Higgs Results at CMS

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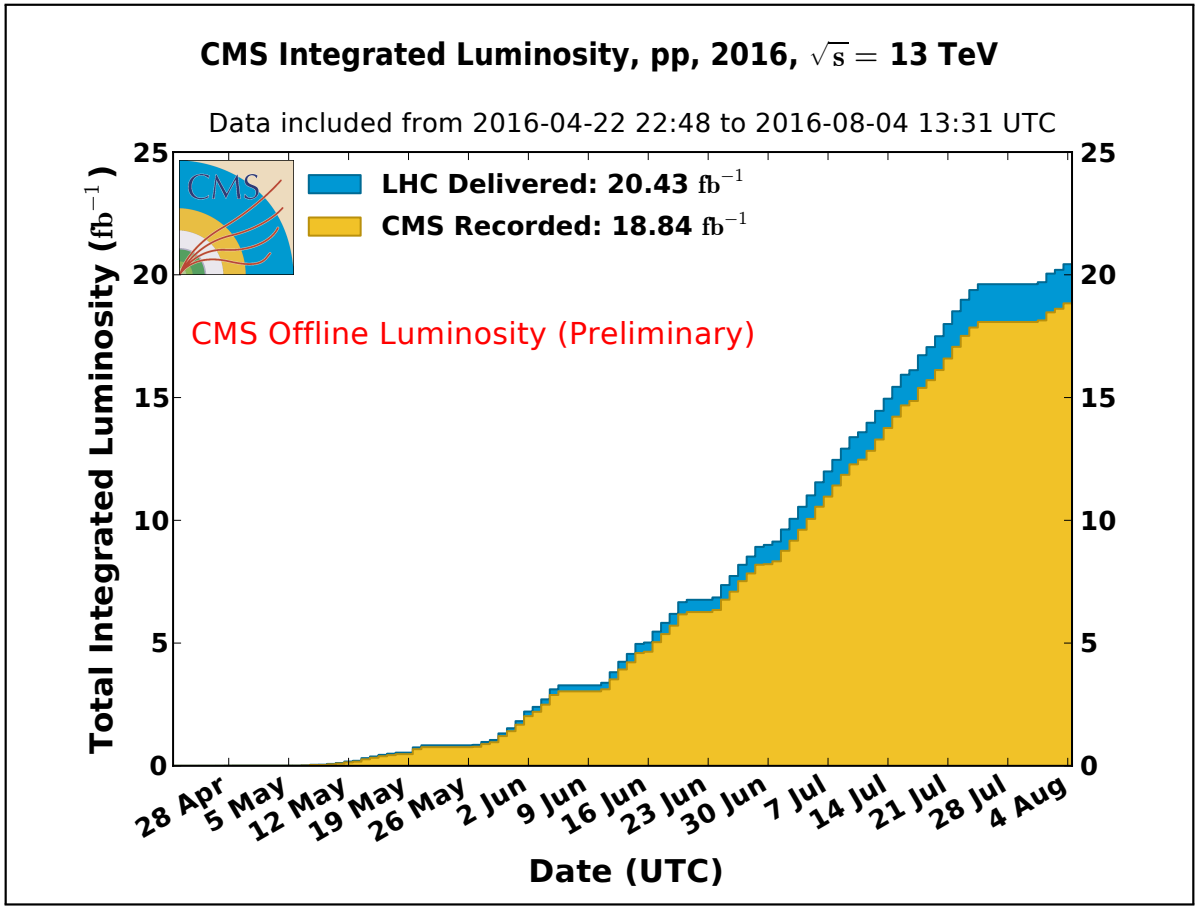
- This is not a fully comprehensive talk, but rather a collection of highlights
- Focus on the most recent 13 TeV results
- Apologize if I left behind your favorite topic, do not hesitate ask if you have questions!

On the upper right side of the slides I include references to the most recent CMS public material

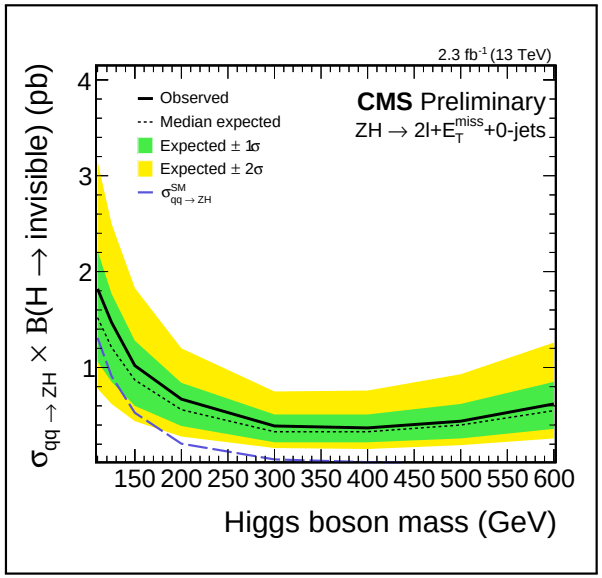
Taking Data at $\sqrt{s} = 13$ TeV



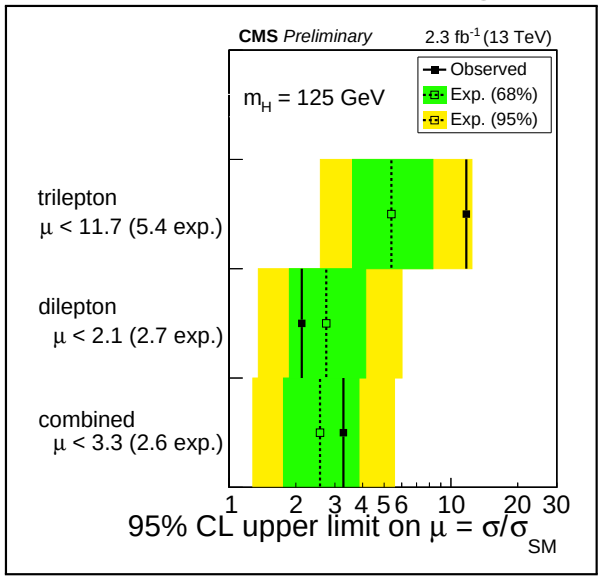
- $\mathcal{L} = 2 - 3$ fb^{-1} in 2015, much faster pace in 2016
- 2016 "ICHEP" dataset: ~ 13 fb^{-1}

Some Terminology

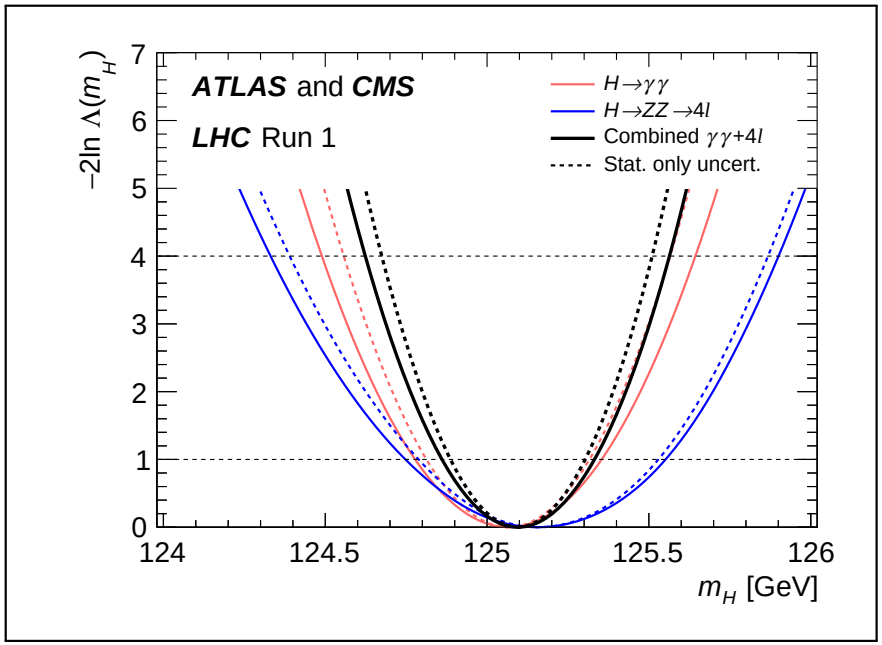
95% Confidence Level (CL) upper limits as a function of the mass



95% CL upper limits for a given mass

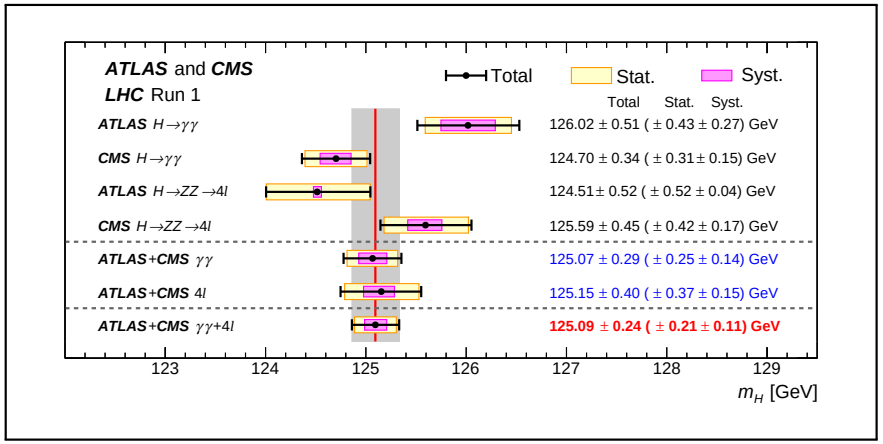


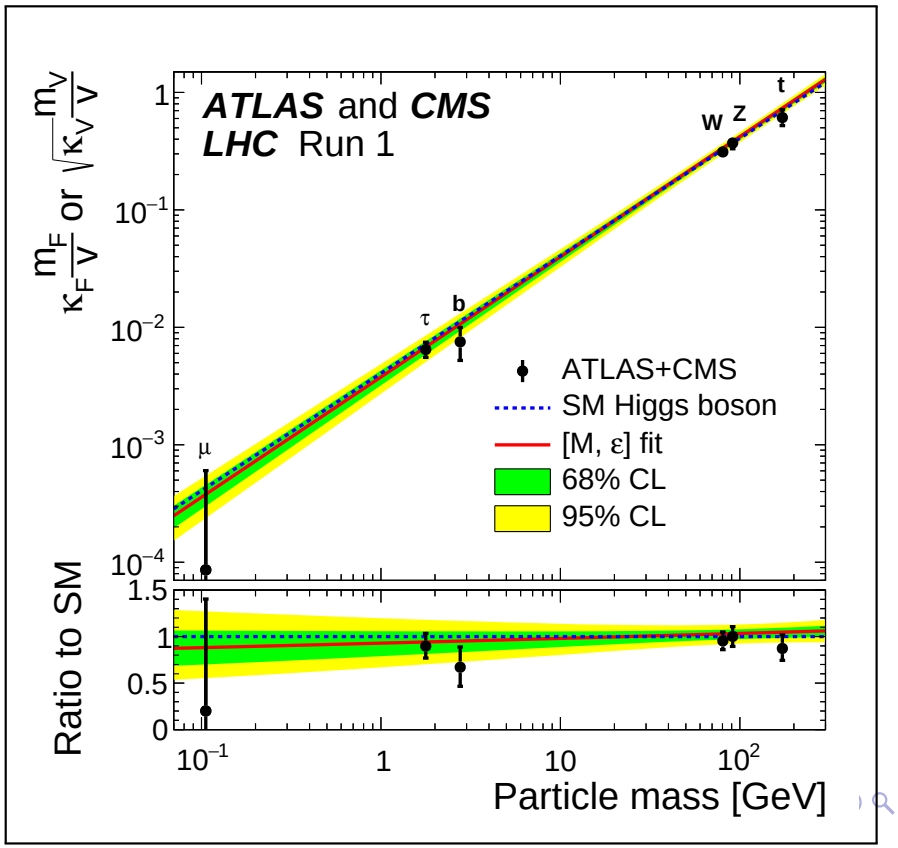
Scans of profile likelihood of a given observable



Summary of Run-I Higgs Results

- Combined measurement using LHC run-I dataset:
  - $m_{\mathrm{H}} = 125.09 \pm 0.21\,(stat.) \pm 0.11\,(syst.)\ \mathrm{GeV}$
  - overall precision 0.19%
- Couplings consistent with Standard Model (SM) Higgs boson
- No additional Higgs bosons found so far



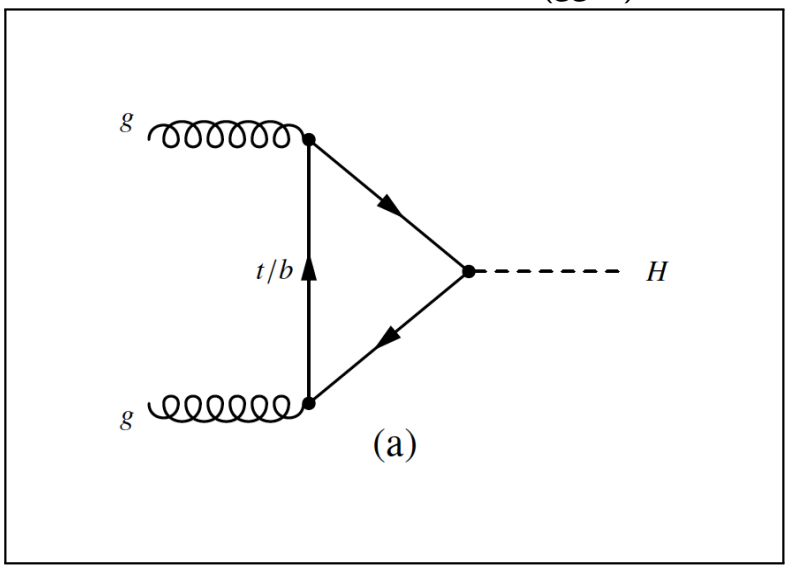


Introduction

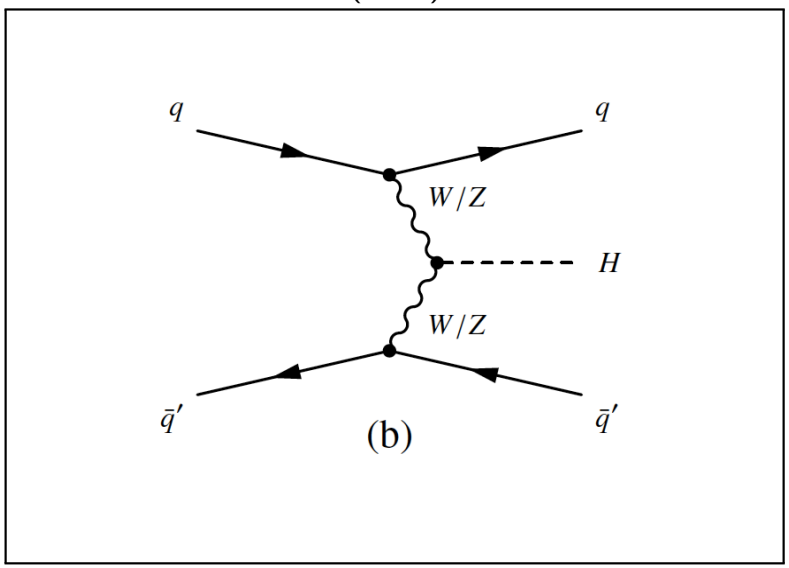
- Several ways to find Physics Beyond the Standard Model (BSM) involving Higgs bosons:
  - measuring couplings and differential distributions of known SM Higgs boson decays:
    - main modes: ZZ, WW, $\gamma\gamma$, $\tau\tau$, $b\bar{b}$
    - (less) rare modes: $\mu\mu$, $\mathrm{Z}\gamma$, $\gamma^{*}\gamma$, ee
    - very difficult modes (at LHC): $s\bar{s}$, $c\bar{c}$, gg
    - production modes: $gg \rightarrow \mathrm{H}$, $qq\mathrm{H}$, VH, $\mathrm{t\bar{t}H}$, $tq\mathrm{H}$, $b\bar{b}\mathrm{H}$
  - searching for additional Higgs bosons:
    - direct searches for low mass (pseudo-)scalars (NMSSM...)
    - direct searches for heavy Higgs bosons (2HDM, $H^{\pm\pm}$...)
  - searching for particle decays involving Higgs bosons, e.g.:
    - $t \rightarrow c\mathrm{H}$
    - $\tilde{\chi}_1^0 \rightarrow \mathrm{H}\tilde{G}$, $\tilde{t}_2 \rightarrow \tilde{t}_1\mathrm{H} \rightarrow t\tilde{\chi}_1^0\mathrm{H}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \mathrm{W}^{\pm}\tilde{\chi}_1^0\mathrm{H}\tilde{\chi}_1^0$
    - $\mathrm{H}+E_{\mathrm{T}}^{\mathrm{miss}}$
  - searching for rare neutral Higgs boson decays:
    - either forbidden or a branching fraction well below the experimental reach within the SM
- Focus on analyses with experimental (public) CMS results

Main Production Modes

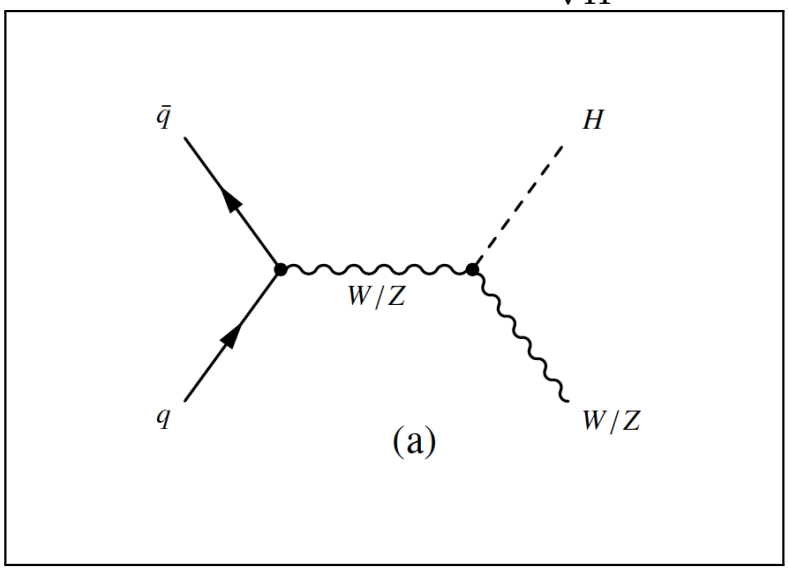
Gluon-fusion (ggH)



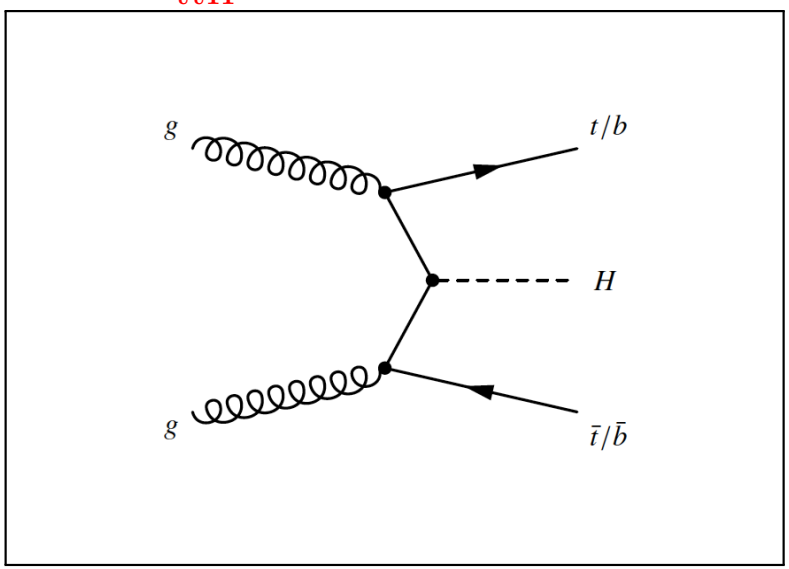
Vector Boson Fusion (VBF)



