Search for rare and BSM Higgs decays

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on behalf of the ATLAS and CMS collaborations

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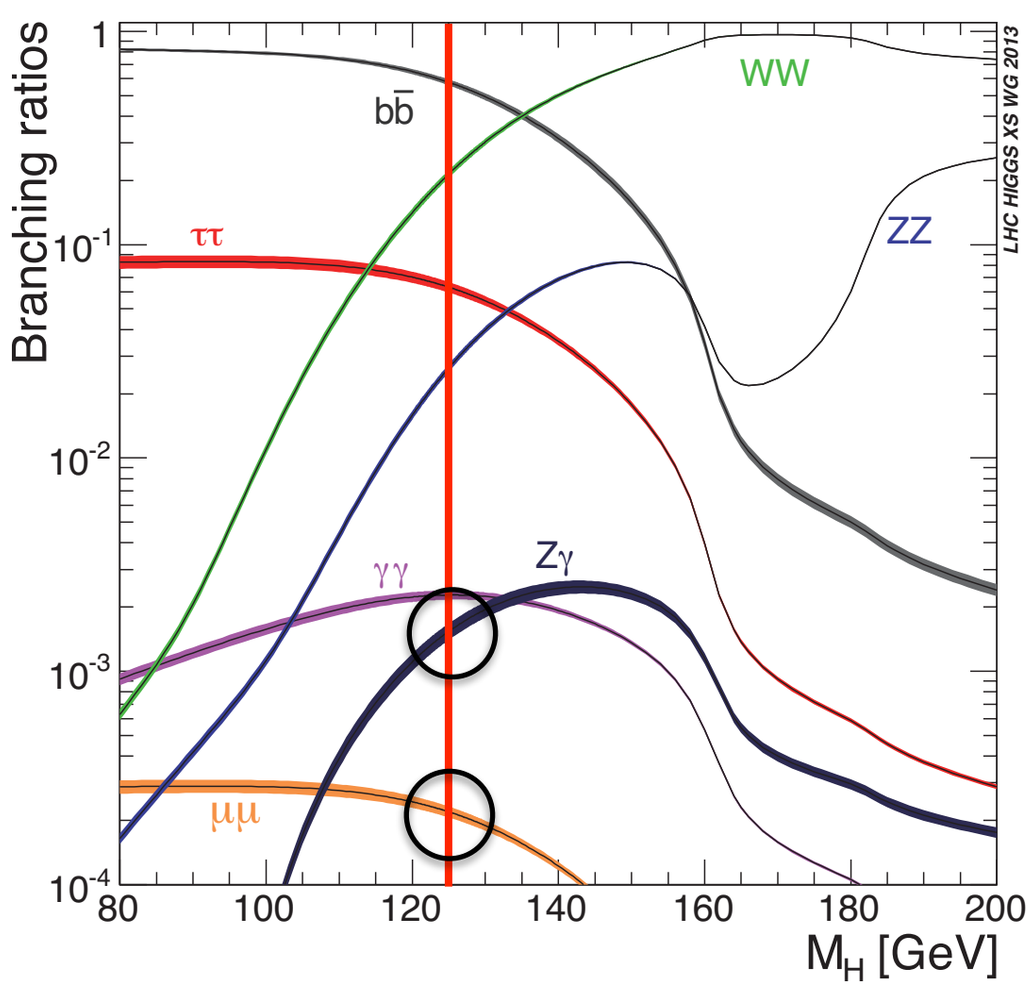
Outline

- Review of recent results of **ATLAS** and **CMS** about rare and Beyond Standard Model (BSM) Higgs decays
  - focus on new results
- Both **indirect limits** from h(125) properties and **direct searches** are highlighted
- Where possible, interpretation in specific models is given
  - EWK Singlet
  - 2HDMs (MSSM)
  - nMSSM
  - Dark matter portal scenario
- **Future prospects** for the LHC are presented

Rare Higgs decays

- After the discovery of a Higgs: need to explore properties in all possible channels
- Rare decays are not expected to be sensitive (yet) at the LHC
  - but new physics may enhance their BRs (loops)

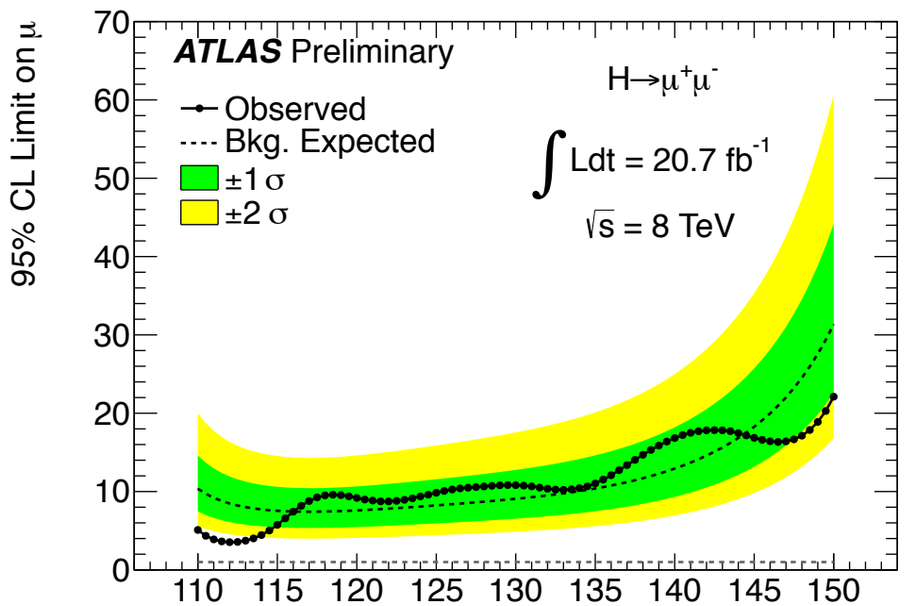
- **H→μμ**
  - SM BR @125 GeV ≃ 2×10^{-4}
  - probes directly 2nd generation Higgs fermion coupling
- **H→Zγ/γ*γ**
  - SM BR @125 GeV ≃ 1×10^{-4} (Z→ee,μμ)
  - constrains new particle contributions in loops
- **H→invisible**
  - SM BR @125 GeV ≃ 1×10^{-3} ($H\to ZZ^{(*)}\to 4\nu$)
  - searches for evidence of invisible-particle decays

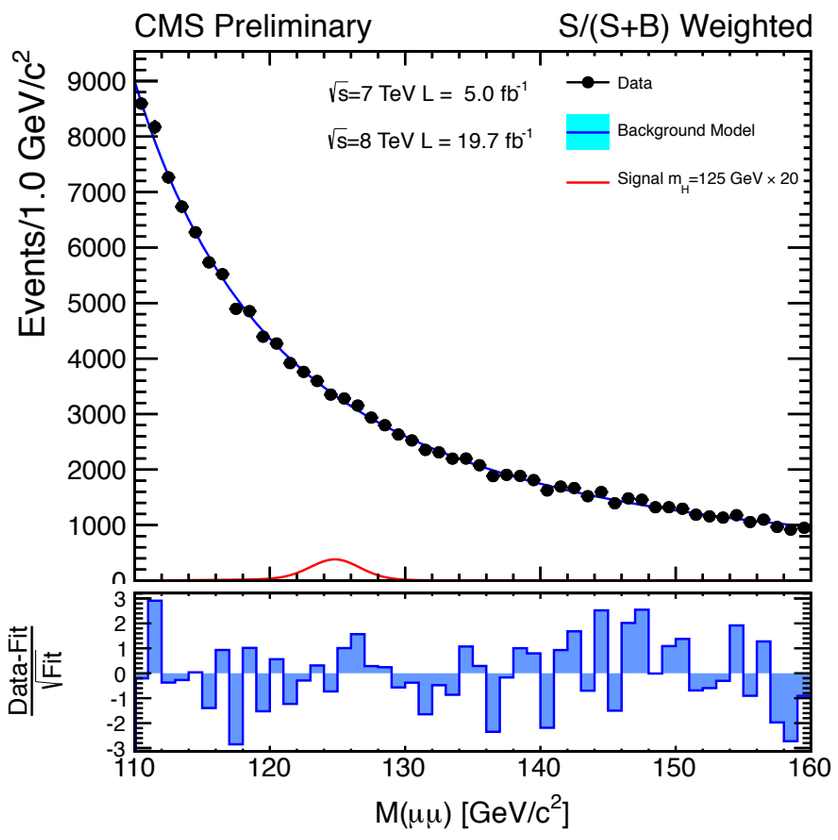


$H \rightarrow \mu\mu$

See talk from A. Kropivnitskaya

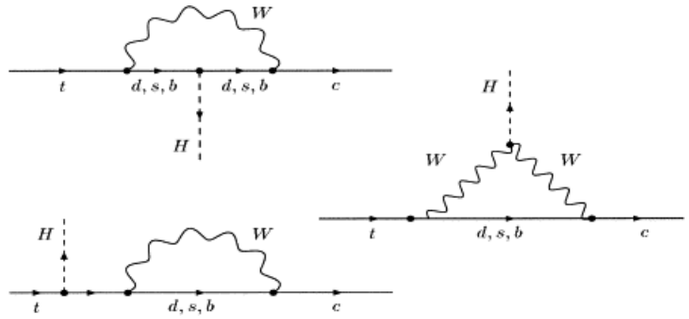
- Clean final state but small BR
- Main backgrounds: Z/γ^* production, tt, WW leptonic
- Categorization of events
  - mass resolution
  - production mechanism
- Unbinned fit to $m_{\mu\mu}$ to extract limits
  - unbiased background model
  - tail of Z Breit-Wigner + exponential for tt and WW





	Datasets	Reference	obs. (exp.) 95% C.L. limit on μ
CMS	7+8 TeV	CMS PAS HIG-13-007	**7.4 (5.1) @125 GeV**
ATLAS	8 TeV	ATLAS CONF 2013-010	**9.8 (8.2) @125 GeV**

