



BSM Higgs searches

Adrien Caudron (UCLouvain – CP3)
on behalf of CMS experiment

Higgs Hunting 2015
30th July – 1st August 2015
Orsay, France

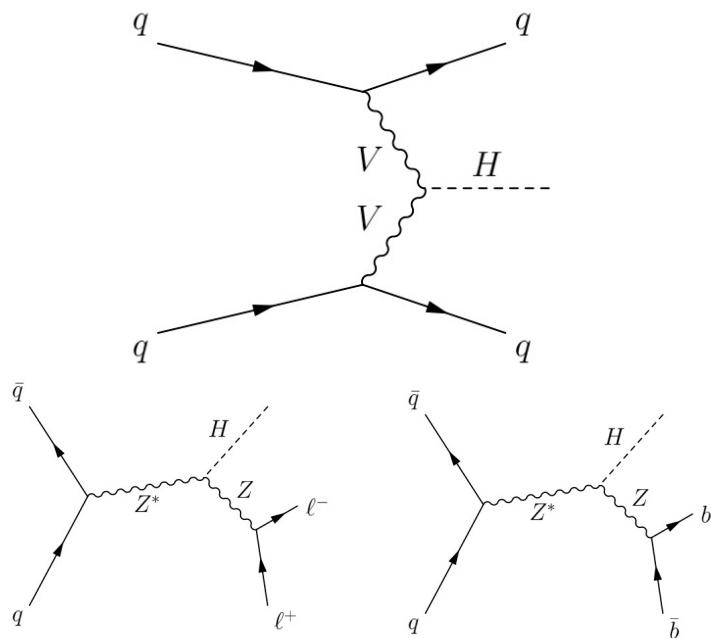
Outline:

- Search for non-SM h decays
- Search for non-SM h production
- Search for other Higgses

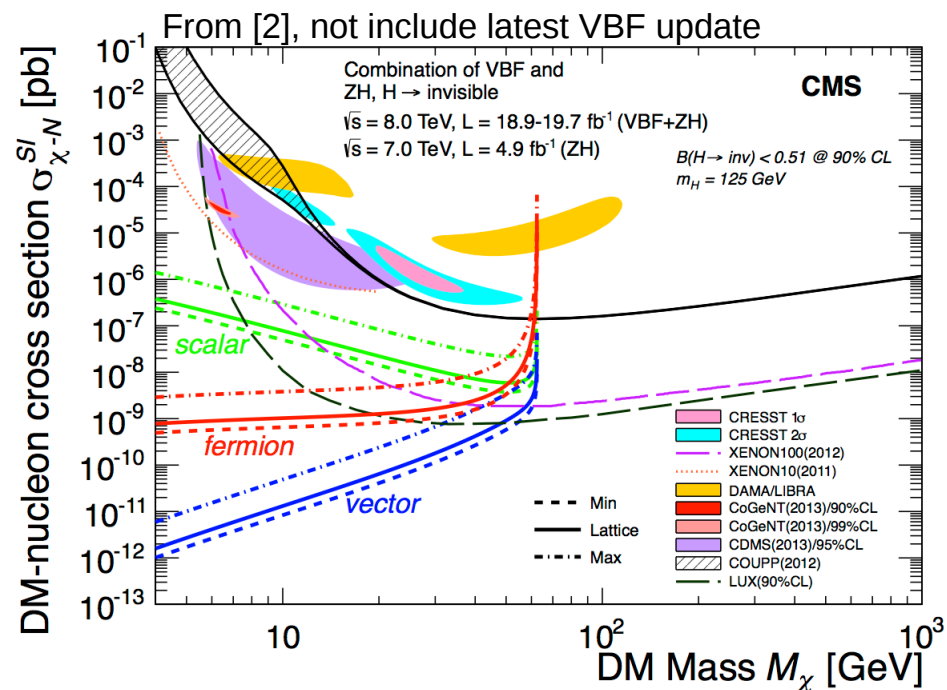


$h \rightarrow \text{invisible}$

- Vector Boson Fusion production of $h \rightarrow$ best sensitivity [1]
- Combination with $Z(\ell\ell)h$ and $Z(bb)h$ [1,2]



- $m_h = 125$ GeV limit on $B(h \rightarrow \text{invisible})$:
 - VBF: 57% (exp. 40%)
 - VBF+ZH: 47% (exp. 35%)
- Possible reinterpretation in terms of limit on a DM candidate
 - spin-independent DM-nucleon cross section in Higgs-portal models comparisons with other DM experiments



[1] CMS-PAS-HIG-14-038

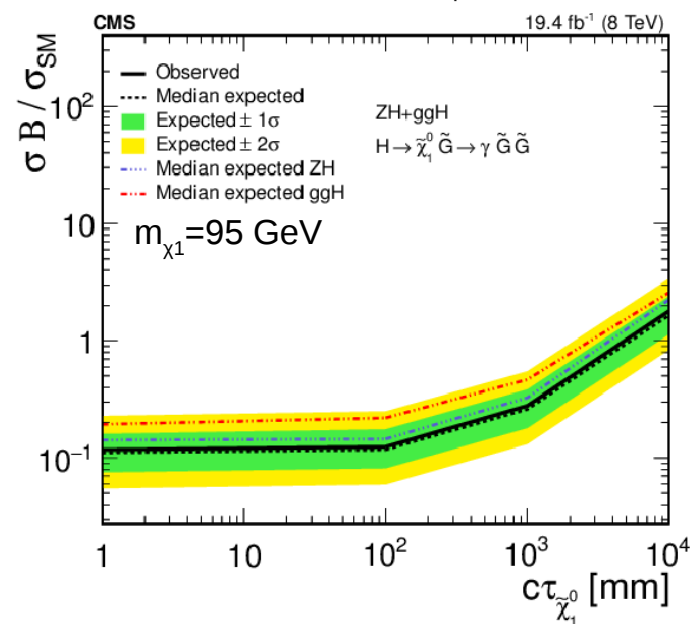
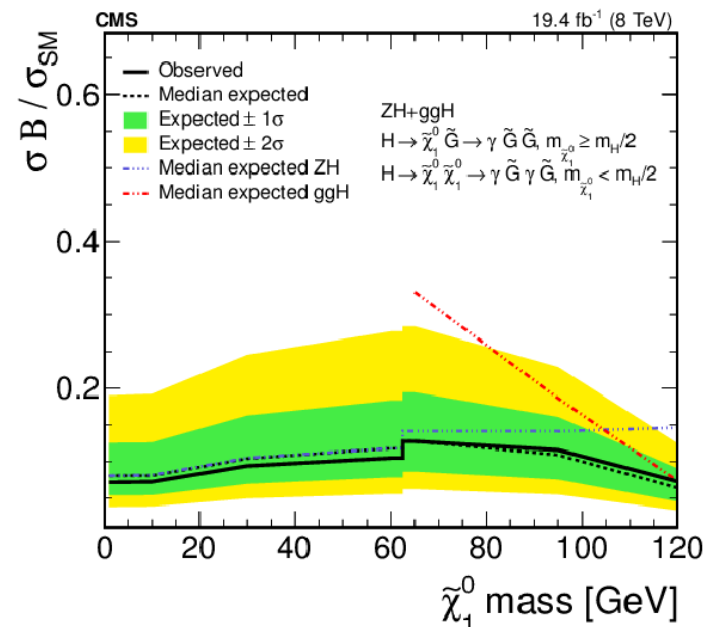
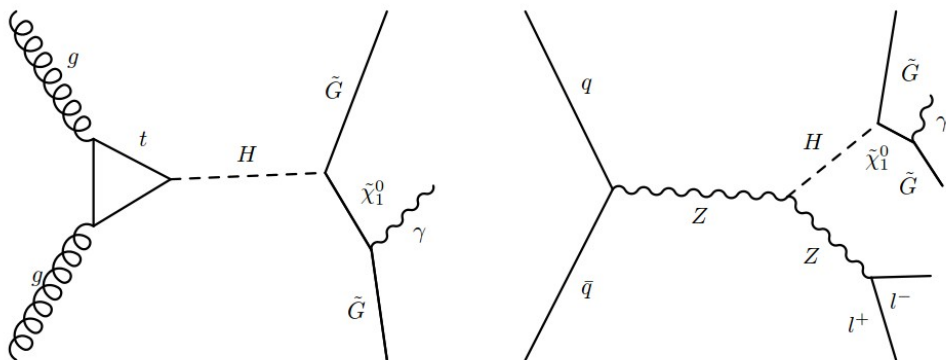
[2] EPJC 74 (2014) 2980



$h \rightarrow \gamma + \text{invisible}$

More on talk from R.Teixeira De Lima later today ([link](#))

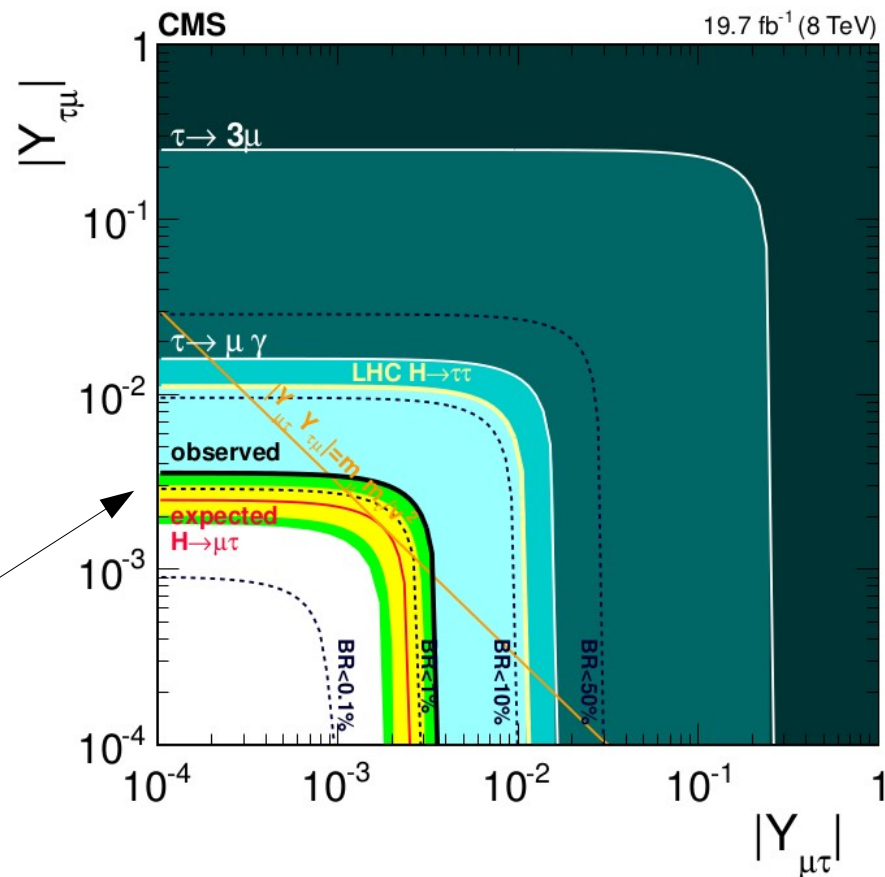
- low-scale SUSY models
 - Gravitino (\tilde{G}) produced by the decay of a Neutralino (χ_1)
 - $\chi_1 \rightarrow \tilde{G} + \gamma$
 - $m_{\tilde{G}}$ negligible and m_{χ_1} ranging from 1 to 120 GeV
 - Two cases:
 - $h \rightarrow \tilde{G} + \chi_1$ ($m_h/2 < m_{\chi_1} < m_h$)
 - $h \rightarrow \chi_1 \chi_1$ ($m_{\chi_1} < m_h/2$)
- Limit expressed as function of m_{χ_1} and $c\tau_{\chi_1}$





Flavour-violating Higgs processes

- Searches for flavour-violating decay or production of the h boson
 - $h \rightarrow \mu\tau$
 - $t \rightarrow ch$
- Limits on branching ratio at 95% CL
 - $B(h \rightarrow \mu\tau) < 1.51\%$ [1]
 - $B(t \rightarrow ch) < 0.56\%$ [2]
- Probe Higgs Yukawa couplings
 - Better limits than previous analyses for $Y_{\mu\tau}$
 - $\sqrt{|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2} < 0.14$



[1] [arxiv:1502.07400](https://arxiv.org/abs/1502.07400), Submitted to Phys. Lett. B

[2] [Phys. Rev. D 90, 112013](https://arxiv.org/abs/1502.07400)

