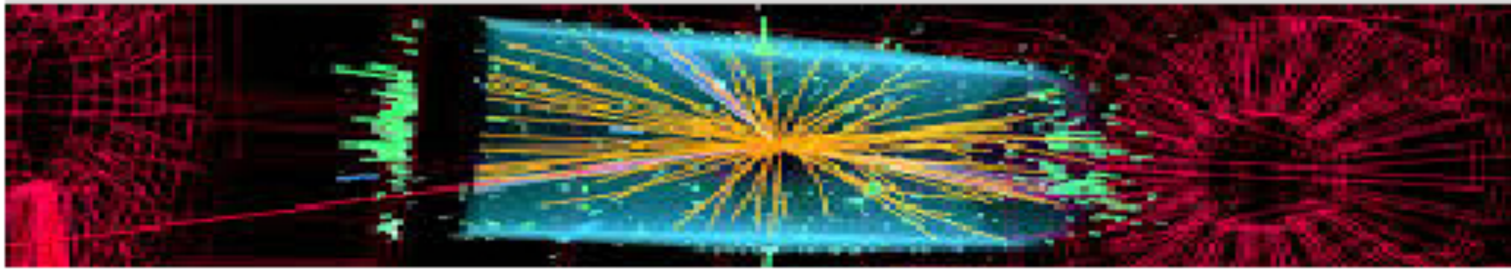

Searches for scalar sector extensions of the standard model via H→ZA→llbb process at CMS

By

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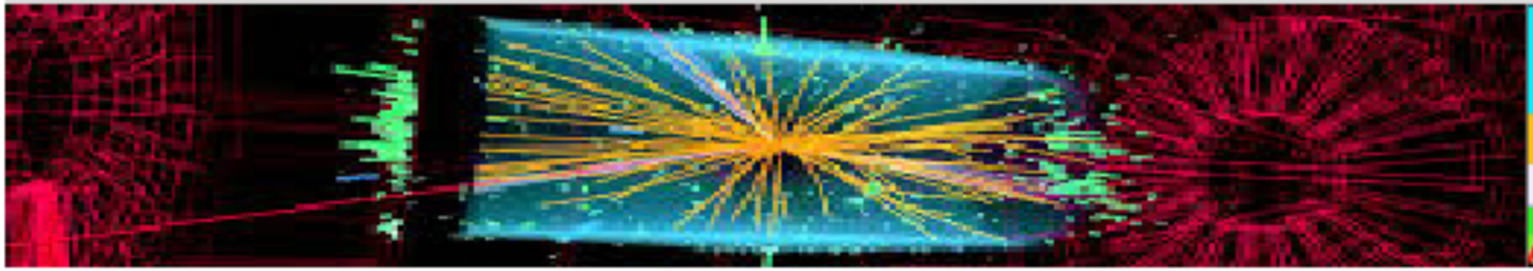
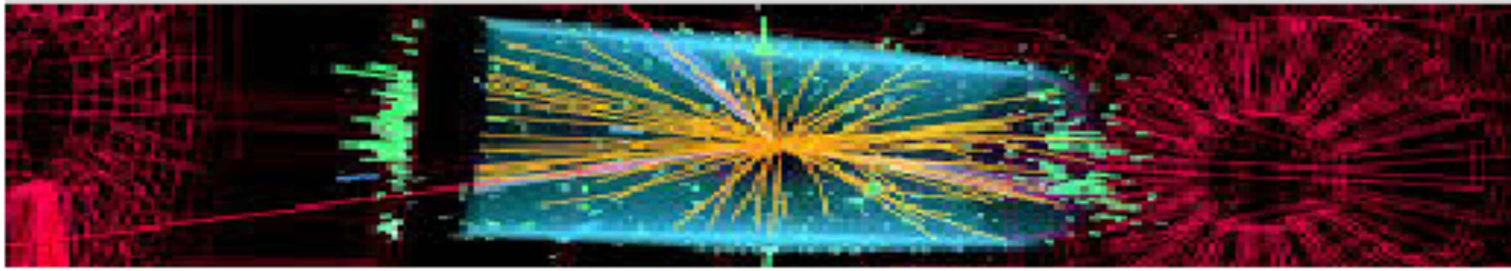
On behalf of the CMS Collaboration

Phenomenology 2020 Symposium, 4-6 May 2020, University of Pittsburgh, United States



Outline

- Introduction
- Motivation
- MC Simulations and Data
- Signal and Background Studies
- Results and Summary



Introduction

- The data collected so far indicates that the Higgs boson is in perfect agreement with the predictions of Standard Model (SM)

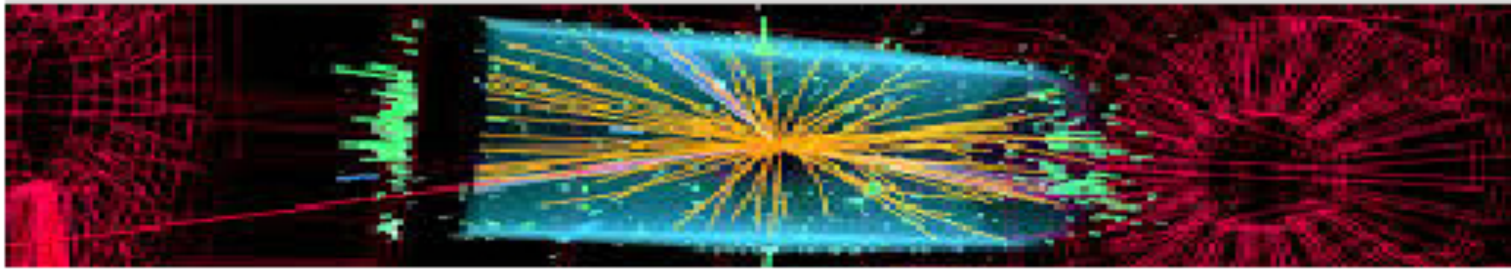
- Many theoretical and experimental indications point out that the SM is only an effective theory at low scale of a more fundamental one

- One common feature of those Beyond SM (BSM) theories is an extended Higgs sector with an extra singlet, doublet, and/or triplet and predict extra neutral and/or charged Higgs states

  - **General 2HDM :**
    - 2 Higgs doublets → 5 Higgs bosons: h, H, A, $H^{\pm}$ [1]
    - Two Scenarios:
      - The A is degenerate in mass with $H^{\pm}$ and heavier allowing A→ ZH decay
      - The scalar H is degenerate in mass with $H^{\pm}$ and heavier than A allowing H→ ZA decay
    - h is compatible with a 125 GeV SM-like scalar alignment limit ($\cos(\beta - \alpha)$ approaches 0)
    - Four types, depending on the coupling of doublets with the quarks and leptons

