# Overview of Higgs Results from CMS

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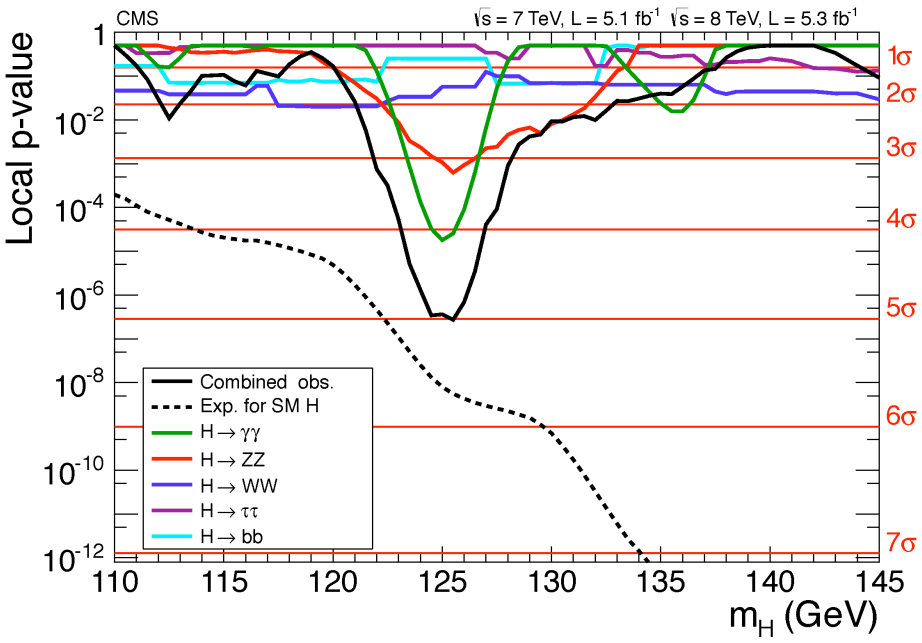
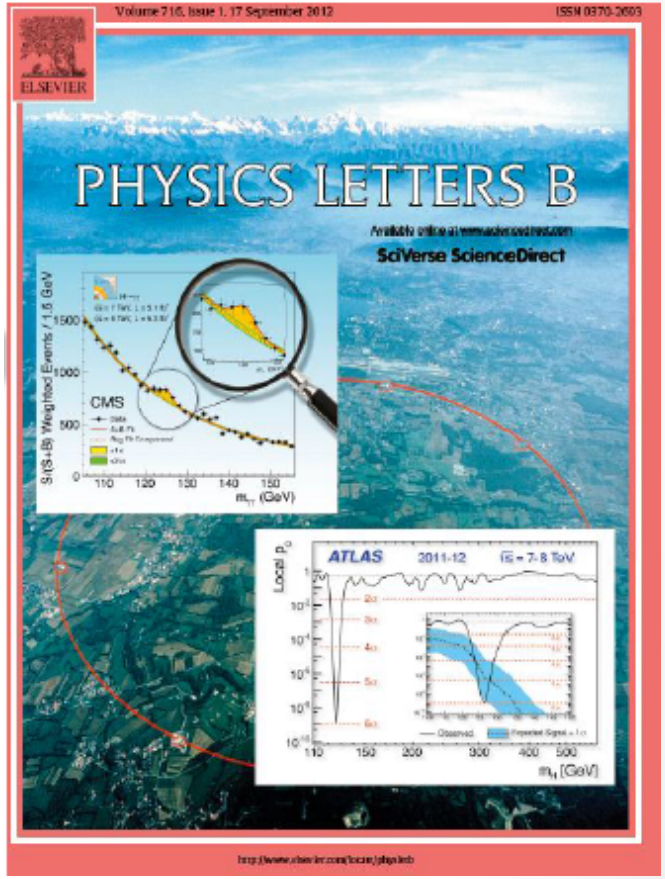
For the CMS Collaboration
ISMD2013 Chicago – 9/16/2013


# Higgs Discovery

- More than one year ago!
- Just the beginning; a lot of work has been done since then.
- Will try to summarize it in this talk.




Phys. Lett. B 716 (2012) 30



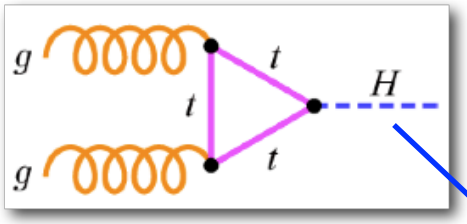
# Is the New Boson the SM Higgs?

- Does it ***couple*** to the SM particles at appropriate level?
- Is the ***signal strength***, where seen, at the correct SM level?
- Is this a ***scalar***, and not a pseudo-scalar or tensor?
- Is this the ***only*** new non-vector boson, and not one of several?
- Does it ***couple to itself*** ?

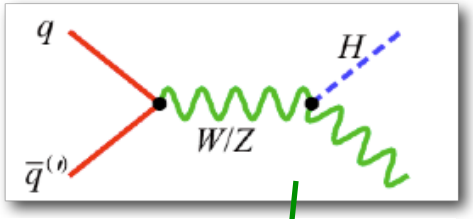
- Luckily, the mass of about 125 GeV allows us to answer many of these questions experimentally ☺
  - Answers began to emerge by Moriond2013 already
  - Others will, with ~100 $fb^{-1}$ (circa 2016)
  - Self-coupling needs O(1000) $fb^{-1}$ – a decade of work ☹

# Standard Model Higgs Production

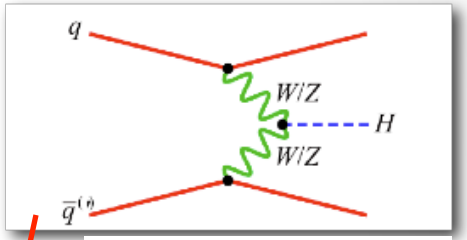
**Gluon fusion**



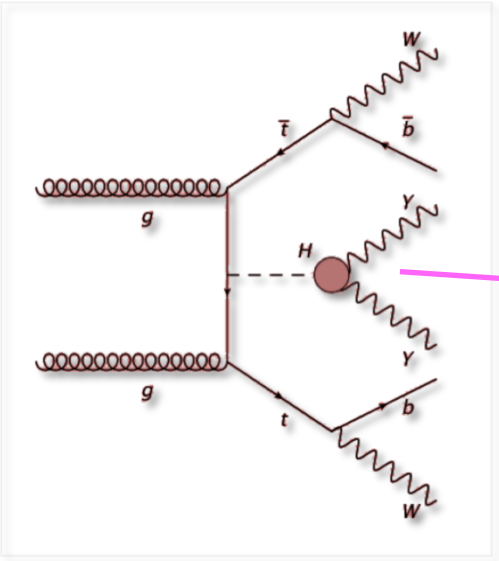

**Associated Production**

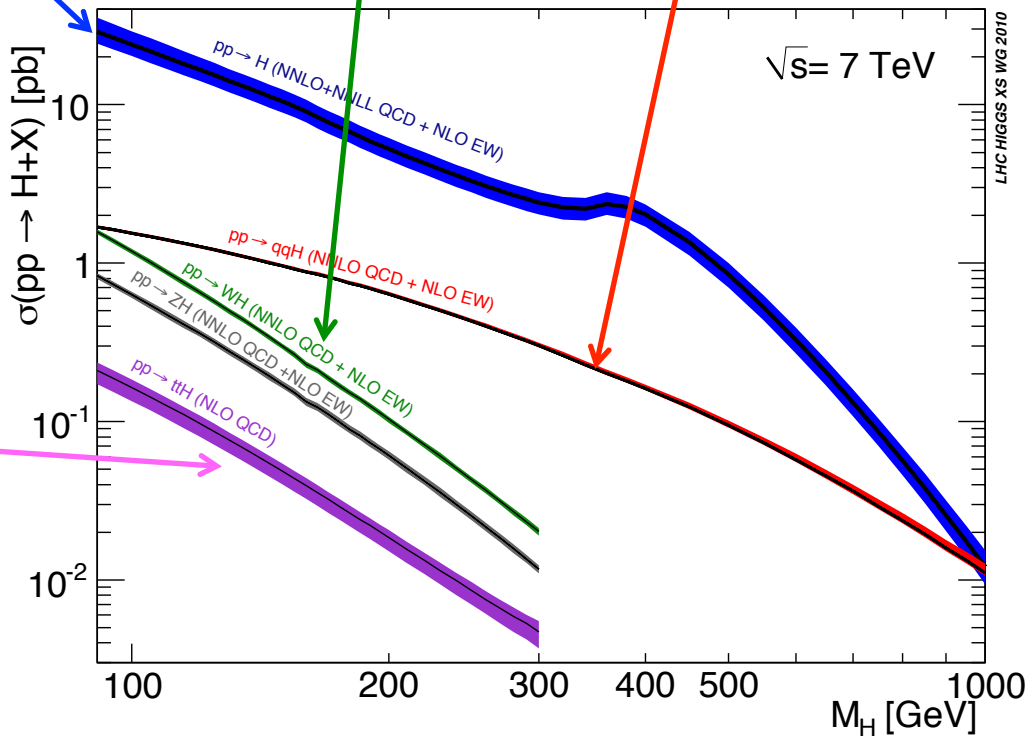



**Vector boson fusion**



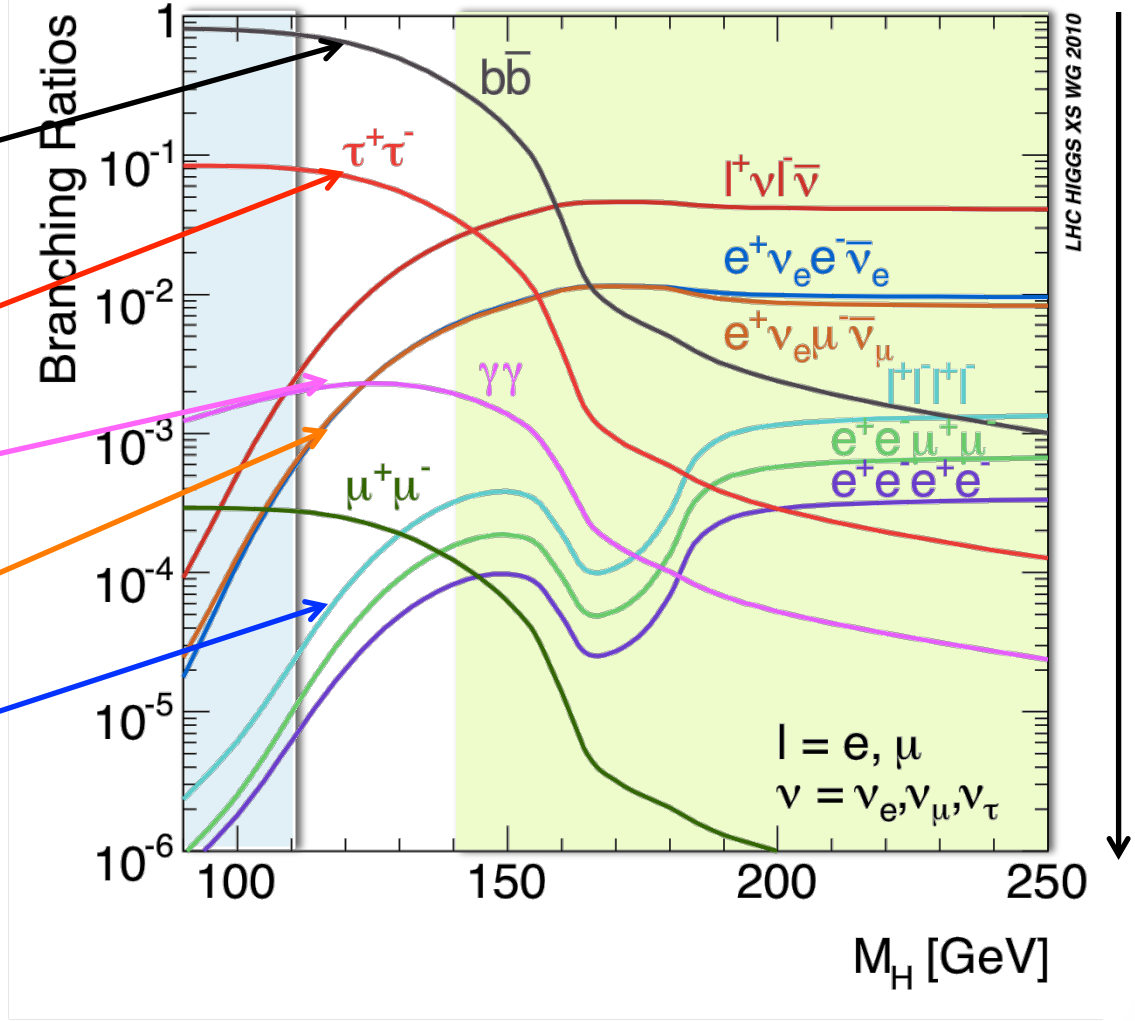

**Top Associated**



# Standard Model Higgs Decay

We search for several Higgs decay channels.




H → bb

H → ττ

H → γγ

H → WW

H → ZZ

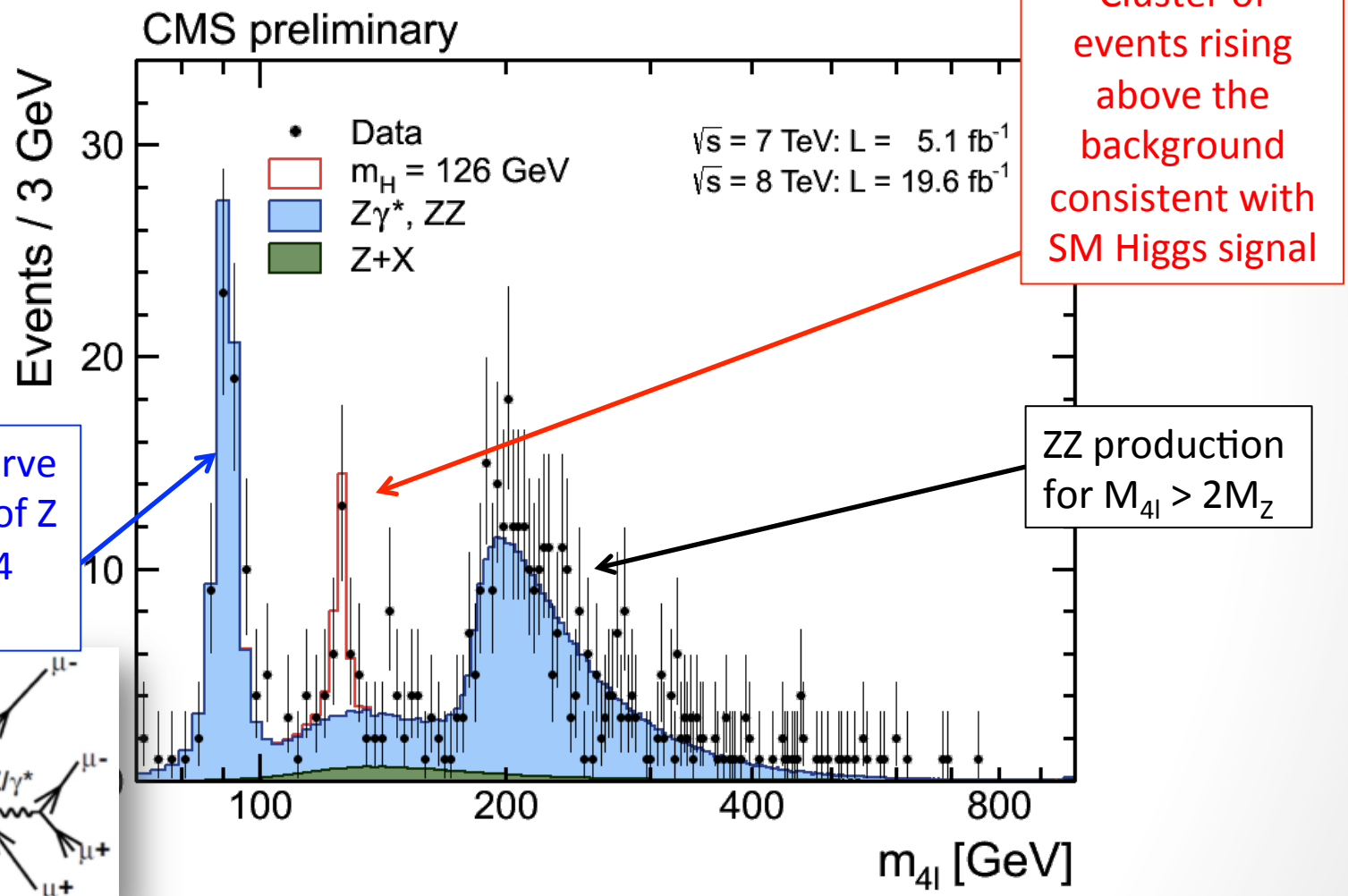
Cleaner Signal

Better Mass Resolution
(for channels without neutrinos)

