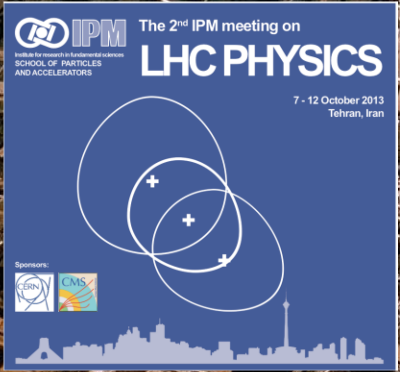
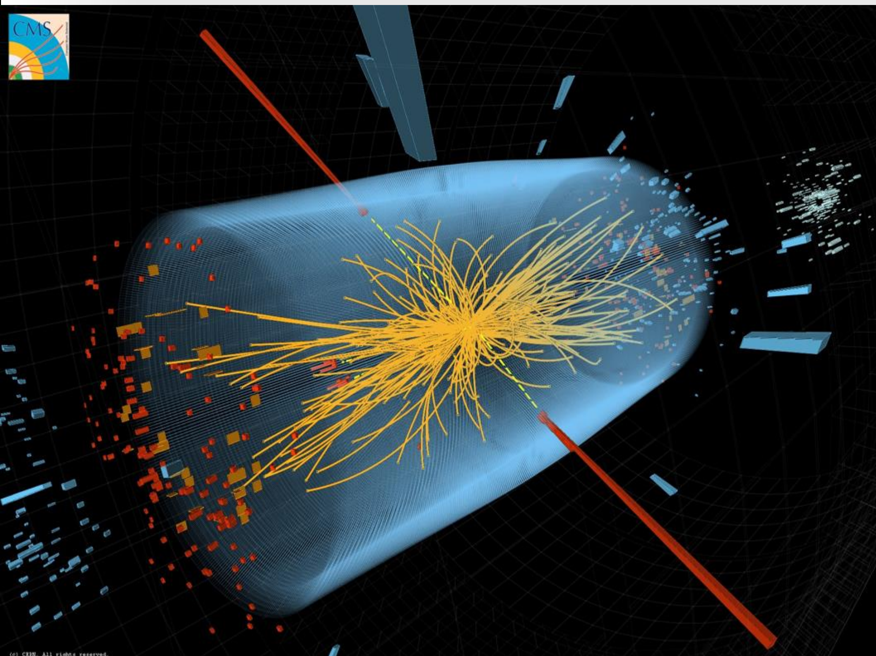
Higgs Physics at CMS

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA

7th October 2013
Tehran, Iran

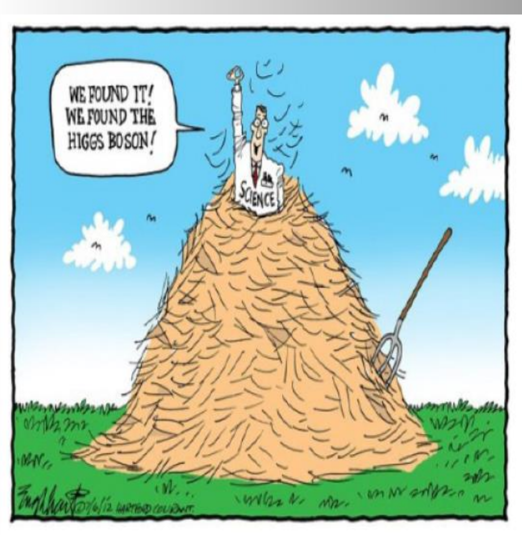




Outline

- Short introduction
- Standard Model Higgs channel studies overview
- Studies of Higgs properties

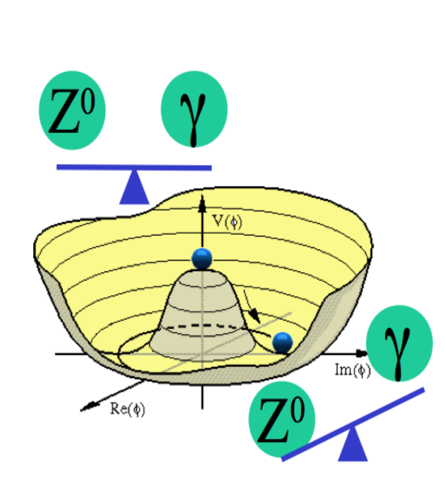
Note: not all slides will be discussed in detail



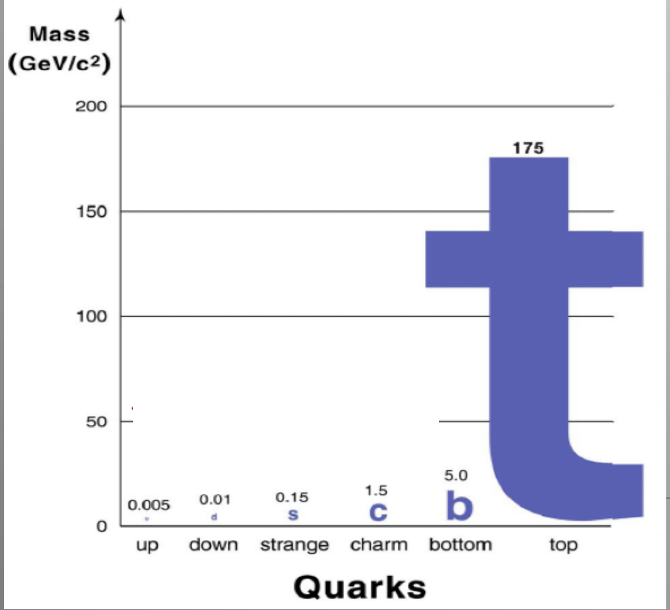
OR: The year after!!
CERN/Melbourne
4th of July

The Origin of Particle Masses

- At ‘low’ energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking: ESB
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary ‘Higgs’ particle,. Extend the mechanism to give mass to the Fermions via Yukawa couplings.



(*) Higgs, Brout Englert, Kibble, Hagen and Guralnik, and…

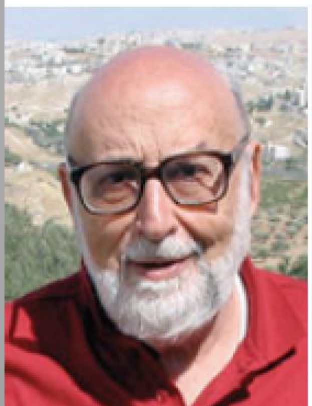


The Higgs (H) particle is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as LEP and the Tevatron, and now at the large hadron collider @ CERN

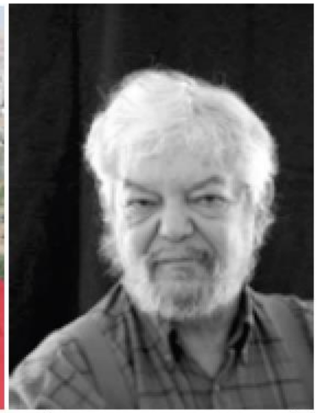
ESB Heroics

The year is 1964

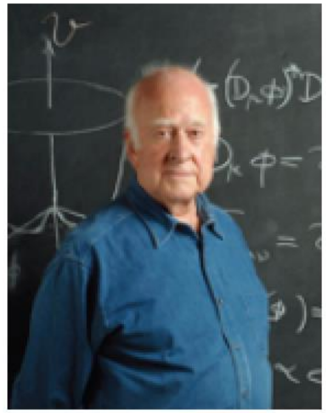
Electroweak Symmetry Breaking



François Englert



Robert Brout



Peter Higgs

Gerald Guralnik

Carl Hagen

Tom Kibble

BROKEN SYMMETRY AND THE MASS OF GAUGE VECT

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxel
(Received 26 June 1964)

BROKEN SYMMETRIES, MA

Tait Institute of Mathemat

VOLUME 13, NUMBER 16 PHYS

BROKEN SYMMETR

CONSERVATION LAWS AND MASSLESS PARTICLES*

S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
rtment of Physics, Imperial College, London, England
(Received 12 October 1964)

LDS

Tomorrow the Nobel Prize Committee will announce the 2013 winners…
Will they reward any of these gentlemen for their very important work done almost 50 years ago?? We will know on December 8th…

The Hunt for the Higgs

Where do the masses of elementary particles come from?

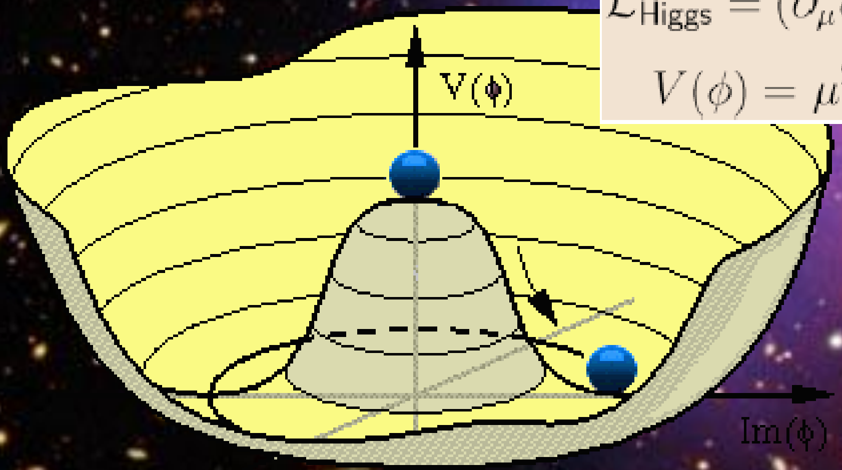
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

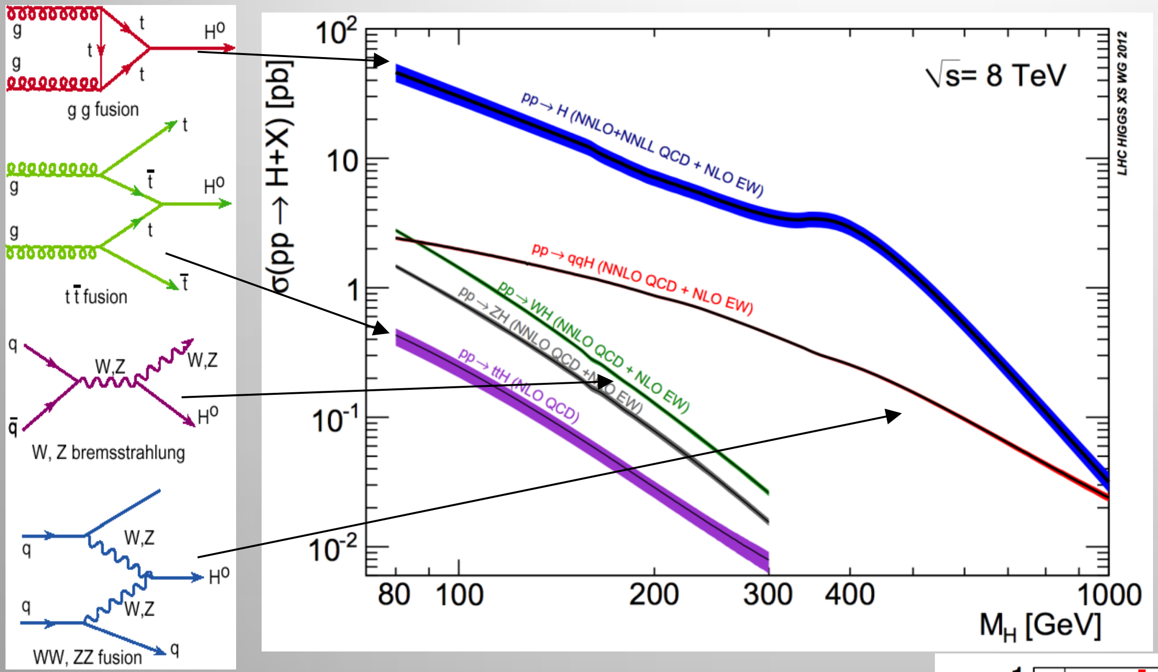
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

It could be anywhere from 114 to ~700 GeV

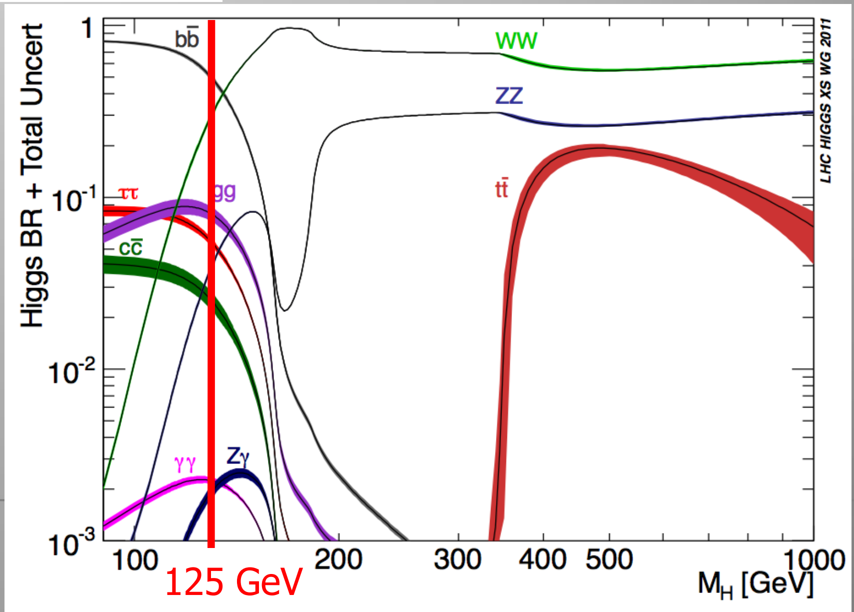
Higgs Production & Decay



Processes

- Gluon fusion
- Vector Boson Fusion
- W/Z associated prod.
- Top associated prod.

Decays



Numbers taken from the LHC Higgs Cross Section WG

YR1: Inclusive cross sections
arXiv:1101.0593

YR2: Differential cross sections
arXiv:1201.3084

YR3: Properties
arXiv:1307.1347

Higgs Hunting in CMS

Processes/decays studied:

Results released | In progress

	untagged	VBF	VH	ttH
H-> gamgam	Results released	Results released	Results released	Results released
H-> ZZ	Results released	Results released	Results released	In progress
H->WW	Results released	Results released	Results released	In progress
H-> bb		Results released	Results released	Results released
H-> tau tau	Results released	Results released	Results released	Results released
H-> Zgamma	Results released	Results released		
H-> mumu	In progress	In progress	In progress	
H-> invisible	In progress	Results released	Results released	In progress

+ more exotic channels

Main decay channel characteristics:

Channel	m_H range (GeV/c^2)	Data used 7+8 TeV (fb^{-1})	m_H resolution
H -> $\gamma\gamma$	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> lnulnu	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

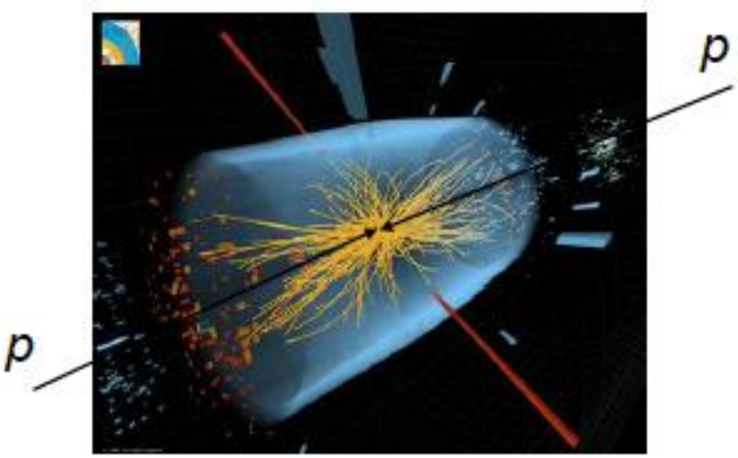
- need high energy:

  $E = mc^2$

- need lots of data

non-deterministic and very rare

order 1 in 10^9



* for us finding the Higgs it was 48 years = 1,513,728,000 sec

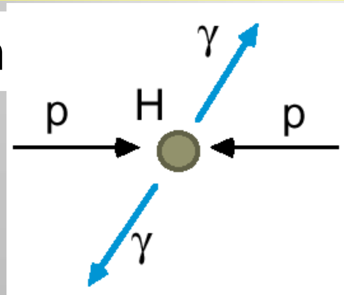
Higgs Boson Searches (simulation)

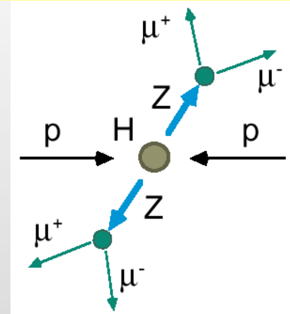
Low M_H < 140 GeV/c²

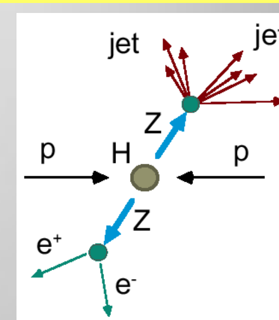
Medium 130<M_H<500 GeV/c²

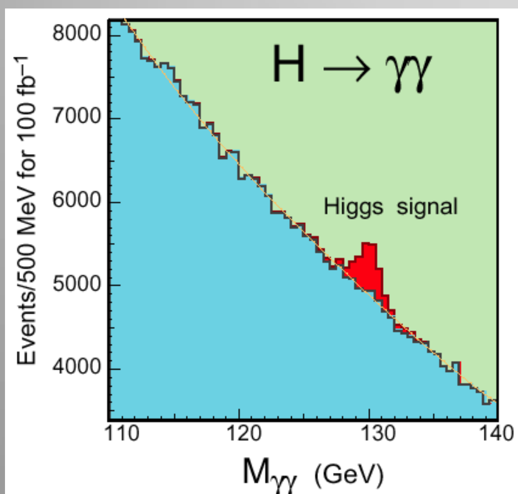
High M_H > ~500 GeV/c²

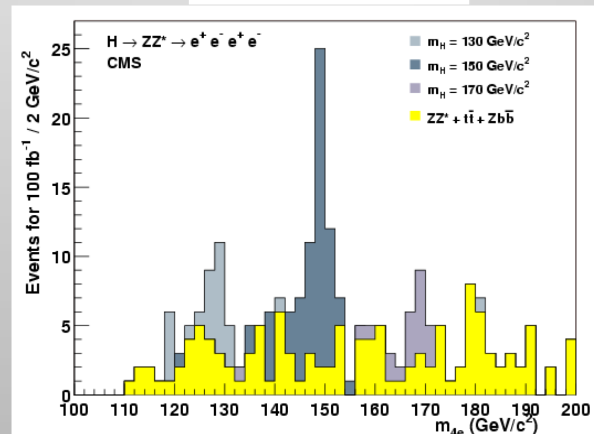
simulation

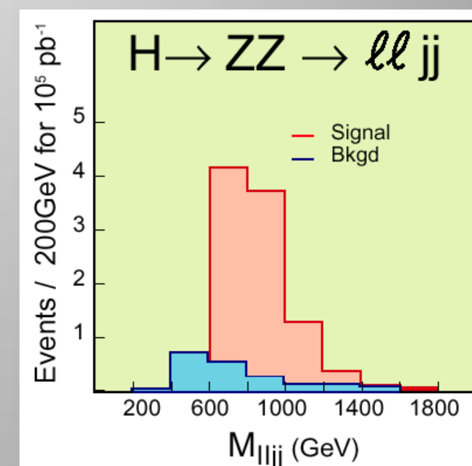


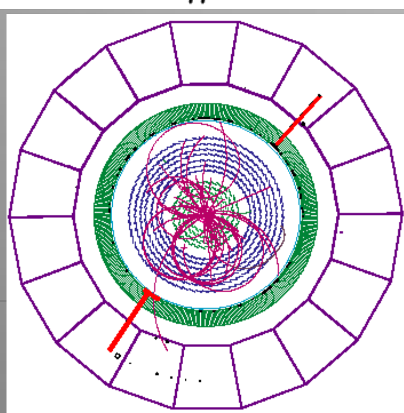


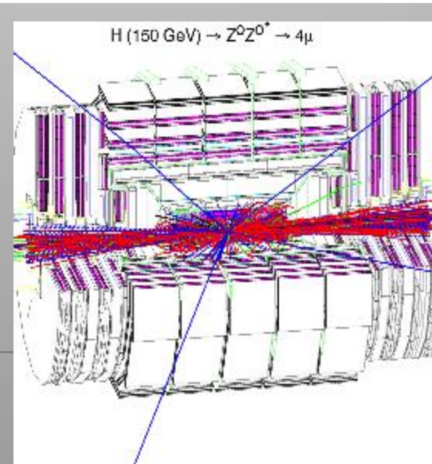


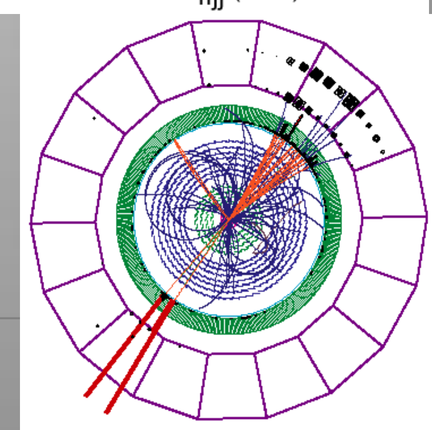


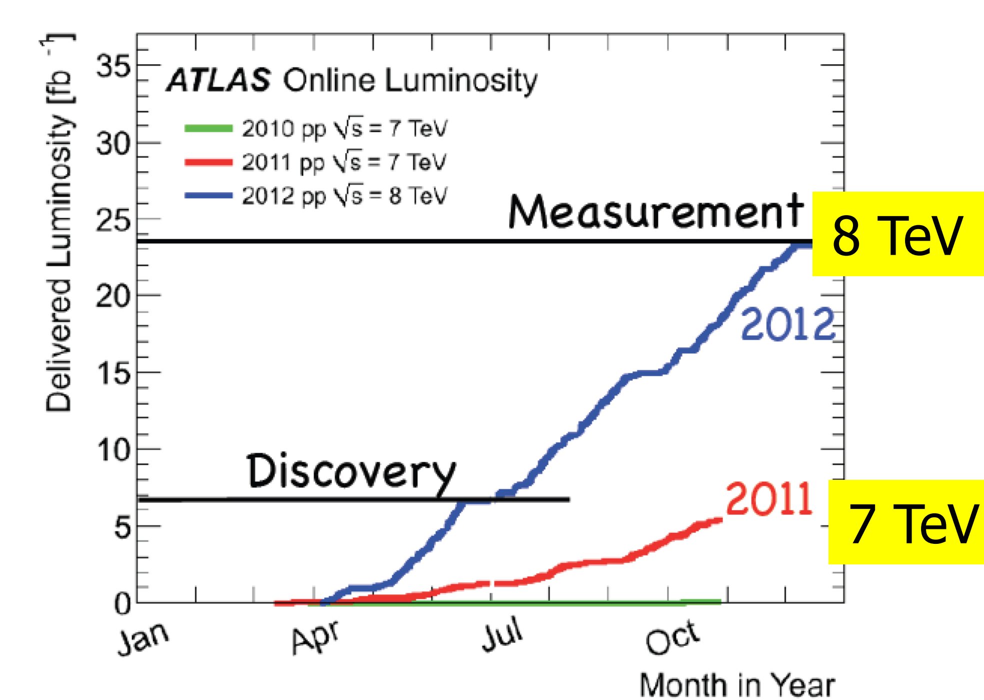












100 meter underground

8 TeV

7 TeV

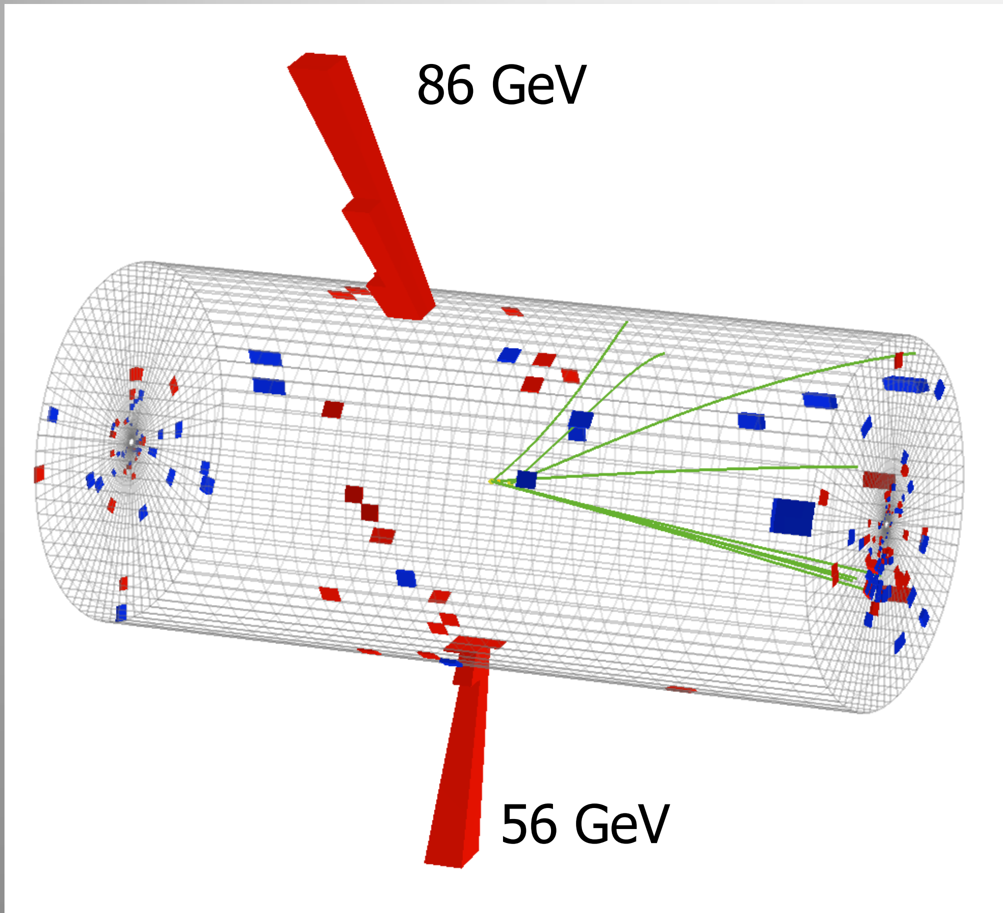
Luminosity = # events/cross section/time

LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present luminosity

Higgs Decay into Bosons

The Decay $H \rightarrow \gamma\gamma$



CMS-PAS-HIG-13-001

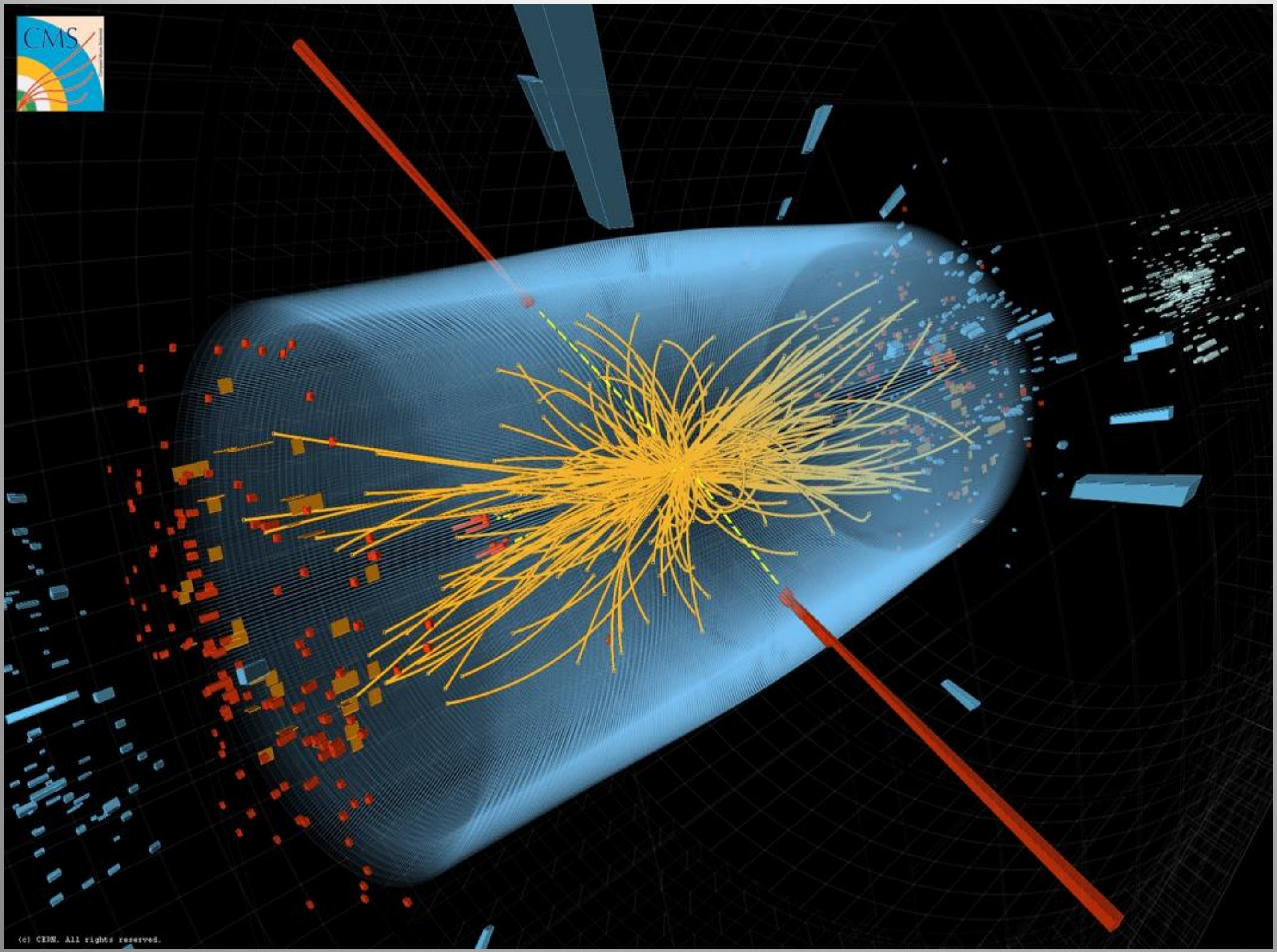
Analysis

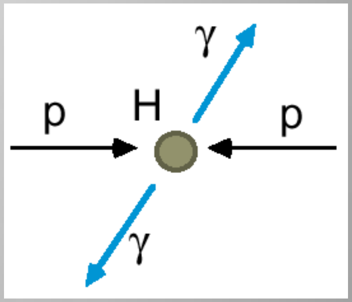
- Two high momentum photons
- Low mass Higgs is narrow
- Two photon resolution is excellent
- Looking for a narrow peak
- Large irreducible background from direct two photons
- Smaller fake photon background

Key analysis features

- Energy resolution (calibration)
- Fake photon rejection
- Optimize use of kinematics

A Collision with two Photons





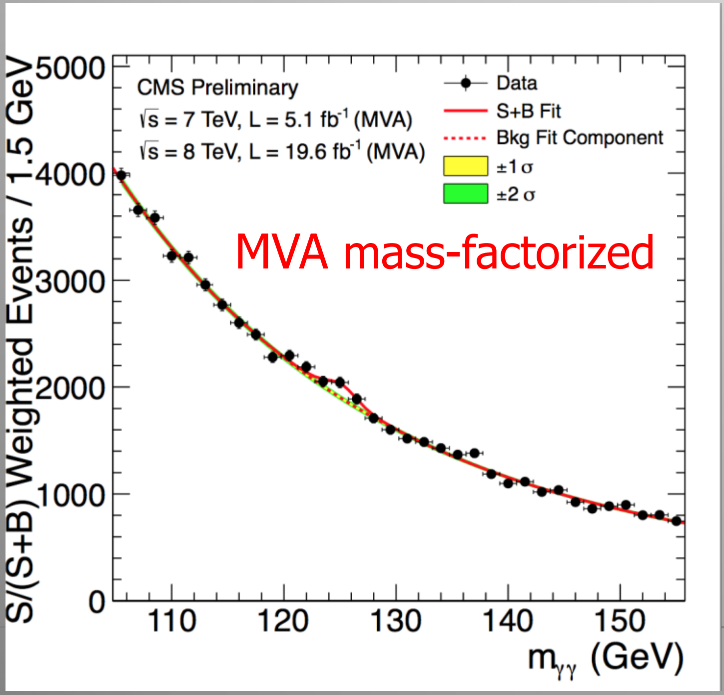
A Higgs or
a ‘background’
process without
a Higgs?

