BSM Higgs Physics with the ATLAS Detector

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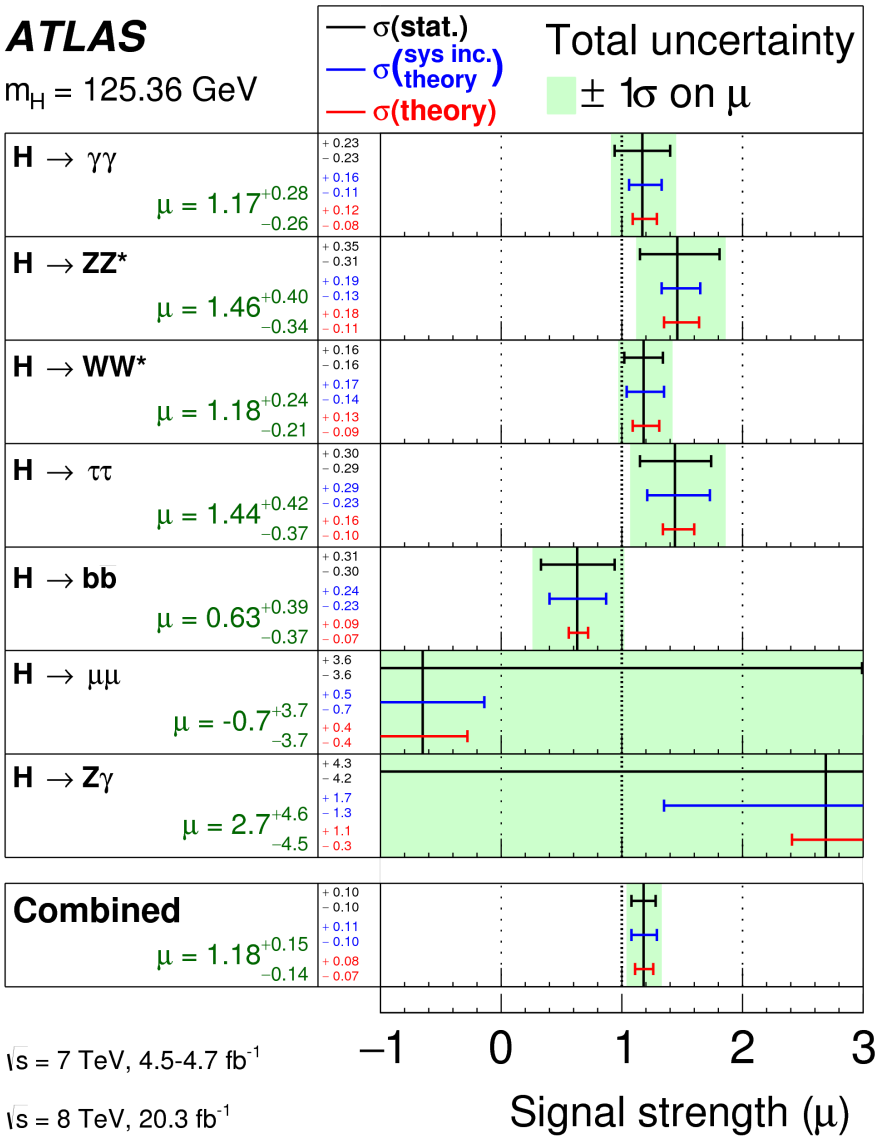
on behalf of the ATLAS Collaboration

Higgs Hunting 2015
Orsay, Paris
30/07/15-01/08/15

Introduction



CERN-PH-EP-2015-125
(see R. Polifka talk)

- Higgs boson discovered in 2012 by ATLAS and CMS
- Since then scrutinised further through CP and coupling measurements
- Currently looks pretty SM-like:
  - $J^P = 0^+$ favoured
  - coupling strengths SM-like to ~20%
- Hence still some wiggle room for extended Higgs sector: searches!

Introduction

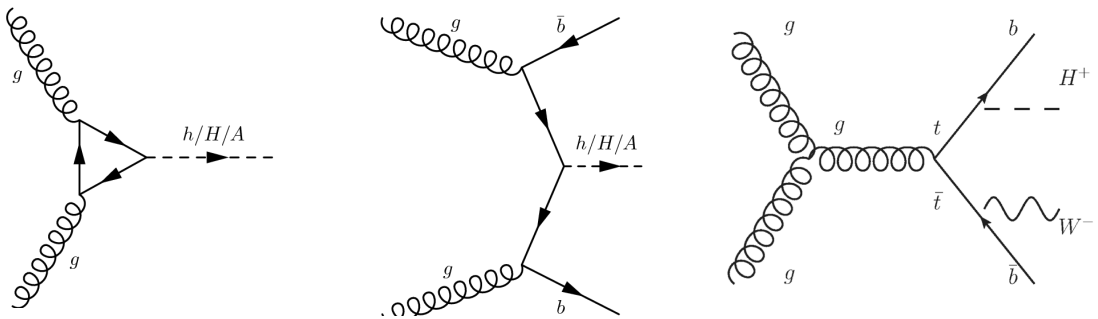
- Many ATLAS BSM Higgs searches in many final states: too many to cover all here!
  - Searches for heavy Higgs (2HDM/MSSM inspired): eg. $H \to \tau\tau/WW/ZZ, \gamma\gamma$, $A \to Zh$, $H \to hh$
  - Searches for charged Higgs bosons (2HDM/MSSM inspired): eg. $H \to \tau\nu/WZ/cs$
  - Searches for light BSM Higgs bosons: eg. in NMSSM $a \to \mu\mu$, $h \to aa \to \mu\mu\tau\tau/4\gamma$
  - Invisible Higgs Decays: eg. VH → hadronic + invisible, $ZH \to ll$ + invisible, VBF H → Invisible
  - Exotics Decays: eg. $H \to Z_{(dark)}Z_{dark}$, LFV $H \to \tau l$, $H \to \gamma\gamma$+MET
- See backup for references to analyses

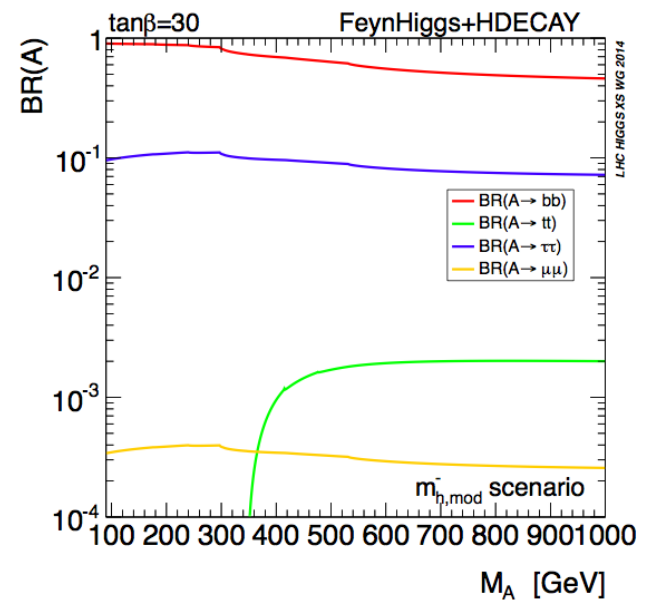
Two Higgs Doublet Models

- Extends SM Higgs sector with two complex Higgs doublets, H_1 and H_2
- Leads to five physical Higgs states: H^+, H^-, A(CP-odd), H, h (CP-even)
  - accommodate observed Higgs boson naturally as h=125 GeV
- Additional 2HDM parameters: ratio of doublet vevs $\tan\beta = v_1/v_2$, CP-even Higgs mixing angle α and m_H
- Four types considered:
  - Type-I: all fermions couple to H_2
  - Type-II: up-type fermions couple to H_2, down-type to H_1
  - Lepton Specific: quark couplings as Type-I, leptons as Type-II
  - Flipped: quark couplings as Type-II, leptons as Type-I

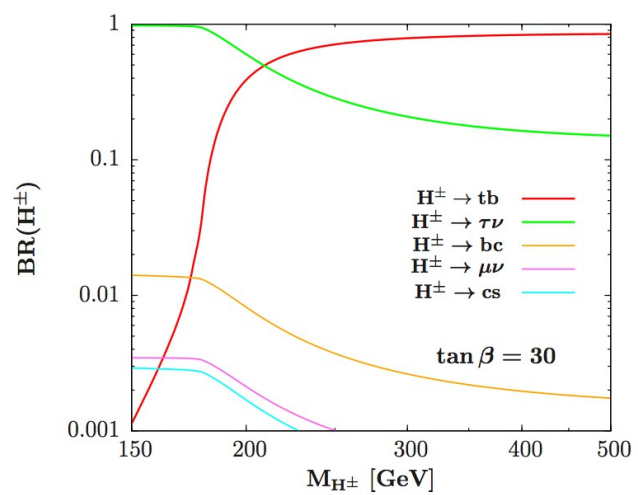
Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$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

MSSM Higgs Sector





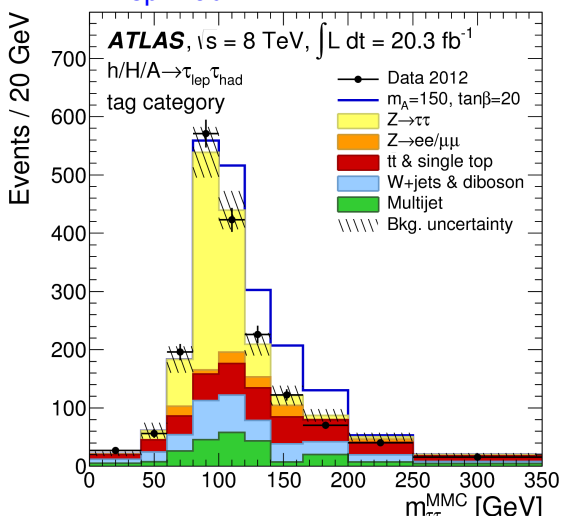
- MSSM Higgs sector is a constrained Type-II 2HDM at tree level
- Tree level MSSM Higgs sector determined by m_A and tanβ
- Consistent with SM-like h=125 GeV
- Neutral Higgs: b-quarks and τ-leptons couplings enhanced for large tanβ, more numerous decay modes at low tanβ (eg. H→WW,ZZ, A→Zh)
- Charged Higgs: decay to τν (tb) dominates below (above) top threshold
- NMSSM: additional singlet on top of MSSM leading to light pseudo-scalar Higgs boson



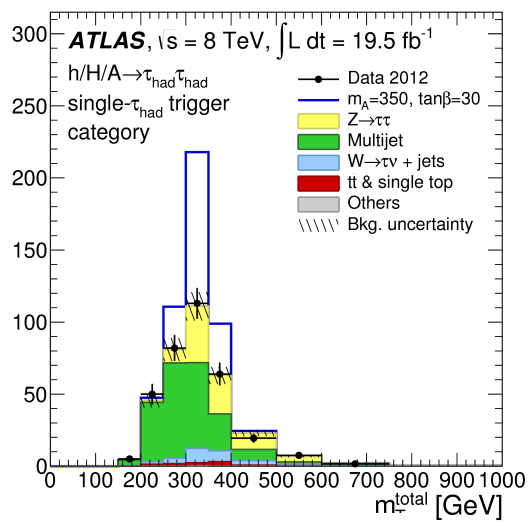
MSSM A/h/H→ττ

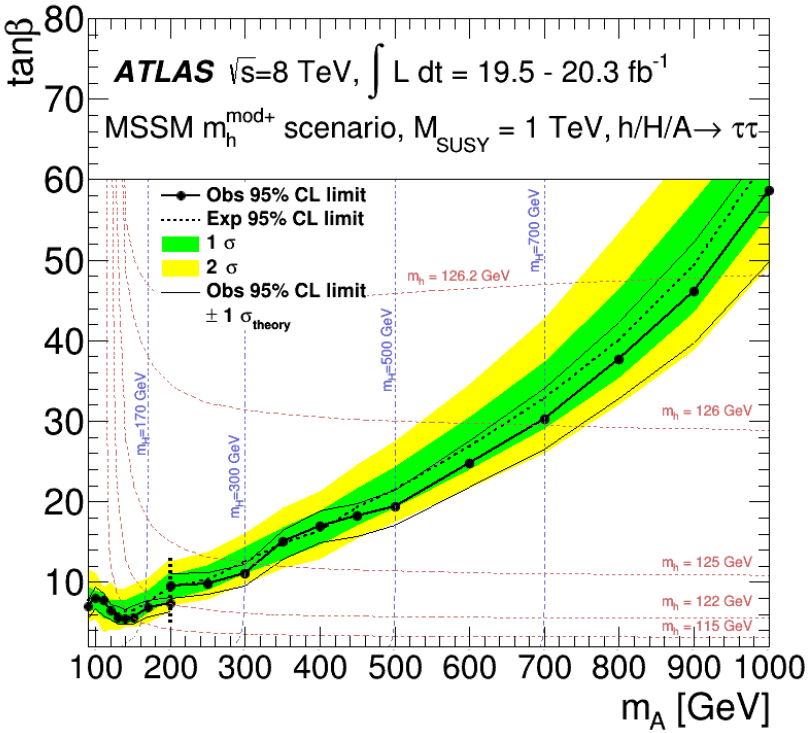
JHEP11(2014)056

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



$\tau_{had}\tau_{had}$ single τ_{had} trigger

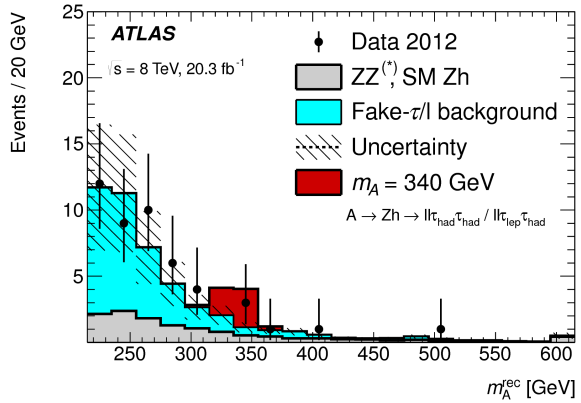


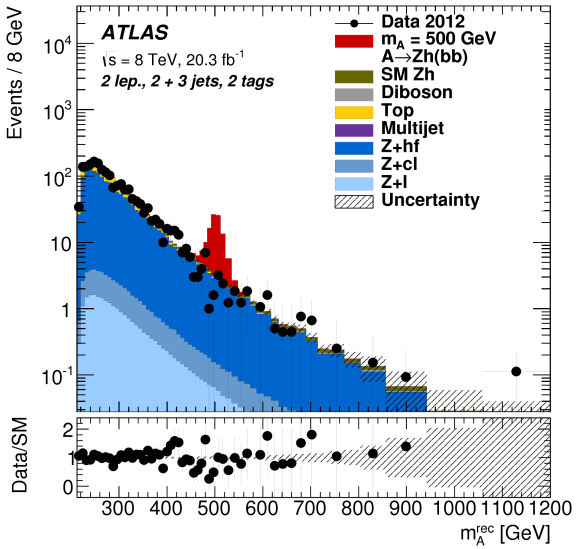


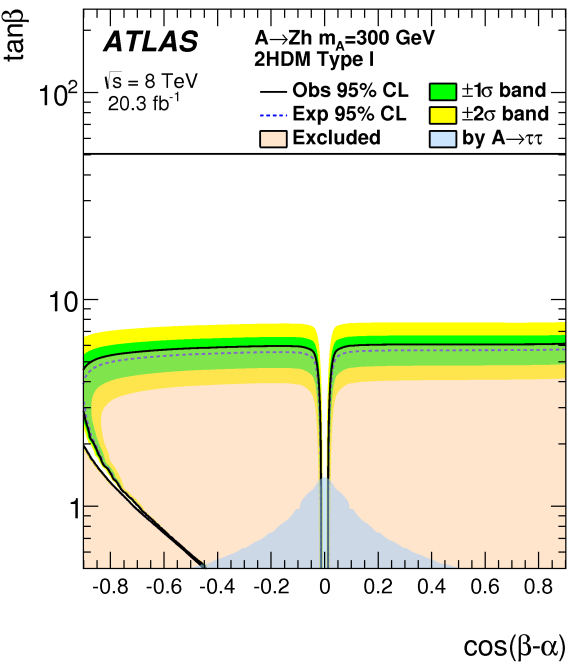
- Three channels, based on tau decay modes - τ(lep)τ(lep), τ(lep)τ(had) and τ(had)τ(had)
- b-tag and b-veto categorisation exploiting b-associated production modes
- Di-tau invariant mass using likelihood based method (MMC)
- Gluon-fusion and b-associated production and model dependent limits over large mass range
- High tanβ significantly constrained for m_A<1 TeV
- Significant proportion of unexcluded phase space still compatible with m(h)= 125 GeV

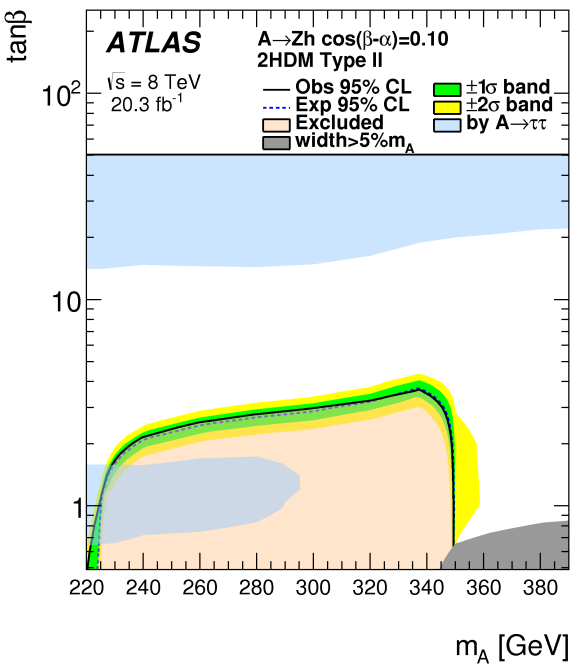
MSSM A→Zh

See P. De Bruin Talk 30/07/15
PLB 744 (2015) 163-183







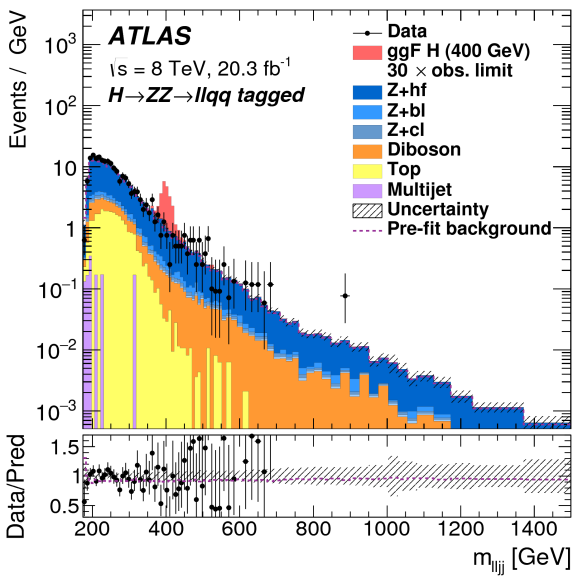


- A→Zh→llττ: three channels, based on tau decay modes - τ(lep)τ(lep), τ(lep)τ(had) τ(had)τ(had)
- m(ττ) from MMC and m_A from m_Z,m_h constrained mass
- A→Zh→llbb, vvbb: N(b-jet)==2, $105<m_{bb}<145$ GeV
- llbb channel: $m^{rec}(A) = m(l_1,l_2,b_1,b_2)$ with m(h)=125 constraint on m(bb)
- vvbb channel: transverse mass
- gluon-fusion cross section and model dependent limits
- Complementary to other searches, with exclusion up to tanβ = 7(3) for Type-I(II) 2HDMs

