# BSM Higgs Boson Searches at the LHC

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On behalf of the ATLAS and CMS collaborations

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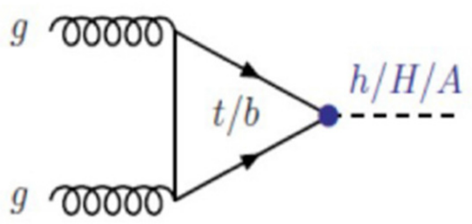
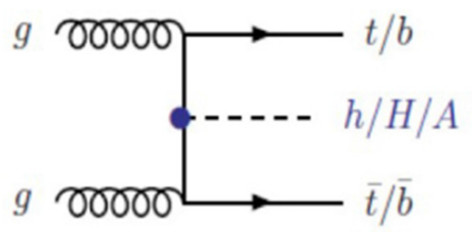
# Introduction

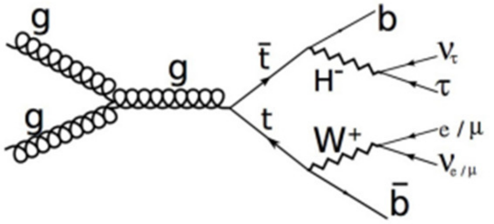
- In the **Standard Model (SM)** only **1 complex Higgs doublet** is responsible for electroweak symmetry breaking: there is one neutral CP even Higgs boson h
- **Two Higgs Doublet Models (2HDM)** extend beyond the SM Higgs sector to include two complex Higgs Doublets . Leads to five physical states $H^+$, $H^-$ , A(CP-odd), H, h (CP-even)
- Is the Higgs observed at the LHC the standard model Higgs or the h from an extended sector?
- **Minimal Supersymmetric Standard Model (MSSM)** solution to "hierarchy problem" ($m_h << m_{Planck}$) and **dark matter (DM)** candidates
- Other models (which may also solve hierarchy problem) include Higgs as a **composite particle**, introduction of an **additional electroweak singlet** to the doublet Higgs field of the SM, NMSSM etc.
- Entering a new realm of exploration: probing the couplings and decays rates of the observed Higgs boson whilst searching for additional Higgs States which could provide window into the underlying physics of EWSB

# Searches

- Number of ways to search:
- *Directly* from decays of neutral and charged Higgs e.g. through Flavour Changing Neutral Currents (FCNC)
- Study *indirectly* by interpreting measured mass and couplings of light Higgs in extensions of the standard model
- Neutral Higgs searches: many searches including b-associated and gg-fusion production with VV, bb, ττ , μμ decays etc.
- Charged Higgs searches: many searches including production in top decays with decay to τν, cs,..
- Many analyses completed on full 8 and 7 TeV data – imposing constraints on models as we approach Run-II



# 2HDM/MSSM Models

- Higgs sector of 2HDM models described by parameters: 4 Higgs masses, tan $\beta$(ratio of vacuum expectation values vev) and $\alpha$ mixing between the two neutral CP even states h,H
- 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
- For more specific MSSM models $m_h$ fully determined at tree level by $m_A$ and tan $\beta$
- In MSSM/2HDM type II models the couplings to b quarks and $\tau$ leptons are enhanced at high tan $\beta$

# Latest Results

## Limits on new Phenomena via coupling measurements

- Higgs measurements interpreted in 2HDM/MSSM/composite/electroweak singlet/Dark matter models
  ATLAS-CONF-2014-010 NEW

## Direct search for H->hh, A->Zh

- Using multilepton final states and diphoton Higgs decays
  CMS-PAS-HIG-13-025

## Search for t->cH

- Using multilepton and diphoton H->$\gamma\gamma$ Higgs decays
  CMS-PAS-HIG-14-001 NEW
- Final results from ATLAS using H->$\gamma\gamma$ submitted to JHEP

## Search for Higgs with single top tHq

- Probe t-H coupling using Higgs to diphoton decays
  CMS-PAS-HIG-13-034 NEW

## Other recently released searches

- MSSM CMS-PAS-HIG-13-021
- Charged Higgs ATLAS-CONF-2013-090

Lots of other searches but not enough time here

- High Mass ZZ,WW searches CMS-HIG-12-024
- ATLAS cascade Higgs arXiv:1312.1956
- NMSSM ATLAS-CONF-2012-079, CMS-PAS-HIG-13-010
- Doubly charged Higgs ATLAS arXiv:1210.5070 ,CMS arXiv:1207.2666
- Fermiophobic Higgs ATLAS-CONF-2012-013, CMS arXiv:1207.1130
- 2HDM WW ATLAS-CONF-2013-027

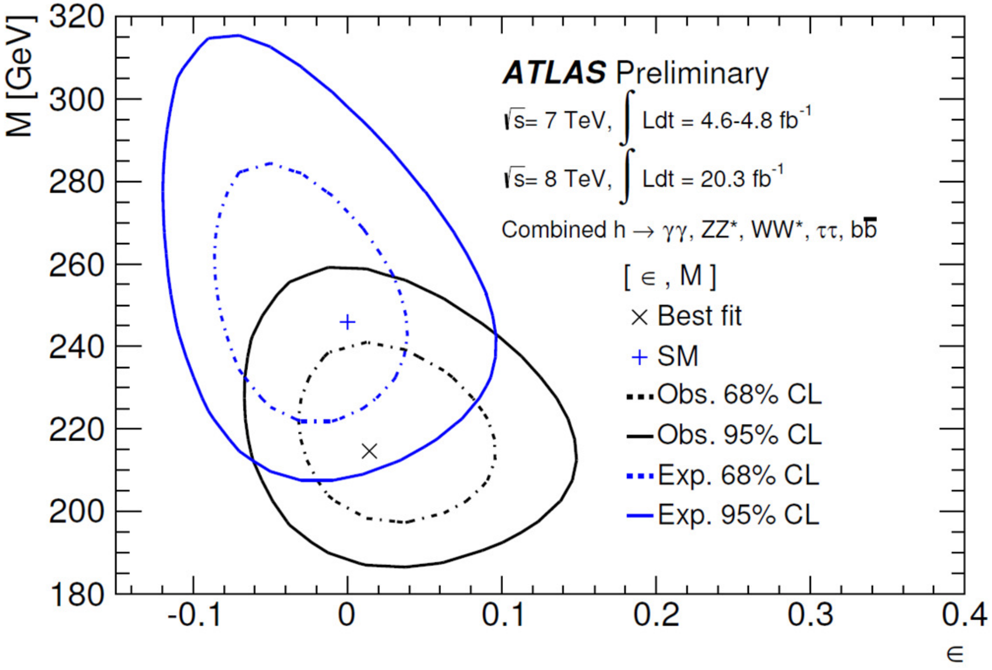
# Limits on new phenomena

ATLAS-CONF-2014-010 NEW

- Constraints on new phenomena via Higgs Boson coupling measurements. Mass scaling of couplings and representative BSM models: Minimal Composite Higgs Model (MCHM), additional EW singlet, 2HDM, Simplified MSSM, Higgs portal to DM
- Use same data and techniques as ATLAS Higgs coupling measurements ATLAS-CONF-2014-009 h->$\gamma\gamma$, ZZ, WW, $\tau\tau$, bb (see talk by Eilam Gross)
- For Higgs portal to DM additional data is used: observed limit of Zh->ll+$E_t^{miss}$ arXiv:1402.3244

# Mass scaling of Higgs Boson Couplings

Probe mass scaling of Higgs boson couplings to fermions and vector bosons



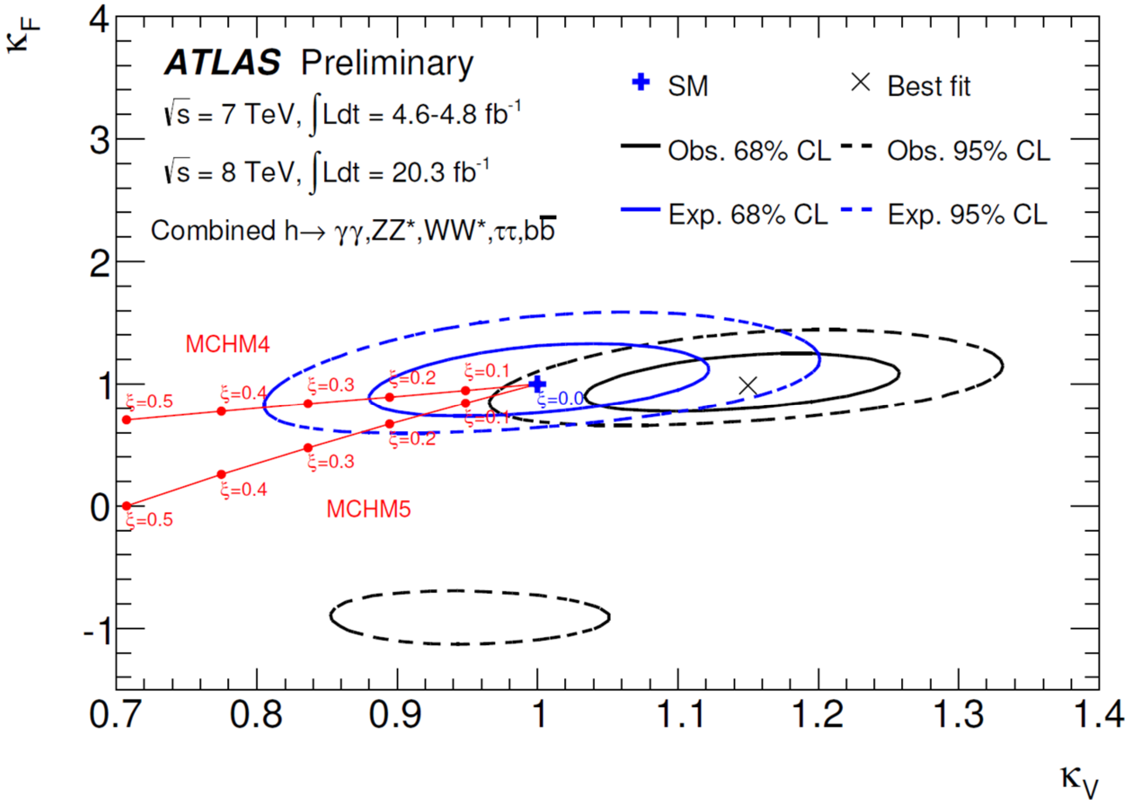

- Production/decay similar to SM but modified couplings to fermions and vector bosons e.g. Ellis and You arXiv:1303.3879 parameterisation. Ratios between modified and SM couplings:

$$\kappa_{f,i} = v \frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}} \qquad \kappa_{V,j} = v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

- ν=246 GeV, ε "mass scaling parameter", and M is the "vev parameter"
- ε=0, M=ν yields SM $\kappa_f = \kappa_V = 1$
- 2 Dimensional likelihood scan: best fit is compatible with SM within 1.5 σ
- Couplings to fermions and vector bosons compatible with linear and quadratic mass dependence (SM), and consistent with v=246 GeV

# Composite Higgs

- Minimal Composite Higgs Model (MCHM) where Higgs is composite pseudo Nambu-Goldstone boson
- Higgs couplings modified w.r.t. SM as a function of Higgs compositeness scale $f$
- MCHM4 model $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$ $\xi = v^2/f^2$
- SM retained for $\xi \to 0$ $f \to \infty$
- Similarly for MCHM5 where $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$




MCHM4 measurement ignoring boundary: observed expected

$$\xi = 1 - \mu_h = -0.30^{+0.17}_{-0.18} \quad 0.00^{+0.15}_{-0.17}$$

95% CL interval accounting for physical boundary: observed(expected)

$0 \leq \xi < 0.12\ (0.29)$

$f$ >710 GeV (460 GeV)

MCHM5

$$\xi = -0.08^{+0.11}_{-0.16} \quad 0.00^{+0.11}_{-0.13}$$

$0 \leq \xi < 0.15\ (0.20)$

$f$ >640 GeV (550 GeV)

# Additional Electroweak Singlet

- Dark matter particle could be additional EW singlet which mixes with h, resulting in heavy Higgs H as well.
- Couplings of h(H) are decreased by factor $\kappa(\kappa')$

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2 \qquad \mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

where $\mathrm{BR}_{H,new}$ denotes new decay modes of H, and $\kappa^2+\kappa'^2=1$ due to unitarity