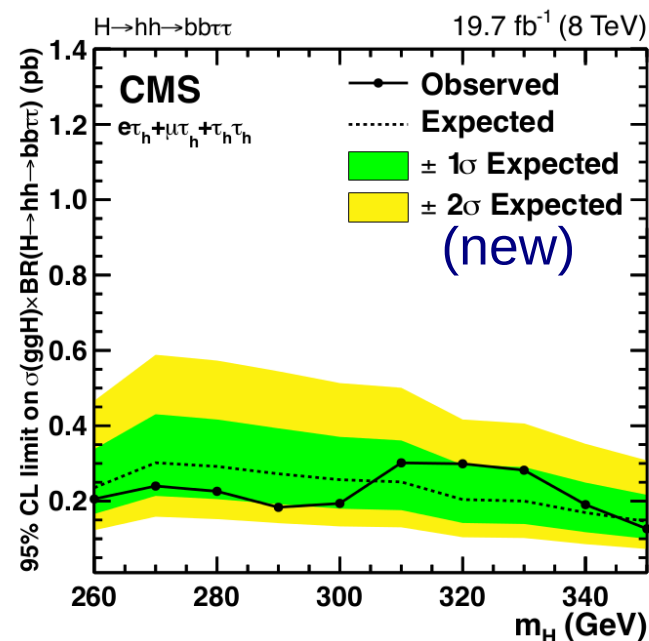
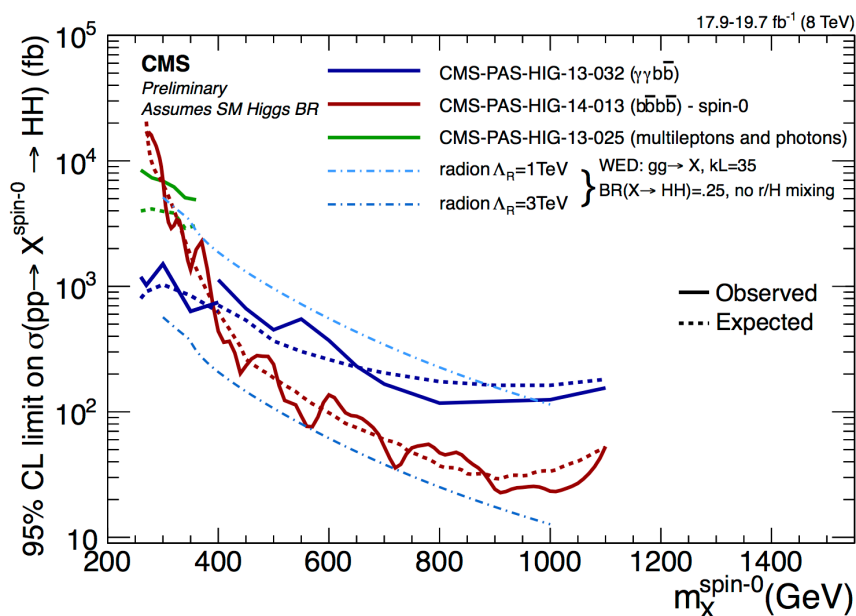
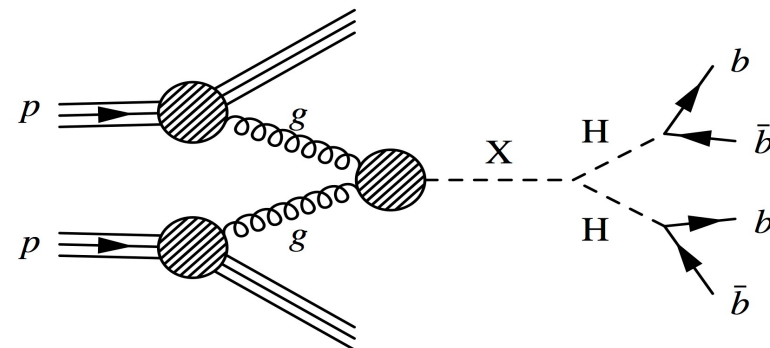


$X \rightarrow hh \rightarrow bbbb, bbyy, \text{multi-lepton and leptons+photons}$ $H \rightarrow hh \rightarrow bb\tau\tau \text{ (new)}$

- Looking for heavy resonances decaying in pair of h bosons

- X can be reinterpreted as:

- Spin-0 radion or spin-2 graviton [1,2]
 - In Warped Extra Dimensions models
- High mass H [3, 4]



[1] CMS-PAS-HIG-13-032

[2] [arXiv:1503.04114](https://arxiv.org/abs/1503.04114), Submitted to Physics Letters B

[3] Phys. Rev. D 90, 112013

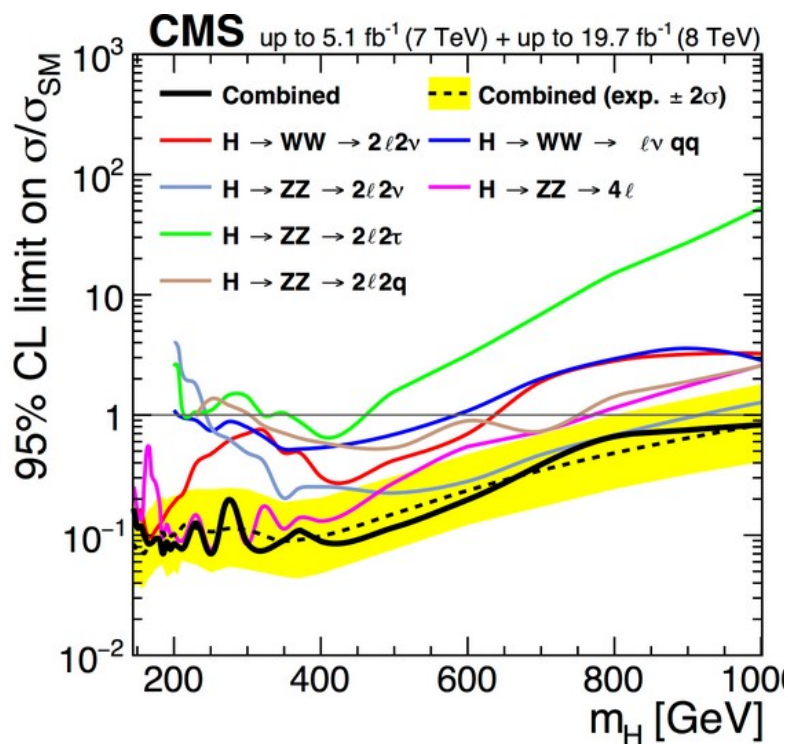
[4] Paper to be submitted soon, EPS talk

More on talk from M.T Grippo this morning ([link](#))

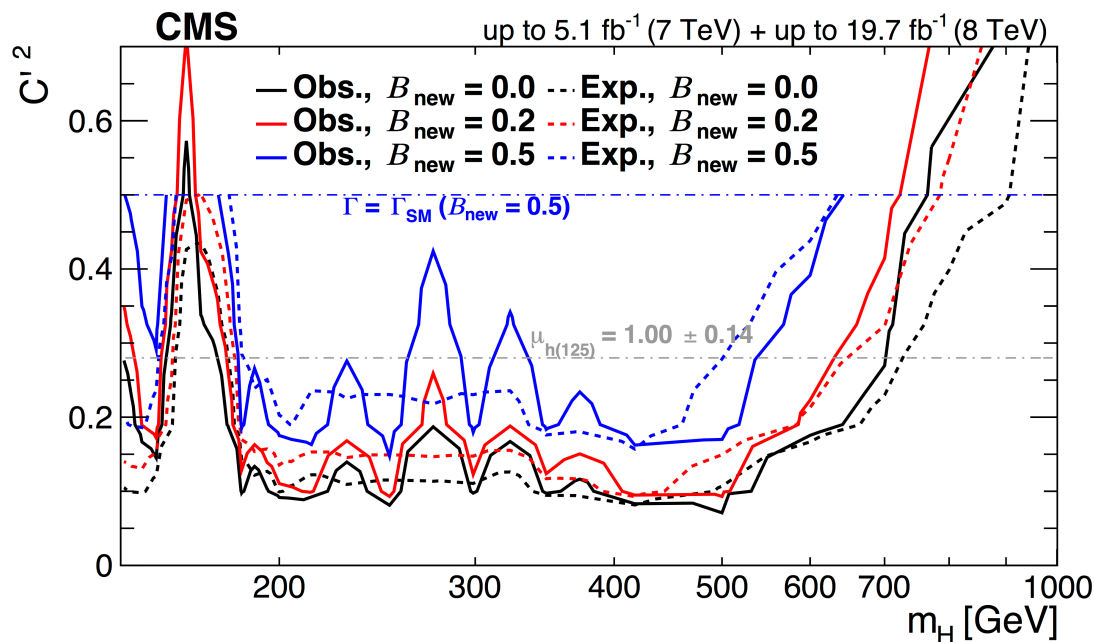


$X \rightarrow ZZ, WW$

- SM h boson search for high mass \rightarrow reinterpreted in term of BSM models
 - Combine $lvlv, lvqq, 4l, llvv, llqq$
- Probe m_X in [145 - 1000] GeV
- Assume SM Higgs-like productions and decays



- Reinterpretation in terms of EW singlet extension of SM in terms of model parameters:
 - B_{new} : branching fraction of the EW singlet to non-SM decay mode
 - C' : the scale factors of the couplings with respect to the SM of the high-mass Higgs boson
- Only consider cases with $\Gamma_H \leq \Gamma_{SM}$
- Results provided independently for each h decays and production mode (ggh, VBF, $h \rightarrow ZZ$, $h \rightarrow WW$)

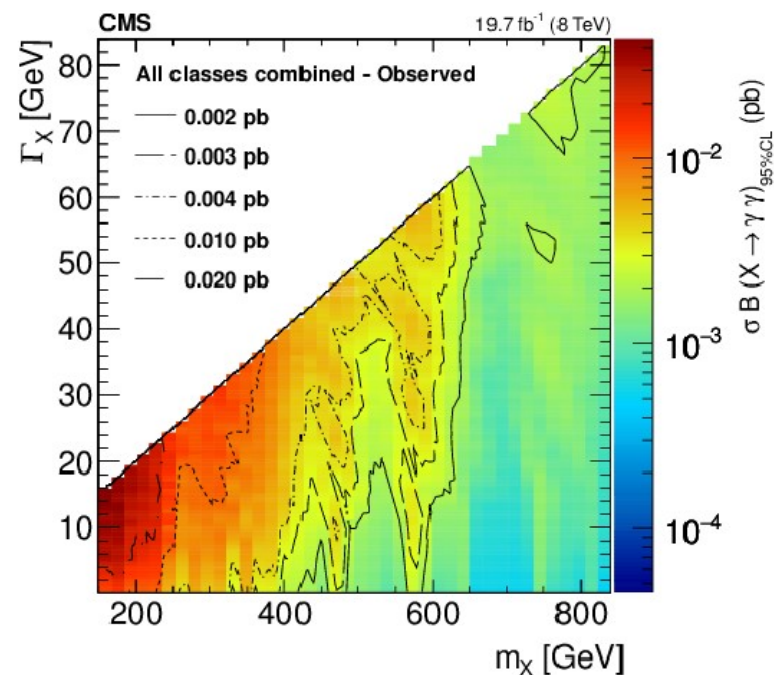
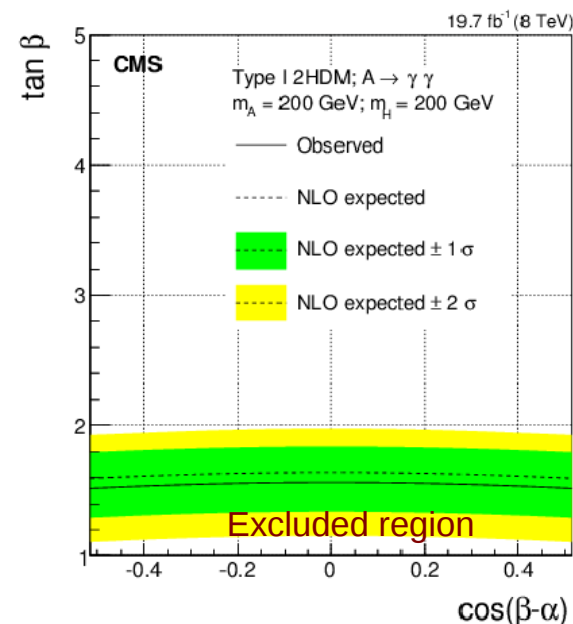
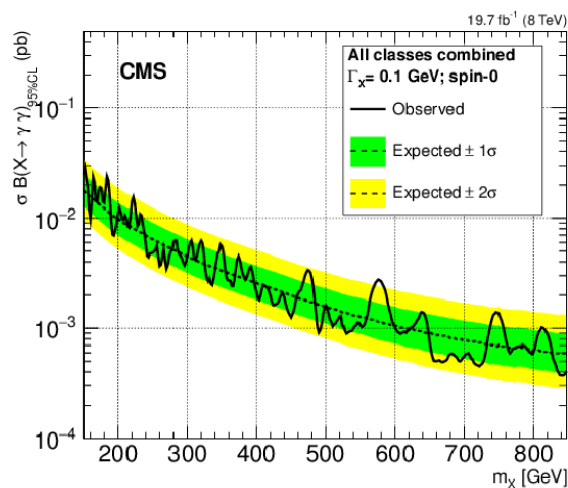
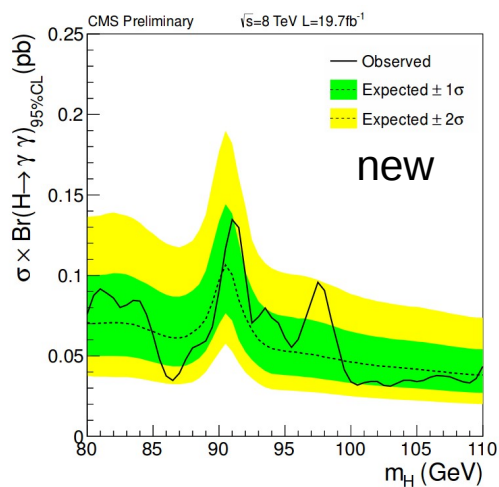




$$X \rightarrow \gamma\gamma$$

More on talk from B.Courbon yesterday ([link](#))

- Low mass search [80-110] GeV (new results) [1]
- High mass search [150-850] GeV [2]:
 - Test different signal width up to 10% of the mass
 - Interpretation for spin-0 and spin-2 resonances
 - Limits as function of:
 - m_X
 - m_X vs Γ_X
 - Model dependent $\tan\beta$ vs $\cos(\beta-\alpha)$ at fix m_X



