26th Rencontres de Blois, Particle Physics and Cosmology, 2014

BSM Higgs Searches at the LHC

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On behalf of the ATLAS and CMS experiments

Introduction

Is the observed Higgs boson from an extended Higgs sector?

A number of possible models investigated by both ATLAS and CMS

- MSSM
- NMSSM
- 2HDM
- “Invisible Higgs”

See theory talk on Monday by S. Dawson
“Higgs physics beyond the standard model”

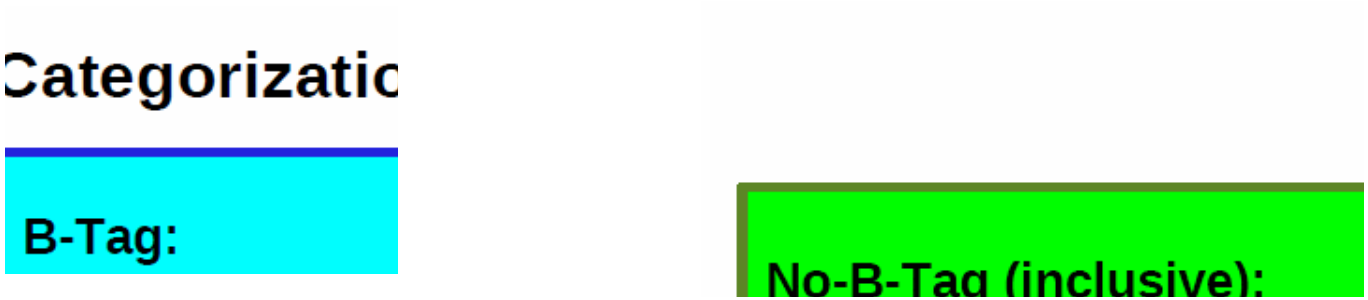
This talk will focus on direct searches.

Many analyses have been performed. Cannot cover all of them!

MSSM neutral Higgs in $\tau\tau$

CMS HIG-13-021 20fb^{-1} ('12) 5 fb^{-1} ('11)
ATLAS JHEP 02 (2013) 095 5fb^{-1} ('11)

- For large tan β $\tau\tau$ decay mode is the most sensitive.
- All neutral Higgs considered Φ □ h^0, H^0, A^0
- Channels considered τ_e τ_{had} , τ_μ τ_{had}, τ_{had} τ_{had} , eμ, $\mu\mu$
- Categories of b-tag and no-b-tag



Dominates at large tan β

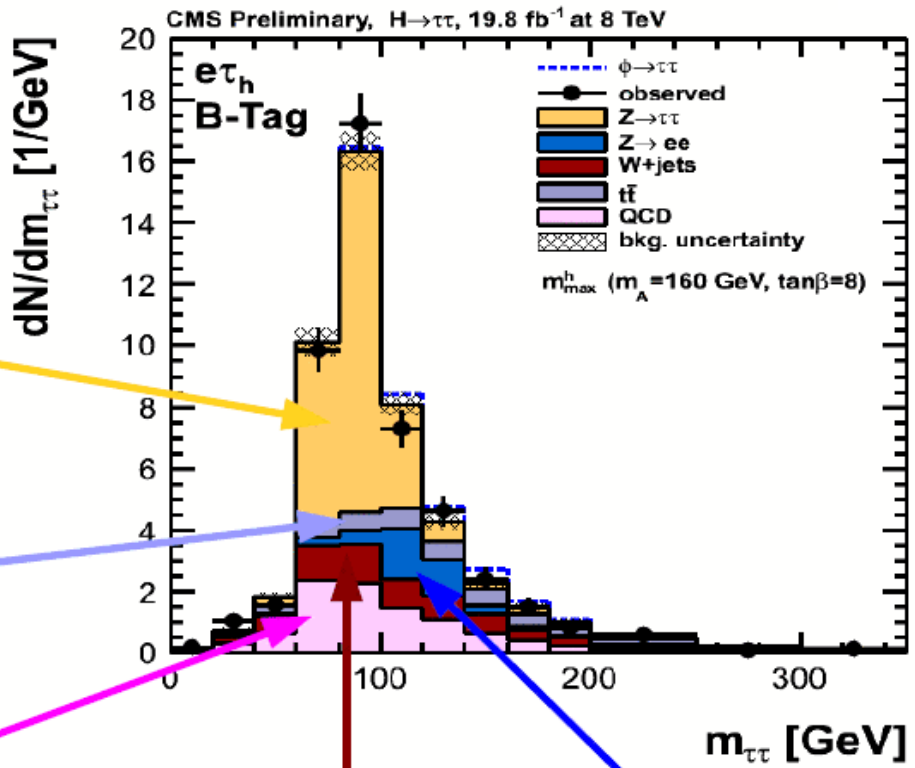
Backgrounds

Background estimation in $\Phi \rightarrow \tau\tau$

$Z/\gamma^* \rightarrow \tau\tau$:
- Embedding: in $Z \rightarrow \mu\mu$, replace μ by sim. τ decay
- Normalized from $Z \rightarrow \mu\mu$ events

ttbar:
- From simulation
- Normalization from sideband

QCD:
- Normalization & shape taken from SS/OS or fakerate

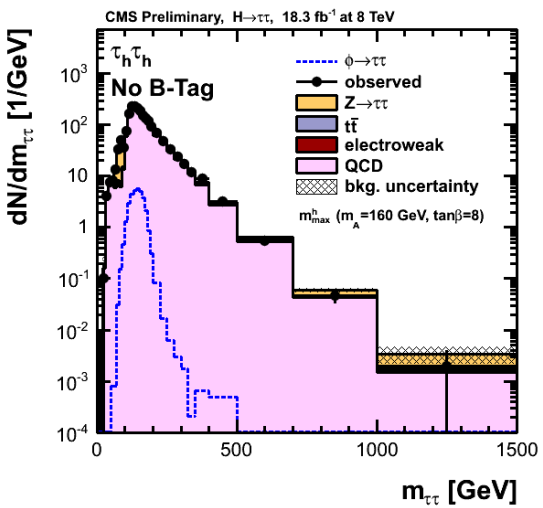


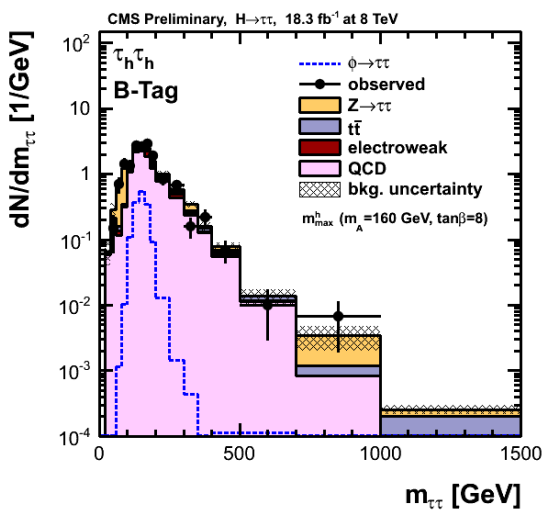
Di-boson/W+jets:
- From simulation or data
- Normalization from sideband

$Z/\gamma^* \rightarrow$ ee ($\mu\mu$):
- From simulation or data
- Corrected for jet $\rightarrow \tau$, $e/\mu \rightarrow \tau$ fakerate

b tag

Hadronic τ decay (CMS)





No b tag

No b tagged jets

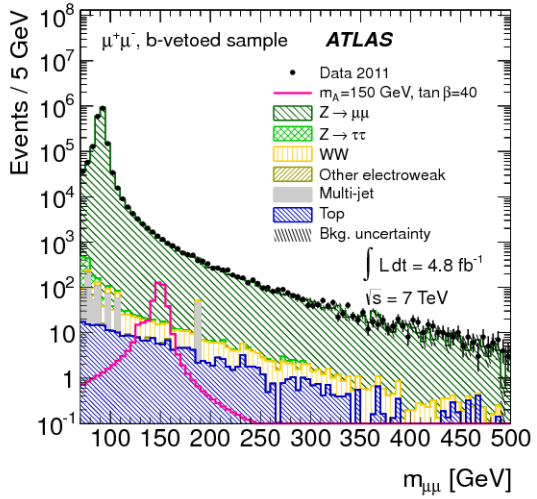
p_T > 20 GeV

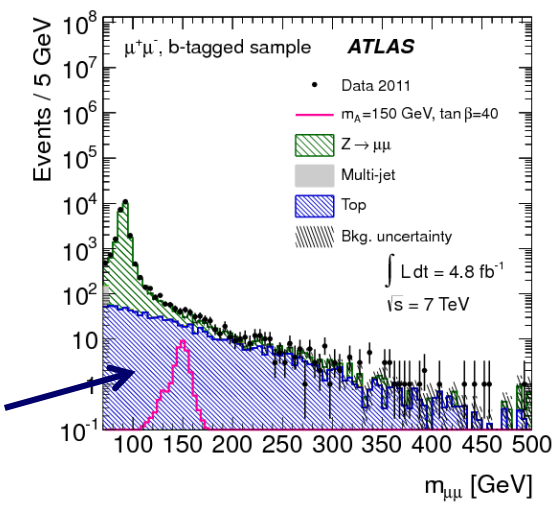
b tag present

At least 1 b tag

> 20 GeV

H → μμ (ATLAS)





