Extended Scalar Searches at ATLAS & CMS

Allison McCarn (University of Michigan)
On behalf of the CMS and ATLAS Collaborations

Rencontres de Moriond EW 2016

Beyond the Standard Model

BSM physics was not observed in run-1, but there are still many possible models to be investigated in run-2.

Higgs Triplet:
An additional scalar triplet results in charged, doubly-charged, and neutral bosons.

Two-Higgs Double Models (2HDM):
Additional Higgs Doublet gives rise to 5 Higgs bosons (H,h,A,H±)

The observed Higgs boson at 125 GeV could be only the beginning.

A few examples out of many…

2HDM+S:
Two Higgs Doublets and an additional complex singlet (e.g. NMSSM)

Minimal Supersymmetric Standard Model:
Higgs Sector is Type-II 2HDM. Current common benchmark is hMSSM.

Electroweak Singlet (EWS):
Additional singlet, resulting in 2 CP-even bosons.

Run-1 Results/Run-2 Prospects

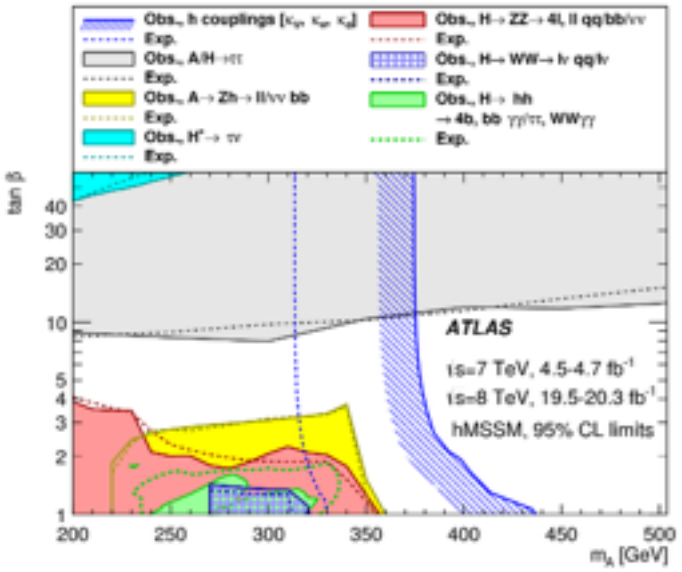
- Many searches were performed in run-1, with 7 and 8 TeV centre-of-mass energy at the LHC, but physics beyond the Standard Model has not yet been observed.

- An example of where we stand and hopes for the future of the LHC can be seen in the hMSSM overlay and prospect plots.
  - Much parameter space is excluded, but there is still room for high mass Higgs to be found!

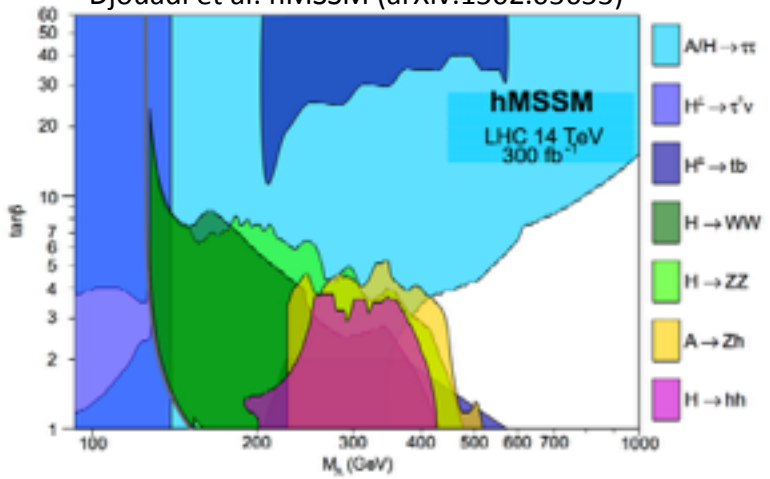
In 2015, ATLAS collected 3.2 fb^{-1} and CMS collected 2.8 fb^{-1} of data at 13 TeV!

This is already enough in many cases to exceed run-1 sensitivity!

Phys. Rev. D 92, 092004 (2015)



Djouadi et al: hMSSM (arXiv:1502.05653)



Beyond the Standard Model Searches in this Presentation

Many searches for run-2, as well as a few final searches for run-1, from ATLAS, CMS, and both.

Charged Higgs

$H^{\pm} \rightarrow \tau\nu$ (13 TeV)

$H^{\pm} \rightarrow tb$ (8 TeV)

$\phi^{\pm\pm}\phi^{\pm\pm} \rightarrow lll\nu/4l$ (8 TeV)

Neutral Higgs

$H \rightarrow \tau\tau$ (13 TeV)

Higgs-to-Higgs

$H \rightarrow 2a$ (8 TeV)

$H \rightarrow ZA$ (13 TeV)

$A \rightarrow Zh(125)$ (13 TeV)

Di-Higgs

$H \rightarrow hh \rightarrow bb\gamma\gamma$ (13 TeV)

$H \rightarrow hh \rightarrow bb\tau\tau$ (8/13 TeV)

Dibosons

$H \rightarrow ZZ \rightarrow 4l$ (13 TeV)

$H \rightarrow ZZ \rightarrow ll\nu\nu$ (13 TeV)

Boosted Resonances (13 TeV)

$H \rightarrow ZZ \rightarrow llqq$ (13 TeV)

ZH, $H \rightarrow$ inv (13 TeV)

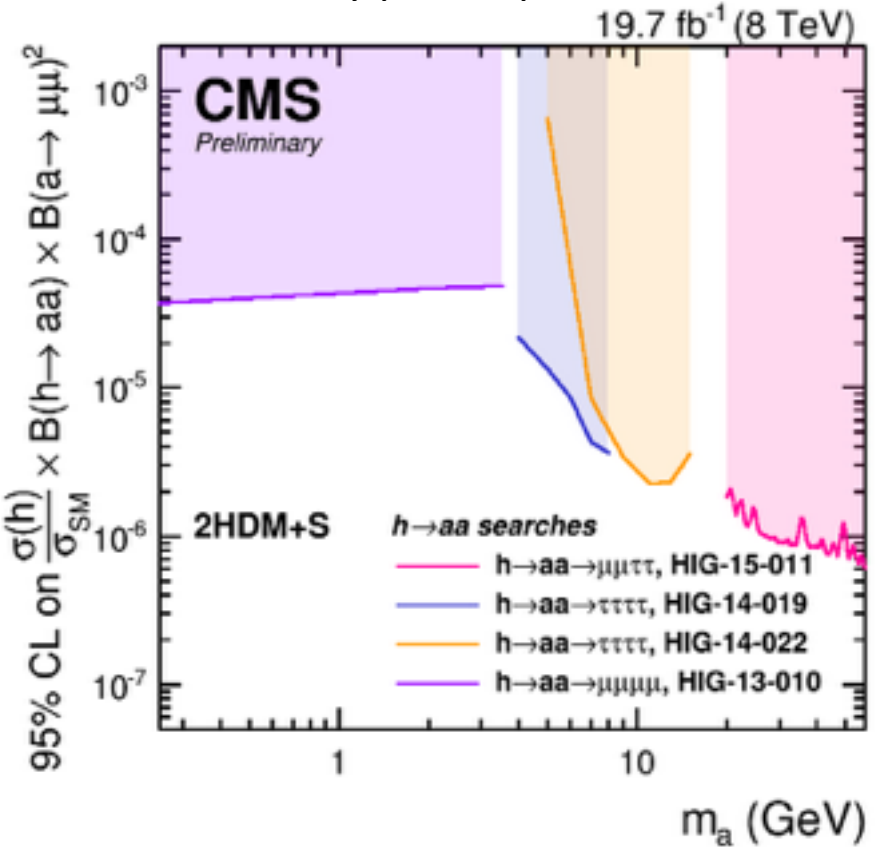
$X \rightarrow Z\gamma$ (13 TeV)

Recent √s = 8 TeV Results

2HDM+S: Search for h(125) →2a

- In a 2HDM+S model, there are 2 singlet states:
  - CP-odd scalar *a*
  - CP-even *s*
- BR(h→BSM) < 0.34, so the decay to 2a can be sizeable.
- Recent results from CMS for **h→2a→2b2μ and h→2a→2μ2τ!**

Summary plot of μ/τ channels



Current channels include:

h→2a→2b2μ (CMS-PAS-HIG-14-041**)**

h→2a→4μ (CMS:Phys. Lett. B 752 (2016) 221)

h→2a→2μ2τ (CMS-PAS-HIG-15-011, ATLAS:Phys. Rev. D92 (2015) 052002)

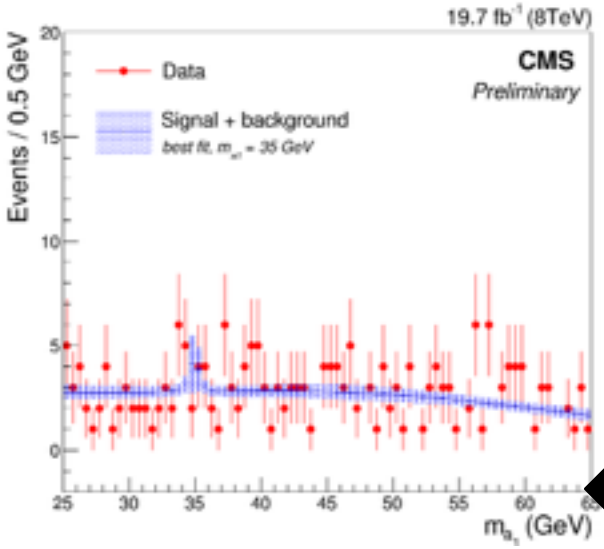
h→2a→4τ (CMS-PAS-HIG-14-022, CMS:JHEP 01 (2016) 079)

h→2a→4γ (ATLAS:CERN-PH-EP-2015-187)

2HDM+S: Search for h(125) →2a

CMS-PAS-HIG-14-041

CMS-PAS-HIG-15-011

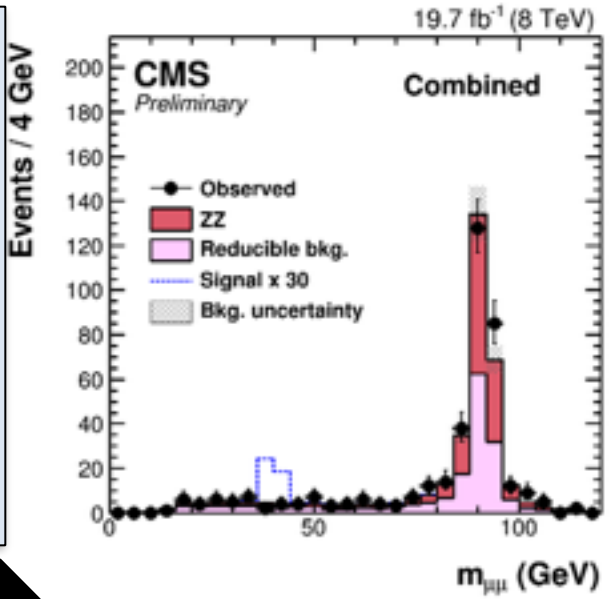


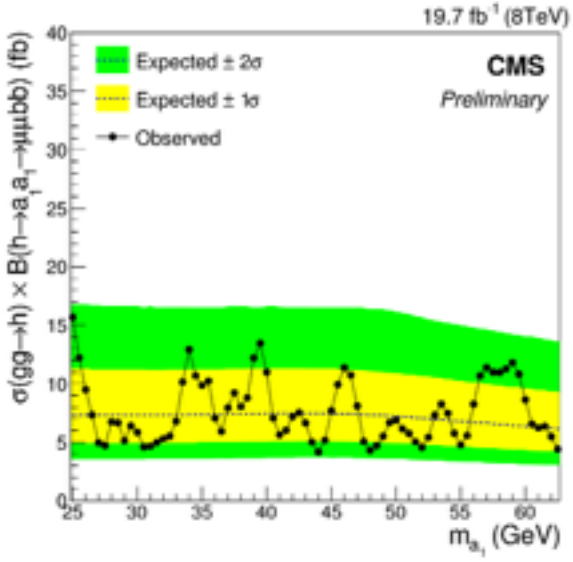
h→2a→2b2μ:

2 b-jets, 2 μ, E_T^{miss} significance < 6

$|M_{bb\mu\mu} - 125| < 25$ GeV

Signal Modeling: Weighted sum of Voigt profile and Crystal ball.
Background Modeling: Polynomial functions, fit to $m_{\mu\mu}$ in data.





h→2a→2μ2τ

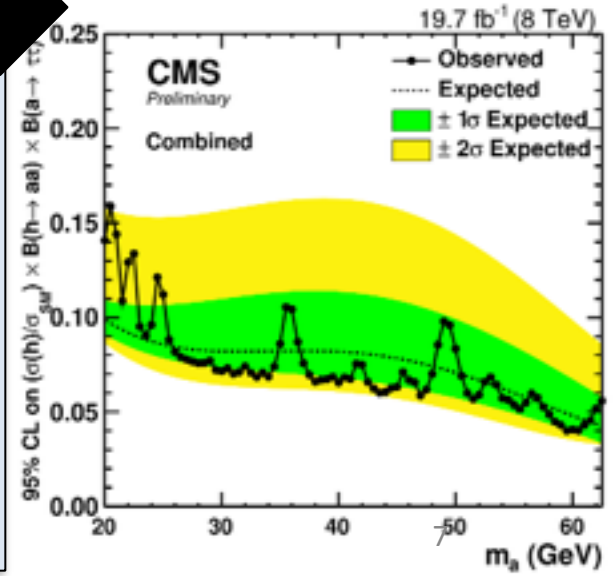
5 final states: $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_\mu\tau_e$, $\mu\mu\tau_{had}\tau_e$, $\mu\mu\tau_{had}\tau_\mu$, $\mu\mu\tau_{had}\tau_{had}$

$|M_{\tau\tau\mu\mu} - 125| < 25$ GeV

$(M_{\mu\mu} - M_{\tau\tau})/M_{\mu\mu} < 0.8$

$|M^{vis}_{ee\mu\mu} - 125| > 15$ GeV

Irreducible backgrounds from MC, reducible from data-driven methods.



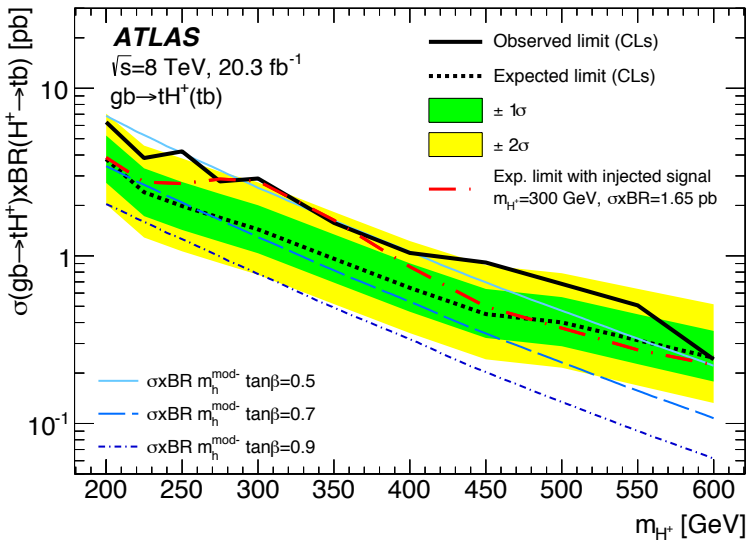
2HDM: Search for $H^{\pm} \rightarrow tb$

ATLAS:CERN-PH-EP-2015-290

CMS: JHEP 11 (2015) 018

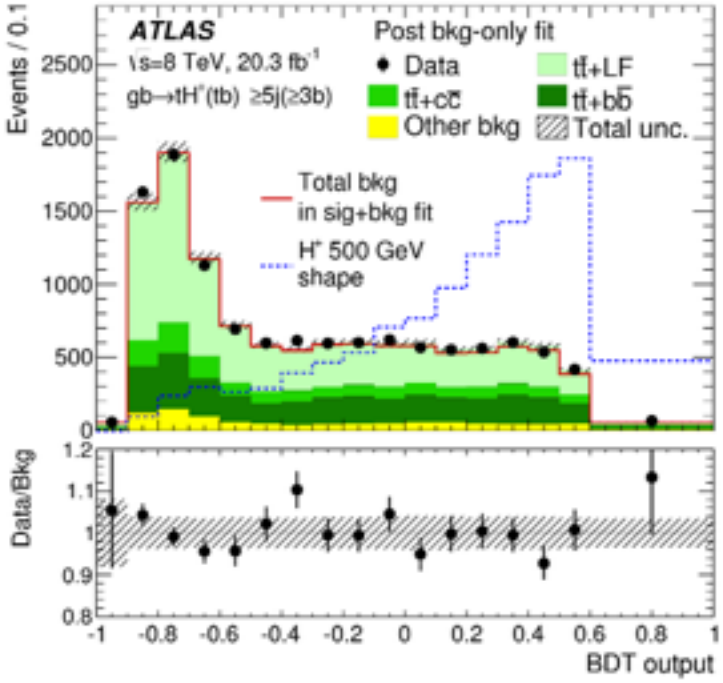
Predicted in models with extended Higgs Sector (e.g. 2HDM):

- ✓ $H^{\pm}$ dominantly produced in association with a top quark.
- ✓ $H^{\pm} \rightarrow tb$ is a dominant decay mode for heavy $H^{\pm}$.