[1] CMS-HIG-14-037

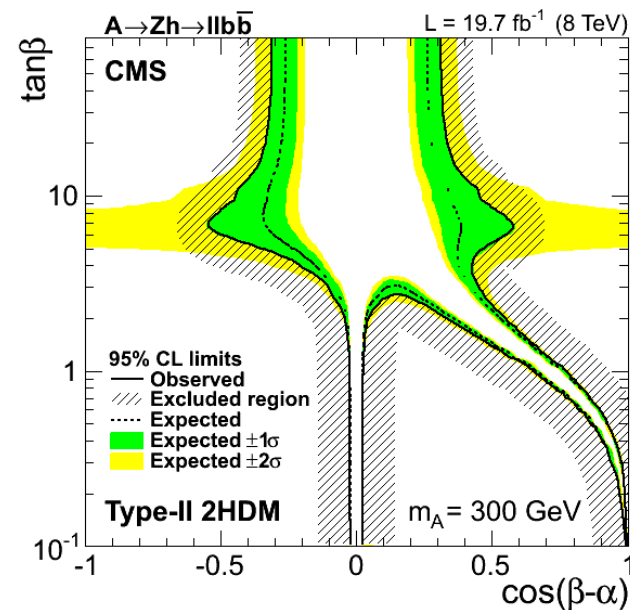
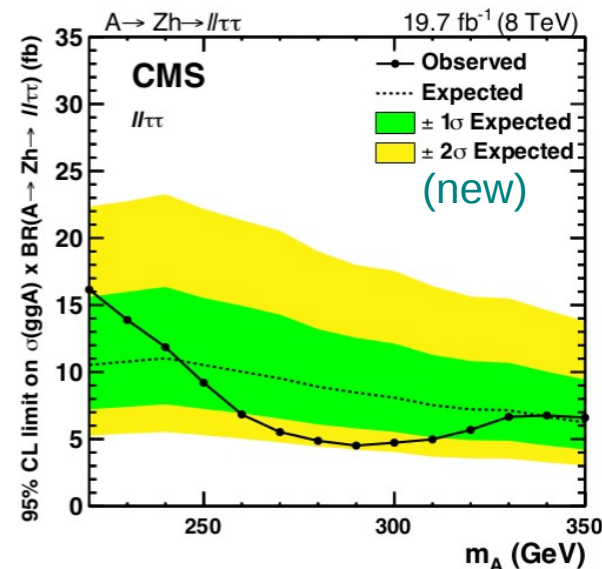
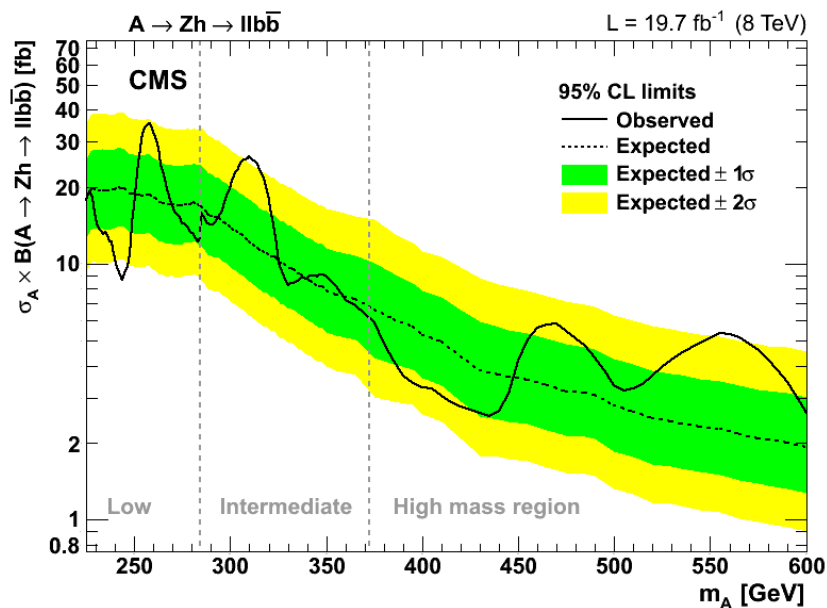
[2] [arXiv:1506.02301](#), Submitted to Phys. Lett. B

Other di-boson search: $X \rightarrow Z\gamma$ (CMS-PAS-HIG-14-031, [backup](#))



$A \rightarrow Zh$

- Several channels
 - $Z(\ell\ell)h(\tau\tau)$ (new) [1]
 - $Z(\ell\ell)h(bb)$ [2]
 - Multi-leptons and leptons+photons [3]
- Target MSSM like models
 - Model dependent and model independent limits

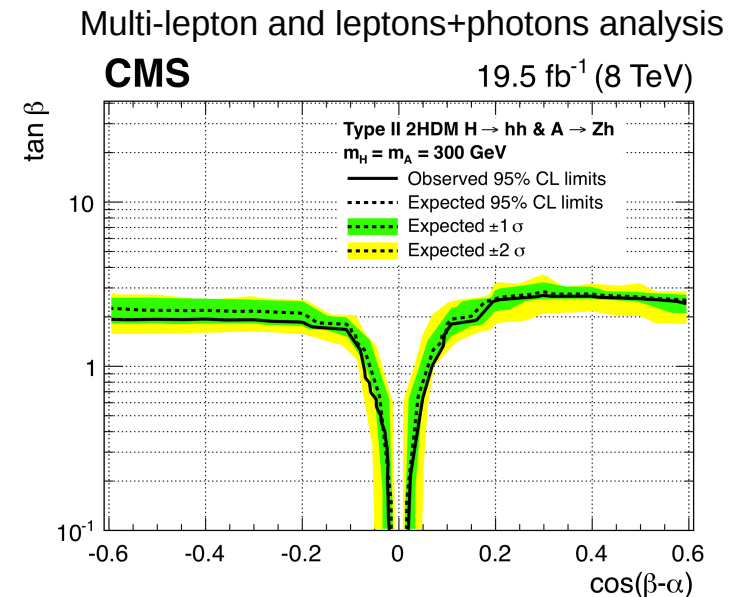
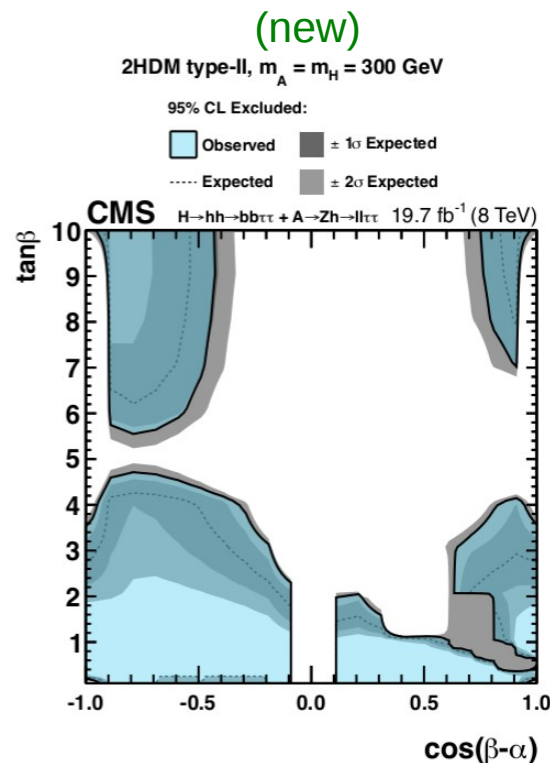
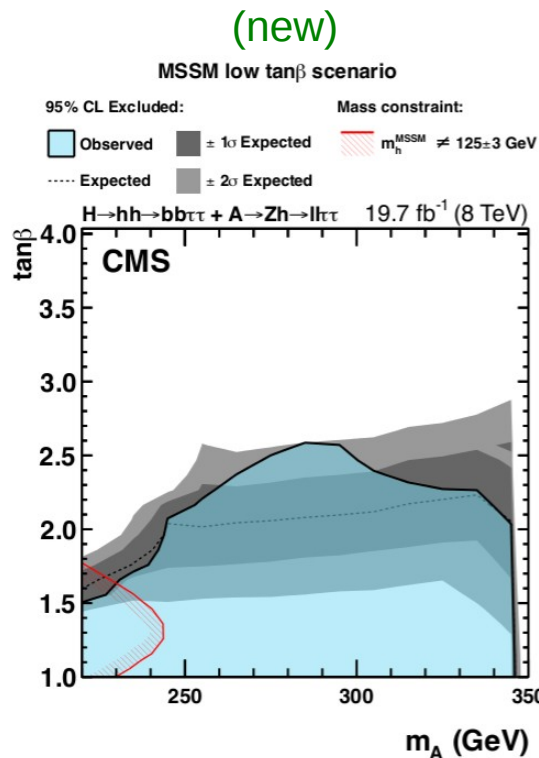


[1] Paper to be submitted soon, [EPS talk](#)
 [2] [arXiv:1504.04710](#), Submitted to Physics Letters B
 [3] [Phys. Rev. D 90, 112013](#)



Combination $H \rightarrow hh$ and $A \rightarrow Zh$

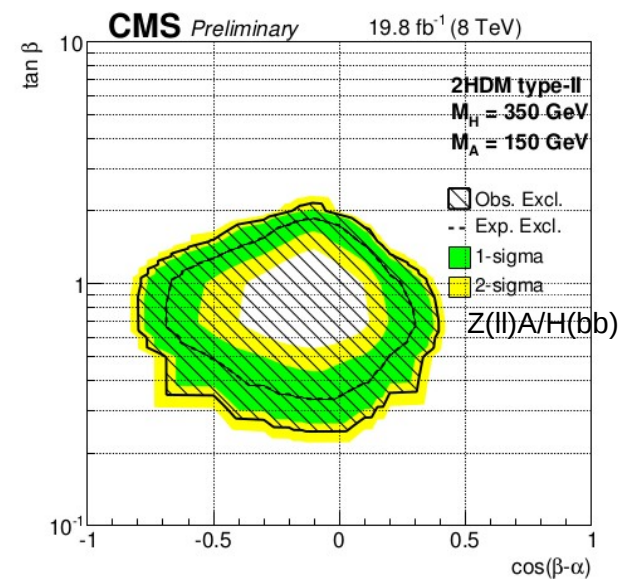
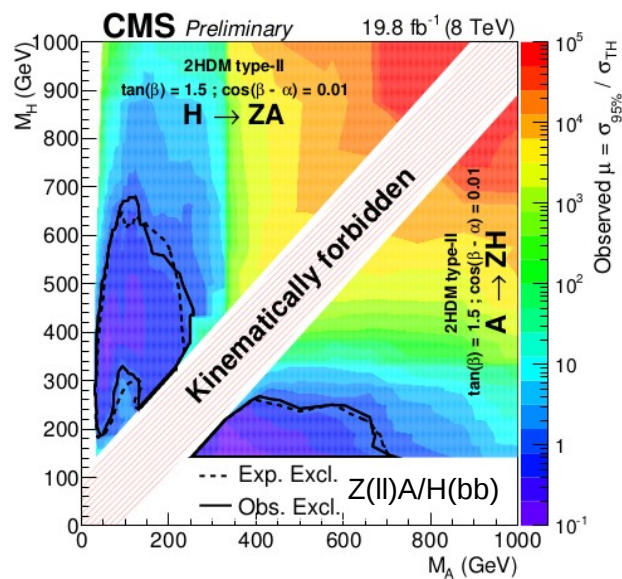
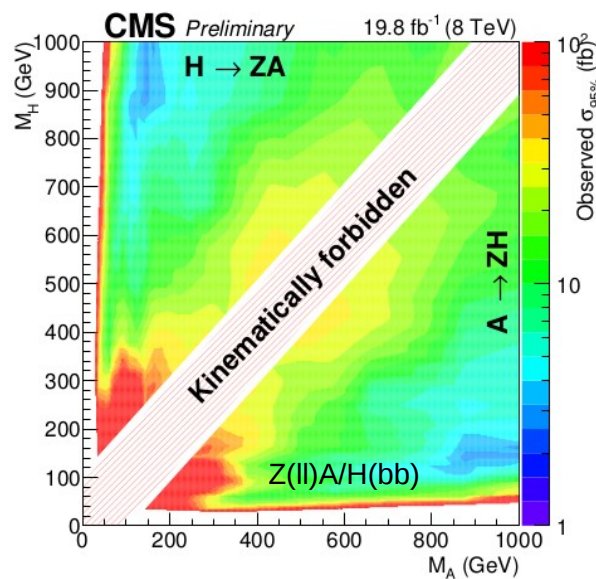
- Several channels can be combined for defined BSM models
 - Example: $H \rightarrow hh + A \rightarrow Zh$
- Limits derived as function of m_A vs $\tan\beta$ and $\tan\beta$ vs $\cos(\beta-\alpha)$





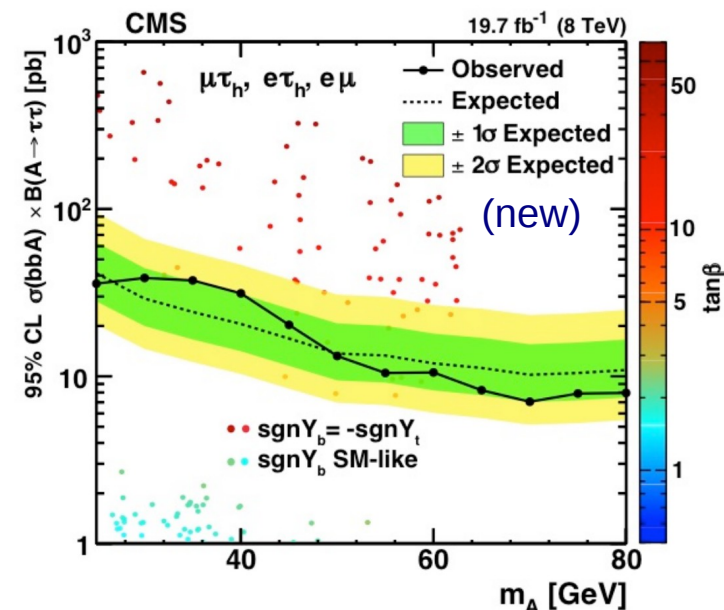
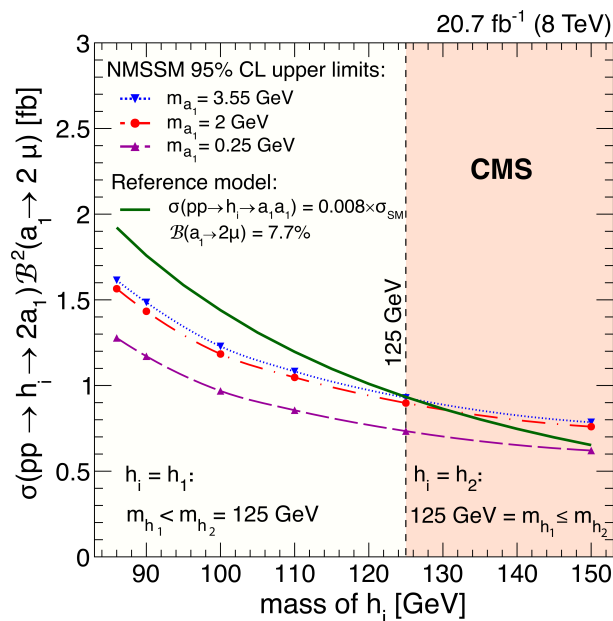
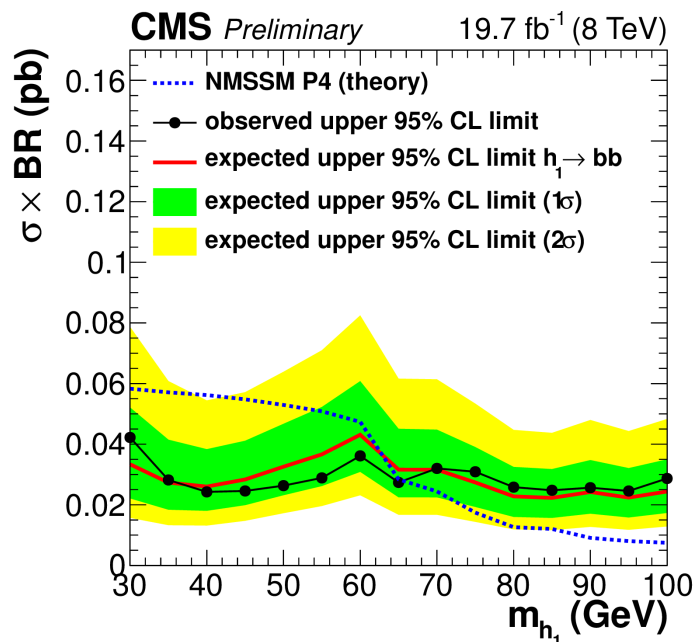
$H \rightarrow ZA, A \rightarrow ZH$

