



Recent results on BSM scalar boson searches at CMS (Run 1 and Run 2)

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on behalf of the CMS collaboration

Outline

Search for heavy scalars

- BSM summary (8 TeV)
HIG-16-007
- $H \rightarrow ZZ \rightarrow 4l, \rightarrow 2l2\nu$ (13 TeV)
HIG-15-005, HIG-16-001
- $H \rightarrow Z(\ell)A(bb)$ (13 TeV)
HIG-16-010

Search for resonant HH production

- $X \rightarrow HH \rightarrow bb\tau\tau, \rightarrow bbWW, \rightarrow 4b$
(13 TeV) HIG-16-013,
HIG-16-011, HIG-16-002

Search for BSM decays of H(125 GeV)

- $H \rightarrow \text{invisible}$ (13 TeV)
HIG-16-009, HIG-16-008 and
combination with LHC Run 1
- $H \rightarrow a_1 a_1 \rightarrow bb\mu\mu, \rightarrow \mu\mu\tau\tau$ (8
TeV) HIG-14-041, HIG-15-011

Not covered

- X(750) – dedicated session on
Thursday
- Anomalous H(125) couplings (
[arXiv:1602.04305](https://arxiv.org/abs/1602.04305))
- Lepton flavour-violating decays
(talk by Michal Bluj)

Heavy scalars: Run 1 summary

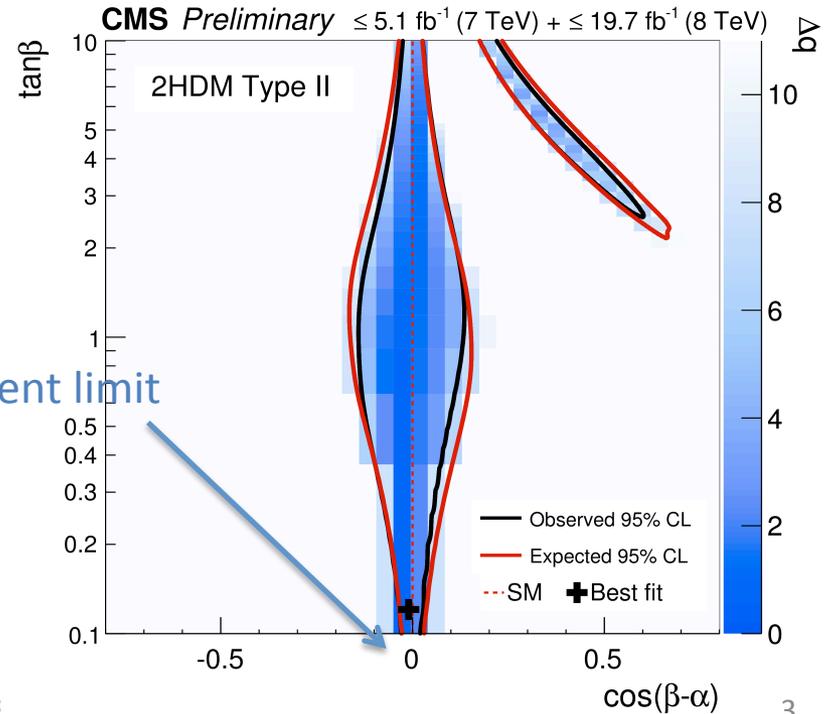
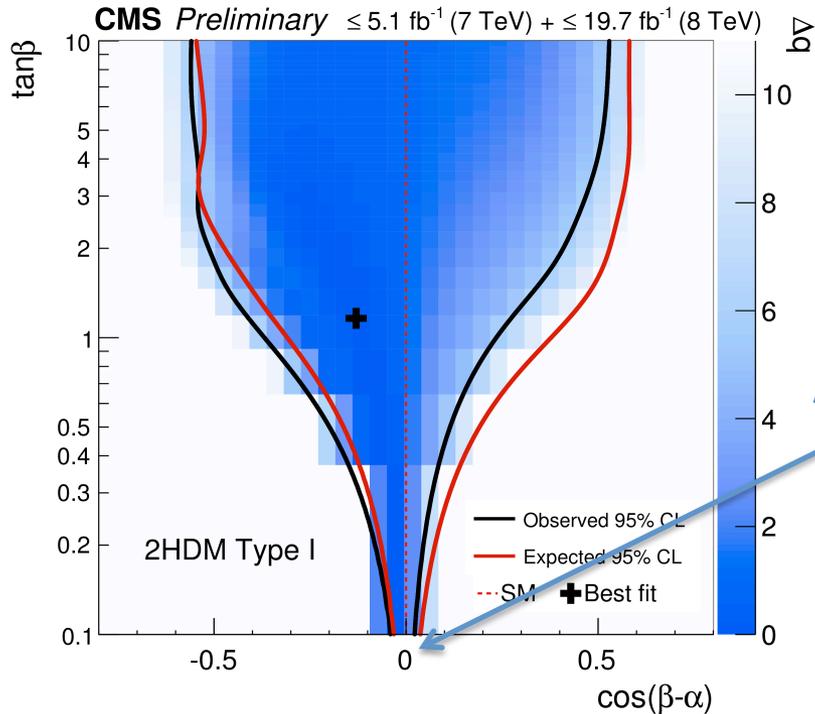
2HDM constraints from H(125)

HIG-16-007

CMS measurements of H(125) couplings strongly constrain heavy scalar sector

	2HDM		hMSSM
	type I	type II/MSSM	
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\frac{s_d + s_u \tan \beta}{\sqrt{1 + \tan^2 \beta}}$
κ_u	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$s_u \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}$
κ_d	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$s_d \sqrt{1 + \tan^2 \beta}$

Interpretation in 2HDM with Type-I and Type-II couplings



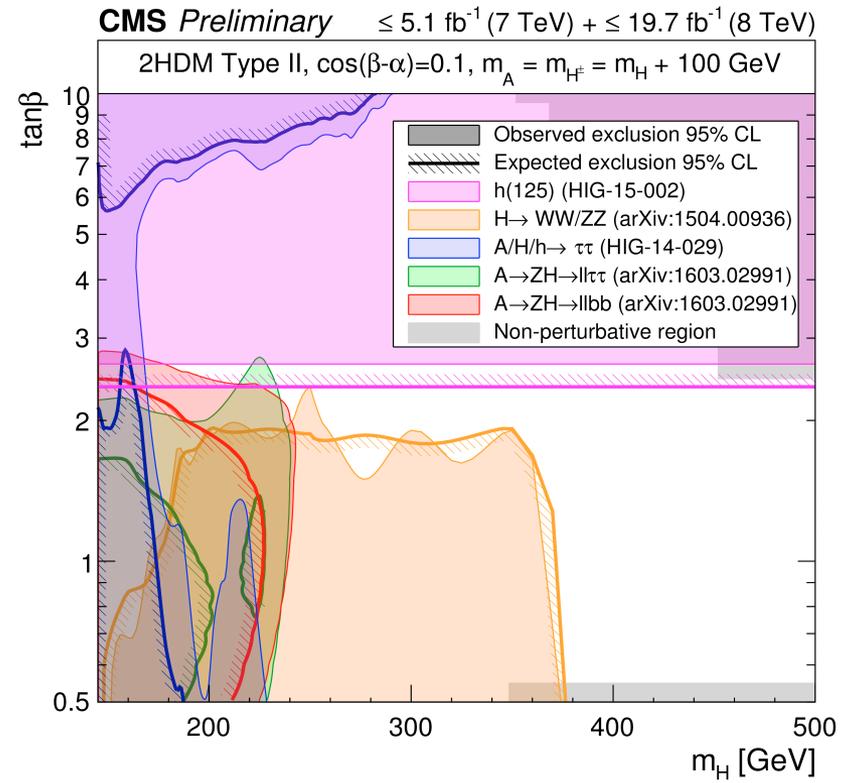
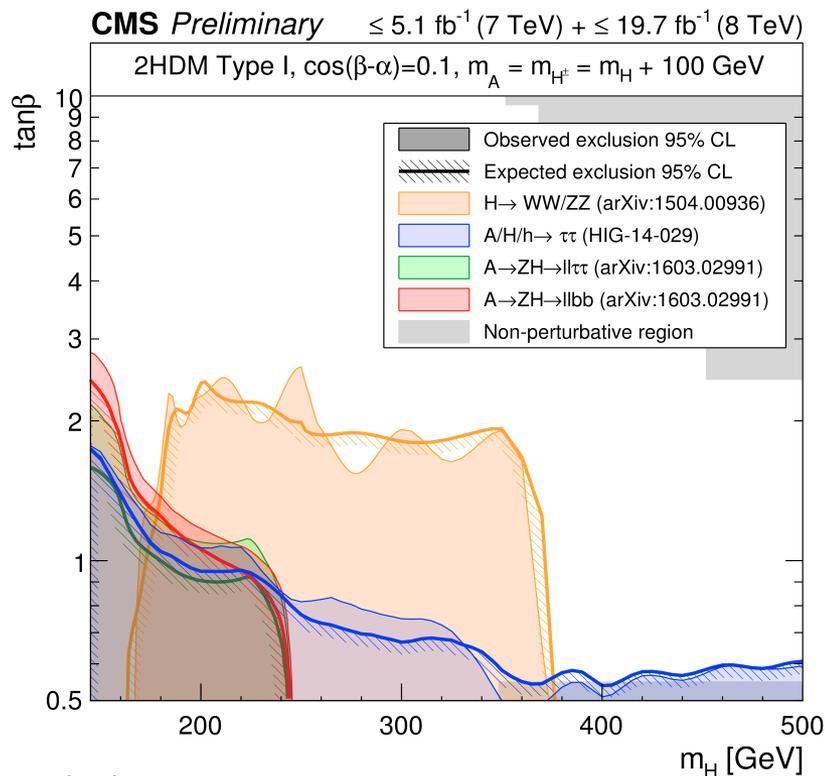
Heavy scalars: Run 1 summary



