Latest results on Higgs final-states with photons in CMS

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on behalf of the CMS collaboration

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In this talk …

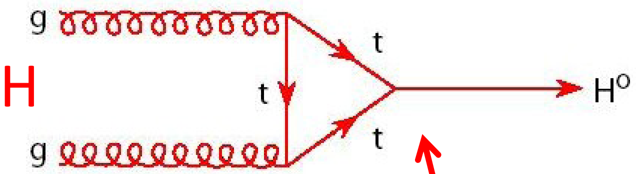
- $H \to \gamma\gamma$ decay *Eur. Phys. J. C (2014) 74:3076*
  - One of the most sensitive channels at the LHC.
  - Loop-mediated decay: measurement of $H \to \gamma\gamma$ coupling sensitive to BSM physics.

- $H \to ll\gamma$ decay
  - Loop-mediated $H \to Z\gamma$ decay: small branching fraction but sensitive to BSM effects *Physics Letters B 726 (2013) 587–609*
  - "Dalitz mode" $H \to \gamma^* \gamma \to u^+u^-\gamma$: sensitive to new-physics due to loops *CMS-PAS-HIG-14-003*

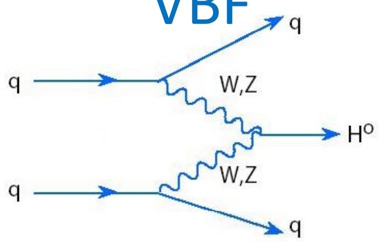
- Double Higgs production through $HH \to bb\gamma\gamma$
  - Sensitive to Higgs self-coupling. *CMS-PAS-HIG-13-032*

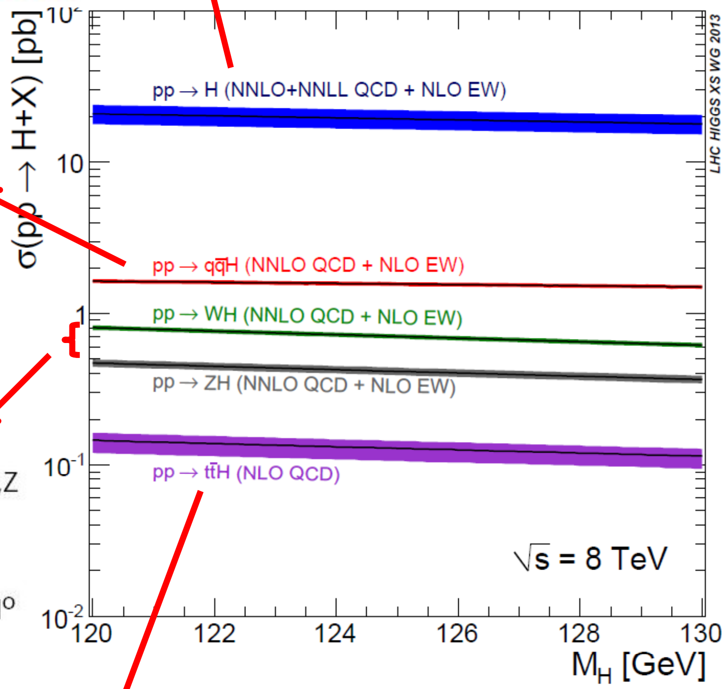
Higgs production and decay

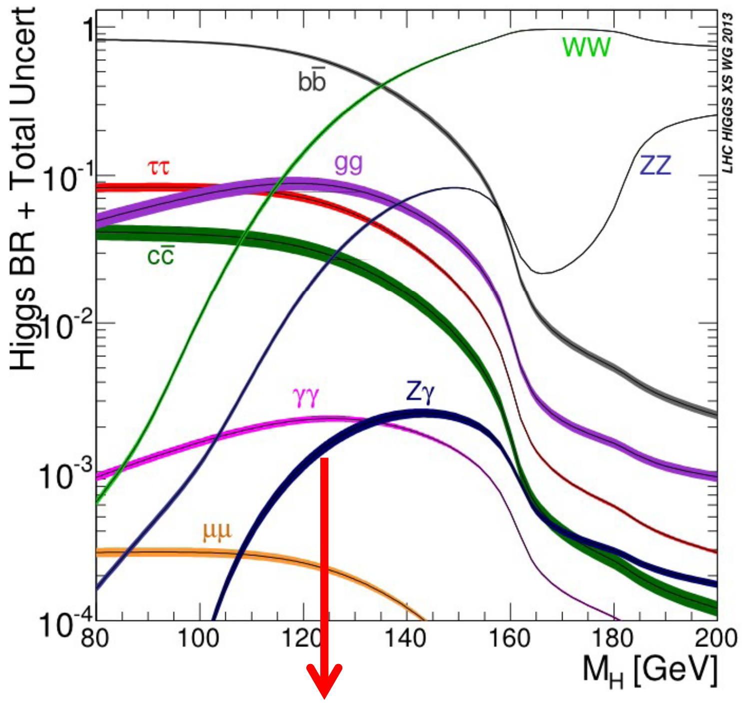
ggH



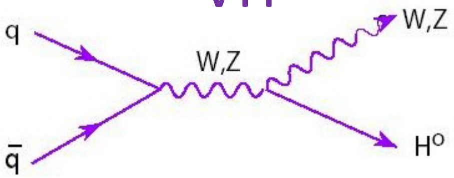
VBF



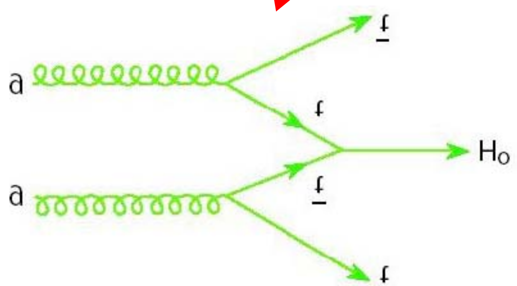




VH



ttH



@ mH=125GeV

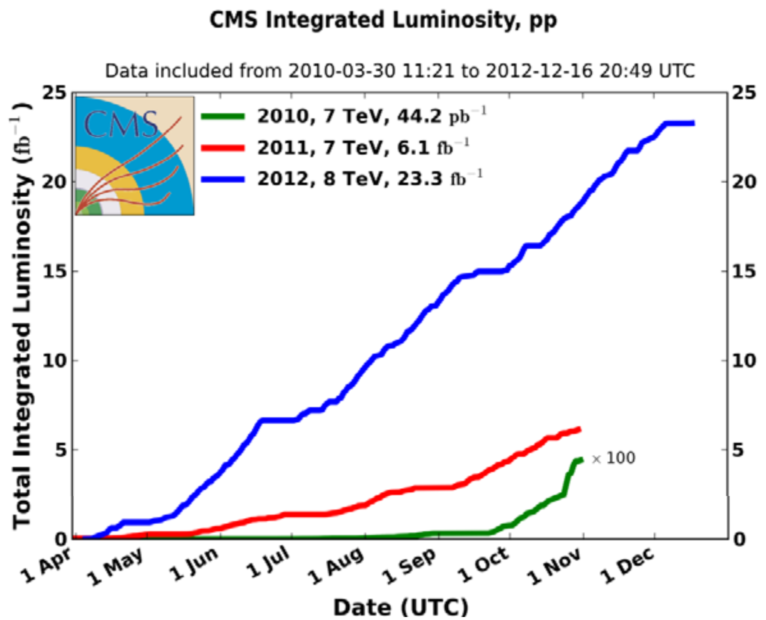
BR(H → γγ) ~ 2x10^{-3}

BR(H →llγ) ~ 10^{-6}

LHC Run 1 dataset

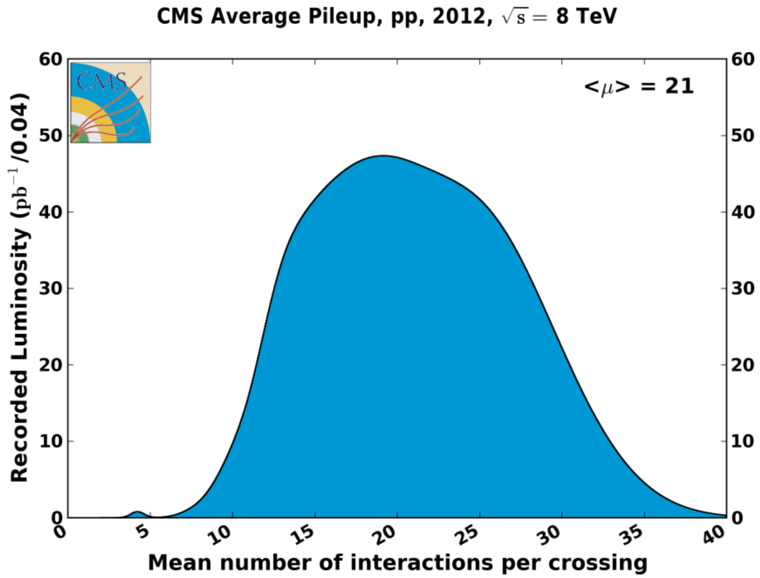
➢ **Excellent performance** of the **LHC** machine and **CMS** detector in **Run 1**:

- ~90% of the delivered data available for offline analysis.
- ~5fb^{-1} at 7TeV + ~20fb^{-1} at 8TeV



