Search for heavy Higgses and di-Higgs resonances in fermionic decay modes with ATLAS

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On behalf of the ATLAS collaboration

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GRADUIERTENKOLLEG
Masse-Spektrum-Symmetrie

ATLAS EXPERIMENT

TECHNISCHE UNIVERSITÄT DRESDEN

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103
ATLAS

Introduction

Heavy BSM Higgs searches in 2HDM:

- 5 physical Higgs bosons: h, H, A, $H^{+/-}$
- Ratio of vacuum expectation values: tan(β)
- neutral CP-even states are mixed with mixing angle: α
- Type I: Φ2 couples to fermions, Φ1 to gauge bosons → “fermiophobic” in absence of mixing
- Type II: Φ1 couples to down-type fermions, Φ2 to up-type fermions

Di-Higgs searches:

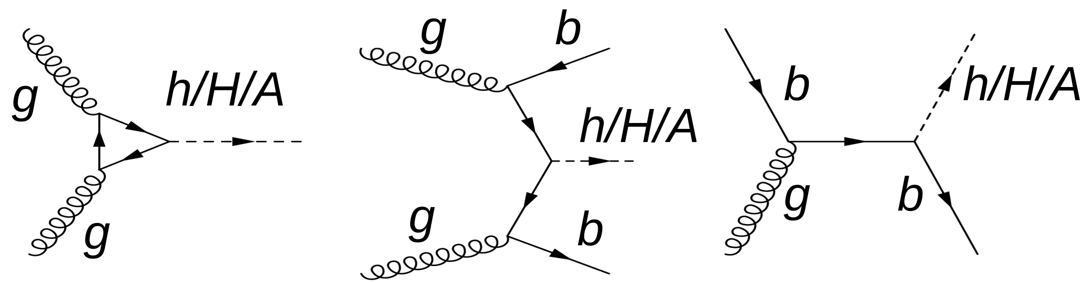
- Resonant production: 2HDM, Randall-Sundrum
- Non-resonant production

Searches:

- $H \rightarrow \tau\tau$
- $H^{+/-} \rightarrow \tau\nu$
- $A \rightarrow ZH \rightarrow ll/\nu\nu\ bb$
- Di-Higgs with 4 b-quark final state

$H^0 \rightarrow \tau\tau$ – Analysis strategy

Production:



Decay:

$h^+ + \nu \leftarrow \tau^+ \leftarrow H \rightarrow \tau^- \rightarrow h^- + \nu$

$e^+/\mu^+ + \nu\nu$ $e^-/\mu^- + \nu\nu$

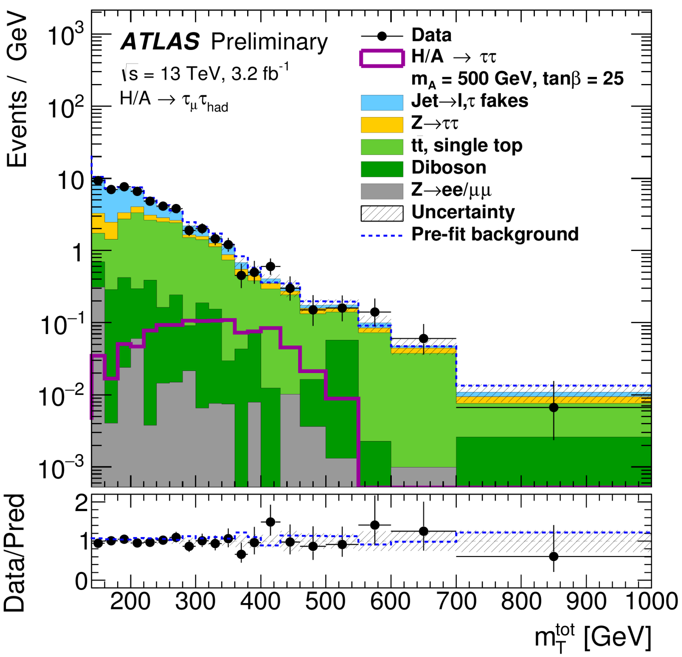
- Select two back-to-back tau decays of opposite charge

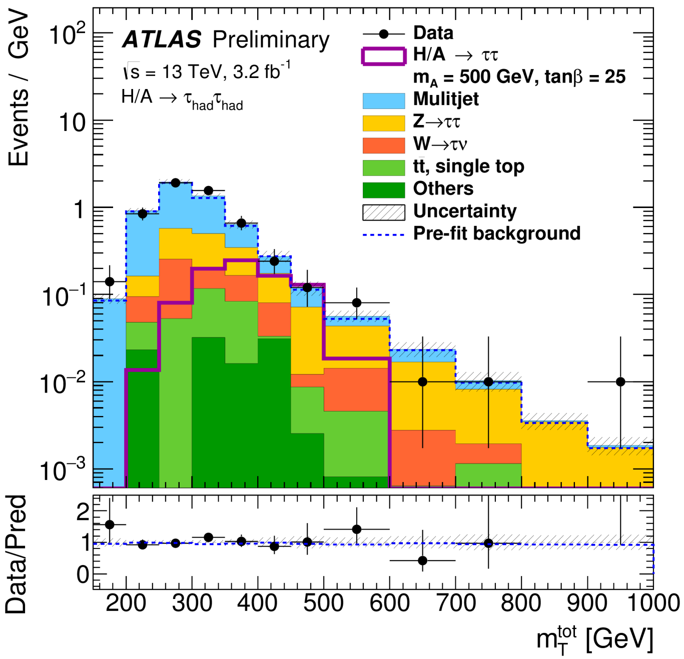
	Muons	Electrons	Trigger	1. Object	2. Object
$\tau_{had}\tau_{had}$	0	0	Single tau	p_T > 135 GeV Medium ID	p_T > 55 GeV Loose ID
$\tau_{\mu}\tau_{had}$	1	0	Single muon	p_T > 30 GeV Medium ID	p_T > 20 GeV Medium ID
$\tau_{e}\tau_{had}$	0	1	Single electron	p_T > 30 GeV Medium ID	p_T > 20 GeV Medium ID

$H^0 \rightarrow \tau\tau$ – Signal Region

- **$\tau_{had}\tau_{had}$ channel:**
  - QCD background estimated from data
  - Simulated W/Z+jets, top and diboson backgrounds with data driven corrections for misidentified τ_{had}
- **$\tau_{lep}\tau_{had}$ channel:**
  - Backgrounds with correctly identified lepton and τ_{had} estimated from simulation
  - Other background estimated from data
- Total transverse mass distribution

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





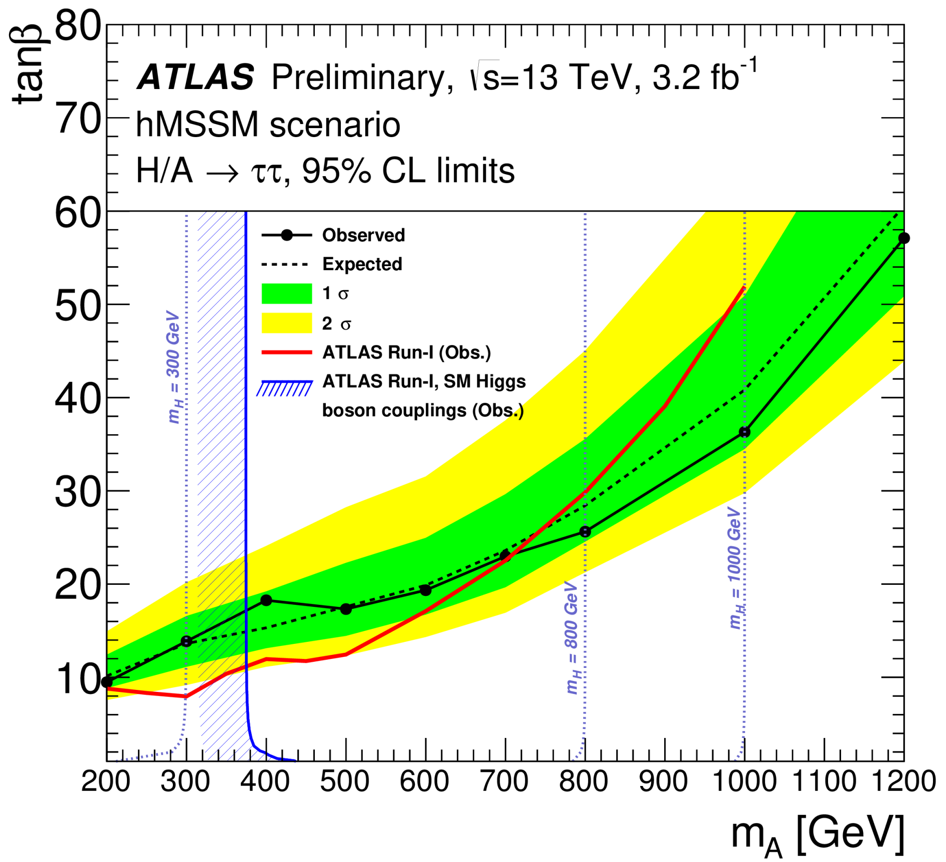
$\tau_e\tau_{\mathrm{had}}$ Channel	Yield
$Z \rightarrow \tau\tau$+jets	5650 ± 750
Fake τ_{had}	9640 ± 490
$Z \rightarrow \ell\ell$+jets	1390 ± 830
Top	543 ± 86
Diboson	102 ± 22
Total prediction	17300 ± 1300
Data	17480

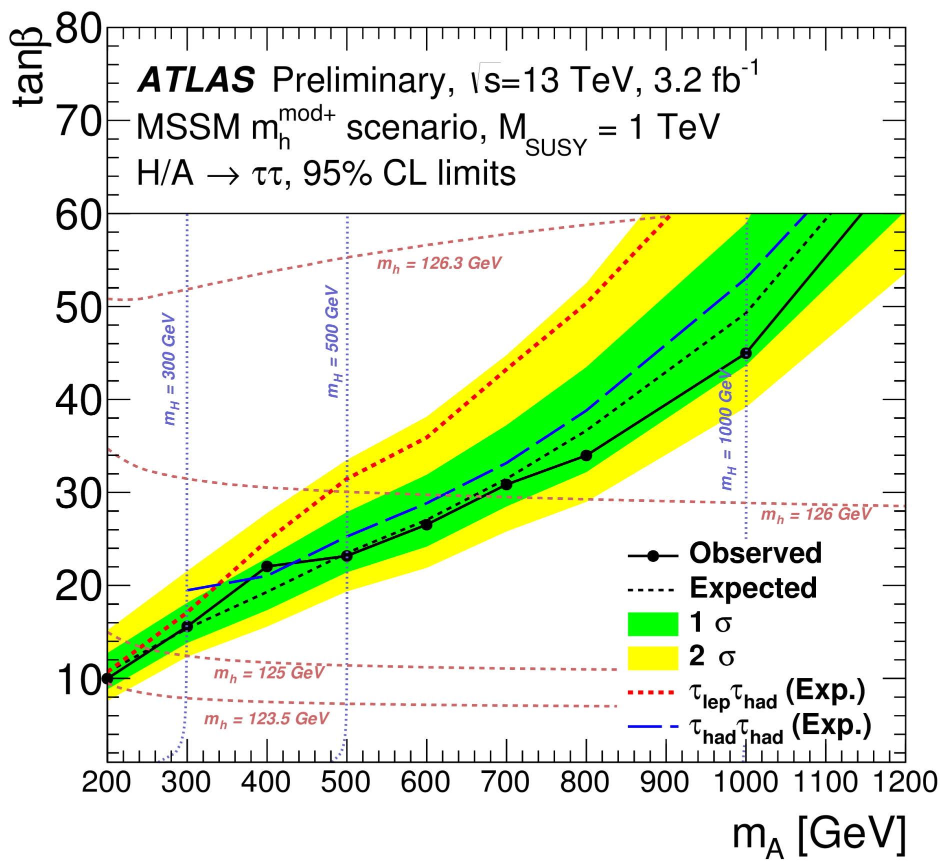
$\tau_\mu\tau_{\mathrm{had}}$ Channel	Yield
$Z \rightarrow \tau\tau$+jets	6720 ± 980
Fake τ_{had}	5840 ± 420
$Z \rightarrow \ell\ell$+jets	710 ± 92
Top	552 ± 80
Diboson	105 ± 22
Total prediction	14000 ± 1100
Data	13374

$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ Channel	Yield
$Z \rightarrow \tau\tau$+jets	52 ± 18
Multijet	175 ± 13
$W \rightarrow \tau\nu$ + jets	23.7 ± 9.6
Top	11.6 ± 5.0
Others	4.5 ± 2.4
Total prediction	268 ± 25
Data	284

$H^0 \rightarrow \tau\tau$ – Exclusion Limits

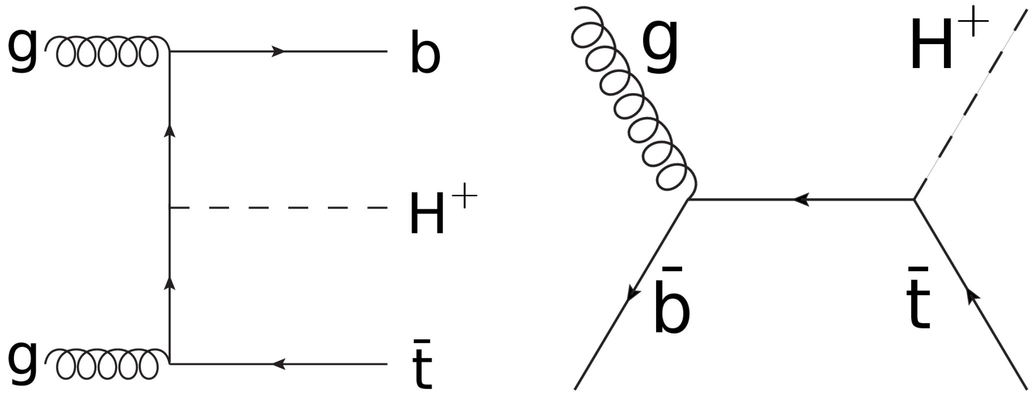
- Background prediction compatible with observation
- 95% CL limits set on various scenarios **hMSSM**, $\mathbf{m_h^{mod+}}$/-, m_h^{max}, light stop, light stau, tauphobic





$H^{+/-} \to \tau\nu$ – Analysis strategy

Production:



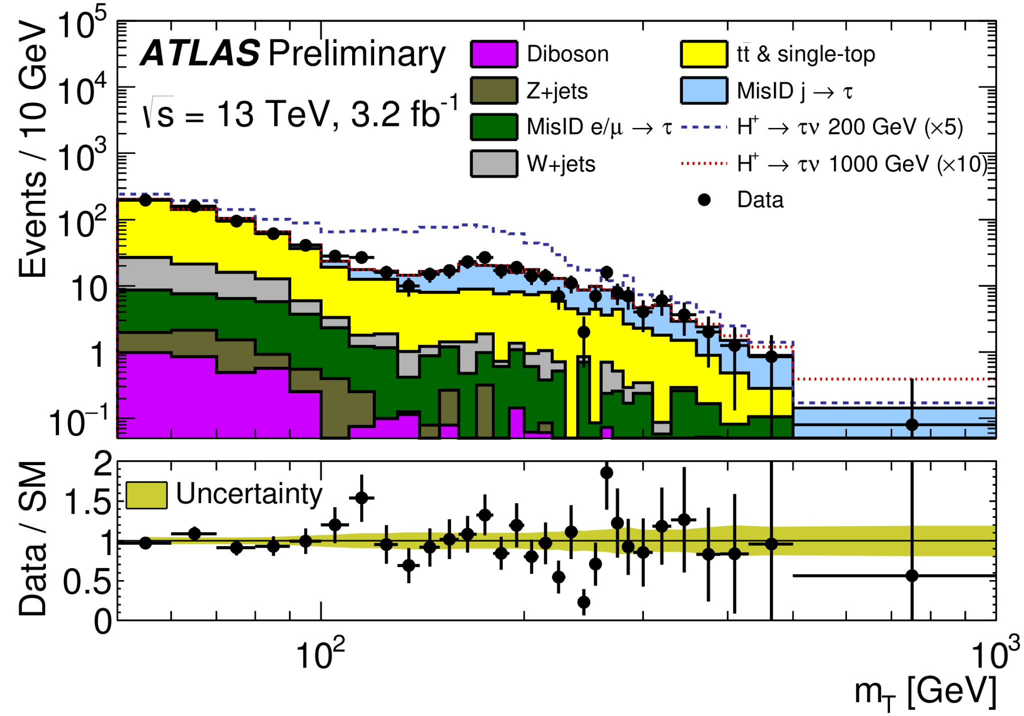
Topology: hadronic top decay $t \to jj+b$ and $H^{+/-} \to \tau_{had}\nu$