Search in **lepton+jets** final state. Fit is performed on 5 regions:

- H_T^{had} in 4 Control Regions: [4j(2b), 5j(2b), ≥6j(2b), 4j(≥3b)]
- **BDT** in 1 Signal Region: [≥5j(≥3b)

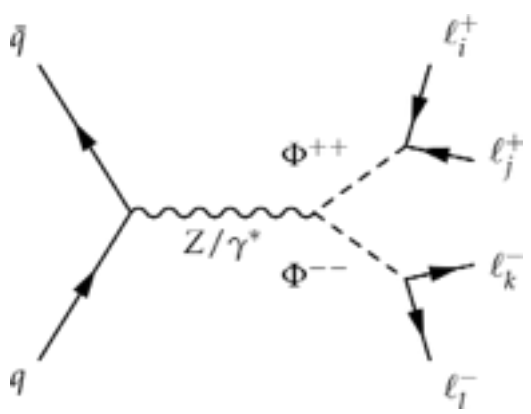


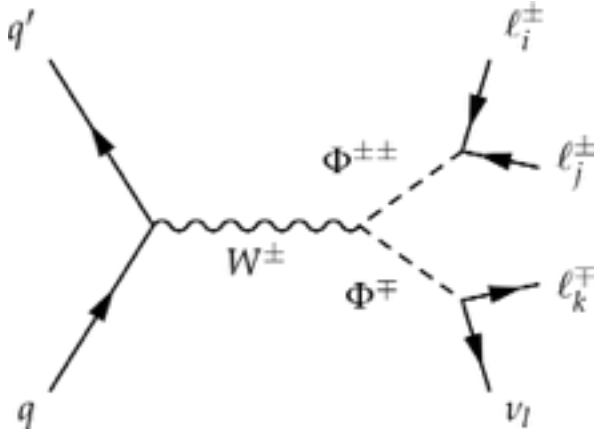
BDT includes H_t^{had}, lead jet p_T, m_{bb} of 2 b-jets closest in ΔR, second Fox-Wolfram moment, and average ΔR between all b-jet pairs.

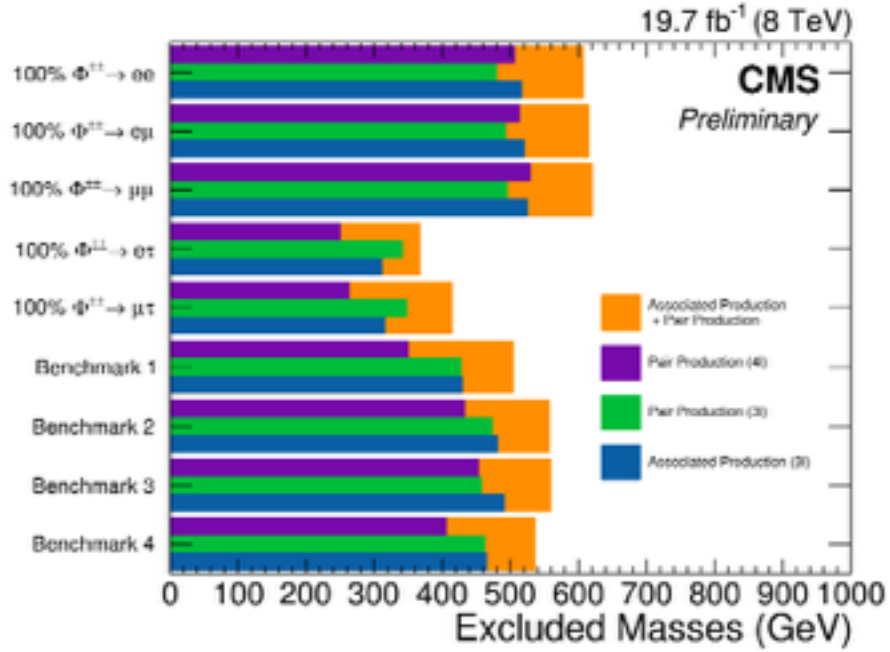
Higgs Triplets: Search for $H^{\pm\pm}$

CMS-PAS-HIG-14-039

- $H^{\pm\pm}$ is predicted by models with a Higgs triplet.
- This search is for associated production or pair-produced left-handed $H^{\pm\pm}$ into 3 or 4 leptons, respectively.







Channel	Expected Signal AP	PP	Expected Background	Observed
$100\% \to ee$	3.63	5.44	0.28	0
$100\% \to e\mu$	3.87	6.07	0.07	0
$100\% \to \mu\mu$	4.14	7.15	0.04	0
$100\% \to e\tau$	0.79	1.36	1.22	0
$100\% \to \mu\tau$	0.86	2.00	1.16	1

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

Scalar Resonance: H→hh→bb$\tau_{had}\tau_{had}$

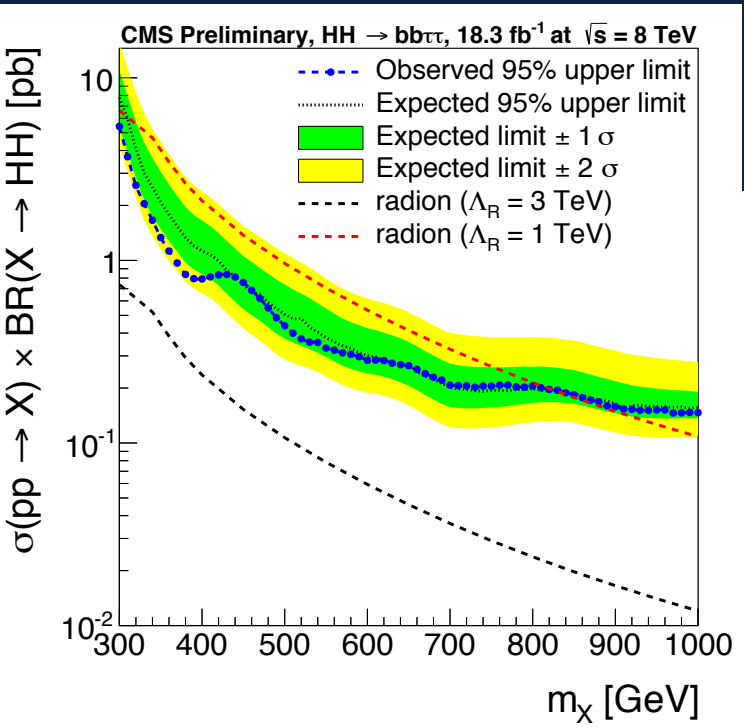
2 hadronic τ_{had} and 2 jets
$80 < m_{\tau\tau} < 140$ GeV and $80 < m_{jj} < 170$ GeV
m_{HH} calculated using a kinematic fit

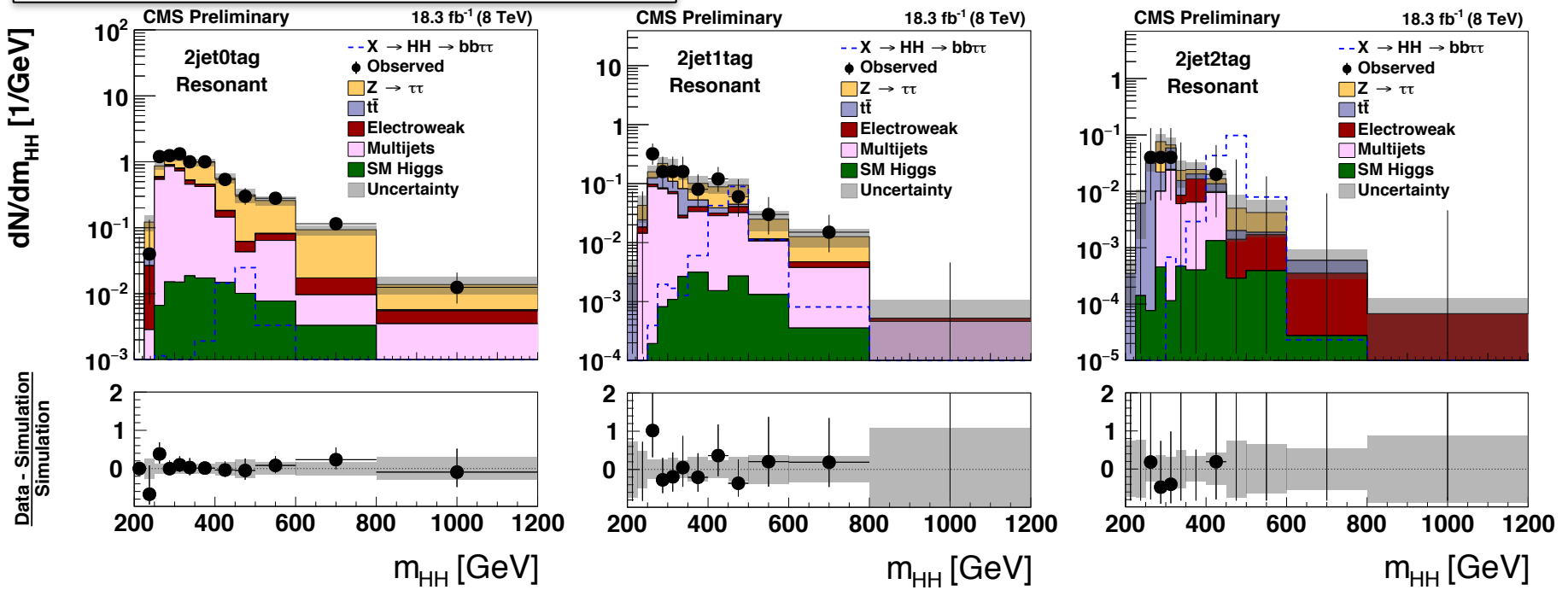
Backgrounds

Multi-jet: Data-driven methods
$Z/\gamma^* \rightarrow \tau_{had}\tau_{had}$: Embedding of μμ data events
Others: Simulation

Fit to three regions with 0, 1, or 2 b-tagged jets.

See Seth Zenz's talk for non-resonant analysis.



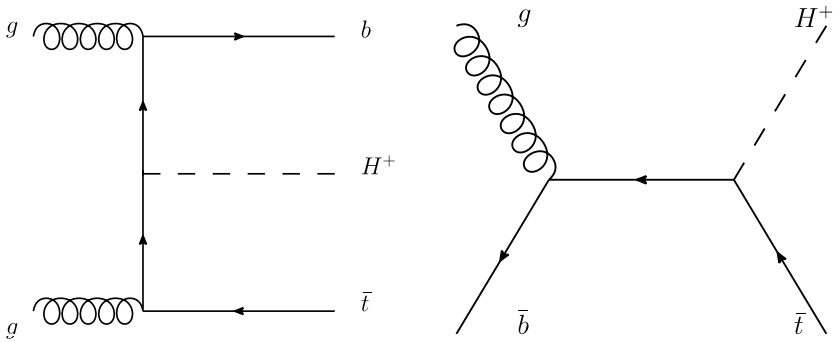


√s = 13 TeV Searches: Fermionic Decays

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

$H^{\pm}$ predicted in 2HDM/MSSM:

- ✓ $H^{\pm}$ dominantly produced in association with a top quark.
- ✓ $H^{\pm} \rightarrow \tau\nu$ decay channel represents a clean signature and substantial BR (~10%) in several MSSM benchmarks.



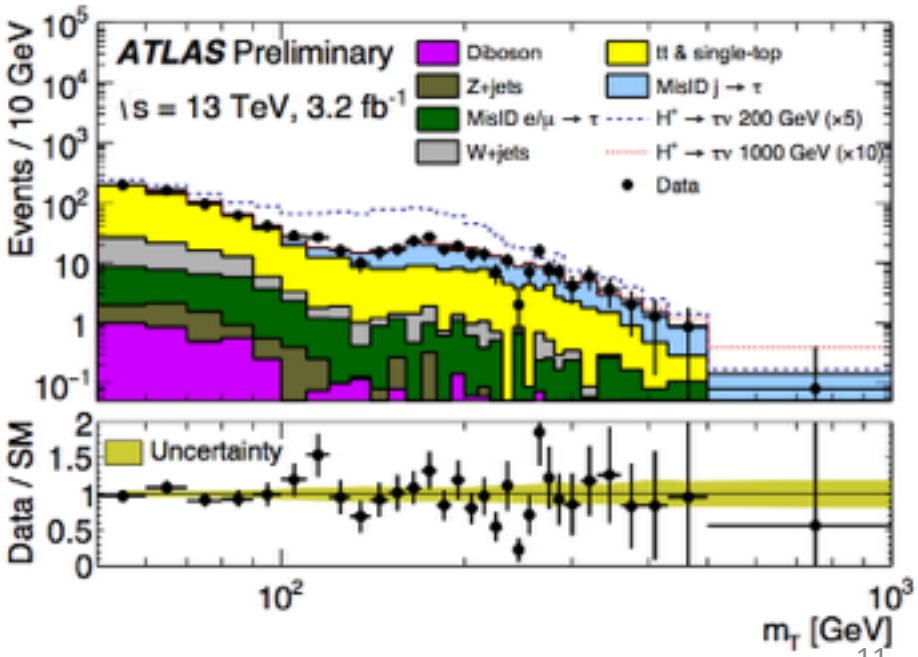
Search is for the decays:

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

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

with the final discriminating variable:

$$m_{\text{T}} = \sqrt{2p_{\text{T}}^{\tau}E_{\text{T}}^{\text{miss}}(1 - \cos\Delta\phi_{\tau_{\text{had-vis}},\text{miss}})}$$



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

Backgrounds:

- **Jet → τ fakes** (multi-jet: data-driven)
- **Events with true τ** (tt, W+jets: from MC, validated in CR)
- **Events with lepton → τ fakes** (top, V+jets, diboson: Shape from MC, norm. from data. ~5% of background.)