VH



$t\bar{t}H$



$+\ b\bar{b}H,\ tHq...$

Signatures

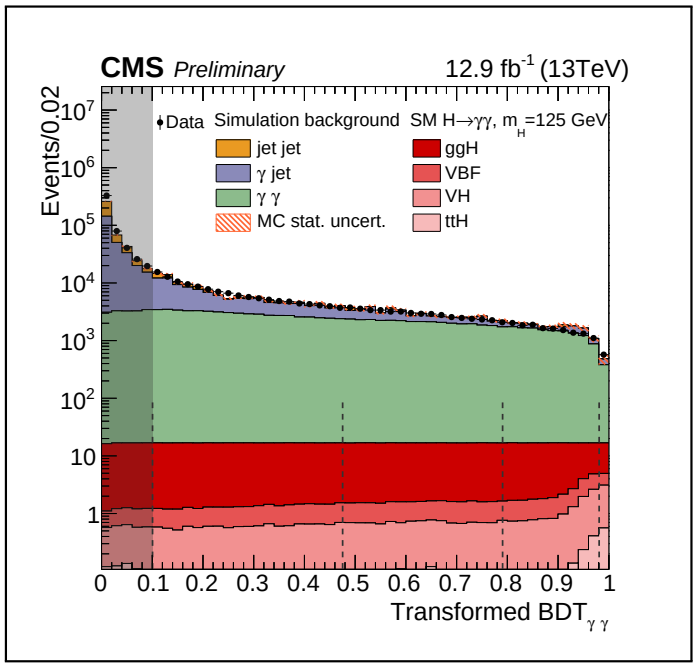
- "SM" Higgs boson and other neutral Higgs bosons
  - $\mathrm{H} \to \gamma\gamma/\mathrm{ZZ}/\mathrm{WW}/\tau\tau/b\bar{b}/\mu\mu/\mathrm{Z}\gamma$
- Rare (or forbidden) Higgs boson decays
  - $\mathrm{H} \to \mathrm{inv.}/\mathrm{inv.} + \gamma/\text{prompt electron} - \text{jets/long lived...}$
- Charged Higgs bosons
  - $\mathrm{H}^+ \to \tau\bar{\nu}/t\bar{b}/c\bar{s}/c\bar{b}/\chi^0\chi^+/W^+\mathrm{H}/\mathrm{W}^+\mathrm{Z}$
- Doubly charged Higgs bosons
  - $\mathrm{H}^{\pm\pm} \to \mathrm{WW}/4\ell$
- Higgs bosons to Higgs bosons decays
  - $\mathrm{H} \to \mathrm{Z}A/\mathrm{Z}h$
- Di-Higgs bosons
  - $(\mathrm{H} \to)hh \to b\bar{b}\gamma\gamma/b\bar{b}\tau\tau/b\bar{b}b\bar{b}/b\bar{b}\mathrm{WW}/\mathrm{WW}\gamma\gamma...$
  - $\mathrm{H} \to a_1a_1 \to \mu\mu\mu\mu/\mu\mu\tau\tau/\tau\tau\tau\tau/b\bar{b}\tau\tau$

In case of a discovery, signatures of new Higgs bosons can also be due to other new particles (e.g. SUSY particles)

Neutral Higgs Bosons

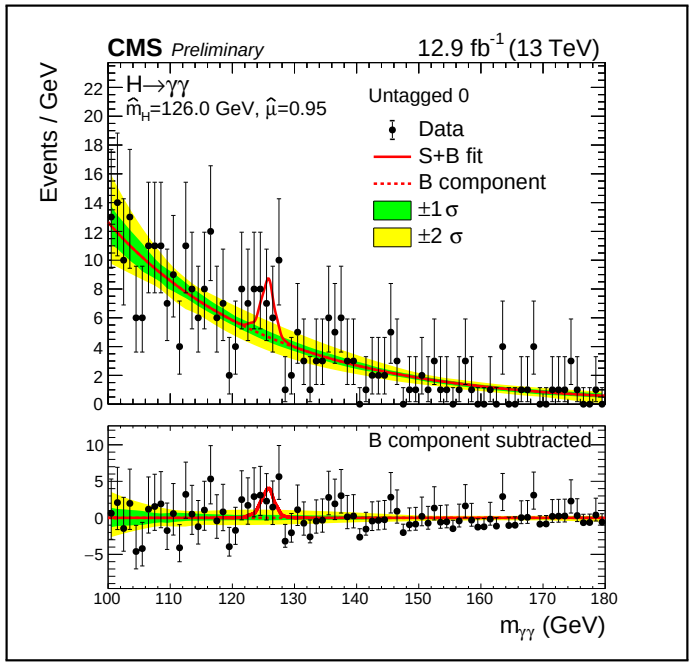
$H \to \gamma\gamma$ - HIG-16-020 (I)

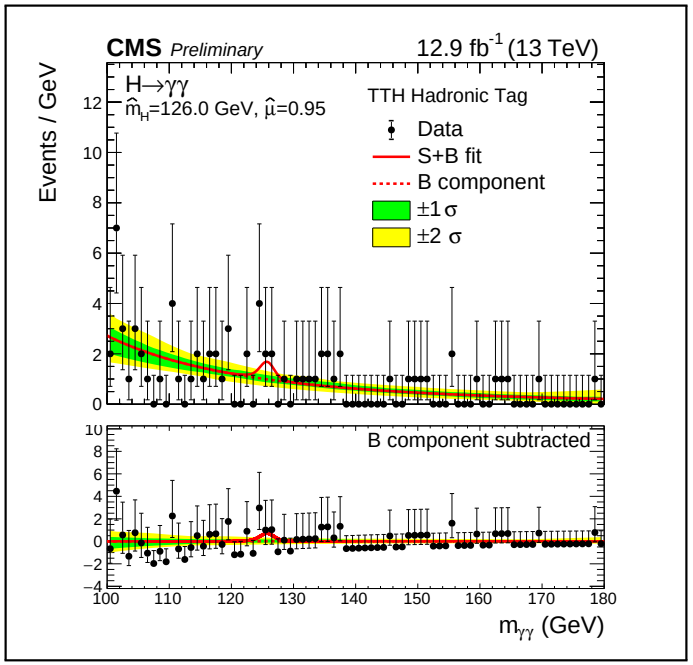
- Clean signature under a huge background
- Complicated analysis to squeeze all the data information
  - Best of the best ECAL calibrations
  - MVA to select event vertex
  - MVA to select photons
  - MVA to select photon pairs
- Split in many categories to improve signal-to-background ratio (S/B) and separate production modes

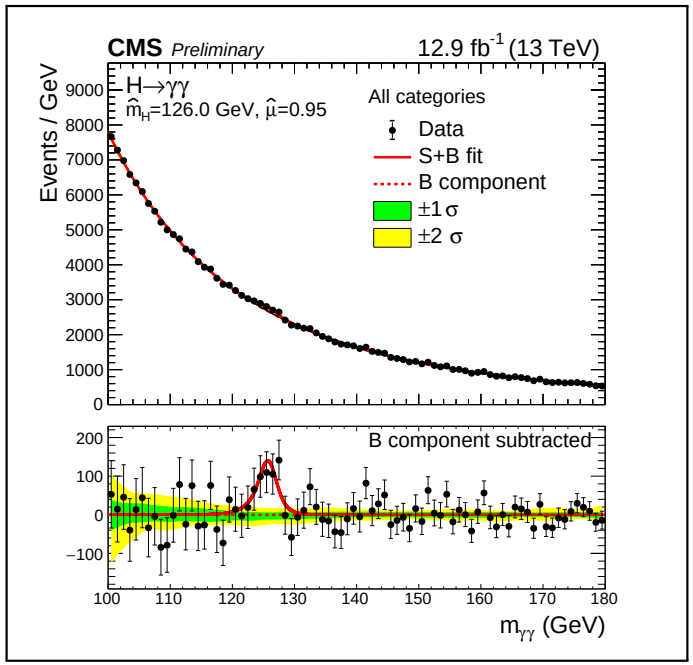


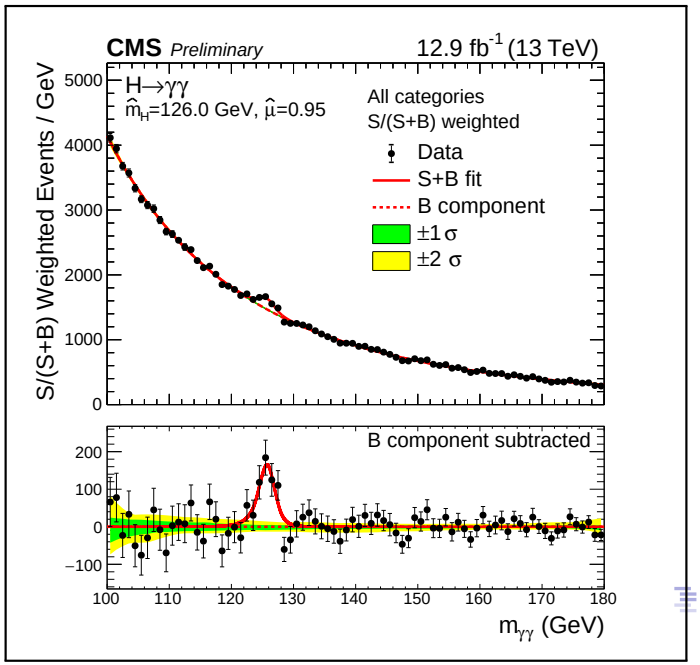
Event Categories	SM 125GeV Higgs boson expected signal							Bkg
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	(GeV^{-1})
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.12
TTH Leptonic Tag	1.14	1.07 %	0.08 %	2.42 %	1.06 %	95.38 %	1.62	0.42
Total	647.79	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	2762.65

$H \rightarrow \gamma\gamma$ - HIG-16-020 (II)

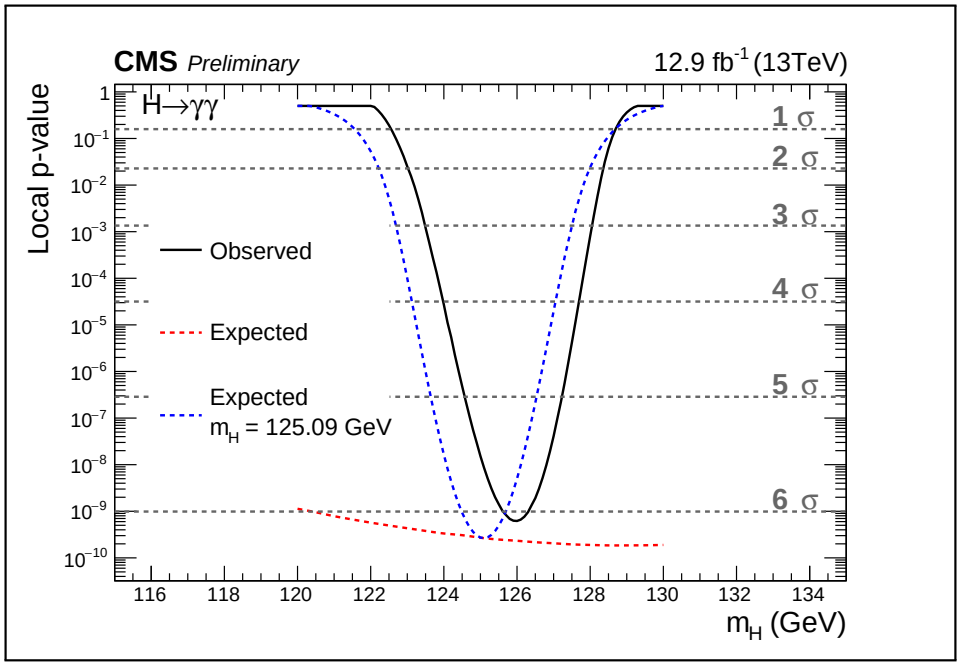


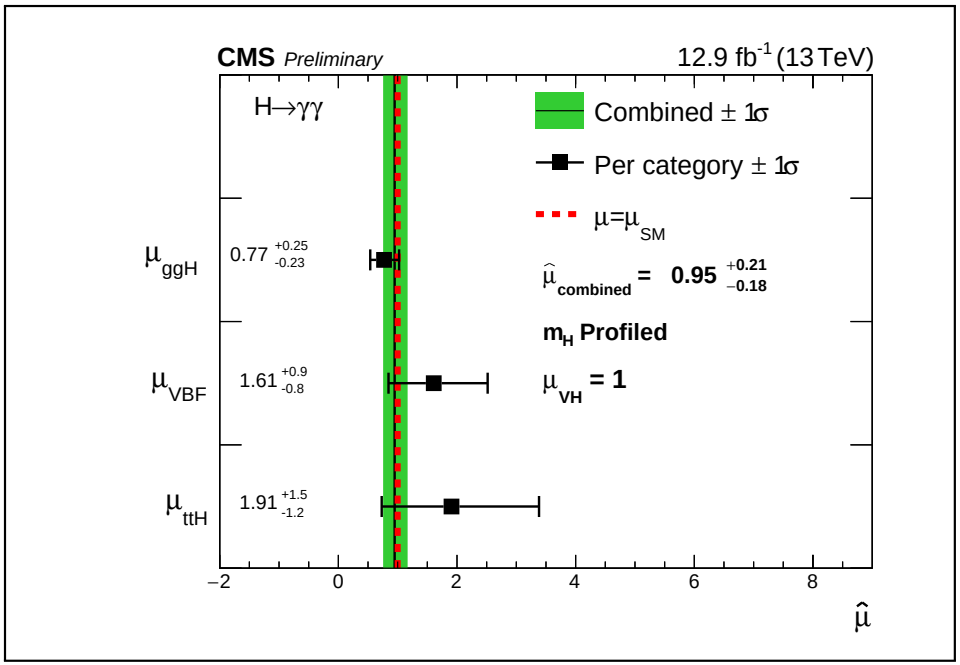


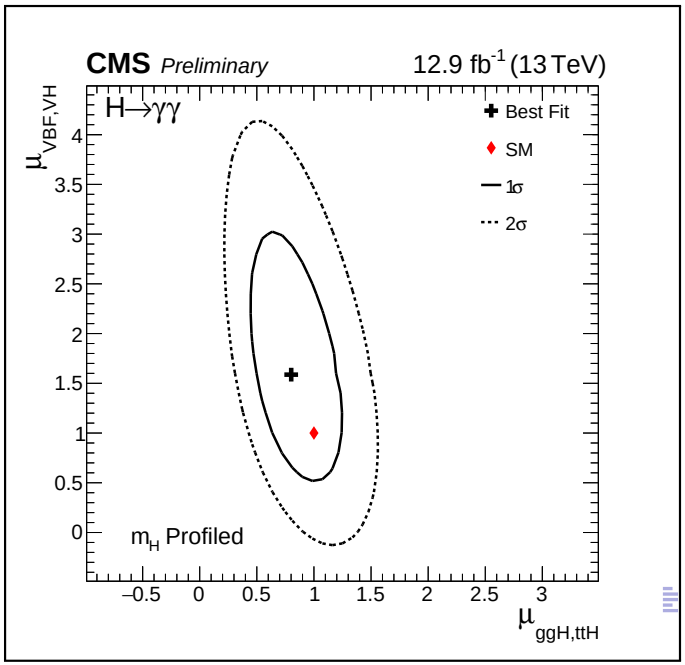




$H \to \gamma\gamma$ - HIG-16-020 (III)

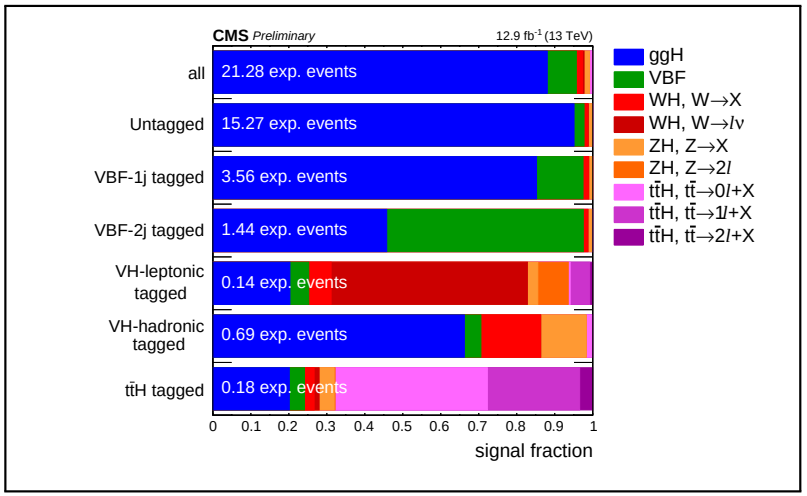


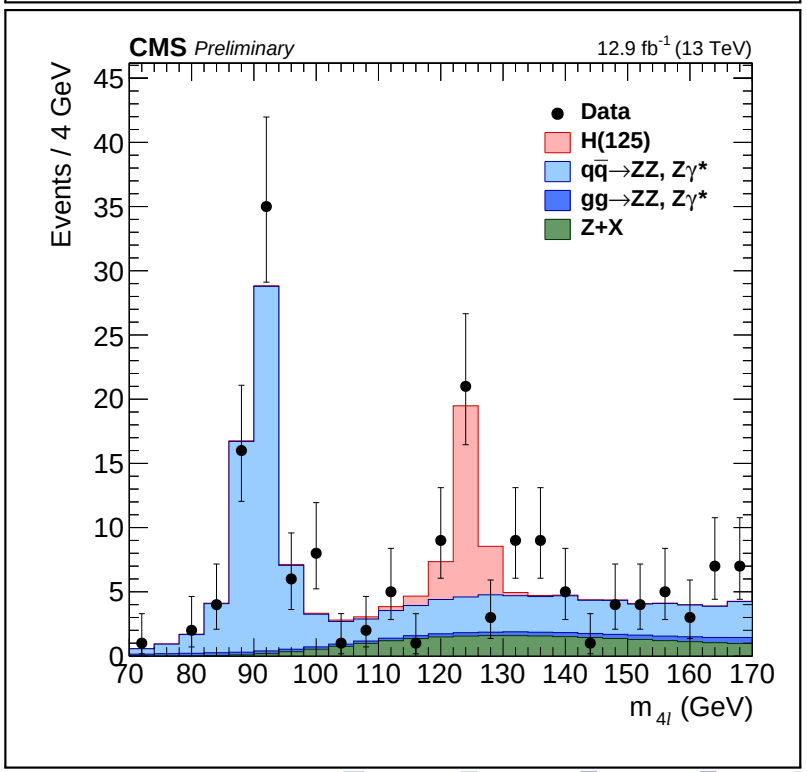




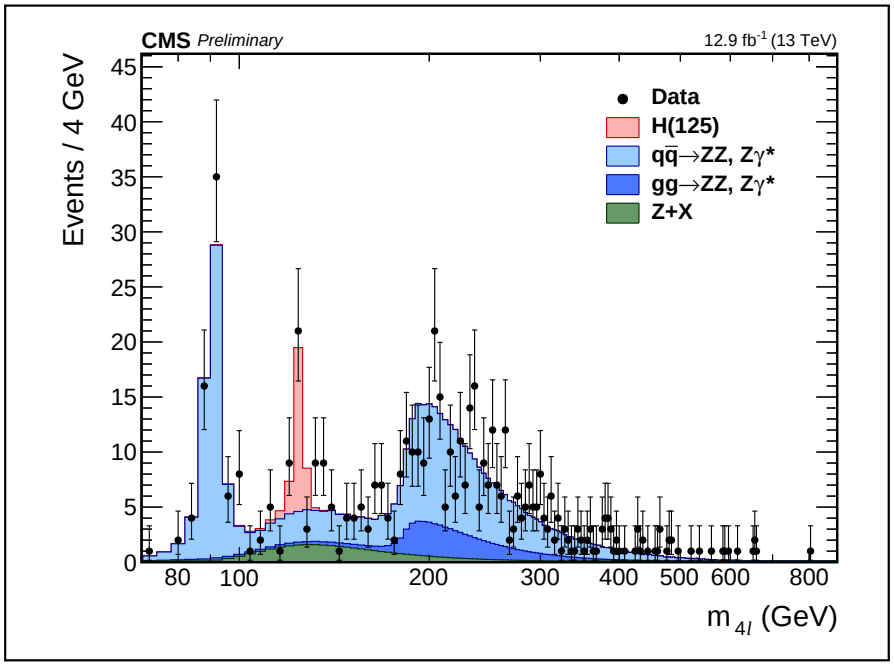
$H \to ZZ \to 4\ell$ - HIG-16-033 (I)

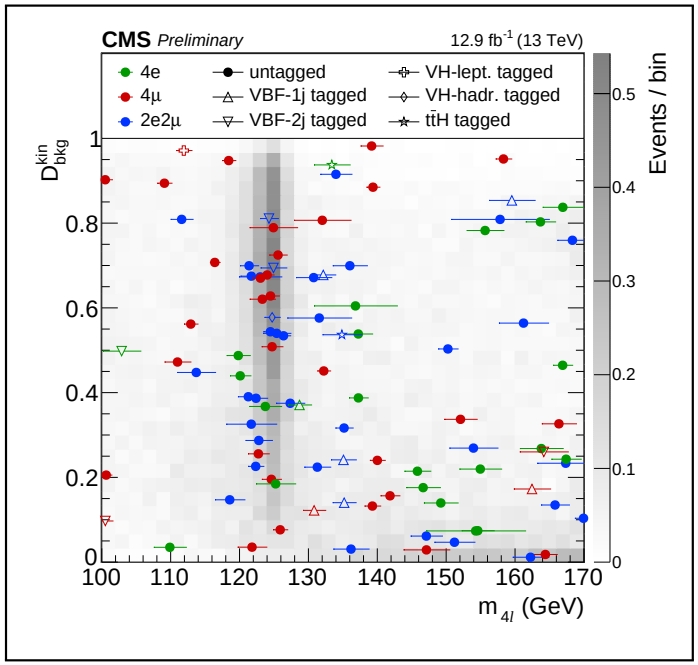
- Clean signature under a small background, but tiny signal yield
- Complicated analysis to add as much sensitivity as possible:
  - make use of $m_{4\ell}$ vs. kinematic discriminator vs. mode categorization
  - make use of low p_T leptons, sophisticated lepton selections
- Differential/fiducial cross section measurements at 13 TeV has also started
- Almost identical analysis used for high mass searches