- Note $\kappa'^2=1-\mu_h$

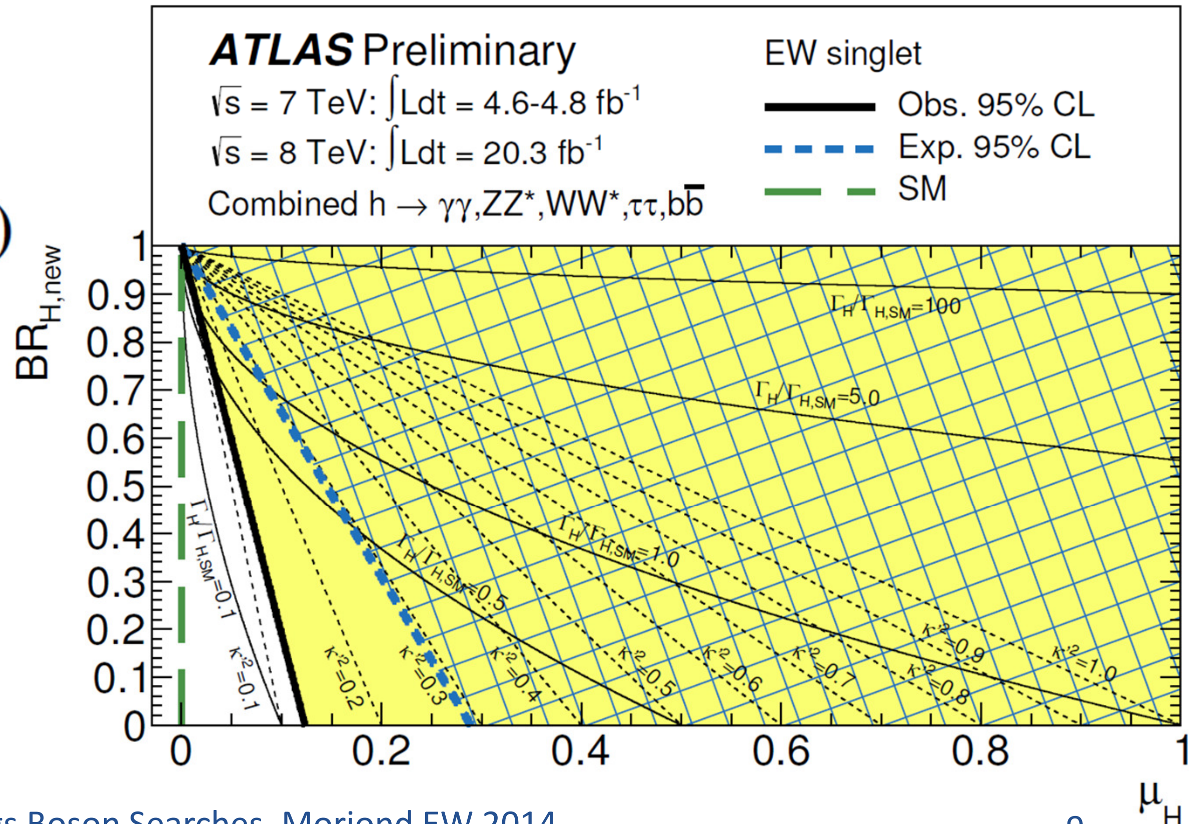
Ignoring the boundary H coupling is:

$$\kappa'^2 = 1 - \mu_h = -0.30^{+0.17}_{-0.18}\left(0.00^{+0.15}_{-0.17}\right)$$

- 95% CL interval with boundary

$$\kappa'^2 < 0.12\ (0.29)$$

- Contours of H total width scale factor to SM H and $k'^2$
- SM corresponds to $k'^2=0$



# 2HDM Models

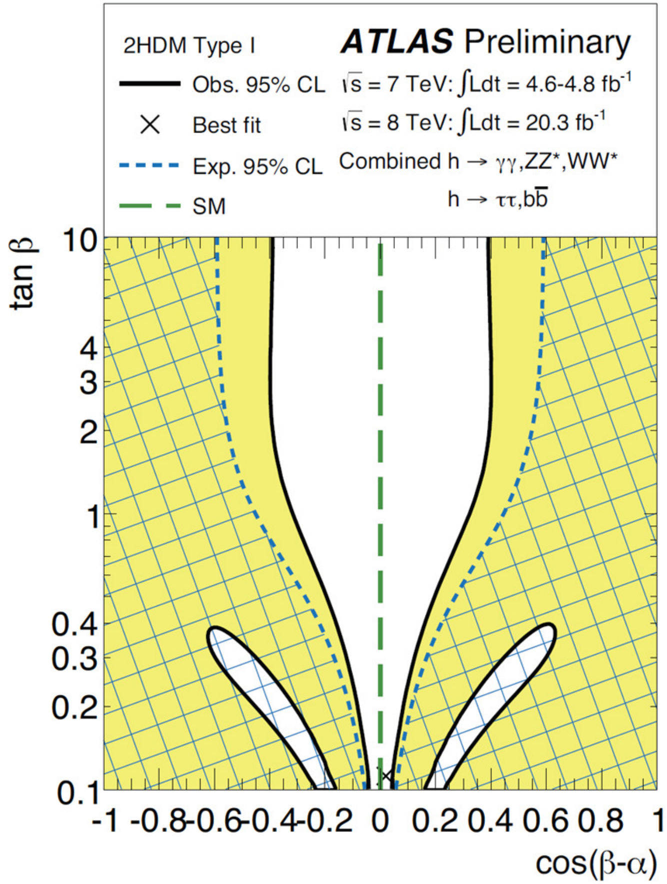
- Assume observed Higgs $m_h$=125.5 GeV is the light Higgs boson h in 2HDM models
- Couplings of to vector bosons, up-type, down-type quarks and charged leptons for 4 types of 2HDMs can be expressed as functions of $\alpha$ (mixing angle) and tan $\beta$ (ratio of vevs)

| Coupling scale factor | Type I | Type II | Type III | Type IV |
|---|---|---|---|---|
| $\kappa_V$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| $\kappa_u$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $\cos(\alpha)/\sin(\beta)$ |
| $\kappa_d$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ |
| $\kappa_l$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ |

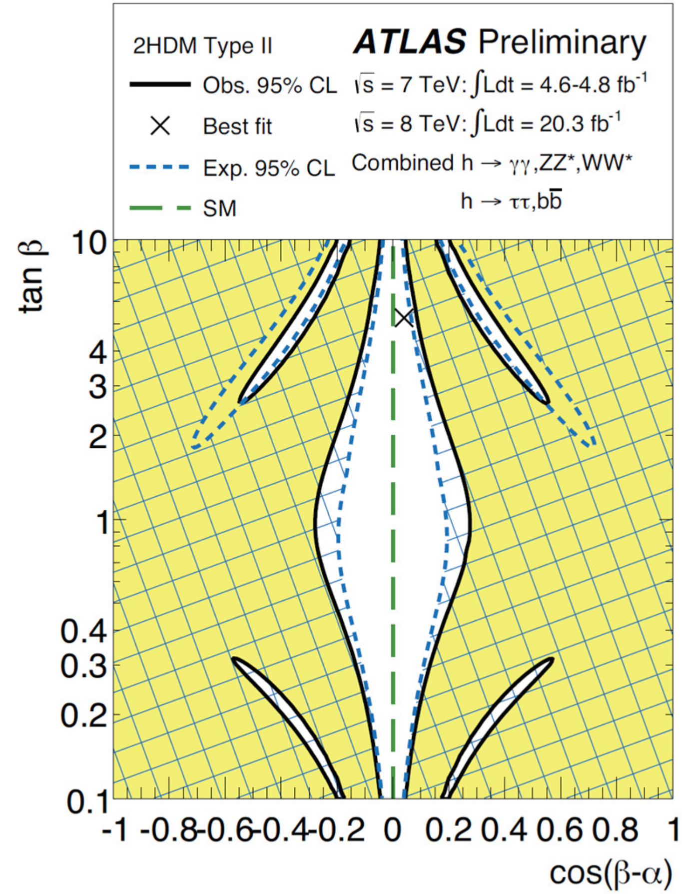
- Correction for $\sigma$(bbh) associated production calculated using SUSHI. Differential distributions not known so assume identical to ggF
- Significant rates at small tan $\beta$ for types I and III and large tan $\beta$ for types II & IV
- Correction generally smaller than 10% of the total production rate for the regions of parameter space compatible with the data at 95% CL

# 2HDM Models

Type I: “fermiophobic”



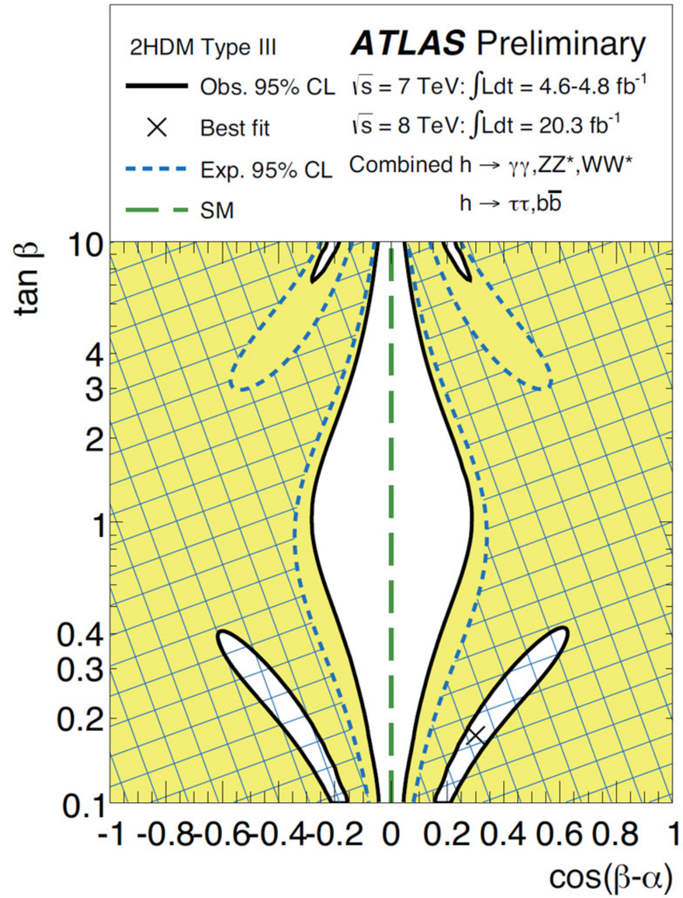

Type II: “MSSM-like”



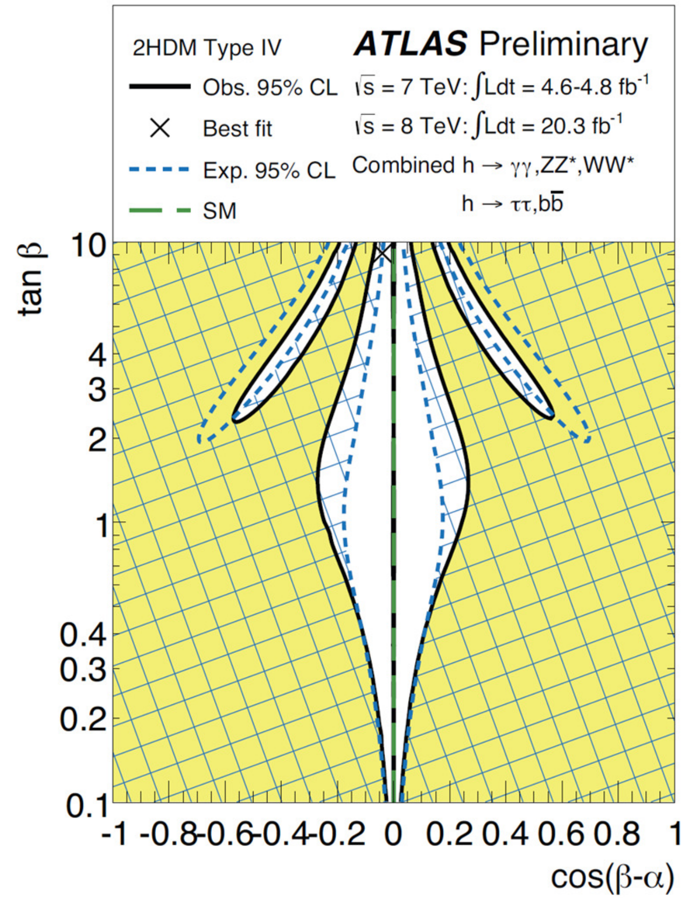

- Observed exclusion limit (95% CL) for four types of 2HDM models in ($\cos(\beta-\alpha)$ , $\tan\beta$) plane
- Compared with expected exclusion limits for SM Higgs Boson
- Data are consistent with SM alignment limit $\cos(\beta-\alpha)=0$ to within 1-2 $\sigma$ for all models