Direct searches **HIG-16-007**

- Summarized in benchmark 2HDM
 - Parameter space chosen where different searches are complementary and theory is consistent
- Type-II models more constrained

Parameter	Value
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^\pm}	$m_H + 100$ GeV
$\cos(\beta - \alpha)$	0.1
m_{12}^2	$\max(1 - \tan^2 \beta, 0) \cdot \frac{1}{2} \sin(2\beta) (m_A^2 + \lambda_5 v^2)$
m_H	scanned
$\tan \beta$	scanned



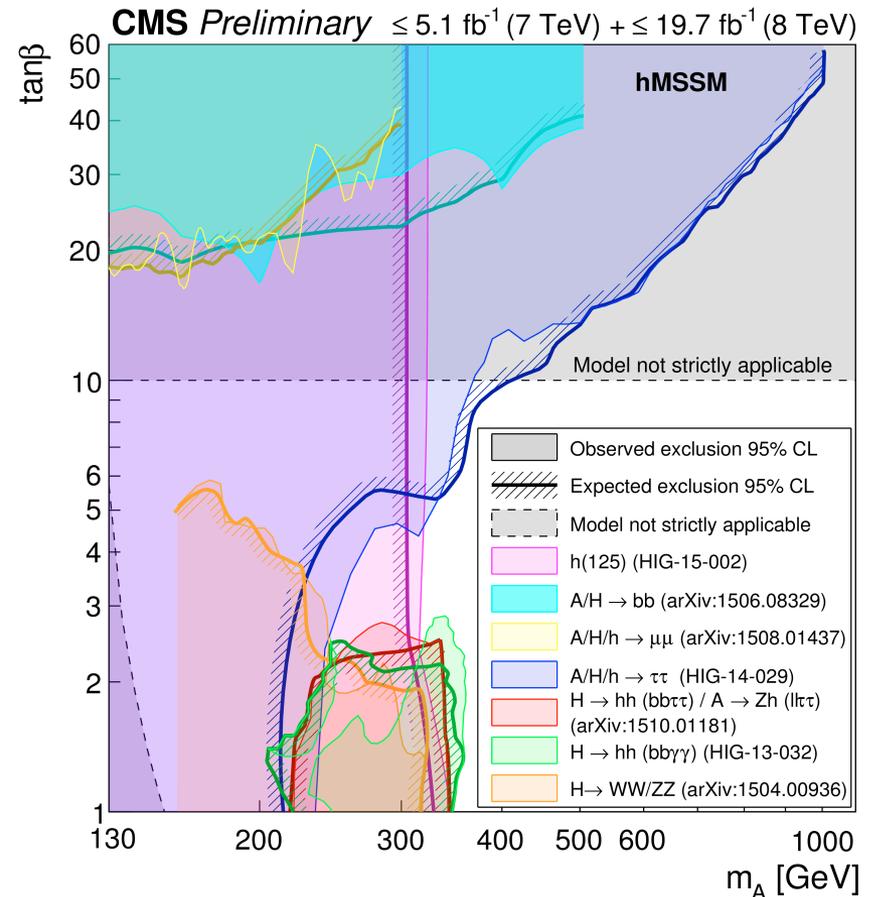
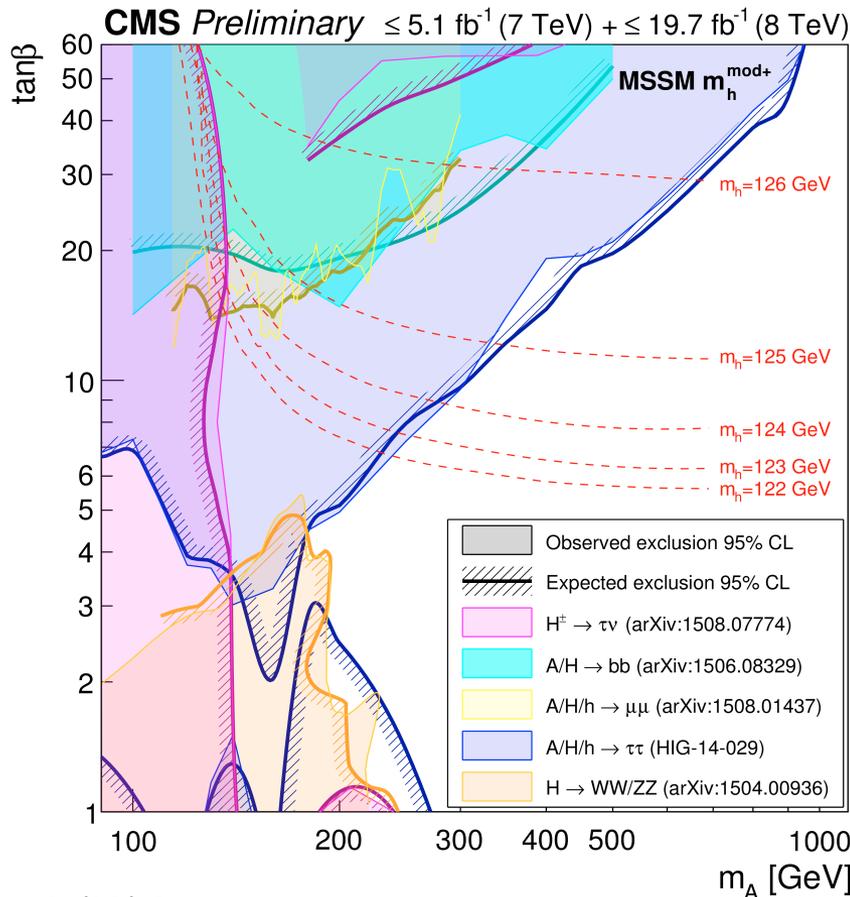
Heavy scalars: Run 1 summary



MSSM constraints from direct searches

HIG-16-007

- Summarized in benchmark MSSM models
 - $m_h^{\text{mod}+}$ ($m_h = 125 \pm 3$ GeV) and hMSSM ($m_h = 125$ GeV)
- Results in $(m_A, \tan \beta)$ plane