Event Selection

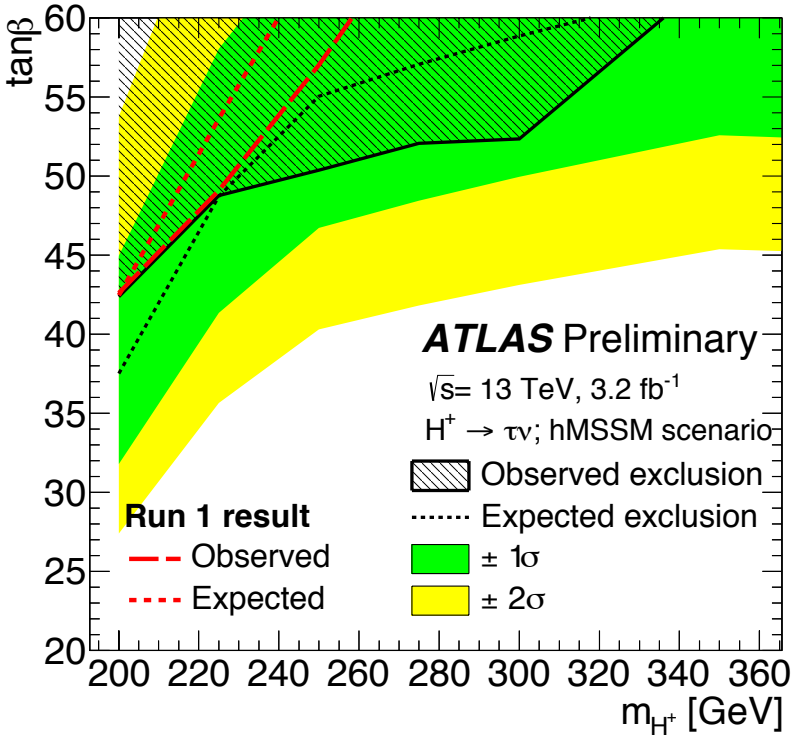
E_T^{miss} trigger

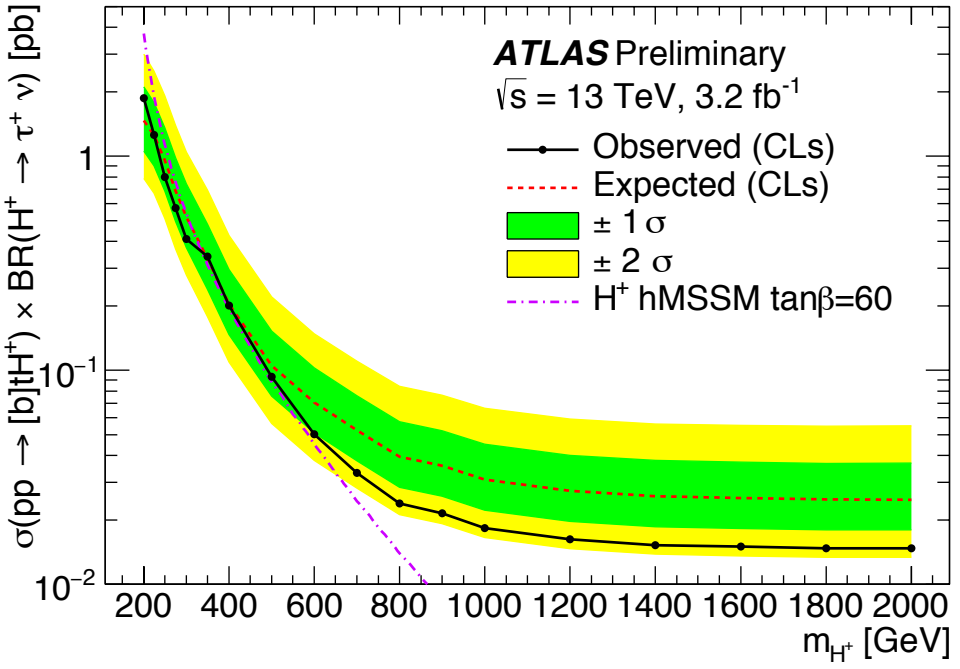
≥3 jets including **≥1 b-tagged jet**

1 τ and no e or μ

E_T^{miss} > 150 GeV

m_T > 50 GeV





ATLAS-CONF-2015-061

Search for H/A →ττ

H→ττ provides sensitivity in MSSM at high tanβ, and in 2HDM at the alignment limit.

Analysis targets two channels with different τ decay modes.

$\tau_{lep}\tau_{had}$ Event Selection

Single lepton triggers

1 τ and 1 OS e/μ and Δϕ(τ, e/μ) > 2.4

M_T(e/μ, MET) < 40 GeV or > 150 GeV

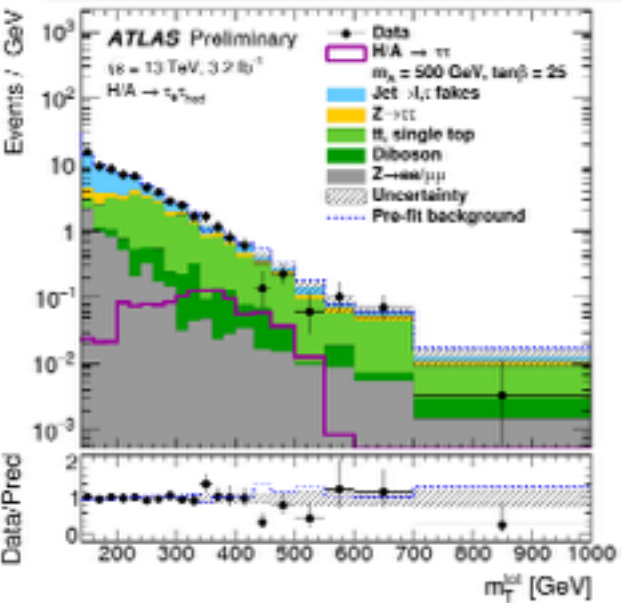
In e-channel: m_{vis} < 80 and > 110 GeV

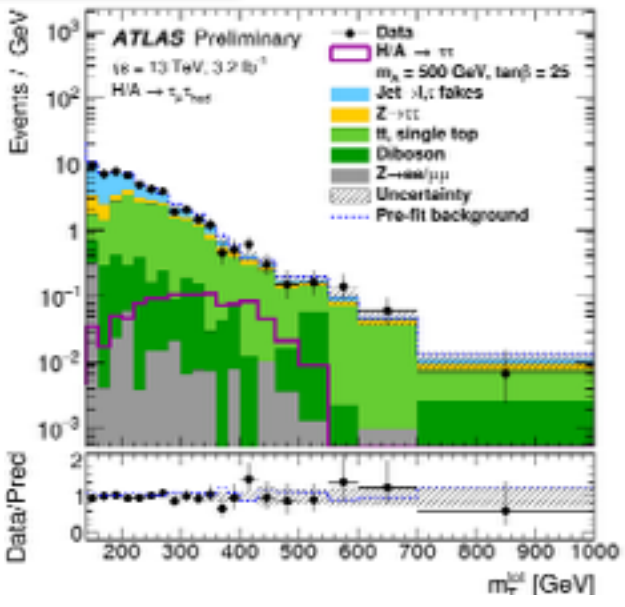
$\tau_{had}\tau_{had}$ Event Selection

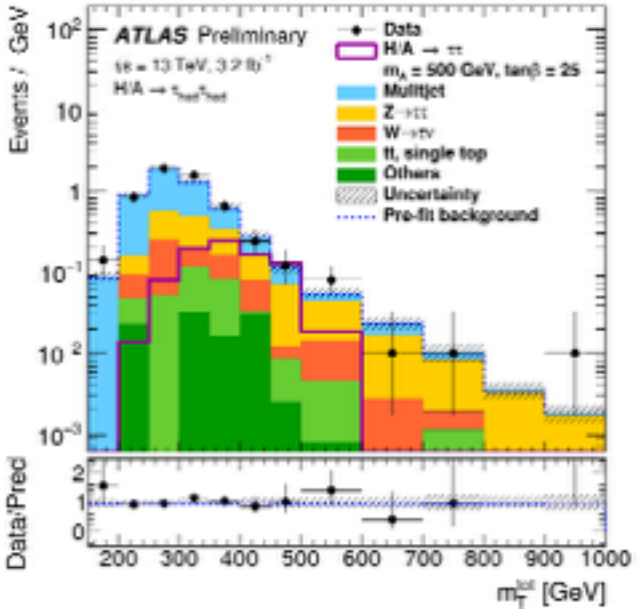
Single τ_{had} trigger

2 τ_{had} with OS charge

$\Delta\phi(\tau_{had,1}, \tau_{had,2}) > 2.7$







Final discriminant in both channels

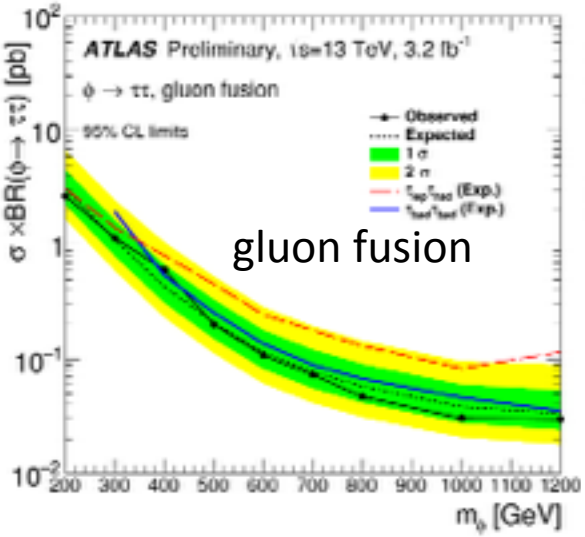
$$m_{\mathrm{T}}^{\mathrm{total}} = \sqrt{m_{\mathrm{T}}^2(\tau_1,\tau_2) + m_{\mathrm{T}}^2(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(\tau_2, E_{\mathrm{T}}^{\mathrm{miss}})}$$

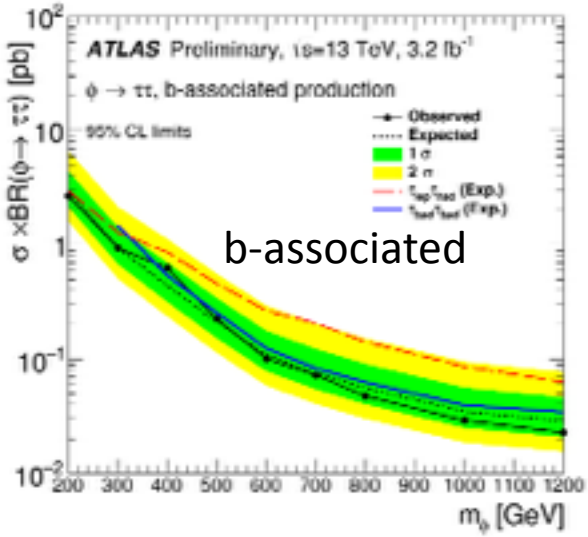
ATLAS-CONF-2015-061

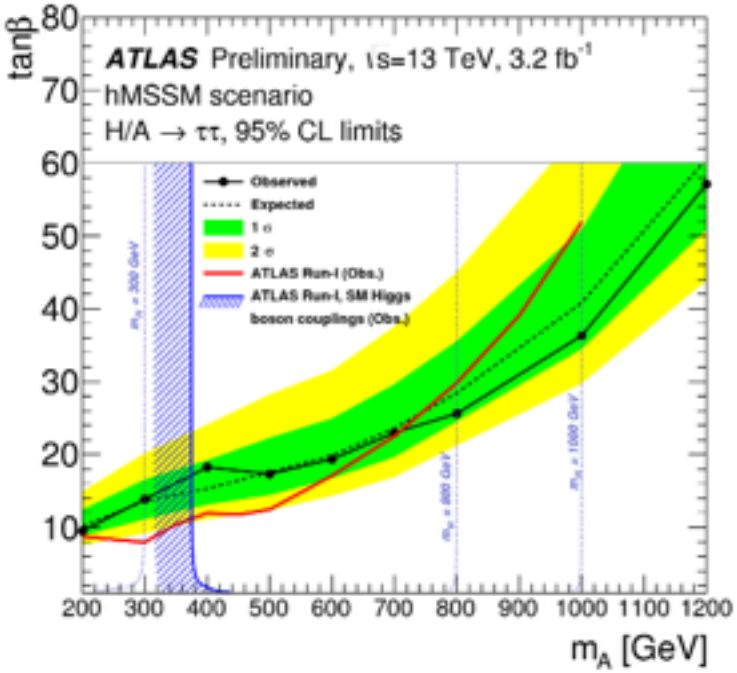
Search for H/A →ττ

Backgrounds

- ✓ **True τ backgrounds** (e.g. Z→ττ, tt) are taken from simulation.
- ✓ **Jet→τ backgrounds** (e.g. W+jets, multi-jets) are estimated using data-driven methods.







No evidence for BSM Higgs, but sensitivity already exceeds run-1.

√s = 13 TeV Searches: Di-Higgs

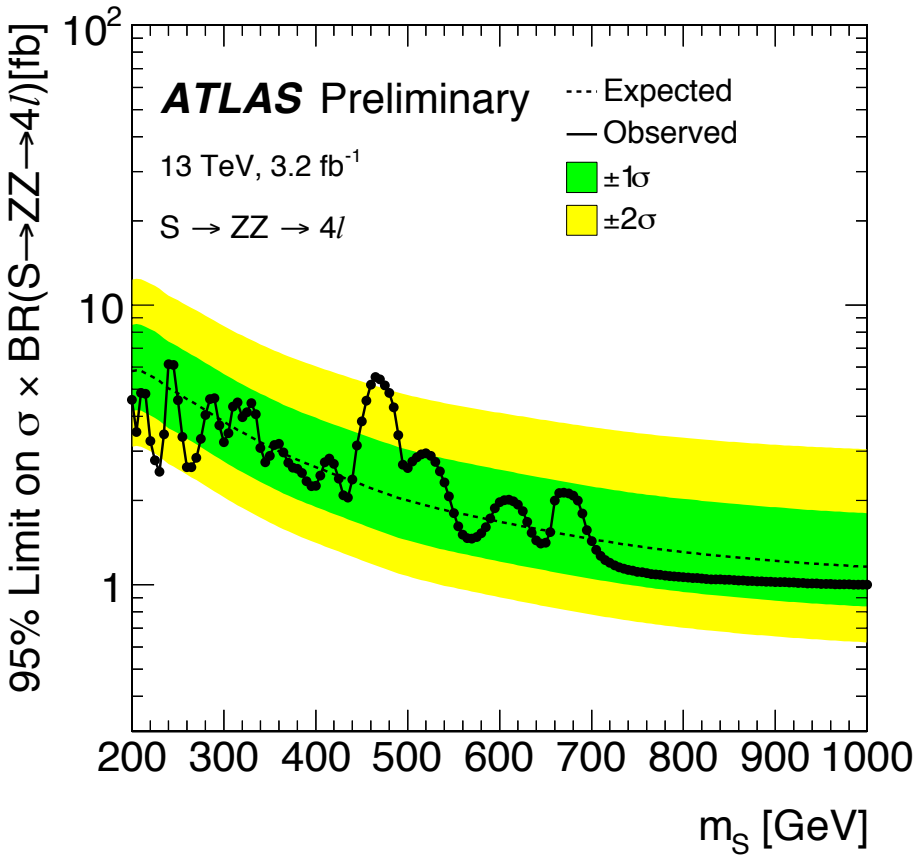
Search for H→ZZ→4l

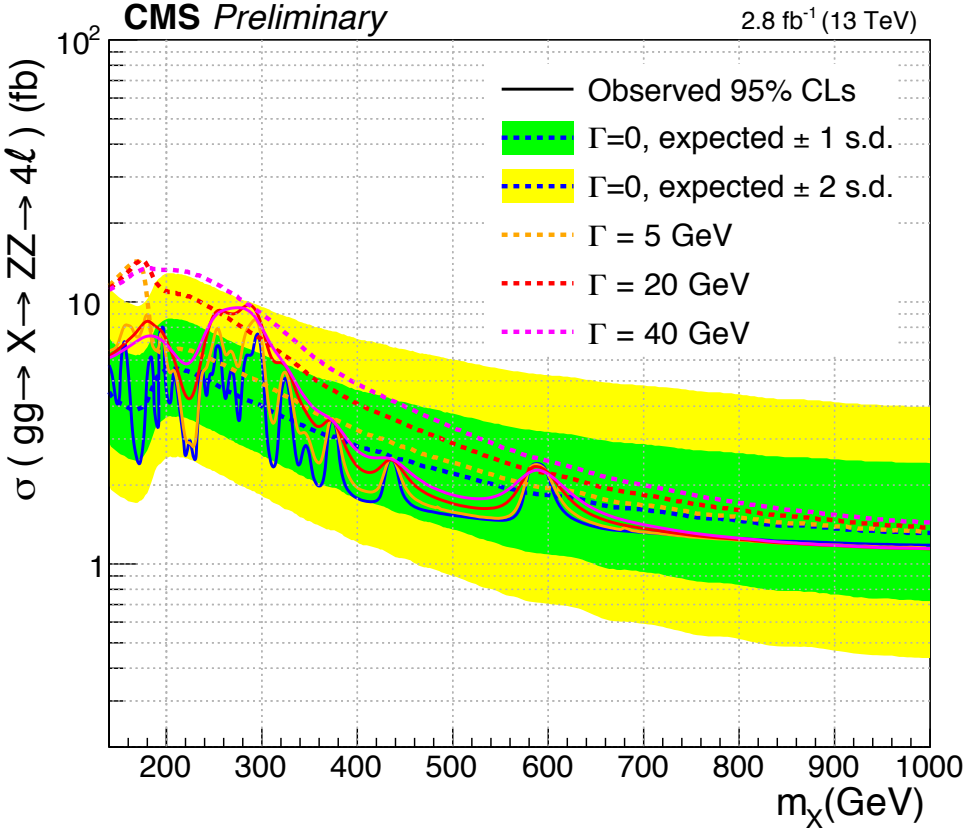
ATLAS-CONF-2015-059

CMS-PAS-HIG-15-004

The 4l final state gives a clean signature with low background, predicted in EWS and 2HDM.

