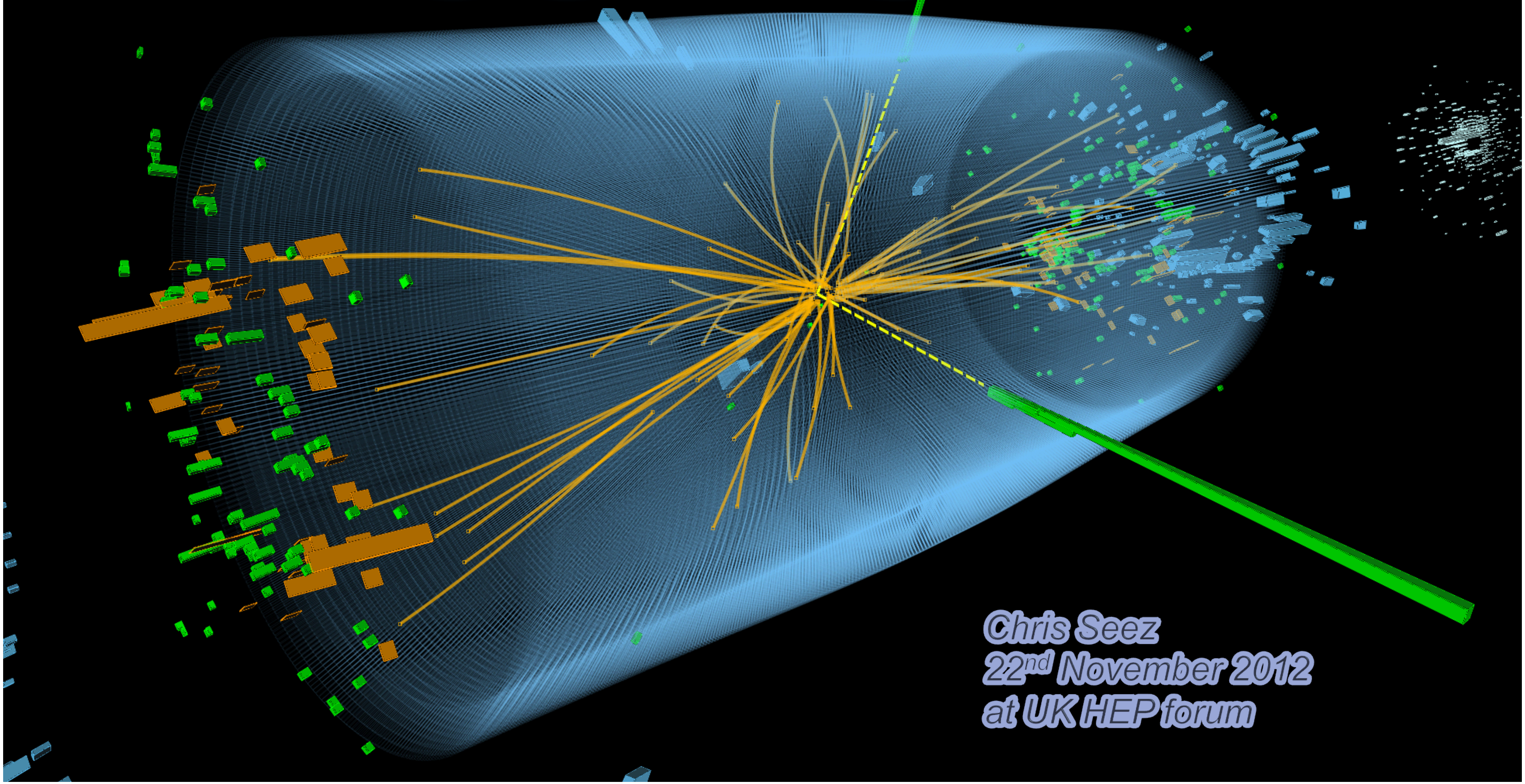
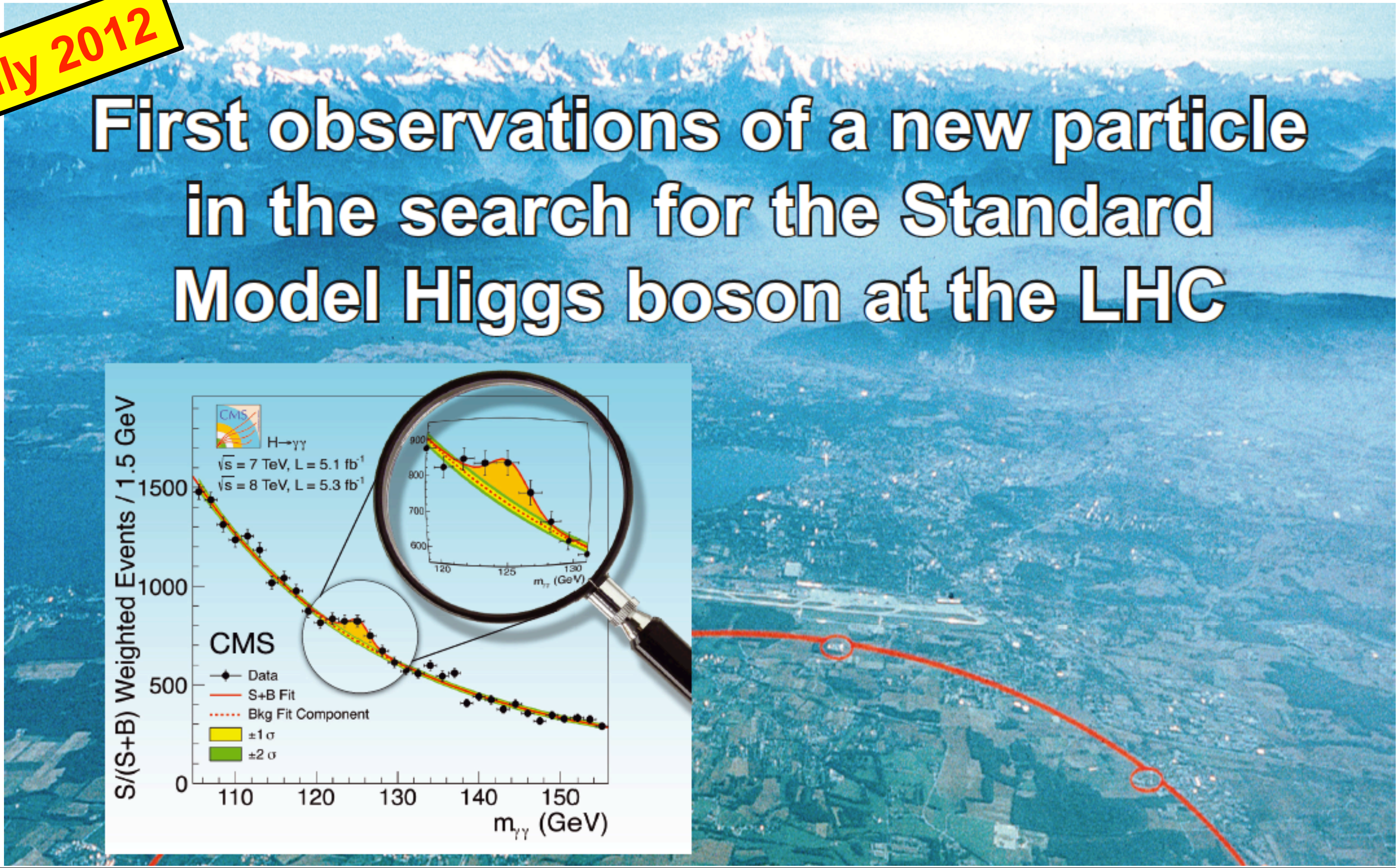
Higgs @ CMS



Chris Seez
22nd November 2012
at UK HEP forum

This talk: after the observation…

July 2012



The CMS detector

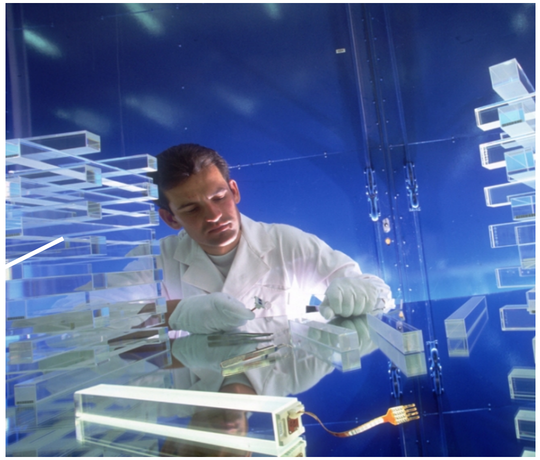
CMS: 3000 scientists from 40 countries

Silicon tracker

Gas ionization chambers

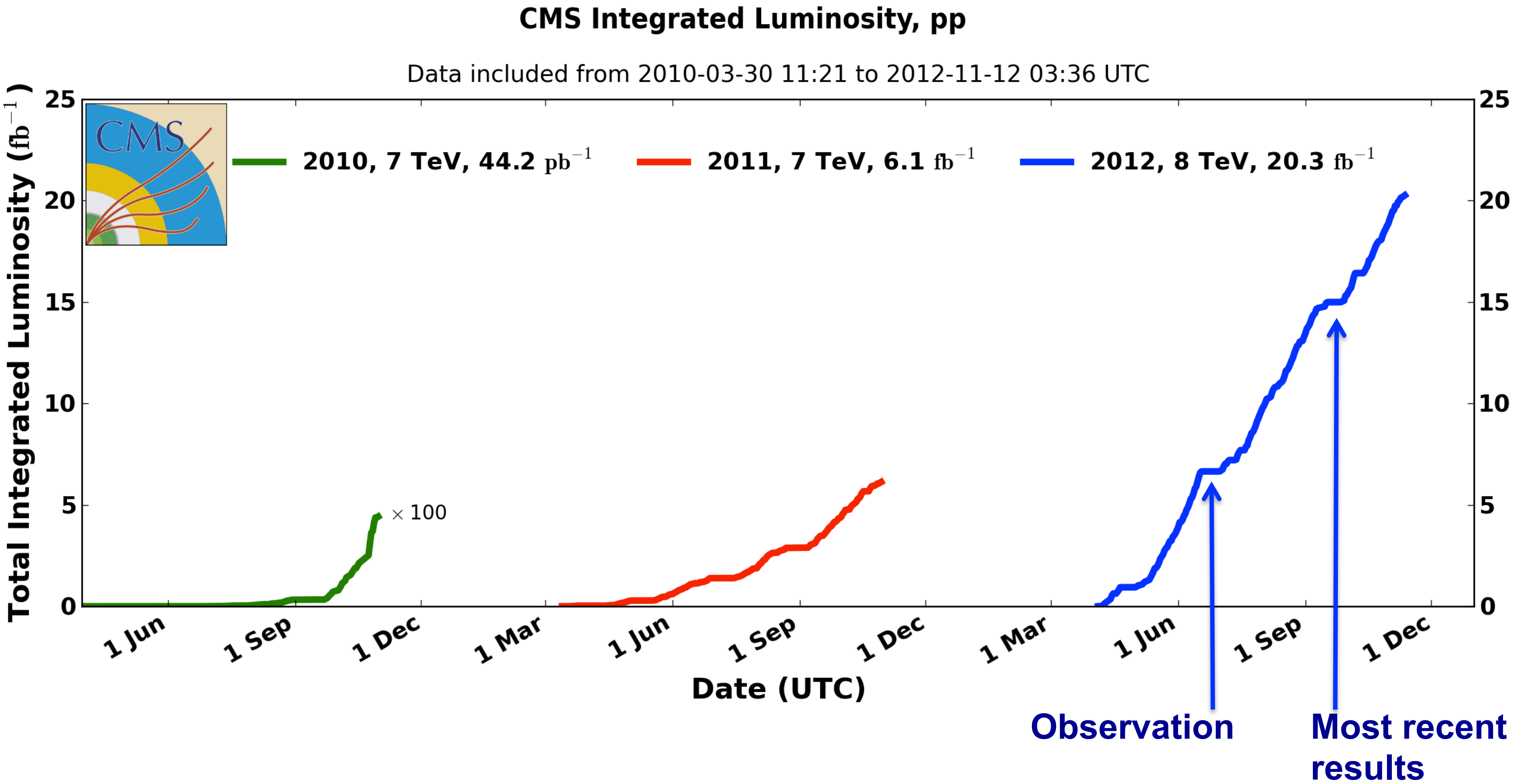
CMS cut in mid-plane

Scintillating crystals



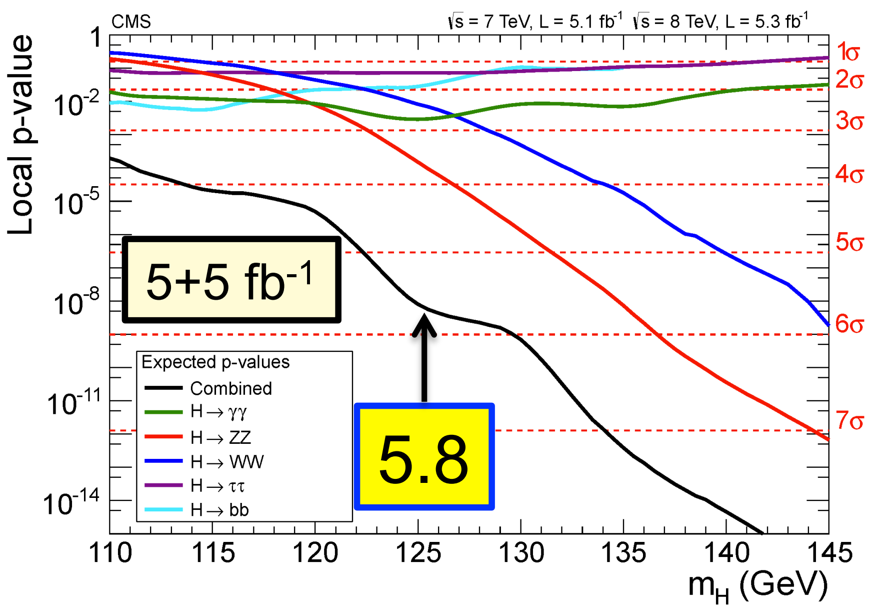
Brass plastic scintillator

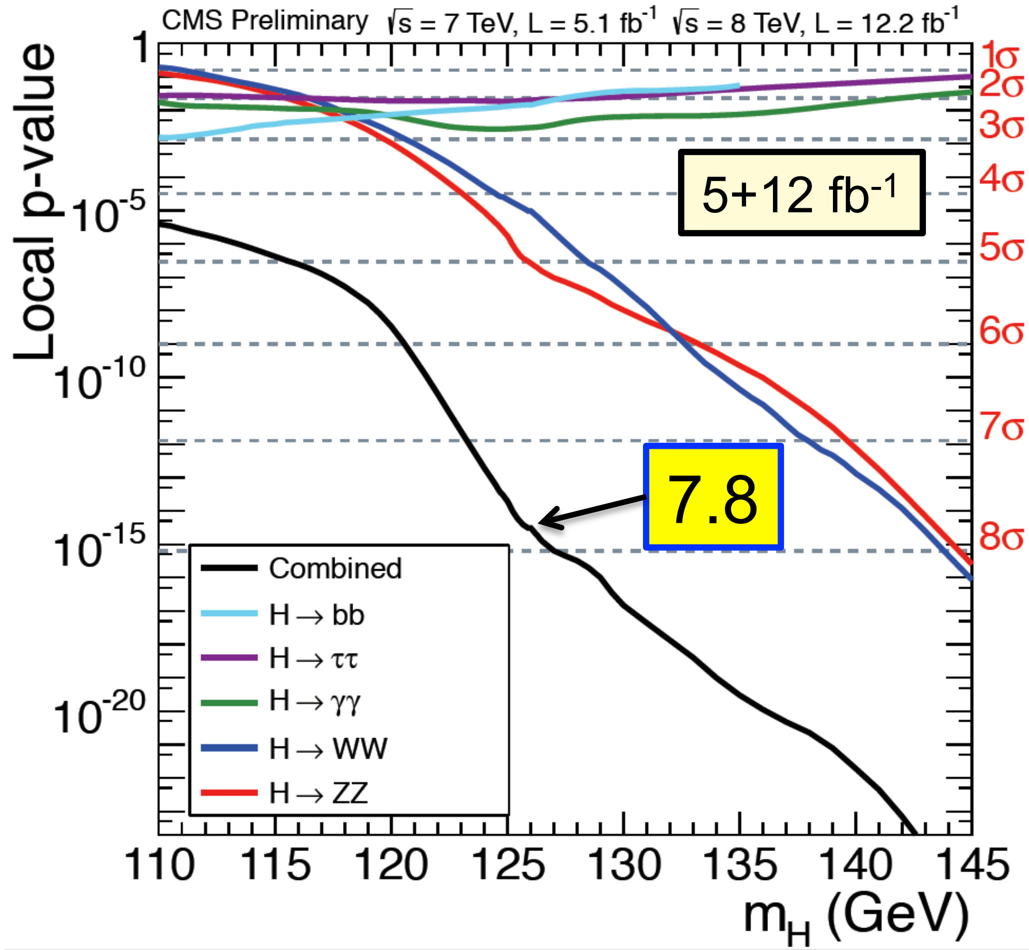
LHC is delivering luminosity



Larger dataset = increased sensitivity

- **Low mass (i.e. near 125 GeV)**
  - **Analyses of five decay modes**
  - **Confirmation of observation and start of study of properties**





- **Expected significance (at best fit mass) increased from 5.8 to 7.8 standard deviations**

Decay modes and production tags

Decay	m_H range (GeV)	Mass resolution	L (fb^{-1}) 7 TeV	L (fb^{-1}) 8 TeV
$\gamma\gamma$	110-150	1-2%	5.1	5.3
$ZZ \rightarrow 4l$	110-1000	1-2%	5.0	12.1
$WW \rightarrow l\nu l\nu$	110-600	20%	4.9	12.1
bb	110-135	10%	5.0	12.1
$\tau\tau$	110-145	20%	4.9	12.1

- **A few other, additional, subchannels are studied outside the low mass region**

Decay	No tag	VBF-tag	VH-tag	ttH-tag
$\gamma\gamma$	✔	✔		
$ZZ \rightarrow 4l$	✔			
$WW \rightarrow l\nu l\nu$	✔	✔	✔	
bb			✔	✔
$\tau\tau$	✔	✔	✔	

