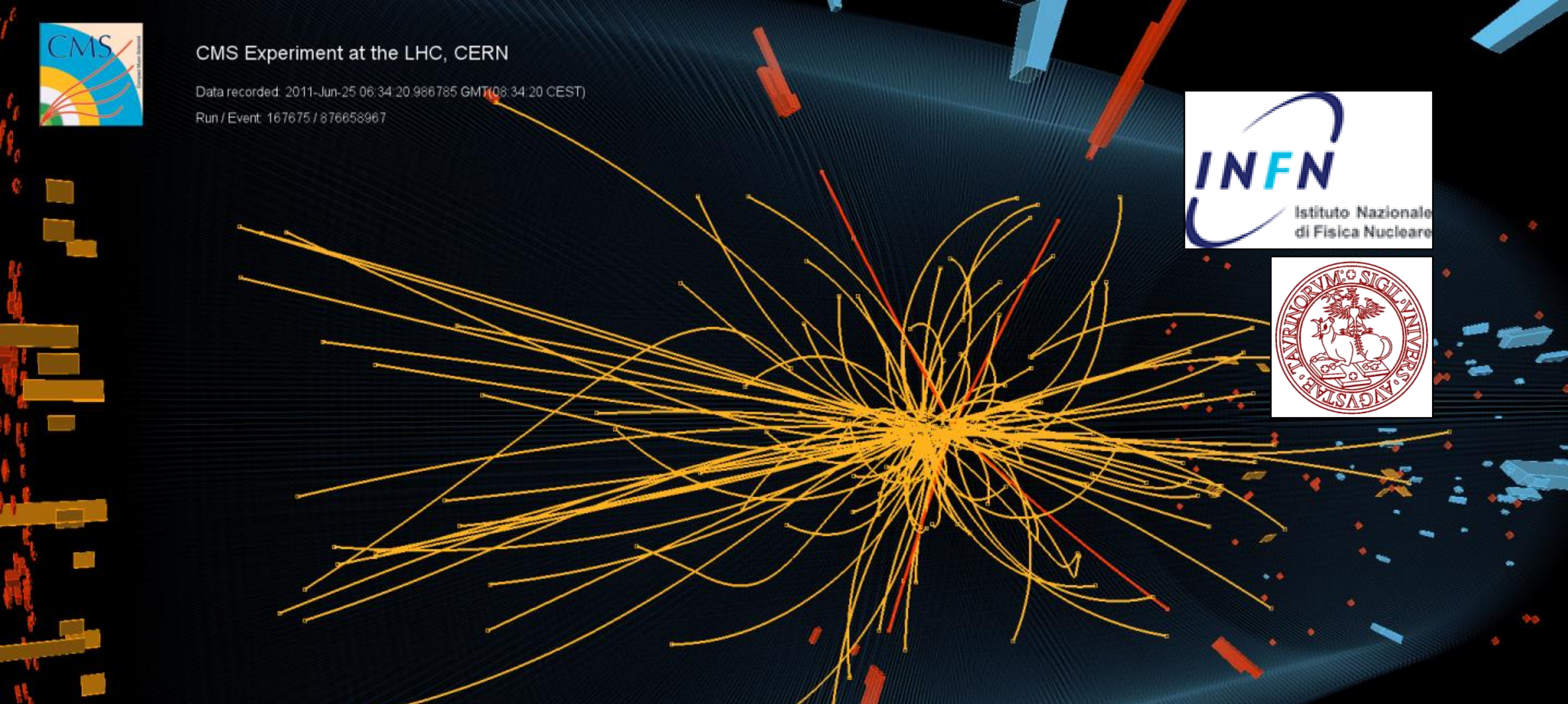


Search for neutral heavy-Higgs decays to VV, Vh and hh at the CMS experiment

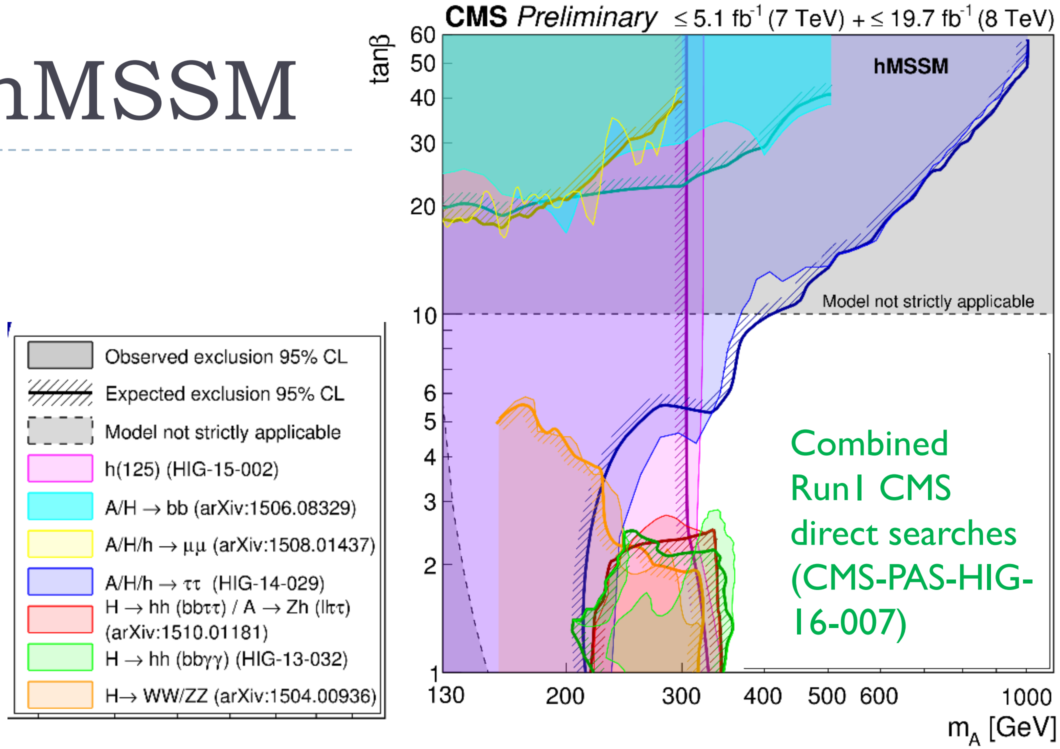
Roberto Covarelli (*University / INFN of Torino*)
on behalf of the CMS collaboration

Charged2018: Prospects for charged Higgs discovery at colliders
Uppsala, 25 - 29 September 2018

Outline

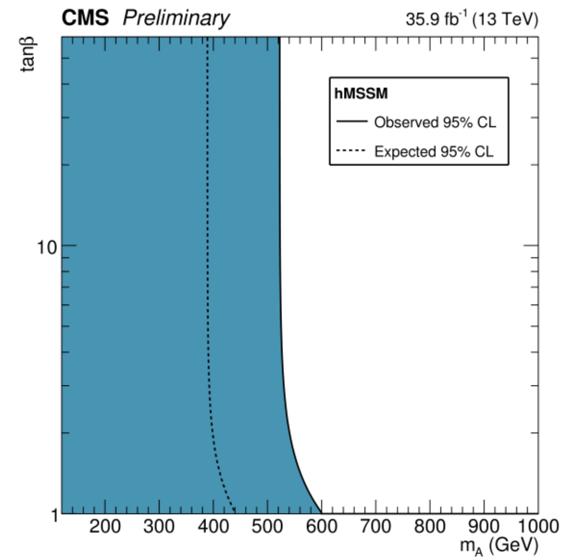
- Phenomenology of extended scalar-sector models
  - Already discussed in detail during this workshop
  - Few examples where $H / A \to VV$ / Vh / hh are relevant
- Recent CMS search results at 13 TeV
  - $H \to ZZ \to 4l$ / $2l2q$ / $2l2\nu$
  - $A \to Zh \to 2l2b$ / $2\nu 2b$
  - $H \to hh \to 2b2\gamma$ / $4b$ / $2b2l2\nu$ / $2b2\tau$
- Disclaimer: there are many other CMS searches targeting the same final states
  - However, they normally address very high-mass (> 1 TeV) narrow resonances → hadronic final states become the most sensitive thanks to the use of large-area jets
  - Not relevant for BSM Higgs, therefore not reported here

hMSSM



Combined Run1 CMS direct searches (CMS-PAS-HIG-16-007)

Constraints from Run2 h(125) coupling modifiers (CMS-PAS-HIG-17-031)



- In remaining phase space, HVV suppression somehow lifted (decoupling delayed at larger M_A, weaker $\tan\beta$ suppression)
  - $H \to VV$ and $A \to Zh$ can have still significant branching ratios, while total widths stay relatively small compared to experimental resolutions

