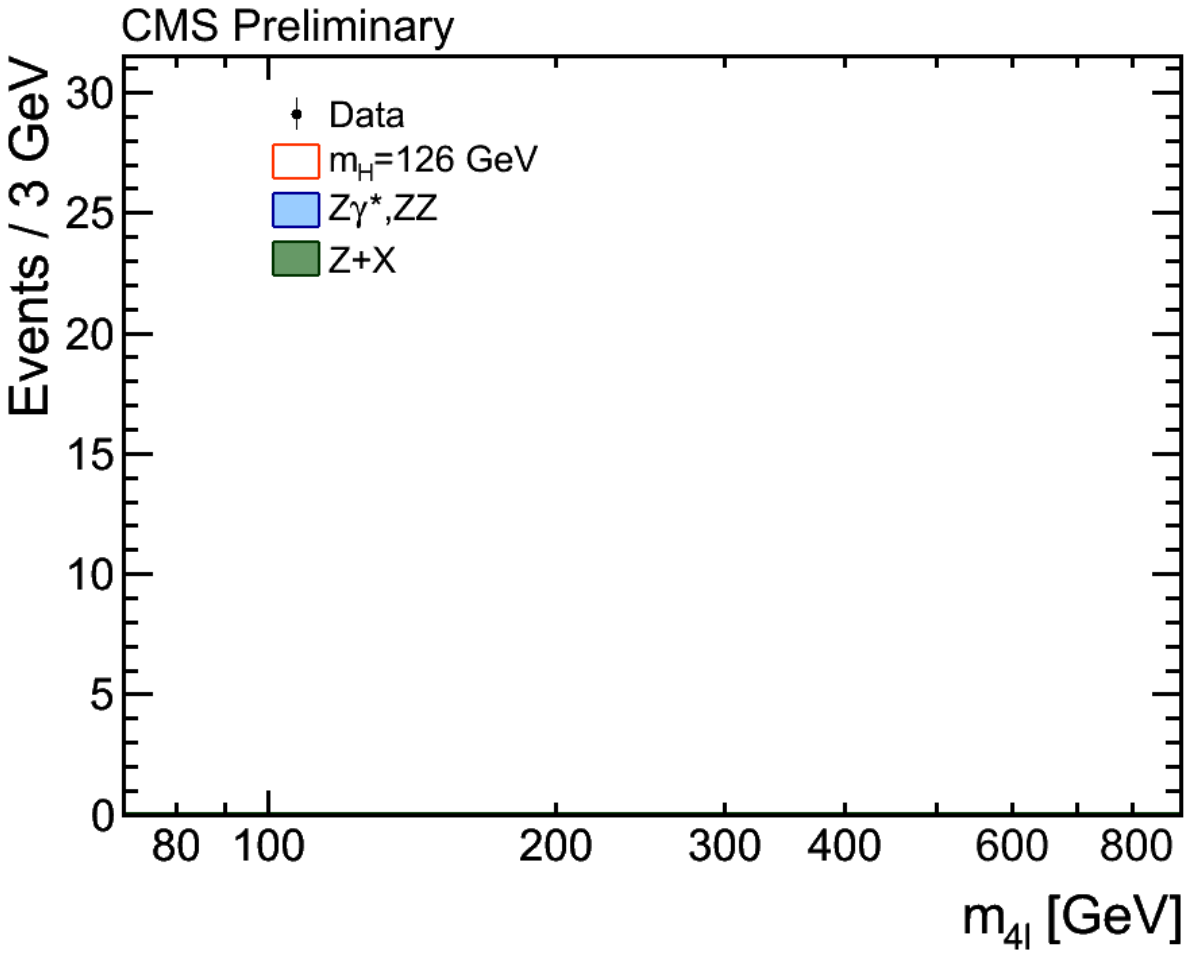
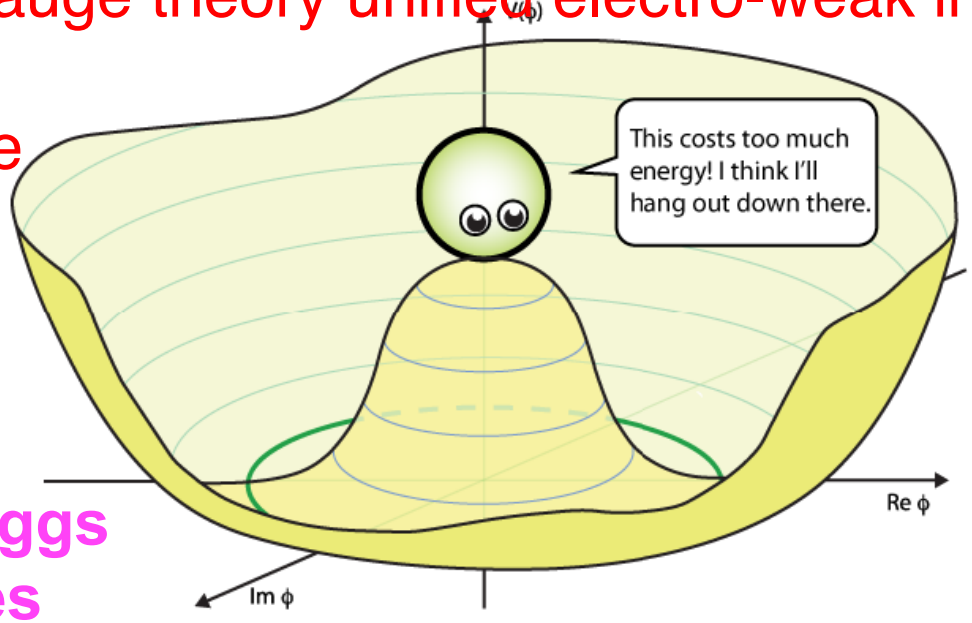
# Recent Results on Higgs Physics from CMS

## Understanding the New Boson



# Electro-Weak Symmetry Breaking

50 years ago, gauge theory unified electro-weak interactions, but could not accommodate non-zero masses for $W^{\pm}$ & Z




**Predicted a remnant scalar particle!**

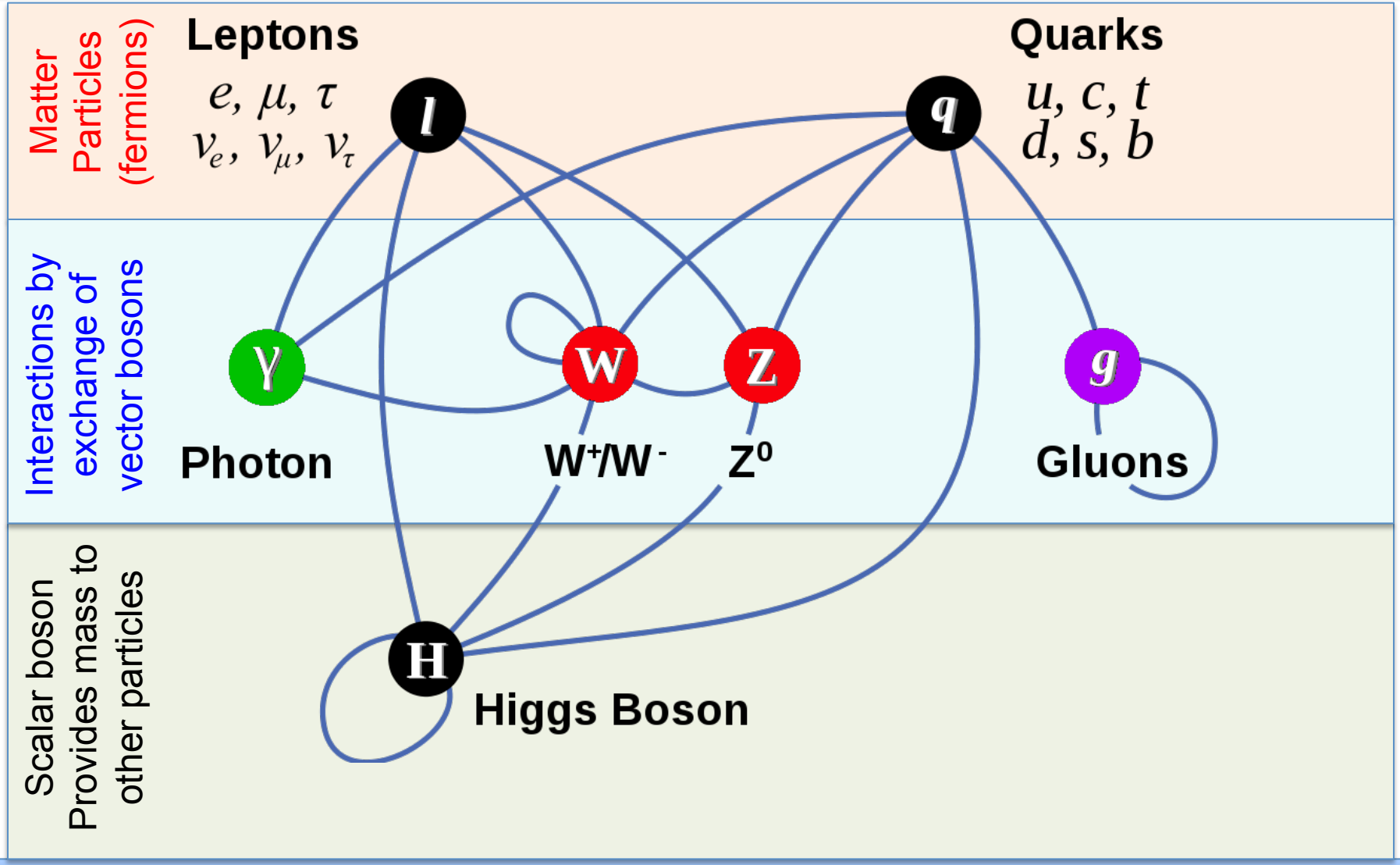
**Coupling to Higgs field provides masses to matter particles!!**

$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$

$$\text{For } \mu^2 < 0, \quad \text{minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

Introduction of a doublet of complex scalar fields with peculiar potential provided masses for $W^{\pm}$ & Z and left $\gamma$ massless!

# Completion of The Standard Model



# 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?

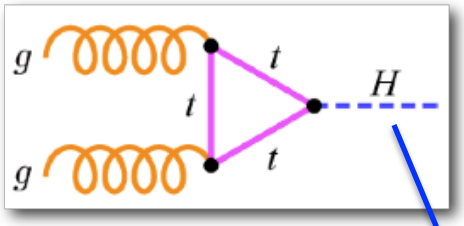
Does it ***couple to itself*** ?

Fortuitously, the mass of about 125 GeV allows us to answer many of these questions experimentally ☺

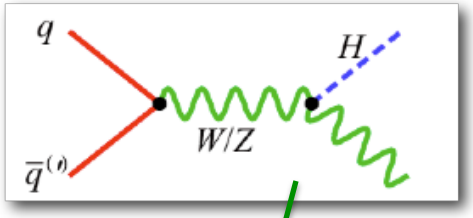
- Answers began to emerge by Moriond already
- Others will, with ~100 $fb^{-1}$ circa 2016
- Self-coupling needs O(1000) $fb^{-1}$ – a decade of work ☹

