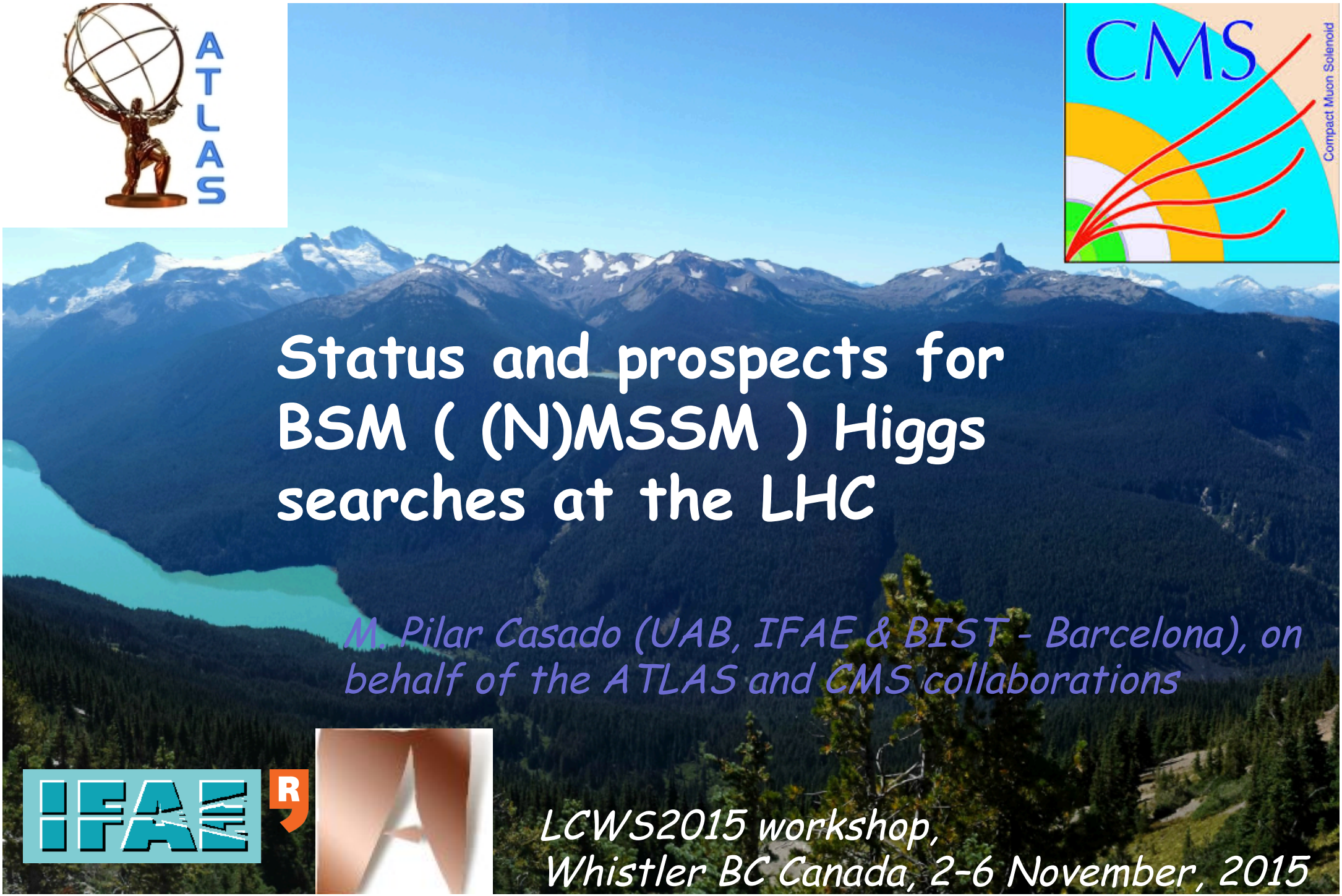


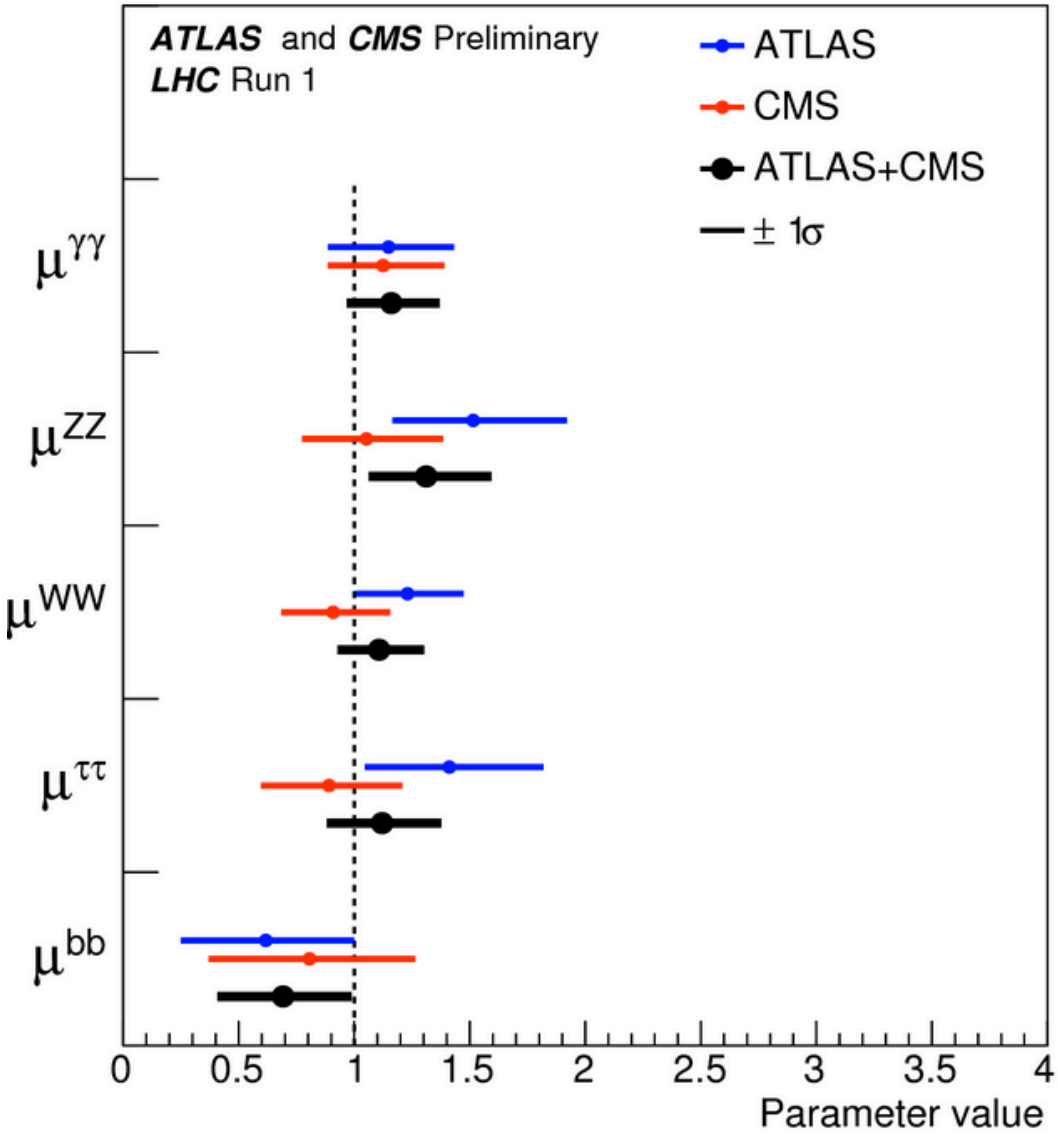
Status and prospects for BSM ((N)MSSM) Higgs searches at the LHC

M. Pilar Casado (UAB, IFAE & BIST - Barcelona), on behalf of the ATLAS and CMS collaborations

LCWS2015 workshop,
Whistler BC Canada, 2-6 November, 2015

Run I legacy on Higgs discovery

ATLAS-CONF-2015-044/
CMS-PAS-HIG-15-002



ATLAS & CMS combined mass:
PRL 114, 191803 (2015)

ATLAS & CMS combined couplings:
ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002

ATLAS J^{CP}: arXiv:1506.05669
CMS J^{CP}: Phys. Rev. D 92, 012004

ATLAS $d\sigma/dx$: arXiv:1508.02507
CMS $d\sigma/dx$: CMS-PAS-HIG-14-028

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

- Looks very much like SM-Higgs boson.
  So where will we find new physics?

Reasons for Beyond Stadard Model (BSM) Higgs

- There is no theoretical reason to have only one Higgs boson.
  - It is an open question wether the observed Higgs is responsible for the generation of all fermion masses (arXiv: 1508.01501)
  - Many theories include extra Higgs boson(s), as SUSY, models with axions, baryogenesis, neutrino masses,…
- So far, no physics observed beyond the SM.
- Reasons to extend SM:
  - Hierarchy problem
  - Dark matter
  - …

Strategies that use Higgs to find new physics

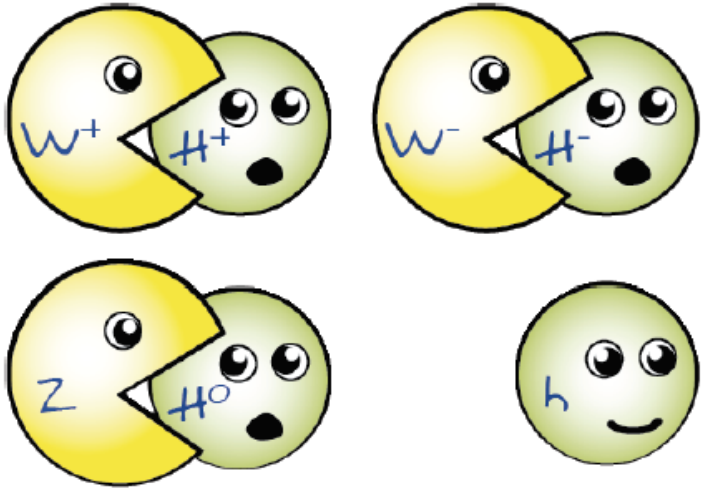
- Direct search for BSM Higgs boson
  - Most models include Two Higgs Double Model (2HDM) →
- Higgs boson −> invisible and dark sector analyses
- Higgs decays not allowed in SM
- New physics in Higgs boson pair production
- Discrepancies in couplings
- Discrepancies in kinematics

SM Higgs field vs 2HDM

SM Higgs field: Complex scalar doublet

4 degrees of freedom of which:

- 3 provide longitudinal components of $W^{\pm}$, Z
- 1 CP-even Higgs boson (h)



2HDM Higgs field: Two complex scalar doublets

More degrees of freedom than SM. For Higgs sector:

- 2 CP-even Higgs bosons (h,H), one of which is the observed 125 GeV resonance
- 1 CP-odd pseudoscalar (A)
- Two charged Higgs bosons ($H^{\pm}$)

Contents

- MSSM and NMSSM.
- Physics analysis:
  - MSSM Higgs searches
    - High tanβ
      - h/H/A -> ττ
      - h/H/A->bb
      - H+-> τν/tb
    - Low tanβ
      - A-> Zh
      - hh decays
      - H-> WW/ZZ
  - NMSSM motivated searches for a light Higgs:
    - a -> μμ
    - h-> aa
    - NMSSM inspired cascades

Common parameters of 2HDM

- Four Higgs masses (m_H, m_h, m_A, $m_{H\pm}$)
  - m_H or m_h = 125 GeV
- Ratio of the vacuum expectation values of the two doubles, $\tan\beta = v_2/v_1$.
- Mixing angle between H and h, α.

2HDM Type	Doublet coupled to up-type quarks	Doublet coupled to down-type quarks	Doublet coupled to leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

MSSM and NMSSM

- MSSM (Minimal Supersymmetric Standard Model) is the simplest extension of SM with Type II 2HDM for Higgs sector.
- NMSSM (Next-to MSSM) is an extension of MSSM with an extra gauge singlet
  - Solves μ-problem (fine-tuning) of MSSM
  - Gain extra CP-even and CP-odd Higgs bosons

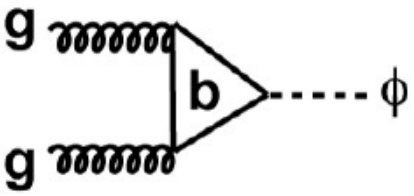
2HDM Type	Doublet coupled to up-type quarks	Doublet coupled to down-type quarks	Doublet coupled to leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

MSSM Neutral Higgses at LHC

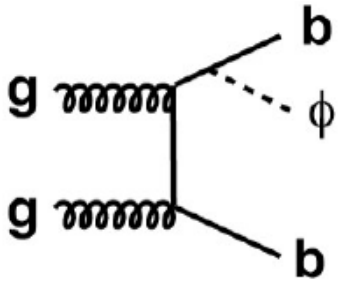
High tanβ

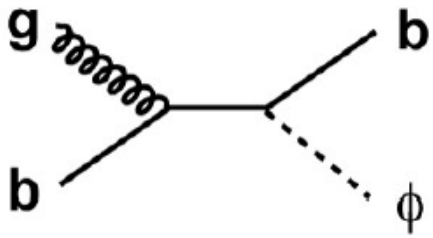
- Neutral Higgs production at the LHC

gluon-fusion



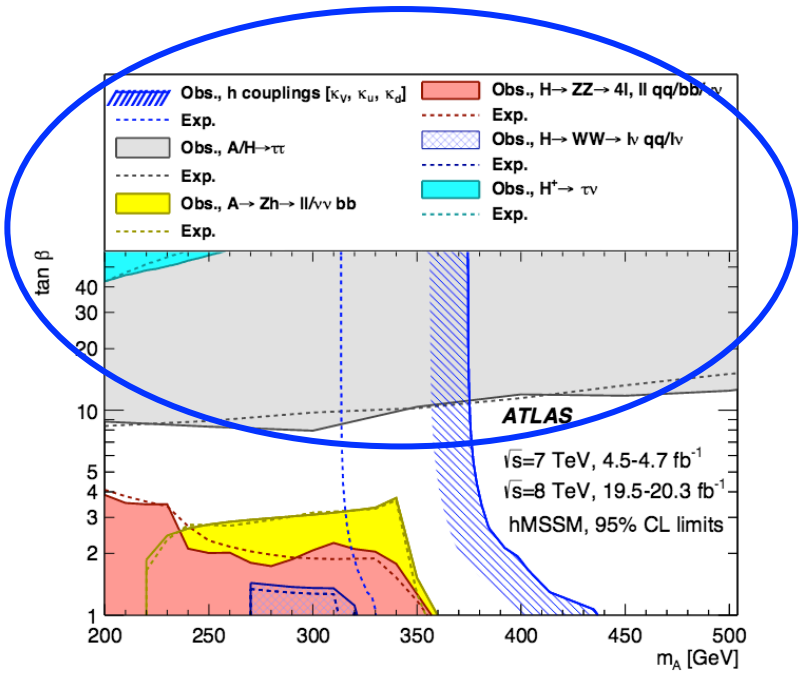
"b-associated" production





- Preferred decays at large tanβ: h/H/A −>ττ and bb
  - BR(h/H/A −>ττ)~10% at high tanβ.
  - "ττ" modes have usually better sensitivity

arXiv:1509.00672 (ATLAS)



