BSM Higgs boson searches at LHC

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DAE-BRNS-2018
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Introduction

- Higgs boson searches beyond the SM: Important aspect of Higgs physics program at LHC
- Complimentary to the SM interpretations/investigation of properties of the observed 125 GeV scalar particle

- BSM searches include:
  - Search for exotic decays not expected within the SM.
  - Searches for more complex Higgs sector
    - ❑ Prediction of additional Higgs bosons from many models beyond SM

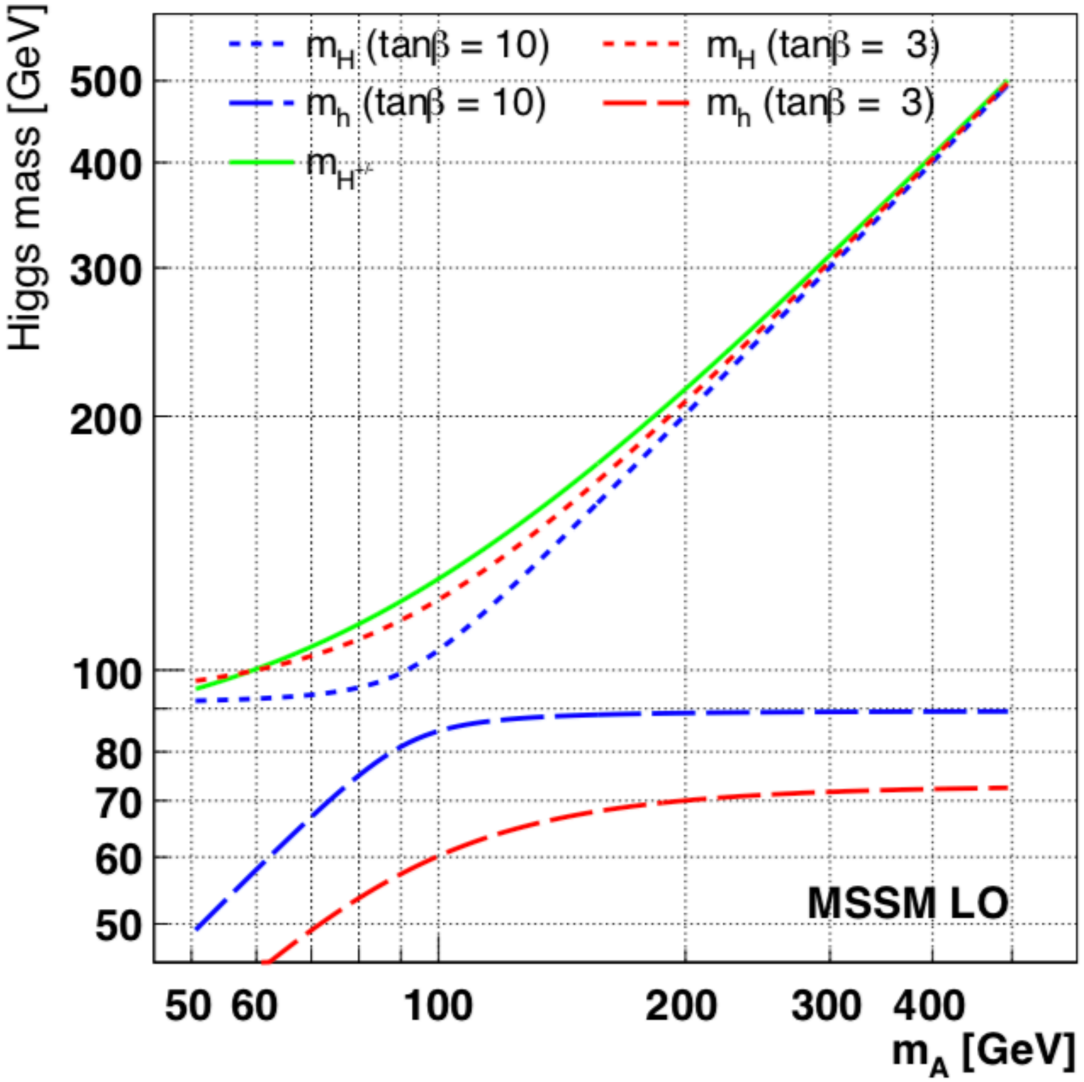
Rich program to search for NEW physics in the Higgs sector

Due to time constraint I will discuss results only from a few prominent searches performed using pp collision data collected at $\sqrt{s}$ = 13 TeV

Higgs boson in MSSM

- Two Higgs doublet => 5 physical bosons
  - Three neutrals : h, H (CP even), A (CP odd)
  - Two charged : $H^{\pm}$
- Controlled by two parameters at tree level
  - m_A and tanβ

LHCHXSWG-2015-002



$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$M_{H^+}^2 = M_A^2 + M_W^2$$

$$M_{h/H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 cos^2 2\beta}\right)$$

$$\tan\alpha = \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4\, m_A^2\, m_Z^2\, \cos^2 2\beta}}$$

: Mixing angle between h & H

Other SUSY parameters are important at higher order corrections

Higgs boson in MSSM

- Approximately 30% of h mass due to higher order corrections

$$(\Delta m_h^2)^{t/\tilde{t}}_{1\mathrm{loop}} \approx \frac{3\, m_t^4}{2\,\pi^2\, v^2}\left(\log \frac{m_{\mathrm{SUSY}}^2}{m_t^2} + \frac{X_t^2}{m_{\mathrm{SUSY}}^2} - \frac{X_t^4}{12\, m_{\mathrm{SUSY}}^4}\right)$$

$$X_t = A_t - \mu \cot\beta$$

- Due to large m_t, large $m_{t\sim}$, large X_t, and large tanβ

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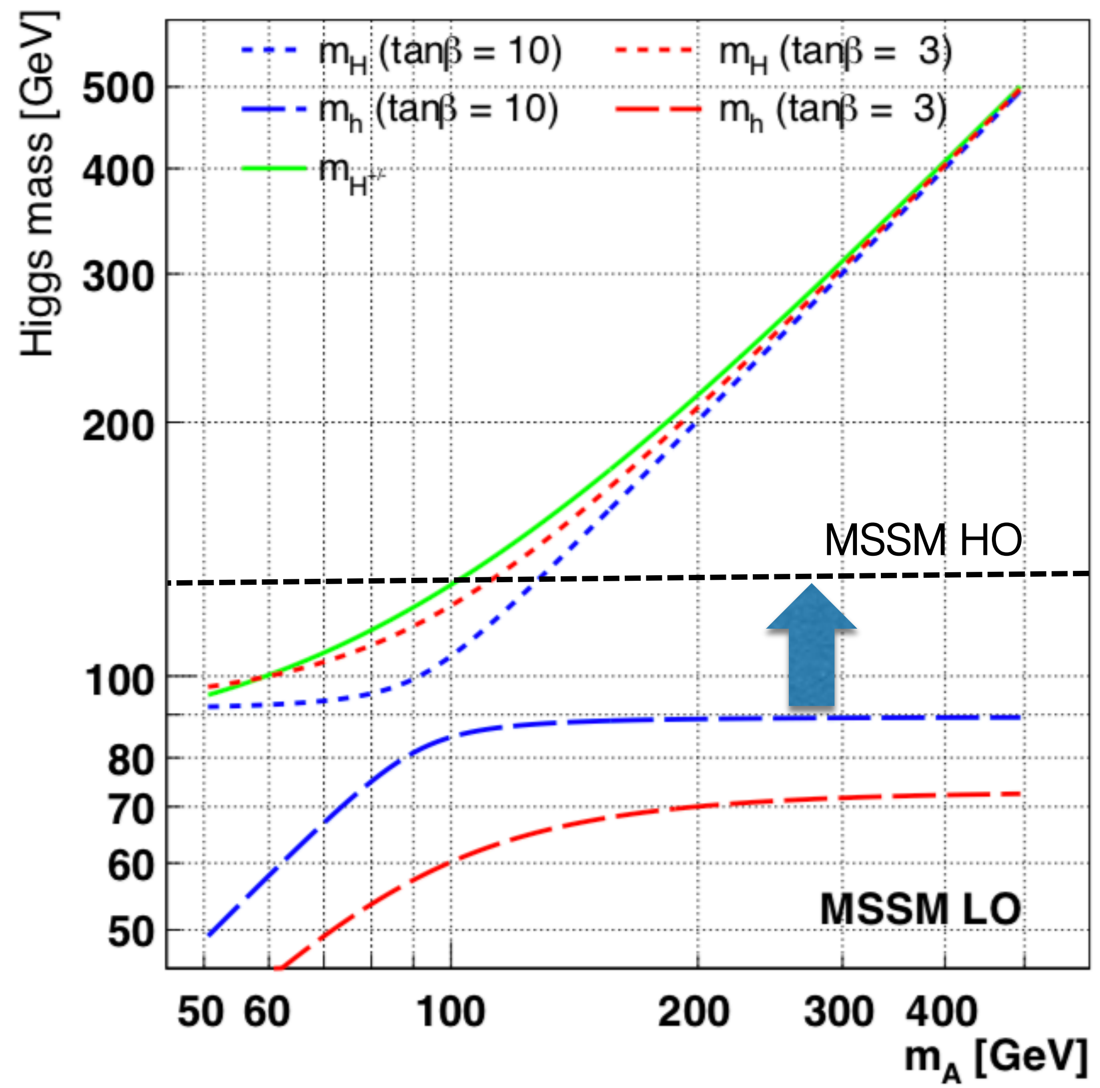

$$M_{H+}^2 = M_A^2 + M_W^2$$

$$M_{h/H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 cos^2 2\beta}\right)$$

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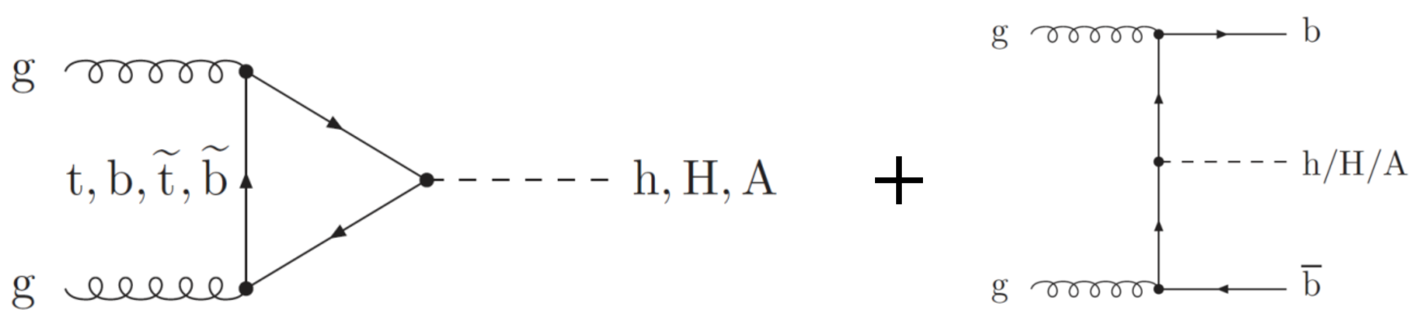
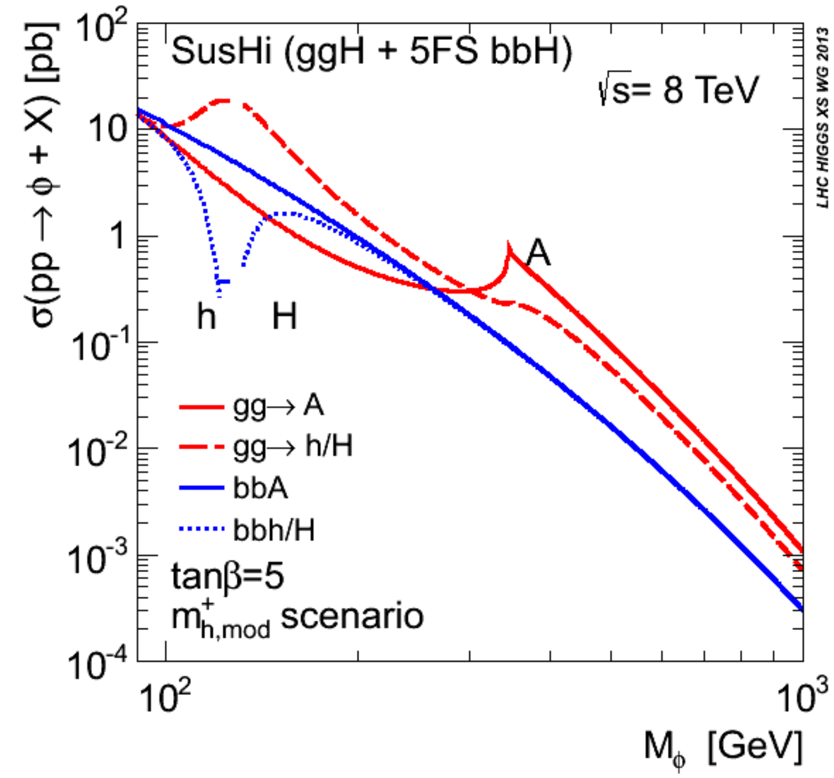
Mixing angle between h & H

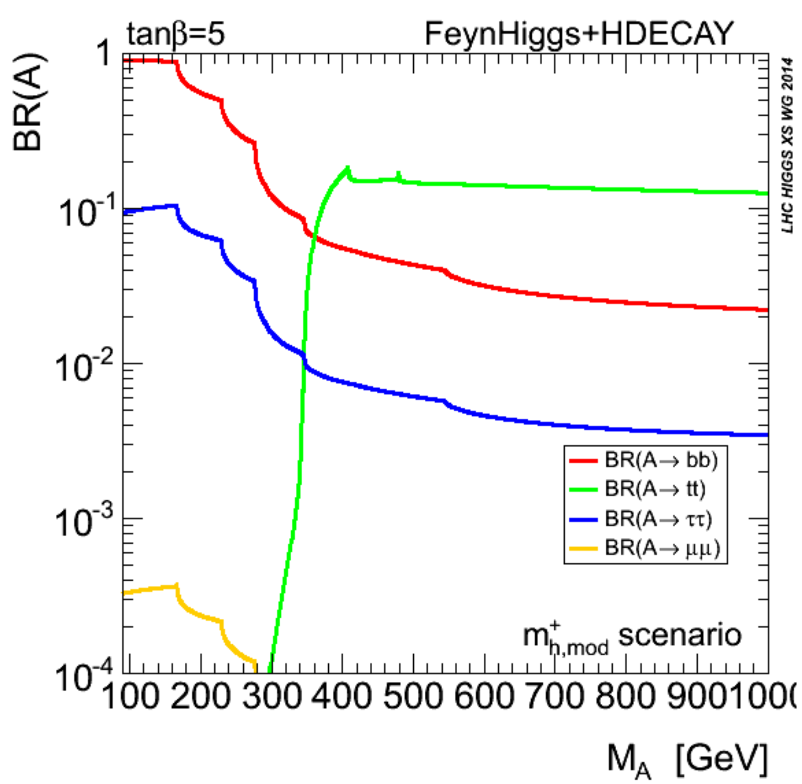
MSSM Neutral Higgs at LHC

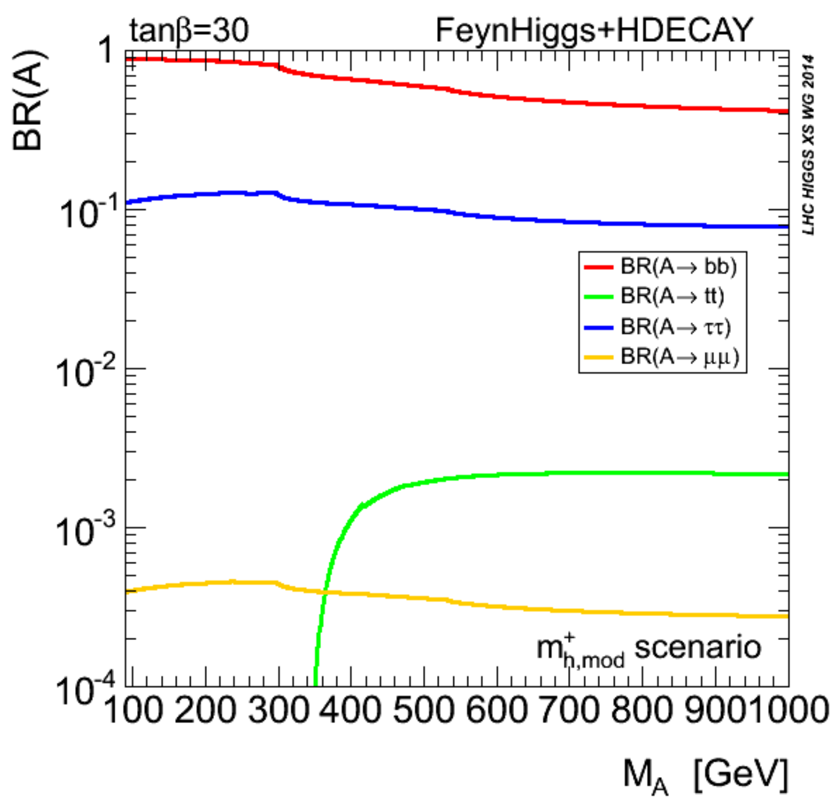
- Neutral Higgs production:

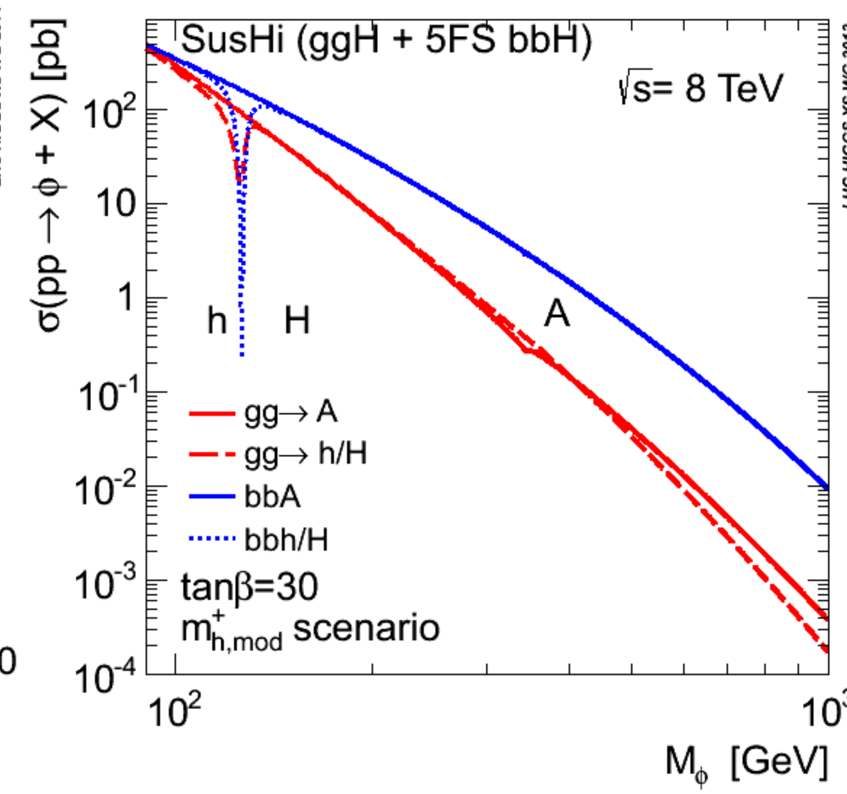


- Dominant decay mode in MSSM: bb and **ττ**







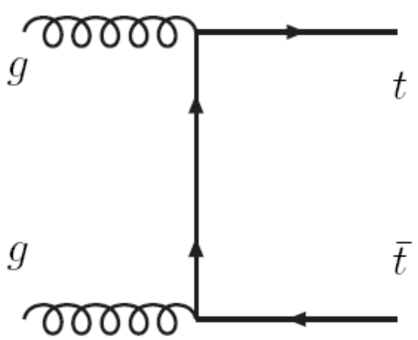


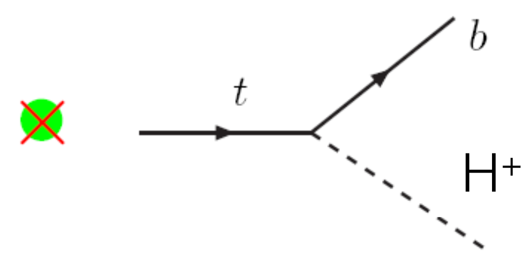
Charged Higgs at LHC

➢ Charged Higgs production and decay :

