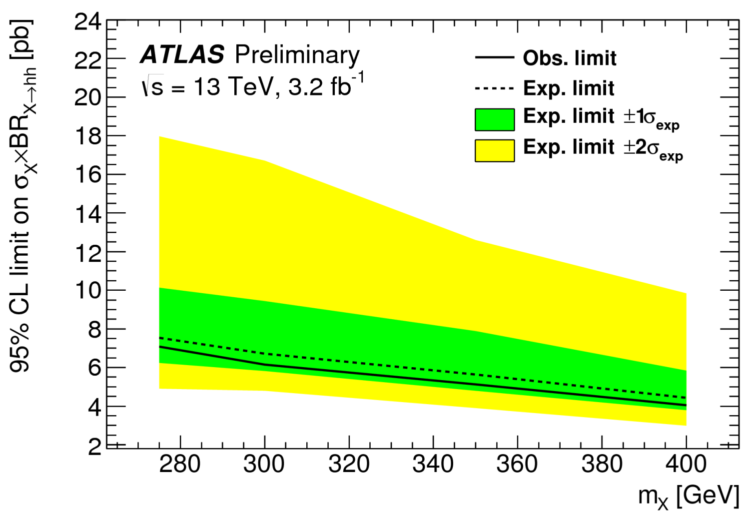
Search for $A \to Zh$, $h \to b\bar{b}$



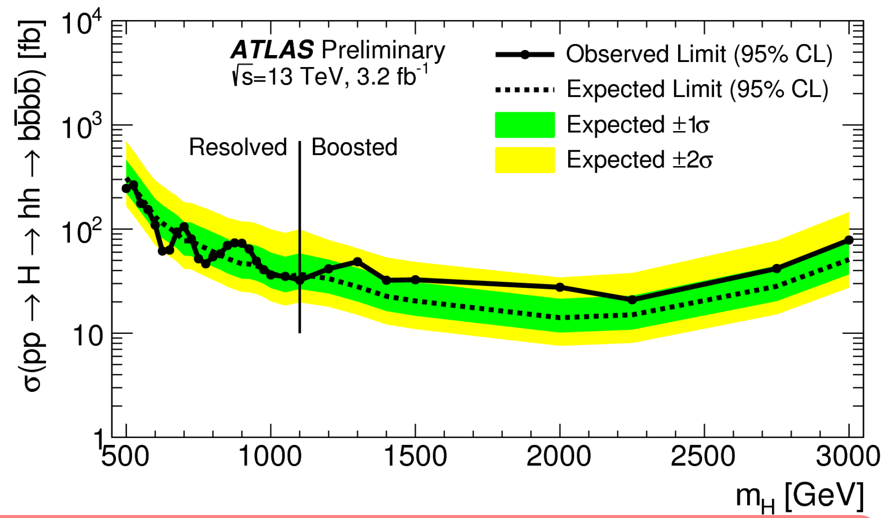
Searches for $H \to hh$

- Heavy Higgs bosons in 2HDM models can decay to lighter Higgs bosons
- $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$ are promising states due to large branching fractions for Higgs decay
- No interpretation done (yet) in terms of 2HDM or MSSM models
- More details in Ben Kaplan's talk in BSM Higgs II (Tuesday at 2:45 pm)

