Recent BSM Higgs Searches from ATLAS

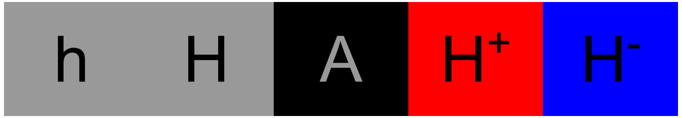
Adam Bailey (CSIC / IFIC)
on behalf of the ATLAS collaboration

LHC Higgs XS WG3 20/09/2018

Universitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa
CSIC Consejo Superior de Investigaciones Científicas
ATLAS Experiment

BSM Higgs

- Several theories predict extended Higgs sectors
- For example, 2HDM has two Higgs doublets, 5 Higgs:



- Theories have to account for the measurements of the 125 GeV Higgs
- Can search for heavy Higgs or di-Higgs signals
- Also low mass results below 125 GeV, typically look for decays of 125 GeV Higgs to scalars.

Contents

Will summarise some recent BSM Higgs results from ATLAS

- 125 GeV Higgs measurements combination
- Di-Higgs: $hh \to bb\tau\tau$, $hh \to bb\gamma\gamma$ (backup)
- Charged Higgs: $H^{\pm} \to \tau\nu$
- H to fermions: $H/A \to \tau\tau$
- H to bosons: $H \to WZ \to$ leptons
- Light Resonances: $H \to bb\mu\mu$, $H \to \gamma\gamma jj$, low mass $H \to \gamma\gamma$

Note - this is not a complete list, selection of some from each channel

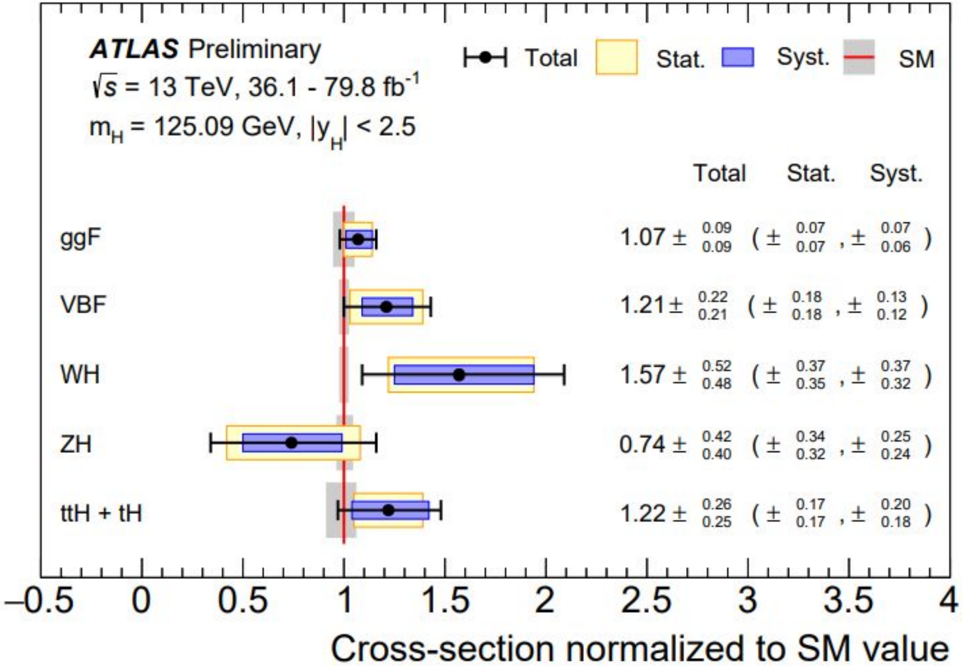
MSSM

- MSSM: Minimal extension of the Standard Model that includes Supersymmetry
  - Unification of forces at high energy
  - Gives a natural dark matter candidate
  - Mass of SUSY particles >> SM partners

- hMSSM: mass of observed Higgs used to predict remaining masses/couplings
- m_h^{max}: m_h is maximised for a given tanβ and large m_A
- $m_h^{mod+/-}$: benchmarks where lightest Higgs matches that observed
  - Modification of m_h^{max}.
  - Mixing in the stop sector is reduced ($|X_t/M_{SUSY}|$) to enable m_h = 125 GeV
  - +/- scenarios are for the sign of X_t

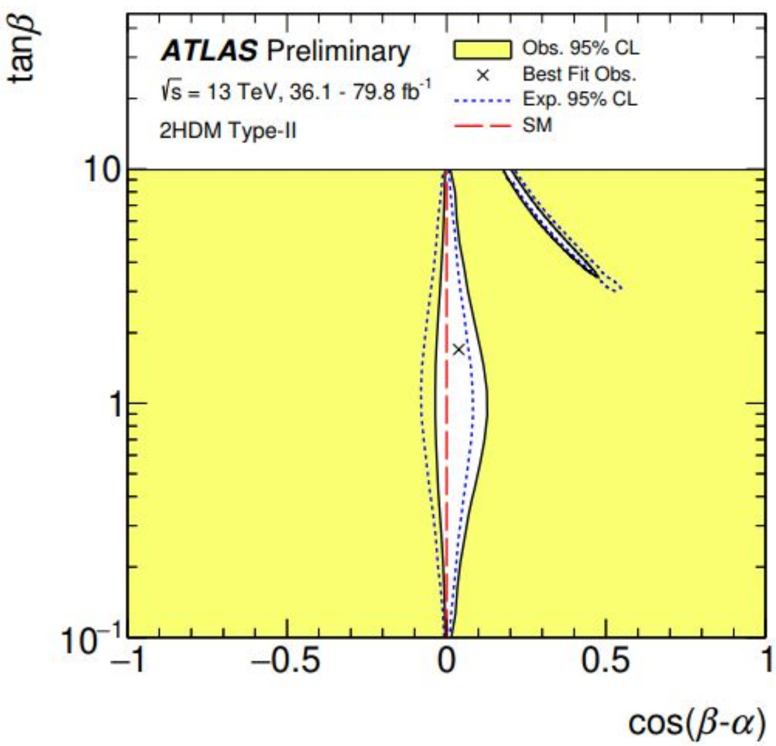
Limits on BSM from 125 GeV Higgs Measurements

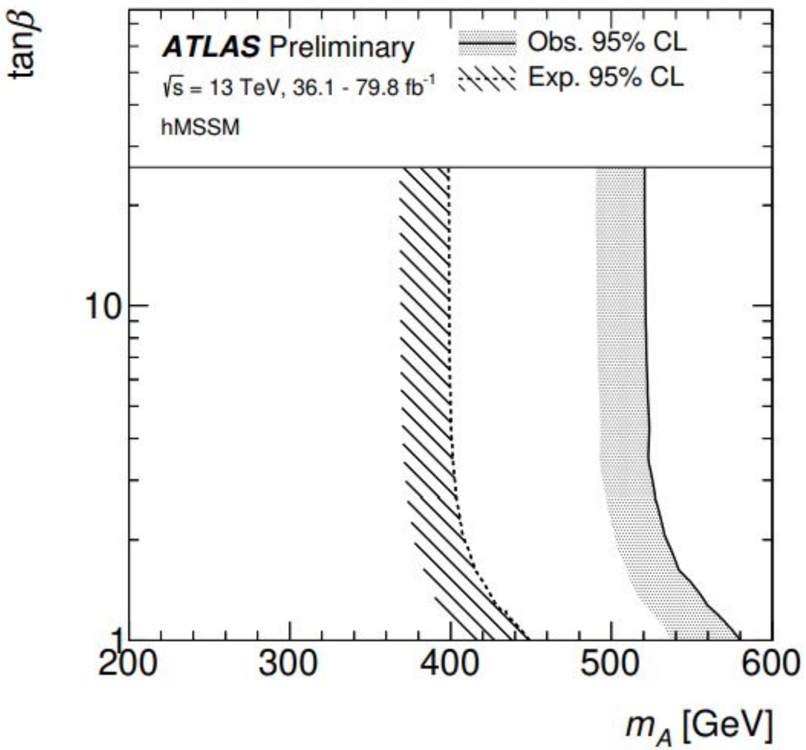
- Combined measurements on 125 GeV Higgs now available
- Indirectly places limits on hMSSM parameter space from the measured production/decay rates



Limits on BSM from 125 GeV Higgs

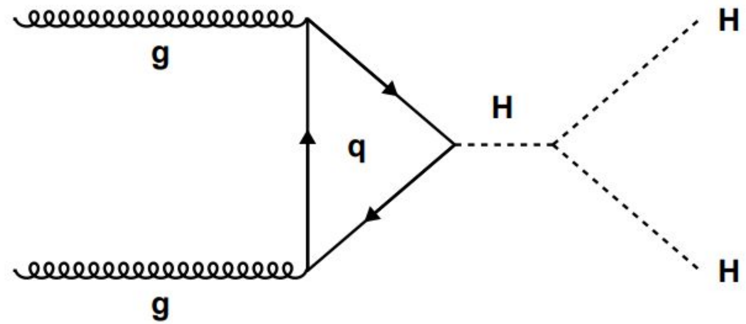
Limits on hMSSM models:

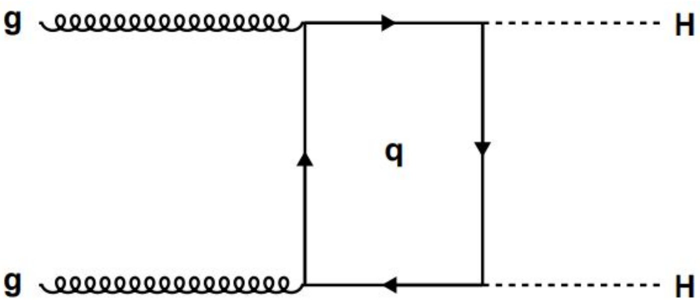




Di-Higgs Searches

- Destructive interference between SM di-Higgs production
- Can be enhanced in BSM theories via new intermediate particles eg. BSM heavy (CP-even) Higgs, spin-2 KK excitons of graviton





- **$b\bar{b}b\bar{b}$**: large number of signal events, but large tt and QCD background
- **$b\bar{b}WW$**: large number of signal events, but large $t\bar{t}$ background
- **$b\bar{b}\tau\tau$**: decent number of signal events, with less background
- **$b\bar{b}\gamma\gamma$**: few signal events, but narrow mass window with low backgrounds

(in backup)

$hh \rightarrow b\bar{b}\tau\tau$: Introduction

- Analysis at $\sqrt{s}$ = 13 TeV with 36.1 fb^{-1}, from Aug 2018
- Final state: 2 b-tagged jets, with $\tau_{had}\tau_{had}/\tau_{had}\tau_{lep}$ (opposite charge), plus E_T^{miss}
- Backgrounds: tt, QCD multijet, and Z + jets (bb/bc/cc).
  - SM H + Z production is irreducible
- Search for both resonant and non-resonant production

$hh \rightarrow b\bar{b}\tau\tau$: Event Selection

$b\bar{b}\tau_{had}\tau_{lep}$	$b\bar{b}\tau_{had}\tau_{had}$
• Single lep trigger (p_T > 25-27 GeV) • If fails that, consider lep+τ_{had} trigger: if e (μ) has p_T > 18 (15) GeV • τ_{had} p_T > 20 (30) GeV for lep (lep+τ_{had}) trigger • Lead jet p_T > 45 GeV (80 GeV for lep-τ_{had} in 2016) • Sub-lead τ_{had} p_T > 20 • $m_{\tau\tau}^{MMC}$ > 60 GeV • 2 b-tagged jets	• Single τ OR di-τ trigger ○ p_T > 40-180 GeV • Lead jet p_T > 45 (80) GeV for single τ (di-τ) trigger • Sub-lead τ_{had} p_T > 20 (30) GeV for single τ (di-τ) trigger • $m_{\tau\tau}^{MMC}$ > 60 GeV • 2 b-tagged jets

$hh \rightarrow b\bar{b}\tau\tau$: BDT Discriminant

- 3 signal regions:
  - $\tau_{had}\tau_{had}$: train against $t\bar{t}$, $Z \rightarrow \tau\tau$ and multijet
  - $\tau_{lep}\tau_{had}$ single lepton trigger (resonant): train against dominant $t\bar{t}$
  - $\tau_{lep}\tau_{had}$ non-resonant and lep+τ trigger: train against dominant $t\bar{t}$

- For BDT: data-driven multijet estimate, $t\bar{t}$ and $Z \rightarrow \tau\tau$ from simulation
- For resonant search: train separately for each signal mass
  - Signal model contains neighbouring masses to allow sensitivity between points
- For non-resonant, signal sample is mixture of box and triangle diagram production

$hh \rightarrow b\bar{b}\tau\tau$: Backgrounds

- Estimate fake τ_{had} from jets using fake factor method
- In $\tau_{lep}\tau_{had}$: fake factors for fake τ_{had} from t, W+jets, multijet (separate for each background)
- In $\tau_{lep}\tau_{lep}$: fake factor for multijet, $t\bar{t}$ from simulation (with fake rate)
- Validate in same-sign regions

$hh \rightarrow b\bar{b}\tau\tau$: Results

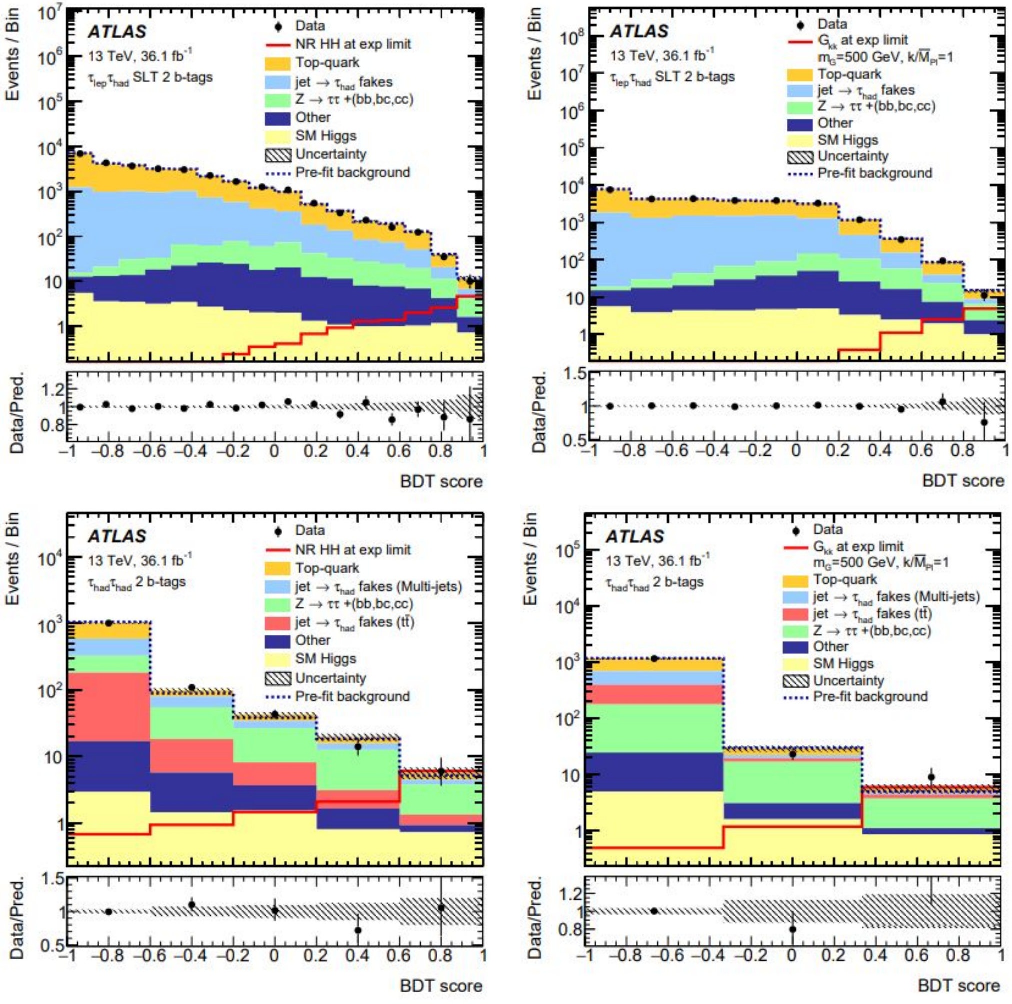
Top: single lepton trigger $\tau_{lep}\tau_{had}$

