SEARCHES FOR AN EXTENDED HIGGS BOSON SECTOR AT CMS

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on behalf of the CMS Collaboration

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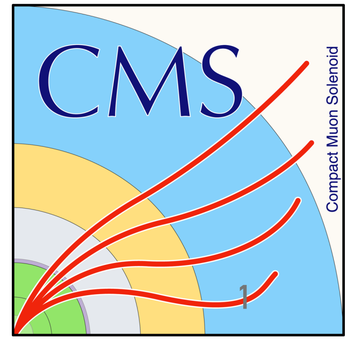


Extension of the Higgs boson sector

- Many BSM theories to solve several phenomena not explained by the SM
  - e.g. 2HDM → the simplest extension of the SM Higgs sector introducing another scalar doublet

2 doublets: $\Phi_1\Phi_2$		
CP-even	CP-odd	Charged
H/h	A	$H^{\pm}$

- Different types of 2HDM depending on how two Higgs doublets couple to the SM particles
  - 4 with natural flavour and CP conservation
  - One (type-III) allows for FCNC: all the SM particles couple with both doublets

Additional extension of 2HDM: 2HDM+S

Complex scalar. Higgs sector mixing allows decays to SM

Type-I	***Type-II (MSSM)***		***Lepton-specific***		***Flipped***		***Type-III***	
Φ_1	Φ_1	Φ_2	Φ_1	Φ_2	Φ_1	Φ_2	Φ_1, Φ_2	
all charged fermions	u	d,e	u,d	e	u, e	d	u, d, e	
	c	s,μ	c, s	μ	c, μ	s	c, s, μ	
	t	b,τ	t, b	τ	t, τ	b	t, b, τ	

Allows for FCNC

CMS BSM searches in this talk

- High mass bosons decaying to bosons:
  - $A \to hZ \to 2\tau 2l$, $A \to hZ \to 2b2l$,
  - $H \to ZA \to llbb$,
  - $H \to WW \to lvl'v'$, $lvqq$
- High mass bosons decaying to fermions:
  - $H \to tt$,
  - $H \to e\tau$, $H \to \mu\tau$
- Charged bosons:
  - $H^+ \to t\bar{b}$,
  - $H^+ \to \tau^+ \nu_\tau$
- 125 GeV boson decaying to low mass bosons:
  - $h \to a_1 a_1 \to 4\tau$,
  - $h \to a_1 a_1 \to 2b2\mu$
- Not covered by this talk as already presented at Blois 2018:
  - High mass bosons:
    - $h/H/A \to \tau\tau$
    - $H/A \to bb$
  - Low mass bosons:
    - $h_{125} \to a_1 a_1 \to 2\mu 2\tau$

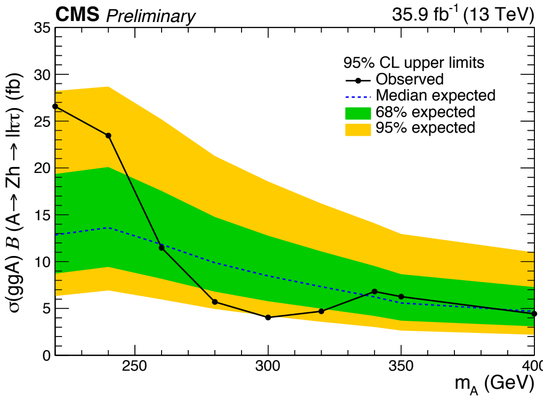
Other interesting analyses available on the CMS Higgs result webpage

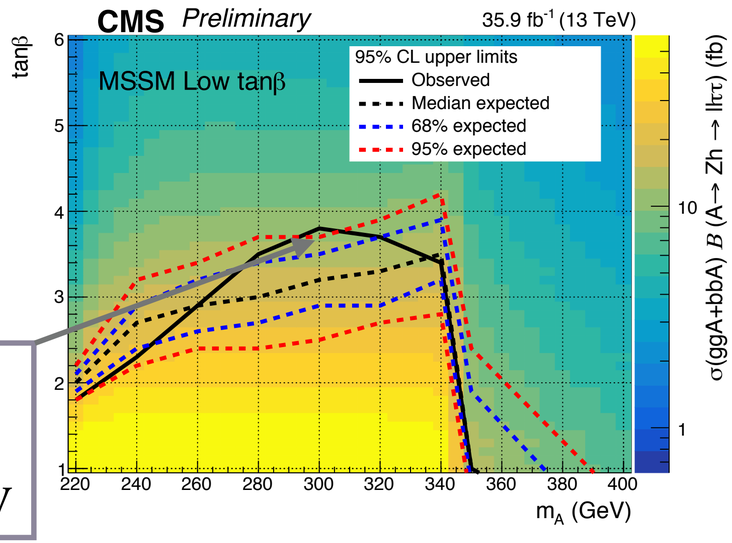
High mass boson: $A \to h_{125} Z$

$m_A < 2m_t$ and low tanβ:
$A \to hZ$ dominant

$A \to h_{125} Z \to 2\tau 2l$ *CMS-PAS-HIG-18-023*

- Two benchmark scenarios: low tanβ and hMSSM
- 8 possible final states: $h_{125} \to \tau_h\tau_h, \tau_\mu\tau_h, \tau_e\tau_h, \tau_e\tau_\mu$, $Z \to ee, \mu\mu$
- signal mass range $220 < m_A < 400$ GeV

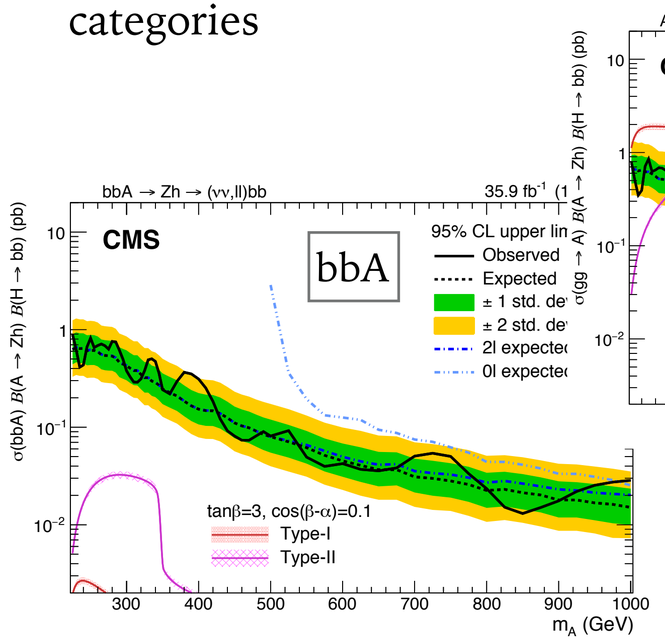


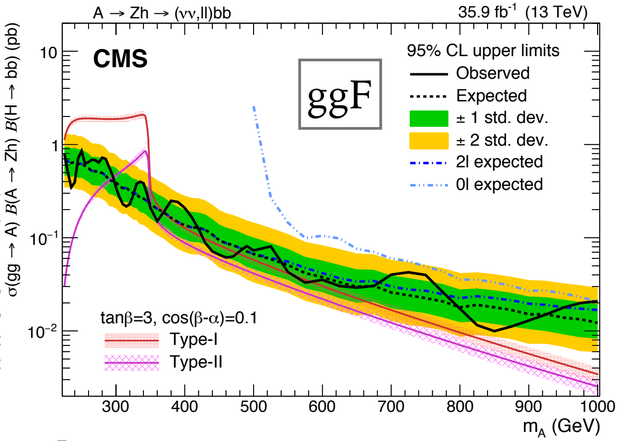


30% better!
CMS RunI limit:
tanβ=2.7(2.4) at m_A=300GeV

$A \to h_{125} Z \to 2b2l$ *CMS-HIG-18-005* *arXiv:1903.00941*

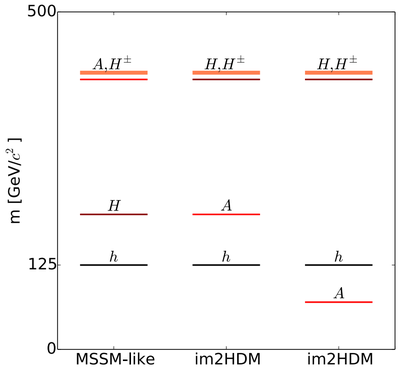
- 3 final state: $h_{125} \to b\bar{b}$, $Z \to ee$, $\mu\mu$, $\nu\nu$, 3 categories: number of b-jets (targeting ggF and bbA)
- A reconstructed by invariant mass ($Z \to ee$, $\mu\mu$) or transverse quantities ($Z \to \nu\nu$)
- Combined fit of CR and SR, separated for the 9 categories



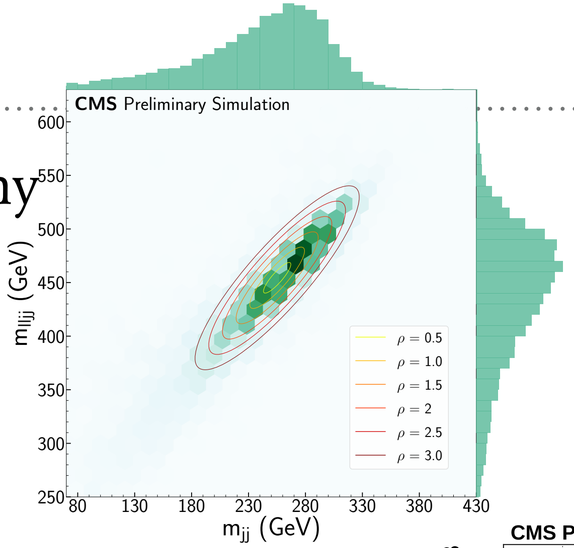


$H \rightarrow ZA \rightarrow llb\bar{b}$

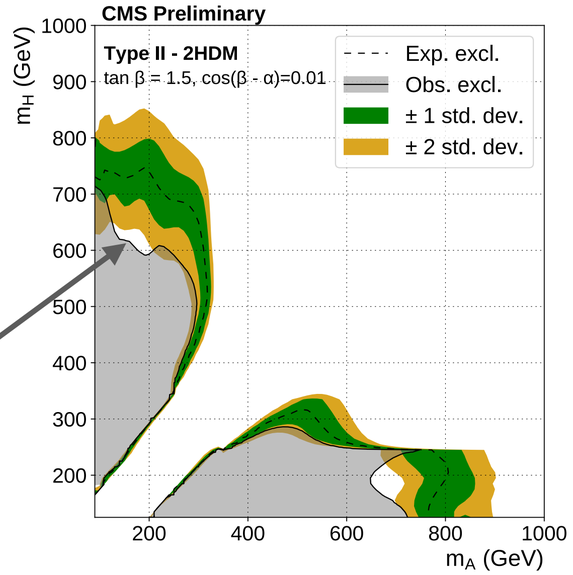
[CMS-PAS-HIG-18-012](#)

