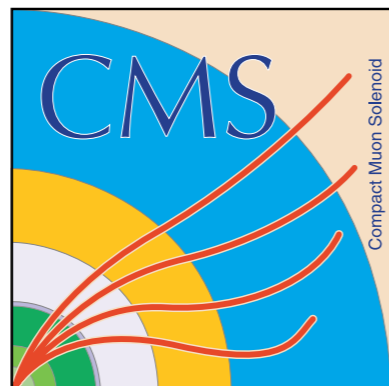


Search for supersymmetric neutral Higgs bosons using CMS Run I data

Francesca Ricci-Tam
(for the CMS collaboration)
August 27, 2015



UC DAVIS
UNIVERSITY OF CALIFORNIA

Motivations

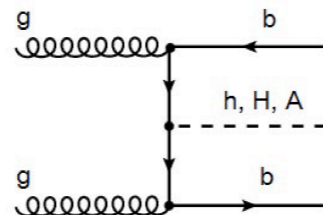
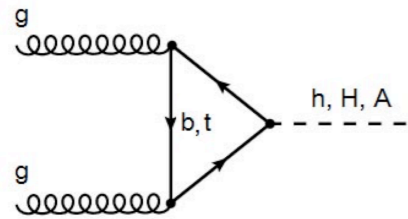


- SUSY provides ways to address the hierarchy problem and other deficiencies of the Standard Model
- Multiple Higgs bosons predicted
 - MSSM: H^\pm , H , h , A
 - NMSSM: H^\pm , h_1 , h_2 , h_3 , a_1 , a_2
 - Is the observed 125-GeV Higgs actually one of several?
- Focus of this talk: recent Run I searches at CMS for neutral Higgs bosons

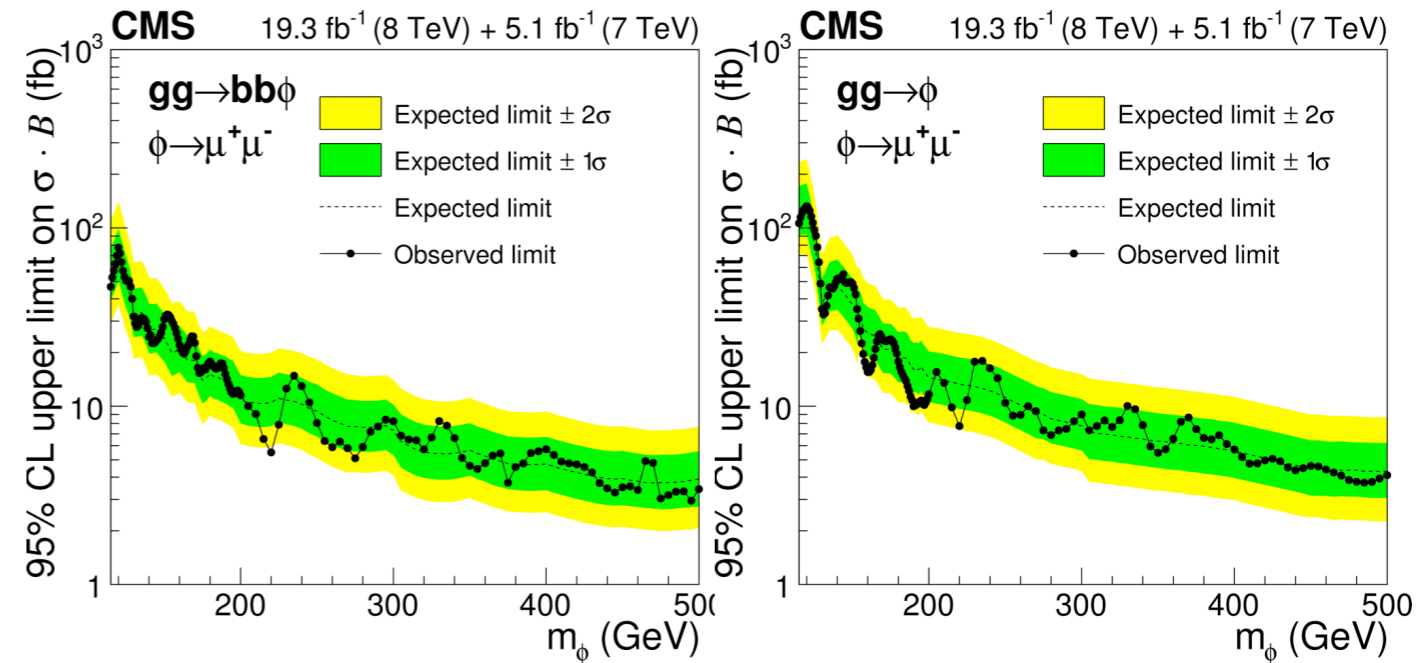
MSSM $\Phi \rightarrow \mu\mu$



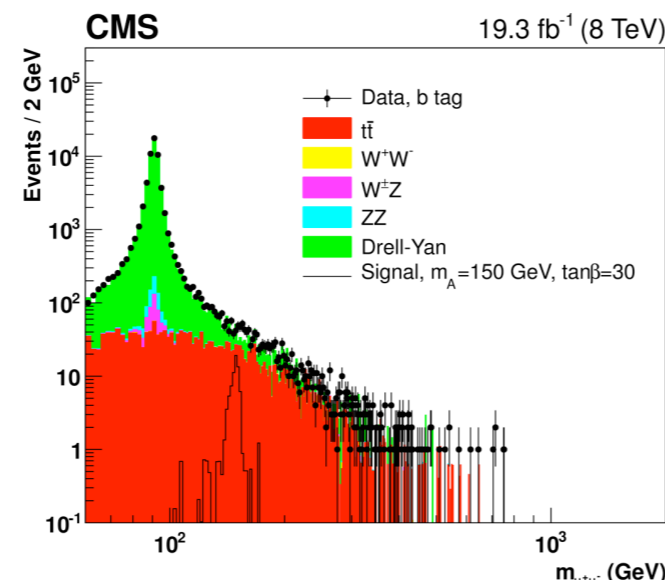
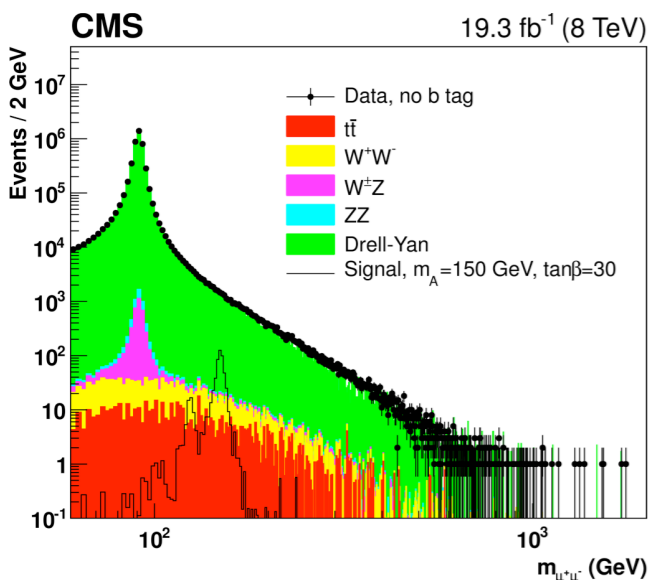
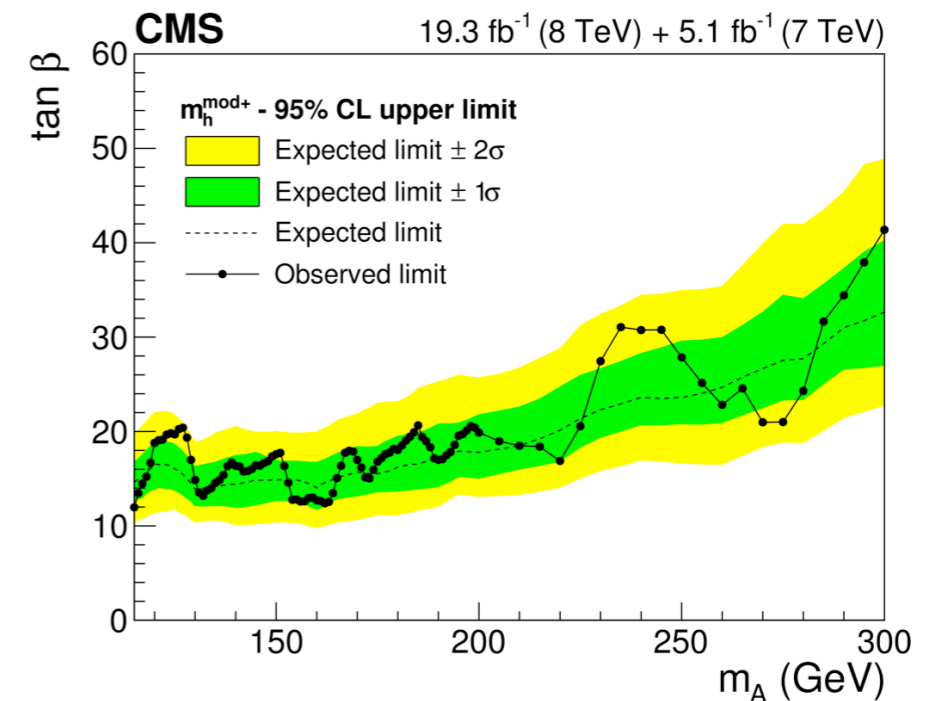
- **HIG-13-024**
- $\Phi = h, H, \text{ or } A$
- Higgs coupling to down-type quarks and charged leptons enhanced at large $\tan\beta$
- Bump hunt in dimuon invariant mass spectrum (115-300 GeV range) for dominant production channels ggH and bbH
- 0 b-jet and ≥ 1 -bjet categories



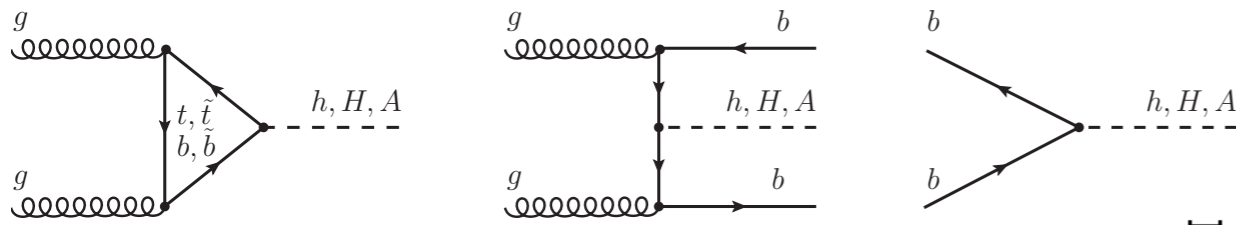
Model-independent limits



Model-dependent limits

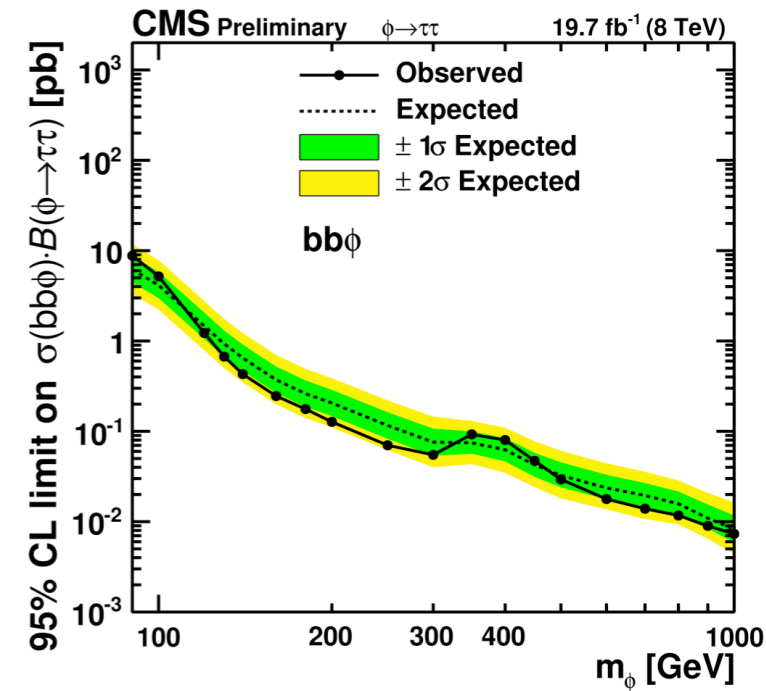
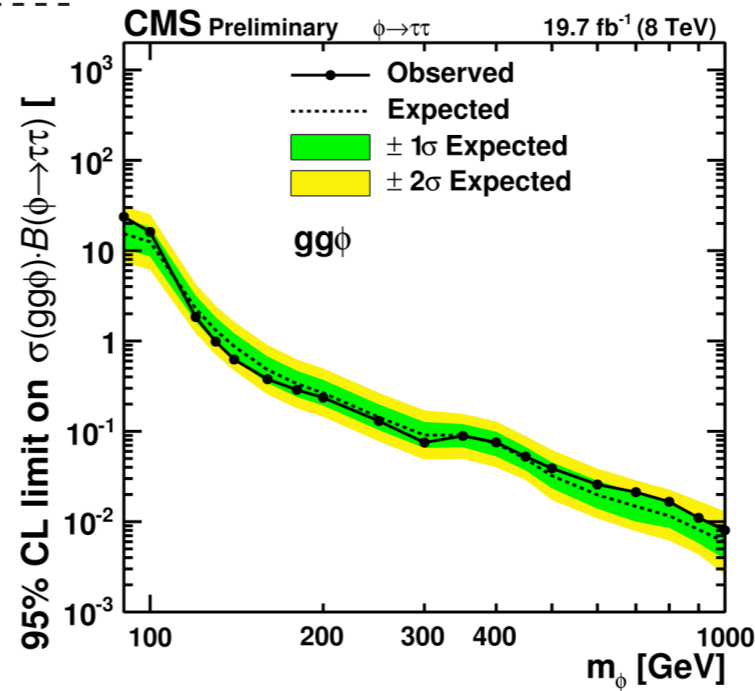


MSSM $\Phi \rightarrow \tau\tau$

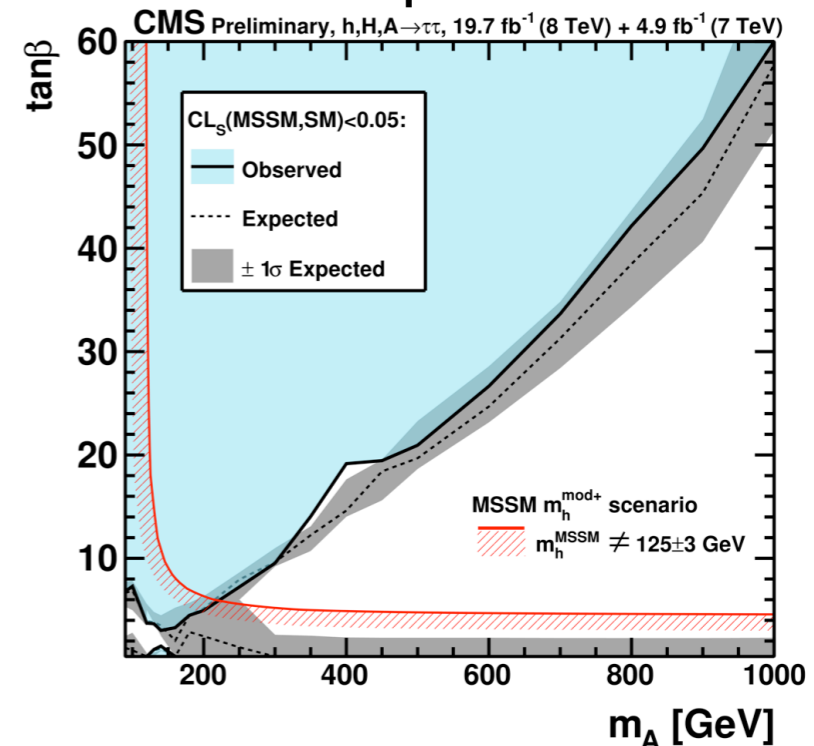


- **HIG-14-029**
- $\Phi = h, H, \text{ or } A$
- $e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h$ channels
- Search in dominant production channels bbH and ggH for excess in ditau invariant mass spectrum (90-1000 GeV range)
- Results can be interpreted in the context of various MSSM benchmarks: m_h^{max} , $m_h^{\text{mod+}}$ (shown), $m_h^{\text{mod-}}$, light stop, light stau

