CMS BSM Higgs

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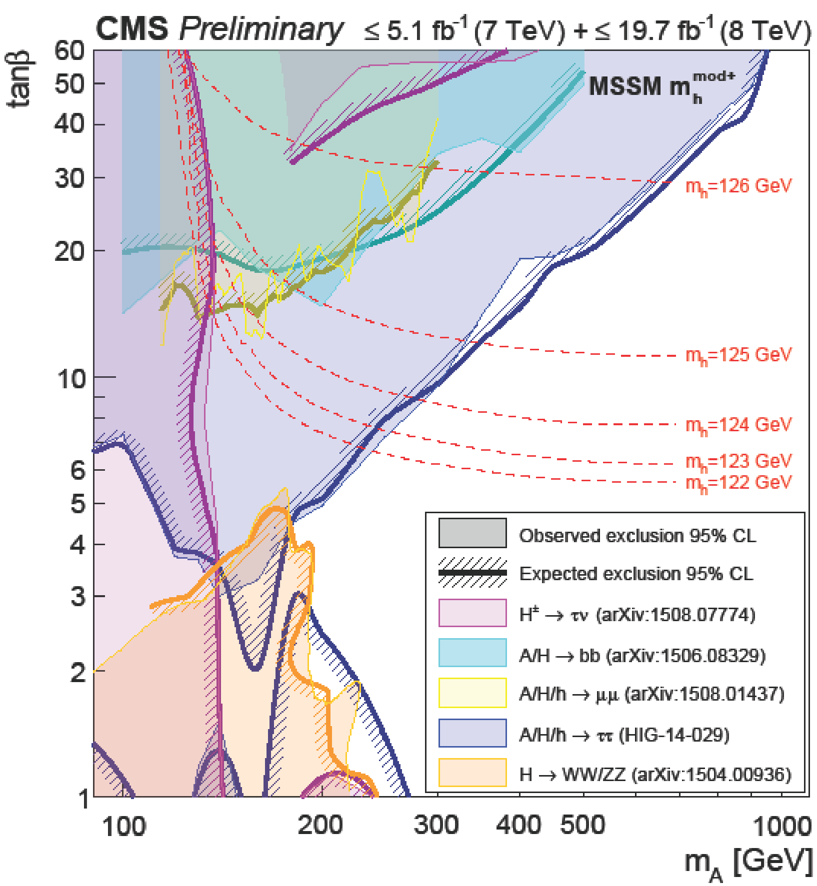
On behalf of the CMS Collaboration
Higgs Hunting 2016, LPNHE Paris

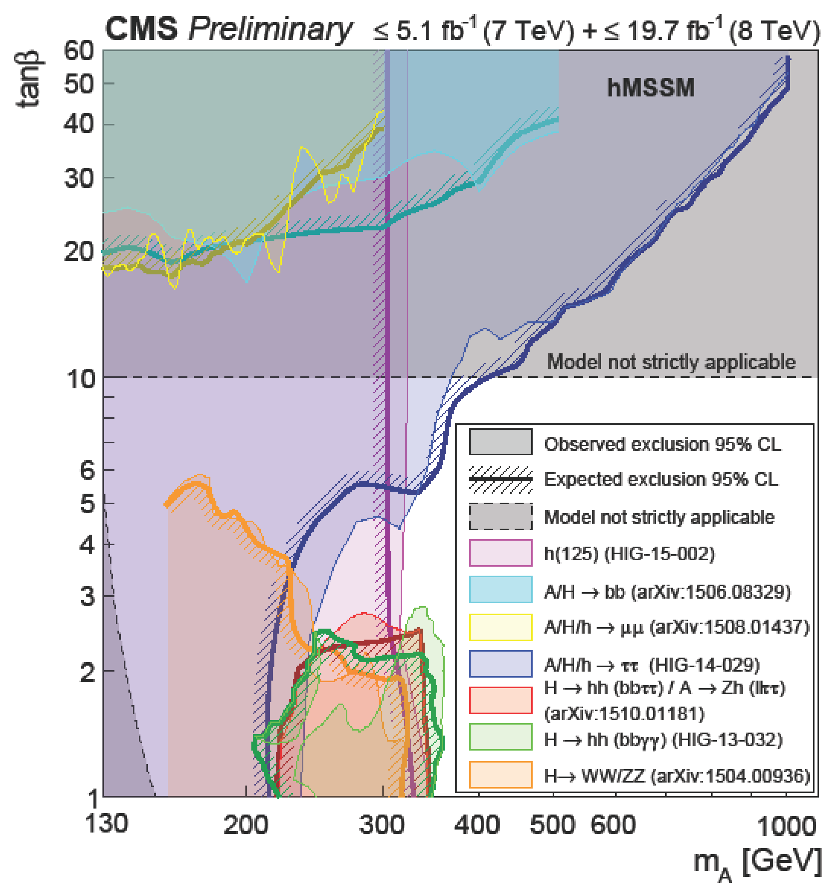
Motivation

- Search for additional Higgs bosons
  - Additional Higgs doublet
    - Two Higgs doublet
    - MSSM
  - Higgs triplet
- Outline
  - MSSM searches
  - Double Higgs
  - Charged Higgs
  - Lepton flavor violating Higgs
  - Invisible Higgs
  - Heavy Higgs

MSSM Run-1 Summary

- Parameterize search as a function of
  - m_A: mass of the pseudoscalar Higgs
  - tan β: ratio of VEV of the two Higgs doublets





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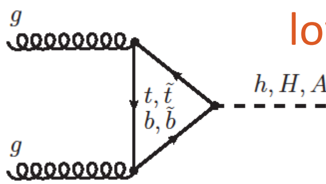
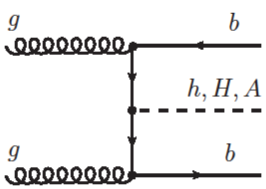
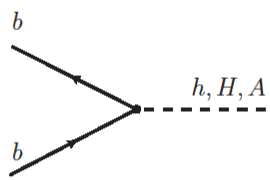
h/H/A → ττ

- Here ϕ = h/H/A
- Binned maximum likelihood fit using the transverse mass of the ditau candidate

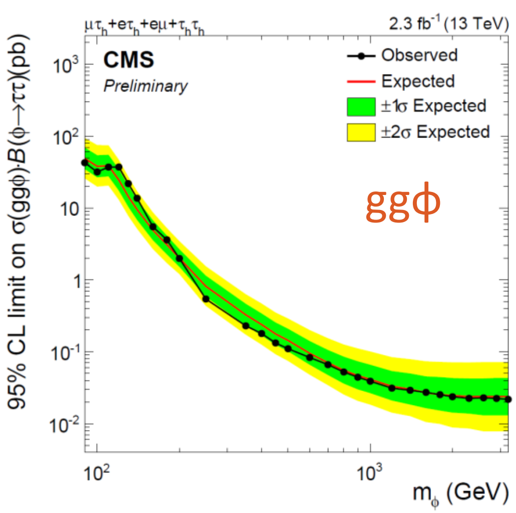


Dominant at low/medium tan β

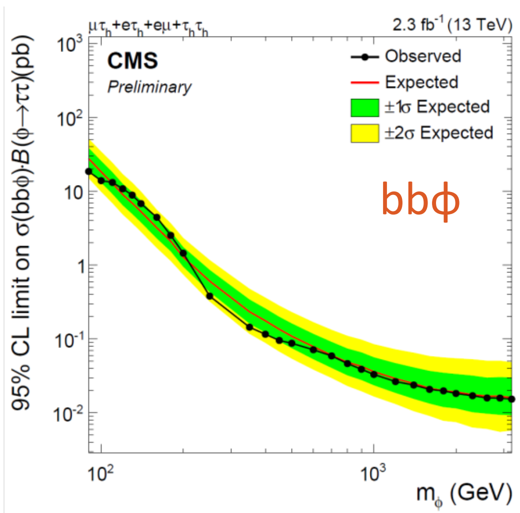




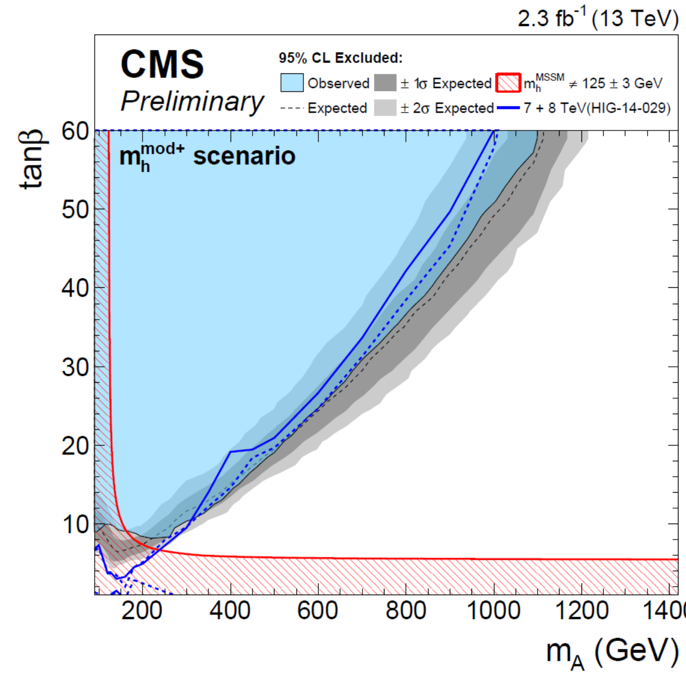
Dominant at high tan β

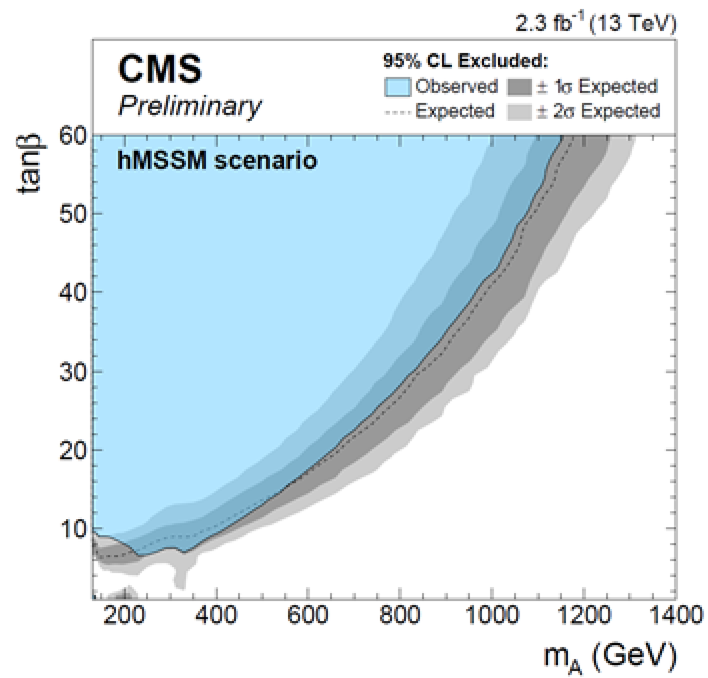


ggϕ



bbϕ





H → ZA → llbb

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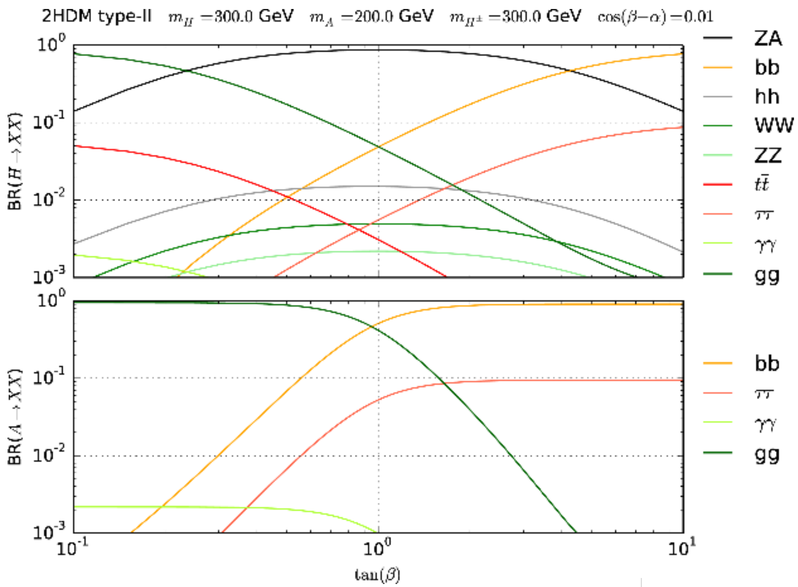
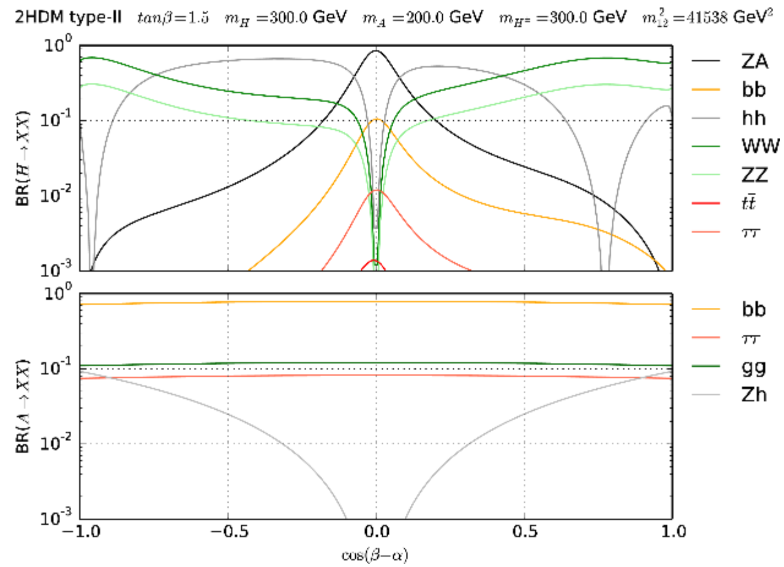
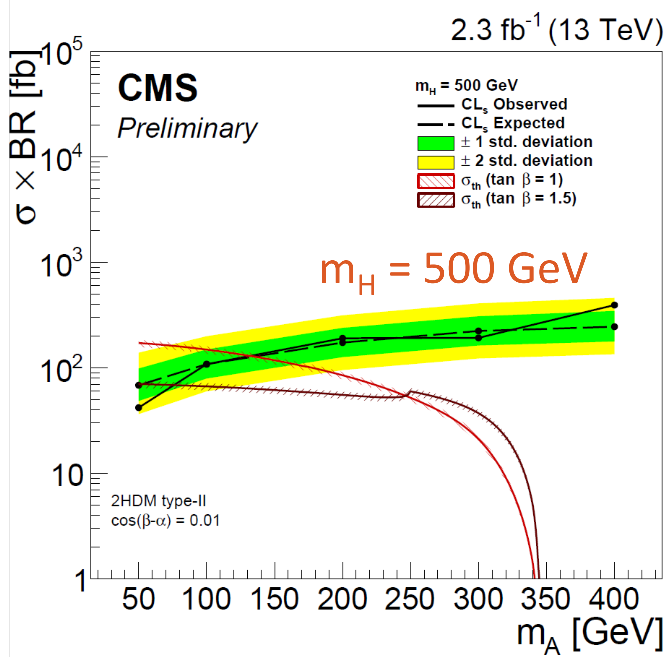