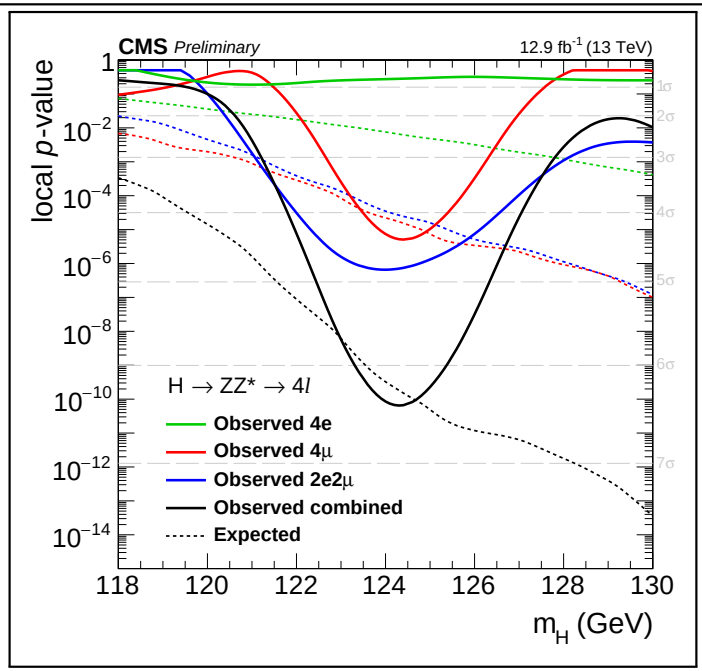


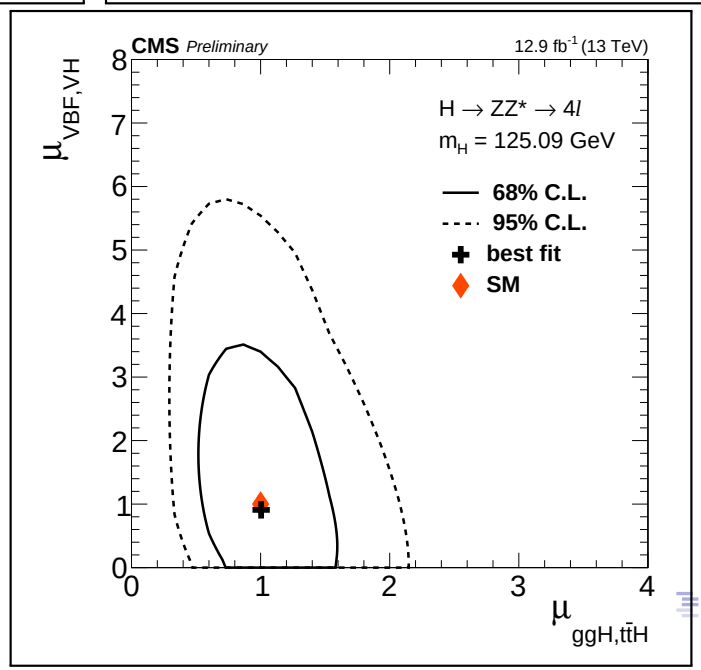


$H \to ZZ \to 4\ell$ - HIG-16-033 (II)



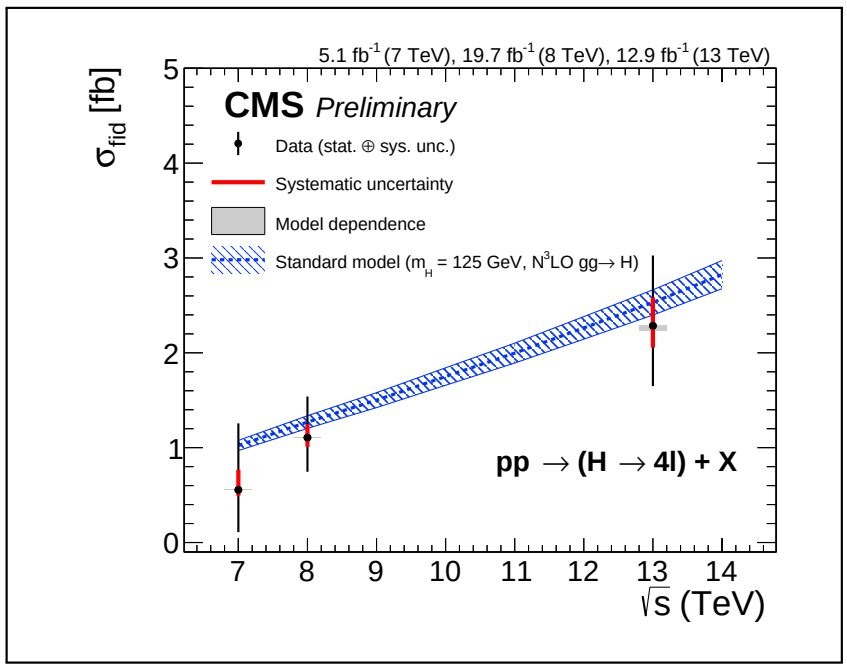


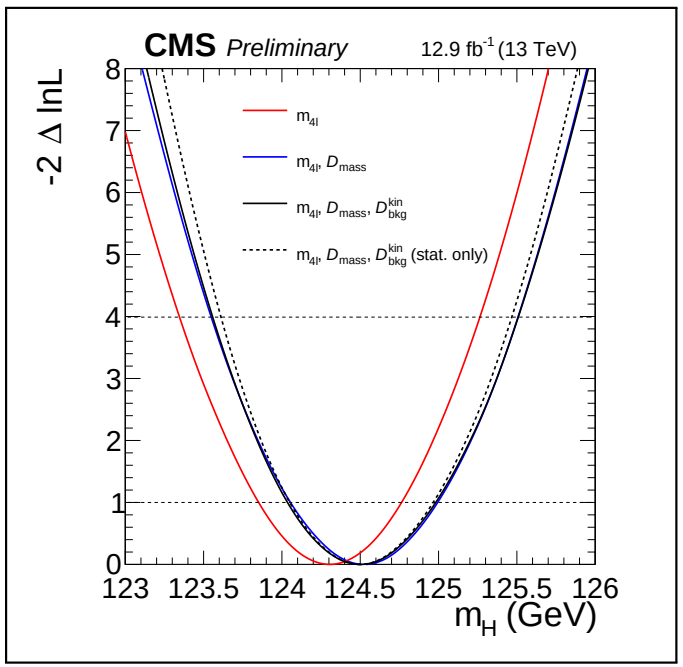




$H \to ZZ \to 4\ell$ - HIG-16-033 (III)

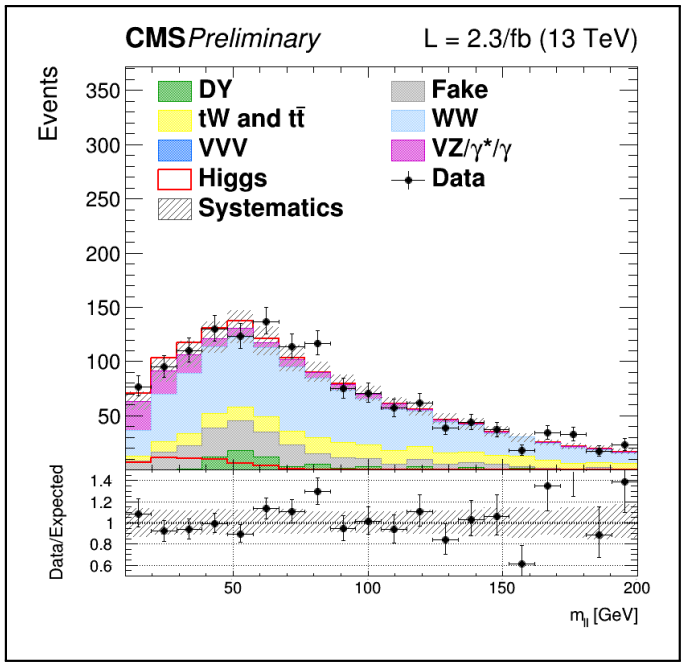
- $\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})$ fb
  $(\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13$ fb$)$
- $m_{\text{H}} = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$ GeV
- Other performed measurements: width, anomalous couplings, high mass searches

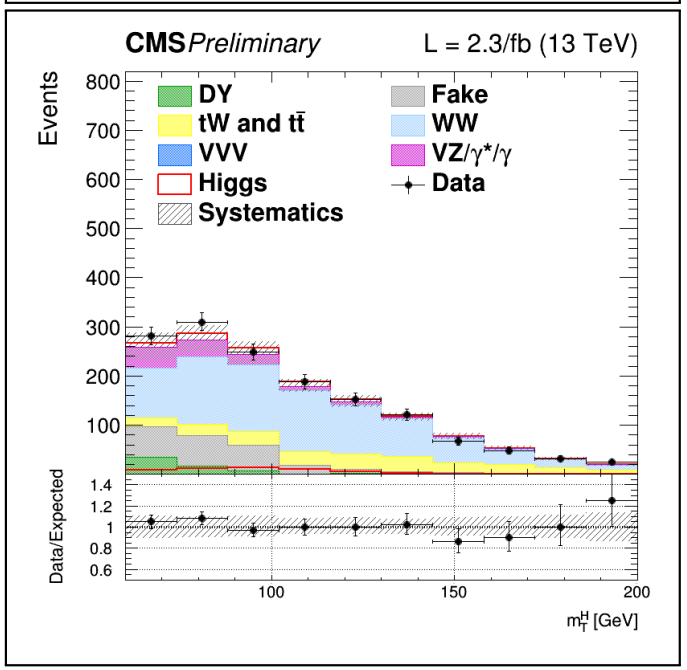




$H \to WW \to 2\ell 2\nu$ - HIG-15-003 (2015)

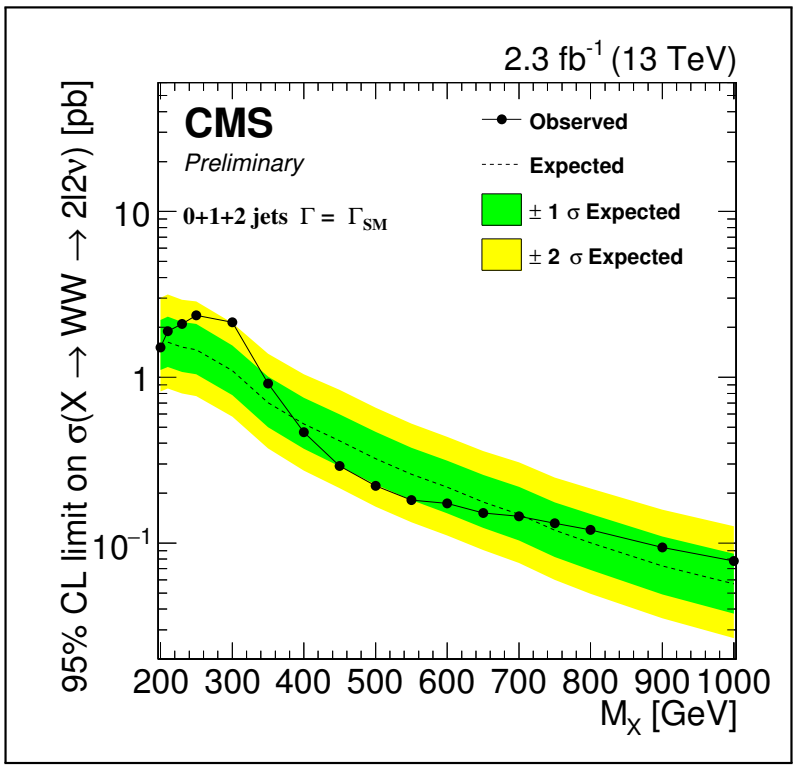
- Two high p_T isolated leptons and moderate E_T^{miss}
- Large $\sigma \times BR$ and clean final state
- No mass peak is the main drawback
- Controlling the background is the key
- Using 0-jet and 1-jet categories only for now (2015 dataset)
- 2D fit: $m_{\ell\ell}$ vs. m_T
- Signal strength: 0.3 ± 0.5
- Significance: 0.7 (2.0) observed (expected)
- Work on including 2016 dataset

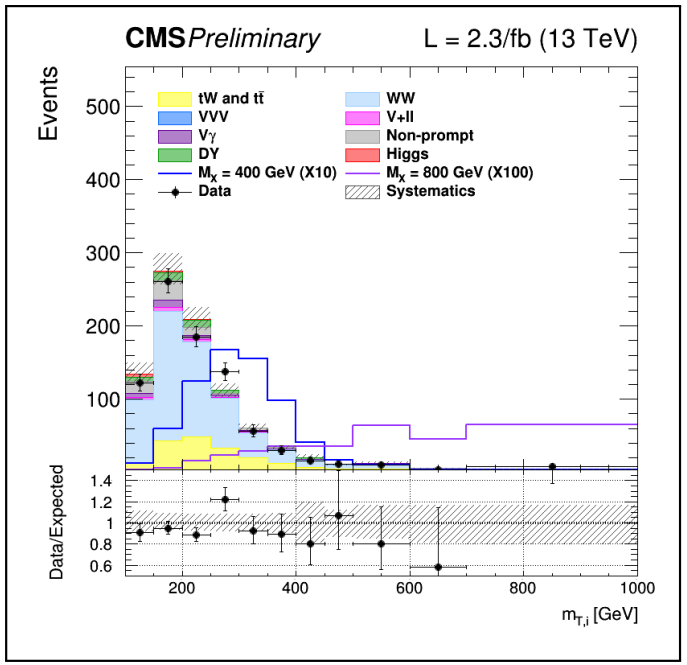


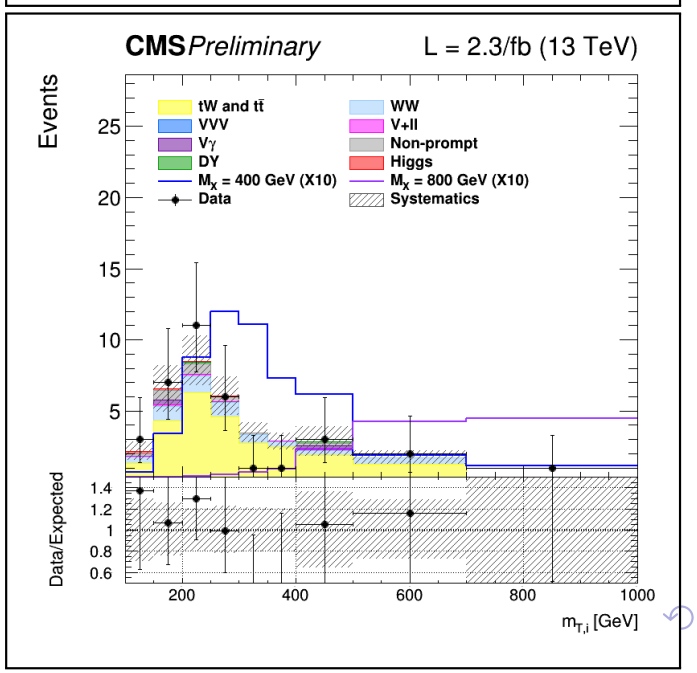


High Mass $H \to WW \to 2\ell 2\nu$ - HIG-16-023 (2015)

- Very similar analysis w.r.t. low mass measurement
- Interference between (high mass) signal and $gg \to WW$ taken into account
- 0-jet, 1-jet, and VBF categories considered
- Using m_T as final discriminant variable
- Providing results for different Higgs boson widths

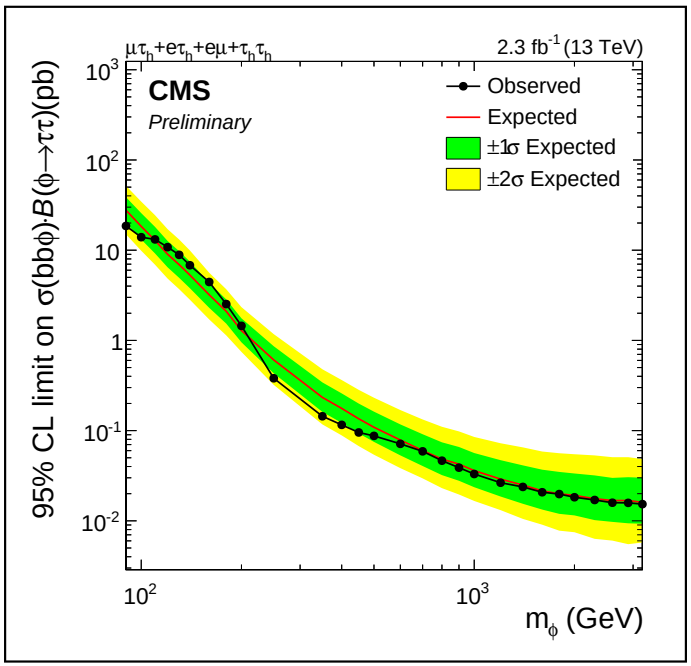


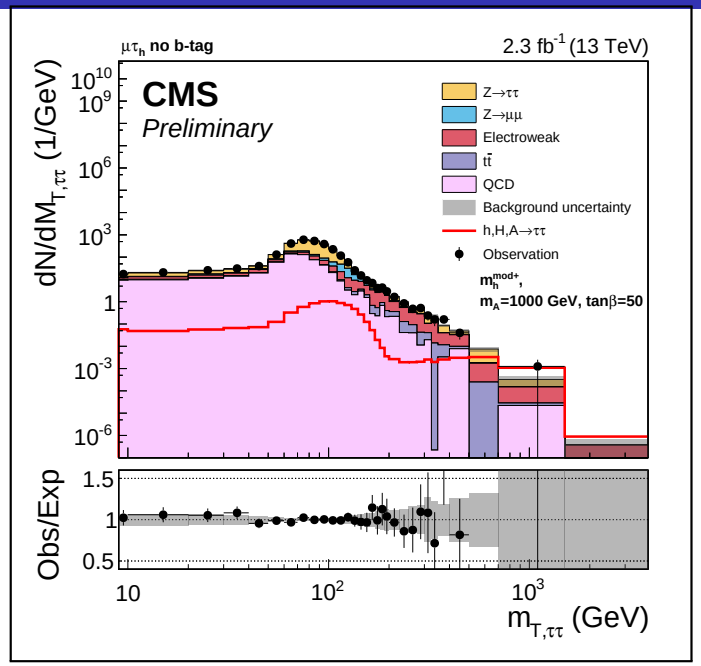


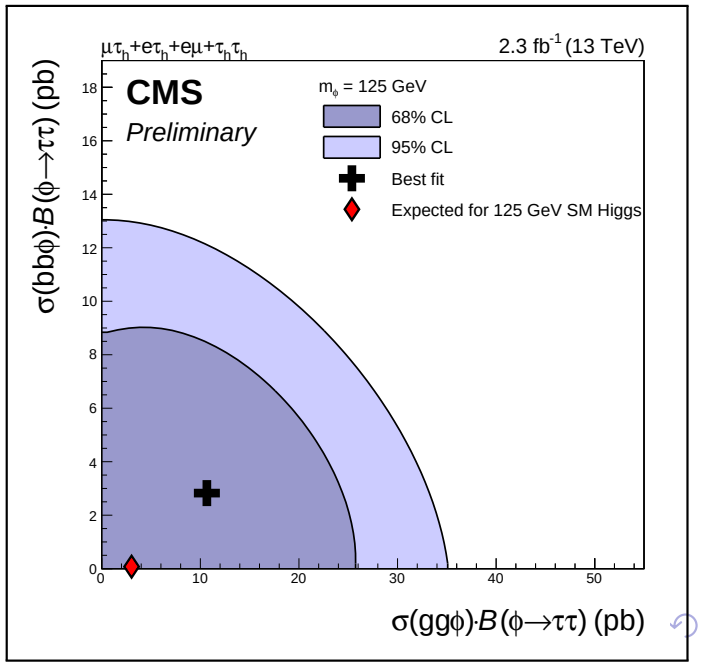


MSSM $H \to \tau\tau$ - HIG-16-006 (2015)

- $H \to \tau\tau$ coupling enhanced in MSSM at high tan β
- $\tau_\ell\tau_{had}$ and $\tau_{had}\tau_{had}$ channels studied
- Using $m_{\tau\tau}$ as a final discriminant
- Separating ggH and b-associated production
- SM analysis closely related