# Couplings to Vector Bosons

CMS HIG-13-002

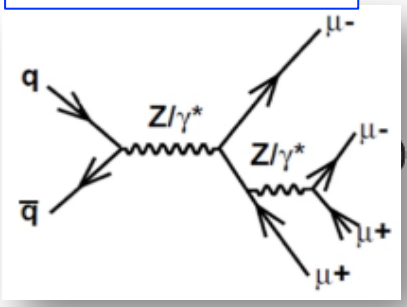
# Decays to ZZ to 4-light leptons




Cluster of events rising above the background consistent with SM Higgs signal

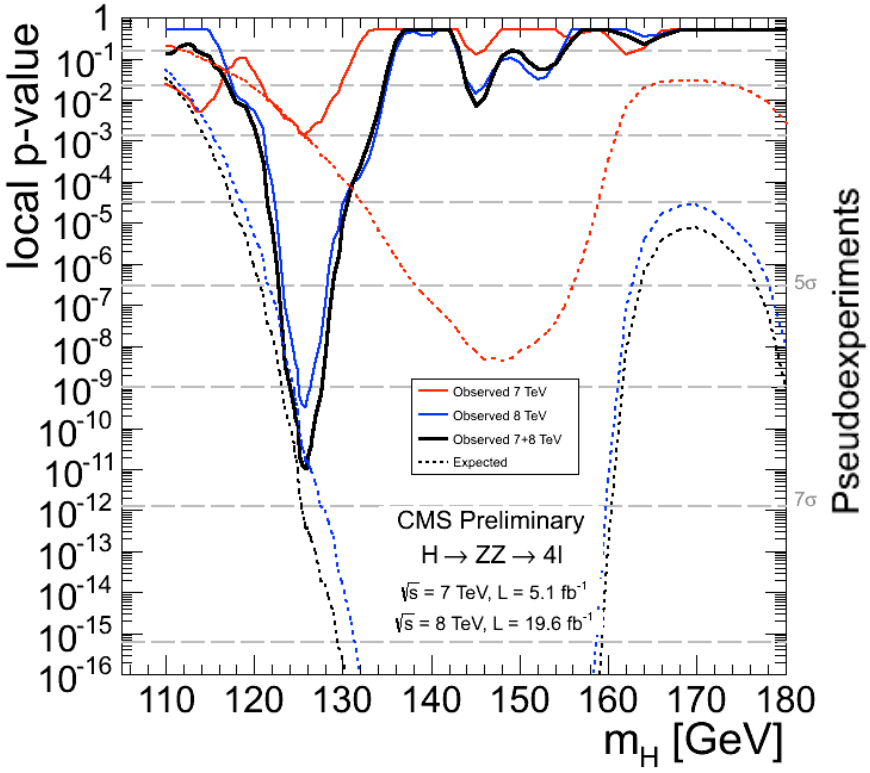
ZZ production for $M_{4l} > 2M_Z$

Clearly observe production of Z decay to 4 leptons

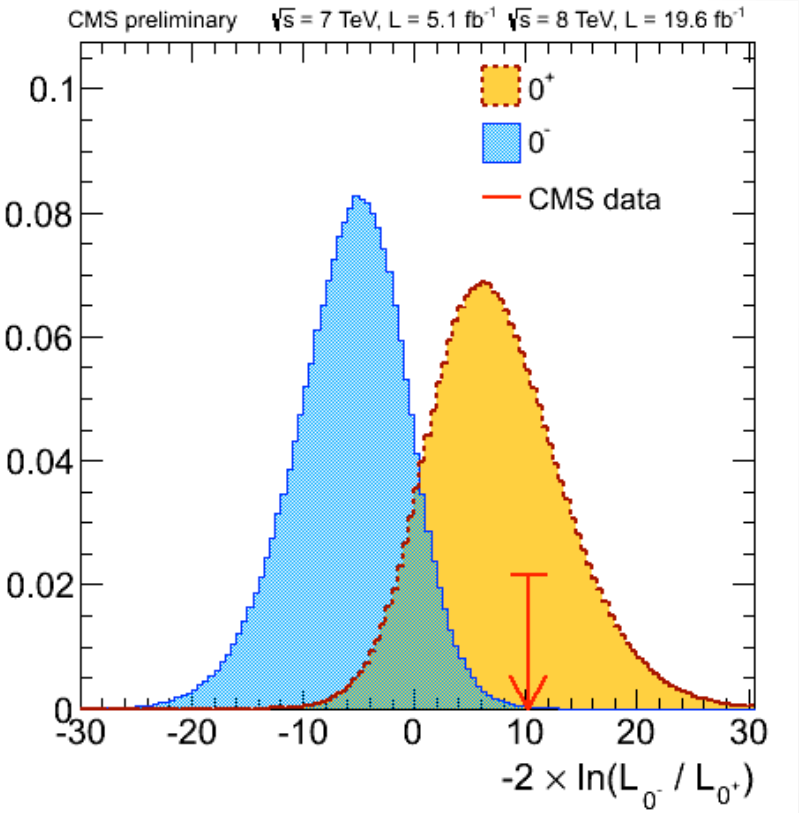


# H→ZZ→4l Results

$$m_H = 125.8 \pm 0.5(stat.) \pm 0.2(sys.)\,GeV$$




Build log likelihood discriminator for various spin and parity hypotheses

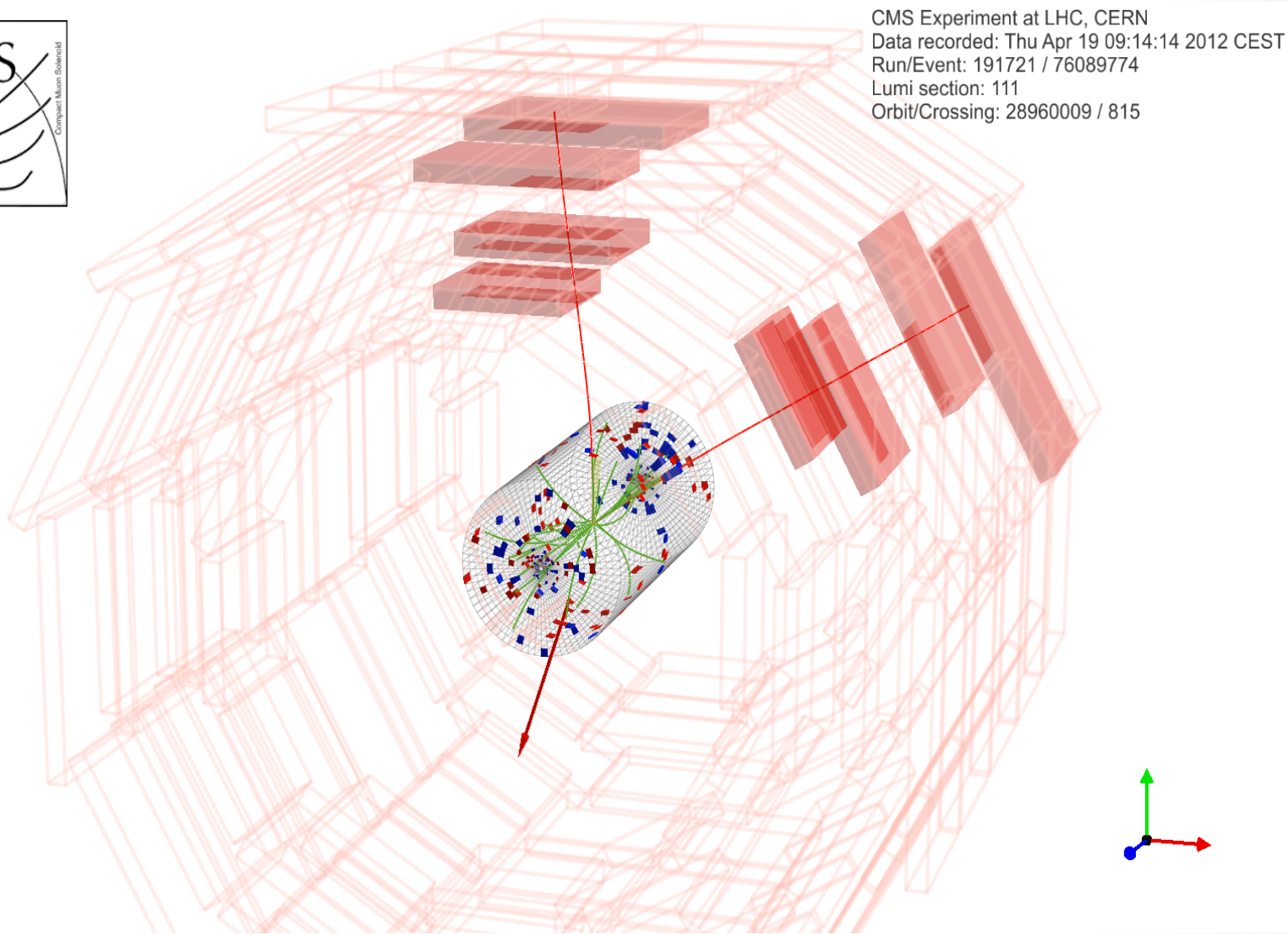



Signal strength:

$$\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$$

$$CLs\left(0^-/0^+\right) = 0.16\%, CLs\left(2^+/0^+\right) = 1.5\%$$

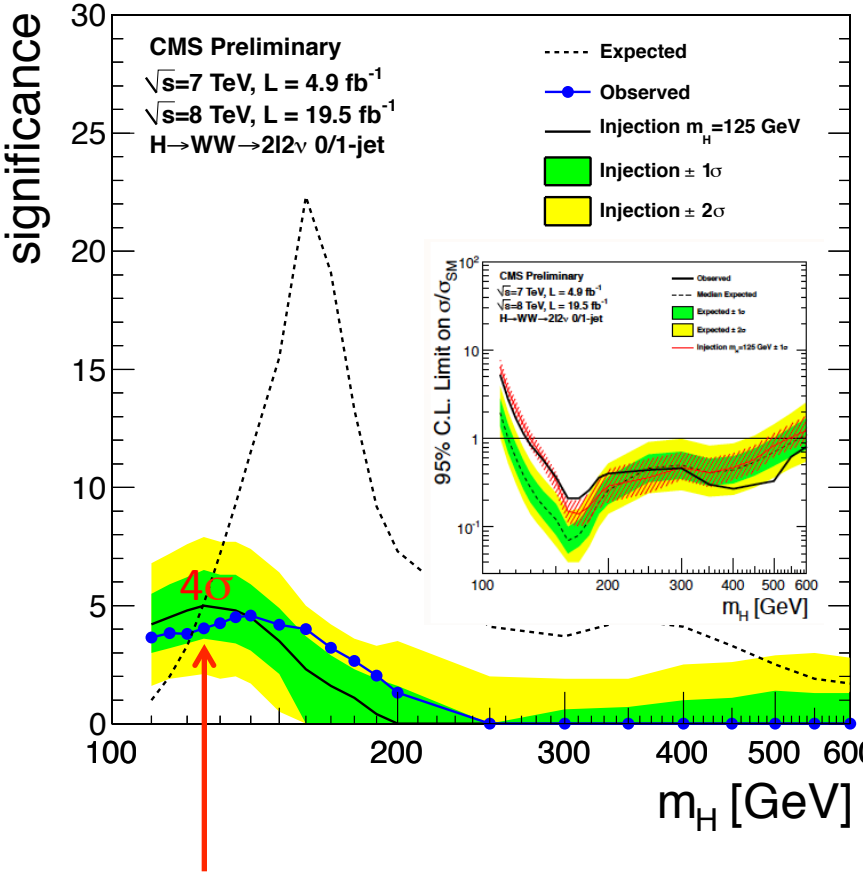
# H→WW→ $l^+ l^-$ MET

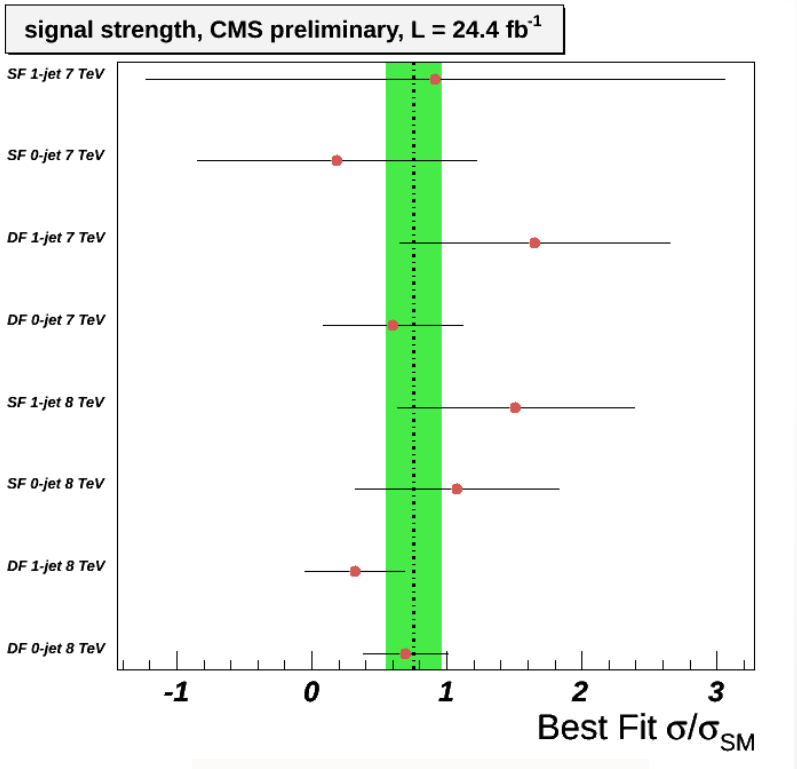

CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012 CEST
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815

CMS HIG-13-003

# Evidence in WW mode

- CMS sees broad enhancement compared to background only hypothesis, consistent with the SM Higgs @ 4σ (expectation @ 5σ)
- Compatibility among different final states

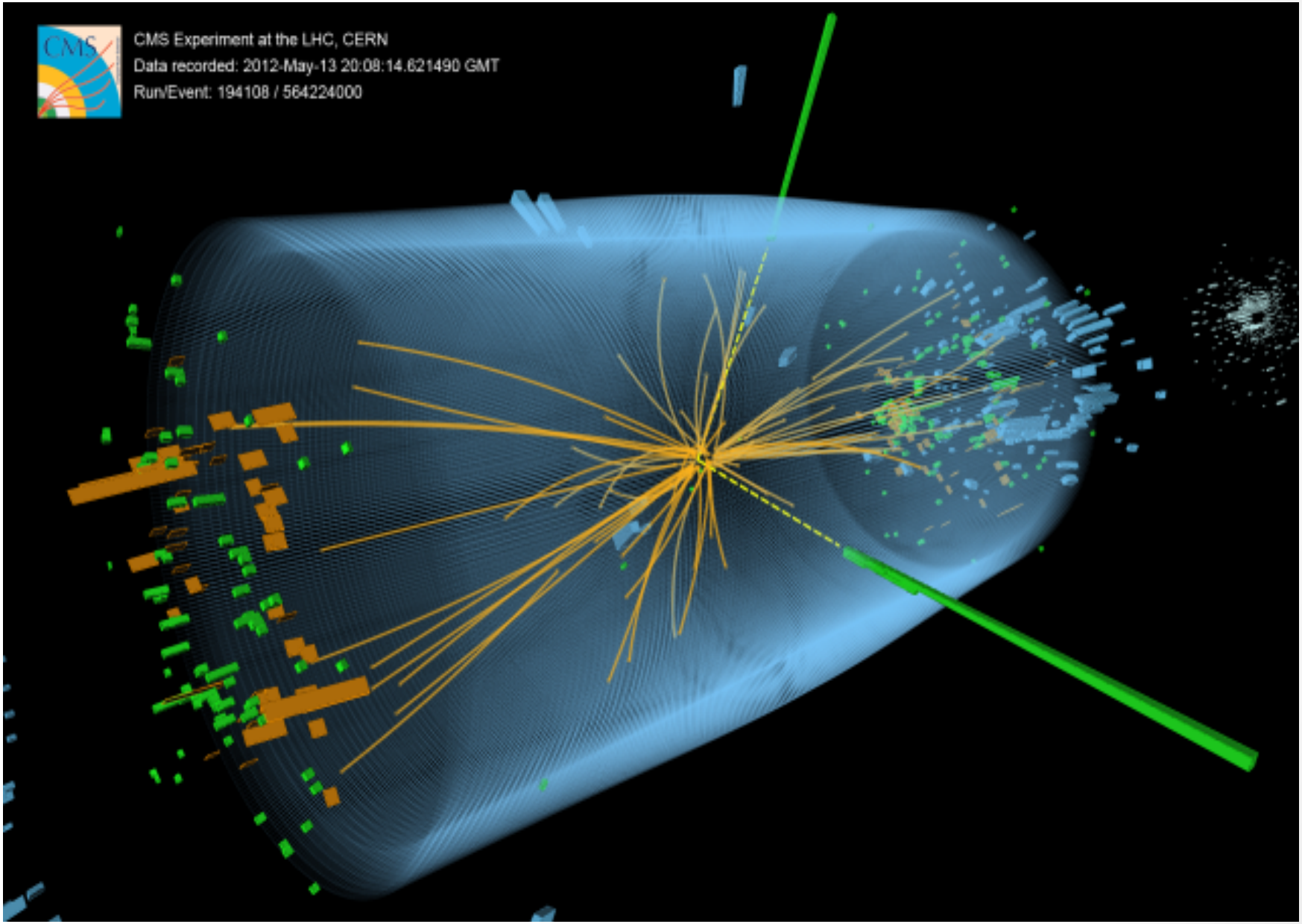



**Signal strenght:**

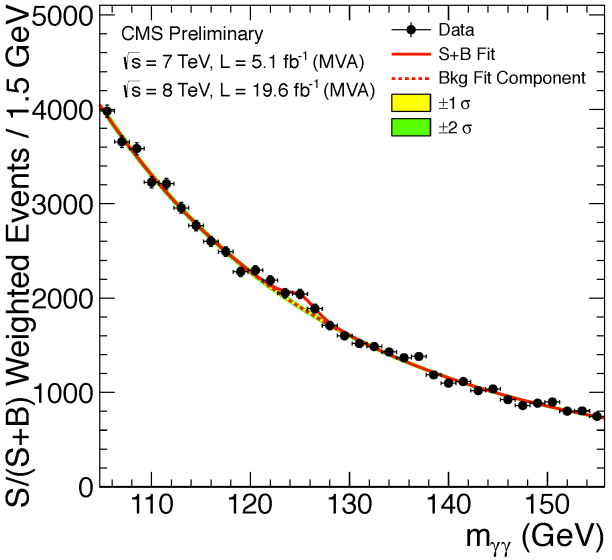
$$\sigma/\sigma_{SM} = 0.76 \pm 0.21$$

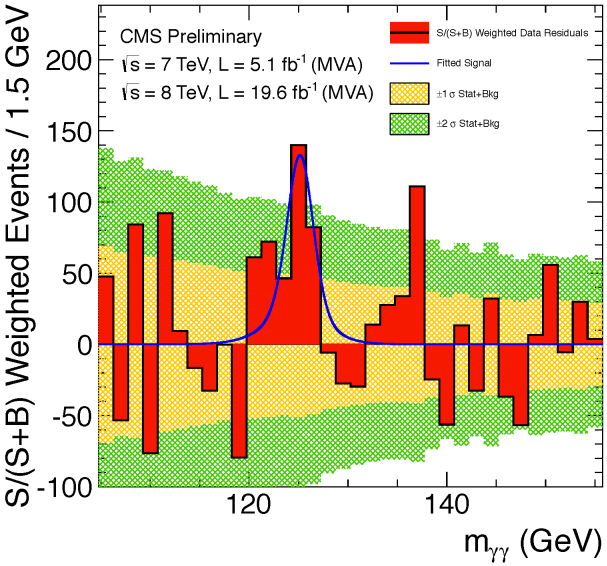
# H→γγ Candidate

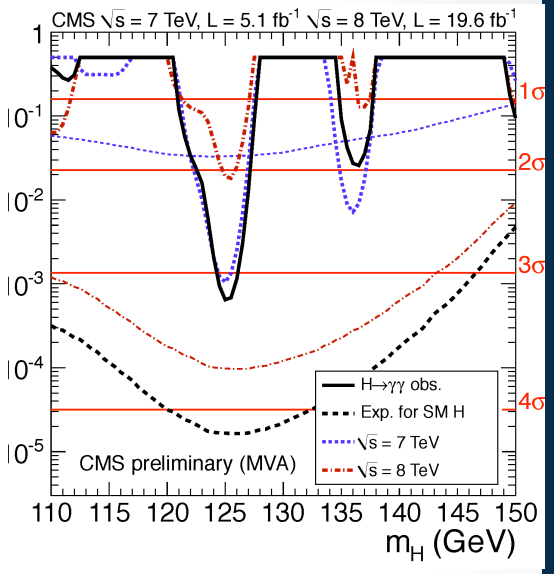


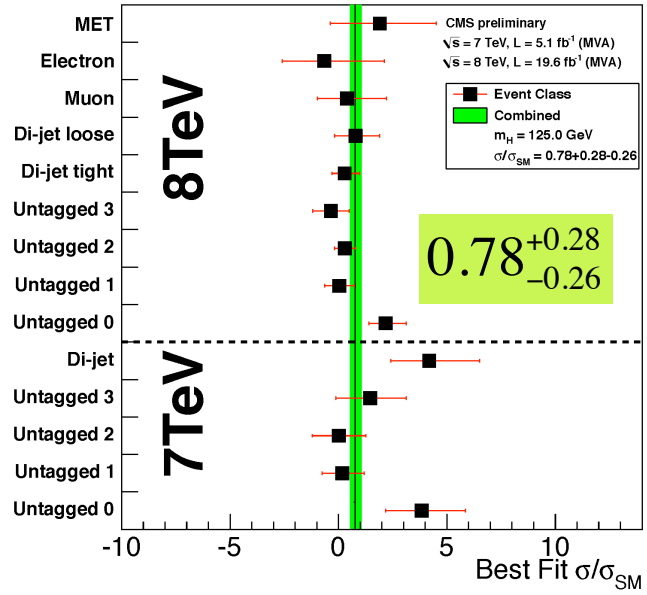
# H→γγ Results

CMS HIG-13-001



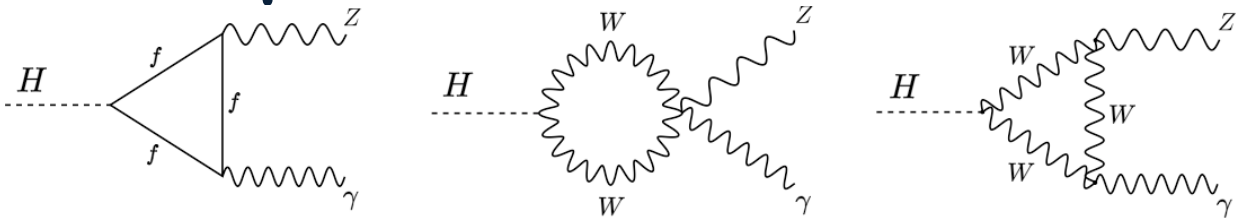

$$m_H = 125.4 \pm 0.5(stat.) \pm 0.6(sys.)\,GeV$$

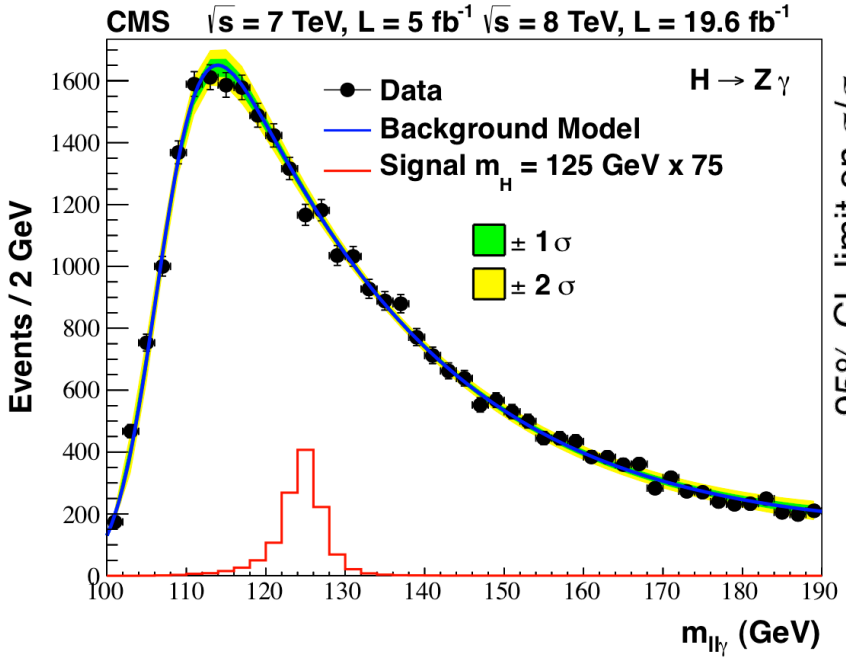
Compatibility results from Spin-Parity analysis

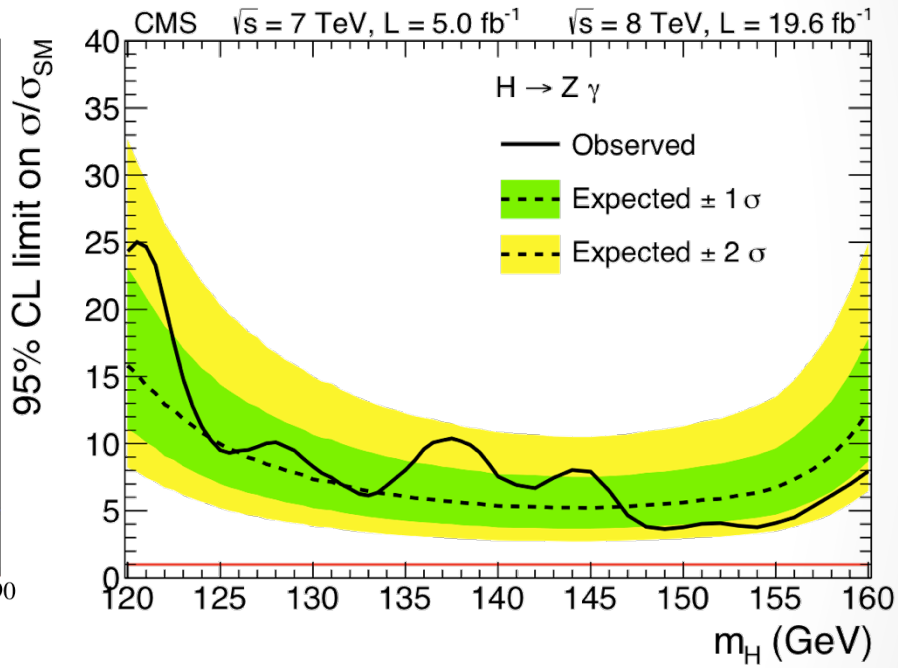
| Source | $\chi^2$ $p$-value |
|---|---|
| Data vs. $0^+$ | 0.68 |
| Data vs. $2^+_m$ (100% $gg$) | 0.91 |
| Data vs. $2^+_m$ (100% $q\bar{q}$) | 0.51 |
| Data vs. $2^+_m$ (50% $gg$, 50% $q\bar{q}$) | 0.81 |

