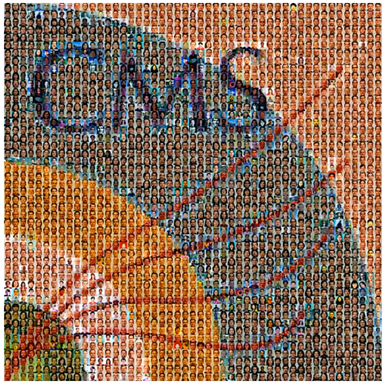

Higgs → Gauge Bosons @ CMS

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On behalf of the CMS collaboration

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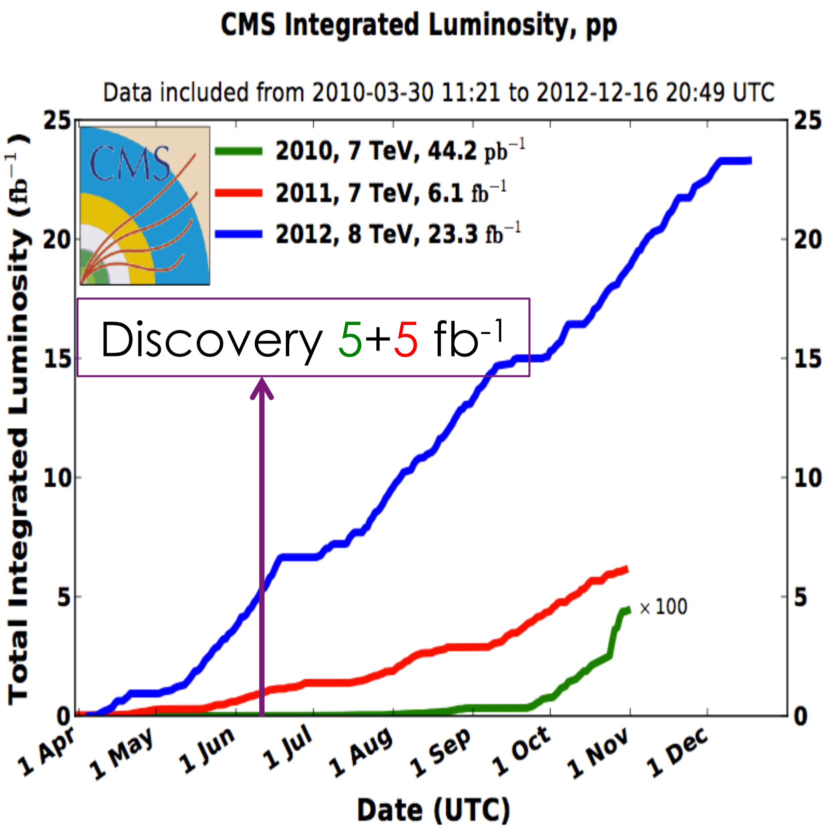
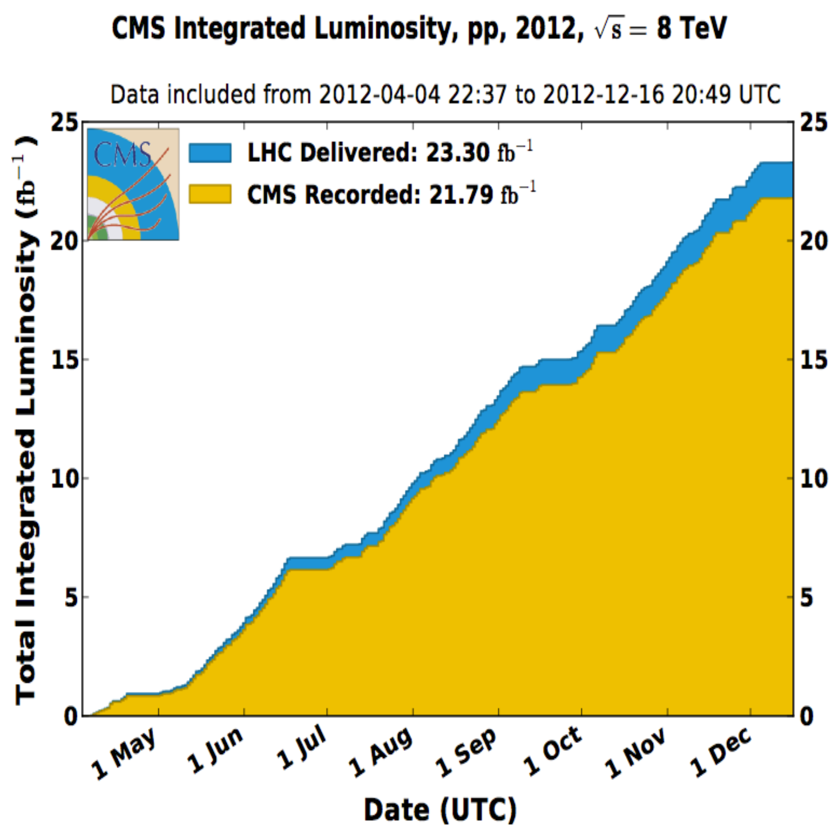
Outline

- Higgs @ LHC
- Overview of CMS data
- Most recent results for H → gauge bosons searches @ CMS experiment
  - $H \to \gamma\gamma$ @ 7 + 8 TeV (arXiv:1407.0558)
  - $H \to ZZ^* \to 4l$ @ 7 + 8 TeV (Phys. Rev. D89 092007 (2014))
  - $H \to ZZ \to 2l2\tau$ @ 7 + 8 TeV (CMS PAS HIG-13-002)
  - $H \to ZZ \to 2l2\nu$ @ 7 + 8 TeV (CMS PAS HIG-13-014)
  - $H \to ZZ \to 2l2q$ @ 7 + 8 TeV (JHEP 04 (2012) 036, CMS PAS HIG-12-024)
  - $H \to WW^* \to l\nu l\nu$ @ 7 + 8 TeV (JHEP 01 (2014) 096)
  - $H \to WW \to l\nu qq$ @ 7 + 8 TeV (CMS PAS HIG-13-027)
  - $H \to Z\gamma$ @ 7 + 8 TeV (CMS PAPER HIG-13-006)
  - $H \to \gamma^*\gamma \to \mu\mu\gamma$ @ 8 TeV (CMS PAS-HIG-14-003)
- Public results @ this link:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Overview of CMS data

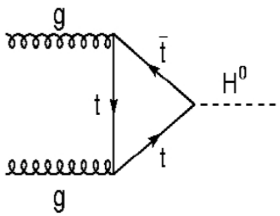


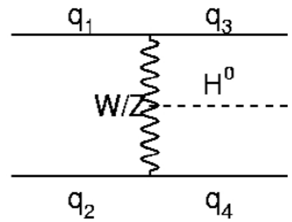


- Very efficient data taking by the CMS experiment in years 2011-12 (>90%)
- Analyses in this presentation correspond to total integrated luminosity of
  - 4.9 to 5.1 fb^{-1} @7TeV
  - 19.4 to 19.7 fb^{-1} @8TeV

Higgs @ LHC

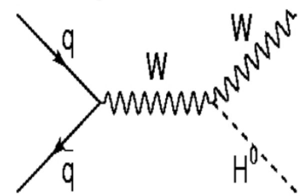
Gluon fusion: gg→H

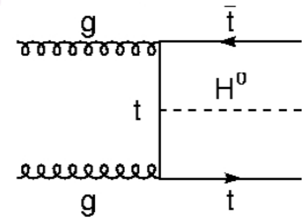




Vector Boson fusion: qq→H

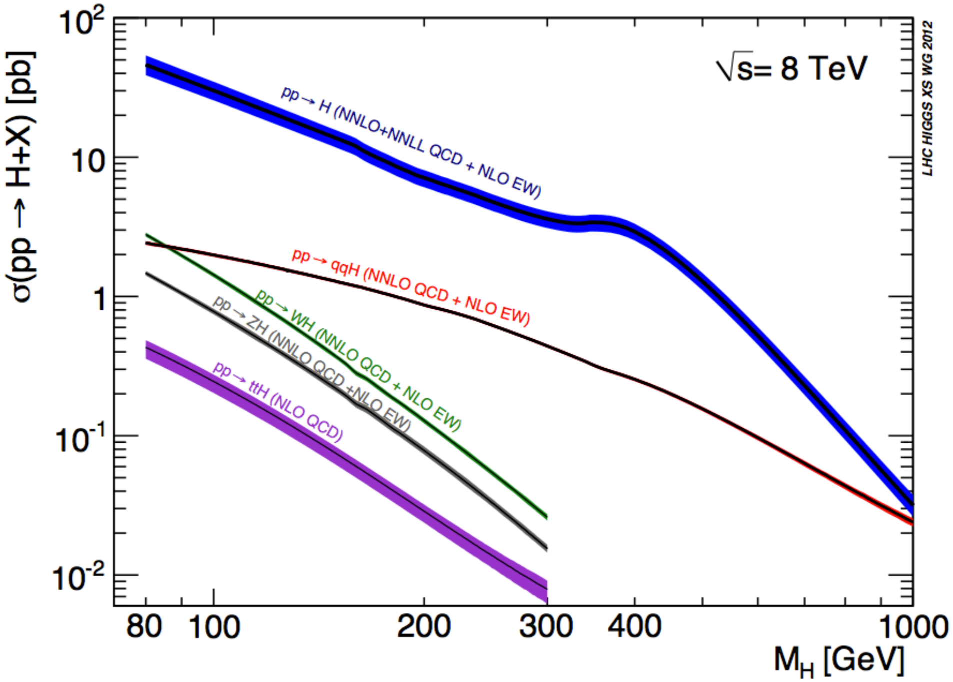
Associated production: WH, ZH

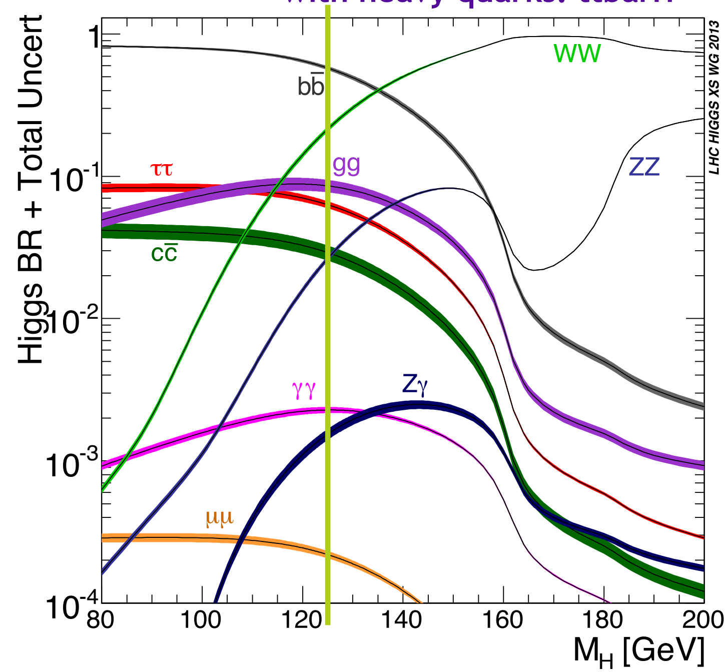




Associated production with heavy quarks: ttbarH

Higgs production modes





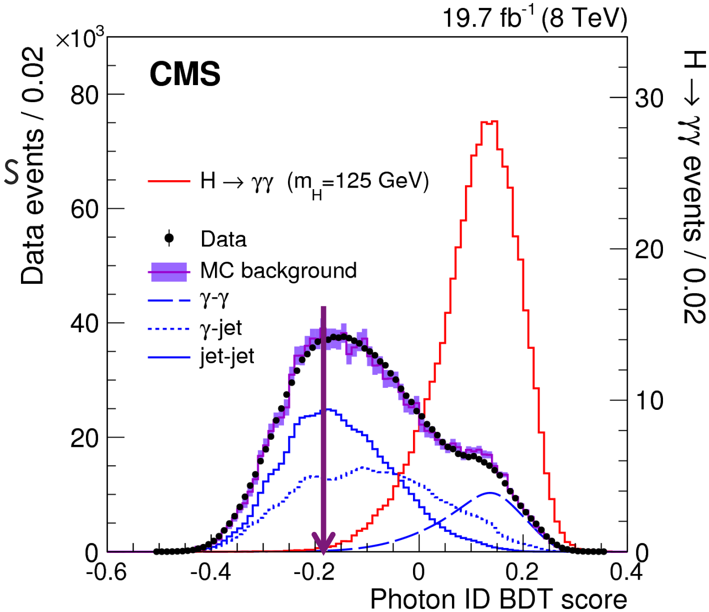
Higgs decay modes

σ @ $m_H = 125$ GeV (pb)				
ggF	VBF	WH	ZH	$t\bar{t}H$
19.3	1.6	0.7	0.4	0.1

BR @ $m_H = 125$ GeV (%)			
WW	ZZ	$\gamma\gamma$	$Z\gamma$
22	2.6	0.23	0.16

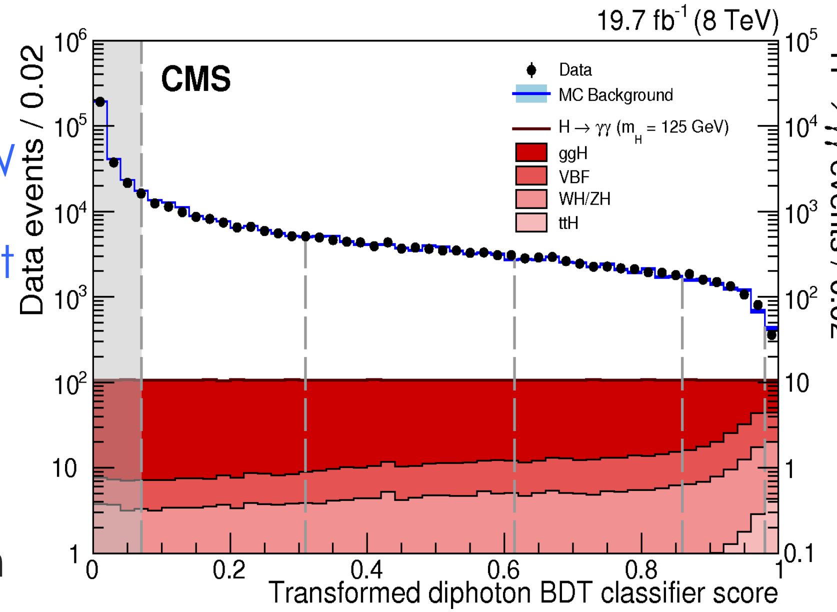
H → γγ

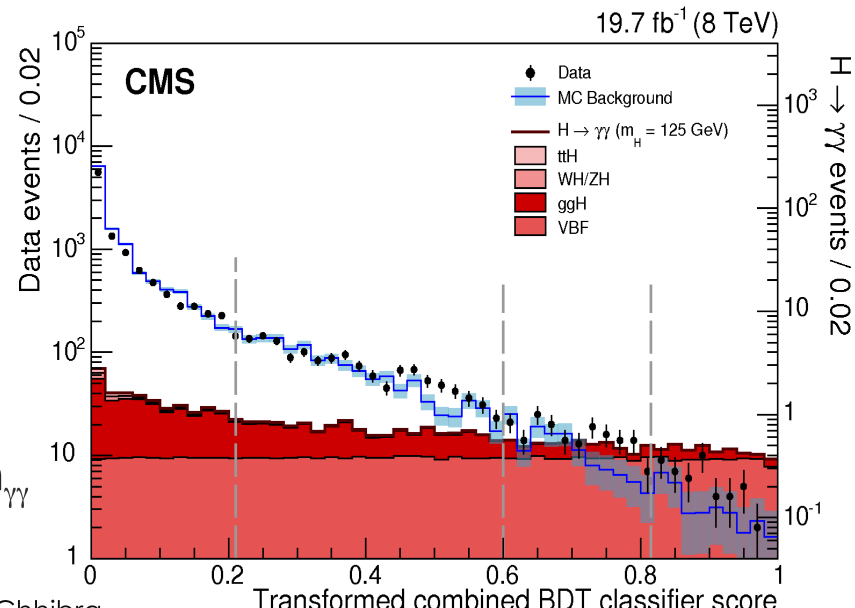
- Clean signature with excellent mass resolution of (1-2%)
- Small peaking signal on gradually falling QCD background
- Signature: a pair of high quality photons
  - Mass range: [110, 150] GeV
- Backgrounds: γγ, γ + jet and jet-jet
  - Background modeling is obtained by fitting the $m_{\gamma\gamma}$ distribution in data
  - The concept is to profile over various fit function choices and allows data to choose the best fit function
- Key points:
  - Precise photon energy clustering and corrections
  - Precise primary vertex finding (~80% efficient)
  - Efficient photon identification to reject fakes (mainly from π^0)
    - Use shower shape and isolation information
  - Event categorization for better sensitivity



H → γγ categorization

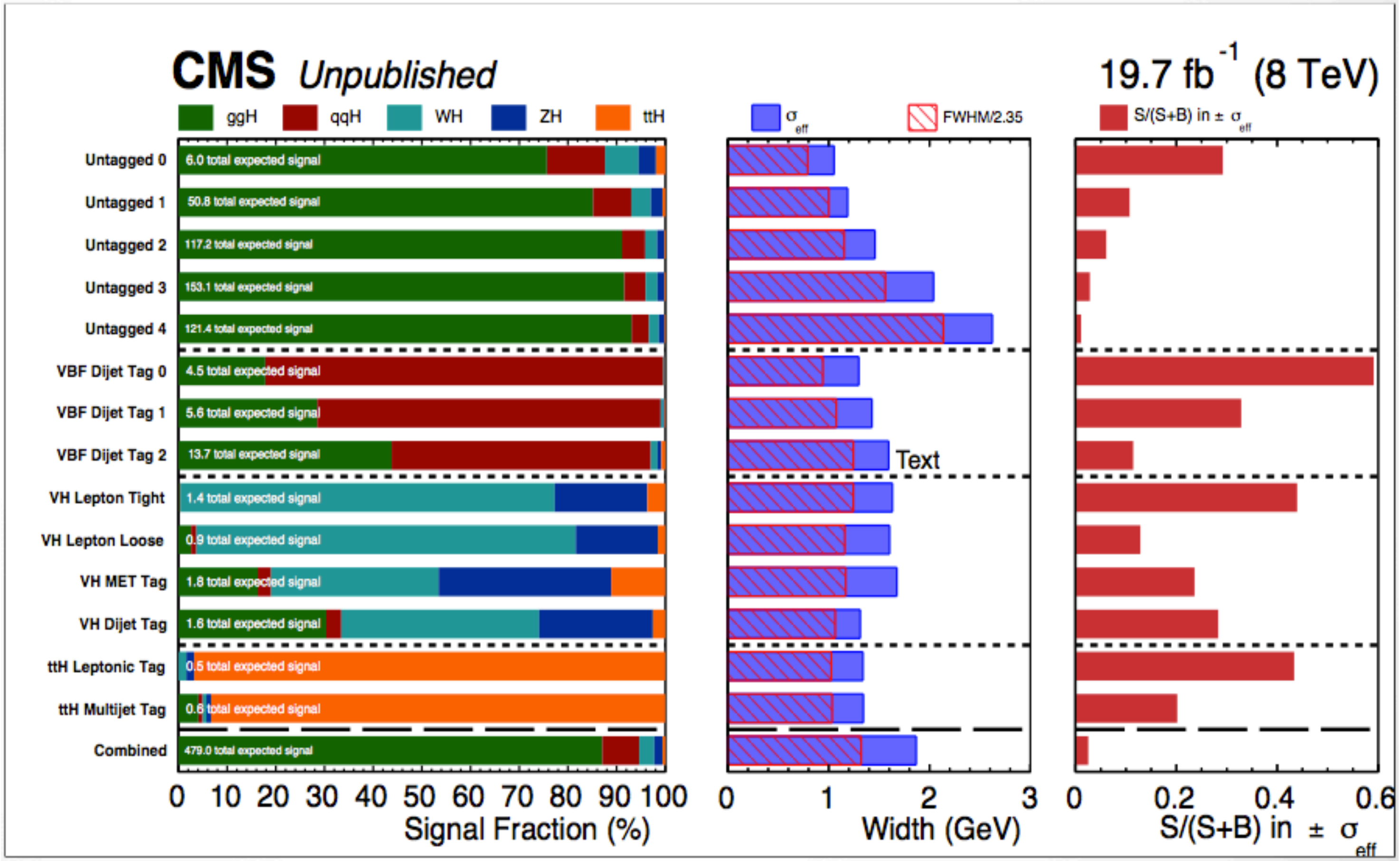
- **Exclusive mode tags:**
  - VH: Lepton, E_T^{miss} and jet consistent with W or Z
  - ttbar H: b-jets, leptons and E_T^{miss} consistent with ttbarH
- **Diphoton boosted decision tree (BDT) classifier:**
  - Use kinematics of dipoton system, $m_{\gamma\gamma}$ resolution and photon quality information
  - Cut values are optimized for maximum sensitivity
- **Dijet BDT classifier:**
  - Trained with VBF events as signal and GGH as background
  - Optimized for VBF signal strength alone
- **Combined diphoton-dijet BDT:**
  - Use diphotpn and dijet BDT score + $p_T^{\gamma\gamma}/m_{\gamma\gamma}$