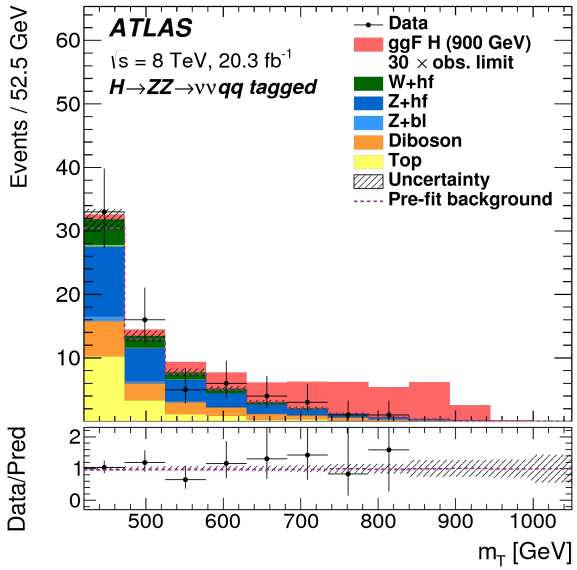
H→ZZ

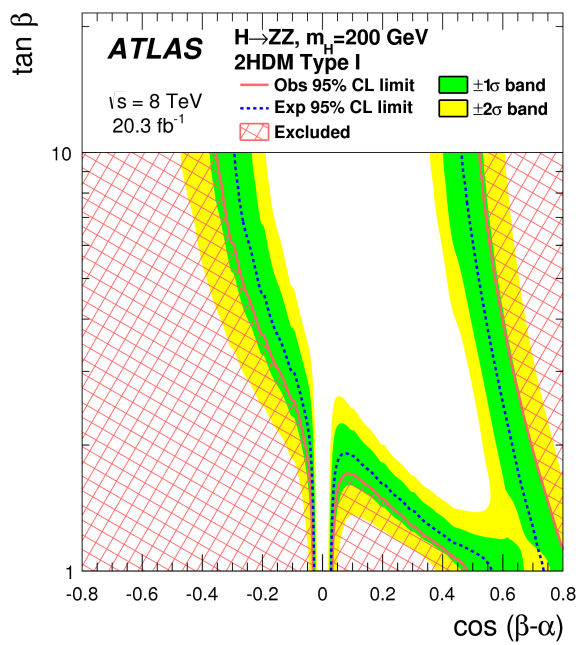
ATLAS-HIGG-2013-20

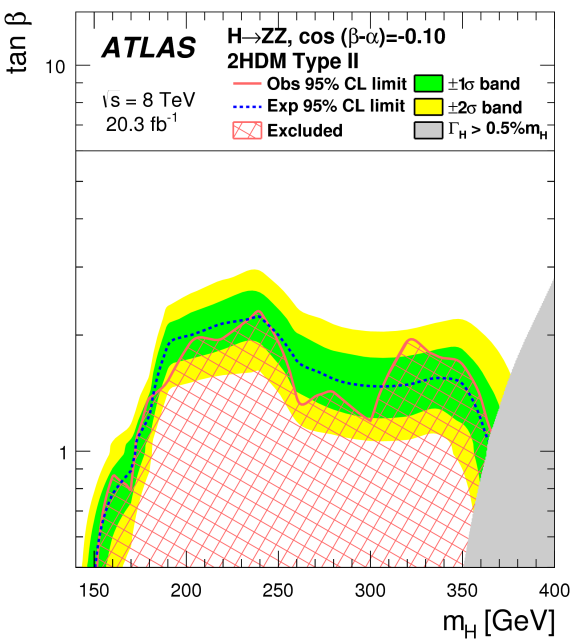
llqq tagged



vvqq untagged



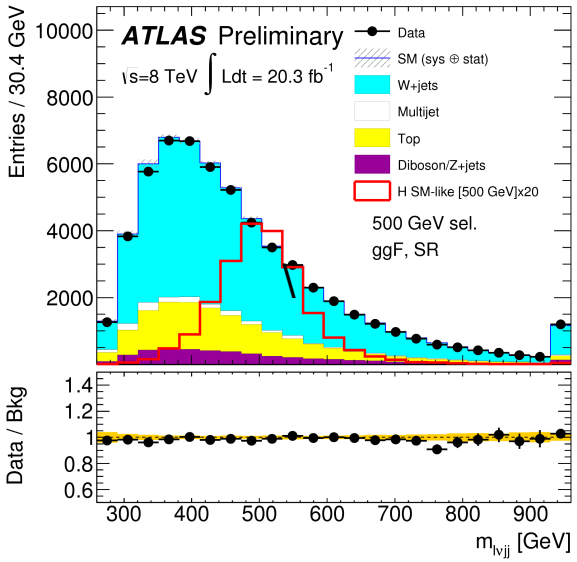


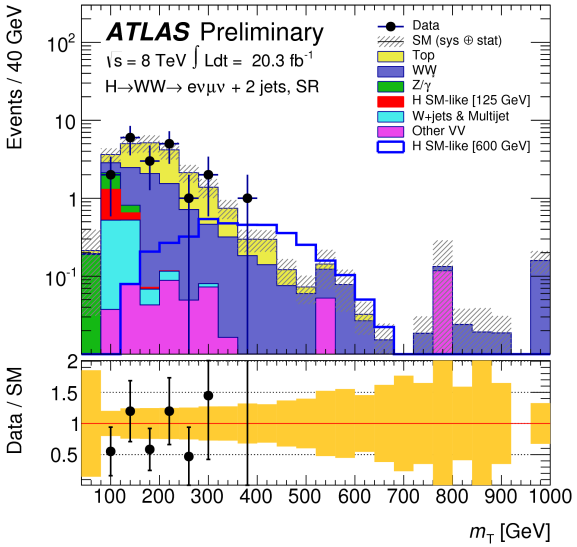


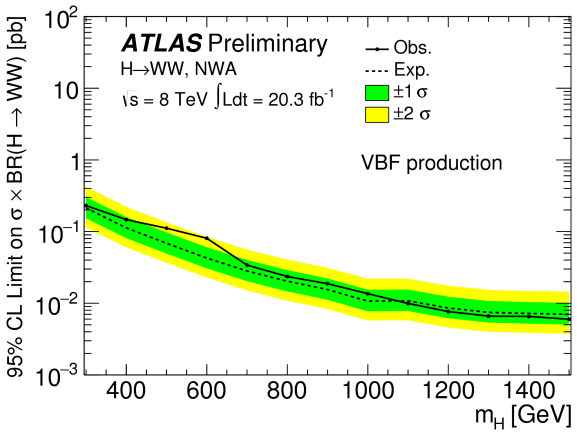
- Four channels, depending on Z decay mode: 4l, 2l2v, 2l2q,2v2q
- Discriminating variables: 4-fermion mass (4l, 2l2q) or transverse mass m_T^{ZZ} (2l2v, 2v2q)
- Cross section limits in ggF and VBF production modes
- 2HDM limits in Narrow Width Approx. region ($\Gamma(H) < 0.5\% \, m_H$)
- Direct limits in new phase space regions
  - Type-I: $\cos(\beta-\alpha) < 2$ and $0.5 < \tan\beta < 2$
  - Type-II: $0.5 < \tan\beta < 2$

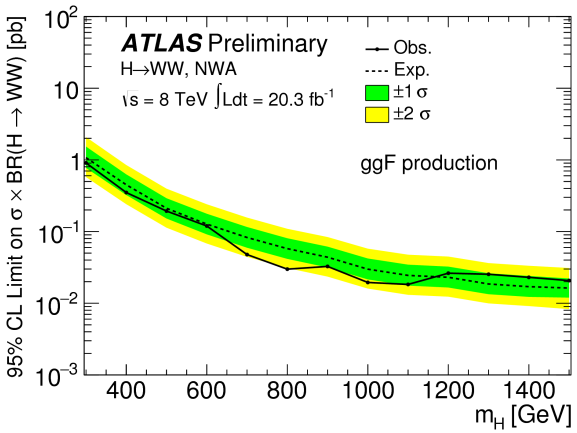
H→WW

ATLAS-HIGG-2013-19





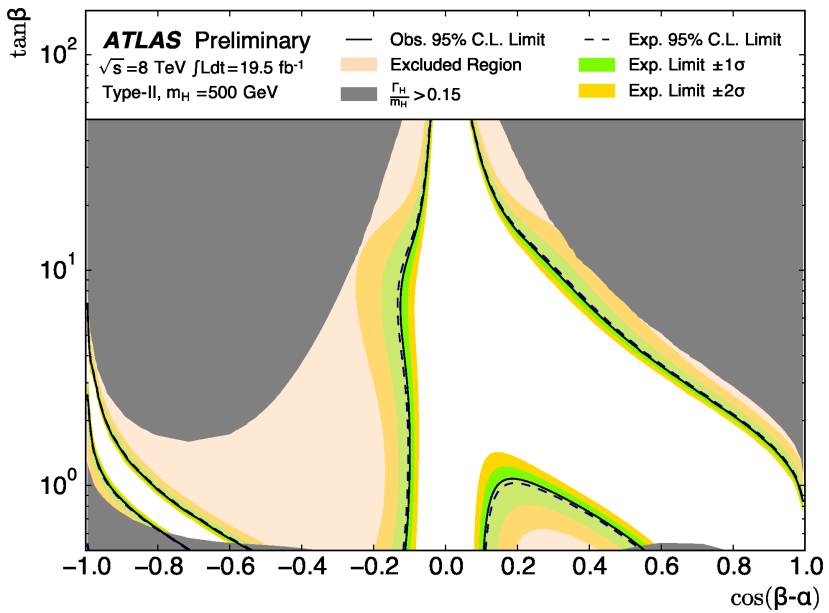


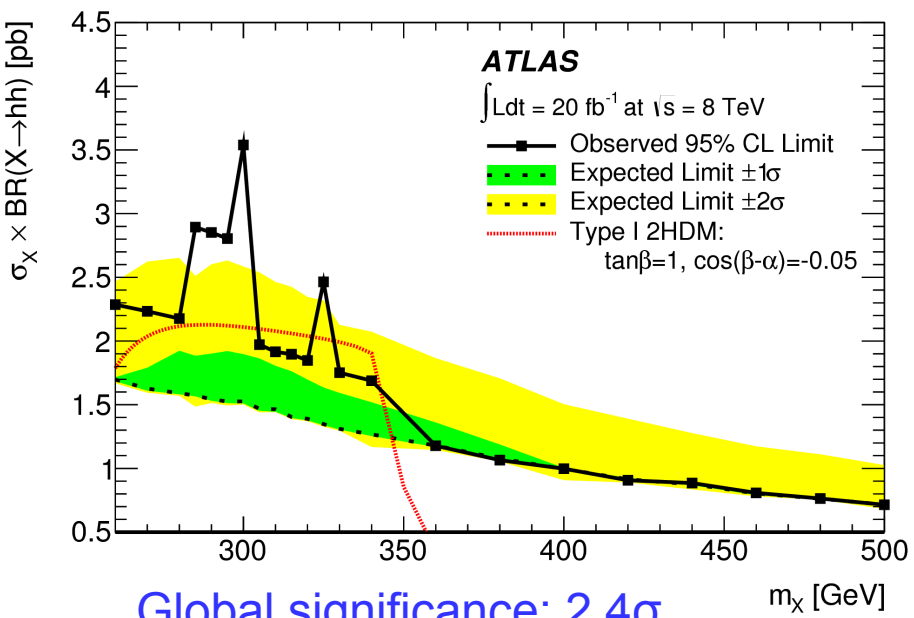


- Search for H→WW→lνlν and lνqq
- N(jet) = 0,1,2 categorisation for sensitivity to gluon-fusion or VBF production modes
- Resolved and merged (C/A R=1.2) jets for sensitivity to large m(H)
- Discriminating variables:
  - lνlν: transverse mass m_T(ll, MET)
  - lνqq: m(l, p_T^{miss}, q, q) with p_T^{miss} constrained by m(lν) = m(W)
- Cross section * BR limits set using SM-like, NWA or intermediate Higgs width scenarios

H→hh

ATLAS-EXOT-2014-11
PRL 114, 081802 (2015)



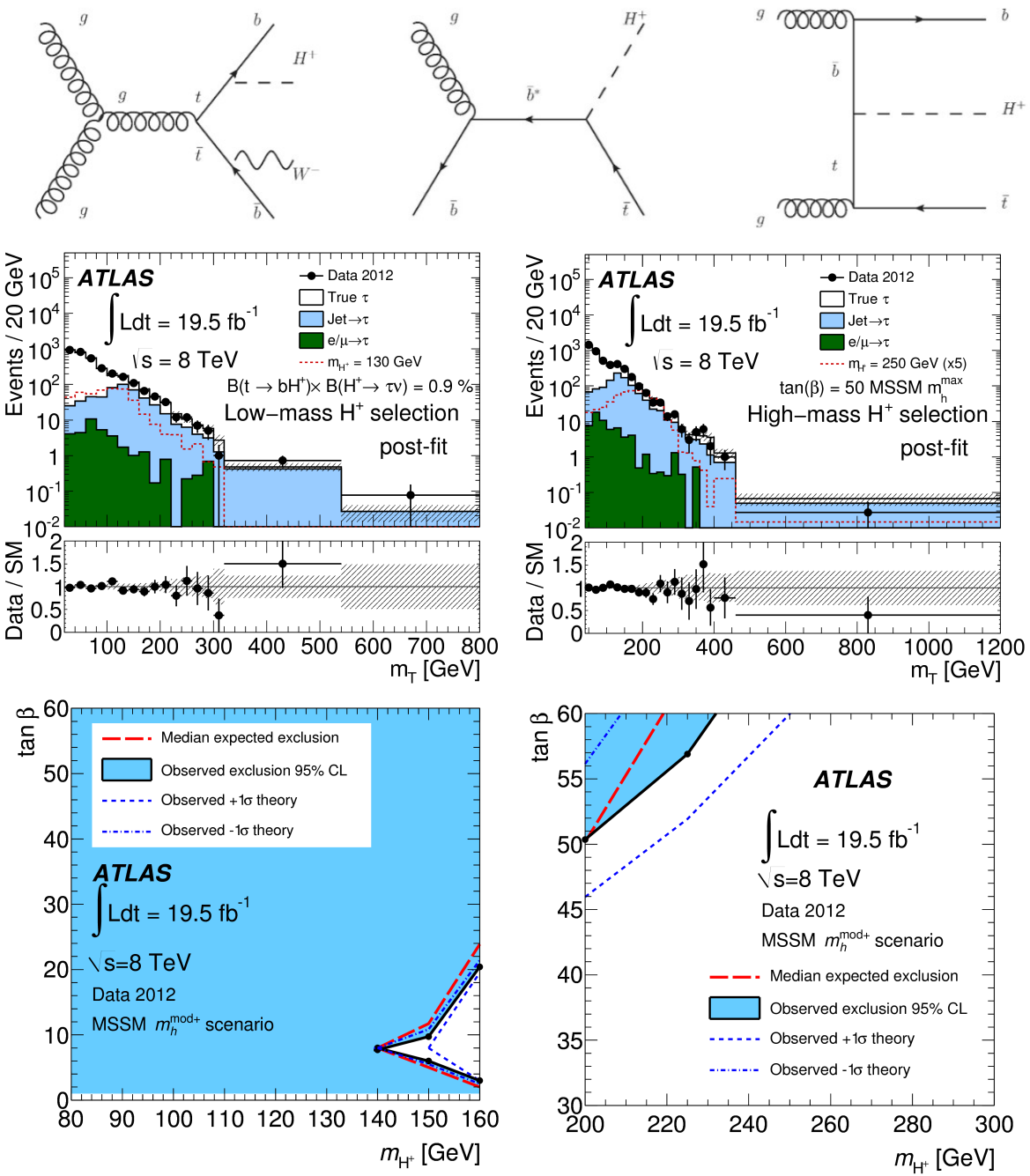


Global significance: 2.4σ

- BSM Higgs searches, but also act as preparation for SM dihggs production
- H→hh→4b search in resolved (4 b-jet) or boosted (2 b-tagged large-R jets)
- Fit m(4j) or m(2J) distributions with m(h) constraints on m(2j) and m(J)
- H→hh→2γ2b search based on 2 photons, at least 2 b-jets with 95<m(jj)<135 GeV
- Non-resonant unbinned fit to m(γγ): continuum + h(125) + BSM hh signal
- Resonant fit to m(γγjj) with additional m(γγ) = 125.5 ± 1.6 GeV constraint
  - sensitivity to tanβ~1 for intermediate masses

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

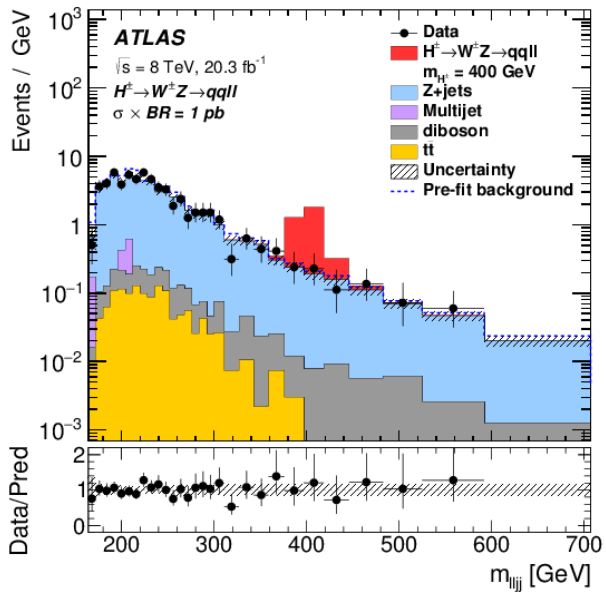
JHEP03 (2015) 088

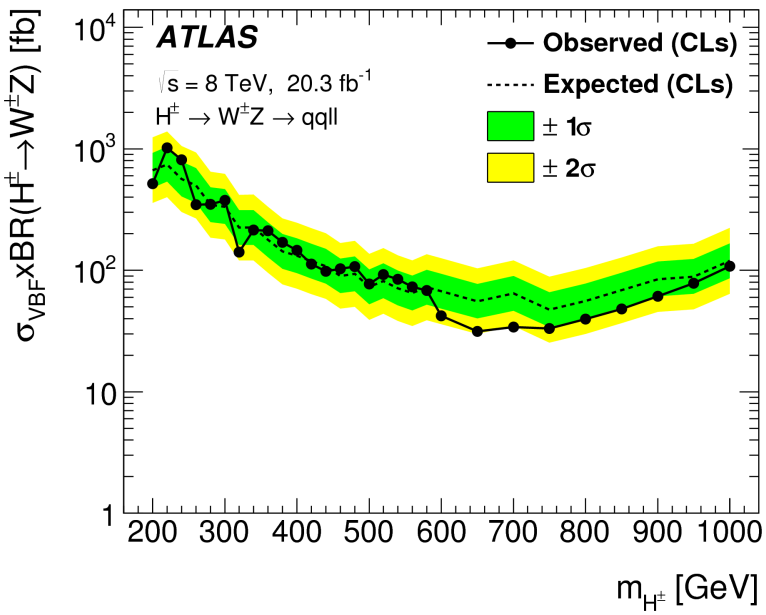


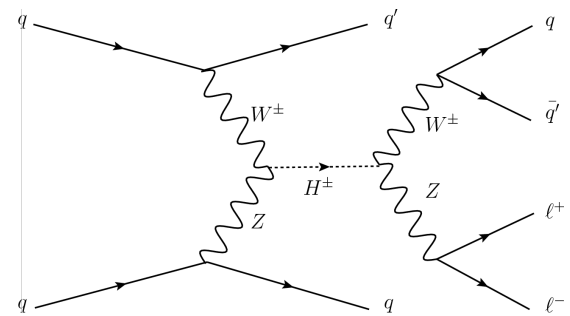
- For $m(H^{+/-})<m_{top}$, $t \rightarrow bH^+$ production dominated
- For $m(H^{+/-})>m_{top}$, t associated production dominated
- Searches in n(jet) = 3(4) + n(b-jet) >=1 + τ(had) + MET channel
- Only MET from $H^{+/-} \rightarrow \tau\nu$ decay: $m_T(\tau, MET)$ discriminating variable
- σxBR and model dependent limits in low/high $m(H^{+/-})$ ranges
- Almost all values tanβ>1 excluded for $80<m(H^{+/-})<160$ GeV

$H^{+/-} \rightarrow WZ$

PRL 114, 231801 (2015)