The search is for a resonance of m_H = 140 (200)-1000 GeV for CMS (ATLAS).





Search is based on selection from h(125) →ZZ→4l analysis.

Search for H→ZZ→llνν

CMS-PAS-HIG-16-001

Event Selection

2 same flavor, opposite sign charge leptons

E_T^{miss} > 125 GeV and Δϕ(nearest jet, E_T^{miss}) > 0.5

No b-tagged jets

3 Signal Region Categories:

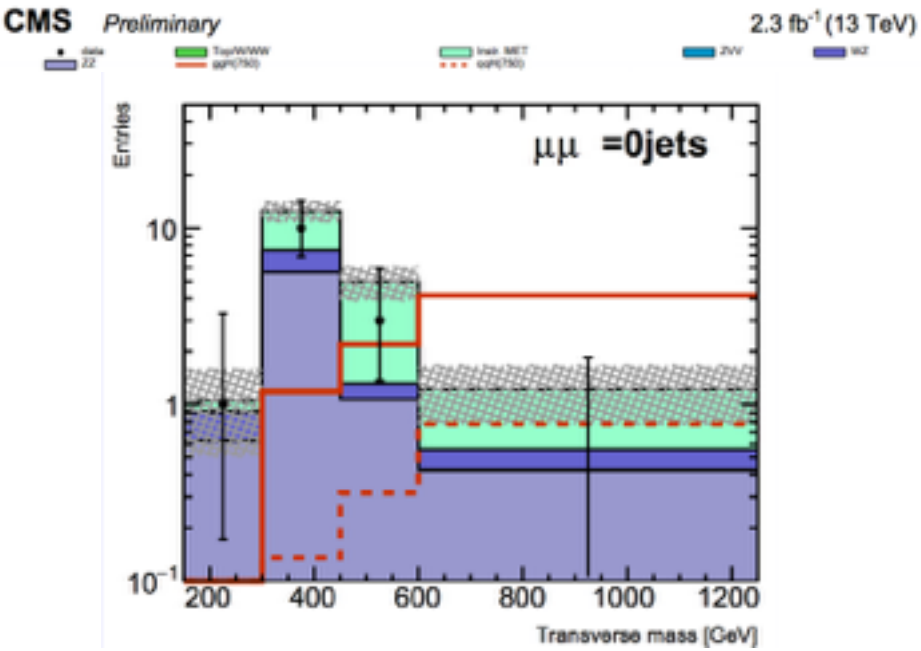
VBF: ≥ 2 forward jets with |Δη| > 4 and m > 500 GeV.

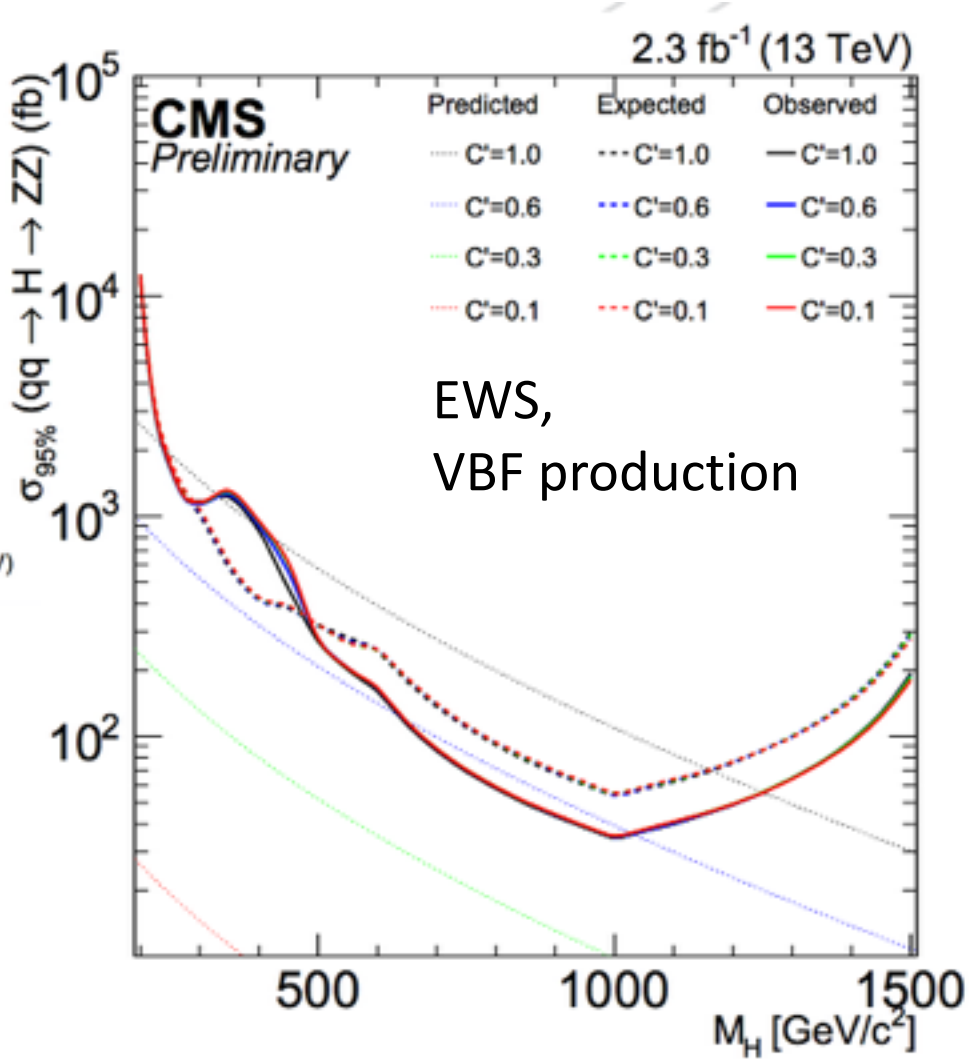
≥ 1 jets: at least 1 jet, fails VBF

= 0 jets: No jets.

Final Discriminant:

$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{\vec{E}_T^{miss\,2} + M_Z^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$



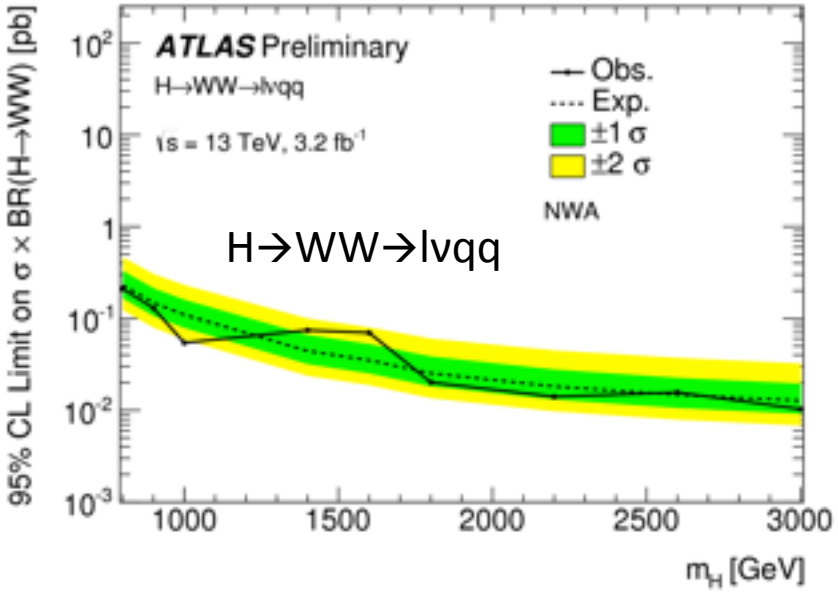


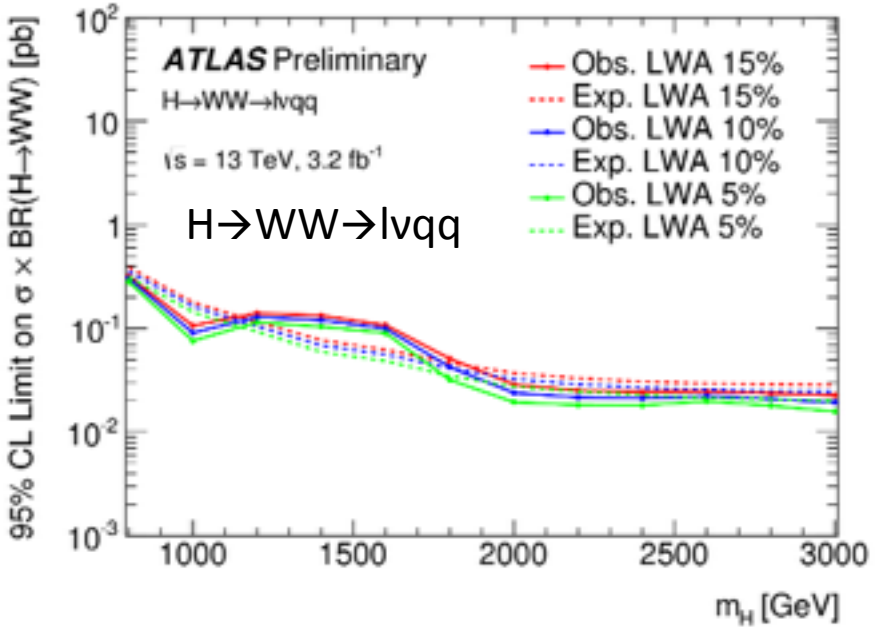
Boosted Diboson Resonances

ATLAS-CONF-2015-075
ATLAS-CONF-2015-071
ATLAS-CONF-2015-068

- Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.
  - For details of the analyses, see Max Bellomo's talk Thursday.

- Limits are set up to 3 TeV:
  - For H→WW→lνqq, H→ZZ→llqq and H→ZZ→ννqq
  - In the narrow width approximation, as well as for widths ranging from 5-15%.
  - No evidence for boosted scalar resonances has been found in any channel.





Search for ZH, H→inv

Motivated by supersymmetry, search is for a scalar boson, *H*, with m=110-600 GeV, decaying to invisible particles.

Analysis Selection

2 same flavor OS e or μ

$|m_{ll}-m_Z| < 15$ GeV and $p_T^{ll} > 60$ GeV

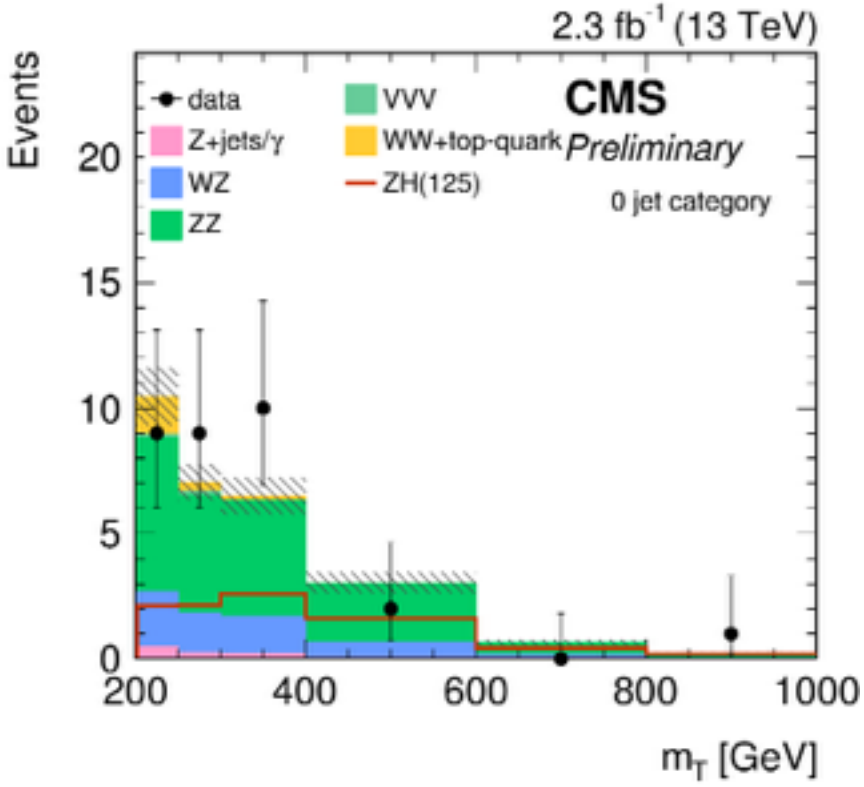
≤ 1 jet, no b-jets or soft muons

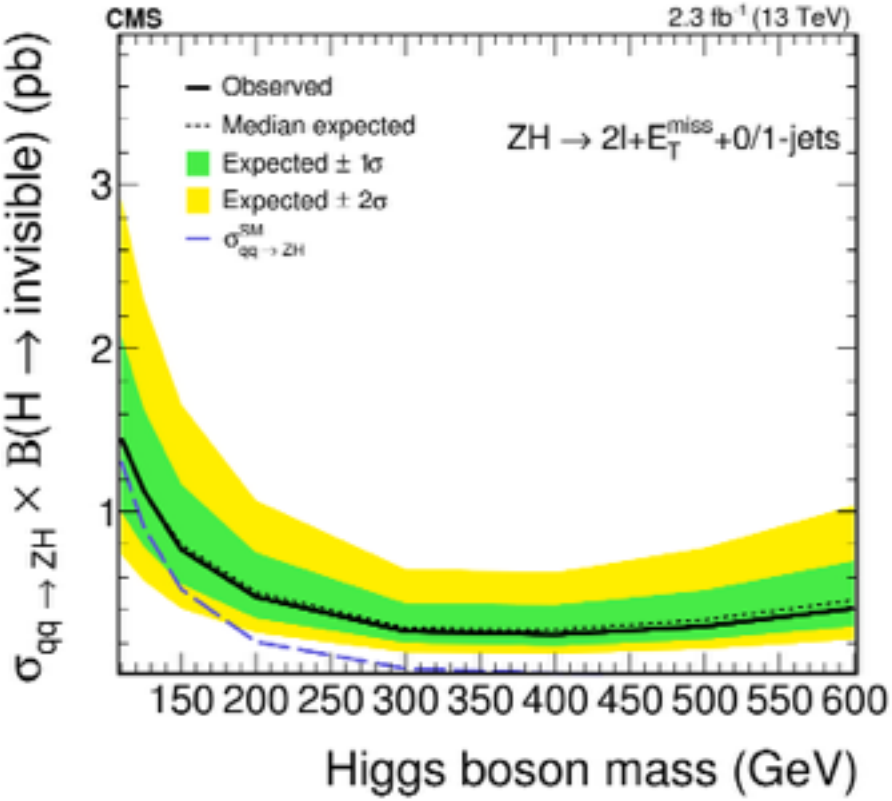
$E_T^{miss} > 100$ GeV, $\Delta\phi(ll, E_T^{miss}) > 2.8$ and $|E_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.4$

Final discriminating variable is:

$$m_T = \sqrt{2\, p_T^{ll}\, E_T^{miss}\, (1 - \cos\Delta\phi(ll, E_T^{miss}))}$$

which must be > 200 GeV.





Search for A→Zh(125), h→bb

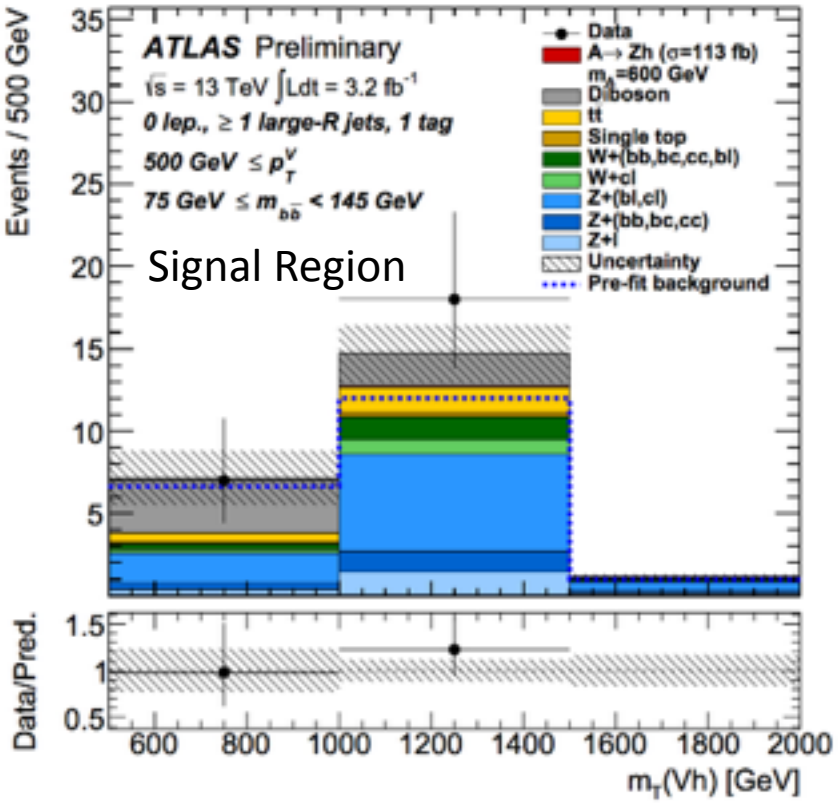
Searching for an additional pseudoscalar boson, as predicted in 2HDM.