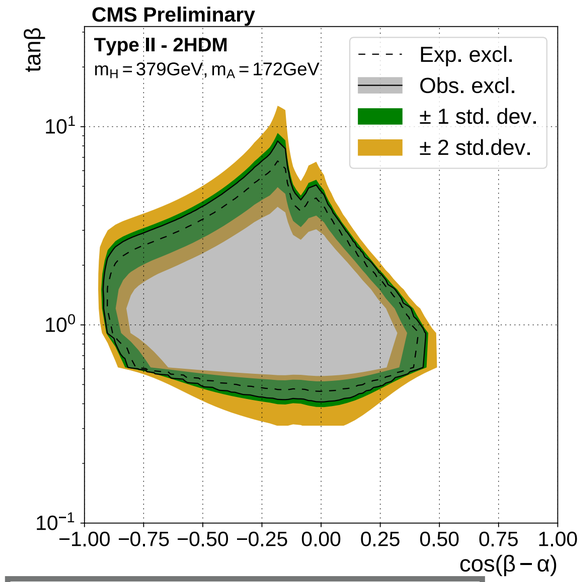


- 2HDM Type II with inverted hierarchy
- Two channels for Z decay: Z→ee, μμ
- Binned max likelihood fit
  - 6 m_{bb}-m_{bbll} bins
  - 1 additional bin (eμ) to constrain top backgrounds



- 95% CL limits for 2HDM benchmark:
  - tanβ=1.5 and cos(β-α)=0.01
  - m_H=379 GeV and m_A=172GeV





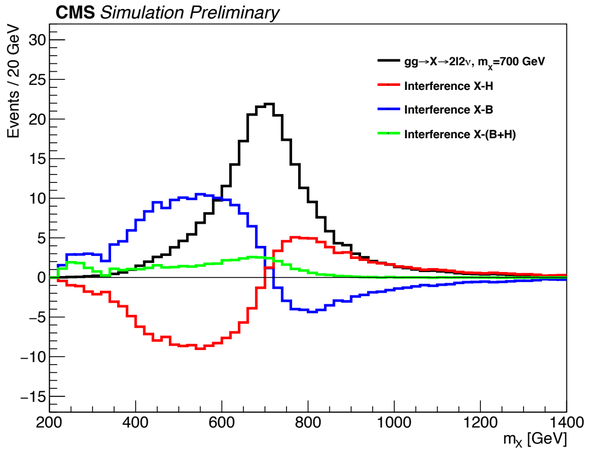
m_H=627GeV m_A=162GeV
local significance = 3.9σ,
accounting for the look-elsewhere effect:
global significance = 1.3σ

larger region excluded
wrt previous searches

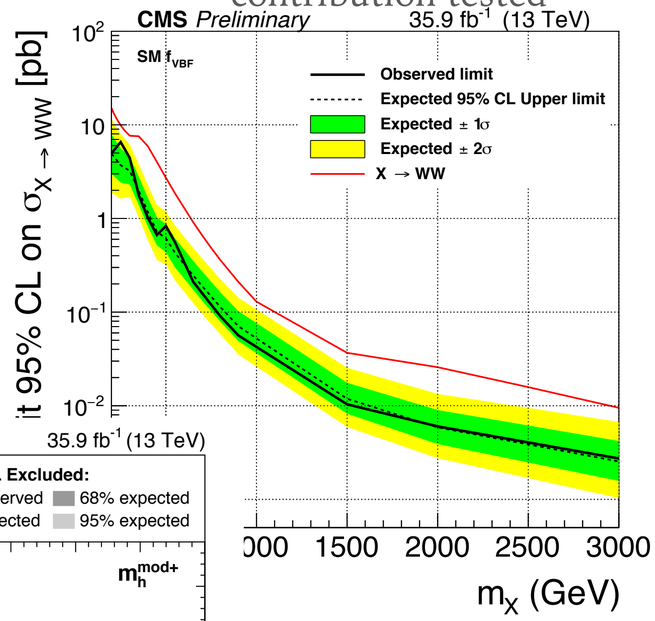
H→WW→lνl'ν', lνqq̄

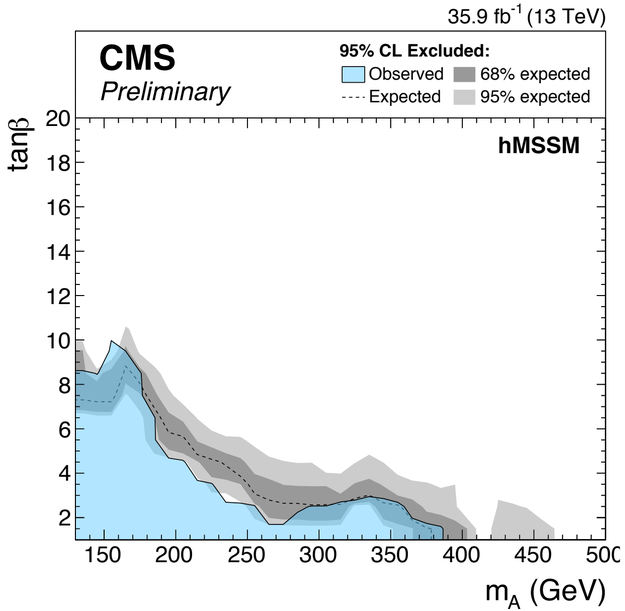
[CMS-PAS-HIG-17-033]

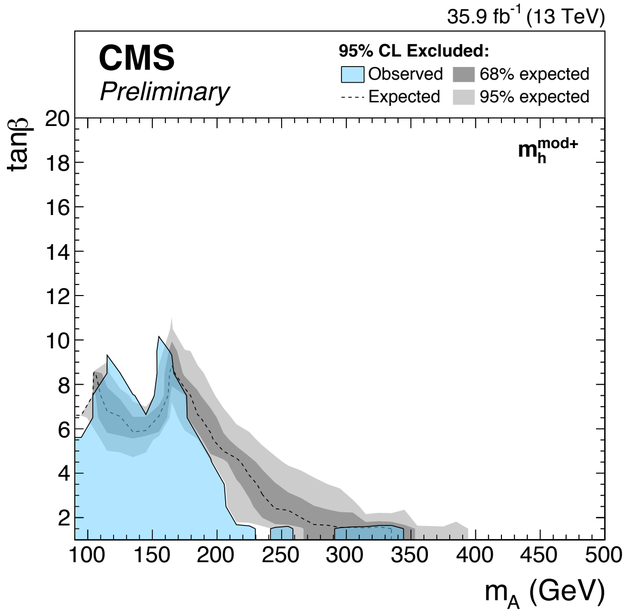
- mass range: 200GeV < mH < 3 TeV
- ggF and VBF production modes
  - signal - SM background interference considered
- 2 channels: di-leptonic, lepton+jets
  - 6 categories for each channel:
    - dilepton: flavour and production mode
    - lepton+jets: jets kinematics and production mode
- Fit to M_T or M_{WW} distributions
  - No evidence of excess at 95% CL
  - Results interpreted in the context of 2HDM type-I and type-II (MSSM: m_h^{mod+} and hMSSM)
    - for compatibility with the observed higgs $\cos(\beta-\alpha)=0.1$



Different hypotheses for ggF-VBF relative contribution tested



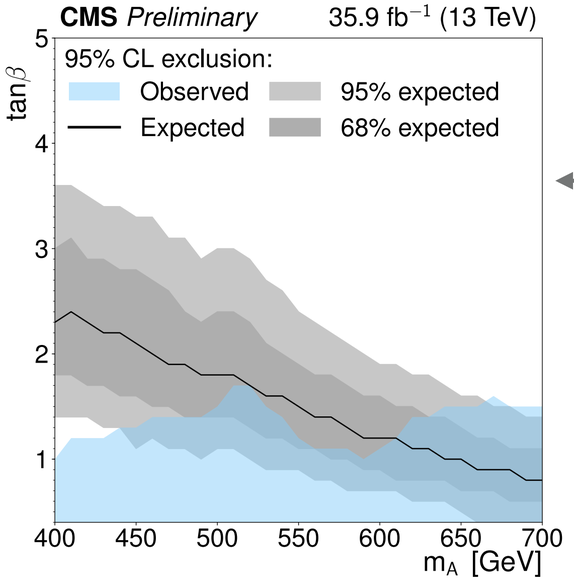




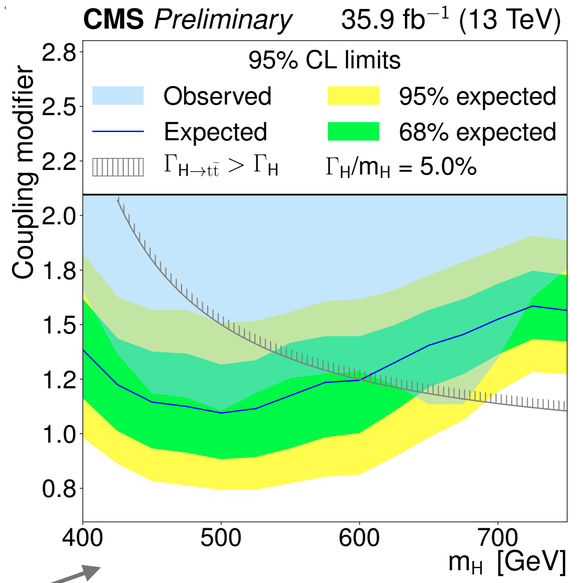
High mass boson: H/A → $t\bar{t}$

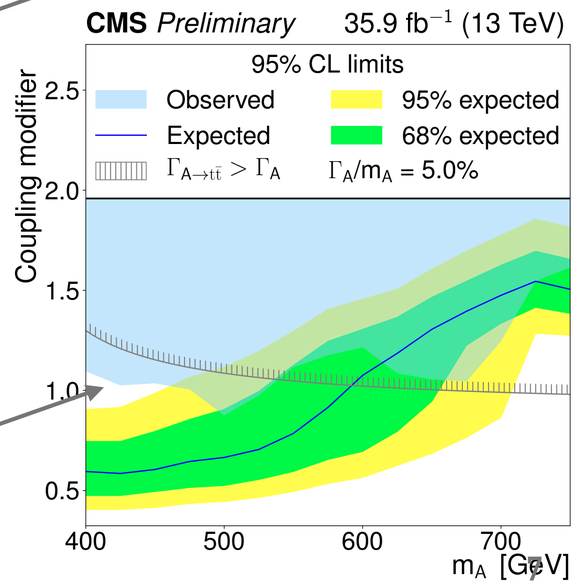
[CMS-PAS-HIG-17-027]

- 2 categories: single-lepton or diepton events
- Analysis exploiting m_{tt} and angular variable
  - Max likelihood fit to extract the yields in bins of m_{tt} and angular variable
    - separate for single-electron, single muon categories, combined dilepton category



- Constrain on coupling strength modifier $g_{\Phi tt}$ as function of boson mass and width
- Interpreted in hMSSM scenario (m_A, tanβ)