Bottom: $\tau_{had}\tau_{had}$

Left: resonance search

Right: KK Graviton search

Plots for $\tau_{lep}\tau_{had}$ trigger in backup

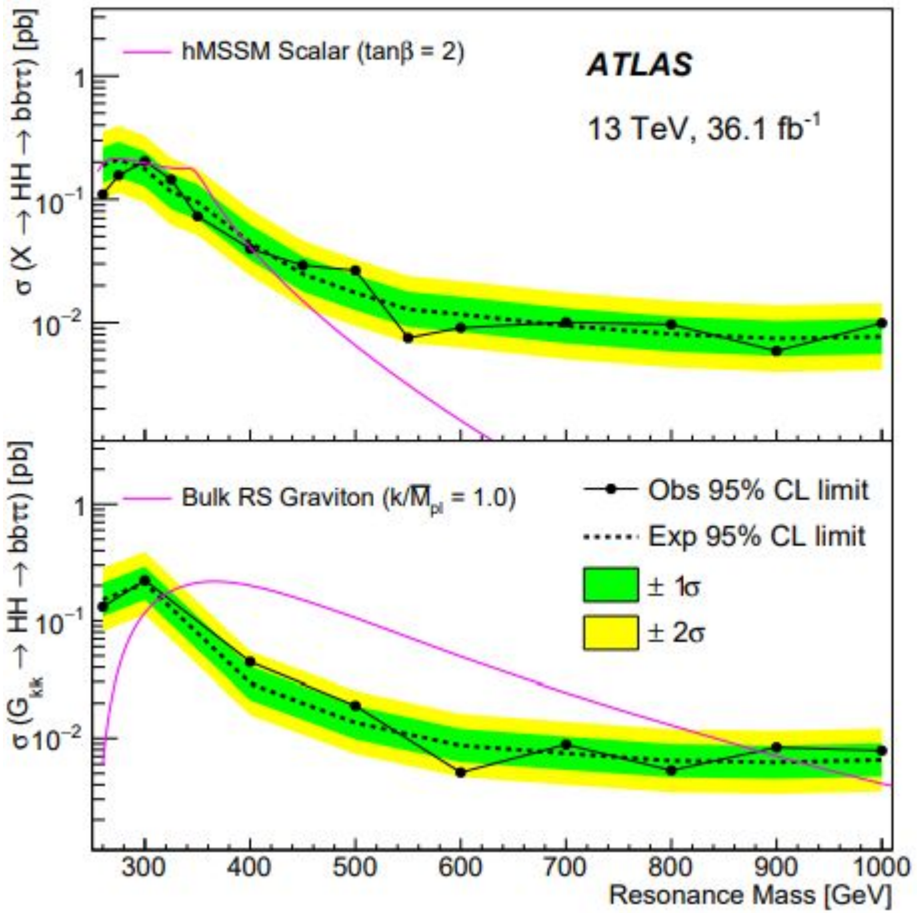


hh → b$\bar{b}$ττ: Limits

Signal regions are combined for statistical fit

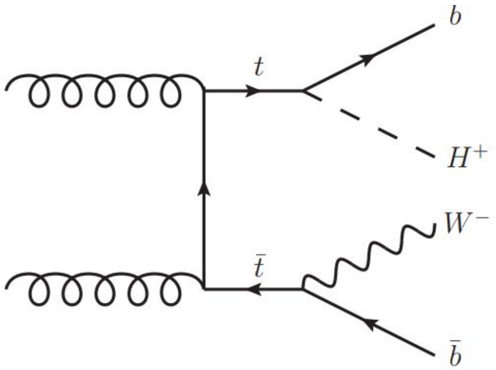
Top: hMSSM scalar

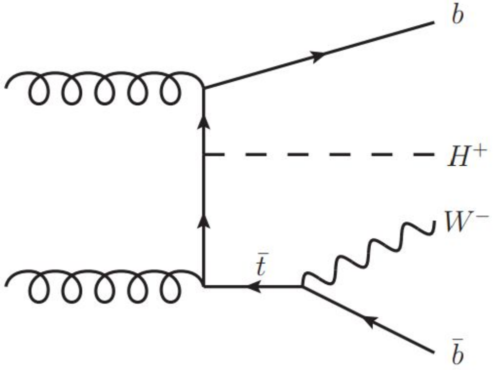
Bottom RS graviton

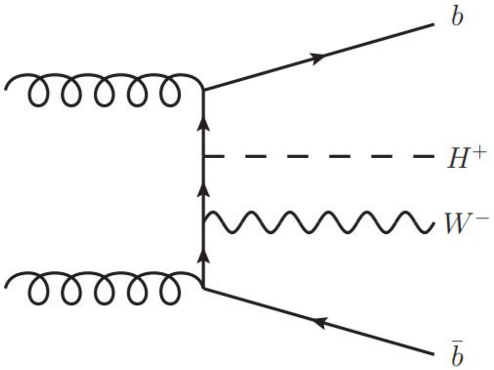


$H^+ \rightarrow \tau\nu$: Introduction

- Results at 13 TeV, with 36.1 fb^{-1}
- Search for t-associated production:
  - τ_{had} + jets, τ_{had} + e, and τ_{had} + μ channels
- For CP conserving 2HDM, properties of H^+ depend on α (mixing angle of the neutral CP-even H bosons) and $\tan\beta$







Main channel for $m_{H+} < m_{top}$

Main channel for $m_{H+} > m_{top}$

$H^+ \rightarrow \tau\nu$: Event Selection

τ_{had} + jets	τ_{had} + e / μ

• E_T^{miss} trigger
  ◦ p_T threshold 70/90/110 GeV
• τ_{had} p_T > 40 GeV
• e and μ veto
• ≥3 jets with p_T > 25 GeV, ≥1 b-tag
• E_T^{miss} > 150 GeV
• m_T (τ_h, E_T^{miss}) > 50 GeV
	• e or μ trigger, with either:
	  ◦ p_T > 24-26 GeV + isolation
	  ◦ p_T > 60-140 GeV with looser isolation requirements
	• l p_T > 30 GeV (trigger matched)
	• ≥1 b-jet with p_T > 25 GeV
	• E_T^{miss} > 50 GeV

τ_{had} passes medium ID:

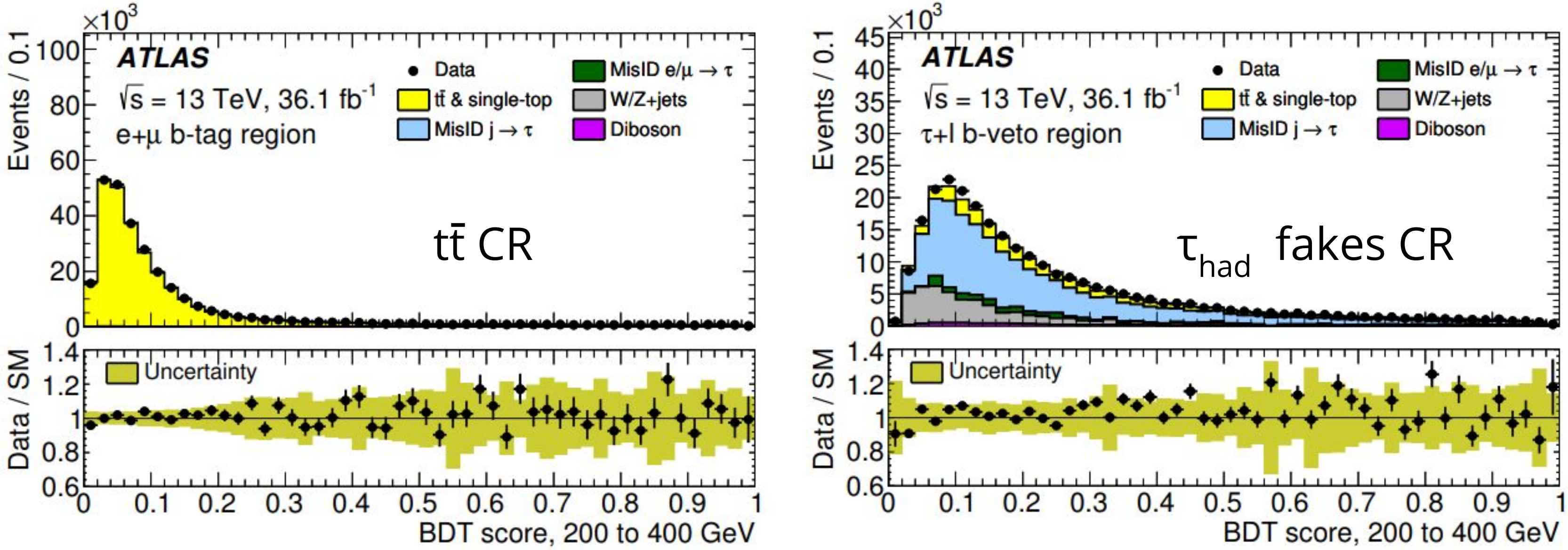
efficiency 75% (60%), QCD multijet rejection ~30 (30) for 1 (3) tracks

$H^+ \to \tau\nu$: Signal Generation

- Use MadGraph5_aMC@NLO, in three mass regions:
  - **90–150 GeV**: Simulate $t\bar{t}$ events, one top-quark decays to charged Higgs boson and a b-quark, at LO
  - **160–180 GeV**, generate full process pp → H^+W bb at LO
  - **200–2000 GeV**, H^+ production in association with a top-quark at NLO

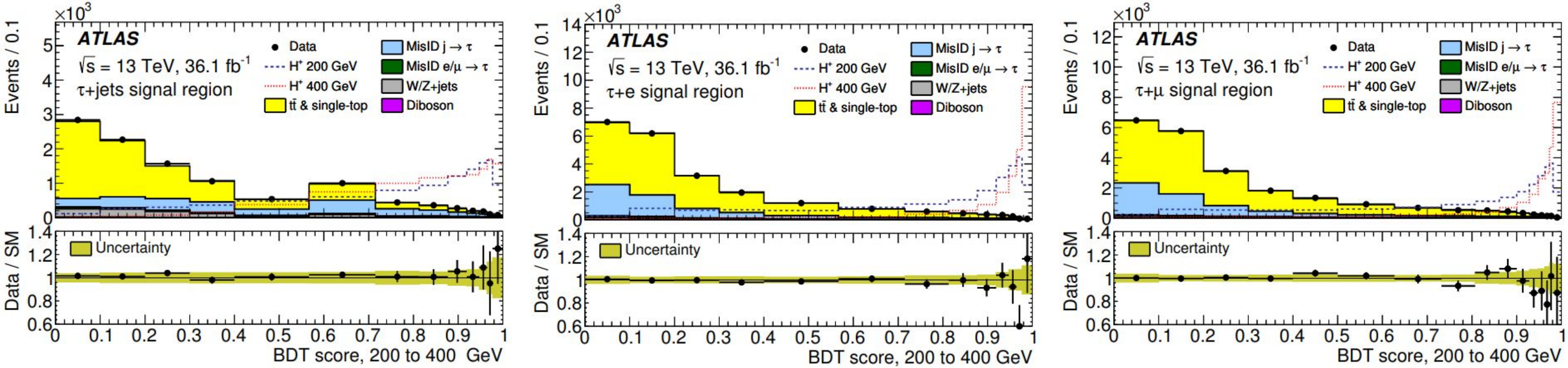
$H^+ \to \tau\nu$: Background Rejection and Modelling

- Main backgrounds: $t\bar{t}$, single t, W+jets, Z/γ+jets, WW/WZ/ZZ, and multijet.
- Simulation for real τ_{had}, data driven fake factors for jets faking τ_{had}
- Obtain $t\bar{t}$ normalisation from region in data (like τ_{had} + lepton, but with e+μ)
- Use multivariate discriminant, in 5 signal mass bins, BDTs for τ_{had}j, τ_{had}l



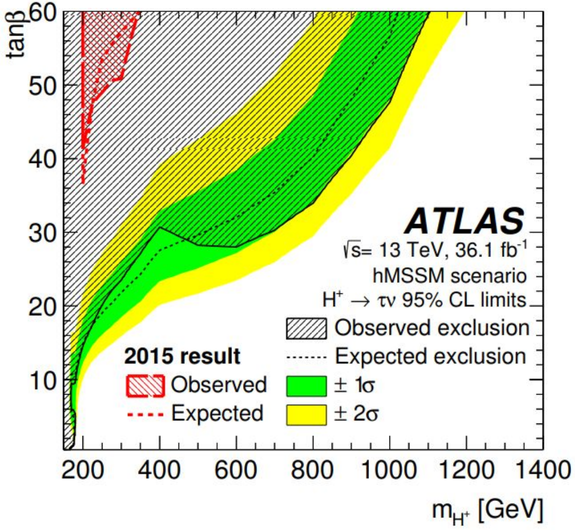
$H^+ \rightarrow \tau\nu$: Postfit Plots

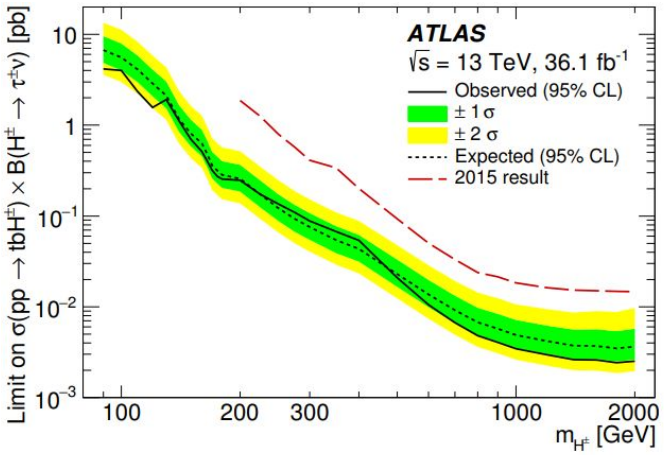
Signal region plots from three channels, for one mass bin (others in paper)

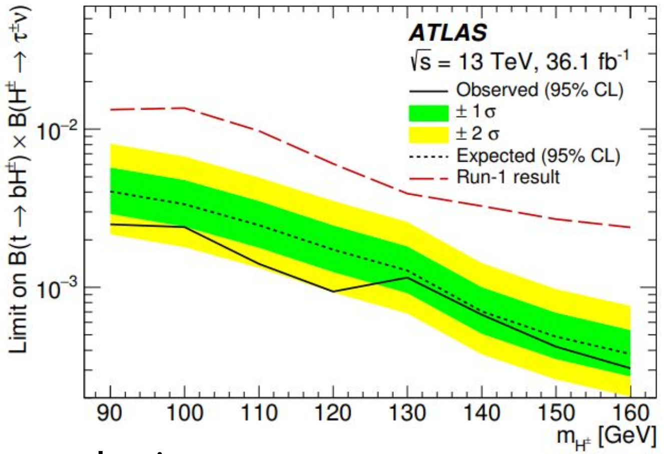


$H^+ \rightarrow \tau\nu$: Limits

- Limits on hMSSM parameter space [left]
- ($pp \rightarrow tbH^+$ production) x ($H^+ \rightarrow \tau^+\nu$) [top right]
- ($t \rightarrow bH^+$ production) x ($H^+ \rightarrow \tau^+\nu$) [bottom right]







- First limits in intermediate mass regions for this analysis

H/A → ττ: Introduction

- 36.1 fb^{-1} of p-p collision data at 13 TeV
- For large tanβ, couplings to down-type fermions are enhanced
    - Higher H → τ branching fraction
    - Enhanced production associated with b-quarks
- Look for two back-to-back τ, opposite charge
- Two channels - $\tau_{lep}\tau_{had}$ (~46%) and $\tau_{had}\tau_{had}$ (~42%)
    - Consider both gg-fusion and b-associated production
    - Therefores, split into b-tagged and b-veto categories

$H/A \to \tau\tau$: Event Selection

$\tau_l \tau_h$	$\tau_h \tau_h$

• Single μ or e trigger
  ○ p_T between 20-140 GeV
• τ_h passes medium jet BDT discrim.
• $\Delta\varphi > 2.4$
• $m_T\,(p_T^l, E_T^{miss}) < 40$ GeV
  ○ Removes W + jets
• 80 GeV $< m_{vis}(p^l, p^\tau) <$ 110 GeV
  ○ Only in e channel, remove $Z \to ee$ peak
	• τ_h trigger
	  ○ $p_T > 80 / 125 / 160$ GeV
	• Lead (sublead) τ passes medium (loose) jet BDT discrim.
	• $\Delta\varphi > 2.7$
	• Sublead τ $p_T > 65$ GeV
	• Veto e and μ

Medium ID: τ efficiency 75% (60%), QCD multijet rejection ~30 (30) for 1 (3) tracks
Loose ID: τ efficiency 85% (75%), QCD multijet rejection ~50 (100) for 1 (3) tracks