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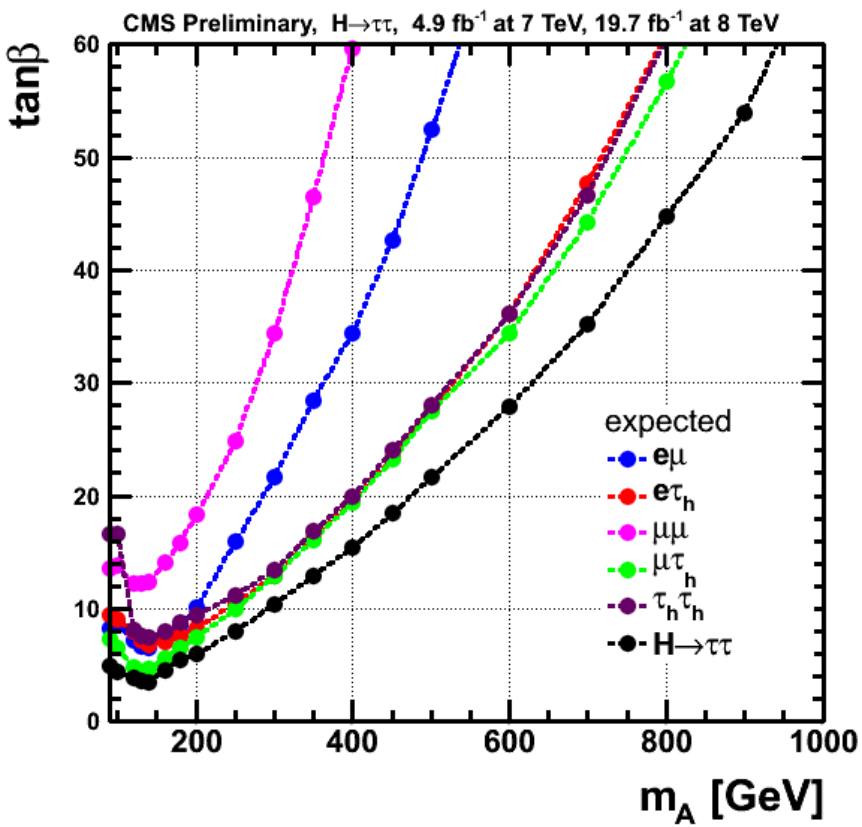
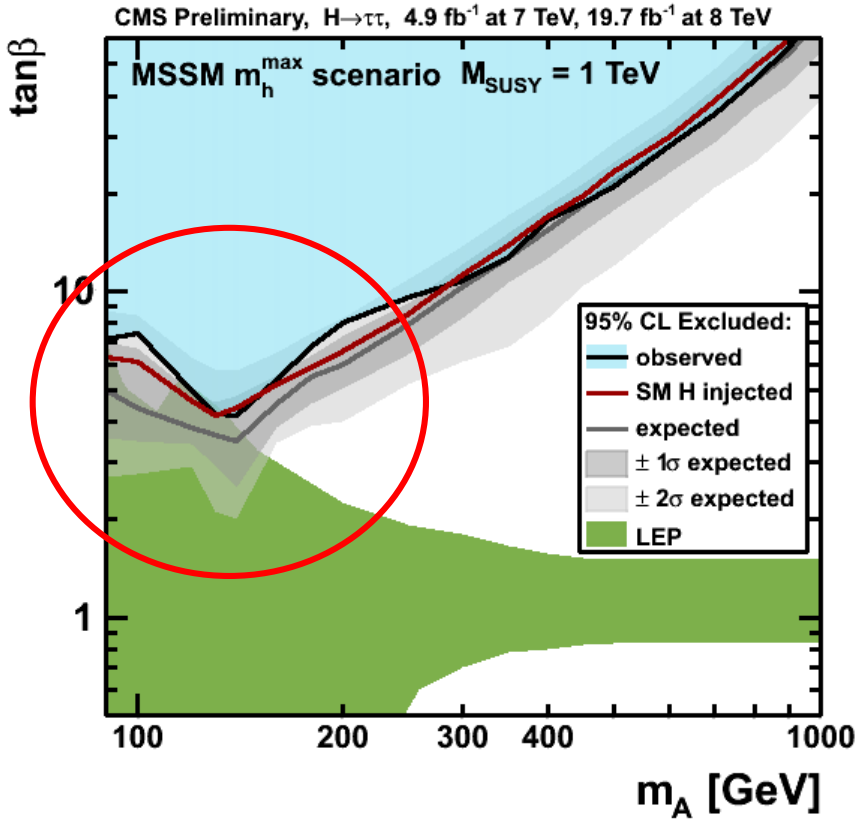
Limits



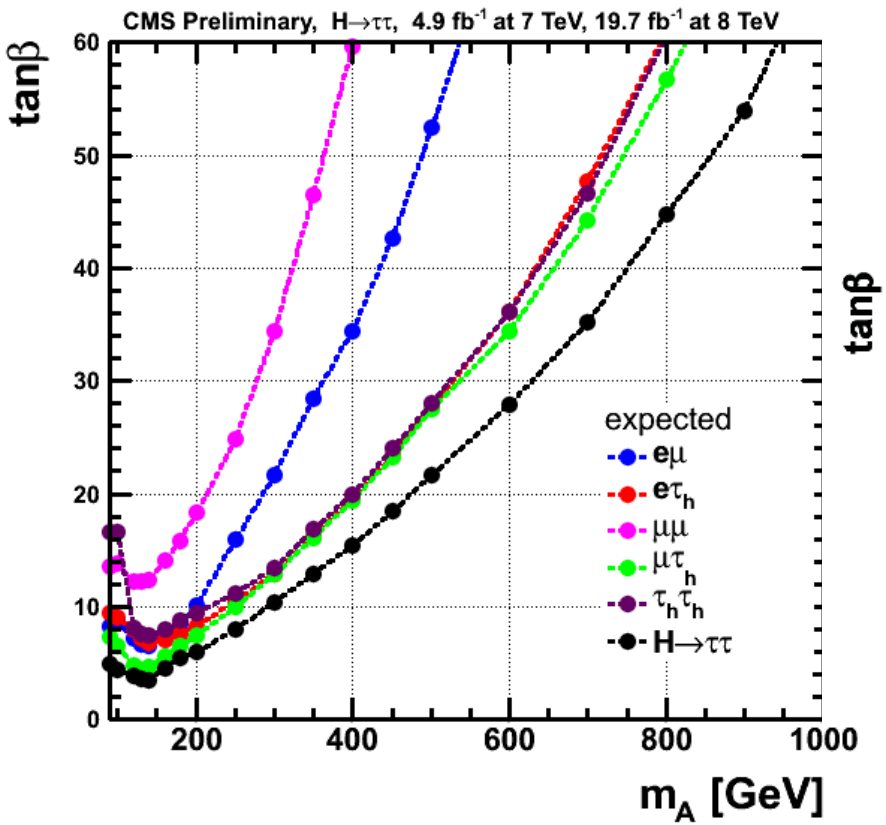


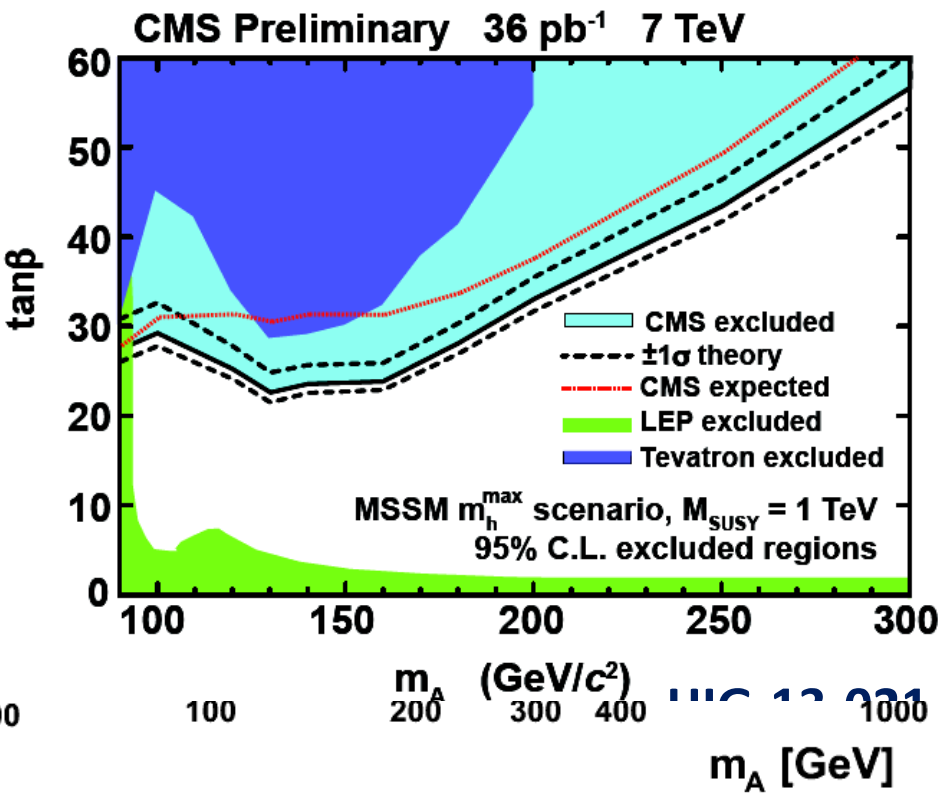
Limits in m_h^{max} scenario

Scenario devised before H(125) discovery. Mods proposed. 1302.7033

Limits

HIG-10-002





Limits in m_h^{max} scenario

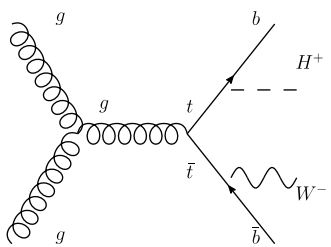
Scenario devised before H(125) discovery. Mods proposed. 1302.7033

Charged Higgs

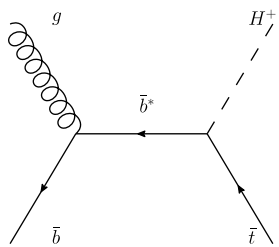
ATLAS-CONF-2013-090 20 fb^{-1} 8 TeV
ATLAS Eur. Phys. J. C, 73 6 (2013) 2465 7 TeV
ATLAS JHEP03(2013)076 7 TeV
CMS HIG-12-052 7 TeV

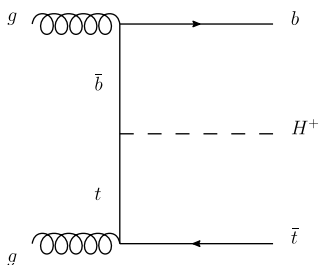
Charged Higgs production

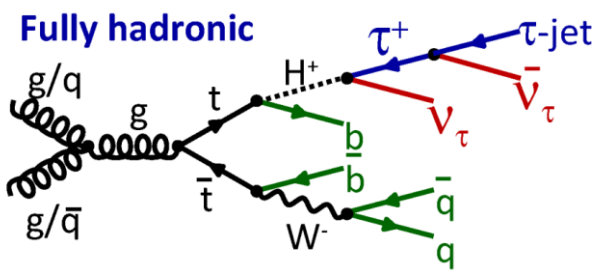
$M(H^+) < M(t)$



$M(H^+) > M(t)$







- 4(3) jets ≥ 1 b-tags
- 1 hadronic tau decay
- E_t^{miss} > 65 (80) light(heavy)

$H^{\pm} \rightarrow \tau\nu$ dominant for $m(H^+) < m(t)$

Search for all masses.