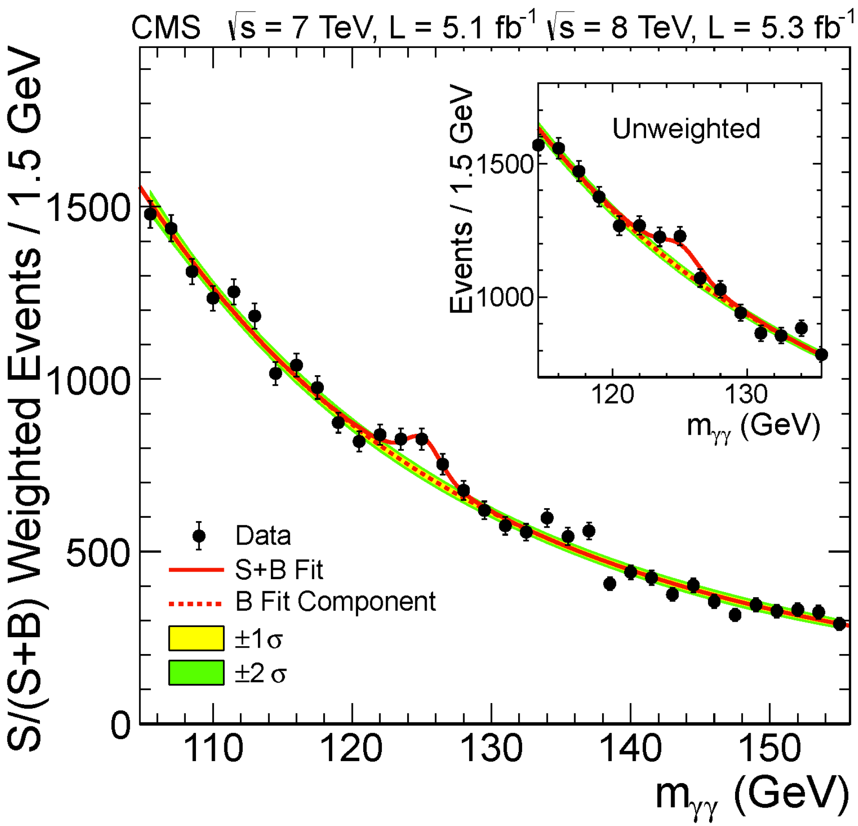
$H \rightarrow \gamma\gamma$

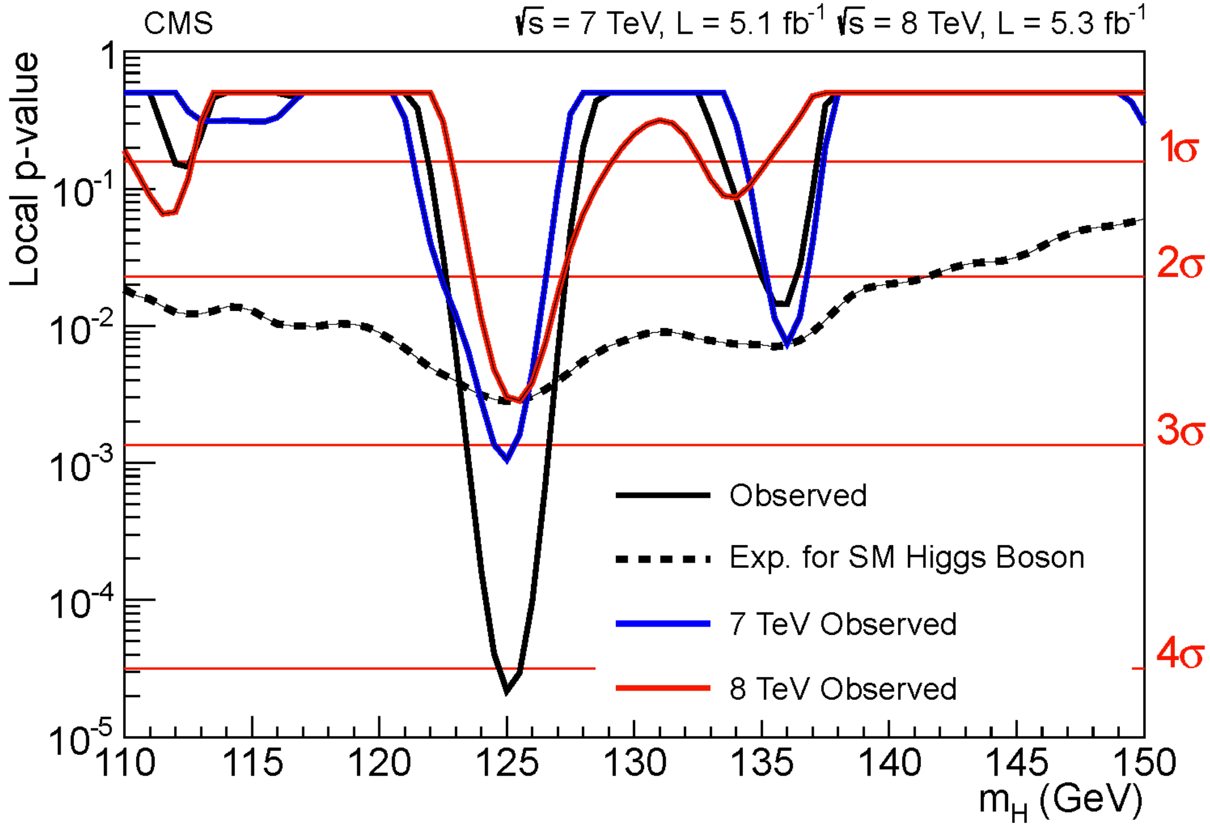
H → γγ – no update since ICHEP

- **Key elements in search strategy:**
  - **Narrow mass peak**
  - **Separate events into classes based on resolution and inclusive S/B**
    - In CMS both energy resolution and inclusive S/B vary in a similar way with respect to:
      - pseudorapidity, η
      - photon conversion flag
  - **Background modeled from data**
  - **Signal model from MC**

- **Multivariate analysis makes use of information about energy resolution, including vertex finding probability, and inclusive S/B, to classify events**

H → γγ results



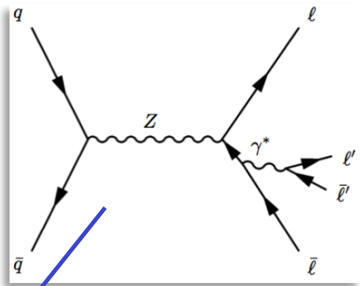


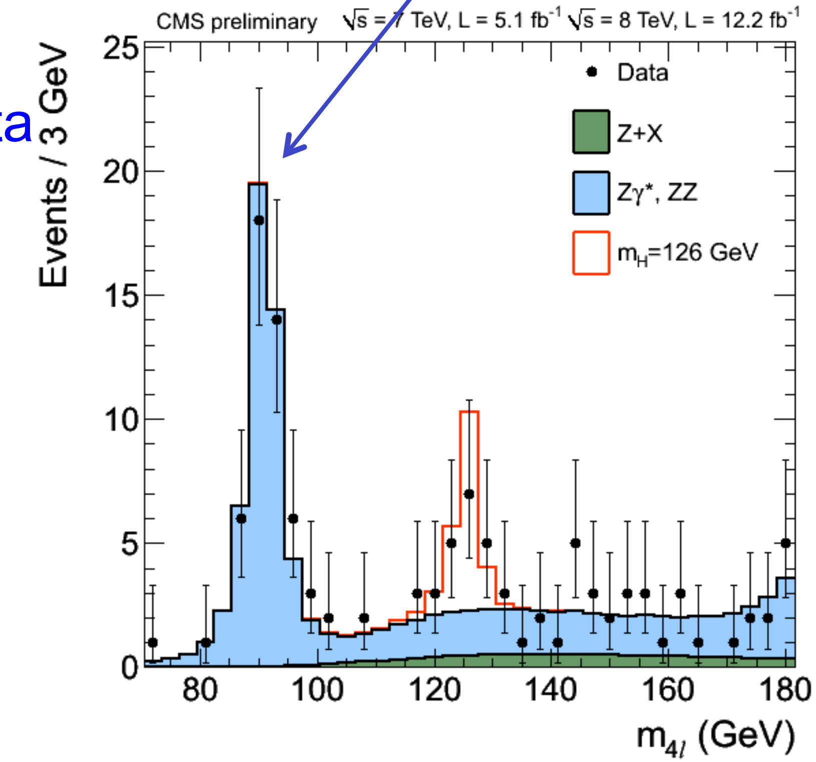
- **Significance of 4.1 observed at 125 GeV (2.8 expected)**
- **Best fit signal strength σ/σ_{SM} = 1.56 ± 0.43**

$H \rightarrow ZZ$

H→ZZ→4l

- **Four isolated high p_T leptons ($p_T(\mu)>5$, $p_T(e)>7$ GeV)**
  - **From common vertex**
  - **Opposite sign pairs consistent with Z decays**
  - **Background ~flat for m_{4l} ~ 125 GeV**
    - Irreducible non-resonant ZZ – well understood: model from theory
    - Reducible (Z+X, Z*bb*, top) – model from data



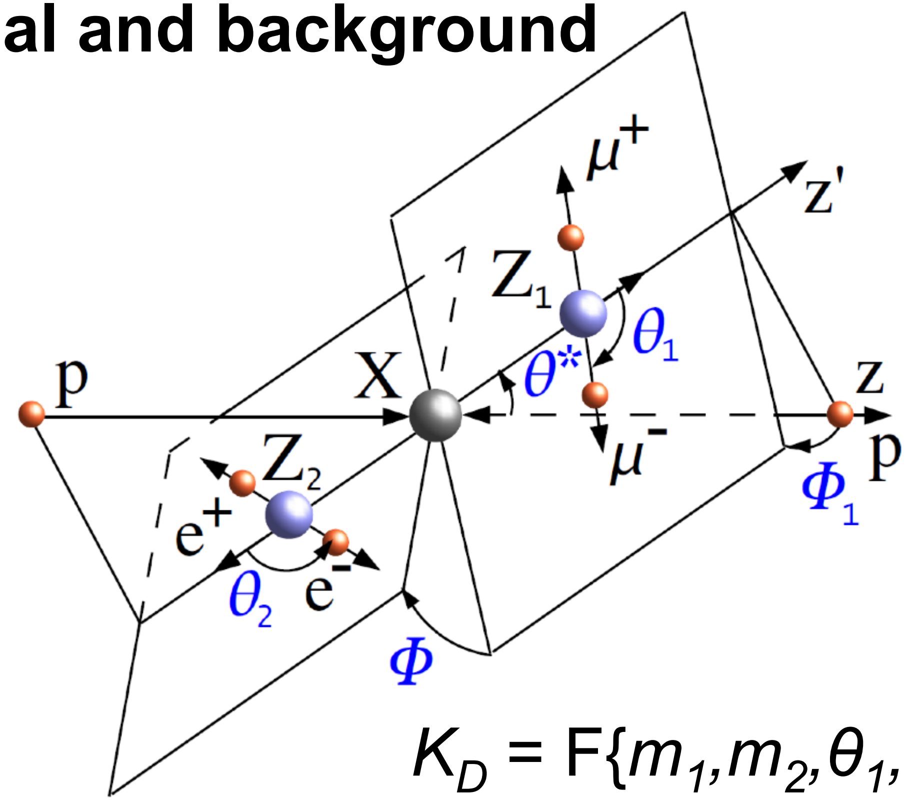


121.5 < m_{4l} < 130.5 GeV

	Exp. Bkg.	m_H = 126	Data
4e	1.25	2.20	3
4μ	2.09	4.26	6
2e2μ	3.14	5.97	8
Total	6.48	12.43	17

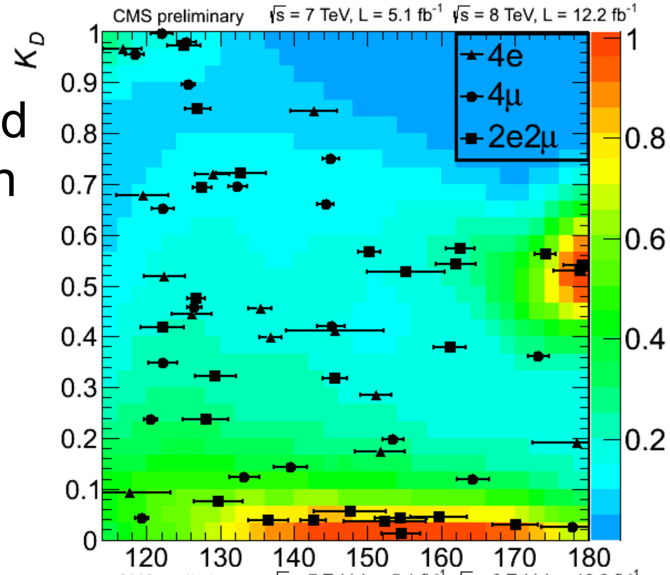
H→ZZ→4l – K_D

- **Detailed kinematic information, dilepton masses and five decay angles, can be exploited to provide further discrimination between signal and background**

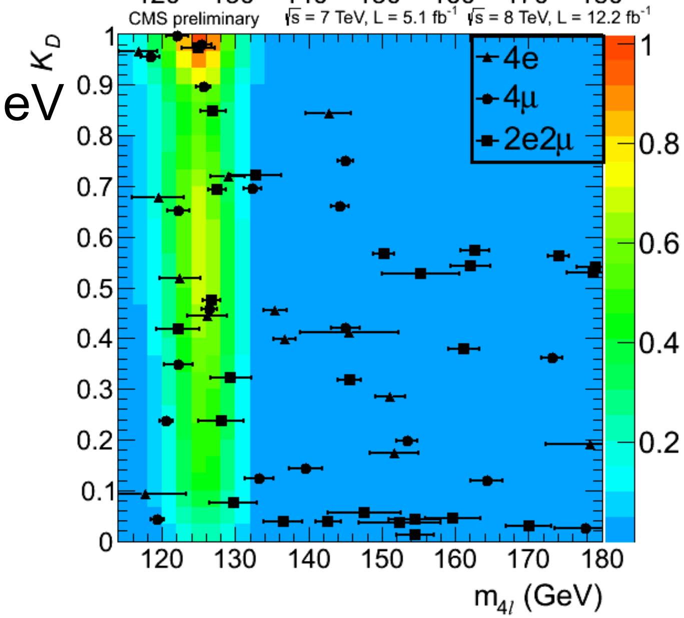


$$K_D = F\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$$

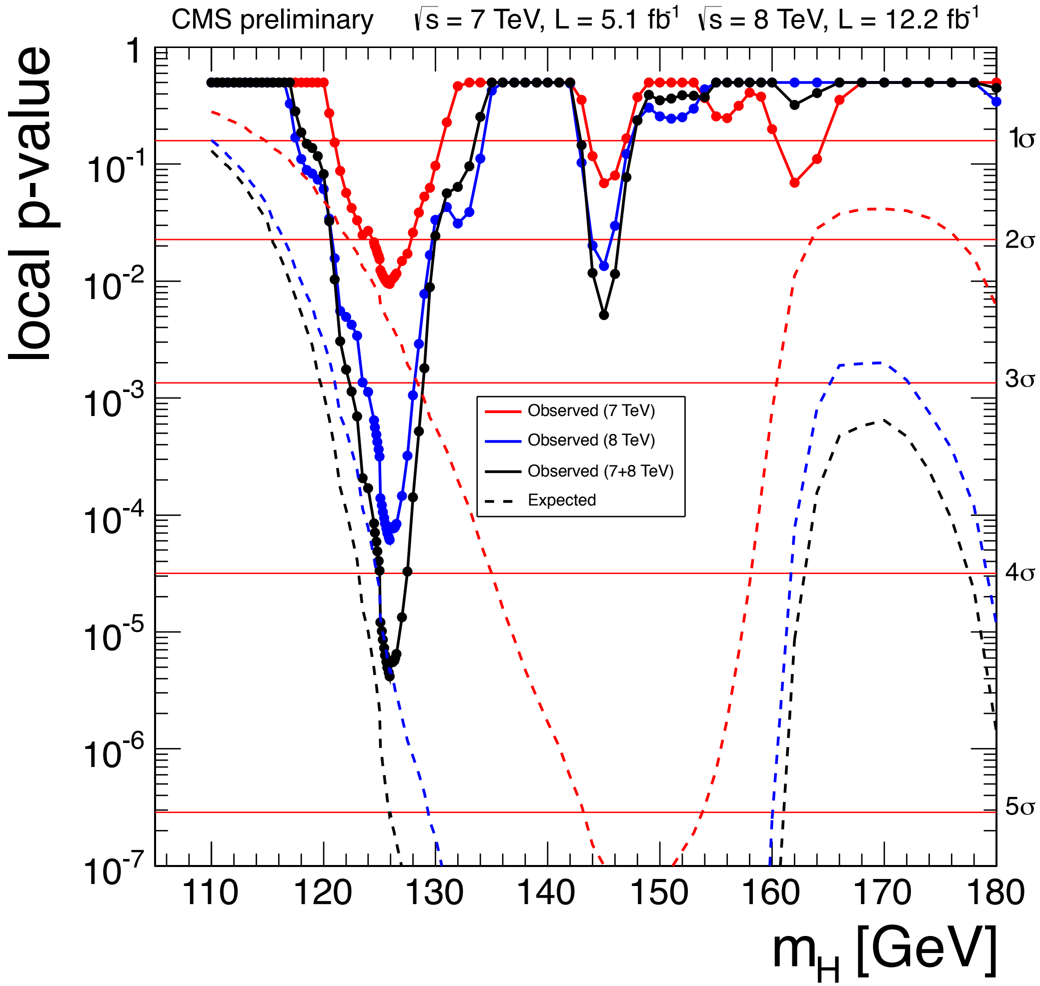
Background expectation



m_H = 126 GeV expectation

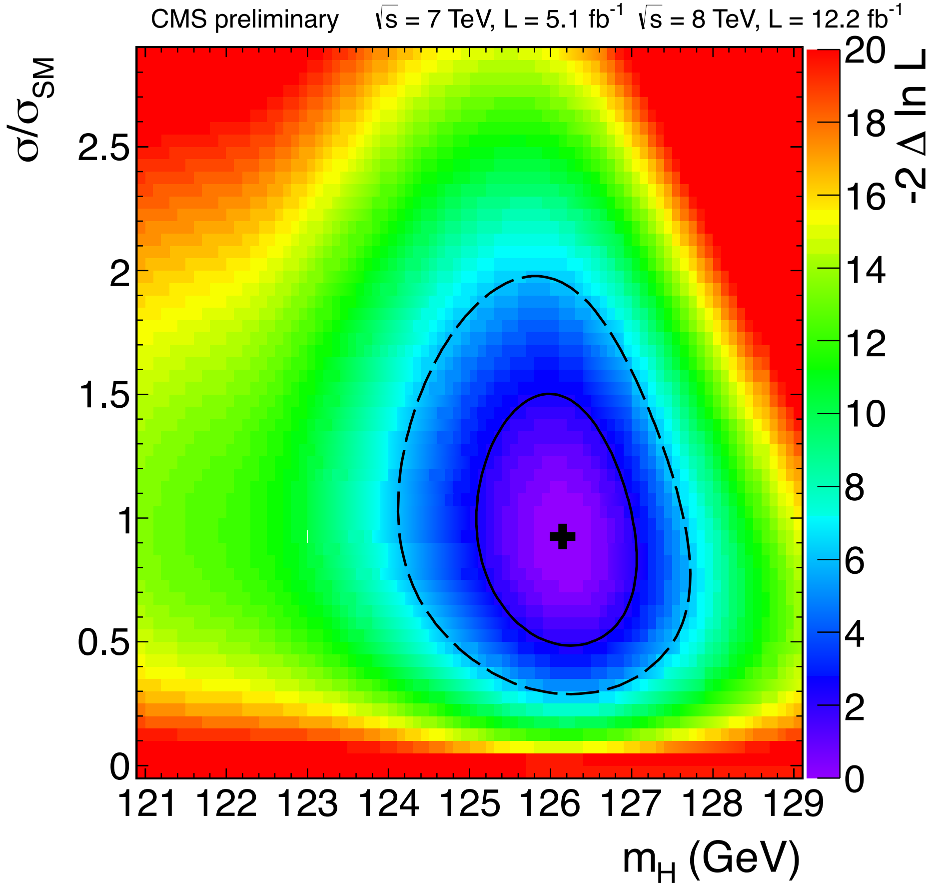


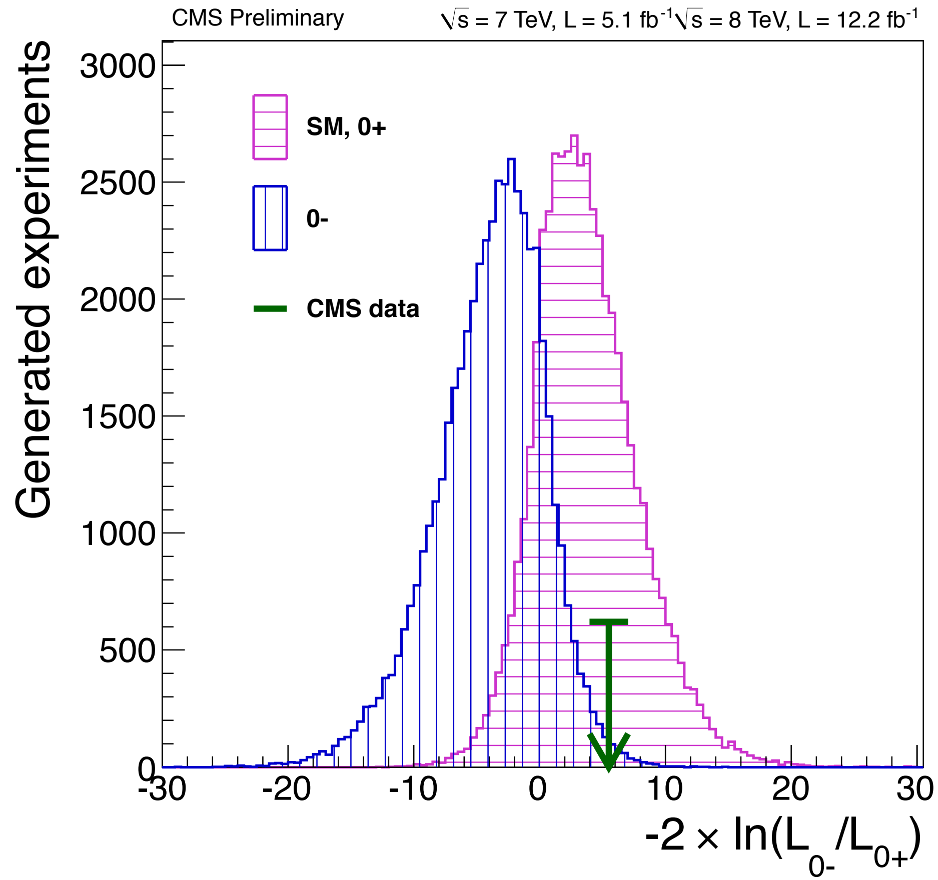
H→ZZ→4l



- **Significance at m_H = 126 GeV: 4.5 (5.0 expected)**
- **Signal strength, $\sigma/\sigma_{SM} = 0.80^{+0.35}_{-0.28}$**