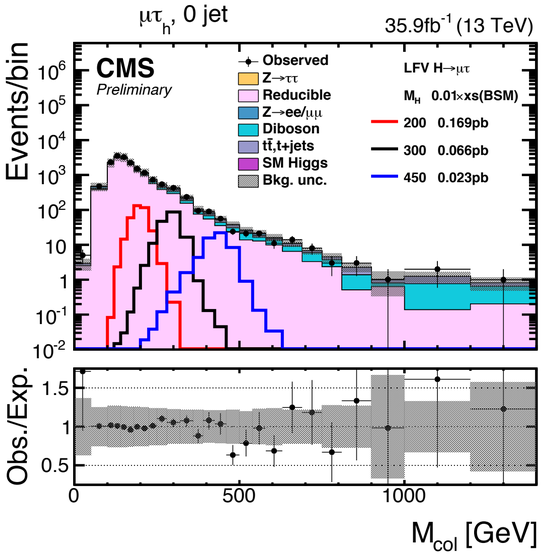


m_A=400 GeV, Γ_A=0.04m_A
local significance = 3.5σ,
accounting for the look-elsewhere effect:
global significance = 1.9σ

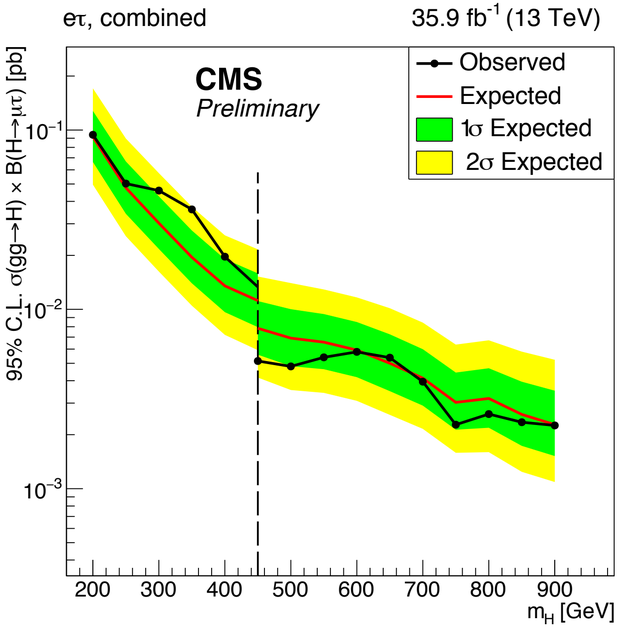
High mass boson LFV decays: H/A→eτ, μτ

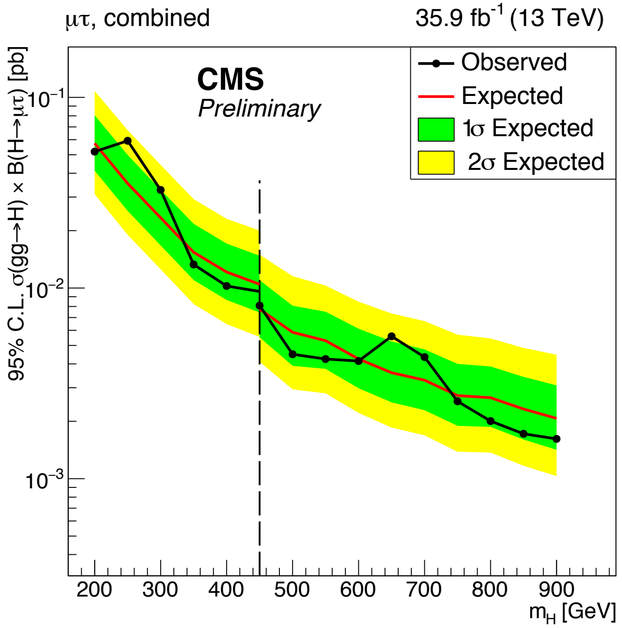
[CMS-PAS-HIG-18-017]

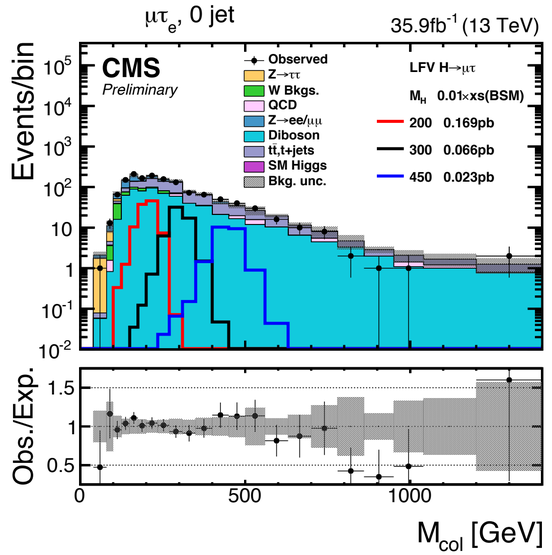
- CMS has extended the search of LFV decay to high mass bosons
  - Model independent search
- Two channels: H→eτ, H→μτ
  - two τ decay modes: H→eτ$_\mu$, H→eτ$_h$, H→μτ$_e$, H→μτ$_h$
  - two categories to target ggF: 0 and 1 jet
  - two mass ranges: 200<m$_H$<450, 450<m$_H$<900



Fit to the collinear mass distribution

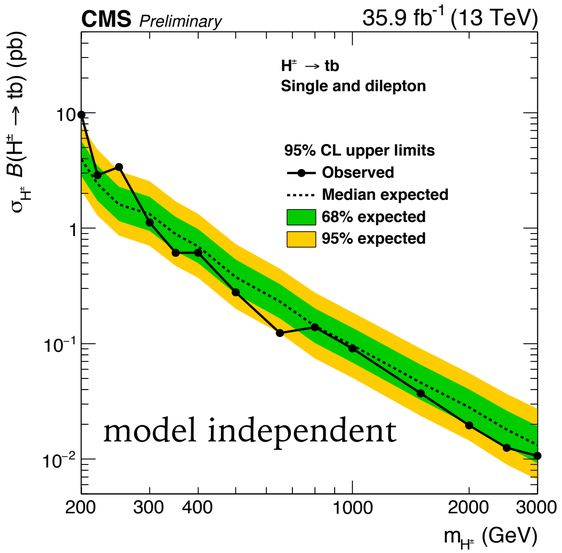


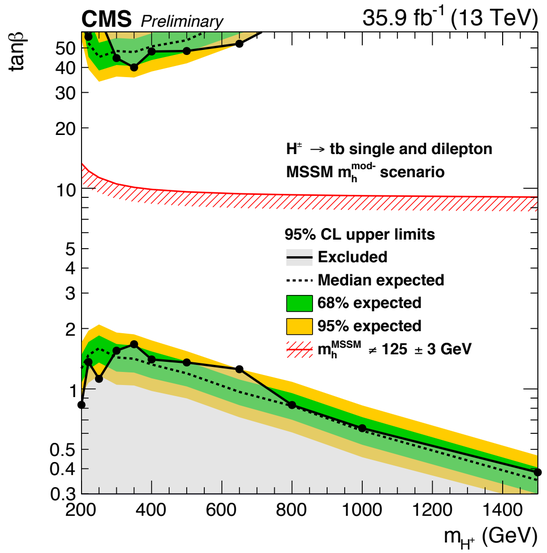




Charged boson: $H^+ \to t\bar{b}$ *CMS-PAS-HIG-18-004*

- search for H^+ with mass 200 GeV < m_{H+} < 3 TeV
- 1 or 2 leptons in final state: e,μ, e^+e^-, $\mu^+\mu^-$,$e^\pm\mu^\mp$
- categorisation for number of jet and b jets:
  - 9 in single lepton, 8 in dilepton
- simultaneous fit to the different categories
  - single lepton dominant at high mass values



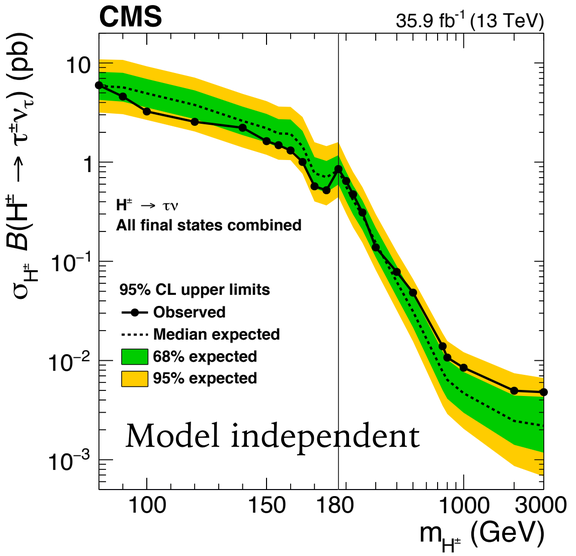


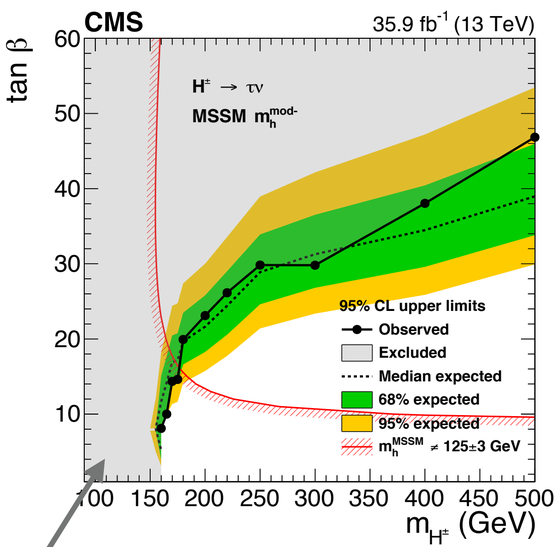
Charged boson: $H^+ \to \tau^+\nu_\tau$

- dominant for $m_{H\pm} < m_t - m_b$
- $m_{H\pm}$ range: 80 — 3000 GeV

CMS-HIG-18-014
arXiv:1903.04560

- Final states: τ_h+jets, l+τ_h, l+no τ_h
- 2 cat. exploiting helicity correlations from opposite polarization states of τ from H and W decays
- Final discriminant is transverse mass





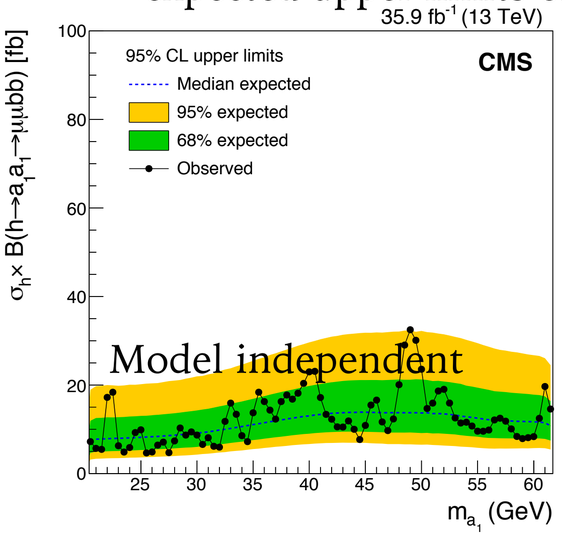
All tanβ values excluded for $m_{H\pm} < 160$ GeV