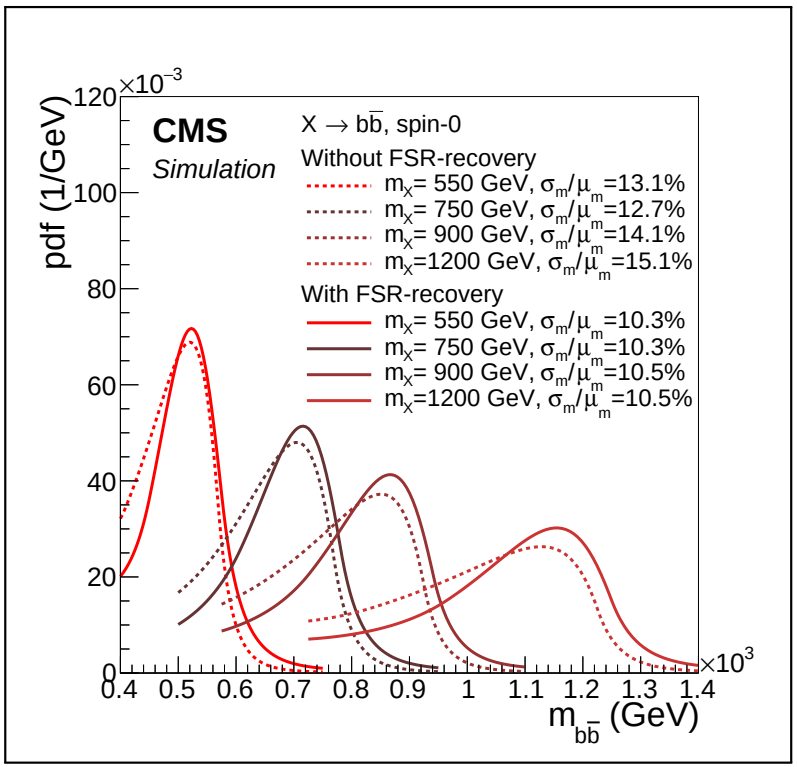


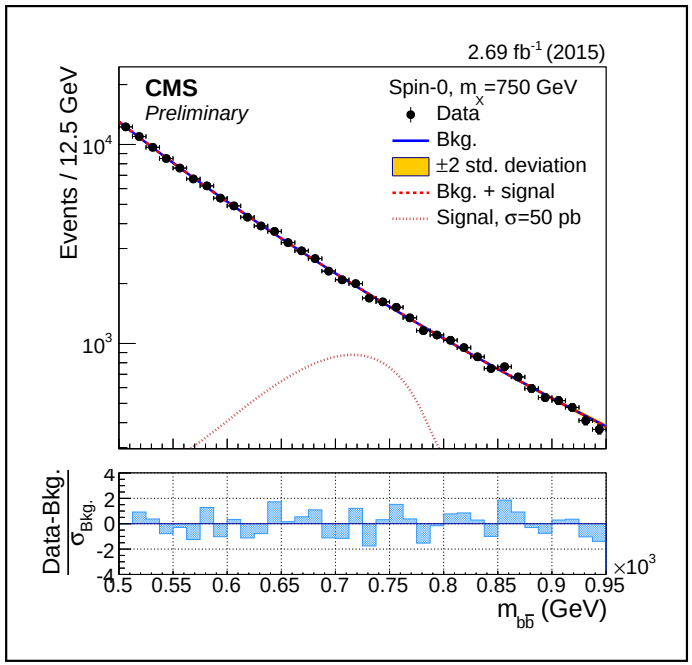


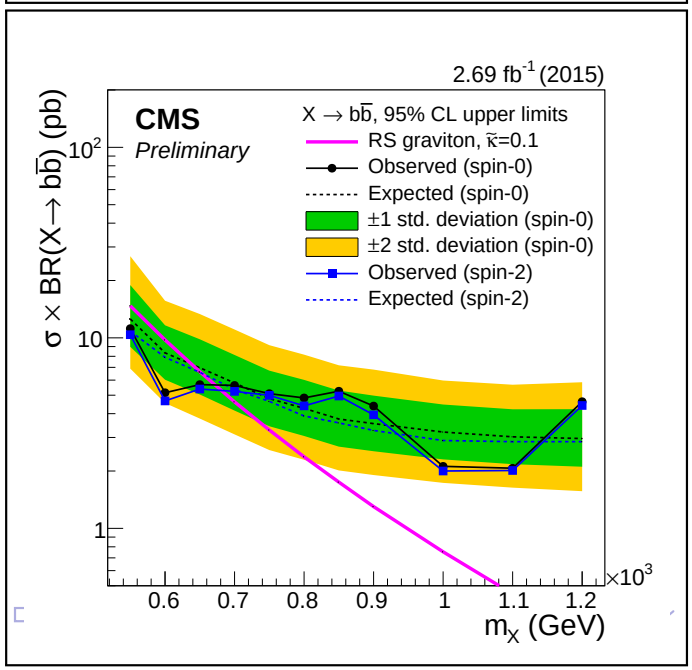


High Mass $H \to b\bar{b}$ - HIG-16-025 (2015)

- Inclusive search for a resonance consistent with $H \to b\bar{b}$
- Making use of standard trigger paths: able to profit for full offline quantities
- FSR recovery adding jets close by the selected b-jets
- Mass fit in a window around the hypothesized mass

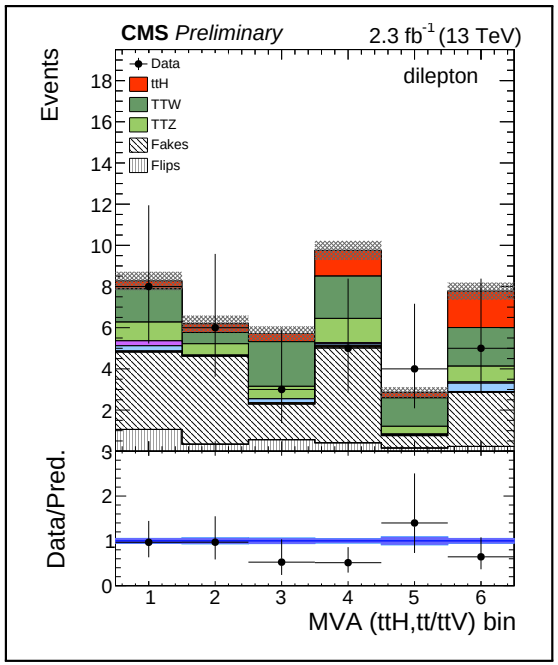


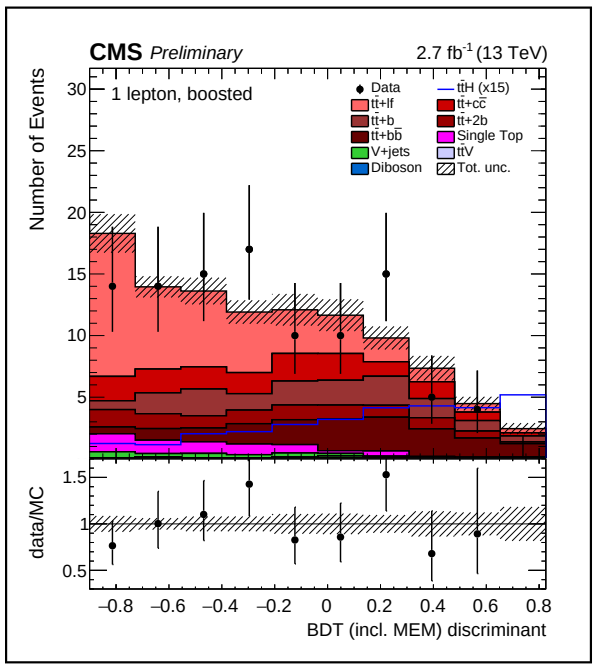


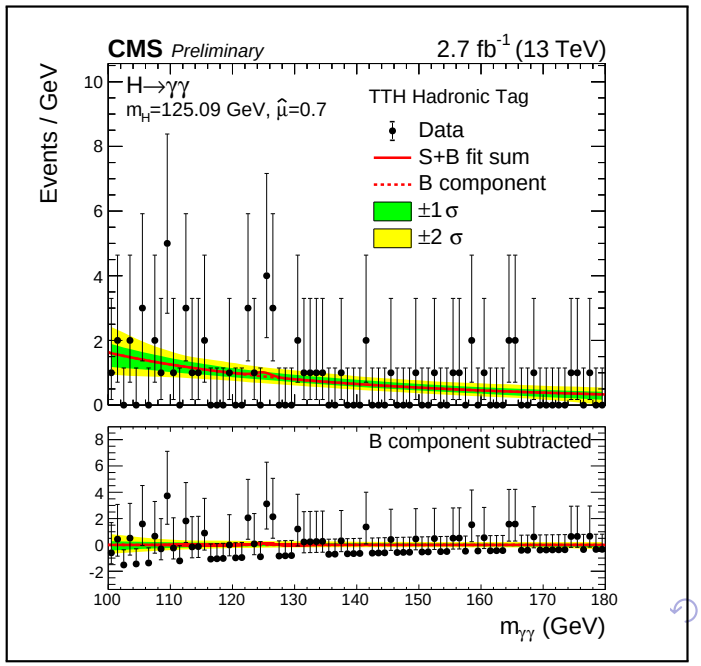


$t\bar{t}H$ (I) - HIG-16-004/HIG-15-008/HIG-15-005 (2015)

- $\sigma^{13\ \mathrm{TeV}}_{t\bar{t}H} / \sigma^{8\ \mathrm{TeV}}_{t\bar{t}H} \sim 4$
- Sensitivity approaching Run 1
- Sensitive to potential new physics contributions
- Final states:
  - $H \rightarrow b\bar{b}$: large BR, low S/B, make use BDT and MEM approaches
  - $H \rightarrow$multilepton: small irreducible background, understanding fake leptons a key
  - $H \rightarrow \gamma\gamma$: small yield, part of main analysis
  - $H \rightarrow \tau\tau$: relatively large BR, but large backgrounds

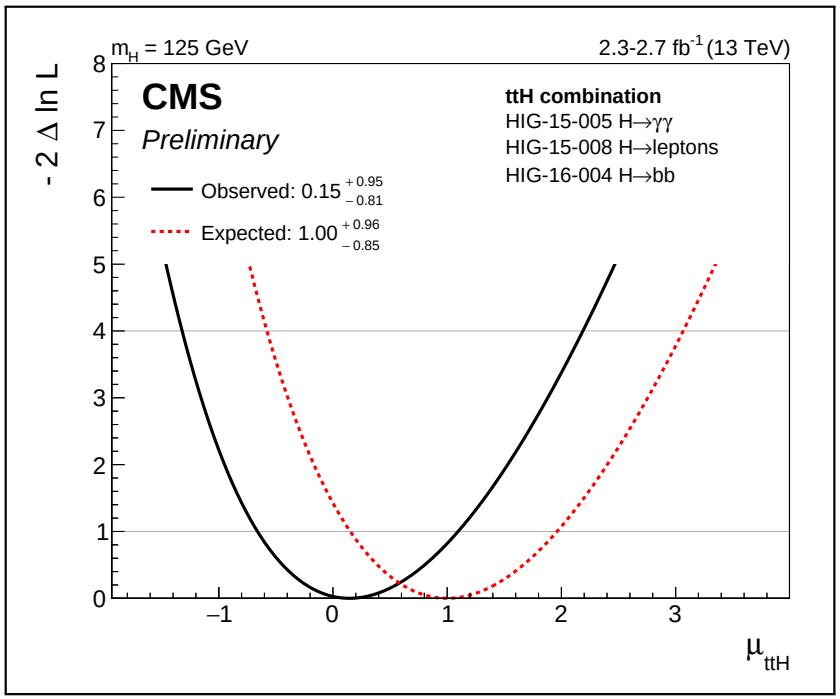


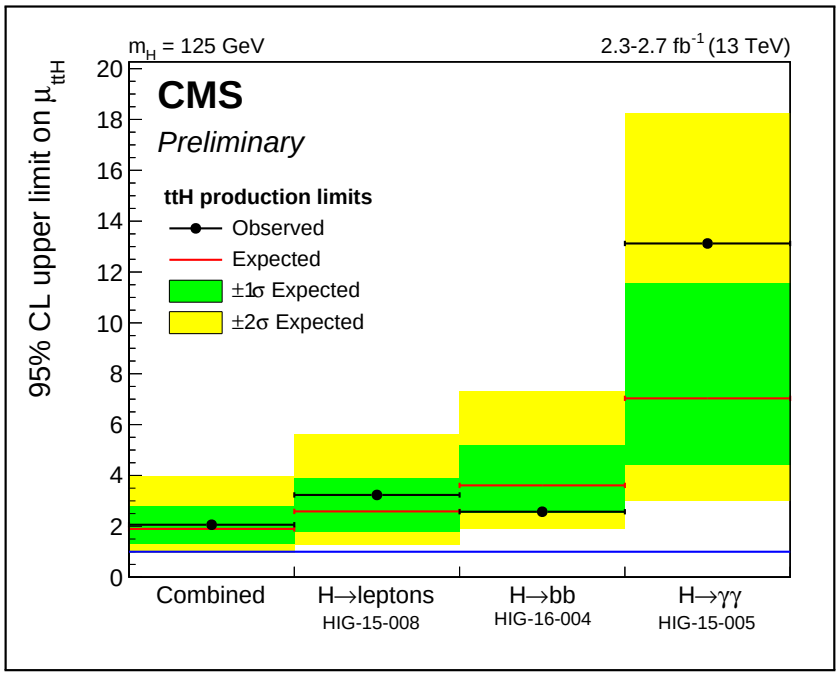




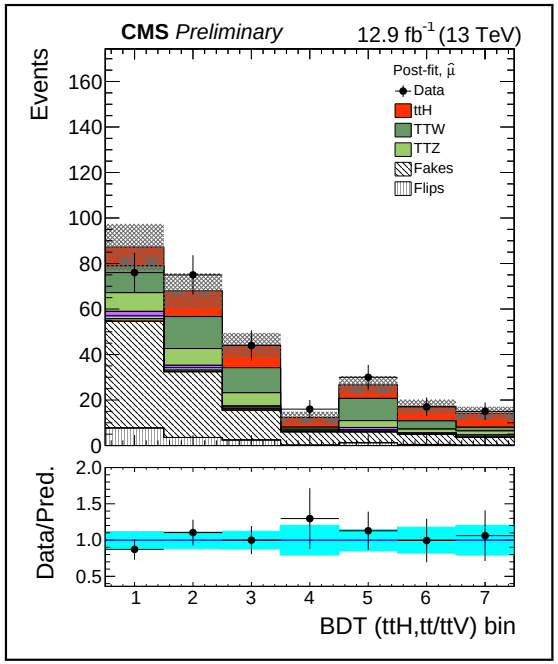
$t\bar{t}H$ (II) - 13 TeV Combination (2015)

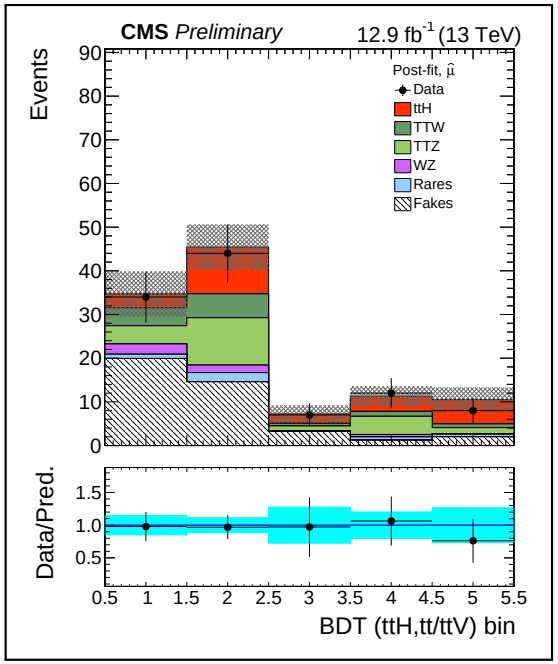
- Combined 13 TeV results more consistent with SM expectation than run-I results
- Need more data to assess conclusions
- High priority analyses in CMS, looking forward the ICHEP results





$t\bar{t}H$ Multilepton with 2016 Data - HIG-16-022



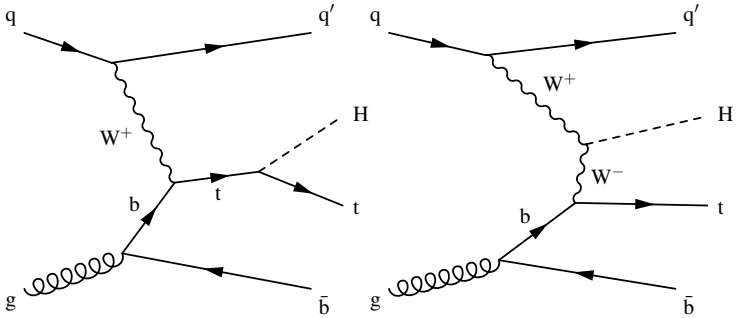


Observed and expected asymptotic 95% CL upper limits on and best fit value of the signal strength

Category	Obs. limit	Exp. limit $\pm1\sigma$	Best fit μ $\pm1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

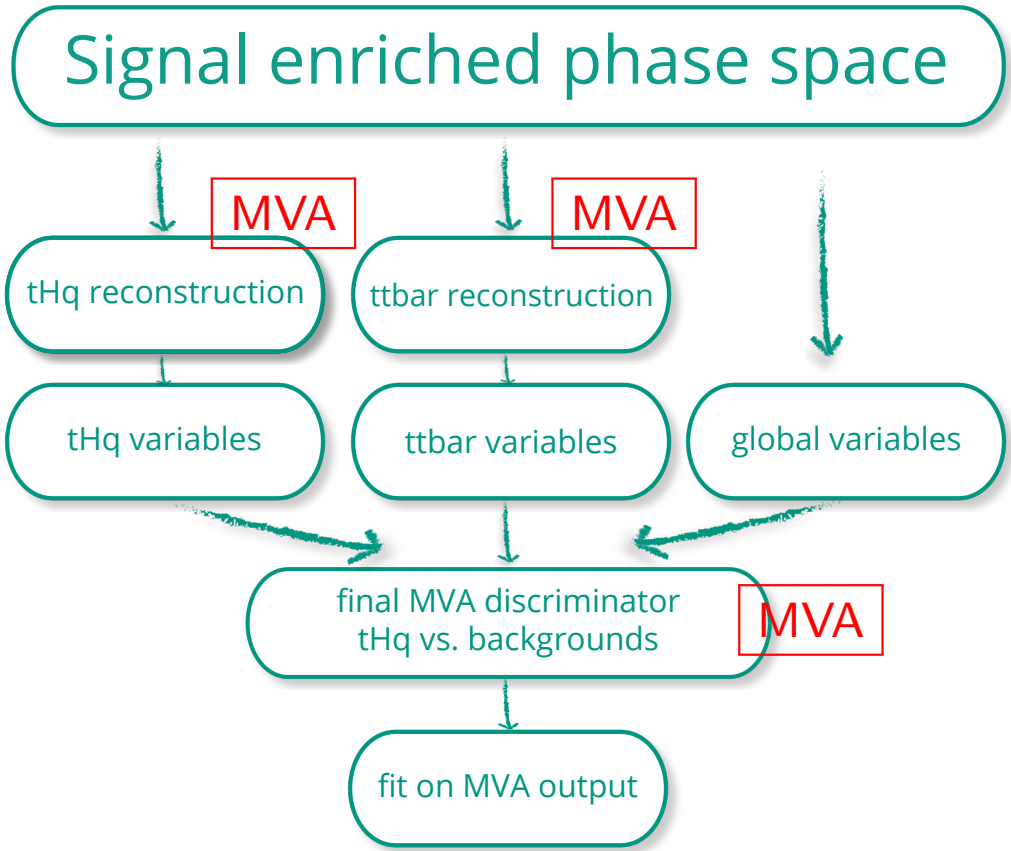
Observed (expected) significance in a background-only hypothesis 3.2σ (1.7σ)

tHq, H $\rightarrow$ b$\bar{\text{b}}$ Overview (2015) - HIG-16-019



- Interference in tHq process because $\mathcal{A} \propto (\kappa_t - \kappa_V)\sqrt{s} +$ const.
- SM: both κ's $= +1$ by construction $\rightarrow$ destructive interference
- Sensitive to deviations from SM. Flipped top Yukawa cross section $\rightarrow$ cross section enhanced by factor 11
- Direct search for 51 points in κ_t-κ_V plane
- Also considering tHW as signal

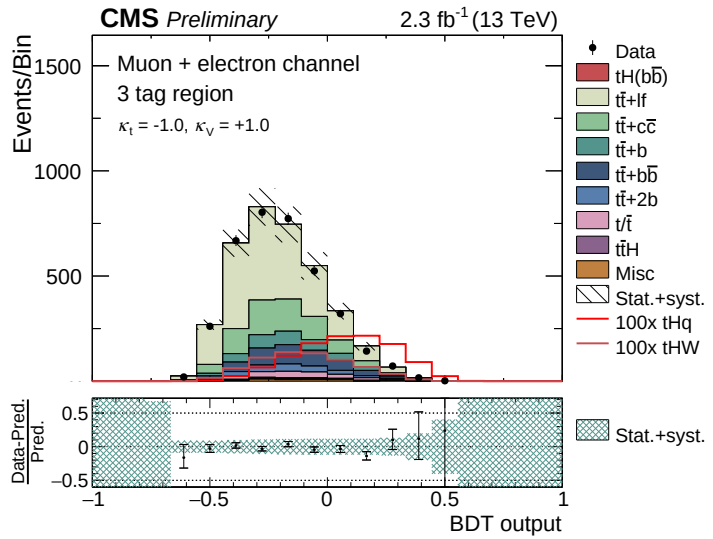
- Challenging multi-jet final state and huge ttbar background requires several layers of MVAs

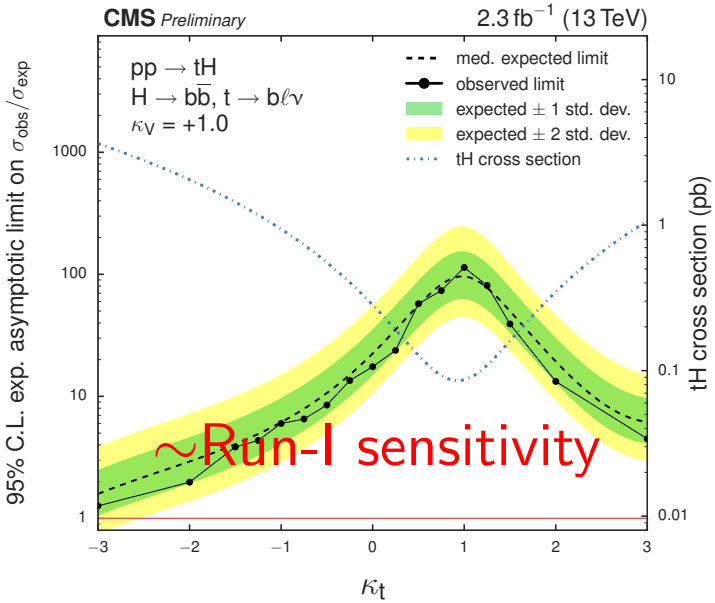


- Validation performed in $\bar{\text{t}}\text{t}$ control region

tHq, H $\rightarrow$ b$\bar{\text{b}}$ Strategy & Results (2015) - HIG-16-019

- Signal region event selection:
  - One muon/electron
  - Three or four b tagged jets
  - At least one untagged jet
- MVA reconstruction for identifying Higgs/top/recoil jet:
  - Train correct jet-parton matches vs. wrong assignments
  - Evaluation: pick assignment that gives highest MVA response
  - Reconstruction efficiency: $> 40\%$
- Finally: MVA for classifying events as tHq or background-like
  - Most important variables: lepton charge, recoil jet η





