Higgs discovery

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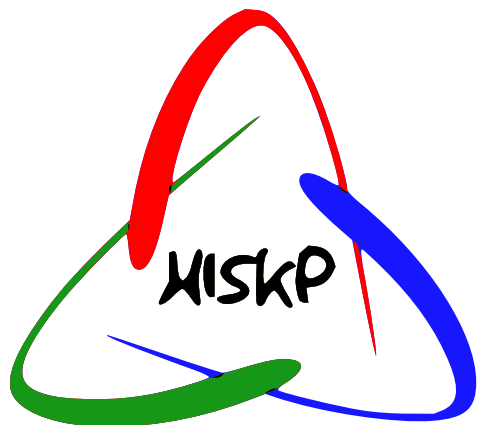
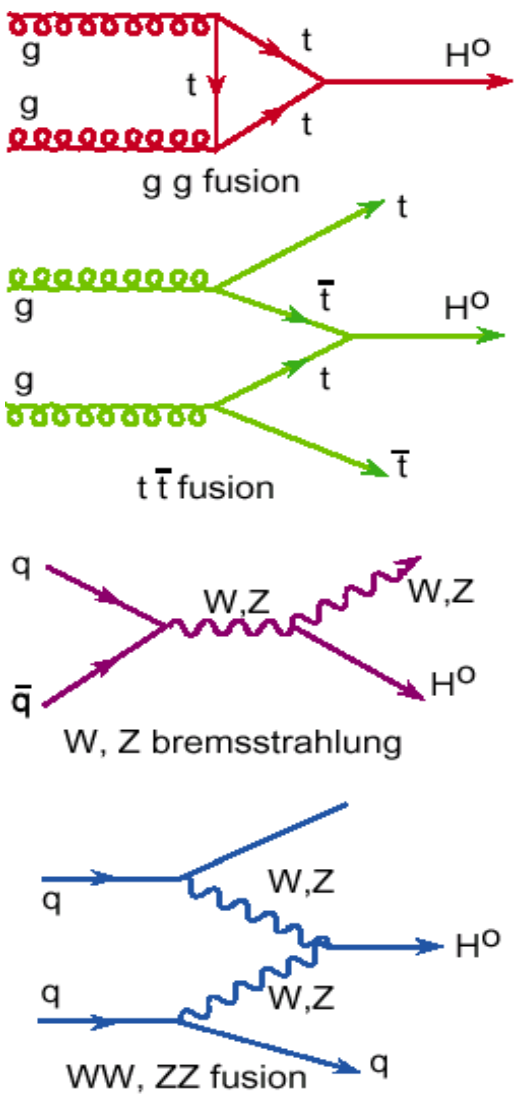