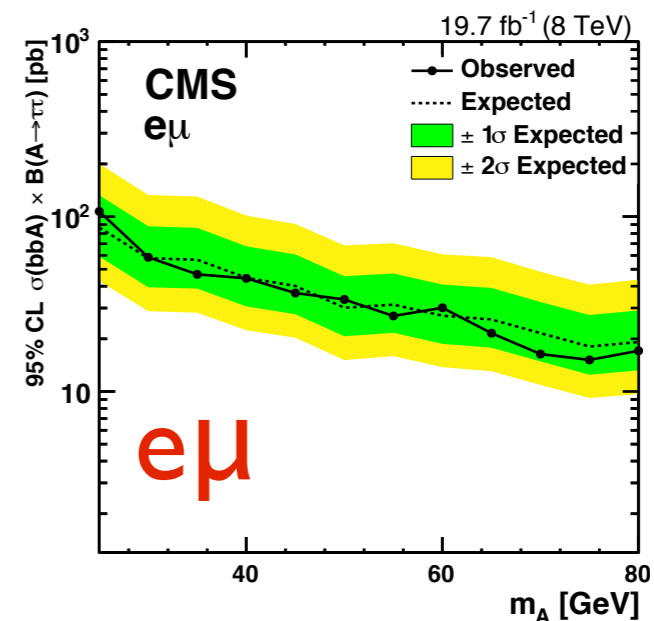
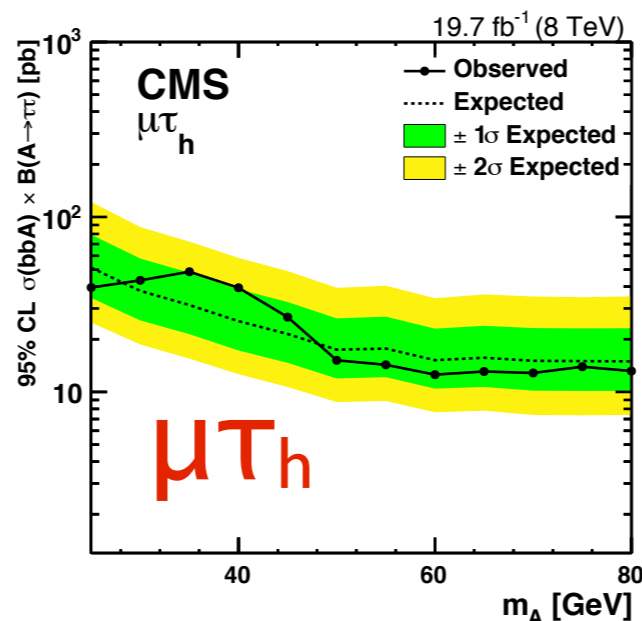
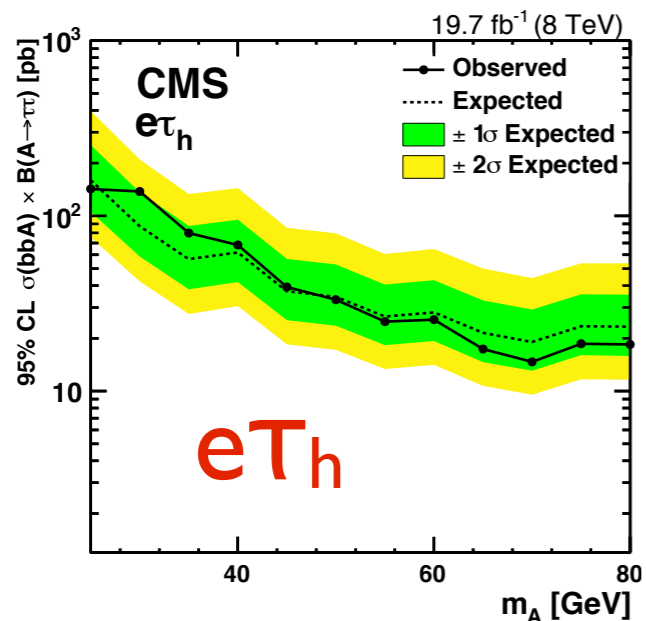
Model-independent limits



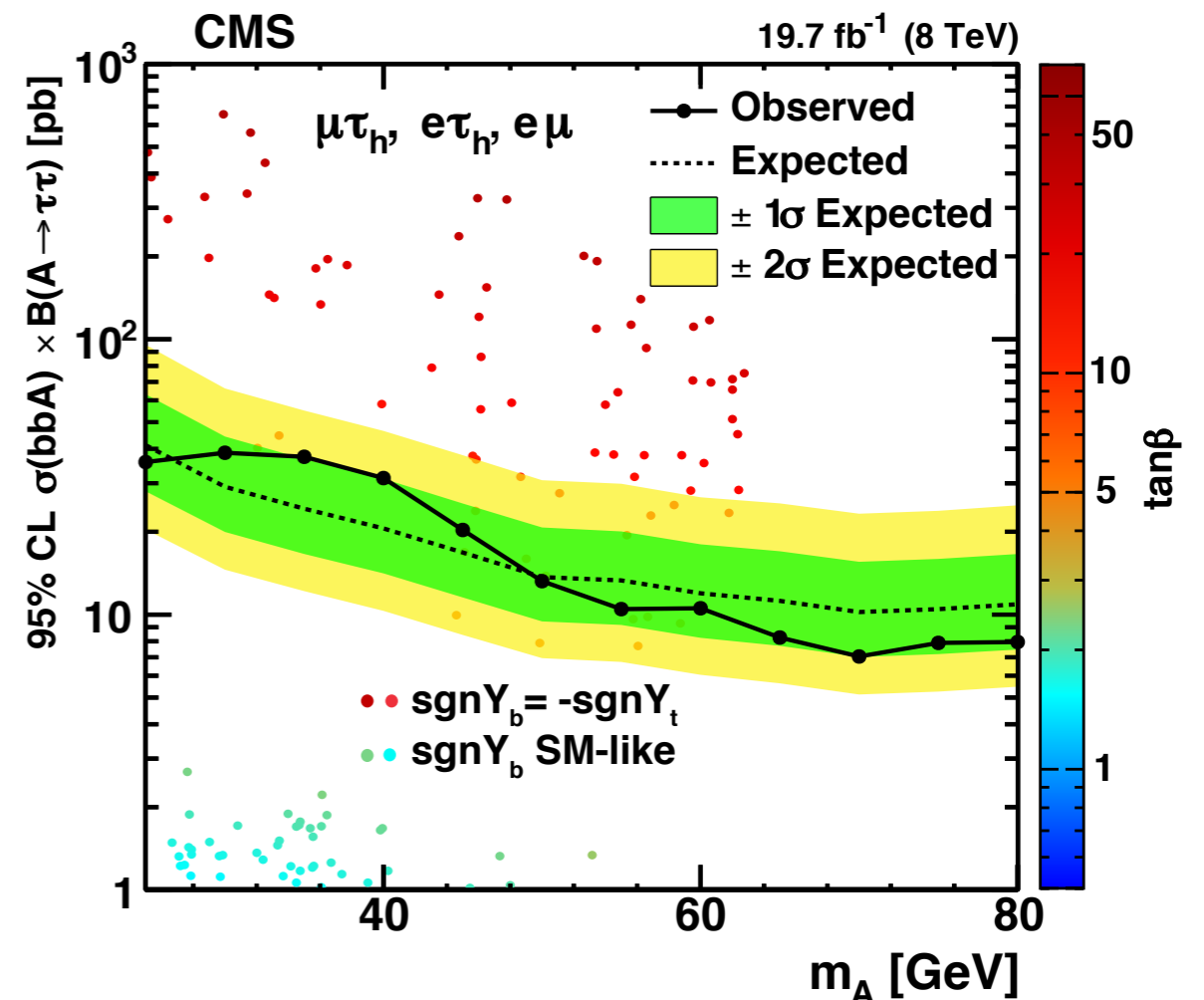
Model-dependent limits



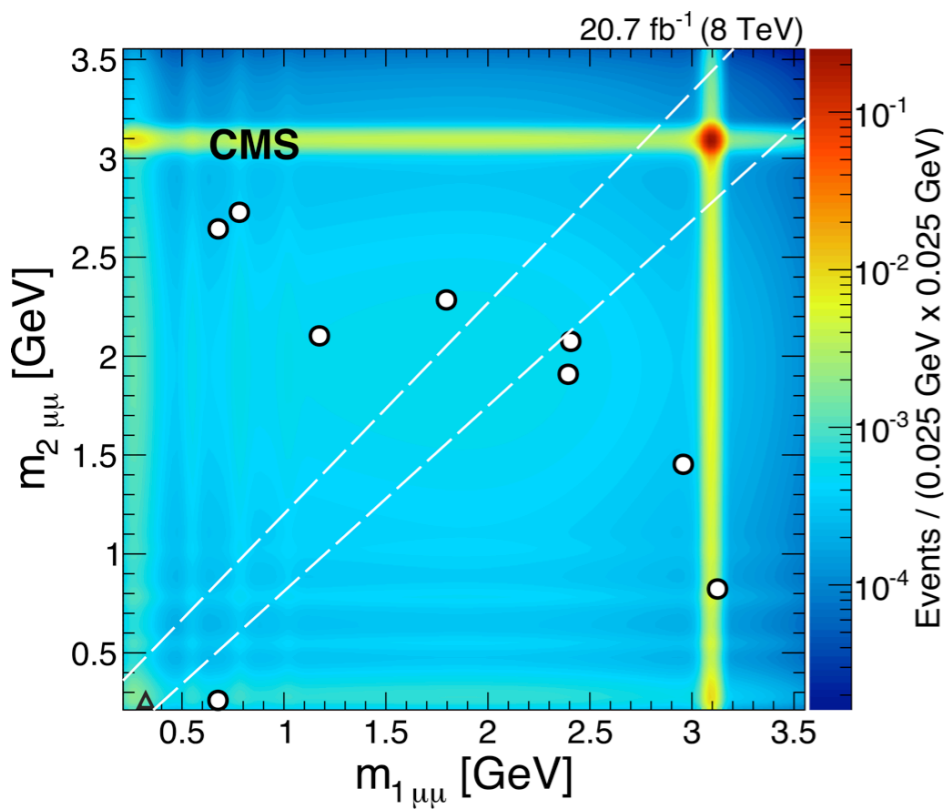
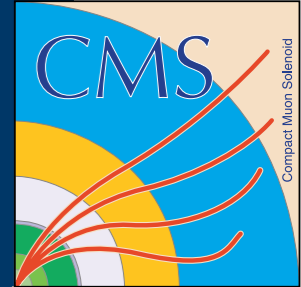
Light $A \rightarrow \tau\tau$



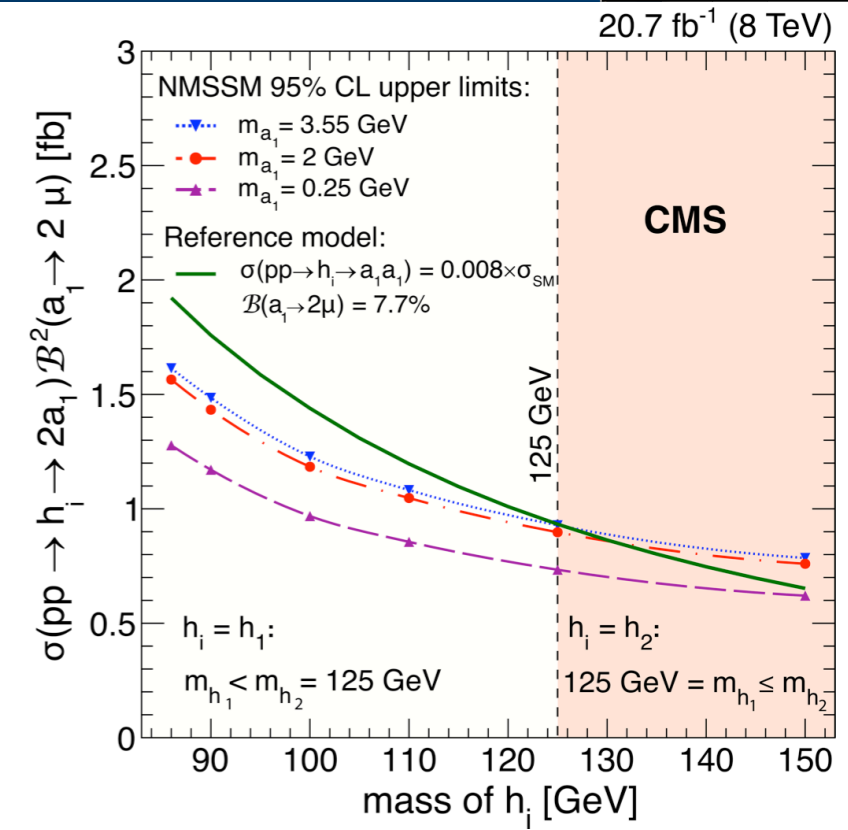
- **HIG-14-033**
- Light A excluded in MSSM but still permitted in some 2HDM scenarios
- m_A range: 25-80 GeV
- $b\bar{b}$ associated production; $e\tau_h$, $\mu\tau_h$, $e\mu$ channels
- Binned likelihood fit to $e\tau_h$, $\mu\tau_h$, $e\mu$ invariant mass spectra
- Model-independent limits
 - above: individual $\tau\tau$ decay mode channels
 - right: decay mode channels combined, overlaid with theory prediction (exclusion of light $A \rightarrow \tau\tau$ in Type II 2HDM with negative Yukawa coupling)



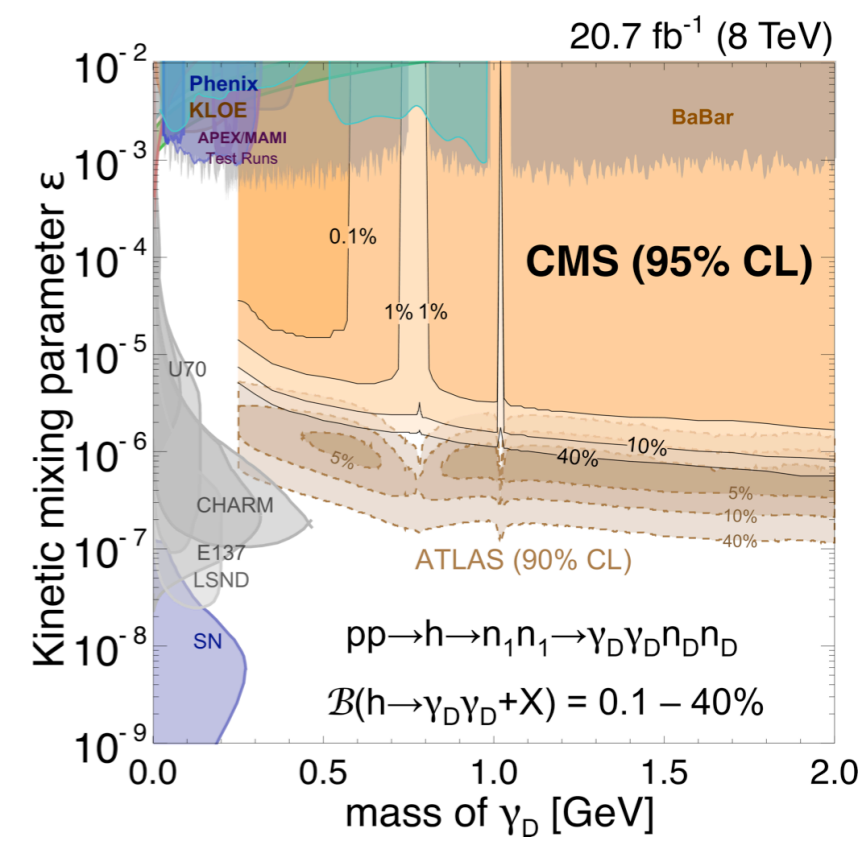
Search for light bosons in 4 μ final state