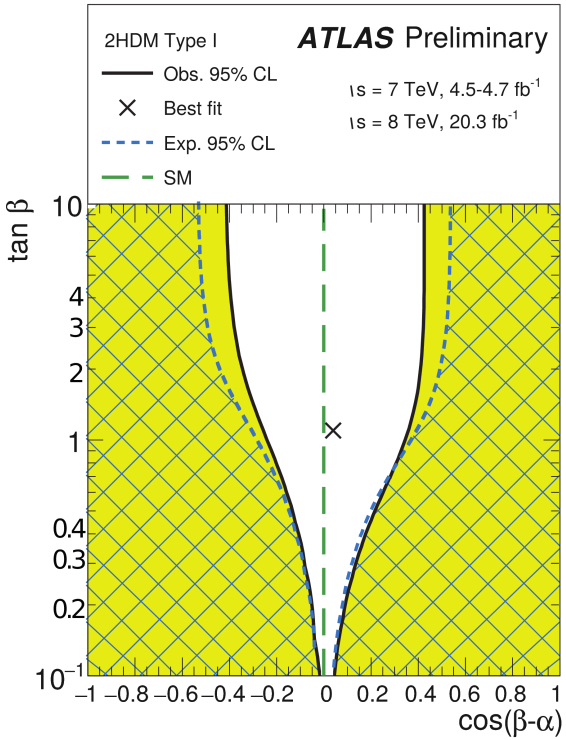


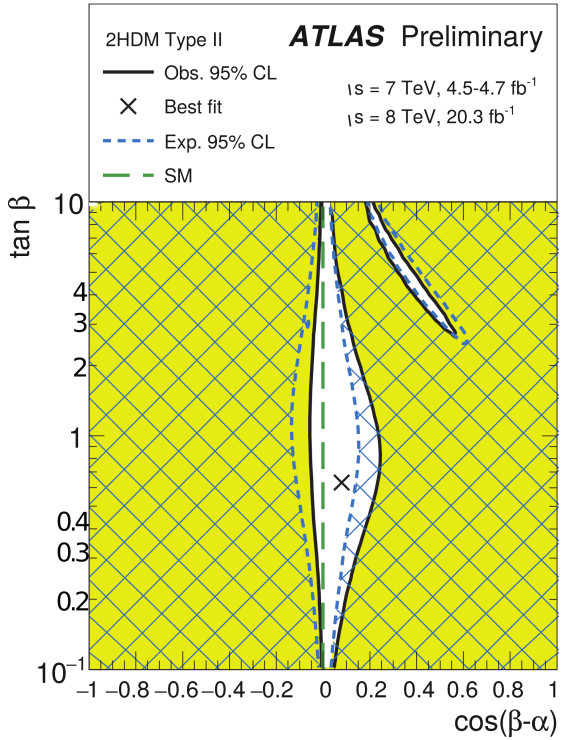


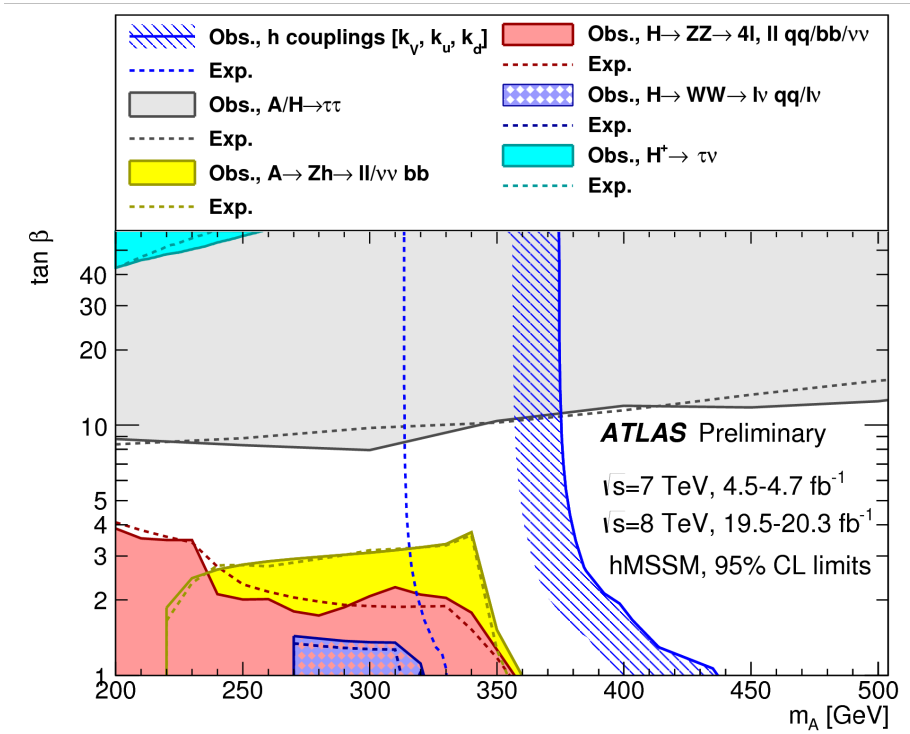
- $H^{+/-} \rightarrow WZ$ contributions at loop level for 2HDM models or tree level for Higgs Triplet Models
- Search using VBF production and $W \rightarrow qq$ and $Z \rightarrow ll$ decay modes
- Discriminating variable m(llqq) with W mass constraint on m(qq)

Constraints from Higgs Couplings

HIGG-2015-03



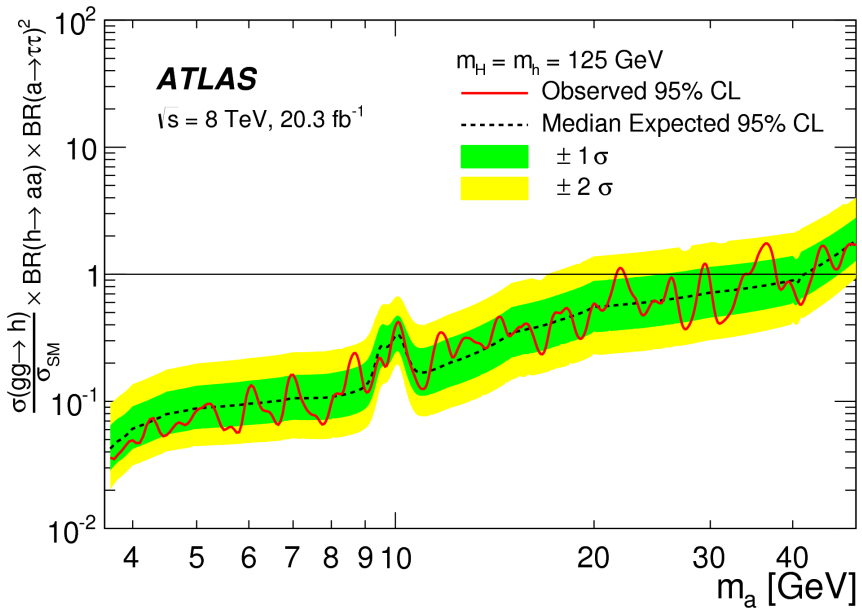


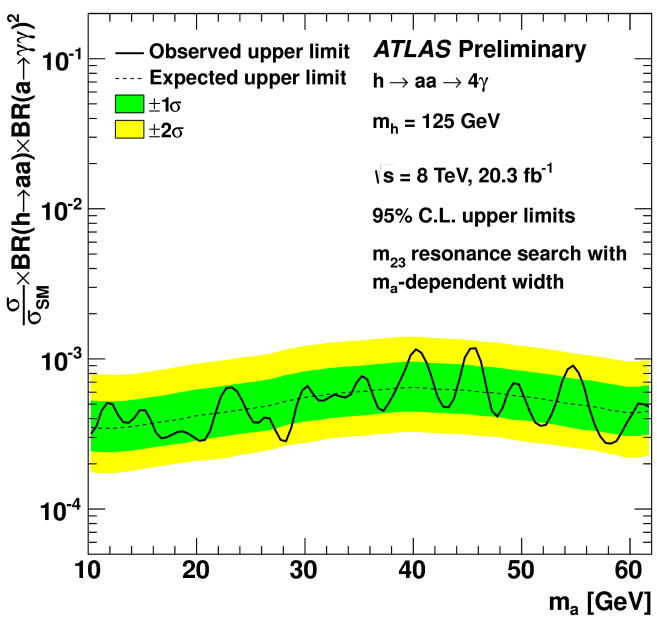


- Combined fit on SM Higgs measurements:
  - $h\to\gamma\gamma$, $h\to ZZ^*\to 4l$, $h\to WW^*\to l\nu l\nu$, $h\to Z\gamma$, $h\to bb$, $h\to\tau\tau$, and $h\to\mu\mu$ and tth with $h\to\gamma\gamma$, $h\to bb$ and multileptons
- Extract coupling scaling factors relative to SM (κ_V, κ_u, κ_d and κ_l) using BSM models
- Significant constraints on 2HDM parameter space
- Interpretation in hMSSM compliments direct searches: observed limit m_A>380 GeV for $1\leq \tan\beta \leq 50$

NMSSM h→aa

ATLAS-HIGG-2014-02
ATLAS-EXOT-2013-24

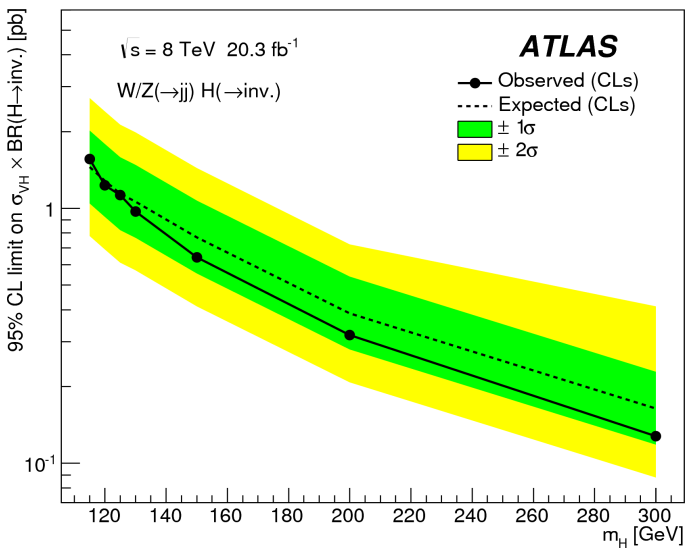


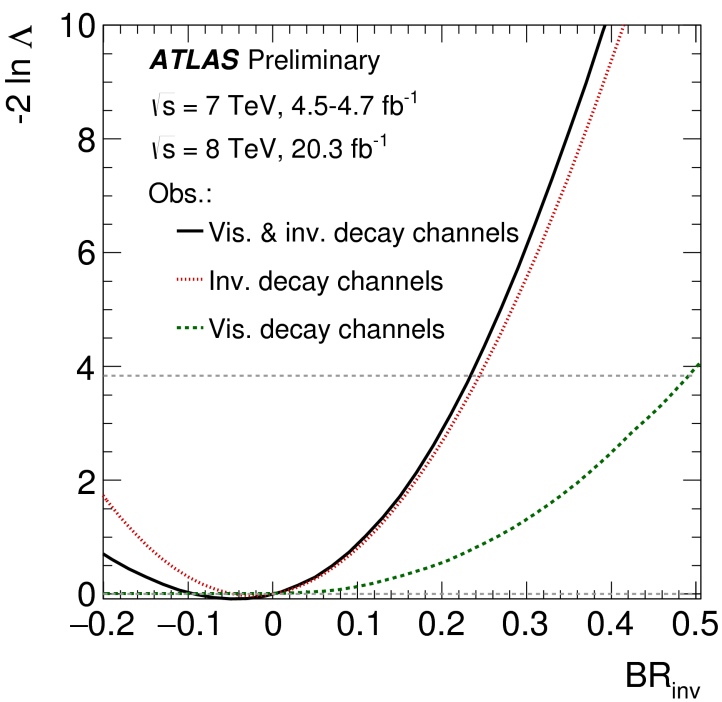


- h→aa→μμττ: ττ decays from boosted a boson lead to collimated ehad or μhad: require lepton with up to three tracks in ΔR<0.4
- Fit m(μμ): σxBR limits set for h(125) and 100<m(H)<500 GeV
  - σxBR = 3.5%*SM (m(a)=3.75 GeV)
- Search in final state with 3 identified photons for Z/Z'→3γ as well as h→aa→4γ sensitivity
- Two collimated + two resolved photons due to boosted a boson
- Fit m(γ_2,γ_3): σxBR limits set for h(125) and 125<m(H)<900 GeV

Higgs → Invisible

EPJC (2015) 75:337
ATLAS-CONF-2015-004

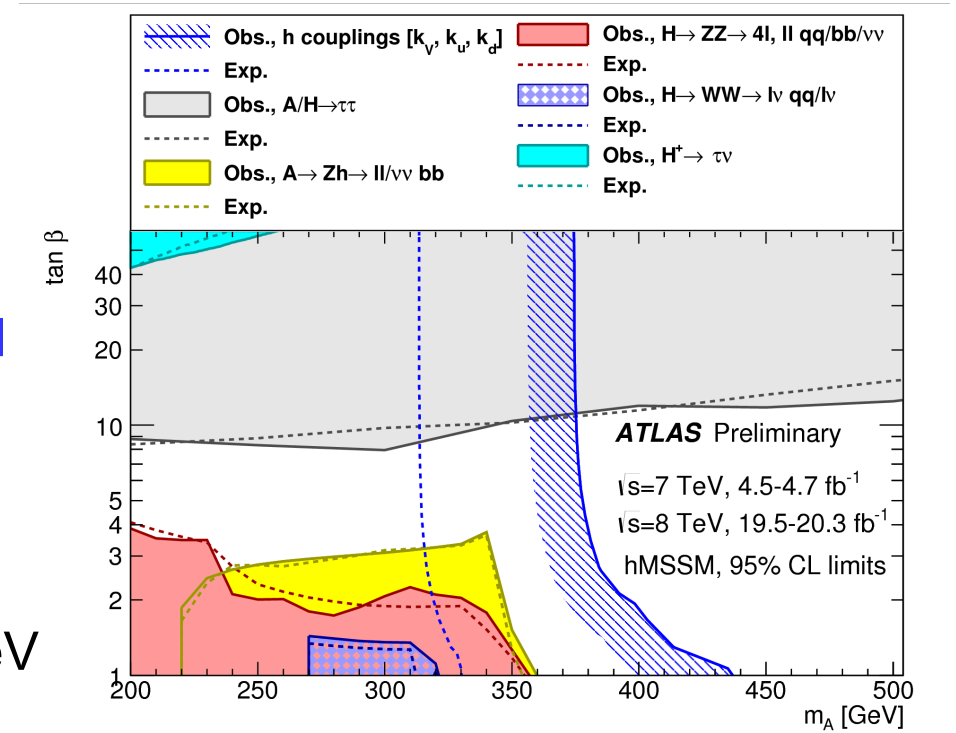




- Search for invisible h decays in g-fusion production in VH→qq+invisible decay mode
  - Two and three jet channels with 0-2 b-jet categorisation
  - σxBR limits set for 115<m_H<300 GeV and upper bound on BR→Inv. for SM h(125) = 78%
- Search for H→Inv. in VBF production: upper bound on BR→Inv. for SM h(125) = 29%
- Combination of VBF H→Inv., VH→qq+Inv. and ZH→ll+Inv.
  - direct search: upper bound on BR→Inv. for h(125) = 24%
  - combined fit including visible decay modes in addition: upper bound on BR→Inv. for h(125) = 17%

Summary

- Wide range of ATLAS searches for BSM Higgs bosons
  - multiple final states with complementary coverage of large regions of phase space
  - not time to cover everything here!
- No discoveries of BSM Higgs sector yet, however stringent limits set in multiple BSM models
- LHC Run2 means plenty of BSM Higgs fun to look forward to
  - Increase in COM energy 8→13 TeV leads to large increase in cross sections for heavy resonances
  - hence drives early searches for heavy H, $H^{+/-}$
  - higher luminosities for searches for rare and exotic processes



Backup: References

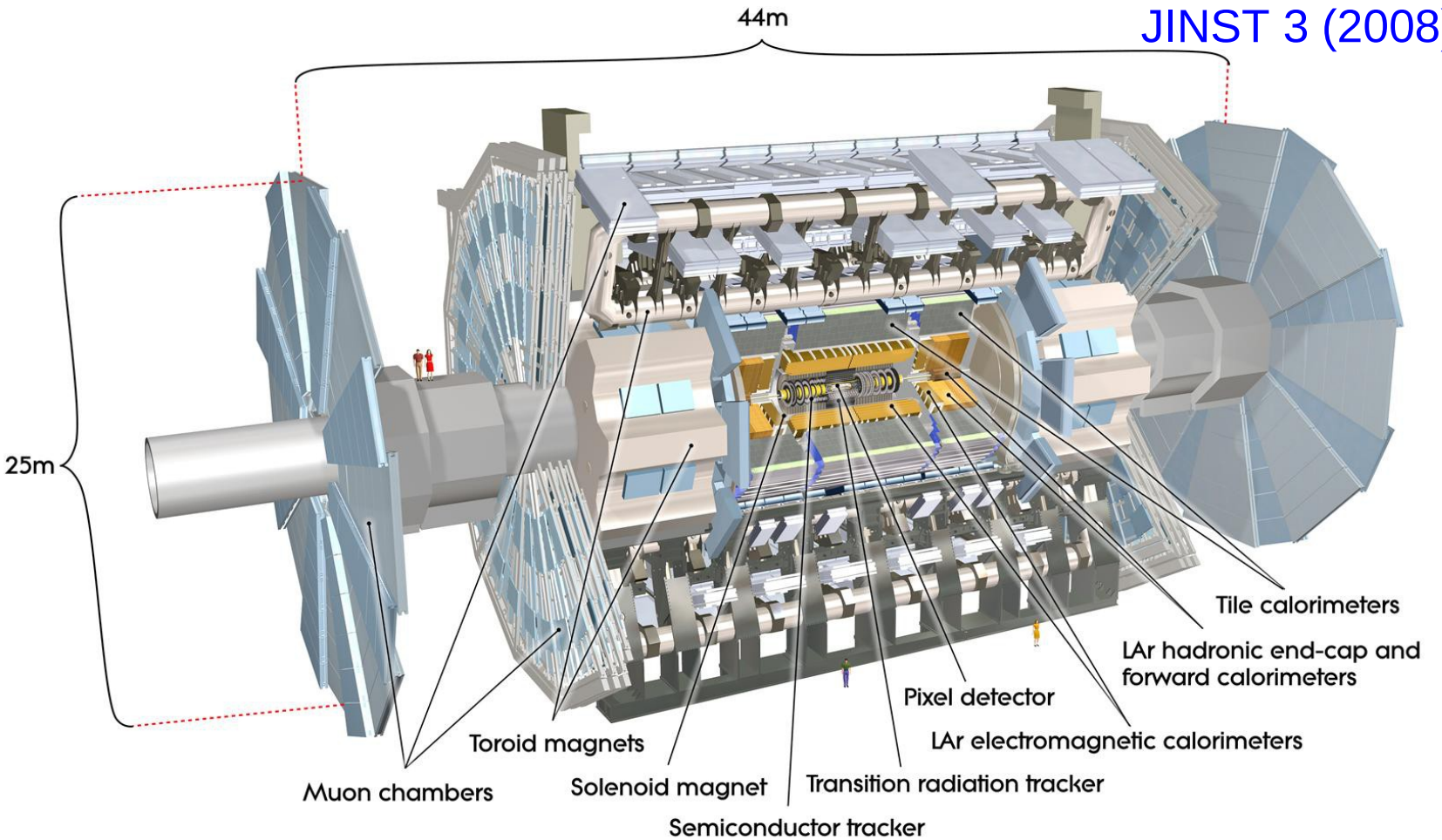
- Neutral Higgs Searches:
  - A/h/H→ττ JHEP11(2014)056
  - A→Zh Physics Letters B 744 (2015) 163-183
  - hh→4b ATLAS-EXOT-2014-11 (Submitted to EPJC)
  - hh→2γ2b Phys. Rev. Lett. 114, 081802 (2015)
  - H→WW ATLAS-HIGG-2013-19 (note: paper in preparation)
  - H→ZZ ATLAS-HIGG-2013-20 (Submitted to EPJC)
- Charged Higgs Searches:
  - $H^{+/-}$→τν JHEP03 (2015) 088
  - $H^{+/-}$→WZ Phys. Rev. Lett. 114, 231801 (2015)
- Light (NMSSM) Higgs Searches:
  - h→aa→μμττ ATLAS-HIGG-2014-02 (Submitted to Phys. Rev. D)
  - h→aa→4γ ATLAS-EXOT-2013-24 (note: paper in preparation)

Backup: References

- Dihiggs Searches:
  - H→hh→4b ATLAS-EXOT-2014-11 (Submitted to EPJC)
  - H→hh→2γ2b Phys. Rev. Lett. 114, 081802 (2015)
- Invisible Higgs decays:
  - VH→qq+Invisible: Eur. Phys. J. C (2015) 75:337
  - VBF H→Invisible: ATLAS-CONF-2015-004
- BSM Higgs Couplings and Invisible Decays: HIGG-2015-03 (note: paper in preparation)

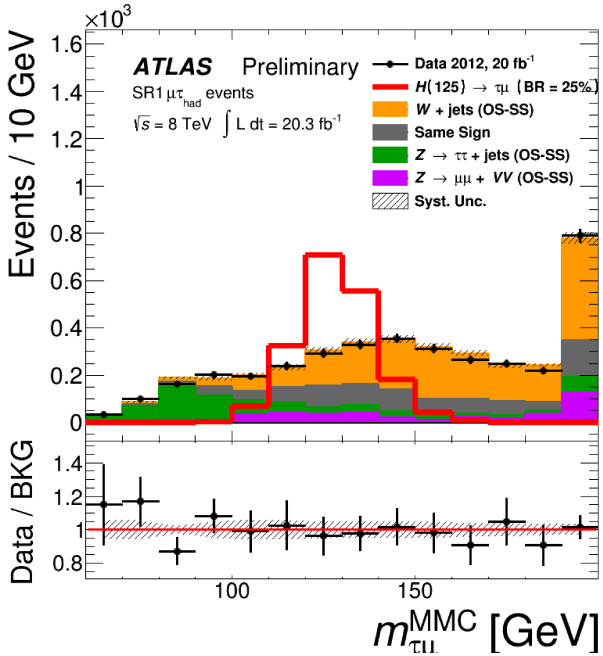
Backup: The ATLAS Detector

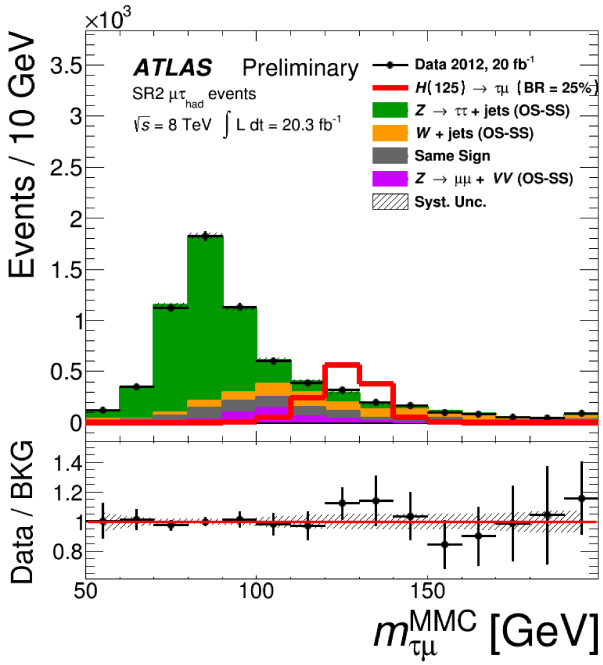
JINST 3 (2008) S08003



- Muon spectrometer |η|<2.4 (air core toroids + muon chambers)
- Hadronic Calorimeter |η|<5 (Fe+scintillator tiles or LAr+W/Cu)
- EM calorimeter |η|<3.2 (Pb/LAr accordion)
- Inner detector |η|<2.5 (2 Tesla solenoid, Si pixels, Si strips + TRT)