➢ **Challenging pile-up conditions**

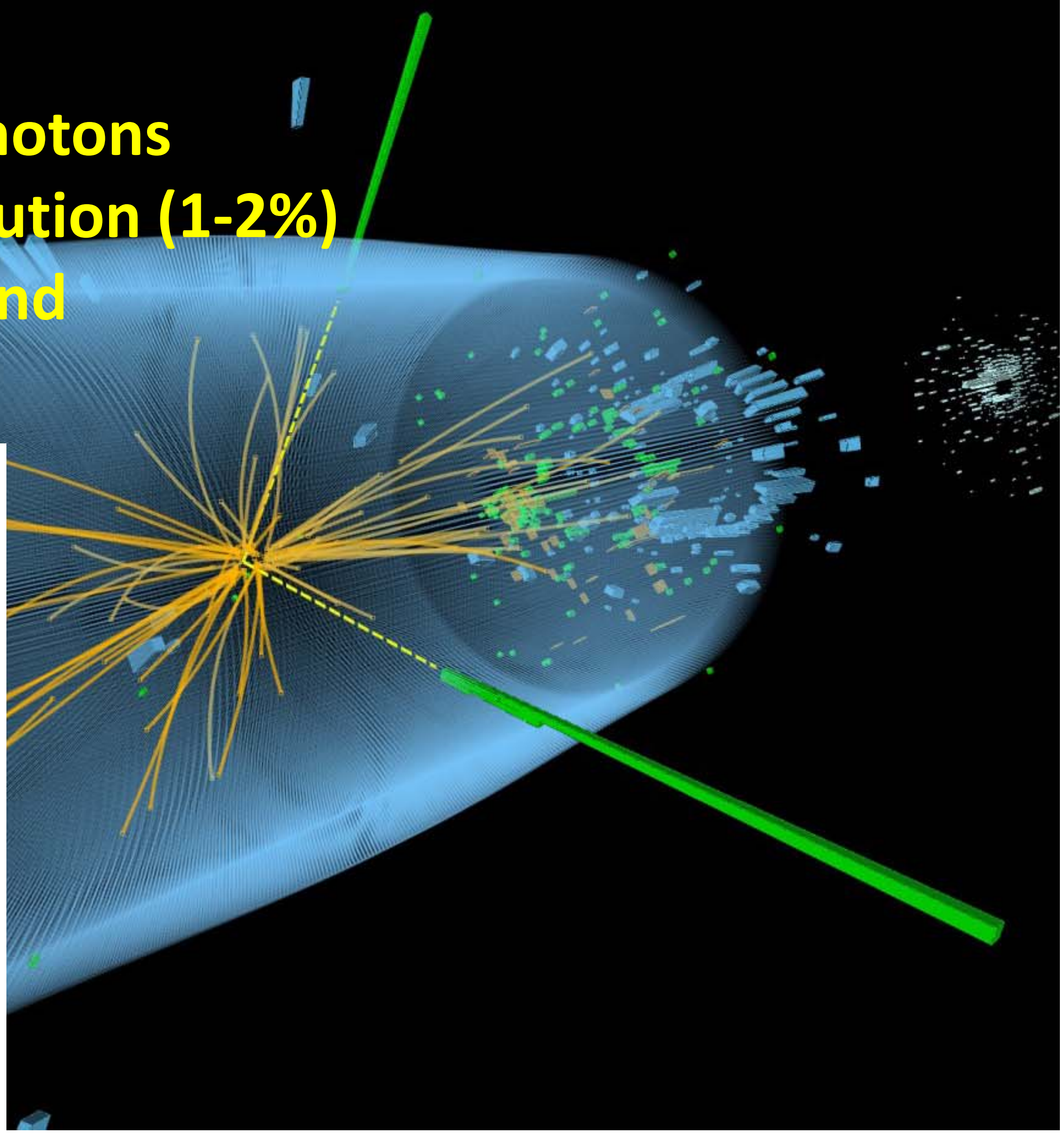
Average PU ~10 events in 2011 and ~20 events in 2012

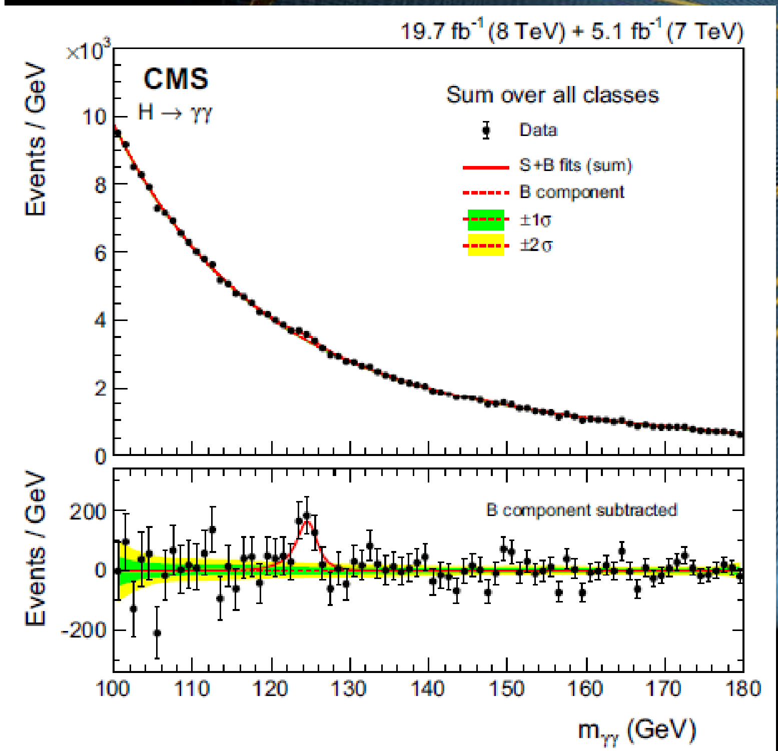


H→γγ

Signature:

- 2 high pT isolated photons
- Excellent mass resolution (1-2%)
- Large QCD background





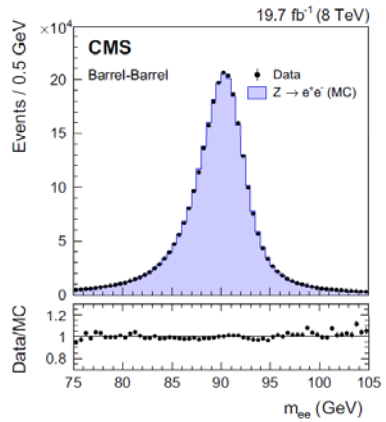
Analysis strategy (1)

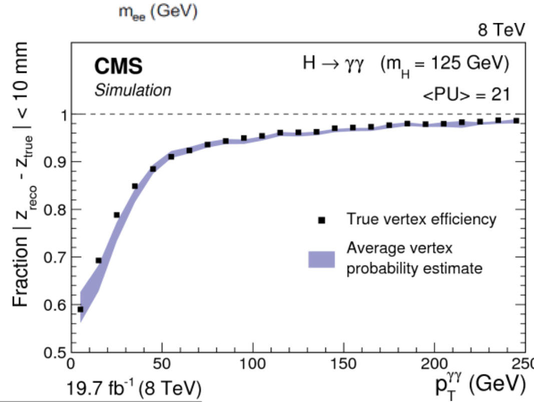
Optimizations on photon objects and events reconstruction to improve s/b:

- **Narrow resonance: good mass resolution**
  - **photon energy** : regression in MVA
  - **Vertex identification**: TMVA BDT classifier:

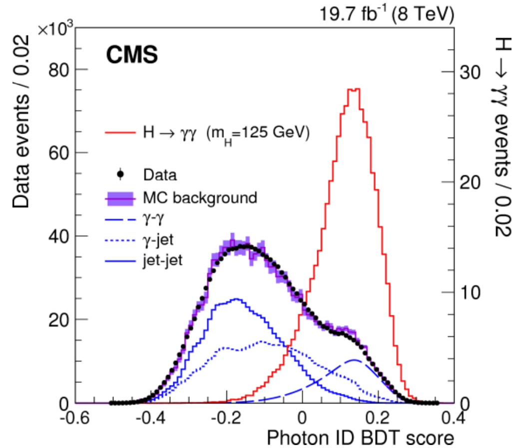
    Vertex tracks pT2, recoil information, pointing information converted photons.

    Also uses a second BDT to estimate probability of correct assignments



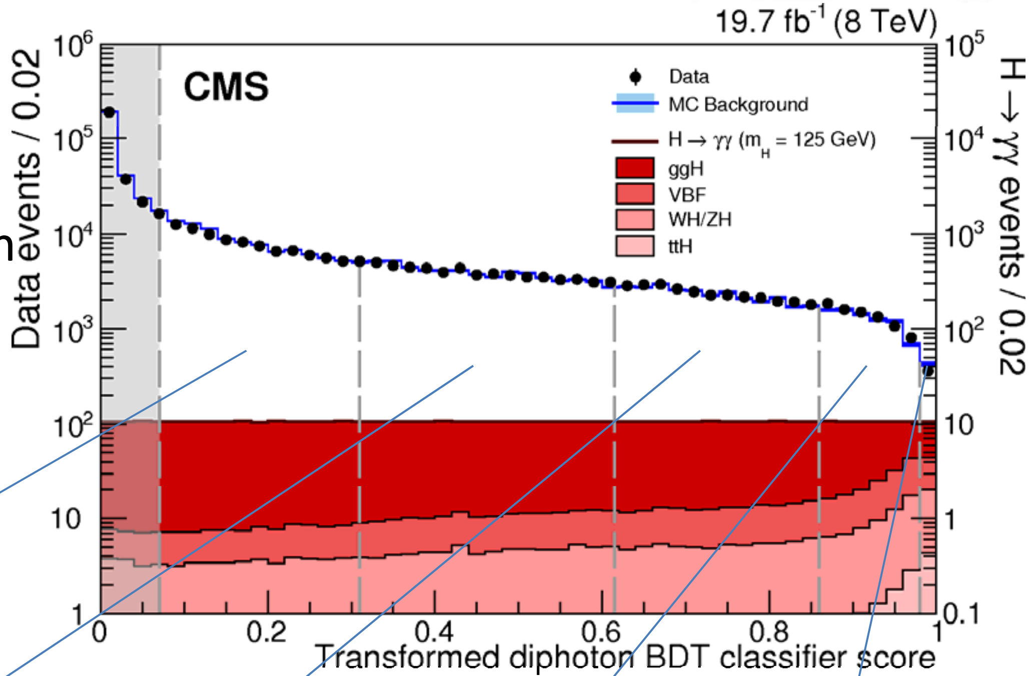


- **Large Background: Photon identification**
  - Using **BDT classifier** (also cross check with categorized cut-base ID)
  - **Looser cut on BDT: >-0.2, keeping 99% MC sig while removing ~24% of events in data**
  - **Two photon BDTs as inputs of event-classification BDT**
  - **Modelling** in data using Z → ee and Z → llγ FSR



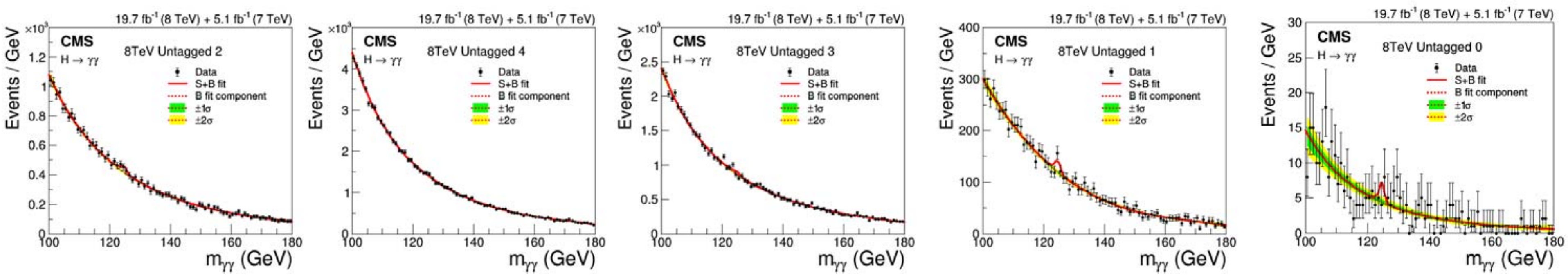
Analysis strategy (2)

Employ **event categories** **to enhance sensitivity:**



- "**Exclusive categories**" are defined in terms of additional object in event (**jets, leptons, missing ET**) to enhance sensitivity to **VBF** and associated production (**WH/ZH/ttH**).