Higgs and top



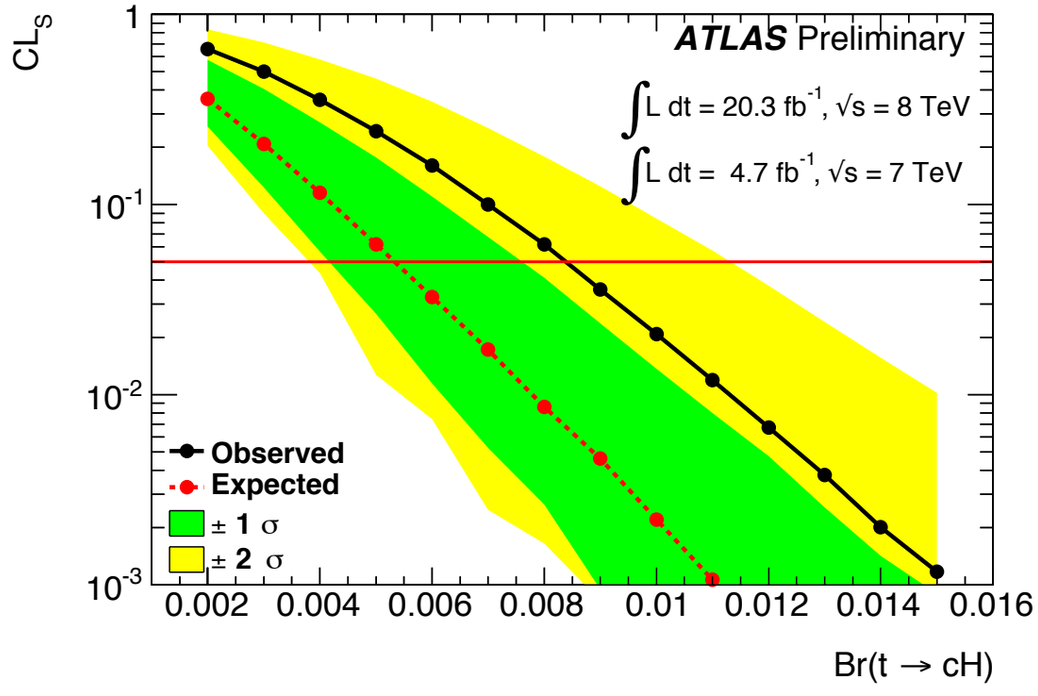
- Evidence of Higgs coupling to top at LHC: gluon-fusion, ttH associated production, H→γγ
- Flavour changing top decay (**t→cH**)
  - extremely rare in SM due to GIM mechanism (~10^{-14})
  - set limits on **BR(t→cH)**
  - interpret results in terms of flavour violating Yukawa couplings

$$\sqrt{|\lambda^{H}_{tc}|^2 + |\lambda^{H}_{ct}|^2}$$

- Single top + Higgs (**tHq**)

See talk from P. Ferrari

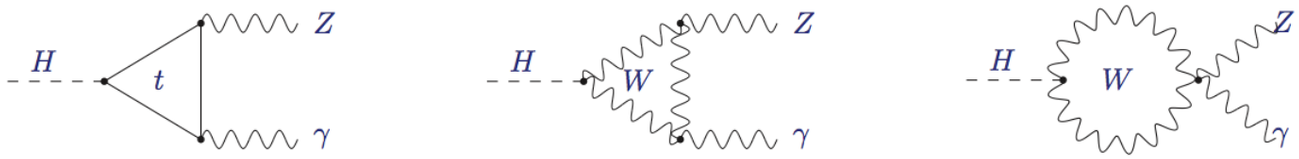
	Reference	obs. (exp.) 95% C.L. on BR(t→cH) & FVY
CMS	CMS PAS HIG-13-034	**0.56 (0.65) % & 0.14 (0.15)**
ATLAS	ATLAS CONF 2013-081	**0.83 (0.53) % & 0.17 (0.14)**



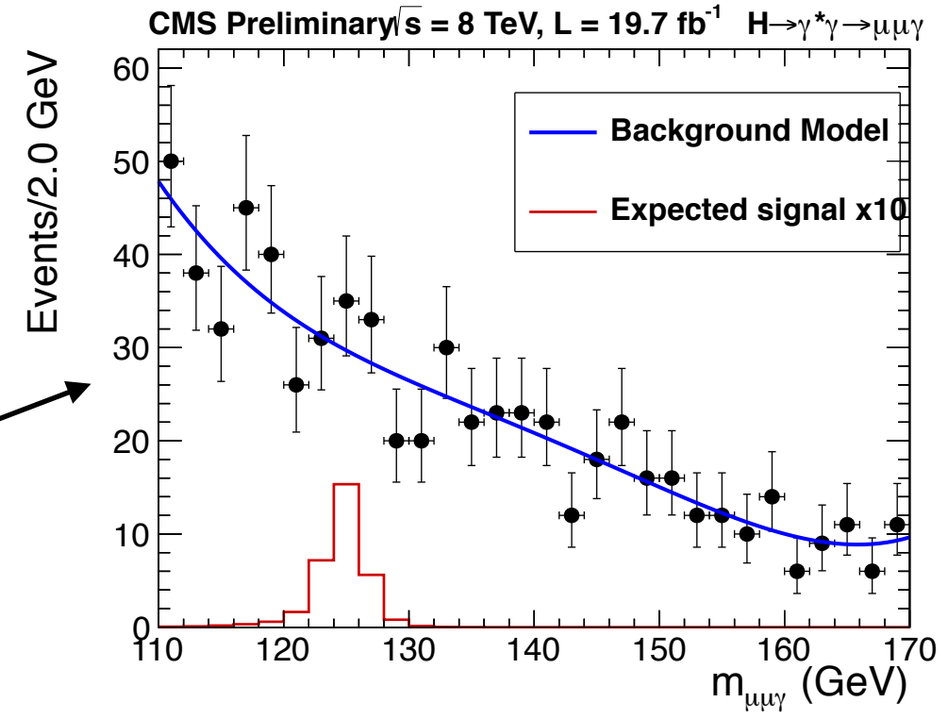
See talk from P. Ferrari

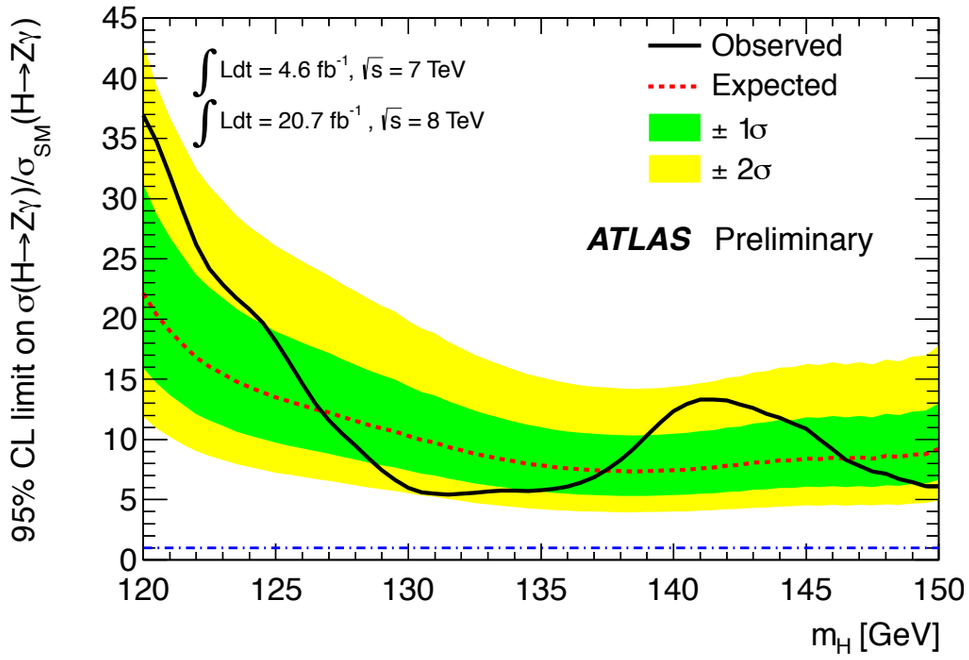
$H \rightarrow Z/\gamma^* + \gamma$

- Analysis sensitive to BSM contributions in loops
  - may enhance SM branching ratio



- Also $H \rightarrow \gamma^* \gamma \rightarrow \mu\mu\gamma$ explored far from the Z-mass
  - require $m_{\mu\mu} < 20$ GeV
  - one photon converts into a muon pair
- $m_{ll\gamma}$ used to extract limits
- Analytical description of background