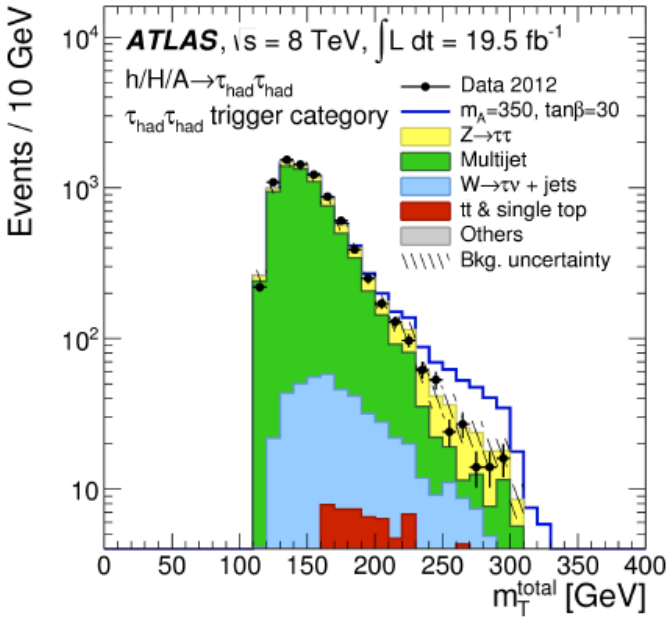
h/H/A−> ττ: arXiv:1409.6064 (ATLAS), arXiv:1408.3316 (CMS), arXiv:1304.2591 (LHC-b)

h/H/A −> bb: arXiv:1302.2892 (CMS), arXiv:1506.08329 (CMS)

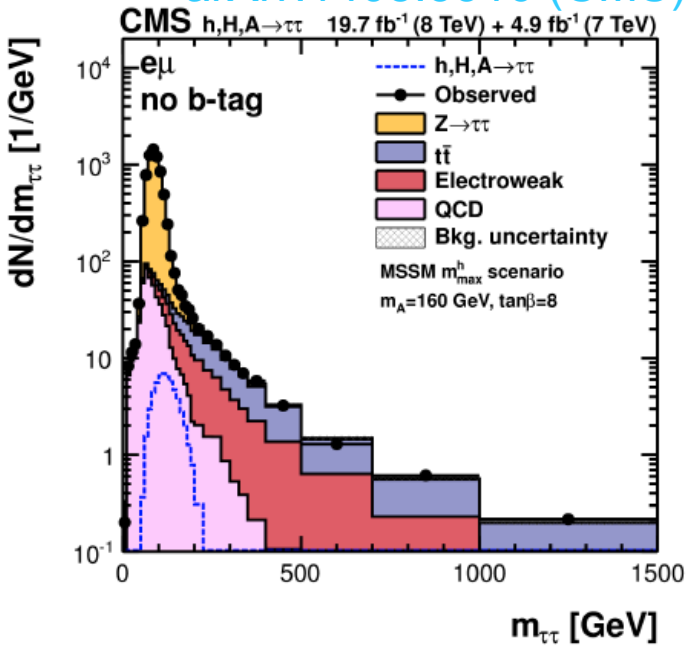
Searches for h/H/A −> ττ

- Categorization based on the following event properties
  - ττ pair decay: τ(e)τ(μ), τ(lep)τ(had), τ(had)τ(had)
  - "b-tag" and "b-veto" to take advantage of the b-associated production
- Most important backgrounds
  - All channels:
    - Z/γ* + jets (estimated with embedding)
    - multi-jet production (estimated from data)
    - top background (estimated from simulation)
  - τ(lep)τ(had) + τ(had)τ(had) only:
    - W + jets (estimated from simulation)
    - Dibosons (estimated from simulation)

arXiv:1409.6064 (ATLAS)

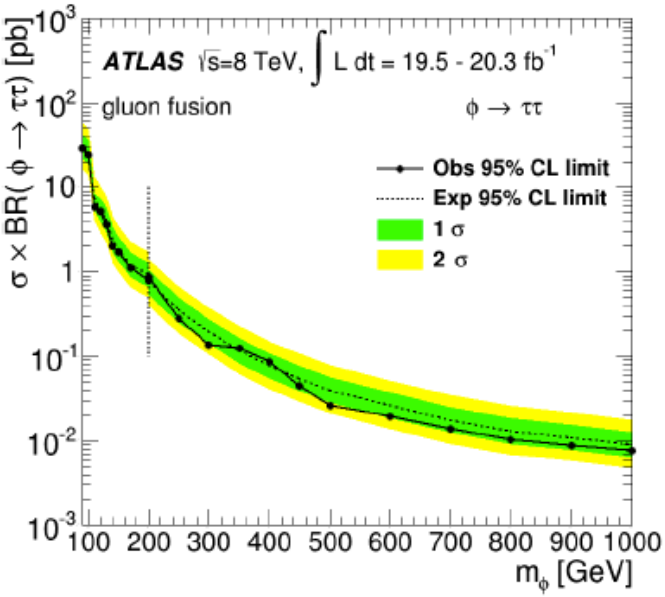


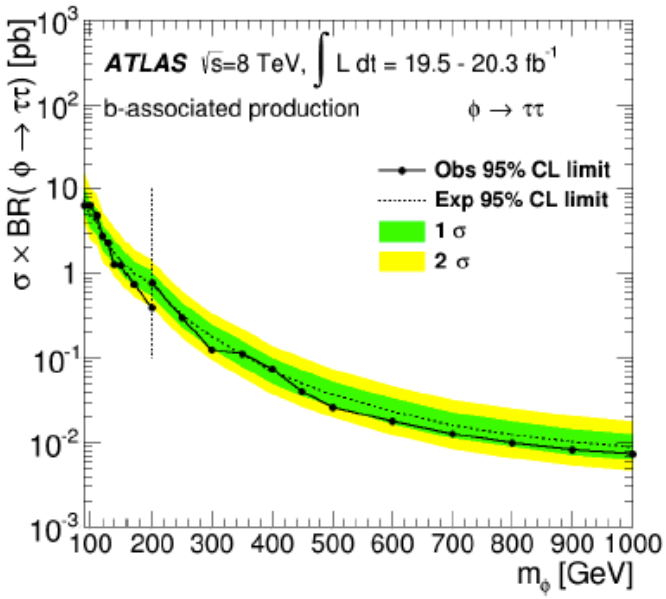
arXiv:1408.3316 (CMS)

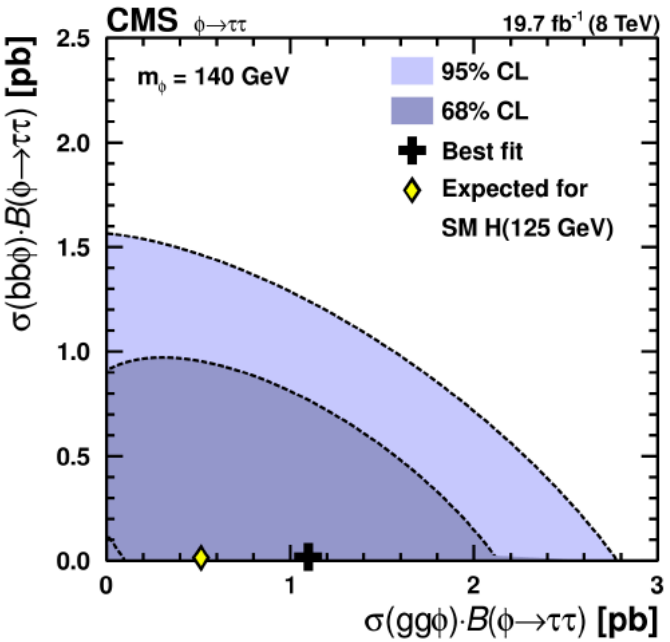


Searches for h/H/A -> ττ

- Cross section limits





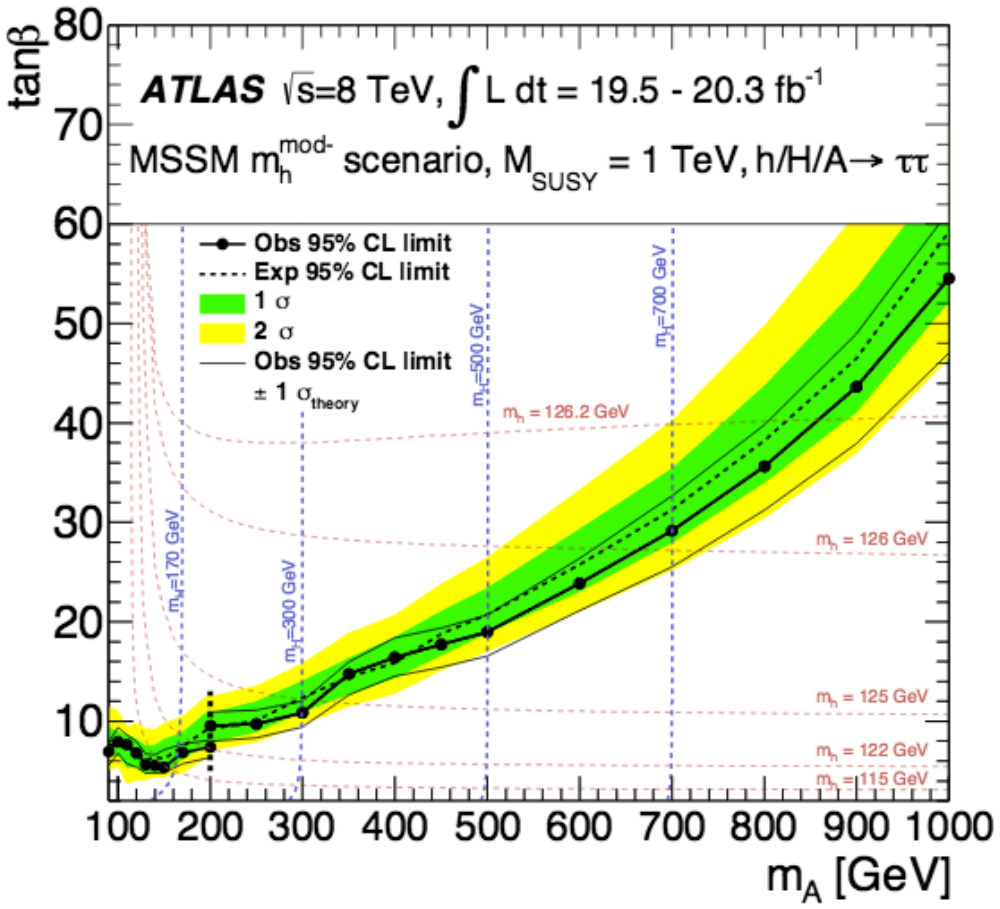


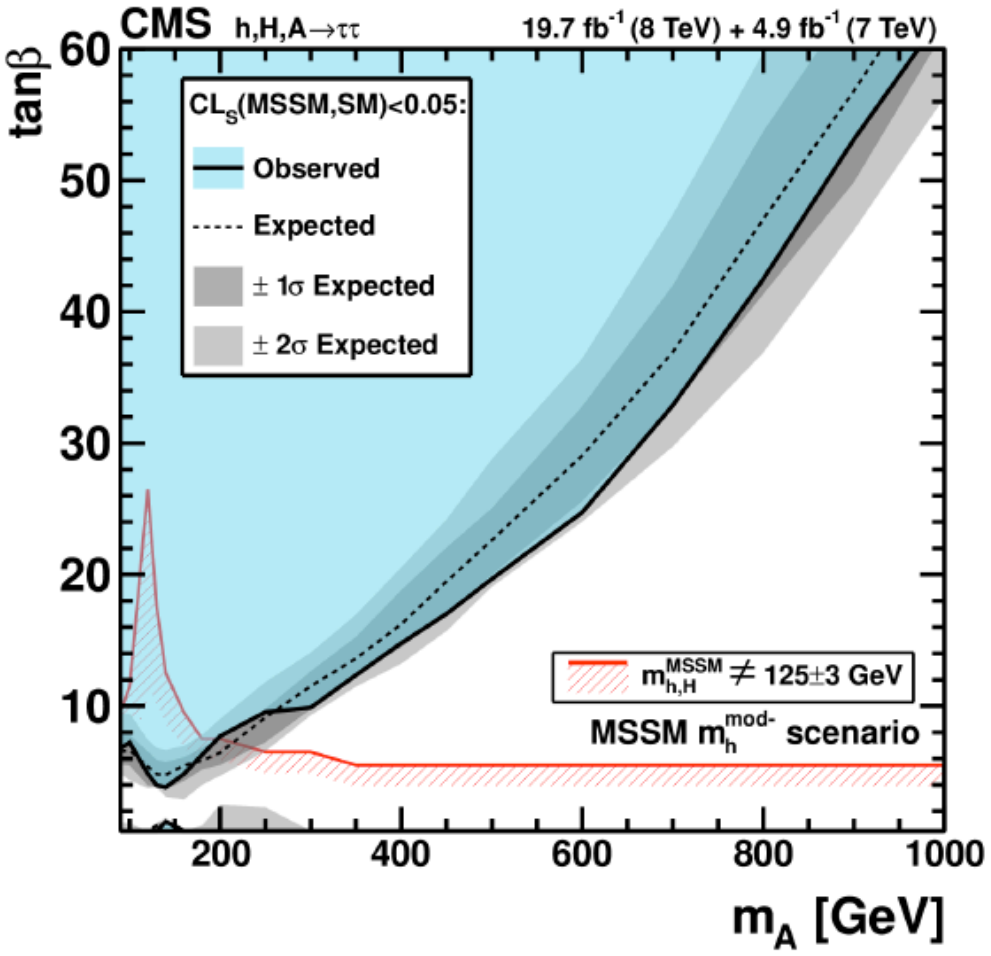
– "Traditional" cross section limits for a single scalar produced either via gluon-fusion or b-associated production from ATLAS

– 2D limit for a scalar particle that is produced by both gluon-fusion and b-associated production for a very fine grid of mass points from CMS

Searches for h/H/A -> ττ

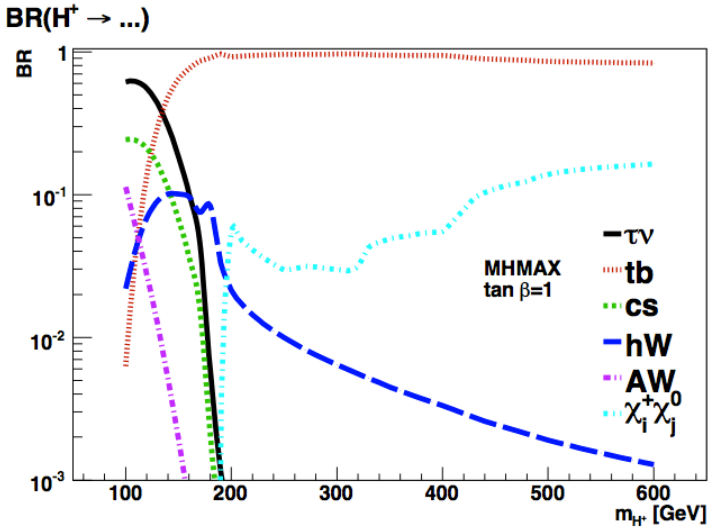
- Interpretation of the search in the m_h^{mod-} benchmark scenario