H/A → ττ: Backgrounds

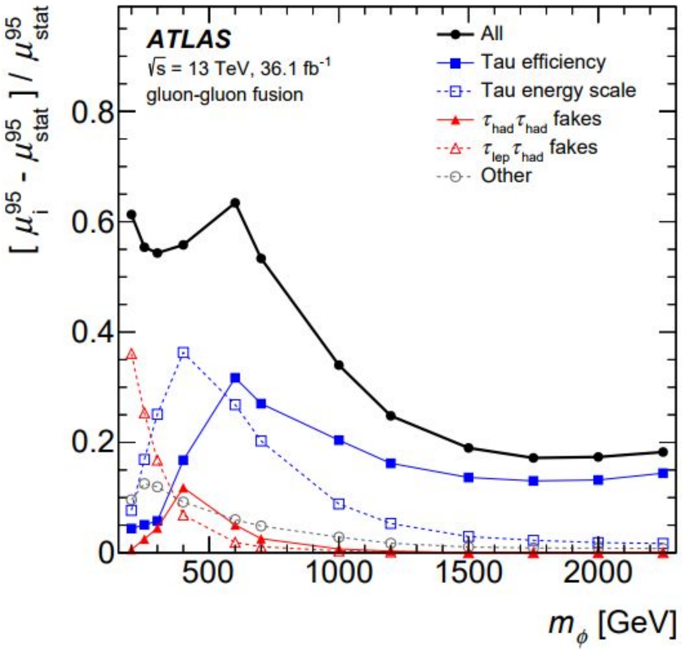
$\tau_l\tau_h$	$\tau_h\tau_h$
• QCD multijet [fake τ_l + fake τ_h] • W + jets (b-tag) / tt (b-veto) [real l, fake τ_h from jet]	• QCD multijet [2 fake τ_h]
• Z/γ* → ττ (b-tag) / $t\bar{t}$ (b-veto) [real τ] • Z/γ* → ll [l fakes τ_h + real l] • Diboson • Single t	• Z/γ* → ττ [2 real τ] • W → τν + jets [real τ + jet fake] • $t\bar{t}$, single top [real τ, or lep/jets fakes] • Others: W → lν + jets, Z/γ* → ll + jets, diboson

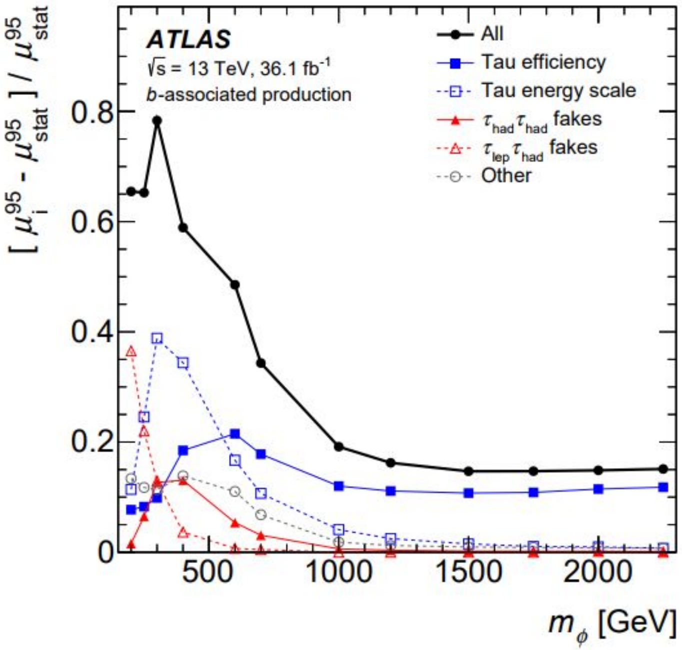
Data-driven fake factor method for fake τ

Simulation for real τ, with fake rate for j → τ_h (in $\tau_h\tau_h$)

H/A → ττ: Systematic Uncertainties

- Assess impact on cross section limits
- μ_{stat}^{95} = limit with no systematics included
- μ_i^{95} = limit including group of systematics i





H/A → ττ: Postfit Plots

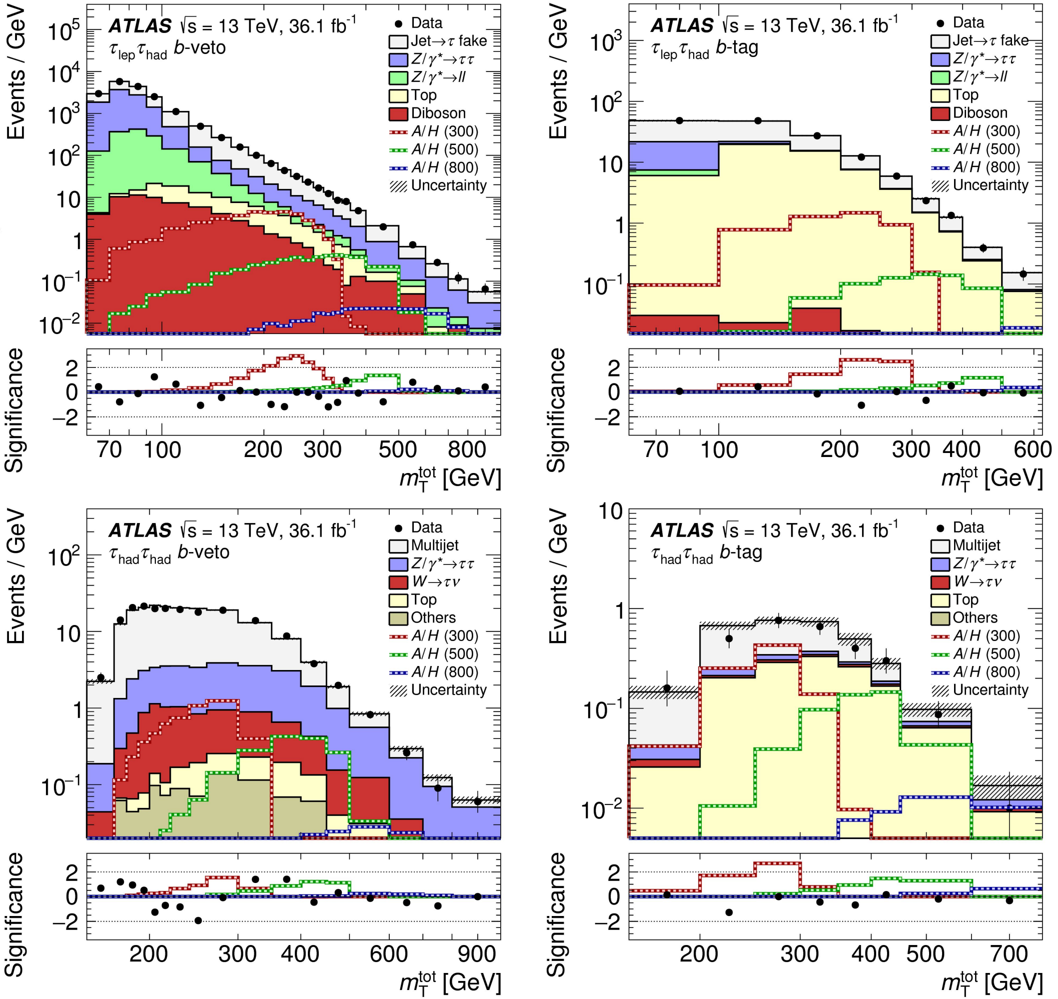
$$m_{\mathrm{T}}^{\mathrm{tot}}(\tau_1, \tau_2, E_{\mathrm{T}}^{\mathrm{miss}}) =$$
$$\sqrt{m_{\mathrm{T}}^2(\tau_1, \tau_2) + m_{\mathrm{T}}^2(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(\tau_2, E_{\mathrm{T}}^{\mathrm{miss}})}$$

Top: $\tau_l \tau_h$

Bottom: $\tau_h \tau_h$

Left: b-veto

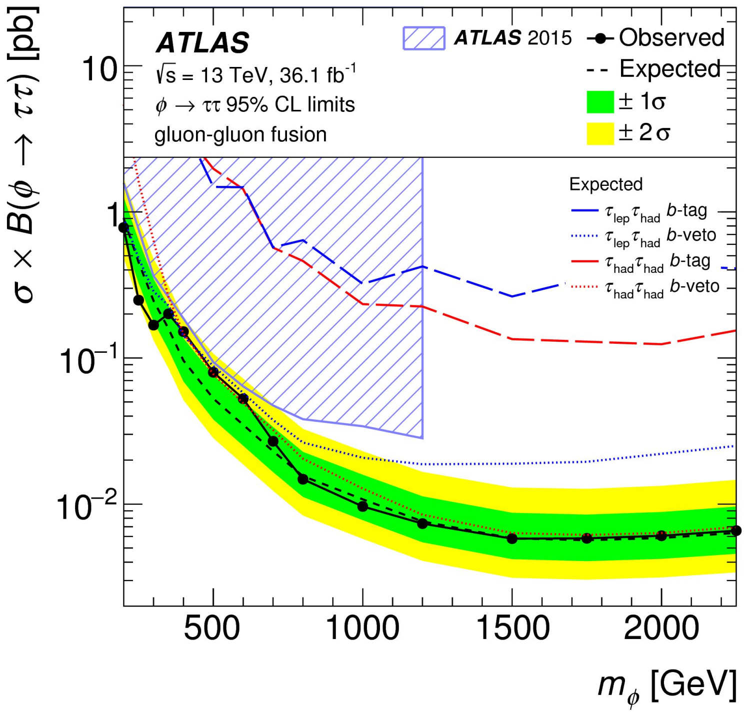
Right: b-tag



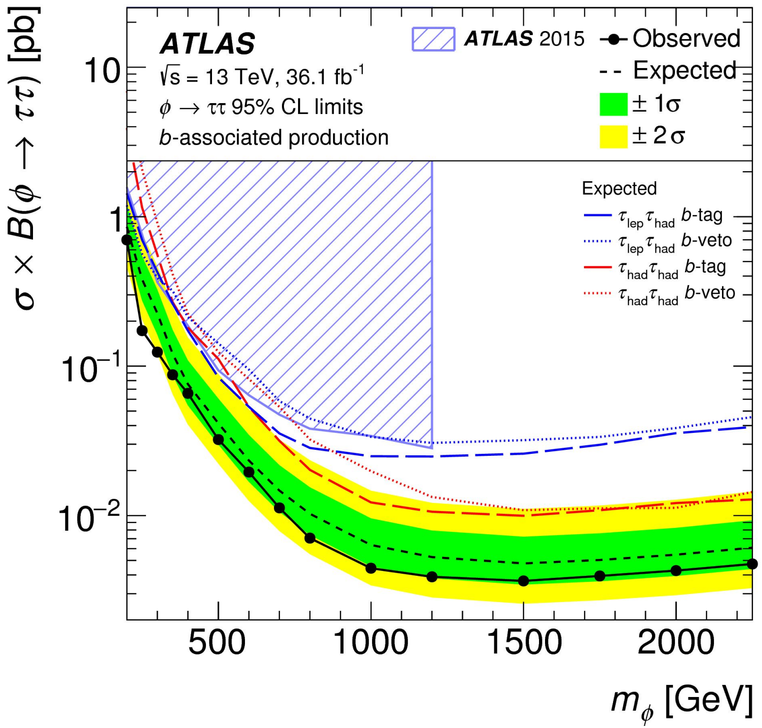
H/A → ττ: Cross Section Limits

- $\tau_{lep}\tau_{had}$ more sensitive below m_H~0.6 TeV, $\tau_{had}\tau_{had}$ more sensitive above.

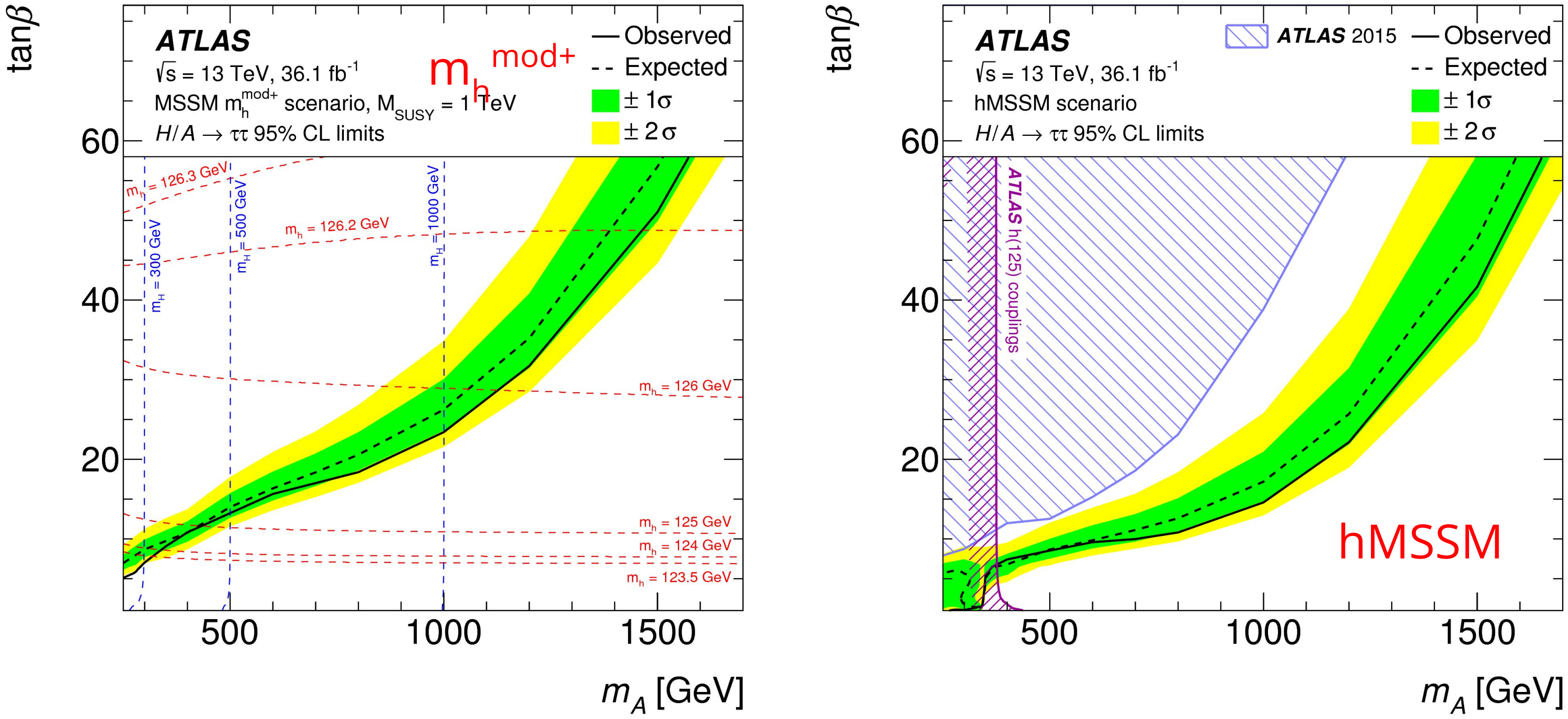
gg-fusion



b-associated

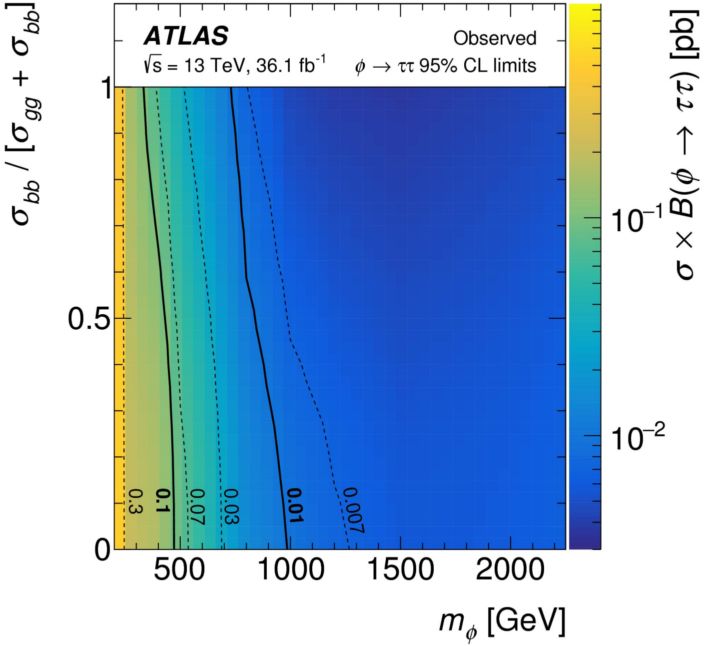


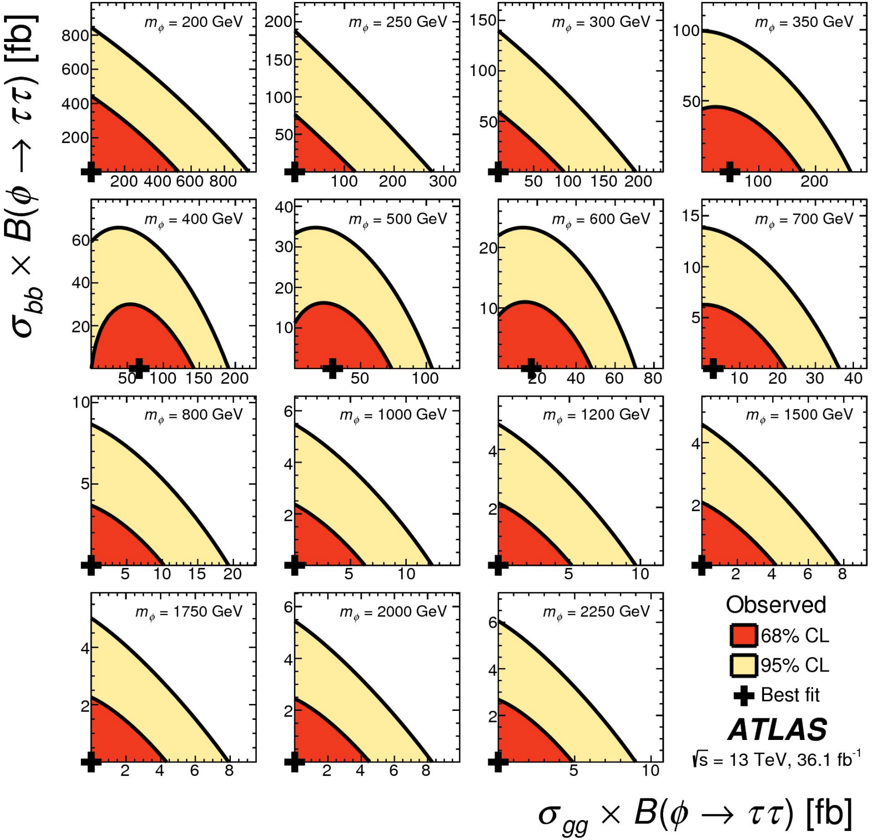
H/A → ττ: tanβ vs m_A Parameter Space



H/A → ττ: Other Limits

- 2D log likelihood scans for different Higgs masses →
- Limits vs b-tag fraction ↓