- Most sensitive at low tan β



Search tan β in range [0.5,1.5]

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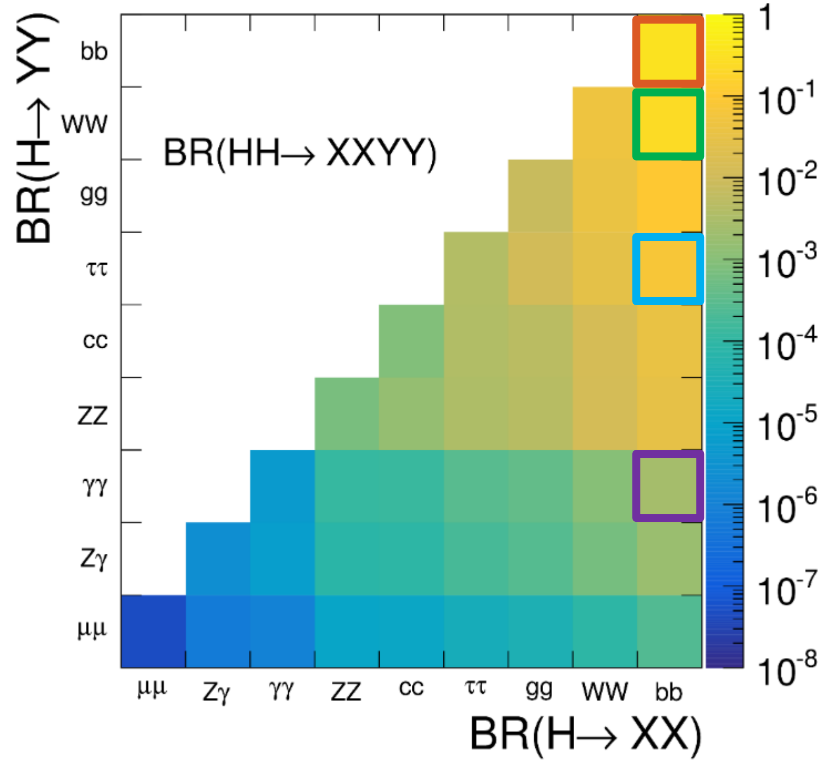
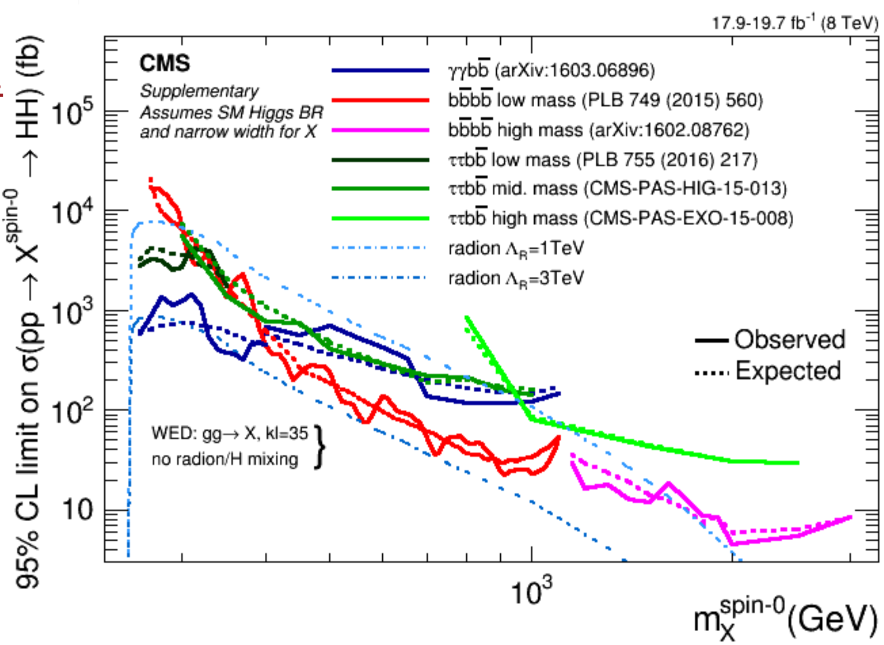
Double Higgs

- Several analyses exploring the production of hh
  - hh → bb bb 34% CMS-PAS-HIG-16-002 CMS-PAS-HIG-16-026
  - hh → bb WW 25% CMS-PAS-HIG-16-011 CMS-PAS-HIG-16-024
  - hh → bb ττ 7.3% CMS-PAS-HIG-16-028 CMS-PAS-HIG-16-029
  - hh → bb γγ 0.26% CMS-PAS-HIG-16-032
- Multiple interpretations
  - Resonant production
    - Spin-0
    - Spin-2
  - Non-resonant production

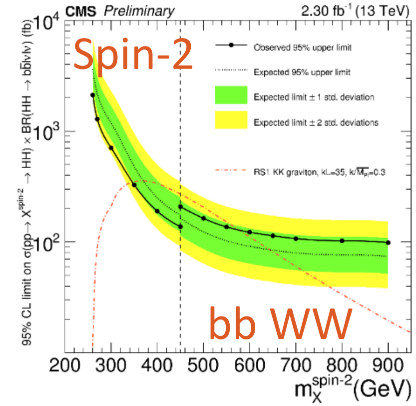




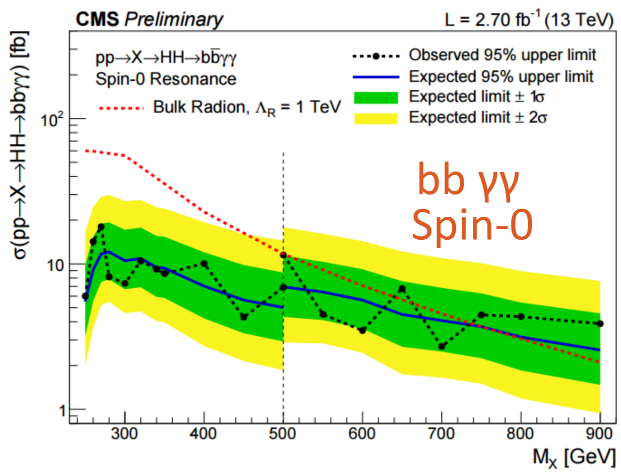
Resonant Double Higgs

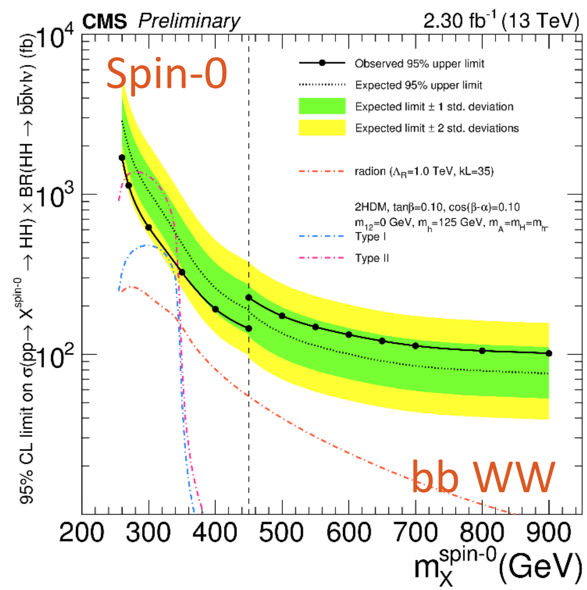
- Fix invariant mass window of m_h to match SM Higgs

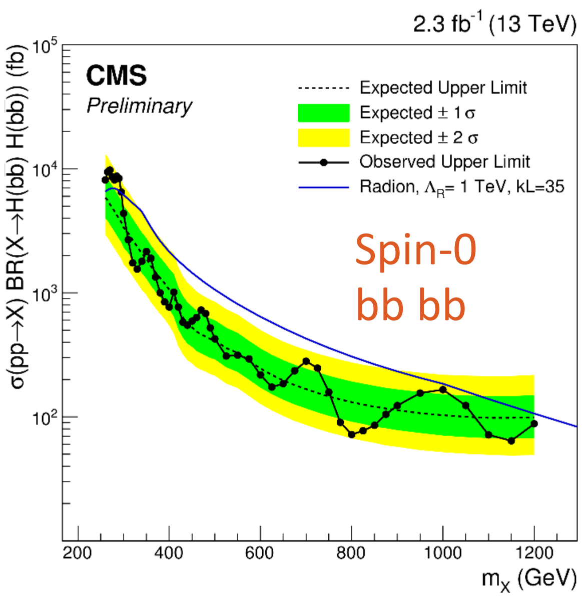
bb WW: new at 13 TeV



bb γγ: high signal to background rejection and good mass resolution

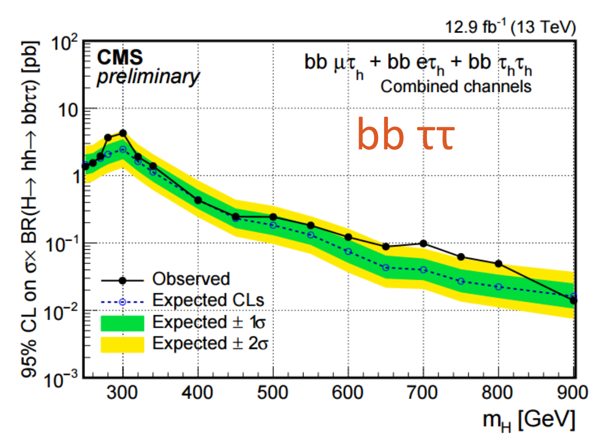






bb bb: largest branching fraction

bb ττ: 12.9/fb



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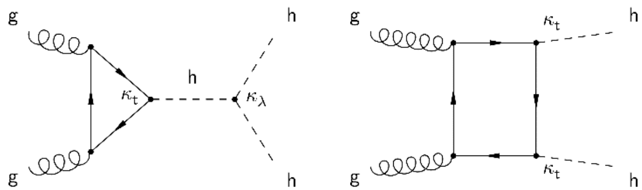
Non-resonant Double Higgs

- Non-resonant: Set limits on the ratio of anomalous trilinear coupling to the SM trilinear coupling
  - $k_\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM}$
  - SM = 33.45 fb

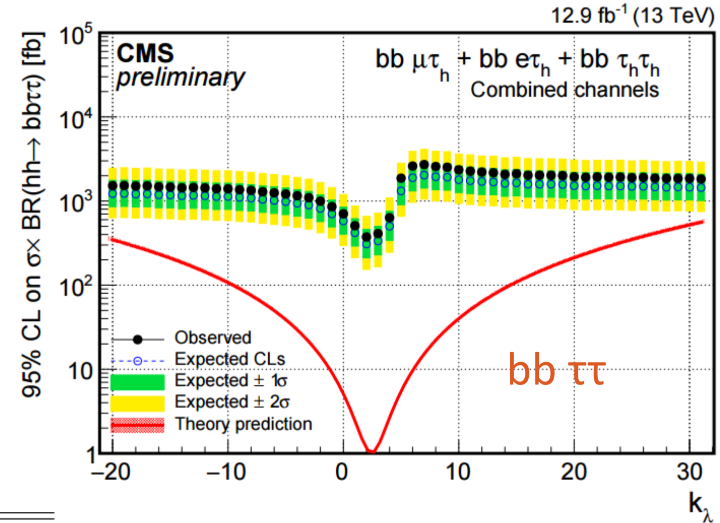


bb bb

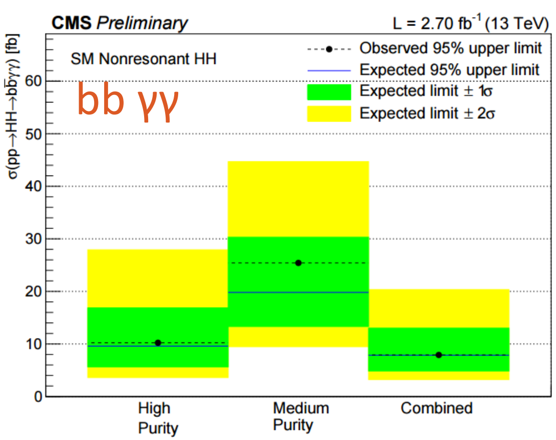
Category	Observed	Expected	-2σ	-1σ	$+1\sigma$	$+2\sigma$
			[fb]			
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350

3880 fb = ~370xSM

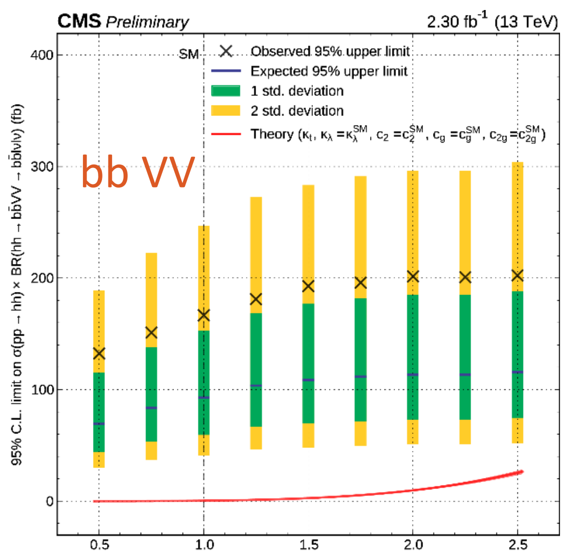
508 fb = ~200xSM

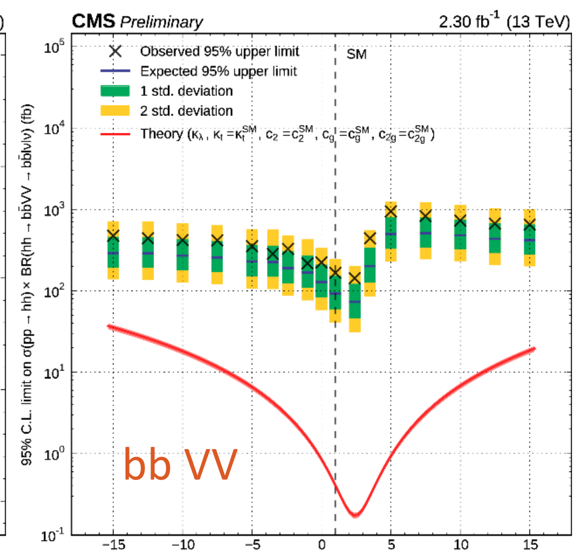


166.7 fb = ~410xSM



7.9 fb = ~90xSM





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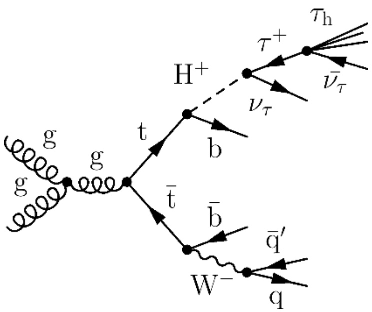
Run-1 Charged Higgs