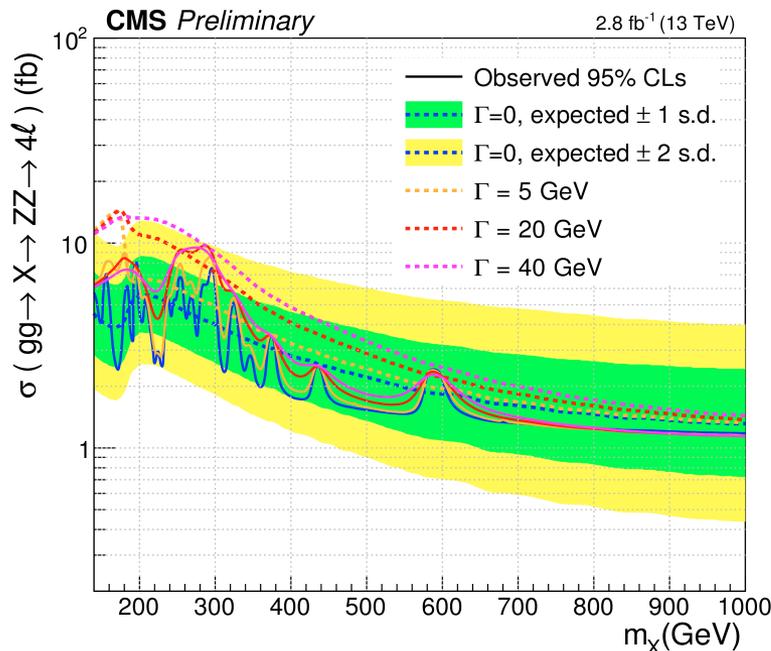


Heavy scalars: 13 TeV

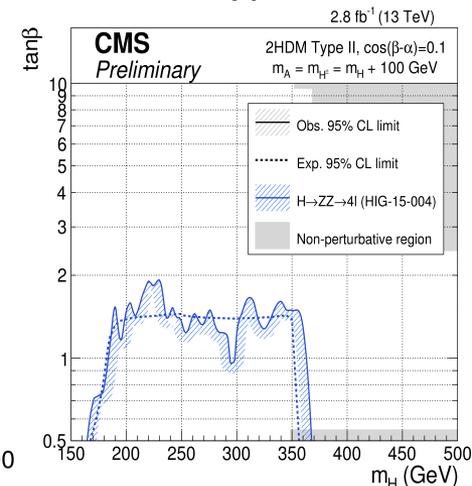


H → ZZ → 4l HIG-15-004

- search using m_{4l}
- Generic cross section limits for several widths



2HDM Type-II



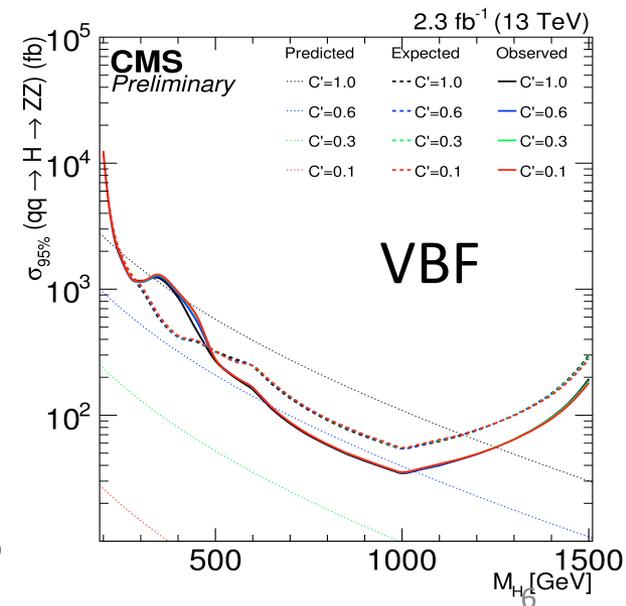
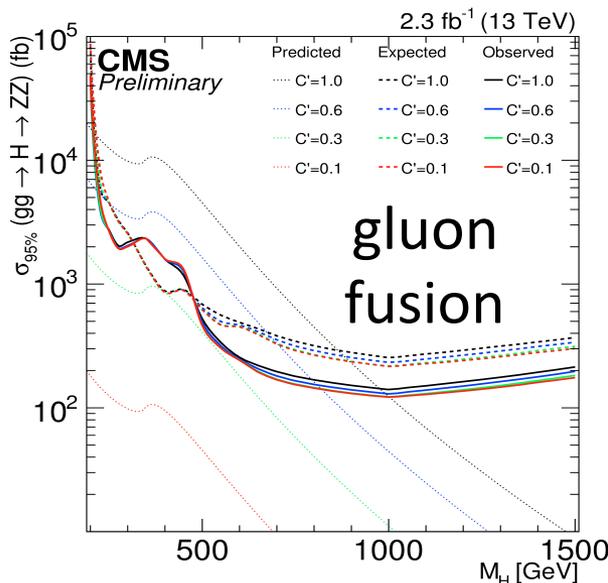
H → ZZ → 2l2ν HIG-16-001

- search using m_T
- EWK singlet model

$$\mu' = C'^2 (1 - \mathcal{B}_{\text{new}})$$

$$\Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{1 - \mathcal{B}_{\text{new}}}$$

- Generic gluon-fusion and VBF cross section limits independent of width

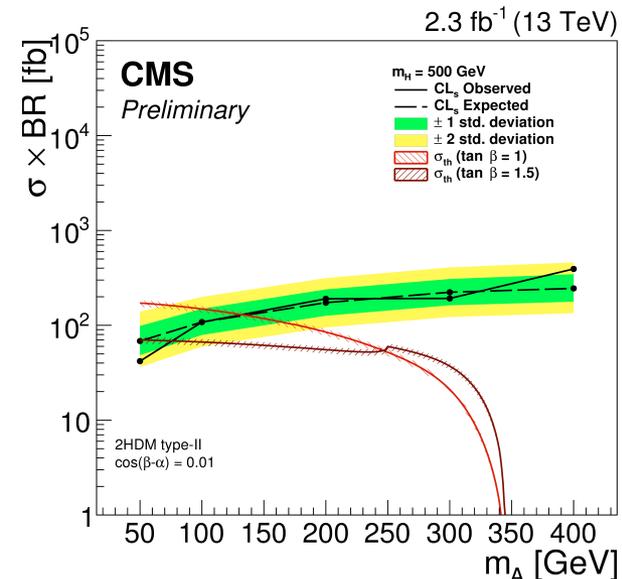
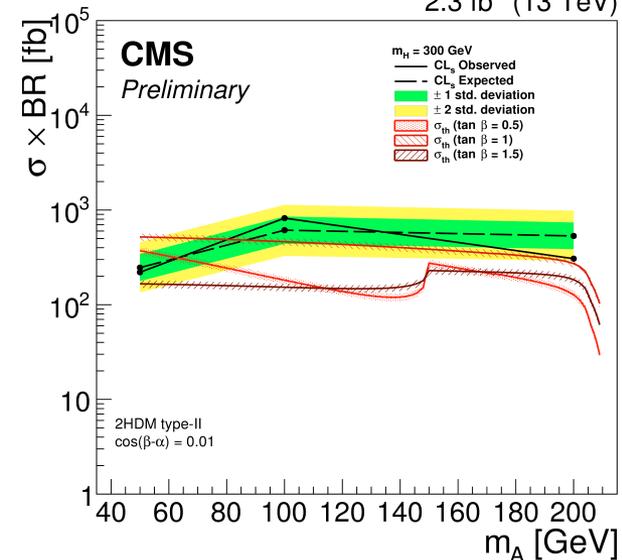
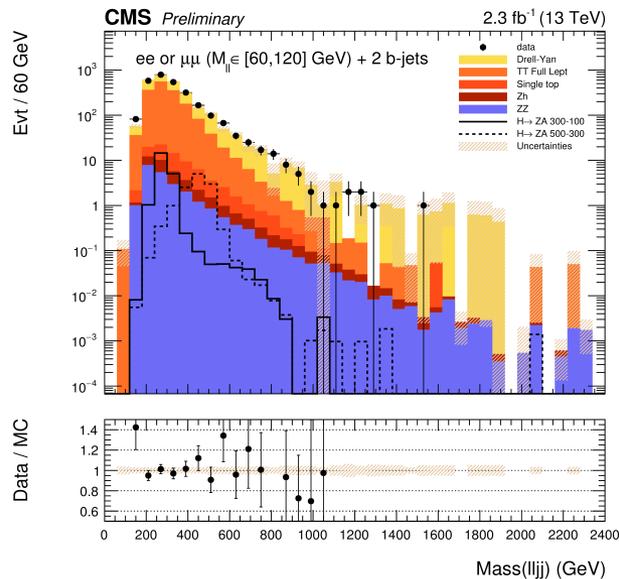
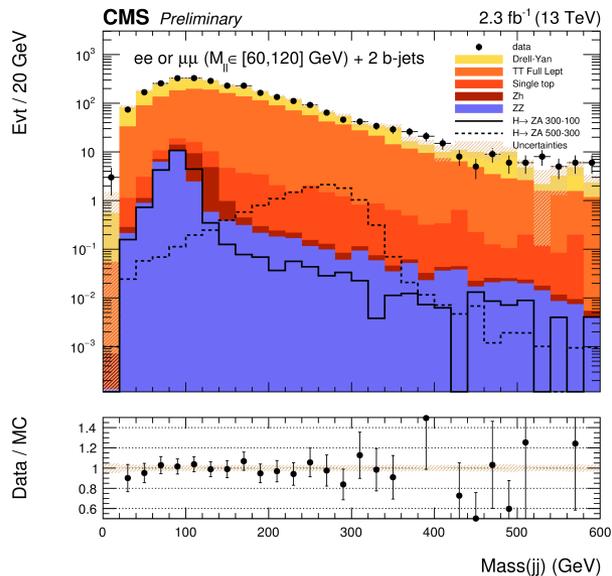


Heavy scalars: 13 TeV



H → Z(l)A(bb) HIG-16-010

- 2HDM with inverted mass hierarchy (light A)
- 2D search in (m_{bb}, m_{llbb}) plane
 - Signal region centered on $(m_A, m_H) + m_{ll}$ around Z peak
 - Background fitted in m_{ll} sidebands
- Type-II 2HDM interpretation





X->hh: 13 TeV

H->hh->bbττ

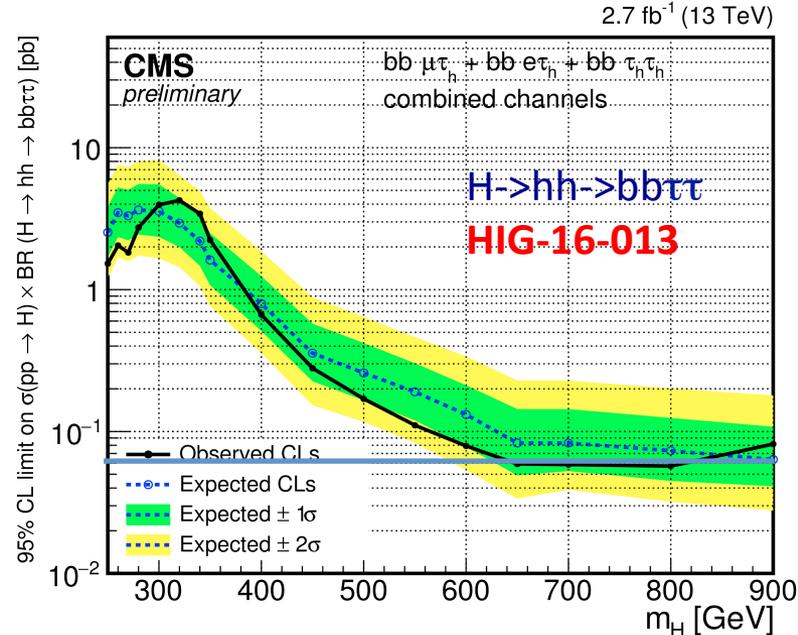
Search using m_H

3 categories: $bb\tau_h$, $bb\mu\tau_h$, $bb\tau_h\tau_h$

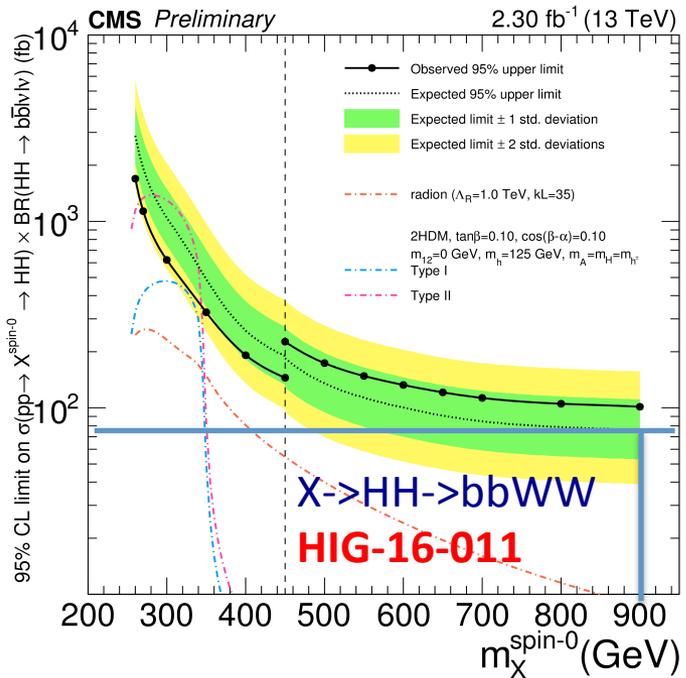
kinematic fit fixing $m_{bb}=m_{\tau\tau}=125$ GeV

