

Search for additional Higgs-like resonances with heavy masses at CMS

Daniel Domínguez Vázquez (CIEMAT)
on behalf of CMS Collaboration

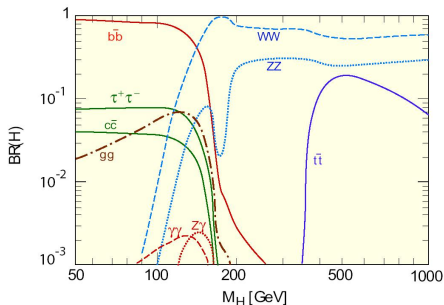
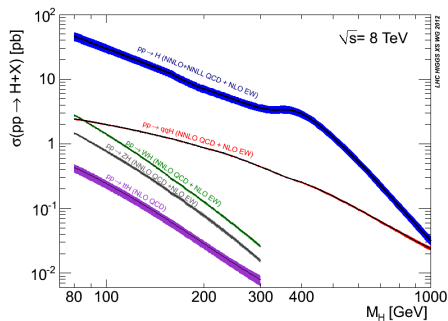
WIN 2013, NATAL

September 19, 2013



Not everything said in Higgs searches at the LHC!!

- Despite the new boson found at ~ 126 GeV, compatible with SM, Higgs-like signatures are **still very interesting at higher masses**.
- Many models predict **Higgs doublets (2HDM)** or **other Higgs-like resonances at higher mass (EWK singlets)**.
- Using **SM Higgs as benchmark**, we look for significant excesses and resonances.
- **ZZ and WW channels final states prevail at high-masses.**





Higgs-like search interpretation

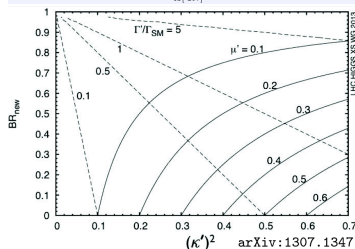
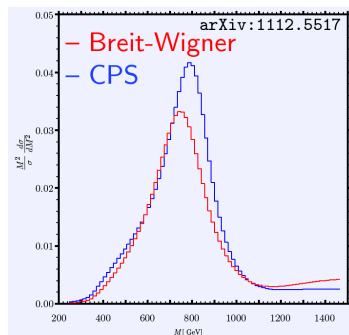
- 2 interpretations of the analysis presented:

- ▶ **SM Higgs searches:**

- ★ Complex Pole Scheme best lineshape approach.
- ★ Interference with $ggZZ$, $ggWW$ included.

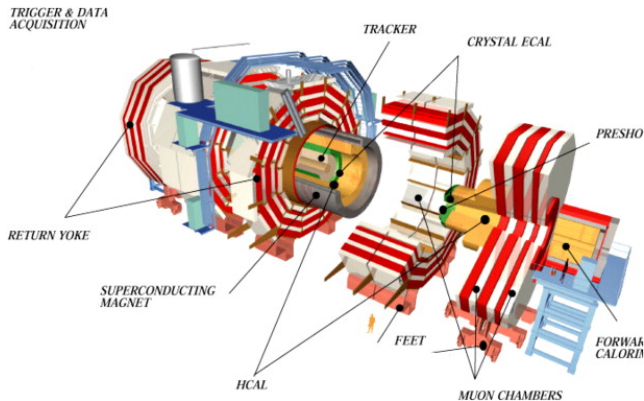
- ▶ **EWK singlet mixed with H(125):**

- ★ Conserve unitarity
 $C_{SM}^2 + C'^2 = 1$
- ★ BR_{new} : heavy boson can have other non-SM decays, including decay to H(125).



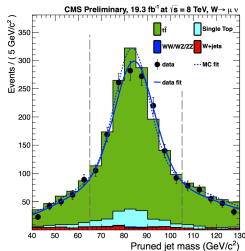
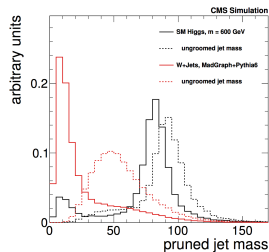
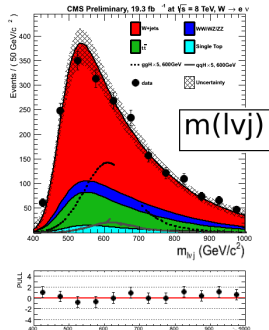
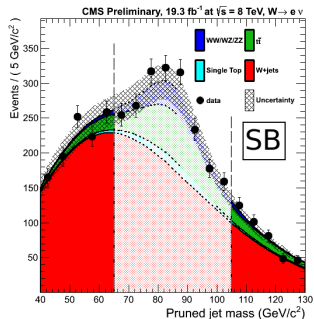
CMS Detector

- CMS design allows **full coverage** to completely reconstruct the event.
- **Excellent performance** since its start.
- Global event description with "particle-flow" algorithm.
- 5 fb^{-1} at $\sqrt{s}=7 \text{ TeV}$ + 20 fb^{-1} at $\sqrt{s}=8 \text{ TeV}$ of data recorded during 2011 and 2012 respectively.
- **Latest results from EPS + new result on VBF $H \rightarrow WW \rightarrow ll\nu\nu$**



$H \rightarrow WW \rightarrow l\nu qq$

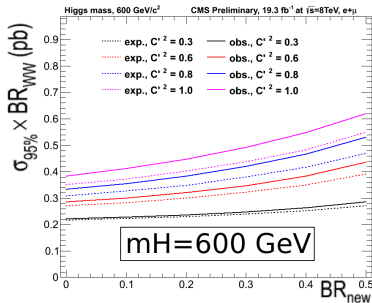
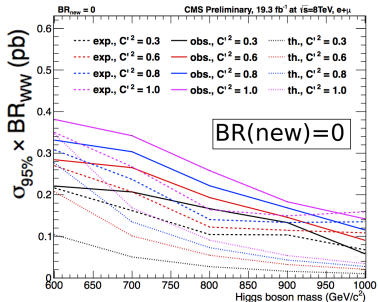
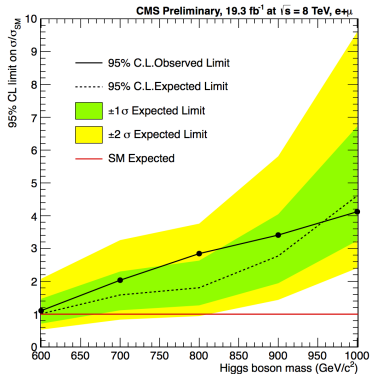
- \mathbf{W}_{lep} reconstructed from $lep + E_T^{miss}$, imposing m_W .
- Boosted $\mathbf{W}_{had} \rightarrow$ merged jets.
- W_{had} reconstructed from jet substructure.
- **Shape analysis using m_{lvj}**
- $W+jets$:
 - ▶ Normalization: fit to m_j in SB
 - ▶ Shape: extrapolation from lower SB with $\alpha_{MC}(m_{lvj})$
- $t\bar{t}, WW, WZ$: from MC



$H \rightarrow WW \rightarrow \nu q q$

- **SM Higgs:** No significant excess, but neither enough sensitivity to exclude.
- **BSM: EWK singlet mixing with H(125):**