adam.bailey@cern.ch

H → WZ: Introduction

- Search in fully leptonic channel (lνll), from qq fusion and VBF production
  - Not the highest branching ratio, but lower backgrounds.
  - Use single lepton triggers
- Vector resonances predicted in various BSM scenarios:
  - GUTs, Little Higgs, composite Higgs etc.
- Results from models with extend Higgs sector
  - Interpretations include heavy vector triplet, Georgi-Machacek model (benchmark for single charged scalar resonance, 1 real 1 complex triplet)

$H \rightarrow WZ$: Selection

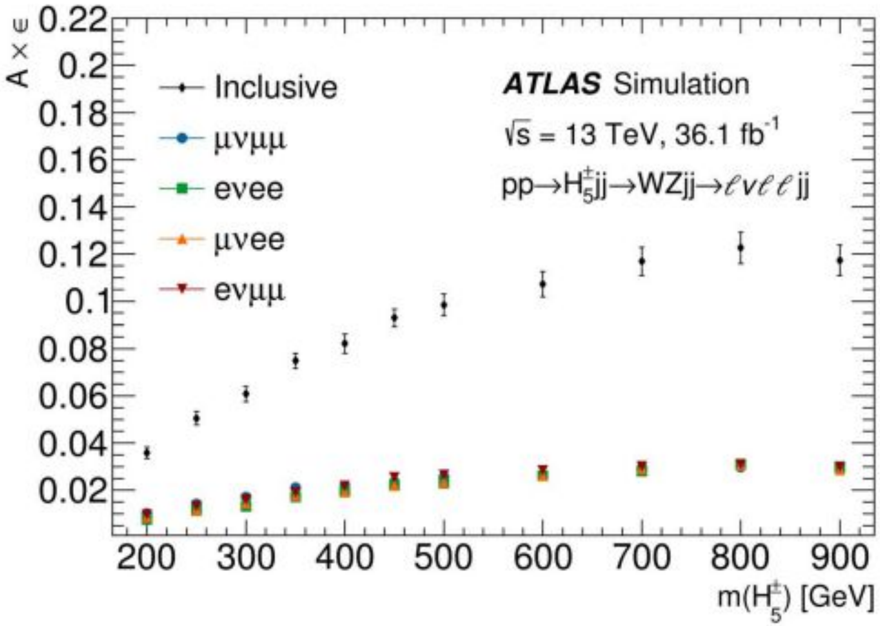
- $Z \rightarrow l^+l^-$ (same flavour). Pick those closest to Z mass, use medium e/μ ID
- $W \rightarrow l\nu$. Require tight lepton ID (background rejection)
  - Veto events with 4 leptons

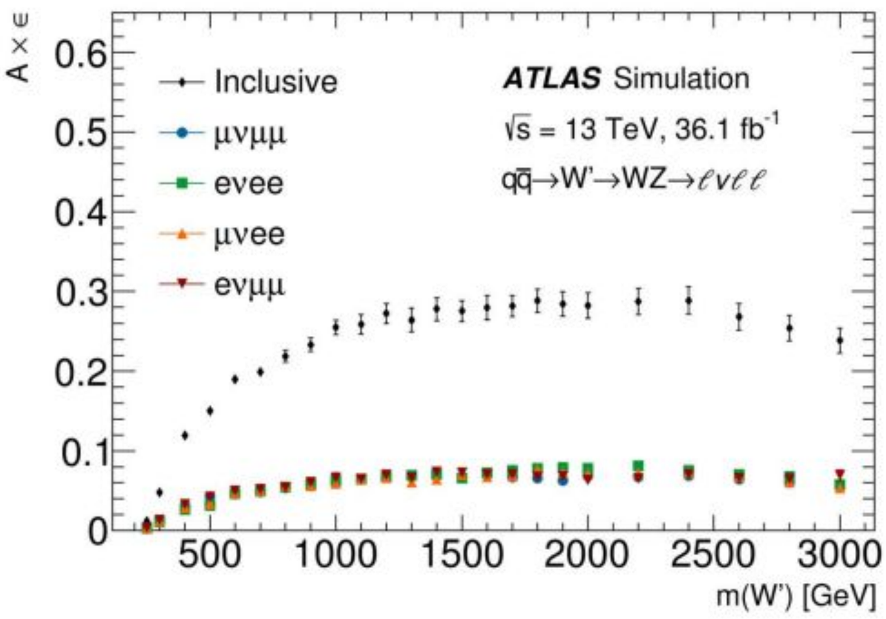
VBF Category	qq Category

• $\geq$ 2 jets (use 2 highest p_T)
• $p_T > 30$ GeV
• $\Delta\eta_{jj} > 3.5$
• $m_{jj} > 500$ GeV
• b-veto to reduce backgrounds
	• W/Z produced via s-channel resonance
	• $m_{WZ} > 250$ GeV
	• Expect E_T^{miss} close to 50% of mass:
	  ○ $p_T^W / m_{WZ} > 0.35$
	  ○ $p_T^Z/m_{WZ} > 0.35$

$H \rightarrow WZ$: Signal Acceptance

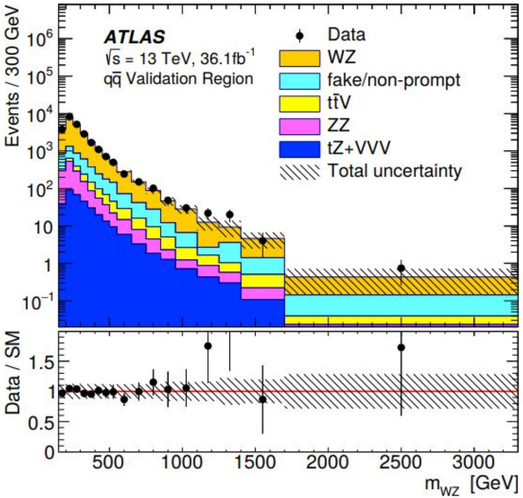
- Left: GM model VBF. (HVT VBF in backup). Right: qq HVT acceptance
- Produced from simulated signal events

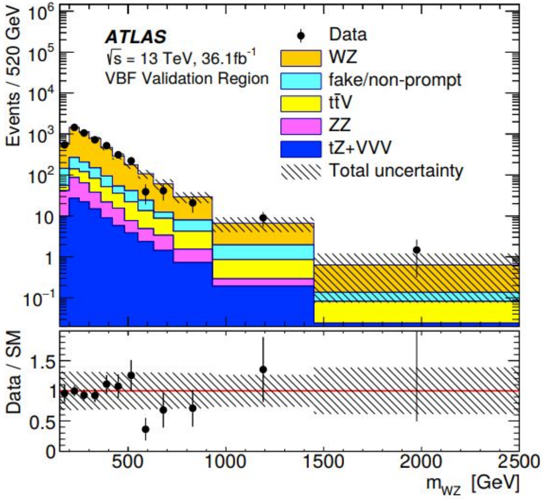




H → WZ: Backgrounds

- For resonance search, SM WZ production:
  - MC estimate, with dedicated validation regions
  - VBF: invert cuts on dijet variables
  - WZ qq: invert p_T / m_{WZ} cuts
- Background from γ or jets faking leptons:
  - Z+jets, Zγ, Wγ, $t\bar{t}$, single t, WW
  - Data driven, using "Matrix Method"
- Others ($t\bar{t}V$, ZZ, tZ, WZbj, triple boson) estimated with MC



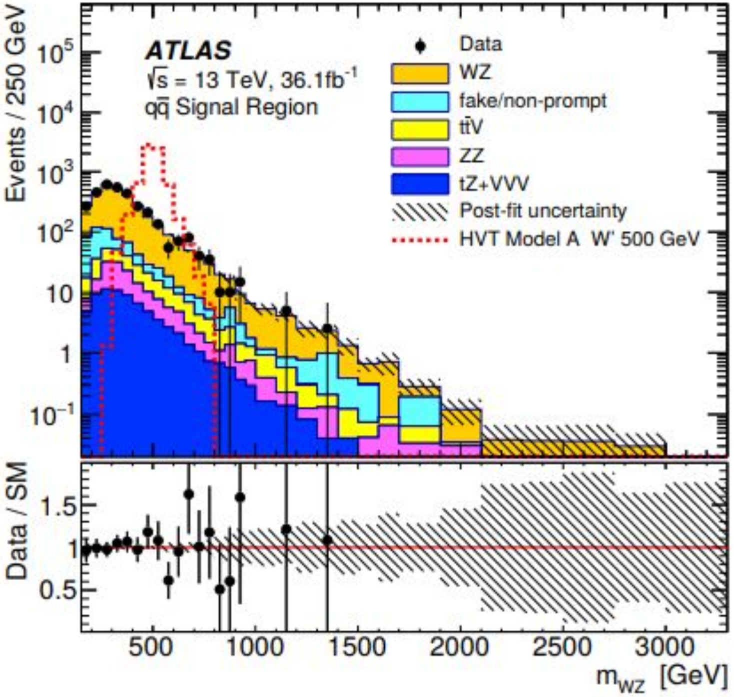


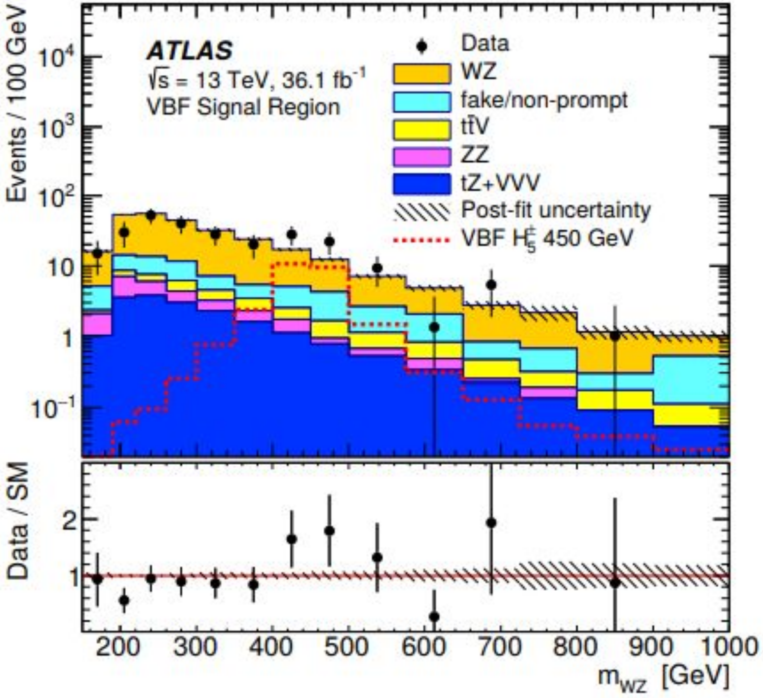
$H \longrightarrow$ WZ: Systematics

Source	$\Delta\mu/\mu$ [%]	
	$q\bar{q}$ Category $m(W') = 800$ GeV	VBF Category $m(H_5^{\pm}) = 450$ GeV
WZ modelling : Scale, PDF	5	11
WZ modelling : Parton Shower	10	6
MC statistical uncertainty	7	8
Electron identification	4	2
Muon identification	3	3
Jet uncertainty	1	8
Missing transverse momentum	2	1
Fake/non-prompt	1	5
Total systematic uncertainty	17	21
Statistical uncertainty	53	52

H → WZ: Results

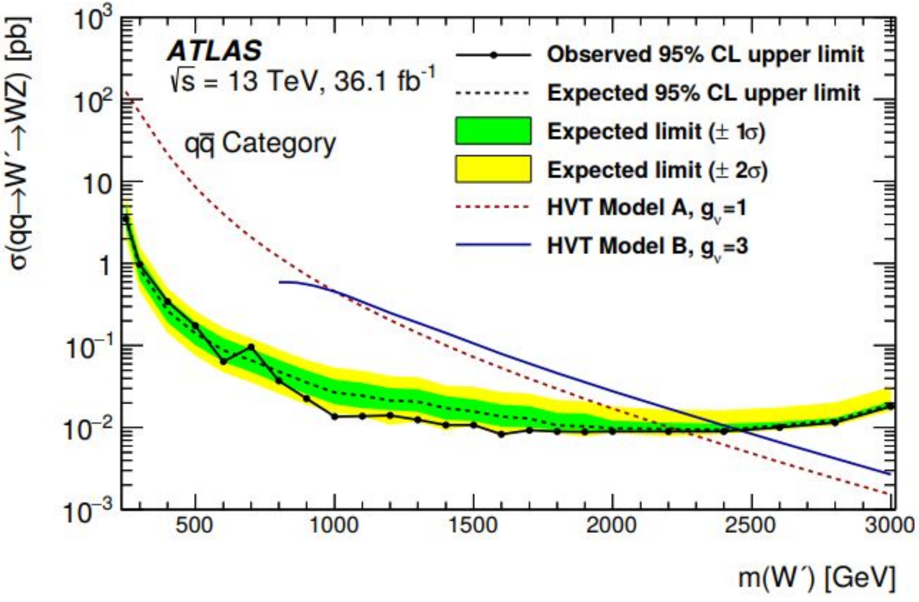
- Postfit plots in signal regions

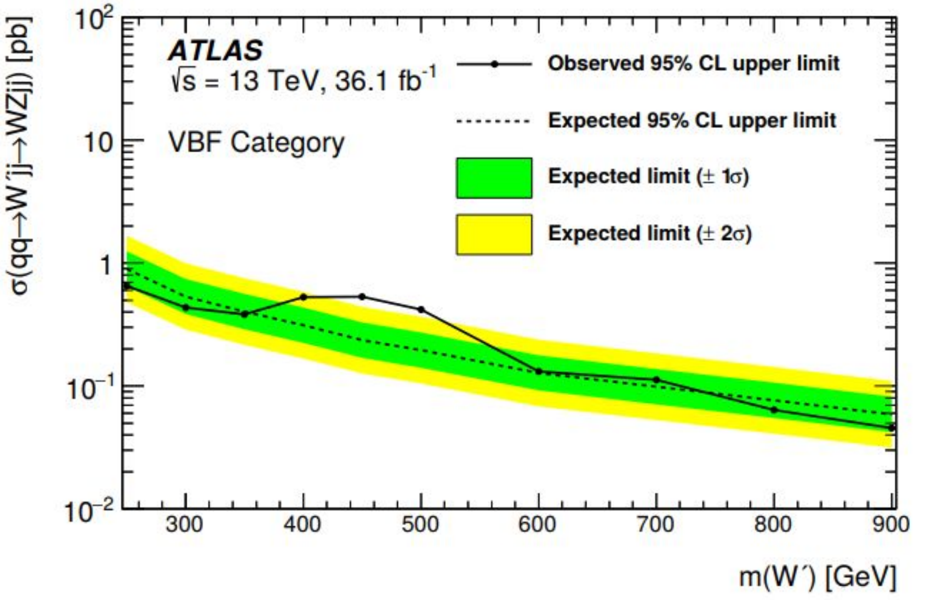




$H \rightarrow WZ$: Branching Fraction Limits

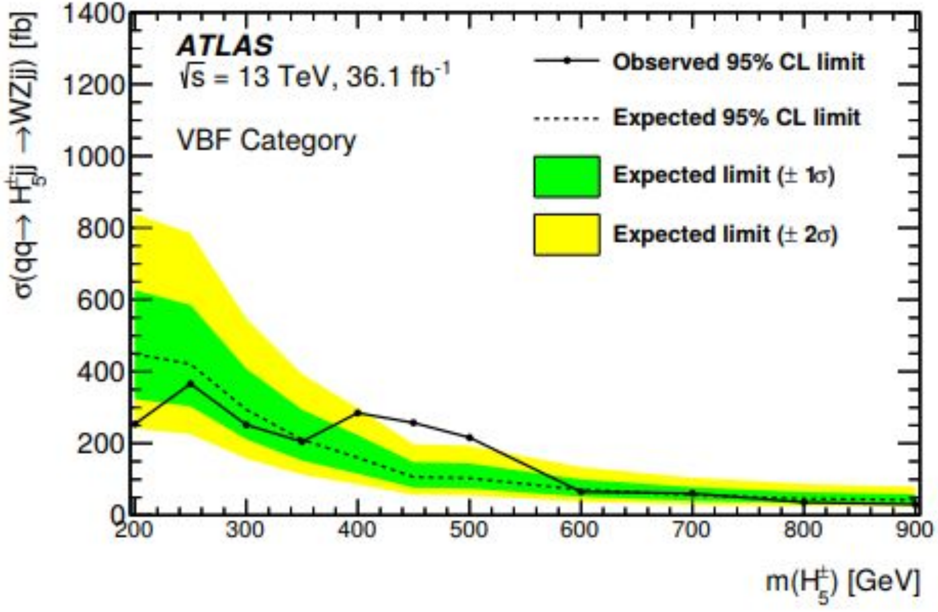
- Local excess in VBF ~450 GeV: 2.9σ (3.1σ) for $H_5^{+/-}$ (heavy vector W')
  - With look-elsewhere effect 1.6σ (1.9σ).