Backup: LFV H→τμ



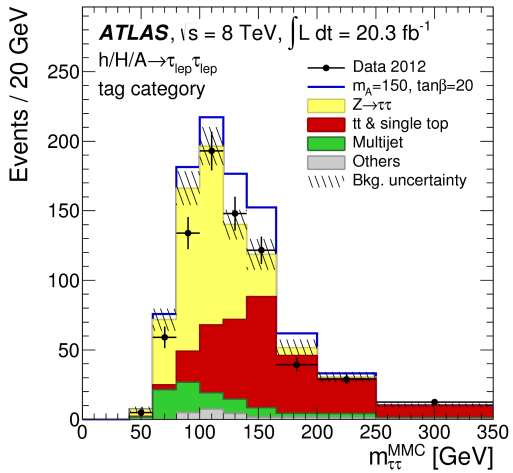


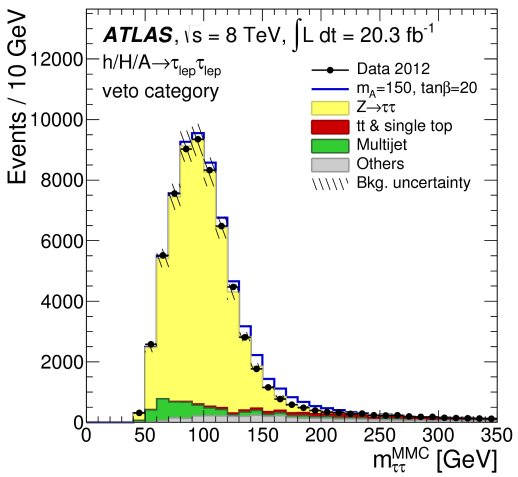
- Search for h(125) decaying to tau(had) + muon
- Two signal regions defined by correlation of $m_T(\mu,MET)$ and $m_T(\tau,MET)$
- MMC (τμ) used as discriminating variable
- Local significance 2.3σ in SR2 for 120 GeV< M_{MMC} <140 GeV
- Combined significance 1.4σ
- Observed (expected) limits on BR(h(125)→τμ) = 1.92% (1.24%)

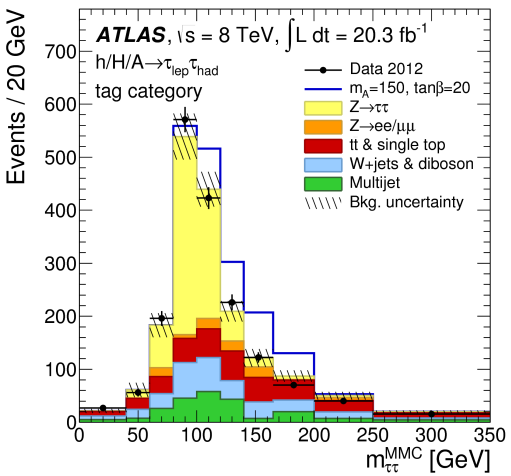
Backup: A/h/H→ττ

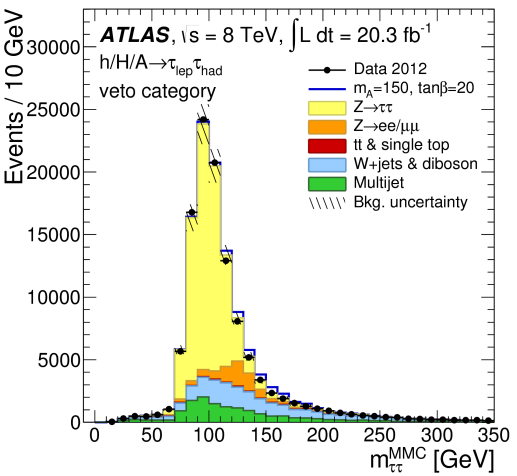
	ττ → eμ	ττ → eτh / μτh	ττ → τhτh
Pre-selection	OS e and μ m(e,μ) > 30 GeV Δφ(e,μ) > 2.0 MET+pT(e)+pT(μ) < 125 GeV ΣcosΔφ(l,MET) > -0.2	OS l and τh -No additional leptons -mT(l,MET) < 30 GeV	Two OS τh No light leptons MET > 25 GeV
b-tagged	Exactly 1 b-jet ΣpT(jets) < 100 GeV	Leading jet b-tagged pT(b-jet) < 50 GeV	Leading jet b-tagged pT(b-jet) < 50 GeV
b-veto	0 b-tagged jets ΣpT(jets) < 150 GeV	Lead jet fails b-tag MET > 20 GeV	Lead jet fails b-tag Lead τh pT > 60 GeV

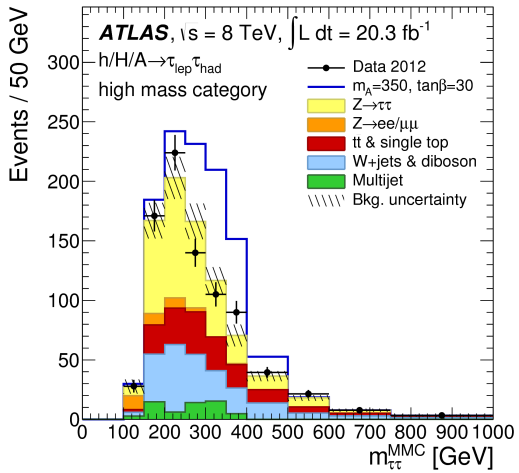
Backup: A/h/H→ττ

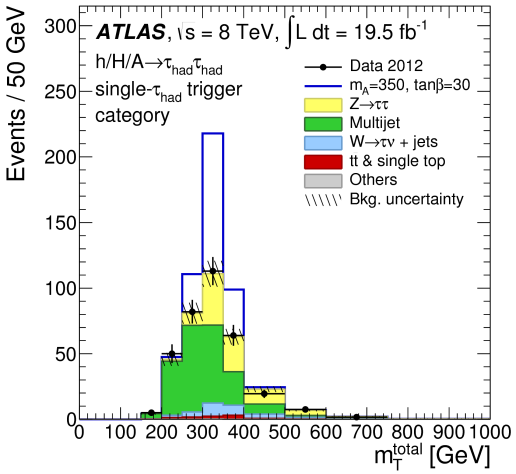


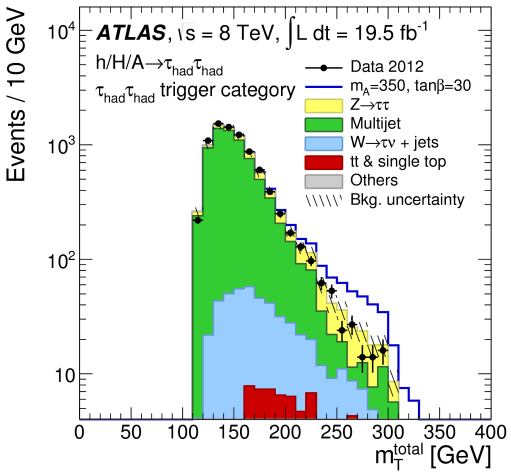




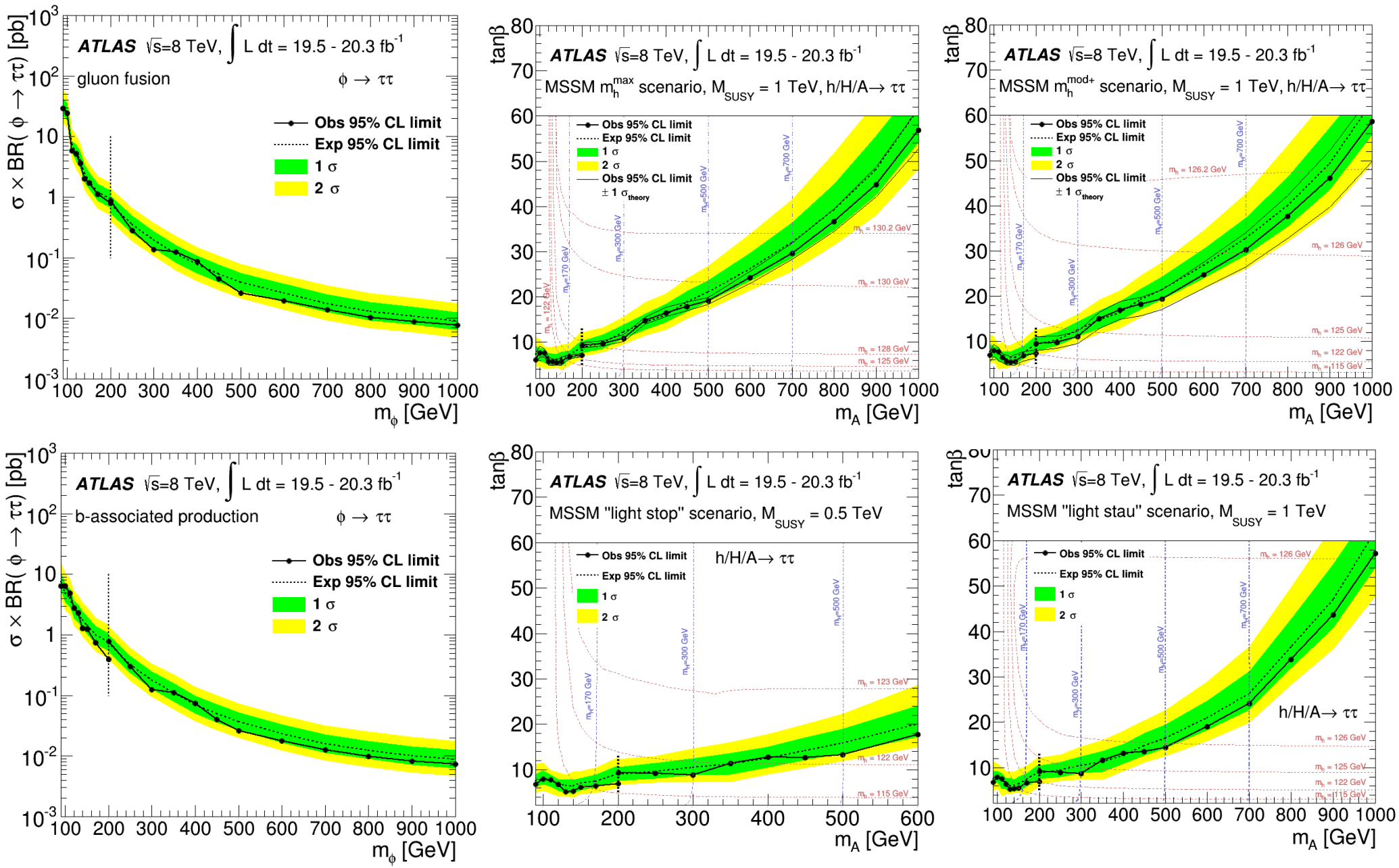








Backup: A/h/H→ττ



Backup: MMC

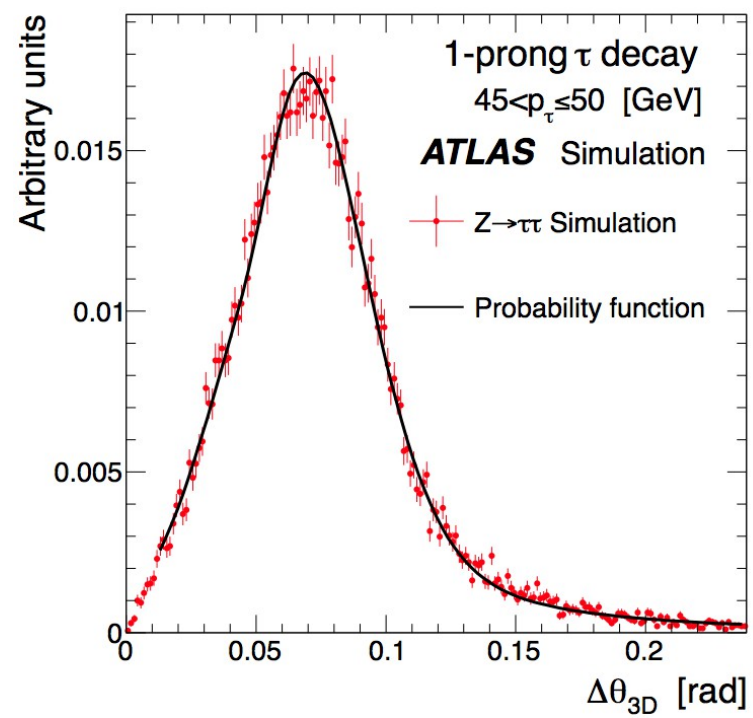
- 6-8 unknowns when reconstructing mass of di-tau invariant mass spectrum, depending on tau decays (depending on number of neutrinos in final state)
- Four constraints: METx, METy, M_{tau1}, M_{tau2}
- Scan parameter space, calculate di-tau invariant mass at each point and weight by tau decay likelihood distribution
- Most probable value of mass used as estimator for di-tau mass

$$\not{E}_{\mathrm{T}_x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \cos\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \cos\phi_{\mathrm{mis}_2}$$

$$\not{E}_{\mathrm{T}_y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \sin\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \sin\phi_{\mathrm{mis}_2}$$

$$M_{\tau_1}^2 = m_{\mathrm{mis}_1}^2 + m_{\mathrm{vis}_1}^2 + 2\sqrt{p_{\mathrm{vis}_1}^2 + m_{\mathrm{vis}_1}^2}\sqrt{p_{\mathrm{mis}_1}^2 + m_{\mathrm{mis}_1}^2} - 2p_{\mathrm{vis}_1}p_{\mathrm{mis}_1}\cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\mathrm{mis}_2}^2 + m_{\mathrm{vis}_2}^2 + 2\sqrt{p_{\mathrm{vis}_2}^2 + m_{\mathrm{vis}_2}^2}\sqrt{p_{\mathrm{mis}_2}^2 + m_{\mathrm{mis}_2}^2} - 2p_{\mathrm{vis}_2}p_{\mathrm{mis}_2}\cos\Delta\theta_{vm_2}$$



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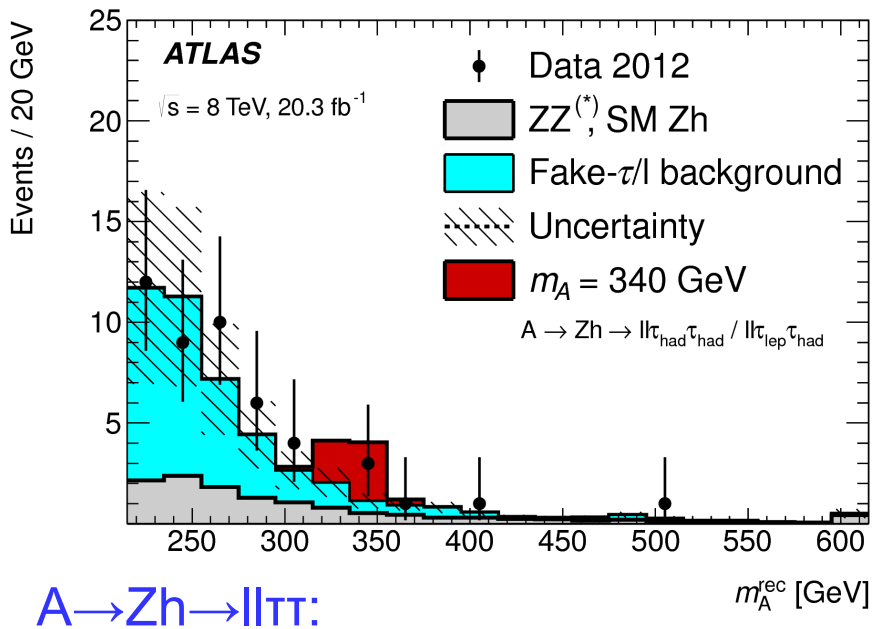
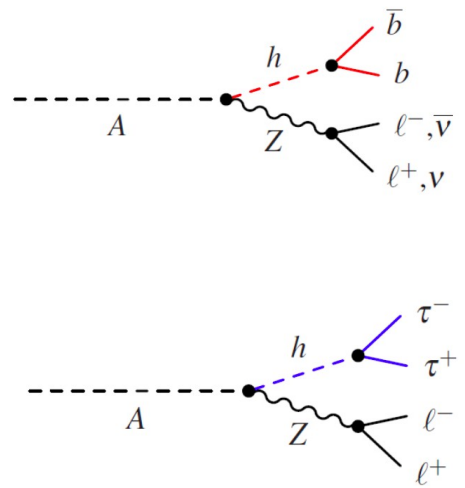
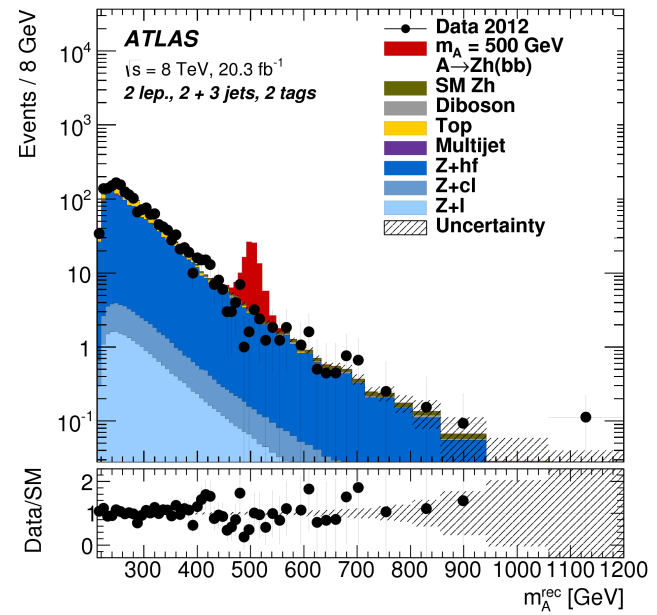
MSSM A→Zh

See P. De Bruin Talk 30/07/15
PLB 744 (2015) 163-183







A→Zh→llττ:

- three channels, based on tau decay modes - τ(lep)τ(lep), τ(lep)τ(had) and τ(had)τ(had)
- m(ττ) from MMC
- $80<m_{ll}<100$ GeV, $75<m_{\tau\tau}<175$ GeV
- high p_T^Z
- m_A from constrained mass:

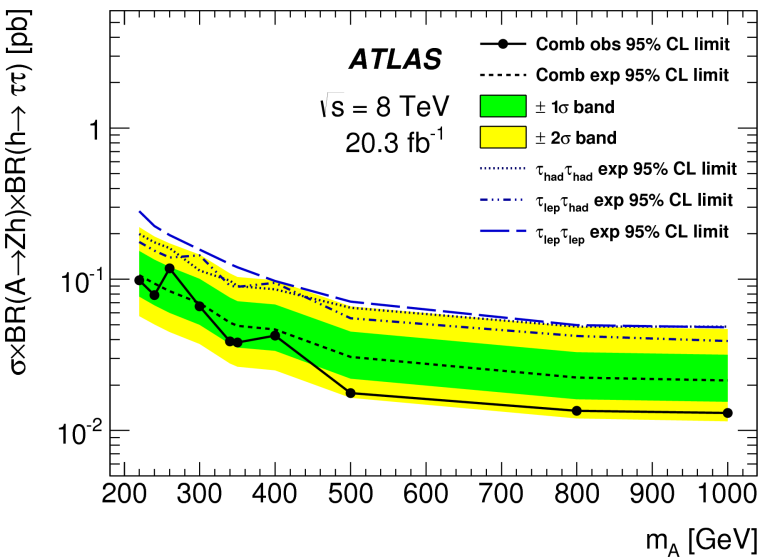
$$m_A^{\rm rec} = m_{\ell\ell\tau\tau} - m_{\ell\ell} - m_{\tau\tau} + m_Z + m_h$$

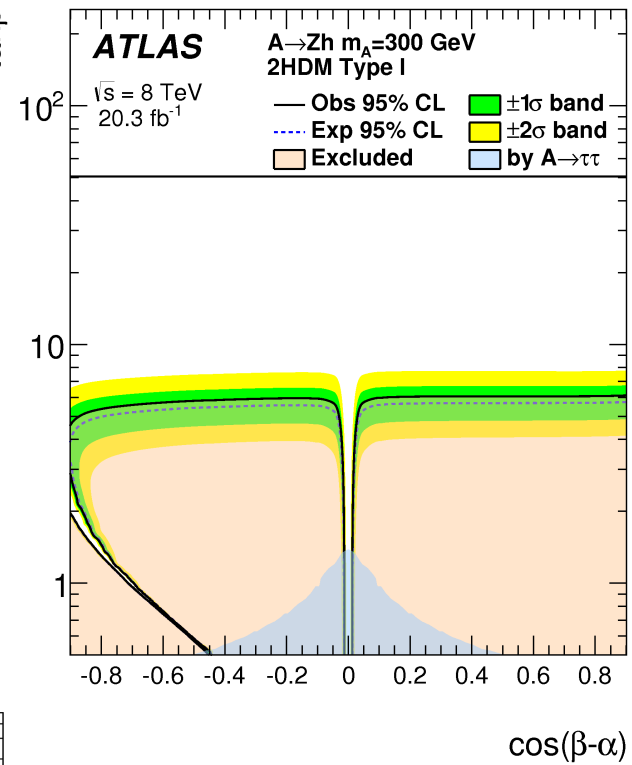
A→Zh→llbb, vvbb:

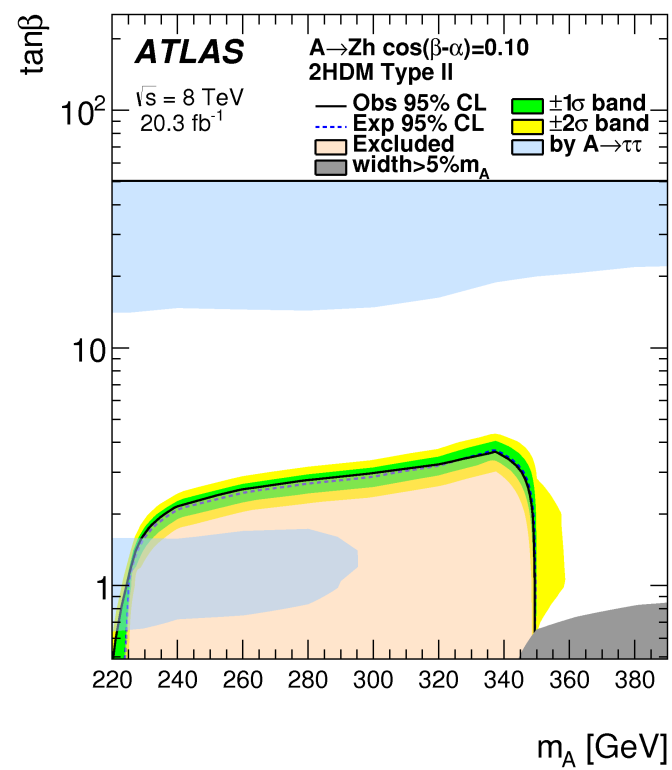
- N(b-jet)==2, $105<m_{bb}<145$ GeV
- llbb channel: $MET/\sqrt{H_T}<3.5$ GeV$^{1/2}$, high p_T^Z, $m^{rec}(A) = m(l_1, l_2, b_1, b_2)$ with m(h)=125 constraint on m(bb)
- vvbb channel: $E_t^{miss}>130$ GeV, $p_T^{miss}>30$ GeV, Δφ(MET, bb)>2.8, transverse mass

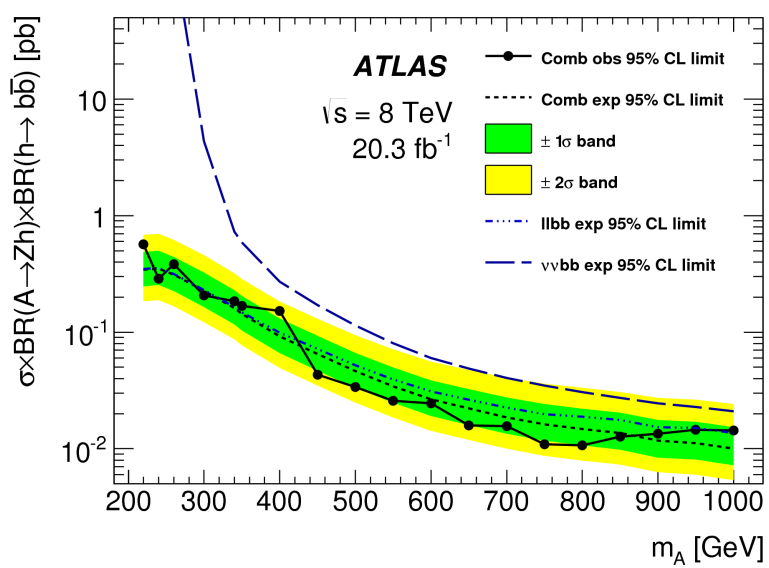
$$m_A^{\rm rec,T} = \sqrt{(E_T^{bb} + E_T^{\rm miss})^2 - (\vec{p}_T^{\,bb} + \vec{E}_T^{\rm miss})^2}$$

MSSM A→Zh



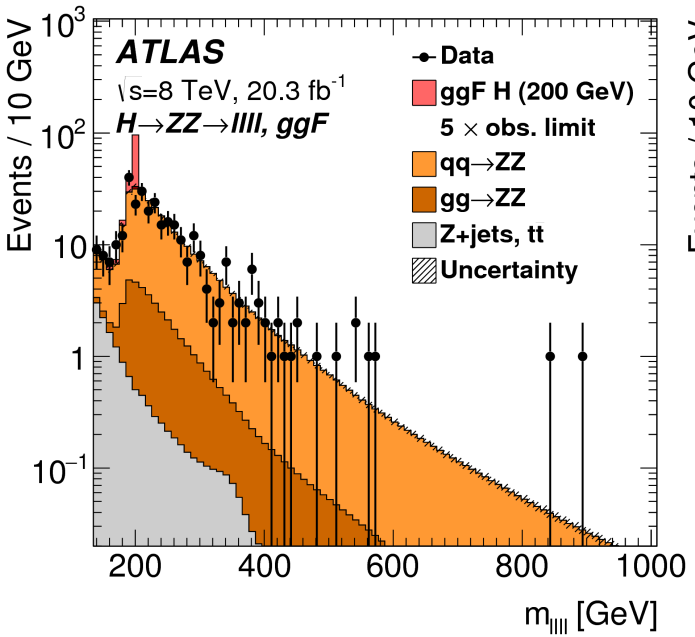


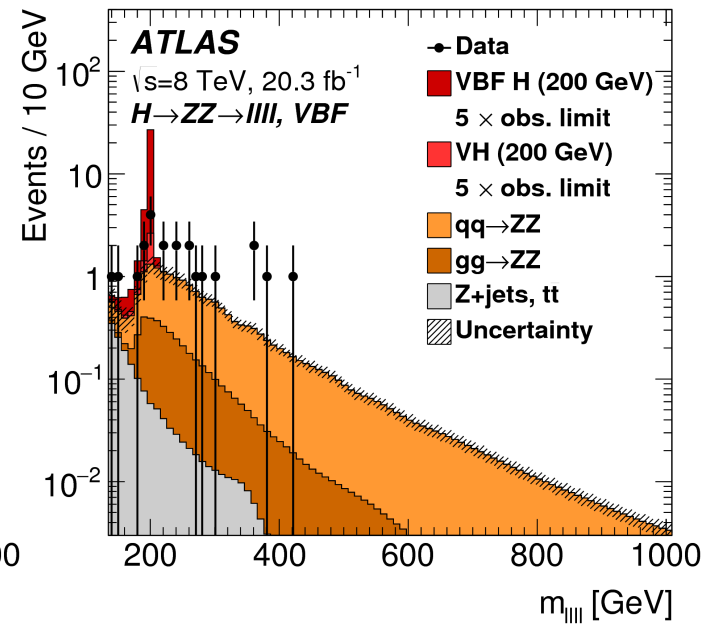


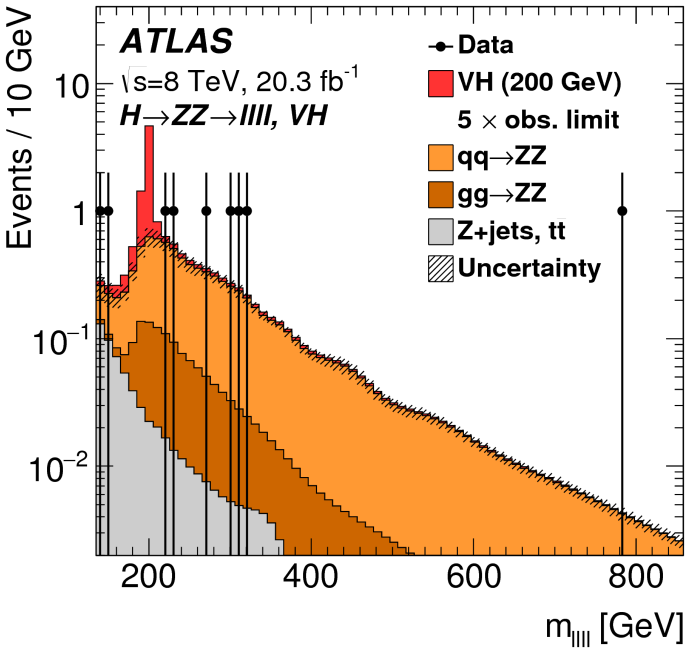


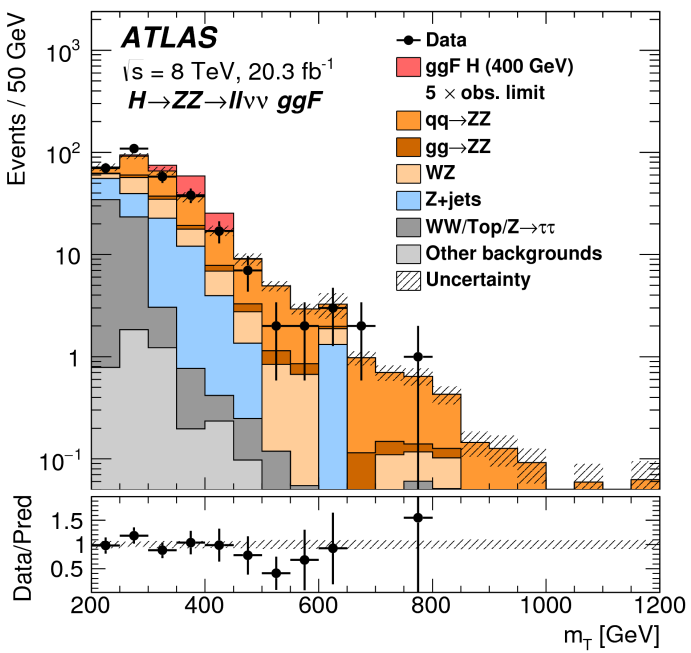
- gluon-fusion cross section and model dependent limits
- Complementary to other searches, with exclusion up to tanβ = 7(3) for Type-I(II) 2HDMs

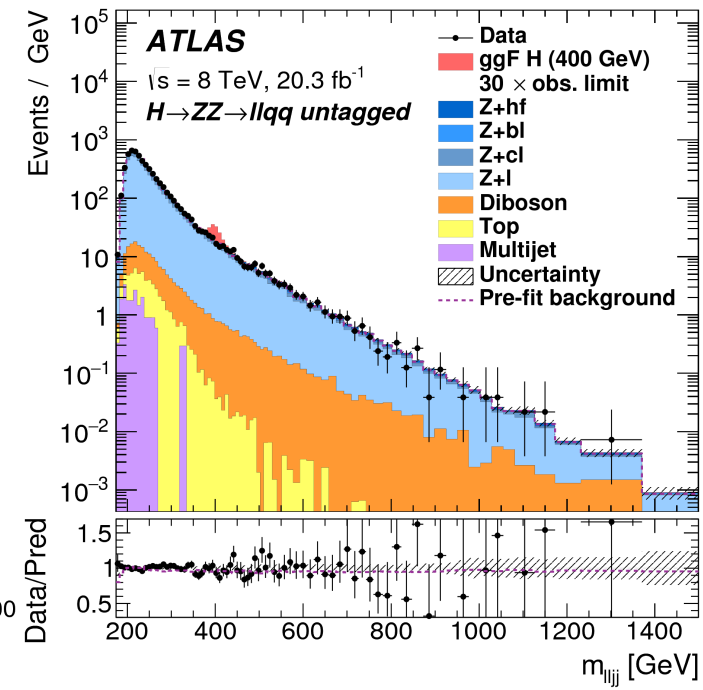
Backup: H→ZZ

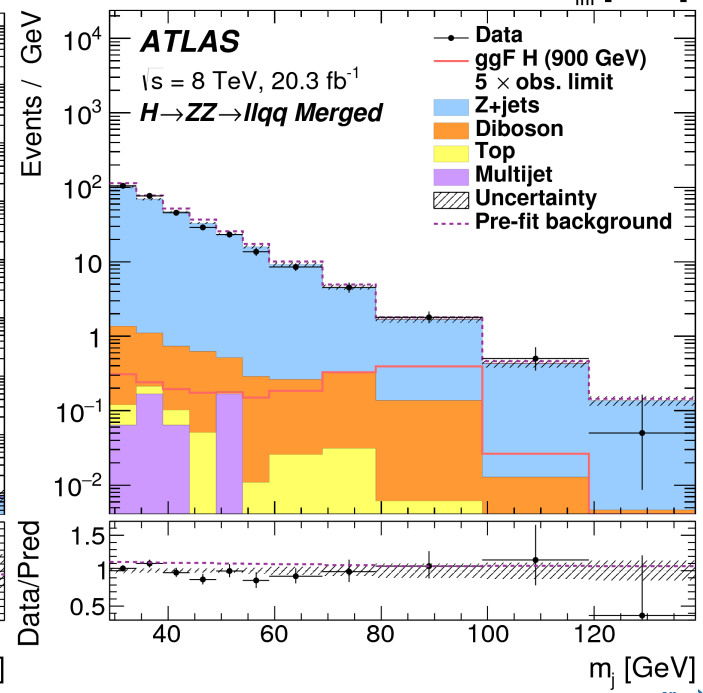

ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, ggF
Data
ggF H (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt
Uncertainty
Events / 10 GeV
m_llll [GeV]


ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, VBF
Data
VBF H (200 GeV)
5 × obs. limit
VH (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt
Uncertainty
Events / 10 GeV
m_llll [GeV]

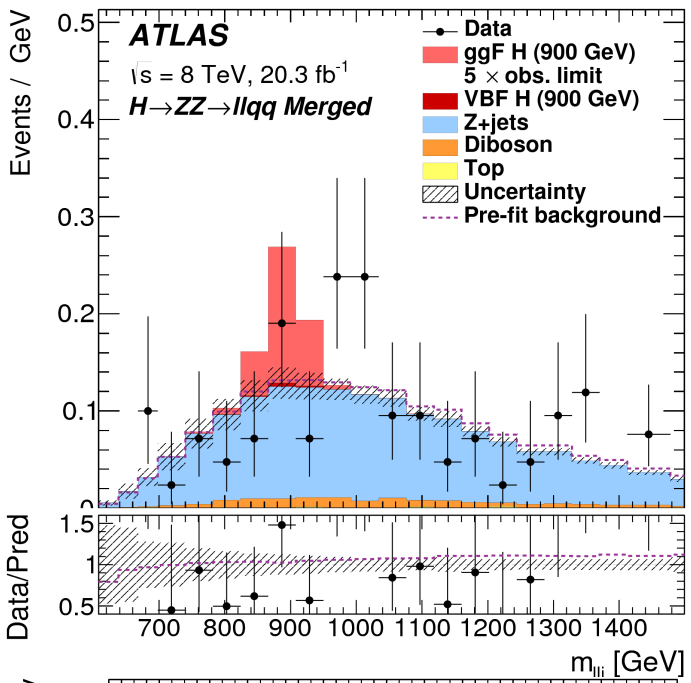

ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, VH
Data
VH (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt
Uncertainty
Events / 10 GeV
m_llll [GeV]

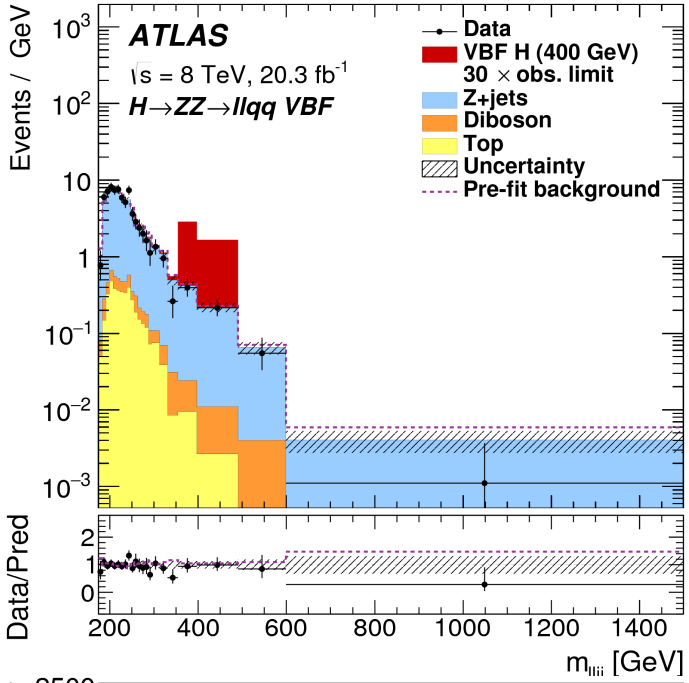

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→llνν ggF
Data
ggF H (400 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
WZ
Z+jets
WW/Top/Z→ττ
Other backgrounds
Uncertainty
Events / 50 GeV
Data/Pred
m_T [GeV]

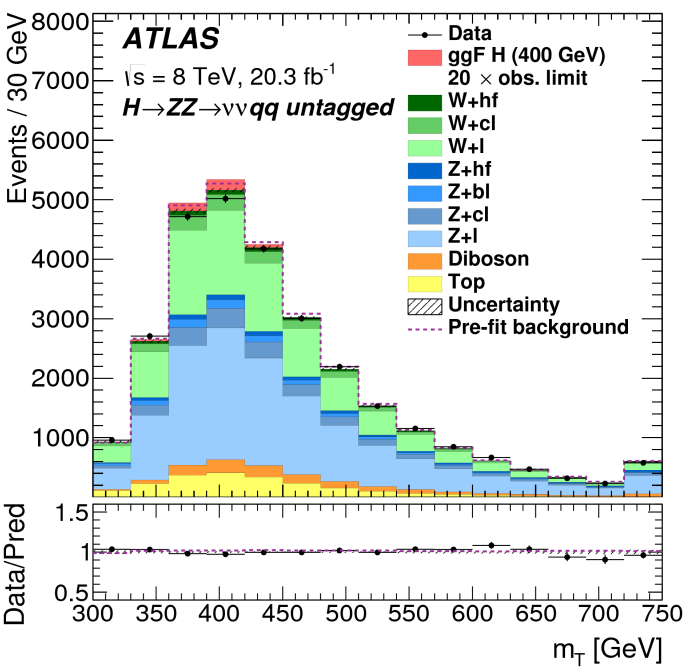

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→llqq untagged
Data
ggF H (400 GeV)
30 × obs. limit
Z+hf
Z+bl
Z+cl
Z+l
Diboson
Top
Multijet
Uncertainty
Pre-fit background
Events / GeV
Data/Pred
m_lljj [GeV]

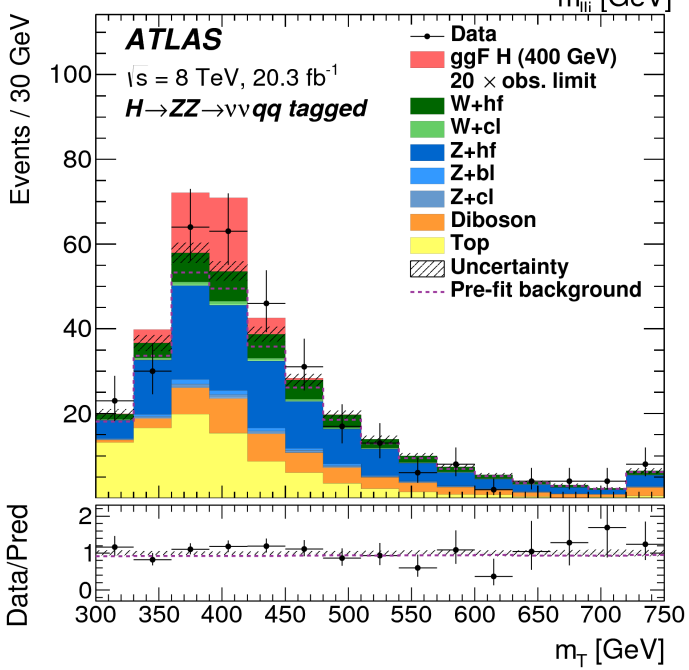

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→llqq Merged
Data
ggF H (900 GeV)
5 × obs. limit
Z+jets
Diboson
Top
Multijet
Uncertainty
Pre-fit background
Events / GeV
Data/Pred
m_j [GeV]