$H \to hh \to b\bar{b}\gamma\gamma$, **narrow-width** X



$H \to hh \to b\bar{b}b\bar{b}$, **spin-0 narrow-width** H

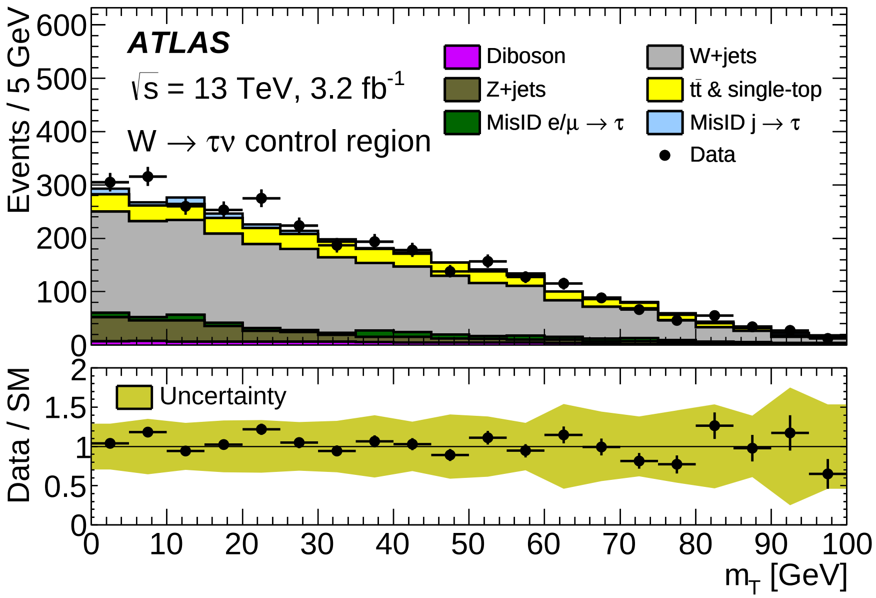


13 TeV hMSSM results (3.2 fb^{-1})

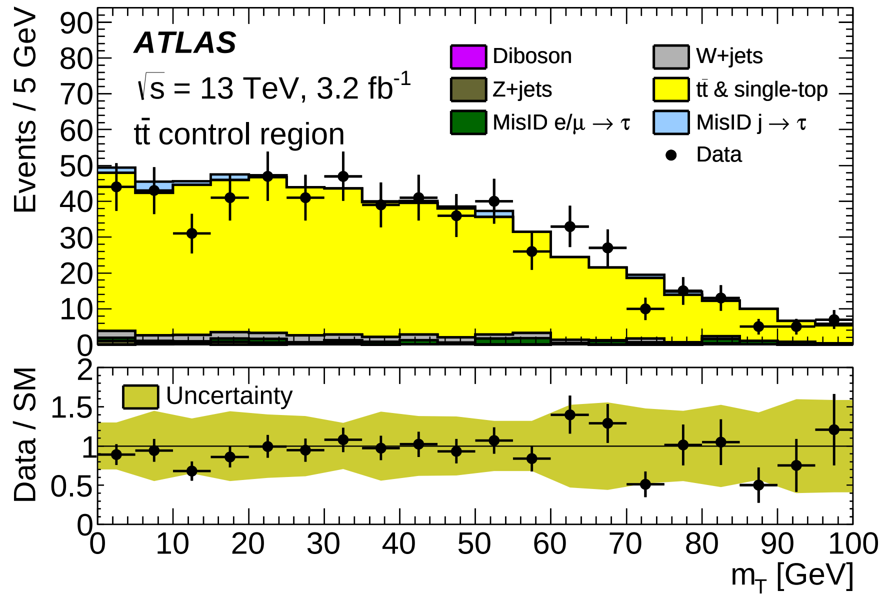
$b\bar{b}\gamma\gamma$: Observed 95% C.L. limits range from 7.0 to 4.4 pb for $275 < m_X < 400$ GeV
$b\bar{b}b\bar{b}$: Observed 95% C.L. limits range from 30 to 300 fb for $500 < m_X < 3000$ GeV

$H^{\pm} \to \tau\nu$ control regions

$W \to \tau\nu$ control region



$t\bar{t}$ control region



- Selection:
  - $m_T < 100$ GeV
  - zero b-tagged jets
- Used to correct normalisation of simulated $W \to \tau\nu$ background

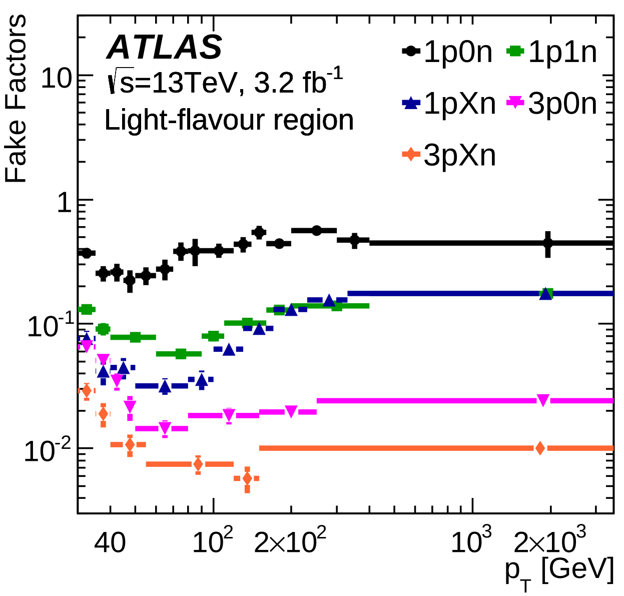
- Selection:
  - $m_T < 100$ GeV
  - two b-tagged jets

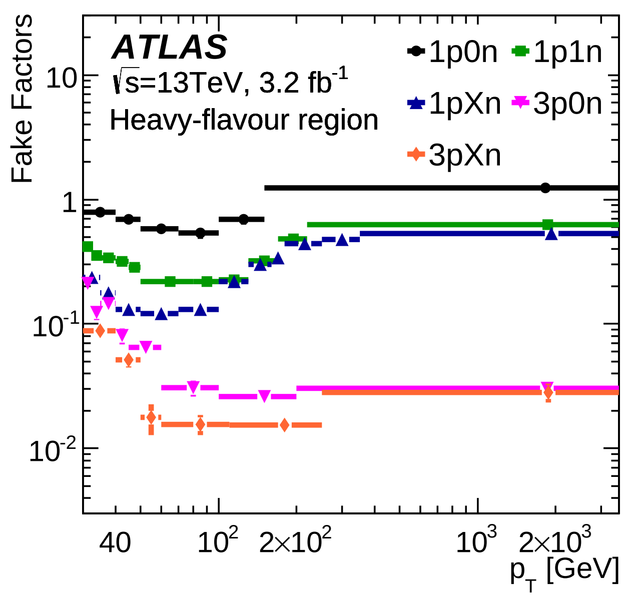
$H^{\pm} \to \tau\nu$ MC samples

- Signal samples:
  - H^{+} produced in association with single t
  - Generated in 4FS at NLO with MadGraph5_aMC@NLO v2.2.2
  - NNPDF23LO for PDFs
  - Pythia8 v8.186 used for showering with A14 tune for underlying event
- Background samples:
  - $t\bar{t}$, single t (s- and Wt-channels): Powheg-Box v2, CT10
  - single t (t-channel): Powheg-Box v1 with 4FS for NLO ME calculations with CT10F4, t decayed with MadSpin
  - W/Z+jets: MadGraph5_aMC@NLO v2.2.2 at LO with NNPDF23LO PDF set, Pythia8
  - Diboson: Powheg-Box v2 with Pythia8, CT10 NO for HS, CTEQ6L1 for parton shower