Selection:

- High missing E_T trigger (> 70 GeV)
- Missing E_T > 150 GeV
- Tau transverse momentum p_T > 40 GeV, medium ID
- At least 3 additional jets with p_T > 25 GeV
  - One of them is b-tagged
- m_T > 50 GeV, with $m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau,miss})}$

$H^{+/-} \rightarrow \tau\nu$ – Signal Region

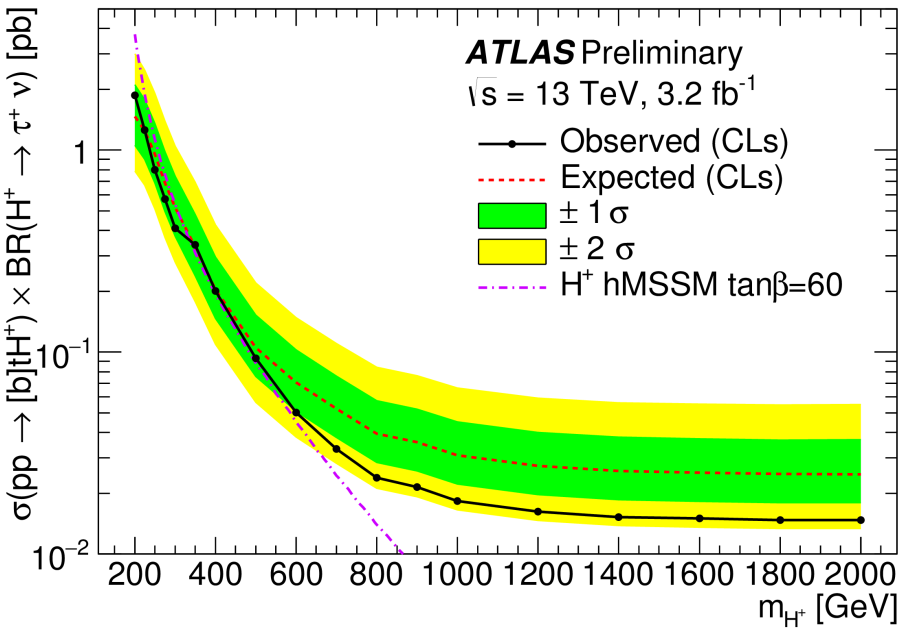
- Jet to τ_{had} fakes estimated from data using fake factors
- Other backgrounds estimated from simulation
  - Additional data driven corrections for fake rate of $e \rightarrow \tau_{had}$
  - W+jets normalization corrected from $W \rightarrow \tau\nu$ control region

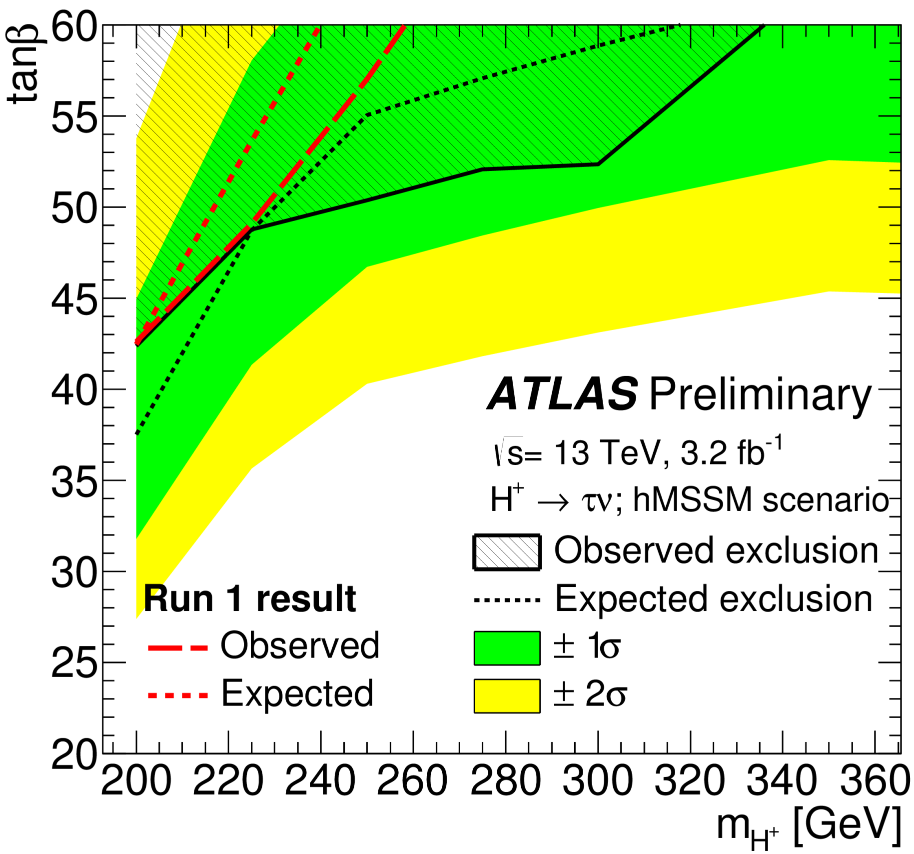


Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	590 $\pm$ 170
$W \rightarrow \tau\nu$	58 $\pm$ 14
$Z \rightarrow \tau\tau$	6.4 $\pm$ 2.0
diboson (WW, WZ, ZZ)	4.3 $\pm$ 1.3
Misidentified e, $\mu \rightarrow \tau_{\text{had-vis}}$	40 $\pm$ 6
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$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

$H^{+/-} \rightarrow \tau\nu$ – Exclusion Limits

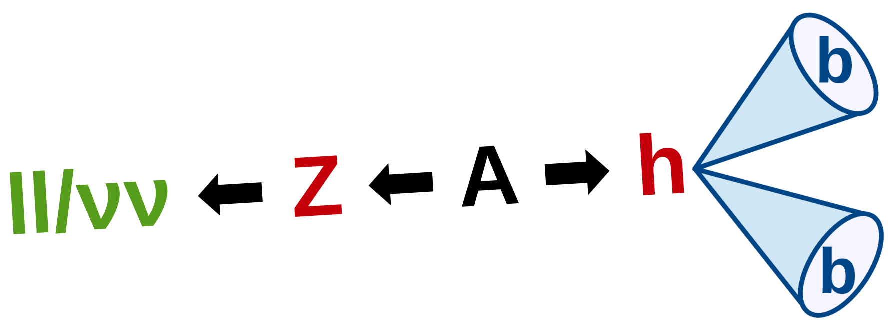
- Largest impact on exclusion limit from:
  - tau energy scale
  - $t\bar{t}$ modeling
  - QCD estimation
- Background prediction compatible with observation
- Supersede run 1 results



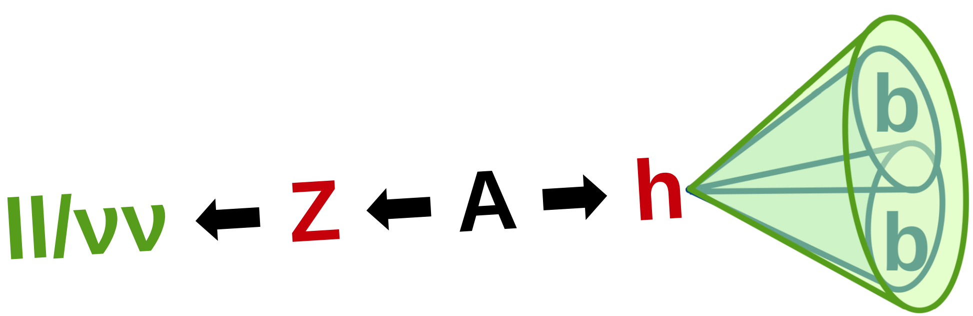


A → ZH → ll/νν bb – Analysis Strategy

- Categories:
  - **Resolved:** p_T of Z candidate < 500 GeV



  - **Boosted:** p_T of Z candidate ≥ 500 GeV



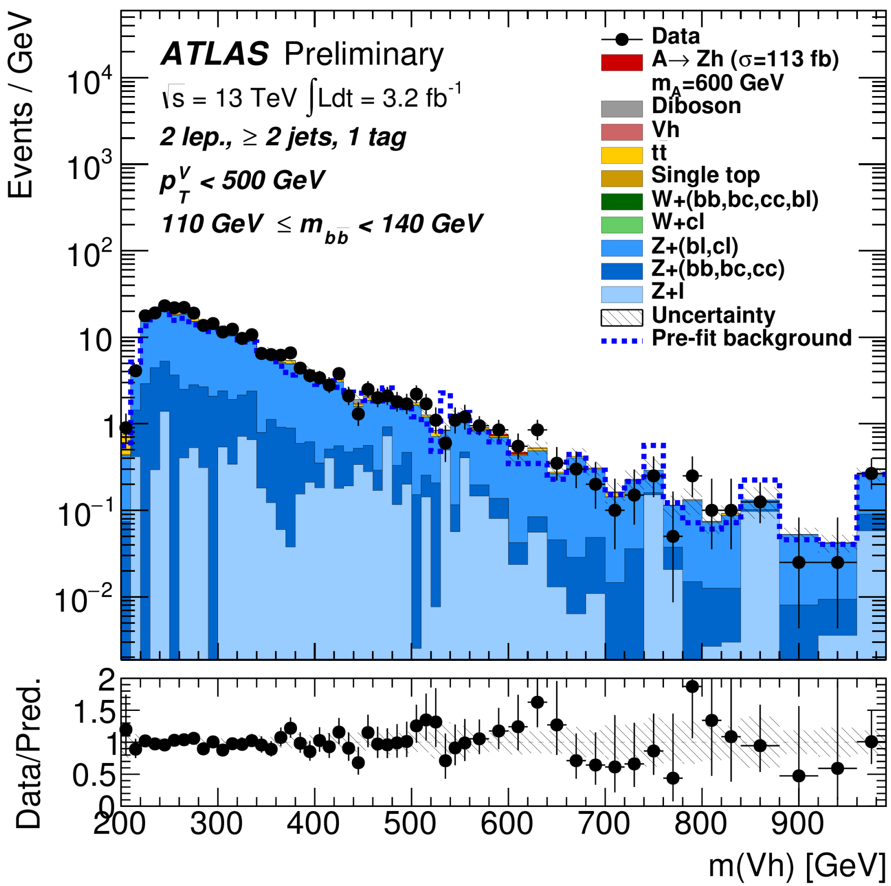
Variable	Low-p_T^Z	High-p_T^Z
Common selection		
p_T^Z [GeV]	<500	≥ 500
$N_{b\text{-tag jet}}$	1,2	1,2
$N_{\text{small-}R\text{ jet}}$	≥ 2	≥ 0
$N_{\text{large-}R\text{ jet}}$	≥ 0	≥ 1
m_{dijet} or m_{jet} [GeV]	110–140	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	–
$\sum_{i=1}^{N_{\text{jet}}=3(2)} p_T^{\text{jet}_i}$ [GeV]	$> 150\ (120)^{(*)}$	–
p_T^{miss} [GeV]	> 30	> 30
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< \pi/2$	$< \pi/2$
$\Delta\phi(\vec{E}_T^{\text{miss}}, h)$	$> 2\pi/3$	$> 2\pi/3$
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{small-}R\text{ jet})]$	$> \pi/9^{(*)}$	$> \pi/9^{(*)}$
$\Delta\phi(j, j)$	$< 7\pi/9$	–
Number of hadronic taus	0	0
Number of b-tag track-jets not associated to the leading large-R jet	–	0
2-lepton selection		
m_{ee} [GeV]	70–110	70–110
$m_{\mu\mu}$ [GeV]	70–110	55–125
$E_T^{\text{miss}}/\sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	< 3.5	–

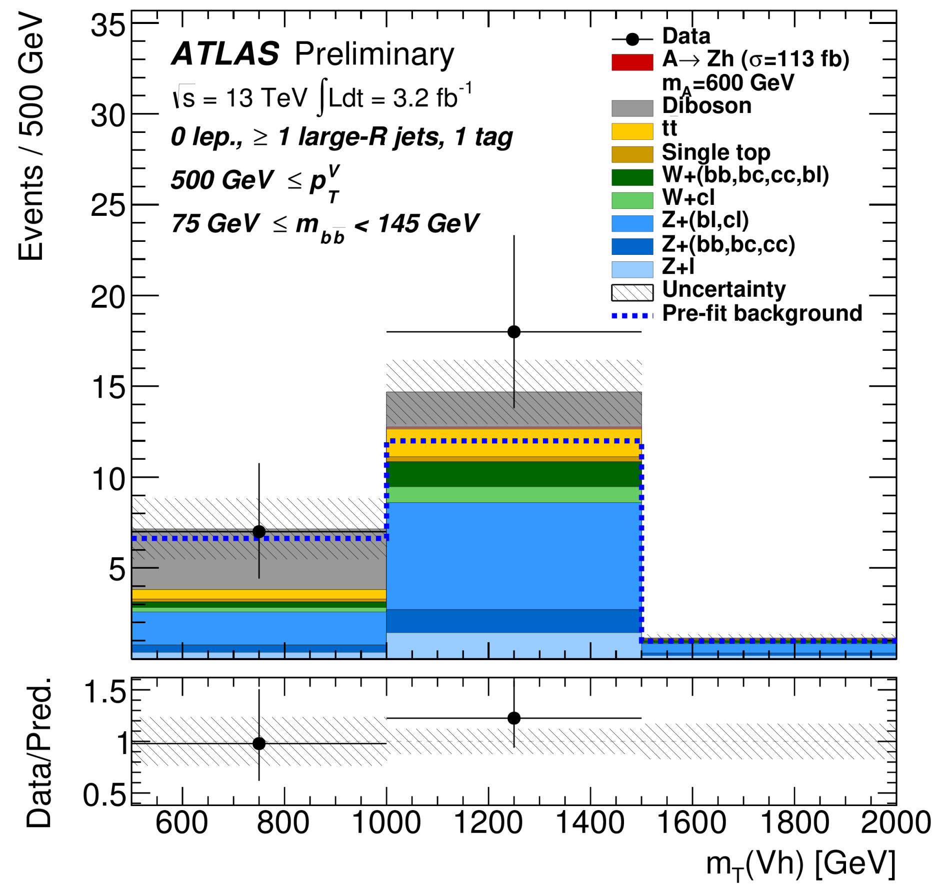
A → ZH → ll/νν bb – Signal Region

- Primary backgrounds: W/Z+jets and $t\bar{t}$
- Diboson and single top at percent level
- Negligible QCD contributions

- Invariant mass for 2-lepton channel
- Transverse mass for 0-lepton channel

$$m_{\mathrm{T}}^{Zh} = \sqrt{(E_{\mathrm{T}}^{h} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T}}^{\,h} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