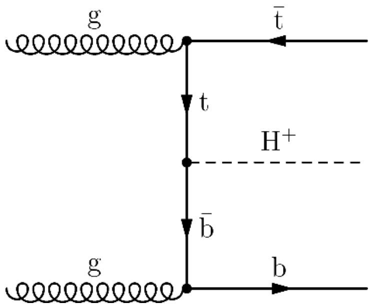
CMS-HIG-14-023

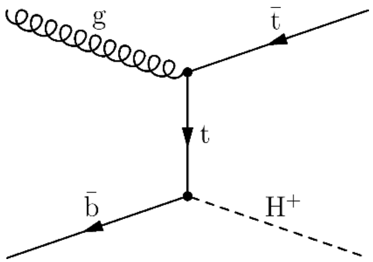
CMS-PAS-HIG-16-030

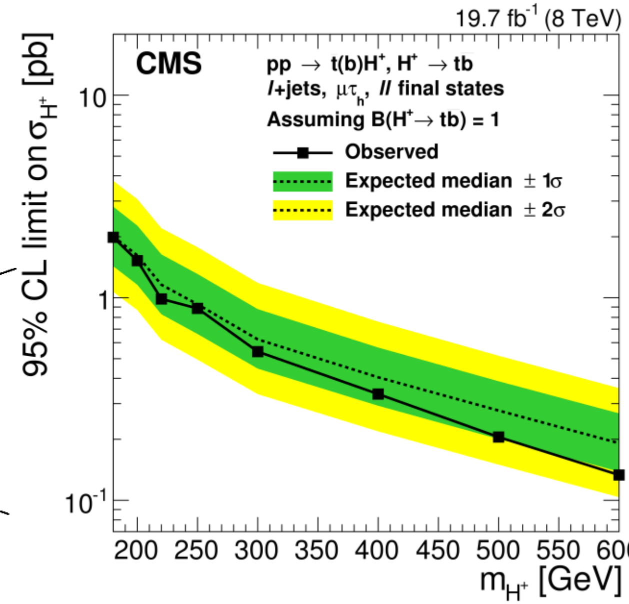


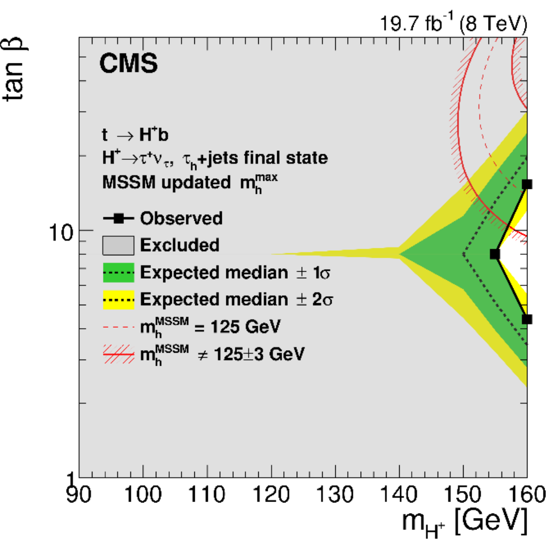
$m_H < m_t - m_b$

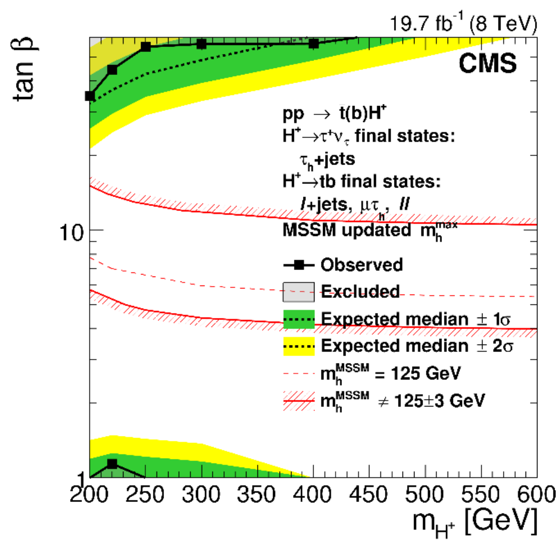
$m_H > m_t - m_b$

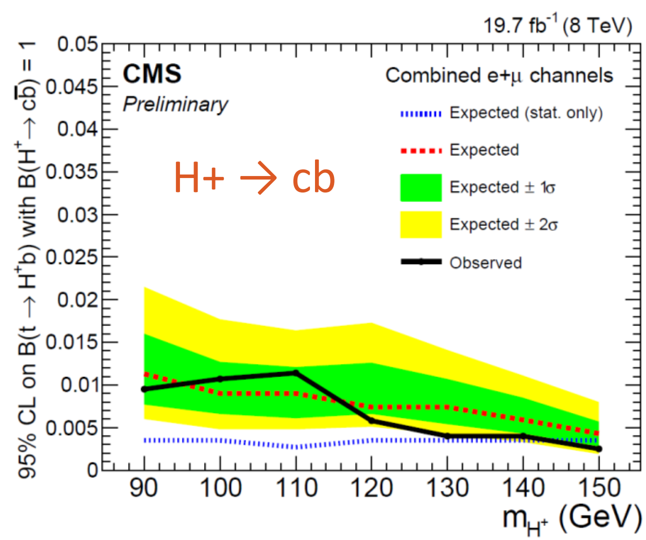












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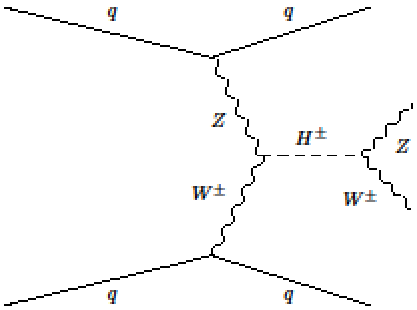
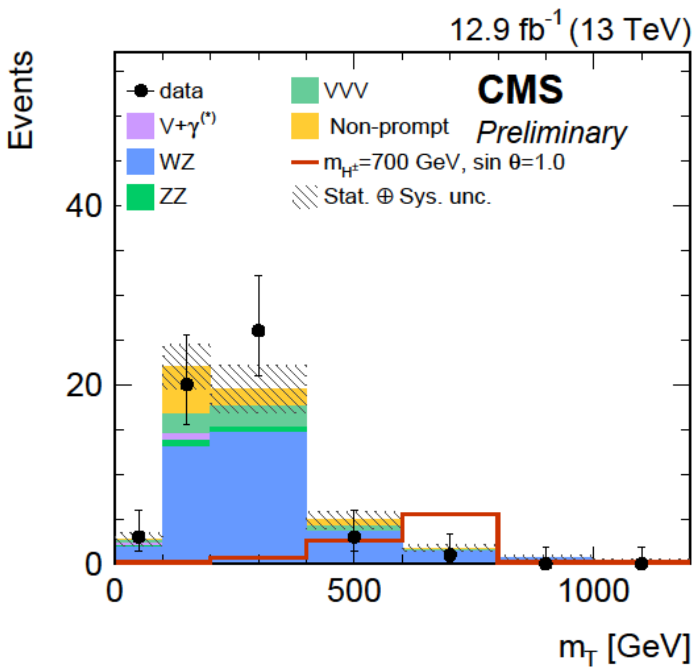
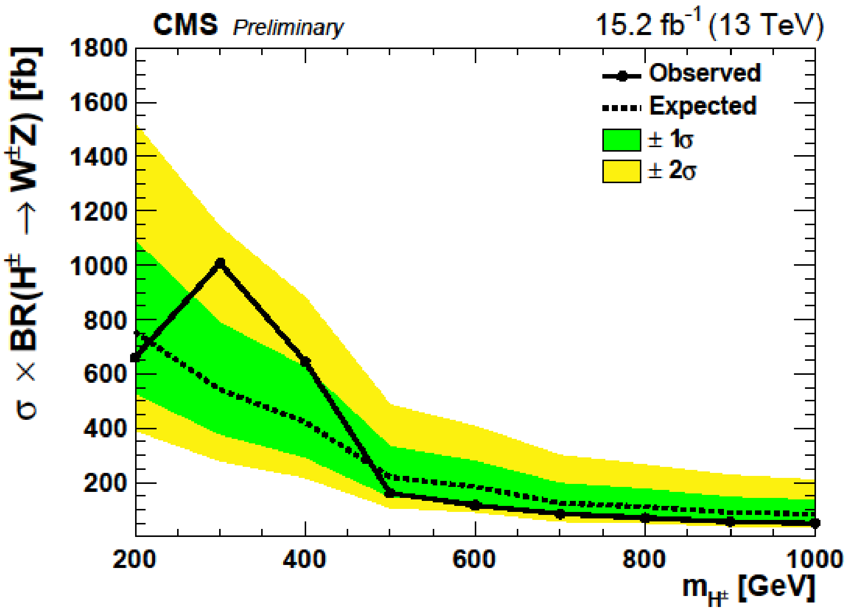
CMS-PAS-HIG-16-027

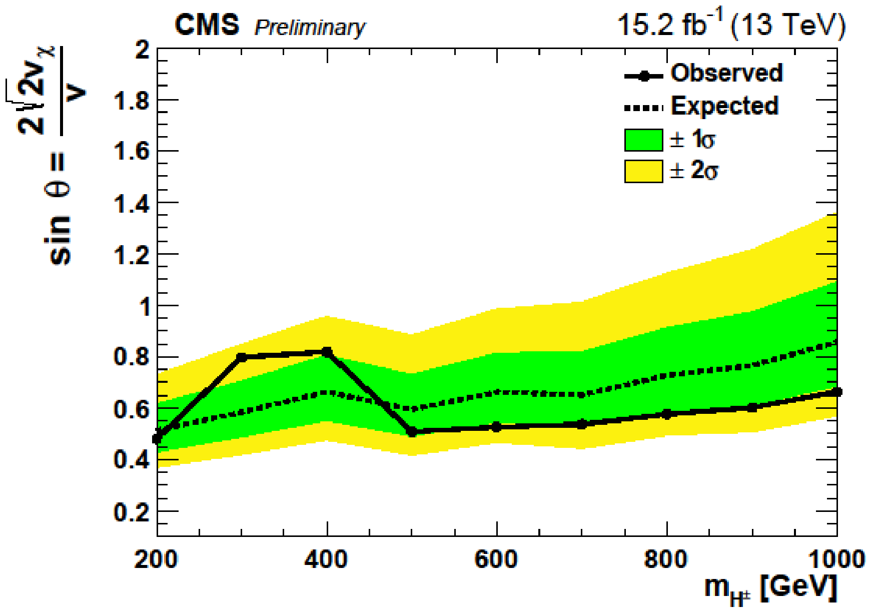
$H^+ \to WZ$

- H+ decays predicted at tree level in Higgs triplet models
  - Georgi-Machacek
- Leptonic WZ
- VBS topology
  - High dijet mass



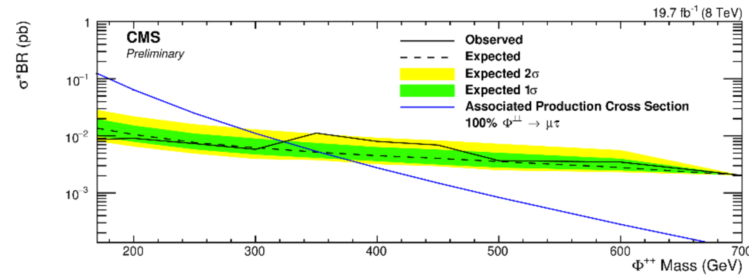


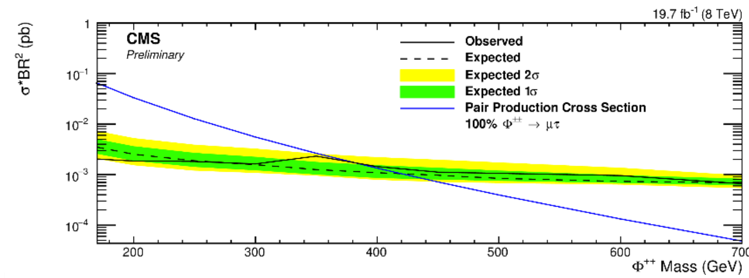


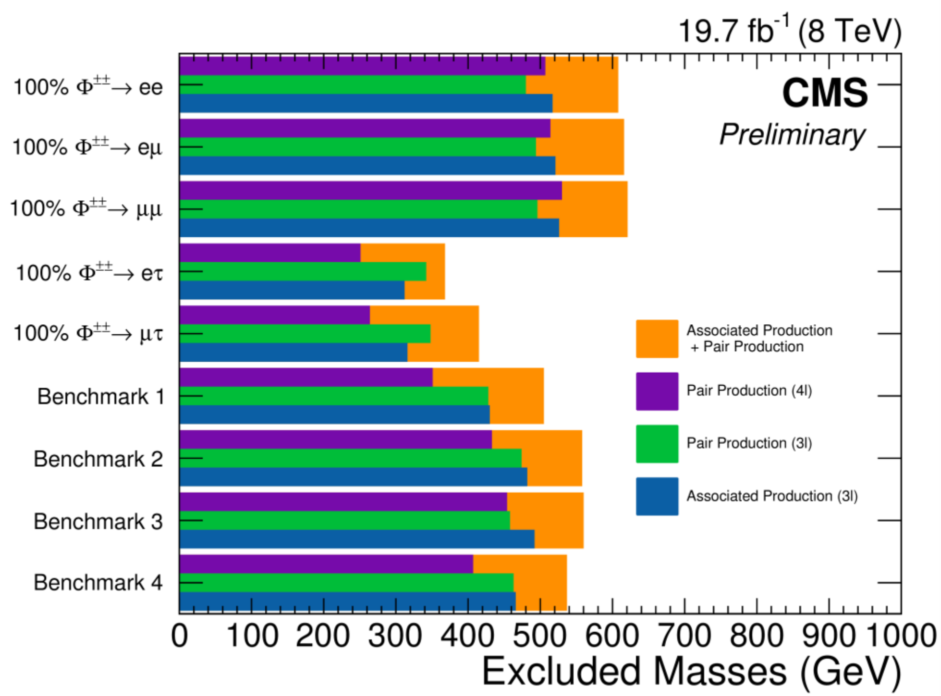


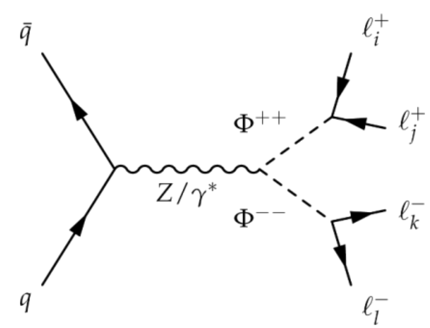
Doubly Charged Higgs

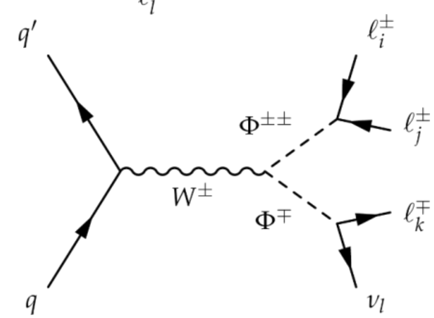
- Addition of a Higgs triplet
  - One neutral, two singly charged, two doubly charged Higgs