- 2HDM with non-degenerate H and A, $m_h = 125$ GeV, $m_{H\pm} = \max(m_H, m_A)$
- Two channels:
 - $Z(\text{II})A/H(bb)$
 - $Z(\text{II})A/H(\tau\tau)$
- Limit as function of m_H and m_A for $\cos(\beta - \alpha) = 0.01$, $\tan\beta = 1.5$
- Limit as function of $\tan\beta$ and $\cos(\beta - \alpha)$ for $m_H = 350$ GeV, $m_A = 150$ GeV



Light Higgses

-
- The figure contains two Feynman diagrams. The left diagram shows a quark q and an antiquark \bar{q} (represented by a shaded circle) annihilating into a Z^0 boson (wavy line). The Z^0 boson then decays into a quark q and an antiquark \bar{q} . The right diagram shows a quark q and an antiquark \bar{q} (represented by a shaded circle) annihilating into a gluino \tilde{g} (wavy line). The gluino then decays into a quark q and a gluon g . Various intermediate states and momenta are labeled, including $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, \tilde{g} , and h_1 .



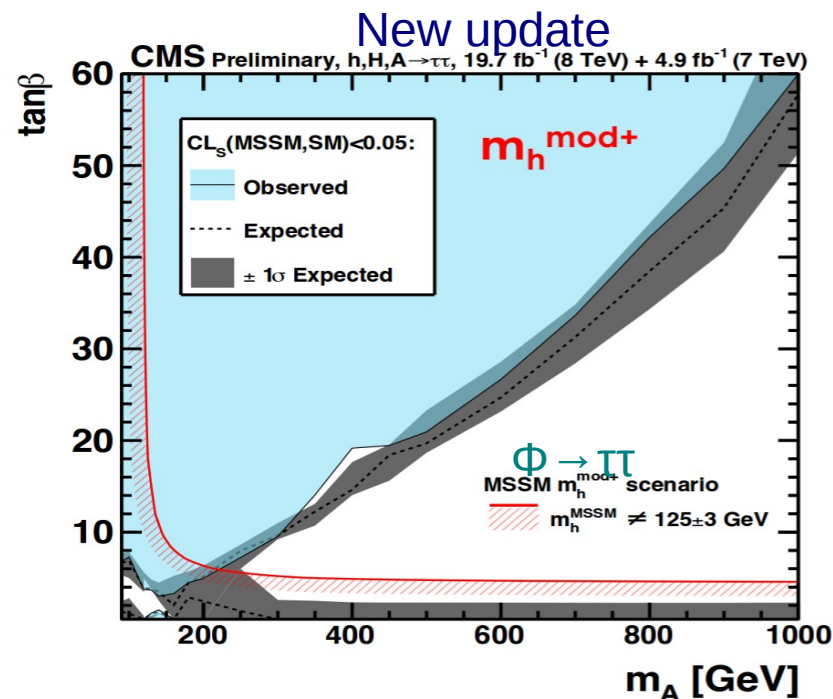
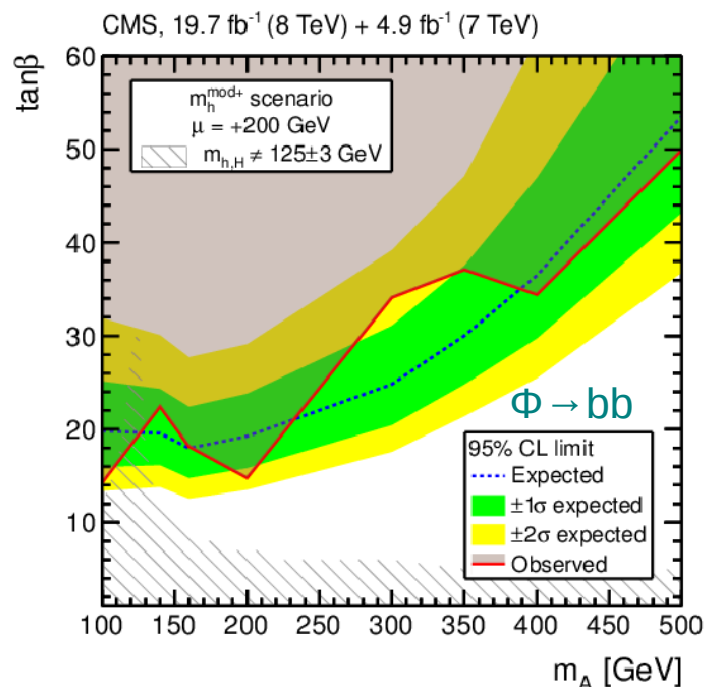
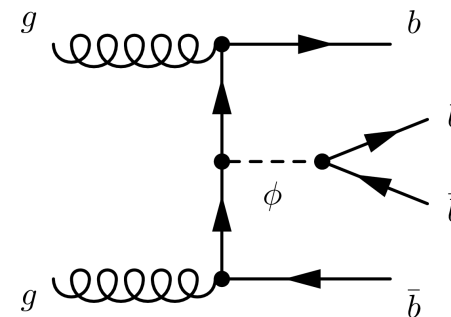
- [1] CMS-PAS-HIG-14-030
- [2] arXiv:1506.00424, Submitted to Physics Letters B
- [3] Paper to be submitted soon, EPS talk



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

- Search for new resonances in $b\bar{b}$ and $\tau\tau$ in the context of MSSM

- Φ can be A, h, H
- $\Phi \rightarrow b\bar{b}$ consider only production with extra b 's [1]
 - Sensitive mainly to large $\tan\beta$
- $\Phi \rightarrow \tau\tau$ consider also $gg\Phi$ production [2]
- 5 scenarios tested: m_h^{\max} , $m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$, light-stop, and light-stau (+ τ -phobic, and low- m_H for $\Phi \rightarrow \tau\tau$)



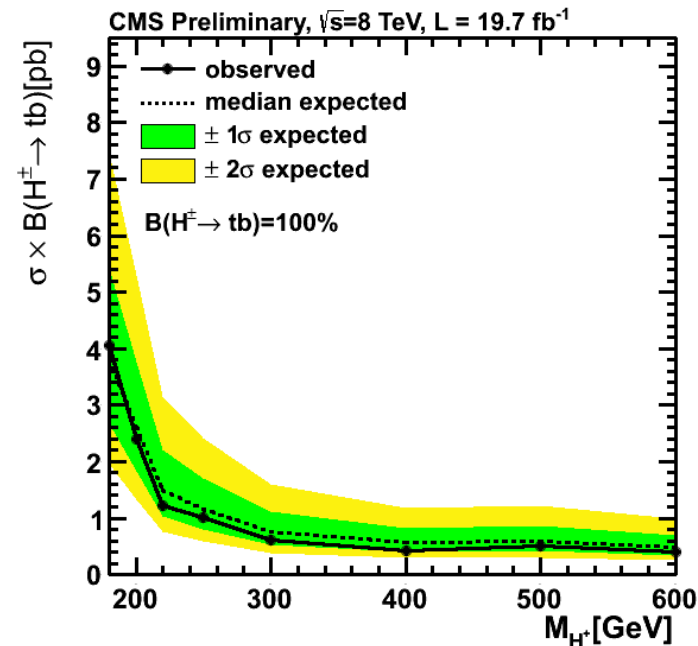
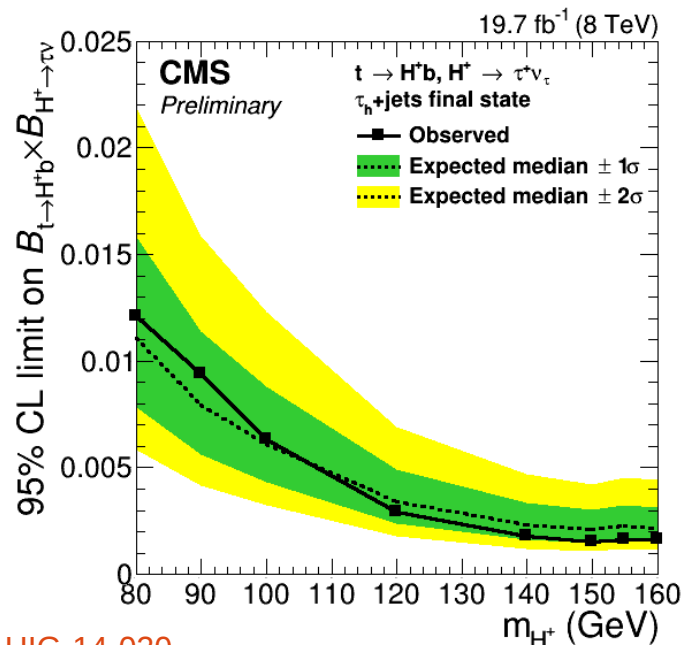
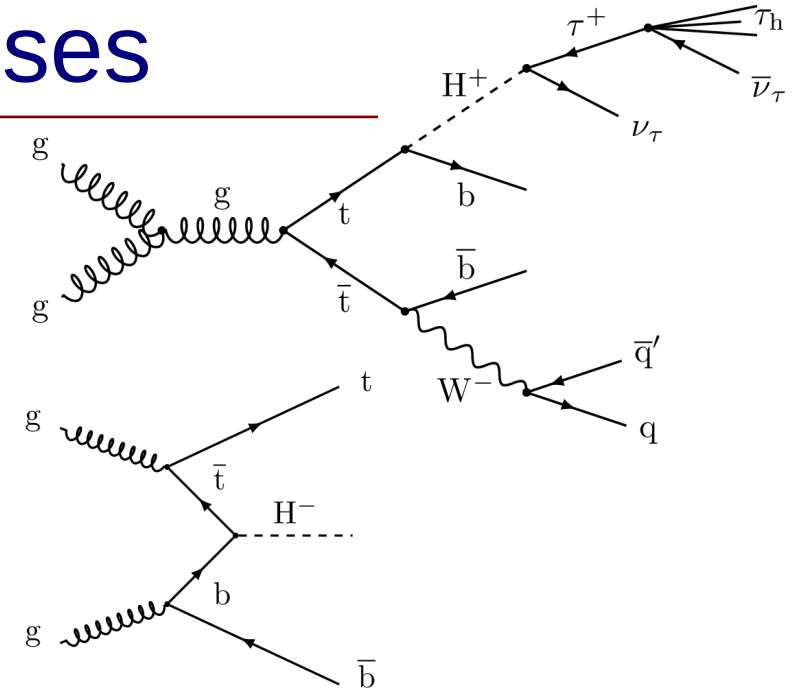
[1] [arXiv:1506.08329](https://arxiv.org/abs/1506.08329), Submitted to the Journal of High Energy Physics

[2] HIG-14-029, [EPS talk](#)



Charged Higgses

- Several channels explored:
 - $tt \rightarrow WbH^\pm b$ ($H^\pm \rightarrow \tau\nu, cs$) [1, 2]
 - $m_{H^\pm} < m_t \rightarrow$ limit on $B(t \rightarrow H^\pm b)$
 - tH^\pm ($H^\pm \rightarrow \tau\nu, tb$) [1, 3]
 - $m_t < m_{H^\pm} \rightarrow$ limit on $\sigma \times B$

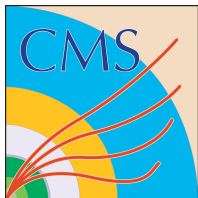




Summary

- Discovery of SM Higgs boson enhance interest for this topic
- Wide CMS BSM Higgs search program during Run1
 - Complementary to SM Higgs precision measurements
- Until now → no evidence of new physics in the Higgs sector observed
 - Large phase space explored
 - Limits set on $\sigma \times B$
 - Sensitivity reached O(10 fb) for several analyses
 - Interpretation of the limits in several BSM models (generic 2HDM, MSSM, NMSSM, DM candidate, singlet...)
- Run2 LHC would allow to push further the searches
 - New ideas for final states and models to explore are always welcomed

