

# Observation of a Higgs boson at 125 GeV and search for an additional low-mass Higgs boson in the diphoton channel in CMS

Benoit Courbon

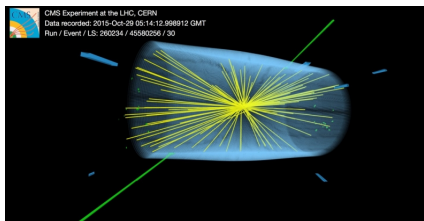
IPN Lyon

LIO International Conference, September 5th 2016



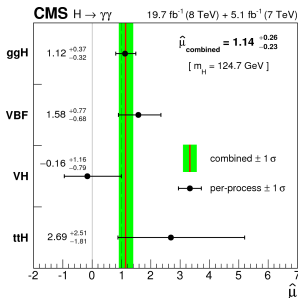
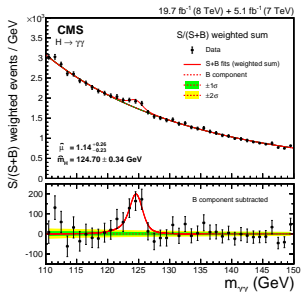
# Introduction

- LHC and CMS are in pretty good shape in 2016 : more than  $25 \text{ fb}^{-1}$  already recorded !
- Main challenges in the Higgs sector :
  - "Rediscover" the 125 GeV Higgs boson
  - Explore further its compability with the Standard Model :
    - Measure its properties with the best precision
    - Interpret its existence in the context BSM models with extended Higgs sector, and search for additional Higgs bosons
- We focus in this talk on the "golden" di-photon channel : clean signature, excellent mass resolution



# Observation of a Higgs boson at 125 GeV in the diphoton channel with 2016 data (CMS-PAS-HIG-16-020)

# Run 1 results in a nutshell



Local significance of  $5.7 \sigma$

$$m_H = 124.70 \pm 0.34 \text{ GeV}$$

$$(\pm 0.31(\text{stat}) \pm 0.15(\text{syst}))$$

$$\mu(m_H = 124.7 \text{ GeV}) = 1.14^{+0.26}_{-0.23}$$

$$(\pm 0.21(\text{stat})^{+0.09}_{-0.05}(\text{syst})^{+0.13}_{-0.09}(\text{theo}))$$

# Analysis overview

- Diphoton channel : **Small branching fraction** ( $\sim 2.10^{-3}$  at  $m_H = 125$  GeV) but **clean signature** : 2 high- $p_T$  isolated photons
  - Analysis strategy : Search for a **narrow peak** on a smoothly decreasing background in the diphoton mass spectra
  - **Large diphoton background** : Reducible (jet-jet or  $\gamma$ -jet with jet faking photon) and irreducible ( $\gamma\text{-}\gamma$ )
  - **Mass resolution** is crucial (energy resolution and vertex identification)
  - **Categorization** of diphoton events to gain in sensitivity and to tag production modes
- 
- We report the **2016 results** presented at ICHEP, corresponding to  $\mathcal{L}=12.9 \text{ fb}^{-1}$  and  $\sqrt{s} = 13$  TeV
  - Challenging **pile-up conditions** :  $\langle \text{PU} \rangle = 18.5$

# Mass resolution

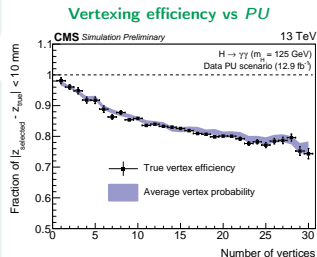
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}$$

## Energy resolution :

- Detector level corrections : crystal intercalibration, crystal transparency loss
- Photon energy regression : multivariate energy correction method taking in account showering, gap/crack effects, PU ...
- Final energy scale and resolution extracted from  $Z \rightarrow ee$  events

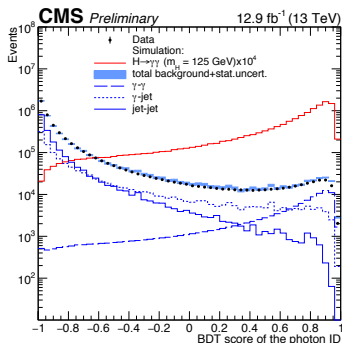
## Vertex identification :