H → γγ results

- 25 categories (11 @ 7TeV, 14 @ 8 TeV) targeting all production modes
  - Resolution varies from 1.1 to 2.6 GeV
  - S/(S+B) is used to weight the events in particular categories



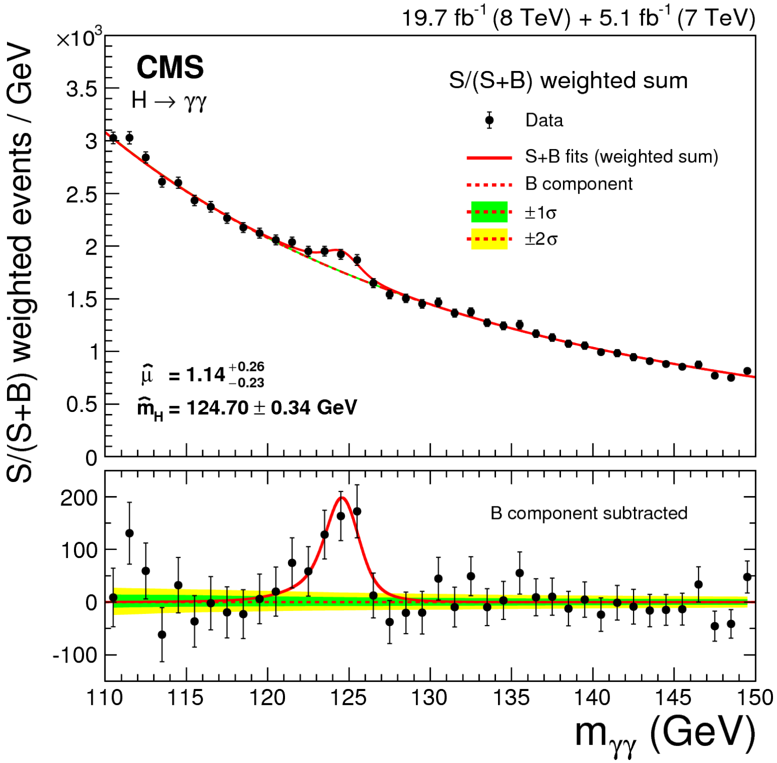
H → γγ mass spectrum and statistical interpretation

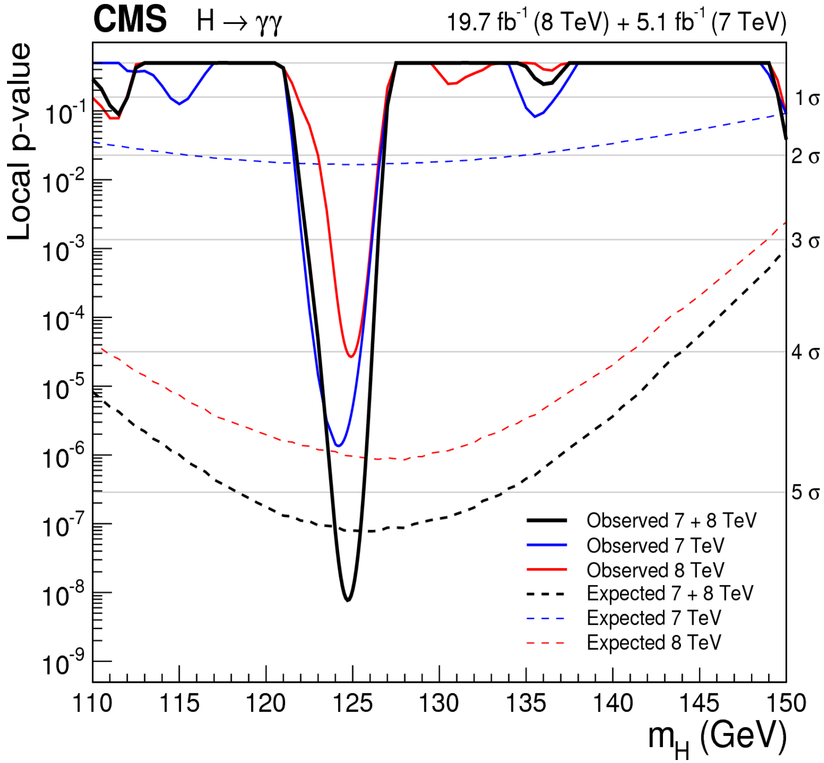
- Visible excess @ ~125 GeV over the expected backgrounds

local p-value @ $m_{\gamma\gamma} = 124.7$ GeV

Expected	5.2σ
Observed	5.7σ

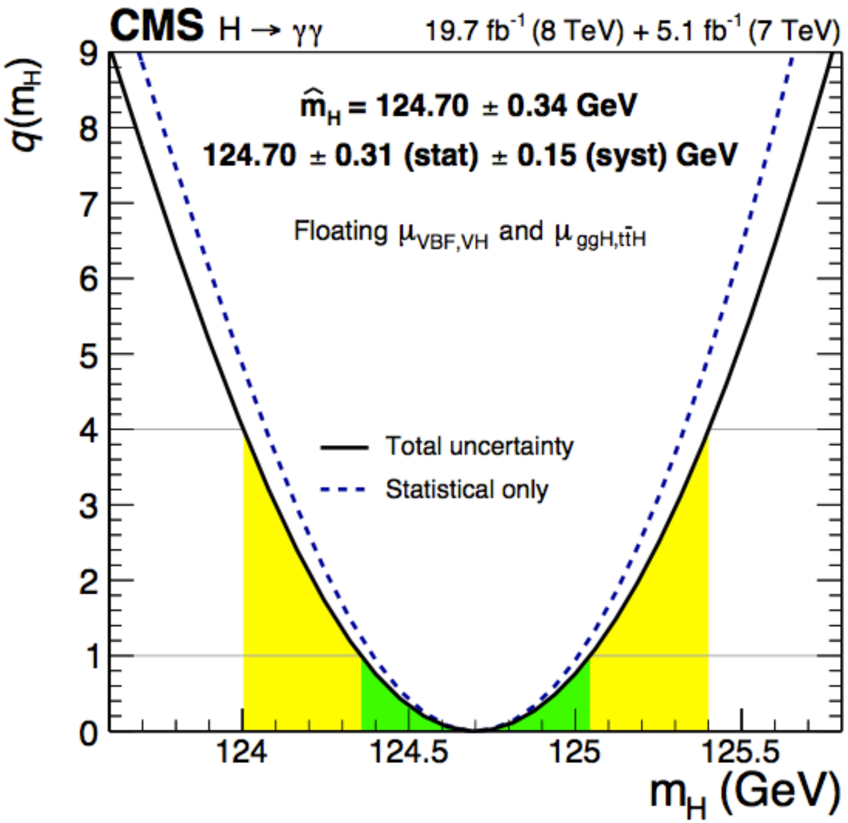
Events weighted by S/(S+B)

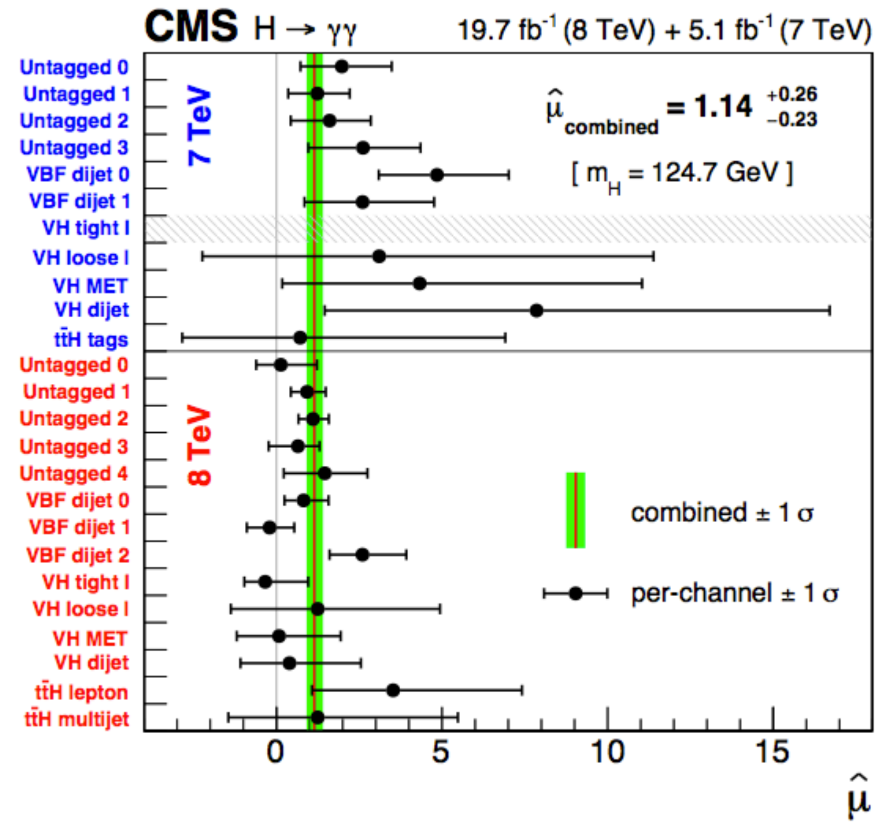




5.7σ excess is observed @ $m_{\gamma\gamma}$ = 124.7 GeV

H → γγ mass and signal strength

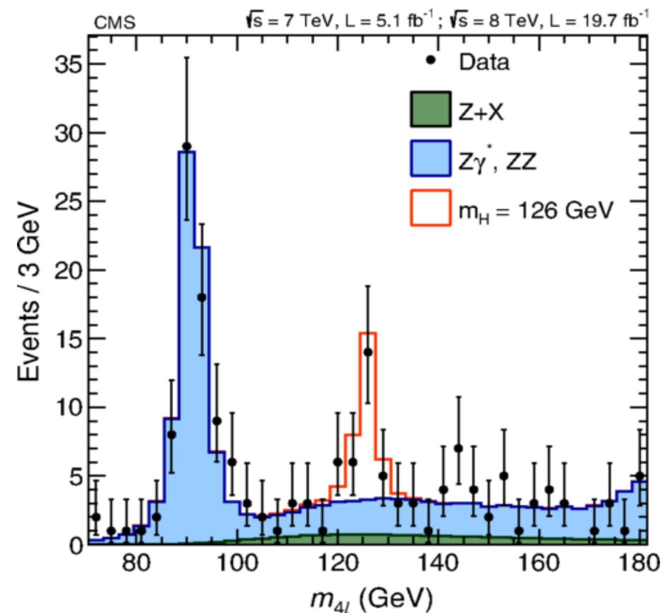


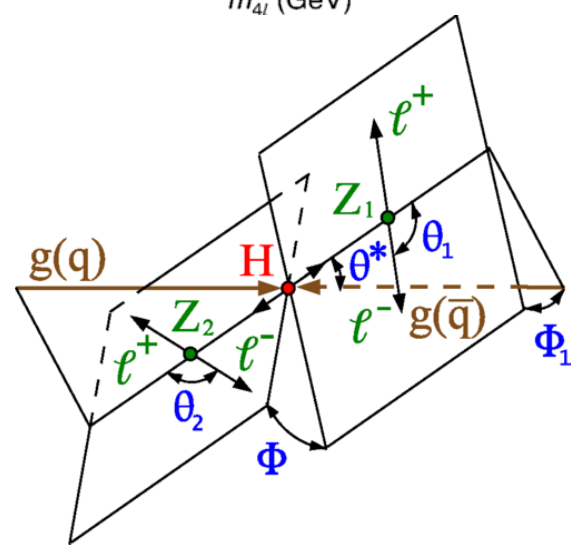


- Best-fit measured mass = $124.70 \pm 0.34 = 124.70 \pm 0.31(stat) \pm 0.15(syst)$
  - A dedicated talk on mass measurement by **S. Nourbakhsh**
- Signal strength @ best-fit mass = $1.14^{+0.26}_{-0.23} = 1.14^{+0.21}_{-0.21}(stat)^{+0.09}_{-0.05}(syst)^{+0.13}_{-0.09}(theo)$

$H \rightarrow ZZ^* \rightarrow 4l$

- "Golden" channel for the Higgs discovery and properties measurements
  - Clean signature with low background
  - excellent mass resolution (1-2%)
- FSR recovery results in $m_{ll\gamma}$ closer to nominal Z mass
- Signature:
  - Both Z's → $e^+e^-(\mu^+\mu^-)$
    - eeee, ee$\mu\mu$, $\mu\mu\mu\mu$
  - Mass range: [110, 1000] GeV
- Backgrounds:
  - Irreducible: SM ZZ and $Z\gamma^*$ (estimated from simulation)
  - Reducible: Z + jets, W + jets and ttbar (from data)
    - Probability of a jet to fake a lepton is exploited to estimate the reducible backgrounds
- Kinematics of production and decay of Z's is exploited to separate signal and background, and spin/parity hypothesis

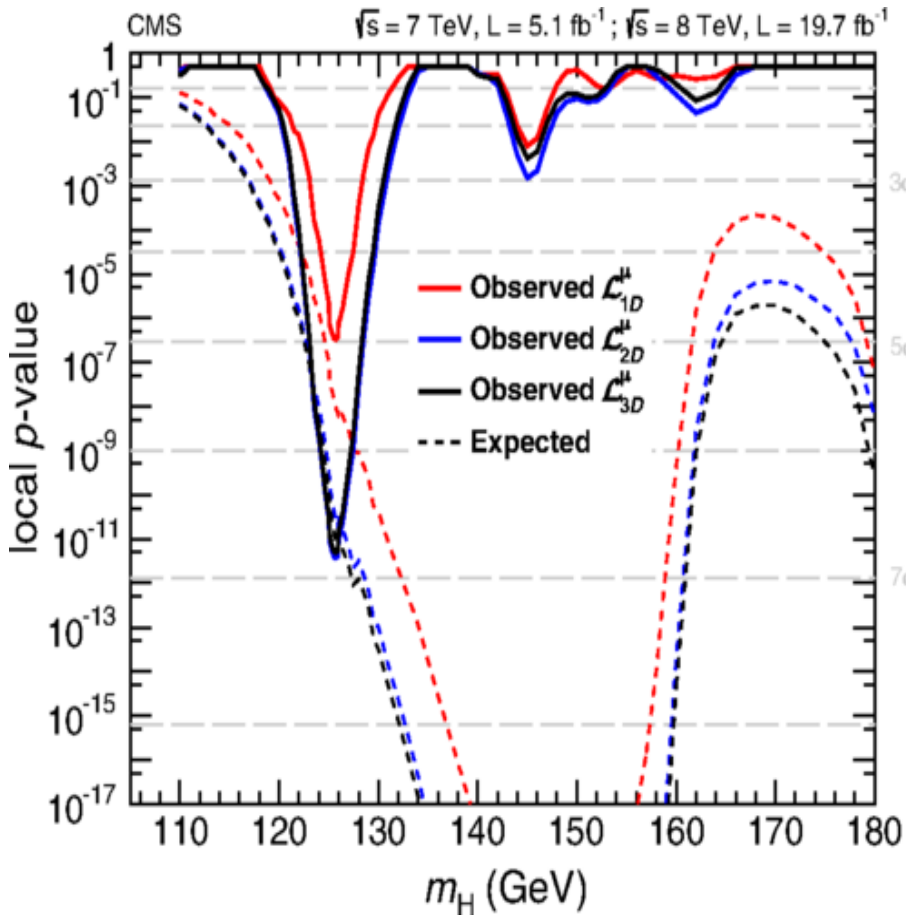




$H \rightarrow ZZ^* \rightarrow 4l$ statistical interpretation

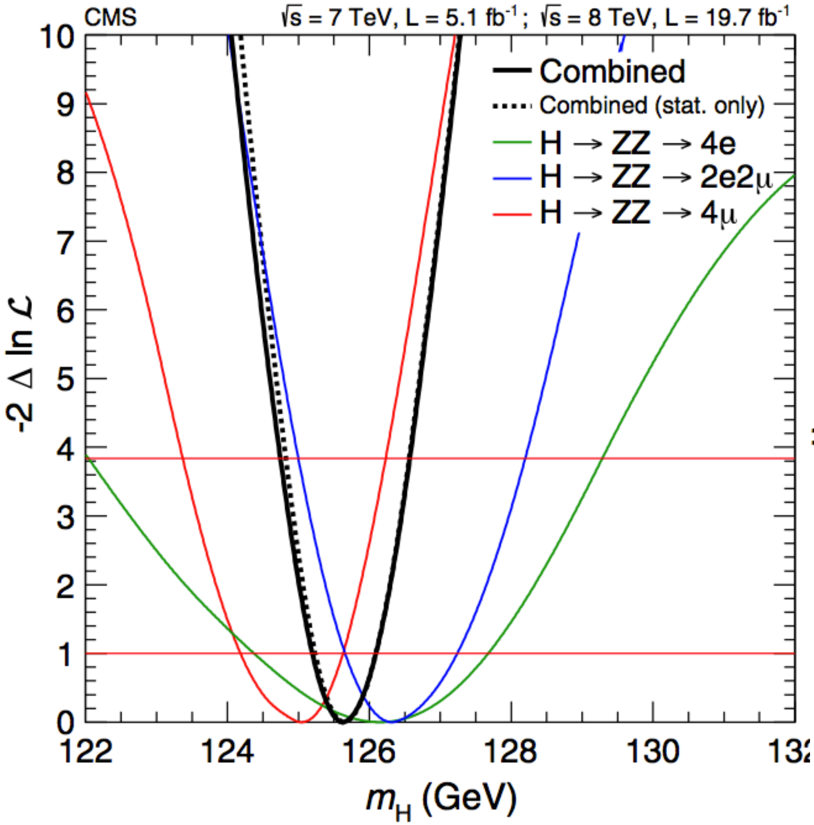
local p-value @ m_{4l} = 125.7 GeV			
	1D	2D	**3D**
Expected	5.6σ	6.6σ	$\mathbf{6.7}\sigma$
Observed	5.0σ	6.9σ	$\mathbf{6.8}\sigma$