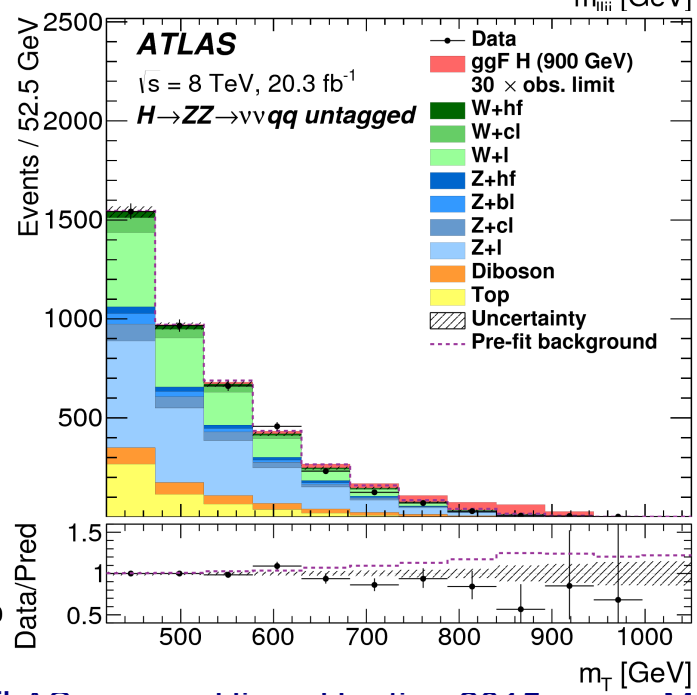
Backup: H→ZZ

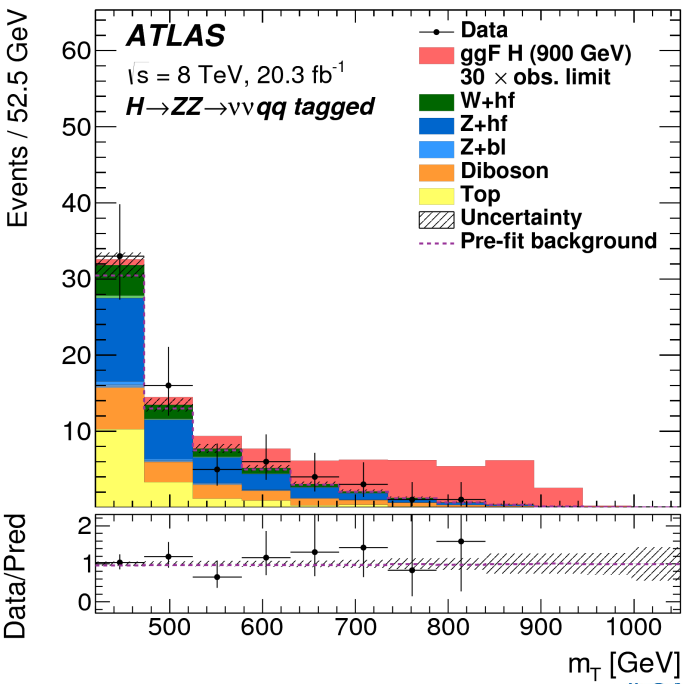

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→llqq Merged
Data
ggF H (900 GeV)
5 × obs. limit
VBF H (900 GeV)
Z+jets
Diboson
Top
Uncertainty
Pre-fit background
Events / GeV
Data/Pred
m_lljj [GeV]


ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→llqq VBF
Data
VBF H (400 GeV)
30 × obs. limit
Z+jets
Diboson
Top
Uncertainty
Pre-fit background
Events / GeV
Data/Pred
m_lljj [GeV]

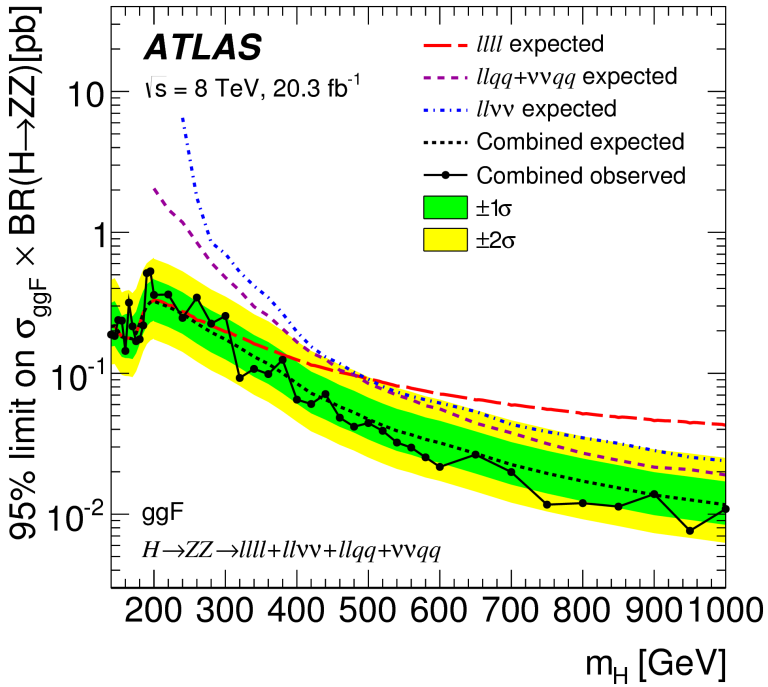

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→ννqq untagged
Data
ggF H (400 GeV)
20 × obs. limit
W+hf
W+cl
W+l
Z+hf
Z+bl
Z+cl
Z+l
Diboson
Top
Uncertainty
Pre-fit background
Events / 30 GeV
Data/Pred
m_T [GeV]

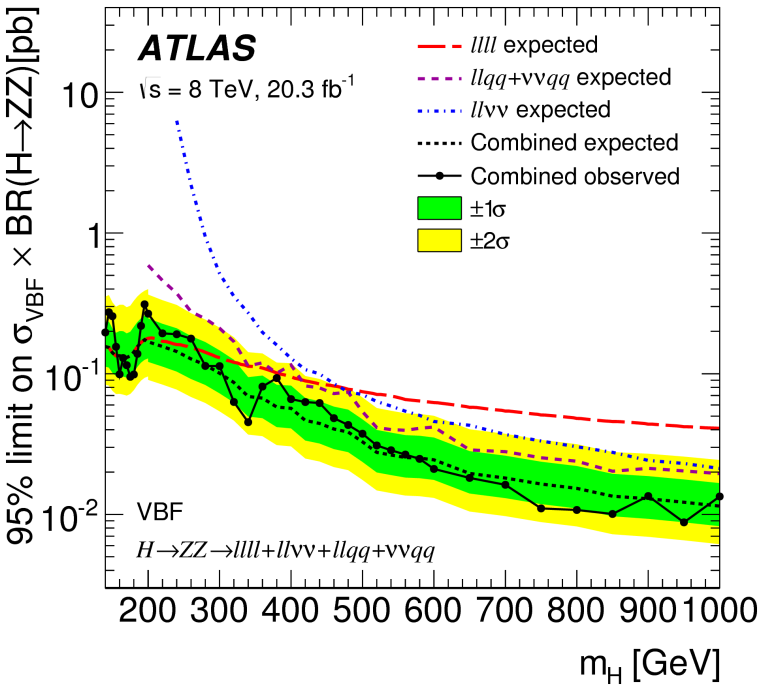

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→ννqq tagged
Data
ggF H (400 GeV)
20 × obs. limit
W+hf
W+cl
Z+hf
Z+bl
Z+cl
Diboson
Top
Uncertainty
Pre-fit background
Events / 30 GeV
Data/Pred
m_T [GeV]

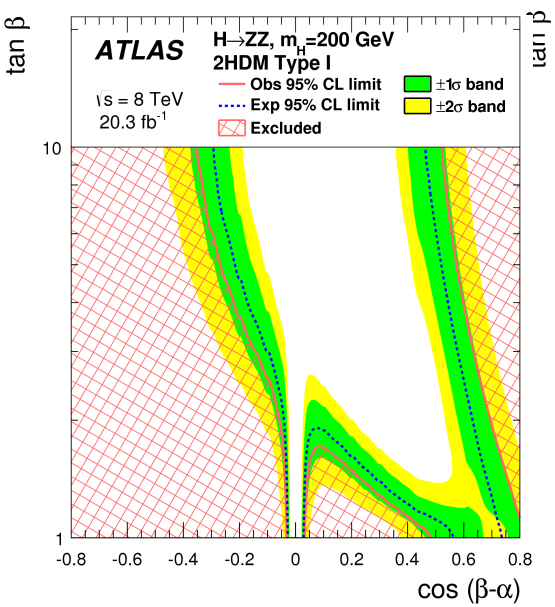

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→ννqq untagged
Data
ggF H (900 GeV)
30 × obs. limit
W+hf
W+cl
W+l
Z+hf
Z+bl
Z+cl
Z+l
Diboson
Top
Uncertainty
Pre-fit background
Events / 52.5 GeV
Data/Pred
m_T [GeV]

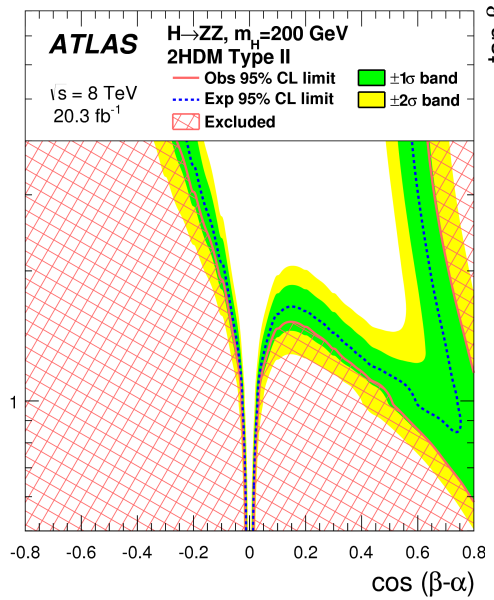

ATLAS
√s = 8 TeV, 20.3 fb-1
H→ZZ→ννqq tagged
Data
ggF H (900 GeV)
30 × obs. limit
W+hf
Z+hf
Z+bl
Diboson
Top
Uncertainty
Pre-fit background
Events / 52.5 GeV
Data/Pred
m_T [GeV]

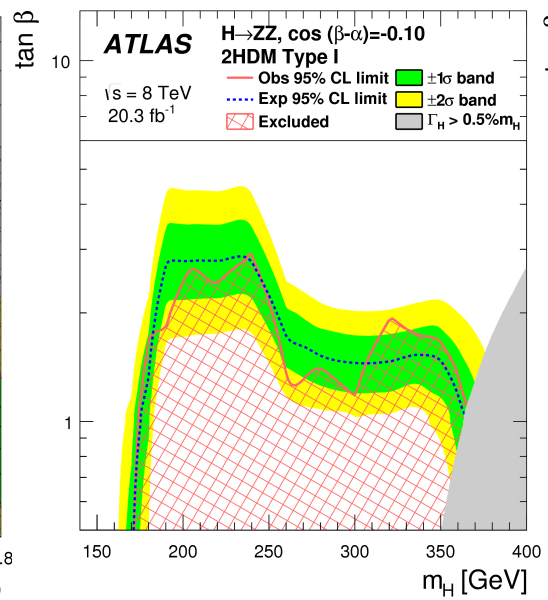
Backup: H→ZZ

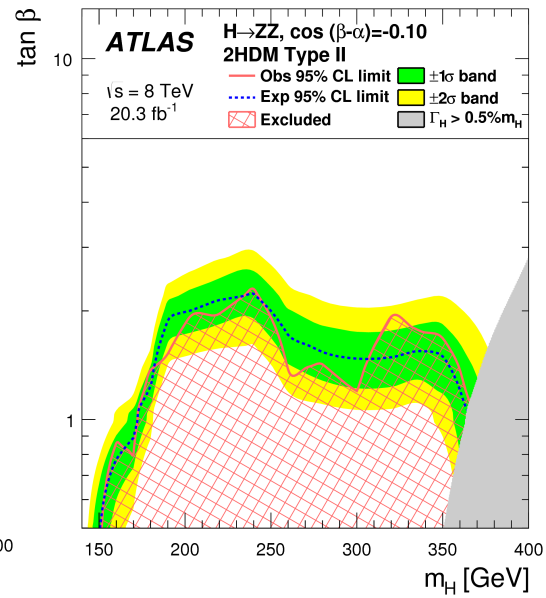

ATLAS
√s = 8 TeV, 20.3 fb-1
llll expected
llqq+ννqq expected
llνν expected
Combined expected
Combined observed
±1σ
±2σ
ggF
H→ZZ→llll+llνν+llqq+ννqq
95% limit on σggF × BR(H→ZZ)[pb]
mH [GeV]


ATLAS
√s = 8 TeV, 20.3 fb-1
llll expected
llqq+ννqq expected
llνν expected
Combined expected
Combined observed
±1σ
±2σ
VBF
H→ZZ→llll+llνν+llqq+ννqq
95% limit on σVBF × BR(H→ZZ)[pb]
mH [GeV]

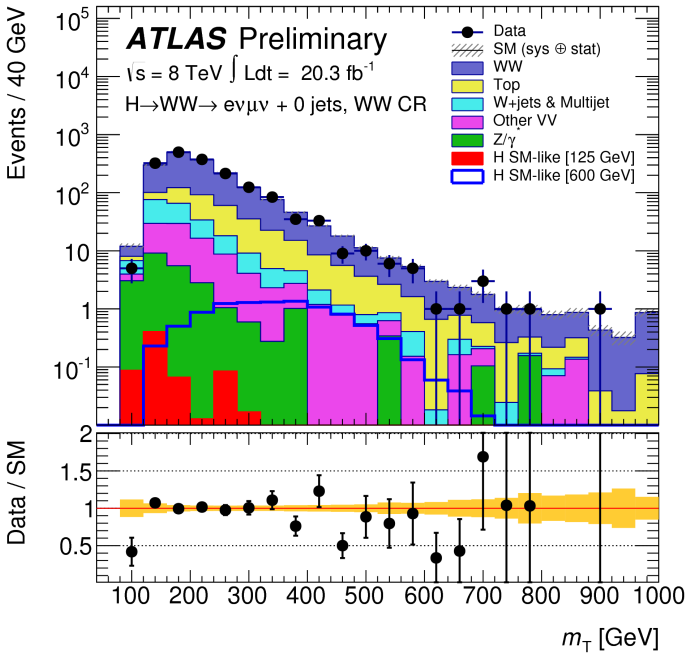

ATLAS
H→ZZ, mH=200 GeV
2HDM Type I
√s = 8 TeV
20.3 fb-1
Obs 95% CL limit
Exp 95% CL limit
Excluded
±1σ band
±2σ band
tan β
cos (β-α)

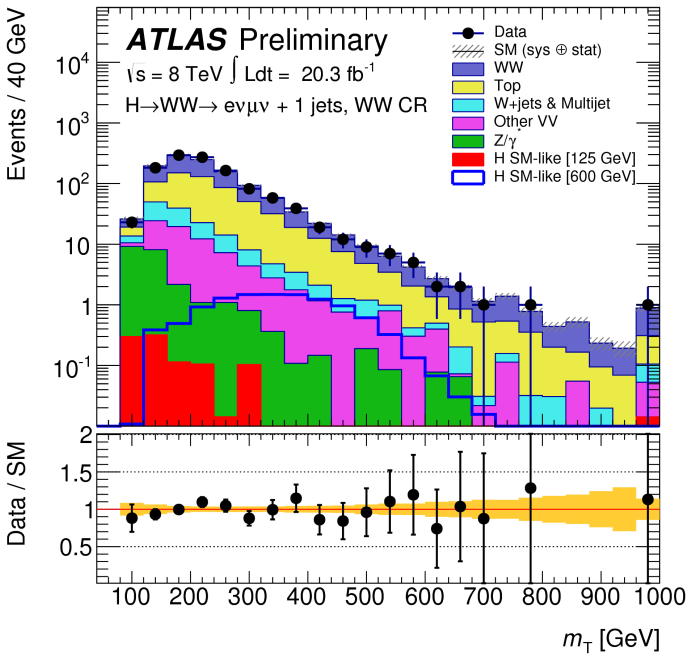

ATLAS
H→ZZ, mH=200 GeV
2HDM Type II
√s = 8 TeV
20.3 fb-1
Obs 95% CL limit
Exp 95% CL limit
Excluded
±1σ band
±2σ band
tan β
cos (β-α)

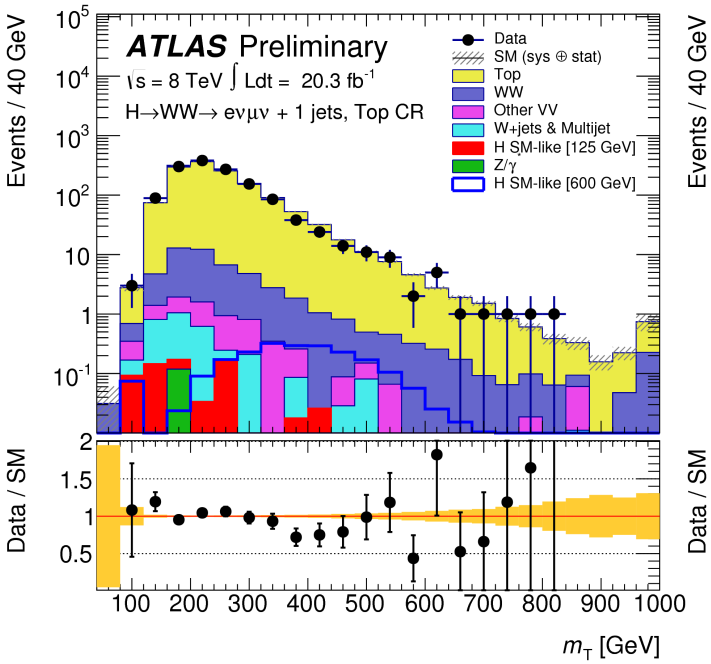

ATLAS
H→ZZ, cos (β-α)=-0.10
2HDM Type I
√s = 8 TeV
20.3 fb-1
Obs 95% CL limit
Exp 95% CL limit
Excluded
±1σ band
±2σ band
ΓH > 0.5%mH
tan β
mH [GeV]

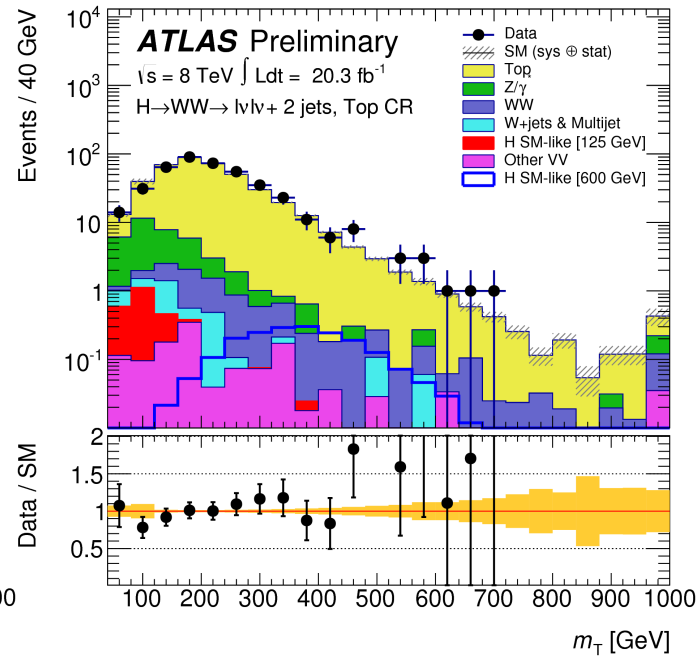

ATLAS
H→ZZ, cos (β-α)=-0.10
2HDM Type II
√s = 8 TeV
20.3 fb-1
Obs 95% CL limit
Exp 95% CL limit
Excluded
±1σ band
±2σ band
ΓH > 0.5%mH
tan β
mH [GeV]

Backup: H→WW

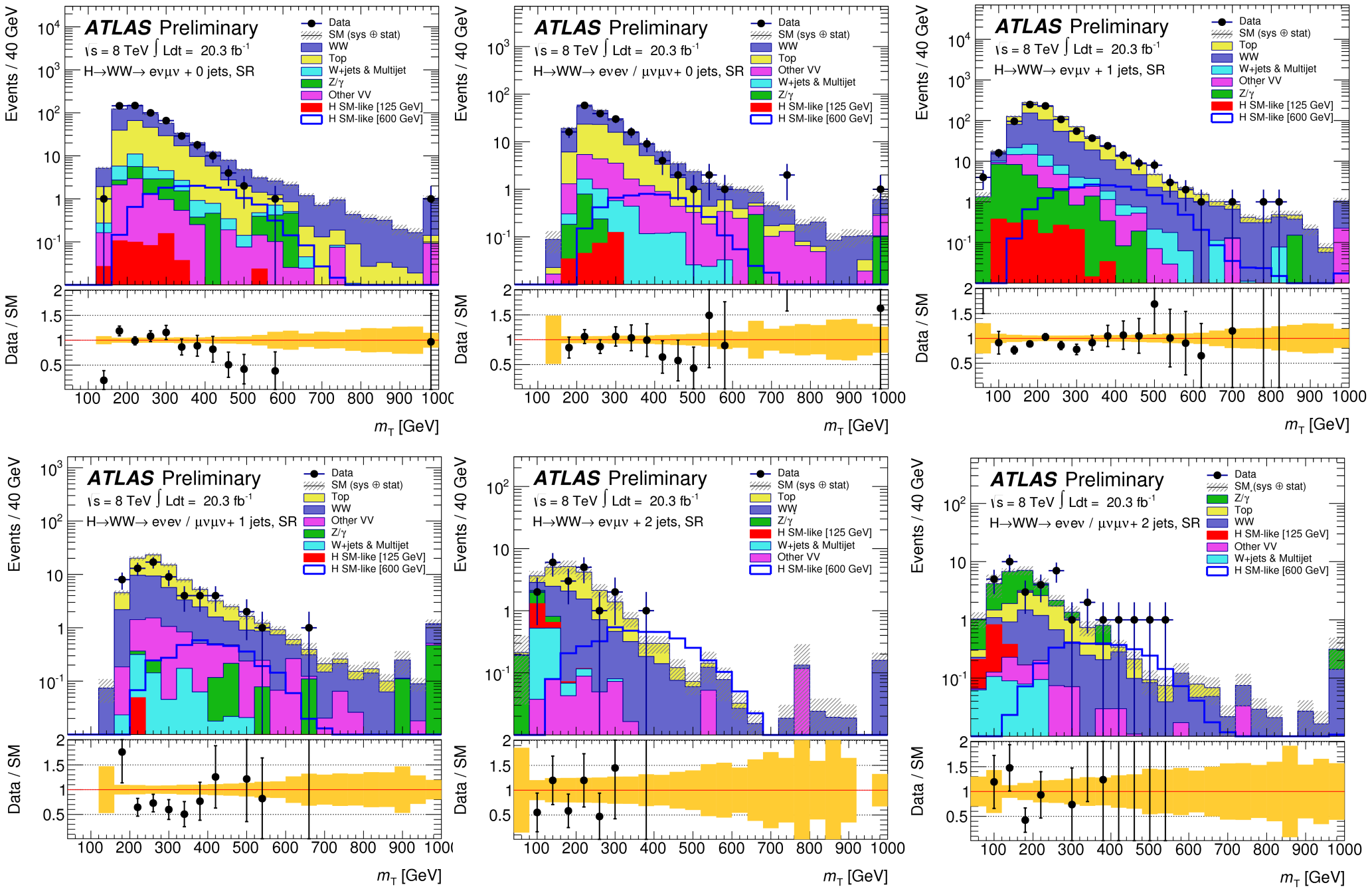

ATLAS Preliminary
√s = 8 TeV ∫ Ldt = 20.3 fb-1
H→WW→ eνμν + 0 jets, WW CR
Data
SM (sys ⊕ stat)
WW
Top
W+jets & Multijet
Other VV
Z/γ
H SM-like [125 GeV]
H SM-like [600 GeV]
Events / 40 GeV
Data / SM
mT [GeV]