# 2HDM Models

Type III: "lepton-specific"



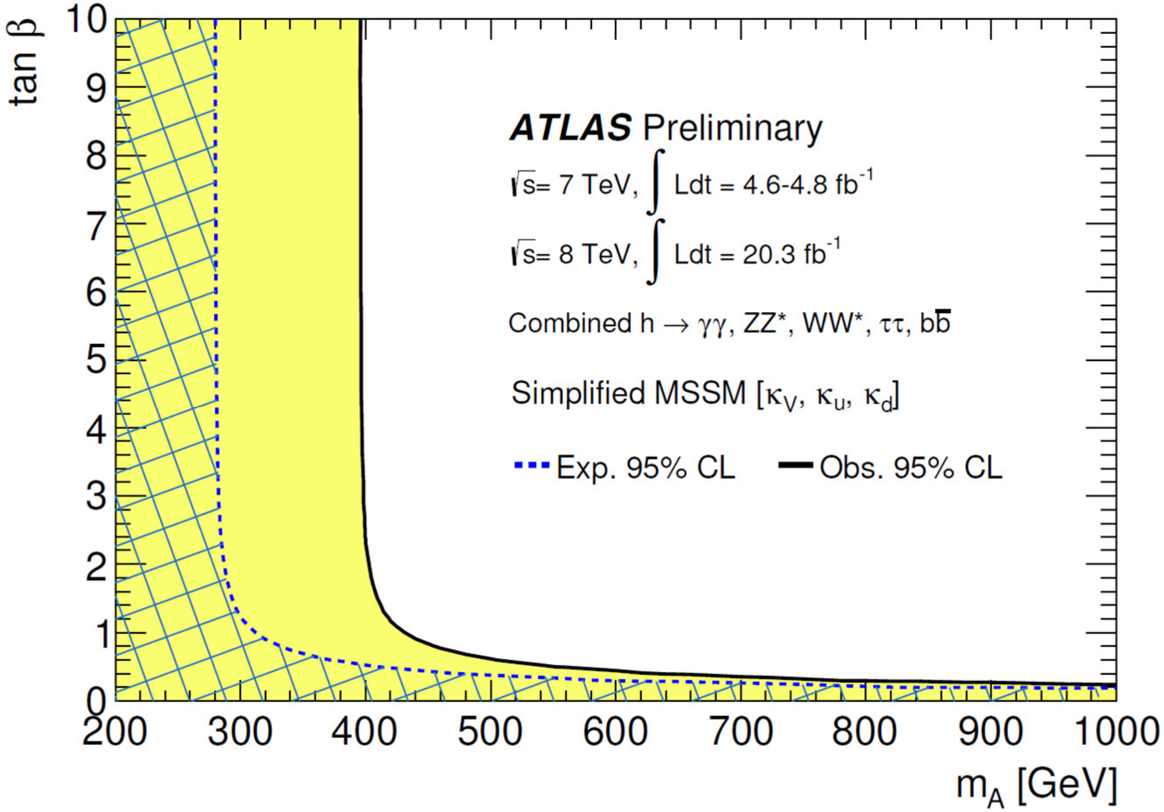

Type IV: "flipped"




- Observed exclusion limit (95% CL) for four types of 2HDM models in (cos(β–α) , tan β) plane
- Compared with expected exclusion limits for SM Higgs Boson
- Data are consistent with SM alignment limit cos (β-α)=0 to within 1-2 σ for all models

# Simplified MSSM

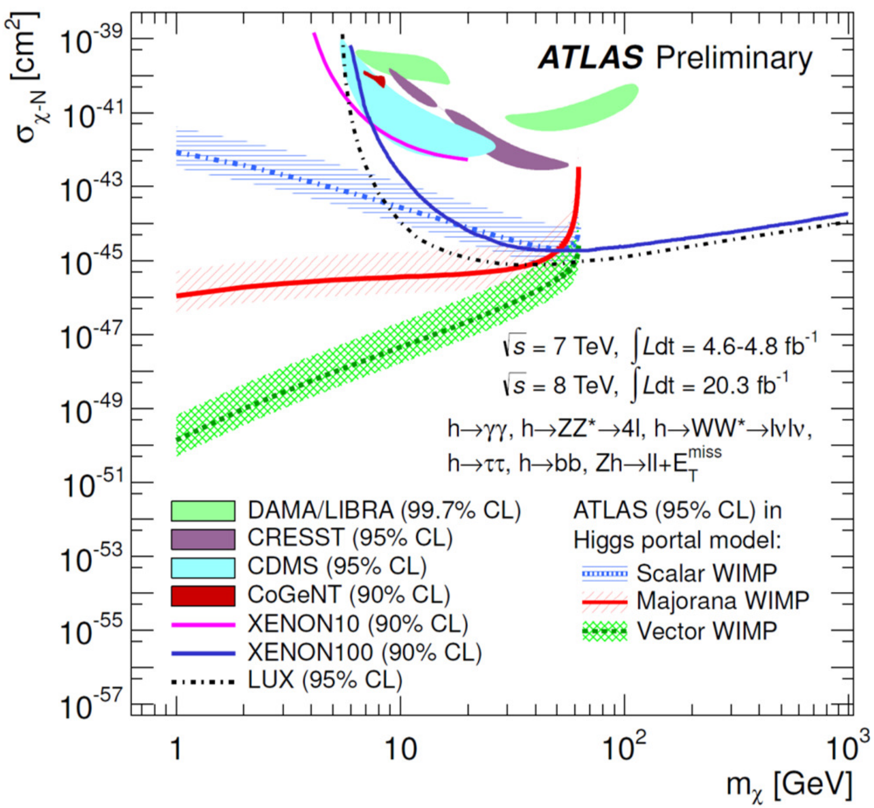
- Measurement of light Higgs mass $m_h$ used to infer radiative corrections (top, stop, ..) in MSSM
- MSSM mixing matrix for h taken with $m_h$=125.5 GeV and used to express light Higgs couplings $k_V,k_u,k_d$ as a function of $m_A$ and tan β and known parameters ($m_h$, $m_Z$) L. Maiani et al arXiv:1305.2172
- Additional corrections from stop are assumed to be small (<3% for $m_{stop}$>500 GeV)
- Additional corrections which break universality $k_d=k_t=k_b$ are sub-leading and ignored A. Djouadi et al arXiv:1307.5205

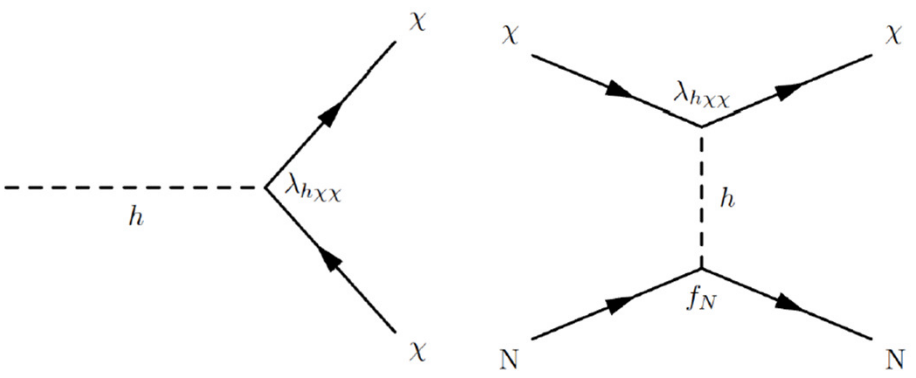



- Correction for bbh associated production included
- For tan β > 2, $m_A$>400(290) GeV observed(expected) at 95% CL
- Limit increases to larger masses at low tan β
- Data consistent with SM decoupling i.e. $m_A$->infinity
- More general models with H->hh, Higgs decays to SUSY, effects of light SUSY particles, etc. not investigated here. M. Carena et al EPJC 73 (2013) 2552 (more scenarios, e.g. $m_h$-mod benchmark)

# Higgs Portal to Dark Matter

- "Higgs Portal" model extends SM to include weakly interacting massive particles (WIMPs) coupling to Higgs boson
- Dark matter-nucleon scattering as well as decay rate inferred from Higgs invisible decays
- Translate $BR_{i,u}$ < 0.37 (0.39) obs. (exp.) at 95% CL (5-channel + Zh) into limits on DM rate (depends on WIMP spin)




- Significantly more sensitive at low mass for vector WIMP than direct detection experiments *assuming Higgs Portal model*
- Sensitivity dominated by 5-channel coupling combination

# 2HDM Searches H->hh, A->Zh

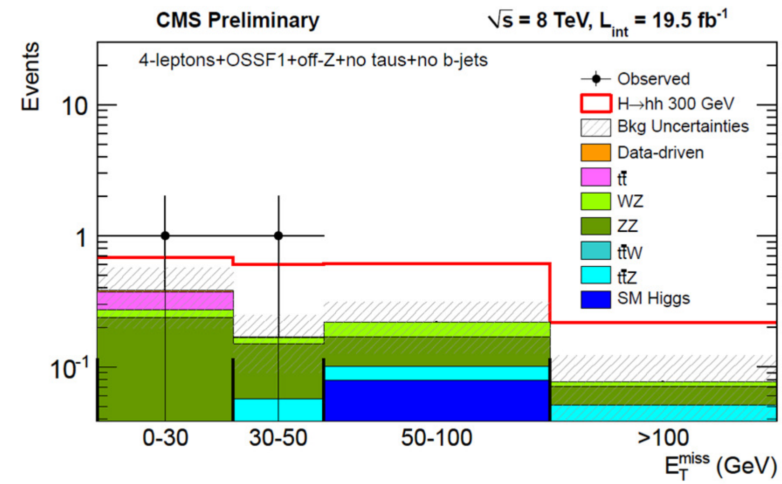
- If $m_H > 2m_h$ then H->hh
- For $m_A$ in range $2m_h < m_A < 2m_t$, then A->Zh dominates
- Assume SM decays of h. Look at leptonic and diphoton decays

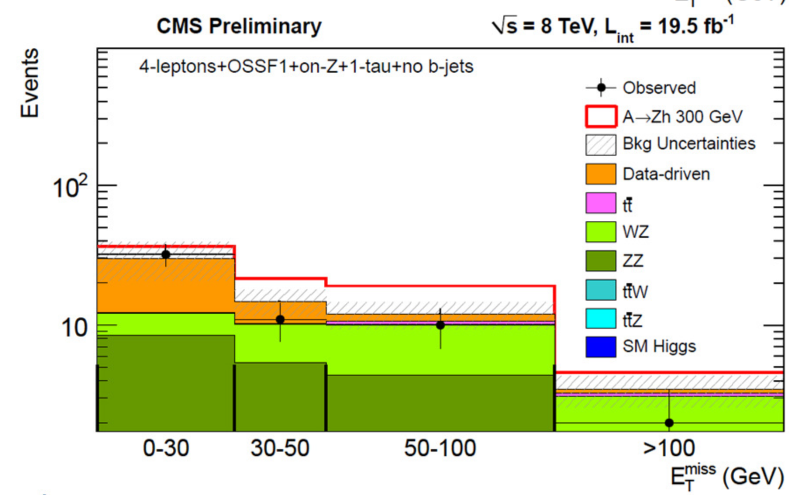
CMS-PAS-HIG-13-025

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

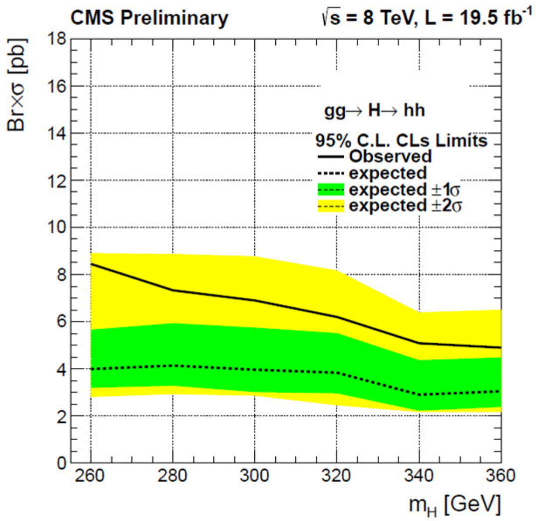
| Leptons | Photons | OSSF pairs | Hadronic $\tau$ | b-tag |
|---|---|---|---|---|
| 4 | 0 | 0, 1 or 2 | 0 or 1 | 0 or 1 |
| 3 | 0 | 0 or 1 | 0 or 1 | 0 or 1 |
| 2 | 2 | 0 or 1 | 0 | - |
| 1 | 2 | - | 0 | - |
| 1 | 2 | - | 1 | - |
| 0 | 2 | - | 1 or 2 | - |