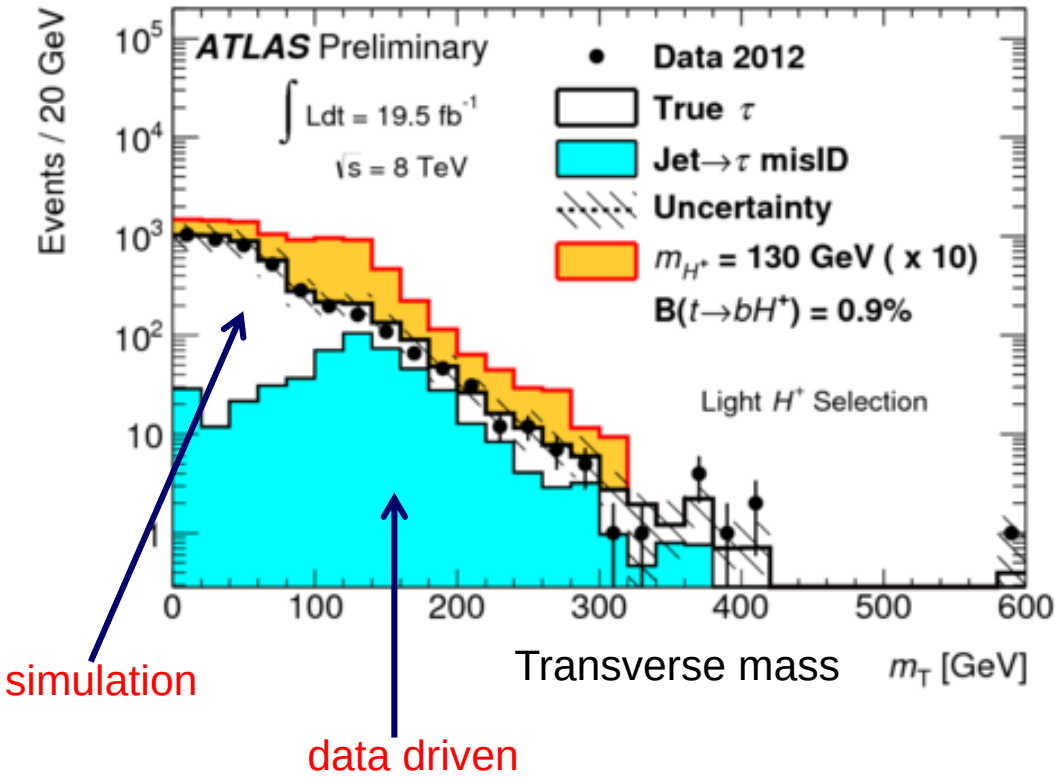
Main backgrounds tt, W + jets, Z + jets, VV, multi-jets

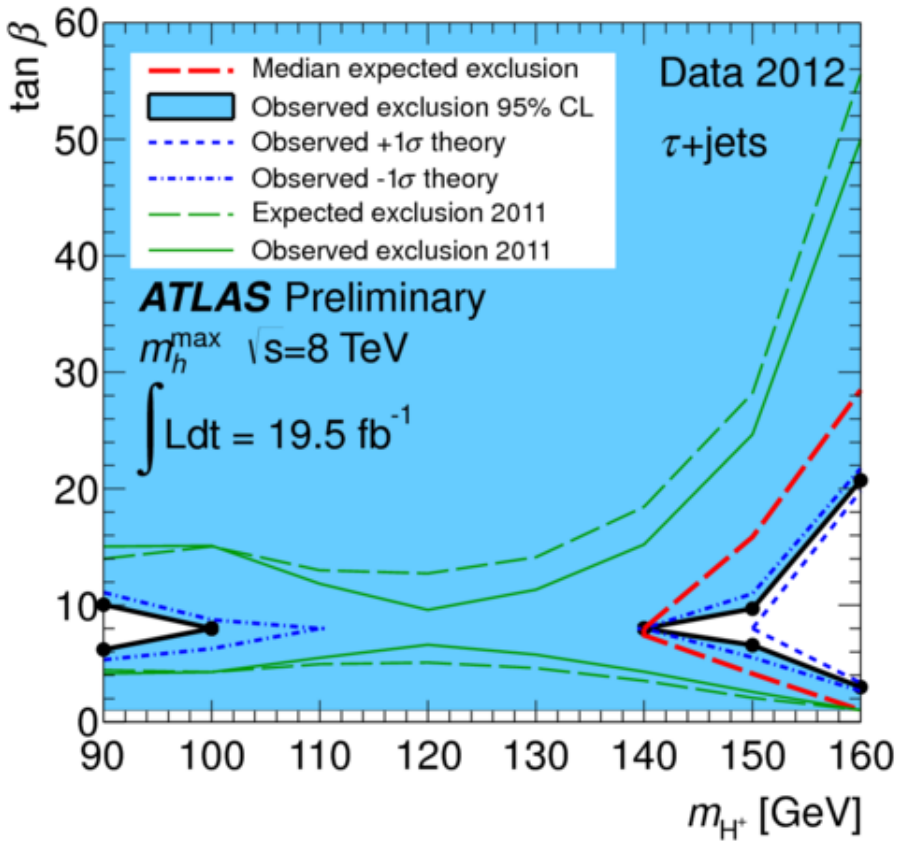
For tan $\beta < 1$ $H^+ \rightarrow cs$ can be dominant

Charged Higgs

ATLAS-CONF-2013-090

19.5 fb^{-1} $\sqrt{s}$ = 8 TeV





Exclusion in MSSM m_h^{max} scenario for a light H^+ (m(H) < m(t))

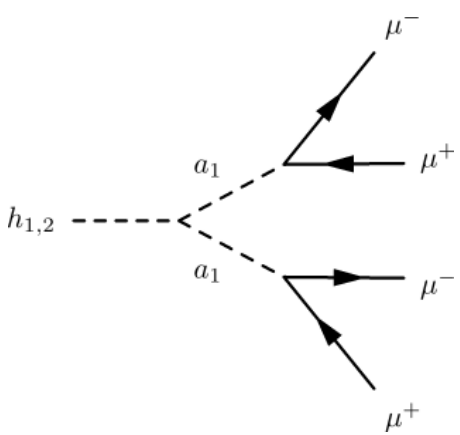
NMSSM

CMS HIG-13-010

NMSSM includes additional singlet superfield, S

Higgs spectrum enlarged: CP-even h_1, h_2 , h_3 ; CP-odd a_1, a_2 ; charged $h^{\pm}$

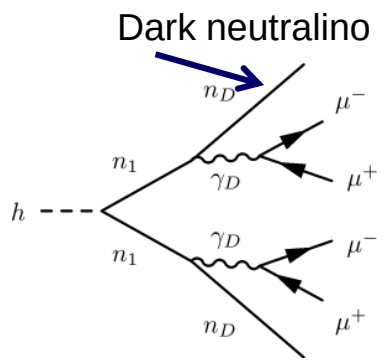
$h_{1,2} \rightarrow a_1\, a_1$ possible where either h_1 or h_2 could be observed 125 GeV state.



$m(a_1) < 2\, m(\tau)$

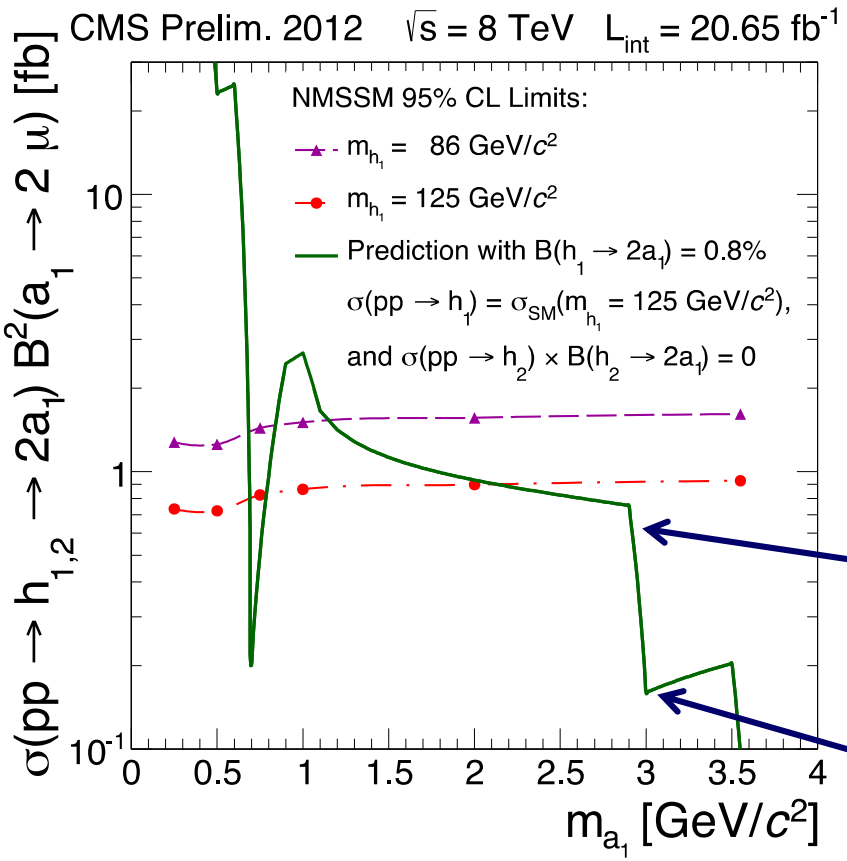
4 isolated μ

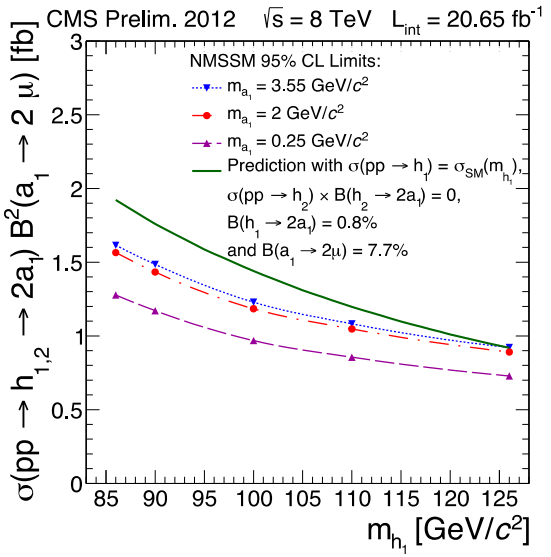
bb, J/Ψ backgrounds



Alternative Dark SUSY interpretation

NMSSM





Fixed a_1 mass

Prediction for

$M(h_1) = 125$ GeV ; $Br(h_1 \to 2a_1) = 0.8\%$

$Br(pp \to h_2) \times Br(h_2 \to 2a_1) = 0$

Structure in prediction due to $Br(a_1 \to gg)$

Dependence on internal quark loop thresholds.