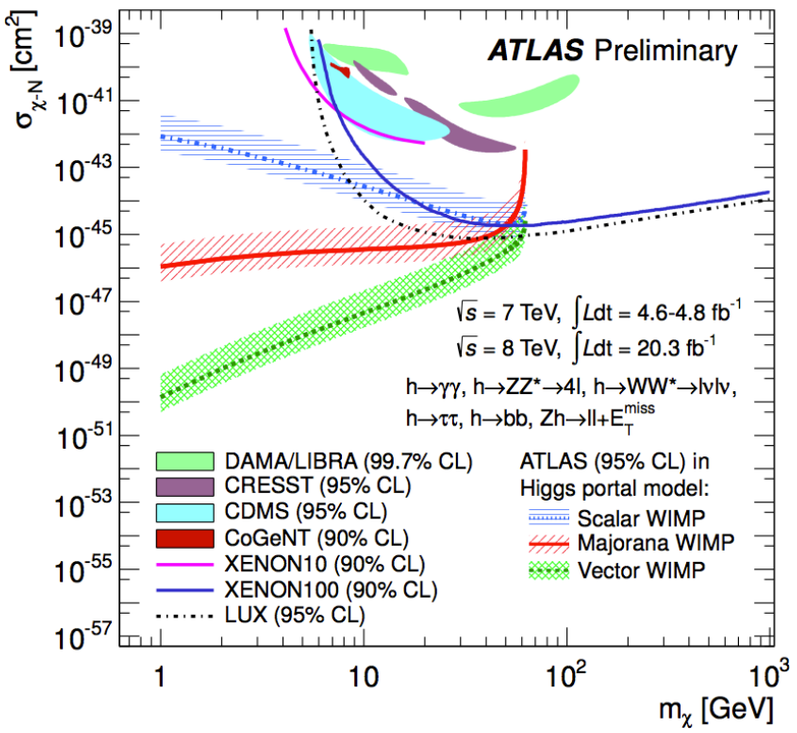


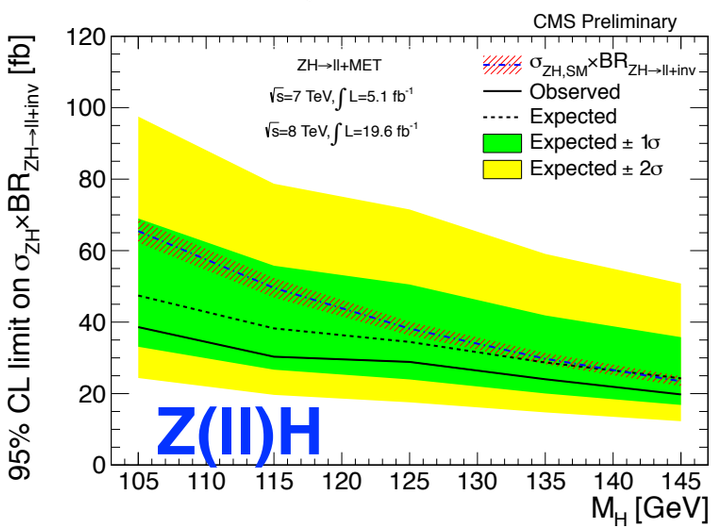
	Datasets	Reference	obs. (exp.) 95% C.L. limit on μ
CMS (Zγ)	7+8 TeV	Phys. Lett. B 726 (2013)	**9.5 (10) @125 GeV**
CMS (m	8 TeV	CMS PAS HIG-14-003	**11 (8) @125 GeV**
ATLAS (Zγ)	7+8 TeV	Phys. Lett. B 732 (2014)	**11 (9) @125 GeV**

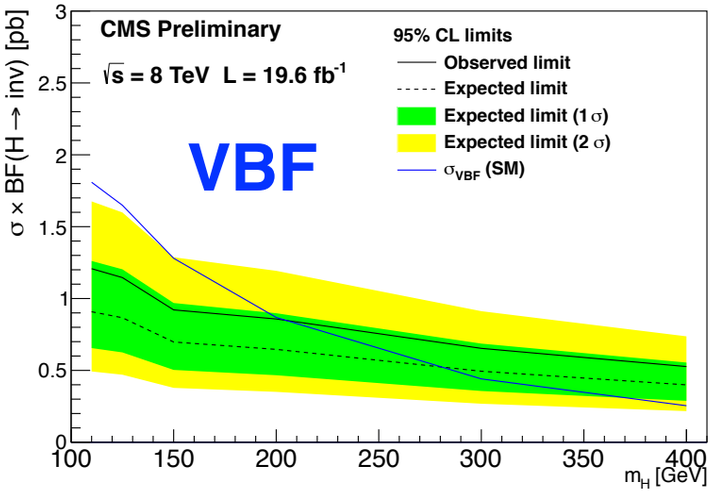
Invisible Higgs decays

- Direct search for invisible Higgs decays used to set limits on:
  - SM h(125) invisible BR
  - Additional Higgs (low-intermediate mass) decaying into invisible particles
  - **Higgs-portal dark matter scenario** (H→χχ)
- VBF and Z(→ll,bb)H associated production are considered

Reference	obs. (exp.) 95% C.L. limit on BR(h→inv.)
ATLAS arXiv:1402.3244 Z(ll)H	**75 (62) %**
ATLAS CONF 2014-010 (dir.+indir.)	**37 (39) %**
CMS PAS HIG-13-013 VBF	**69 (53) %**
CMS PAS HIG-13-018 Z(ll)H	**75 (91) %**
CMS PAS HIG-13-030 (ZH, VBF comb.)	**58 (44) %**
CMS PAS HIG-13-028 Z(bb)H	**182 (199) %**
CMS PAS HIG-13-005 (indir.)	**52 (56) %**







EWK Singlet: constraints from h(125)

- One more **electroweak singlet** field mixed with SM doublet
- Light (h) and heavier (H) Higgs states have SM-like couplings and width but rescaled by the mixing parameter
  - unitarity imposes $k^2+\mathbf{k'}^2=1$
  - $\mathbf{BR_{new}}$ for H may arise from $H \rightarrow hh$ decays if $m_H > 2m_h$
- Indirect constraints arise from fitting the couplings of h(125)

Heavy Higgs

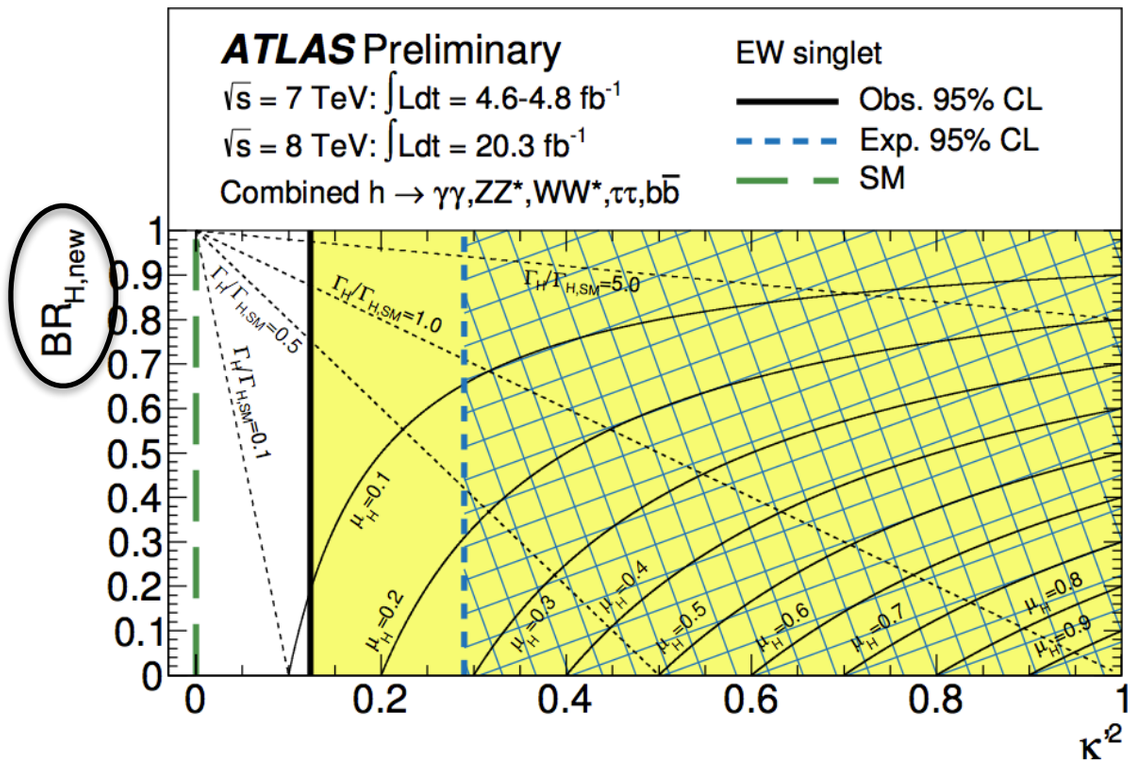
$$\mu_H = k'^2 \left(1 - BR_{H,new}\right)$$
$$\Gamma_H = \frac{k'^2}{1 - BR_{H.new}} \times \Gamma_{H,SM}$$

Light Higgs

$$\mu_h = k^2$$
$$\Gamma_h = k^2 \times \Gamma_{h.SM}$$

ATLAS CONF 2014-010

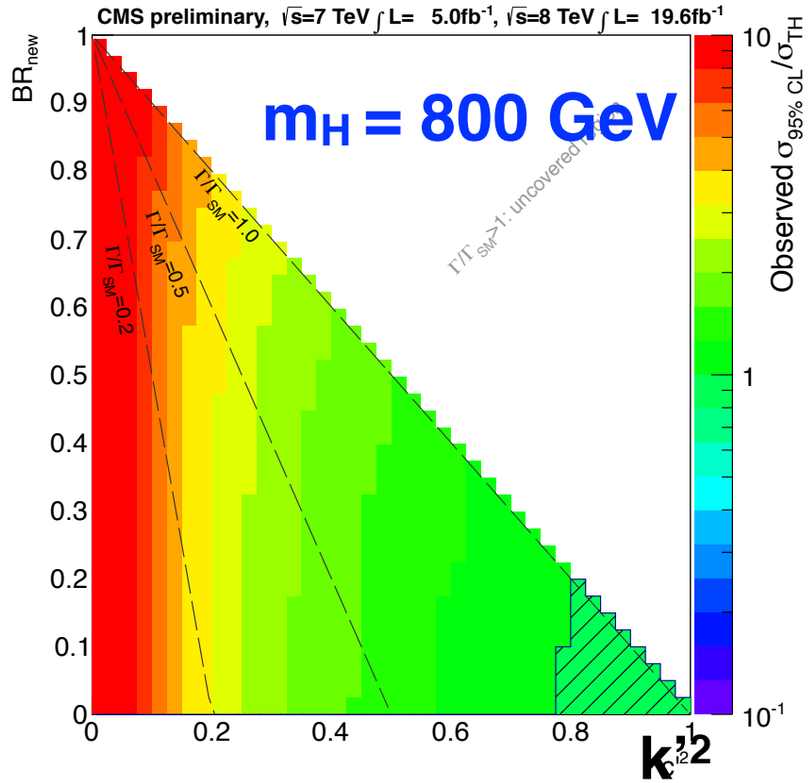
$k'^2 < 0.12$ (0.29) @95% C.L.