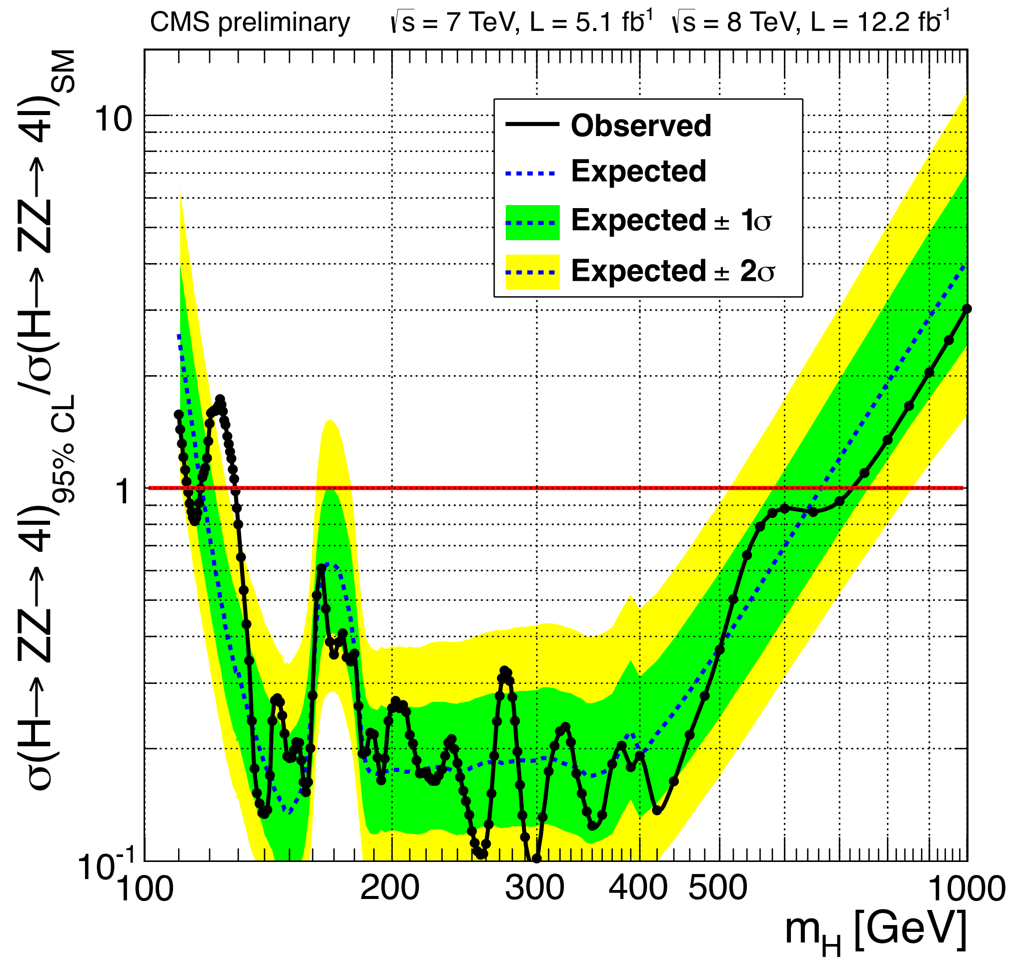
Mass, spin/parity





- **Mass measurement: 126.2 ± 0.6 (stat) ± 0.2 (syst) GeV**
- **Under the assumption of spin 0, the data disfavour the 0^- (pseudoscalar) hypothesis with a CL_S value of 2.4%**
  - **(Data are consistent with 0^+)**

H→ZZ – high mass region



- **Exclusion at 95% CL in the mass range 129 < m_H < 720 GeV**

$H \to WW$

$H \to WW \to l\nu l\nu$

- Search for: 2 opposite sign leptons (e or μ) + E_T^{miss}
- No mass peak – background estimation plays key role
- New since ICHEP (for 8 TeV data):
  - 2D shape analysis (m_{ll}, m_T) used for the most sensitive categories (different flavour 0 and 1-jet)

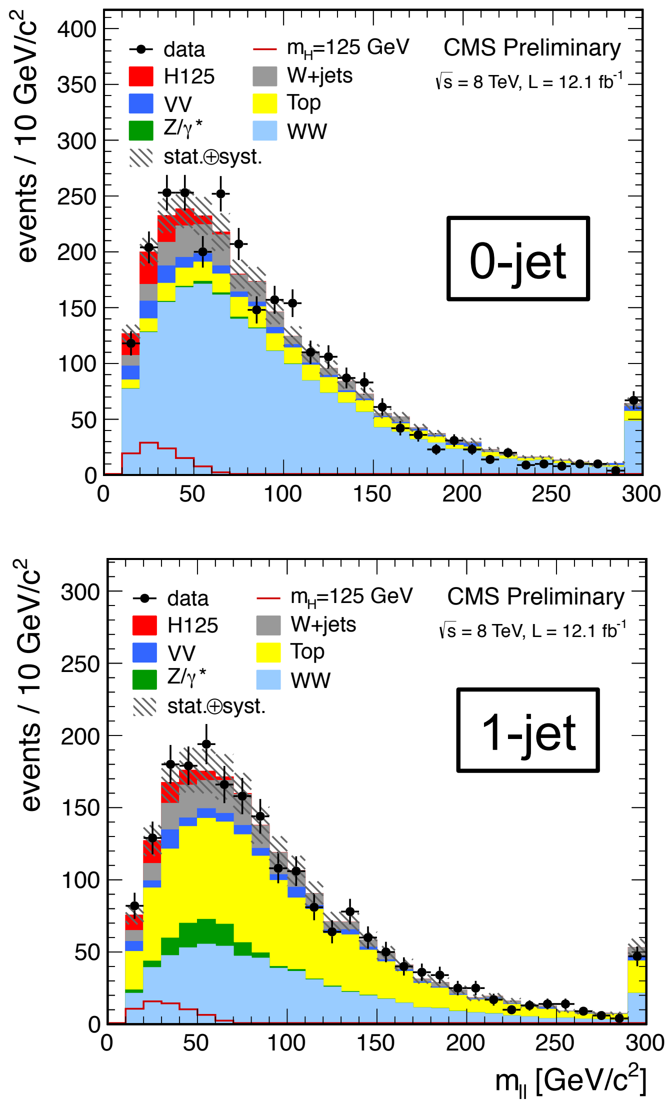
	0-jet	1-jet	2-jet
DF: $e\mu$	2D shape	2D shape	Cut and count
SF: ee, $\mu\mu$	Cut and count	Cut and count	Cut and count

2-jet selection optimized to tag VBF production

- $p_T(l_1) > 20$, $p_T(l_2) > 10$ GeV
- p_T(jets) > 30 GeV
- Pre-selection pays particular attention to:
  - Rejection of Z+jets background (mass cut, dedicated MVA etc)
  - Rejection of top background (soft muon veto, jet anti-b-tagging)
  - Rejection of non resonant WW (require small $\Delta\phi_{ll}$)

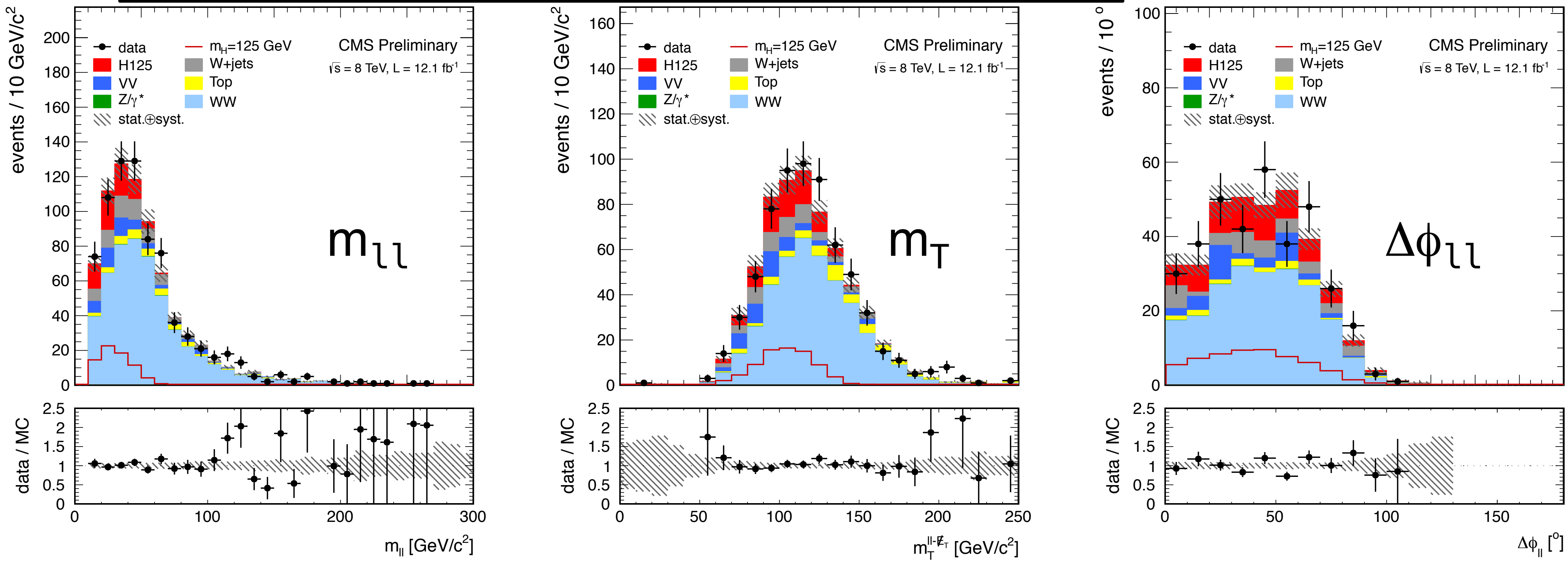
H→WW→lνlν – background estimation

- **WW: (for m_H < 200 GeV) estimate in m_{ll} > 100 GeV control region, and extrapolate to signal region with simulation**
- **Top: estimate by counting top-tagged events, and independently determining top-tagging efficiency**
- **W+jets: estimate from "tight-loose" dilepton control sample and apply efficiency, ε_{loose} (measured independently)**
- **Z+jets: count events in tight mass window round m_Z, and extrapolate using simulation**
- **Other backgrounds from simulation**



H→WW→lνlν – cut and count

Cuts, tuned for each m_H, applied on these three variables:

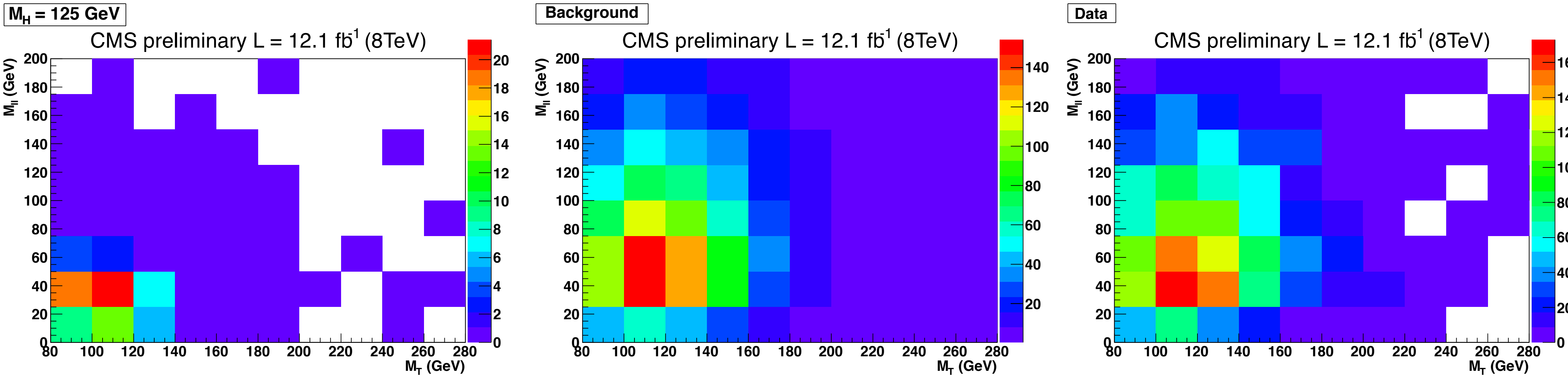


- **Example of 0-jet, eμ final state – table shows three mass hypotheses**

m_H	signal	WW	WZ+ZZ	top	W+jets	Wγ*	Sum	data
125	58 ± 12	203 ± 19	6.6 ± 0.6	11.0 ± 2.5	44 ± 16	25.6 ± 9.5	291 ± 27	349
200	95 ± 21	204 ± 19	6.3 ± 0.6	28.9 ± 6.4	7.7 ± 3.5	1.3 ± 0.9	278 ± 21	309
600	6.6 ± 2.3	42.2 ± 4.8	2.5 ± 0.3	16.5 ± 3.8	4.4 ± 2.0	2.4 ± 1.8	67.9 ± 6.7	64

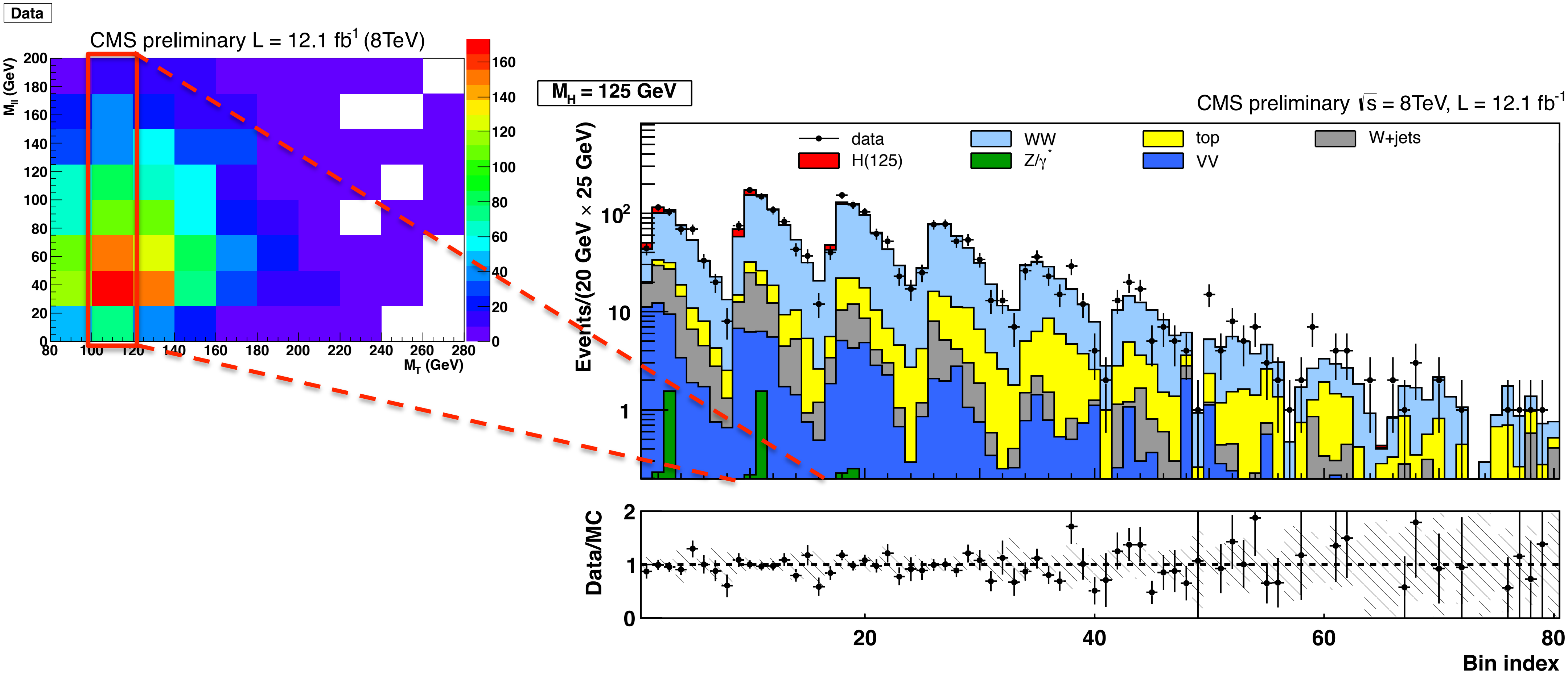
$H \rightarrow WW \rightarrow l\nu l\nu$ – 2D shape (m_{ll}, m_T)

- **Separation of signal and background in two dimensions**
- **Improves analysis sensitivity since 2D distribution of main backgrounds differs from that of signal**