For $M_{H+} \leq m_{top}$:

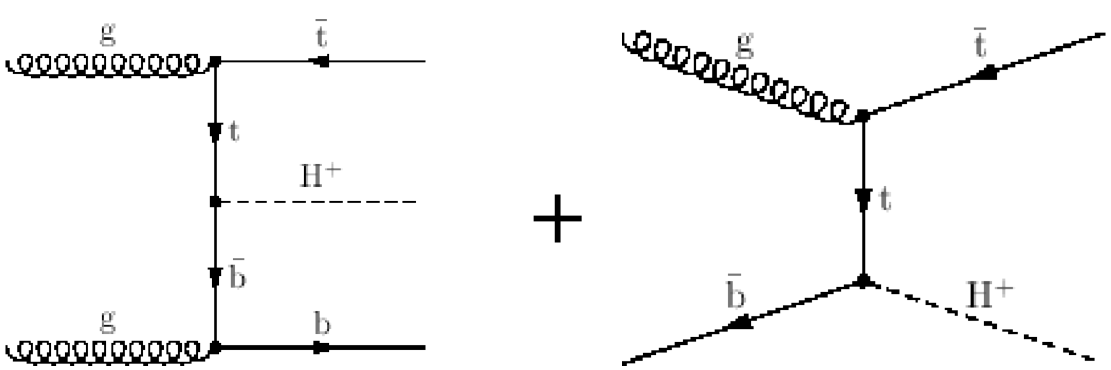
$$pp \to t\bar{t} \to bH^{\pm}\bar{b}W^{\mp} \quad \text{with} \quad t \to bH^{+}$$

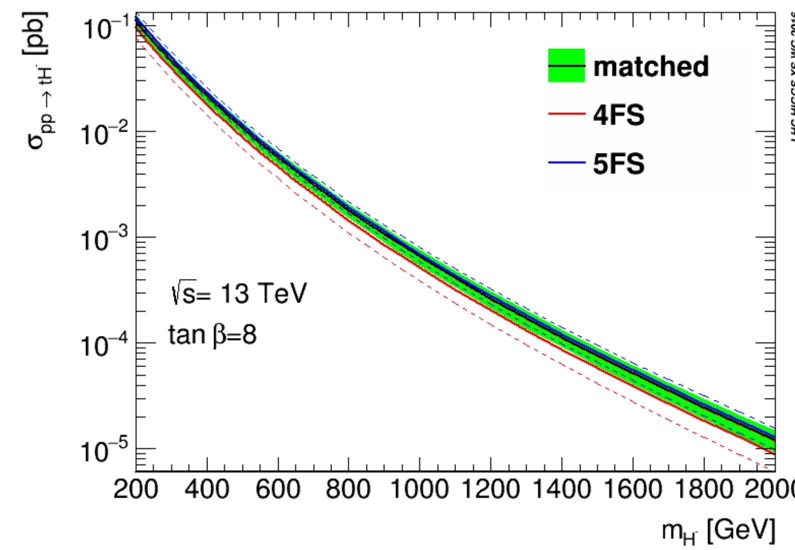


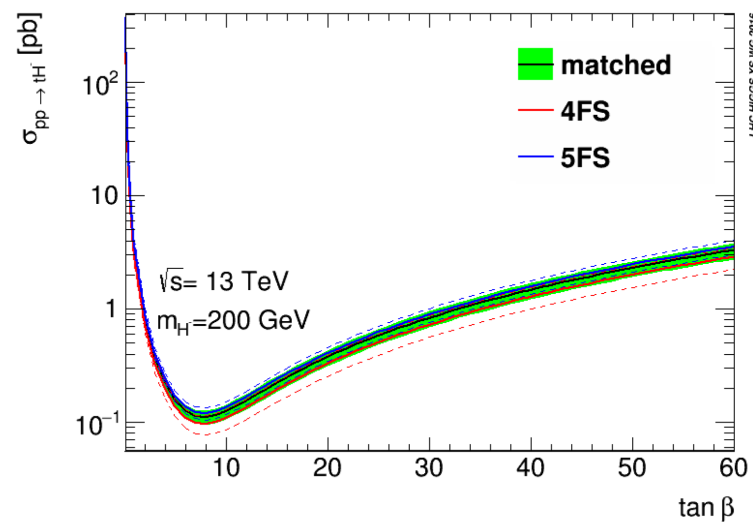


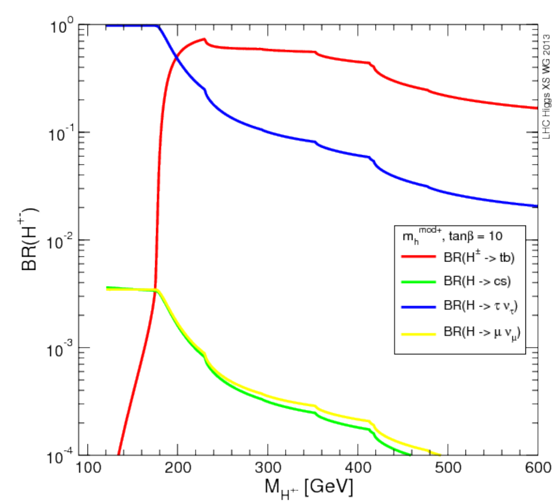
For $M_{H+} \geq m_{top}$:

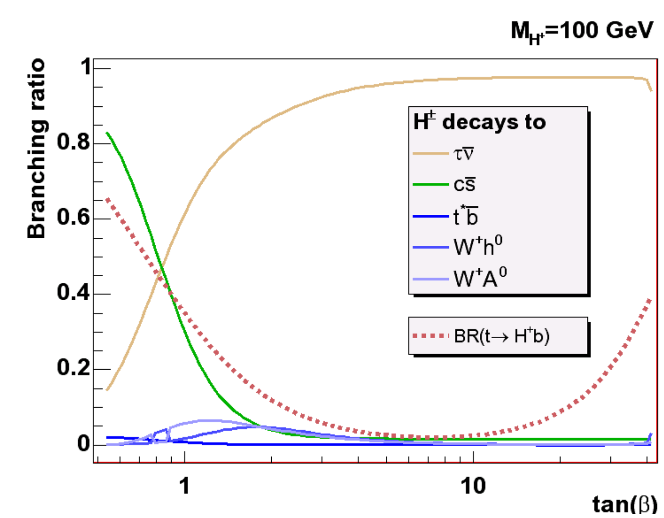
$$pp \to tbH^{\pm}$$











Next-to-MSSM Higgs sector

- Extend the MSSM Higgs sector by one more singlet field:

$$W_{NMSSM} = W_{MSSM} + \lambda S \phi_u \phi_d + \frac{1}{3}\kappa S^3$$

S self-coupling

Higgs relevant part of Superpotential in the MSSM

Coupling of to Higgs doublet fields ϕ_u and ϕ_d

$$m_h^2 \approx m_Z^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta \right) + \Delta m_h^2$$

LO MSSM part to m_h^2

LO NMSSM part to m_h^2

- Solves "μ-problem"
- Additional term to m_h^2 at LO
- Adds more degrees of freedom:

5 + 2 = 7 Higgs bosons:

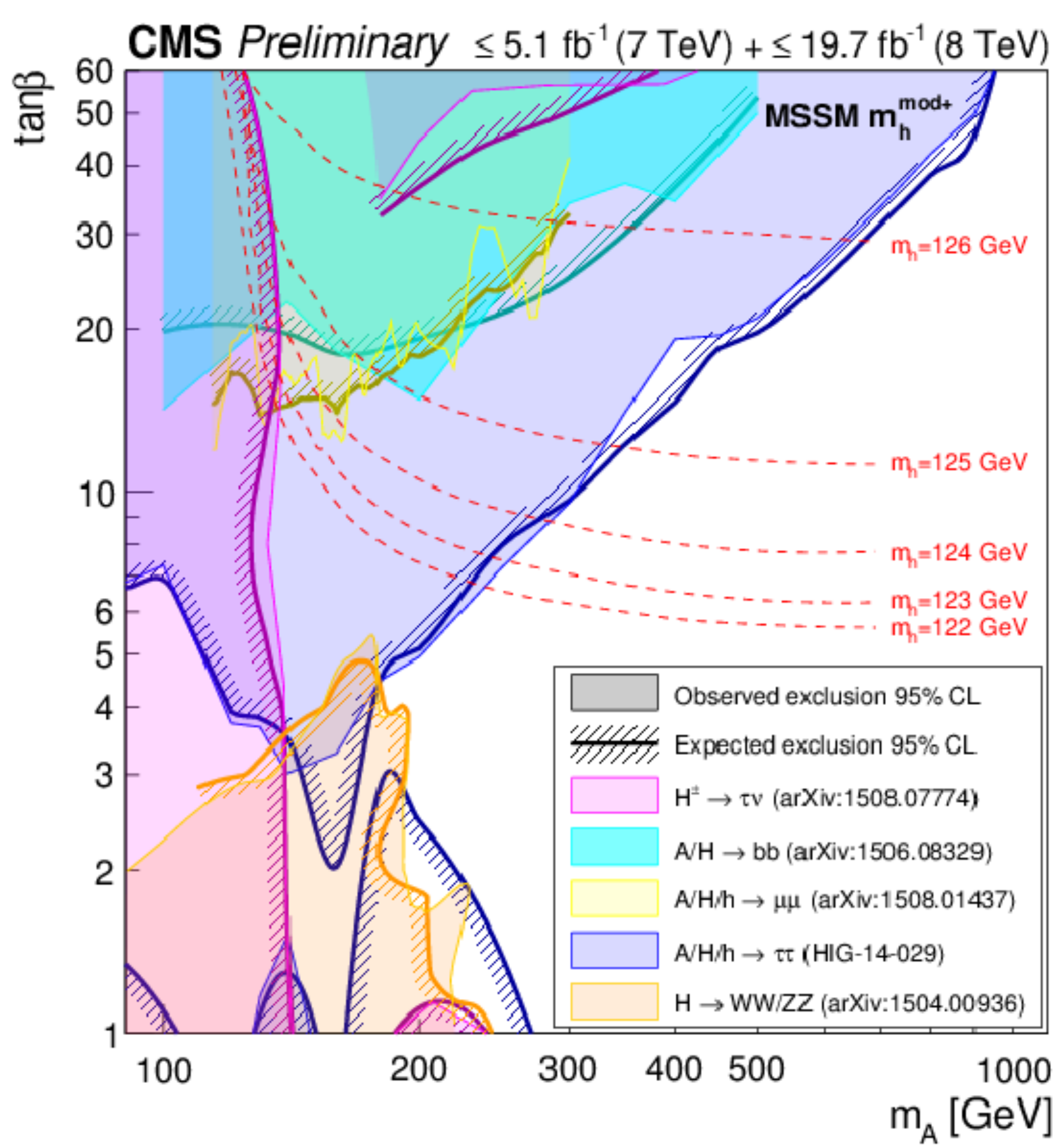
h_1, h_2, H_3, A_2, a_1, $H^\pm$

6 parameters @ LO: tanβ, λ, κ, A_κ, A_λ, μ_{eff}

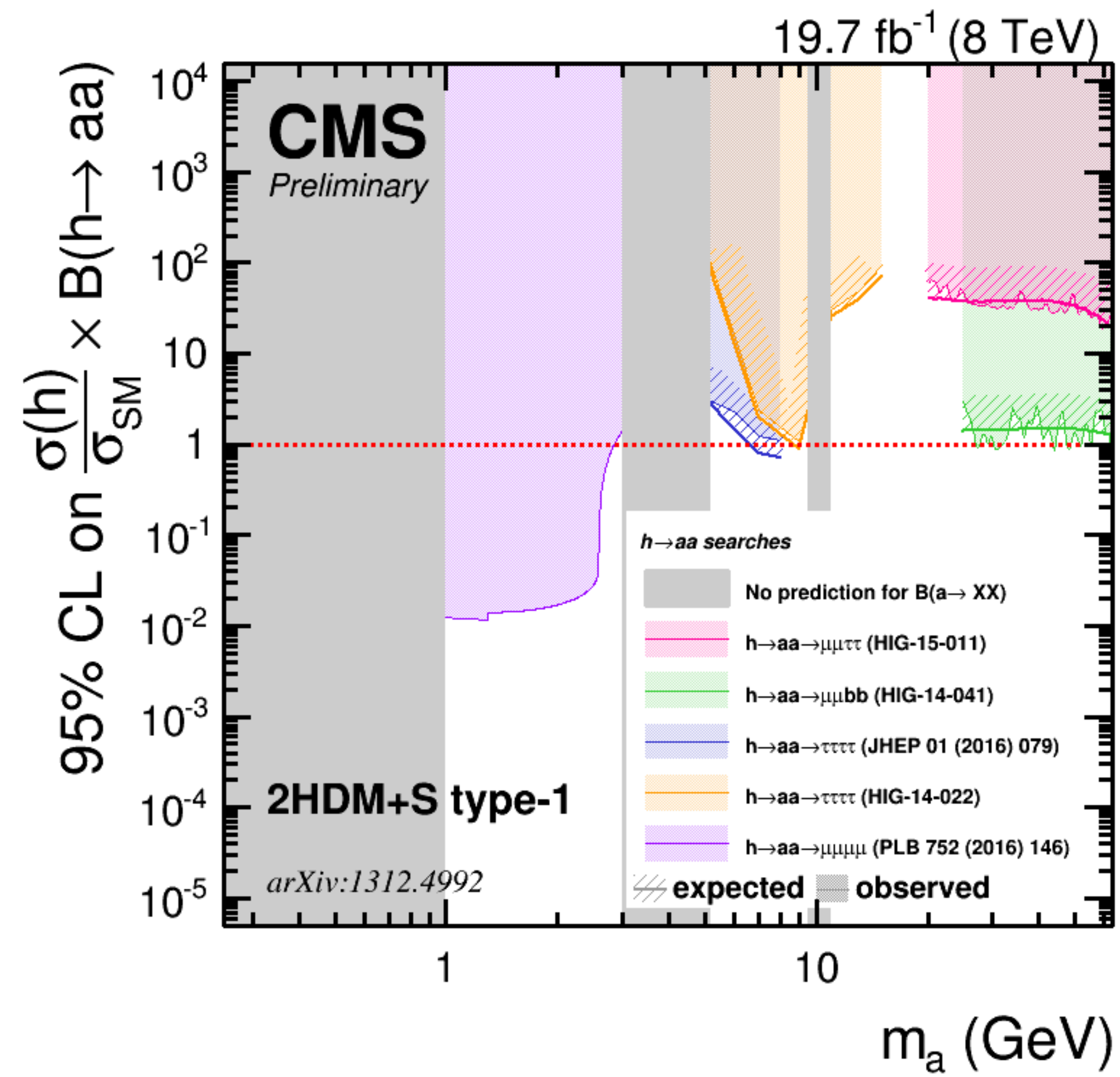
- More complex phenomenology (14 benchmark points in YR-4).
- Higgs bosons with large singlet admixture can become undetectable.

Summary of Run-1 Searches

Searches for heavy Higgs bosons in down-type fermions final states



Searches for *h* → *aa* decays in various final states



- Huge parameter space in MSSM systematically explored, NMSSM exploration ramping up.
- Also more general model independent limits and effective 2HDM(+S) interpretations.

Run-2 Searches

2HDM / MSSM Searches:

$h / H / A \rightarrow$
- bb (JHEP 08 (2018) 113, arXiv:1805.12191)
- $\tau\tau$ (JHEP 01 (2018) 055, arXiv:1803.06553)
- $\mu\mu$

$H^{\pm} \longrightarrow$
- $\tau\nu$ (CMS-PAS-HIG-16-031, PLB 759 (2016), ATLAS-CONF-tbp)
- WZ (PRL 119 (2017) 141802)
- tb (ATLAS-CONF-tbp)
- cb (CMS-HIG-16-030)
- cs (JHEP 12 (2015) 1, EPJC 73 6 (2013) 2465)

NMSSM-like searches:

Low mass $h \rightarrow \gamma\gamma$ (CMS-PAS-HIG-17-013, ATLAS-CONF-2018-025)

$h(125) \longrightarrow aa \longrightarrow$
- (bb)(bb) (arXiv:1806.07355)
- (bb)($\mu\mu$) (arXiv:1807.00539)
- ($\gamma\gamma$)(gg) (PLB 782 (2018) 750)
- ($\mu\mu$)($\mu\mu$) (CMS-PAS-HIG-16-035, arXiv:1812.00380)
- ($\mu\mu$)($\tau\tau$) JHEP 11 (2018) 018 (arXiv:1805.04865)
- (bb)($\tau\tau$) PLB 785 (2018) 462 (arXiv:1805.10191)

MSSM H/A → bb

$pp \to \phi b, \phi \to bb$, φ : h, H, A

Event Selection :

Trigger :
>= 2 b-tagged jets,
$p_T > 100$ GeV, $|\Delta\eta| < 1.6$

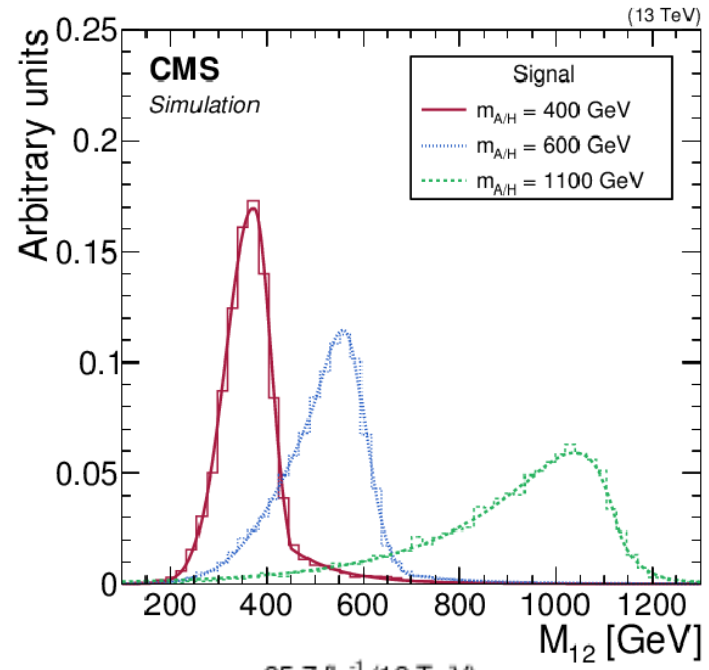
Offline :
>= 3 b-tagged jets
(Thresholds vary according to analysis)

One of the jet contains a muon in semi-leptonic analysis.