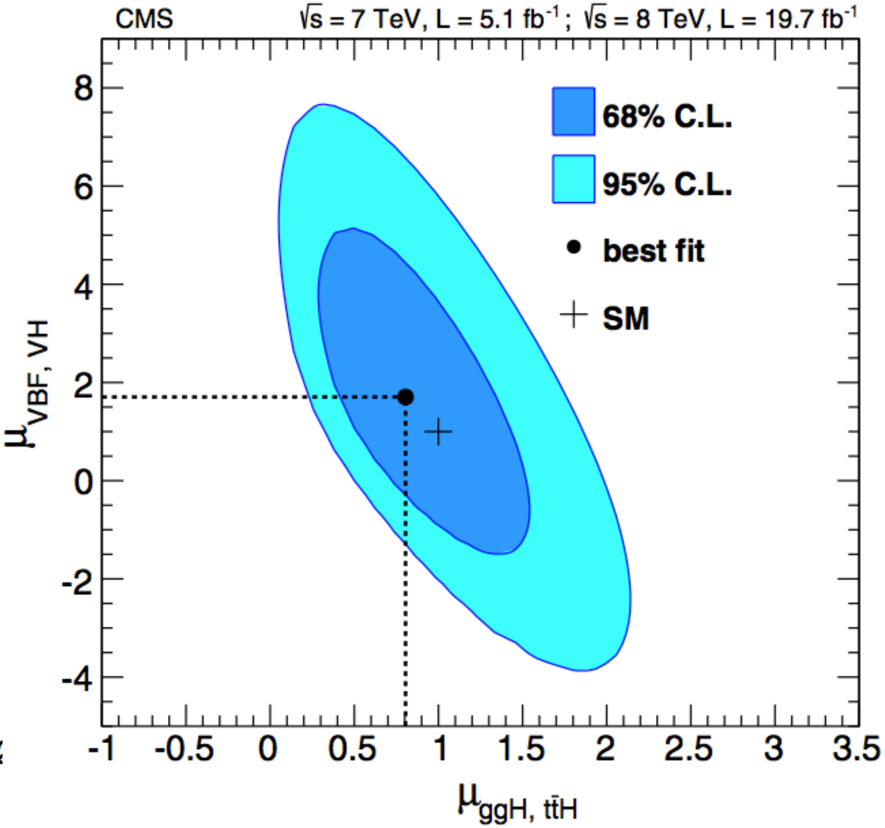
- 1D: m_{4l} only
- 2D: m_{4l} and kinematic discriminant
- 3D: m_{4l}, kinematic discriminant and dijet discriminant (p_T of 4l system)



6.8σ excess is observed @ m_{4l} = 125.7 GeV

H → ZZ* → 4l mass and signal strength

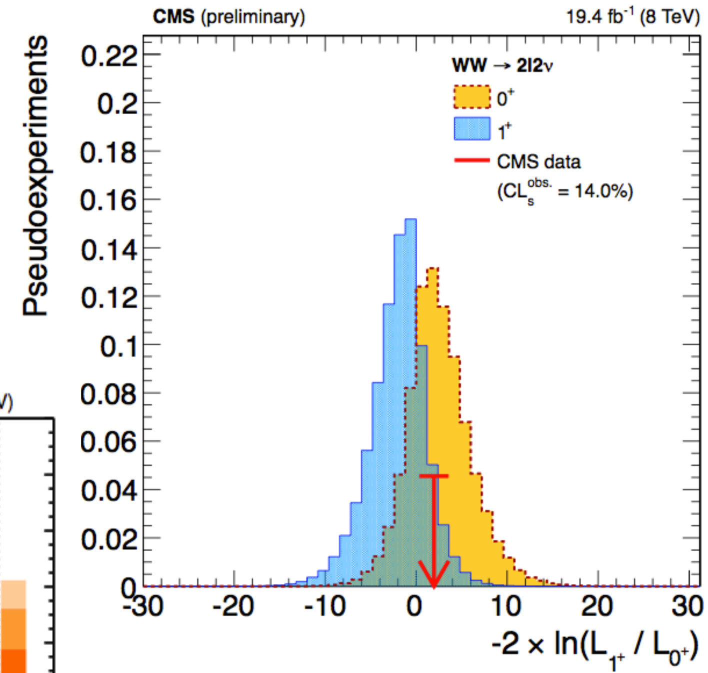


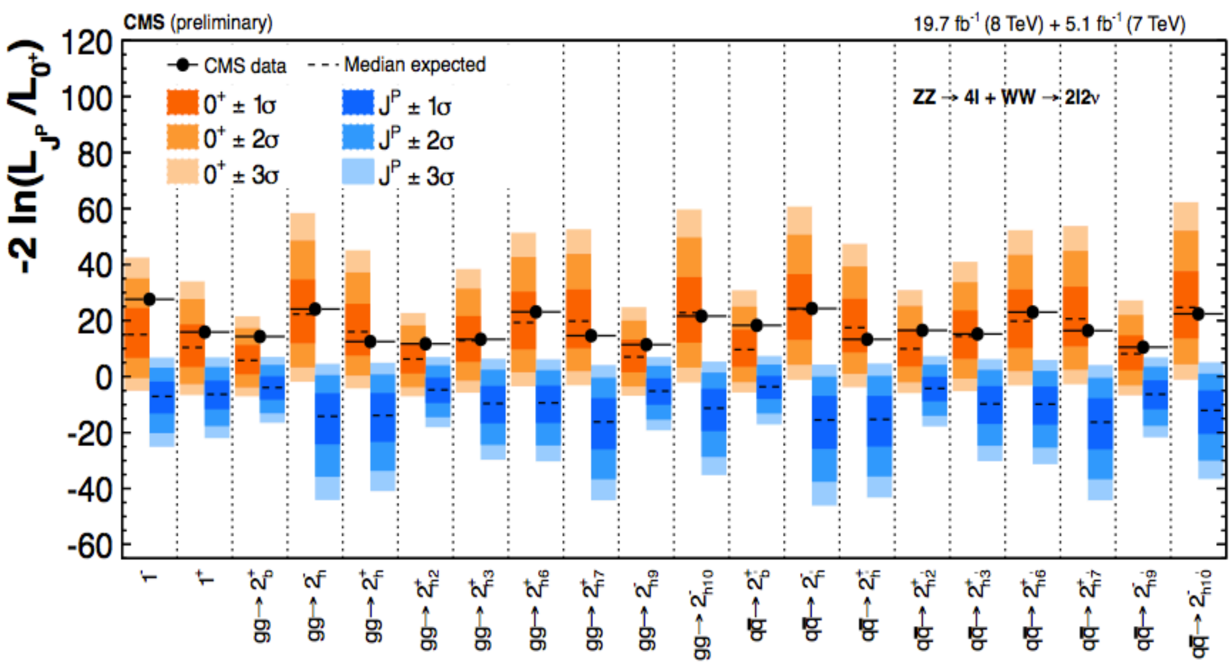


- Best-fit measured mass = $125.6 \pm 0.45 = 125.6 \pm 0.4(stat) \pm 0.2(syst)$
  - Consistent for all 4l final states
  - A dedicated talk on mass measurement by **S. Nourbakhsh**
- Signal strength @ best-fit mass = $0.93^{+0.29}_{-0.25} = 0.93^{+0.26}_{-0.23}(stat)^{+0.13}_{-0.09}(syst)$

Hypotheses tests for J = 1, 2

- Combined results for ZZ^* and WW^*
  - All alternate hypothesis than SM (0^+) are excluded @ 99.9% CL





A dedicated talk on coupling and spin studies by **C. Martin**

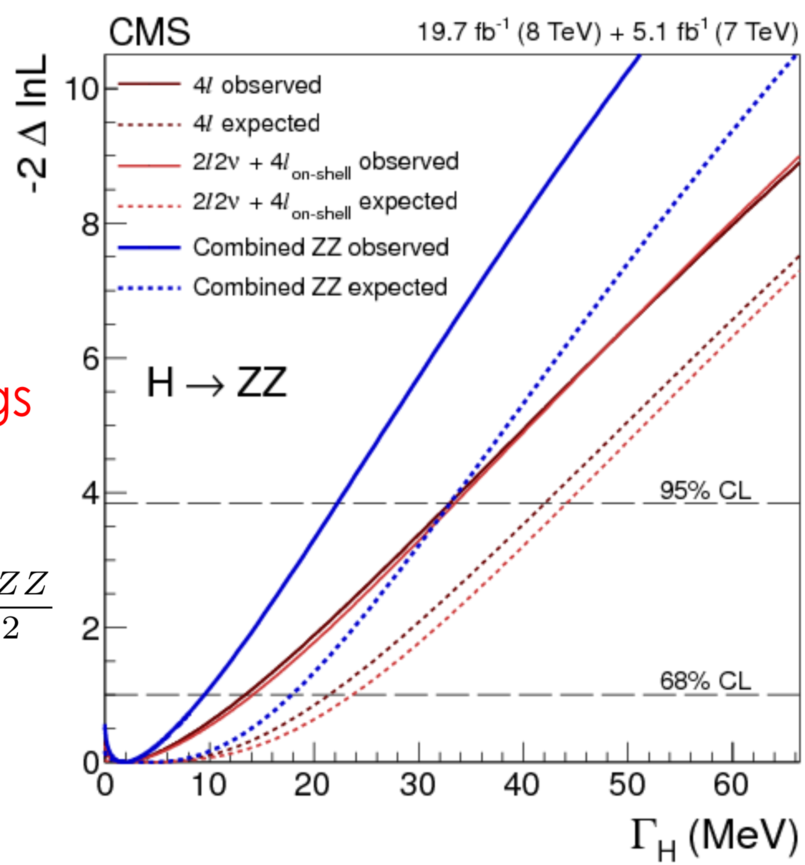
Higgs width bounding in H → ZZ

- Direct measurement of Higgs width by fitting the observed signal resonance is limited by detector resolution (~1 GeV)
  - Bounds Γ_H < 3.4 GeV
  - SM Γ_H = 4.15 MeV (for m_H = 125.6 GeV)
- Indirect measurement performed by exploiting the on-shell and off-shell Higgs production rates

$$\sigma^{on-shell}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}, \quad \sigma^{off-shell}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

- Expected width < 30 MeV @ 95% CL
- Observed width < 22 MeV

ZZ → 4l + ZZ → 2l2ν



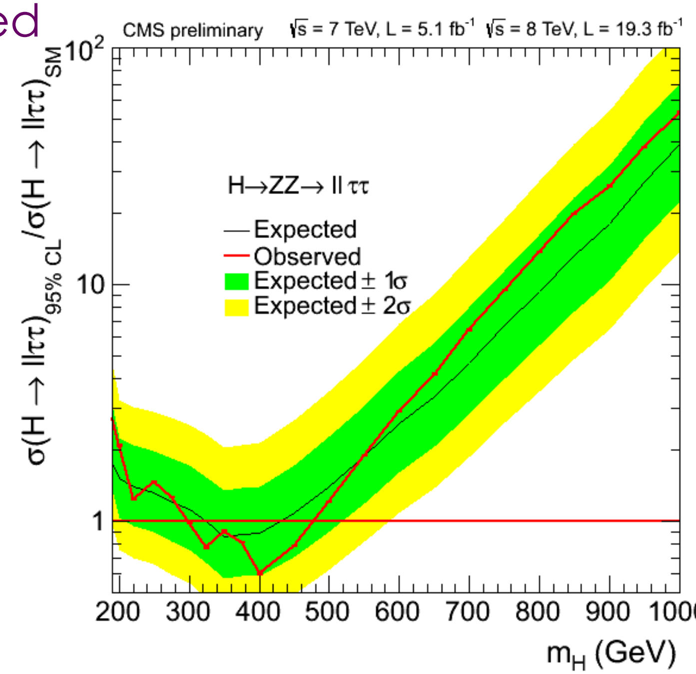
- A dedicated talk on Higgs width bounding by **M. Dalchenko**

CMS PAS HIG-14-002

$H \rightarrow ZZ \rightarrow 2l2\tau$

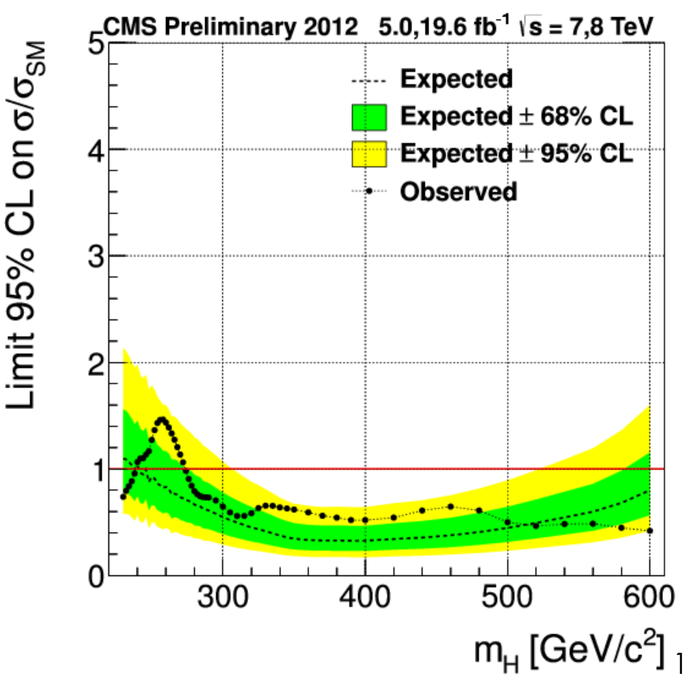
- **Signature:**
  - Leading $Z \rightarrow e^+e^-(\mu^+\mu^-)$ and sub-leading $Z \rightarrow \tau^+\tau^-$
    - $ee\tau_h\tau_h$, $ee\tau_l\tau_h$, $ee\tau_l\tau_l$, $\mu\mu\tau_h\tau_h$, $\mu\mu\tau_l\tau_h$, $\mu\mu\tau_l\tau_l$
  - Mass range: [190, 1000] GeV
- **Backgrounds:**
  - Irreducible: SM ZZ (estimated from simulation)
  - Reducible: WZ + jets, Z + jets and ttbar (from data)
    - Probability of a jet to fake a τ_l or τ_h is exploited to estimate the reducible backgrounds
- **No evidence of SM-like Higgs**
- **Upper limits are set on the ratio of $\sigma(pp \rightarrow H)$ x $BR(H \rightarrow ZZ \rightarrow 2l2\tau)$ @ 95% CL and SM x-section**
  - Observed exclusion: [300, 470] GeV
  - Expected exclusion: [320, 420] GeV

Channel	$2l2\tau$
ZZ background	27.4 ± 3.6
Z + X background	22.9 ± 7.8
All background	50.3 ± 8.6
$m_H = 500$ GeV	3.7 ± 0.4
$m_H = 800$ GeV	0.4 ± 0.1
Observed	57



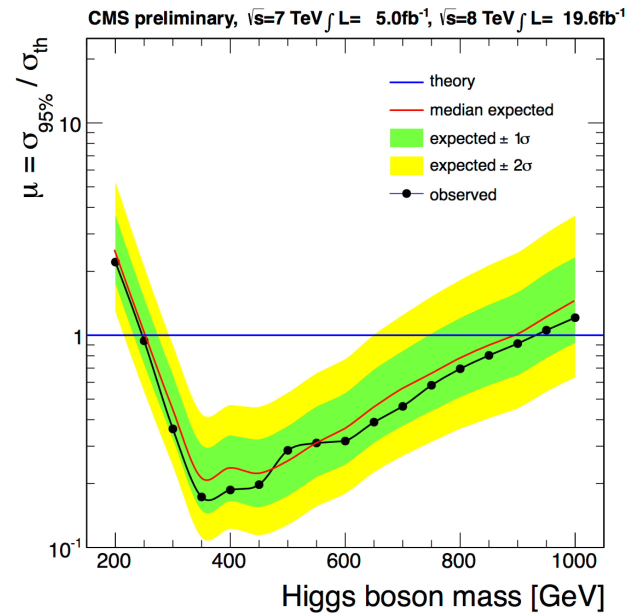
H → ZZ → 2l2q

- Signature:
  - Leading Z → $e^+e^-(\mu^+\mu^-)$ and sub-leading Z → qqbar (q = u, d, c, s and b)
  - Mass range: [230, 600] GeV
- Backgrounds:
  - Irreducible: SM ZZ and WZ (estimated from simulation)
  - Reducible:
    - Z + jets: (estimated from simulation)
    - ttbar, WW + jets and Z → ττ: estimated from data using $e^+\mu^-(e^-\mu^+)$ events
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of σ(pp→H) x BR(H→ZZ→2l2q) @ 95% CL and SM x-section
  - Observed exclusion: [290, 600] GeV
  - Expected exclusion: [275, 600] GeV



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

- Signature:
  - $Z \rightarrow e^+e^-(\mu^+\mu^-) + E_T^{miss}$
  - Mass range: [200, 1000] GeV
- Backgrounds:
  - Irreducible: SM ZZ and WZ (estimated from simulation)
  - Reducible:
    - Resonant: Z + jets (from data)
      - Estimated using γ + jets events reweighted for kinematics and # vertices
    - Non-resonant: WW, W + jets, $Z \rightarrow \tau\tau$, ttbar and tW (from data)
      - Estimated by scaling the # $e^+\mu^-(e^-\mu^+)$ events(N_l) in the side-bands by $\alpha_l = \frac{N_{ll}}{N_{e\mu}}$
      - Events with m_{ll} in [40, 70] and [100, 200] GeV fall in side-bands
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of $\sigma(pp \rightarrow H) \times BR(H \rightarrow ZZ \rightarrow 2l2\nu)$ @ 95% CL and SM x-section
  - Observed exclusion: [248, 930] GeV
  - Expected exclusion: [254, 898] GeV



$H \rightarrow ZZ \rightarrow 2l2\nu$ beyond SM

- EWK singlet model: a hidden scalar field coupled with SM Higgs boson field (h, H are mass eigenstates)

JHEP **0703** (2007) 036

$$\phi_{SM} = \cos\omega h + \sin\omega H$$

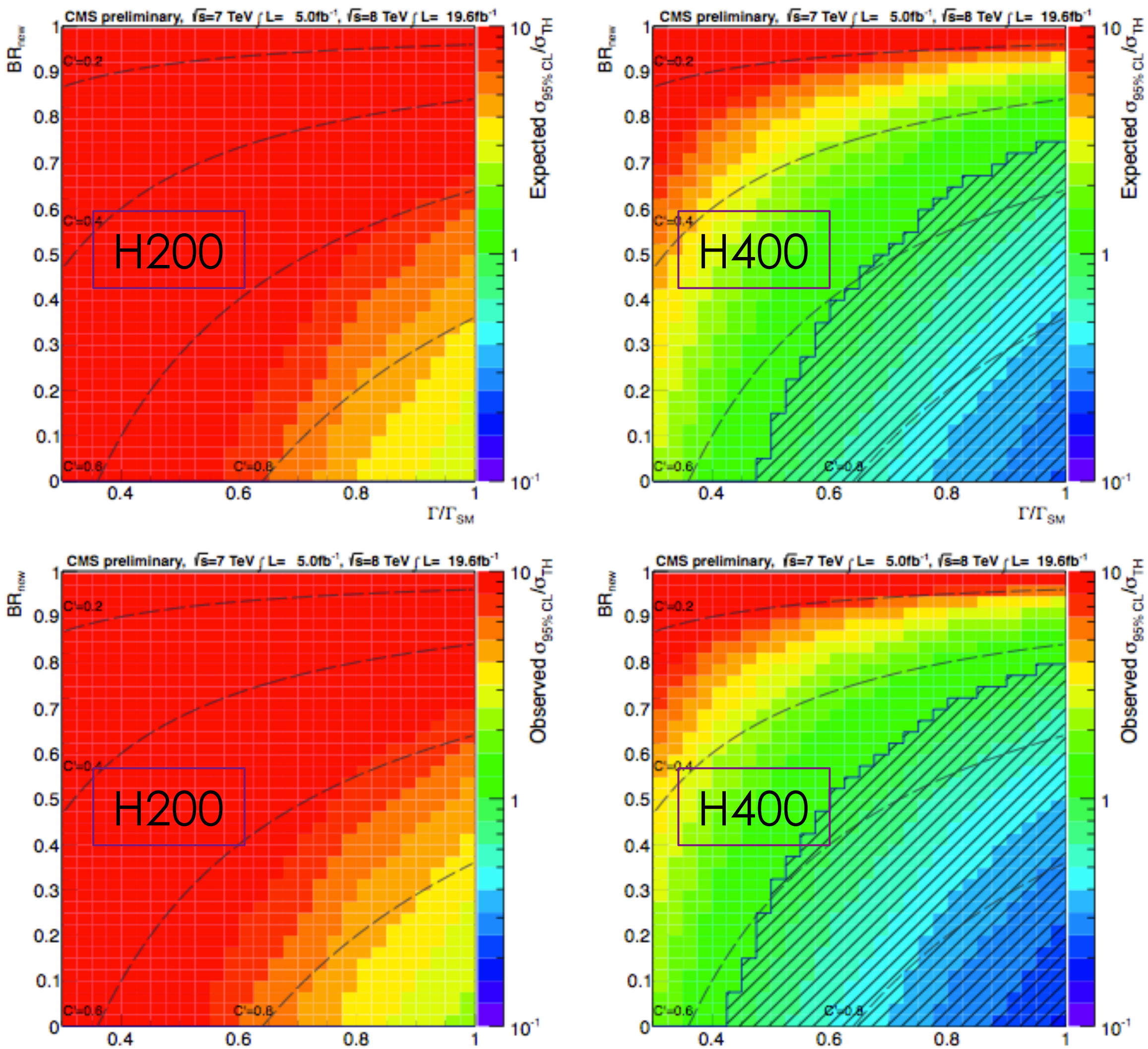
$$\phi_H = -\sin\omega h + \cos\omega H$$