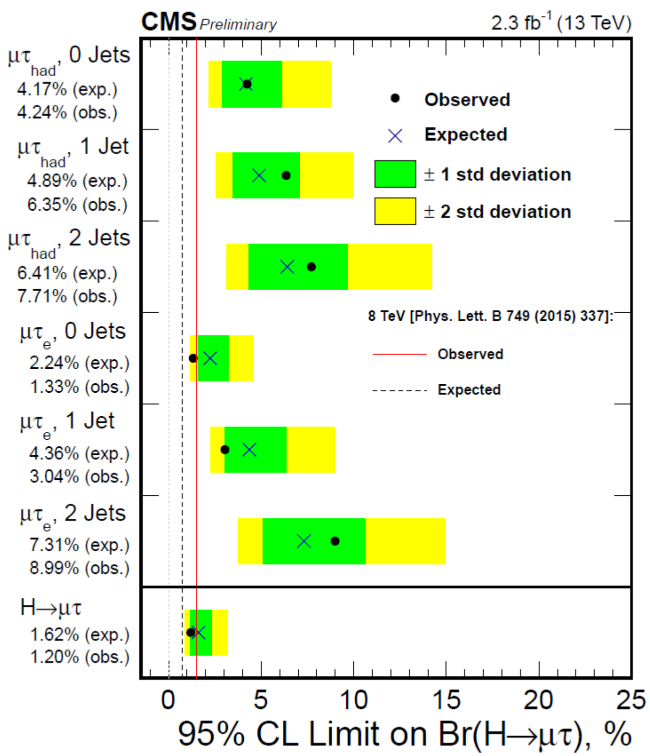


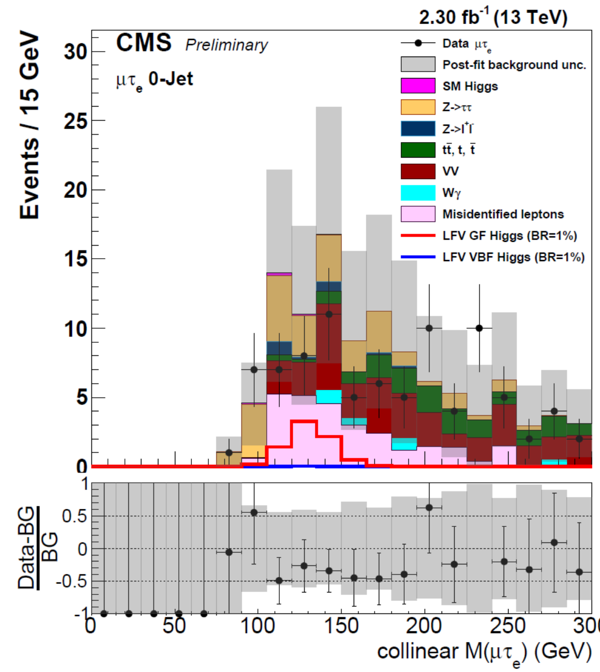


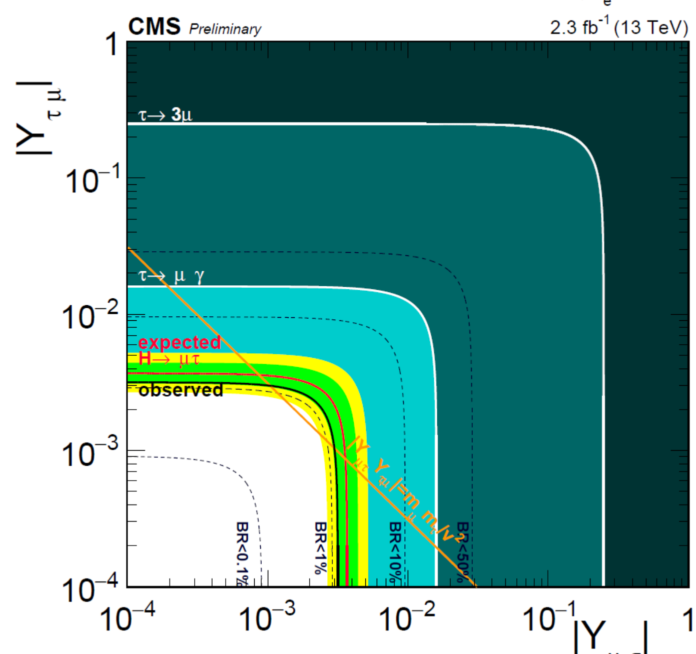


LFV H → μτ

- Lepton flavor violating decays arise naturally in models with multiple Higgs doublets
- Two final states: eμ, $\mu\tau_h$
- Search performed in multiple jet bins

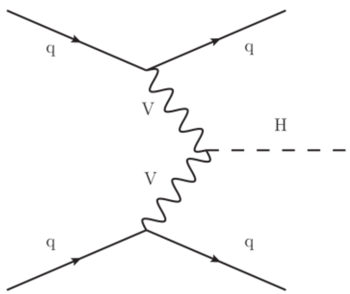






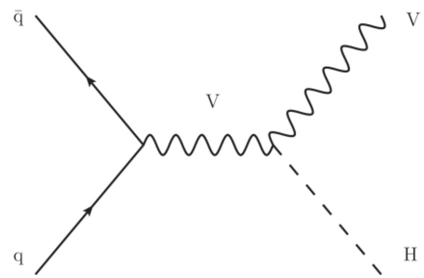
Higgs Invisible

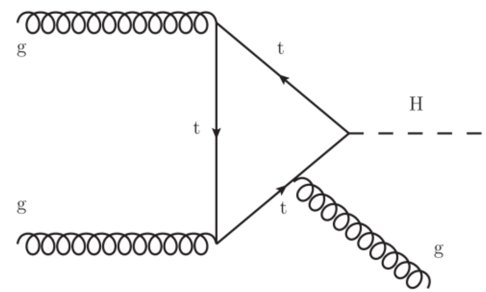
- SM BR(H → inv.) ~1.2e-3
  - H → 4ν



VBF

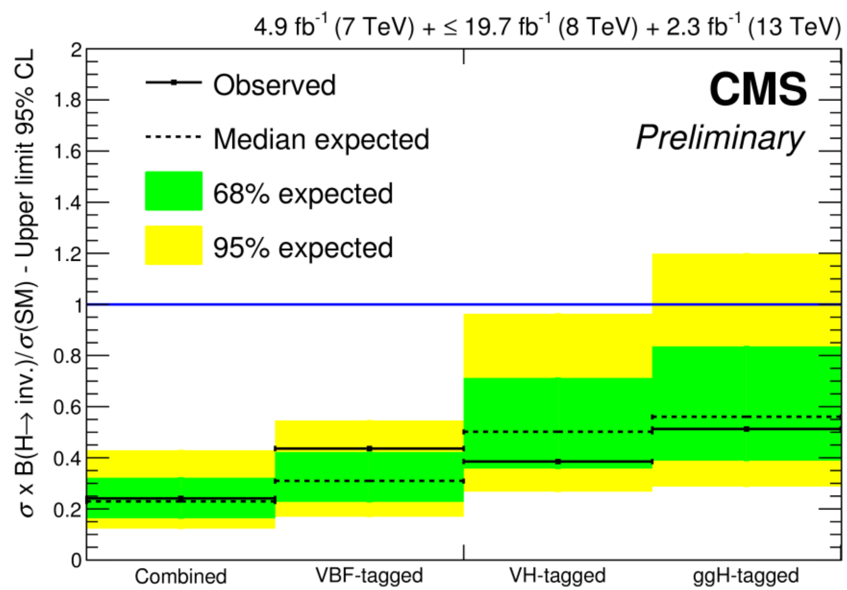
VH





ggH

- Dedicated VBF trigger
  - Large η separation
  - High dijet invariant mass

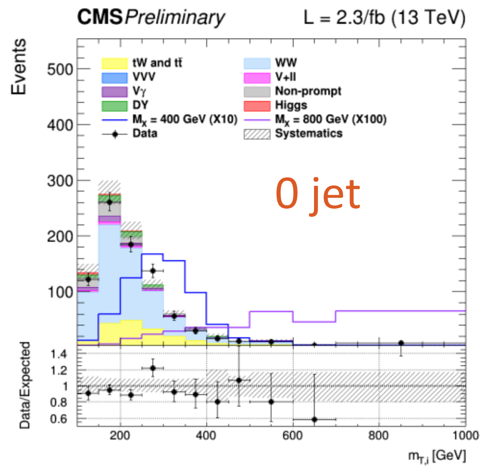


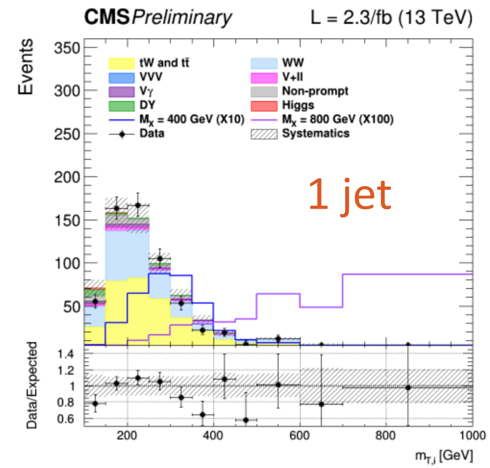
Combination of several analyses in 7, 8, and 13 TeV

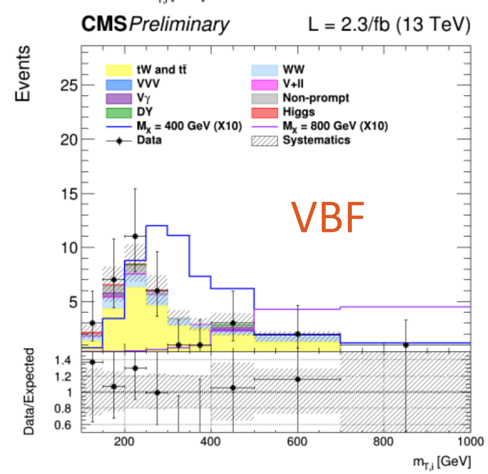
CMS-PAS-HIG-16-023

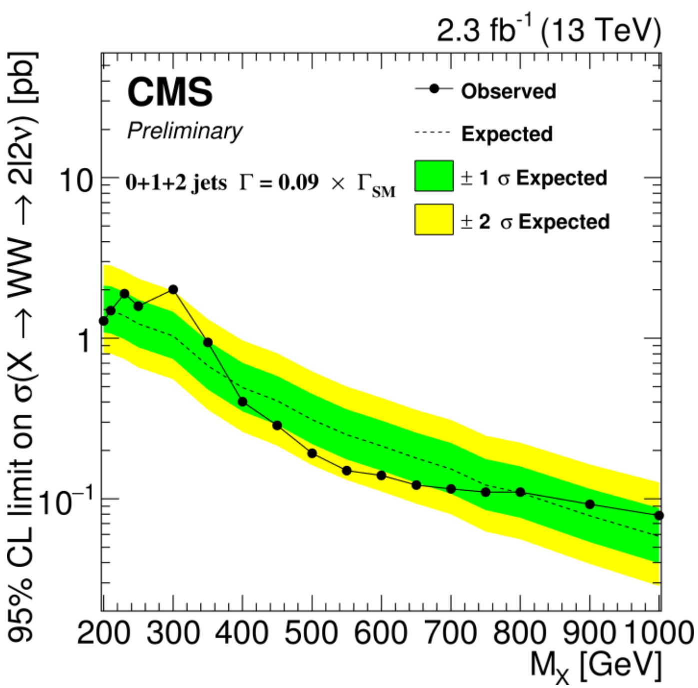
High Mass H → WW

- Leptonic decays of WW
- Categorize based on number of jets
  - 0, 1 jet ggH
  - 2 jet VBF