- **Remain events are classified** based on diphoton **BDT** combining kinematics and mass resolution.



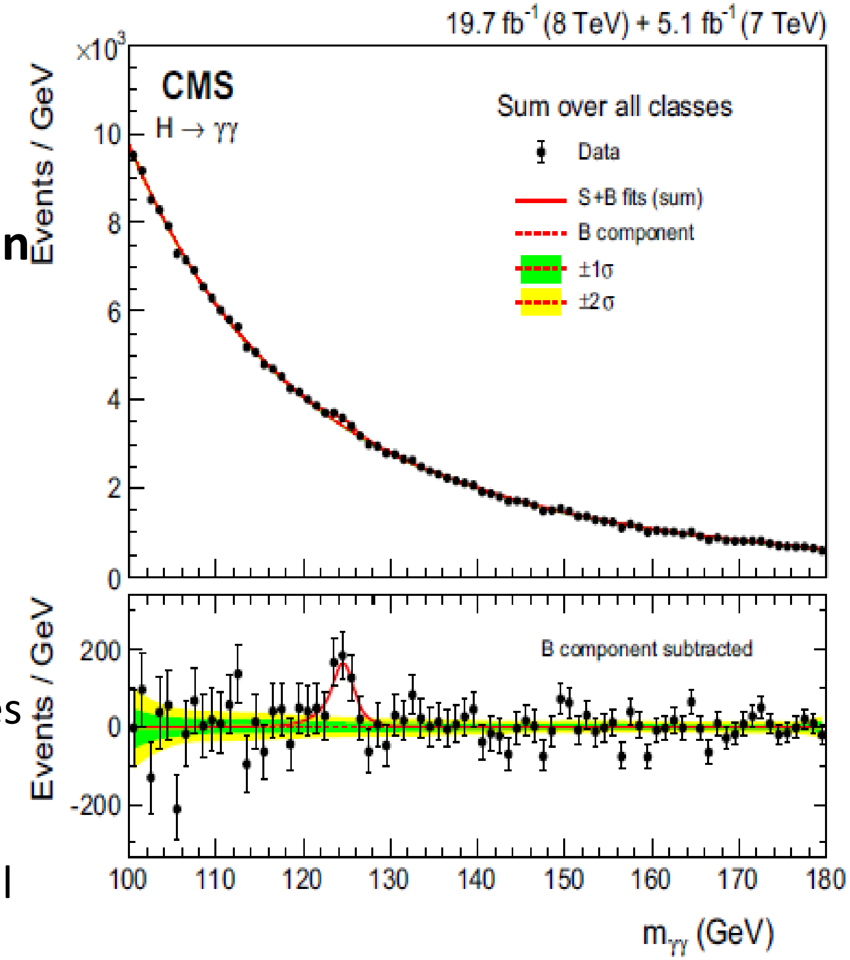
Analysis strategy (3)

Signal and background modelling for statistical methodology:

➢ **Signal model** is derived from **MC simulation** after applying the corrections determined from data/MC comparisons of Z → e^+e^- and Z → $u^+u^-\gamma$ events

➢ **Background modelling**:

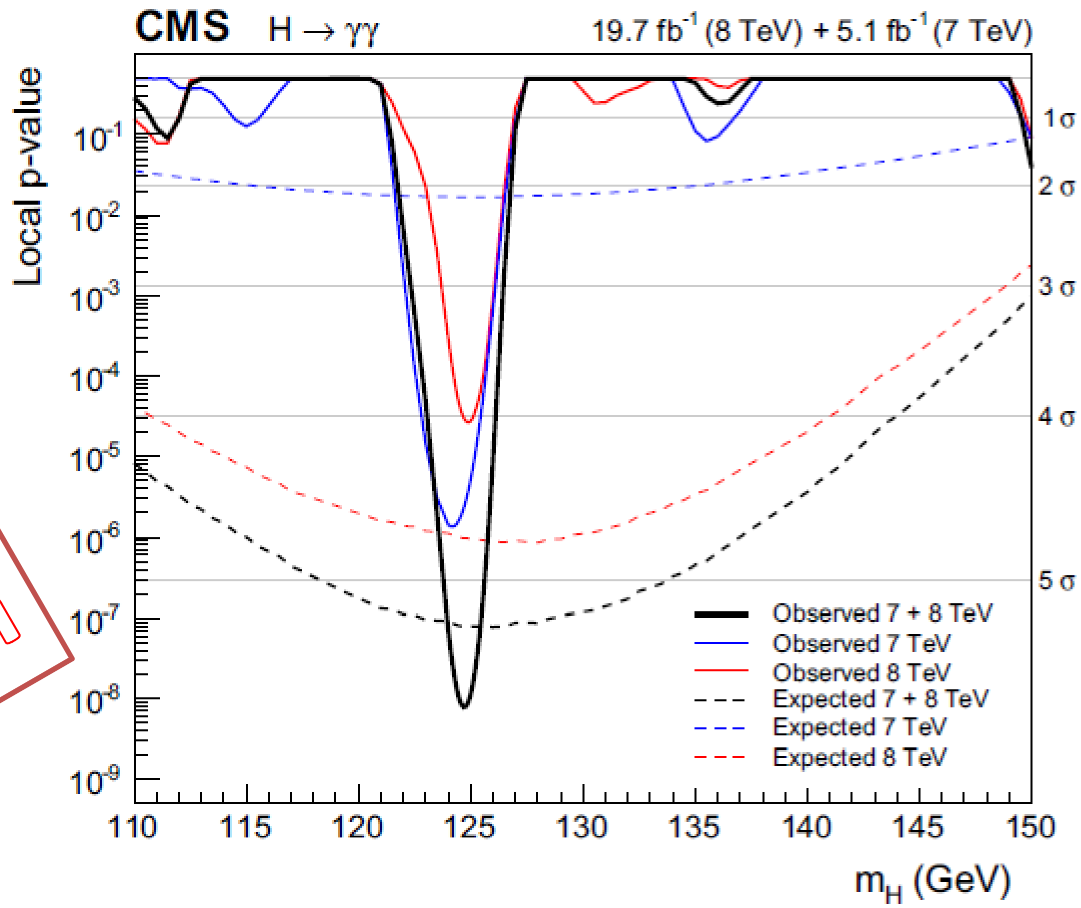
- Using **$m_{\gamma\gamma}$ sidebands** to constrain bkg
- Choice of **bkg functional form**: potential biases are small (namely <~15% of the statistical uncertainty)
- **Discrete profiling method**: choice of bkg model as a discrete nuisance parameter (*difference between models included in uncertainties*)
- Ensure that **the resulting model** is equivalent to other possible choices allowed by the data



Results from H→γγ (1)