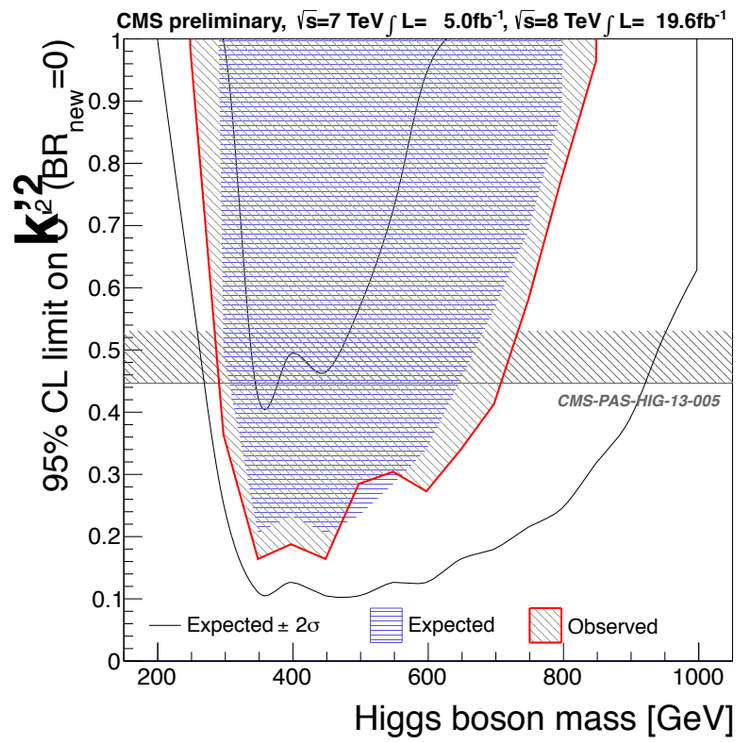


EWK Singlet: H→ZZ

CMS PAS HIG-13-014

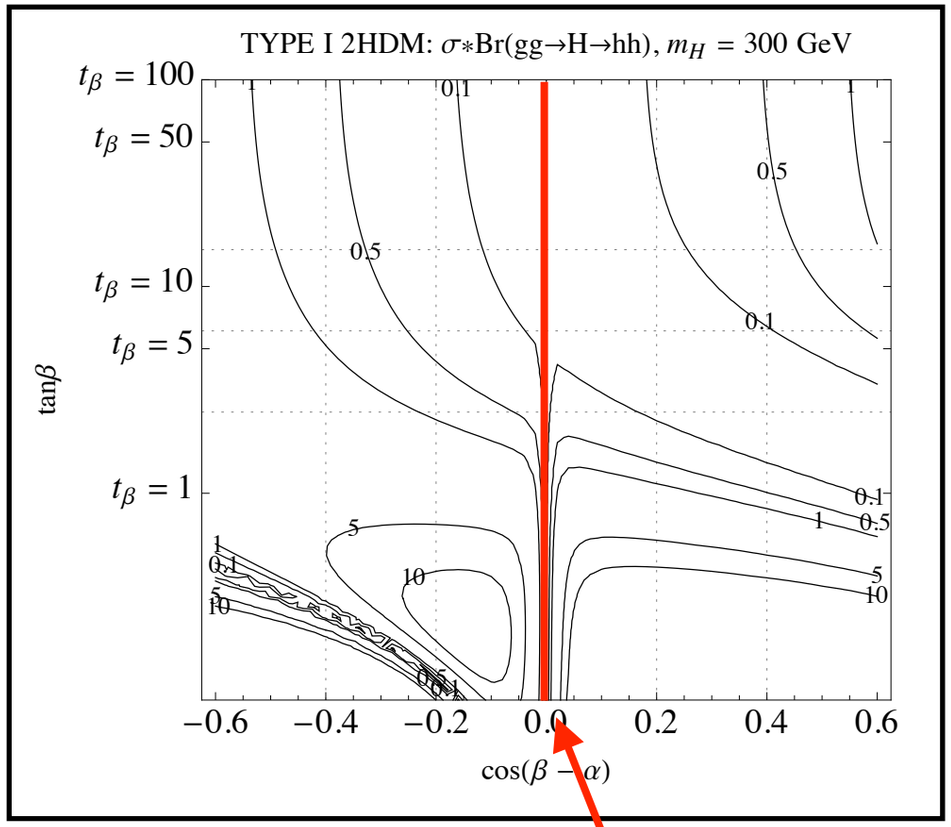
- **ZZ/WW** channels are the most sensitive in direct heavy Higgs searches
  - H→ZZ→2l2v alone excludes SM cross sections up to ~ 1 TeV
- Interpretation also given in terms parameter space of the **EWK Singlet** model
  - direct search, complementary to h(125) constraints
  - in 300-700 GeV limits are better than the indirect ones ($k'^2 < 0.1$-0.45)
- Full combination of WW/ZZ “high mass” channels with Run1 data is in preparation





2HDM overview

- 2 complex scalar doublets Φ_1, Φ_2 with different interactions
- 4 types of models allowed by Paschos-Glashow-Weinberg conditions
- 5 physical particles: $H^{\pm}$,h and H (CP even), A (CP odd)
- Couplings described by 2 parameters:
  - **tanβ**=v_1/v_2
  - **α** h/H mixing angle
- Phenomenology depends on the masses of the physical fields (free parameters)



Alignment limit

Couplings are expressed in terms of ratio to the prediction of the SM:

$k_i=g_i/g_{i,SM}$

light *CP*-even h couplings

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

2HDM: constraints from h(125)

- Measured production/decay rates in $\gamma\gamma$,ZZ,WW,$\tau\tau$,bb channels interpreted in each type of **2HDM**
  - assume h(125) to be the **light *CP*-even** neutral Higgs
  - rescale rates according to k_i for the SM production modes (bbH included as correction scaling with the square of b-quark coupling)
  - extracting from k_i information on **tanβ** and **cos(β-α)**

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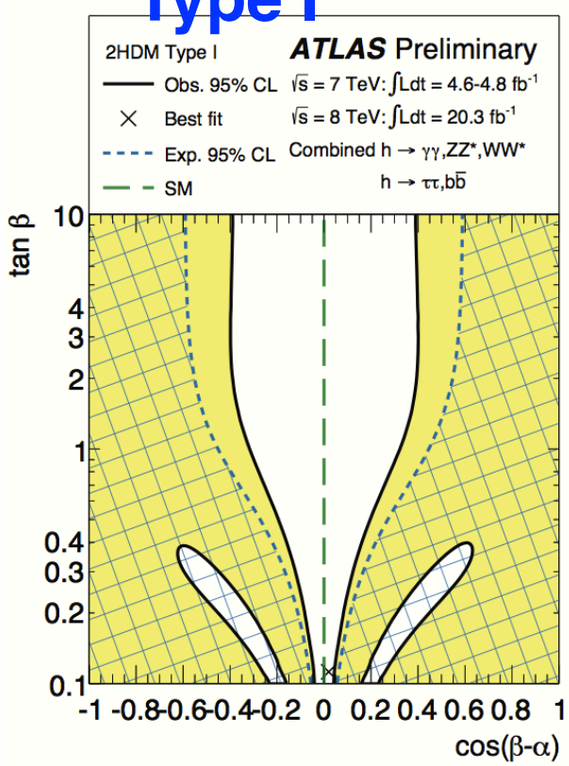
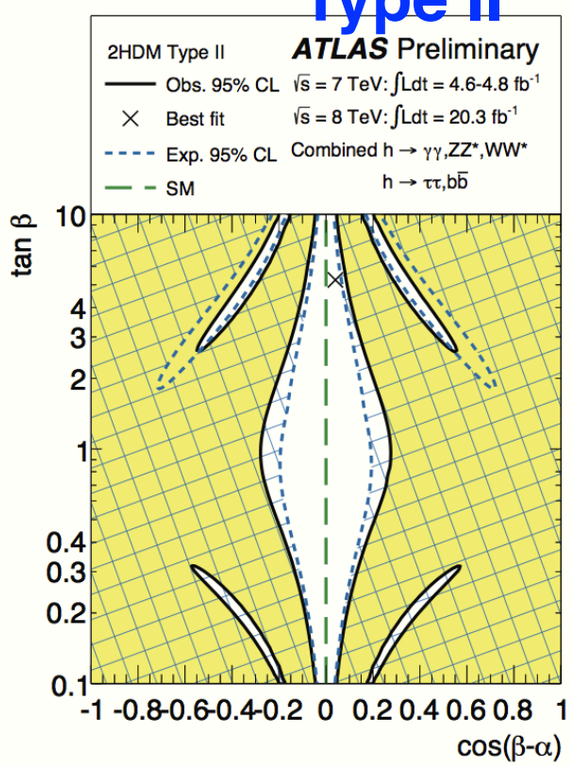
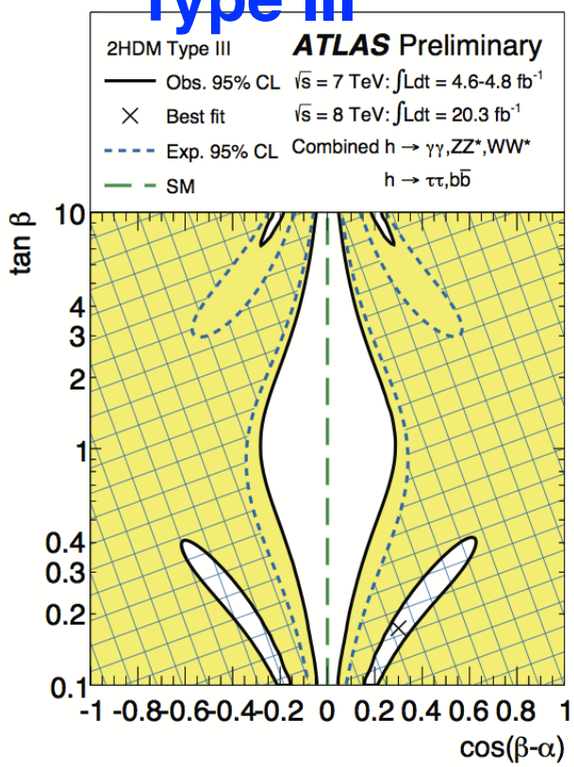
Type I