The search is for a narrow resonance of m_H = 200-2000 GeV.

Analysis Strategy

- Targeting A→Zh→vvbb/llbb
- Makes use of categories:
  1. 0/2-leptons
  2. p_T^Z < or > 500 GeV (defining the resolved/ boosted transition)
  3. 1/2 b-tagged jets
- Final discriminant is invariant m_{llbb} for 2-lepton and for 0-lepton:

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

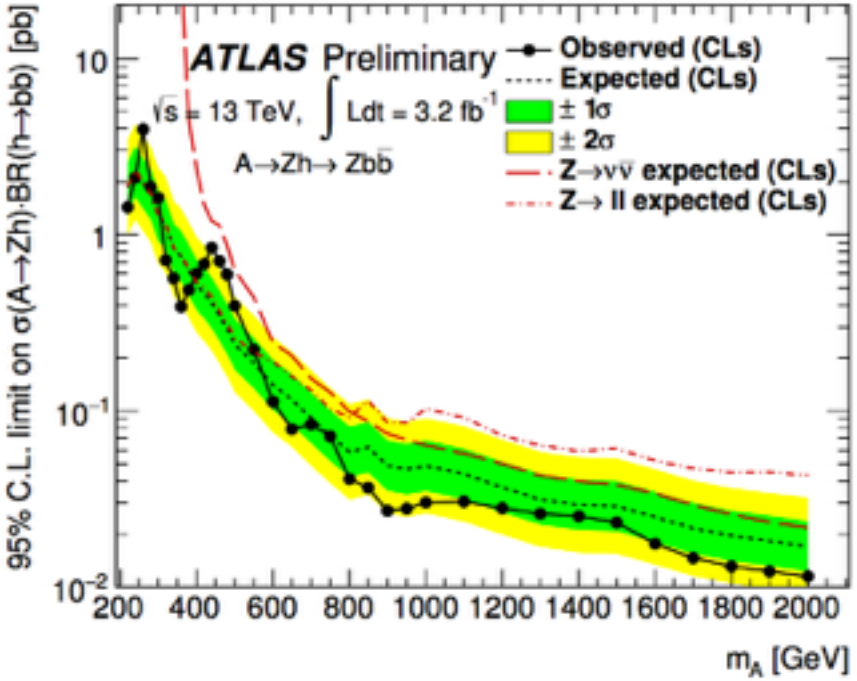


See talk in YSF4 by Carlo Pandini for more details.

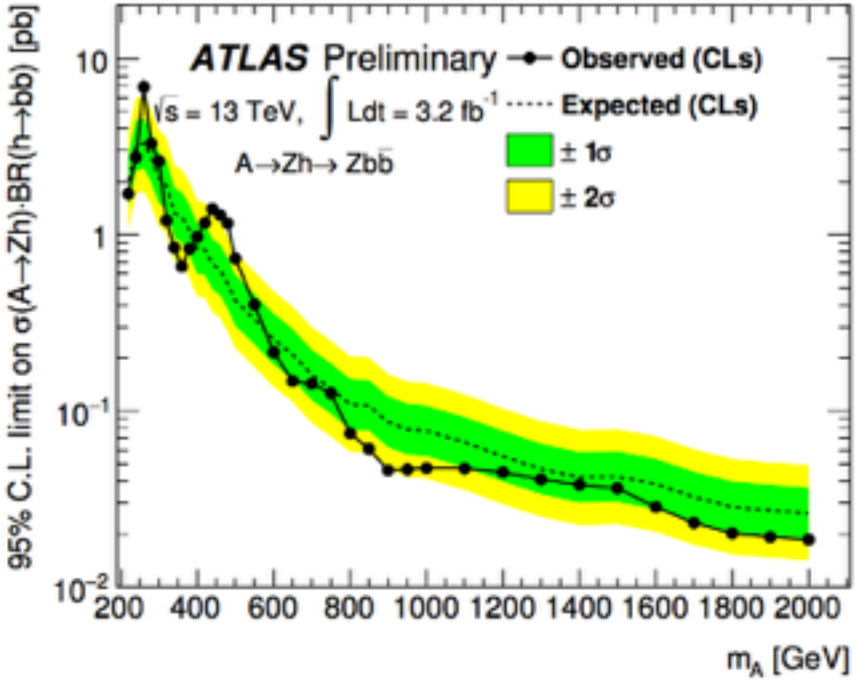
Dominant backgrounds of Z+jets and ttbar are validated and constrained in control regions.

Search for A→Zh(125), h→bb

ATLAS-CONF-2015-015



(a) Pure gluon fusion production



(b) Pure *b*-quark associated production

Limits on ggF and b-associated production from simultaneous binned-likelihood fit for signal and control regions.

Search for H→ZA, Z→ll and A→bb

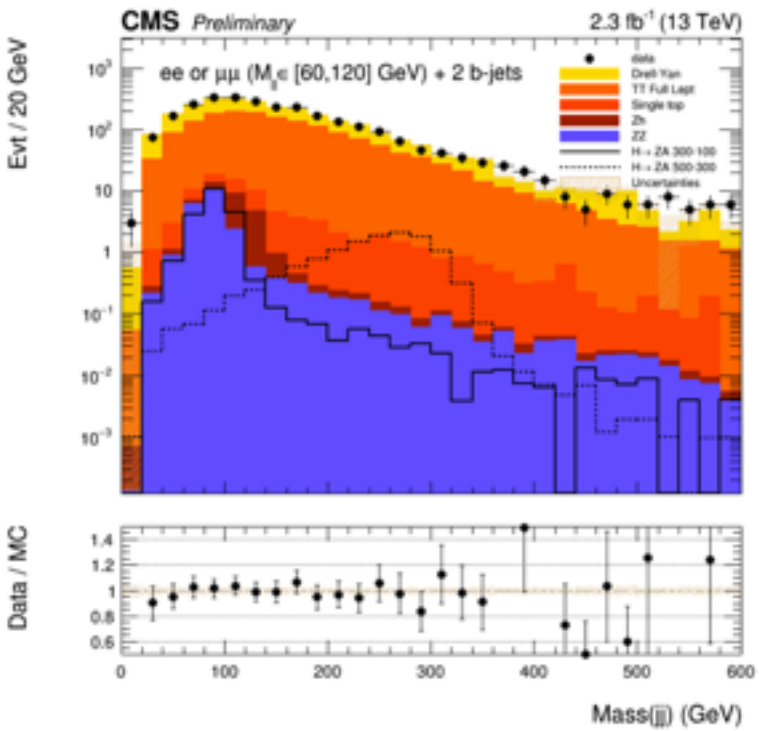
Motivated by 2HDM with twisted custodial symmetry, which gives a heavier scalar H and a lighter pseudoscalar A boson.

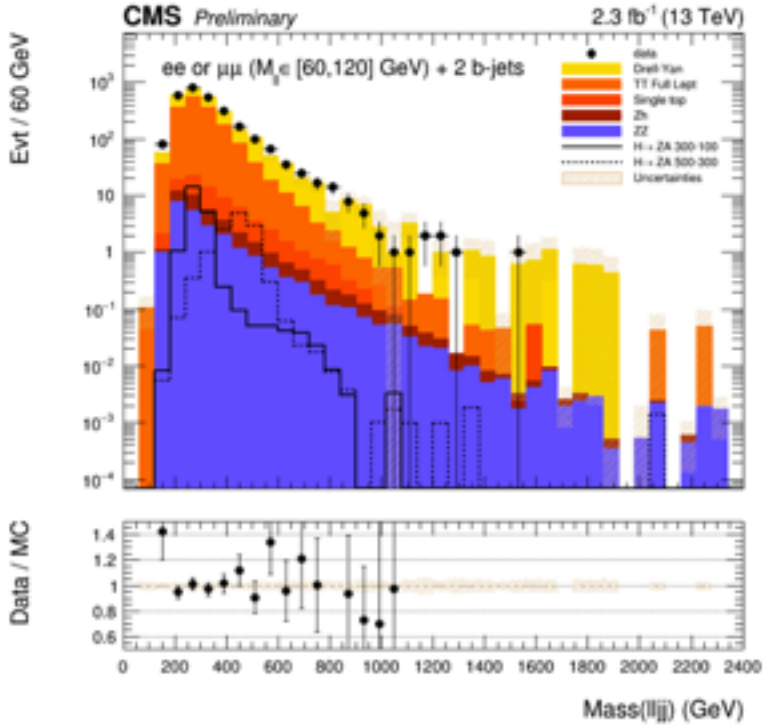
Analysis Strategy

A signal region (S) is defined for each m_A-m_H hypothesis in the plane of m_{bb}-m_{llbb}

tt and Drell-Yan processes are corrected through a fit to data of the m_{ll} distribution for events not in S.

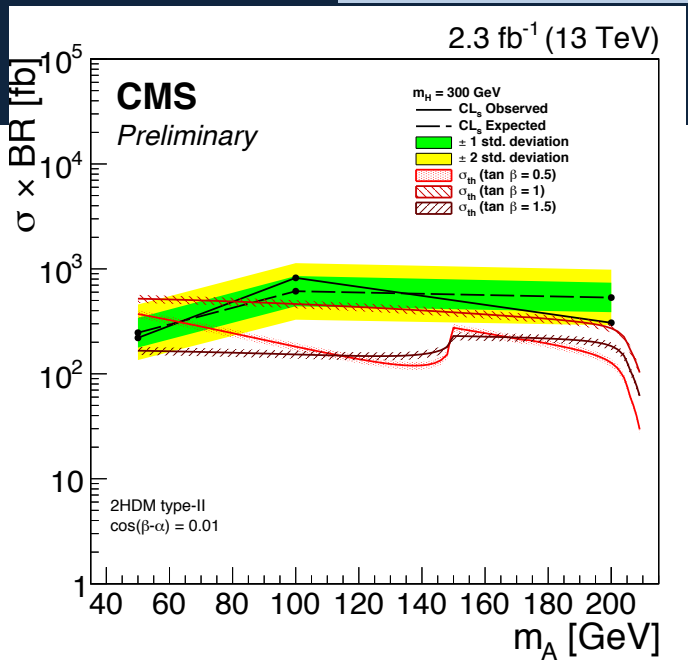
The final limit is calculated from the single bin of S.

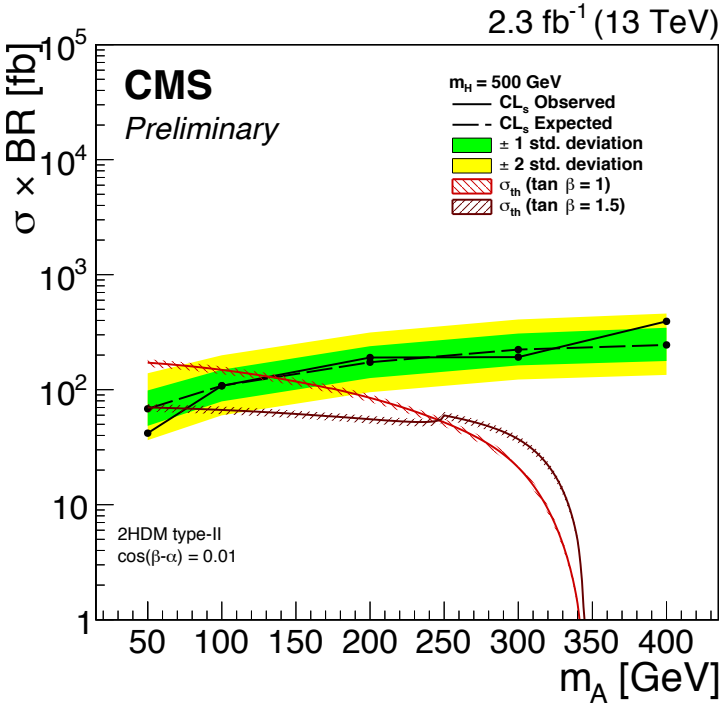


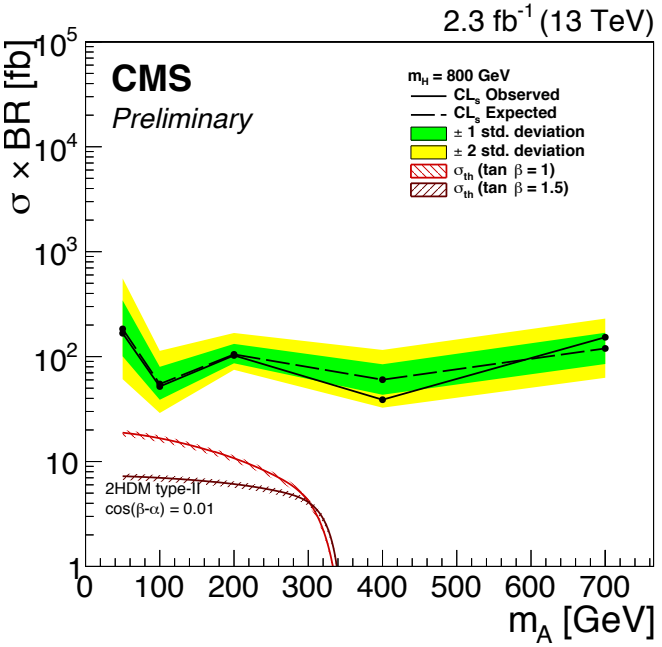


Search for H→ZA, Z→ll and A→bb

Limits are set on cross section times branching ratio for three m_H hypotheses, as a function of m_A.





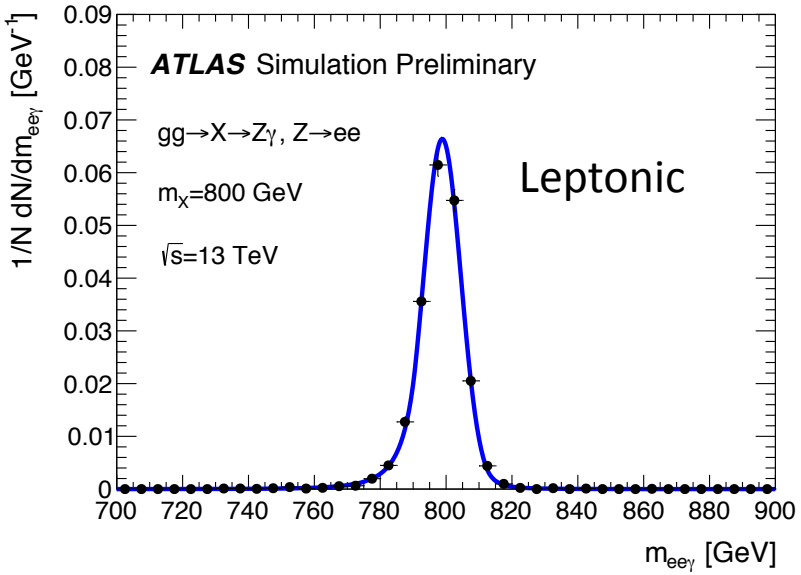


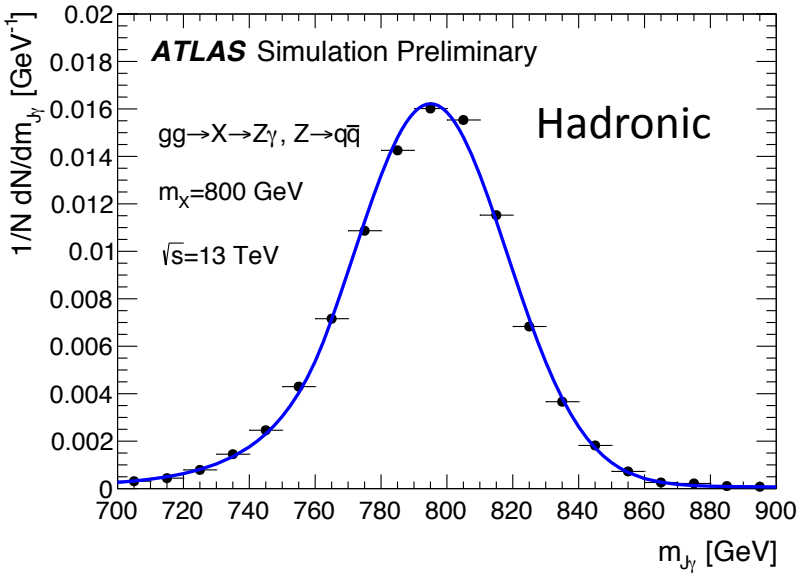
Search for X→Zγ

Searching for an additional neutral boson (X), with a narrow width.