$H^\pm \to \tau\nu$ fake factor method

- Jet $\to \tau_{\text{had-vis}}$ background includes processes where a jet is reconstructed as a $\tau_{\text{had-vis}}$
- Control region consisting of misidentified $\tau_{\text{had-vis}}$ used to measure fake rate
- Selection same as signal selection except:
  - $E_T^{\text{miss}} < 80$ GeV
  - zero b-tagged jets
- Fake factor (FF) defined as number of misID $\tau_{\text{had-vis}}$ candidates fulfilling nominal selection to number of misID $\tau_{\text{had-vis}}$ candidates satisfying "anti-$\tau_{\text{had-vis}}$" selection
- anti-$\tau_{\text{had-vis}}$ selection: inverted $\tau_{\text{had-vis}}$ ID criteria with loose requirement on BDT output





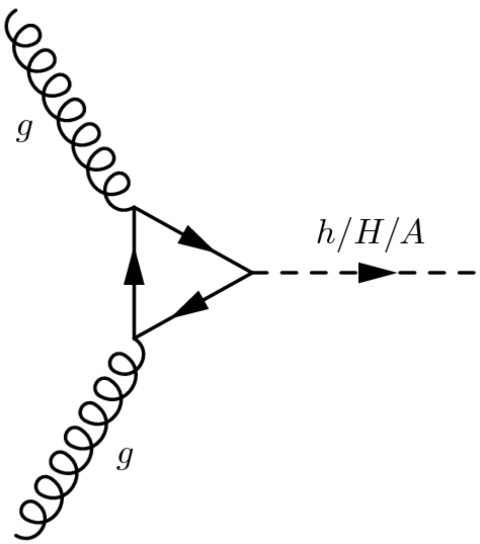
$H^{\pm} \to \tau\nu$

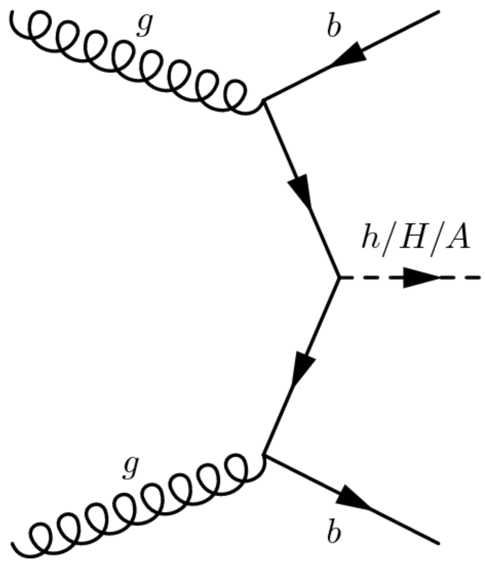
Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	590 ± 170
$W \to \tau\nu$	58 ± 14
$Z \to \tau\tau$	6.4 ± 2.0
diboson (WW, WZ, ZZ)	4.3 ± 1.3
Misidentified e, $\mu \to \tau_{\text{had-vis}}$	40 ± 6
Misidentified jet $\to \tau_{\text{had-vis}}$	196 ± 24
All backgrounds	900 ± 170
H^+ (200 GeV), hMSSM $\tan\beta = 60$	175 ± 28
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	2.0 ± 0.2
Data	890

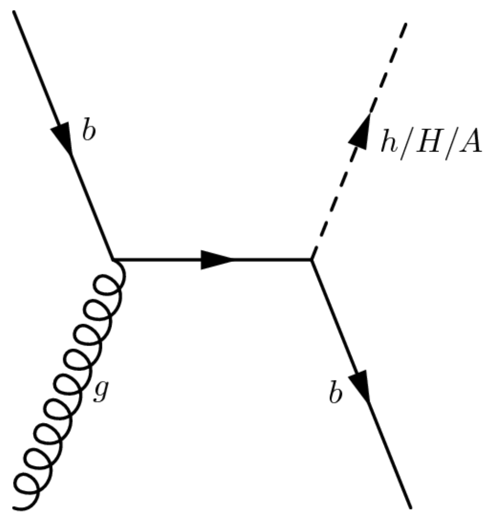
$H^{\pm} \to \tau\nu$

Source of systematic uncertainty	Impact on the expected limit (in %) $m_{H^+} = 200\ GeV$	$m_{H^+} = 1000\ GeV$
Experimental		
luminosity	2.0	1.1
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	2.7	1.1
jet	0.4	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.3	< 0.1
Fake factors		
statistical limitation	4.5	0.7
true τ_{had} contamination	< 0.1	< 0.1
anti-$\tau_{\text{had-vis}}$ BDT score	0.2	0.6
Signal and background models		
$t\bar{t}$ cross section	0.2	< 0.1
$t\bar{t}$ modelling	7.5	1.0
H^+ signal modelling	1.4	1.3