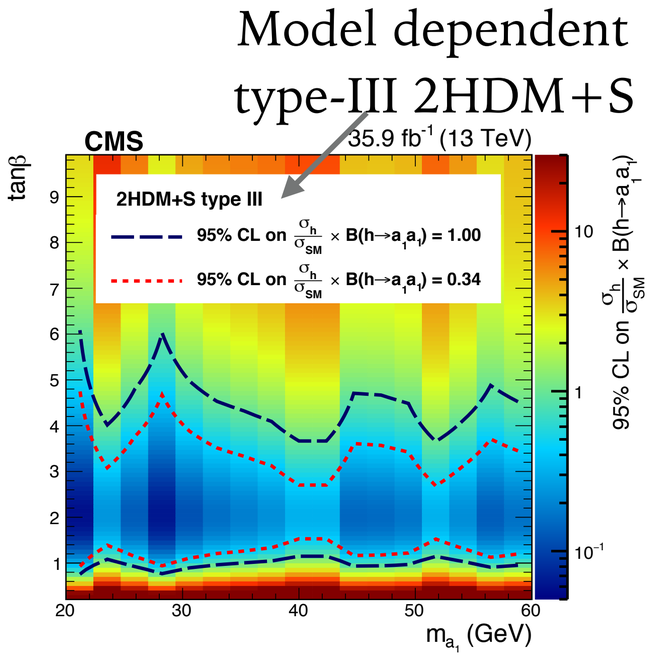
Low mass scalar: $h \rightarrow a_1 a_1$

2HDM+S model. S=SR+iSI. a1 pseudoscalar mostly SI

$h \rightarrow a_1 a_1 \rightarrow 2b2\mu$

- benchmark BR(h→aa)~10%
- $20 < m_a < 62.5$ GeV
- m(μμ) final discriminant
- expected upper limits on BR improved of a factor 2 wrt Run1

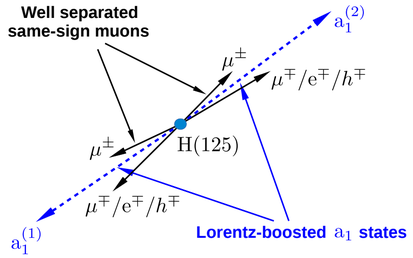




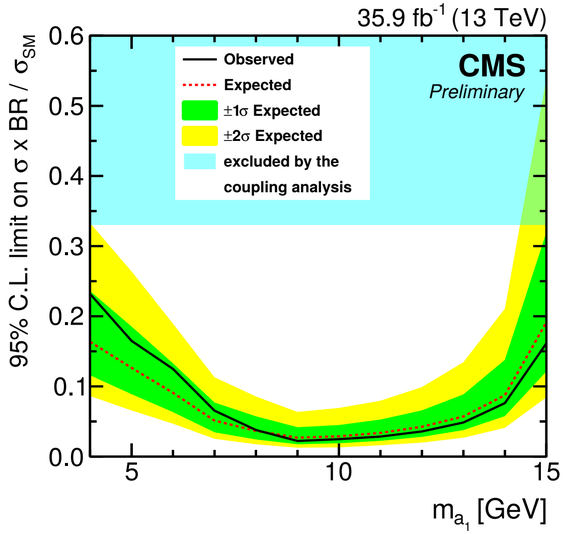
CMS-HIG-18-011

arXiv:1812.06359

$h \rightarrow a_1 a_1 \rightarrow 4\tau$ (2μ2τ)



- $4 < m_a < 15$ GeV
- complement of h→a1a1 in 2μ2τ, 2τ2b, 4μ
- each a_1 identified by one muon and one nearby charged particle (e, μ or τ one-prong)



Improves Run1 CMS limits:
30% (low masses)
80% (intermediate masses)

CMS-PAS-HIG-18-006

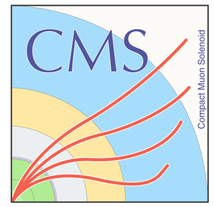
Summary

- Rich CMS program to search for new higgs-like bosons
  - High mass scalars/pseudoscalars, charged bosons, low mass scalars
  - covering almost all possible final states
    - topologies with heavy objects (t or b quarks, τ leptons) favoured

- No significant excess has been observed yet but BSM Higgs searches as powerful tool to test the SM
  - Many more analyses in both low and high-mass regions are still ongoing in CMS
- Looking forward to analyses of the full LHC Run-2 dataset with more than 150 fb^{-1}

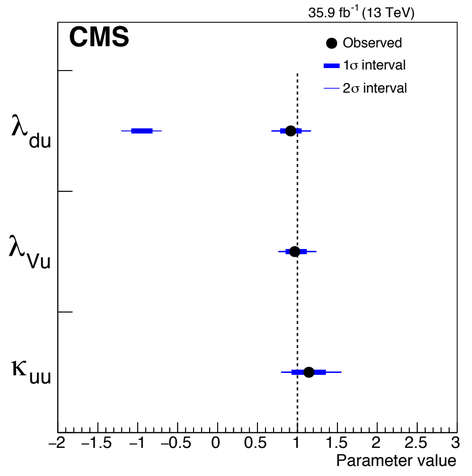
- CMS Higgs results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Backup slides



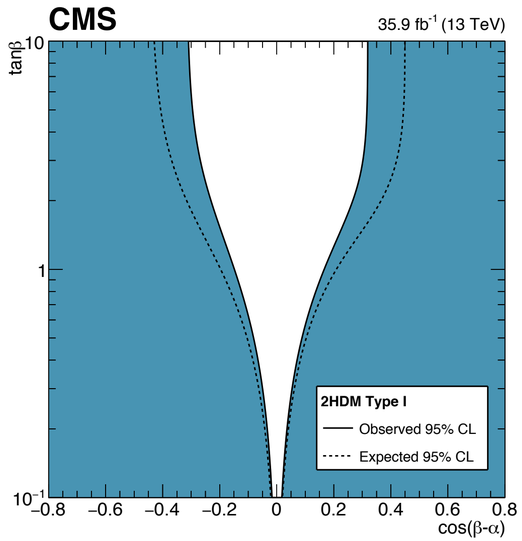
Constrains from SM Higgs boson measurements

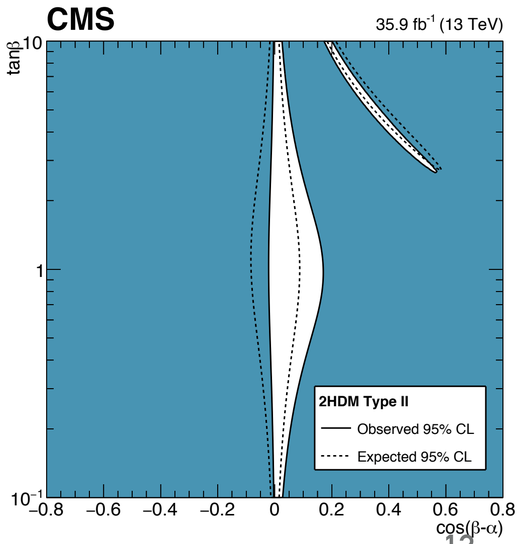
- Searches for deviations from the SM in H(125) measurements set constraints on 2HDM / MSSM scenarios
  - Couplings, CP, spin
- translate 2HDM parameters to couplings and use 3D likelihood scans of parameterizations in $\{\lambda_{du}, \lambda_{Vu}, \kappa_{uu}\}$ or $\{\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}\}$



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

[CMS-HIG-17-031]





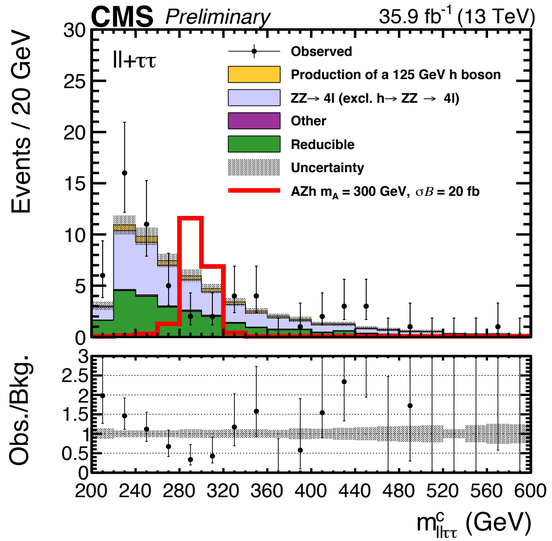
High mass boson: $A \to h_{125}Z \to 2\tau 2l$

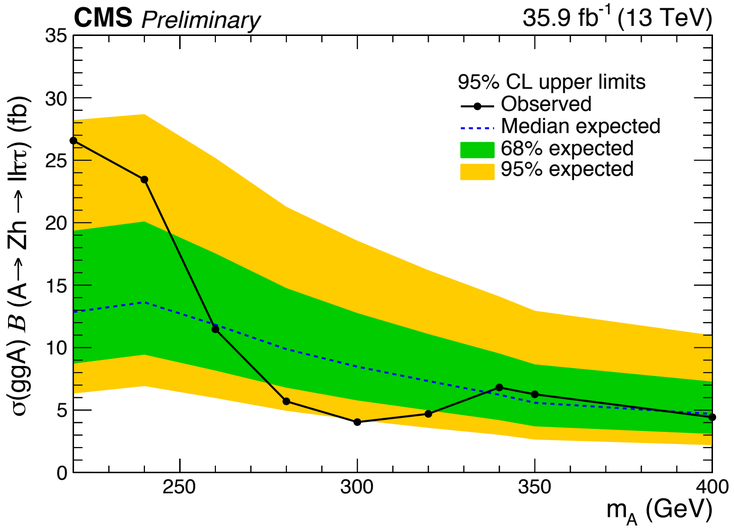
$m_A < 2m_t$ and low tanβ:
$A \to hZ$ dominant

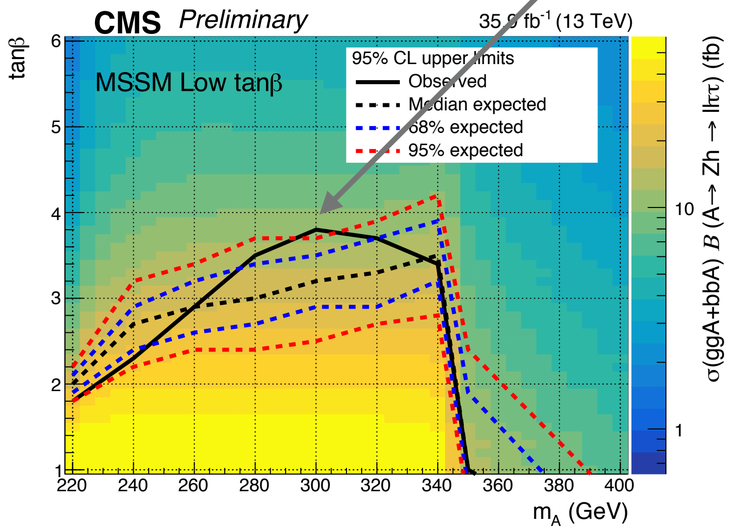
[CMS-PAS-HIG-18-023]

