BSM HIGGS SEARCHES

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on behalf of CMS and ATLAS collaborations

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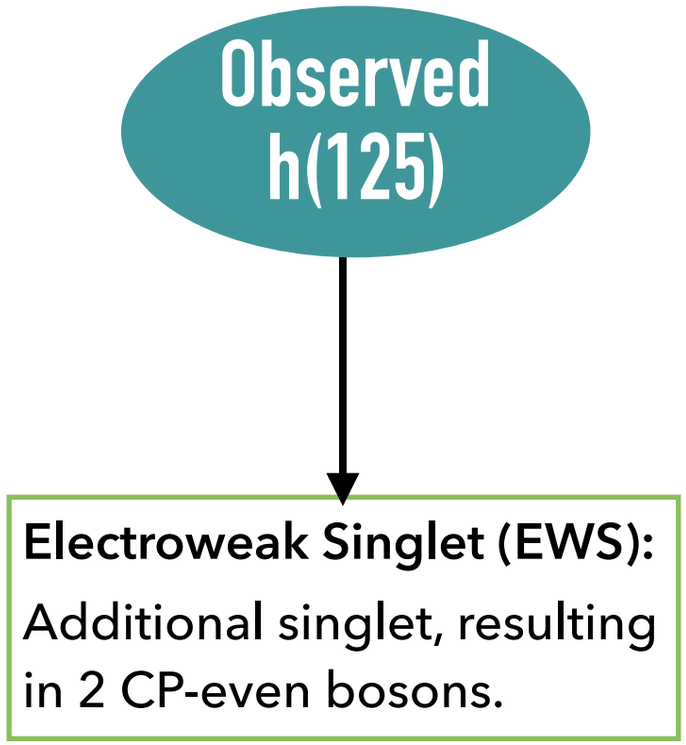
BEYOND THE STANDARD MODEL

- Discover of a 125 GeV particle compatible with the SM Higgs boson hypothesis
- Use this new particle to explore/expand our knowledge
- Few models out of many:



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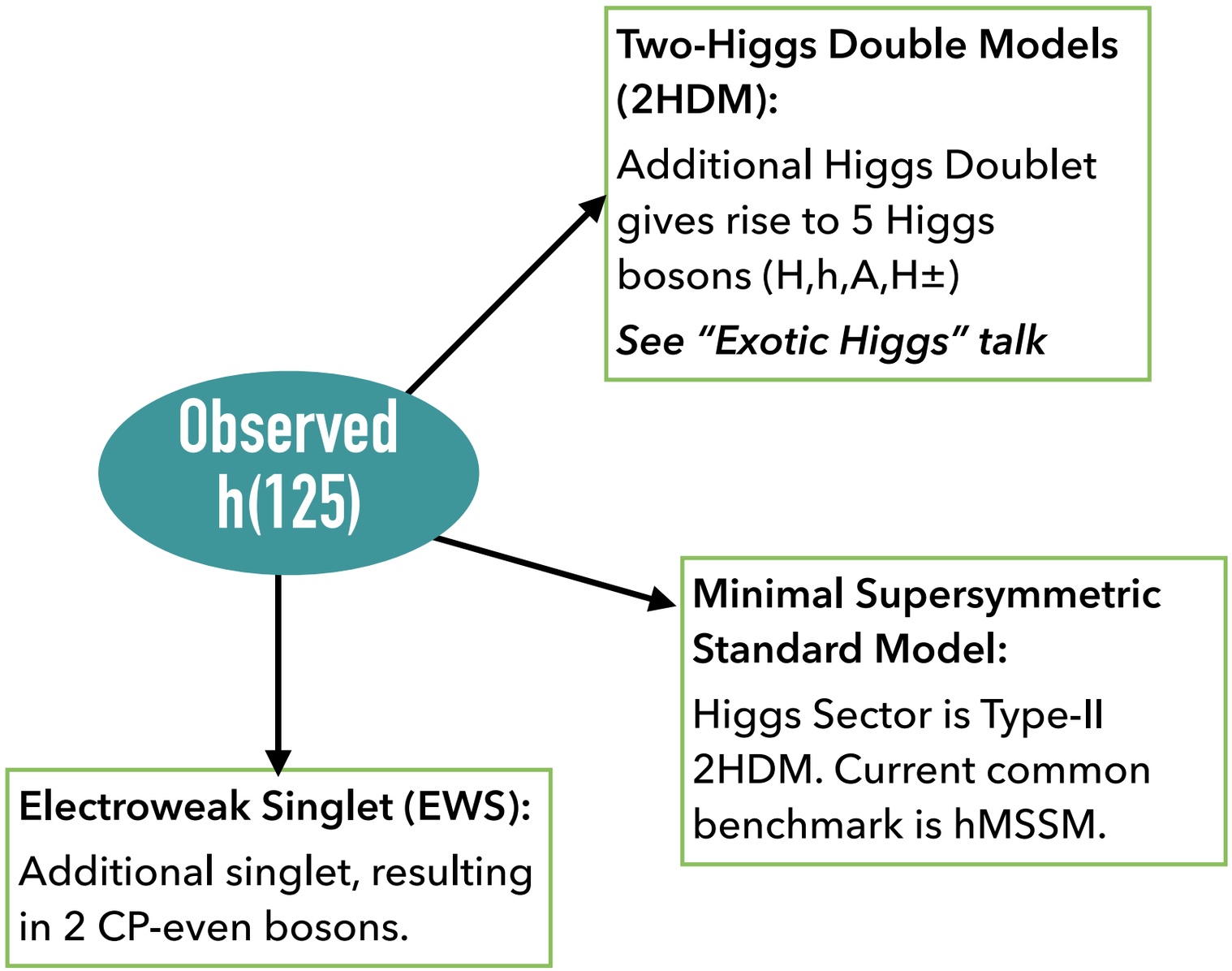

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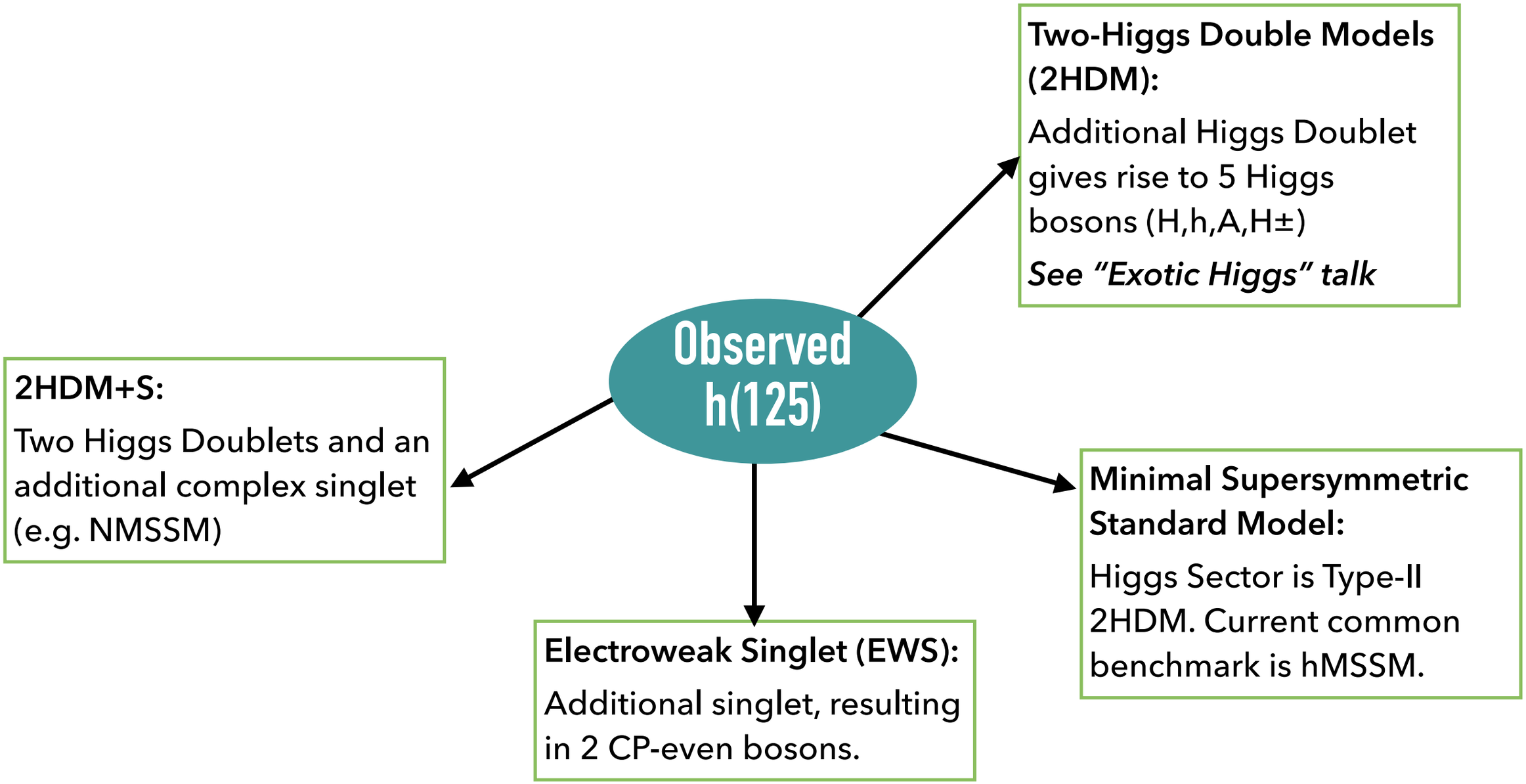

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Higgs Triplet:

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±)

See "Exotic Higgs" talk

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.

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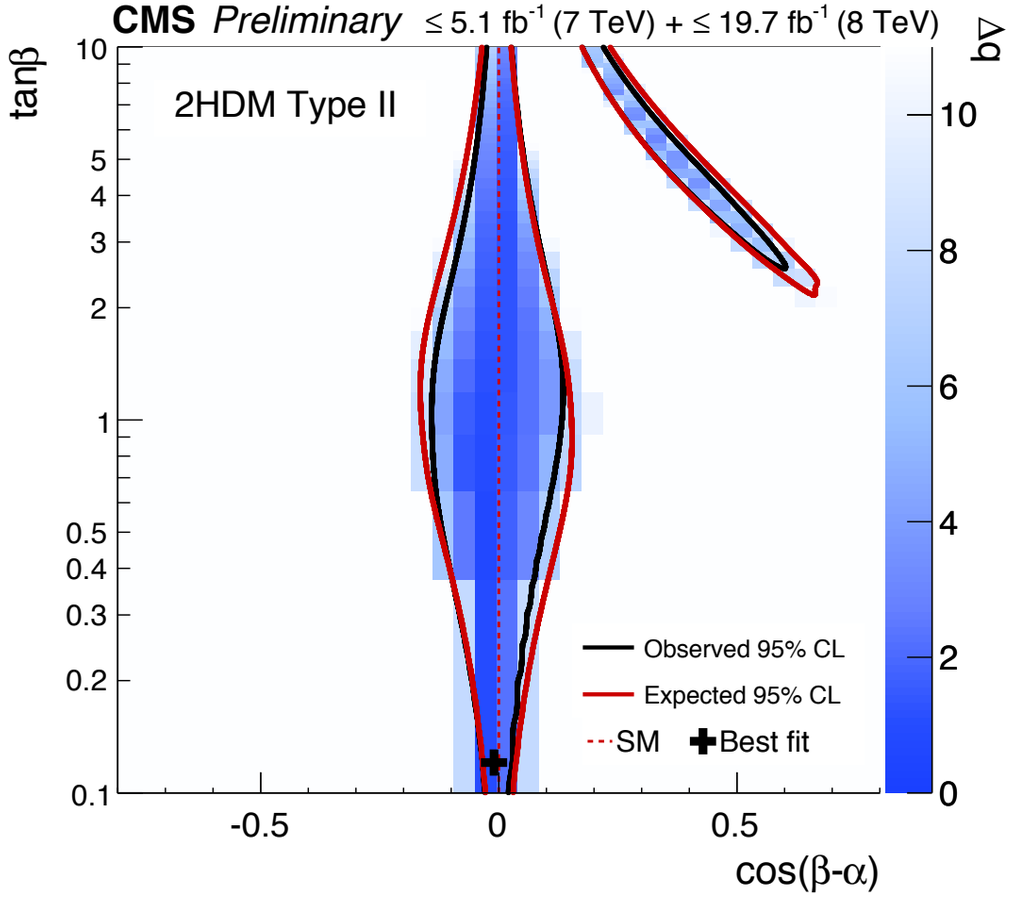
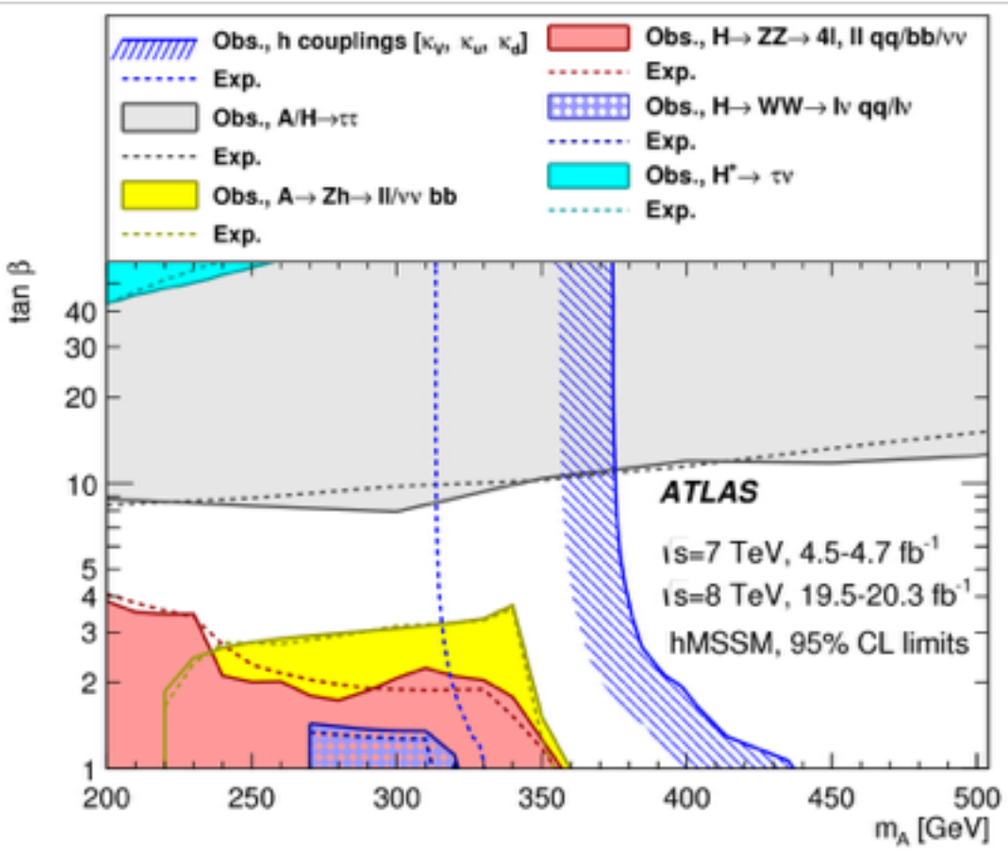
MSSM Consideration from Run1

ATLAS: JHEP11(2015)206
CMS: CMS-PAS-HIG-16-007

- 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.
- Much parameter space is excluded, but there is still room for high mass Higgs to be found
- **Coupling $H_{VV} \propto \cos(\beta - \alpha) < 0.1$** from h_{125} couplings
  - **Fermionic channels are interesting in this configuration**

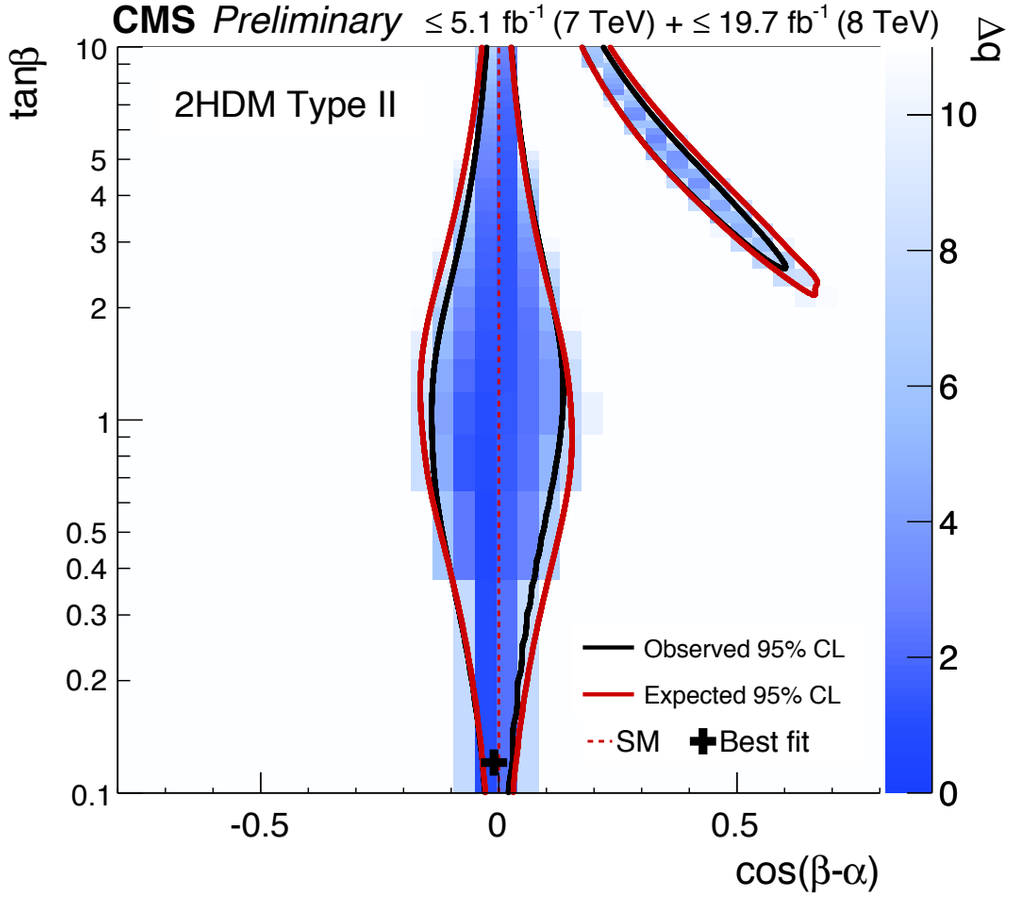


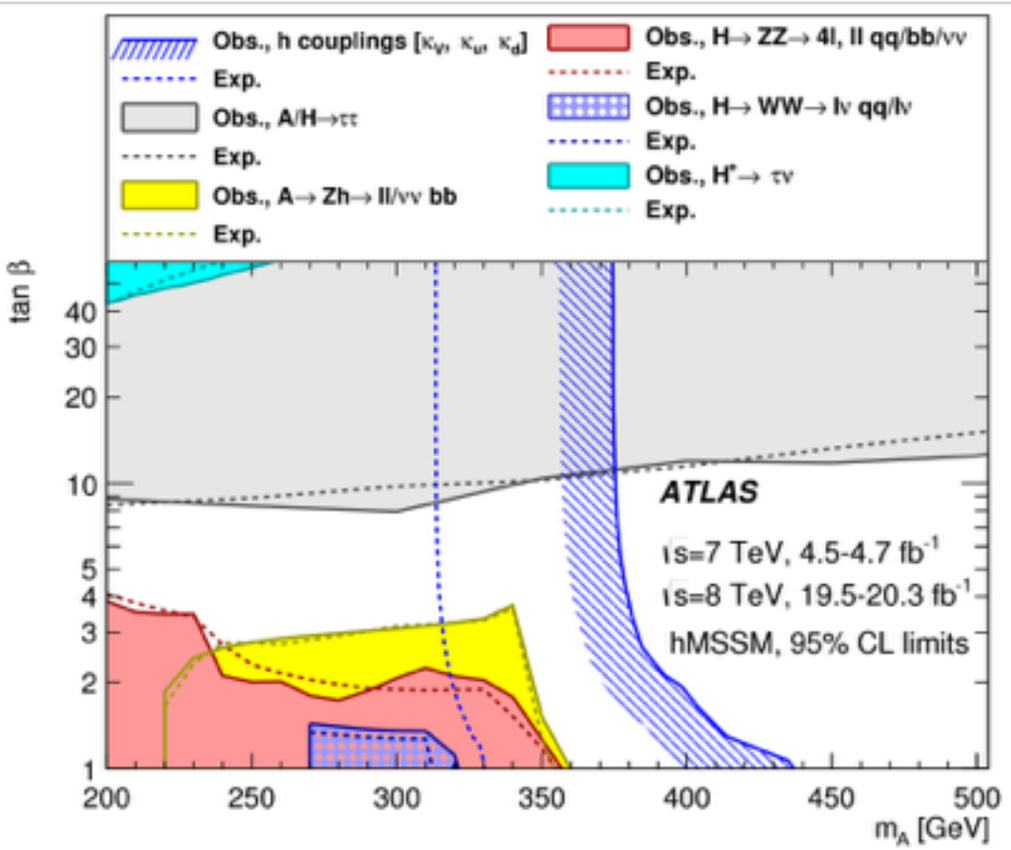


MSSM Consideration from Run1

ATLAS: JHEP11(2015)206
CMS: CMS-PAS-HIG-16-007

- In the limit $\cos(\beta - \alpha) = 0$ (decoupled SUSY sector)
  - $g_{H\tau\tau}$ and $g_{Hbb} \propto \tan\beta$ => useful for large $\tan\beta$;
  - $g_{Htt} \propto (\tan\beta)^{-1}$ => useful for low $\tan\beta$;
  - $g_{H\pm\tau} \propto \tan\beta$ => high $\tan\beta$;
  - $g_{H\pm q} \propto [c1*\tan\beta*m_d + c2*(\tan\beta)^{-1} * m_u]$ => low/high $\tan\beta$;





BSM SEARCHES IN THIS PRESENTATION

BEYOND STANDARD MODEL SEARCHES

- **Neutral Higgs:**
  - Fermionic decay:
    - $H \rightarrow \tau\tau$ (13 TeV)
    - $H \rightarrow bb$, $H \rightarrow \mu\mu$ (8TeV)
  - Bosonic Decay
    - $H \rightarrow ZZ$ (13TeV)
    - $H \rightarrow WW$ (13 TeV)

- **Di-Higgs:**
  - $H \rightarrow hh \rightarrow bb\gamma\gamma$ (13 TeV)
  - $H \rightarrow hh \rightarrow bb\tau\tau$ (13 TeV)
  - $H \rightarrow hh \rightarrow bbWW$ (13 TeV)
  - $H \rightarrow hh \rightarrow bbbb$ (13 TeV)

- **Charged Higgs:**
  - $H^{\pm} \rightarrow \tau\nu$ (13 TeV)
  - $H^{\pm} \rightarrow tb$ (8 TeV)
  - $\varphi^{\pm\pm}\varphi^{\pm\pm} \rightarrow lll\nu/4l$ (8 TeV)

- **Higgs-to-Higgs:**
  - $H \rightarrow 2a$ (8 TeV)
  - $H \rightarrow ZA$ (13 TeV)
  - $A \rightarrow Zh(125)$ (13 TeV)

Neutral Higgs

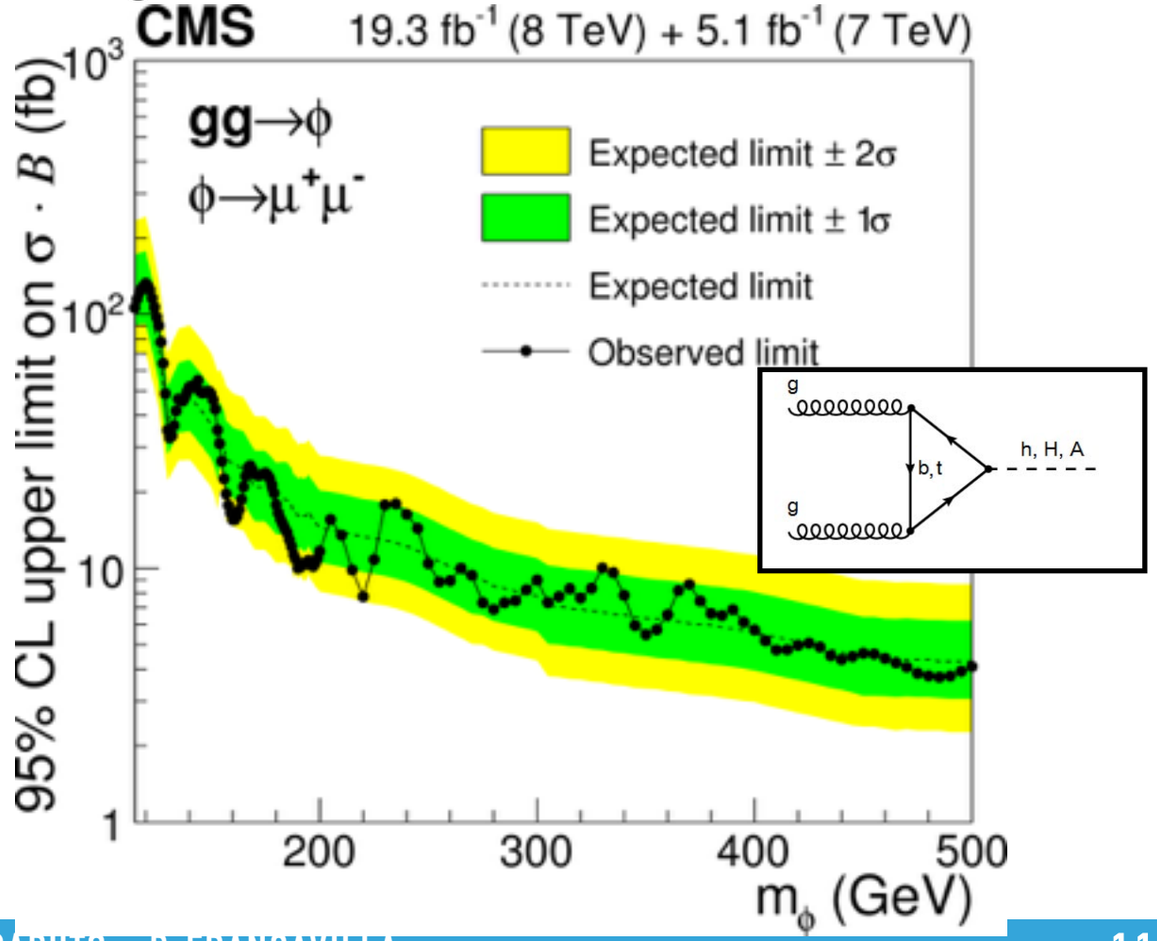
FERMIONIC DECAYS

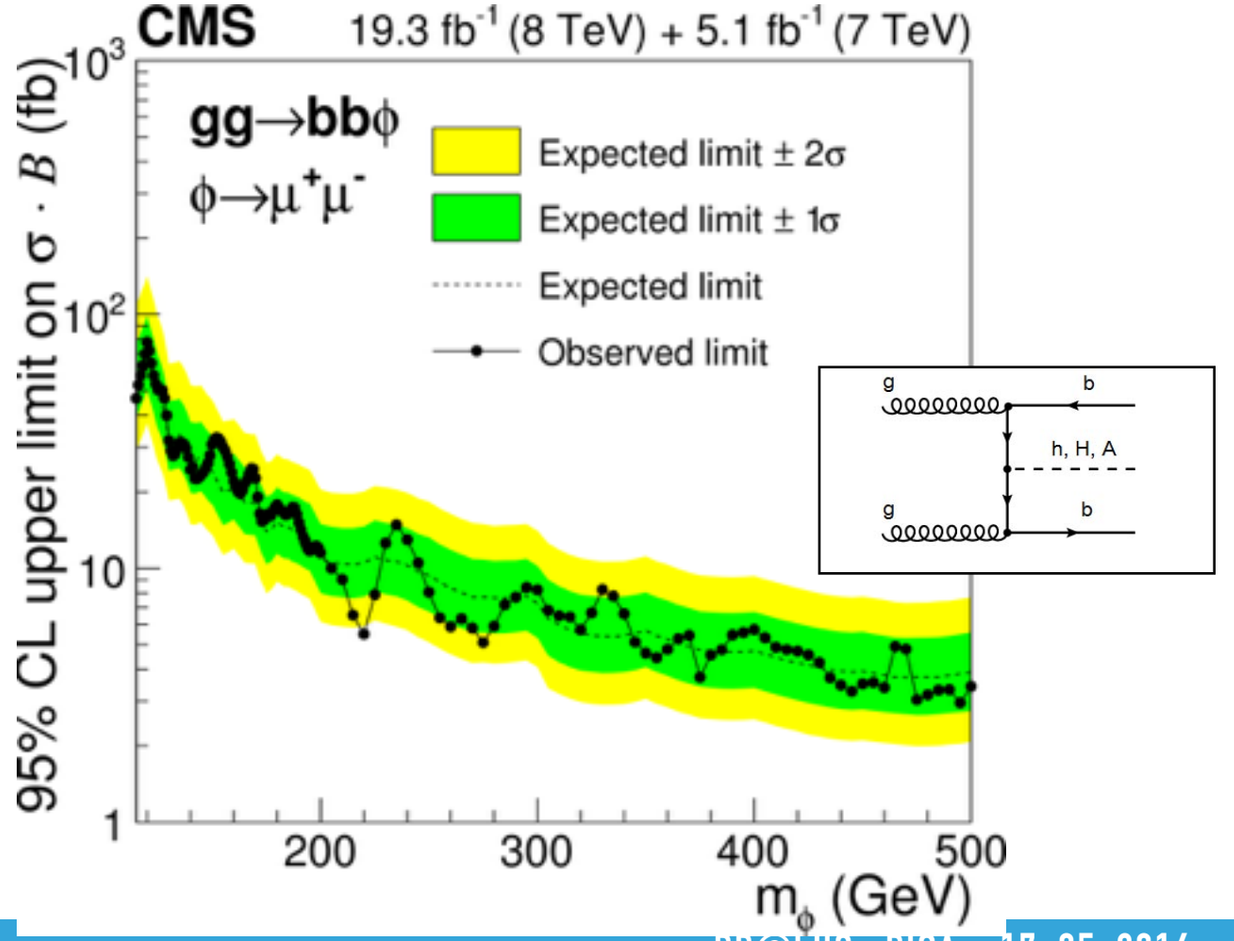
Search for H/A→μμ

CMS: Phys. Lett. B 752 (2016) 221

- Predicts the existence of two Higgs doublet fields
- 5 Higgs bosons: a CP-odd neutral scalar A, 2 charged scalars $H^{\pm}$, and two CP-even neutral scalar particles h and H
- h, A, and H, referred to as φ
- Production mechanism: associate produced (AP) and gluon fusion (GF).

Common selection	
Single muon trigger	$p_T > 24\,\text{GeV}$ + isolation + $\lvert\eta\rvert < 2.1$
Event primary vertex	$\lvert z_{PV}\rvert < 24\,\text{cm}$
Muon selection	2 opposite-charged muons, $p_T > 24\,\text{GeV}$, $\lvert\eta\rvert < 2.1$, track quality cuts, $\lvert d_{xy}\rvert < 0.02\,\text{cm}$, $\lvert d_z\rvert < 0.1\,\text{cm}$, angular matching with trigger, isolation
E_T^{miss}	$E_T^{miss} < 35\,\text{GeV}$
Category C1	
b tag	1 or 2 b-tagged jets, $p_T^{jet} > 20\,\text{GeV}$, $\lvert\eta^{jet}\rvert < 2.4$
Category C2	
No b tag	Events with no b-tagged jets

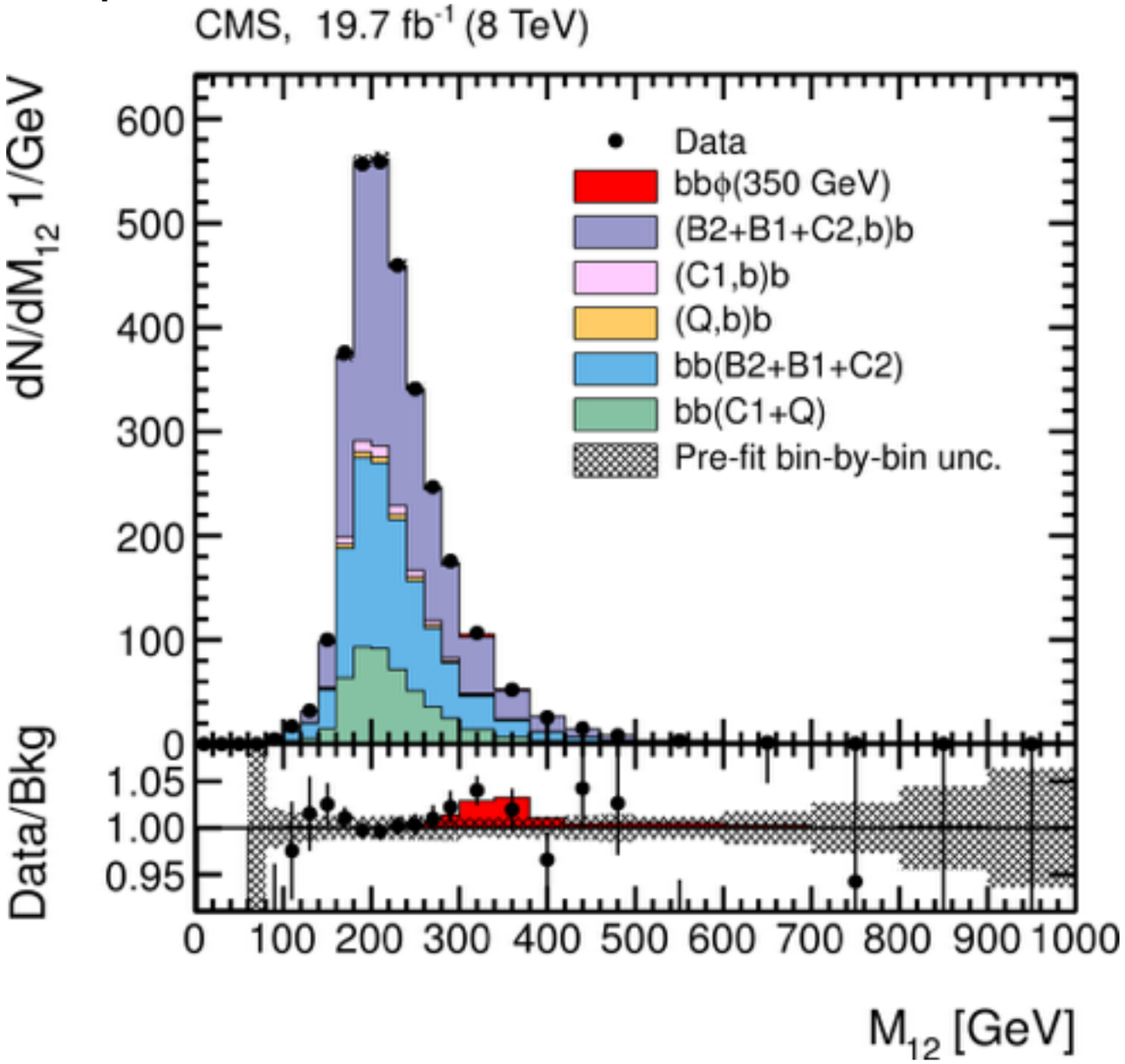


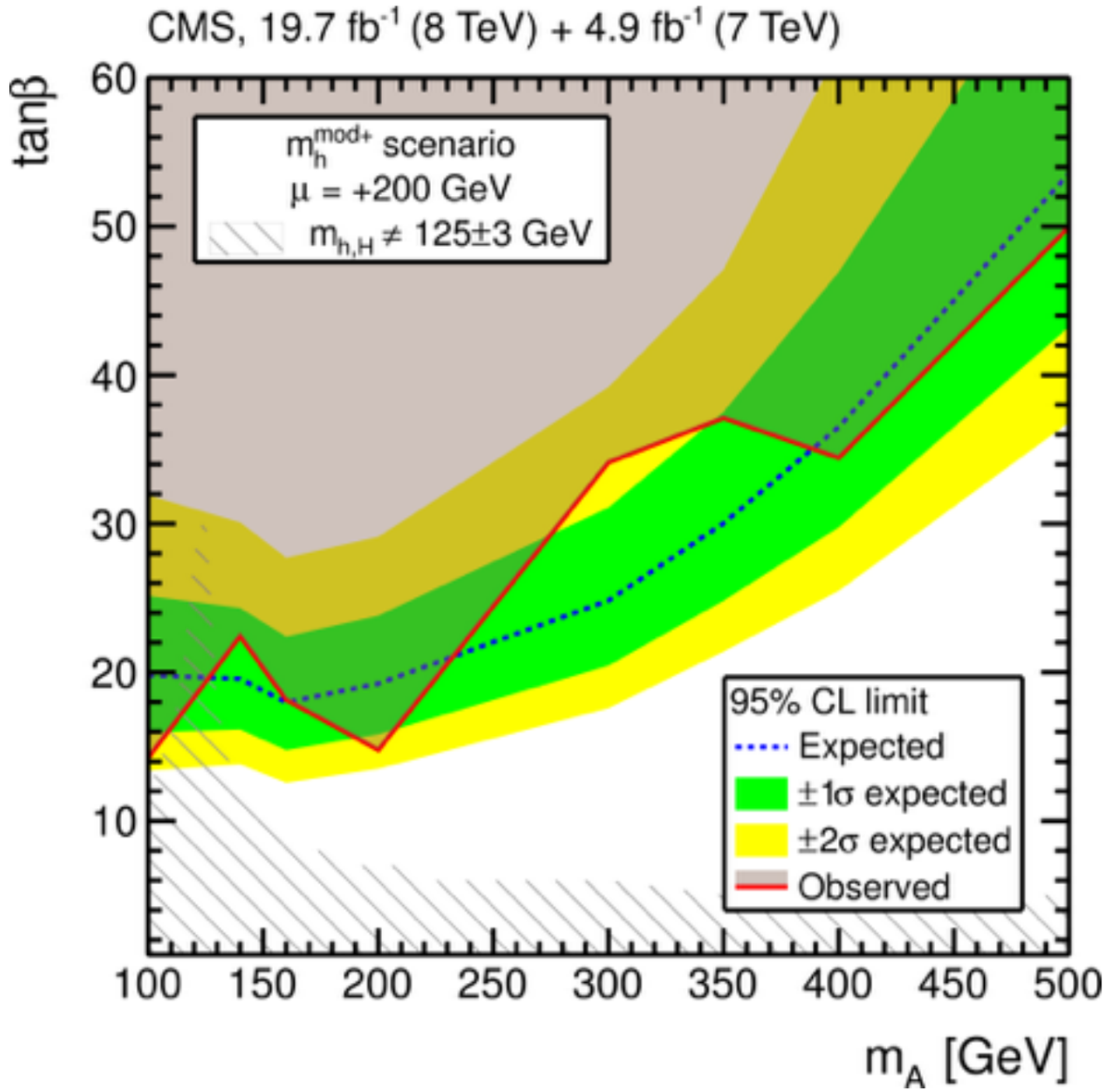


Search for H/A→bb

CMS: J. High Energy Phys. 11 (2015) 071

- φ produced in association with at least one b quark and decay to bb
- final states characterised by at least three b-tagged jets
- Events selected by specialised triggers that identify b jets already at the online level
- searches for a peak in the invariant mass distribution of the two b jets with the highest pT values





