Search for the SM Higgs boson at CMS

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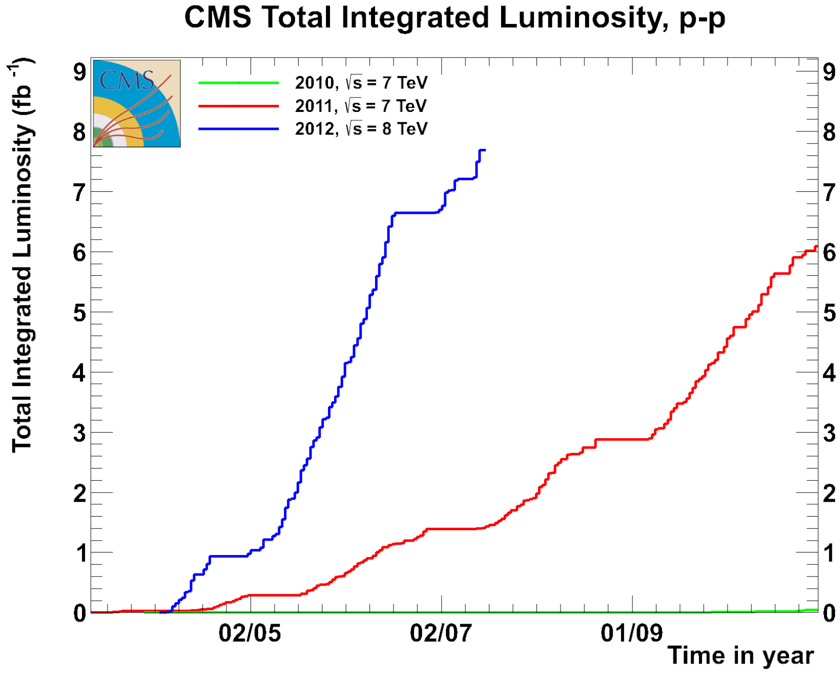
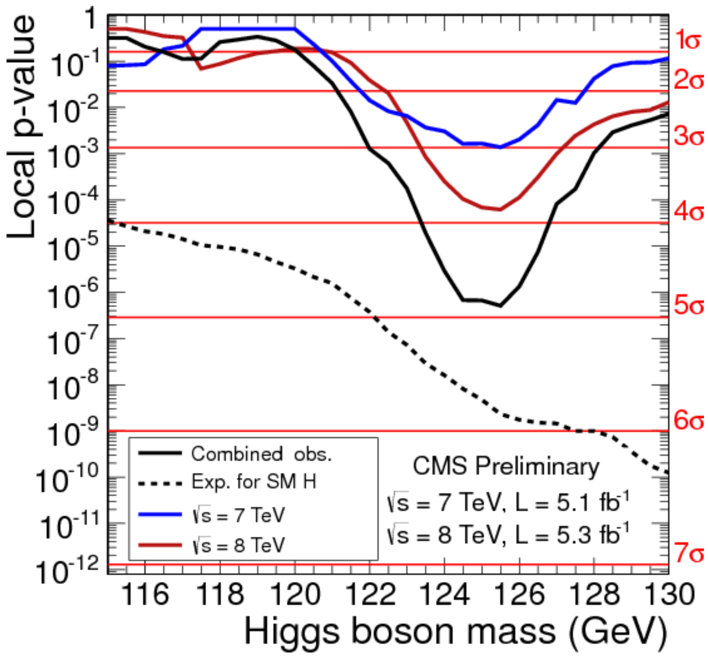
On behalf of the CMS Collaboration



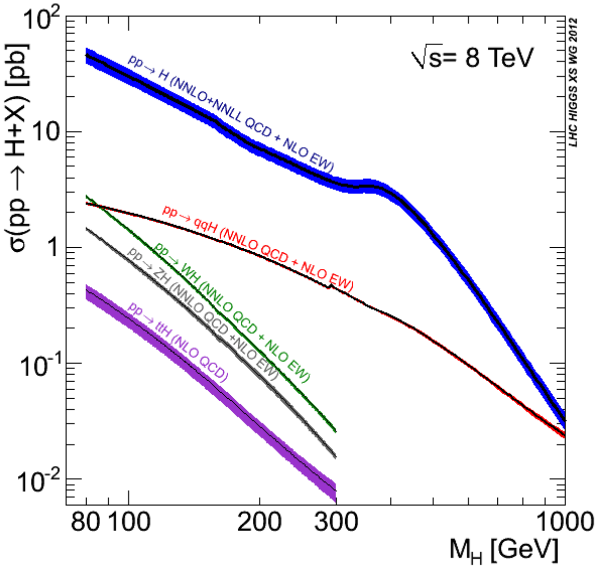


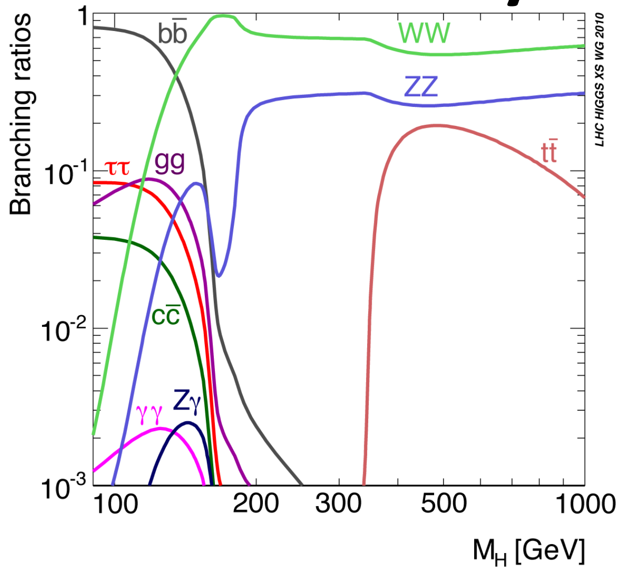
Introductory remarks

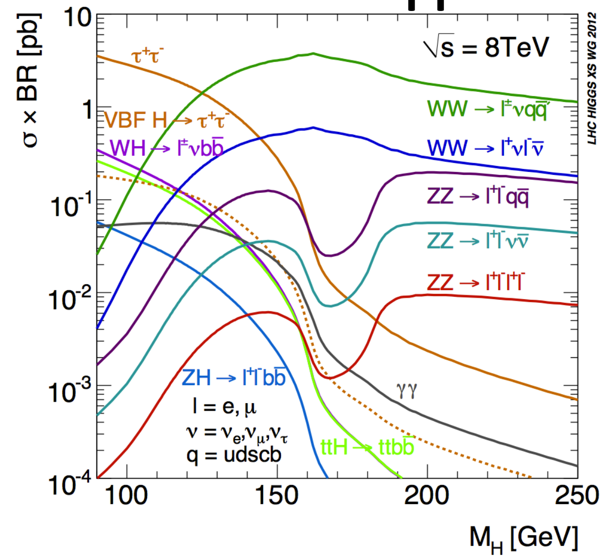
- Open window [115-130] for SM Higgs boson before July 4th, 2012
  - Focus of today's talk
- High mass: gain higher confidence (more in backup)
- Statistical methodology: same as before since last year

  ATLAS and CMS Collaborations, LHC Higgs Combination Group, "Procedure for the LHC Higgs boson search combination in Summer 2011"

Production and decays at low m_H

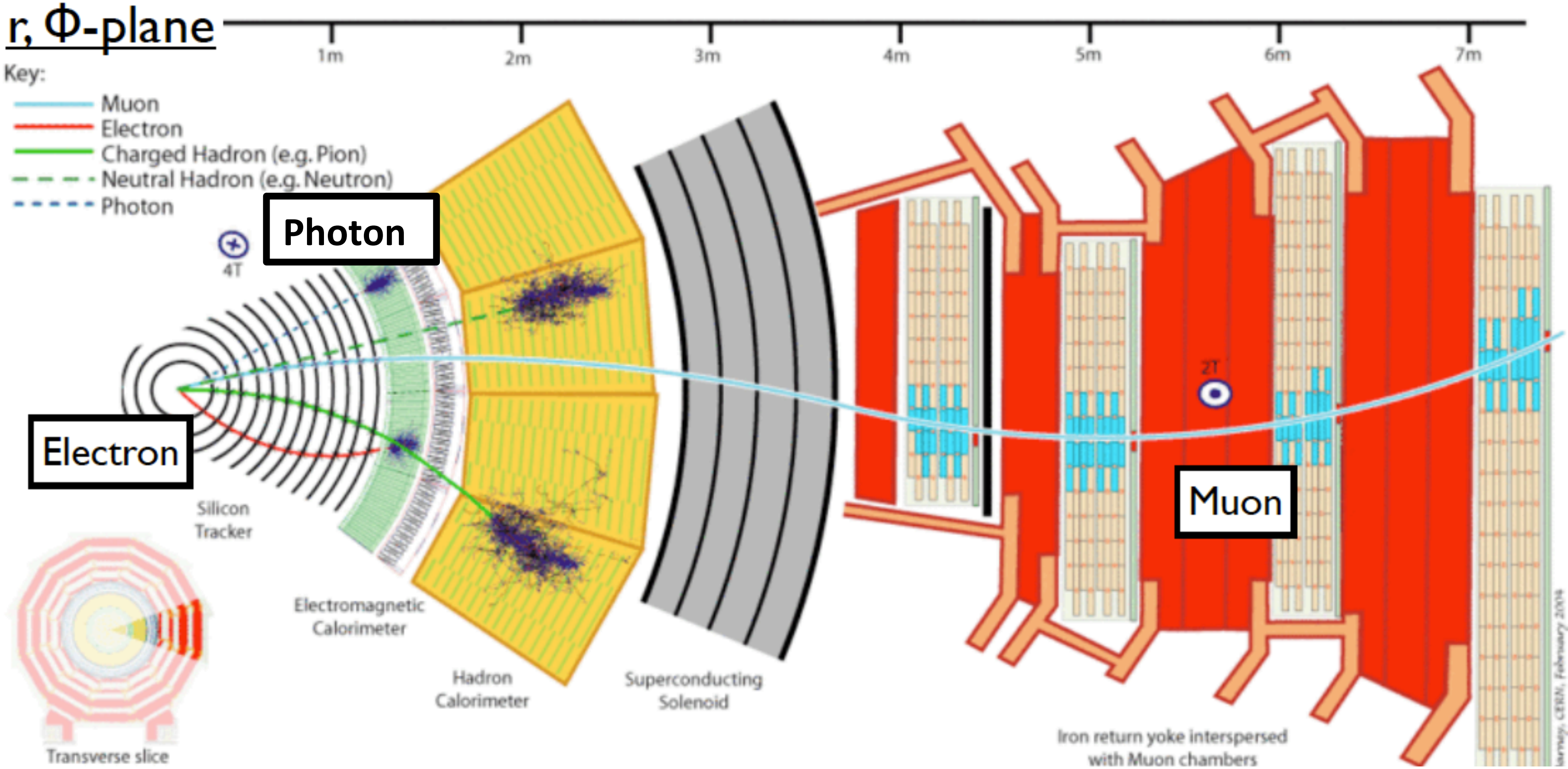






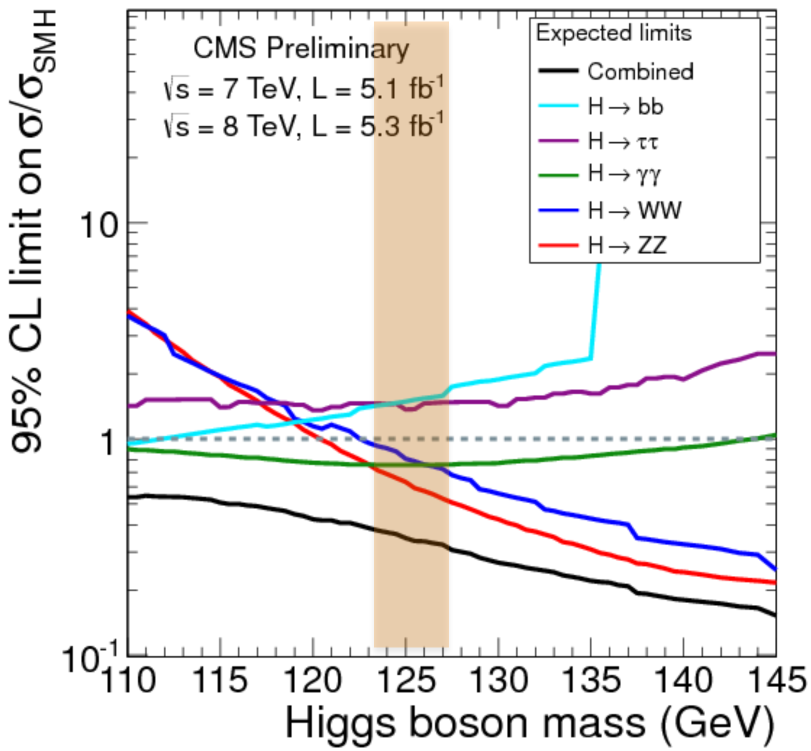
	untagged		VBF-tag		VH-tag		ttH-tag	
H→γγ	7 TeV	8 TeV	7 TeV	8 TeV				
H→bb					7 TeV	8 TeV	7 TeV	
H→ττ	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV			
H→WW	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV			
H→ZZ	7 TeV	8 TeV						

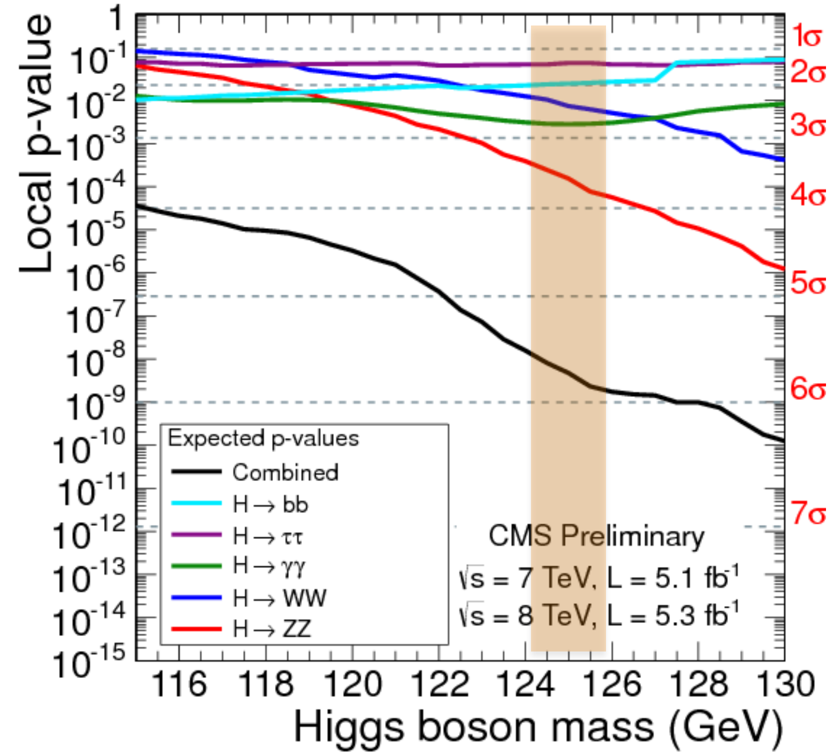
CMS Detector



- **huge efforts put on improving objects selection and optimizing analyses**
- **e.g. 7 TeV search sensitivity improved from 3σ to 4σ around m_H = 125**