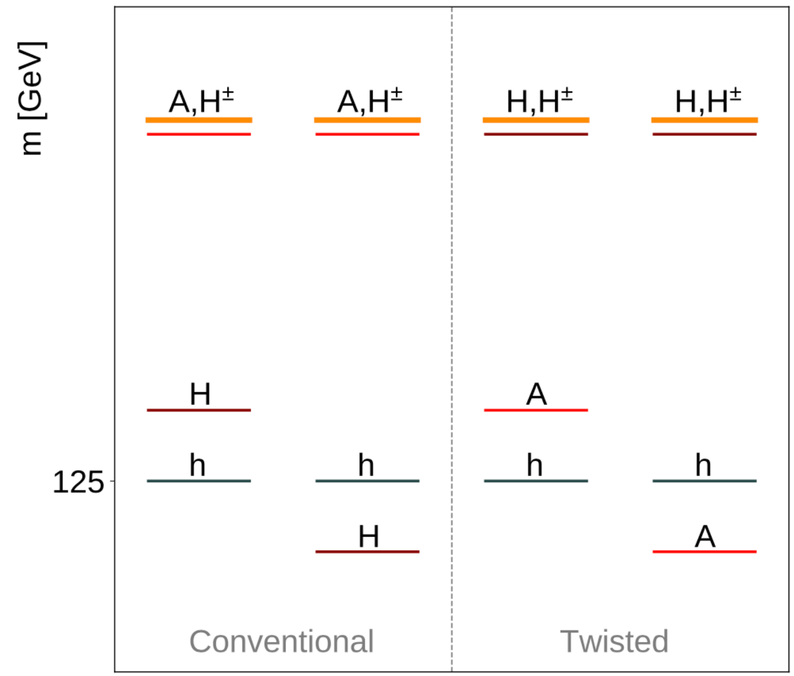
- A discovery of another or several additional Higgs bosons would be considered as a clear evidence of a departure from the SM

[1] Phys. Rept. 516 (2012) 1



Introduction

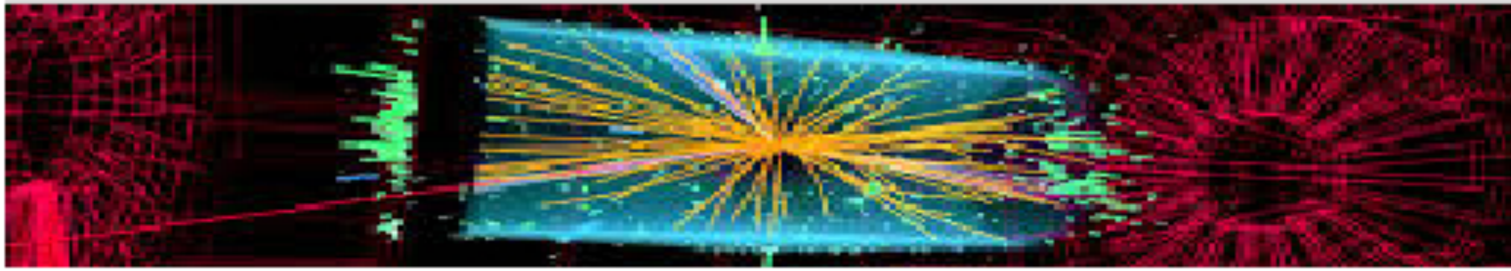
- **Possible 2HDM mass hierarchies:**
  - **Conventional: A is degenerate in mass with the charged scalars**
  - **Twisted, where H is degenerate in mass with the charged scalars.**
  - **In both scenarios, the lighter of the A and H bosons can be either heavier or lighter than the observed Higgs boson h (125)**



- **Analysis performed under the twisted mass hierarchy scenario [1], and subsequently extended to the conventional scenario by interchanging the masses of the two bosons**

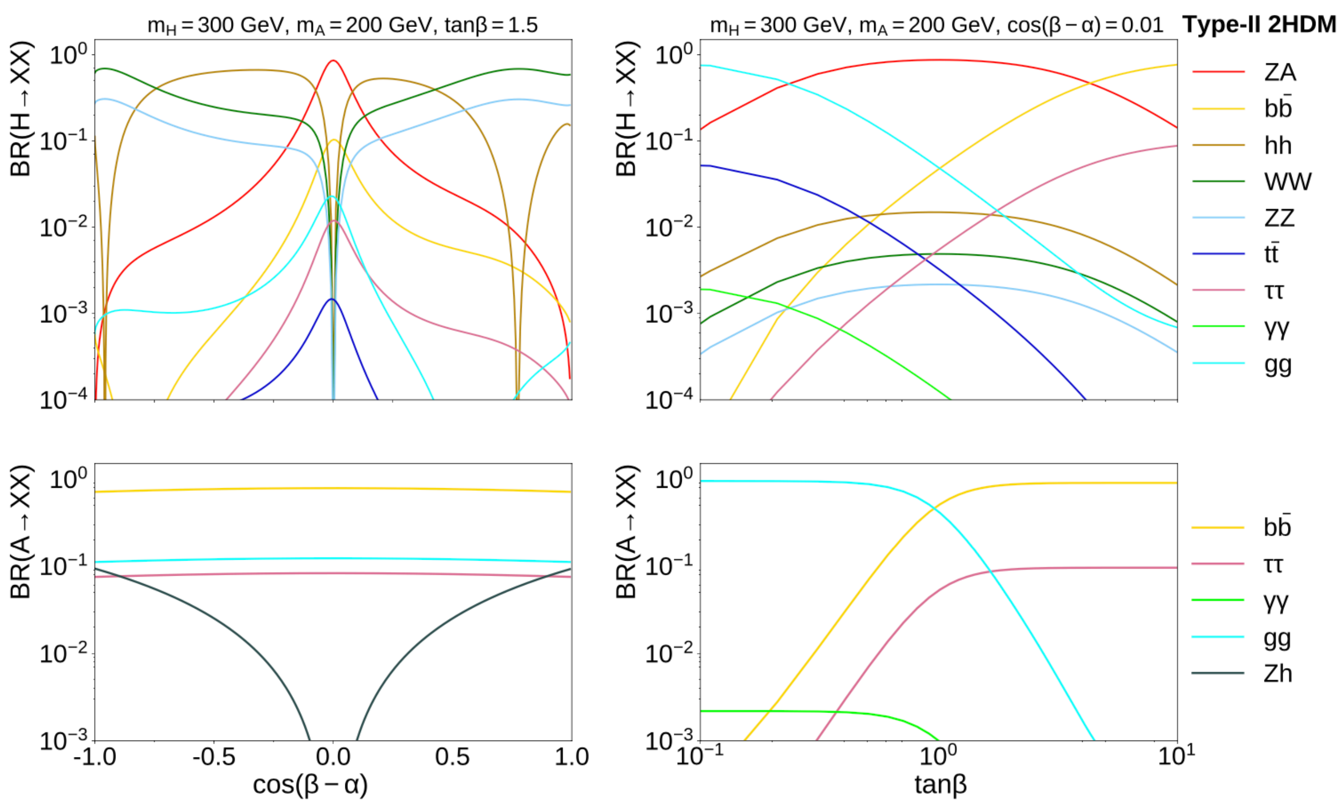
- **Not so crucial when setting model independent upper limits but interesting for theoretical interpretation of the results in the context of the 2HDM, since the theoretical cross sections differ in the two scenarios**