M_A = 500 GeV, $\tan\beta$ = 3	
BR($H \to VV$)	2.6%
Γ(H) (GeV)	2.04

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMNeutral

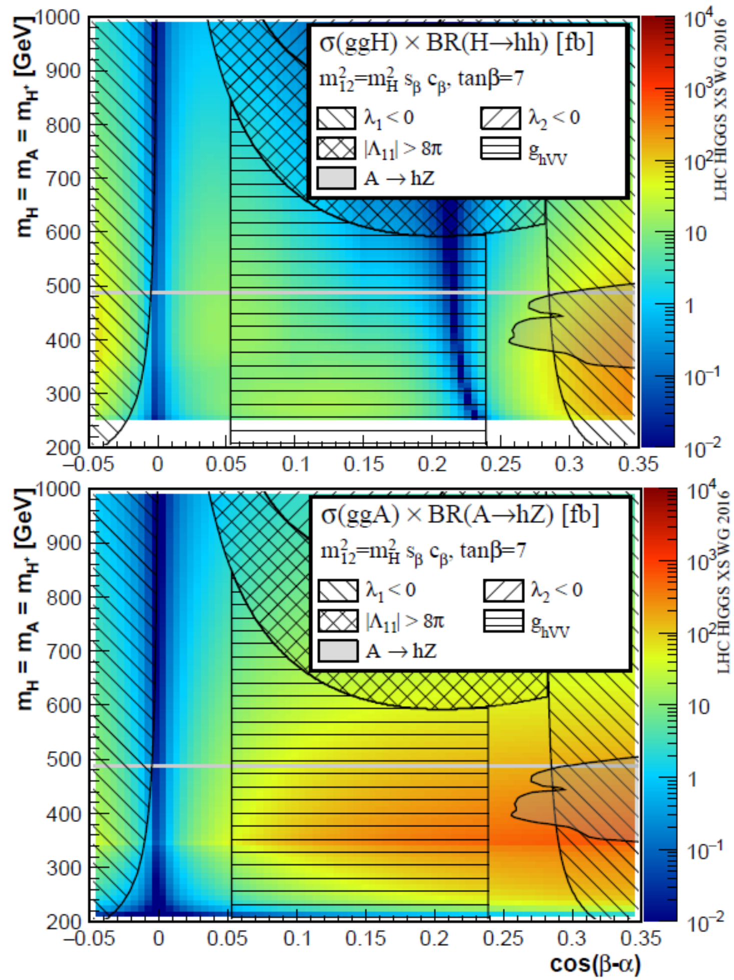
Other extended scalar-sector models

- <u>2HDM</u>:
  - Sensitivity / exclusion depending on specific phenomenology
    - Example of benchmark planes →

      F. Kling, J.M. No and S. Su, *JHEP* **09** (2016) 093, etc.
  - Some parameter choices enhancing importance of bosonic decays
    - Example: Fermiophobic heavy H

      D. Lòpez-Val et al., arXiv:1610.07922, etc.
- <u>Scalar singlet</u>:
  - VV and hh heavy-Higgs decays dominant in both real and complex SM extensions

    T. Robens and T. Stefaniak, *Eur. Phys. J* **C76** (2016) 268
    R. Costa et al., *JHEP* **06** (2016) 034, etc.



Experimental analyses

- Recent CMS search results at 13 TeV
  - $H \to ZZ \to 4l / 2l2q / 2l2\nu$

    CMS collaboration, *JHEP* **06** (2018) 127
  - $A \to Zh \to 2l2b / 2\nu 2b$

    CMS collaboration, CMS-PAS-HIG-18-005
  - $H \to hh \to 2b2\gamma$ — CMS collaboration, arXiv: 1806.00408, submitted to *Phys.Lett.B*
  - $\to 4b$ — CMS collaboration, *JHEP* **08** (2018) 152
  - $\to 2b2l2\nu$ — CMS collaboration, *JHEP* **01** (2018) 054
  - $\to 2b2\tau$ — CMS collaboration, *Phys.Lett.B* **778** (2018) 101
  - Combined — CMS collaboration, CMS-PAS-HIG-17-030

$$H \to ZZ$$

Analysis method

- Combined search for a heavy resonance to ZZ in the 4l / 2l2q / 2l2ν final states
- Model-independent search, in a wide range of masses (m in [m_L, 3 TeV]) and widths (Γ/m in [0, 30%]), where:
  - m_L = 160 GeV for 4l
  - m_L = 300 GeV for 2l2ν
  - m_L = 550 GeV for 2l2q
- Cross-section limits obtained from 2D likelihood function:

$$\mathcal{P}^{i,k}_{vv}(m_{ZZ}, D_{\text{bkg}}) = \mathcal{M}^{\text{reco}}_{vv}(m_{ZZ})\mathcal{T}(D_{\text{bkg}}|m_{ZZ}).$$

i = signal/background components
k = analysis channels/categories

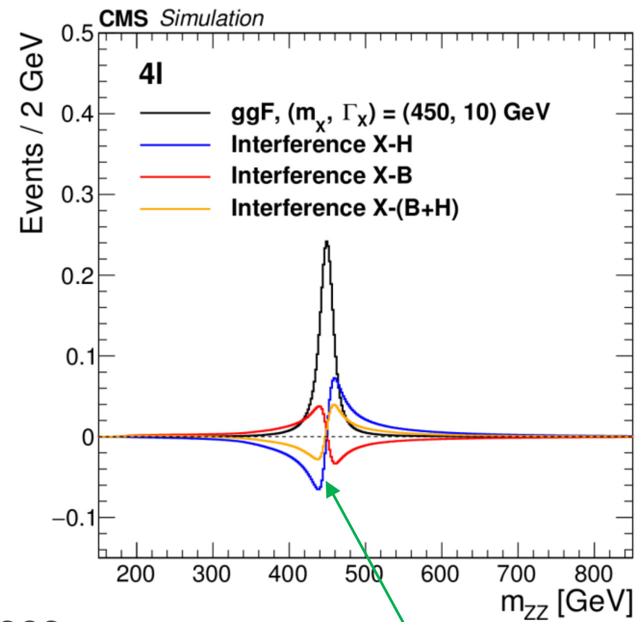
  - m_{ZZ} : reconstructed ZZ mass (transverse mass for 2l2ν)
  - D_{bkg} : discriminant based on fermion kinematics from the ZZ decays (not used for 2l2ν, with undetected neutrinos)

BSM signal model (I)

- Assumed production from either ggF, or VBF, or both with a free cross-section fraction (f_{VBF})
  - Resonance kinematics (p_T spectrum) from POWHEG
- m_{ZZ} modeling:

$$\mathcal{M}^{\rm reco}_{vv}(m_{ZZ}) = \left(\mathcal{E}(m^{\rm Gen}_{ZZ})\mathcal{M}_{vv}(m^{\rm Gen}_{ZZ}|m_X,\Gamma_X)\right) \otimes \mathcal{R}(m_{ZZ}|m^{\rm Gen}_{ZZ}).$$

  - Only efficiency (ε) and resolution ($\mathcal{R}$) from detector simulation → model not dependent on signal width choice
  - In case of significant resonance width, interference with SM h(125) + continuum in the relative production mode fully taken into account
    - Achieved through the MELA package, which uses amplitudes from MCFM and JHUGen MC tools



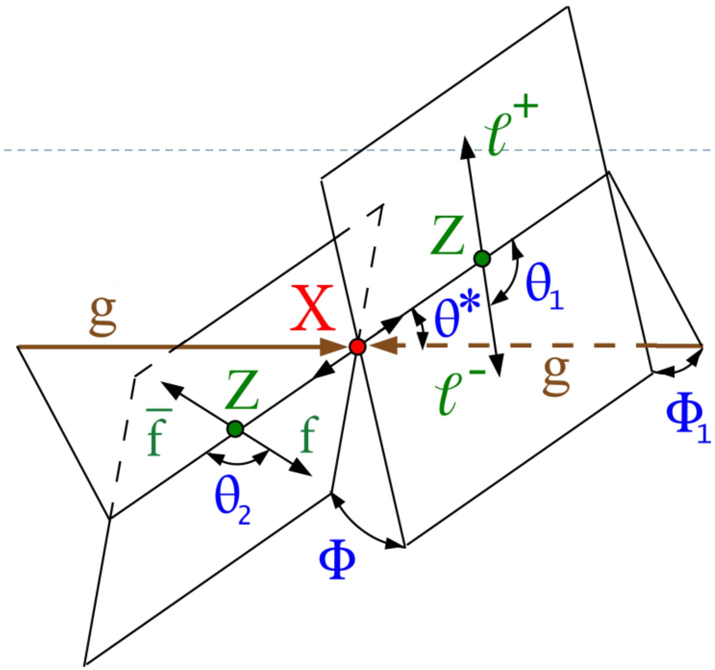
Large effect of H-h interference because of ZZ offshell tail

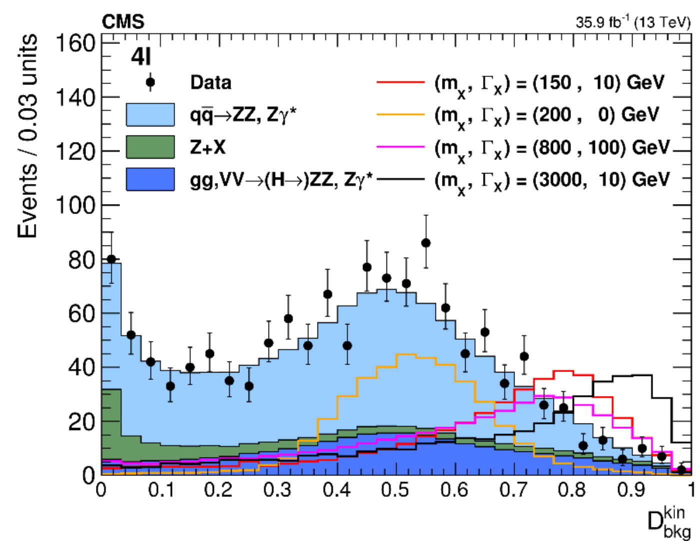
BSM signal model (II)