Relative sensitivities at low m_H

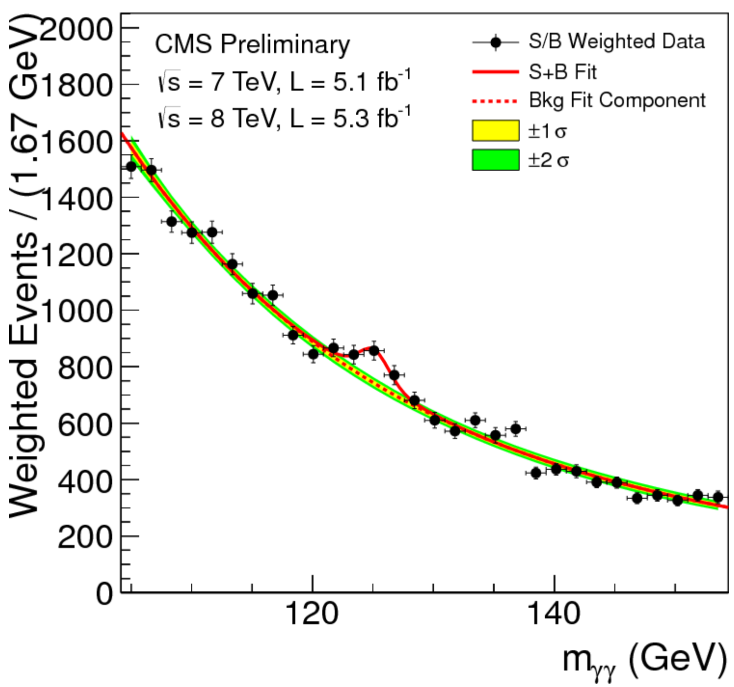


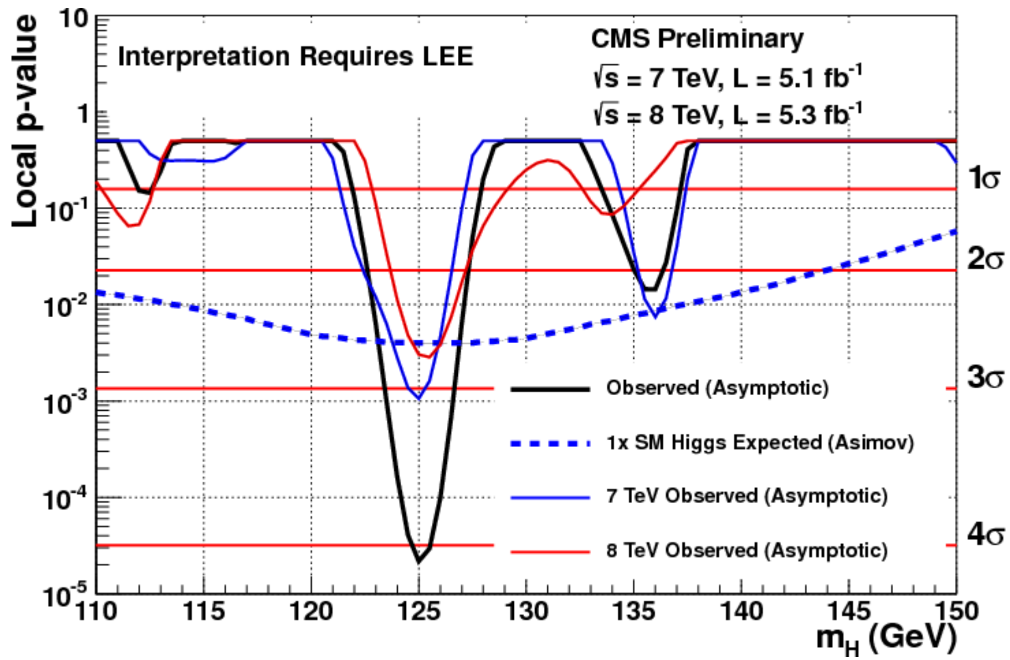


- **all 5 decay models give fair sensitivities**
- **at m_H~ 125 GeV, the highest sensitivity is achieved in the ZZ, γγ and WW channels, followed by ττ and bb**

talk by Y. Chang

Summary of channels: H→γγ

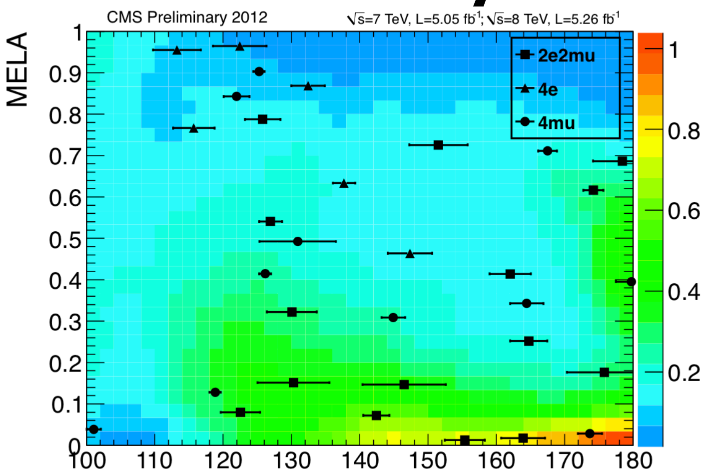


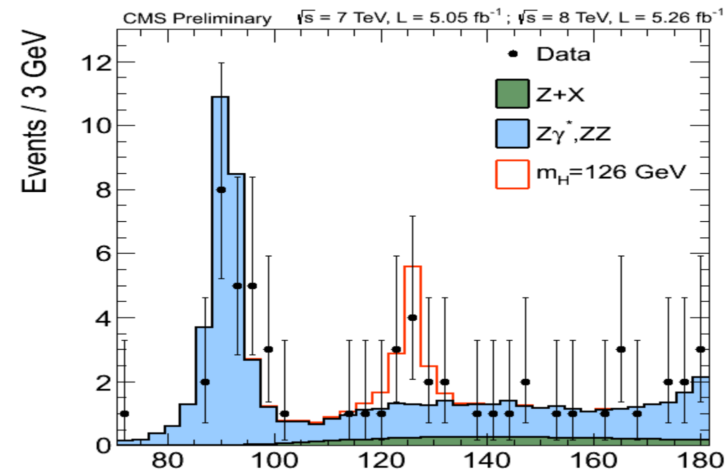


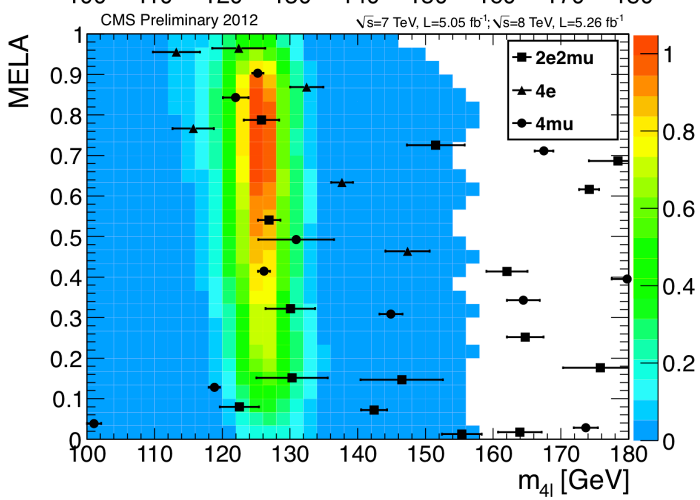
- **fit mass distribution based on MVA output**
- **5 categories in 7 TeV and 6 categories in 8 TeV**
- **4.1σ (expected 2.8σ) excess at 125 GeV**

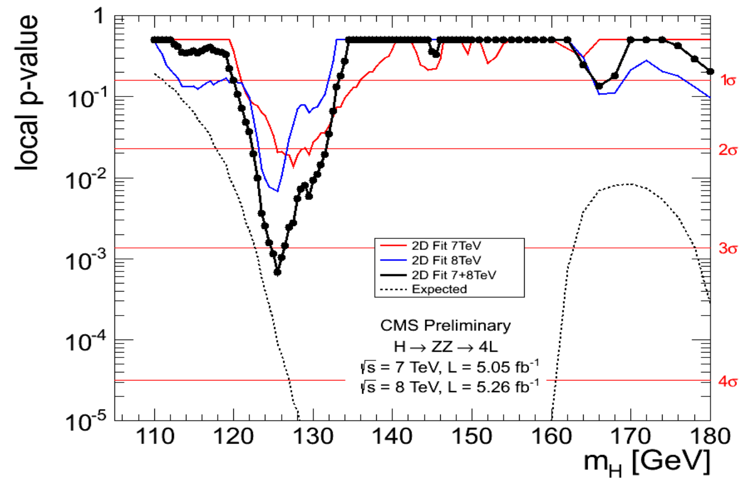
talk by S. Baffioni

Summary of channels: H→ZZ→4l





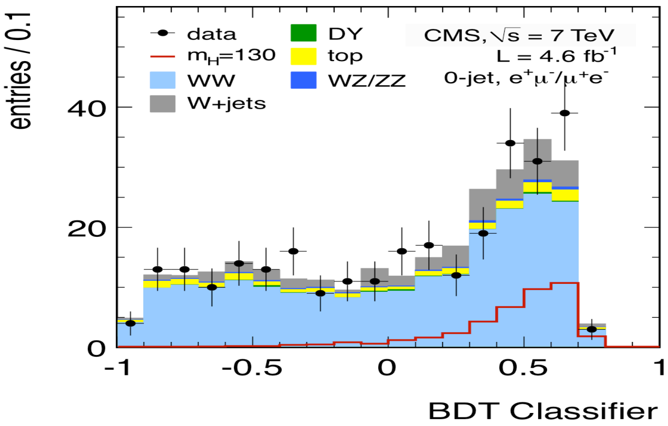


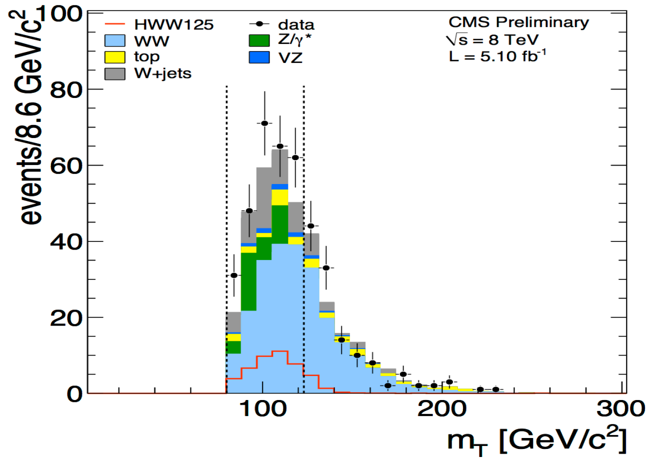


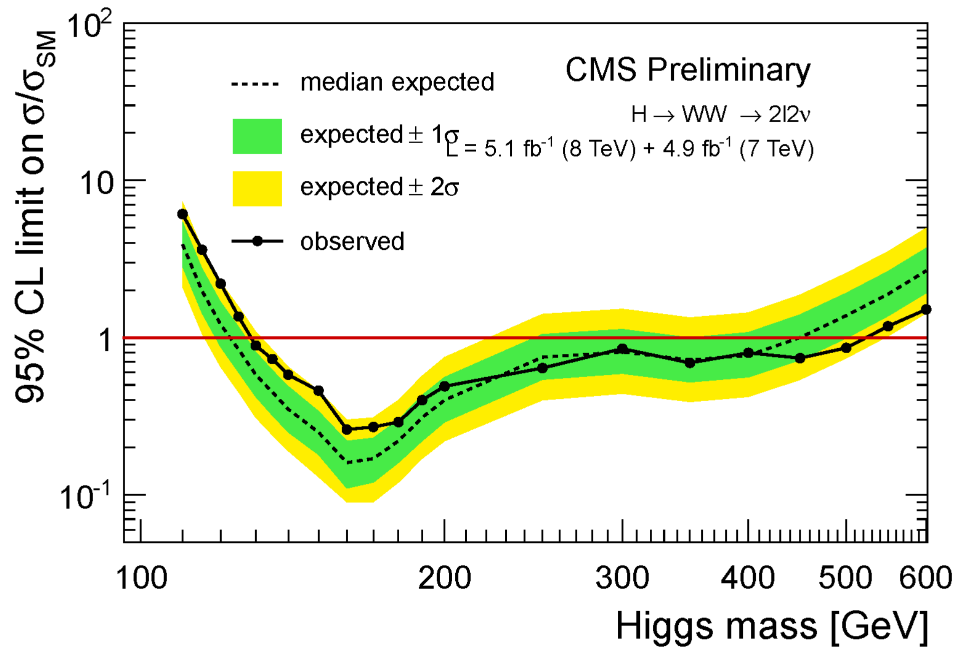
- **4l mass and MELA 2D final analysis**
- **3.2σ (expected 3.8σ) excess at 125.5 GeV**