Search for H/A→ττ

ATLAS:CERN-PH-EP-2016-061

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

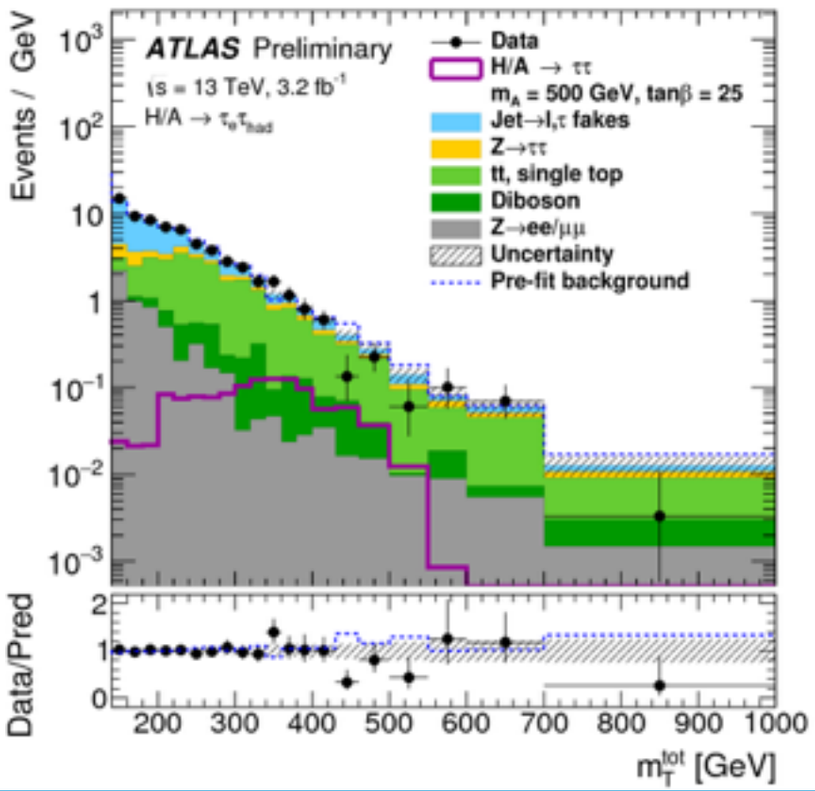
- Single lepton triggers
- 1 τ and 1 OS e/μ and Δφ(τ, e/μ) > 2.4
- M_T(e/μ, MET) < 40 GeV or > 150 GeV
- In e-channel: m_{vis} < 80 and > 110 GeV

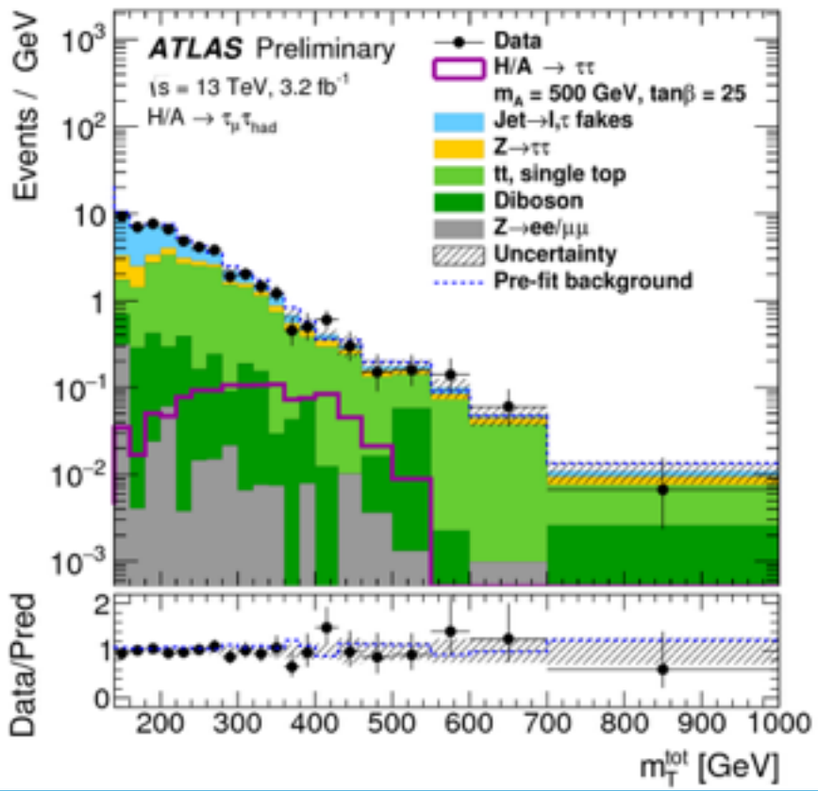
$\tau_{had}\,\tau_{had}$ Event Selection

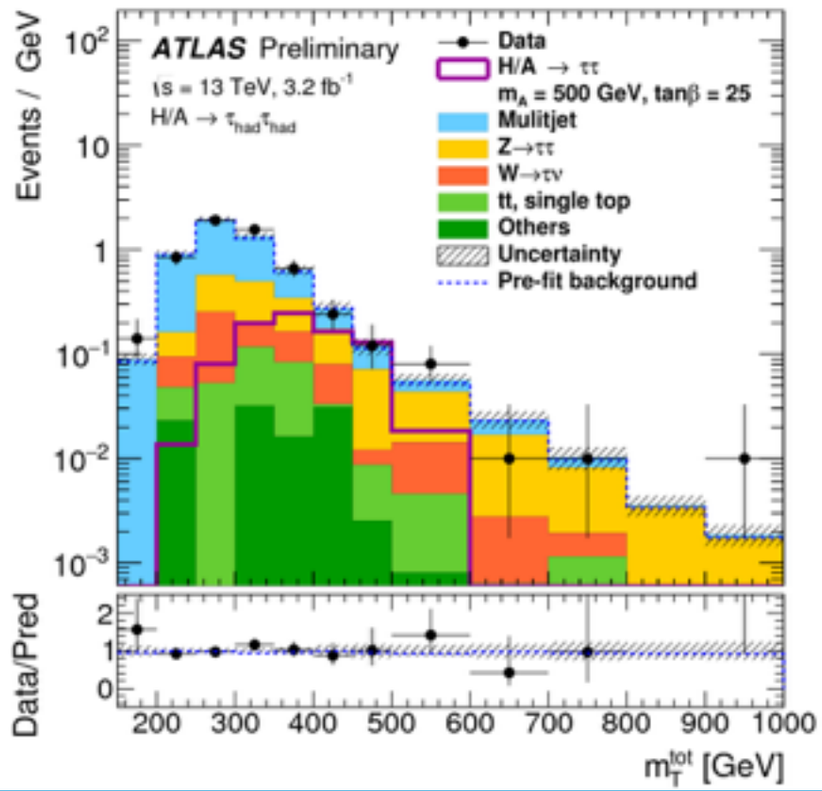
- Single τ_{had} trigger
- 2 τ_{had} with OS charge
- Δφ($\tau_{had,1}$, $\tau_{had,2}$) > 2.7

- Final discriminant:

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







Search for H/A – Results

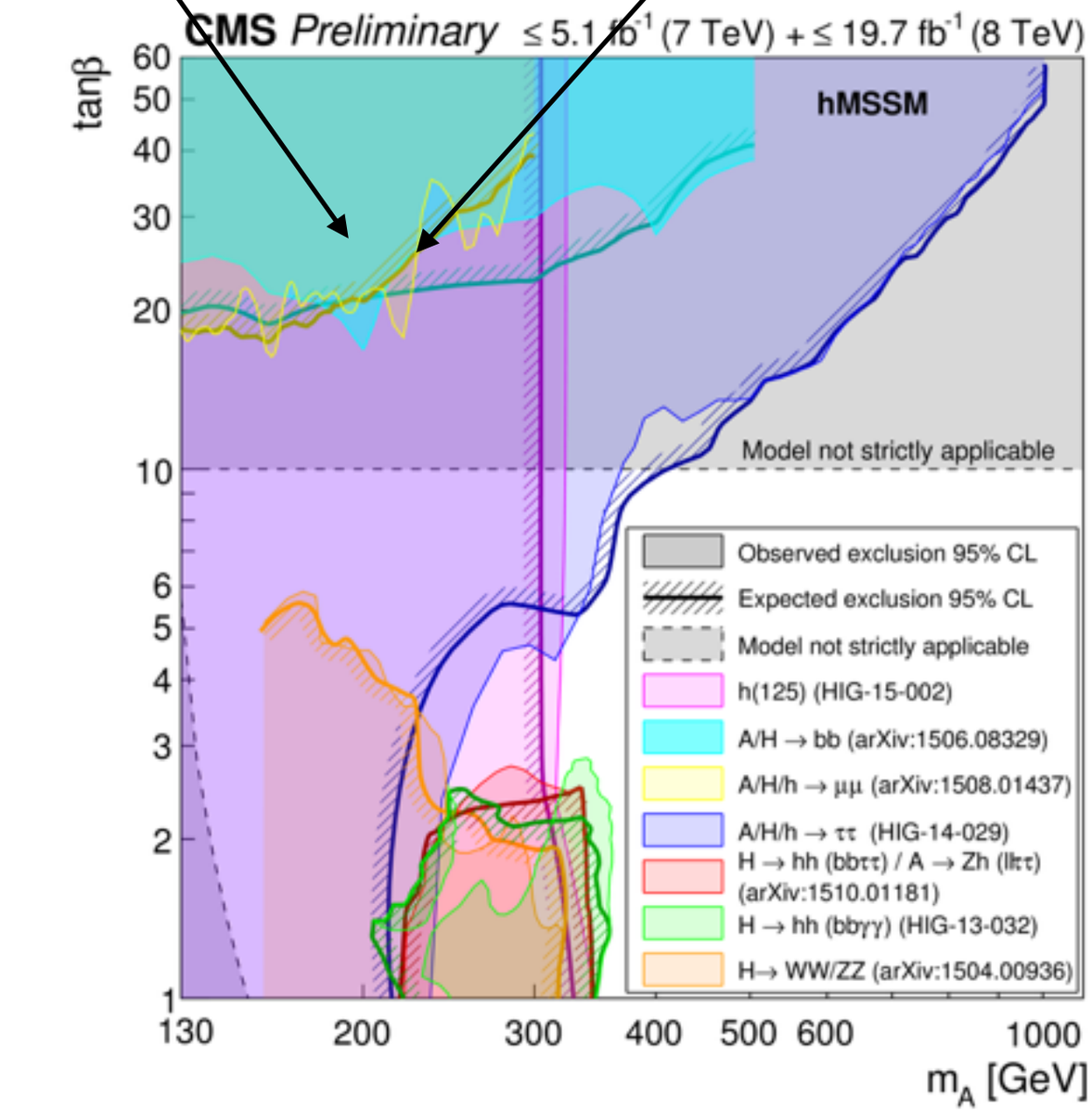
ATLAS:CERN-PH-EP-2016-061
CMS: J. High Energy Phys. 11 (2015) 071

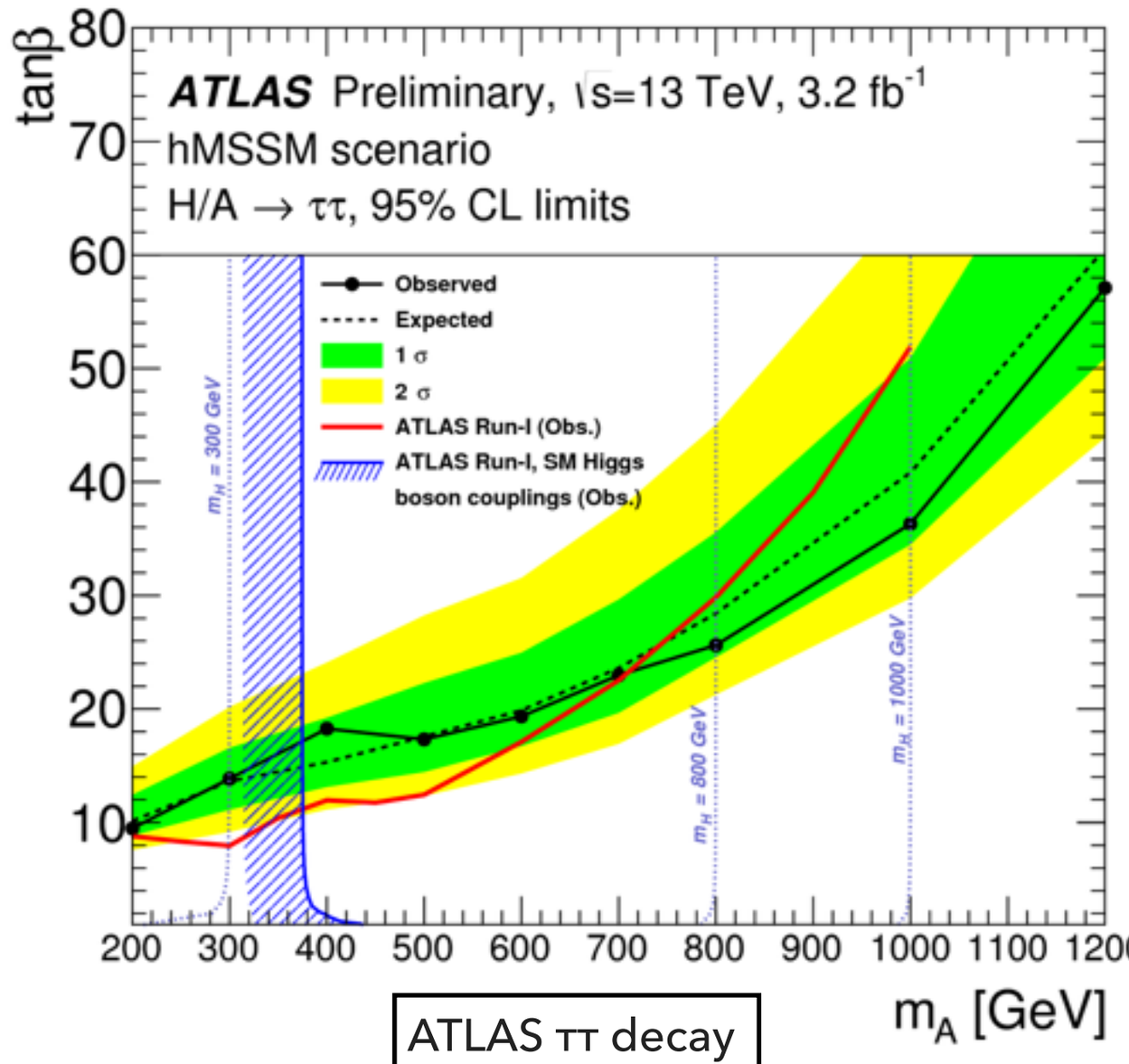
- ττ decay shows a good sensitivity wrt to the bb channel
- Exclusion limits for 13TeV are already competitive with the run-1 limits

CMS bb decay

CMS μμ decay

hMSSM





ATLAS ττ decay

Neutral Higgs

BOSONIC DECAYS

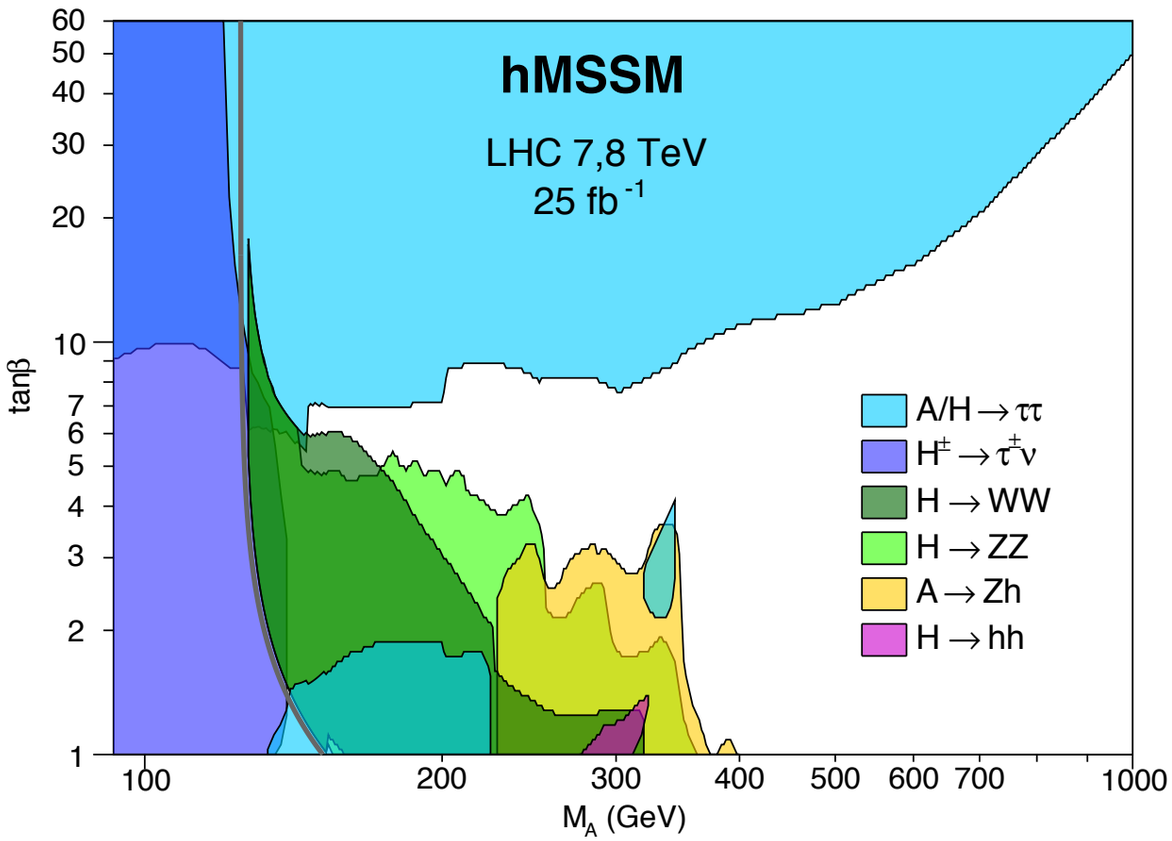
Search for H→VV– Results

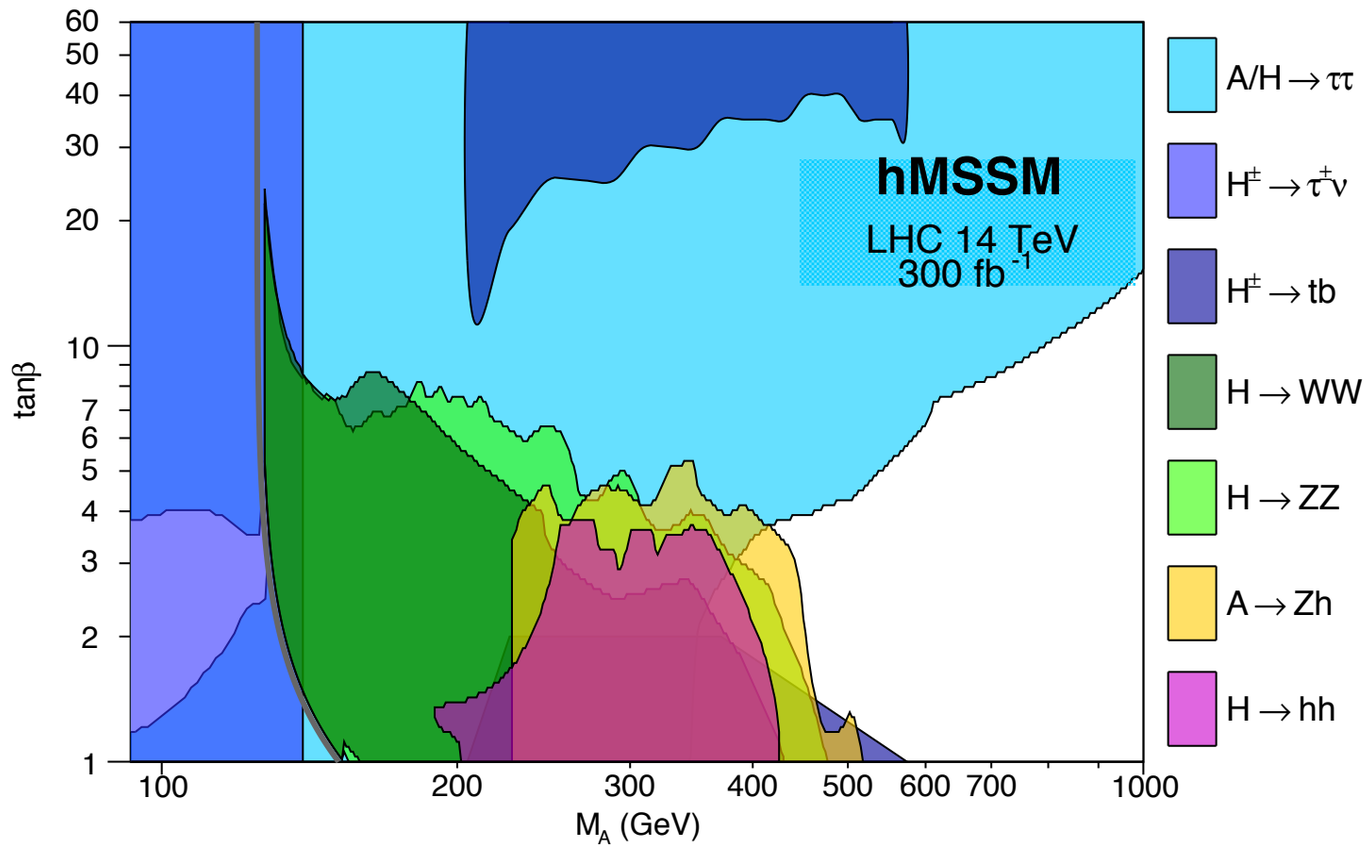
Bosonic Decay

- H→ZZ (13TeV)
- H→WW (13 TeV)

See **Higgs Exotic** talk

- Run1 DiBoson searches are interesting to give complementary infos to low/int region in tan B in the mass range $2m_W$ $2m_t$
- Run2 projections show a limited improvement of the covered phase space.
  - Other channels and h_{125} couplings will cover a larger PS including the one covered by DiBoson





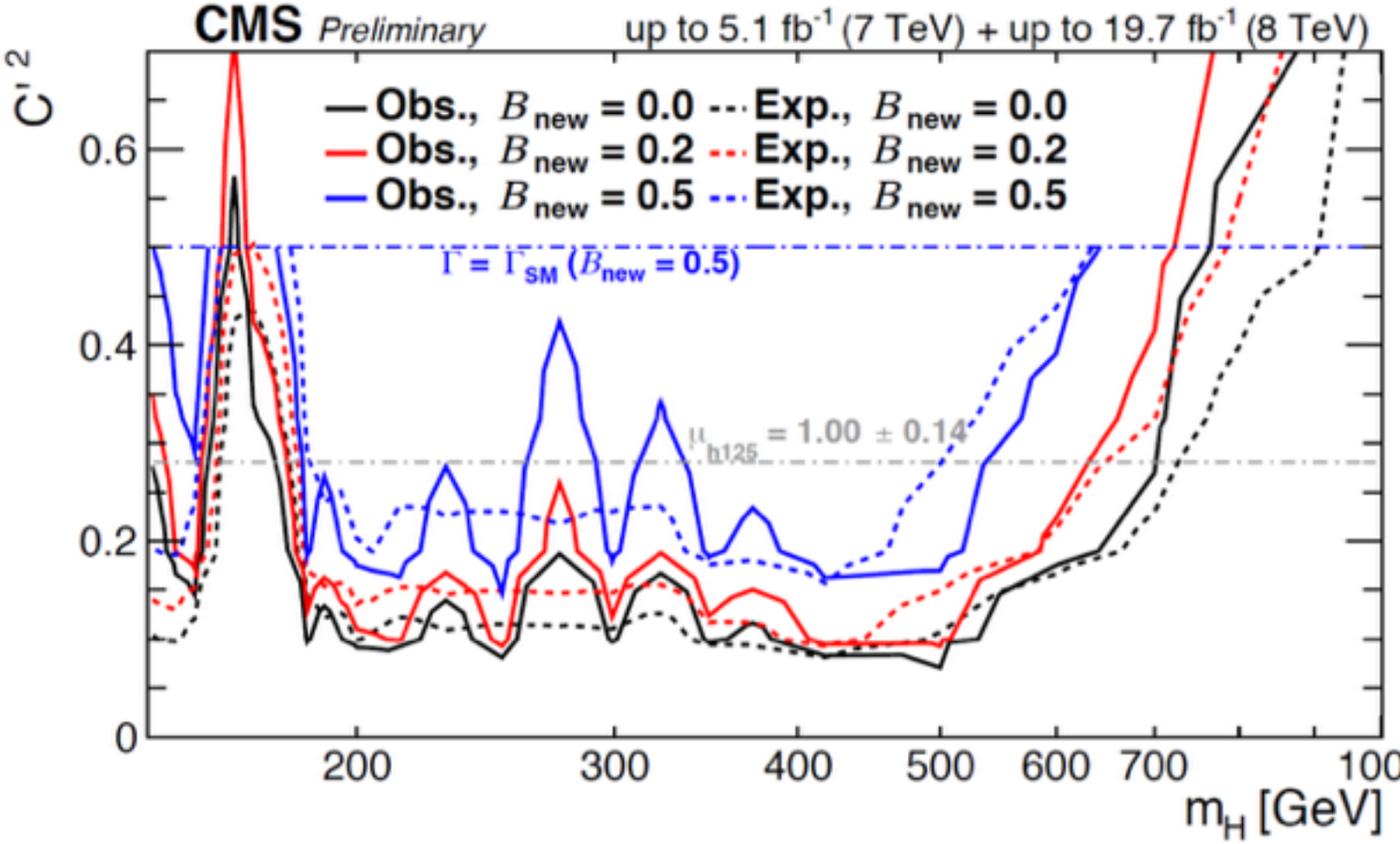
- Di Boson are a good probe for Singlet (+Doublet) Models

Search for H→VV- Results

- Minimal extension of the Higgs sector obtained by adding an electroweak singlet to the "SM doublet"
- Two observable states: h1 and h2
- No hypothesis made on the origin of the singlet

$$C = \frac{g_{h_1VV,meas}}{g_{h_1VV,SM}} \qquad C' = \frac{g_{h_2VV,meas}}{g_{h_2VV,SM}} \qquad C^2 + C'^2 = 1$$

- No dependence on the Higgs masses!Implies rescaling of the SM cross section and width for h2 wrt SM
- Grey line indirect limit by SM signal strength (mu)
- B_{new} to account for new decay mode for h_2 (H)
- For example h2 -> h1h1 (Di Higgs Searches)



Di-Higgs

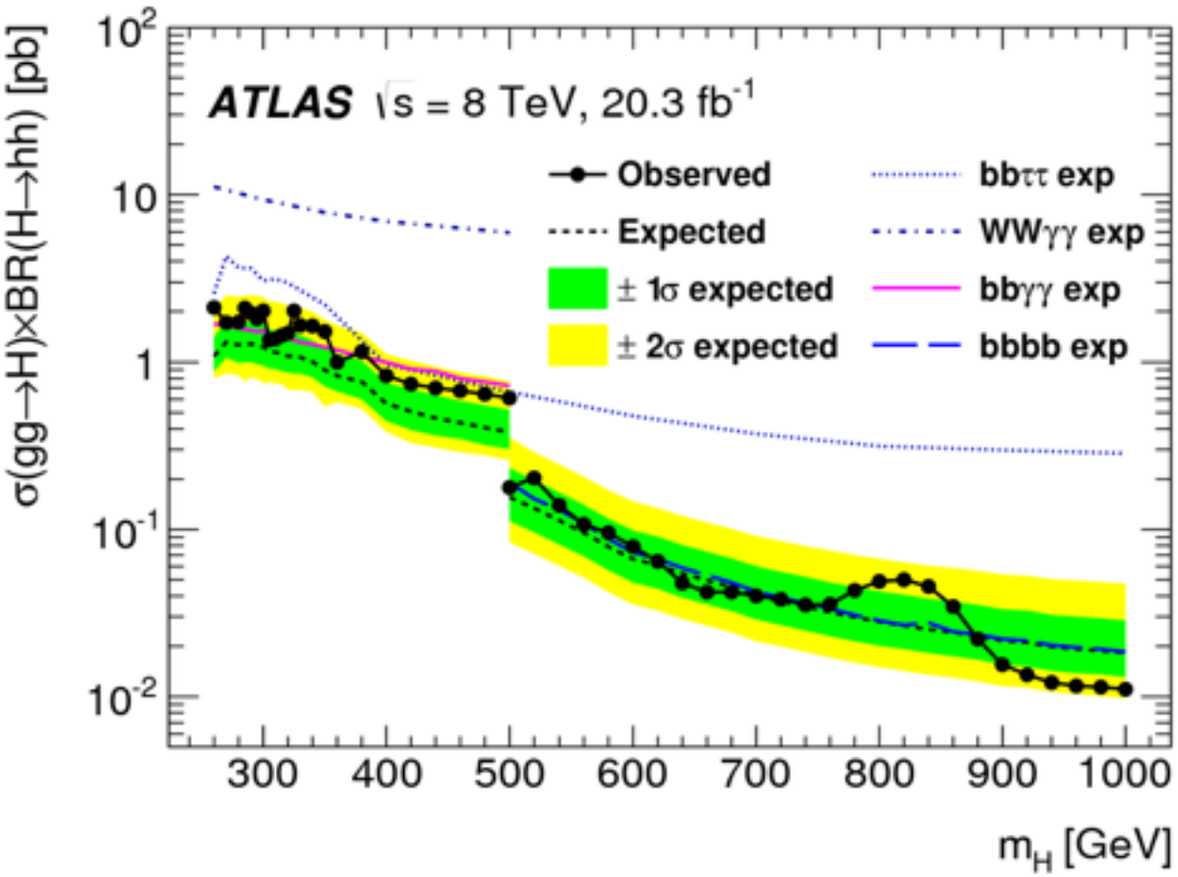
Search for H→hh – Run1 Results

ATLAS: Phys. Rev. D 92, 092004 (2015)
CMS: Twiki

- H→hh could arise in many models and can be use to search for BSM
- Many final states covered during Run1

ATLAS

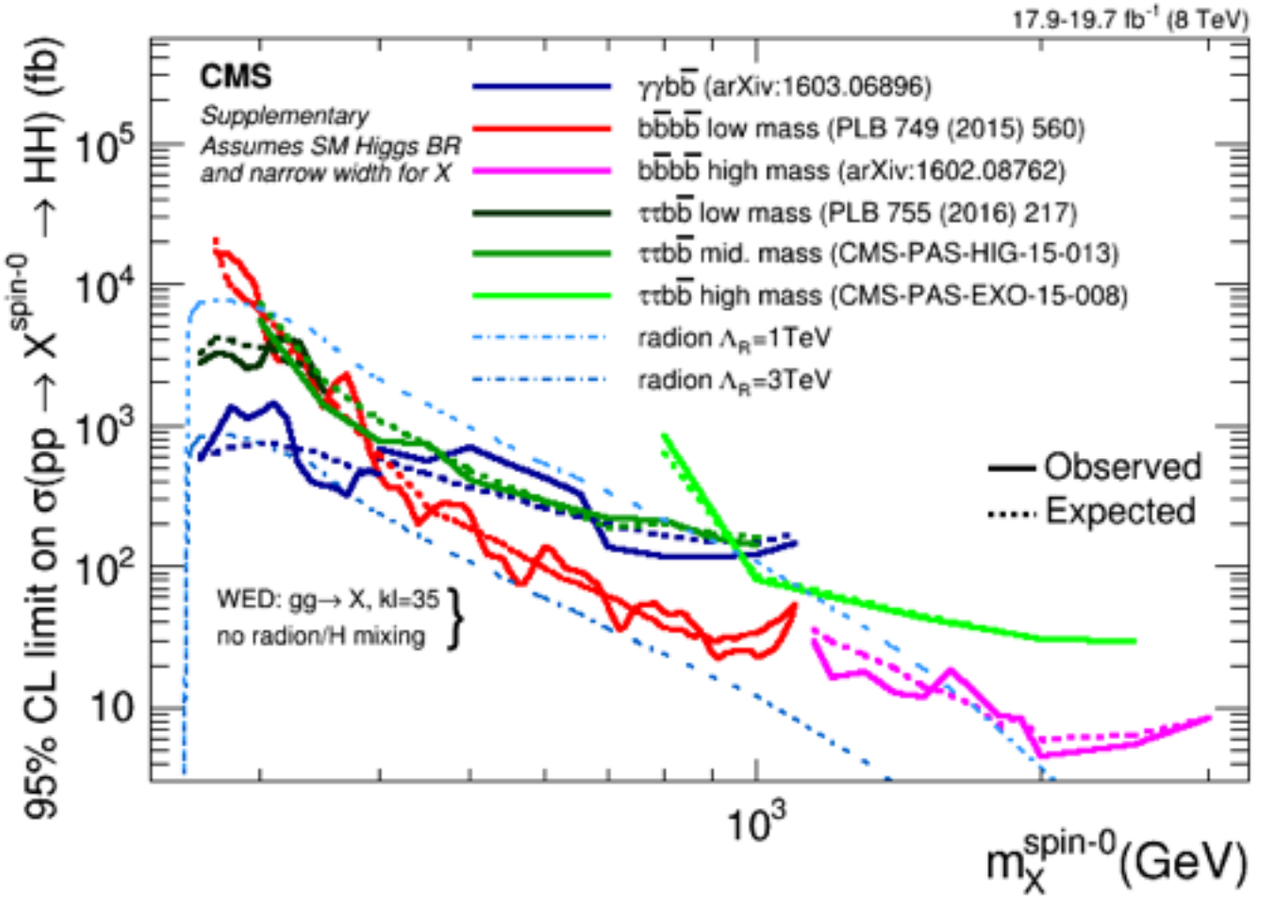
Run1 Results Combination:
2b2γ, 2b2τ, 4b e 2γ2W



CMS

Run1 Results Superposition

- Results for m_X > 1TeV



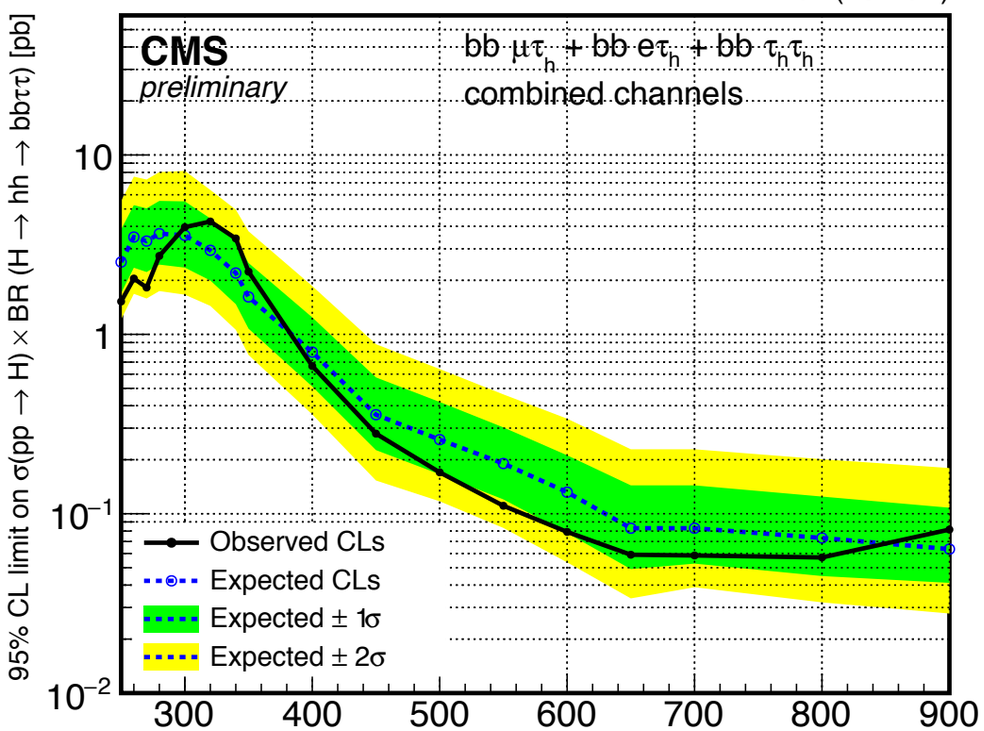
Search for H→hh→bbττ

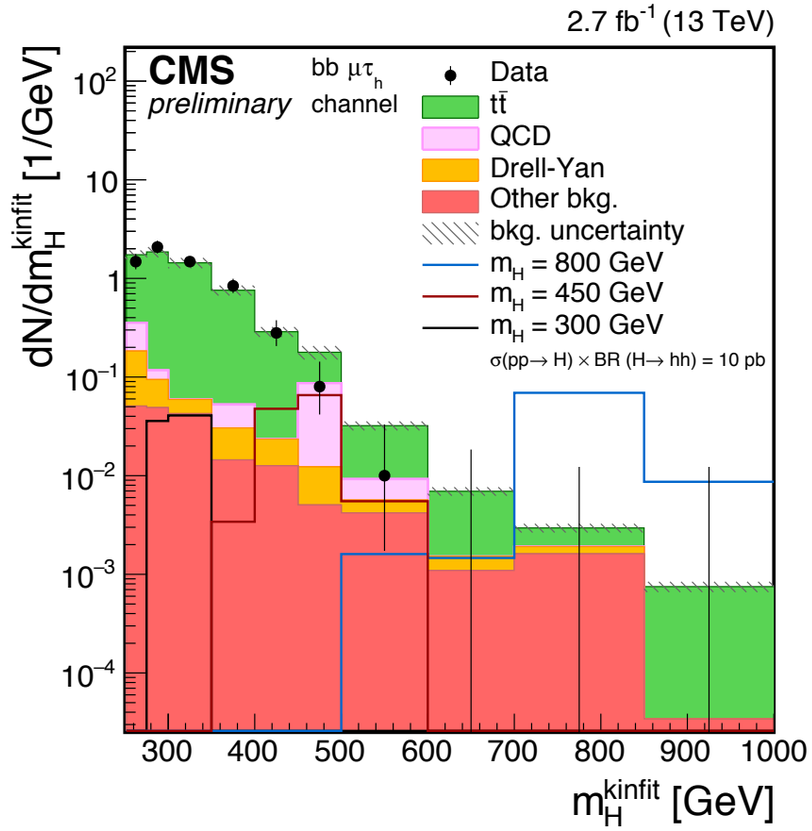
CMS: CMS-PAS-HIG-16-013

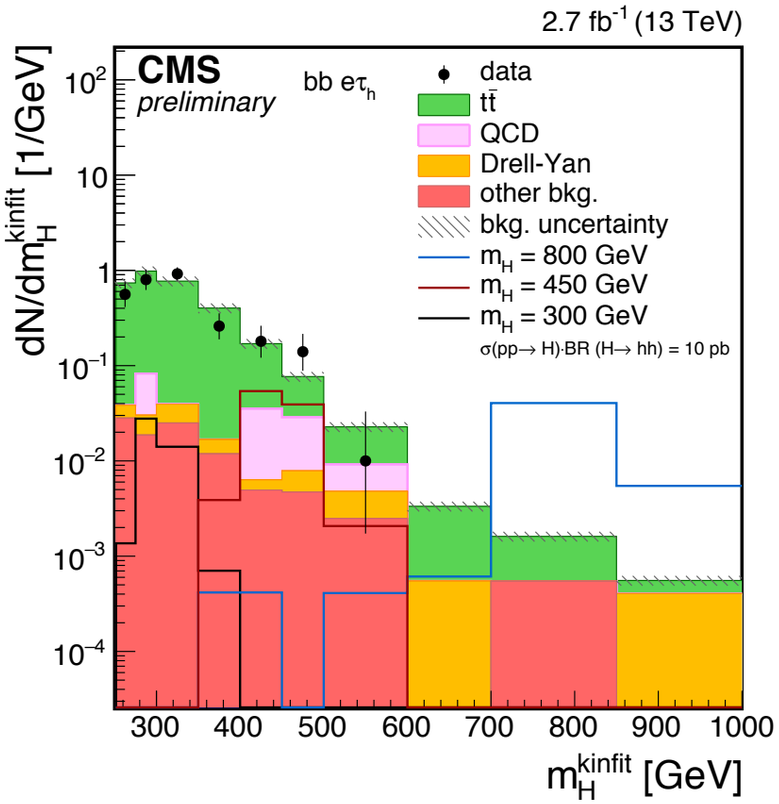
Mass range form 260 GeV to 900 GeV

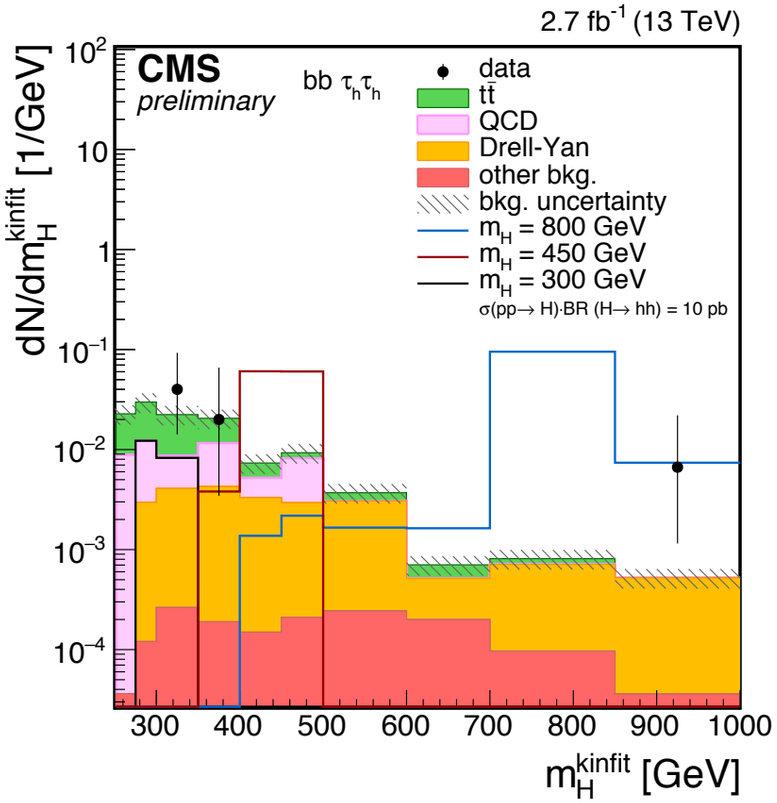
Search for three channel:

- $\tau_{had}\tau_{\mu}$, $\tau_{had}\tau_{e}$ and $\tau_{had}\tau_{had}$
- Exactly two OS objects
- 2 b-tagged jets
- Final mass variable mH constructed using a kinematic fit.