# Standard Model Higgs Production

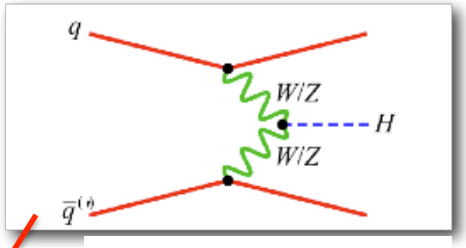
**Gluon fusion**



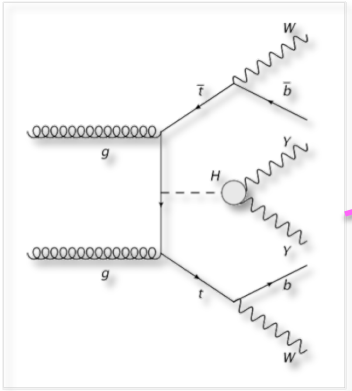

**Associated Production**

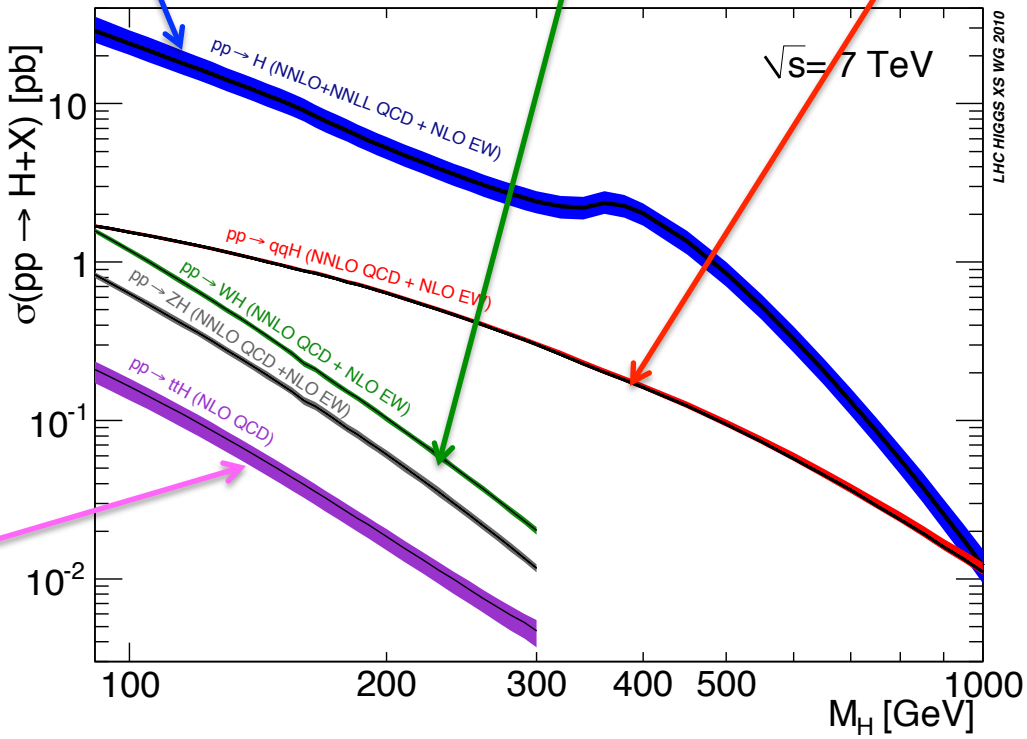



**Vector boson fusion**



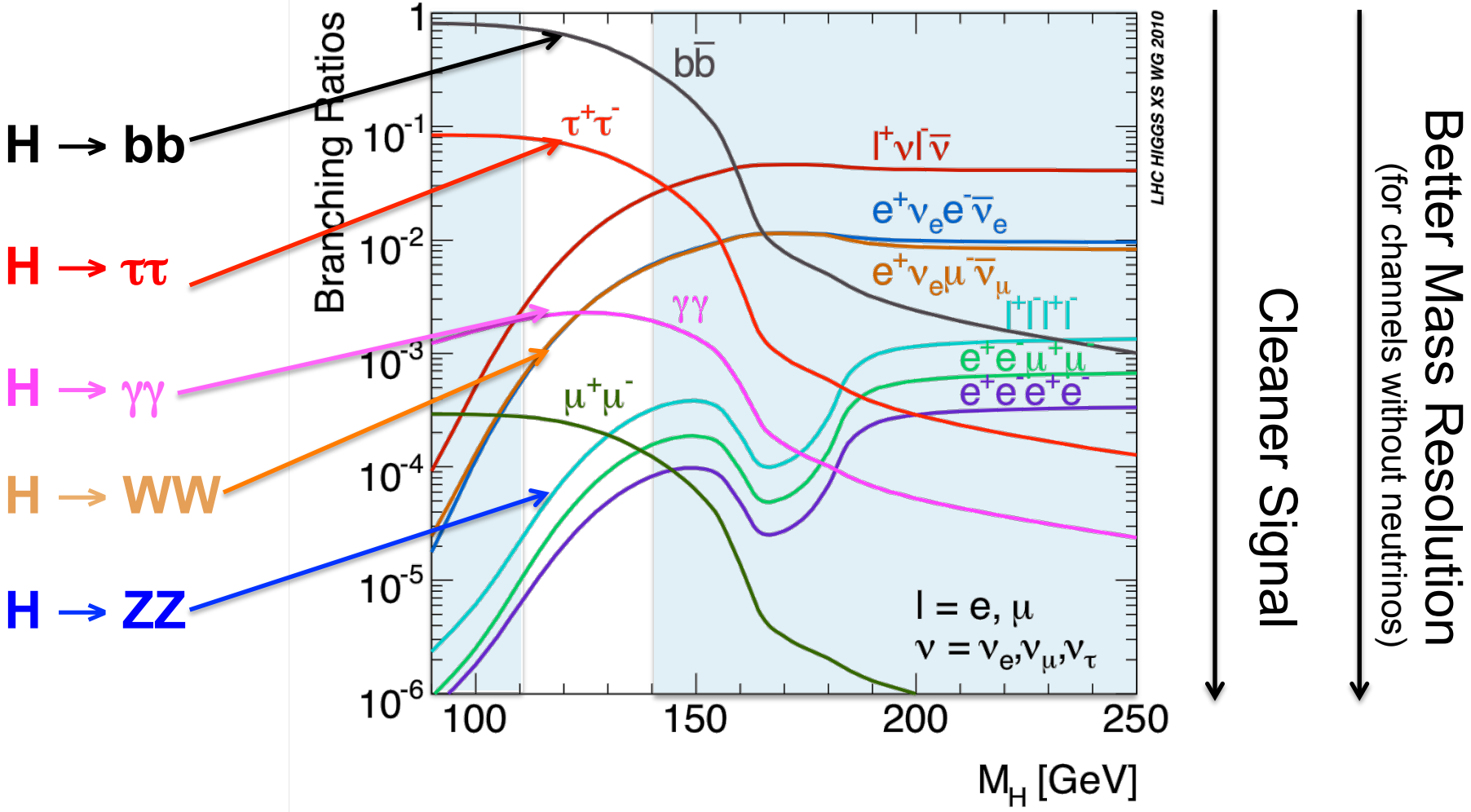

**Top Associated**

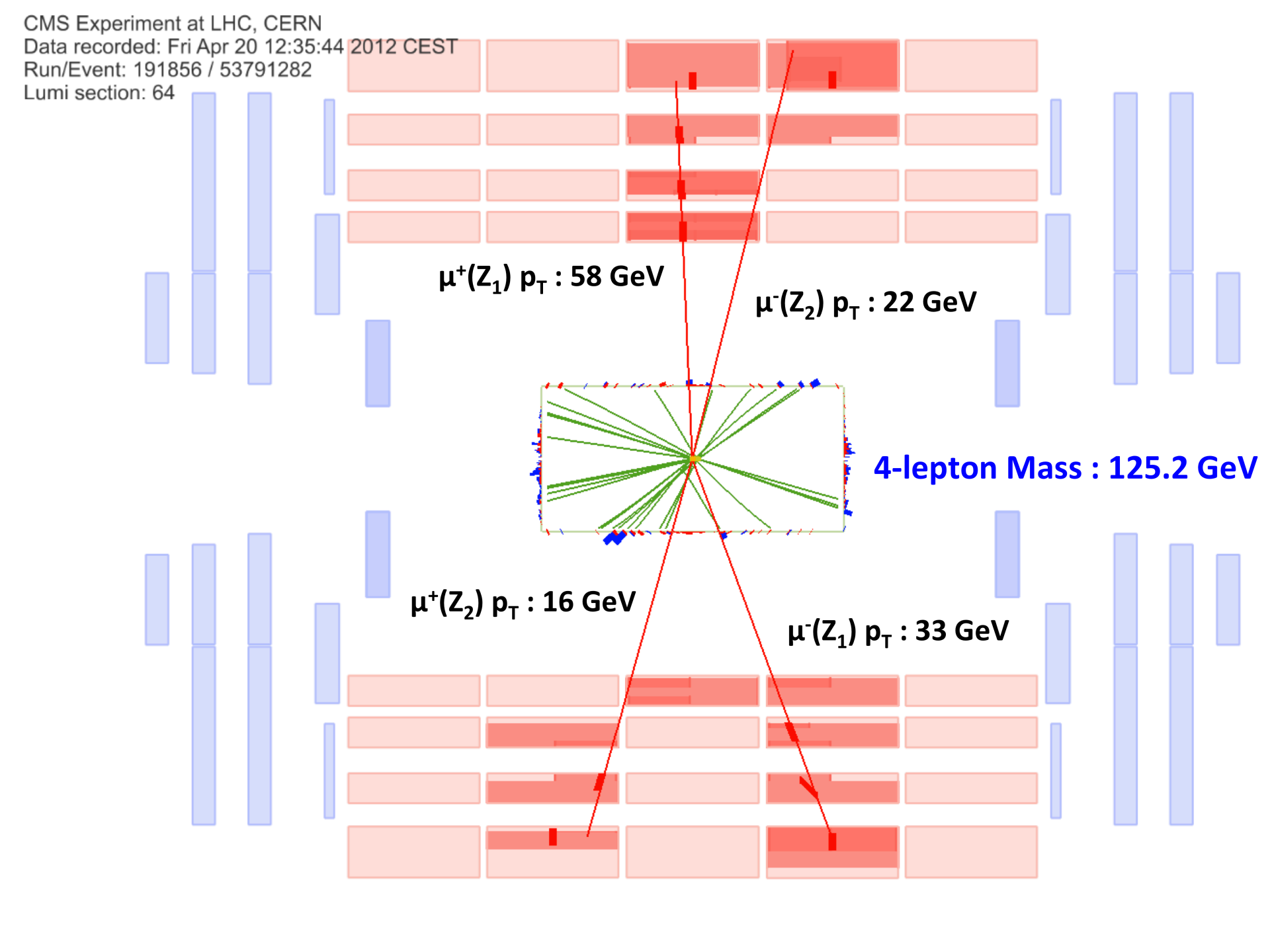


# Standard Model Higgs Decay

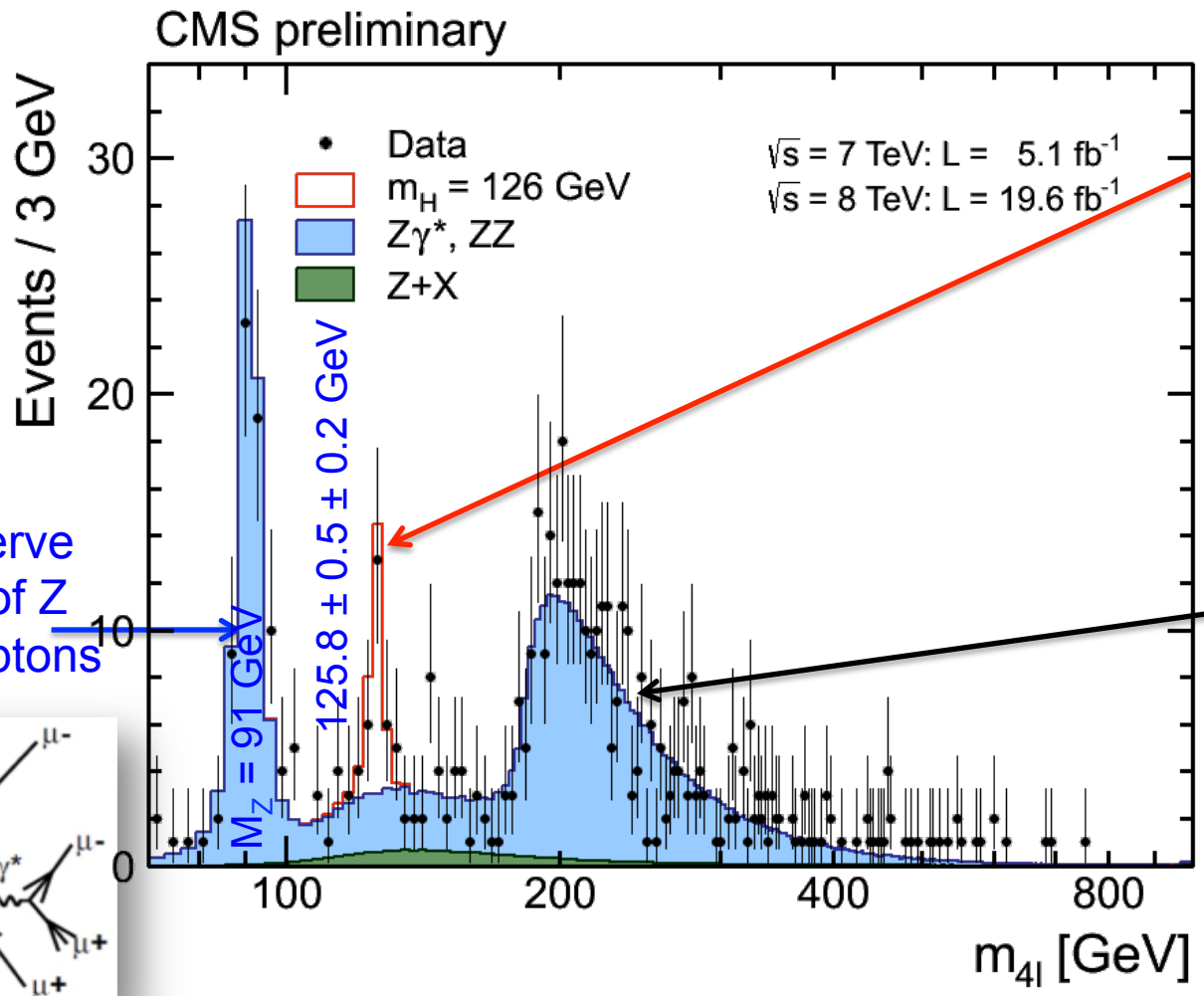
We search for several Higgs decay channels.




CMS Experiment at LHC, CERN
Data recorded: Fri Apr 20 12:35:44 2012 CEST
Run/Event: 191856 / 53791282
Lumi section: 64
μ+(Z1) pT : 58 GeV
μ-(Z2) pT : 22 GeV
4-lepton Mass : 125.2 GeV
μ+(Z2) pT : 16 GeV
μ-(Z1) pT : 33 GeV

# Decays to ZZ to 4-light leptons

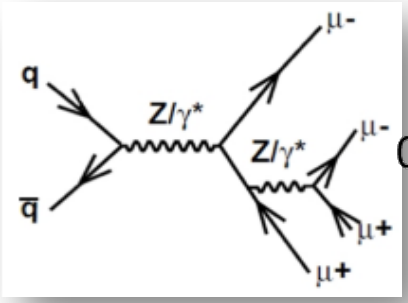
CMS HIG-13-002




Cluster of events rising above the background consistent at 4.7σ level with SM Higgs signal

Clearly observe production of Z decay to 4 leptons

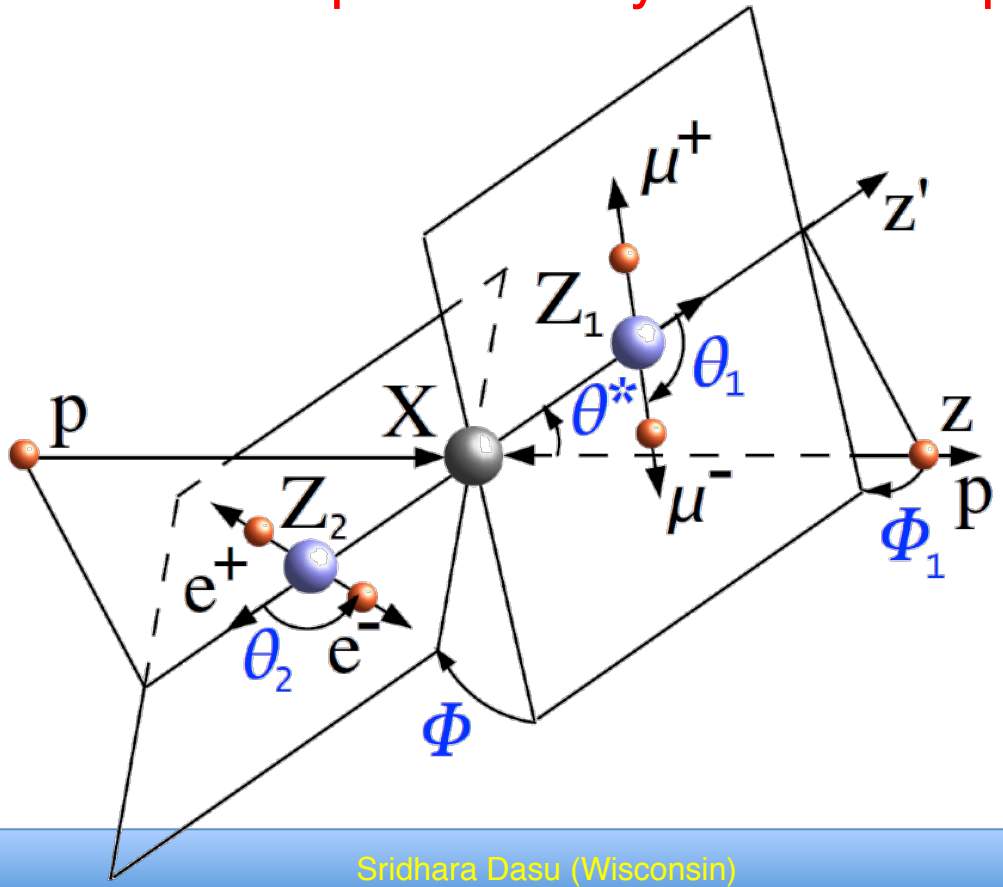
ZZ production for $M_{4l} > 2M_Z$



# Use Angular Information

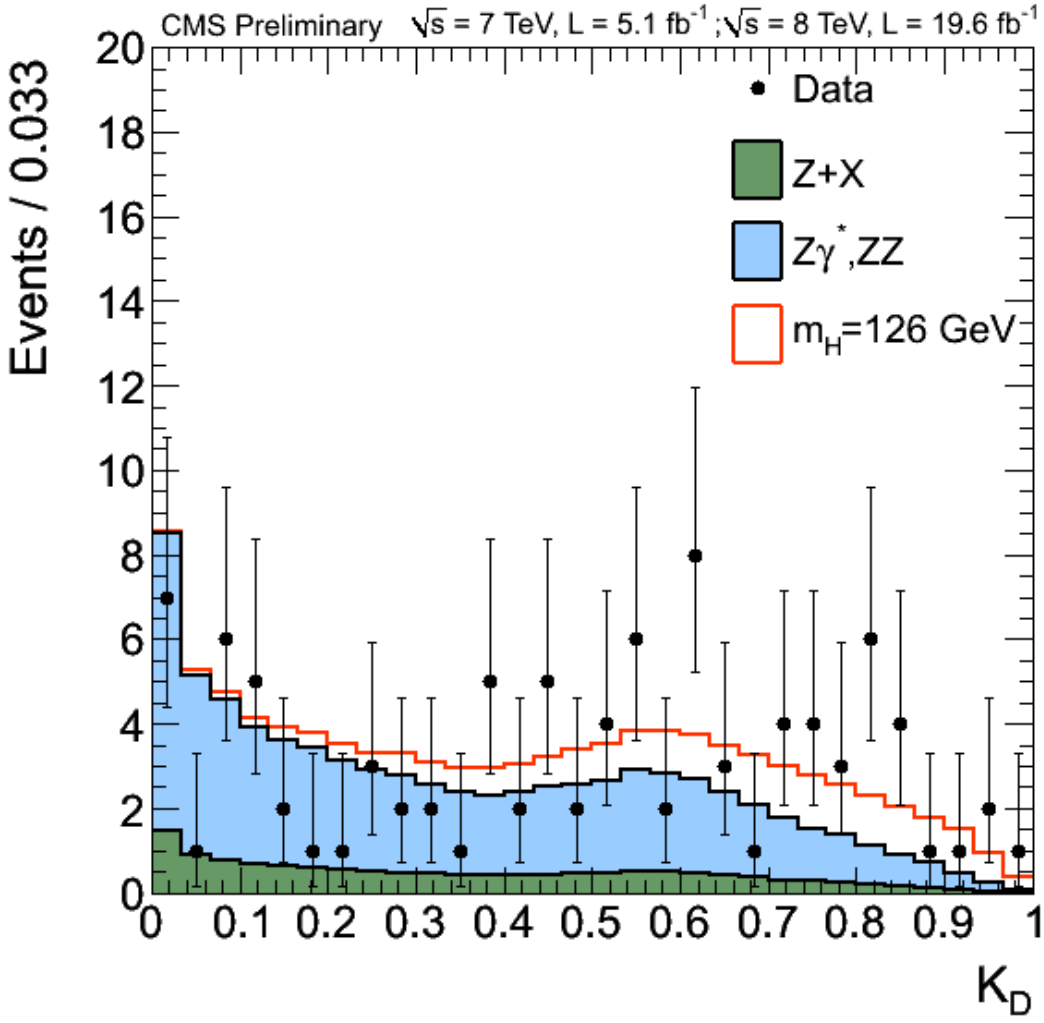
Reduce BG further & study additional properties of these events

- Angles shown carry information of scalar (SM H), pseudo-scalar vs spin-2 decay versus ZZ production



# Kinematic Discriminator

CMS HIG-13-002

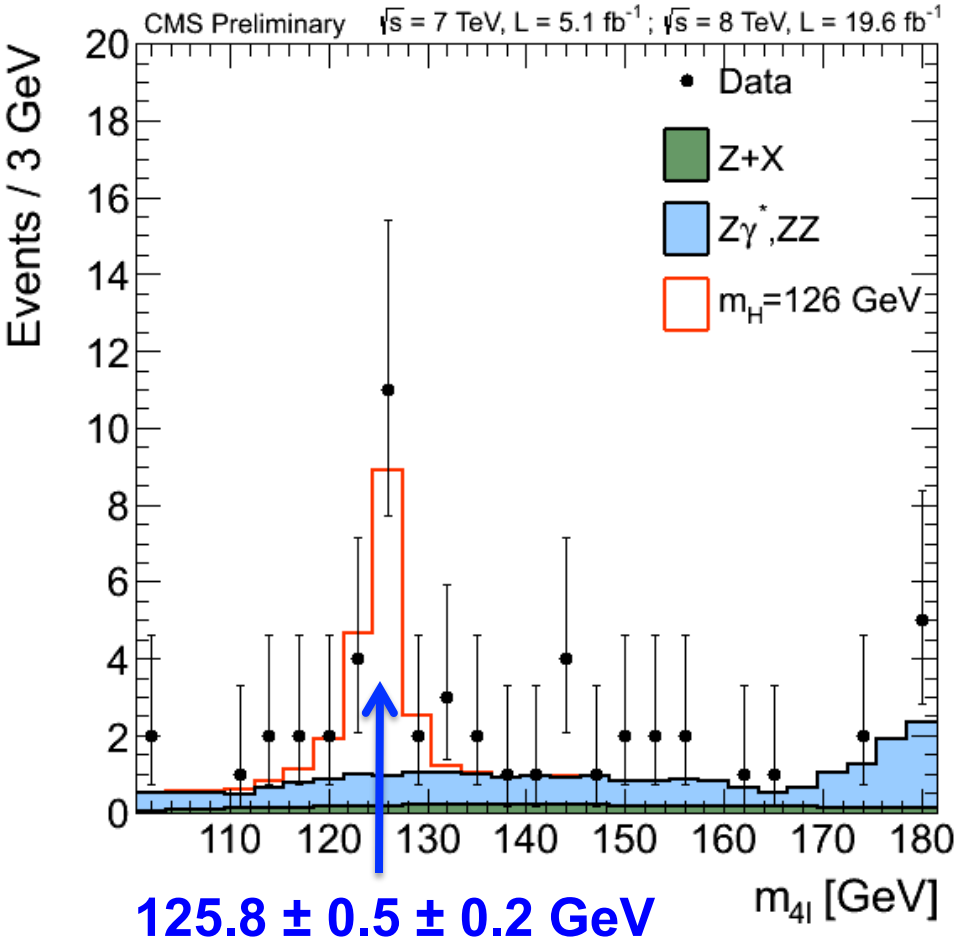


# Strong Evidence in decays to ZZ

CMS HIG-13-002

Boost using angular information from 4.7 to 6.7 sigma

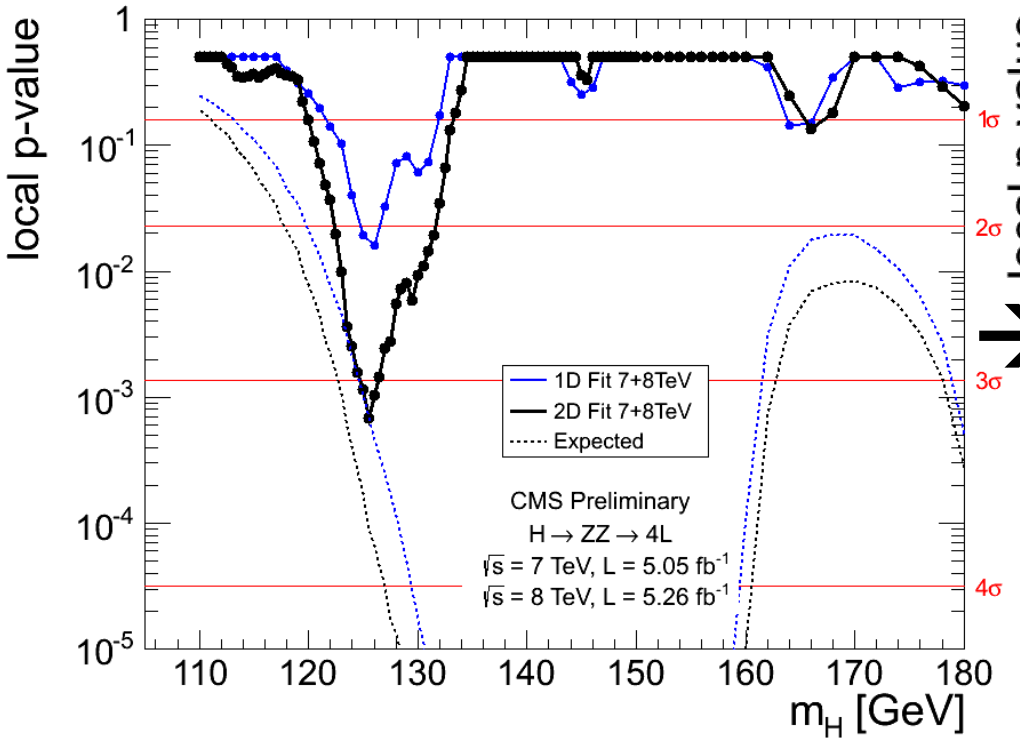
- Reduce background, while keeping signal-like events