talk by D. Evans

Summary of channels: H→WW→2l2ν



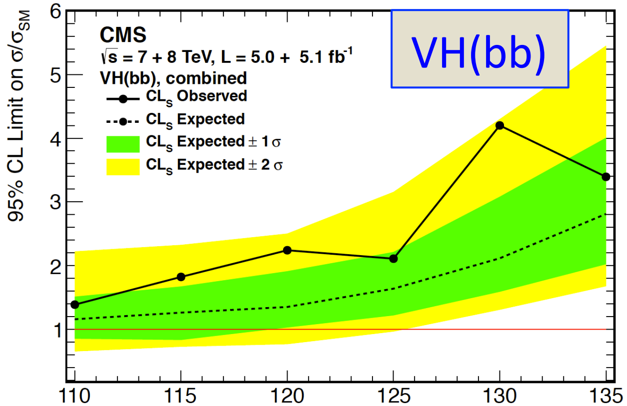


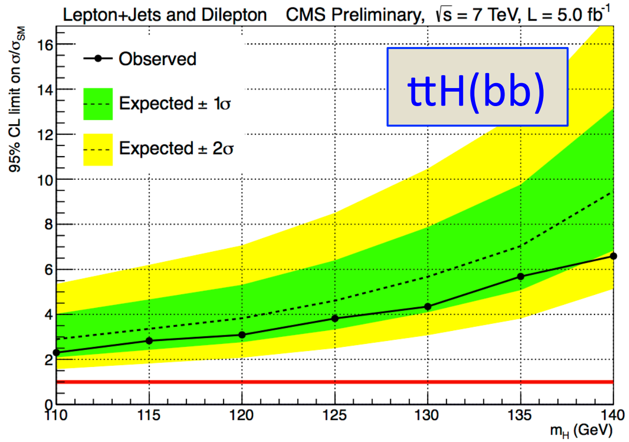


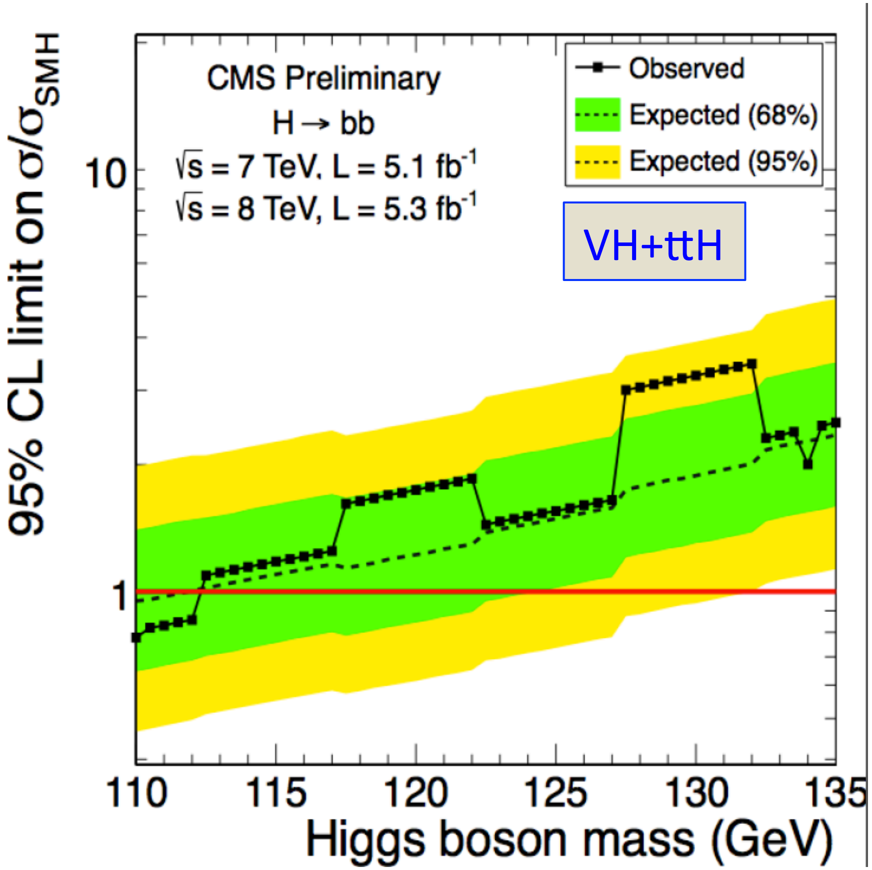
- **7 TeV: MVA shape for 0,1-jet and cut based VBF analysis**
- **8 TeV: cut based analysis**
- **~1.5 σ broad excess seen at low mass region**

talks by P. Bortignon and M. Gruttola

Summary of channels: H→bb



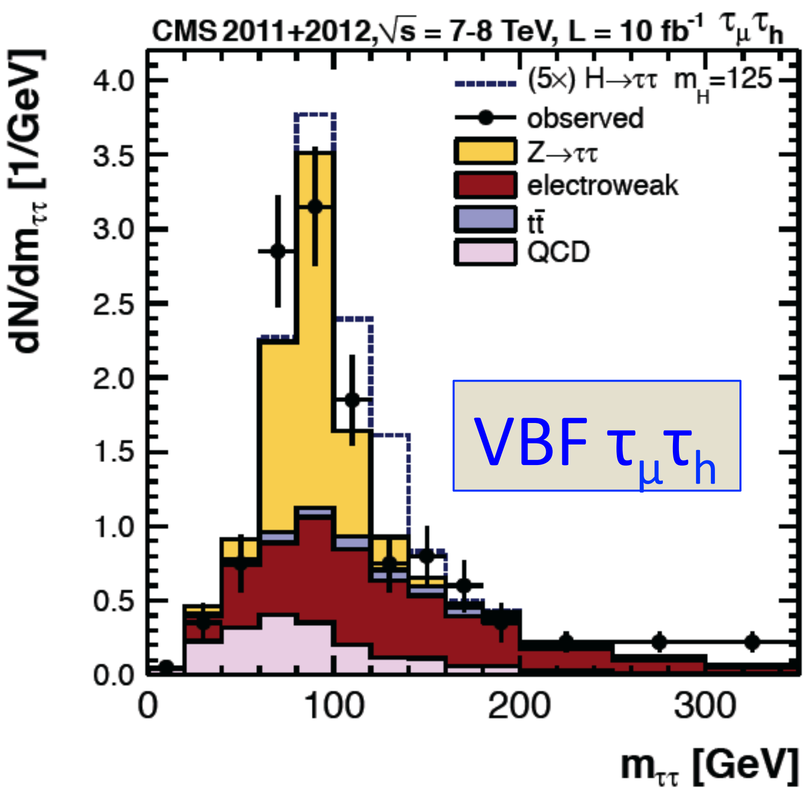


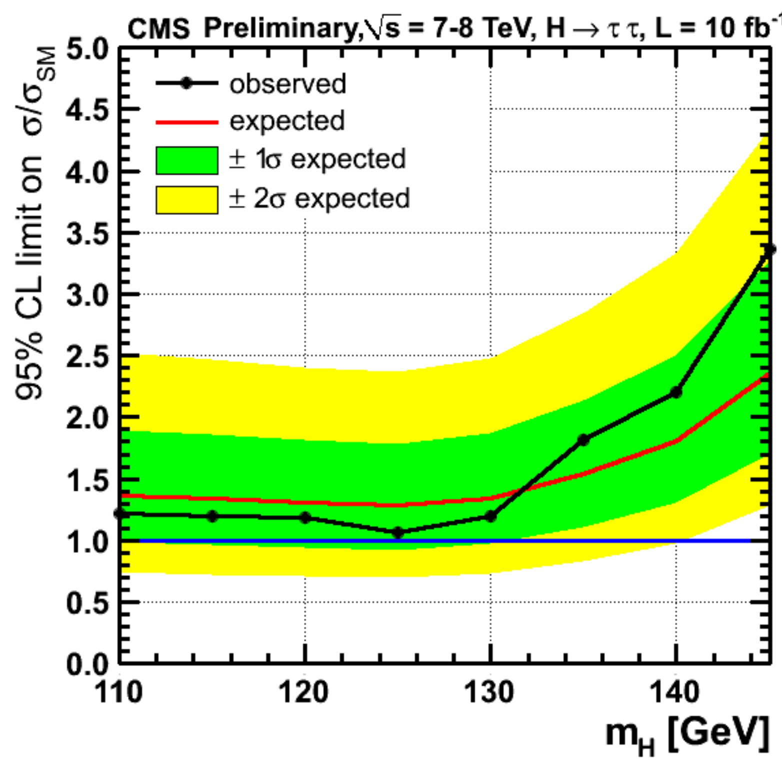


- **MVA shape based analyses**
- **ttH(bb): first LHC study of this production mode**
- **observation compatible with background-only hypothesis**

talk by M. Gruttola

Summary of channels: H→ττ

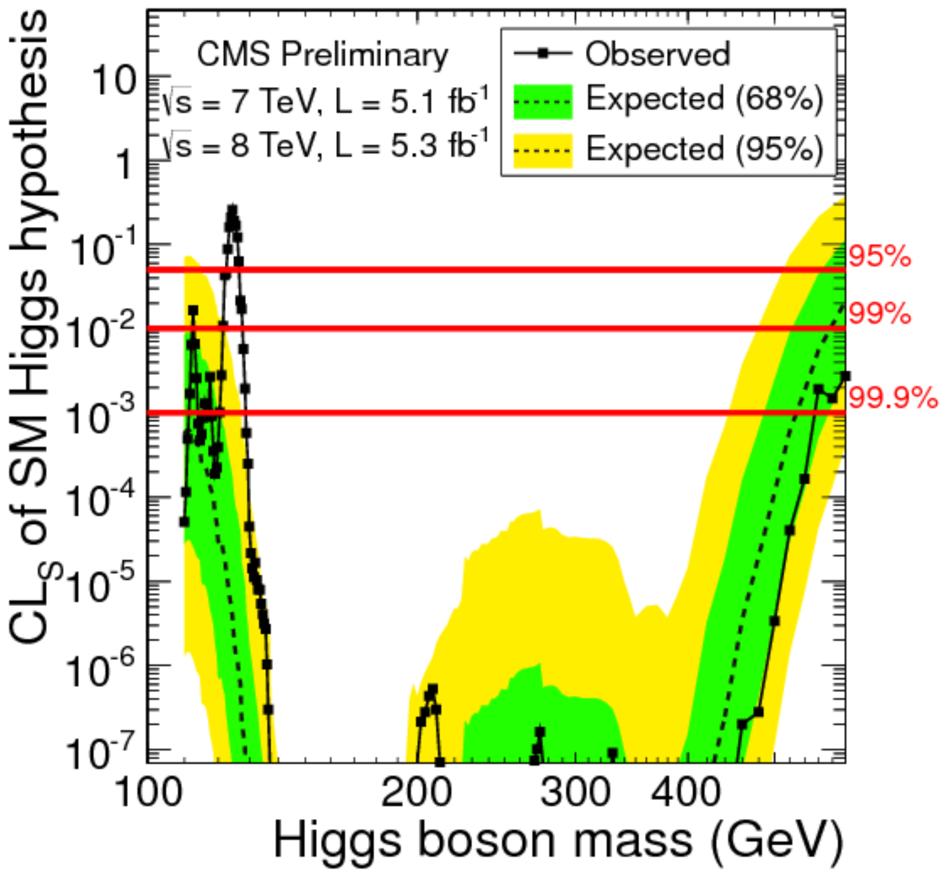


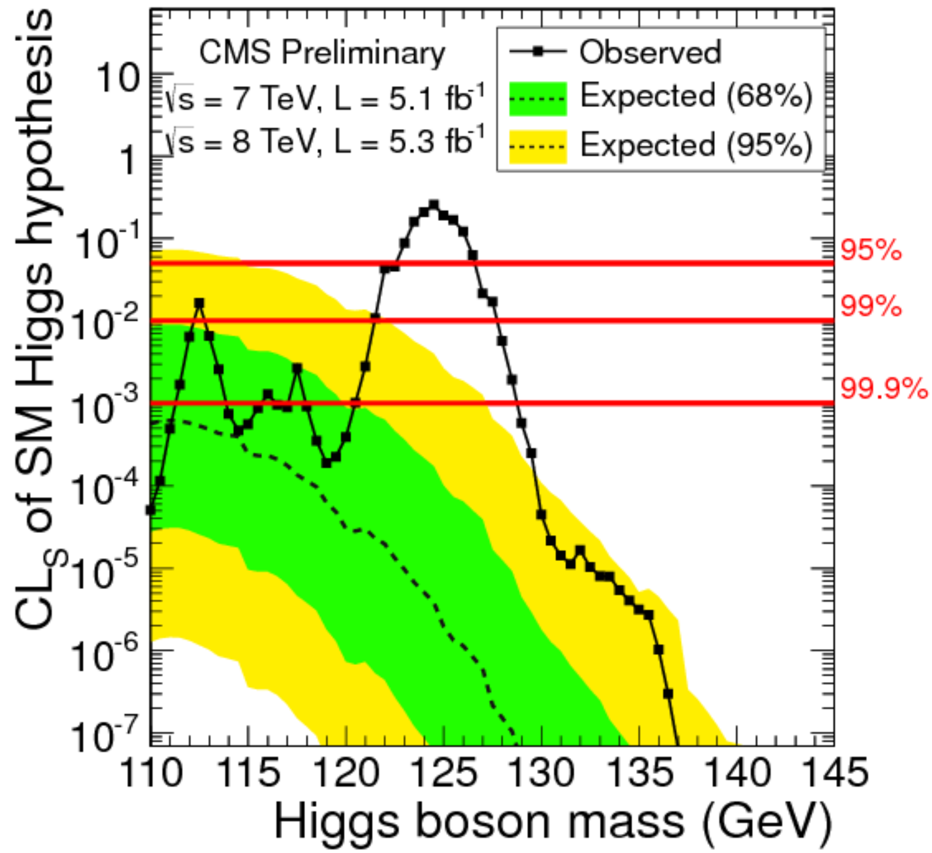


- **observation compatible with background-only hypothesis (-1σ deficit at m_H=125)**