- One coupling modifier:
  - $C'^2 = \sin^2\omega$
  - Scales Γ and x-section

$$\Gamma' = \frac{C'^2}{1 - BR_{new}}\Gamma_{SM}$$

$$\mu' = C'^2(1 - BR_{new})$$

  - BR_{new} is BR of new decay modes (not allowed in SM)
- The whole analysis is re-interpreted and exclusion upper limits are derived
  - Expected (upper plots)
  - Observed (lower plots)

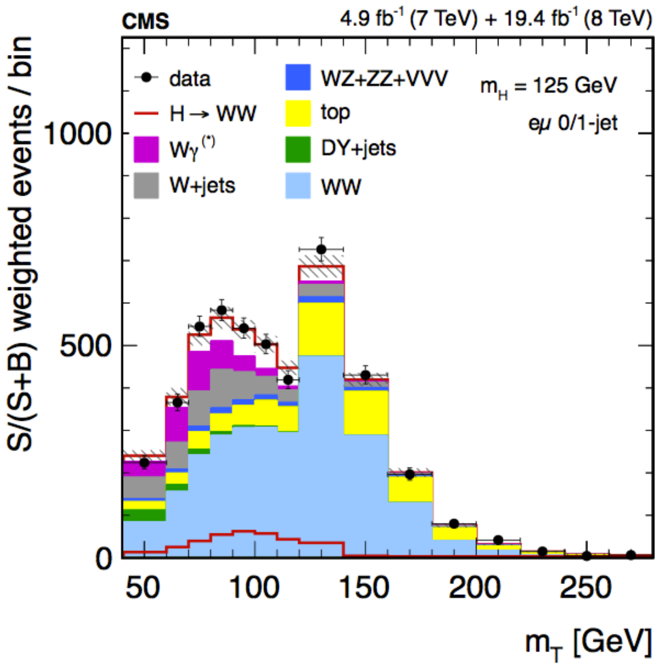


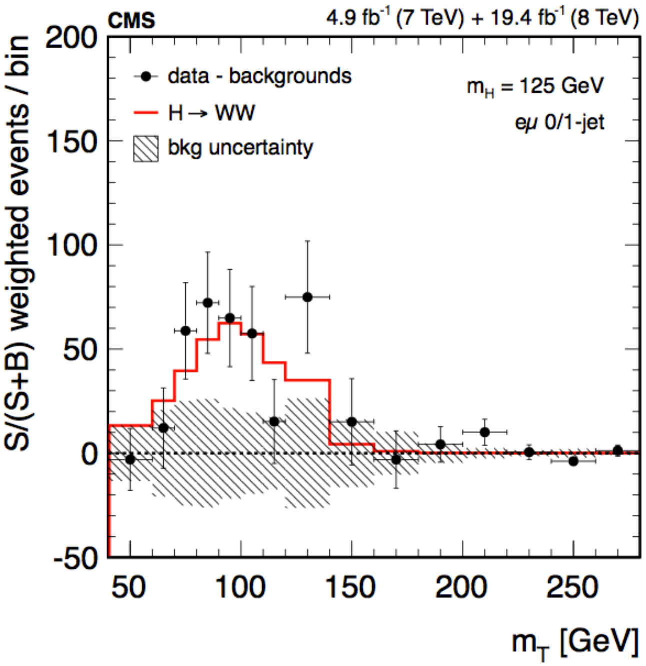
$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Signature:
  - Two or three charged leptons + E_T^{miss} (trilepton states to probe the VH production mode)
  - Mass range:
    - GGF and VBF: [110, 600] GeV
    - VH: [110, 200] GeV since the x-section is very small for high masses
- Key points:
  - m_{ll}, m_T and $\Delta\phi$ between leptons
  - Categorization is done for better sensitivity
- Backgrounds:
  - Non-resonant WW, WZ and ZZ for dilepton, trilepton categories respectively (estimated from simulation)
  - ttbar and tW for high jet multiplicity states (from data)
    - Probability of a jet to be a b-tagged jet is exploited to estimate this backgrounds part
  - Reducible W + jets (from data)
    - Probability of a jet to fake a lepton is exploited to estimate this backgrounds part
  - Reducible Z + jets (from data)
    - Z + jets off-peak contribution is estimated by scaling the # events in a narrow mass window around Z by ratio of # events in and outside of window (after subtracting the non-resonant contribution)

H → WW* → lνlν categorization

- Dilepton categories:
  - 0,1 jet(s) same flavor or different flavor: GGH
  - 2 jets same or different flavor: VBF
  - 2 jets same or different flavor: WH, ZH
    - Jets from the decay of associated vector boson
    - Different characteristics from VBF topology
- Trilepton categories:
  - WH → 3l3n
  - ZH → 3ln + 2jets

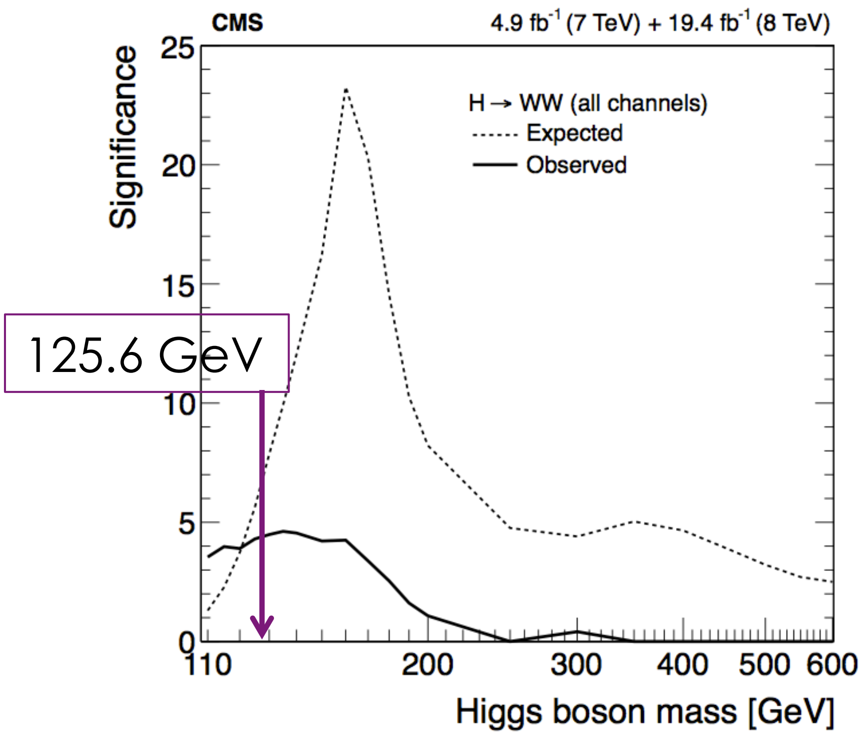


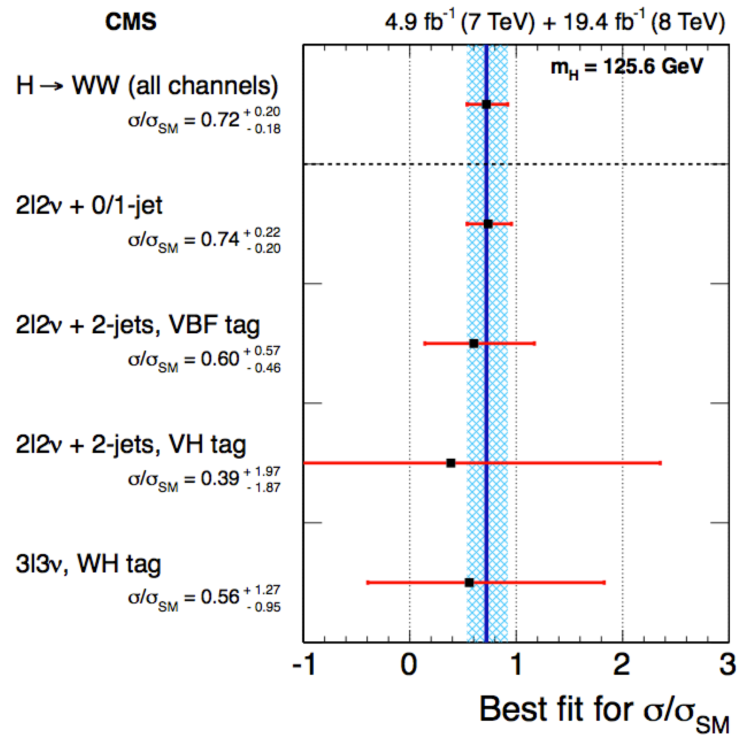


- Excess of events is observed over a broad background

$H \rightarrow WW^* \rightarrow l\nu l\nu$ statistical interpretation

local p-value @ $m_{l\nu l\nu}$ = 125.6 GeV	
Expected	5.8σ
Observed	4.3σ



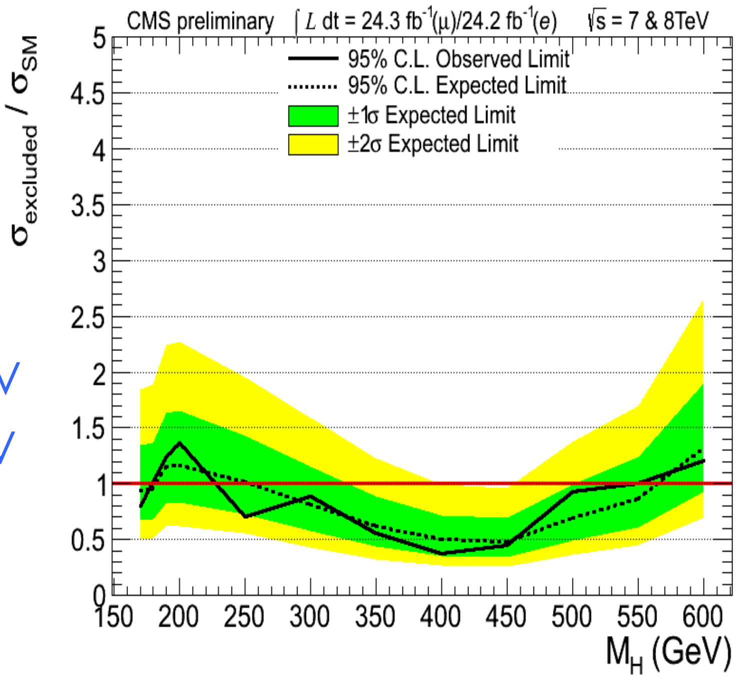


- Signal strength @ 125.6 GeV = $0.72^{+0.20}_{-0.19} = 0.72^{+0.12}_{-0.12}(stat)^{+0.1}_{-0.1}(syst)^{+0.12}_{-0.10}(theo)$

A dedicated talk on coupling and spin studies by **C. Martin**

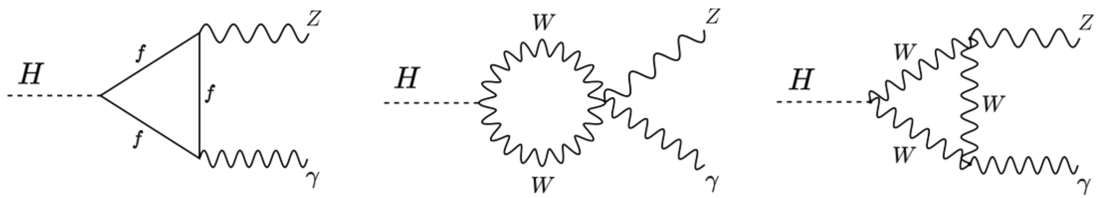
H → WW → lνqq

- Signature:
  - 1 charged lepton + E_T^{miss} + qqbar (q = u, d, c, s and b)
  - Mass range: [170, 600] GeV
- Backgrounds:
  - Irreducible: SM WW, WZ and ZZ
  - Reducible: W + jets, Z + jets, single top and ttbar
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of σ(pp→H) x BR(H→WW→lνqq) @ 95% CL and SM x-section
  - Observed exclusion: [170, 180], [255, 565] GeV
  - Expected exclusion: [170, 180], [230, 545] GeV

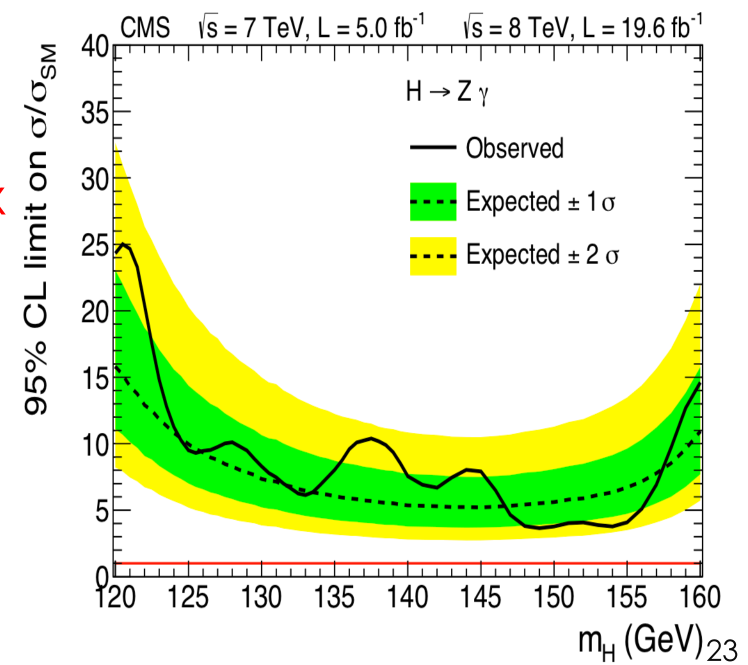


$H \rightarrow Z\gamma$

- Signature: $Z \rightarrow e^+e^-(\mu^+\mu^-) + \gamma$ (sensitive to the physics beyond the SM)
  - Proceeds via top and W loops like $H \rightarrow \gamma\gamma$
  - Mass range: [120, 160] GeV

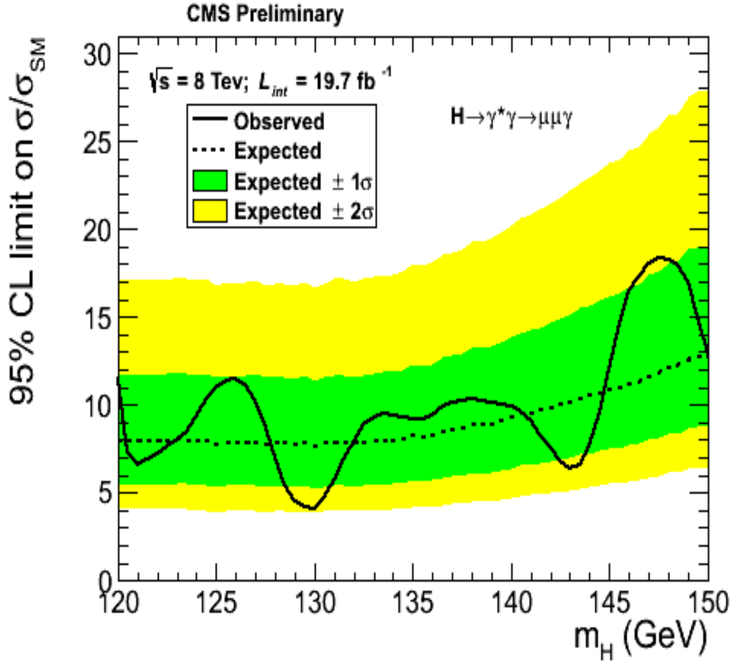


- Backgrounds: SM $Z\gamma$, $Z \rightarrow ll$ + FSR, Z + jets and ttbar
  - Background modeling is obtained by fitting the $m_{ll\gamma}$ in distribution in data
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of $\sigma(pp \rightarrow H) \times BR(H \rightarrow Z\gamma)$ @ 95% CL and SM x-section
  - Observed limit: 4 to 25 times the SM x-section
  - Expected limit: 5 to 16 times the SM x-section



$H \rightarrow \gamma^{*}\gamma \rightarrow \mu\mu\gamma$

- Signature: Clean $\mu^{+}\mu^{-} + \gamma$ signature with mass resolution of 1.5%
  - Mass range: [120, 150] GeV
- Backgrounds: Z + ISR, Z + FSR and Z + jets
  - Background modeling is obtained by fitting the $m_{\mu\mu\gamma}$ in distribution in data
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of $\sigma(pp \rightarrow H) \times BR(H \rightarrow \gamma^{*}\gamma \rightarrow \mu\mu\gamma)$ @ 95% CL and SM x-section
  - Observed limit: 4 to 19 times the SM x-section
  - Expected limit: 8 to 13 times the SM x-section



Summary

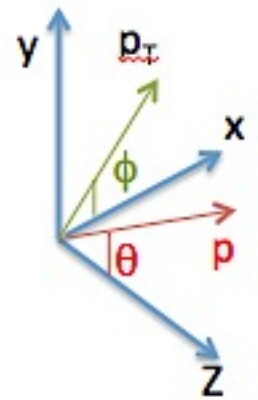
- H → gauge bosons searches @ CMS are presented for complete Run I
- A Higgs boson is discovered in H → diboson channels

Channel	H→ $\gamma\gamma$	H→ $ZZ^* \to 4l$	H→ $WW^* \to l\nu l\nu$
Expected significance	5.2σ	6.7σ	5.8σ
Observed significance	5.7σ	6.8σ	4.3σ
Signal strength	$1.14^{+0.26}_{-0.23}$	$0.93^{+0.29}_{-0.25}$	$0.72^{+0.20}_{-0.19}$