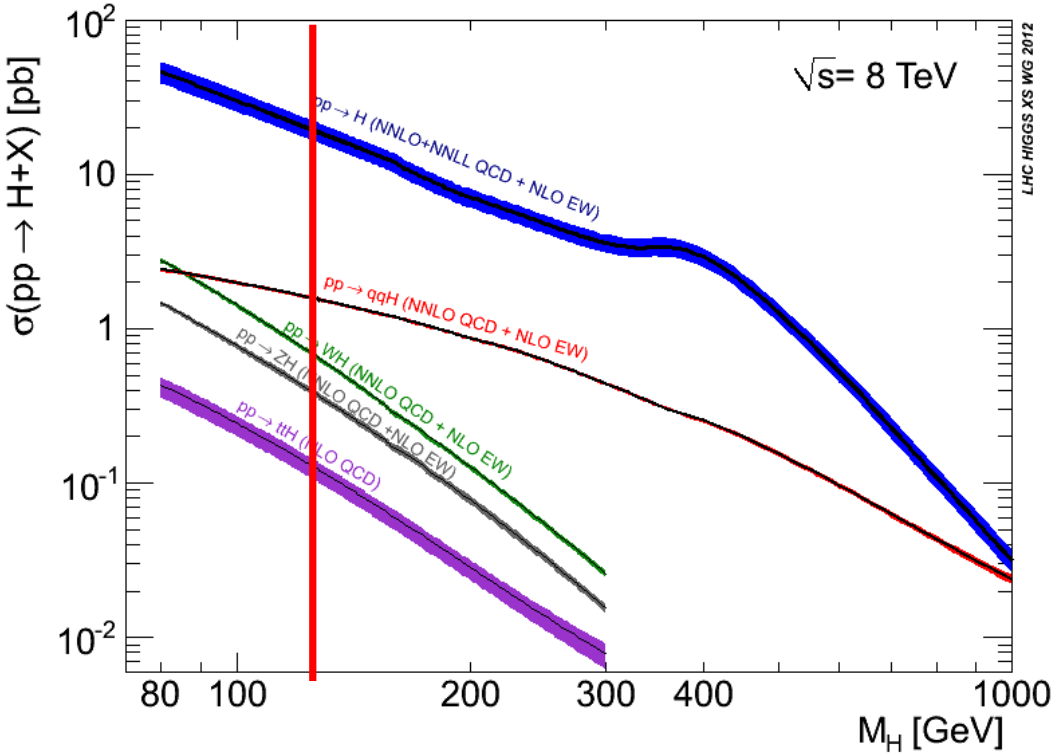
Higgs mechanism

see blackboard

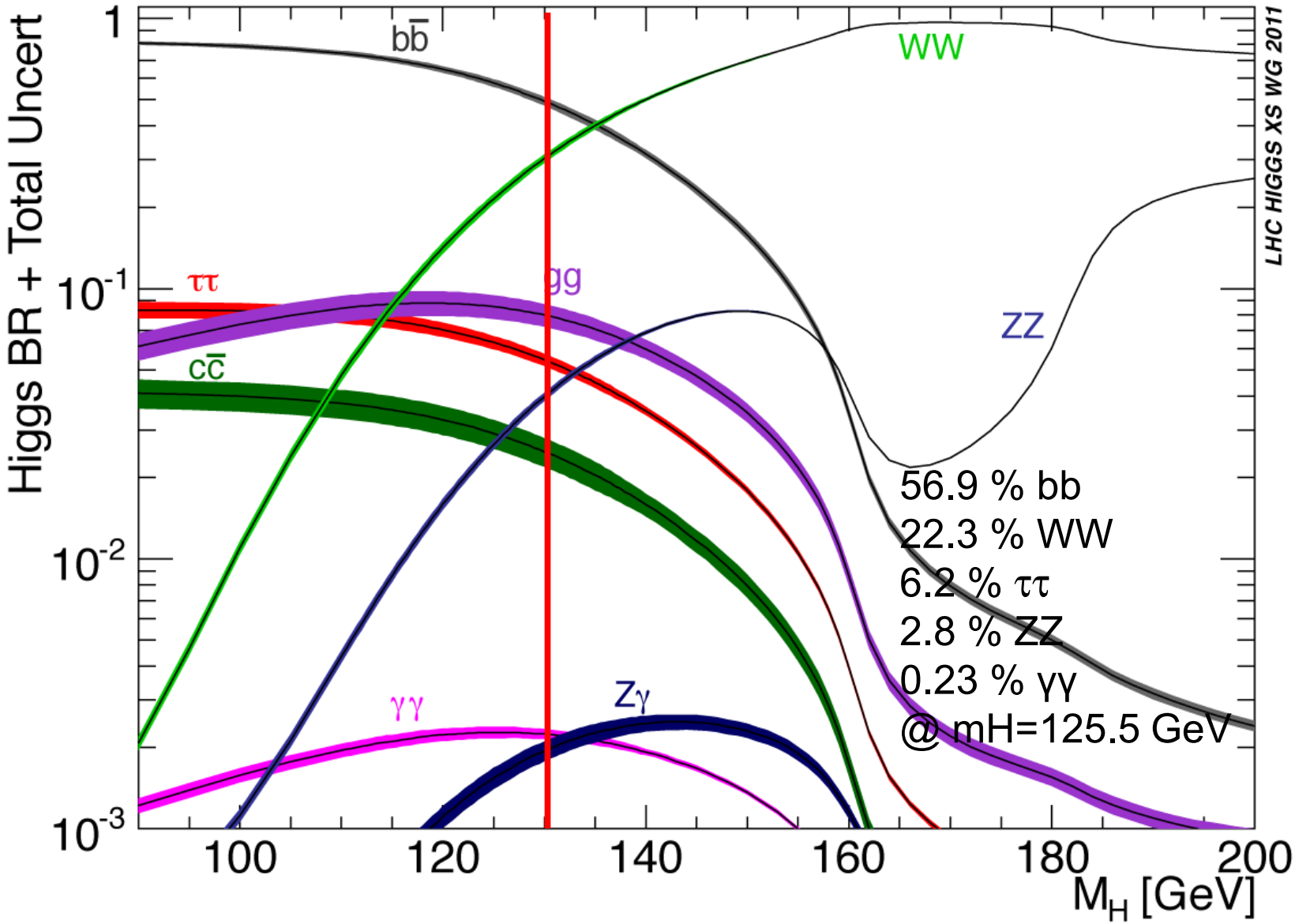
Higgs Production mechanisms



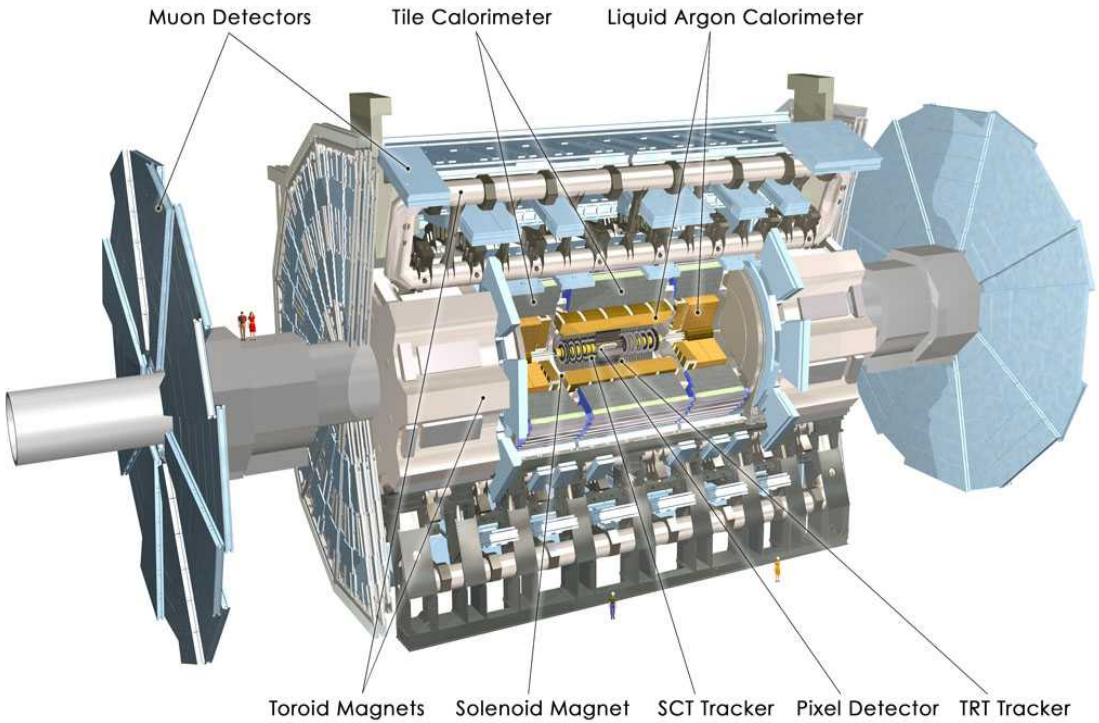
Cross sections at 8 TeV [pb]	
ggH	19.4
VB Fusion	1.6
WH+ZH	1.1
ttH	0.1



Decay modes of SM Higgs



The ATLAS detector



- Diameter 25 m
- Length : 46 m
- Barrel toroid length 26 m
- Overall weight 7 000 tonnes
- ~ 100 million electronic channels
- ~ 3 000 km of cables

Inner tracker

$$\frac{\sigma(p_T)}{p_T} \approx 0.05\%\ p_T \oplus 1\%$$

Calorimetry

EM : $\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Had : $\frac{\sigma(E)}{E} \approx \frac{50\%}{\sqrt{E}} \oplus 3\%$

Muon spectrometer

$$\frac{\sigma(p_T)}{p_T} \approx 2\% \quad \text{@50 GeV}$$

$$\frac{\sigma(p_T)}{p_T} \approx 10\% \quad \text{@ 1 TeV}$$

Magnets

solenoid : 2 T

toroid : 0.5 T (barrel), 1 T (endcap)