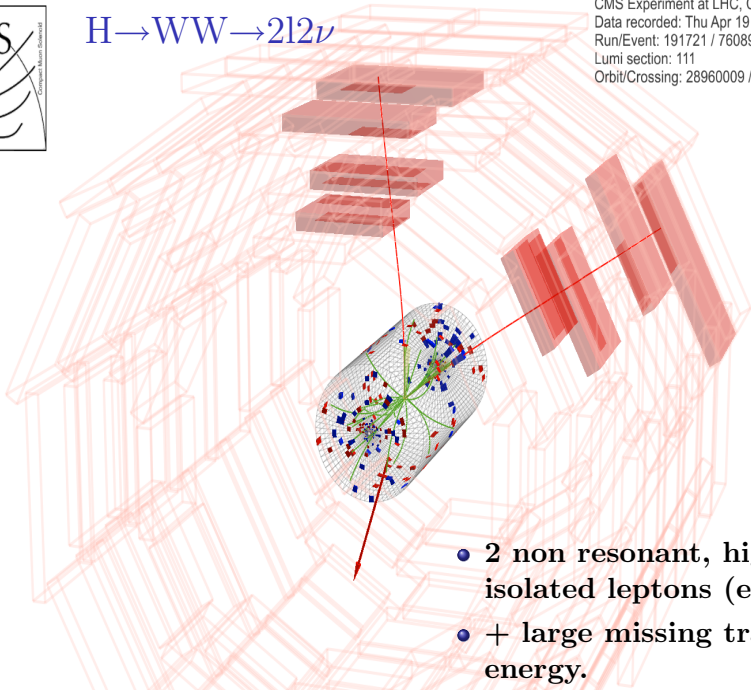
- ▶ Upper limits set for $BR_{new} = 0$ hypothesis and for different m_H as $f(BR_{new})$.





$H \rightarrow WW \rightarrow 2l2\nu$

CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012 CEST
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815

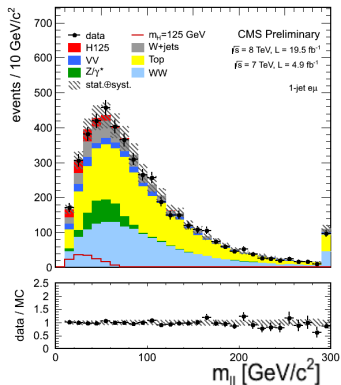


- **2 non resonant, high- p_T isolated leptons ($ee, \mu\mu$).**
- **+ large missing transverse energy.**

$H \rightarrow WW \rightarrow 2l2\nu$

- 9 exclusive channels: $(ee, \mu\mu, e\mu) \times (0j, 1j, \underline{2j \text{ (VBF)}}) \leftarrow \underline{\text{NEW}}$
- 2 analysis: **cut based**, **2D shape analysis on m_T, m_{ll}**
- Same flavour: cut based** analysis ($p_{T,l}, m_{ll}, m_T, \Delta\Phi_{ll}, m_H$)
- Different flavour: shape analysis**

- SM WW: MC**
- Top**: MC normalized from top enriched data sample
- W+Jets, QCD**: data-driven estimation relaxing leptons
- Z/ γ^*** : data driven from m_{ll} in the m_Z peak.

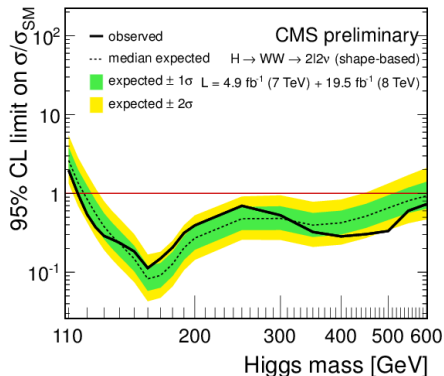
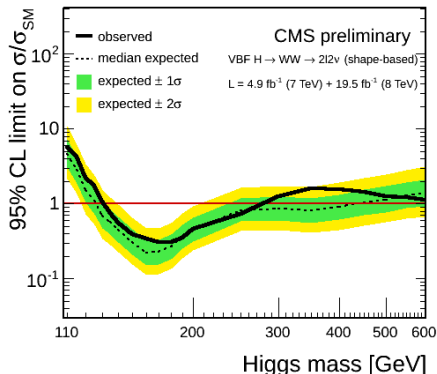


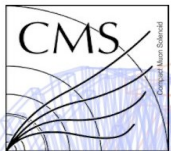
$$m_T = \sqrt{2p_T(ll) + E_T^{miss}(ll)(1 - \cos(\Delta\Phi(E_T^{miss}, ll)))}$$

$H \rightarrow WW \rightarrow 2l2\nu$

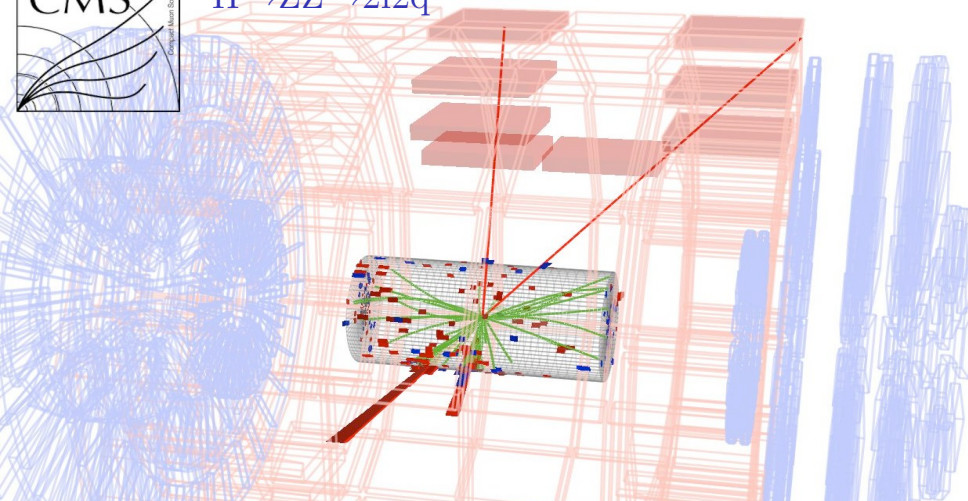
- **VBF** devoted analysis:
 - ▶ MVA for PU rejection
 - ▶ b-veto and soft muon veto (top rejection)
 - ▶ veto on 3rd jet $\eta_{j1} < \eta_{j3} < \eta_{j2}$

- **ggH**: No significant excess observed over expected background:
- 95% CL exclusion of SM Higgs in range $128 < m_H < 600$ GeV (115-575 expected)





$H \rightarrow ZZ \rightarrow 2l2q$

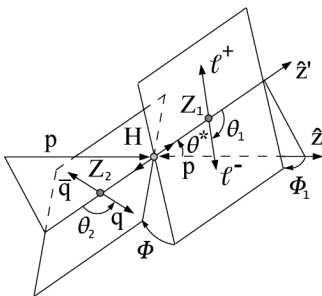
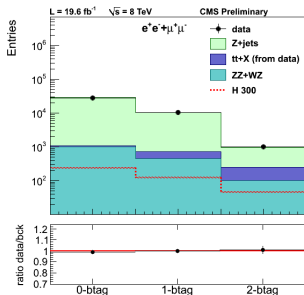


CMS Experiment at LHC, CERN
Data recorded: Sat Jun 11 06:39:40 2011 CEST
Run/Event: 166841 / 181395659
Lumi section: 166
Orbit/Crossing: 43326129 / 3396

- 2 resonant high- p_T isolated leptons ($ee, \mu\mu$) and 2 resonant jets.
- Full m_{lljj} reconstruction