- D_{bkg} modeling:
  - Also achieved through the MELA package

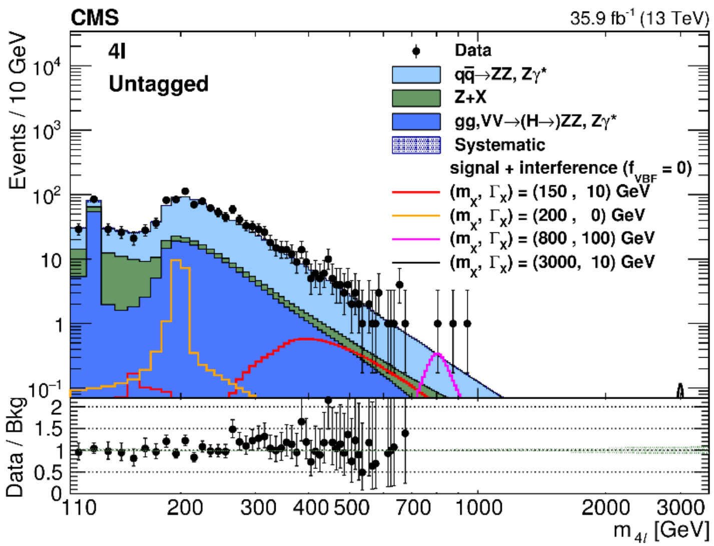
$$\mathcal{D}_{\rm bkg}^{\rm kin} = \left[1 + \frac{\mathcal{P}_{q\bar{q}\to 4\ell}(\vec{\Omega}^{X\to 4\ell}|m_{ZZ})}{\mathcal{P}_{X\to 4\ell}(\vec{\Omega}^{X\to 4\ell}|m_{ZZ})}\right]^{-1}$$

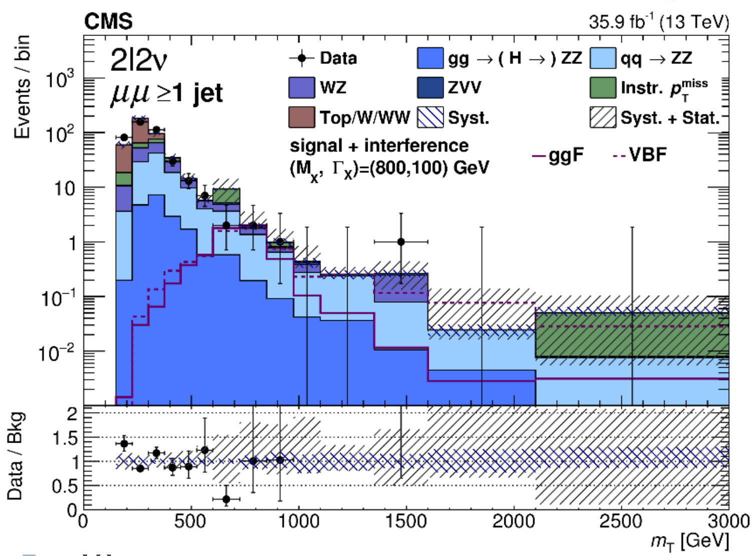
  - Ratio of weighted probabilities built:
    - from signal and (dominant) background amplitudes
    - using information from production/decay angles and di-fermion invariant masses





Event selection: 4l and 2l2ν

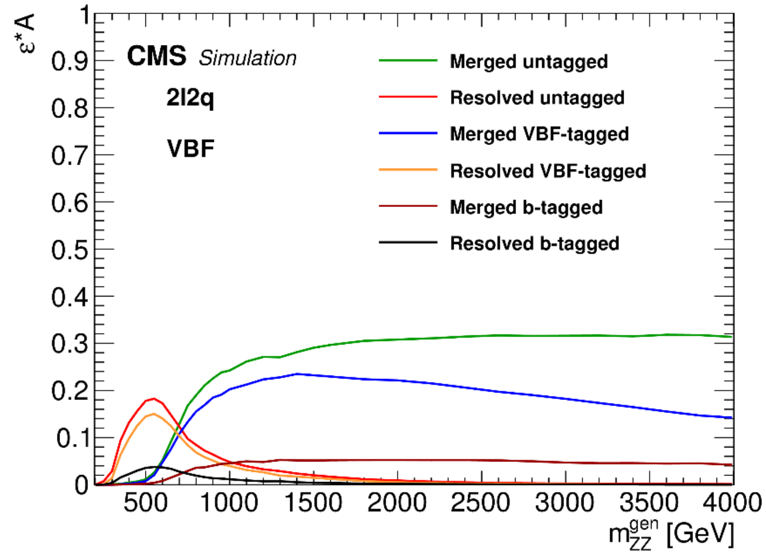


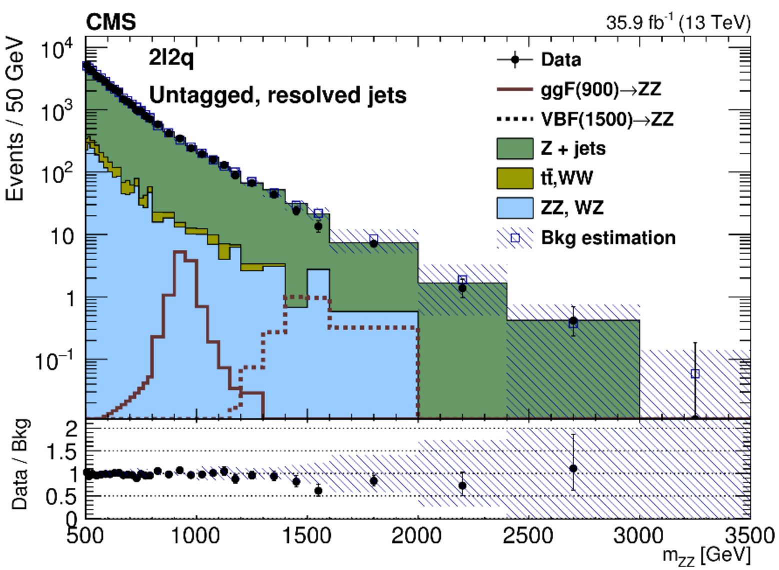


- **4l**
  - 4 e or μ, at least 2 with high p_T, identification cuts
  - 3 analysis categories:
    - With 2 VBF-tagging jets
    - With reduced electron selection
    - All the rest («untagged»)
- **2l2ν**
  - 2 e or μ + large missing p_T
  - b-tag (3rd lepton) vetoes to reject $t\bar{t}$ (WZ)
  - Transverse mass used as analysis variable (no D_{bkg})
  - 3 categories: 0, 1 jets, VBF-tagged

Event selection: 2l2q

- 2 separate analyses covering regions with large/small p_T of hadronic Z
  - «Resolved»: two anti-kT jets (R = 0.4) detected
  - «Merged»: a single CA jet (R = 0.8) containing all Z-decay products
- Similar lepton/jet selection. For merged events:
  - Selection on large-jet «pruned» mass (after removing soft/collinear components) and «subjettiness»
  - MELA built using sub-jet directions
- 3 analysis categories: VBF-tagged, tagged as Z → bb, untagged

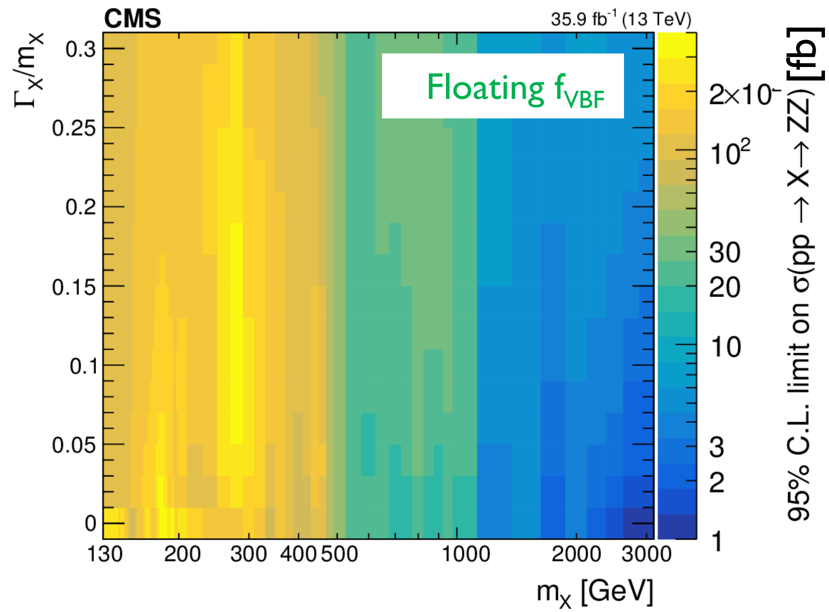


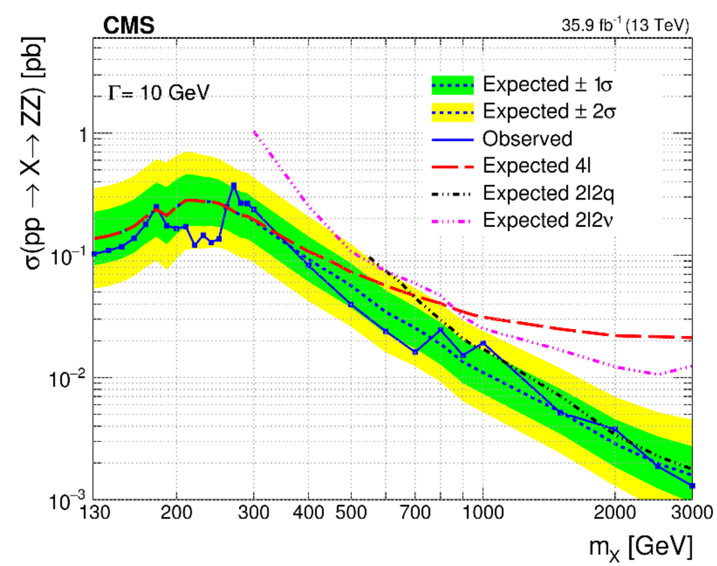


R. Covarelli

Background estimation and results

- Background estimation
  - MC-based for most backgrounds (e.g. SM ZZ)
  - Methods using data control regions for Z+jets
    - m_{jj} sideband estimation in 2l2q
    - Extrapolating γ+jets in 2l2ν
- (σ x BR) 95%-CL limits in a specific BSM model can be extracted from 2D plots
  - Projection example for Γ_H = 10 GeV with channel breakdown →