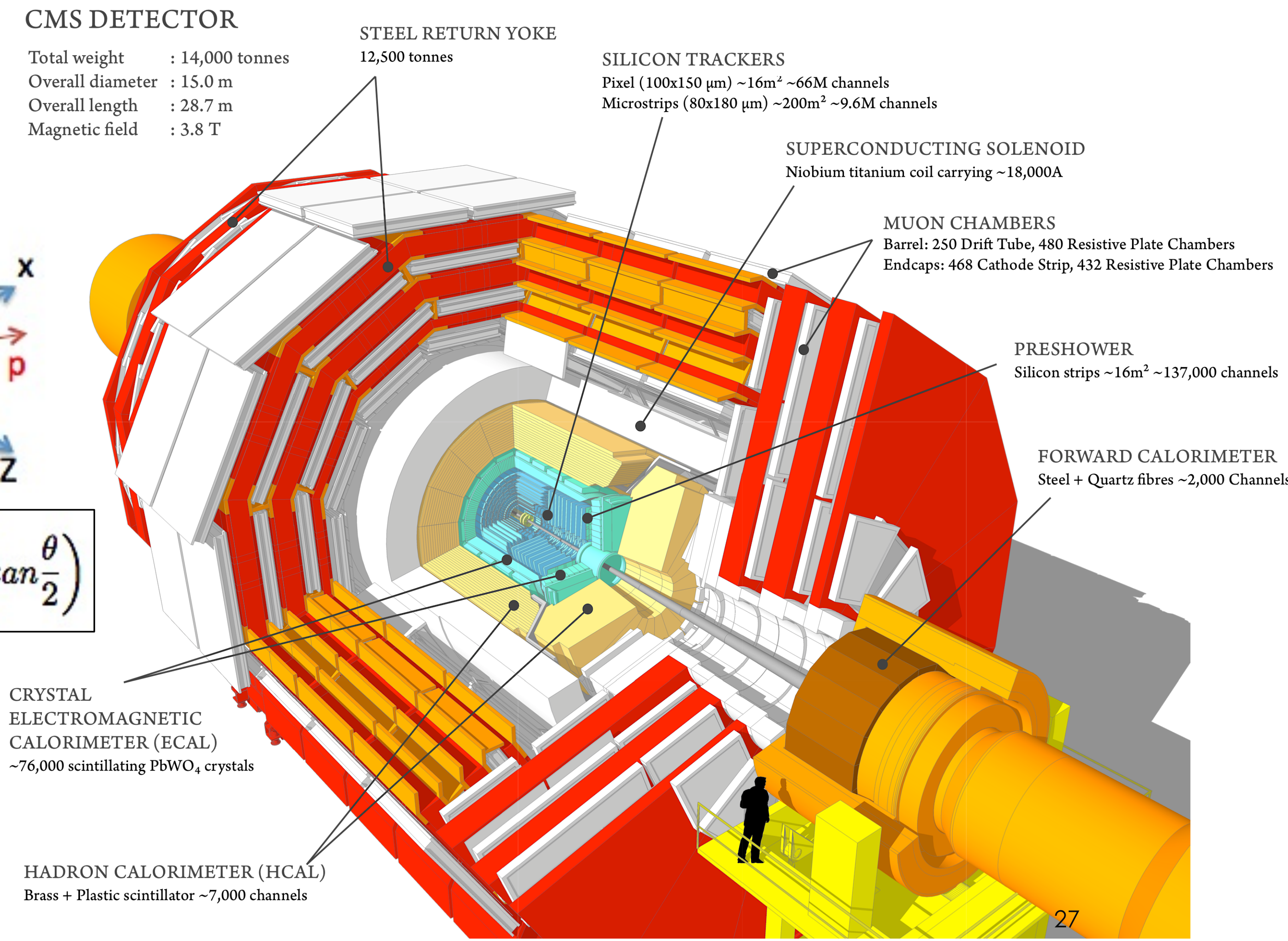
- Signal strength is consistent with SM prediction
- Measured mass:
  - 124.70 ± 0.34 GeV in H → γγ channel
  - 125.6 ± 0.45 GeV in H → ZZ^* → 4l channel
- Higgs boson properties measurements:
  - Higgs boson Mass measurement **(S. Nourbakhsh)** tomorrow
  - Higgs boson couplings and spin studies **(C. Martin)** tomorrow
  - Bounding the Higgs boson width **(M. Dalchenko)** today

Back up

The CMS experiment



$$\eta = -log\left(tan\frac{\theta}{2}\right)$$



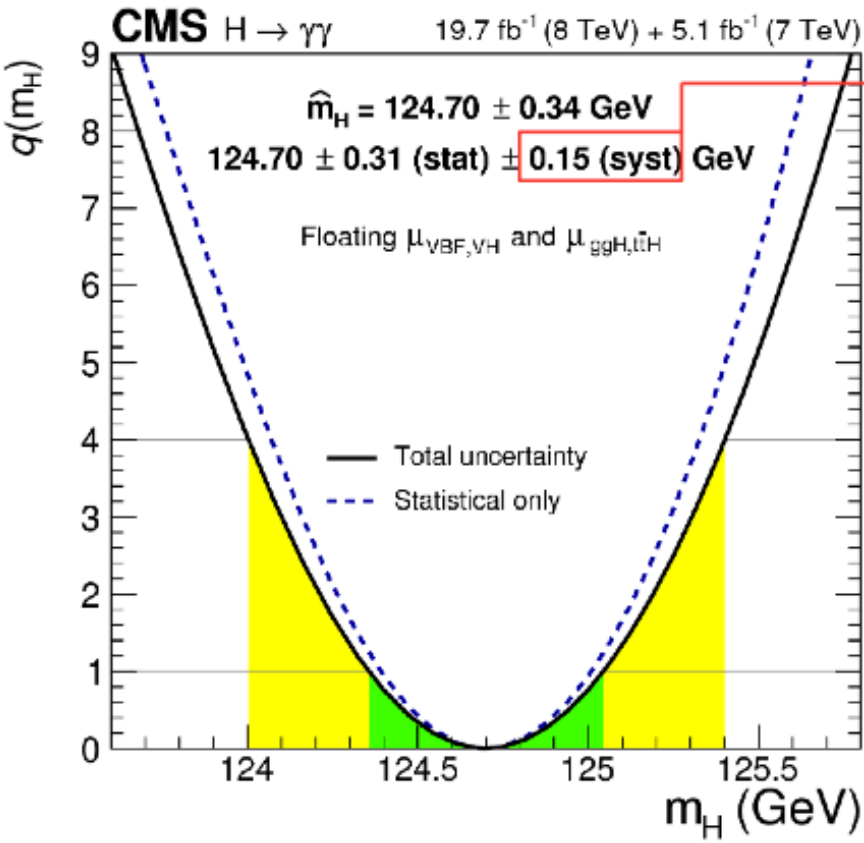
H → γγ categorization

Table 2: Event classes for the 7 and 8 TeV datasets and some of their main selection requirements. Events are tested against the selection requirements of the classes in the order they are listed here.

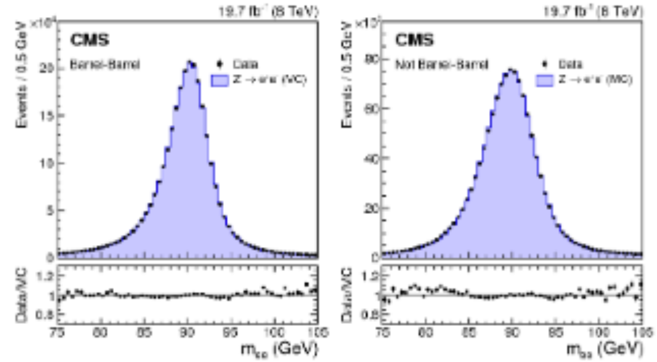
Label	No. of classes 7 TeV	No. of classes 8 TeV	Main requirements
$t\bar{t}$H lepton tag	⋆	1	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ 1 b-tagged jet + 1 electron or muon
VH tight ℓ tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ [e or μ, $p_T > 20$ GeV, and $E_T^{miss} > 45$ GeV] or [2e or 2μ, $p_T^{\ell} > 10$ GeV; $70 < m_{\ell\ell} < 110$ GeV]
VH loose ℓ tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ e or μ, $p_T > 20$ GeV
VBF dijet tag 0-2	2	3	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ 2 jets; classified using combined diphoton-dijet BDT
VH E_T^{miss} tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ $E_T^{miss} > 70$ GeV
$t\bar{t}$H multijet tag	⋆	1	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ 1 b-tagged jet + 4 more jets
VH dijet tag	1	1	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ jet pair, $p_T^{j} > 40$ GeV and $60 < m_{jj} < 120$ GeV
Untagged 0-4	4	5	The remaining events, classified using diphoton BDT

⋆ For the 7 TeV dataset, events in the $t\bar{t}$H lepton tag and multijet tag classes are selected first, and combined to form a single event class.

H → γγ mass uncertainties

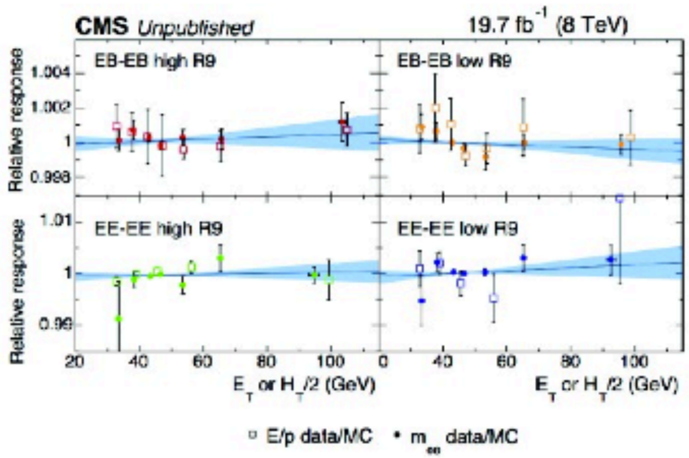


Photon Calibration @ ~ 45 GeV with $Z \rightarrow e^+e^-$



±0.05 GeV

Boosted Zs: Higher ET



±0.10 GeV

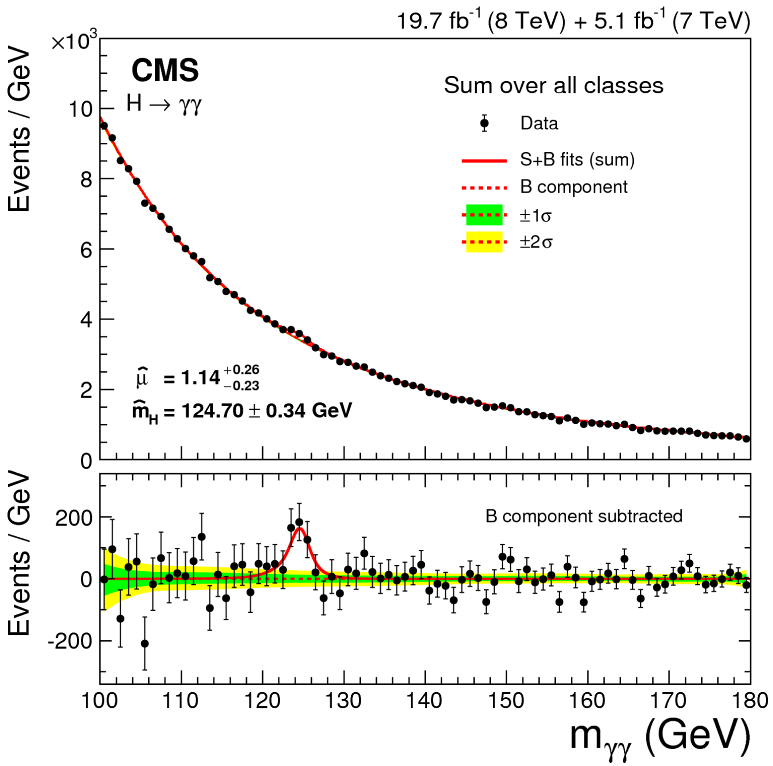
Photon/ Electron differences studied in the simulation [main effect from the material]

±0.10 GeV

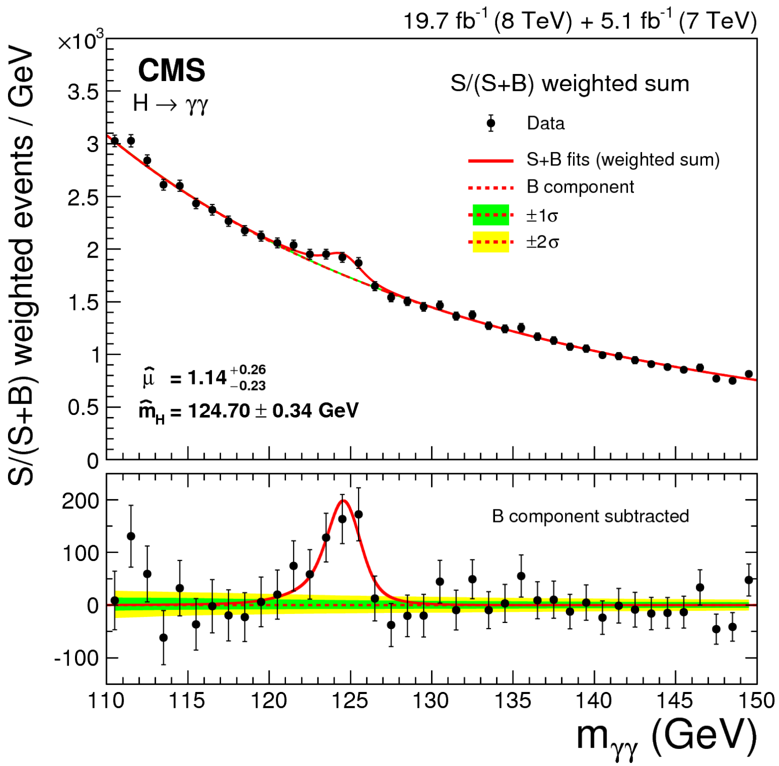
H → γγ mass spectrum

- More clearly visible signal peak on the expected background for S/(S+B) weighted events, near a mass of 125 GeV

all events have equal weight



Events weighted by S/(S+B)

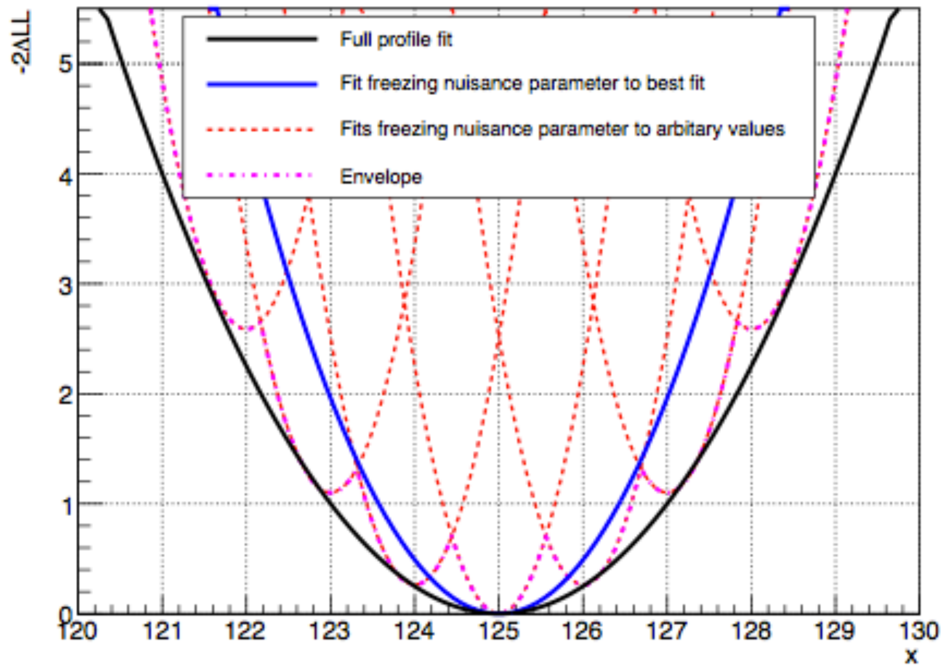


H → γγ background modeling

- Imagine a simple case with one POI, x, and one nuisance parameter, θ
    - Black line – standard likelihood scan of x profiling θ
    - Blue line – standard likelihood scan of x freezing θ (stat only)
    - Red lines – standard likelihood scans of freezing θ to different values
    - Pink line – Envelope around this

NEW METHOD

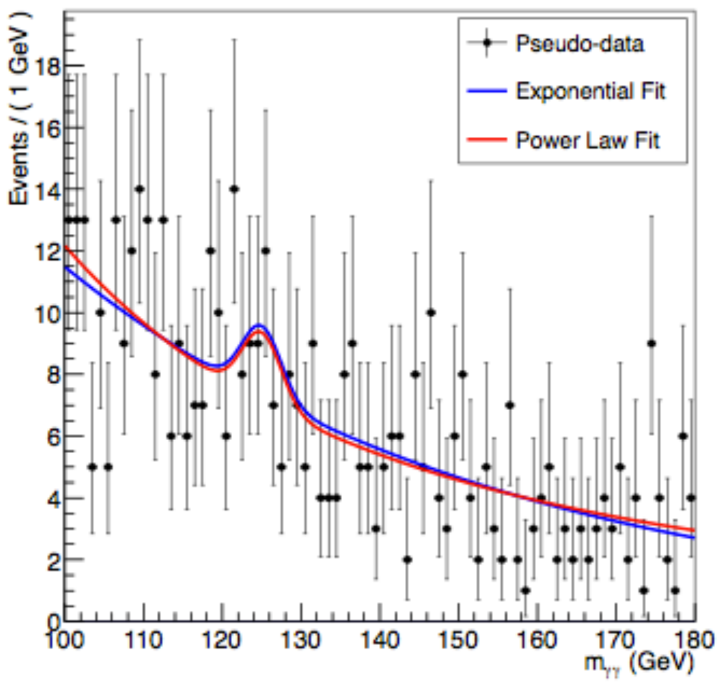
- If you sample enough of the infinite θ phase-space eventually you can reproduce the black curve with the pink "envelope"

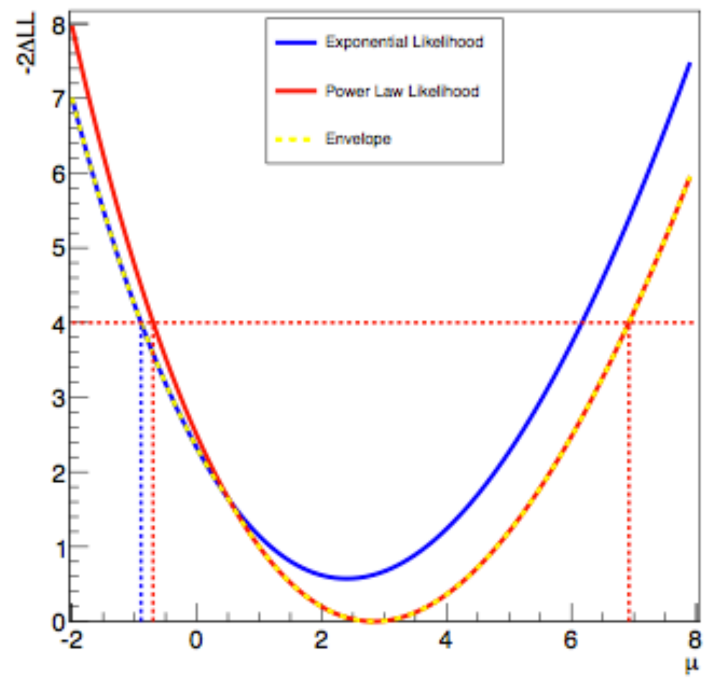


H → γγ background modeling

- For a toy example
  - one category
  - two function choices, e^{-px} and x^{-p}, both with 1 free param
- Profile "envelope" gives best fit with x^{-p}
- 2 sigma error is enlarged by the envelope
- In principle envelope method will increase uncertainty because of different function choices