ATLAS Preliminary
√s = 8 TeV ∫ Ldt = 20.3 fb-1
H→WW→ eνμν + 1 jets, WW CR
Data
SM (sys ⊕ stat)
WW
Top
W+jets & Multijet
Other VV
Z/γ
H SM-like [125 GeV]
H SM-like [600 GeV]
Events / 40 GeV
Data / SM
mT [GeV]

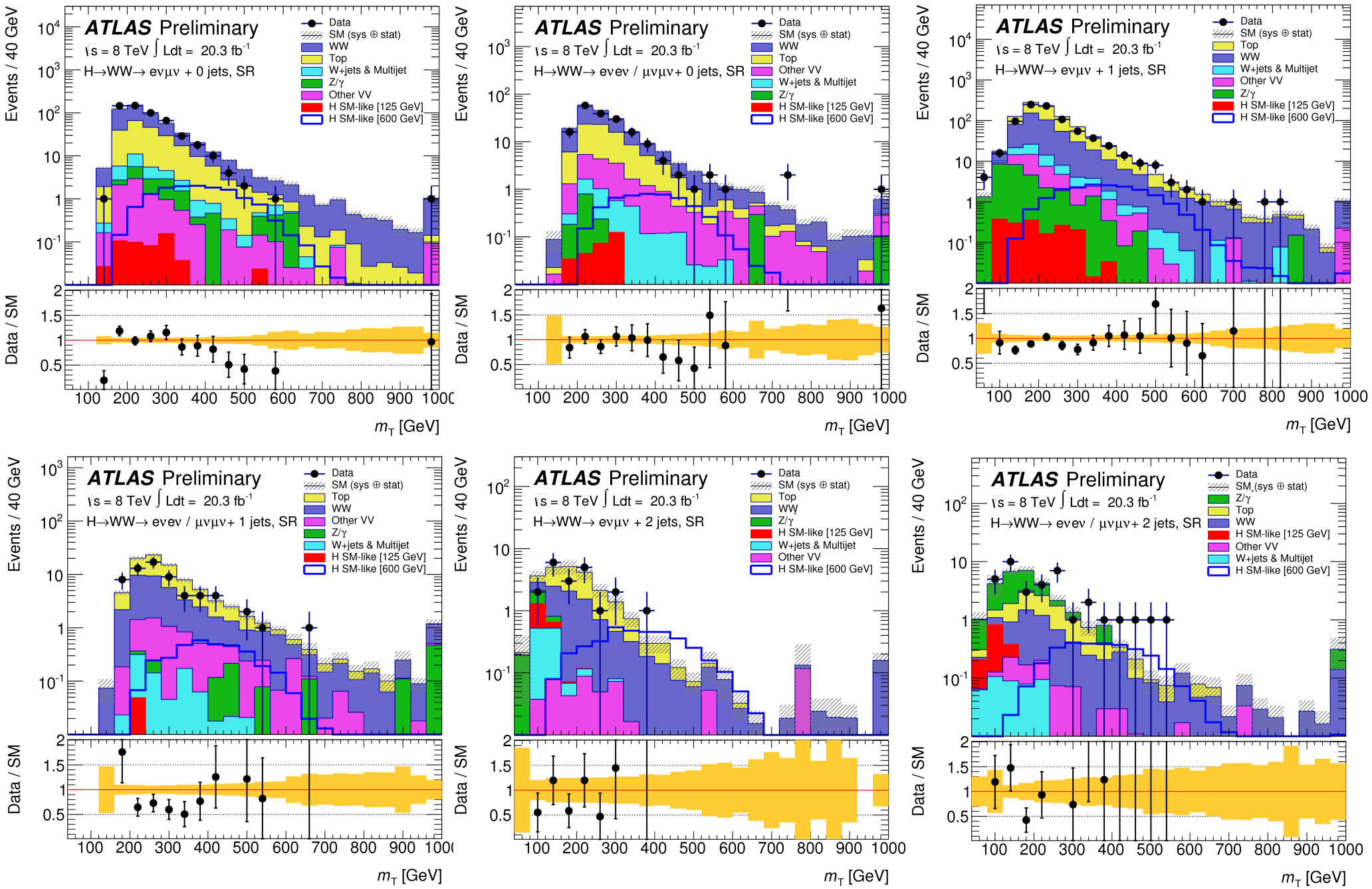

ATLAS Preliminary
√s = 8 TeV ∫ Ldt = 20.3 fb-1
H→WW→ eνμν + 1 jets, Top CR
Data
SM (sys ⊕ stat)
Top
WW
Other VV
W+jets & Multijet
H SM-like [125 GeV]
Z/γ
H SM-like [600 GeV]
Events / 40 GeV
Data / SM
mT [GeV]


ATLAS Preliminary
√s = 8 TeV ∫ Ldt = 20.3 fb-1
H→WW→ lνlν+ 2 jets, Top CR
Data
SM (sys ⊕ stat)
Top
Z/γ
WW
W+jets & Multijet
H SM-like [125 GeV]
Other VV
H SM-like [600 GeV]
Events / 40 GeV
Data / SM
mT [GeV]

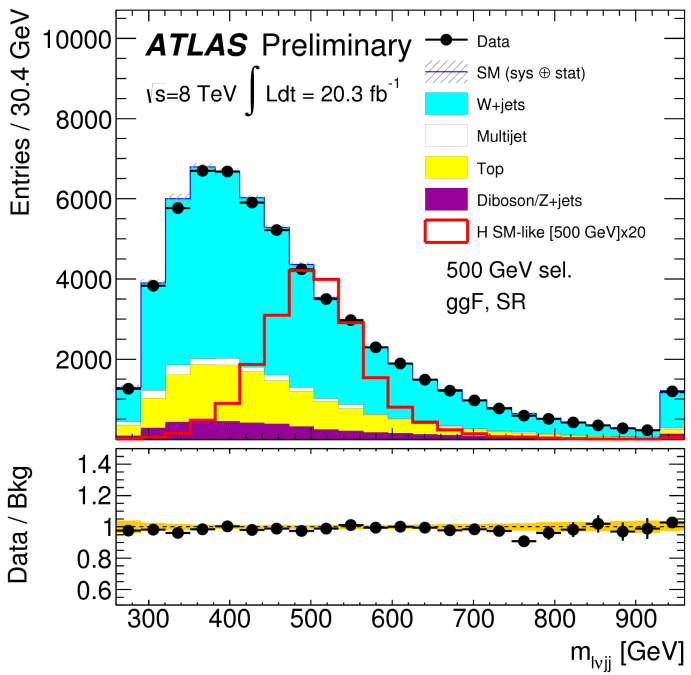
Backup: H→WW (Signal Regions)

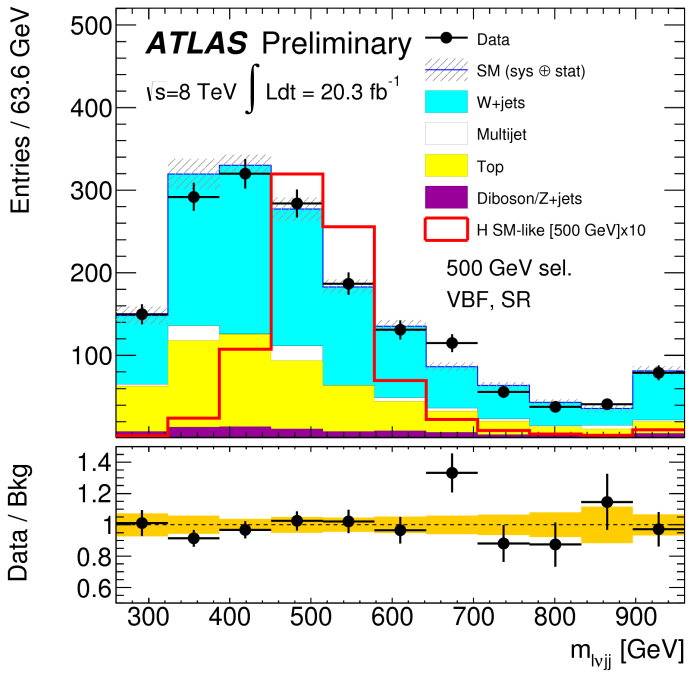


Backup: H→WW (Signal Regions)

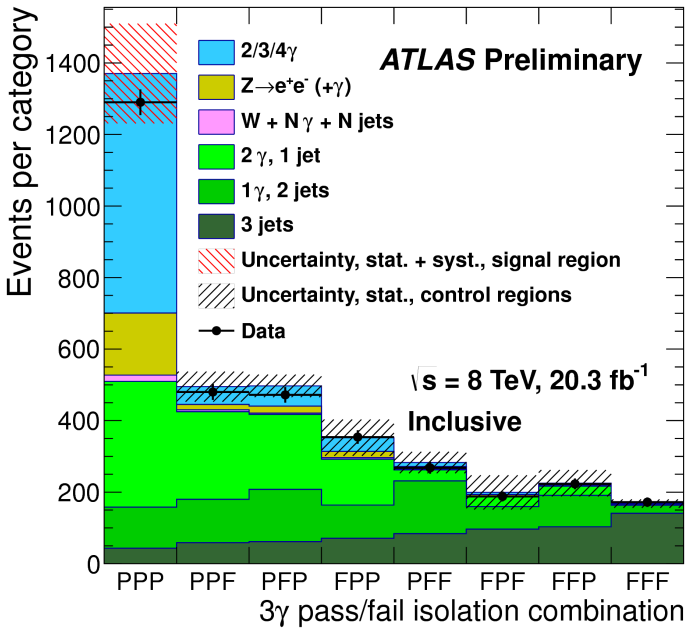


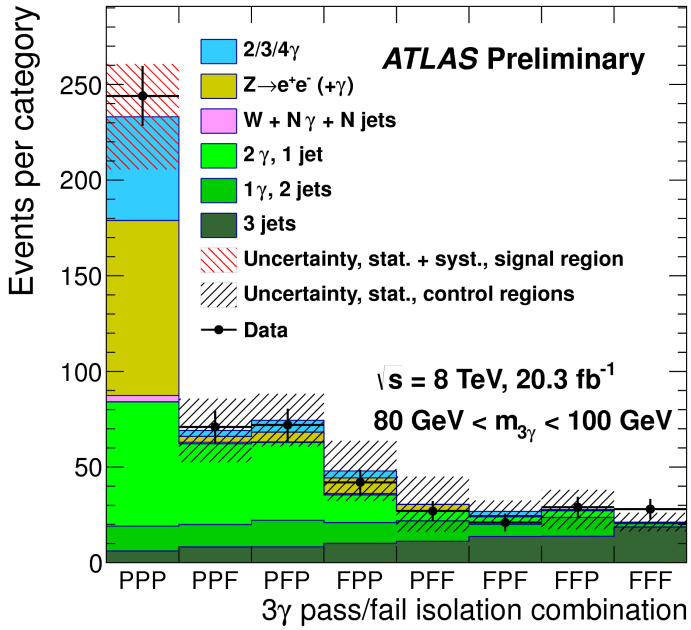
Backup: H→WW

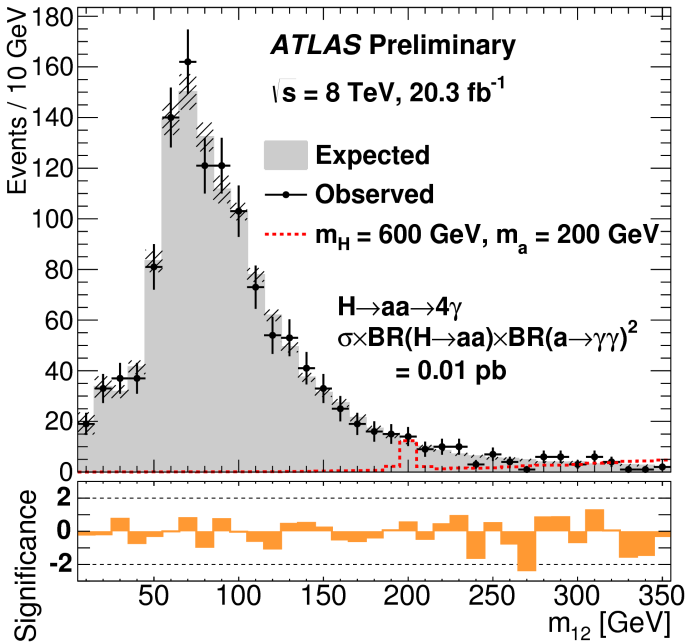

ATLAS Preliminary
√s=8 TeV ∫ Ldt = 20.3 fb-1
Data
SM (sys ⊕ stat)
W+jets
Multijet
Top
Diboson/Z+jets
H SM-like [500 GeV]x20
500 GeV sel.
ggF, SR
Entries / 30.4 GeV
Data / Bkg
m_lνjj [GeV]

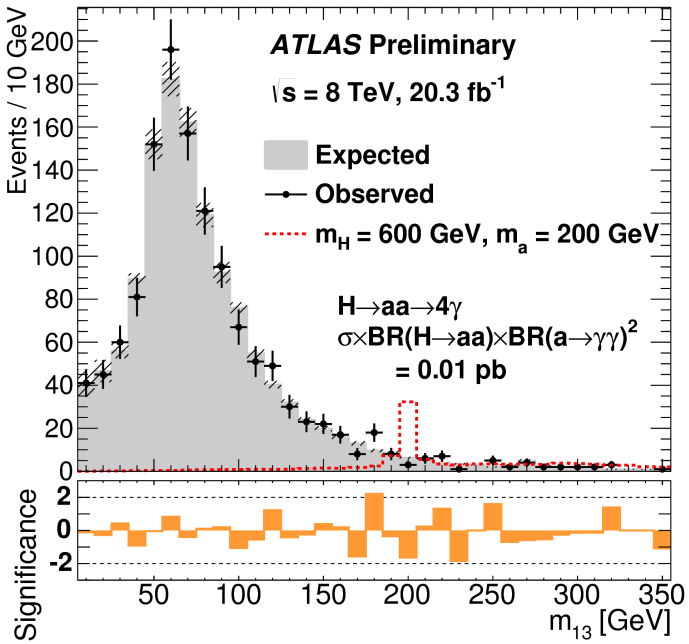

ATLAS Preliminary
√s=8 TeV ∫ Ldt = 20.3 fb-1
Data
SM (sys ⊕ stat)
W+jets
Multijet
Top
Diboson/Z+jets
H SM-like [500 GeV]x10
500 GeV sel.
VBF, SR
Entries / 63.6 GeV
Data / Bkg
m_lνjj [GeV]