Combined results

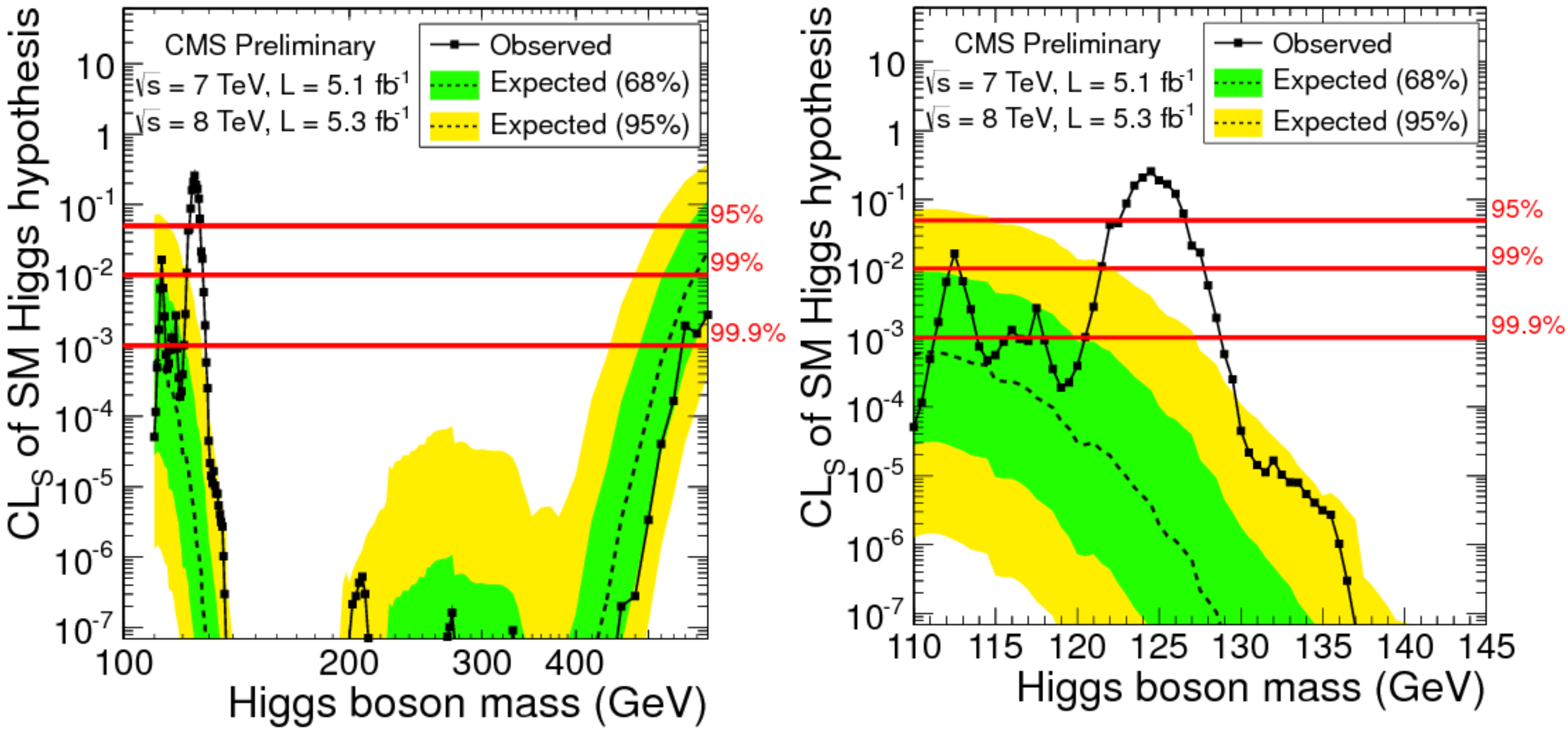
SM Higgs exclusion





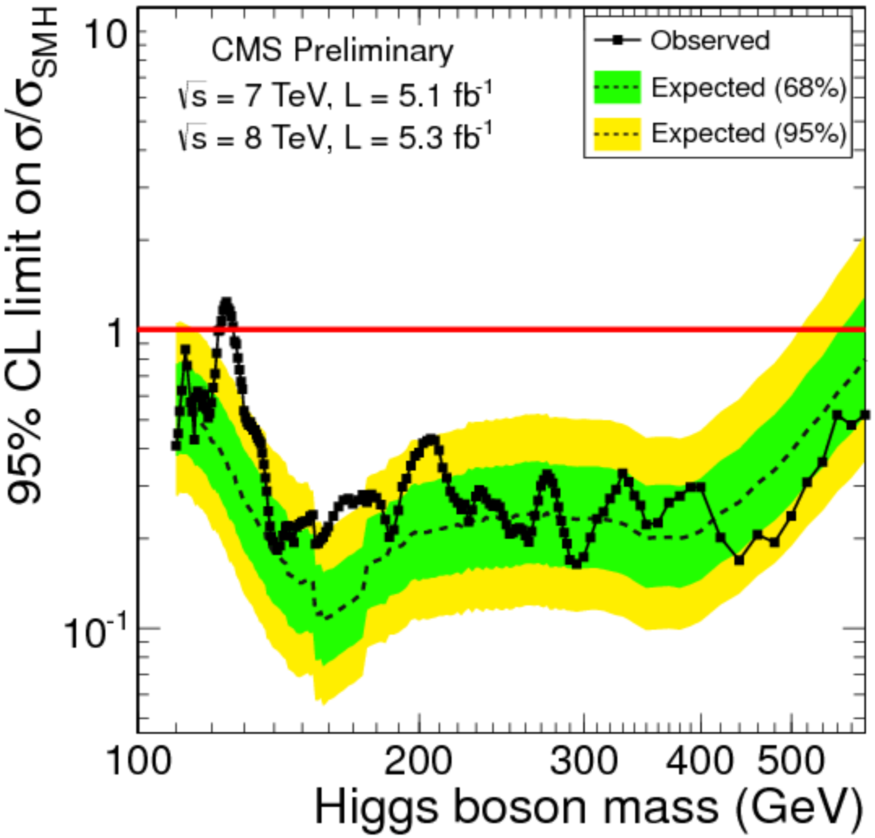
Expected in absence of SM Higgs boson: **110 – 600 GeV at 95% CL**

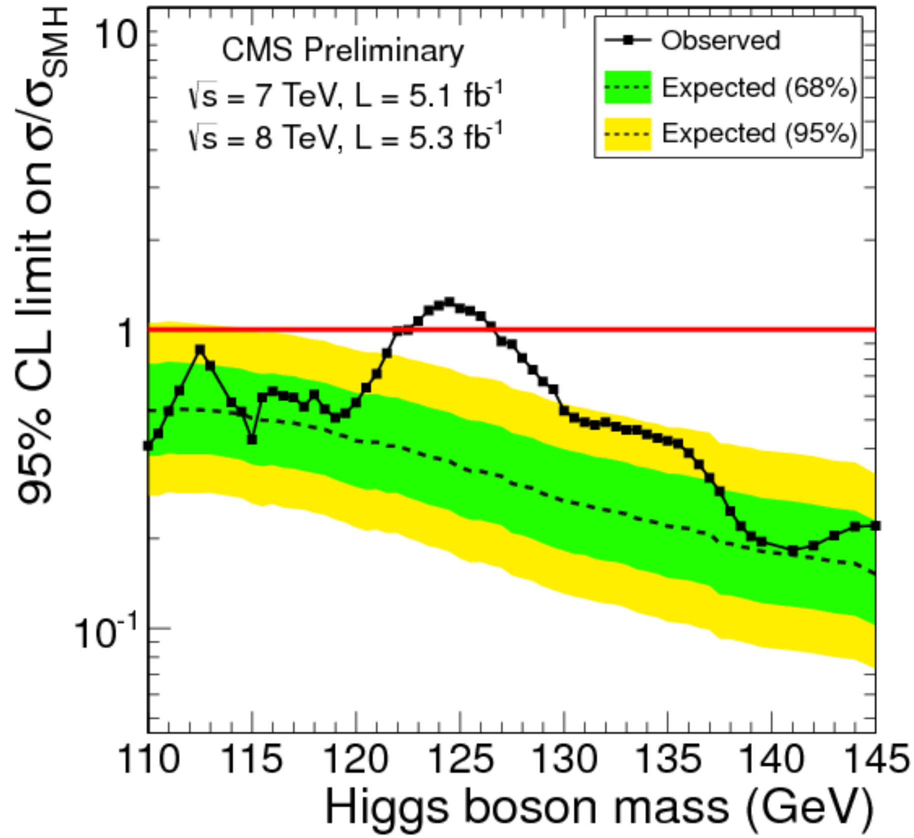
SM Higgs exclusion



Observed: **[110 – 122.5] ..?.. [127 – 600] GeV at 95% CL**

Excluded σ/σ_{SM} at 95% CL



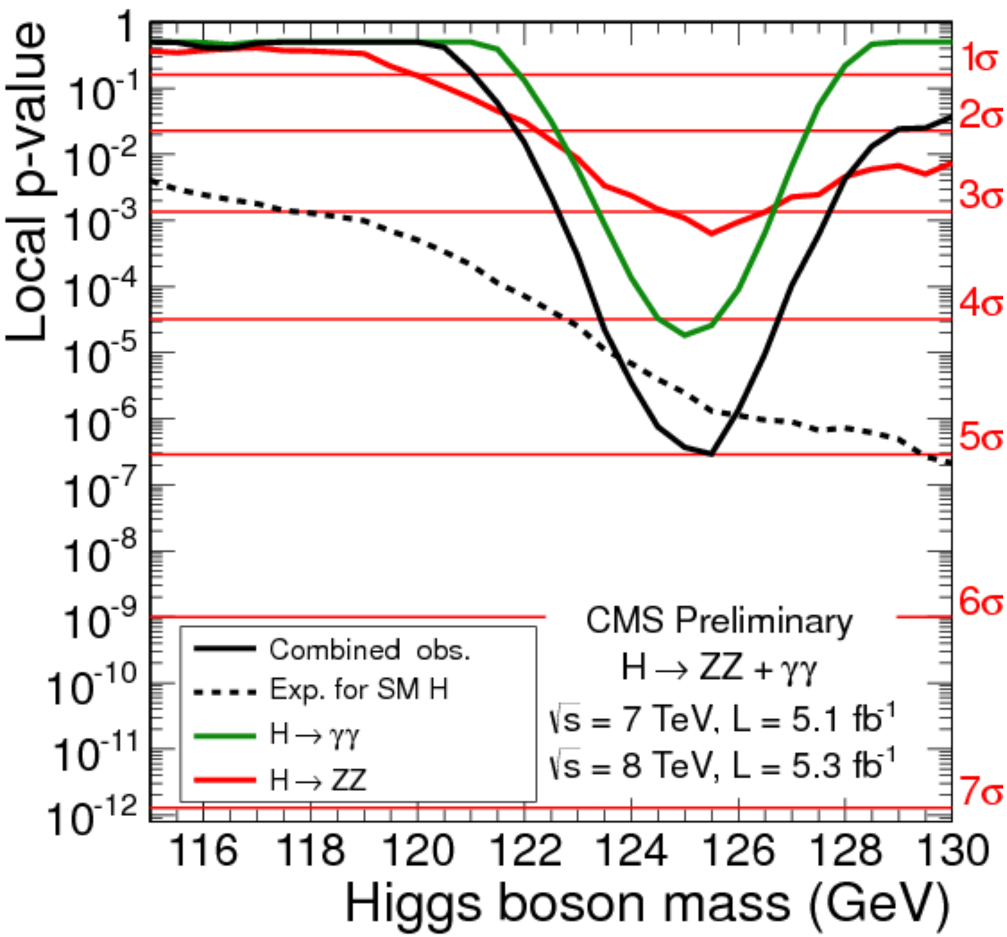


Observed: [110 – 122.5] ..?.. [127 – 600] GeV at 95% CL

(same as on the previous slide)

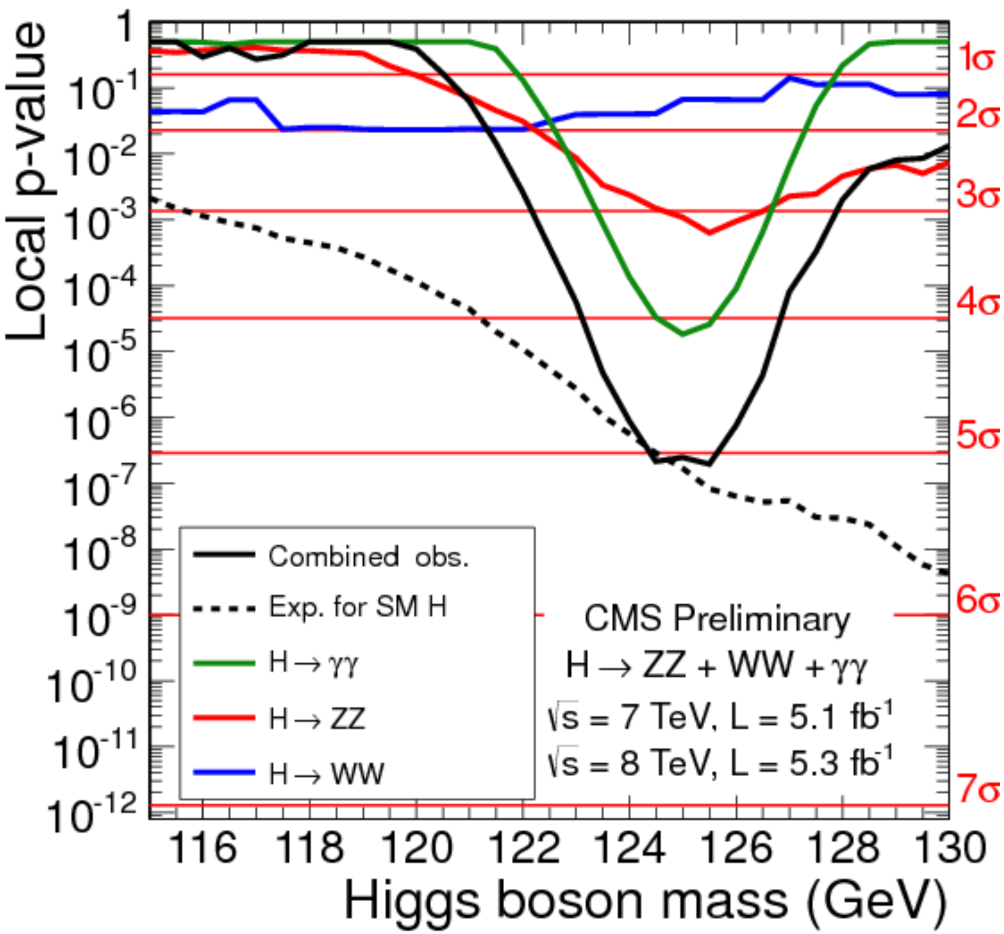
Characterization of the excess

Excess characterization (122-127 GeV)



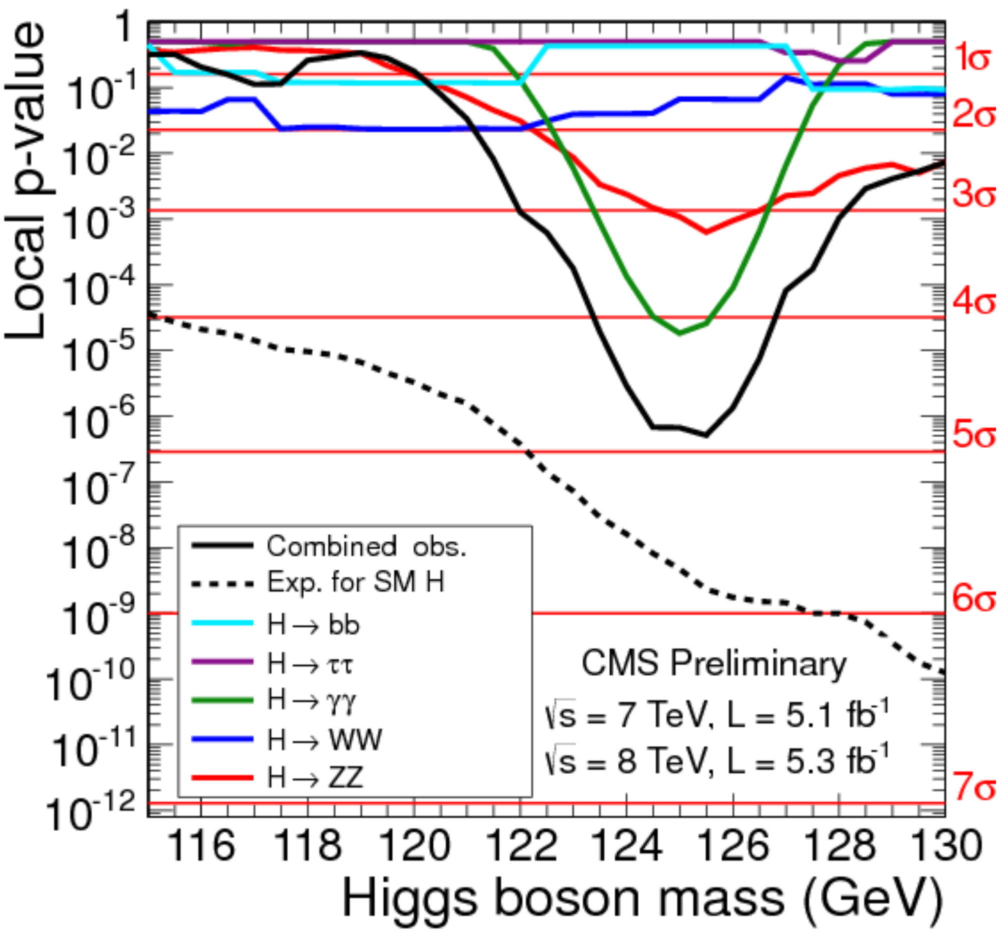
- **driven by channels with high mass resolution**
- **observed in γγ (4σ) and 4l (3σ) decay modes, at the <u>same mass</u>**
- **comb. significance of γγ and 4l : 5.0σ (expected 4.7σ) at 125 GeV**