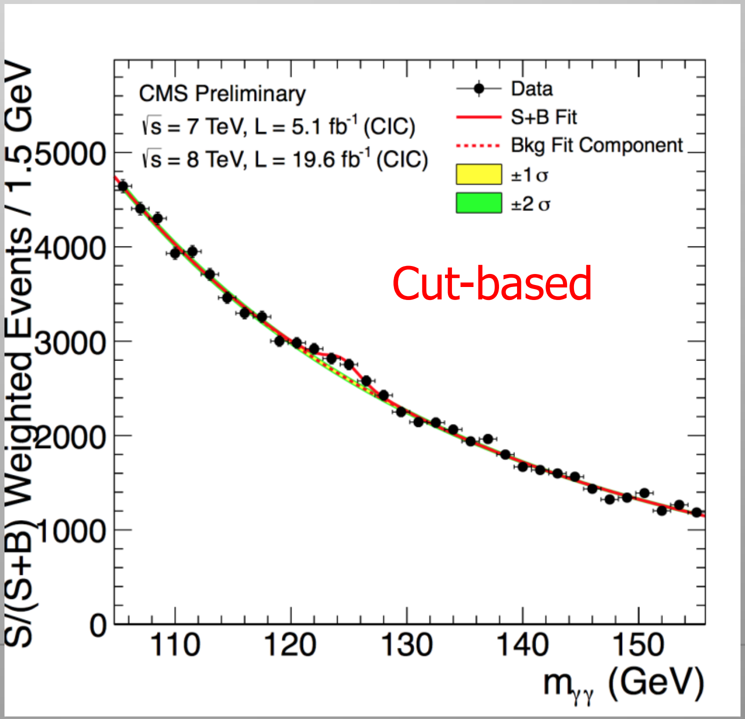
CMS: The Decay H→ γγ

- Two inclusive analyses:
  - MVA: photons selected with an MVA. Variable in the MVA: photon kinematics, photon ID MVA score (shower shape, isolation), di-photon mass resolution. 4 MVA categories with different S/B
  - Cut-based: photons selected with cuts. 4 categories based on: γ in Barrel/Endcap, (un)converted γ. Each category has different mass resolution and S/B

PRIMARY

CROSS-CHECK

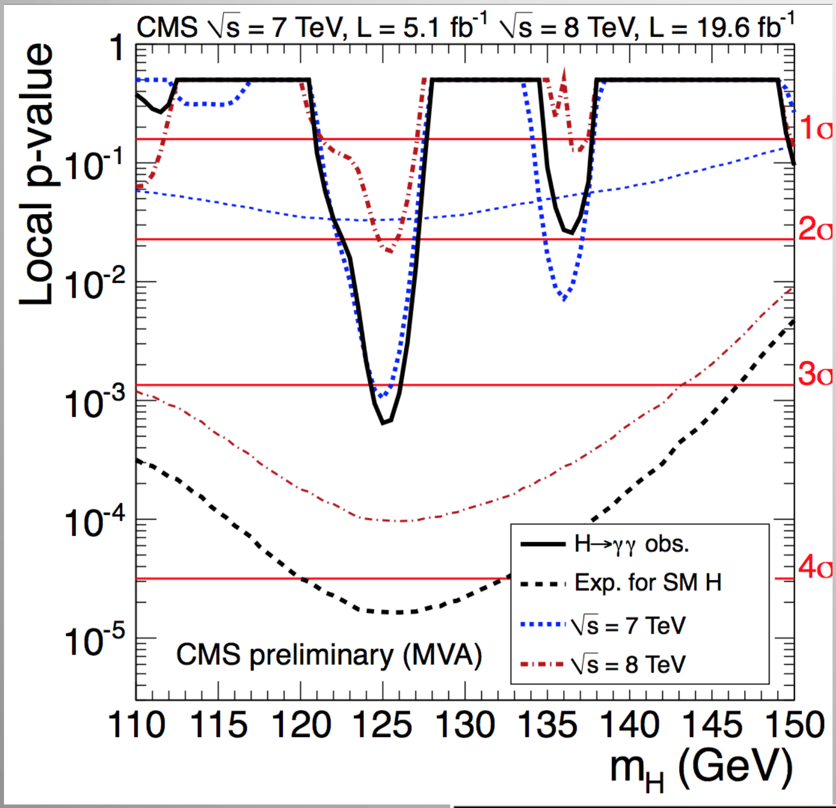




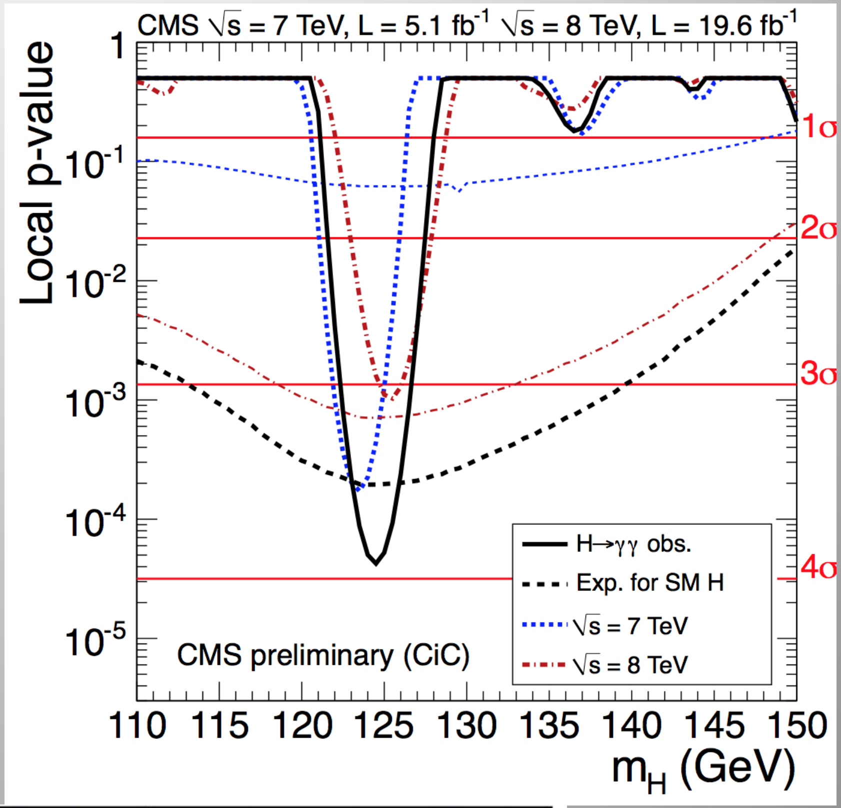
Event categories weighted by S/(S+B) for visualization

CMS: The Decay H→ γγ

MVA mass-factorized



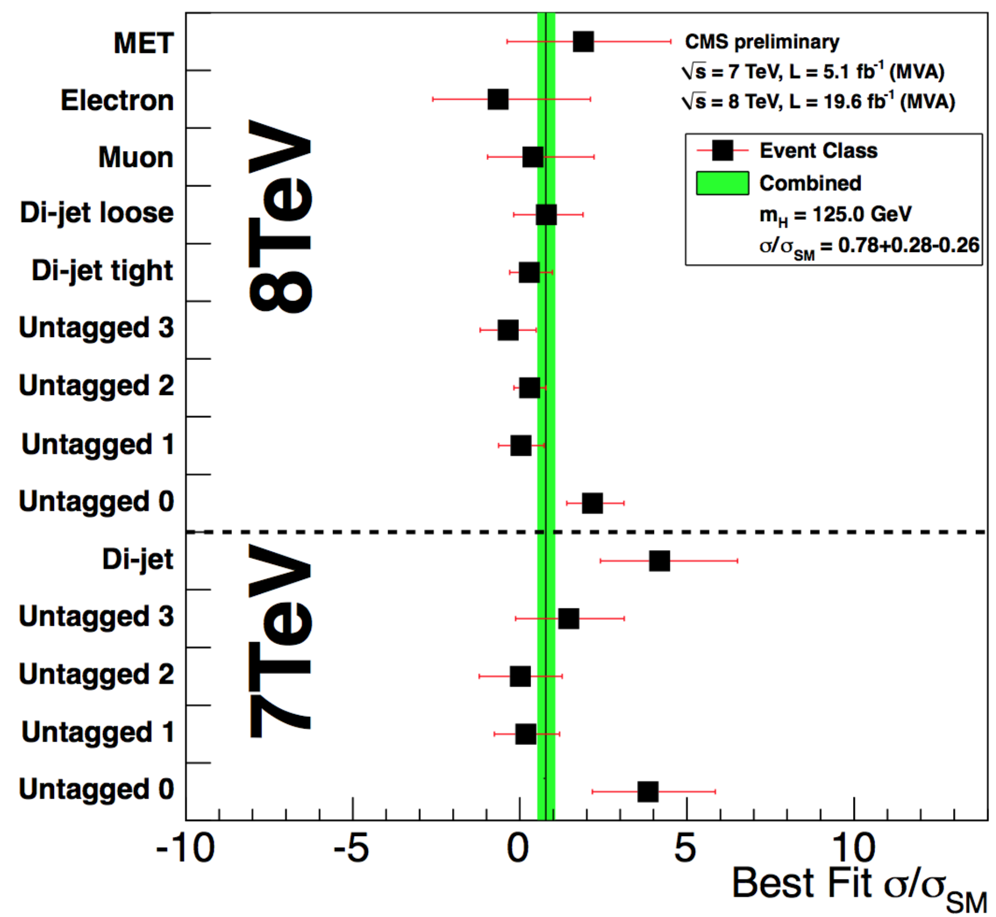
Cut-based

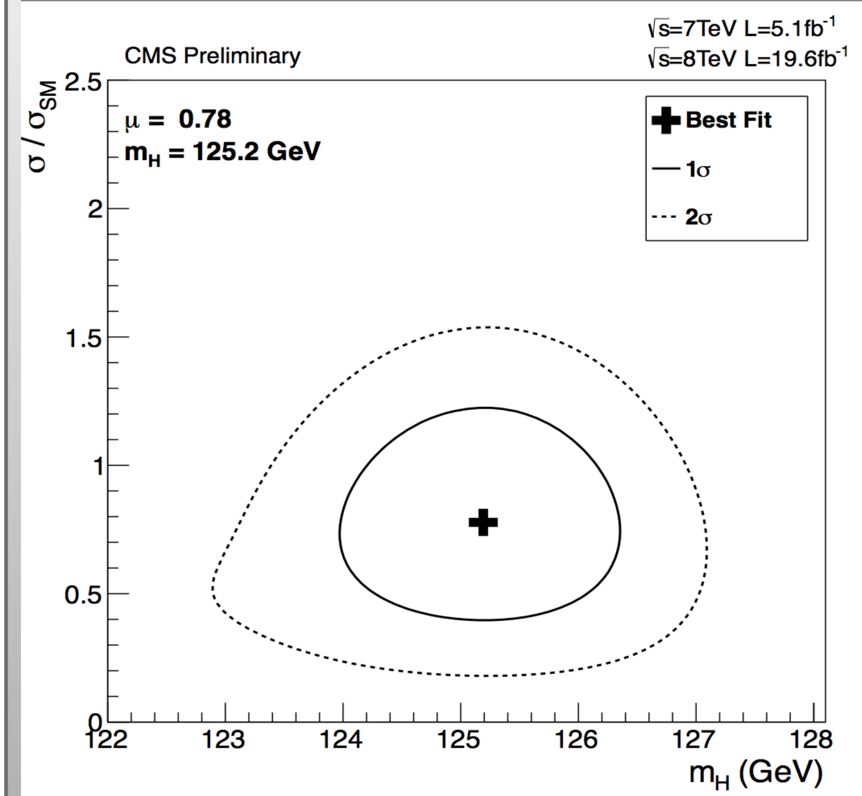


	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

The Decay $H \to \gamma\gamma$

MVA mass-factorized

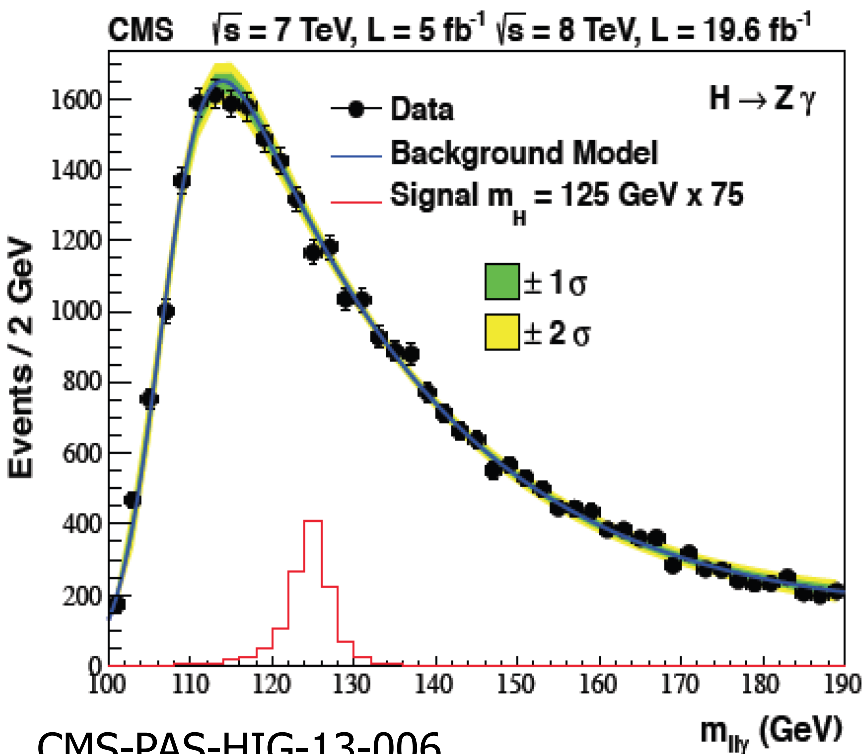


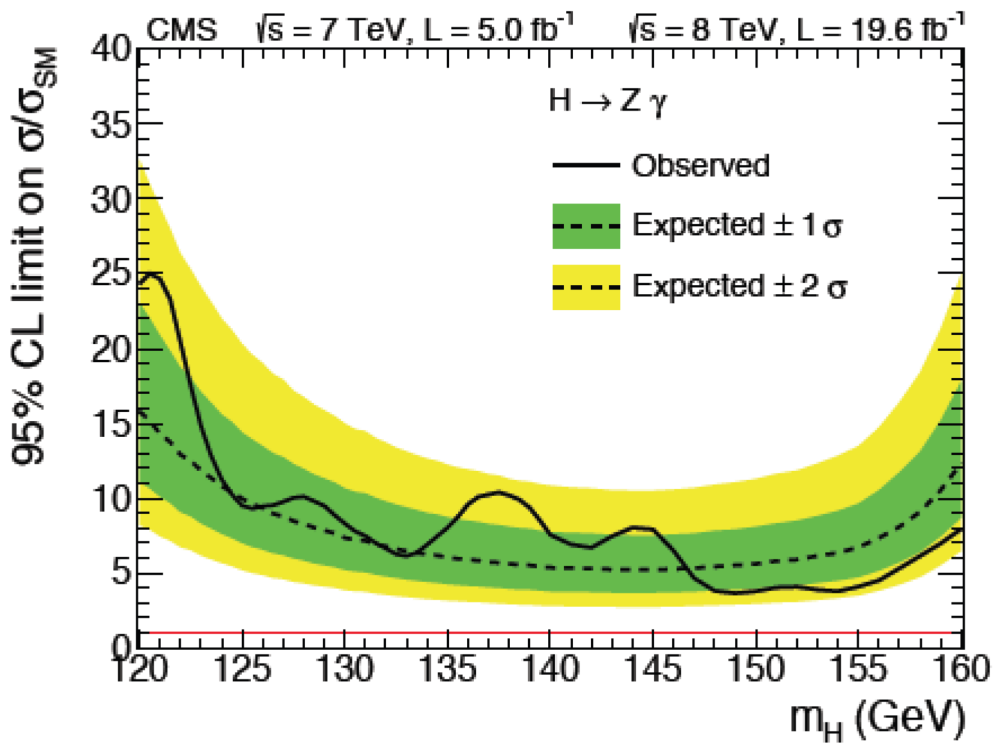


$M_H = 125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$

7+8 TeV: σ/σ_{SM} for a mass of 125.0 GeV = $0.78^{+0.28}_{-0.26}$

The Decay H→ Zγ



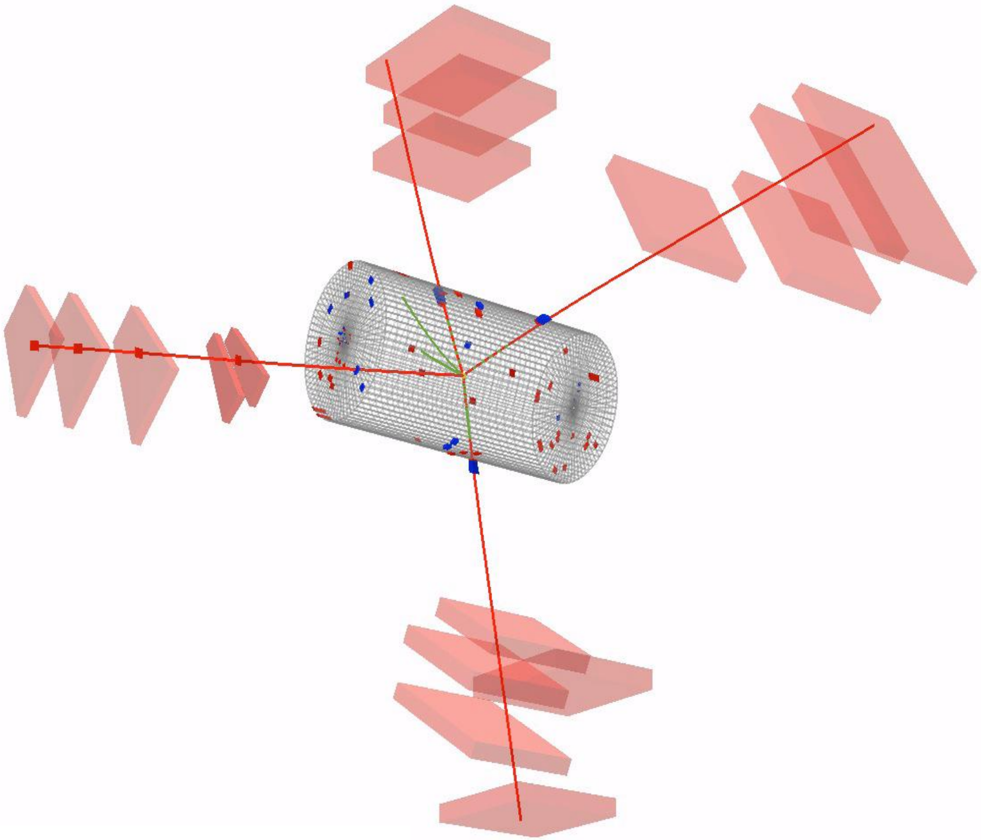


CMS-PAS-HIG-13-006

- Z decays into 2 charged leptons. The BR (H → Z γ) is comparable to BR(H → γγ) , but BR (Z → ll) reduces sensitivity (factor 15)
- Search for a narrow llγ peak on top of a falling background, as for H → γγ
- No significant excess seen over the entire search region

In certain models this channel could be largely enhanced

The Decay H → ZZ → 4l



CMS-PAS-HIG-13-002

Analysis

- 4 isolated high p_T leptons consistent with Z decays from same vertex
- Use a di-jet tagged and untagged category, and kinematics
- Clear mass peak
- Little background, main comes from non-resonant ZZ production, also Zbb and top (2l2ν2b), fakes

Analysis procedure rather stable since ICHEP2012

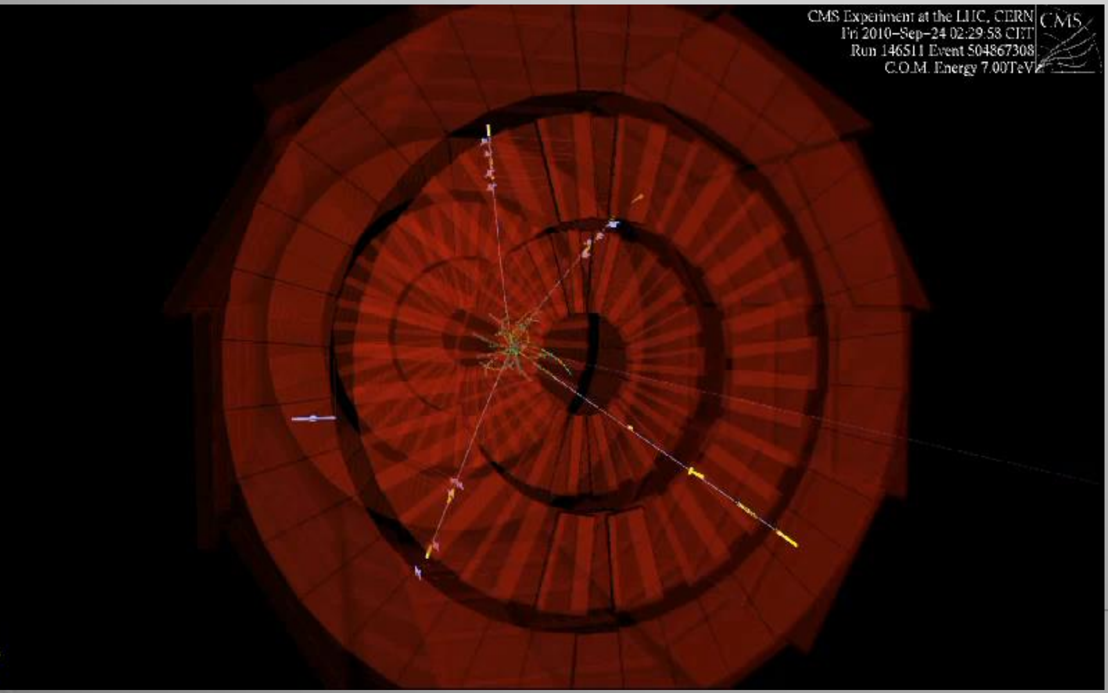
Searches for the Higgs Particle

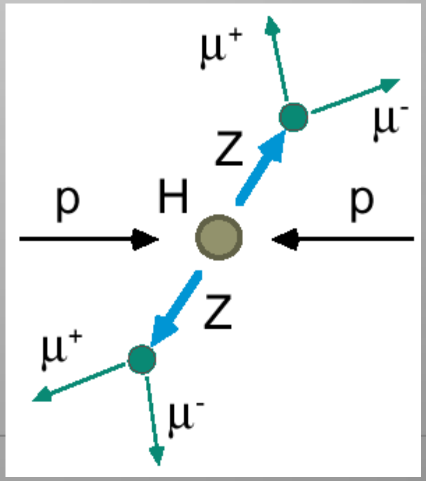
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

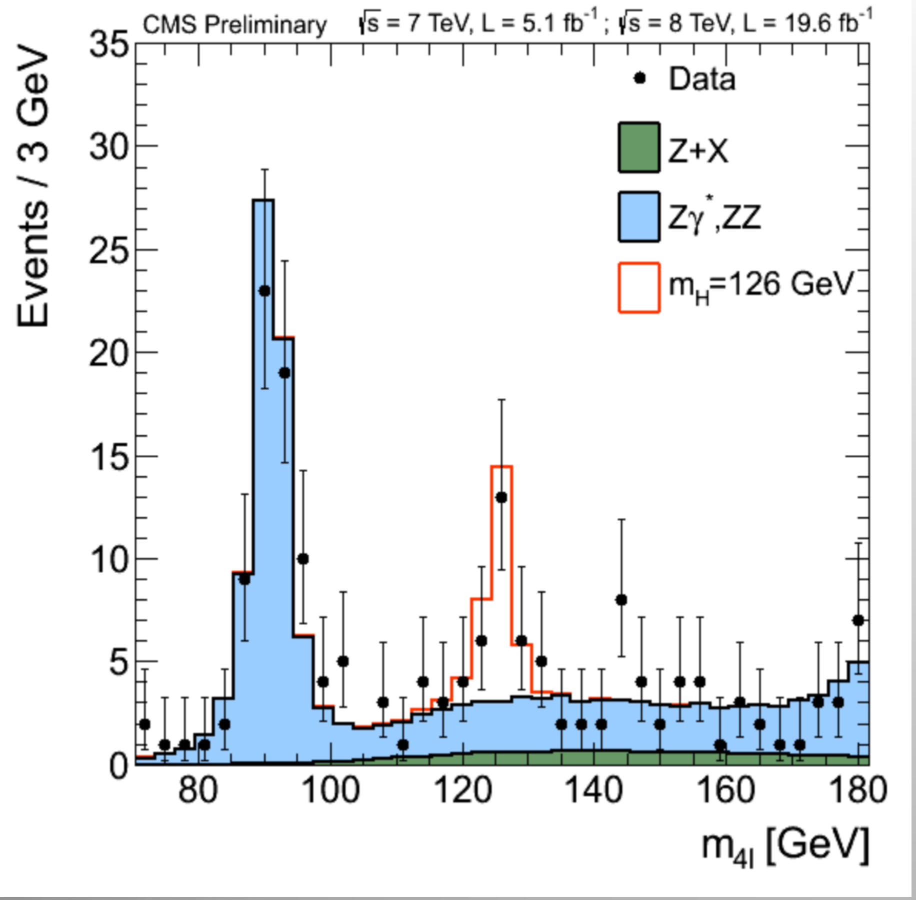
So we look for 4 muons in the detector

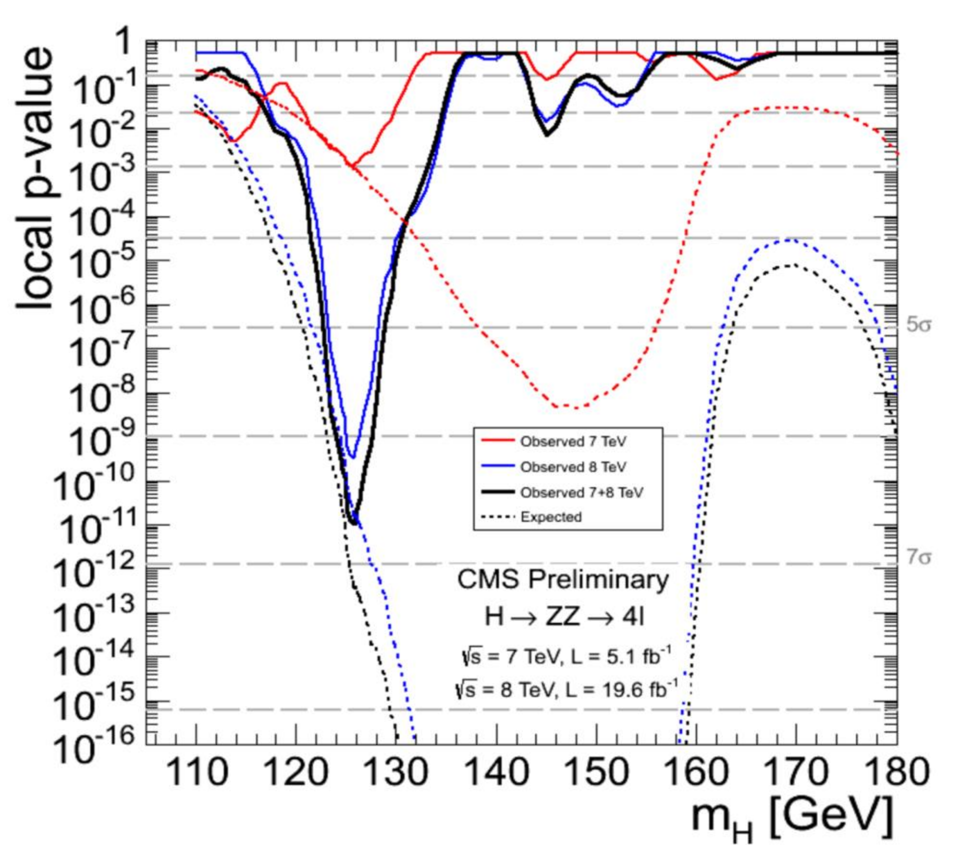
But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)