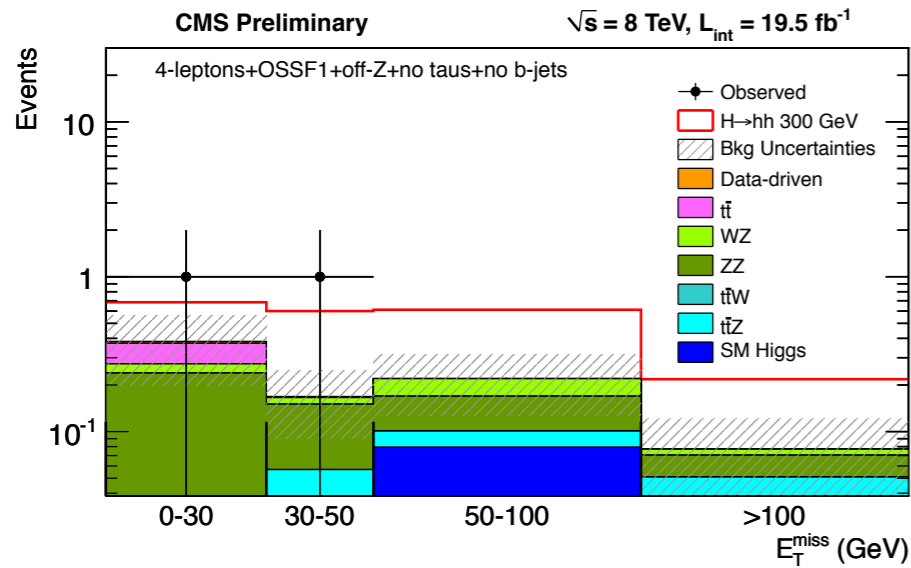
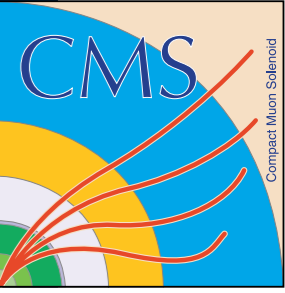
- **HIG-13-010**
- Clean final state
- 2D likelihood template for $m_{1\mu\mu}$ vs $m_{2\mu\mu}$



- Limits interpreted in context of two supersymmetric scenarios
- NMSSM benchmark
 - $h_1 \rightarrow a_1 a_1 \rightarrow 4\mu$ (m_a : 0.25-3.55 GeV, m_H : 90-150 GeV)
- Dark SUSY benchmark
 - $h \rightarrow 2n_1 \rightarrow 2\gamma_D 2n_D$, each $\gamma_D \rightarrow 2\mu$ (γ_D mass 0.25-2.0 GeV, SM-like Higgs)
 - new, large area of (m_{γ_D} , ϵ) parameter space constrained
- Weak model dependence allows interpretations in other contexts as well



Searches for massive neutral (pseudo)scalars: $H \rightarrow hh$ and $A \rightarrow Zh$



$H \rightarrow hh$ final states

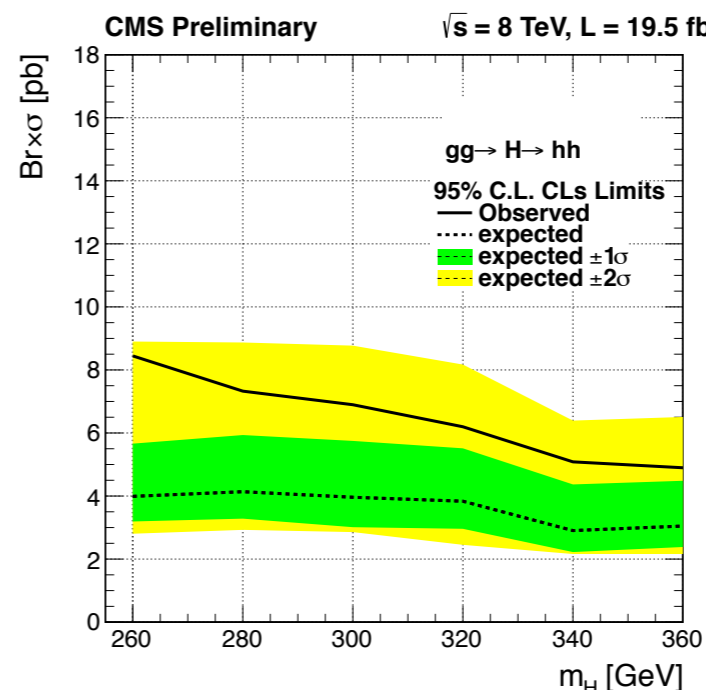
	$h \rightarrow WW^*$	$h \rightarrow ZZ^*$	$h \rightarrow \tau\tau$	$h \rightarrow bb$	$h \rightarrow \gamma\gamma$
$h \rightarrow WW^*$	✓	✓	✓	X	✓
$h \rightarrow ZZ^*$	-	✓	✓	✓	✓
$h \rightarrow \tau\tau$	-	-	✓	X	✓
$h \rightarrow bb$	-	-	-	X	X
$h \rightarrow \gamma\gamma$	-	-	-	-	X

$A \rightarrow Zh$ final states

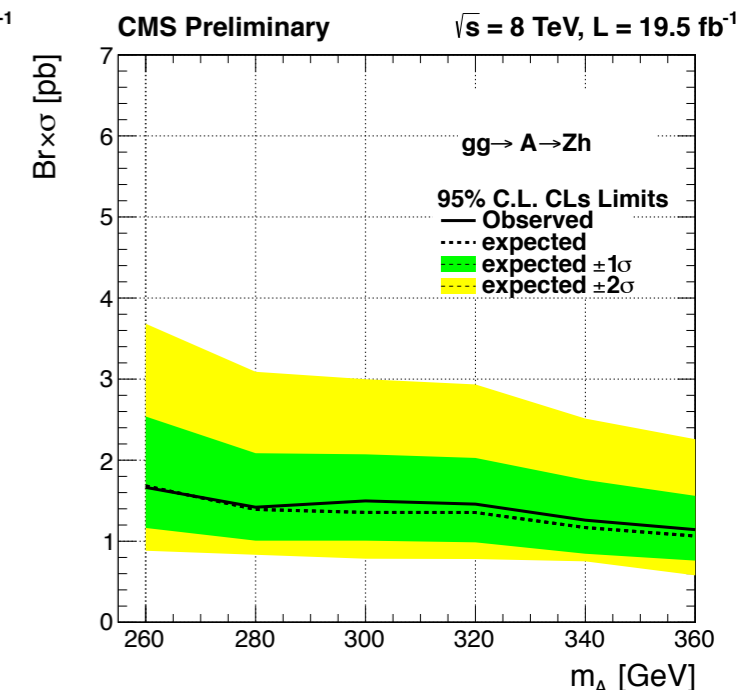
	$h \rightarrow WW^*$	$h \rightarrow ZZ^*$	$h \rightarrow \tau\tau$	$h \rightarrow \gamma\gamma$
$Z \rightarrow ll$	✓	✓	✓	✓
$Z \rightarrow qq$	X	✓	X	X
$Z \rightarrow \nu\nu$	X	✓	X	X

- **HIG-13-025: (>3)-lepton final state or diphoton+(>1)-lepton final state**
- $H \rightarrow hh$ and $A \rightarrow Zh$ signatures
- h decays to diboson, ditau, or diphoton final states
- Searches in multiple exclusive channels
 - 1-2 leptons + 2γ (lepton = $e, \mu, \text{or } \tau_h$)
 - 3+ leptons
 - Further classification based on on/off-Z lepton pairs, presence of τ_h , b-tagging, MET
- Expected backgrounds taken from MC and data control regions
- Limits set on $\sigma \cdot \text{Br}$ for $H \rightarrow hh$ and $A \rightarrow Zh$

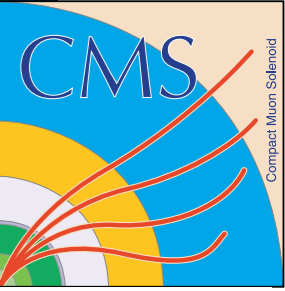
$gg \rightarrow H \rightarrow hh$



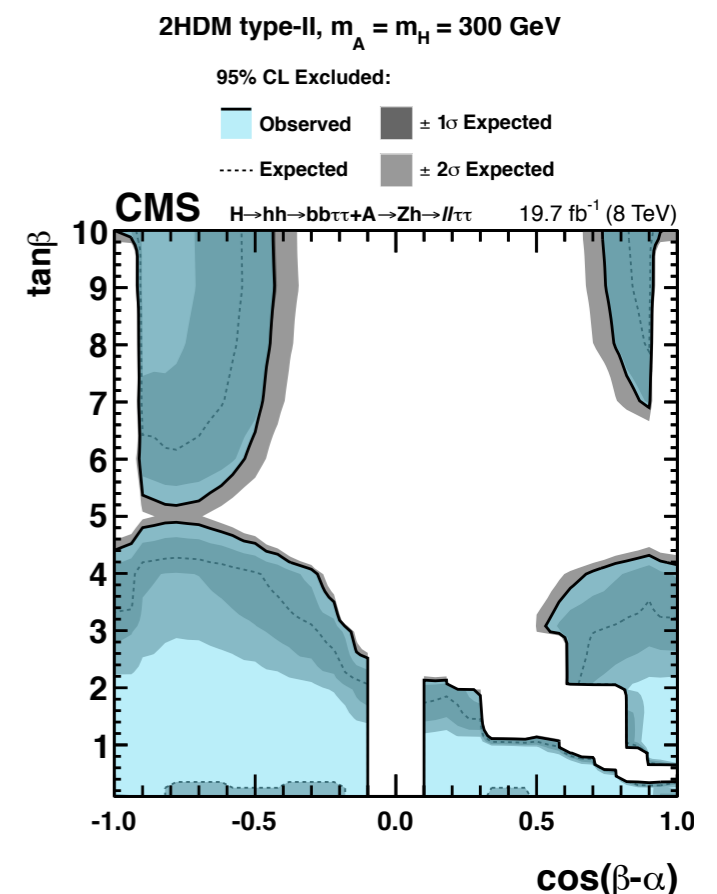
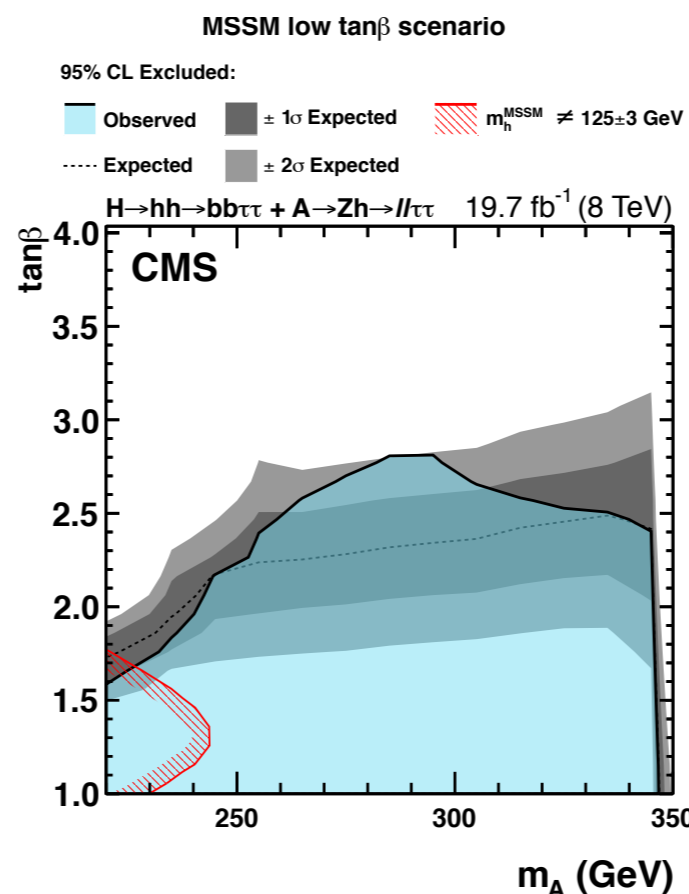
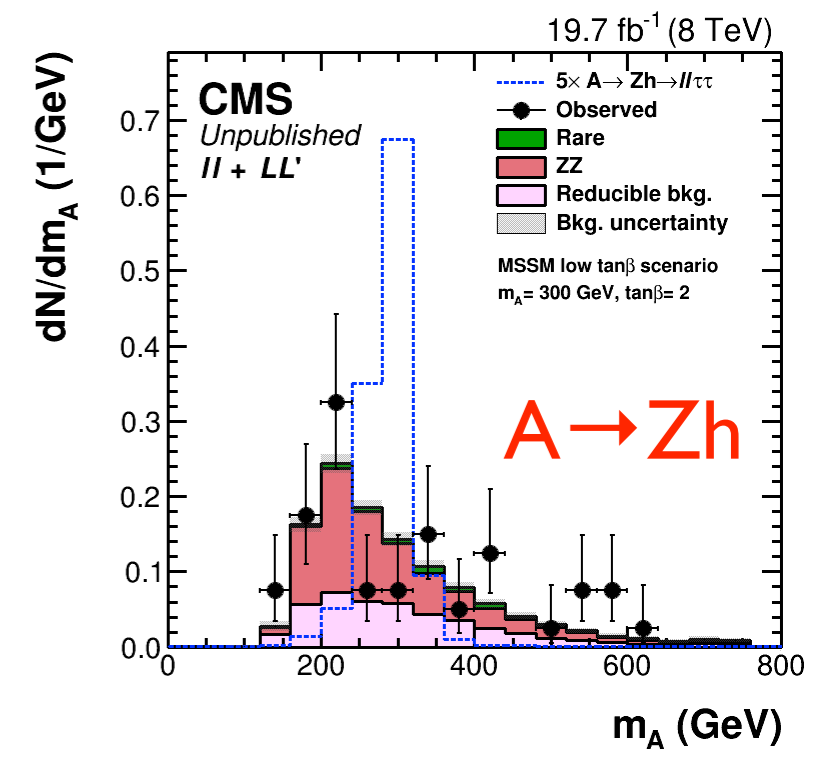
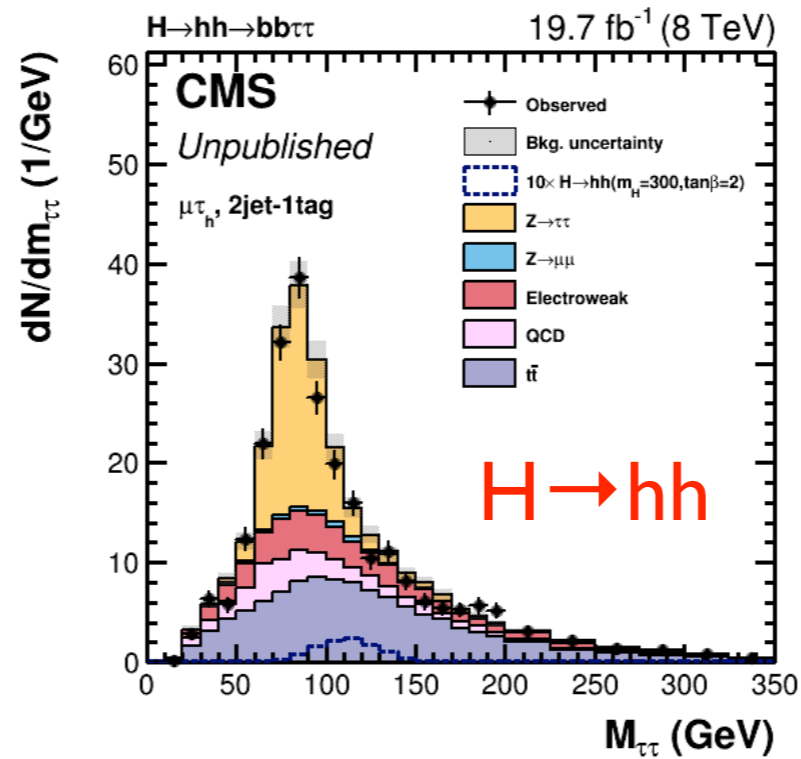
$gg \rightarrow A \rightarrow Zh$



Searches for massive neutral (pseudo)scalars: $H \rightarrow hh$ and $A \rightarrow Zh$