Trigger

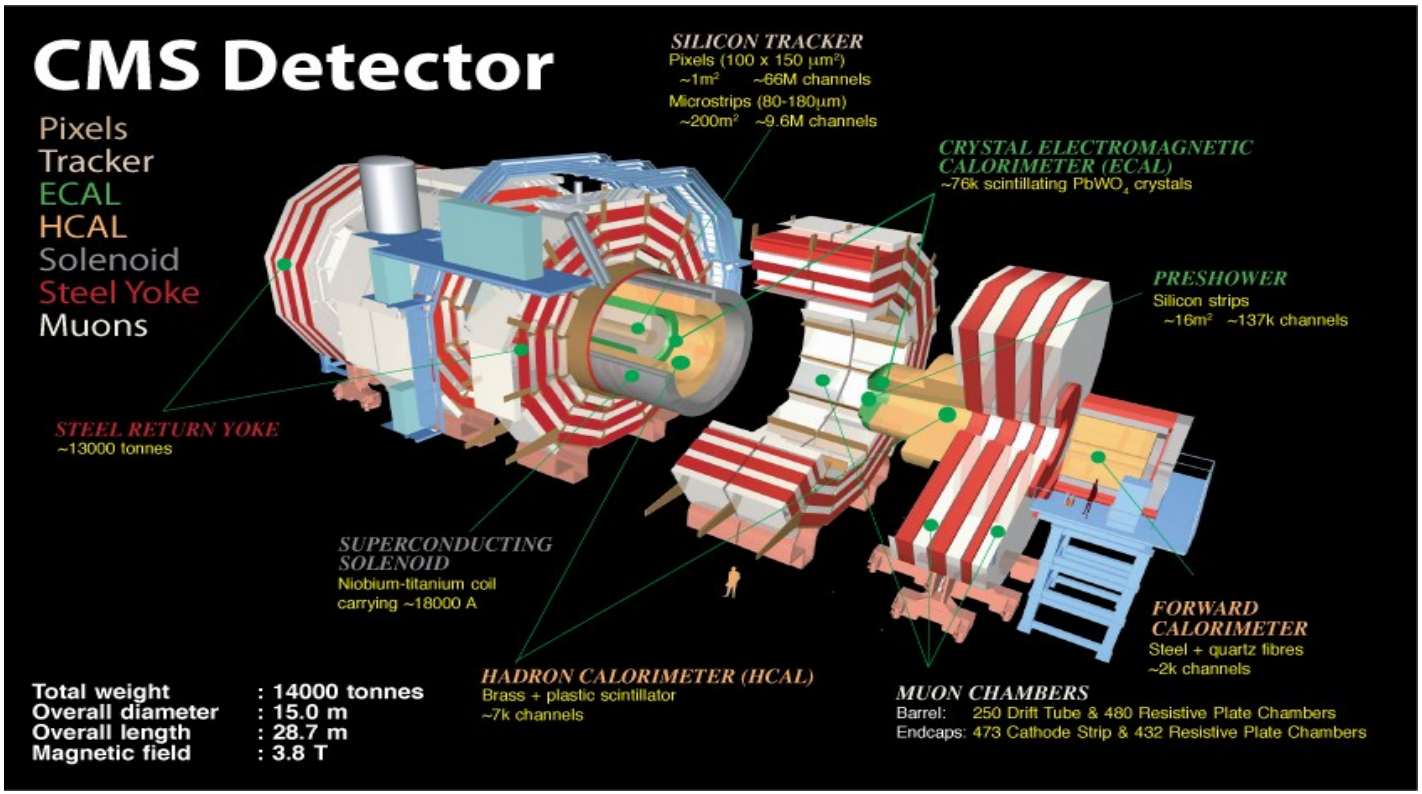
3 Levels, 40 MHz → 200 Hz

The CMS detector

3.8T superconducting solenoid envelops

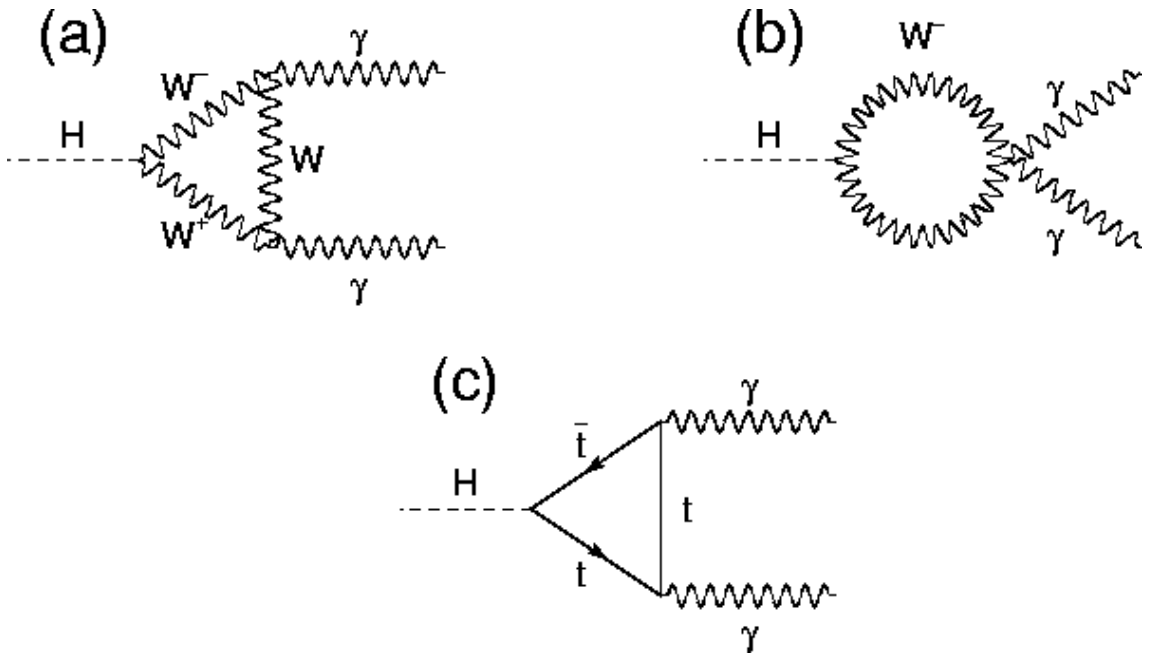
- **Tracker (silicon and strip det.) $|\eta| < 2.5$**
- **ECAL ($PbWO_4$ crystals)**
- **HCAL (brass/scintill. samplers)**

  Barrel $|\eta| < 1.48$
  Endcap $1.48 < |\eta| < 3.0$
- **Muon Chambers -gas ionization det. in steel return yoke outside the solenoid $|\eta| < 2.4$ Drift Tubes, Cathode Stripe and Resistive Plate Chambers**



Decay mode: $H \to \gamma\gamma$

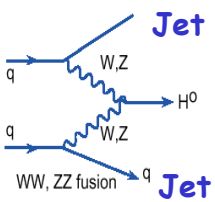
- Higgs does not couple to photons

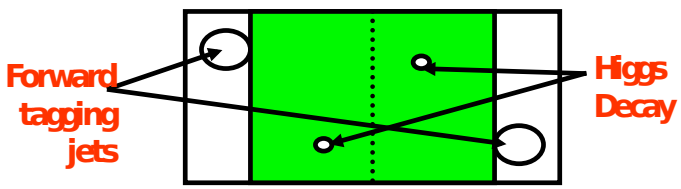


Decay mode: $H \to \gamma\gamma$

Data analysis:

- multivariate analysis used for selection and classification of events
- multivariate analysis uses the following criteria
  - γ: shower shape (for ECAL calibration $Z \to ee$ is used), isolation variables (sum of transverse momentum in distance of photon candidate), kinematics: reconstr. in ECAL $1.44 < |\eta| < 1.57$, $p_T^{\gamma 1} > \frac{m_{\gamma\gamma}}{3}$ and $p_T^{\gamma 2} > \frac{m_{\gamma\gamma}}{4}$
  - the expected mass resolution
  - the reconstructed primary vertex of diphoton
  - if dijets are measured (from VBF): p_T thresholds at 30 and 20 GeV, η separation > 3.5, invariant mass of dijets$>$ 350 GeV or 500 GeV ("tight"), angular cuts in relation to diphoton system





Decay mode: $H \to \gamma\gamma$

Event classification and expected number of events:

Event categories		SM Higgs boson expected signal ($m_H = 125\,GeV$)							Background $m_{\gamma\gamma} = 125\,GeV$ (events/GeV)
		Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2 ± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

Decay mode: $H \to \gamma\gamma$

- invariant mass fitted for each event category with polynomial functions with degree ranges from 3-5 (potential bias is smaller than stat. accuracy)
- independent sideband-background model and cross-check analyses were performed
- events are weighted according to event category