$H/A \to \tau\tau$ production





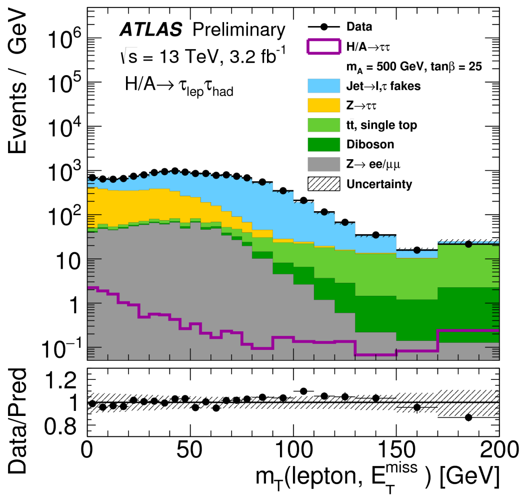


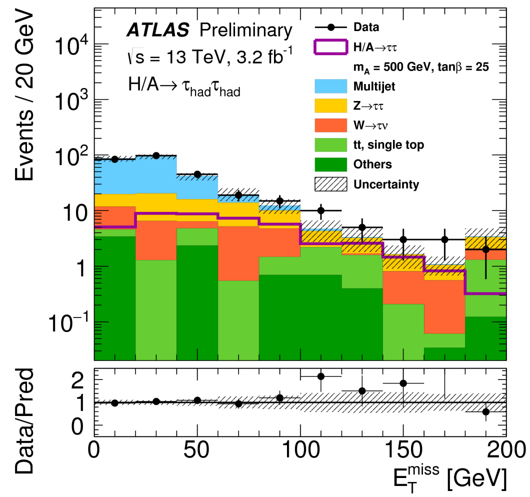
$H/A \to \tau\tau$ MC samples

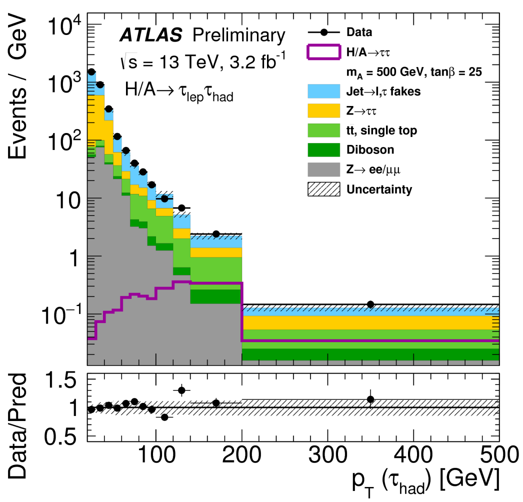
- Signal samples:
  - b-associated production: MadGraph5_aMC@NLO 2.1.2 for 9 masses between 200 and 1200 GeV
  - Gluon fusion: same masses generated with Powheg
  - Pythia 8.2 for parton shower, underlying event and hadronisation
- Background samples:
  - W/Z+jets (except $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$): Powheg-Box v2 with CT10 PDF set, Pythia8.186
  - W+jets for $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$: Sherpa 2.1.1 up to 2 partons at NLO, 4 partons at LO usign Comix and OpenLoops, meged with Sherpa PS model using ME+PS@NLO (# events with high p_T^W too small with Powheg)
  - $t\bar{t}$, single t (s- and Wt-channels): Powheg-Box v2, CT10
  - single t (t-channel): Powheg-Box v1 with 4FS for NLO ME calculations with CT10F4, t decayed with MadSpin
  - Diboson: Sherpa 2.1.1, calculated up to 1 additional parton at NLO, and up to 3 additional partons at LO using Comix and OpenLoops, merged with Sherpa PS model using ME+PS@NLO prescription

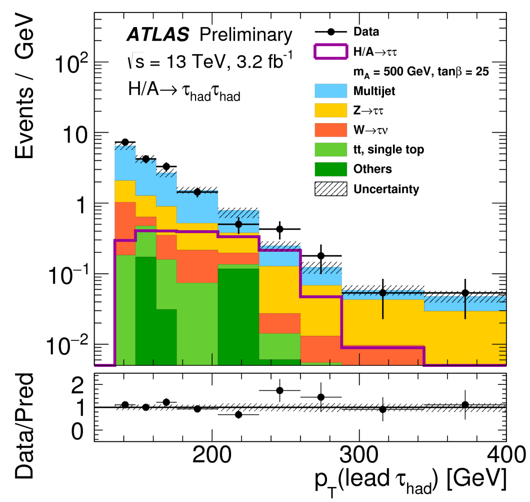
$H/A \to \tau\tau$ data-MC comparisons

$\tau_{\mathbf{had}}\tau_{\mathbf{had}}$	$\tau_{\mathbf{lep}}\tau_{\mathbf{had}}$