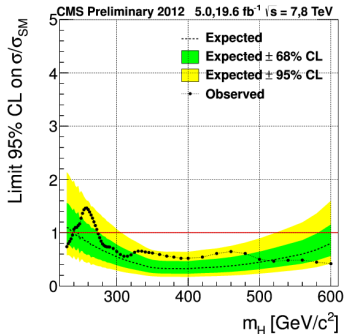
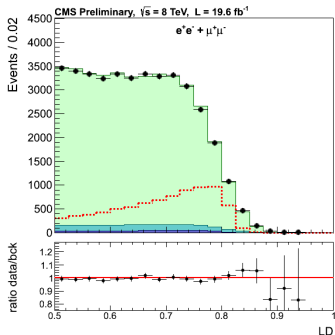
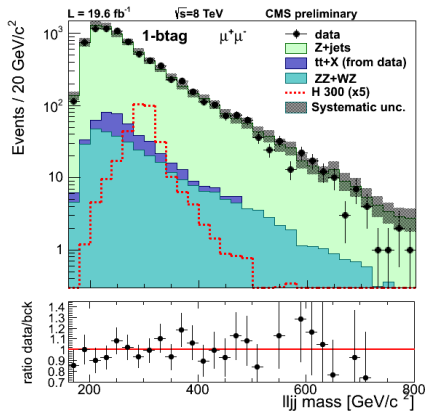
$H \rightarrow ZZ \rightarrow 2l2q$

- Higher cross section: $BR(ZZ \rightarrow 2l2q) > BR(ZZ \rightarrow 4l), BR(ZZ \rightarrow 2l2\nu)$.
- 3 categories according to the tagged b-jets (0, 1 or 2) to take advantage of the higher S/B in the 2l2b channel.
- Large Z+Jets background: MC normalized in the m_{jj} SB.
- Other background processes:
 - ▶ t+X (data-driven) from $e\mu$ control sample.
 - ▶ ZZ, WZ (MC): small contribution.
- Full kinematics of the process described by the five decay angles.



$H \rightarrow ZZ \rightarrow 2l2q$

- Shape analysis m_{lljj} as discriminant.
- 95% CL exclusion of SM Higgs in range $275 < m_H < 600$ GeV (240-600 exp.)
- In progress, extension to 1 TeV with boosted jets.



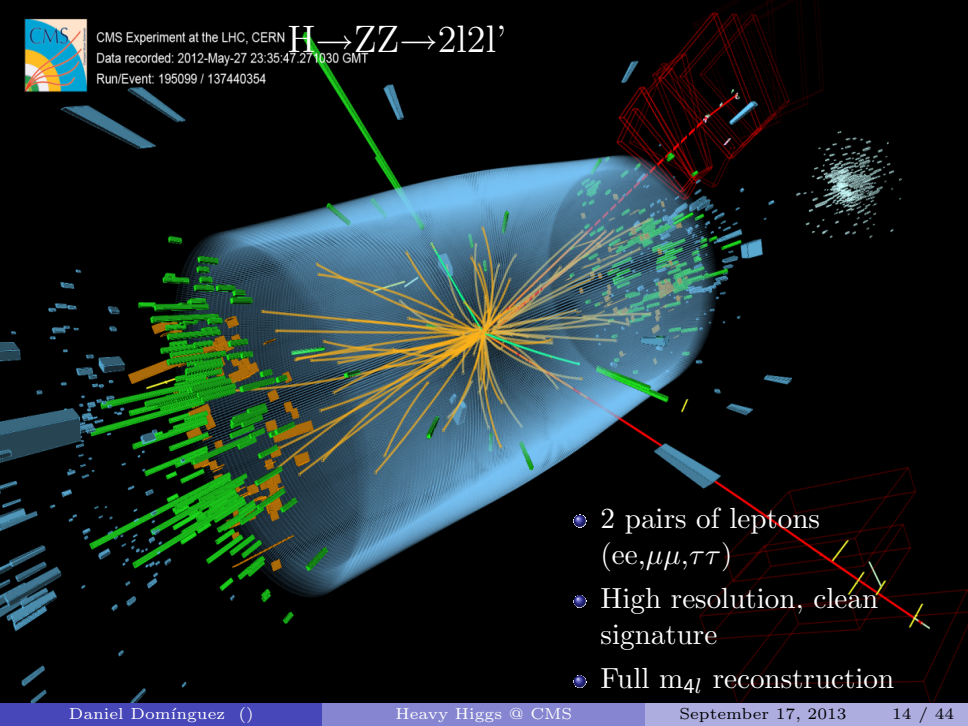


CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354

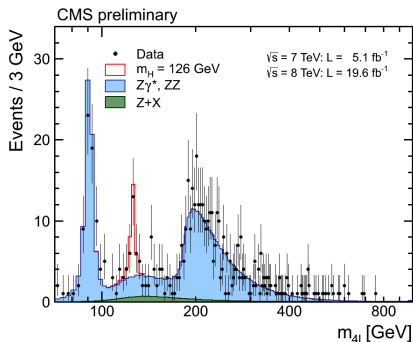
$H \rightarrow ZZ \rightarrow 2l_1 2l_2'$



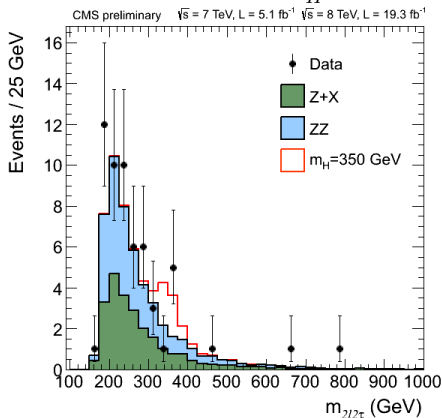
- 2 pairs of leptons
($ee, \mu\mu, \tau\tau$)
- High resolution, clean signature
- Full m_{4l} reconstruction

$H \rightarrow ZZ \rightarrow 2l2l'$

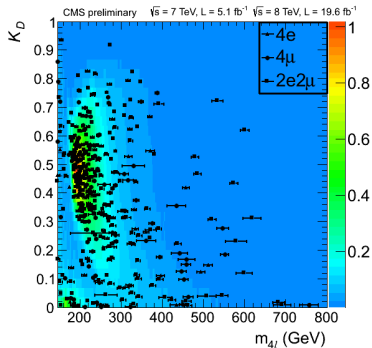
- High S/B
- 12 categories:
 - ▶ 3 flavours ($ee, \mu\mu, \tau\tau$) x 2 data periods x 2 production modes (ggH, VBF).



- $V_D(\Delta\eta_{jj}, m_{jj})$ discriminator for VBF.
- $H \rightarrow ZZ \rightarrow 2l2\tau$, with τ decaying to $e, \mu, \text{hadrons}$
 - ▶ Sensitive for $m_H > 180$