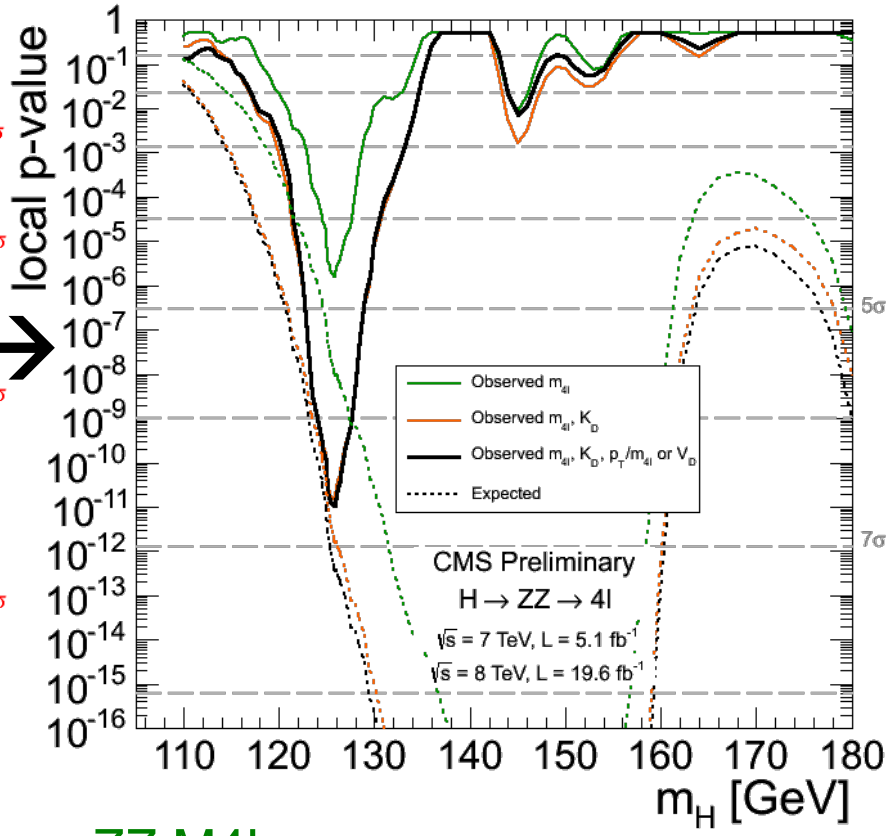


# ZZ Signal Strength

CMS HIG-13-002

Adding statistics → Cleaned up nicely




ZZ M4L

ZZ M4L & MELA

ZZ M4L

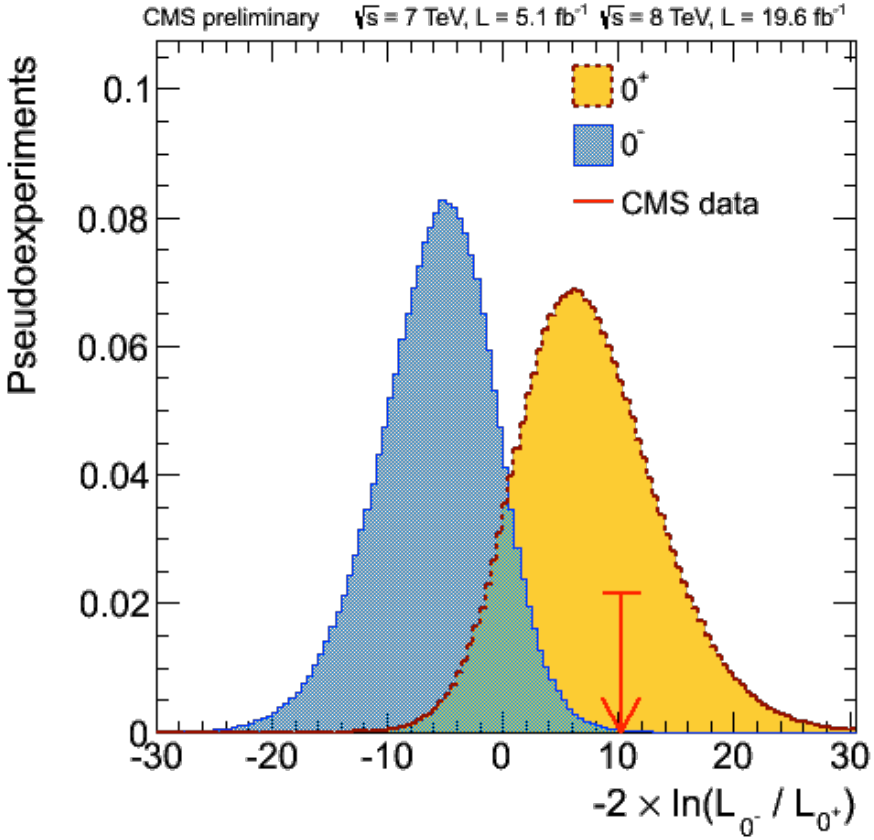
ZZ M4L, KD and $P_T$

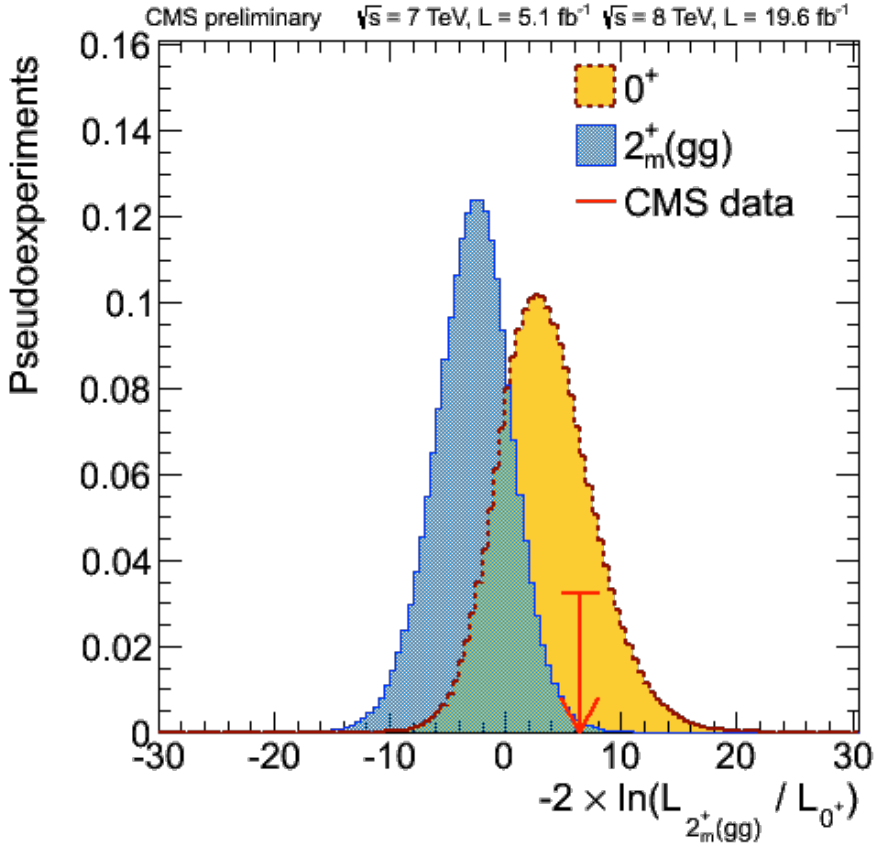
# The new boson is scalar like!

CMS HIG-13-002

Angular analysis of ZZ using KDs for $0^+$, $0^-$, 1 and $2^+$

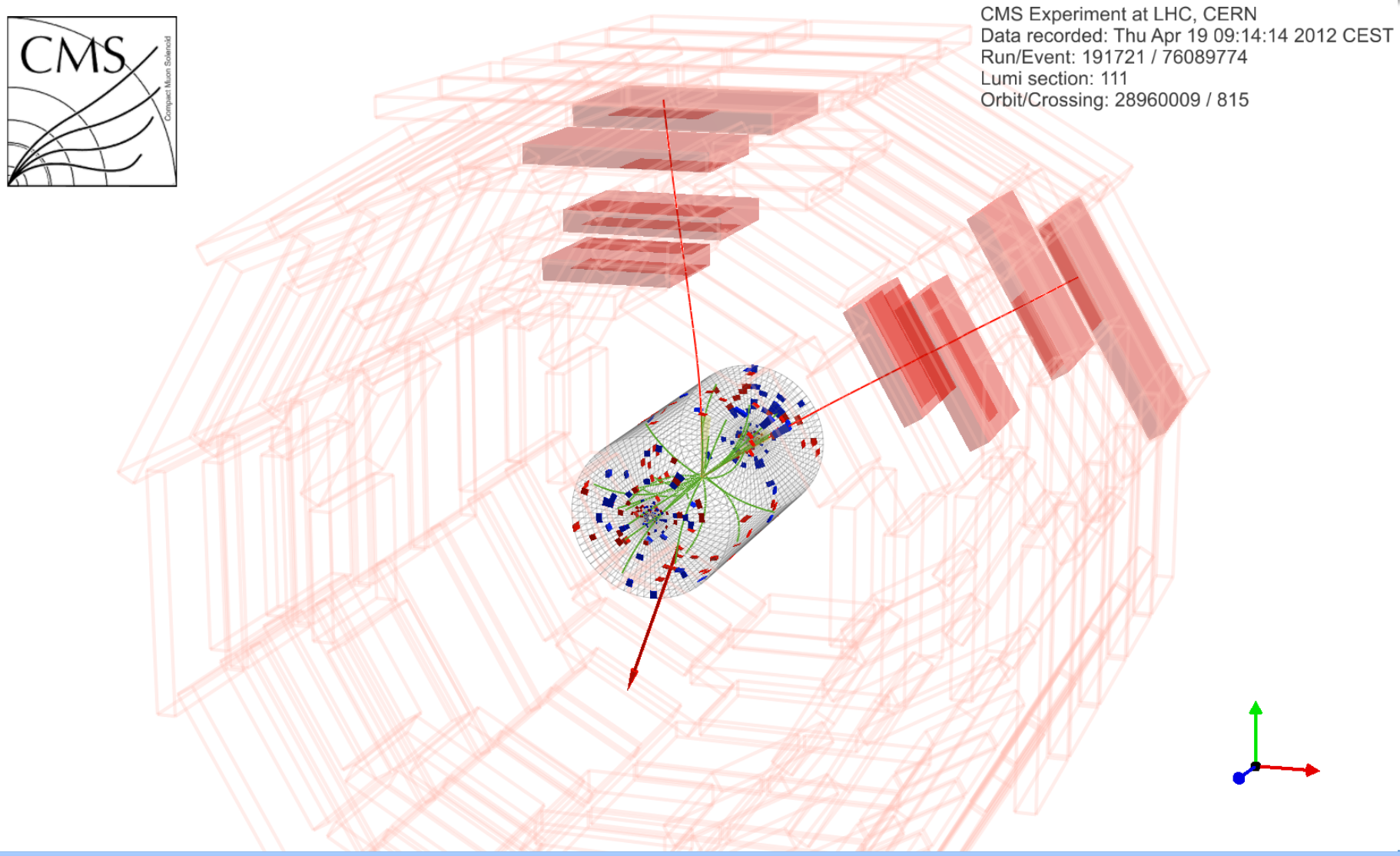
Disfavors $0^-$ over $0^+$ by $CL_S$ value of 0.16% and $2^+$ by 1.5%




Spin 1 disfavored by a lot

# WW → $\ell^+ \ell^-$ MET

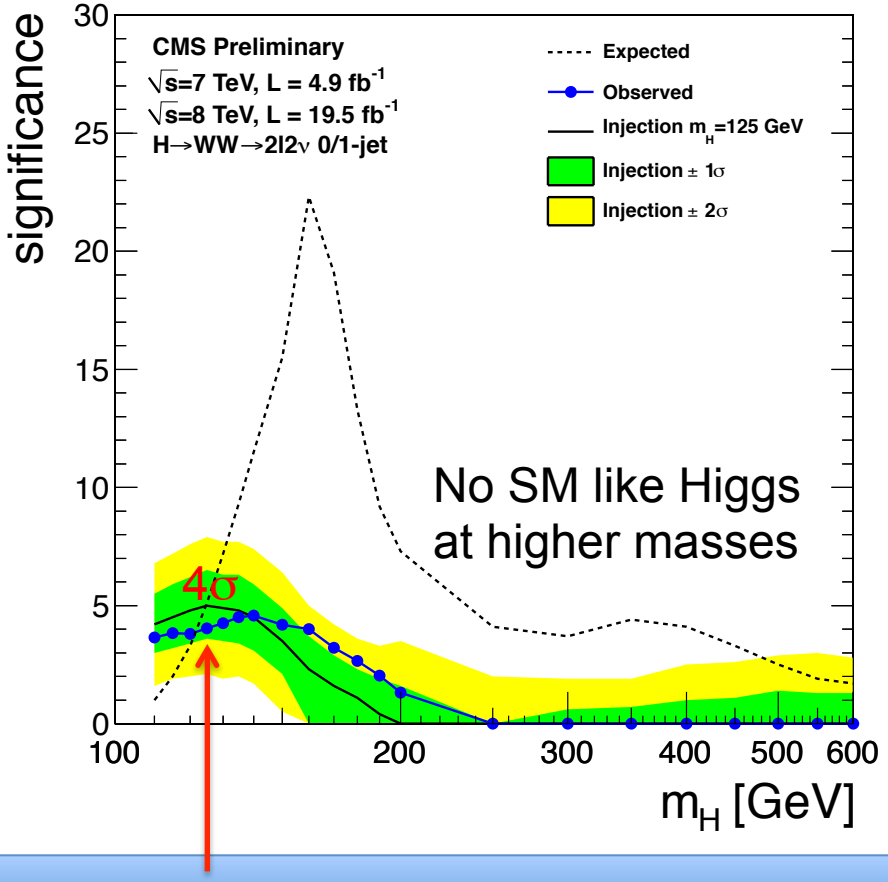


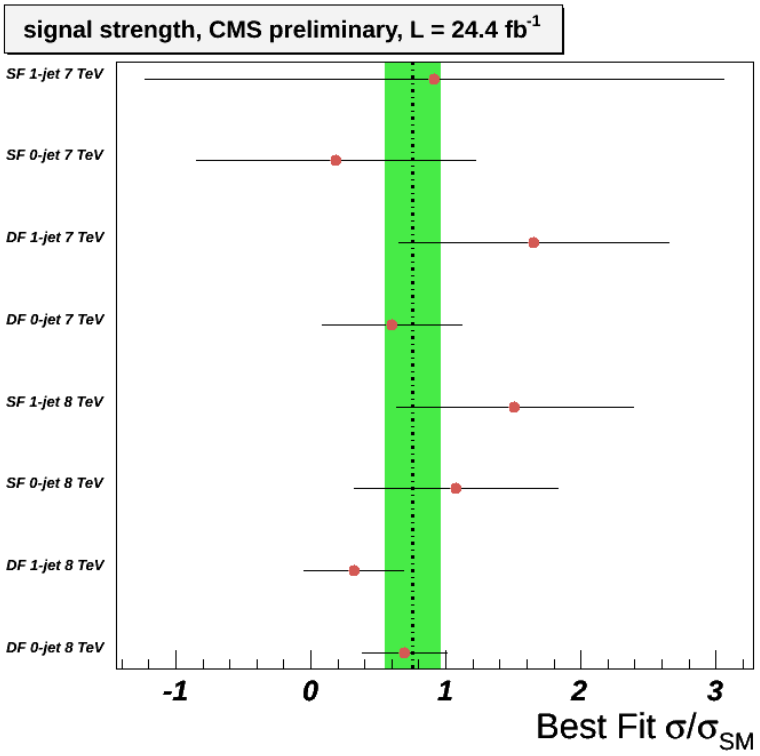
# Evidence in WW mode

CMS HIG-13-003

CMS sees broad enhancement compared to background only hypothesis, consistent with the SM Higgs @ 4σ (expectation @ 5σ)

- 2D shape analysis of the DF di-leplon invariant and transverse masses



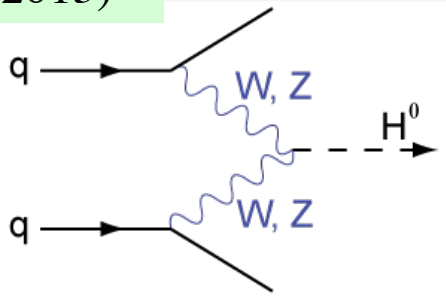



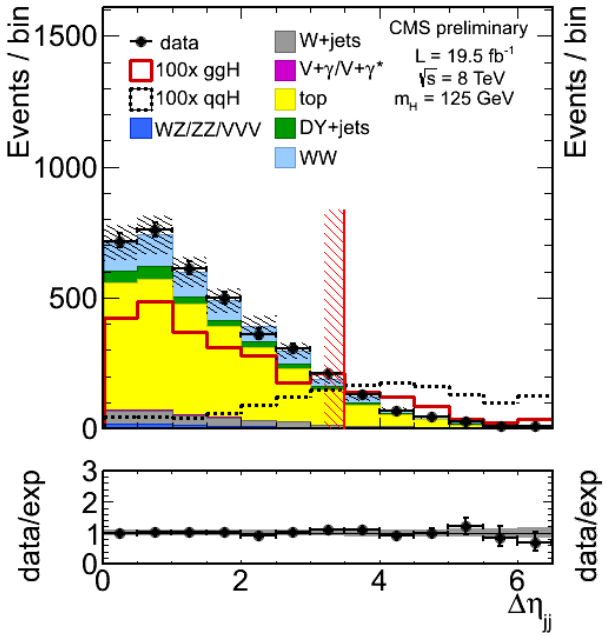
# VBF Production: H→WW → $\ell^+ \ell^-$ MET

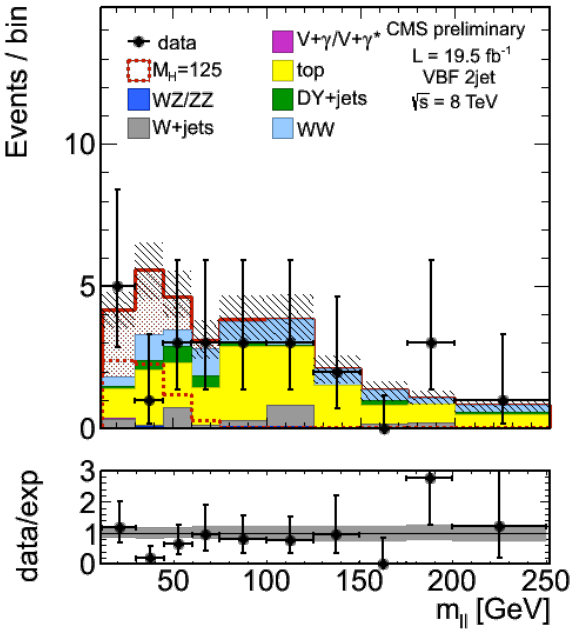
CMS HIG-13-022 (New for SUSY2013)

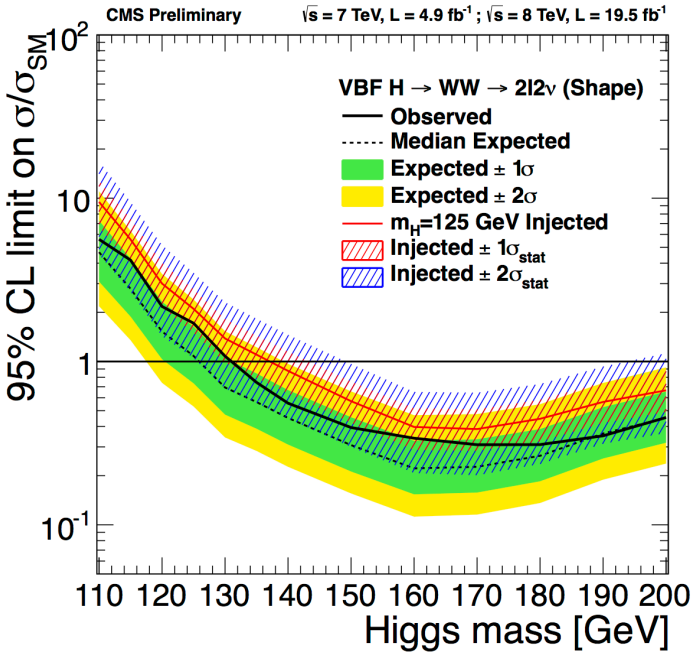
VBF enhanced by requiring tag jets

- Is the signal due to vector boson fusion?
  - Consistent with SM level
    - Need ~100 $fb^{-1}$ at 13 TeV for discovery



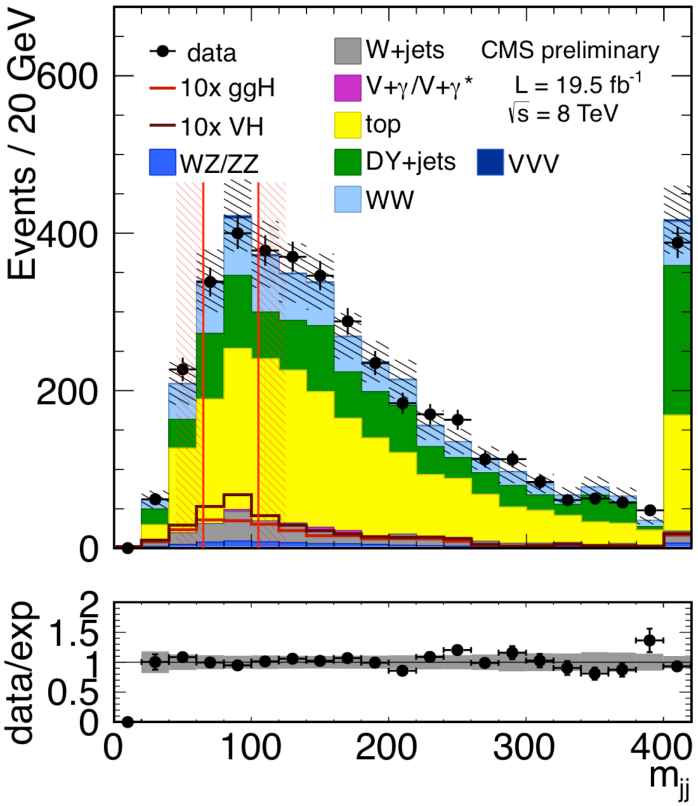



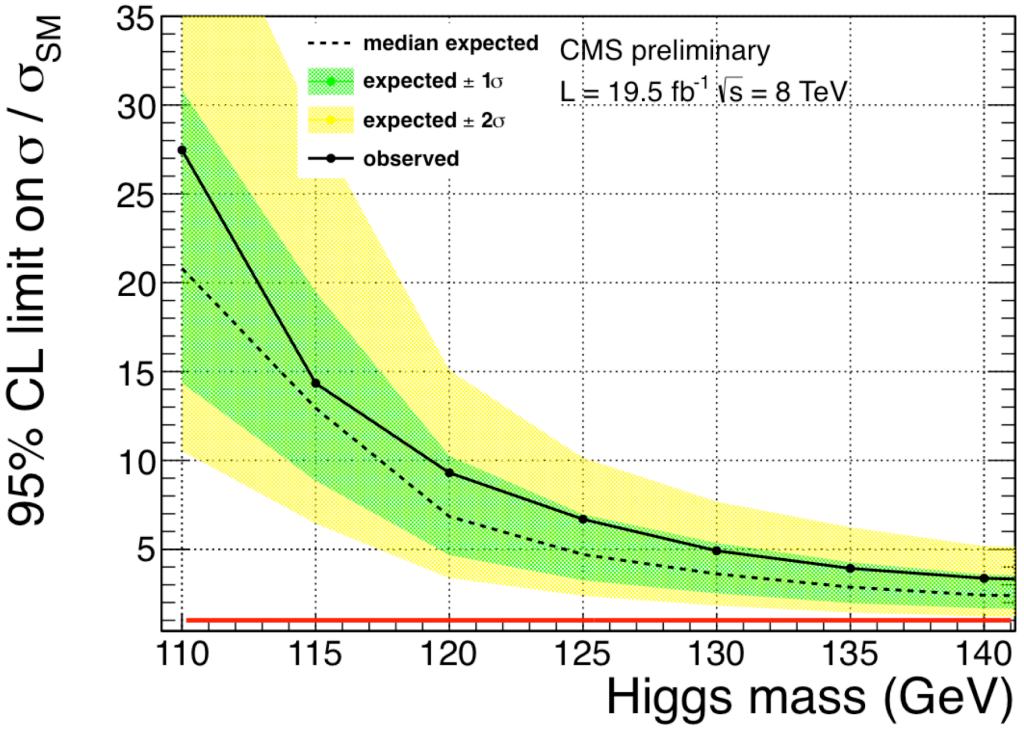
# Search for VH, V→jj & H→WW → $\ell^+\ell^-$ MET