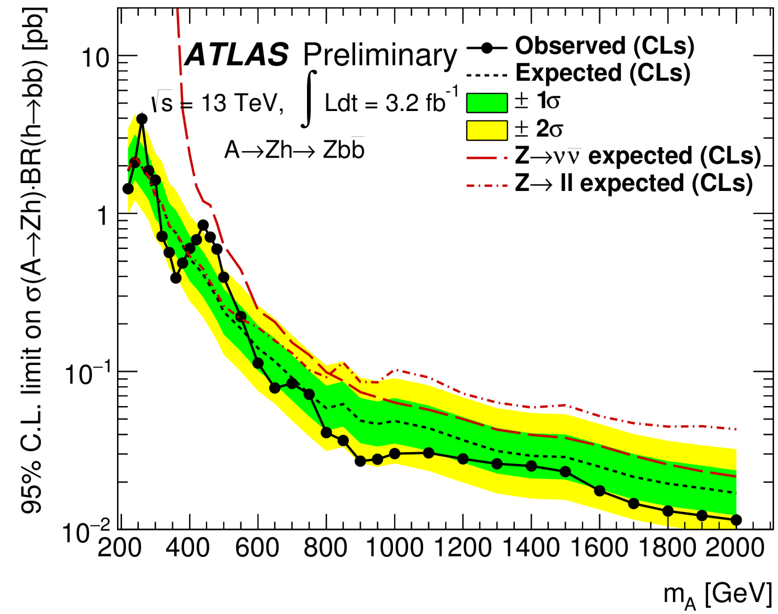




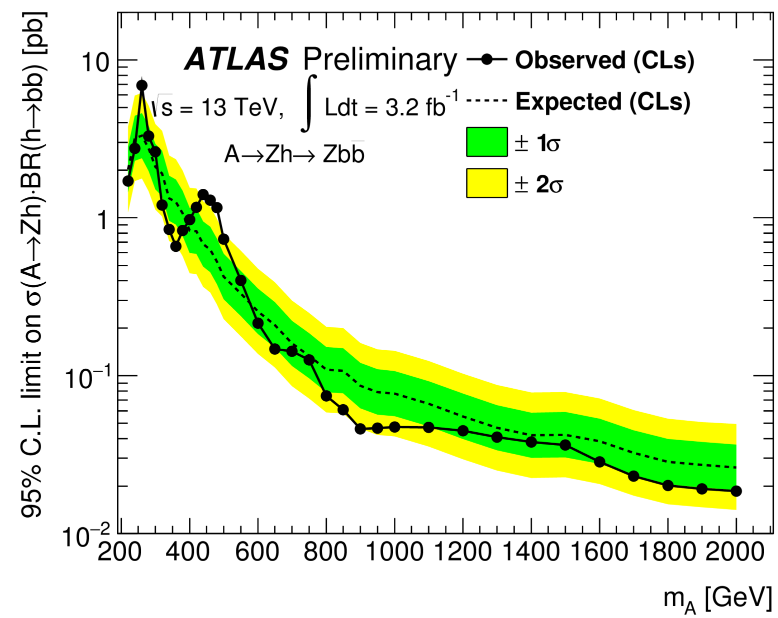
A → ZH → ll/νν bb – Results

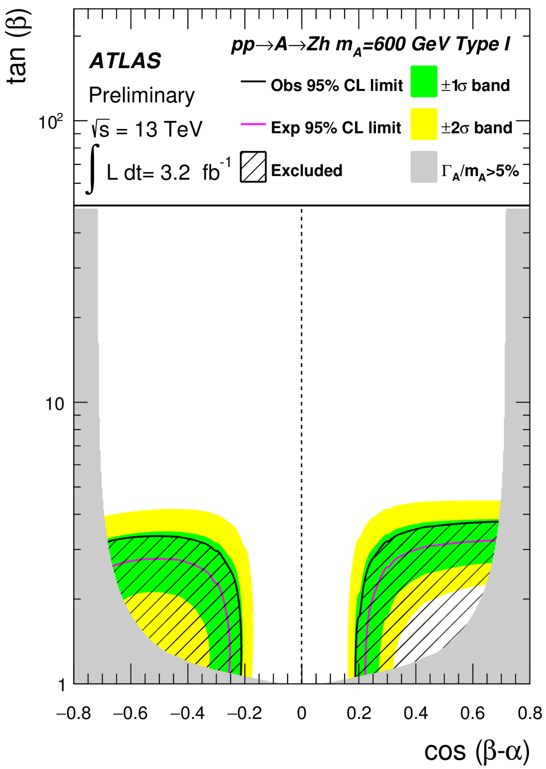
- 95% CL limits on σ x BR
- Interpretation in context of type I and type II 2HDM

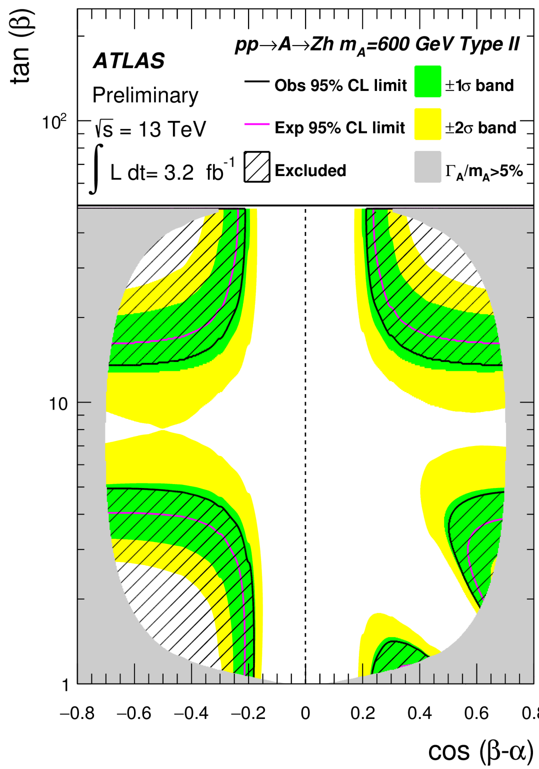
Pure gluon fusion production



Pure b-quark associated production







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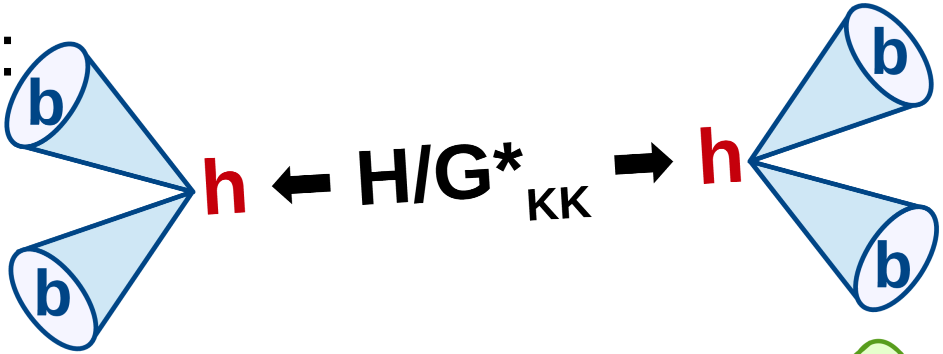
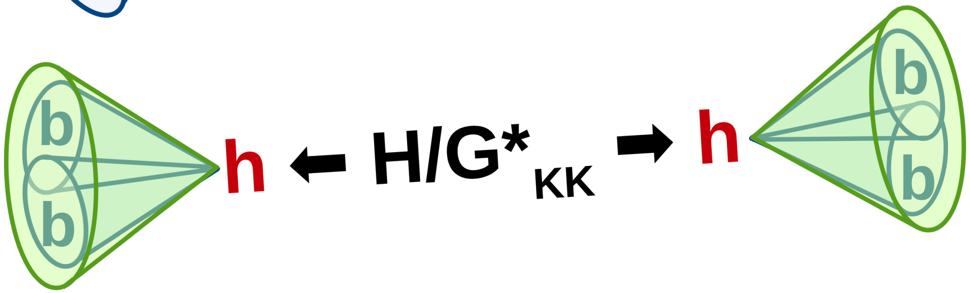
hh → $b\bar{b}b\bar{b}$ – Analysis Strategy

- Resonant di-Higgs production:
  - **Resolved:**
    resonance mass > 500 GeV



  - **Boosted:**
    resonance mass > 1100 GeV

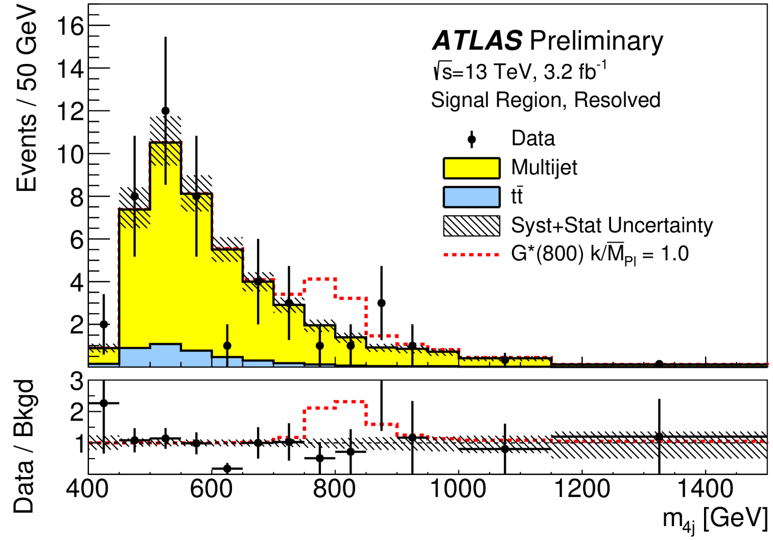


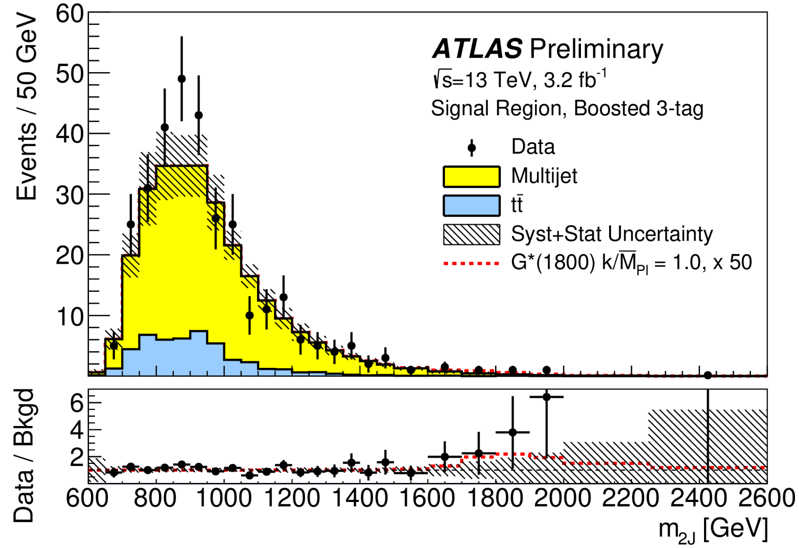
	Trigger	B-tagged jets	1. Object	2. Object
resolved	**1 or 2 b-jets**	**At least 4**	**p_T > 200 GeV**	**p_T > 150 GeV**
boosted	**1 large-R jet**	**Either 3 or at least 4**	**p_T > 350 GeV**	**p_T > 250 GeV**

- Non-resonant di-Higgs production similar to resolved resonant category

hh → $b\bar{b}b\bar{b}$

- Multijet estimated from data
- $t\bar{t}$ shape estimated from simulation, normalization estimated from data
- Z+jets estimated from simulation (contributes less than 1%)
- Largest systematic uncertainties due to b-tagging efficiency and jet energy/mass scale/resolution





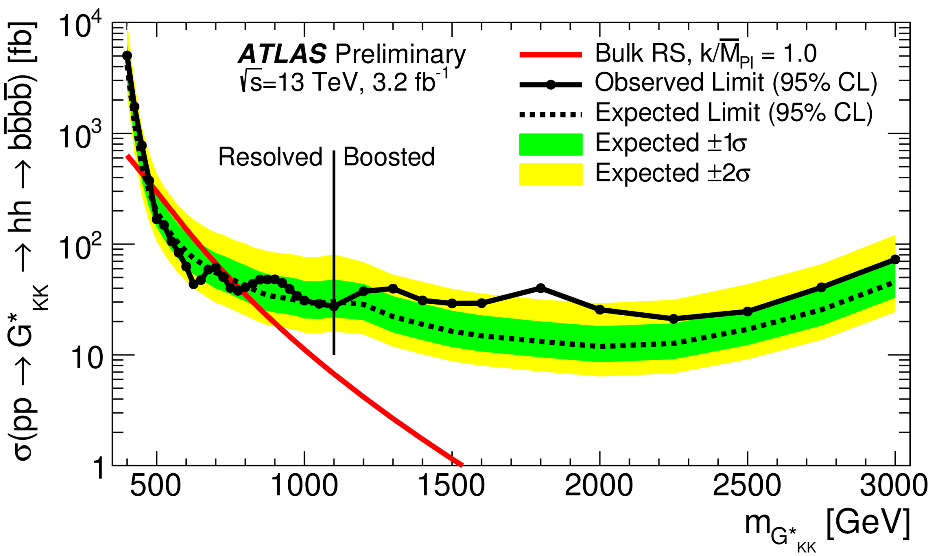
Sample	Signal Region Yield
Multijet	43.3 ± 2.3
$t\bar{t}$	4.3 ± 3.0
Z+jets	-
Total	47.6 ± 3.8
Data	46
SM hh	0.25 ± 0.07
G^*_{KK} (800 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	5.7 ± 1.5

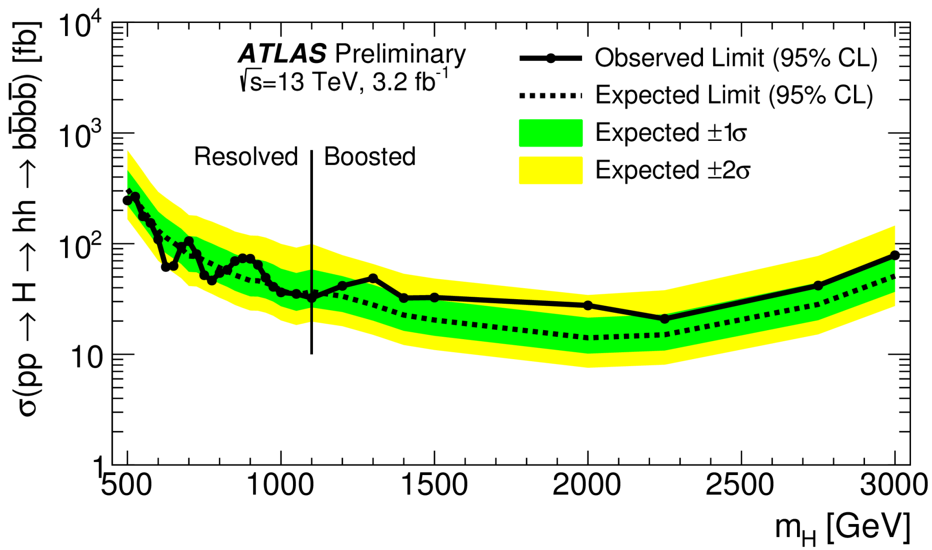
Sample	Signal Region (3-tag)	Signal Region (4-tag)
Multijet	235 ± 14	13.5 ± 2.4
$t\bar{t}$	48 ± 22	1.2 ± 1.0
Z+jets	2.0 ± 2.2	-
Total	285 ± 19	14.6 ± 2.4
Data	316	20
G^*_{KK} $(1000\,GeV)$, $k/\bar{M}_{\mathrm{Pl}} = 1$	3.4 ± 0.9	2.9 ± 1.1

$H \to hh \to b\bar{b}b\bar{b}$ – Results

- Prediction and observation are in agreement
- No significant local excess
- Resolved category: largest deviation at 900 GeV → less than 2σ
- Boosted category: largest deviation at 1.7 TeV → less than 2σ for G^*_{KK} and $k/\overline{M}_{Pl} = 1$
- Non-resonant di-Higgs: $\sigma(pp \to hh \to b\bar{b}b\bar{b}) < 1.22$ pb

  compared to SM prediction: $\sigma(pp \to hh \to b\bar{b}b\bar{b}) = 12.9^{+1.5}_{-1.6}$ fb
- 95% CL upper limits on G^*_{KK} and $k/\overline{M}_{Pl} = 1$ or 2 and narrow width H





Summary

- Presented first 13 TeV results for new physics introducing heavy Higgses and di-Higgs resonances
- No significant excess above the SM prediction observed
- Looking forward to 2016 data taking