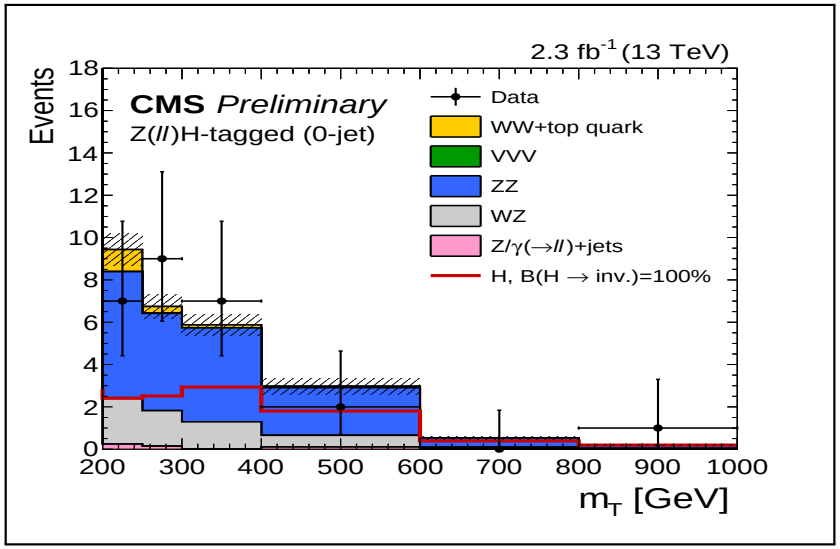
Exotic Searches

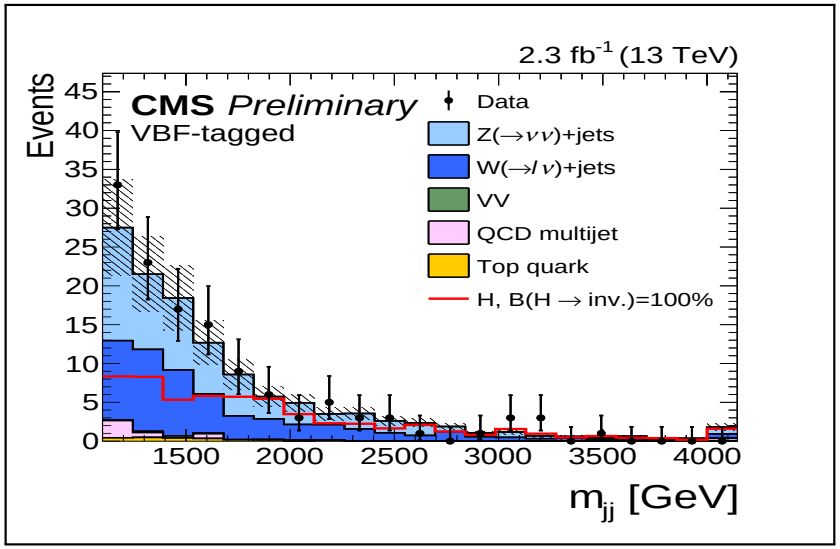
Invisible Higgs Decays (I)

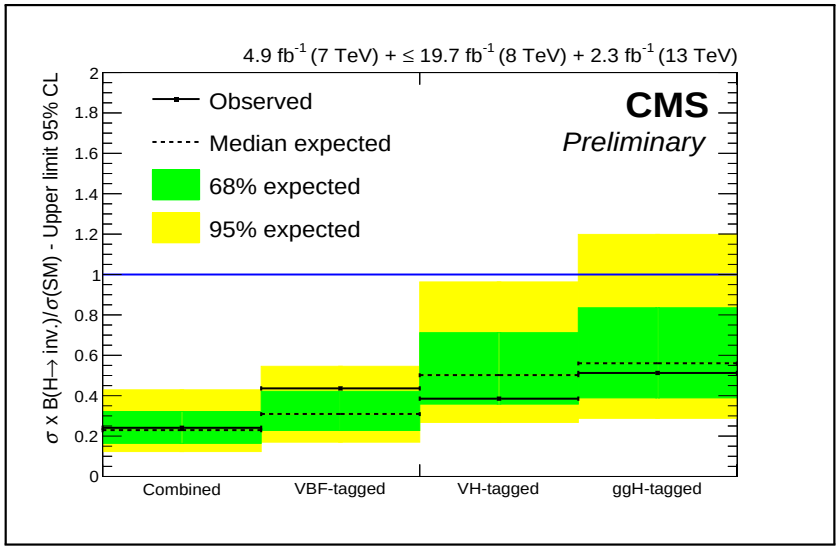
- The most extensive set of rare decays searches by far
- It exists in the SM, but extremely rare: $BR(\mathrm{H} \to \mathrm{ZZ} \to 4\nu) \sim 0.1\%$
- Observation of a large rate would be a sign of BSM:
  - LSPs in SUSY (neutralinos, gravitinos)
  - Graviscalars (large extra-dimensions)
  - Dark Matter (DM) $\rightarrow$ limits competitive with other DM searches
- Large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) is the general pattern of all these searches
- Several production modes can be studied:
  - $qq\mathrm{H}$ (VBF): two forward/backward jets with high $\Delta\eta_{jj}$ & m_{jj}
  - $\mathrm{Z}(\ell\ell/b\bar{b})\mathrm{H}$: two leptons/two b-jets compatible with a Z boson
  - $\mathrm{Z/W}(q\bar{q}')\mathrm{H}$: two jets compatible with a Z/W boson
  - $\mathrm{t\bar{t}H}$: two top-quarks
  - $gg \to \mathrm{H} +$ jet: one high p_{T} jet
- DM searches can directly be re-used for these studies

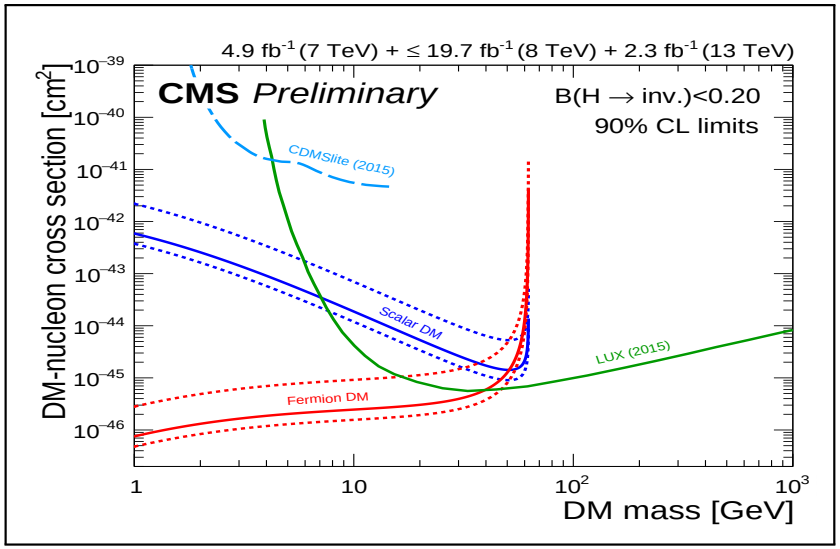
Invisible Higgs Decays (II) - HIG-16-016 (2011, 2012, 2015 comb.)

- A large set of analyses coming up
- More complex techniques exploited by having a single fit combining signal and background regions
- For $m_{\mathrm{H}} = 125\ \mathrm{GeV}$ will profit from a larger dataset



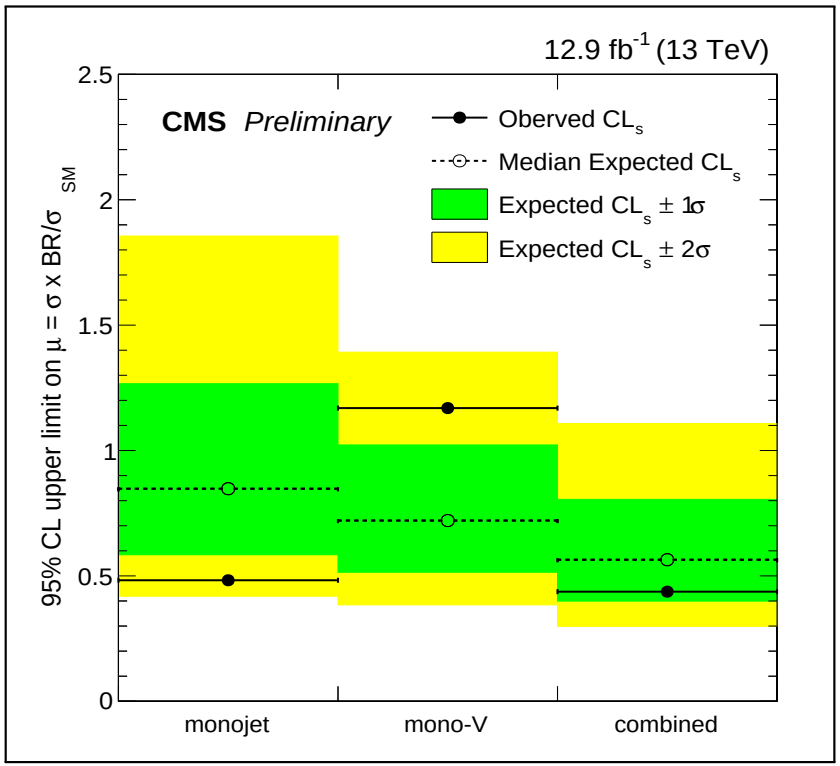


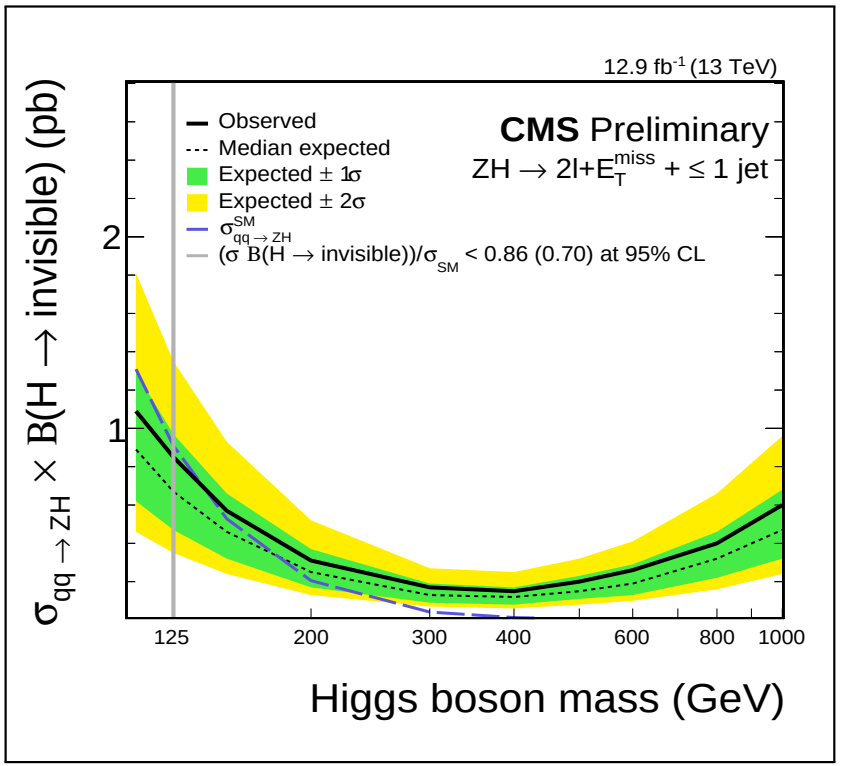




Invisible Higgs Decays with 2016 Data - EXO-16-037/EXO-16-038

- Mono-jet analysis: multi-fit approach of several signal and control regions
- Mono-$Z(\rightarrow \ell\ell)$ analysis: single fit to $E_{\mathrm{T}}^{\mathrm{miss}}$ with several regions to control different background processes
  - sentivity already better than run-I
- Mono-W (hadronic) and mono-Z (hadronic and leptonic) final states start playing a key role, stat./syst. interplay at higher luminosities

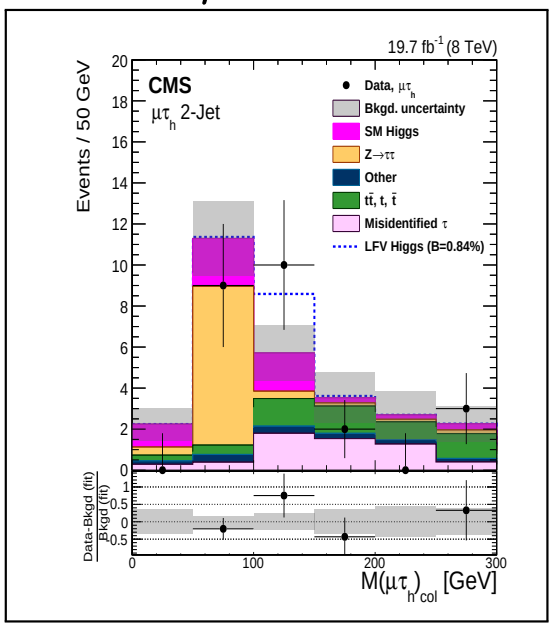




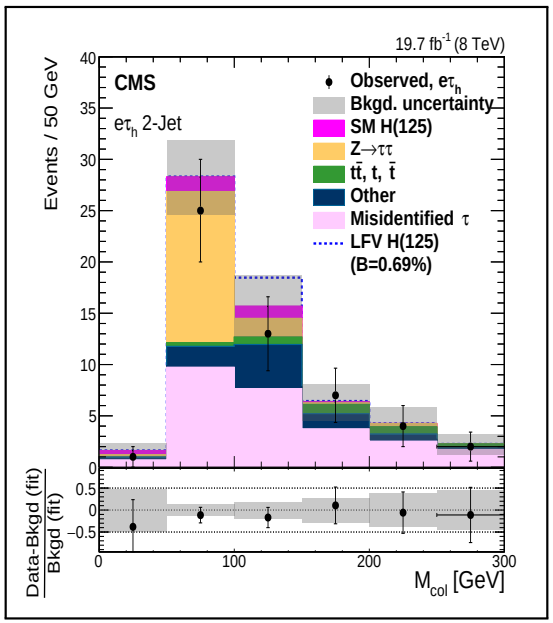
LFV $H \to \mu\tau/e\tau/e\mu$ (I) - HIG-14-005/HIG-14-040/HIG-16-005

- Search for a mass peak at $m_H \sim 125$ GeV in $\mu\tau/e\tau/e\mu$ pairs
- Split in 0/1/2-jet and in τ decays categories
- Direct limits on $BR(H \to \mu\tau/e\tau/e\mu)$ can be established
- Interesting upper fluctuation in the $\mu\tau$ final state at 8 TeV

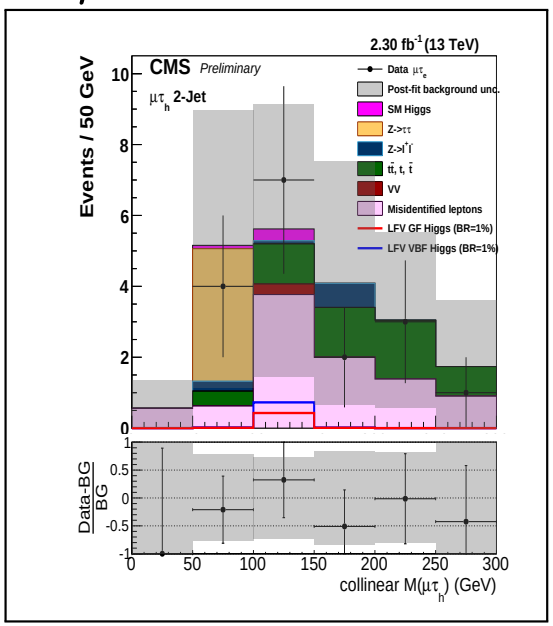
$\mu\tau$ 8 TeV



$e\tau$ 8 TeV

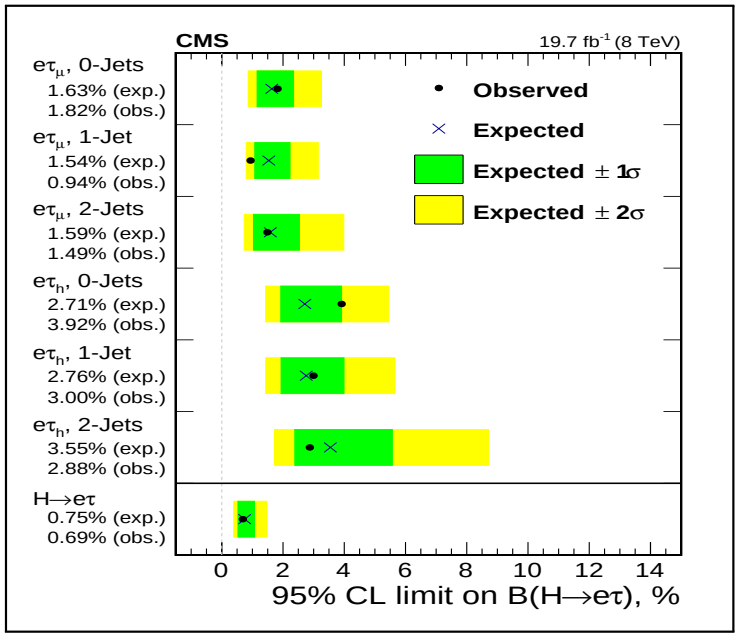


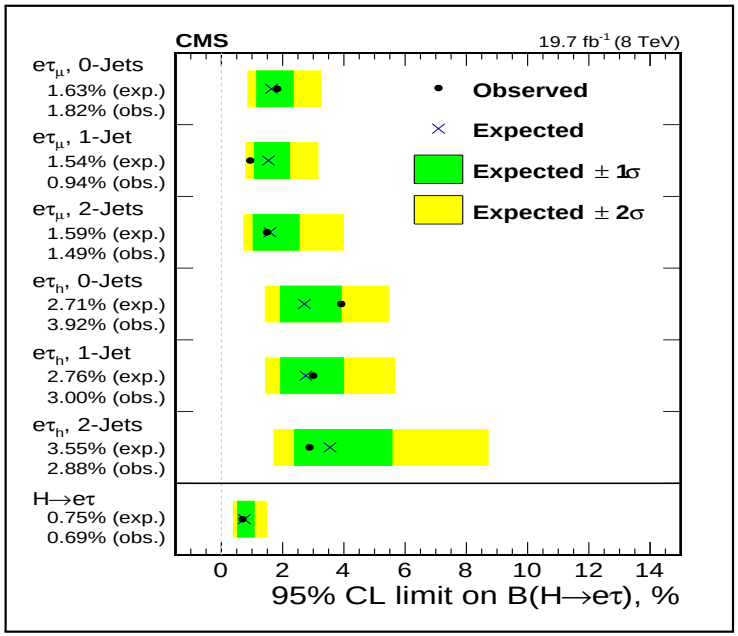
$\mu\tau$ 13 TeV

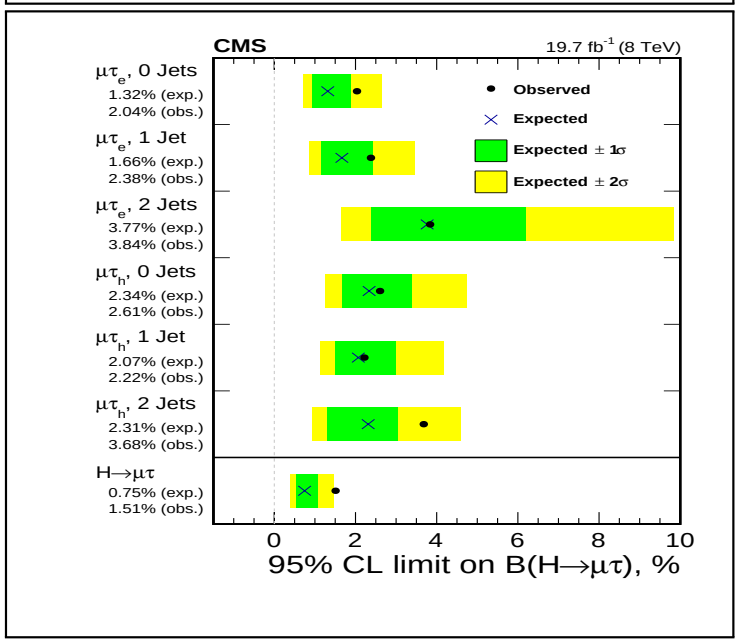


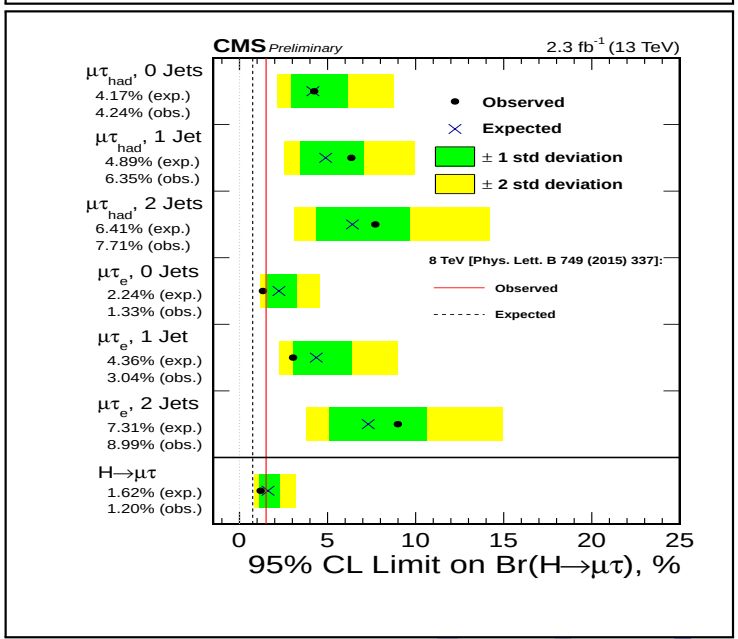
HIG-14-040, $e\tau/e\mu$ analyses at 8 TeV, recently submitted for publication