2HDM

Addition of second complex Higgs double to SM. Five Higgs ; h, H, A^0, $H^{\pm}$
MSSM is a type II 2HDM

- Type I: One doublet couples to V("fermiophobic"), one to fermions
- Type II: "MSSM like" model, one doublet couples to up-type quarks, one to down-type quarks
- Type III: "Lepton-specific" model, Higgs bosons have same couplings to quarks as type I and to leptons as in type II
- Type IV: "Flipped" model, Higgs bosons have same couplings to quarks as in type II and to leptons as in type I

2HDM

Search for $H \rightarrow hh$, $H \rightarrow Ah$ ($A \rightarrow Zh$) .

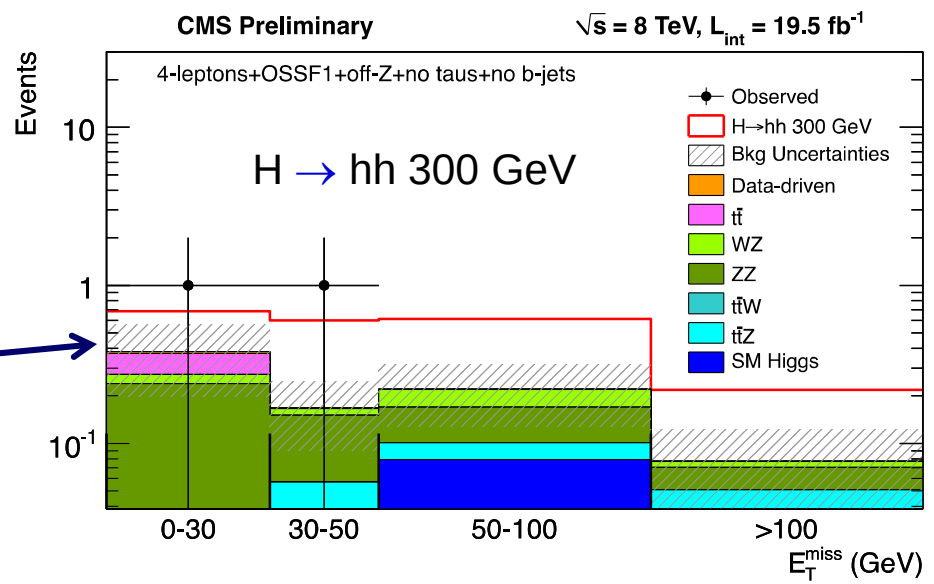
Comprehensive set of mutlilepton + $\gamma\gamma$ states.
Assume SM decays of h.

CMS-13-025

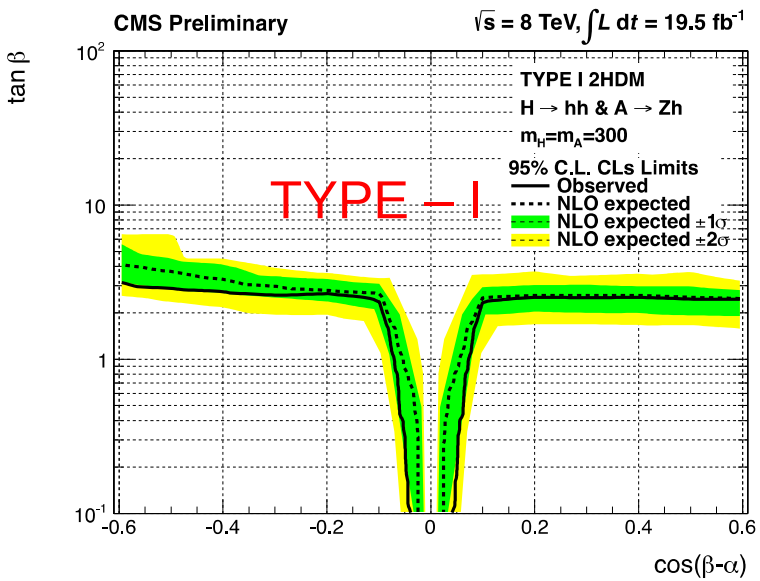
Leptons	Photons	OSSF pairs	Hadronic τ	b-tag
4	0	0, 1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

Final states from *hh* decays	Search Channels *h* decays populate
WW^*WW^* $WW^*\tau\tau$ $\tau\tau\tau\tau$ $ZZ^*\tau\tau$ ZZ^*bb	Three or four leptons (upto one τ_h), OSSF pair off-Z or no OSSF pair in bins of E_T^{miss} and b-tag
$\gamma\gamma WW^*$ $\gamma\gamma ZZ^*$ $\gamma\gamma\tau\tau$	2photons ($M_{\gamma\gamma}$ within higgs bin) + 1 or more leptons(upto 2 τ_h),in bins of E_T^{miss}

4 leptons , 1 OSSF pair, no pair with Z mass, no taus and no b-jets.