X (spin-0 or 2)->HH->bbW(lν)W(lν)

- Search using yields in 4 event categories
 - On/offpeak m_{bb} x low/high BDT score
- BDT trained at $m_X = 400$ and 650 GeV

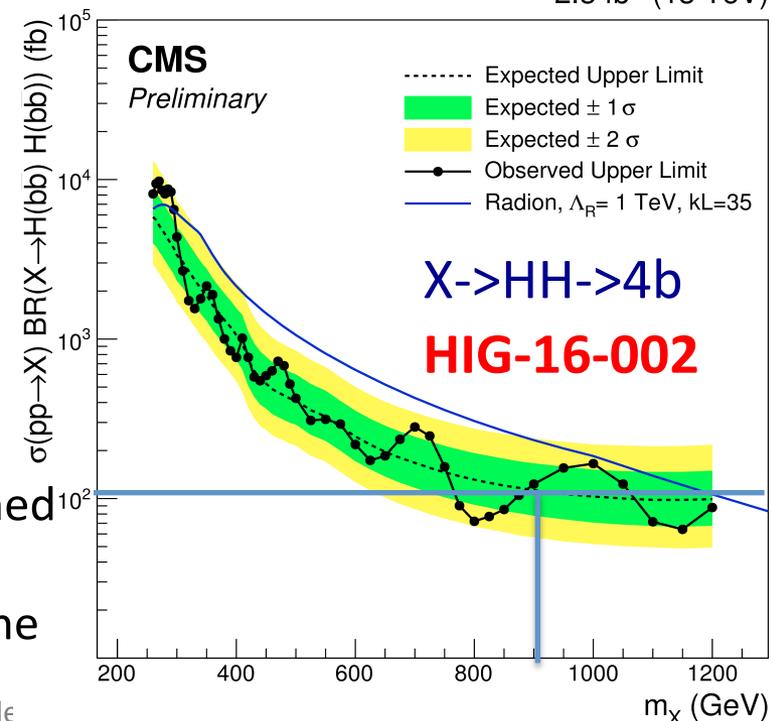


2.3 fb⁻¹ (13 TeV)



X->HH->4b

Search using m_X kinematic fit;
Bkg shape obtained from sidebands in (m_{H1}, m_{H2}) plane





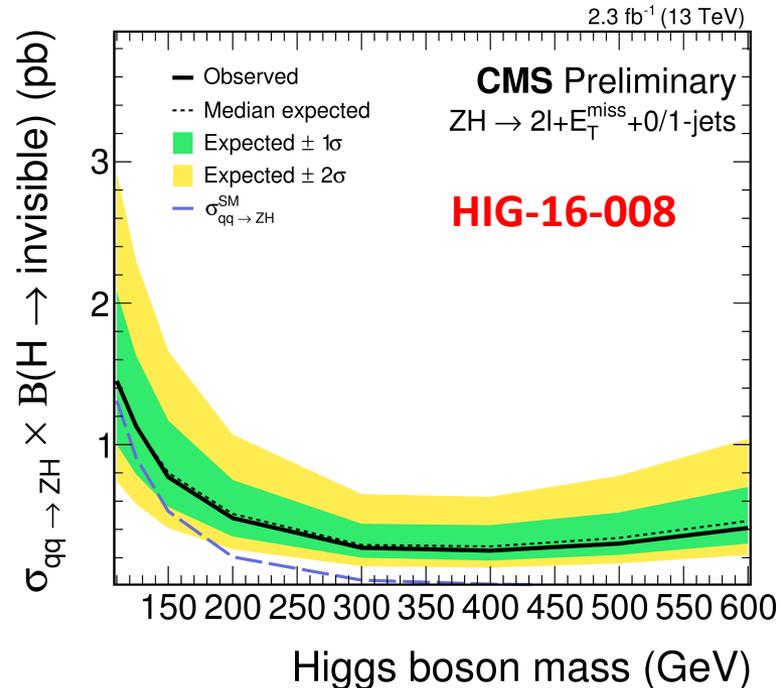
H->invisible

ZH->ll+MET 13 TeV

Search using m_T in jet categories

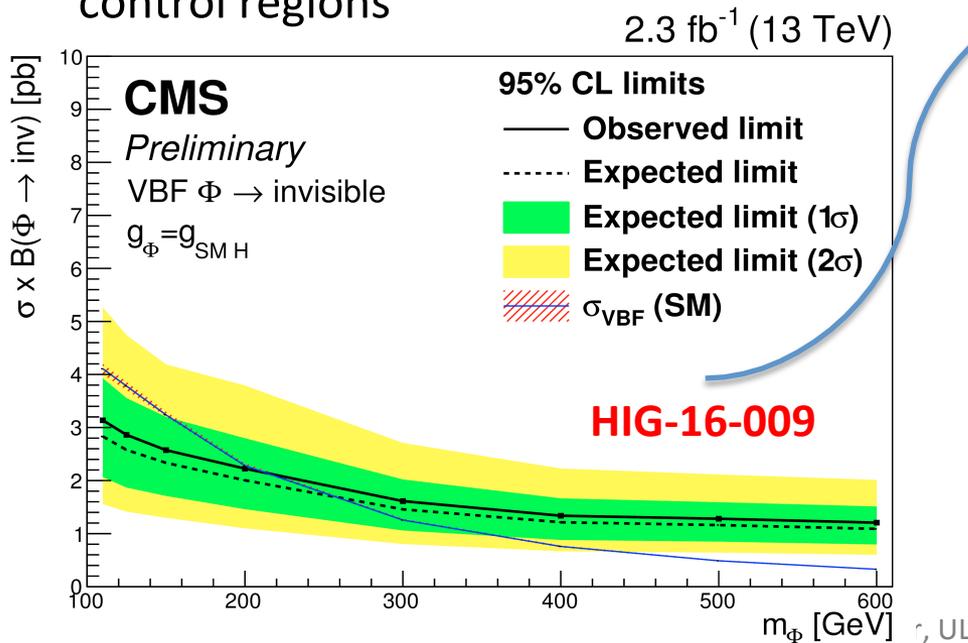
ZZ background from simulation

Z+jets from γ +jet data



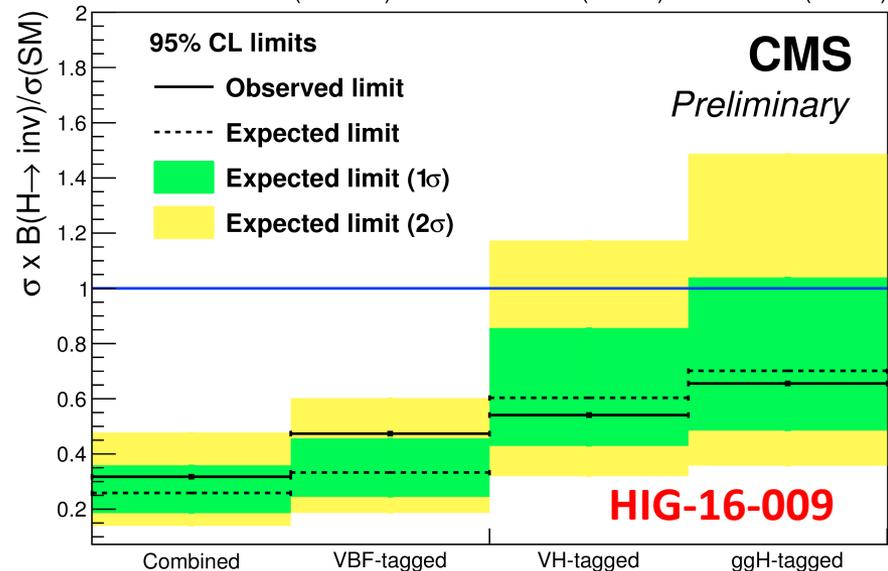
VBF qqH->jj+MET 13 TeV

- ✓ Trigger; MET and jet (VBF) cuts
- ✓ Signal region: window in m_{jj} x $\min\Delta\phi(j, MET)$
- ✓ Search using yields in signal and multiple control regions



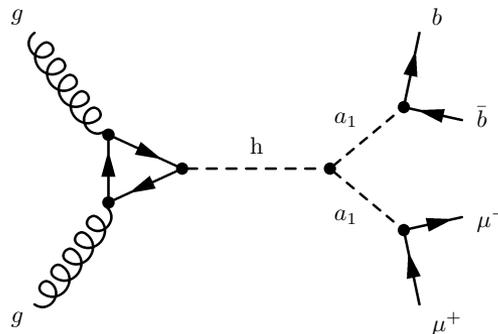
H(125) combined Run 1 + 13 TeV

0-2.3 fb⁻¹ (13 TeV) + 18.9-19.7 fb⁻¹ (8 TeV) + 0-4.9 fb⁻¹ (7 TeV)