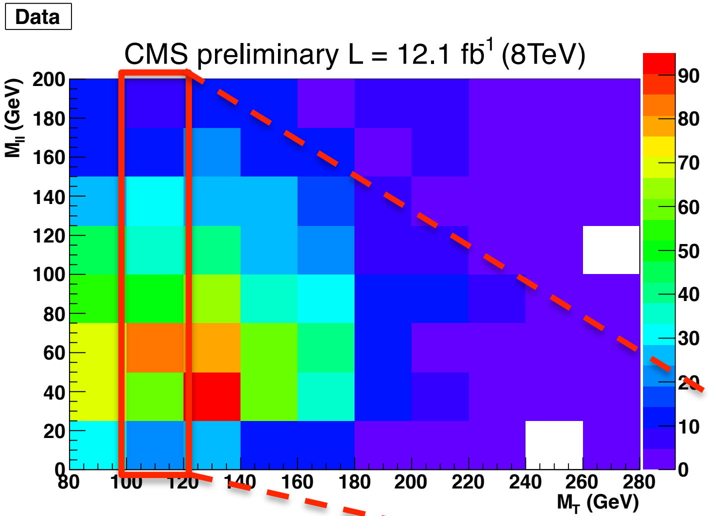
(m_{ll}, m_T) signal and background models, and data in 0-jet bin

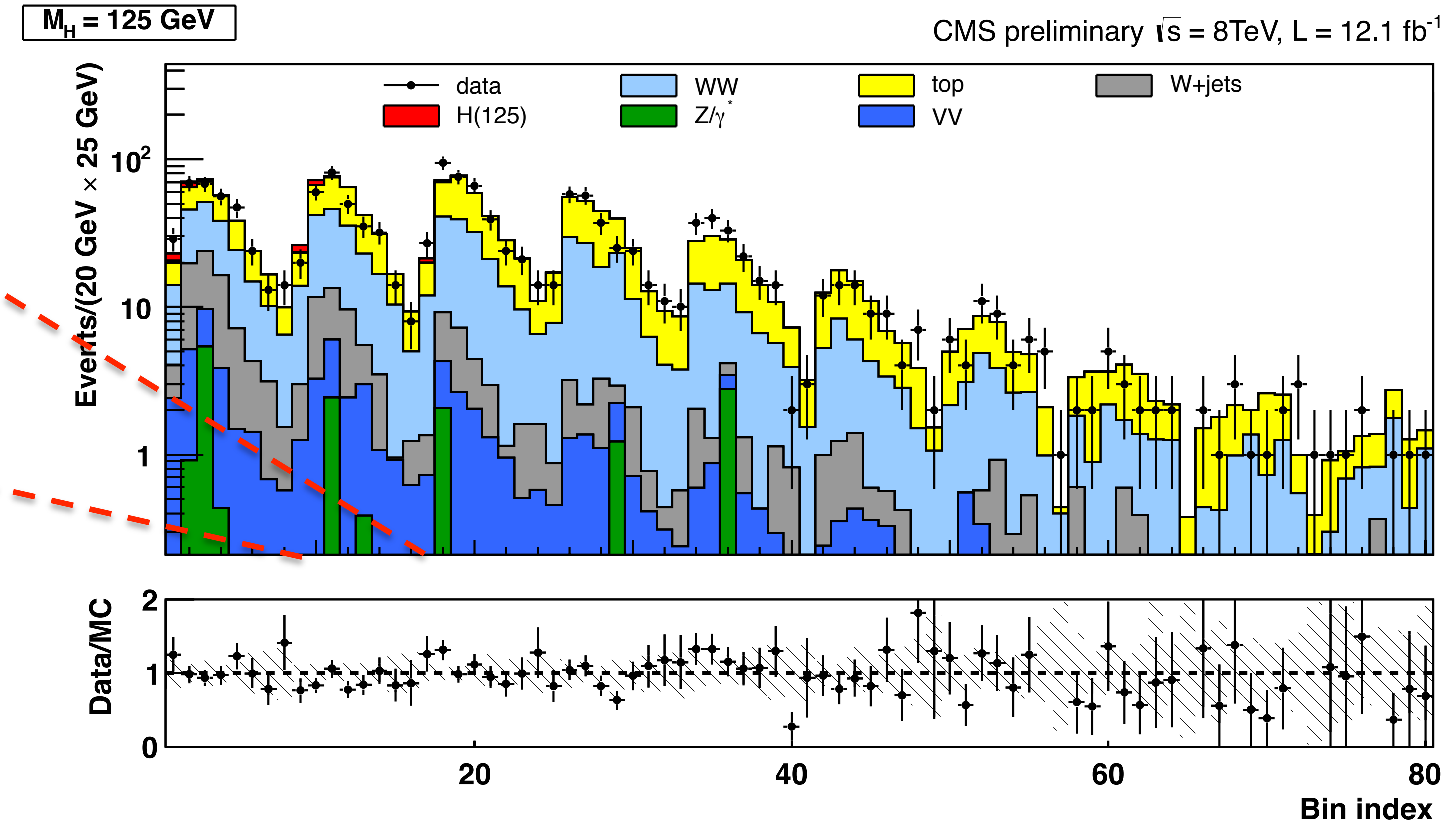
$H \rightarrow WW \rightarrow l\nu l\nu$ – 2D-shape – 0-jet bin



- **The 2D distribution "unrolled" for detailed examination**

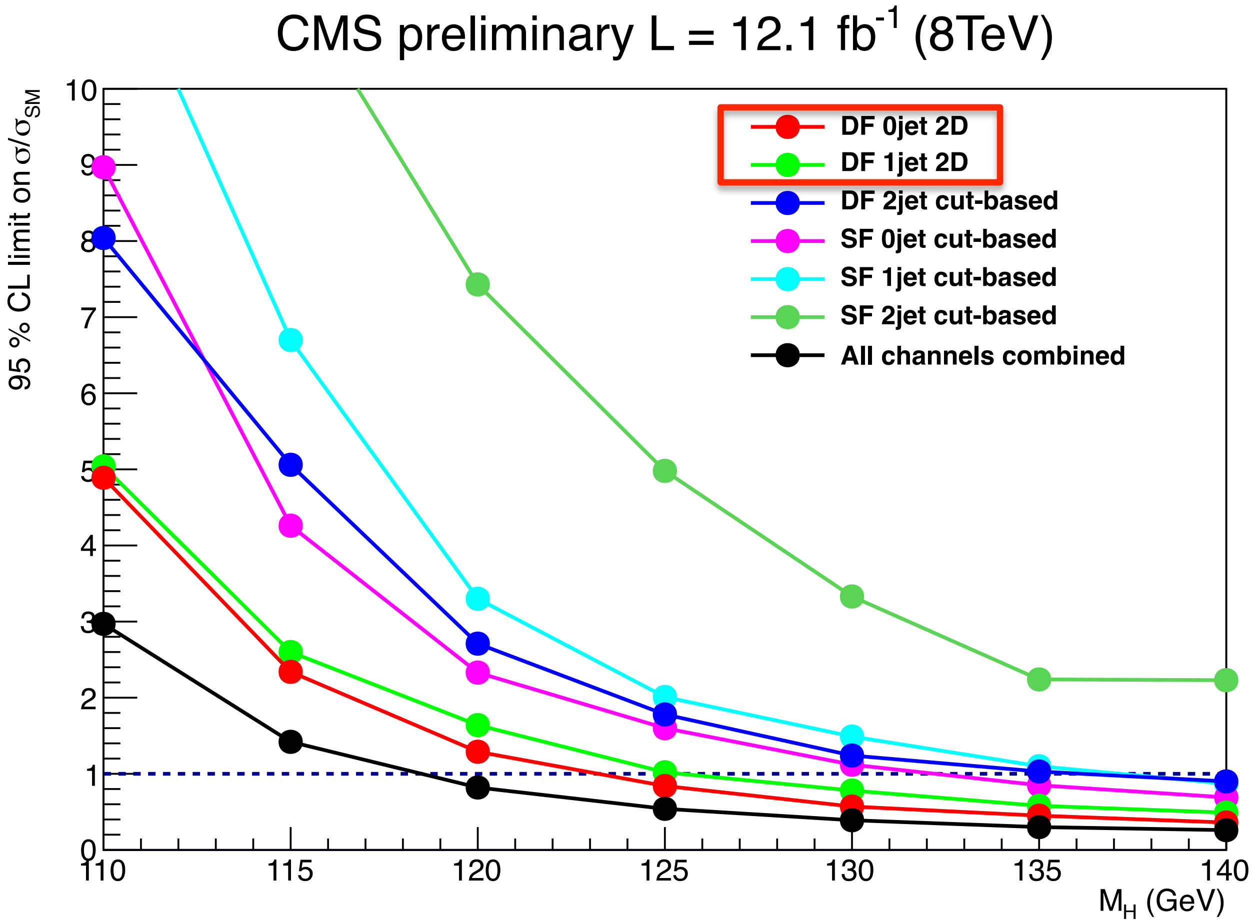
H→WW→lνlν – 2D-shape – 1-jet bin





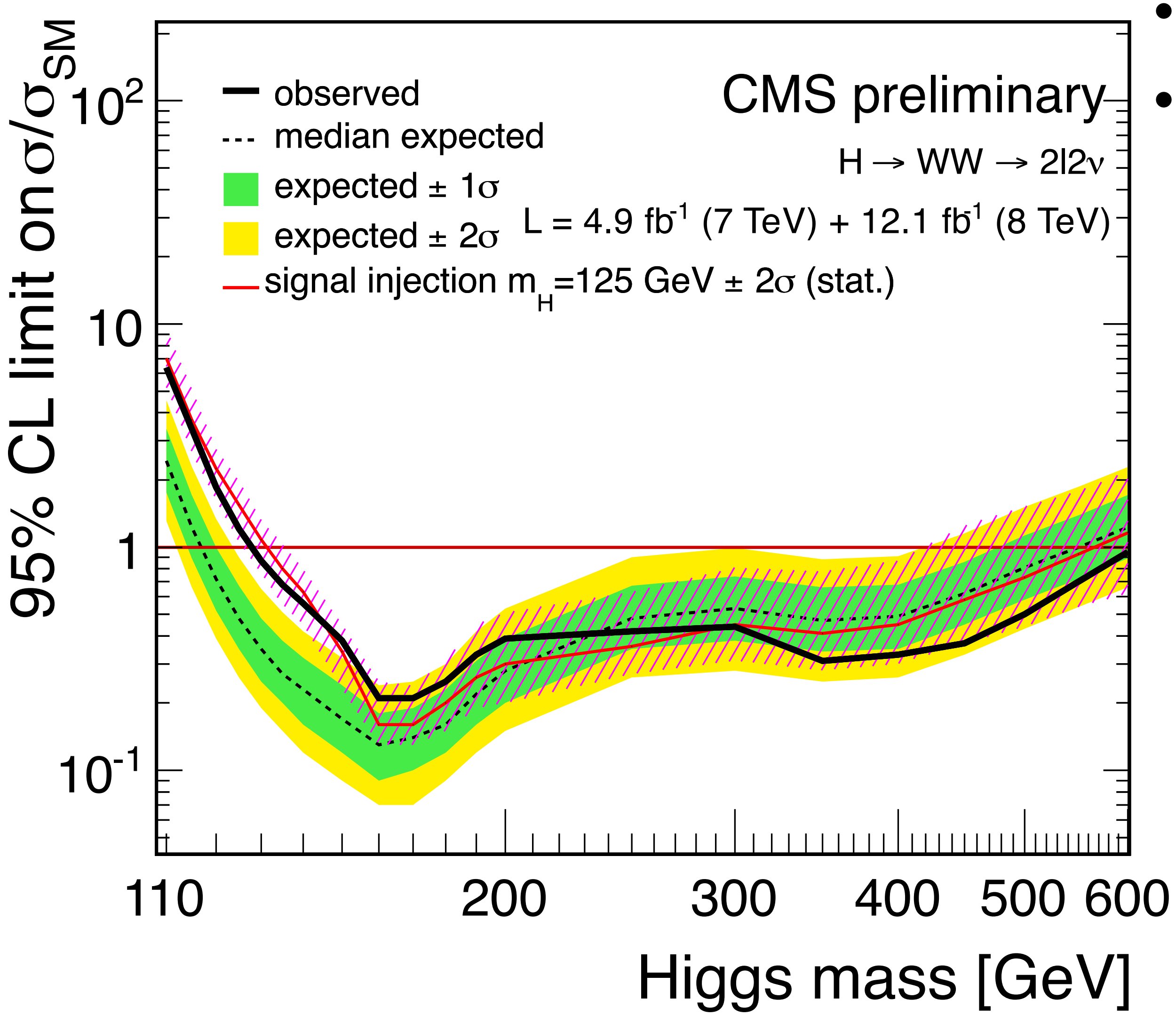
- **The 2D distribution "unrolled" for detailed examination**

H→WW→lνlν – sensitivity of cats.



- **The eμ (different flavour) 2D provides most of the sensitivity**

$H \to WW \to l\nu l\nu$ – results



- **Excess in low mass region**
- **For m_H = 125 GeV:**
  - **Significance: 3.1 (exp.: 4.1)**
  - **Best fit signal strength σ/σ_{SM} = 0.74 ± 0.25**
  - **Expected limit in the presence of m_H = 125 GeV shown as red hatched area**

$H \rightarrow \tau\tau$

$H \rightarrow \tau\tau$

- **Tau leptons detected by:**
  - **decays to electrons or muons: τ_e, τ_μ**
  - **decays to hadrons: τ_h**
    - Reconstructed as either: a single charged track, a charged track plus calorimeter energy, three charged tracks
- **Five final states used:** $\boxed{\tau_\mu\tau_\mu,\ \tau_\mu\tau_e,\ \tau_\mu\tau_h,\ \tau_e\tau_h,\ \tau_h\tau_h}$
- **Performance of tau (τ_h) reconstruction:**
  - **Reconstruction efficiency > 60% (flat for $p_T(\tau)$ > 30GeV), fake rate 1-3%**
  - **Efficiency and momentum resolution almost independent of pileup**
- **Invariant mass of di-tau system is determined using a maximum likelihood method for assignment of E_T^{miss}**

$H \rightarrow \tau\tau$ – event categories

N_{jet}

2-jet; selection optimized for VBF production
- m_{jj} > 500GeV, $|\Delta\eta|$ > 3.5, central jet veto (p_T^{jet} > 30 GeV)
- Most sensitive single category

1-jet, $p_T(\ell)$ < 30 GeV
Many events in this category

1-jet, $p_T(\ell)$ > 30 GeV
- Good $m_{\tau\tau}$ resolution
- Small $Z \rightarrow \tau\tau$ background

Background fit only: constrains background for all categories →

0-jet, $p_T(\ell)$ < 30 GeV

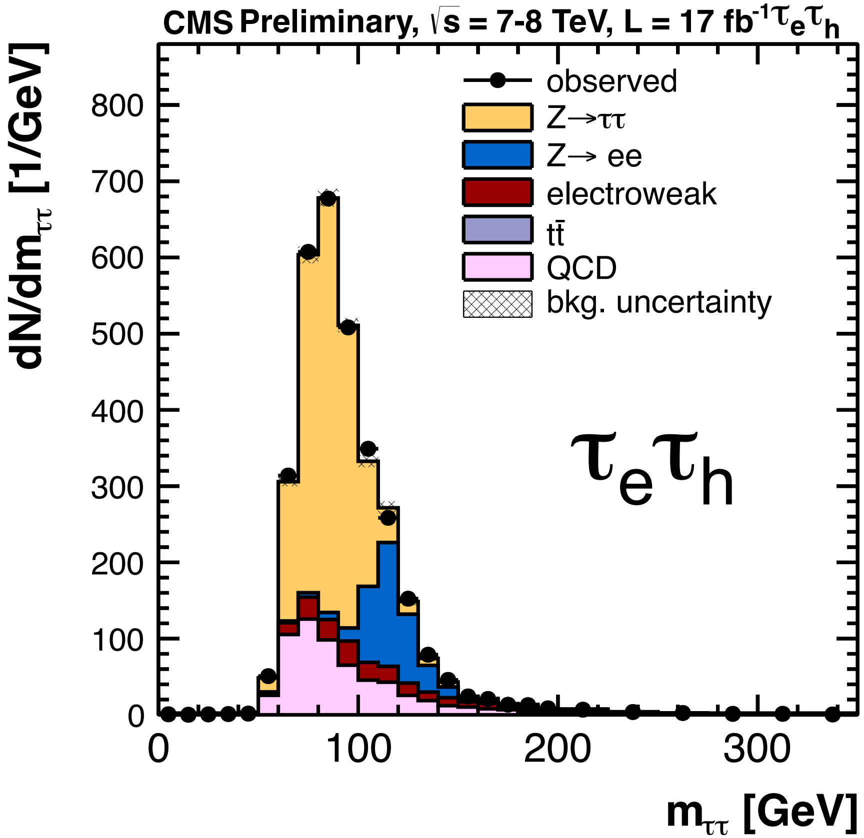
0-jet, $p_T(\ell)$ > 30 GeV

$p_T(\ell)$

- **Fit to $m_{\tau\tau}$ distribution, using templated background, and signal +background models**

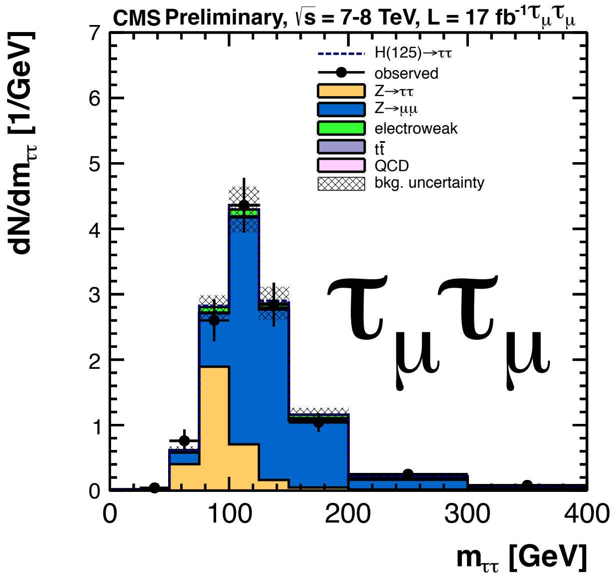
H→ττ – background modeling

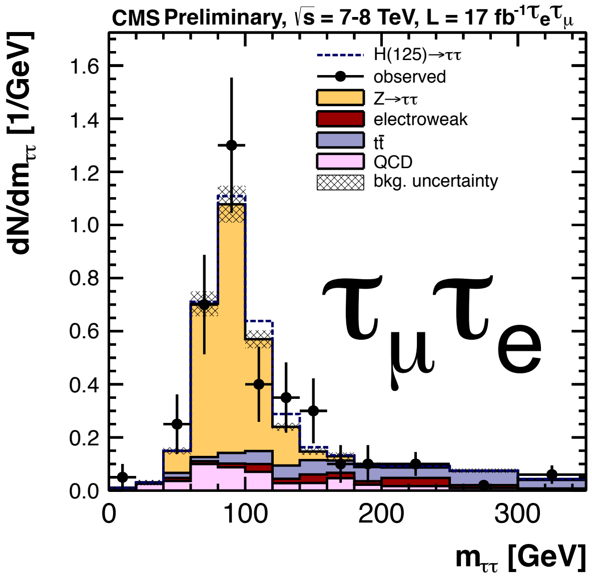
- **Z→ττ**
  - Estimated from Z→μμ with muon replaced by simulated tau decay – normalization from Z→μμ
- **QCD**
  - Shape and normalization from LS/OS or fakerate
- **Z→ee(/μμ)**
  - From simulation: POWHEG, corrected for measured rates for jets and e/(μ) to fake a τ
- **Diboson/W+jets**
  - From simulation: MADGRAPH, normalization from sideband
- **ttbar**
  - From simulation:MADGRAPH, normalization from sideband