CMS: The Decay $H \to ZZ \to 4l$





Use event kinematics (MELA)

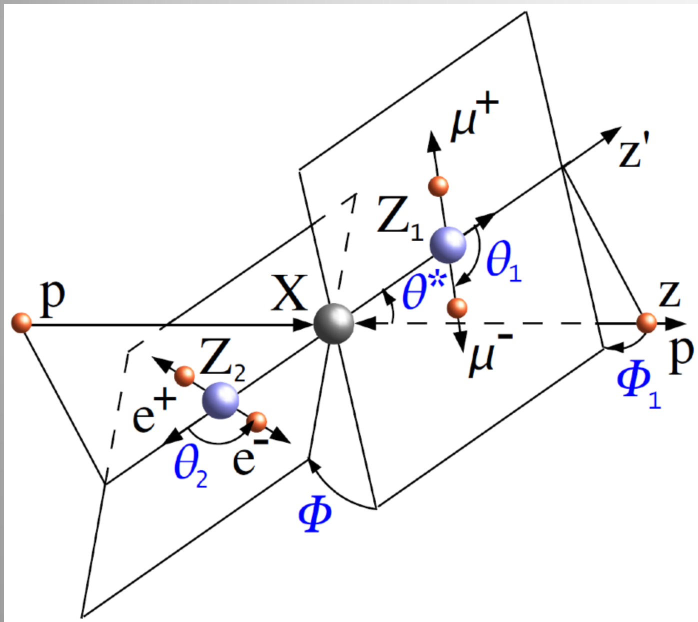
Significance Expected: 7.1σ

Observed: 6.7σ

σ/σ_{SM} at 125.7 GeV = 0.92 ± 0.28

Significance is well over 6 standard deviations in this channel

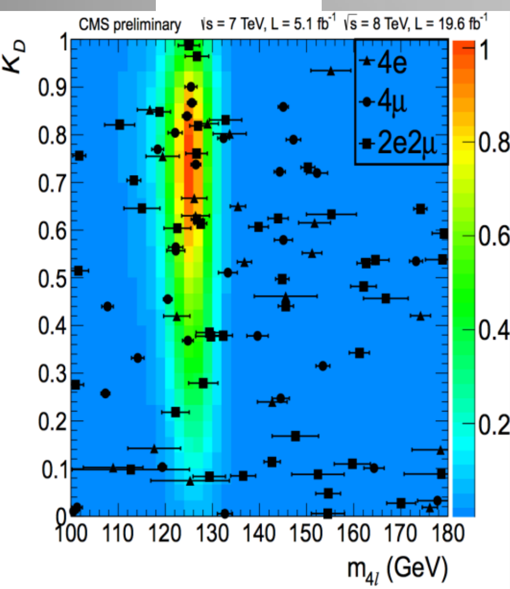
The Decay H → ZZ → 4l



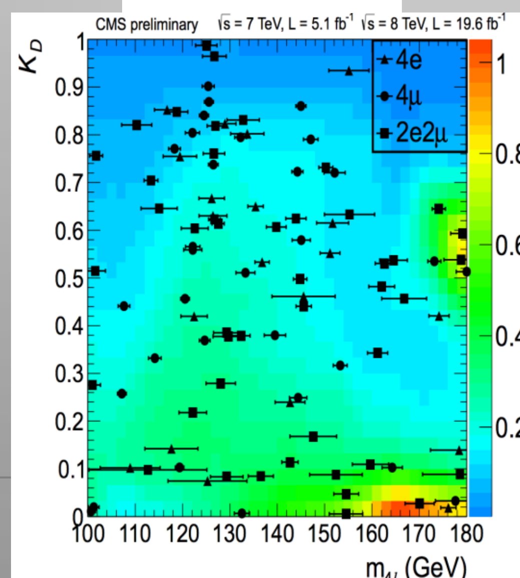
Matrix **E**lement **L**ikelihood **A**nalysis:
uses kinematic inputs to build a kinematic discriminant (K_D) for signal to background discrimination using $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

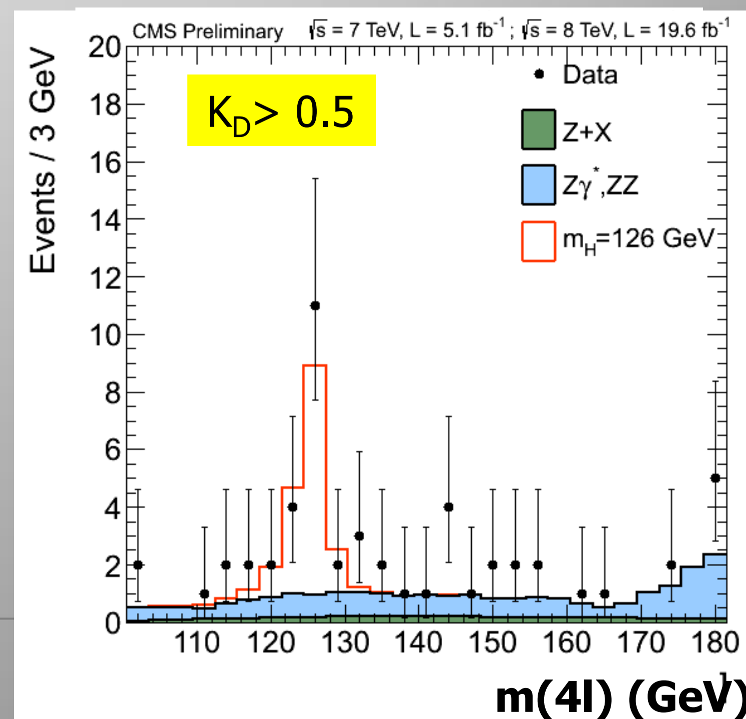
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

SIGNAL



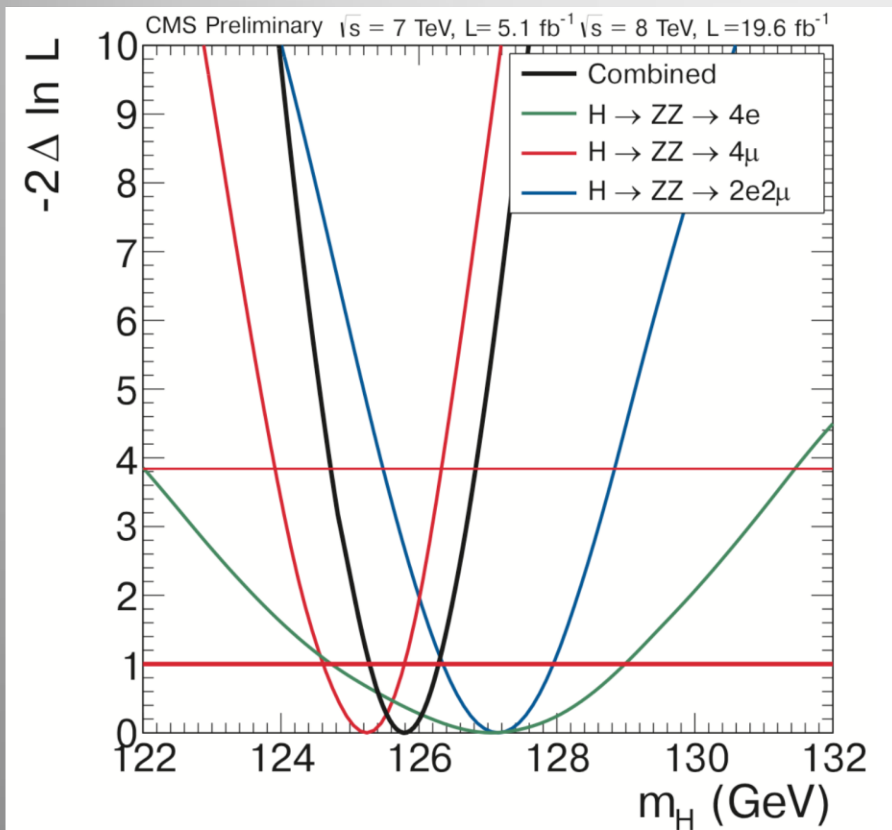
BACKGROUND





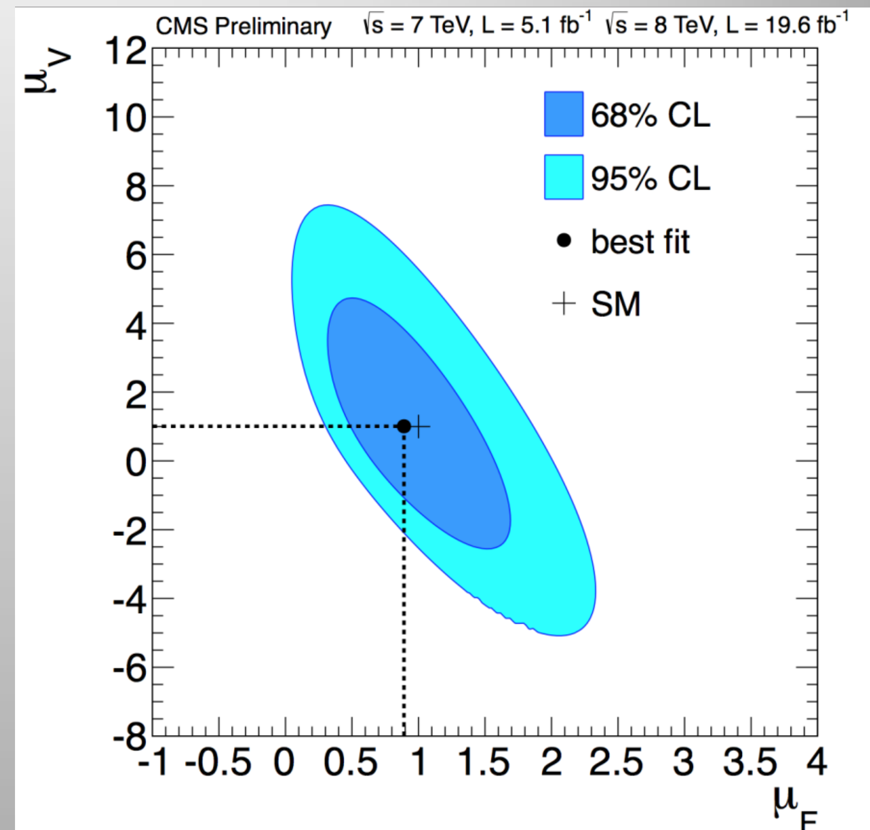
The Decay $H \rightarrow ZZ \rightarrow 4l$

Mass Measurements



M_H= 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV.

Coupling scale factors to vector bosons and fermions

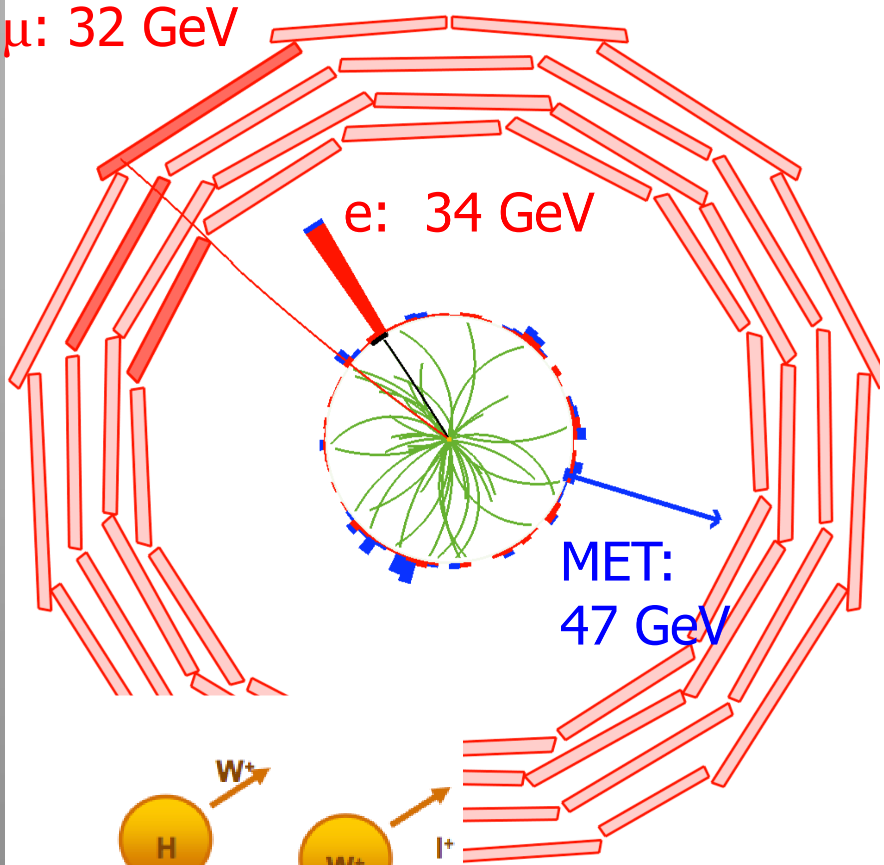


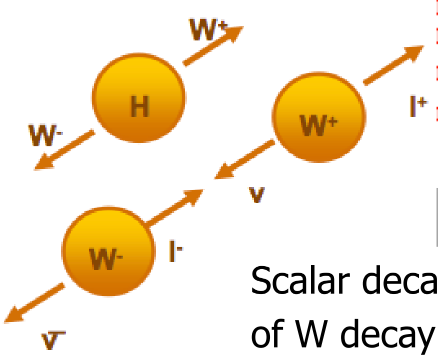
$$\mu_V\ (qqH,\ ZH,\ WH) = 1.0^{+2.4}_{-2.3}$$

$$\mu_F\ (gg \rightarrow H,\ t\bar{t}H) = 0.9^{+0.5}_{-0.4}$$

The Decay H → WW → 2l 2ν

CMS-PAS-HIG-13-003





Scalar decay and V-A structure of W decay lead to a small opening angle between leptons

Analysis

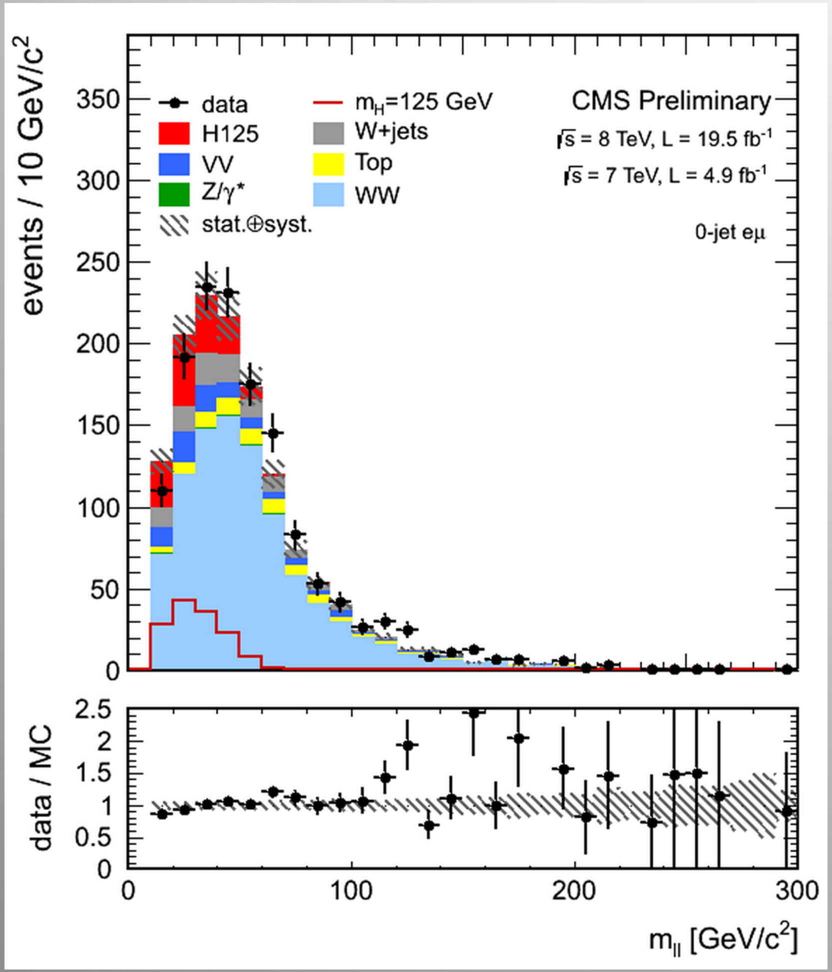
- Two opposite charged leptons (leptons only e, μ)
- Two neutrinos == missing transverse energy (MET)
- No Higgs mass peak
- Counting & 2D shape analyses
- Enhance sensitivity by subdividing into + (0,1,2) jets categories

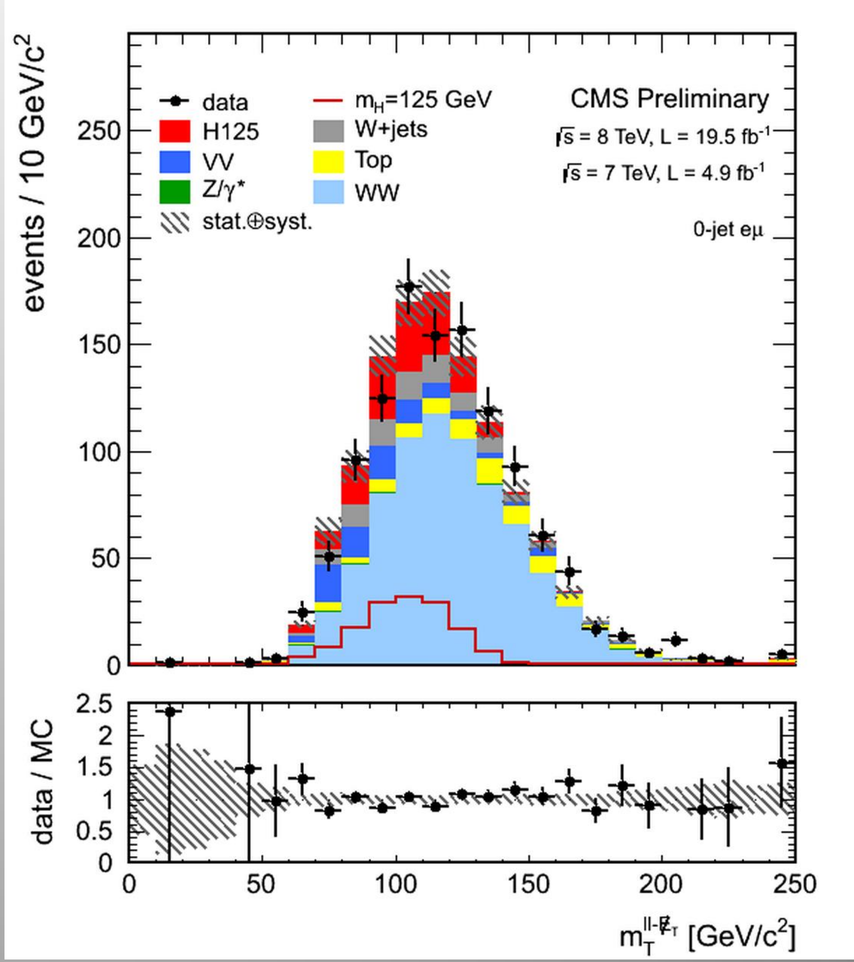
Analysis challenges

- Understand backgrounds WW, W+jets, top, Drell-Yan
- Determined from control regions

The Decay H → WW → 2l 2ν

Events with 0 jets and different flavour leptons (7+8 TeV Data)

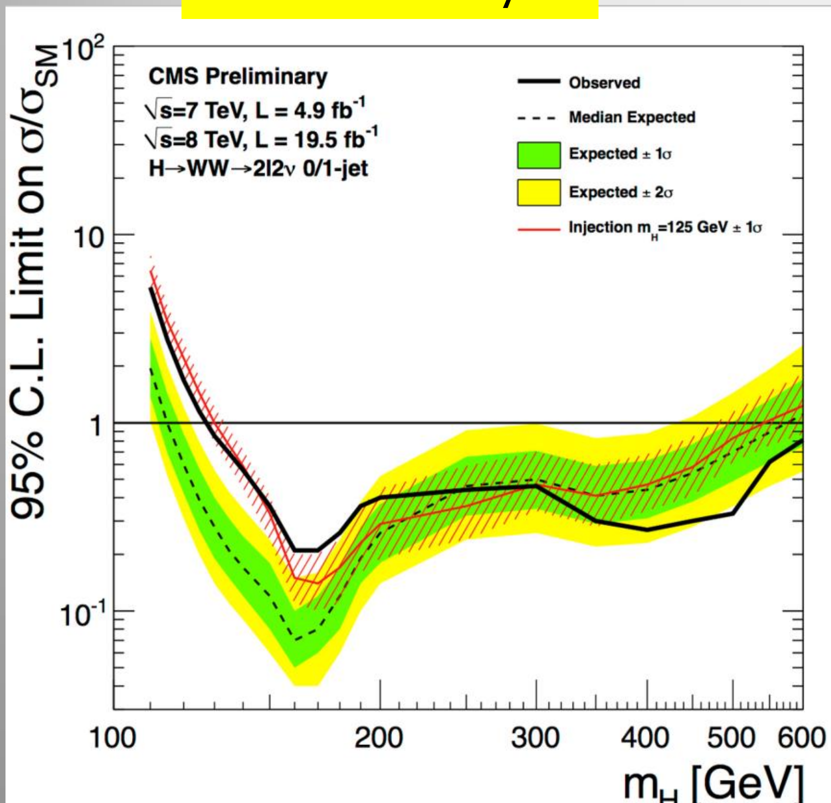




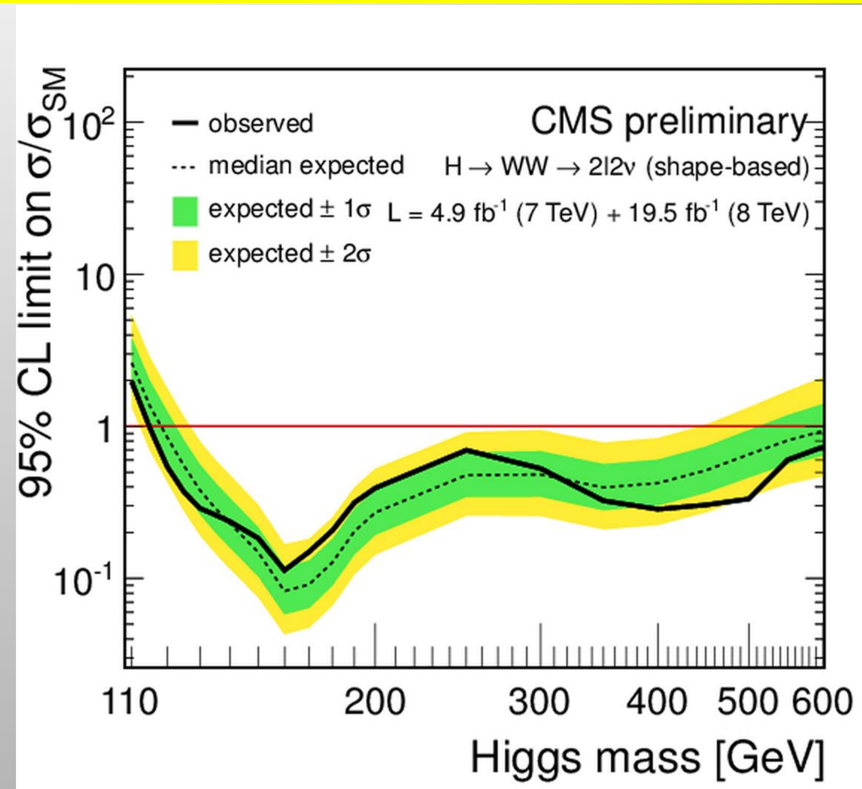
A significant excess is observed…

The Decay H → WW → 2l 2ν

Standard Analysis

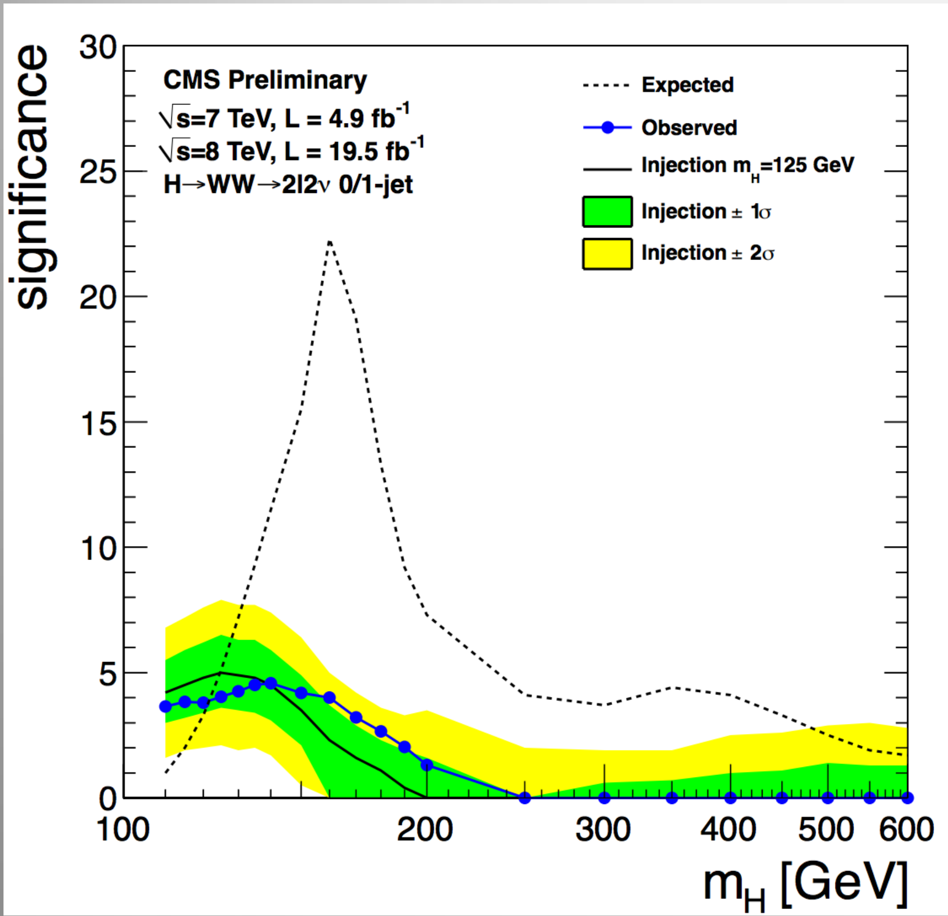


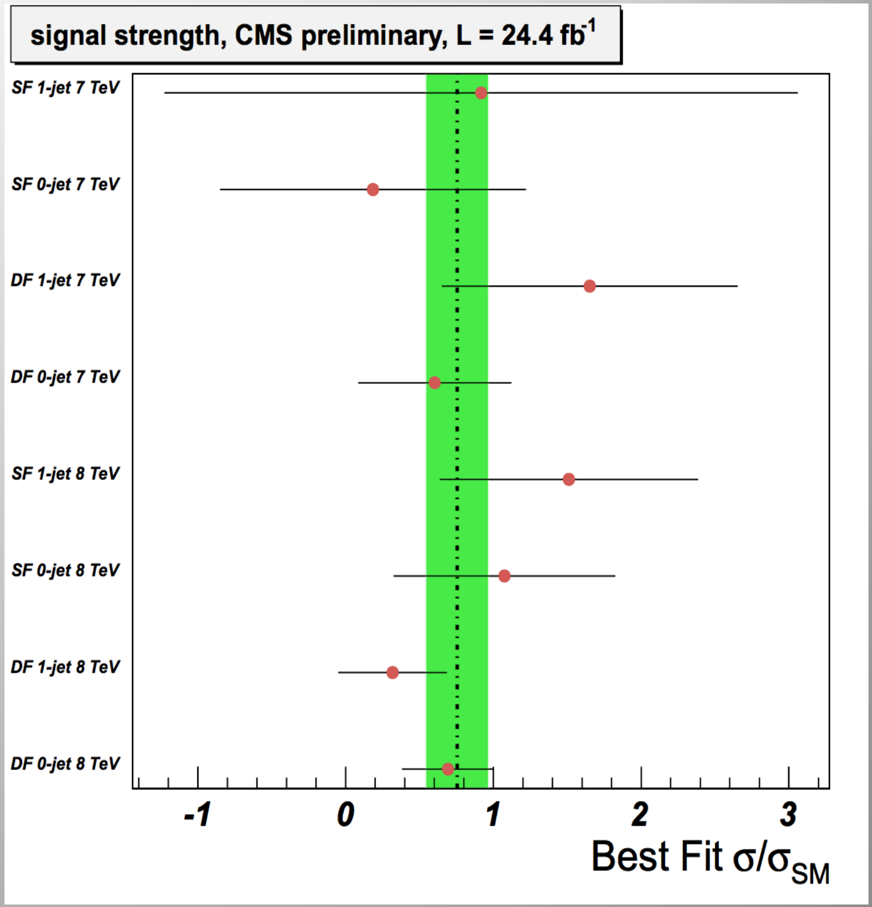
Using m_H = 125 GeV as a "background"



- Exclusion at 95% in the mass range 128-600 GeV
- Large excess in the low mass region
- When including M_H=125 GeV as part of the background, no significant excess is seen over the entire mass range