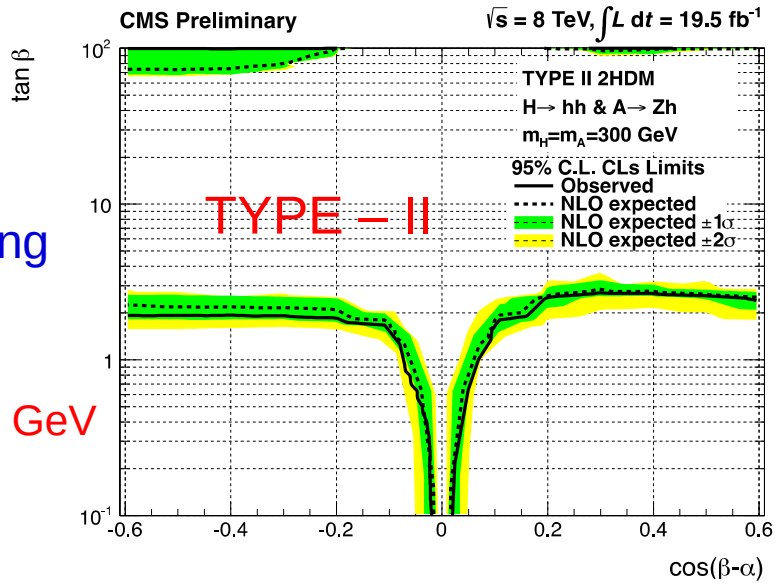


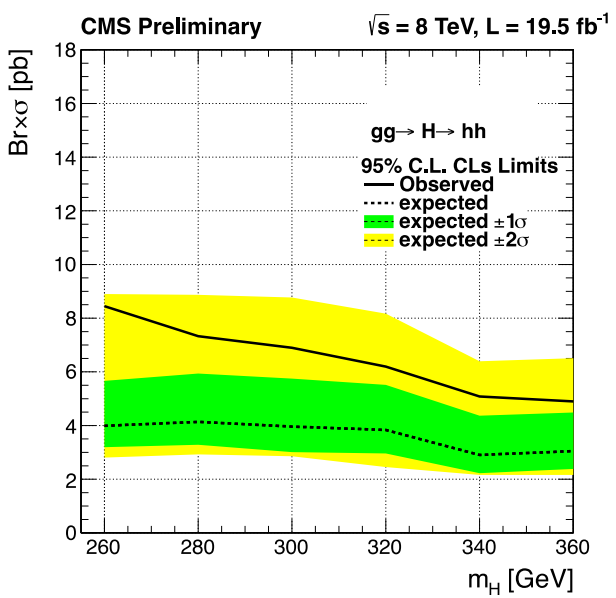
2HDM

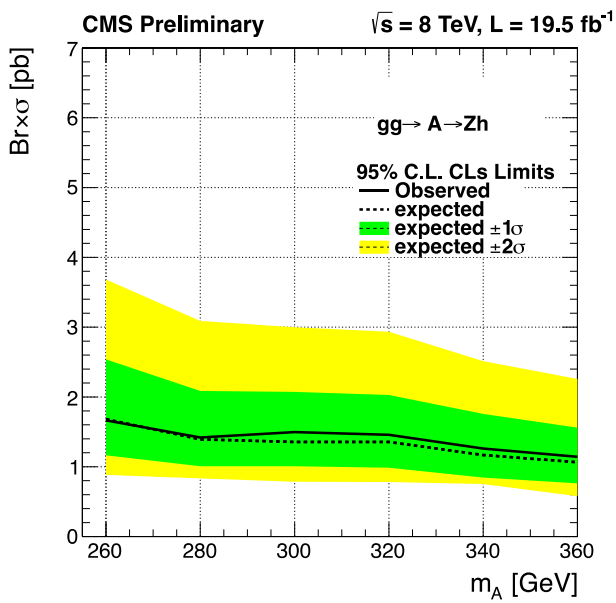


α H h mixing angle

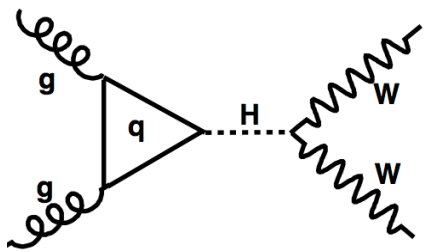
m_H, m_A = 300 GeV

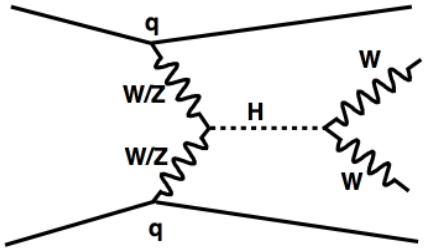


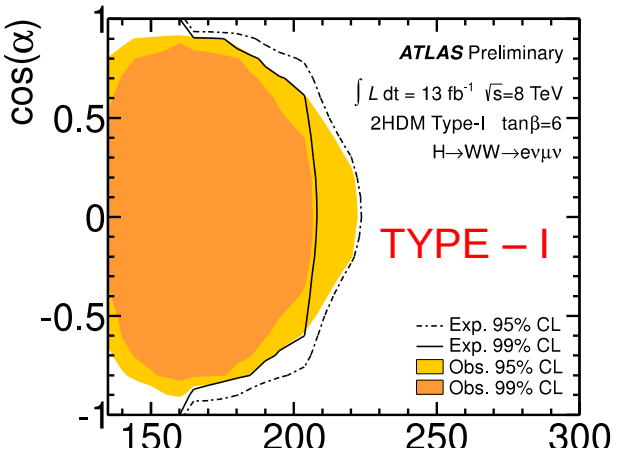




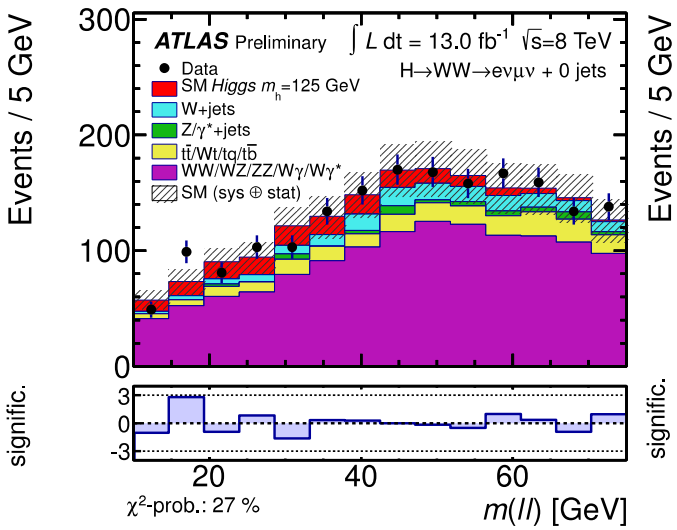
2HDM

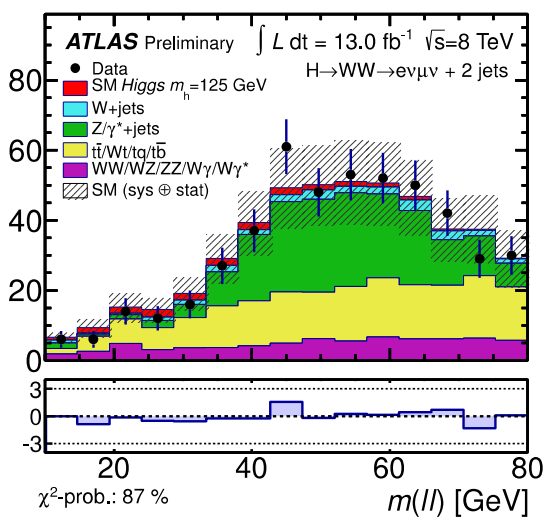


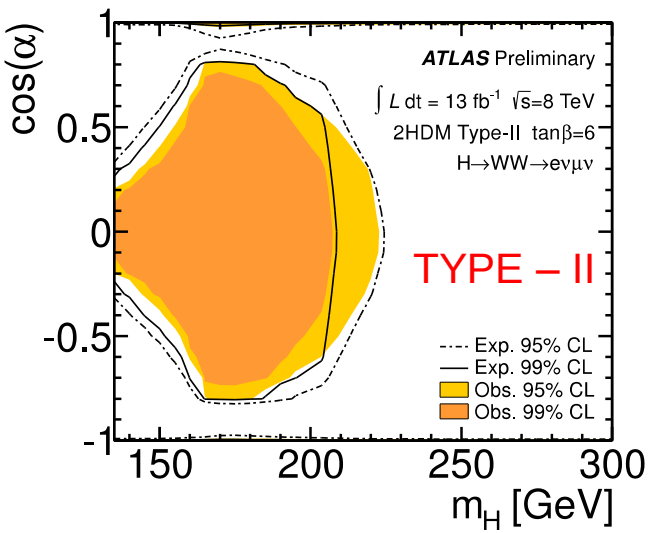




Search using WW final state WW → eν μν





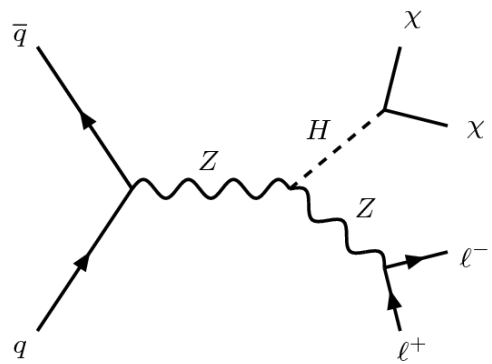


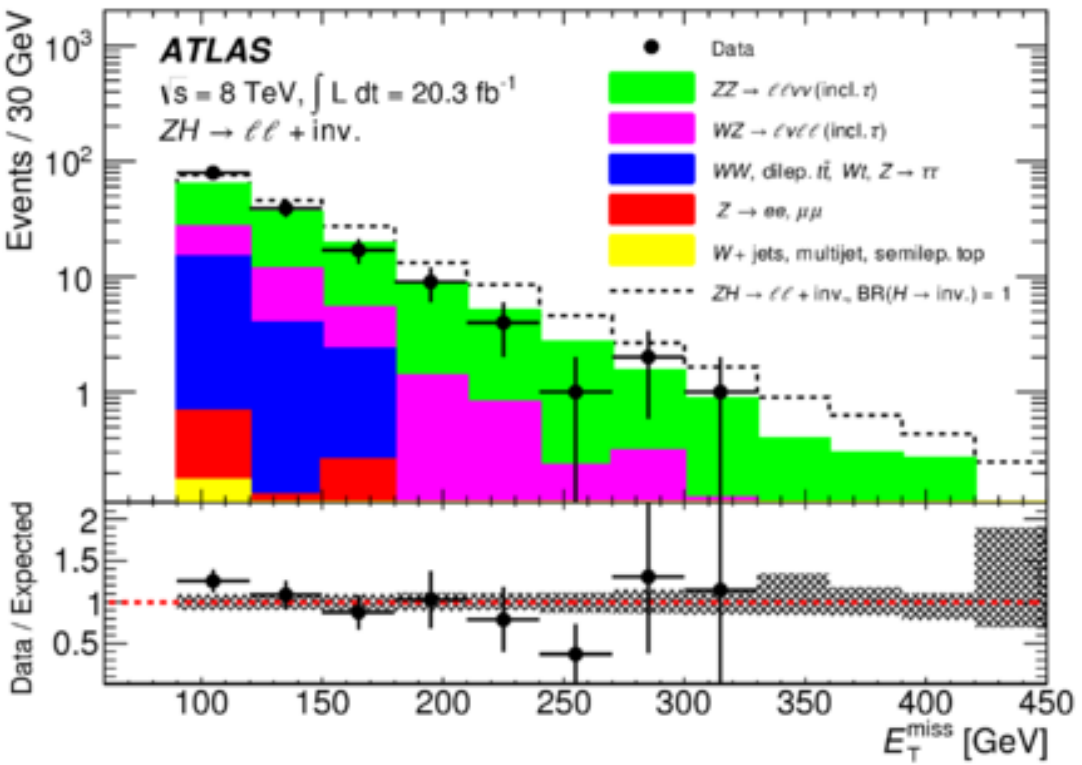
0 jets - VV bg dominant

2 jets - Z +jets bg dominant

ATLAS-CONF-2013-027

Invisible Higgs





Require dileptons from Z

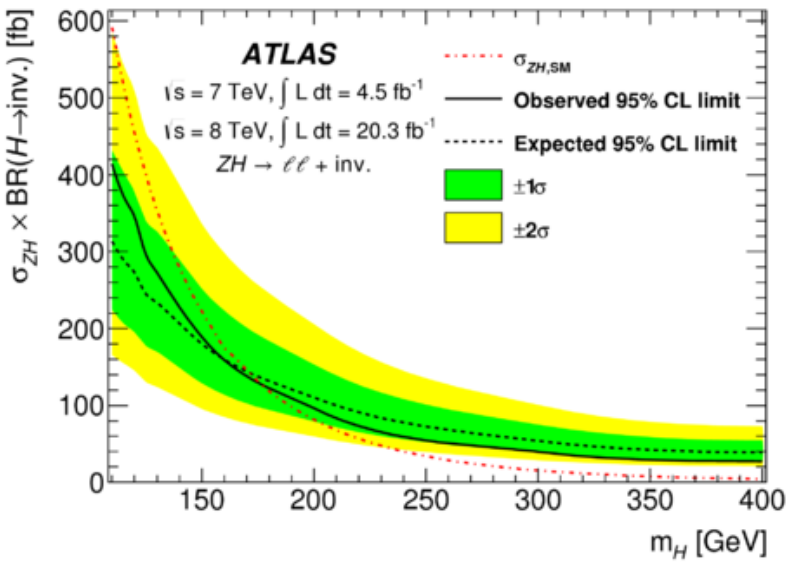
Back to back Missing E_T and $p_T(\ell\ell)$

No jets

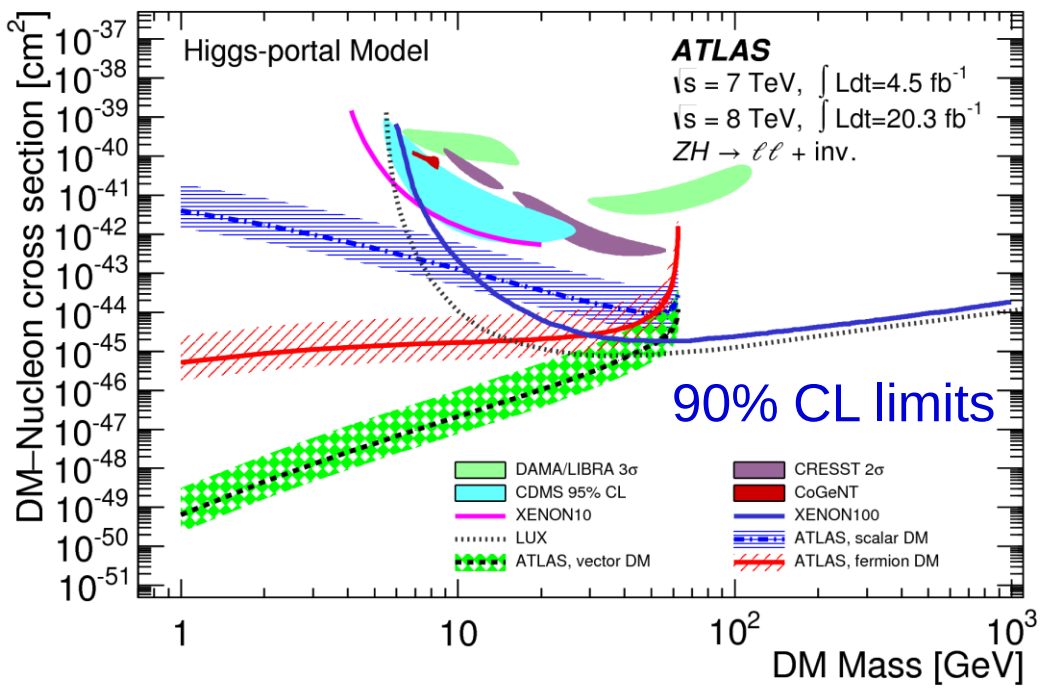
Main backgrounds ZZ, WZ

ATLAS accepted by Phys. Rev. Lett.