- Not trivial due to the non-longitudinal segmentation of ECAL and the presence of PU
- Boosted Decision Trees (BDT) used to select the vertex, based on the kinematic of recoil tracks and conversion tracks if present
- Second BDT to estimate the probability of good vertex identification ( $\Delta z < 1$  cm)
- Average vertexing efficiency : 80 %
- Methods validated on data with  $Z \rightarrow \mu\mu$  events



# Photon selection

- Trigger and pre-selection based on loose cuts on transverse energy,  $m_{\gamma\gamma}$ , isolation and shower shape variables
- Main photon background : neutral mesons ( $\pi^0$ ) inside jets decaying into a pair of boosted (unresolved) photons
- BDT based method to discriminate prompt photons from background : "Photon ID"
- Inputs : shower shape , isolation, kinematic, PU-related variables
- Loose Photon ID score cut applied, then this score is used for event classification



# Event categorization ("untagged" classes)

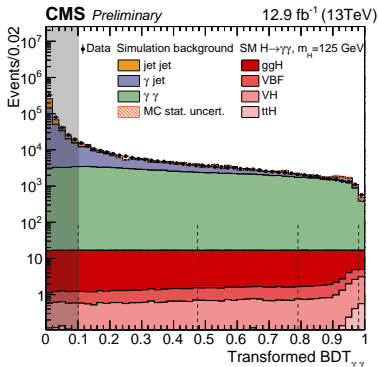
- To improve the analysis sensitivity, categorization of events into classes according to compability with  $H \rightarrow \gamma\gamma$  signal and mass resolution
- BDT based classifier :  
"DiPhoton BDT"

- Inputs :

- diphoton pair kinematic
- Photon ID scores
- mass resolution under correct / incorrect vertex selection hypotheses
- vertex identification probability

All inputs are normalized by  $m_{\gamma\gamma}$   
so no mass region is favored

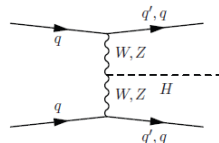
- Build 4 "Untagged" classes by cutting on DiPhoton BDT score



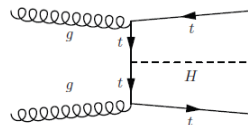
# Event categorization ("tagged" classes)

- Build additional classes in order to tag specific production modes : VBF and ttH
- VBF signature : 2 high- $p_T$  jets with large rapidity gap
- First BDT ( $\text{BDT}_{jj}$ ) to select diphoton events with a jet pair compatible with VBF mode
- Inputs : dijet - diphoton system kinematics
- Second BDT ( $\text{BDT}_{jj\gamma\gamma}$ ) combining  $\text{BDT}_{jj}$  and DiPhoton BDT information
- 2 VBF Tag classes ("tight" and "loose") based on cuts on  $\text{BDT}_{jj\gamma\gamma}$  score
- ttH : pair of tops decaying into 2 b-quarks and 2 W bosons
- ttH leptonic Tag class : at least 2 jets including 1 b-jet, at least 1 lepton ( $e, \mu$ ) in the diphoton event
- ttH hadronic Tag class : at least 5 jets including 1 b-jet, no lepton

VBF

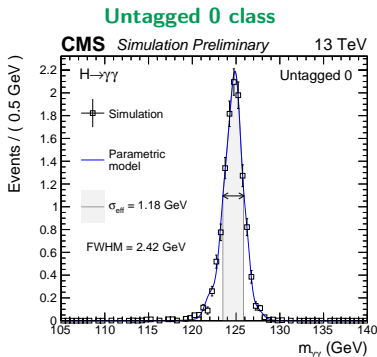
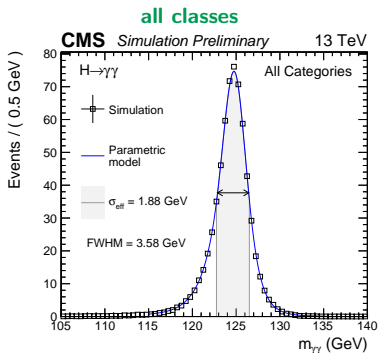