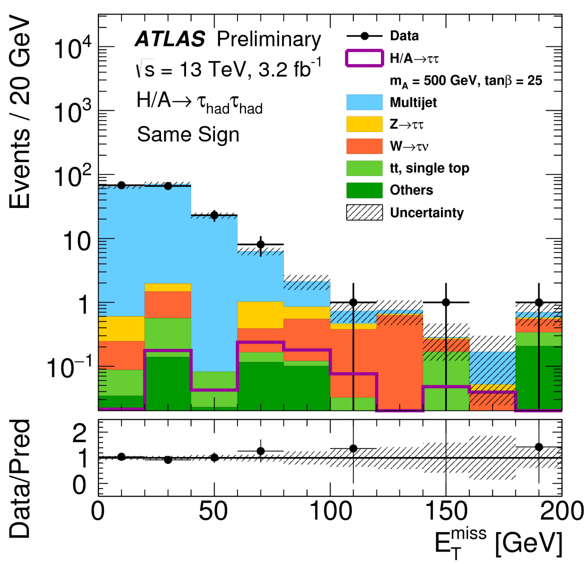


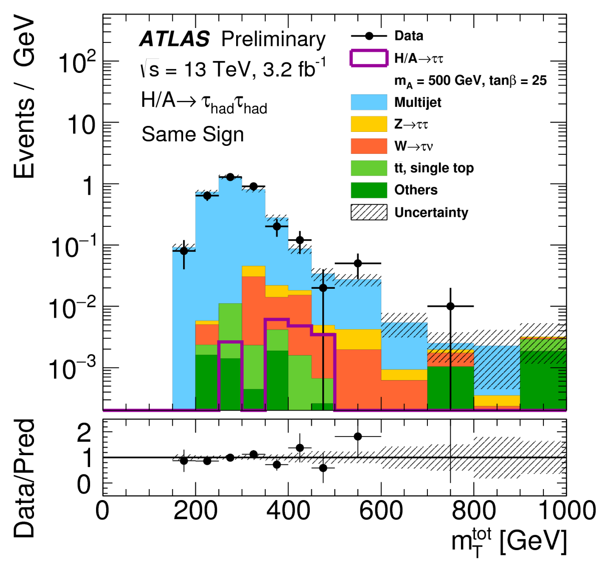




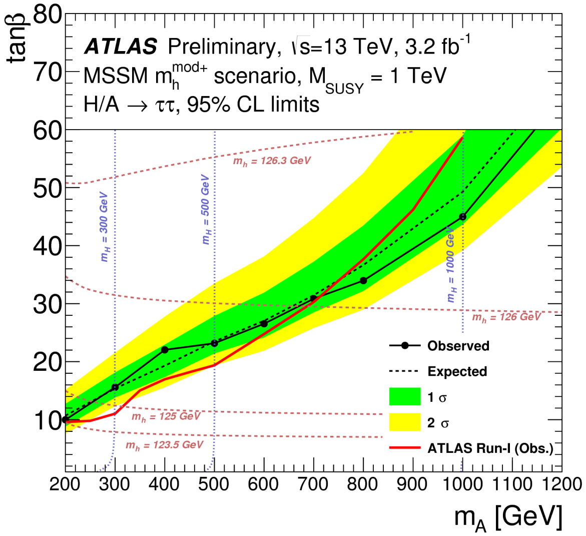
$H/A \to \tau\tau$ fake factor

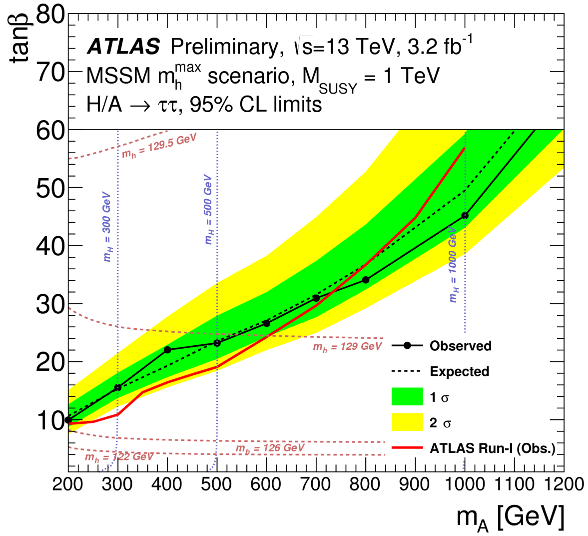
- Jet $\to \tau_{\text{had-vis}}$ background includes processes where a jet is reconstructed as a $\tau_{\text{had-vis}}$
- Control region consisting of misidentified $\tau_{\text{had-vis}}$ used to measure fake rate
- Selection same as signal selection except following:
  - W+jets lep-had: $60(70) < m_T(\ell, E_T^{\text{miss}}) < 150$ GeV for $\tau_\mu\tau_{\text{had}}(\tau_e\tau_{\text{had}}$
  - Multijet lep-had: isolation requirement inverted for lepton
  - Multijet had-had: no b-tag requirement
- Fake factor (FF) defined as number of misID $\tau_{\text{had-vis}}$ candidates fulfilling nominal selection to number of misID $\tau_{\text{had-vis}}$ candidates satisfying "anti-$\tau_{\text{had-vis}}$" selection
- anti-$\tau_{\text{had-vis}}$ selection: inverted $\tau_{\text{had-vis}}$ ID criteria with "very loose" requirement on BDT output