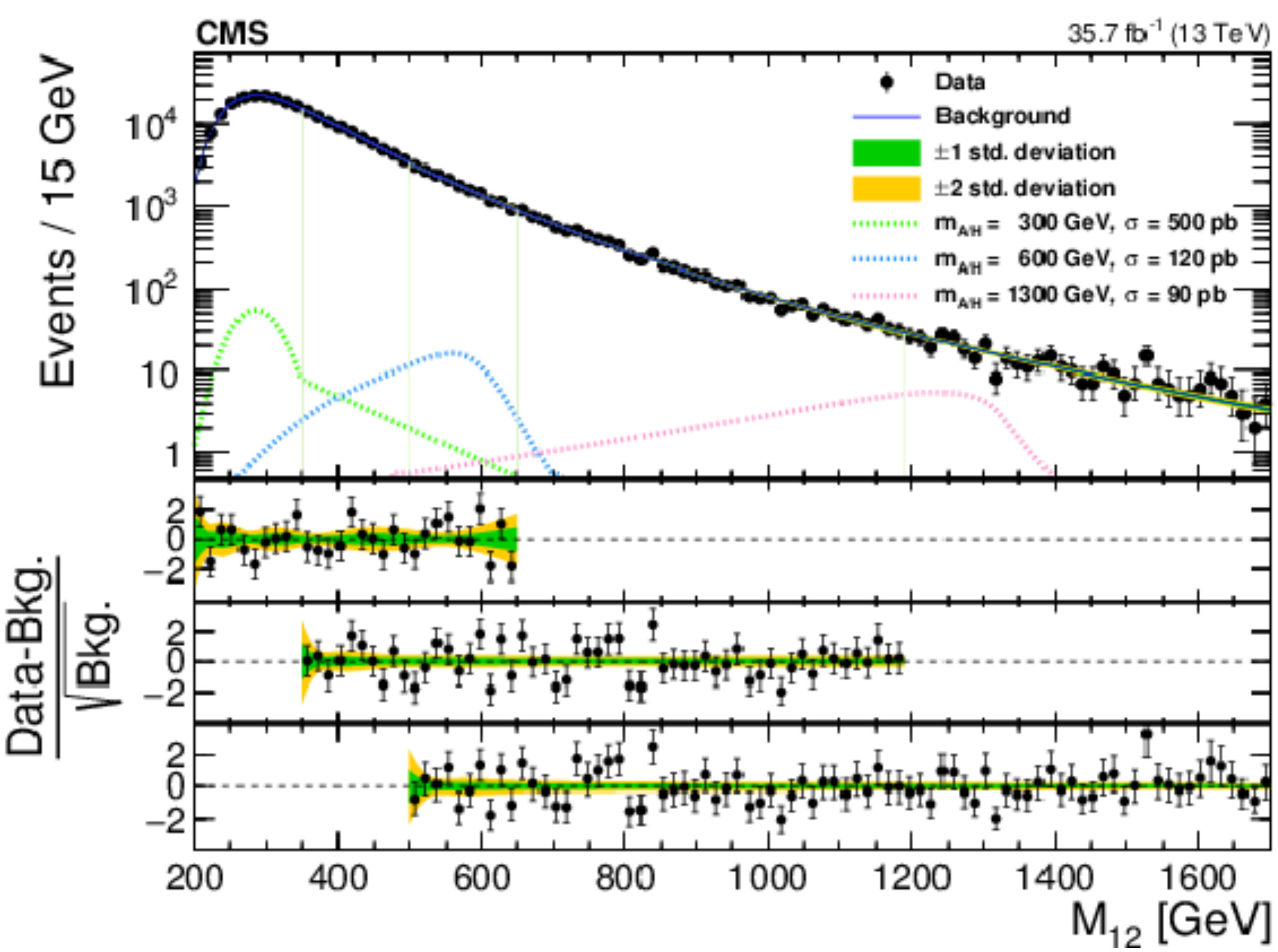
Backgrounds :
Major background : qcd bbbar, Measured from data

Final Discriminant:
Invariant mass of two leading b-jets

The natural width of the mass peak for a mass of 600 GeV is found to be <19% of the full width at half maximum of the reconstructed mass distribution

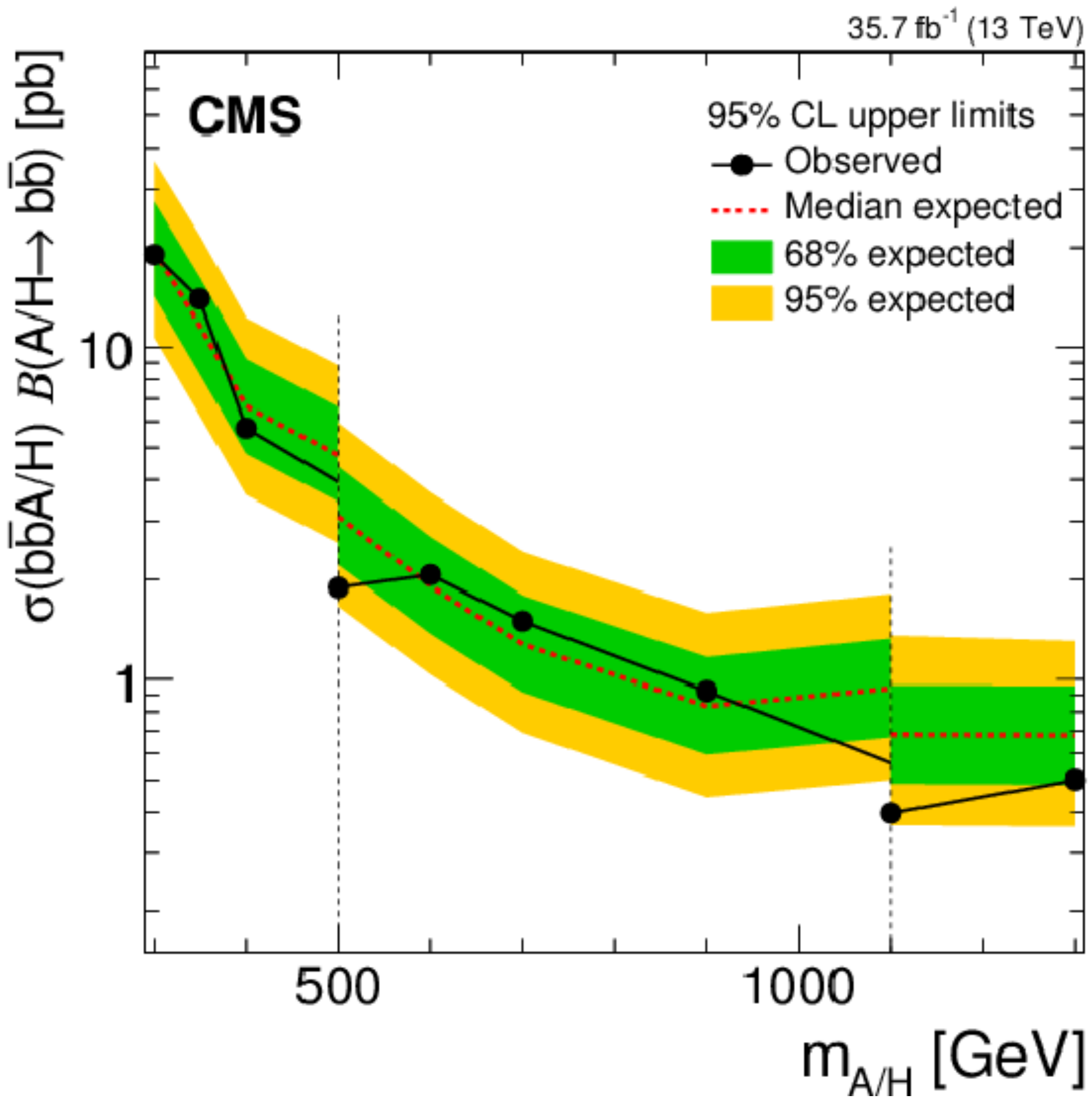


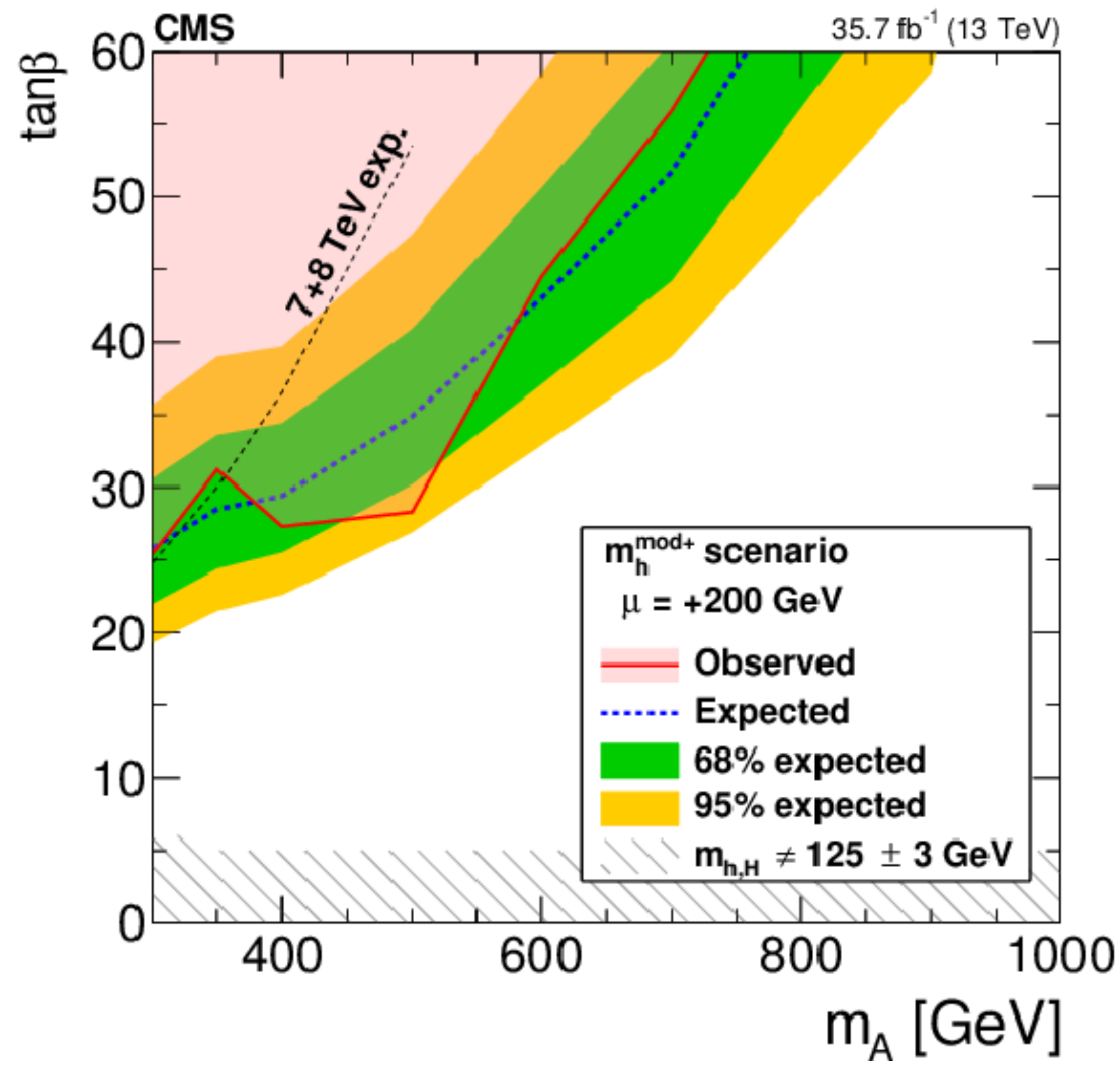
Different shapes of signal and background motivate separation into three (overlapping) categories in



ϕ → bb Exclusion Limits

JHEP 08 (2018) 113





Upper Limit on pp → φb, φ→bb production by fitting observed M_{12} distribution.

Interpretations provided in many MSSM as well as 2HDM scenarios

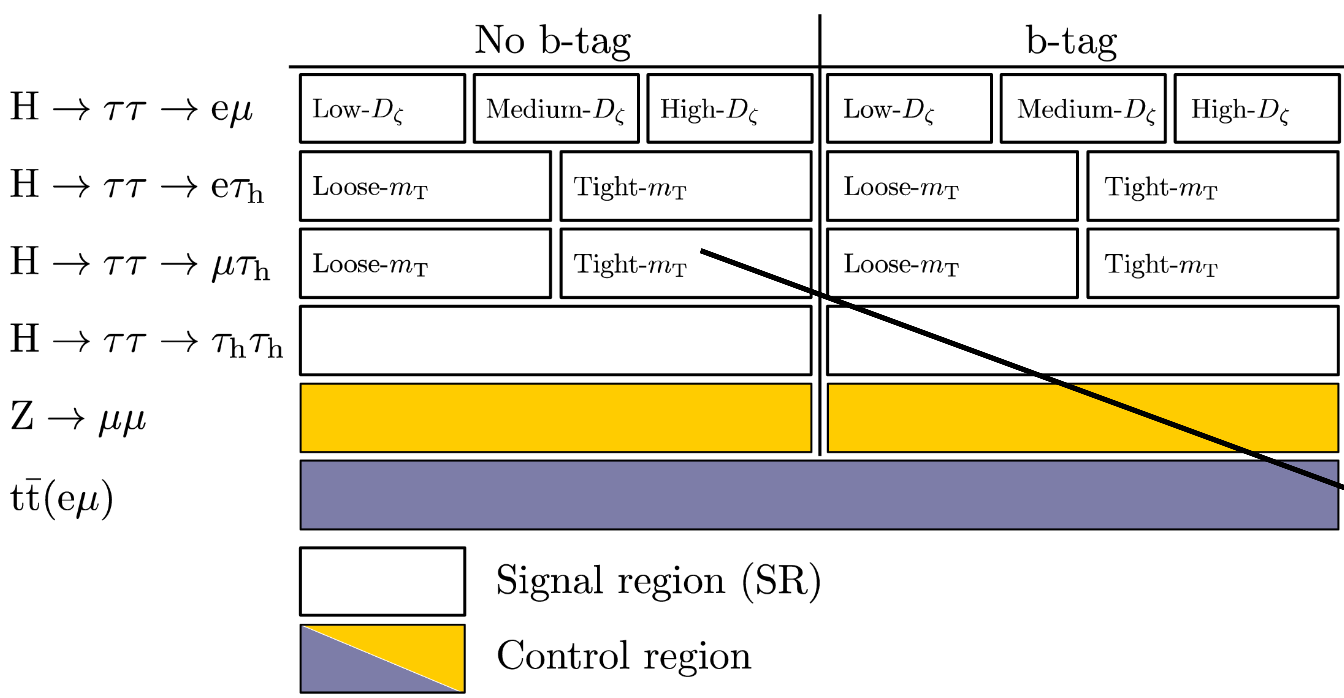
MSSM Higgs → ττ

pp → ϕ, ϕ → ττ , φ : h, H, A

Flagship analysis for MSSM Higgs search at LHC

- Enhanced coupling
- Better separation of signal from backgrounds compared to bb channel

Event categories exploit topological and kinematic peculiarities of MSSM motivated production

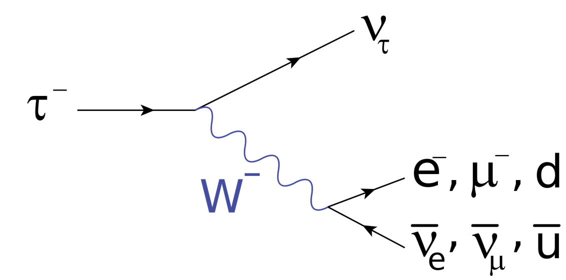


Signal extraction based on

$$m_T^{tot} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{miss}) + m_T^2(p_T^{\tau_2}, p_T^{miss})},$$

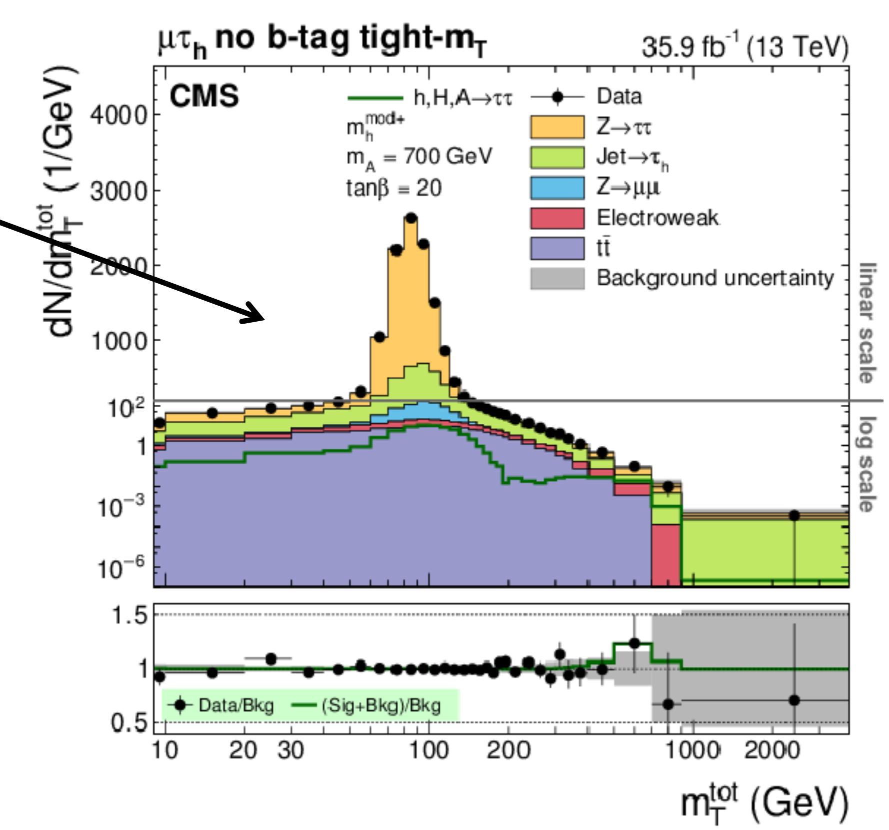
Analysis performed in 4 final states :