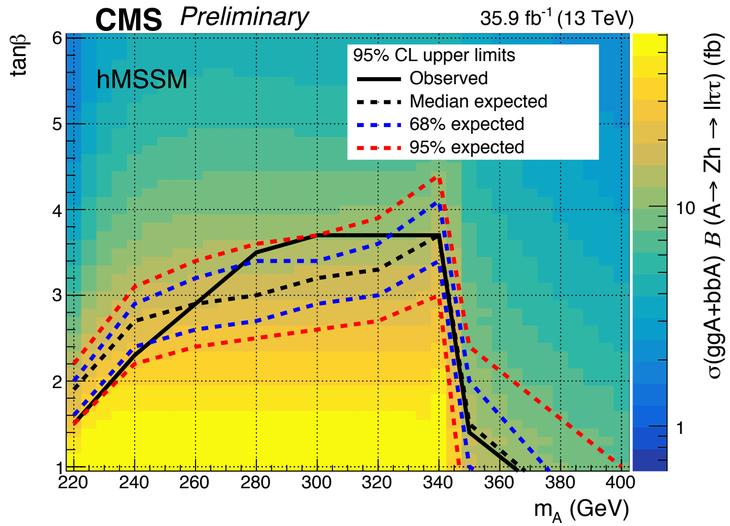
- Two benchmark scenarios: low tanβ and hMSSM
- 8 possible final states: $h_{125} \to \tau_h\tau_h, \tau_\mu\tau_h, \tau_e\tau_h, \tau_e\tau_\mu$, $Z \to ee, \mu\mu$
- Sensitivity increased thanks to the constraint to the SM Higgs mass
- Limits from 8 final state simultaneous fit to m_A
  - 8 final states fitted separately
  - signal mass range $220 < m_A < 400$ GeV

30% better!
CMS RunI limit:
$\tan\beta = 2.7(2.4)$ at $m_A = 300$GeV







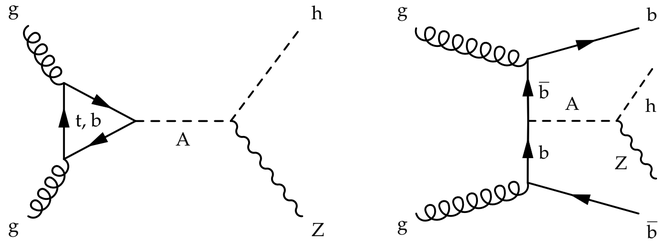


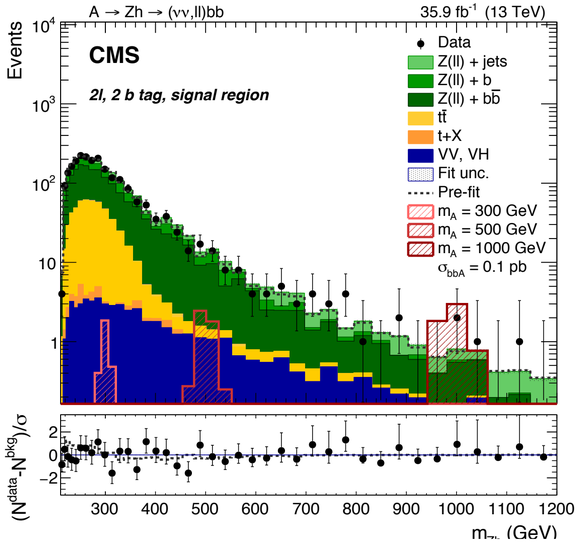
High mass boson: $A \to h_{125}Z \to 2b2l$

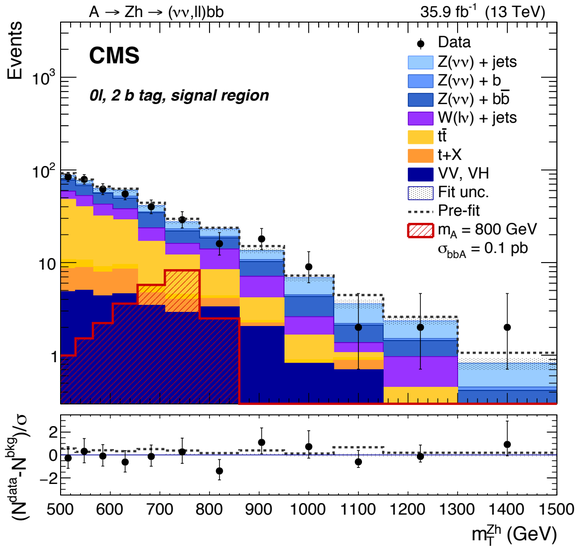
$m_A < 2m_t$ and low tanβ:
$\sigma(A) > 1$pb and $A \to hZ$ dominant

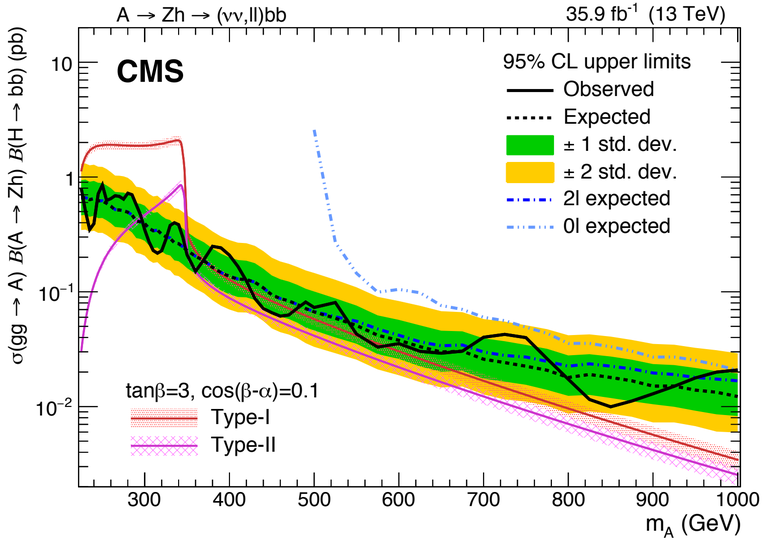
CMS-HIG-18-005
arXiv:1903.00941

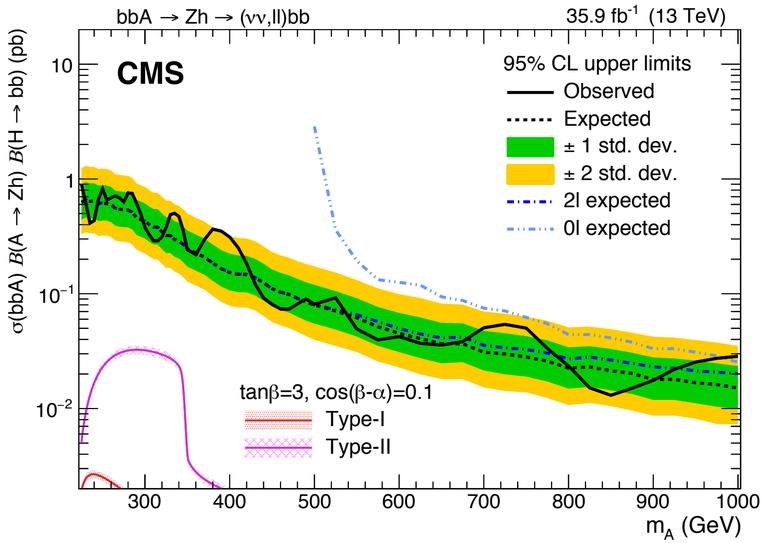
- 3 final state: $h_{125} \to b\bar{b}$, $Z \to ee$, $\mu\mu$, $\nu\nu$
  - 3 categories depending on the number of b-jets
- A reconstructed by:
  - invariant mass of visible particle if $Z \to ee$, $\mu\mu$
  - transverse quantities for $Z \to \nu\nu$
- $m(h_{125})$ used as constraint
- Combined fit of CR and SR, separated for the 9 categories





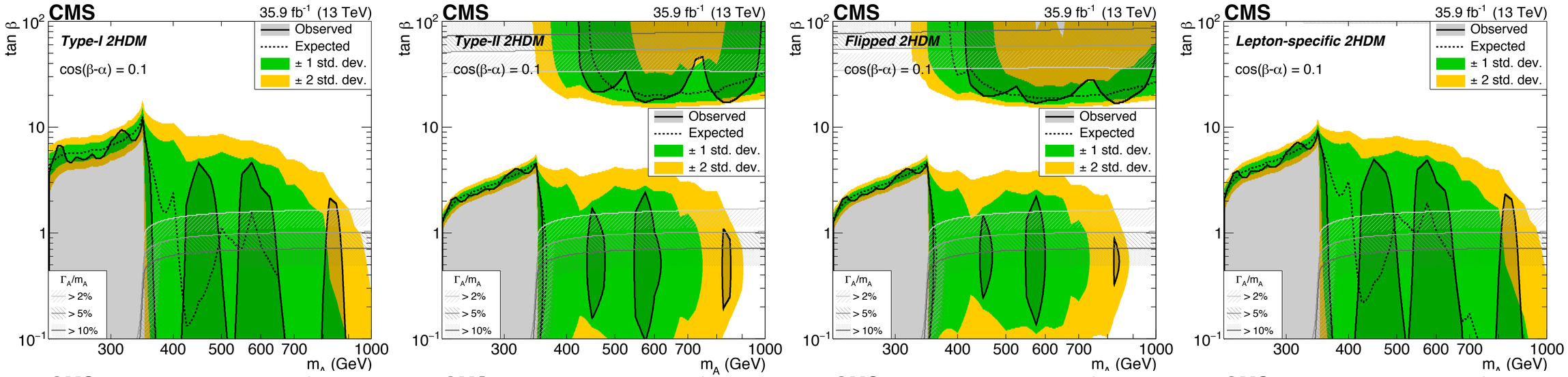






High mass boson: A→h125Z→2b2l

CMS-HIG-18-005
arXiv:1903.00941



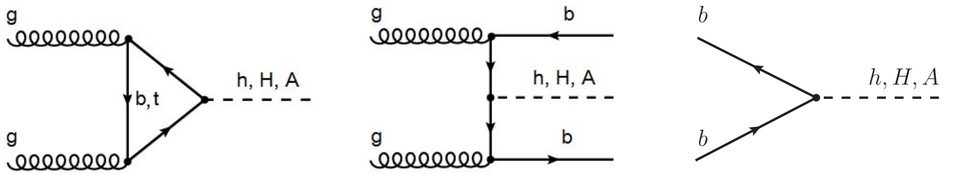
α→±π/2

Not accessible due to the suppressed σ(A) and BR(A→Zh)

α→0

α→±π/2

High mass boson: H/A → 2μ

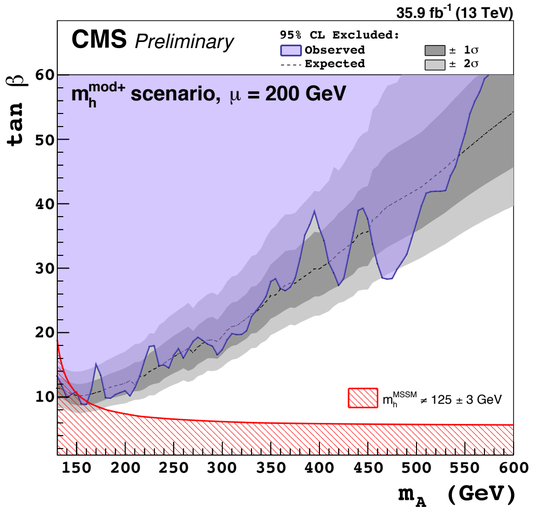


[CMS-PAS-HIG-18-010]