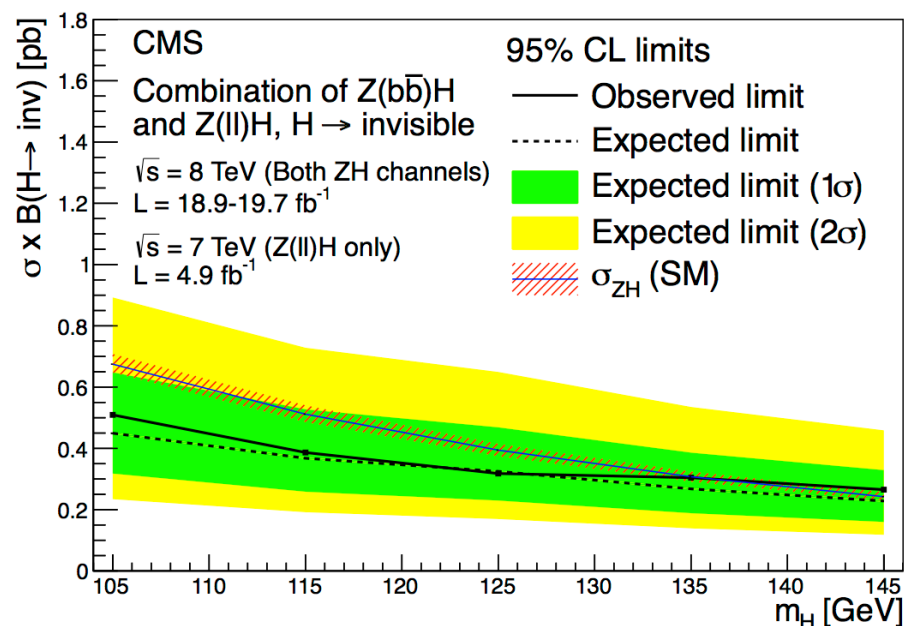
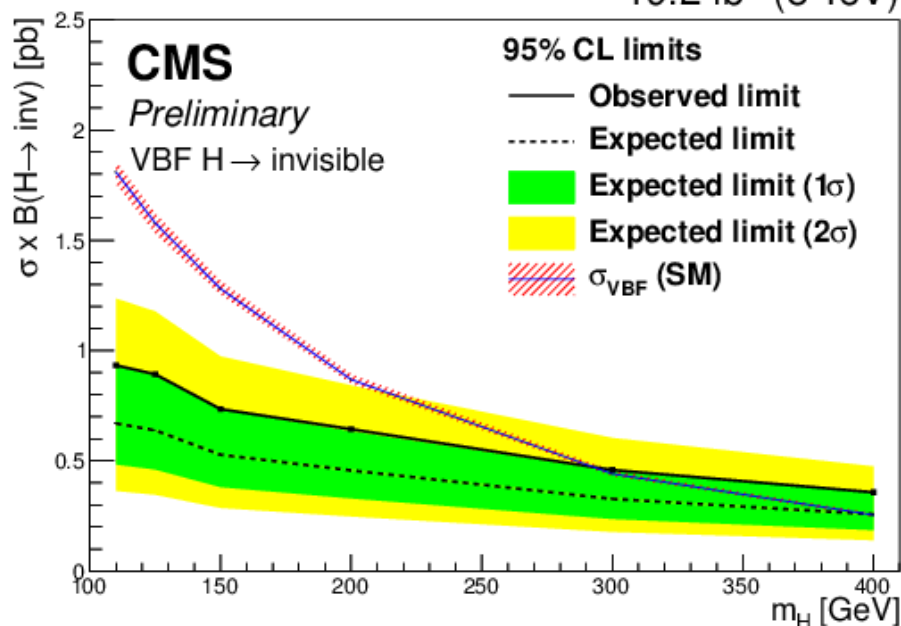
Backup



$h \rightarrow \text{invisible}$ (additional information)

- Vector Boson Fusion production of $h \rightarrow \text{invisible}$ → best sensitivity [1]
 - Improvement w.r.t. to [2] due to “parked” data recorded in 2012 and reconstructed in 2013
 - Lower trigger threshold → larger acceptance → improvement on the selection to increase the sensitivity
 - Expected limits on $B(h \rightarrow \text{inv})$: 0.49% → 0.40%
- Other result: assuming SM Higgs-like particle $H \rightarrow \text{invisible}$ → limit on $\sigma \times B(H \rightarrow \text{inv})$ vs m_H

19.2 fb⁻¹ (8 TeV)

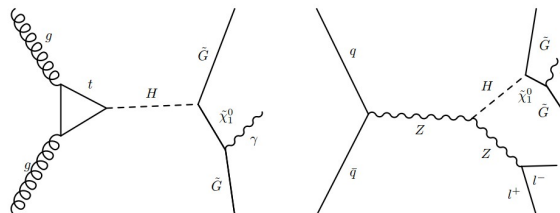


[1] CMS-PAS-HIG-14-038

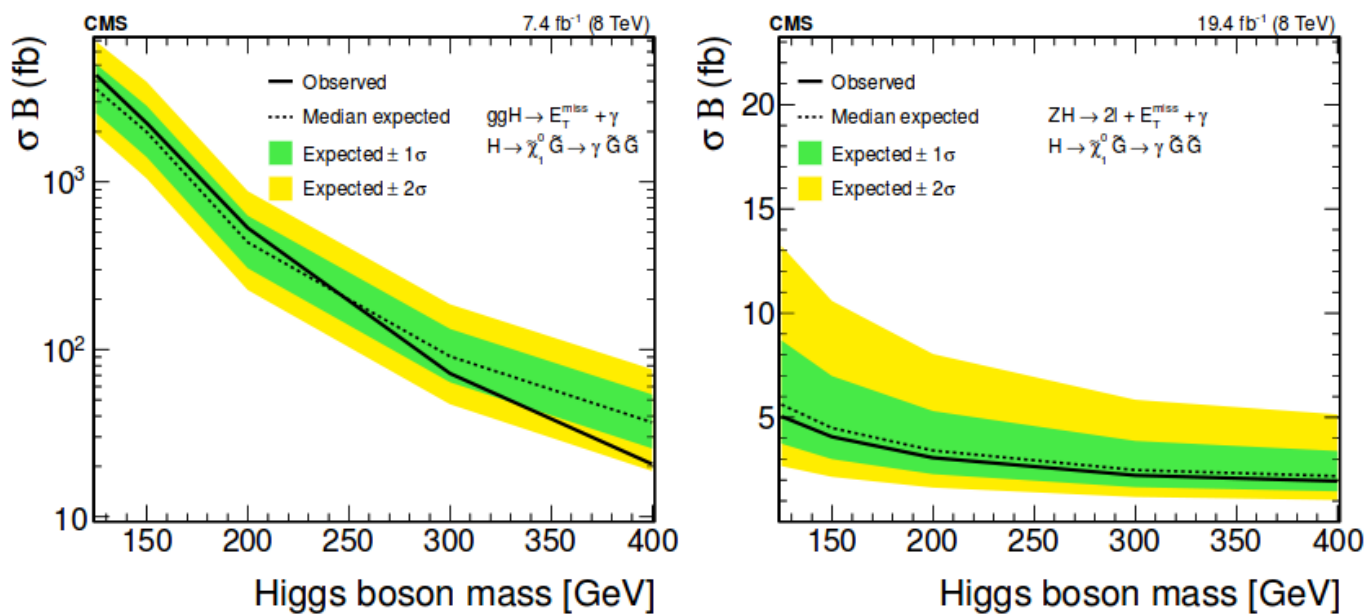
[2] EPJC 74 (2014) 2980



$h \rightarrow \gamma + \text{invisible (other results)}$



- Results also expressed in function of m_H where H is a SM-like H boson





$h \rightarrow \mu\tau$ and $t \rightarrow ch$ (additional material)

- Limits on branching ratio at 95% CL by channels and compared to expectation

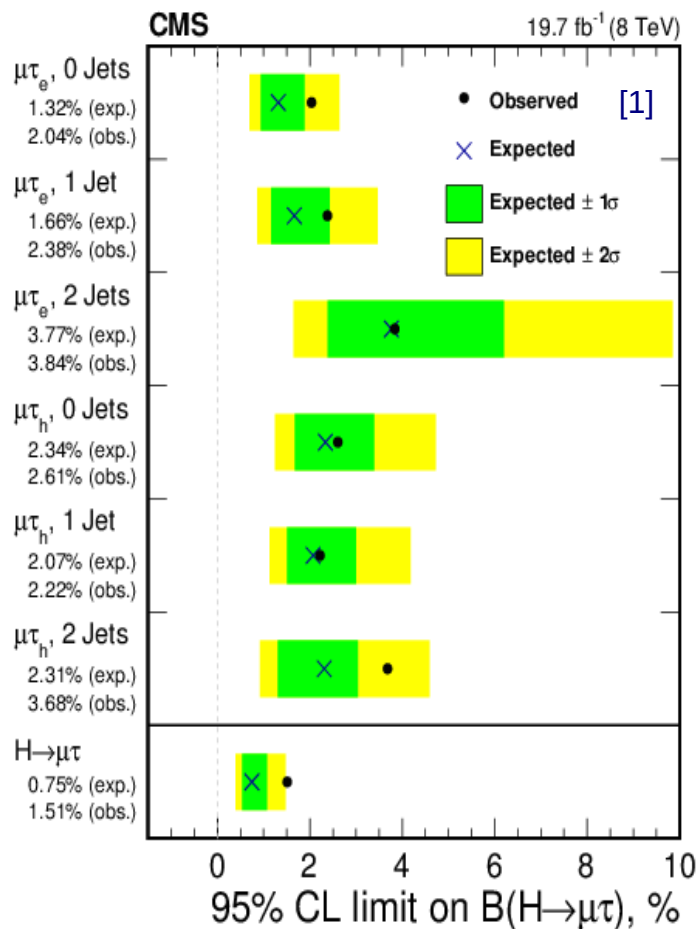


TABLE IX. Comparison of the observed and expected 95% C.L. limits on $B(t \rightarrow ch)$ from individual Higgs boson decay modes along with the 68% C.L. uncertainty ranges. [2]

Higgs boson decay mode	Obs.	Upper limits on $B(t \rightarrow ch)$	
		Exp.	68% C.L. range
$B(h \rightarrow WW^*)$	$= 23.1\%$	1.58%	1.57% (1.02–2.22)%
$B(h \rightarrow \tau\tau)$	$= 6.15\%$	7.01%	4.99% (3.53–7.74)%
$B(h \rightarrow ZZ^*)$	$= 2.89\%$	5.31%	4.11% (2.85–6.45)%
Combined multileptons ($WW^*, \tau\tau, ZZ^*$)		1.28%	1.17% (0.85–1.73)%
$B(h \rightarrow \gamma\gamma)$	$= 0.23\%$	0.69%	0.81% (0.60–1.17)%
Combined multileptons + diphotons		0.56%	0.65% (0.46–0.94)%

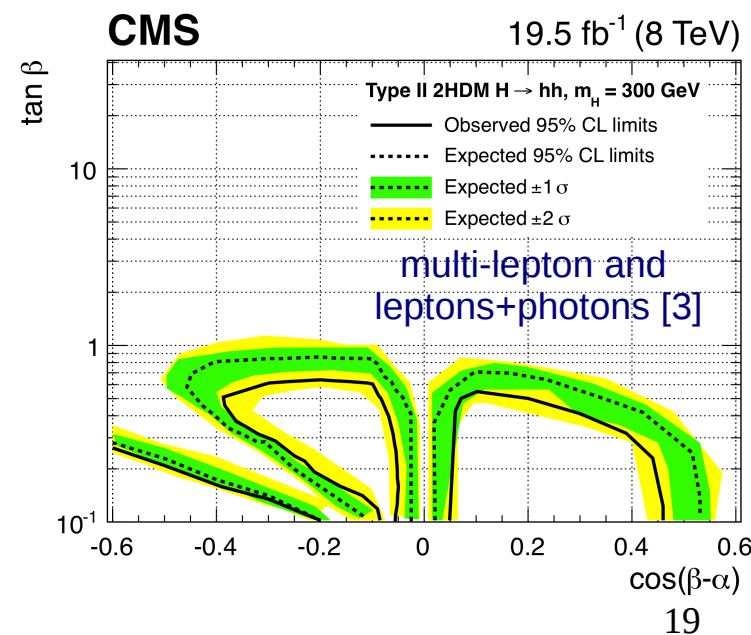
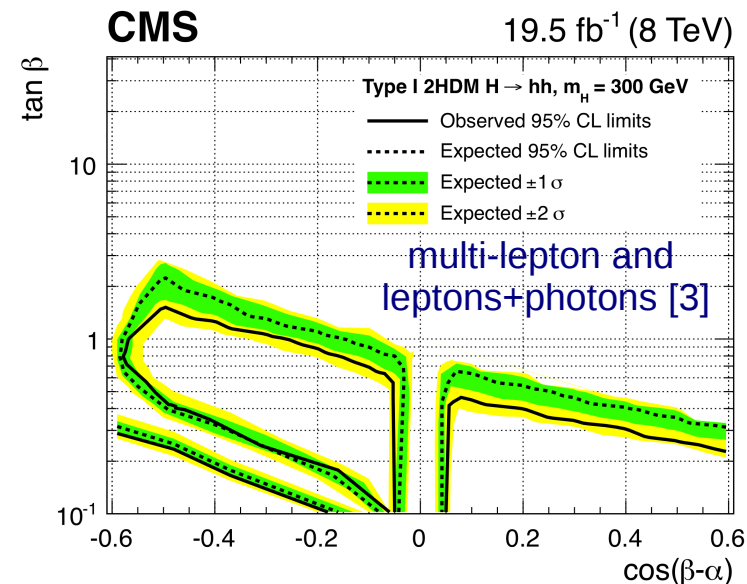
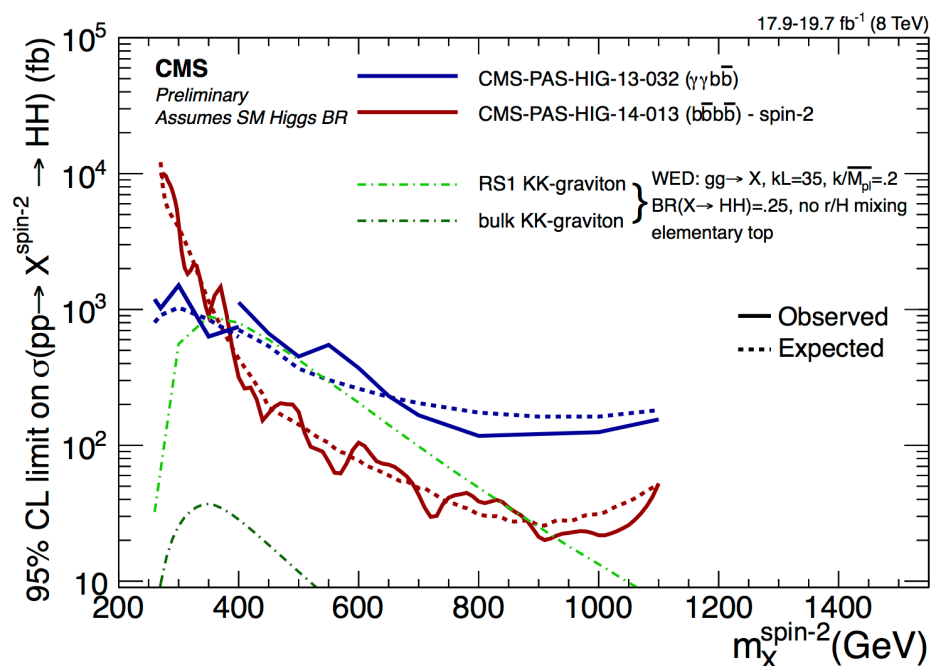
[1] CMS-PAS-HIG-14-005