Invisible Higgs



Upper limit Br to inv. 75%

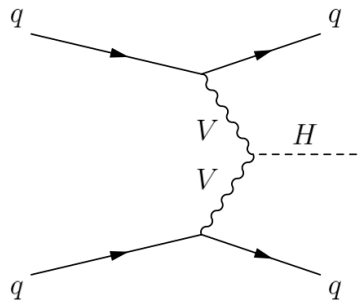


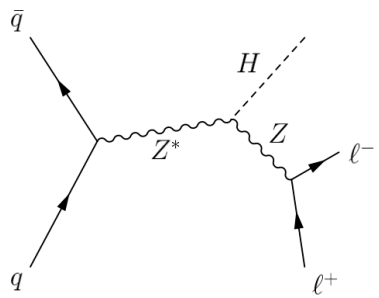
Upper limit interpreted as limit on DM-nucleon scattering cross section
Fox et al. Phys. Rev. D 85 050611

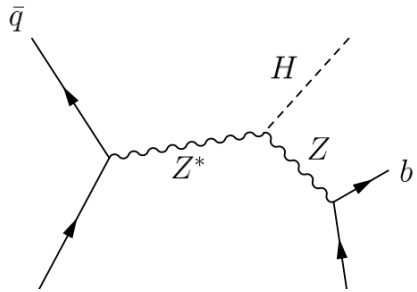
DM scenarios scalar, vector or Majorana fermion

Higgs-nucleon coupling $0.33\ ^{+0.30}_{-0.07}$ Djouadi et al. Phys. Lett. B 709 65 (2012)

Invisible Higgs





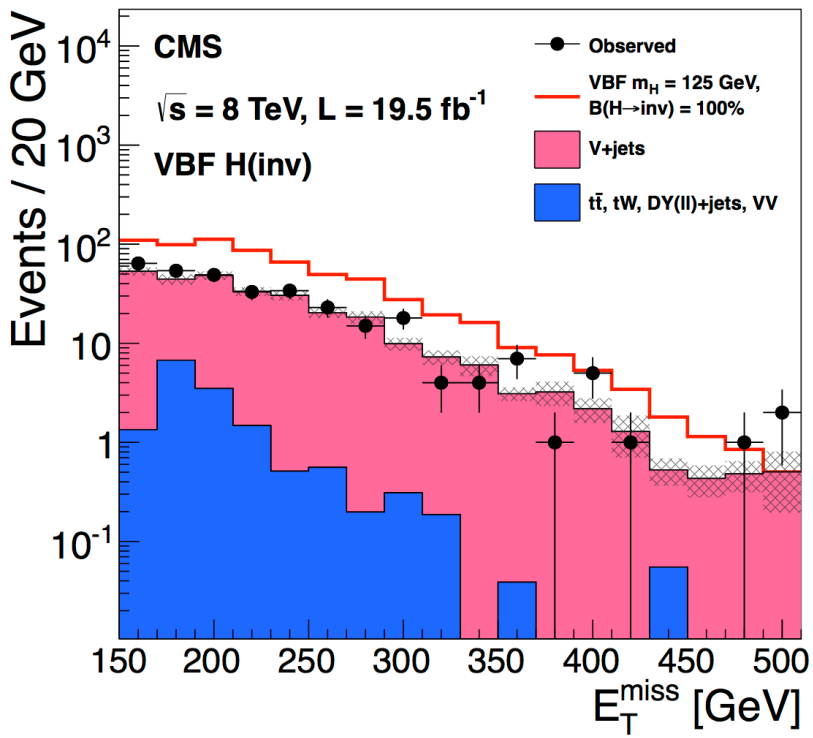


Search in VBF and ZH , $Z \rightarrow ll$ and bb

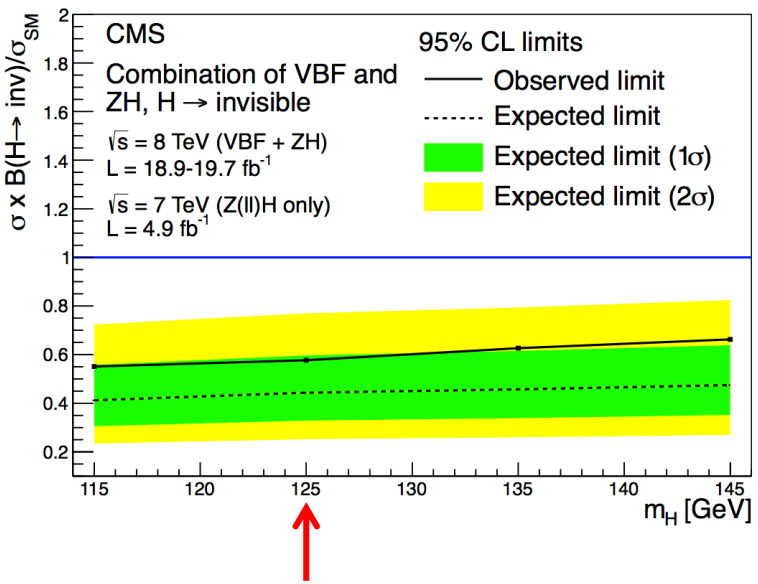
VBF mode requires 2 jets in forward region ($\Delta\eta_{jj} > 4.2$) , $E_t^{miss} > 130$ GeV

Central jet veto on any jet $p_T > 30$ GeV.

Dominant beckgrounds
$Z(\nu\nu)$ + jets, $W(l\nu)$ + jets

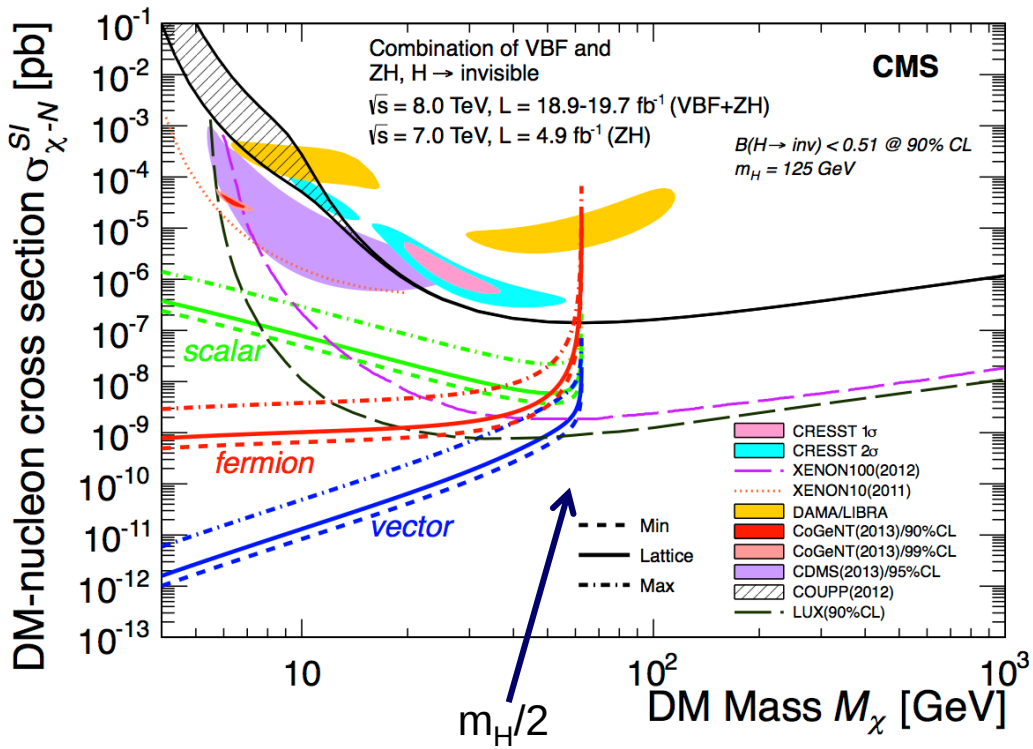


Invisible Higgs



Upper limit on Br to invisible
0.58 for Higgs mass 125 GeV

7 TeV 4.9 fb^{-1} 8 TeV ~ 19 fb^{-1}

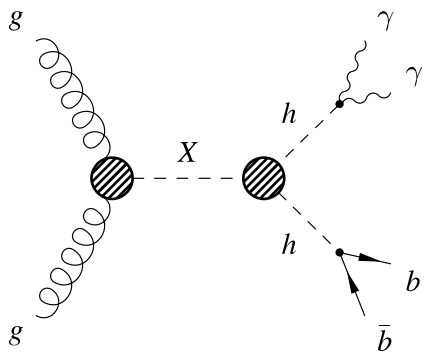


Higgs nucleon coupling 0.33 (range 0.26 - 0.63)

DM scenarios scalar, vector or Majorana fermion

$X \rightarrow HH$

Search for two Higgses from a resonance



Require $\gamma\gamma$ and bb inv. Mass = M(Higgs)

Main background non-resonant QCD

The resonance could be a heavy Higgs e.g. MSSM H -> hh.