The Decay H → WW → 2l 2ν



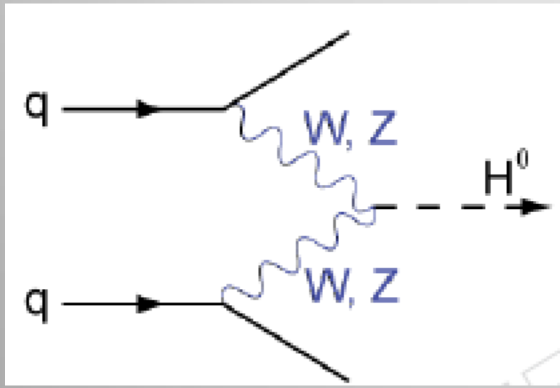


A 4.0σ (5.1σ) observed (expected) significance at m_H ~ 125 GeV

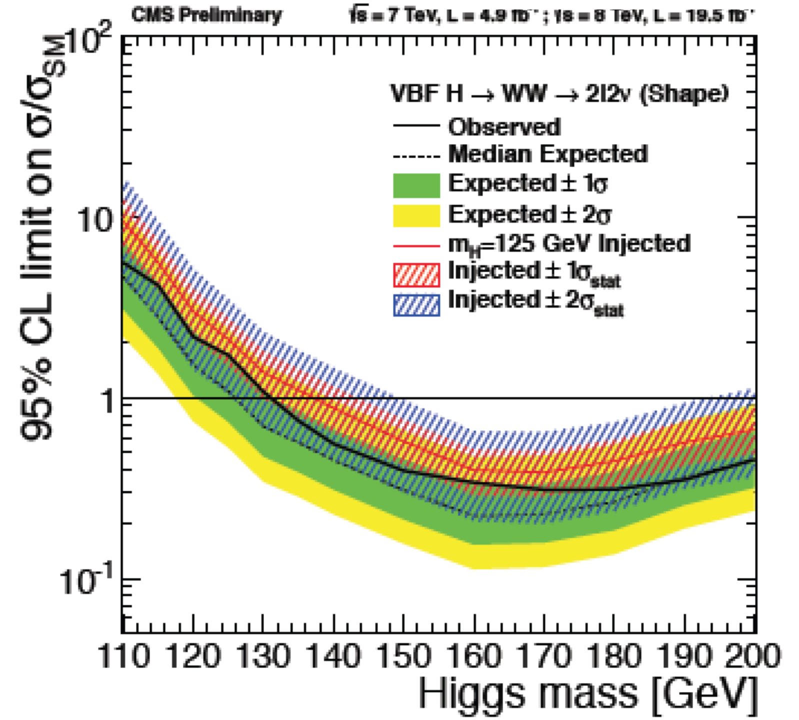
σ/σ_{SM} signal strength: 0.76 ± 0.21

VBF: H → WW → 2l 2ν

2-jet category in CMS
(VBF dominated)



CMS-PAS-HIG-13-022



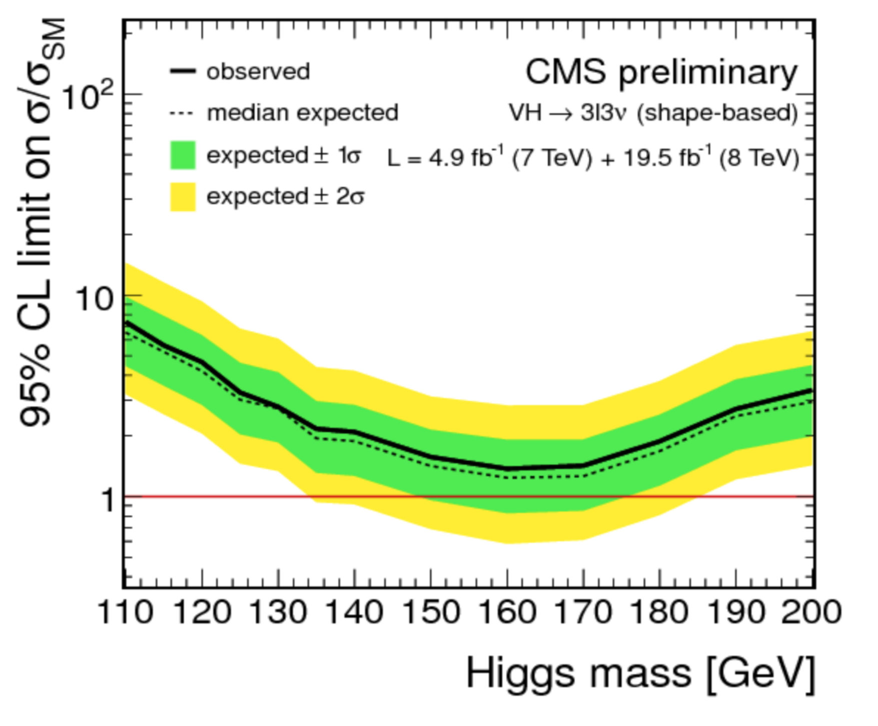
Mild broad excess in the low mass

analysis	limits expected / observed	significance expected / observed	best μ observed
VBF, $e\mu$ and $ee/\mu\mu$ final states combined			
7 + 8 TeV (cut-based)	1.1 / 0.9	2.0 / 0.0	$-0.35^{+0.43}_{-0.45}$
7 + 8 TeV (fit to $m_{\ell\ell}$)	1.1 / 1.7	2.1 / 1.3	$0.62^{+0.58}_{-0.47}$

Associated Production VH H →WW

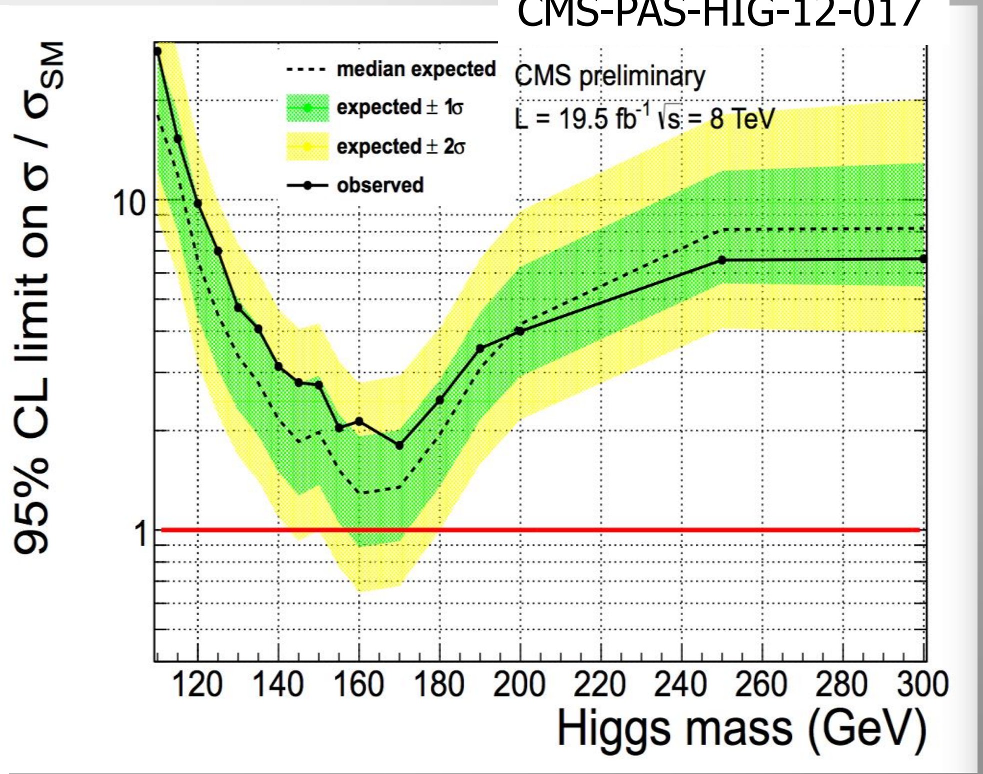
WH → WWW → 3l 3ν

CMS-PAS-HIG-13-009



VH → VWW→2l 2ν + V→jj

CMS-PAS-HIG-12-017



- Three high p_T leptons with moderate missing transverse momentum

- WW analysis cuts plus two central jets

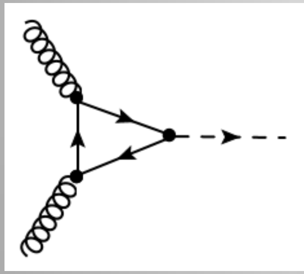
Limited Standard Model Higgs sensitivity (~ 3.5-4•SM at 125 GeV)

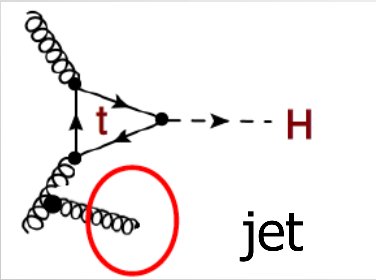
Higgs Decay into Fermions

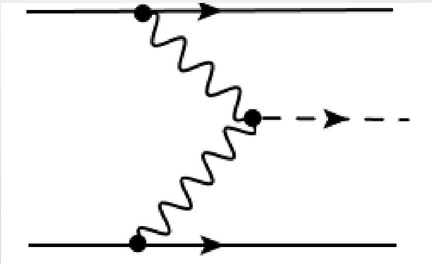
The Decay H $\rightarrow\tau\tau$

Topologies studied

CMS-PAS-HIG-13-004







Inclusive 0-jets	Boosted 1-jet	VBF 2-jets

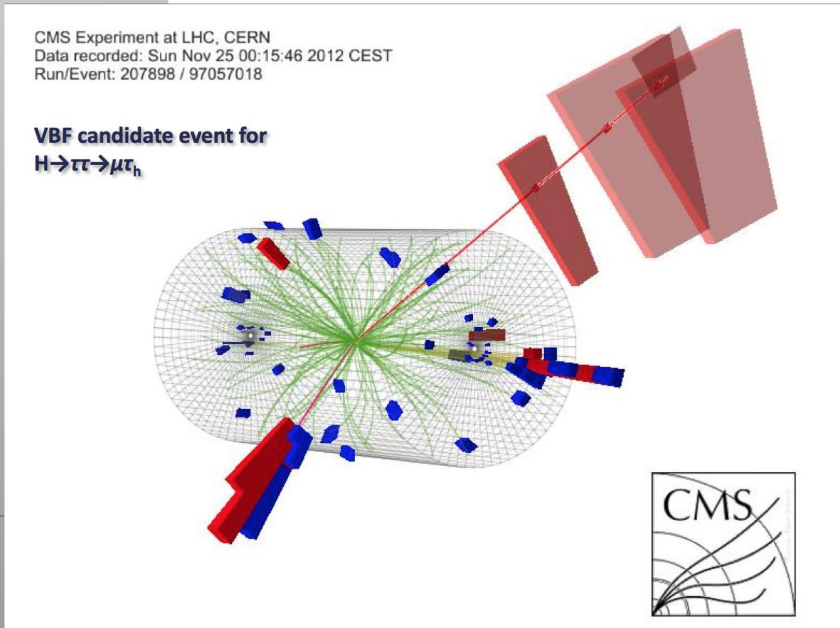
Analysis

- Tau decays to e, μ, τ_{had} used to reconstruct a tau
- Reconstruct corrected $\tau\tau$ invariant mass
- Use many categories to increase the sensitivity

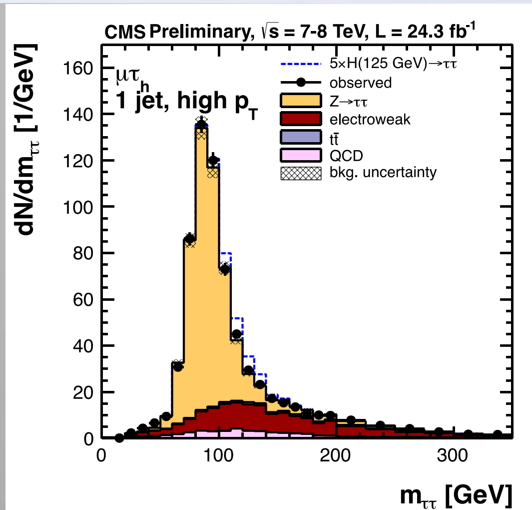
jets with p_T > 30 GeV →

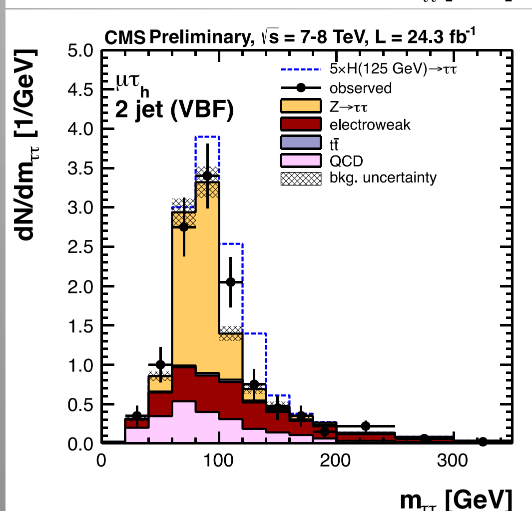
reconstructed tau p_T ↓

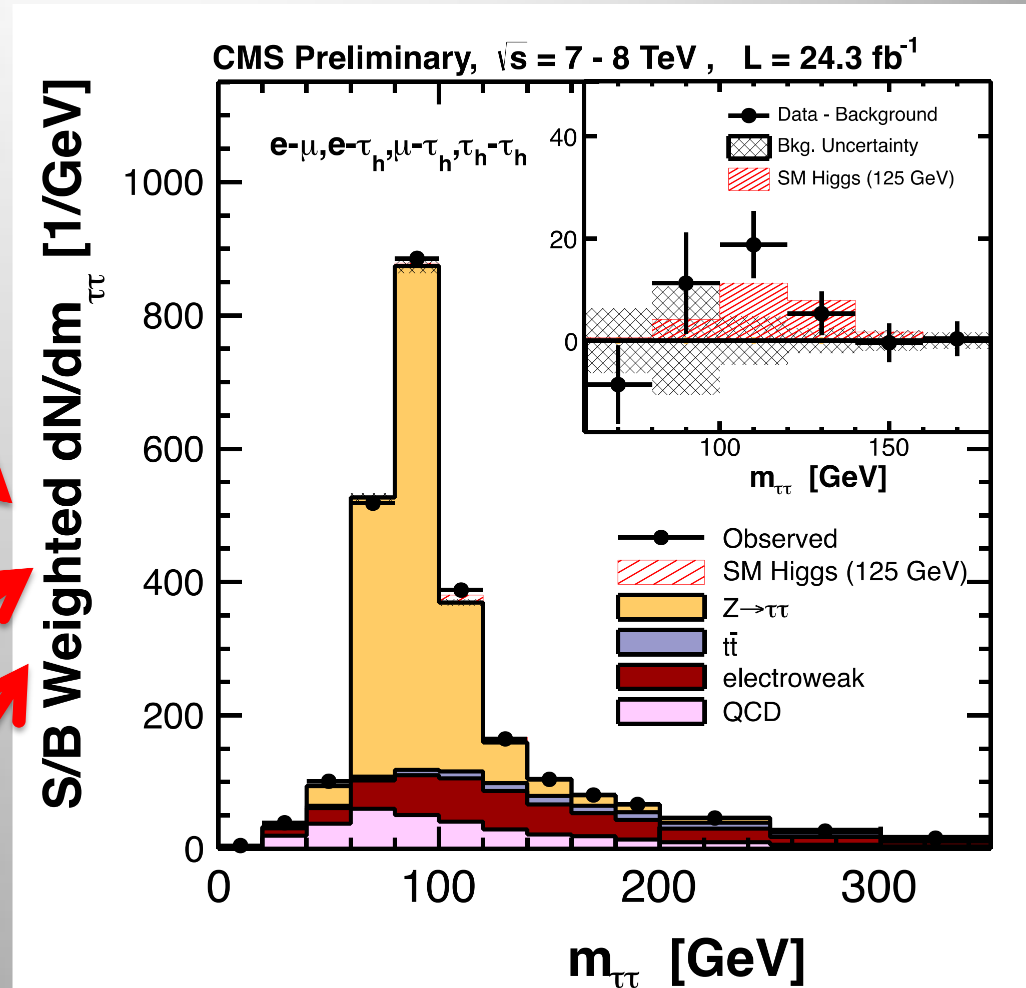
0-jets, low p_T	1-jets, low p_T
0-jets, high p_T	1-jets, high p_T



The Decay H →ττ





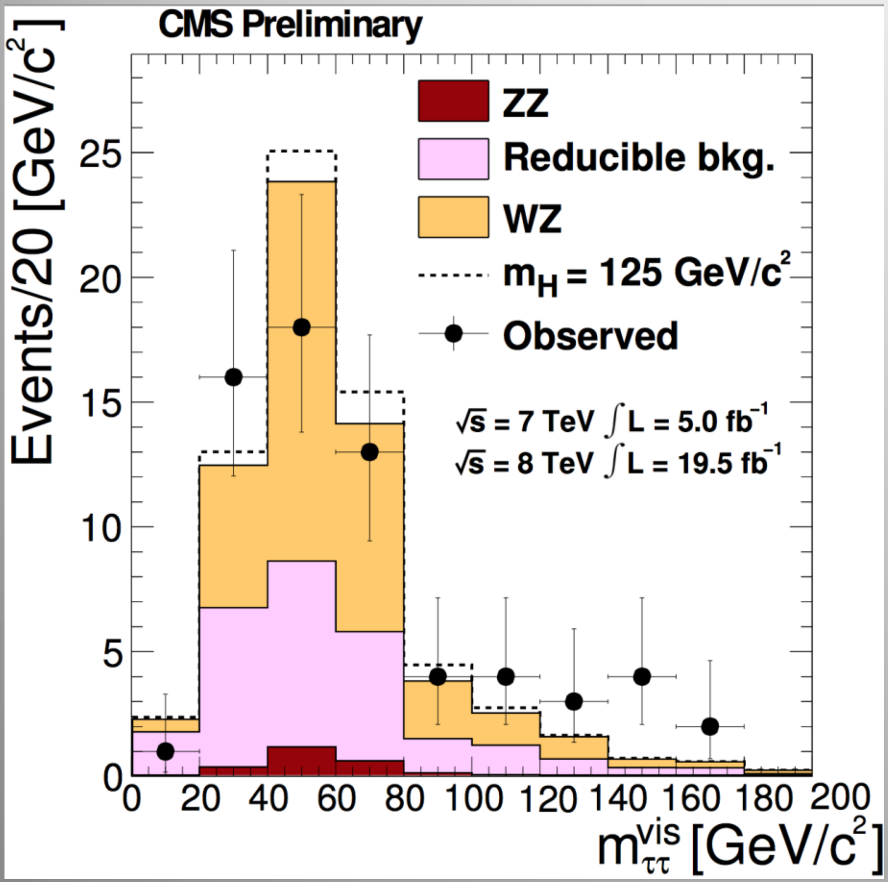


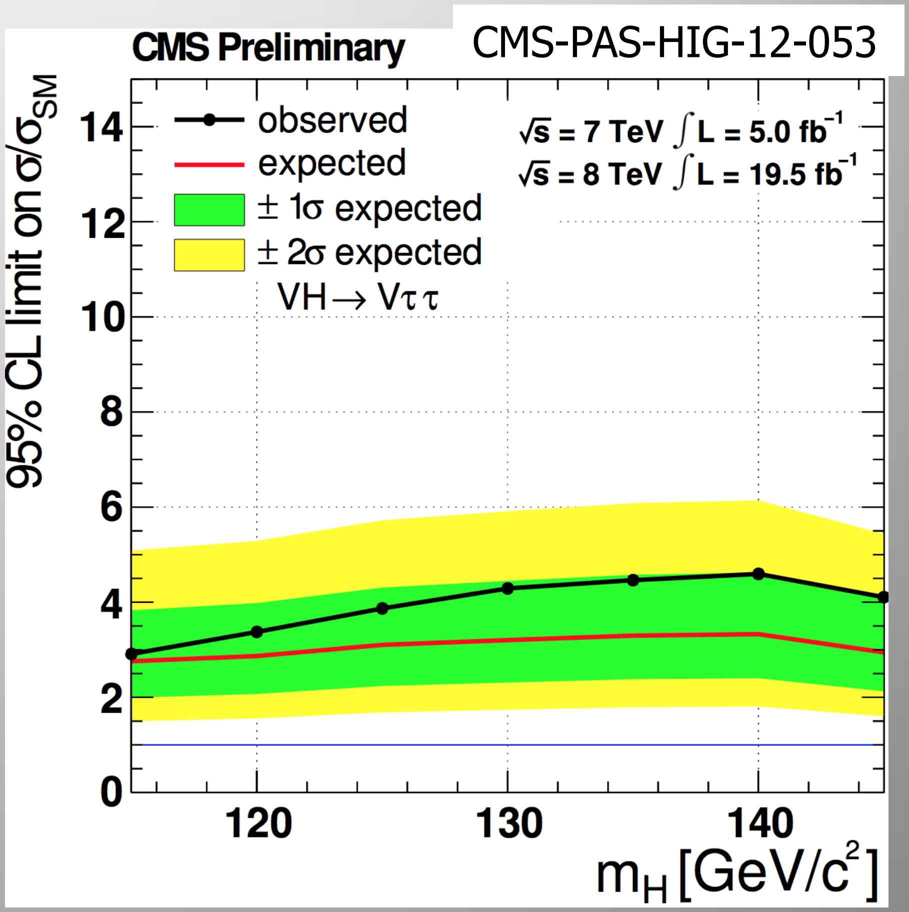
…plus all other tau decay modes: $e\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$

Combine the sensitive categories of all channels with a S/B weight

Associated Production VH → Vττ

- Study topologies of 3 and 4 lepton final states
- Use tau decay channels into electrons muons and hadronic final states

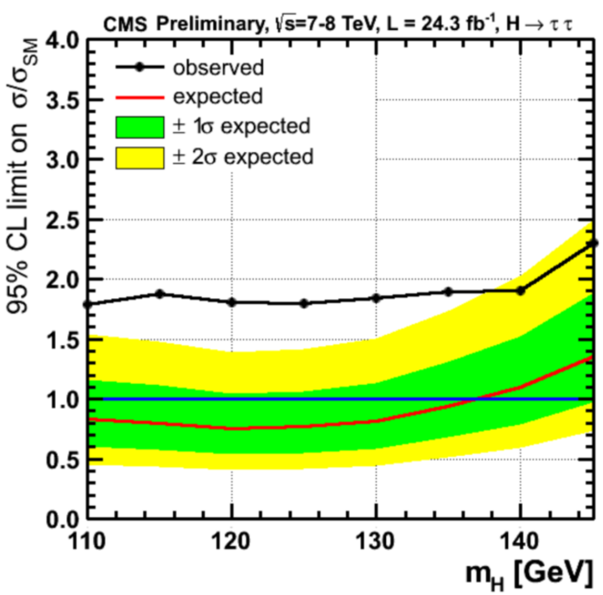


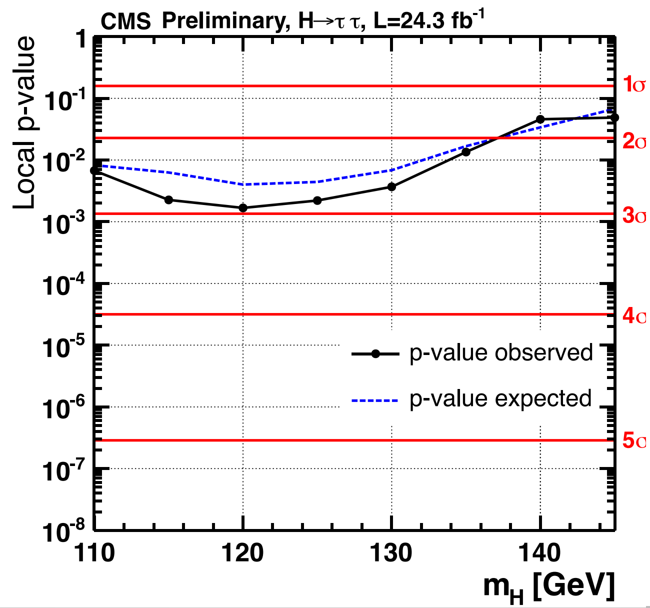


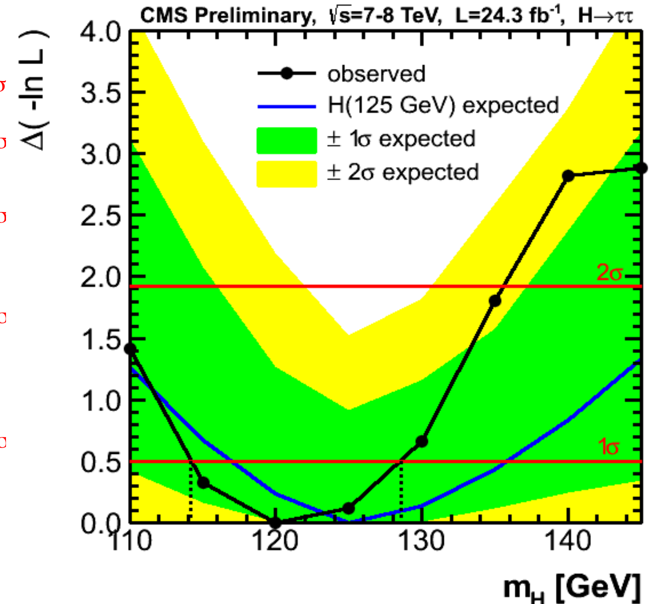
Upper limits of 2.9 to 4.6 times the predicted Standard Model value for σ•BR at 95% CL.

The Decay H $\rightarrow \tau\tau$

Results include also the VH channels







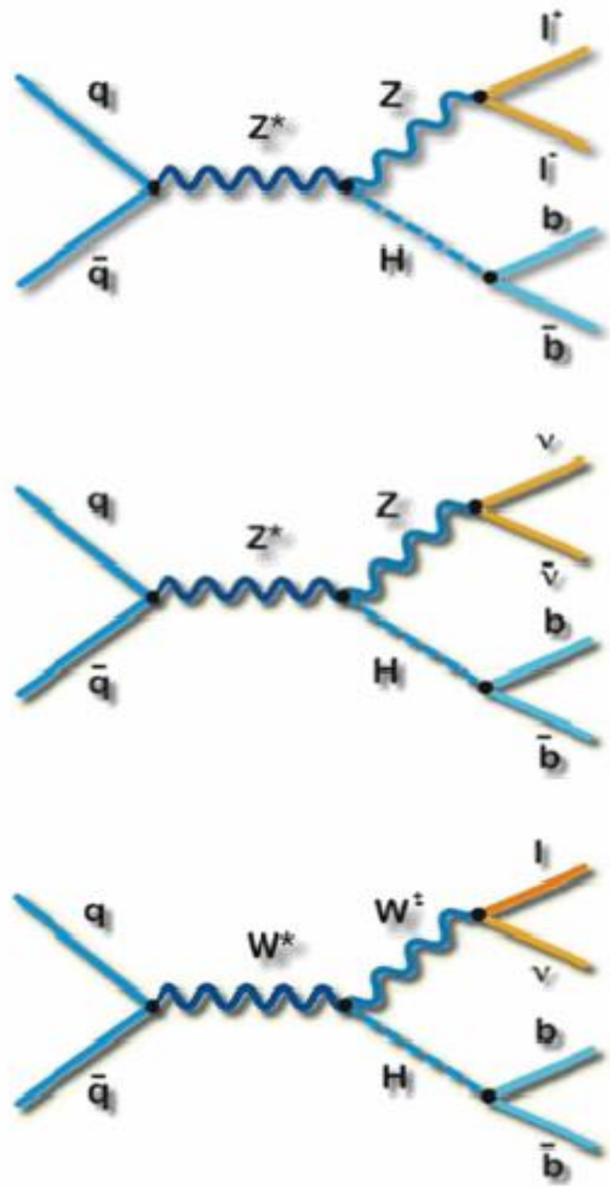
Significance:
2.93σ for m_H = 120 GeV
2.85σ for m_H = 125 GeV