[1] Phys. Rev. Lett. 98 (2007) 251802

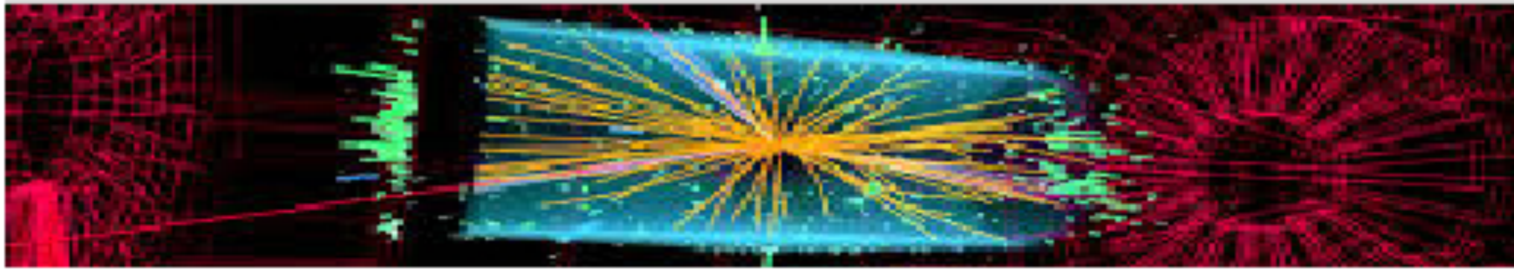


Why H→ZA→llbb?

- **The search H→ZA→llbb:**
  - The Z→ll, (where l = e, μ) takes advantage of the clean leptonic final state (Z→μμ has a clear peak)
  - The final state allows full reconstruction of the A boson's decay kinematics
  - A→bb has its largest branching ratio (depends on the model type and its parameters)



- **The H and A branching fractions (highest) as a function of cos(β − α) and tanβ in Type-II 2HDM for specific set of parameters**



Recent efforts

H→ZA→llbb

Run-I results (8 TeV) for llbb:

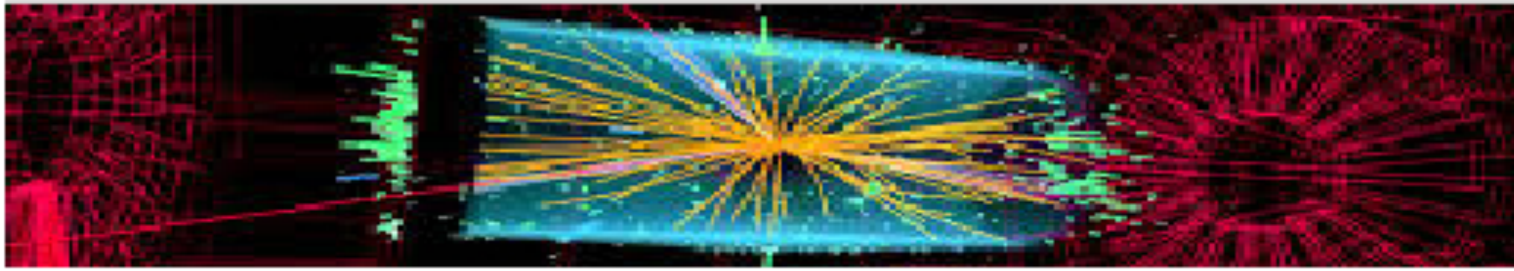
- ◆CMS collaboration, Phys. Lett. B 748 (2015) 221
- ◆ATLAS collaboration, Phys. Lett. B 744 (2015) 163

Recent results with 2016 dataset at 35.9 (36.1) fb^{-1} (13 TeV):

- ◆CMS collaboration, JHEP 03 (2020) 055
- ◆ATLAS collaboration, Phys. Lett. B 783 (2018) 392

Talk covers results for H→ZA→llbb

- ◆ CMS PAS HIG-18-012, CMS collaboration, JHEP 03 (2020) 055
- ◆ A is a new CP-even (odd) neutral Higgs boson decaying into Z and a lighter CP-odd (even) neutral Higgs boson
- ◆ The Z decays into an opposite-sign electron or muon pair
- ◆ The light Higgs boson into a b quark pair
- ◆ Search uses proton–proton collision data at $\sqrt{s}$ = 13TeV corresponding to an integrated luminosity of 35.9 fb^{-1} recorded by the CMS experiment during the year 2016



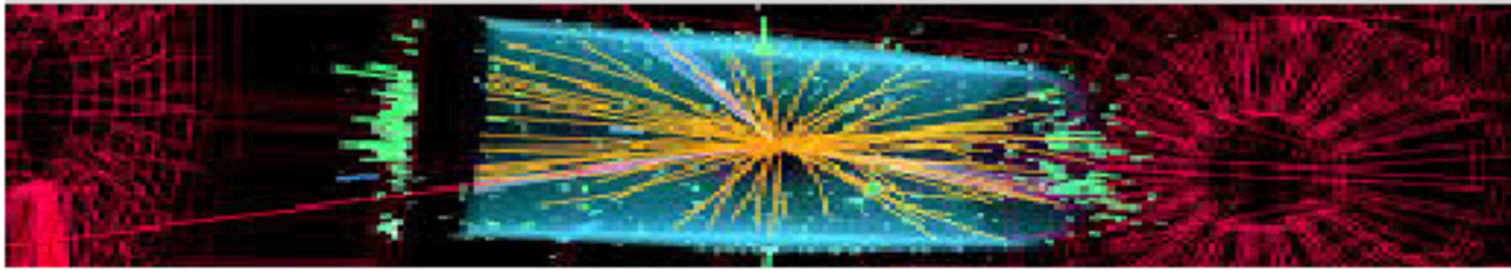
MC Simulations

- The signal samples are produced using MadGraph5_amc@nlo 2.3.2 interfaced with pythia 8.212 for simulation of the parton shower, hadronisation

- Samples of 207 different mass hypotheses have been produced for the process $H \to ZA \to llbb$, with m_H and m_A ranging from 120 to 1000GeV and from 30 to 1000GeV, respectively

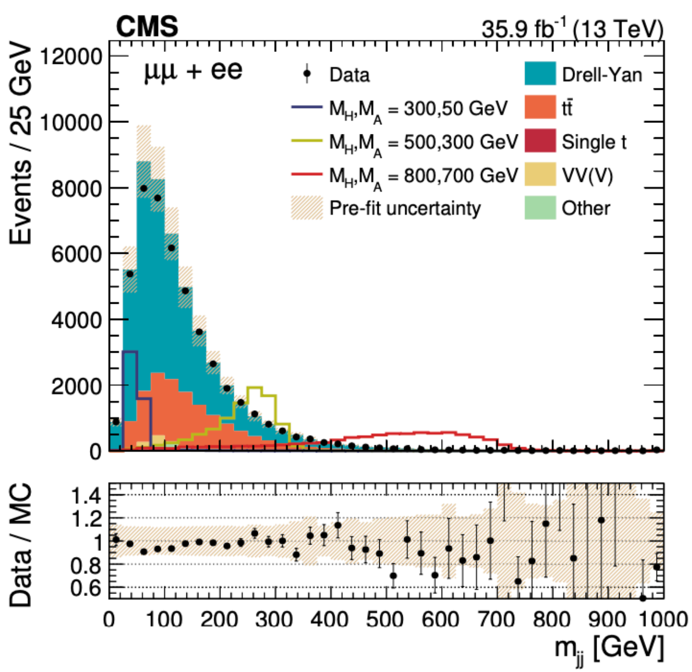
- The choice of the mass hypotheses is strongly motivated by the need of achieving a complete coverage of the parameter space.