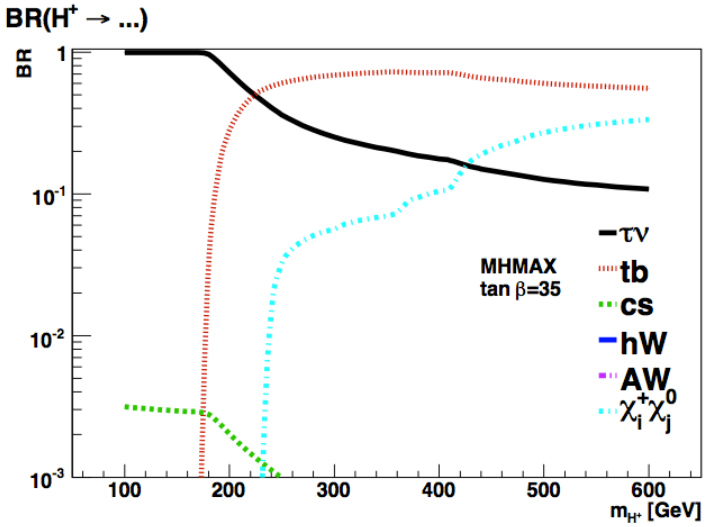


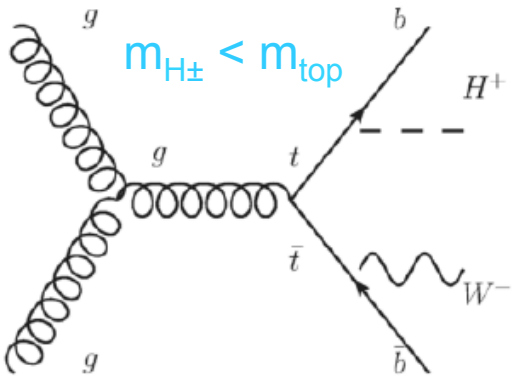


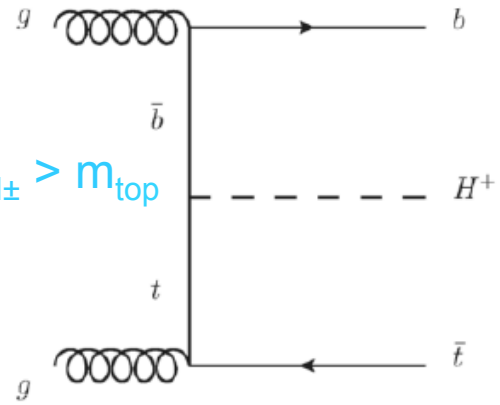
ATLAS and CMS search for $H^{\pm}$

- 2HDM/MSSM (NMSSM) predict the existence of $H^{\pm}$
- The BR($H^{\pm}$) is presented for m_h^{max} model of the MSSM
- $H^{\pm} \rightarrow \tau\nu$ is relevant in a large parameter range, specially for low $m_{H\pm}$ (below m_{top})
- For $m_{H\pm}$ above m_{top} $H^{\pm} \rightarrow tb$ is the predominant decay
- $H^{\pm} \rightarrow W^{\pm}Z$ also searched in the context of Higgs triplet model (not MSSM) arXiv: 1503.04233 (ATLAS)

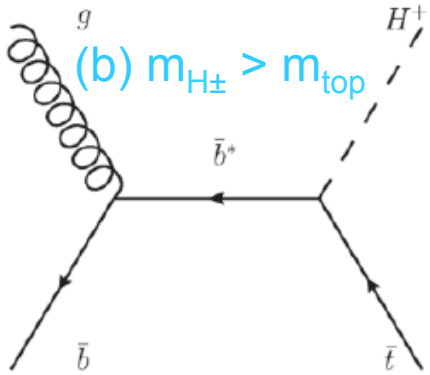








(a) $m_{H\pm} > m_{top}$

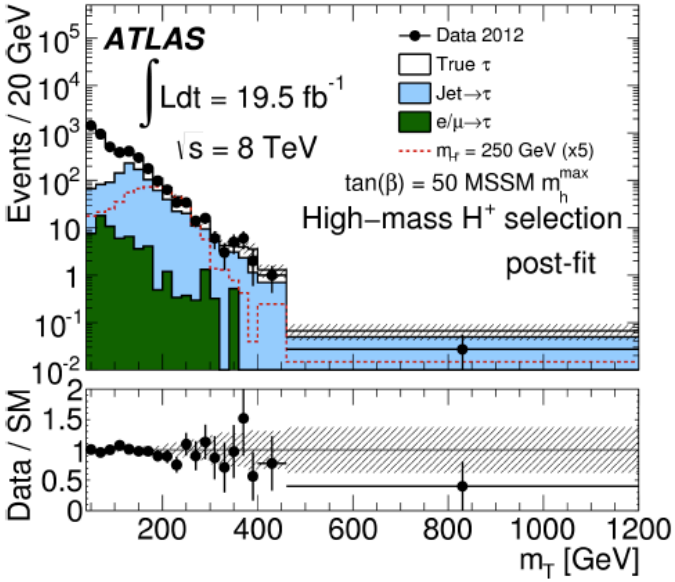


(b) $m_{H\pm} > m_{top}$

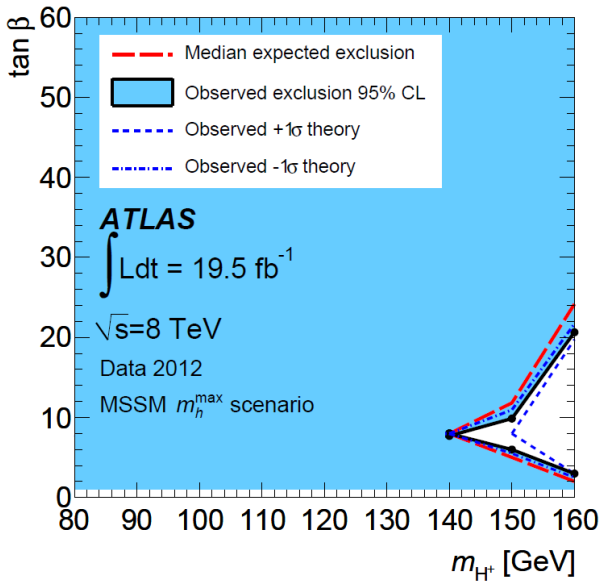
Search for $H^{\pm}\to\tau\nu$

- Similar strategies in both ATLAS and CMS at the search for a light and heavy $H^{\pm}\to\tau\nu$
- In the ATLAS search:
  - "tau+jets" channel: one hadronic tau decay and jets from the full hadronic top decays
  - tau+Missing E_T trigger: very involved
  - High and low mass categories are separated
- Example from the final discriminating distribution from the high mass category

arXiv:1412.6663 (ATLAS)



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

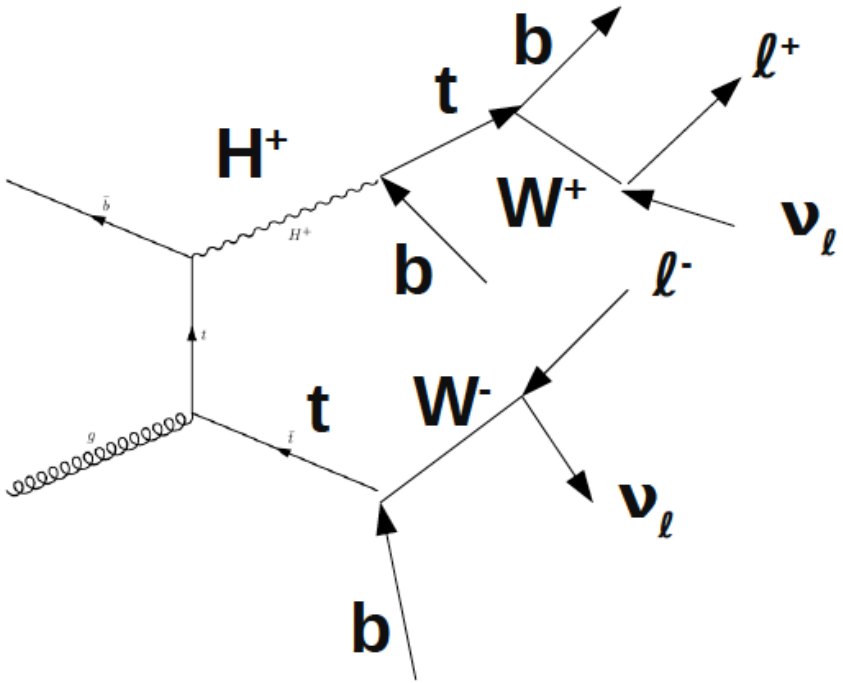


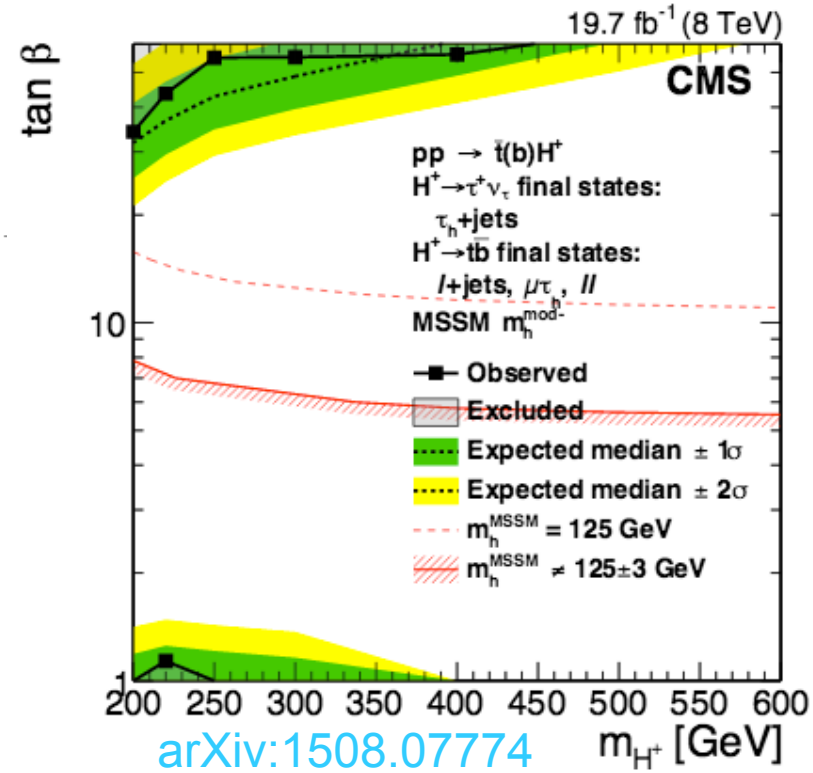
95% CL exclusion limits on tanβ as a function of m_{H+} in the context of m_h^{max} benchmark scenario of the MSSM, for mH+ < m_{top} search.

For CMS:arXiv:1508.07774

Search for $H^{\pm}$−>tb

- Most predominant decay at high mass.
- First results from LHC already available.





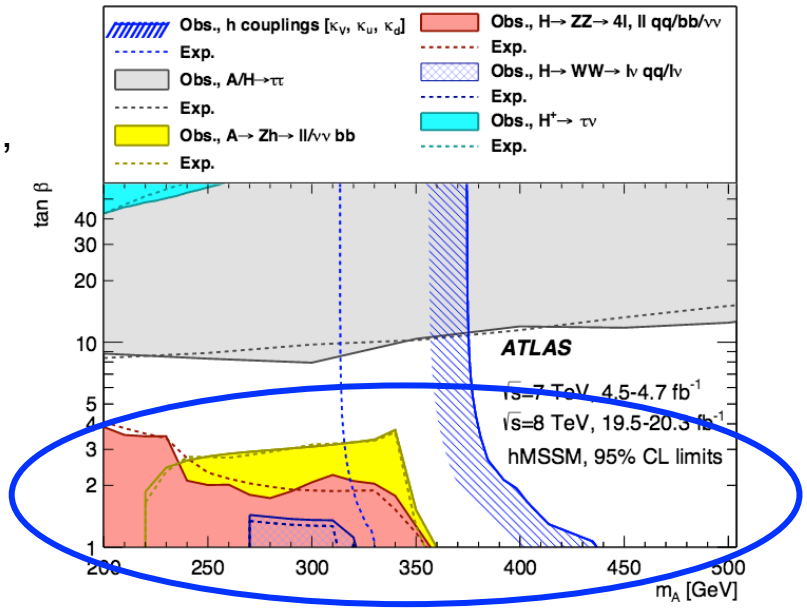
- Recent paper from CMS combining searches in τν and tb channels: arXiv:1508.07774 (CMS)

Remaining parameter space in the MSSM

Low tanβ

- The low tanβ regime in the MSSM has a very rich decay spectrum of MSSM Higgs bosons
  - However, the discovery of a light CP-even Higgs boson at 125 GeV has imposed very strong constraints: SUSY scale should be very high.
  - Examples:
    - A-> Zh:
      - Phys. Lett. B 744 (2015) 163-183 (ATLAS), arXiv:1504.04710 (CMS)
    - hh decays:
      - arXiv:1509.04670 (ATLAS), CMS-PAS-HIG-13-032
    - H-> WW/ZZ:
      - arXiv:1504.00936 (CMS), arXiv:1507.05930 (ATLAS), arXiv: 1509.00389 (ATLAS)

arXiv:1509.00672 (ATLAS)

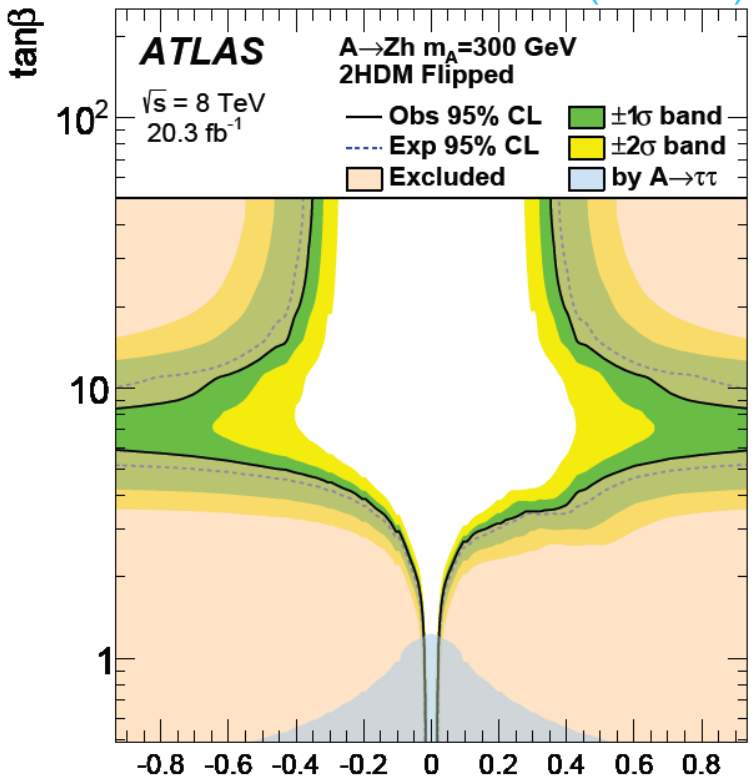


A−> Zh -> llττ/llbb/ννbb in ATLAS and CMS

Phys. Lett. B 744 (2015), 163-188, arXiv:1504.04710, arXiv:1510.01181

- Look for decays of new, heavy Higgs bosons to 125 GeV Higgs + Z boson
- Take advantage of Z−>ll / Z −>νν decays
- Use highest branching ratio of Higgs boson decays (bbbar/ττ).
- Typically use knowledge of masses of Z/h to select events, constrain the system and improve 4-object mass resolution.

Phys. Lett. B 744 (2015), 163-188 (ATLAS)

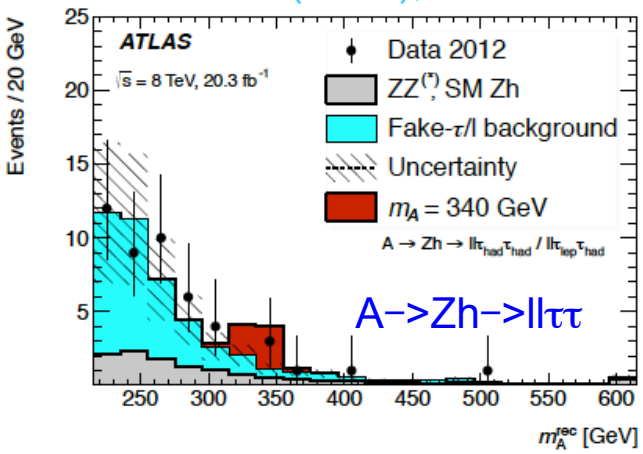


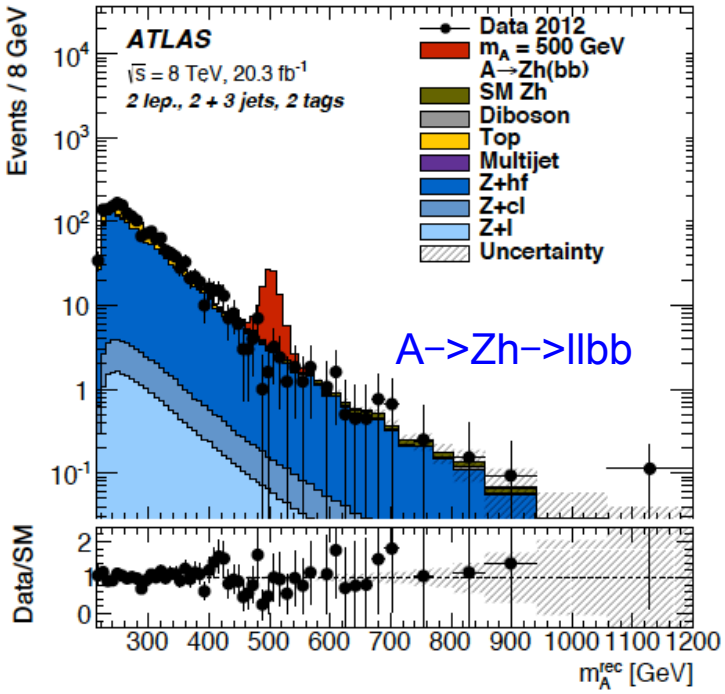
This type of search constrains parameter region in (tanβ, cos(β−α)) plane. The figure shows the 95% CL allowed region of parameter space for type II 2HDMs from ATLAS Run 1 measurements.