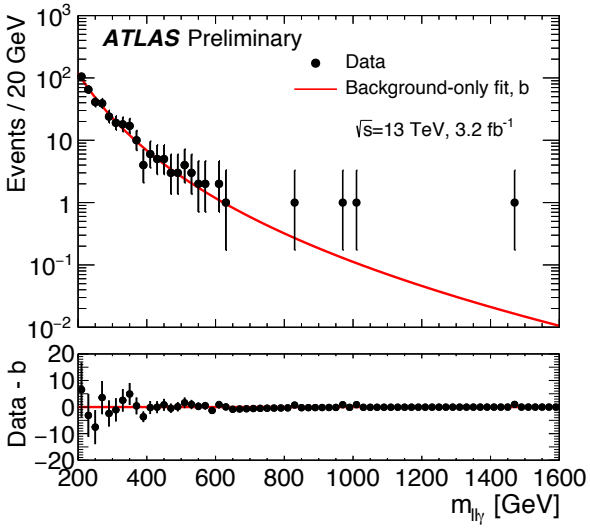
Analysis Strategy

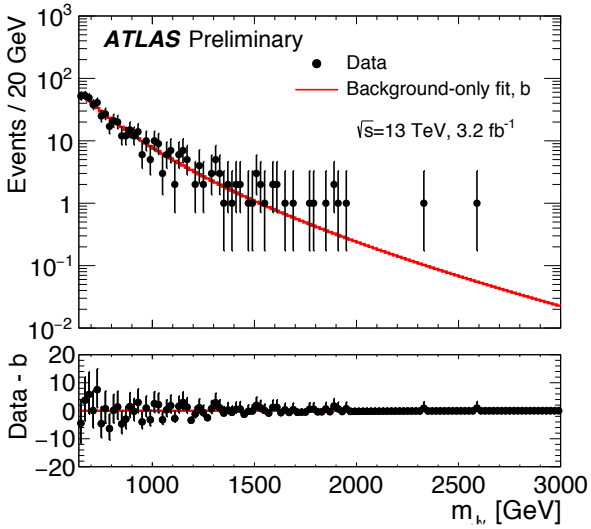
- Z→ll (250-1500 GeV):
  - 2 same flavor, **opposite sign leptons** consistent with Z.
- Z→qq (720-2750 GeV):
  - Jets reconstructed as a **single large-radius jet** with pT > 200 GeV.
- Both channels use Zγ invariant mass as a final discriminant.





Search for X→Zγ

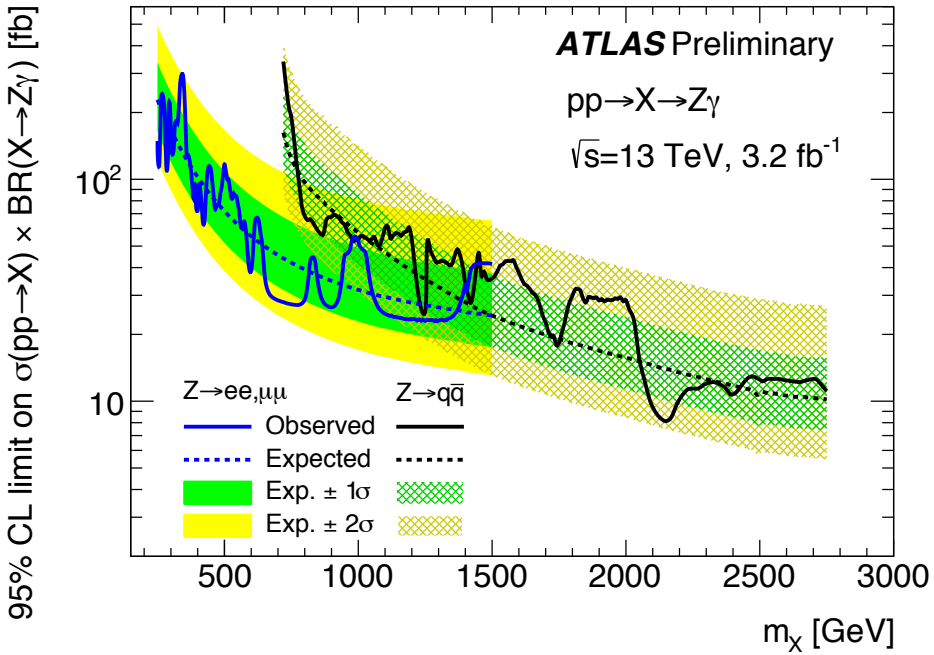




Background Modeling

- Dominant background is continuum production of Z+γ (leptonic) and γ +jets events (hadronic).
- In both, background is smoothly falling spectrum as a function of m_{inv}, parameterized as:

$$f_{bkg}(m_{inv}) = N(1-x^k)^{p_1+\xi p_2} x^{p_2}$$



Largest deviation from background is 2σ at 350 GeV.

Observed limits range between 295 fb at m_X = 340 GeV to 8.2 fb at m_X = 2.15 TeV.

In Summary

- There have already been a variety of searches for extended scalars at 13 TeV, but this is just the beginning!

- Searches investigate a variety of models (2HDM, 2HDM+S, MSSM, etc.) and many final states.

- 2016 should be an interesting year for Beyond-Standard-Model searches in high energy physics!

Public documents for analyses covered in this talk are either available now, or will become available in the following days.

Backup

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

- The Background contributions are split up by the origin of the τ in the event:
  - **Jet → τ fakes** (data-driven)
  - **Events with true τ** (from MC, validated in CR)
  - **Events with lepton → τ fakes** (Shape from MC, norm. from data)

Event Selection

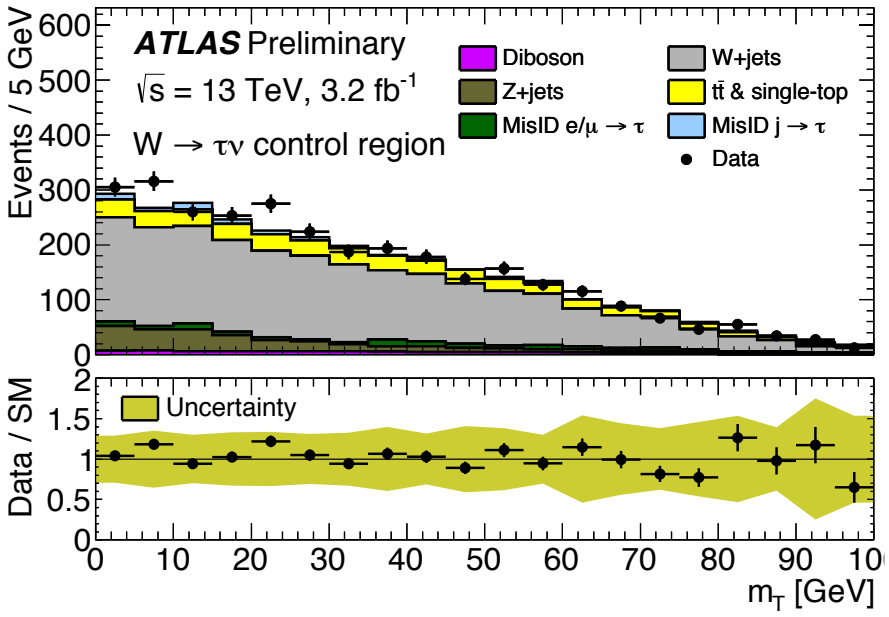
E_T^{miss} trigger

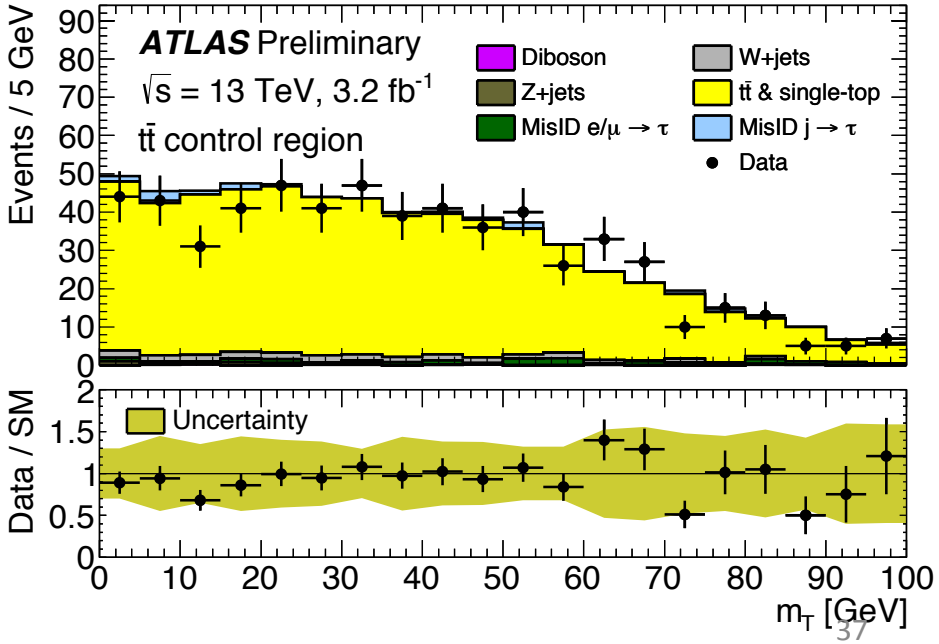
≥3 jets including **≥1 b-tagged jet**

1 τ and no e or μ

E_T^{miss} > 150 GeV

m_T > 50 GeV





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

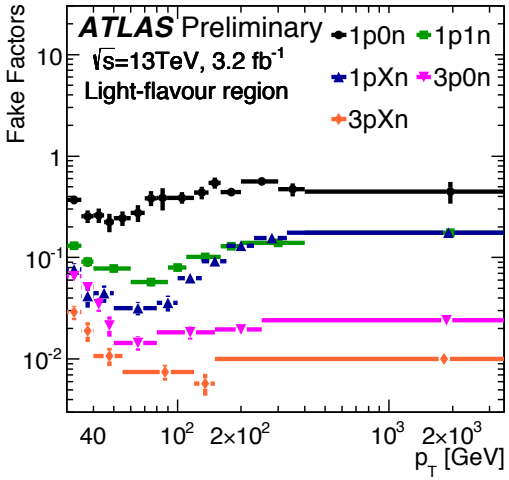
A fake factor (FF) is measured in a multi-jet control region, defined as:

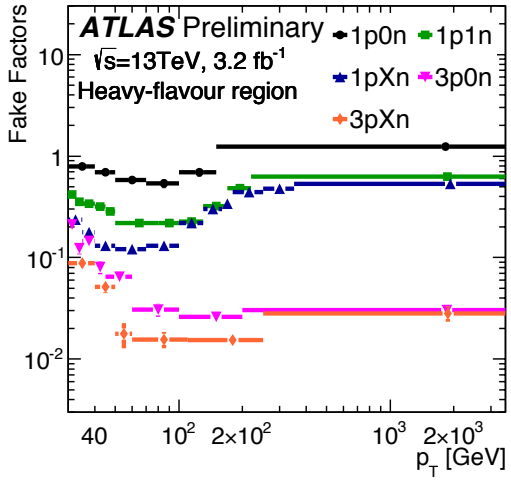
$$FF = \frac{N_{fail}}{N_{pass}}$$

where N_{fail} event τ candidates fail the full τ selection, and N_{pass} pass.

FF parameterized in:

- ✓ τ p_T ,
- ✓ τ decay mode,
- ✓ Light/heavy flavor bins based on b-tagging algorithm.



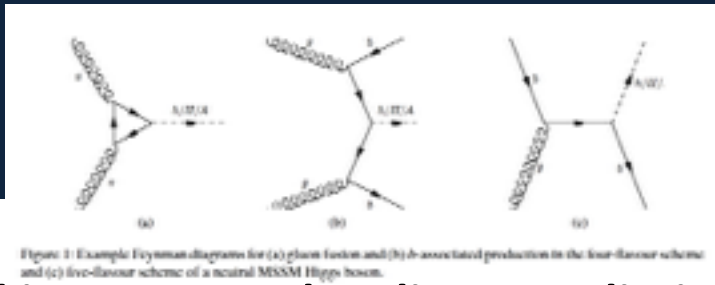


Final Contribution Defined by:

$$N_{\text{fakes}}^{\tau_{\text{had-vis}}} = \sum_i N_{\text{anti}-\tau_{\text{had-vis}}}(i) \times FF(i),$$

ATLAS-CONF-2015-061

Search for H/A →ττ



H→ττ provides sensitivity in MSSM at high tanβ, and in 2HDM at the alignment limit.

Analysis targets two channels with different τ decay modes.

$\tau_{lep}\tau_{had}$ Event Selection

Single lepton triggers

1 medium τ, p_T > 20 GeV

1 medium, isolated e/μ, p_T > 30 GeV

τ and e/μ of opposite sign charge

$\Delta\phi(\tau, e/\mu) > 2.4$

M_T(e/μ, MET) < 40 GeV or > 150 GeV

In e-channel: m_{vis} < 80 and > 110 GeV

$\tau_{had}\tau_{had}$ Event Selection

Single τ_{had} trigger

2 τ_{had} with OS charge

No loose e/μ

$\Delta\phi(\tau_{had,1}, \tau_{had,2}) > 2.7$

Leading τ_{had} is medium, trigger-matched, p_T > 135 GeV

Subleading τ_{had} is loose, p_T > 55 GeV

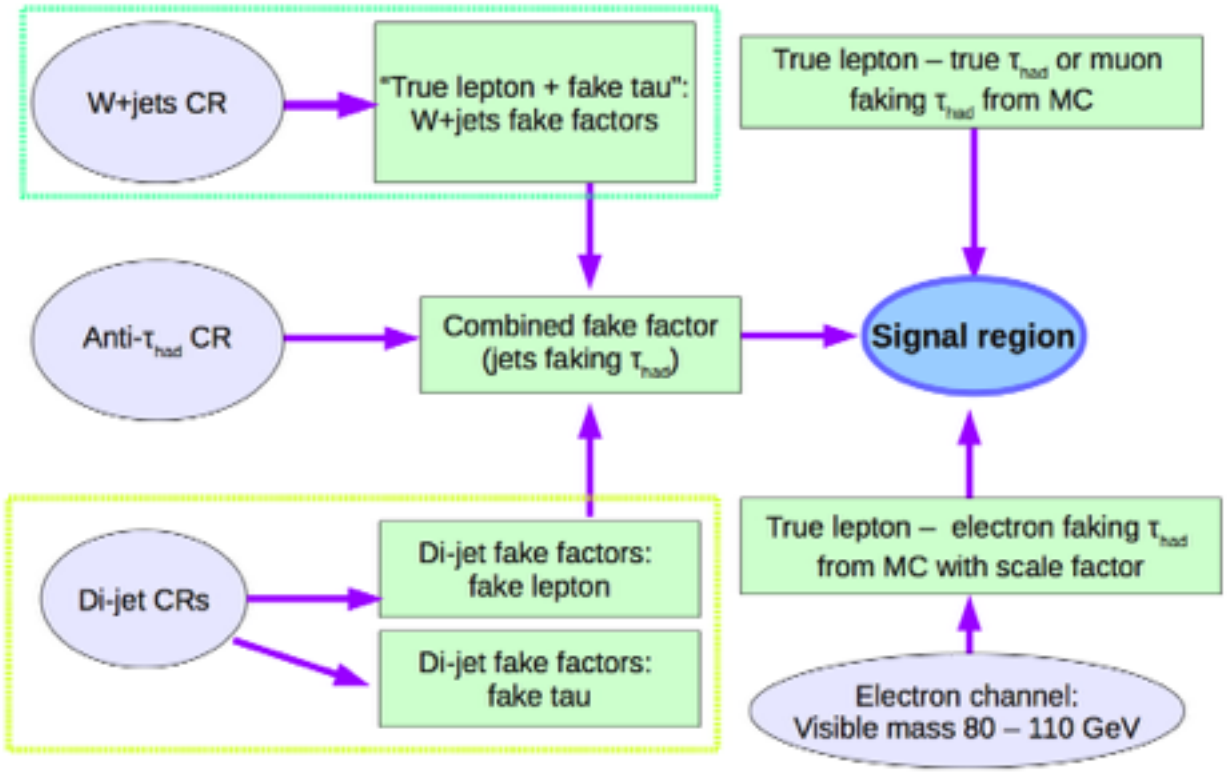
Final discriminant in both channels

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

Search for H/A →ττ: $\tau_{lep}\tau_{had}$ Backgrounds

True τ backgrounds (Z->ττ, tt) are taken from simulation.
Jet→τ backgrounds are estimated using "Combined Fake Factor" Method