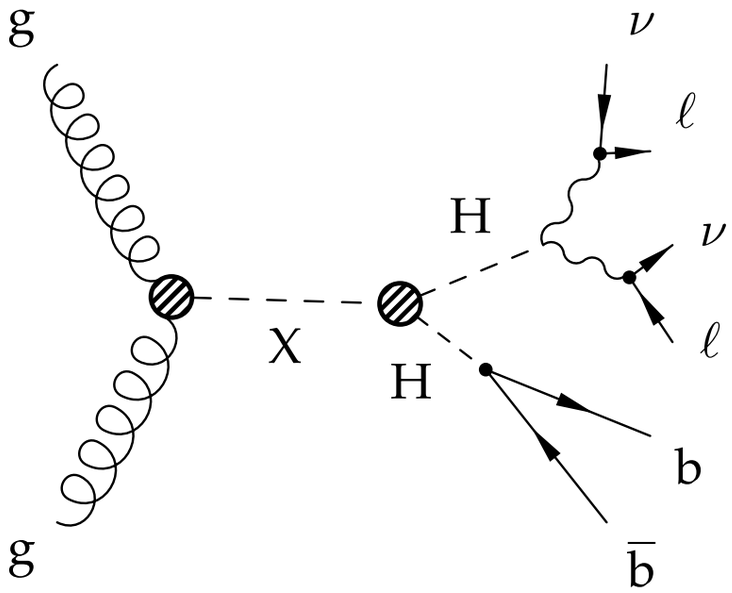




Search for H→hh→bbWW

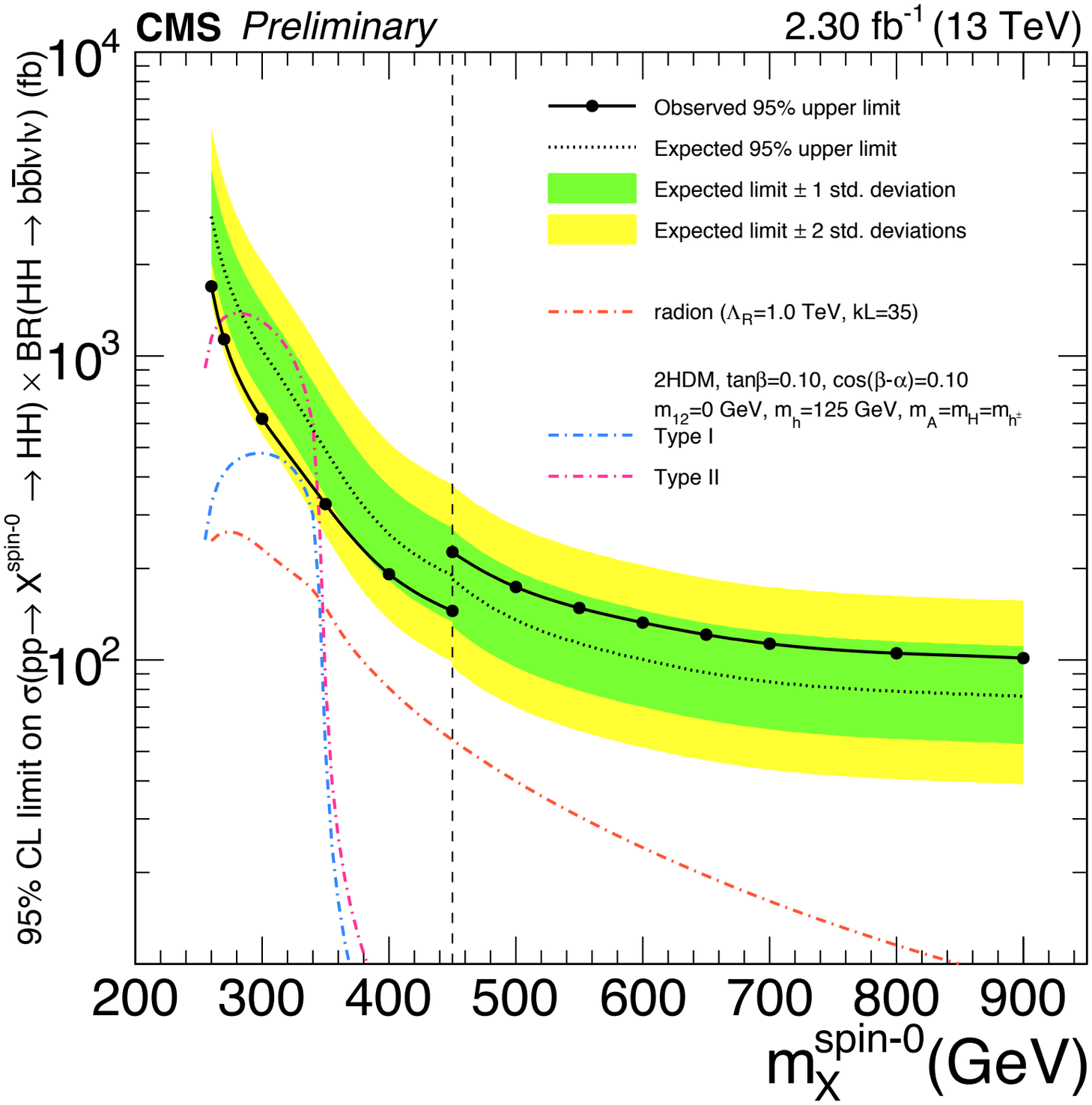
CMS: CMS-PAS-HIG-16-011

Mass range form 260 GeV to 900 GeV



Signal extraction:

- **Four** different regions:
  - High-BDT-score, Low-BDT-score
  - 95 GeV < m_{jj} < 135 GeV , m_{jj} <95 GeV && m_{jj} > 135 GeV.



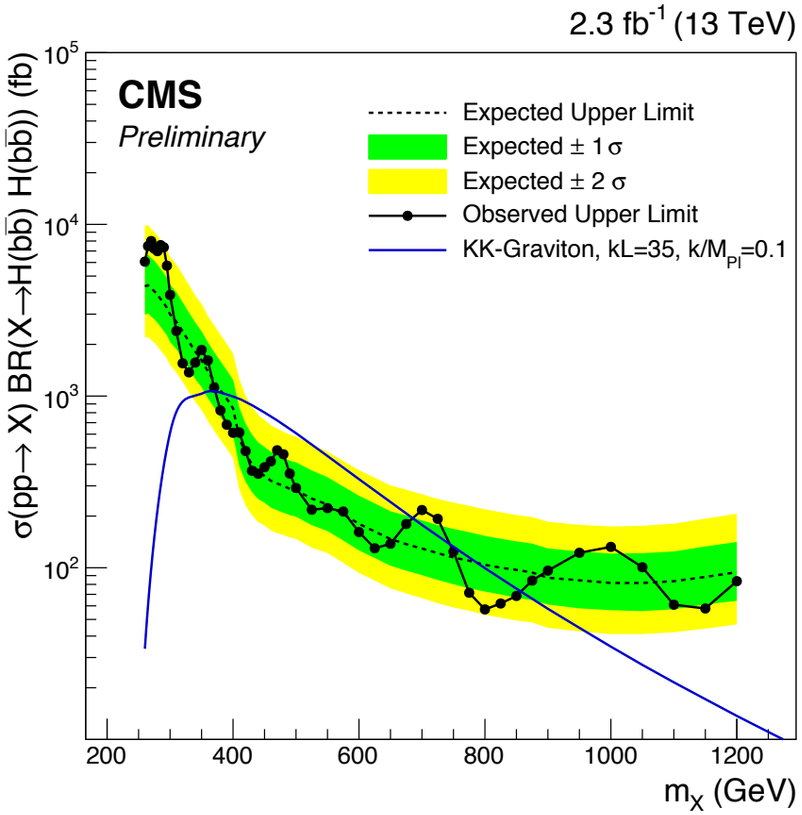
Search for H→hh→bbbb

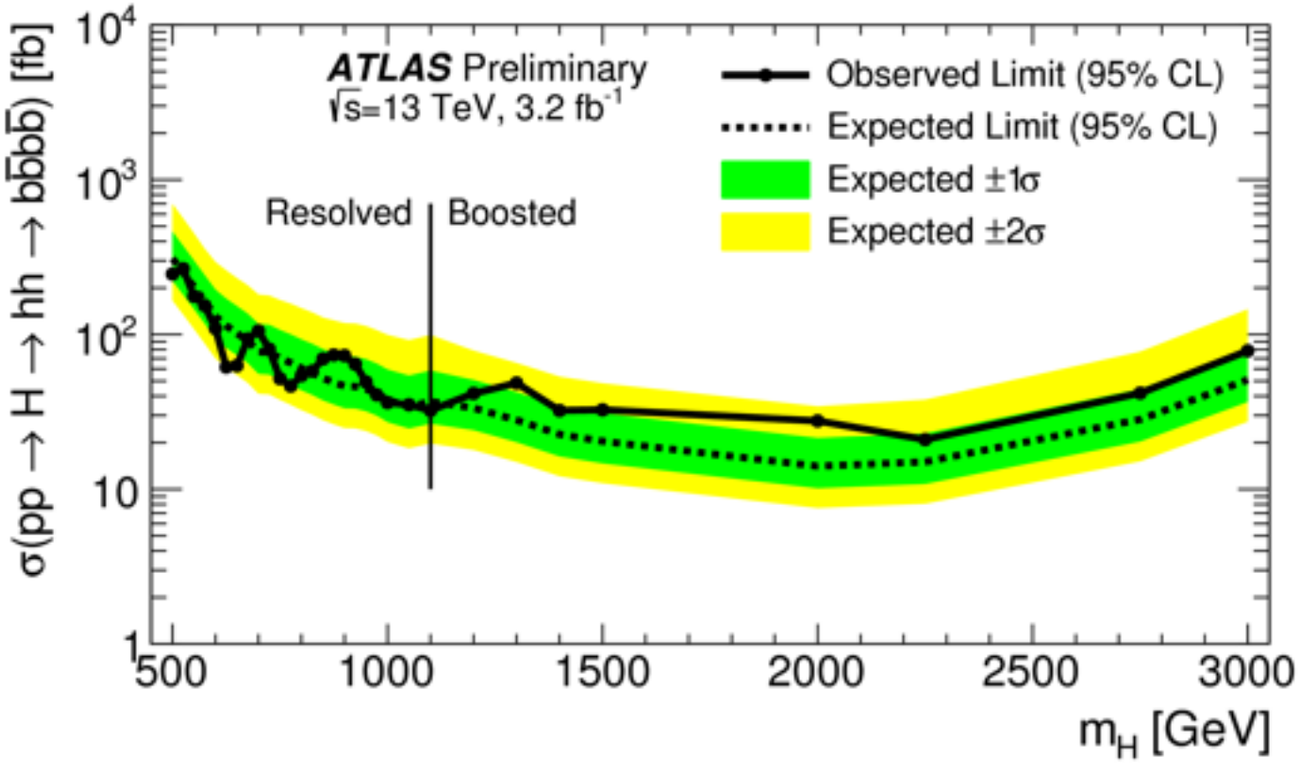
ATLAS: ATLAS-CONF-2016-017
CMS: CMS-PAS-HIG-16-002

Search strategy:

Mass range form 260 GeV to 3000 GeV

- two main kinematic regions:
  - low-mass region (LMR) from 260 GeV to 400 GeV ($|m_H - 115\ \text{GeV}| < 34\ \text{GeV}$ for each candidate Higgs boson)
  - medium mass region (MMR) from 400 GeV to 1200 GeV (ΔR between the jets within the dijet system is smaller than 1.5.)
  - Boosted region above 1200 GeV
- 4 b-tagged jets
  - bb pairs done using: $\chi^2 = \left(\frac{m_{H1} - 115\ \text{GeV}}{\sigma_H}\right)^2 + \left(\frac{m_{H2} - 115\ \text{GeV}}{\sigma_H}\right)^2$ $\quad X_{hh} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 124\,\text{GeV}}{0.1\, m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 115\,\text{GeV}}{0.1\, m_{2j}^{\text{subl}}}\right)^2}$
  - Signal Region for χ<1 (1.6)





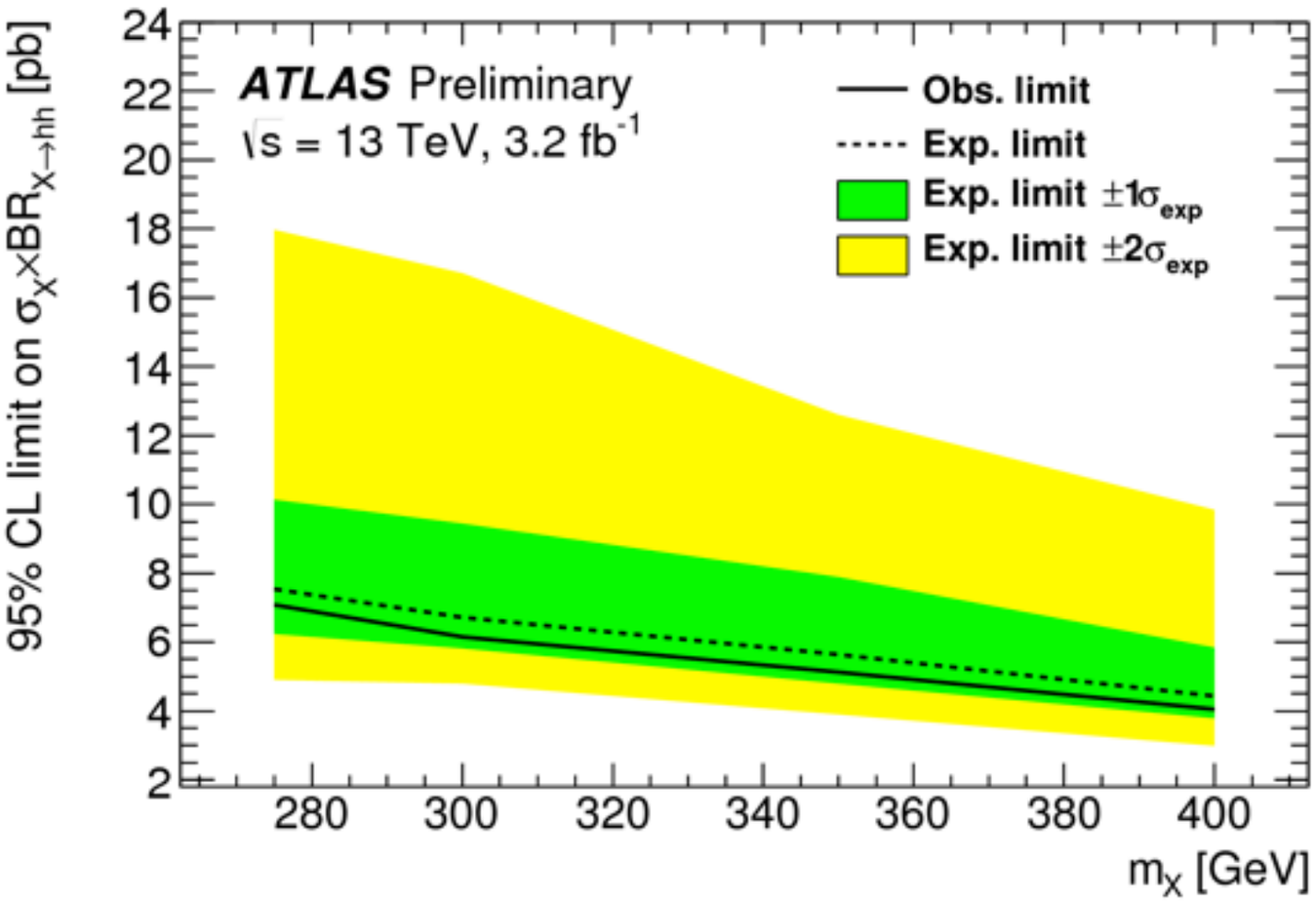
Search for H→hh→bbγγ

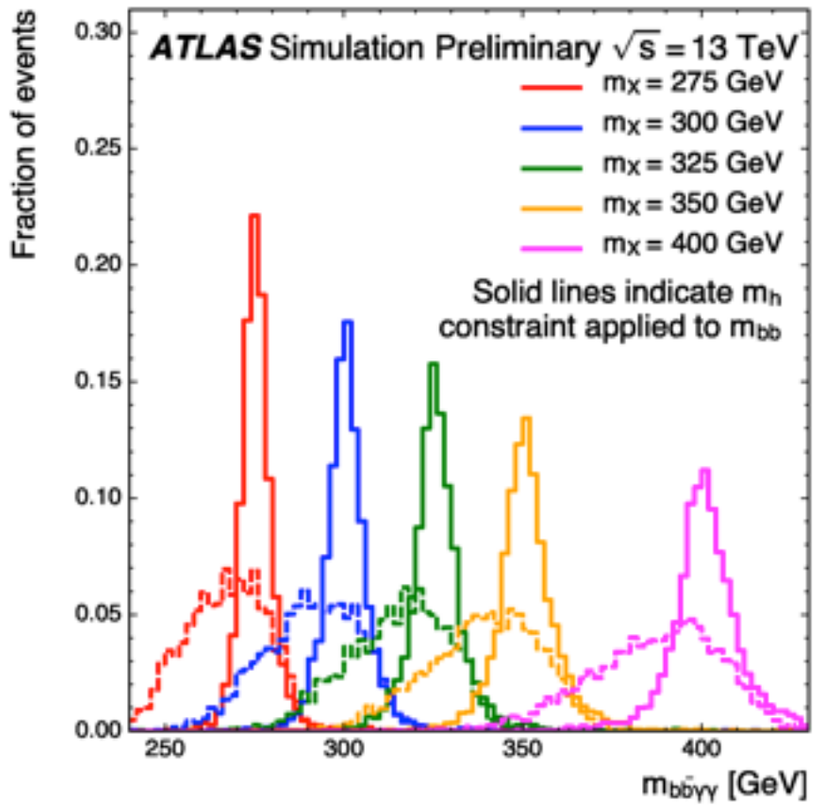
ATLAS: ATLAS-CONF-2016-004

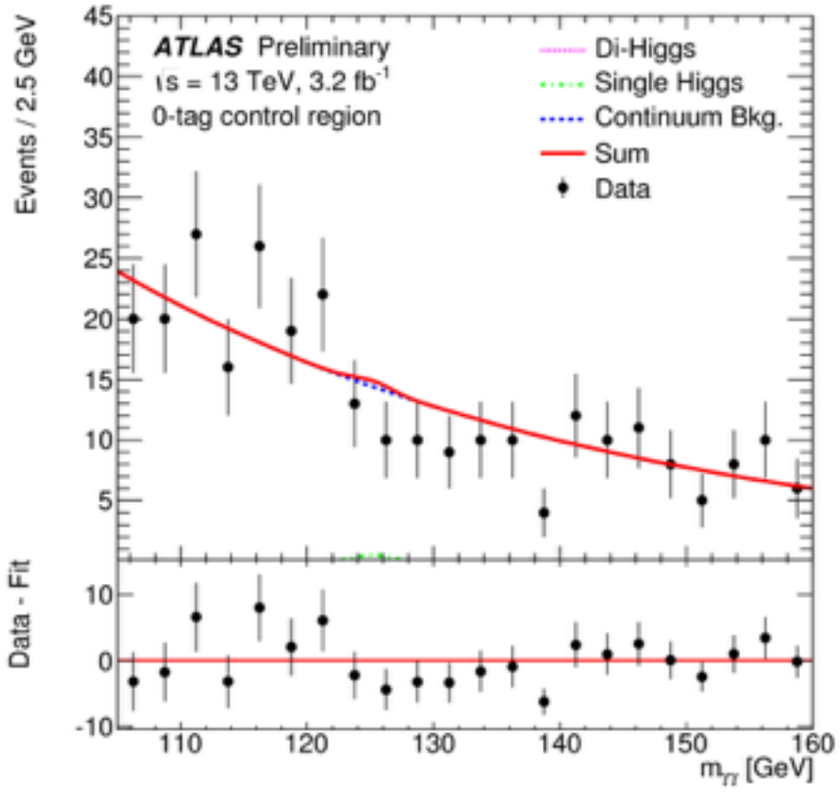
Mass range form 275 GeV to 400 GeV

Event Selection

- 2γ within 105 < mγγ < 160 GeV
- 2 central jets within 95 < mjj < 135 GeV
- 2 (0) b-tag as SR (CR) at 85% efficiency bb 4-momenta scaled by mh/mbb
- |mγγ – mh| < 2σ(mγγ)
- Mbbγγ within window of 95% signal efficiency





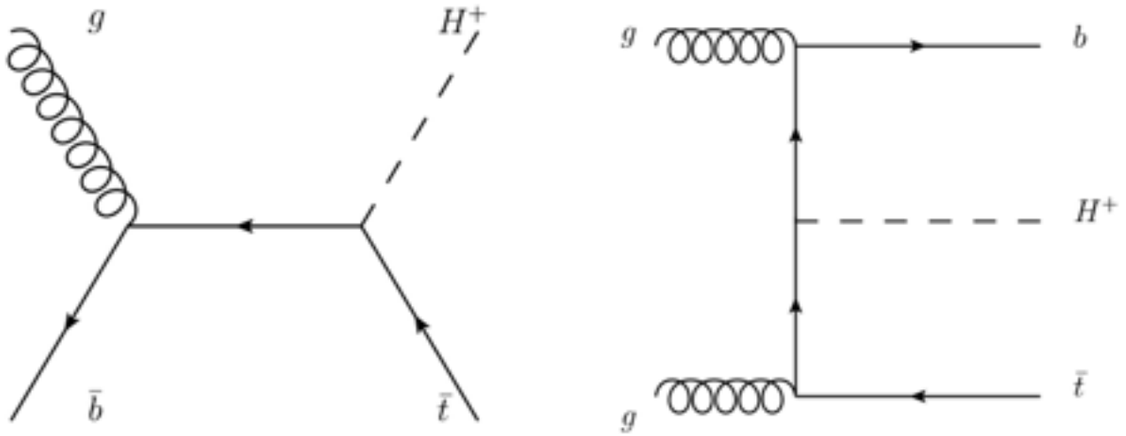


Charged Higgs

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

ATLAS:CERN-PH-EP-2016-056
CMS: JHEP 11 (2015) 018

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

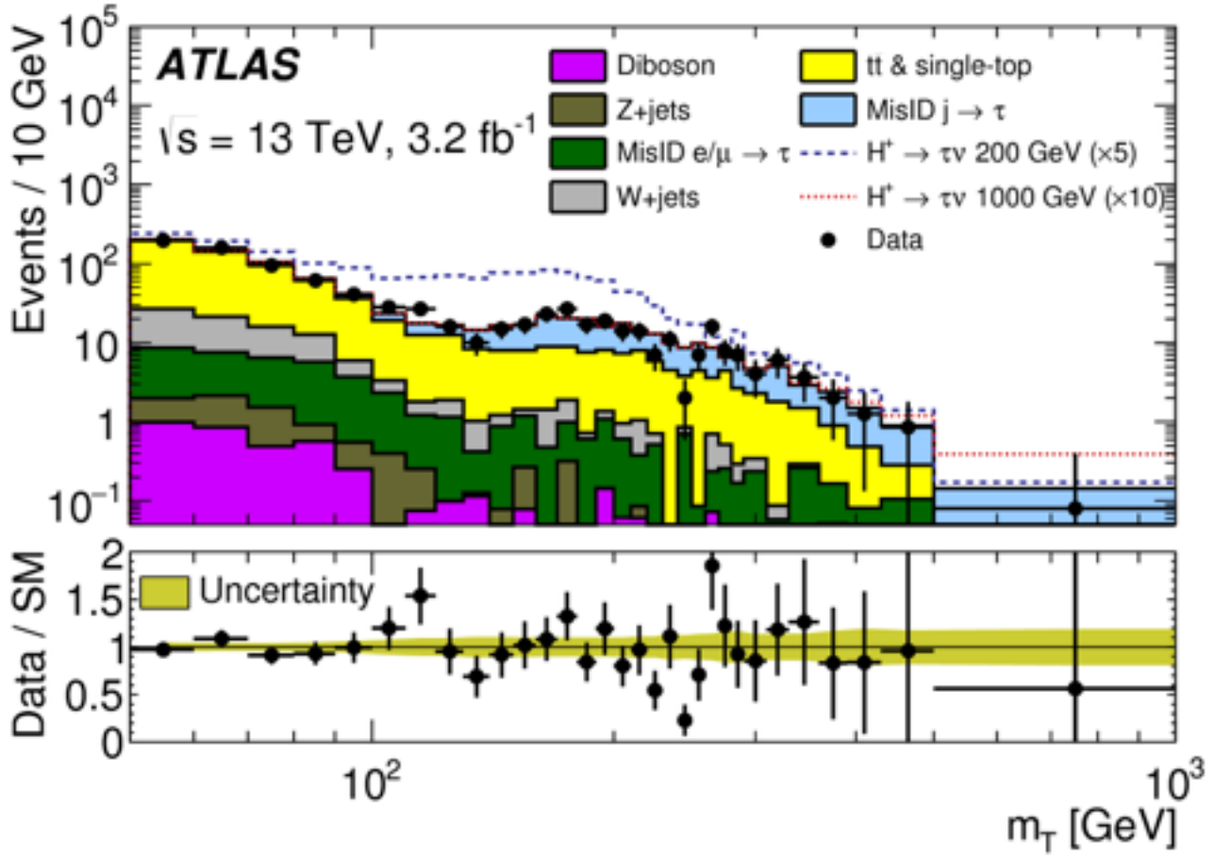


$$g\bar{b} \to [\bar{t}]\,[H^+] \to [q\bar{q}\bar{b}]\,[\tau^+_{\text{had-vis}} + \nu_\tau]$$

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

final discriminant variable

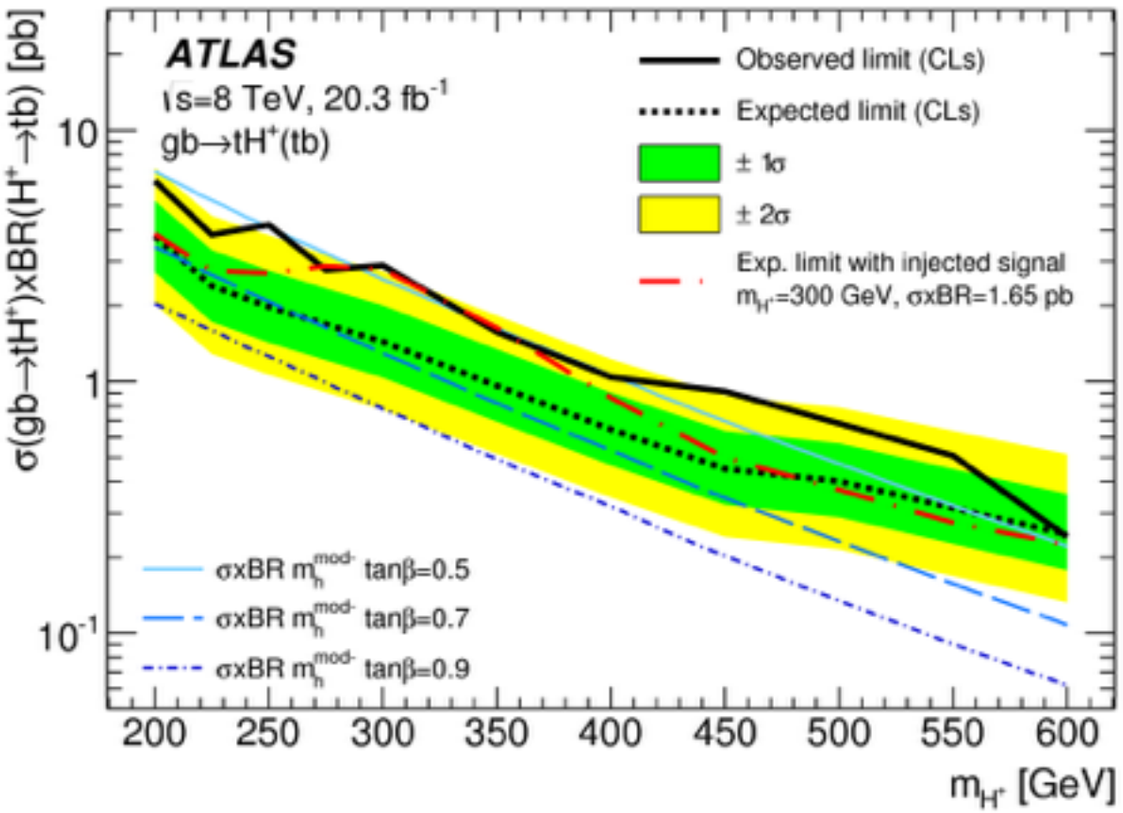
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau_{\mathrm{had-vis}},\mathrm{miss}})}$$

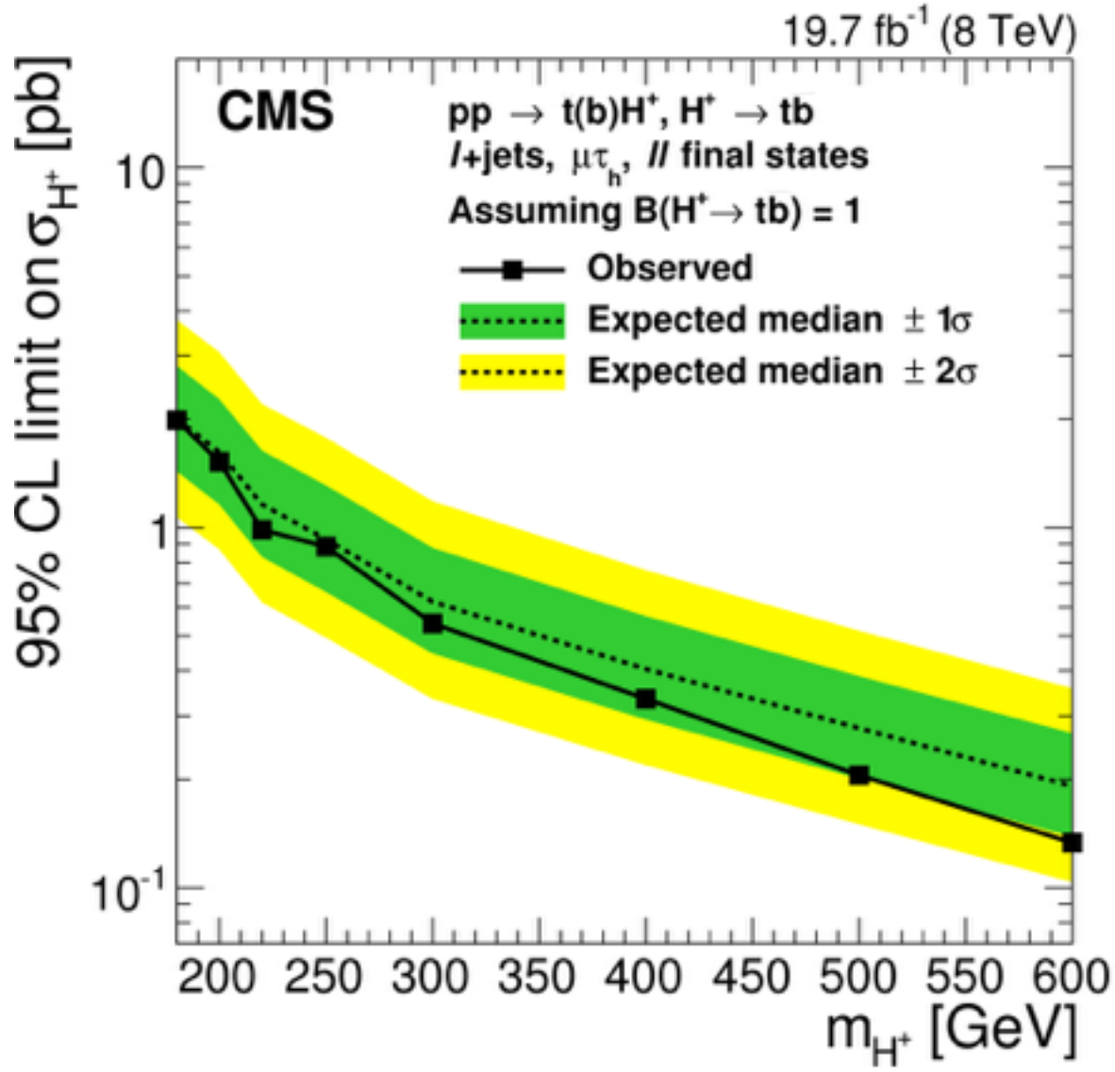


Search for $H^{\pm} \rightarrow tb$

ATLAS:CERN-PH-EP-2015-290
CMS: JHEP 11 (2015) 018

- Predicted in models with extended Higgs Sector:
  - $H^{\pm}$ dominantly produced in association with a top quark.
  - $H^{\pm} \rightarrow tb$ is a dominant decay mode for heavy $H^{\pm}$.
  - Coupling with quark cover low/high tanβ

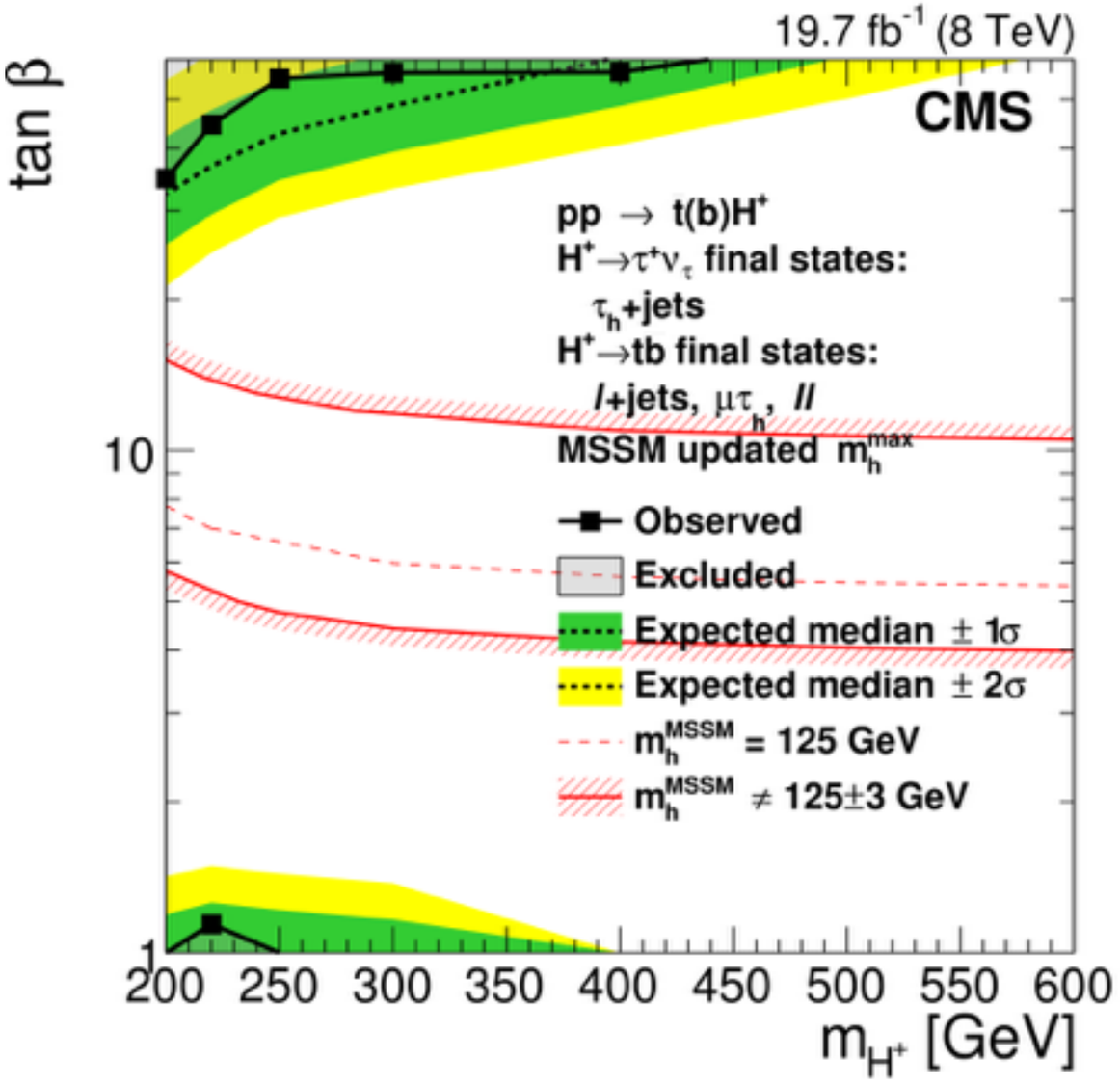


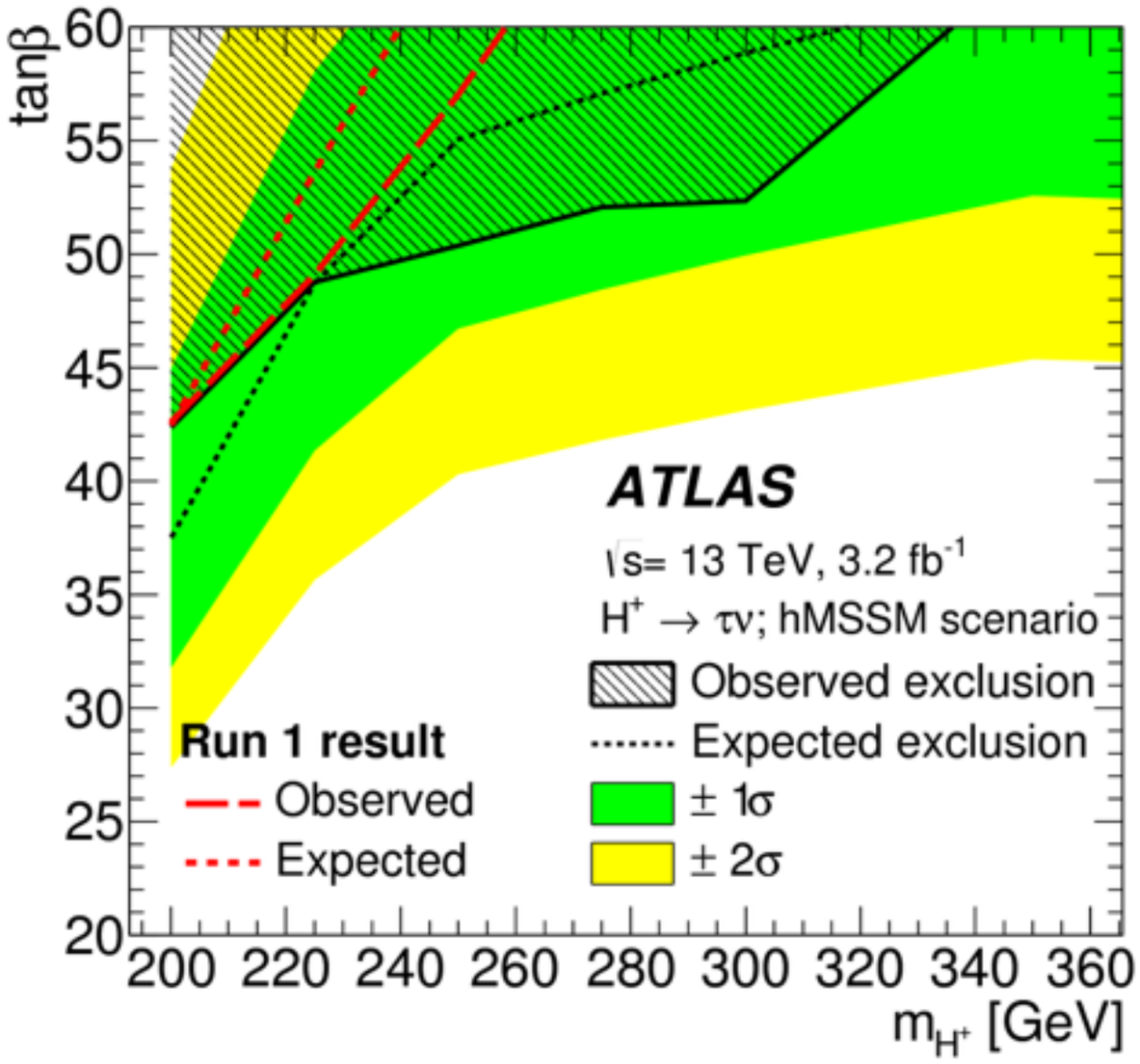


Search for $H^{\pm}$ – Results

ATLAS:CERN-PH-EP-2016-056

- Run1 $H^{\pm} \rightarrow \tau\nu$ and $H^{\pm} \rightarrow \tau b$ combination able to exclude low and high tan b region in $mH^{\pm}$ Vs tan B plane
- First Run2 result in $H^{\pm} \rightarrow \tau\nu$ already extend the Run1 excluded region