ATLAS search for A−> Zh -> llττ/llbb/ννbb

Phys. Lett. B 744 (2015), 163-188

- h−>ττ, Z−>ll
  - Categorized based on τ decays
  - Shape of hadronic tau fakes from SS events plus taus failing ID criteria. Normalization from sidebands.
- h−>bb, Z−>ll and νν
  - For Z−>νν use track MET and transverse mass.
  - Multijet backgrounds:
    - μμbb negligible
    - eebb estimated by fitting mll to templates with inverted isolation
    - ννbb estimated by inverting cuts on track versus calo MET.
  - V+HF constrained with V+0/1 btag versus number of jets.

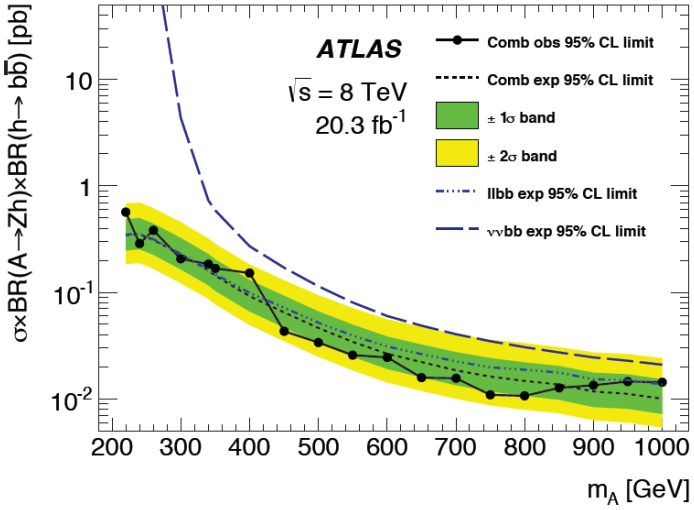




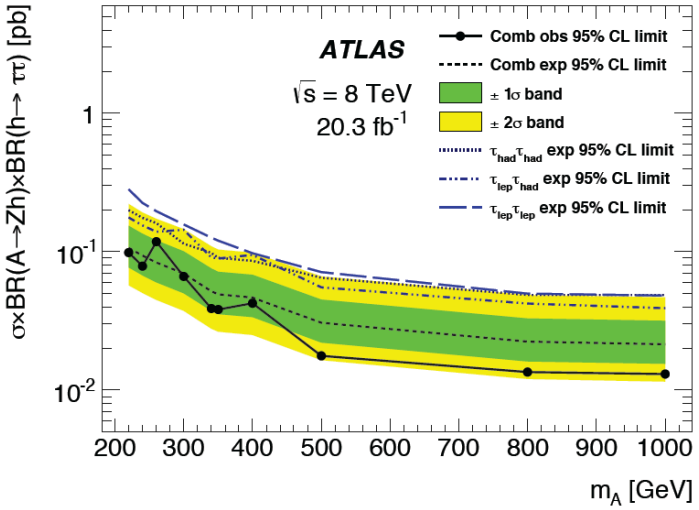
ATLAS search for A–> Zh -> llττ/llbb/ννbb

Phys. Lett. B 744 (2015), 163-188

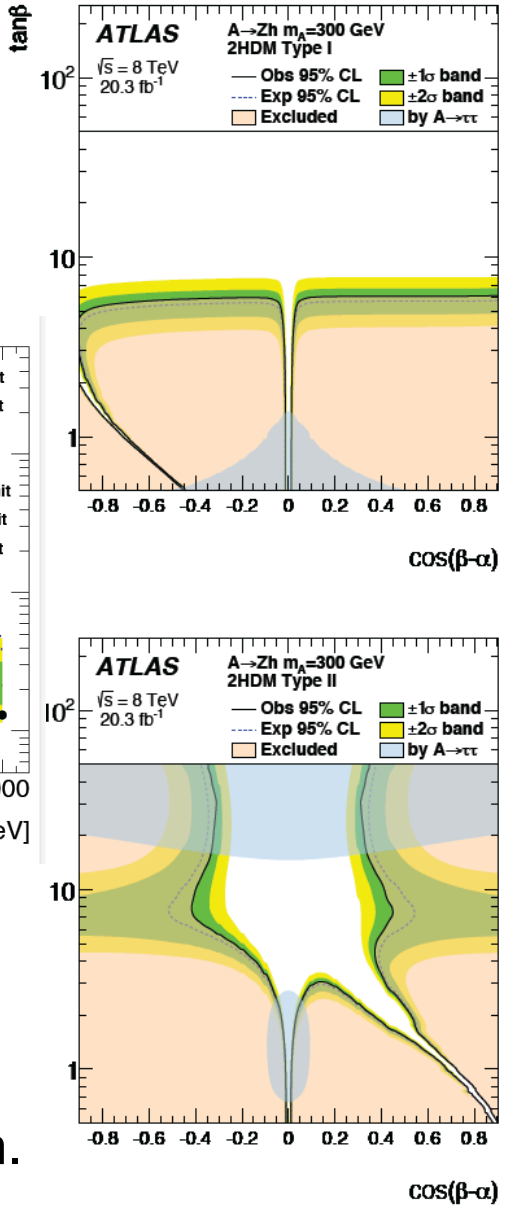
- Constraints for a gluon-fusion and b-associated produced heavy CP-odd Higgs boson A
- No evidence for new physics



A–>Zh, h–>bb



A–>Zh–>llττ

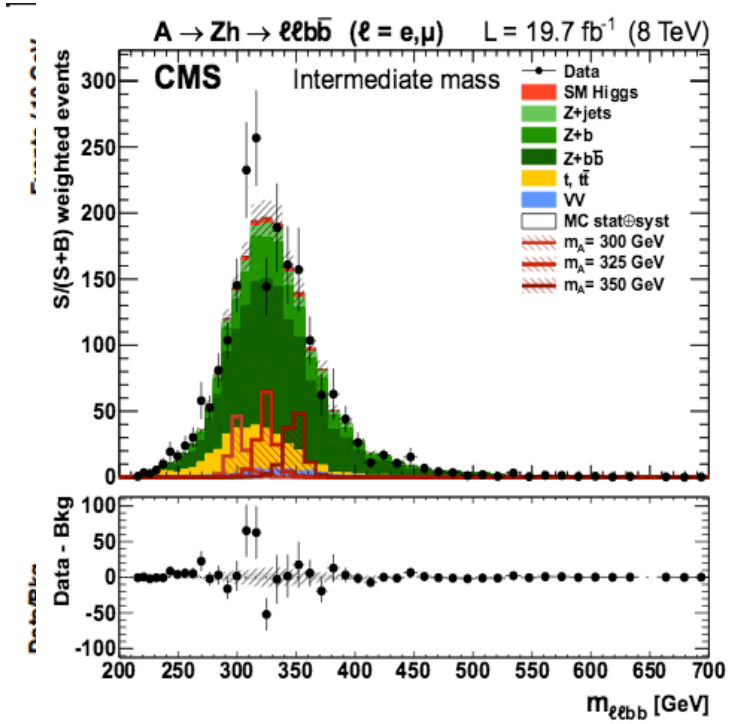


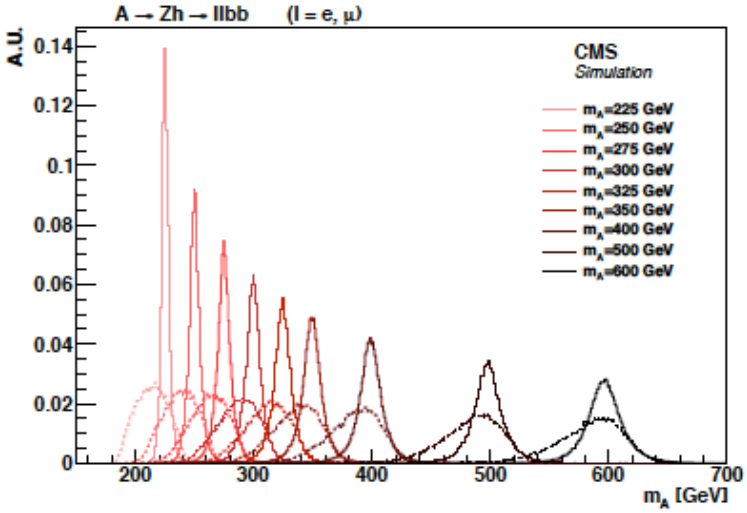
Cross-section times BR limits use gluon-fusion only, while plots on the right also use b-associated production.

CMS search for A−> Zh -> llbb

arXiv:1504.04710 (CMS)

- Use loose and tight b-tagging
- Study 0/1/2 btag regions but m_{bb} far from m_h
- Kinematic fit to improve mass resolution
- Multivariate BDT trained separately for different m_A values
- Results from fit to 2D distributions of BDT and m_{llbb}

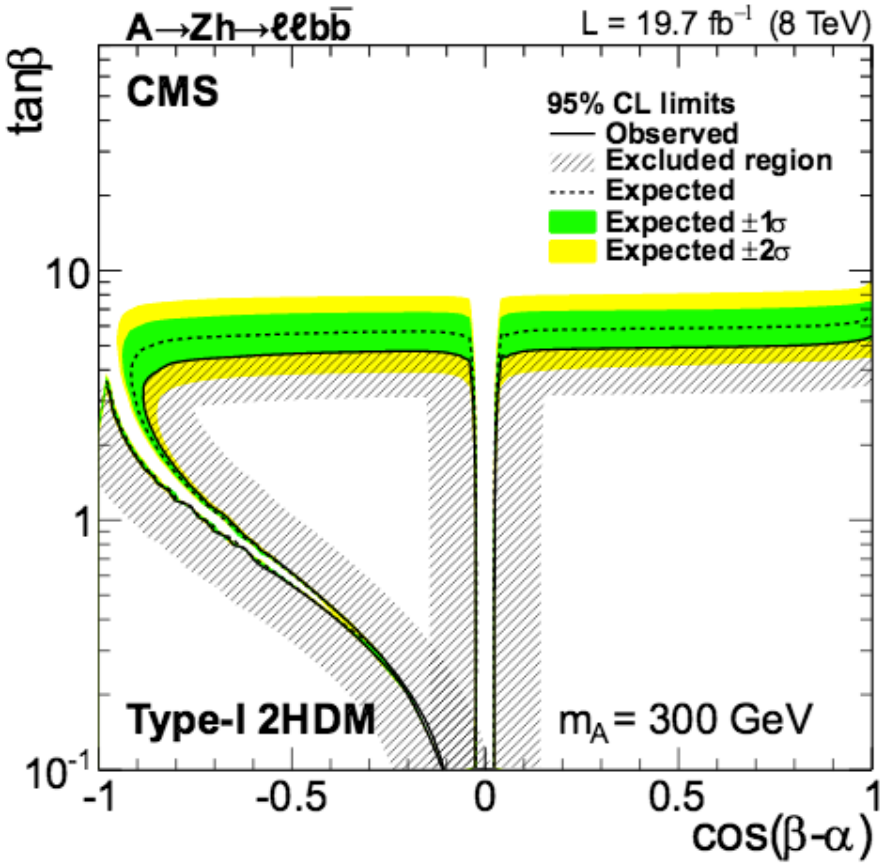


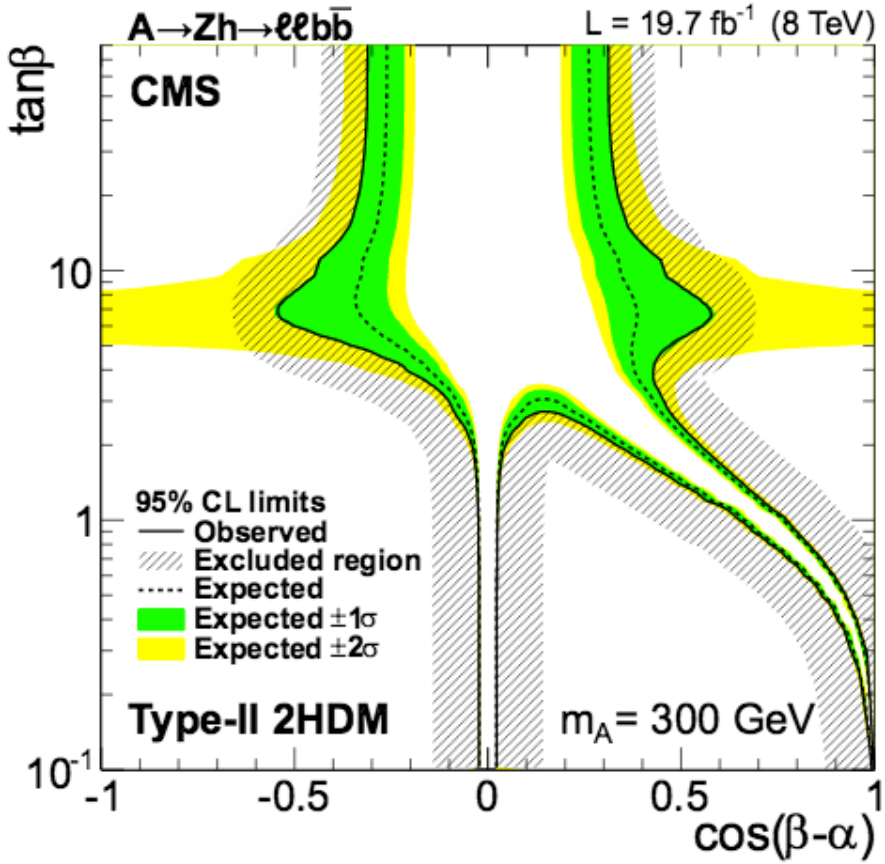


CMS search for A−> Zh −> llbb

arXiv:1504.04710

- BDT adding significant additional information:
  - Using 1D fit only worsens limits by 10-20%