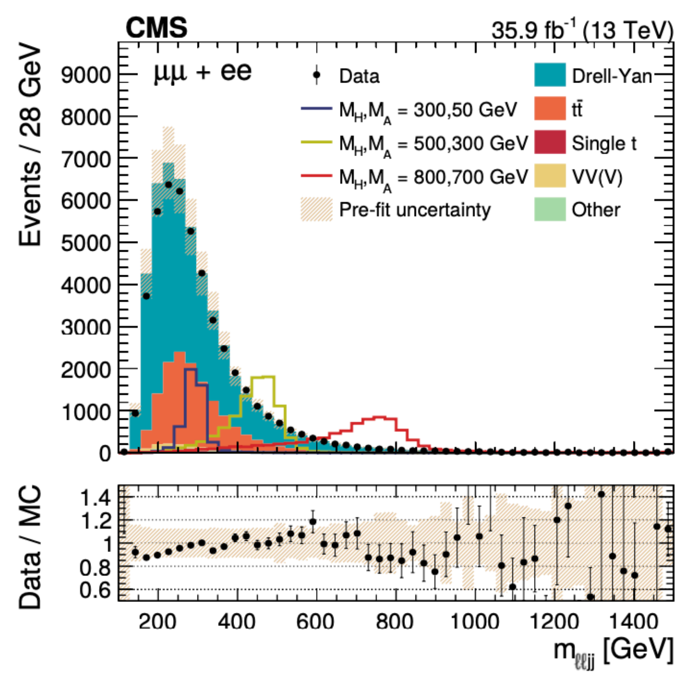
- The spacing between two adjacent mass hypotheses is chosen so as to take into account the worsening of the signal resolution as the mass increases, such that the signal shape can be interpolated with good accuracy over the whole search region

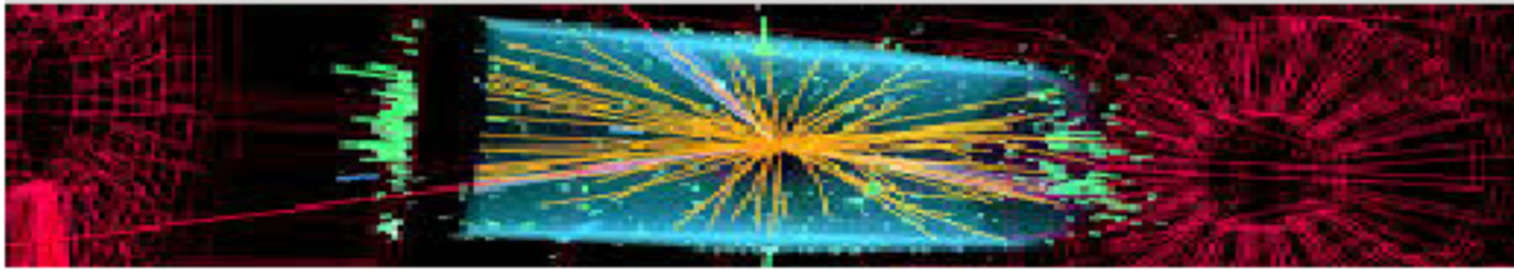


Data-MC Distributions

- Look for the m_{jj} and m_{lljj} distributions
- Events are selected after considering all the optimized selections for μμ + ee categories
- The background shapes and normalisations are obtained from simulation







Signal Extraction

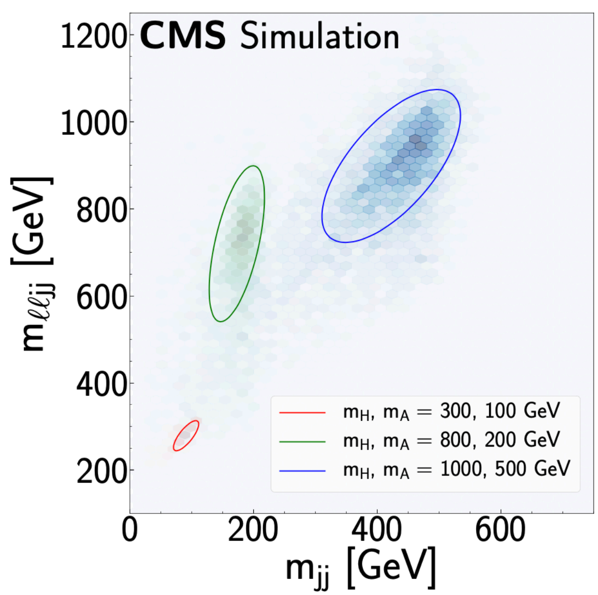
- The m_{jj} and m_{lljj} distributions are positively correlated in 2D plane under a particular signal hypothesis and he elliptical signal region is chosen to optimize the search sensitivity

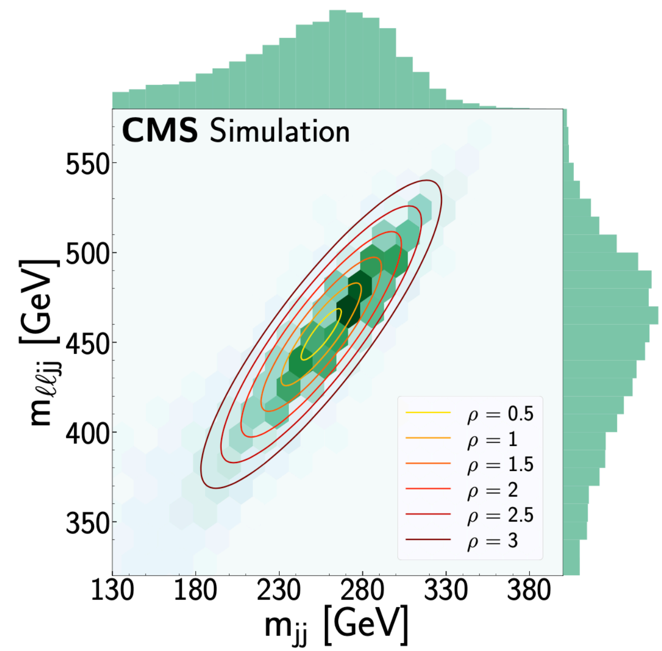
- The shape of the signal is driven by the energy resolution of the final-state objects, ellipses take different sizes and tilt angles, depending on the masses being considered