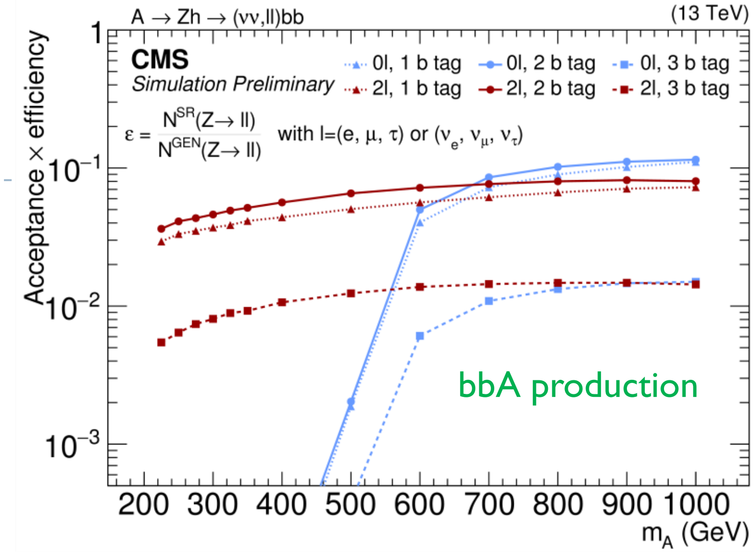
$$A \rightarrow Zh$$

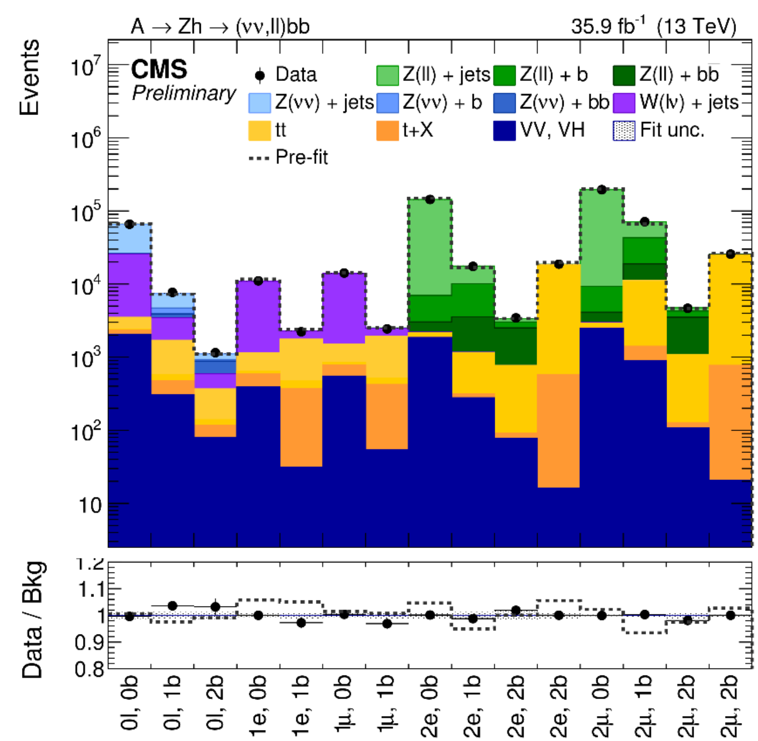
Analysis method and models

- Search for high-mass resonances decaying to Zh in the 2l2b or 2ν2b final states
  - Range of investigated masses: [225 GeV, 1 TeV]
- BSM signal model: 2HDM
  - ggF and bbA, A → Zh (MadGraph+MadSpin @ LO QCD)
  - Narrow width assumption (in the investigated m_A range valid for tanβ >~ 1)
- Result interpretation
  - Limits set on cross-section times BR
  - Interpreted as constraints in the (cos(β–α), tanβ) and (M_A, tanβ) planes for all 4-type 2HDMs (predictions obtained at NNLO using 2HDMC and SusHi)

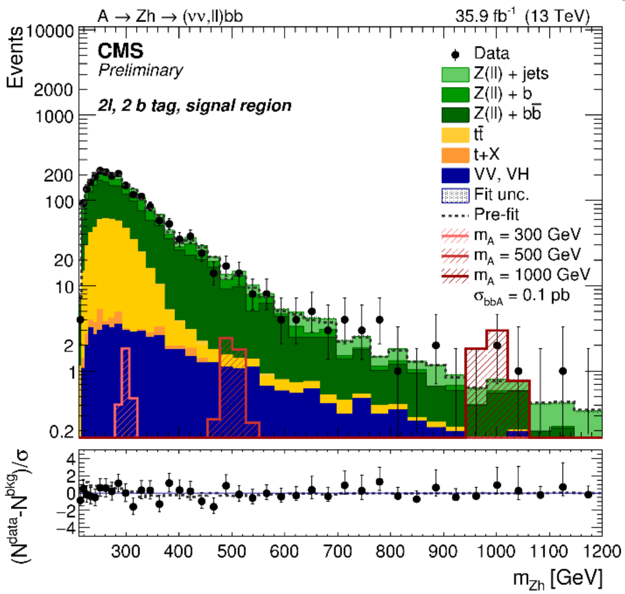
Event selection (I)

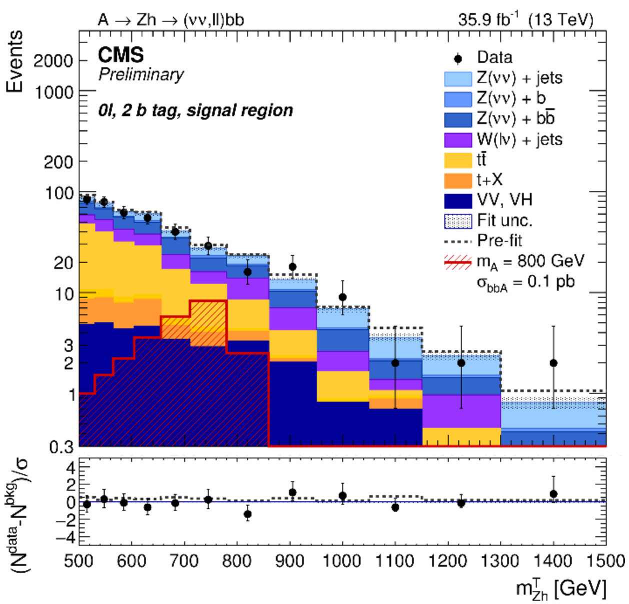
- h signal region in $100 < m_h < 140$ GeV, sidebands for control regions
  - Kinematic fit to m(Zh) constraining m_h = 125 GeV
- νν channel (high-mass A only)
  - $p_T(h) > 200$ GeV
  - $m_T(Zh) > 500$ GeV
- ll channel
  - Standard Z → ll reconstruction
- 1-, 2- and 3-b-tagged jets categories, the last targeting bbA
- <u>Dominant backgrounds</u>:
  - Z+jets, $t\bar{t}$ (W+jets relevant in the νν channel)