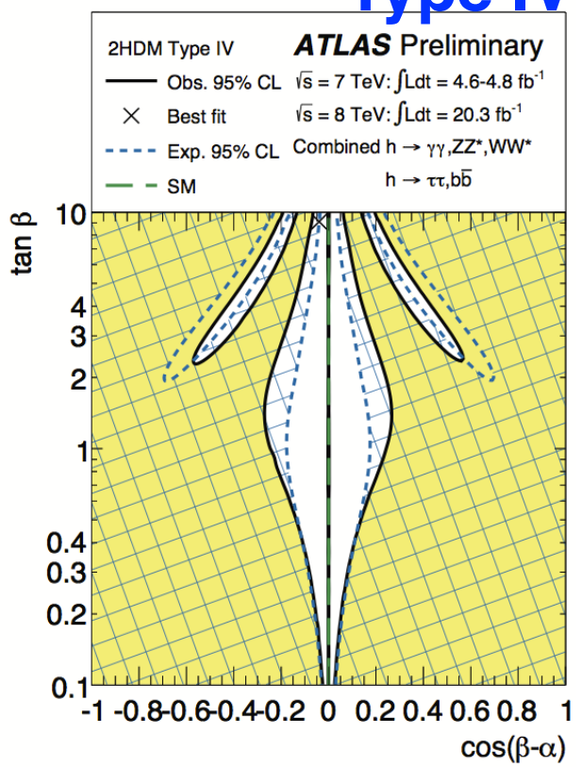
Type II



Type III



Type IV



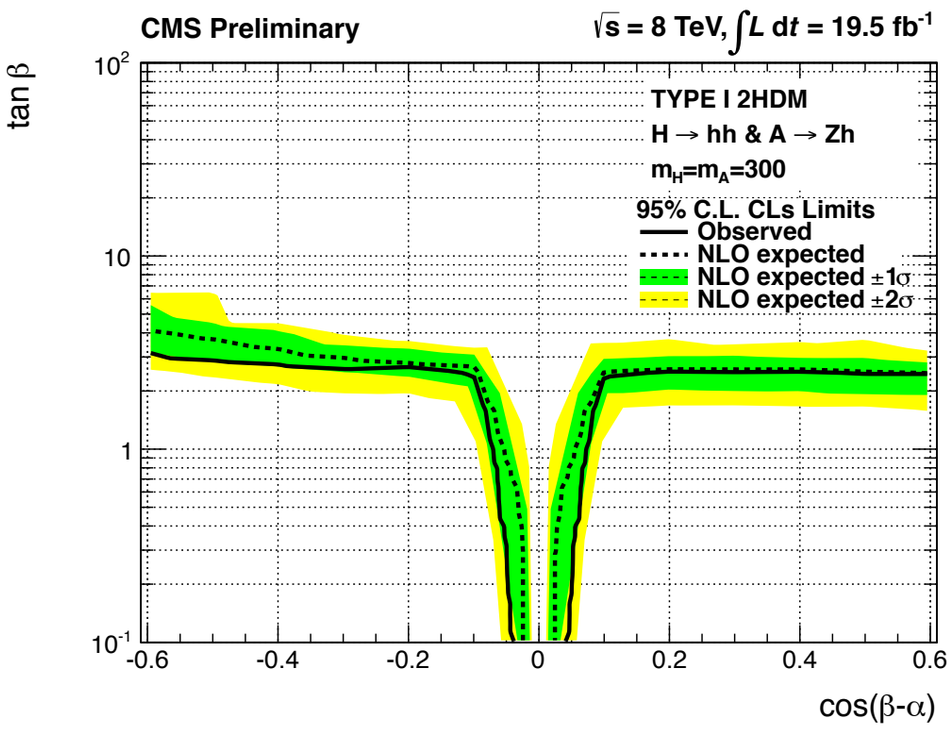
2HDM: H→hh, A→Zh

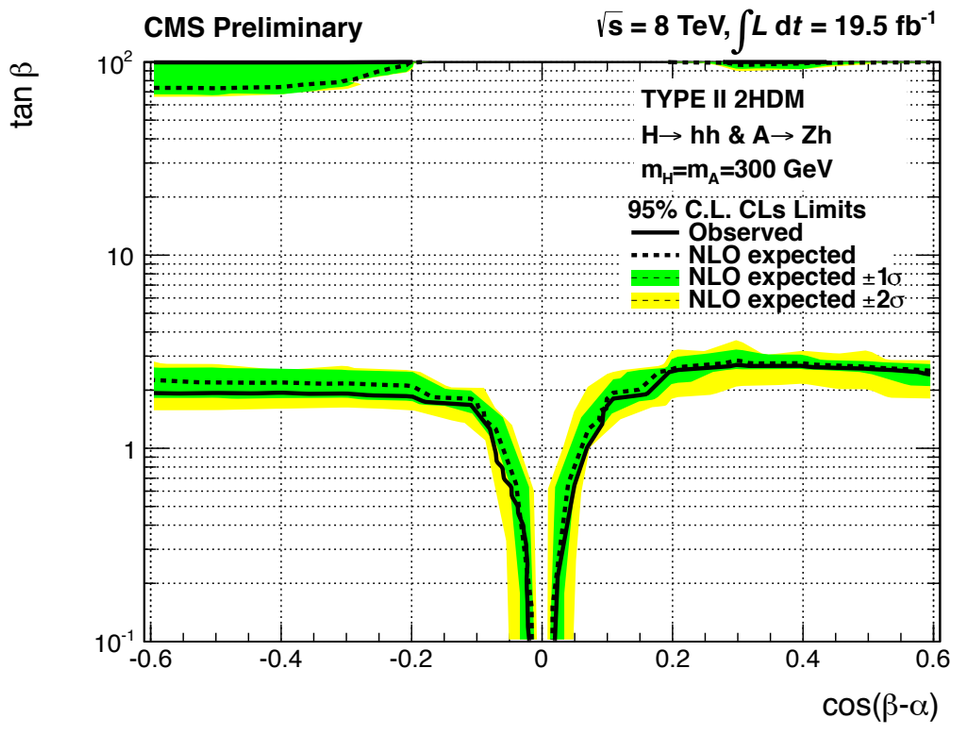
- h is the SM-like Higgs boson with mass 126 GeV
  - **H→hh** dominant in $2m_h<m_H<2m_t$
  - **A→Zh** dominant in $m_h+m_Z<m_A<2m_t$
- Several final states of h and Z are considered

CMS PAS HIG-13-025

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	X	✓
$h \to ZZ^*$	-	✓	✓	✓	✓
$h \to \tau\tau$	-	-	✓	X	✓
$h \to bb$	-	-	-	X	X
$h \to \gamma\gamma$	-	-	-	-	X

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X



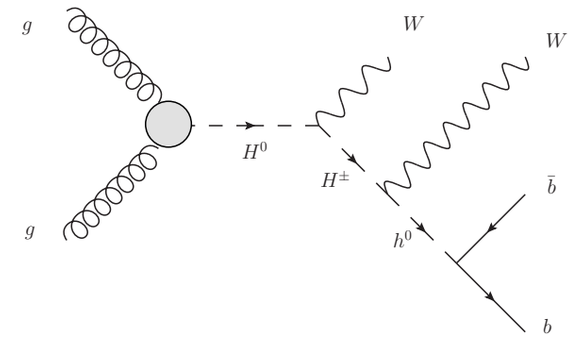


2HDM: cascade decays

- Phenomenology of 2HDM may allow for **cascade decays**:

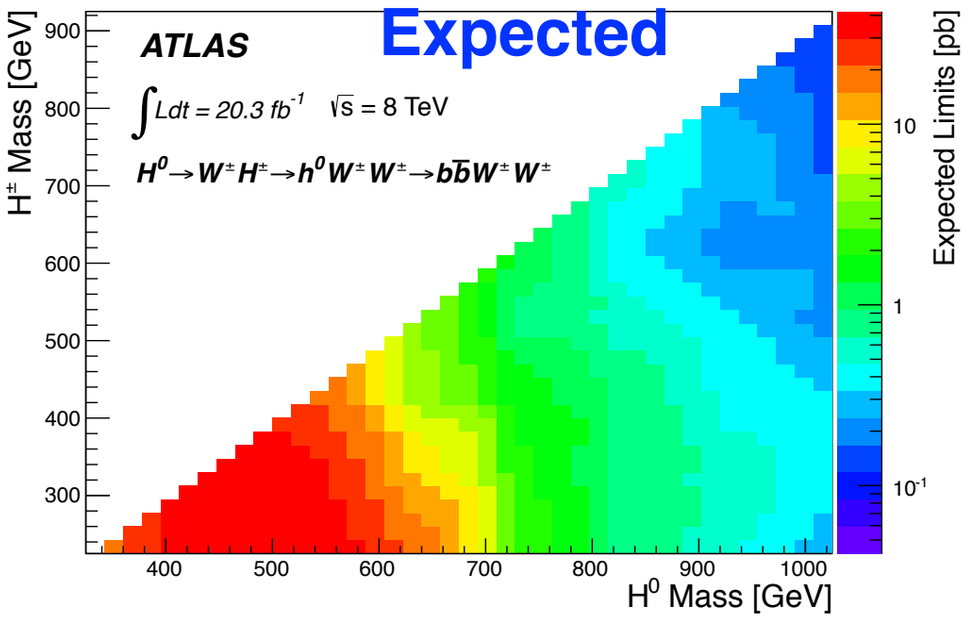
  H→W±**H**∓→W±W∓**h**→W±W∓bb

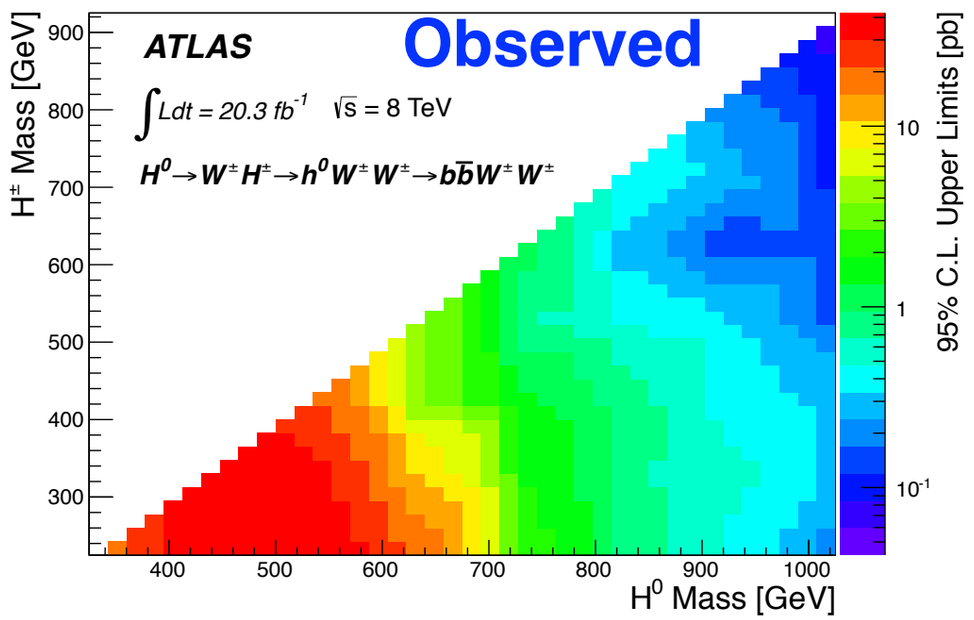
  - exploit **h(125)→bb** decay to gain statistics
  - drawback is: same final state as tt
  - use multivariate analysis to discriminate against background



- Produce upper limits on the cross section in the (m_H,$m_{H\pm}$) plane
- Limits range from 0.07-43 pb

ATLAS Phys. Rev. D 89 032002 (2014)





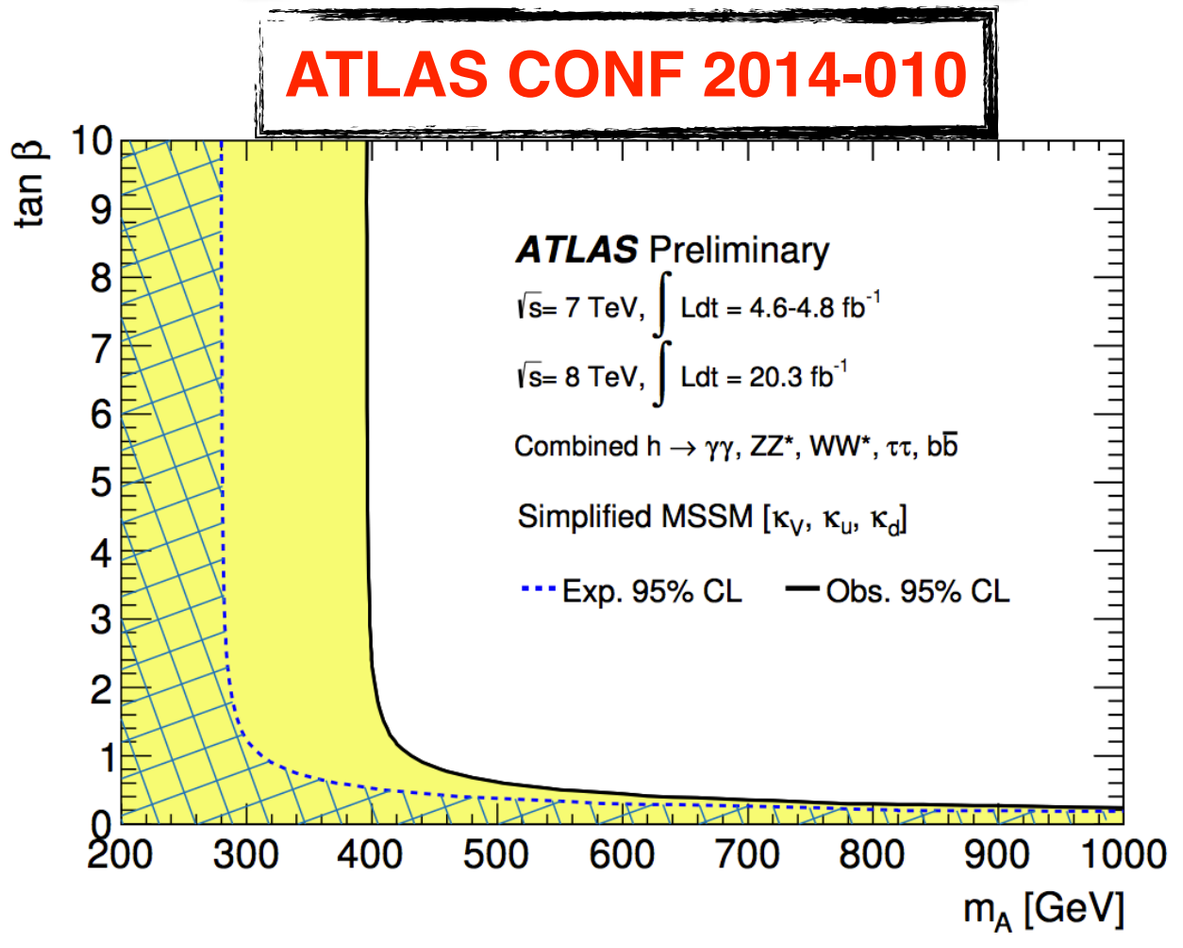
MSSM: constraints from h(125)

- MSSM is a particular Type II 2HDM
  - phenomenology is described with **tanβ** and $\mathbf{m_A}$ (tree level)
- **Simplified MSSM**
  - m_h=125.5 GeV is used to extract radiative corrections in the mass-mixing matrix
  - k_V, k_u, k_d fully determined by $(\tan\beta, m_A)$
  - loop corrections to ggH and H→γγ from *stops* are neglected (<5% for m_{stop}>500 GeV)
  - other corrections that break universality are neglected

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

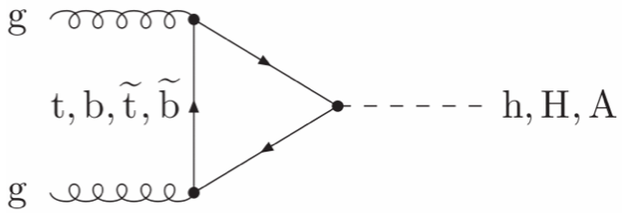
$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

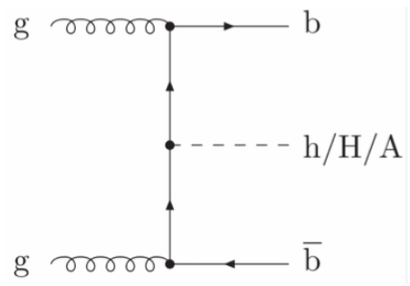
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}$$