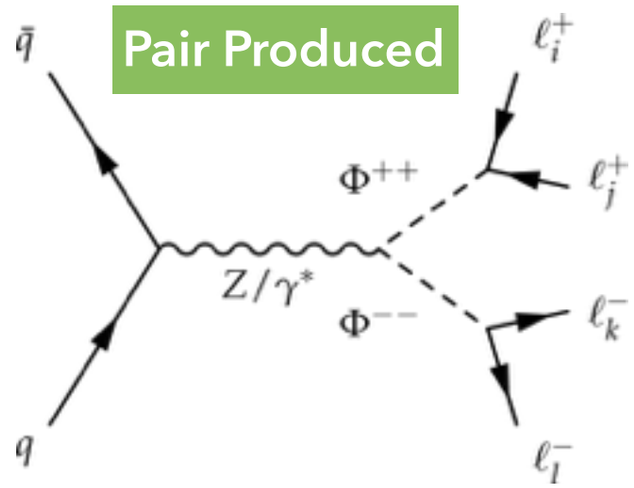


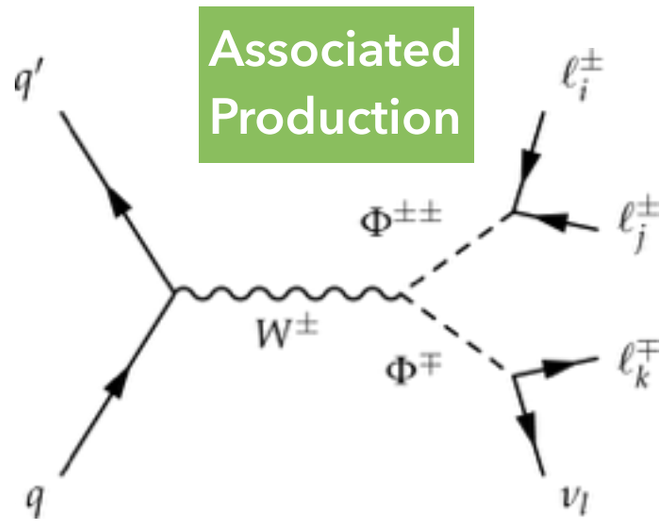


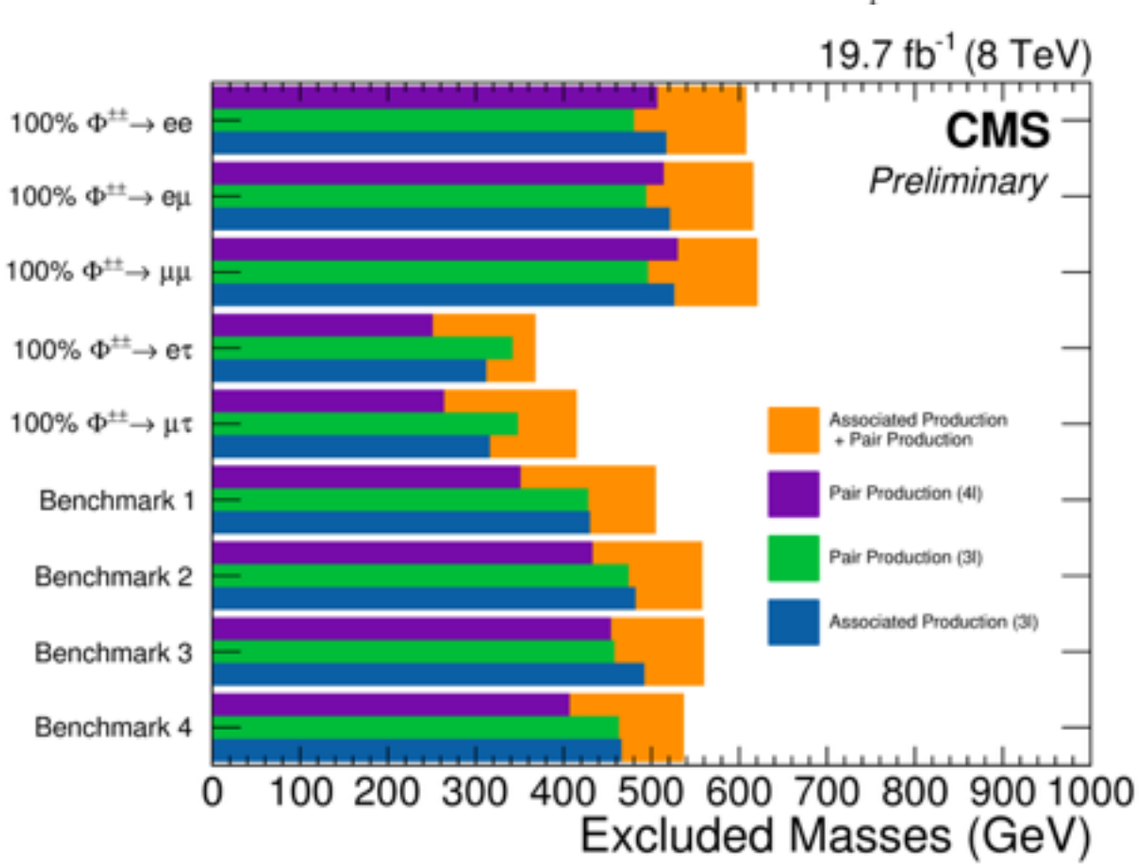
Higgs Triplets: Search for $H^{\pm\pm}$

CMS-PAS-HIG-14-039

- Models that introduce a triplet predict a new pair of bosons: $H^{\pm\pm}$
- Model that attempt to expand the SM and accommodate neutrino masses







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

Benchmark	AP [GeV]	PP [GeV]			Combined [GeV]
	3ℓ	3ℓ	4ℓ	3ℓ+4ℓ	
100% ee	517	480	507	550	608
100% $e\mu$	521	494	514	569	616
100% $\mu\mu$	526	496	530	576	621
100% $e\tau$	312	342	251	353	368
100% $\mu\tau$	316	348	264	381	415
BP1	430	428	351	456	505
BP2	482	474	433	513	558
BP3	492	458	454	512	560
BP4	466	463	407	500	537

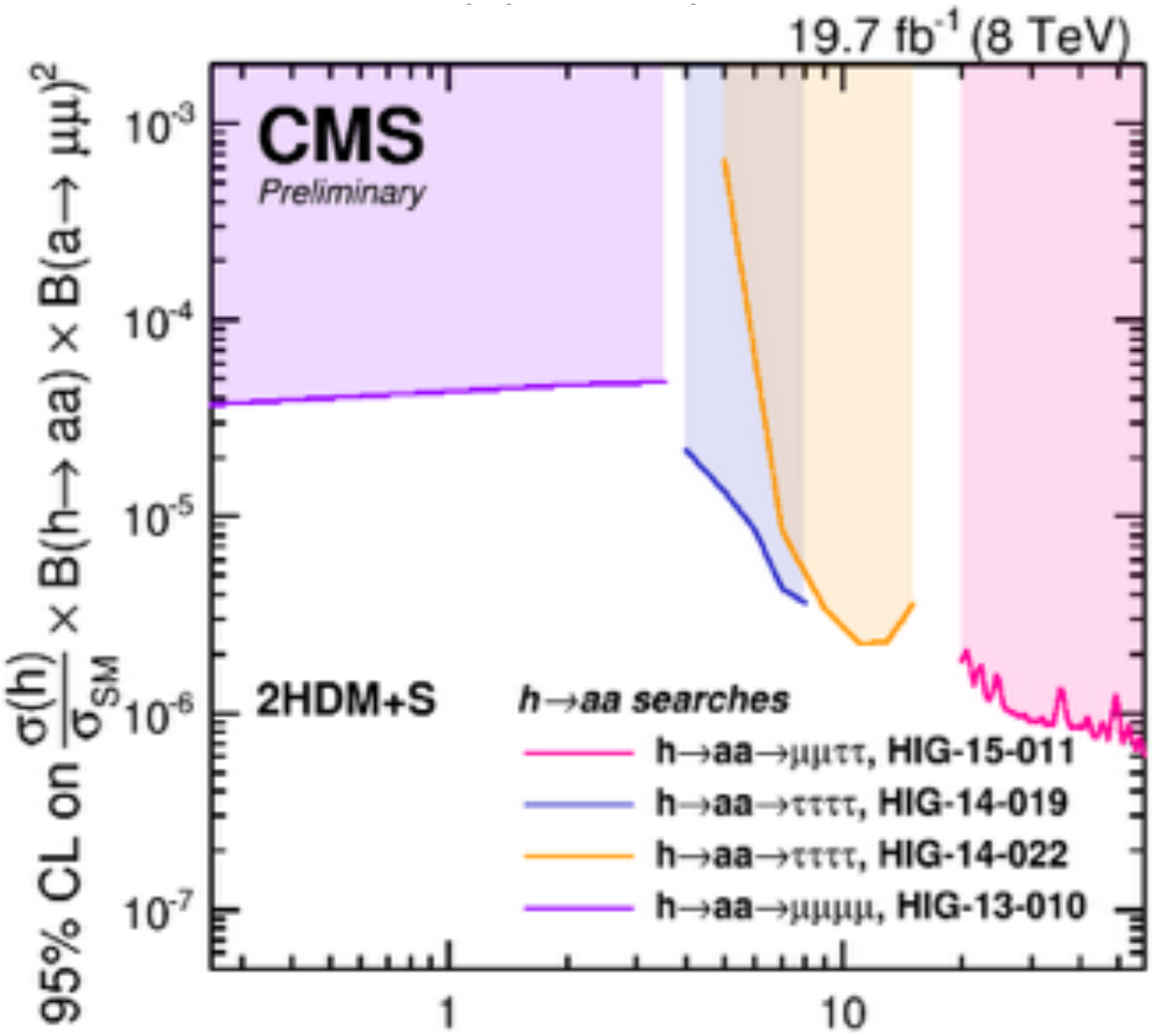
What if light Scalars?

Search for h(125)→2a

CMS: CMS-PAS-HIG-15-011

- In a 2HDM+S model (NMSSM), there are 2 singlet states:
  - CP-odd *scalar* a
  - CP-evens

- BR(h→BSM) < 0.34, so the decay to 2a can be sizeable.



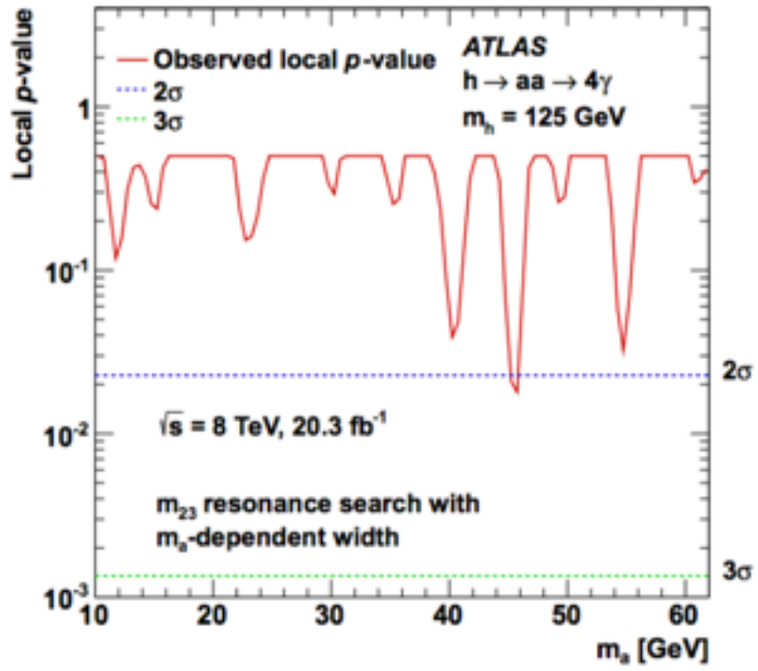
$$\frac{\Gamma(a \to \mu\mu)}{\Gamma(a \to \tau\tau)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_a)^2}}.$$

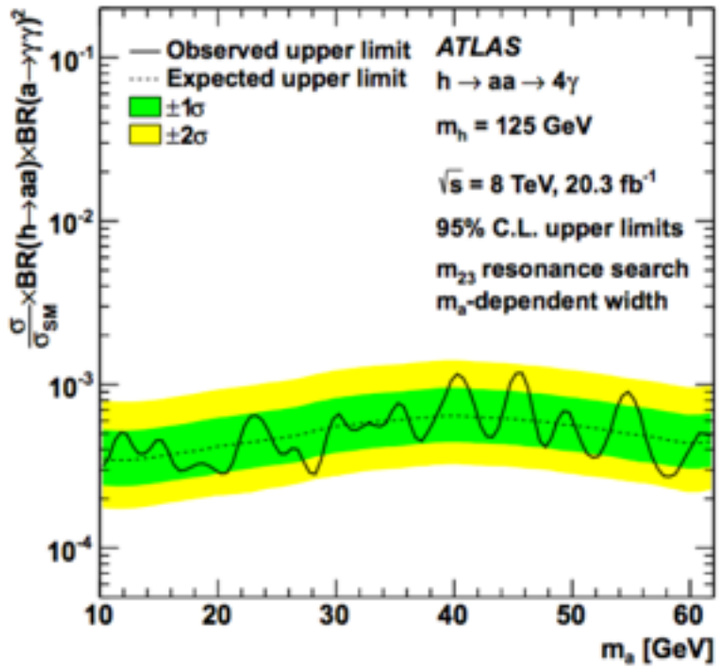
- 8TeV analysis:
  - h→2a→2b2μ (CMS-PAS-HIG-14-041)
  - h→2a→4μ (CMS:Phys. Lett. B 752 (2016) 221)
  - h→2a→2μ2τ (CMS-PAS-HIG-15-011, ATLAS:Phys. Rev. D92 (2015) 052002)
  - h→2a→4τ (CMS-PAS-HIG-14-022, CMS:JHEP 01 (2016) 079)

Search for h/H→2a→γγγγ

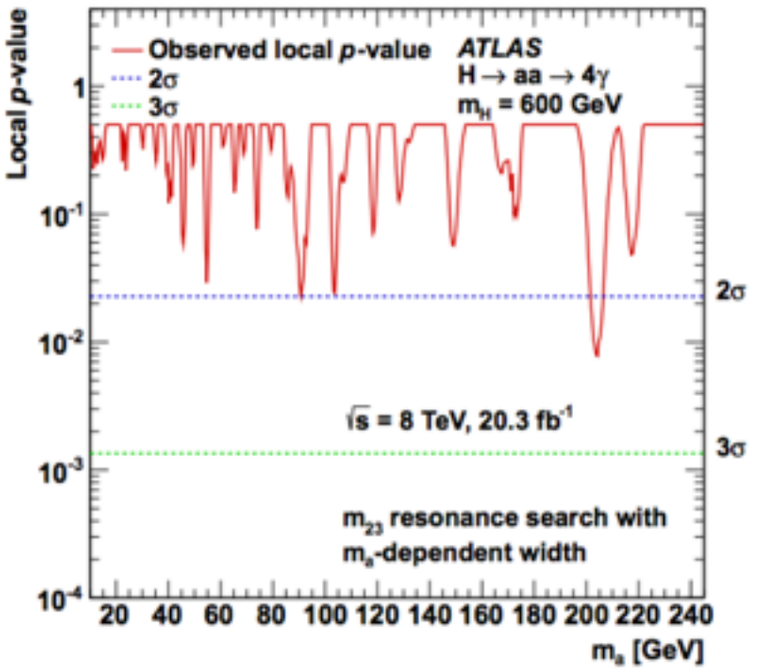
ATLAS: :CERN-PH-EP-2015-187

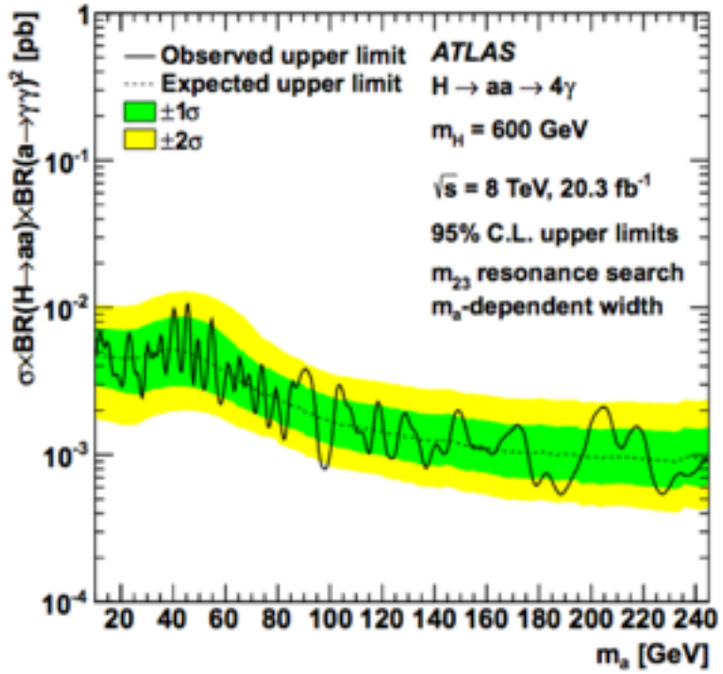
- In a 2HDM+S model (NMSSM), there are 2 singlet states:
  - CP-odd *scalar* a
  - CP-evens





Observed (expected) 95% C.L. upper limits				
m_H [GeV]	m_a [GeV]			
	$\sigma_H \times \mathrm{BR}(H \to aa) \times \mathrm{BR}(a \to \gamma\gamma)^2$ [fb]			
	20	50	100	140
300	48 $\left(60^{+13}_{-10}\right)$	33 $\left(40^{+9}_{-8}\right)$	29 $\left(35^{+9}_{-7}\right)$	28 $\left(34^{+8}_{-6}\right)$
	50	100	200	290
600	31 $\left(38^{+10}_{-7}\right)$	27 $\left(34^{+7}_{-7}\right)$	25 $\left(31^{+7}_{-6}\right)$	25 $\left(31^{+7}_{-6}\right)$
	50	100	200	440
900	36 $\left(44^{+11}_{-8}\right)$	27 $\left(33^{+7}_{-6}\right)$	26 $\left(33^{+7}_{-6}\right)$	26 $\left(32^{+7}_{-5}\right)$





Conclusions

Summary

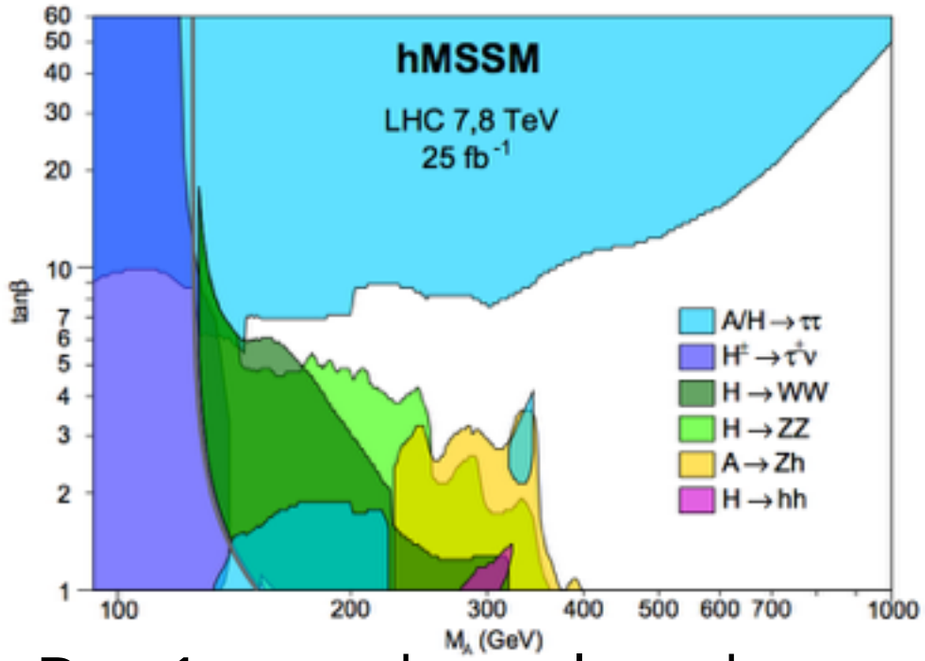
- Discover of a 125 GeV starting point for Higgs BSM searches
- No evidence of BSM in Run1 searches for extended Higgs sector
  - Direct searches and constraint from h_{125} couplings already exclude a part of m_A tanβ space
- Run2 Searches in good shape
  - Results with 2015 Dataset already competitive, in some cases, with Run1 results
- **2016 will be an exiting year for BSM Searches!!**

Discussion

PROJECTIONS

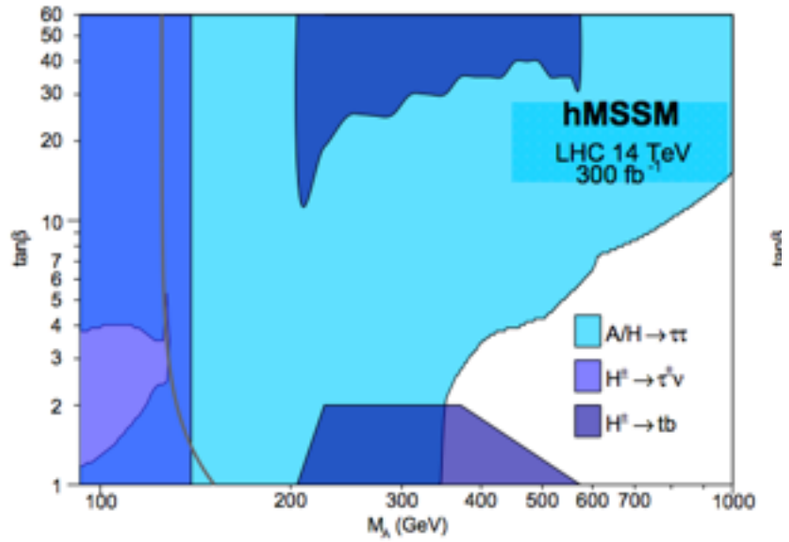
1502.05653

Run 1



Run1 searches already covering the majority of the phase space for mA<2mtop

14 TeV - 300 fb-1

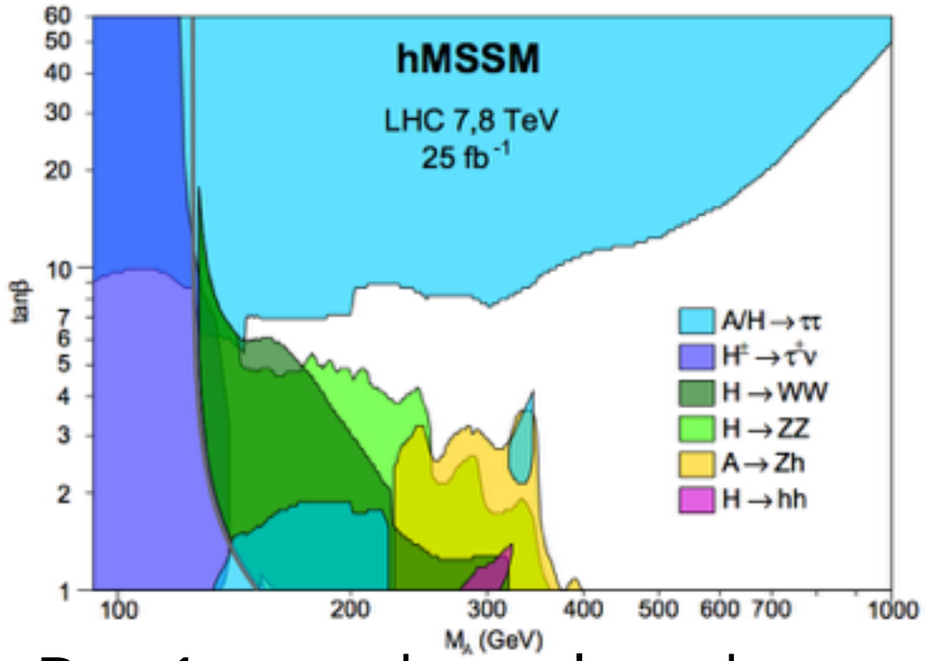


A/H->ττ will cover alone good part of the phase space

PROJECTIONS

1502.05653

Run 1



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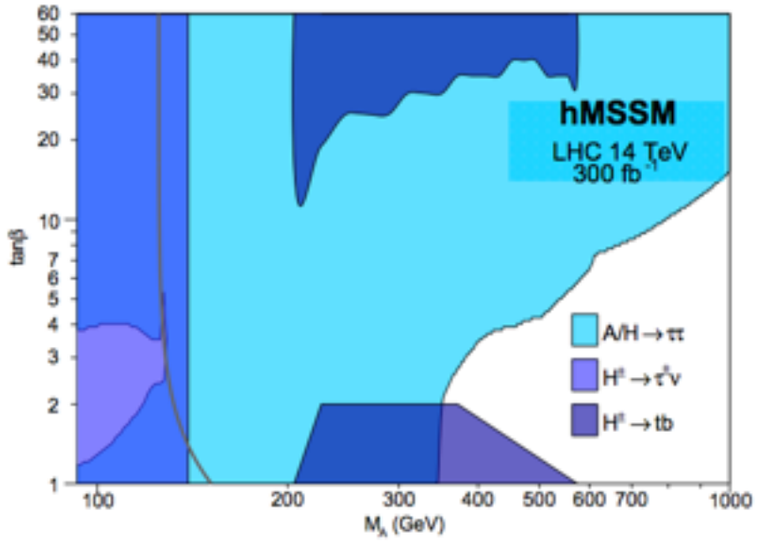
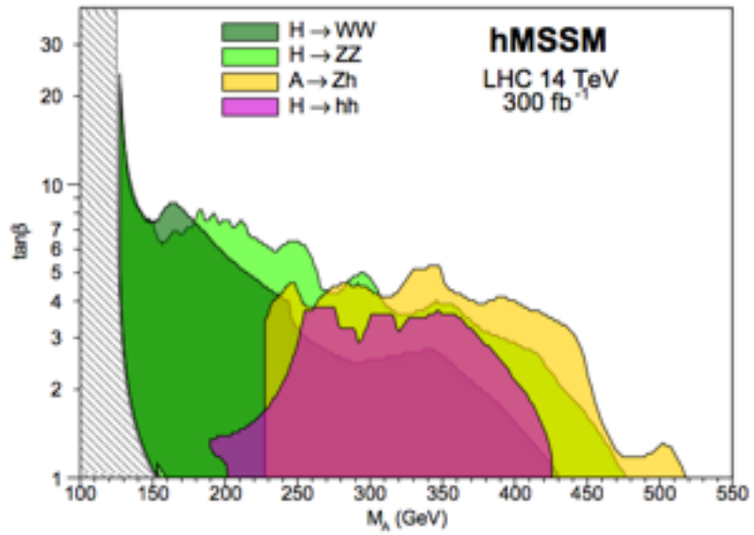


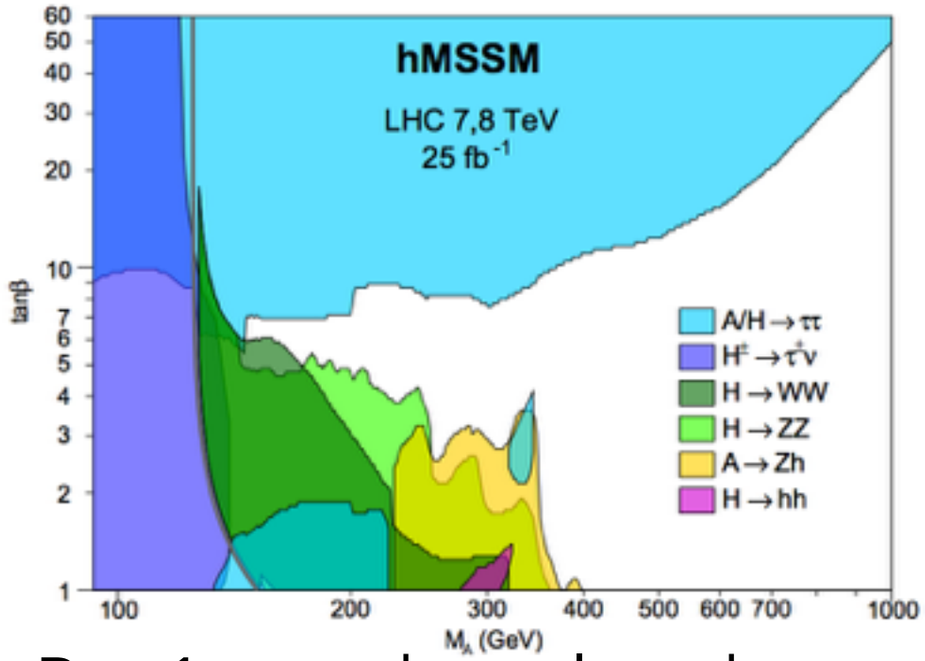


A/H->ττ will cover alone good part of the phase space

PROJECTIONS

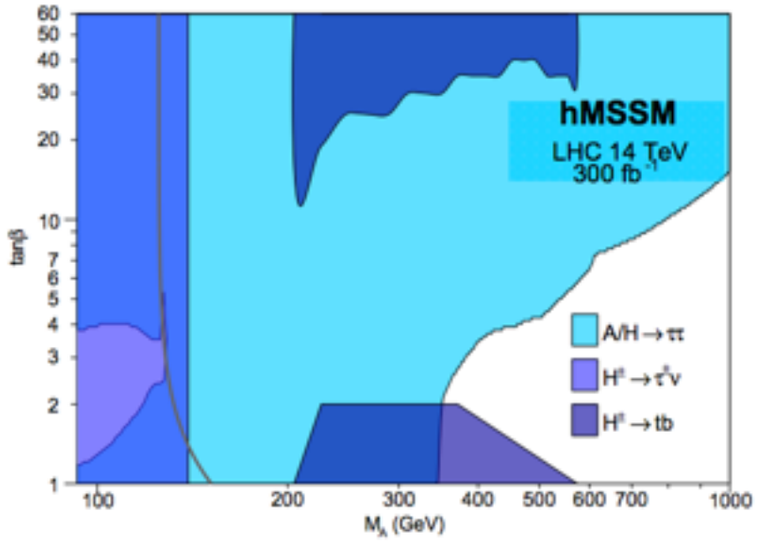
1502.05653

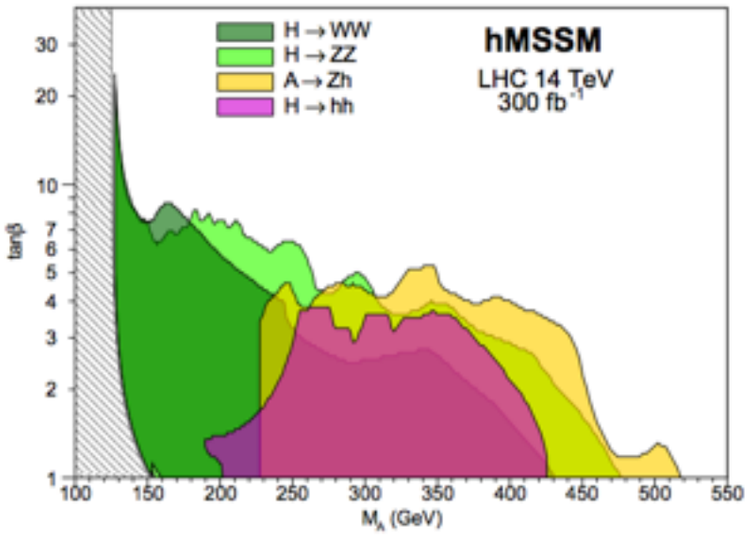
Run 1



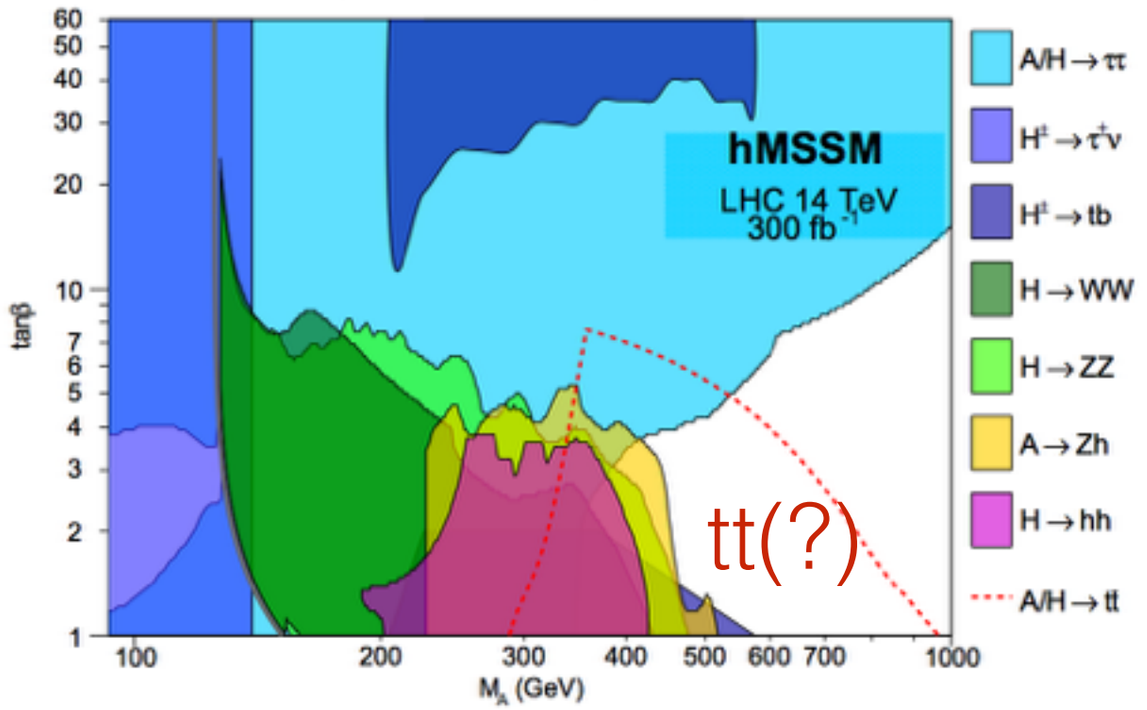
Run1 searches already covering the majority of the phase space for mA<2mtop

14 TeV - 300 fb-1





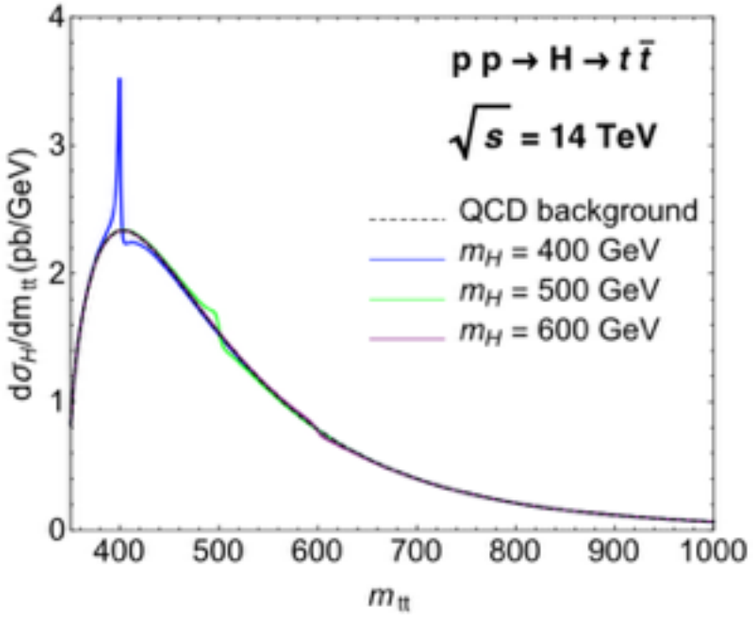
A/H->ττ will cover alone good part of the phase space

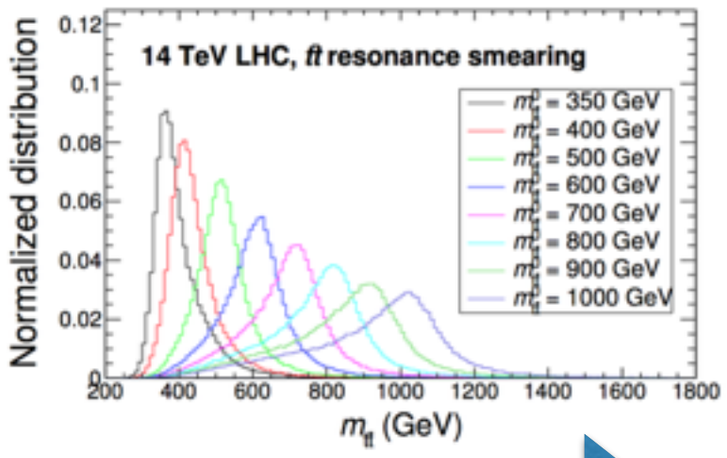


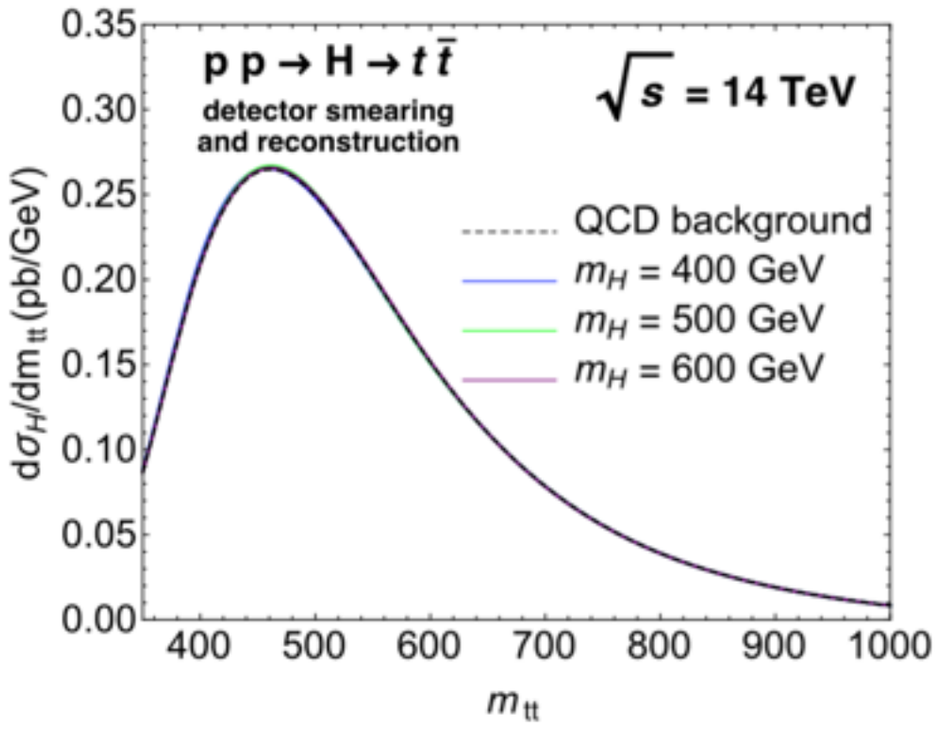
A/H->TTBAR?