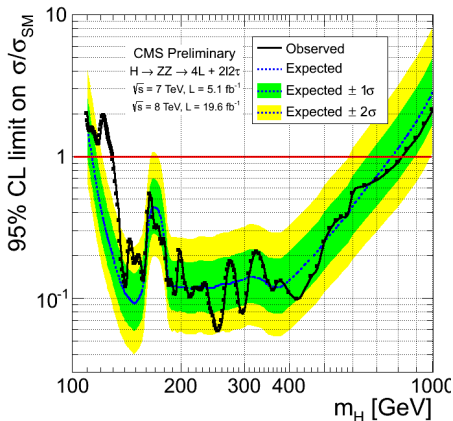


$H \rightarrow ZZ \rightarrow 2l2l'$

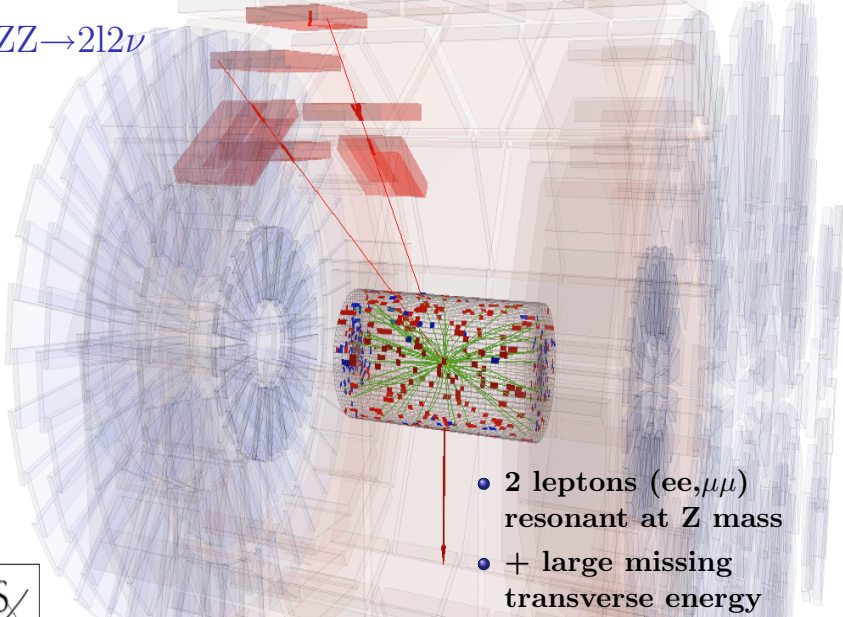


- Final discriminator:
 - ▶ ggH: m_{4l}, K_D
 - ▶ VBF: m_{4l}, K_D, V_D
- 95% CL exclusion of SM Higgs in range $130 < m_H < 827$ GeV (113.5-778 exp.)

- Main background: SM $\rightarrow ZZ$ (MC)
- Other: $Z+X, t\bar{t} \rightarrow$ data-driven from $Z+X$ samples
- Matrix Element discriminator $K_D(m_{Z_1}, m_{Z_2}, 5 \text{ angles})$



$H \rightarrow ZZ \rightarrow 2l2\nu$



- 2 leptons ($ee, \mu\mu$) resonant at Z mass
- + large missing transverse energy
- Best S/B at very high mass hypothesis.



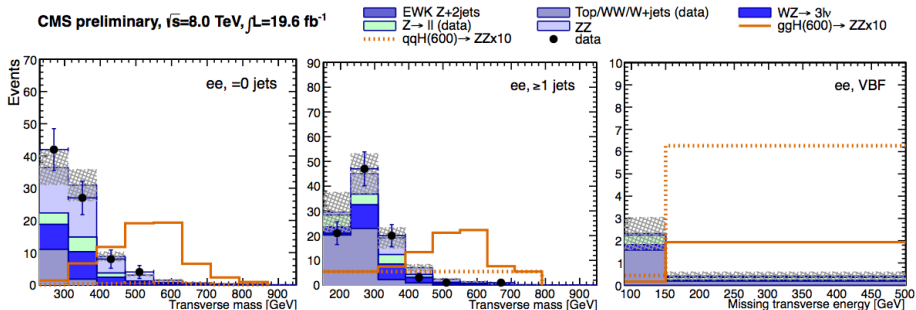
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 14 20:12:21 2012 CEST
Run/Event: 207269 / 219613713
Lumi section: 181

H → ZZ → 2l2ν

- m_T and E_T^{miss} final discriminators
- 6 categories: 2 flavours (ee, μμ) x (0jet, 1jet, VBF)
- 2 analysis: cut&count, **shape analysis**.
- Z+Jets: data-driven from Z+γ
- tWW, Wlt̄: data-driven from eμ sample
- minor ZZ, WW: from MC

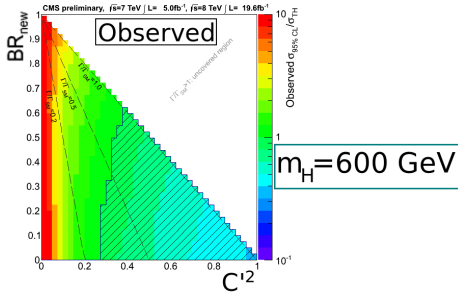
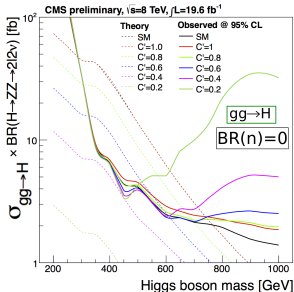
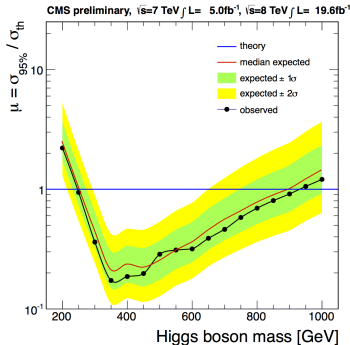
$$M_T^2 = \left(\sqrt{p_T(l)^2 + M(l)^2} + \sqrt{E_T^{miss^2} + M(l)^2} \right)^2 - (\vec{p}_T(l) + \vec{E}_T^{miss})^2$$

CMS preliminary, $\sqrt{s}=8.0$ TeV, $\mathcal{L}=19.6$ fb⁻¹



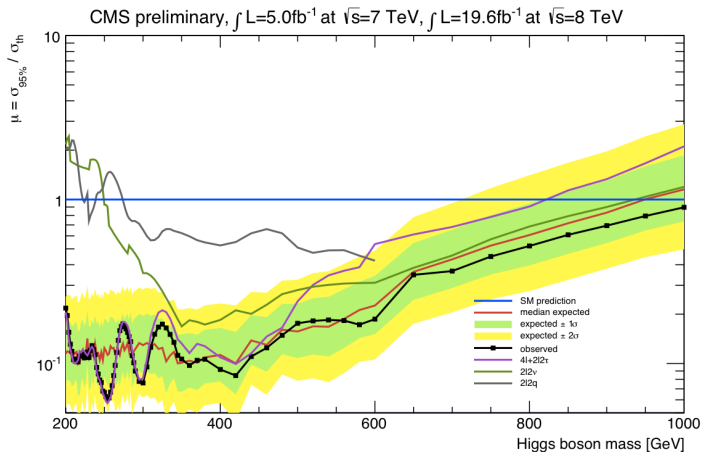
$H \rightarrow ZZ \rightarrow 2l2\nu$

- 95% CL limits on SM Higgs $248 < m_H < 930$ GeV (254-898 GeV expected).
- BSM interpretation: mixed EW singlet:
 - Assuming $BR_{new}=0$:
 - 95% CL upper limit on $\sigma \times BR$ under different C' assumptions
 - $C' > 0.446$ excluded at 95% CL with H(125) constraints.
 - Varying BR_{new} and C' for several mass hypothesis: large region of phase space excluded.



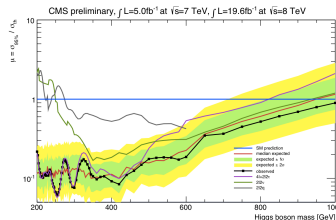
H \rightarrow ZZ Combination

- All H \rightarrow ZZ combined in the SM Higgs search.
- **SM Higgs excluded range at 95% CL in the whole range 200-1000GeV (200-950 exp.).**



Conclusions

- Besides the discovery of the H(125) boson, extended searches of Higgs-like resonances are necessary at higher mass.
- $H \rightarrow ZZ$ and $H \rightarrow WW$ analyses performed with **4.9 fb⁻¹ at 7TeV** and **19.6 fb⁻¹ at 8TeV**.
- BSM EWK singlet mixing with H(125) search has already been included in some of the analyses.
- No significant excess over the predicted background has been observed up to 1TeV.
- BSM EWK singlet for all analyses, as well as 2HDM models, coming soon.