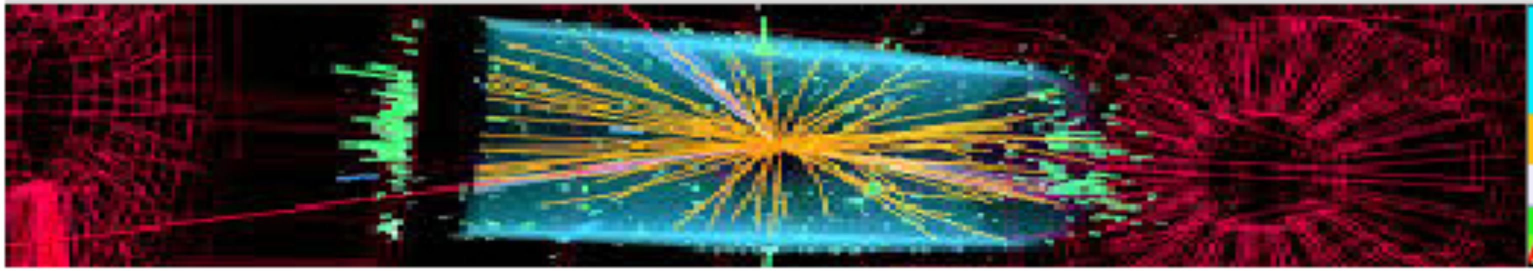
- Concentric elliptically shaped regions are defined in the parameter space using a parameter "ϱ" and an ellipse with ϱ = i contains roughly the fraction of signal events expected within i standard deviations in a 2D distribution

- Selected events in the m_{lljj} vs. m_{jj} plane are classified in six regions around the center of the ellipse defined for each signal point.

- The regions are built in ϱ steps of 0.5, from 0 to 3, and leads to a template containing six bins used to perform the statistical analysis

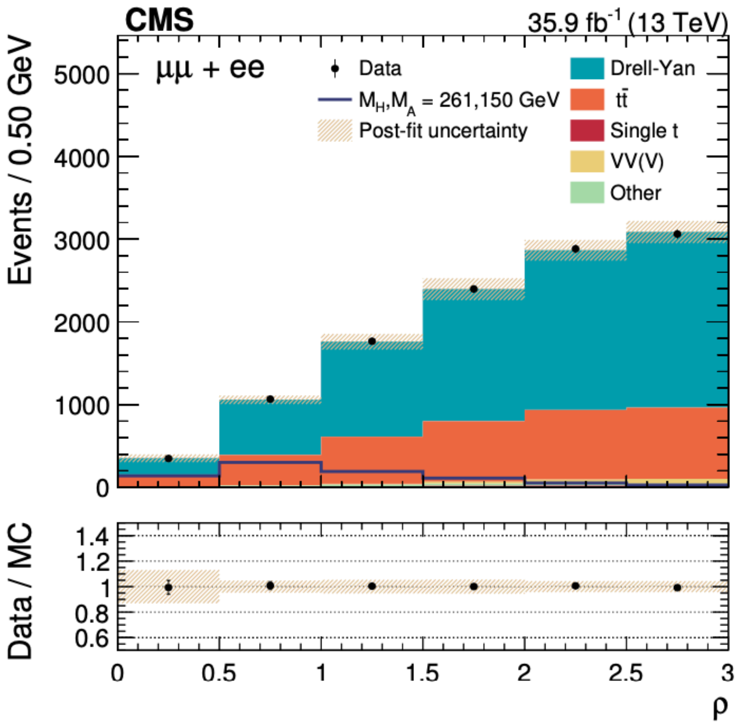


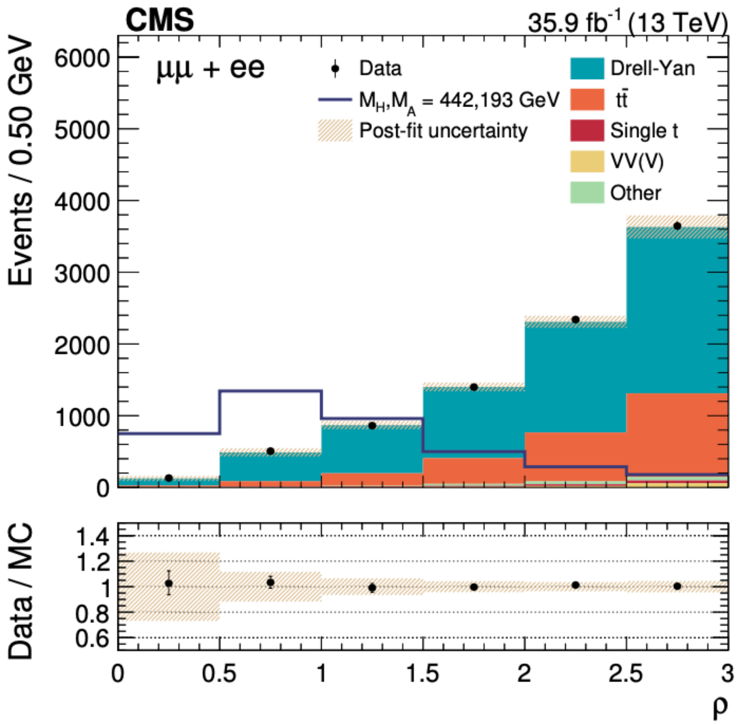


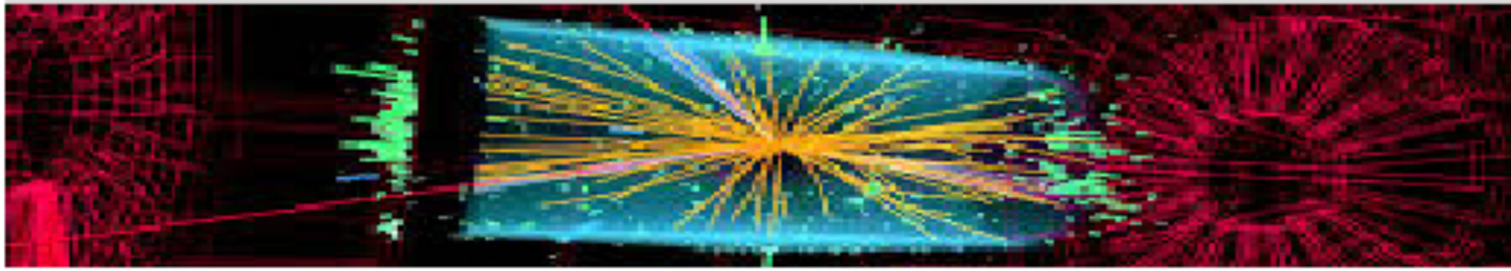


Postfit Data-MC Distributions

- A binned maximum likelihood fit using the six binned templates is performed in the ee and μμ channels in order to extract best fit signal cross sections
- The systematic uncertainties are introduced as nuisance parameters in the fit