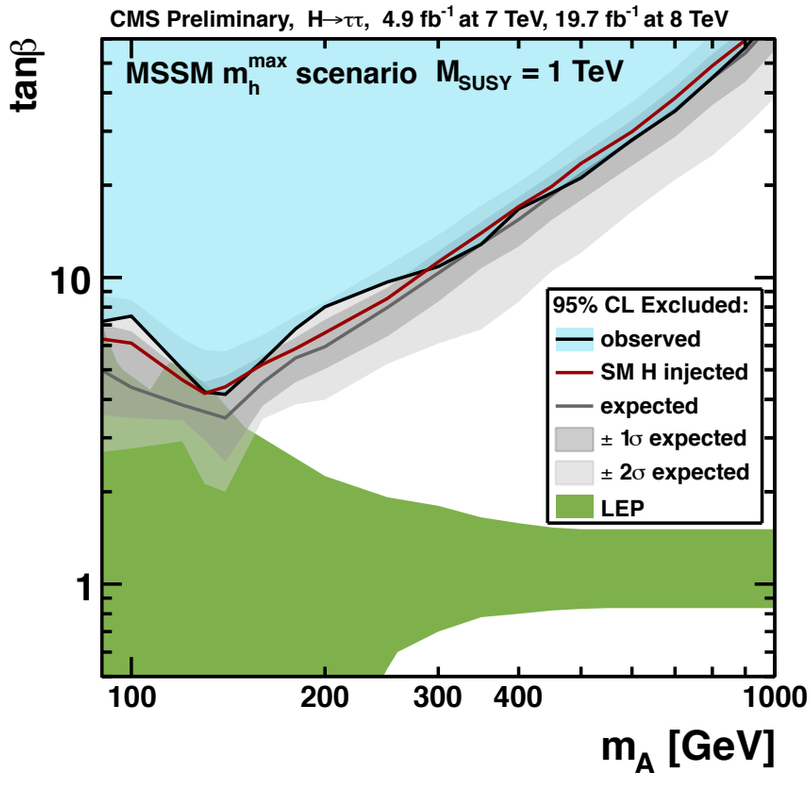
MSSM: $\phi \rightarrow \tau\tau$

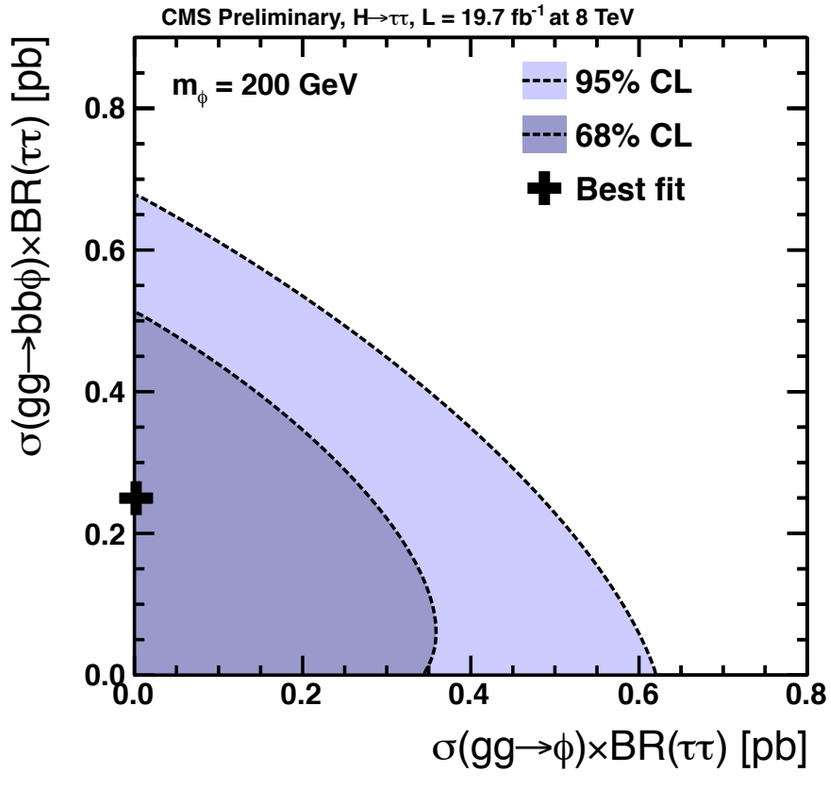
- **small-moderate tanβ**: gluon-fusion production is dominant
- **high tanβ**: b-associated is enhanced
  - Both processes are considered and separate limits are computed
- Limits are extracted in the **m_h^{max}** scenario
  - σ x BR($\tau\tau$) has mild dependence on the benchmark





CMS PAS HIG-13-021





MSSM: $H^{\pm} \rightarrow \tau^{\pm}\nu$

Light charged Higgs

$m_{H^{\pm}} < m_{top}$

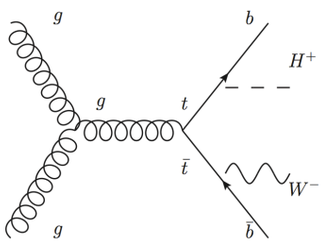
- Production in $t \rightarrow Hb$ decay
- $BR(H^{\pm} \rightarrow \tau^{\pm}\nu) \sim 100\%$ for $\tan\beta > 3$
- Search exclude almost all the parameter space in $m_{H^{\pm}} \subset [90,160]$ GeV

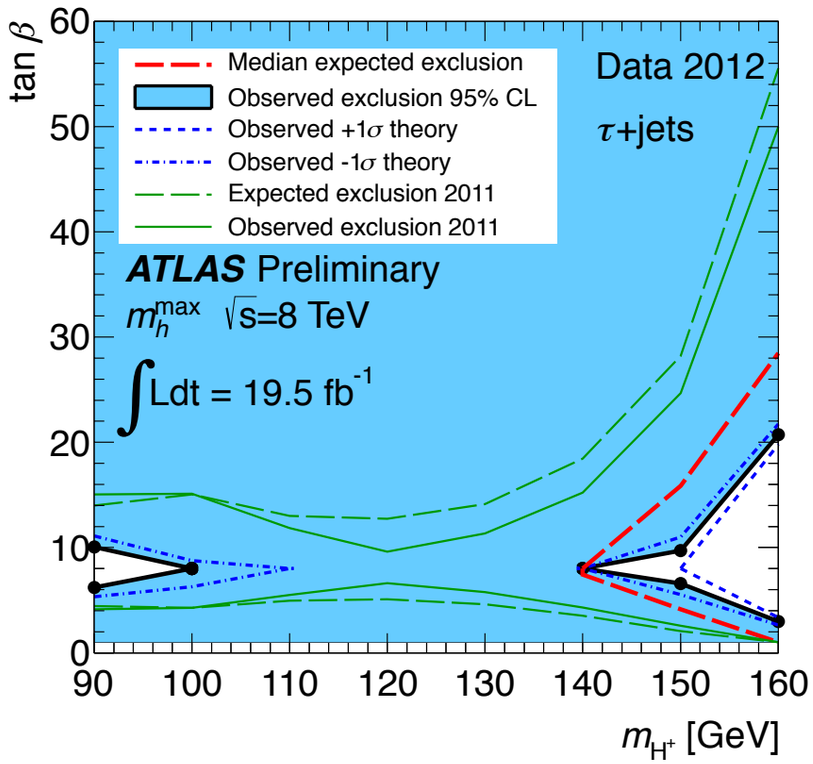
Heavy charged Higgs

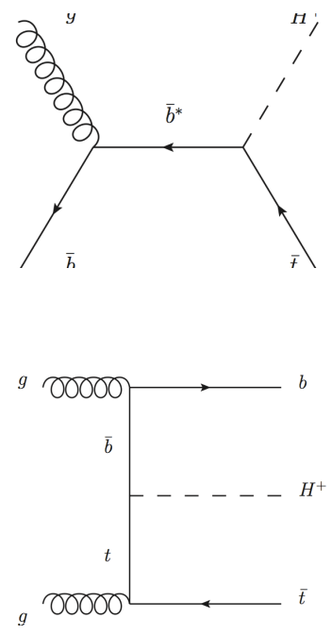
$m_{H^{\pm}} > m_{top}$

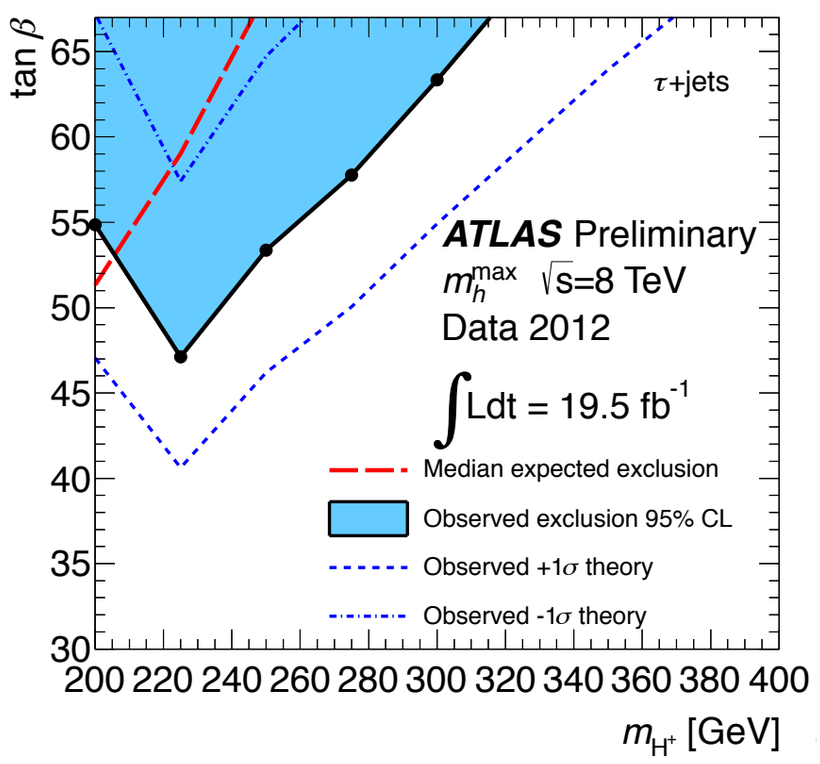
- Associated production with top: tH(b)
- $BR(H^{\pm} \rightarrow \tau^{\pm}\nu)$ still sizeable but cross section is reduced