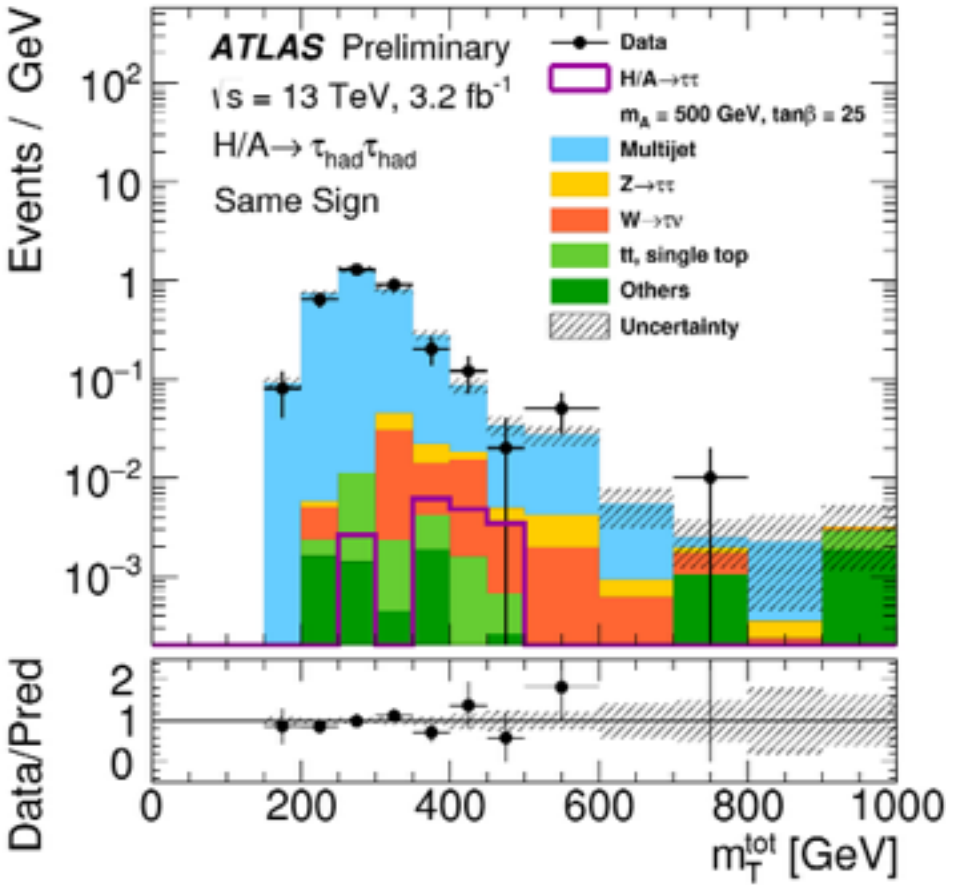
$$\text{Combined FF} = FF_{W+jets} r_{W+jets} + FF_{QCD} r_{QCD}$$



The Combined FF is applied to events where τ fails ID requirement.

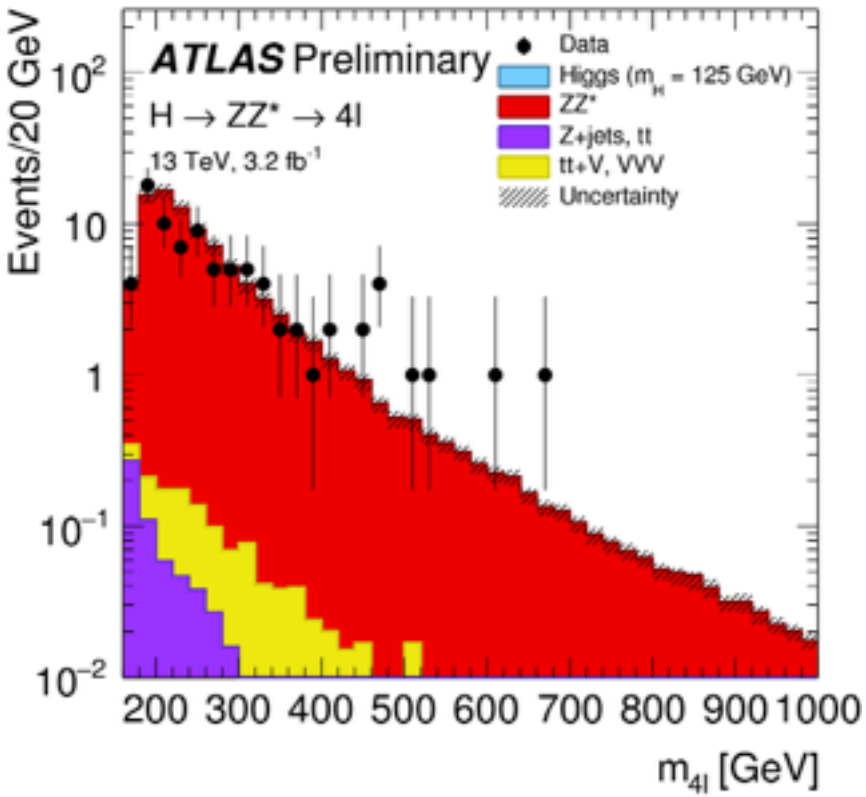
Search for H/A →ττ: $\tau_{had}\tau_{had}$ Backgrounds

- ✓ **True τ backgrounds (Z->ττ, tt) are taken from simulation.**
- ✓ **Jet→τ backgrounds are estimated by applying fake rate from data in place of simulated τ ID response.**
- ✓ **Multi-jet backgrounds are estimated using a fake factor measured in a dijet CR.**



Background estimation is validated in same-sign control region.

ATLAS: H→ZZ→4l



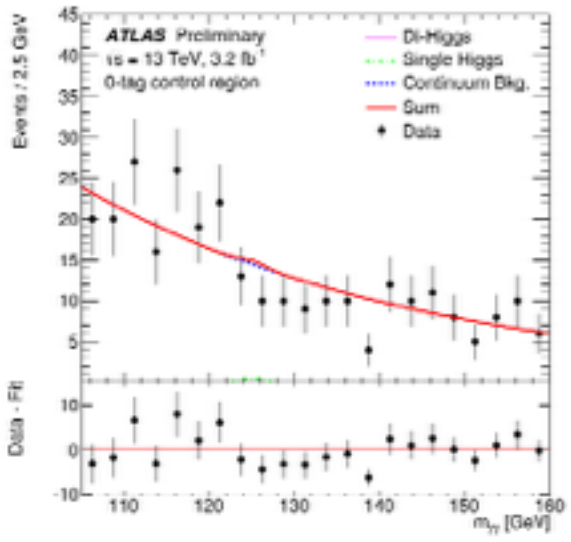
Expected and Observed events for the ATLAS high mass H->ZZ->4l analysis.

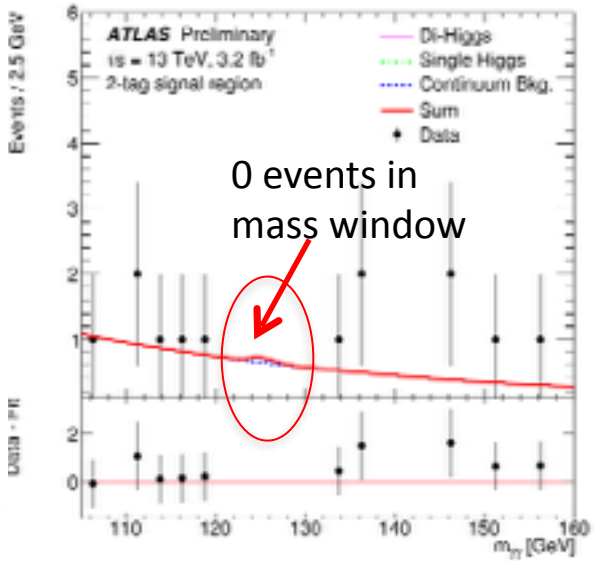
Final state	ZZ^*	$Z+\text{jets}, t\bar{t}, WZ$	$t\bar{t}V, VVV$	Expected	Observed
4μ	22.1 ± 2.2	0.05 ± 0.02	0.23 ± 0.01	22.4 ± 2.2	20
$2e2\mu$	16.9 ± 1.6	0.05 ± 0.02	0.21 ± 0.01	17.2 ± 1.6	17
$2\mu 2e$	18.1 ± 2.6	0.06 ± 0.02	0.19 ± 0.01	18.3 ± 2.6	13
$4e$	13.9 ± 2.1	0.06 ± 0.02	0.18 ± 0.01	14.1 ± 2.1	12
Total	71 ± 8	0.23 ± 0.04	0.81 ± 0.04	72 ± 8	62

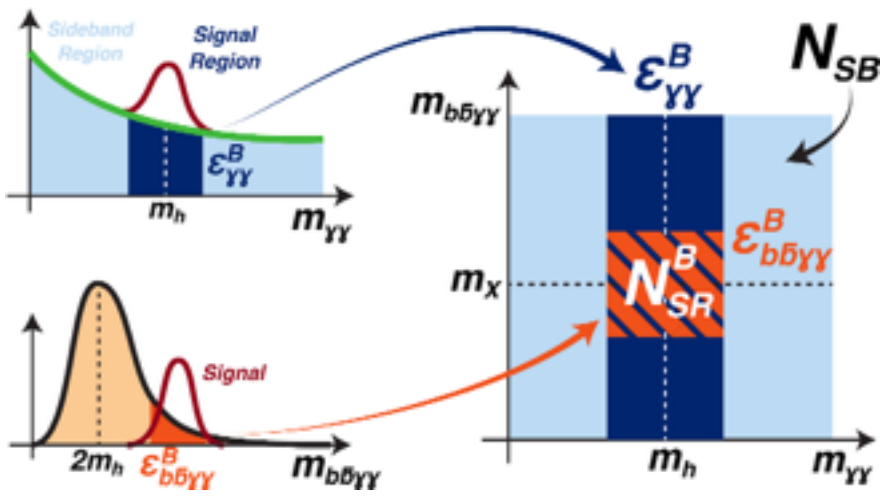
Search for H→hh→bbγγ

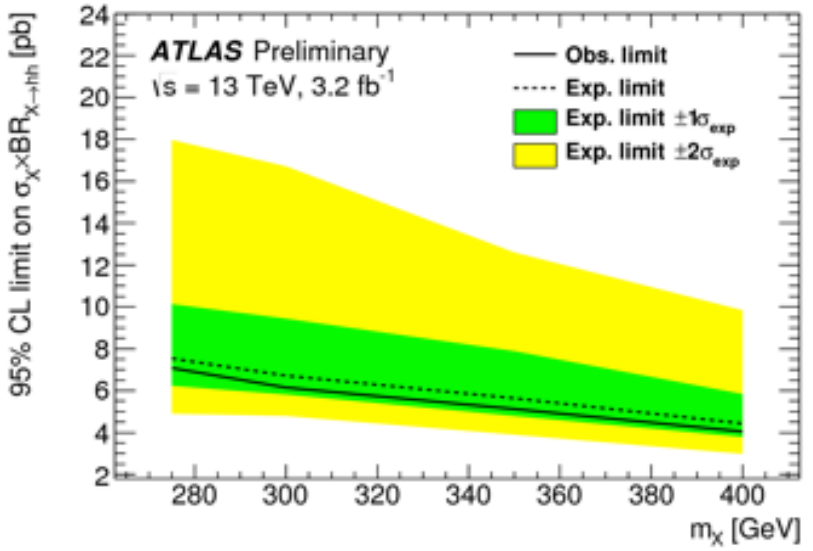
- Background:
  - Continuum from data
  - SM h & hh from MC
  - Cut-and-count in 95% $m_{bb\gamma\gamma}$ window with data-driven continuum background:

$$N_{SR}^{B} = N_{SB}\frac{\varepsilon_{m_{\gamma\gamma}}}{1-\varepsilon_{m_{\gamma\gamma}}}\varepsilon_{m_{bb\gamma\gamma}}$$

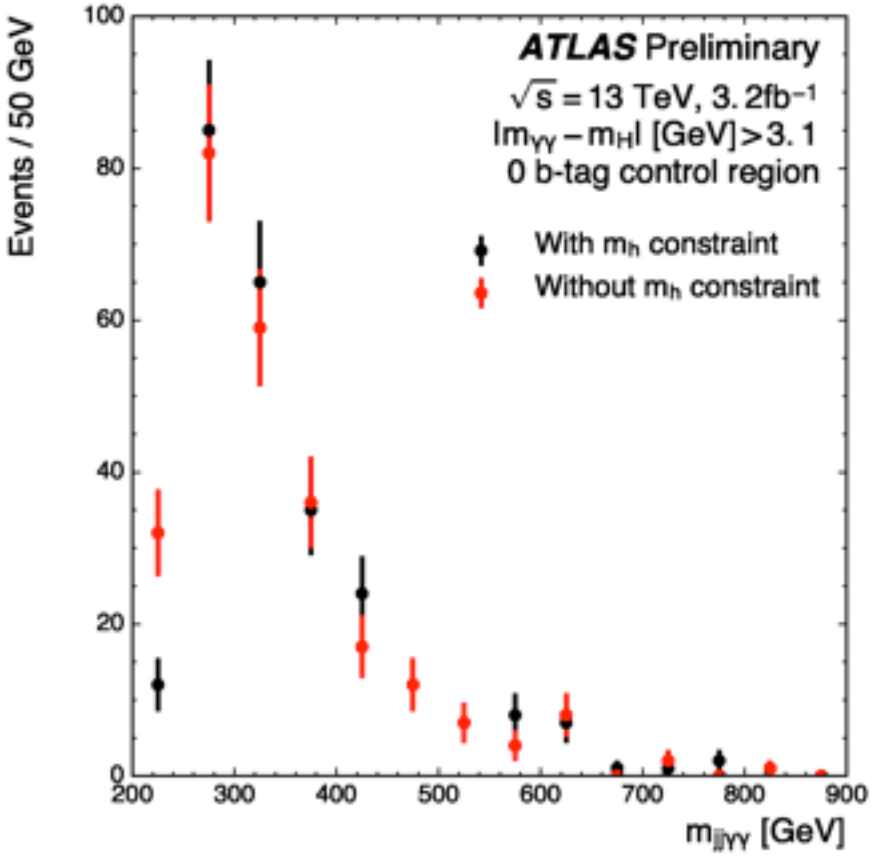




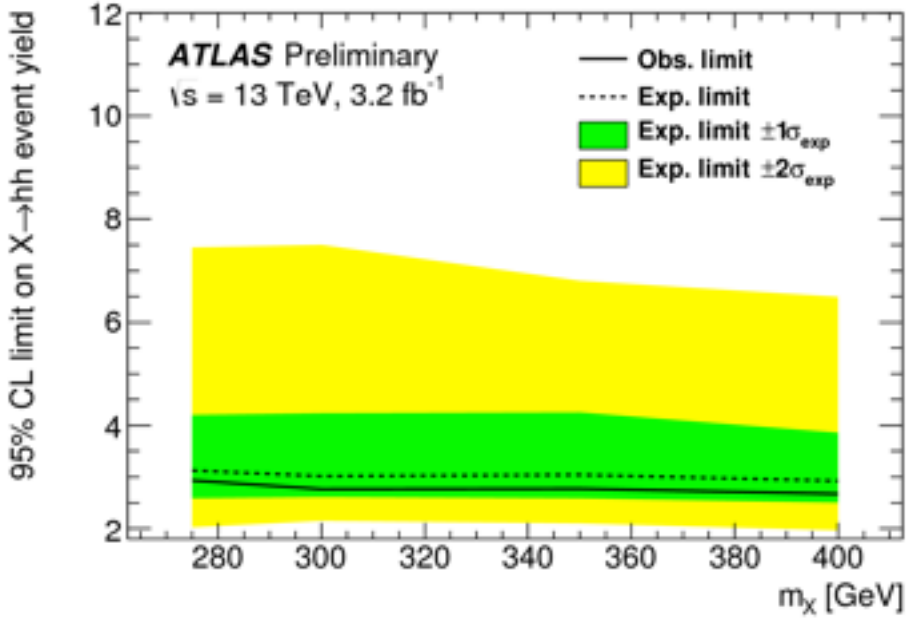




Search for H→hh→bbγγ



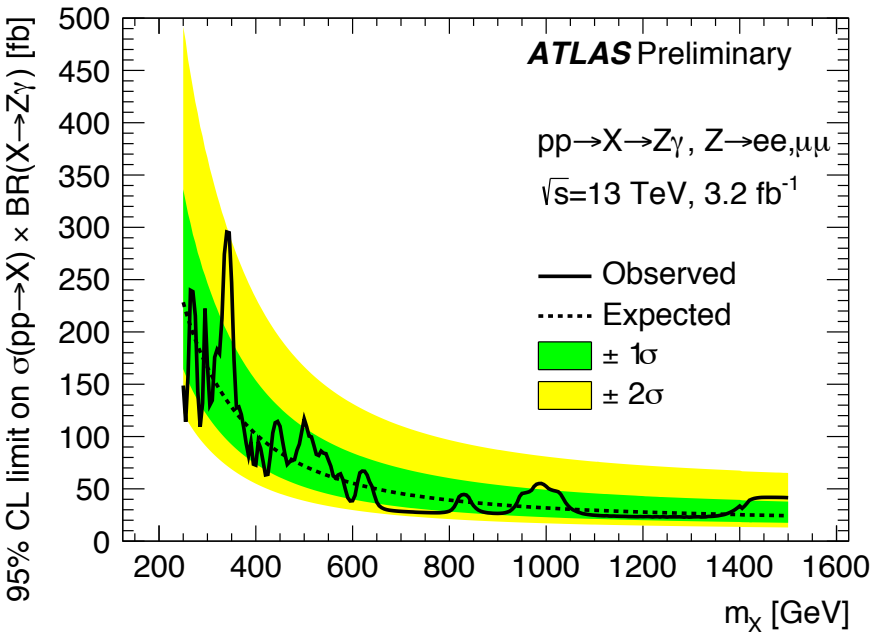
Mass constraint does not dramatically change the background shape.