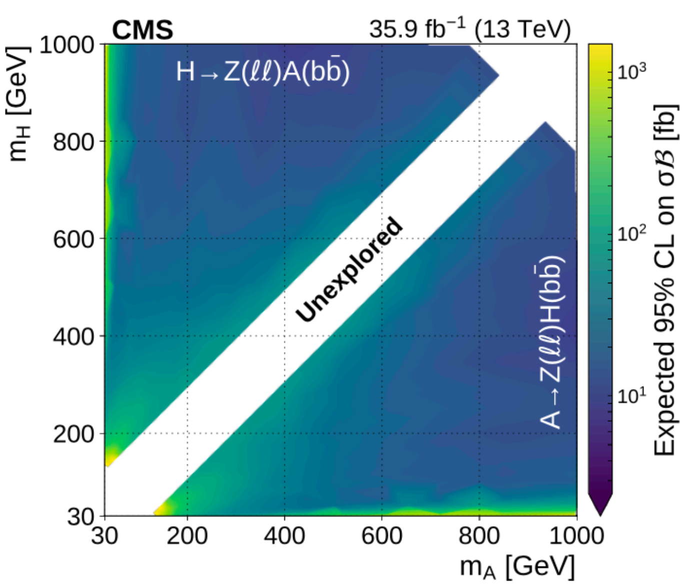




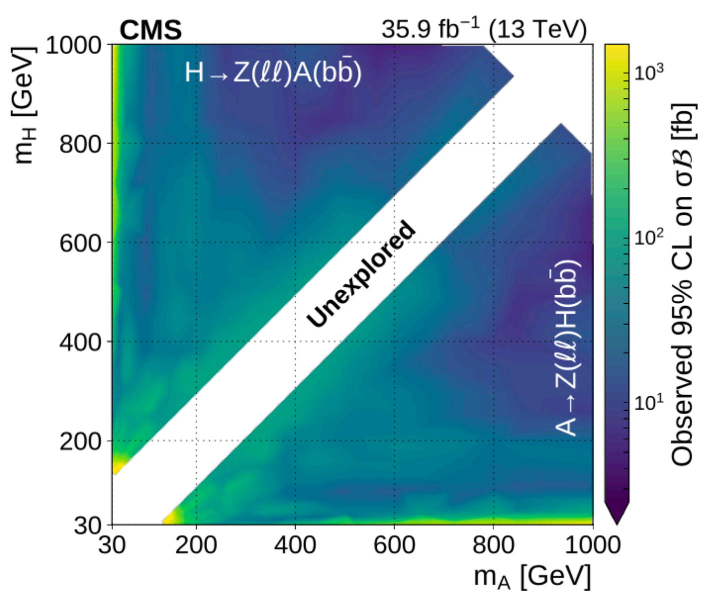
Results

◆ Expected and observed limits

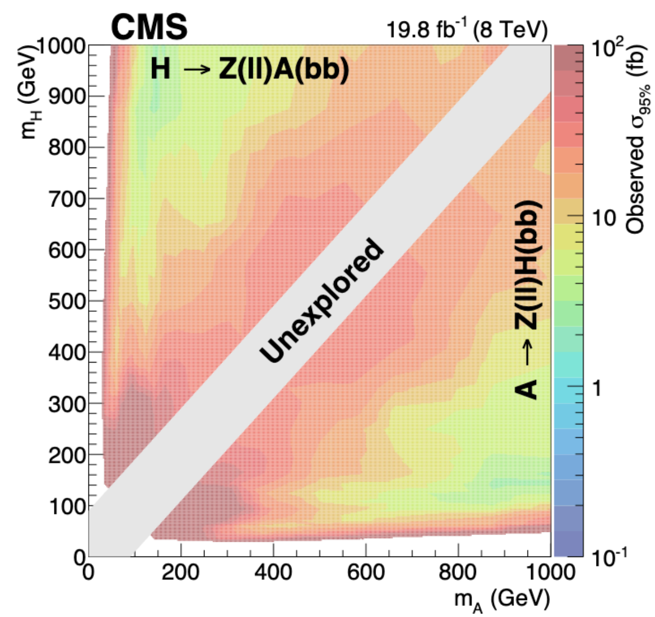
- No significant deviations from the standard model expectations are observed
- 95% CL upper limits on the product of the production cross section and branching fraction σB for H(A) → ZA(H) → llbb as a function of m_A and m_H