$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$



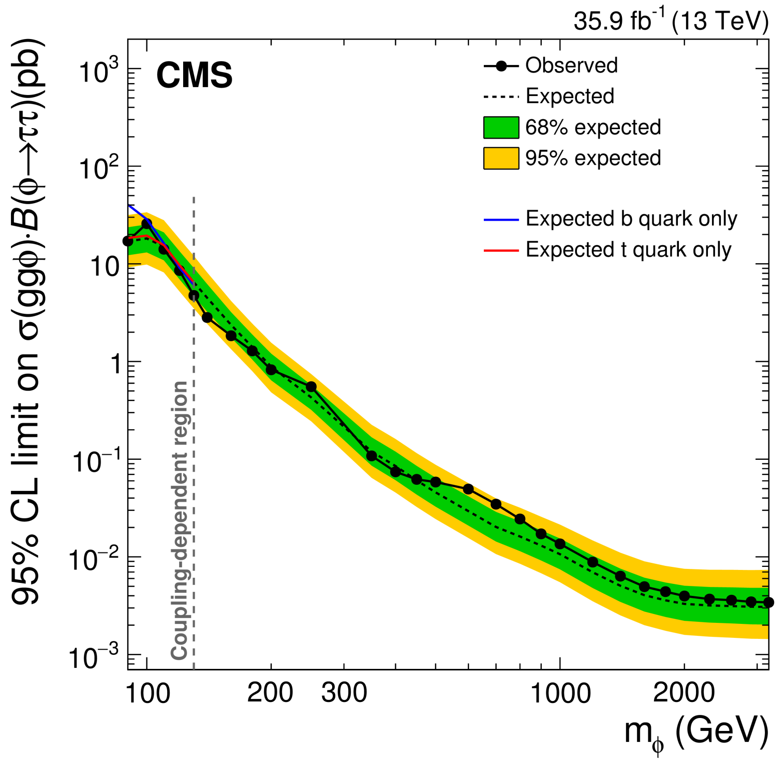
Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$		17.8
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^-\nu_\tau$		11.5
$\tau^- \to h^-\pi^0\nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^-\pi^0\pi^0\nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^-h^+h^-\nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$		4.8
Other		3.3

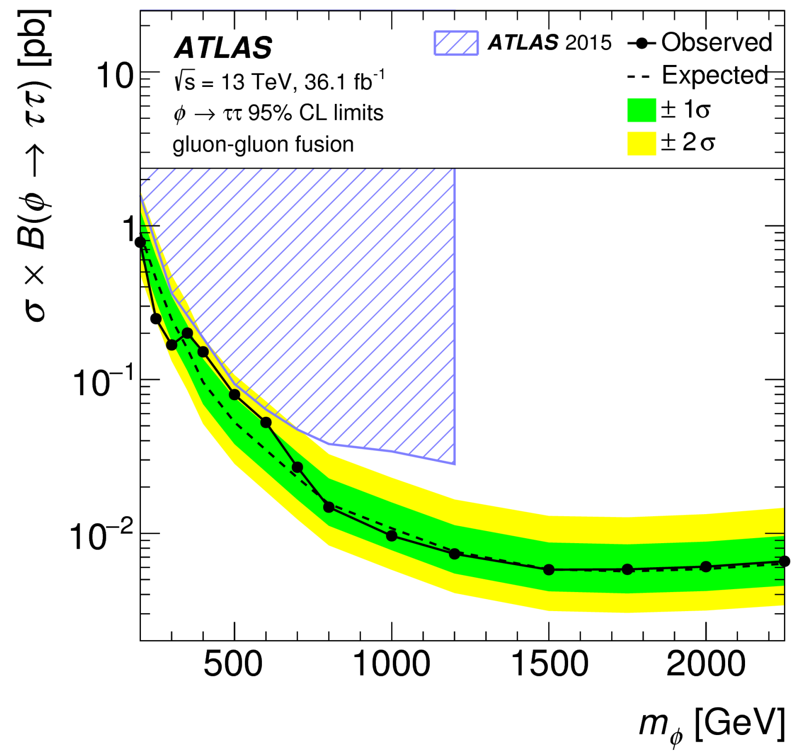
~90% of all ττ final states contain at least one τ_h



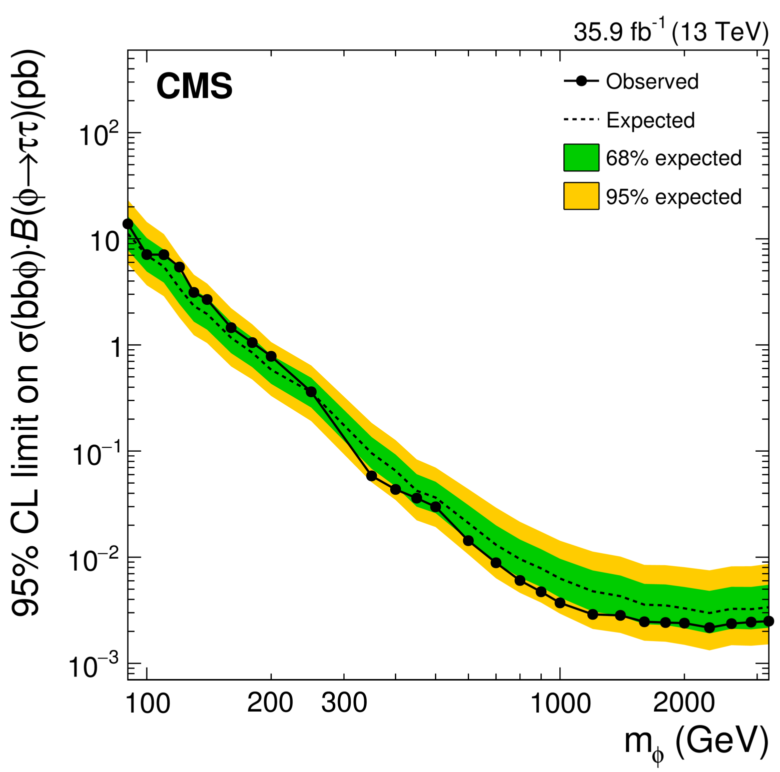
φ → ττ Exclusion Limit

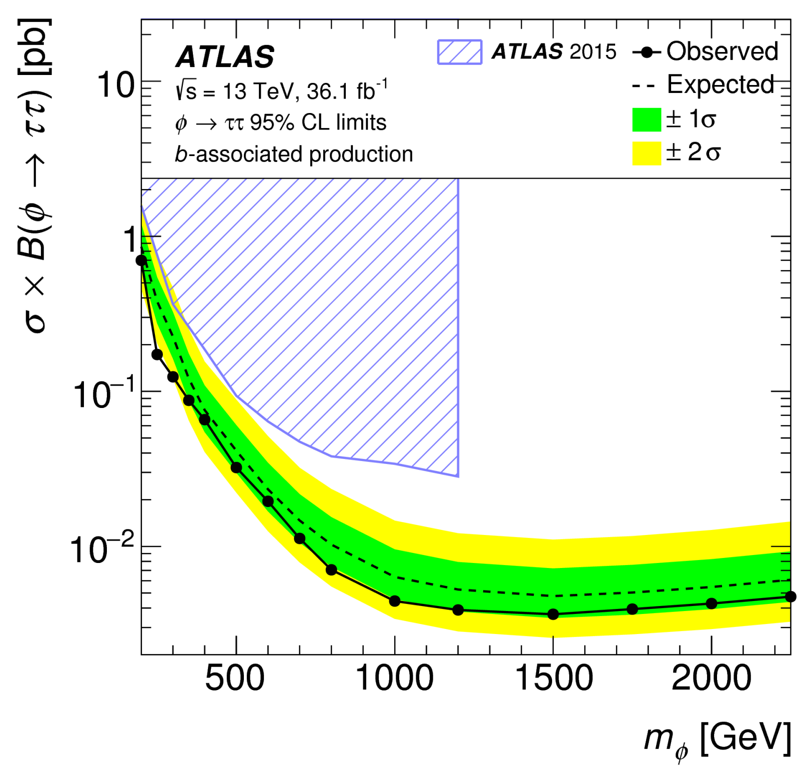
b associated production



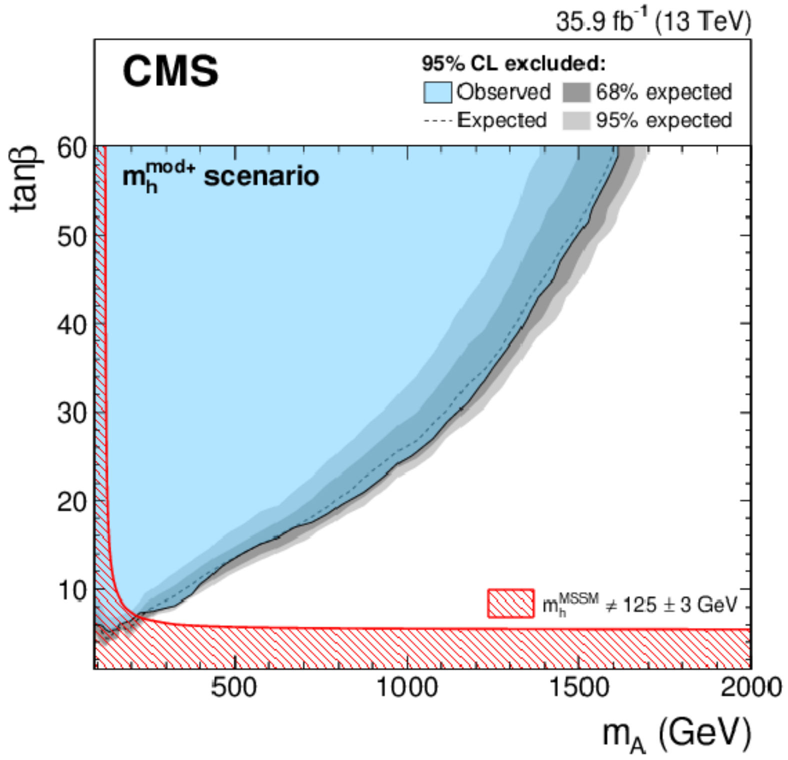


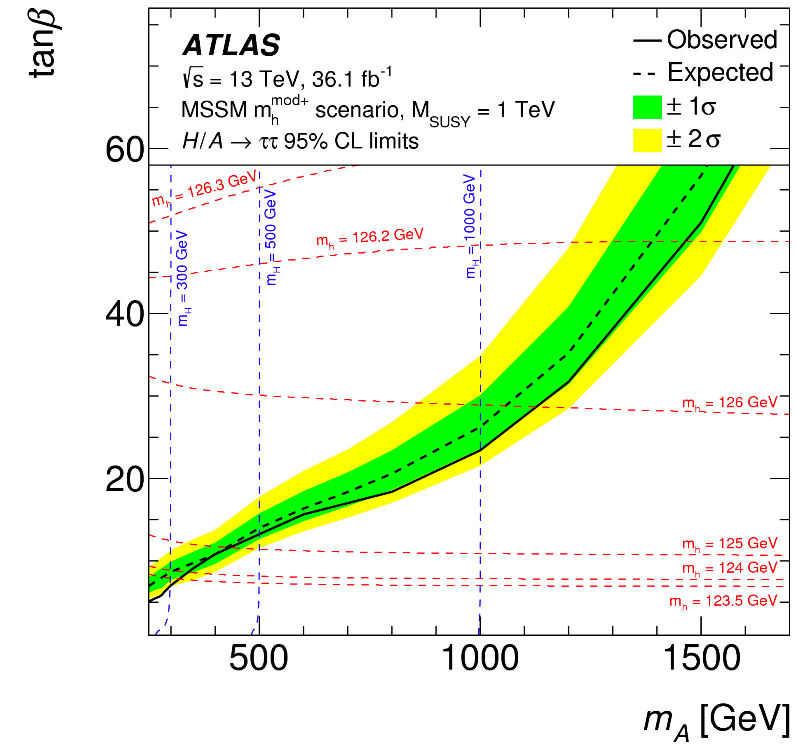
gluon fusion





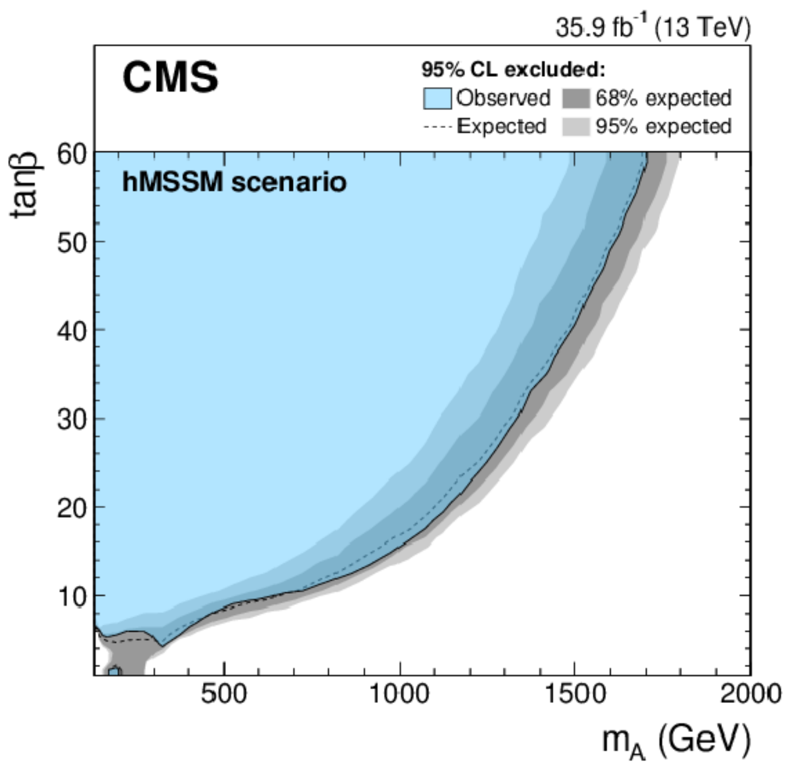
MSSM Interpretation

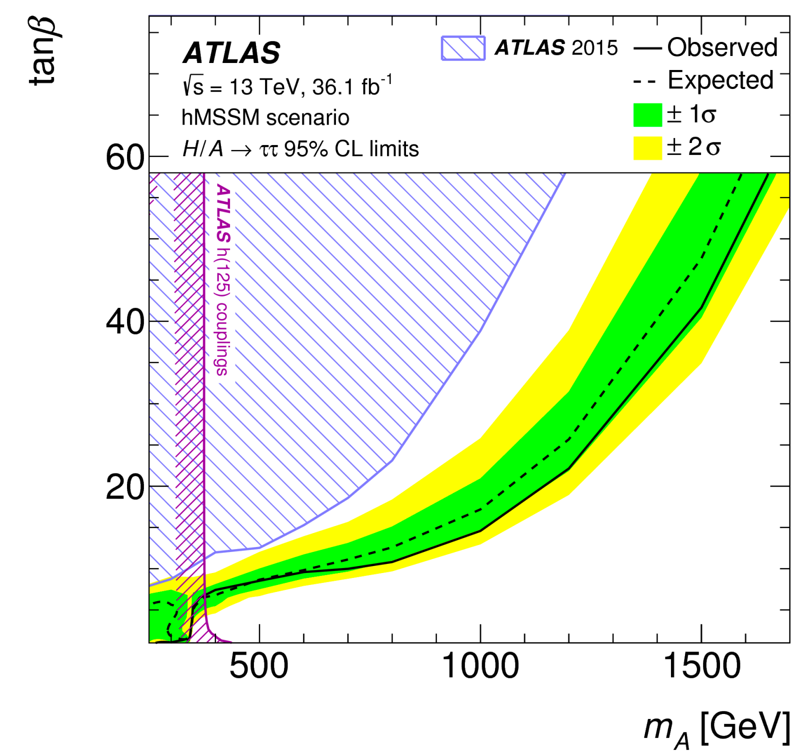




m_h^{mod+} scenario

Large part of parameter space already excluded
M_A > 1 TeV for tanβ > 20





hMSSM scenario

Charged Higgs

Search Channels:

- $H^{\pm} \rightarrow \tau\nu$ (Low & High mass) →
  JHEP 09 (2018) 139, CMS-PAS-HIG-18-014

CMS: Reconstruct $\tau\nu$ transverse mass in both leptonic and hadronic τ decays

$$m_{\mathrm{T}}(\tau_{\mathrm{h}}/\ell) = \sqrt{2 p_{\mathrm{T}}(\tau_{\mathrm{h}}/\ell) p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}(\tau_{\mathrm{h}}/\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))}.$$

ATLAS: BDT distributions in 5 bins of m_{H+} in $\tau+\ell$ channel

- $H^{\pm} \rightarrow$ tb (High mass) →
  JHEP 11 (2018) 085

Lepton(s) + jets final states
Categorize in number of b-Tagged jets
Extract signal from BDT discriminant

- $H^{\pm} \rightarrow$ cs (Low mass)
  JHEP 12 (2015) 1
- $H^{\pm} \rightarrow$ cb (Low mass)
  CMS-HIG-16-030

→ Reconstruct full tt events with kinematic fit, use invariant mass of two jets assigned to $H^{\pm}$ as the final discriminant

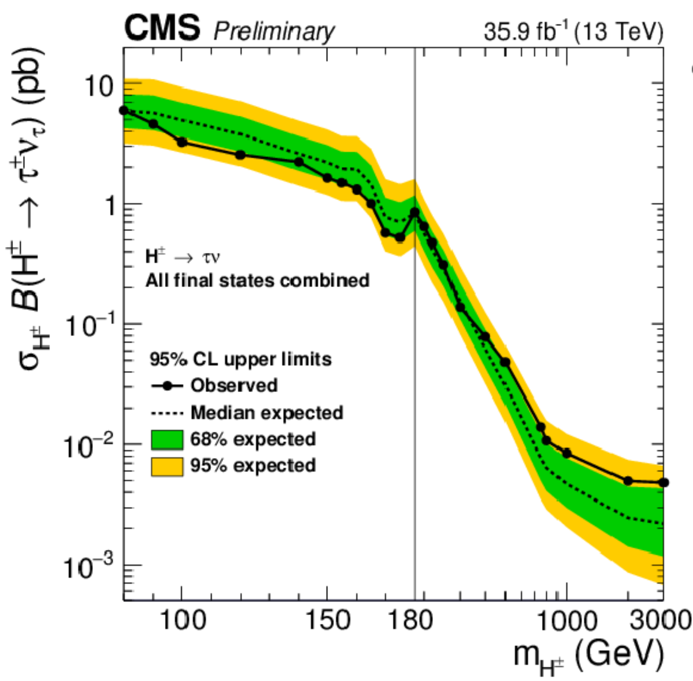
- $H^{\pm} \rightarrow$ WZ (High mass) →
  PRL 119 (2017) 141802