THANK YOU

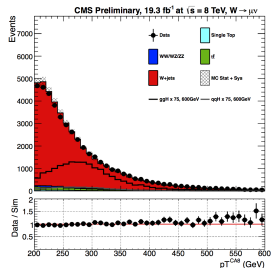
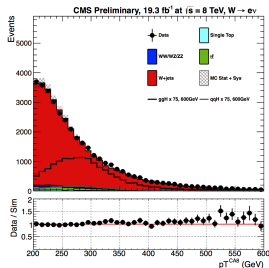
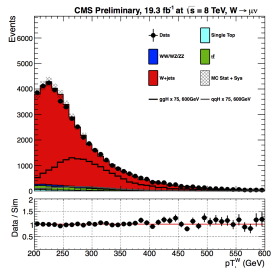
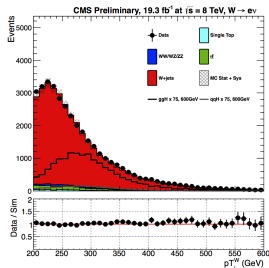
BACKUP

BACKUP

Some Info about standard SM Higgs Simulation

- Higgs signal simulated with: WW, ZZ: POWHEG at NLO for ggH and qqH WH,ZH,ttH: PYTHIA
- Corrected with total $\sigma(pp \rightarrow H)$ including NNLO and NNLL
- Corrected the lineshape on the complex-pole scheme
- Interference with ggWW and ggZZ backgrounds taken into account.

H \rightarrow WW \rightarrow l ν qq: p_T objects after basic kinematic selection

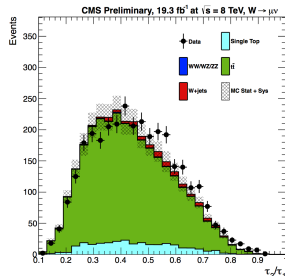
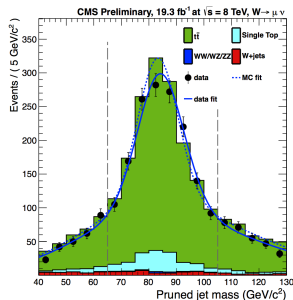
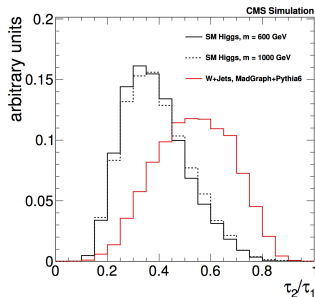


$H \rightarrow WW \rightarrow l\nu qq$: W_{had} identification

- C-A($\Delta R=0.8$) algorithm, pruning jet.
- m_j and τ_2/τ_1 used to identify W.
- Validated with top samples.
- full $m_{l\nu j}$ reconstructed from ungroomed jet.

$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min(\Delta R_{1,i}, \Delta R_{2,i} \dots \Delta R_{N,i})$$

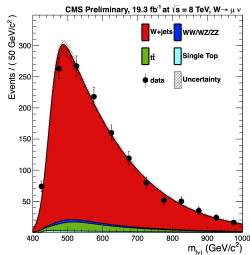
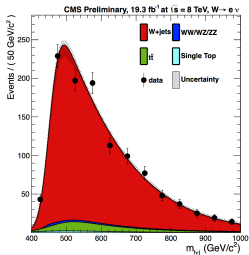
$$d_0 = \sum_i p_{T,i} R_0^\beta$$



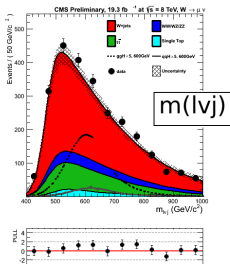
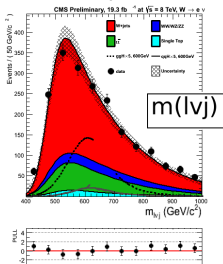
$H \rightarrow WW \rightarrow l\nu qq$: W +Jets determination

SR=(65,105) GeV. SIDEBAND=(40,65)+(105,130) GeV (in m_j)

- $m_{l\nu j}$ in the low Sideband (electron and muon channel).



- Final $m_{l\nu j}$ in Signal region (electron and muon channel)

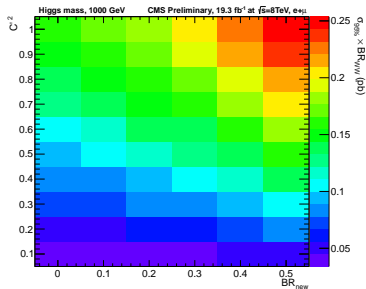
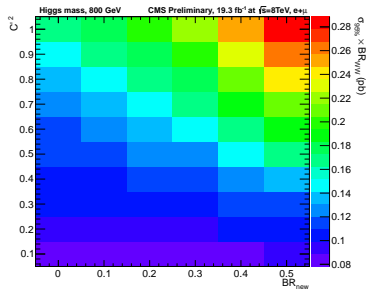
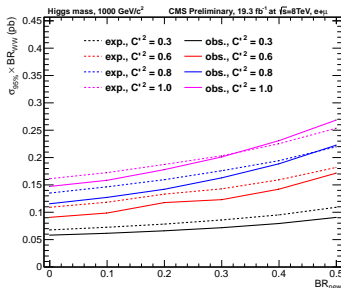
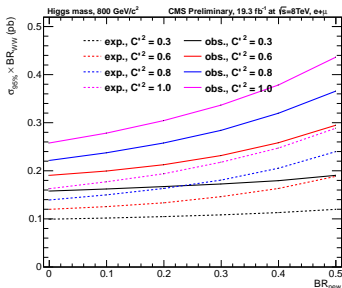


$H \rightarrow WW \rightarrow l\nu qq$: Systematics

Syst. uncertainty	sig, ggH	sig, VBF	W+jets	$t\bar{t}$	single t	WW/WZ
lumi	4.4%	4.4%	-	4.4%	4.4%	4.4%
Higgs QCD scale	6.5% †	1.3% †	-	-	-	-
Higgs PDF+ α_s	12.1% †	5.9% †	-	-	-	-
Intf (sig/bkg)	10.0%	50.0%	-	-	-	-
Bkg cross-section	-	-	-	-	30.0%	30.0%
W+jets norm.	-	-	8%	-	-	-
W-tagging	10.0%	10.0%	-	-	-	10.0%
$t\bar{t}$ norm.	-	-	-	6.0%	6.0%	-
Jet mass/energy scale	2%	2%	-	2%	2%	2%
W+jets shape	-	-	see Sec. 6	-	-	-
b-tagging	2.5%	2.5%	-	-	2.5%	2.5%
Trigger (e & μ)	1%	1%	-	-	1%	1%
Selection Eff. (e & μ)	2%	2%	-	-	2%	2%

Table 1: Summary of systematic uncertainties related to normalization of expected signal and background yields. The symbol † denotes a mass-dependent uncertainty.