1504.04630v1

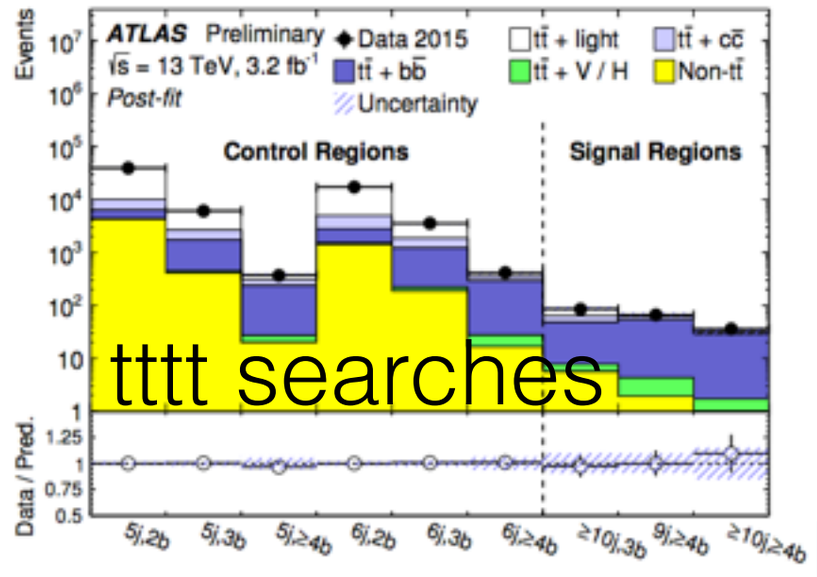
- The ATLAS and CMS performed searches for Spin1 heavy states decaying into $t\bar{t}$ pairs
- More complicated Higgs situation: Interference with QCD tt production.







- Any chance?
- Other production mechanisms?
  - tttt (mH=700 GeV, tanβ=1 -> 5 fb)?

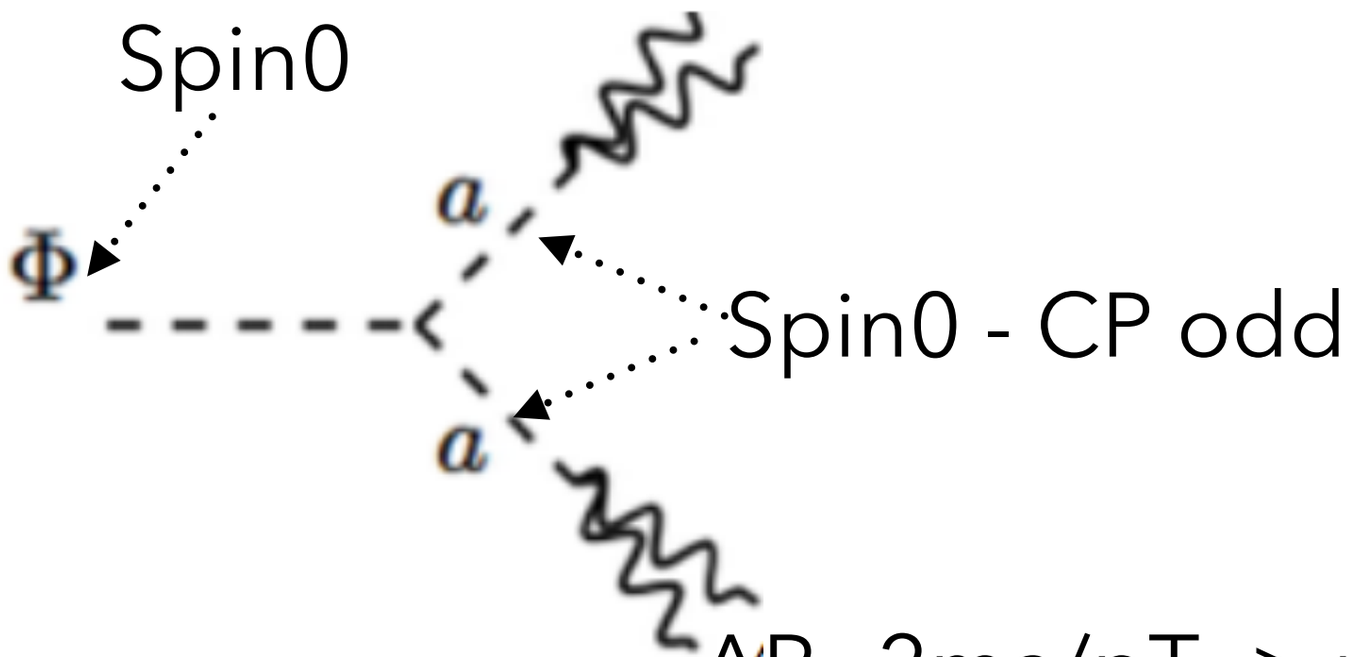


tttt searches

X(750 GEV) IN NMSSM

1602.07691v2

1602.00949



neutral spin 0 in NMSSM:
3 CP even h1,h2,h3, 2 CP odd A a

- Can we (ATLAS/CMS) distinguish them from single photons?
- Run1 ATLAS H->aa->γγγγ:
  - Limits for 10<ma<440 GeV, mH<900 GeV
- Other channels?
  - X(750)->aa->4μ?
  - a->2e?

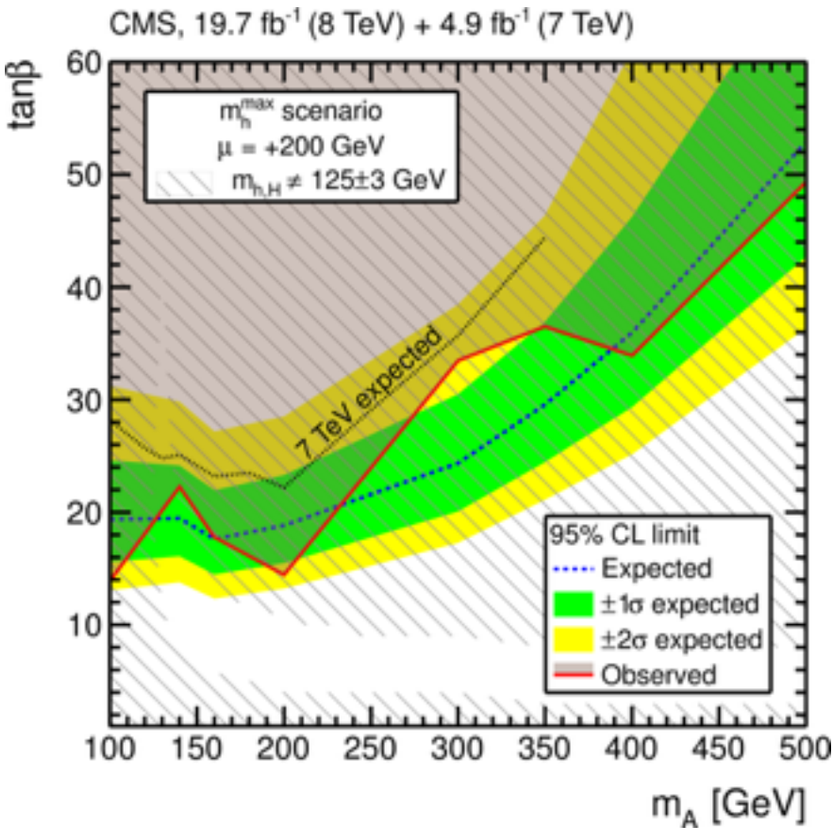
Backup

Search for H/A→bb- Results

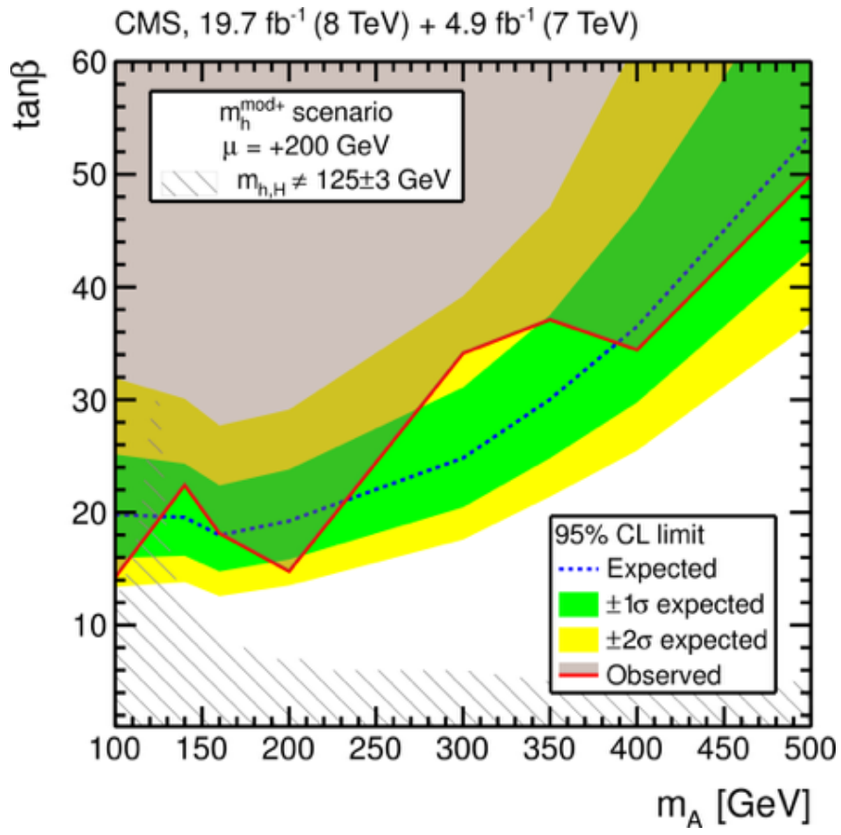
CMS: J. High Energy Phys. 11 (2015) 071

- Expected and observed upper limits at 95% CL for the MSSM parameter **tanβ Vs m_A** in the m_h^{max},m_h^{mod+}, m_h^{mod-}, light-stop, and light-stau benchmark scenarios with μ=μ=+200 GeV

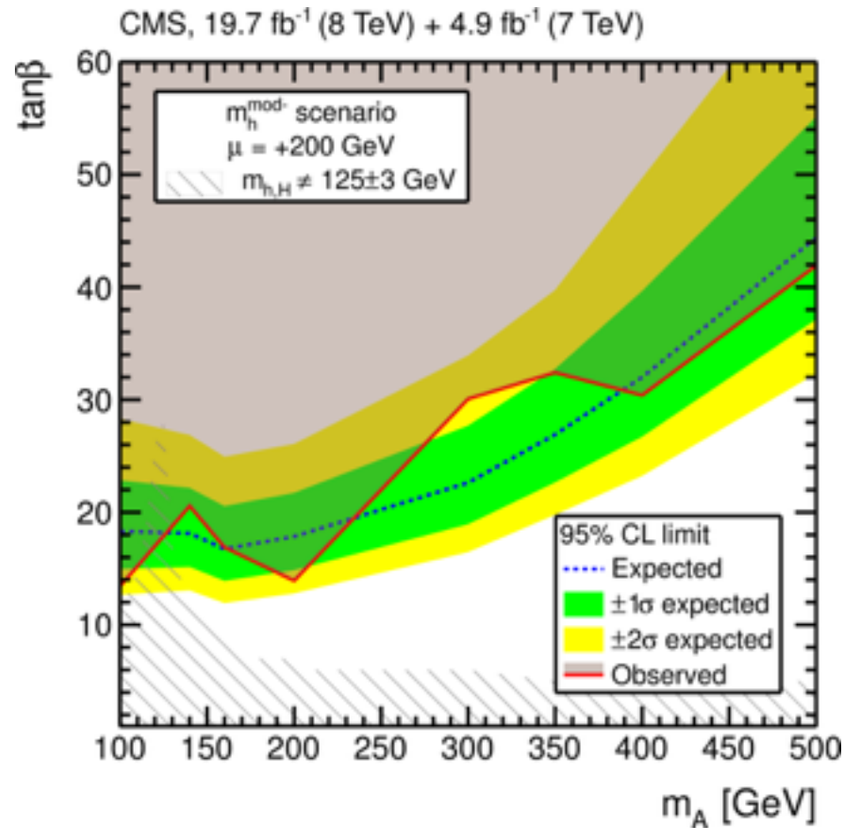
m_h^{max}



m_h^{mod+}



m_h^{mod--}

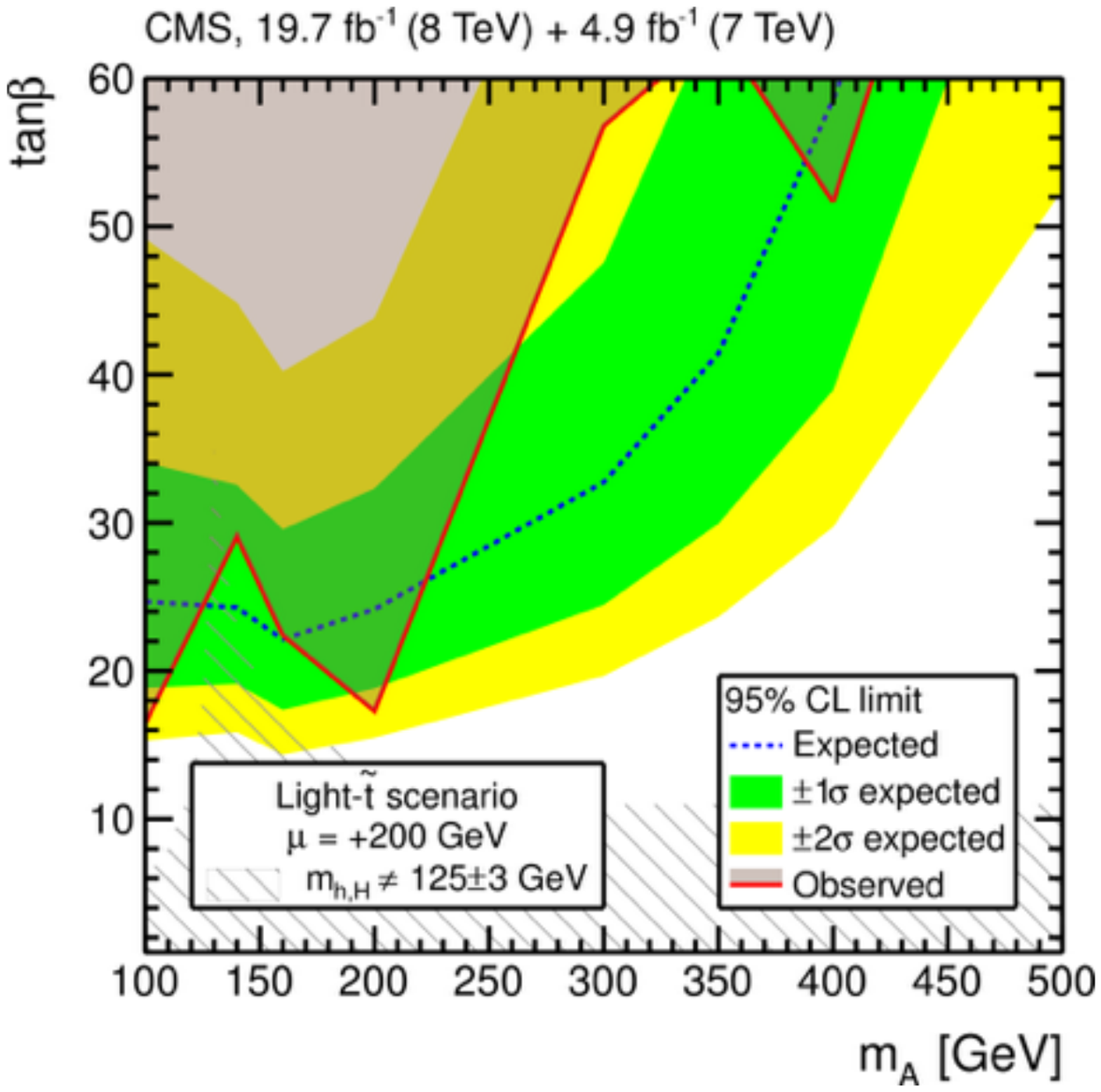


MSSM: Search for H/A→bb

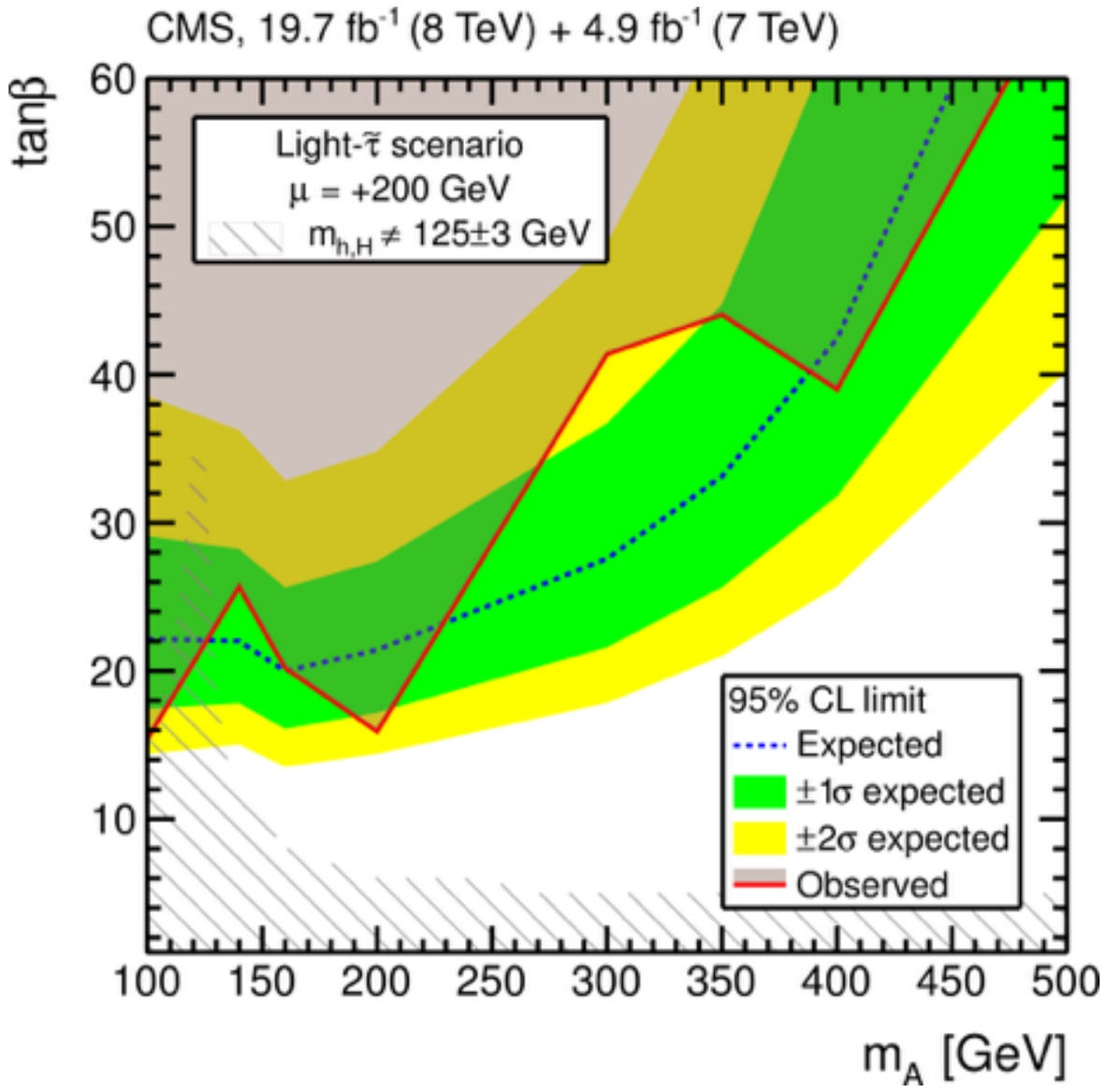
CMS: J. High Energy Phys. 11 (2015) 071

- Expected and observed upper limits at 95% CL for the MSSM parameter **tanβ Vs m_A** in the m_h^{max},m_h^{mod+}, m_h^{mod-}, light-stop, and light-stau benchmark scenarios with μ=μ=+200 GeV

light-stop



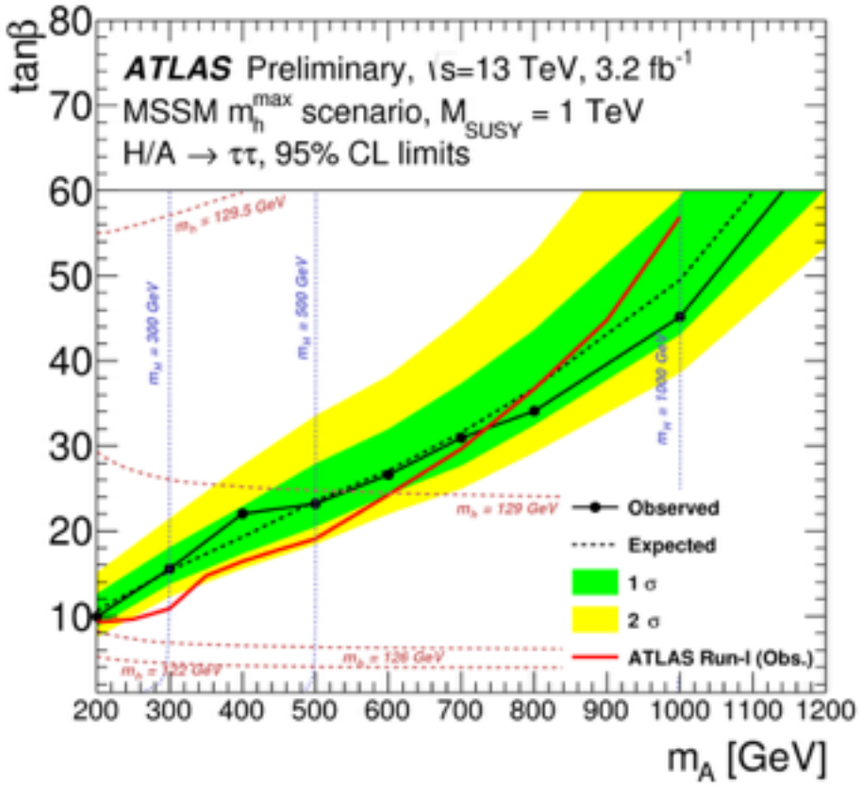
light-stau



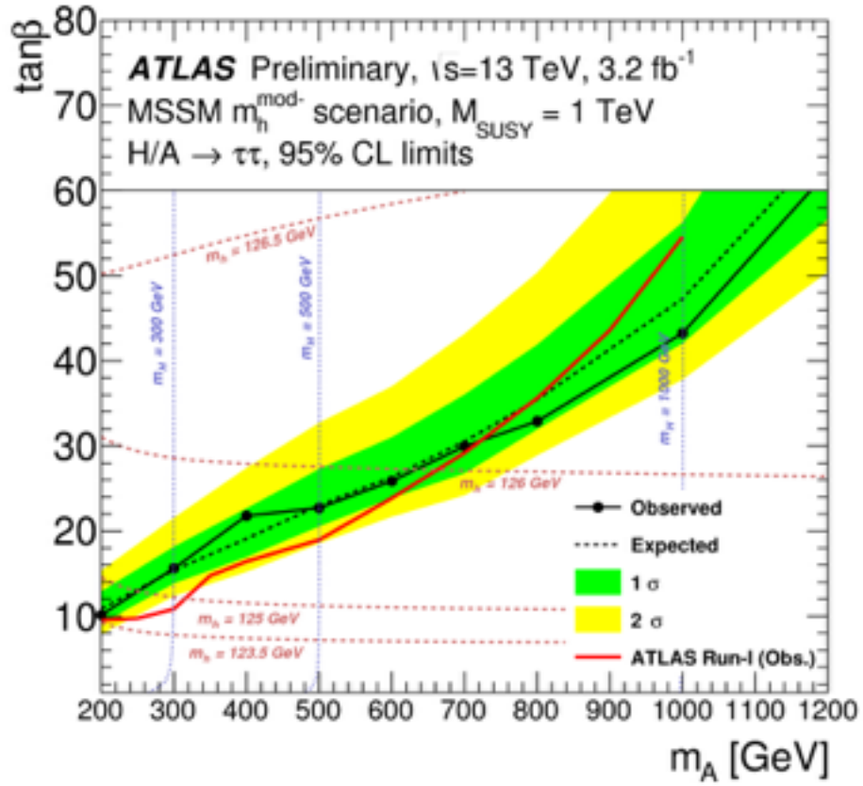
Search for H/A - Results

CMS: J. High Energy Phys. 11 (2015) 071

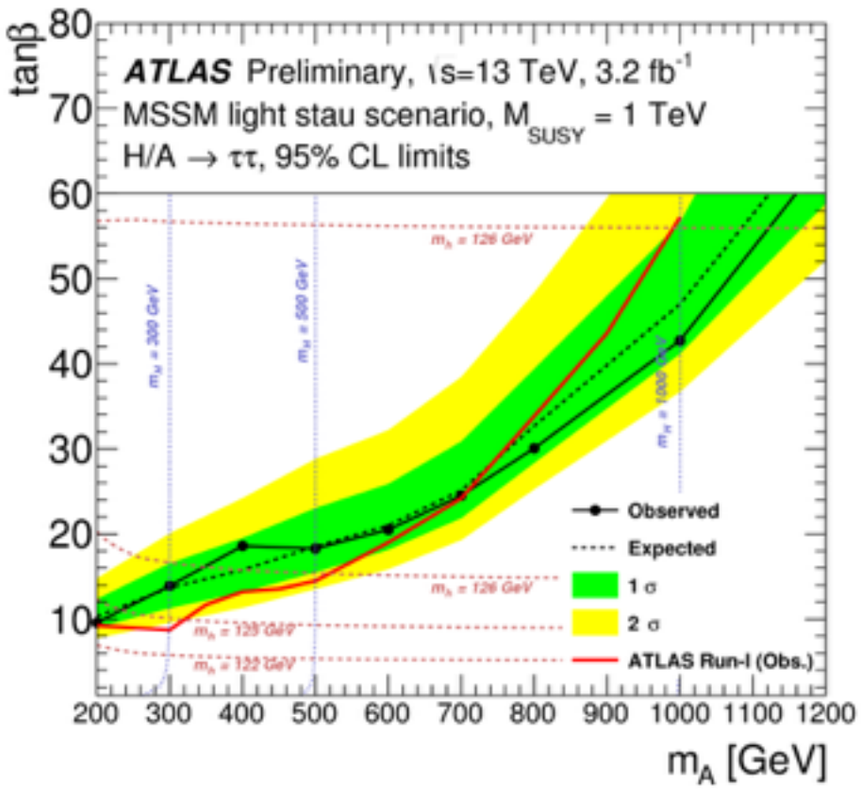
m_h^{max}



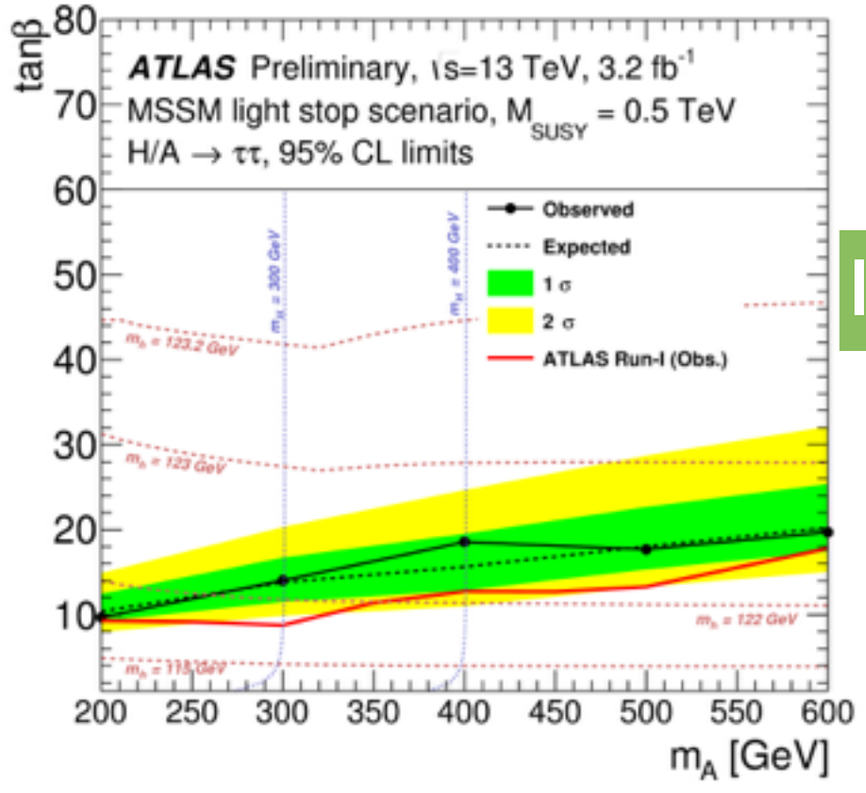
m_h^{mod--}



light Stau



light Stop



Search for H→ZZ→llνν

ATLAS: ATLAS-CONF-2016-012
CMS: CMS-PAS-HIG-16-001

Searching for an additional scalar boson, as predicted in EWS/2HDM.

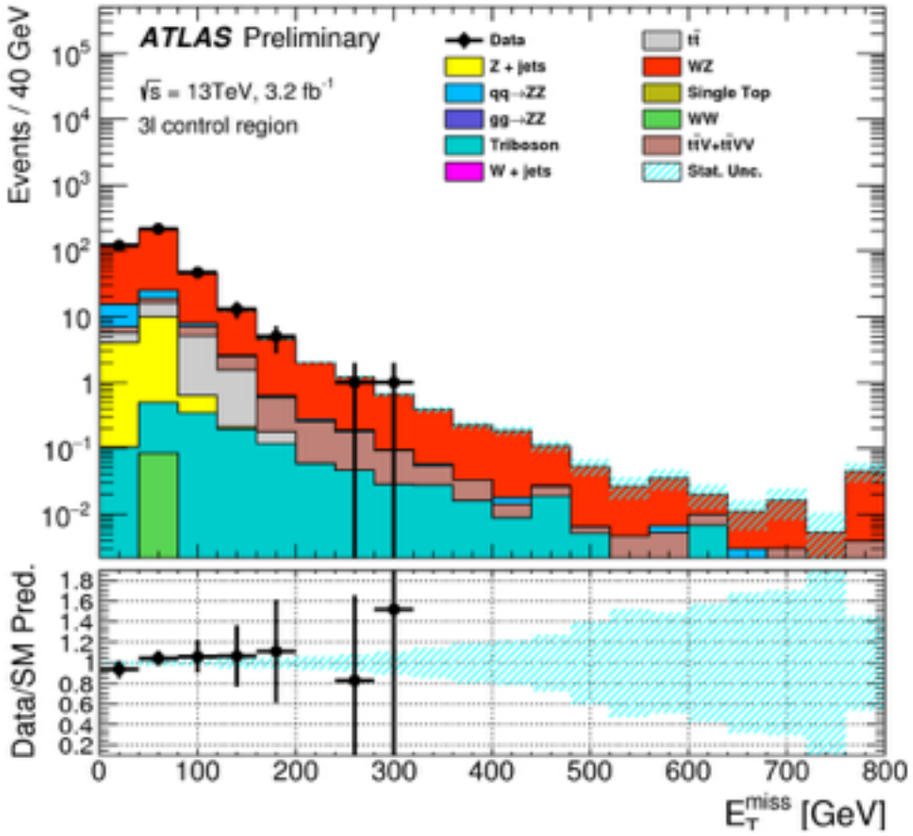
The search is for a narrow resonance of mH = 300-1000 GeV (ATLAS) or 200-1500 GeV (CMS)

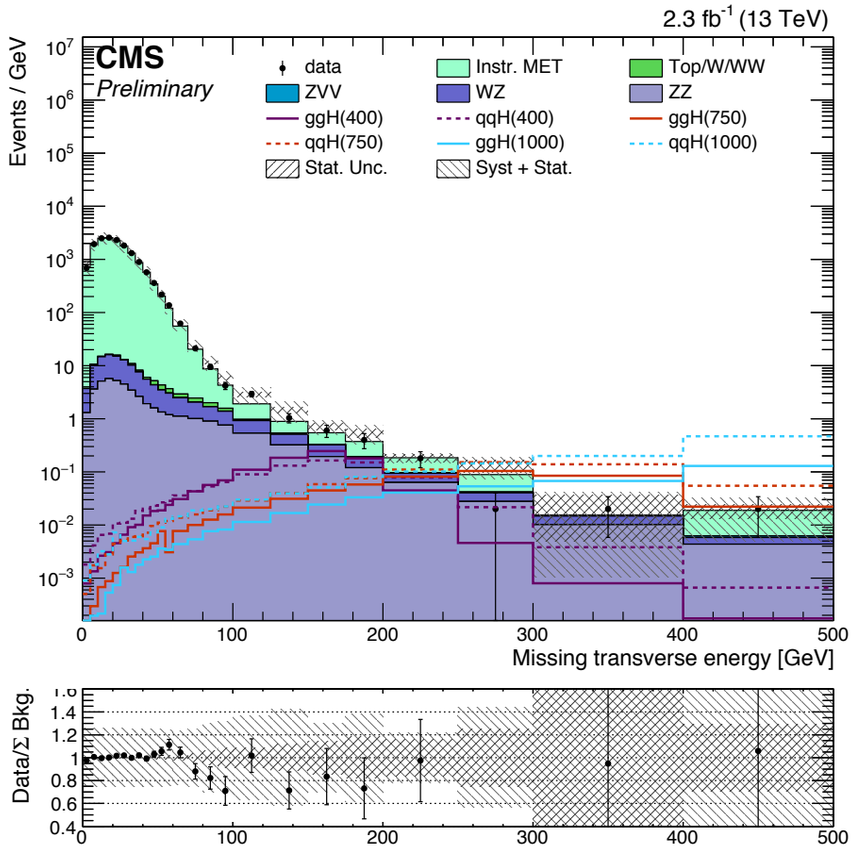
- search is for2 leptons (e or μ) and high E_T^{miss}
- **Final Discriminant:**

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

Background

- **ZZ/WZ**: From simulation,WZ scaled using data-driven methods (ATLAS)
- **Others**: Predicted using data-driven methods.



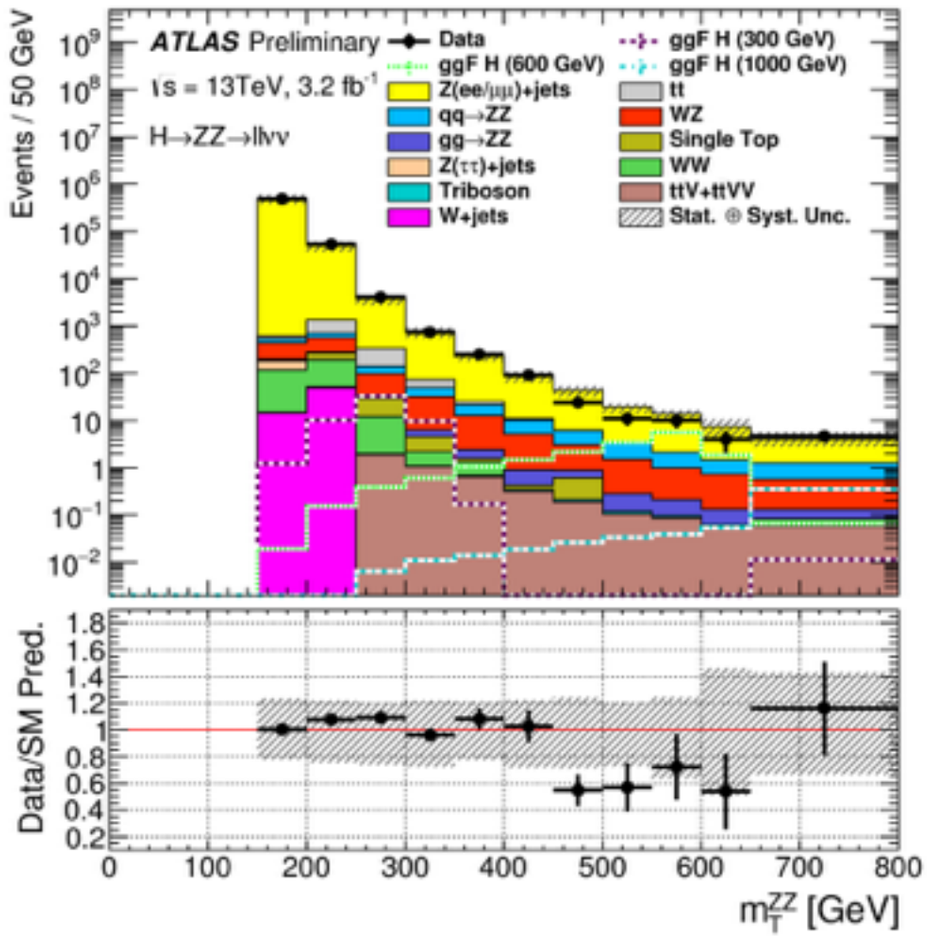


Search for H→ZZ→llνν

ATLAS: ATLAS-CONF-2016-012
CMS: CMS-PAS-HIG-16-001

ATLAS Selections

- 2 same flavor, opposite sign charge leptons
- $76<m_{ll}<106$ GeV and $E_T^{miss}>120$ GeV
- $\Delta R_{ll} < 1.8$ and $\Delta\varphi(Z, E_T^{miss}) > 2.7$
- Fractional p_T difference > 0.4
- $\Delta\varphi$(jet (p_T > 100 GeV), E_T^{miss}) > 0.4
- $Z_{PT}/M_T < 0.7$ and no b-jet

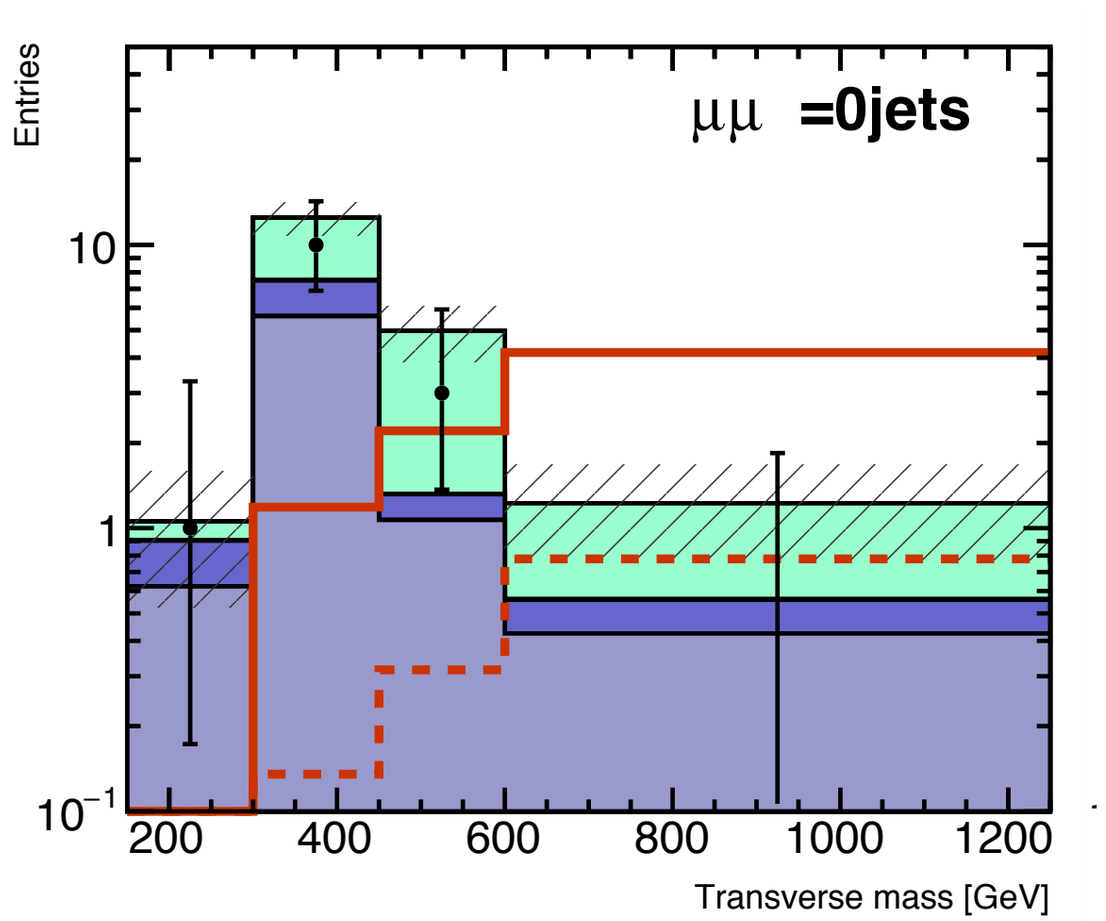


CMS Selections

- 2 same flavor, opposite sign charge leptons
- E_T^{miss} > 125 GeV and $\Delta\varphi$(nearest jet, E_T^{miss}) > 0.5
- No b-tagged jets

Signal Regions

- **VBF: ≥ 2** jets with $|\Delta\eta| > 4$ and m > 500 GeV
- **≥ 1 jets:** at least 1 jet, fails VBF
- **= 0 jets:** No jets.