Expected

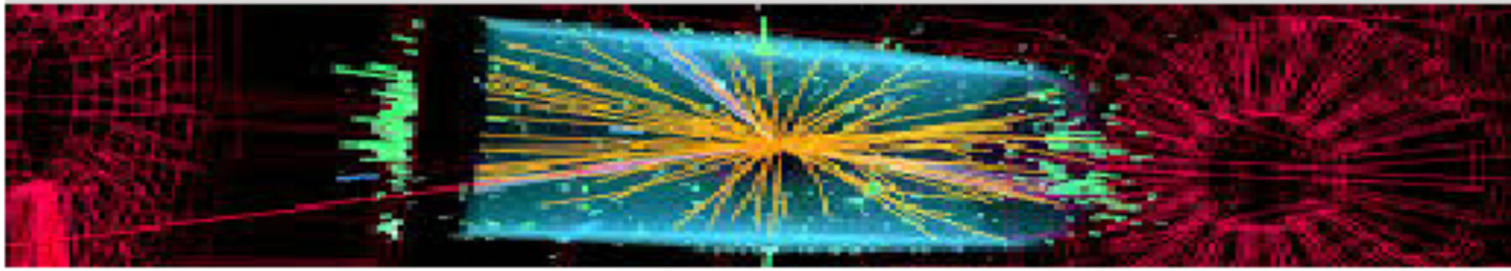


Observed



Run-I observed

CMS-HIG-15-001

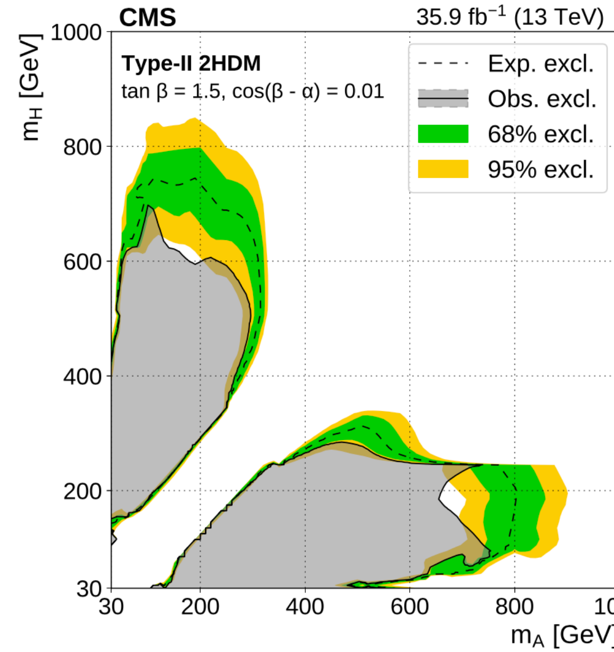


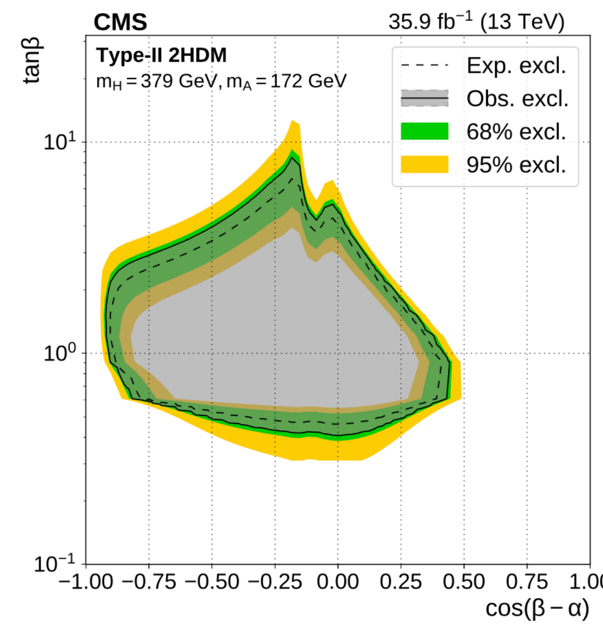
Results

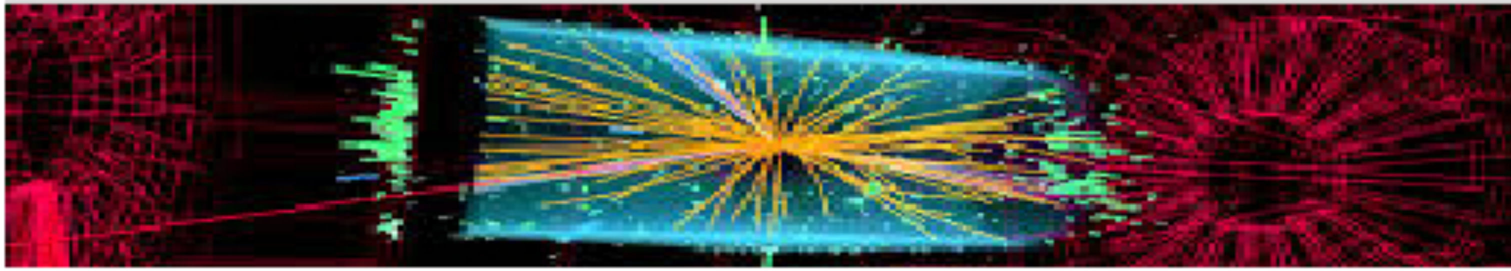
Limits are also set on the parameters of the 2HDM (assuming the Type-II formulation)

- **Expected and observed 95% CL exclusion contours**
  - **For the Type-II 2HDM benchmark tanβ=1.5 and cos(β−α) = 0.01 as a function of m_A and m_H regions with m_H in the range 150–700GeV and m_A in the range 30–295GeV with $m_H > m_A$, or alternatively for m_H in the range 30–280GeV and m_A in the range 150– 700 GeV with $m_H < m_A$ are excluded at 95% confidence level**
  - **With m_H in the range 200–700 GeV and m_A in the range m_A 20–270 GeV for the decay H⟶ZA, and similarly in the range m_A = 200–700 GeV and m_H= 120–270 GeV for the A⟶ZH decay (Run-I results)**
  - **For m_H = 379 GeV and m_A = 172 GeV as a function of tanβ and cos(β − α), the region with cos(β − α) in the range −0.9–0.3 and tanβ in the range 0.5–7.0 is excluded**
  - **The area contained within the solid line shows the parameter space excluded for the chosen mass pair, where cos(β − α) lies between -0.7 and 0.3 and tanβ in the range 0.5 and 2.3 (Run-I results)**

- **The limits are computed using the asymptotic CL_s method, combining the ee and μμ channels.**



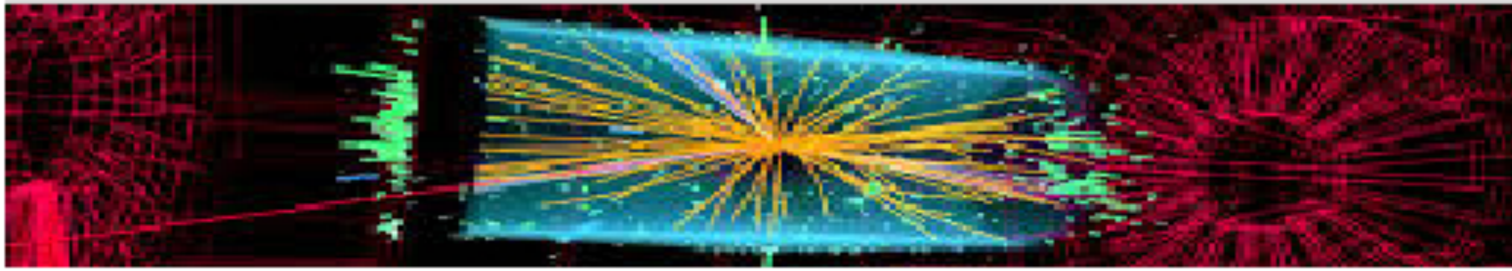




Summary

- Extensive program for heavy Pseudo scalar searches at CMS is already underway
- The talk reported on a search for $H \rightarrow ZA \rightarrow llbb$ @35.9 fb^{-1}
- No significant deviations from the standard model expectations are found and the results are reported in the form of model independent upper limits on the $\sigma\mathcal{B}$
- The exclusion limits have been used to constrain the two-dimensional plane of the 2HDM parameters [cos(β–α), tanβ] with a fixed pseudosacalr mass in the range $0.1 \leq \tan\beta \leq 100$ and $-1 \leq \cos(\beta-\alpha) \leq 1$
- The results extend the search for a 2HDM pseudoscalar boson for mass up to 1 TeV, which is a kinematic region previously unexplored by CMS in the 8 TeV analysis
- The sensitivity of the search is limited by the amount of data but is comparable to the ATLAS results
- Work continues and stay tuned……