H → WW → lν qq: BSM Interpretation



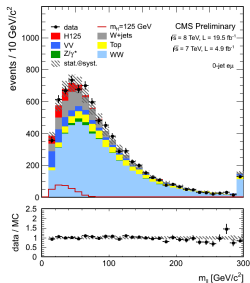
H \rightarrow WW \rightarrow ll $\nu\nu$: Selection

- $p_T(l_1, l_2) > (20, 10) / (20, 15)$ at 8 / 7 TeV.
- $E_T(\text{jets}) > 30$ GeV.
- MVA for PU rejection in VBF analysis.
- Projected E_T^{miss} .
- b-veto, soft muon veto to reject $t\bar{t}$.
- $p_T(ll) > 30(45)$ GeV at 8 (7) TeV.
- $m_{ll} > 12(20)$ GeV at 8 (7) TeV.
- **VBF:**
 - ▶ $|m_{ll} - m_Z| > 15$ for same flavour.
 - ▶ $p_T(jj) > 500$ GeV, $\Delta\eta(jj) > 3.5$
 - ▶ Rejection if 3rd jet inside eta region of j_1, j_2
 - ▶ Rejection if leptons outside eta region of j_1, j_2

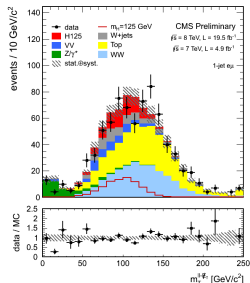
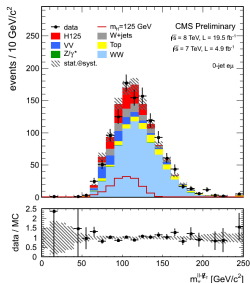
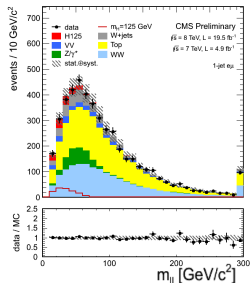
m_H	$p_T^{\ell, \text{max}}$	$p_T^{\ell, \text{min}}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	m_T
[GeV]	[GeV]	[GeV]	[GeV]	[°]	[GeV]
	>	>	<	<	[,]
120	20	10	40	115	[80,120]
125	23	10	43	100	[80,123]
130	25	10	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]

$H \rightarrow WW \rightarrow \ell\ell\nu\nu$: $m_{\ell\ell}$ and m_T full cut based selection

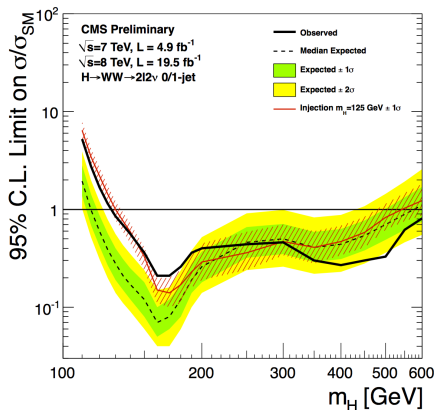
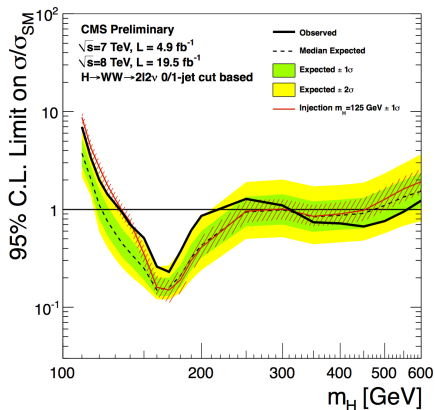
0-jet category.



1-jet category.



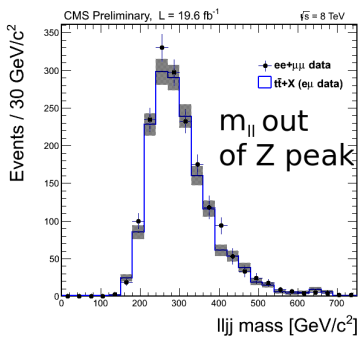
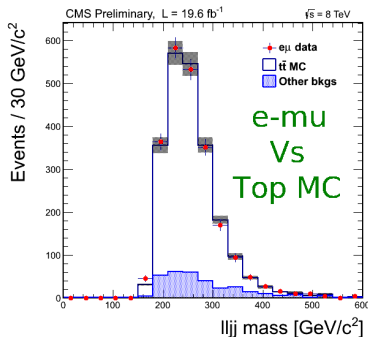
$H \rightarrow WW \rightarrow ll\nu\nu$: Limits



$H \rightarrow ZZ \rightarrow 2l2q$: Selection, Top background determination

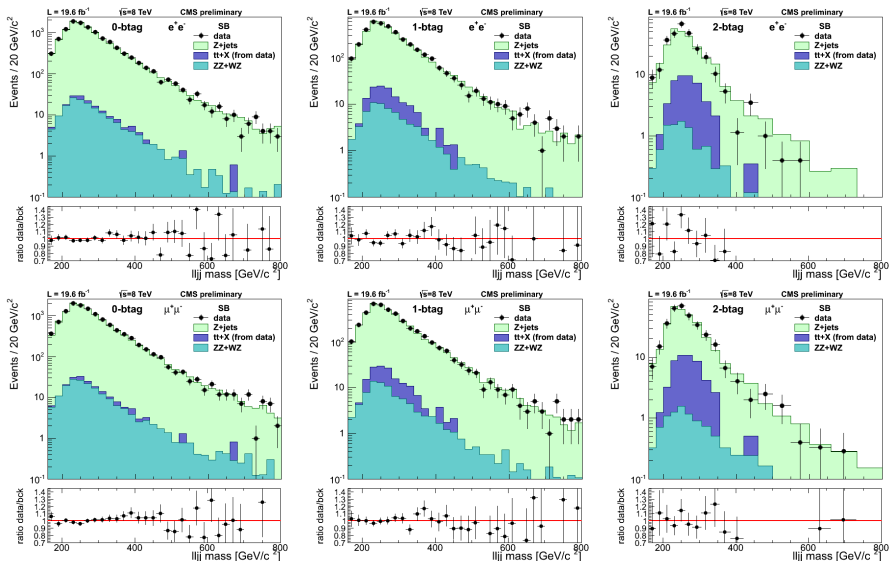
preselection			
$p_T(\ell^\pm)$	lowest $p_T > 20 \text{ GeV}/c$, highest $p_T > 40 \text{ GeV}/c$		
$p_T(\text{jets})$	$> 30 \text{ GeV}/c$		
$ \eta (\ell^\pm)$	$e^\pm < 2.5, \mu^\pm < 2.4$		
$ \eta (\text{jets})$	< 2.4		
	0 b-tag	1 b-tag	2 b-tag
b-tag	none	one loose	medium & loose
LD	> 0.5		
$\lambda(\vec{B}_T)$	< 10		
m_{jj}	$\in [71, 111] \text{ GeV}/c^2$		
$m_{\ell\ell}$	$\in [76, 106] \text{ GeV}/c^2$		

- Top estimated directly from the $e\mu$ data



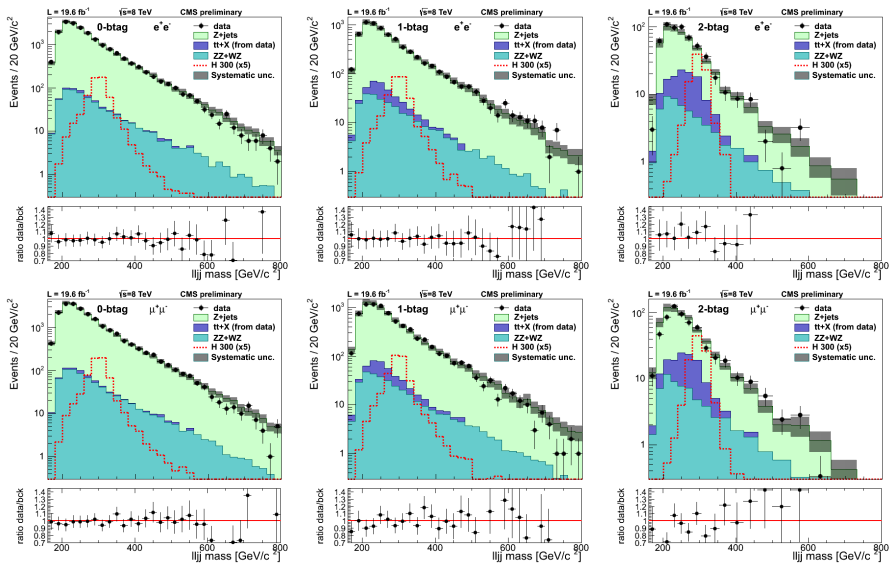
$H \rightarrow ZZ \rightarrow 2l2q$: m_{lljj} in the m_j Sideband region

- 6 categories: $ee, \mu\mu \times 0b\text{-jets}, 1b\text{-jet}, 2b\text{-jets}$.