Excess characterization (122-127 GeV)



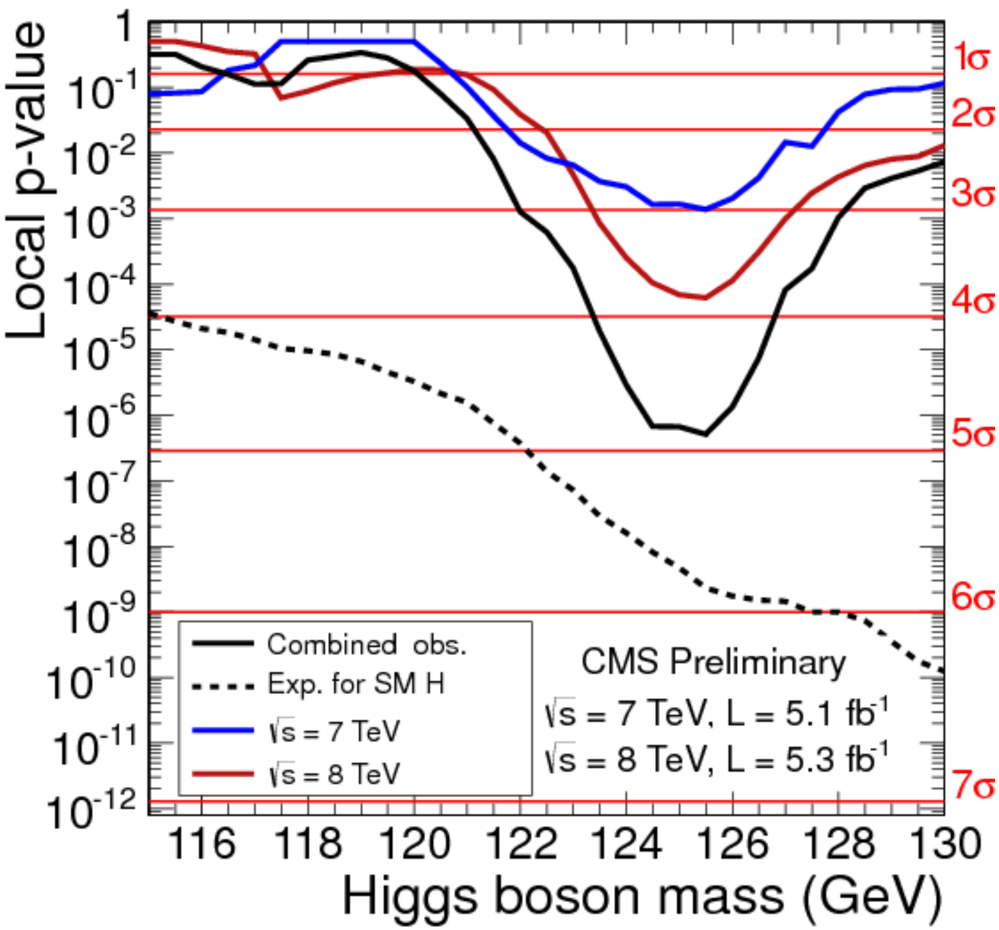
- **adding high sensitivity but low mass resolution channel WW**
- **comb. significance: 5.1σ (expected 5.2σ) at 125 GeV**

Excess characterization (122-127 GeV)



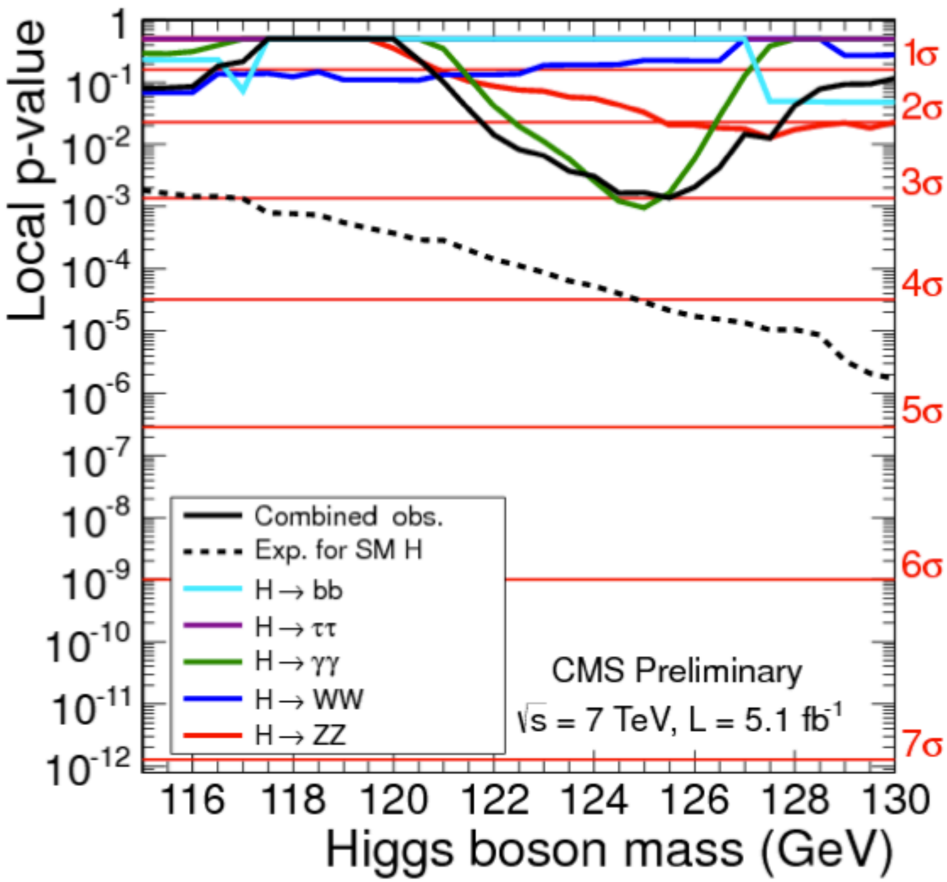
- **full combination: 4.9σ (expected 5.9σ) at 125 GeV**

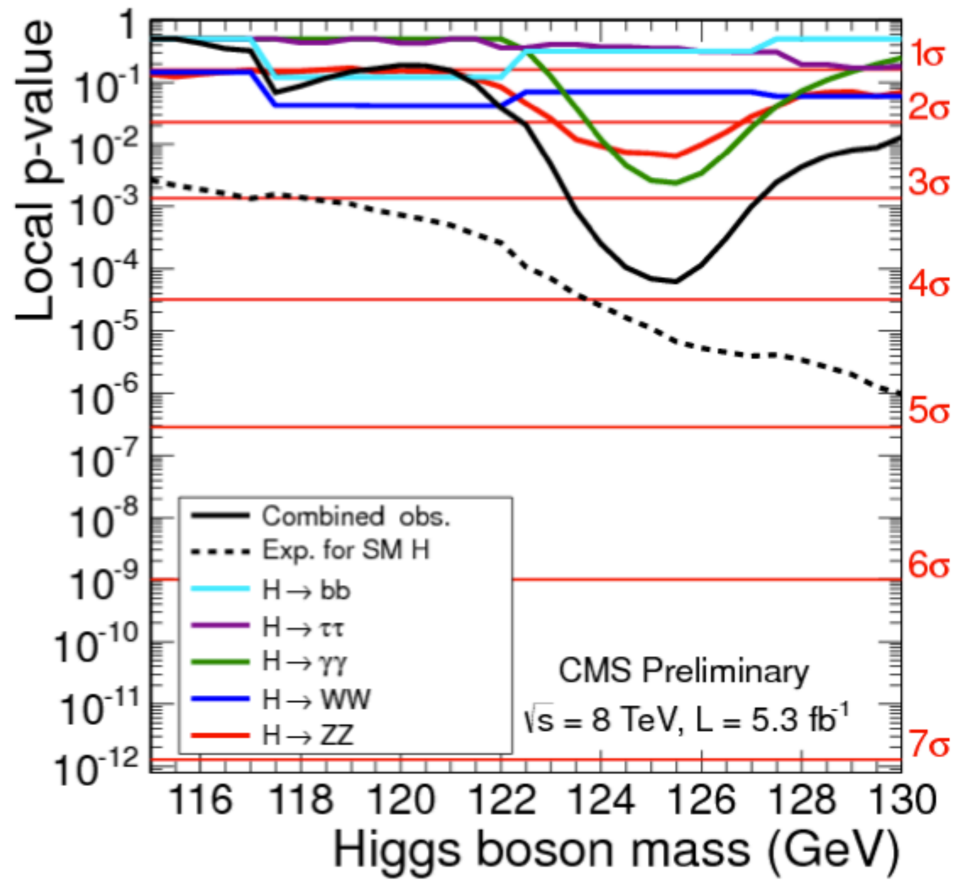
Excess characterization (122-127 GeV)



- **full combination: 4.9σ (expected 5.9σ) at 125 GeV**
- **observed in both 7 TeV and 8 TeV datasets 3σ and 3.8σ respectively, at the <u>same mass</u>**

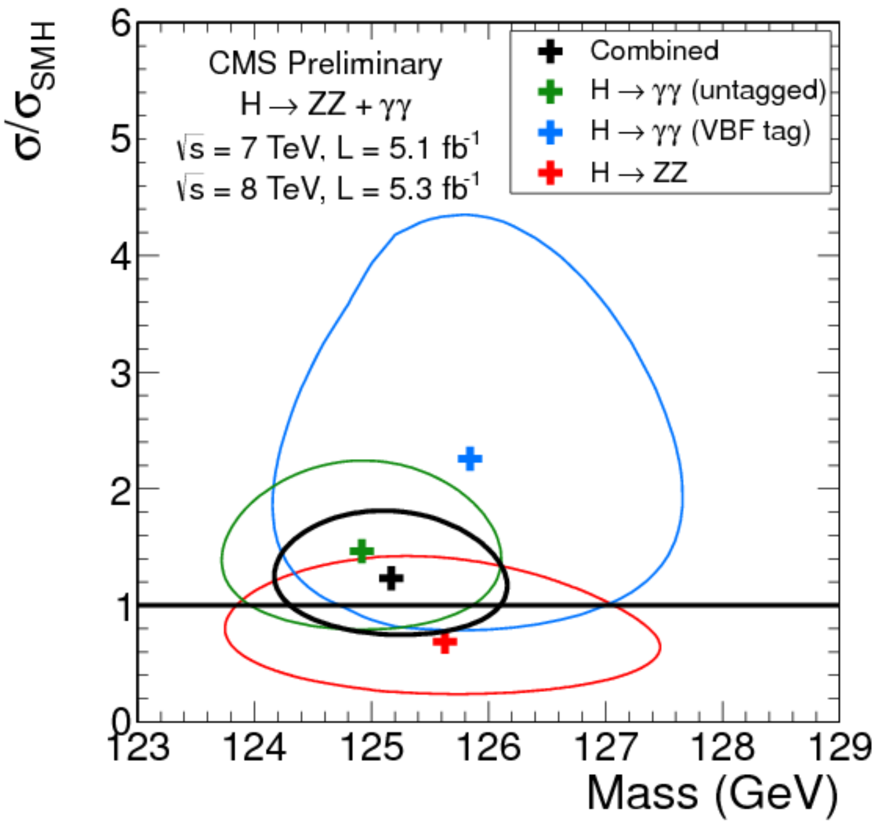
Excess characterization (122-127 GeV)





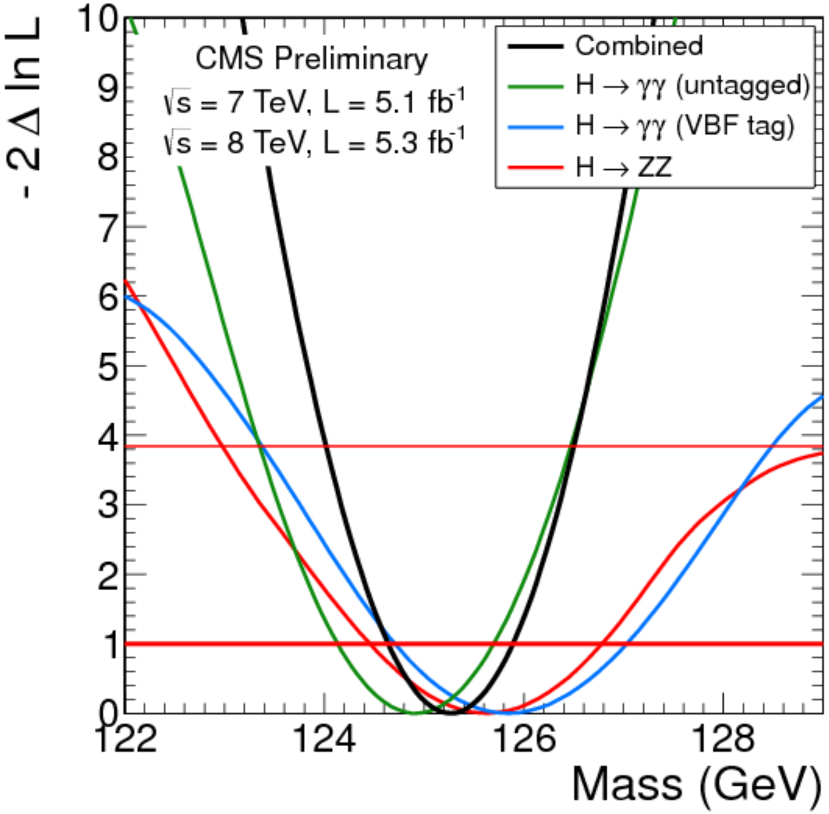
- **consistent pattern of observations in different channels in 7 TeV and 8 TeV datasets**