ttH



# Signal Model

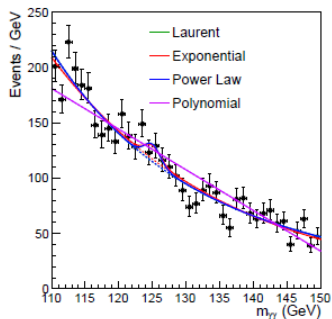
- Use  $H \rightarrow \gamma\gamma$  MC samples with  $m_H=120, 123, 124, 125, 126, 127$  and  $130$  GeV
- Fit the signal shape with a sum of gaussians for each category  $\times$  process  $\times$  correct / incorrect vertexing
- Model interpolated between the mass points
- Physical nuisances allowed to float in the model



# Background Model

- Fit directly on data
- "Discrete profiling method"
- Build an envelope of functions with good fit to data, selected among general class of functions
- Choice of the fit function inside the envelope treated as a nuisance parameter

Example with pseudodata



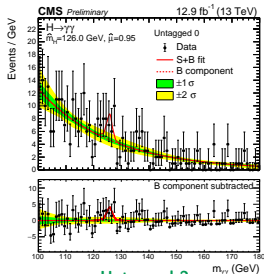
[Dauncey et al., "Handling uncertainties in background shapes", 1408.6865]

# Systematics

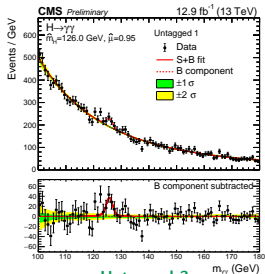
- Theory uncertainties : PDFs,  $\alpha_s$ , QCD scale, underlying event and parton shower,  $H \rightarrow \gamma\gamma$  branching fraction
- Trigger, vertex selection and preselection, integrated luminosity
- Photon energy scale and resolution
- Photon ID and per-photon energy resolution from regression
- Non-uniformity of light collection, non-linearity, detector simulation, modeling of material budget, shower shape corrections
- ggH contamination in VBF and ttH categories
- Jet energy scale and smearings
- b-tagging efficiency, electron and muon ID efficiency

# Mass spectra, untagged classes

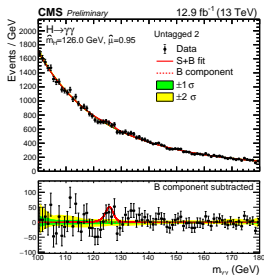
Untagged 0



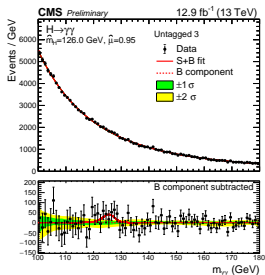
Untagged 1



Untagged 2

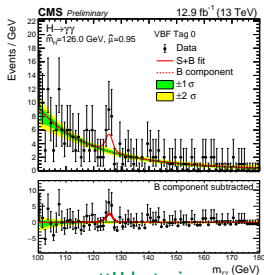


Untagged 3

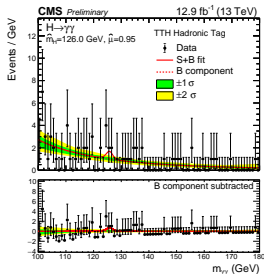
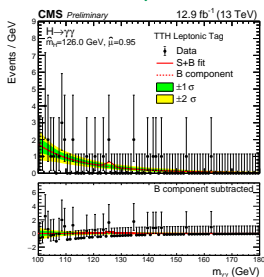
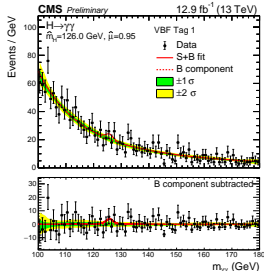