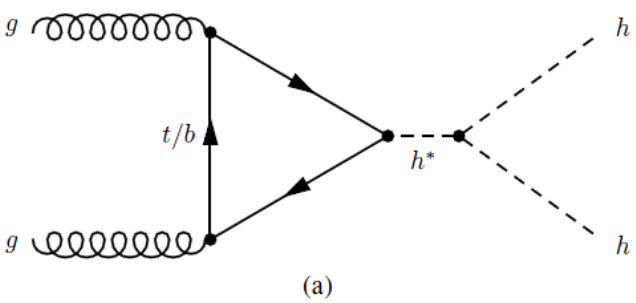


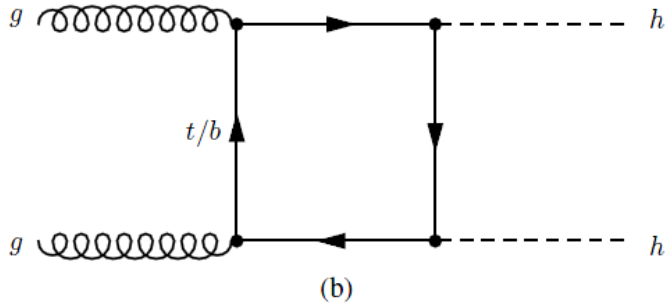
Search for hh->bbγγ/bbbb/bbττ/WWγγ

arXiv:1509.04670 (ATLAS),
CMS-PAS-HIG-13-032

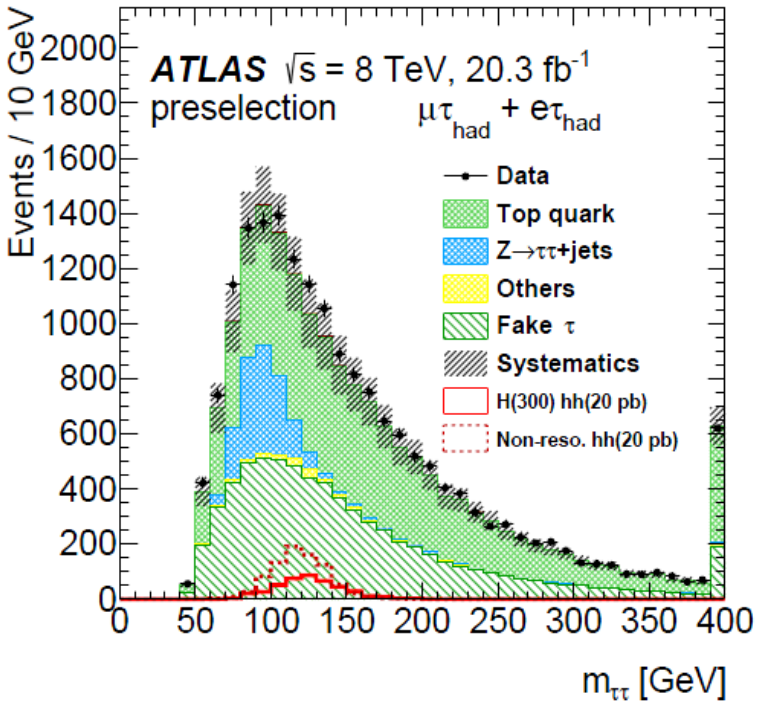
- Search for both resonant and nonresonant Higgs boson pair production

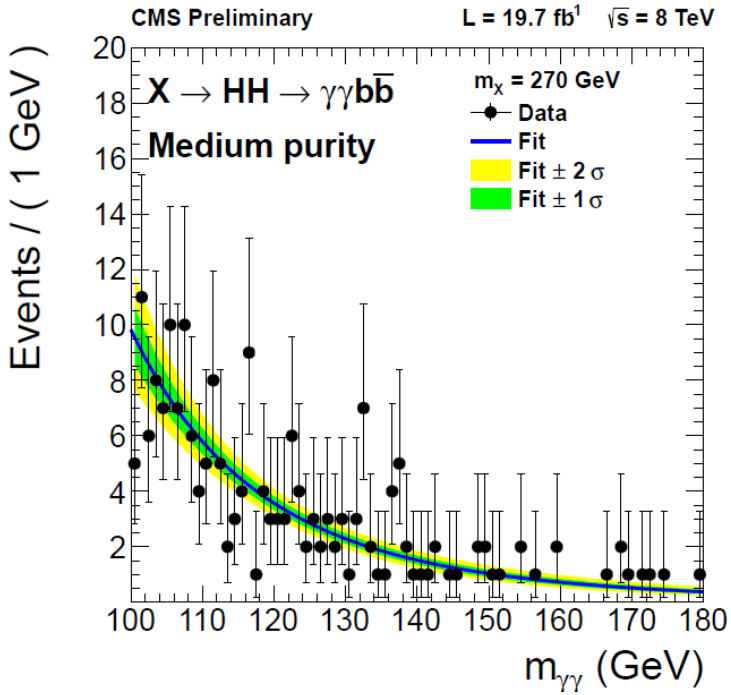
New





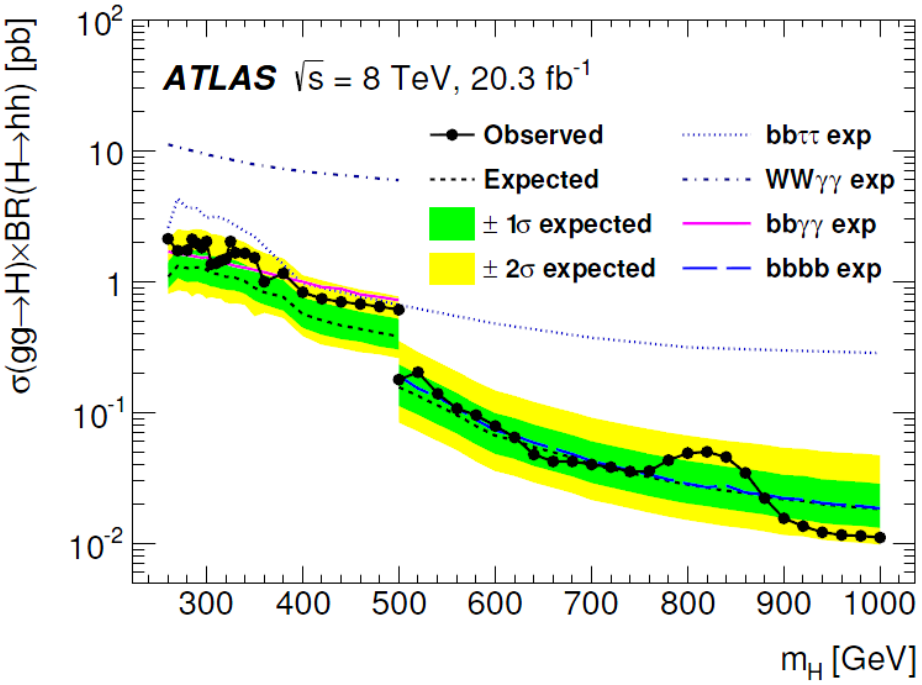
hh -> bbττ channel



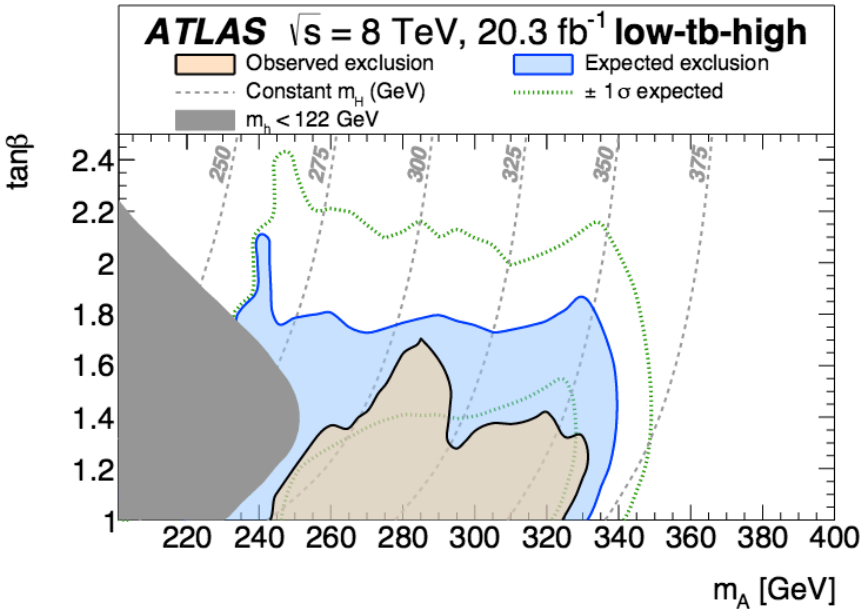


Nonresonant background fits in mγγ for one of the categories (medium purity) for the resonance mass hypothesis of 270 GeV.

Search for hh->bbγγ/bbbb/bbττ/WWγγ



Results combining all channels. The improvement above 500 GeV is due to the sensitivity of the hh->bbbb channel.

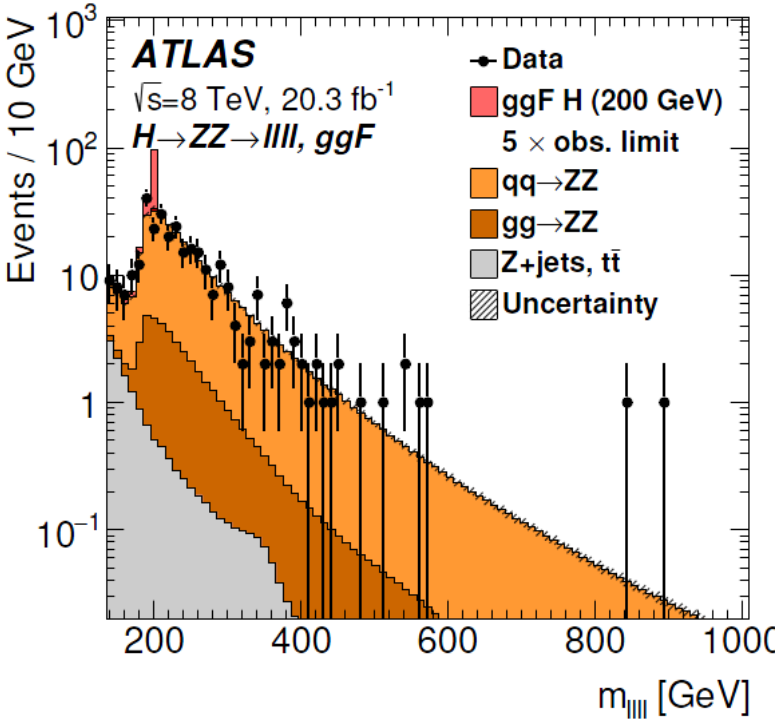


Observed and expected 95% CL exclusion regions in ($\tan\beta$,m_A) plane for the low-$\tan\beta$-high MSSM scenario. The observed exclusion region in this plane is smaller than the expectation, reflecting a small excess observed in data.

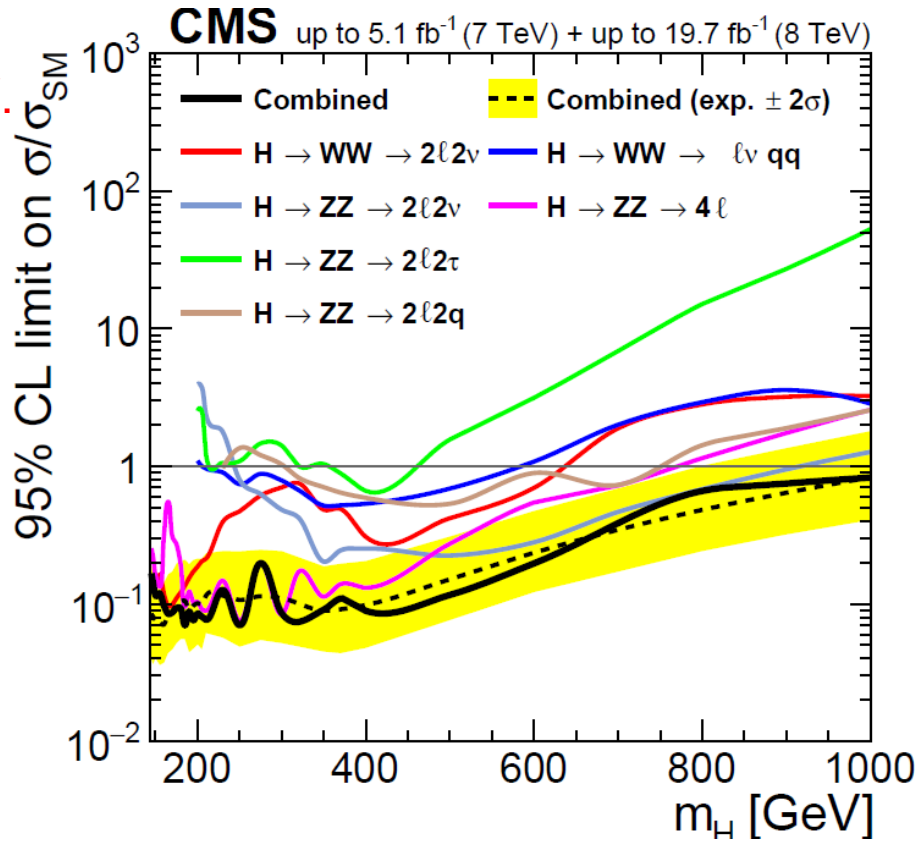
Search for H−> WW/ZZ

New−> arXiv:1507.05930 (ATLAS), arXiv:1504.00936 (CMS)

- In this search the Higgs is either produced by gluon fusion, VBF or VH processes
  - Mass range from 140-400 GeV up to 1 TeV.



Distribution used in a likelihood fit of the four-lepton invariant mass (m_{llll}) for H−>ZZ−>llll search in the gluon-fusion production mode. No events are observed beyond the upper limit of the plot.



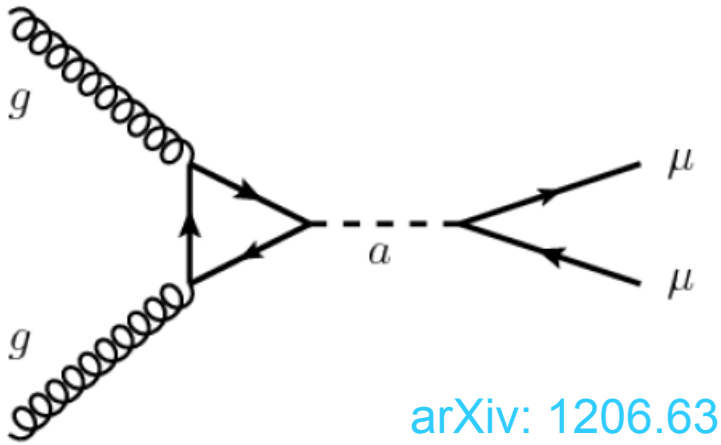
Upper limits at 95% CL for each of the contributing final states and their combination. The theoretical cross section, σ_{SM}, is computed in arXiv:1307.1347.