CMS HIG-13-017

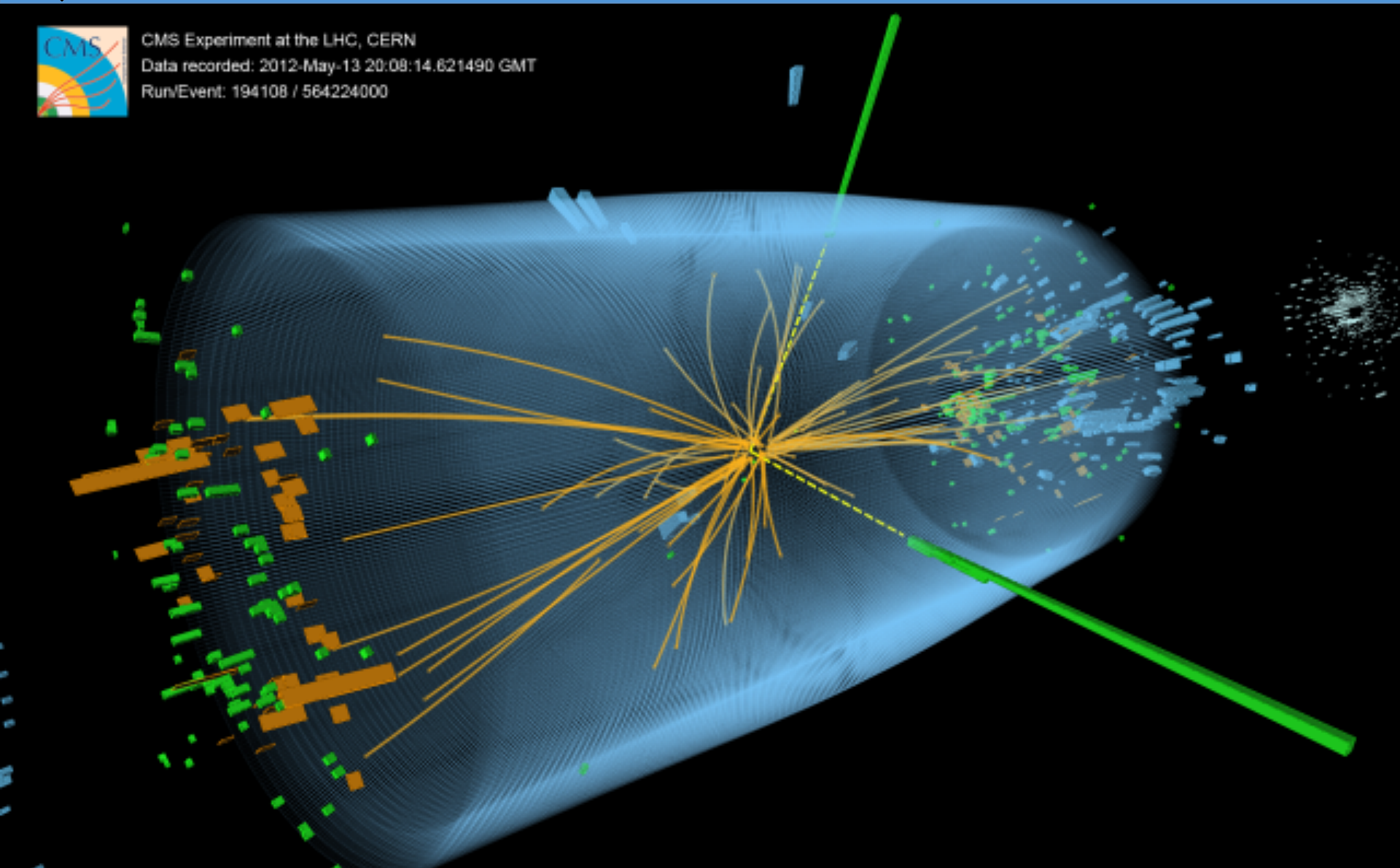
Interesting test of production of ggH vs VH

- Not yet sensitive at expected SM level



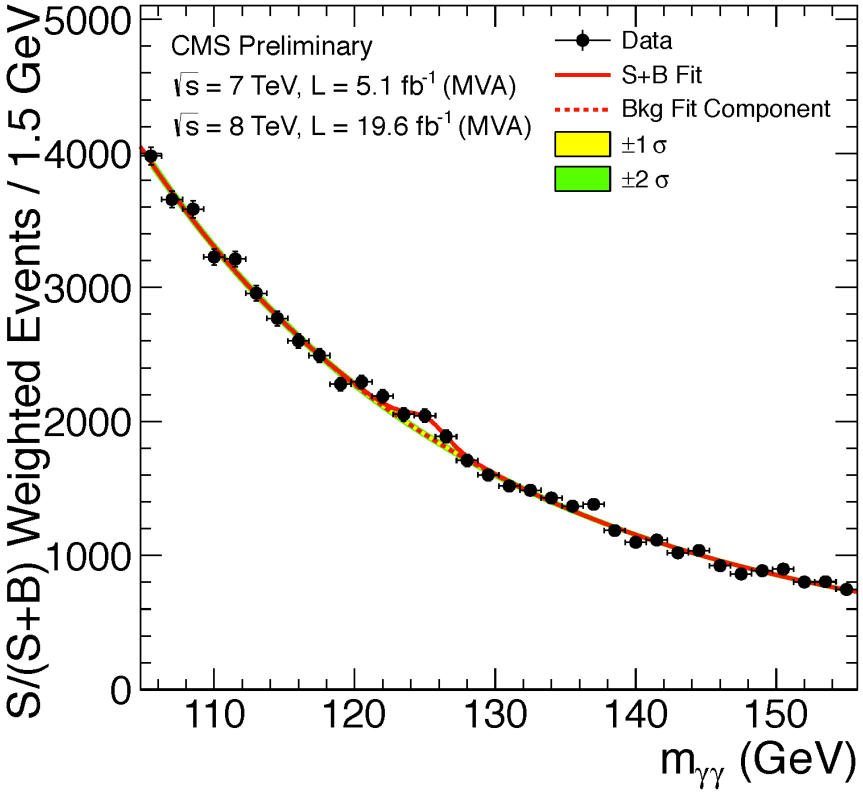



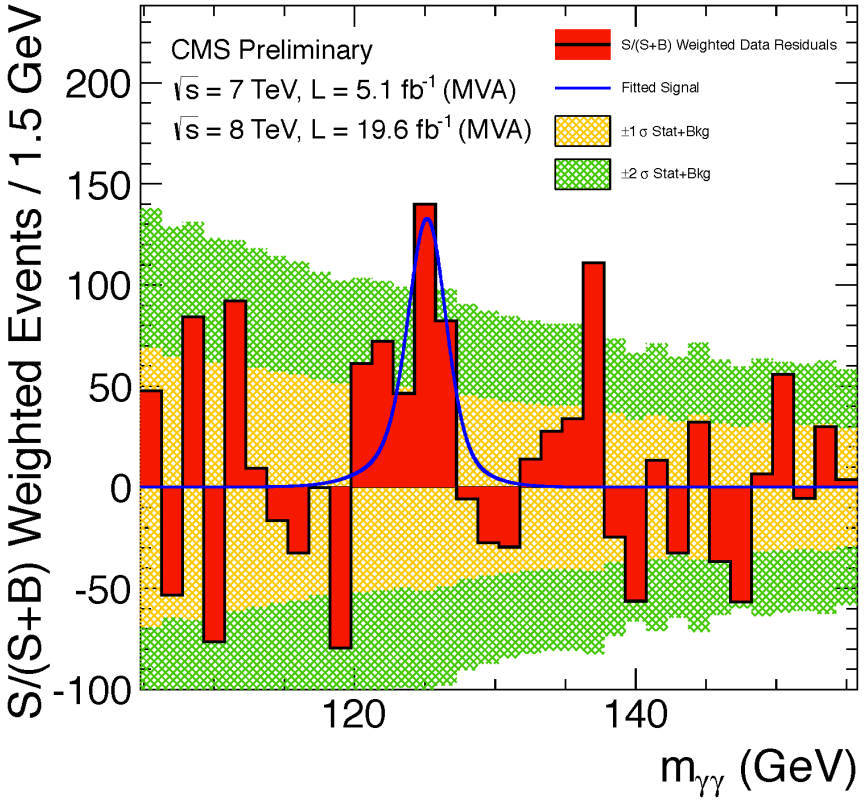
# Candidate 2-Photon Event



# Combined Weighted γγ Spectrum

CMS HIG-13-001



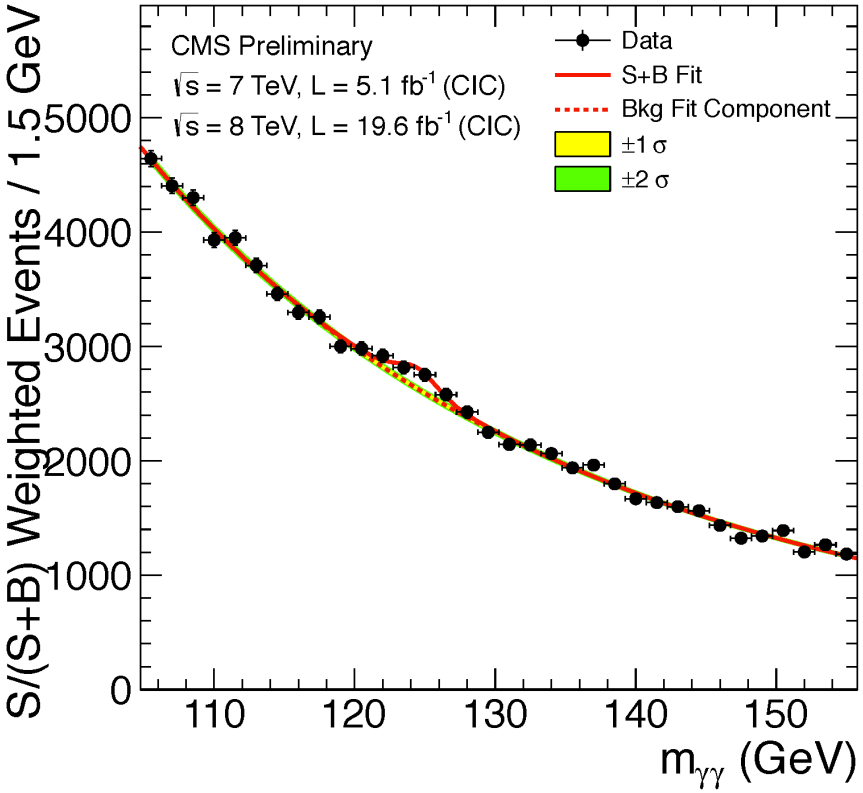

MVA – Mass Fit Analysis combining several event classes and both years

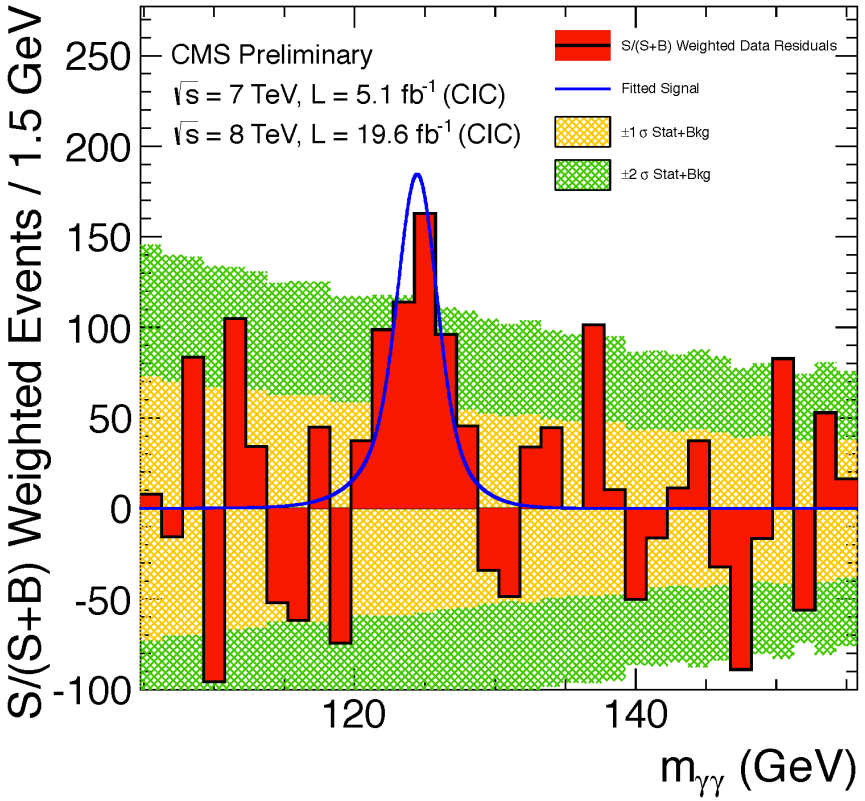
Baseline Analysis – higher performance than Cuts-in-Categories Analysis

The best-fit signal strength, $\sigma/\sigma_{SM}$: 0.78±0.27 & mass: 125.4 ± 0.5(stat.) ± 0.6(syst.)

# Combined Weighted γγ Spectrum

CMS HIG-13-001



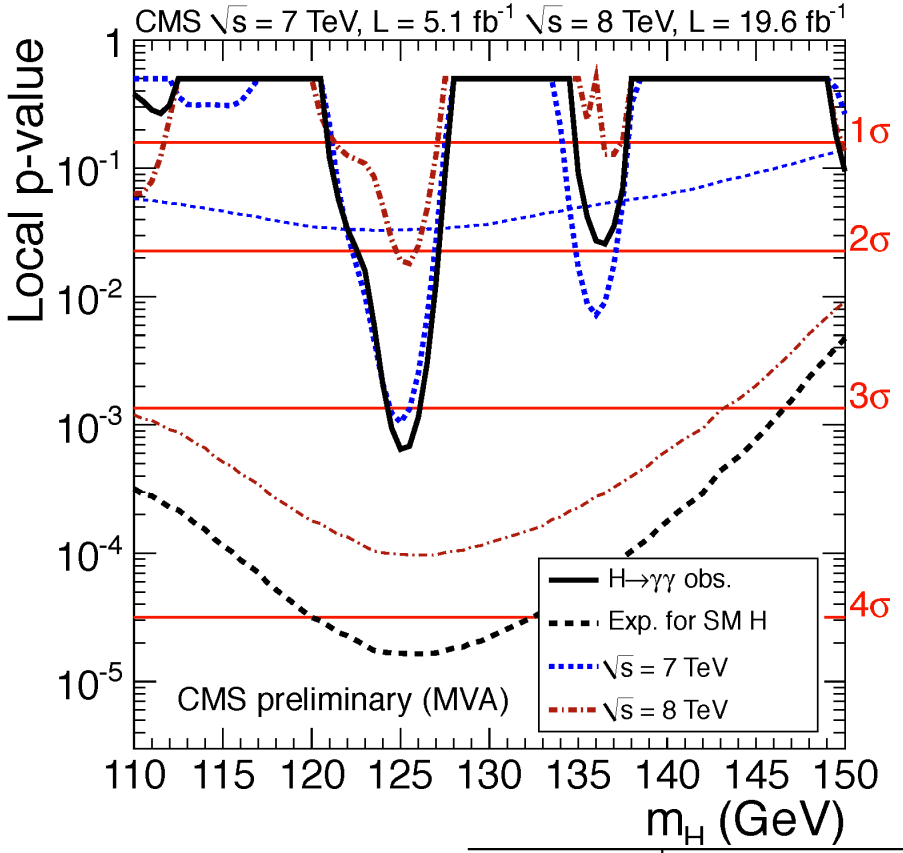

Cuts in Categories combining all categories and both years

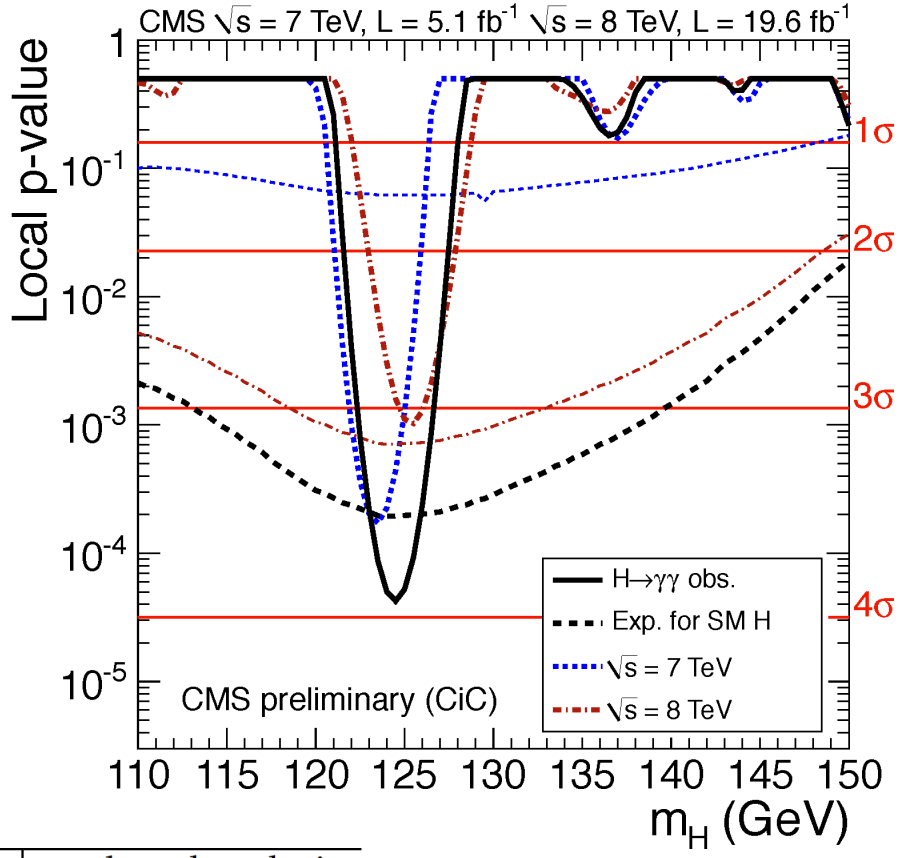
Cross-check Analysis with lower sensitivity, but is simpler in some respects.