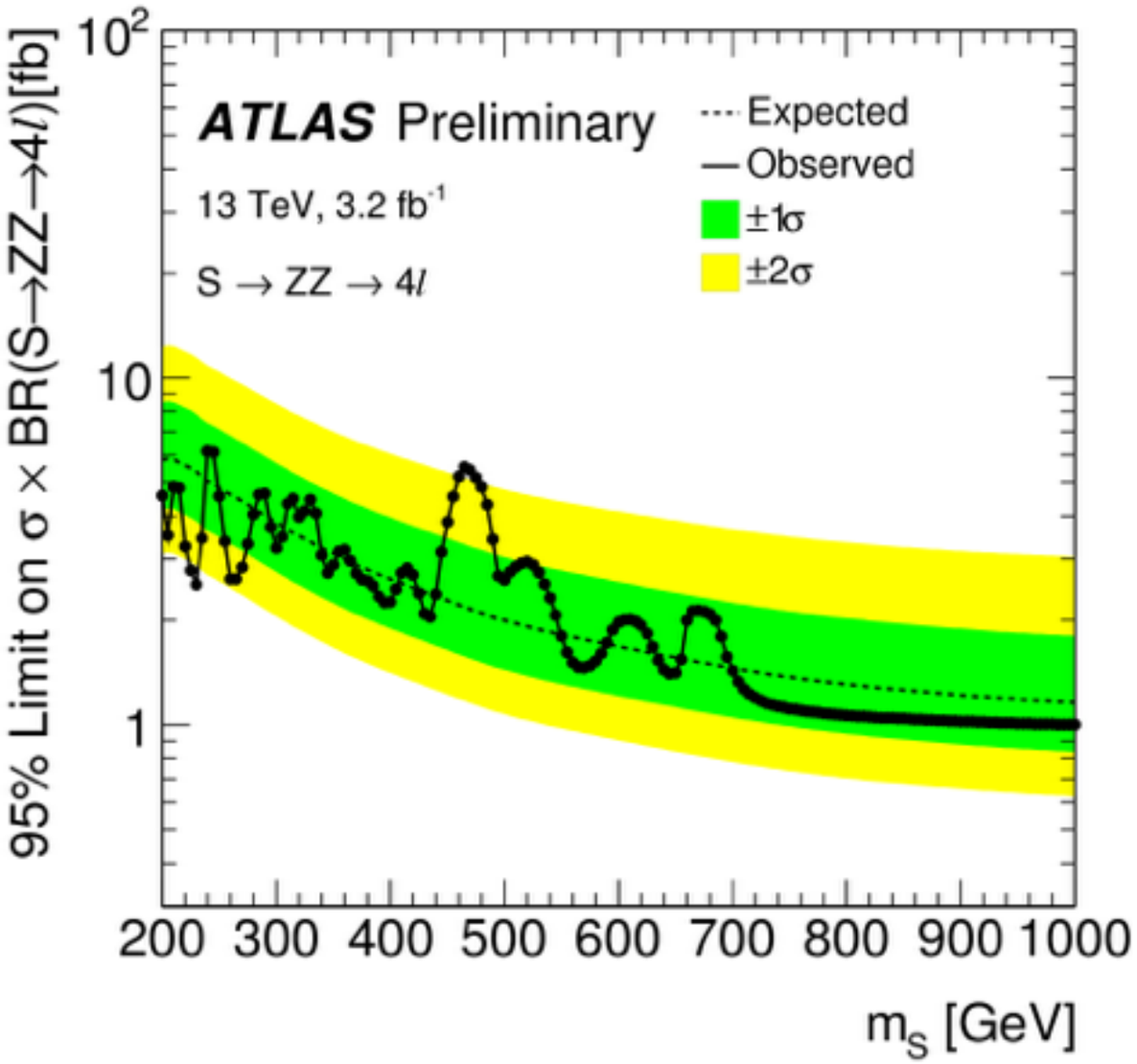
Search for H→ZZ→4l

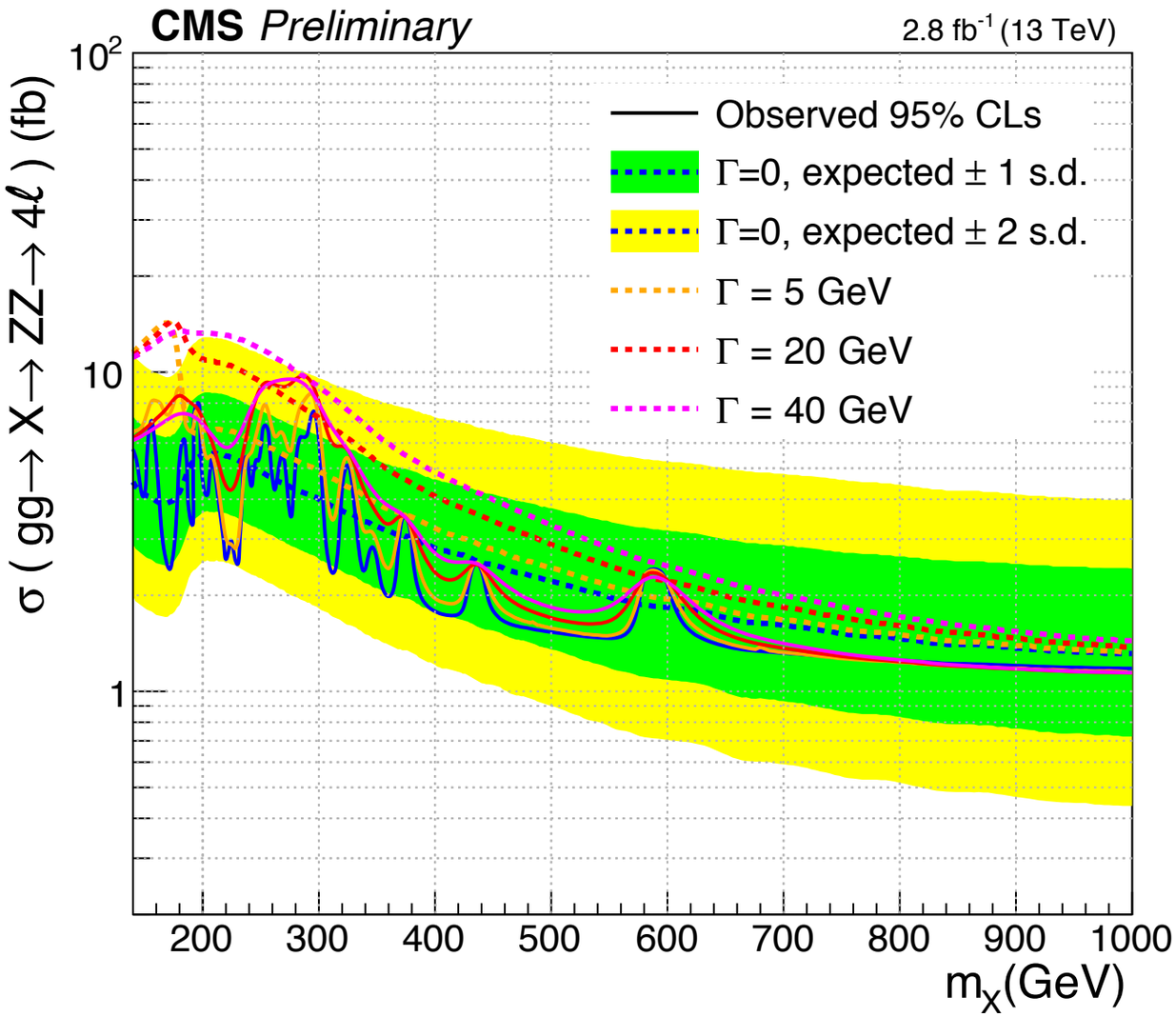
ATLAS: ATLAS-CONF-2015-059
CMS: CMS-PAS-HIG-15-004

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

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

Selections are the one used in h(125) 4l search.





Search for H→ZZ→llνν

ATLAS: ATLAS-CONF-2016-012
CMS: CMS-PAS-HIG-16-001

Searching for an additional scalar boson, as predicted in EWS/2HDM.

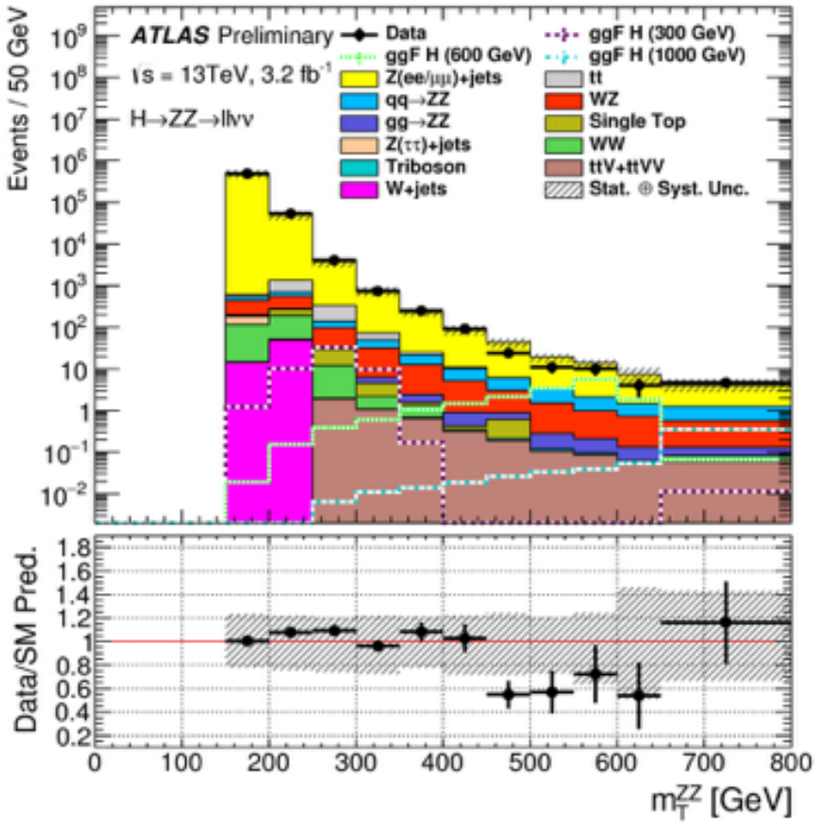
The search is for a narrow resonance of mH = 300-1000 GeV (ATLAS) or 200-1500 GeV (CMS)

- search is for2 leptons (e or μ) and high E_T^{miss}
- **Final Discriminant:**

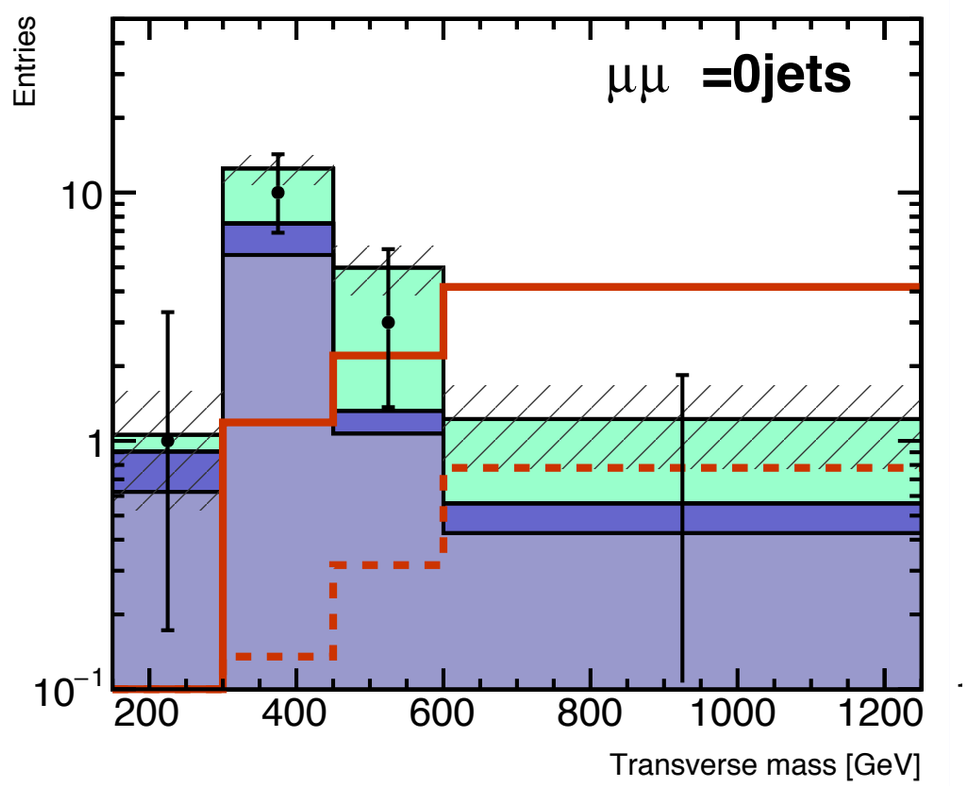
$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M_Z^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$

Background

- **ZZ/WZ**: From simulation,WZ scaled using data-driven methods (ATLAS)
- **Others**: Predicted using data-driven methods.



VBF Categorisation



Search for H→ZZ→llqq

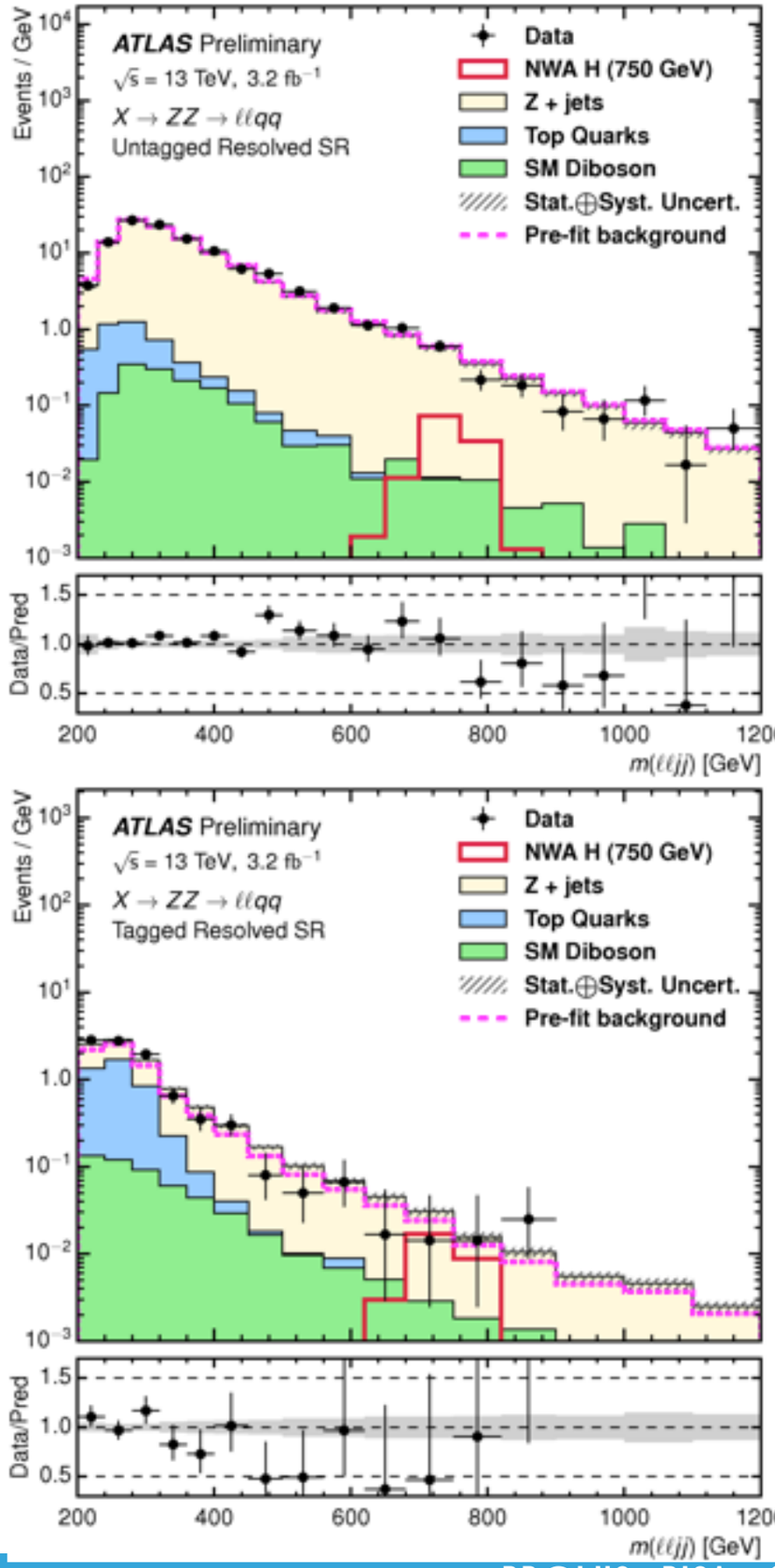
ATLAS: ATLAS-CONF-2016-016

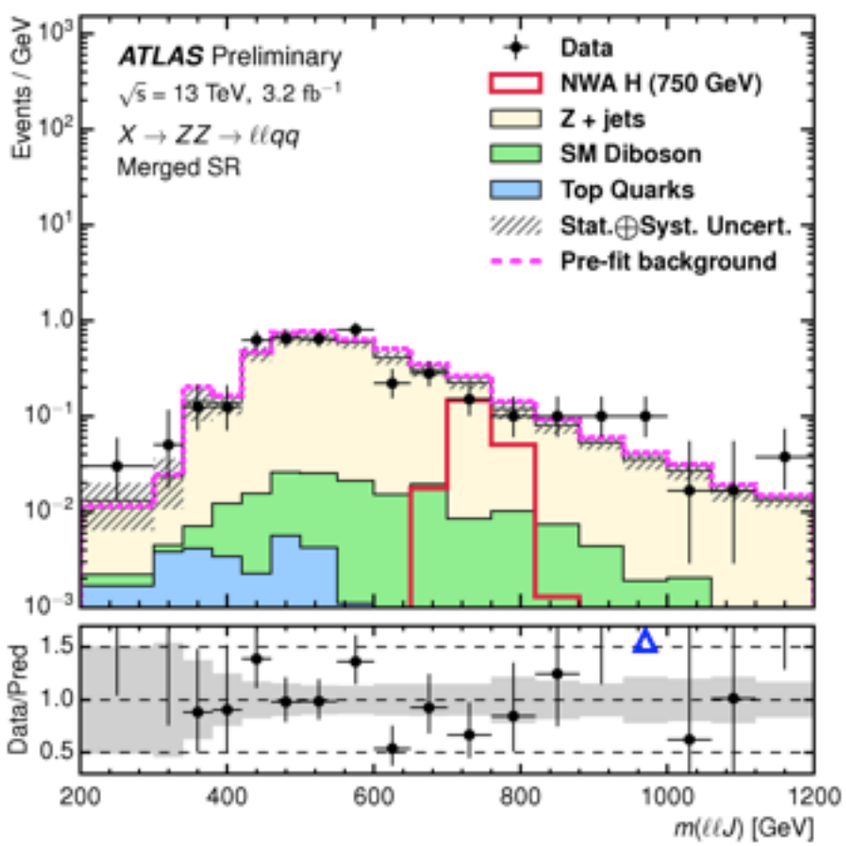
Merged Analysis

- 2 same flavor leptons
- 1 large-R jet (pT > 200 GeV) consistent with Z decay
- $p_T(ll) > 0.3\ m_{ll}$

Resolved Analysis

- 2 same flavor leptons
- 2 Small-R jets consistent with Z decay
- $\sqrt{[p_T^2(ll) + p_T^2(jj)]}/m_{lljj} > 0.5$
- Two categories: 2 and <2 b-tagged jets





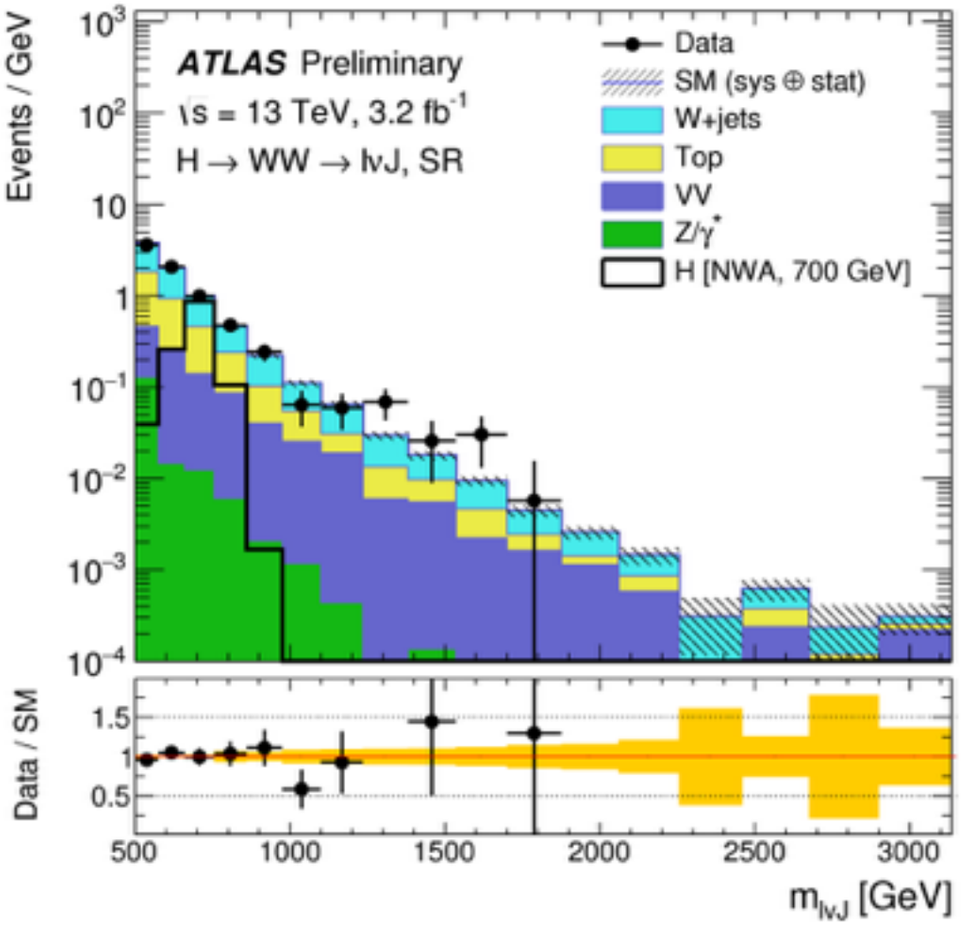
Search for H→WW

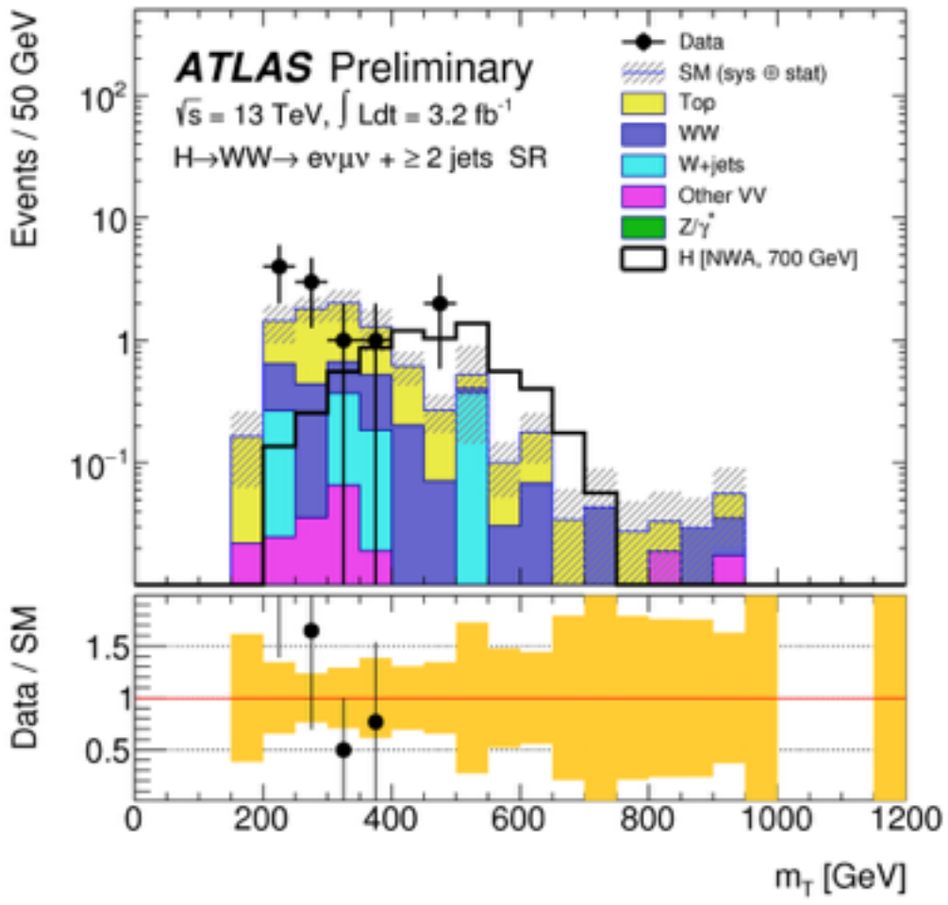
ATLAS: ATLAS-CONF-2016-021

H → WW → lνlν analysis

- The zero- and one-jet sensitive to gluon-gluon fusion (ggF)
- two jet category used for vector boson fusion (VBF)
- Different-flavour lepton pairs are considered.
- Discriminating variable: transverse mass (m_T)

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2},$$



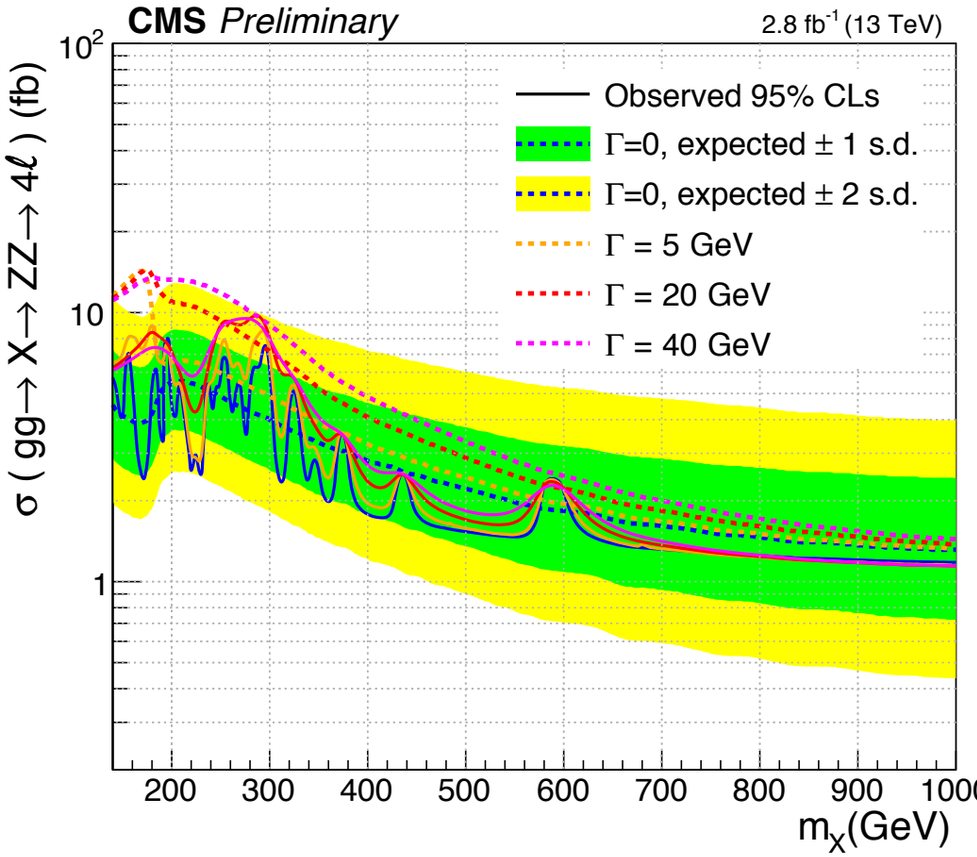


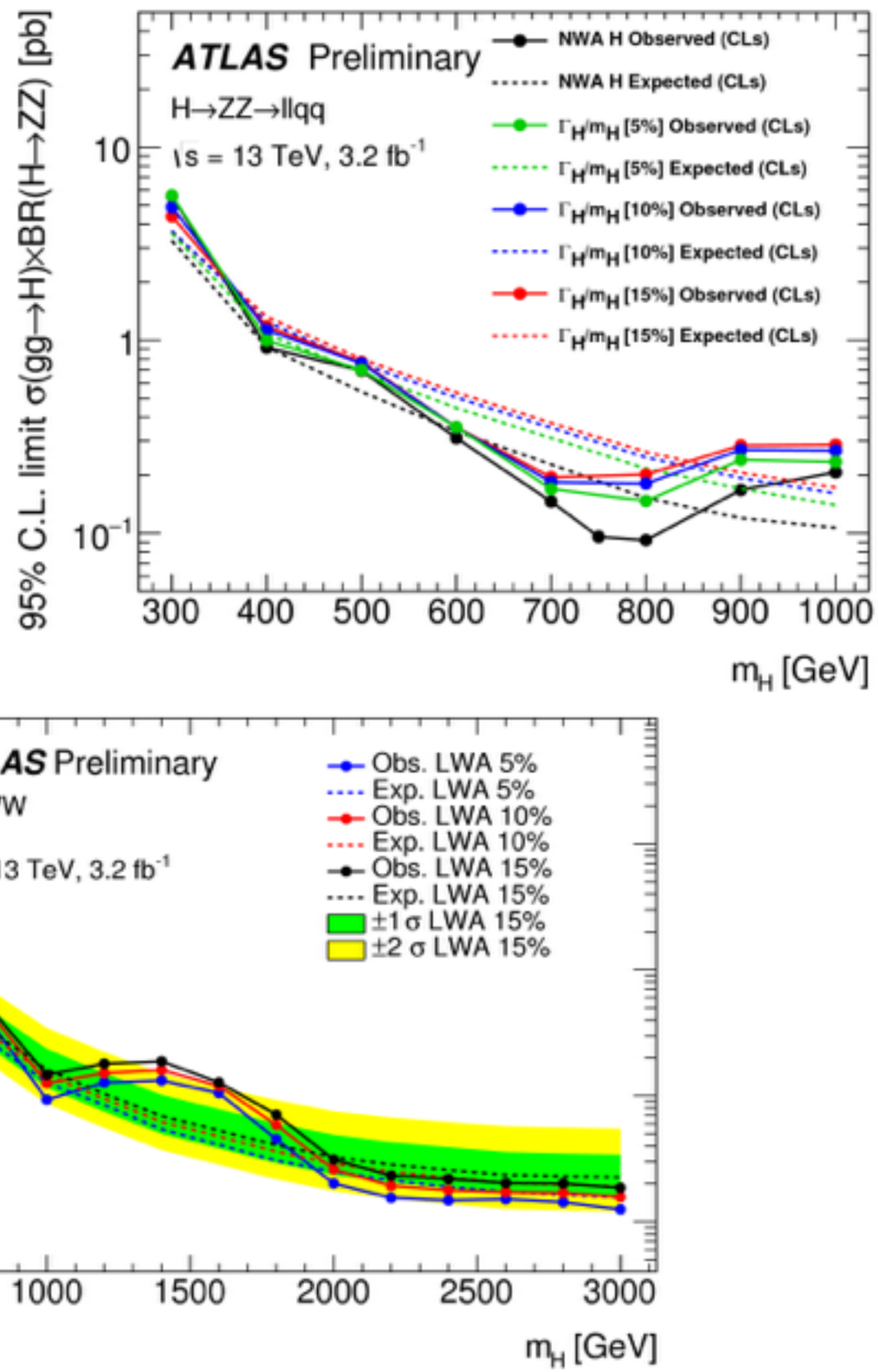
H → WW → lνqq analysis

- qq final state is reconstructed as one single large jet (“J”)
- Discriminating variable: invariant mass, $m_{lνJ}$