[2] CMS-PAS-HIG-13-034, Phys. Rev. D 90, 112013



$X \rightarrow hh \rightarrow bbbb, bbyy, \text{multi-lepton and leptons+photons}$ (other results)

- Looking for heavy resonances decaying in pair of h bosons
- X can be reinterpreted as spin-2 graviton [1,2]
 - In Warped Extra Dimensions models
- High mass $H \rightarrow$ limits on 2HDM models parameter [3]



[1] CMS-PAS-HIG-13-032

[2] arXiv:1503.04114, Submitted to Physics Letters B

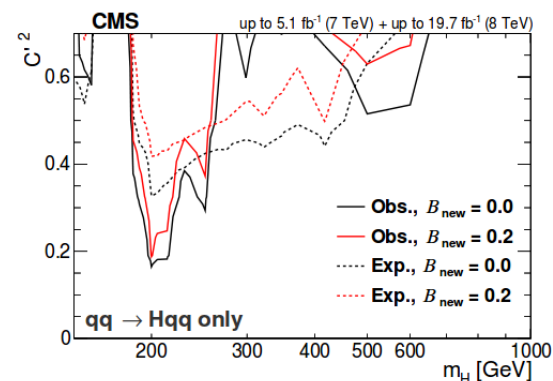
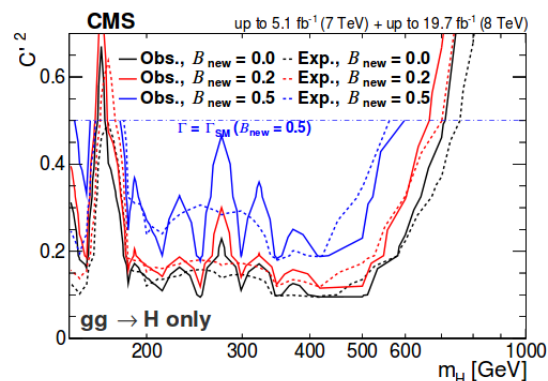
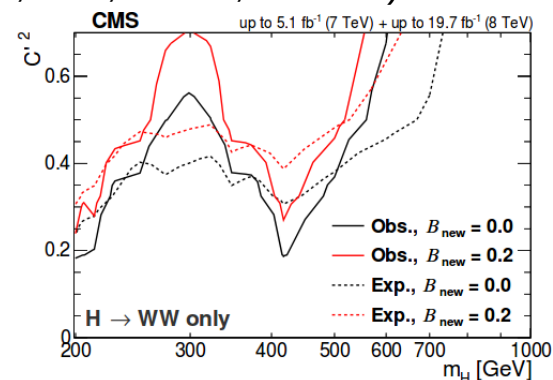
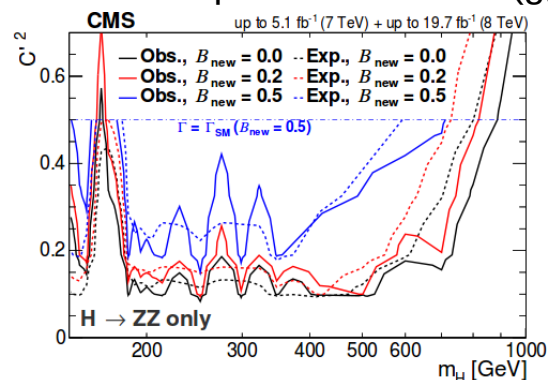
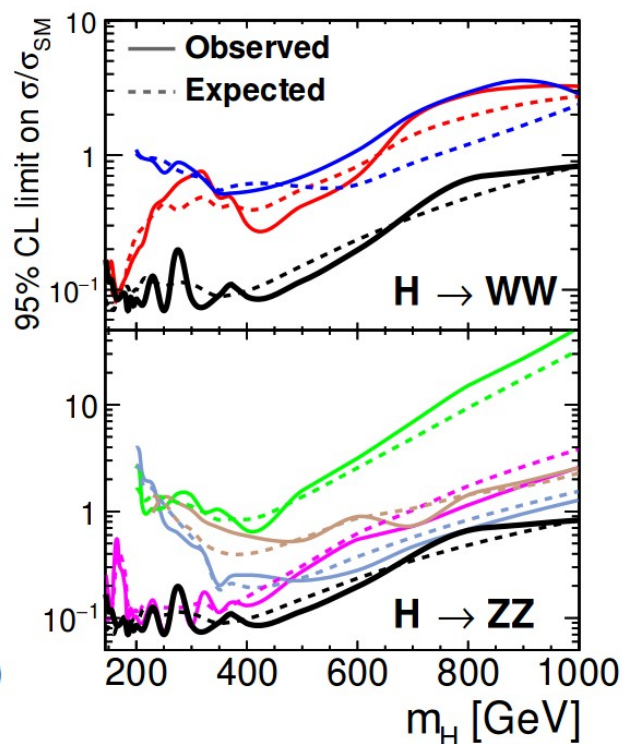
[3] Phys. Rev. D 90, 112013



$X \rightarrow ZZ, WW$ (split results)

- SM h boson search for high mass \rightarrow reinterpreted in term of BSM models
 - Combine $lvlv, lvqq, 4l, llvv, llqq$
- Probe m_X in [145 - 1000] GeV
- Assume SM Higgs-like production and decay

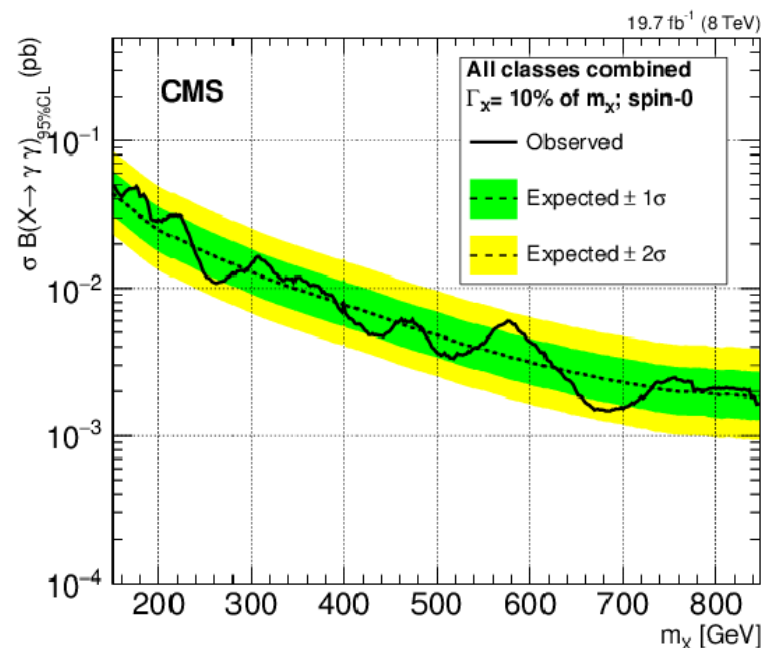
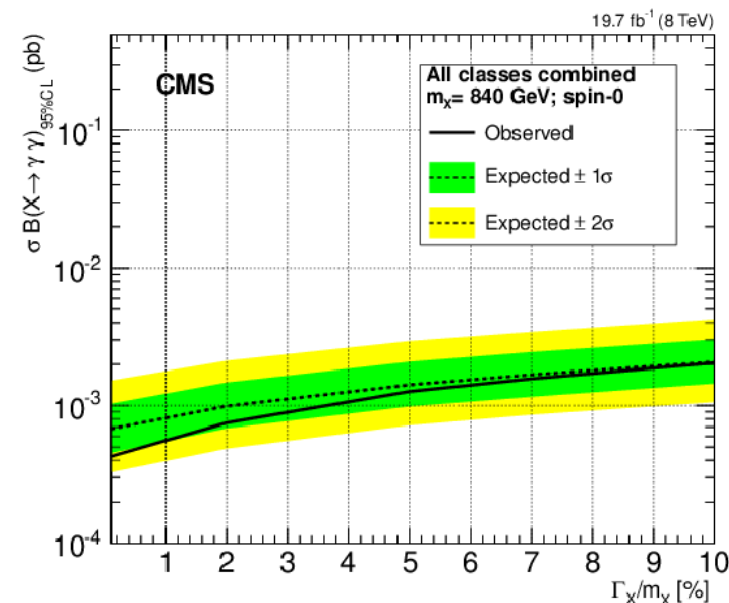
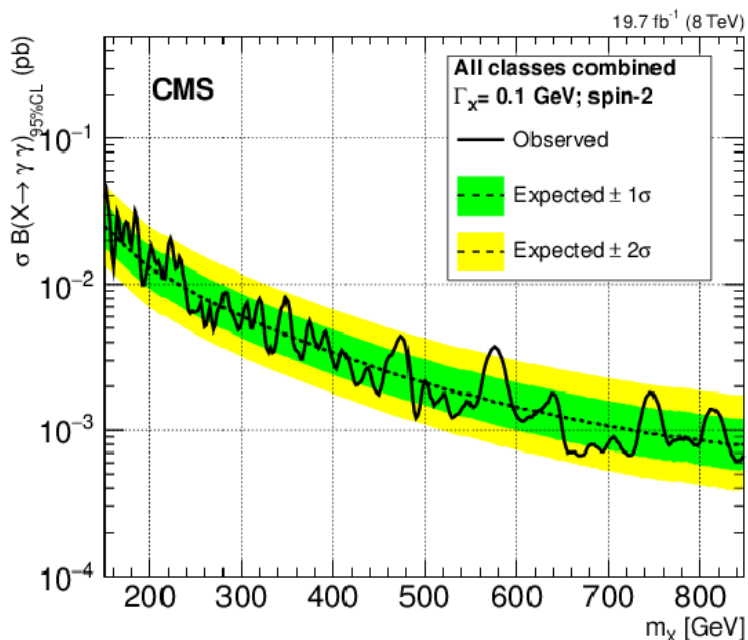
- Reinterpretation in terms of EW singlet extension of SM in terms of model parameters:
 - B_{new} : branching fraction of the EW singlet to non-SM decay mode
 - C' : the scale factors of the couplings with respect to the SM of the high-mass Higgs boson
- Only consider cases with $\Gamma_H \leq \Gamma_{SM}$
- Results provided independently for each h decays and production mode (ggh, VBF, $h \rightarrow ZZ$, $h \rightarrow WW$)





$X \rightarrow \gamma\gamma$ (other results)

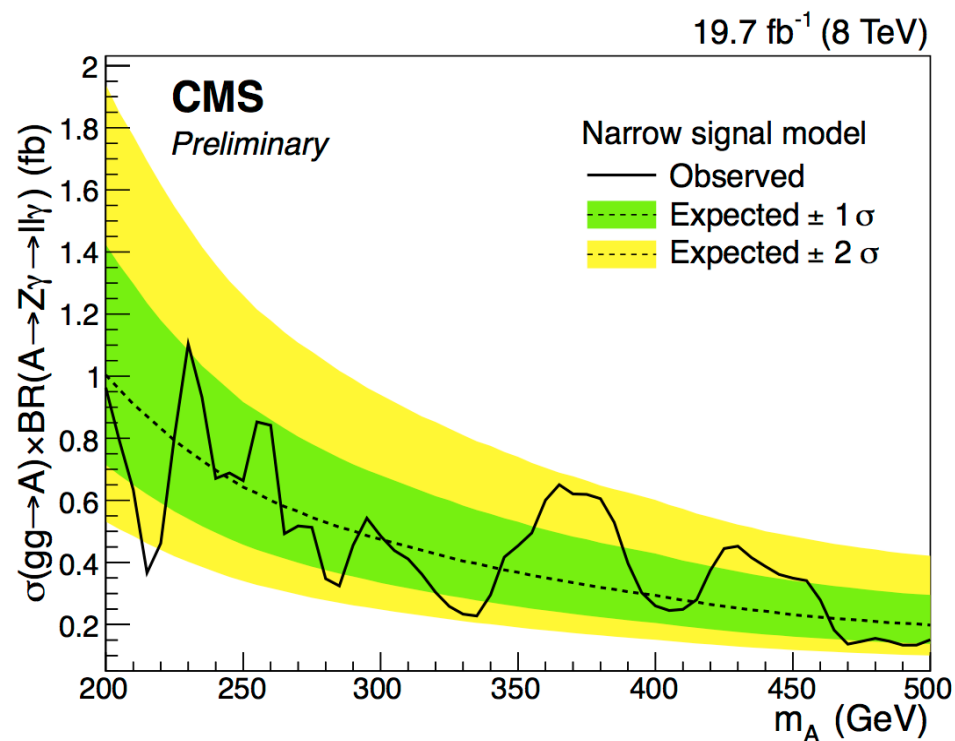
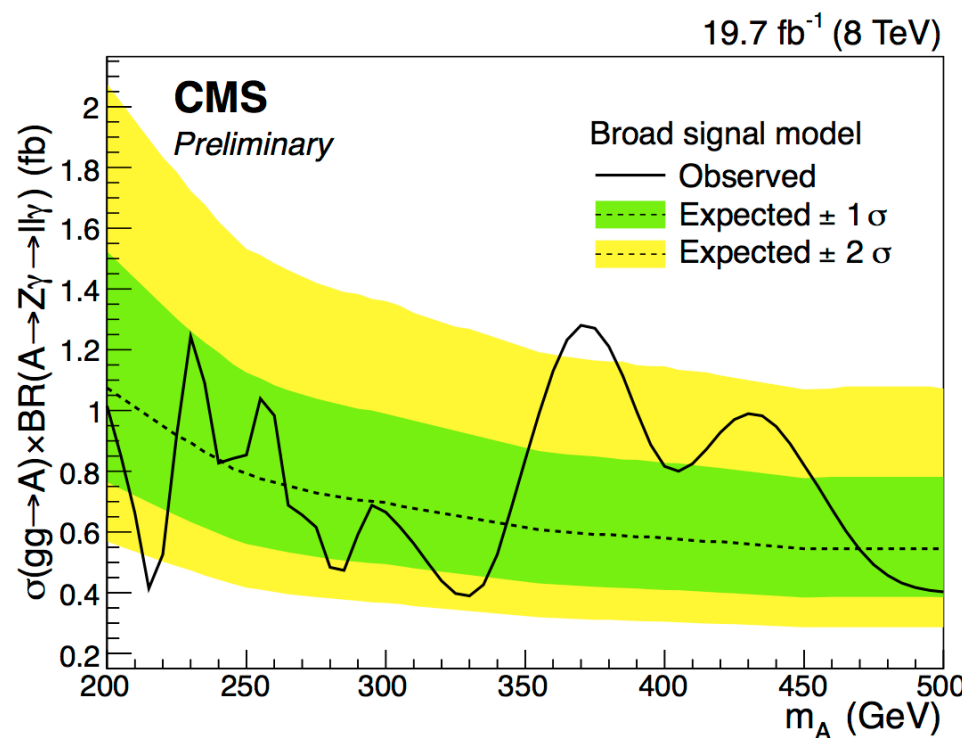
- Search for excess on top of background
 - Test different signal width up to 10% of the mass
- Range explored: [150-850] GeV
- Interpretation for spin-0 and spin-2 resonances
- Limits as function of:
 - m_X (spin-2 small width, spin-0 large width)
 - Γ_X for $m_X = 840$ GeV