MVA and background estimation

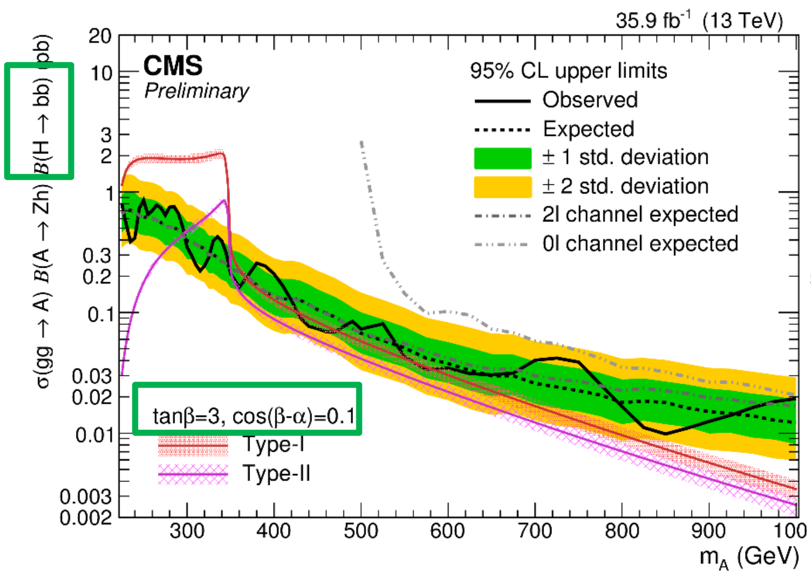


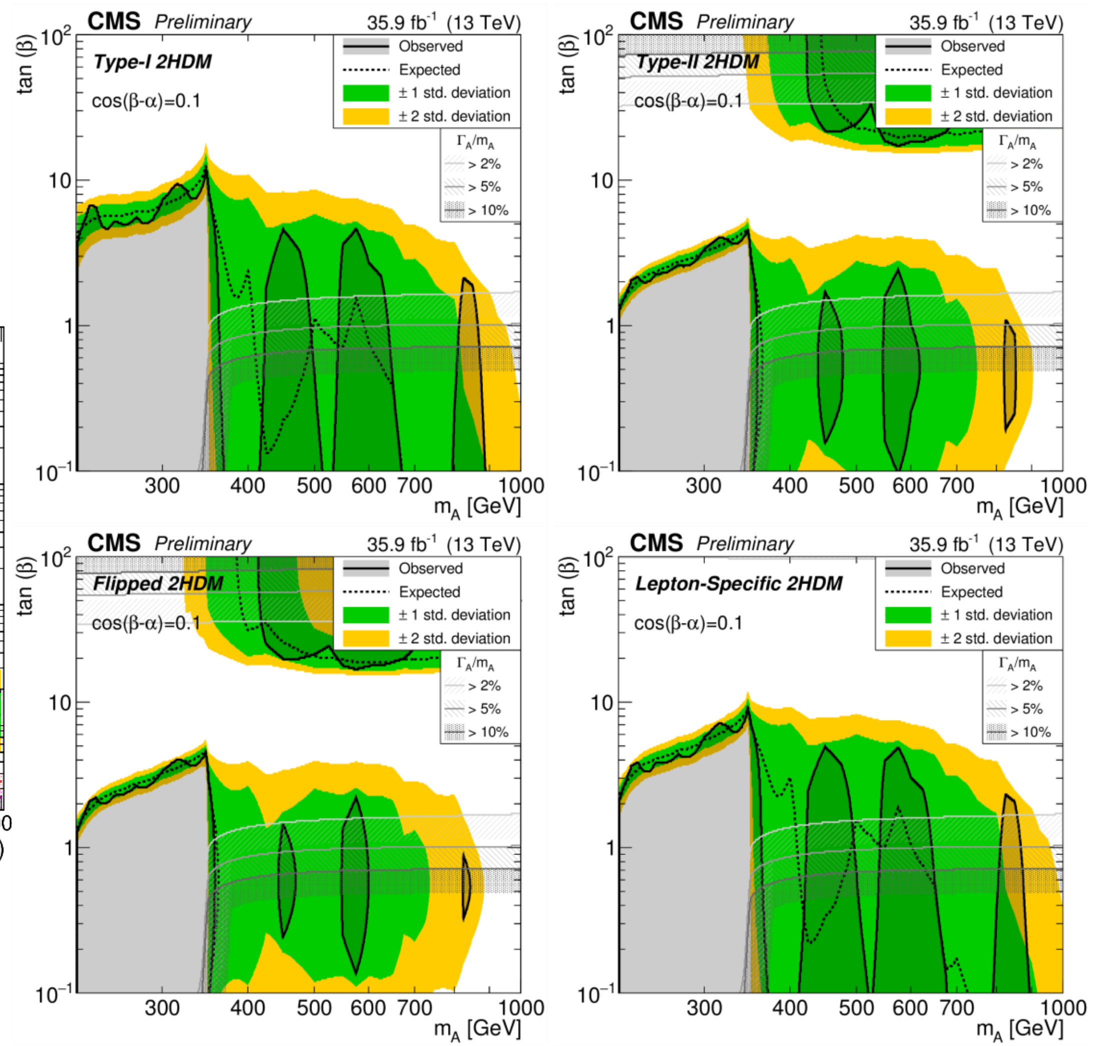


- Additional likelihood-ratio MVA discriminators for the ll channel
  1. Based on angular variables (similar concept as MELA)
  2. Based on m_{ll} and missing p_T (optimizing against top-quark background)
- Background estimation
  - Shapes from MC (MC statistics and modeling resulting as the dominant systematic uncertainties)
  - Normalizations obtained by fitting simultaneously m_{Zh} distributions in signal region and yields in control regions

Cross-section limits and 2HDM constraints

ggF production





$$H \to hh$$

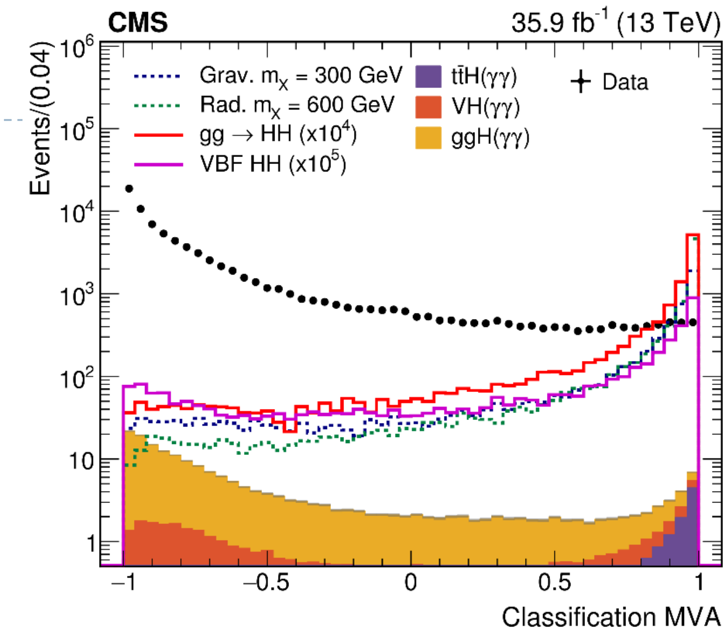
Analysis methods

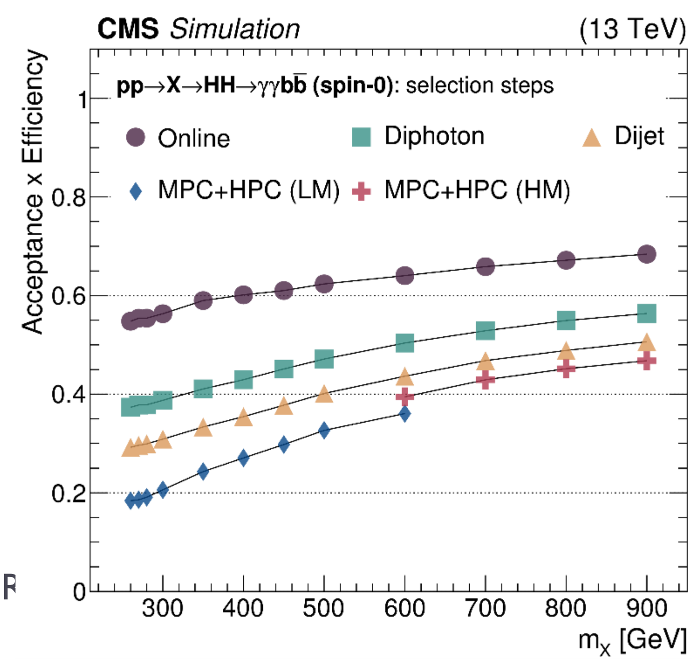
- Several analyses depending on hh final states: here showing $2b2\gamma$, 4b, $2b2l2\nu$ and $2b2\tau$
  - Range of investigated masses: [$2m_H$, 900-1200 GeV]
- BSM signal model
  - ggF $H \to hh$ (MadGraph @ LO QCD)
  - Narrow width assumption (wide would require full calculation of interference with SM hh)
  - Other BSM scenarios with spin-2 resonances, or obtained from SM hh production by modifying the least experimentally known h couplings (λ_{hhh} and y_t) → not relevant for H-like resonance searches
- Result interpretation
  - Limits set on cross-section times BR (compared to spin-0 radions in Warped Extra-Dimension models, can be easily recasted)

$H \to hh \to 2b2\gamma$

- Small $h \to 2\gamma$ BR, but excellent signal purity
- Event selection
  - Stringent b-tagging and photon identification/isolation criteria
  - Additional selection and categorization based on hh BDT (b-tagging scores, p_T/m of bb and $\gamma\gamma$ pairs, helicity angles)

$m_X > 600\,\mathrm{GeV}$	HPC: MVA $>$ 0.5
	MPC: $0 <$ MVA $<$ 0.5
$m_X < 600\,\mathrm{GeV}$	HPC: MVA $>$ 0.96
	MPC: $0.7 <$ MVA $<$ 0.96