- **Significance**
- Signal strength
- Mass
- Couplings
- Decay width

Observation



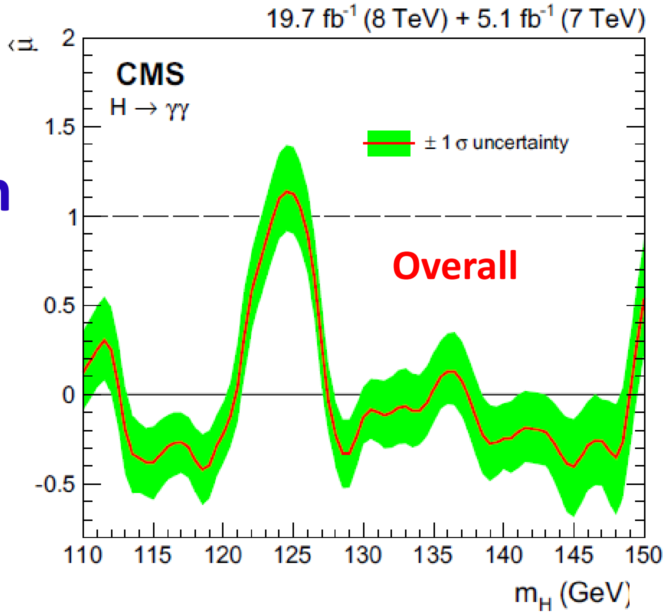
@ ~124.7 GeV

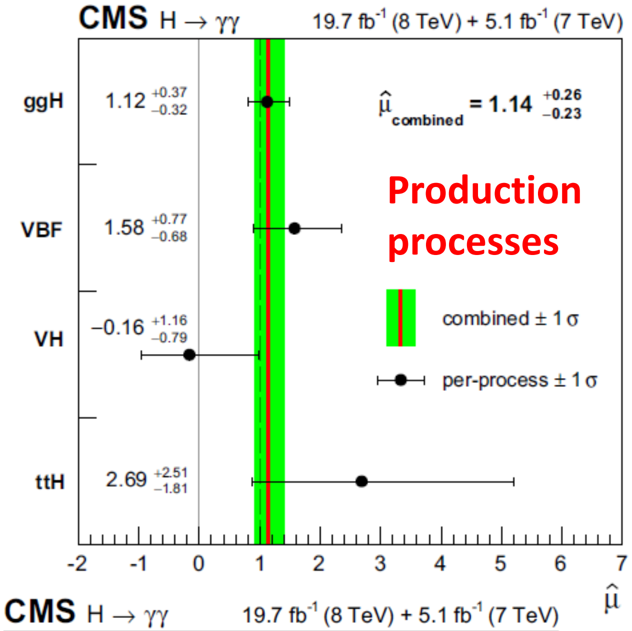
Observed local significance **5.7σ**

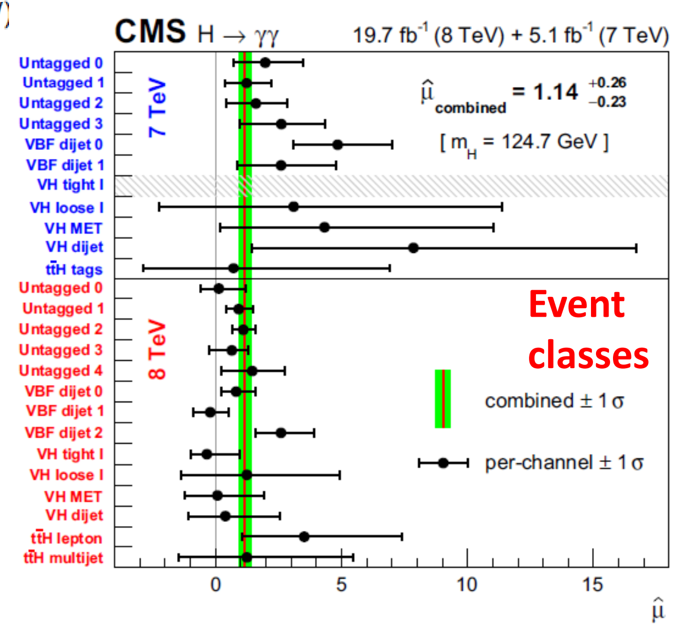
Expected local significance **5.2 σ**

Results from H→γγ (2)

- Significance
- **Signal strength**
- Mass
- Couplings
- Decay width







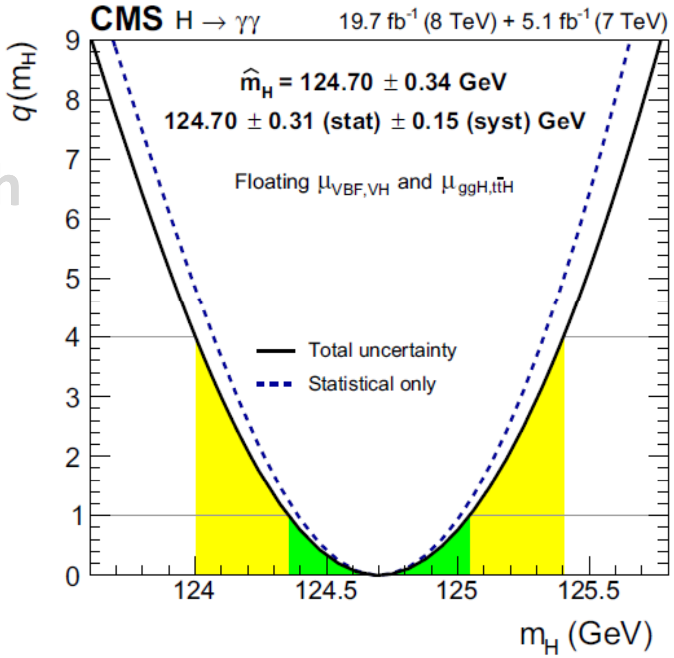
Overall σ/σ_{SM} @ 124.7GeV

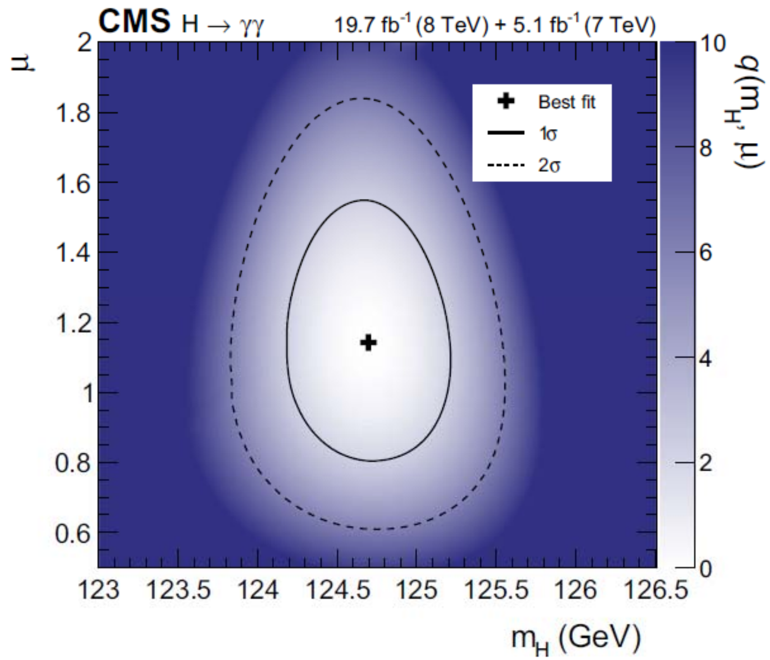
$$1.14^{+0.26}_{-0.23} = 1.14 \pm 0.21\,(\text{stat})\ ^{+0.09}_{-0.05}\,(\text{syst})\ ^{+0.13}_{-0.09}\,(\text{theo})$$

Well in agreement with SM predictions

Results from H→γγ (3)

- Significance
- Signal strength
- **Mass**
- Couplings
- Decay width





H → γγ channel provides the best measurement of m_H:

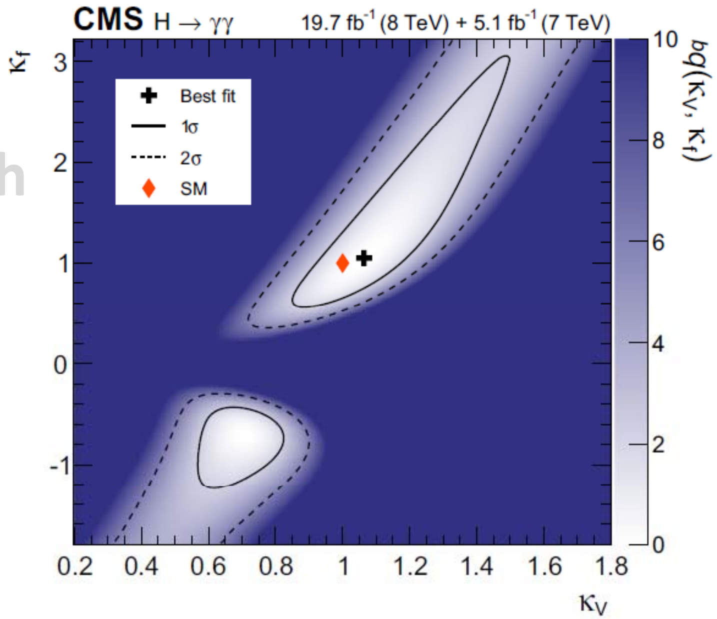
$$\widehat{m}_{\mathrm{H}} = 124.70 \pm 0.31\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})\ \mathrm{GeV}$$

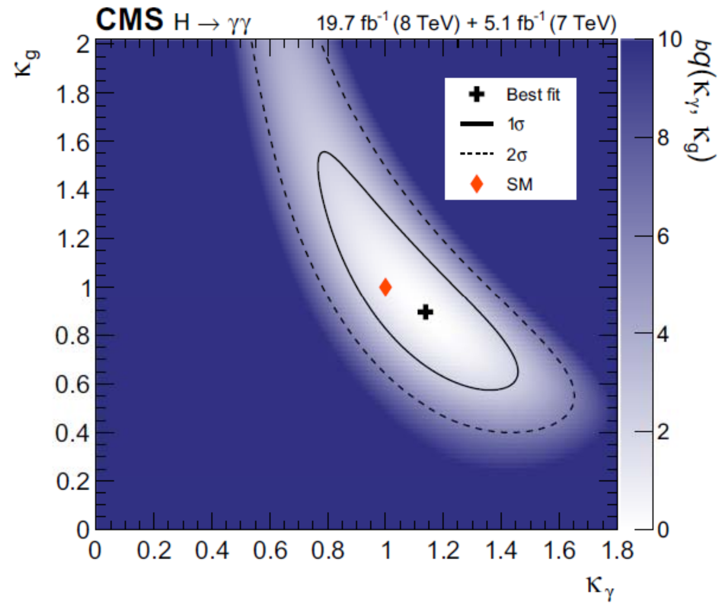
- **To minimize model dependence, production modes signal strengths are allowed to vary independently.**

- **Consistent analysis for mass and overall signal strength.**

Results from H→γγ (4)

- Significance
- Signal strength
- Mass
- **Couplings**
- Decay width





Best fit points (cross): (κ_V , κ_f)=(1.06, 1.05), (κ_γ , κ_g)=(1.14, 0.90)