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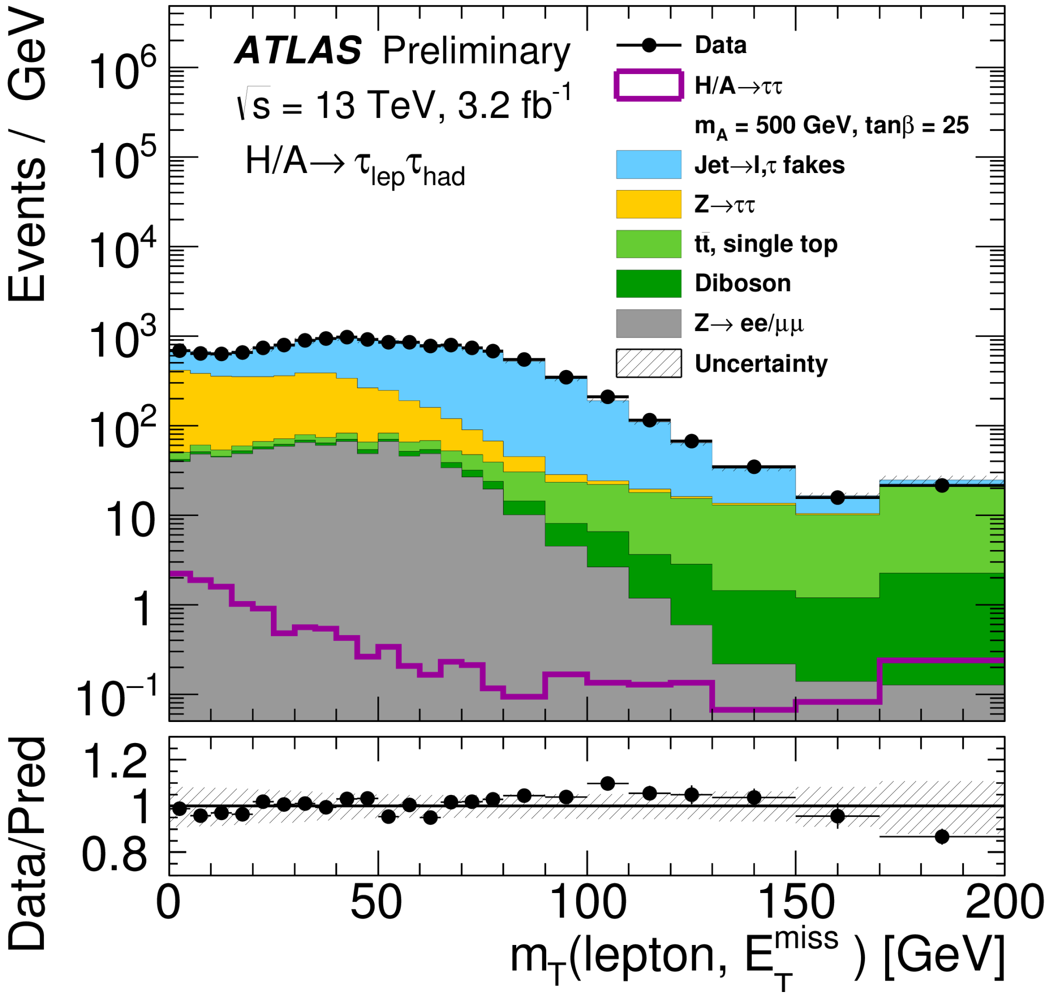
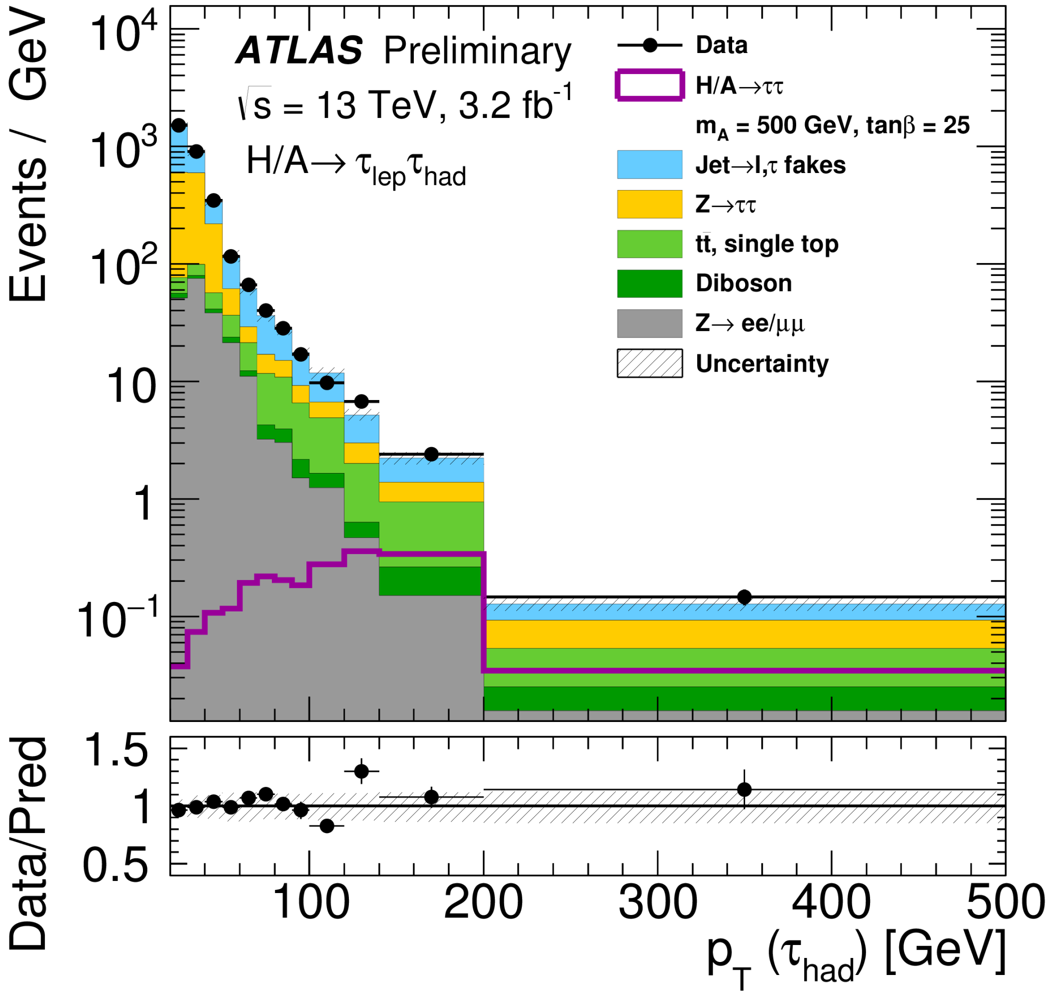
BACKUP

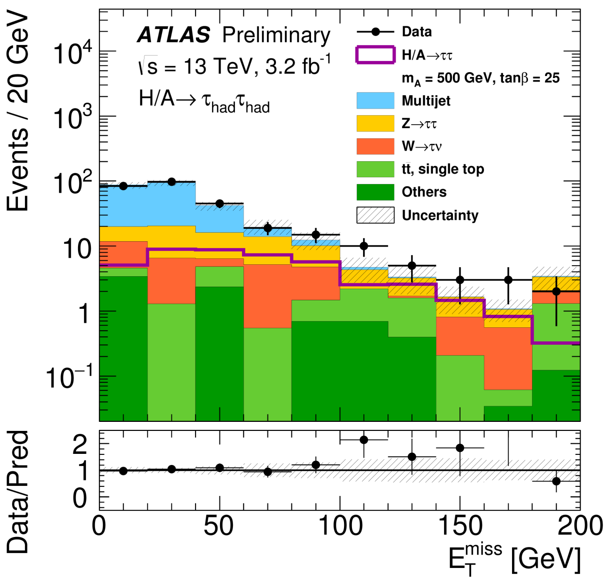
H → ττ – lephad channel

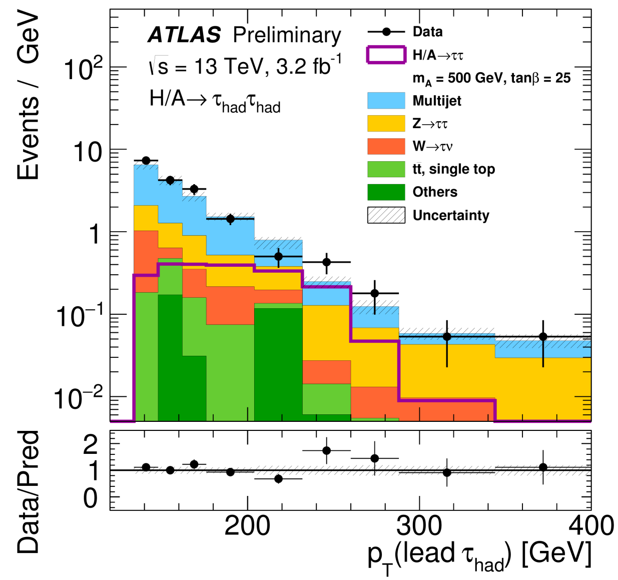
- After Δϕ cut but before m_T cut
- After full selection