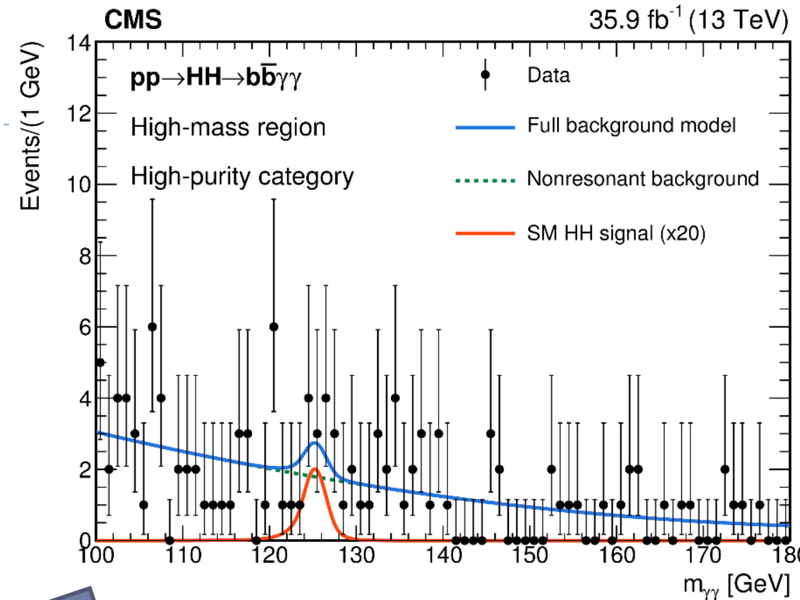
$H \rightarrow hh \rightarrow 2b2\gamma$

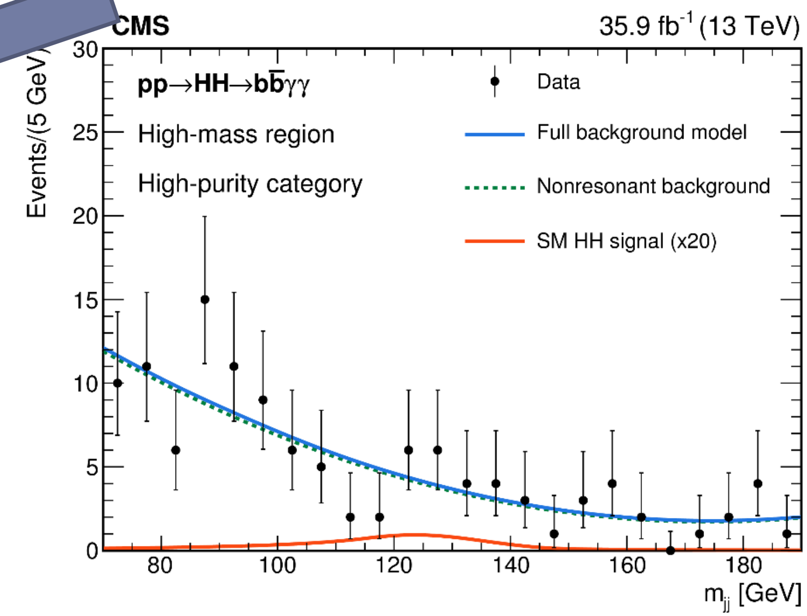
- Shifting signal search region defined by the variable:

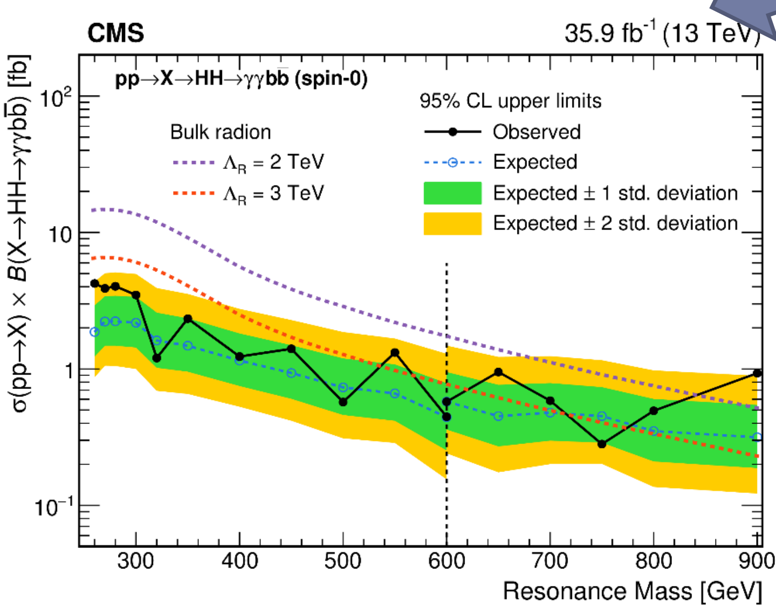
$$\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

being in a range which contains most of the signal at m_H

- Signal extracted by 2D fit to m_{bb} and $m_{\gamma\gamma}$

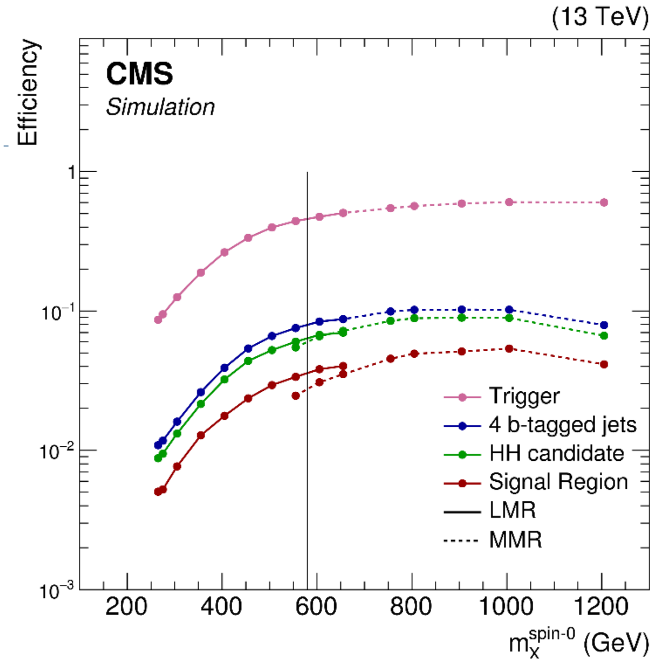


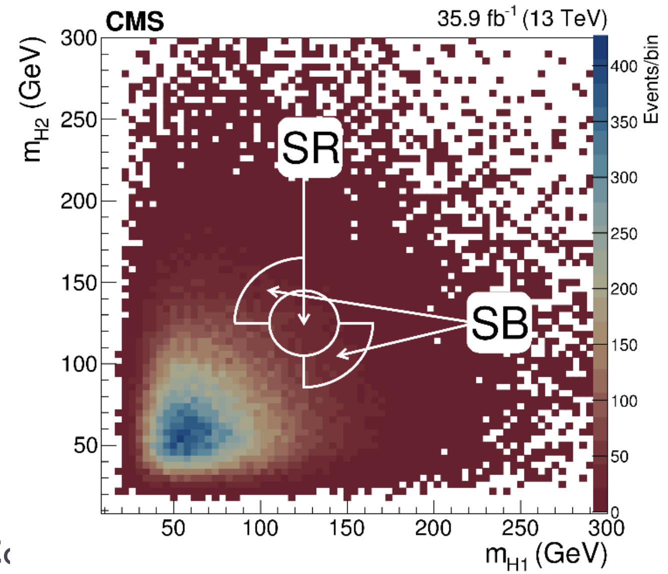




$H \rightarrow hh \rightarrow 4b$

- Largest BR, but huge multijet background
- Targeting «Low» and «Medium» Mass Regions: [260, 1200] GeV
  - Requirement of 4 resolved and b-tagged AK4 jets with invariant mass in a (large) region around 125 GeV
- Signal resolution improvement through:
  - «multivariate regression» (dedicated jet corrections)
  - Double mass constraint on m_{h1}, m_{h2}
- Signal region definition as a circle in the (m_{h1}, m_{h2}) plane





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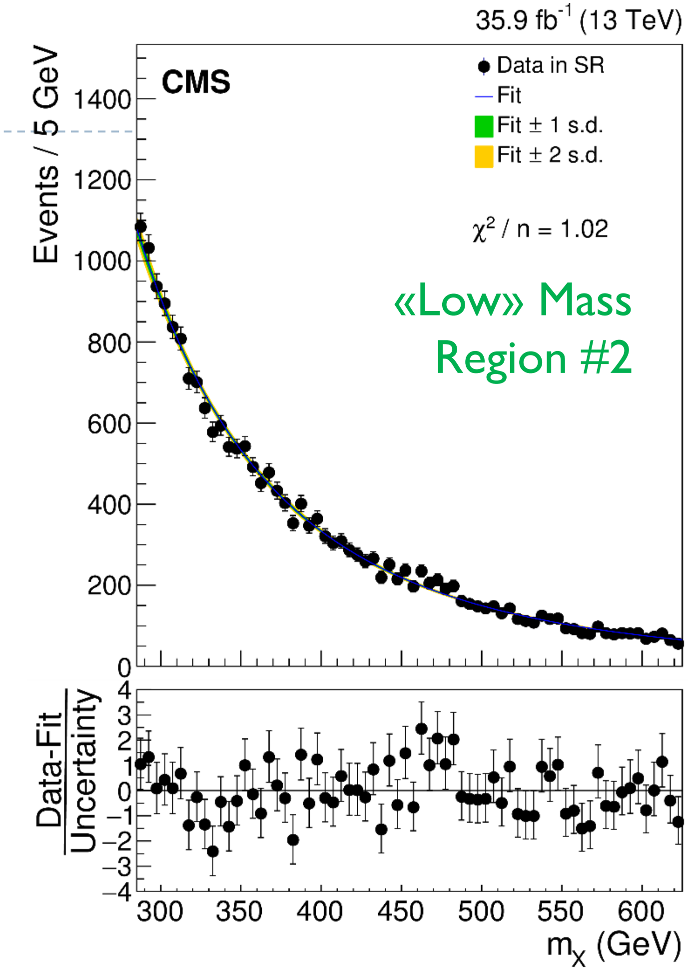
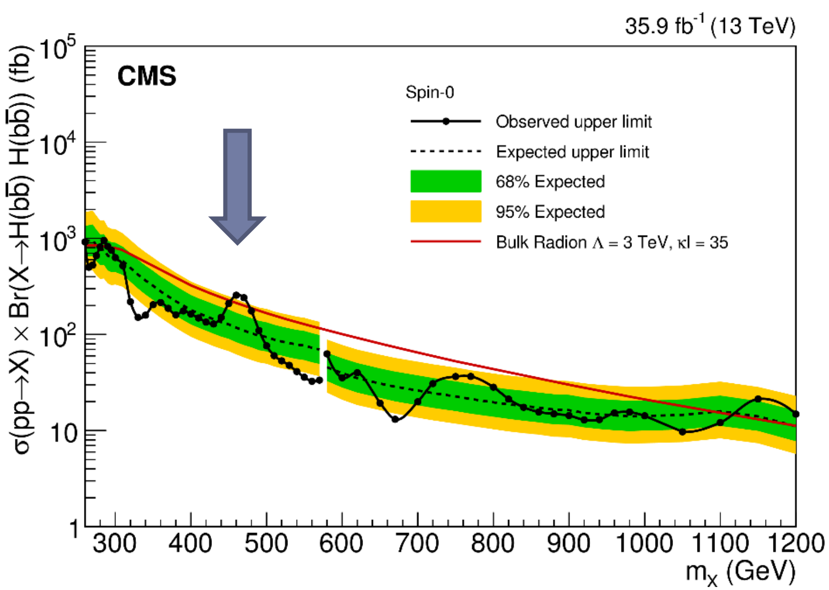
$H \to hh \to 4b$