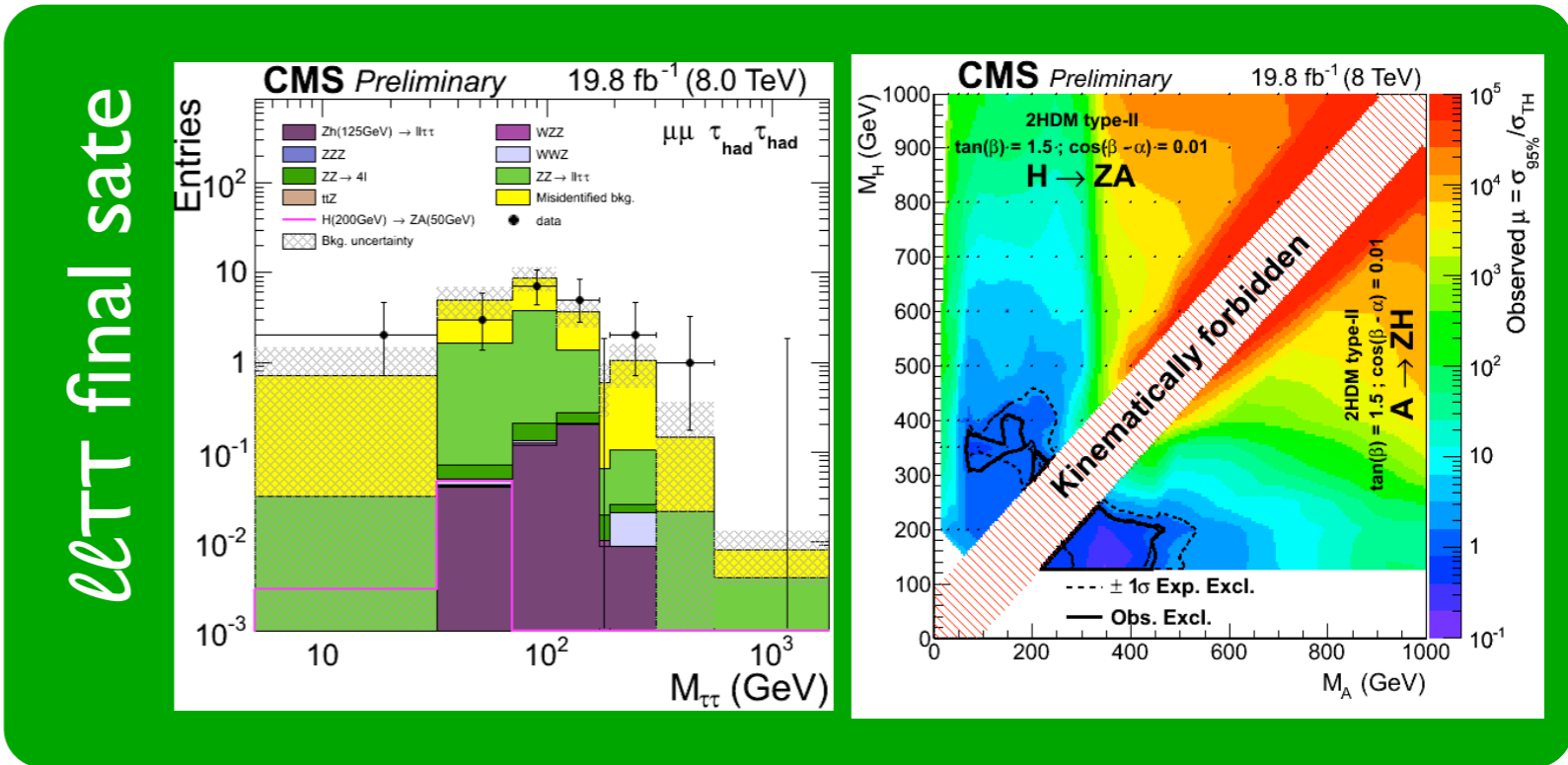
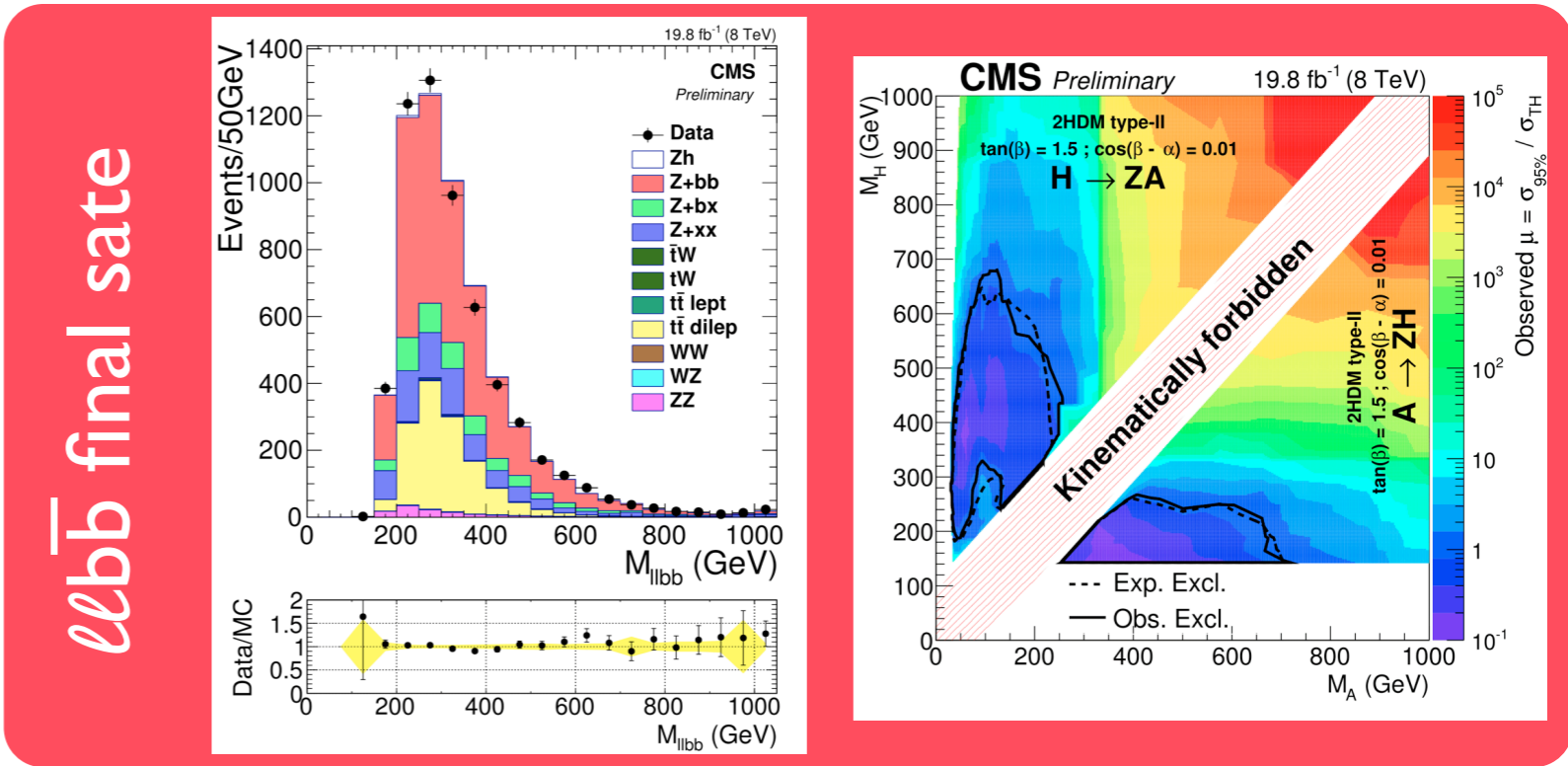
- **HIG-14-034: $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$, $A \rightarrow Zh \rightarrow \ell\ell\tau\tau$**
- $\ell = e, \mu$
- $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_h\tau_h$ modes
- Four-body mass used as distribution for signal extraction
- $H \rightarrow hh$: four-body mass reconstructed from kinematic fit
- $A \rightarrow Zh$: four-body mass reconstructed from Z candidate and ditau mass
- No excess found; results interpreted in the context of MSSM low $\tan\beta$ and 2HDM Type II scenarios



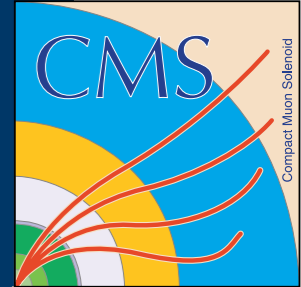
Searches for massive neutral (pseudo)scalars: $H(A) \rightarrow ZA(H)$



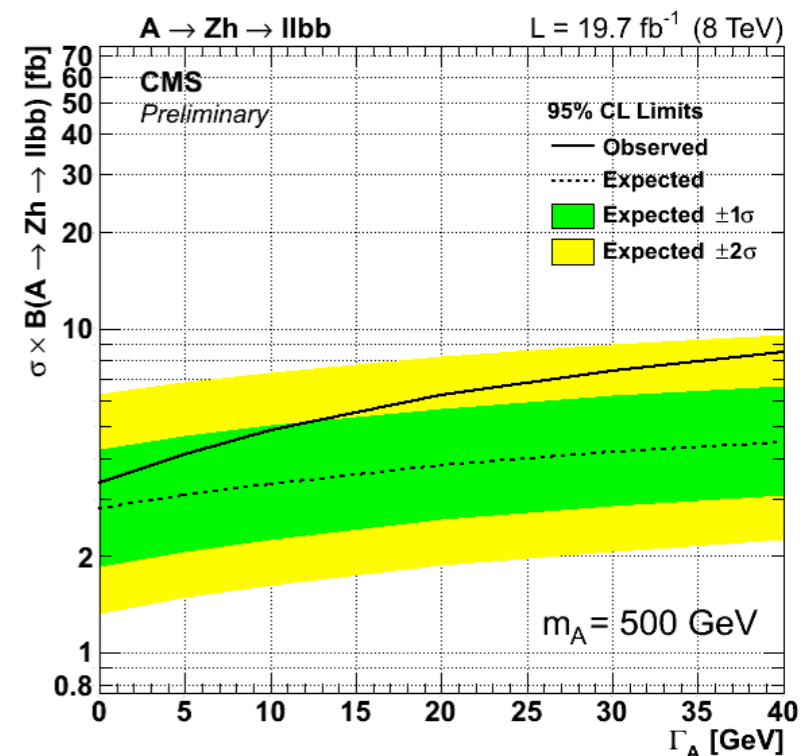
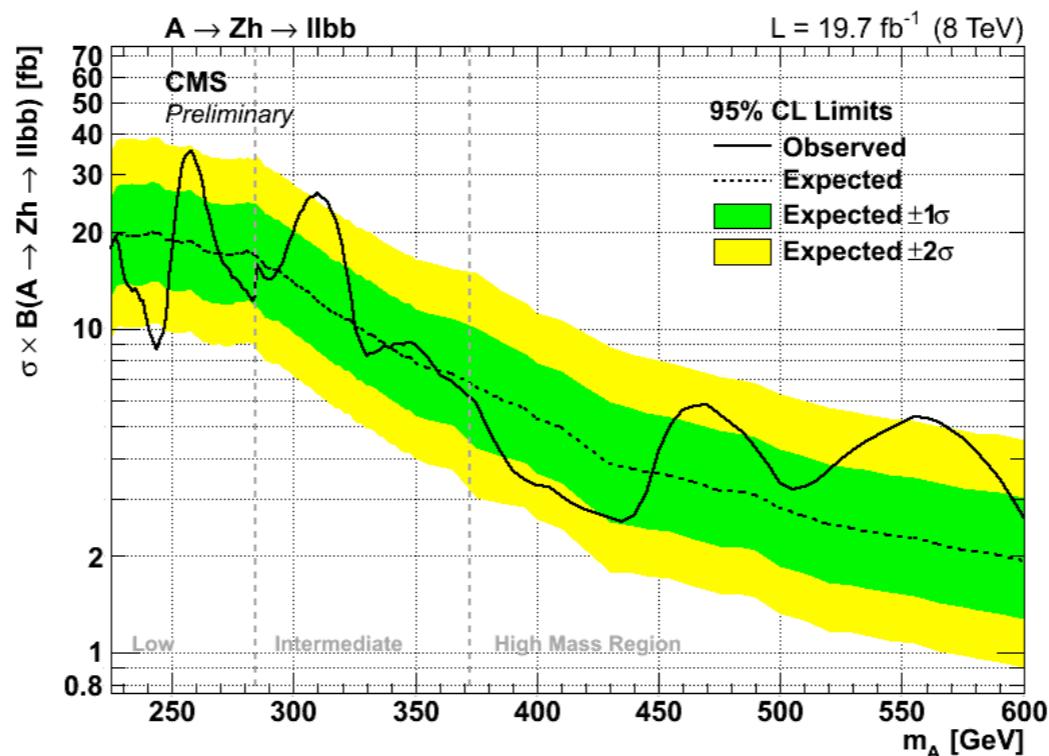
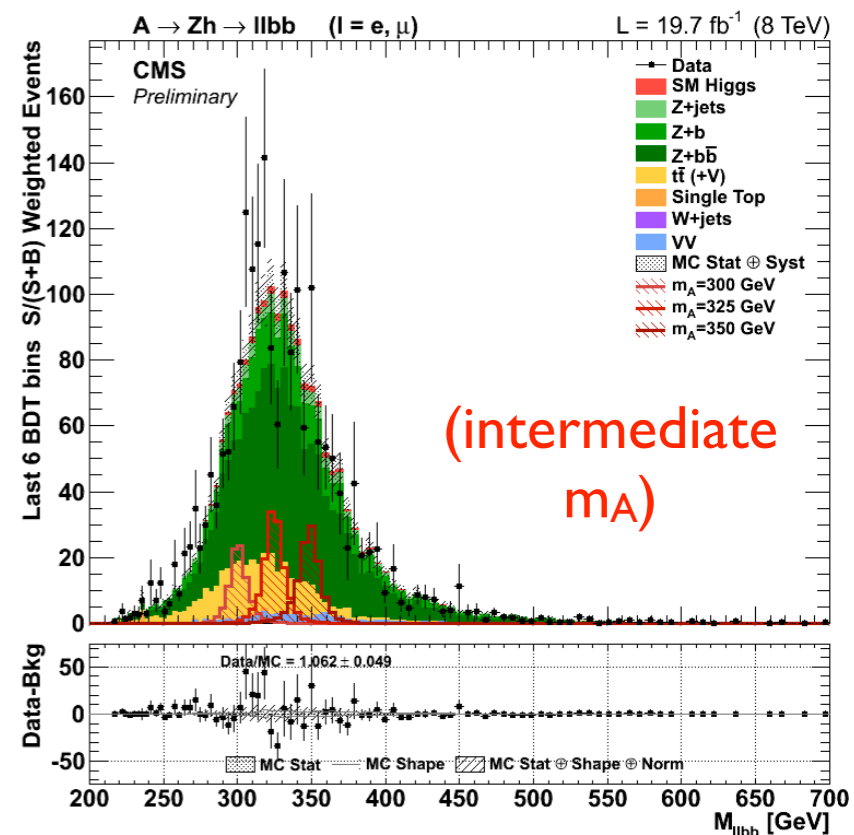
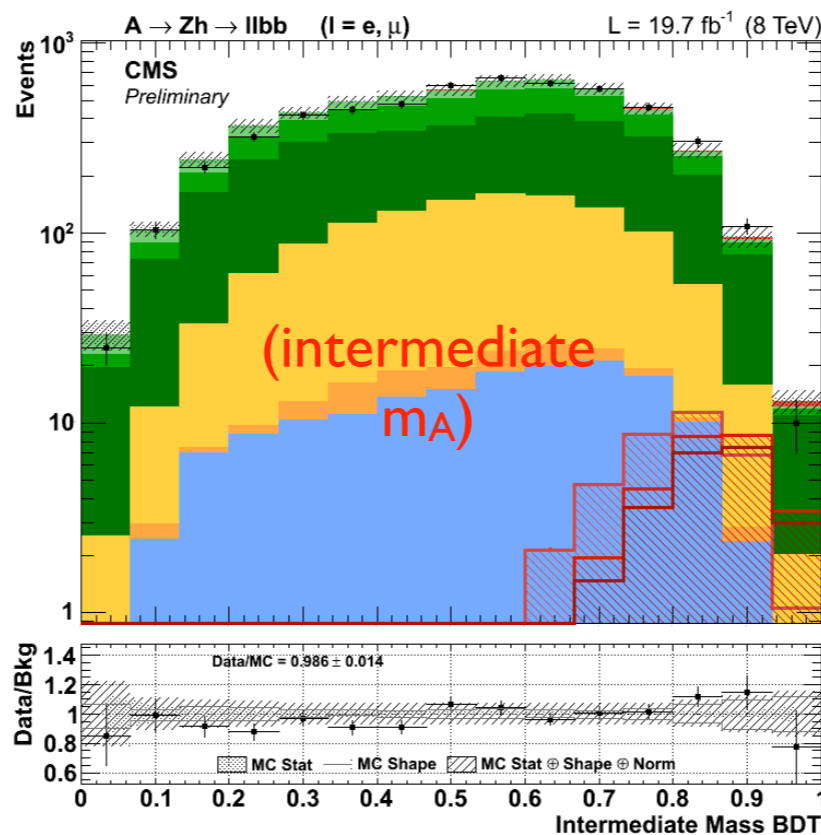
- $H(A) \rightarrow ZA(H) \rightarrow \ell\ell b\bar{b}$ and $H(A) \rightarrow ZA(H) \rightarrow \ell\ell\tau\tau$ (HIG-15-001)
- In alignment limit, large H/A mass splitting (>100 GeV) could provide explanation for baryogenesis
- $m_{H/A}$ and $m_{A/H}$ varied within [200, 1000] GeV and [15, 900] GeV respectively; $\ell = e, \mu$; $\cos(\beta - \alpha) = 0.01$; $\tan\beta = 1.5$
- $\ell\ell b\bar{b}$ final state: counting experiment in $(M_{b\bar{b}}, M_{\ell\ell b\bar{b}})$ for more model-independence
- $\ell\ell\tau\tau$ final state: shape-based search in based on $m_{\tau\tau}$ shape, for more sensitivity to model
- counting experiment also performed as cross-check
- Two mild excesses in $\ell\ell b\bar{b}$ search at $(M_{b\bar{b}}, M_{\ell\ell b\bar{b}}) = (93, 286)$ GeV and $(575, 662)$ GeV become 1.5σ and 1.9σ after accounting for LEE
- No excesses observed in $\ell\ell\tau\tau$