Signal strength
$\mu = 1.1 \pm 0.4$

Mass: all $\tau\tau$ channels combined
$m_H = 120^{+9}_{-7}$ (stat+syst) GeV

Excess building up in the region 120-130 GeV

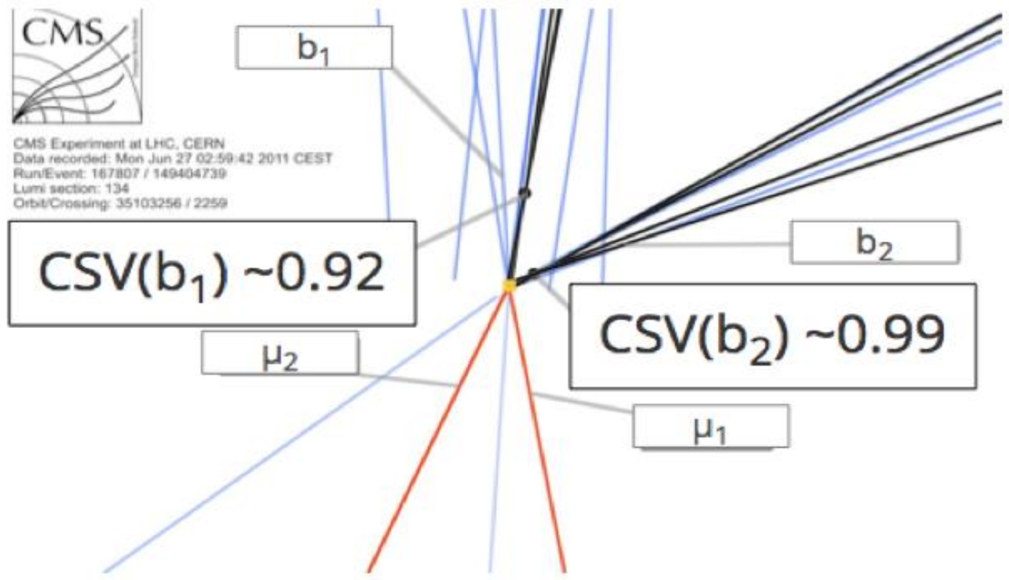
The Decay H→bb



CMS-PAS-HIG-13-012

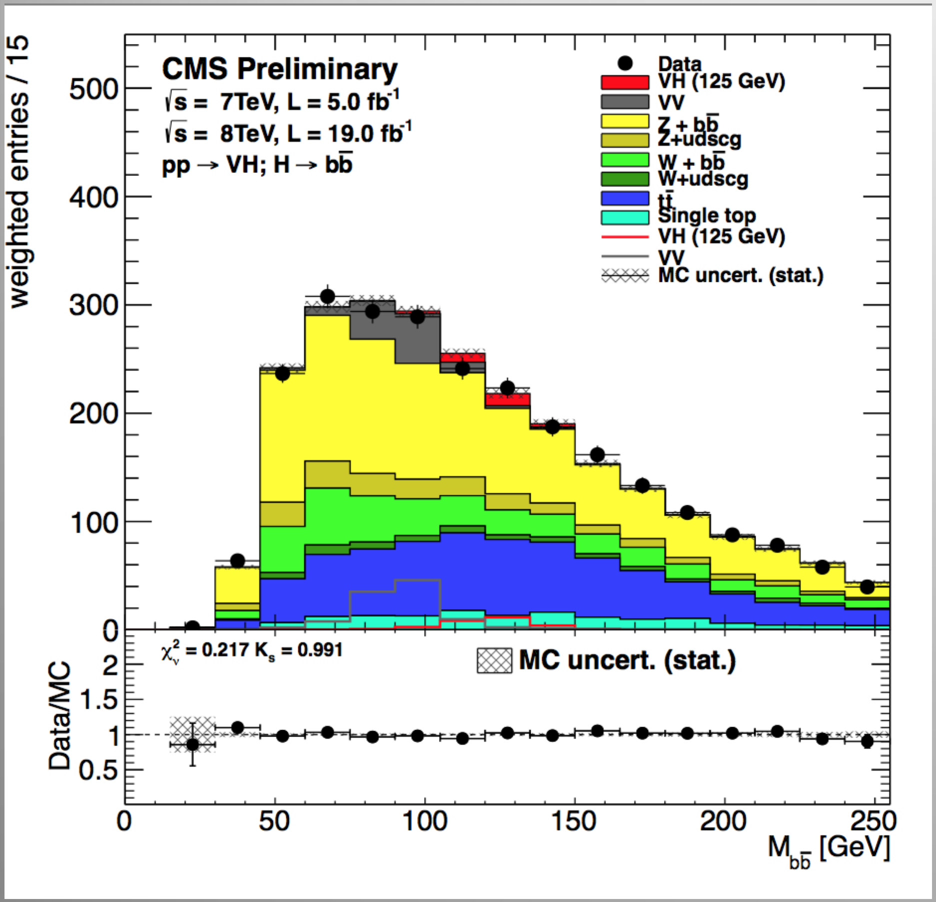
Analysis

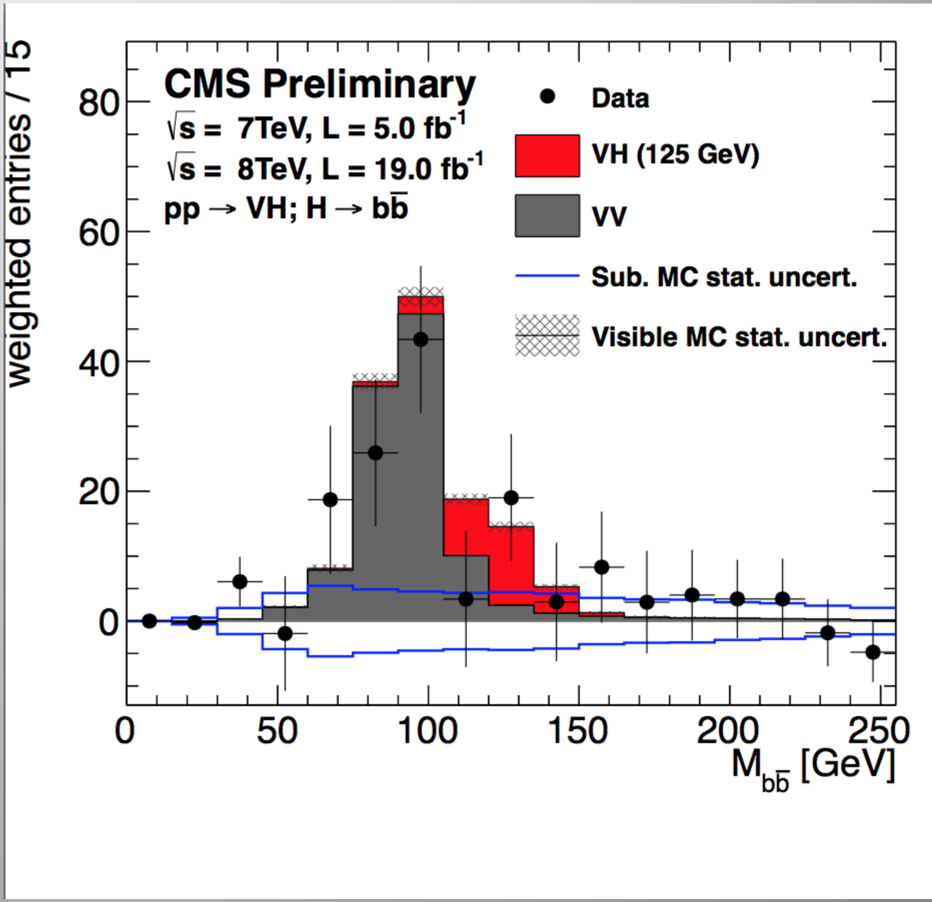
- •By far largest number of Higgs decays
- •But lots of QCD background (jets)
- •Trigger based on leptons and missing E_T
- •b-jets identified through displaced tracks
- •Go to high p_T where Higgs is enhanced
- •Main background W/Z+jets and top



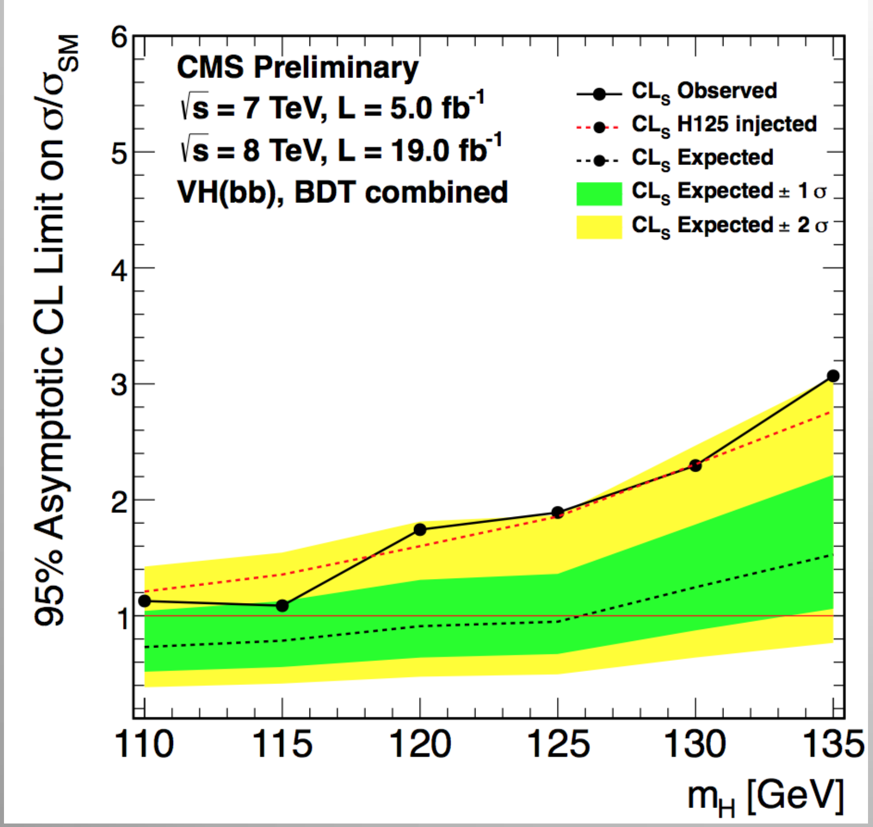
The Decay H→bb

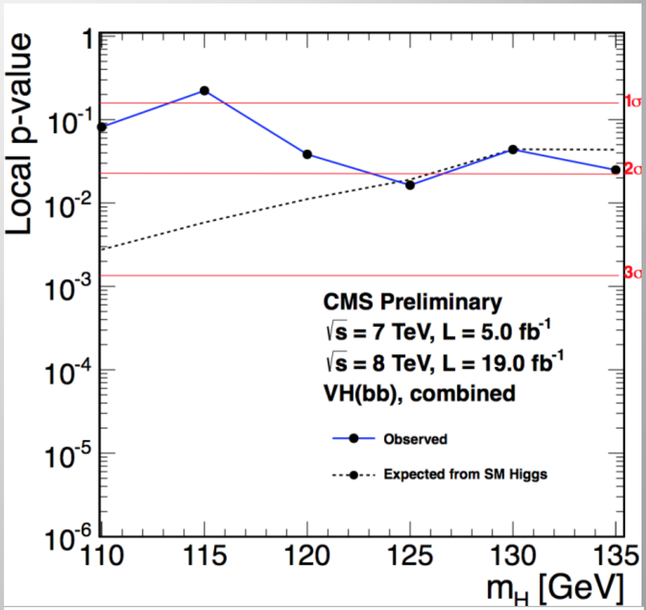
M_{bb} for all categories and 7+8 TeV

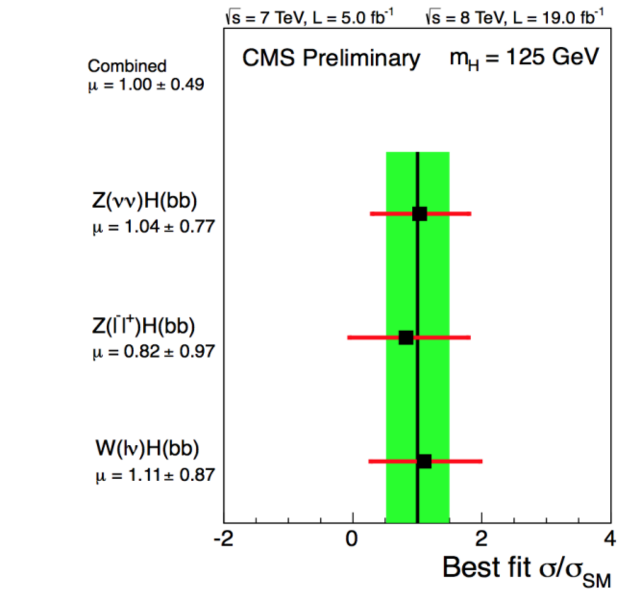




The Decay H→bb





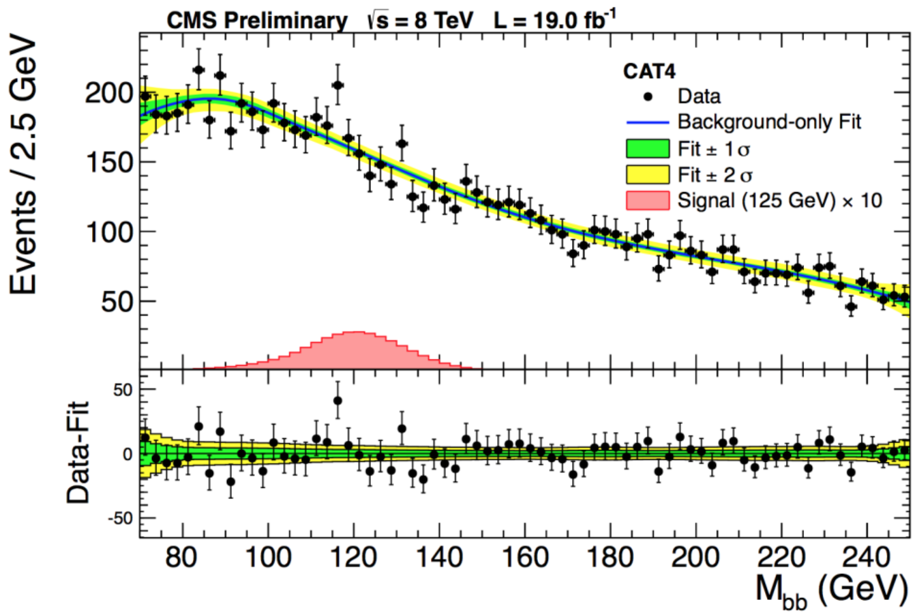


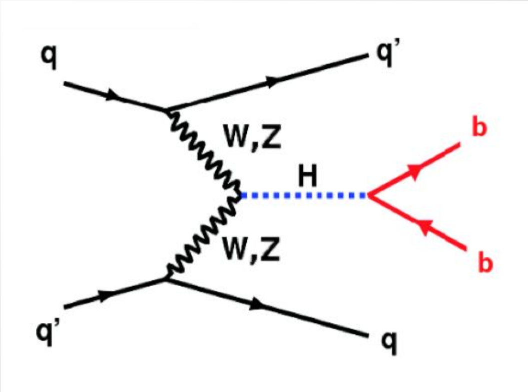
For 125 GeV:

- Significance = 2.1σ (2.1σ expected)
- Signal strength μ = 1.0± 0.5

Mild excess observed in data.

VBF Process with H→bb

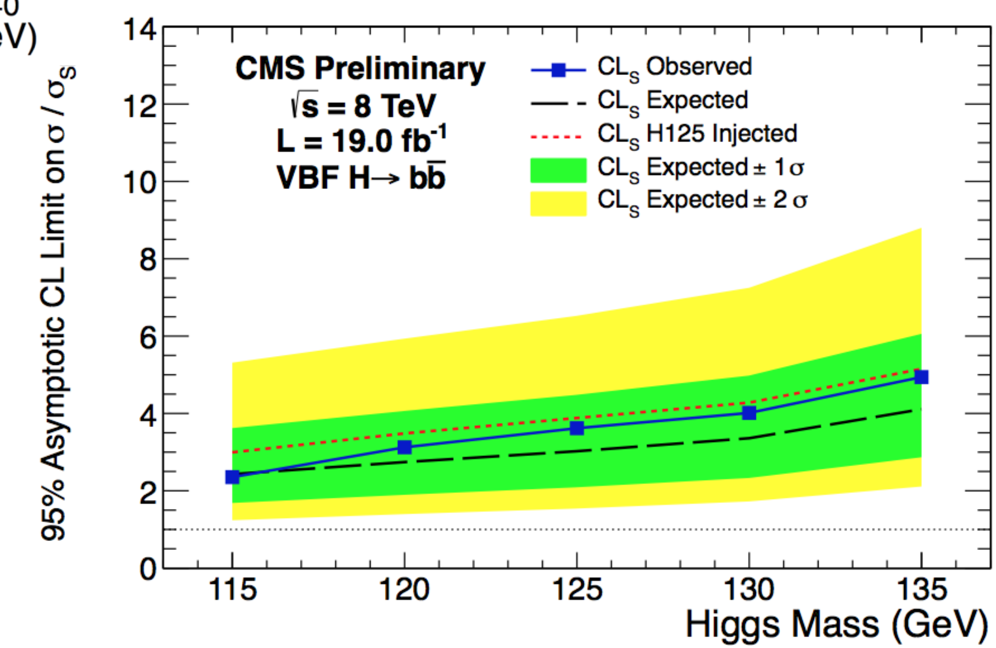




bb event + ≥ 2 non-b jets at large Δη

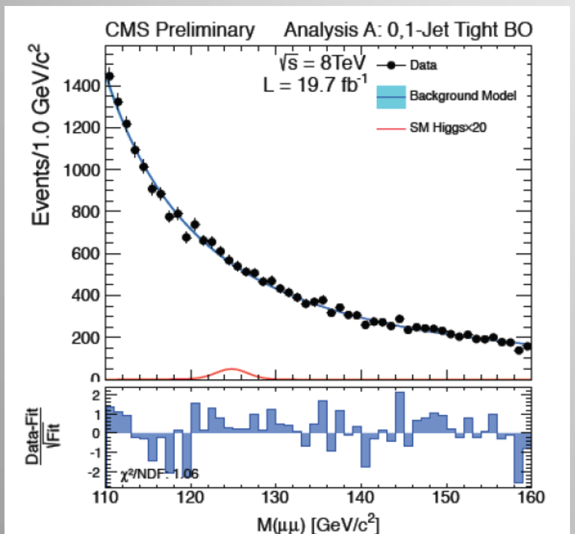
CMS-PAS-HIG-13-011

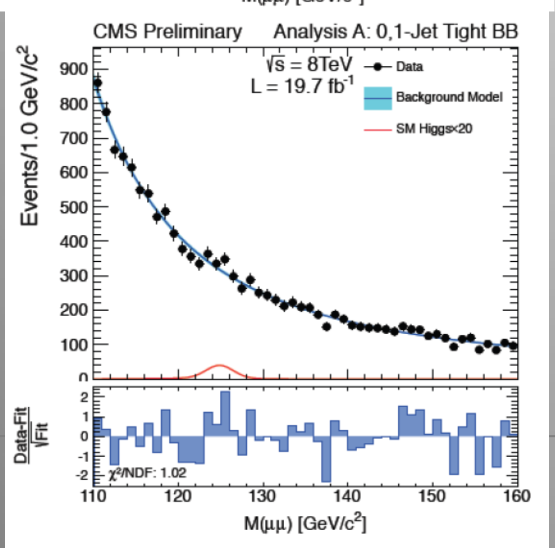
At 125 GeV the upper limit on σ•BR = 3.6•SM (3.0 exp.)

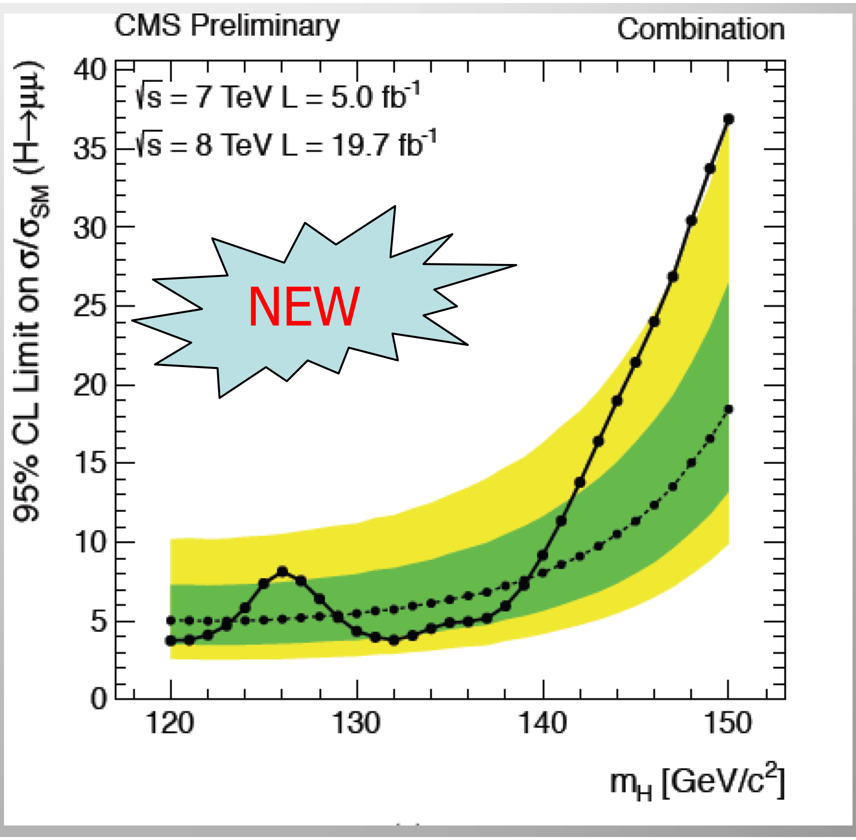


New: Higgs Decay into two muons

We do not expect to see any signal yet in this channel if it is really a Higgs particle that we have found





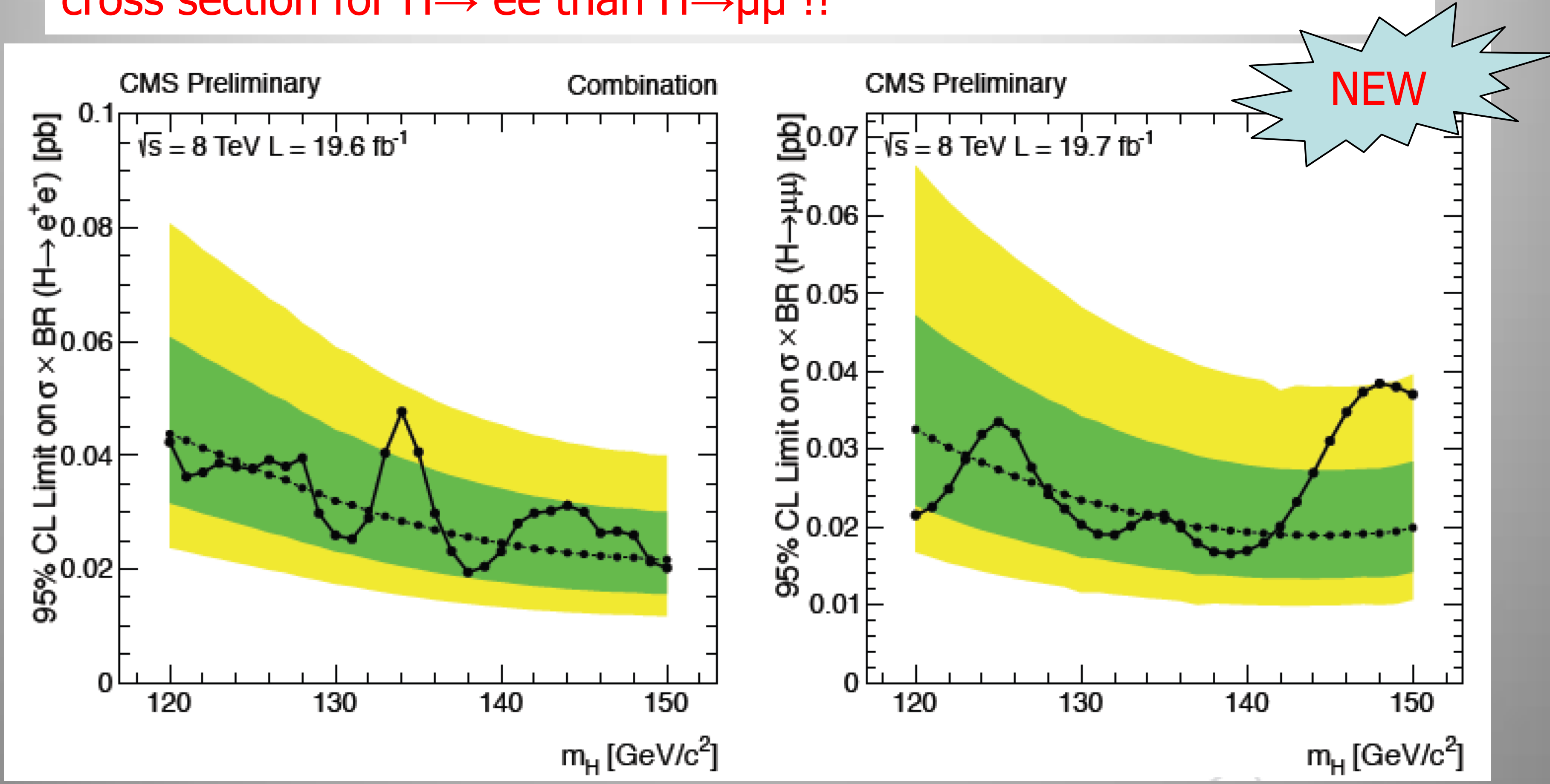


No significant excess observed

- Limits at 125 GeV 7.4 (5.1) observed (expected)
- Excess at 125 GeV is 1.1σ
- Excess at high mass -148 GeV- is 2.3σ(0.8 with LLE)

Higgs Decay into two Electrons

This is even less expect to to be observed: about 4000 times lower cross section for H→ ee than H→μμ !!



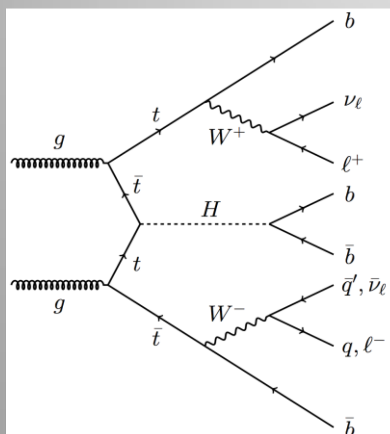
No significant excess observed

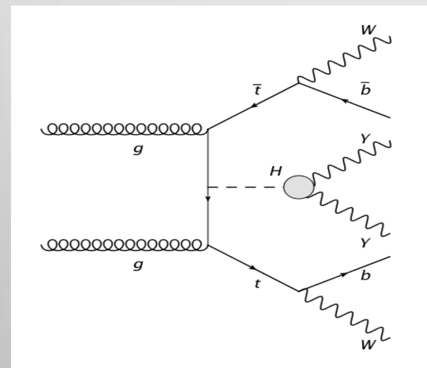
- Limits No signal at 125 GeV, as expected
- Sensitivity in ee and μμ channel very similar

Higgs Associated with Top Production

Direct measurement of top-Higgs coupling

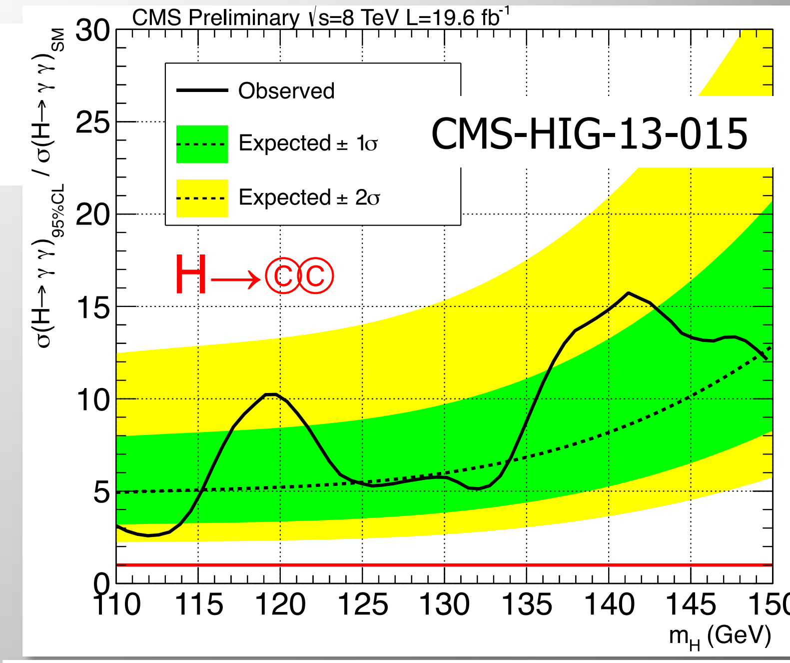
Channels studied H→©© and H→bb+ | |

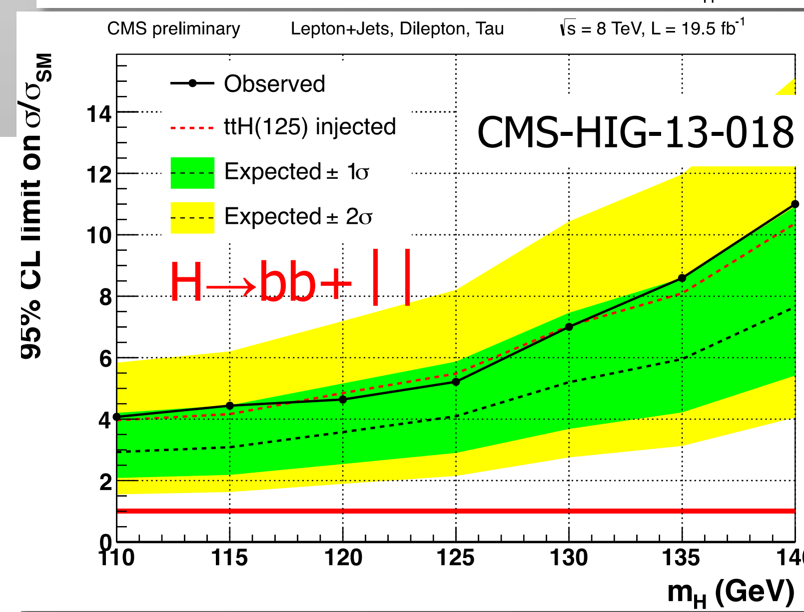




Select top events with additional Higgs

- A recent result in ttH(©©) channel
  - μ < 5.4 (5.3 exp.) @ 95% CL, m_H = 125 GeV
- New ttH(bb+ | |) results:
  - μ < 5.2 (4.1 exp.) @ 95% CL, m_H = 125 GeV



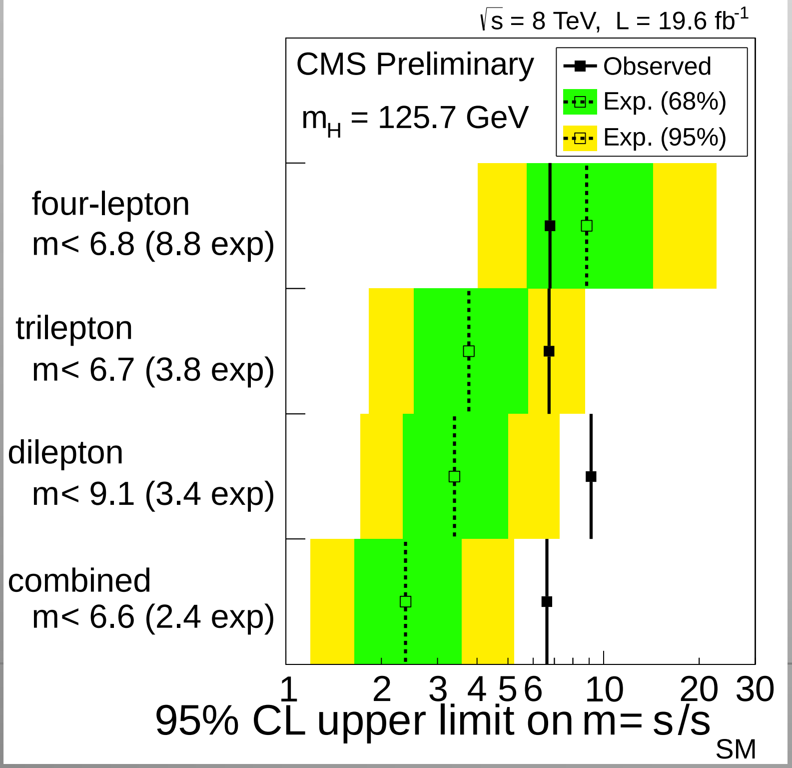


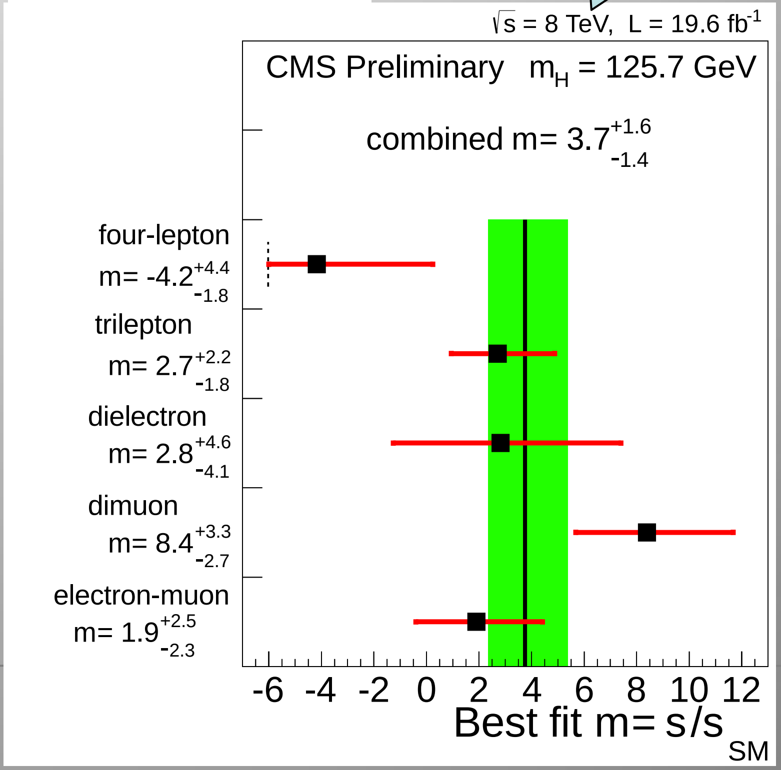
Higgs Associated with Top Production

- New analysis exploring various top and Higgs decays resulting in like-sign di-lepton, tri-lepton, and quadri-lepton final states ($H \rightarrow WW$ etc…)
- An excess (~2.5σ) seen in like-sign dimuons has been extensively scrutinized and shown to have all the features of a statistical fluctuation
- Overall consistency with the SM: 3%