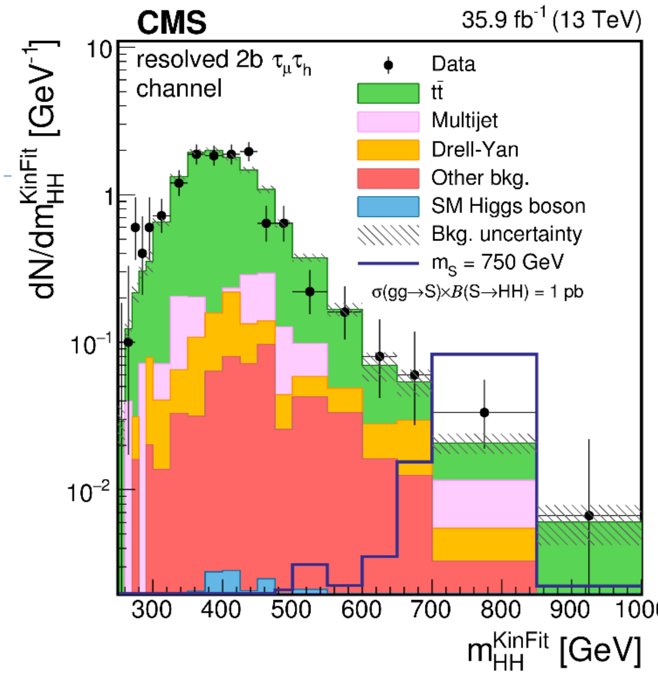
- Signal extraction through parametric fit to m_{4b} distribution in 3 different mass ranges
  - Thorough validation of background shape using sideband regions
- Largest excess over predicted background (around 460 GeV) has a 2.6σ significance

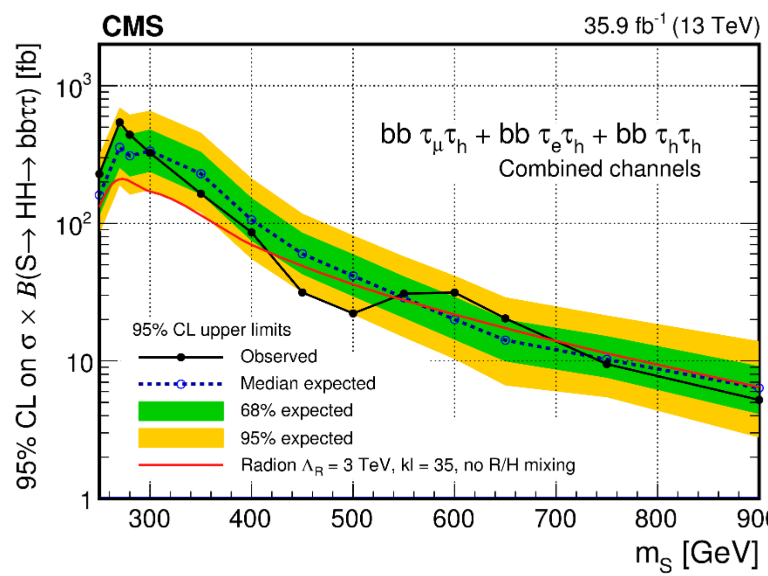




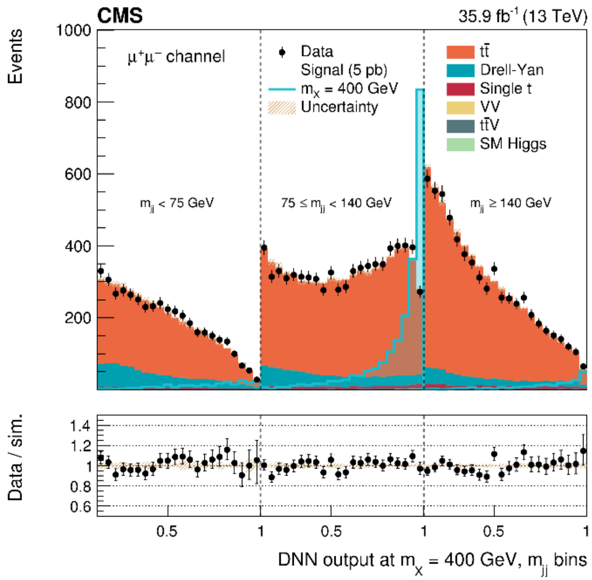
$H \rightarrow hh \rightarrow 2b2\tau$

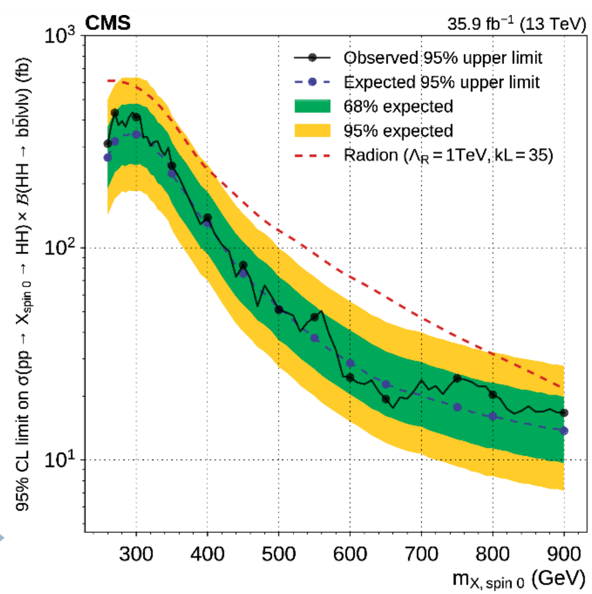
- Intermediate BR, very challenging final states
- Analysis in categories based on:
  - τ final states ($e\nu\nu$, $\mu\nu\nu$, or hadronic)
  - Resolved or boosted b-jets
  - Number of b-tagged jets (1 or 2)
- $t\bar{t}$ as dominant background
  - From MC, suppressed using BDTs trained separately for each region
- Signal extracted using kinematically fitted m_{HH}
  - Takes into account missing momentum in $\tau\tau$ system and double mass constraint (in 2 steps)