✓ **From signal strength to couplings: "k-framework",** simplest parametrization of Higgs-couplings deviations from SM values

$$\mu_{pd} = \frac{k_p^2 \cdot k_d^2}{k_H^2}$$

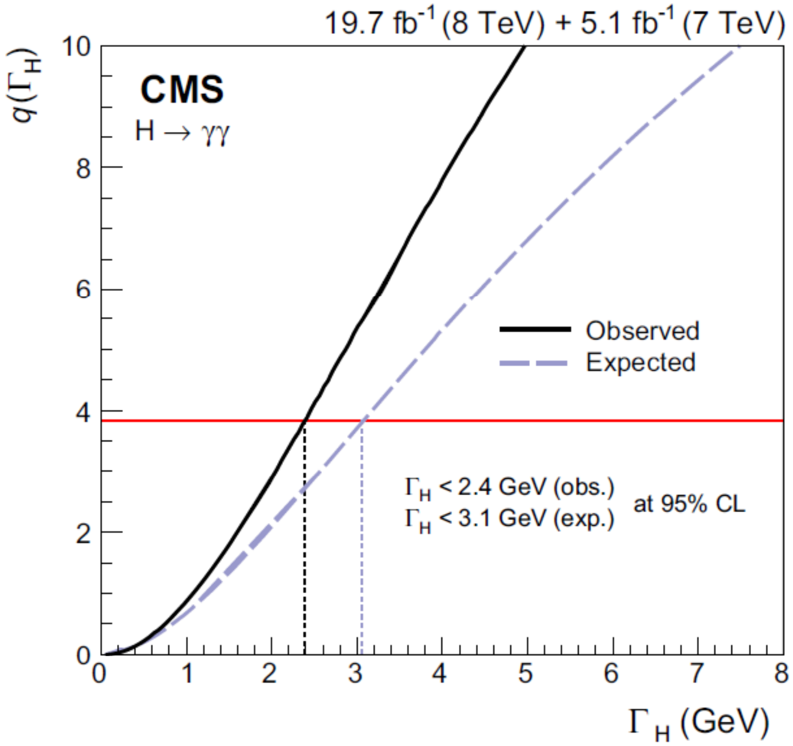
✓ **Can test different assumptions on relation between k's:**

couplings to vector bosons (κ_V) and to fermions(κ_f)

coupling to photons (κ_γ) and to gluons (κ_g)

Results from H→γγ (5)

- Significance
- Signal strength
- Mass
- Couplings
- **Decay width**



Set upper limit on the width of the observed signal @ 95% CL:

Observed: 2.4GeV

Expected: 3.1GeV

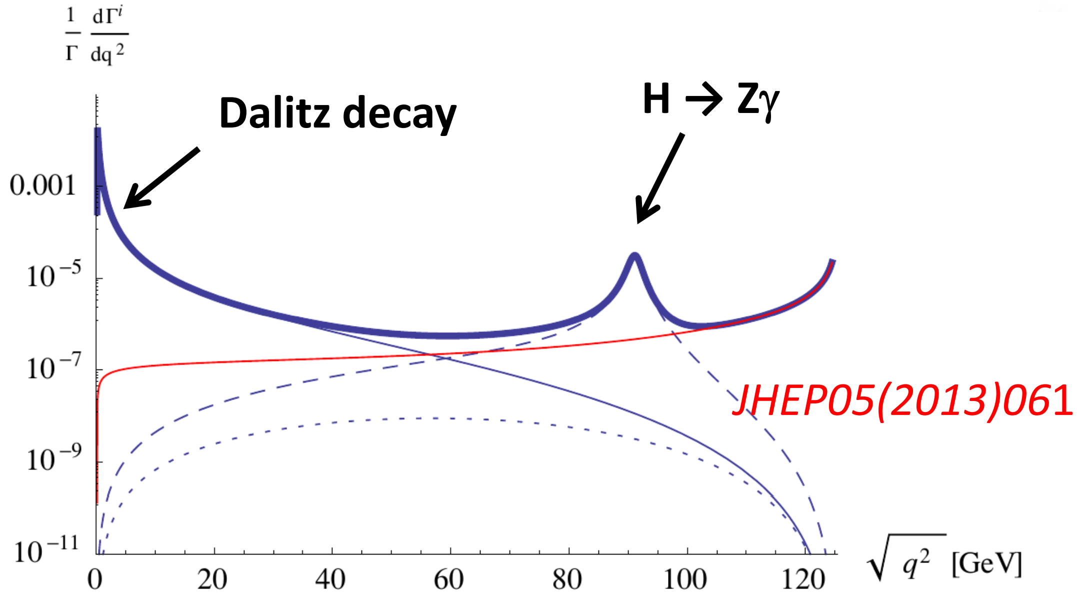
H→llγ

➢ Higgs decay channels with **2 leptons and a photon** are not as sensitive as H → γγ channel.

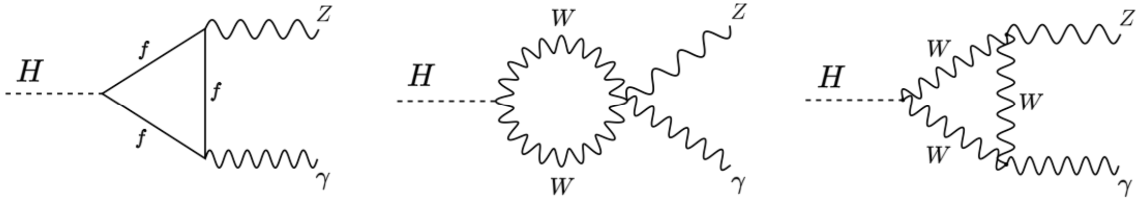
➢ **Important to study:**

- H → Zγ : Loop mediated HZγ coupling.

- "Dalitz mode" H → γ* γ → u⁺u⁻γ: sensitive to new-physics due to loops

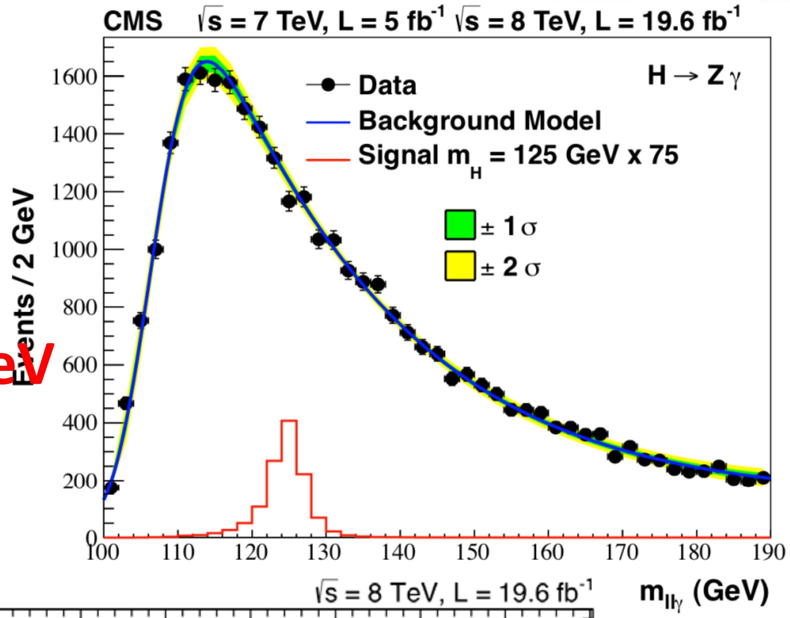


Invariant mass distribution of h→ u⁺u⁻γ normalized by Γ(h → γγ)



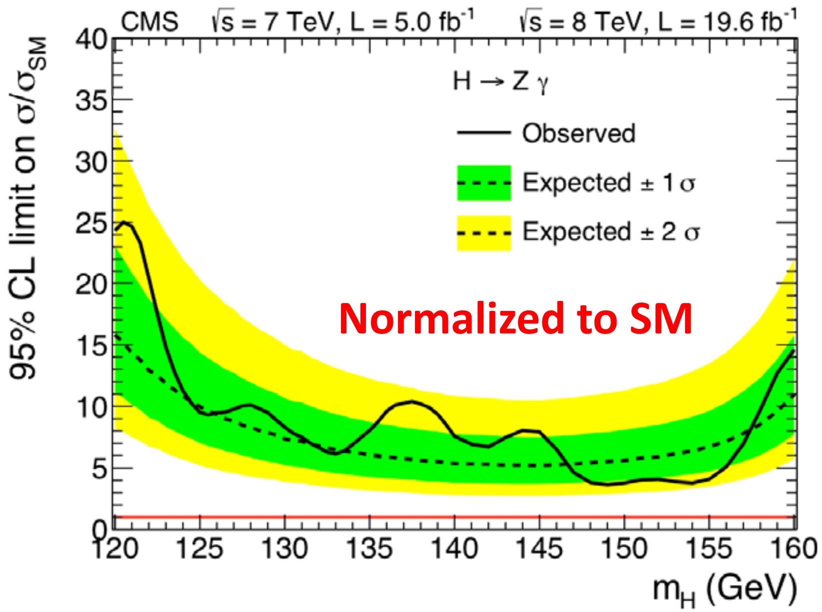
$H \rightarrow Z\gamma \rightarrow ll\gamma$

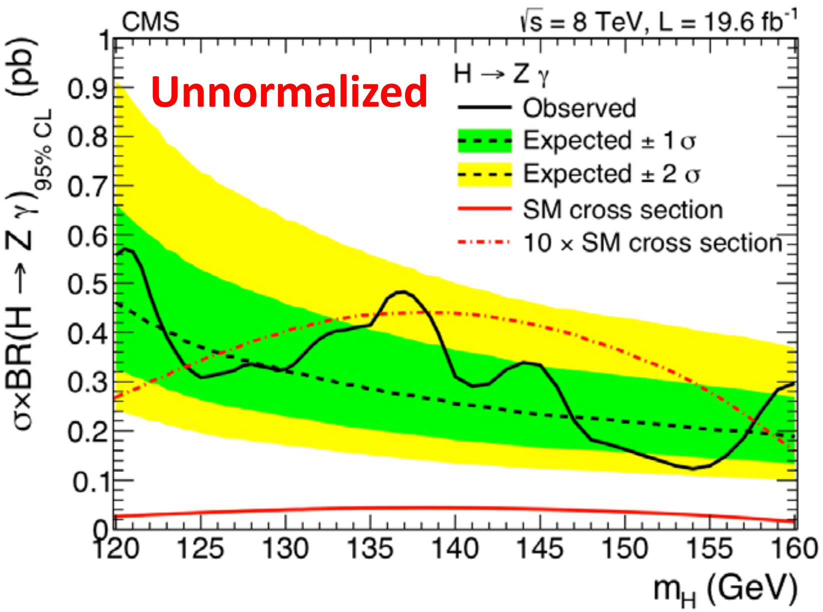
- **Similar strategy to $H \rightarrow \gamma\gamma$** .
  - **Events categorized according to resolution**
  - **Also uses VBF selections**
  - **Limits from simultaneous fit to $m_{ll\gamma}$**