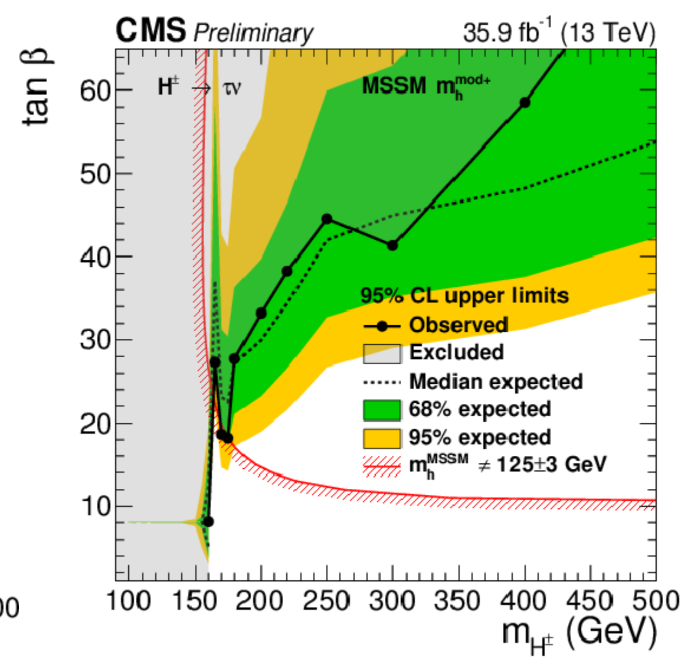
VBF $H^{\pm}$ production predicted by Georgi Machacek model
Events selected requiring 3 leptons from decay of W and Z bosons
m_T(WZ) used as the final discriminant to extract signal

Charged Higgs Results

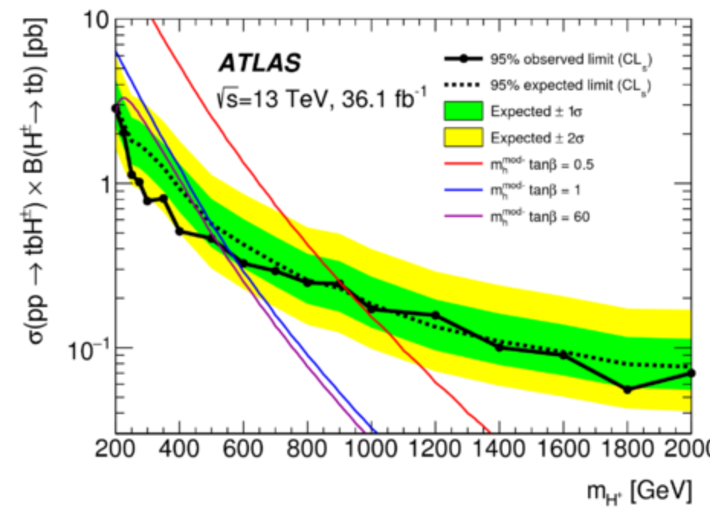
$H^{\pm} \rightarrow \tau\nu$ (Low & High mass)

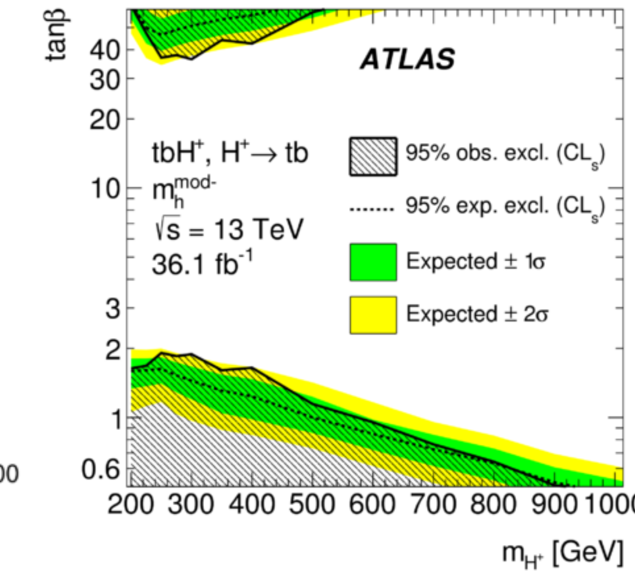
JHEP 09 (2018) 139, CMS-PAS-HIG-18-014

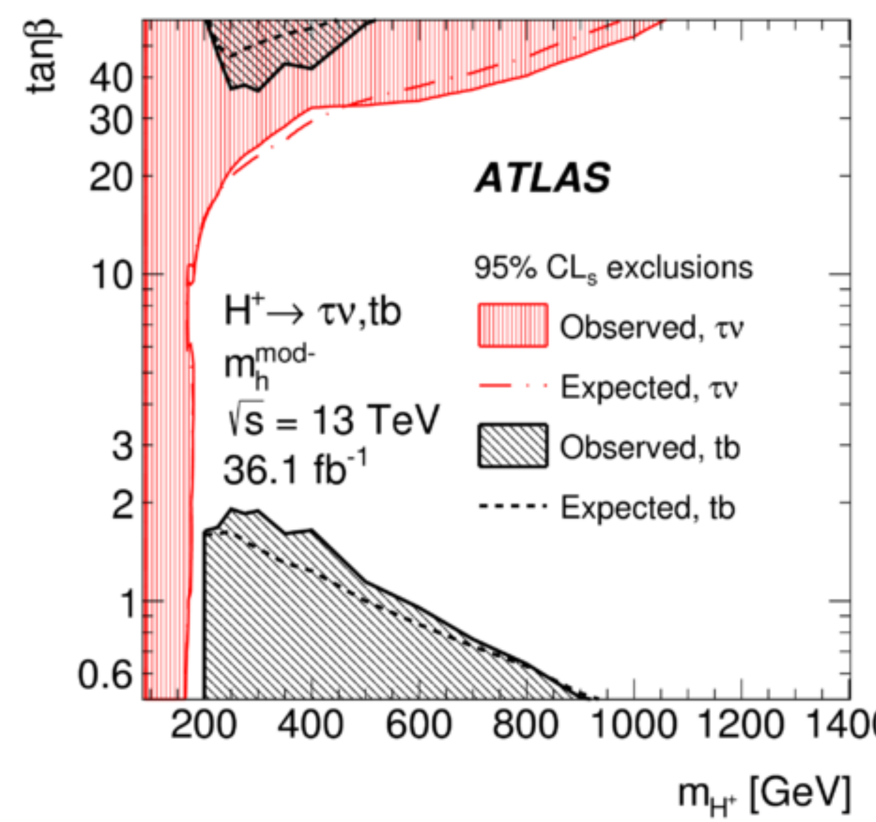




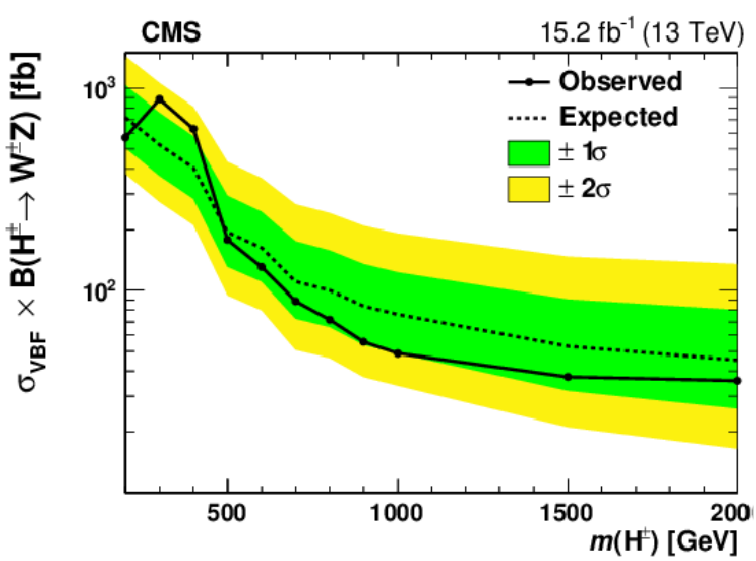
$H^{\pm} \rightarrow tb$ (High mass) (JHEP 11 (2018) 085)

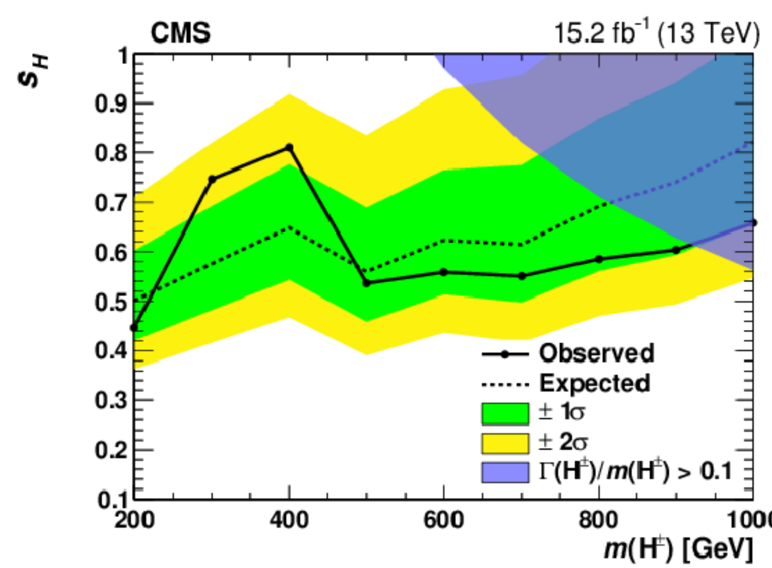






$H^{\pm} \rightarrow WZ$ (High mass) (PRL 119 (2017) 141802)





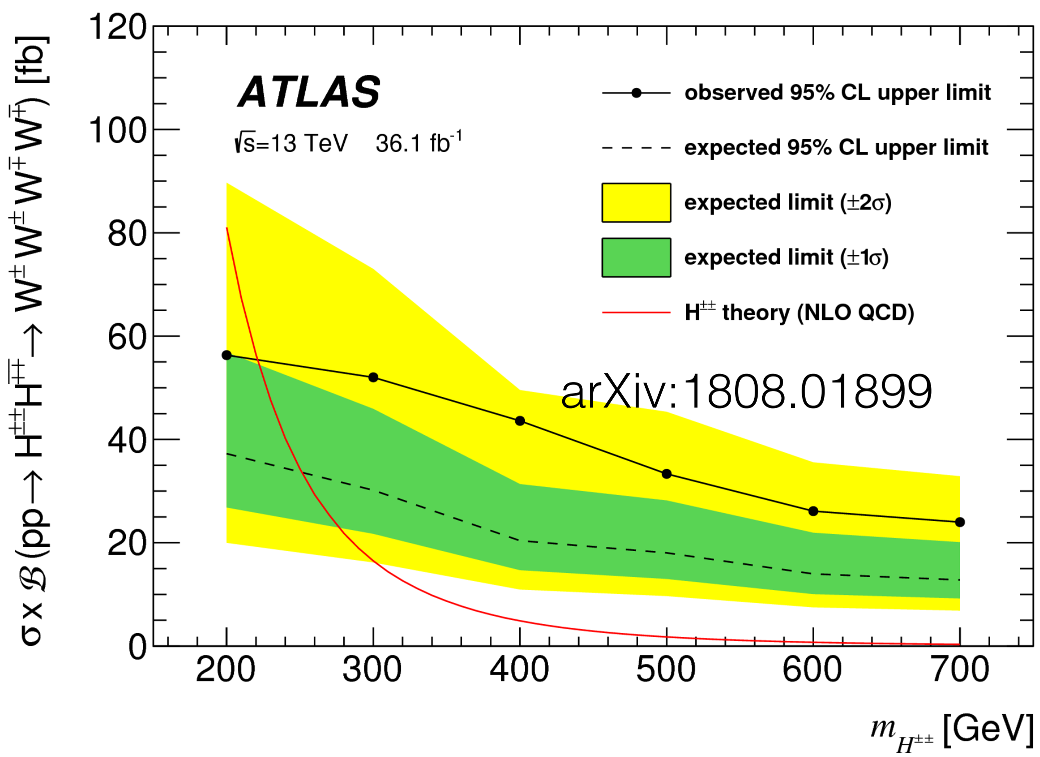
PRL 119 (2017) 141802

Doubly Charged Higgs boson

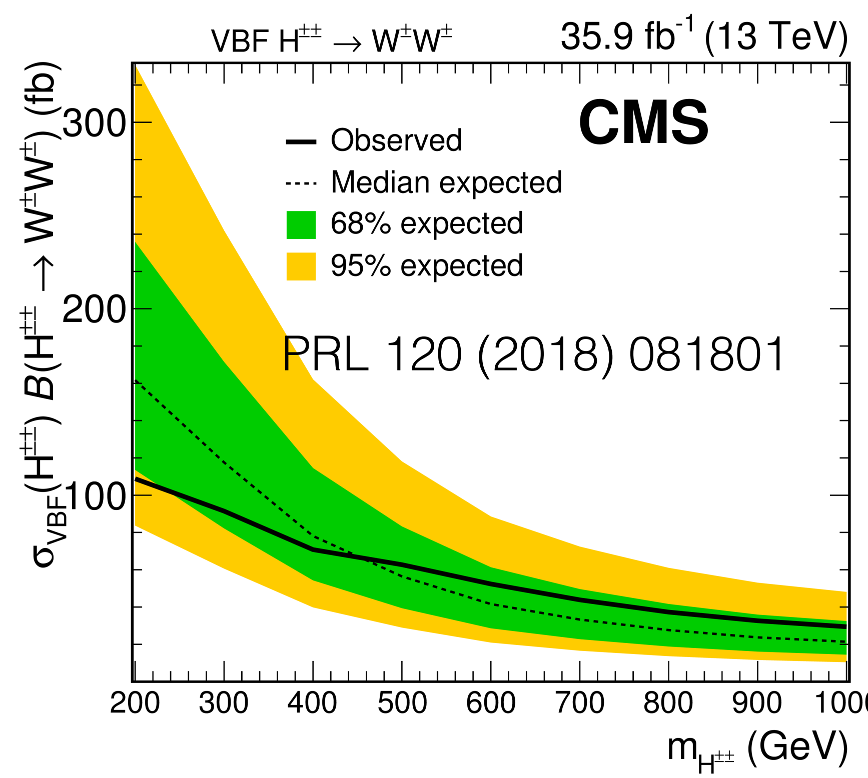
Higgs Triplet Models:

- Addition of scalar triplet(s)
  - **Georgi-Machacek model**: Add one real and one complex SU(2) triplet
- H^+ phenomenology different from the doublet models
  - **H^+WZ couplings** at tree level
  - Double-charged Higgs bosons (H^{++})

- ATLAS considered pair production: pp → $H^{++}H^{--}$
- CMS considered VBF production: pp → qqH^{++}
- Decay pre-dominantly to EWK bosons $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$
- Signal Categories: $2\ell^{ss}$, 3ℓ, 4ℓ
- Additional selections on p_T^{miss}, nJets, b-Jet veto etc..
- Signal Extraction:
  - ATLAS did a rectangular cut optimization using TMVA
  - CMS used simultaneous fit to ($m_{\ell\ell}$,m_{jj}) 2D distribution and m_{jj} in WZ control region

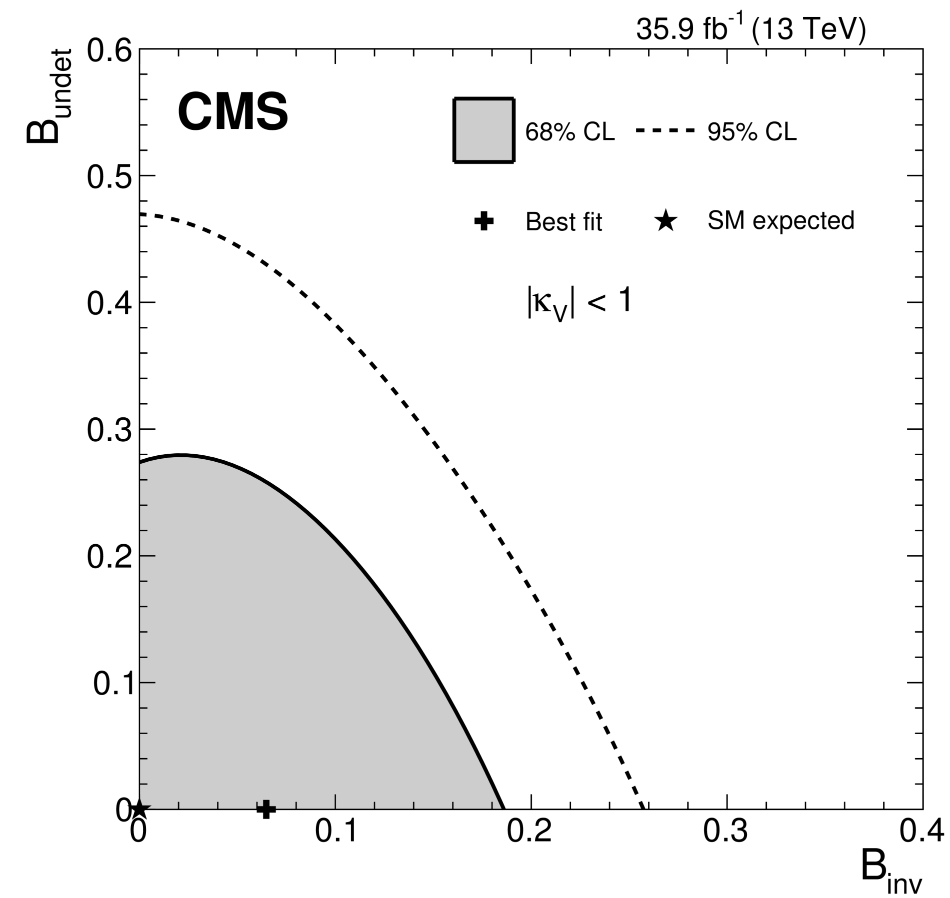


CMS result is lso interpreted in Georgi-Machacek model



h(125) → aa

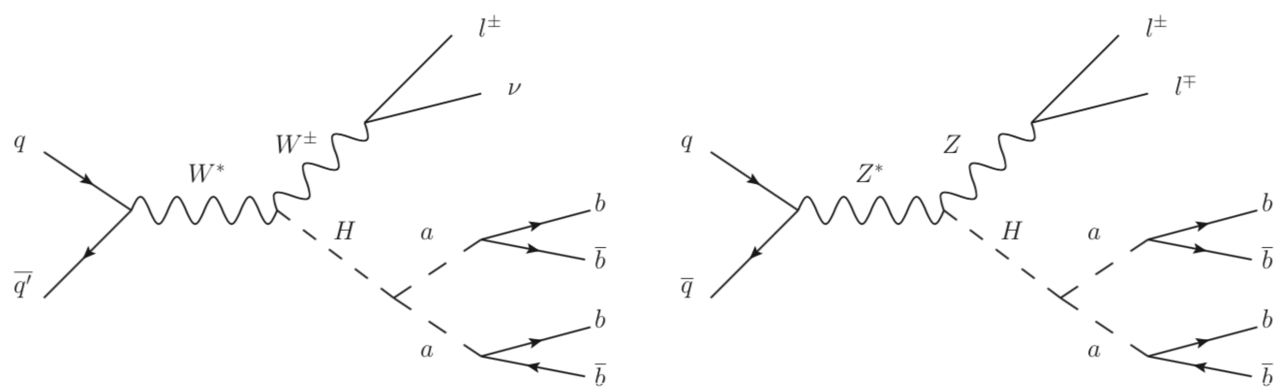
- Constraint on *BR*(h → BSM) from fits for couplings still allows for up to 20-30% decays into unobserved particles.
- h(125) → aa decay mode possible in NMSSM scenarios, where "a" stands for just a Higgs boson that could be scalar or pseudo-scalar
- Many final states analyzed for varying m_a values, up to $m_a \leq m_h/2$