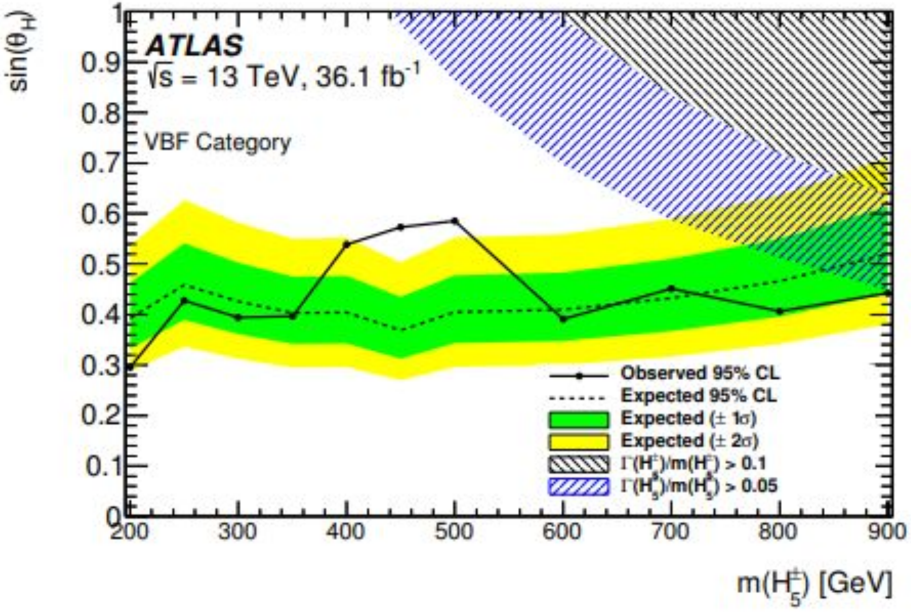




H → WZ: GM Model Limits

- Limits on specific GM model





$H \rightarrow aa \rightarrow b\bar{b}\mu\mu$: Introduction

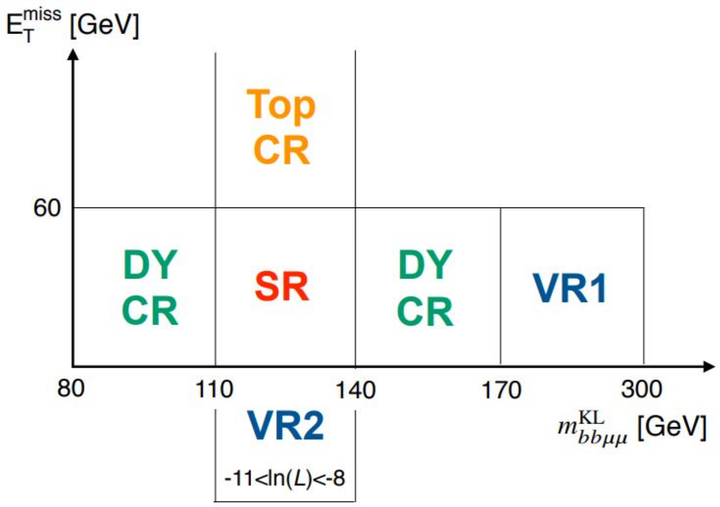
- 125 GeV Higgs to new spin-zero light resonances a (scalar or psuedoscalar)
  - Predicted with extended Higgs sector, dark matter models and more
- Usually high b branching ratio, paired with μμ gives distinctive signature
- Characterised by $m_{\mu\mu} \approx m_{bb}$, and $m_{bb\mu\mu} \approx 125$ GeV

Selection:

- 2 b-jets (p_T >20 GeV), $\mu^+\mu^-$ (p_T > 27, 7 GeV).
- $16 < m_{\mu\mu} < 64$ GeV
- Use kinematic likelihood (KL) fit to test $m_{\mu\mu} \approx m_{bb}$.
- Gives max likelihood value ($\ln(L^{max})$): quantifies how well event fits constraints
- $|m_{bb\mu\mu}(KL) - m_H| < 15$ GeV, $\ln(L^{max}) > -8$, $E_T^{miss} < 60$ GeV.

$H \to aa \to b\bar{b}\mu\mu$

- Dominant backgrounds:
  - DY μμ events + b-quarks
  - $t\bar{t}$, where both W from tops decay to μ



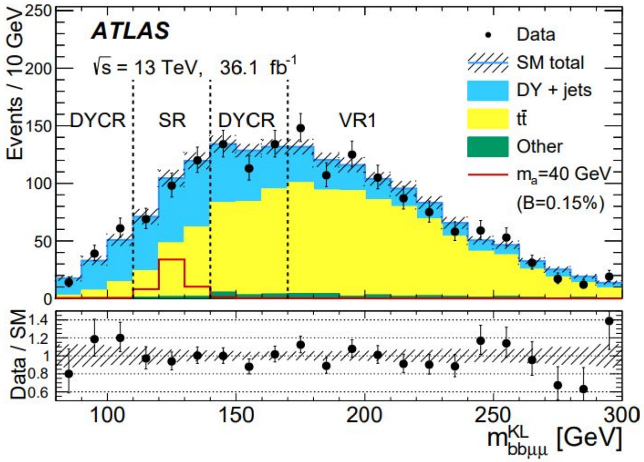
- Use several control regions:
  - Top CR: invert E_T^{miss} cut
  - DY CR: invert requirement on $m_{bb\mu\mu}$ invariant mass
- Model $t\bar{t}$ kinematics using simulation, plus two validation regions
- DY templates: define template regions by using zero b-tag requirement

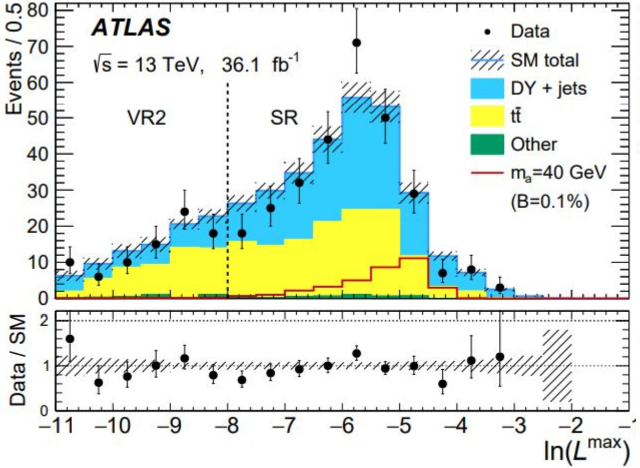
$H \to aa \to b\bar{b}\mu\mu$ Systematics

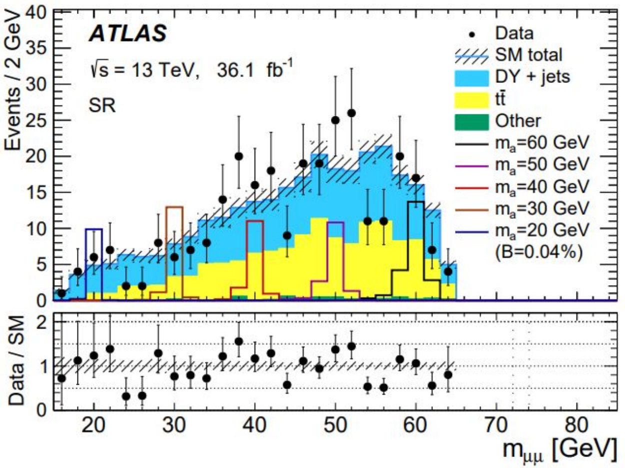
Source	Total background [%]	Signal [%]
DY: normalisation	9.3–15	–
DY: flavour composition	6.9–11	–
DY: background subtraction	0.4–2.4	–
$t\bar{t}$: hard-scatter generation	3.6–8.6	–
$t\bar{t}$: hadronisation/parton-shower	3.2–7.7	–
$t\bar{t}$: normalisation	2.1–5.0	–
$t\bar{t}$: ISR/FSR	1.0–2.4	–
MC statistics	2.4–4.9	2.3–4.6
b-tagging	0.6–1.5	17–19
Jet-energy resolution	0.3–2.9	5.2–8.4
Jet-energy scale	0.3–2.9	3.9–6.5
Muon-p_T resolution	0.1–2.2	0.3–1.2
Luminosity	< 0.01	2.1
Signal: QCD scale	–	6
Signal: ISR/FSR	–	4
Signal: ggF cross-section		
- missing higher-order QCD	–	3.6–3.8
- PDF & α_S	–	2.8–3.0
Signal: VH contribution	–	3.5
Signal: $p_T(H)$ reweighting	–	2.3–2.5

H → aa → $b\bar{b}\mu\mu$: Results

- First do background only fit: only top CR and DY CR constrain backgrounds
  - Verifies post-fit background yields agree in validation/signal regions.
- Signal and control regions:

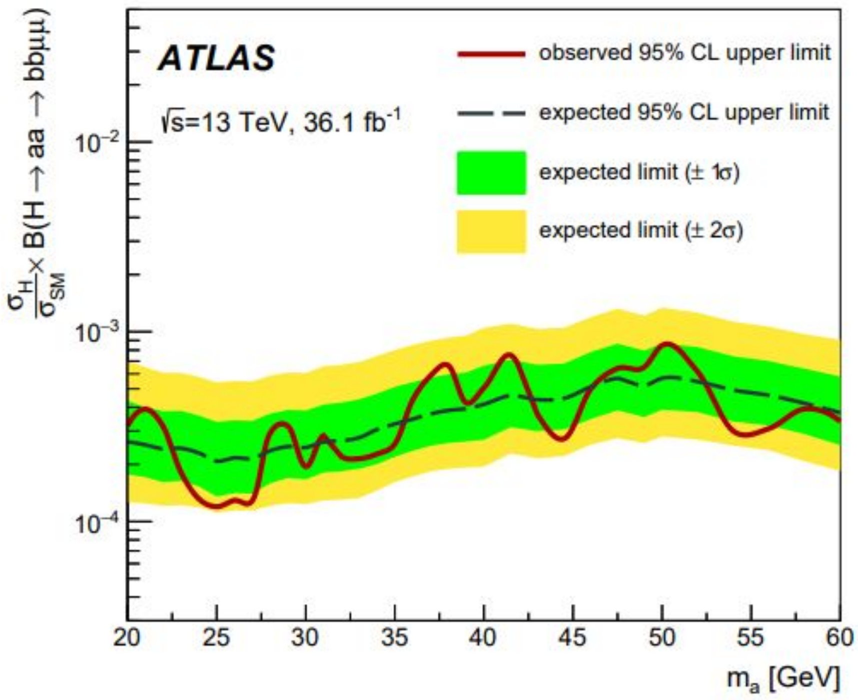


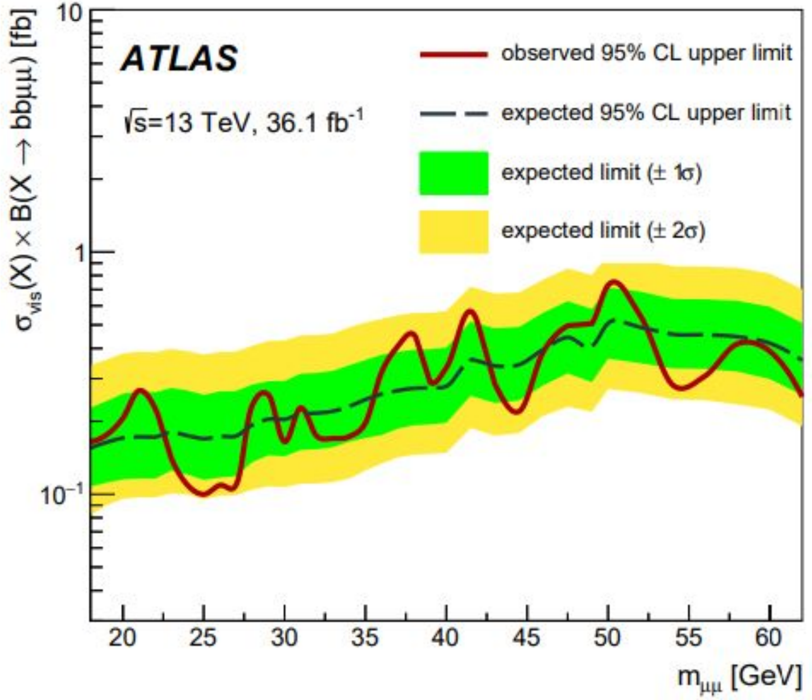




$H \to aa \to b\bar{b}\mu\mu$: Limits

- Limits presented on $H \to aa \to b\bar{b}\mu\mu$ branching (left), and model independent limits on new physics in $b\bar{b}\mu\mu$ final state (right)





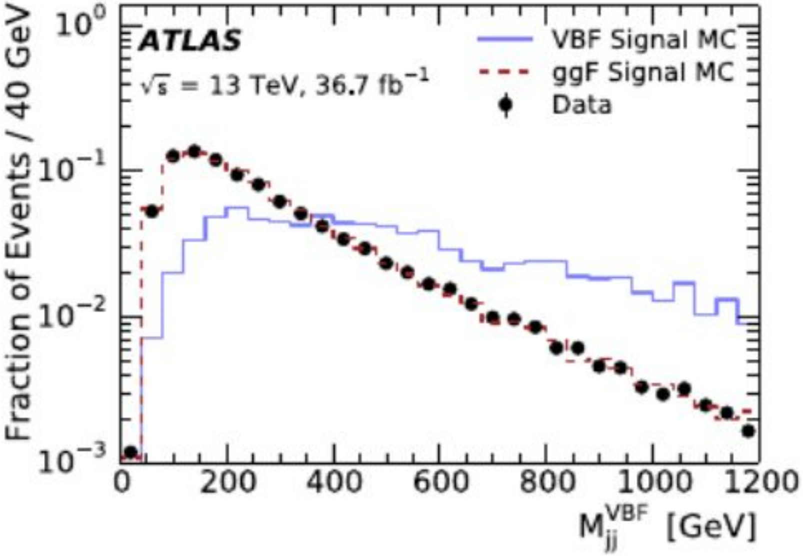
$H \rightarrow aa \rightarrow \gamma\gamma jj$: Summary