$$X \rightarrow Z\gamma$$

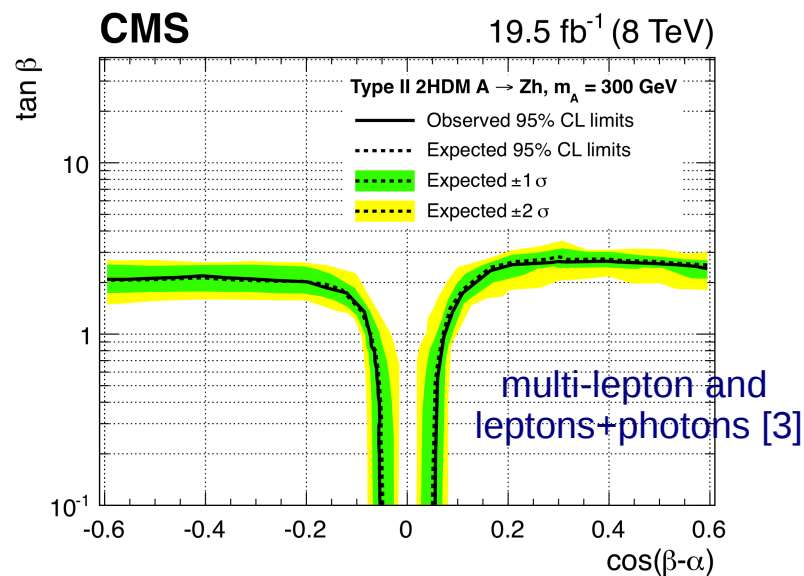
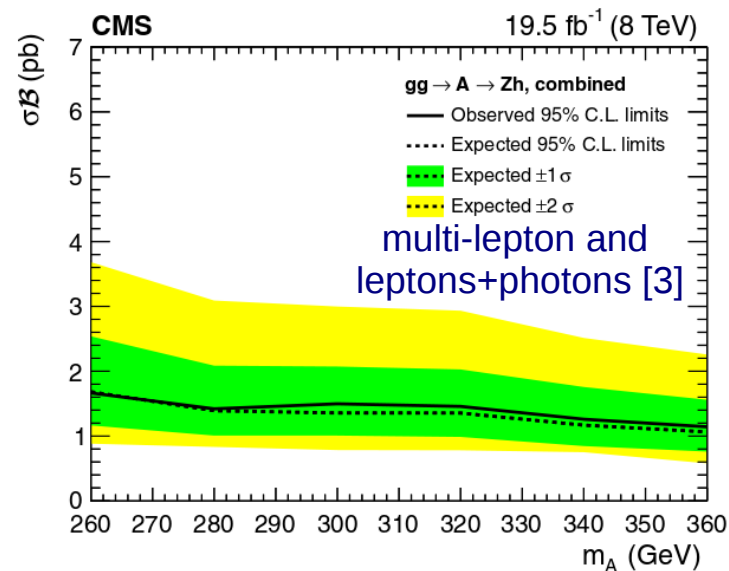
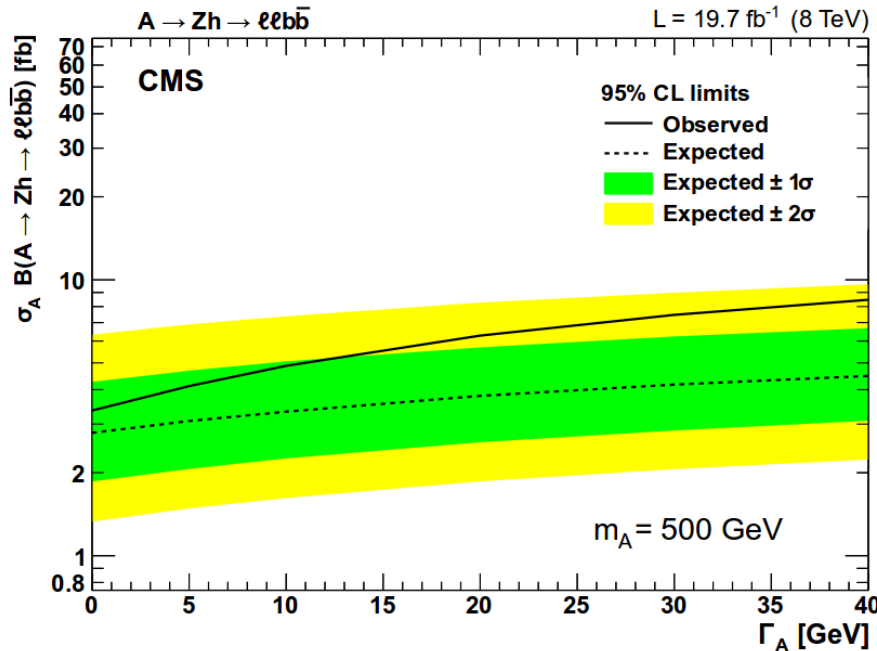
- Search for an excess in $Z(l\bar{l})\gamma$ with $l = e, \mu$
- Explore mass range [200-500]
- Test several X width hypothesis
 - Broad width: SM-like H width
 - Narrow width: 1% of m_X





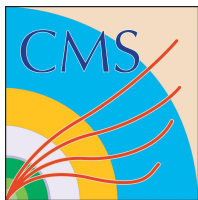
$A \rightarrow Zh$ (more results)

- Several channels
 - $Z(\ell\ell)h(bb)$ [1]
 - Multi-leptons and leptons+photons [2]
- Target MSSM like models
 - Model dependent and model independent limits



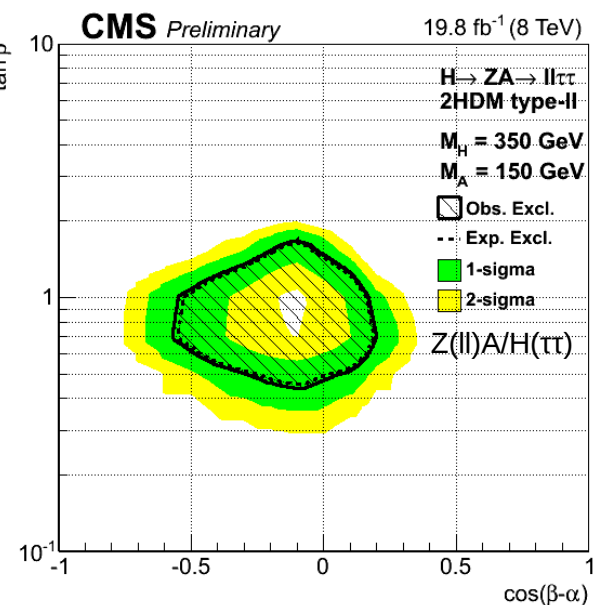
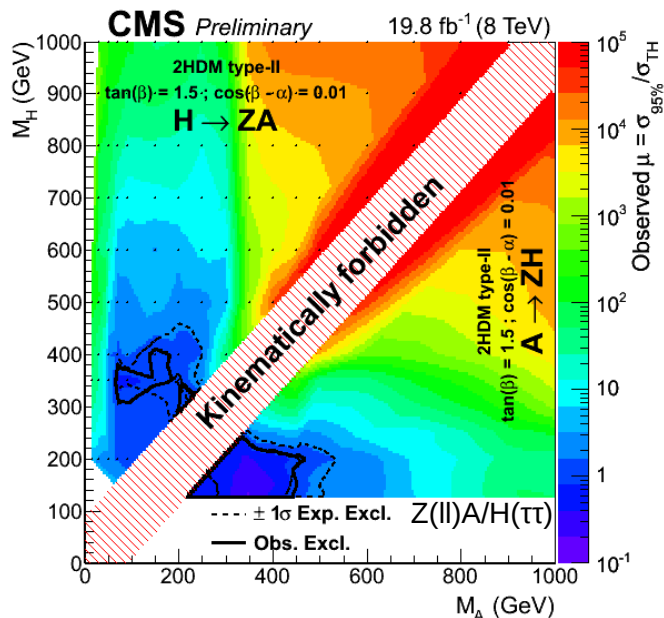
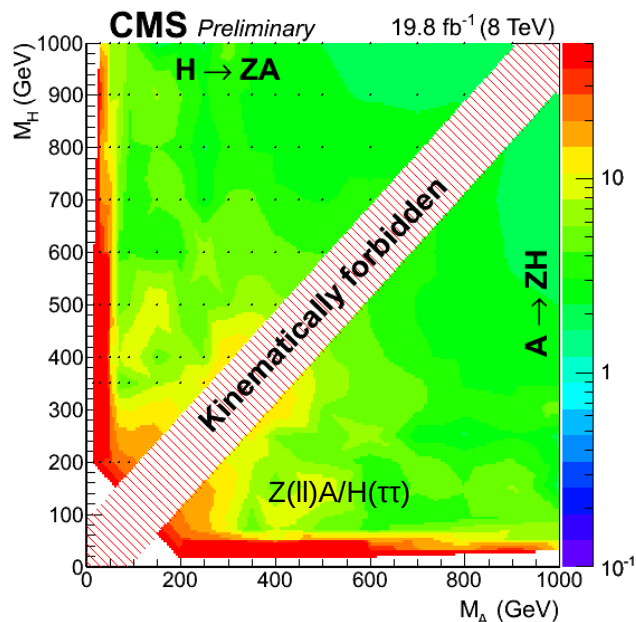
[1] [arXiv:1504.04710](https://arxiv.org/abs/1504.04710), Submitted to Physics Letters B

[2] [Phys. Rev. D 90, 112013](https://arxiv.org/abs/1504.04710)



$H \rightarrow ZA, A \rightarrow ZH$ ($ll\tau\tau$ results)

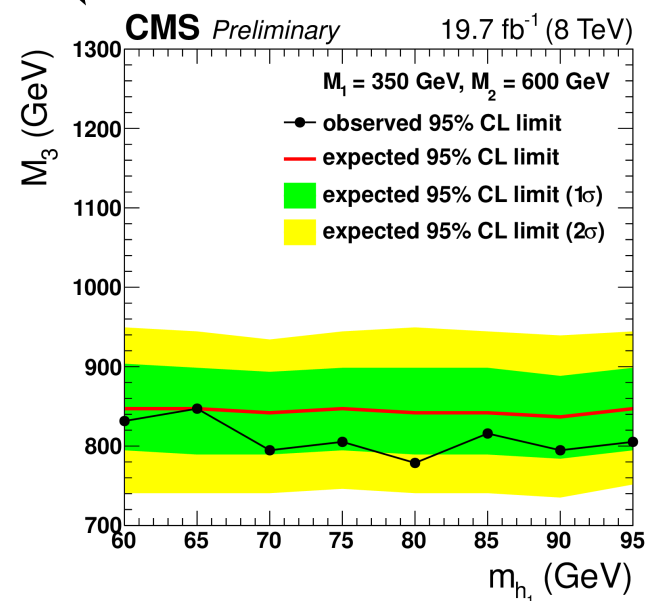
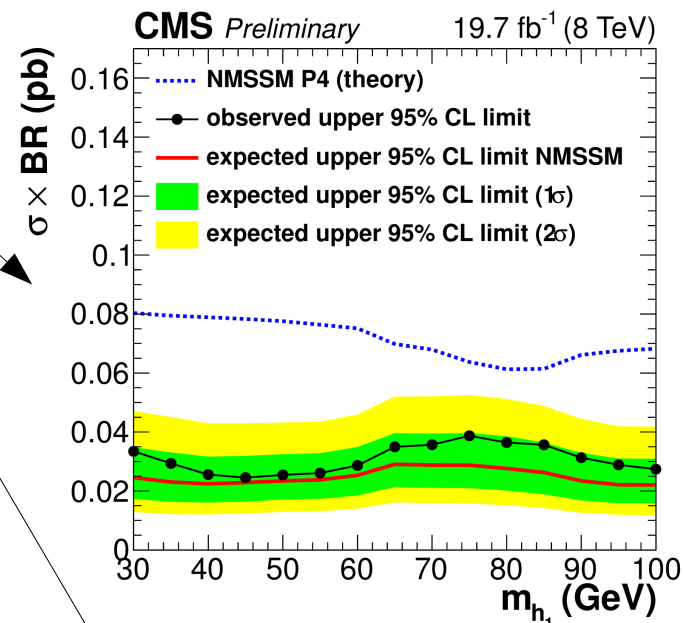
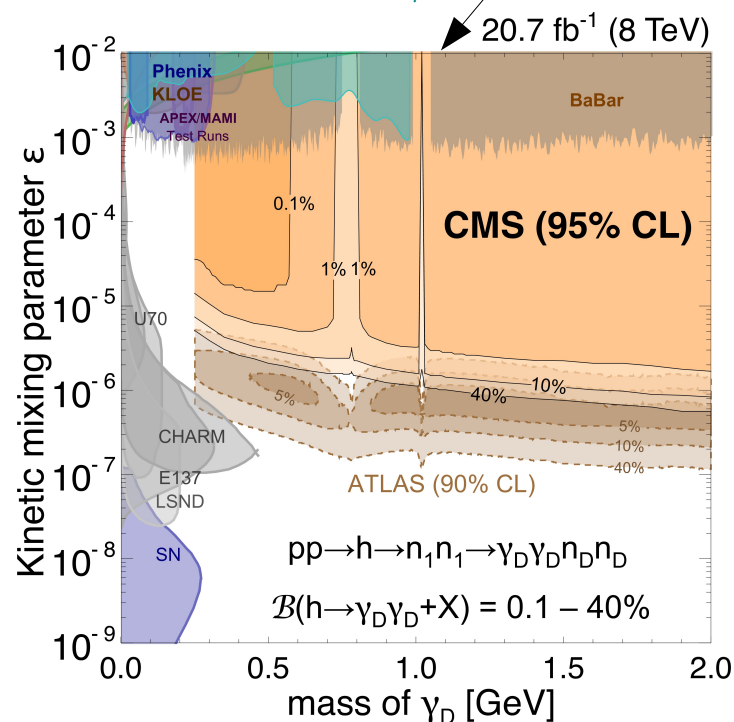
- 2HDM with non-degenerate H and A, $m_h = 125$ GeV, $m_{H\pm} = \max(m_H, m_A)$
- Two channels:
 - $Z(ll)A/H(bb)$
 - $Z(ll)A/H(\tau\tau)$
- Limit as function of m_H and m_A for $\cos(\beta - \alpha) = 0.01$, $\tan\beta = 1.5$
- Limit as function of $\tan\beta$ and $\cos(\beta - \alpha)$ for $m_H = 350$ GeV, $m_A = 150$ GeV