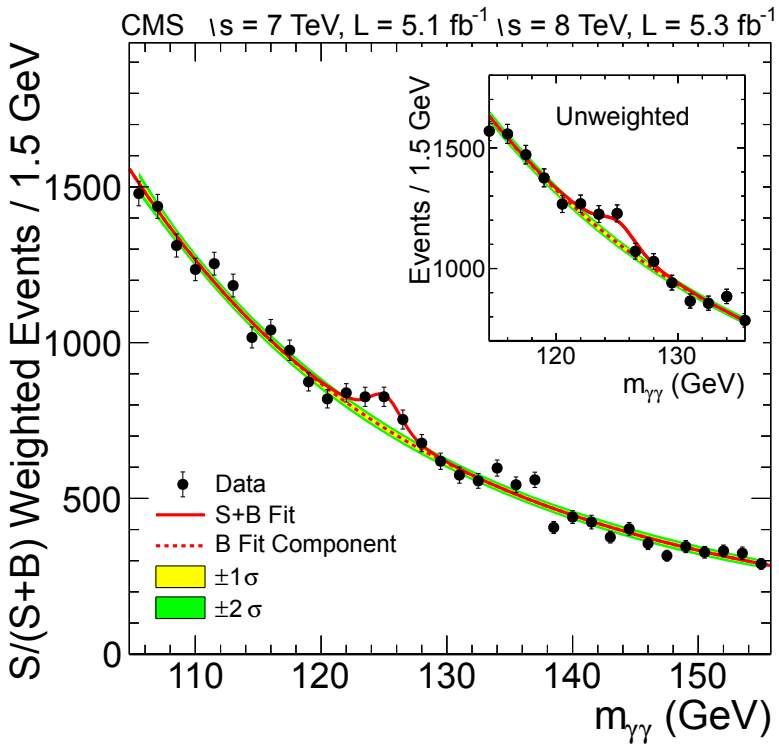
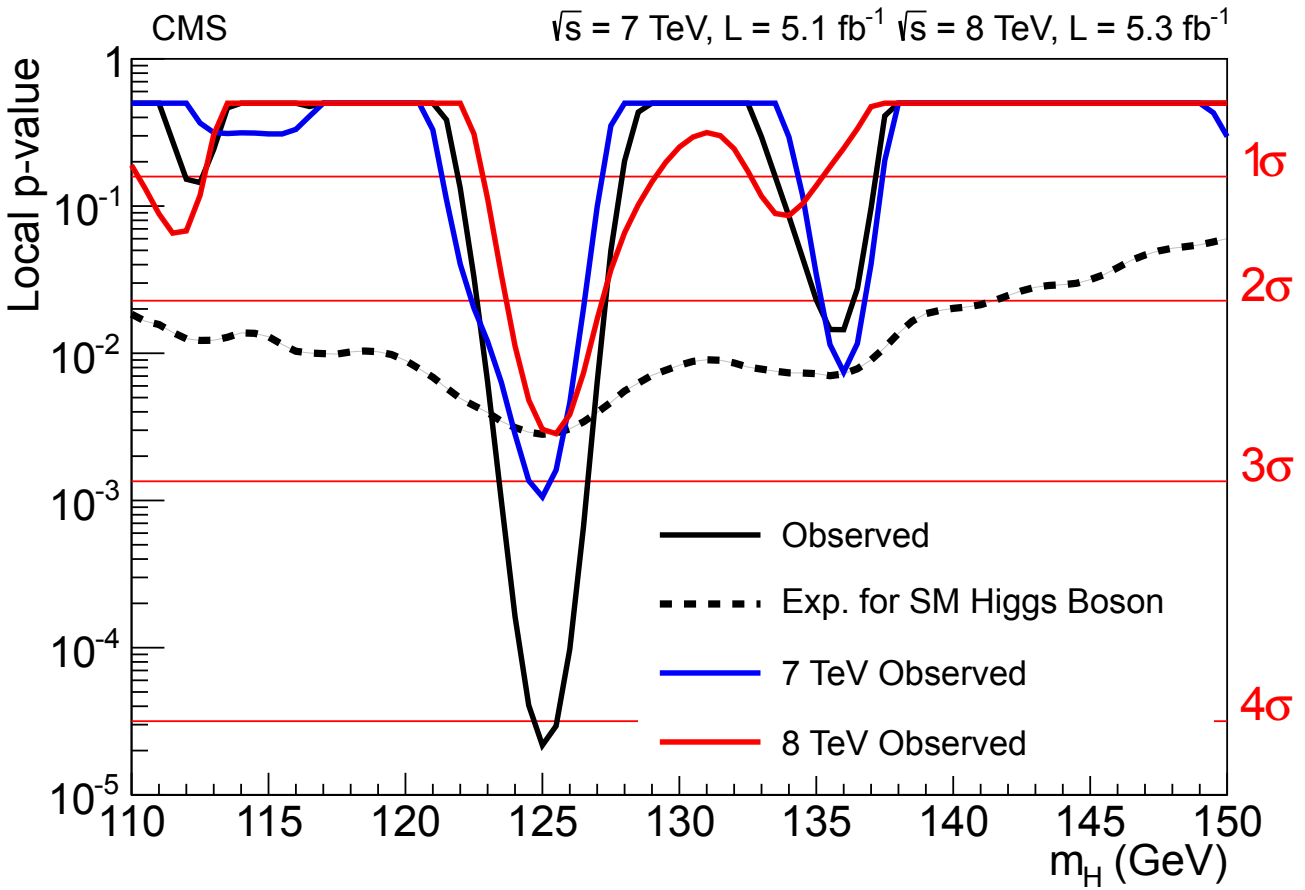


Figure 3: The diphoton invariant mass distribution with each event weighted by the S / (S + B) value of its category. The lines represent the f tted background and signal, and the coloured bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution.

Decay mode: $H \to \gamma\gamma$

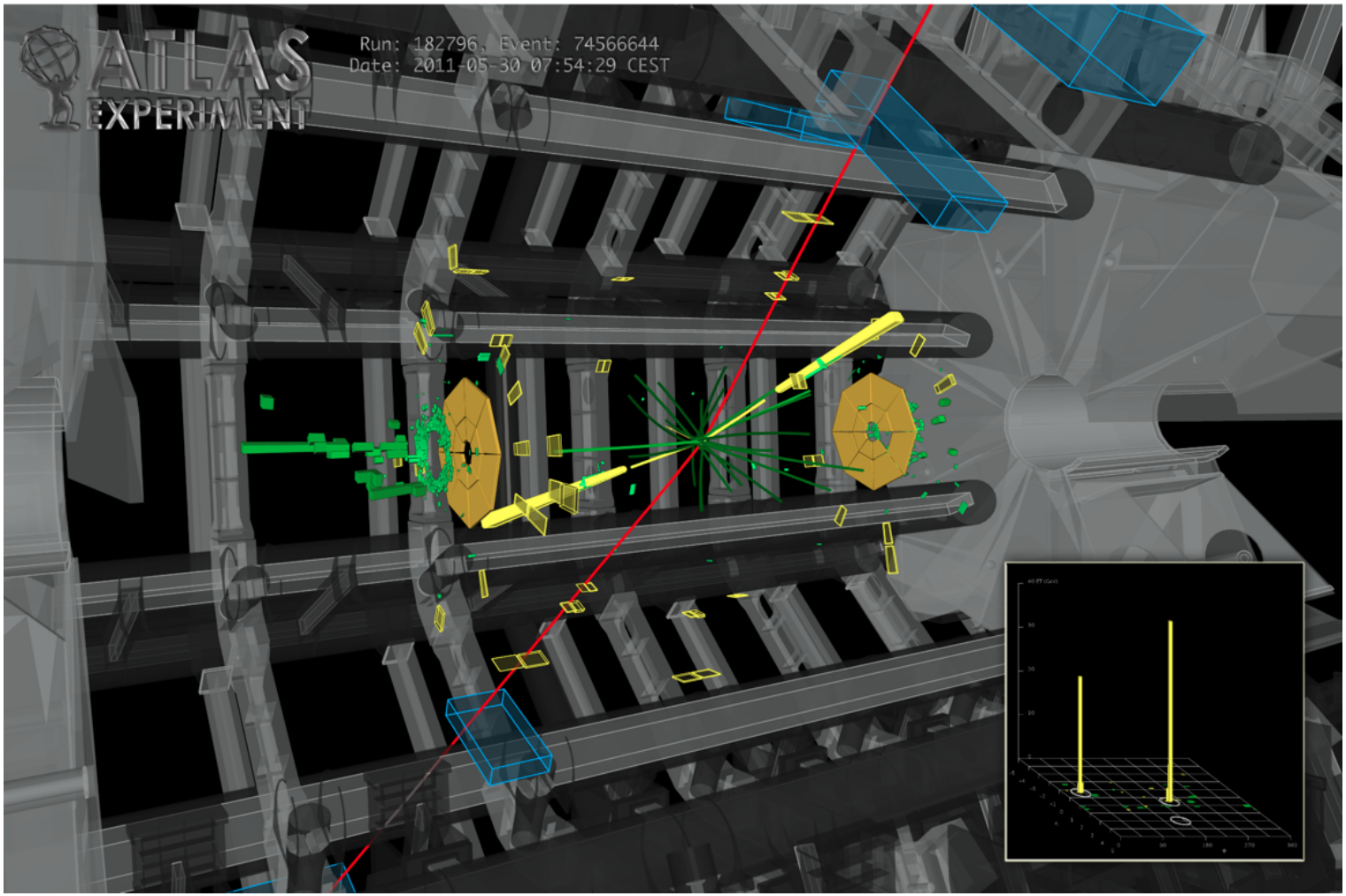
- p-value: "probability for a background fluctuation to be at least as large as the maximum excess"