# Rare H→Zγ

CMS HIG-13-006
arXiv:1307.5515



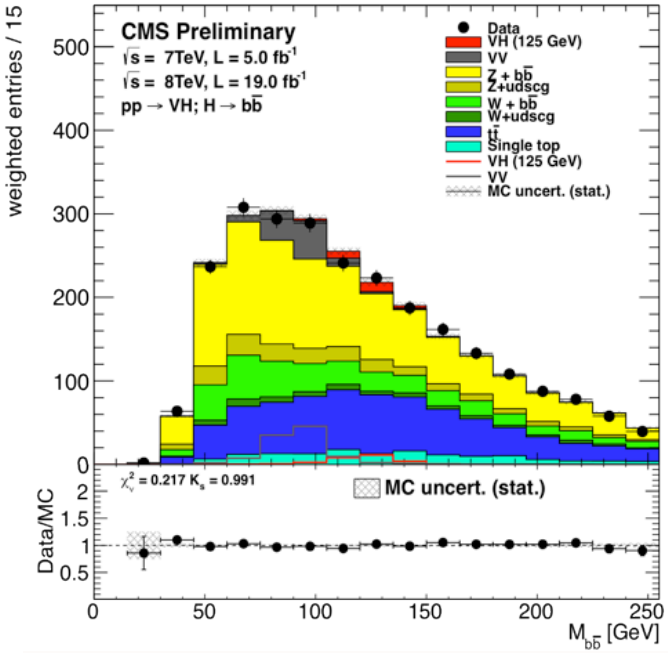

- Not yet sensitive at SM level
  - Search motivated by potential new physics contribution
  - Interesting mode for HL-LHC

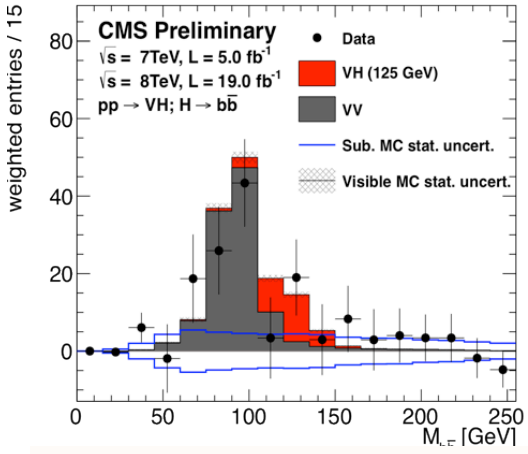
# Couplings to Fermions

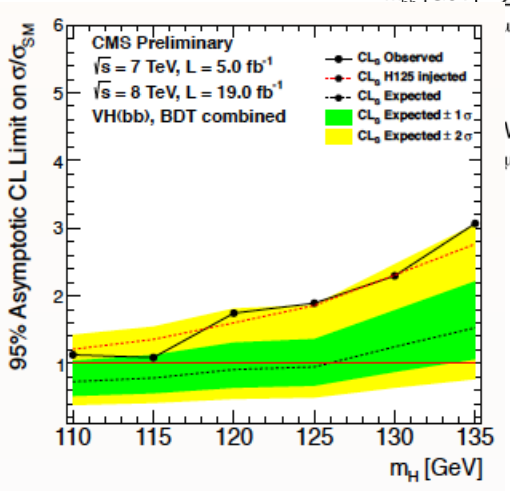
CMS HIG-13-012

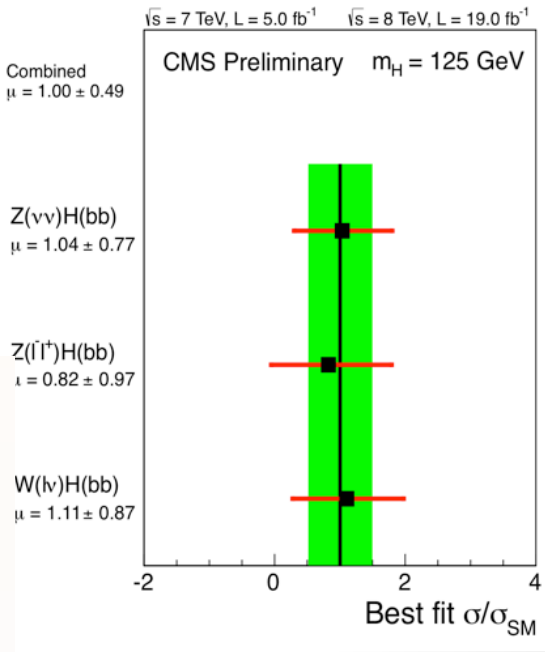
# H→bb (VH)

- Gluon fusion signal is overwhelmed by QCD
- Associated production with W (lν), Z(ll, νν) probed
- Observe a broad excess compatible with signal at low mass



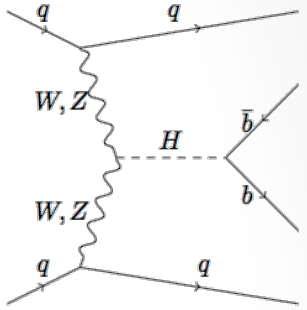

**Significances for $m_H$=125 GeV:**
observed 2.1$\sigma$, expected 2.1$\sigma$

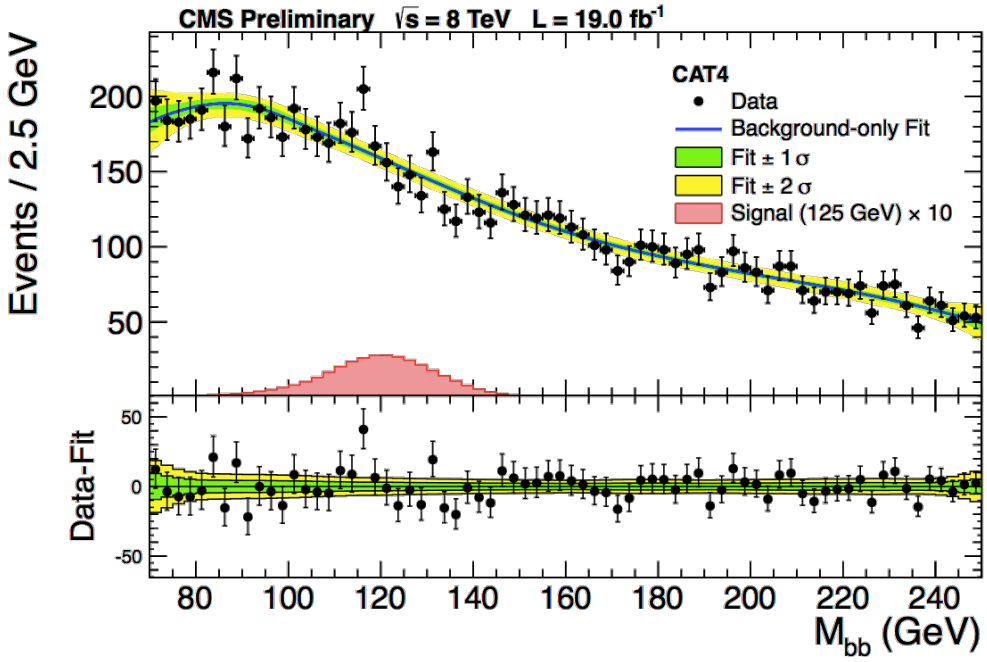
**Signal strenght:**
$\sigma/\sigma_{SM} = 1.0 \pm 0.5$

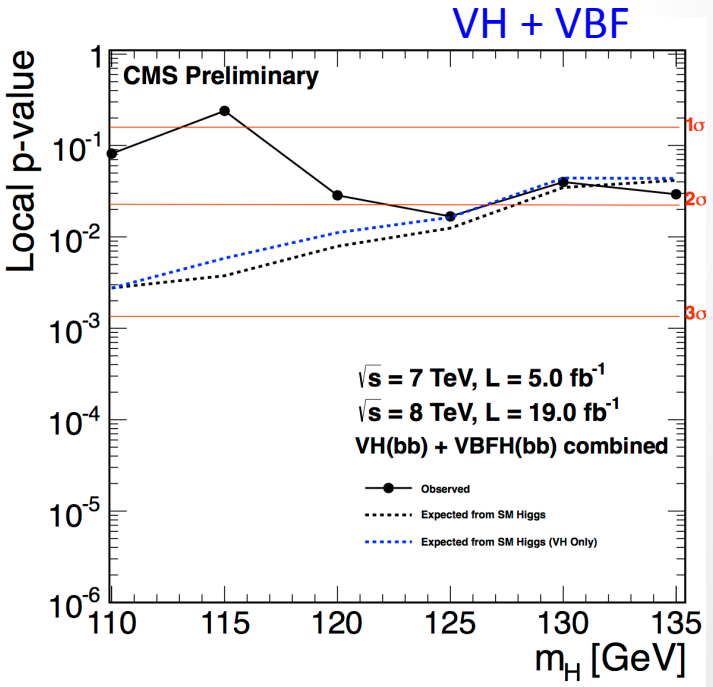
CMS HIG-13-011

# H→bb (VBF)

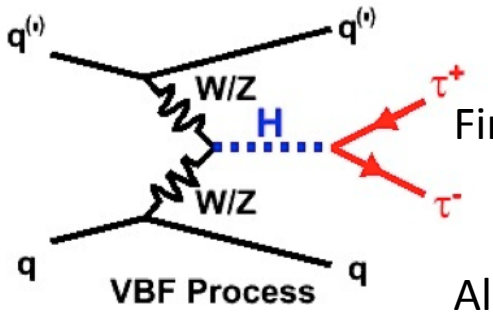
- Vector Boson Fusion Production Tagged by Forward Jets
- Difficult to trigger – 4 jets (+ 2 b-tags at Higher Levels)
- MVA with b-tag sorted jets
  kinematics
  gluon likelihood



# H→ττ Results

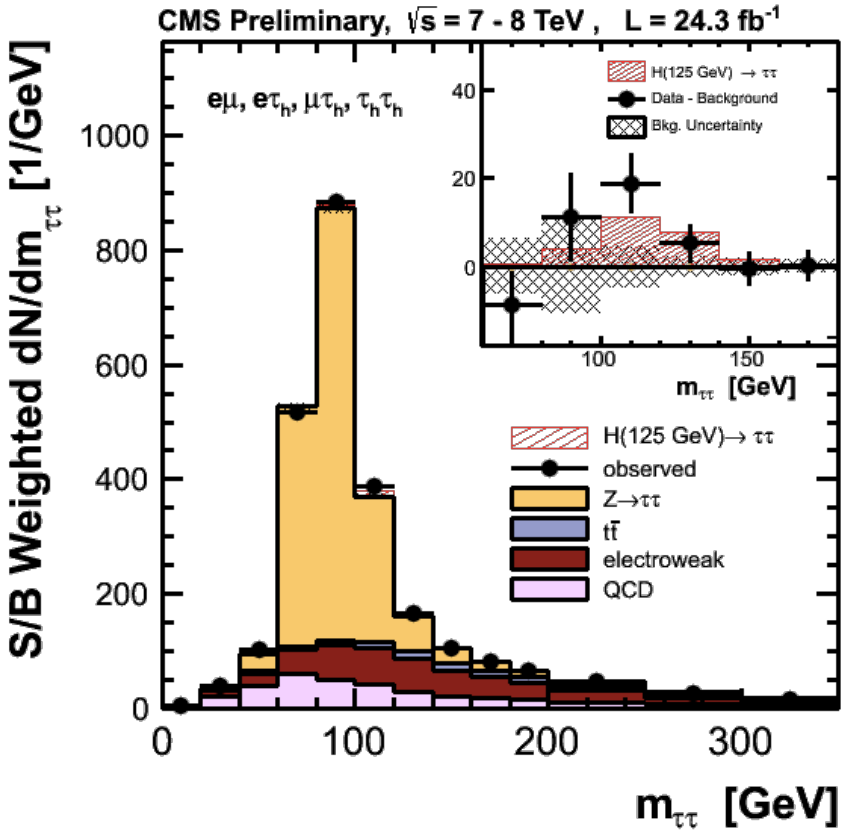


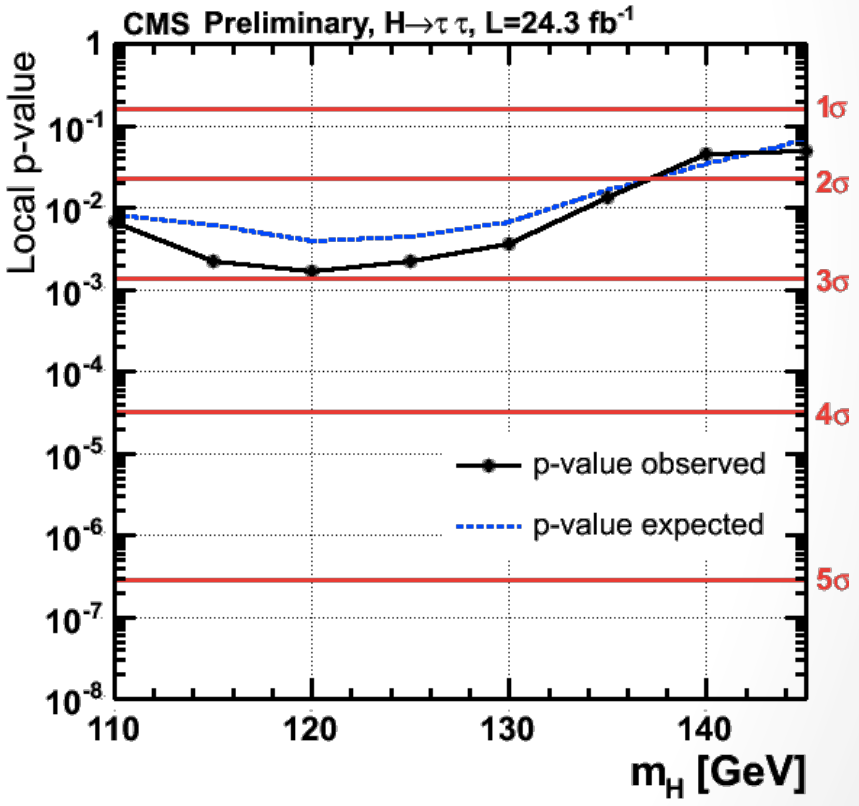

CMS HIG-13-004

Final states VBF + GF:
eμ, μμ, eτ$_h$, μτ$_h$, τ$_h$τ$_h$

Also, VH (WH & ZH)
ℓℓτ$_h$, ℓτ$_h$τ$_h$, ℓℓτ$_h$τ$_h$

- A 2.9σ signal @ 125 GeV is emerging (expected 2.6σ)



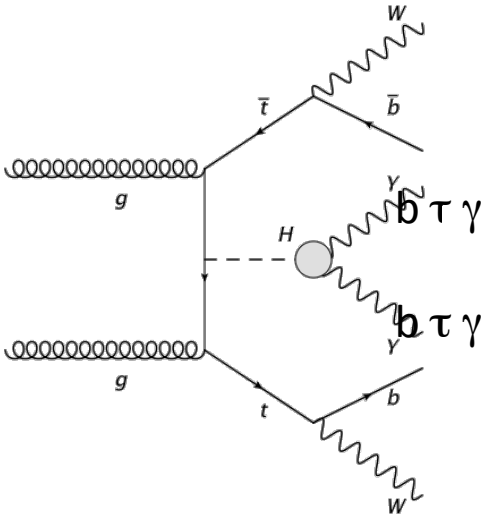



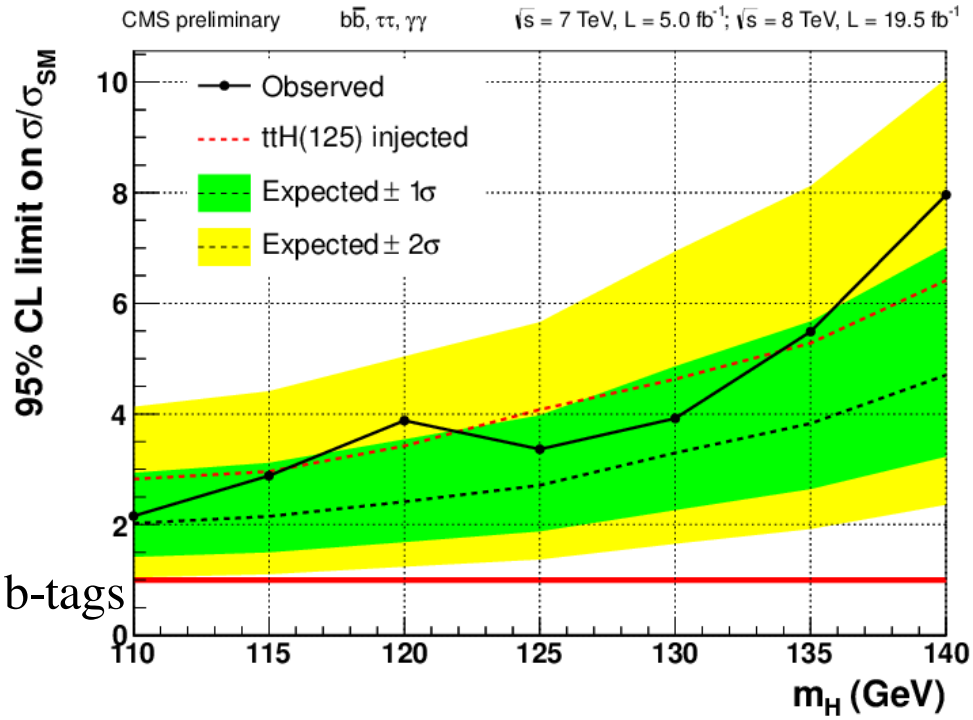

- 3.4σ evidence for fermion coupling combined with bb.

CMS HIG-13-019

# Direct Search for Top Coupling

Search for decays to two b-jets, τ-pairs or γ-pairs accompanied with top-pair




MVA + Classes $(lj,\ 2l,\ 2\tau)$ with b-tags

$ttH(bb) \rightarrow l + 4b + 2j + \nu$

$ttH(bb) \rightarrow 2l + 4b + 2\nu$

$ttH(bb) \rightarrow 2\tau + 4b + 2\nu$

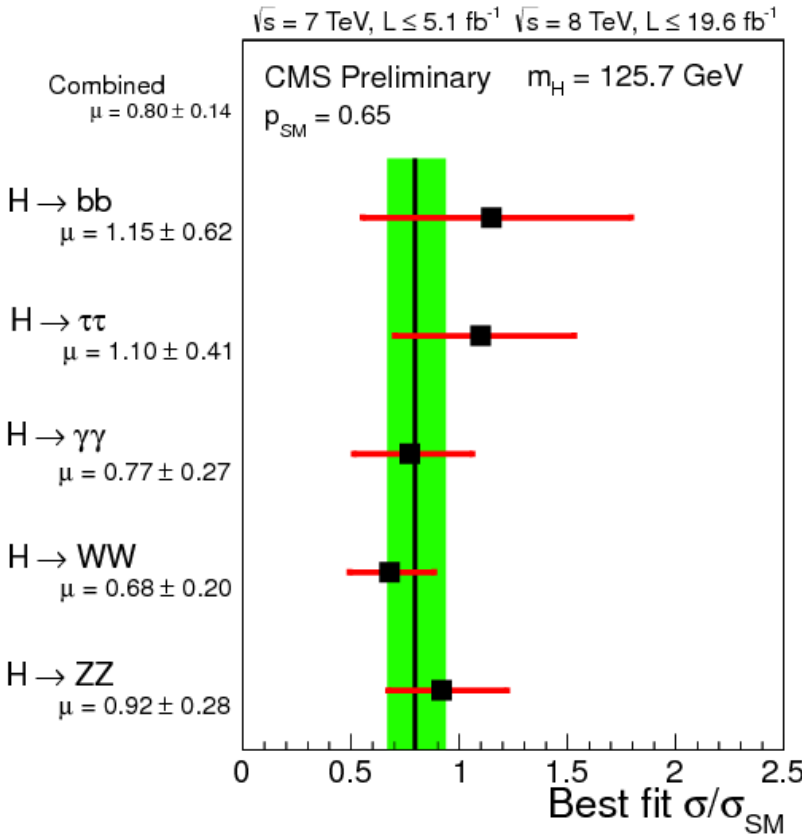
$ttH(\tau\tau) \rightarrow 2\tau + 4j + 2b$

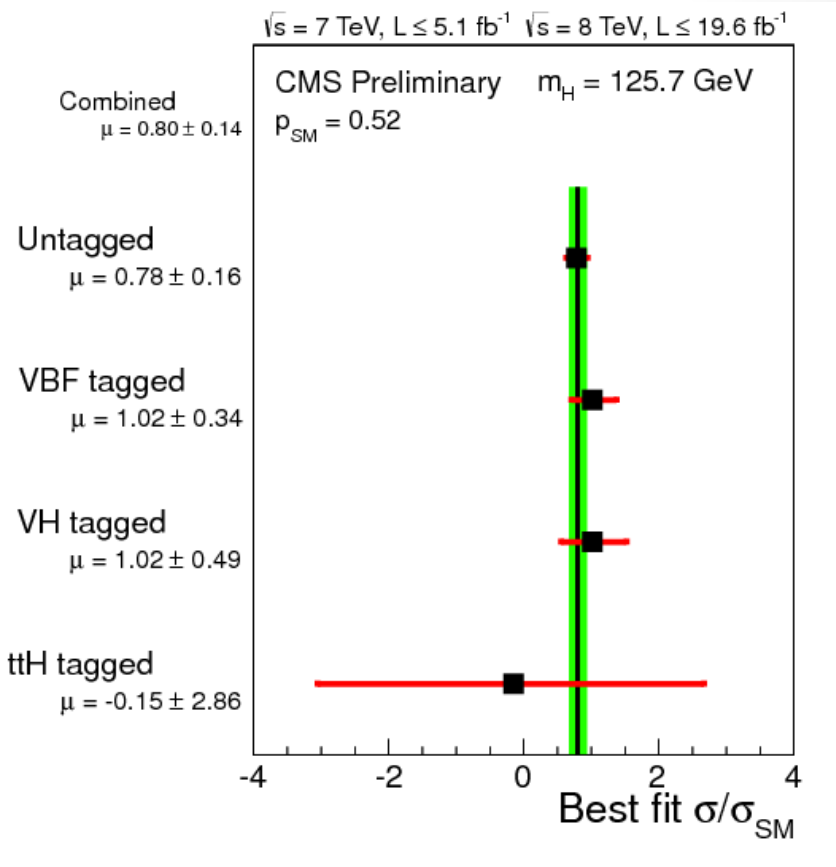
Not at SM sensitivity level yet, but compatible with injected signal of $M_H$=125 GeV