# Mass spectra, tagged classes

## VBF tight



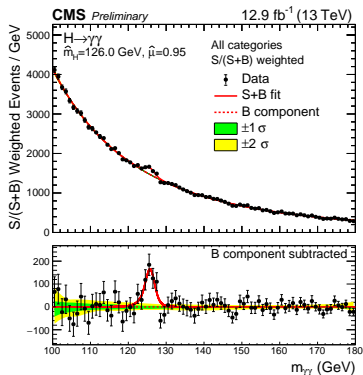
## VBF loose



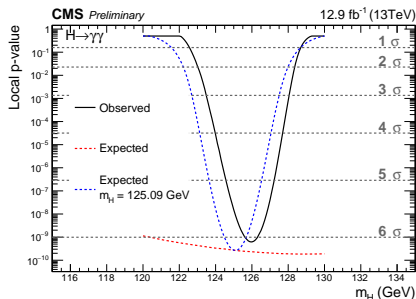
# Results : significance

- Rediscovery of the Higgs boson in the diphoton channel
- Observed significance at  $m_H=125.09$  GeV :  $5.6 \sigma$  (6.2 expected)
- Maximum observed significance is  $6.1 \sigma$  at 126.0 GeV

## Weighted total spectra



## Local P-value

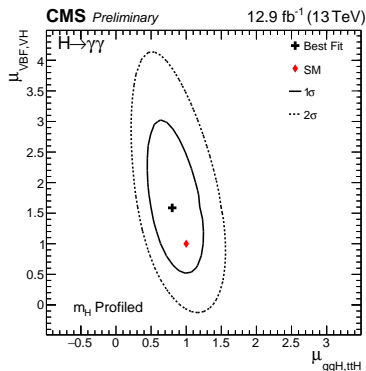
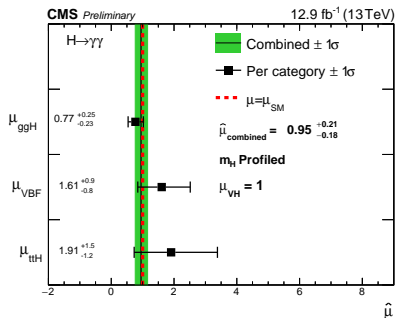


# Results : signal strengths

$$\mu = 0.95^{+0.21}_{-0.19} = 0.95 \pm 0.17(stat)^{+0.10}_{-0.07}(syst)^{+0.08}_{-0.05}(theo)$$

$$\mu_{ggH, ttH} = 0.80^{+0.14}_{-0.18}$$

$$\mu_{VBF, VH} = 1.59^{+0.73}_{-0.45}$$

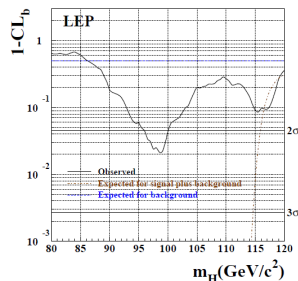
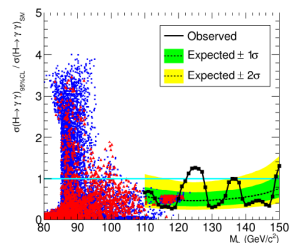


# Search for an additional low-mass Higgs boson in the diphoton channel with 2012 data (CMS-PAS-HIG-14-037)

# Motivations

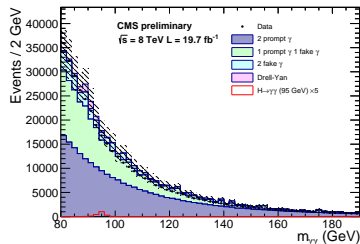
- Some BSM models, such as 2HDM and NMSSM, feature an extended Higgs sector
- One can identify  $H_{125}$  as the next-to-lightest scalar and then search for the lightest one  $h$
- Accessible signal strengths predicted in the diphoton channel within those scenarios :
  - 2HDM :  $\sigma(h \rightarrow \gamma\gamma)$  up to 100 fb  
[Cacciapaglia et al., 1607.08653]  
**See more in next talk by S. Le Corre**
  - NMSSM :  $\sigma(h \rightarrow \gamma\gamma)/\sigma(h \rightarrow \gamma\gamma)_{SM}$  up to 3.5  
[J.Fan et al., 1309.6394]
- Di-photon channel : good mass resolution  $\rightarrow$  ability to explore the Higgs sector close to the Z peak
- Small excess at LEP at  $m_h \sim 98$  GeV in  $bb / \tau\tau$  channels (3 of 4 experiments)  
[LEPHWG, Phys. Lett. B565 :61-75,2003]

J.Fan et al.