Search for H→VV – Results

ATLAS: ATLAS-CONF-2016-021

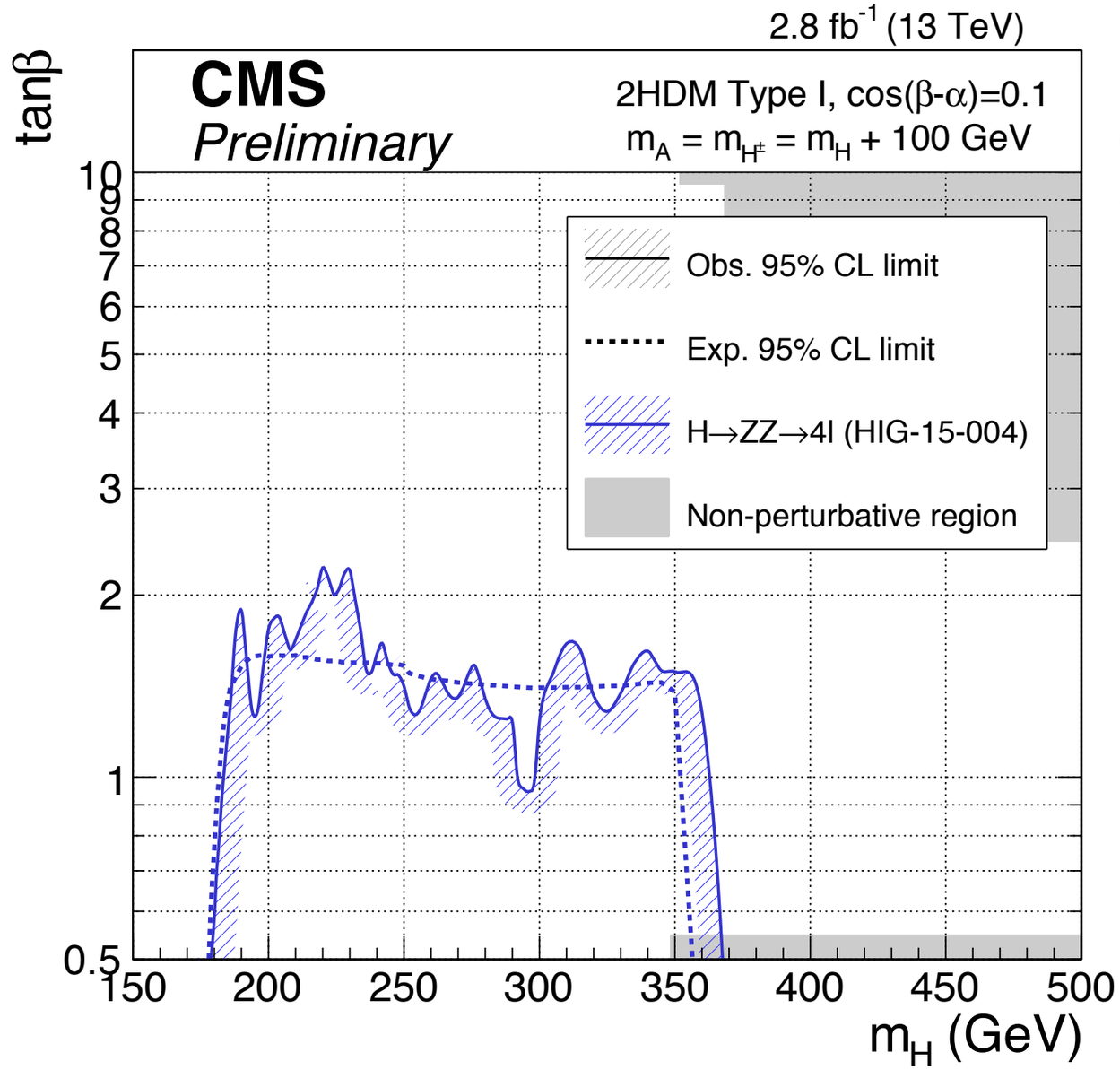


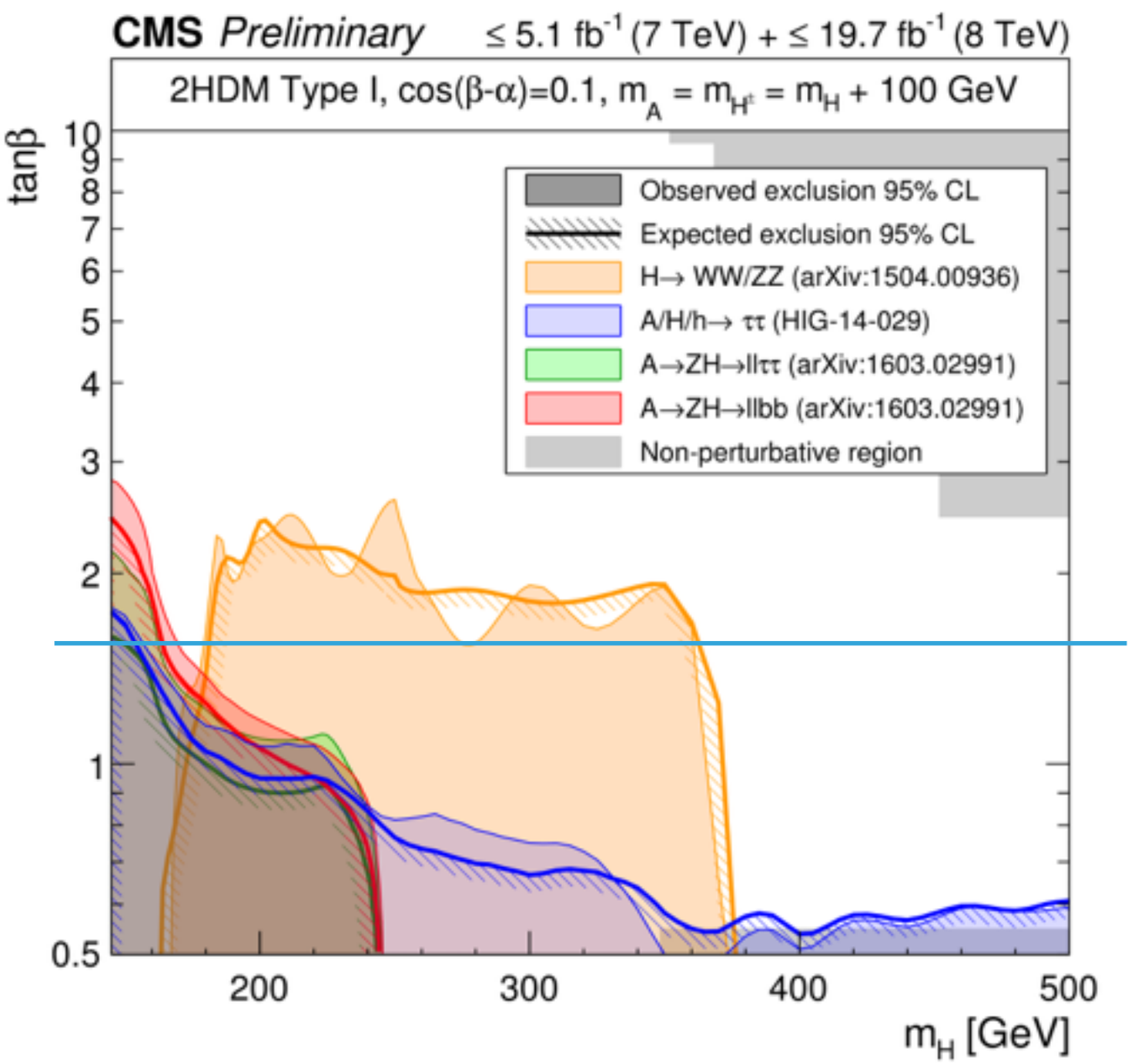


Search for H→VV – Results

CMS: CMS-PAS-HIG-15-004

H→ZZ→4l Results have also been interpreted Type-I and Type-II (Backup) 2HDM

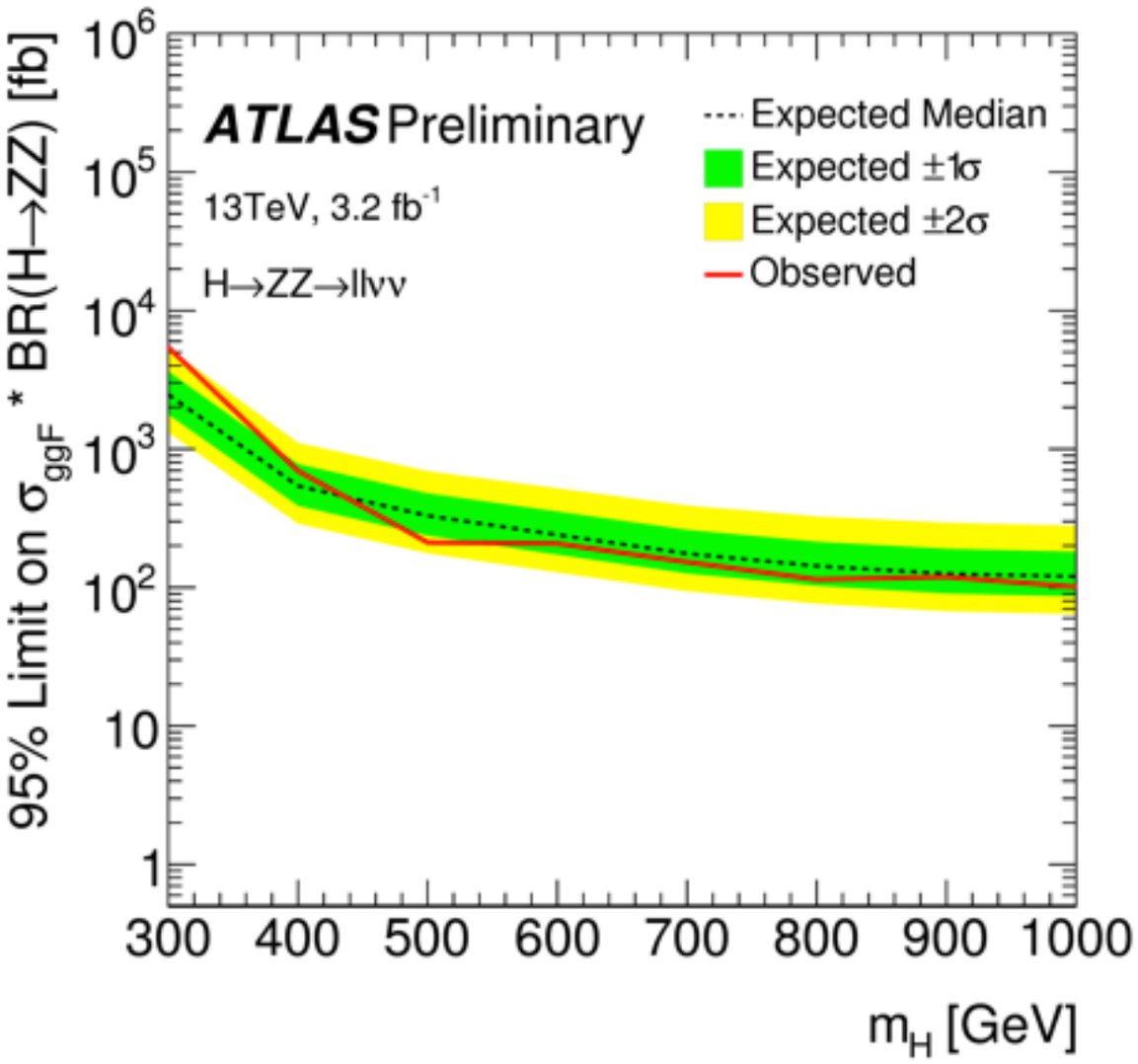




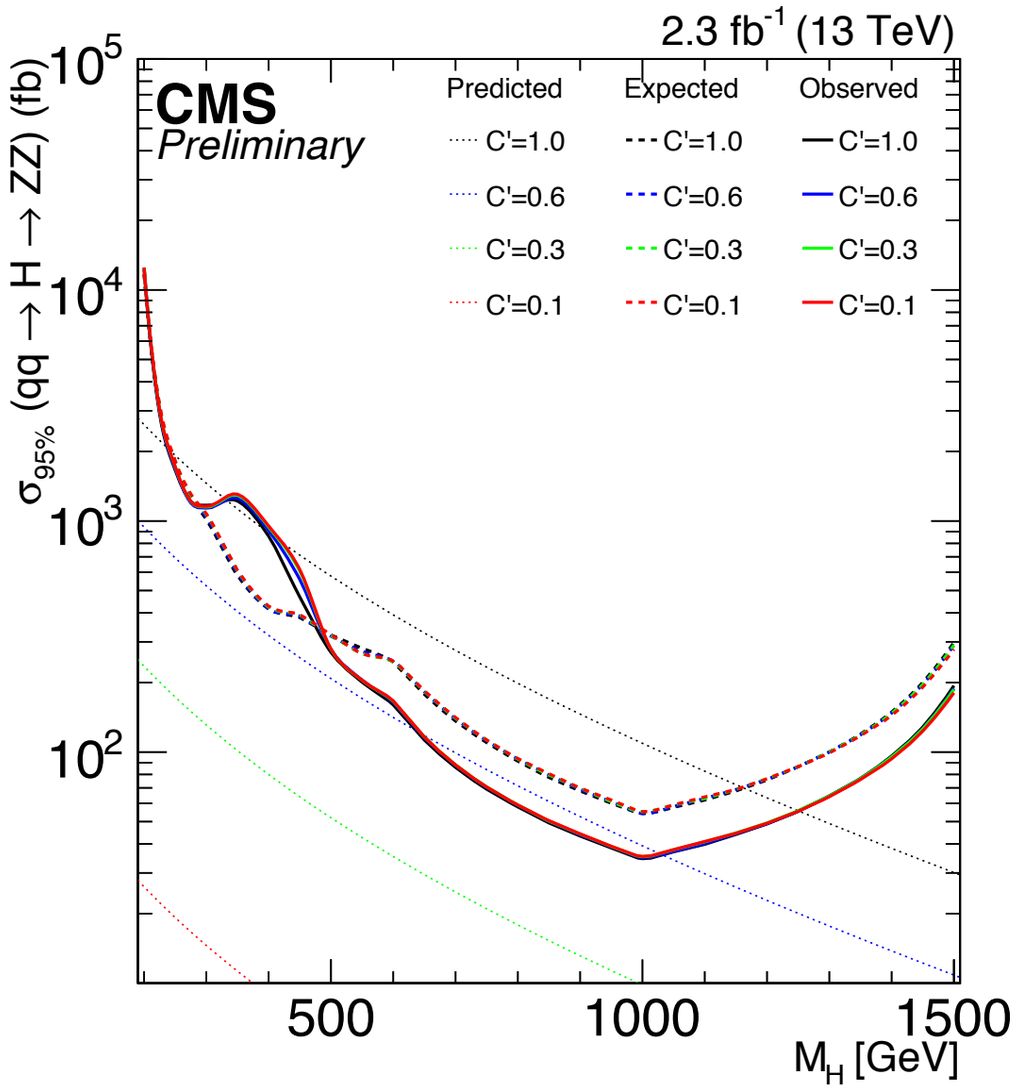
Search for H→ZZ→llνν

ATLAS: ATLAS-CONF-2016-012
CMS: CMS-PAS-HIG-16-001

ATLAS 95% CL Limit on the Gluon Fusion production cross section



CMS 95% CL Limit on the VBF production cross section

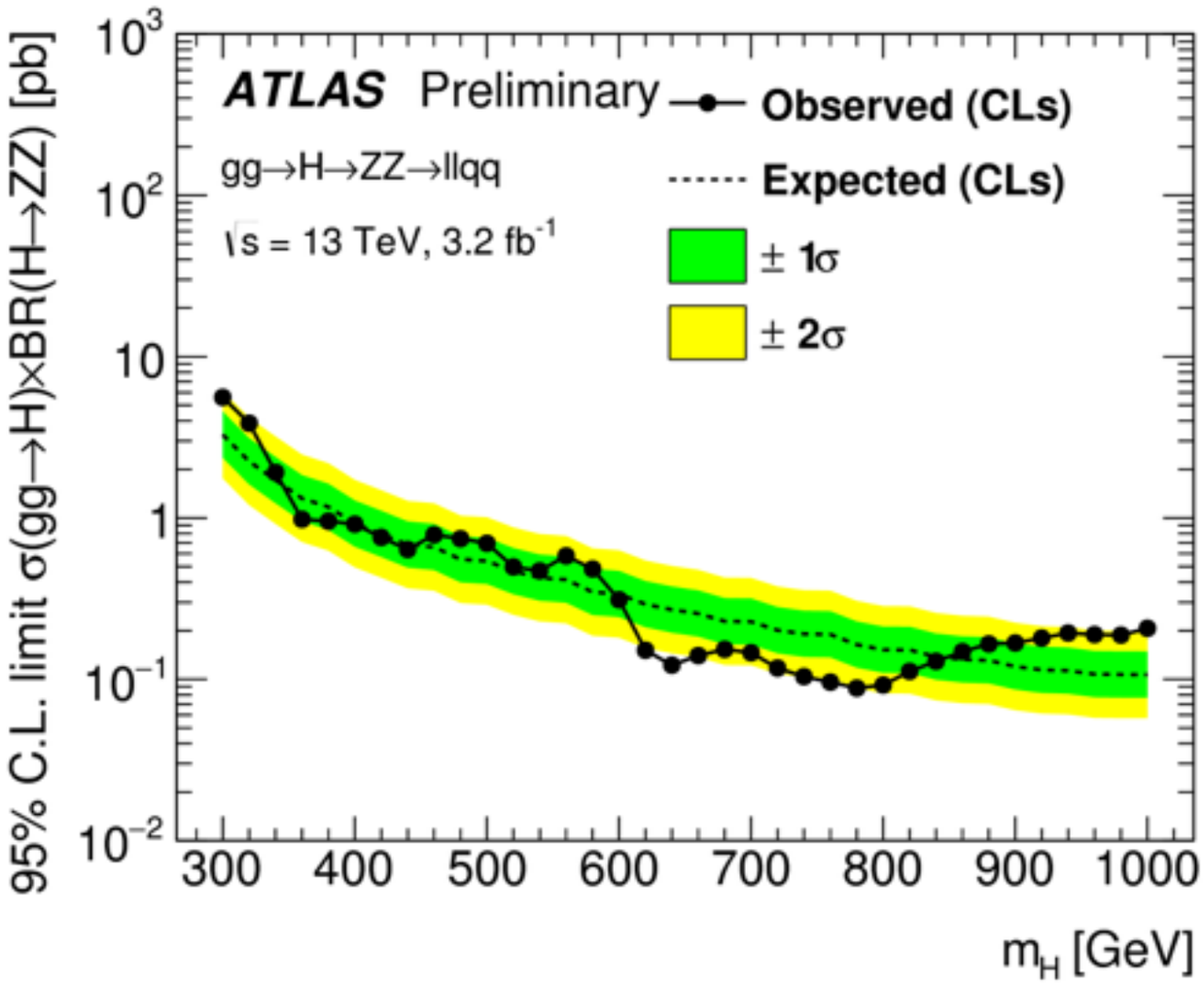


Search for H→ZZ→llqq

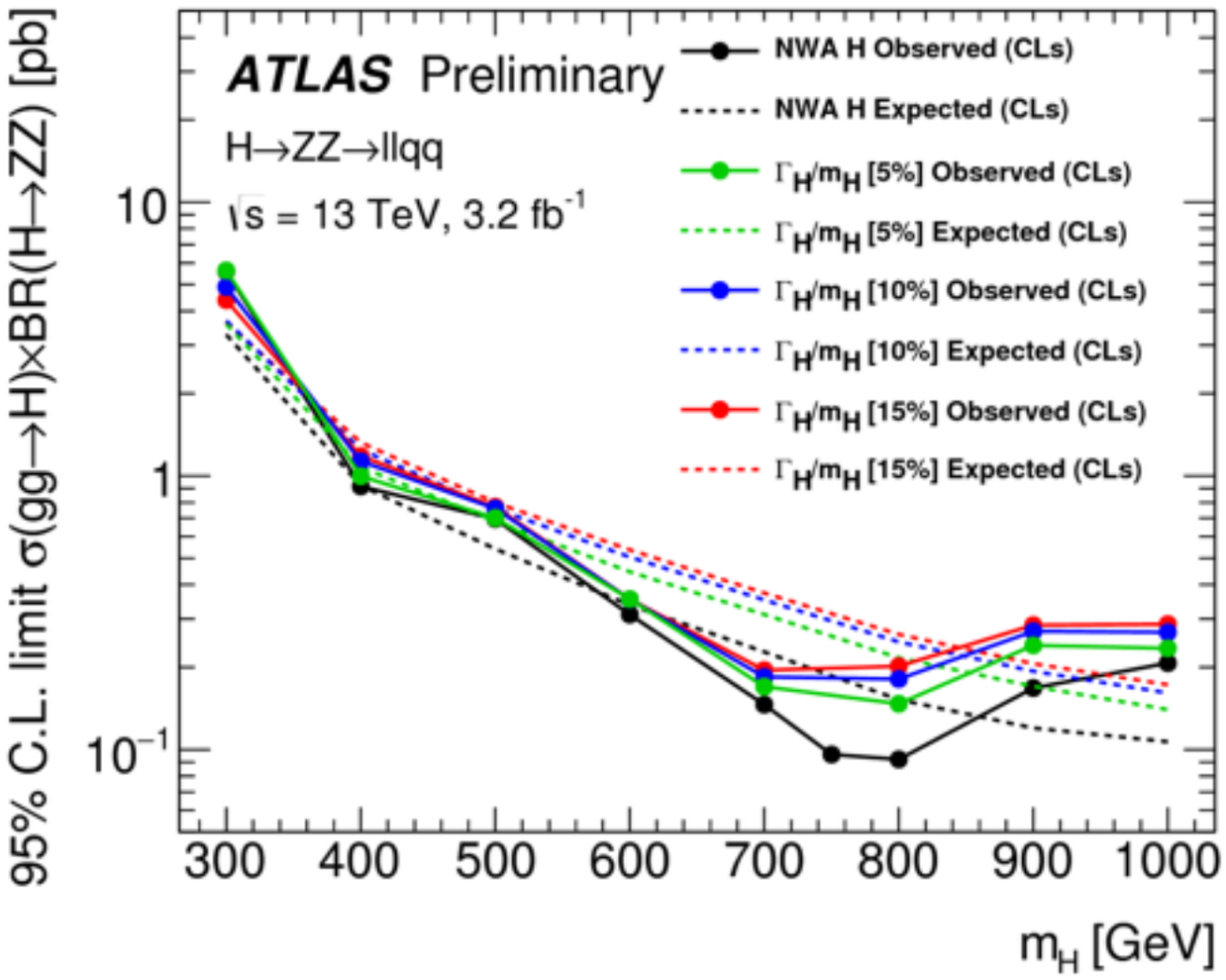
ATLAS: ATLAS-CONF-2016-016

Observed and expected 95% CL upper limits on the production cross section, combining the merged and resolved analyses.

Narrow Width



Large Width

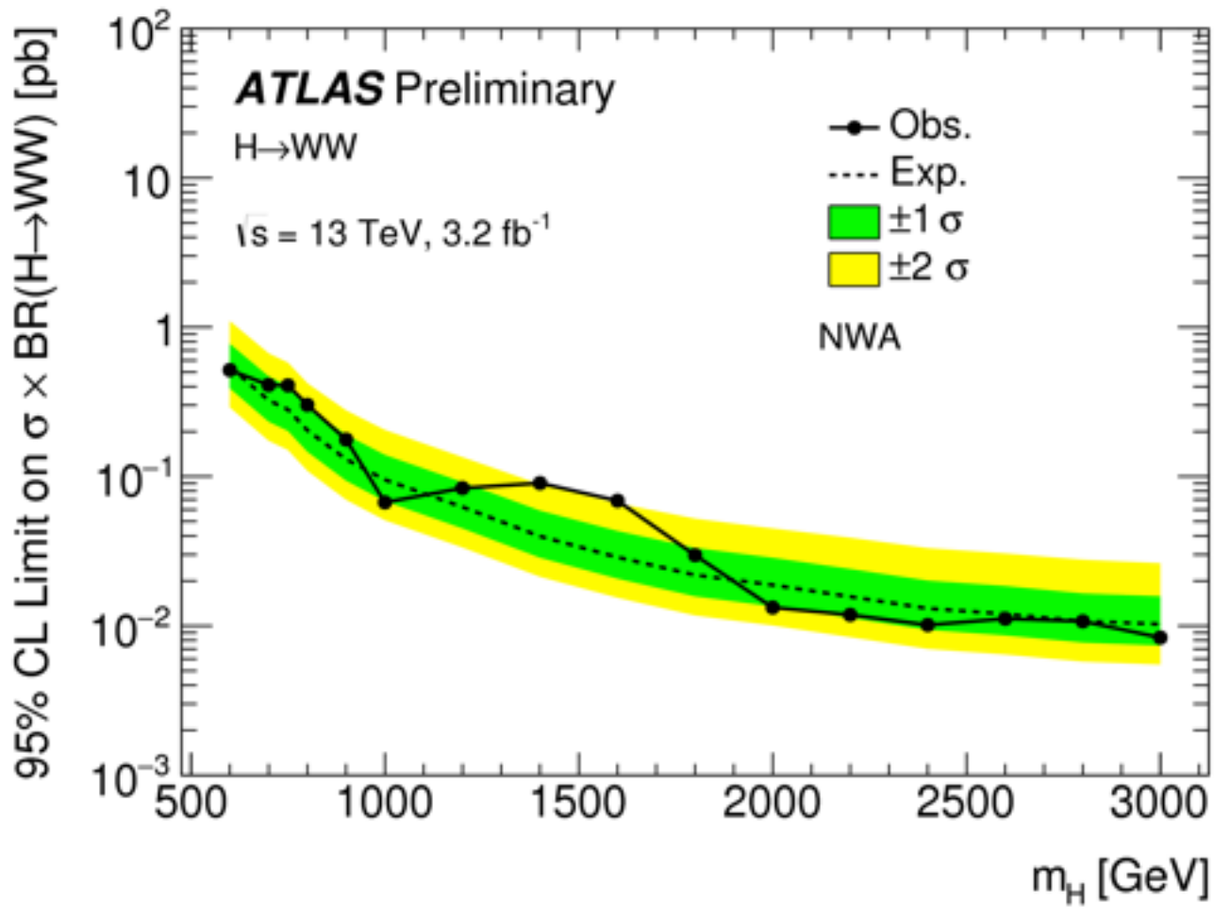


Search for H→WW

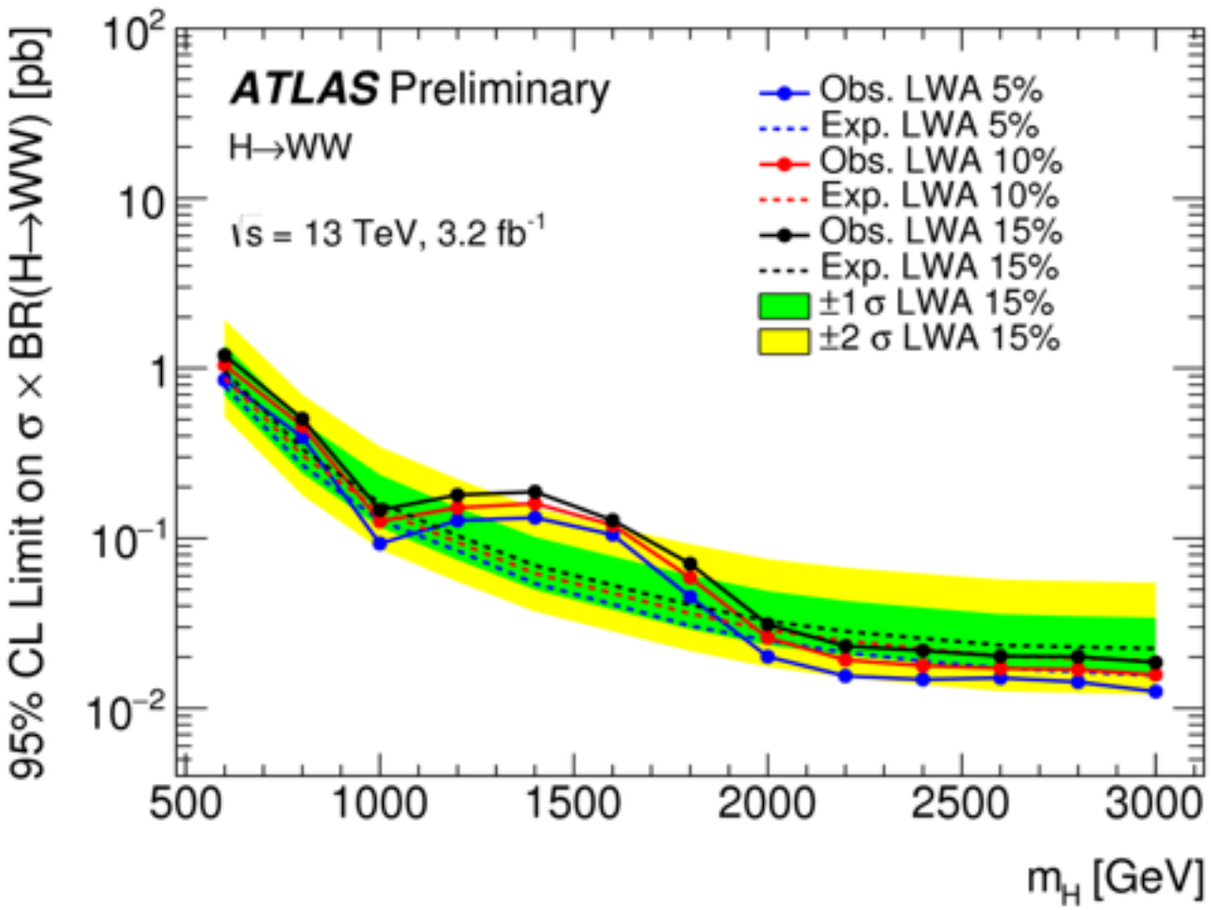
ATLAS: ATLAS-CONF-2016-021

Observed and expected 95% CL upper limits on the production cross section, combining **lvlv** and **lvqq**.

Narrow Width



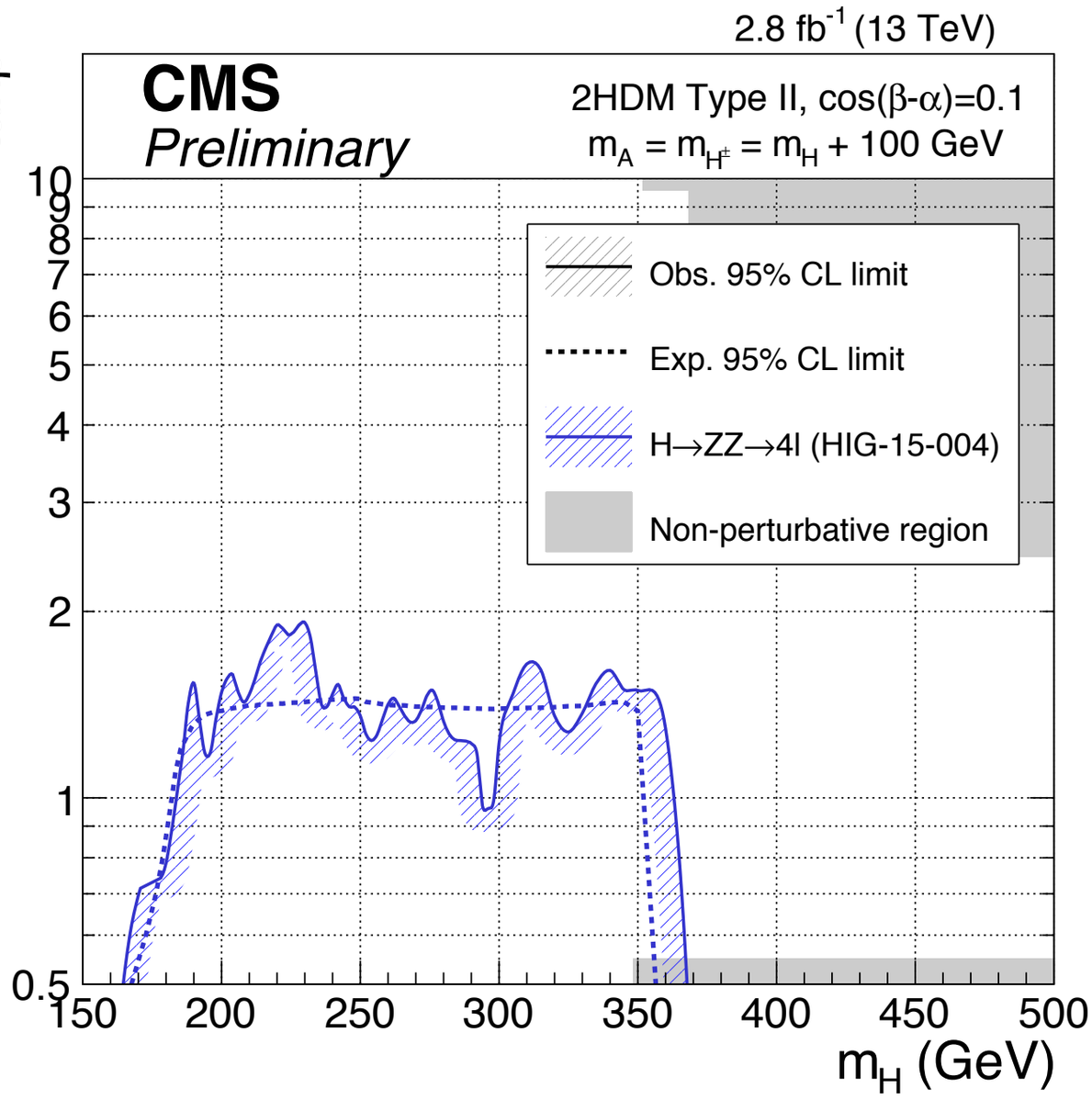
Large Width

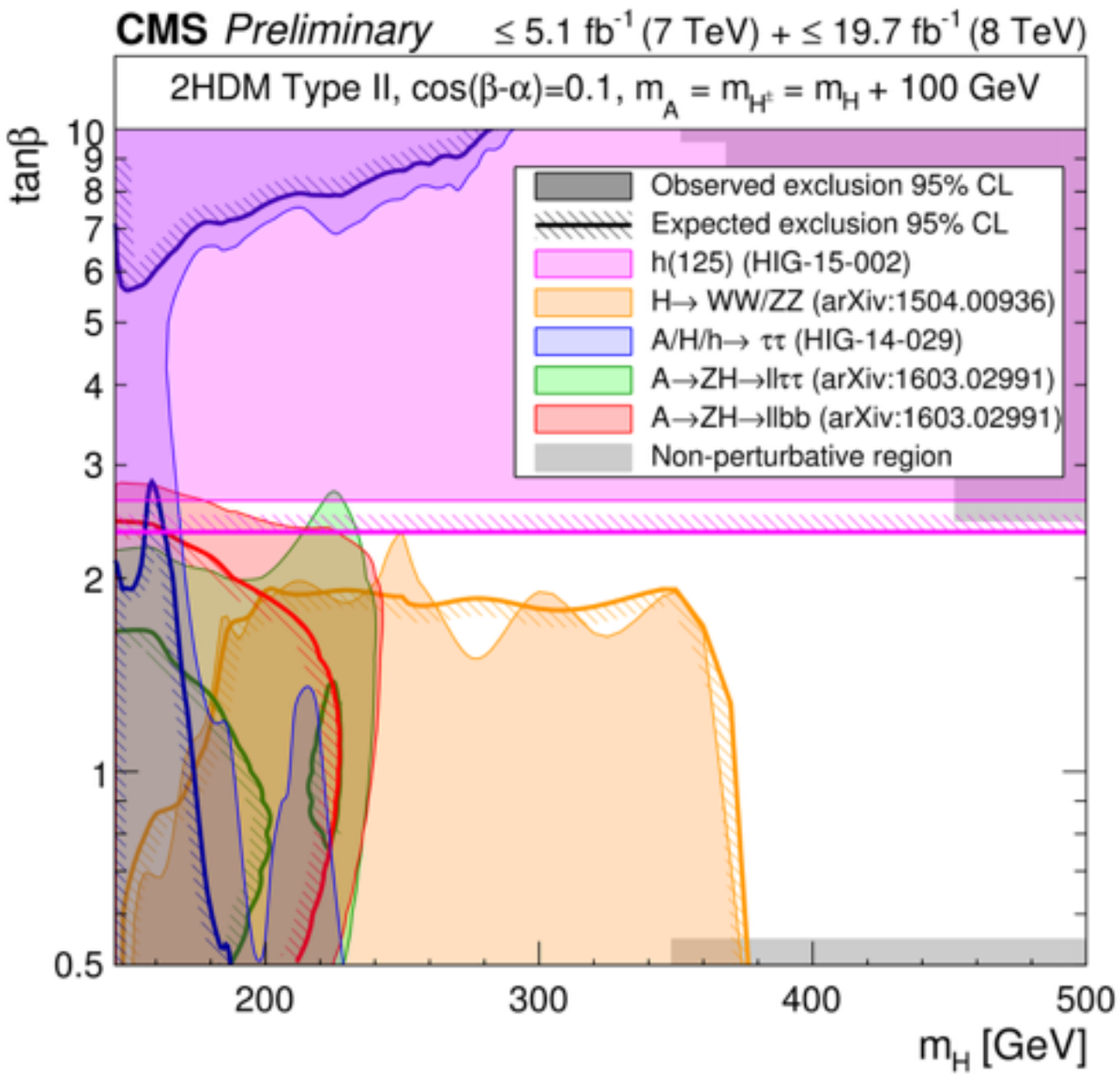


Search for H→VV – Results

CMS: CMS-PAS-HIG-15-004

H→ZZ→4l Results have also been interpreted Type-II 2HDM





CP odd Higgs

Search for H→ZA, Z→ll and A→bb

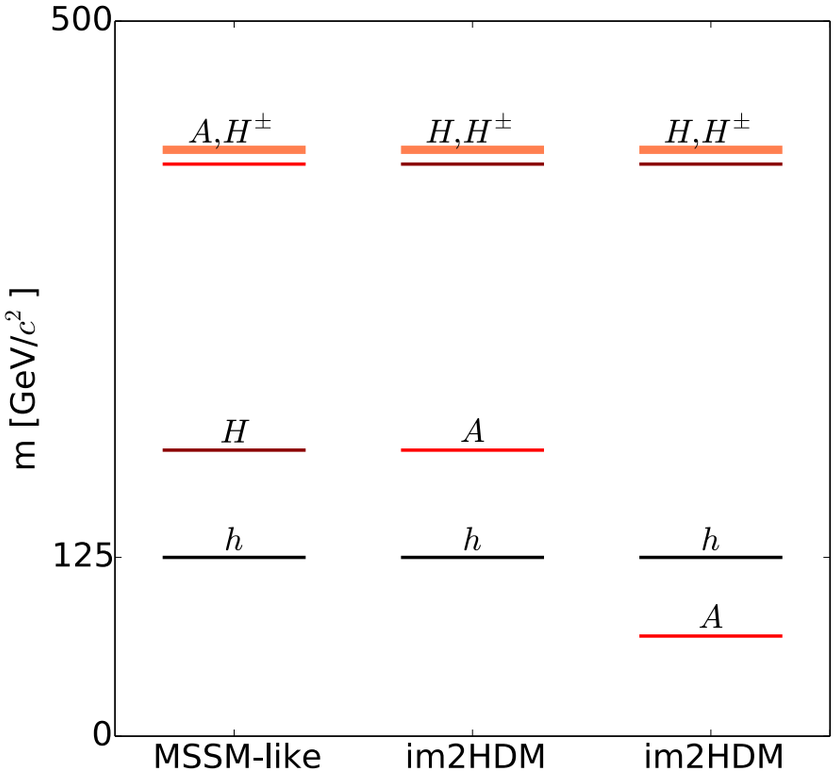
CMS: CMS-PAS-HIG-16-010

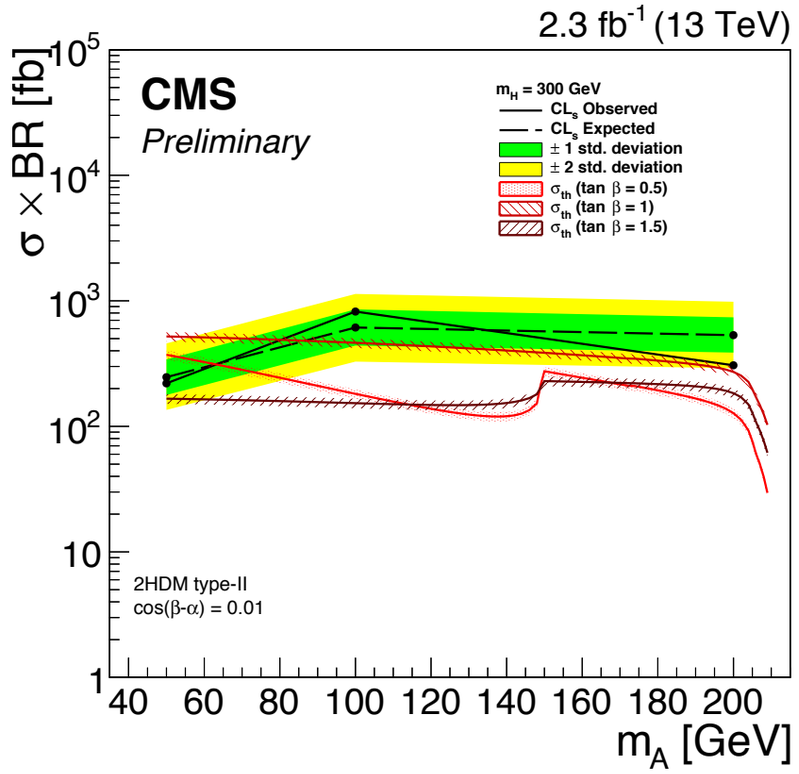
Motivated by 2HDM with twisted custodial symmetry, which gives a heavier scalar H and a lighter pseudoscalar A boson.

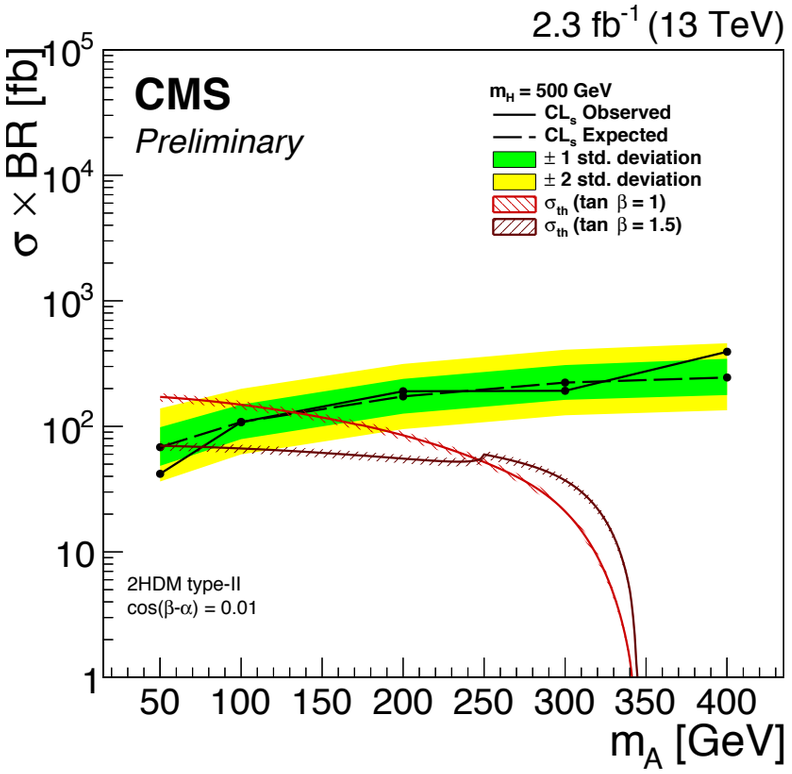
Analysis Strategy

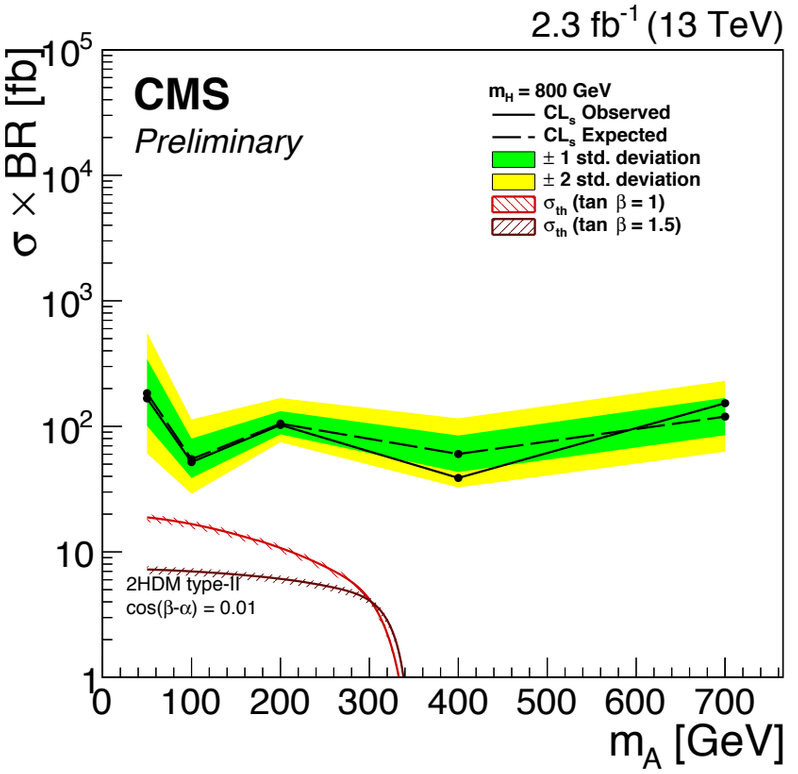
- A signal region (S) is defined for each mA-mH hypothesis in the plane of m_{bb}-m_{llbb}
- The final limit is calculated from the single bin of S.

Limits for three m_H hypotheses, as a function of m_A.