# Standard Model Combination

CMS HIG-13-005

# SM Higgs Signal Strength (25 fb$^{-1}$)




- All channels compatible with SM Higgs hypothesis, both for decay and production modes
- Will improve sensitivity in Run2

CMS HIG-13-005

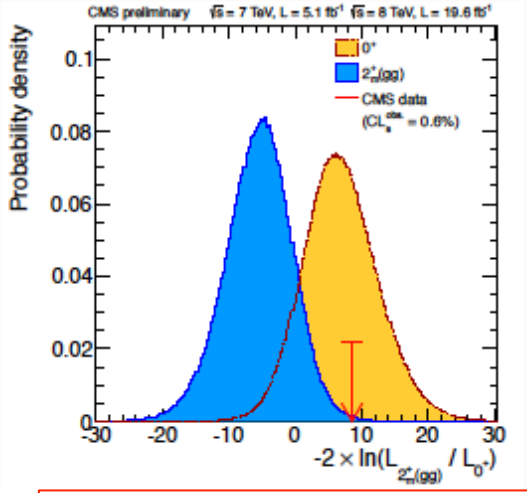
# Higgs Properties: Mass, Couplings, Spin

**Mass of the observed state**

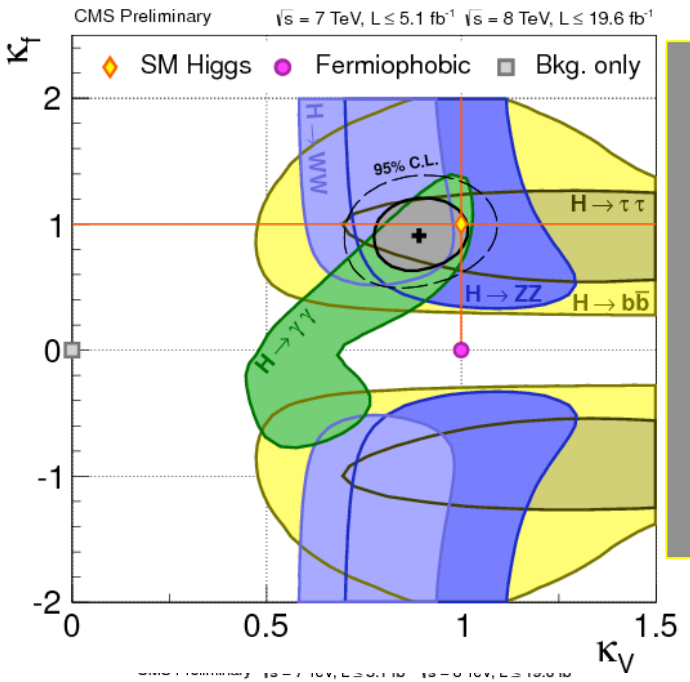
$m_X = 125.7 \pm 0.3$ (stat.) $\pm 0.3$ (sys.) GeV = **125.7 ± 0.4 GeV**

Several alternative models: $0^-$, $1^+$, $1^-$, $2^+$ tested against the SM Higgs $0^+$ hypothesis

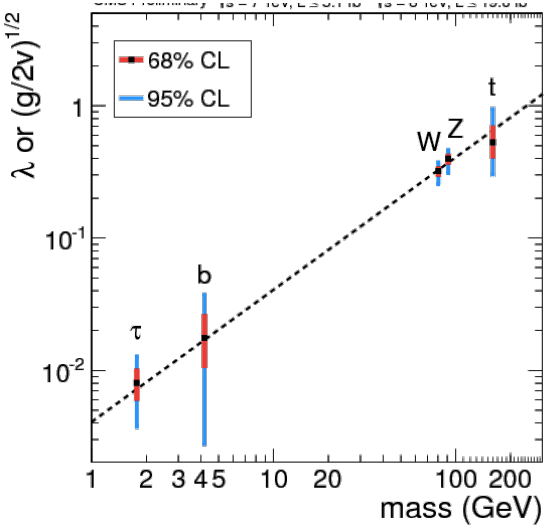
Example $0^+$ vs $2^+$ (WW + ZZ)




Preferred solution: $0^+$ (SM)




Compatible at 20% level with SM Higgs



# Beyond the Standard Model

**There are many possibilities that change the precise predictions of the minimal higgs sector of the Standard Model**

- **Fourth (heavy) generation of fermions modify H couplings**
  - **Enhances SM4 higgs cross section over SM**
  - **Already ruled out in entire parameter space with 2011 data**
- **Fermiophobic – fermion mass of different origin than higgs**
  - **Changes low mass higgs production & decays dramatically**
  - **Also ruled out for 126 GeV object**

- **Beyond minimal higgs doublet field**
  - **Two higgs doublet model (2HDM)**
    - **Multiple higgs bosons: 3 neutral and 2 charged**
    - **Minimal Supersymmetric Model (MSSM) requires 2HDM**
  - **NMSSM, triplets … have even more higgses**
    - **Very light pseudoscalar higgs, Doubly charged …**
- **We are looking for additional Higgs bosons**

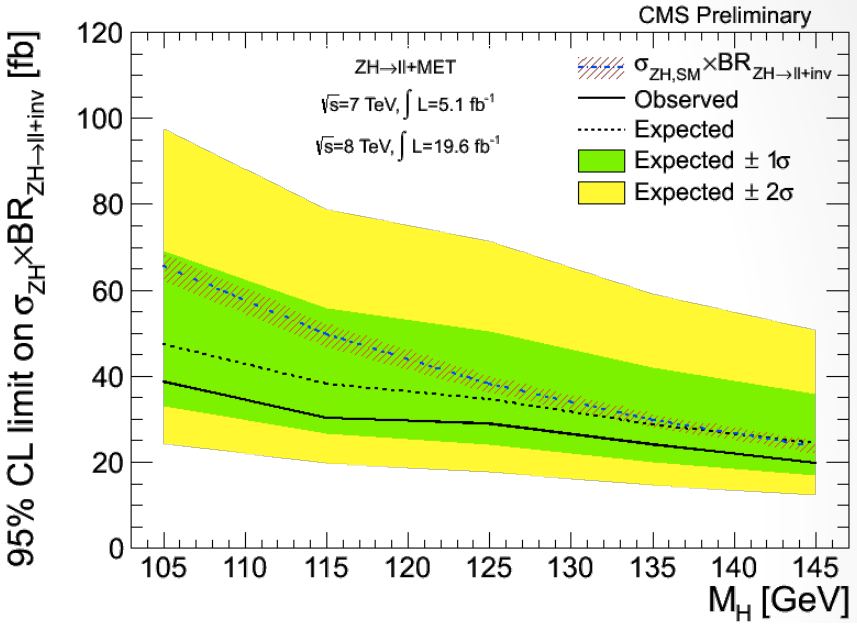
# H→Invisible: VH & VBF

CMS HIG-13-018

H associate production with Z(ℓℓ)

- Requiring high reduced $E_T^{Miss}$
  Balance of $P_T^{\ell\ell}$ and recoil
- Jet and additional lepton veto
- Analyze shape of $M_T$(Z,H)

95% CL upper limit on
BF(invisible) = 75% (91% expected)

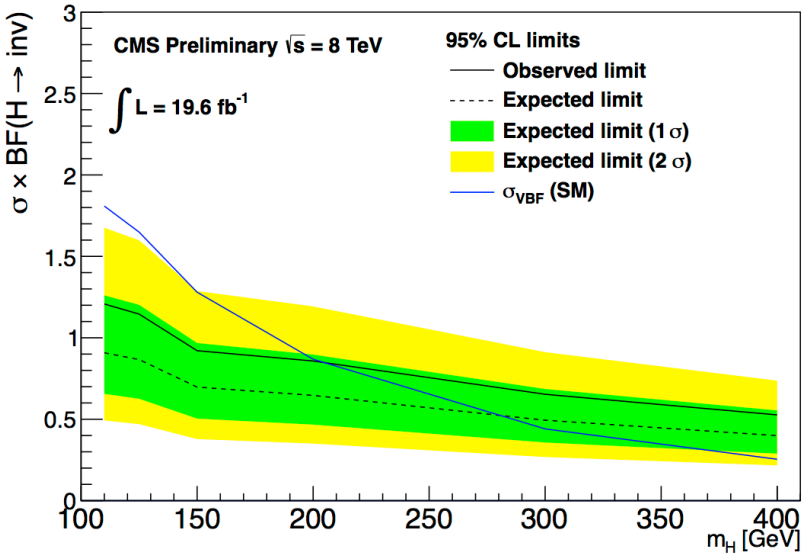



CMS HIG-13-013

VBF associated higgs production

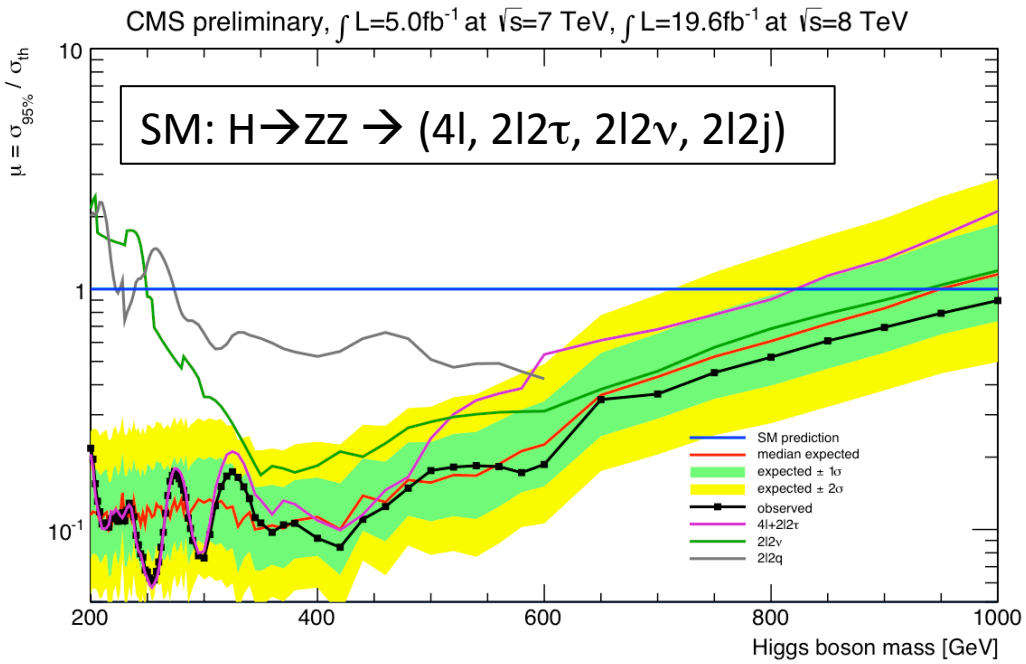
- Special VBF+MET triggers & big effort to reduce QCD BG
- Z(νν)+Jets background predicted using Z(μμ)

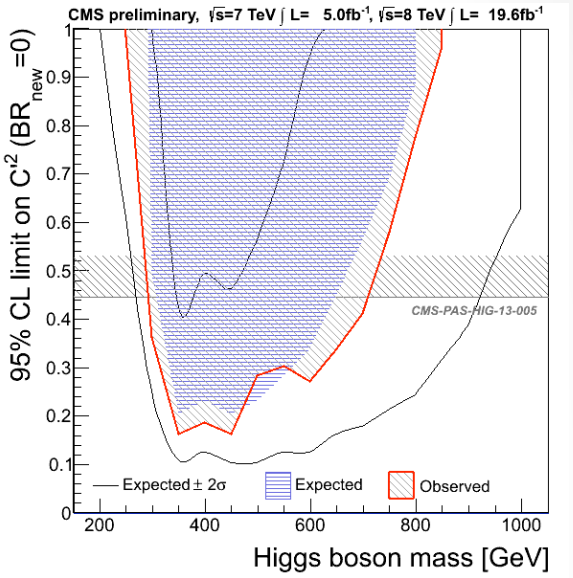
95% CL upper limit at 125 GeV on
BF(invisible) = 69% (53% expected)

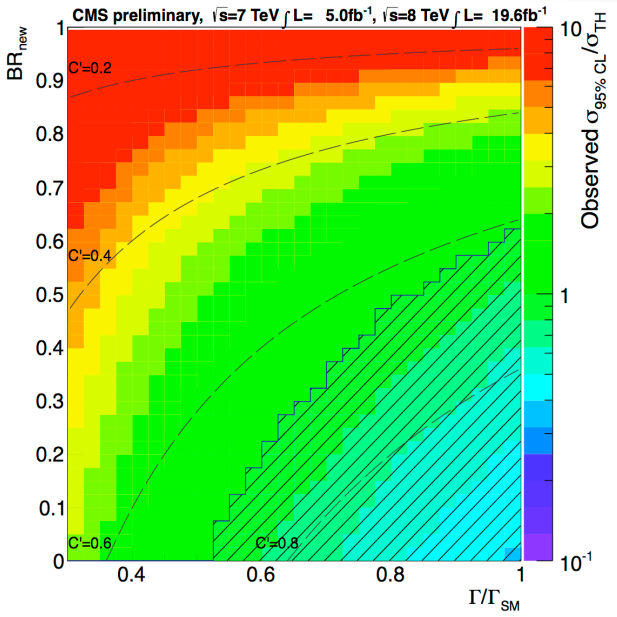


CMS HIG-13-014

# Search for a high mass higgs




- Search for EWK singlet partner of H(126)
- Assume similar gg/qq contributions to total production
- Scan different relative widths and BR

# Summary

- Impressive performance of the LHC and the CMS detector
- The CMS Collaboration successfully covered a large Higgs program over the past years
- The observation of the new boson was confirmed by the latest data
- Everything points to a SM-like Higgs
- Waiting for new data! 2015 will be the starting point for a new era: precision measurements of Higgs properties, new channels, BSM searches…

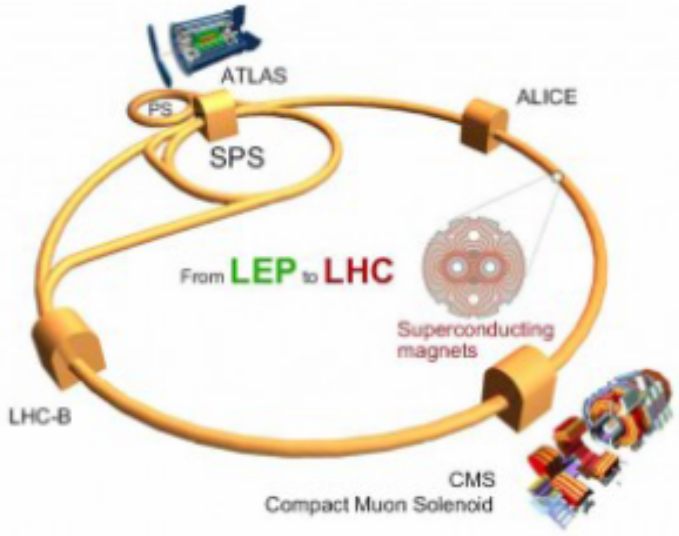
More details on the public CMS web page:
http://cms.web.cern.ch/org/cms-higgs/results

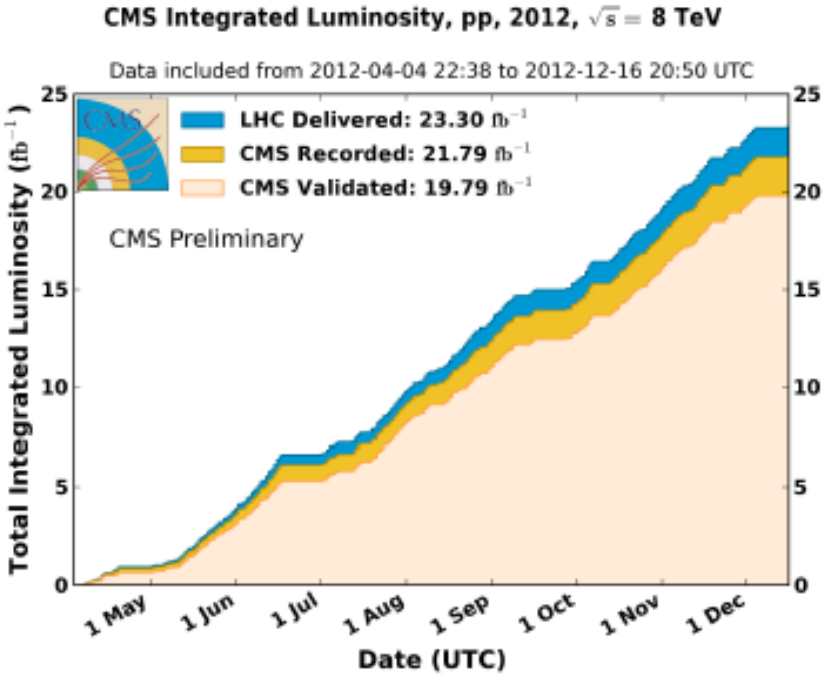
# BACKUP

# The LHC

## High luminosity pp collisions

- 2011: 6.1$fb^{-1}$ at 7 TeV
- 2012: 23.3$fb^{-1}$ at 8 TeV



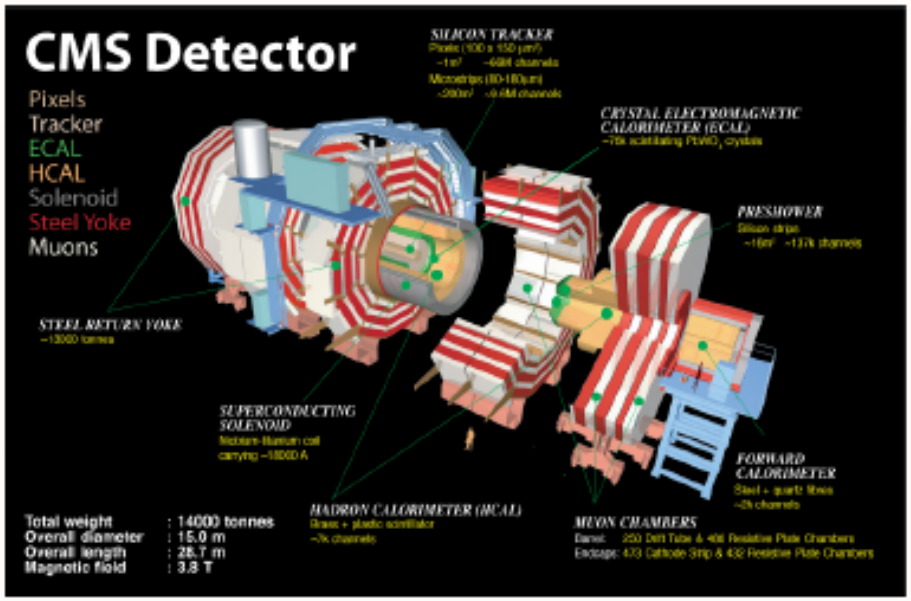




**Congratulations to the accelerator teams for the excellent performance !!**

# The CMS detector

CMS is a fast-electronics detector, embedded in a 3.8 T solenoid, providing a precise 3D event reconstruction.

- Inner Tracker (silicon pixel and strip detectors)
- ECAL ($PbWO_4$ crystals)
- HCAL (brass/scintillator samplers)
- Muon Chambers: Drift Tubes, Cathode Strips, and Resistive Plate Chambers

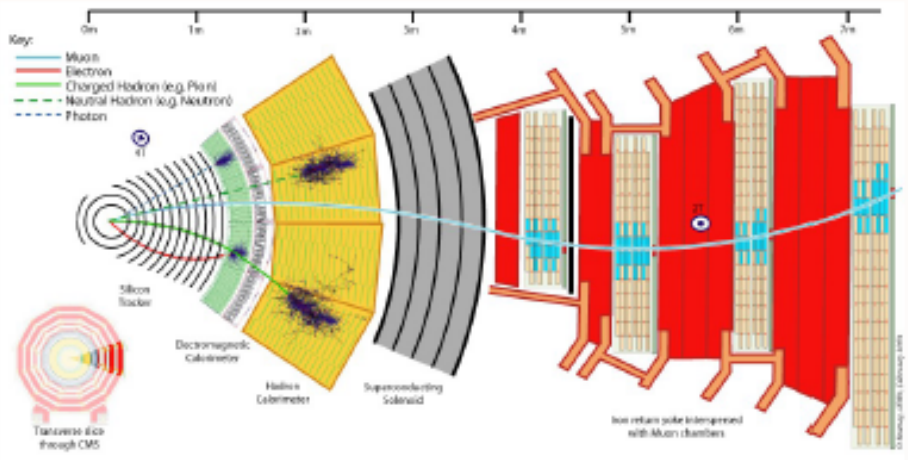



Taking data during 3 years with an efficiency above 96% in all subdetectors !!!!

# Object Reconstruction

The Particle Flow algorithm attempts to reconstruct all the individual particles in the event: photons, charged and neutral hadrons, electrons, and muons.