$A \rightarrow Zh \rightarrow b\bar{b}$



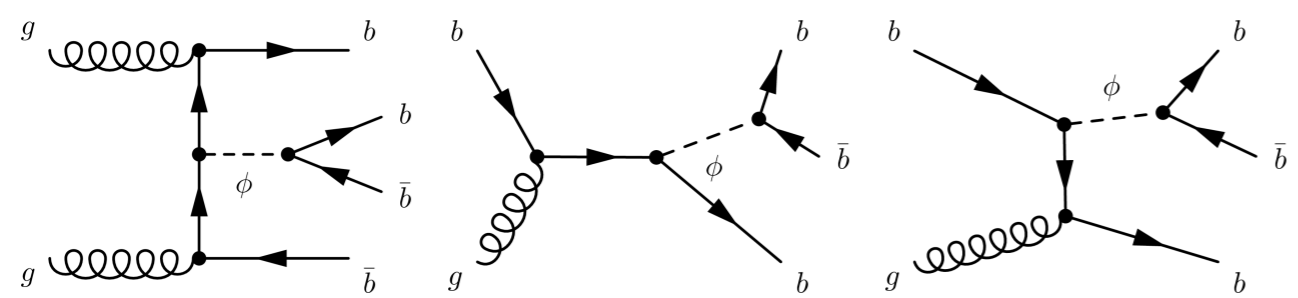
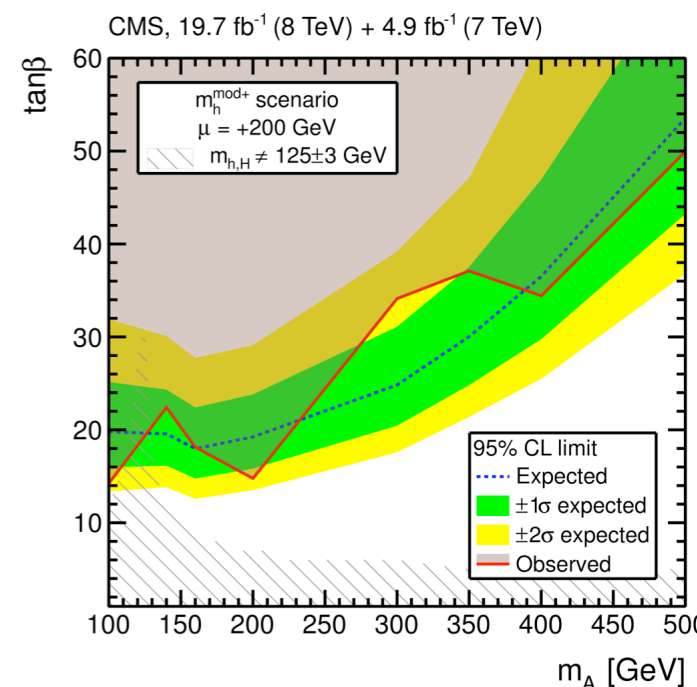
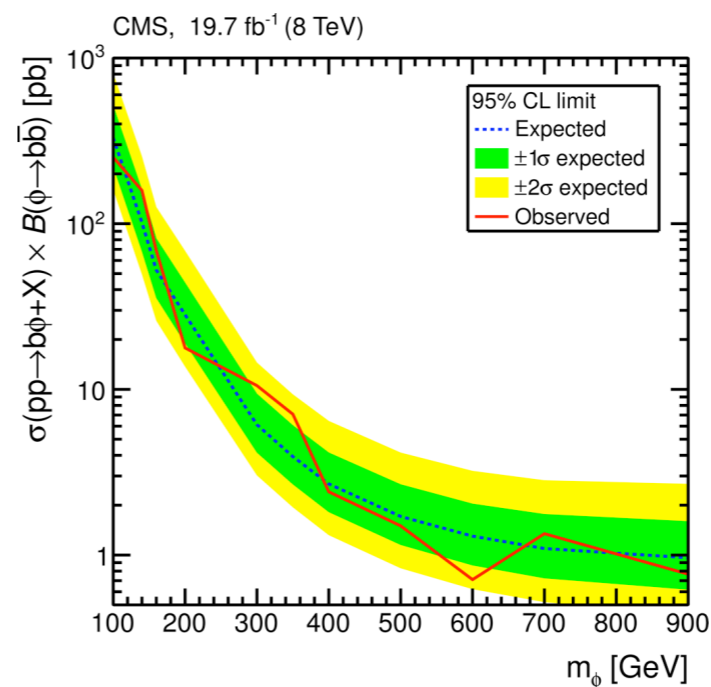
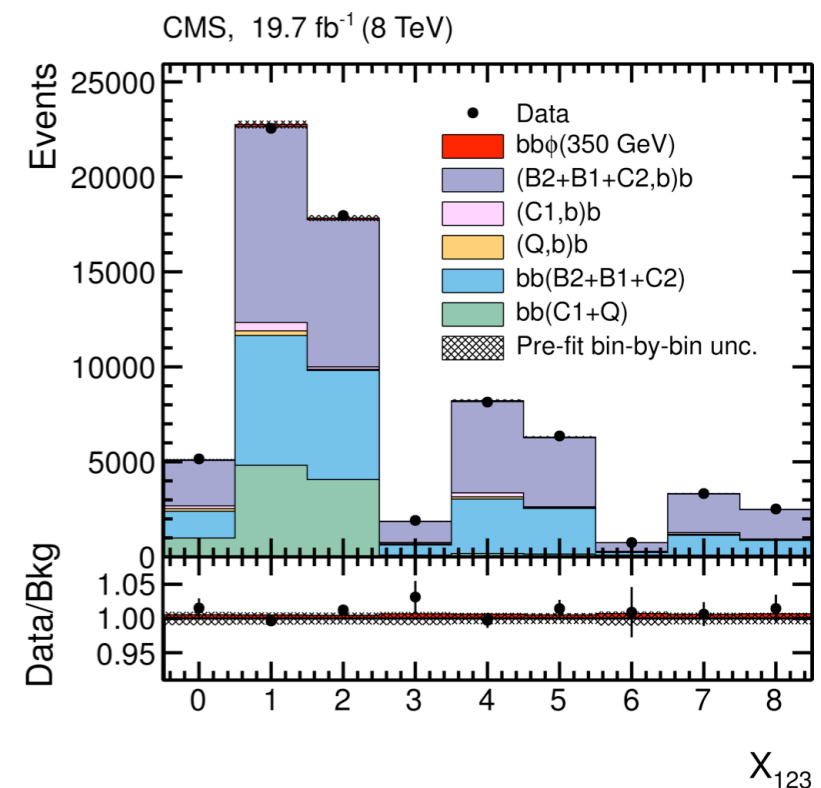
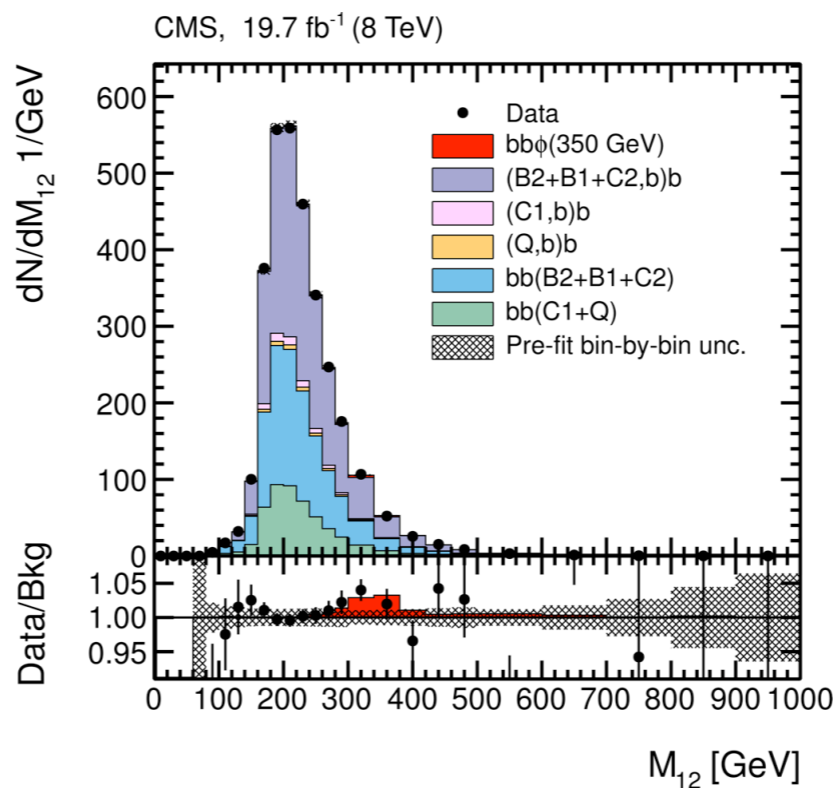
- **HIG-14-011**
- m_A range 225-600 GeV
- $\tan\beta$ varied between 0.1 to 100, $\cos(\beta-\alpha)$ between ± 1
- Selection of Z and h candidates; bump hunt in $m_{\ell b\bar{b}}$ spectrum
- For signal-to-background discrimination, separate BDTs trained for m_A regions 225-275, 300-350, and 400-600 GeV
- 2D fit to BDT vs $m_{\ell b\bar{b}}$ reveals no significant deviation from SM expectations
- Model independent and dependent limits were set
- Mild local excesses shown to be not significant after look-elsewhere effect is accounted for



MSSM $\Phi \rightarrow b\bar{b}$



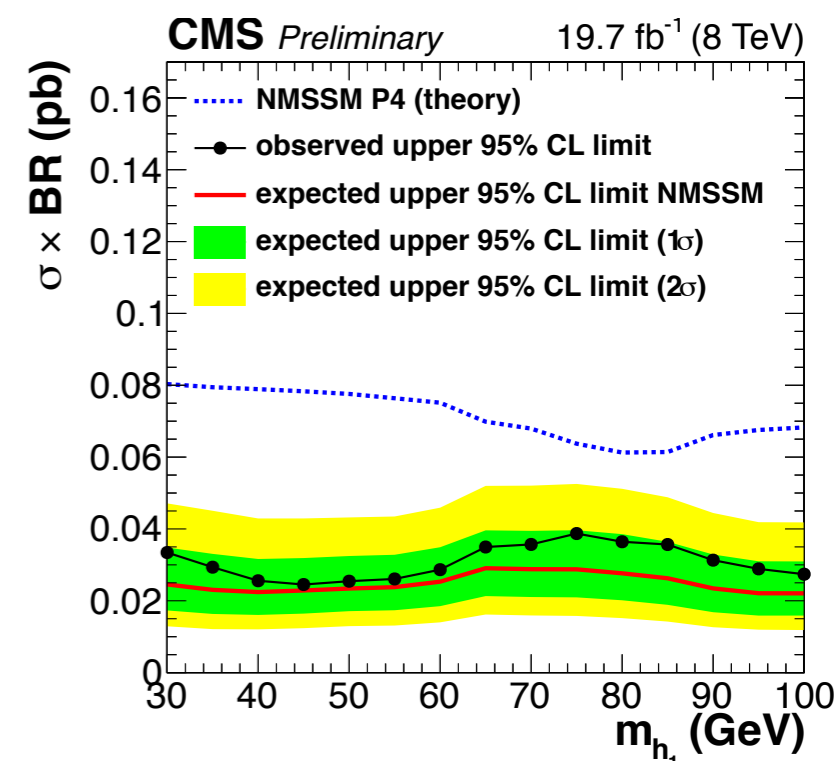
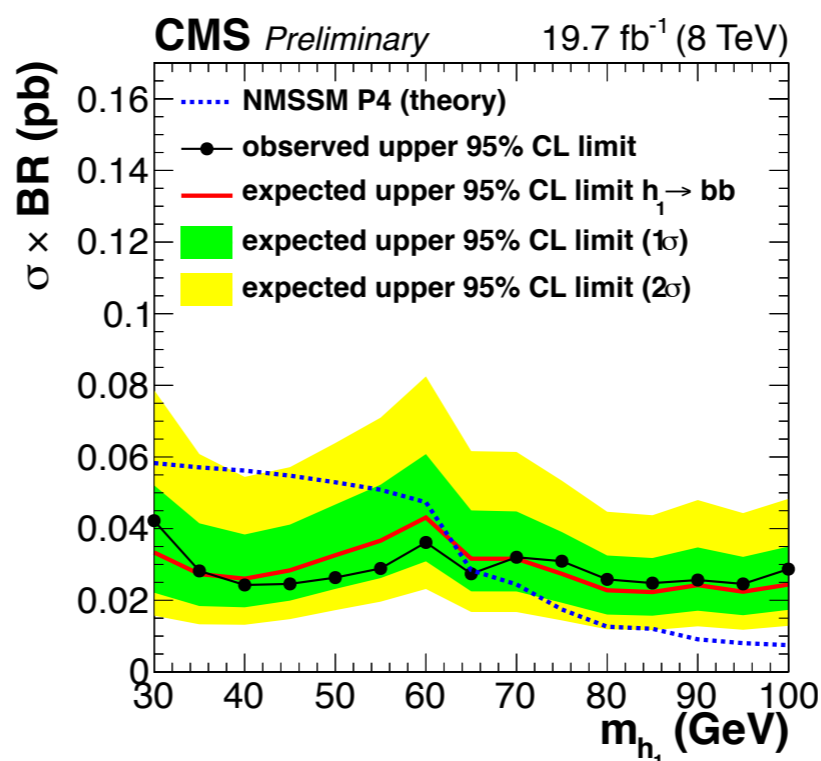
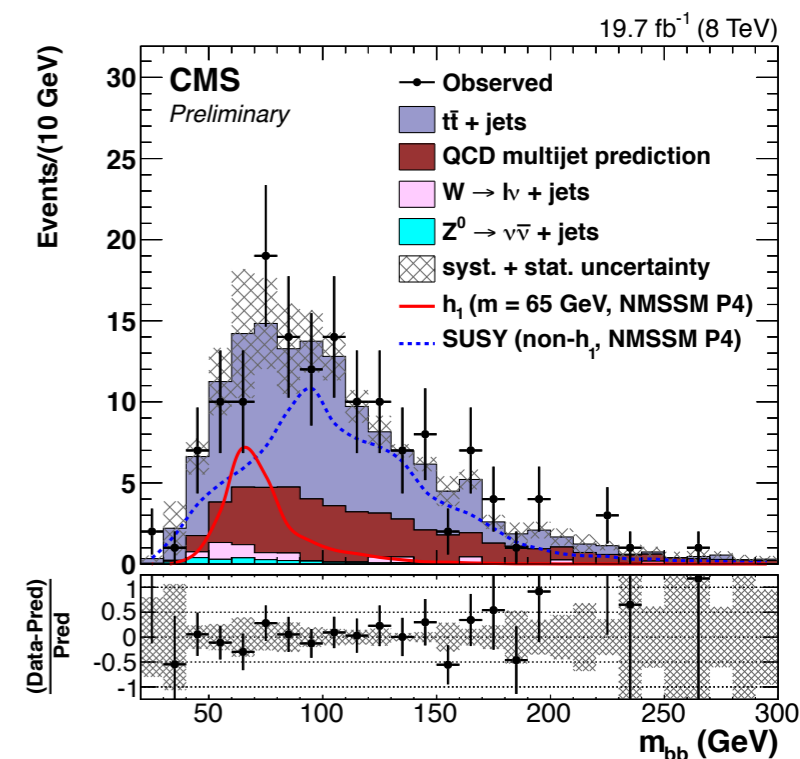
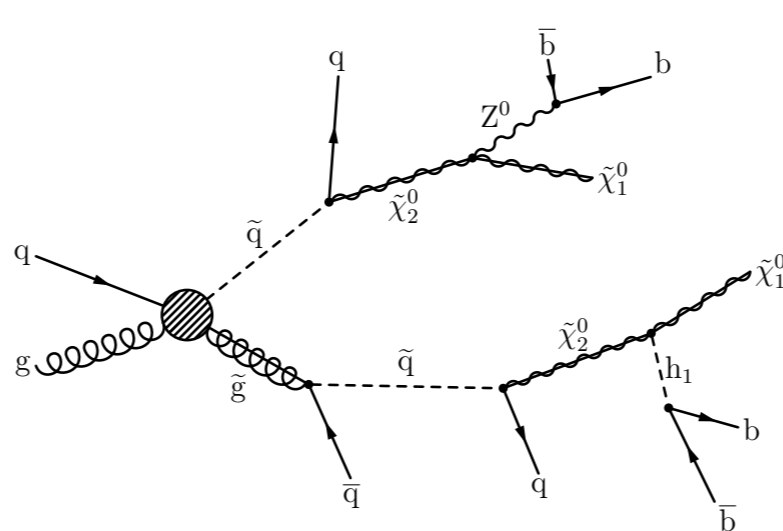
- **HIG-14-017**
- Search for $\Phi \rightarrow b\bar{b}$ ($\Phi = h, H, \text{ or } A$) in mass range $m_\Phi = [100, 900]$ GeV
- Dijet trigger with online b-tagging
- Offline selection applies p_T cuts and tight b-tag to leading 3 jets
- M_{12} : invariant mass of leading two jets
- X_{123} : event b-tagging estimator calculated from secondary vertex mass sum info of the three leading jets
- 2D distribution in (M_{12}, X_{123}) fitted to bkg-only and sig+bkg templates with binned likelihood technique
- No excesses observed; limits calculated for $\sigma \cdot \text{Br}$ (bottom left plot)
- Interpretations: m_h^{max} (bottom right), $m_h^{\text{mod+}}$, $m_h^{\text{mod-}}$, light stop, light stau