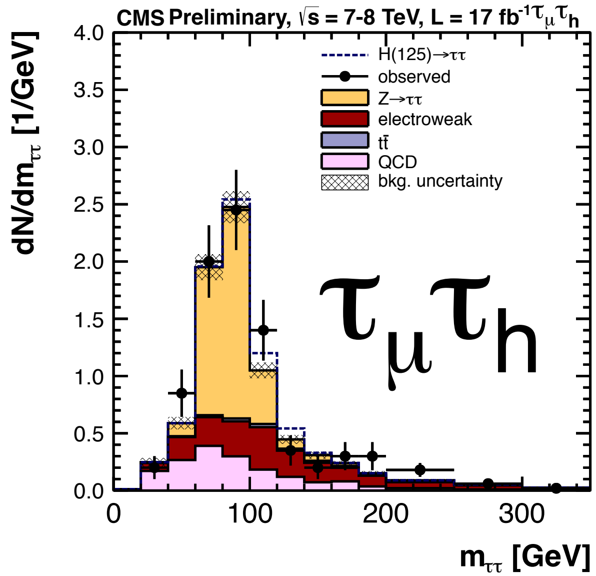


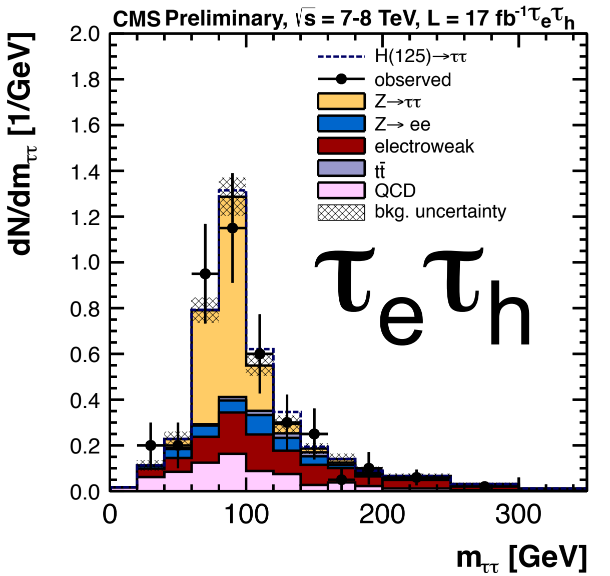
Background:
example of 0-jet category, $\tau_e\tau_h$ final state

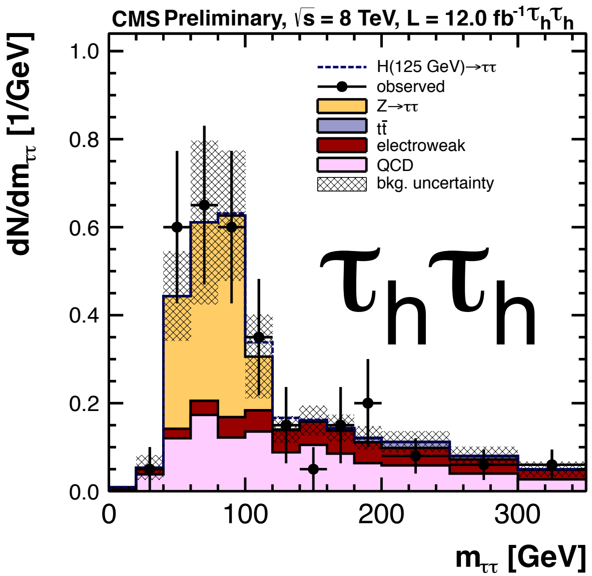
H→ττ – after fit (VBF category)





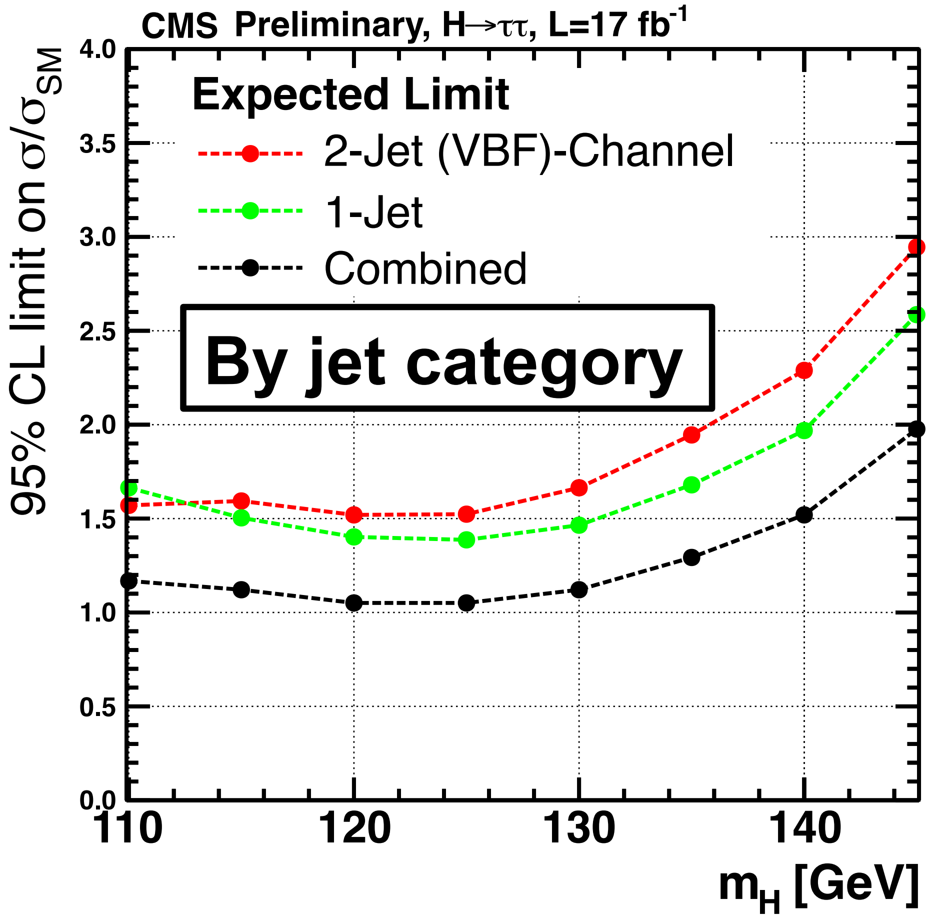


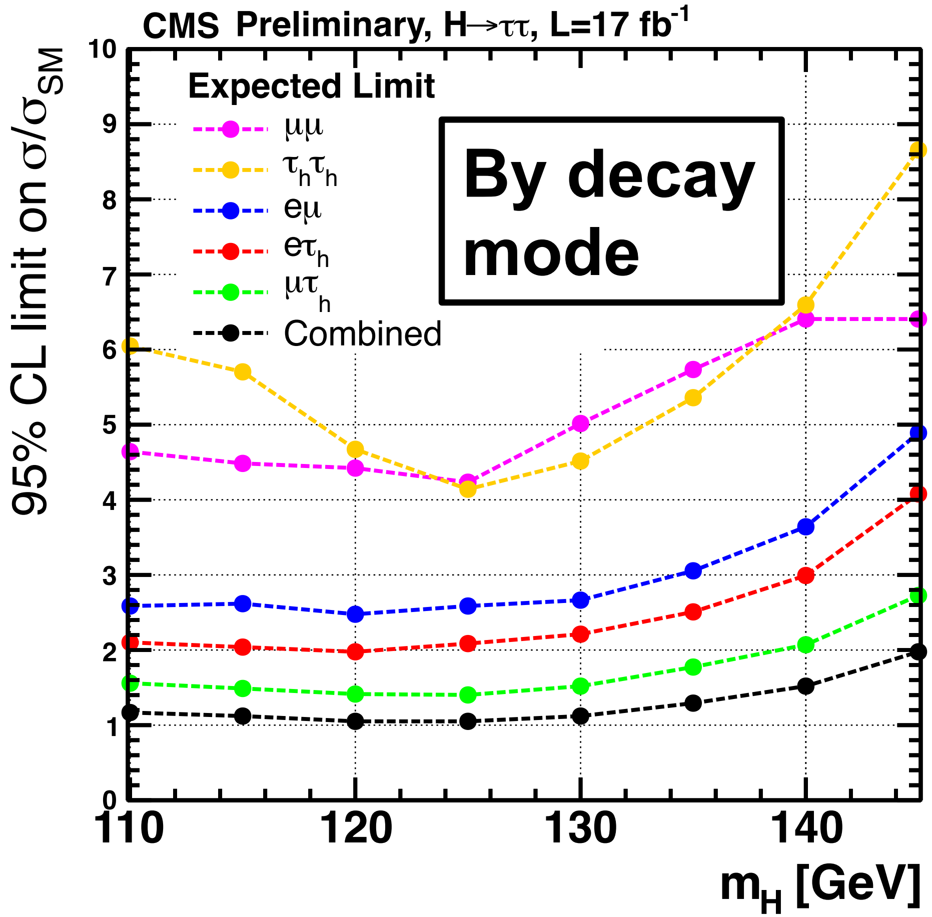




- **Shaded bands correspond to uncertainties after fit**

H→ττ – sensitivity by cat. and mode

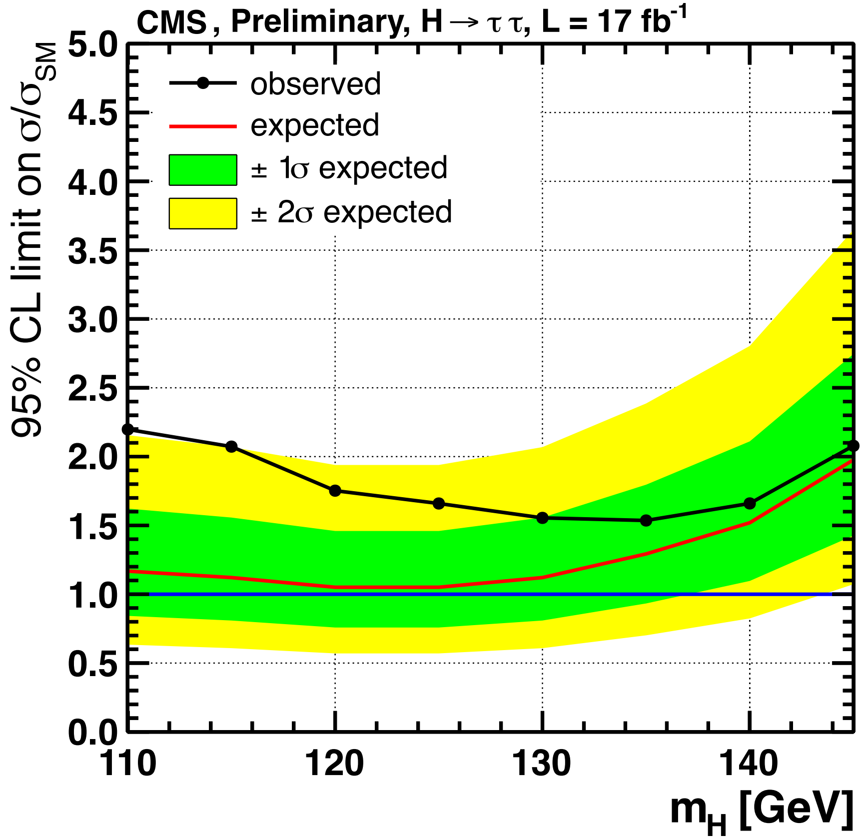




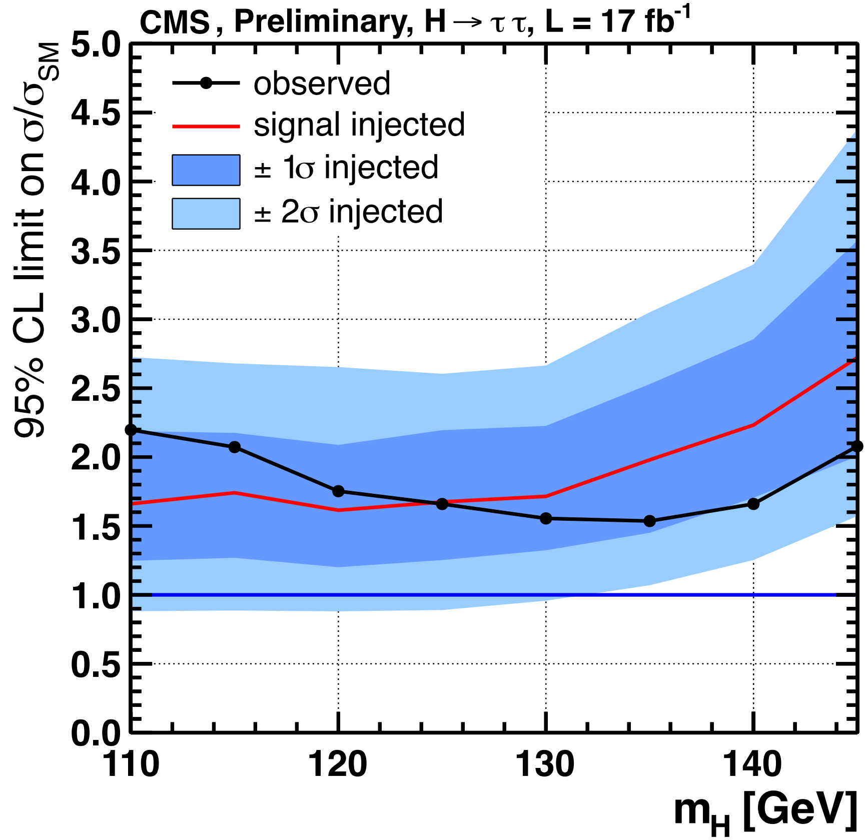
- Jet categories not very dissimilar in sensitivity at m_H = 125 GeV
- Most sensitive decay mode is $\tau_\mu\tau_h$

$H \rightarrow \tau\tau$ – limits

Expectation w/o Higgs

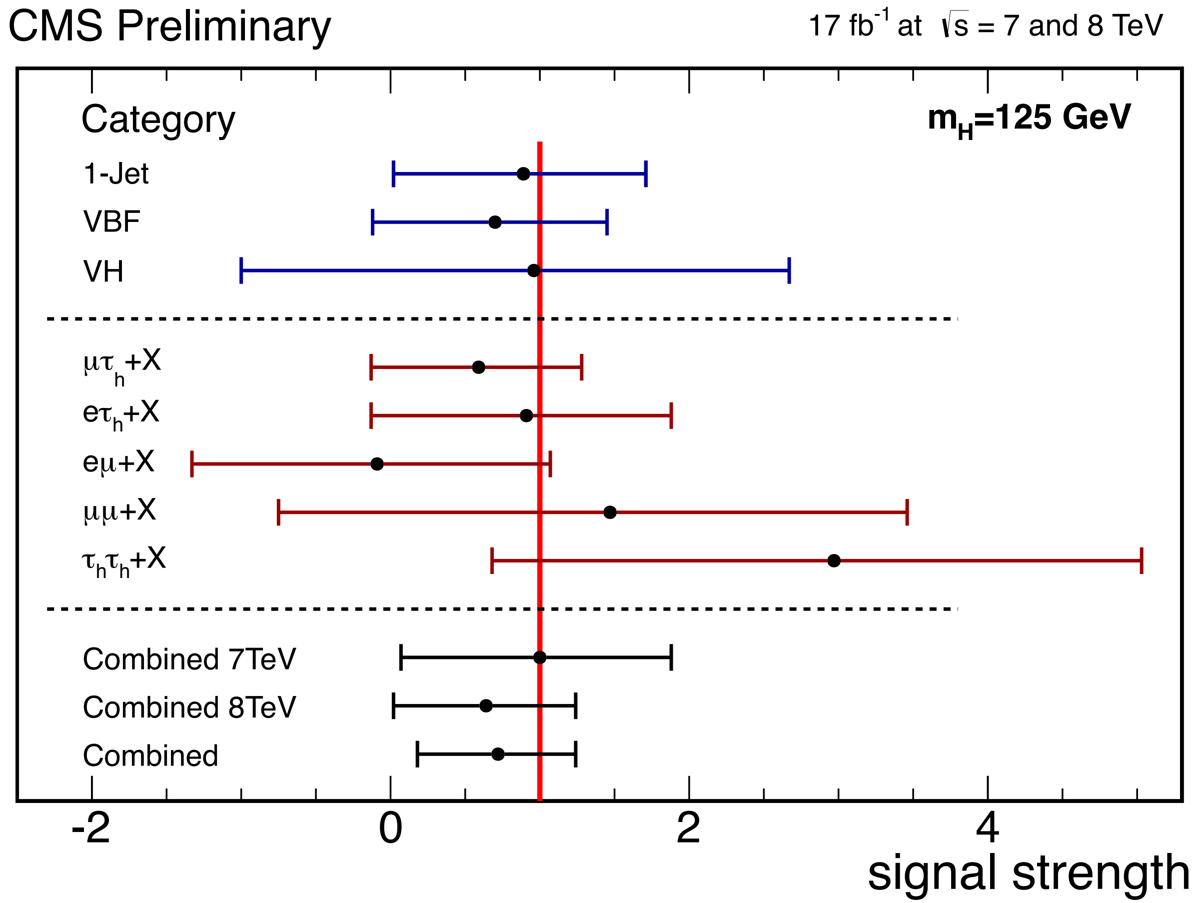


Expectation with SM m_H =125 GeV injected (no prefit to data)



- **Result compatible with both background only hypothesis and with Higgs signal at 125 GeV**

H→ττ – signal strength



- **Best fit signal strength, for m_H = 125 GeV, is σ/σ_{SM} = 0.72 ± 0.52**
- **Significance of excess for $m_H \approx$ 125 GeV is: 1.8 (expected is 2.1)**