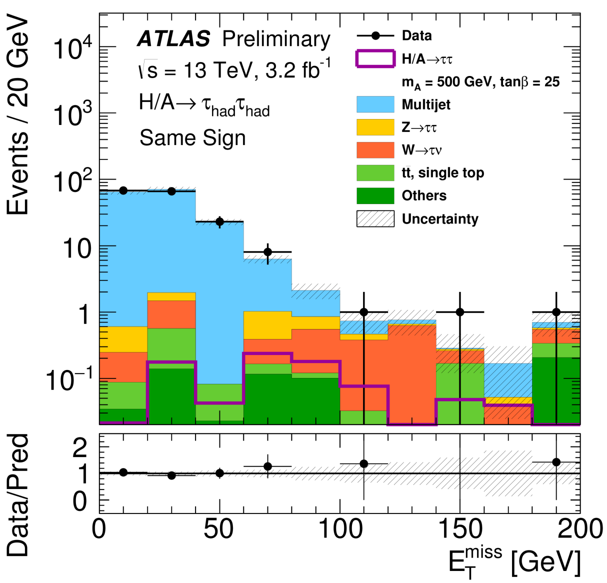


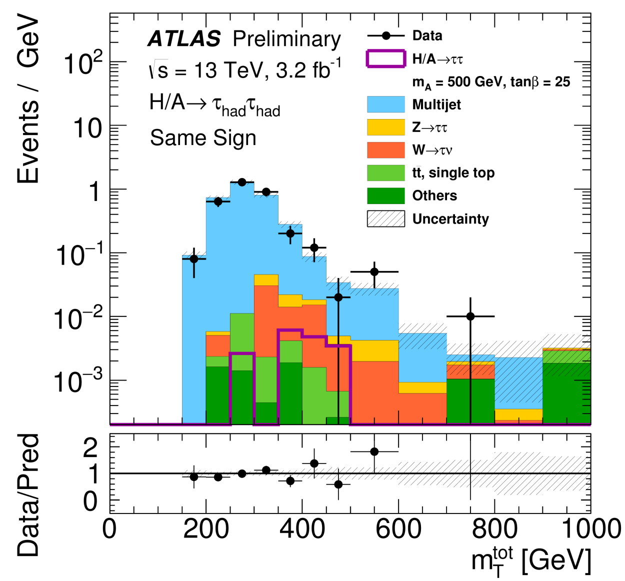
H→ττ – hadhad channel





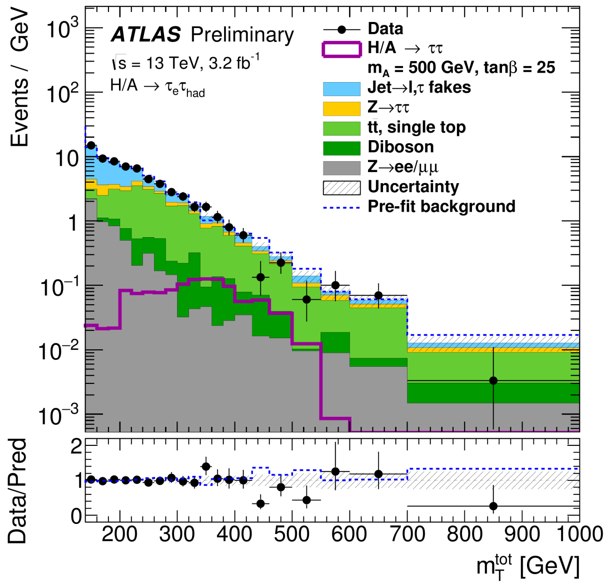
Signal region

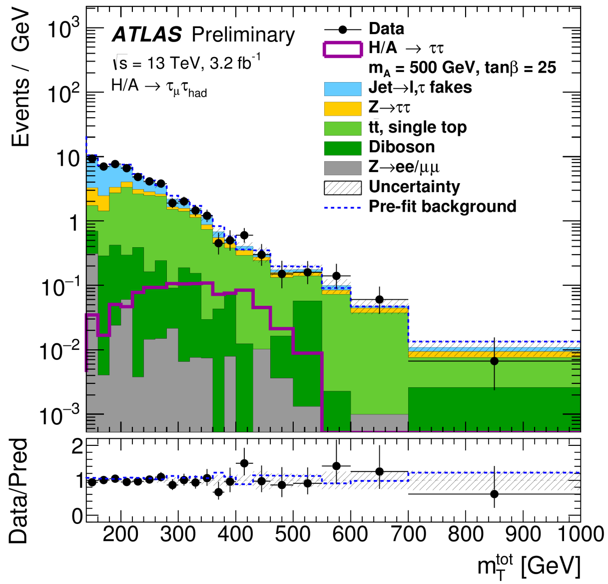


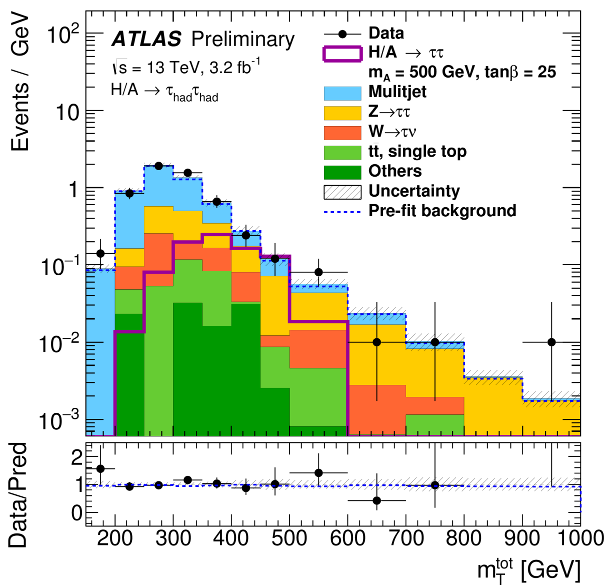


Same sign control Region

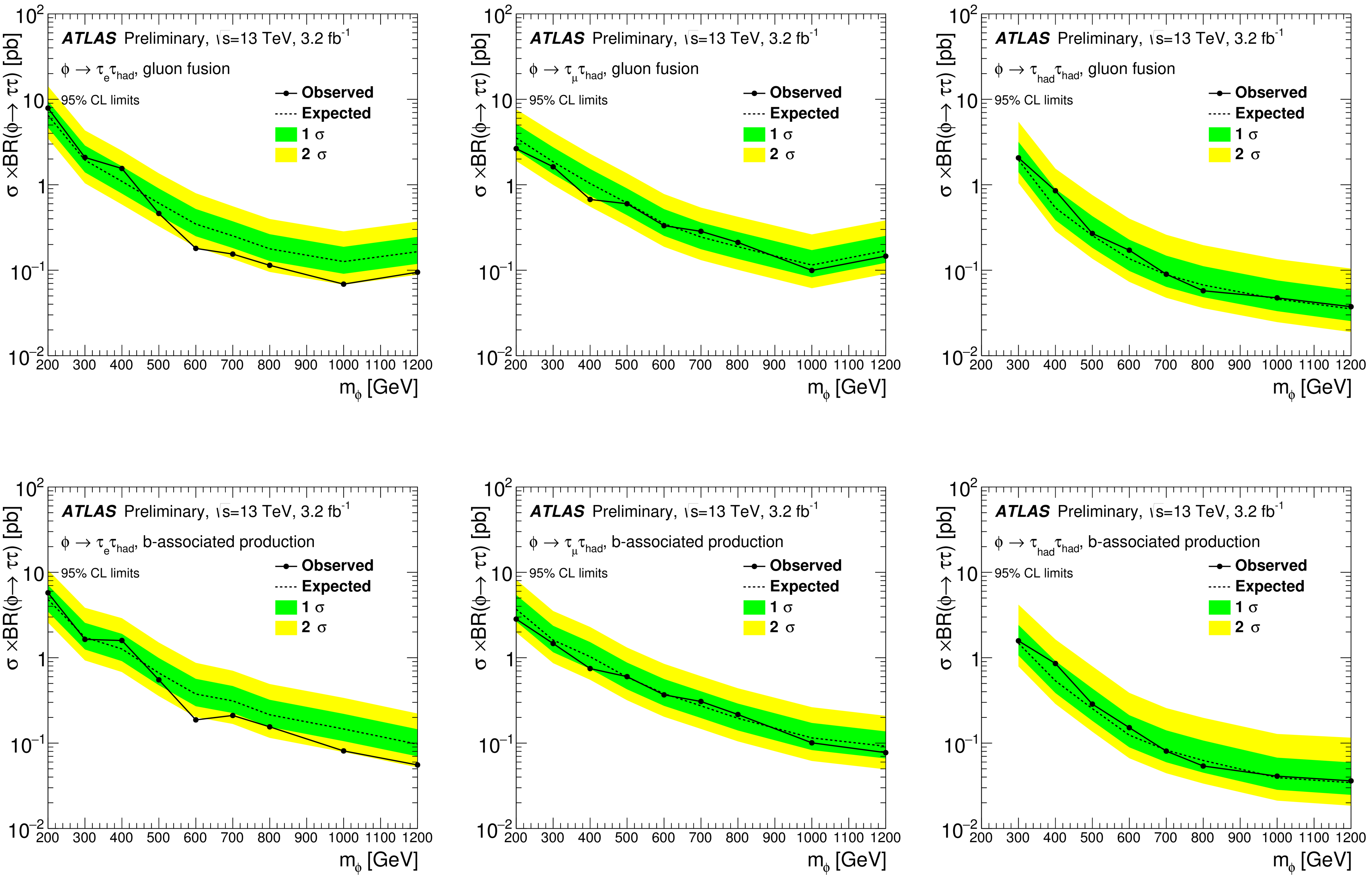
H → ττ – Total Transverse Mass





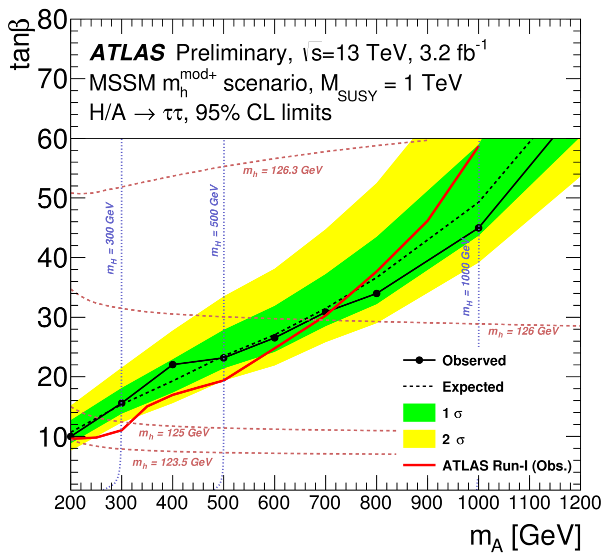


H → ττ – Limits

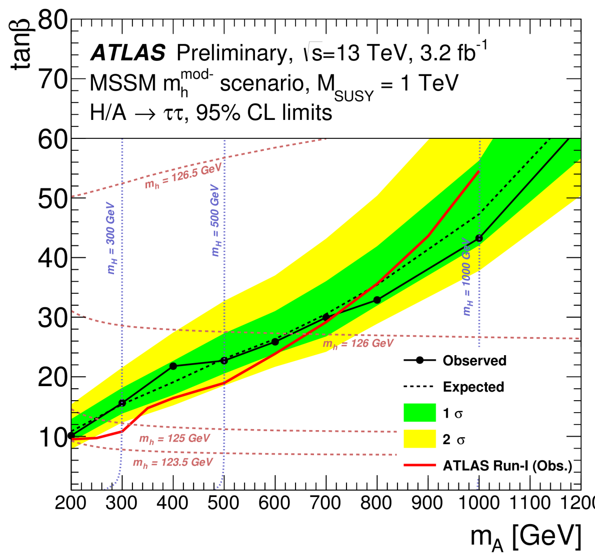


ATLAS Preliminary, √s=13 TeV, 3.2 fb⁻¹
ϕ → τ_e τ_had, gluon fusion
ϕ → τ_μ τ_had, gluon fusion
ϕ → τ_had τ_had, gluon fusion
ϕ → τ_e τ_had, b-associated production
ϕ → τ_μ τ_had, b-associated production
ϕ → τ_had τ_had, b-associated production
95% CL limits
Observed
Expected
1 σ
2 σ
σ ×BR(ϕ→ ττ) [pb]
m_ϕ [GeV]

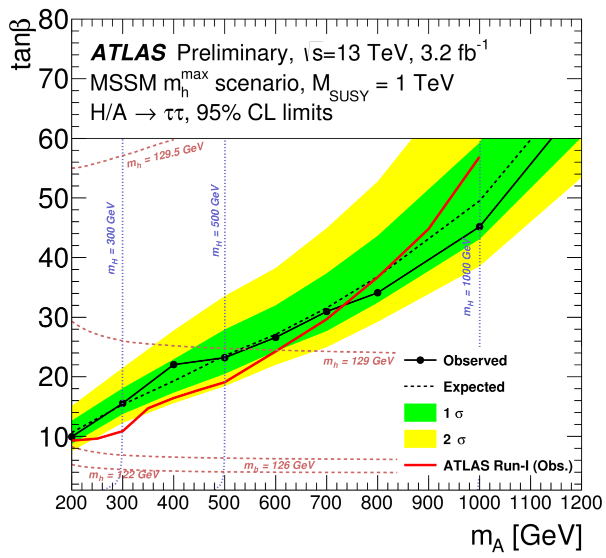
H → ττ – Limits



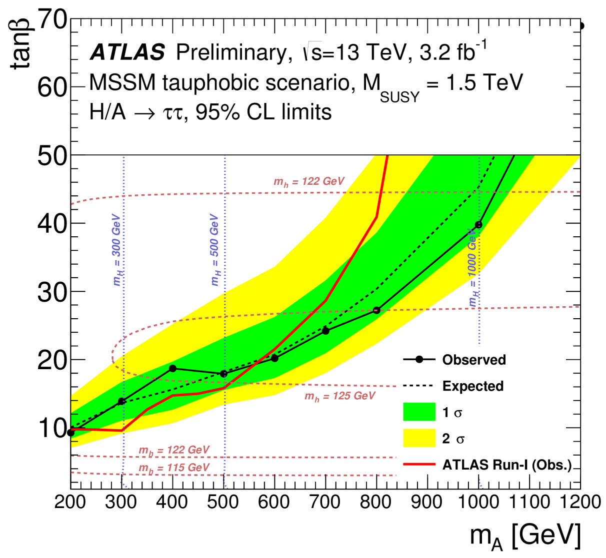
ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM m_h^mod+ scenario, M_SUSY = 1 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 126.3 GeV
m_h = 126 GeV
m_h = 125 GeV
m_h = 123.5 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV



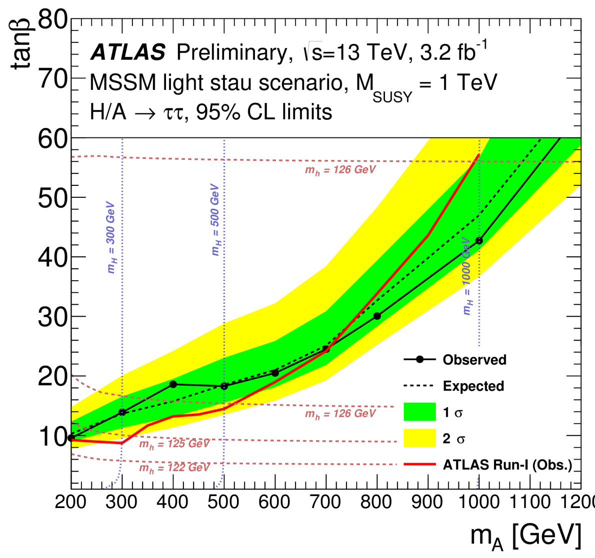
ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM m_h^mod- scenario, M_SUSY = 1 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 126.5 GeV
m_h = 126 GeV
m_h = 125 GeV
m_h = 123.5 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV



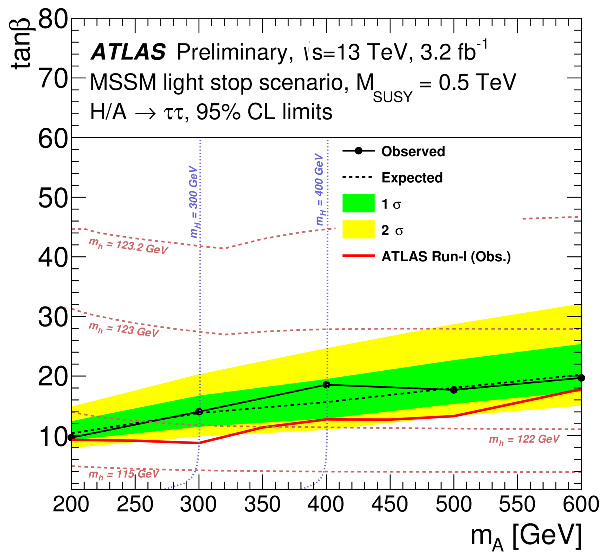
ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM m_h^max scenario, M_SUSY = 1 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 129.5 GeV
m_h = 129 GeV
m_h = 126 GeV
m_h = 122 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV



ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM tauphobic scenario, M_SUSY = 1.5 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 122 GeV
m_h = 125 GeV
m_h = 115 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV



ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM light stau scenario, M_SUSY = 1 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 126 GeV
m_h = 125 GeV
m_h = 122 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV



ATLAS Preliminary, √s=13 TeV, 3.2 fb-1
MSSM light stop scenario, M_SUSY = 0.5 TeV
H/A → ττ, 95% CL limits
tanβ
m_A [GeV]
Observed
Expected
1 σ
2 σ
ATLAS Run-I (Obs.)
m_h = 123.2 GeV
m_h = 123 GeV
m_h = 122 GeV
m_h = 115 GeV
m_H = 300 GeV
m_H = 400 GeV

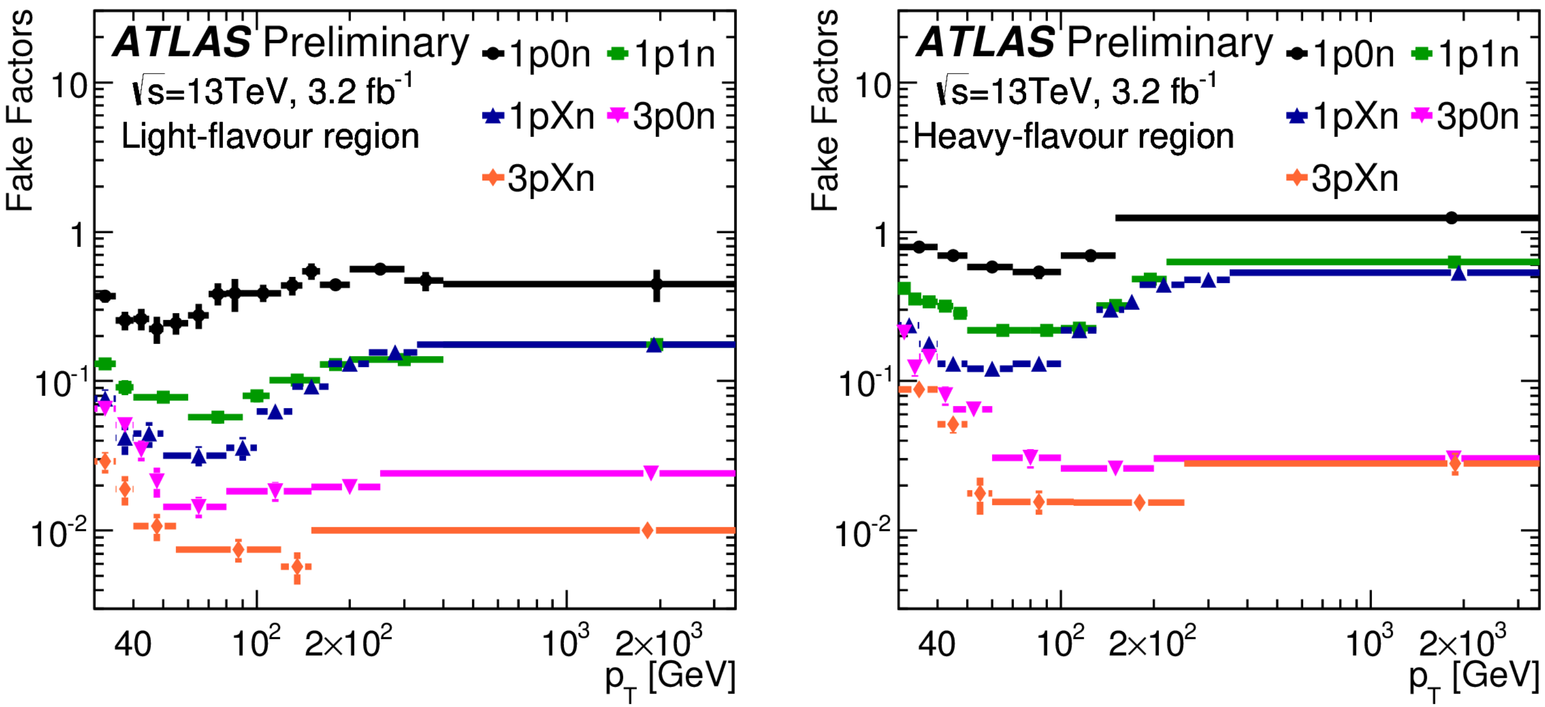
$H \to \tau\tau$ – Limits

Lowest excluded values of tan β for different masses of the MSSM CP-odd Higgs boson, m_A, for the m_h^{mod+} scenario

m_A [GeV]	observed	expected	$+2\sigma$ [pb]	$+1\sigma$	-1σ	-2σ
200	10	11	15	13	9.1	7.9
300	16	15	22	18	13	12
400	22	19	28	23	17	15
500	23	23	33	28	21	19
600	27	27	38	32	24	22
700	31	31	45	37	28	25
800	34	37	52	43	33	29
1000	45	49	> 60	59	43	39
1200	> 60	> 60	> 60	> 60	60	53

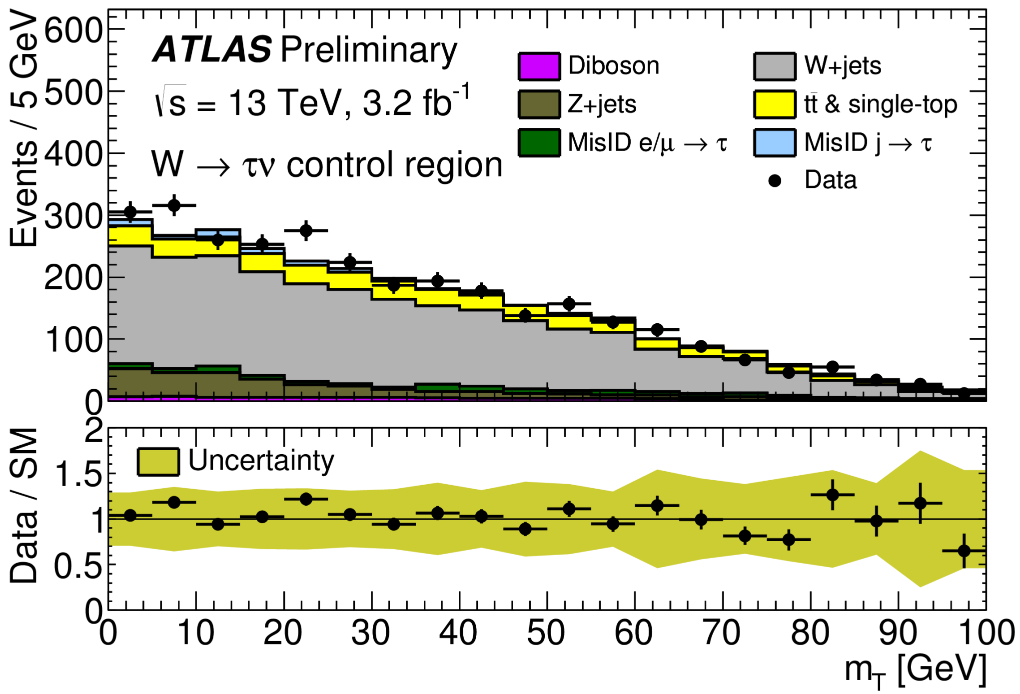
$H^{+/-} \rightarrow \tau\nu$ – Fake Factors