Decay mode: $H \to ZZ^{(*)} \to 4l$

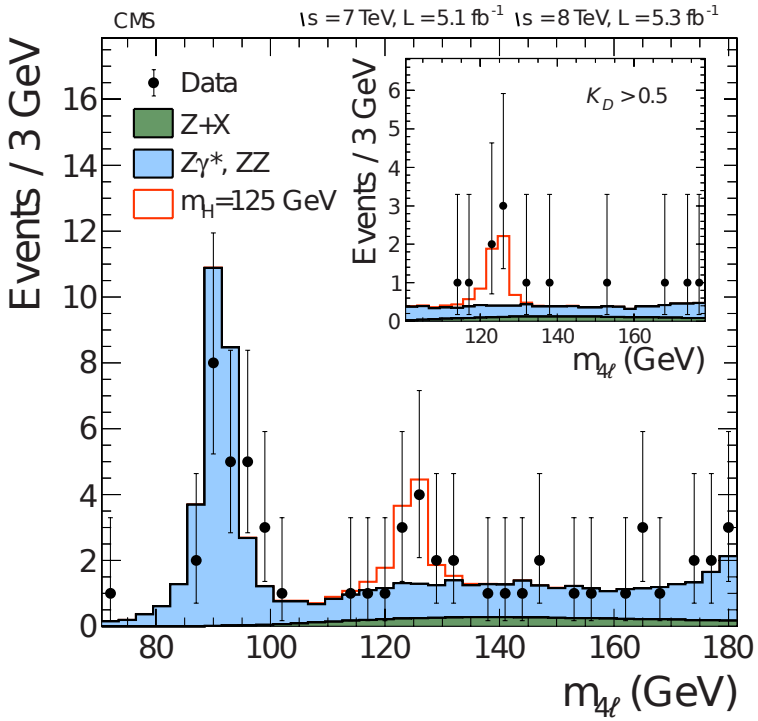
- 3 subchannel: 4e, 2e2μ, 4μ
- 2 pair of same-flavour, opposite charge leptons required
- e: $p_T > 7$GeV, $|\eta| < 2.5$, shower shape (ECAL), isolated, inner tracker and ECAL info combined
- μ: $p_T > 5$GeV, $|\eta| < 2.4$, isolated, inner tracker and μ spectrometer info combined
- electron and muon should originate from same primary vertex
- cut on invariant mass of leptons: 40-120 GeV
- background: direct ZZ production (irreducible), $Z + bb$, tt, Z+jets, WZ+jets (reducible: jets are misidentified as leptons)
- background simulated with MC
- three final states and two data sets: 6 simultaneous two dimensional maximum-likelihood fits are performed with m_{4l} and K_D (kinematic discriminant $= P_{sig}/(P_{sig} + P_{bkg})$)