LFV H $\rightarrow \mu\tau/e\tau/e\mu$ (II) - HIG-14-005/HIG-14-040/HIG-16-005



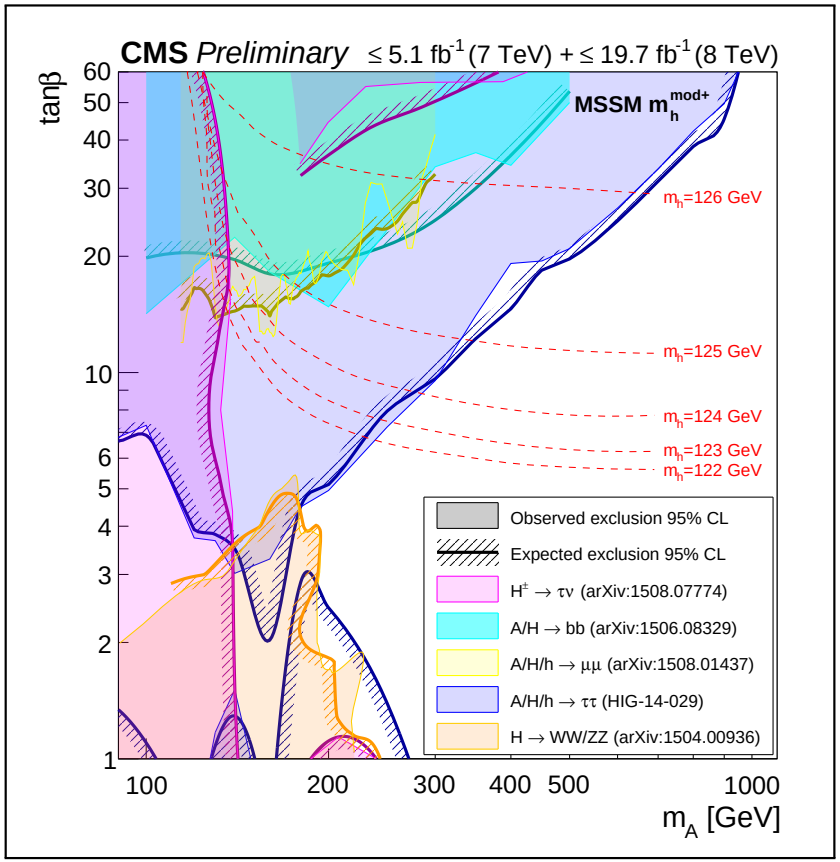


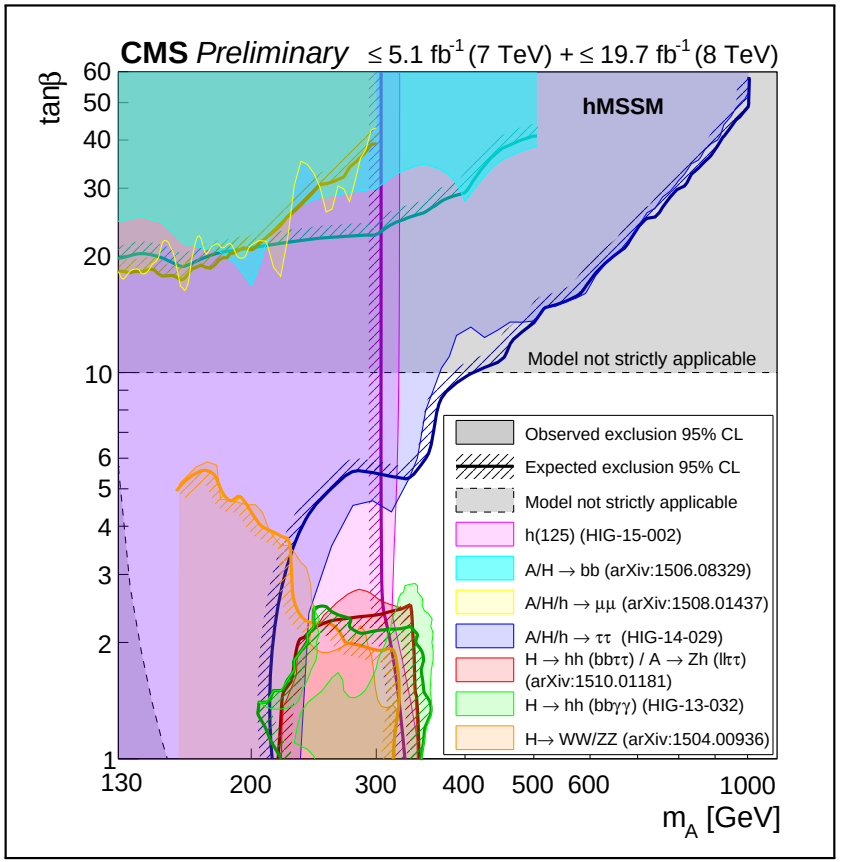




Need more 13 TeV data to draw conclusions

Summary of BSM Run-I Searches



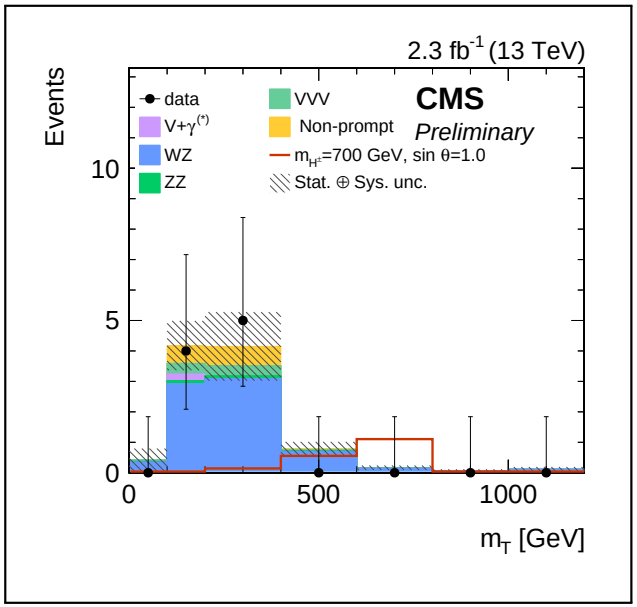


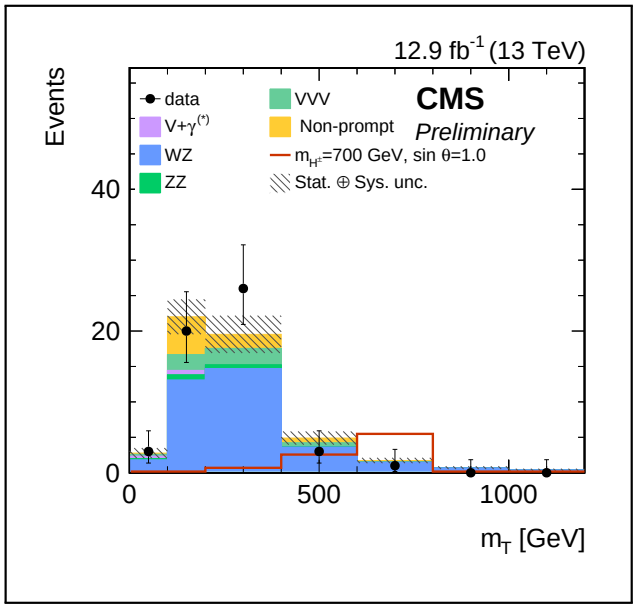
Parameter	Value (type I or type II)
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^+}	$m_H + 100$ GeV
$\cos(\beta-\alpha)$	0.1
m_{12}^2	$\max(1-\tan\beta^{-2}, 0)\cdot\frac{1}{2}\sin(2\beta)(m_A^2+\lambda_5 v^2)$
	m_H and $\tan\beta$ scanned.

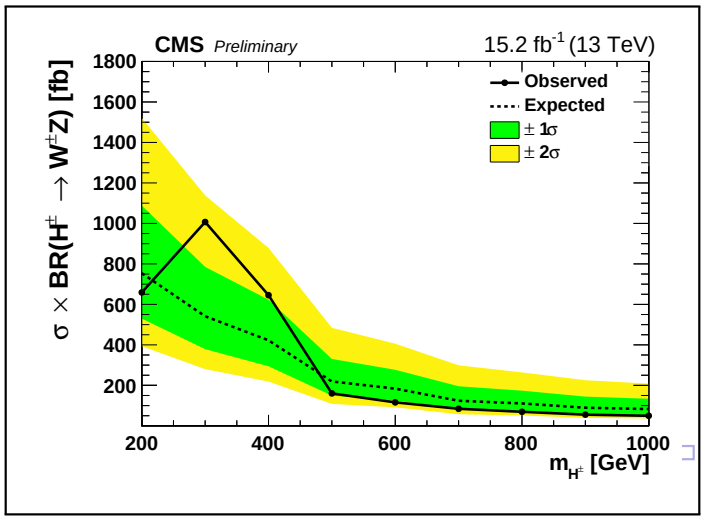
	2HDM		hMSSM
	type I	type II/MSSM	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

Search for VBF $H^{\pm} \rightarrow W^{\pm}Z \rightarrow 3\ell\nu$ - HIG-16-027

- Predictions from Georgi-Machack Higgs Triplet Models
- Selecting WZ events with two jets compatible with VBF topology
- Large benefit from a larger dataset and increase on $\sqrt{s}$
- Performed for first time in CMS, using 2015 and 2016 datasets

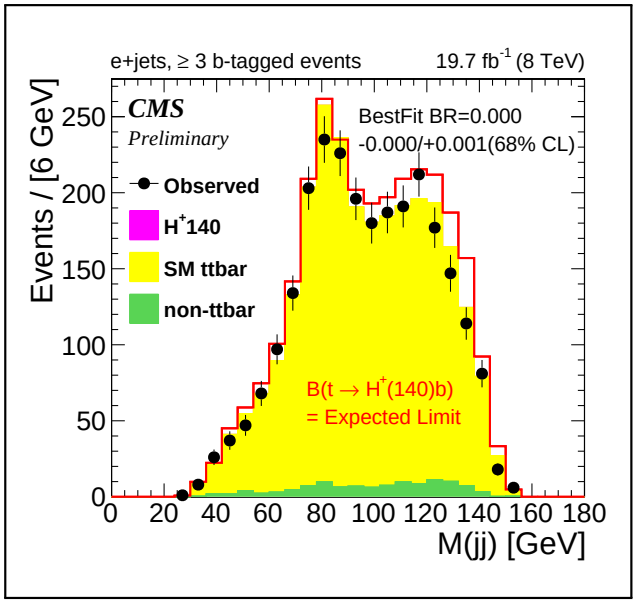


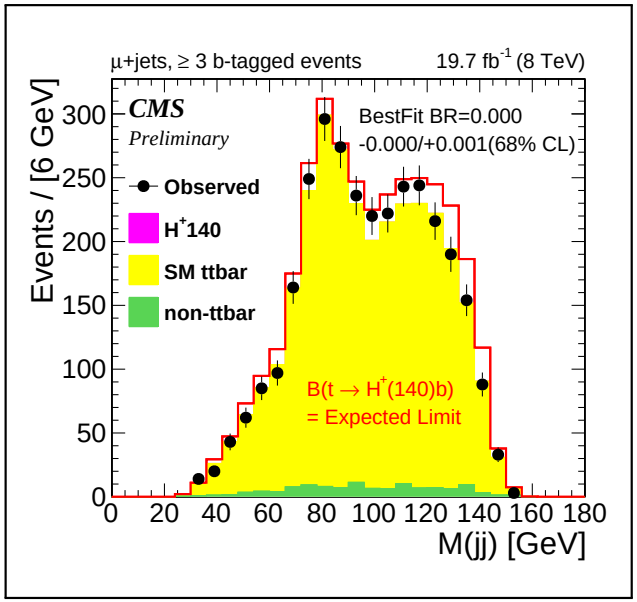


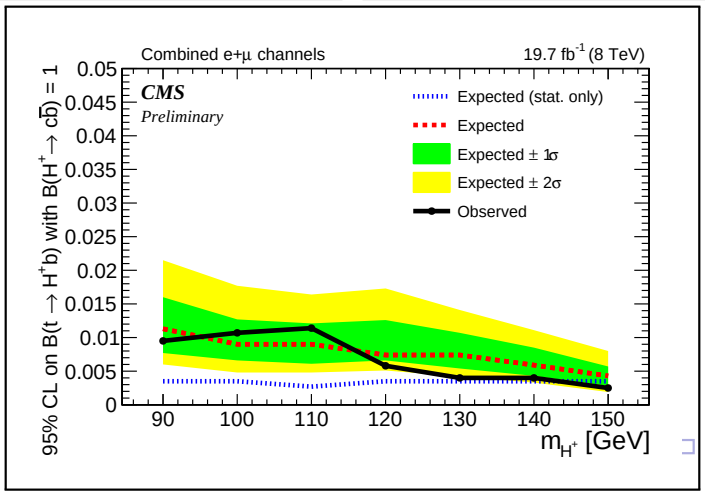


Search for $H^{\pm} \to c\bar{b}$ - HIG-16-030

- Search for $t\bar{t} \to (H^{+}b)(W^{-}\bar{b}) \to (c\bar{b}b)(l^{-}\bar{\nu}\bar{b})$ decays
- Look for a dijet mass bump compatible with $H^{\pm} \to c\bar{b}$
- Dijet pair selected from at least four jets in an event by a kinematic fitter
- 95% CL limits as a function of $m_{H^{\pm}}$ assuming $B(H^{+} \to c\bar{b}) = 100\%$.



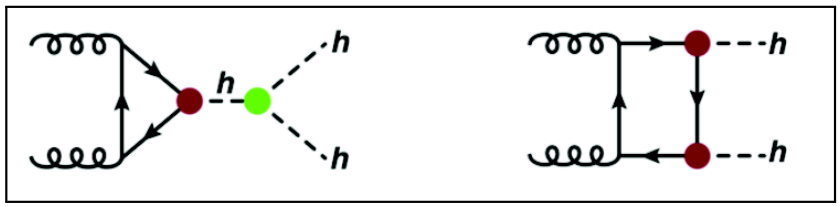




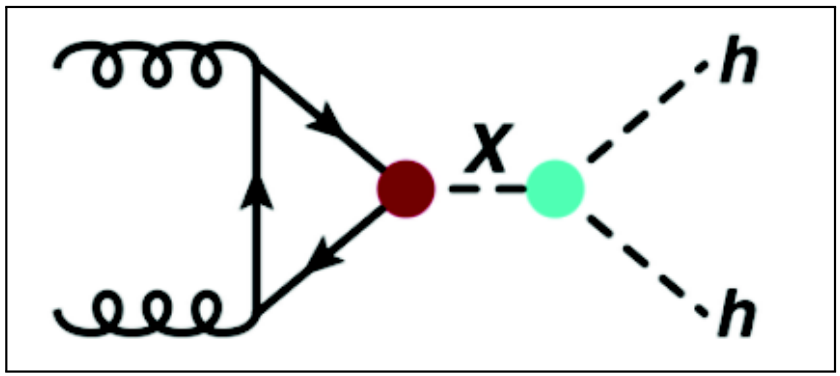
Double Higgs Boson Production

Di-Higgs Production

- Exciting prospects of the HL-LHC
  - process like di-Higgs production has not been observed yet
  - gluon fusion cross section is only ~ 40 fb
  - vector boson fusion cross section is ~ 2 fb
  - challenging measurements
  - enhancement due to new physics scenarios
- Destructive interference in gluon fusion



- Resonant production
  - enhance production cross section

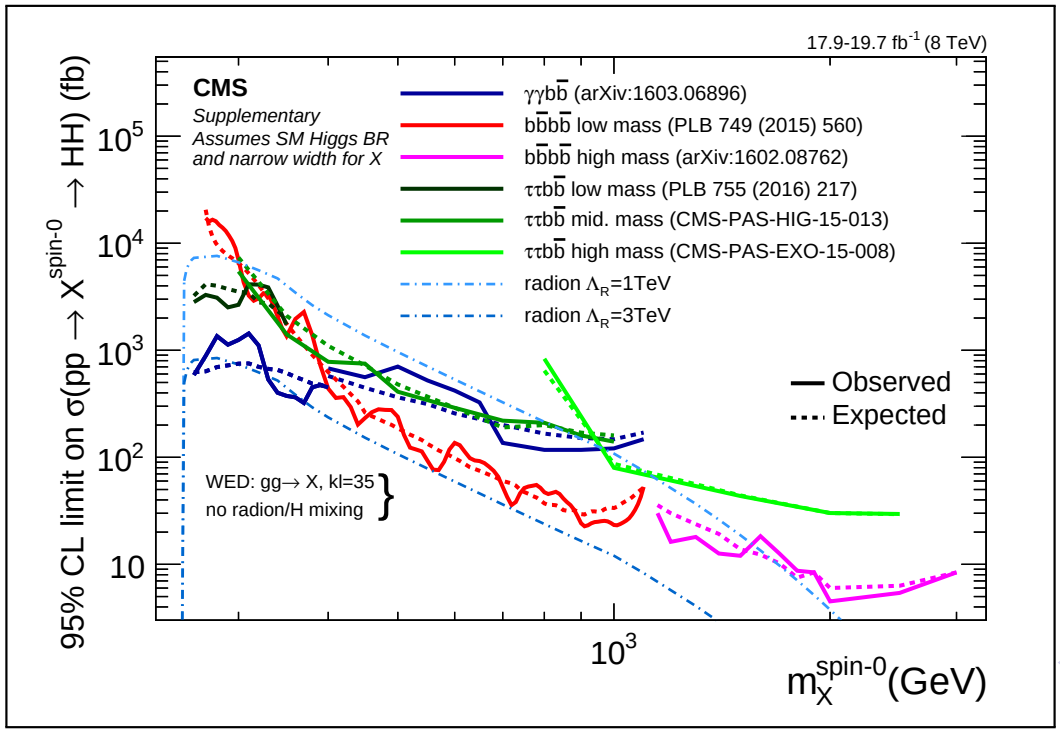


Search for (Non-)Resonant HH Decays

- Analyses getting mature, but a long way to get SM reach
- One of the high priority LHC analyses in the long term
- Room for improvements and new channels to be added
- Good agreement between data and background prediction so far

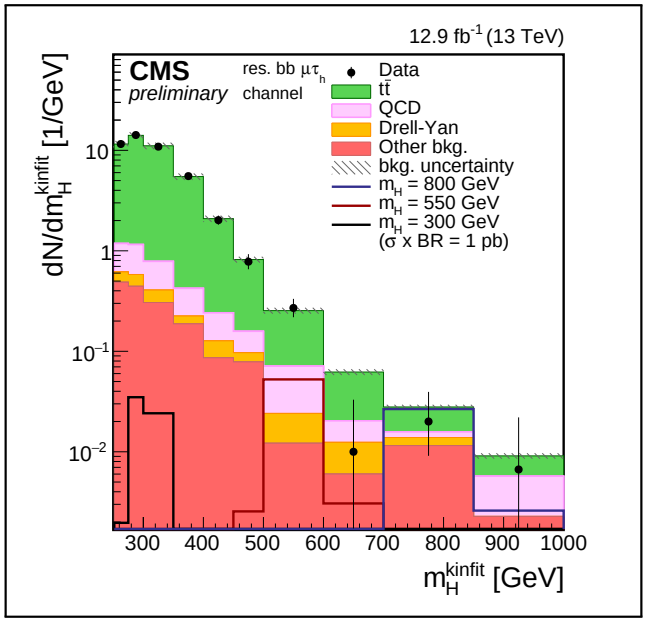
Final state	Resonant 8 TeV	Non-resonant 8 TeV	Resonant 8 TeV	Non-resonant 13 TeV
$b\bar{b}b\bar{b}$	HIG-14-013	-	HIG-16-002	On-going
$b\bar{b}WW$	-	-	HIG-16-011	HIG-16-024
$b\bar{b}\tau\tau$	HIG-15-013	HIG-15-013	HIG-16-013 HIG-16-028	HIG-16-012 HIG-16-029
$b\bar{b}\gamma\gamma$	HIG-13-032	HIG-16-032	On-going	On-going