ATLAS CONF 2013-090





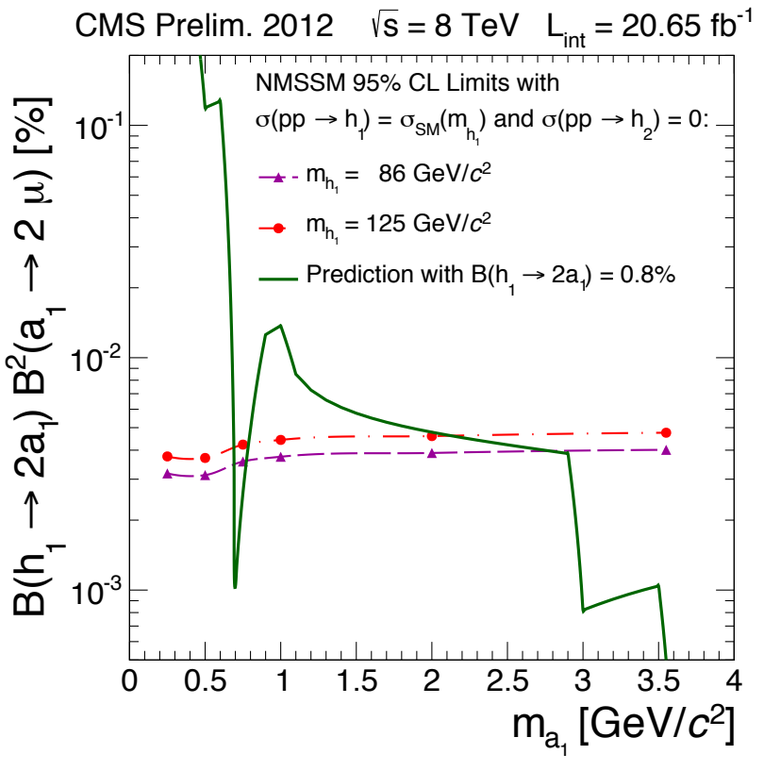


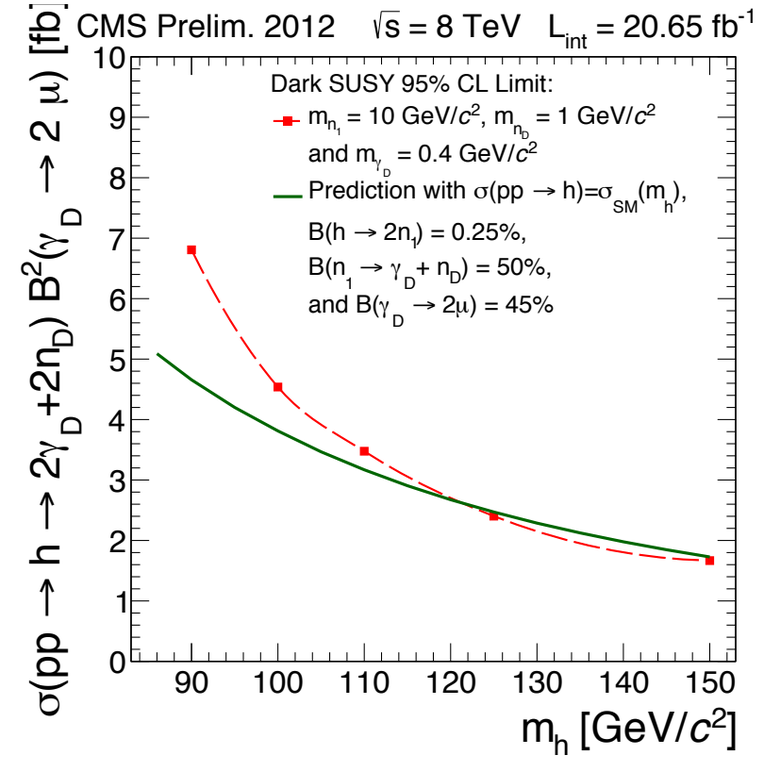


$h \rightarrow a_1 a_1$

CMS PAS HIG-13-010

- Search for pair production of a **light boson a_1** from the decay of a (SM-like) Higgs boson h
- 4μ final state is explored
- Motivated by
  - **nMSSM**
    - $h_{1,2}$ (SM-like Higgs) decays to 2 a_1 (*CP*-odd)
    - BR($a_1 \rightarrow \mu\mu$) dominant if $2m_\mu < m_{a1} < 2m_\tau$ (~90%)
  - **dark SUSY**
    - $h \rightarrow 2n_1 \rightarrow 2n_D 2\gamma_D \rightarrow 2n_D 4\mu$
    - n_1 lightest neutralino, n_D dark neutralino, γ_D dark photon
    - BR($\gamma_D \rightarrow \mu\mu$) up to 45% depending on γ_D mass





Prospects for Run2/3

- Extrapolation of physics results with 300/3000 fb^{-1} at $\sqrt{s}$ =14 TeV
  - Precision **coupling measurements** ($k_V \lesssim 5\%$, $k_f \lesssim 10\%$) allow to constrain 2HDM space around the SM-like limit
  - **Direct searches** will be able to explore regions not covered by indirect limits ($H \to ZZ^{(*)} \to 4l$, $A \to Zh(bb)$,…)

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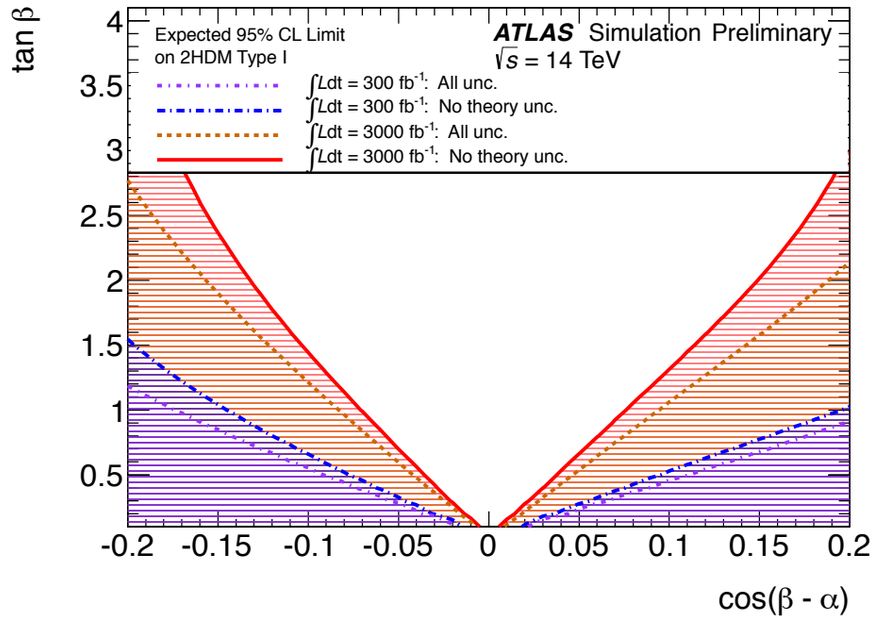

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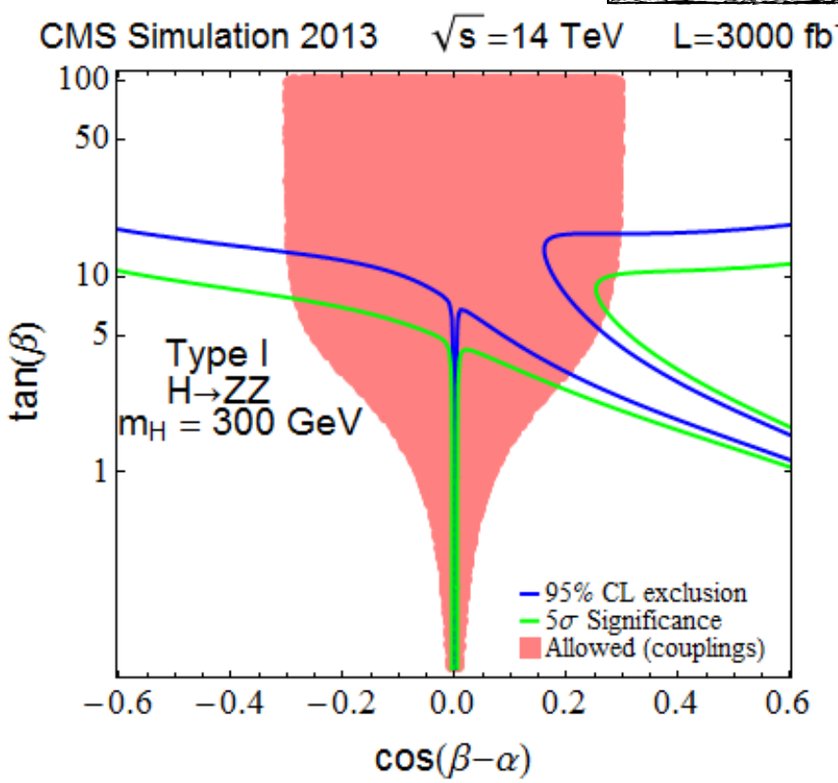

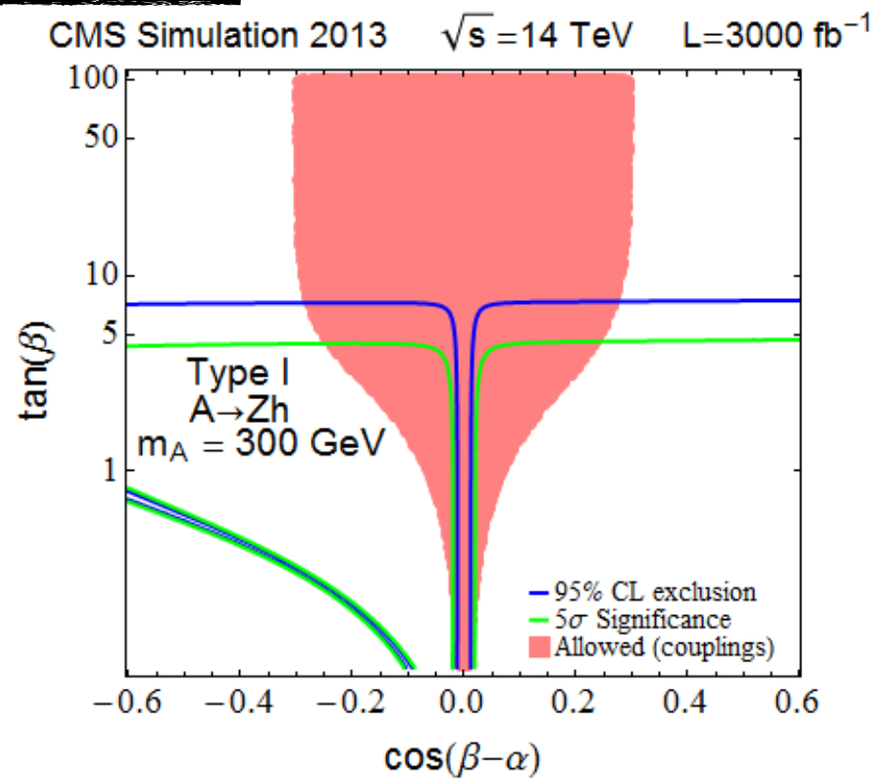

Conclusions

- **Run1** has been a success
  - outstanding performances of both LHC and CMS and ATLAS detectors
- A **Higgs boson** has been discovered
  - Analysis moved from search to measurement
  - No evidence for deviation from SM predictions
  - Much BSM parameter space has been ruled out …
  - … but still room for new physics!
- Twofold strategy for testing new physics during **Run2/3**
  - improving precision in coupling fits
  - focus direct searches in regions of the BSM space not covered by precision measurement

Exciting times ahead in Higgs physics!