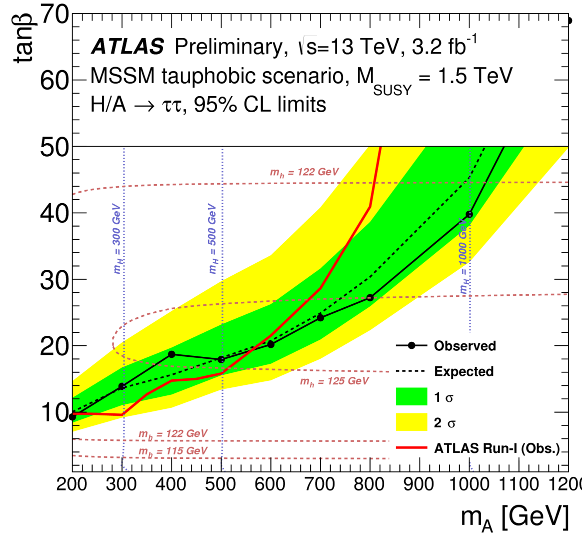


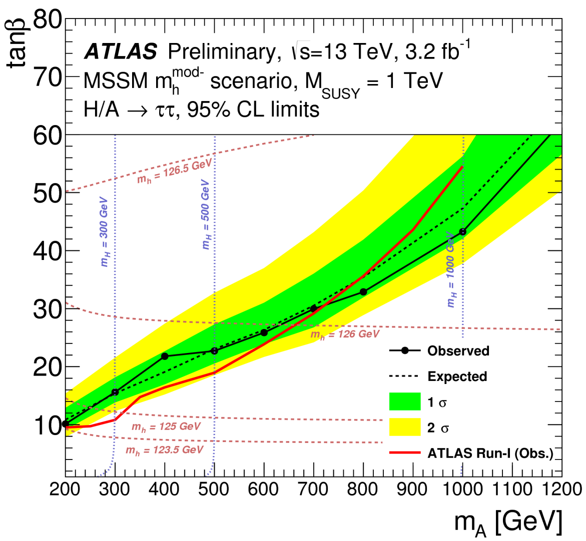


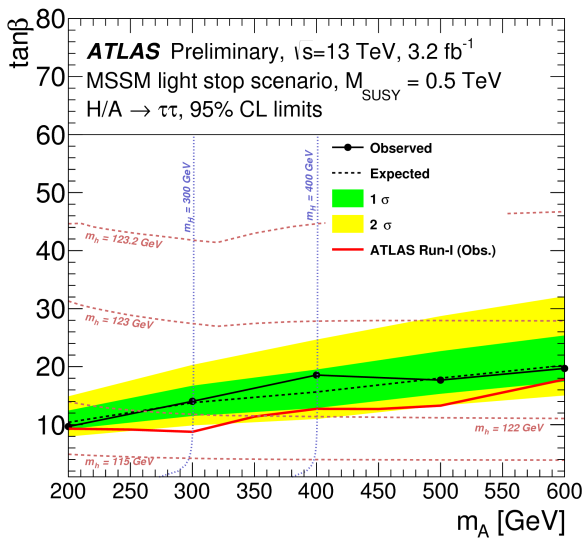
$H/A \to \tau\tau$ MSSM results

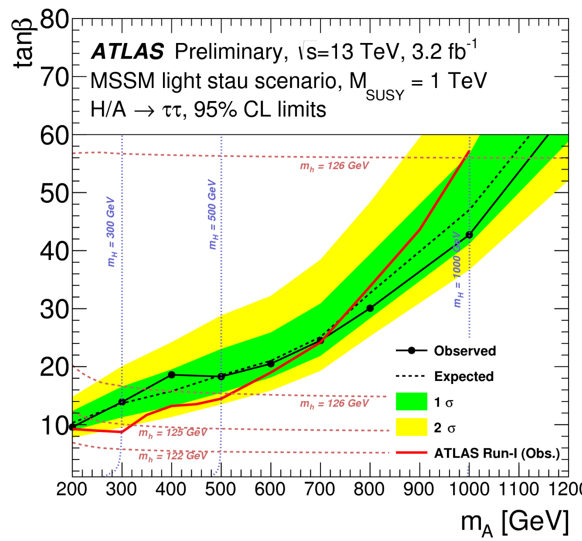










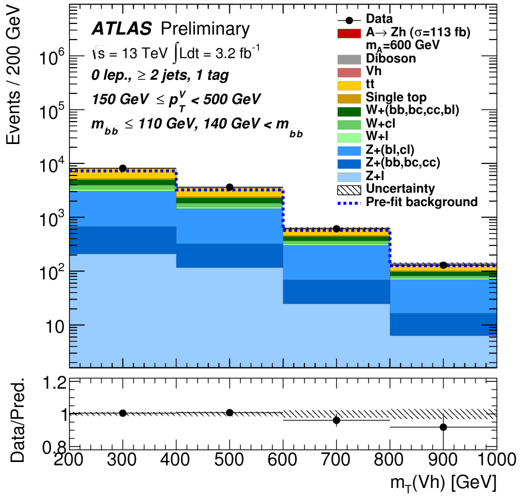


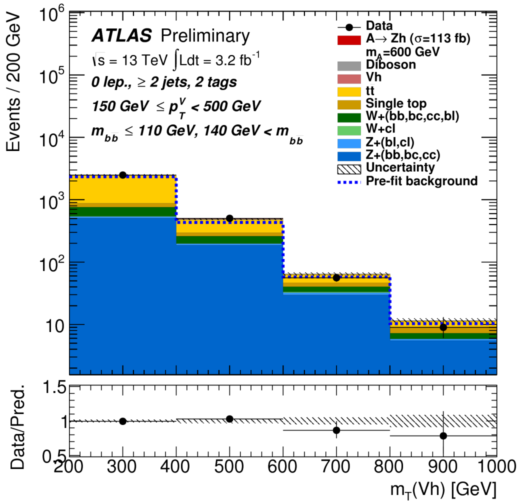
$A \to Zh$ MC samples

- Signal samples:
  - m_A varied from 220 to 2000 GeV using narrow-width approximation
  - $A \to Zh$ generated using MadGraph5_aMC@NLO 2.2.2 (ggF, bbh)
  - NNPDF23LO for PDFs
  - Pythia8 v8.186 used for showering with A14 tune for underlying event
  - m_h fixed at 125 GeV
  - m_A width smeared to values expected for α, $\tan\beta$
  - Wh, Zh generated using Pythia8.186 for q-induced, Powheg+Pythia8.186 for g-induced Zh
- Background samples:
  - W/Z+jets: Sherpa 2.1.1 with CT10 PDFs
  - $t\bar{t}$, single t (s- and Wt-channels): Powheg-Box v2, CT10 with Pythia6.428
  - single t (t-channel): Powheg-Box v1 with 4FS for NLO ME calculations with CT10F4, t decayed with MadSpin
  - Diboson: Sherpa 2.1.1 with CT10 PDFs, normalised to NLO cross-section