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

# Signal Significance & Strength

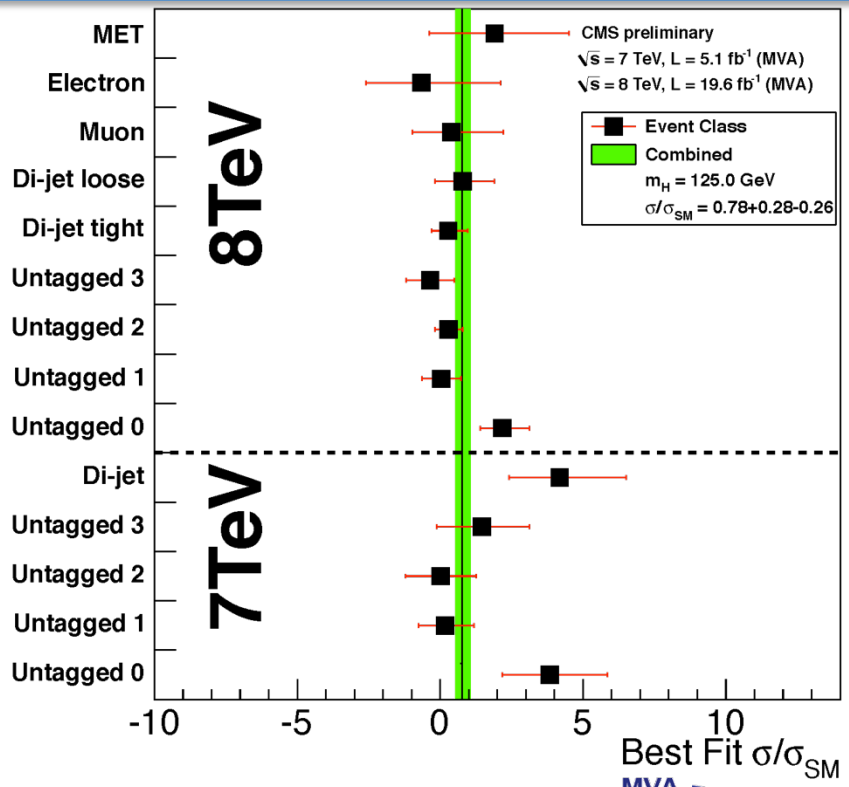
CMS HIG-13-001

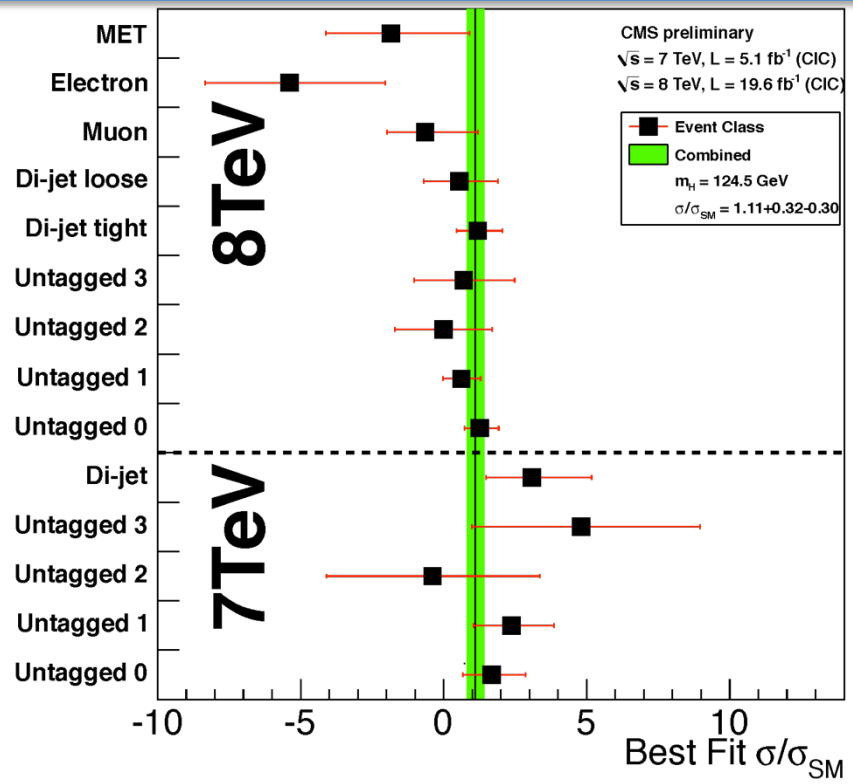


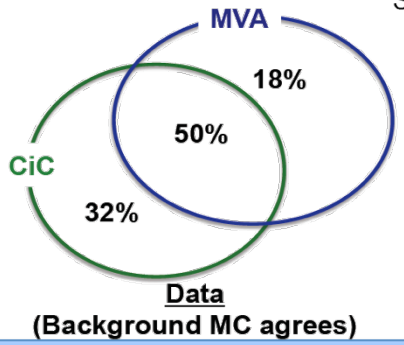



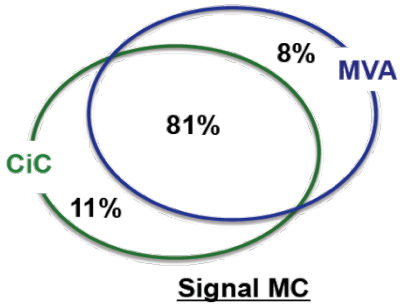

| | MVA analysis (at $m_H$=125 GeV) | cut-based analysis (at $m_H$=124.5 GeV) |
|---|---|---|
| 7 TeV | $1.69^{+0.65}_{-0.59}$ | $2.27^{+0.80}_{-0.74}$ |
| 8 TeV | $0.55^{+0.29}_{-0.27}$ | $0.93^{+0.34}_{-0.32}$ |
| 7 + 8 TeV | $0.78^{+0.28}_{-0.26}$ | $1.11^{+0.32}_{-0.30}$ |

# Signal Strength by Event Class



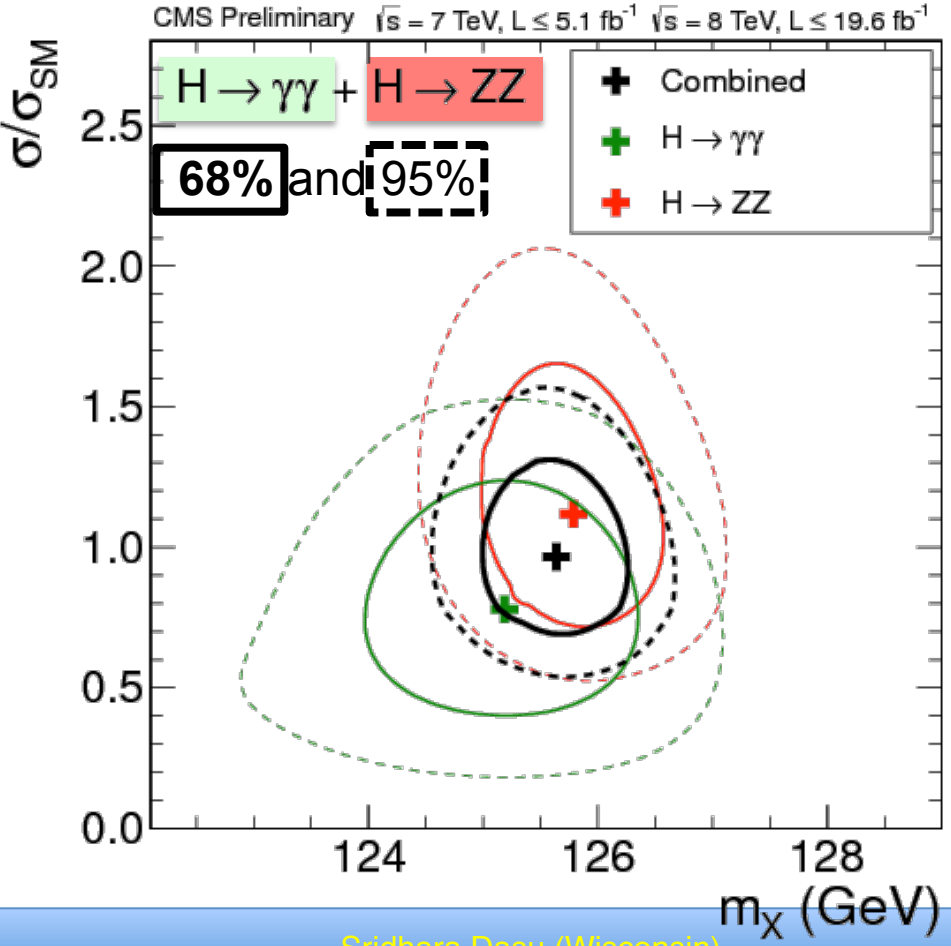

CMS HIG-13-001

# Compatibility with Being SM Higgs

CMS HIG-13-005

Excesses seen in ZZ, WW and γγ in both experiments

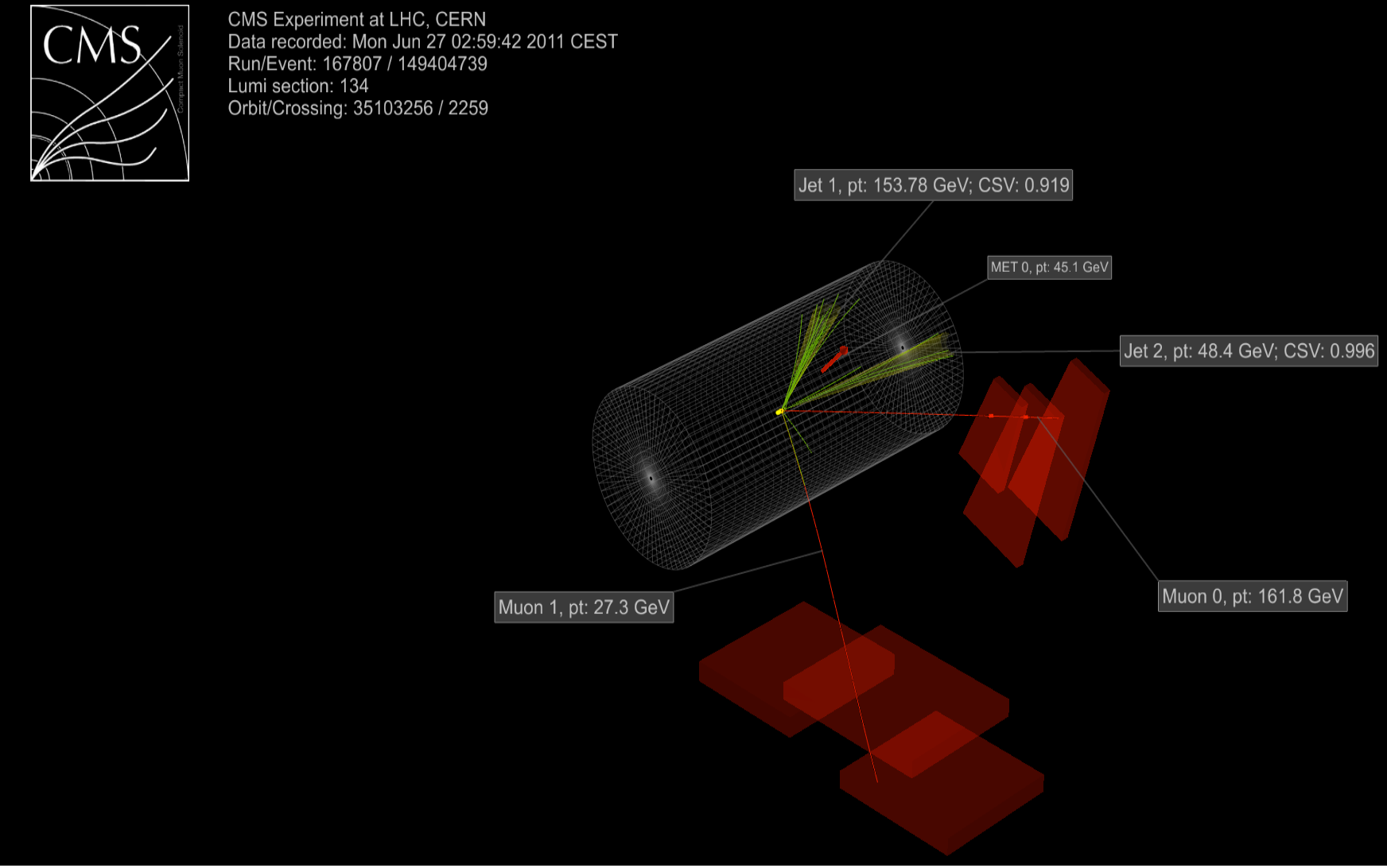
Signal strength ~consistent with SM Higgs




Statistical and systematic errors included

Details on CMS Higgs combination: Roberto Covarelli's talk in Monday parallel session.

# Does the New Boson Couple to Fermions?

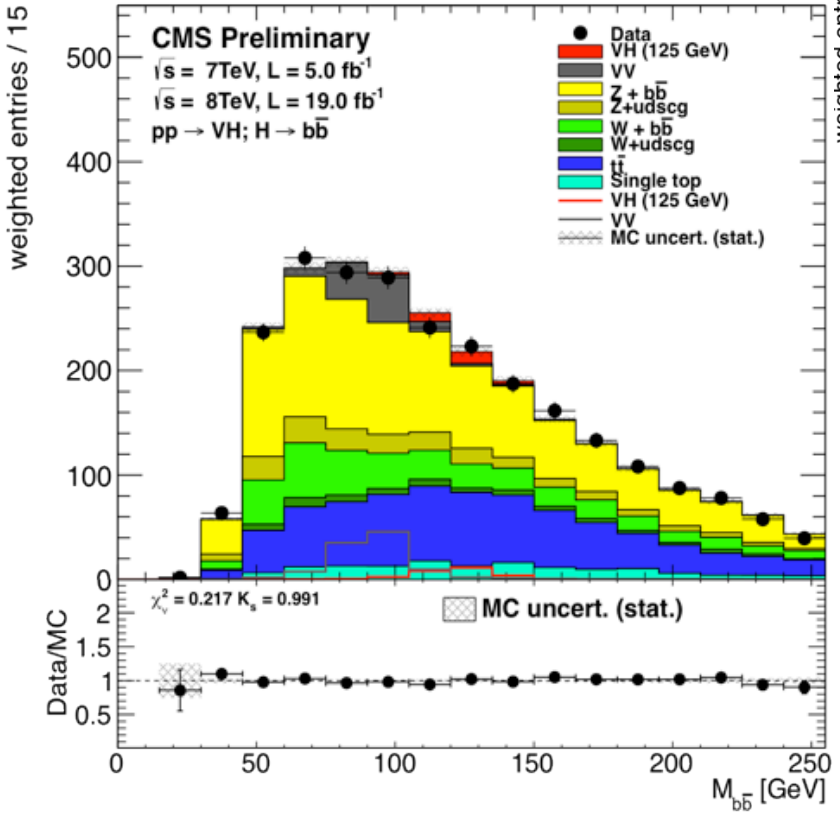


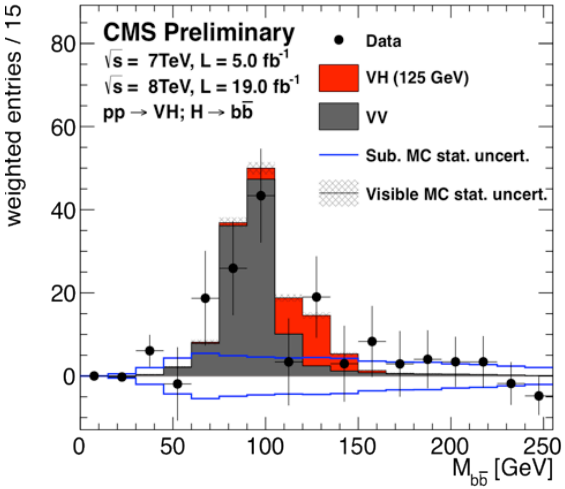
# Higgs Decay to Bottom Quarks (VH)

CMS HIG-13-012

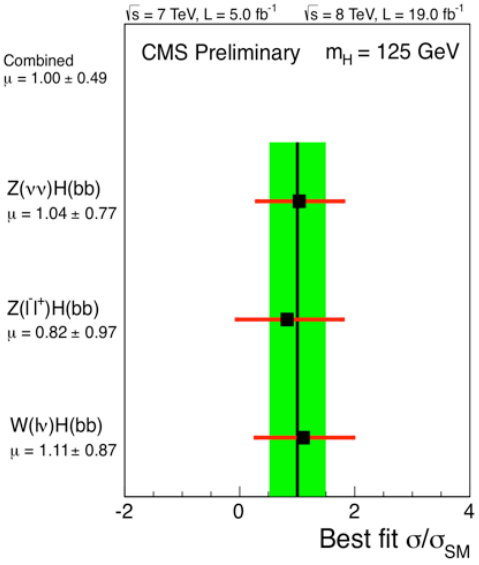
Gluon fusion signal is overwhelmed by QCD

Associated production with W (lν), Z(ll, νν) probed




A 2.1σ excess seen (as expected)



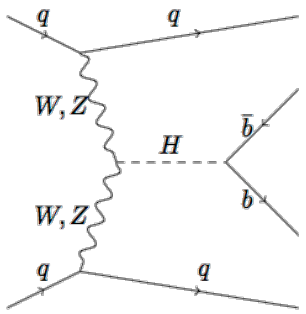
# Higgs Decay to Bottom Quarks (VBF)

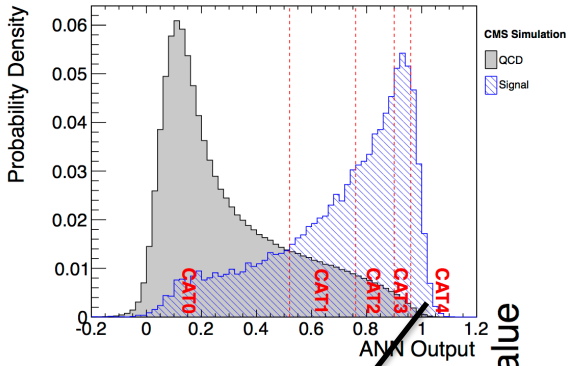
CMS HIG-13-011

Vector Boson Fusion Production Tagged by Forward Jets

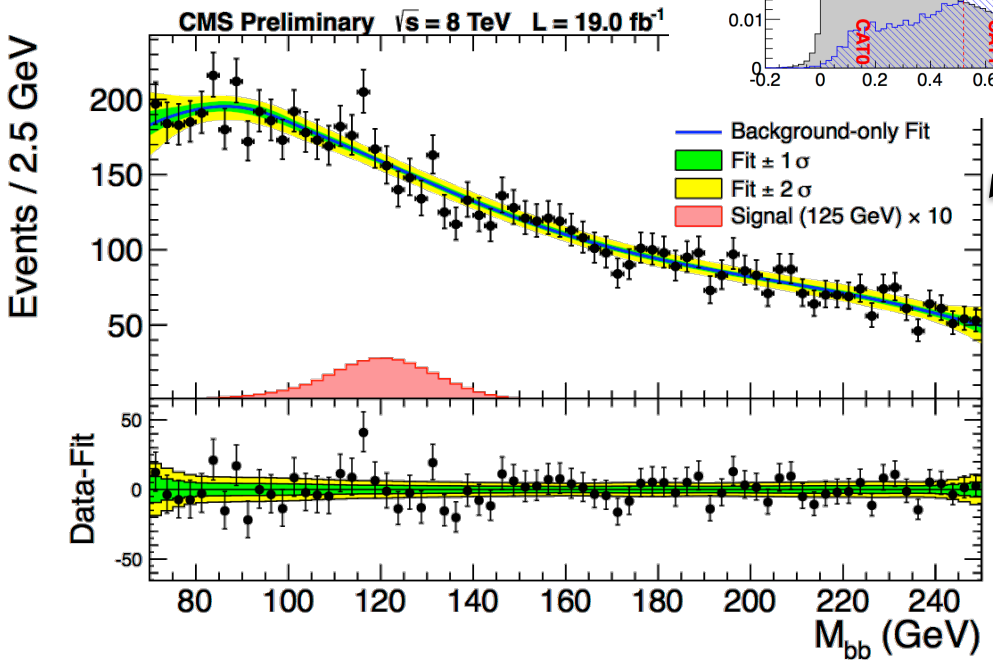
Difficult to trigger – 4 jets (+ 2 b-tags at Higher Levels)

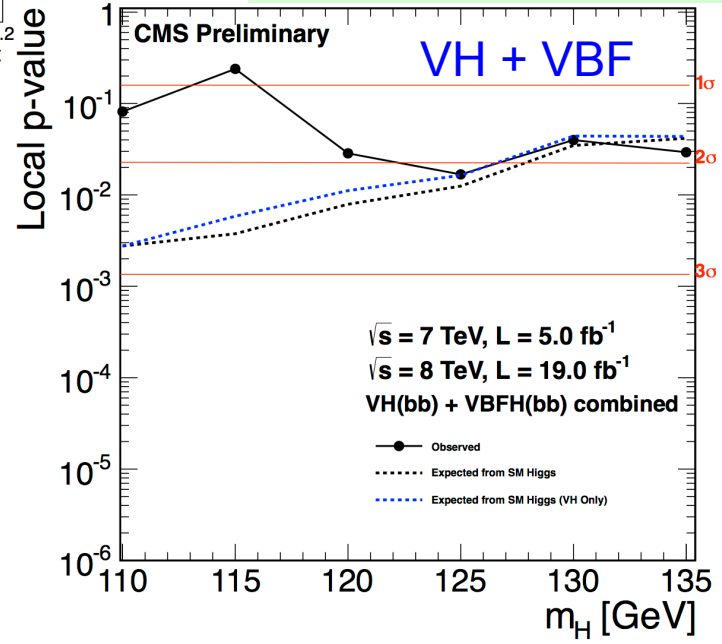
MVA with b-tag sorted jets
- kinematics
- gluon likelihood