$H \rightarrow ZZ \rightarrow 2l2q$: m_{lljj} in the m_j Signal region

- 6 categories: $ee, \mu\mu \times 0b\text{-jets}, 1b\text{-jet}, 2b\text{-jets}$.

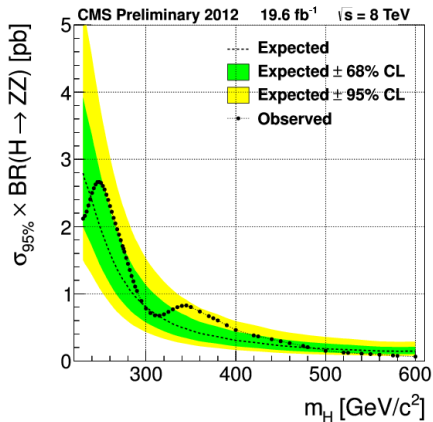
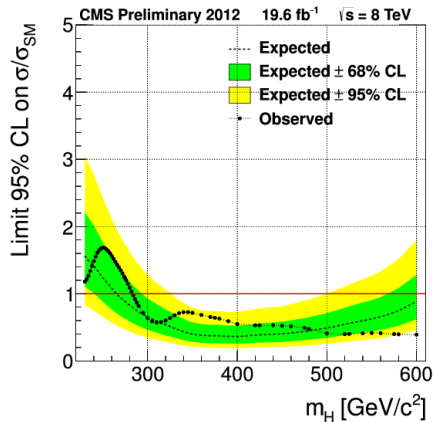


H \rightarrow ZZ \rightarrow 2l2q: Systematics

Source	0 <i>b</i> -tag	1 <i>b</i> -tag	2 <i>b</i> -tag
Muon trigger & ID		2.7%	
Electron trigger & ID		2%	
Electron energy scale		0.2%	
Muon momentum scale		0.1%	
Jet reconstruction		1-4%	
<i>b</i> -tagging eff. and mistag rate	1-4%	1-5%	5-8%
MET		< 1%	
Pile-up		1-2%	
Production mechanism (PDF)		1.5%	
Production mechanism (lineshape)		0-3%	
Luminosity		4.4%	
Higgs cross-section (for R)		13-15%	

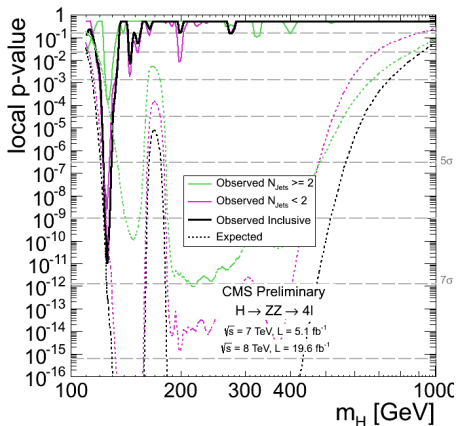
Source		Normalization	Shape
Muon trigger & ID		2.7%	
Muon momentum scale		0.1%	
Electron trigger & ID		2.0%	
Electron energy scale		0.5%	
Jet energy scale		5.5%	0-4%
<i>b</i> -tagging efficiency SF	0-tag	+0.4%	
	1-tag	-0.8%	
	2-tag	-4.5%	
Mistag SF	0-tag	-1.9%	
	1-tag	+7.8%	
	2-tag	+6.2%	
\cancel{H}_T		0.3%	
Pile-up		0.1%	
$p_T^{\ell\ell jj}$ weighting		0.8%	0-3%
Diboson cross section		15%	
Luminosity		4.4%	
Residual differences	0-tag		0-15%
	1-tag		0-30%
	2-tag		0-40%

$H \rightarrow ZZ \rightarrow 2l2q$: 8 TeV-only limits

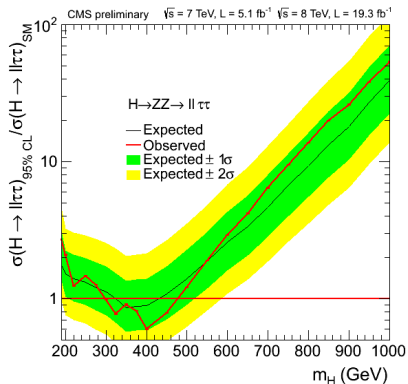
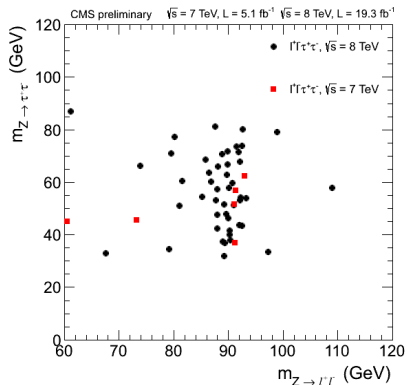


$H \rightarrow ZZ \rightarrow 2l2l'$

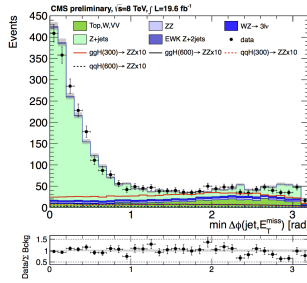
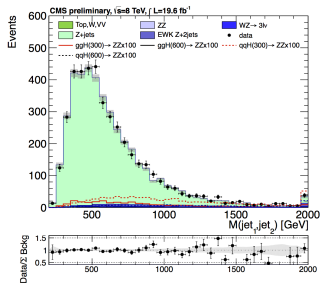
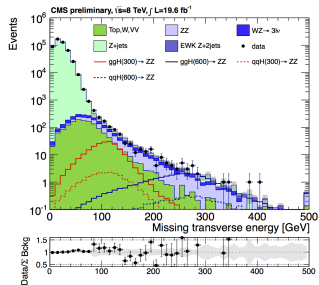
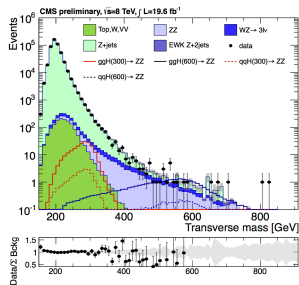
Channel	4e	4 μ	2e2 μ	2 ℓ 2 τ
ZZ background	78.9 \pm 10.9	118.9 \pm 15.5	192.8 \pm 24.8	27.4 \pm 3.6
Z+X	6.5 \pm 2.6	3.8 \pm 1.5	9.9 \pm 4.0	22.9 \pm 7.8
All background expected	85.5 \pm 11.2	122.6 \pm 15.5	202.7 \pm 25.2	50.3 \pm 8.6
$m_H = 125$ GeV	3.5 \pm 0.5	6.8 \pm 0.8	8.9 \pm 1.0	–
$m_H = 126$ GeV	3.9 \pm 0.6	7.4 \pm 0.9	9.8 \pm 1.1	–
$m_H = 500$ GeV	5.1 \pm 0.6	6.8 \pm 0.8	12.0 \pm 1.3	3.7 \pm 0.4
$m_H = 800$ GeV	0.7 \pm 0.1	0.9 \pm 0.1	1.6 \pm 0.2	0.4 \pm 0.1
Observed	86	125	240	57