$H \rightarrow \tau\tau$ – MSSM

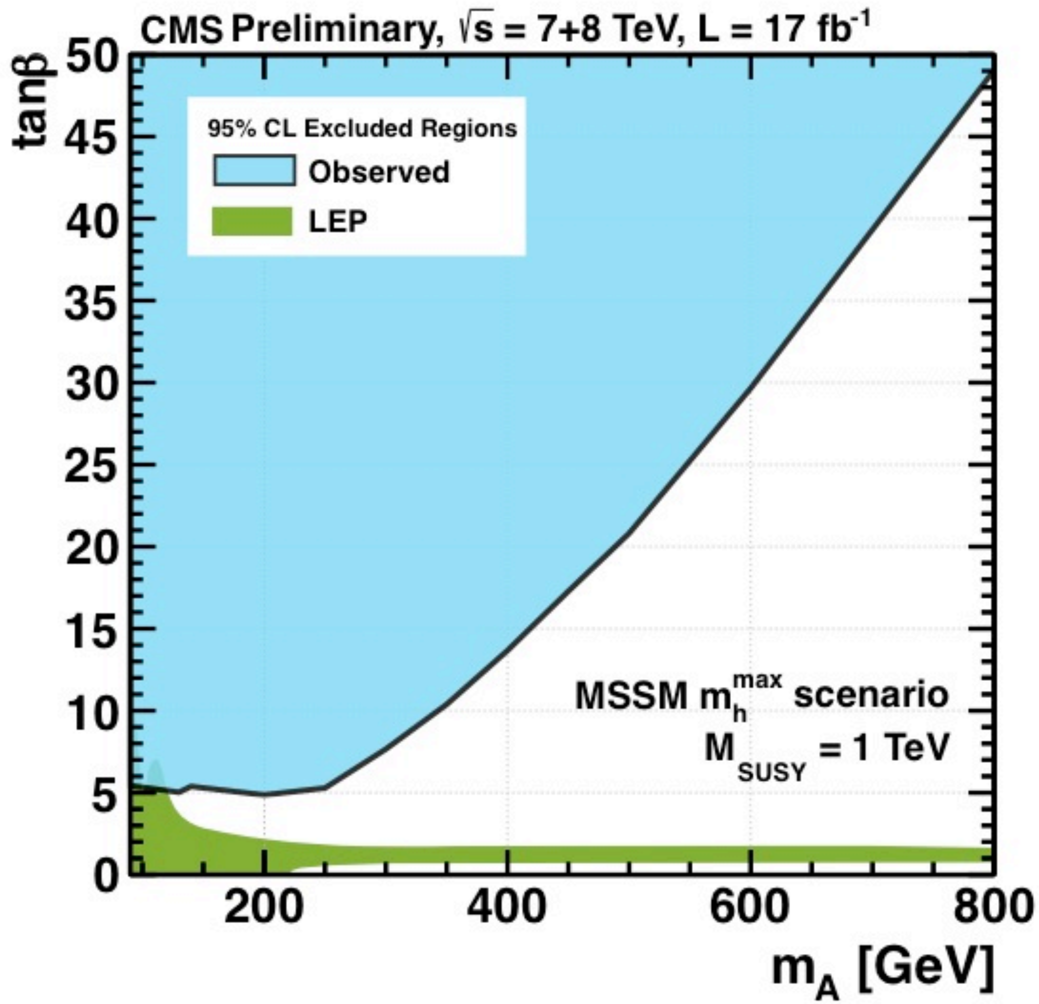
- **Using final states: $e\tau$, $\mu\tau$, $e\mu$, $\mu\mu$**
- **Define *b*-tagged:**

> ≥ 1 *b*-jets with p_T > 20 GeV/c
> < 2 jets with p_T > 30 GeV/c

- **and not-*b*-tagged categories:**

> No *b*-jets with p_T > 20 GeV/c

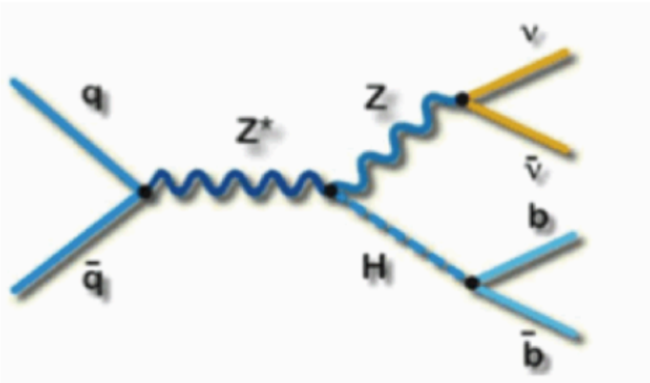
- **The analysis targets enhanced coupling to *b*-quarks at large tan(β)**

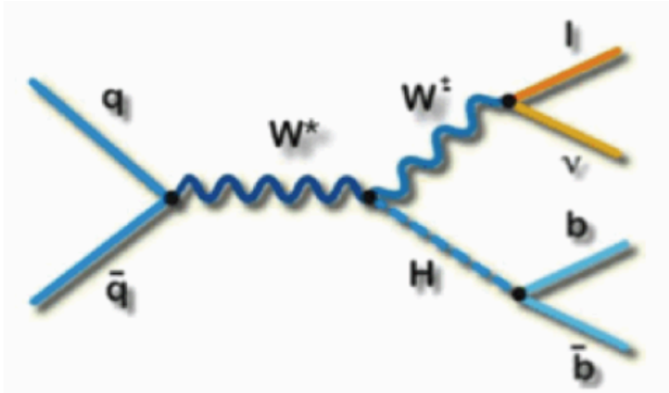


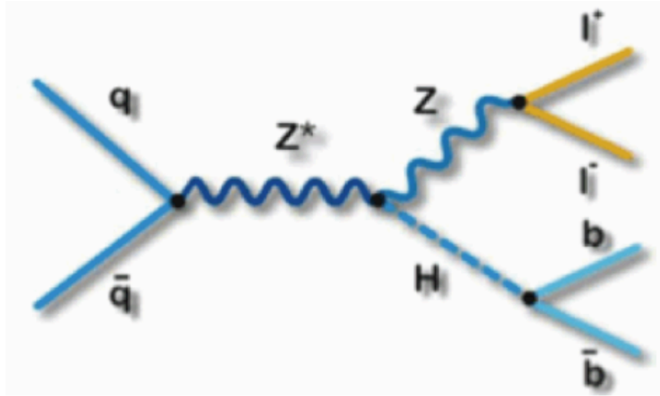
H→*bb*

H→*bb* – overview

- Very large branching ratio, and very large background
- Search for associated production: VH → V*bb*



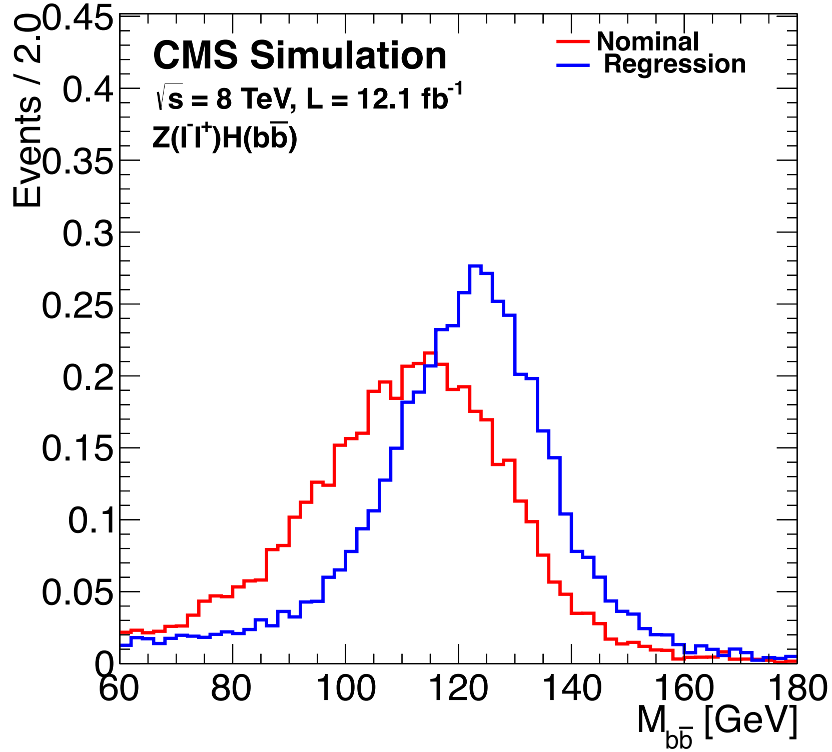




- Five final states depending on W/Z decay
- Trigger on leptons and E_T^{miss}
- *b*-jets identified by track impact parameters and secondary vertices
- Main backgrounds: V+jets, *tt*
- Enhance S/B by selecting high $p_T(V)$ – dividing into low/high $p_T(V)$ categories

H→*bb* – analysis details

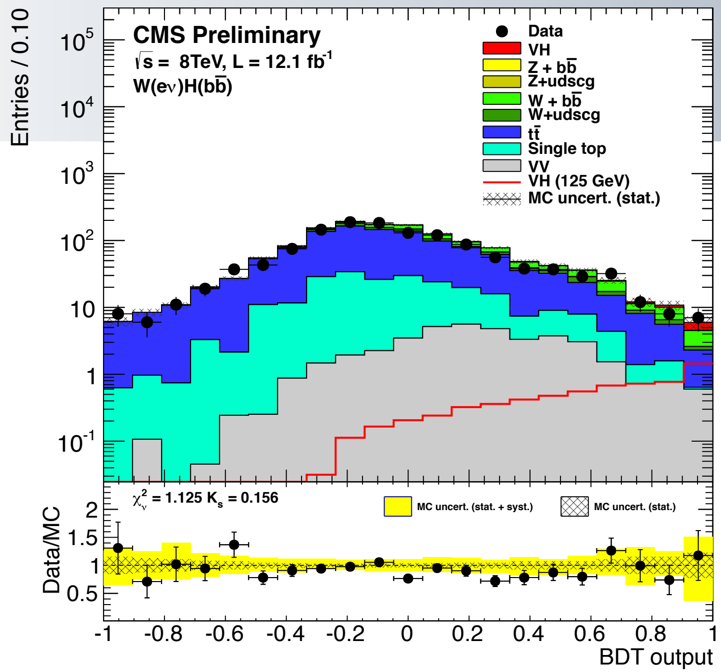
- ***b*-jet energy regression BDT trained on simulated VH signal events (new since ICHEP2012)**
- **Mass resolution improved by ~15%**
  - **10-20% improvement in sensitivity**

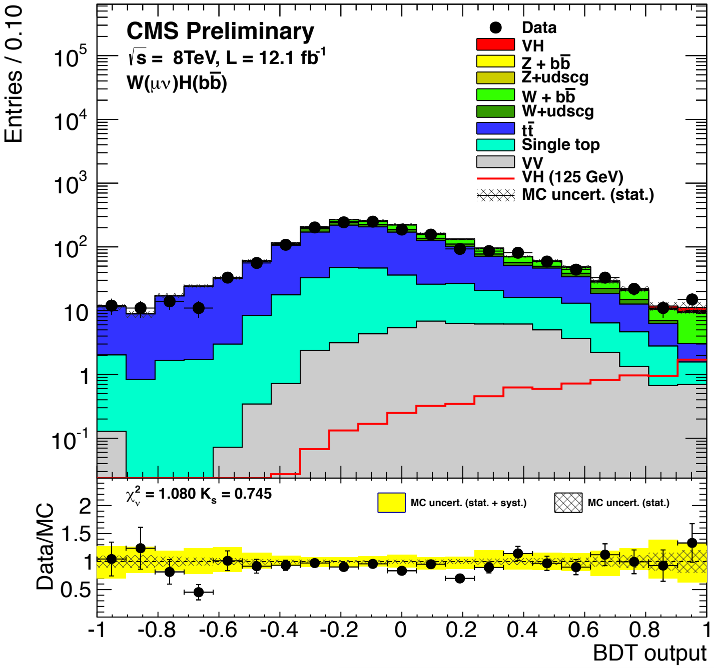


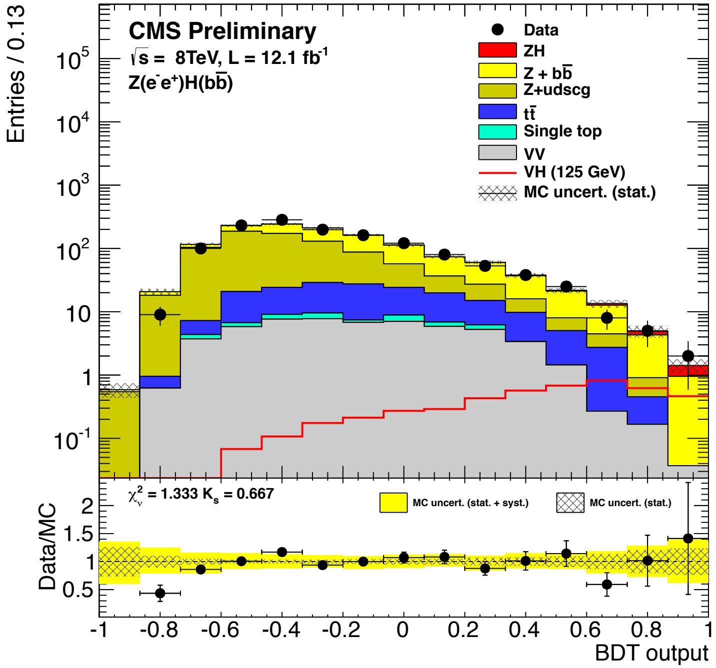
- **A BDT is trained to identify signal events**
- **Results are obtained from a fit to the shape of the BDT output**

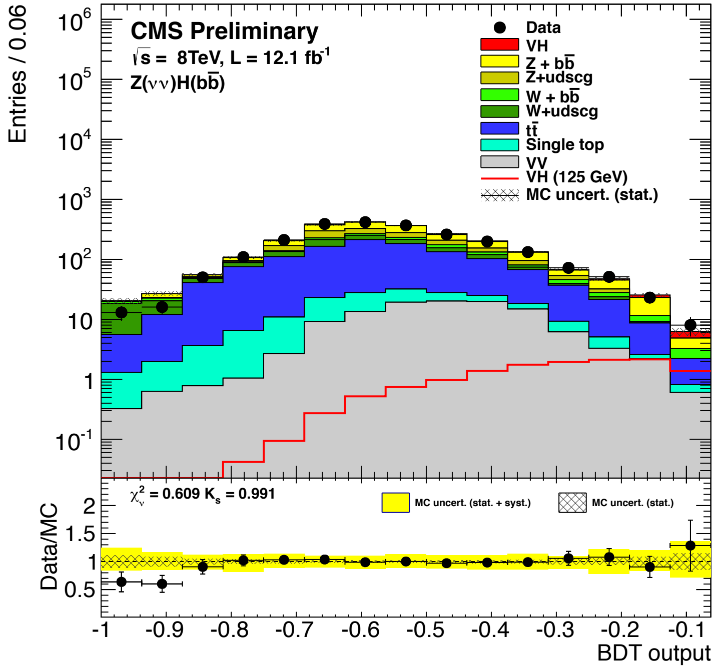
BDT distributions

- Examples for high p_T(W/Z) categories
- An excess of events is observed at high BDT score in all categories