- Muon: Matching tracks in inner tracker and muon chambers
- Electron: EM cluster with an associated track
- Photon: EM cluster without an associated track
- Jet: Cluster in EM and hadronic calorimeters (and inner tracker)

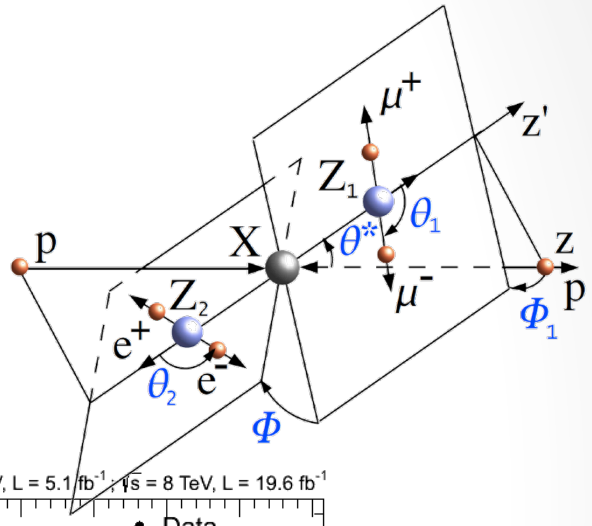


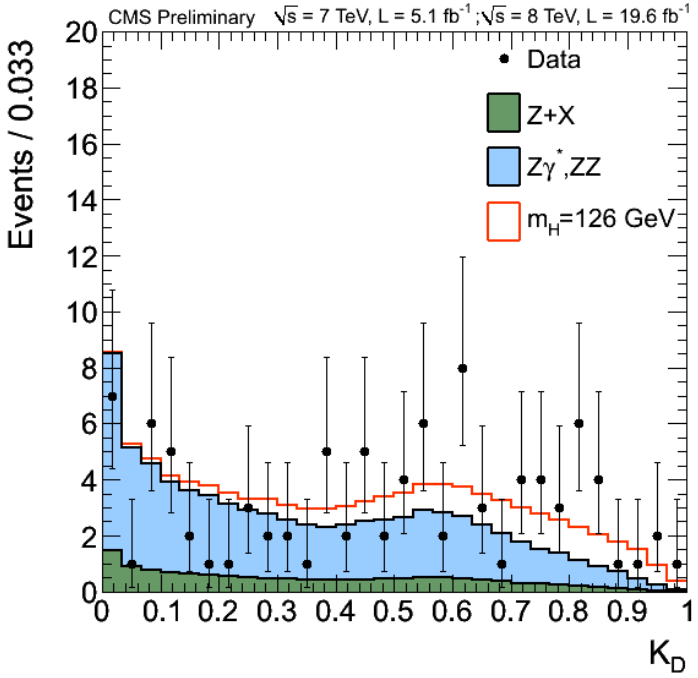

- Tau lepton : Narrow jet with matching track(s)
- MET: $p_T$ required to balance all of these

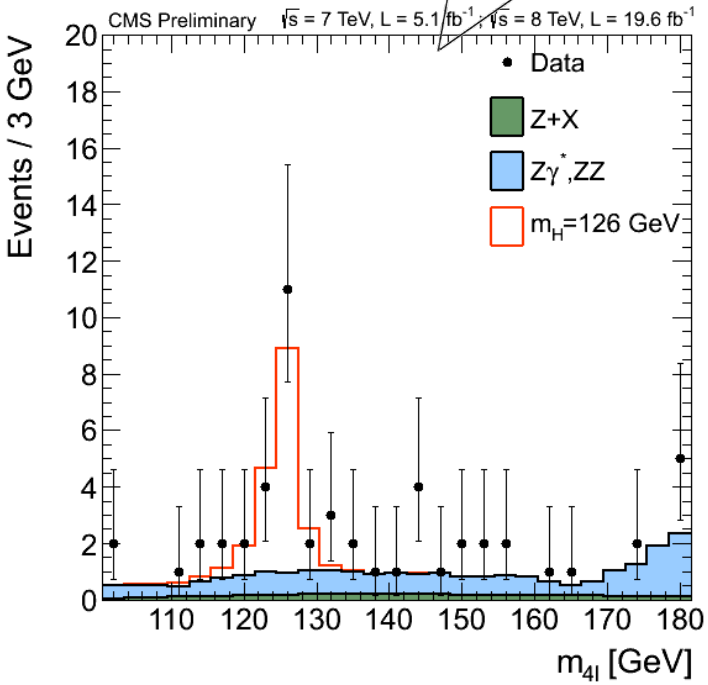
# H→ZZ

# H→ZZ→4l Kinematic Discriminant

- Decay angles carry information of scalar (SM H), pseudo-scalar vs spin-2 decay versus ZZ production → build kinematic discriminant KD
- Cut on KD cleans up signal and reduces background



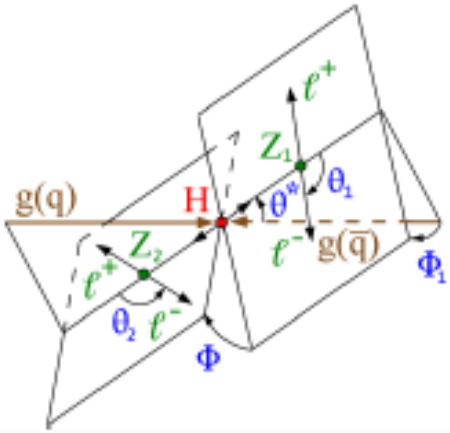



# Use Angular Information

- Reduce BG further & study additional properties of these events
  - Angles shown carry information of scalar (SM H), pseudo-scalar vs spin-2 decay versus ZZ production

**$J^P$-dependent Kinematic Discriminant ($K_D$)**

$$K_D = P_{sig}/(P_{sig} + P_{back}),$$

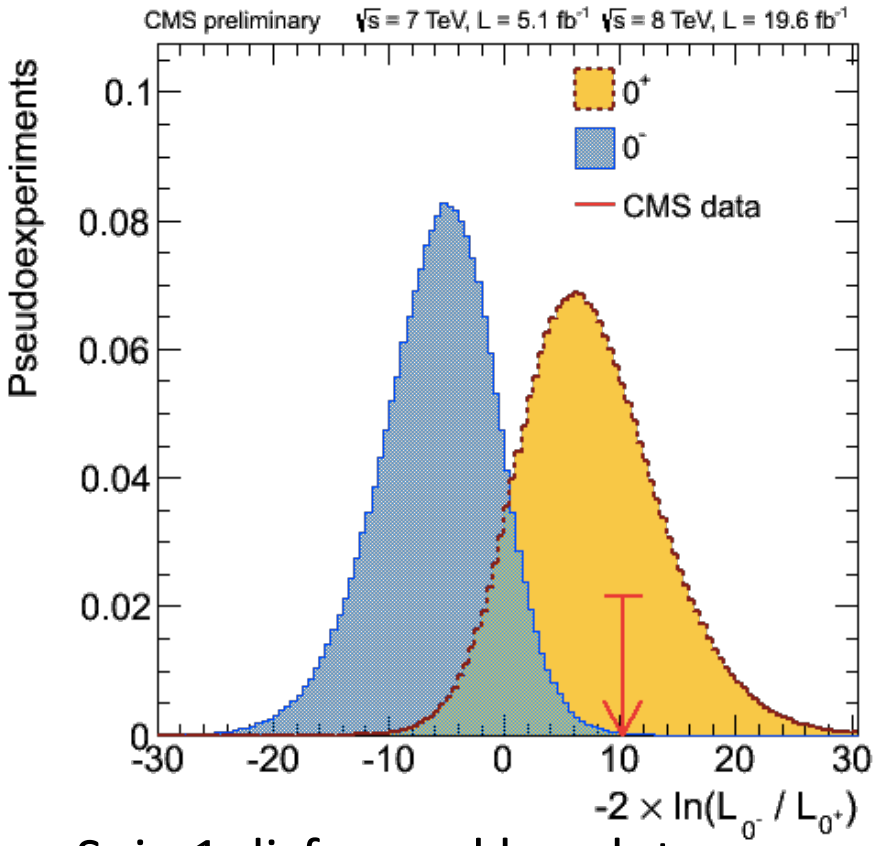


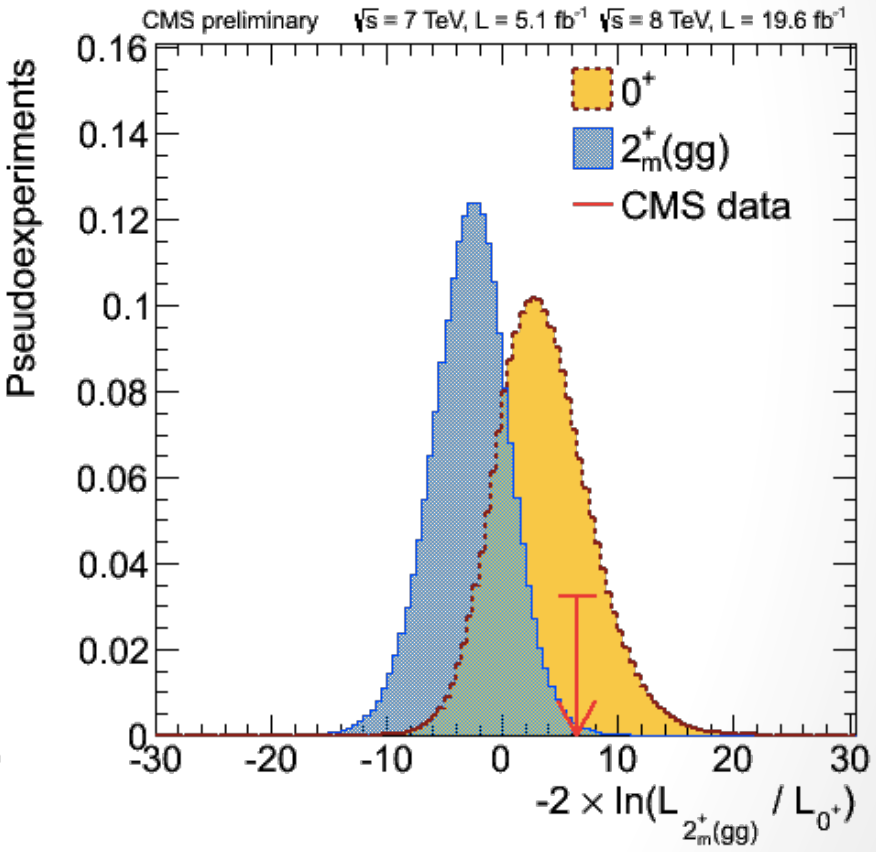

where

$$P_{sig,back} = f(m_1, m_2, \theta_1, \theta_2, \phi_1, \theta^*, \phi^* | m_{4l})$$

# The new boson is scalar like!

- Angular analysis of ZZ using KDs for $0^+$, $0^-$, 1 and $2^+$
- Disfavors $0^-$ over $0^+$ by $CL_S$ value of 0.16% and $2^+$ by 1.5%



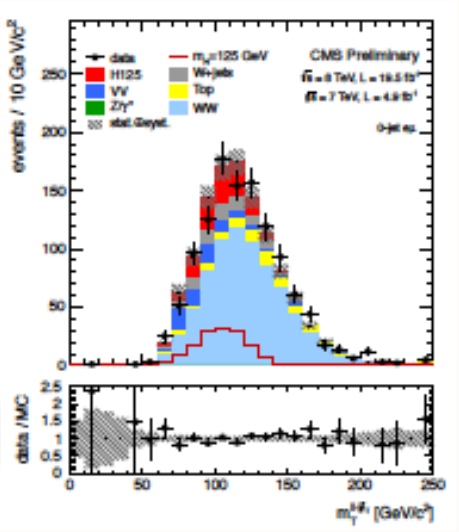

- Spin 1 disfavored by a lot

# H→WW

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

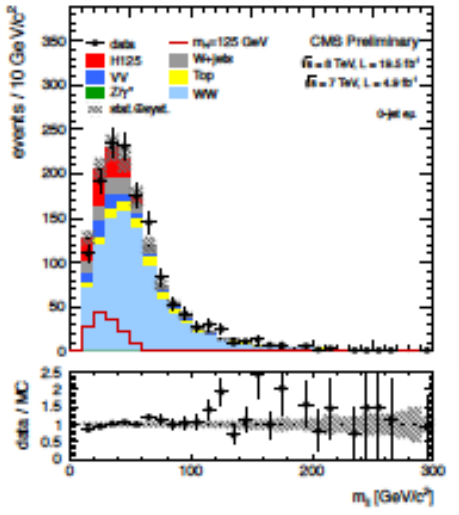
- Two high $p_T$ OS isolated leptons, large $\not{E}_T$, mass not reconstructed ($m_T$)
- Large branching ratio
- No mass peak

3 jet categories: 0,1 and 2 jets (**VBF**)




**Two analyses in the 0 and 1 jet category:**

- Same Flavour: Cut-based ($\Delta\phi_{ll}, p_T^{lmax}, p_T^{lmin} m_{ll}, m_T$)
- Different Flavour: 2D shape $m_T$ and $m_{ll}$



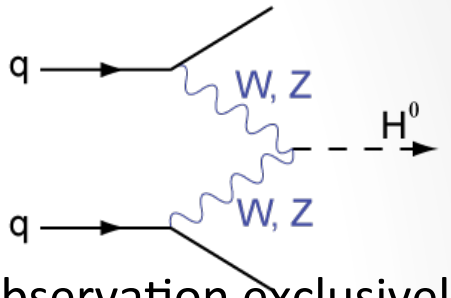

**Two analyses in the VBF category:** New

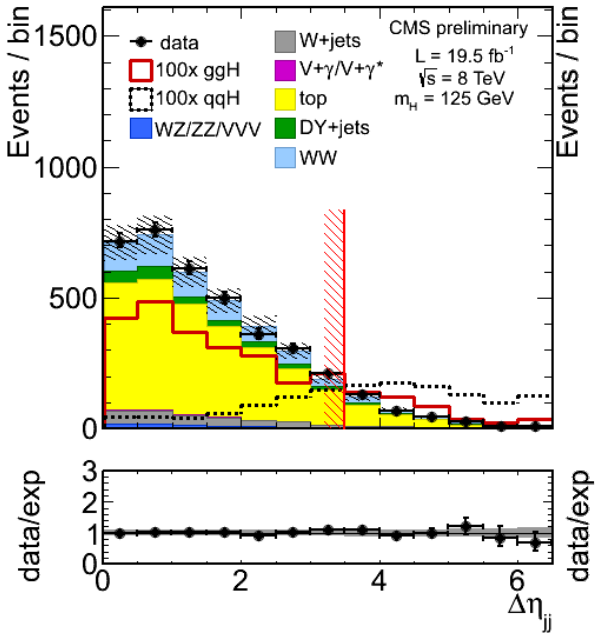
- Same Flavour: Cut-based
- Different Flavour: Shape analysis $m_{ll}$

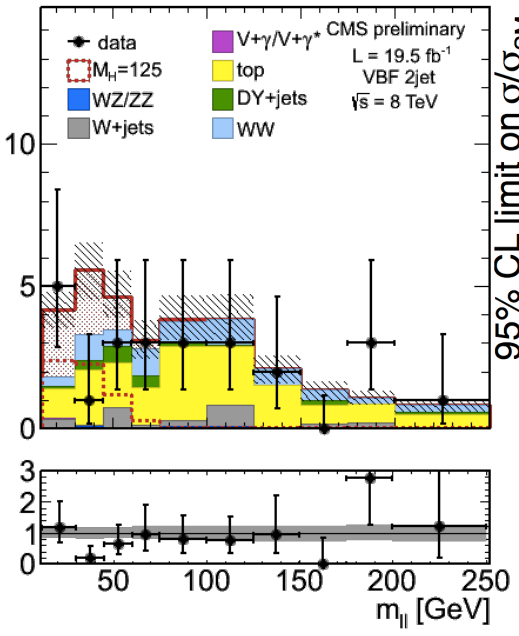
CMS HIG-13-022

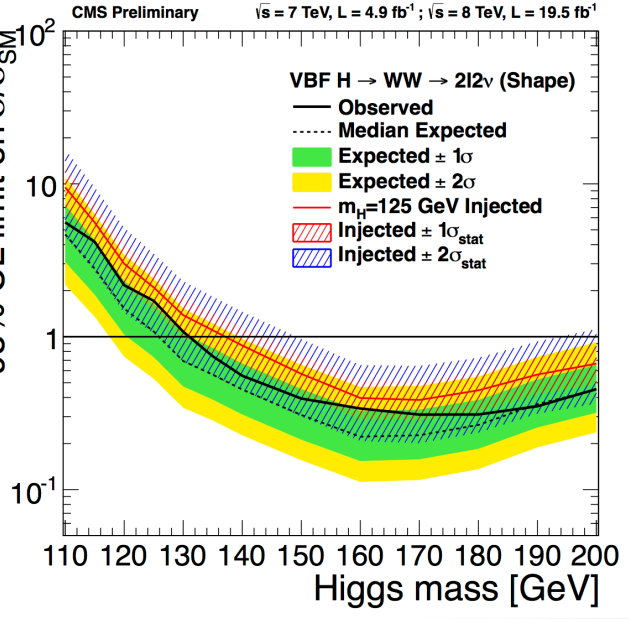
# VBF Production: H→WW → $l^+ l'^-$ MET

- VBF enhanced by requiring tag jets
  - Is the signal due to vector boson fusion?
  - Small excess observed
  - More data are required: ~100 $fb^{-1}$ at 13 TeV for observation exclusively in this channel



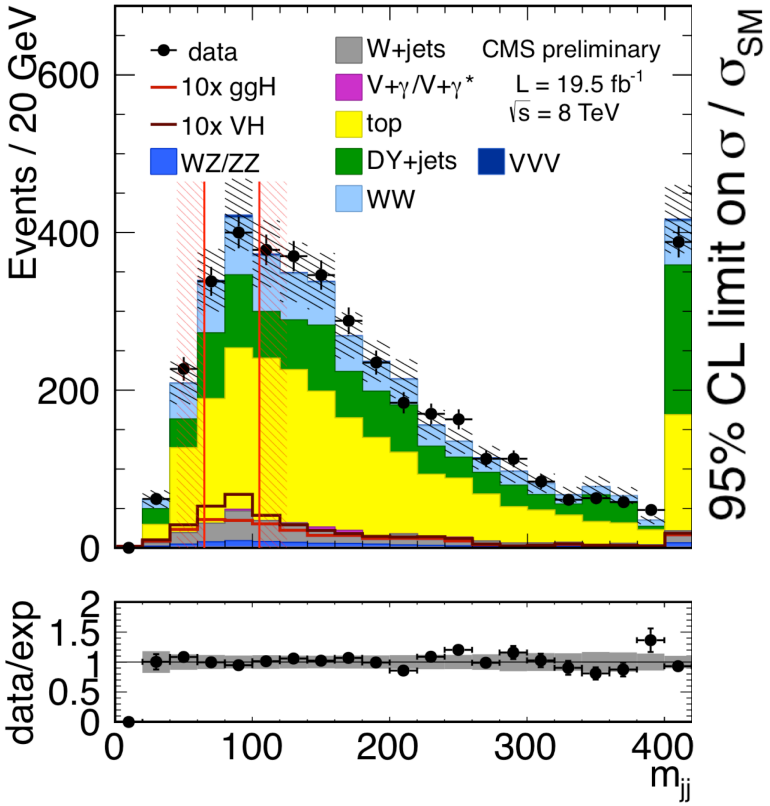



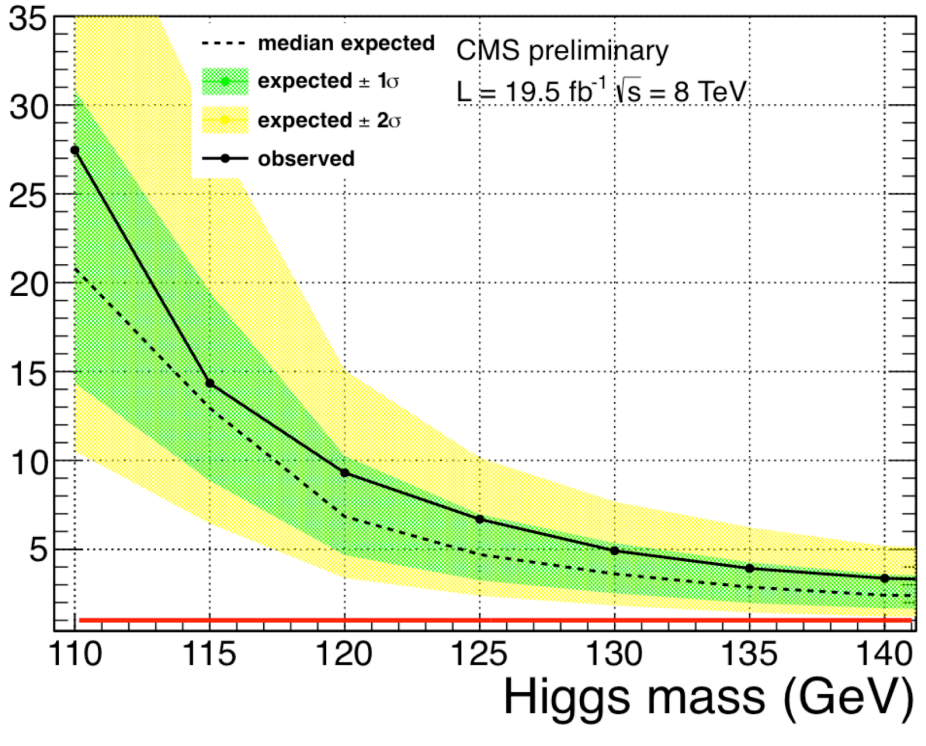



CMS HIG-13-017

# Search for VH, V→jj & H→WW → $l^+ l^-$ MET

- Interesting test of production of ggH vs VH
  - Not yet sensitive at expected SM level

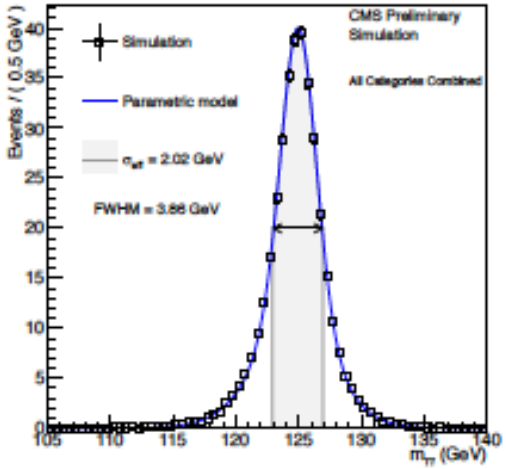


# $H \rightarrow \gamma\gamma$

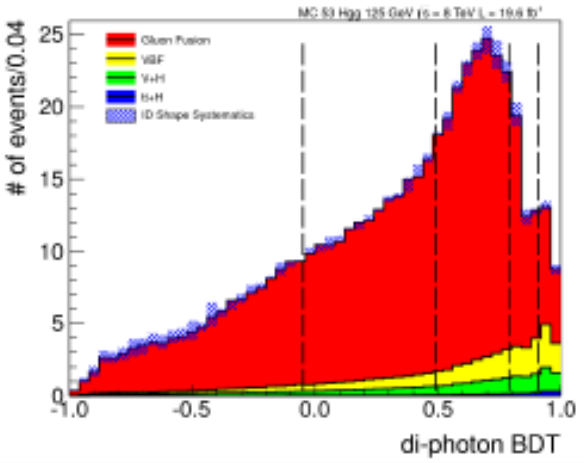
# $H \to \gamma\gamma$

- Two isolated high $p_T$ photons
- Search for a narrow mass peak, $m_{\gamma\gamma}$, in a steeply falling background distribution
- Small branching fraction