NEW METHOD

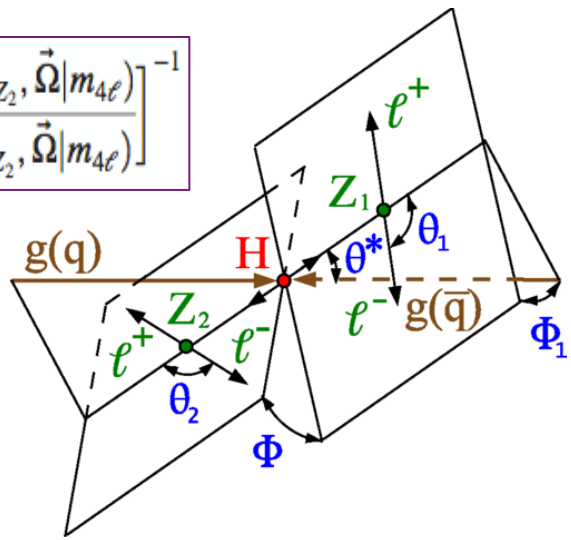


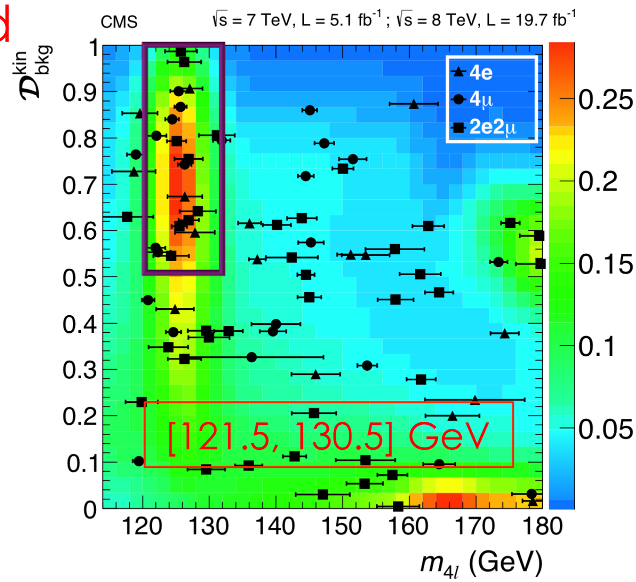


H → ZZ* → 4l key points

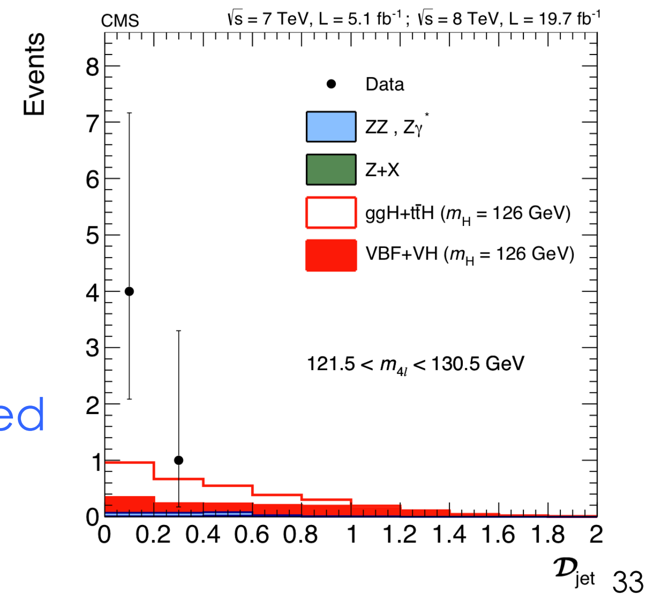
- Kinematics of the production and decay mechanism of Z's have been exploited to separate the signal and background
  - Signal events are concentrated in region $D^{kin} > 0.5$

$$\mathcal{D}^{\rm kin}_{\rm bkg} = \frac{\mathcal{P}^{\rm kin}_{0^+}}{\mathcal{P}^{\rm kin}_{0^+} + \mathcal{P}^{\rm kin}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$





- Categorization of events is done for the better sensitivity
  - Untagged (GGH) and dijet tagged events (VBF)
  - Untagged events: p_T of the 4l system is exploited to separate GGH and VBF
  - Dijet tagged events: A linear discriminant is exploited to separate GGH and VBF

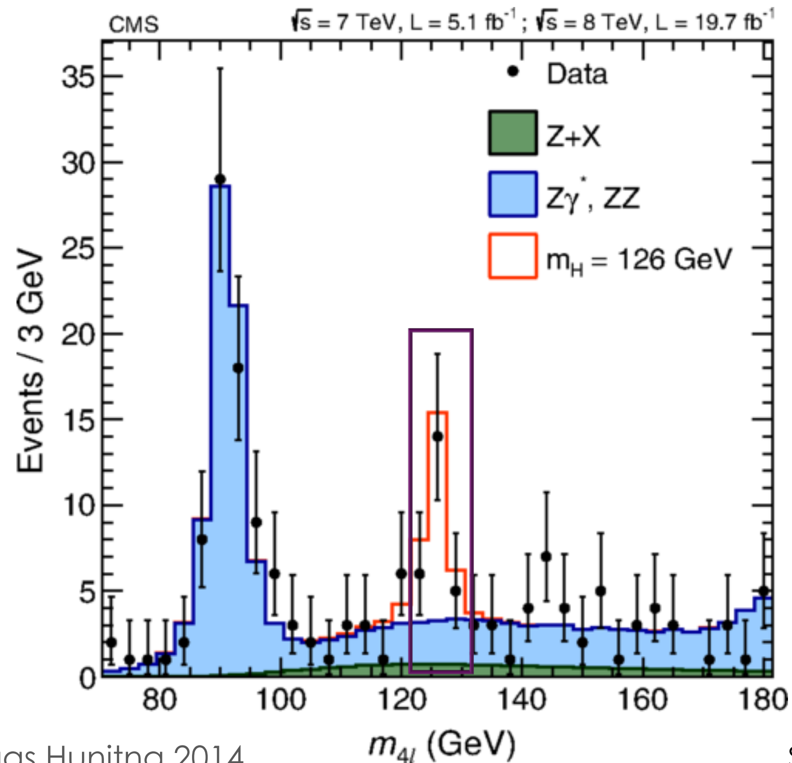


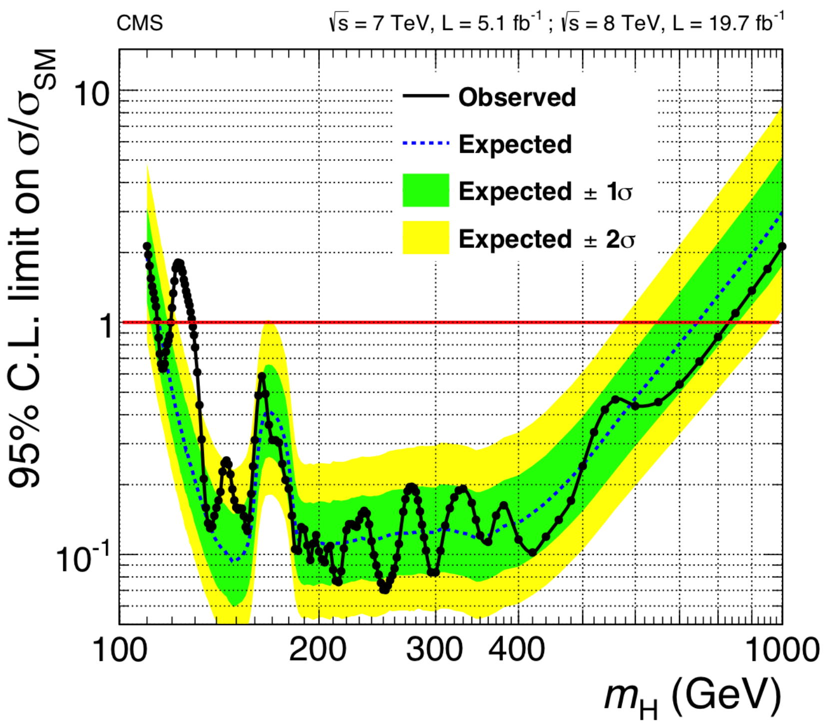
H → ZZ* → 4l results and statistical interpretation

Phys. Rev. D89 092007 (2014)

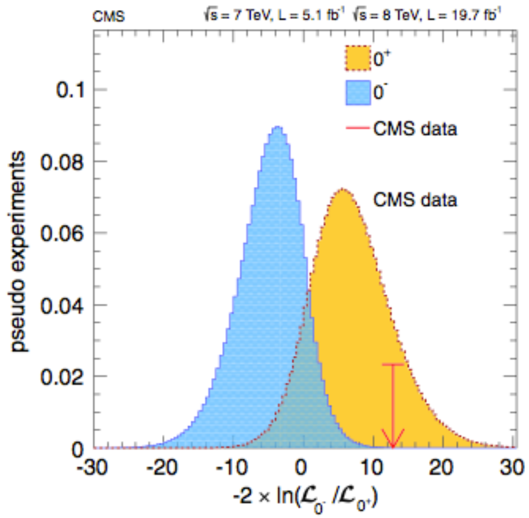
- Observed events, expected background and expected signal event yields for 125 and 126 GeV SM Higgs in [121.5, 130.5] GeV

Channel	4e	2e2μ	4μ	4l
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All background	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
m_H = 125 GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
m_H = 126 GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25





- An excess of events is observed over the expected background around 125 GeV



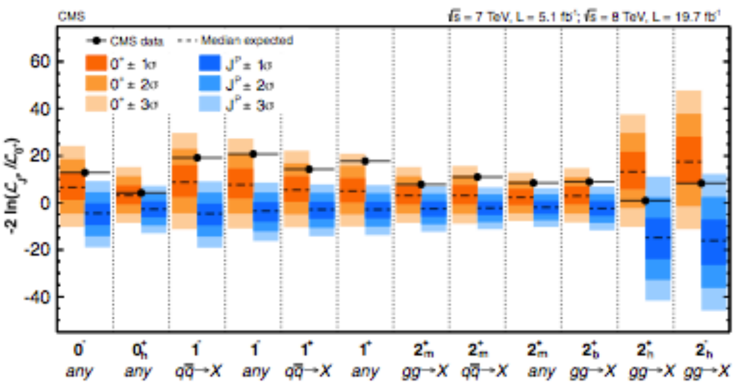


FIG. 27 (color online). Summary of the expected and observed values for the test-statistic q distributions for the twelve alternative hypotheses tested with respect to the SM Higgs boson. The orange (blue) bands represent 1σ, 2σ, and 3σ around the median expected value for the SM Higgs boson hypothesis (alternative hypothesis). The black point represents the observed value.

TABLE VIII. List of models used in the analysis of the spin and parity hypotheses corresponding to the pure states of the type noted. The expected separation is quoted for two scenarios, where the signal strength for each hypothesis is predetermined from the fit to data and where events are generated with SM expectations for the signal cross section ($\mu = 1$). The observed separation quotes consistency of the observation with the 0^+ model or J^P model and corresponds to the scenario where the signal strength is floated in the fit to data. The last column quotes the CL_s value for the J^P model.

J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-1.0σ	$+3.8\sigma$	0.05%
0_h^+	any	1.7σ (1.9σ)	-0.3σ	$+2.1\sigma$	4.5%
1^-	$q\bar{q} \to X$	2.7σ (2.7σ)	-1.4σ	$+4.7\sigma$	0.002%
1^-	any	2.5σ (2.6σ)	-1.8σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.02%
1^+	any	2.0σ (2.1σ)	-2.1σ	$+4.8\sigma$	0.004%
2_m^+	$gg \to X$	1.9σ (1.8σ)	-1.1σ	$+3.0\sigma$	0.9%
2_m^+	$q\bar{q} \to X$	1.7σ (1.7σ)	-1.7σ	$+3.8\sigma$	0.2%
2_m^+	any	1.5σ (1.5σ)	-1.6σ	$+3.4\sigma$	0.7%
2_b^+	$gg \to X$	1.6σ (1.8σ)	-1.4σ	$+3.4\sigma$	0.5%
2_h^+	$gg \to X$	3.8σ (4.0σ)	$+1.8\sigma$	$+2.0\sigma$	2.3%
2_h^-	$gg \to X$	4.2σ (4.5σ)	$+1.0\sigma$	$+3.2\sigma$	0.09%

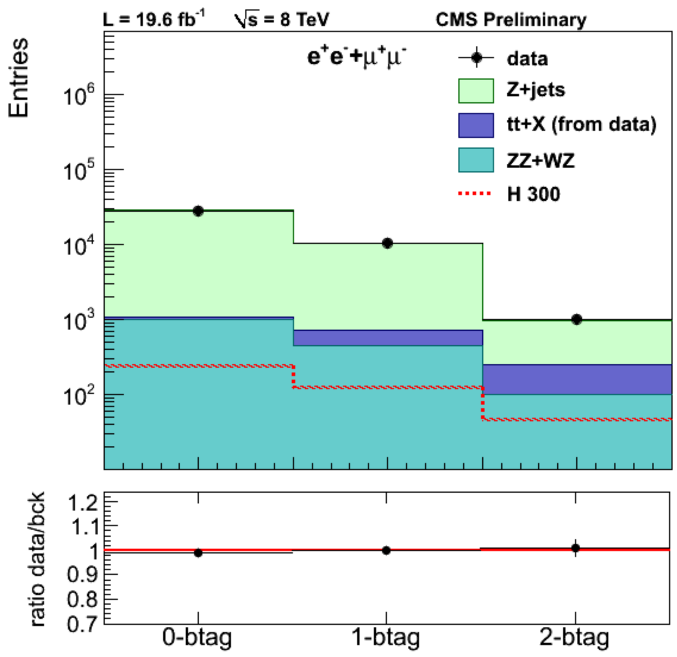
$H \rightarrow ZZ \rightarrow 2l2q$

- Largest BR of all $H \rightarrow ZZ$ channels but large Z + jets background
- Signature:
  - Leading $Z \rightarrow e^+e^-(\mu^+\mu^-)$ and sub-leading $Z \rightarrow$ qqbar (q = u, d, c, s and b)
  - Mass range: [230, 600] GeV
- Backgrounds:
  - Irreducible: SM ZZ and WZ (estimated from simulation)
  - Reducible:
    - Z + jets: (estimated from simulation)
    - ttbar, WW + jets and $Z \rightarrow \tau\tau$: estimated from data using $e^+\mu^-(e^-\mu^+)$ events
- Event selection:
  - Well identified and isolated leptons from leading Z decay ($p_T > 40(20)$ GeV for leading(sub-leading))
  - Geometrically separated jets from isolated leptons ($p_T > 30$ GeV)
- Kinematics of decay mechanism and balance of E_T^{miss} in p_T for the signal events are exploited to reduce the background
- Categorization is done on basis of # b-jets for the better sensitivity
  - 0, 1 and 2 b-jet(s) events

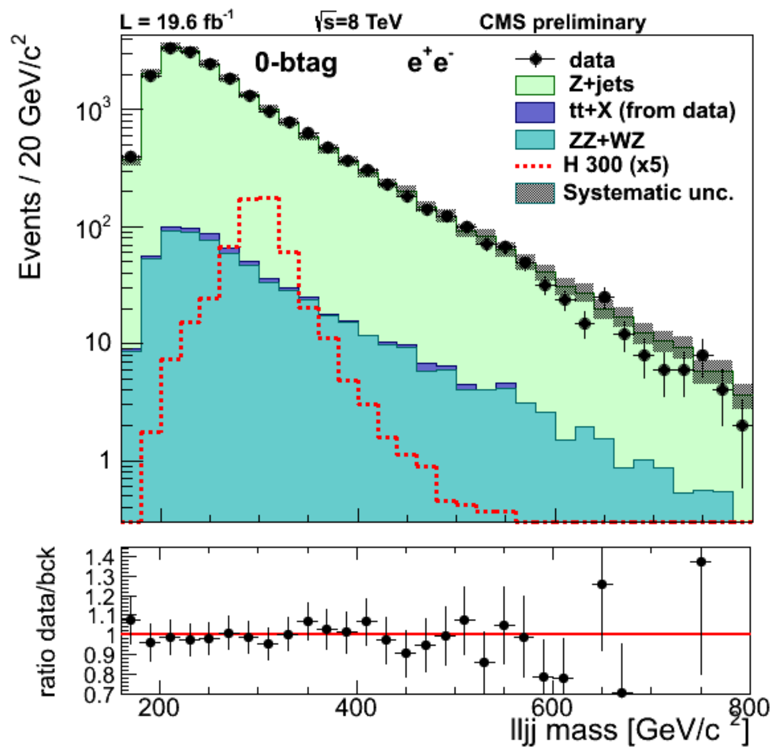
H → ZZ → 2l2q results

- Observed events, expected background and expected signal event yields for few SM Higgs mass points

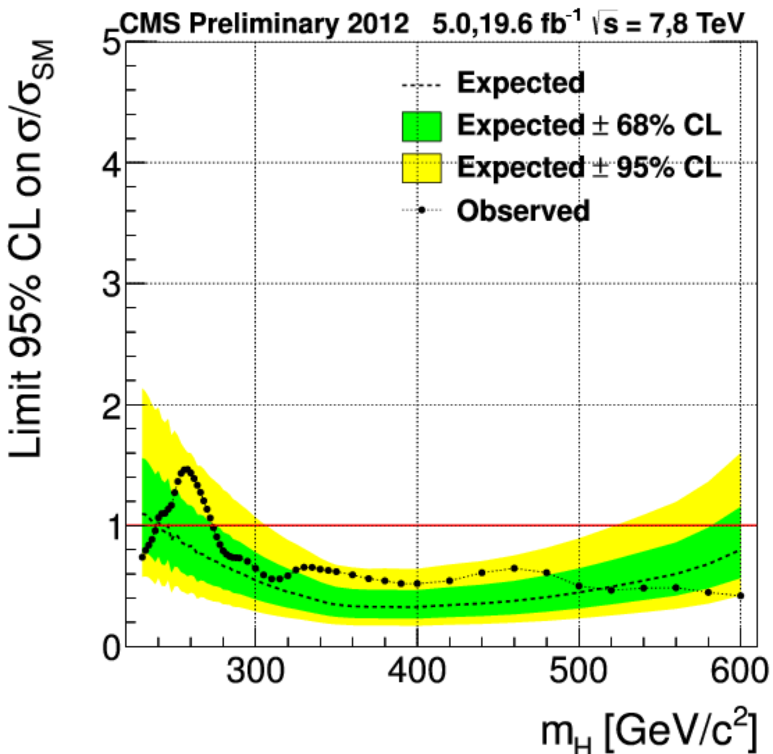
	0 btag		1 btag		2 btag	
	$\mu^+\mu^- jj$	$e^+e^- jj$	$\mu^+\mu^- jj$	$e^+e^- jj$	$\mu^+\mu^- jj$	$e^+e^- jj$
expected background	14809	13490	5478	4786	525	440
observed data	14697	13312	5458	4819	522	461
M_H (GeV/c^2)	signal expectation					
250	110.6	100.8	55.8	51.1	18.4	16.9
300	124.4	112.3	66.6	57.0	24.5	21.0
400	121.9	107.2	68.2	60.4	27.4	24.1
500	57.0	52.1	33.4	29.9	13.8	12.3
600	21.7	19.7	13.2	11.9	5.4	4.9

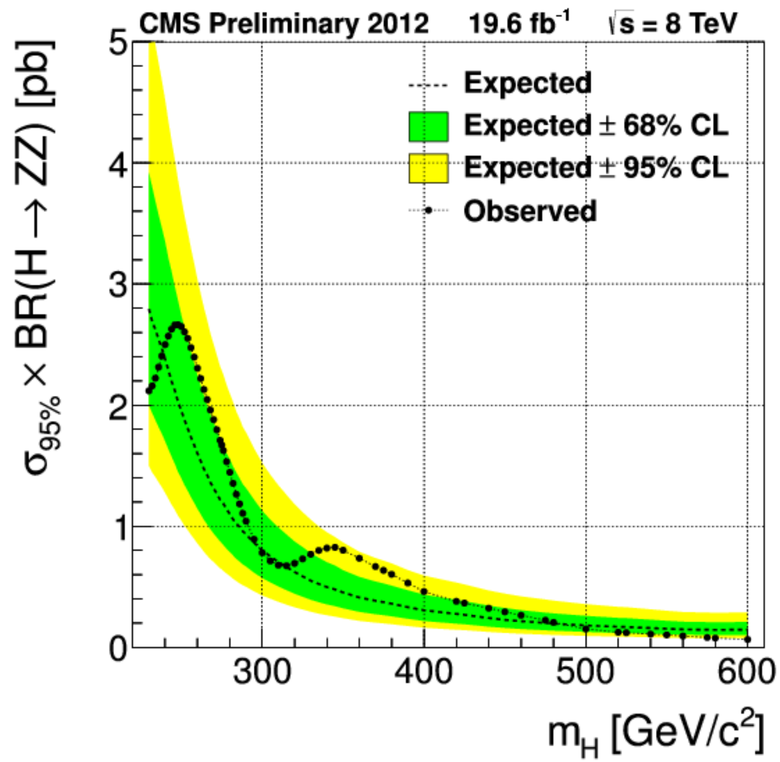


- m_{ZZ} invariant mass distribution in 0 b-tag category for final state with electrons