NMSSM $h_1 \rightarrow b\bar{b}$

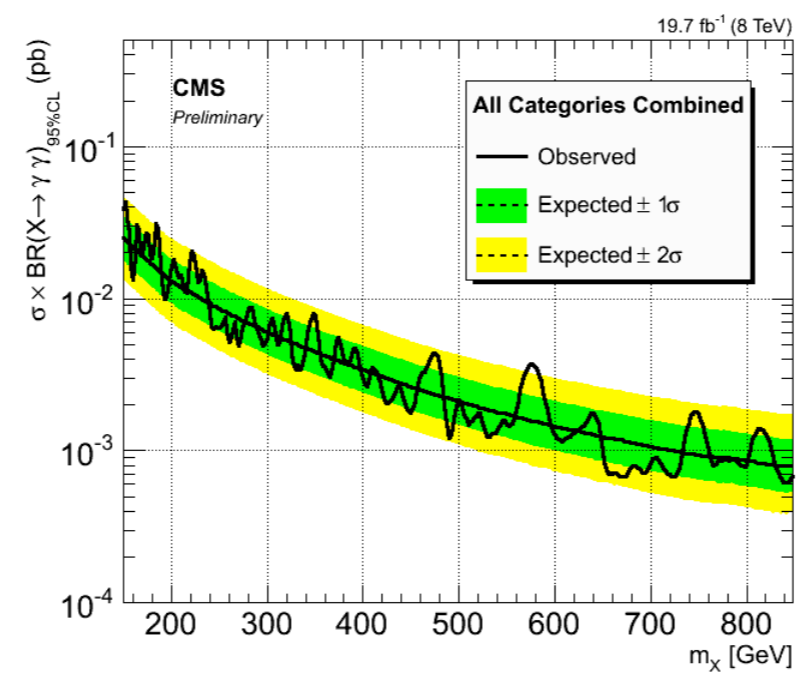
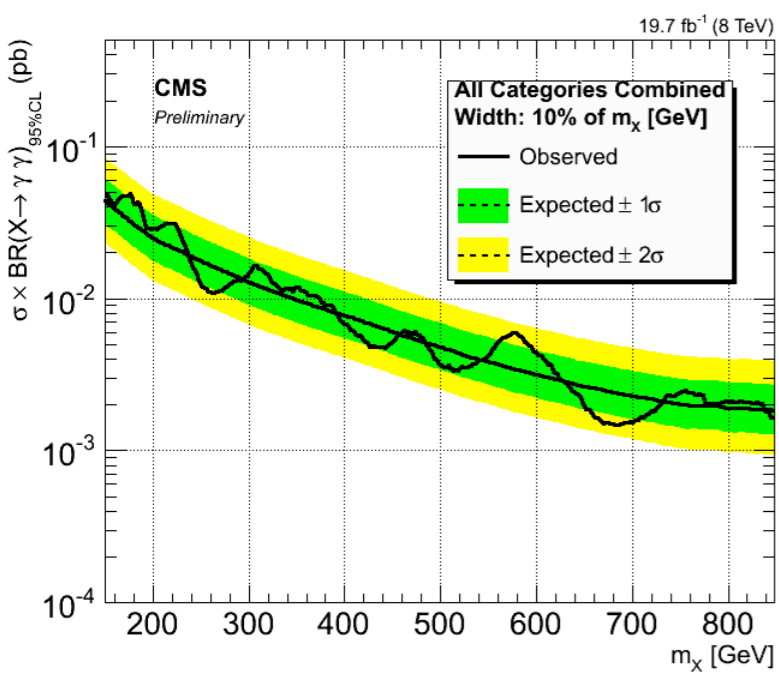
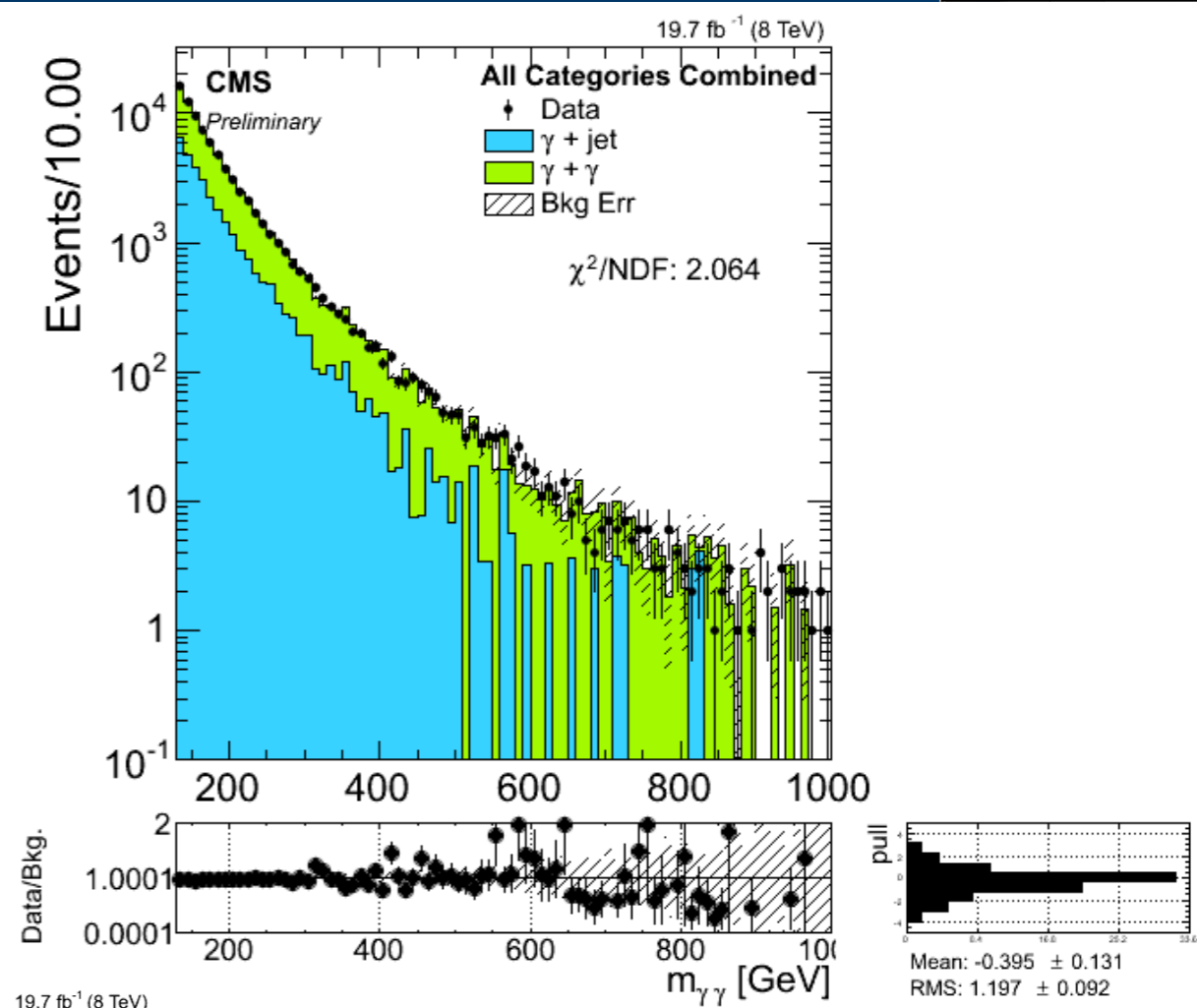


- **HIG-14-030**
- Mass range $m_{h_1} = [30, 100]$ GeV
- Cut on $H_T > 750$ GeV
- Bump hunt in $m_{b\bar{b}}$ spectrum; expected background modelled with combination of MC and data-driven methods
- Background-only template fit to $m_{b\bar{b}}$ distribution shows good agreement between data and SM prediction
- Limits set on $\sigma(pp \rightarrow h_1 + X) \cdot \text{Br}(h_1 \rightarrow b\bar{b})$ in NMSSM P4 scenario
 - Bottom left: h_1 signal only
 - Bottom right: h_1 and non- h_1 decays to $b\bar{b}$ considered as signal



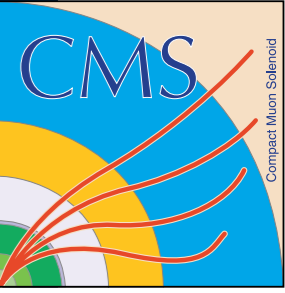
Heavy Higgs $\rightarrow \gamma\gamma$

- **HIG-14-006**
- Model-independent search for $X \rightarrow \gamma\gamma$ (X = Higgs-like particles, such as in 2HDM, or even spin-2 boson) in mass range $m_X = [150, 850]$ GeV
- $m_{\gamma\gamma}$ spectrum binned in 4 categories based on diphoton η and R_9 to optimize search sensitivity
- Fit bkg templates to $m_{\gamma\gamma}$ spectrum to search for excesses
- Limits shown below:
 - Left: Higgs-like X (scenario: $\Gamma_X \sim 10\%$ of m_X)
 - Right: spin-2 resonance interpretation

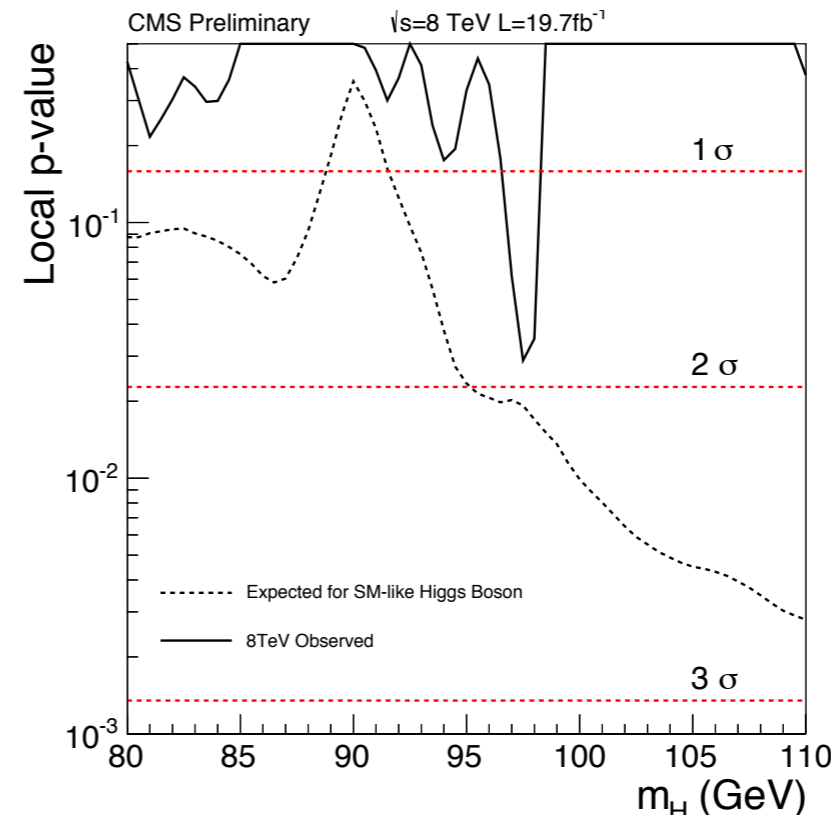
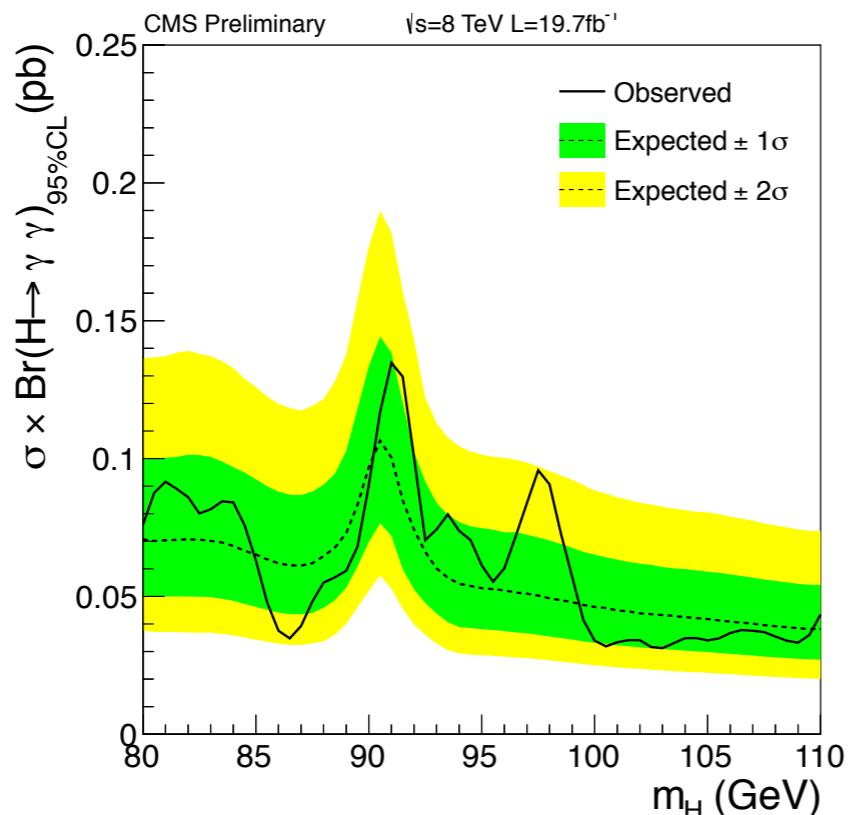
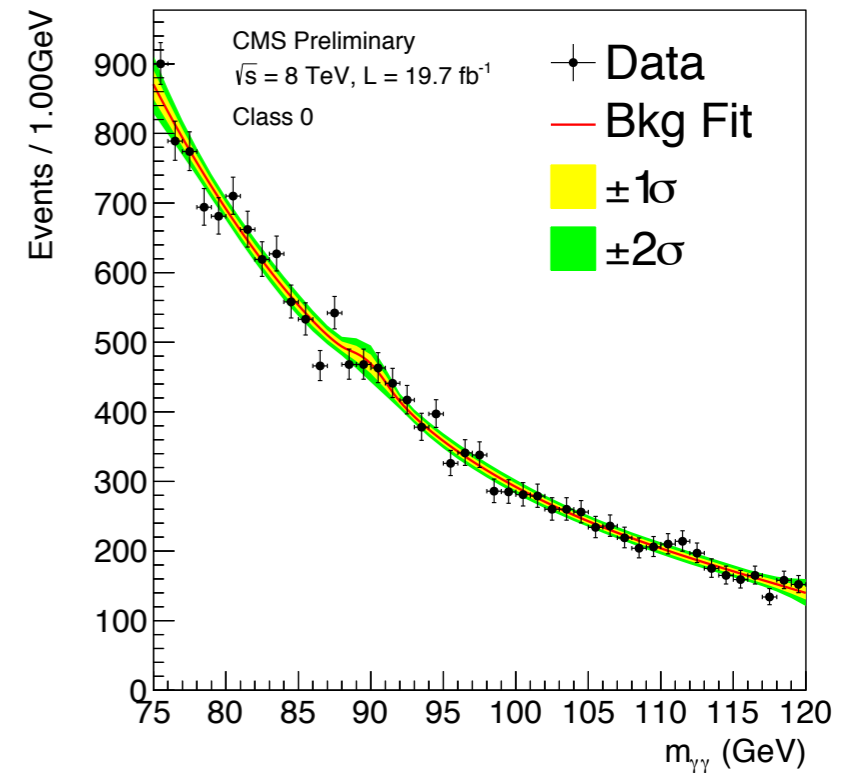