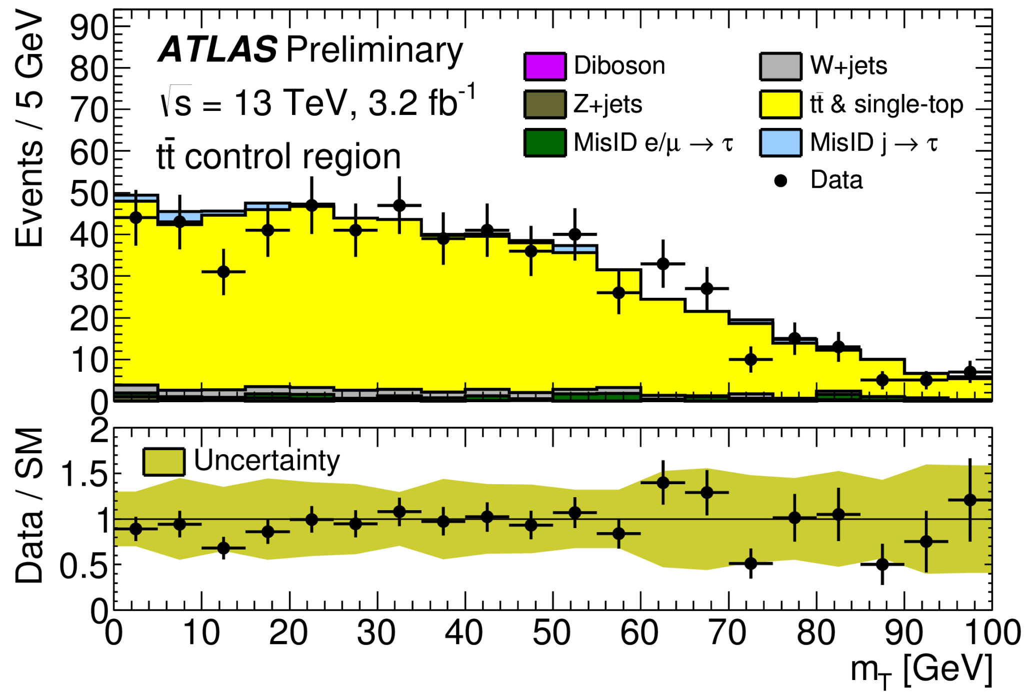
- control region populated primarily with misidentified τ had-vis candidates:
  - same requirements as for the signal region, except: missing E_T < 80 GeV, no b-tagged jets
- FF is defined as the number of misidentified medium $\tau_{had\text{-}vis}$ candidates over number of misidentified not medium but loose $\tau_{had\text{-}vis}$ candidates
- FFs are parameterised in: τ p_T, number of charged and neutral pions, b-tagging score
- threshold on the b-tagging score of the τ had-vis candidate is optimized to keep sufficient statistics in each of the two bins, below and above the threshold.



$H^{+/-} \rightarrow \tau\nu$ – Control Regions

- m_T < 100 GeV (instead of m_T > 50 GeV)
- $W \rightarrow \tau\nu$: no b-tagged jets
- $t\bar{t}$: at least 2 b-tagged jets

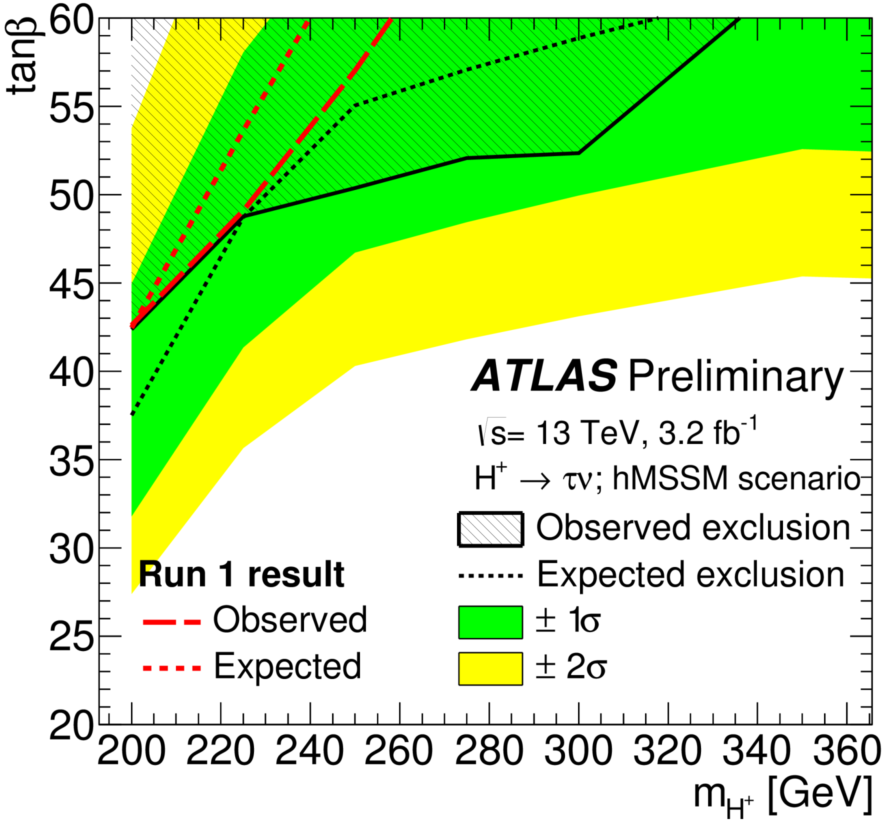


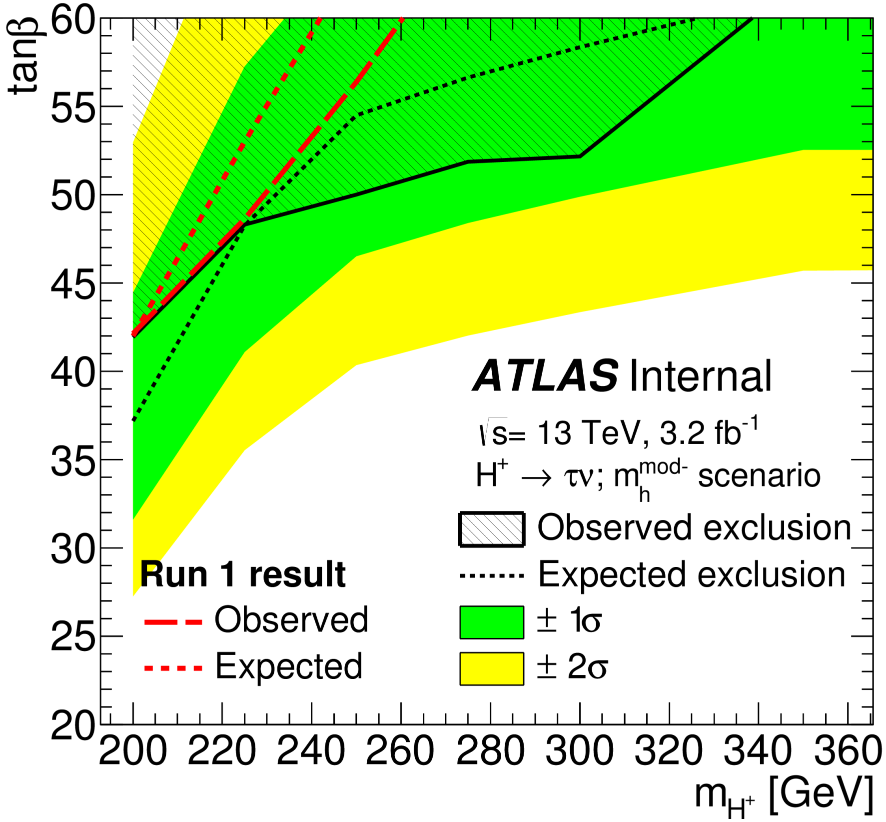


$H^{+/-} \to \tau\nu$ – Systematics

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

$H^{+/-} \rightarrow \tau\nu$ – Limits





$H^{+/-} \rightarrow \tau\nu$ – Limits

H^+ mass [GeV]	Observed	Expected	$-2\ \sigma$	$-1\ \sigma$	$+1\ \sigma$	$+2\ \sigma$
200	1.9	1.5	0.79	1.1	2.1	3
225	1.3	1.3	0.67	0.9	1.8	2.5
250	0.8	0.95	0.51	0.69	1.4	1.9
275	0.57	0.69	0.37	0.49	0.98	1.4
300	0.41	0.52	0.28	0.37	0.74	1
350	0.34	0.33	0.18	0.24	0.48	0.69
400	0.2	0.2	0.11	0.15	0.3	0.43
500	0.093	0.11	0.056	0.076	0.15	0.22
600	0.05	0.071	0.038	0.051	0.1	0.15
700	0.033	0.052	0.028	0.038	0.076	0.11
800	0.024	0.039	0.021	0.028	0.058	0.084
900	0.021	0.036	0.019	0.026	0.052	0.076
1000	0.018	0.031	0.017	0.022	0.045	0.066
1200	0.016	0.027	0.015	0.02	0.04	0.059
1400	0.015	0.026	0.014	0.019	0.038	0.056
1600	0.015	0.025	0.014	0.018	0.037	0.055
1800	0.015	0.025	0.013	0.018	0.037	0.055
2000	0.015	0.025	0.013	0.018	0.037	0.055

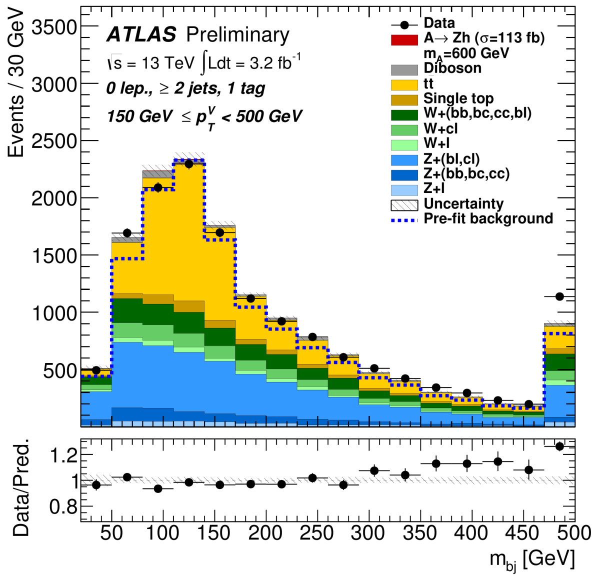
$A \to ZH \to ll/\nu\nu\ bb$ – Selection

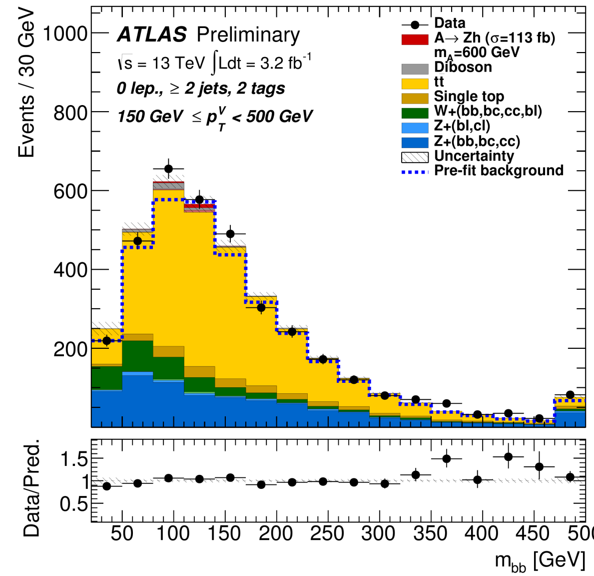
Variable	Low-p_T^Z	High-p_T^Z
Common selection		
p_T^Z [GeV]	<500	$\geq$ 500
$N_{b\text{-tag jet}}$	1,2	1,2
$N_{\text{small-}R\text{ jet}}$	$\geq$2	$\geq$0
$N_{\text{large-}R\text{ jet}}$	$\geq$0	$\geq$1
m_{dijet} or m_{jet} [GeV]	110–140	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	–
$\sum_{i=1}^{N_{\text{jet}}=3(2)} p_T^{\text{jet}_i}$ [GeV]	$> 150\ (120)^{(*)}$	–
p_T^{miss} [GeV]	> 30	> 30
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{ miss}})$	$< \pi/2$	$< \pi/2$
$\Delta\phi(\vec{E}_T^{\text{miss}}, h)$	$> 2\pi/3$	$> 2\pi/3$
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{small-}R\text{ jet})]$	$> \pi/9^{(*)}$	$> \pi/9^{(*)}$
$\Delta\phi(j, j)$	$< 7\pi/9$	–
Number of hadronic taus	0	0
Number of b-tag track-jets not associated to the leading large-R jet	–	0
2-lepton selection		
m_{ee} [GeV]	70–110	70–110
$m_{\mu\mu}$ [GeV]	70–110	55–125
$E_T^{\text{miss}}/\sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	< 3.5	–