- The decay products of "a" boson boosted for low m_a values:
  - Challenging final states
  - Special care needed to reconstruct and identify leptons
- Results are presented in terms of upper limits on cross section times branching fractions

h(125) → aa → 4b

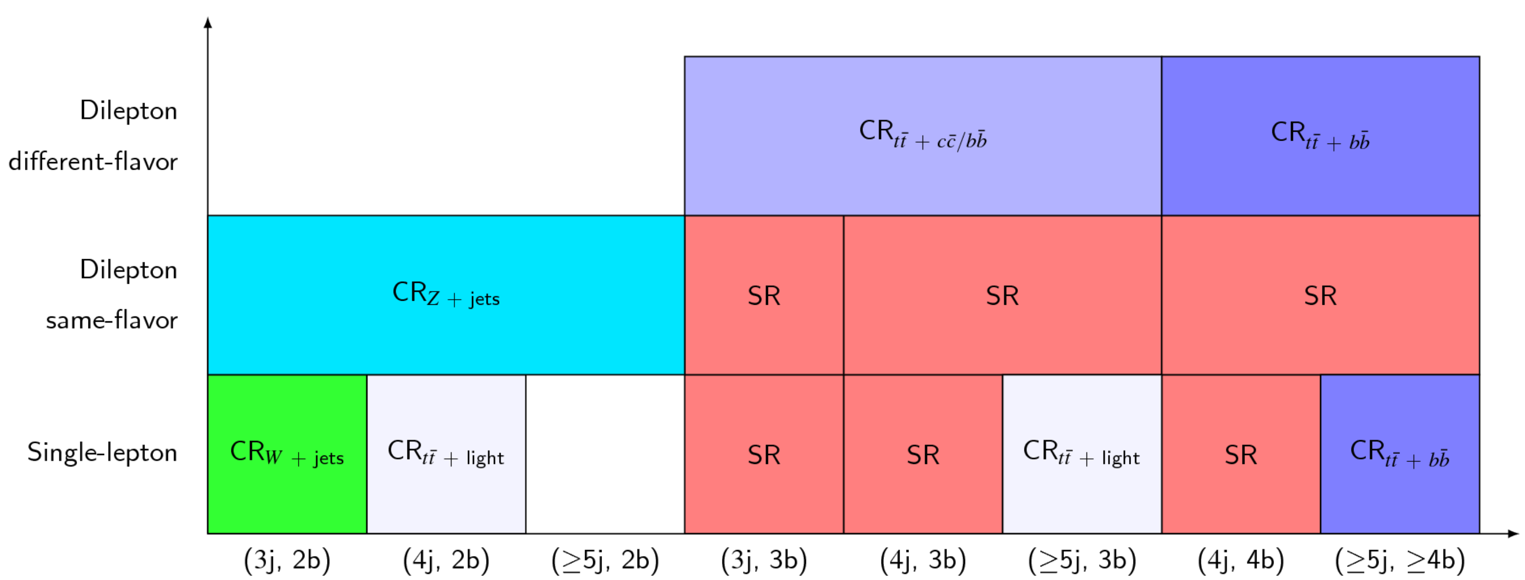
h(125) production in association with a vector boson, where W/Z decays to leptons



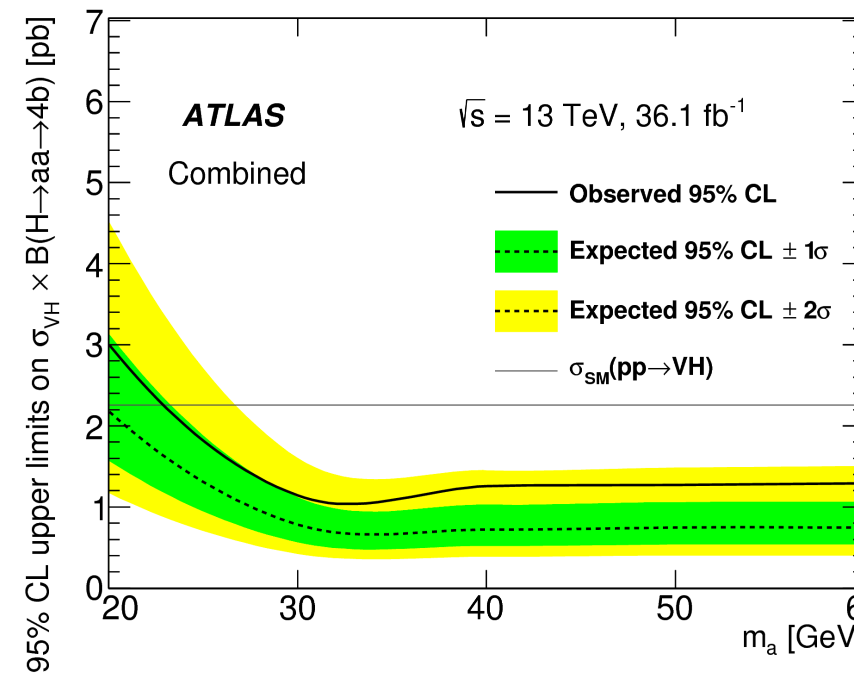
Search mass region: 20 GeV ≤ m_a ≤ 60 GeV

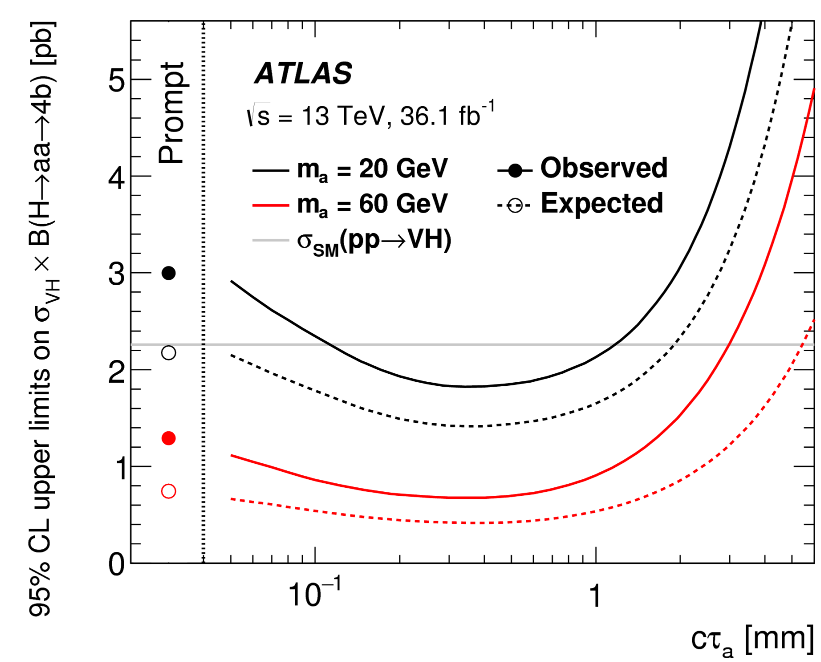
BDT discriminant to extract signal

Event Categories



Upper limits are obtained on σ x BR as function of mass and lifetime

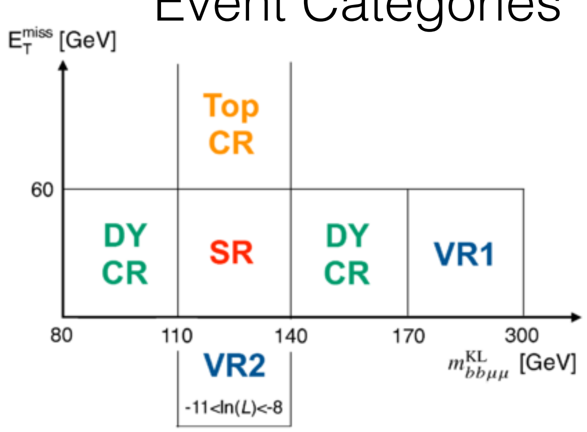




h(125) → aa → bbμμ

- For $m_a \geq 10$ GeV this means the "a" boson decays preferentially into bb
- However, in models with enhanced lepton couplings such as the Type-III 2HDM, the a → μμ branching ratio can also be relatively large
- Presence of a clean dimuon resonance provides a distinctive signature
  - Used for triggering and precision mass reconstruction
  - Helps to suppress background
- A kinematic-likelihood (KL) fit exploiting the symmetry of H → aa decays is performed
  - Tests the compatibility of an event with the $m_{bb} \approx m_{\mu\mu}$ hypothesis
  - Improve the $m_{bb\mu\mu}$ resolution in signal events

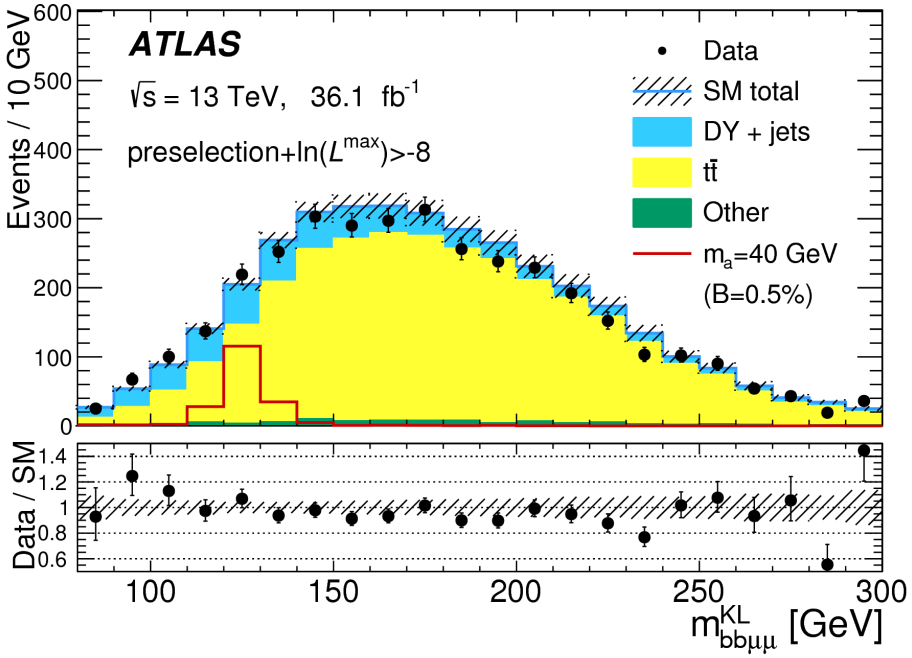
Event Categories

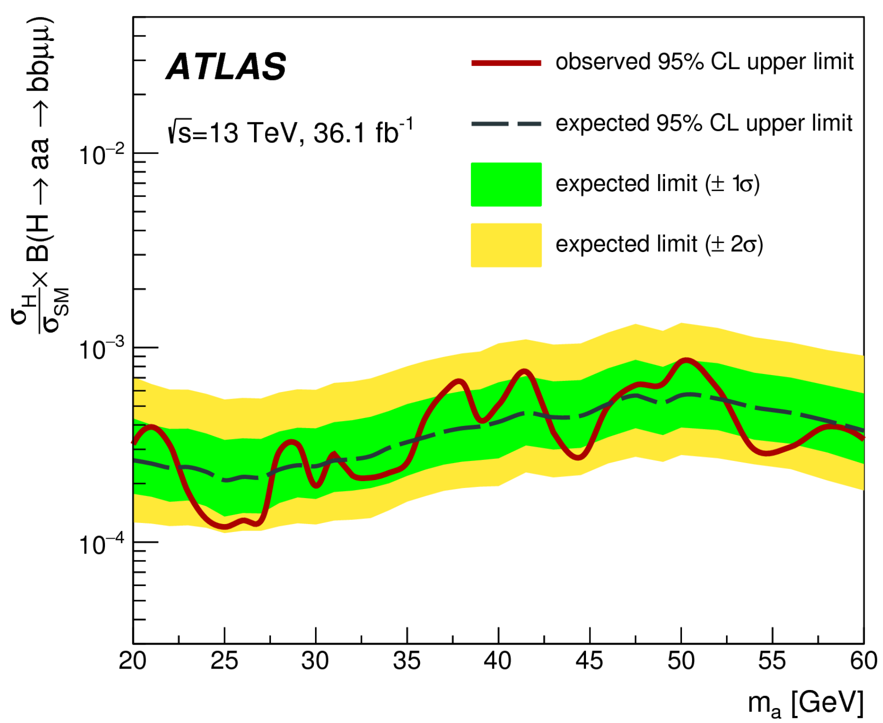


Background normalizations are obtained from Control regions and validated in Validation regions

Search mass region: 20 GeV ≤ m_a ≤ 60 GeV

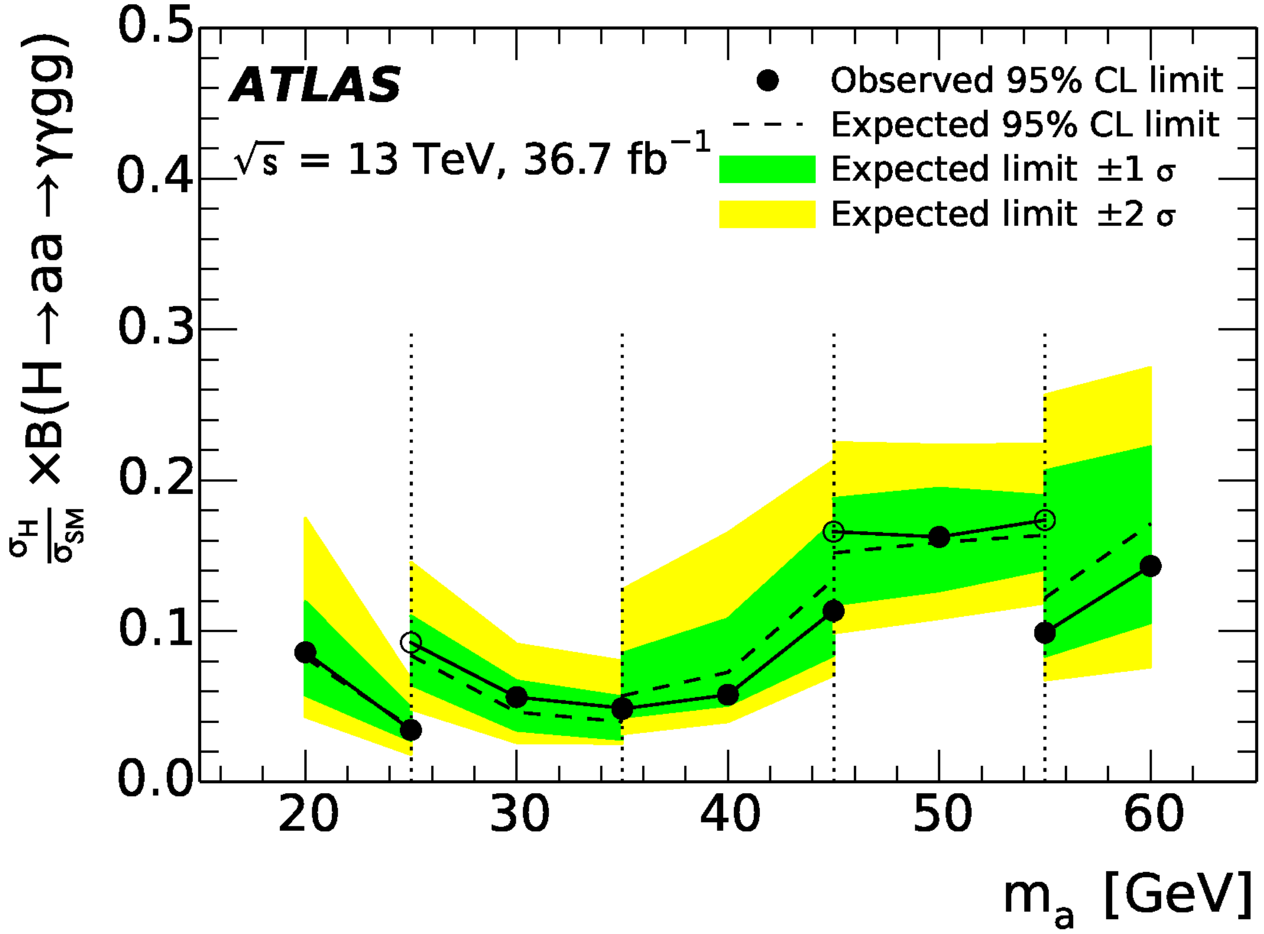
Upper limits are obtained on σ x BR as function of mass