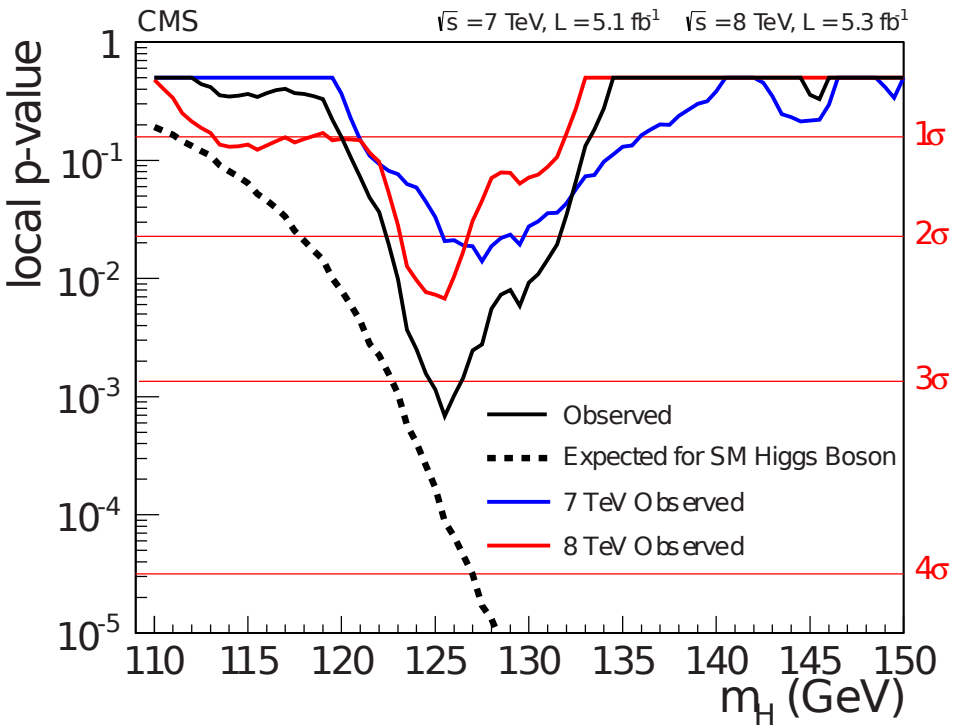
Decay mode: $H \to ZZ^{(*)} \to 4l$



$m_{4\mu} = 124.6$ GeV, $m_{ee} = 76.8$ GeV, $m_{\mu\mu} = 45.7$ GeV

Decay mode: $H \to ZZ^{(*)} \to 4l$



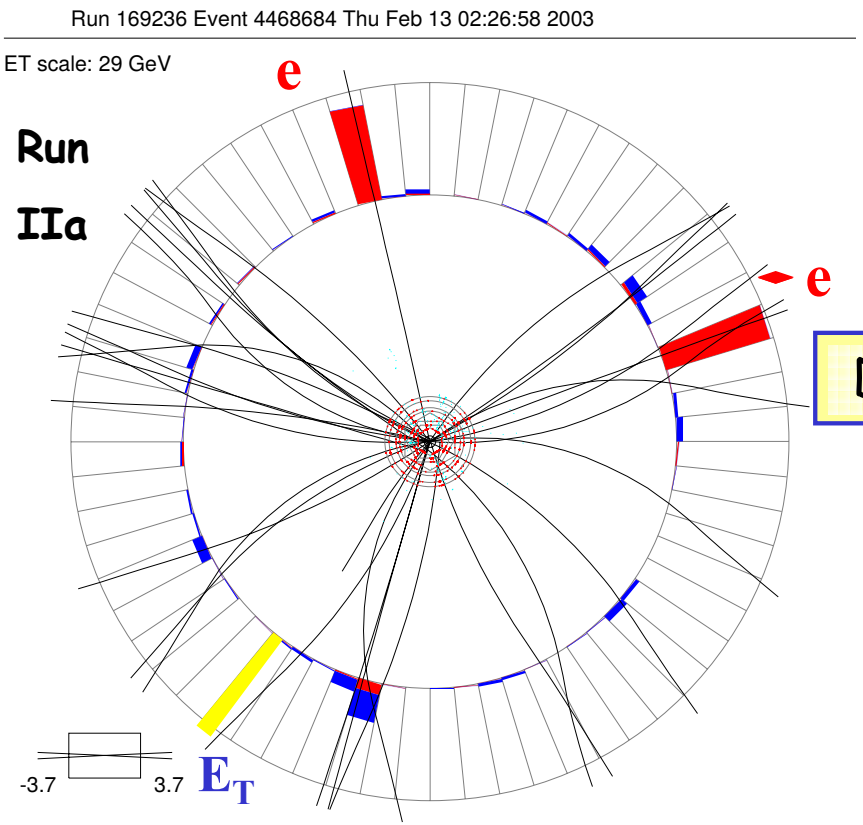


Decay mode: $H \to WW^{(*)} \to 2l2\nu$

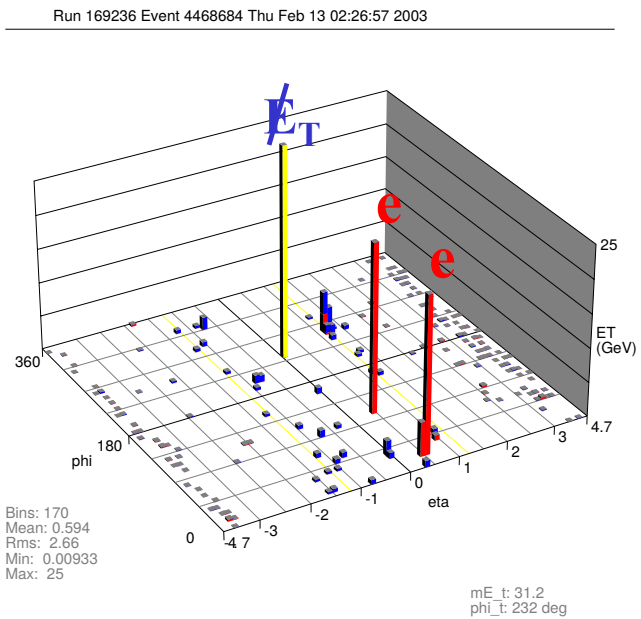
- 2 isolated,oppositely charged leptons (ee, $e\mu$, $\mu\mu$)
- large E_T^{miss} (due to neutrinos)
  transverse momentum of all final state particles should cancel if no non-interacting particle is produced
- event classification according to number of jets (0,1,2) and lepton flavours
- p_T thresholds for leptons and jets
- background: direct WW production (irreducible), reducible: W+jets (misidentified jet as lepton), same flavour category (Drell-Yan, top-quark decays) through E_T^{miss} and b-jet tagging
- b-jet tagging: look within jet for particles that originate from a different place where the bottom quark was formed, jets are wider, have higher multiplicity, higher transverse momentum
- data is analyzed with boosted decision trees for Higgs boson mass hypothesis

Higgs (130-190 GeV) → WW [2 TeV]

T.Hebbeker



$H \to WW^{(*)} \to e^+e^-\nu\nu$



Background: $WW^{(*)}, Z\gamma^{(*)}, tt$

Decay mode: $H \to WW^{(*)} \to 2l2\nu$

Category:	0-jet eμ	0-jet	1-jet eμ	1-jet	2-jet eμ	2-jet
WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
W + jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All backgrounds	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal ($m_H = 125\,GeV$)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7

Decay mode: $H \to WW^{(*)} \to 2l2\nu$

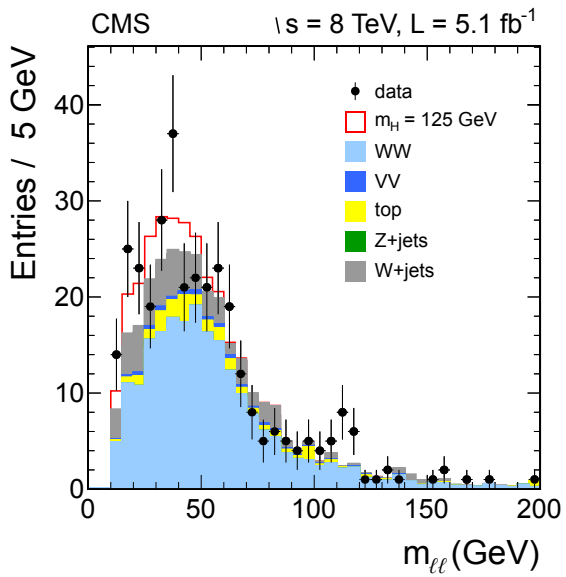
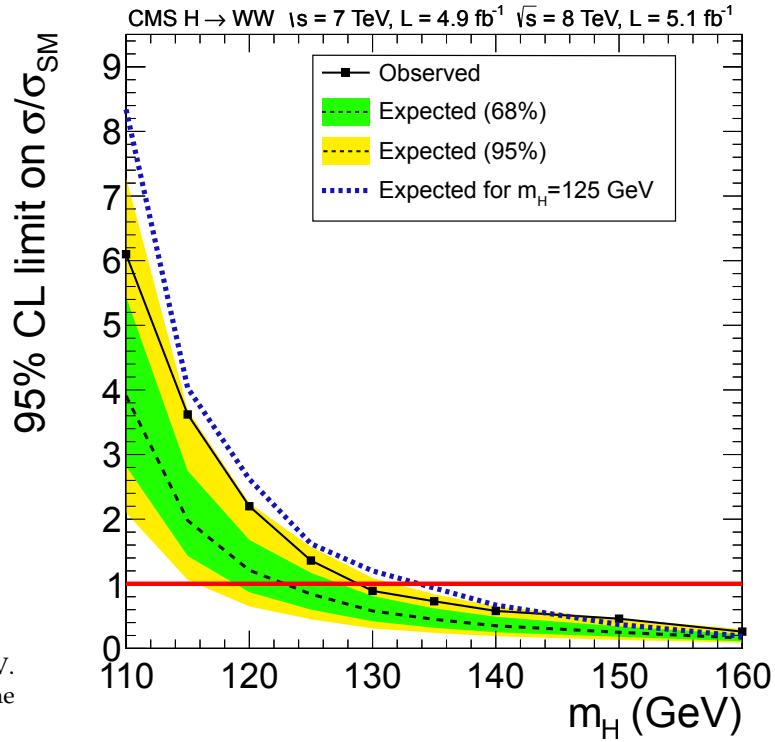


Figure 7: Distribution of m for the zero-jet eμ category in the H → WW search at 8 TeV. The signal expected from a Higgs boson with a mass m_H = 125 GeV is shown added to the background.



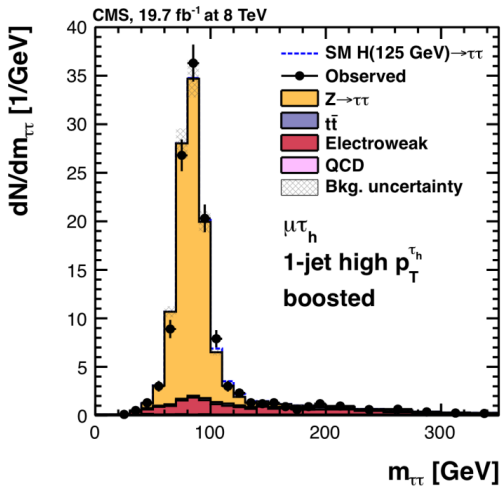
Decay mode: $H \to \tau\tau \to 2l4\nu/3\pi1\nu$

Decay final states: $\mu + \tau_h$, $e + \tau_h$, $\mu + e$, $\mu\mu$, ee , $\tau_h + \tau_h$

Improve sensitivity:

Different categories based on jet multiplicity and τ p_t

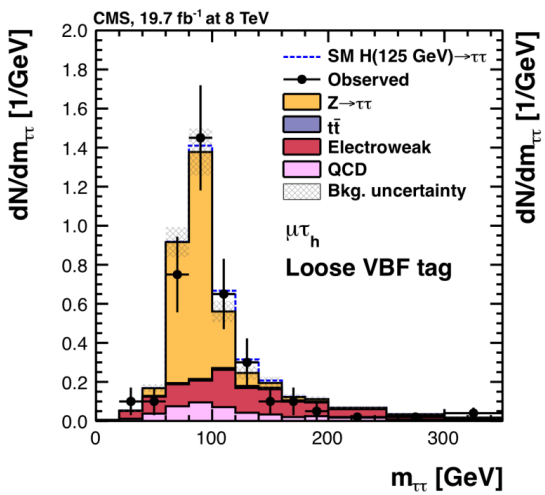
Optimized τ_{had}-isolation and $e,\mu \to \tau_{had}$ fake rejection