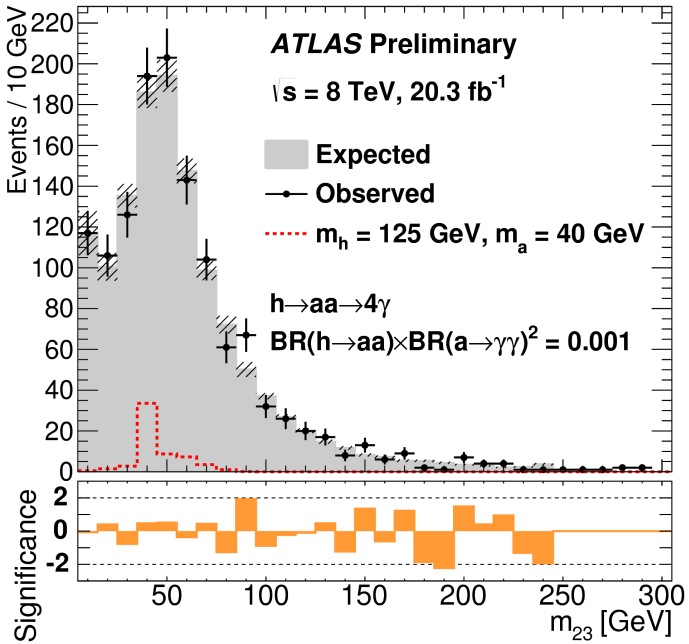
Backup: h→aa→4γ

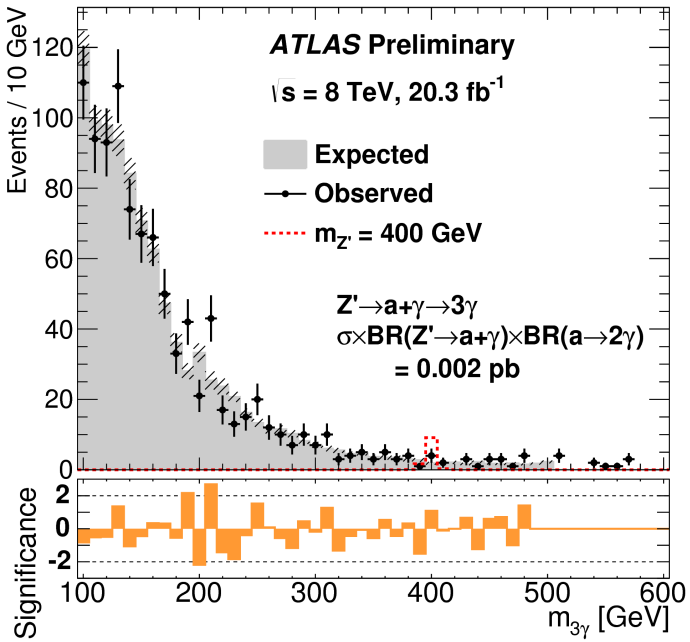




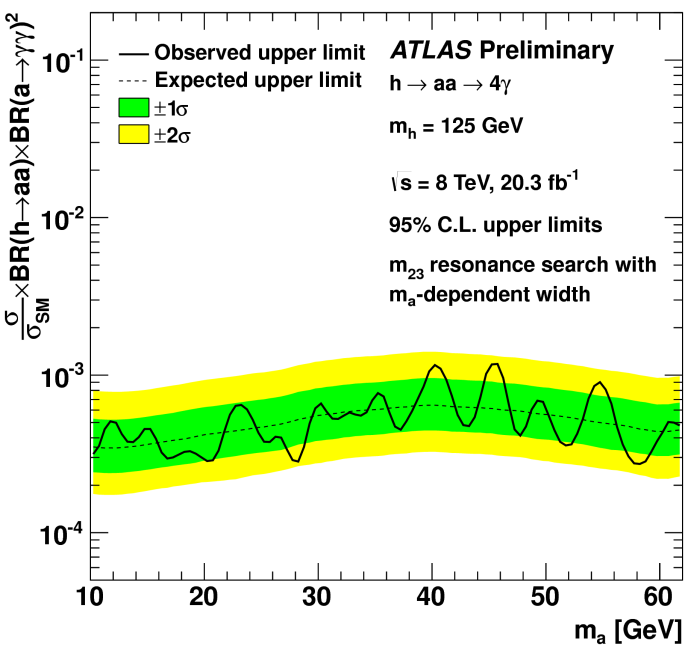


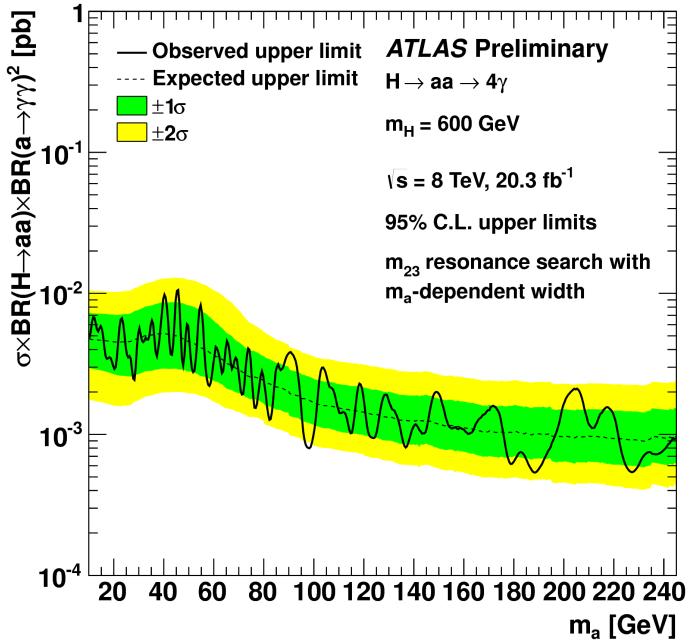


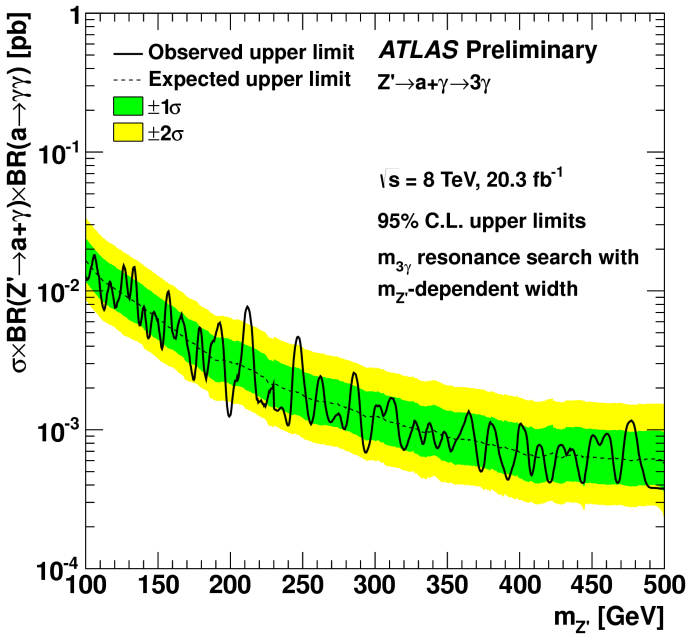




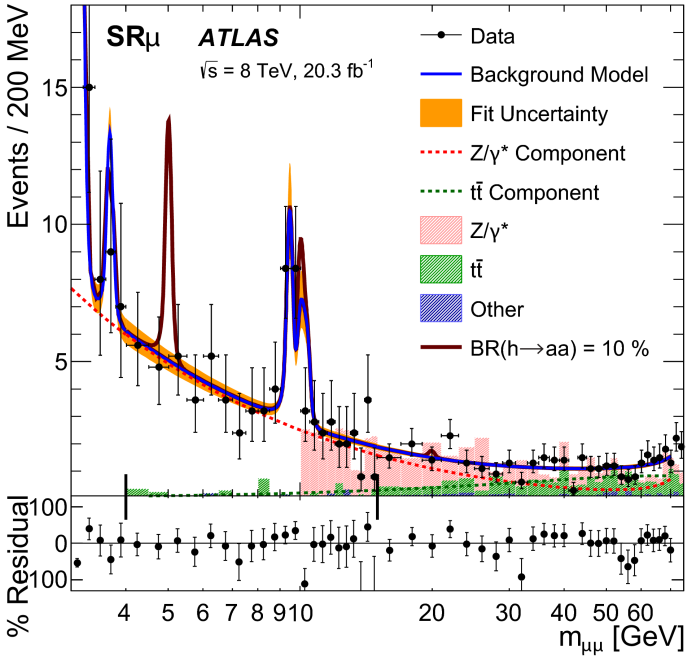
Backup: h→aa→4γ

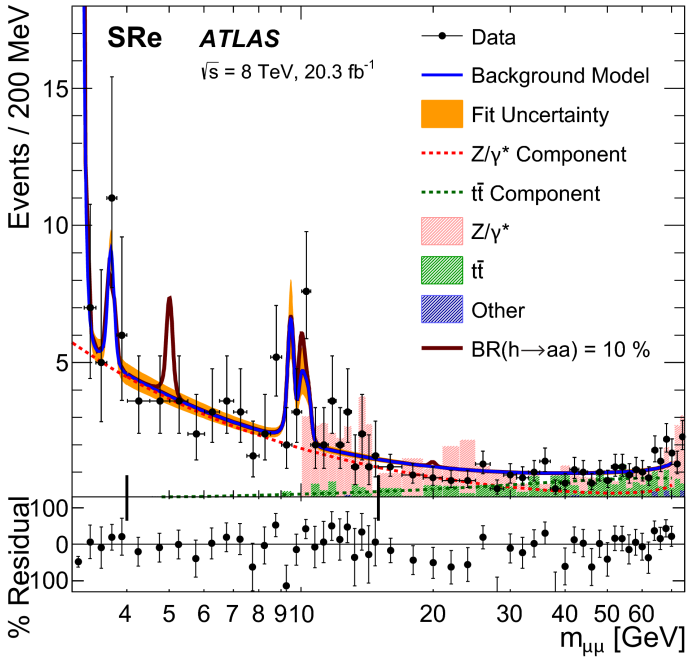




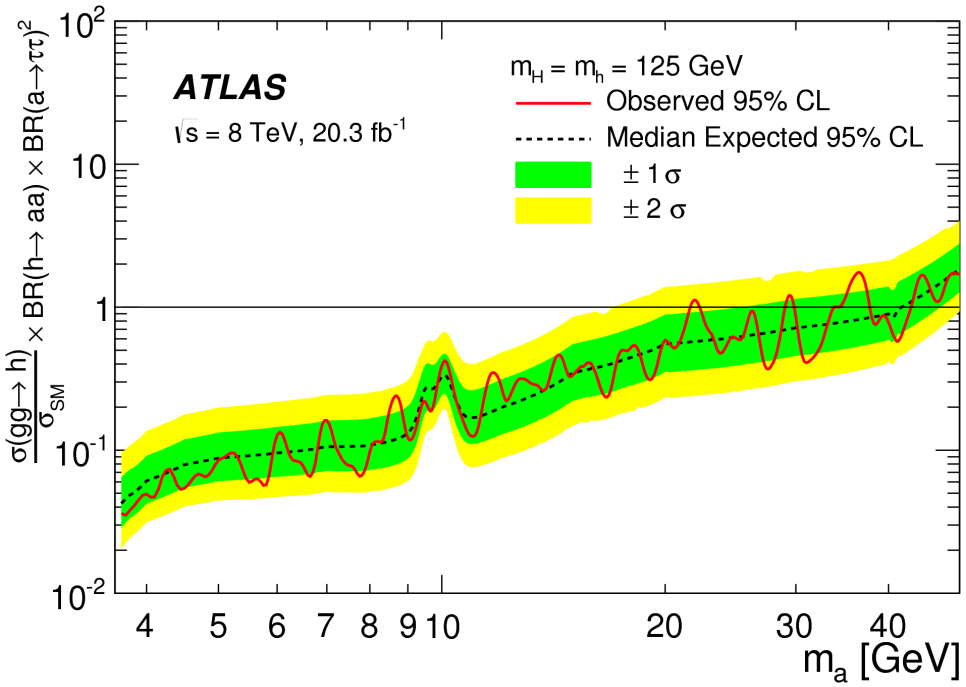


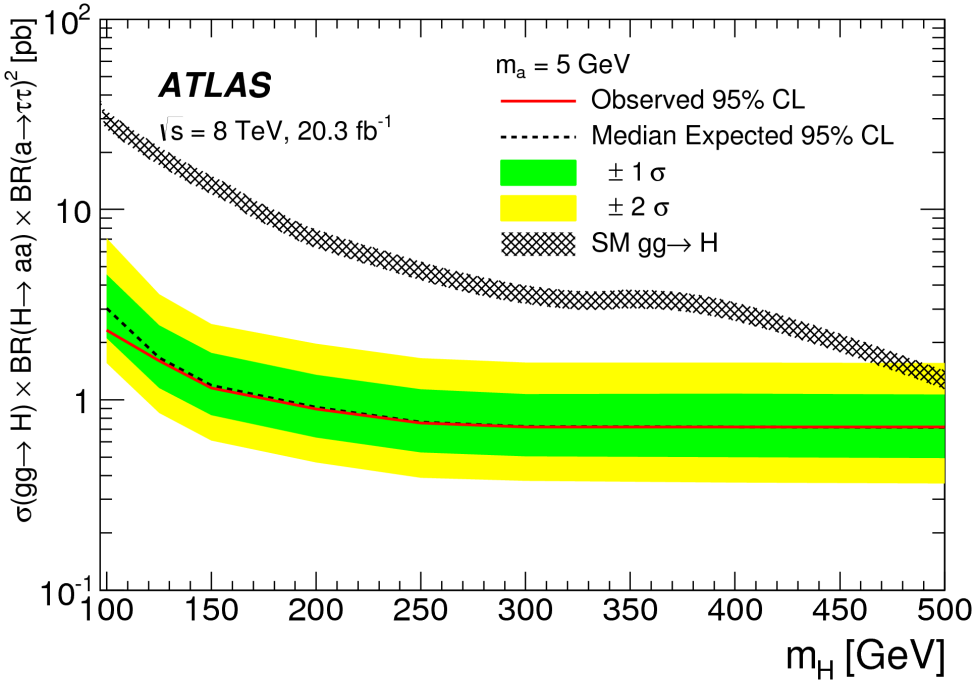
Backup: h→aa→μμττ



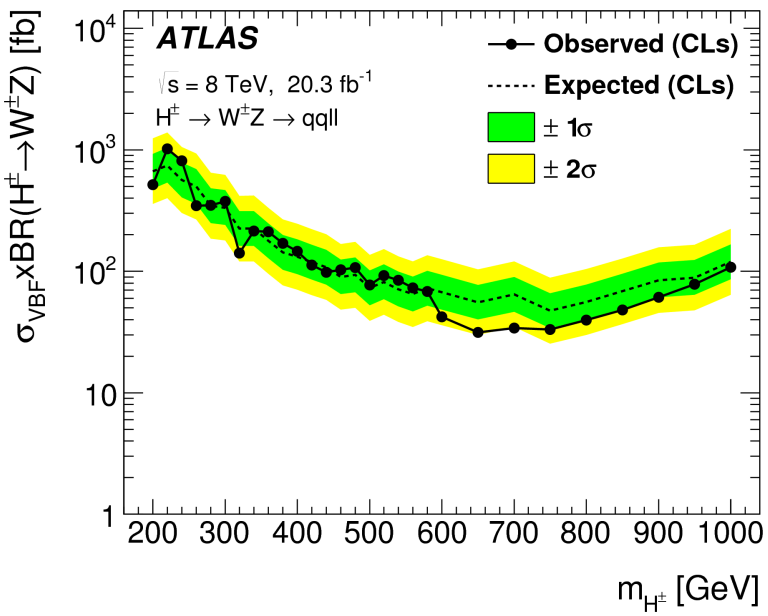


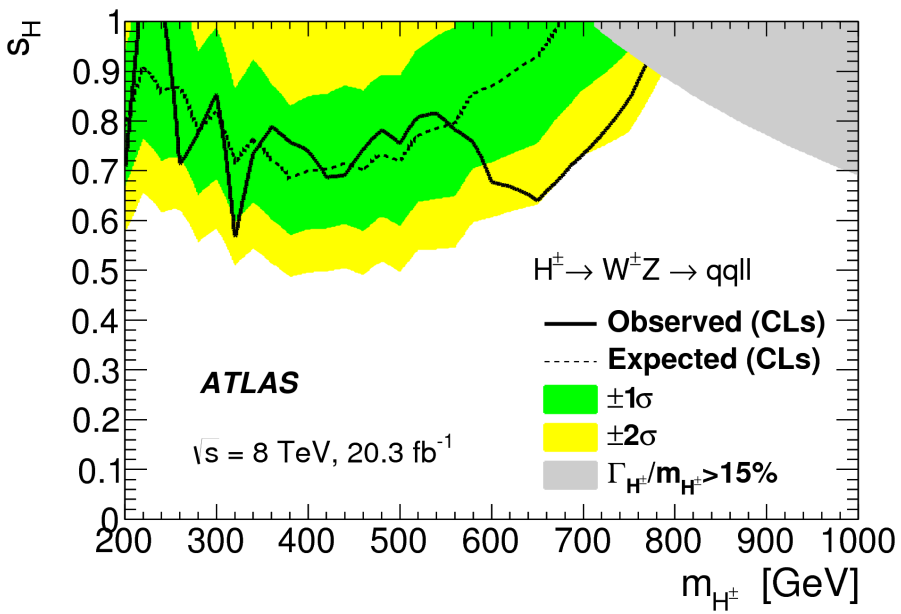
Selection	Relative efficiency (%)	
Generator-level	0.41±0.00	
Pass trigger	67.6±0.3	
Two selected muons	77.8±0.3	
Opposite charge (μ,μ)	100.0±0.0	
p_T $(\mu\mu) > 40$ GeV	98.1±0.1	
2.8 GeV $< m_{\mu\mu} <$ 70 GeV	100.0±0.0	
	SRμ (%)	SRe (%)
Third lepton	18.2±0.3	7.8±0.2
$\Delta\phi\,(\mu\mu,\ell)$	95.5±0.4	93.7±0.7
1,2 or 3 nearby tracks	91.4±0.5	82.8±1.1
Opposite charge (ℓ, lead-track)	91.2±0.9	88.1±1.1
Lepton isolation	75.5±0.9	84.6±1.3





Backup: $H^{+/-} \rightarrow WZ$

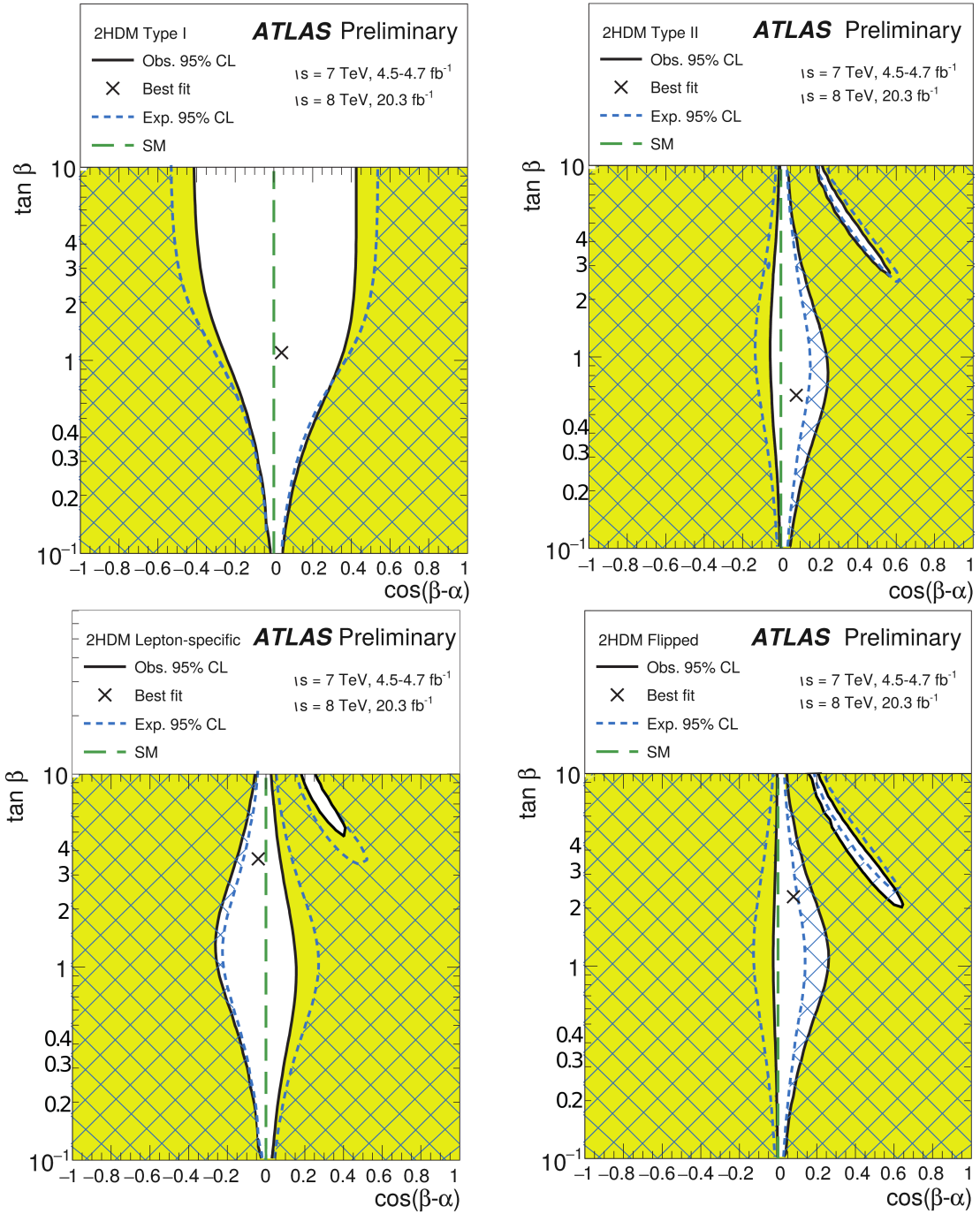




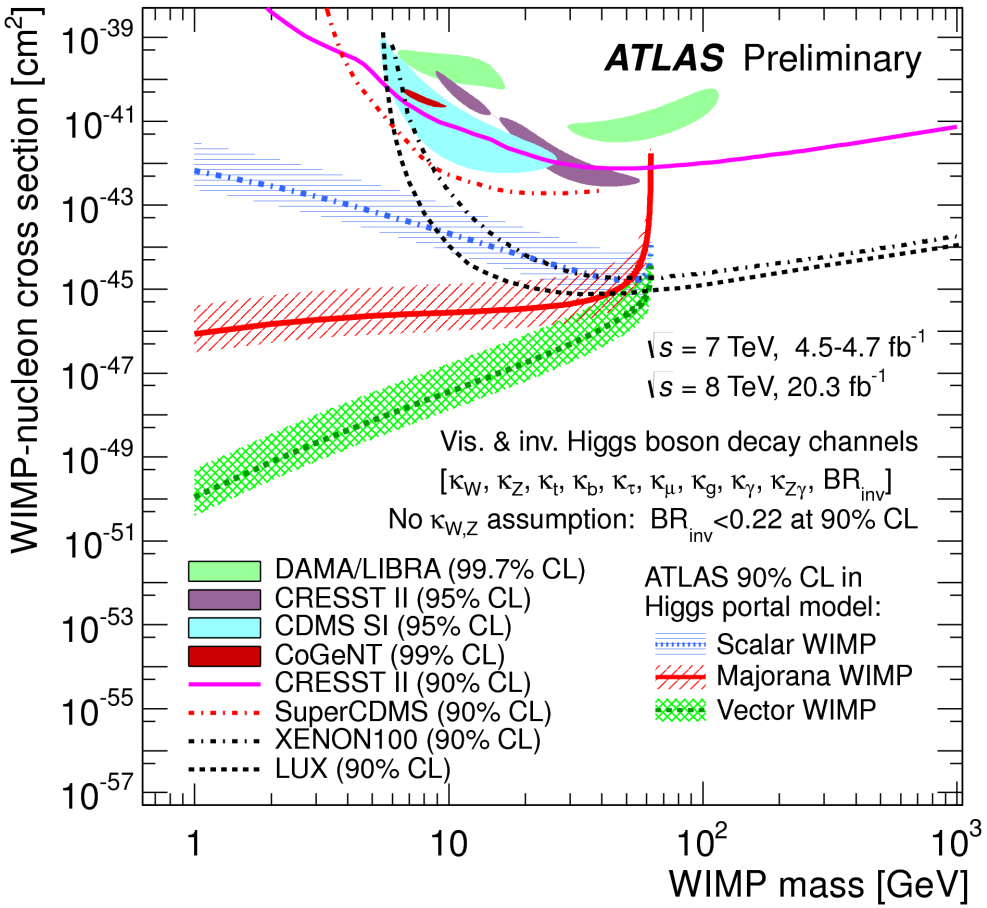
- $H^{+/-} \rightarrow WZ$ contributions at loop level for 2HDM models of tree level for Higgs Triplet Models
- Search using VBF production and $W \rightarrow qq$ and $Z \rightarrow ll$ decay modes
  - two leptons with $83<m(ll)<99$ GeV
  - two highest pT jets in opposite hemisphere with $m(jj)>500$ GeV and $|\Delta\eta|>4$
  - next two highest pT jets: $60<m(jj)<95$ GeV
  - $MET/\sqrt{H_T}<3.5$ GeV$^{1/2}$
  - high p_T^{ll} and low $\Delta\varphi(ll)$

Discriminating variable m(llqq) with W mass constraint on m(qq)

Backup: Coupling Combination



Backup: Coupling Combination



ATLAS upper limit at the 90% CL on the WIMP-nucleon scattering cross section in a Higgs portal model as a function of the mass of the dark matter particle, shown separately for a scalar, Majorana fermion, or vector boson WIMP. It is determined using the limit BRinv.<0.22 at the 90% CL derived using both visible and invisible Higgs boson decay channels. The hashed bands indicate the uncertainty resulting from the form factor fN. Excluded and allowed regions from direct detection experiments at the confidence levels indicated are also shown [105-113]. These are spin-independent results obtained directly from searches for nuclei recoils from elastic scattering of WIMPs, rather than being inferred indirectly through Higgs boson exchange in the Higgs portal model.