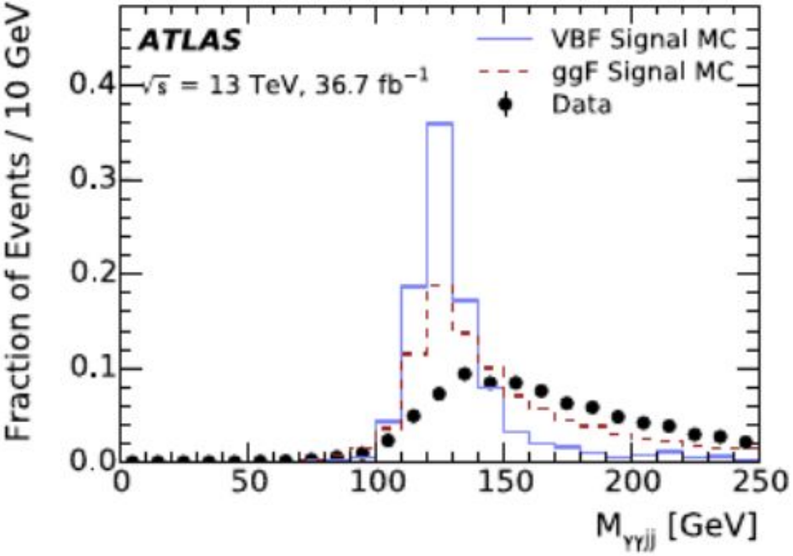
- Another search for new scalars (20-60 GeV)
- Covers models where fermionic decays are suppressed
- First direct search in this channel (36.7 fb^{-1})
- Production via VBF:
  - Produces 2 additional light quark jets, with large angular separation, large invariant mass: 4 jets in total
  - Pair with highest invariant mass taken as those from VBF (m_{jj}^{VBF})
  - Other two taken as "signal jets" (m_{jj})
- Good $m_{\gamma\gamma}$ resolution (~1.3 GeV) - use 5 regions to take advantage of this

$m_{\gamma\gamma}$ regime	Definition	Range of m_a values	x_R [GeV]
1	$17.5\ \text{GeV} < m_{\gamma\gamma} < 27.5\ \text{GeV}$	$20\ \text{GeV} \leq m_a \leq 25\ \text{GeV}$	12
2	$22.5\ \text{GeV} < m_{\gamma\gamma} < 37.5\ \text{GeV}$	$25\ \text{GeV} \leq m_a \leq 35\ \text{GeV}$	12
3	$32.5\ \text{GeV} < m_{\gamma\gamma} < 47.5\ \text{GeV}$	$35\ \text{GeV} \leq m_a \leq 45\ \text{GeV}$	16
4	$42.5\ \text{GeV} < m_{\gamma\gamma} < 57.5\ \text{GeV}$	$45\ \text{GeV} \leq m_a \leq 55\ \text{GeV}$	20
5	$52.5\ \text{GeV} < m_{\gamma\gamma} < 65.0\ \text{GeV}$	$55\ \text{GeV} \leq m_a \leq 60\ \text{GeV}$	24

$H \to aa \to \gamma\gamma jj$: Selection and Kinematics

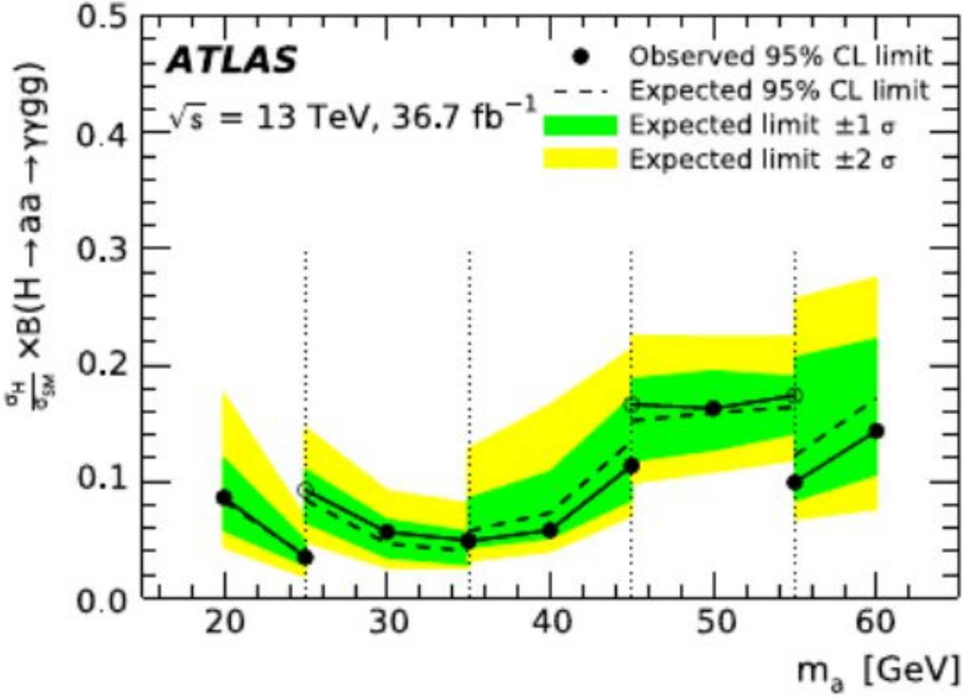
- Selection: Based on jet kinematics
- $m_{jj}^{VBF} > 500$ GeV, p_T lead VBF jet > 60 GeV, $100 < m_{jj\gamma\gamma} < 150$ GeV,
- Kinematic distributions before m_{jj}^{VBF} cuts:





$H \rightarrow aa \rightarrow \gamma\gamma jj$: Results

- Main background is γγ + multijet
  - Data driven estimate from 2D sidebands ABCD method
- Set limits in each region:



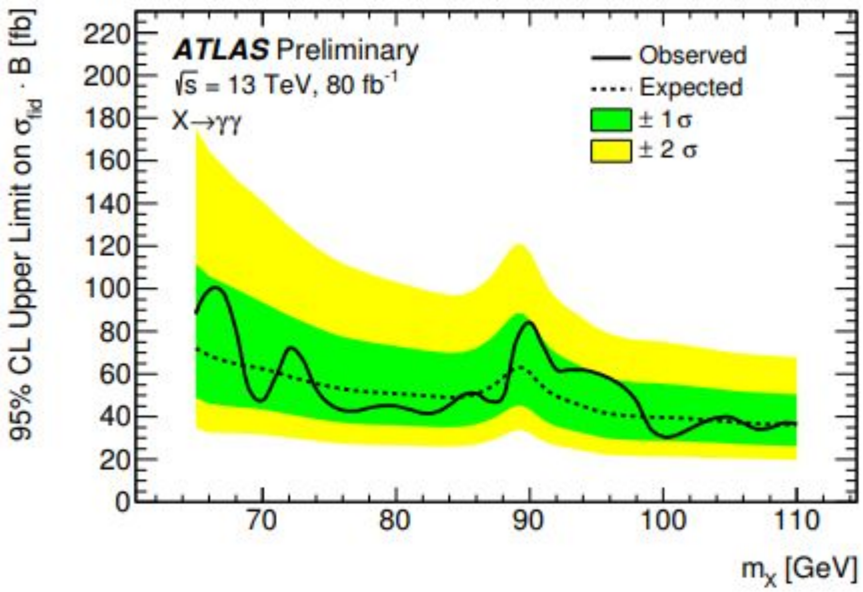
Low Mass γγ: Summary

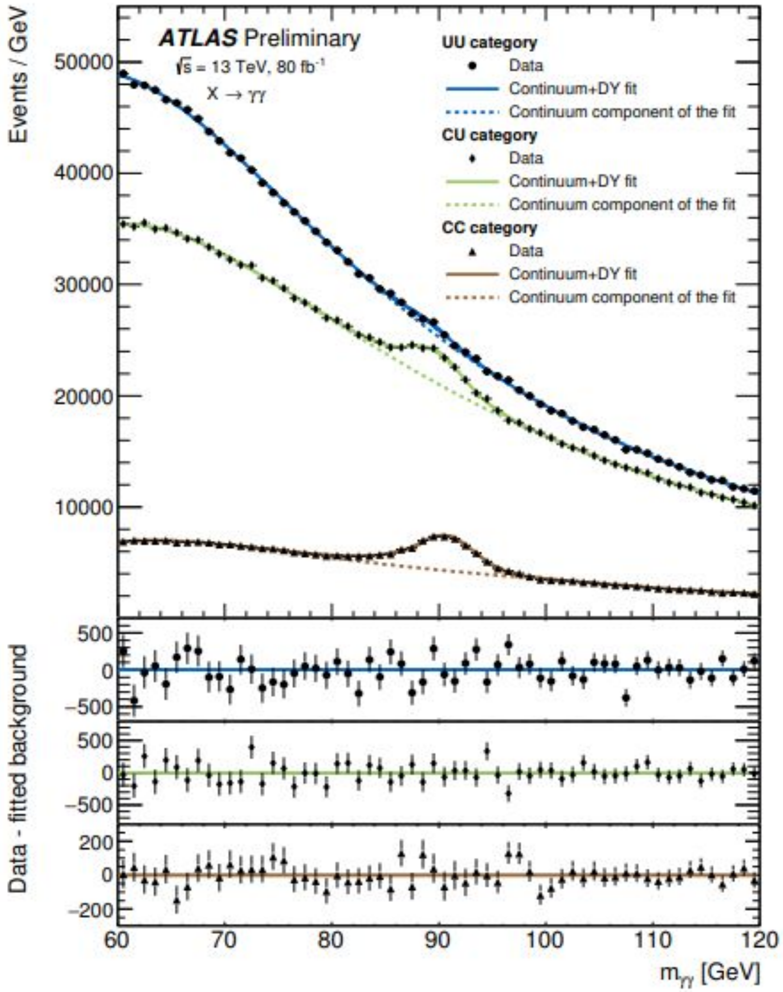
- Search for new resonances decaying to photons
- Diphoton signature in 65 - 110 GeV range, isolated γ with high p_T
- Continuum photon background + γj, jj, DY peak from $Z/\gamma^* \rightarrow ee$
  - Shape of DY from $Z \rightarrow ee$ sample (with $e \rightarrow \gamma$)
  - Continuum fit on data
- 3 categories, based on converted (C) or unconverted (U) photons:
  - UU, CU, CC