Measuring mass (model-**dependent**)



- 2D likelihood scans for
  - untagged γγ
  - VBF-tagged γγ
  - ZZ→4l
- results are consistent and thus can be combined
- **combination**, in assumption of relative yields tied by SM Higgs

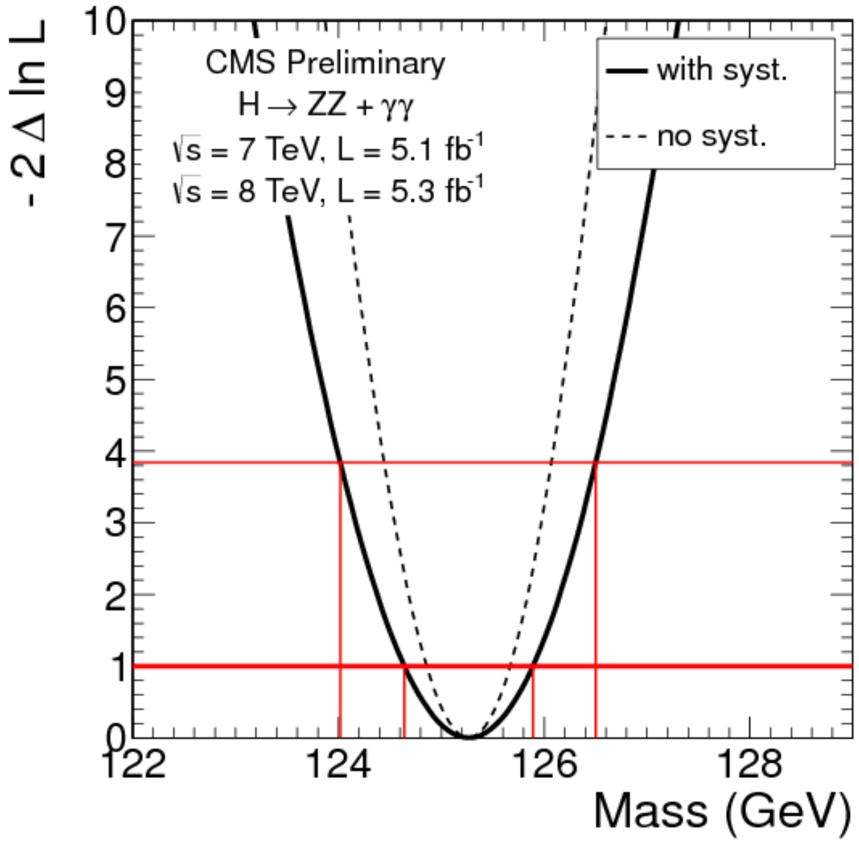
Measuring mass (model-**independent**)



- 1D likelihood scans for
  - untagged γγ
  - VBF-tagged γγ
  - ZZ→4l
- **combination**, in no assumptions on relative yields, gives **m = 125.3 ± 0.6 GeV**

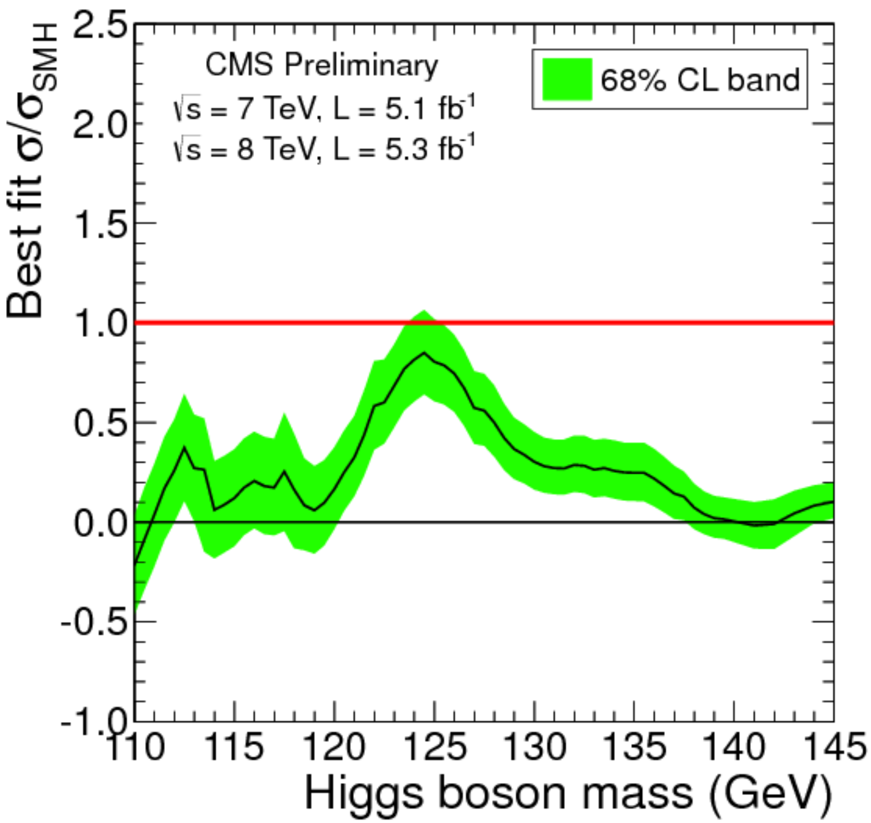
Observed excess's mass =

125.3 ± 0.4 (stat) ± 0.5 (sys) GeV

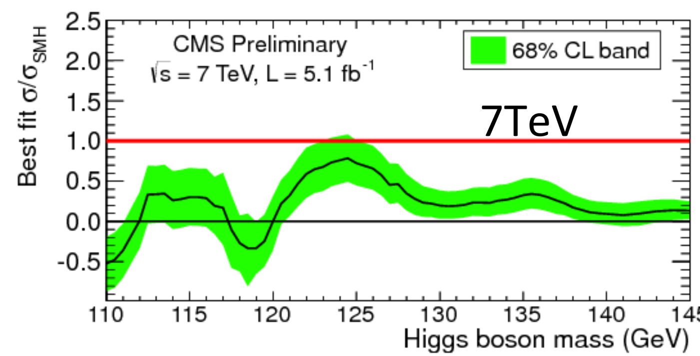


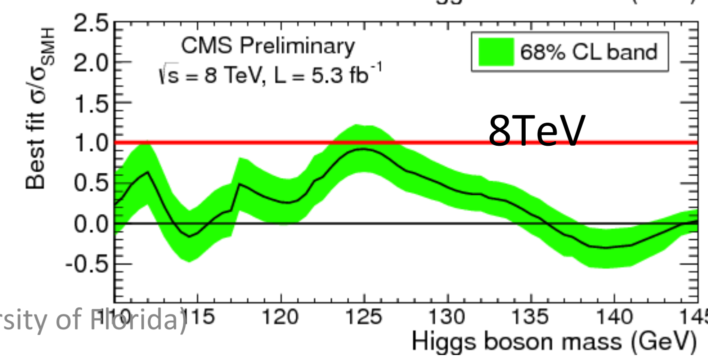
Is it the/a Higgs ?

Compatibility of the observation with SM Higgs boson

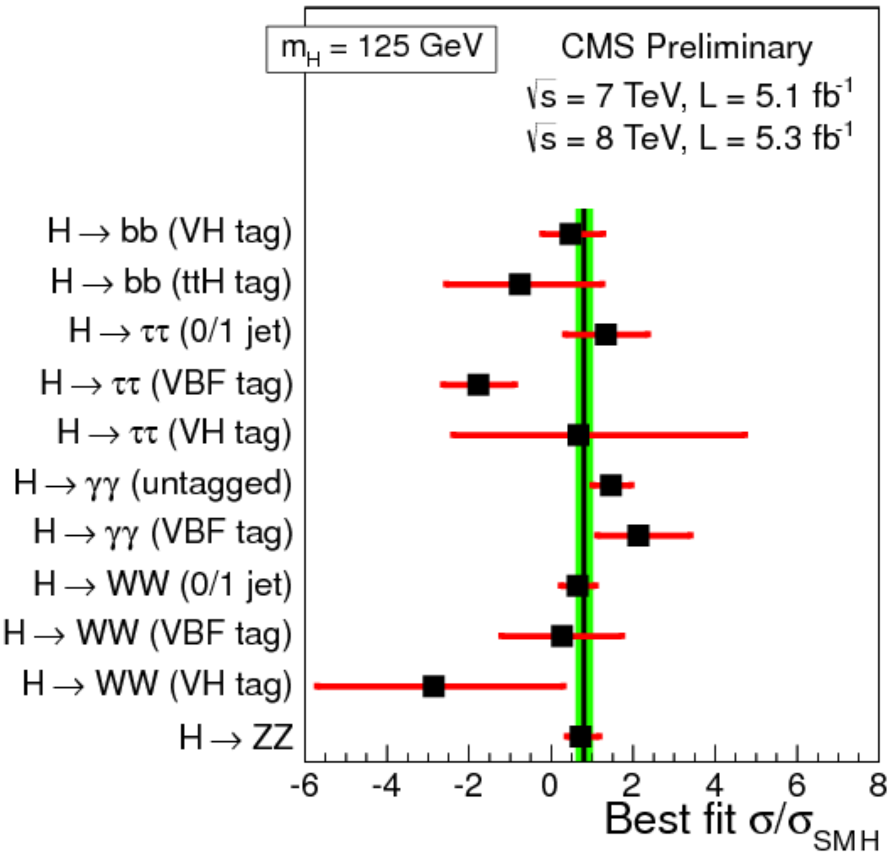


- overall signal strength modifier at m_H=125
  $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.22$



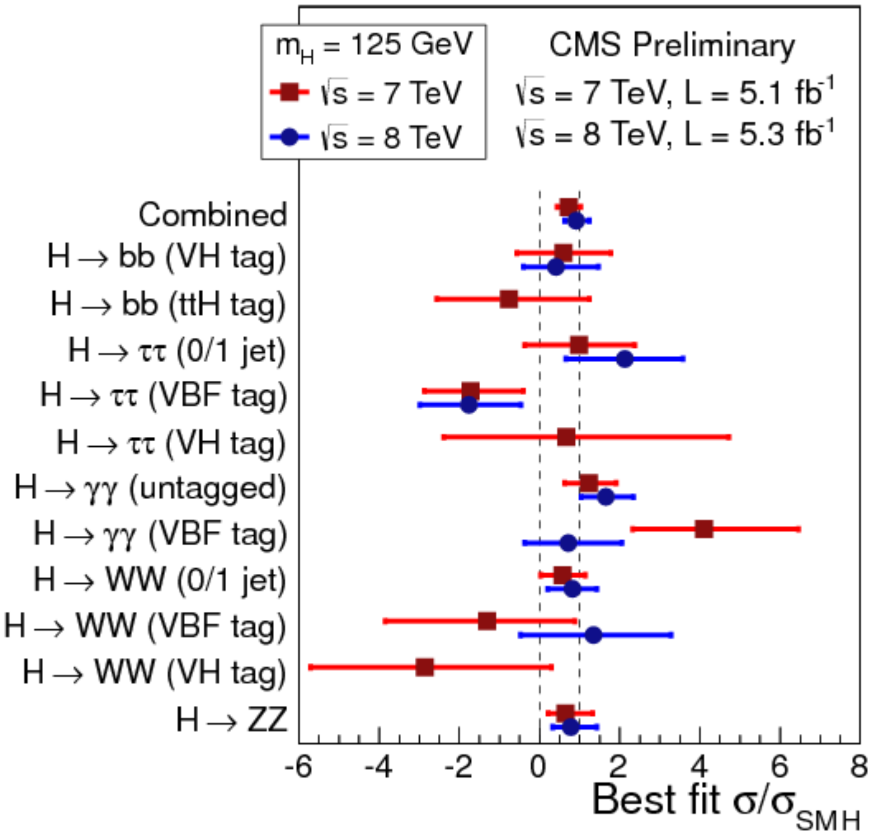


Compatibility of the observation with SM Higgs boson



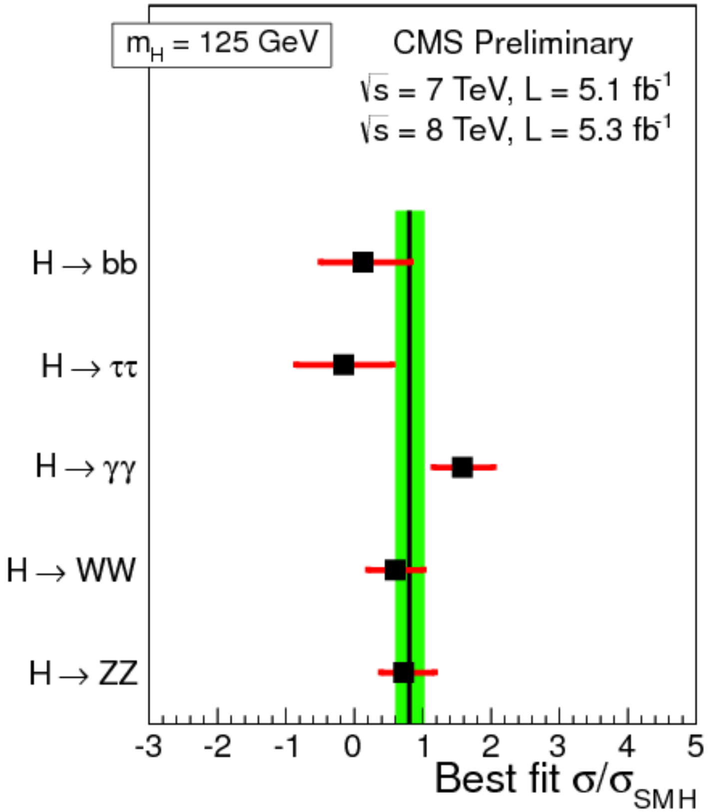
- all channels are fairly consistent with the SM Higgs, albeit with very limited sensitivity