Two incusive analyses:

- MVA-based selection: MVA for $\gamma$ shower shape and isolation, kinematics and $m_{\gamma\gamma}$ resolution
- Cut-based selection (cross check)

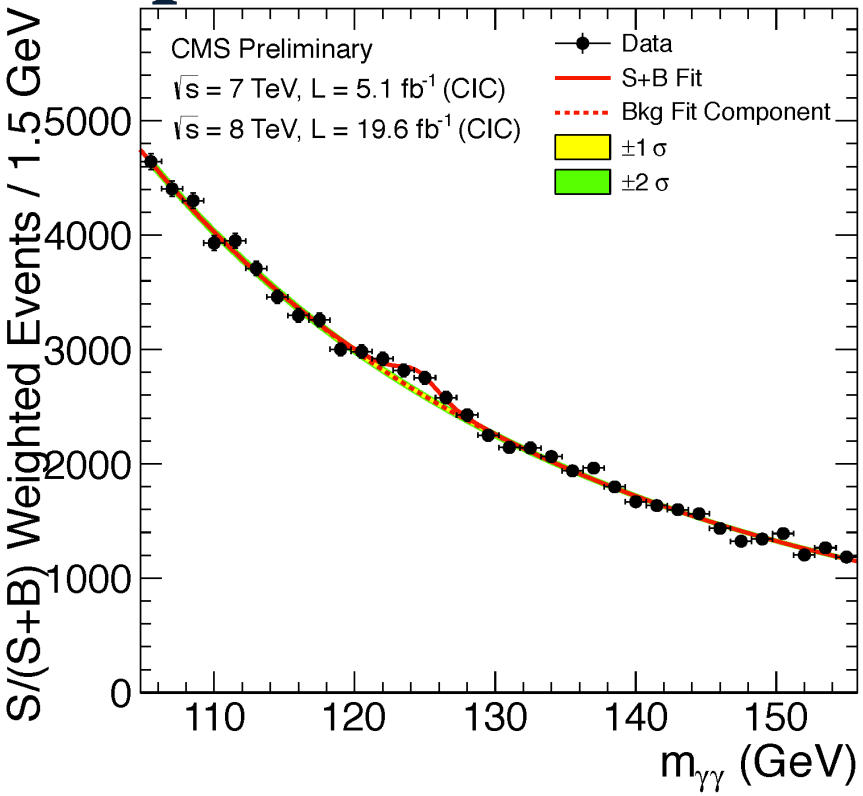


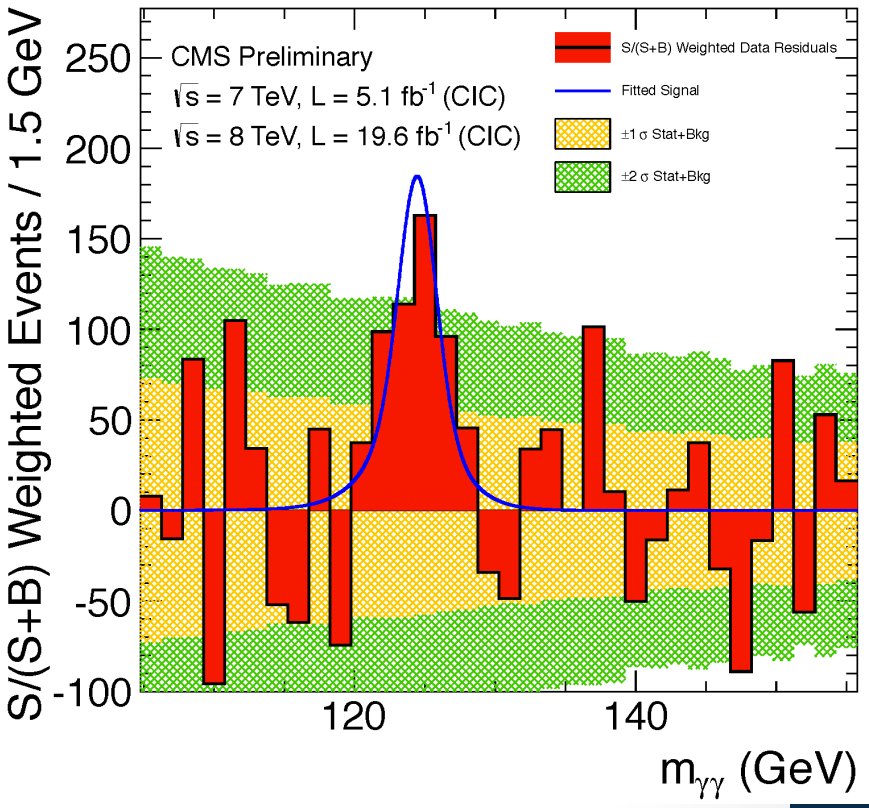

Exclusive analyses:

- VH: e, $\mu$, and MET
- VBF: 2 dijet categories

# Combined Weighted γγ Spectrum

CMS HIG-13-001




Cuts in Categories combining all categories and both years

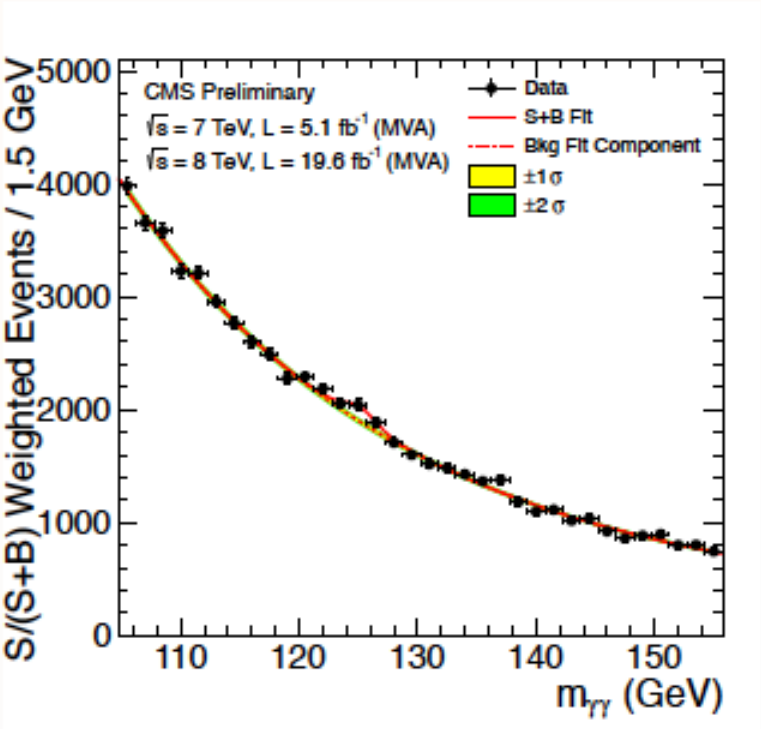
Cross-check Analysis with lower sensitivity, but is simpler in some respects.

The best-fit signal strength, $\sigma/\sigma_{SM}$: 1.11±0.31 at $m_H$=124.5 GeV

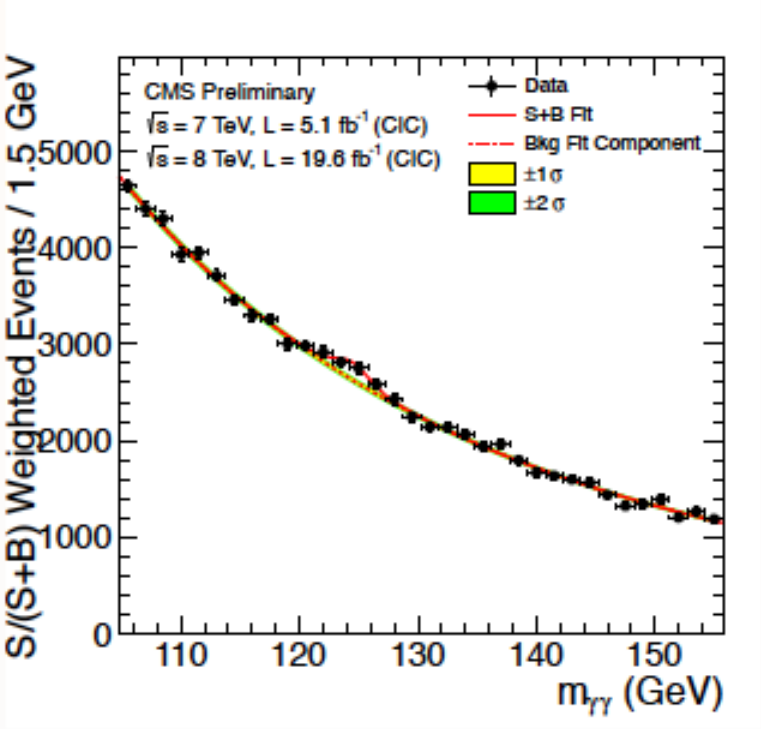
# $H \to \gamma\gamma$

**Weighted mass distributions (for visualisation only).**

Events weighted by the S/(S+B) of its category.



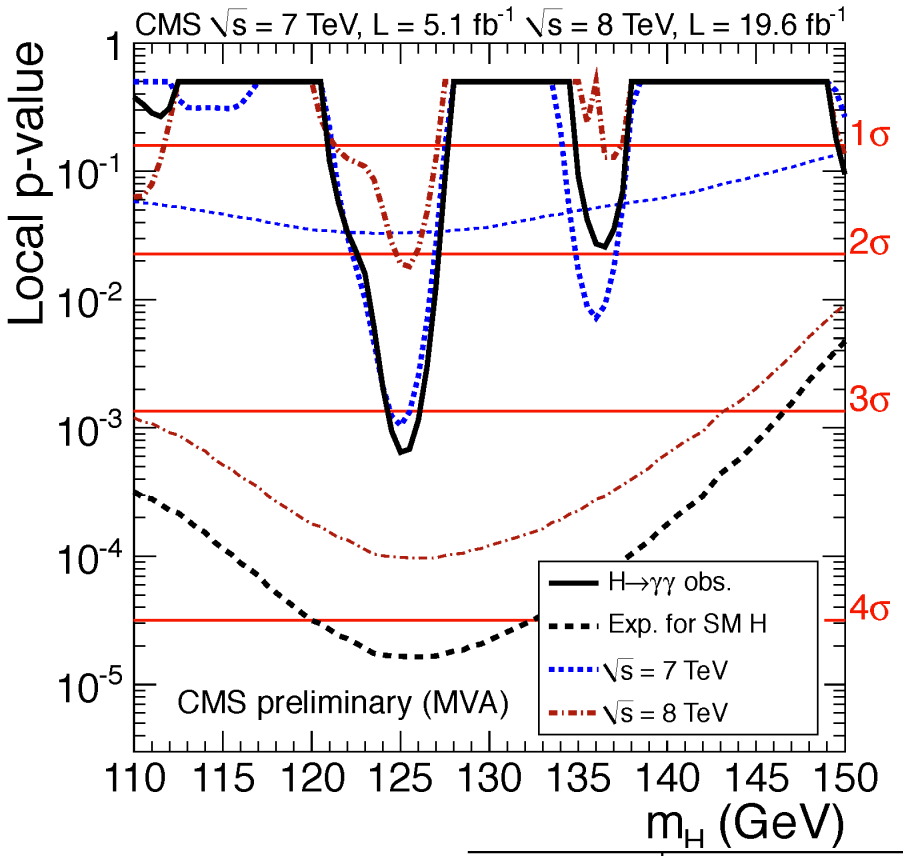

**MVA analysis**

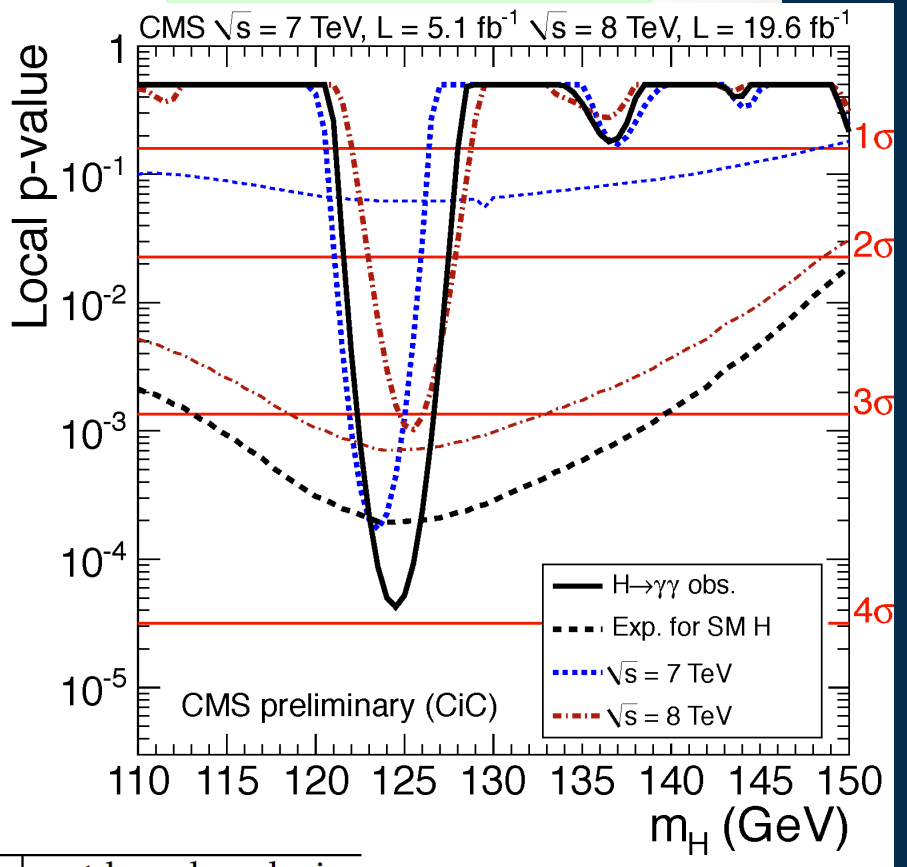



**Cut-based analysis**

# Signal Significance & Strength

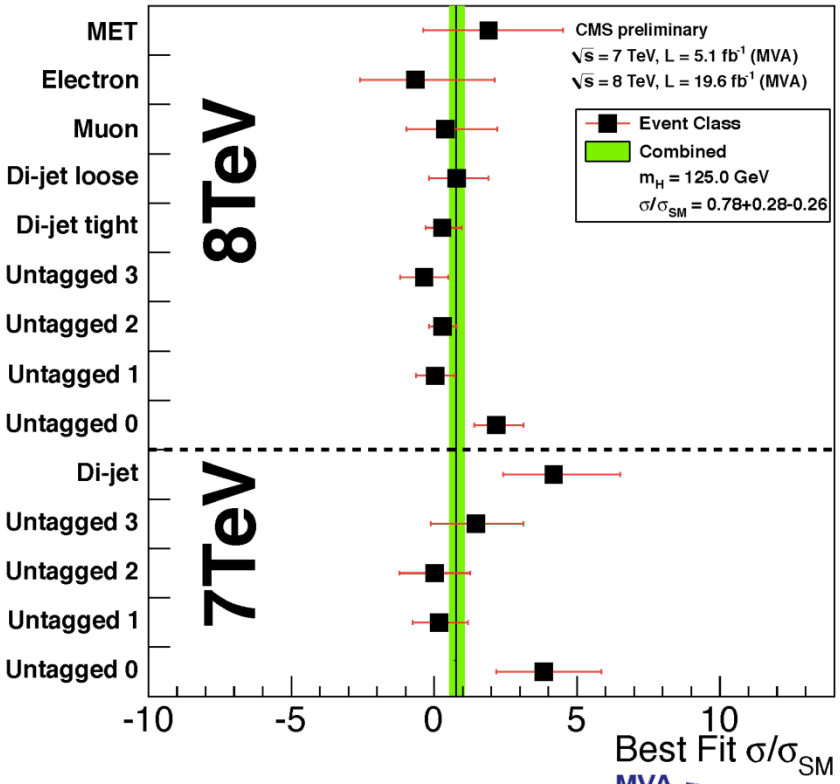
CMS HIG-13-001

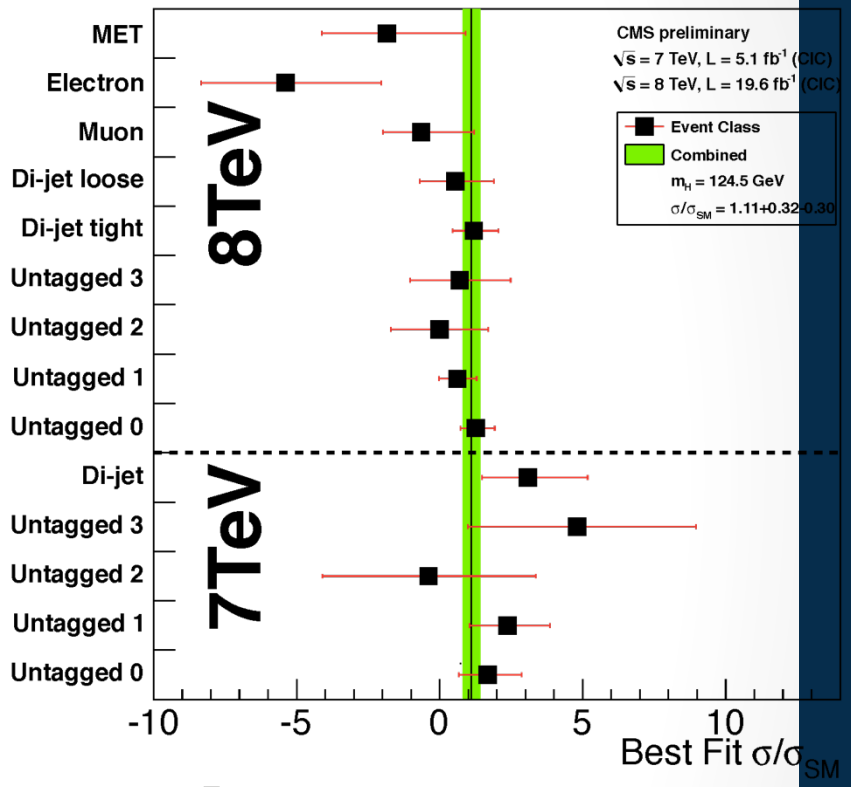


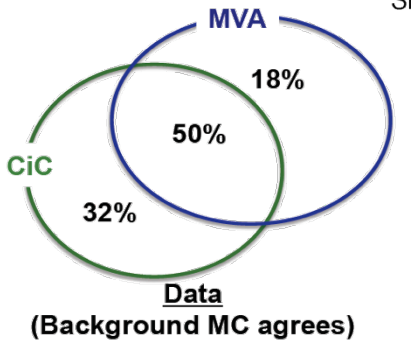



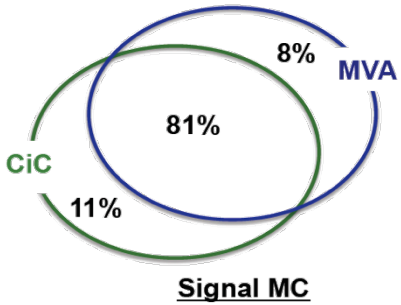

| | MVA analysis (at $m_H$=125 GeV) | cut-based analysis (at $m_H$=124.5 GeV) |
|---|---|---|
| 7 TeV | $1.69^{+0.65}_{-0.59}$ | $2.27^{+0.80}_{-0.74}$ |
| 8 TeV | $0.55^{+0.29}_{-0.27}$ | $0.93^{+0.34}_{-0.32}$ |
| 7 + 8 TeV | $0.78^{+0.28}_{-0.26}$ | $1.11^{+0.32}_{-0.30}$ |