- **Exclusion sensitivity ~10 x SM @125GeV**

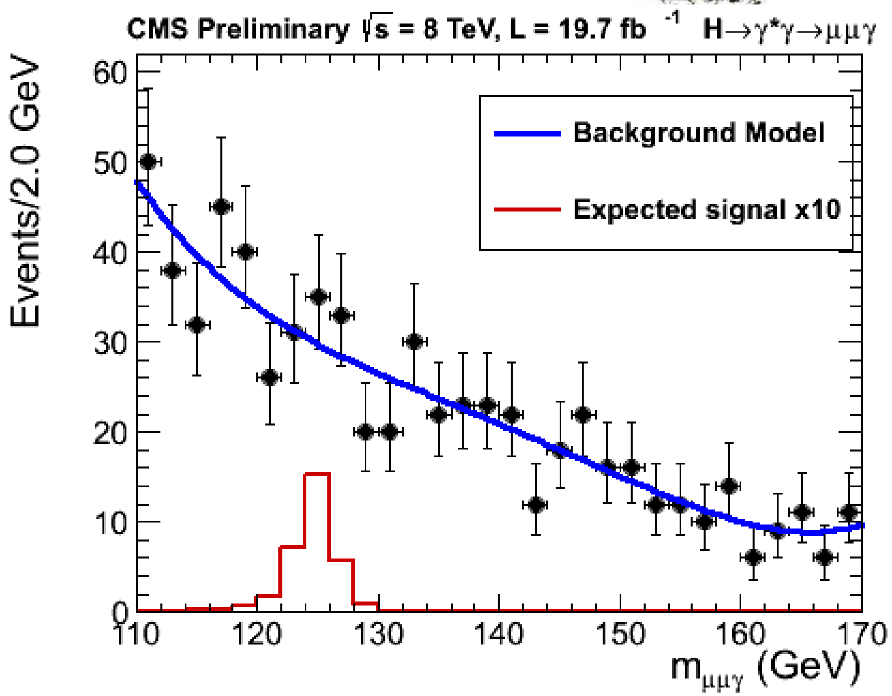
Will probe **branching ratios** close to SM by the end of LHC Run 2



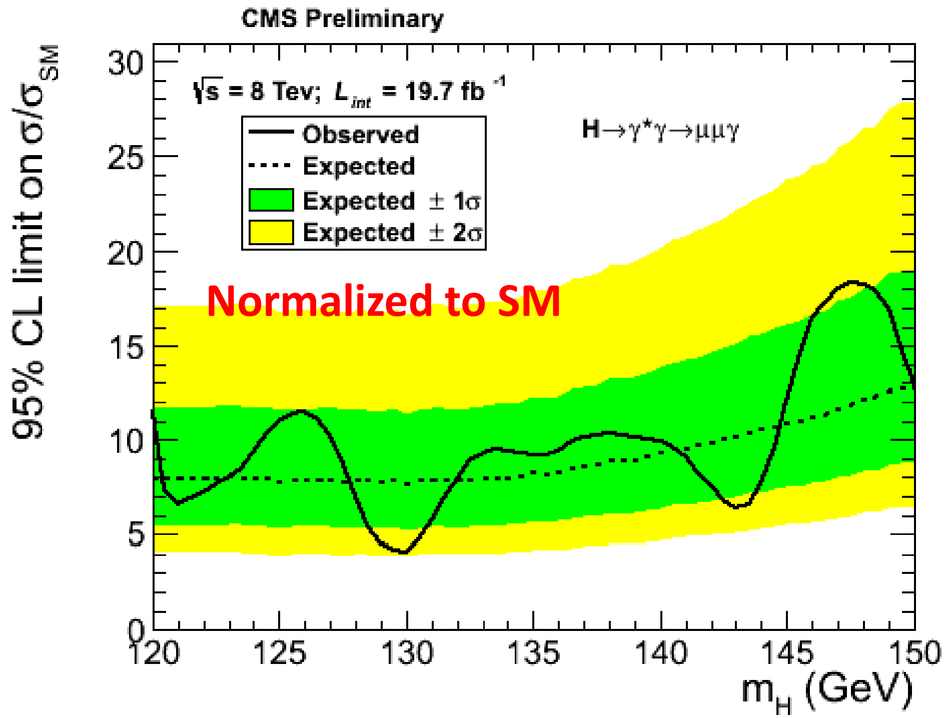


$H \rightarrow \gamma^*\gamma \rightarrow u^+u^-\gamma$

- **Analysis strategy**
  - **Basic selections on objects**
  - **Limits from simultaneous fit to $m_{uu\gamma}$**



- **First limit of σ*BR of $H \rightarrow \gamma^* \gamma \rightarrow u^+u^-\gamma$ at LHC**

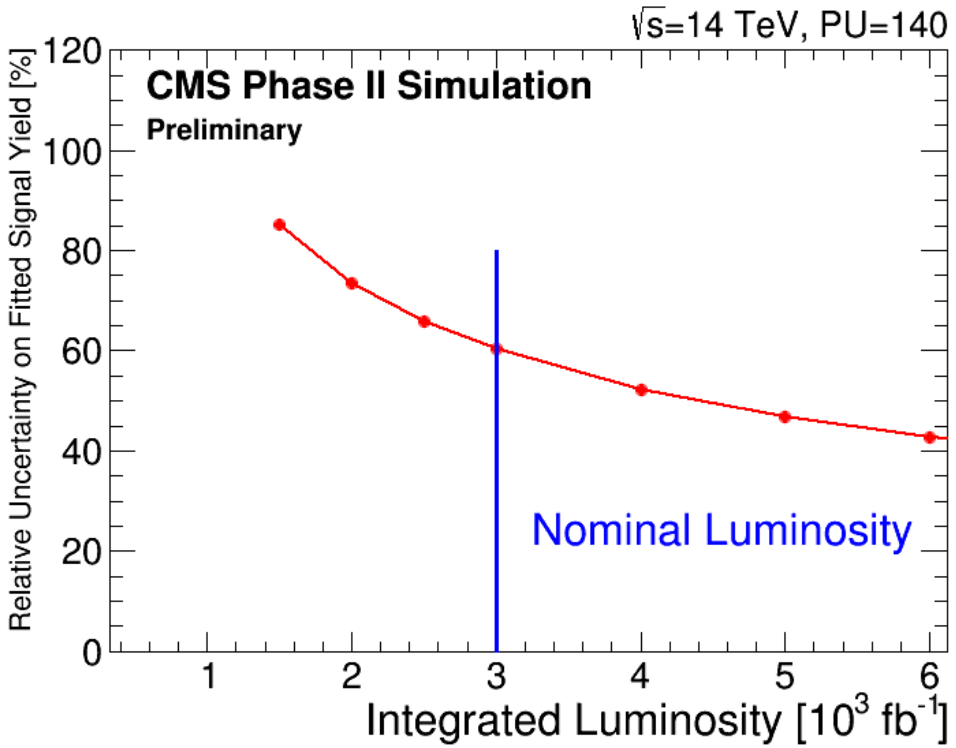


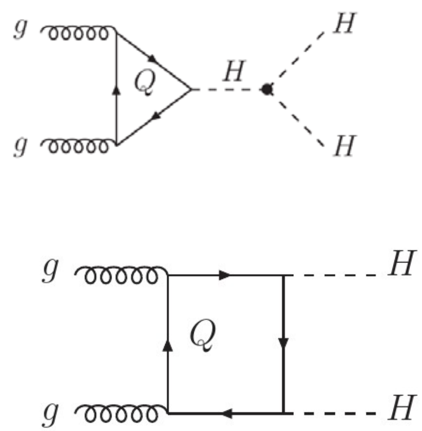
Observed limit for $m_{uu\gamma}$ at 125 GeV and m_{uu} < 20 GeV: ~ 10 x SM

Double Higgs production

- Long term goal is to constrain Higgs field self-coupling
  - **HH → bbγγ is the most promising channel**
  - **Expect 1-2σ sensitivity for 3000 fb^{-1}**

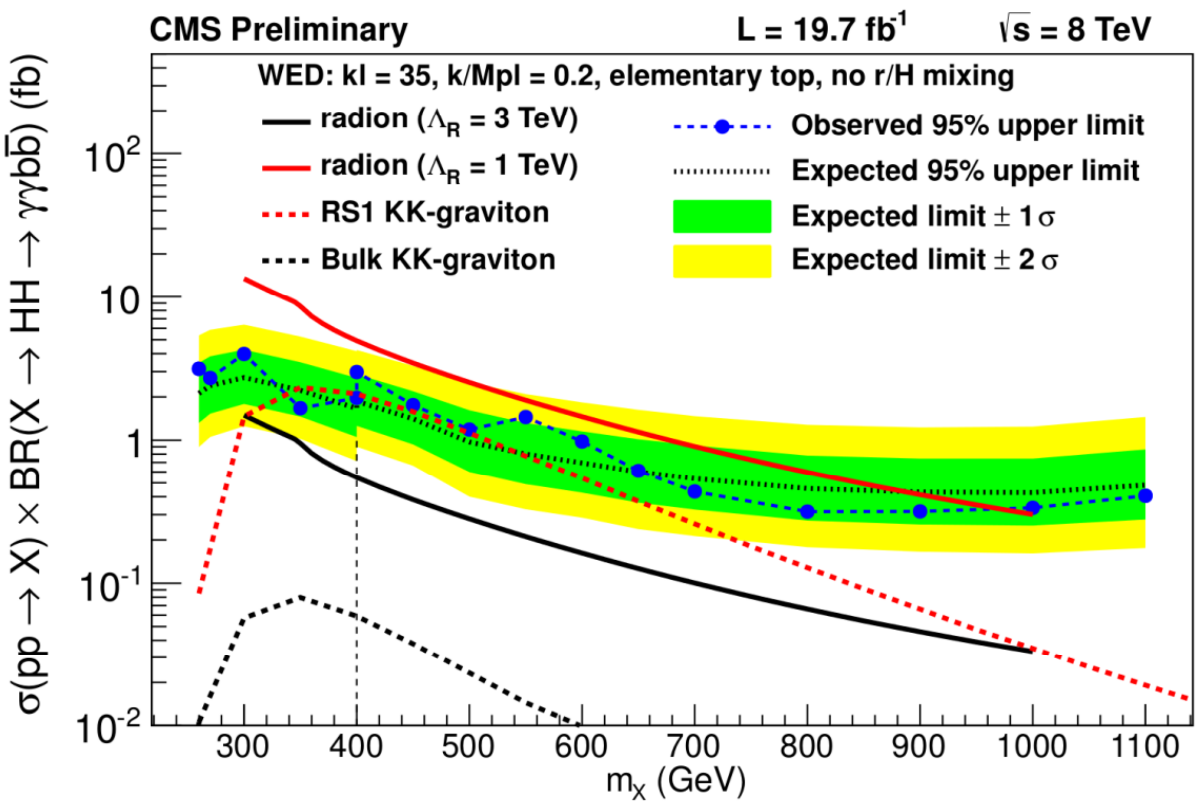
- For LHC Run 1 (and 2) focus is on resonant production.
  - **Set limit on exotic physics and extended Higgs sector**