H(125)->a₁a₁: 8 TeV

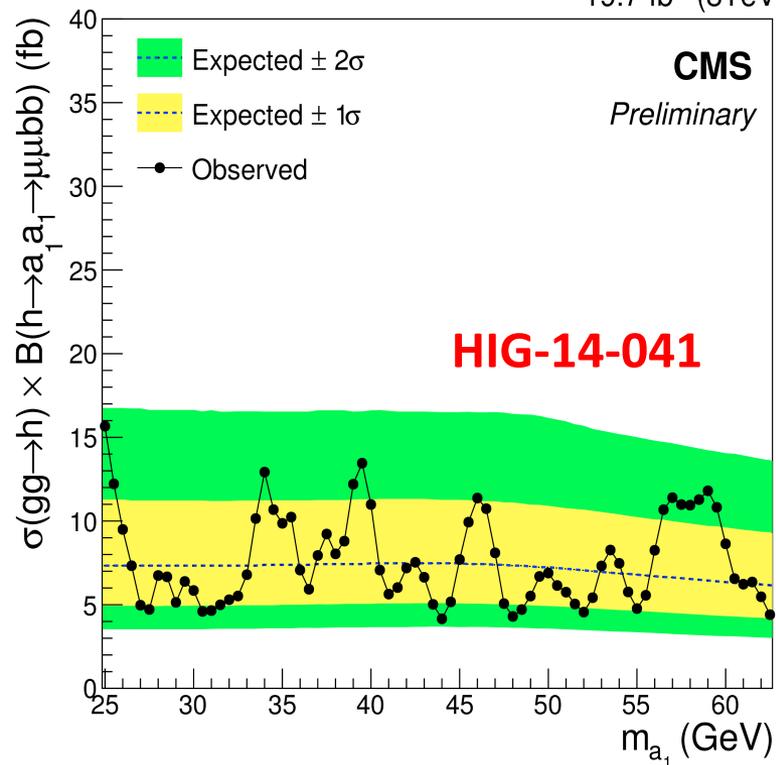
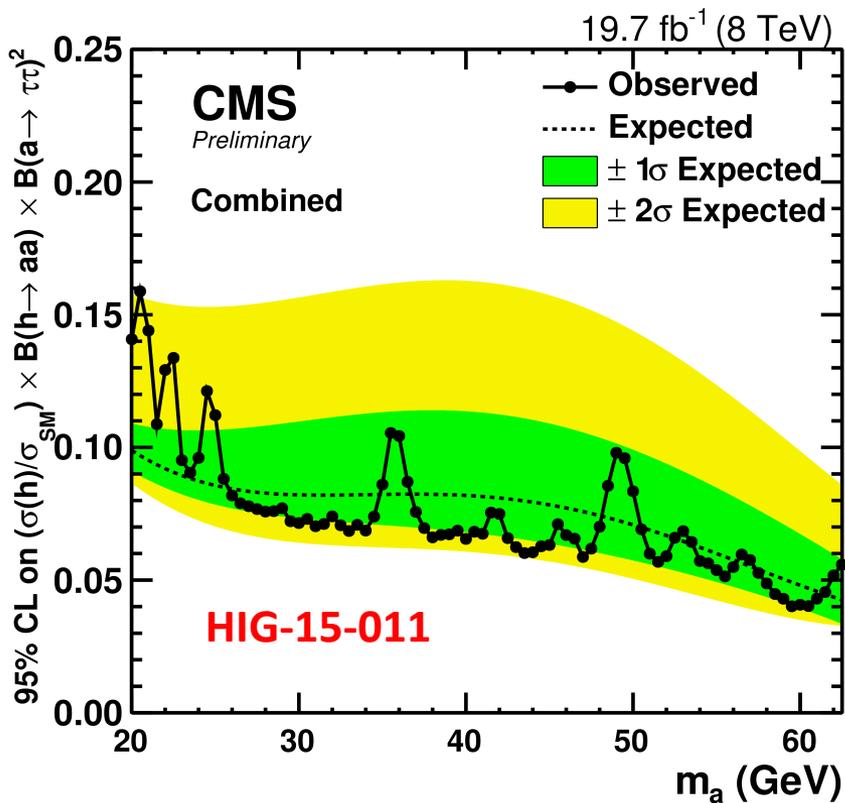


H->a₁a₁->μμbb

$$20 < m_{a_1} < 70 \text{ GeV}$$

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

Search for peak in $m_{\mu\mu}$



H->a₁a₁->μμττ

- ✓ 5 different τ decay modes
- ✓ 20 < m_{a1} < 62.5 GeV
- ✓ |m_{μμττ} - 125| < 25 GeV
- ✓ |m_{μμ} - m_{ττ}| / m_{μμ} < 0.8

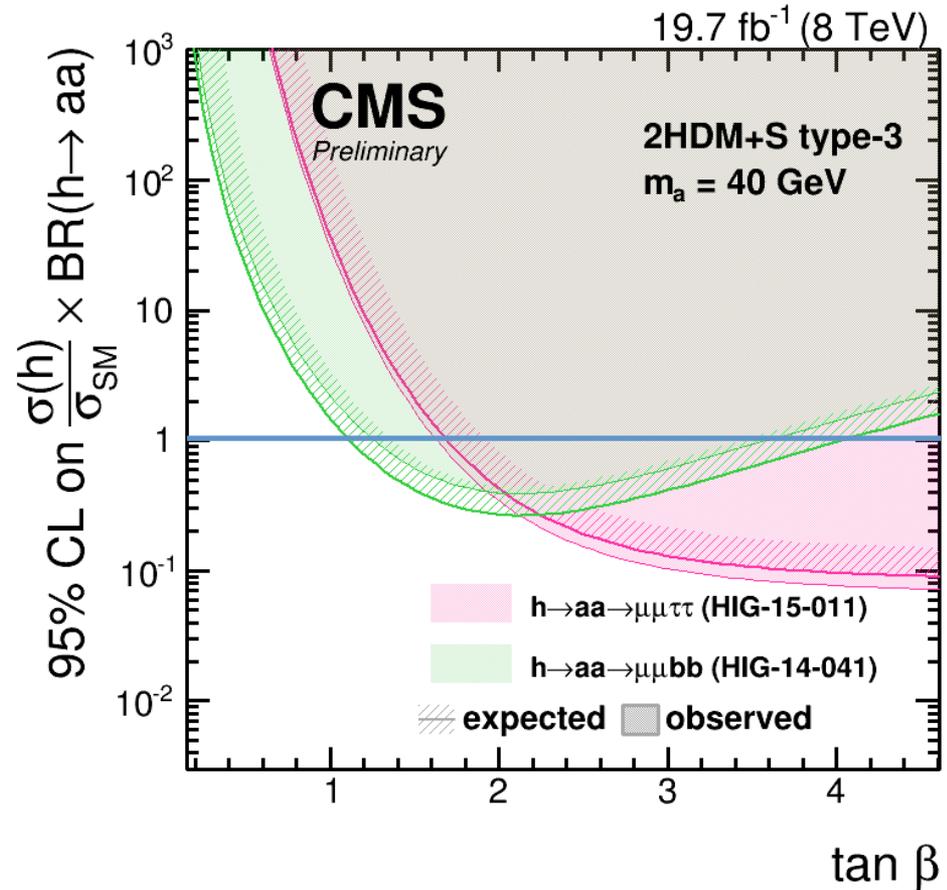
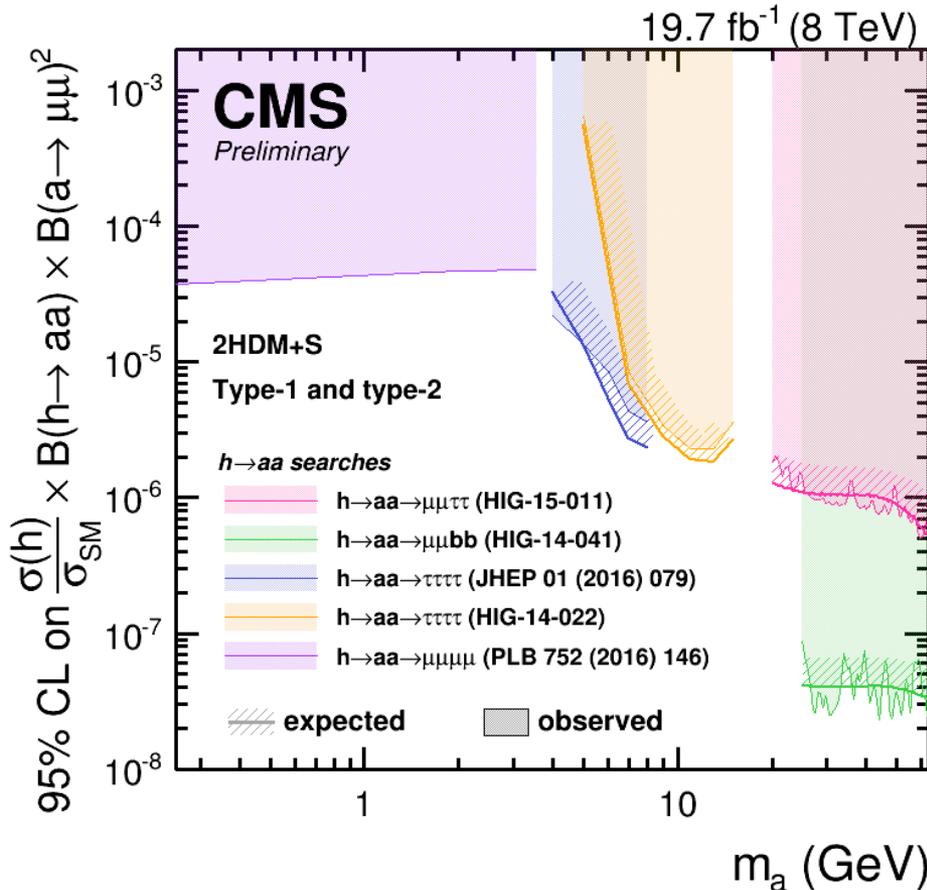
H(125)->a₁a₁: 2HDM+S summary