Light Higgses (other results)

- $h_1 + X \rightarrow bb + X$ [1] \rightarrow interpretation of the limits:
 - considering whole NMSSM P4 benchmark with fixed $M_3 \sim 1\text{TeV}$ (gluino mass)
 - Limit on M_3 for fixed M_1 (bino) and M_2 (wino) masses
- $h \rightarrow \gamma_D(\mu\mu)\gamma_D(\mu\mu) + X$ [2] in SUSY model with dark sector
 - $h=h_{\text{SM}}(125)$
 - Limit vs ϵ (kinetic mixing parameter between SM γ and the dark γ_D) and m_{γ_D}



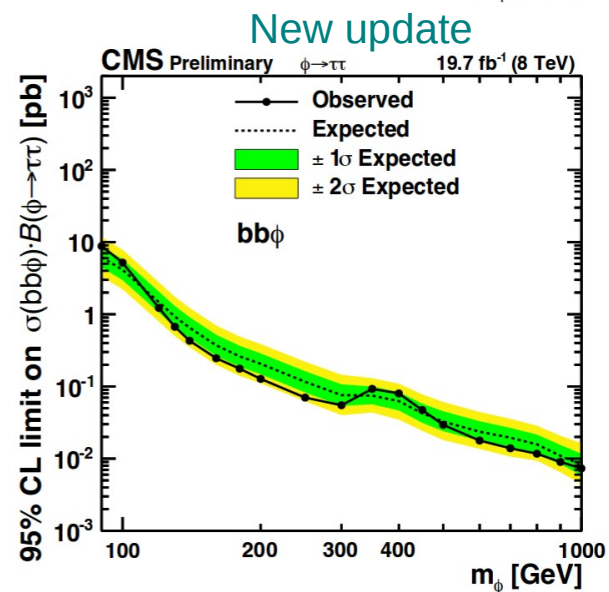
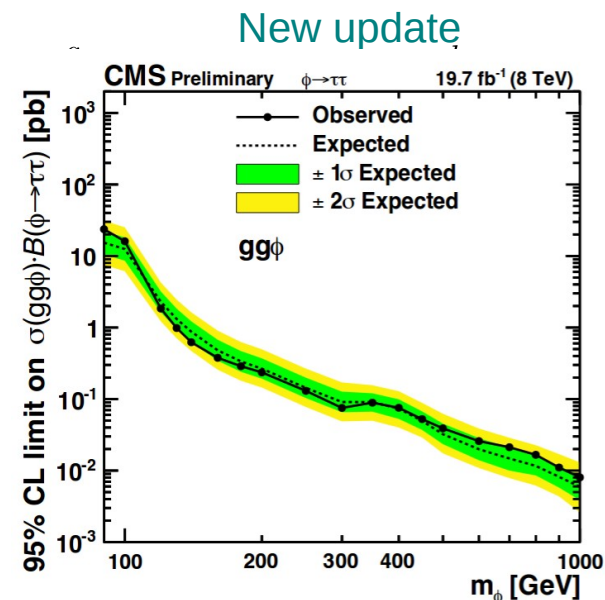
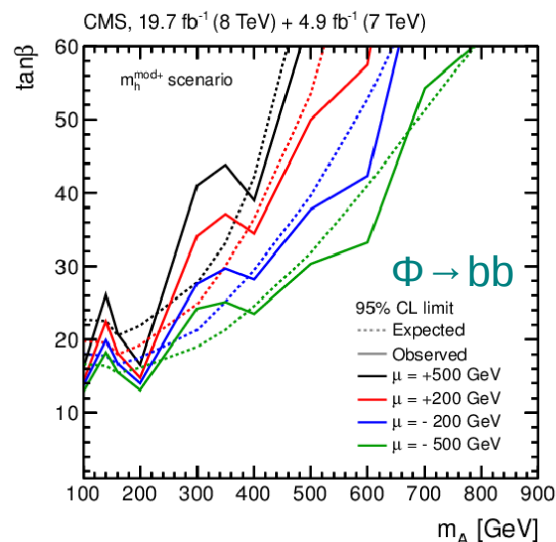
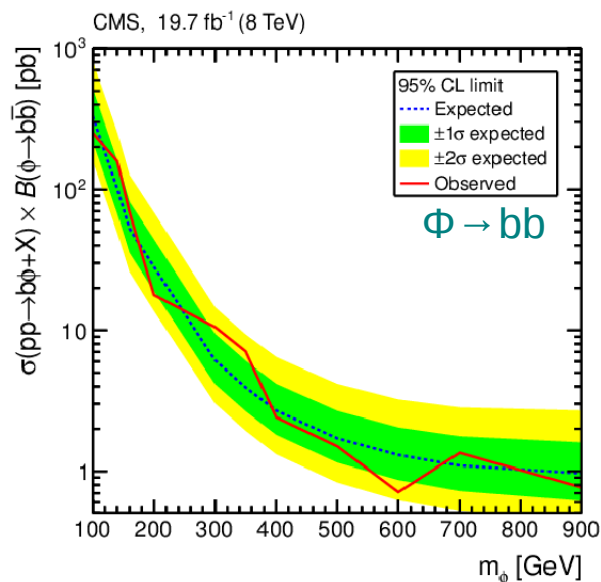
[1] CMS-PAS-HIG-14-030

[2] arXiv:1506.00424, Submitted to Physics Letters B



MSSM $\Phi \rightarrow b\bar{b}, \tau\tau$ (additional results)

- Search for new resonances in $b\bar{b}$ and $\tau\tau$ in the context of MSSM
 - Φ can be A, h, H
 - $\Phi \rightarrow b\bar{b}$ consider only production with extra b 's [1]
 - Sensitive mainly to large $\tan\beta$
 - $\Phi \rightarrow \tau\tau$ consider also $gg\Phi$ production [2]
 - 5 scenarios tested: m_h^{\max} , $m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$, light-stop, and light-stau (+ τ -phobic, and low- m_H for $\Phi \rightarrow \tau\tau$)

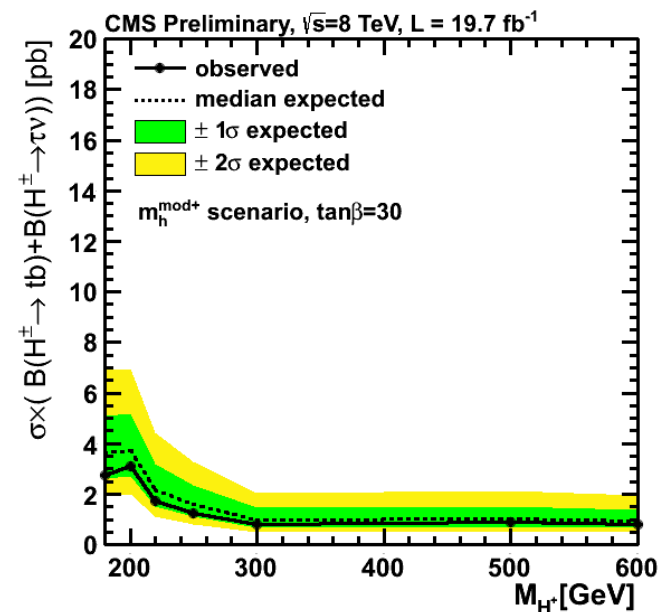
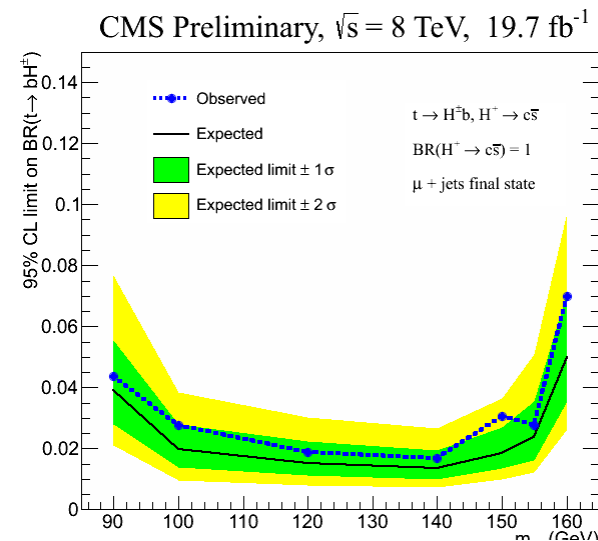
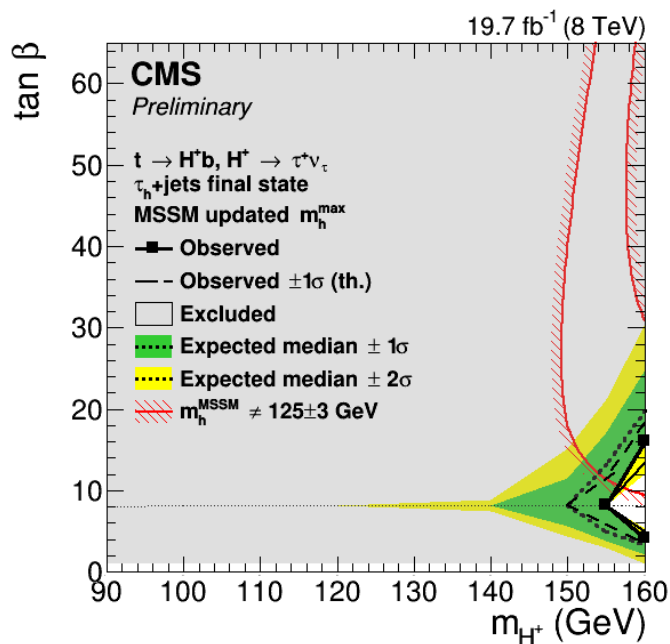
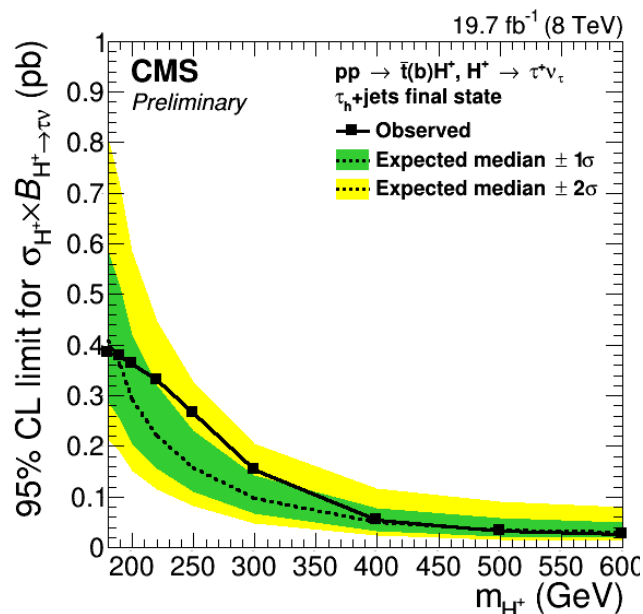


[1] [arXiv:1506.08329](https://arxiv.org/abs/1506.08329), Submitted to the Journal of High Energy Physics

[2] HIG-14-029, [EPS talk](#)

Charged Higgses (more results)

- Several channels explored:
 - $tt \rightarrow WbH^\pm b$ ($H^\pm \rightarrow \tau\nu, cs$) [1, 2]
 - $m_{H^\pm} < m_t \rightarrow$ limit on $B(t \rightarrow H^\pm b)$
 - tH^\pm ($H^\pm \rightarrow \tau\nu, tb$) [1, 3]
 - $m_t < m_{H^\pm} \rightarrow$ limit on $\sigma \times B$



[1] CMS-PAS-HIG-14-020

[2] CMS-PAS-HIG-13-035

[3] CMS-PAS-HIG-13-026



Doubly charged Higgses $\Phi^{\pm\pm}$

- 6 channels
 - $ee, \mu\mu, e\mu, e\tau, \mu\tau, \tau\tau$
- Interpretation for 4 benchmark models