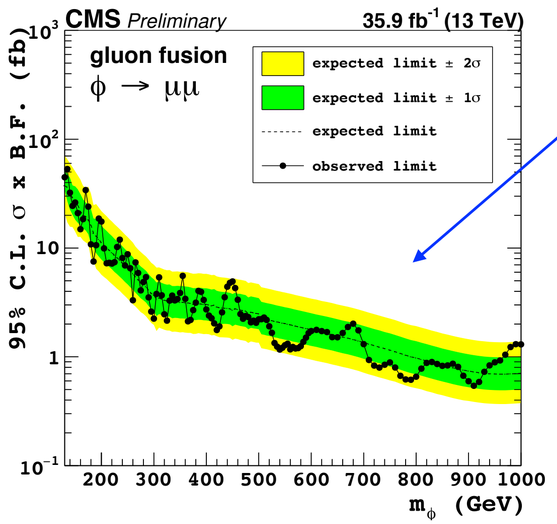
- three production modes: b associated productions and ggF
- three interpretations:
  - MSSM context: m_h^{mod+} and hMSSM scenarios
  - model independent
- event signature: 2 high p_T muons
  - + b-jets for the b associated productions
- Limits extracted from the fit to the invariant mass spectrum
  - separate fit for the two categories: b-tag and no b-tag events
- independent limit on σxBR obtained assuming the narrow-width or width equal to $0.1 m_\Phi$

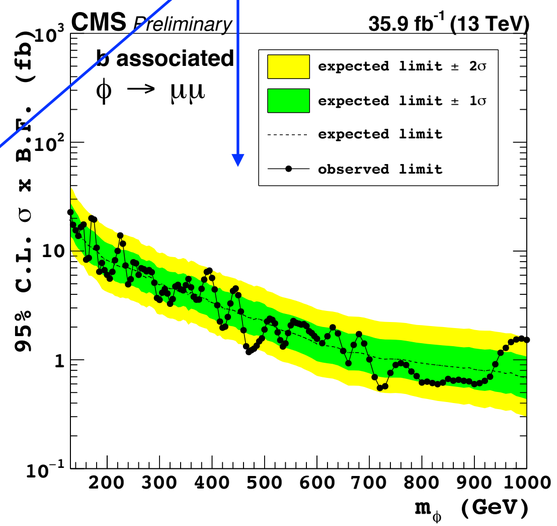
Limits reduced of ~50% for m_A=200GeV

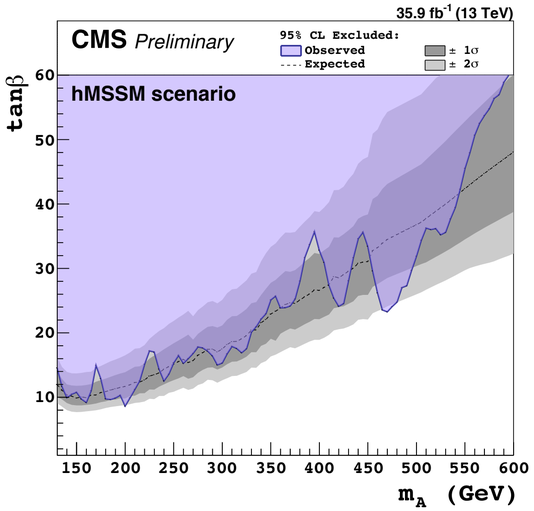
Mass range extended up to 600 GeV



Narrow width approximation



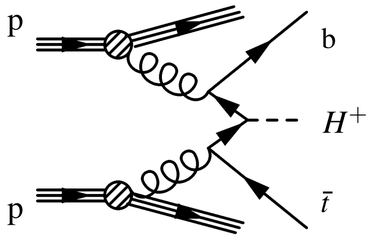




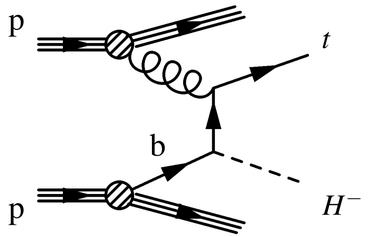
Charged boson: $H^+ \to t\bar{b}$

[CMS-PAS-HIG-18-004]

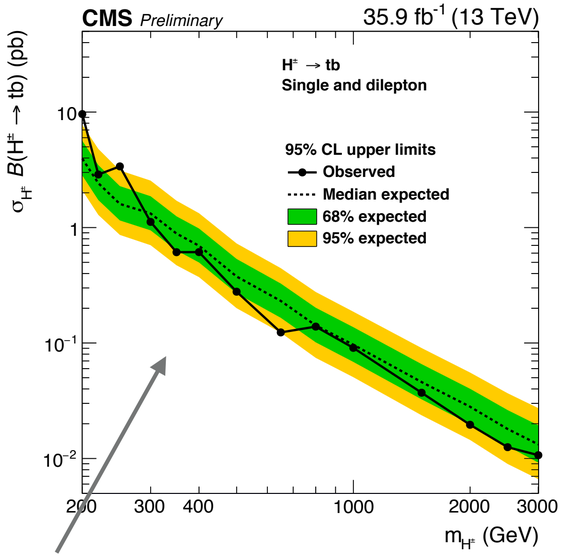
- search for H^+ with mass 200 GeV < m_{H+} < 3 TeV
- 2 W bosons: 1 or 2 leptons in final state
  - e,μ, e^+e^-, $\mu^+\mu^-$,$e^\pm\mu^\mp$
- categorisation for number of jet and b jets:
  - 9 categories for single lepton
  - 8 categories for dilepton
- simultaneous fit to the different categories
  - single lepton dominant at high mass values



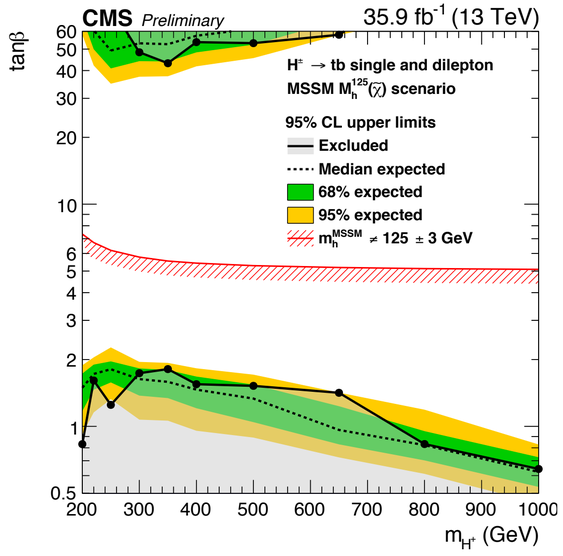
association with t and b: 4 flavour scheme (4FS)

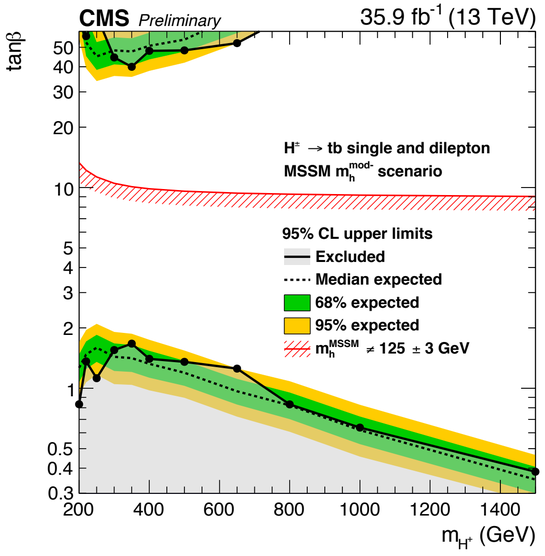


association with t: 5 flavour scheme (5FS)



model independent

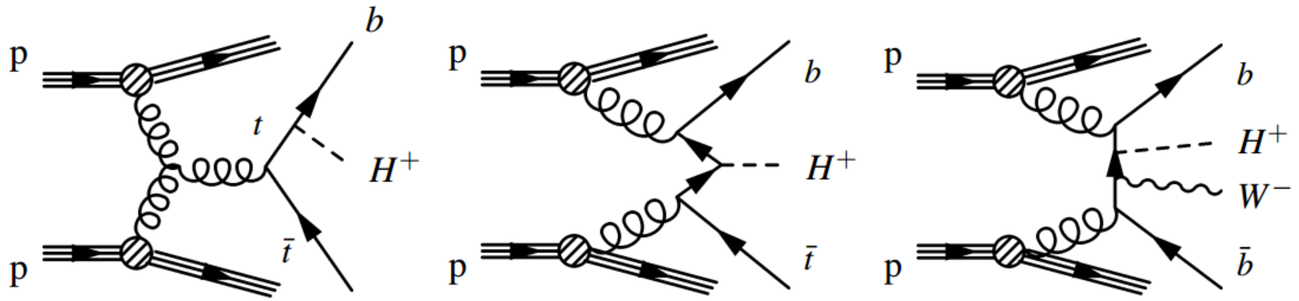


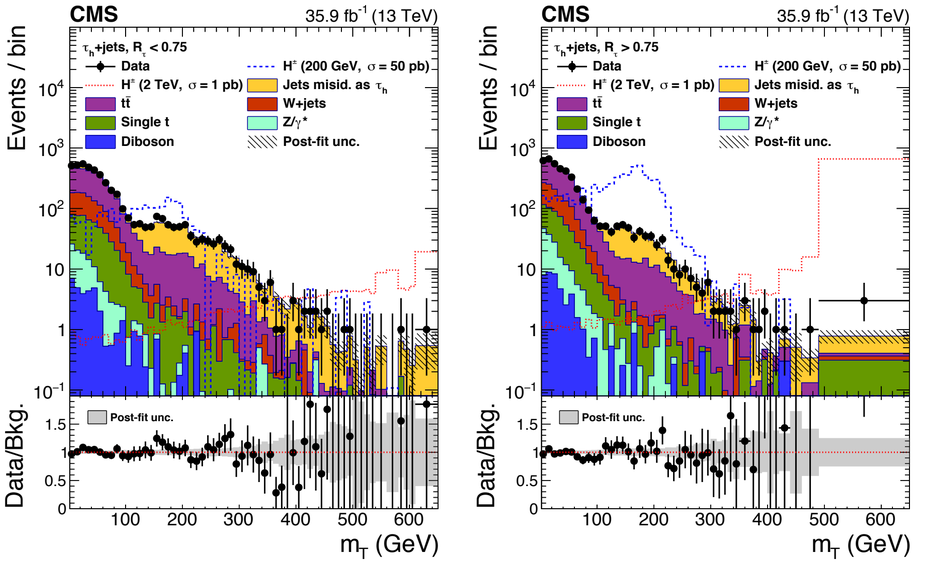


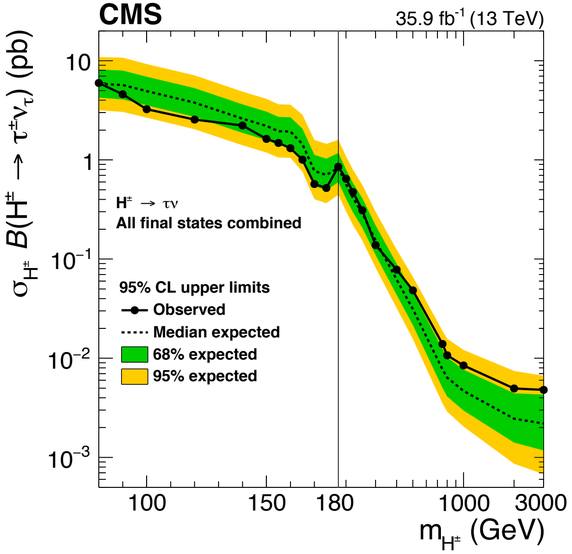
Charged boson: $H^+ \rightarrow \tau^+\nu_\tau$