<https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/SummaryResultsHIG>

a₁ couplings to fermions depend on model type and tanβ

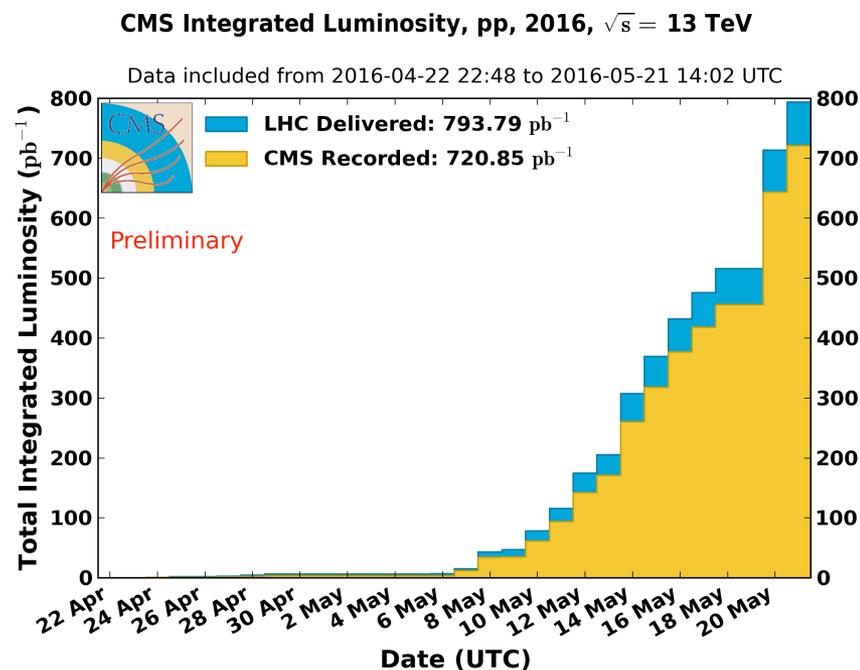
Type-1 and -2 limits are ~indep. of tanβ

Sensitivity to B(h->aa) in Type-3 and -4



Conclusions

- CMS searches for BSM scalar sector in LHC Run 2 are well under way
 - Sensitivity close to Run 1 already with 2.7 fb^{-1} of data
- The analysis methods are continuously improving
- LHC and CMS are performing very well
 - More results coming soon



BACKUP

H- \rightarrow ZZ+WW analysis

- In [140, 1000] GeV mass range
- Search in $WW \rightarrow \ell\nu\ell\nu$, $WW \rightarrow \ell\nu jj$, $WW \rightarrow \ell\nu J$, $ZZ \rightarrow \ell\ell\ell\ell$, $ZZ \rightarrow \ell\ell\tau\tau$, $ZZ \rightarrow \ell\nu\nu$, $ZZ \rightarrow \ell\ell qq$ final states
- Several models considered:
 - Heavy scalar with SM couplings
 - Electroweak singlet mixing with light scalar
 - Couplings of h and H states are universally rescaled by C and C', constrained by unitarity and h(125) signal strength

$$C^2 + C'^2 = 1$$

- Heavy H is allowed to decay into new modes with a B.F. \mathcal{B}_{new} :

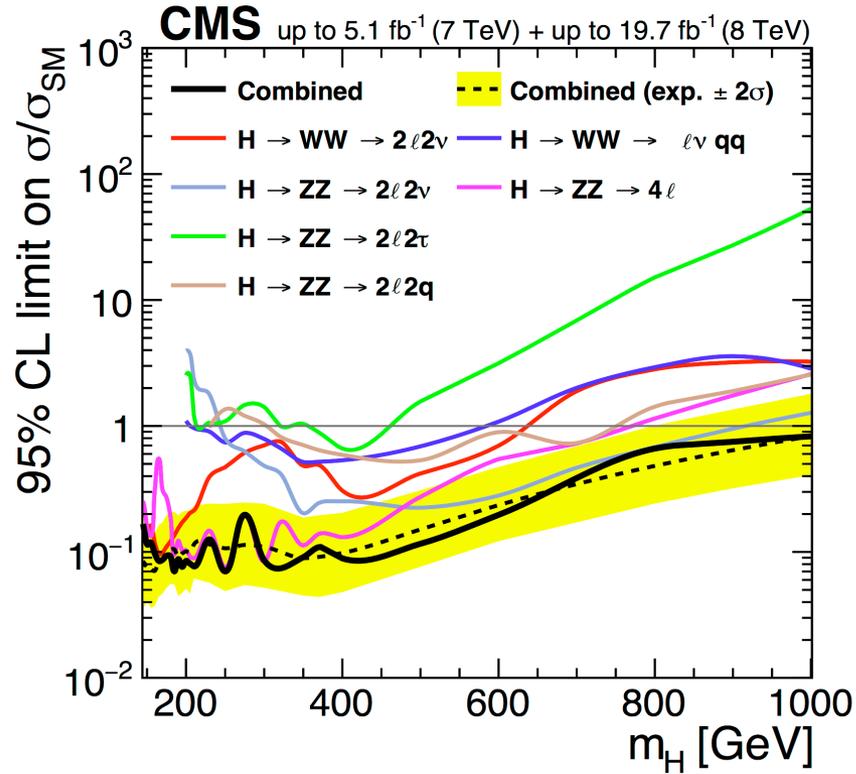
$$\mu' = C'^2 (1 - \mathcal{B}_{\text{new}})$$

$$\Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{1 - \mathcal{B}_{\text{new}}}$$

- Results also interpreted as a **generic 2D limit on mass and width**

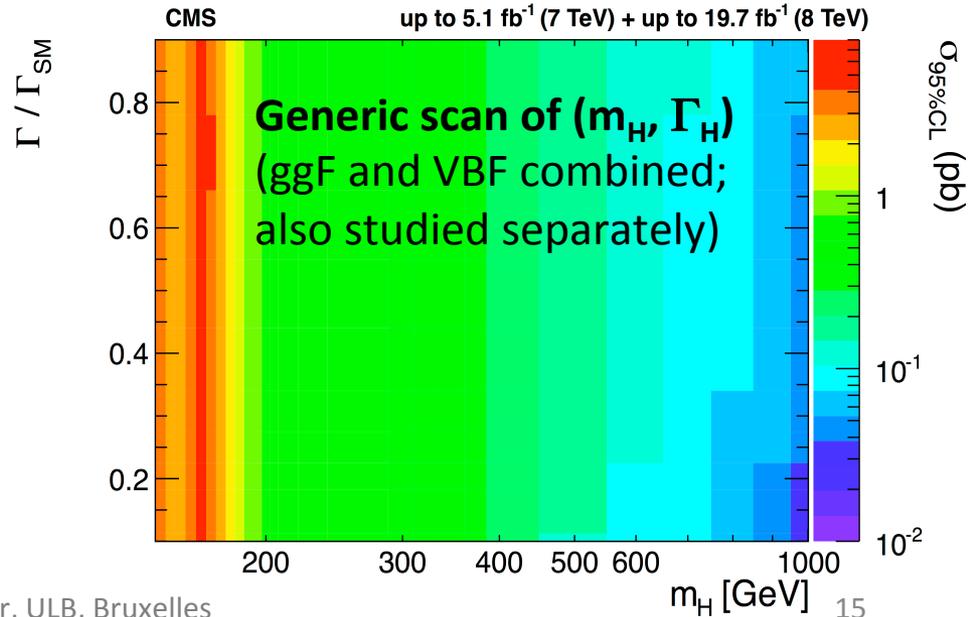
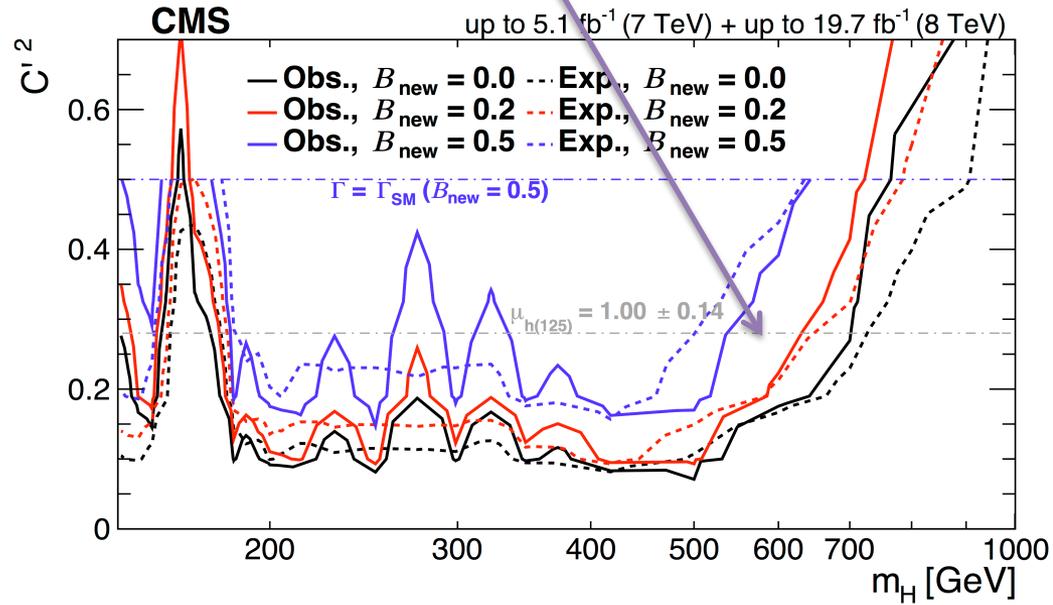