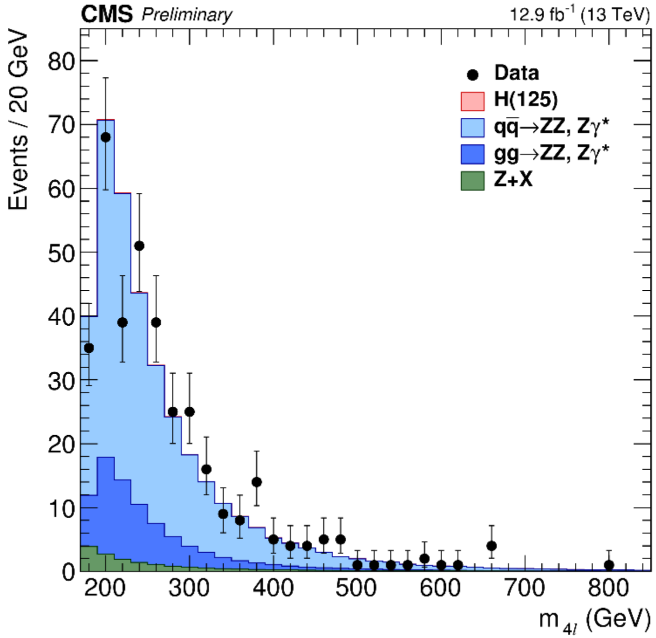


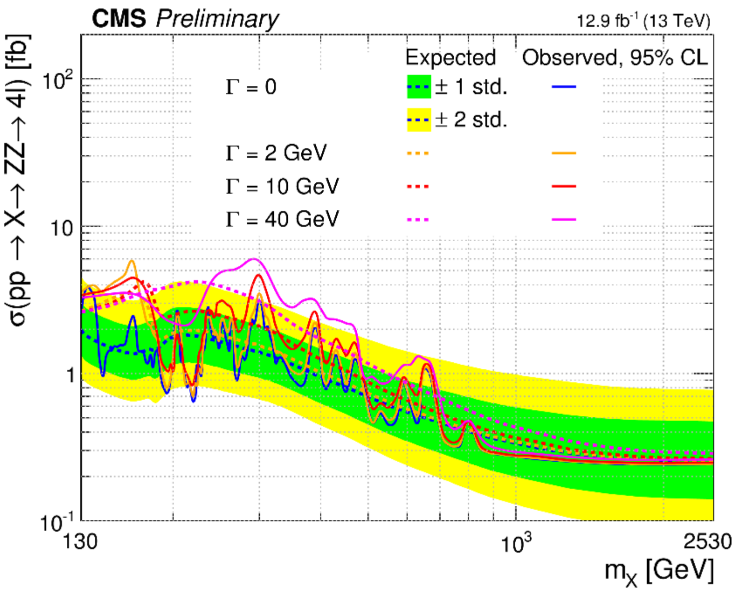


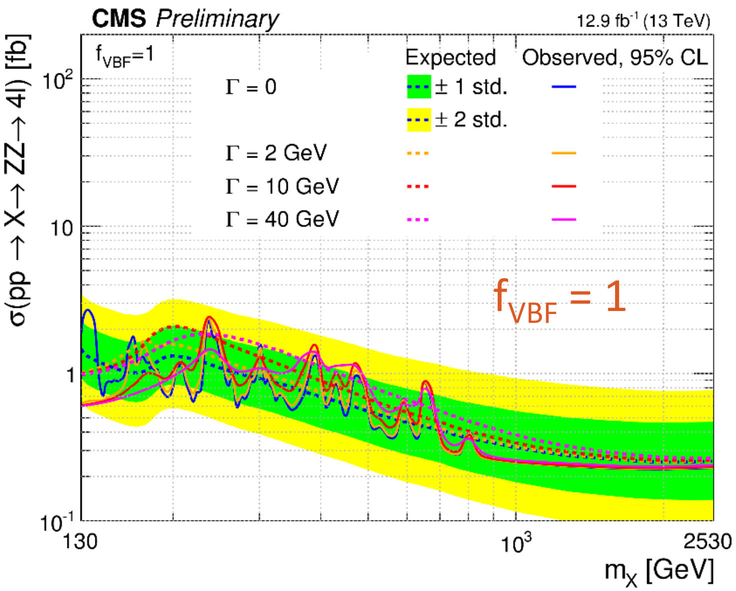
- Limits reported with several assumptions on Higgs width (narrow width shown)
  - ggH + VBF cross section

High Mass H → ZZ

- Search for high mass scalar resonance in ZZ 4l final state
- Production is allowed to be ggH, VH, VBF
  - Relative fraction of VBF parameterized via f_{VBF} and allowed to float

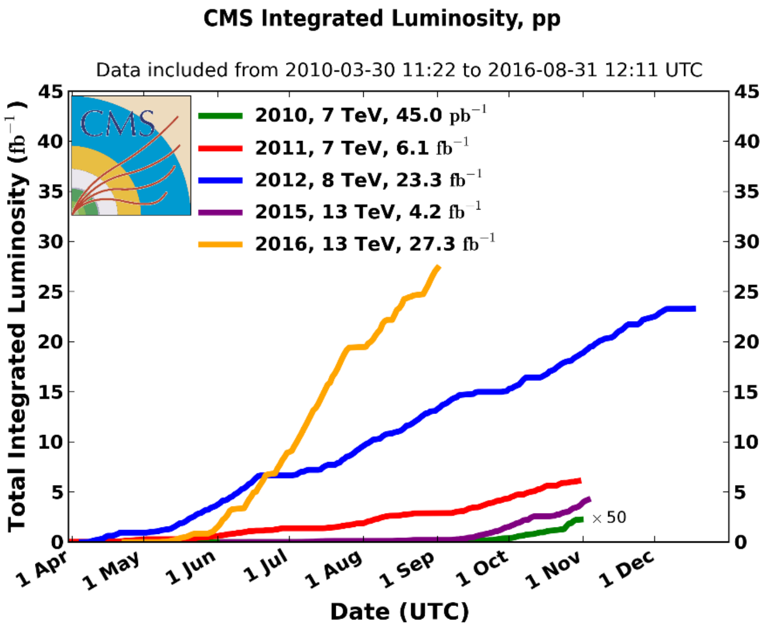






Conclusion

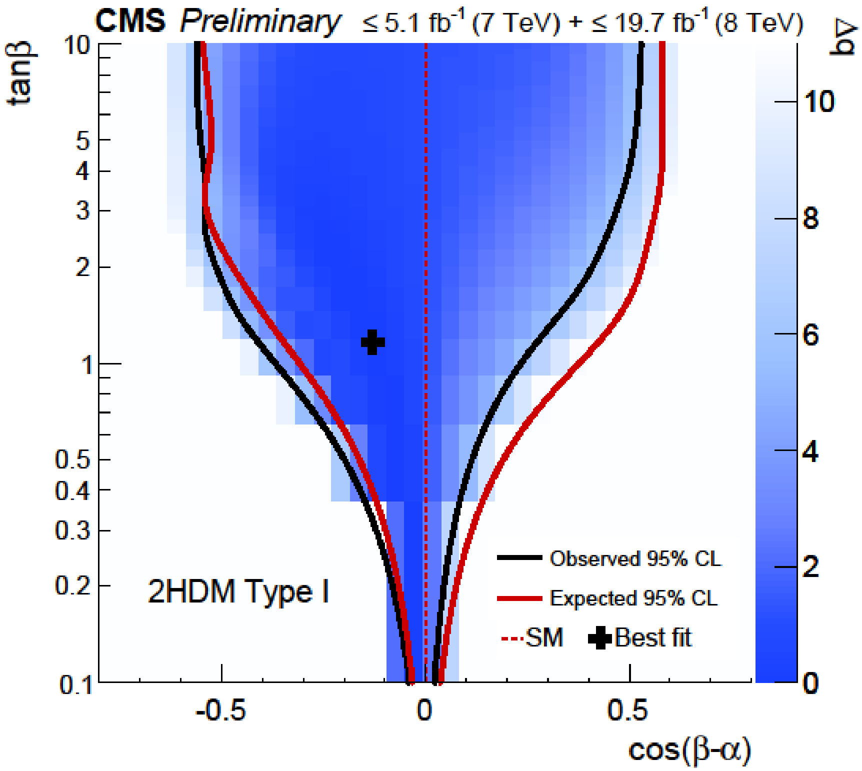
- Many interesting BSM searches performed at CMS
  - Multitude of final states
  - Wide range of models and phase spaces tested
- 13 TeV: 2.3 – 12.9/fb
  - Better reach than 7/8 TeV in many scenarios
  - Much more data coming