Summary of run-I resonant analyses

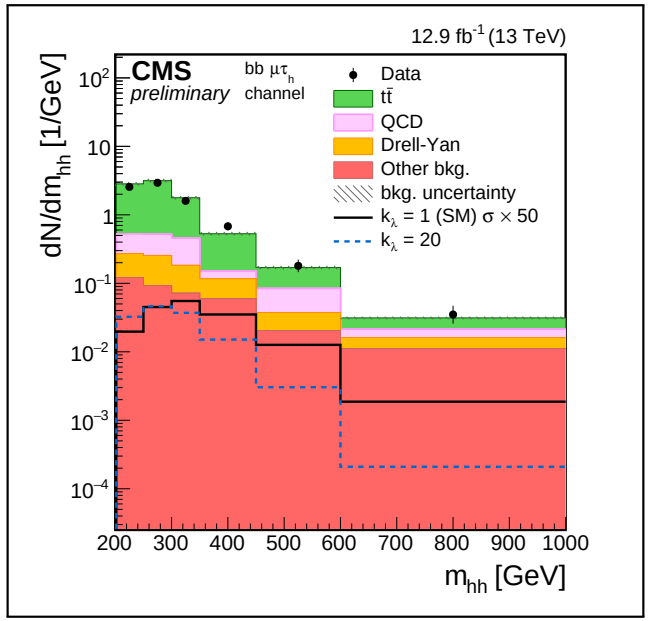


HH Analyses with 2016 Data - HIG-16-029/HIG-16-028/HIG-16-024

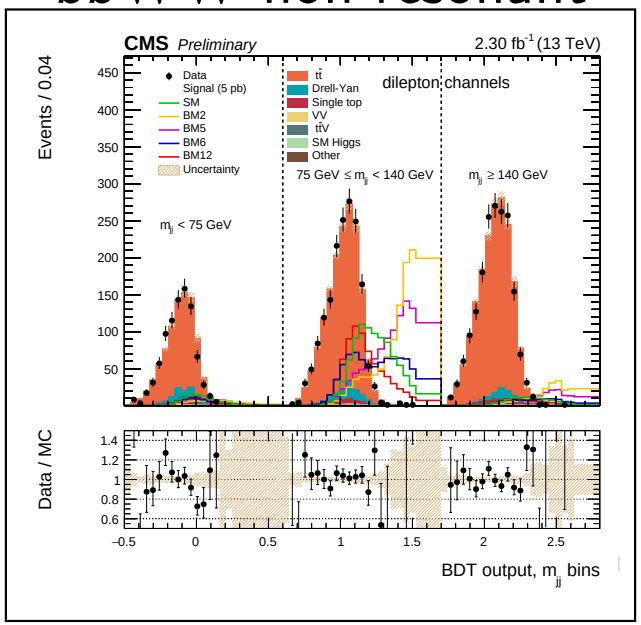
$b\bar{b}\tau\tau$ resonant



$b\bar{b}\tau\tau$ non-resonant



$bb\mathrm{WW}$ non-resonant



Summary

- The $\mathrm{H}(125)$ boson measurements start becoming rather precise with 2016 data
- A lot of room for improvements at $\sqrt{s} = 13\ \mathrm{TeV}$, fun has just started
- No sign of new physics in Higgs sector yet, but stay tuned!
- You can find all CMS Higgs results on: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

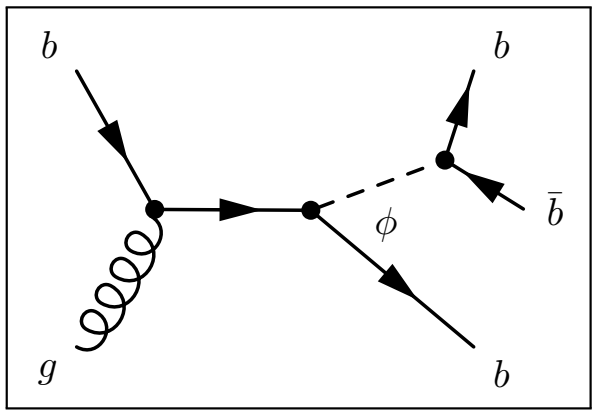
Most Recent CMS Higgs Results

- HIG-16-020: $\mathrm{H} \to \gamma\gamma$ (2016)
- HIG-16-033: $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ (2016)
- HIG-16-022: $\mathrm{t\bar{t}H}$-multilepton (2016)
- HIG-16-029: $X \to \mathrm{HH} \to b\bar{b}\tau\tau$ (2016)
- HIG-16-028: non-resonant $\mathrm{HH} \to b\bar{b}\tau\tau$ (2016)
- HIG-16-024: non-resonant $bb\mathrm{WW}$ (2016)
- HIG-16-023: high mass $\mathrm{H} \to \mathrm{WW}$ (2015)
- HIG-16-025: high mass $\mathrm{H} \to b\bar{b}$ (2015)
- HIG-16-027: VBF $\mathrm{H}^{\pm} \to \mathrm{WZ}$ (2015+2016)
- HIG-16-030: $\mathrm{H}^{\pm} \to c\bar{b}$ (8 TeV)
- HIG-16-019: $t\mathrm{H}q$ (2015)
- HIG-16-016: $\mathrm{H} \to$ invisible (2011+2012+2015)
  - EXO-16-027: mono-jet (2016)
  - EXO-16-038: mono-Z (2016)

Back-Up Slides

$H \to b\bar{b}$ (MSSM) - HIG-14-017

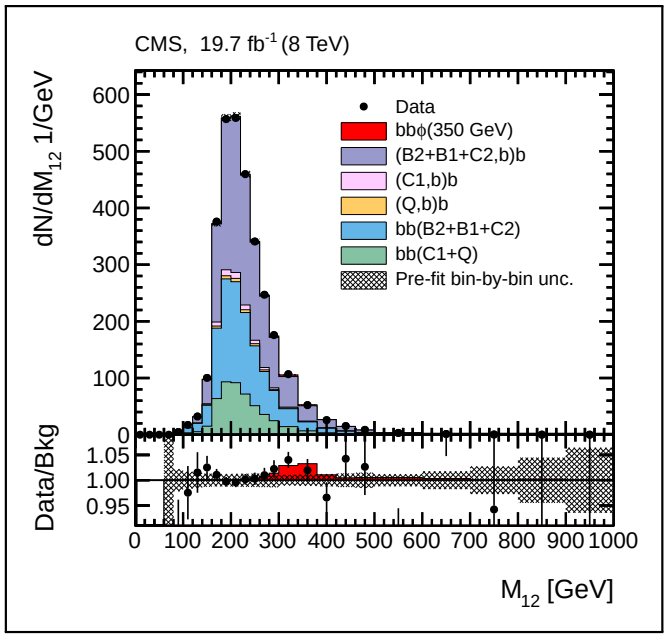
- Search for $H \to b\bar{b}$ resonances at high mass
- Final states usually have additional b-quarks
- Dedicated trigger paths to select these events (no high p_T leptons/photons, no high E_T^{miss})

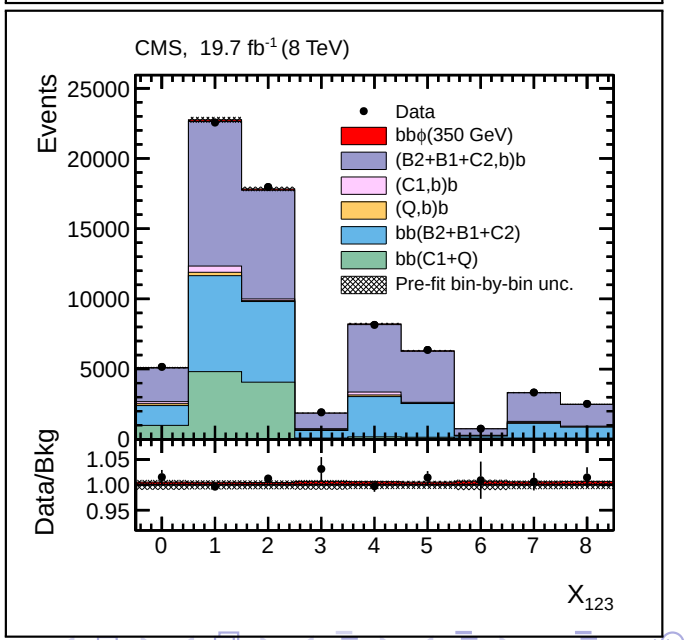


- $X_{123} = (B_1 + B2) + (B_3)$ to split in categories

$\Sigma M_{SV,j}$ [GeV]	B_j
0–1	0
1–2	1
2–3	2
>3	3

B_3	$B_1 + B_2$		
	0–1	2–3	4–6
0–1	0	1	2
2	3	4	5
3	6	7	8



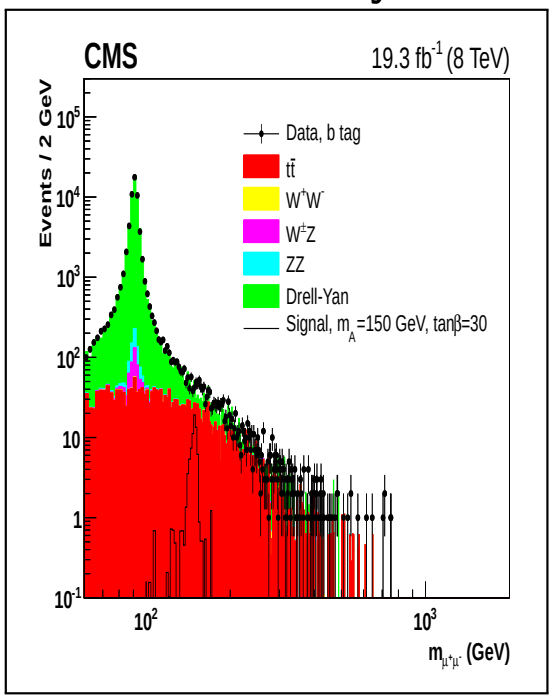


No significant excess seen

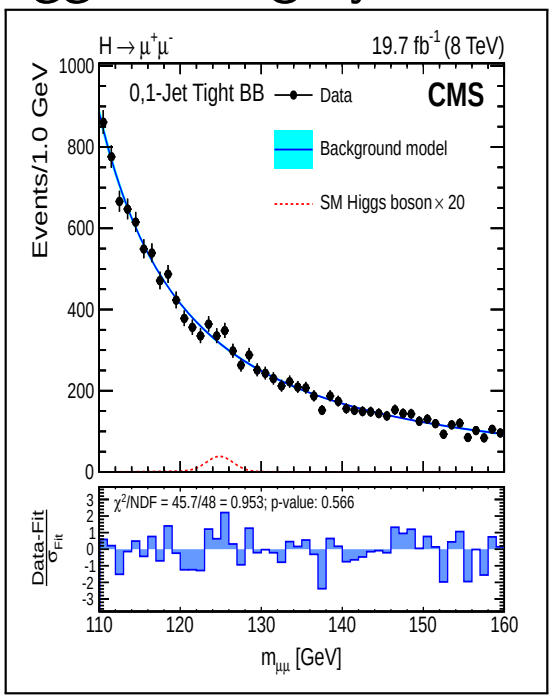
$H \rightarrow \mu^+\mu^-$ - HIG-13-024/HIG-13-007

- Two isolated muons in the final state
- Split in several categories to improve S/B and mass resolution
- Cross section limits about 5-8 times the SM expectation

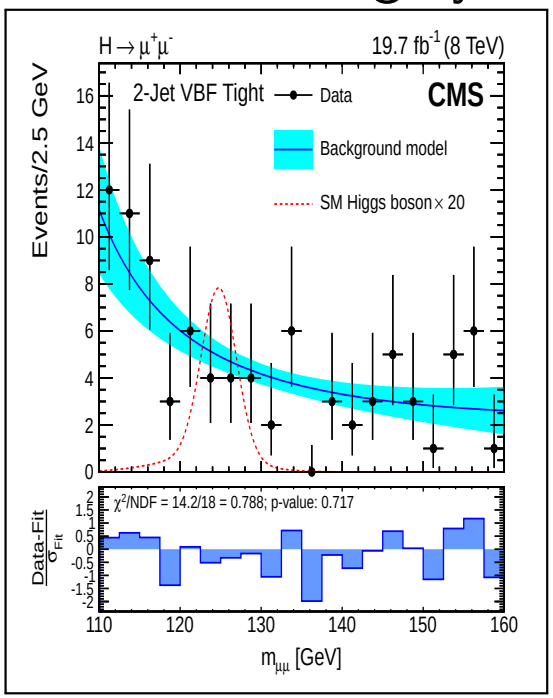
MSSM analysis



$gg\mathrm{H}$ category

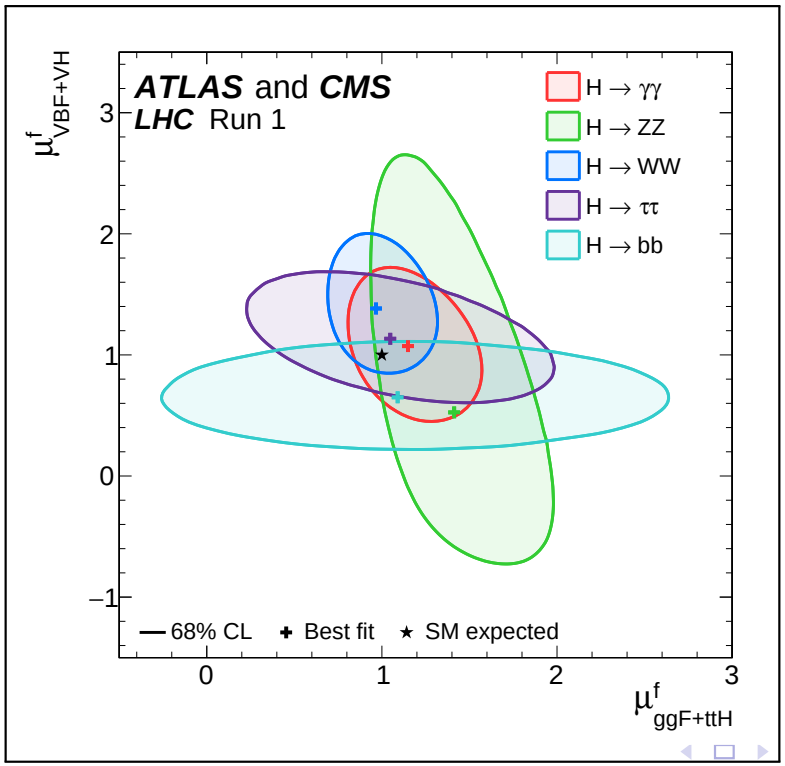


VBF category



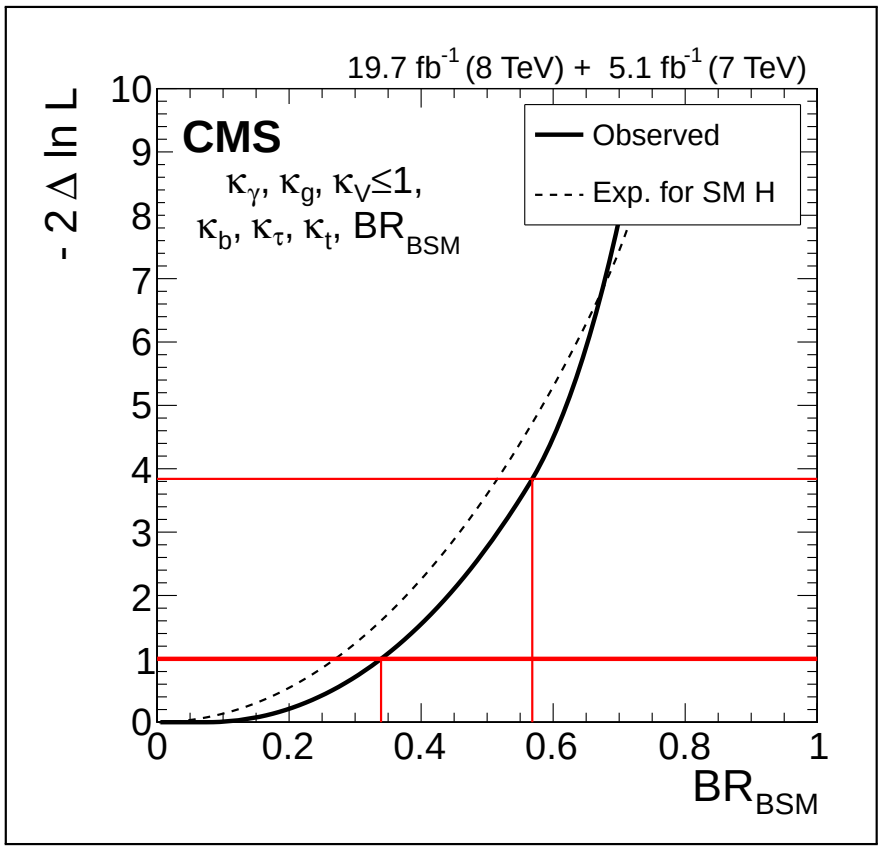
Event Rates $\longrightarrow$ Coupling Deviations

- $\sigma(xx \to \mathrm{H}) \times BR(\mathrm{H} \to yy) \propto \Gamma_{xx}\Gamma_{yy}/\Gamma_{tot}$
- Parameters: Γ_{WW}, Γ_{ZZ}, Γ_{tt}, $\Gamma_{\tau\tau}$, $\Gamma_{b\bar{b}}$, $\Gamma_{\gamma\gamma}$, Γ_{gg}, Γ_{BSM} (assumed $\equiv 0$ in most of studies), Γ_{tot}
- Coupling modifiers: $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$ (production processes) or $\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$ (decays processes)
- (κ_V, κ_f): $\kappa_{\mathrm{V}} = \kappa_{\mathrm{W}} = \kappa_{\mathrm{Z}}$, $\kappa_f = \kappa_b = \kappa_{top} = \kappa_\tau$, $\kappa_\gamma = f(\kappa_V, \kappa_f)$
- All tests performed at a given mass, i.e. the measured m_{H} value

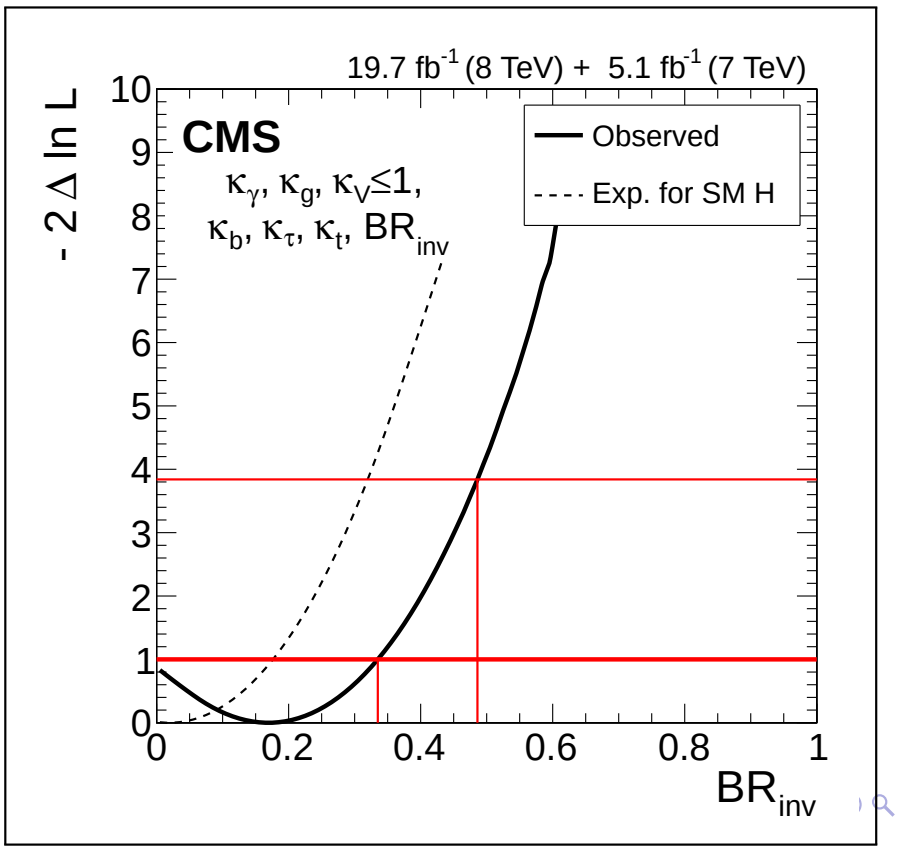


Indirect Limits on Invisible Higgs Decays

- $BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$
  - All κ_i modifiers are profiled
  - $\kappa_V \leq 1$



- $BR_{inv} = \Gamma_{inv}/\Gamma_{tot}$
  - Combining with data from the $\mathrm{H} \rightarrow \mathrm{inv}$ searches, thus assuming that $BR_{BSM} = BR_{inv}$, i.e. $BR_{undet} = 0$
  - All κ_i modifiers are profiled
  - $\kappa_V \leq 1$