Results of HH → bbγγ

- **CMS performed X → HH → γγbb with m_X [260, 1100] GeV**
- **Observations are consistent with expectations from SM**
- **Results interpreted in terms of warped extra dimensional (WED) models**



Summary

- **Results on Higgs final-states with photons in CMS are summarized and presented**

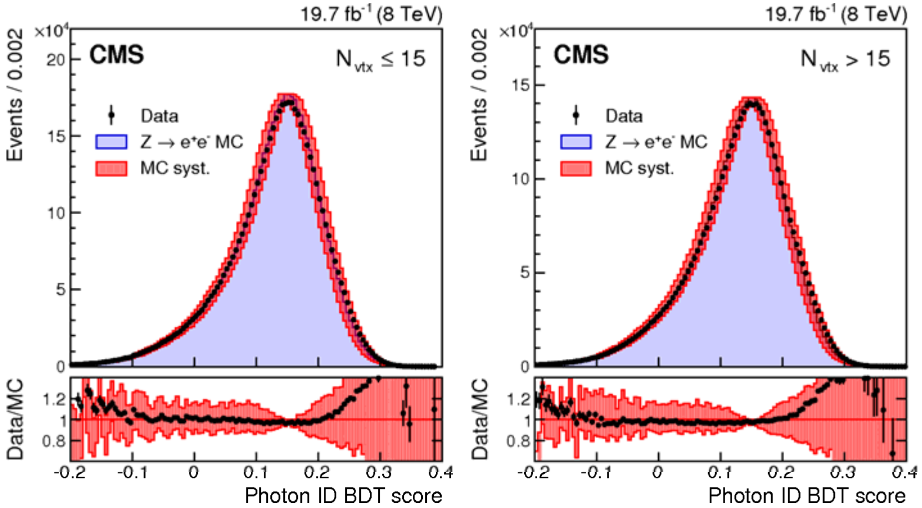
- **H → γγ channel is one of the most sensitive ones**
  - ✓ Higgs observation: **5.7σ (5.2σ) observed (expected) @ 124.7GeV**
  - ✓ Mass: **124.70 ± 0.31 (stat) ± 0.15 (syst) GeV**
  - ✓ **Properties (strength, couplings,..) are consistent with SM predictions**

- **Search for rare decays of H → llγ allow to constrain BSM contributions to Higgs decay loops**

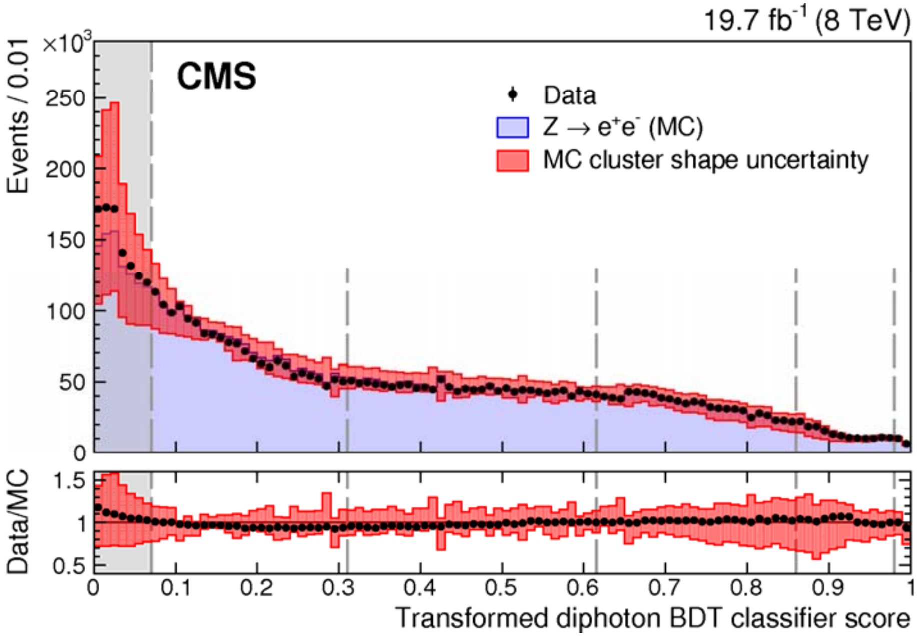
- **In the long run HH → bb γγ expected to provide information on the Higgs field self-coupling**

Backup

Additions of H→γγ (1)

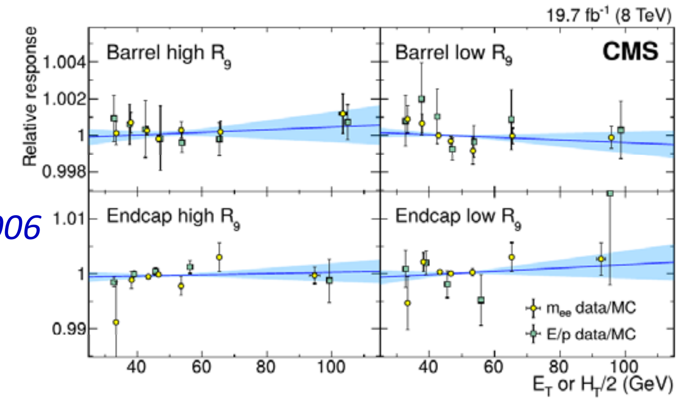


Photon ID MVA and diphoton MVA validations



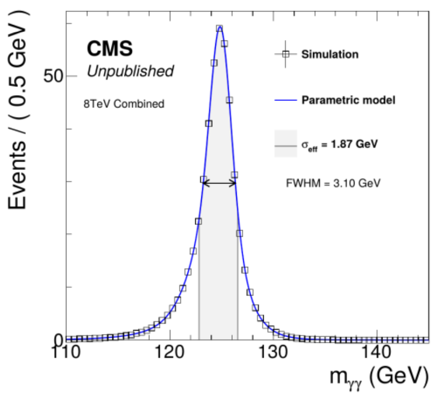
Photon energy scale and resolution corrections derived from Z → ee events:

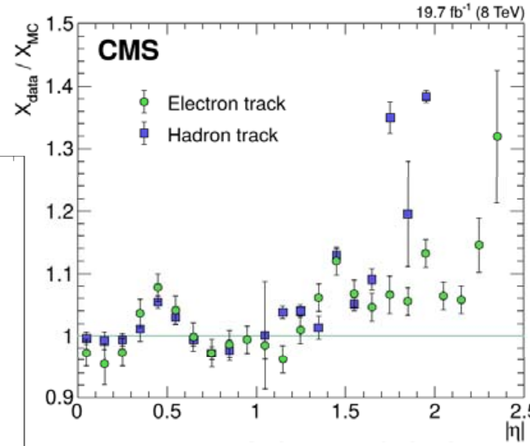
1) Extrapolation to higher pT through boosted Z production



CMS-EGM-14-001, CERN-PH-EP-2015-006 arXiv:1502.02702

2) Extrapolation from electrons to photons through MC simulation (Z → llγ low-ET cross-check)





Additions of H→γγ (2)

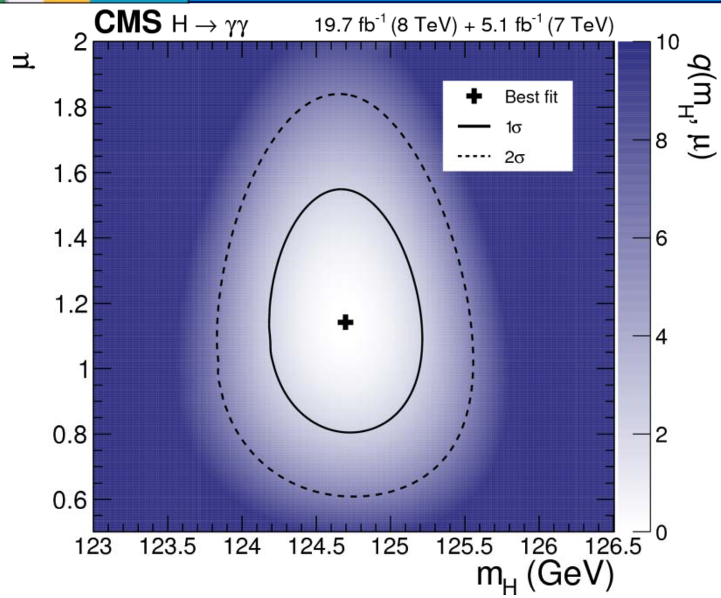
Label	No. of classes 7 TeV	No. of classes 8 TeV	Main requirements
$t\bar{t}$H lepton tag	⋆	1	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ 1 b-tagged jet + 1 electron or muon
VH tight ℓ tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ [e or μ, $p_T > 20\,\text{GeV}$, and $E_T^{miss} > 45\,\text{GeV}$] or [2e or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

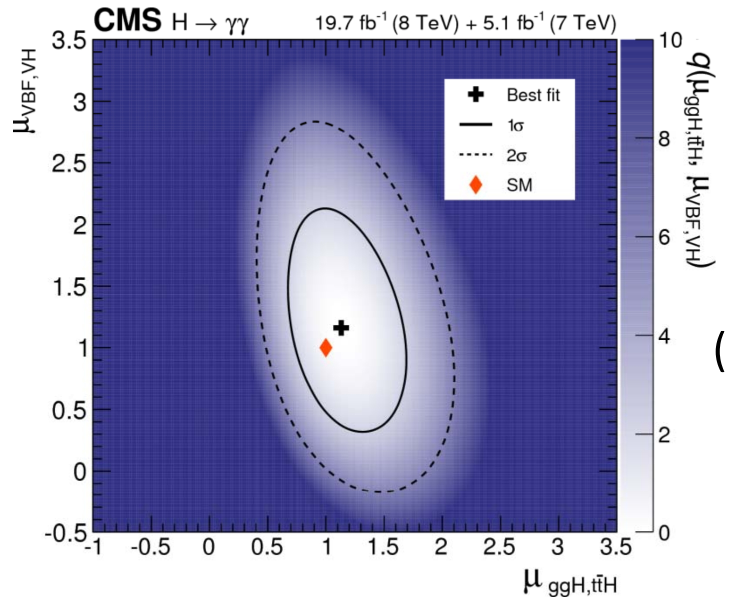
⋆ For the 7 TeV dataset, events in the $t\bar{t}$H lepton tag and multijet tag classes are selected first, and combined to form a single event class.