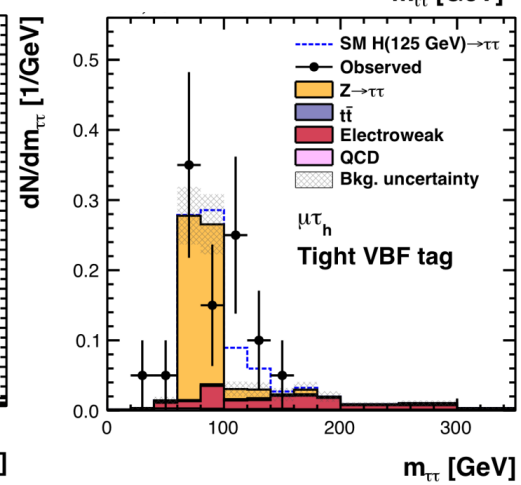


0 – jet category: constrains background, id efficiencies, energy scales

1 – jet category: improves the resolution of Higgs mass

2 – jet category: VBF process - high S/B ratio





Decay mode: $H \to \tau\tau \to 2l4\nu/3\pi1\nu$

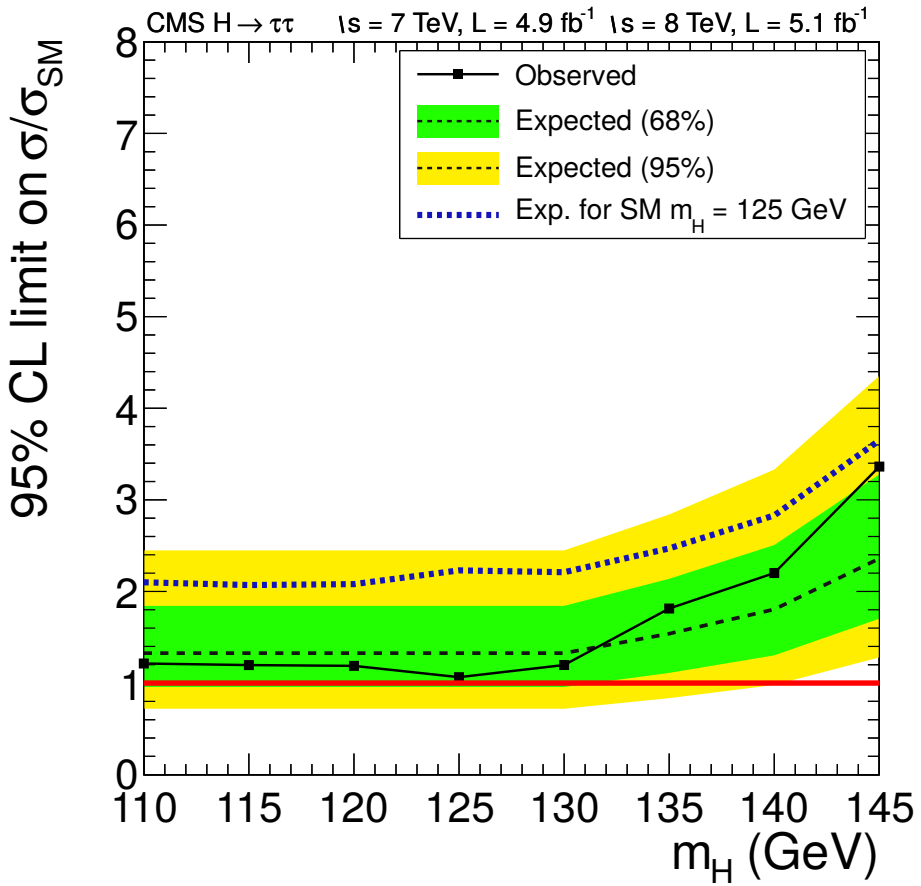


Figure 10: The 95% CL limit on the signal strength σ/σ_{SM} for a Higgs boson decaying to τ pairs, for the combined 7 and 8 TeV data sets. The symbol σ/σ_{SM} denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands. The dotted curve shows the median expected limit for a SM Higgs boson with $m_H = 125\,GeV$.

Decay mode: $H \rightarrow bb$

- largest branching fraction, but high background from QCD production of bb
- use Higgs production with W(ll, lν) or Z(ll, $\nu\nu$) $\rightarrow$ look for dijets with high p_T, $\nu\nu$: high E_T^{miss}
- two b-jets from Higgs decay (use trained BDT algorithm)
- background contribution: W/Z+bjets (from top quarks)