NEW

CMS-HIG-13-020

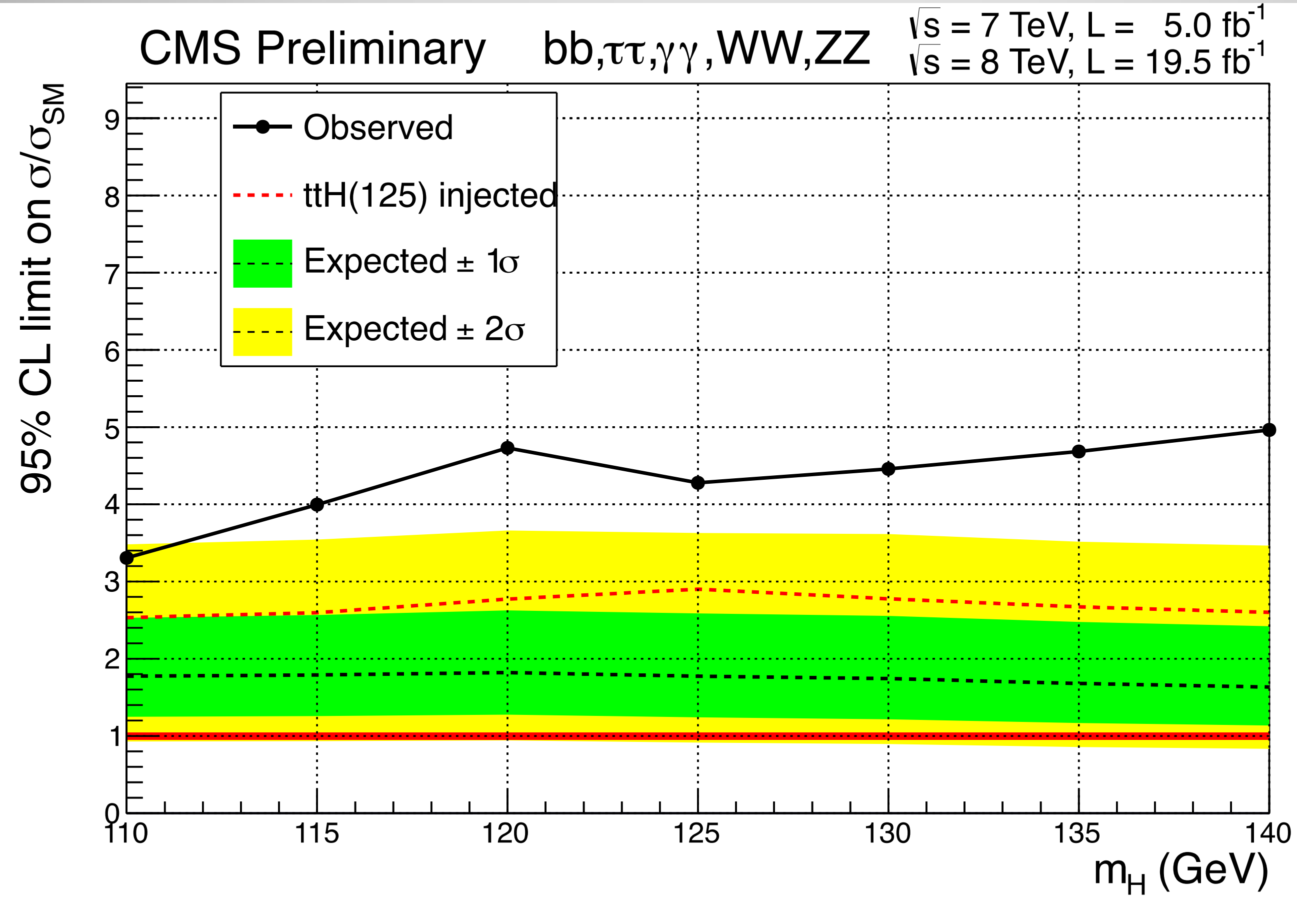




All Channel ttH Combination

- All channels combined
- Impressive expected sensitivity μ < 2!

Excess is driven by the di-muon excess in the multi-lepton analysis



Sensitivity is between 1 and 2 times the SM Expectation!

Channel Combination & Higgs Properties

April 2013 Combination

Since fall 2012 we have been especially concentrating on measurements of properties of the new particle

Summary of the Five Main Channels

For a mass of m_H = 125.7 GeV

CMS-PAS-HIG-13-005

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

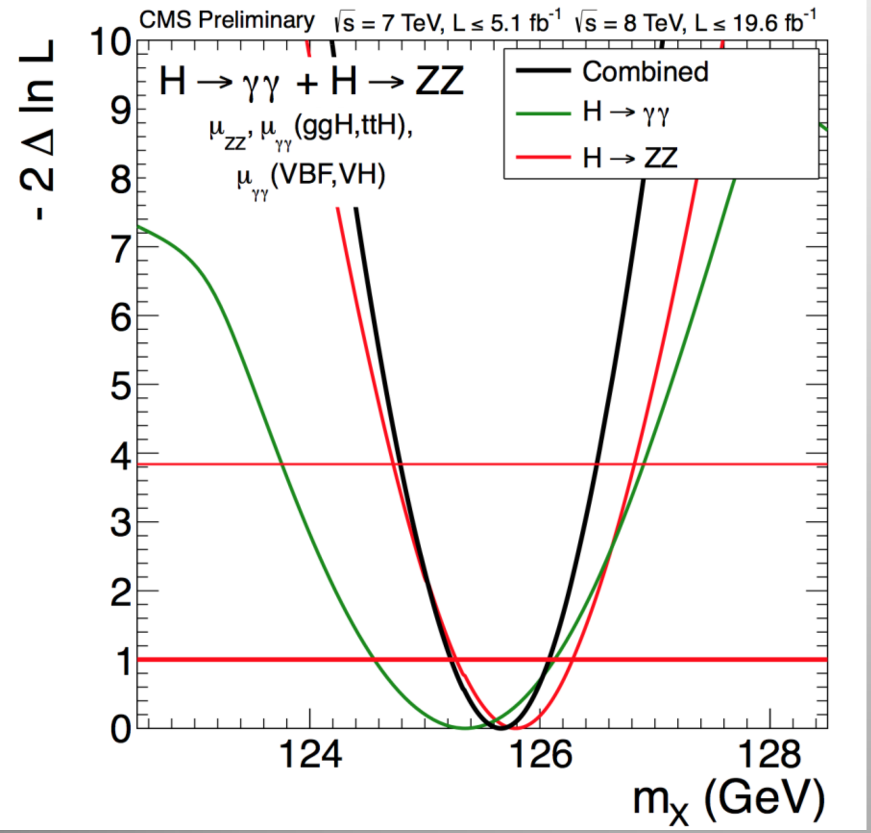
bb and ττ: 3.4 σ combined!

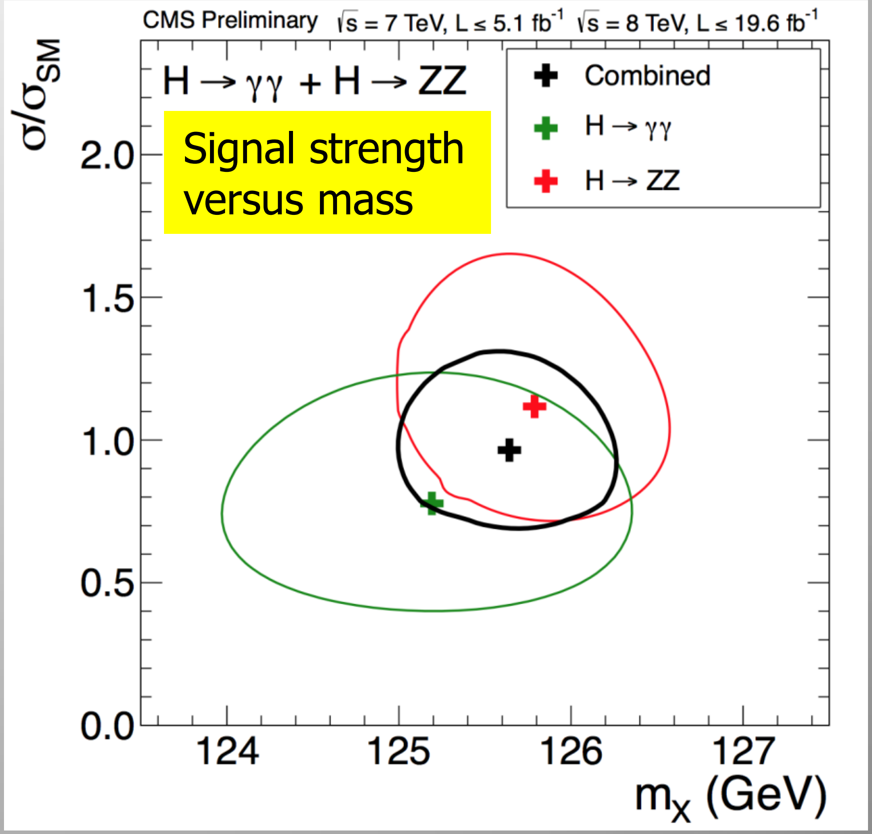
bb: includes VH and VBF
WW: includes ggF, VH, VBF

Mass of the New Particle

H →ZZ→4l: m_H = 125.8 ± 0.5 (stat.) ±0.2 (syst.) GeV

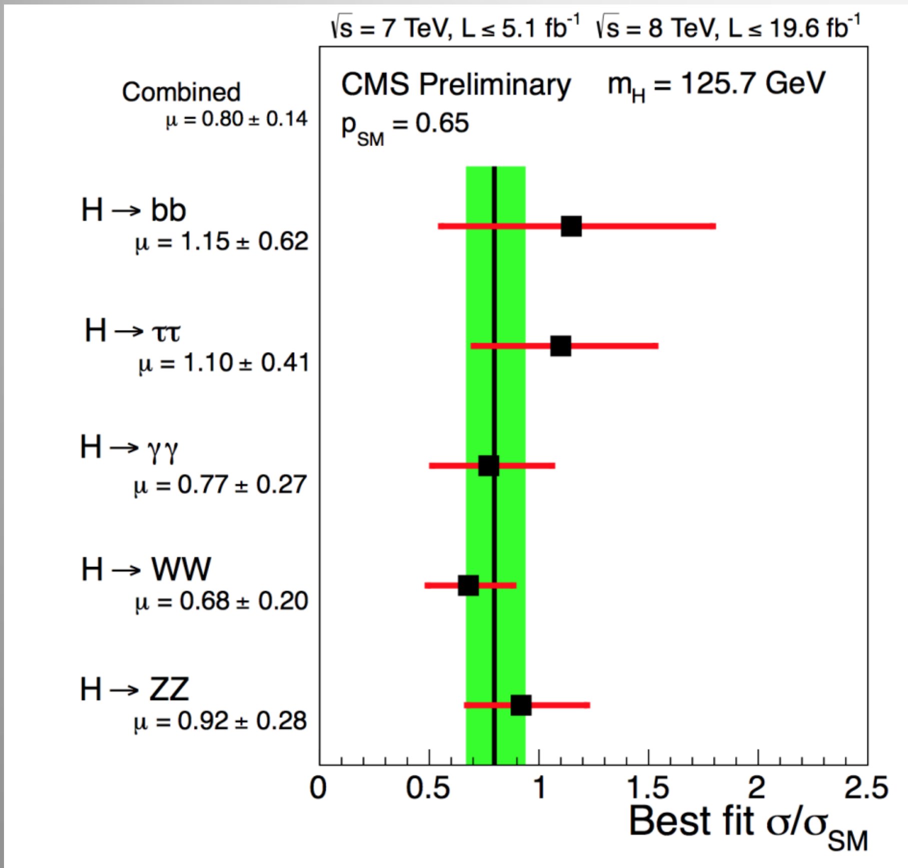
H →γγ: m_H = 125.4 ± 0.5 (stat.) ±0.6 (syst.) GeV

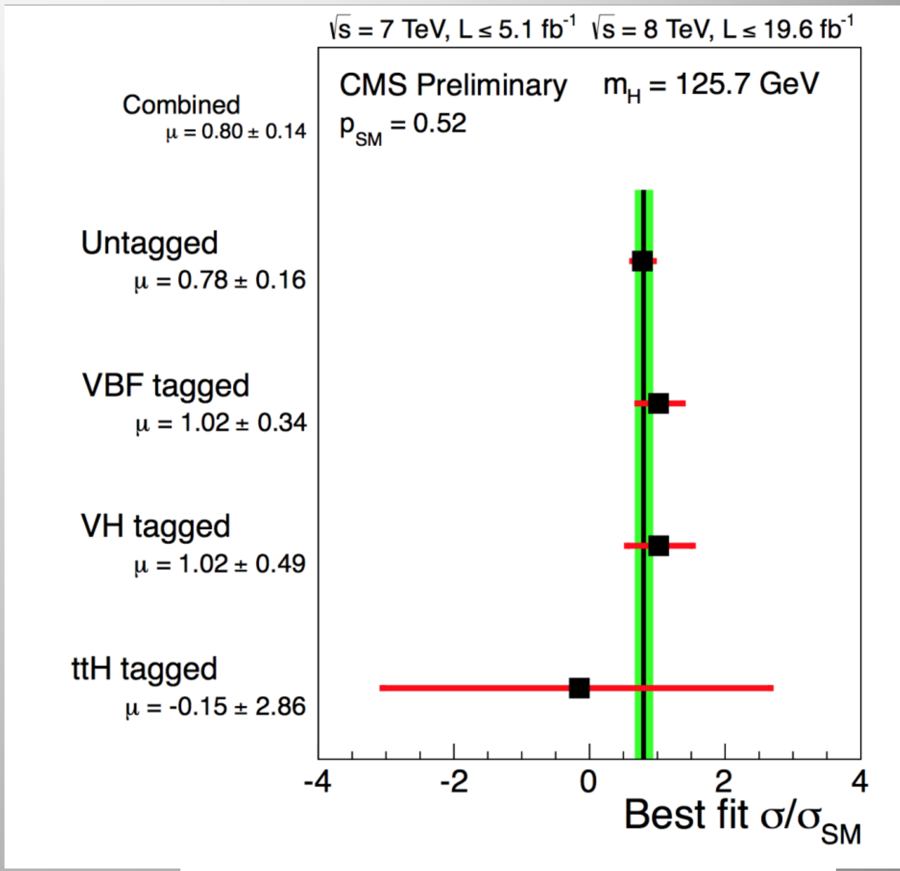




$$m_H = 125.7 \pm 0.3^{(stat)} \pm 0.3^{(syst)}\ \text{GeV}$$
$$= 125.7 \pm 0.4\ \text{GeV}$$

Consistency with SM Hypothesis





p-value= 0.65 w.r.t. μ=1

p-value= 0.52 w.r.t. μ=1

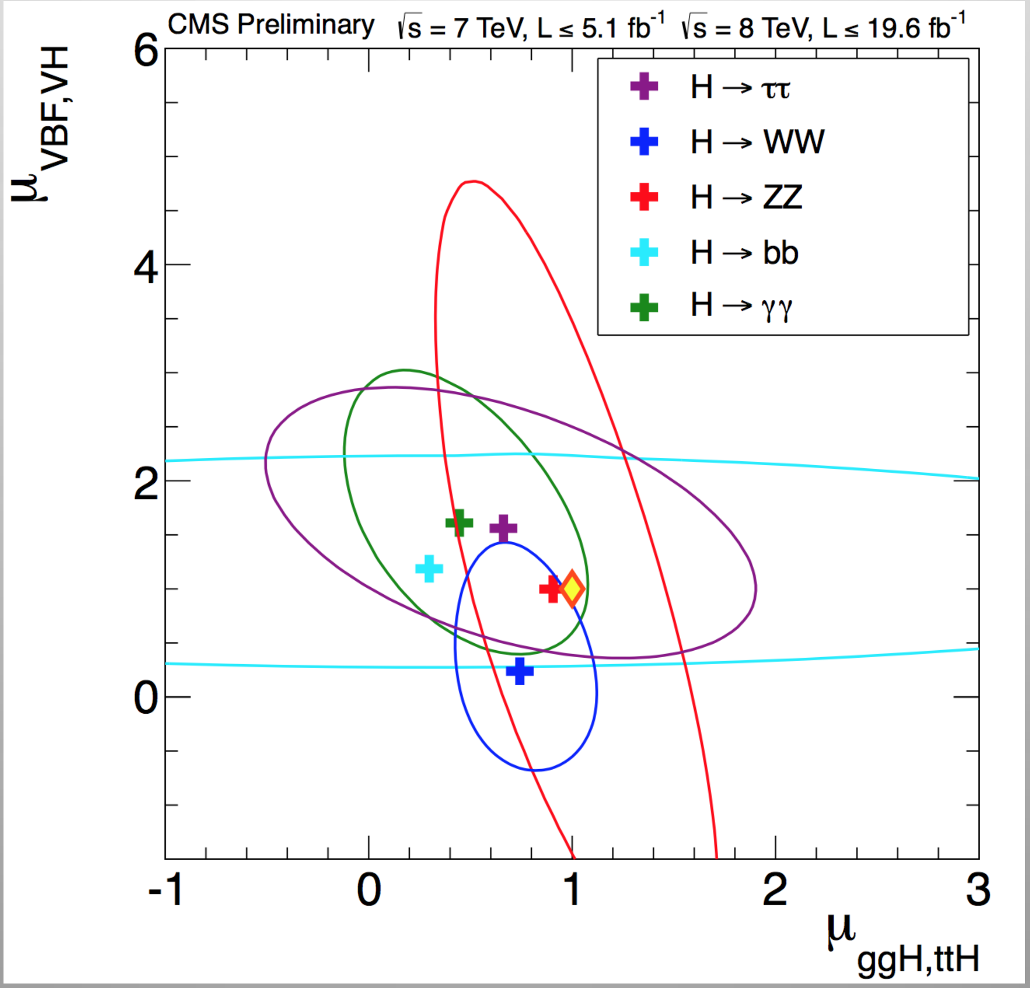
Combined signal strength: μ=0.80±0.14

Here and further: bb results based on 12 fb^{-1} at 8 TeV and 5 fb^{-1} at 7 TeV

Consistency with SM Hypothesis

2-dimensional view: test production modes in the various decay modes

Vector Boson Couplings

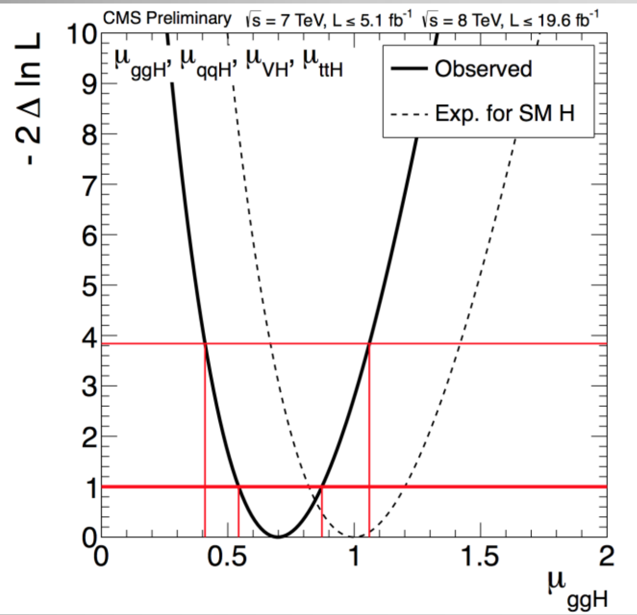


Fermion Couplings

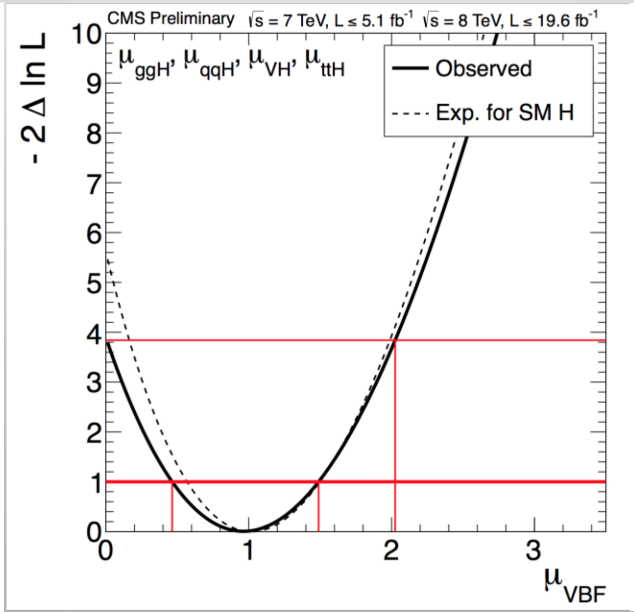
Signal Strength for Different Modes

Likelihood scans versus the different μ values, using all decay modes

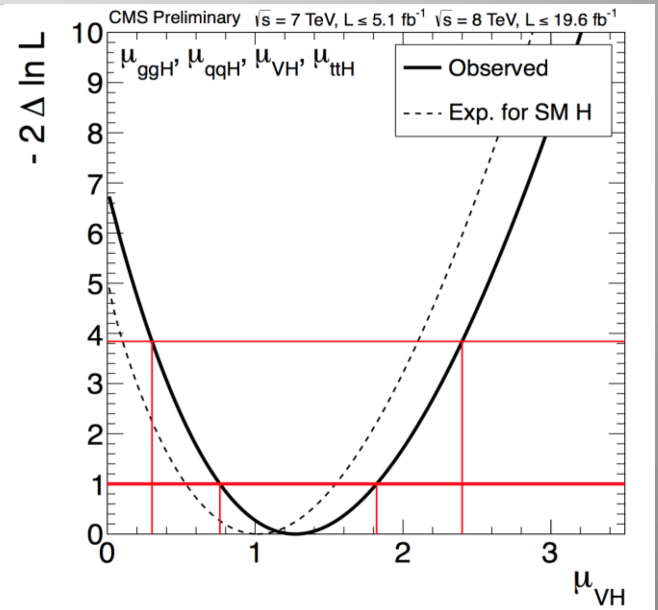
Gluon Gluon Fusion



Vector Boson Fusion



Associated production



Data in good agreement with the expectation

Approximately a 2σsignificance for the VBF channel

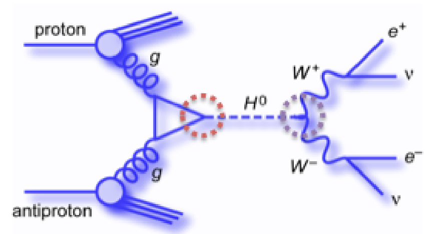
Couplings to Fermions and Bosons

Couplings scaled by κ_X:

Hff: κ_f *HVV:* κ_V

HWW: κ_W $\lambda_{WZ} = \kappa_W / \kappa_Z$

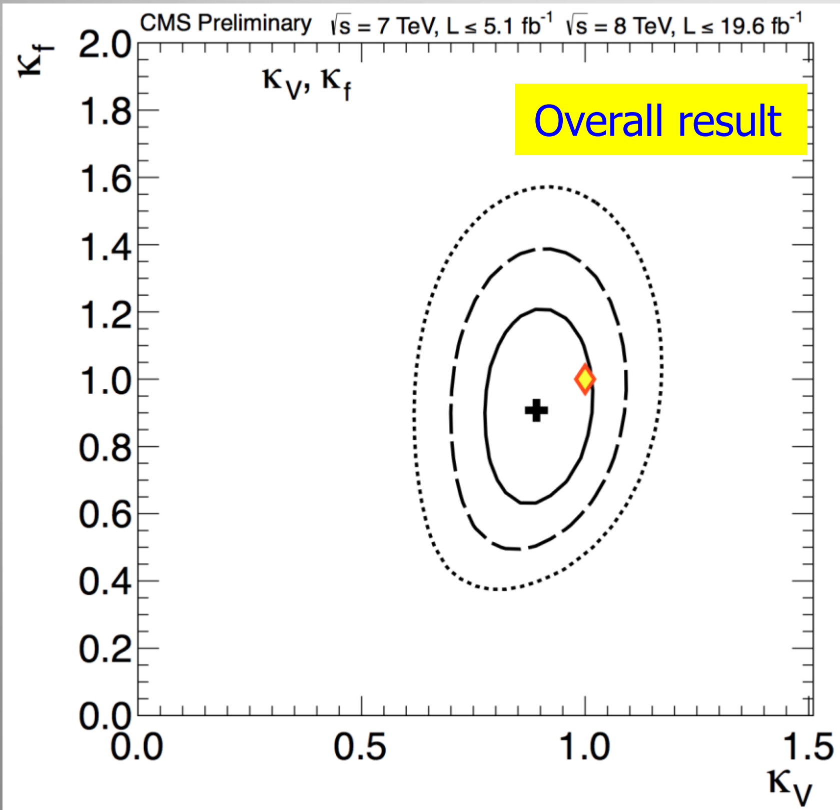
HZZ: κ_Z *In SM,* $\kappa_X = 1$



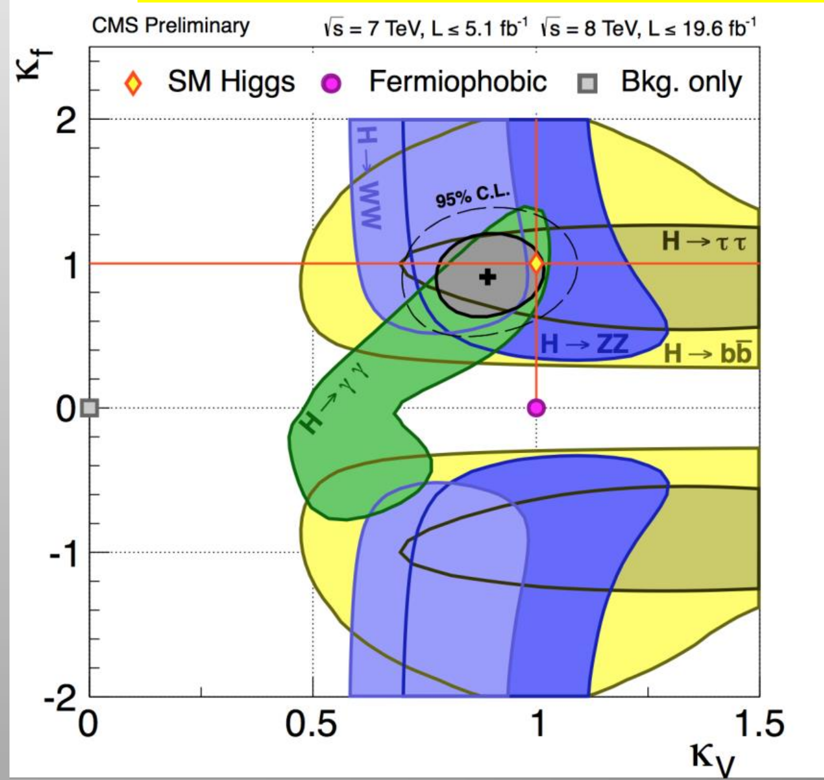
For m_H = 125.7 GeV

$\Gamma(H \rightarrow \gamma\gamma) \sim |\alpha\, \kappa_V + \beta\, \kappa_f|^2$