# Signal Strength by Event Class



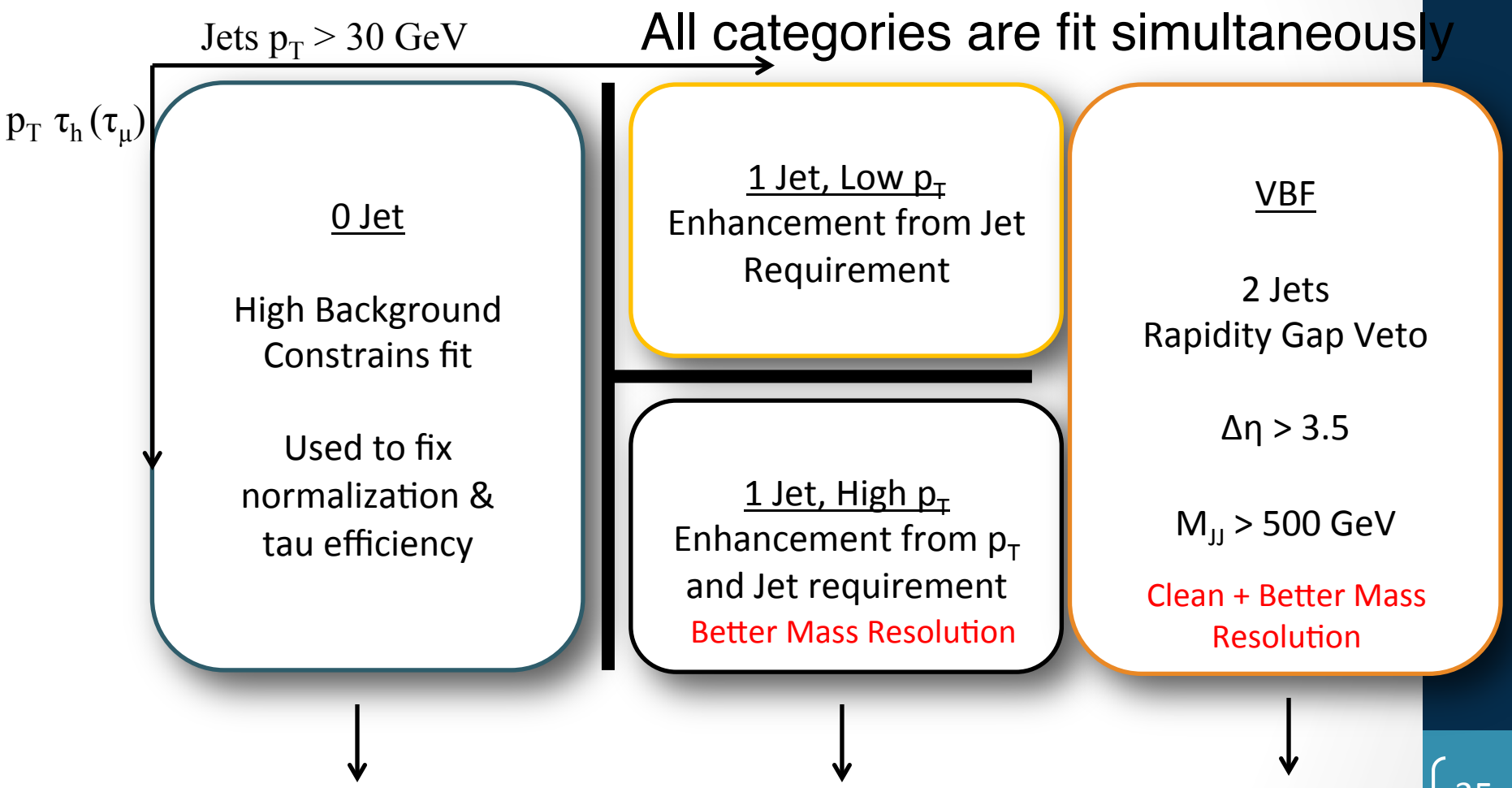



# $H \rightarrow \tau\tau$

# VBF / GF Event Characterization



# $H \to \tau\tau$

**Final states:**

$\mu\tau_h, e\tau_h, \tau_h\tau_h, \mu\mu, e\mu, VH(\tau\tau)$

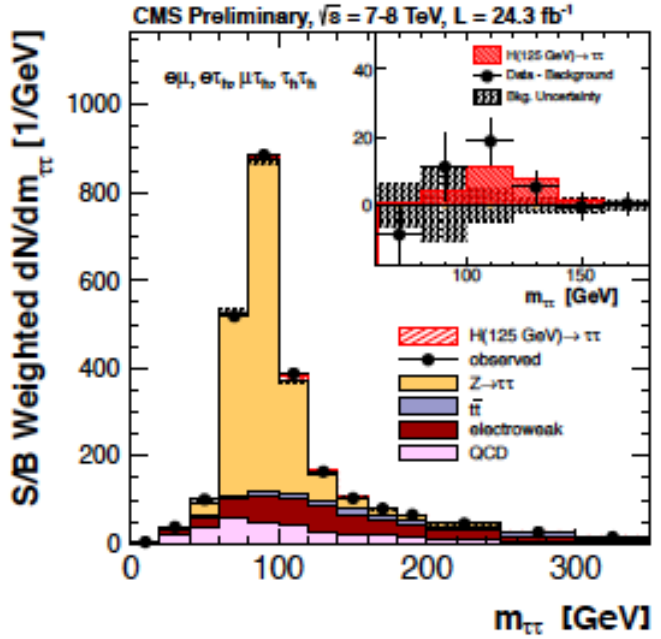
Divided in jet categories: 0 jet (control), 1 jet, and 2 jets (VBF)

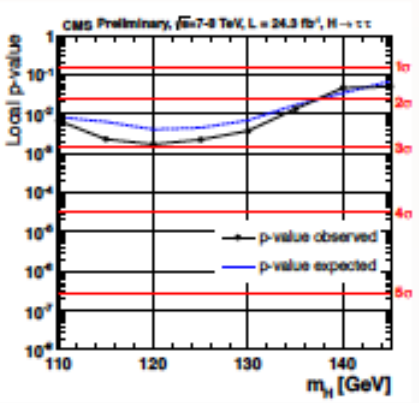
Broad excess compatible with a Higgs signal at low mass.

**Significances for $m_H$=125 GeV:**
observed 2.9$\sigma$, expected 2.6$\sigma$

**Signal strenght:** $\sigma/\sigma_{SM} = 1.1 \pm 0.4$

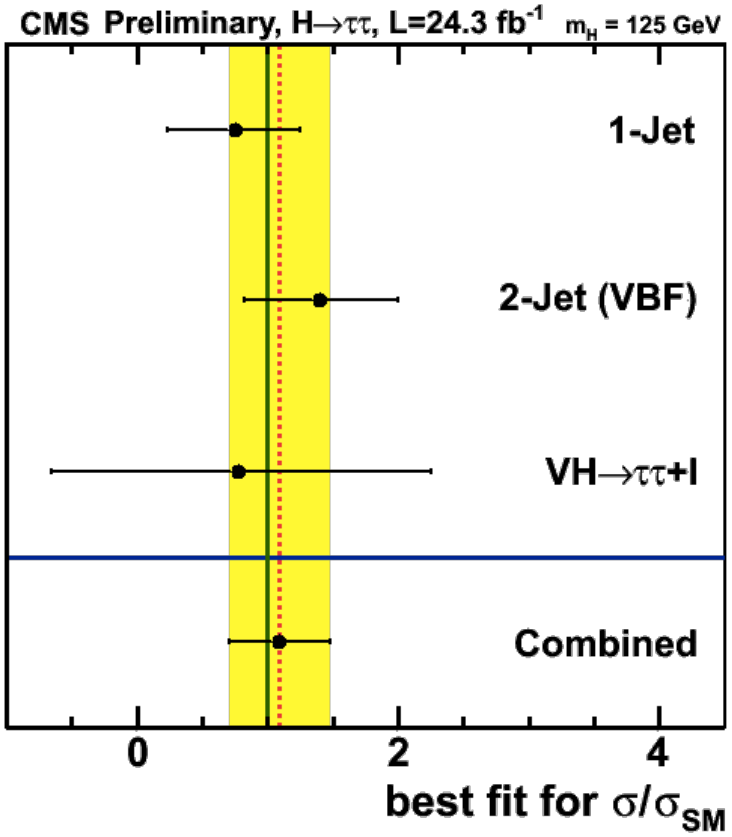
Combined with VH($b\bar{b}$): 3.4$\sigma$ evidence for H to fermions coupling

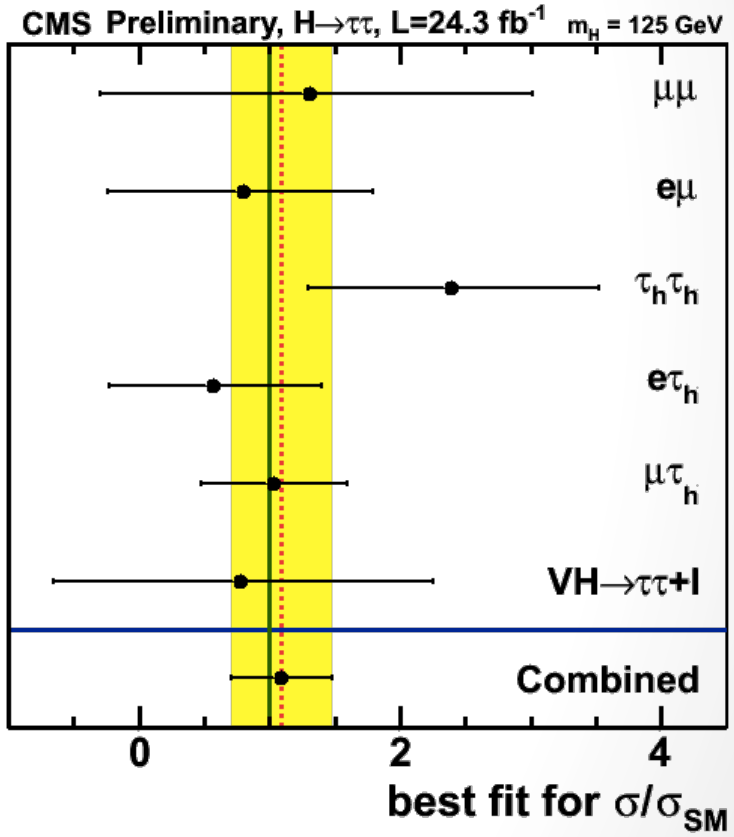


# Signal Strength for H to ττ

- Breakdown by category & by channel



# H→bb

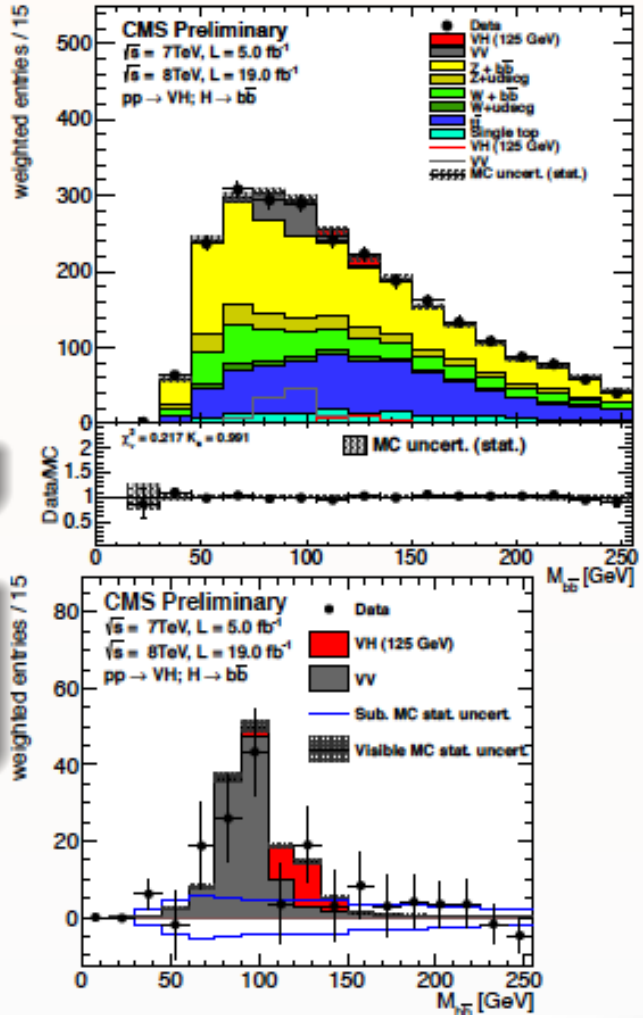
# VH($b\bar{b}$)

- Final state with 2 central b-jets plus the decay products of the associated V (leptons and/or $\nu$'s)
- Main backgrounds: V+jets, VV, top.

**Important to test coupling to fermions**

**Signal optimization:** BDT shape analysis based on jet and V kinematics, and b tagging.

Dijet ($b\bar{b}$) mass distribution for all the channels combined, weighted according to its S/(S+B)

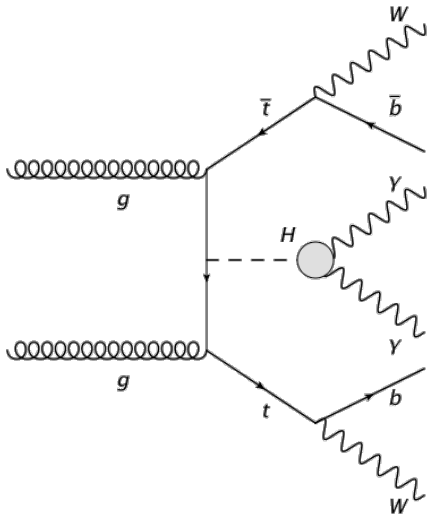


# ttH

CMS HIG-13-015

# Direct Search for Top Coupling

Search for Higgs decay to two photons with top-pair

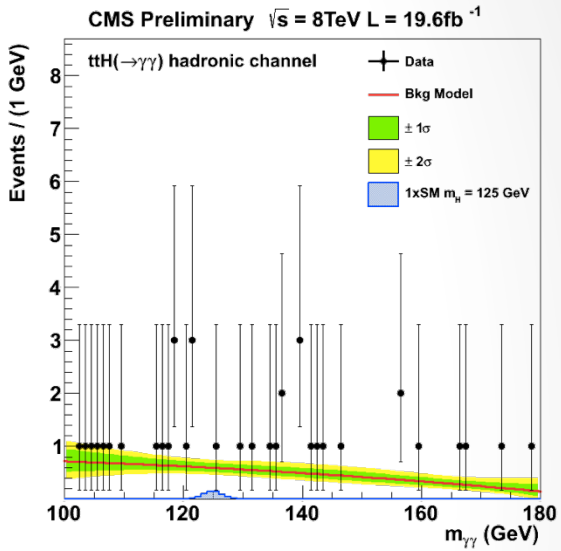


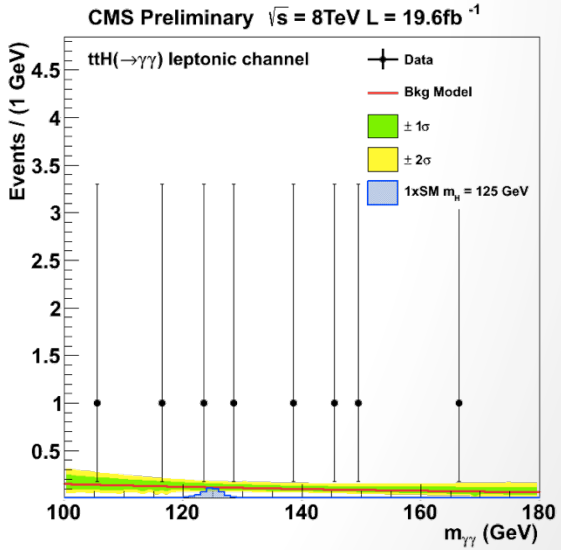

Hadronic:

4j, 2b, 2γ

Leptonic:

2ℓ, MET, 2γ




| Process | Hadronic Channel | Leptonic Channel |
|---|---|---|
| $t\bar{t}H$ | 0.567 (87%) | 0.429 (97%) |
| $gg \to H$ | 0.059 (9%) | 0 (0%) |
| VBF $H$ | 0.006 (1%) | 0 (0%) |
| $WH/ZH$ | 0.019 (3%) | 0.013 (3%) |
| Total signal | 0.65 | 0.44 |

# ttH($\gamma\gamma$)

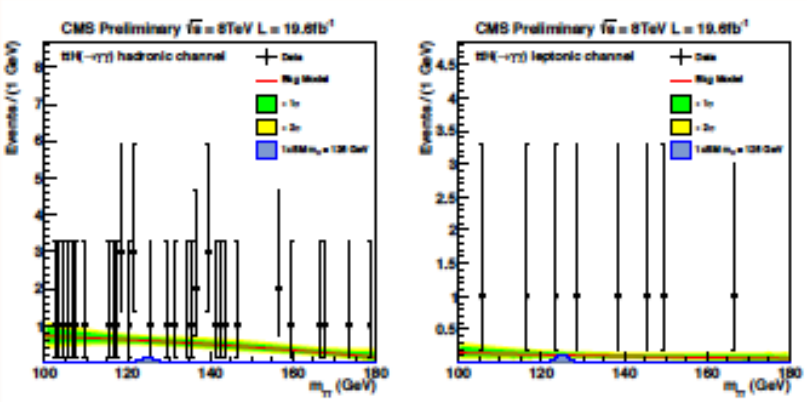
Two different analyses to maximize the sensitivity:

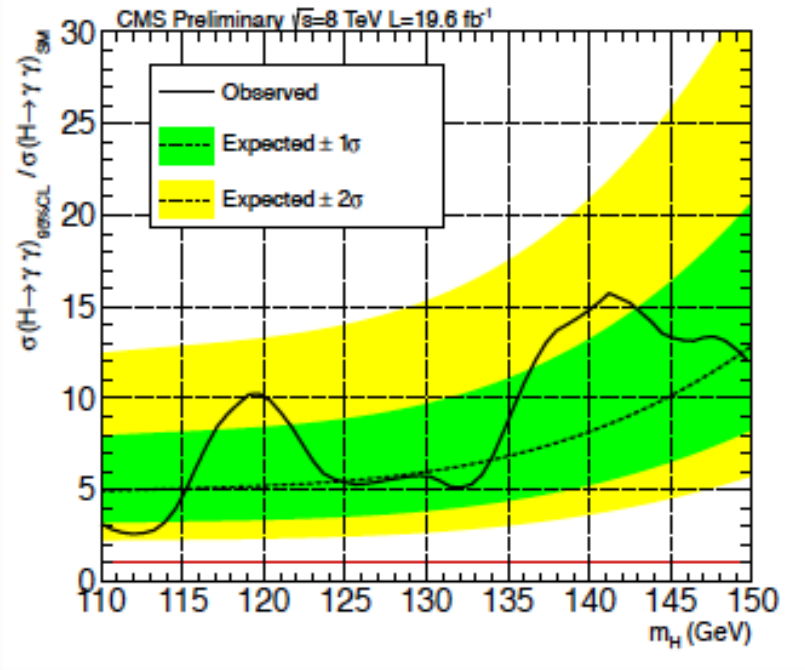
- Leptonic $t\bar{t}$ decays
- Hadronic $t\bar{t}$ decays

**Search for a narrow peak in the diphoton mass distribution**

**Limits @125 GeV:**

- Observed: 5.4 $\times\sigma_{SM}$, 95% CL
- Expected: 5.3 $\times\sigma_{SM}$, 95% CL



# ttH($b\bar{b} + \tau\tau$)

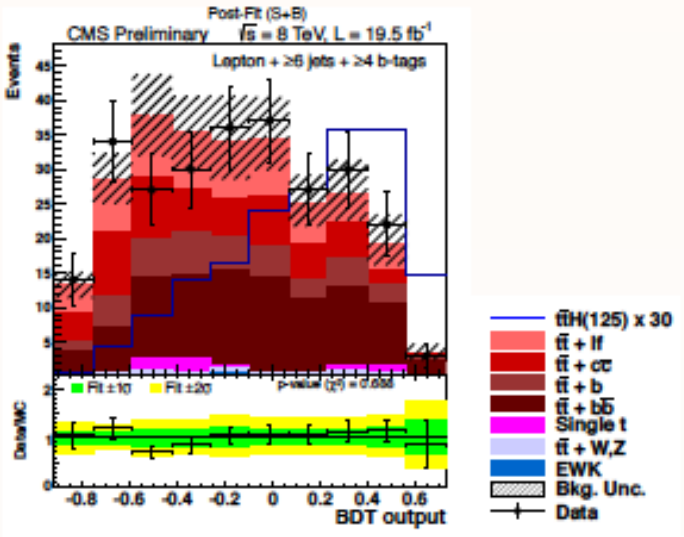
- H$\to b\bar{b}$: 2 or more b jets; tt in the dilepton and lepton+jets channels
- H$\to \tau\tau$: $\tau_h\tau_h$; tt into lepton+jets (with 1 or 2 b-tagged jets)

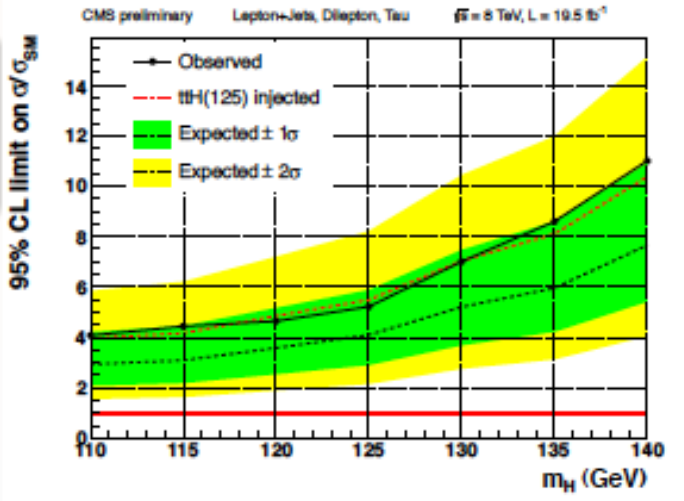
Analysis performed in several categories divided in jet and b-jet multiplicity

Signal optimization via BDT's based mainly in kinematics and b-tag information.

