CMS Higgs(125) diboson results

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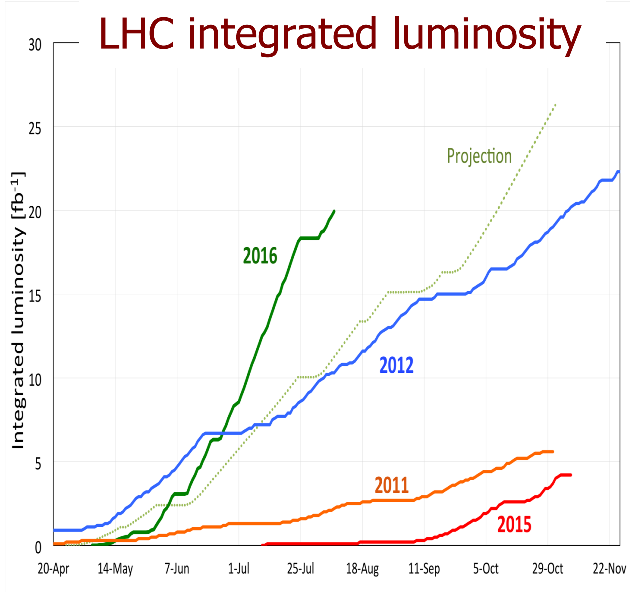
on behalf of the CMS collaboration

Outline

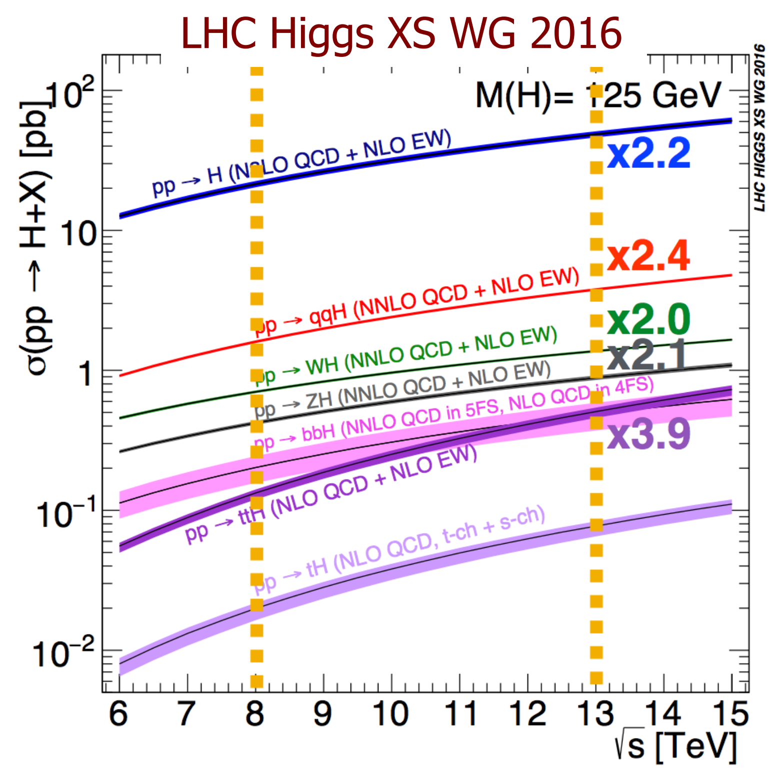
- Focus on the most recent 13 TeV results:
  - Most analysis with 2016 dataset of ~13 fb^{-1}
  - Some results using only 2015 data (~3 fb^{-1})
  - Included also some recent results using Run I data
- Production modes and decay channels included in this talk:
  - Production modes: ggH, VBF, VH and ttH
  - Decay modes: HWW, Hγγ and HZZ
- Recent measurements on fiducial and differential cross section and higgs width

Higgs boson in Run II

- LHC restarted in 2015 with a collision energy of 13 TeV and 25 ns bunch spacing
  - Increased sensitivity to tails of differential distributions and BSM
  - Increased sensitivity to large partonic center–of–mass (e.g. ttH production)
- RunII dataset ~20 fb^{-1}
  - Already produced more Higgs bosons than in Run I
- Most analyses follow closely methods and strategies developed during Run I