Results



SM-like scalar: sensitivity down to $0.1 \times \sigma_{SM}$ across a large mass range

EWK singlet: direct search is competitive with indirect constraint from $h(125 \text{ GeV})$

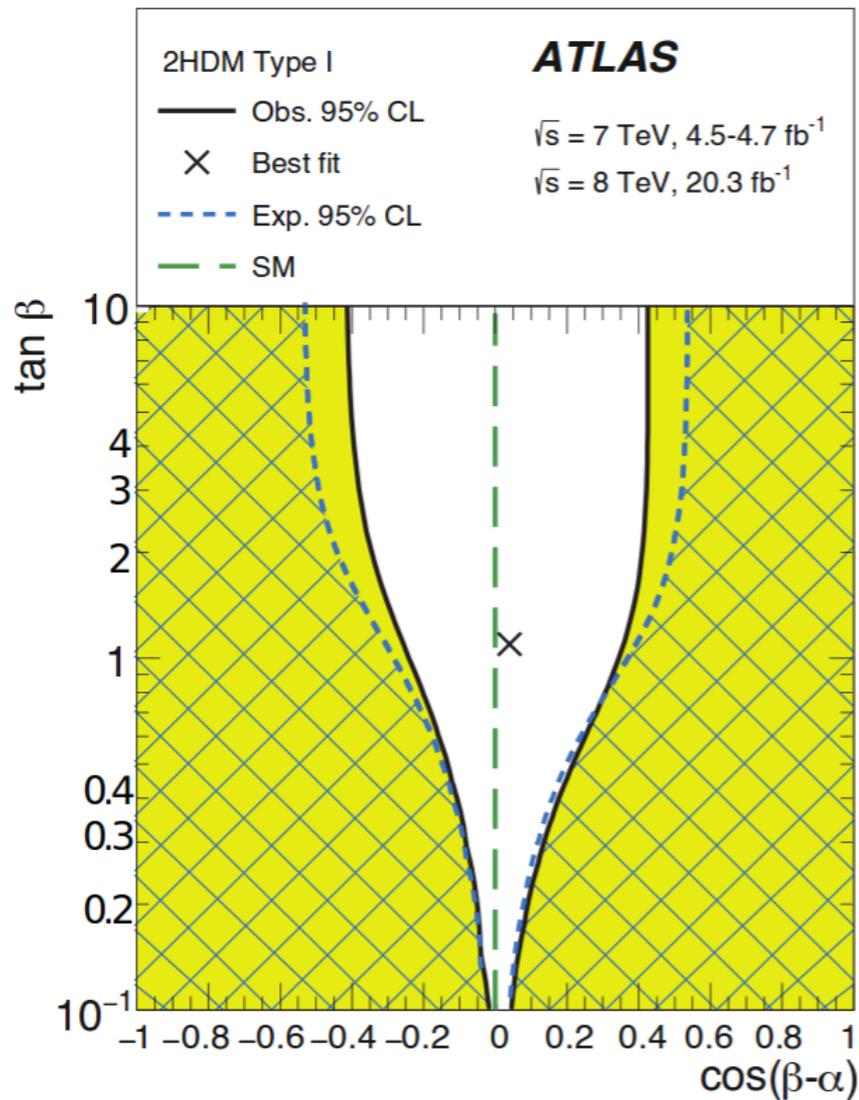
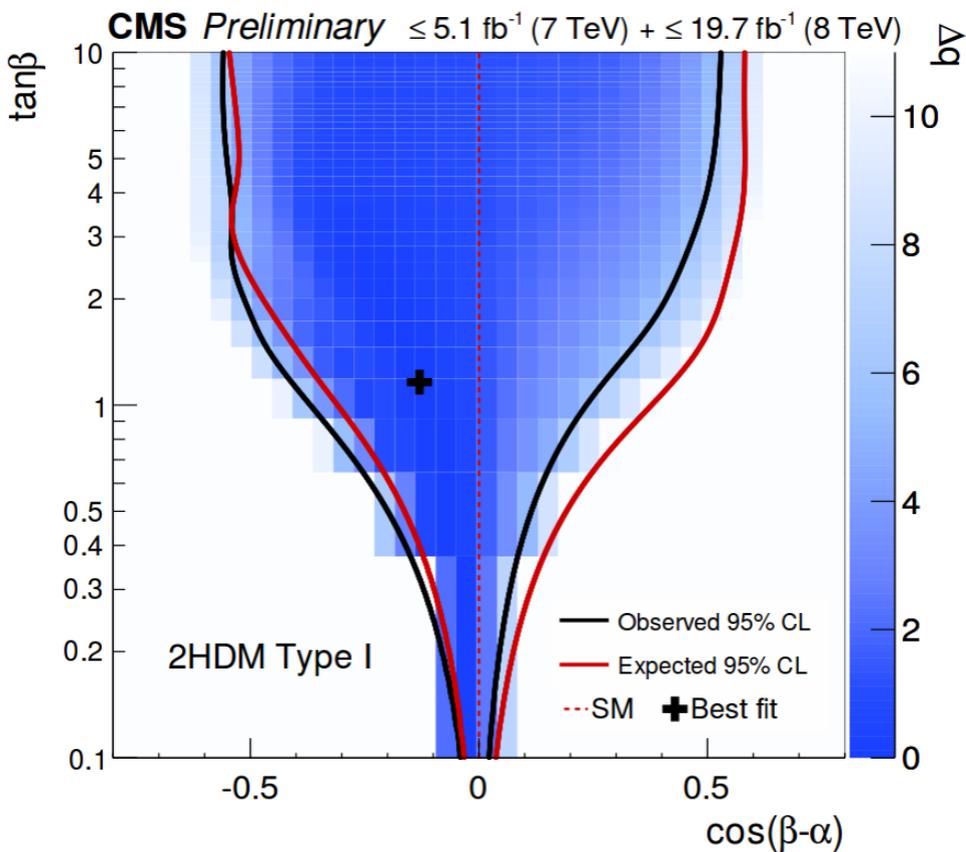