**Limits @125 GeV:**

- Observed: 5.2 $\times\sigma_{SM}$ @ 95% CL
- Expected: 4.1 $\times\sigma_{SM}$ @ 95% CL



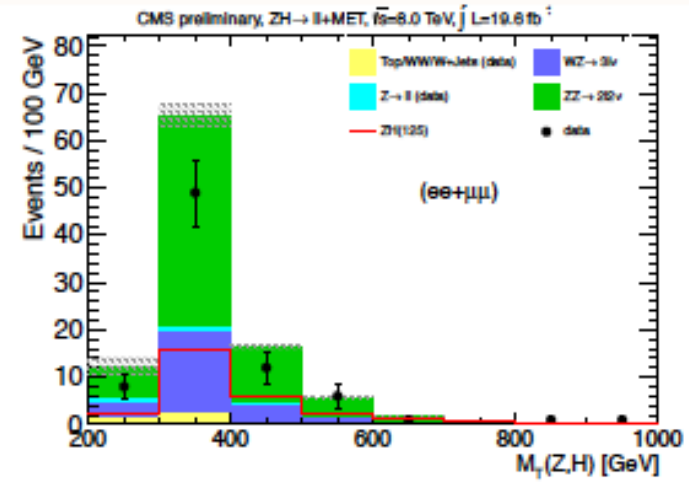



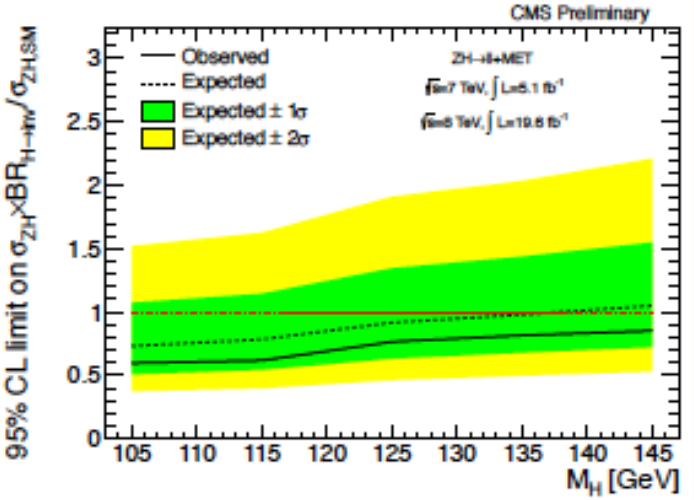
# H→Invisible

# Higgs to invisible

- Higgs decaying into invisible particles i.e. non-SM decays
- You can always find a model that predicts such a decay, and anything you want :-)
- Search for associated production with a Z boson
- Z boson decaying into leptons (ee, $\mu\mu$)

**For $m_H$ = 125 GeV:**
BR(H $\rightarrow \chi\chi$) $<$ 75% ($<$ 91% expected) @ 95% CL



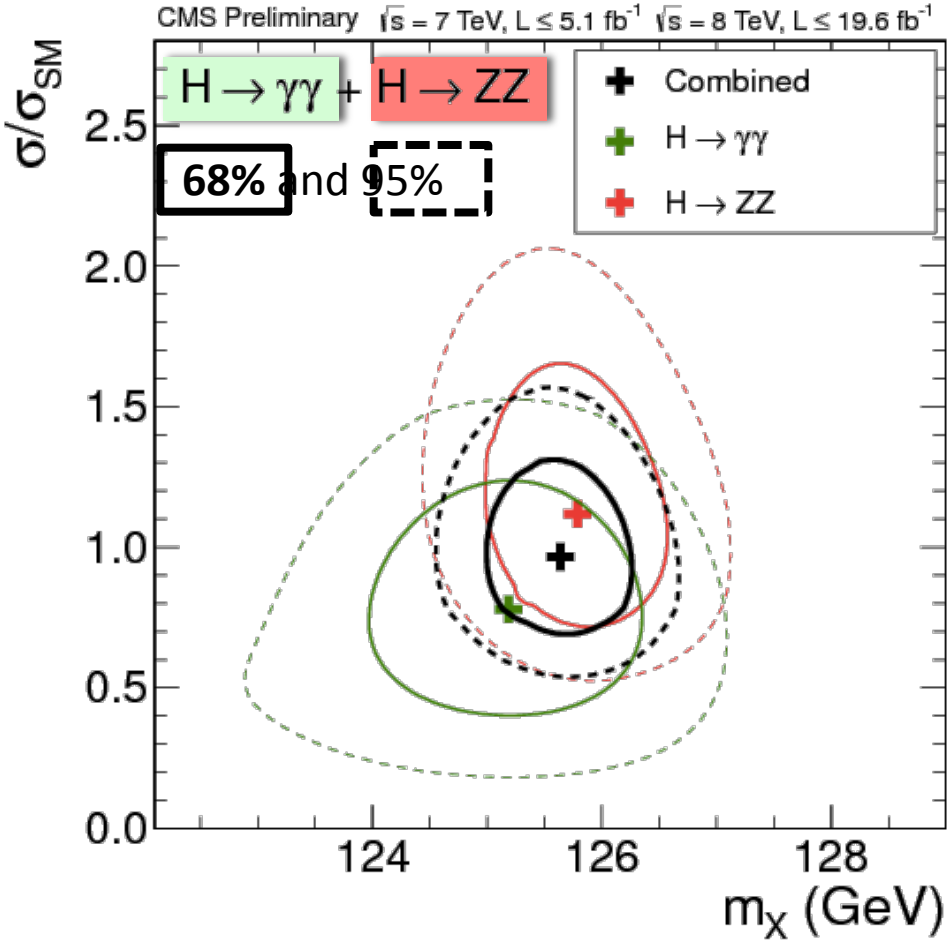



# Combination

CMS HIG-13-005

# Compatibility with Being SM Higgs

- Excesses seen in ZZ, WW and γγ in both experiments
- Signal strength ~consistent with SM Higgs



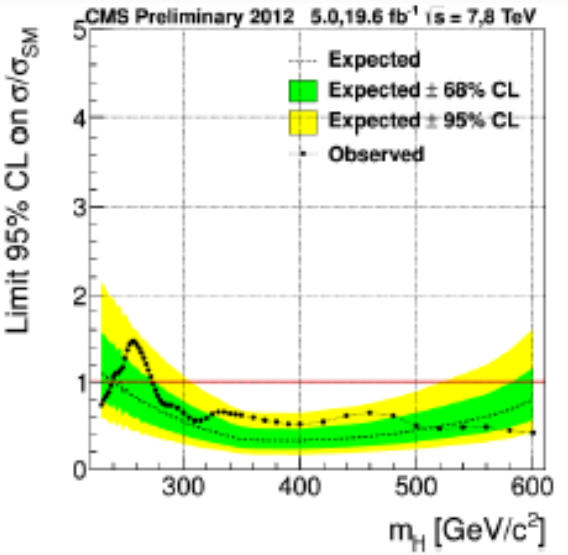

Statistical and systematic errors included

# High mass higgs

# $H \rightarrow ZZ$ - High mass

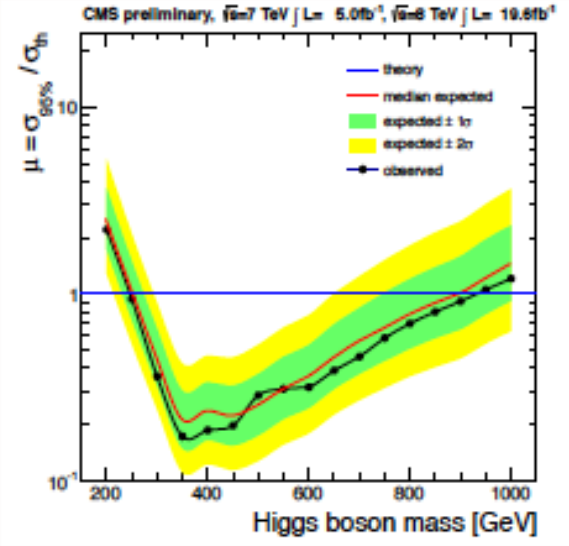
## $H \rightarrow ZZ \rightarrow 2l2q$

- 3 categories (0, 1, and 2 bjets)
- Signal optimization based on decay angles




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

- Two leptons + $\not{E}_T$ from the $\nu$'s
- Optimized for gluon fusion and VBF




Both analysis combined with $H \rightarrow ZZ \rightarrow 4l$ from 200 GeV to 1 TeV

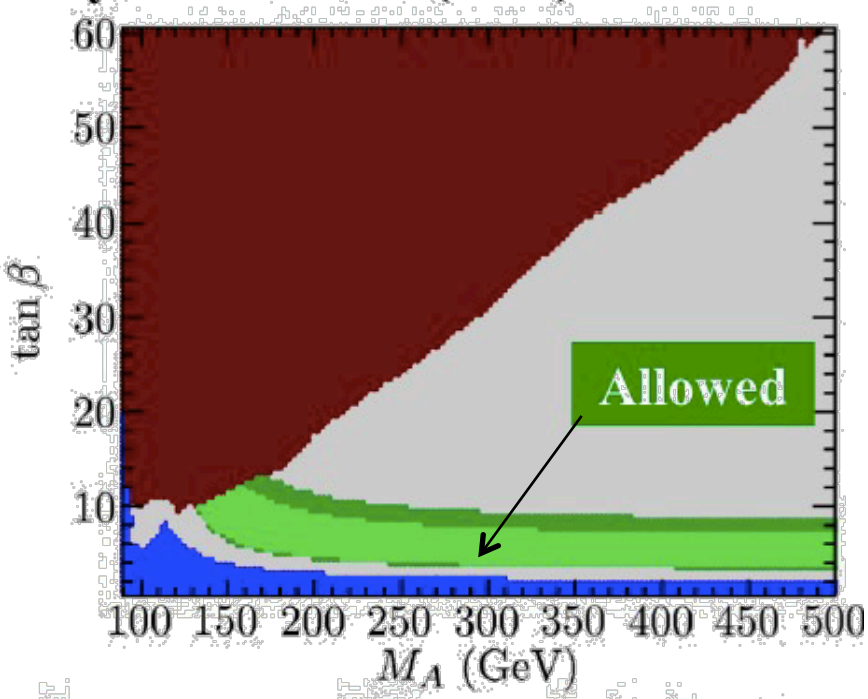
# MSSM Higgs

# MSSM Higgs

- Higgs sector in SUSY theory is more complicated
  - Need 2 higgs doublets each with 4 degrees of freedom
    - Results in the Standard Model like Higgs ($h^0$)
    - Plus, two neutral higgs ($A^0$, $H^0$) and charged ($H^{\pm}$)
    - However, only 2 parameters ($M_A$, tanβ – ratio of the two doublets)
    - Masses of higgses and Z related: Search in ($M_A$, tanβ) plane
  - Neutral Higgs
    - Look for $\phi=(h^0, A^0, H^0)$ in decays to tau-leptons
  - Charged Higgs
    - Look for $H^{\pm}$ in top decays
- Enhanced $\phi=(h^0, A^0, H^0)$ coupling to b-quarks and τ-leptons
  - Production rate enhanced × $\tan^2\beta$
    - Gluon fusion with b,t loops + associated b quark production
  - Decays to b-quark and τ-lepton pairs enhanced at all masses

# Implications of SM Like H126 on MHMAX scenario

**Phys. Lett. B 710 (2012) 201**

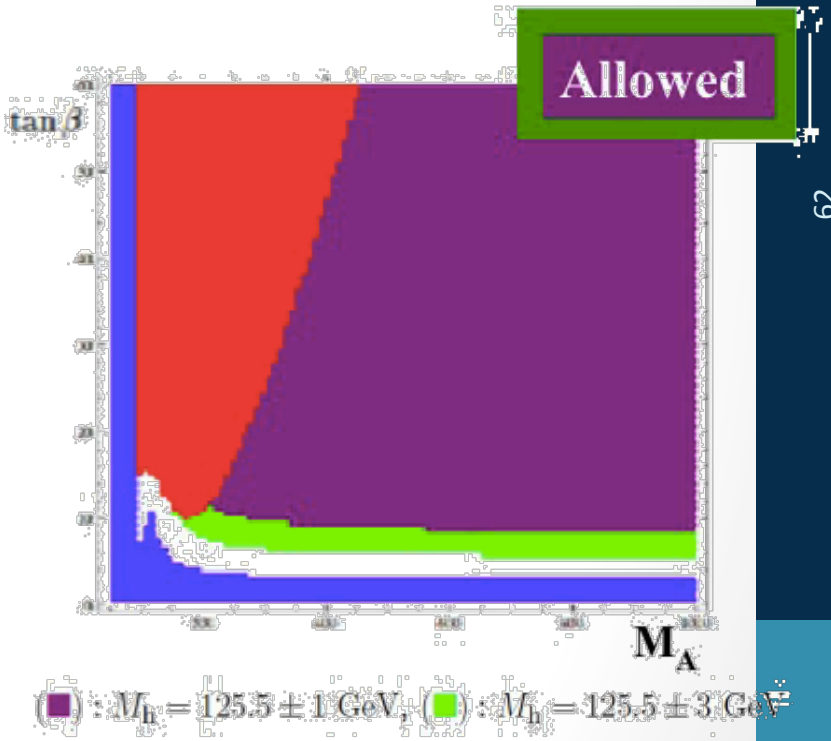



**Interpret as CP-even light h with**
**$123 < M_h < 127$ GeV**
**(theoretical uncertainty on $M_h + m_{top}$)**

**Allowed region strip in $M_A$-tanβ**

**mhmax scenario**

**Modified $m_{h,max}$ scenario**
**$X_t$ ~1300 GeV**

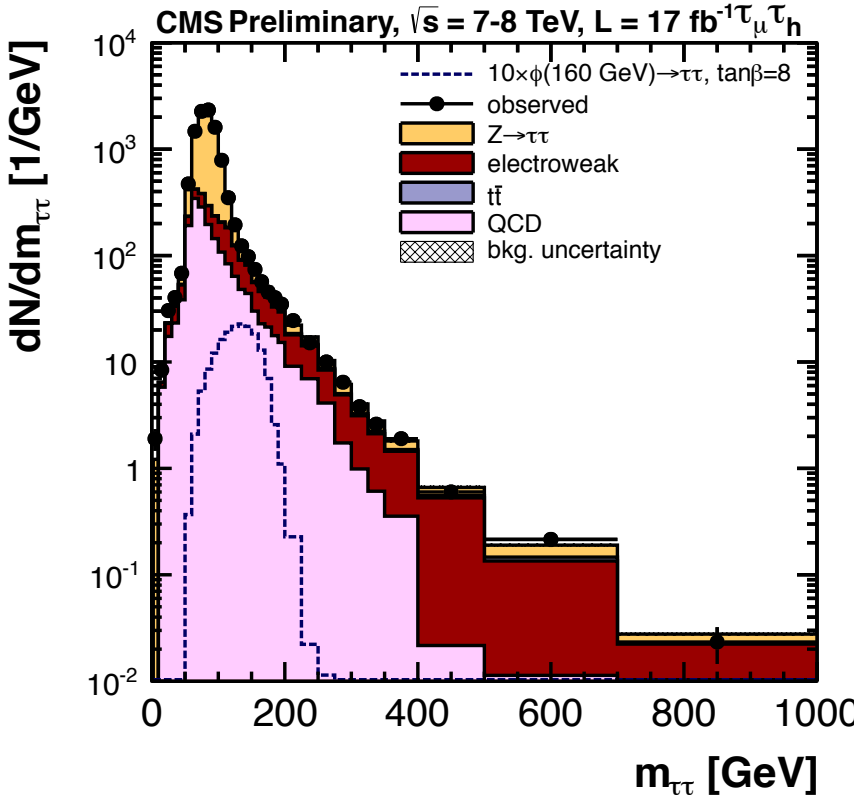


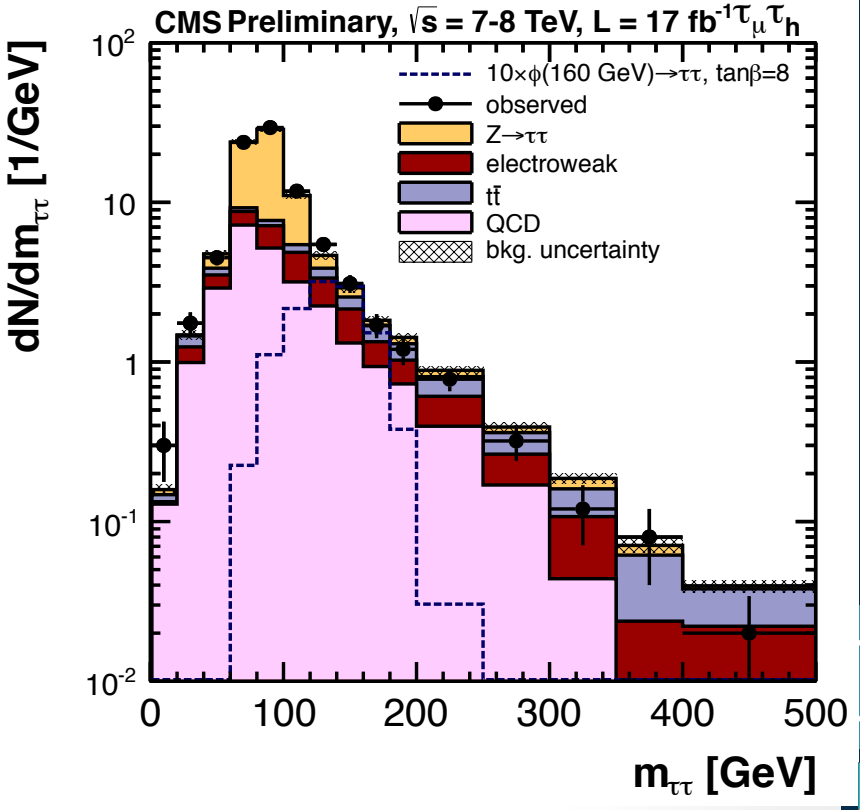

**$X_t$: stop mixing paramater**

# Mass of ττ : 17 fb$^{-1}$ Data

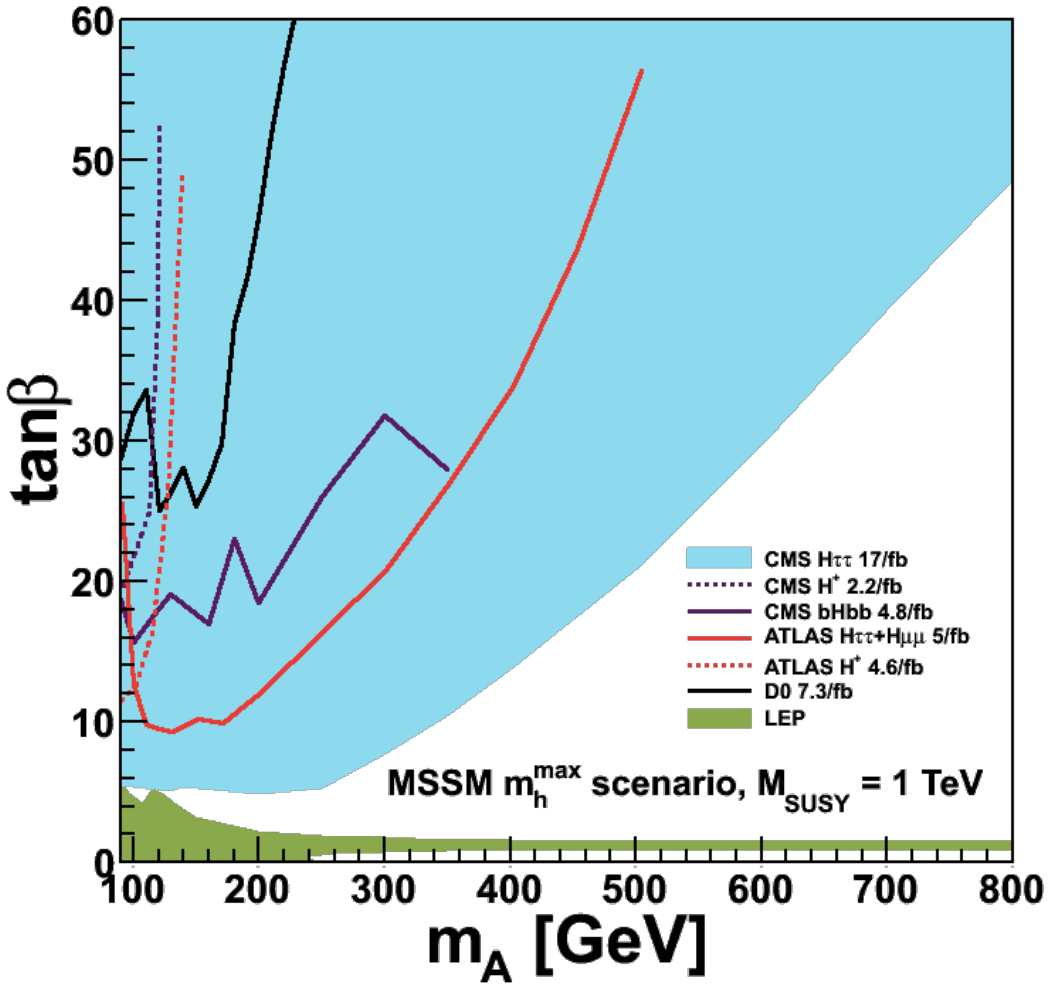
CMS HIG-12-050

Tau pairs reconstructed in decays to muon + hadrons (1 or 3 prong)
Kinematic fit to obtain tau pair mass – used to search for H to ττ contribution
Two categories: non-b-tagged and b-tagged to enhance bbϕ



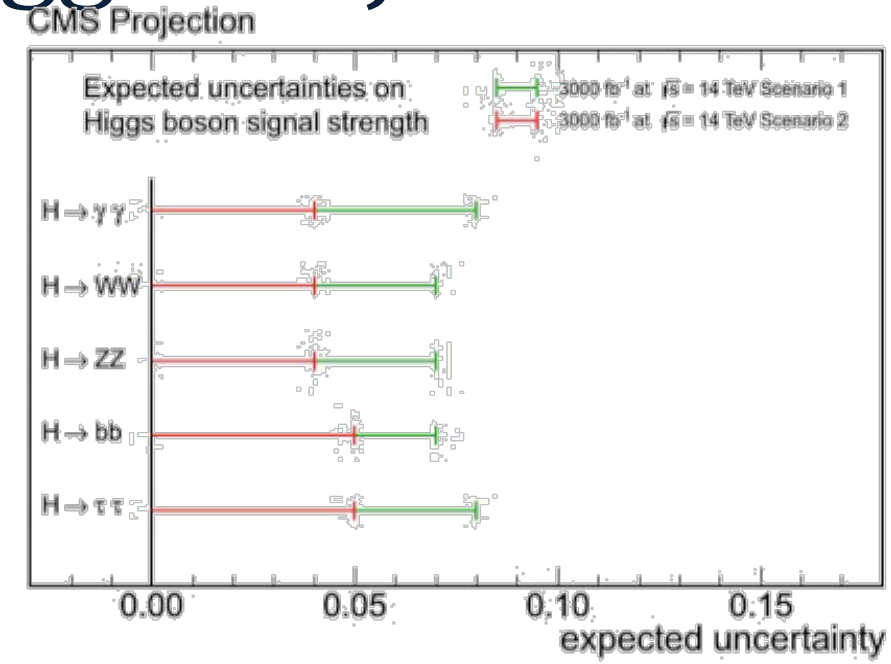
# MSSM Higgs Summary




ATLAS CONF 2012-11

CMS PAS HIG-12-033
CMS PAS HIG-11-019
CMS PAS HIG-12-050

# CMS Higgs Projections




| L (fb$^{-1}$) | $H \to \gamma\gamma$ | $H \to WW$ | $H \to ZZ$ | $H \to bb$ | $H \to \tau\tau$ | $H \to Z\gamma$ | $H \to$ inv. |
|---|---|---|---|---|---|---|---|
| 300 | [6, 12] | [6, 11] | [7, 11] | [11, 14] | [8, 14] | [62, 62] | [17, 28] |
| 3000 | [4, 8] | [4, 7] | [4, 7] | [5, 7] | [5, 8] | [20, 24] | [6, 17] |

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest $\propto 1/\sqrt{L}$

Extrapolated from 2011/12 results