Compatibility of the observation with SM Higgs boson



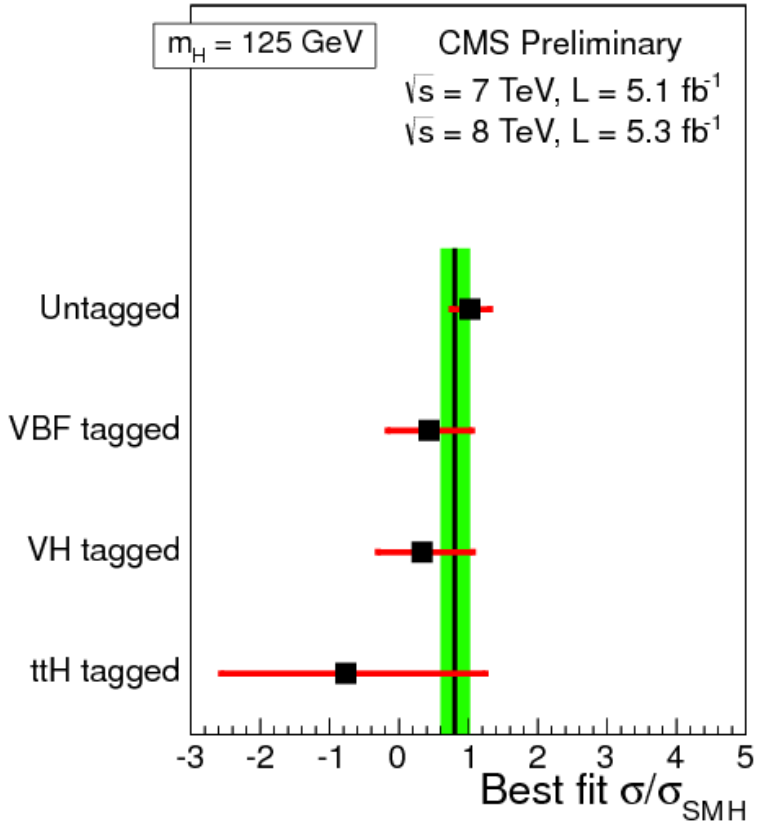
- all channels are fairly consistent with the SM Higgs, albeit with very limited sensitivity
- 7 TeV and 8 TeV dataset results within a channel are also self-consistent

Compatibility of the observation with SM Higgs boson



- 7+8 TeV combined by decay mode
- **OK**

Compatibility of the observation with SM Higgs boson



- 7+8 TeV combined by production mechanism
- **OK too**

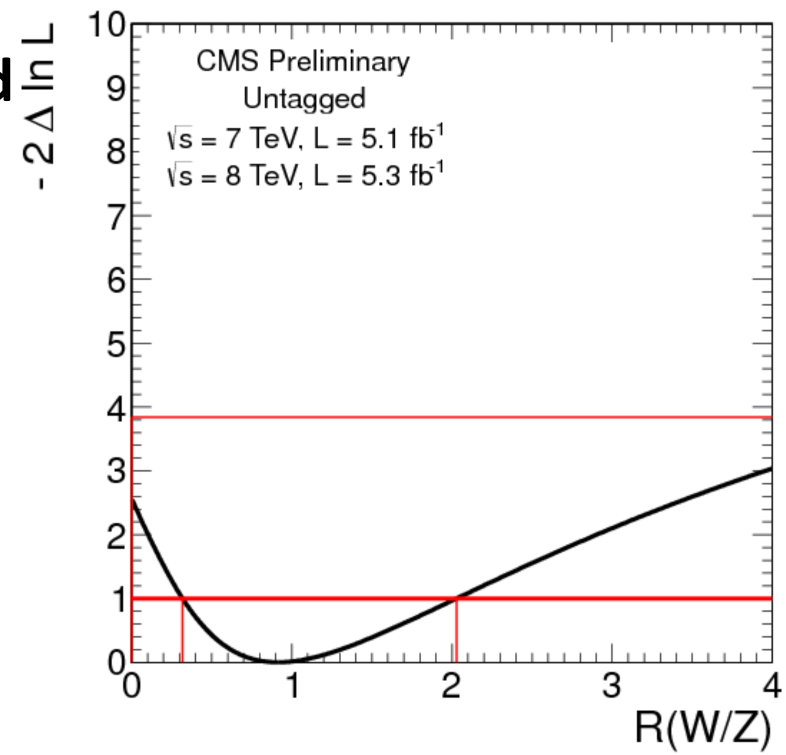
Compatibility: (H→WW)/(H→ZZ)

- this ratio is mostly driven by the **ratio of Higgs couplings to WW and ZZ**, which is protected by the custodial symmetry

- combination of untagged WW and ZZ and fitting for the difference wrt to the expectation:

$$R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$$

- compatible with SM prediction within uncertainty



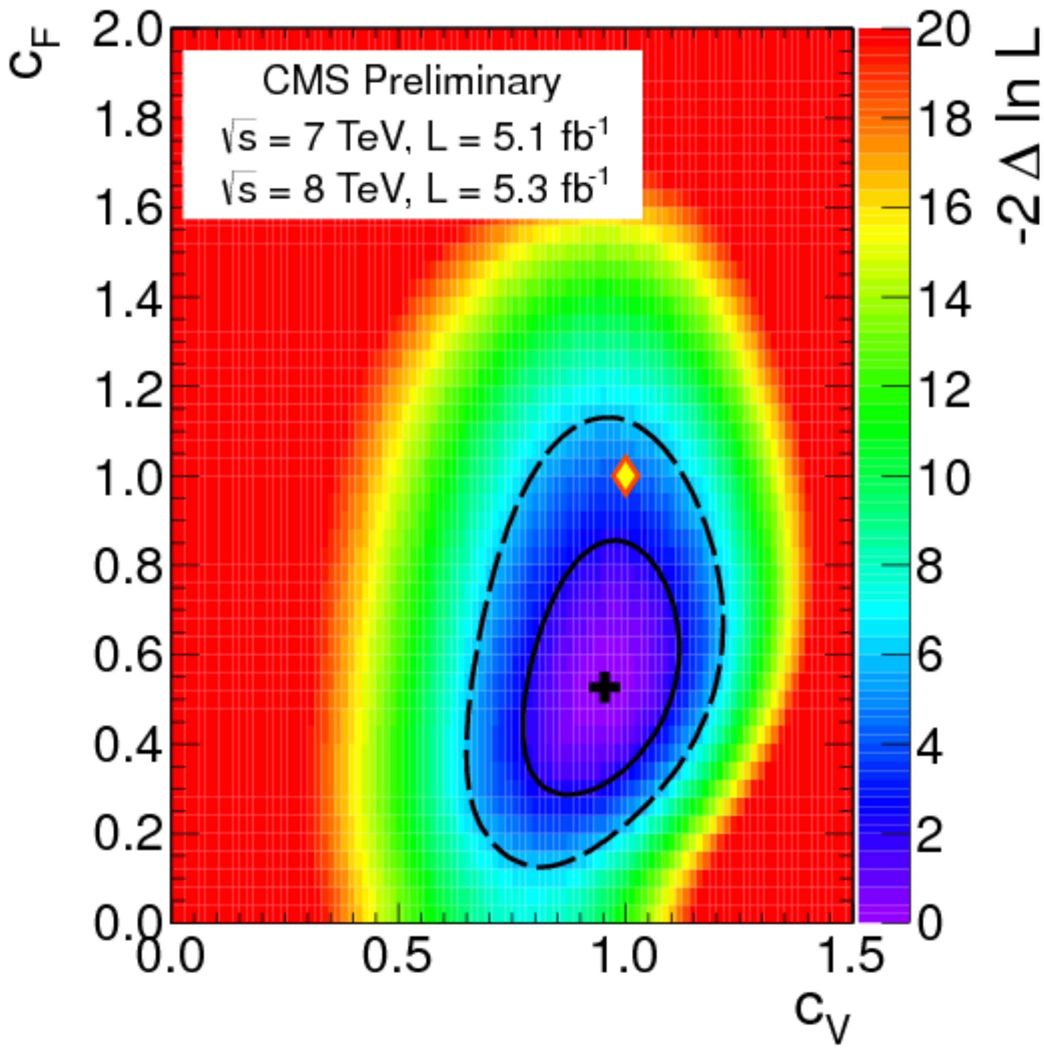
Couplings: (C_V, C_F)

- C_V(C_F) scales the SM Higgs boson couplings to vector bosons (fermions)
- LO approximation
- **Γγγ** is induced via loop diagrams, scales as **|α C_V + β C_F|**^{2}
  - α and β are taken from theory
- most sensitive analyses:
  - WW, ZZ, inclusive γγ sensitive to C_V
  - VBF γγ sensitive to both C_V and C_F

Production	Decay	LO	SM
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF/VH	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF/VH	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$

Couplings: (C_V, C_F)

- C_V(C_F) scales the SM Higgs boson couplings to vector bosons (fermions)
- LO approximation
- **Γγγ** is induced via loop diagrams, scales as $|\alpha\, C_V + \beta\, C_F|^2$
  - α and β are taken from theory
- most sensitive analyses:
  - WW, ZZ, inclusive γγ sensitive to C_V
  - VBF γγ sensitive to both C_V and C_F
- in agreement with the SM within the 95% confidence range



Summary

- Excluded range at 95% CL: **[110-122.5]** and **[127-600] GeV**
- Observed a new boson with **4.9σ** near **125** GeV
  - global significance > 4**σ**
- Two dominant contributors (high resolution, high sensitivity):
  - X→γγ with **4.1σ**
  - X→4l with **3.2σ**
  - both excesses occur at about same mass
  - measured mass = **125.3 ± 0.4 (stat) ± 0.5 (sys) GeV**
- The results obtained in all search channels are consistent with the expectations for a SM Higgs boson within the uncertainties
- More data are needed to establish firmly the nature of the new boson

Stay tuned !

Thanks！

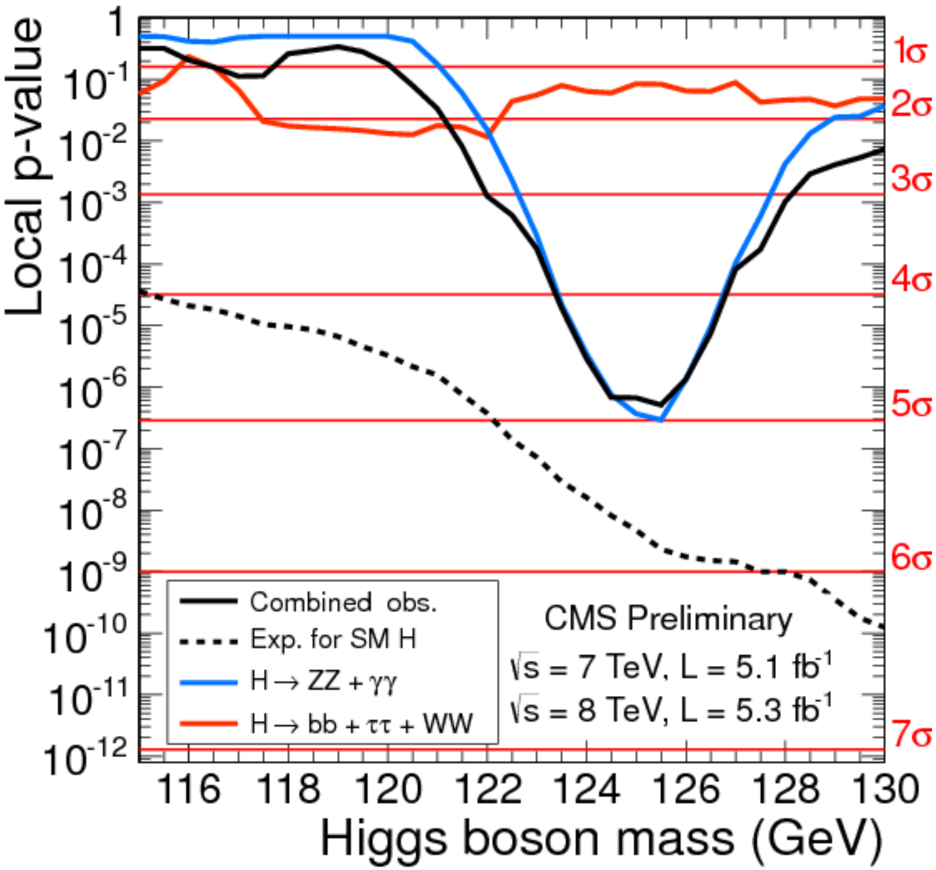
References

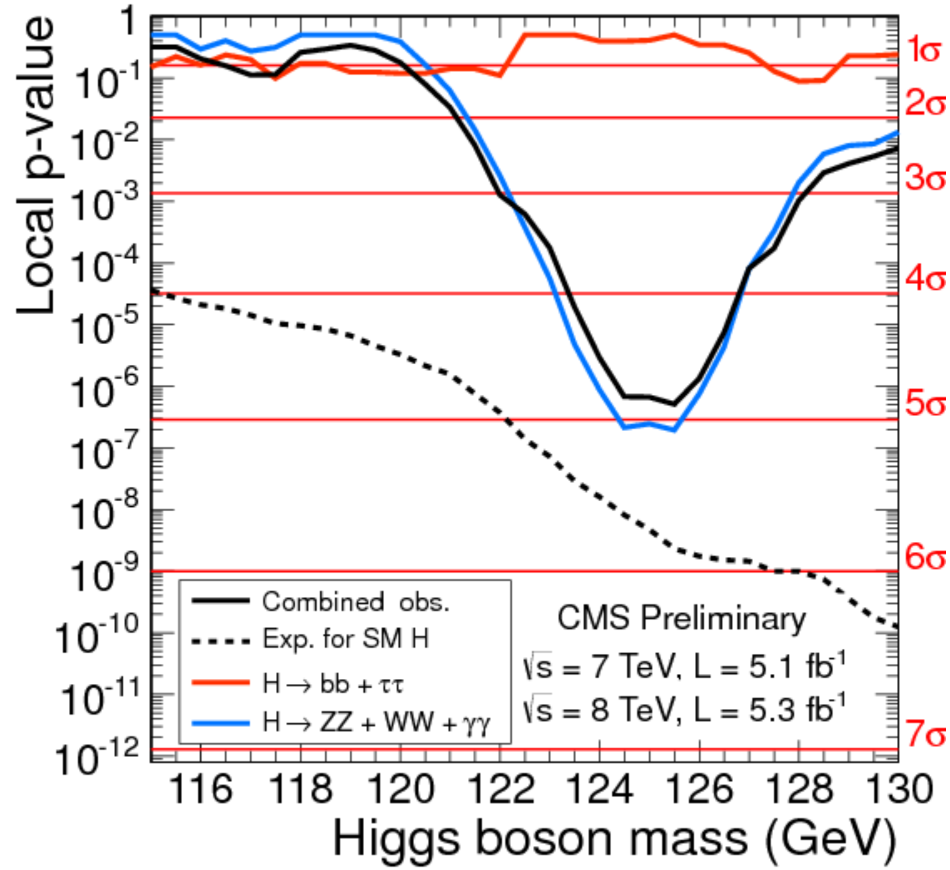
- Webpage of CMS Public Higgs Results
- July 4th seminar
- ICHEP talks
- Combination paper in preparation