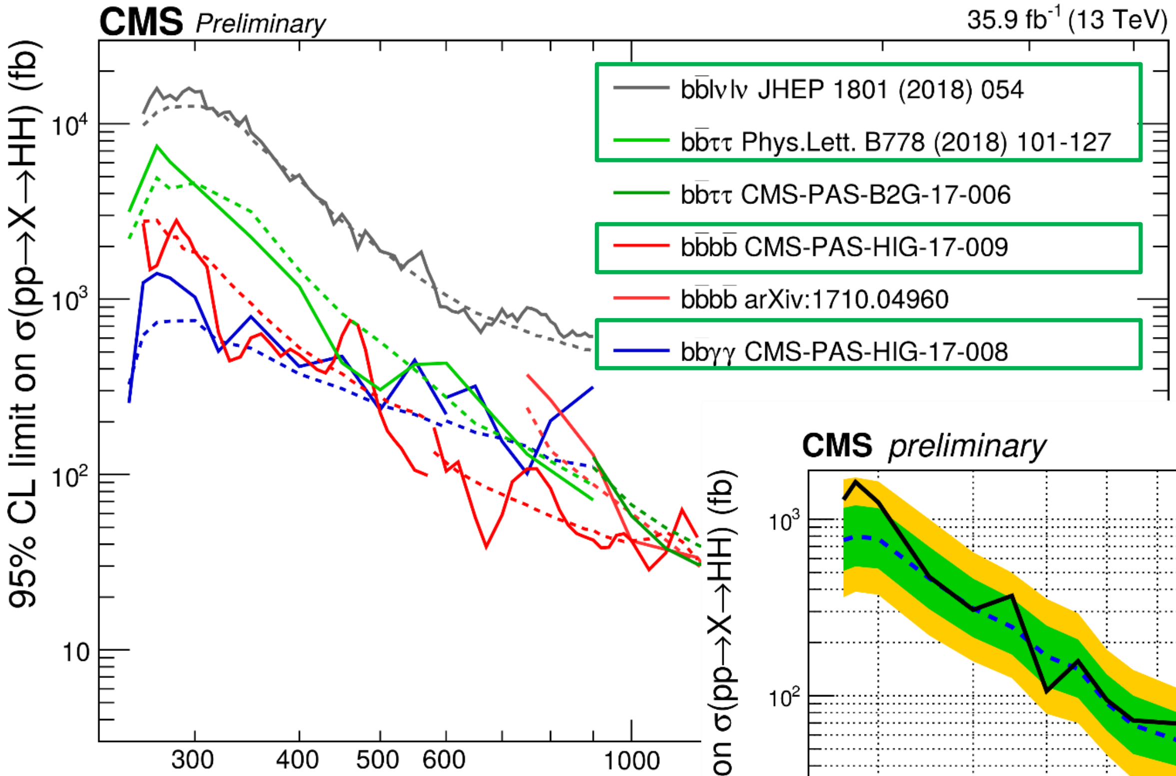
H → hh → 2b2l2ν

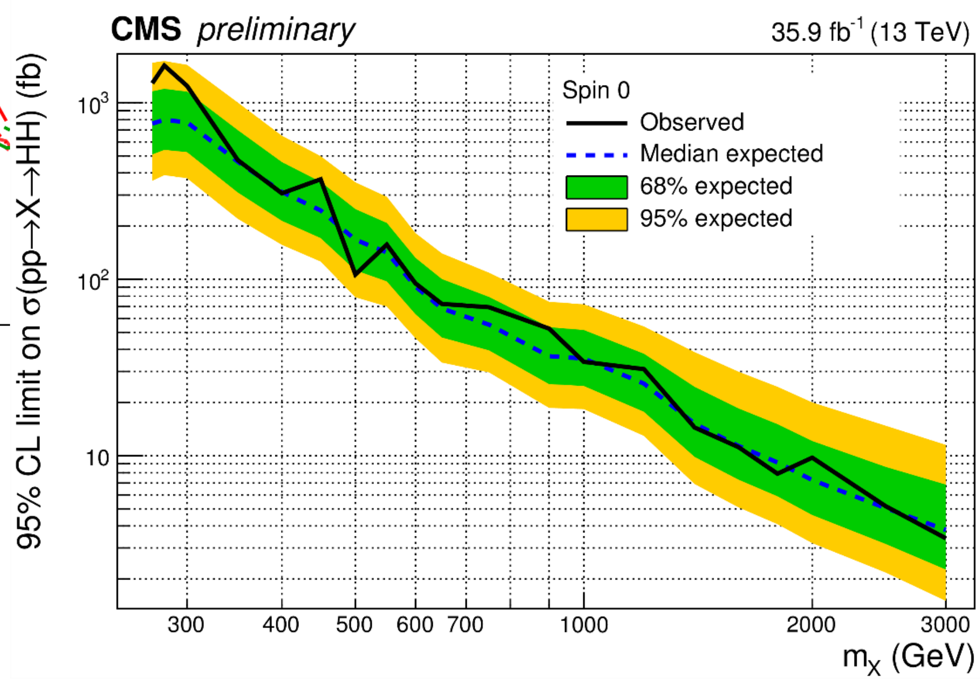




- Quite low BR, challenging final state (same as dileptonic tt)
- Three channels:
  - ee, eμ, μμ
- Signal extracted from a Deep Neural Network discriminator
  - Based on 8 variables
  - Trained by machine learning
  - Distribution fitted in signal-enriched and 2 background-enriched m_{bb} regions
- Backgrounds from MC
  - except (small) contribution of Drell-Yan in ee and μμ channel from data control regions

Combination of H → hh





Summary

- Certain theoretical extensions of SM predict high-mass spin-0 resonances with significant decay widths to VV, Vh or hh
  - Full models (e.g. scalar singlet)
  - Specific regions of parameter phase spaces (e.g. single-digit tanβ and average m_A for 2HDM)
- Extensive searches for such resonances performed in CMS (here showing those targeting m_H <~ 1 TeV)
  - No BSM signals observed, small excess in $H \rightarrow 4b$ not significant
  - $A \rightarrow Zh$ significantly more constraining than 8 TeV result (also excluding parts of the high-m_A region)
  - hh and ZZ searches in many final states constrain H production with similar sensitivities (for both 95% CL exclusions of the order of pb's, exact relative sensitivity depending on model parameters)

Back up

Systematics (H → ZZ)

Source of uncertainty [%]	$X \to ZZ \to 4\ell$	$X \to ZZ \to 2\ell 2q$	$X \to ZZ \to 2\ell 2\nu$
Experimental sources			
Integrated luminosity	2.5	2.5	2.5
ℓ trigger and selection efficiency	2.5–9	4–8	6–8
ℓ momentum/energy scale (*)	0.04–0.3	0.1–0.3	0.01–0.3
ℓ resolution (*)	20	20	—
JES, JER, p_T^{miss} (*)	1–30	1–10	1–30
b tagging/mistag	—	5–7	2–4
Background estimates			
Z + jets	36–43	10–50	20–50
top quark, WW	—	15	10
$W\gamma^*$, WZ	—	3–10	15
Theoretical sources			
Renorm./factor. scales	3–10	3–10	5–10
PDF set	3–4	3–5	1–4
EW corrections ($q\bar{q} \to ZZ$) (*)	1	1	2
NNLO ($gg \to ZZ$) K factor	10	10	10

Systematics (A → Zh)

Table 1: Summary of statistical and systematic uncertainties for backgrounds and signals. The uncertainties marked with (✓) are also propagated to the m_{Zh} and m_{Zh}^{T} distributions.

	Shape	Main backgrounds (Drell-Yan, $t\bar{t}$)	Other electroweak (single-top, VV, Vh)	Signal
Lepton and trigger efficiency	✓	-	2-3%	2-3%
Jet Energy Scale	✓	-	5%	2-6%
Jet Energy Resolution	✓	-	2%	1-2%
b-tagging	✓	-	4%	4-12%
Unclustered p_{T}^{miss}	✓	-	1%	1%
Pile-up	✓	-	1%	1%
PDF	✓	-	3-5%	4-8%
top quark p_T	✓ (only $t\bar{t}$)	8–15%	-	-
Factorization and renormalization scale	✓	2-6%		6-14%
Monte Carlo modeling	✓	1-15 %		-
Monte Carlo statistics	✓	1–20%		-
Interpolation to SR		2–10%		-
Extrapolation to 3 b tag SR		20–46% (3 b-tag only)		-
Cross section		-	2-10%	-
Luminosity		-	2.5%	2.5%

Systematics (H → hh)

Sources of systematic uncertainties	Type	Value (%)
Integrated luminosity	Normalization	2.5
Photon related uncertainties		
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0
Photon identification	Normalization	1.0
PES ($\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}}$)	Shape	0.5
PER ($\frac{\Delta \sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	5.0
Jet related uncertainties		
Dijet selection (JES+JER)	Normalization	0.5
JES ($\frac{\Delta m_{jj}}{m_{jj}}$)	Shape	1.0
JER ($\frac{\Delta \sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0
Resonant analysis specific uncertainties		
Mass window selection (JES+JER)	Normalization	3.0
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Nonresonant analysis specific uncertainties		
$\widetilde{M}_X$ Classification	Normalization	0.5
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Theoretical uncertainties in the SM single-Higgs boson production		
QCD missing orders (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	0.4–5.8
PDF and α_S uncertainties (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	1.6–3.6
Theoretical uncertainty $b\bar{b}$H	Normalization	20
Theoretical uncertainties in the SM HH boson production		
QCD missing orders	Normalization	4.3–6
PDF and α_S uncertainties	Normalization	3.1
m_t effects	Normalization	5

Source of systematic uncertainty	Impact in LMR (%) Signal	Impact in MMR (%) Signal
Luminosity	2.5	2.5
Jet energy scale	0.2–1.8	0.9–2.9
Jet energy resolution	0.9–2.1	1.0–1.5
b tagging scale factor	6.5–6.9	6.9–8.6
Trigger efficiency	6.4–9.0	5.3–7.0
PDF	1.5–2.2	2.1–3.5

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	1.0–1.4%
Jet b tagging (light-flavour jets)	0.3%	0.3–0.4%
Muon isolation	0.2–0.3%	0.1–0.2%
Jet energy scale	<0.1–0.3%	0.7–1.0%
Jet energy resolution	0.1%	<0.1%
Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.)		
μ_R and μ_F scales	12.8–12.9%	
$t\bar{t}$ cross section	5.2%	
Simulated sample size	<0.1%	
Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.)		
μ_R and μ_F scales	24.6–24.7%	
Simulated sample size	7.7–11.6%	
DY cross section	4.9%	
Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.)		
Simulated sample size	18.8–19.0%	
Normalisation	5.0%	
Affecting only single top quark (2.5–2.9% of the total bkg.)		
Single t cross section	7.0%	
Simulated sample size	<0.1–1.0%	
μ_R and μ_F scales	<0.1–0.2%	
Affecting only signal	SM signal	$m_X = 400$ GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3%/−6.0%	signals
Theory unc.	5.9%	signals