CMS-HIG-18-014
arXiv:1903.04560

$m_{H^\pm} < m_t - m_b$ $\qquad$ $m_{H^\pm} > m_t - m_b$

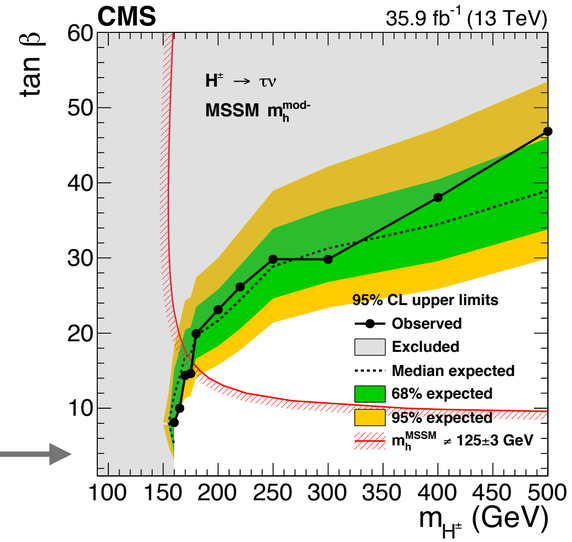






Model independent

- $m_{H^\pm}$ range: 80 — 3000 GeV
- Final states: τ_h+jets, l+τ_h, l+no τ_h
- 2 cat. exploiting helicity correlations from opposite polarization states of τ from H and W decays
- Final discriminant is transverse mass

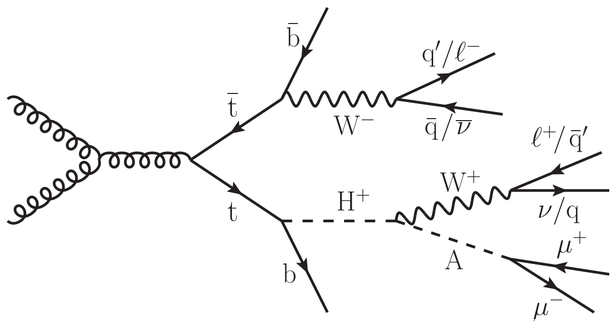


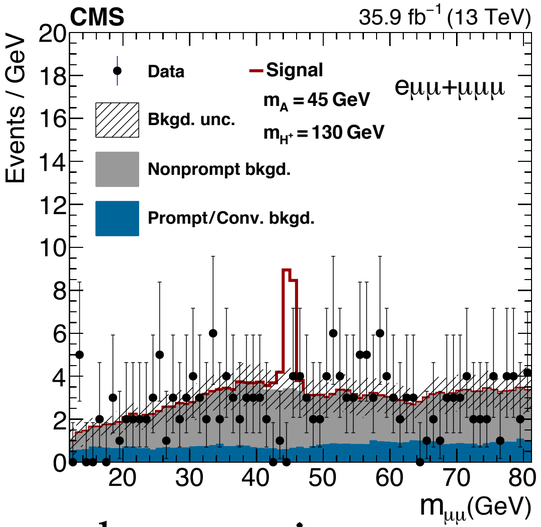
All tanβ values excluded for $m_{H^\pm} < 160$ GeV

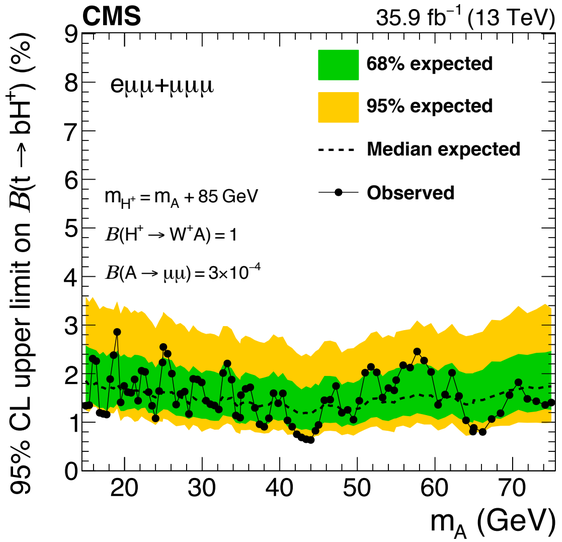
Charged boson: $H^+ \rightarrow W^+A$

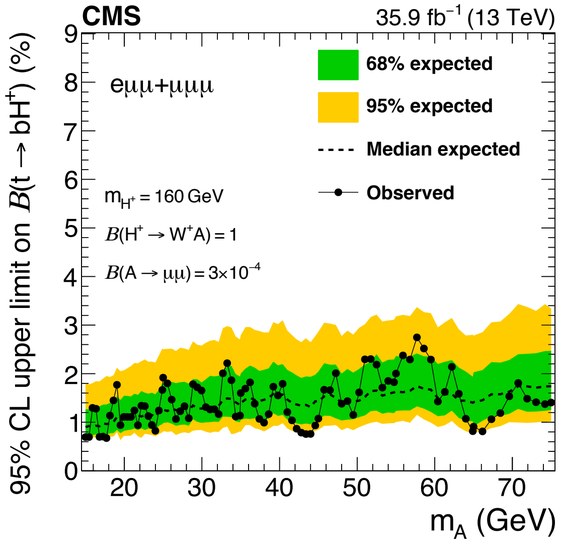
CMS-HIG-18-020
arXiv:1905.07453

- H^+ from a top quark in top pairs events
  - $A \rightarrow \mu\mu$, $WW \rightarrow l\nu q\bar{q}$
- $15 < m_A < 75$ GeV
- $m_A + 85\text{GeV} < m_{H^+} < 160$ GeV
- Signal estimated from event yield in $m_{\mu\mu}$ in mass windows
- Limits on $BR(t \rightarrow bH^+)$ from combined likelihood of yields from $e\mu\mu$ and $\mu\mu\mu$ channels assuming $BR(H^+ \rightarrow WA) = 1$ and $BR(A \rightarrow \mu\mu) = 3\times10^{-4}$
  - $B(t \rightarrow bH^+) > 2.9\%$ is excluded at 95% CL in the whole mass range
  - observed upper limits varies between 0.63% and 2.9%







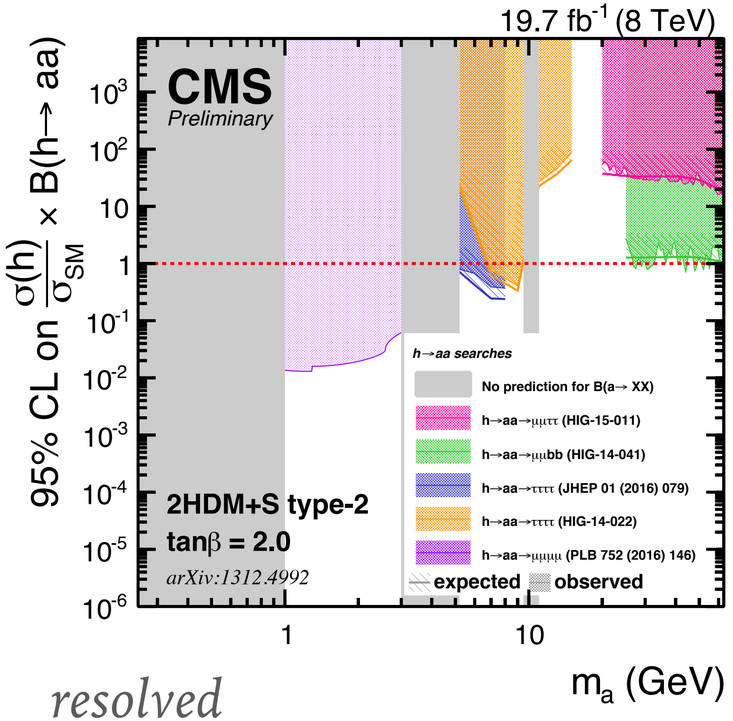


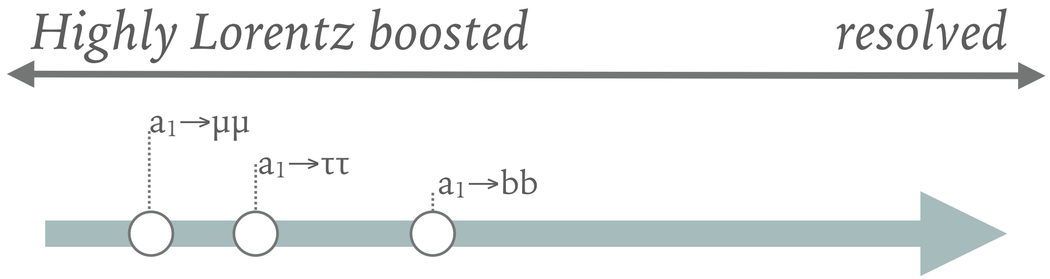
Low mass scalar: $h \rightarrow a_1 a_1$

- $a_1 \rightarrow bb$
  - pros:
    - Large BR
  - cons:
    - Hard to trigger
    - Low identification efficiency
    - High p_T thresholds
    - Large jet-backgrounds

- $a_1 \rightarrow \tau\tau$
  - pros:
    - Large BR
    - Possible to trigger on leptonic τ decays
  - cons:
    - Low τ_h identification efficiency
    - τ_h high p_T thresholds (> 20 GeV)

- $a_1 \rightarrow \mu\mu$
  - pros:
    - Excellent mass resolution
    - Easy to trigger
    - Easy identification, with low p_T
    - Open for any $m_a > 2m_\mu$
  - cons:
    - Low BR