Thank You

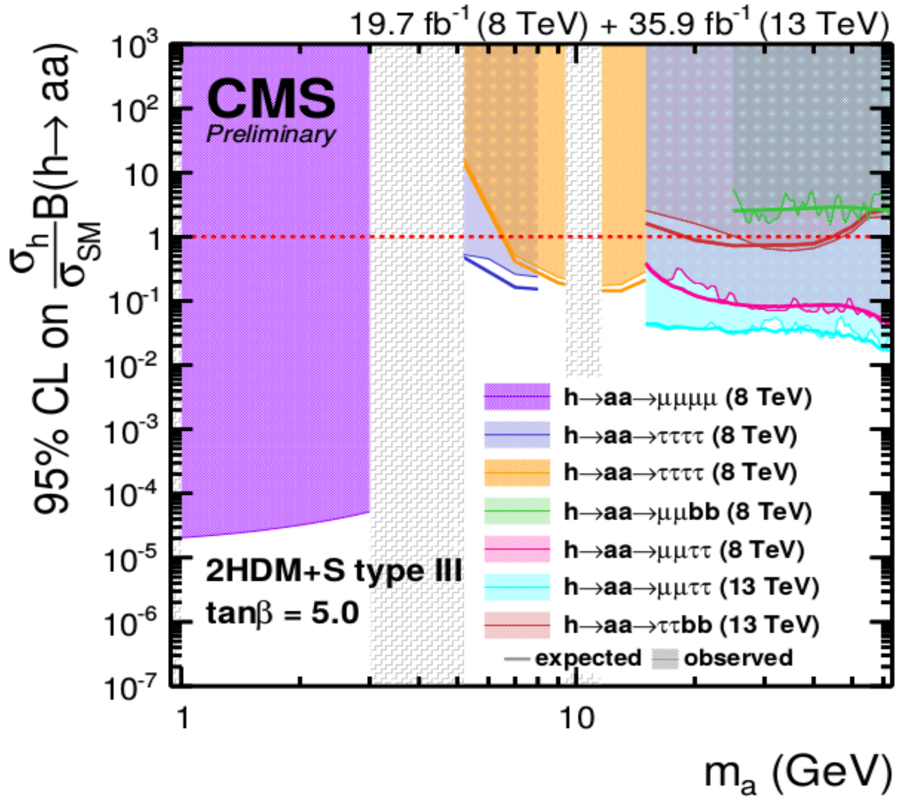


Back-Up

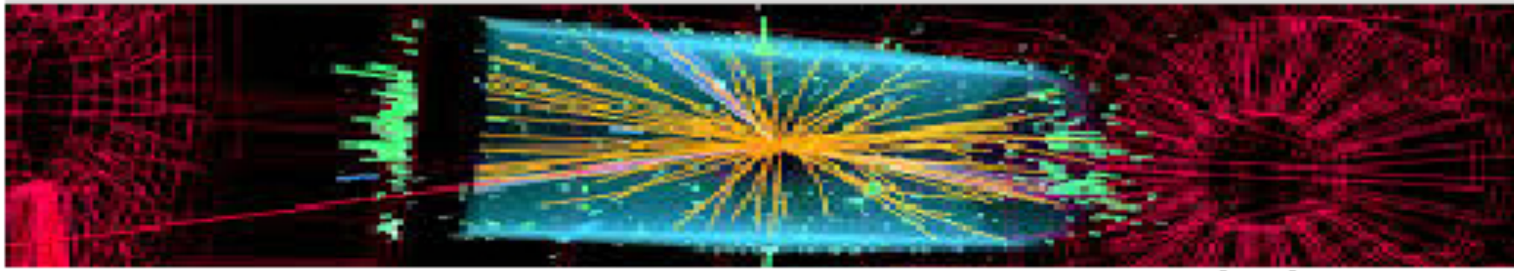
Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.7%	2.6%
Integrated luminosity	2.5%	2.5%
Jet energy scale	2.1–2.4%	0.1–0.3%
b tagging (heavy-flavour jets)	2.3%	2.0%
PDFs	1.0%	0.5%
Pileup	0.3–0.9%	0.7–1.3%
b tagging (light-flavour jets)	0.7–0.8%	<0.1%
Muon identification and isolation	0.5%	0.4%
Trigger efficiency	0.1–0.3%	0.1–0.3%
Jet energy resolution	0.2%	0.2%
Affecting only $t\bar{t}$ (31.8% of the total bkg.)		
μ_R and μ_F scales	12.2–12.3%	
$t\bar{t}$ cross section	5.3%	
Affecting only Drell-Yan (64.5% of the total bkg.)		
μ_R and μ_F scales	9.6%	
Drell-Yan cross section	4.9%	
Drell-Yan additional uncertainty	2.1–2.2%	
Simulated sample size	0.5–1.3%	
Affecting only VV (1.1% of the total bkg.)		
μ_R and μ_F scales	4.3–4.8%	
Affecting only signal		
μ_R and μ_F scales		1.8%

Table 2. Summary of the systematic uncertainties prior to the fit and the variation, in percentages, that they induce on the total event yields for the dominant background and signal processes, under a particular signal hypothesis with $m_H = 379\,\text{GeV}$ and $m_A = 172\,\text{GeV}$.

Back-Up



19.7 fb⁻¹ (8 TeV) + 35.9 fb⁻¹ (13 TeV)
CMS
Preliminary
2HDM+S type III
tanβ = 5.0
h→aa→μμμμ (8 TeV)
h→aa→ττττ (8 TeV)
h→aa→ττττ (8 TeV)
h→aa→μμbb (8 TeV)
h→aa→μμττ (8 TeV)
h→aa→μμττ (13 TeV)
h→aa→ττbb (13 TeV)
expected
observed
95% CL on σh/σSM B(h→ aa)
ma (GeV)



Process	Dataset	σ [pb]
$t\bar{t}$	TT$_{\text{Tune}}$CUETP8M2T4_13TeV-powheg-pythia8	831.76
$t\bar{t}$	TTTo2L2Nu_13TeV-powheg	87.31
Drell-Yan	DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8_ext1	18610.0
	DYToLL_0J_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8 (+ext1)	4758.9
	DYToLL_1J_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	929.1
	DYToLL_2J_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	337.1
VV	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	3.22
	ZZTo2L2Nu_13TeV_powheg_pythia8	0.564
	ZZTo4L_13TeV_powheg_pythia8	1.256
	WWToLNuQQ_13TeV-powheg	49.997
	WWTo2L2Nu_13TeV-powheg	12.178
	WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	5.595
	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin_pythia8	3.033
	WZTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin_pythia8	10.71
	WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	4.42965
single-t	ST_t-channel_top_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1	136.02
	ST_t-channel_antitop_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1	80.95
	ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.36
	ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.5545
	ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.5545
W+ jets	WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7
$t\bar{t}+V$	TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.4062
	TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.2043
	TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.5297
	TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2529
Zh($h \to WW$)	HZJ_HToWW_M125_13TeV_powheg_pythia8	0.0406
$t\bar{t}h$($h \to$ non-$b\bar{b}$)	ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8	0.2151
Zh($h \to b\bar{b}$)	ZH_HToBB_ZToLL_M125_13TeV_amcatnloFXFX_madspin_pythia8	0.173
Zh($h \to b\bar{b}$)	ggZH_HToBB_ZToLL_M125_13TeV_powheg_pythia8(_ext1)	0.00695
Zh($h \to b\bar{b}$)	ggZH_HToBB_ZToNuNu_M125_13TeV_powheg_pythia8(_ext1)	0.00695
$t\bar{t}h$($h \to b\bar{b}$)	ttHTobb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8	0.2934
VVV	WWW_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2086
	WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651
	WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565
	ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398