R_9 : energy sum of 3x3 ECAL crystals centered on most energetic crystal in supercluster, divided by energy of supercluster

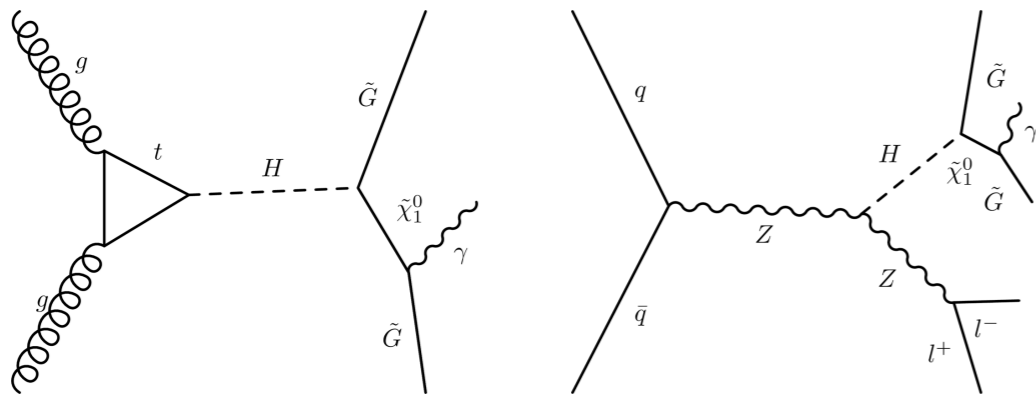
Light Higgs $\rightarrow \gamma\gamma$



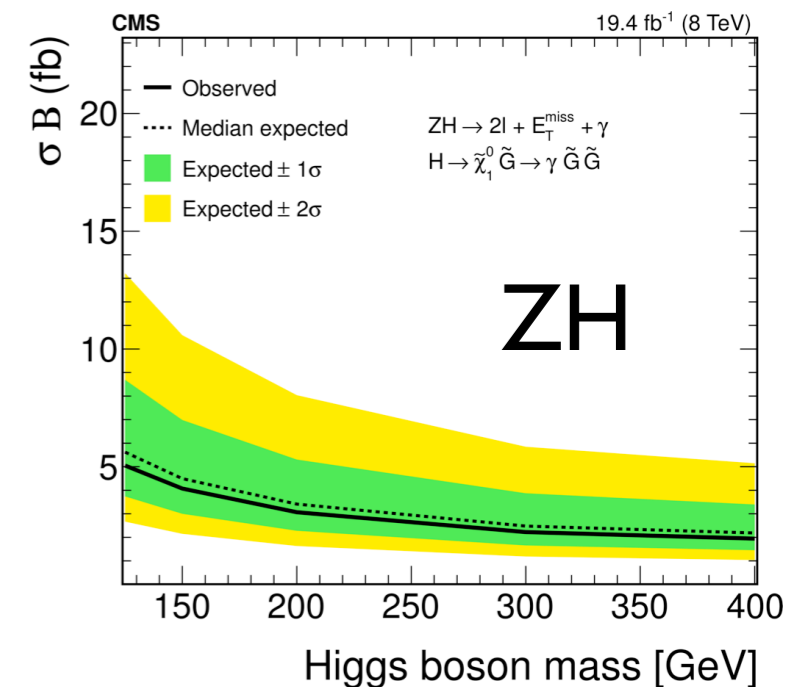
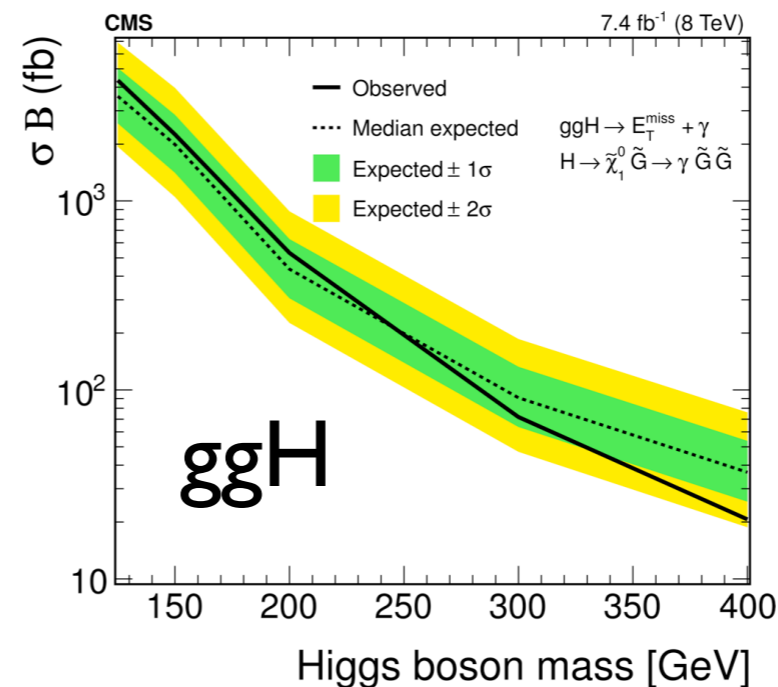
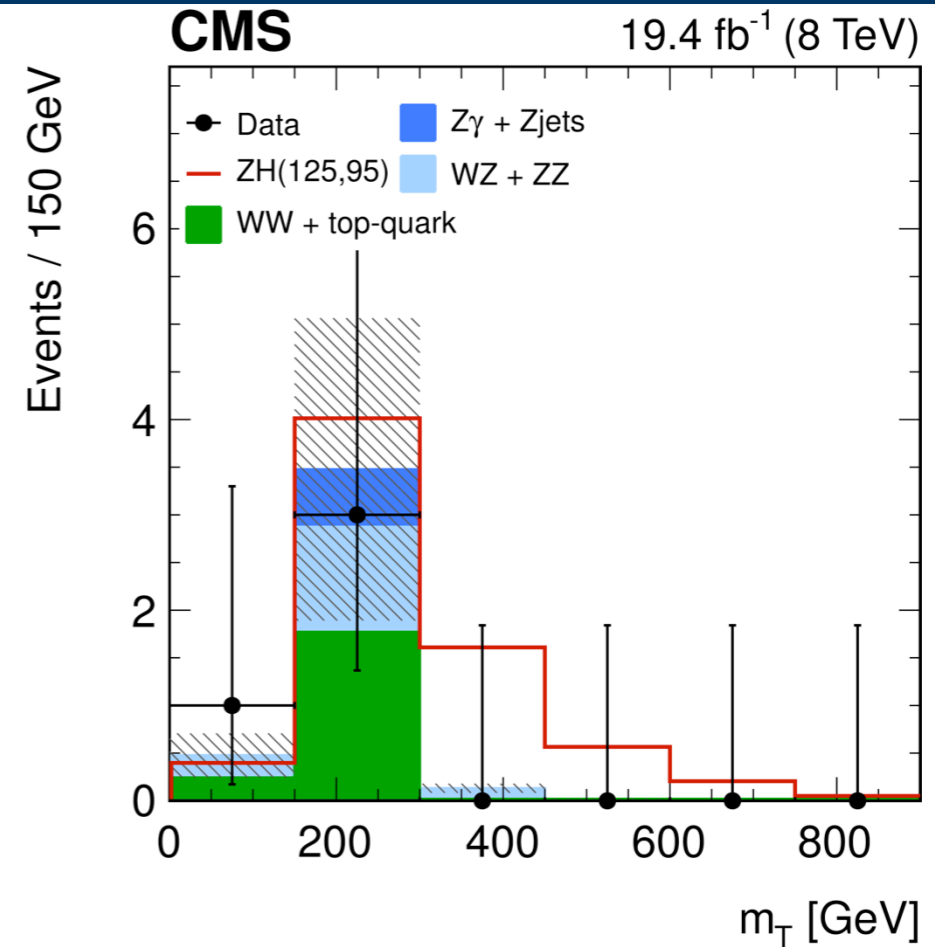
- **HIG-14-037**
- Model-independent search for $H \rightarrow \gamma\gamma$ in mass range $m_H = [80, 110]$ GeV
- To optimize search sensitivity, $m_{\gamma\gamma}$ spectrum binned in 4 categories based on score of BDT used for rejecting non-prompt photons
- Simultaneous likelihood fit of signal and bkg models in all categories to $m_{\gamma\gamma}$ spectrum
- Limits set on $\sigma \cdot \text{Br}$; no significant excesses observed



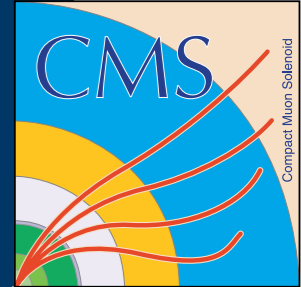
H → semi-invisible



- **HIG-14-025**
- ggH/ZH → gravitinos, neutralinos with radiation of γ
- Signal models considered:
 - low-scale SUSY breaking: $m_H = 125$ GeV, $m(\chi_1^0)$: 1-120 GeV
 - m_H : 125-400 GeV, $m(\chi_1^0) = m_H - 30$ GeV
- Photon m_T distribution: data vs expectation and signal
- No excess observed
- Various model-dependent limits
 - example: ggH and ZH channel limits on $\sigma \cdot Br$ vs m_H

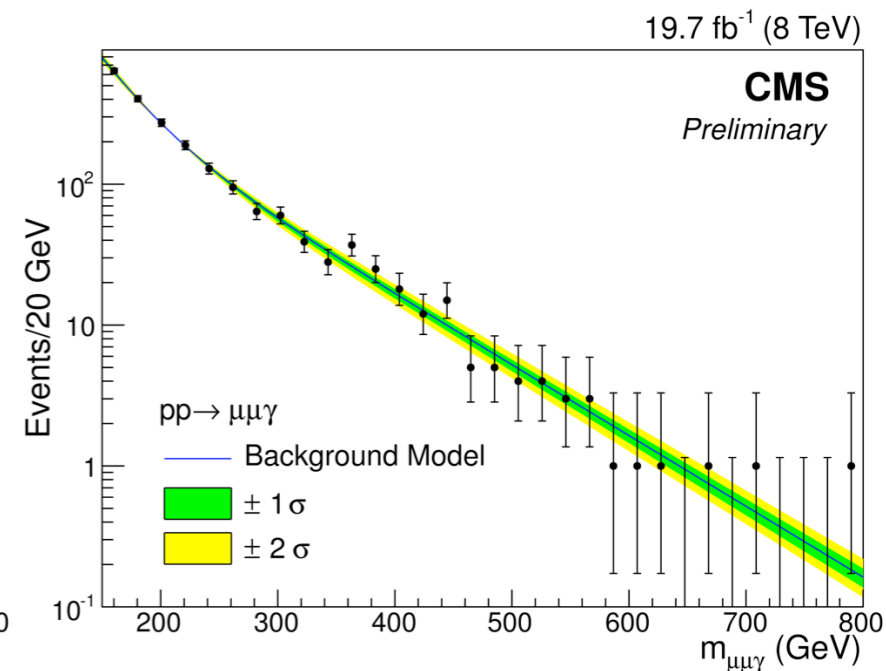
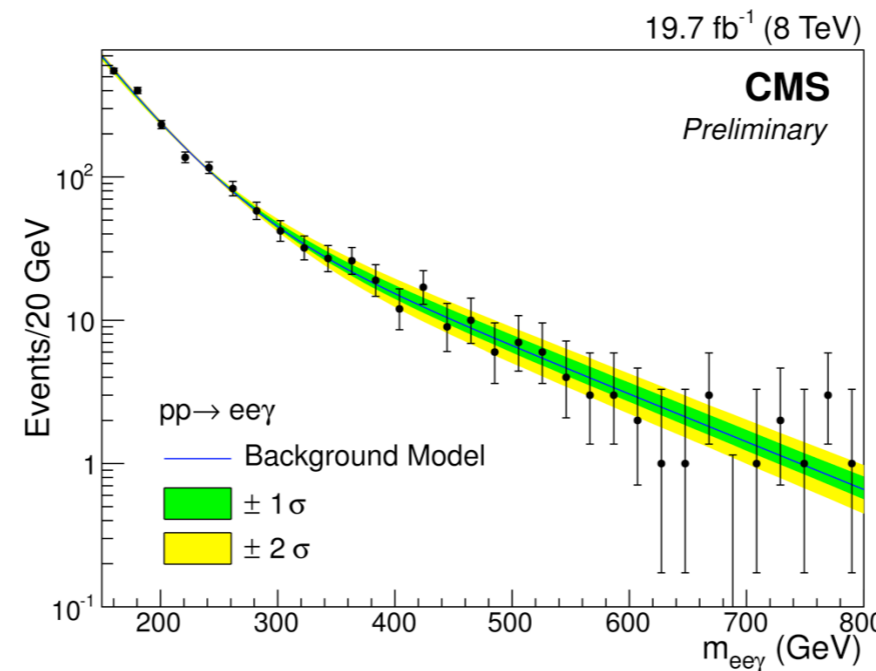


$A \rightarrow Z\gamma$

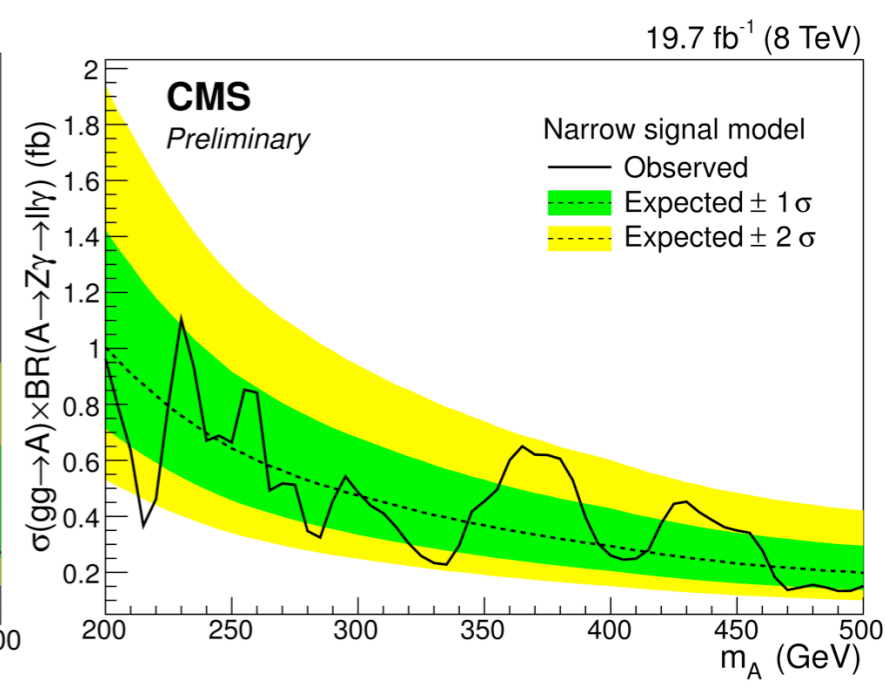
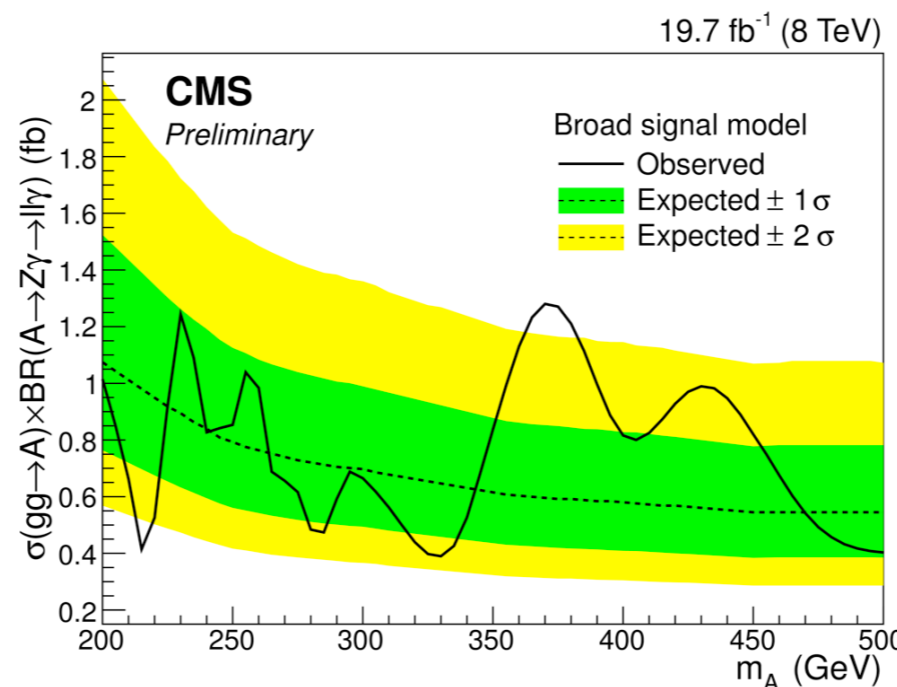