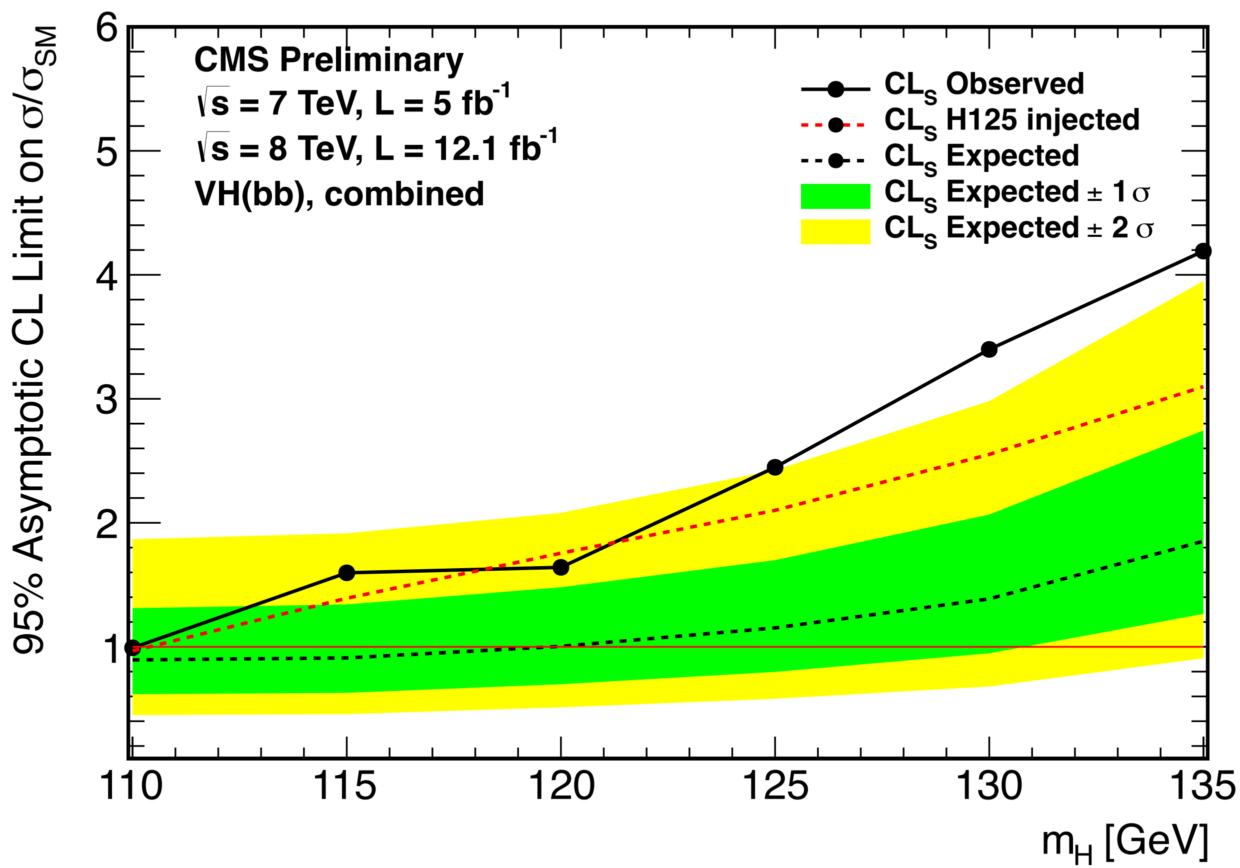


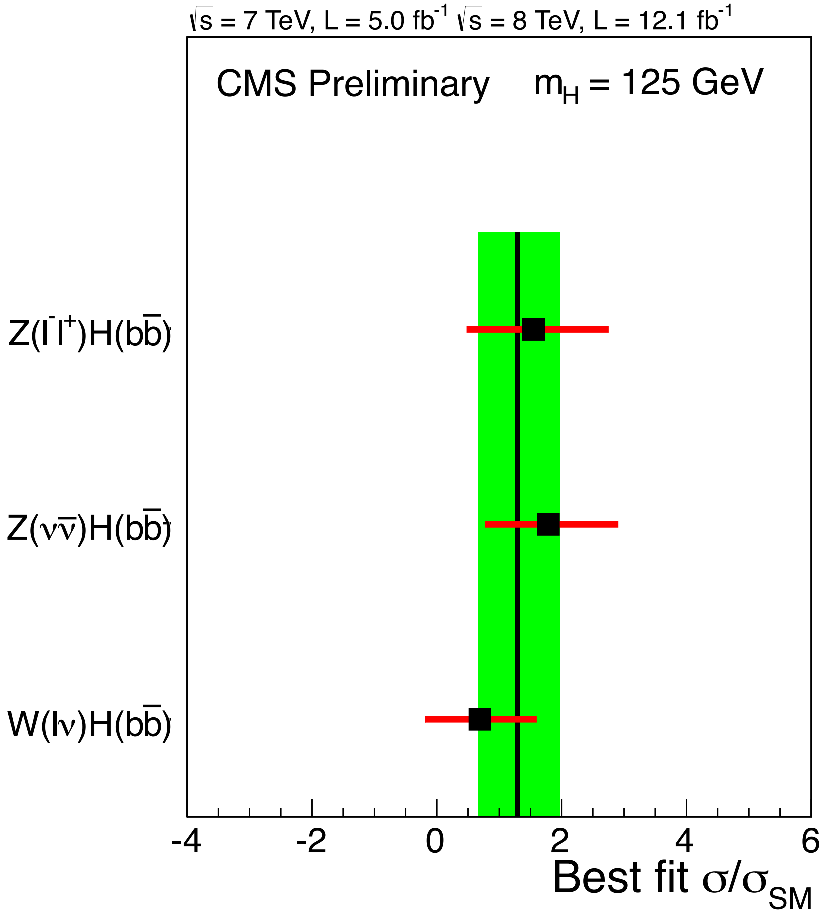






W/ZH, H→*bb* – results

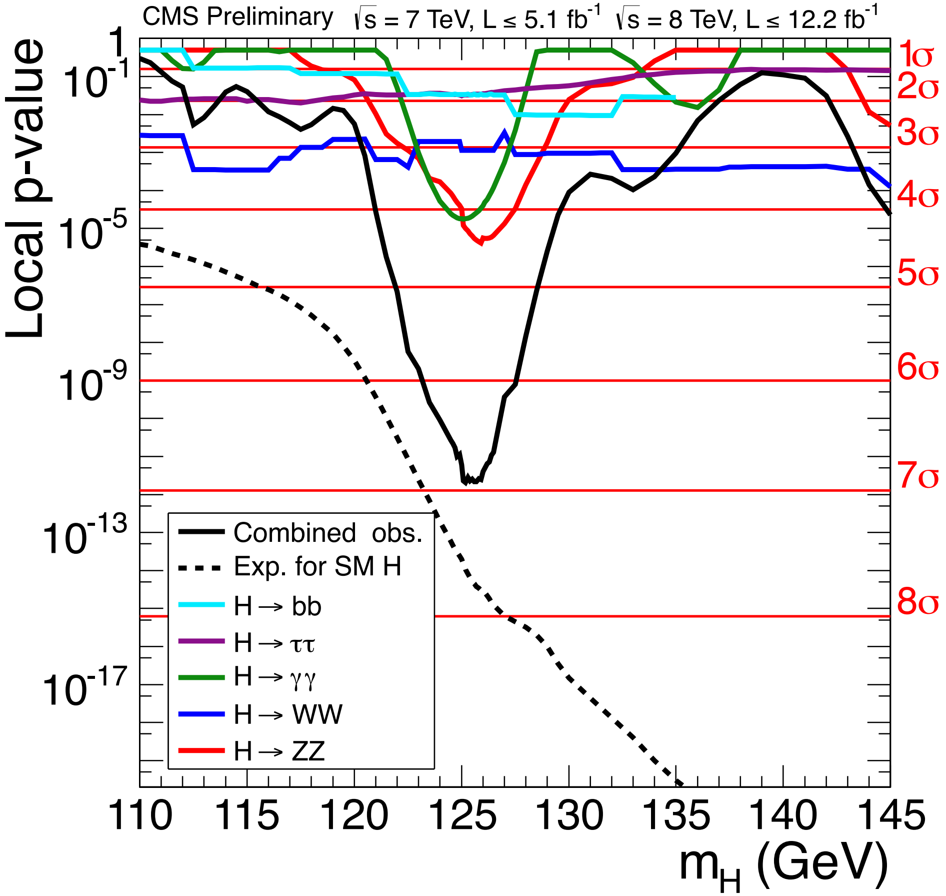




- **Significance of excess for $m_H \approx 125$ GeV is: 2.2 (expected is 2.1)**
- **There is, additionally, a *tt*H→*bb* analysis for the 7 TeV data**

Combination…

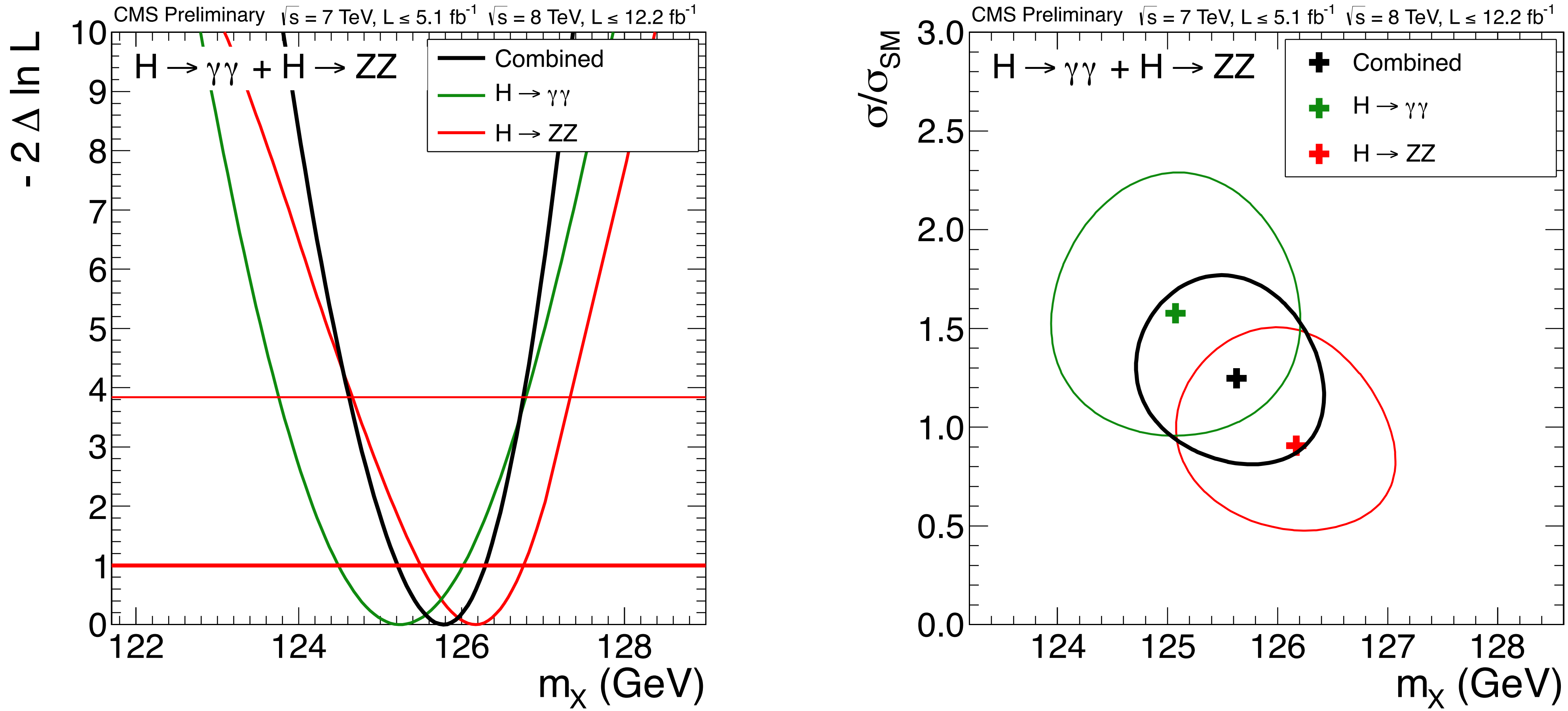
Combined results



Significance of excess for m_H = 125.8 GeV		
Channel	**Expected (σ)**	**Observed (σ)**
ZZ	5.0	4.4
γγ (5+5 fb^{-1} only)	2.8	4.0
WW	4.3	3.0
bb	2.2	1.8
ττ	2.1	1.8
ZZ + γγ	5.7	5.8
ZZ+γγ+WW+bb+ττ	7.8	6.9

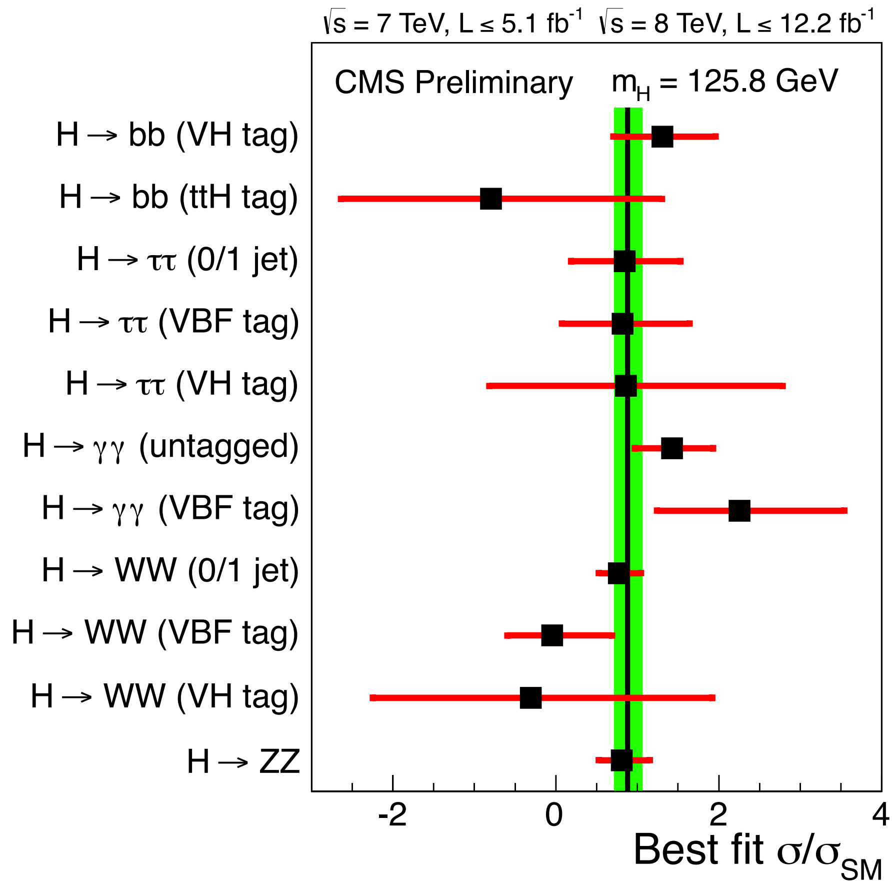
- **Observed significance of excess, evaluated for m_H = 125.8 GeV: 6.9 (expected: 7.8)**

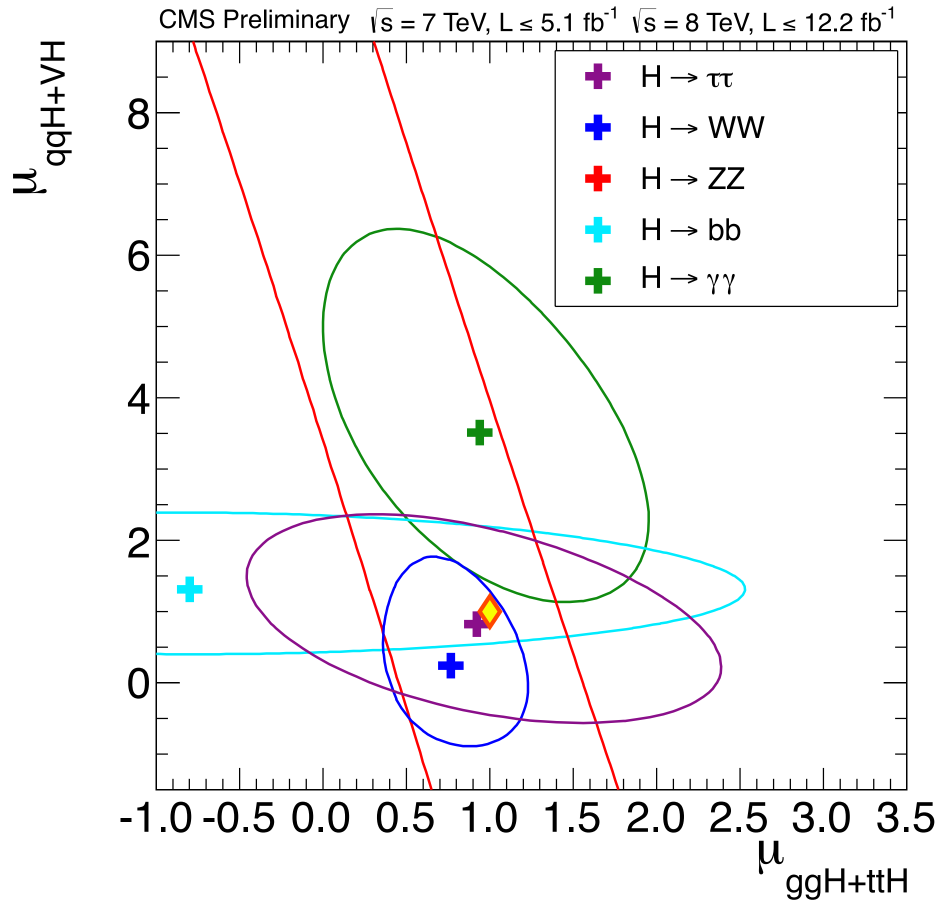
Combined results – mass



- **Mass measurement: 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV**

Combined results – signal strength

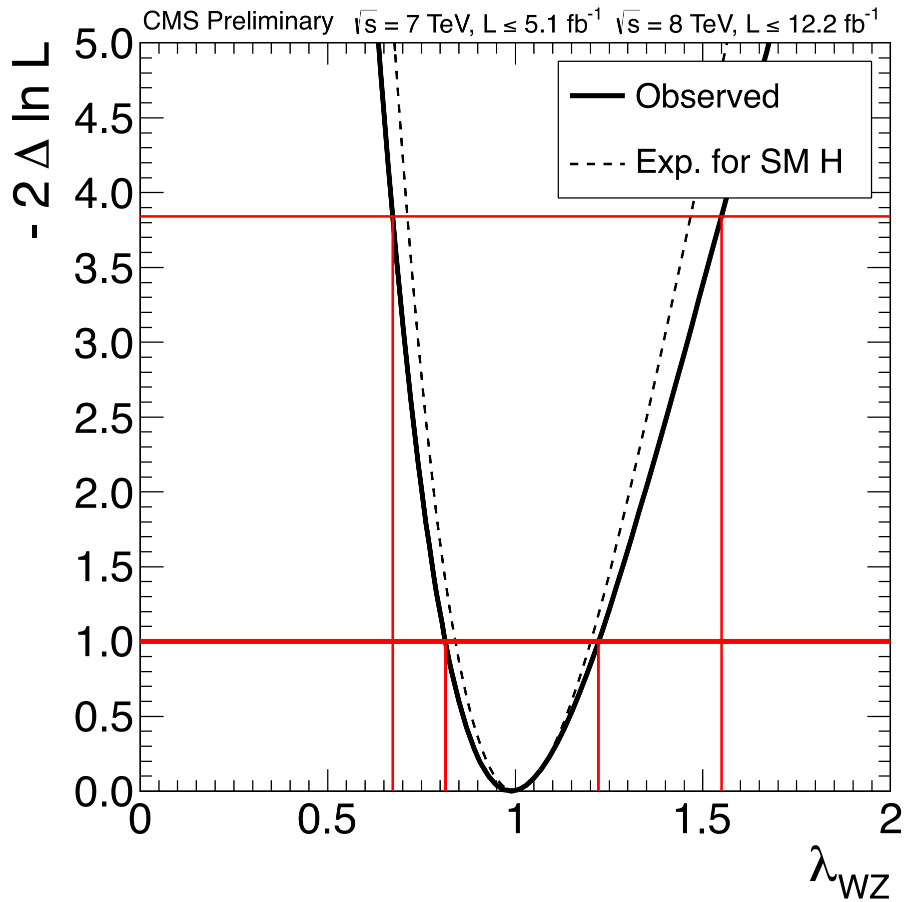


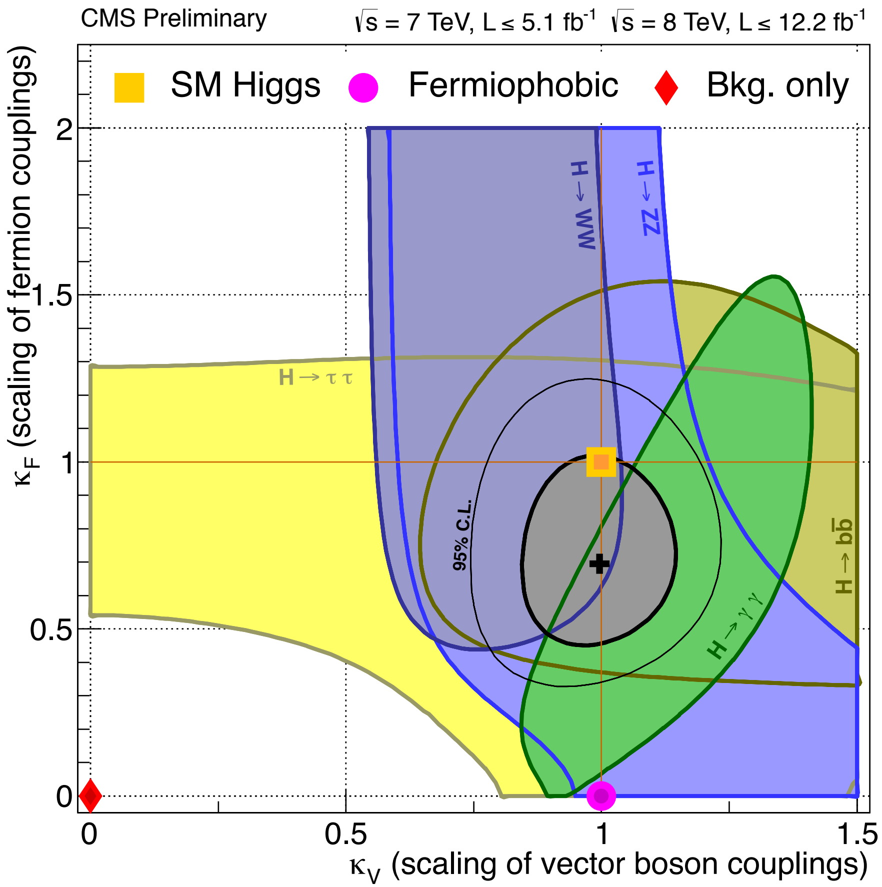


- **Best fit signal strength, σ/σ_{SM} = 0.88 ± 0.21**

Combined results – couplings

- **Framework from the Higgs XSWG, based on effective field theory approach (arXiv 1209.0040)**
- **Couplings largely consistent with SM**





Conclusions

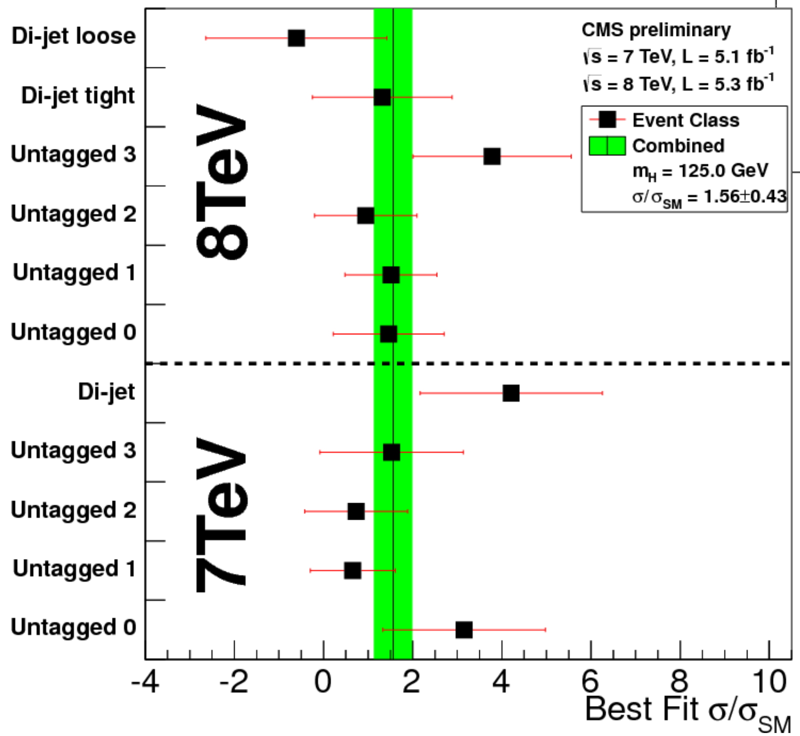
- The significance of the signal near 125 GeV is now 6.8 standard deviations
- The mass of the observed particle is measured to be
  125.8 ± 0.4 (stat) ± 0.4 (syst) GeV
- Some excess starting to show in the fermionic decay modes, although results are still compatible with both a background only hypothesis and SM Higgs near 125 GeV
- The signal strengths and couplings are consistent with expectations for a SM Higgs boson (well within two standard deviations)