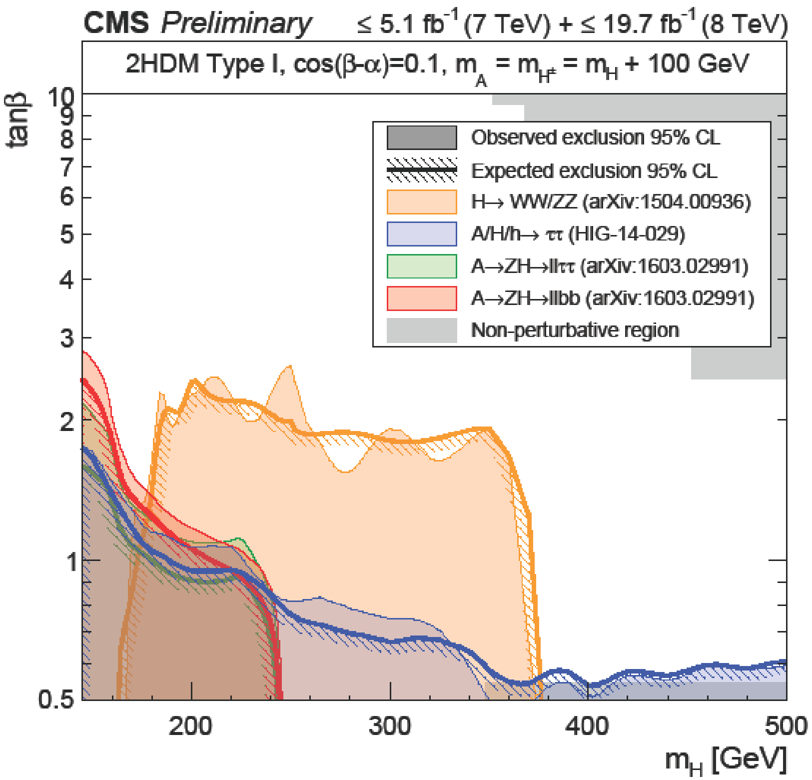


BACKUP

Run-1 2HDM Type I

- 2HDM Type I

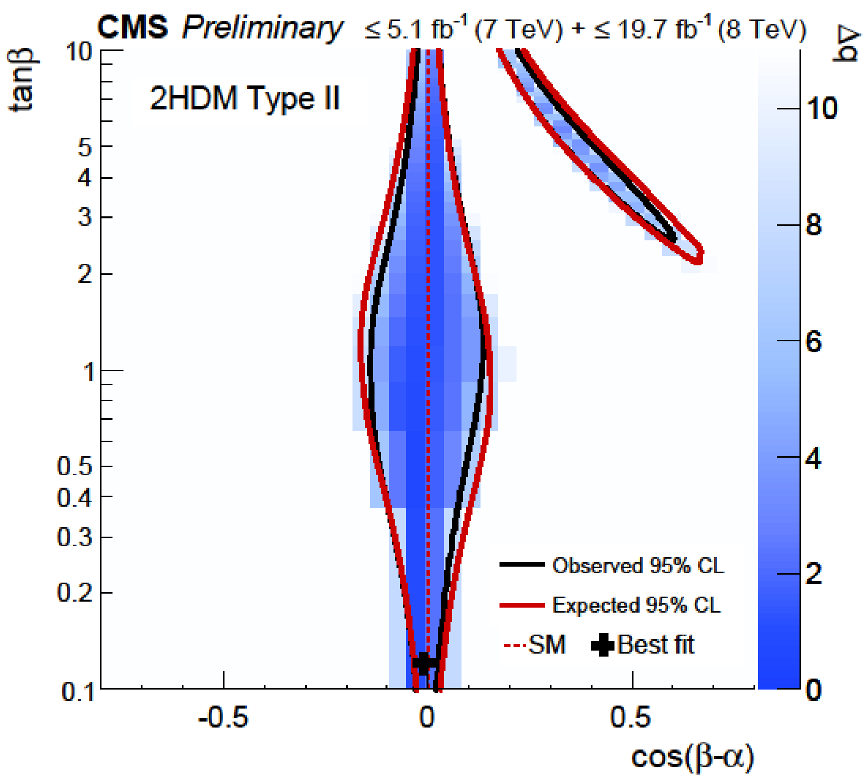


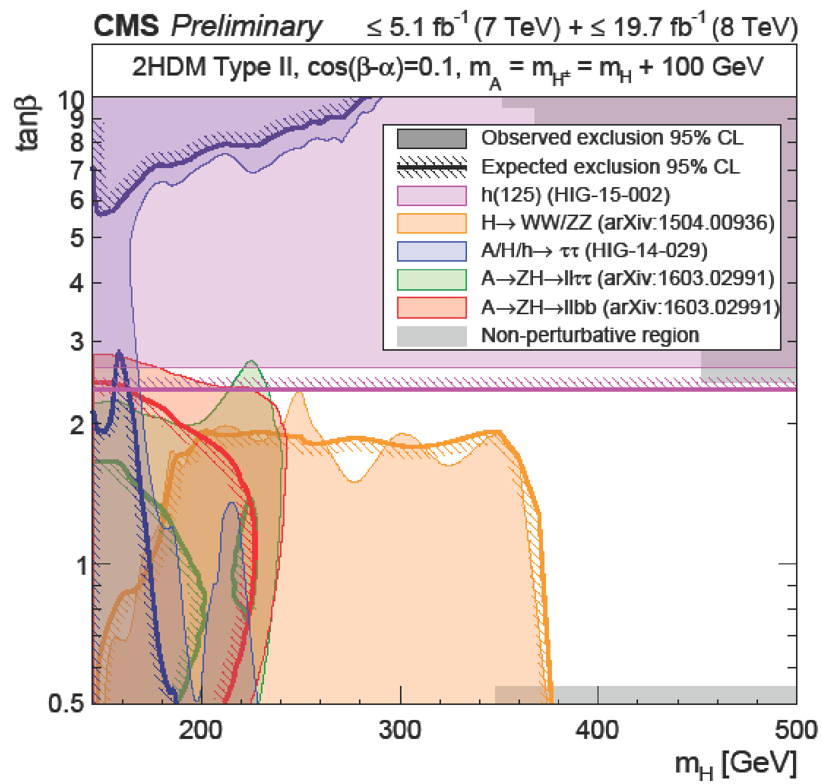


CMS-PAS-HIG-16-007

Run-1 2HDM Type II

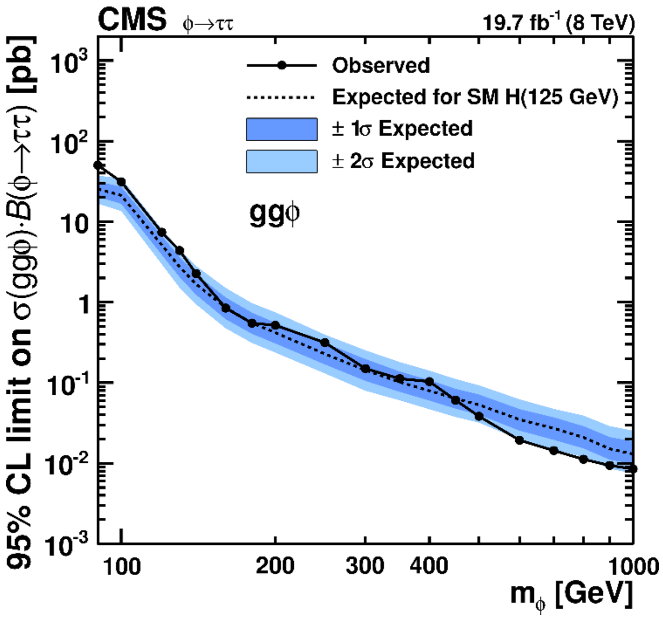
- 2HDM Type II

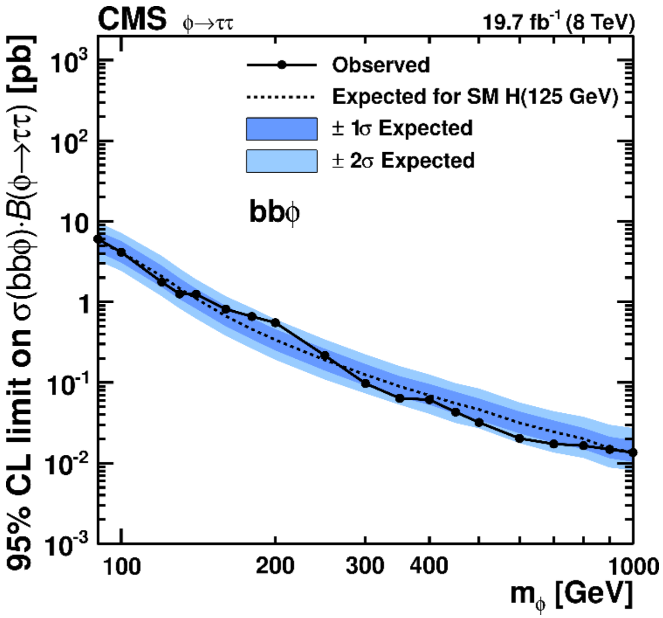


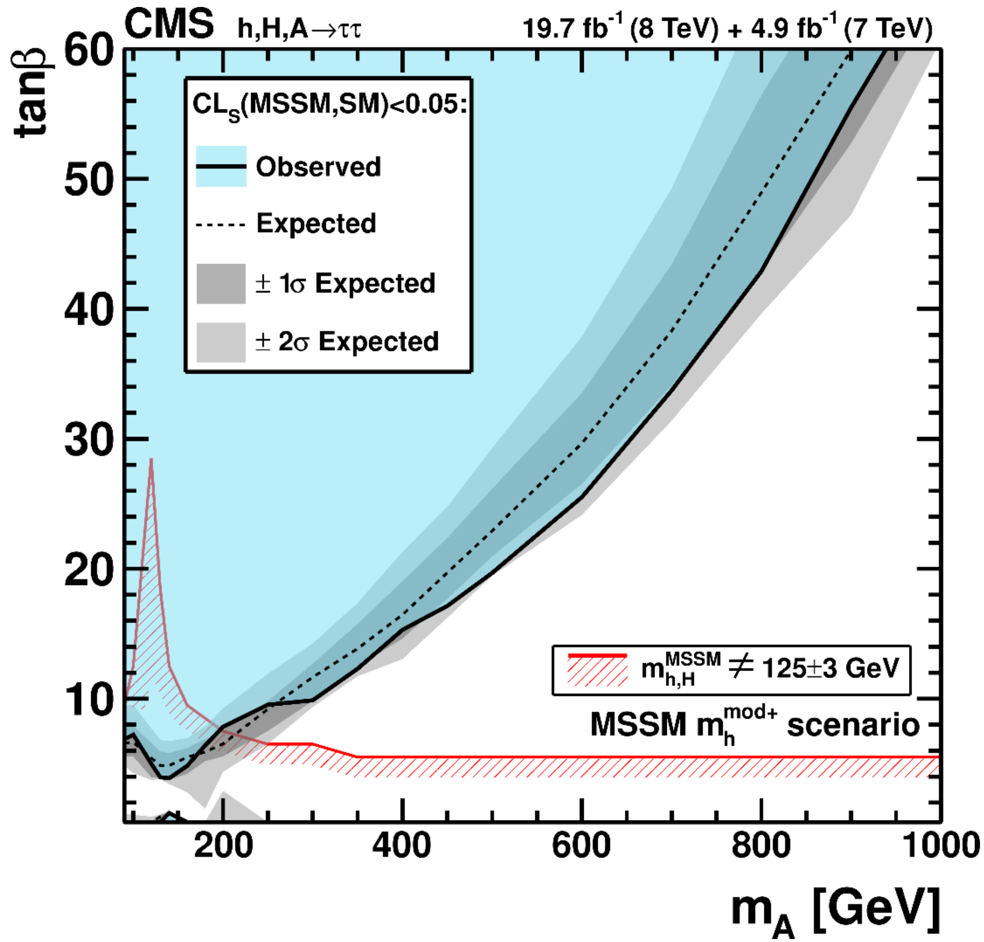


Run-1 MSSM h/H/A → ττ

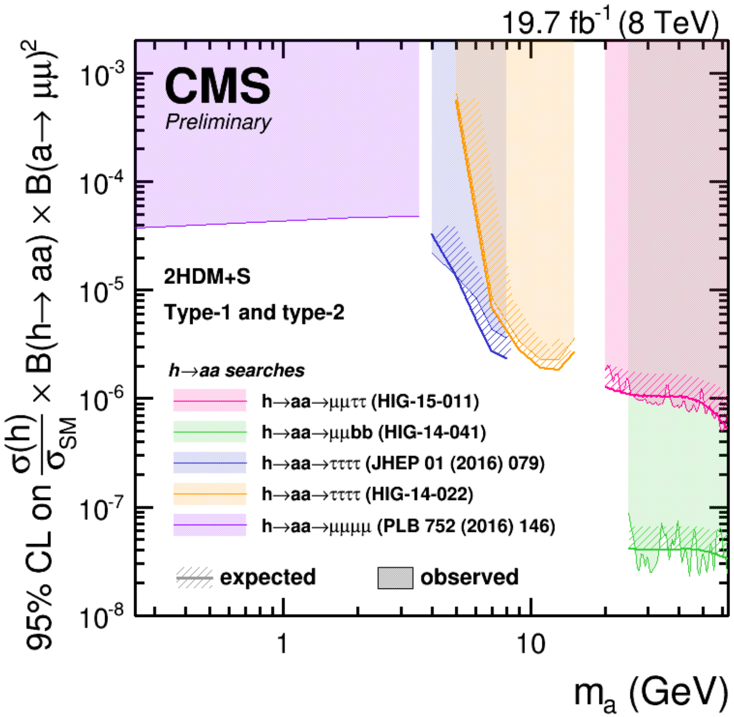
CMS-HIG-13-021

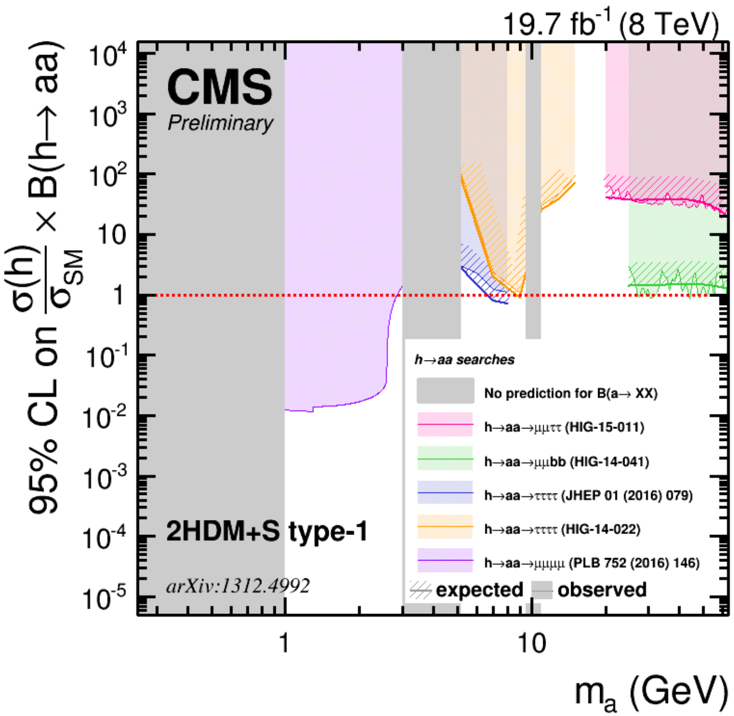






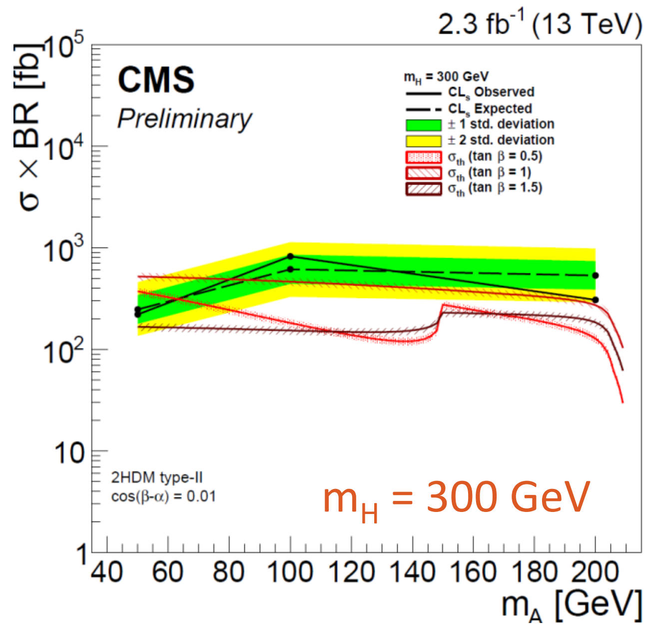
Low mass pseudoscalar

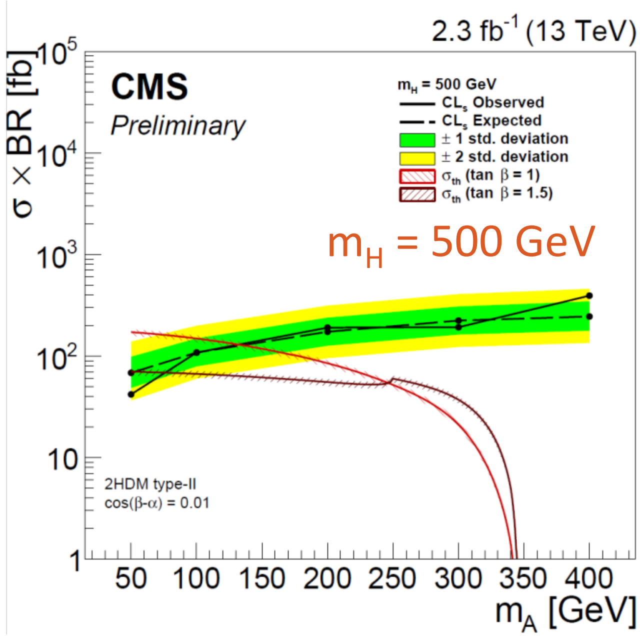


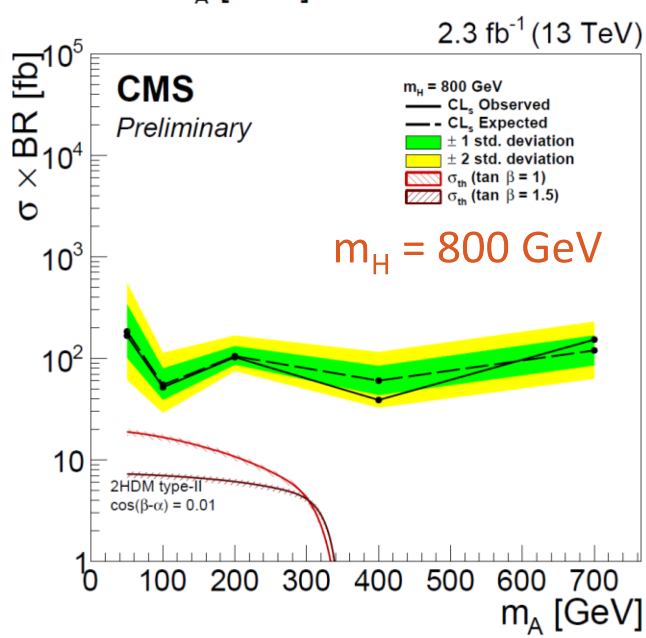


CMS-PAS-HIG-16-010

$H \to ZA \to llbb$

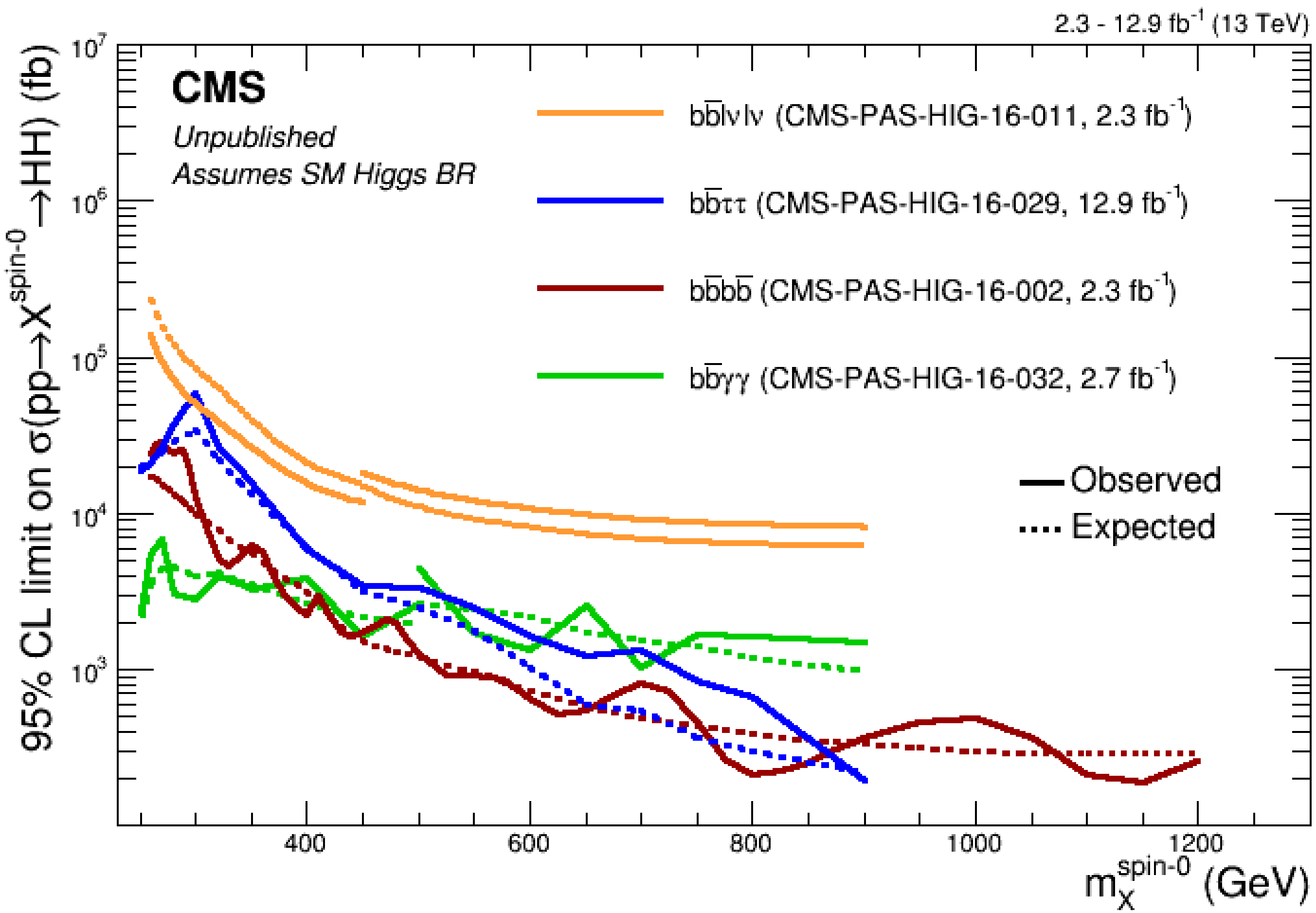






H → hh Summary

- Summary plots for double Higgs searches



Systematics – (Non-)Resonant hh

bb bb

Source of systematic uncertainty	Impact in LMR (%) Signal	Impact in MMR (%) Signal
Jet energy scale	1.2 – 4.2	0.5 – 2.8
Jet energy resolution	0.1 – 1.4	0.5 – 1.1
b-tagging scale factor	9.6 – 10.4	9.3-10.6
Trigger efficiency	10.2 – 20.9	5.2 – 10.3