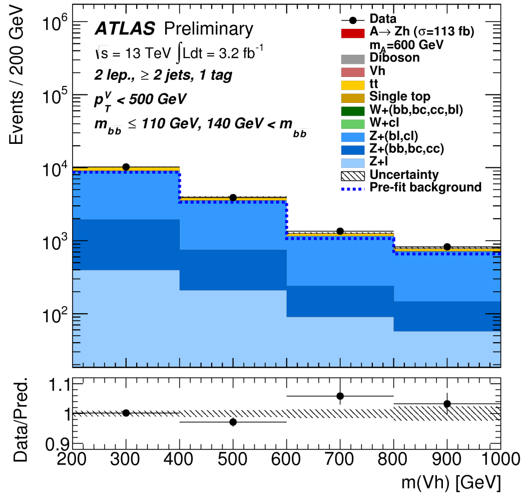
$A \to Zh$ control regions

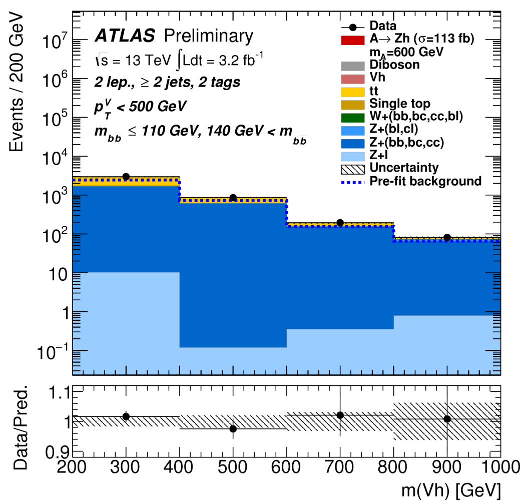
W/Z+jets, 0-lep, low p_T^V



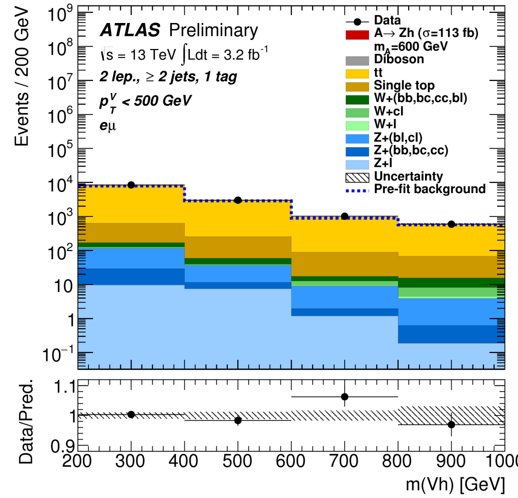


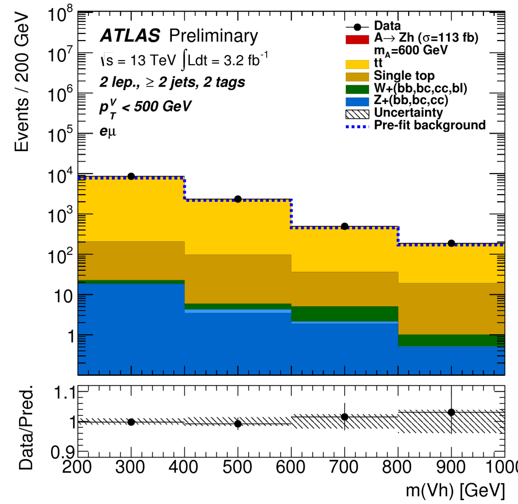
W/Z+jets, 2-lep, low p_T^V





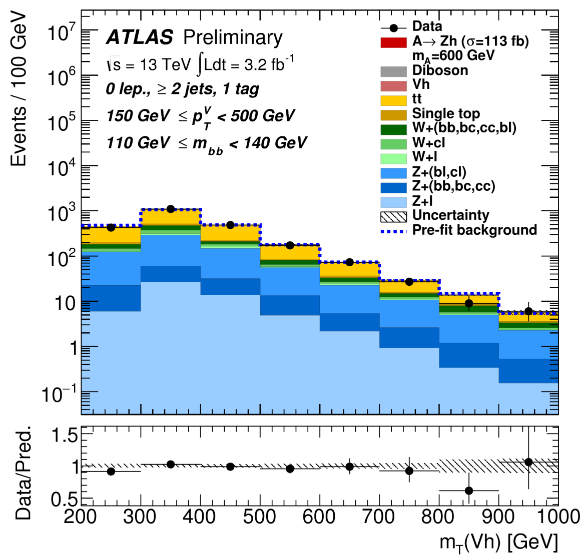