Low Mass γγ: Results

Right: background-only fit in each category

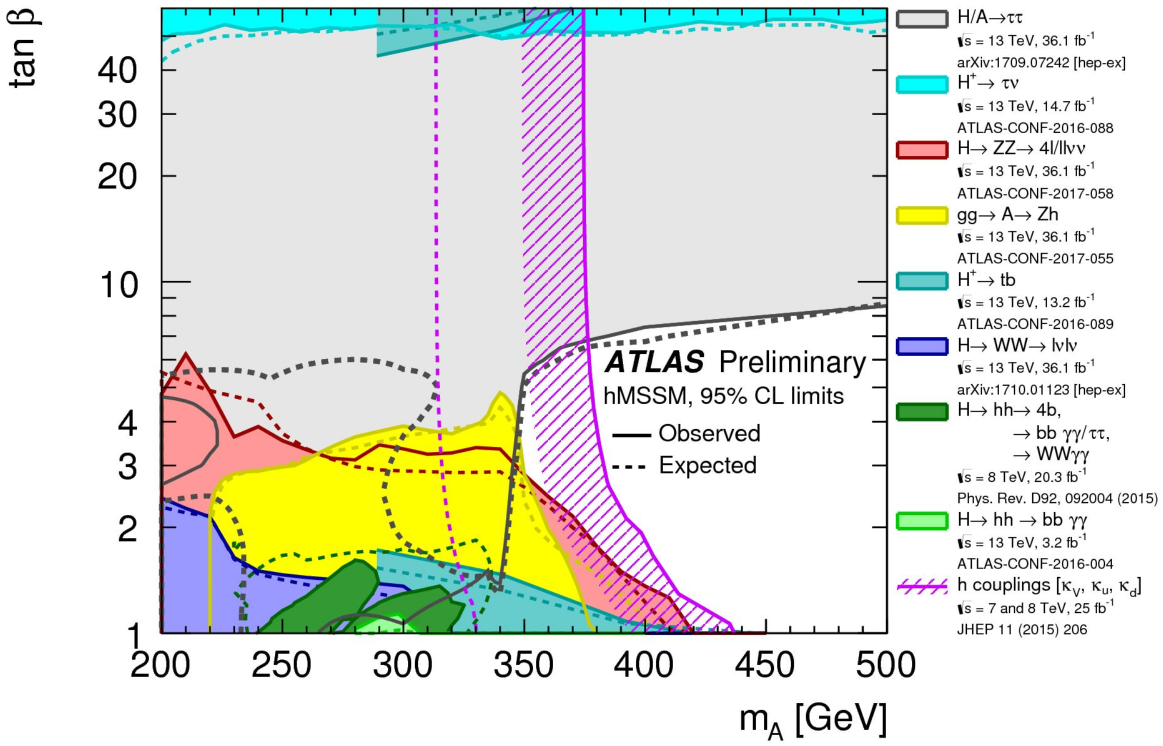
Bottom: Combined limits on σ





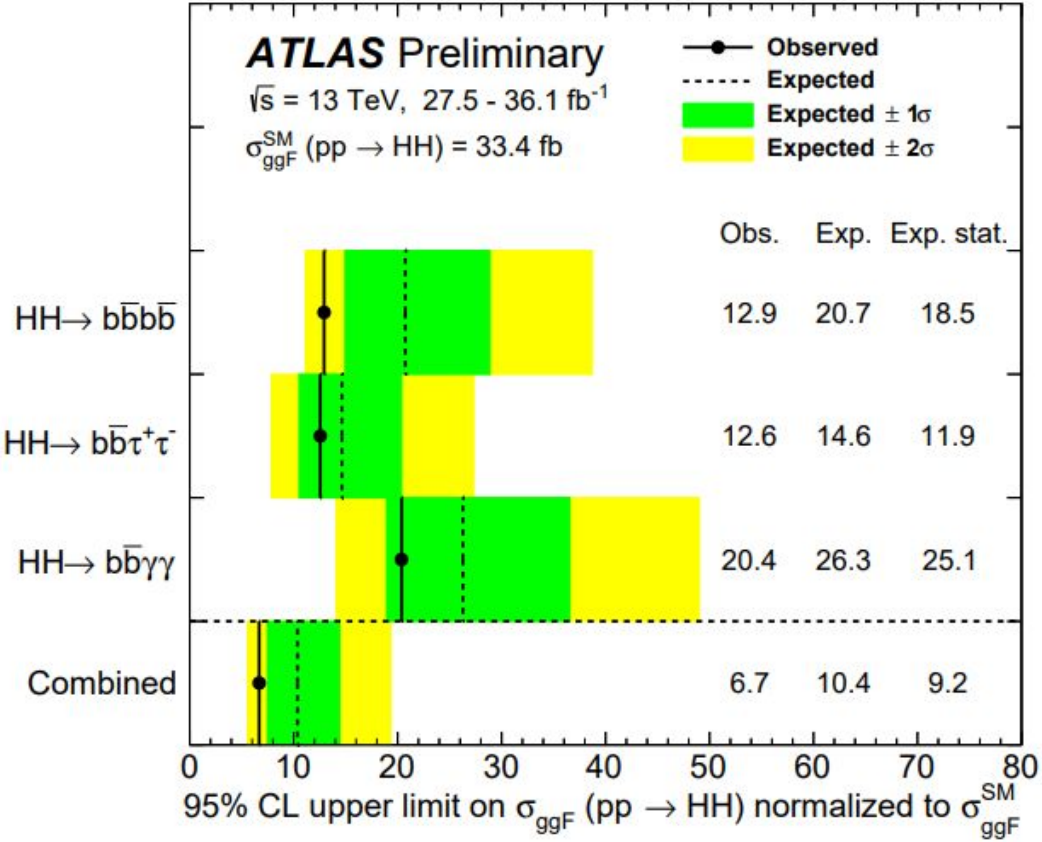
hMSSM Summary Plot

- Summary of early Run 2 results - updates in progress



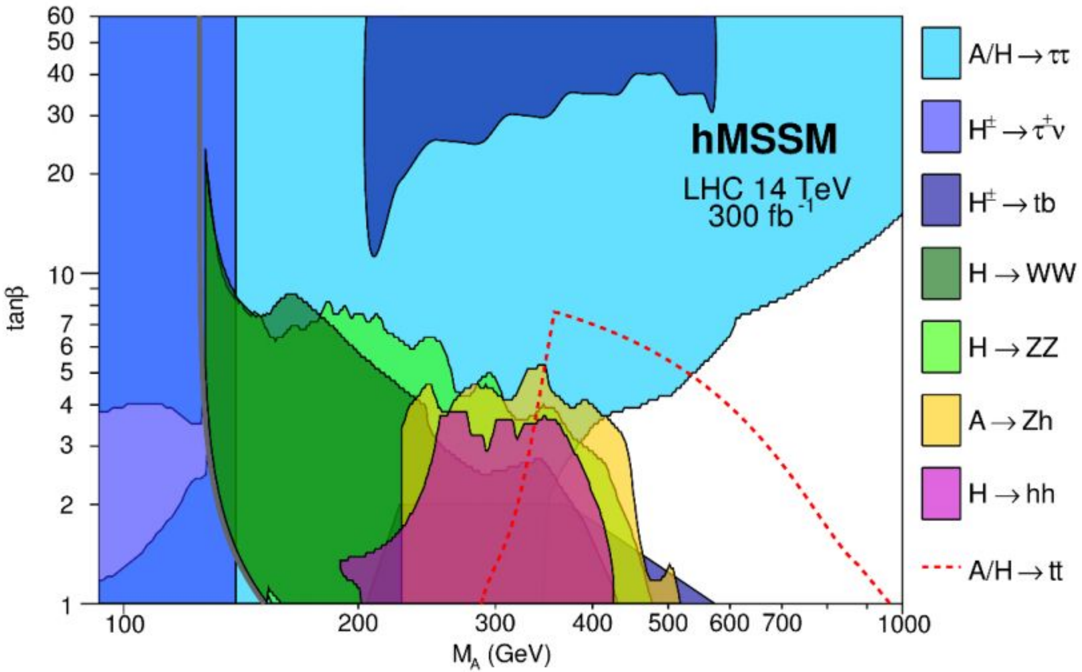
HH Summary Plot

Summary of HH limits



Future Prospects

- Projections from Djouadi et al. for 300 fb^{-1}

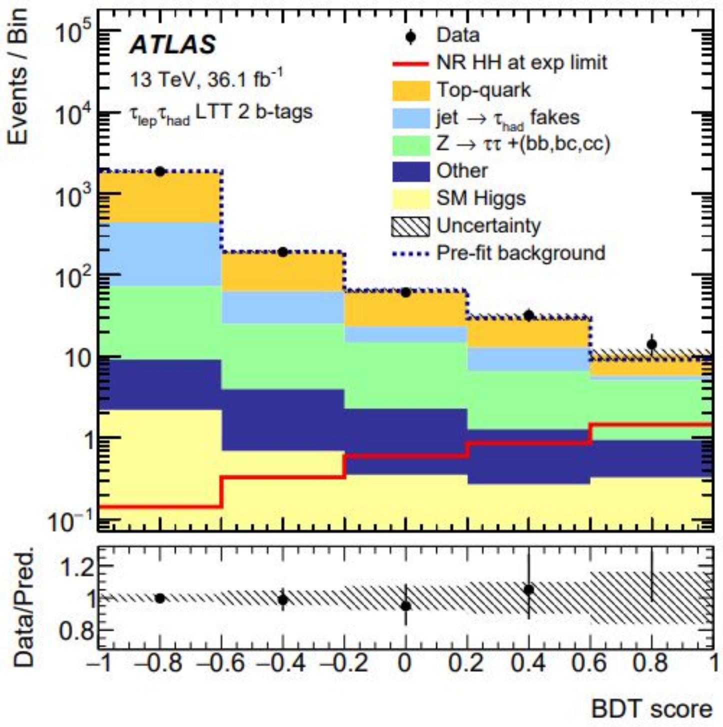


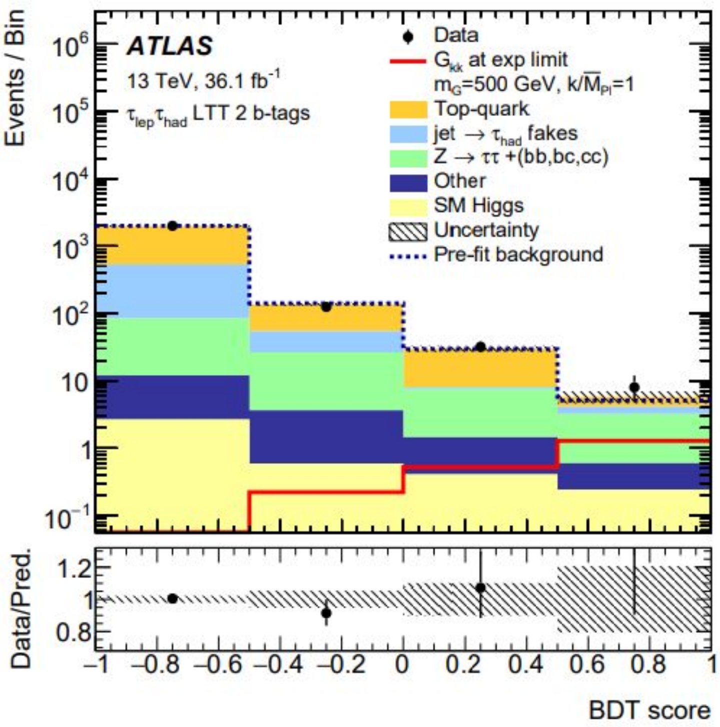
- Expect more Run 2 results from ATLAS
- Full Run 2 will be ~150 fb^{-1}, good prospects for analyses.

Backup: HH → $b\bar{b}\tau\tau$ BDT

Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT resonant)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau, \tau)$	✓	✓	✓
$\Delta R(b, b)$	✓	✓	✓
$E_{\text{T}}^{\text{miss}}$	✓		
$E_{\text{T}}^{\text{miss}}$ ϕ centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(H, H)$	✓		
$\Delta p_{\text{T}}(\text{lep}, \tau_{\text{had-vis}})$	✓		
Sub-leading b-jet p_{T}	✓		

Backup: HH → $b\bar{b}\tau\tau$, $\tau_{lep}\tau_{had}$ trigger BDT Score





Backup: $hh \rightarrow b\bar{b}\gamma\gamma$: Introduction

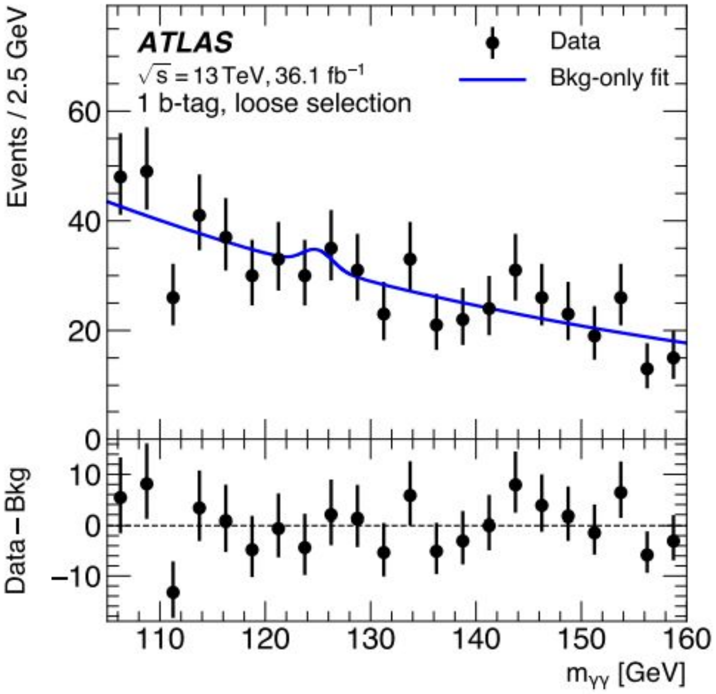
- Analysis at $\sqrt{s}$ = 13 TeV with 36.1 fb^{-1}, from Aug 2018
- 2 isolated γ, ≥2 jets with m_{jj} ~125 GeV. At least 1 b-jet
  - γγ trigger (E_T > 35 and 25 GeV)
  - Split into 1 b-tag, 2 b-tag categories
  - Tight selection: higher-mass resonances (m_X > 500 GeV) and non-resonant (typically higher p_T)
  - Loose selection: low-mass resonances (m_X ≤ 500 GeV) and non-SM Higgs self coupling
- Use $m_{\gamma\gamma}$ for non-resonant search, $m_{\gamma\gamma jj}$ for resonant

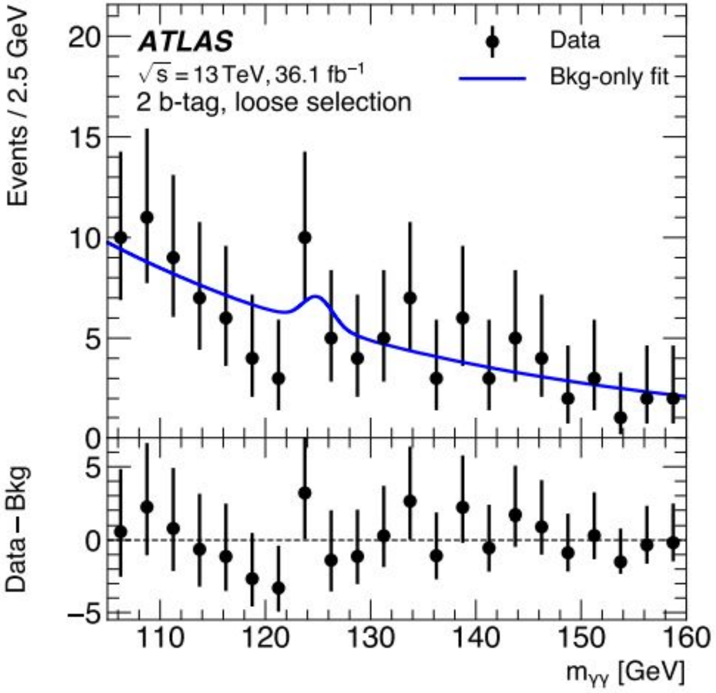
Backup: hh $\rightarrow$ $b\bar{b}\gamma\gamma$: Selection

- Main backgrounds: single H (from ggH, ZH, $t\bar{t}H$, tH), non-resonant continuum spectra ($\gamma\gamma$, γj, jj in association with jets)
  - Use data-driven estimates
- Loose: jet p_T > 40, 25 GeV, $80 < m_{jj} < 140$ GeV
- Tight: jet p_T > 100, 30 GeV, $90 < m_{jj} < 140$ GeV
- Resonant: $m_{\gamma\gamma}$ within 4.7 (4.3) GeV of Higgs mass in loose (tight)
- Use BDT for resonant: simulate continuum events and resonance signals

Backup: hh → $b\bar{b}\gamma\gamma$: Results

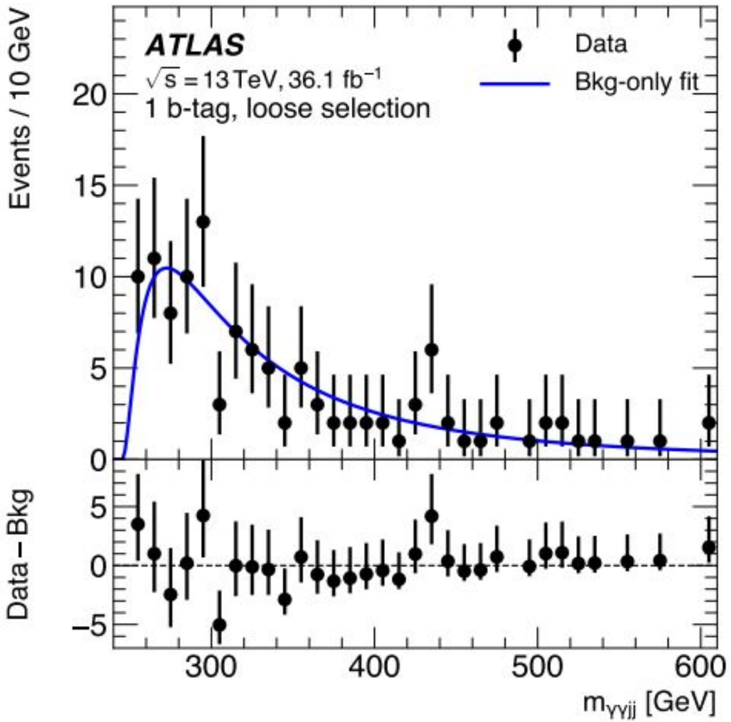
Non-resonant search

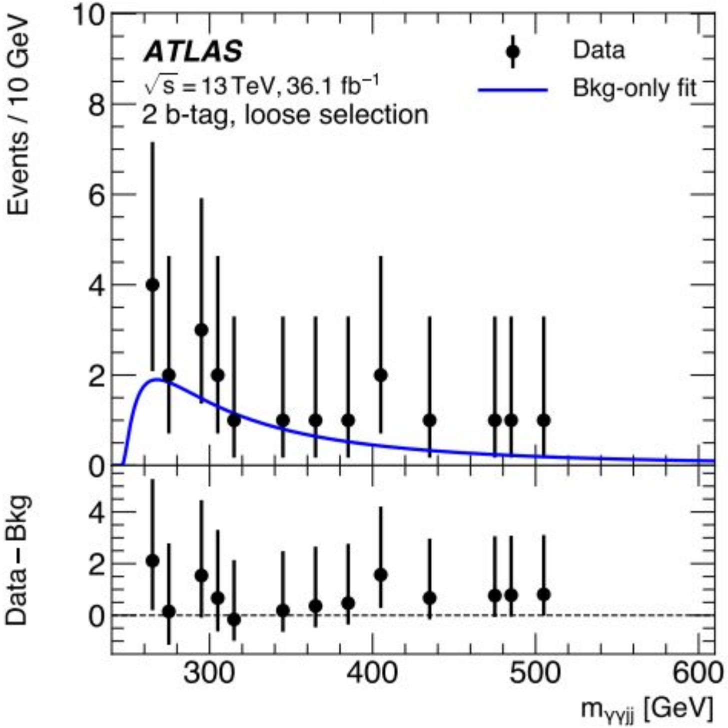




Backup: hh → $b\bar{b}\gamma\gamma$: Results

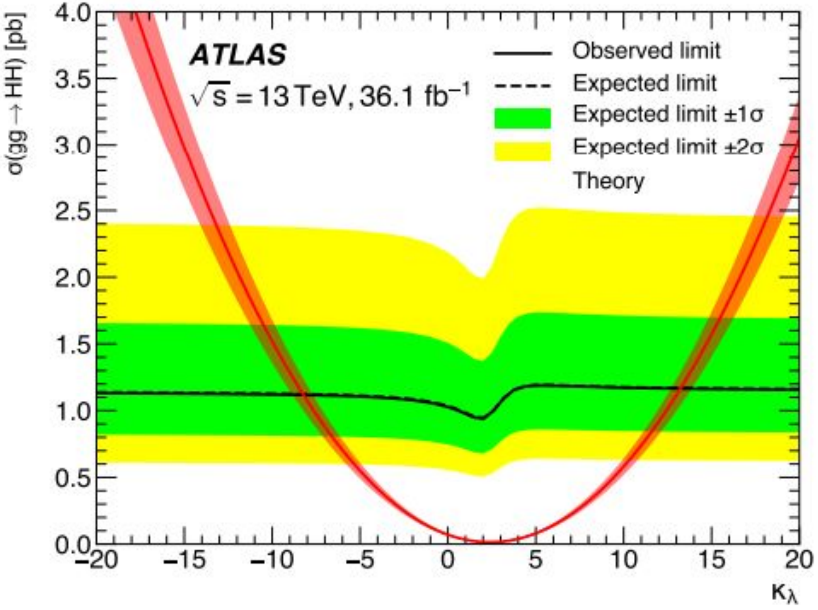
Resonant search

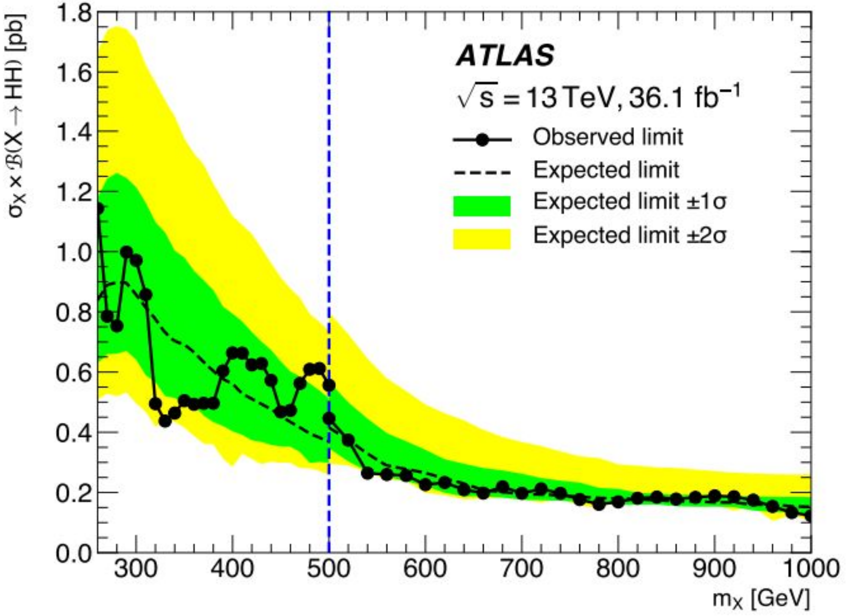




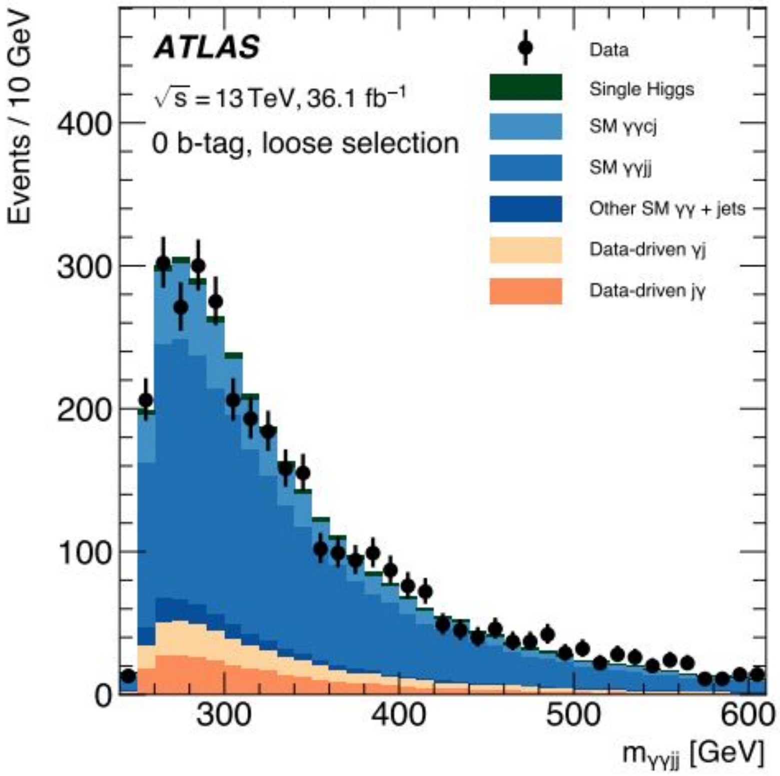
Backup: hh → $b\bar{b}\gamma\gamma$: Limits