Dataset	Event classes	Expected SM Higgs boson signal yield (m_H=125 GeV) Total	ggH	VBF	WH	ZH	$t\bar{t}$H	σ_{eff} (GeV)	σ_{HM} (GeV)	Bkg. (GeV^{-1})
7 TeV 5.1 fb^{-1}	Untagged 0	5.8	**79.8%**	9.9%	6.0%	3.5%	0.8%	1.11	0.98	11.0
	Untagged 1	22.7	**91.9%**	4.2%	2.4%	1.3%	0.2%	1.27	1.09	69.5
	Untagged 2	27.1	**91.9%**	4.1%	2.4%	1.4%	0.2%	1.78	1.40	135.
	Untagged 3	34.1	**92.1%**	4.0%	2.4%	1.3%	0.2%	2.36	2.01	312.
	VBF dijet 0	1.6	19.3%	**80.1%**	0.3%	0.2%	0.1%	1.41	1.17	0.5
	VBF dijet 1	3.0	38.1%	**59.5%**	1.2%	0.7%	0.4%	1.65	1.32	3.5
	VH tight ℓ	0.3	—	—	**77.2%**	20.6%	2.2%	1.61	1.31	0.1
	VH loose ℓ	0.2	3.6%	1.1%	**79.1%**	15.2%	1.0%	1.63	1.32	0.2
	VH E_T^{miss}	0.3	4.5%	1.1%	41.5%	**44.6%**	8.2%	1.60	1.14	0.2
	VH dijet	0.4	27.1%	2.8%	**43.7%**	24.3%	2.1%	1.54	1.24	0.5
	$t\bar{t}$H tags	0.2	3.1%	1.1%	2.2%	1.3%	**92.3%**	1.40	1.13	0.2
8 TeV 19.7 fb^{-1}	Untagged 0	6.0	**75.7%**	11.9%	6.9%	3.6%	1.9%	1.05	0.79	4.7
	Untagged 1	50.8	**85.2%**	7.9%	4.0%	2.4%	0.6%	1.19	1.00	120.
	Untagged 2	117.	**91.1%**	4.7%	2.5%	1.4%	0.3%	1.46	1.15	418.
	Untagged 3	153.	**91.6%**	4.4%	2.4%	1.4%	0.3%	2.04	1.56	870.
	Untagged 4	121.	**93.1%**	3.6%	2.0%	1.1%	0.2%	2.62	2.14	1400.
	VBF dijet 0	4.5	17.8%	**81.8%**	0.2%	0.1%	0.1%	1.30	0.94	0.8
	VBF dijet 1	5.6	28.5%	**70.5%**	0.6%	0.2%	0.2%	1.43	1.07	2.7
	VBF dijet 2	13.7	43.8%	**53.2%**	1.4%	0.8%	0.8%	1.59	1.24	22.1
	VH tight ℓ	1.4	0.2%	0.2%	**76.9%**	19.0%	3.7%	1.63	1.24	0.4
	VH loose ℓ	0.9	2.6%	1.1%	**77.9%**	16.8%	1.5%	1.60	1.16	1.2
	VH E_T^{miss}	1.8	16.3%	2.7%	34.4%	**35.4%**	11.1%	1.68	1.17	1.3
	VH dijet	1.6	30.3%	3.1%	**40.6%**	23.4%	2.6%	1.31	1.06	1.0
	$t\bar{t}$H lepton	0.5	—	—	1.6%	1.6%	**96.8%**	1.34	1.03	0.2
	$t\bar{t}$H multijet	0.6	4.1%	0.9%	0.8%	0.9%	**93.3%**	1.34	1.03	0.6

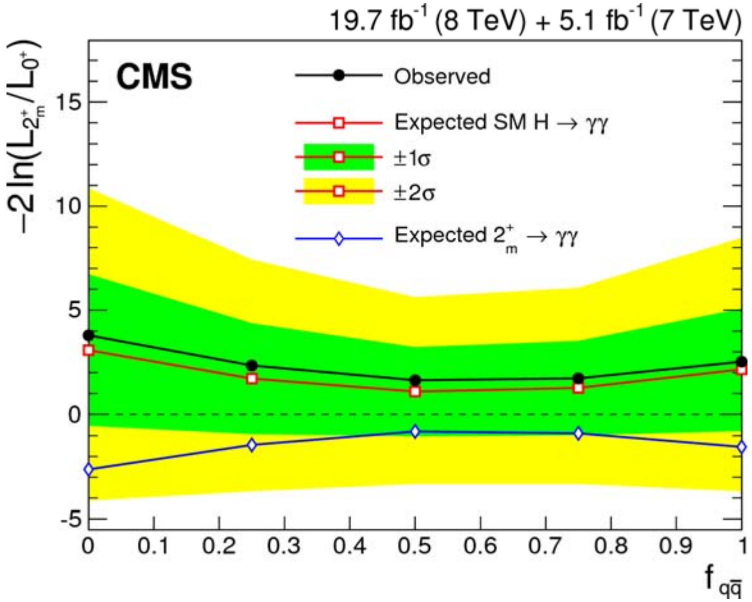
	$\hat{\mu}$	$\hat{m}_H$ (GeV)
7 TeV	$2.22^{+0.62}_{-0.55}$	124.2
8 TeV	$0.90^{+0.26}_{-0.23}$	124.9
Combined	$1.14^{+0.26}_{-0.23}$	124.7

Additions of H→γγ (3)



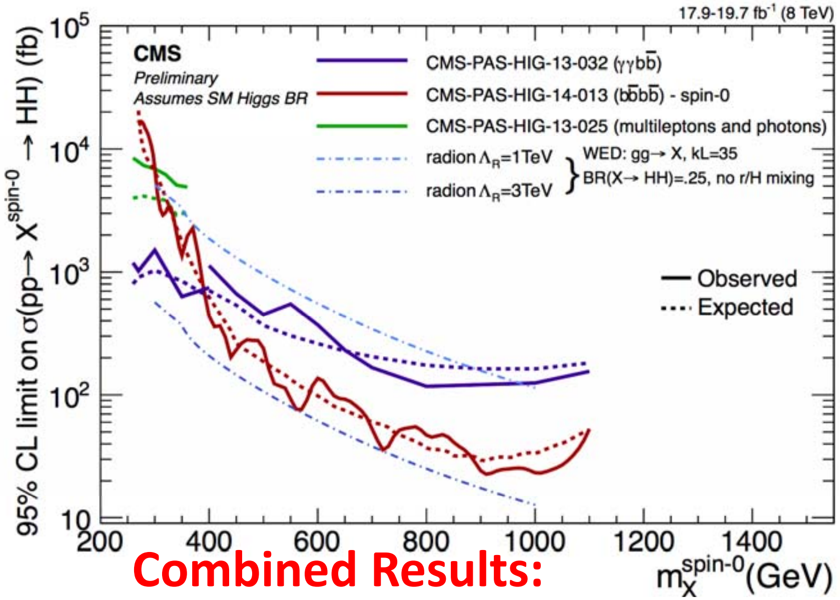


(1.13, 1.15)



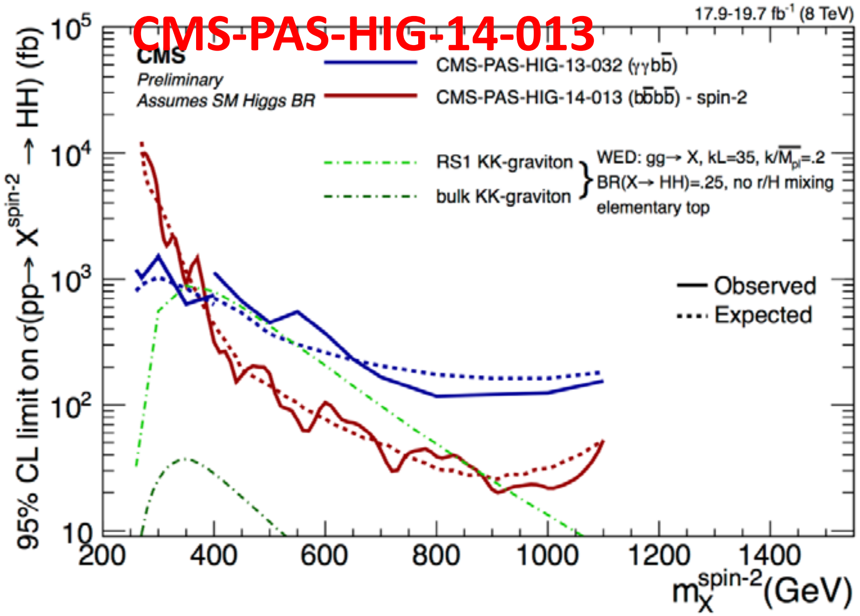
$f_{q\bar{q}}$	$1-\mathrm{CL_s}$ expected	$1-\mathrm{CL_s}$ observed
0	0.92	0.94
0.25	0.78	0.83
0.50	0.64	0.71
0.75	0.69	0.75
1	0.83	0.85

Additions of HH



Combined Results:

CMS-PAS-HIG-14-013



- ✓ **HH production in SM (pp→HH) ~10 fb at 8TeV**
- ✓ **Nonresonant HH production in beyond SM:** can be enhanced by altering the couplings of the Higgs
- ✓ **Resonant HH production in beyond SM**