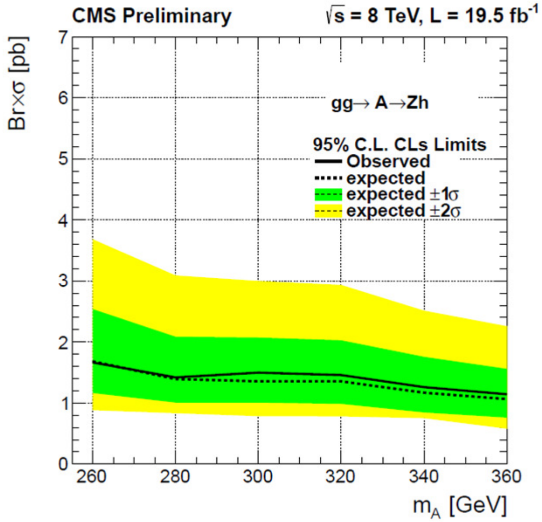


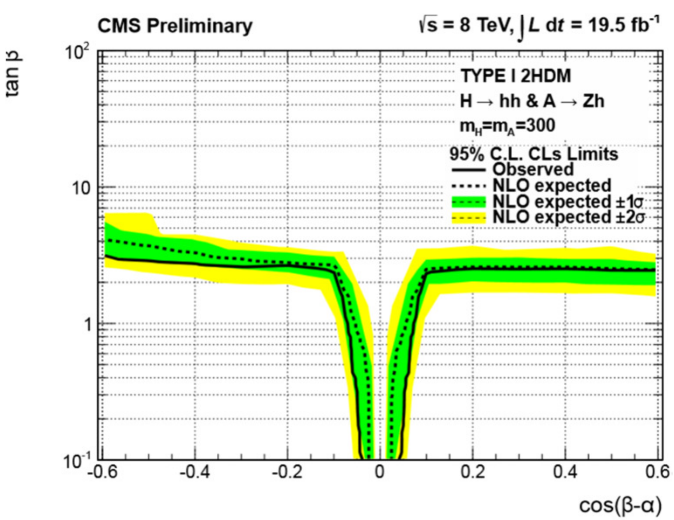
# 2HDM Limits

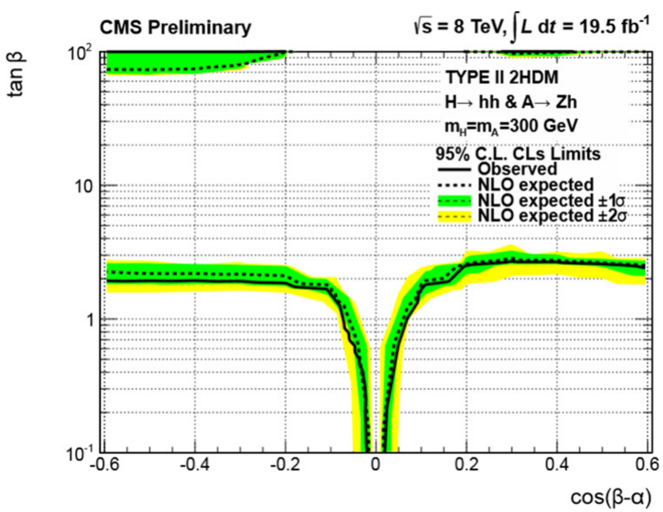
- Limits on Br*sigma. 95% CL of 7pb for H->hh and 2pb for A->Zh




- Limits on 2HDM Type I and Type II in the tan β, cos(β–α) plane



# t->cH (CMS)

- Flavour Changing Neutral Current t->cH highly suppressed in SM due to Glashow-Iliopoulos-Maiani mechanism with branching ratio $10^{-13}$-$10^{-15}$
- With large tt cross section and large t coupling to Higgs the LHC is ideally placed
- For t->cH possible new physics rate higher than SM by ~$10^{10}$-$10^{12}$

- Study multilepton (CMS-PAS-SUS-13-002) and diphoton (CMS-PAS-HIG-13-025) final states
- H->WW->lνlν, H->ττ, H->ZZ->jjll,ννll,llll, and H->γγ

CMS-PAS-HIG-13-034

NEW

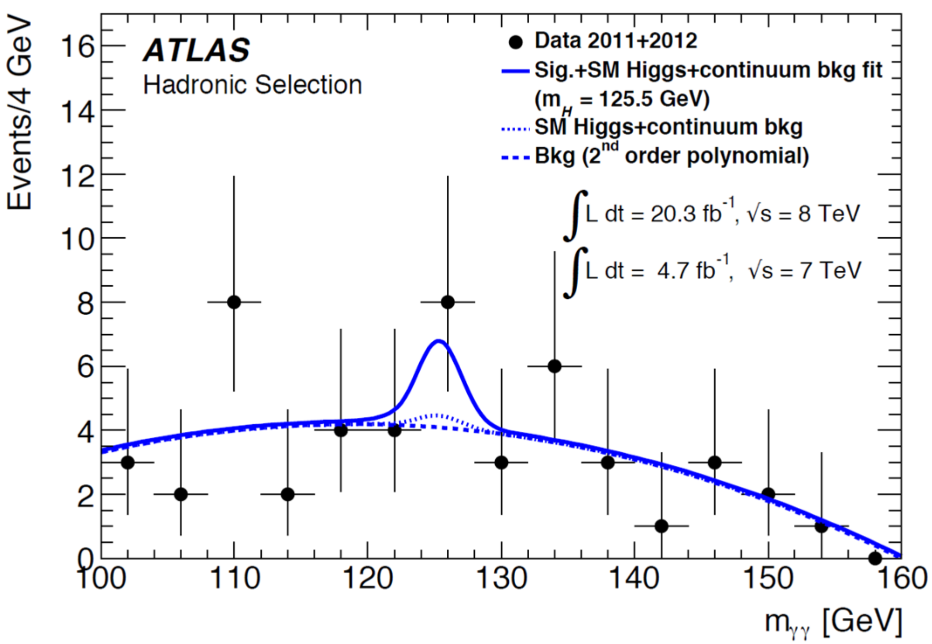
- Limits yielded *B*(t->cH ) < 0.56 (0.65) % for observed (expected)
- Can be used to place limit on coupling $\lambda_{tc}^{H}$ < 0.14 (observed)

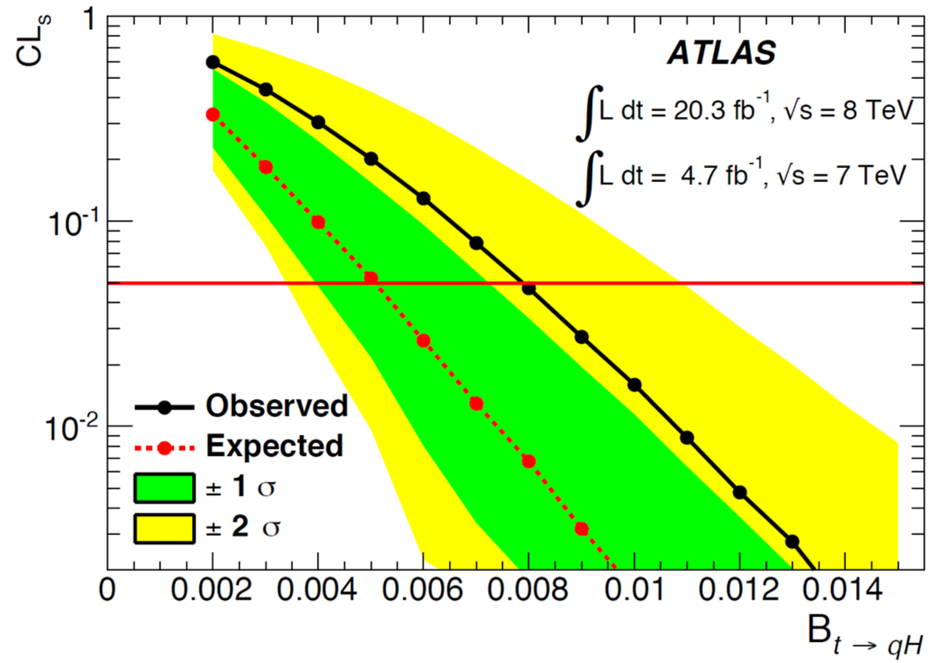
| Higgs Decay Mode | observed | expected | $1\sigma$ range |
|---|---|---|---|
| $H \to WW^*$ ($\mathcal{B} = 23.1\,\%$) | 1.58 % | 1.57 % | (1.02–2.22) % |
| $H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$) | 7.01 % | 4.99 % | (3.53–7.74) % |
| $H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$) | 5.31 % | 4.11 % | (2.85–6.45) % |
| combined multileptons ($WW^*$, $\tau\tau$, $ZZ^*$) | 1.28 % | 1.17 % | (0.85–1.73) % |
| $H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$) | 0.69 % | 0.81 % | (0.60–1.17) % |
| combined multileptons + diphotons | 0.56 % | 0.65 % | (0.46–0.94) % |

# t->qH (ATLAS)

- Flavour Changing Neutral Current t->qH, where H->γγ
- Other t->bW, both leptonic and hadronic W decays used
- Full 7 TeV and 8 TeV data sample

ATLAS final result submitted to JHEP



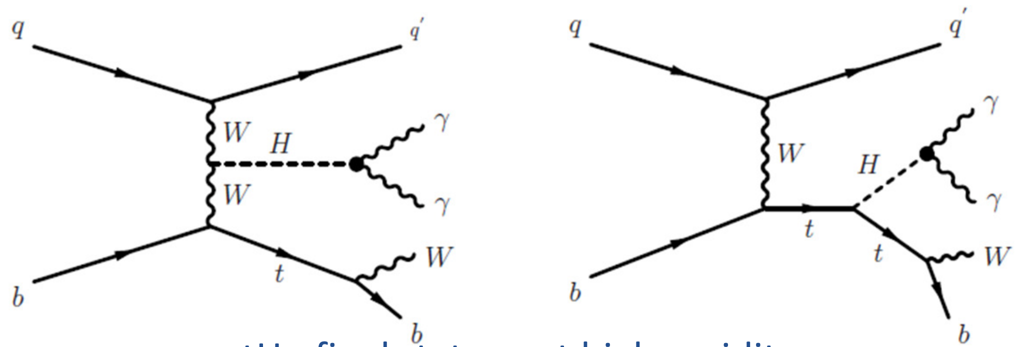




- Limit on branching ratio *B*(t->cH) < 0.83(0.53)% at 95% CL converted to limit on Higgs Yukawa coupling t->cH < 0.17(0.14) observed(exp.)
- Analysis equally sensitive to t->cH and t->uH, so limit can be expressed as

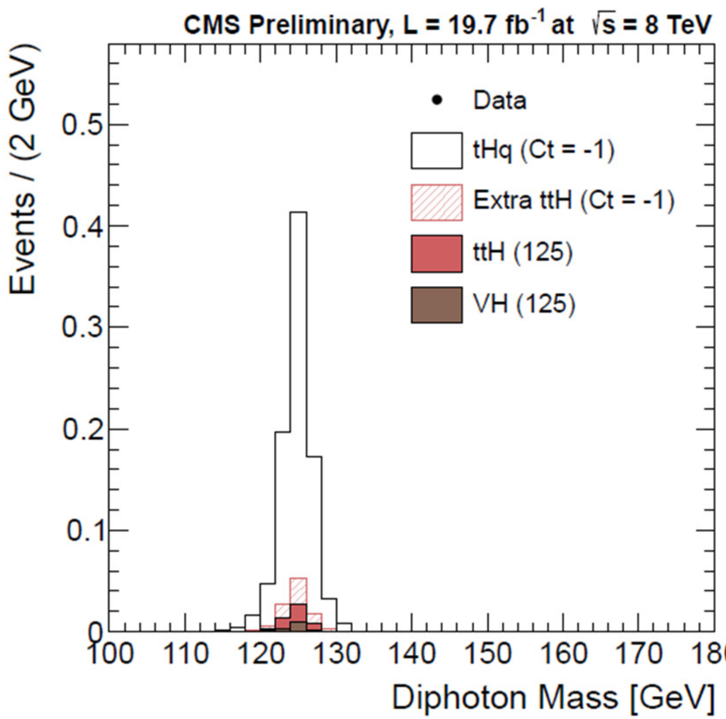
$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