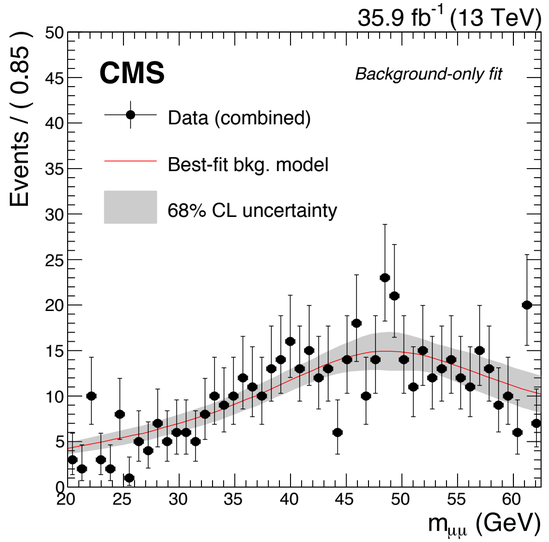
With SM-like couplings:

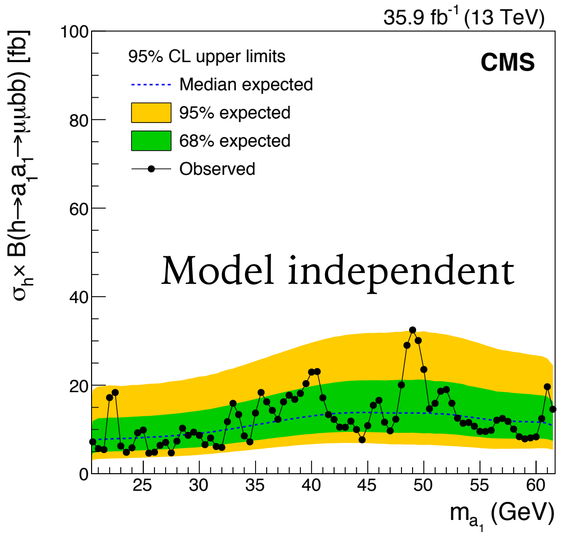
$\mathrm{BR}(a \rightarrow bb) \sim 9\,\mathrm{BR}(a \rightarrow \tau\tau) \sim 1700\,\mathrm{BR}(a \rightarrow \mu\mu)$

Low mass scalar: $h \rightarrow a_1 a_1 \rightarrow 2b2\mu$

CMS-HIG-18-011
arXiv:1812.06359

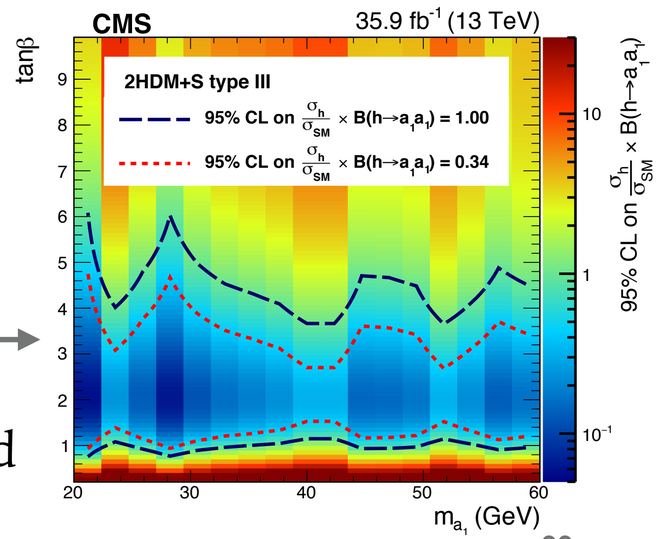
- 2HDM+S model. S=SR+iSI. a1 pseudoscalar mostly SI
  - benchmark BR(h→aa)~10%
- $20 < m_a < 62.5$ GeV
- SR: $m(\mu\mu) \simeq m(bb) \simeq m_a$
- Categories defined according to b-tag WP (TT, TM, TL)





- $m(\mu\mu)$ final discriminant
- Signal selection optimised for 2μ2b process, but $h \rightarrow aa \rightarrow 2\mu 2\tau$ contributes if τ_h misidentified as b-jet

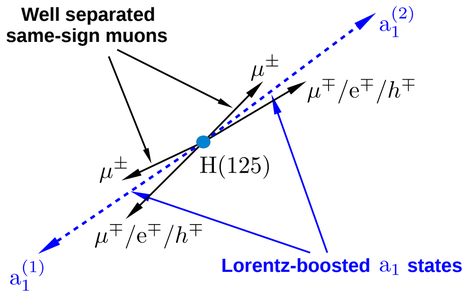
Model dependent type-III 2HDM+S including 2μ2τ signal from b-jets mis-id

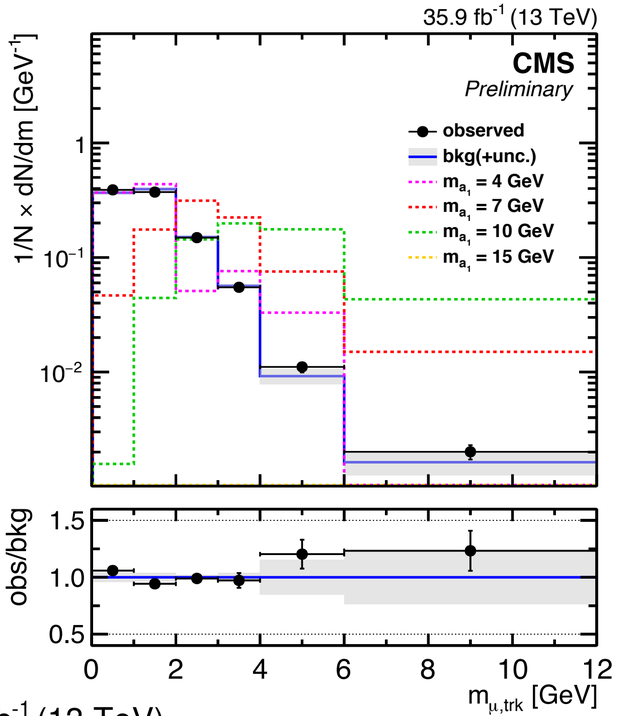


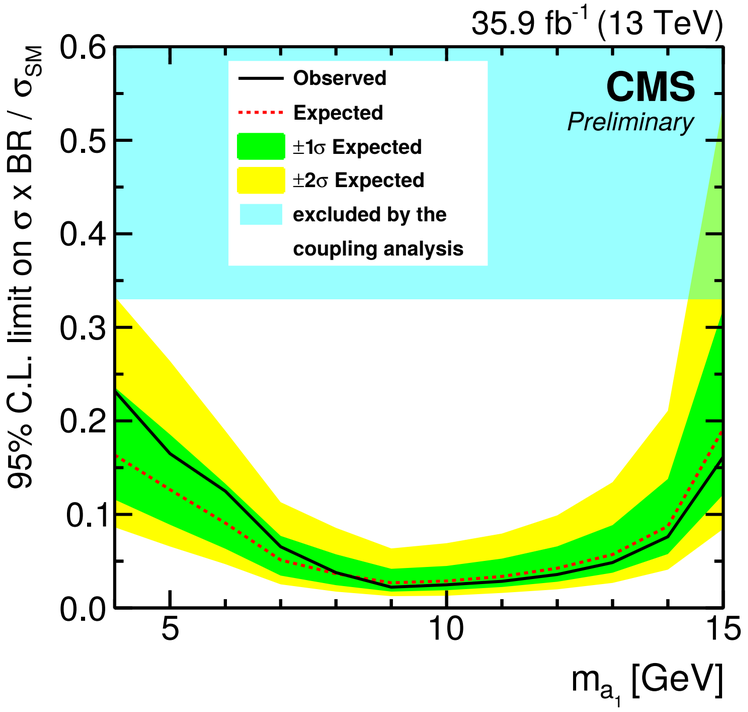
Low mass scalar: $h \rightarrow a_1 a_1 \rightarrow 4\tau$, $2\mu 2\tau$

[CMS-PAS-HIG-18-006]

- 2HDM+S model. S=SR+iSI. a_1 pseudoscalar mostly SI
- $4 < m_a < 15$ GeV
- complement of $h \rightarrow a_1 a_1$ in $2\mu 2\tau$, $2\tau 2b$, 4μ
- each a_1 identified by one muon and one nearby charged particle (e, μ or τ one-prong)
  - targeting mainly ggF or ggF+ISR
- 2D search in $(m(\mu_1, trk_1), m(\mu_2, trk_2))$ plane
- **Improves Run 1** CMS limits of 30% (low masses) - 80% (intermediate masses)



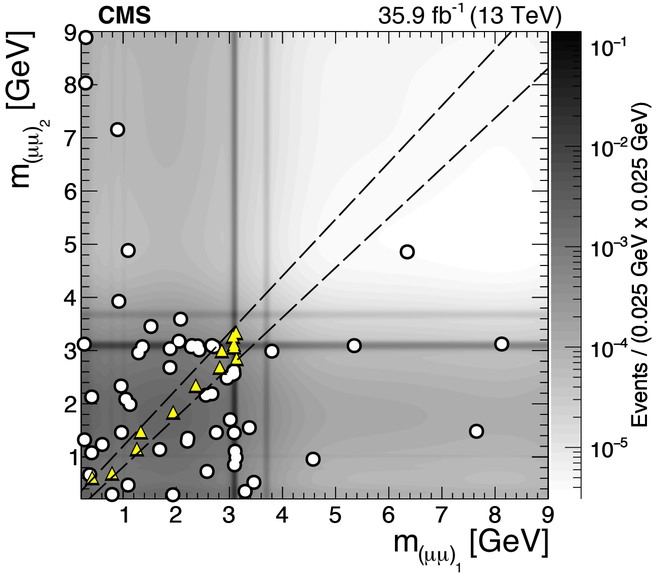




Low mass scalar: $h \rightarrow a_1 a_1 \rightarrow 4\mu$

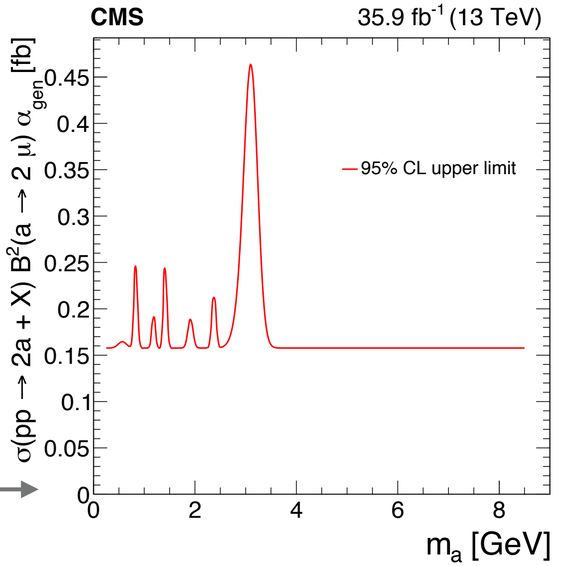
CMS-HIG-18-003
arXiv:1812.00380

- m_a range: 0.25 ÷ 8.5 GeV
- Di-muons constructed from pairs of OS muons sharing a common vertex and $m(\mu\mu) < 9$ GeV
- SR: $m(\mu\mu)_1 \approx m(\mu\mu)_2$



- 13 events in SR (▲)
- expected from SM:
  $9.90 \pm 1.24\ (\text{stat}) \pm 1.84\ (\text{syst})$
- No significant excess observed

model independent →



simplified scenario →