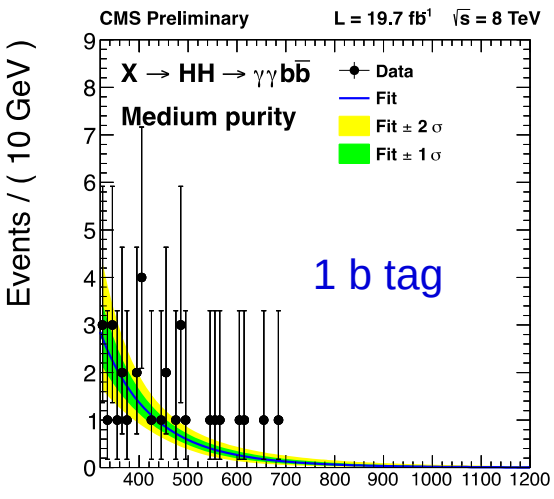
Interpreted within Warped Extra Dimension model (Randel & Sundrum '99)

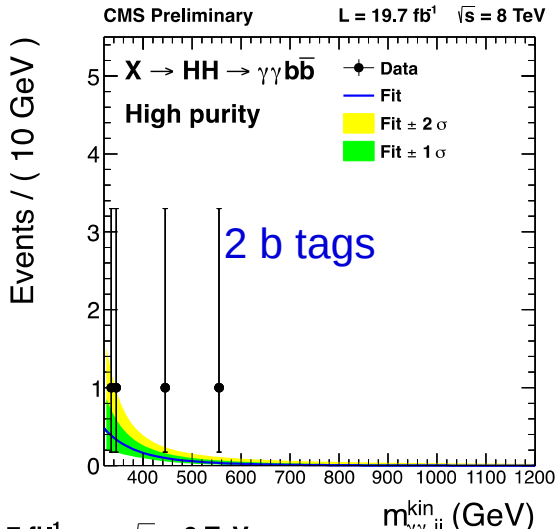
Radion a spin 0 object therefore kinematics of analysis the same as for H.

Radion benchmark signal model:

- KK-graviton (spin 2) SM field localized ED bulk (Fitzpatrick et al. Br to 2H ~ 7% for 1 TeV.
- RS1 model SM localized on TeV brane. Br ~ 0.05% for 1 TeV KK-graviton
- Radion (spin 0). Production cross section depends on scale Λ_R

$X \rightarrow HH$

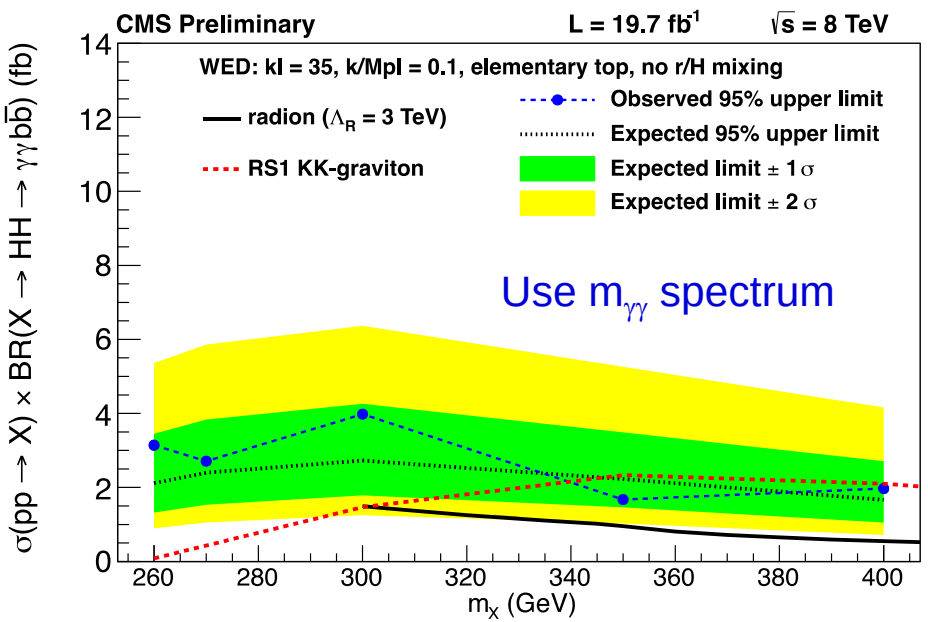


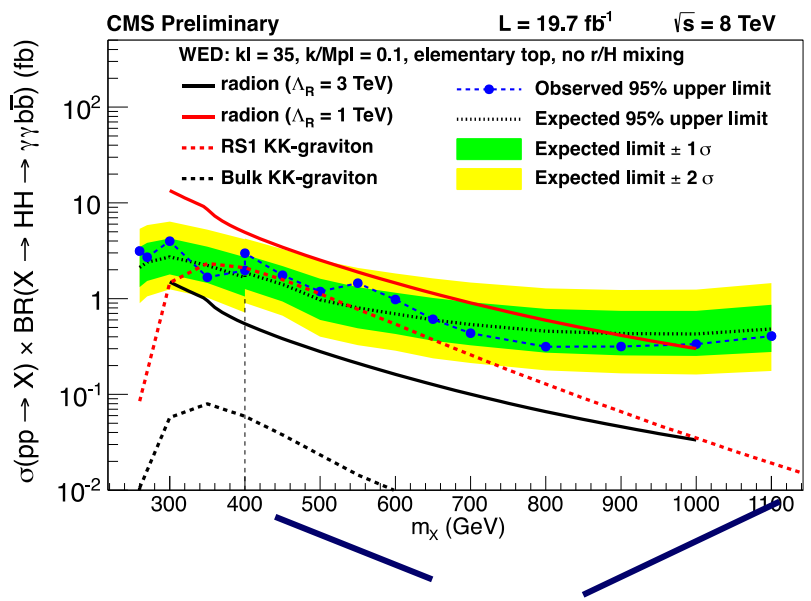


CMS HIG-13-032

Use for heavy Higgs exclusion

Radion (Λ_R = 1 TeV) excluded below 0.97 TeV





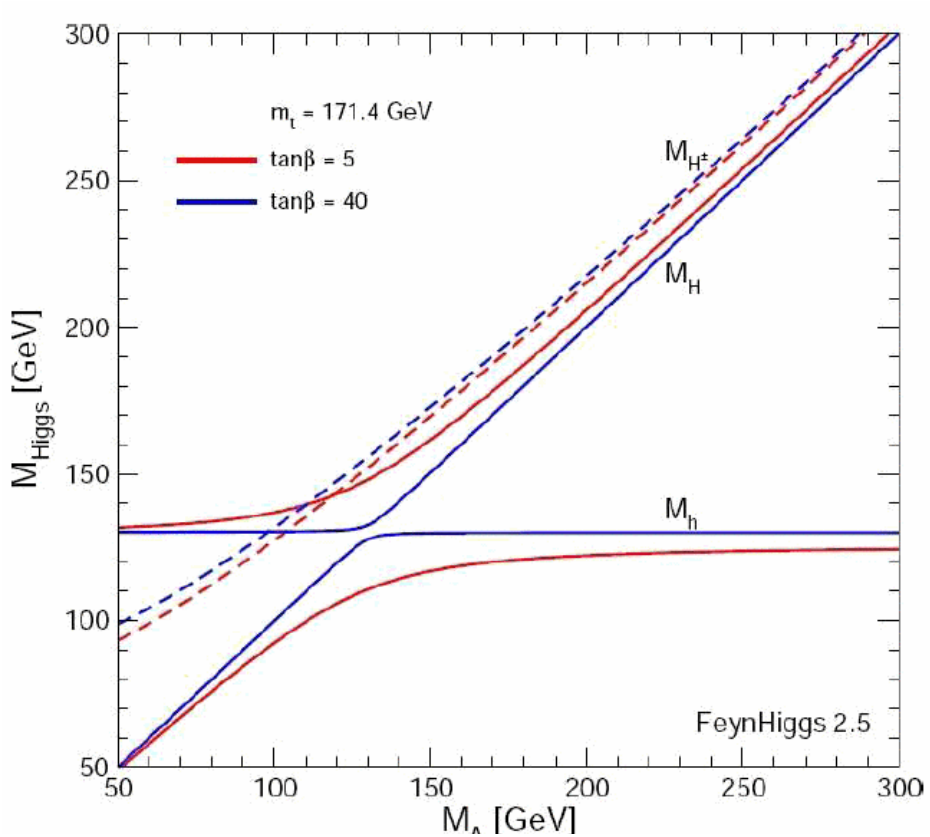
Use $m_{\gamma\gamma bb}$ spectrum

Conclusions

- Large number of direct searches for BSM Higgs
  (Many not covered here)
- No evidence of BSM Higgs (yet)
- More results in pipeline from 8 TeV data
- Exciting prospects for 13 TeV data.

THE END

MSSM



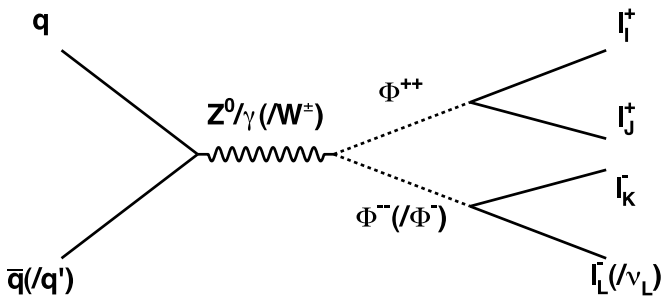
Five Higgs bosons in MSSM CP-even h,H CP-odd A, $H^{\pm}$

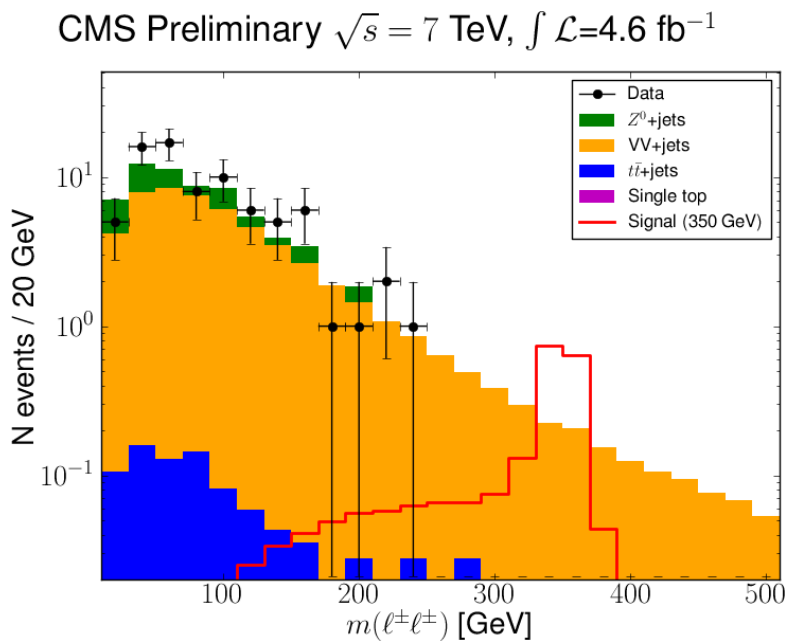
Which one have we found? (if any)