Next-to-MSSM (NMSSM)

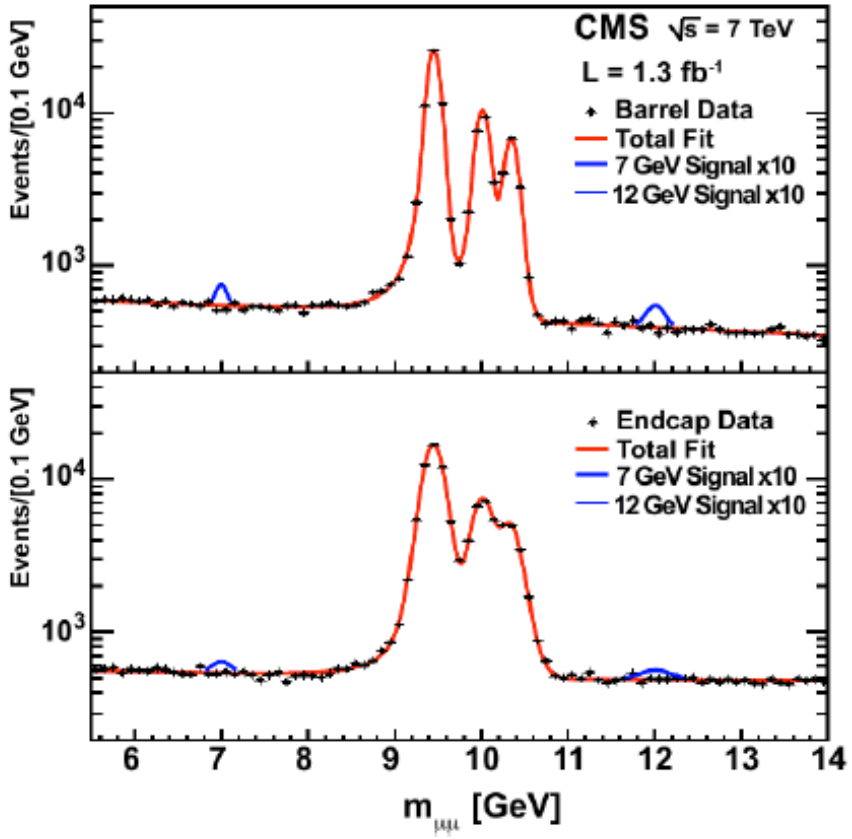
- NMSSM: next to minimal supersymmetric Standard Model
  - Addition of a singlet in the Higgs sector
  - 2 more Higgses and one more neutralino with respect to MSSM; more freedom with respect to the MSSM
    - Higgs sector not necessarily CP conserving at lowest order (although usually CP-conservation is assumed)
    - Tree level MSSM relation "$m_h < m_Z$" is not valid any more
  - Typical signatures involve a light CP-odd Higgs
    - a->μμ arXiv: 1206.6326 (CMS)
    - h->aa->μμττ/μμμμ arXiv:1506.00424 (CMS), 1505.01609 (ATLAS)
    - h_1->bb in cascades CMS-PAS-HIG-14-030
    - …

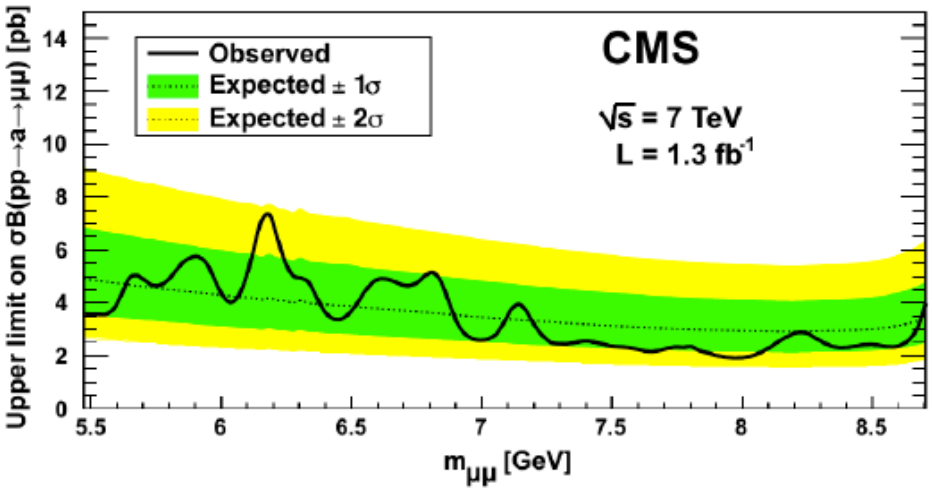
Search for a->μμ

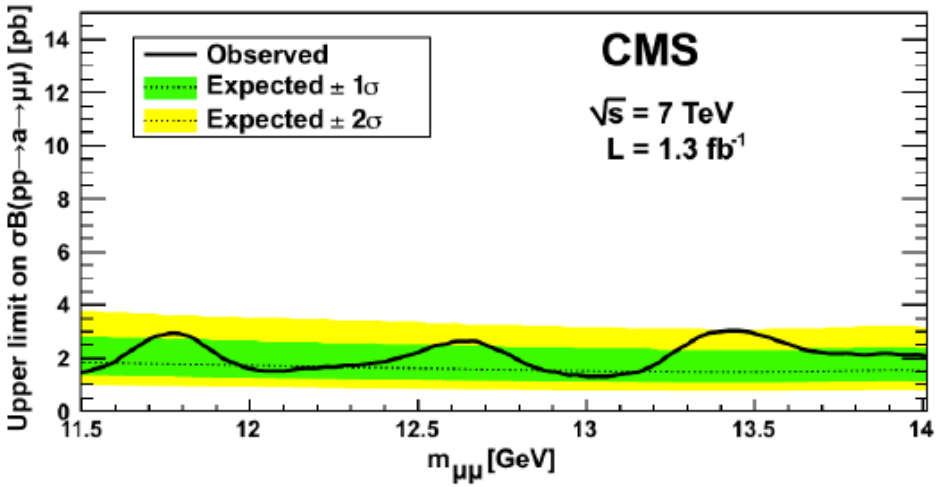
- Search for a gluon-fusion produced, light CP-odd Higgs boson decaying to μμ



arXiv: 1206.6326 (CMS)

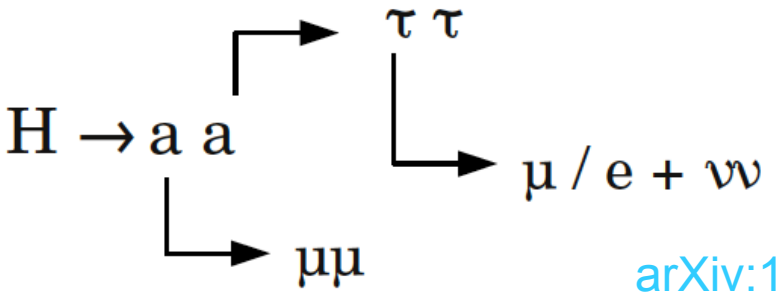


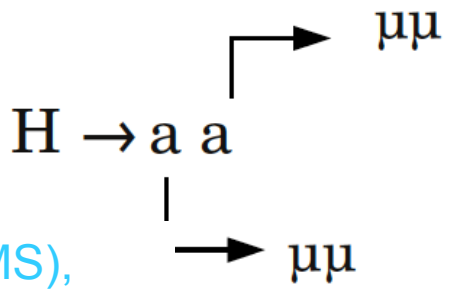




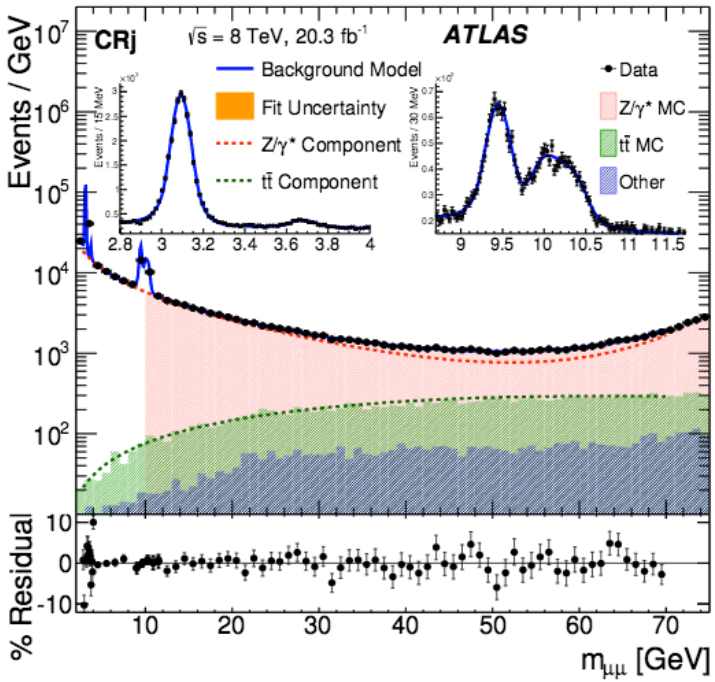
Search for h ->aa->μμττ / μμμμ

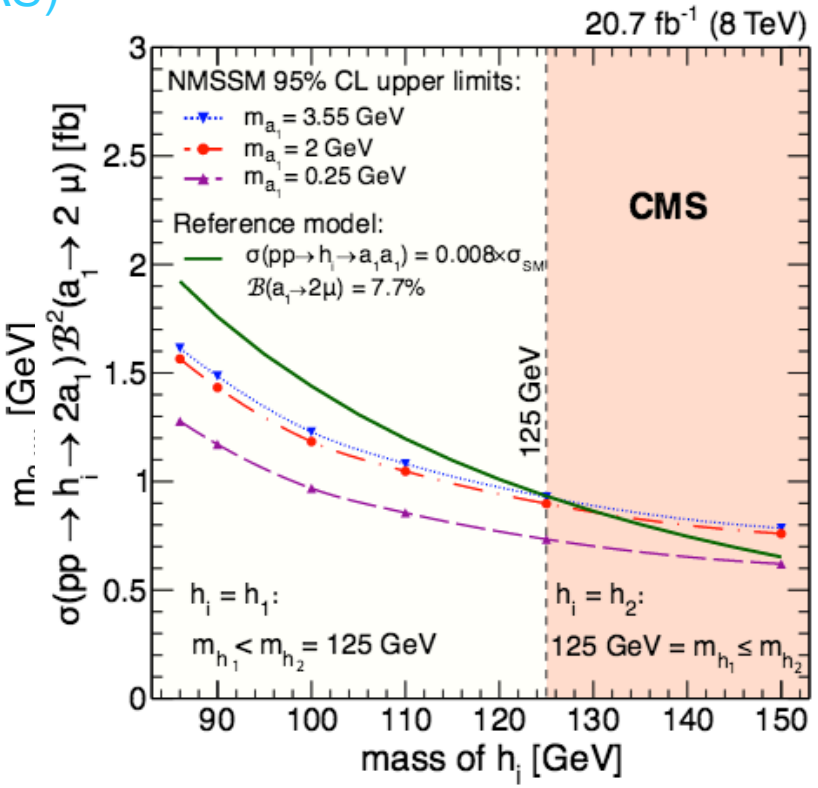
- Search for this decay in multi-lepton events, with several resonances involved





arXiv:1506.00424 (CMS),
1505.01609 (ATLAS)



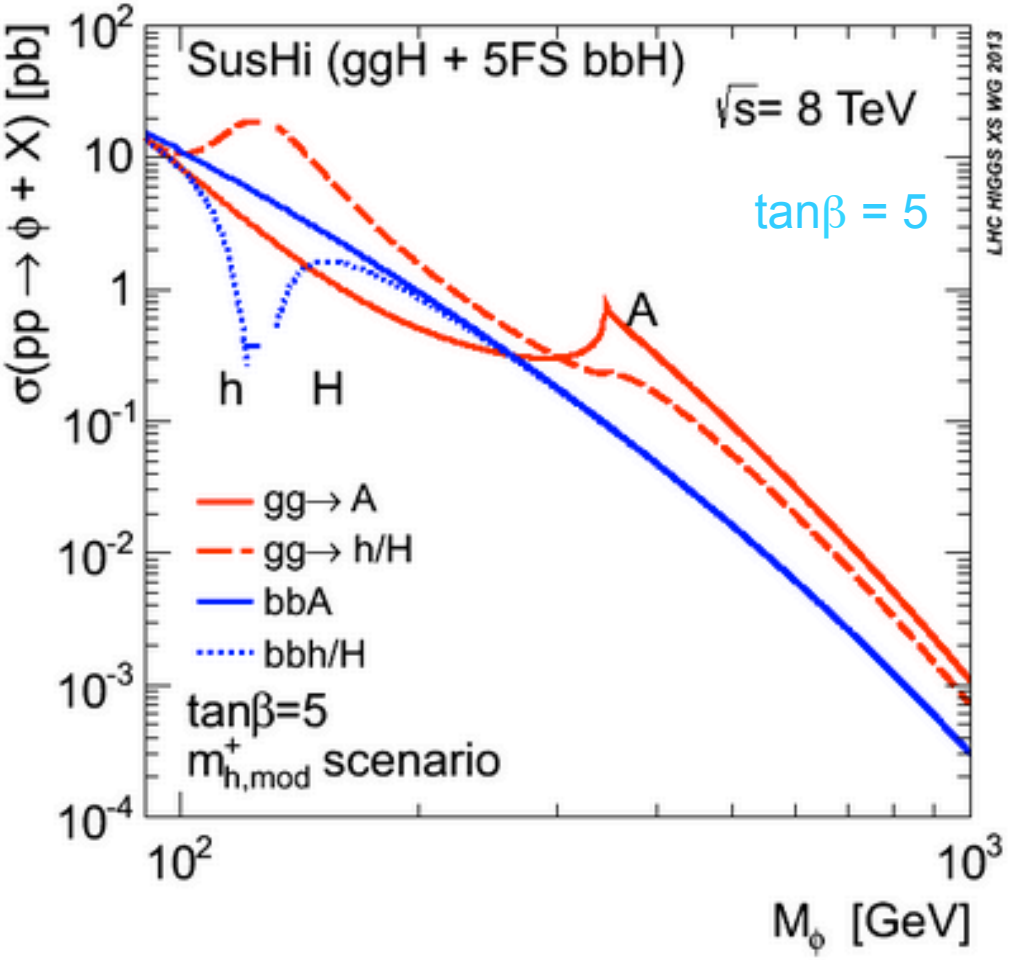


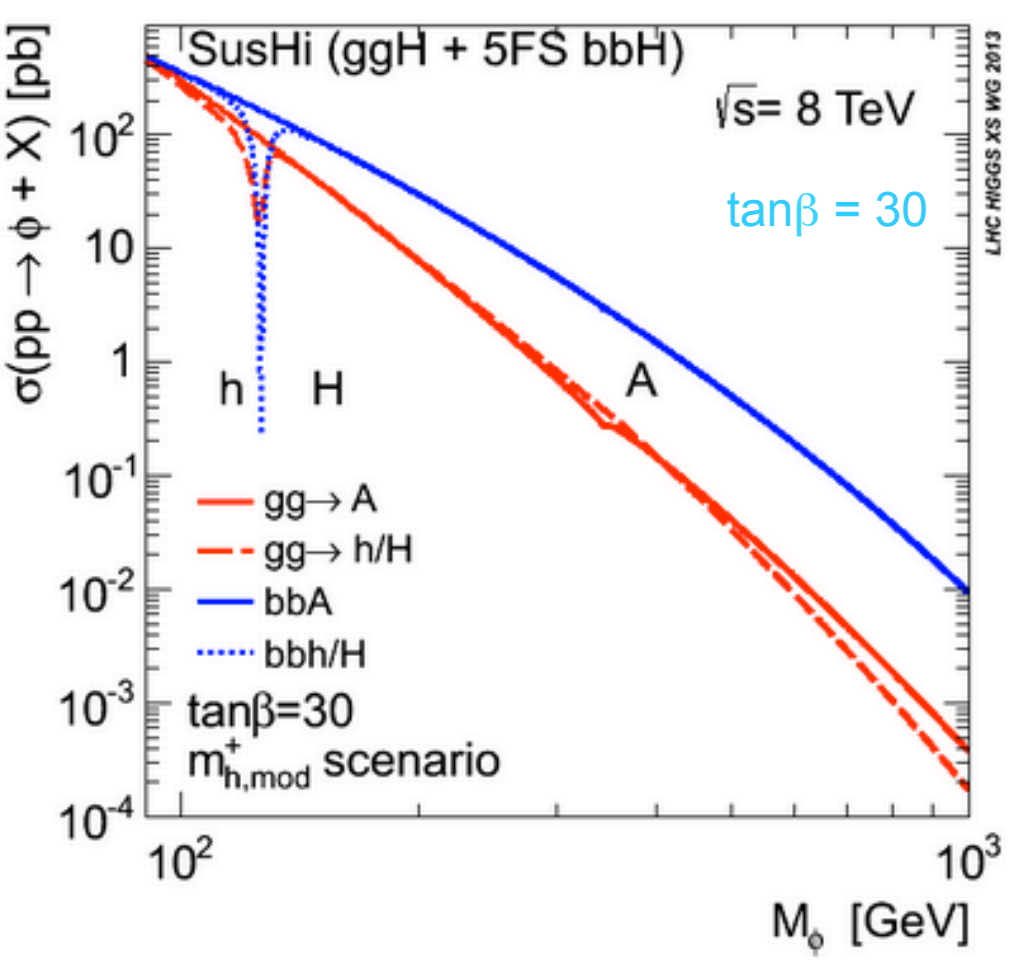
Conclusions

- No evidence for BSM Higgs yet.
- Current searches constrain large parts of parameter space
  - There are still many things to do be done, and many searches that are still starting up.
  - Expect that this will continue to be a hot area in Run-II.
- For the coming months expect early results in high mass searches.
- For Moriond, search of intermediate-high mass Higgs bosons with full 2015 dataset.
- For summer, update with searches sensitive to additional data collected in 2016.