$\alpha/\beta = -0.2$, $\Gamma_{BSM} = 0$

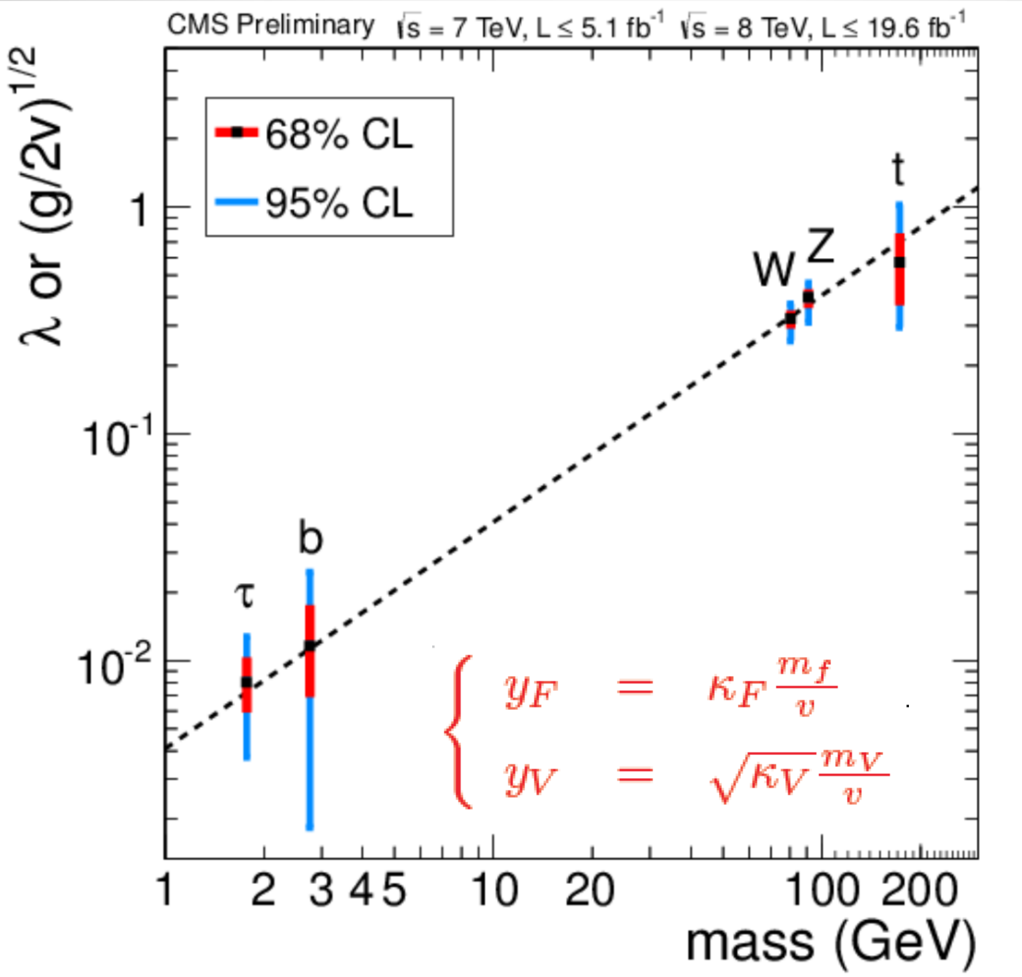


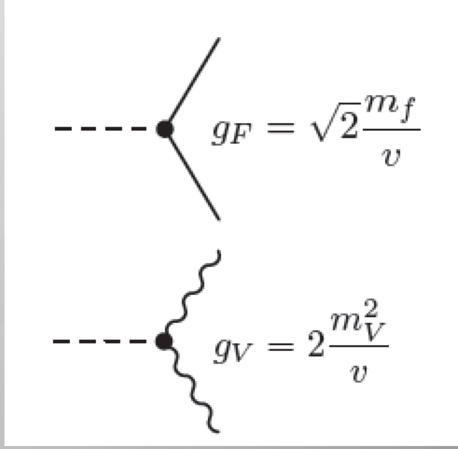
Contributions from all decay channels



Results within 1σ of the Standard Model Prediction

Summary of the Couplings Test



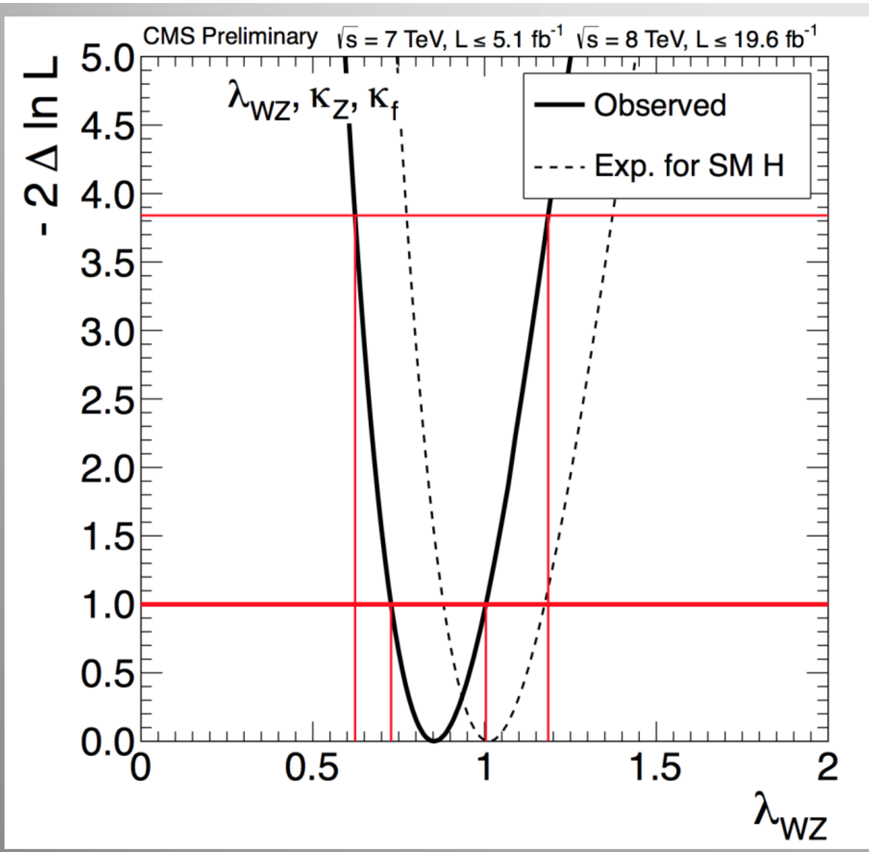


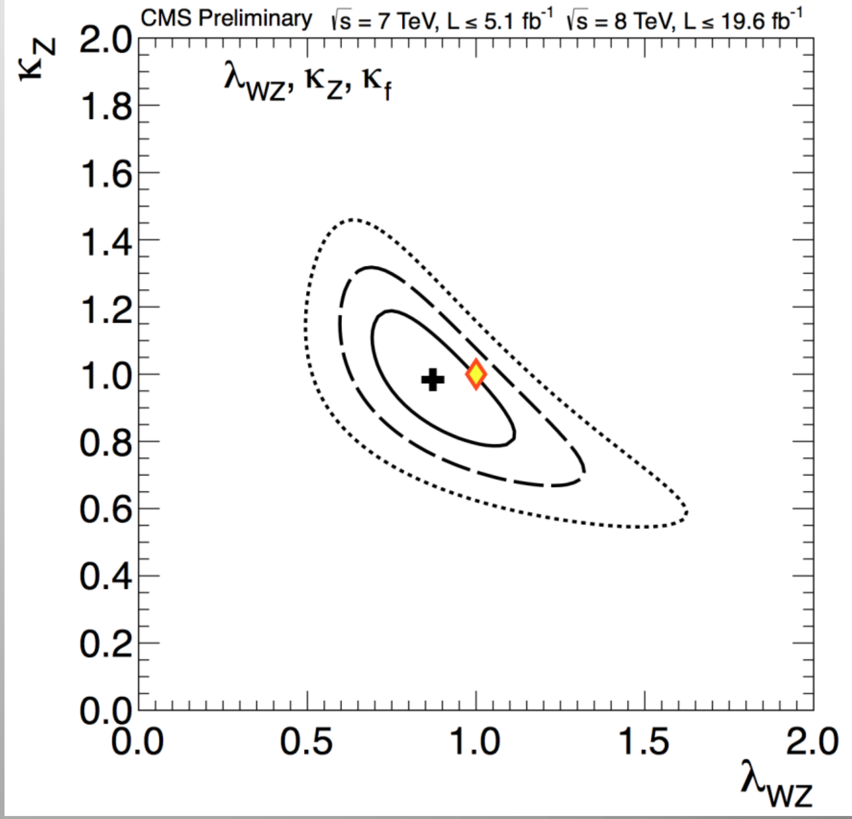
For the fermions, the values of the fitted yukawa couplings are shown, while for vector bosons the square-root of the coupling for the hVV vertex divided by twice the vacuum expectation value of the Higgs boson field. _

Custodial Symmetry Test

Modify the SM Higgs boson couplings to the W and Z bosons introducing two scaling factors κ_W and κ_Z and perform combinations to assess if

$$\lambda_{WZ} = \kappa_W/\kappa_Z = 1 \qquad \text{for } m_H = 125.7 \text{ GeV}$$



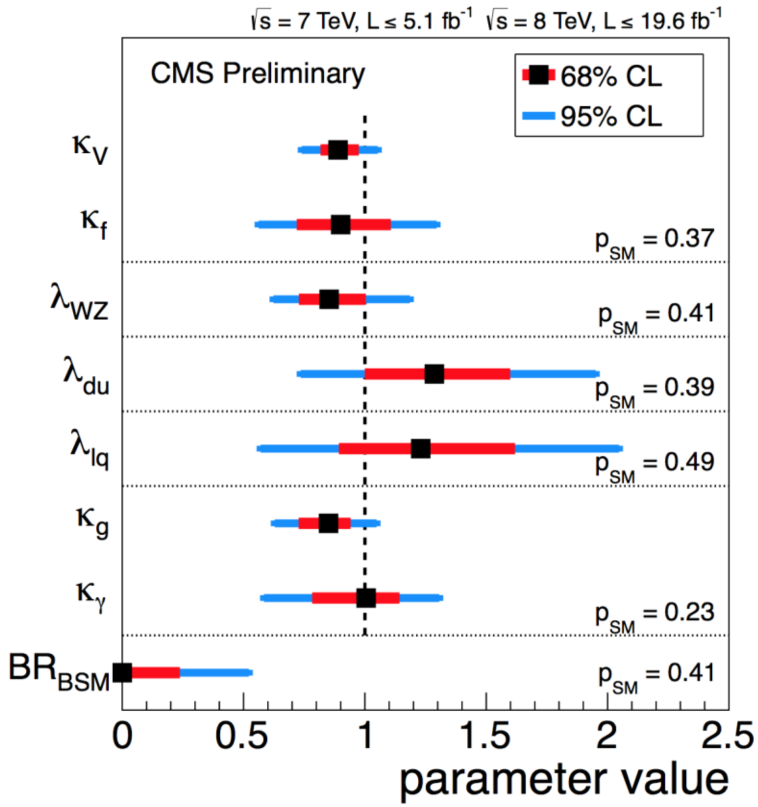


95% CL interval for λ_{WZ} : [0.62,1.19]

Summary of the Couplings Test

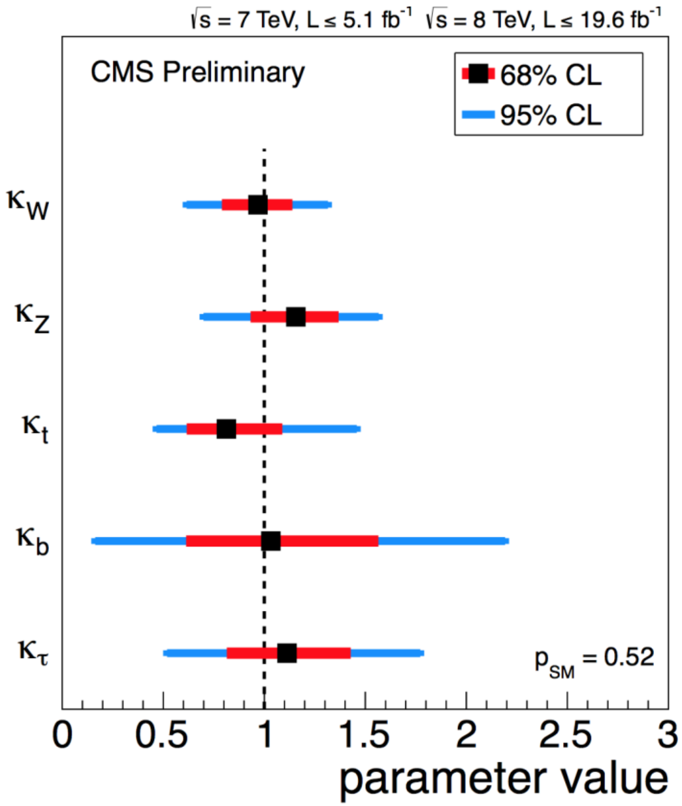
Summary of the fits for deviations in the couplings

for a LHC XS WG benchmark model parametrisation (arXiv:1209.0040)



$\Gamma_{BSM} = 0$

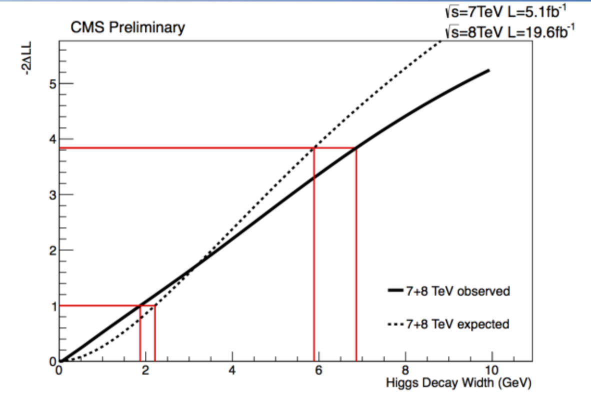
for a generic five parameter model (no eff. loop couplings)



The best fit values of the most interesting parameters are shown, with the corresponding 68% and 95% CL intervals, and the overall p-value p_{SM} of the SM Higgs hypothesis is given.

Higgs Properties from H→γγ

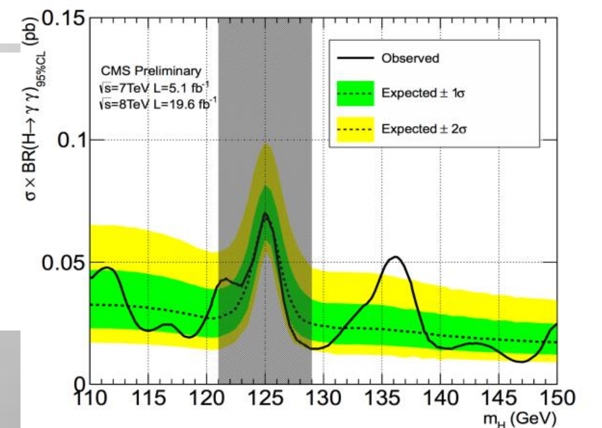
CMS-PAS-HIG-13-016



Upper limit on the Higgs width

- Dominated by experimental resolution
- Breit-Wigner + Gaussian fit
- Observed (exp) upper limit = 6.9 (5.9) GeV 95% CL

Use interference? arXiv:1305.3854 & more

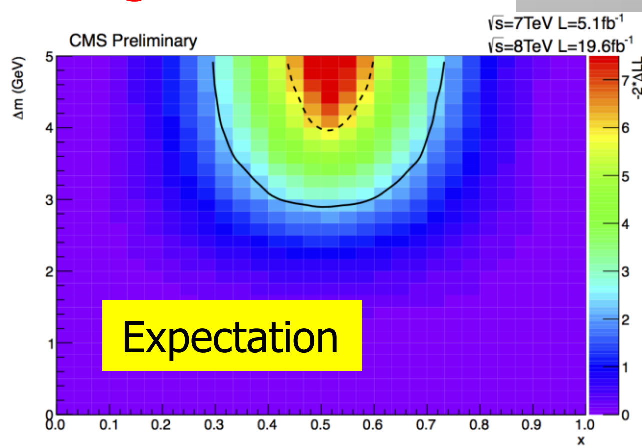


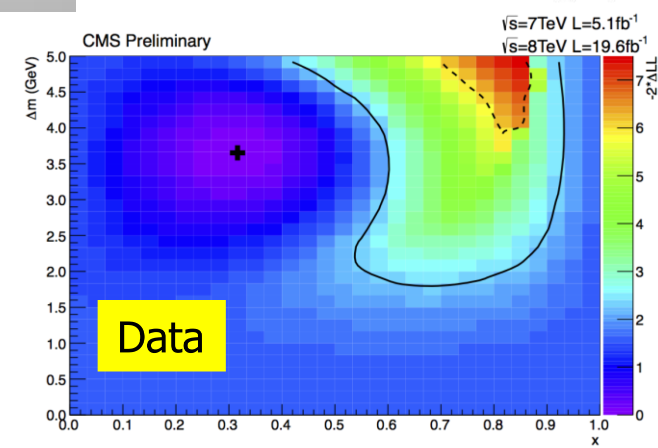
Additional Higgs-like states:

- Take SM 125 GeV as part of the background
- Search for additional Higgses
- Largest excess: 136.5 GeV with 2.9σ(<2σ after LEE)

Search for near mass degenerate states

- Two signals with relative strength x mass difference Δm
- Perform a 2D scan
- No signal at 95% CL for Δm> 4 GeV

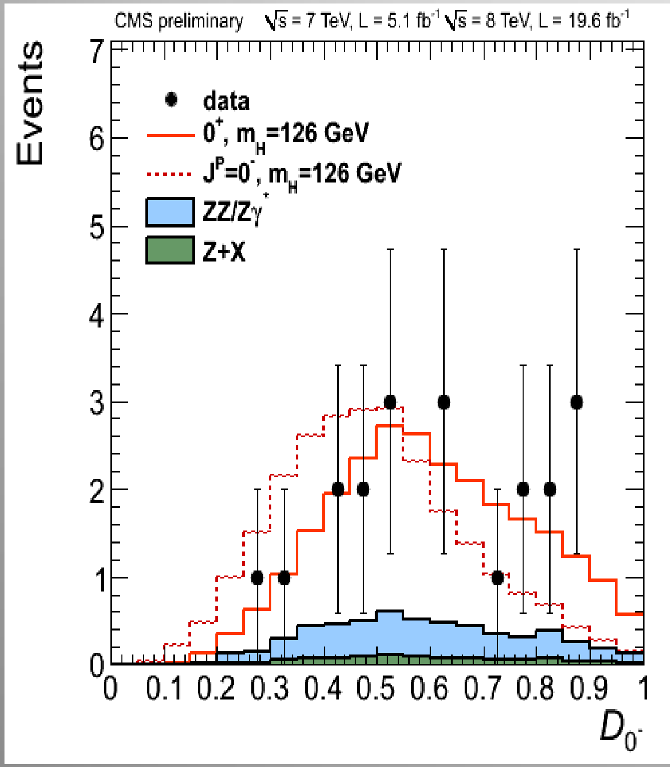


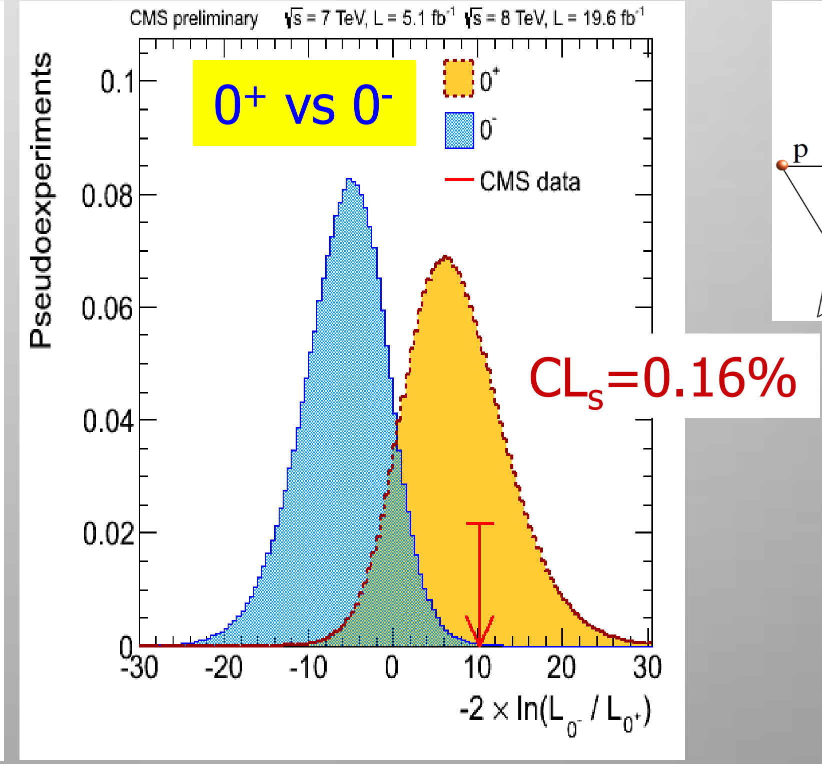


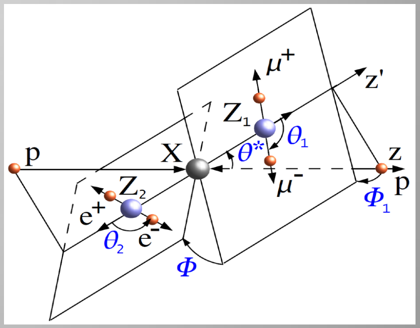
Spin/Parity Hypothesis Tests

Spin/parity hypothesis tests: $H \rightarrow ZZ \rightarrow 4l$ channel

Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a "Higgs"







More J^P hypotheses have been tested in a similar way →

J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

Summary

- The mid-2012 discovery has been confirmed with more added collisions. Moving on to measuring properties.
- Rare processes now studied: $H \to Z\gamma$, ttH, ($H \to \mu\mu$)…
- The spin/parity is compatible with a 0^+ state and not with (simple) 0^- or spin 2 states
- The mass value by CMS is 125.7 ± 0.4 GeV
- Signs of decays into fermion decay channels. The significance of the combined τ+b channels is ~3.4σ
- The couplings to bosons and fermions are consistent with SM predictions, but these are tested so far up to ~20-30% precision only; Surprises still possible!!
- Hunt for rare decays & processes is going on…
- ATLAS is having similar results (see backup slides)

Tomorrow ???

Fingers crossed….

Search for Other Higgses

- High mass search for SM-like Higgses
- Invisible Higgs
- MSSM Neutral Higgs (μμ, bb, ττ)
- MSSM Charged Higgs
- Double Charged Higgs
- Light pseudoscalar a1 production
- Fermiophobic/SM4 studies
- …

See talk by A. Nikitenko

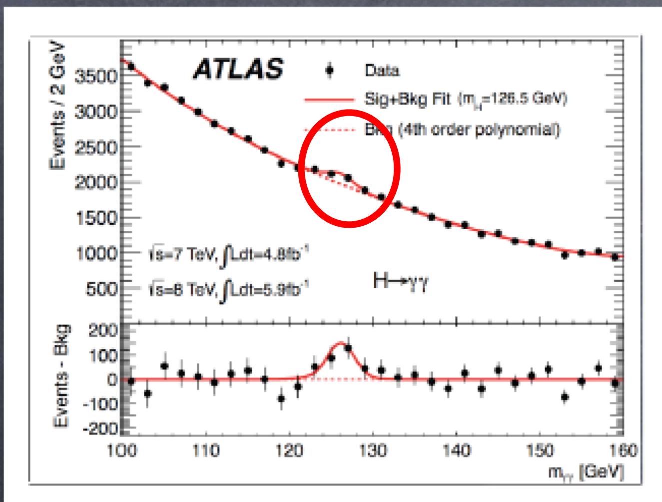
Backup: Comparison with ATLAS

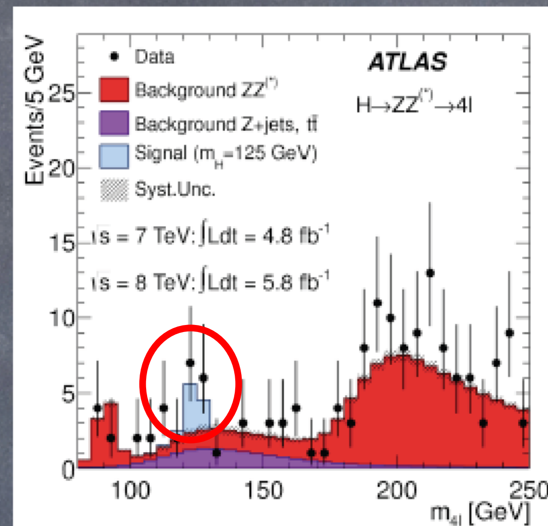
Summer 2012: Results

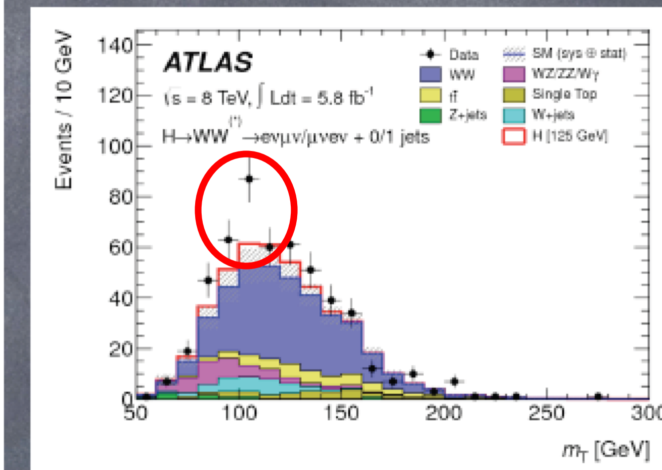
Higgs → 2 photons!!

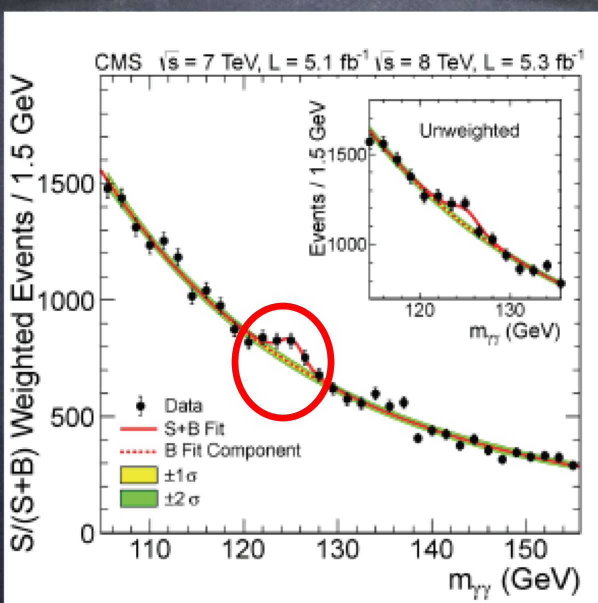
Higgs → 2Z →4 leptons!!

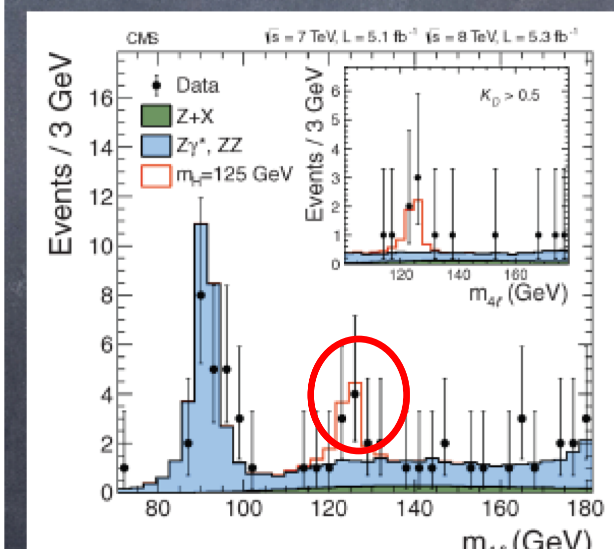
Higgs → 2W →2l2v!!