Additional material

H → γγ event classes

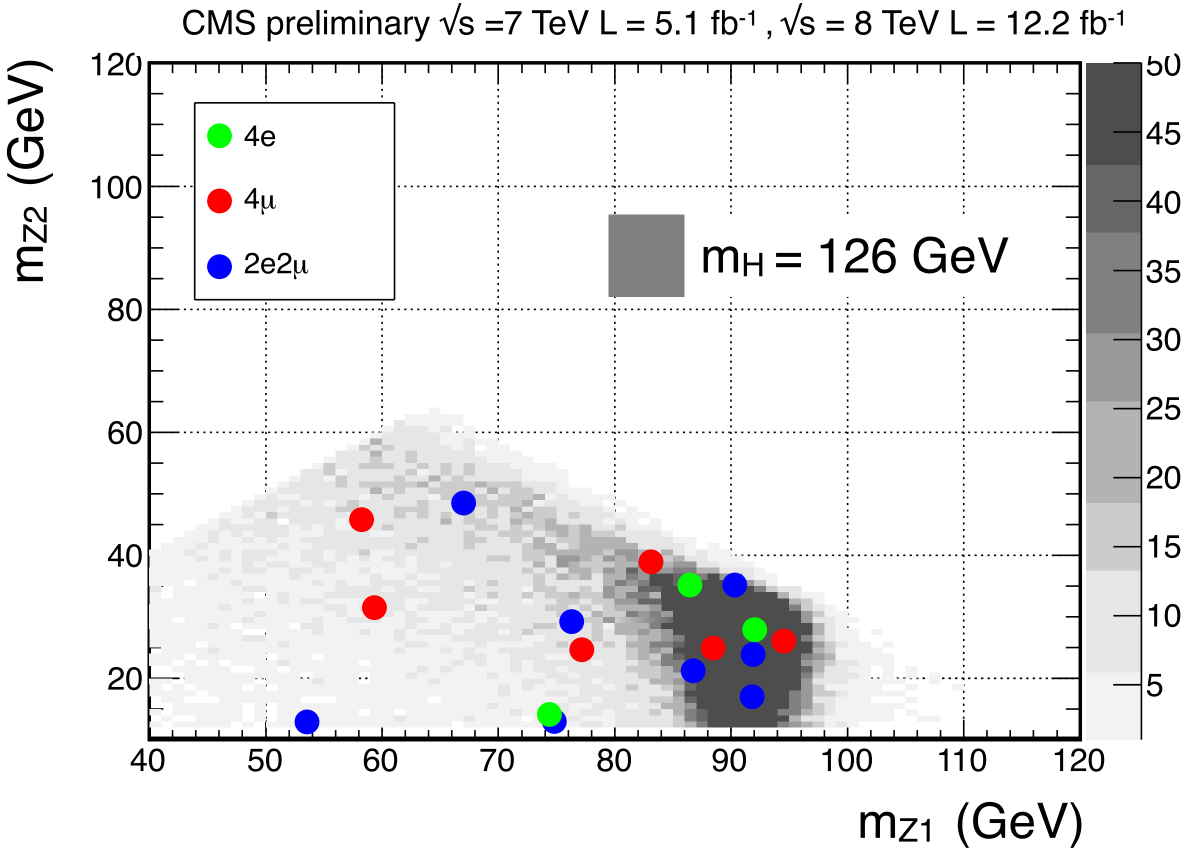
Expected signal and estimated background

	Event classes	SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 $\pm$ 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 $\pm$ 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 $\pm$ 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 $\pm$ 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 $\pm$ 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 $\pm$ 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 $\pm$ 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 $\pm$ 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 $\pm$ 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 $\pm$ 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 $\pm$ 0.4



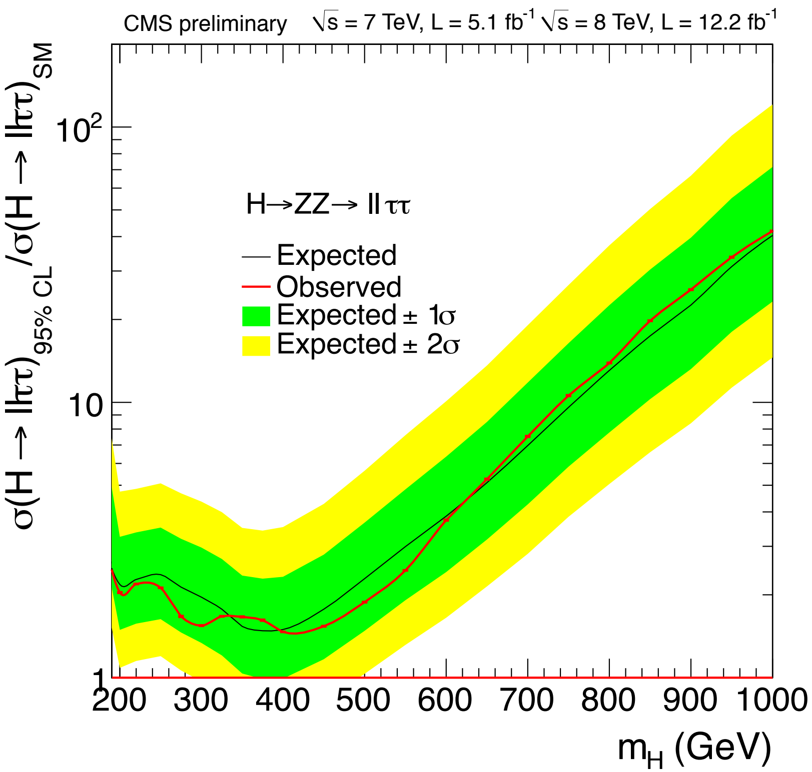
$H \to ZZ \to 4l$

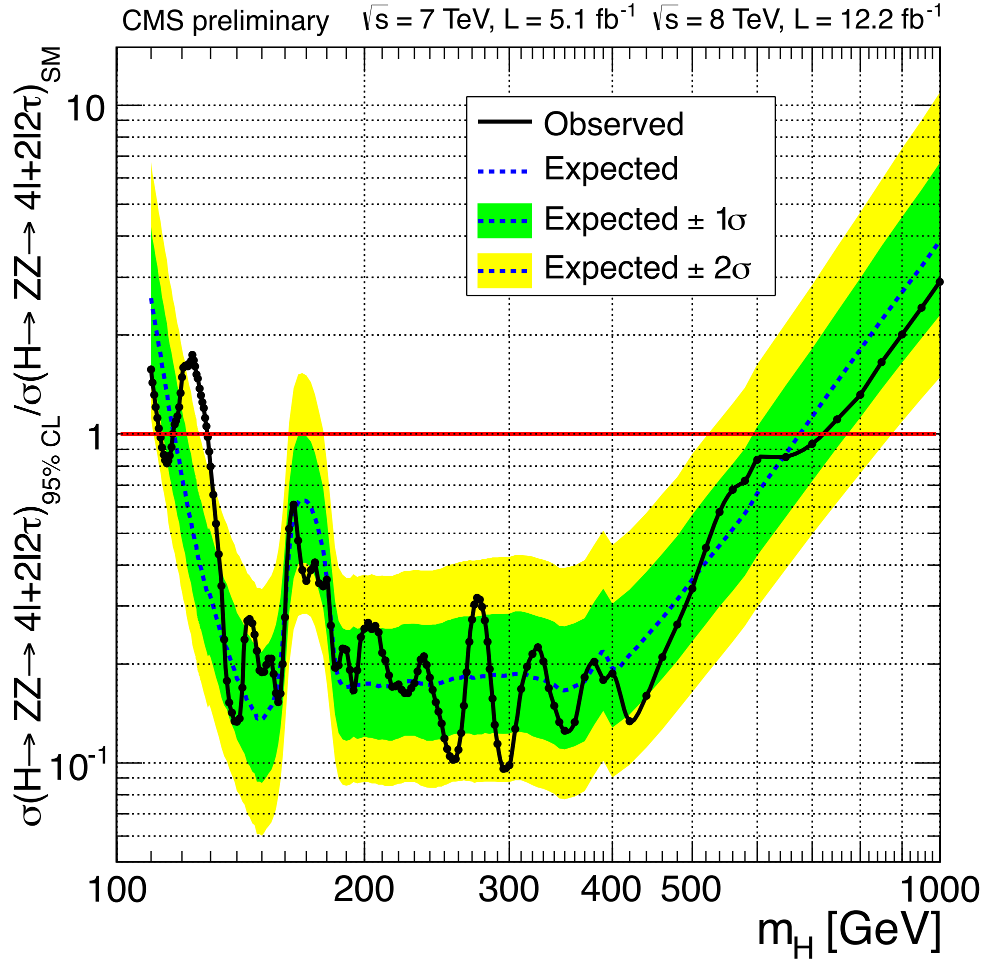
Events with $121.5 < m_{4l} < 130.5$ GeV



- **Distribution of events in m_{Z1}, m_{Z2} now agreeing well with expectation**

H→ZZ including 2l2τ final state

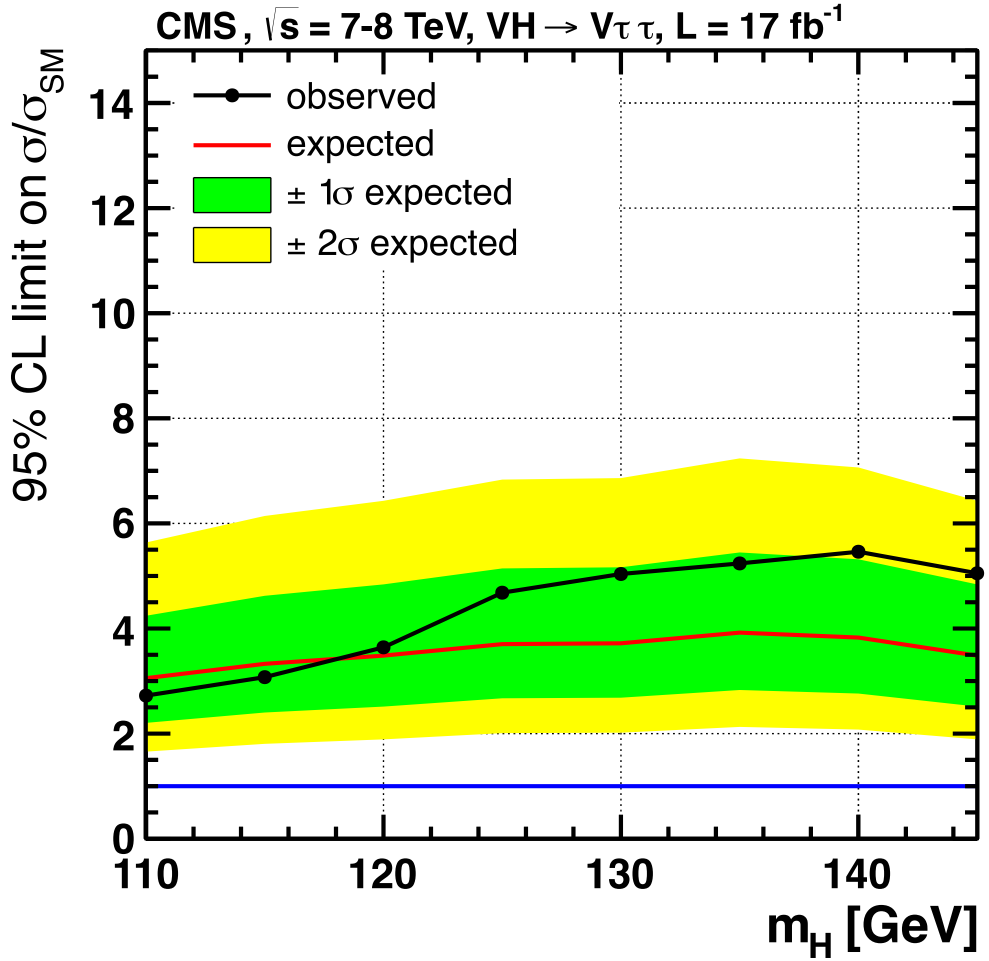




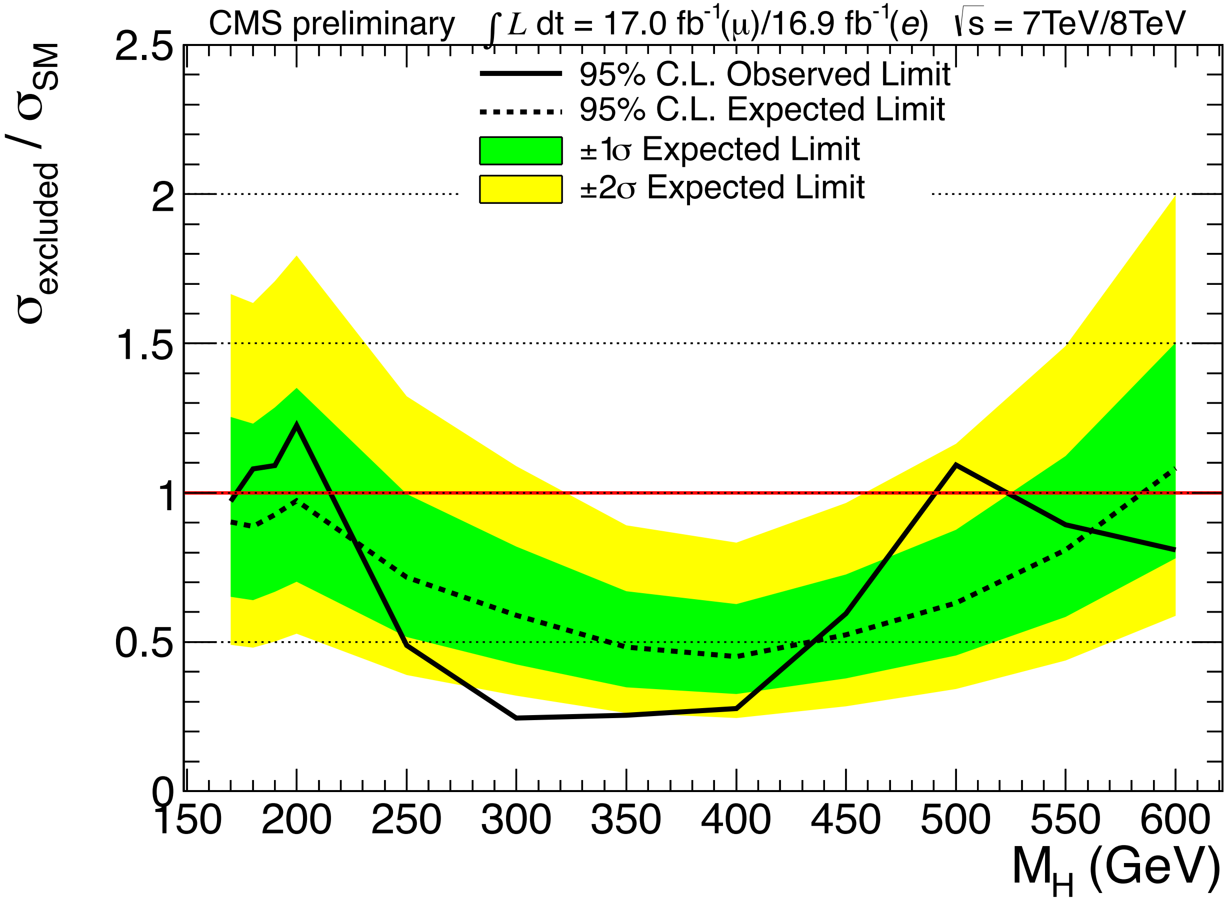
- **Search also for the final state 2l2τ in the mass range 180–1000 GeV**

H→ττ – VH category

- Associated production with vector boson also studied
  - With W/Z decaying to e or μ

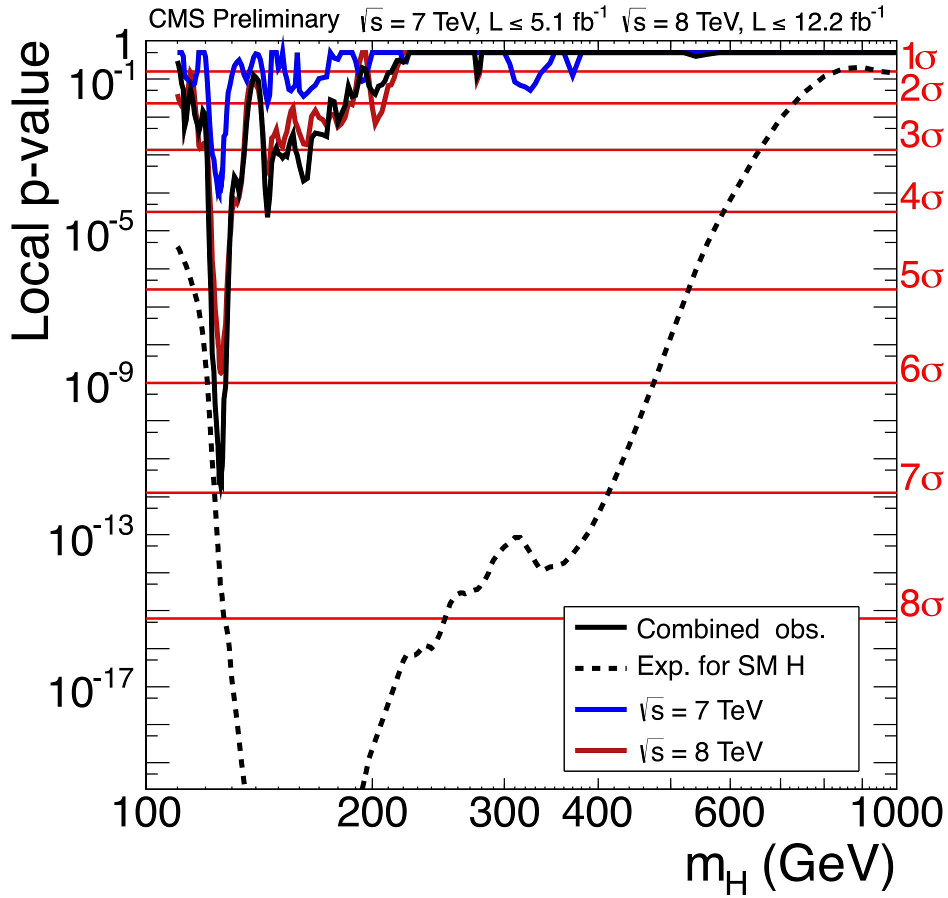


H→WW→lνqq



CMS preliminary ∫L dt = 17.0 fb-1(μ)/16.9 fb-1(e) √s = 7TeV/8TeV
95% C.L. Observed Limit
95% C.L. Expected Limit
±1σ Expected Limit
±2σ Expected Limit
σexcluded / σSM
MH (GeV)
0
0.5
1
1.5
2
2.5
150
200
250
300
350
400
450
500
550
600

p-values – full mass range



Significance of excess for m_H = 125.8 GeV

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