2HDM

arxiv:1507.04281

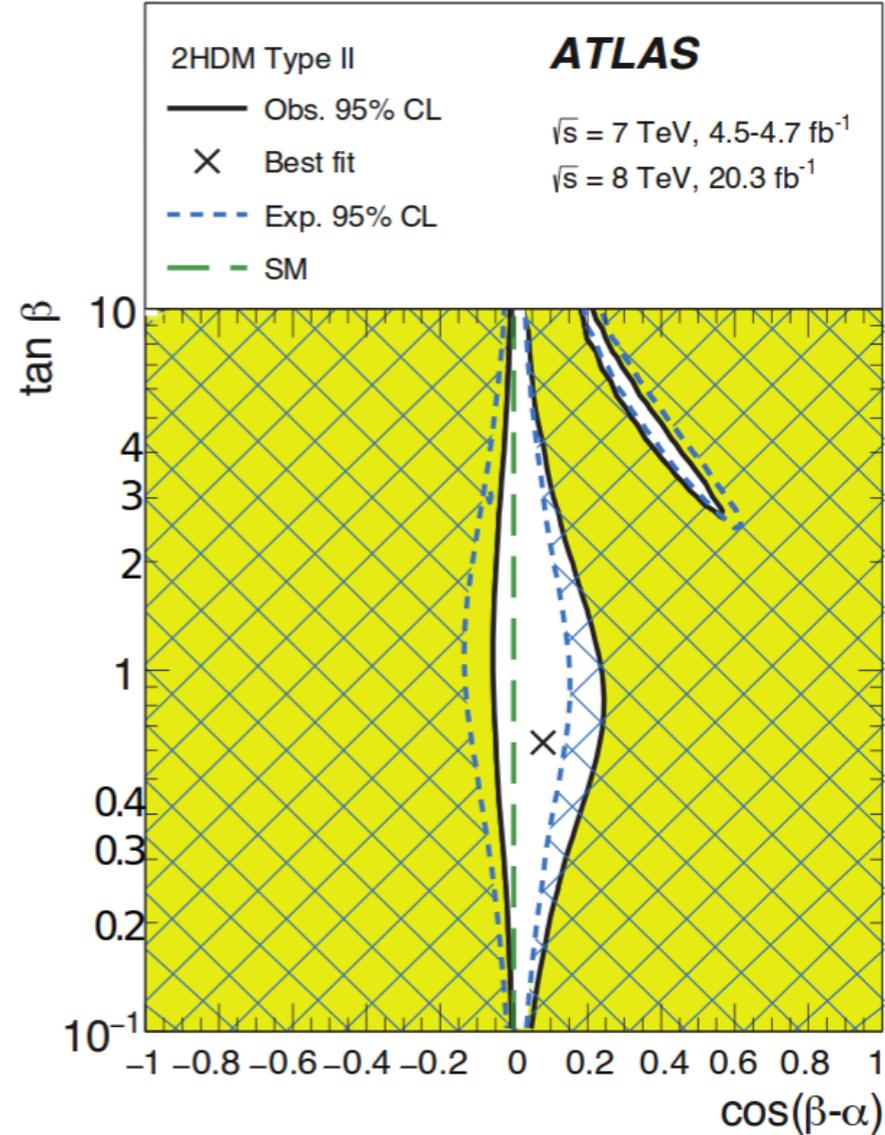
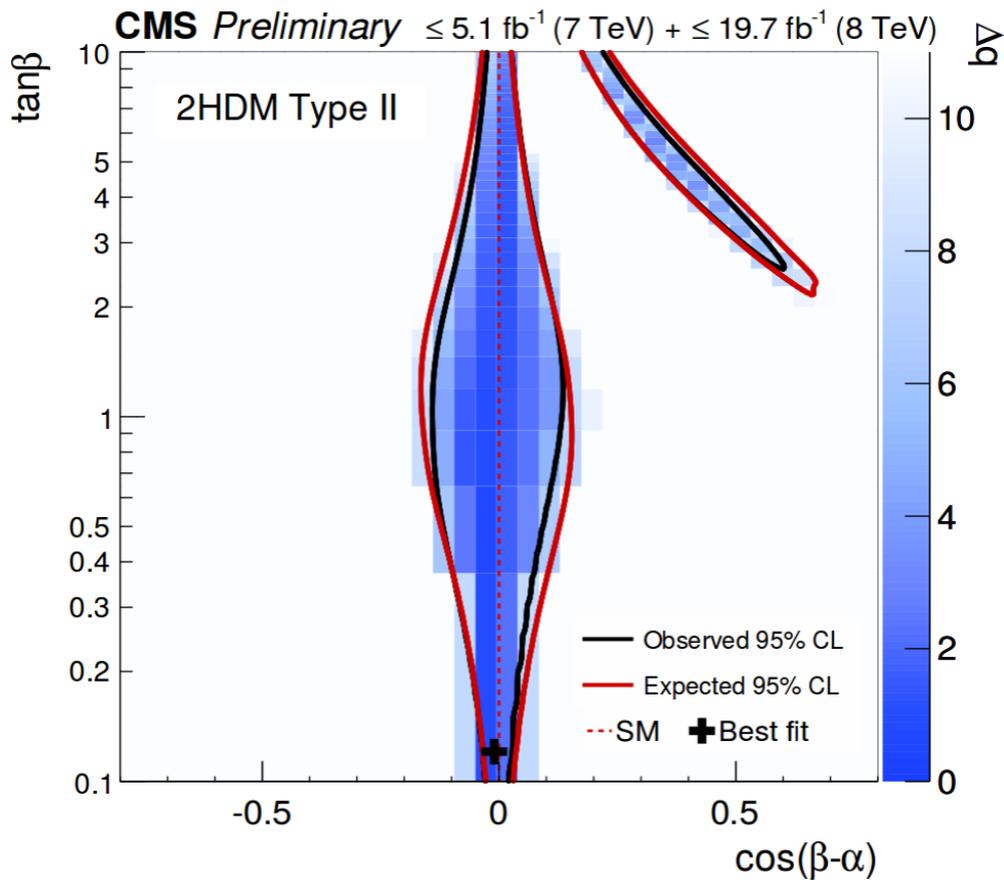
	$h\bar{U}U$	$h\bar{D}D$	$h\bar{E}E$	$H\bar{U}U$	$H\bar{D}D$	$H\bar{E}E$	$iA\bar{U}\gamma_5U$	$iA\bar{D}\gamma_5D$	$iA\bar{E}\gamma_5E$
Type I	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$-\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$-\cot \beta$	$-\tan \beta$	$-\tan \beta$
Type X	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$-\cot \beta$	$\cot \beta$	$-\tan \beta$
Type Y	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$-\cot \beta$	$-\tan \beta$	$\cot \beta$

2HDM



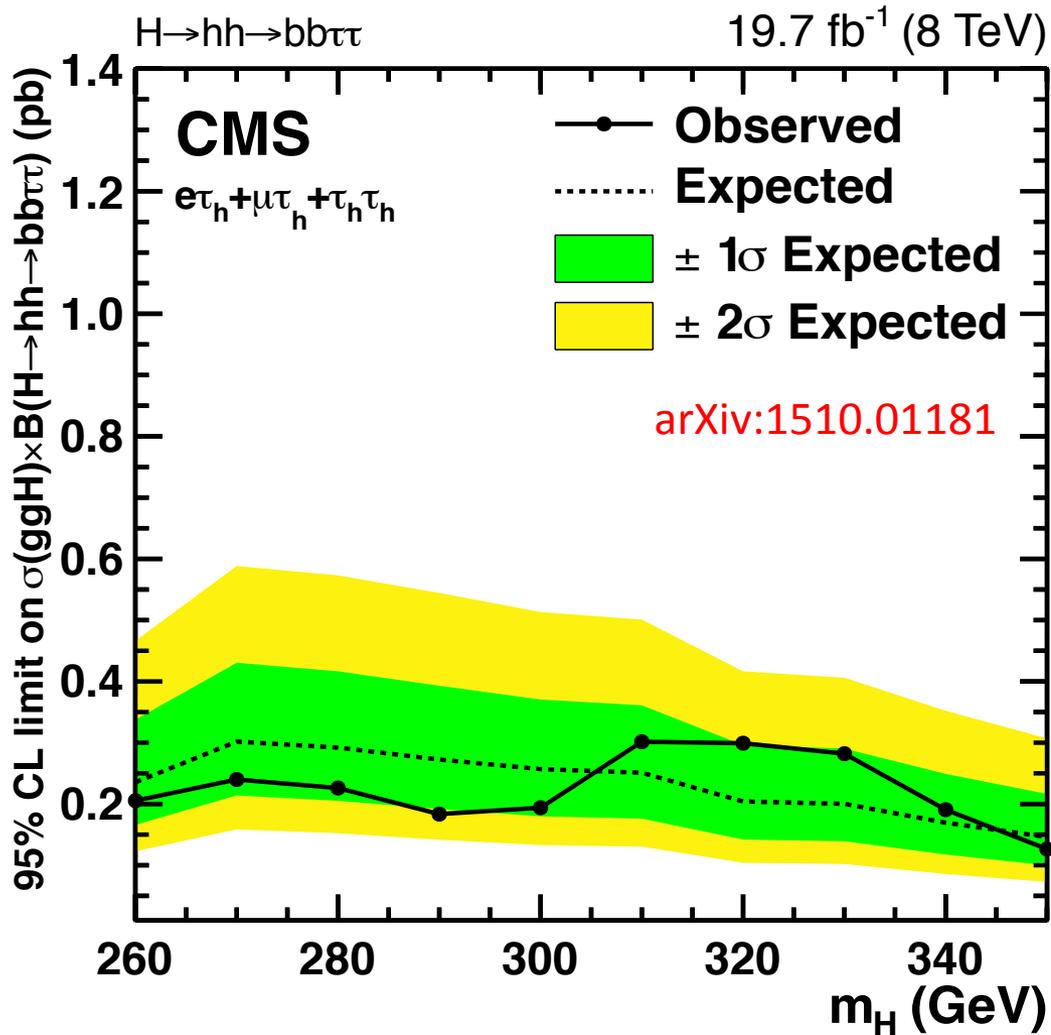
arxiv:1509.00672

2HDM



arxiv:1509.00672

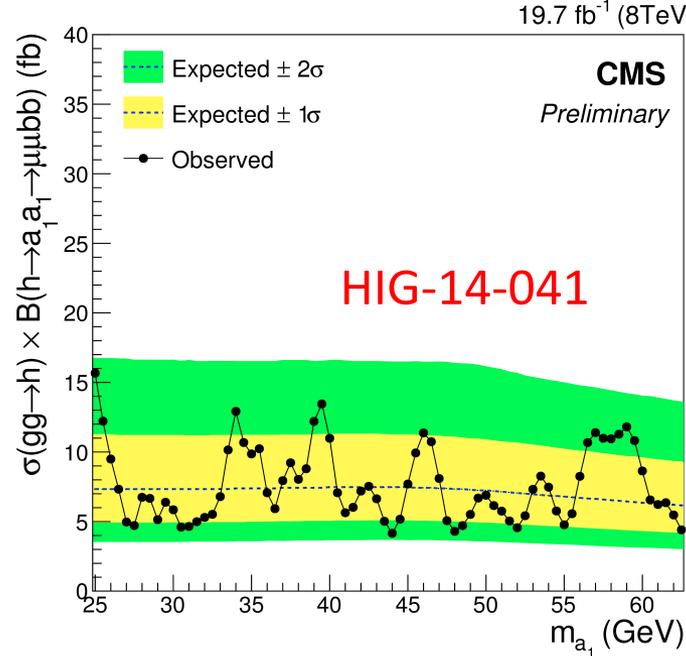
H→hh→bbττ 8 TeV



H(125)->a₁a₁ : 8 TeV NMSSM and 2HDM+S

H->a₁a₁->μμbb

- 25 < m_{a₁} < 65 GeV
- Signal region: |m_{μμbb} - 125| < 25 GeV
- Search for a sharp peak in m_{μμ}



H->a₁a₁->μμττ HIG-15-011

- 2HDM+S Type-3 and Type-4
- 20 < m_{a₁} < 62.5 GeV
- |m_{μμττ} - 125| < 25 GeV
- |m_{μμ} - m_{ττ}| / m_{μμ} < 0.8