Source	Affects	Exp. limit variation
Bkg norm.	bkg	33.1%
Bkg shape	bkg	29.4%
Luminosity	sig	<0.5%
QCD scale	sig	<0.5%
PDF unc.	sig	<0.5%
Pileup	sig	<0.5%
JER	sig	2.2%
JES	sig	20.7%
B-tagging eff.	sig	5.2%
Trigger eff.	sig	3.7%

bb γγ

Sources of Systematical Uncertainties	Type	Value
General uncertainties		
Integrated luminosity	Normalization	2.7%
Photon related uncertainties		
Photon energy scale ($\frac{\Delta M(\gamma\gamma)}{M(\gamma\gamma)}$)	Shape	1.0%
Photon energy resolution ($\frac{\Delta\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	1.0%
Diphoton pre-selection (with trigger uncertainties)	Normalization	2.0%
Photon Identification	Normalization	1.0%
Jet related uncertainties		
Jet energy scale ($\frac{\Delta M(jj)}{M(jj)}$)	Shape	2.0%
Jet energy resolution ($\frac{\Delta\sigma_{jj}}{\sigma_{jj}}$)	Shape	8.0%
Resonant specific uncertainties		
Mass window selection (with jet selection uncertainty)	Normalization	5.0%
b tagging efficiency (Low Mass, high purity)	Normalization	2.5%
b tagging efficiency (Low Mass, medium purity)	Normalization	1.0%
b tagging efficiency (High Mass)	Normalization	1.0%
Nonresonant specific uncertainties		
Jet Selection plus $\tilde{M}_X > 350$ GeV	Normalization	3.0%
b tagging efficiency (high purity)	Normalization	4.5%
b tagging efficiency (medium purity)	Normalization	1.0%

Systematics – (Non-)Resonant hh

bb WW

Source	Sig. ($m_X = 400$ GeV)	Sig. ($m_X = 650$ GeV)	Background
Trigger efficiency	5.1 - 6.0%	6.7 - 7.4%	4.5 - 5.3%
Jet b-tagging	4.9 - 6.5%	5.7 - 7.3%	5.1 - 6.0%
Jet energy scale	1.6 - 3.0%	0.6 - 3.9%	1.0 - 3.6%
Jet energy resolution	0.5 - 4.1%	1.8 - 3.5%	0.1 - 2.4%
Electon ID & ISO	1.3 - 1.6%	1.3 - 1.7%	1.4 - 1.5%
Muon ID & ISO	0.9 - 1.4%	1.0 - 1.1%	1.2 - 1.5%
Pileup	0.4 - 1.8%	0.1 - 0.6%	0.5 - 2.2%
Parton distributions	0.4 - 0.5%	0.2 - 0.5%	0.5 - 0.6%
QCD scale	0.3 - 0.4%	0.2 - 0.4%	0.8 - 2.4%
Luminosity	2.7%		
Signal MC stat.	1.4 - 2.4%	0.9 - 3.2%	-
Affecting only $t\bar{t}$ (87.0 - 95.3% of the total bkg.)			
$t\bar{t}$ cross section	-	-	6.5%
$t\bar{t}$ modeling	-	-	10%
$t\bar{t}$ MC stat.	-	-	0.6 - 2.3%
Affecting only Drell-Yan (1.8 - 7.1% of the total bkg.)			
Drell-Yan modeling	-	-	30%
Drell-Yan MC stat.	-	-	4.4 - 22.7%
Affecting only single top (2.5 - 4.6% of the total bkg.)			
Single top modeling	-	-	20%
Single top MC stat.	-	-	6.6 - 24.4%
Affecting only other backgrounds (0.4 - 1.4% of the total bkg.)			
Other backgrounds MC stat.	-	-	3.5 - 24.6%

Source	Background yield variation	SM signal yield variation
Jet b-tagging	3.6%	3.5%
Trigger efficiency	3.3%	4.0%
Luminosity	2.7%	2.7%
Jet energy scale	1.7%	1.4%
Muon ID	1.2%	1.2%
Muon ISO	0.9%	0.7%
Parton distributions	0.6%	0.2%
Electron ID & ISO	0.5%	0.5%
Pileup	0.2%	0.2%
Jet energy resolution	$< 0.1\%$	$< 0.1\%$
Affecting only $t\bar{t}$ (90.7% of the total bkg.)		
QCD scale	12.9%	
$t\bar{t}$ cross-section	5.2%	
MC stat.	$< 0.1\%$	
Affecting only Drell-Yan (6.0% of the total bkg.)		
QCD scale	15.2%	
Drell-Yan cross-section	4.9%	
MC stat.	4.5%	
Affecting only Single top (2.6% of the total bkg.)		
Single top cross-section	7.0%	
MC stat.	0.7%	
QCD scale	0.3%	
Affecting only SM signal		
QCD scale	24.3%	
MC stat.	$< 0.1\%$	

bb ττ

Systematic	value	processes
luminosity	6.2%	all but multijet, Z+jets
Jet energy scale	2-4%	all
MC cross-section	1-10%	backgrounds, not Z+jets, multijet
b-tag efficiency	2-6%	all
lepton efficiency	2-6%	all
Z+jets SF uncertainty	1-10%	Z+jets
τ energy scale	3-10%	all
scale unc.	$+4.3/-6\%$	theory
PDF variation	3.1%	theory

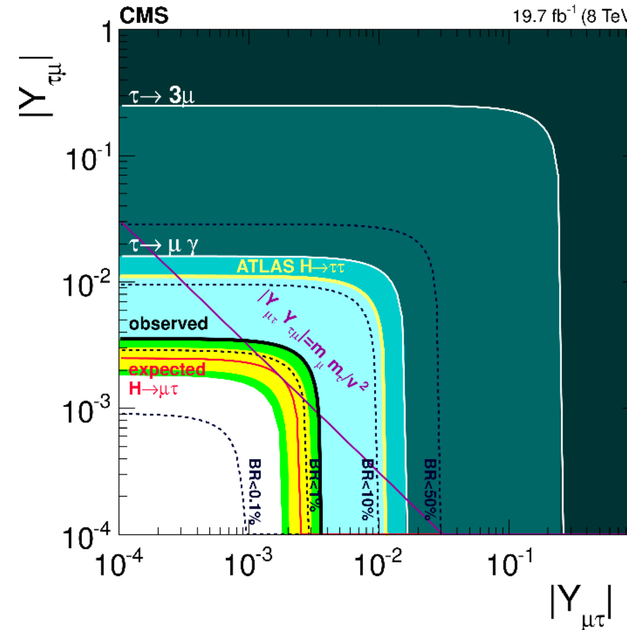
Systematics – H+ → WZ

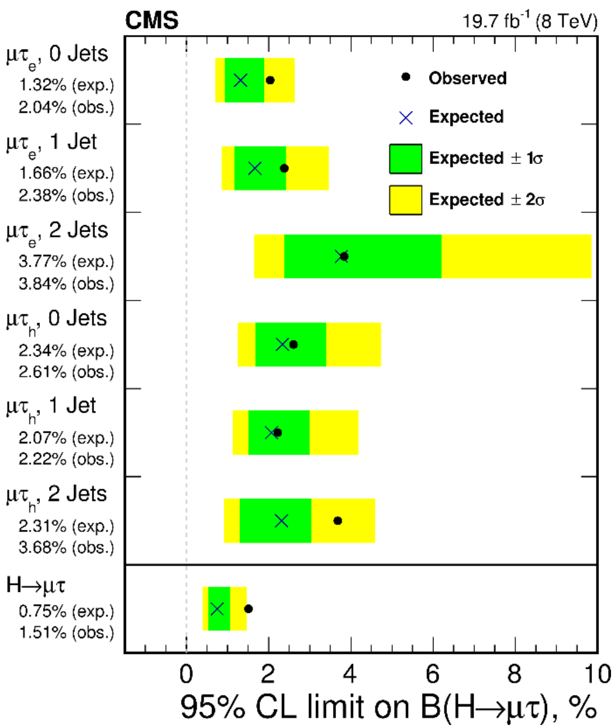
Source	Signal	WZ	VVV	$Z\gamma$	ZZ	Non-prompt
Luminosity	2.7-6.2	—	2.7-6.2	2.7-6.2	2.7-6.2	—
Lepton efficiency	4.0	—	4.0	4.0	4.0	—
Lepton momentum scale	1.0	1.0	1.0	1.0	1.0	—
Jet momentum scale	2.0 - 5.0	8.0	6.0	30.0	13.0	—
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	5.0	1.7	1.0	—	7.0	—
B-tagging	2.0	—	2.0	2.0	2.0	—
WZ normalization	—	21-23	—	—	—	—
Non-prompt normalization	—	—	—	—	—	30-81
GM uncertainties	8	—	—	—	—	—

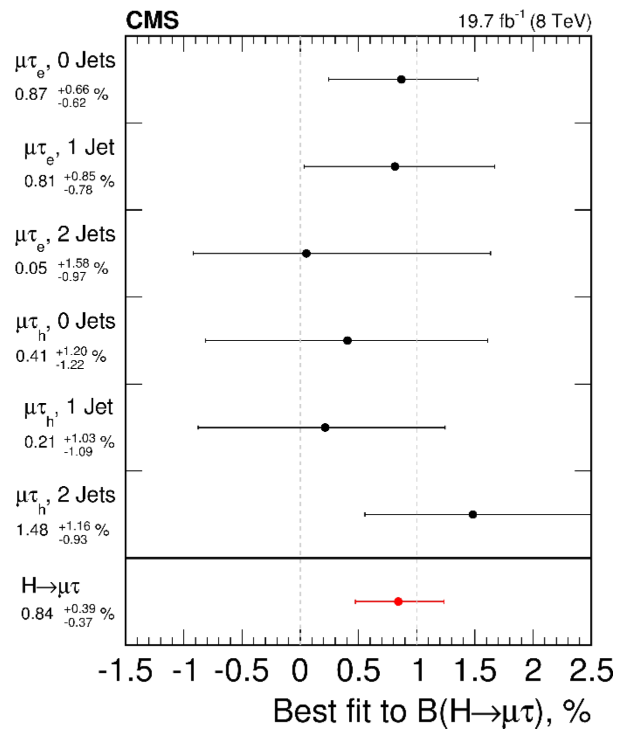
CMS-HIG-14-005

Run-1 LFV H → μτ

- Best fit 0.84% BR(H → μτ)
- 2.4σ excess







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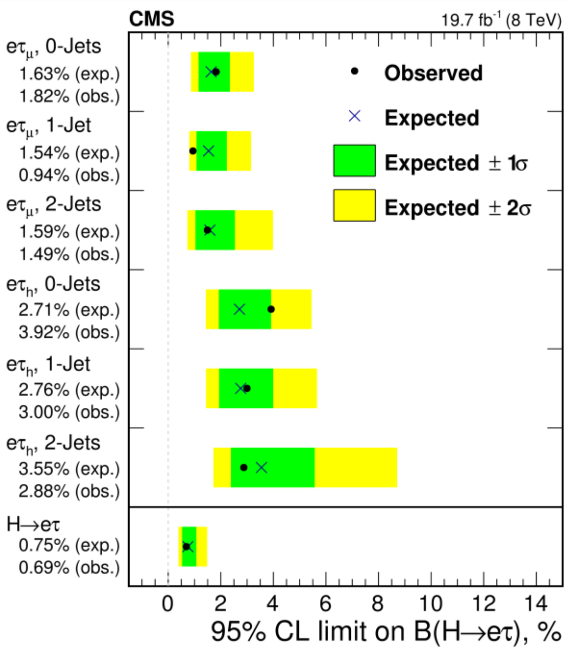
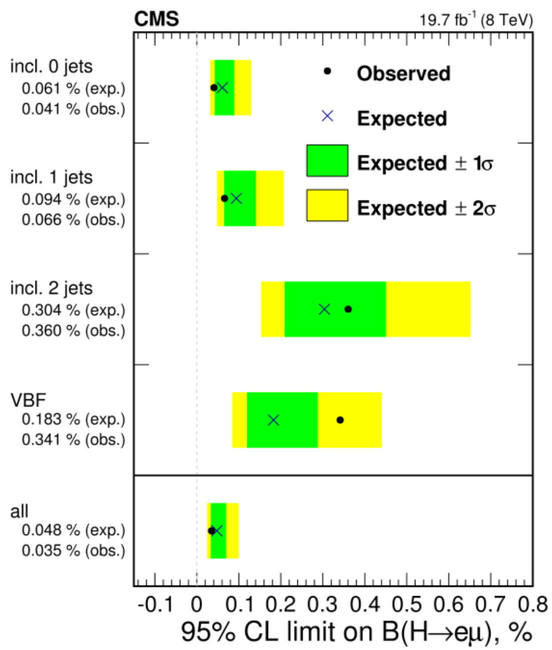
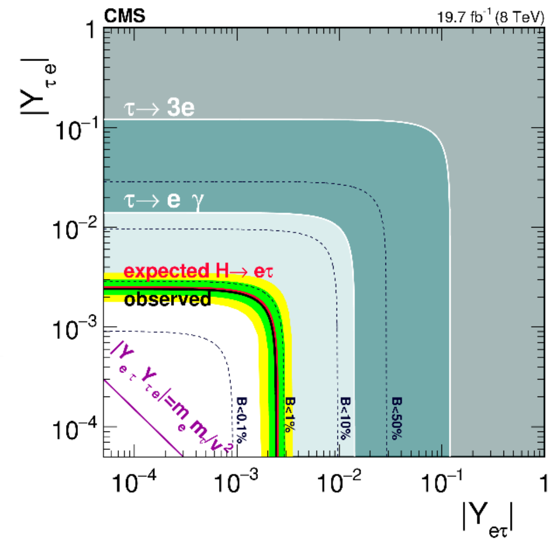
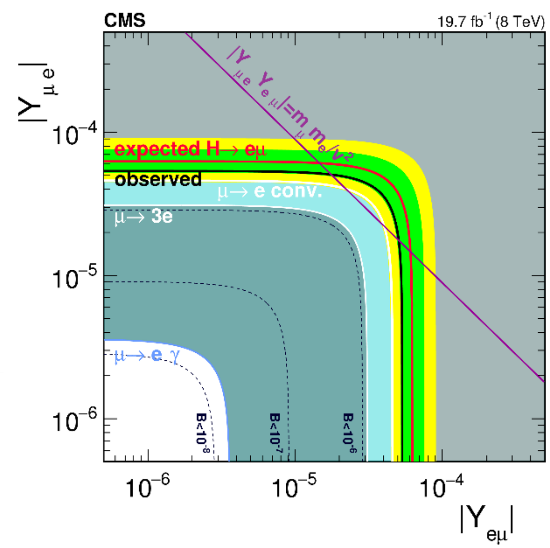
Run-1 LFV H → eτ, eμ