# Higgs with single top

- Production mode sensitive to t-H coupling
- Negative coupling of H to fermions $C_t$=-1 would lead to enhanced (x15) tHq rates plus (x2) H->γγ decay rate
- High rate also expected in BSM models such as composite Higgs with heavy top partner (700-800 GeV) decaying to tH




tHq final state, q at high rapidity



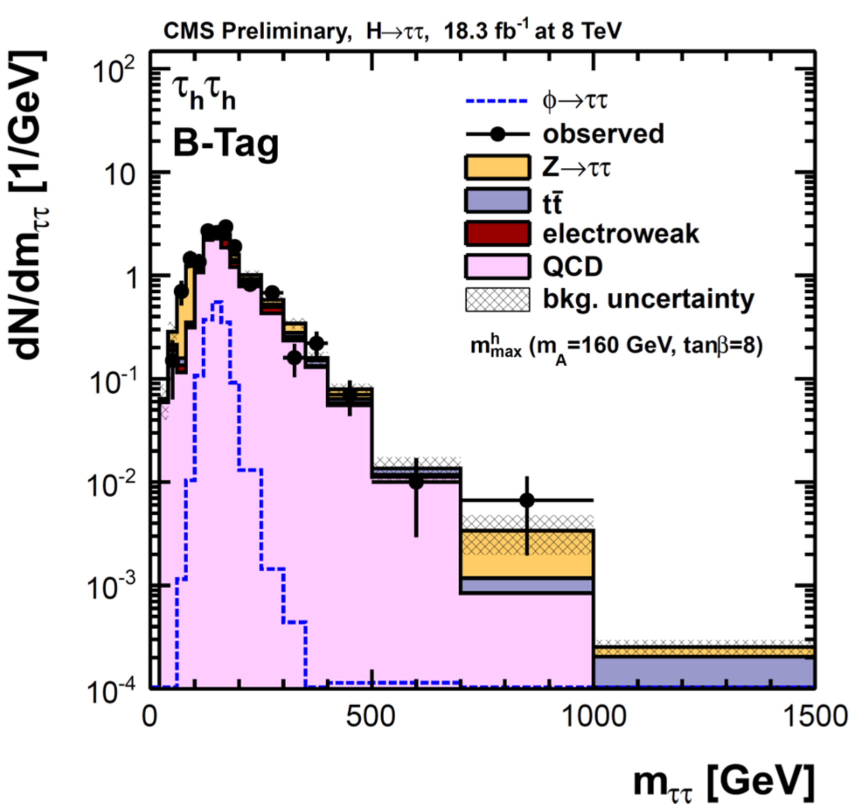

CMS-PAS-HIG-14-001 NEW

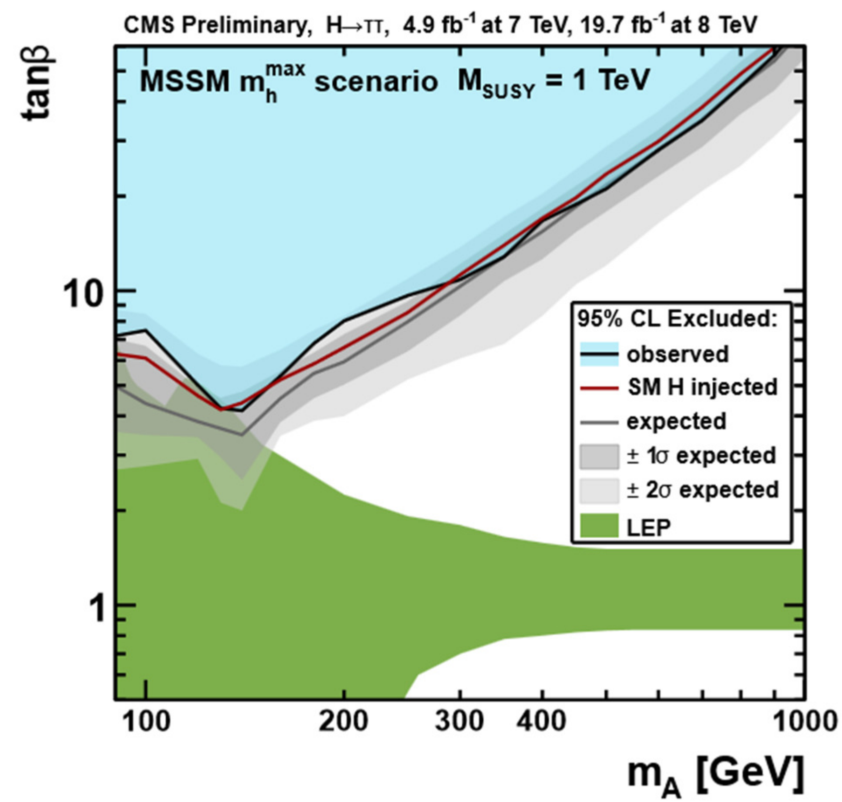
- Use h->γγ and t->blν where l=e,μ
- Likelihood used to reduce ttH background
- ttH yield ~doubled by extra $C_t$=-1 events
- Expected significance 1.2σ
- No events observed
- Place 95% limits on:
  cross section x Br(H->γγ) of 4.1 ($C_t$=-1)

# MSSM Higgs searches to ττ

- Study neutral MSSM Higgs, H,A,h->ττ
- Constraints on $m_A$, tan β phase space
- To enhance sensitivity categories with 0 and 1 b-jet
- Extension to larger $m_A$ and exclude down to tan β=4.2 at $m_A$=140 GeV

CMS-PAS-HIG-13-021

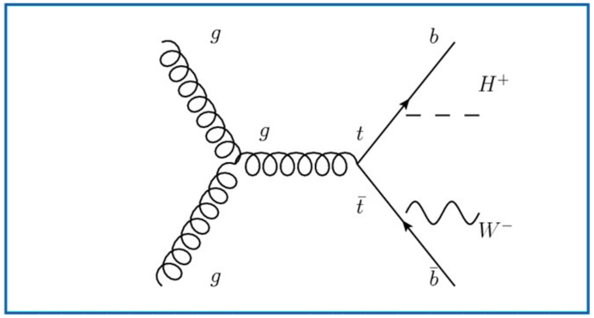


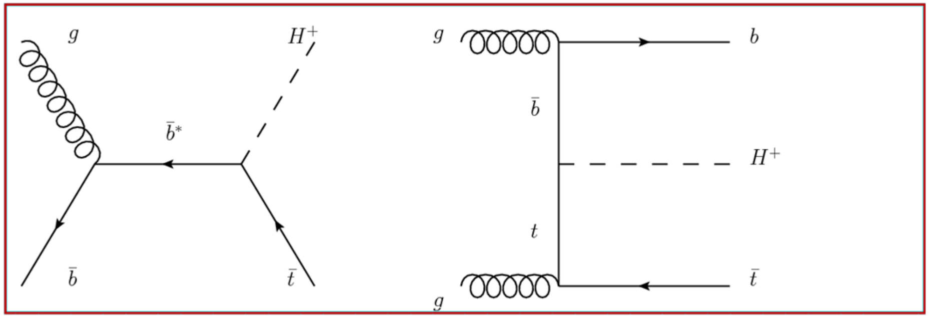



# Charged Higgs

- Search for H->τν , using assumption B(H->τν=1)
- Different channels dominate depending on $m_H/m_t$

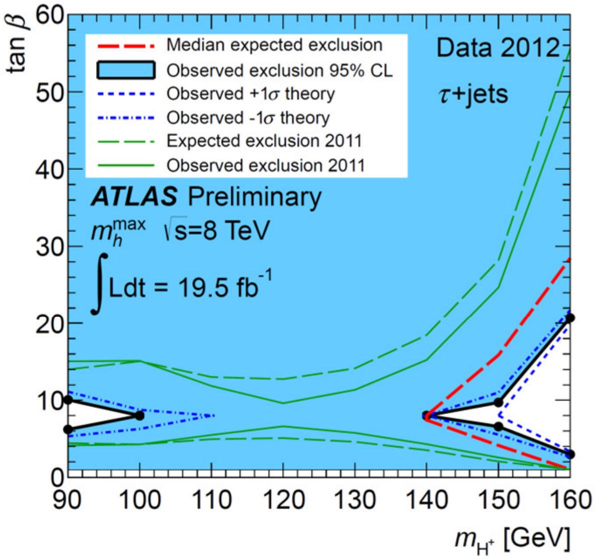
ATLAS-CONF-2013-09



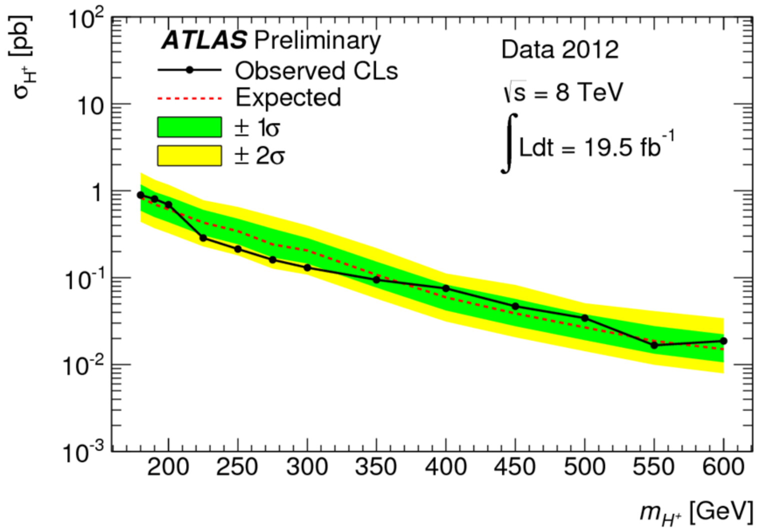


Light Higgs ($m_H$<$m_t$), tt->HbWb

Heavy Higgs ($m_H$>$m_t$)




Branching fraction B(t->Hb),0.24-2.1%




tH cross section limits:0.017-0.9pb

# Summary

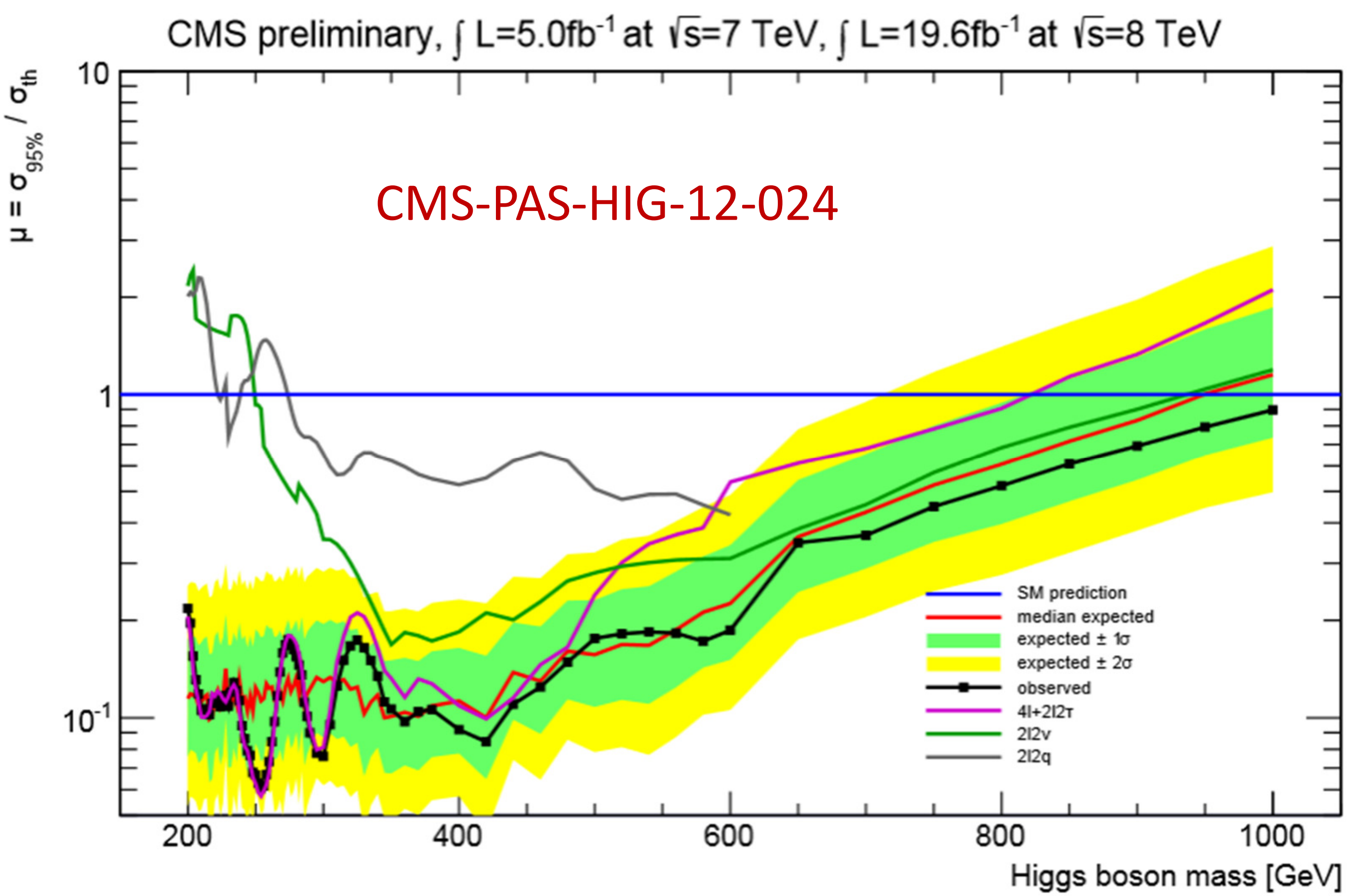
- We are entering a new era in Higgs BSM physics where we study the couplings of the observed Higgs boson in more detail and search for additional Higgs states
- Wide range of new/recent results on Higgs physics BSM from ATLAS and CMS
- Limits on new phenomena from Higgs Couplings ATLAS-CONF-2014-010
- Search for t->cH CMS-PAS-HIG-14-001 plus final results from ATLAS
- Search for Higgs with single top tHq CMS-PAS-HIG-13-034
- As we prepare for Run-II we know where in the phase space to focus our efforts…stay tuned!