Higgs Sector in MSSM

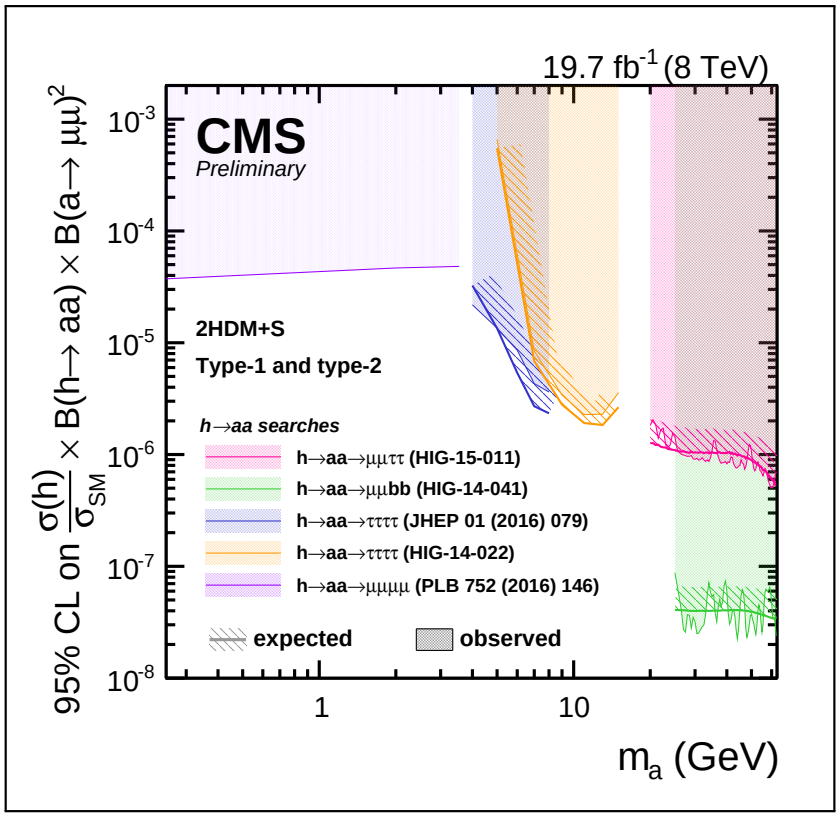
- Higgs sector in SUSY contains two scalar doublets:
  - five physical Higgs bosons:
    - 3 neutral: CP-even $\Phi = \mathrm{h}$ & H; CP-odd A
    - 2 charged: $\mathrm{H}^{\pm}$
  - SM-like Higgs boson: h
- Neutral Higgs "Φ" decay modes:
  - $BR(\Phi \to b\bar{b}) \sim 90\%$
  - $BR(\Phi \to \tau\tau) \sim 10\%$
  - $BR(\Phi \to \mu\mu) \sim 0.1\%$
- Two main production modes:
  - $gg \to \mathrm{H}$
  - $b\bar{b}\mathrm{H}$
- B-tagged topologies make analyses rather different w.r.t. SM searches
- Observation of $H(125)$ does not exclude a heavy MSSM Higgs boson in a wide range of $tan\beta$, still fits both SM and MSSM
- Signal extraction based on looking for a mass resonance
- Showing $\Phi \to \mu\mu$ case here, other analyses in Susan Gascon-Shotkin's talk

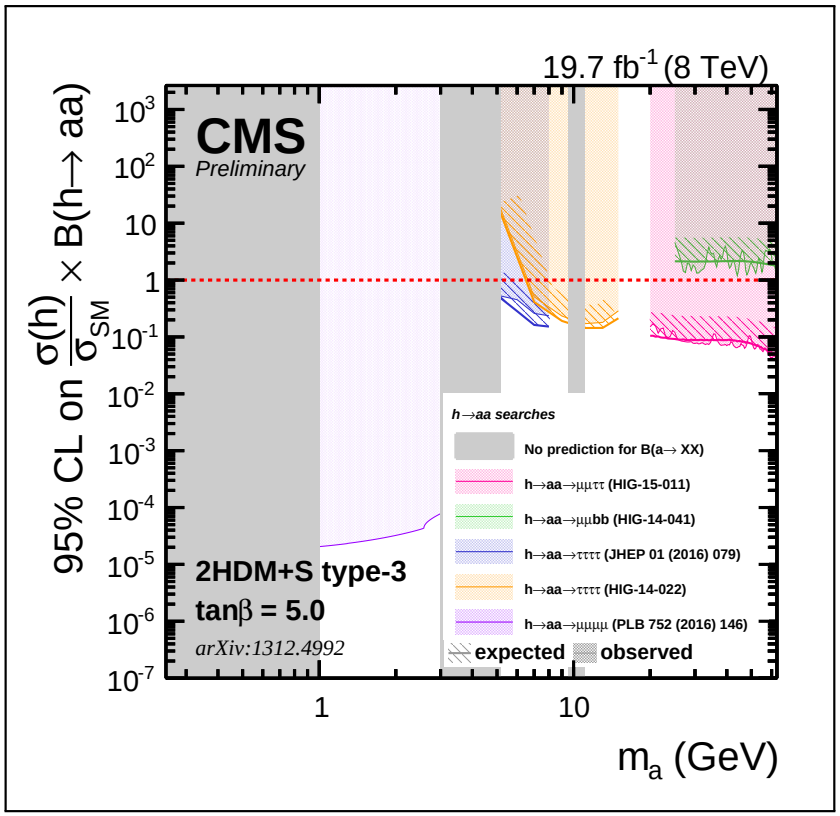
Extended Higgs Sector

- Electroweak Singlets
  - 2nd CP-even boson
- Two-Higgs Doublet Models (2HDM)
  - 5 Higgs bosons (H,h,A,H$^\pm$)
  - MSSM prominent example; hMSSM common benchmark
- 2HDM + singlets
  - NMSSM prominent example
  - 7 Higgs bosons (a_1, a_2, h_1, h_2, h_3, $H^\pm$)
- Triplet Models
  - adding doubly charged Higgs bosons to 2HDM phenomenology
- ... and more

Summary of $H \to a_1 a_1$ Run-I Searches

- Summary of several $H \to a_1 a_1$ Run-I searches for several scenarios
- $\sigma_{13\ \mathrm{TeV}}/\sigma_{8\ \mathrm{TeV}} \sim 2.3$
- These analyses more suitable for larger datasets at this point





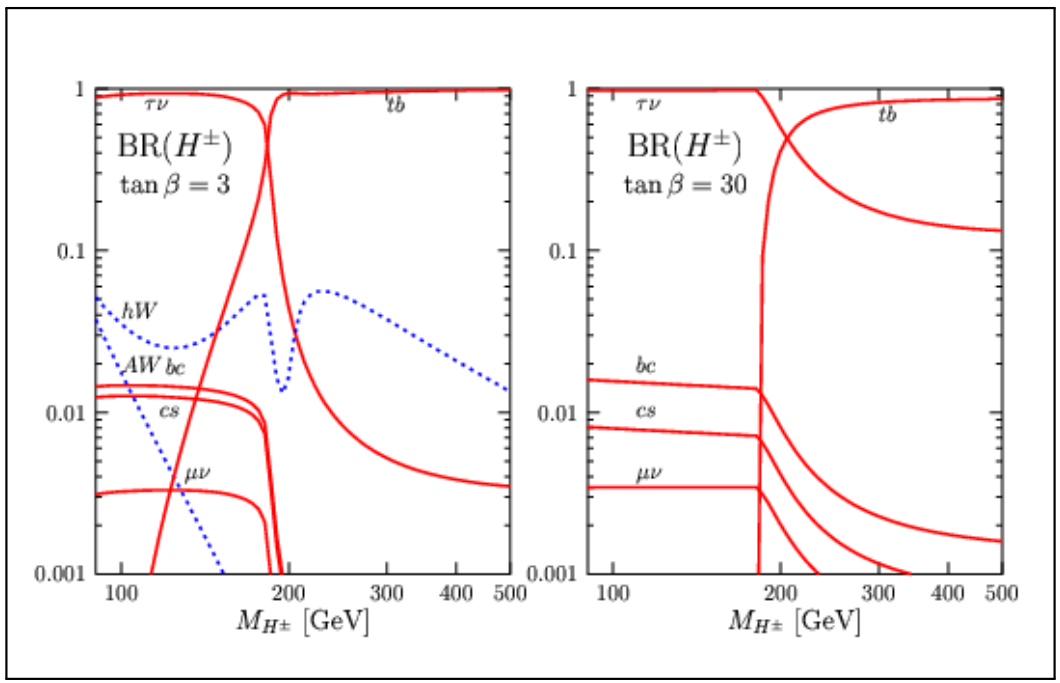
Other Possible Rare Decays

A summary can be found in e.g. arXiv1312.4992

- $\mathrm{H} \to XX \to 4b$
- $\mathrm{H} \to aa \to 2b2\tau/2b2\mu/4\tau/2\tau2\mu$
  - multilepton analyses may be used to put limits on them
- $\mathrm{H} \to XX \to 4j$
- $\mathrm{H} \to XX \to 2j2\gamma$
- $\mathrm{H} \to XX \to 4\gamma$
- $\mathrm{H} \to a\mathrm{Z}$
- $\mathrm{H} \to Z_D\mathrm{Z}/\mathrm{Z}_D\mathrm{Z}_D$, with Z_D a new gauge boson
- $\mathrm{H} \to \chi_1\chi_2 \to \gamma/2\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to \ell/\ell\ell/b\bar{b}/\tau\tau + E_{\mathrm{T}}^{\mathrm{miss}}$
  - SUSY analyses may be used to put limits on them
- $\mathrm{H} \to \text{one/two prompt leptons} - \text{jets} + X$

Search for Charged Higgs Bosons - HIG-14-023/HIG-13-035

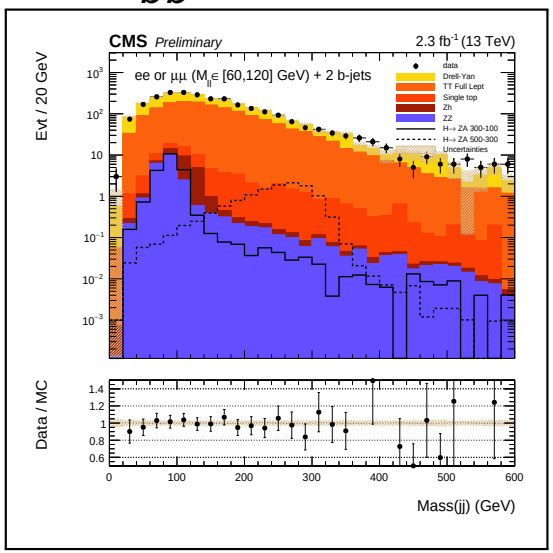
- Predicted in several new Physics scenarios
- For $m_{\mathrm{H}^\pm} < m_{top}$, search for $top \to \mathrm{H}^\pm b$ decays
- For $m_{\mathrm{H}^\pm} > m_{top}$, mostly search for $t\mathrm{H}^\pm(b)$ decays
- $\mathrm{H} \to \tau\nu$ dominates a large phase space, but several other decay modes possible
- A large room for gain at 13 TeV, this is a long term project



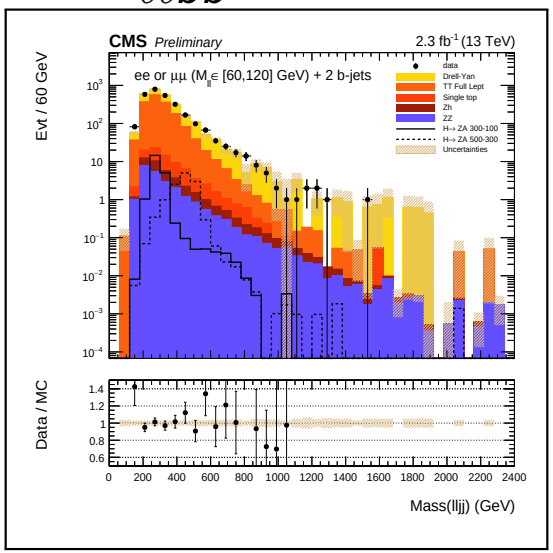
Search for $A/H \to ZH/A$ Decays - HIG-15-001/HIG-16-010

- Search for $A/H \to ZH/A \to \ell\ell b\bar{b}$ decays, $H/A \to \tau\tau$ also considered in run-I analysis
- Signal region defined in $m_{b\bar{b}}$ - $m_{\ell\ell b\bar{b}}$ plane for each m_H-m_A hypotheses
- Simple cut-and-count approach, backgrounds from sideband
- Large room for improvements, e.g. by fitting signal and sidebands regions simultaneously or by having a more sophisticated template fit
- Limits on $\sigma x BR$ for m_H hypotheses as function of m_A

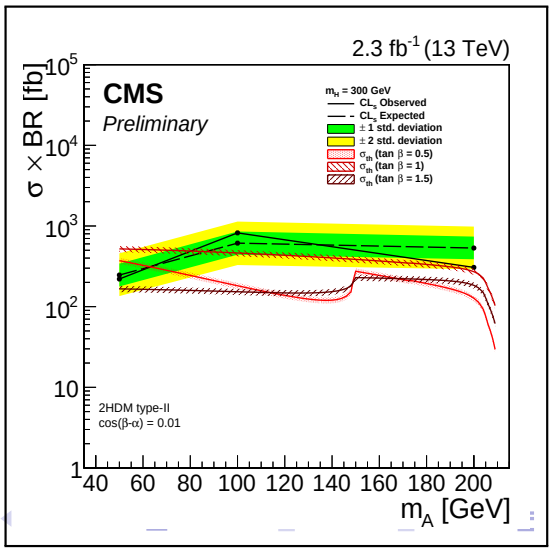
$m_{b\bar{b}}$



$m_{\ell\ell b\bar{b}}$



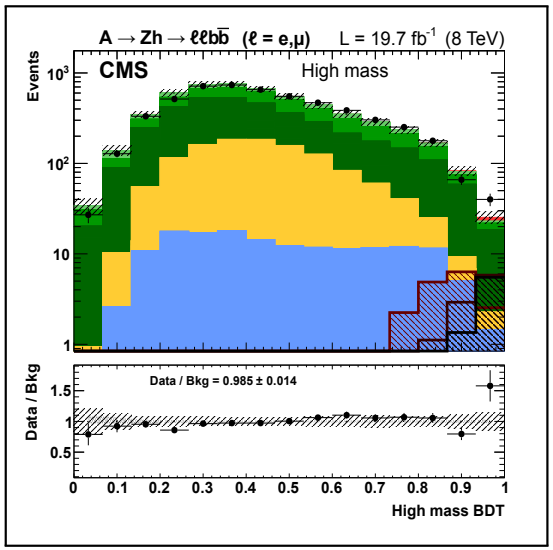
95% CL limits

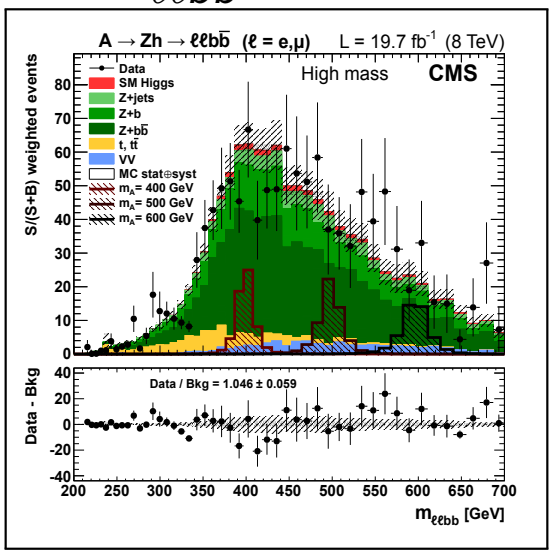


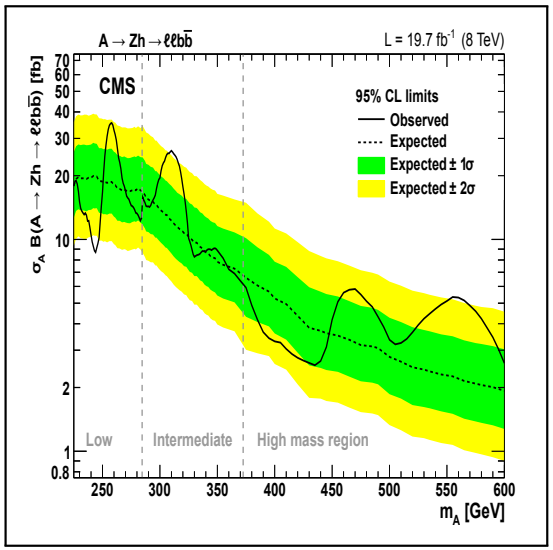
Search for $A \to Zh(125)$ Decays - HIG-14-011

- Search for $A \to Zh(125) \to \ell\ell b\bar{b}$ decays
- A particular region of a more general A-H phase space
- Analysis split in three regions: low/intermediate/high masses
- Two-dimensional BDT vs. $m_{\ell\ell b\bar{b}}$ to discriminate signal and backgrounds

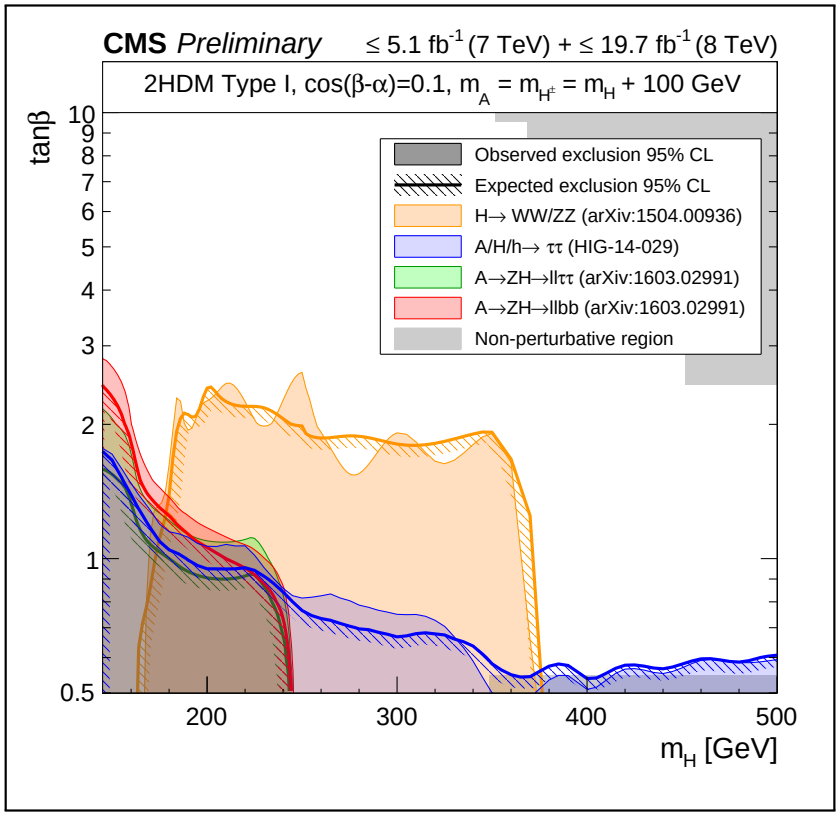
BDT high mass region $m_{\ell\ell b\bar{b}}$ at high BDT 95% CL limits

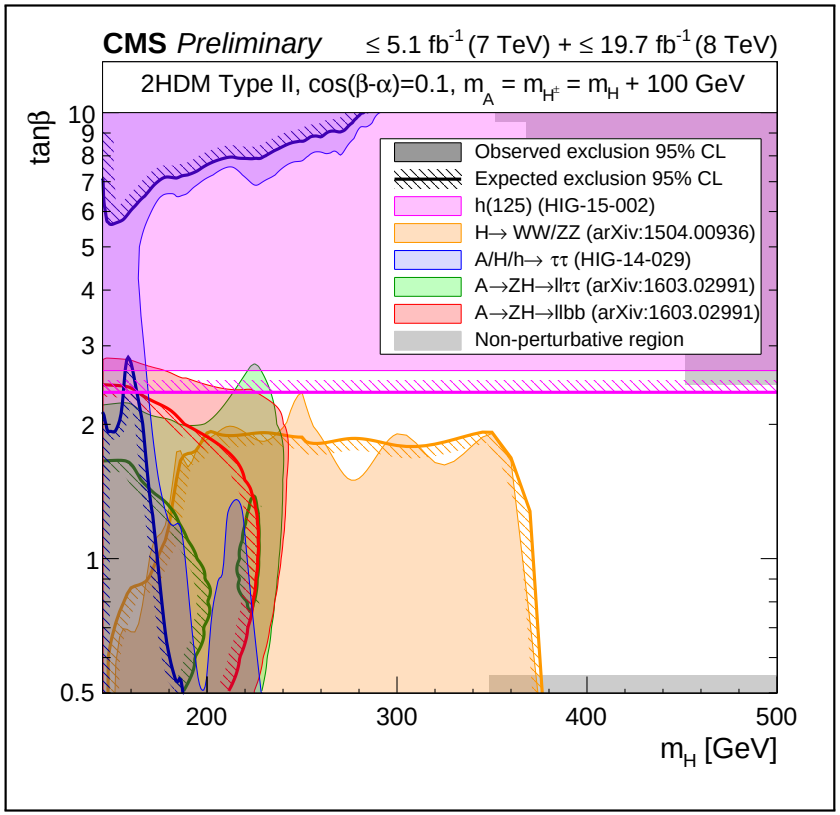






More on Summary of BSM Run-I Searches





Parameter	Value (type I or type II)
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^+}	$m_H + 100$ GeV
$\cos(\beta-\alpha)$	0.1
m_{12}^2	$\max(1-\tan\beta^{-2}, 0) \cdot \frac{1}{2}\sin(2\beta)(m_A^2 + \lambda_5 v^2)$
	m_H and $\tan\beta$ scanned.

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