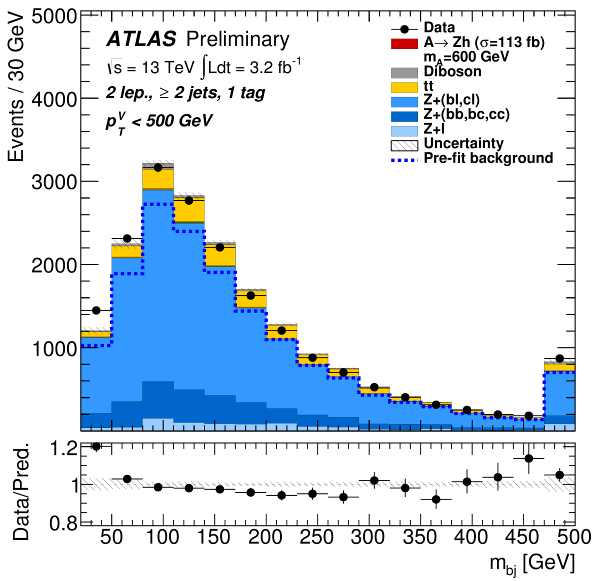
A→ZH→ll/νν bb – Selection

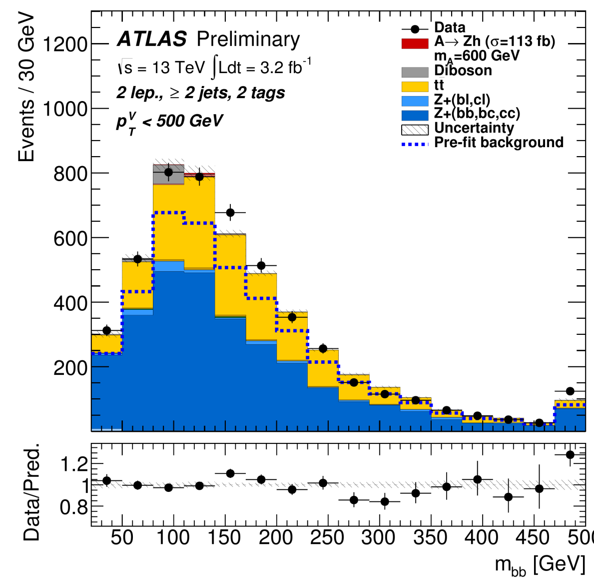
One b-tag				
	0-leptons low-p_T^Z	0-leptons high-p_T^Z	2-leptons low-p_T^Z	2-leptons high-p_T^Z
$Z + l$	55 ± 31	2.0 ± 1.0	118 ± 38	0.57 ± 0.28
$Z + (cl, bl)$	518 ± 54	8.2 ± 1.8	1943 ± 65	3.18 ± 0.65
$Z + (bb, bc, cc)$	82 ± 13	1.82 ± 0.35	391 ± 23	0.74 ± 0.13
$W + l$	48 ± 22	–	–	–
$W + cl$	111 ± 42	1.17 ± 0.45	0.67 ± 0.28	–
$W + (bb, bc, cc, bl)$	185 ± 71	1.80 ± 0.63	10.1 ± 4.2	–
$t\bar{t}$	1202 ± 77	2.05 ± 0.72	276 ± 22	–
single top	99 ±10	0.49 ± 0.11	15.3 ± 1.6	–
diboson	27.2 ± 4.6	5.3 ± 1.0	26.3 ± 6.1	0.67 ± 0.32
$(W/Z)h$	3.3 ± 1.6	0.16 ± 0.08	3.7 ± 1.8	0.04 ± 0.02
total background	2332 ± 45	23.0 ± 2.6	2784 ± 47	5.2 ± 0.9
expected $A \to Zh$ (gluon-fusion)	5.00 ± 0.41	–	1.73 ± 0.12	–
expected $A \to Zh$ (b-quark-associated)	3.05 ± 0.26	–	1.01 ± 0.08	–
data	2295	25	2769	8
Two b-tags				
	0-leptons low-p_T^Z	0-leptons high-p_T^Z	2-leptons low-p_T^Z	2-leptons high-p_T^Z
$Z + l$	0.13 ± 0.44	0.01 ± 0.01	–	–
$Z + (cl, bl)$	4.7 ± 1.8	0.06 ± 0.03	9.6 ± 4.0	0.02 ± 0.01
$Z + (bb, bc, cc)$	81 ± 13	0.75 ± 0.15	490 ± 22	0.36 ± 0.05
$W + l$	–	0.02 ± 0.01	–	–
$W + cl$	3.6 ± 2.1	0.04 ± 0.02	–	–
$W + (bb, bc, cc, bl)$	37 ± 14	0.28 ± 0.09	0.42 ± 0.20	–
$t\bar{t}$	392 ± 24	0.22 ± 0.11	284 ± 22	–
single top	27.8 ± 2.9	–	6.39 ± 0.60	–
diboson	6.1 ± 3.1	0.05 ± 0.03	0.57 ± 0.23	–
$(W/Z)h$	5.4 ± 2.6	0.10 ± 0.05	7.6 ± 3.7	0.03 ± 0.01
total background	557 ± 18	1.53 ± 0.25	799 ± 23	0.42 ± 0.05
expected $A \to Zh$ (gluon-fusion)	9.21 ± 0.76	–	3.65 ± 0.29	–
expected $A \to Zh$ (b-quark-associated)	5.85 ± 0.47	–	2.21 ± 0.17	–
data	577	0	788	0

A → ZH → ll/νν bb – SR + W/Z CR

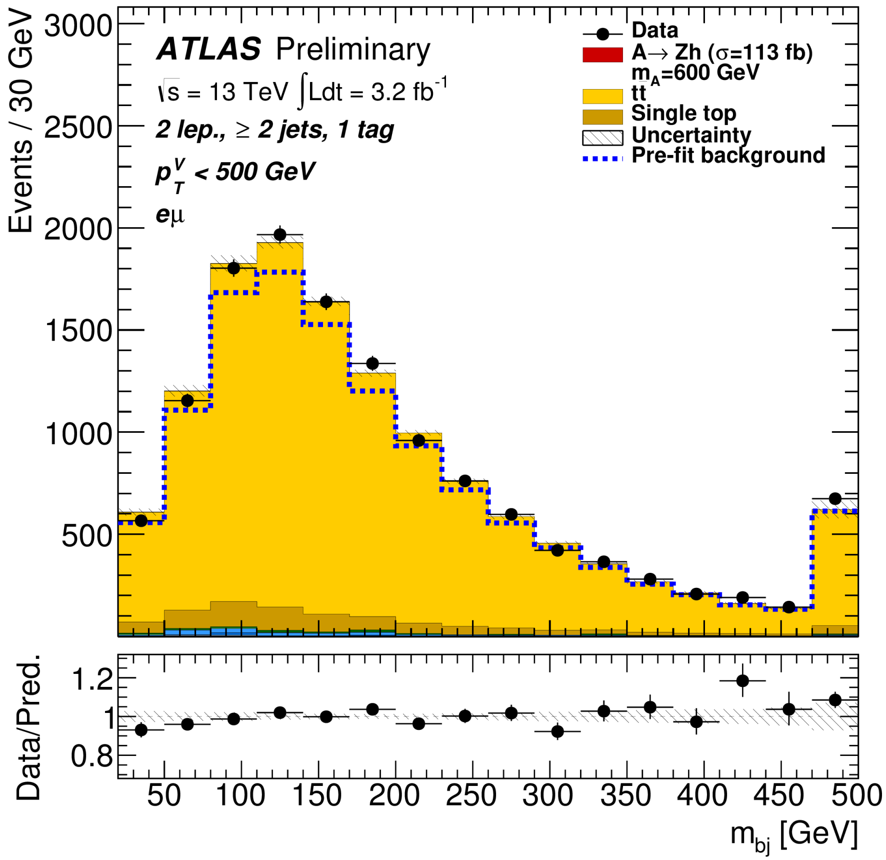


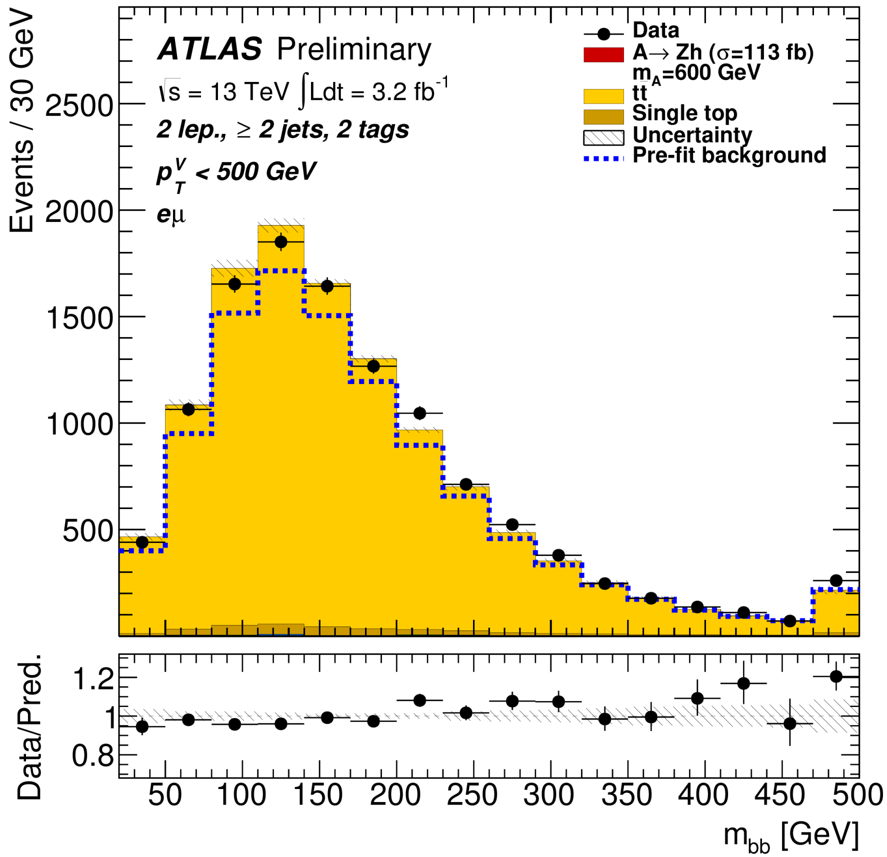




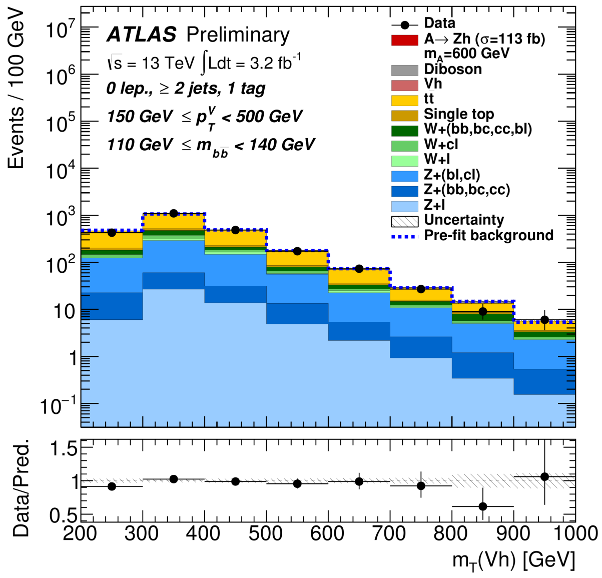


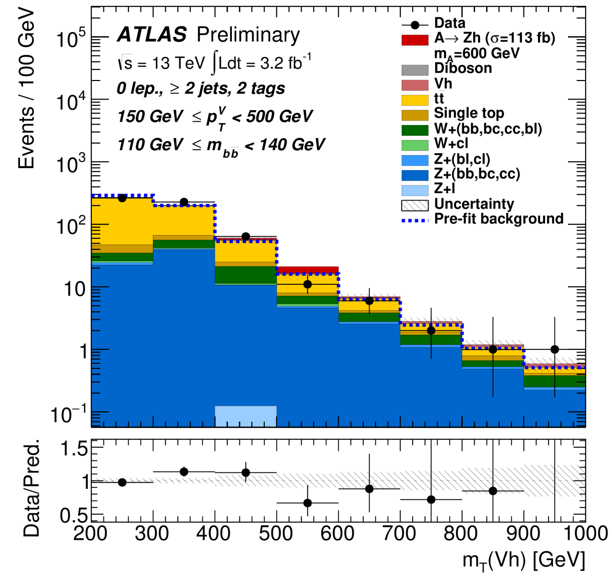
$A \to ZH \to ll/\nu\nu\ bb$ – $t\bar{t}$ CR