$t\bar{t}$, 2-lep, low p_T^V

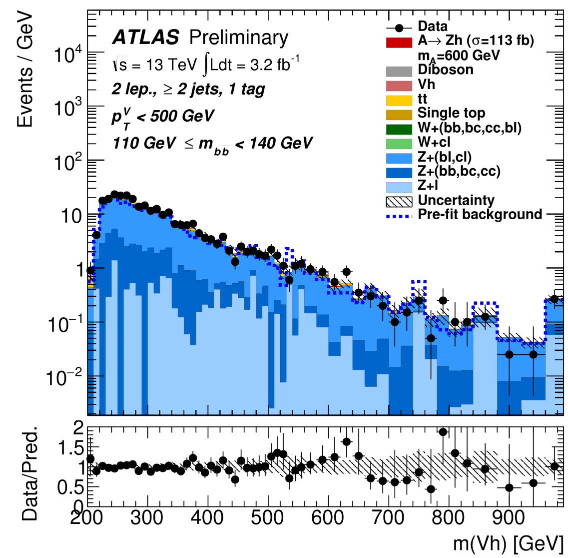


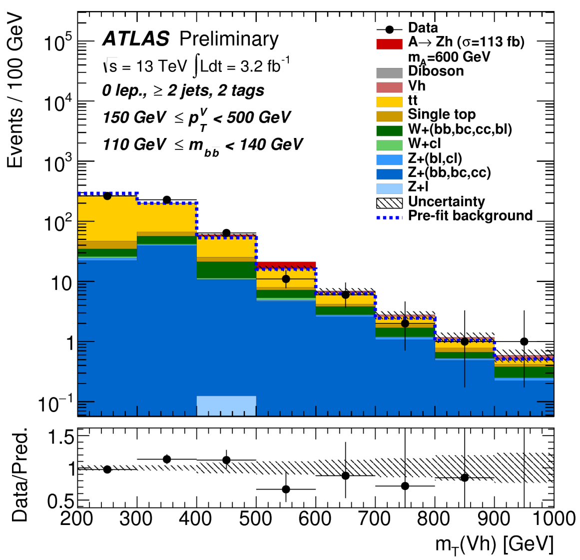


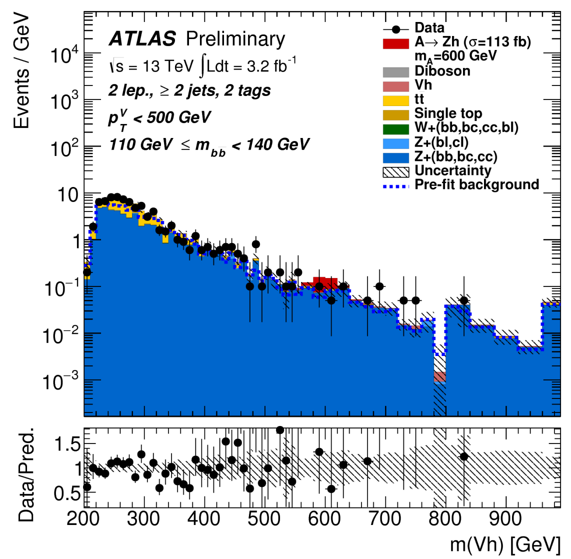
$A \to Zh$, low p_T^V categories

0-lep | **2-lep**



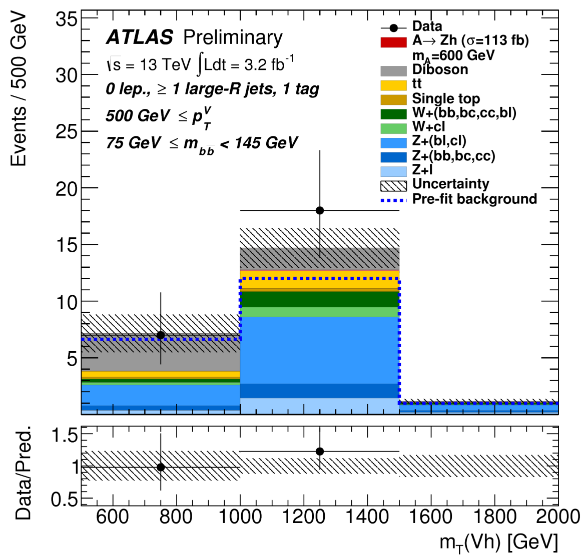






$A \to Zh$, high p_T^V categories

0-lep



2-lep