Search for A→Zh, h→bb

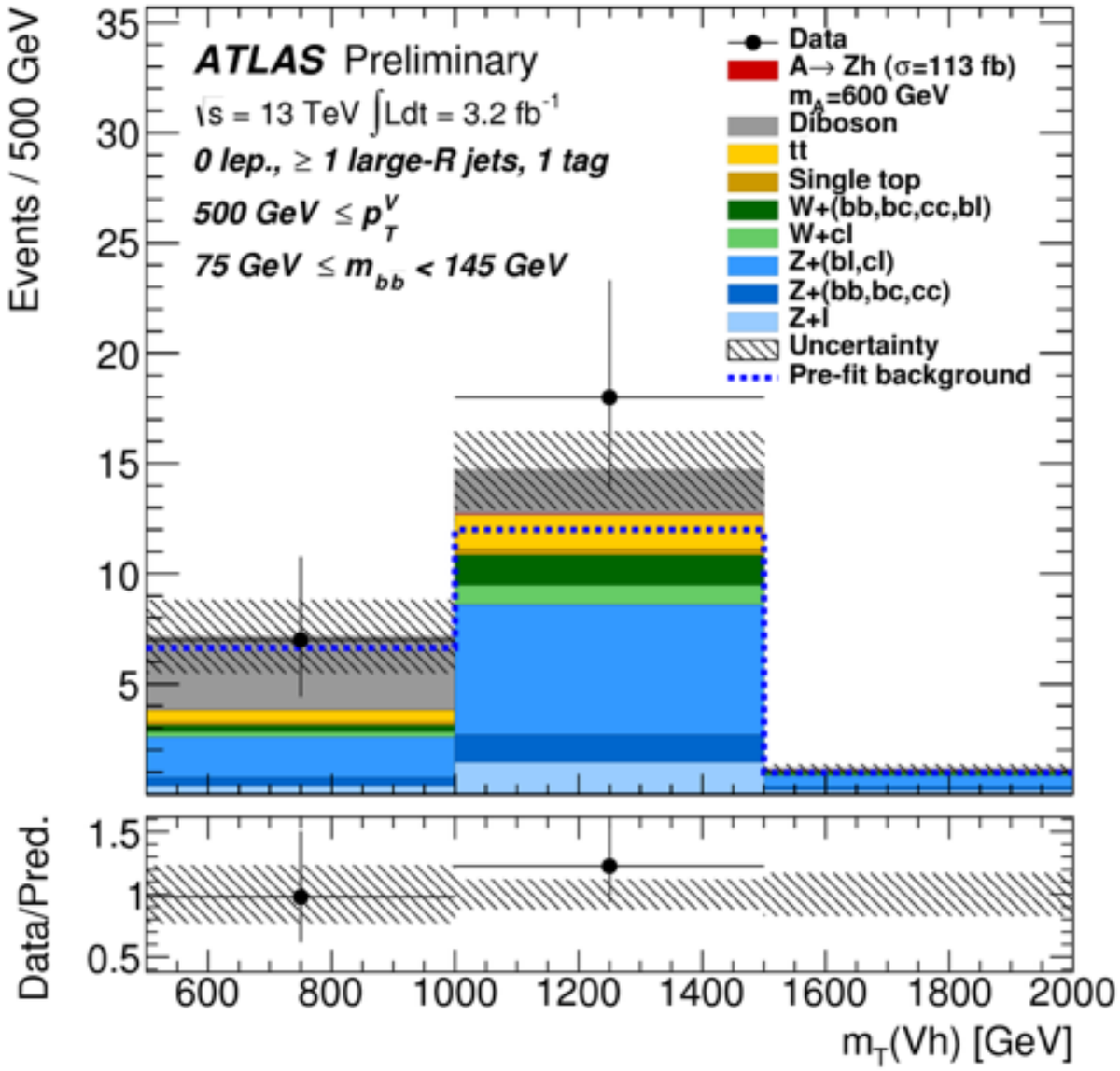
ATLAS: ATLAS-CONF-2016-015

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

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

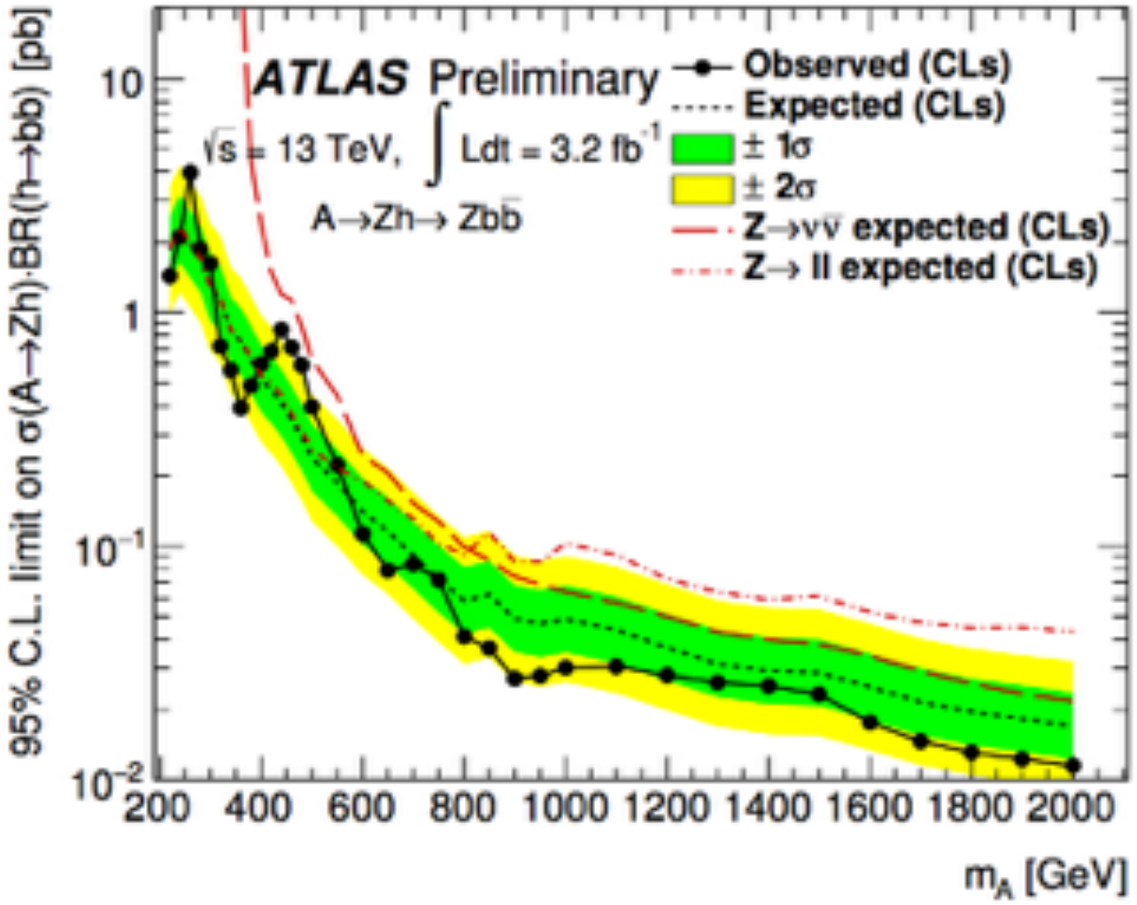
- Targeting A→Zh→vvbb/llbb
- Makes use of categories:
  - 0/2-leptons
  - p_T^Z < or > 500 GeV (defining the resolved/ T
  - boosted transition)
  - 1/2 b-tagged jets
- Final discriminant:
  - 2- lepton invariant m_{llbb} for
  - 0-lepton:

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

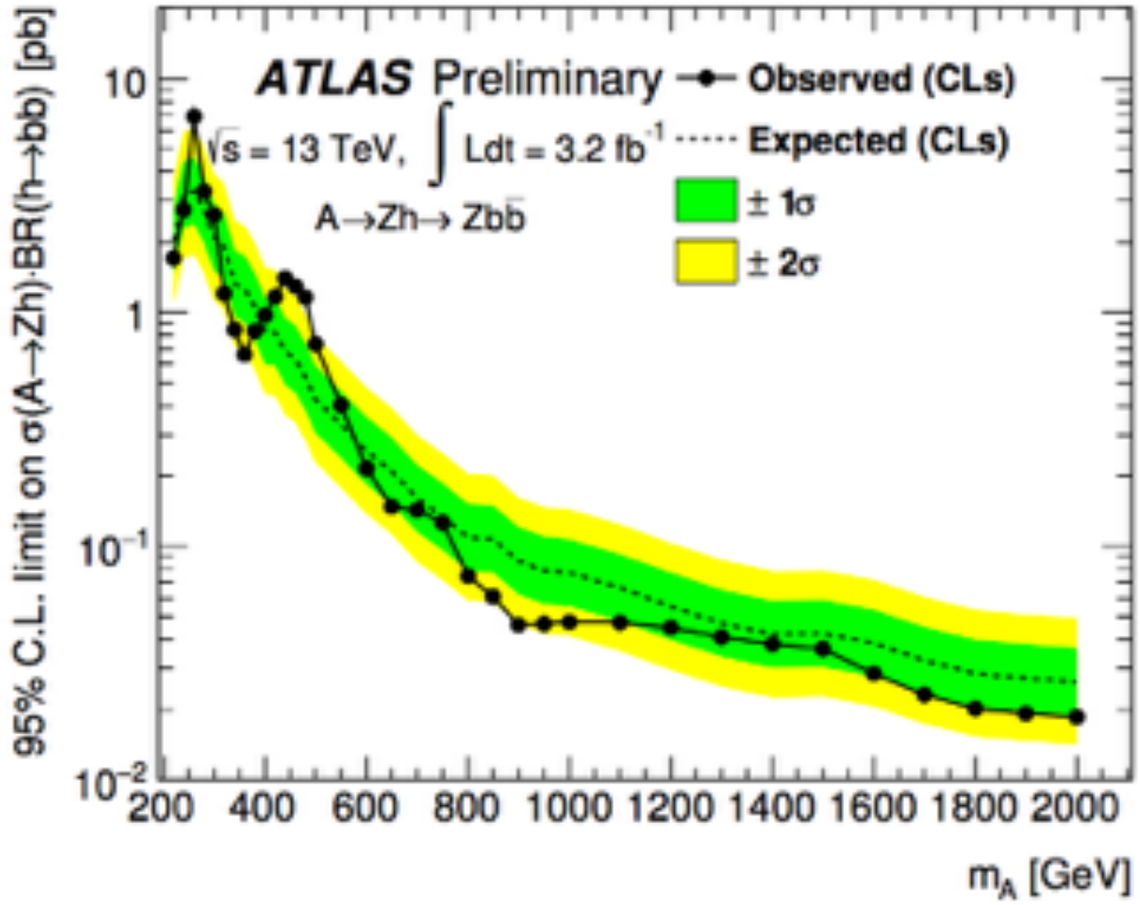


Search for A→Zh, h→bb

ATLAS: ATLAS-CONF-2016-015



(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→WW

ATLAS: ATLAS-CONF-2016-021

H → WW → lνlν analysis

- The zero- and one-jet sensitive to gluon-gluon fusion (ggF)
- two jet category used for vector boson fusion (VBF)
- Different-flavour lepton pairs are considered.
- Discriminating variable: transverse mass (m_T)

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2},$$

Preselection cuts: lepton different flavor, opposite charge, $p_{\mathrm{T}}^{\mathrm{lead}} > 25\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\,\mathrm{GeV}$, third lepton veto, $p_{\mathrm{T}} < 15\,\mathrm{GeV}$							
	SR			WW CR		Top CR	
	$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$	$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$
$\lvert\Delta\eta_{\ell\ell}\rvert$	< 1.8	< 1.8	< 1.8	> 1.8	> 1.8		
$N_{b\text{-jet}}$		$= 0$	$= 0$		$= 0$	$= 1$	$= 1$
$p_{\mathrm{T}}^{\mathrm{lead}}$	$> 120\,\mathrm{GeV}$	$> 120\,\mathrm{GeV}$	$> 120\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$		
$p_{\mathrm{T}}^{\mathrm{sublead}}$		$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$		
$p_{\mathrm{T}}^{\mathrm{miss}}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$		$> 20\,\mathrm{GeV}$	$> 20\,\mathrm{GeV}$		
$m_{\ell\ell}$	$> 100\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$	$> 150\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$	$> 150\,\mathrm{GeV}$
m_{jj}			$> 650\,\mathrm{GeV}$				
$\lvert\Delta y_{jj}\rvert$			> 4.25				

H → WW → lνqq analysis

- qq final state is reconstructed as one single large jet ("J")
- Discriminating variable: invariant mass, $m_{l\nu J}$

Preselection	one lepton with $p_{\mathrm{T}} > 25$ GeV one large-R jet with $p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$ $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV $p_{\mathrm{T}}(\ell\nu) > 200$ GeV $p_{\mathrm{T}}(J)/m_{\ell\nu J} > 0.4$ $p_{\mathrm{T}}(\ell\nu)/m_{\ell\nu J} > 0.4$
SR	W jet substructure W mass cut: $70.2 < m_W < 96.2$ GeV no b-tagged jets in small-R jets
W+jets CR	W mass cut inverted no b-tagged jets
Top CR	W mass cut ≥ 1 b-tagged small-R jet (j_b) with $\Delta R(J, j_b) > 1.0$

Search for H/A→bb

CMS: J. High Energy Phys. 11 (2015) 071

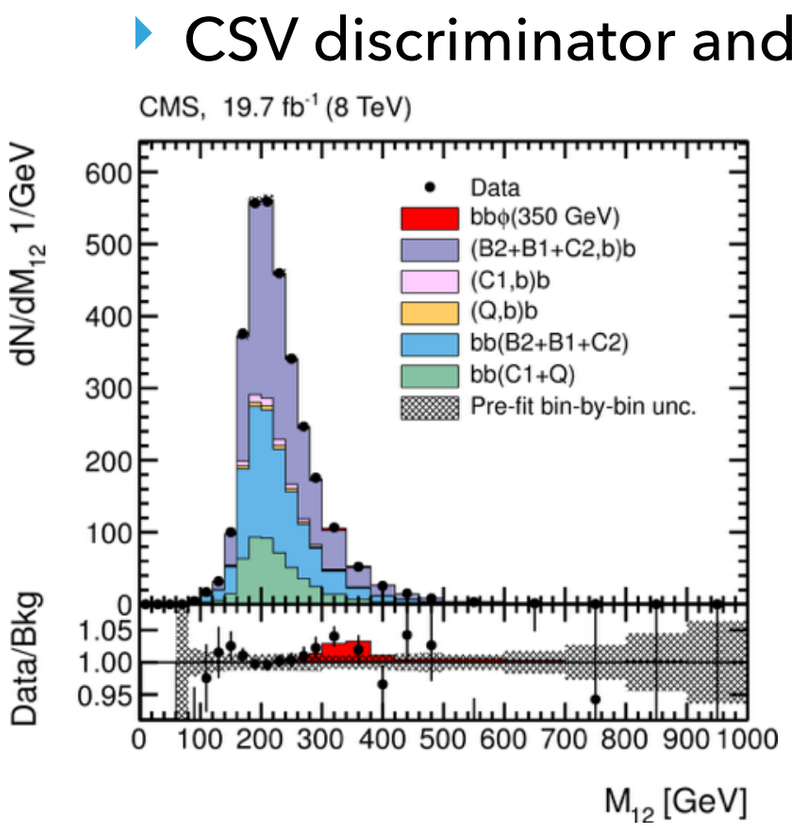
- φ produced in association with at least one b quark and decay to bb
- final states characterised by at least three b-tagged jets
- Events selected by specialised triggers that identify b jets already at the online level
- searches for a peak in the invariant mass distribution of the two b jets with the highest pT values:
  - 2 jets $|\eta| \leq 1.65$, $p_T > 80$ (70) GeV
  - third jet $|\eta| \leq 2.2$, $p_T > 20$ GeV
  - jet1 and jet2 $|\Delta\eta_{12}| \leq 1.4$
  - minimal pairwise separation of $\Delta R > 1$

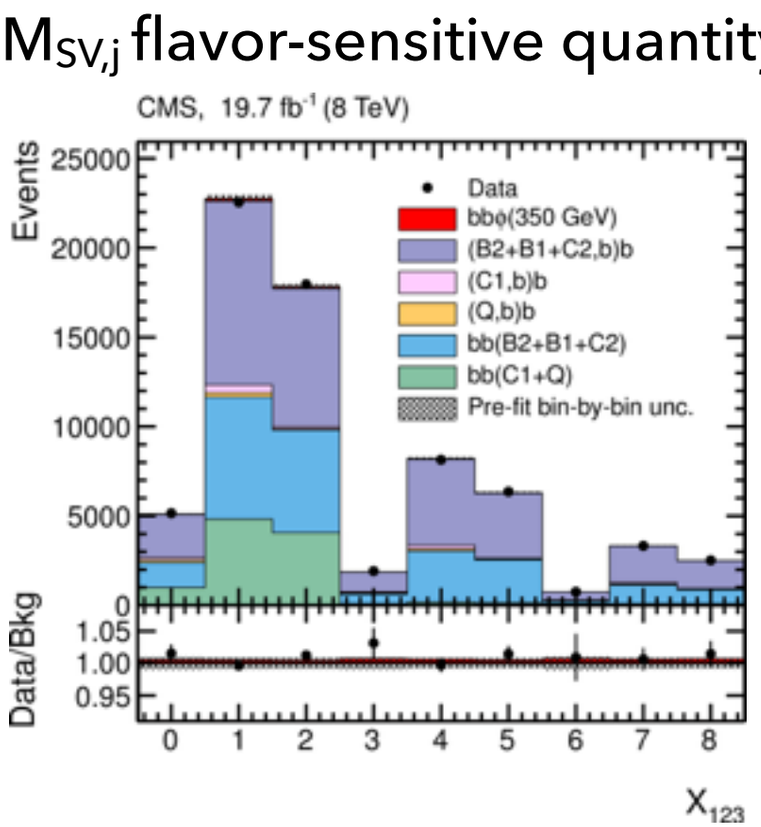
$\Sigma M_{SV,j}$ [GeV]	B_j
0–1	0
1–2	1
2–3	2
>3	3

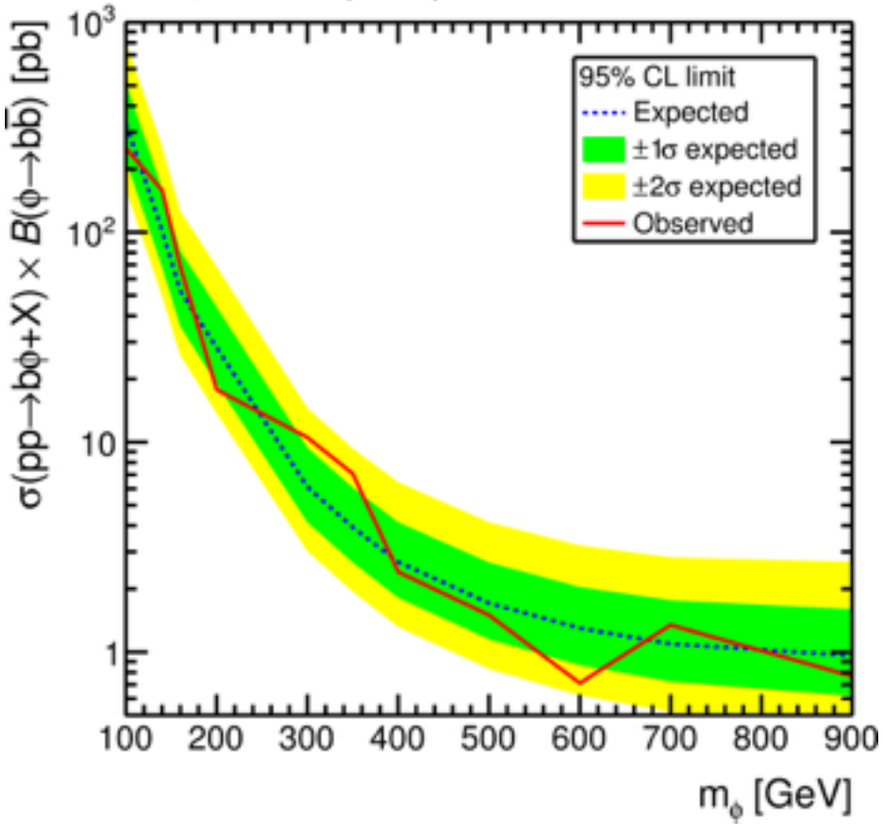
B_3	$B_1 + B_2$		
	0–1	2–3	4–6
0–1	0	1	2
2	3	4	5
3	6	7	8

CMS, 19.7 fb^{-1} (8 TeV)

- CSV discriminator and $\Sigma M_{SV,j}$ flavor-sensitive quantity



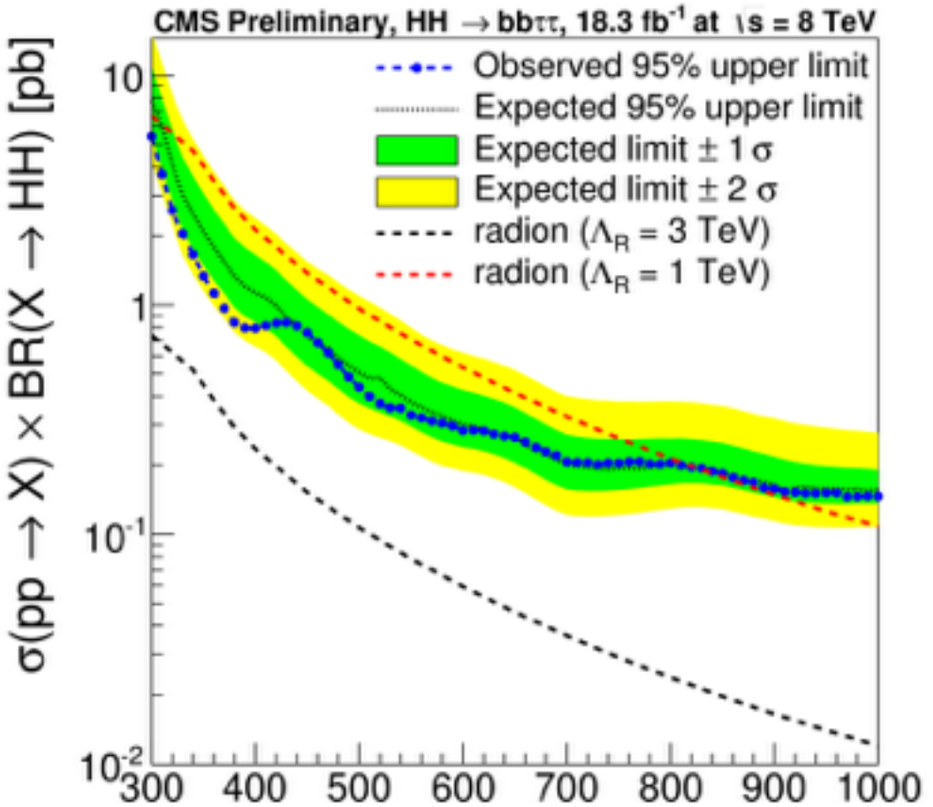


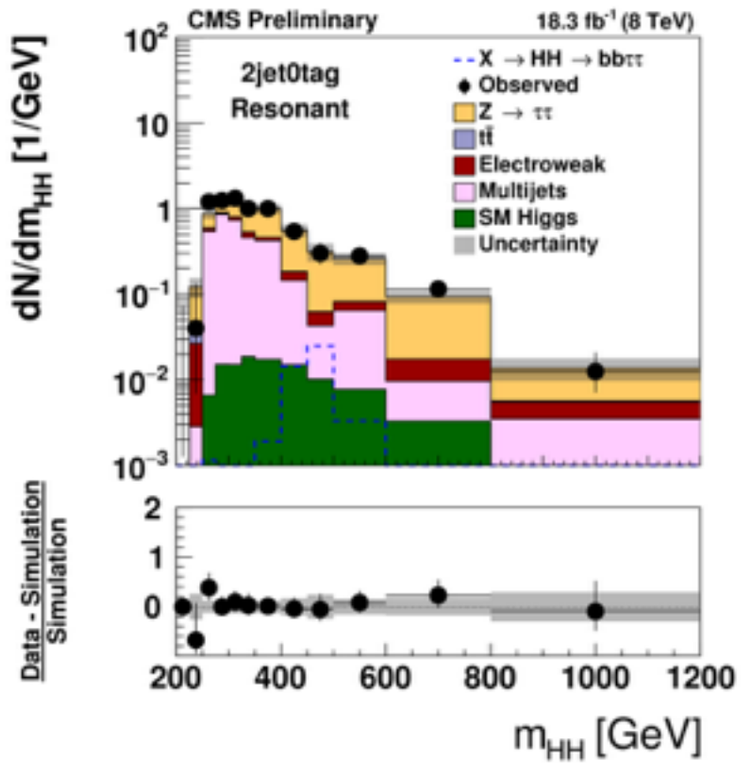


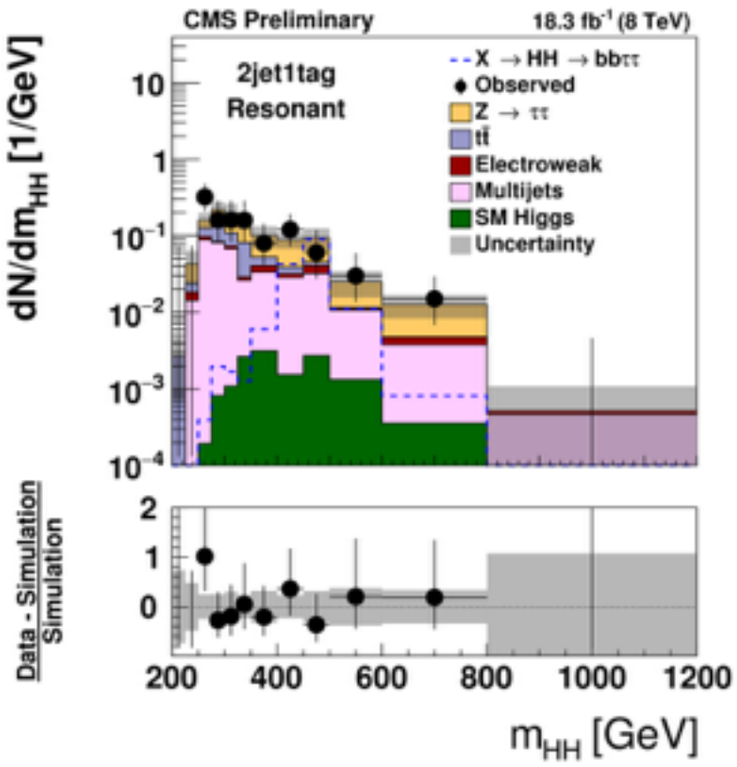
Scalar Resonance: Search for H→hh→bbττ

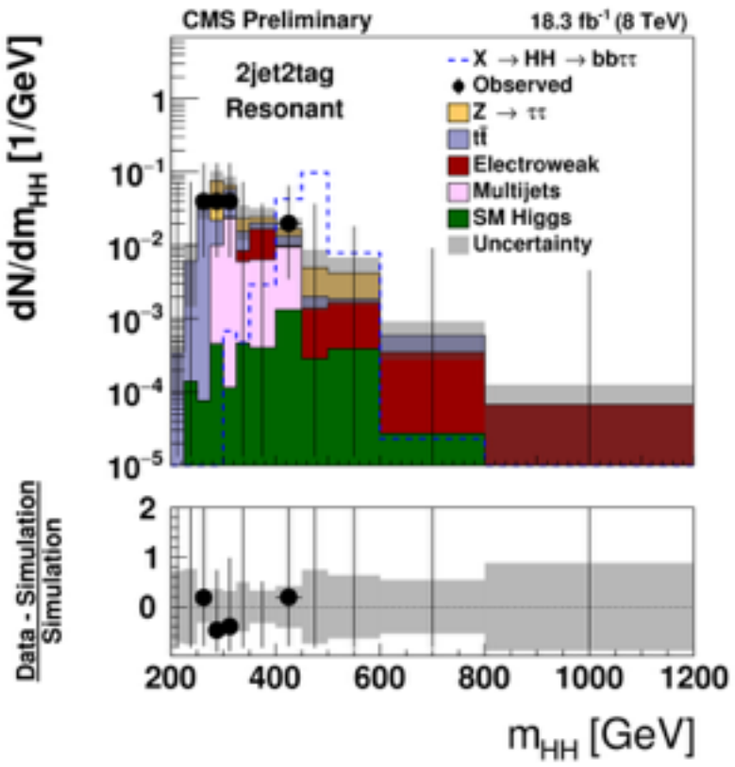
ATLAS: Phys. Rev. D 92, 092004 (2015)
CMS: CMS-PAS-HIG-15-013

- 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.









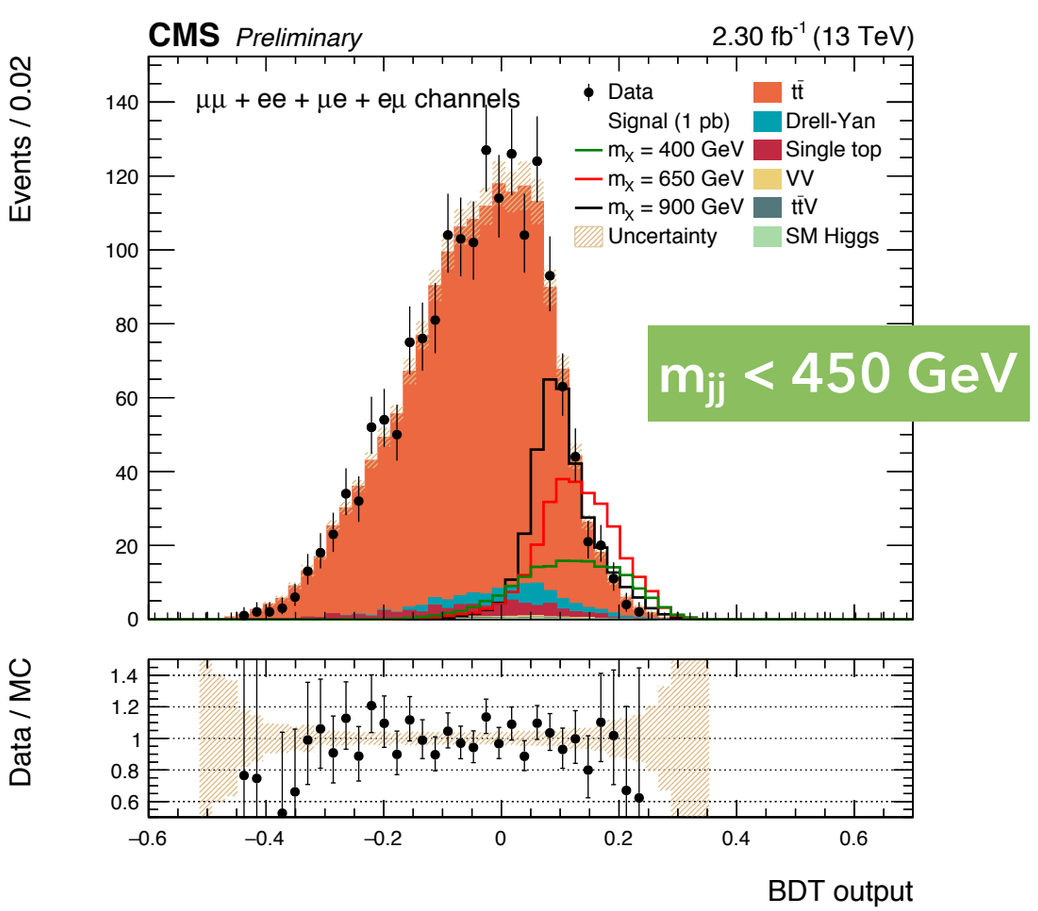
Search for H→hh→bbWW

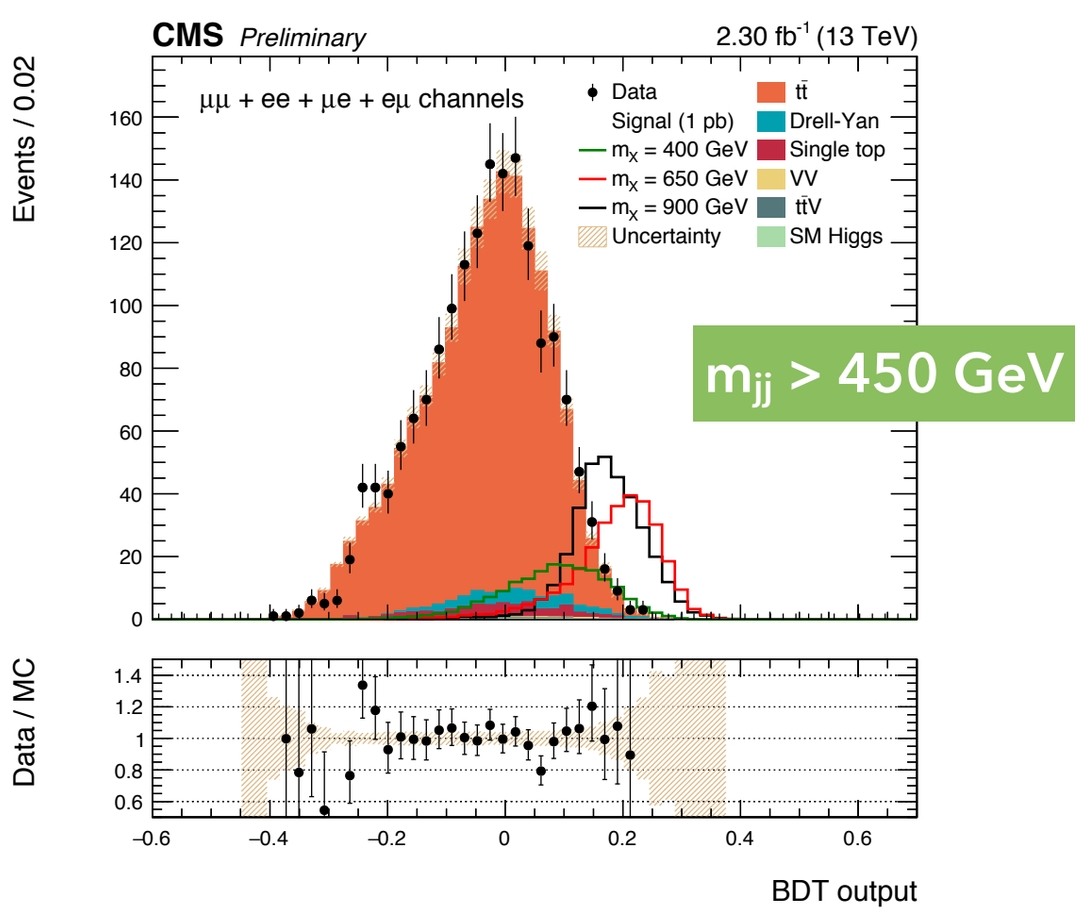
CMS: CMS-PAS-HIG-16-011

Mass range form 260 GeV to 900 GeV

Search strategy:

- dilepton triggers
- two oppositely charged leptons (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)
- 2 b-tagged jets
- BDT: m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\varphi_{ll,jj}$,p_T^{ll}, p_T^{jj}, min($\Delta R_{j,l}$) and MT(ll,MET)
  - Two BDT trained for m_H<450 GeV and for m_H>450 GeV
  - tt, Drell-Yann, single top production, SM Higgs as background

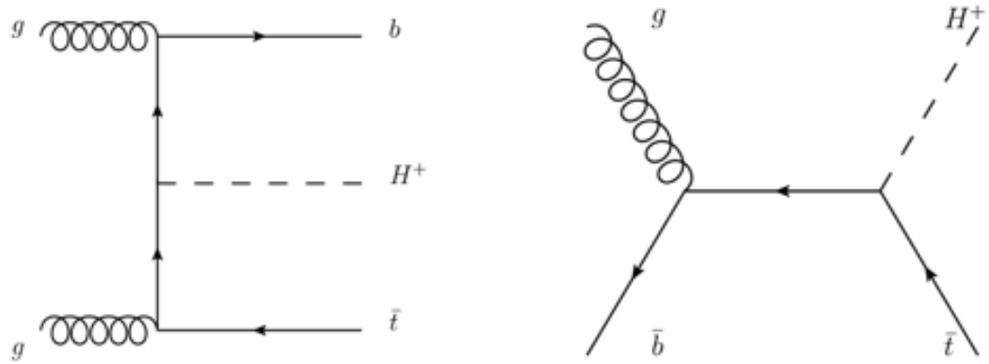




Search for $H^{\pm} \rightarrow \tau\nu$

ATLAS:CERN-PH-EP-2016-056
CMS: JHEP 11 (2015) 018

- $H^{\pm}$ 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.



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

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

Event Selection

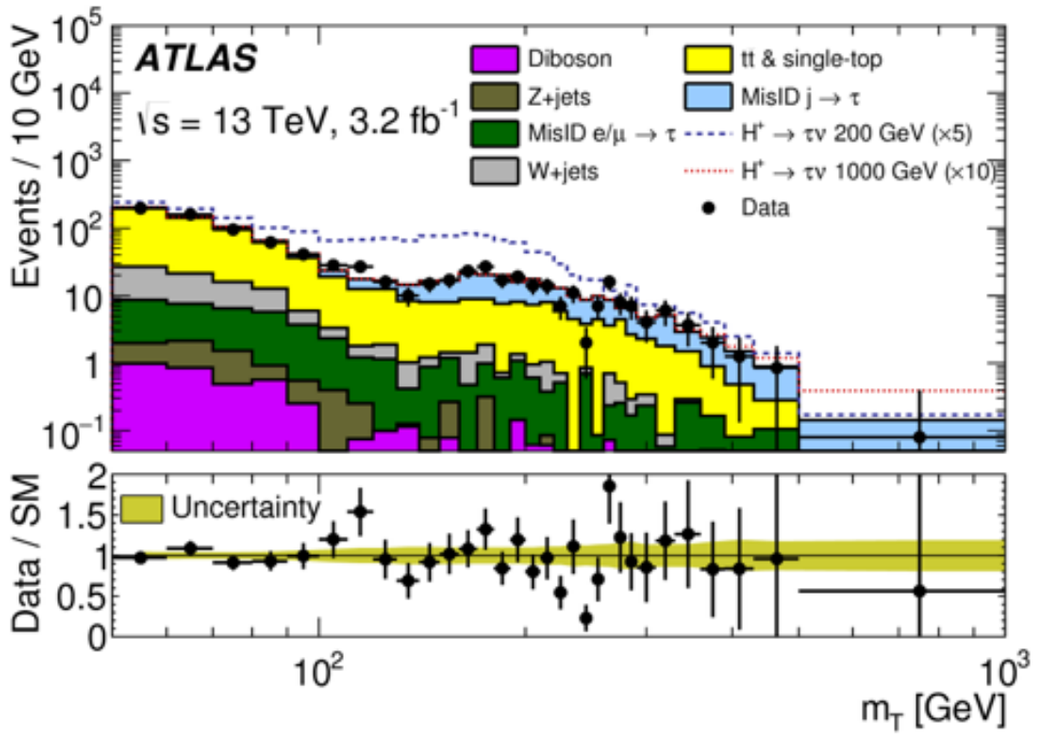
- E_T^{miss} trigger
- ≥3 jets including ≥1 b-tagged jet
- 1 τ and no e or μ
- $E_T^{miss} > 150$ GeV
- $m_T > 50$ GeV

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.)

final discriminant variable

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



2HDM+S: Search for h(125)→2a

CMS-PAS-HIG-14-041
CMS-PAS-HIG-15-011

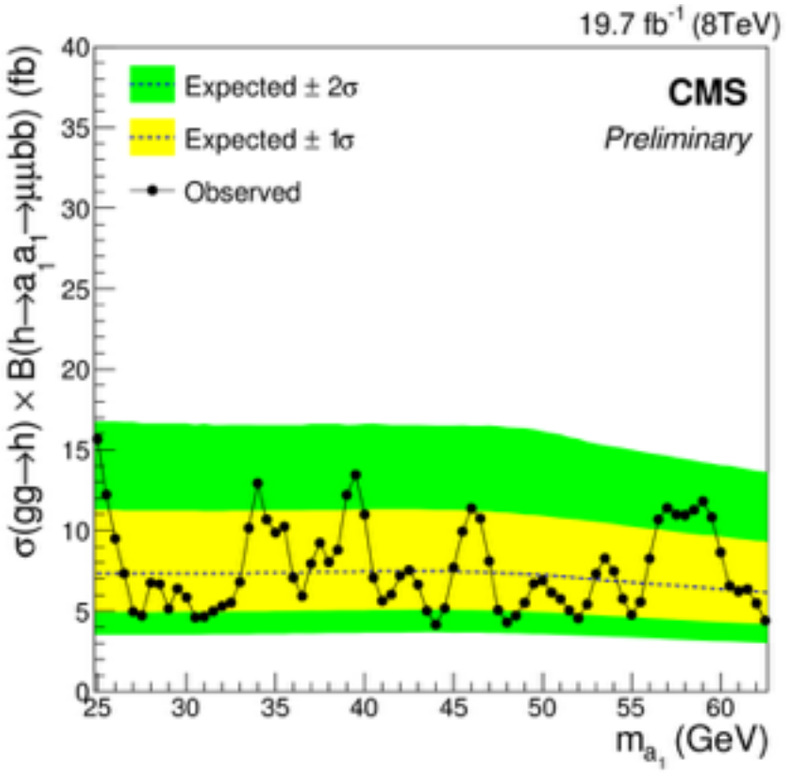
h→2a→2b2μ:

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

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

Fit the signal and background:

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



h→2a→2b2τ:

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

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

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

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

Fit of the signal ad background:

Irreducible backgrounds from MC, reducible from data-driven methods