# Back up

# High Mass Higgs Searches

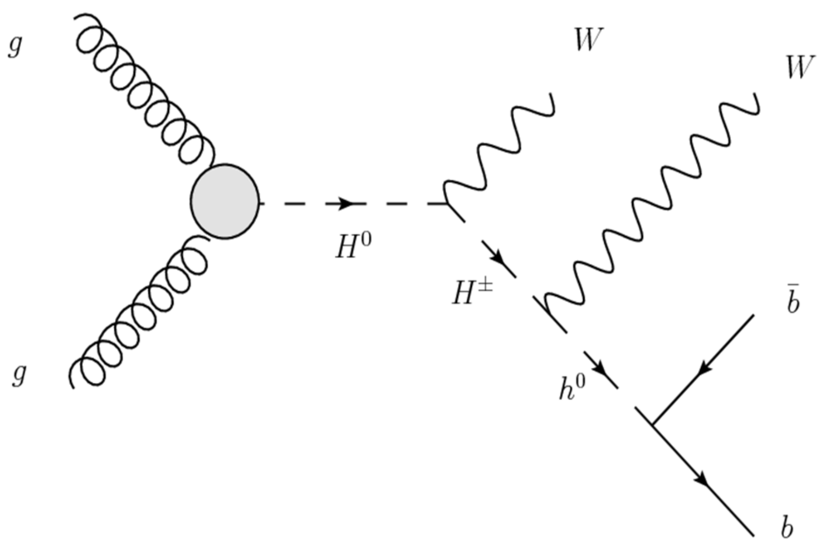
- Search for high mass SM-like Higgs using H->ZZ->llqq, where qq includes bb
- SM Higgs excluded from $m_H$>290 GeV using llqq alone
- Combine with searches using H->WW, ZZ in leptonic decays
- Observed follows expected. Excluded at 95% CL across whole range

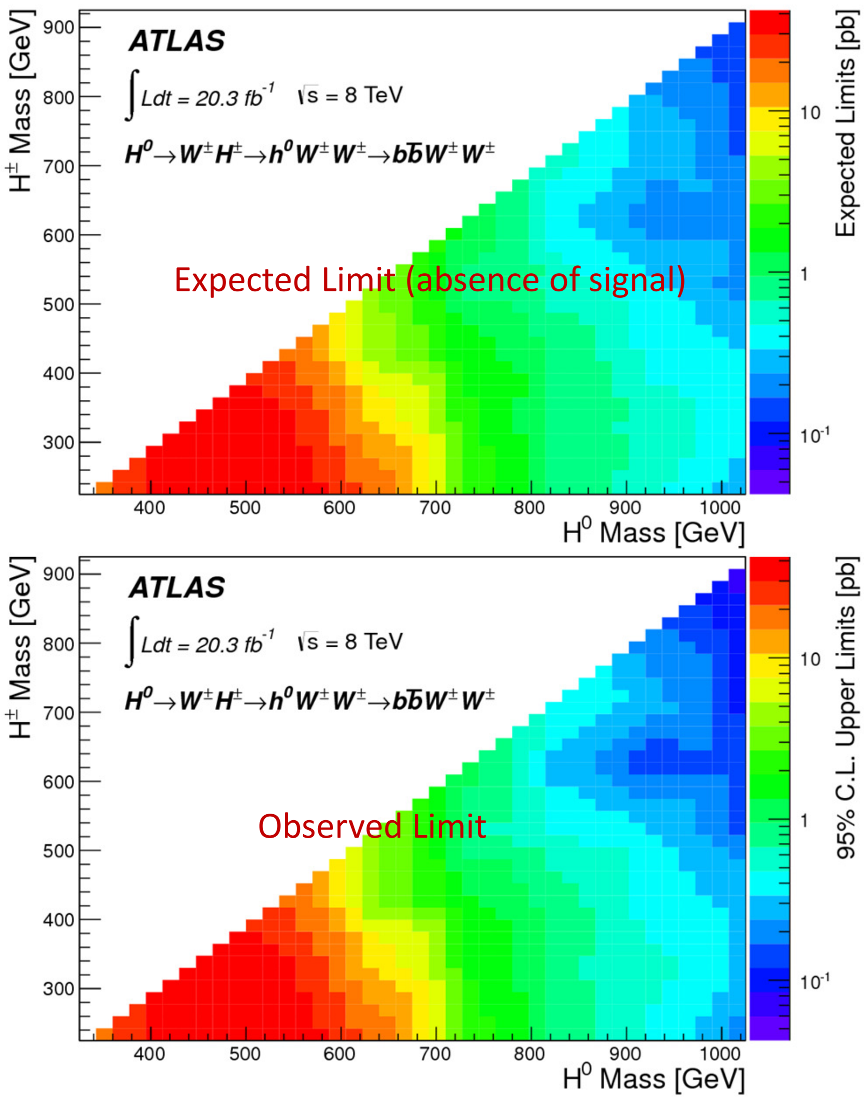
Eur.Phys.J. C73 (2013) 2469



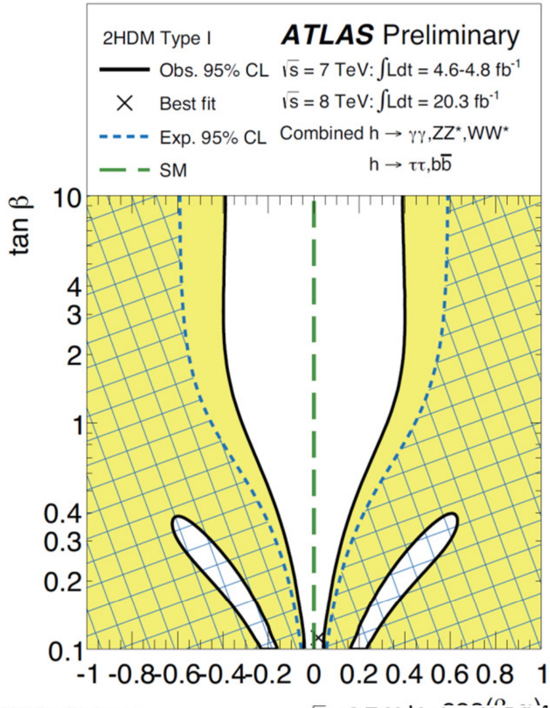
# Cascade Higgs Decay Search

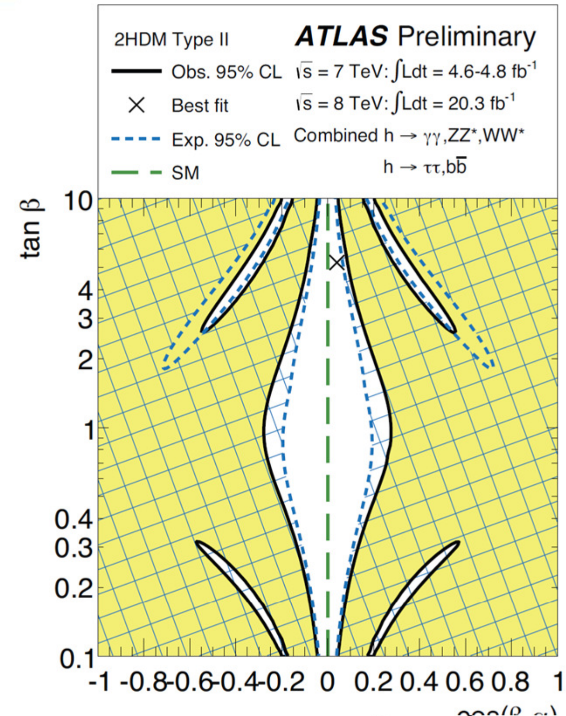
- ATLAS Recently published **Phys.Rev. D89 (2014) 032002** http://inspirehep.net/record/1268153
- WWbb final state, W->jj and W->lν
- BDTs used to separate cascade decay from ttbar
- No significant excess above SM expectation found
- Most sensitive at high $m_H$,$m_H$