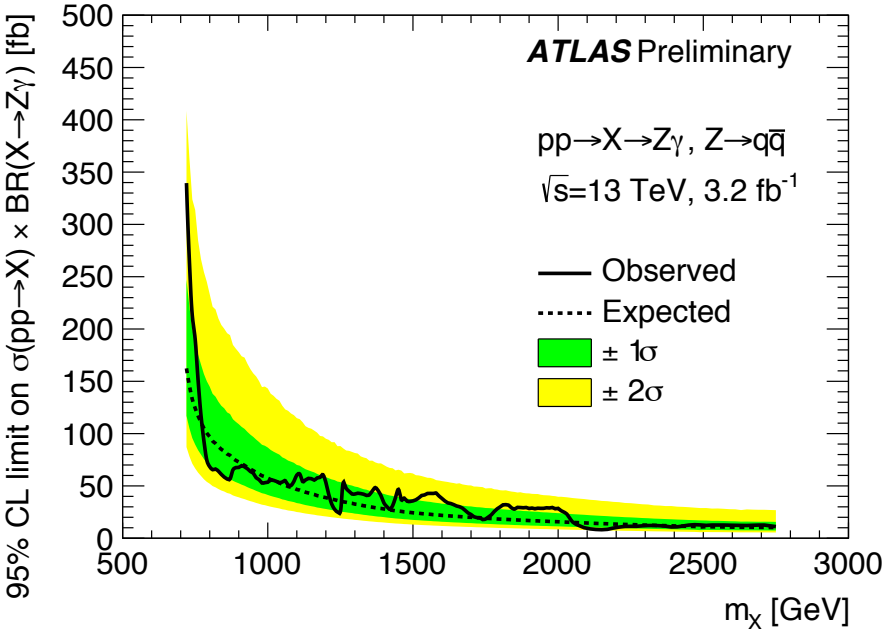


Limit in terms of # of events.

Search for X→Zγ

Not Yet Available

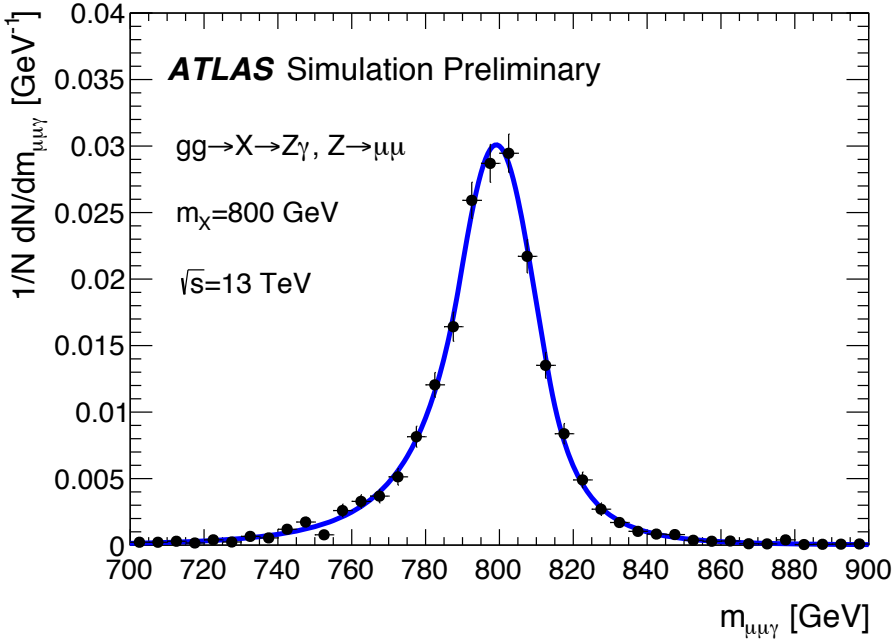


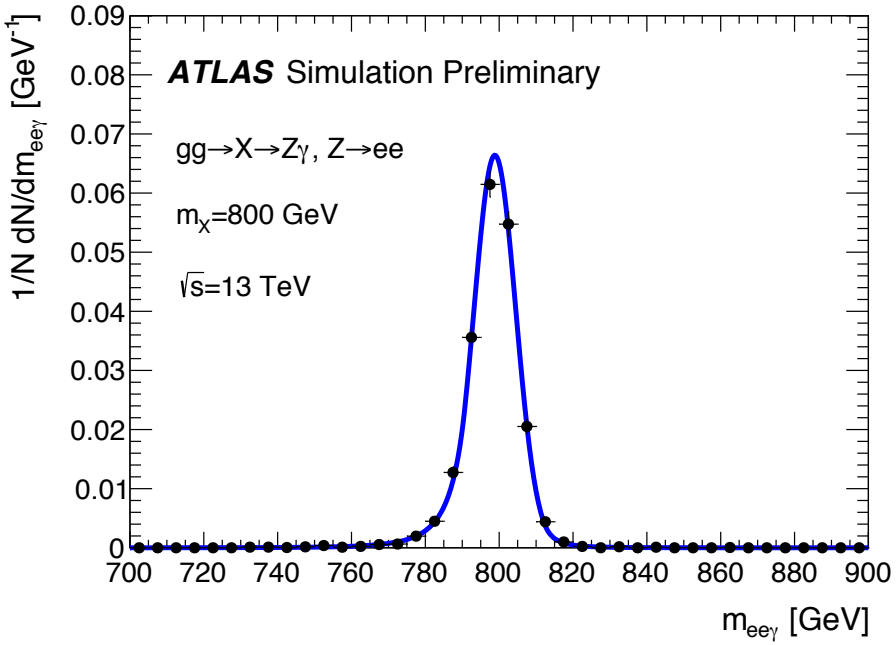


Limits split into leptonic and hadronic.

Search for X→Zγ

Not Yet Available

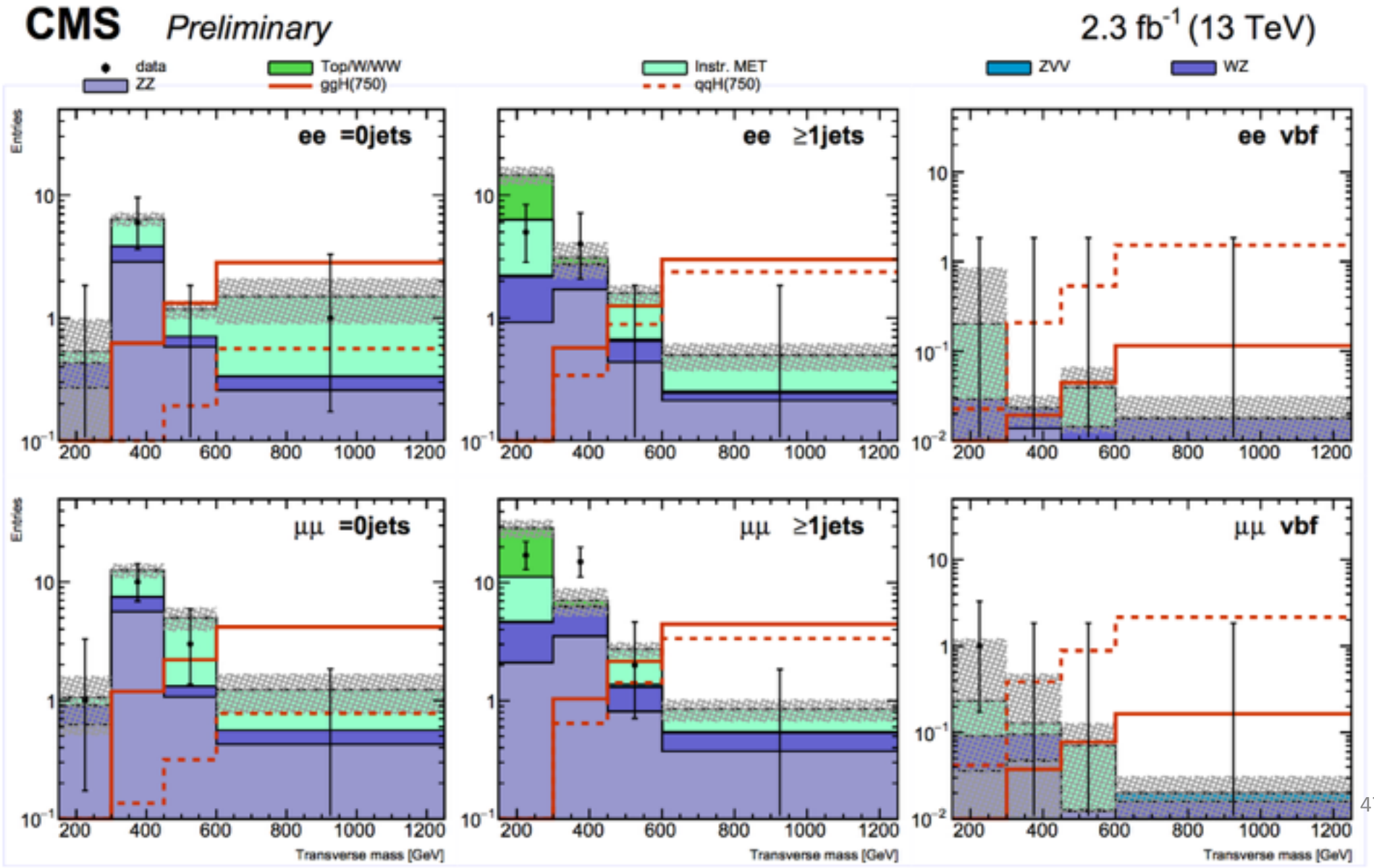




Comparison of ee and mumu signal resolution

CMS-PAS-HIG-16-001

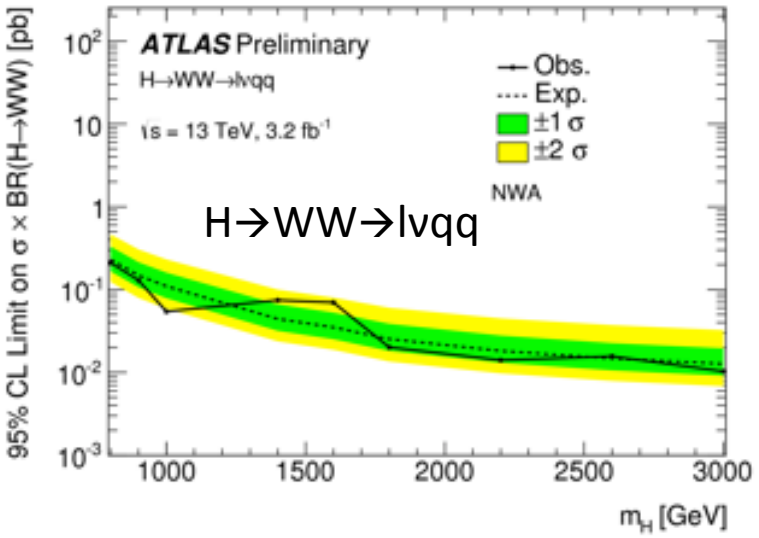
Search for H→llvv

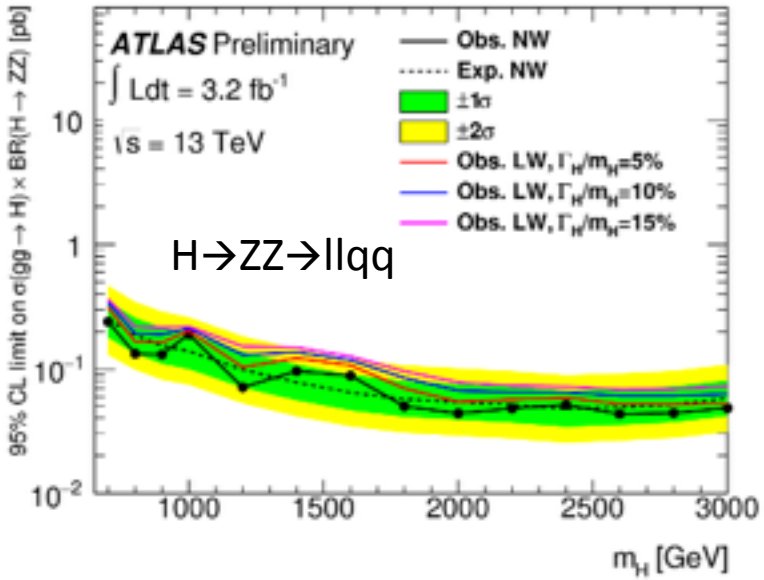


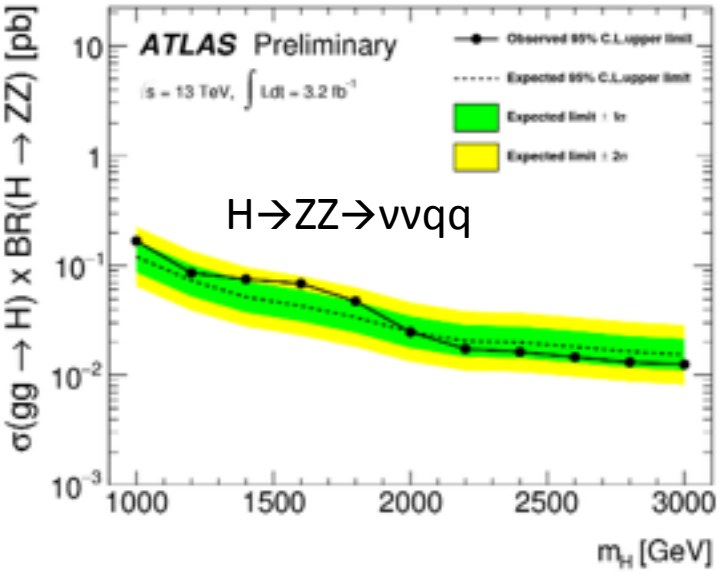
Boosted Diboson Resonances

ATLAS-CONF-2015-075
ATLAS-CONF-2015-071
ATLAS-CONF-2015-068

- Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.
  - For details of the analyses, see Max Bellomo's talk Thursday.
- Limits are set in the narrow width approximation, as well as for widths ranging from 5-15%.







Boosted Diboson Resonances

ATLAS-CONF-2015-075
ATLAS-CONF-2015-071
ATLAS-CONF-2015-068

- Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.
  - For details of the analysis, see Max Bellomo's talk Thursday.
- Limits are set in the narrow width approximation, as well as for widths ranging from 5-15%.