# Analysis overview

- During Run 1, standard  $H \rightarrow \gamma\gamma$  analysis search range was [110,150] GeV  
→ Extension of the search in the range [80,110] GeV
- Low-mass bound set by the trigger, featuring a 70 GeV mass cut during Run 1
- 2012 data,  $L=19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$ ,  $\langle \text{PU} \rangle = 19.5$



- Many ingredients inherited from the standard  $H \rightarrow \gamma\gamma$  analysis : Photon reconstruction and energy corrections, vertex identification, Photon ID, DiPhoton BDT
- Low-mass specificity : Drell-Yan background, with electrons from the Z misidentified as photons :
  - Use of a strict electron veto based on the pixel detector
  - Include relic DY contribution in background model
- 4 untagged classes, no tagged classes (not enough DY statistic)

# Signal and Background Models

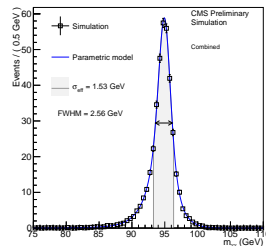
## Signal

- Same signal modelling method as the standard analysis
- We assume that the signal shape correspond to that of a standard Higgs boson

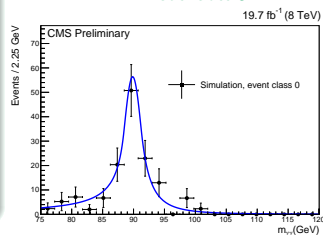
## Background

- We model the relic Drell-Yann contribution with a double-sided Crystal-Ball (DCB)
- Fit performed on MC DY events passing all our selection
- We model the continuum background with Bernstein polynomials (proven not to bias the signal strength)
- Final background model : Bernsteins + DCB, with DCB fraction let floating
- Fit performed on the data

Signal model, all classes



DY model class 0



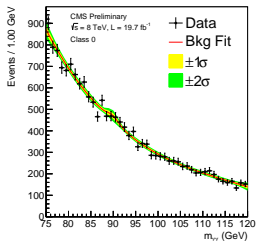
# Systematics

- Systematics common to the standard analysis :
  - Theory (PDFs, QCD scale, BR)
  - Luminosity, trigger, vertex identification
  - Photon energy scale and resolution, preselection, Photon ID
- Systematics specific to the low-mass analysis related to the Z peak modelling
- Choose a region with no signal : "single-fake" selection (1 photon and 1 electron passing our selection)
- Compute differences on DCB parameters (peak,  $\mu$  and width,  $\sigma$ ) between "single-fake" data and MC
- Final uncertainty on these parameters : quadrature sum of the data / MC differences and the purely statistical errors

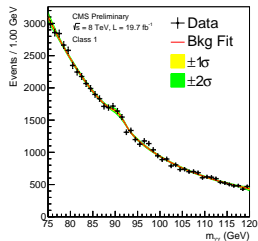
Class	$\mu$ (GeV)	$\Delta\mu$ (GeV)	$\sigma$ (GeV)	$\Delta\sigma$ (GeV)
0	89.9	0.8	1.5	2.2
1	90.6	0.8	1.8	2.2
2	89.6	0.8	1.8	2.2
3	89.2	0.8	3.2	2.2