Systematics – LFV H → μτ

Systematic uncertainty	$H \to \mu\tau_e$	$H \to \mu\tau_h$
Muon trigger/ID/isolation	3%	3%
Electron trigger/ID/isolation	3%	—
Hadronic τ efficiency	—	10%
b-tagging veto	3%	—
$Z \to \tau\tau$ background	10%$\oplus$5%	10%$\oplus$5%
$Z \to \mu\mu, ee$ background	10%$\oplus$5%	10%$\oplus$5%
Misidentified μ, e background	40%$\oplus$10%	—
Misidentified τ_h background	—	30%$\oplus$10%
WW, ZZ background	10%$\oplus$5%	10%$\oplus$5%
$t\bar{t}$ background	20%$\oplus$5%	20%$\oplus$5%
$W + \gamma$ background	10%$\oplus$5%	—
Single top production background	10%	10%
Jet energy scale	3-20%	3-20%
Hadronic τ energy scale	—	3%
Misidentified lepton shape	$\pm\sigma$	$\pm\sigma$
Theory uncertainty	10%	10%
Luminosity	2.7%	2.7%

Syst. – Higgs Invisible

VBF

Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale+resolution	6.0%
QCD multijet normalisation	4.3%
PU mis-modelling	4.2%
Lepton efficiencies	2.5%
Luminosity	2.2%
Signal specific	
ggH acceptance	3.8%
QCD scale + PDF (qqH)	1.8%
QCD scale + PDF (ggH)	$< 0.2\%$
Total statistical only	$-27/+28\%$
Total uncertainty	$-33/+32\%$

Vjj

Systematic uncertainty	Impact
Common	
γ+jets/Z($\nu\nu$)+jets ratio theory	32%
W($l\nu$)+jets/Z($\nu\nu$)+jets ratio theory	21%
Jet energy scale+resolution	12%
V-tagging efficiency	12%
Lepton veto efficiency	13%
Electron efficiency	13%
Muon efficiency	8.6%
b jet tag efficiency	5.7%
Photon efficiency	3.1%
E_T^{miss} scale	4.6%
Top quark background normalisation	6.0%
Diboson background normalisation	$< 1\%$
Luminosity	$< 1\%$
Signal specific	
ggH p_T-spectrum	12%
QCD scale + PDF (ggH)	3.0%
QCD scale + PDF (VH)	1.4%
Total statistical only	$-46/+50\%$
Total uncertainty	$-69/+74\%$

Zll

Systematic uncertainty	Impact
Common	
ZZ background theory	16%
luminosity	8.4%
b jet tag efficiency	6.2%
Electron efficiency	6.2%
Muon efficiency	6.2%
Electron energy scale	3.2%
Muon momentum scale	3.2%
Jet energy scale	2.2%
Diboson normalisation	5.3%
eμ region extrapolation	4.0%
$Z(l^+l^-)$normalisation	4.8%
Signal specific	
QCD scale + PDF (qqZH)	7.4%
QCD scale + PDF (ggZH)	4.0%
Total statistical only	$-50/+56\%$
Total uncertainty	$-55/+62\%$

ggH

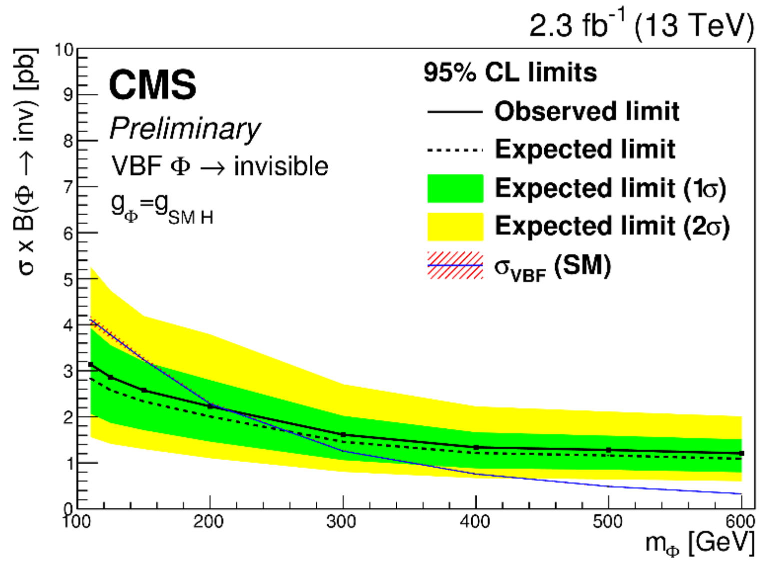
Systematic uncertainty	Impact
Common	
Muon efficiency	24%
Electron efficiency	22%
Lepton veto efficiency	16%
b jet tag efficiency	3.2%
W($l\nu$)+jets/Z($\nu\nu$)+jets ratio theory	16%
γ+jets/Z($\nu\nu$)+jets ratio theory	5.8%
Jet energy scale+resolution	10%
E_T^{miss} scale	1.8%
Luminosity	3.0%
Diboson background normalisation	2.7%
Top quark background normalisation	$< 1\%$
Signal specific	
ggH p_T-spectrum	15%
QCD scale + PDF (ggH)	5.8%
Total statistical only	$-22/+25\%$
Total uncertainty	$-55/+62\%$

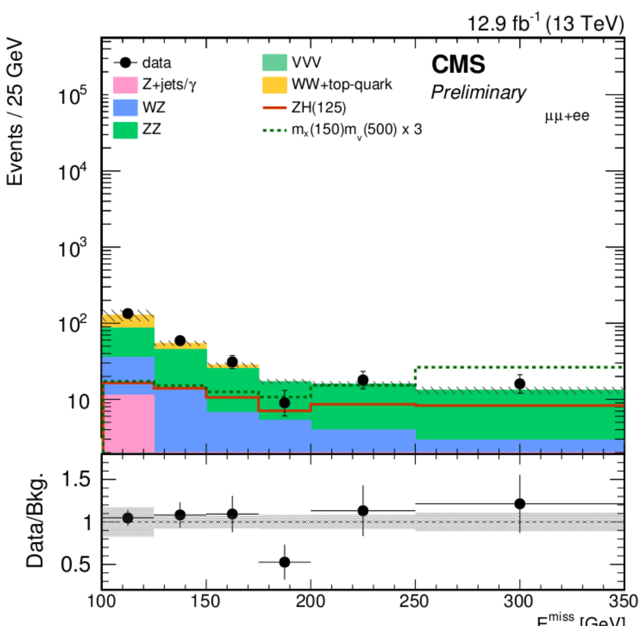
Higgs-like Scalar

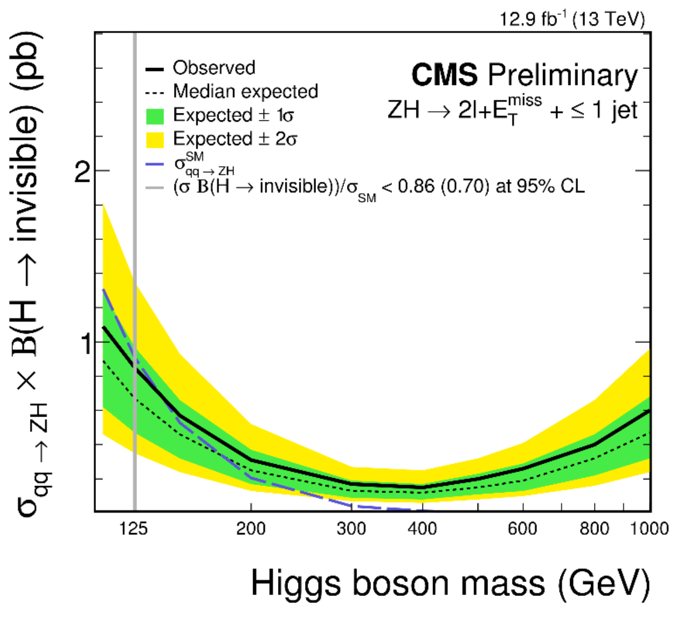
CMS-PAS-HIG-16-009

CMS-PAS-EXO-16-038

- VBF and VH searches using invisible decays







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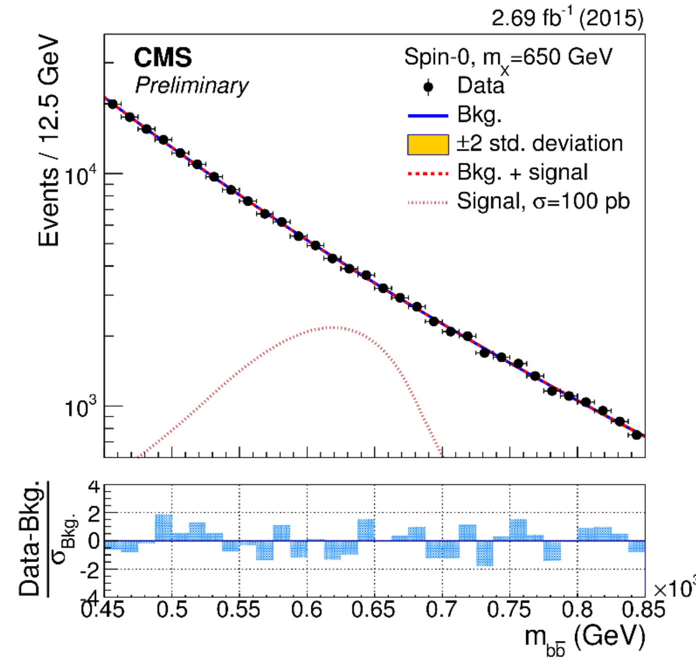
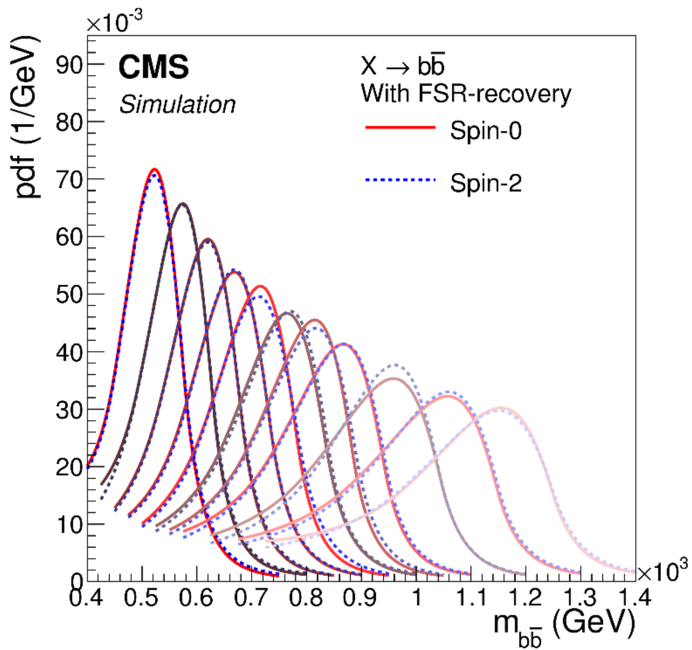
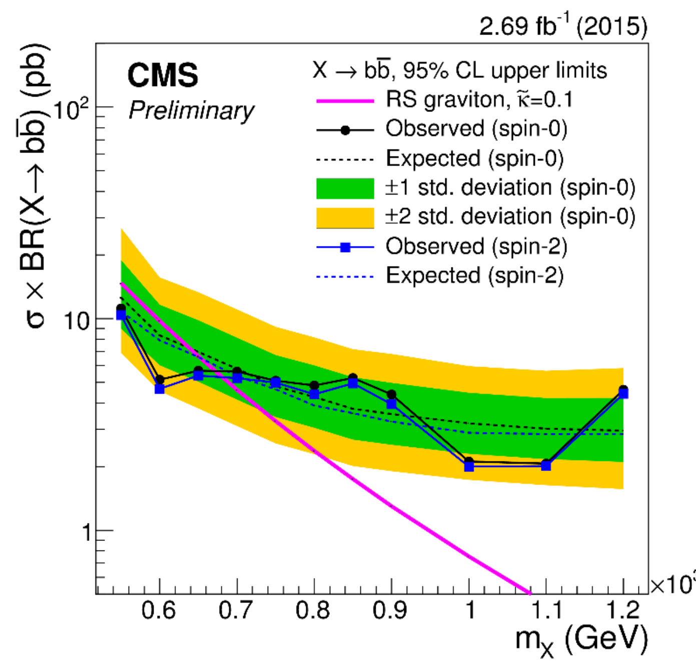
High Mass H → bb

CMS-PAS-HIG-16-025

- Search for heavy resonance in bb final state
  - Spin-0 and spin-2
- Binned maximum likelihood fit in the m_{bb} distribution







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