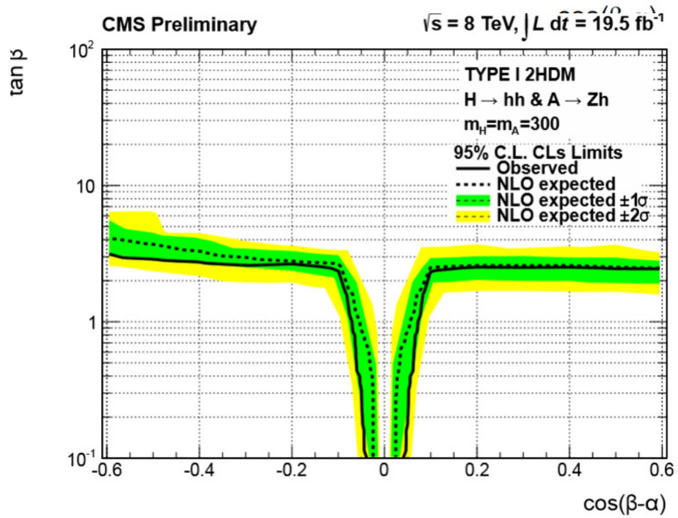


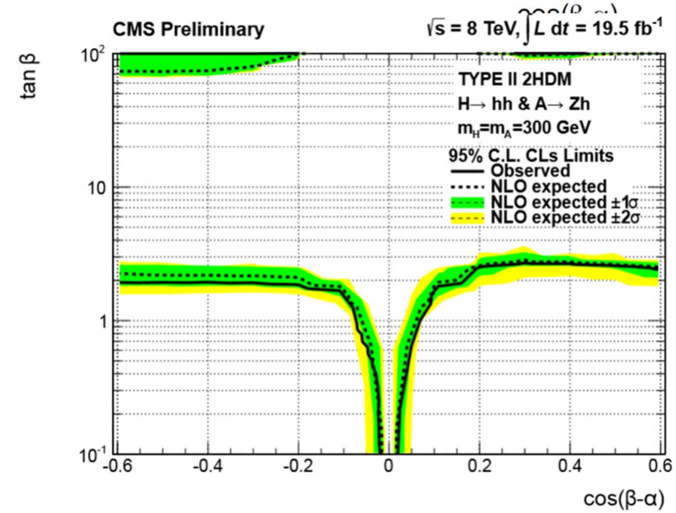



# Compare 2HDM Limits

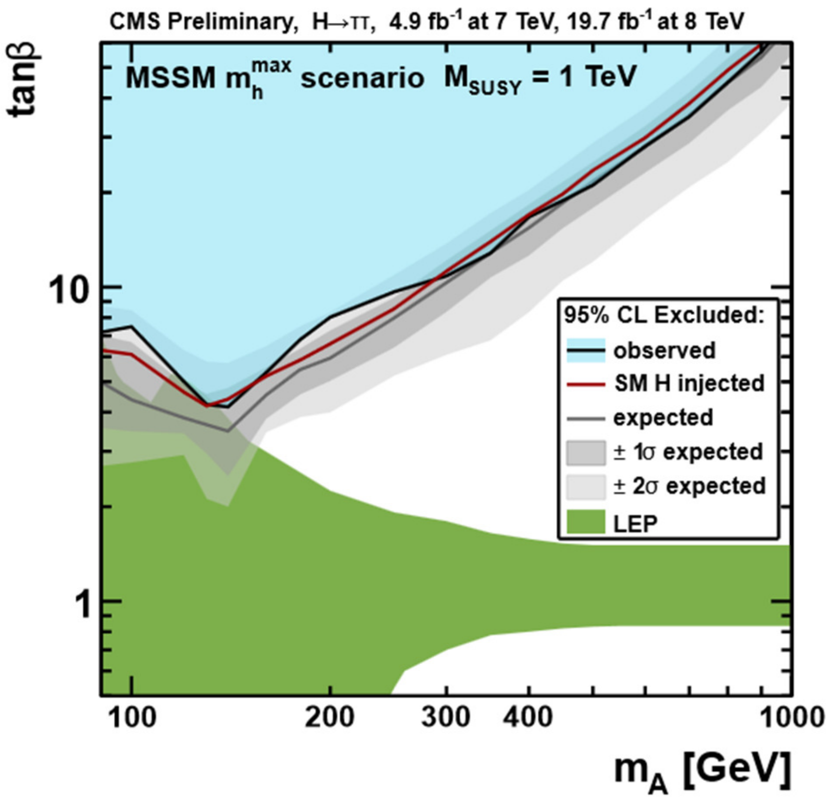


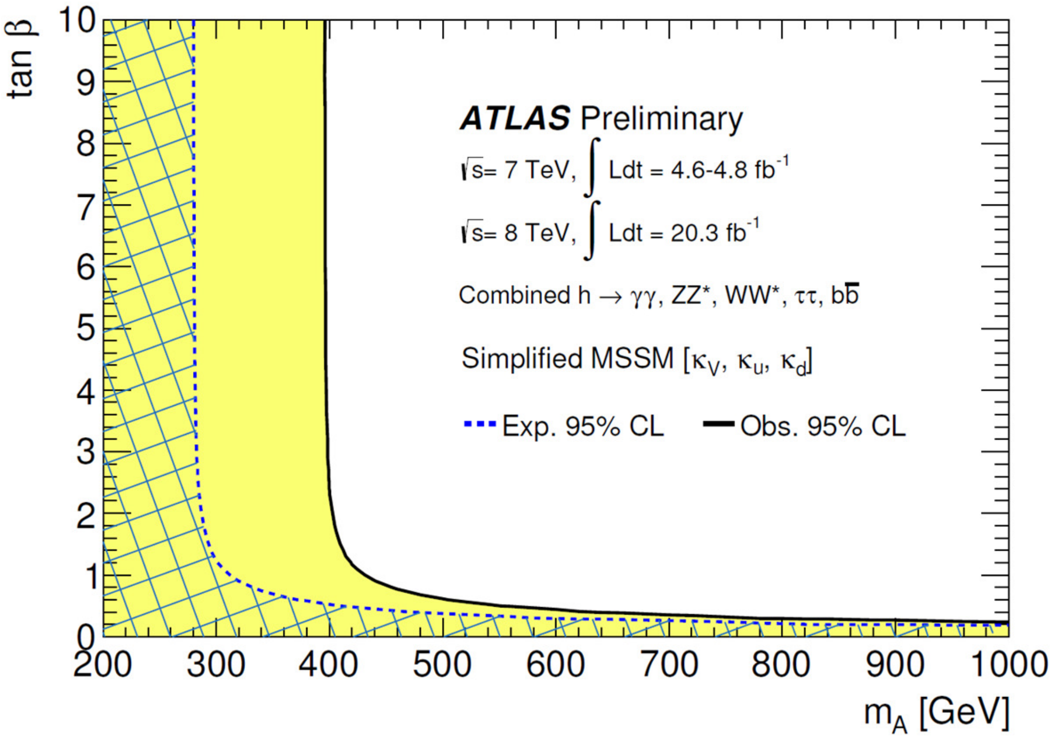



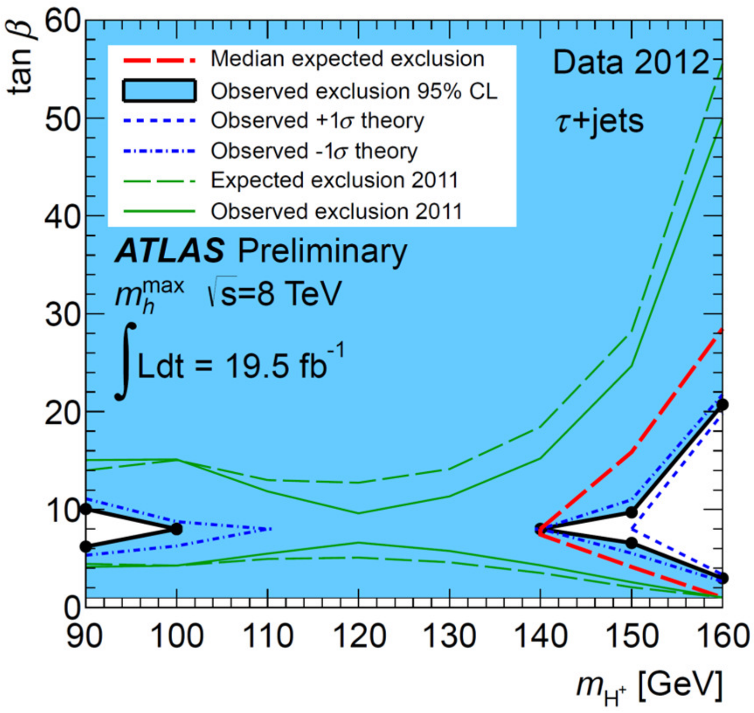
# Compare direct/Simplified MSSM

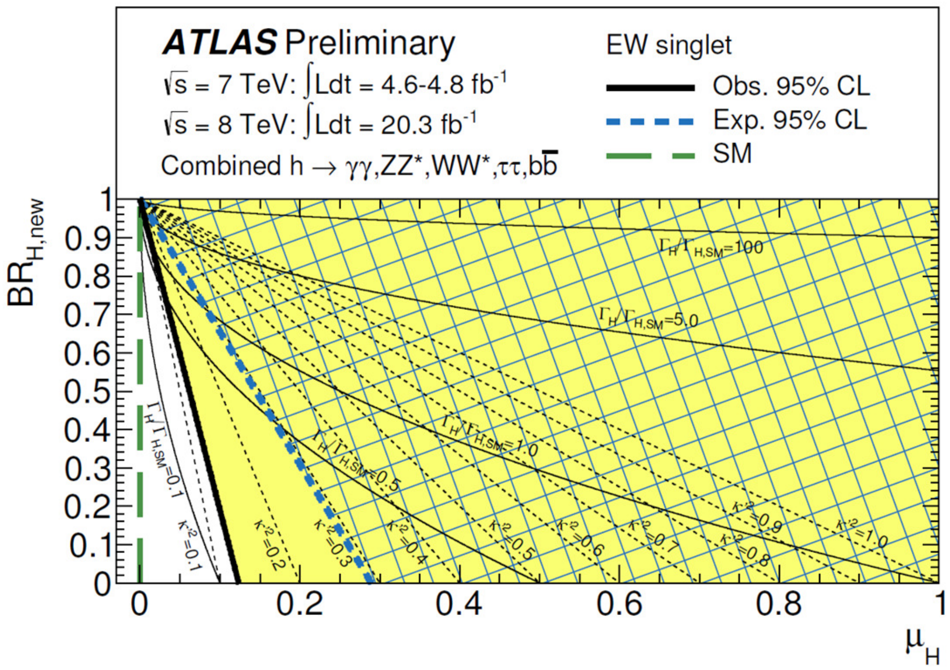



- More general models with H->hh, Higgs decays to SUSY, effects of light SUSY particles, etc. not investigated here. M. Carena et al EPJC 73 (2013) 2552 (more scenarios, e.g. $m_h$-mod benchmark)

# Compare MSSM/EW Singlet



# Simplified MSSM

MSSM matrix element for h, δ1 and δ rad. corr. Involving top and stop

$$\mathcal{M}_S^2 = (m_Z^2 + \delta_1)\begin{bmatrix} \cos^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \sin^2(\beta) \end{bmatrix} + m_A^2 \begin{bmatrix} \sin^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \cos^2(\beta) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2(\beta)} \end{bmatrix}$$

To get couplings, take trace, set $m_h$, neglect subleading $\delta_1$ A. Djouadi et al arXiv:1307.5205, substitute for δ. Diagonalize to find eigenvectors L. Maiani et al arXiv:1305.2172

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

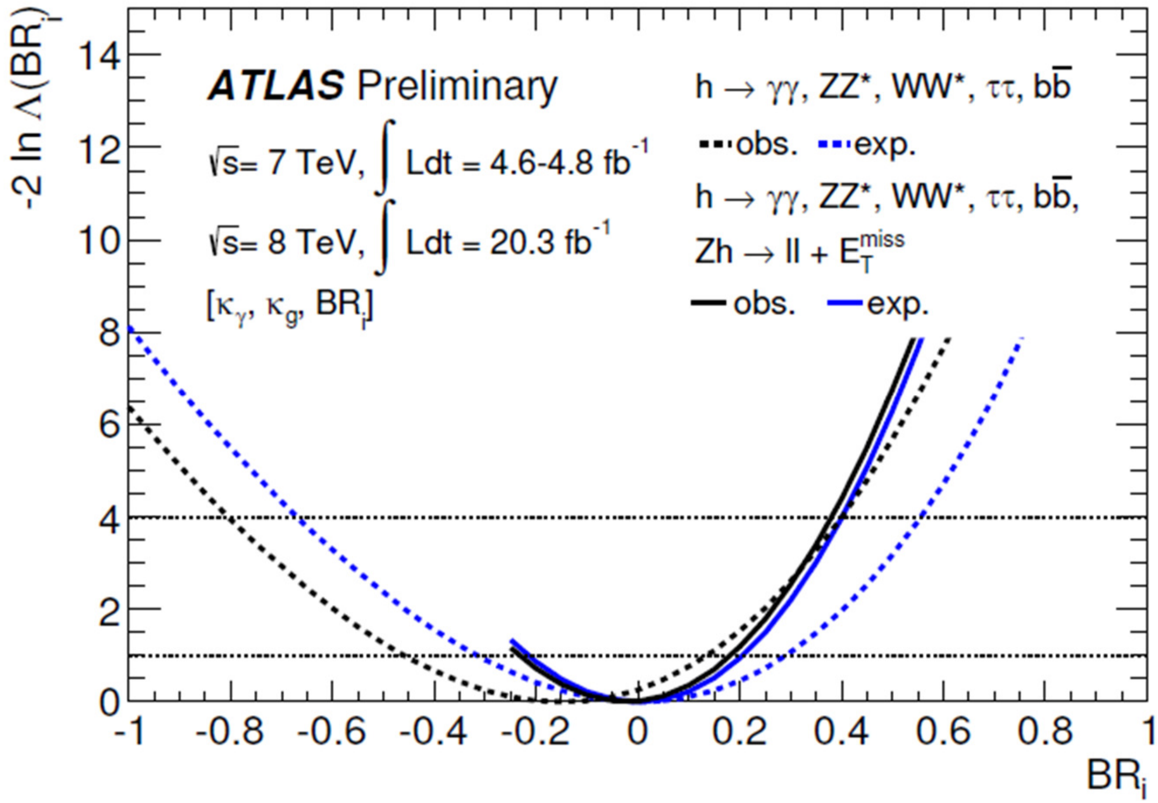
$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

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

$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta))^2}}}$$

$$s_d = \frac{(m_A^2+m_Z^2)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta)}\ s_u$$

# Higgs Invisible BR



# Higgs Portal to DM

$$\text{scalar } S: \quad \Gamma^{\text{inv}}(h \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128\pi m_h}$$

$$\text{fermion } f: \quad \Gamma^{\text{inv}}(h \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64\pi}$$

$$\text{vector } V: \quad \Gamma^{\text{inv}}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)$$