Search channels

Analyses: H decay	H prod	Exclusive final states	No. of channels	$m_{\rm H}$ range (GeV)	$m_{\rm H}$ resolution	Lumi (fb^{-1}) 7 TeV	8 TeV	Ref
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3	[73]
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3	[73]
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\otimes$ (low or high p_T^V)	10	110–135	10%	5.0	5.1	[74]
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\otimes$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-	[75]
$\mathrm{H} \to \tau\tau$	0/1-jets	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high $p_T^{\tau\tau}$) $\times$ (0 or 1 jets)	16	110–145	20%	4.9	5.1	[76]
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) + $(jj)_{VBF}$	4	110–145	20%	4.9	5.1	[76]
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-	[77]
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-	[78]
$\mathrm{WW} \to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\otimes$($(jj)_{\rm W}$ with 0 or 1 jets)	4	170–600		5.0	5.1	[79, 80]
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\otimes$ (0 or 1 jets)	4	110–600	20%	4.9	5.1	[81, 82]
$\mathrm{WW} \to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	5.1	[81, 82]
$\mathrm{WW} \to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200		4.9	-	[83]
$\mathrm{WW} \to \ell\nu\ell\nu$	VH-tag	$\ell\nu\ell\nu + (jj)_V$ (DF or SF dileptons)	2	118–190		4.9	-	[84]
$\mathrm{ZZ} \to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–600	1-2%	5.0	5.3	[85]
$\mathrm{ZZ} \to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	200–600	10-15%	5.0	5.3	[85]
$\mathrm{ZZ} \to 2\ell 2q$	inclusive	(ee, $\mu\mu$)$\times$($(jj)_{\rm Z}$ with 0, 1, 2 b-tags)	6	130–164; 200–600	3%	4.9	-	[86]
$\mathrm{ZZ} \to 2\ell 2\nu$	untagged	((ee, $\mu\mu$) with MET) $\otimes$ (0 or 1 or 2 non-VBF jets)	6	200–600	7%	4.9	5.1	[87]
$\mathrm{ZZ} \to 2\ell 2\nu$	VBF-tag	(ee, $\mu\mu$) with MET and $(jj)_{VBF}$	2	200–600	7%	4.9	5.1	[87]

Sub-combinations

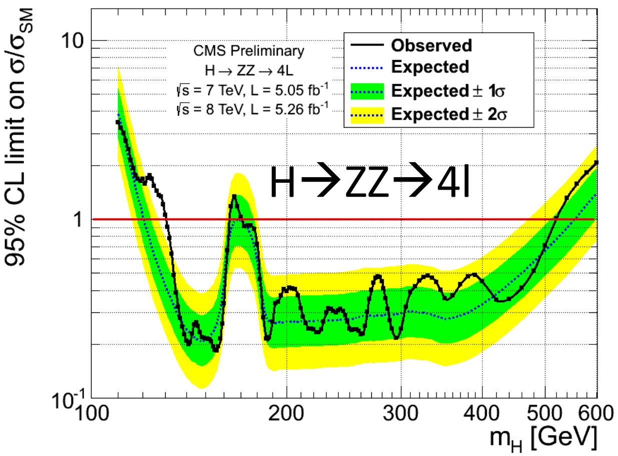


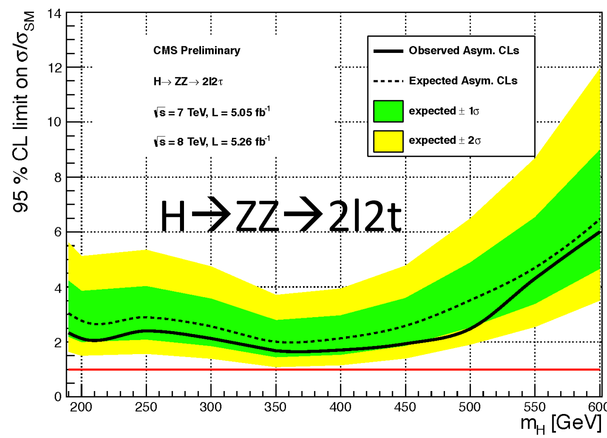


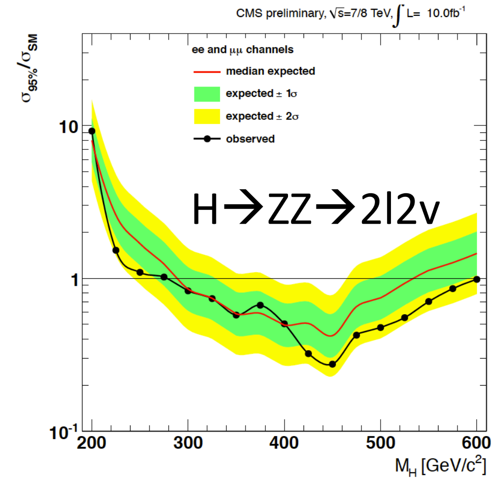
Sub-combinations in terms of good and poor mass resolutions

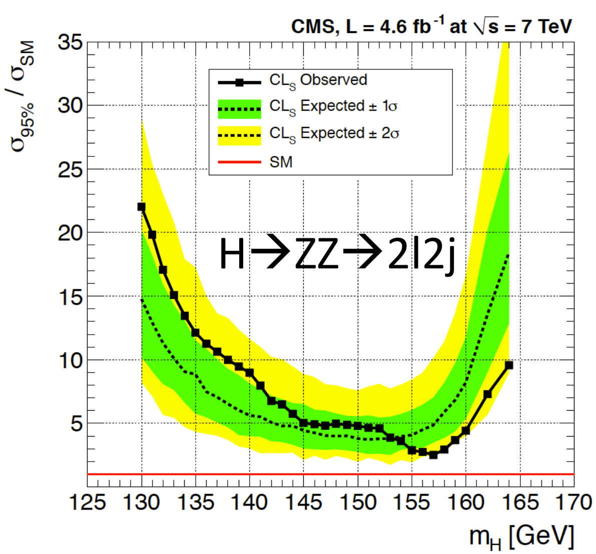
Bosonic and Fermionic sub-combinations

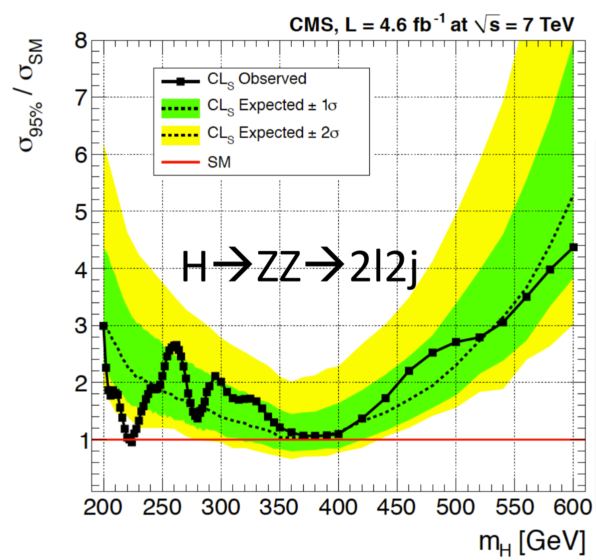
High mass searches : ZZ



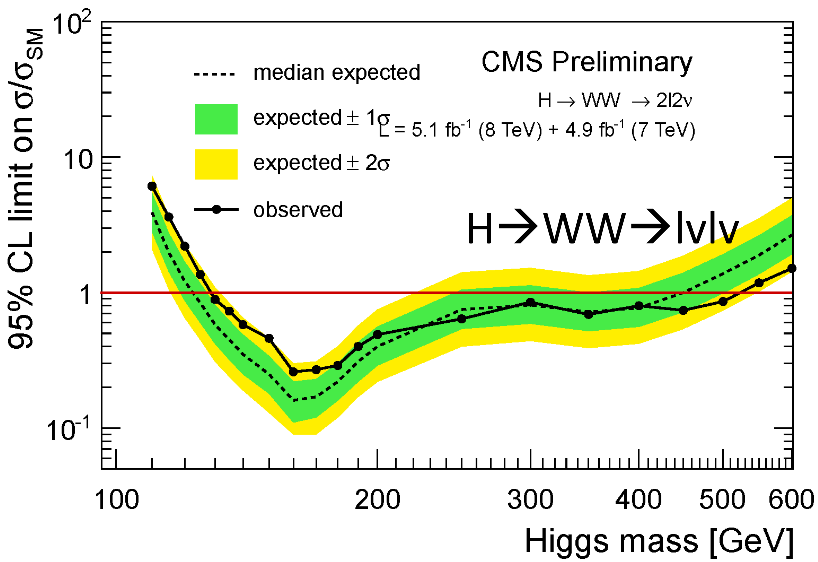


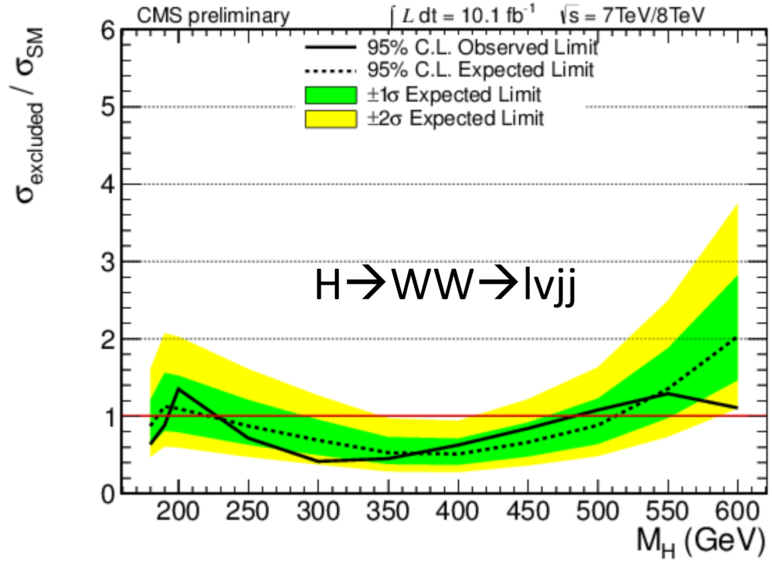


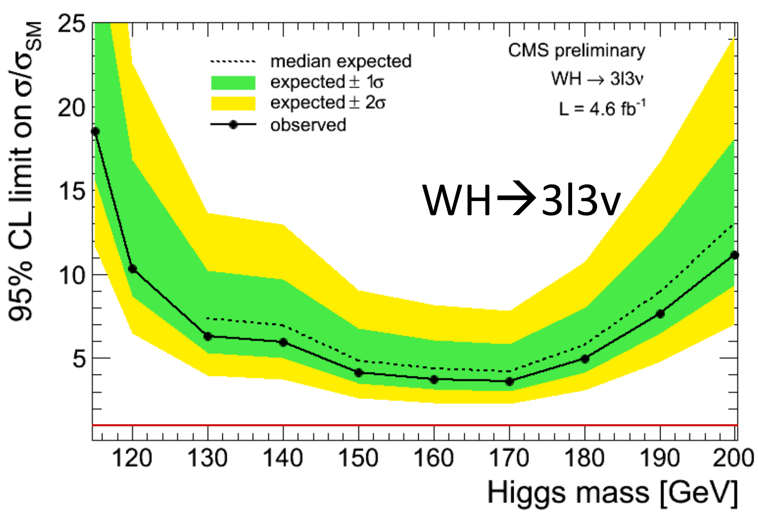


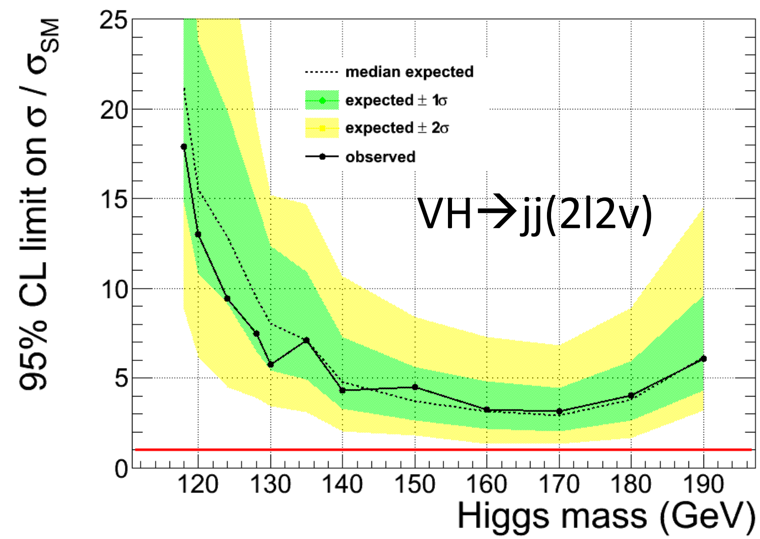


High mass searches : WW









Quantifying significance of excess

To quantify the presence of an excess of events over what is expected for the background, we use the test statistic where the likelihood appearing in the numerator is for the background-only hypothesis:

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, b, \hat{\theta}_0)}{\mathcal{L}(\text{obs} \,|\, \hat{\mu} \cdot s + b, \hat{\theta})}, \tag{3}$$

The statistical significance Z of a signal-like excess is computed from the probability p_0

$$p_0 = \text{P}(q_0 \geq q_0^{obs} \,|\, \text{b}), \tag{4}$$

henceforth referred to as the p-value, using the one-sided Gaussian tail convention.

$$p_0 = \int_Z^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) \, \mathrm{d}x.$$

Look elsewhere effects

In the Higgs boson search, we scan over Higgs boson mass hypotheses and look for the one giving the minimum local p-value $p_{\mathrm{local}}^{\mathrm{min}}$, which describes the probability of a background fluctuation for that particular Higgs boson mass hypothesis. The probability to find a fluctuation with a local p-value lower or equal to the observed $p_{\mathrm{local}}^{\mathrm{min}}$ anywhere in the explored mass range is referred to as the global p-value, p_{global}:

$$p_{\mathrm{global}} = \mathrm{P}(p_0 \leq p_{\mathrm{local}}^{\mathrm{min}} \,|\, \mathrm{b}), \tag{6}$$

The fact that the global p-value can be significantly larger than $p_{\mathrm{local}}^{\mathrm{min}}$ is often referred to as the look-elsewhere effect (LEE). The global significance (and global p-value) of the observed excess can be evaluated in this case by generating pseudo-datasets, which, however, becomes too CPU-intensive and not practical for very small p-values. Therefore, we use the method suggested in Ref. [94]. The relationship between global and local p-values is given by:

$$p_{\mathrm{global}} = p_{\mathrm{local}}^{\mathrm{min}} + C \cdot e^{-Z_{\mathrm{local}}^2/2} \tag{7}$$

The constant C is found by generating a relatively small set of pseudo-data and then is used to evaluate the global p-value corresponding to $p_{\mathrm{local}}^{\mathrm{min}}$ observed in the experiment.

For a very wide mass range, the constant C can be evaluated directly from data [89] by counting upcrossings N_{up} of $\hat{\mu}(m_{\mathrm{H}})$ with the line $\mu = 0$ and setting $C = N_{\mathrm{up}}$.