Doubly Charged Higgs

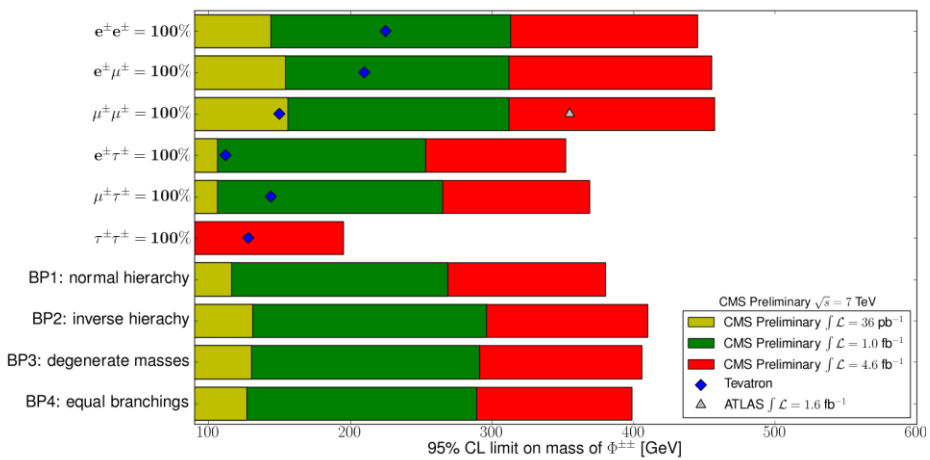
- Doubly charged pair produced $H^{++} \rightarrow l^+l^+, \tau^+\tau^+$
- Arises in models with extra Higgs triplets
  - Φ^{++}, Φ^{+}, Φ^{0}
- Triplet responsible for small neutrino mass
- Unknown neutrino mass matrix
  → unknown branching ratios → broad search
- Below M ≈$2M_W$, only leptonic decays

3l f.s.

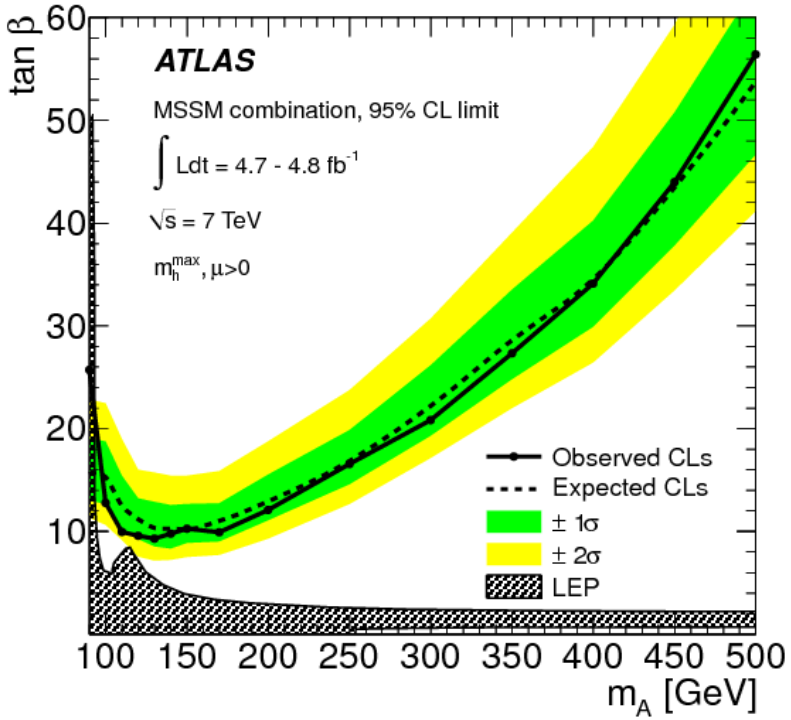




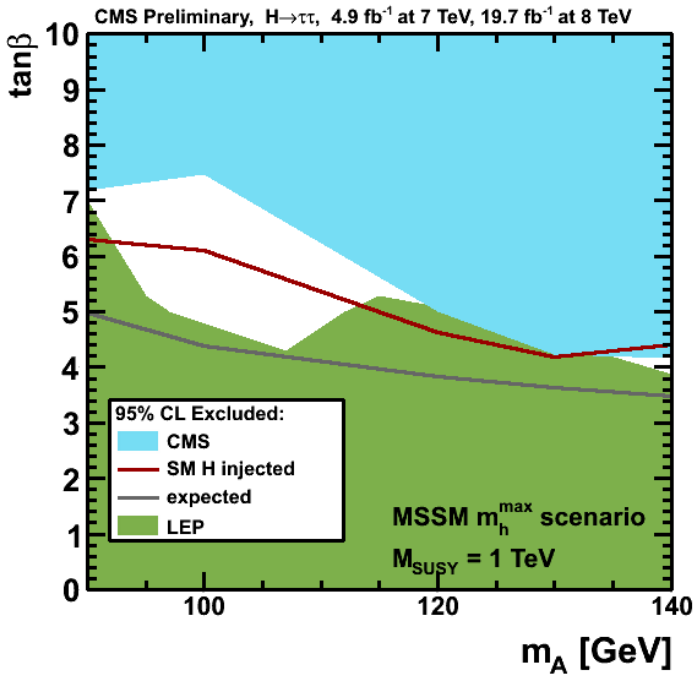
3 or 4 leptons in final state used for search



Neutral MSSM



ATLAS limits 4.7-4.8 fb^{-1} 7 TeV



CMS Blow up low mass region

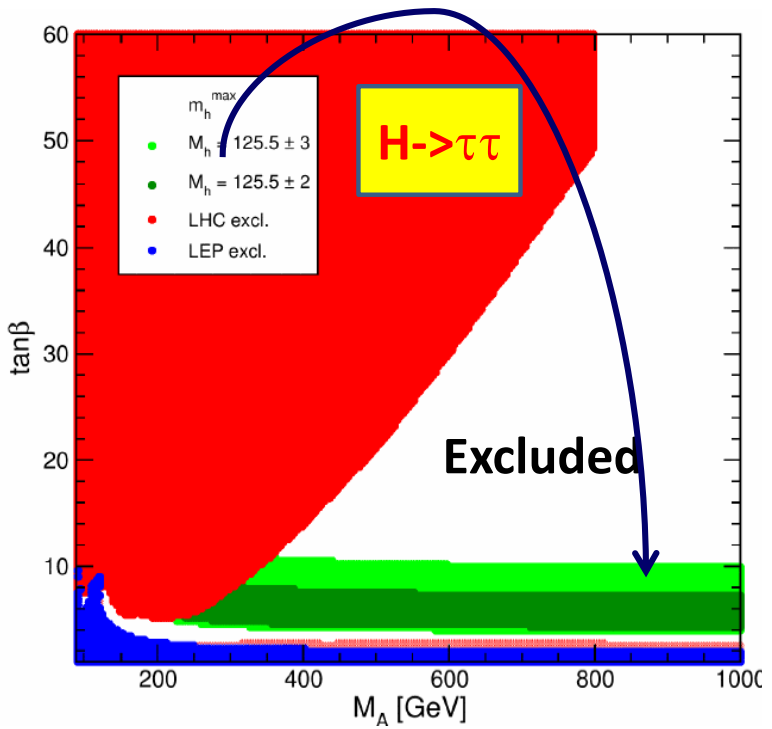
Carena et al. benchmarks

MSSM benchmark scenarios (I)

(from M. Carena et al arXiv:13027033)

- **m_h^{max} updated scenario:**
  - **green strip is allowed region of M_A-tanβ**

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$



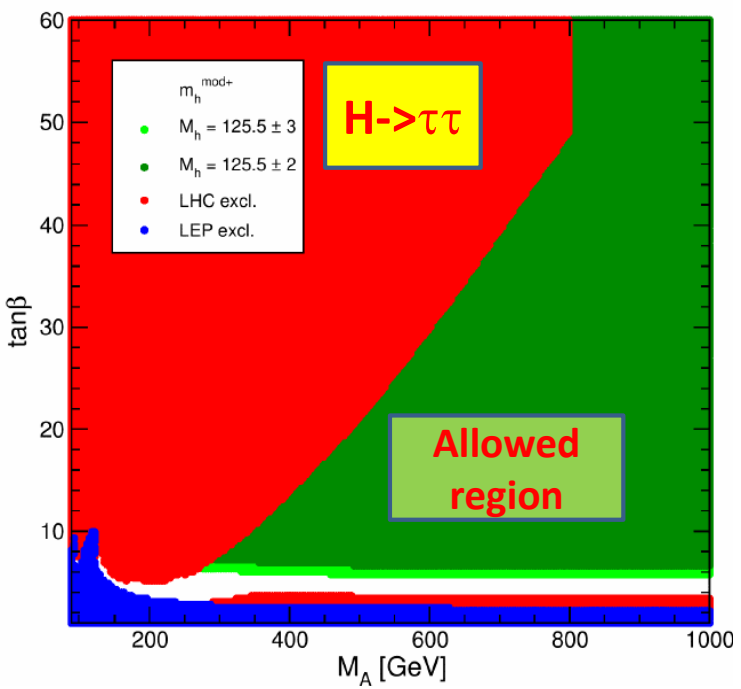
Carena et al. new benchmark

MSSM benchmark scenarios (II)

(from M. Carena et al arXiv:13027033)

- **m_h^{mod} scenario:**
  - **green area is allowed region of M_A-tanβ**

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 1.5\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= 1.6\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$



Charged Higgs (tan $\beta < 1$)

For tan $\beta < 1$ $H^+ \rightarrow cs$ large. Events with $t \rightarrow H^+b$ look similar tt.