Couplings to DM

$$\lambda_{hSS},\ \lambda_{hff}/\Lambda, \text{ and } \lambda_{hVV}$$

Kinematic factor due to decay

$$\beta_\chi = \sqrt{1 - 4m_\chi^2/m_h^2}$$

$$\text{scalar } S: \quad \sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

$$\text{fermion } f: \quad \sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

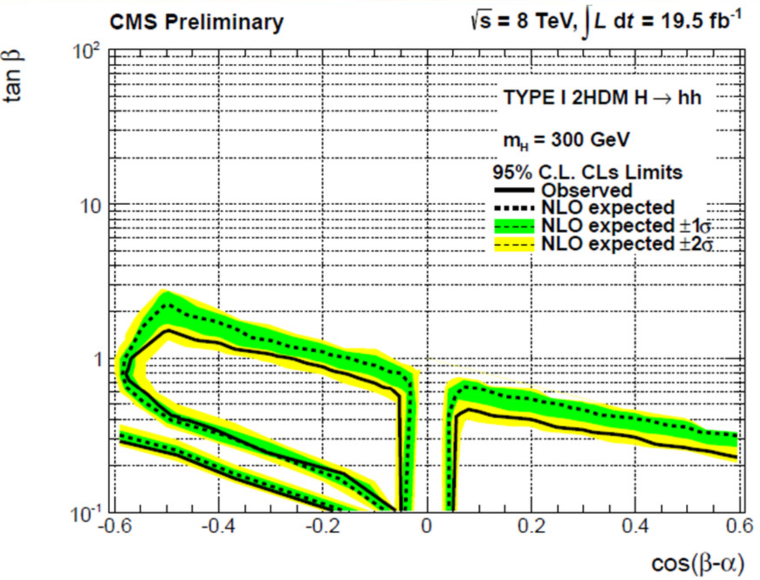
$$\text{vector } V: \quad \sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$$

$$m_N \sim 0.94 \text{ GeV}$$

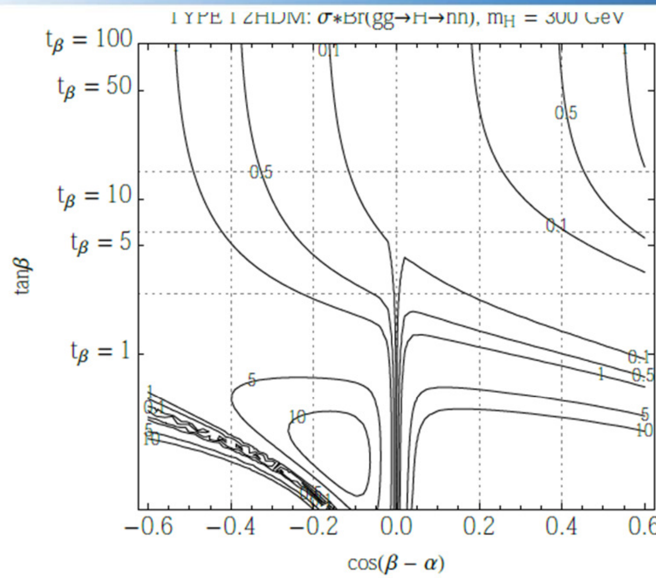
$$f_N = 0.33^{+0.30}_{-0.07}$$

Form factor for h-nucleon scattering calculated from lattice QCD

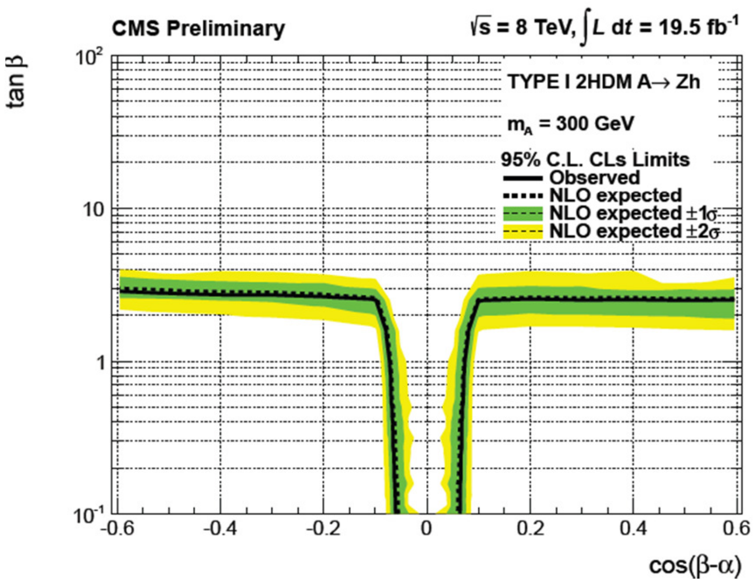
# Type 1 2HDM



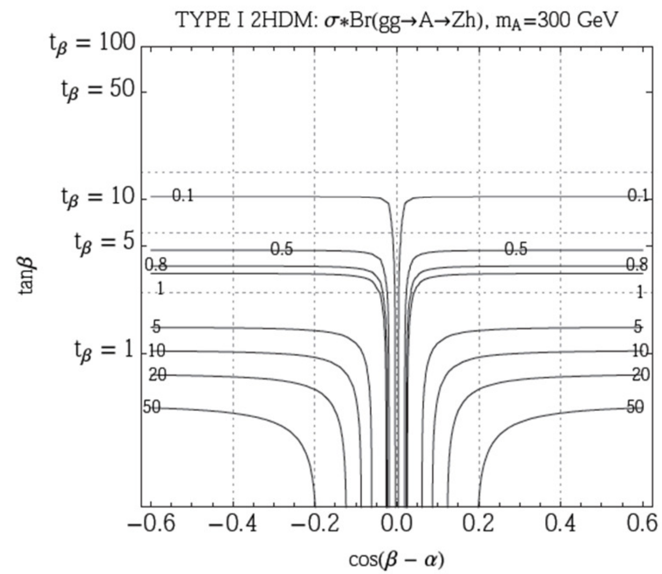
CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb⁻¹
TYPE I 2HDM H → hh
m_H = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
tan β
cos(β-α)

TYPE I 2HDM: σ∗Br(gg→H→hh), m_H = 300 GeV
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
tanβ
cos(β − α)

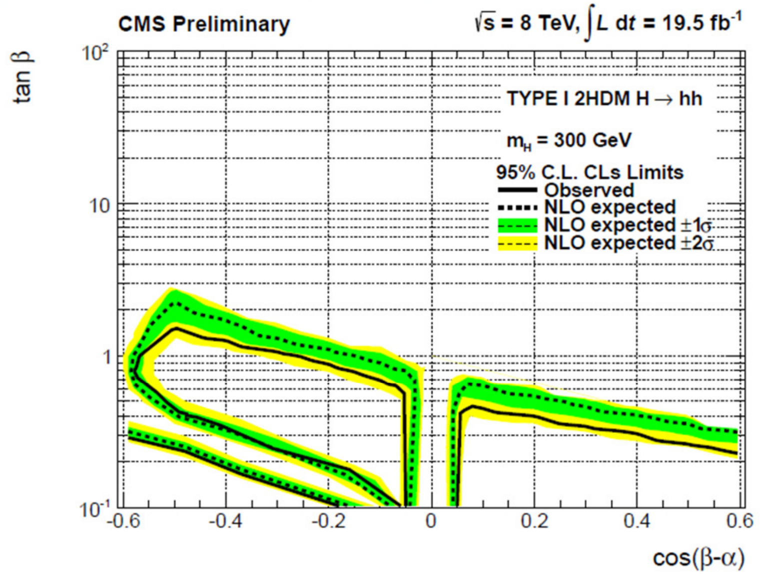



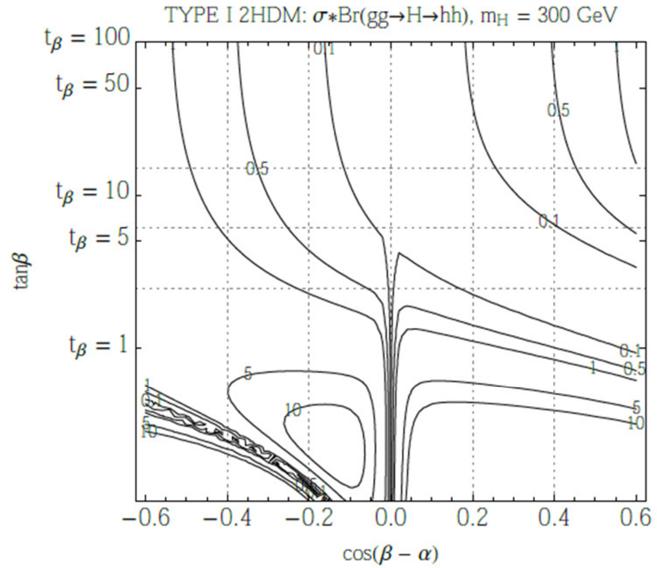
CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb⁻¹
TYPE I 2HDM A→ Zh
m_A = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
tan β
cos(β-α)

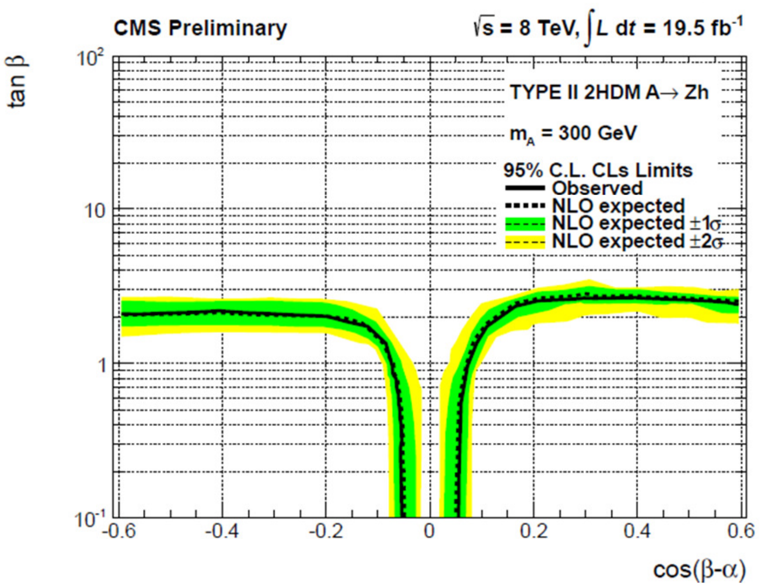



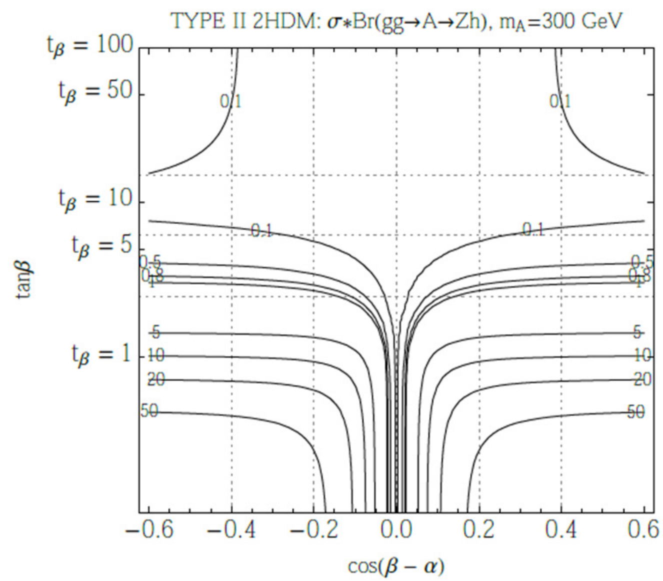
TYPE I 2HDM: σ∗Br(gg→A→Zh), m_A=300 GeV
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
tanβ
cos(β − α)

# Type II 2HDM


CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb⁻¹
TYPE I 2HDM H → hh
m_H = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
tan β
cos(β-α)


TYPE I 2HDM: σ∗Br(gg→H→hh), m_H = 300 GeV
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
tanβ
cos(β − α)


CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb⁻¹
TYPE II 2HDM A→ Zh
m_A = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
tan β
cos(β-α)


TYPE II 2HDM: σ∗Br(gg→A→Zh), m_A=300 GeV
t_β = 100
t_β = 50
t_β = 10
t_β = 5
t_β = 1
tanβ
cos(β − α)