$H \rightarrow ZZ \rightarrow 2l2\tau$



H \rightarrow ZZ \rightarrow 2l2 ν : Preselection



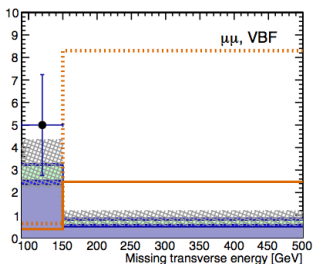
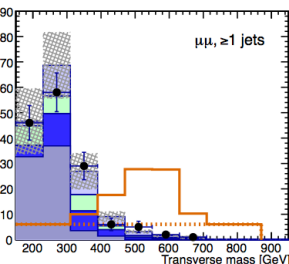
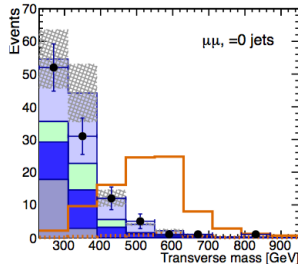
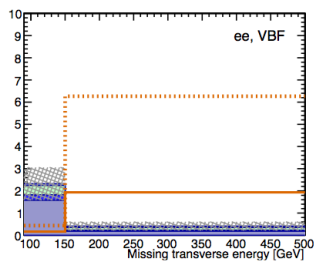
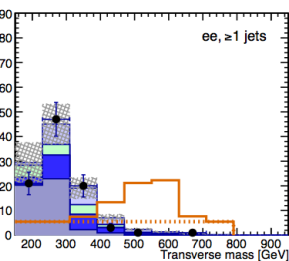
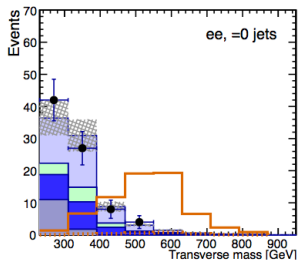
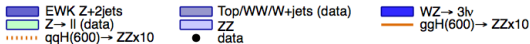
$H \rightarrow ZZ \rightarrow 2l2\nu$: Cut based selection & Systematics

m_H (GeV)	200	300	400	500	≥ 600
E_T^{miss} (GeV)	> 80	> 100	> 110	> 110	> 110
M_T (GeV)	180 – 220	180 – 270	350 – 450	400 – 600	500 – ∞

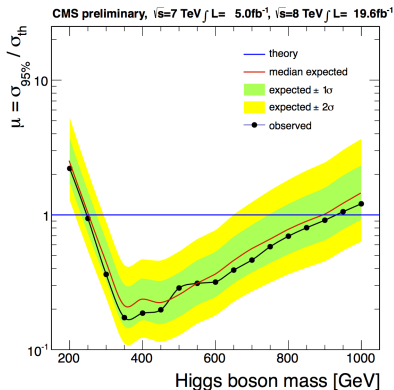
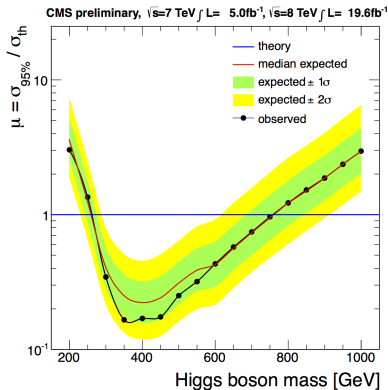
Source	Uncertainty [%]	Type	
Experimental	b -veto	1-3	shape
	Lepton ID+Isolation	2-3.5	rate
	Lepton momentum scale	1-2	shape
	Jet energy scale/resolution	1	shape
	Pile-up effects, E_T^{miss}	1-3	shape
	Trigger	2	rate
	Non-resonant background estimation from data	25	rate
	Z+jets estimation from data	100	shape
Simulation statistics	1-2	shape	
Luminosity	2.2 (7 TeV), 4.4 (8 TeV)	rate	
Theory	PDF, gluon-gluon initial state	6-11	rate
	PDF, quark-quark initial state	3.3-7.6	rate
	QCD scale, gluon-gluon initial state (ggH)	7.6-11	rate
	QCD scale, quark-quark initial state (VBF)	0.2-2	rate
	QCD scale, gluon-gluon initial state (ggZZ)	20	rate
	QCD scale, quark-quark initial state (qqVV)	5.8-8.5	rate
	Line shape uncertainty	2-8	shape
Contribution from ZZ interference	2-13 (100 in BSM)	rate	

$H \rightarrow ZZ \rightarrow 2l2\nu$: m_T and E_T^{miss} in the 6 categories

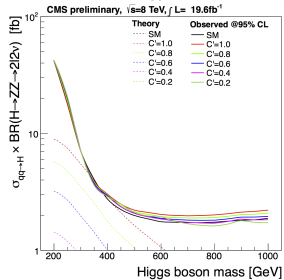
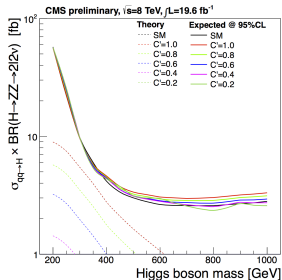
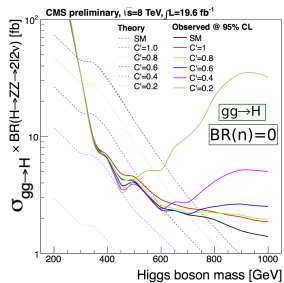
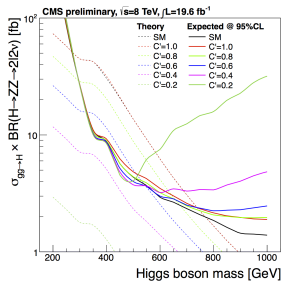
CMS preliminary, $\sqrt{s}=8.0$ TeV, $\mathcal{L}=19.6$ fb $^{-1}$



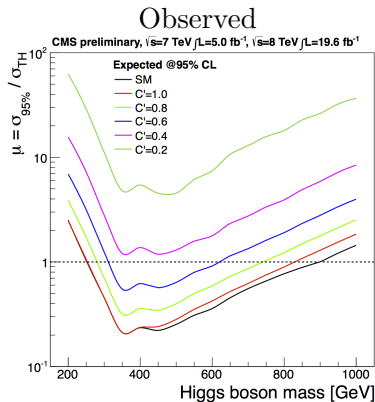
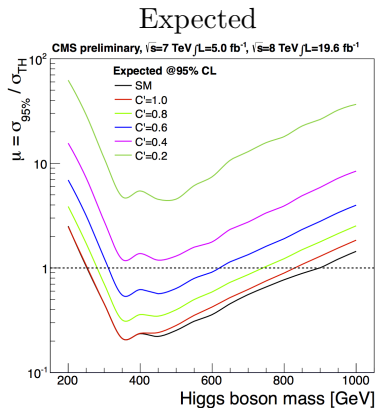
$H \rightarrow ZZ \rightarrow 2l2\nu$: Total Signal Strength for Cut&Count, shape



$H \rightarrow ZZ \rightarrow 2l2\nu$: Expected (left) and observed (right) upper limits on $\sigma_{gg \rightarrow H}$ of a EWK singlet Higgs boson, for ggH (up) and VBF(bottom).



$H \rightarrow ZZ \rightarrow 2l2\nu$: signal strength, of a singlet scalar with modified couplings C' and width Γ with respect to the SM.



$H \rightarrow ZZ \rightarrow 2l2\nu$: Expected (Up) and Observed (bottom) upper limits at 95% CL on the signal strength as function of BR_{new} and Γ/Γ_{SM} .