CMS HIG-13-011+12

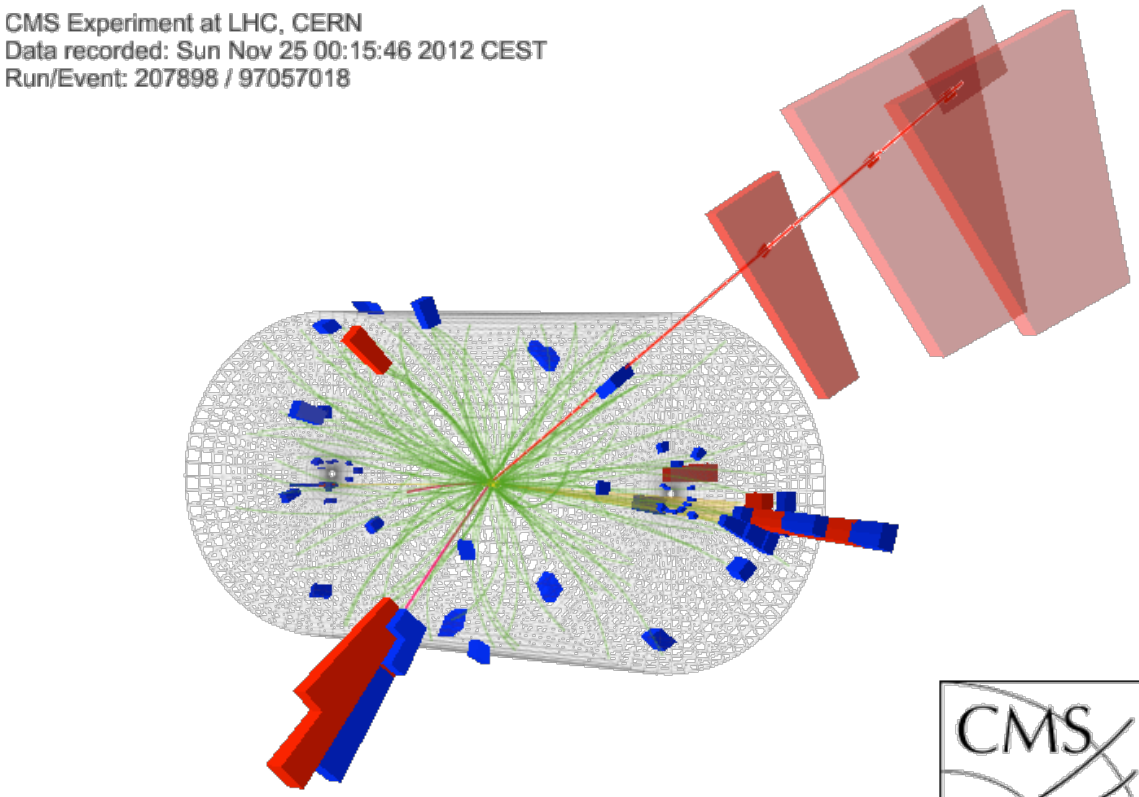


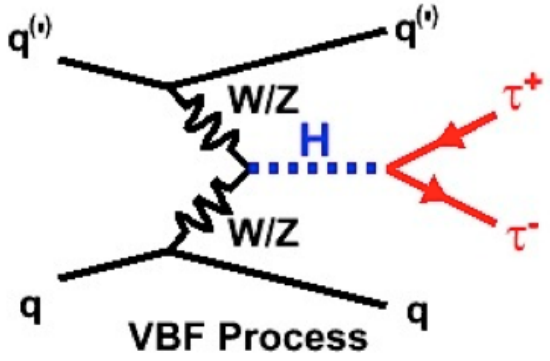



# Higgs Decay to Tau Pairs

CMS HIG-13-004

Taus with high branching fraction can probe in all production modes:
W and Z boson fusion; Gluon fusion and W, Z, top associated production



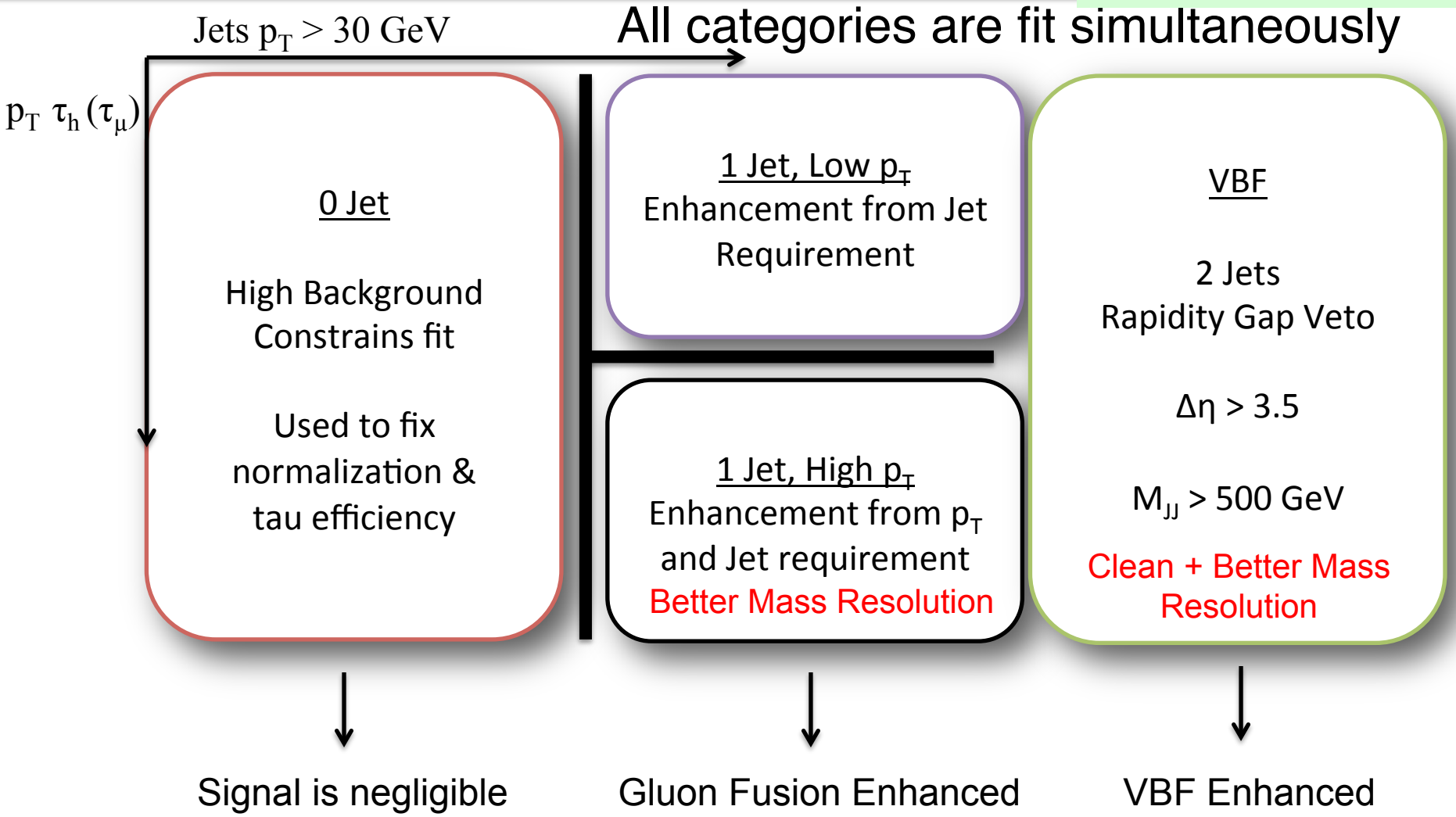

Final states VBF + GF:
$e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Also, VH (WH & ZH)
$\ell\ell\tau_h$, $\ell\tau_h\tau_h$, $\ell\ell\tau_h\tau_h$

Details on CMS Higgs to Taus:
Mauro Verzetti's talk in parallel session.

# VBF / GF Event Characterization

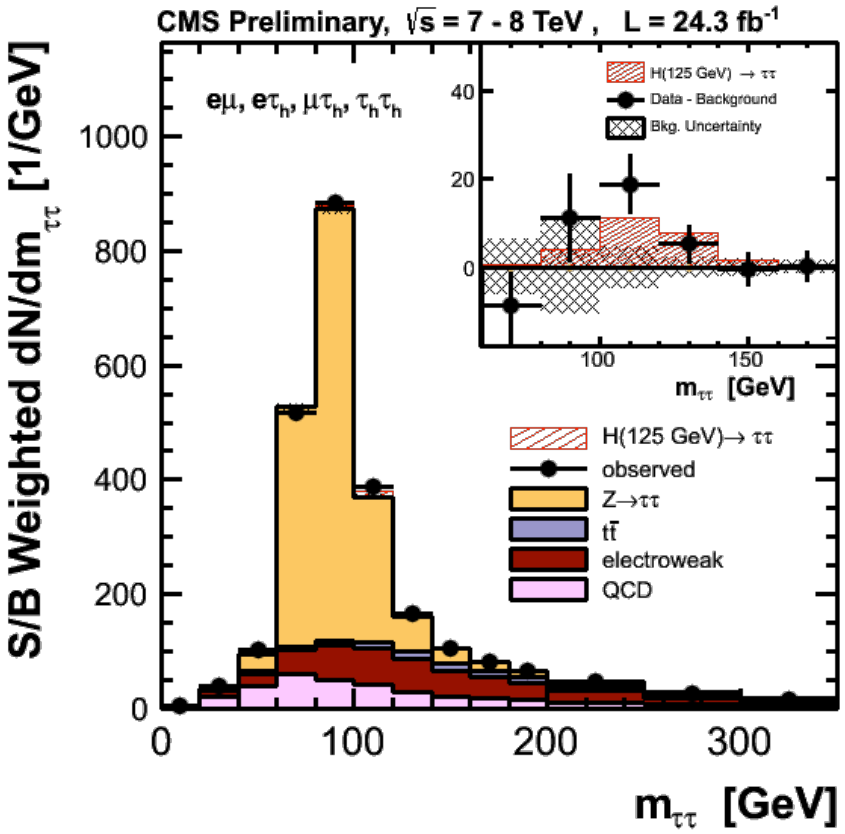
CMS HIG-13-004

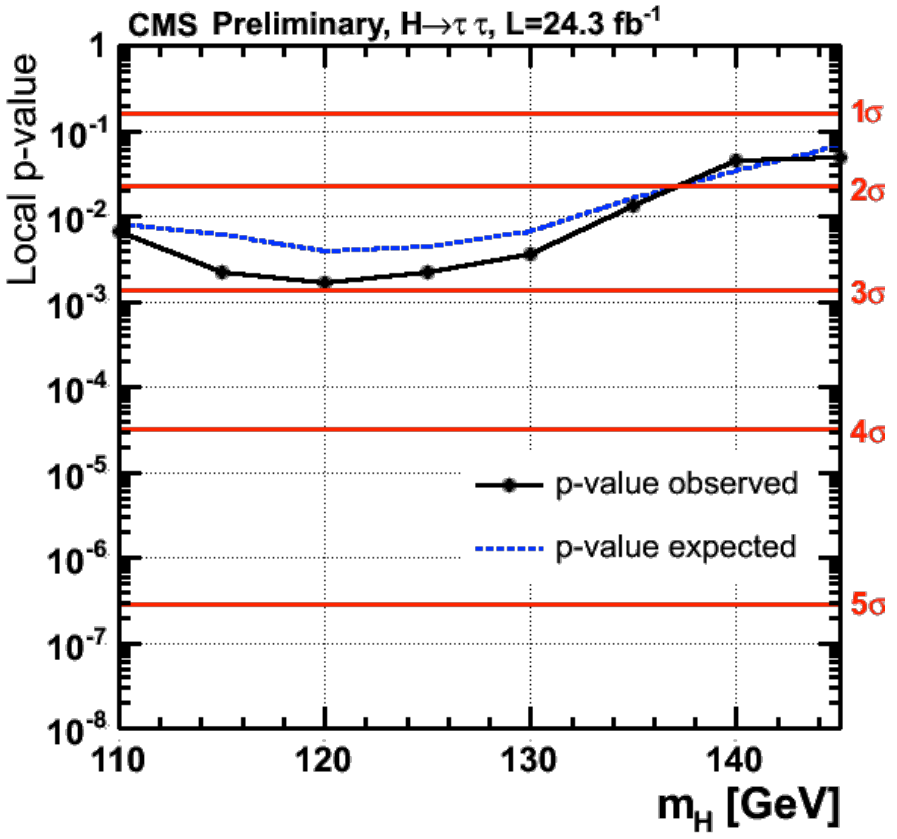


# Combination of ττ
# All Categories + Channels

CMS HIG-13-004

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



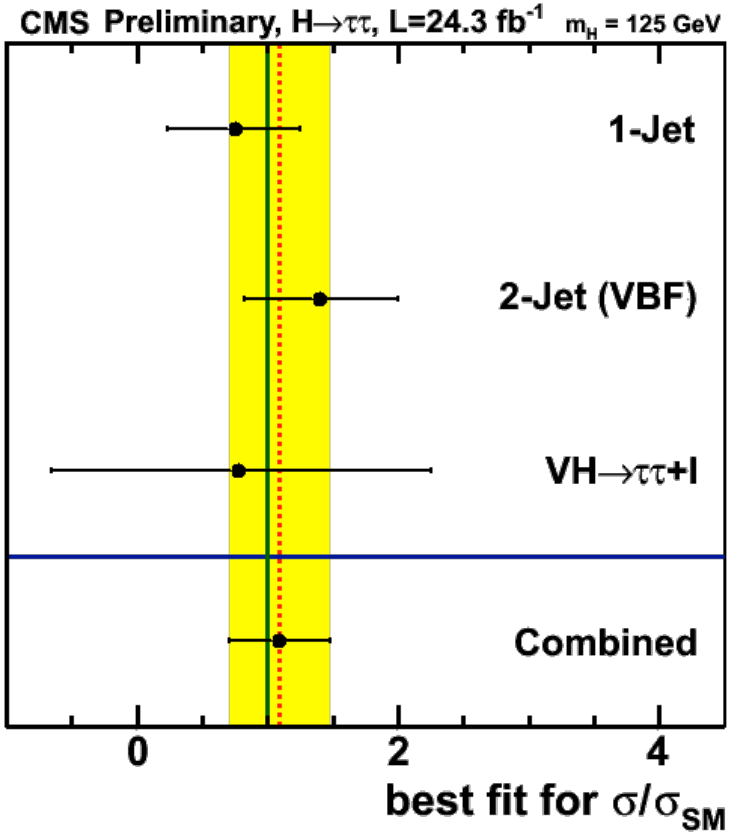



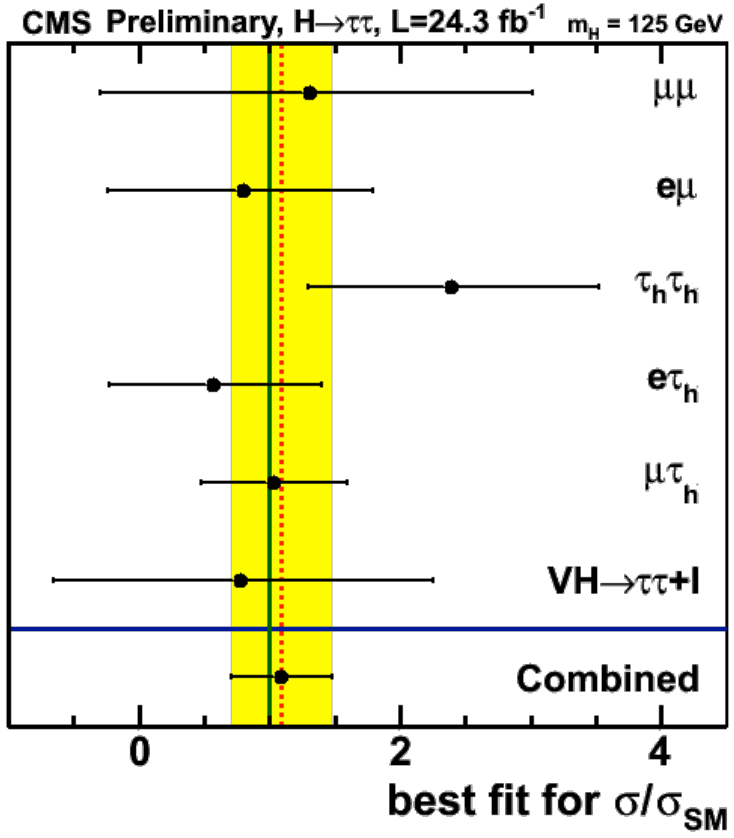

3.4σ evidence for fermion coupling combined with bb.

# Signal Strength for H to ττ

CMS HIG-13-004

Breakdown by category & by channel

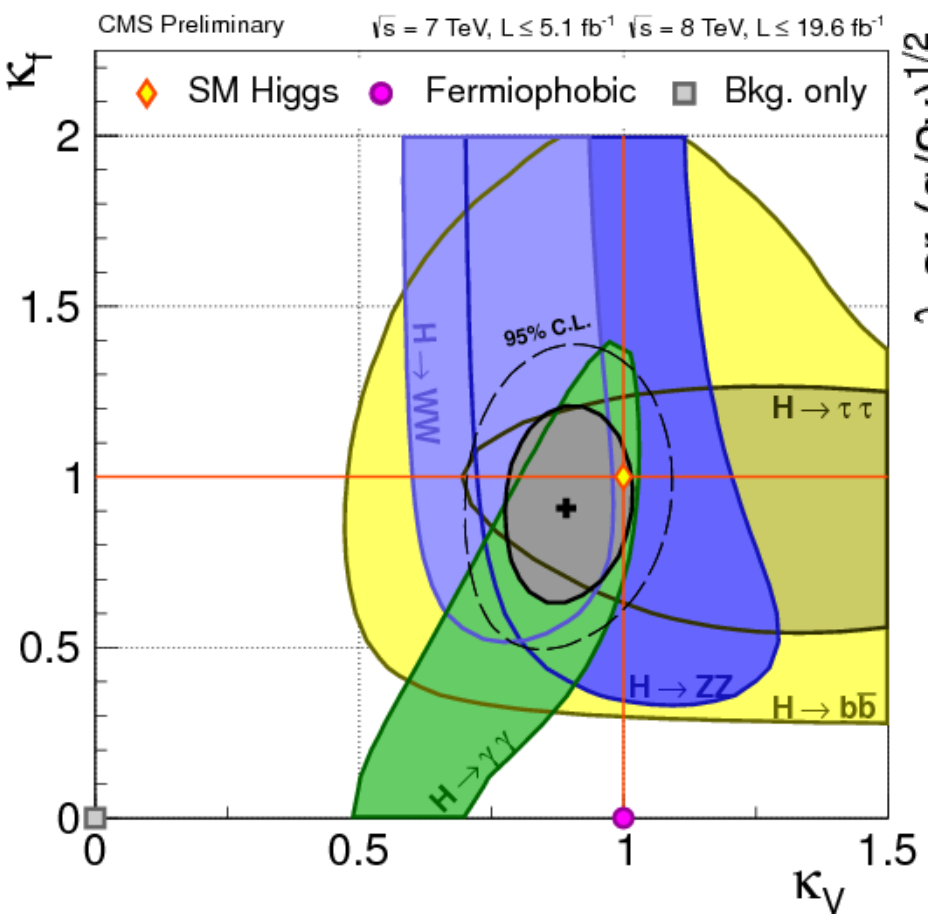


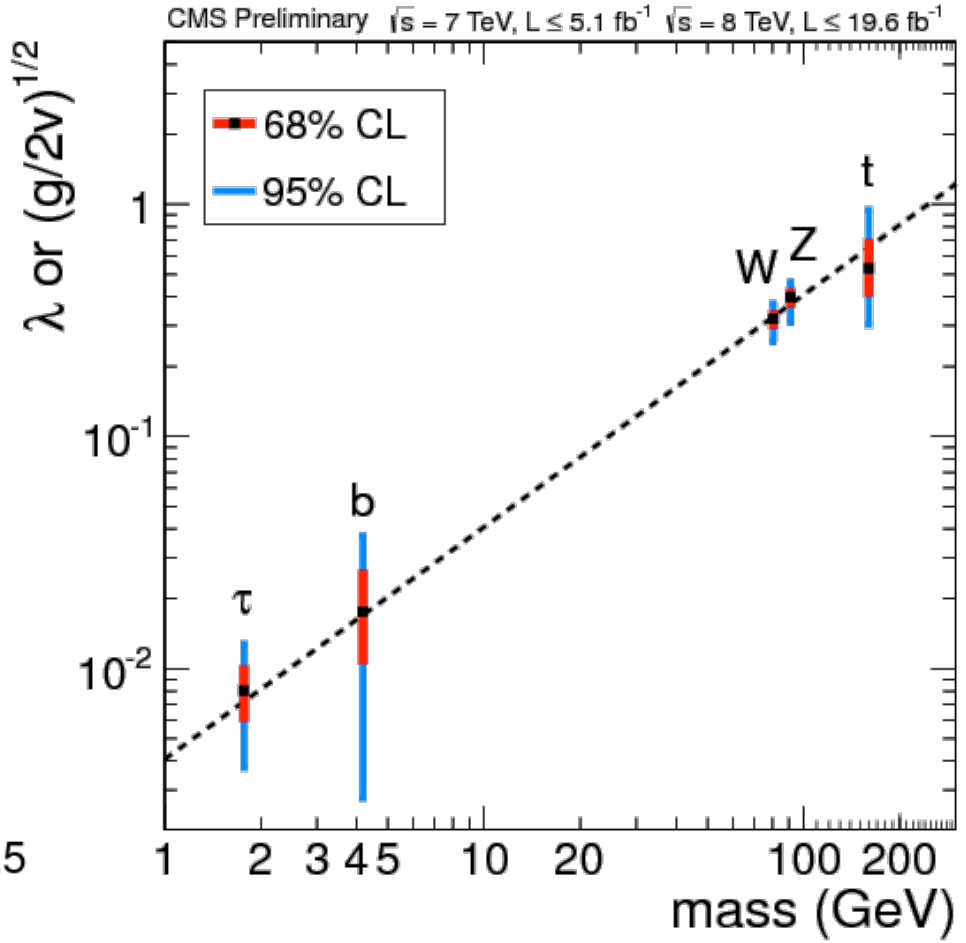



# Couplings Scan

CMS HIG-13-005

Details on CMS Higgs combination: Roberto Covarelli's talk in parallel session.