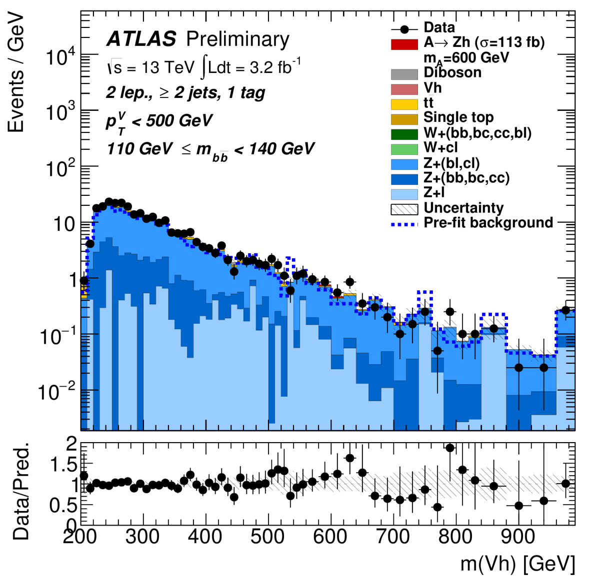


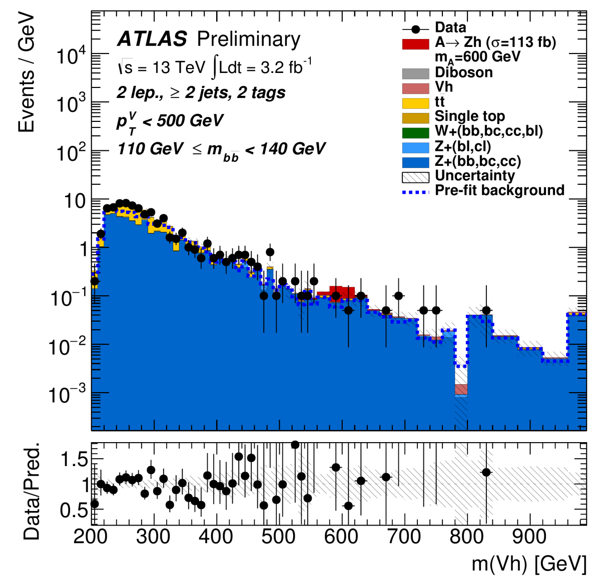


A→ZH→ll/νν bb – Mass Distributions

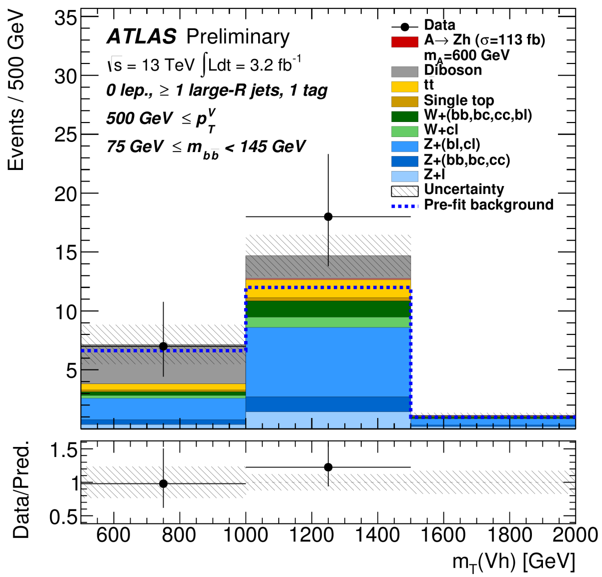


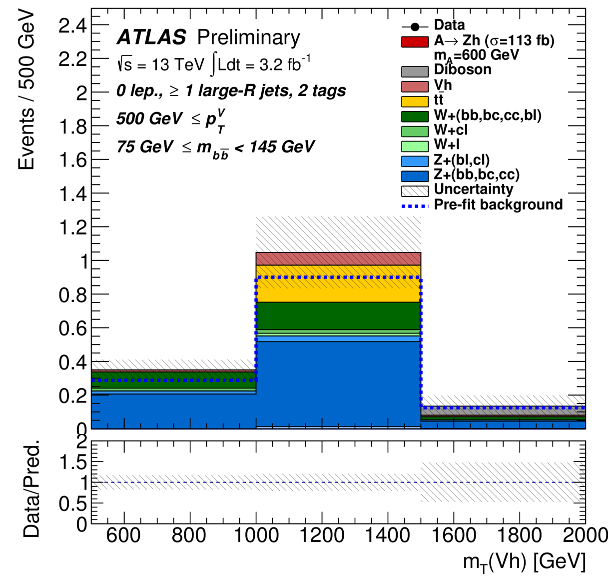


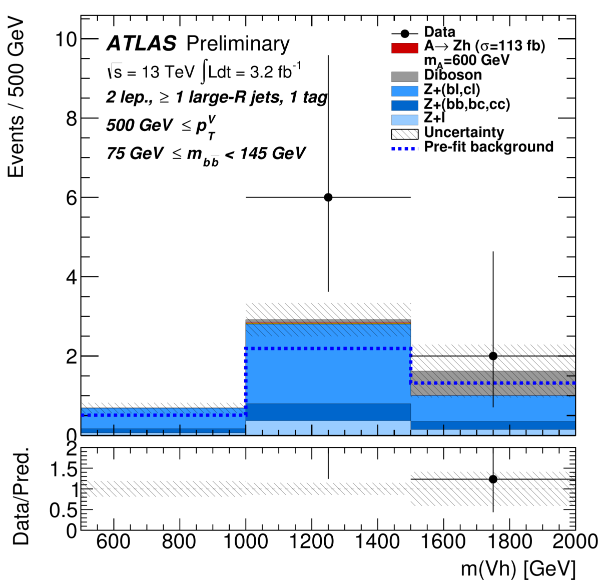


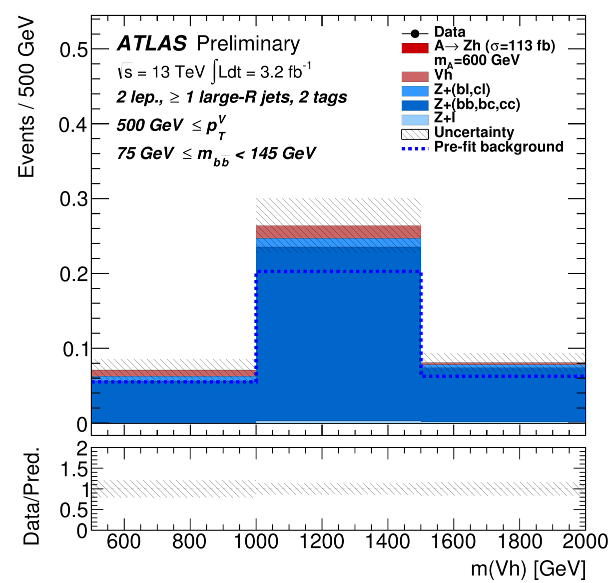


A→ZH→ll/νν bb – Mass Distributions

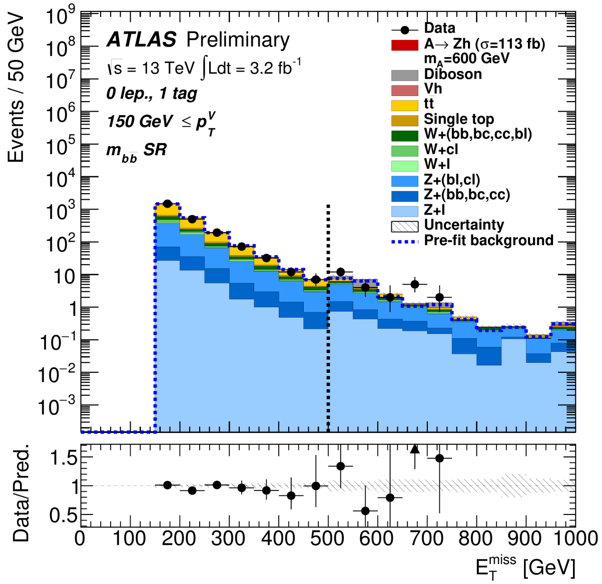


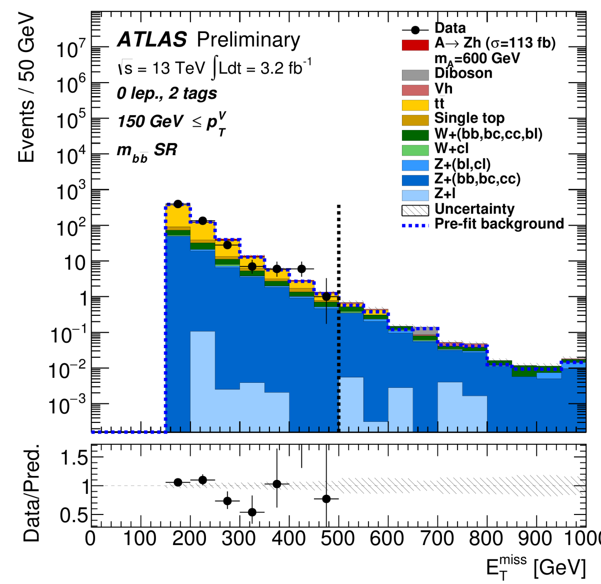


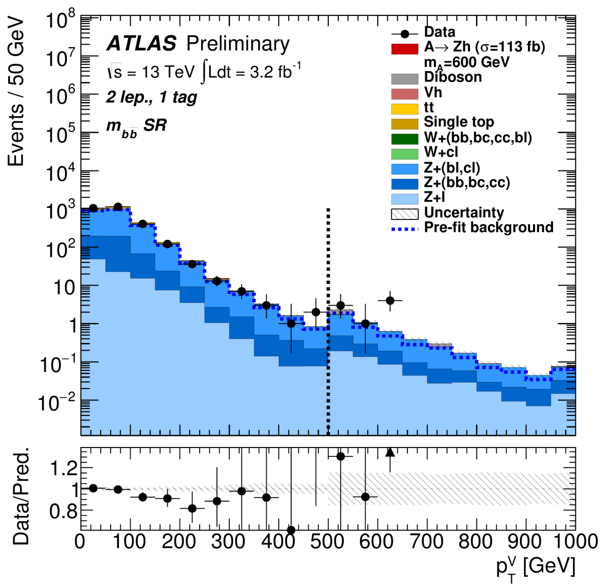


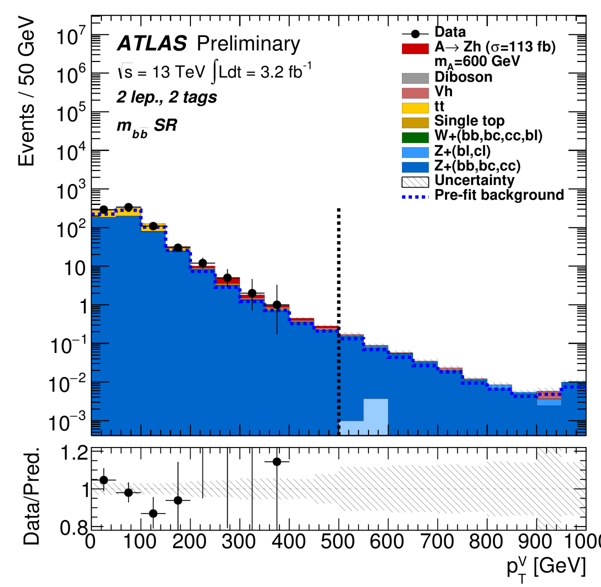


A → ZH → ll/νν bb – Resolved vs. Boosted

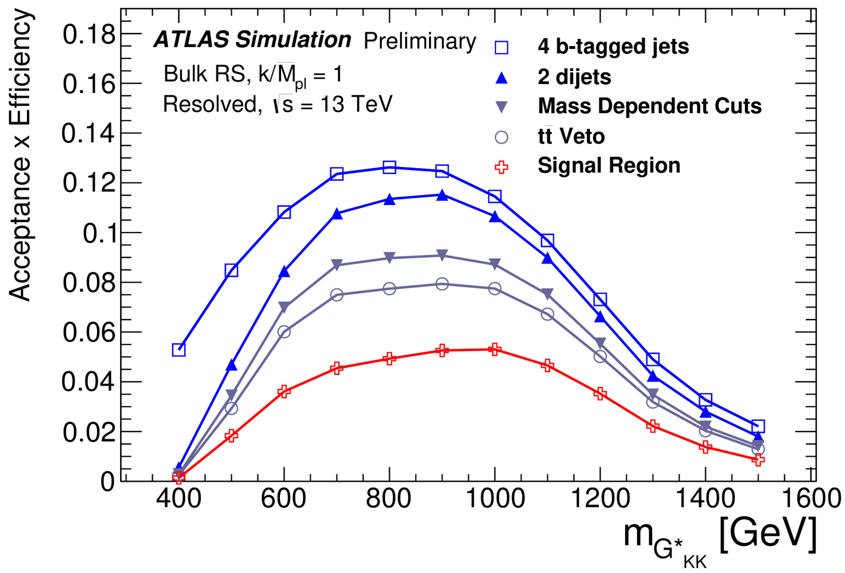


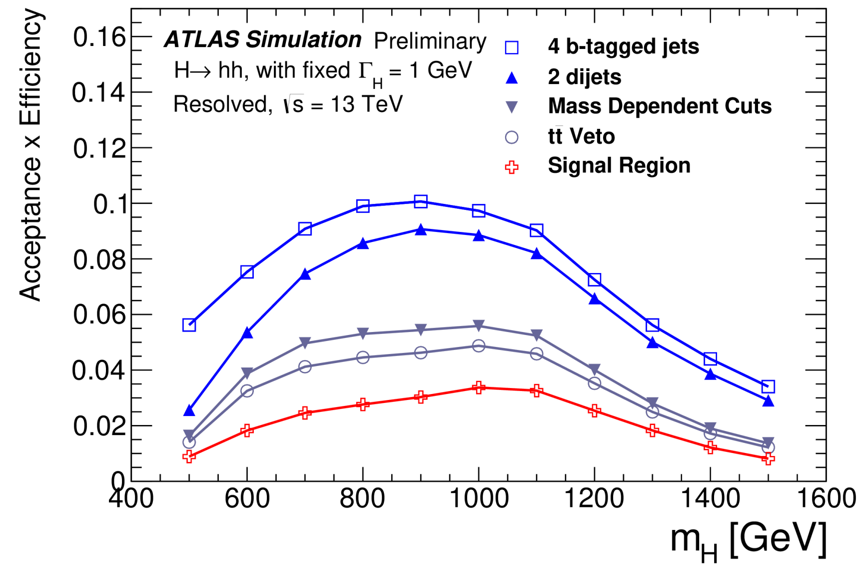


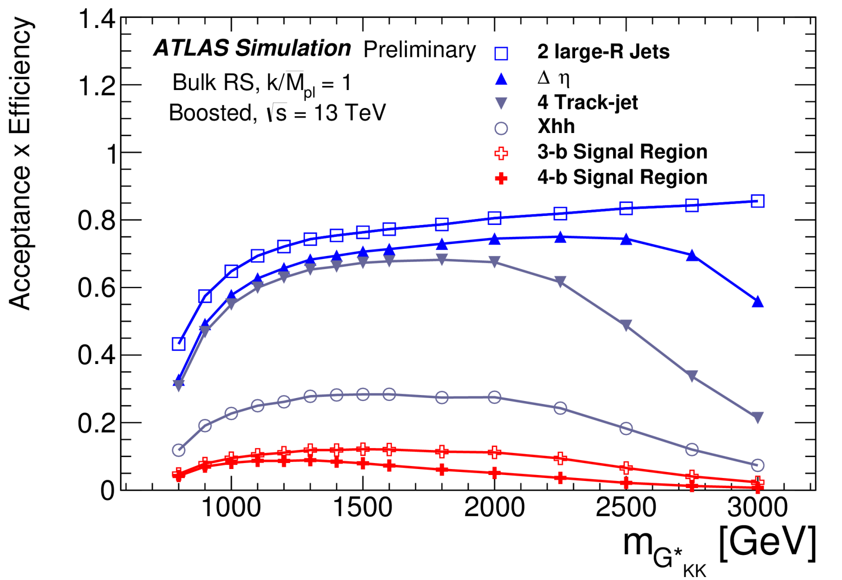


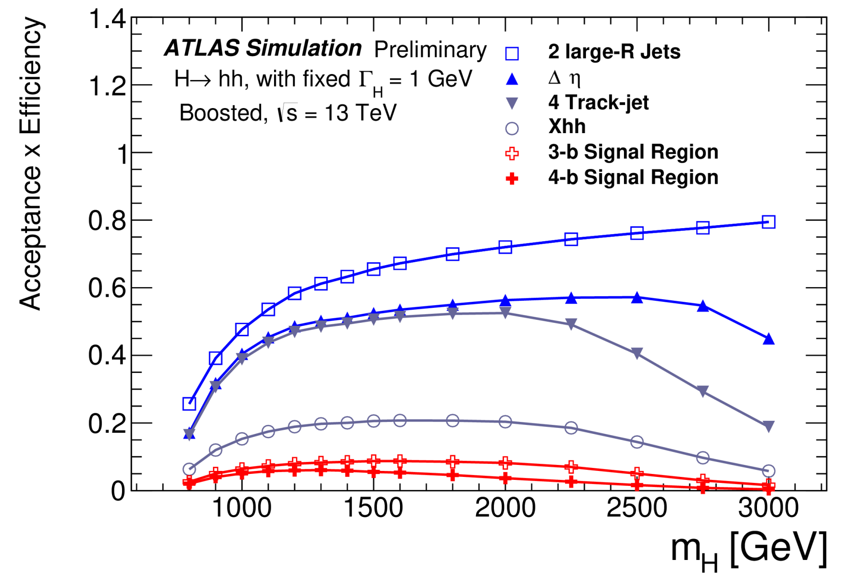


$hh \rightarrow b\bar{b}b\bar{b}$

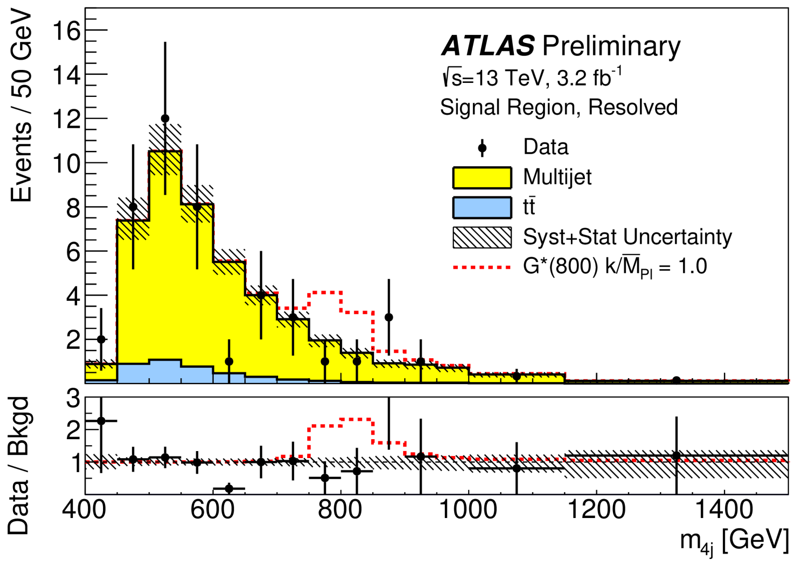


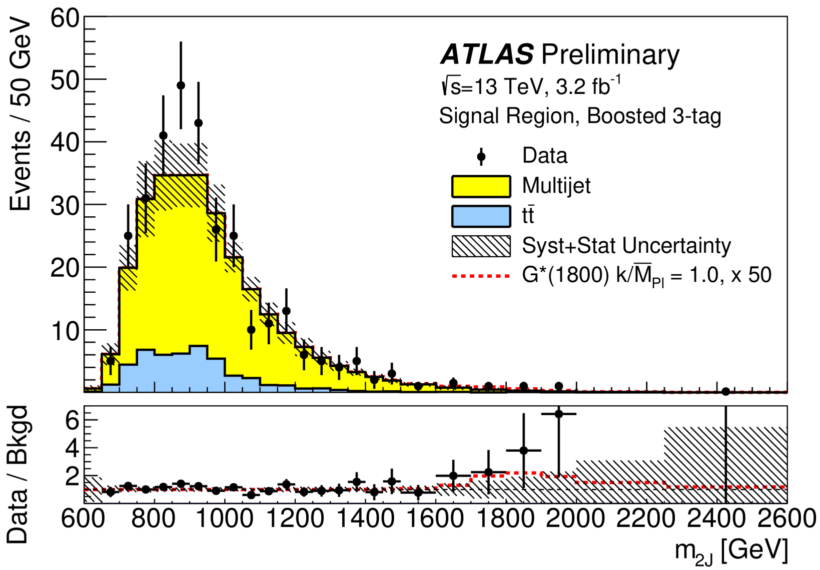


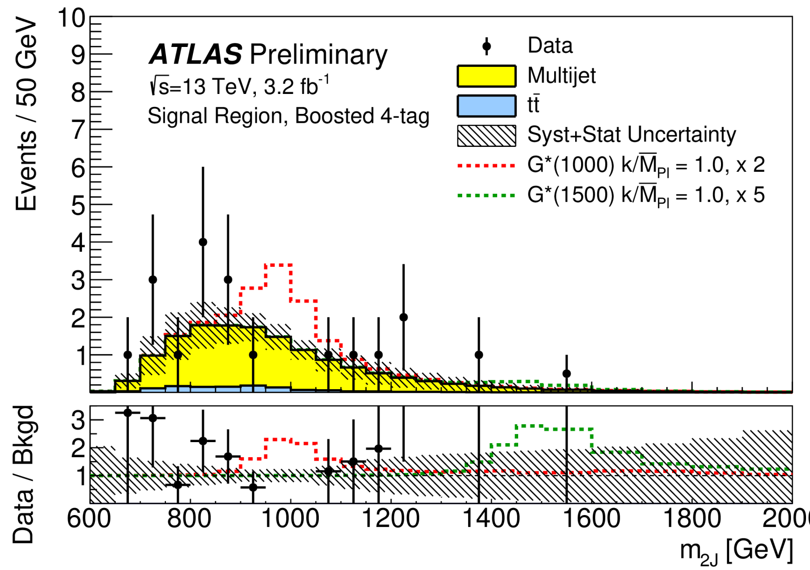




$hh \to b\bar{b}b\bar{b}$







$hh \rightarrow b\bar{b}b\bar{b}$ – Limits