H → ZZ → 2l2q statistical interpretation





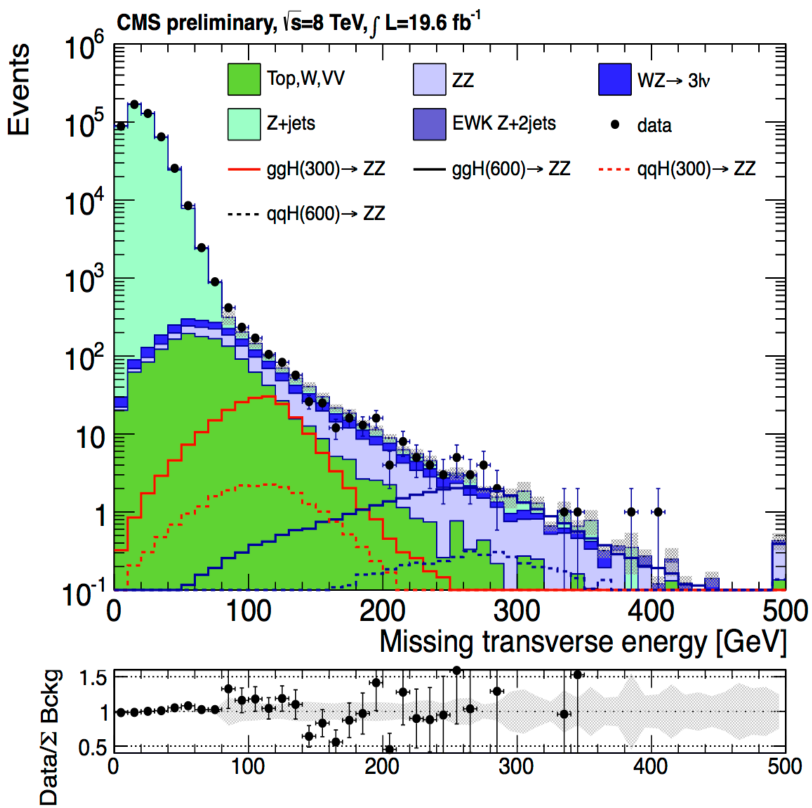
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of σ(pp→H) x BR(H→ZZ→2l2q) @ 95% CL and SM x-section
  - Observed exclusion: 290 to 600 GeV
  - Expected exclusion: 275 to 600 GeV
- Upper limit @ 95% CL is set on the σ(pp→H) x BR(H→ZZ→2l2q) @ 8 TeV

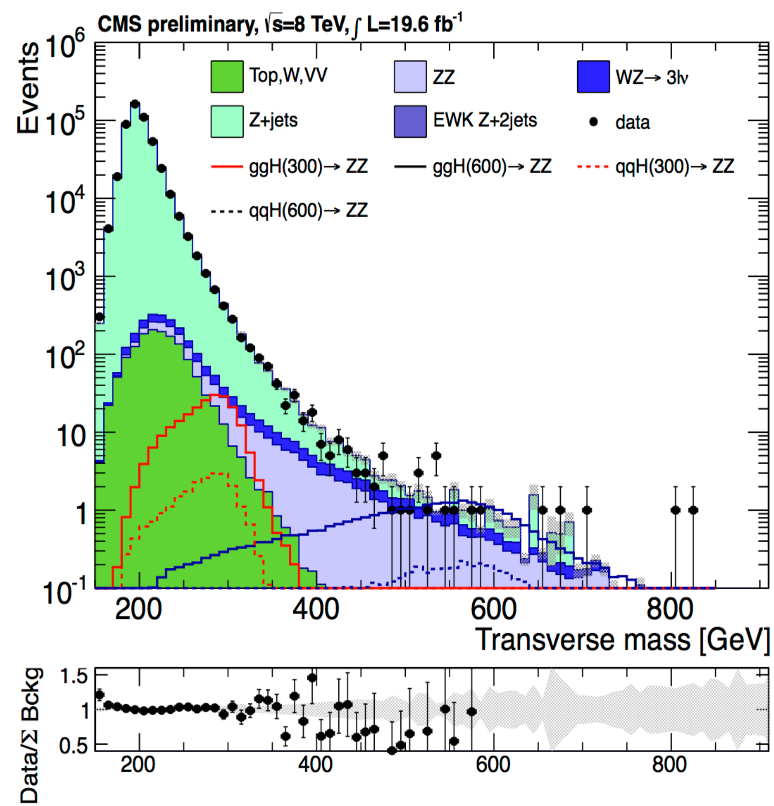
$H \rightarrow ZZ \rightarrow 2l2\nu$

- Signature:
  - $Z \rightarrow e^+e^-(\mu^+\mu^-) + E_T^{miss}$
  - Mass range: [200, 1000] GeV
- Backgrounds:
  - Irreducible: SM ZZ and WZ (estimated from simulation)
  - Reducible:
    - Resonant: Z + jets (from data)
      - Estimated using γ + jets events reweighted for kinematics and # vertices
    - Non-resonant: WW, W + jets, $Z \rightarrow \tau\tau$, ttbar and tW (from data)
      - Estimated by scaling the # $e^+\mu^-(e^-\mu^+)$ events(N_l) in the side-bands by $\alpha_l = \frac{N_{ll}}{N_{e\mu}}$
      - Where the events with m_{ll} in [40, 70] and [100, 200] GeV fall in side-bands
- Large E_T^{miss} for the signal events are exploited to reduce the background
- Event selection:
  - Well identified and isolated leptons from leading Z decay (both with p_T > 20 GeV)
  - Mass dependent selection (based on E_t^{miss} and m_T)
- Categorization is done on basis of # reconstructed jets for the better sensitivity
  - 2 jets tagged events for VBF and 0, >=1 jet(s) tagged events for GGH

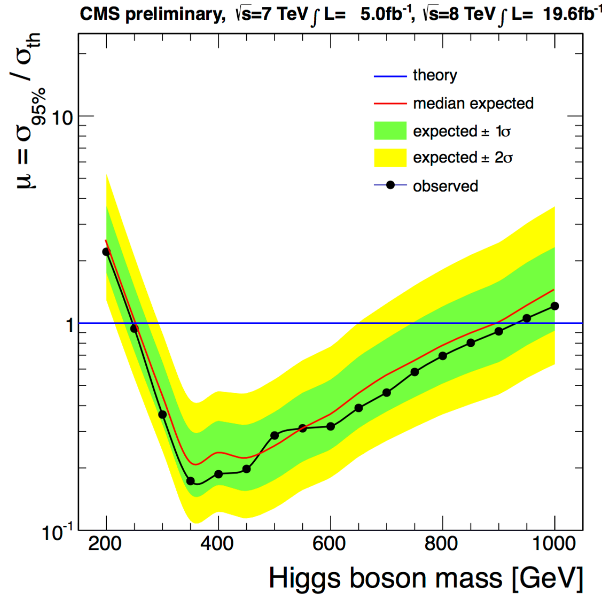
H → ZZ → 2l2ν distributions

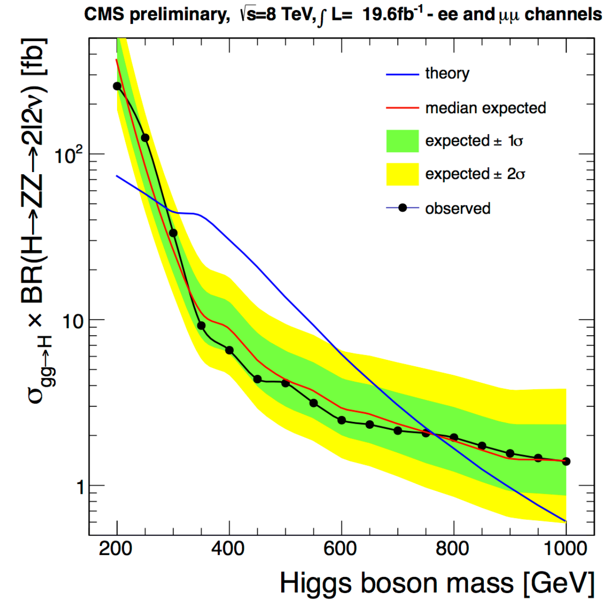
- m_T and E_T^{miss} comparison of data and estimated backgrounds along with event yields for 300 and 600 GeV SM Higgs @ 8TeV
  - combined for all categories and final states with electrons and muons
  - Good agreement is observed validating the background estimations

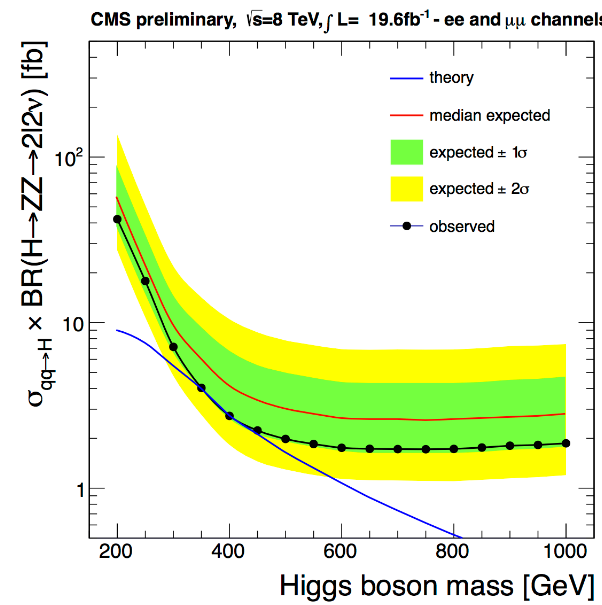




H → ZZ → 2l2ν statistical interpretation







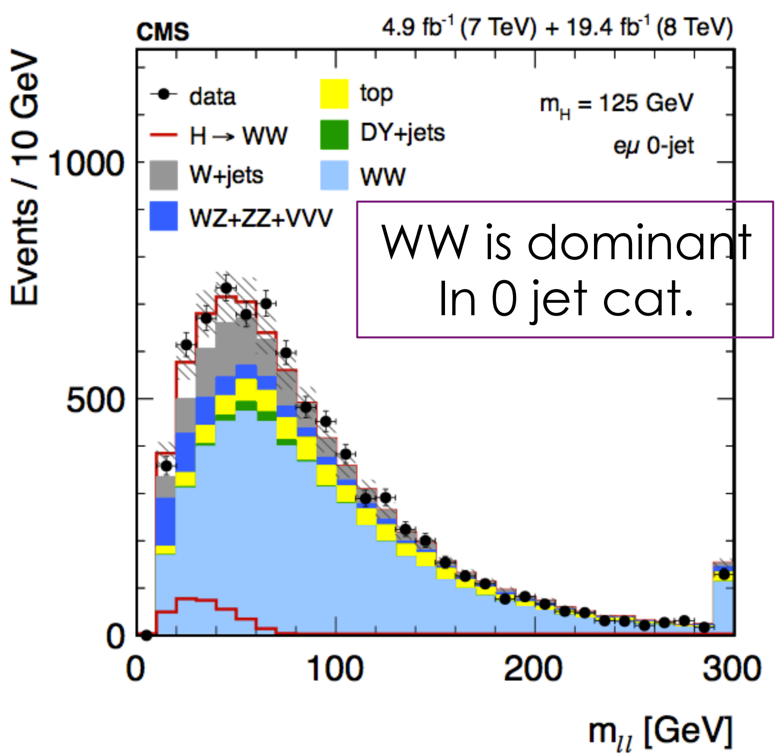
- No evidence of SM-like Higgs
- Upper limits are set on the ratio of σ(pp→H) x BR(H→ZZ→2l2ν) @ 95% CL and SM x-section (left plot)
  - Observed exclusion: 248 to 930 GeV
  - Expected exclusion: 254 to 898 GeV
- Upper limit @ 95% CL is set on the σ(pp→H) x BR(H→ZZ→2l2ν) @ 8TeV
  - Right plots: GGH(upper) and VBF(lower)
  - Cross-contamination is excluded

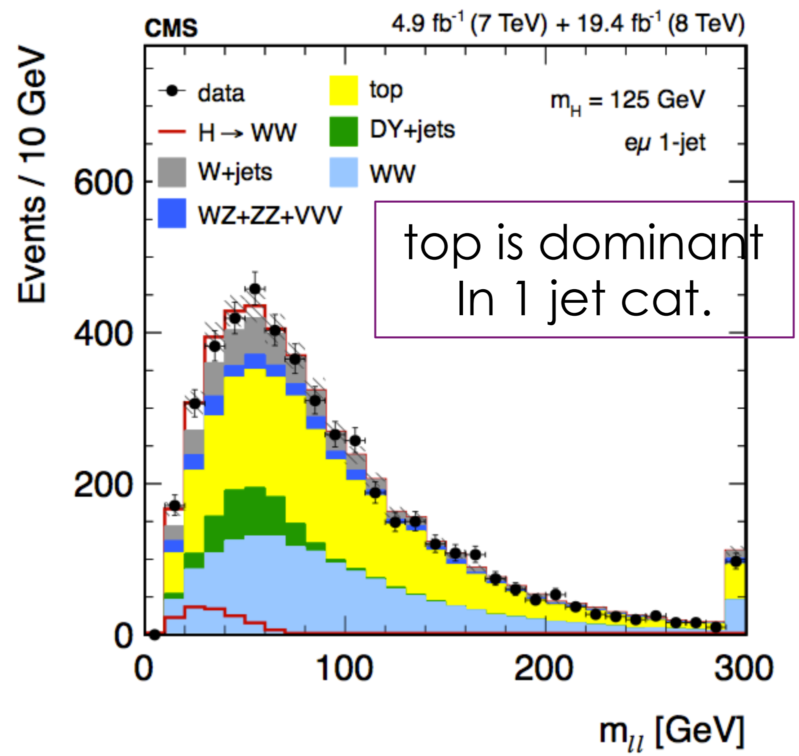
H → WW* → lνlν

- Signature:
  - Two or three charged leptons + E_T^{miss} (trilepton states to probe the VH production mode)
  - Mass range:
    - GGF and VBF: [110, 600] GeV
    - VH: [110, 200] GeV since the x-section is very small for high masses
- Key points:
  - m_T, m_{ll} and $\Delta\phi$ between leptons
  - Categorization is done for better sensitivity
- Backgrounds:
  - Non-resonant WW, WZ and ZZ for dilepton, trilepton categories respectively (estimated from simulation)
  - ttbar and tW for high jet multiplicity states (from data)
    - Probability of a jet to be a b-tagged jet is exploited to estimate this backgrounds part
  - Reducible W + jets (from data)
    - Probability of a jet to fake a lepton is exploited to estimate this backgrounds part
  - Reducible Z + jets (from data)
    - Z + jets off-peak contribution is estimated by scaling the # events in a narrow mass window around Z by ratio of # events in and outside of window (after subtracting the non-resonant contribution)

H → WW* → lνlν categorization

- Dilepton categories:
  - 0,1 jet(s) same flavor or different flavor: GGH
  - 2 jets same or different flavor: VBF
  - 2 jets same or different flavor: WH, ZH
    - Jets from the decay of associated vector boson
    - Different characteristics from VBF topology
- Trilepton categories:
  - WH → 3l3n
  - ZH → 3ln + 2jets





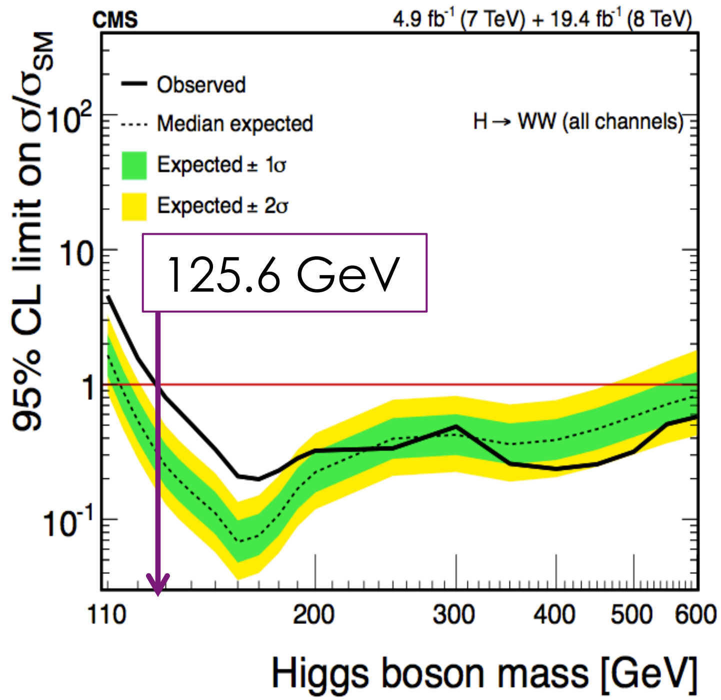
$H \rightarrow WW^* \rightarrow l\nu l\nu$ categorization

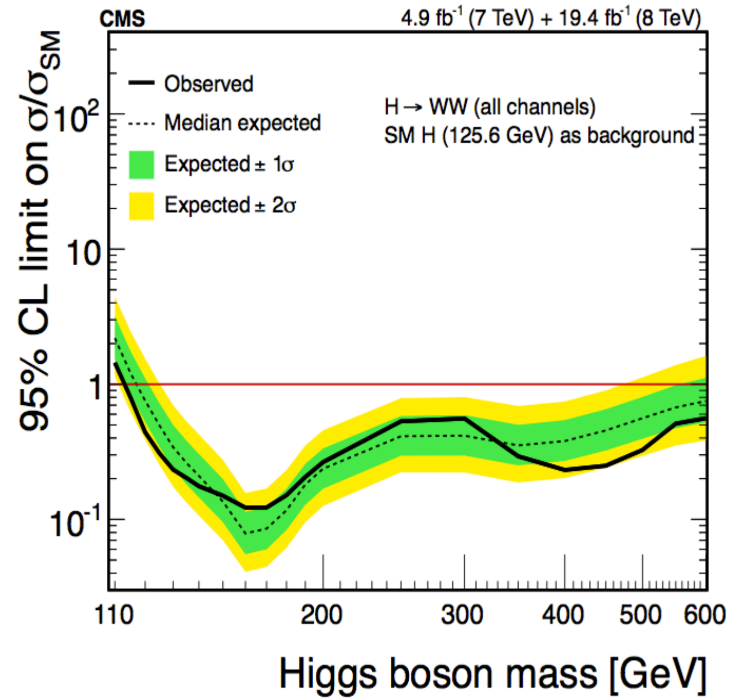
Category	ggH (%)	VBF (%)	VH (%)	Total $H \to WW$ yield $\sqrt{s} = 7$ TeV	Total $H \to WW$ yield $\sqrt{s} = 8$ TeV
Two-lepton analyses					
0-jet different-flavor (shape-based)	95.7	1.2	3.1	52.6	245
0-jet same-flavor (counting)	98.1	0.9	1.0	10.4	58.5
1-jet different-flavor (shape-based)	81.6	10.3	8.1	19.8	111
1-jet same-flavor (counting)	83.6	11.2	5.2	3.1	19.6
2-jet VBF tag different-flavor (shape-based)	22.3	77.7	0.0	1.3	6.4
2-jet VBF tag same-flavor (counting)	14.2	85.8	0.0	0.3	2.3
2-jet VH tag different-flavor (counting)	55.5	4.7	39.8	0.8	4.3
2-jet VH tag same-flavor (counting)	65.1	4.1	30.8	0.2	2.8
Three-lepton analyses					
$WH \to 3\ell 3\nu$ (shape-based)	0.0	0.0	100.0	0.7	3.8
$ZH \to 3\ell\nu 2$ jets (shape-based)	0.0	0.0	100.0	0.3	1.0