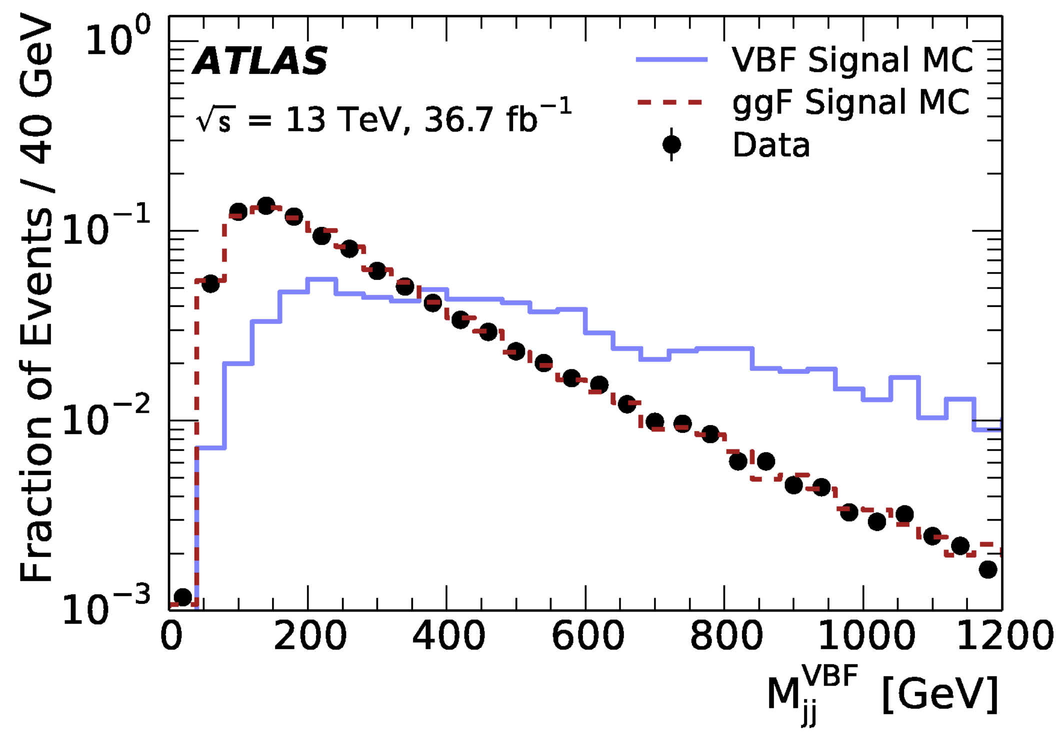
VBF h(125) → aa →γγgg

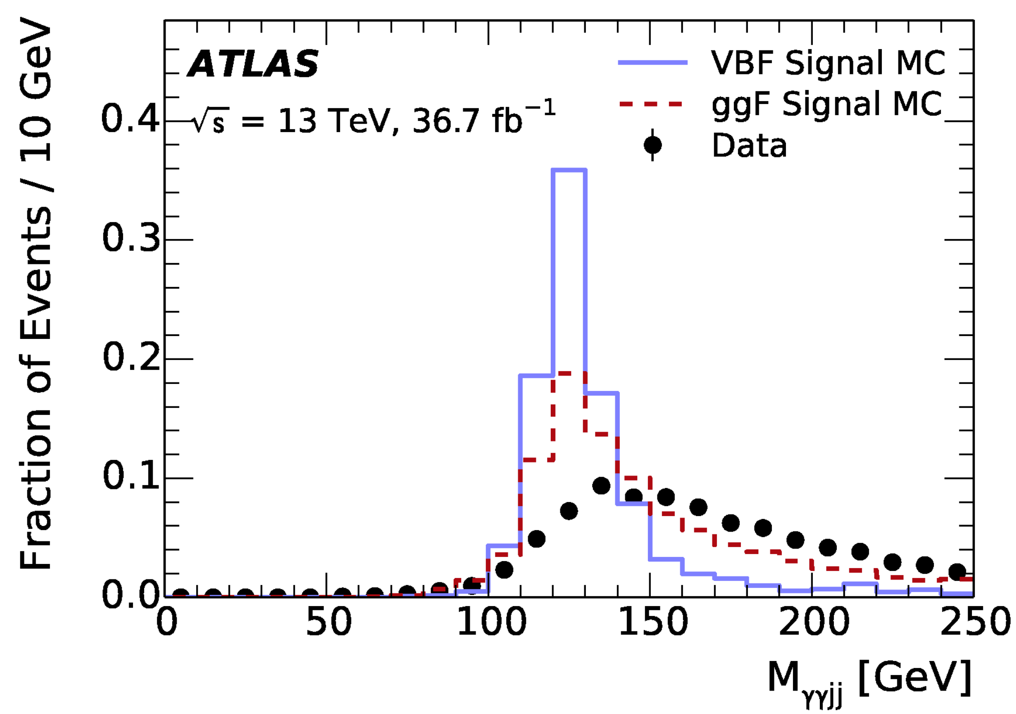
- Much larger branching fractions than h → aa → 4γ, assuming same ratio of photon and gluon couplings SM h and "a" bosons.
- VBF production mode to suppress overwhelming γγ+multi-jet background



Search mass region: 20 GeV ≤ m_a ≤ 60 GeV

Upper limits are obtained on σ x BR as function of mass



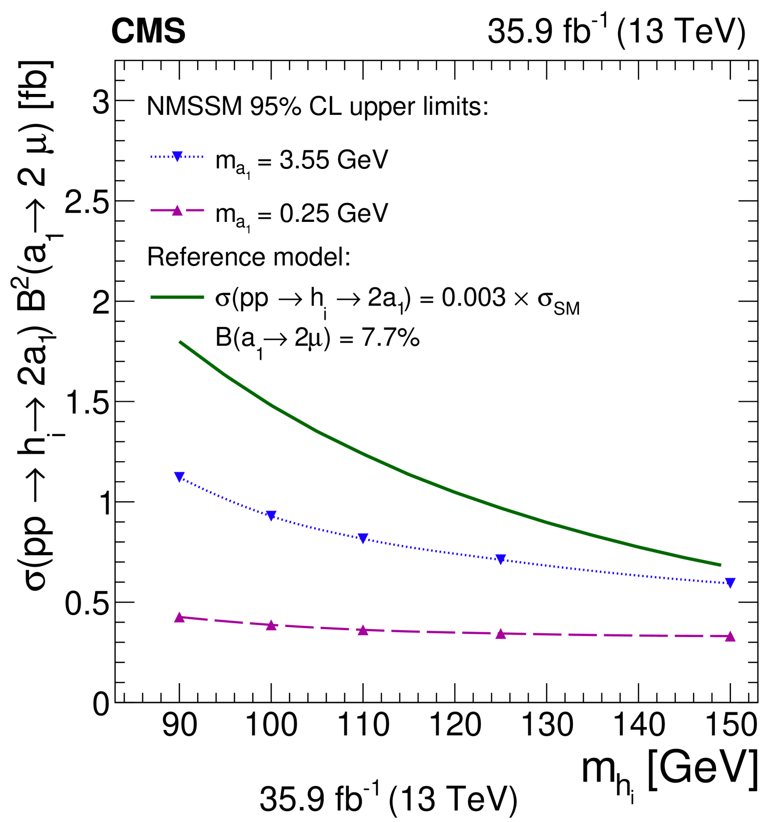


h→ aa →4μ

- Generic search for non-SM decay of Higgs boson to a pair of new light bosons (a), which subsequently decay to boosted pairs of oppositely charged muons.
- Predicted in models like NMSSM, dark SUSY etc..
- Benchmark Scenarios :
  - NMSSM Higgs Sector :
    - Possible Signature at LHC : $h_{1,2} \to 2a_1 \to 4\mu$
    - Typical Higgs masses : $90 \lesssim m_{h1} \lesssim 120-135$ GeV
  - Dark Susy : New light dark boson γ_D
    - Possible Signature at LHC :

$$h_1 \to 2n_1 \to 2n_D + 2\gamma_D \to 2n_D + 4\mu$$

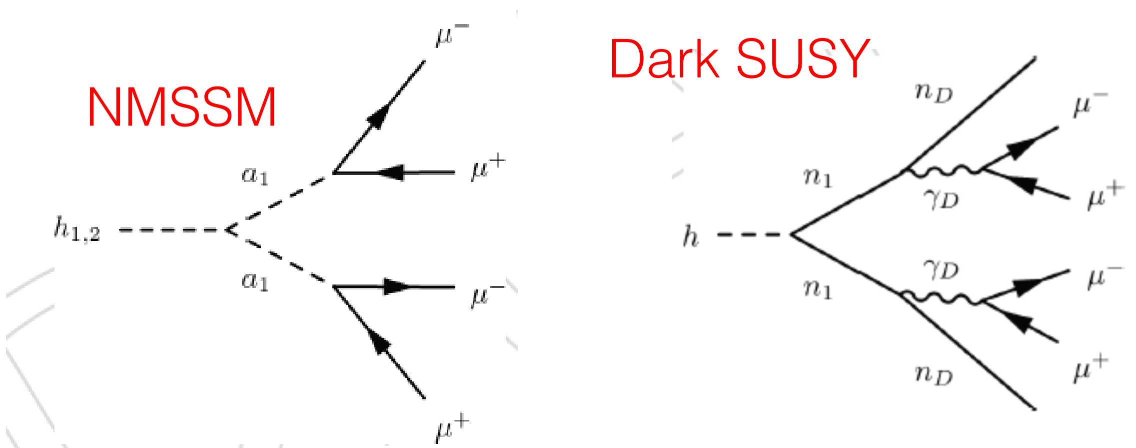
Model independent limits

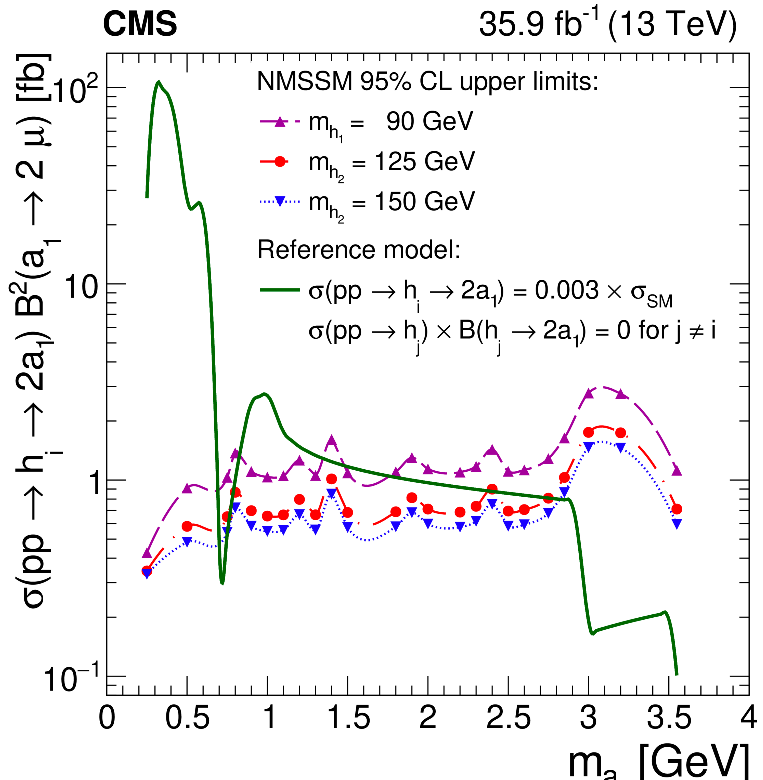


Search assumption

$0.25 < m_{a1} < 3.55$ GeV

$(2m_\mu \lesssim m_{a1} \lesssim 2m_\tau)$





Significant improvement in limits wrt 8 TeV results.

Limits also interpreted in Dark-SUSY scenario

h(125) → aa → μμττ

- The signal combines two decay modes:

  h → aa → 2μ2τ
  h → aa → 4τ
  (two of the τs decay to μs)

  Assuming 2HDM-like scenarios

$$\frac{\mathcal{B}(a \to 2\mu)}{\mathcal{B}(a \to 2\tau)} = \frac{m_\mu^2 \sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2 \sqrt{1-(2m_\tau/m_a)^2}} \simeq \frac{m_\mu^2}{m_\tau^2}.$$

- Four different final states are studied, depending on τ decay modes

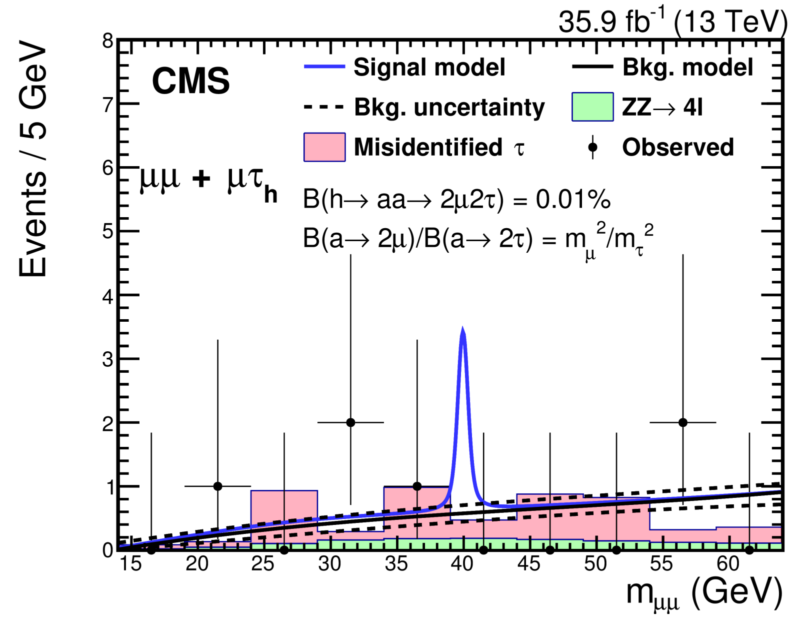
  μμ + eμ, μμ + eτ$_h$, μμ + μτ$_h$, μμ + τ$_h$τ$_h$

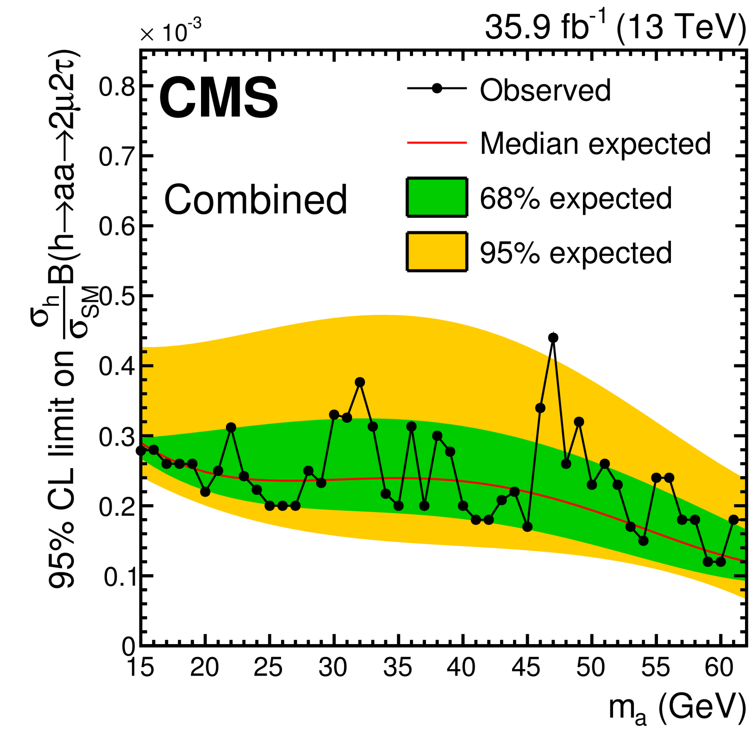
- Signal extracted by unbinned maximum likelihood fit to M(μμ)

- Probed mass region:
  15 GeV ≤ m_a ≤ 62.5 GeV

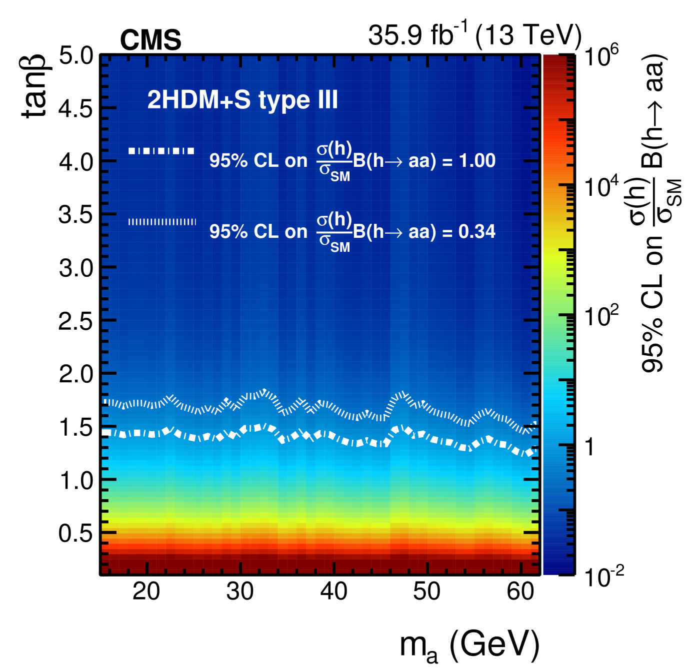
Result improved (w.r.t 8 TeV) by a factor of ≥ 2

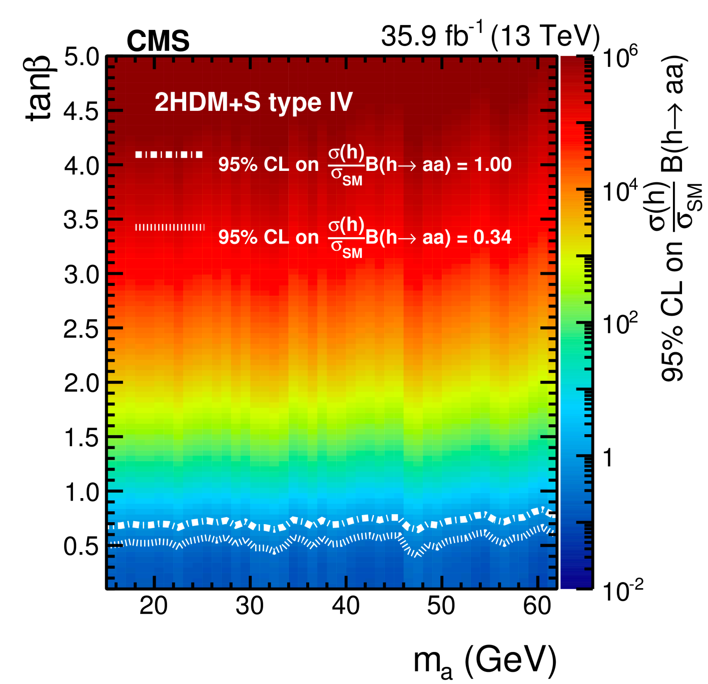
Upper limits are obtained on σ x BR as function of mass of "a" boson