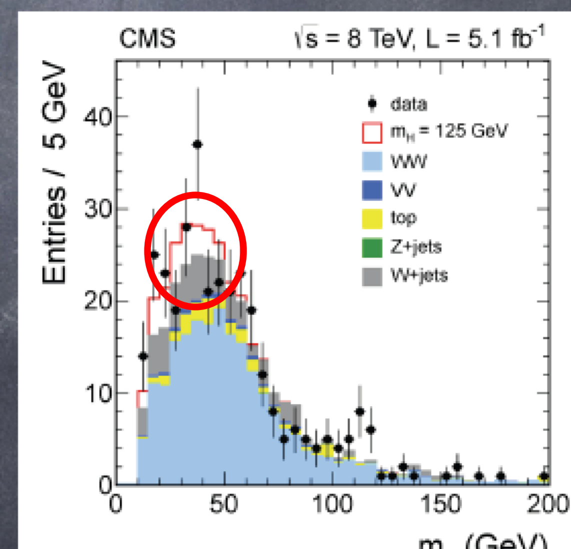












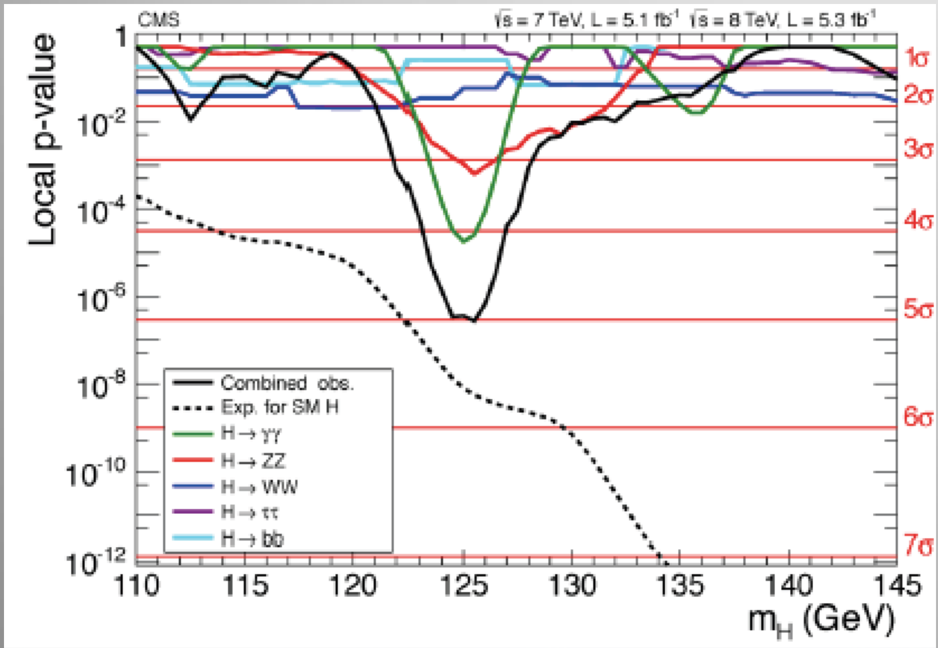
Summer 2012: Results

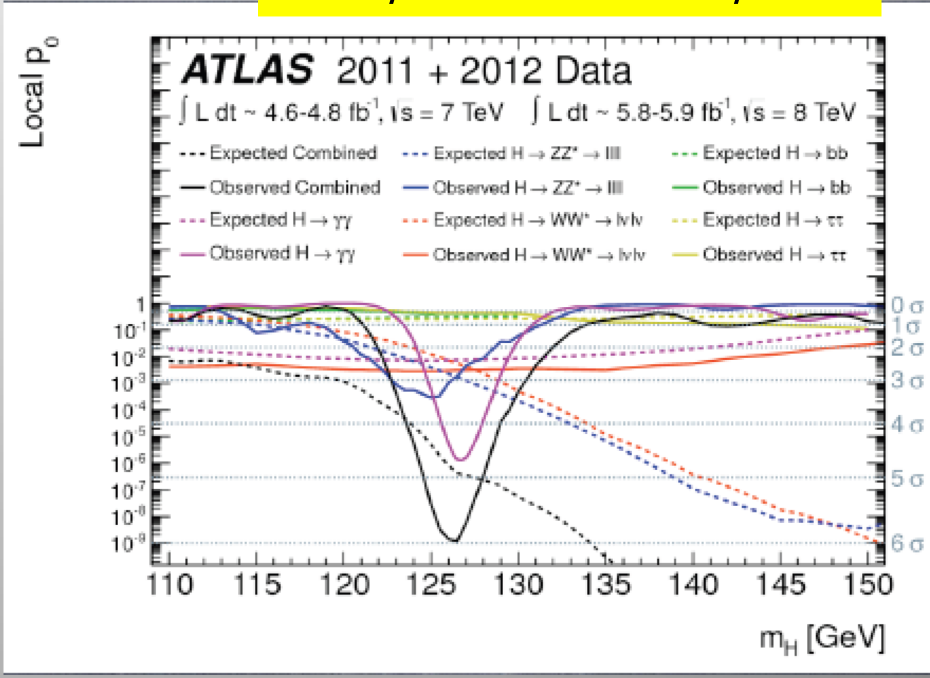
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Adding up al the channels gives the following combination

Shown is the compatibility with a 'background only hypothesis"

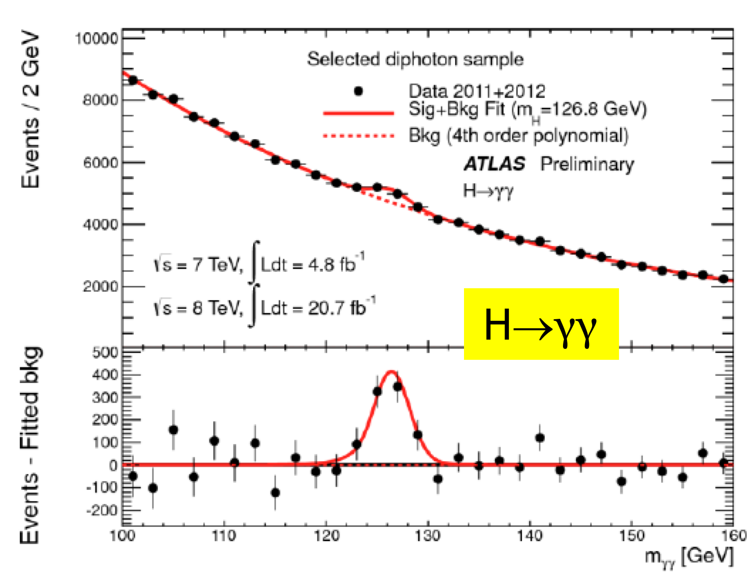
5 fb^{-1}/2011 and 5 fb^{-1}/2012

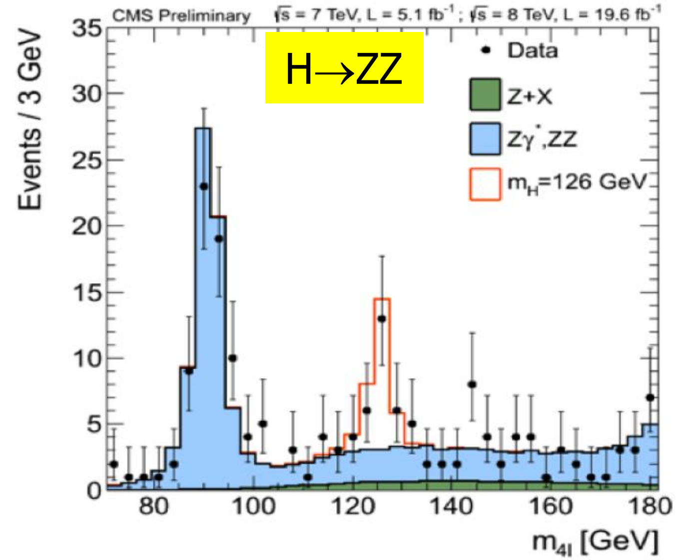


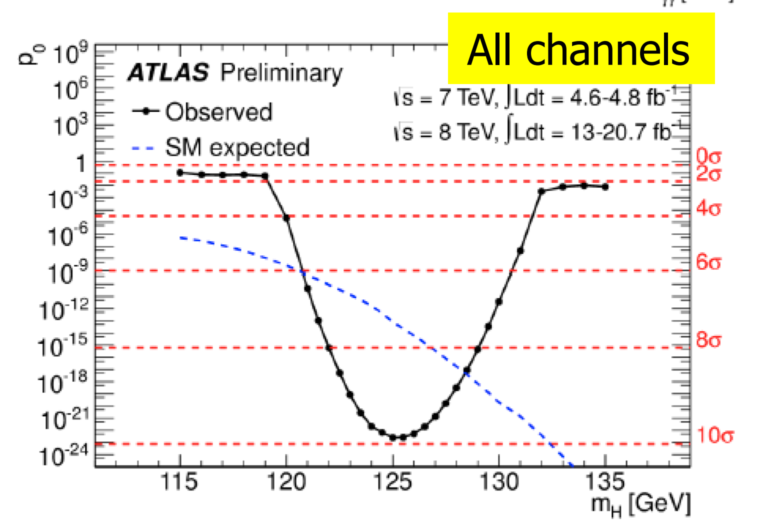


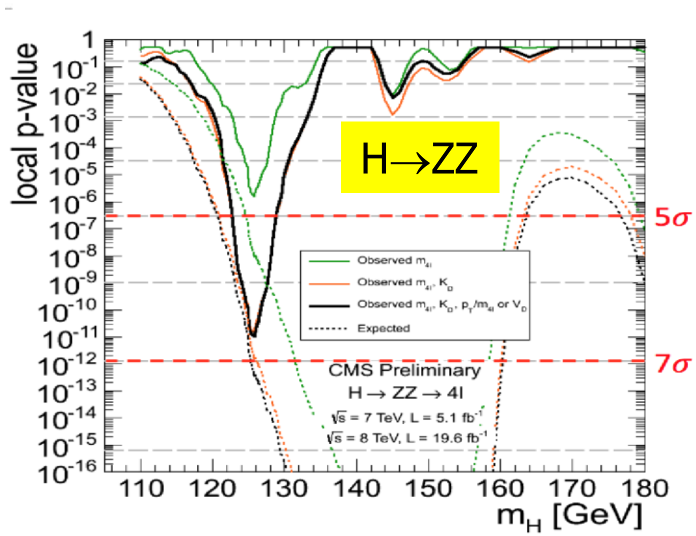
CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

Update with the Full 2012 Data Sample







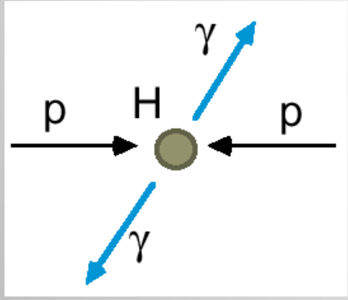


Increased data sample with a factor of ~3

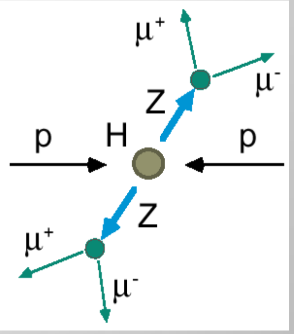
The particle is clearly still with us, now with a significance of >10σ !!

We now enter the phase of measuring the properties of the new particle

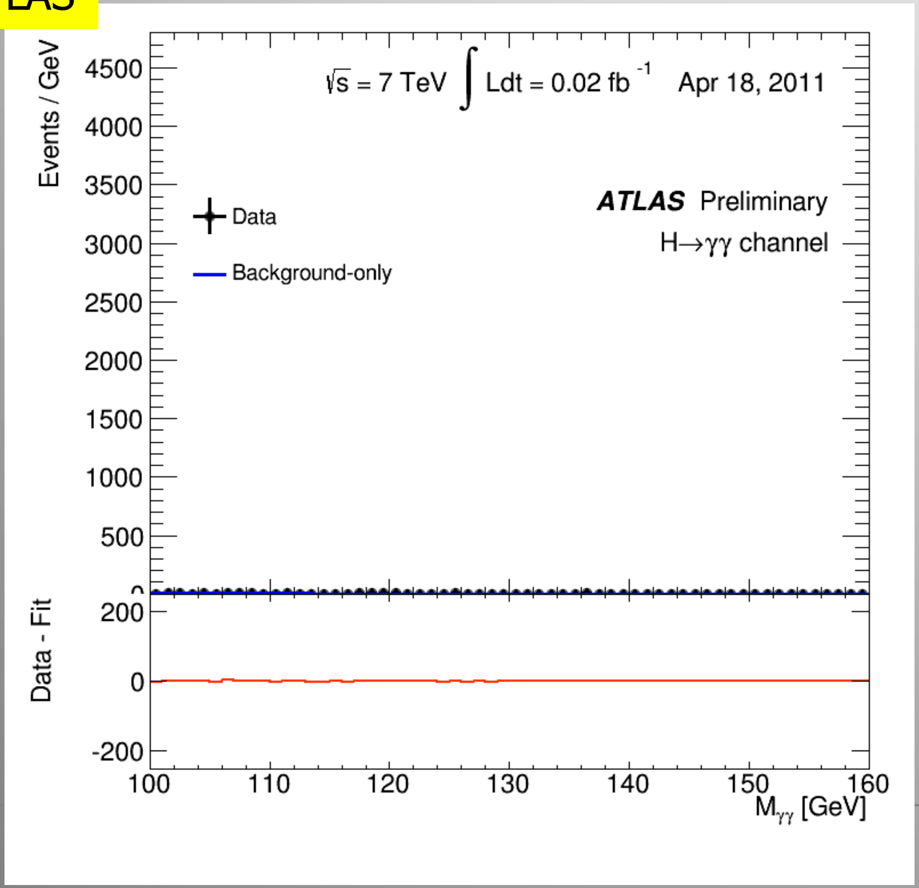
The Birth of a Particle



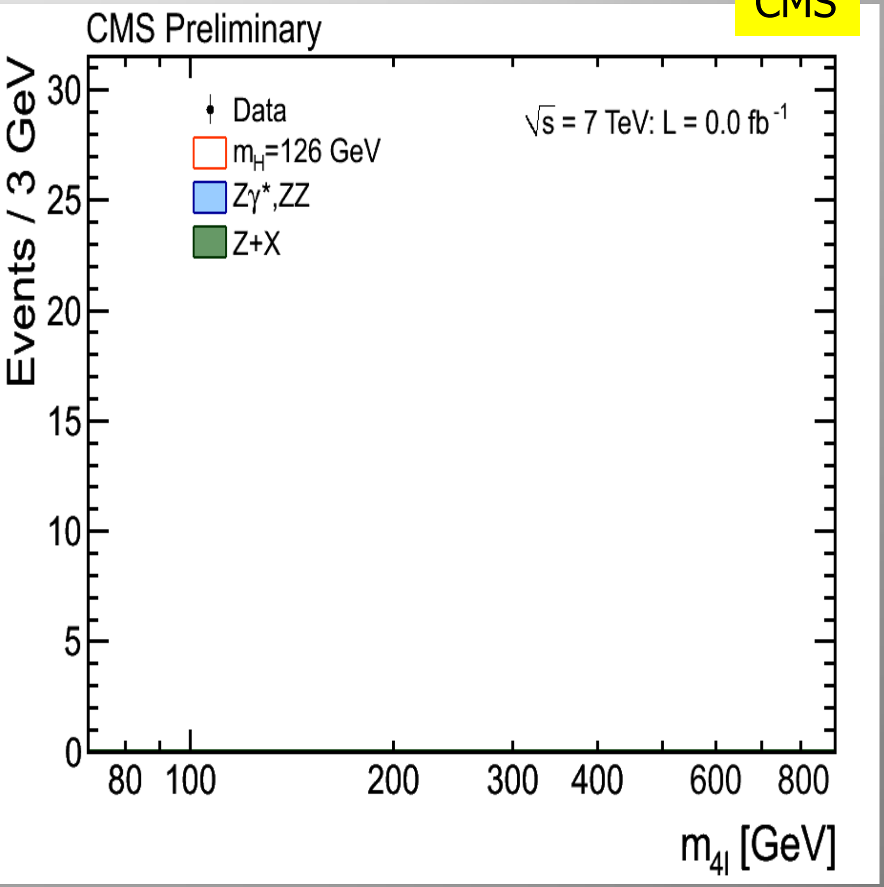
"History" of the data accumulation during the last two years



ATLAS



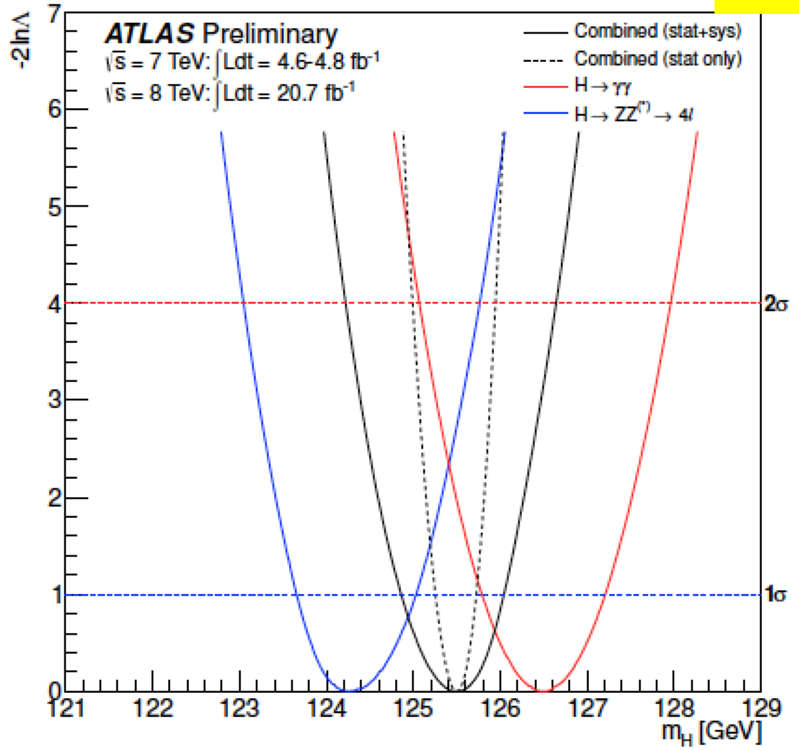
CMS



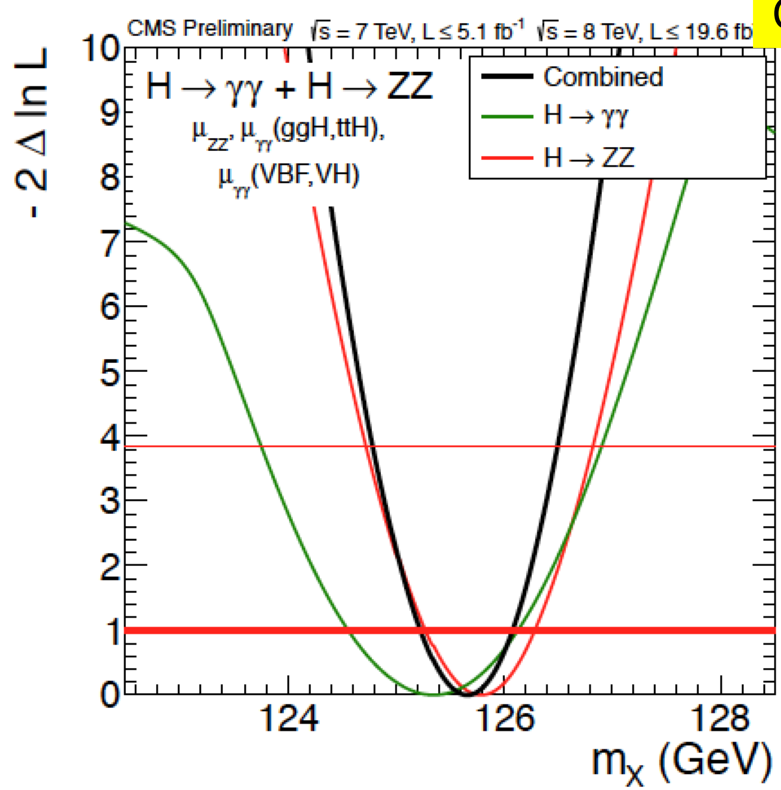
The Mass of the Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

ATLAS



CMS



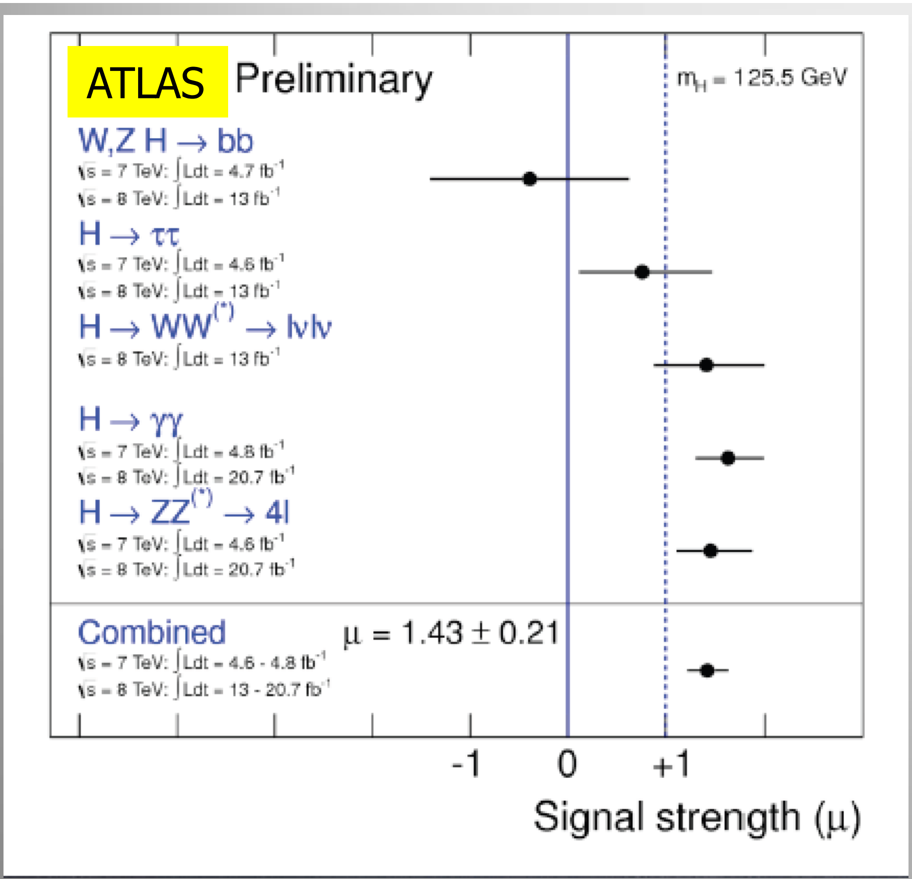
$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)$ GeV

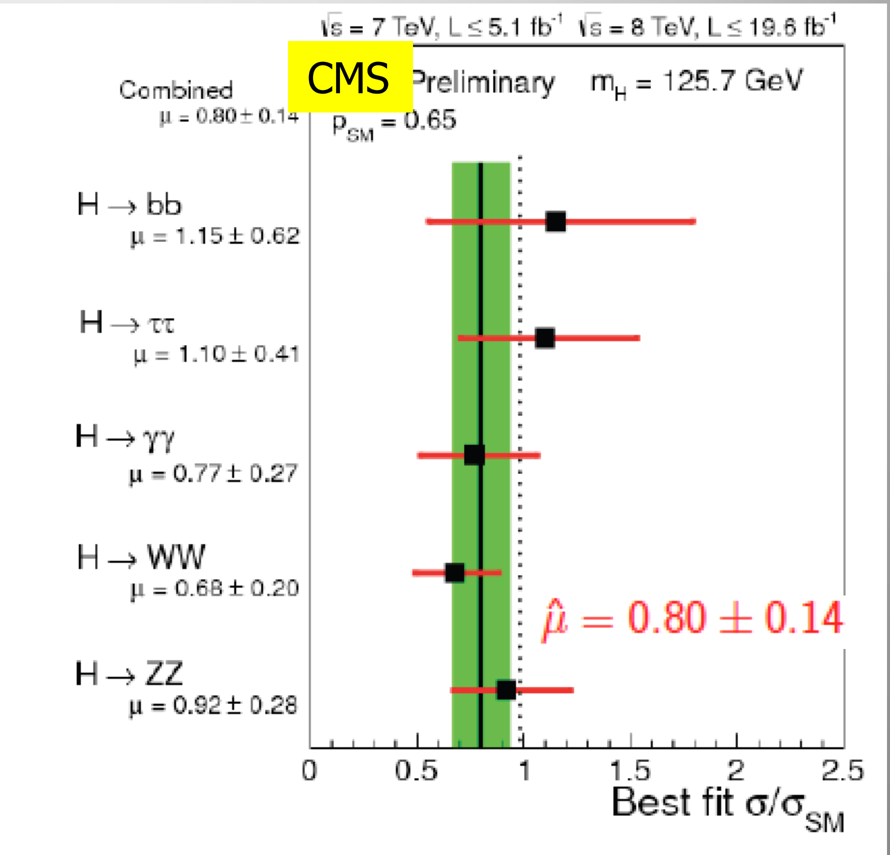
$\hat{m}_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)$ GeV

ATLAS and CMS observe the same particle!! ☺

Signal Strength

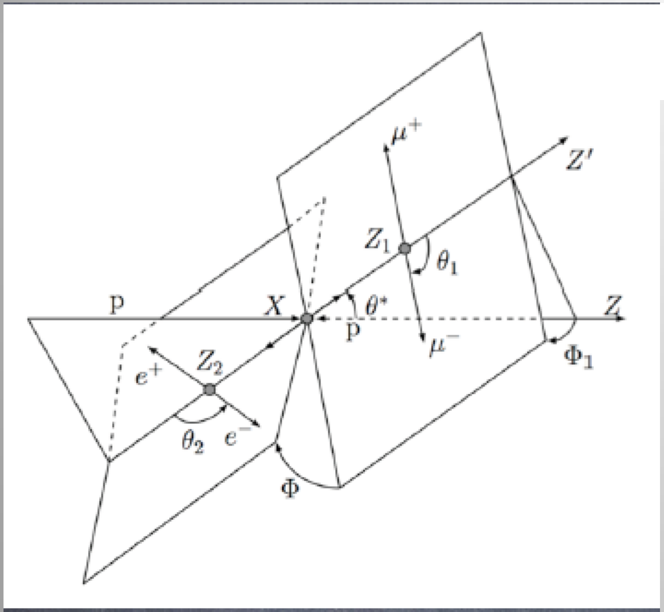
- Signal strength μ is the observed over Standard Model expected cross section
- For μ=1 the production rate is compatible with Standard Model expectation





ATLAS a bit above and CMS a bit below μ=1…

The Spin of the New Particle

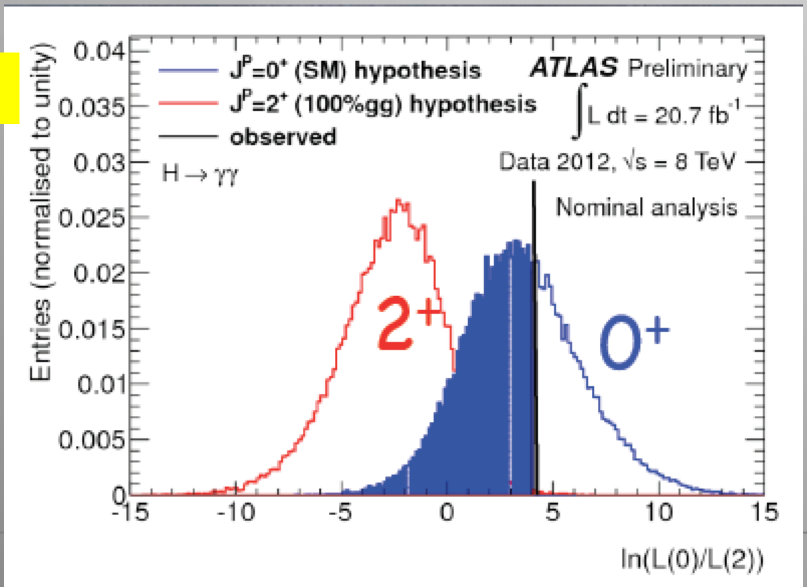


A Higgs particle should be a spin 0^+ state

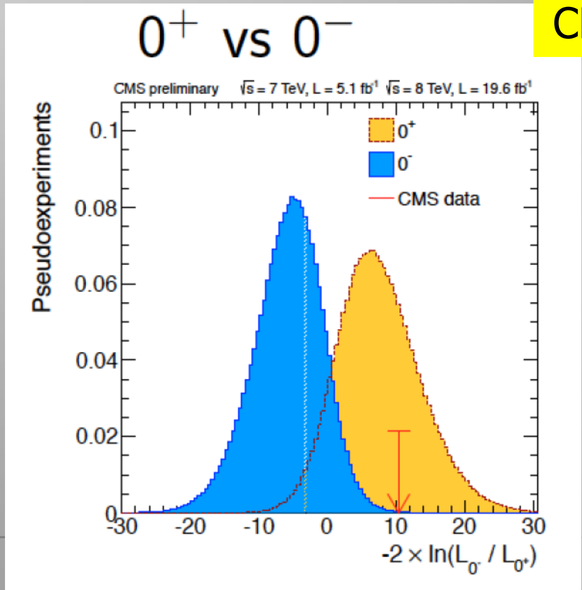
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle is consistent with a 0^+ state!!

ATLAS

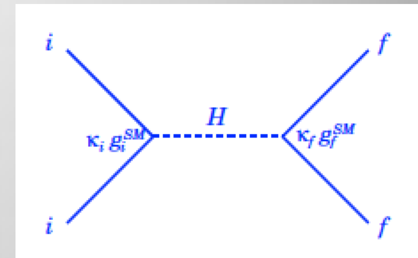


CMS

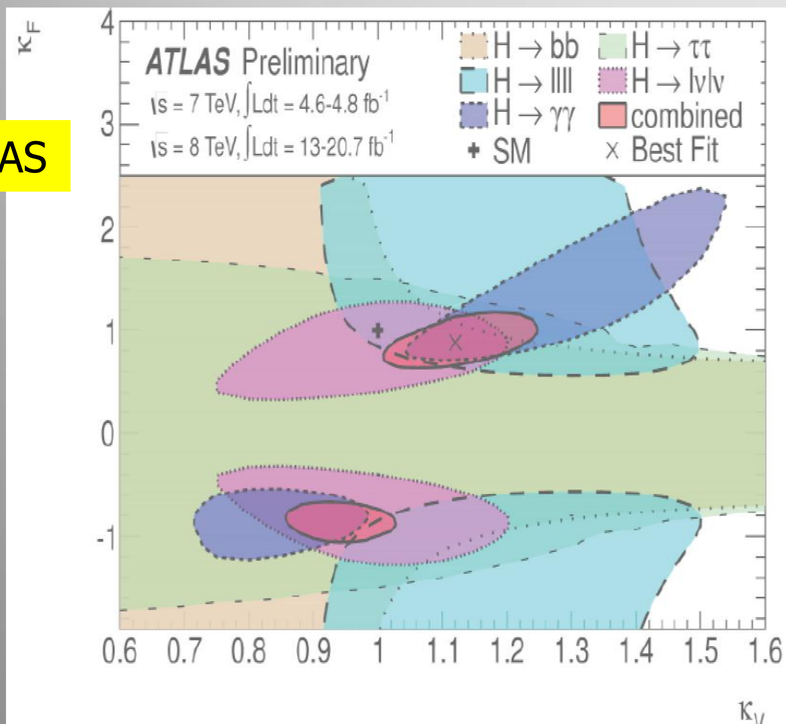


Couplings to the New Particle

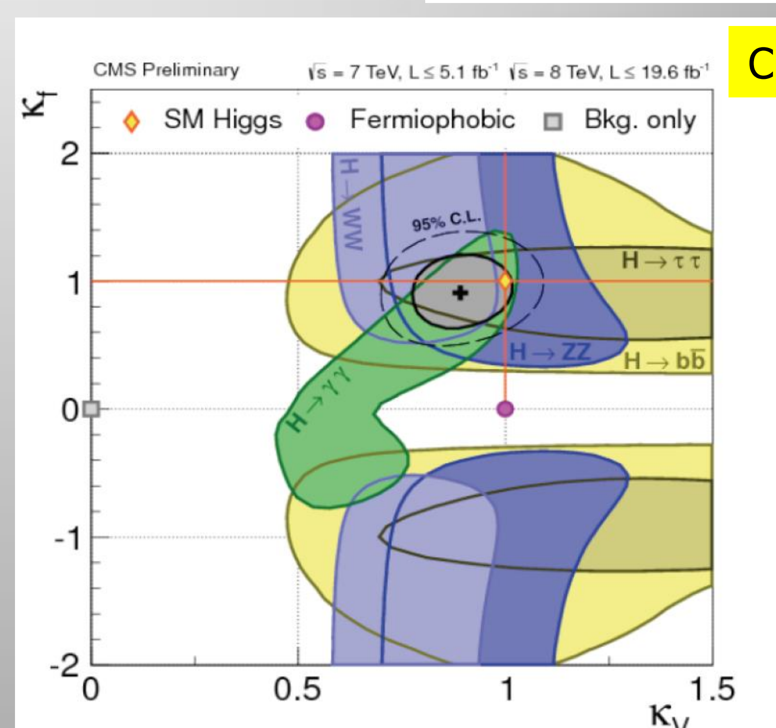
- Use information of all production and decay channels
- κ_f and κ_V are scale factors w.r.t. the Standard Model values for fermions and vector bosons



ATLAS



CMS



⇒ Couplings compatible Standard Model values, but large uncertainties
…Future data will decide…