- Same flavor: Counting analysis using cut-based analysis
  - Difficult to model Z/γ^* background
- Different flavor category: 2D template fit to extract the signal and background in m_T, m_{ll} phase space

H → WW* → lνlν statistical interpretation

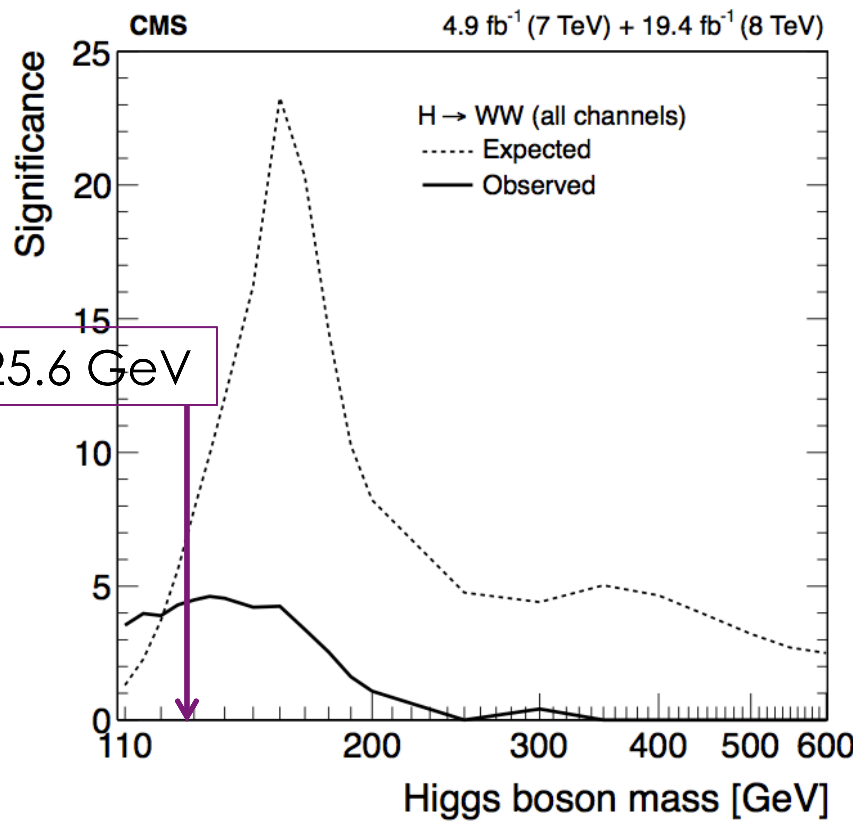
- Upper limits are set on the ratio of σ(pp→H) x BR(H→WW*→lνlν) @ 95% CL and SM x-section
  - @ 125.6 GeV, an upper limit of 1.1 is observed for 0.3 expected
  - Observed exclusion: [127, 600] GeV
  - Expected exclusion: [115, 600] GeV
- Additional test is performed taking SM Higgs of mH = 125.6 GeV as a background process
  - Observed exclusion: [114, 600] GeV

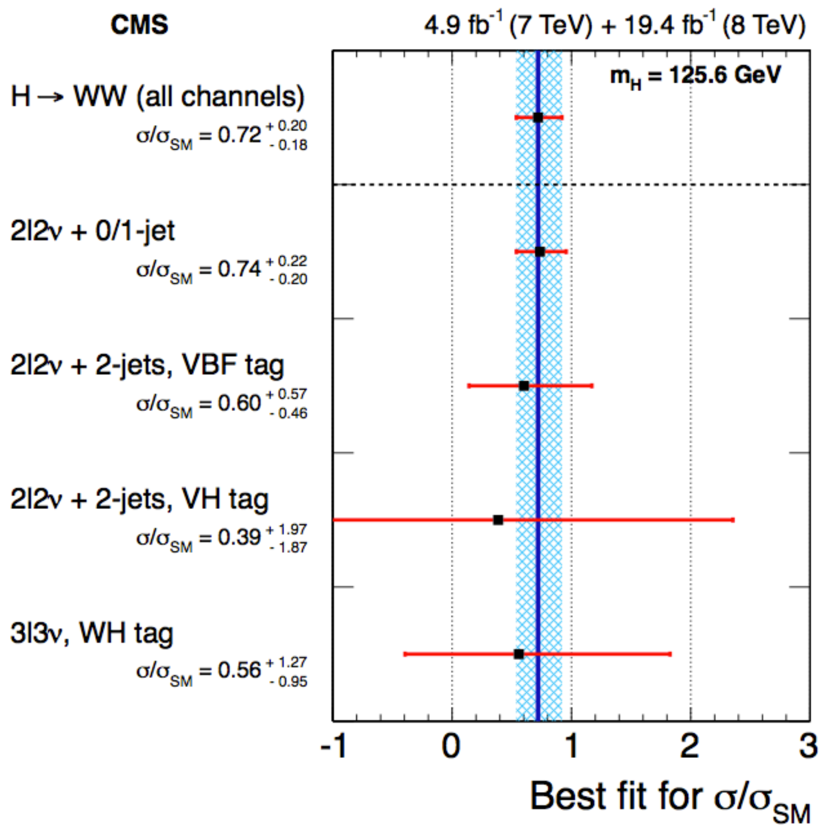




H → WW* → lνlν statistical interpretation

- Significance of 4.3σ is observed for 5.8σ expected @ 125.6 GeV
  - Very large significance @ ~160 GeV since the BR ~1

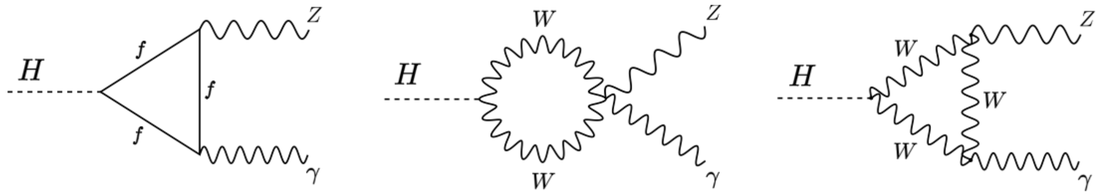




- Signal strength @ 125.6 GeV = $0.72^{+0.12}_{-0.12}(stat)^{+0.1}_{-0.1}(syst)^{+0.12}_{-0.10}(theo)$

H → Zγ

- Decay is sensitive to the physics beyond the SM
  - Proceeds via top and W loops like H → γγ
  - Mass range: [120, 160] GeV



- Signature: Z → $e^+e^-(\mu^+\mu^-) + \gamma$
- Backgrounds (estimated using data-driven technique):
  - Irreducible: SM Zγ
  - Reducible: Z → ll + FSR, Z + jets and ttbar
- Event selection:
  - Well identified and isolated leptons from Z decay (p_T > 20(10) GeV for leading(sub-leading))
  - Well identified and isolated photon (p_T > 15 GeV)
- Categorization is done on basis of # reconstructed jets for better sensitivity
  - 2 jets tagged events for VBF and untagged events for GGH

H → Zγ categorization

Untagged

- **Class 1 and 2:** both leptons and the photon are in barrel
  - photon conversion is taken into account
  - Highest S/B of untagged category
  - Resolution = 1.9(1.6) GeV for eeγ(μμγ) state
- **Class 3:** one of the leptons is in endcaps, and one lepton and photon are in barrel
  - Resolution = 2.1(1.9) GeV for eeγ(μμγ) state
- **Class 4:** the photon is in the endcaps, and leptons can be in barrel or endcaps
  - Resolution = 3.3(3.2) GeV for eeγ(μμγ) state

Dijet tagged

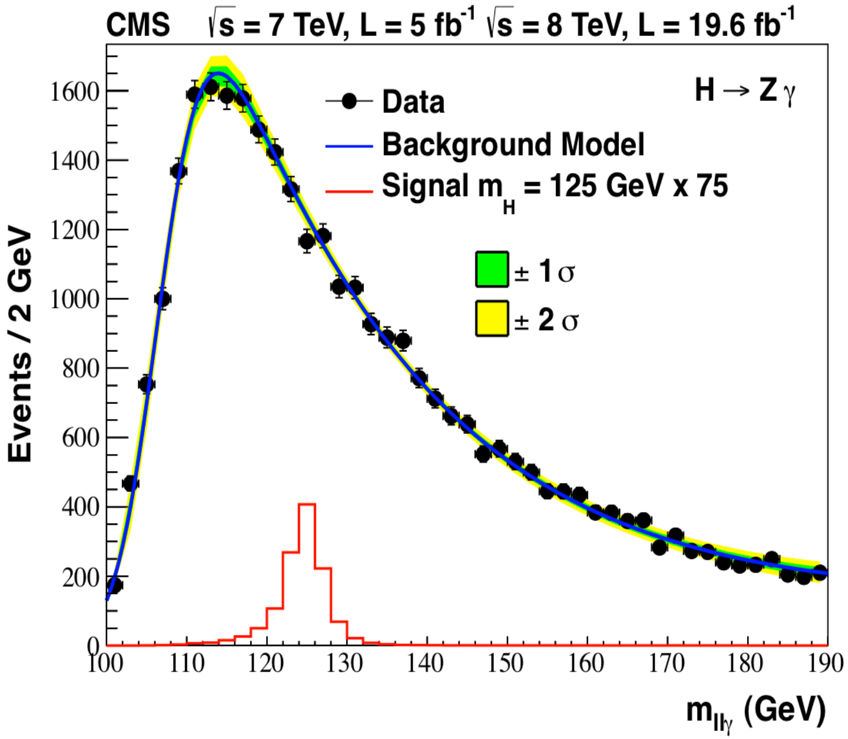
- **VBF dijet tagged:** better S/B than untagged category
  - Enhance the sensitivity by 10 to 15 %

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 1.44$ $R_9 > 0.94$	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 > 0.94$
Data	17%	20%
Signal	29%	33%
σ_{eff} (GeV)	1.9 GeV	1.6 GeV
FWHM (GeV)	4.5 GeV	3.7 GeV
	Event class 2	
	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 1.44$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Data	26%	31%
Signal	27%	30%
σ_{eff} (GeV)	2.1 GeV	1.9 GeV
FWHM (GeV)	5.0 GeV	4.6 GeV
	Event class 3	
	Photon $0 < \lvert\eta\rvert < 1.44$ At least one lepton $1.44 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	26%	20%
Signal	23%	18%
σ_{eff} (GeV)	3.1 GeV	2.1 GeV
FWHM (GeV)	7.3 GeV	5.0 GeV
	Event class 4	
	Photon $1.57 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.57 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	31%	29%
Signal	19%	17%
σ_{eff} (GeV)	3.3 GeV	3.2 GeV
FWHM (GeV)	7.8 GeV	7.5 GeV
	VBF class	
	Photon $0 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	0.1%	0.2%
Signal	1.8%	1.7%
σ_{eff} (GeV)	2.6 GeV	2.2 GeV
FWHM (GeV)	4.4 GeV	3.8 GeV

H → Zγ results

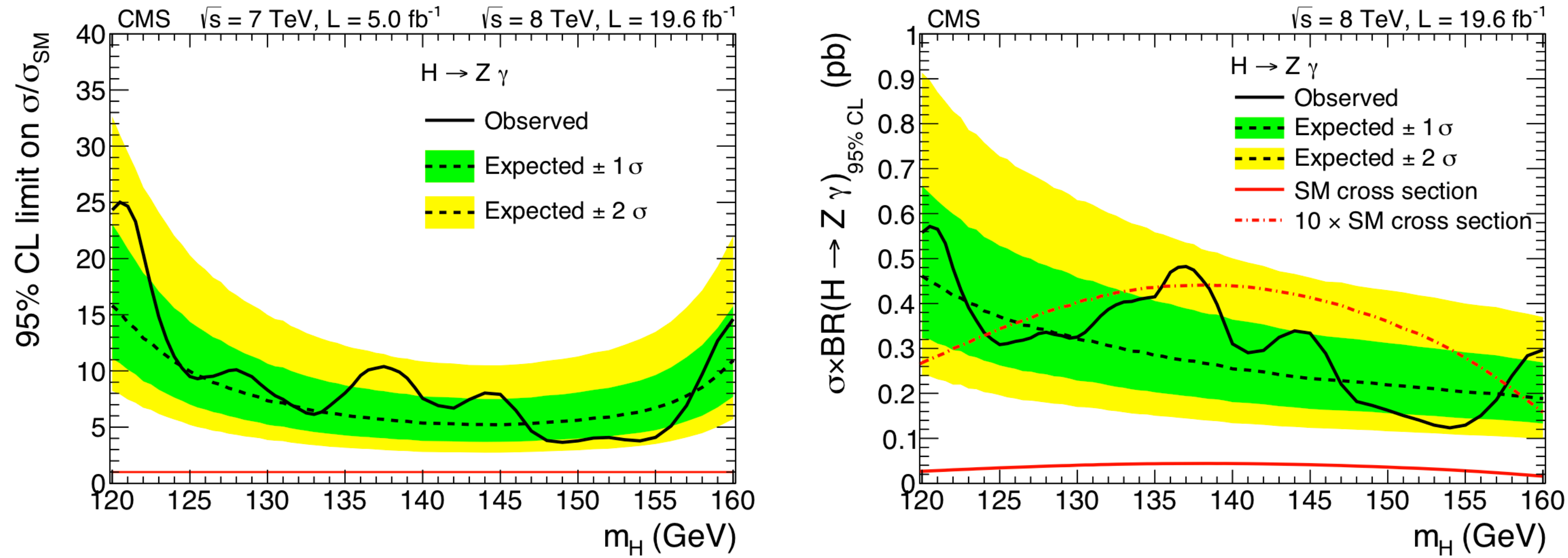
- Observed and expected event yields for a 125 GeV SM Higgs

Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190\,GeV$	Expected number of signal events for $m_H = 125\,GeV$
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0



- Background model is obtained by fitting the $m_{ll\gamma}$ distribution for both categories
  - Peaks at 110 to 115 GeV with gradually falling tail on the right
  - Potential bias model is accounted by performing different background models fits on pseudo data ("truth model")

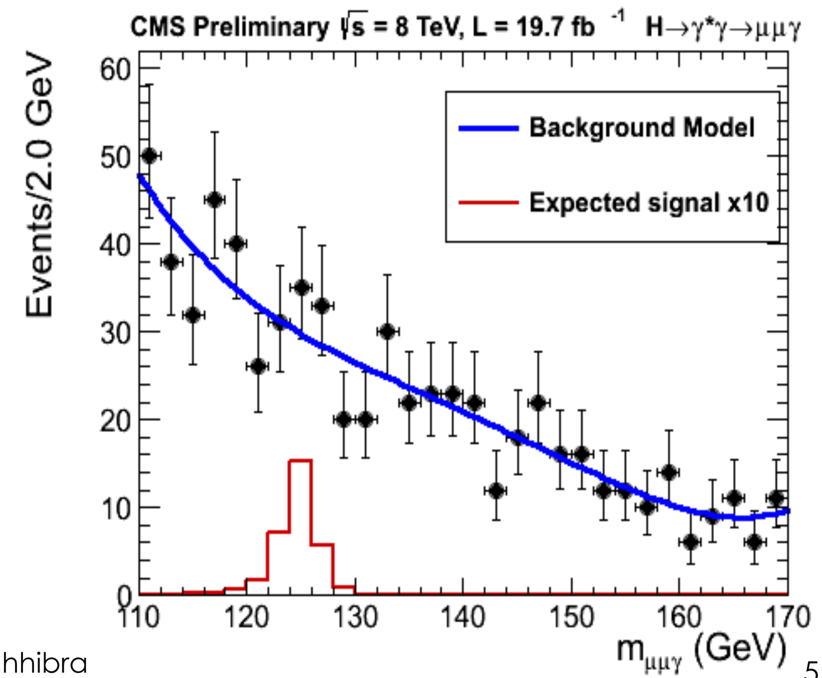
H → Zγ statistical interpretation



- No evidence of SM-like Higgs
- Upper limits are set on the ratio of σ(pp→H) x BR(H→Zγ) @ 95% CL and SM x-section
  - Observed limit: 4 to 25 times the SM x-section
  - Expected limit: 5 to 16 times the SM x-section
  - @ 125 GeV: both observed and expected limits are ~10 times the SM x-section
- An exclusion of σ(pp→H) x BR(H→Zγ)@ 95% CL in the mass range of [125, 157] GeV is expected for 10 times SM x-section @ 8TeV

$H \rightarrow \gamma^{*}\gamma \rightarrow \mu\mu\gamma$

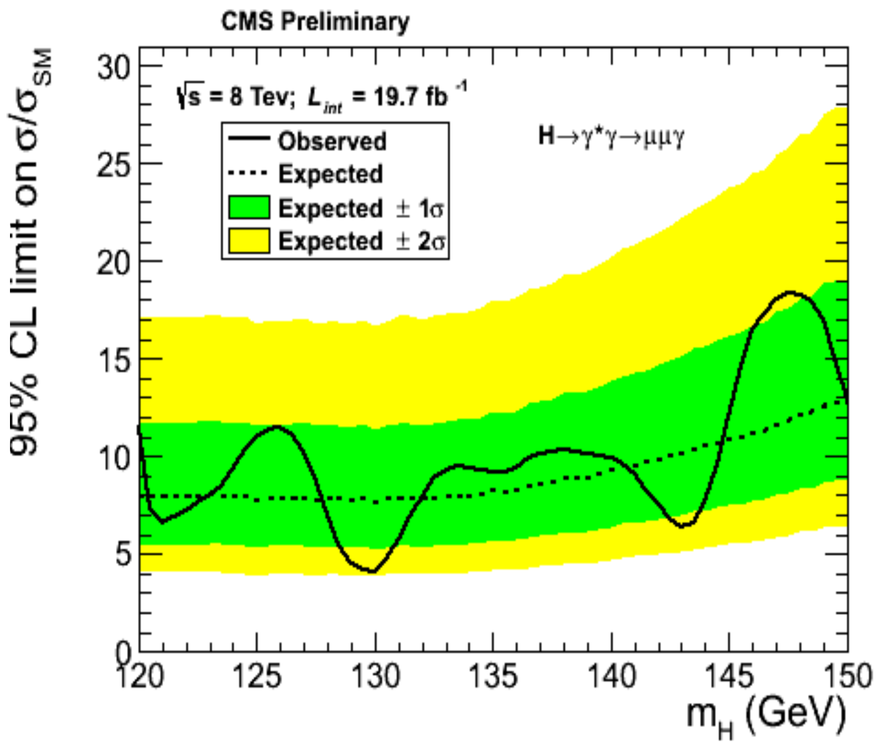
- **Signature:** Clean $\mu^{+}\mu^{-} + \gamma$ signature with mass resolution of 1.5%
  - Mass range: [120, 150] GeV
- **Backgrounds:** Z + ISR, Z + FSR and Z + jets
- **Event selection**
  - Well identified and isolated muons (p_T > 23(4) GeV for leading(sub-leading))
  - Well identified and isolated photon (p_T > 25 GeV)
  - Events with $m_{\mu\mu}$ in [2.9, 3.3] and [9.3, 9.7] GeV are vetoes to reject J/Ψ and Υ
- **Key variables:**
  - Geometrical separation between each lepton and photon, $m_{\mu\mu}$
- **Background modeling is obtained by fitting the $m_{\mu\mu\gamma}$ in distribution in data**
  - Similar to $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ analyses



H → $\gamma^*\gamma$ → $\mu\mu\gamma$ results and statistical interpretation

- Observed and expected event yields for a 125 GeV SM Higgs

Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta R(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9



- No evidence of SM-like Higgs

- Upper limits are set on the ratio of σ(pp→H) x BR(H→$\gamma^*\gamma$→$\mu\mu\gamma$) @ 95% CL and SM x-section @ 8TeV
  - Observed limit: 4 to 19 times the SM x-section
  - Expected limit: 8 to 13 times the SM x-section
  - @ 125 GeV: both observed and expected limits are ~10 times the SM x-section