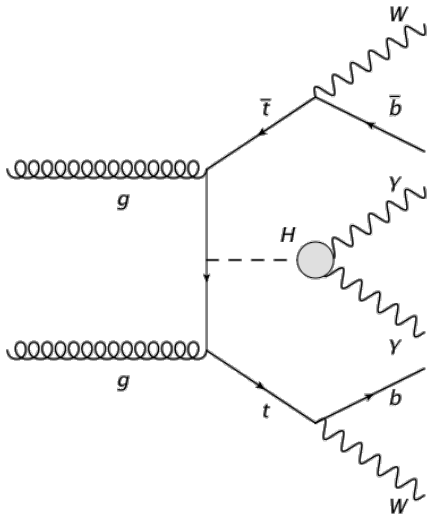


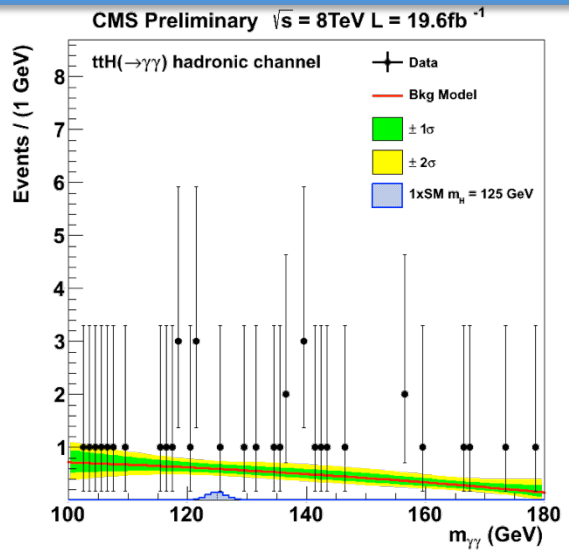
# Direct Search for Top Coupling

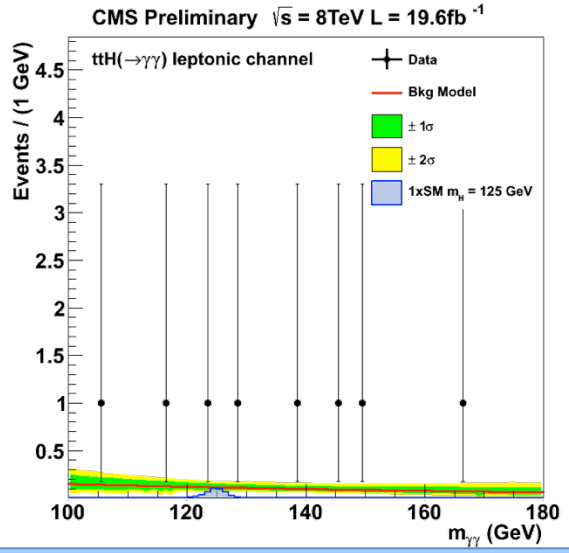
CMS HIG-13-015

Search for Higgs decay to two photons with top-pair




Hadronic:
4j, 2b, 2γ
Leptonic:
2ℓ, MET, 2γ



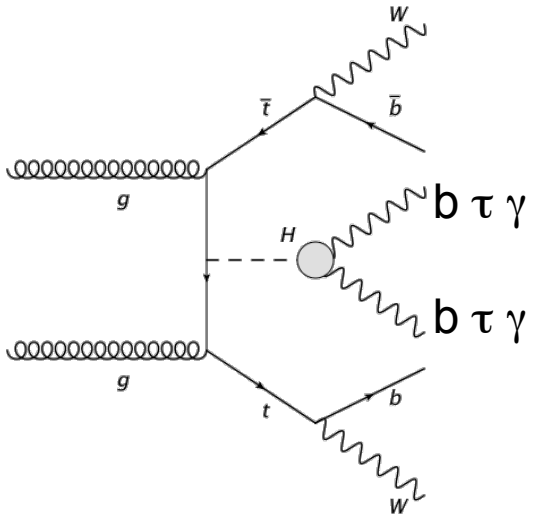




| Process | Hadronic Channel | Leptonic Channel |
|---|---|---|
| $t\bar{t}H$ | 0.567 (87%) | 0.429 (97%) |
| $gg \to H$ | 0.059 (9%) | 0 (0%) |
| VBF $H$ | 0.006 (1%) | 0 (0%) |
| $WH/ZH$ | 0.019 (3%) | 0.013 (3%) |
| Total signal | 0.65 | 0.44 |

# Direct Search for Top Coupling

CMS HIG-13-019

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



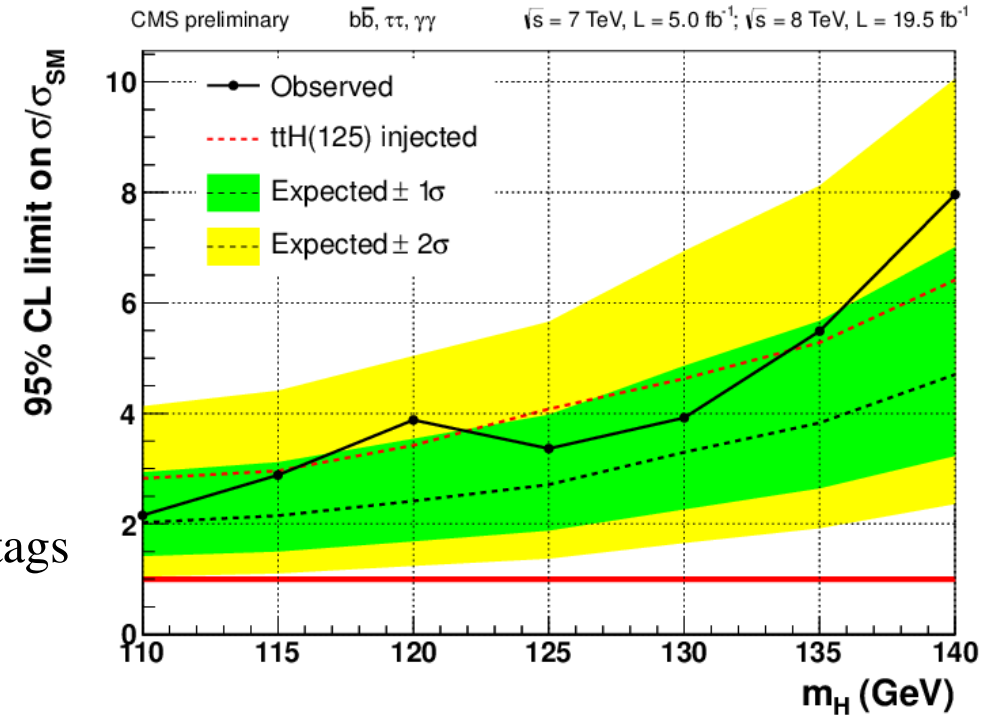

MVA + Classes $(lj,\ 2l,\ 2\tau)$ with b-tags

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

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

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

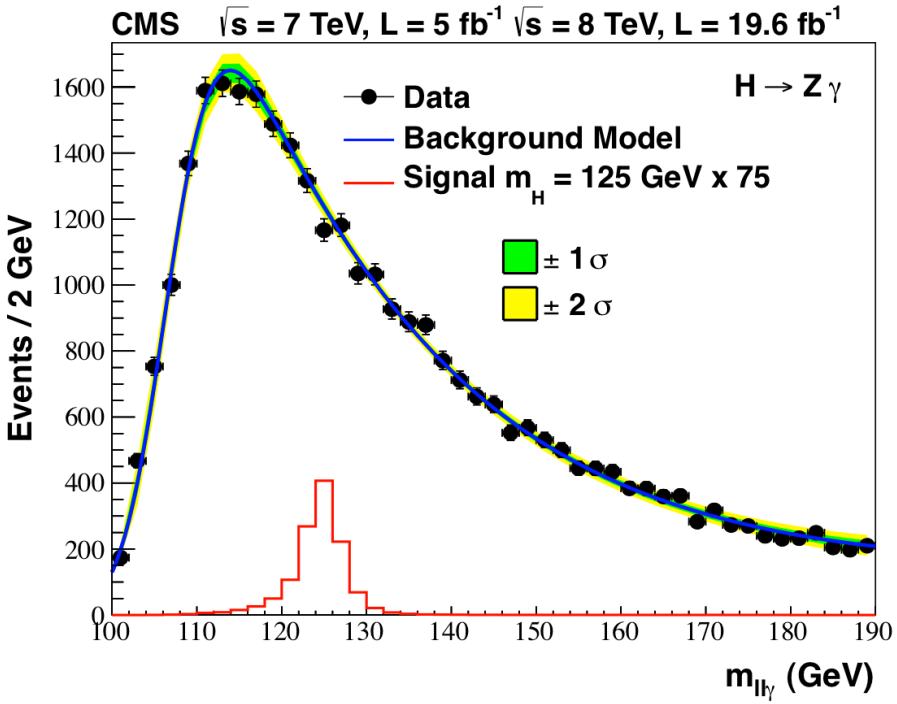
$ttH(\tau\tau) \rightarrow 2\tau + 4j + 2b$

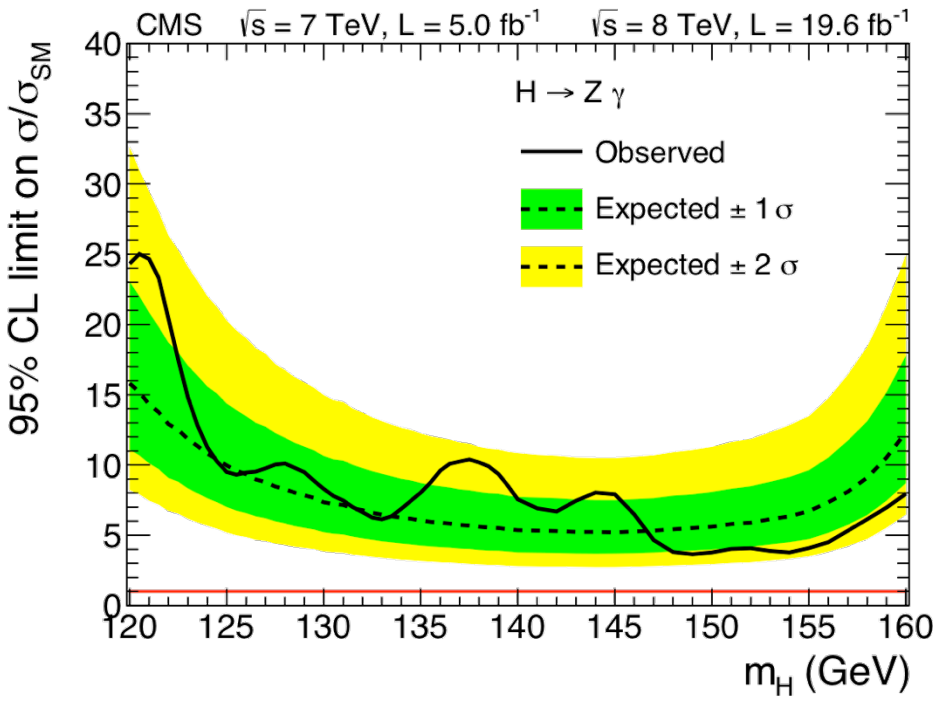



Not at SM sensitivity level yet, but compatible with injected signal of $M_H$=125 GeV

# Rare H Decay to Zγ

CMS HIG-13-006, arXiv:1307.5515



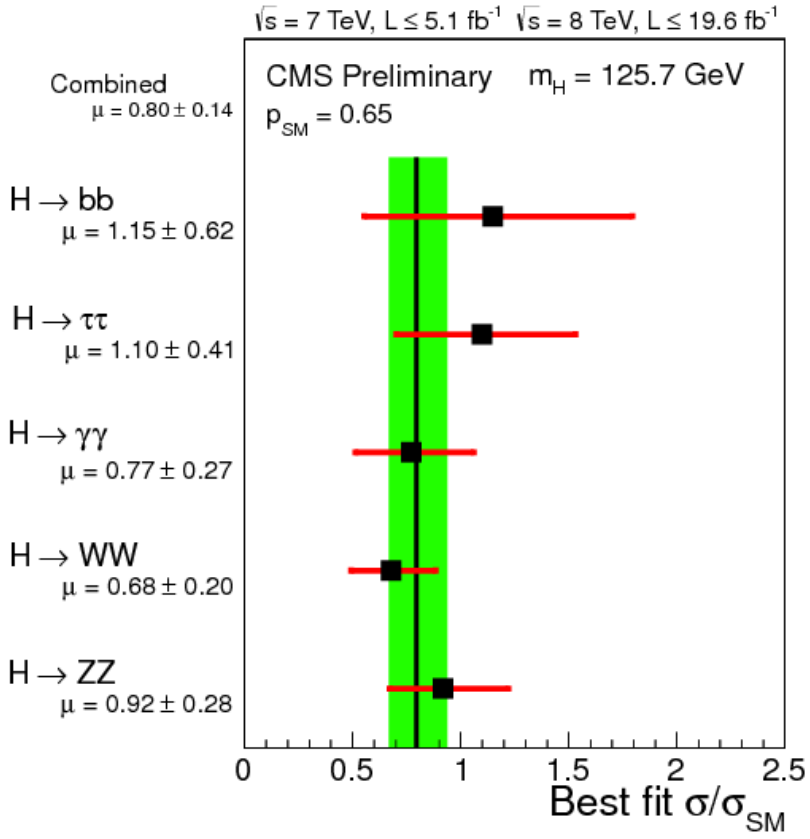

Not yet sensitive at SM level

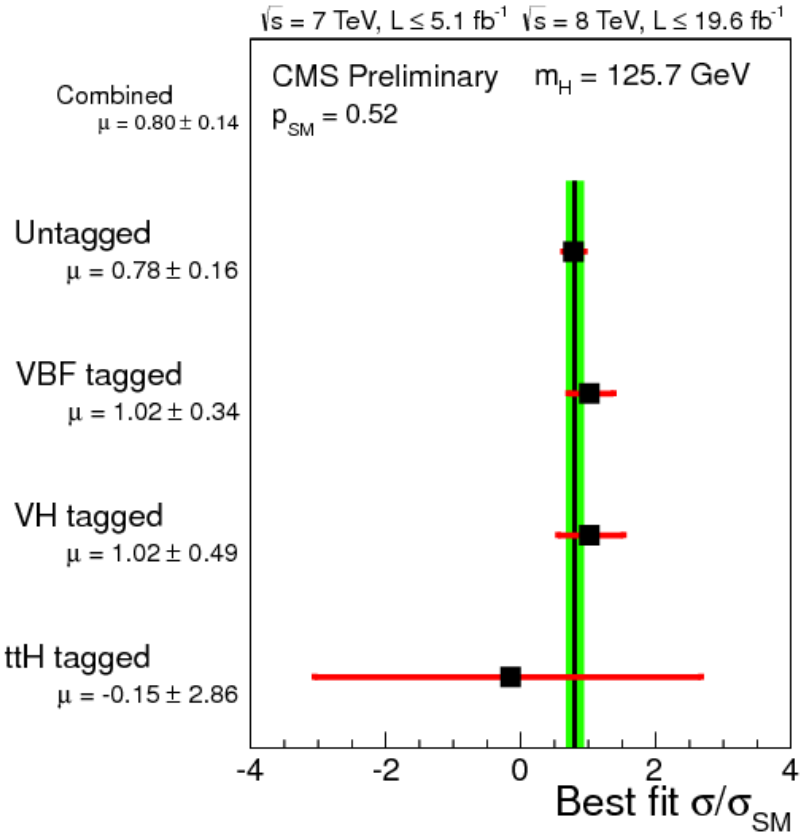
- Search motivated by potential new physics contribution
- Interesting mode for HL-LHC

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

CMS HIG-13-005

Details on CMS Higgs combination: Roberto Covarelli's talk in parallel session.




With small push 3σ evidence in τ-pair soon. Run 2 for bb, μμ, Zγ

Self-coupling will take longer O(1) ab$^{-1}$ at HL-LHC

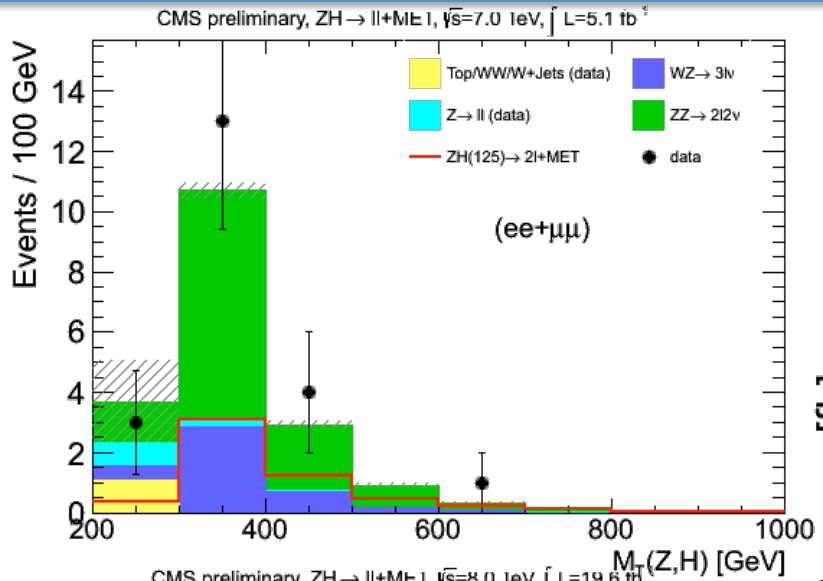
# Beyond the Standard Model

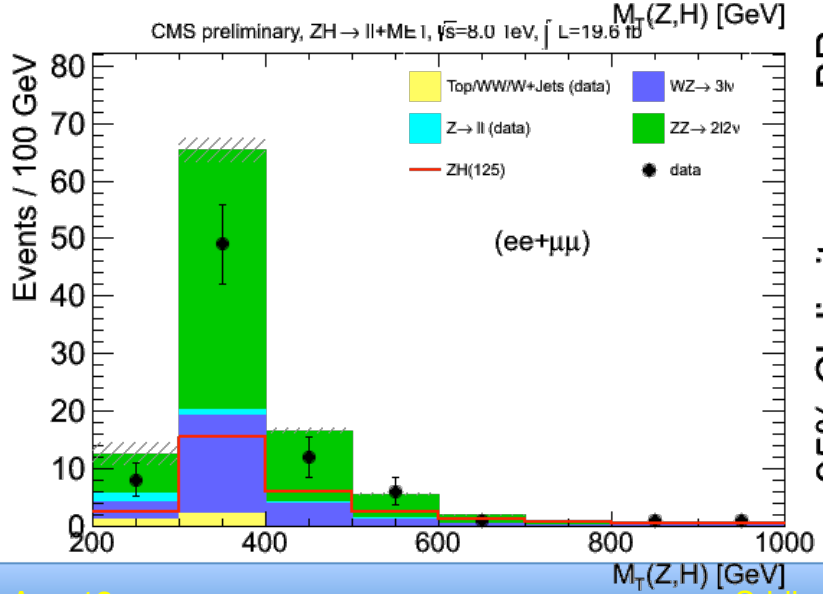
**There are many possibilities that change the precise predictions of the minimal higgs sector of the Standard Model**

- **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 have been looking for these exotic Higgs bosons**