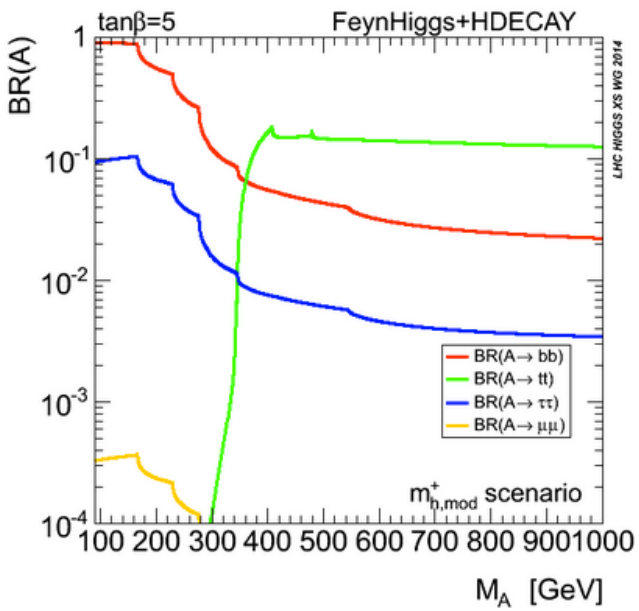
Backup

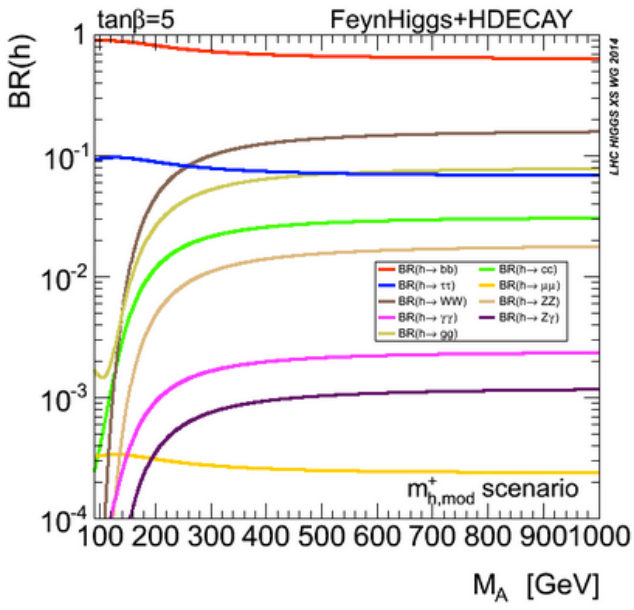
Production modes in MSSM

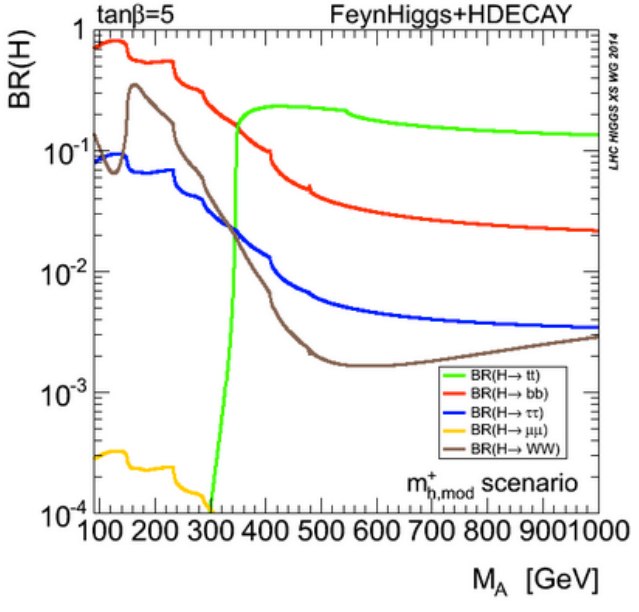


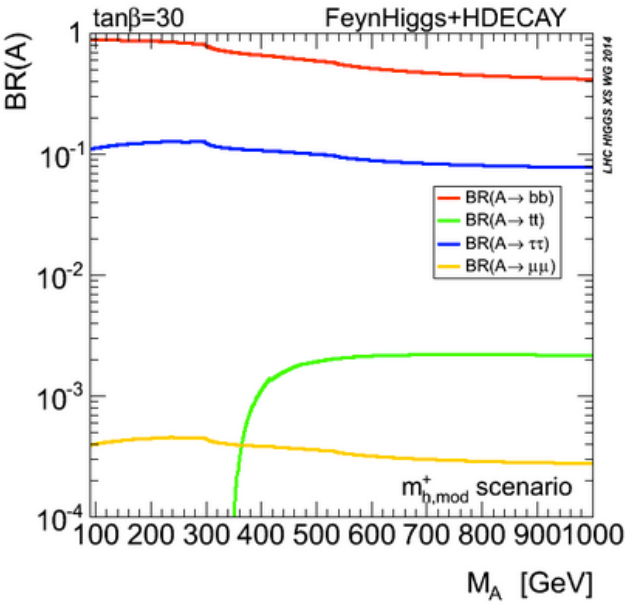


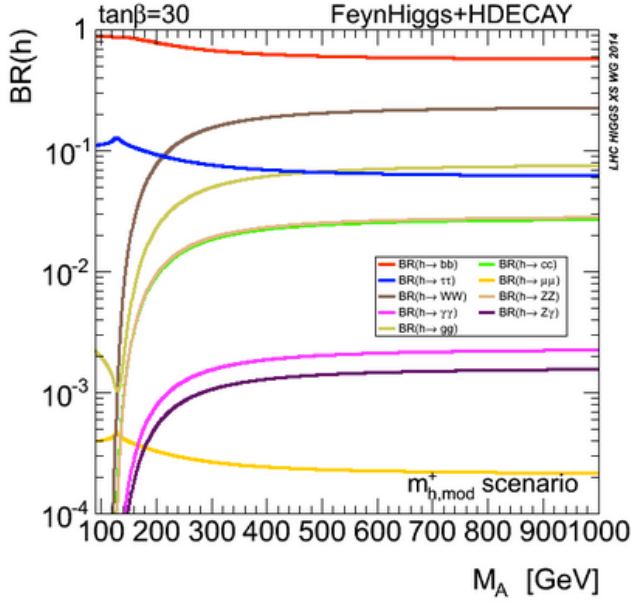
Branching ratios in MSSM

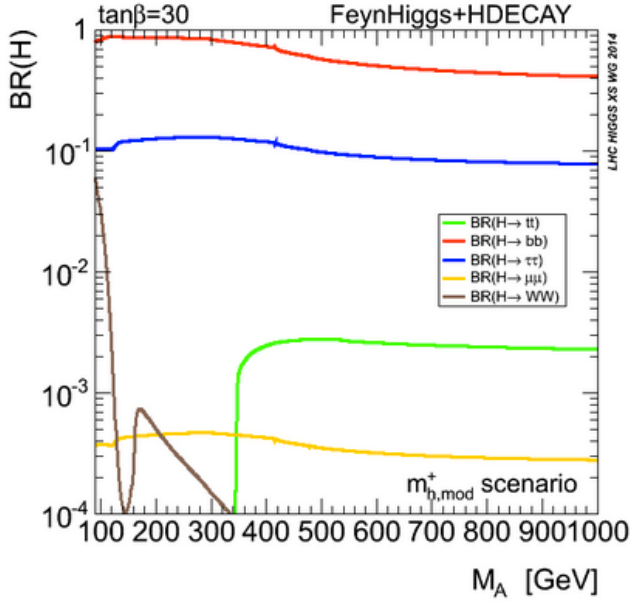










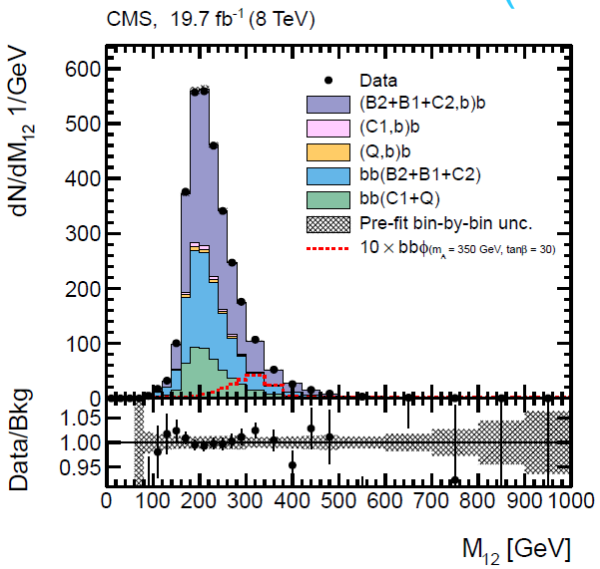


Searches for h/H/A ->bb

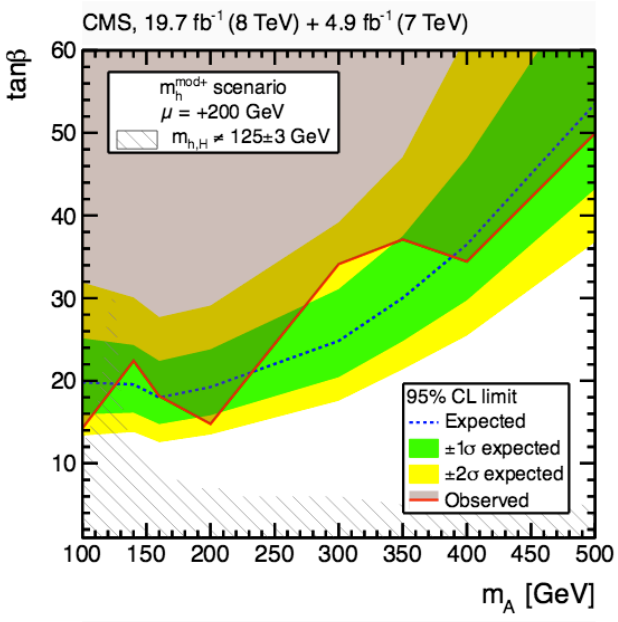
High tanβ

- Trigger selection: 2 high p_T b-jets inclusive. Offline selection: 3 tight b-tag inclusive.
- Most important background: QCD, estimated from data with control samples.
- Categorize the events according to flavor of jets: 2b, 1b, 2c, 1c, LF jets.
- Use different templates for each category and merge according to weight from simulation

arXiv:1506.08329 (CMS)



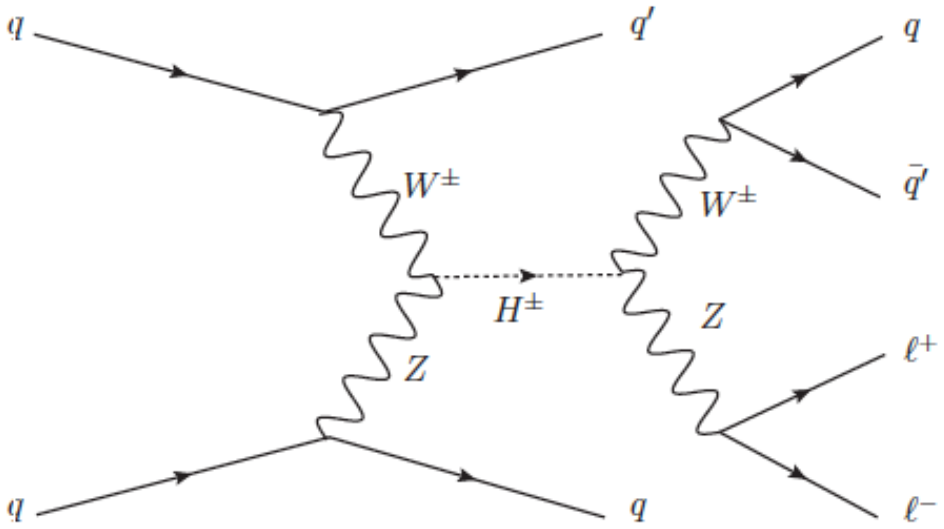
Projection of the dijet mas M_{12} in the triple-b-tag sample, together with the corresponding projections of the fitted background templates.



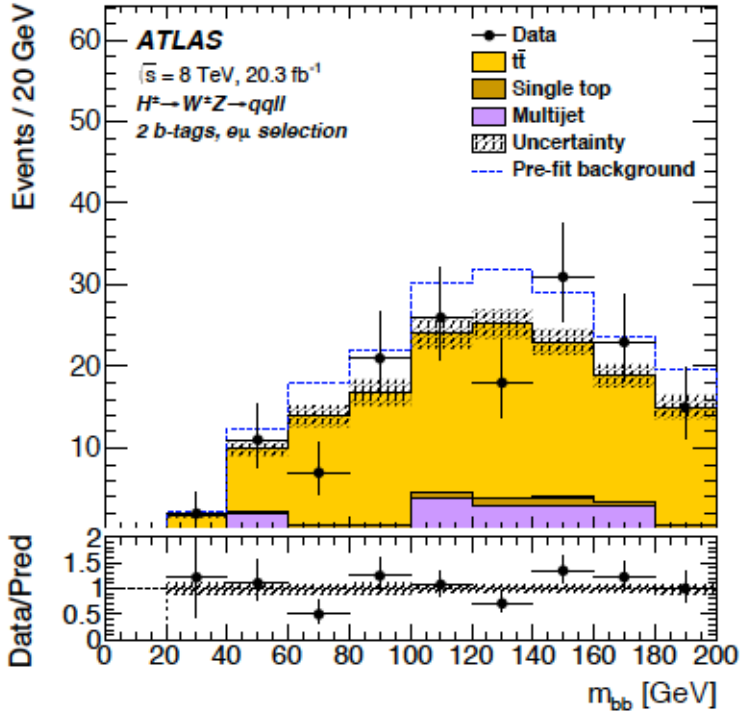
Expected and observed upper limits at 95%CL for the MSSM parameter tanβ versus m_A in the m_h^{mod+} benchmark scenario with μ=+200 GeV. Regions where the mass of neither of the CP-even MSSM Higgs bosons h or H is compatible with the discovered Higgs boson of 125 GeV within a range of 3 GeV are marked by the hatched areas.