# Mass spectra

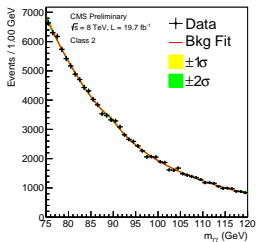
Untagged 0



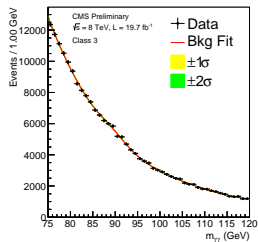
Untagged 1



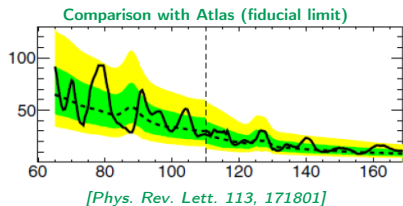
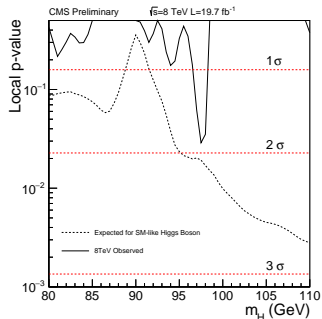
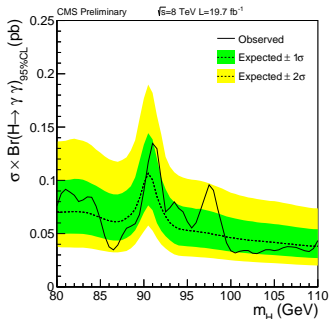
Untagged 2



Untagged 3



# Results



- No evidence for new particle
- Small deviation at  $m_h=97.5$  GeV ( $1.9 \sigma$ ), not observed by Atlas
- See S. Le Corre talk for 2HDM interpretation !

# Plans for Run 2

- Analysis to be continued with Run 2 data
- Use of a dedicated trigger allowing to extend the search range down to 65 - 70 GeV
- Many analysis improvements foreseen (tagged categories, envelope method for the background ...)
- Most ingredients are in place, full analysis workflow tested successfully with 2015 data
- Public results coming soon with 2016 data

# Conclusions

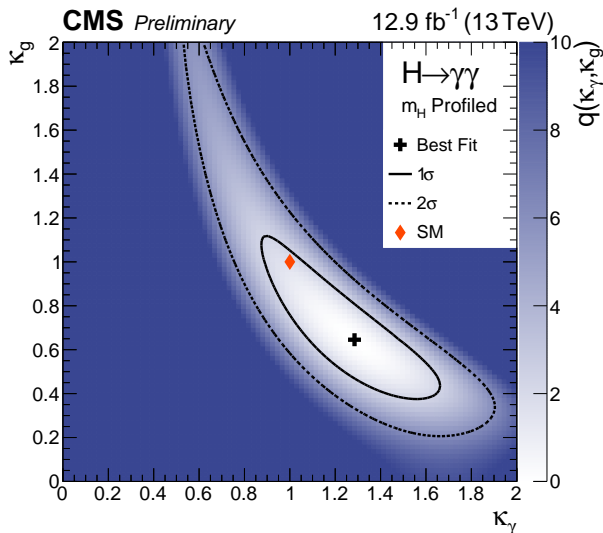
- 125 GeV Higgs boson rediscovered in the diphoton channel with 2016 data
- All couplings consistent with the Standard Model
- Additional Higgs bosons searches performed in the interval [80,110 GeV], in the diphoton channel, with 2012 data
- No evidence for new particles reported
- Search continued with Run 2 data
- The precise property measurements of  $H_{125}$  and the search for additional Higgs bosons are two complementary approaches to explore the compatibility of the Higgs sector with the Standard Model

# BACK-UP

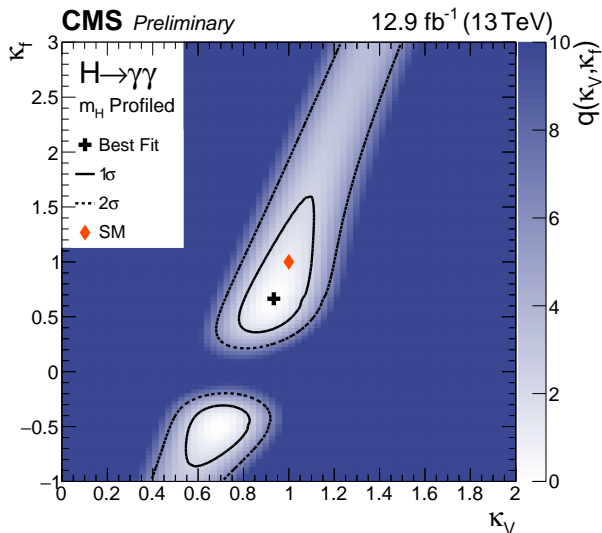
# Event classes

Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV <sup>-1</sup> )
	Total	ggh	vbf	wh	zh	tth	$\sigma_{eff}$	$\sigma_{HM}$	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

# H125 Reduced couplings



# H125 Reduced couplings



# H125 Fiducial cross section