# VH: Higgs Decay to Dark Particles

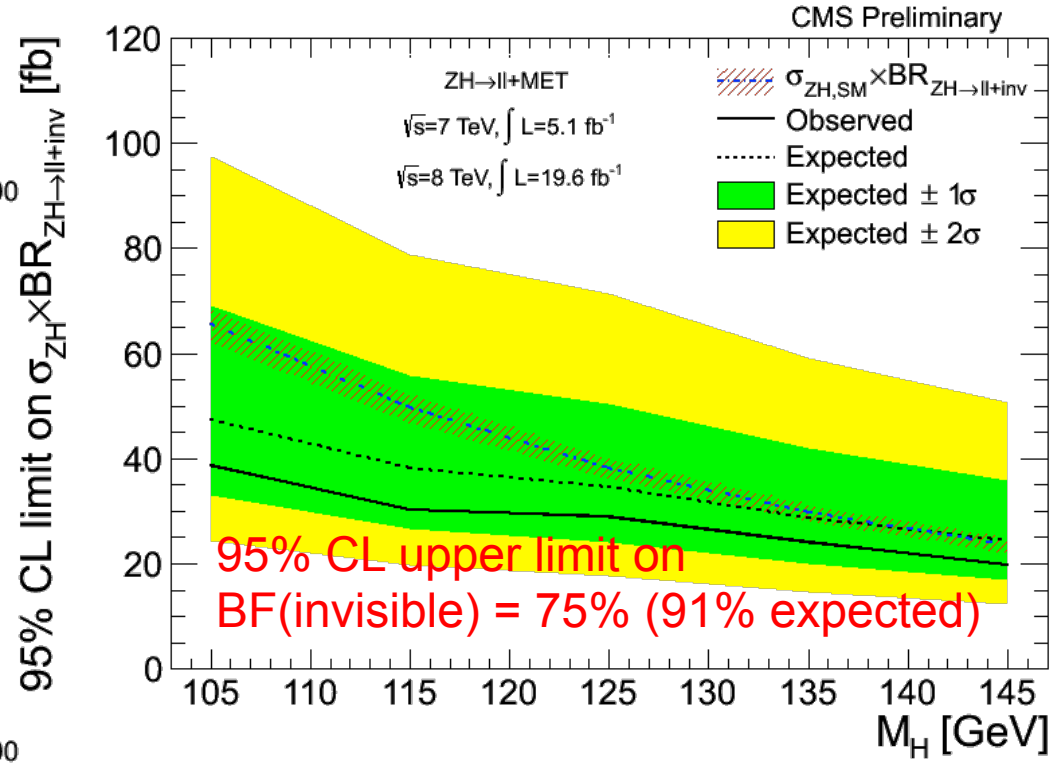
CMS HIG-13-018




H associate production with $Z(\ell\ell)$

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

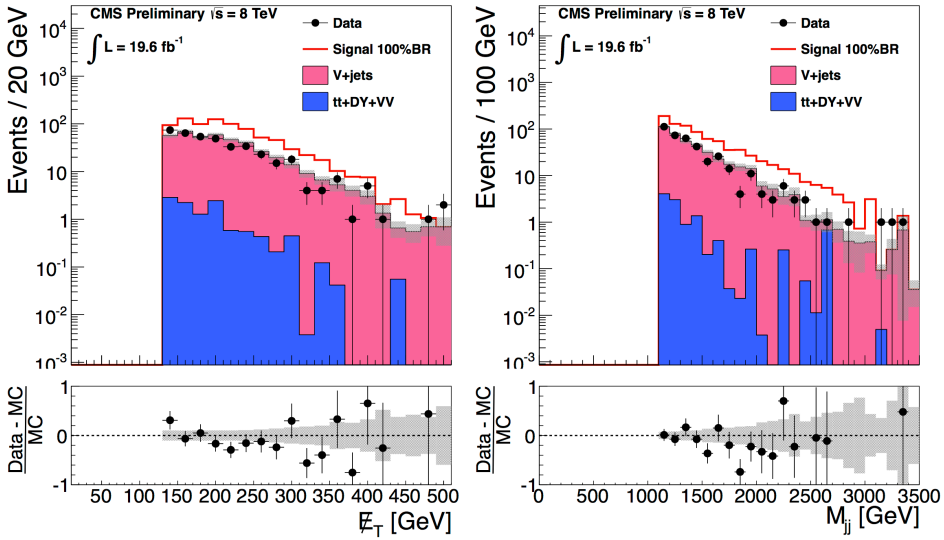


# VBF: Higgs Decay to Dark Particles

CMS HIG-13-013 (New for SUSY2013)

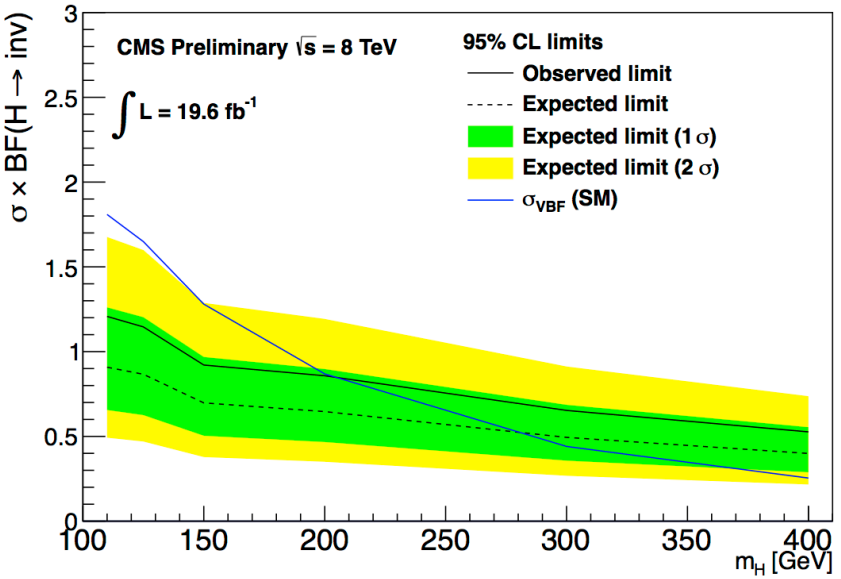
VBF associated higgs production

- Special VBF+MET L1&HL triggers & big effort to reduce QCD BG
- Z(νν)+Jets background predicted using Z(μμ)




Data agrees with SM background dominated by V+Jets

Signal histogram plotted is for 100% Invisible BR




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

# MSSM Higgs

Higgs sector in SUSY theory is more complicated

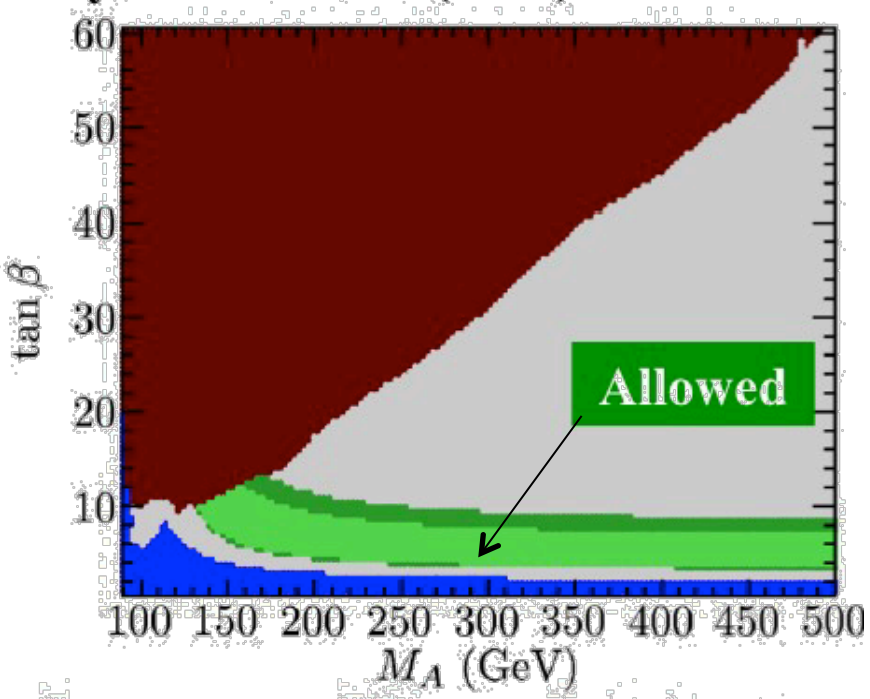
- Need 2 higgs doublets each with 4 degrees of freedom
  - Results in the Standard Model like Higgs ($h^0$)
  - Plus, two neutral higgs ($A^0$, $H^0$) and charged ($H^{\pm}$)
  - However, only 2 parameters ($M_A$, tanβ – ratio of the two doublets)
  - Masses of higgses and Z related: Search in ($M_A$, 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**

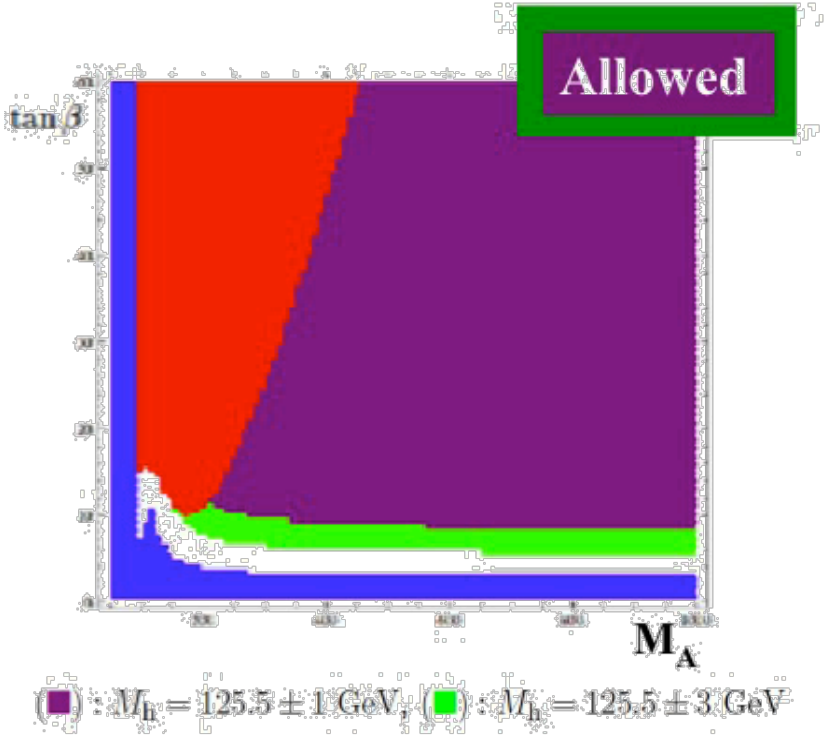
**$123 < M_h < 127$ GeV**

**(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**

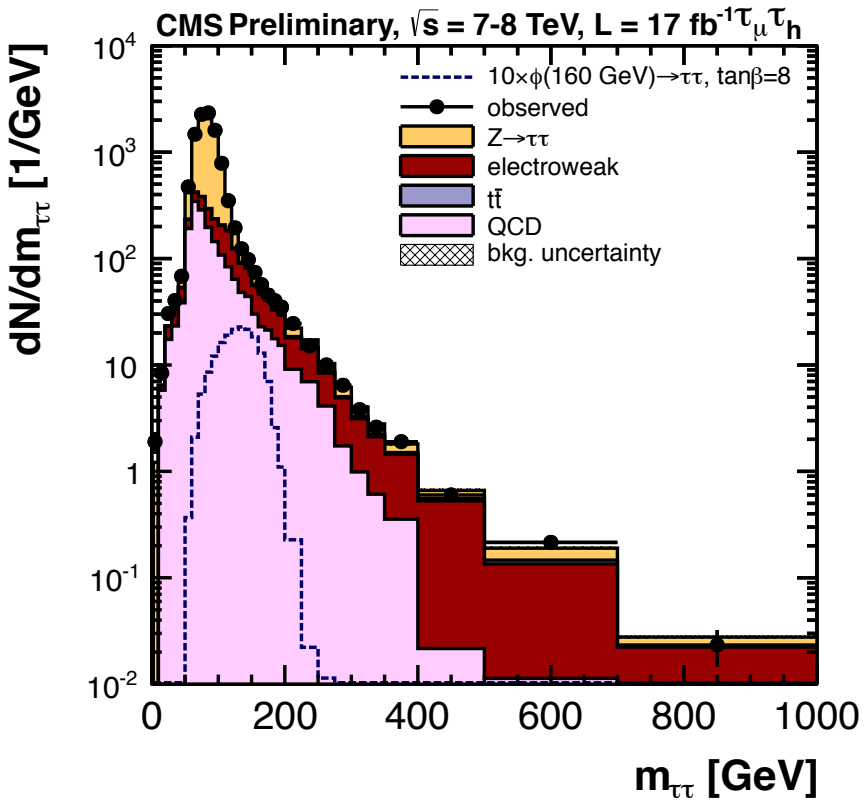


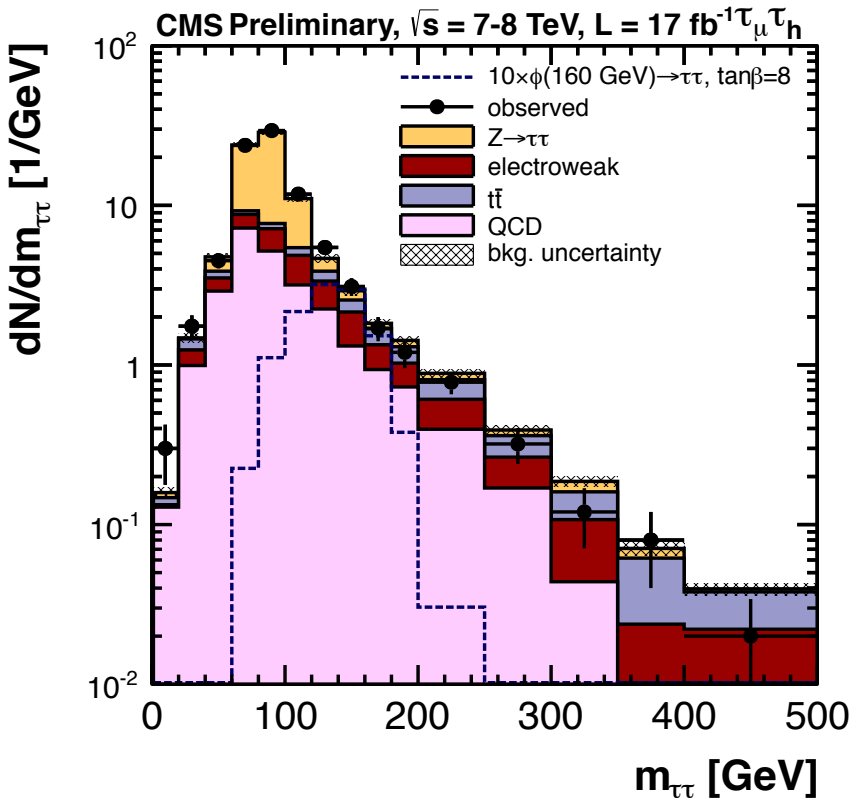

**$X_t$: stop mixing paramater**

# Mass of ττ : 17 fb$^{-1}$ Data

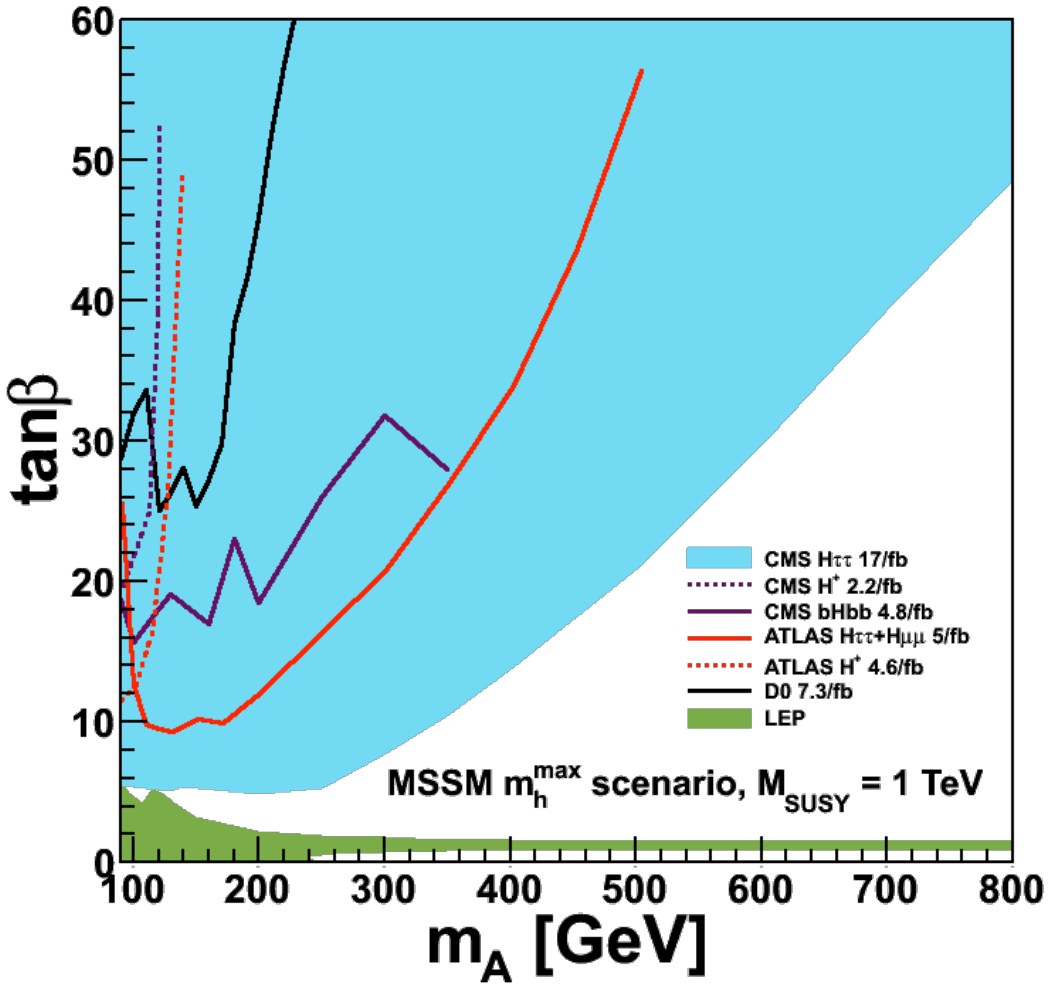
CMS HIG-12-050

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

Friis (Wisconsin)

# Summary

LHC discovered a new particle

- Both ATLAS & CMS see the same thing at the same mass
- ZZ* decay mode is providing excellent measurements of properties

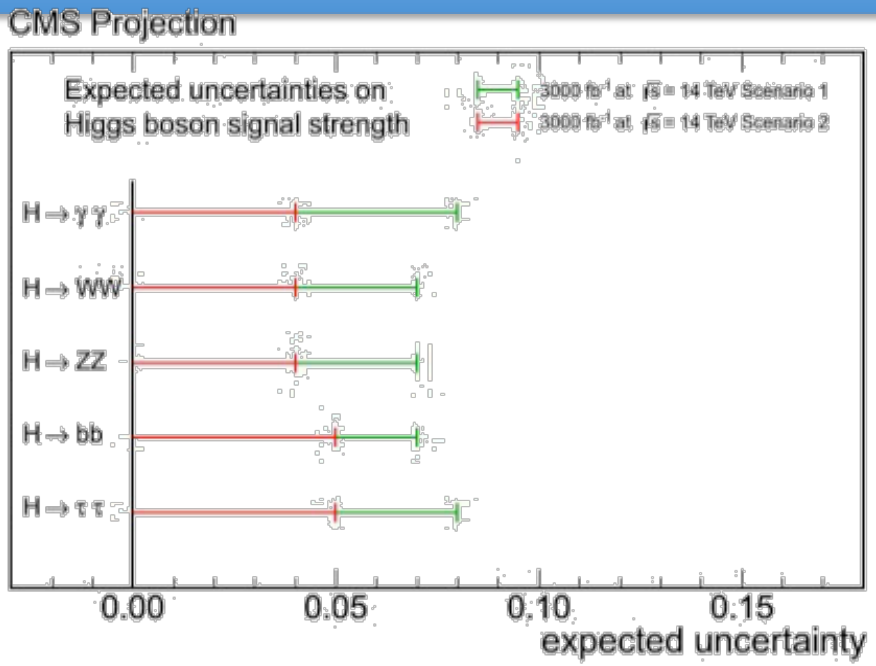
Is it the Standard Model Higgs Boson?

- Its mass is in the right window – consistency with SM
- It does appear to be a scalar particle!
- However, its other properties are yet to be determined
- Confirmed that the new boson couples to W-bosons also
- Fermion channels are consistent with it being SM Higgs
  - Will the hints seen in preliminary analysis be confirmed?

LHC has performed well in 2012 but will be down 2013-2014

- Both experiments collected ~ 25 $fb^{-1}$ in Run-1
  - Analysis improvements underway for final summer publications
- It may take ~100 $fb^{-1}$ 14 TeV to measure SM couplings, 2015-2016?
  - Except self-coupling ☹, which is much more difficult → HL-LHC
- Higgs is the new portal to BSM, expect much excitement @ LHC!

# 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: $\Delta$ theory / 2, rest $\propto 1/\sqrt{L}$

Extrapolated from 2011/12 results