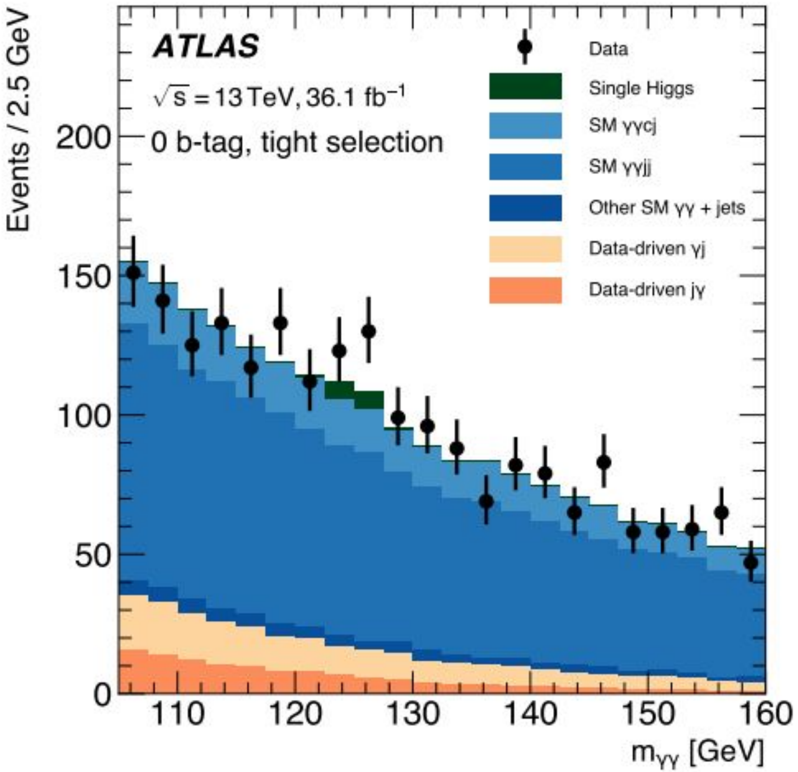
- Left: Non-resonant, set limits on: $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
  - Red is prediction if κ_λ is varied, but other couplings fixed at SM
  - Observed limit is 22 x SM cross-section
- Right: resonant limit





Backup: hh → $b\bar{b}\gamma\gamma$ 0 b-tag control region





Backup: $H^+ \rightarrow \tau\nu$ BDT

- Polarisation of the τ-lepton included via Υ:

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^{\tau}} \approx 2\frac{p_T^{\tau\text{-track}}}{p_T^{\tau}} - 1$$

- Only defined for 1-prong τ_{had}. Used for 90-400 GeV signal mass, where 1p/3p are split. Otherwise BDT is prong inclusive.

BDT input variable	$\tau_{\text{had-vis}}$+jets	$\tau_{\text{had-vis}}$+lepton
E_T^{miss}	✓	✓
p_T^{τ}	✓	✓
$p_T^{b\text{-jet}}$	✓	✓
p_T^{ℓ}		✓
$\Delta\phi_{\tau_{\text{had-vis}},\,\text{miss}}$	✓	✓
$\Delta\phi_{b\text{-jet},\,\text{miss}}$	✓	✓
$\Delta\phi_{\ell,\,\text{miss}}$		✓
$\Delta R_{\tau_{\text{had-vis}},\,\ell}$		✓
$\Delta R_{b\text{-jet},\,\ell}$		✓
$\Delta R_{b\text{-jet},\,\tau_{\text{had-vis}}}$	✓	
Υ	✓	✓

Backup: H/A → ττ Fake Factors

- Usually the probability of faking τ/lepton not well-modelled in MC:
  - Requires data driven methods
- Use several control regions (CR) and fake factors
- CR with ID requirement inverted, weight those events by a fake factor *f*:

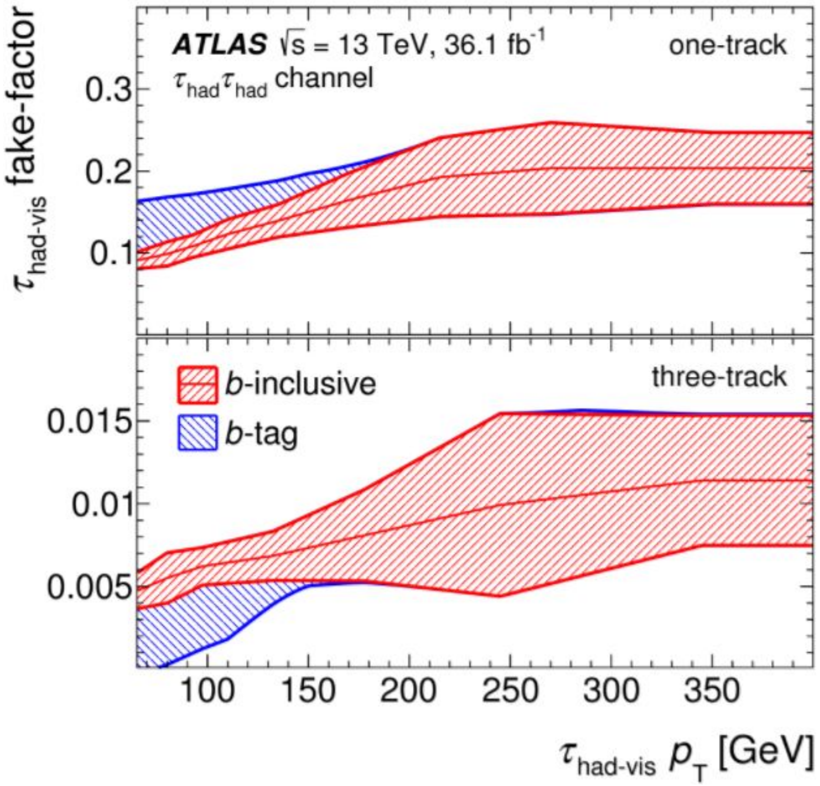
$$N^{\mathrm{SR}}_{\mathrm{background}}(v;\mathbf{x}) = f(\mathbf{x})\times[N^{\mathrm{CR}}_{\mathrm{data}}(v;\mathbf{x}) - N^{\mathrm{CR}}_{\mathrm{other\ bg}}(v;\mathbf{x})]$$

- Fake factor calculated in background-enriched region, defined as:

$$f(\mathbf{x}) = \frac{N^{\mathrm{pass}}_{\mathrm{data}}(\mathbf{x})}{N^{\mathrm{fail}}_{\mathrm{data}}(\mathbf{x})}$$

Backup: H/A → τ_{had} τ_{had} Multijet Background

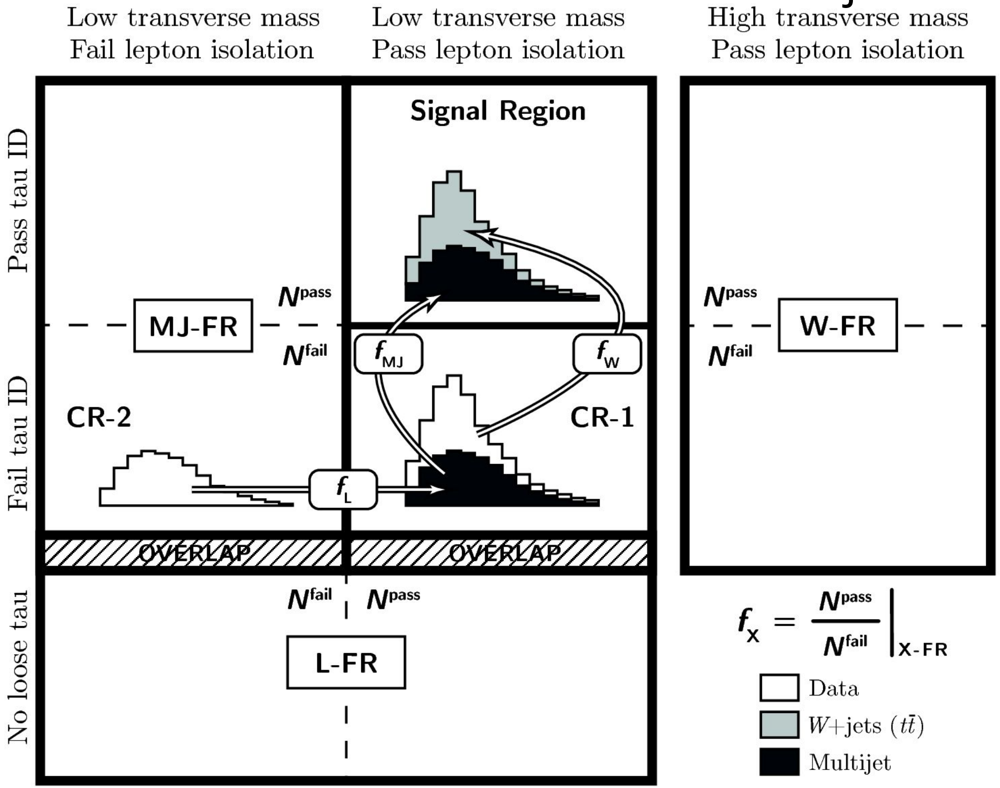
- Estimate non-multijet backgrounds using MC, and subtract them.
- Fake factor, $\mathbf{f_{DJ}}$ calculated in region dominated by multijet events
- $\mathbf{f_{DJ}}$ = N τ_2 pass loose / N τ_2 fail loose
- Applied to region like SR, but sub-lead τ fail loose ID

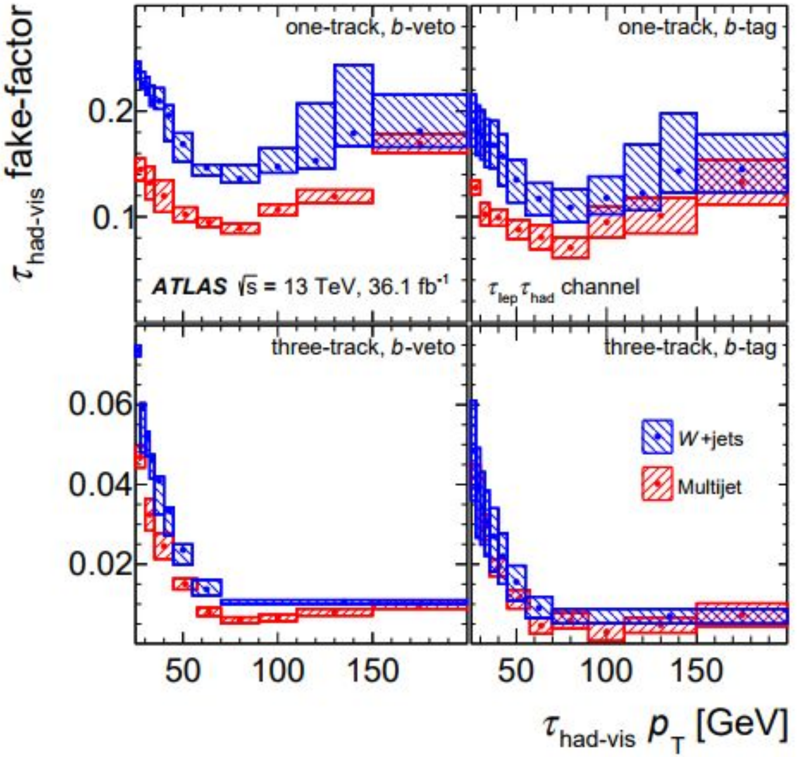


Fake factors show agreement in b-tag/veto/inclusive categories. Use b-inclusive, with extra stat uncertainty when using b-tag.

Backup: H/A → $\tau_{lep}\ \tau_{had}$ Data Driven Backgrounds

- Events with fake τ are mixture of W + jet and multijet, different fake factors



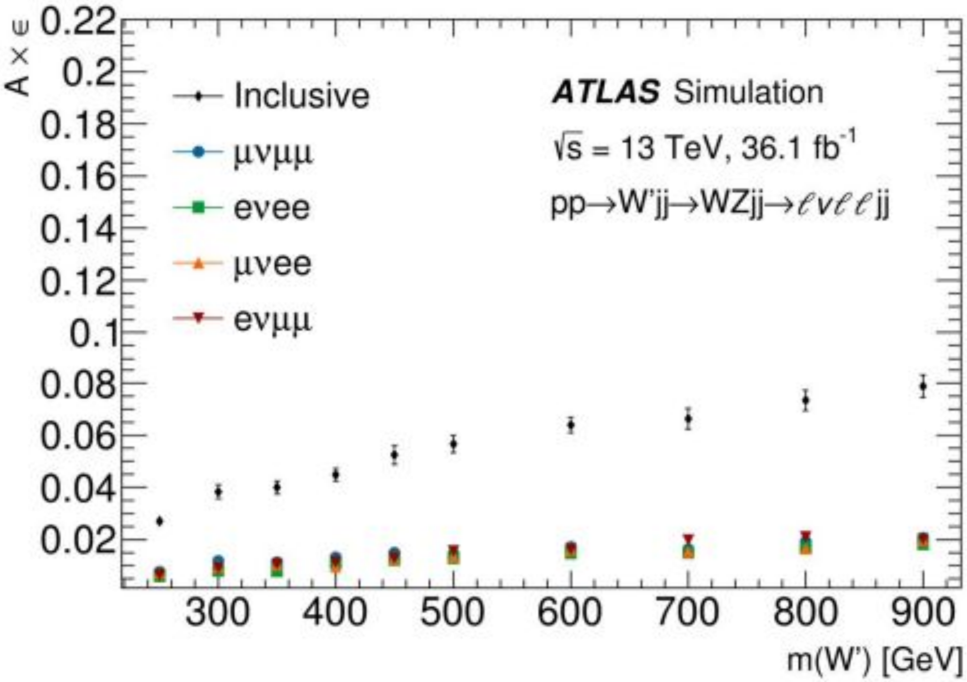


H/A → $\tau_h \tau_h$ Fake Rates

- For non-multijet backgrounds, estimate from simulation.
- Don't apply τ ID to simulation - instead weight simulation by fake rate
  - Ensures correct fake rate and uses all MC stats
- Lead τ: N pass ID and τ trigger / N total
- Subleading τ: N pass ID / N total

- Use two regions, enriched in tt or W+jets events:
  - **For W + jets,**: μ trigger (isolated) $p_T > 55$ GeV, τ_1 (no ID) $p_T > 50$ GeV, e-veto, $\Delta\varphi > 2.4$ $m_T(p_T^{\mu}, E_T^{miss}) > 40$, no b-tagged jets.
  - **For tt**: Same, but with at least 1 b-tagged jet

Backup: H → WZ acceptance in HVT models



Backup: Low Mass γγ p-value