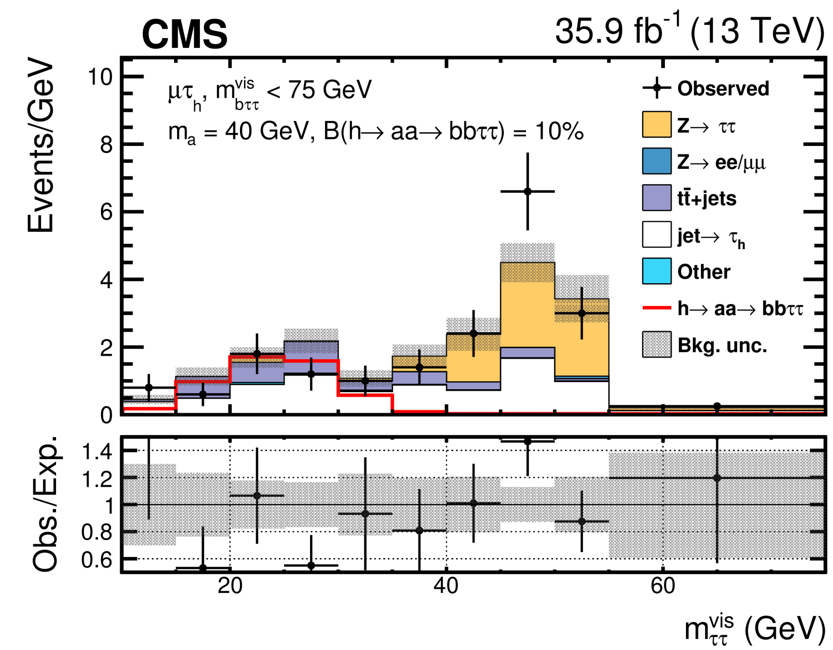
Interpretation in 2HDM+S type models

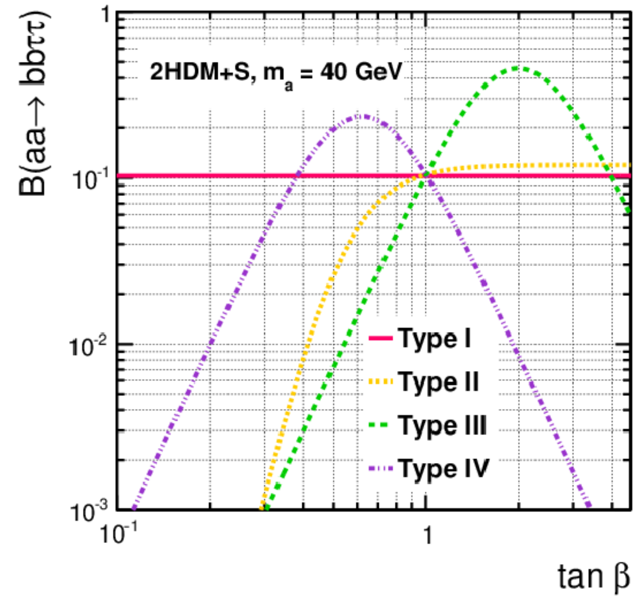




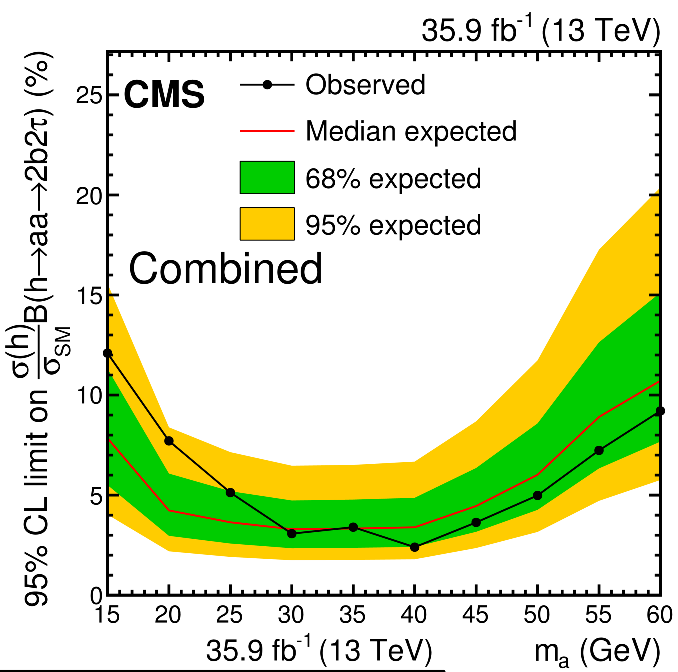
h(125) → aa → bbττ

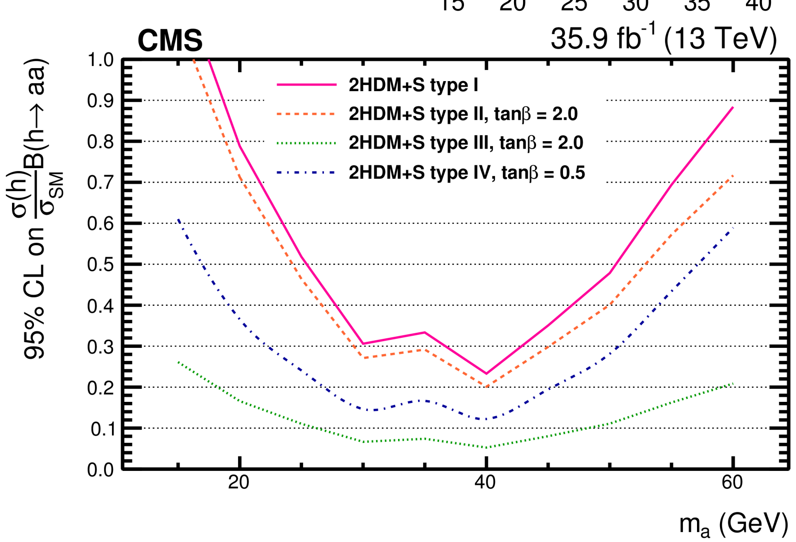
- Br(aa → 2b2τ) = 10 – 50% depending on scenarios and parameters
- signature: 1b + 1ℓ +1τ or 1b + 2ℓ
  - 3 different ττ final states: eμ, $e\tau_h$, $\mu\tau_h$
- 4 $m^{vis}_{b\tau\tau}$ categories
- probed mass range: $15<m_a<60$ GeV
- Binned maximum likelihood to $m^{vis}(\tau\tau)$



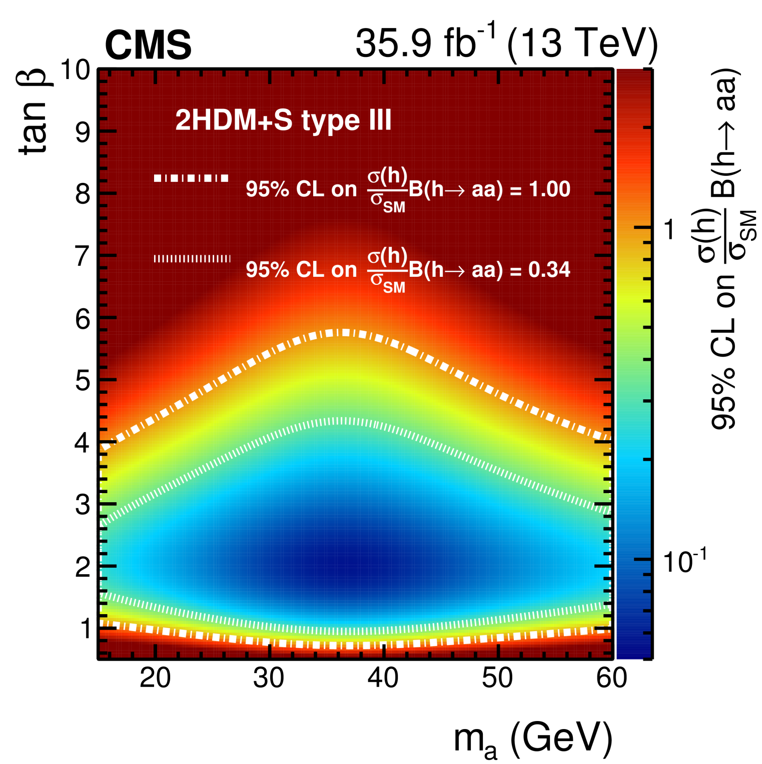


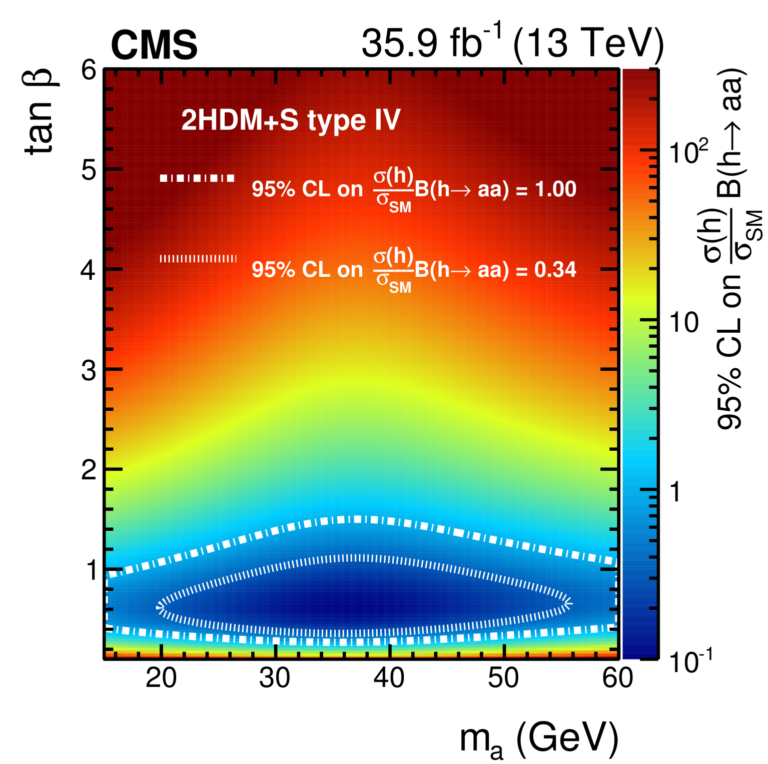
Model independent limits





Interpretation in 2HDM+S type models





LFV: h → e/μ + τ

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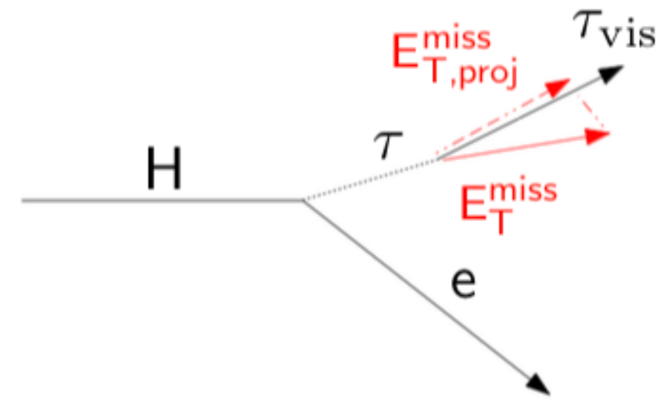
- Forbidden in SM, but allowed in many BSM models
- Search performed in two decay channels: h → **eτ, μτ**
  - 2 tau decay modes: $\boldsymbol{\tau_h}$ **or** $\boldsymbol{\tau_{\mu/e}}$
  - 4 event categories designed to enhance the contribution of different Higgs production mechanisms: **0-jet, 1-jet, 2-jets (ggH), and VBF**
- BDT classifier to extract signal
  - Collinear mass fit as a cross check



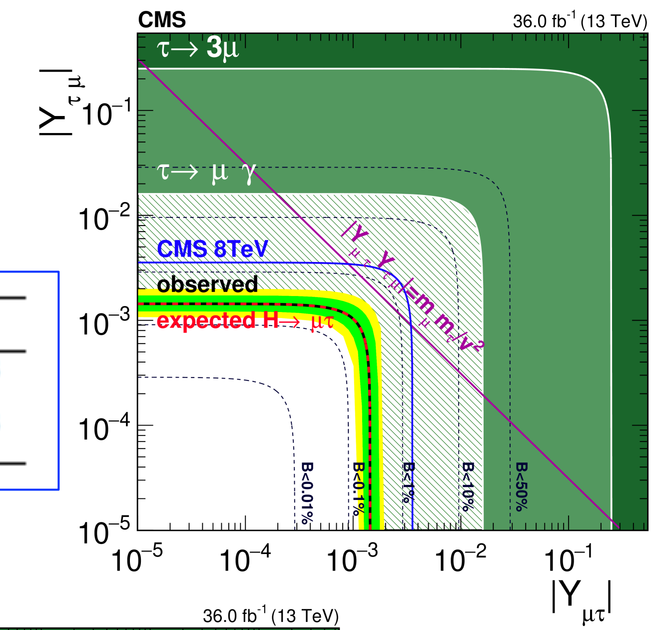
$$p_T^{\nu} = \vec{E}_T^{miss} \cdot \hat{p}_T^{\tau_{vis}}$$

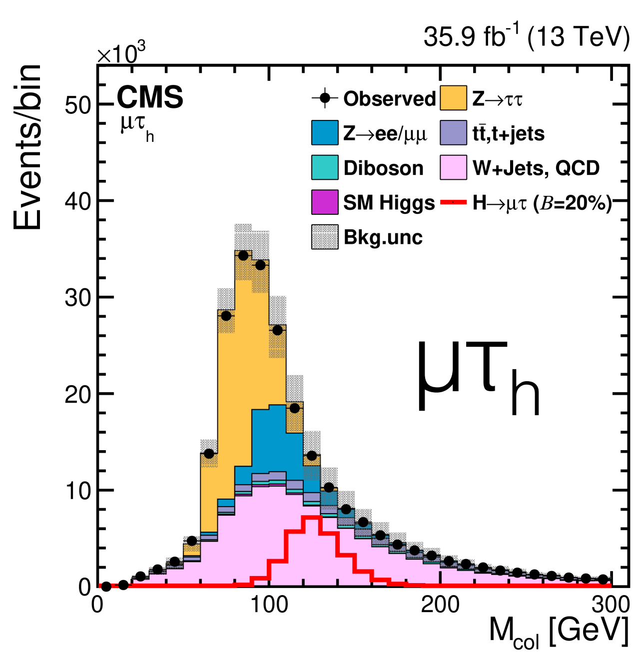
$$x_{vis} = \frac{|\vec{p}_T^{\tau_{vis}}|}{|\vec{p}_T^{\tau_{vis}}| + |\vec{p}_T^{\nu}|}$$

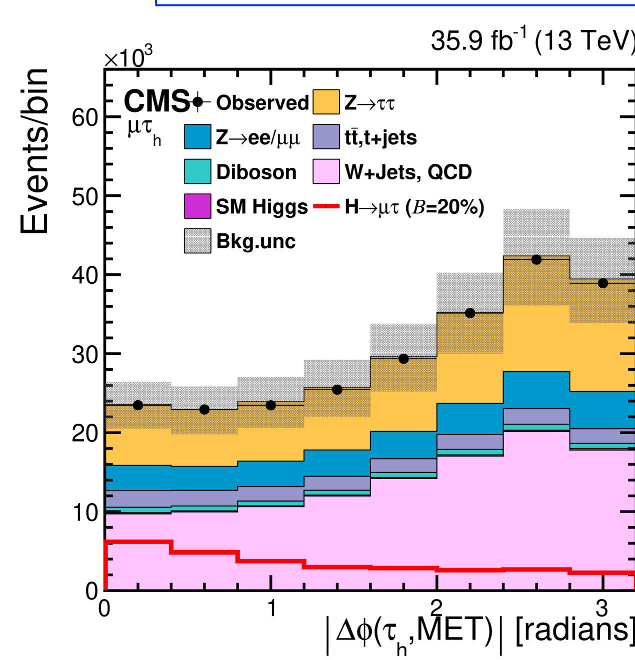
$$M_H \simeq M_{col} = \frac{M_{vis}}{\sqrt{x_{vis}}}$$

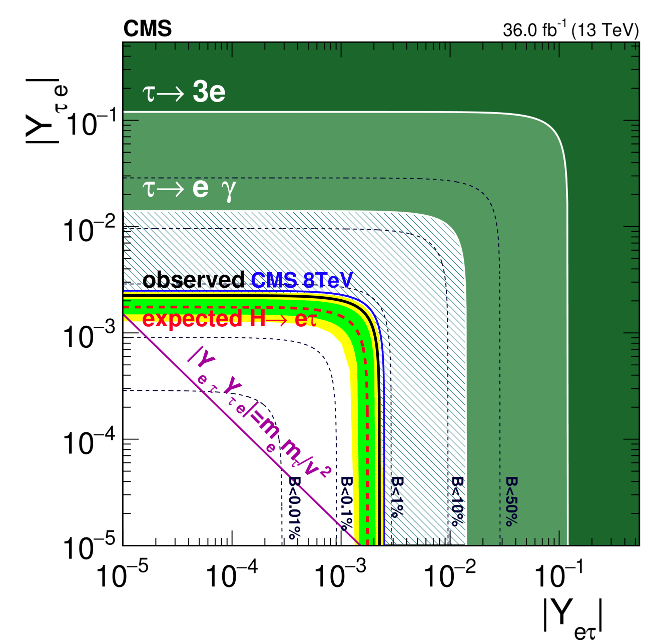
$\mathcal{B}$(h → μτ) < 0.25% (0.25%)
$\mathcal{B}$(h → eτ) < 0.61% (0.37%)

	BDT fit	M_{col} fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$	$< 2.05 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.26 \times 10^{-3}$	$< 2.45 \times 10^{-3}$









Summary

- Rich program to search for new physics in the Higgs sector at LHC
- Both ATLAS and CMS experiments search for non-SM decays of the observed 125 GeV scalar as well as presence of additional Higgs bosons
- Many models such MSSM, NMSSM, See-Saw etc.. predict additional neutral as well as charged Higgs bosons
- Large parameter space of the MSSM benchmark scenarios are already excluded. However, analyses are not yet sensitive to exclude parameter space in NMSSM.
- Results are presented mostly for 13 TeV data collected during 2016.
- Lot of improvements in the analysis search sensitivities compared to Run-1 results.
- ~4 times more data is already collected during run-2 and are being analyzed now
- Looking for more exciting results soon

BACKUP

MSSM Scenarios

Table 1: MSSM benchmark scenarios.

Parameter	m_h^{max}	m_h^{mod+}	m_h^{mod-}
m_A	90–1000 GeV	90–1000 GeV	90–1000 GeV
$\tan\beta$	0.5–60	0.5–60	0.5–60
M_{SUSY}	1000 GeV	1000 GeV	1000 GeV
μ	200 GeV	200 GeV	200 GeV
M_1	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$
M_2	200 GeV	200 GeV	200 GeV
X_t	$2\ M_{SUSY}$	$1.5\ M_{SUSY}$	$-1.9\ M_{SUSY}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{l}_3}$	1000 GeV	1000 GeV	1000 GeV

Parameter	light-stop	light-stau	τ-phobic	low-m_H
m_A	90–600 GeV	90–1000 GeV	90–1000 GeV	110 GeV
$\tan\beta$	0.7–60	0.5–60	0.9–50	1.5–9.5
M_{SUSY}	500 GeV	1000 GeV	1500 GeV	1500 GeV
μ	400 GeV	500 GeV	2000 GeV	300-3100 GeV
M_1	340 GeV	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$
M_2	400 GeV	200 GeV	200 GeV	200 GeV
X_t	$2\ M_{SUSY}$	$1.6\ M_{SUSY}$	$2.45\ M_{SUSY}$	$2.45\ M_{SUSY}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t, A_\tau = 0$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{l}_3}$	1000 GeV	245 GeV	1000 GeV	1000 GeV

2DHM scenarios

arXiv: 1507:04281

1. Type-I Yukawa couplings: $h_1^U = h_1^D = h_1^L = 0$,
2. Type-II Yukawa couplings: $h_1^U = h_2^D = h_2^L = 0$.
3. Type-X Yukawa couplings: $h_1^U = h_1^D = h_2^L = 0$,
4. Type-Y Yukawa couplings: $h_1^U = h_2^D = h_1^L = 0$.

$$\rho_F \propto \kappa_F = \frac{\sqrt{2}}{v} M_F$$

Barger, Hewitt, Philips, PRD41 (1990)

Type	U_R	D_R	L_R	ρ^U	ρ^D	ρ^L
I	$+$	$+$	$+$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
II	$+$	$-$	$-$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$
III	$+$	$-$	$+$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$
IV	$+$	$+$	$-$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

Type III = Type Y = "Flipped"   Type IV = Type X = "Lepton-spec."