Fit to $e\bar{e}\gamma$ and $\mu\bar{\mu}\gamma$ mass spectra

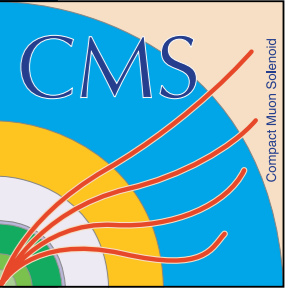
- **HIG-14-031**
- SU(4) chiral symmetry breaking: composite scalar h (SM-like properties) and heavier pseudoscalar A
- First search for this decay mode
- m_A range: 200-500 GeV
- unbinned max likelihood fit to $m_{\ell\ell\gamma}$ spectrum ($\ell = e, \mu$)
- Interpretations in different signal width models: broad ($\Gamma_A = \text{SM } \Gamma_H$) and narrow (Γ_A restricted to 1% of m_A)



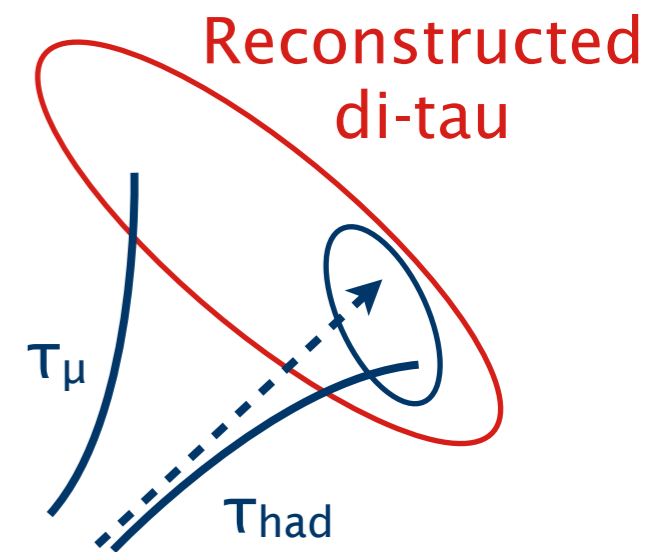
Limits for different Γ_A models



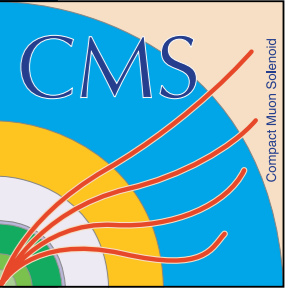
Conclusions



- CMS has searched for supersymmetric neutral Higgses in Run I data
 - many different channels and strategies
 - no excesses observed yet
- Others still under way
 - coming soon: NMSSM analysis with boosted di-tau ID
- Looking forward to what Run II will bring...



BACKUP

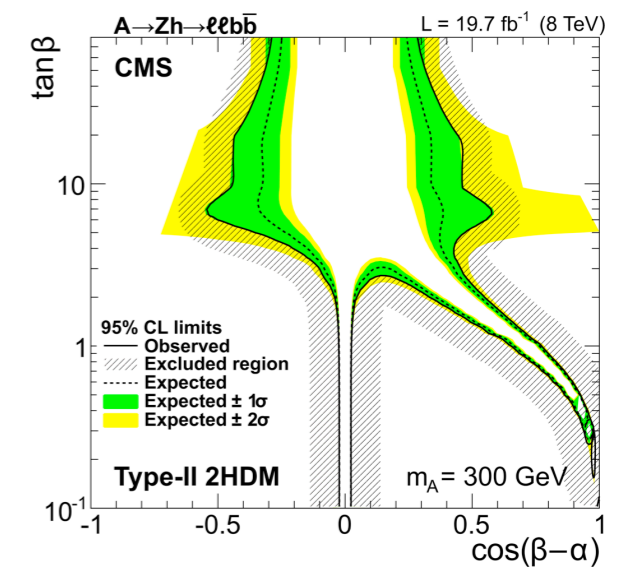
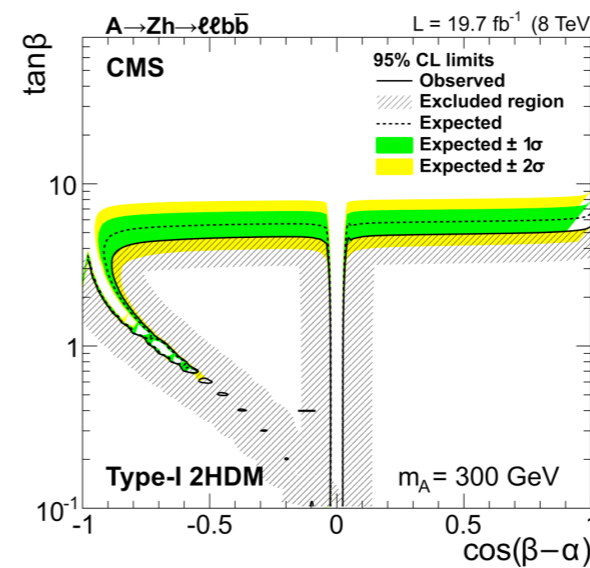


- MSSM benchmark scenario m_h^{\max} : parameters chosen so that m_h is maximized (~ 135 GeV; see arXiv:1302.7033 for detailed discussion)
- $m_h^{\text{mod}+}$: starting from m_h^{\max} , modified so that m_h is compatible with discovered 125-GeV resonance and stop mixing parameter agrees best with $(g-2)_\mu$ measurement
- $m_h^{\text{mod}-}$: similar to $m_h^{\text{mod}+}$, except that stop mixing parameter is modified to agree best with measured rate of $b \rightarrow s\gamma$

$A \rightarrow Zh \rightarrow b\bar{b}$



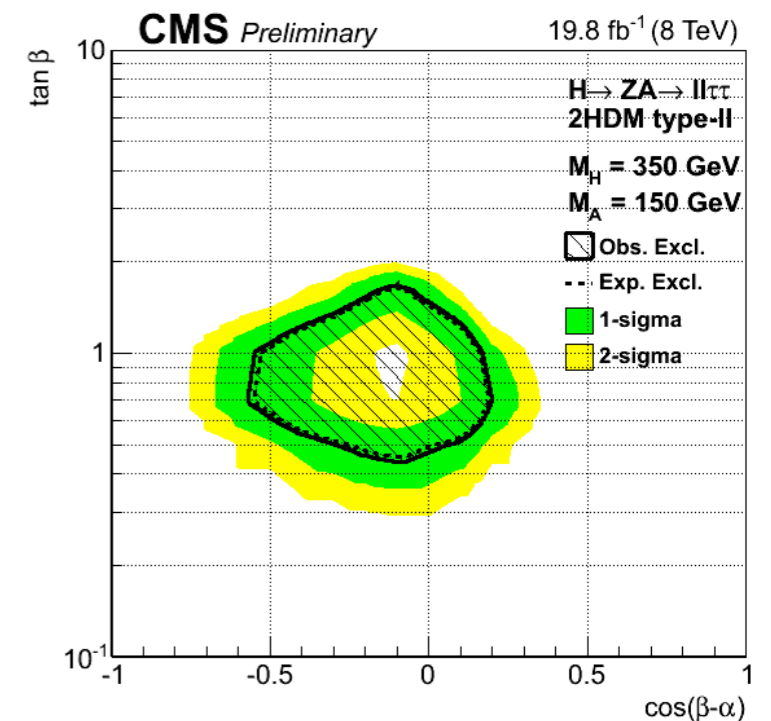
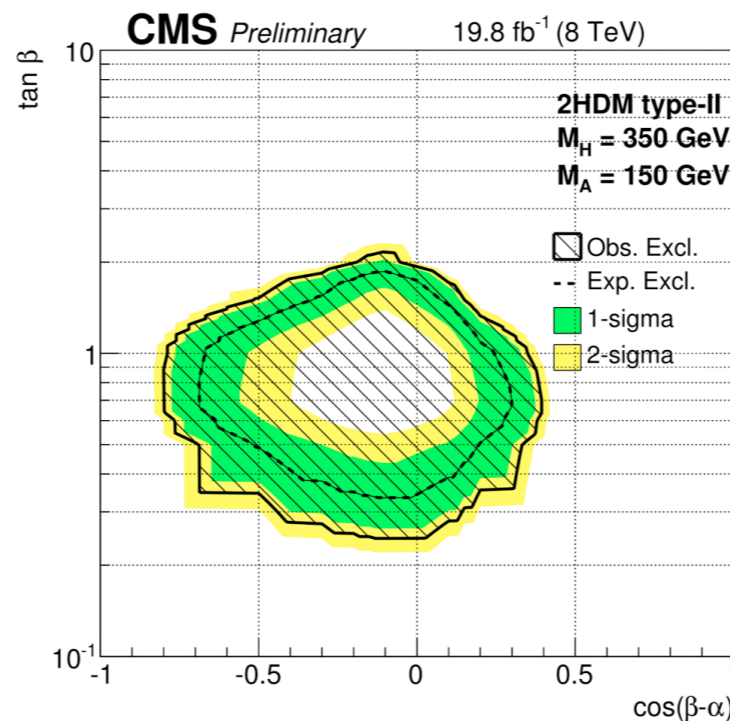
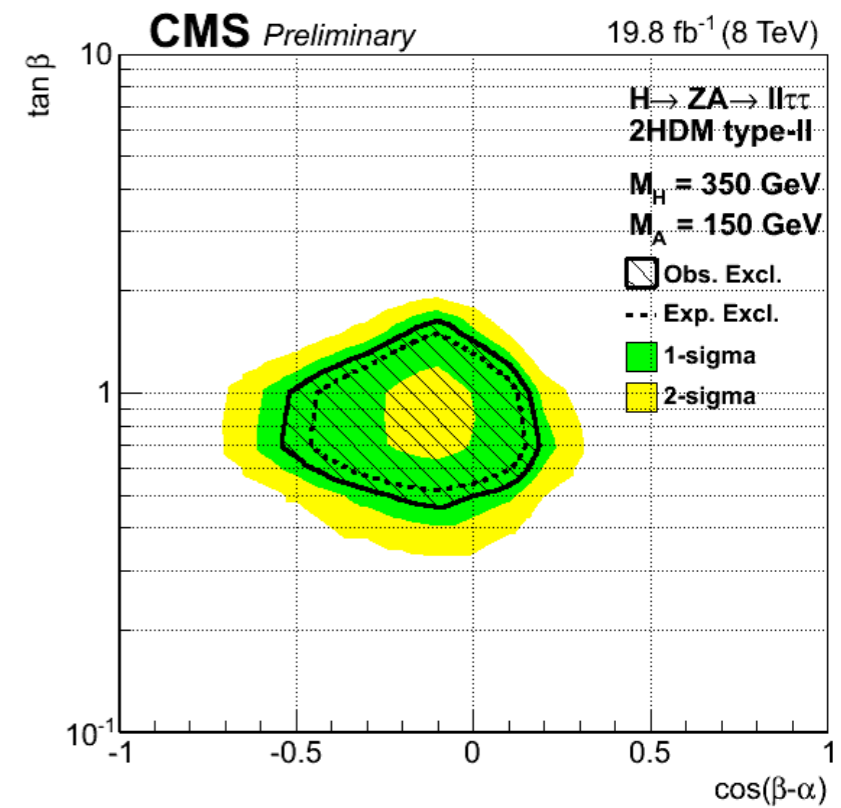
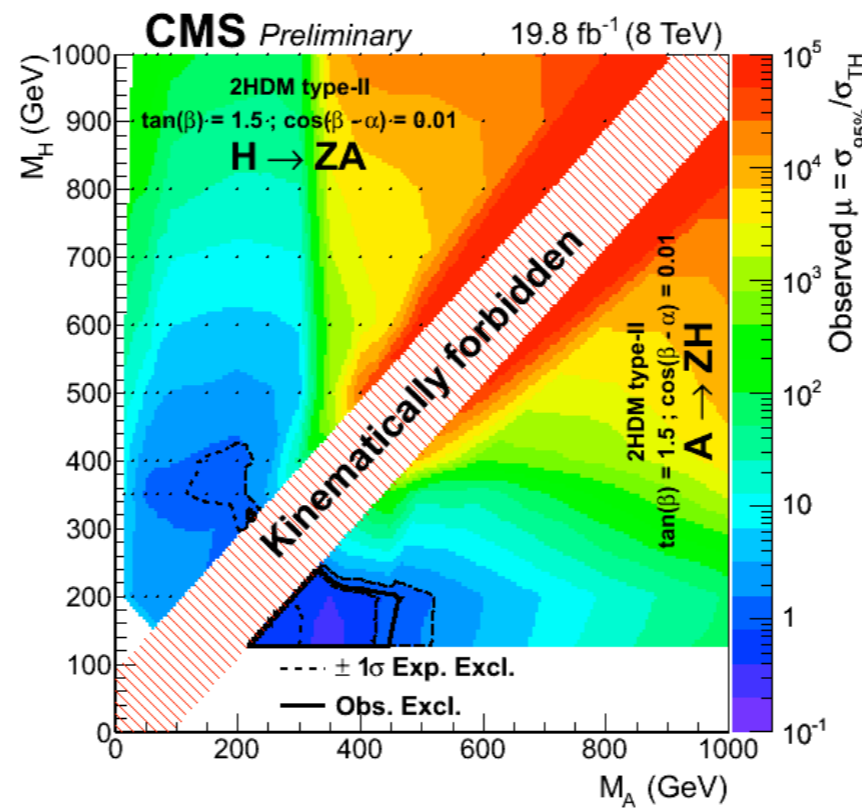
- $A \rightarrow Zh \rightarrow \ell\ell b\bar{b}$
(HIG-14-011)
- Example limits in $(\tan\beta, \cos(\beta-\alpha))$ plane for $m_A = 300$ GeV



Searches for massive neutral (pseudo)scalars



- $H(A) \rightarrow ZA(H) \rightarrow \ell \ell b \bar{b}$ and $H(A) \rightarrow ZA(H) \rightarrow \ell \ell \tau \tau$ (HIG-15-001)
- Counting experiment results shown above for $\ell \ell \tau \tau$
- Below: other exclusion limits for $\ell \ell b \bar{b}$ (left) and $\ell \ell \tau \tau$ (right)

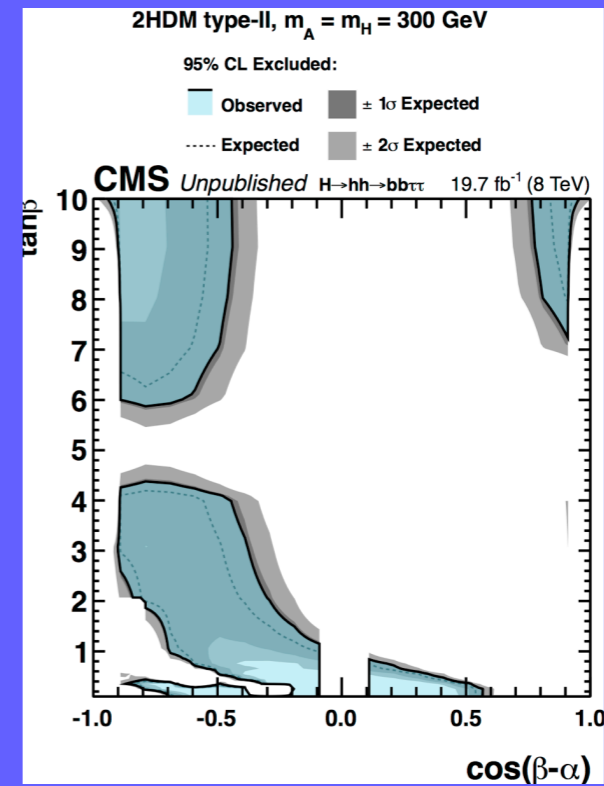


Searches for massive neutral (pseudo)scalars



- **HIG-14-034:**
 $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$,
 $A \rightarrow Zh \rightarrow \ell\ell\tau\tau$
- $\tan\beta$ vs $\cos(\beta-\alpha)$ limits

$H \rightarrow hh \rightarrow b\bar{b}\tau\tau$



$A \rightarrow Zh \rightarrow \ell\ell\tau\tau$