Decay mode: $H \to bb$

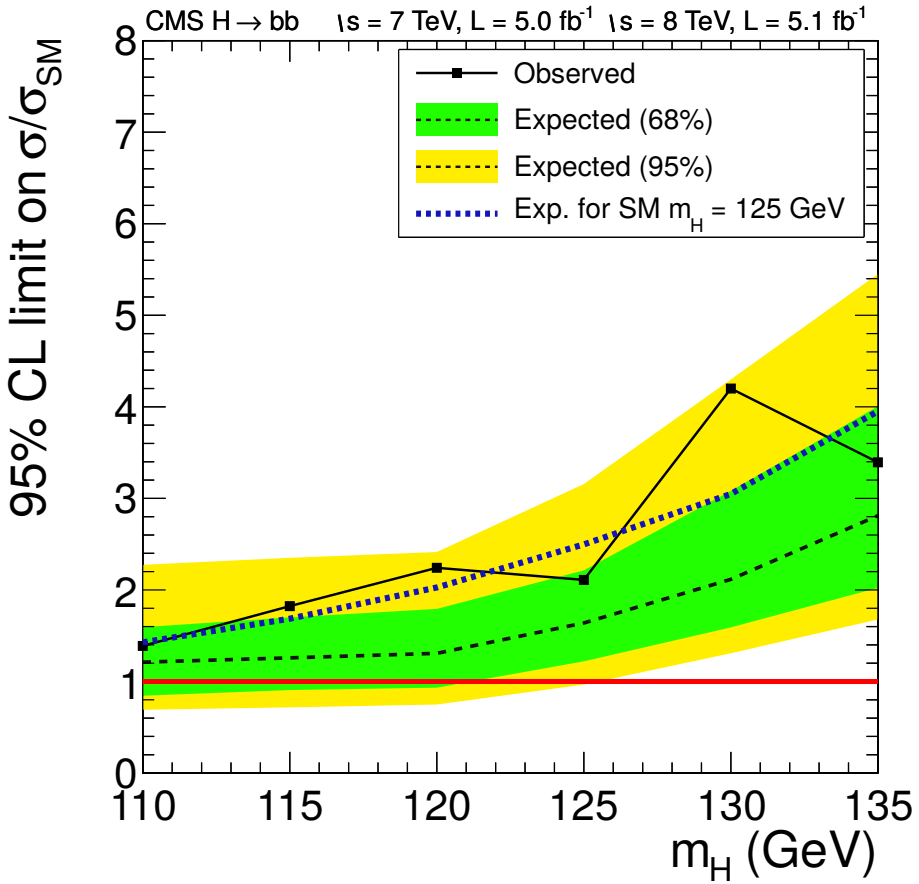


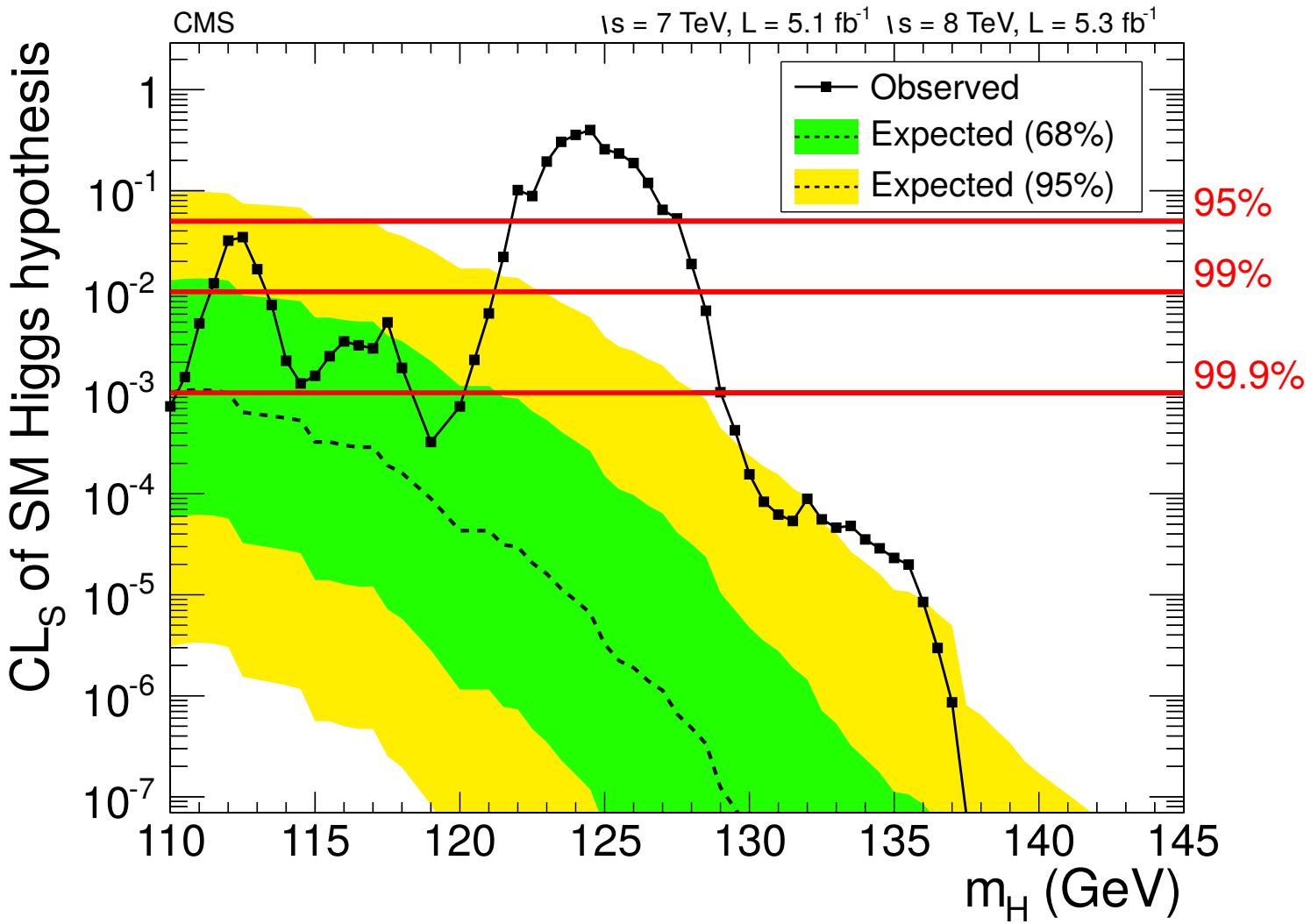
Figure 12: The 95% CL limit on the signal strength σ/σ_{SM} for a Higgs boson decaying to two b quarks, for the combined 7 and 8 TeV data sets. The symbol σ/σ_{SM} denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands. The dotted curve shows the median expected limit for a SM Higgs boson with $m_H = 125\,GeV$.

Significance of results

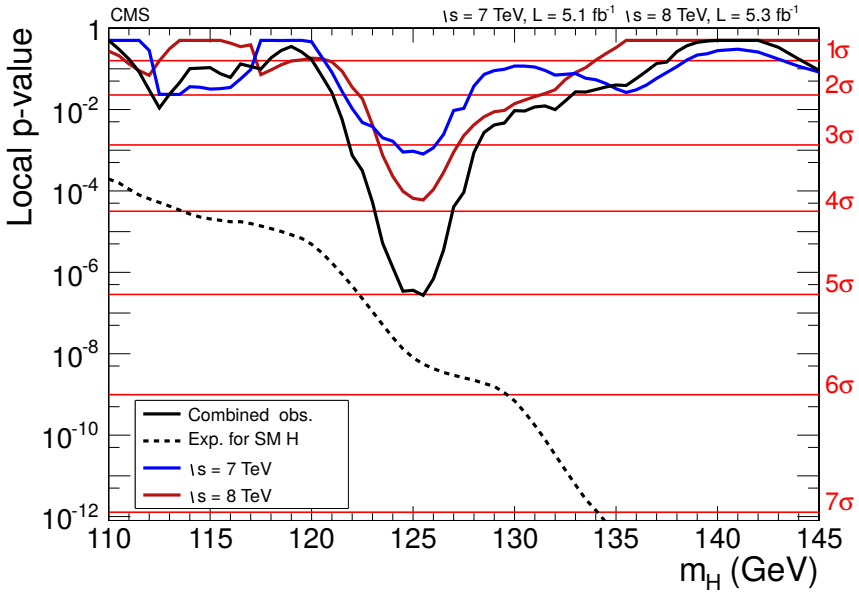
Hypothesis testing and exclusion limits

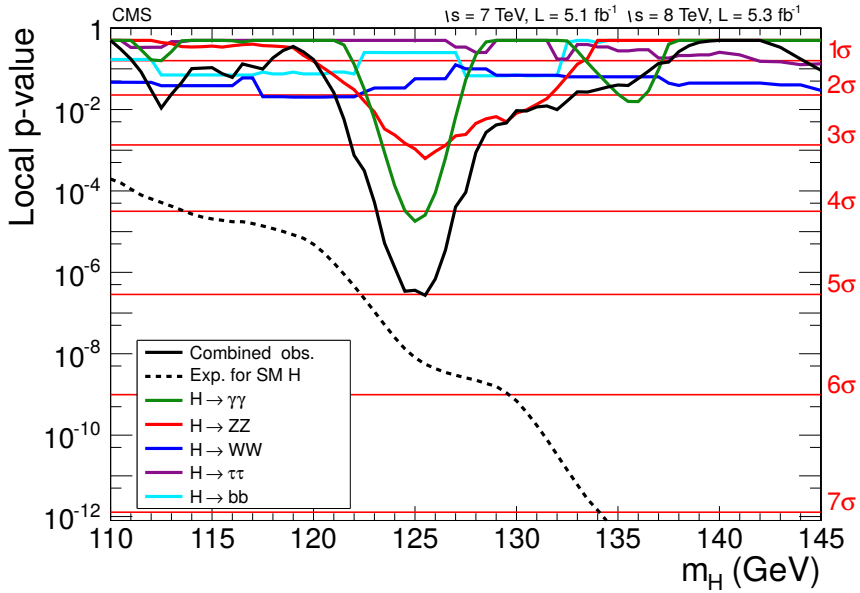
- b: Try to reject the null hypothesis (e.g. only background hypothesis, No Higgs $\rightarrow$ test background compatibility)
- s+b: data consistent with Higgs+SM-background (exclusion test, limit)
- calculate CL_S: define probability density function $-2ln(\frac{L(s+b)}{L(b)})$, $L(\mu, \theta)$ being likelihood function for hypothesis
- to access whether the measured data are compatible with hypothesis, a test statistic is constructed, $CL_S = \frac{p_{s+b}}{1-p_b}$
- if $CL_S < 5\%$, the SM Higgs boson is excluded with 95% confidence level.

Significance of results



Significance of results





Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0