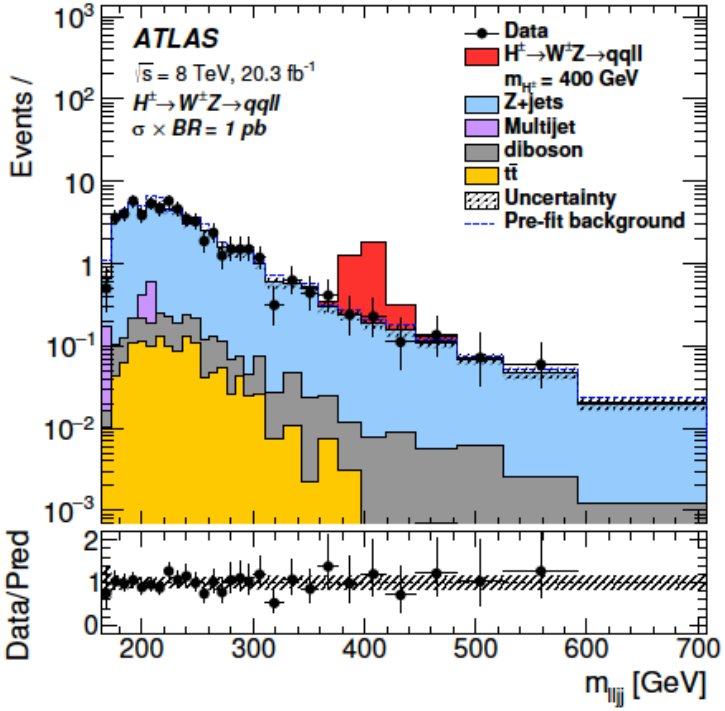
Search for $H^{\pm}$–>$W^{\pm}Z$

- Higgs triplet model (not MSSM).
- Require two forward separated jets in η with large dijet mass



arXiv: 1503.04233 (ATLAS)

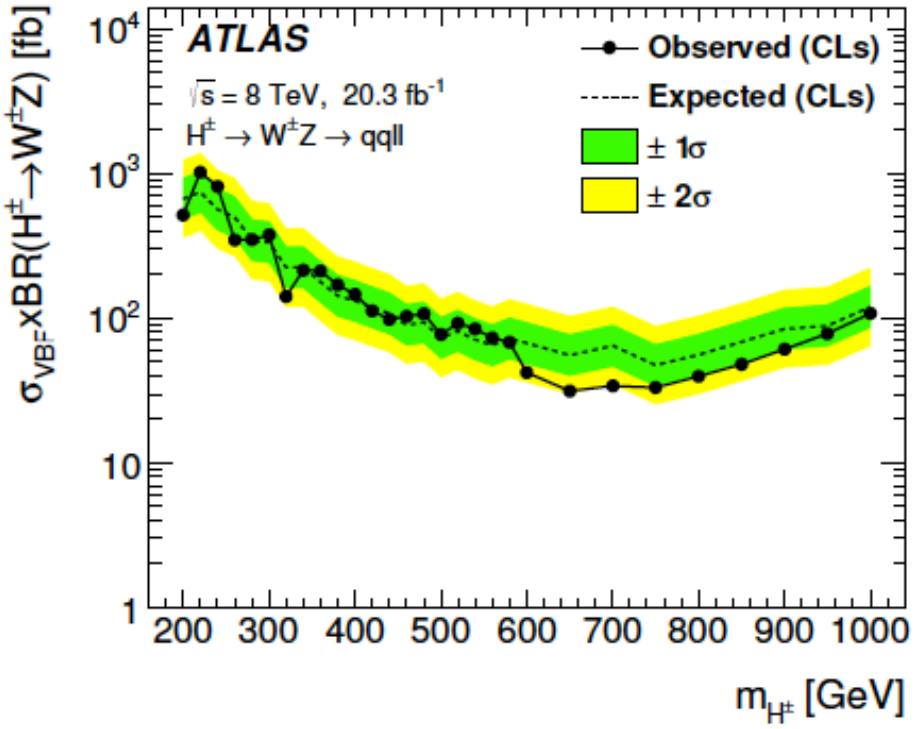


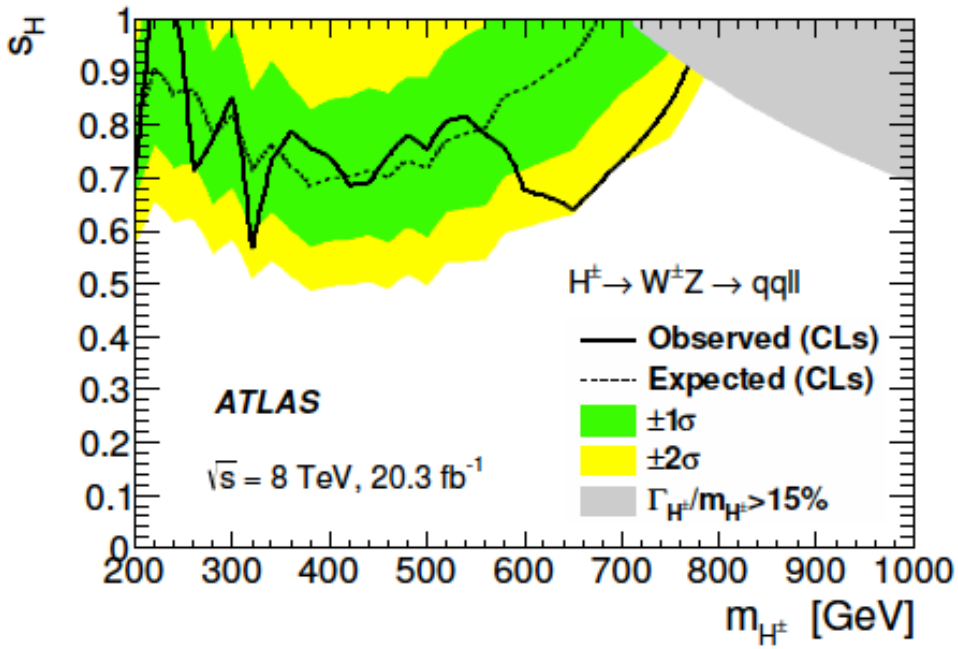


Search for $H^{\pm}$–>$W^{\pm}Z$

- Set limits as a function of $m_{H\pm}$
- $(s_H)^2$ is the fraction of vector boson mass squared (m_W^2/m_Z^2) generated by triplet vev (free parameter) in Georgi-Machacek Higgs Triplet Model.

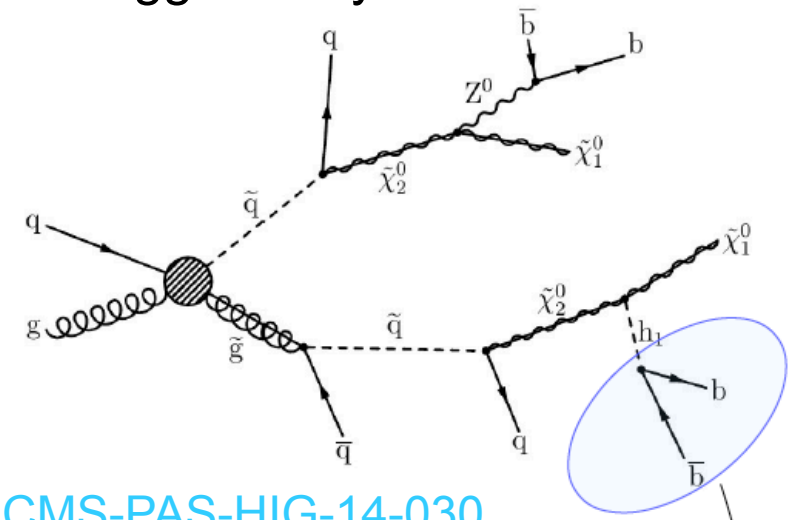
arXiv: 1503.04233 (ATLAS)



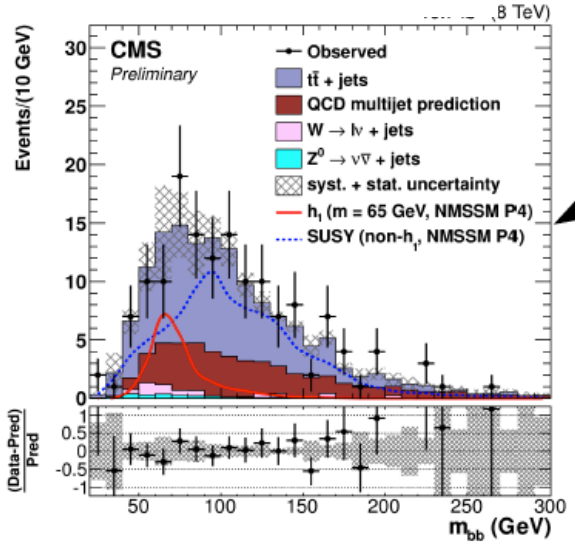


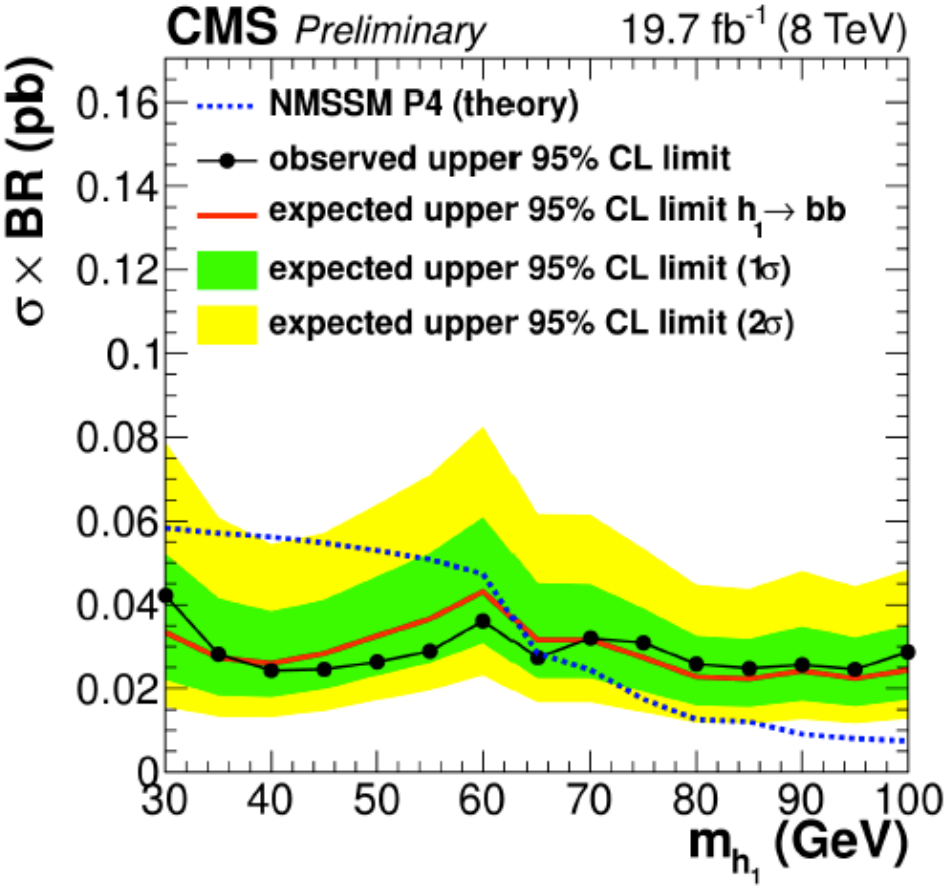
Search for h_1 ->bb in cascades

- A light boson produced in a SUSY-inspired cascade: hard jets, MET and b-jets from Higgs decay



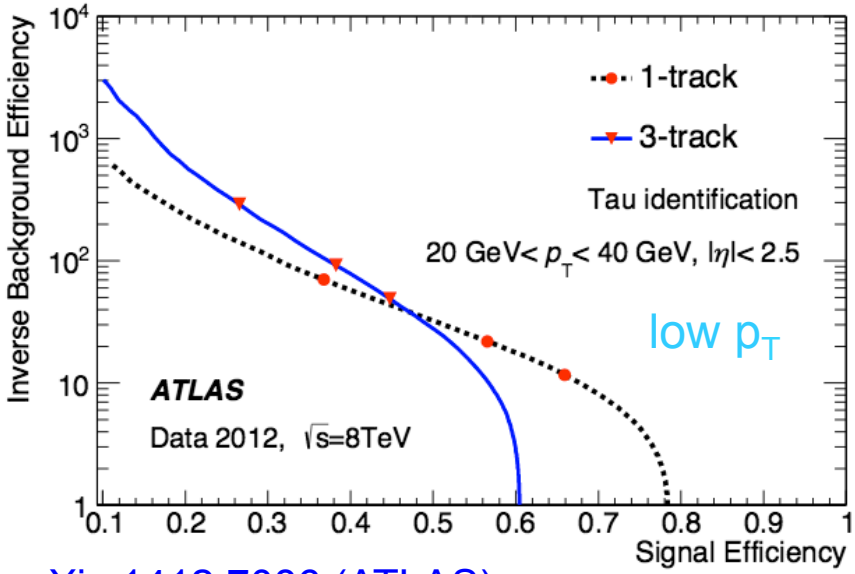
CMS-PAS-HIG-14-030



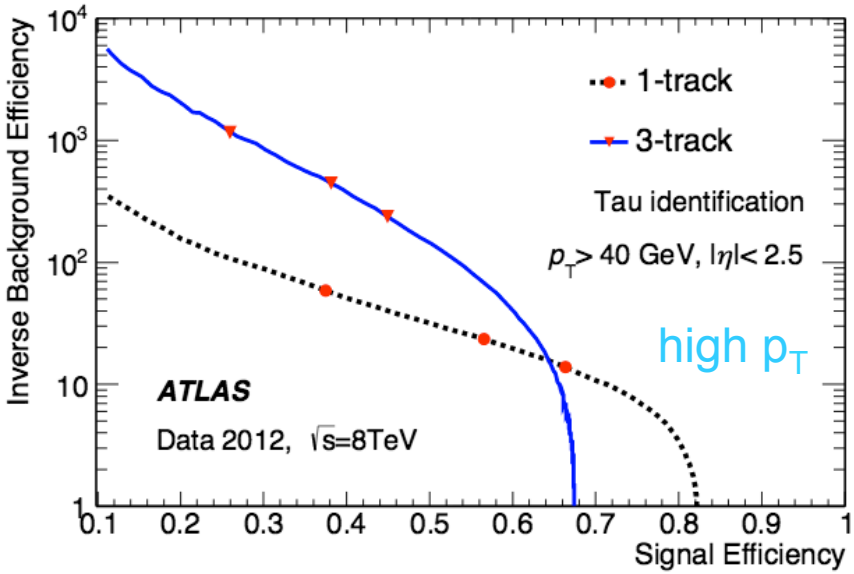


- The shown prediction from an NMSSM benchmark is taken from arXiv:0801.4321

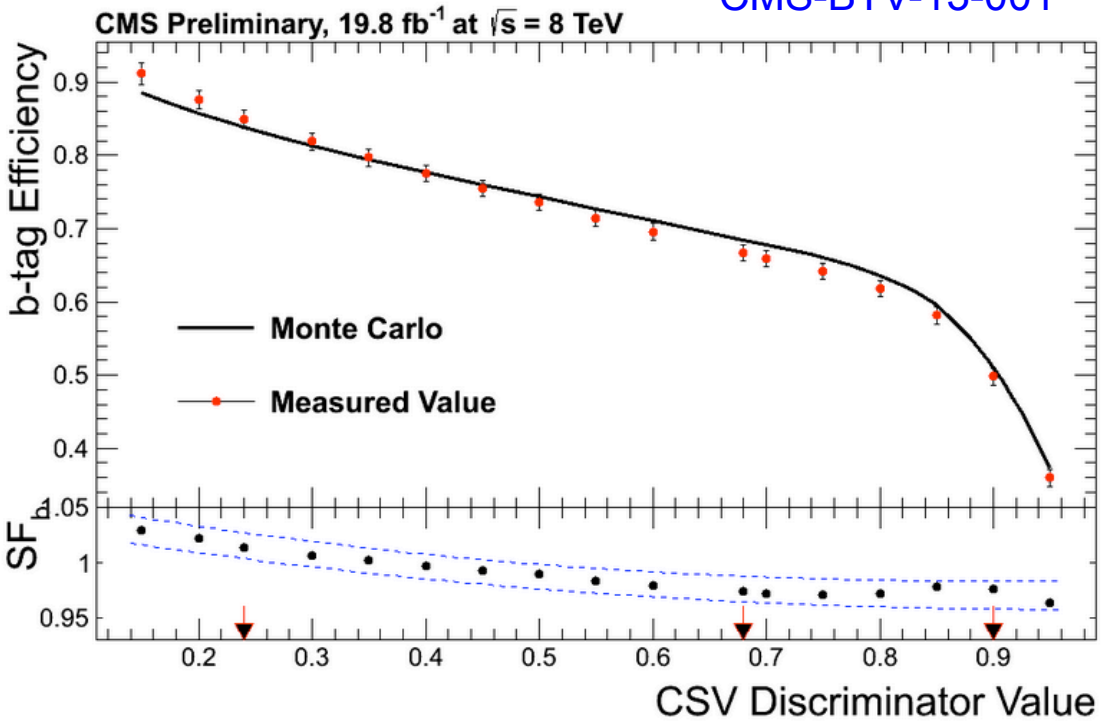
Tau CP / Flavour tagging



arXiv:1412.7086 (ATLAS)



CMS-BTV-13-001



(Left) Inverse background efficiency versus signal efficiency for the offline tau identification.

(Right) b-tagging efficiency as a function of the discriminator for the CSV algorithm.