https://cds.cern.ch/journal/CERNBulletin/2016/28/News%20Articles/2197580

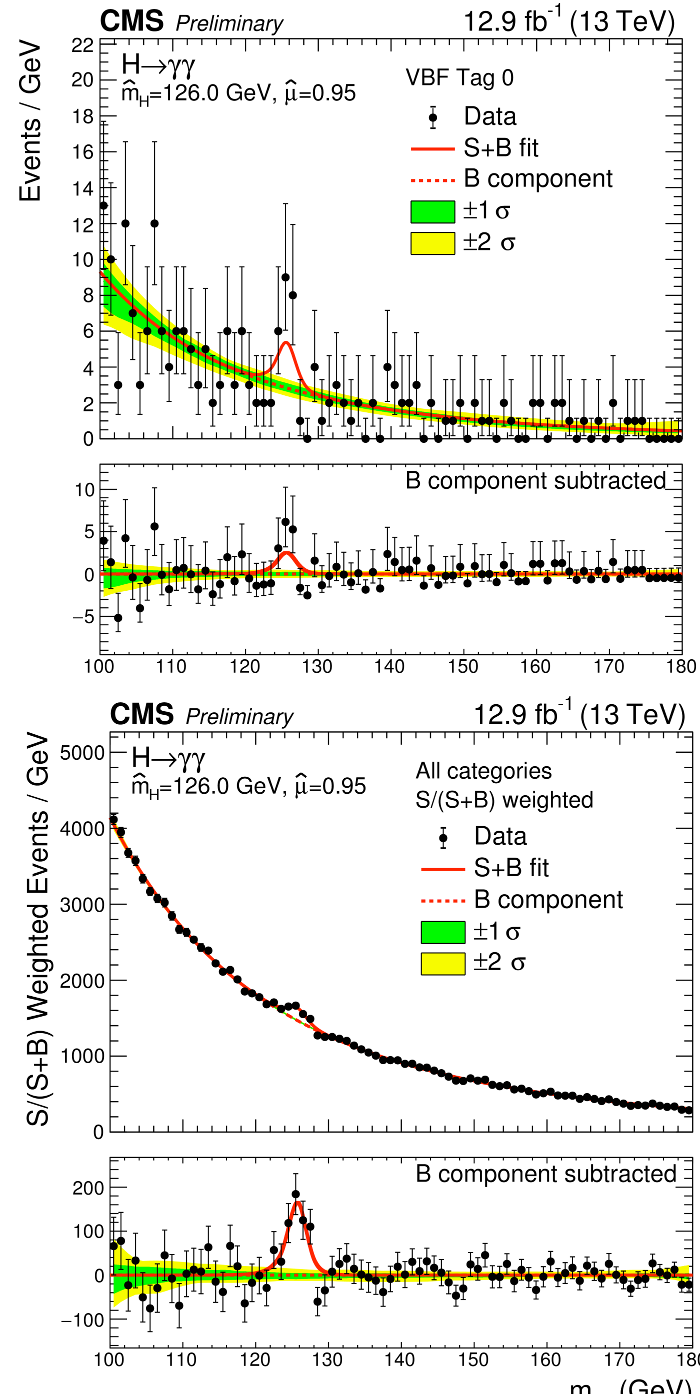


H→γγ HIG-16-020

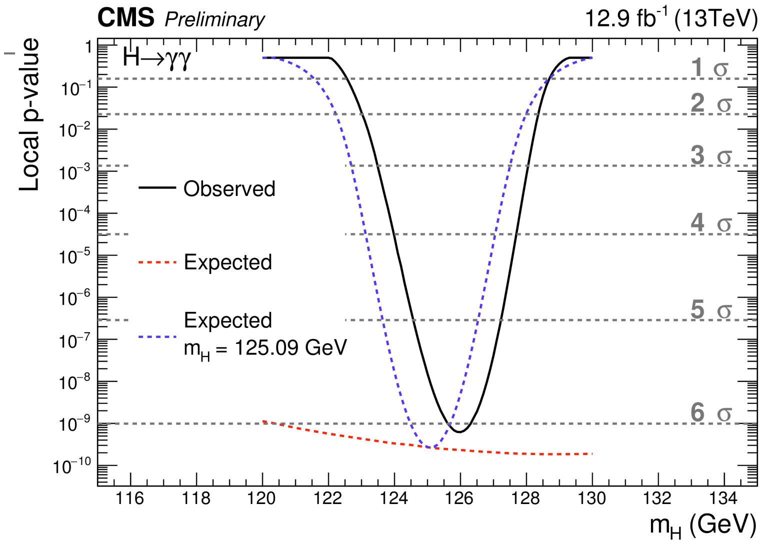
- Clean signature under a huge background (S/B < 1)
- Signature: 2 isolated photons
  - production modes included ggH, VBF and ttH event
- Large QCD backgrounds (γγ, γj, jj)

- Analysis strategy:
  - Events categorized into classes (S/B, mass resolution, additional particles, BDT) to improve the analysis sensitivity.
  - Extraction of signal through fit of di-photon invariant mass spectrum in each category

- Dominant systematic uncertainty: photon energy resolution and background fit choice bias

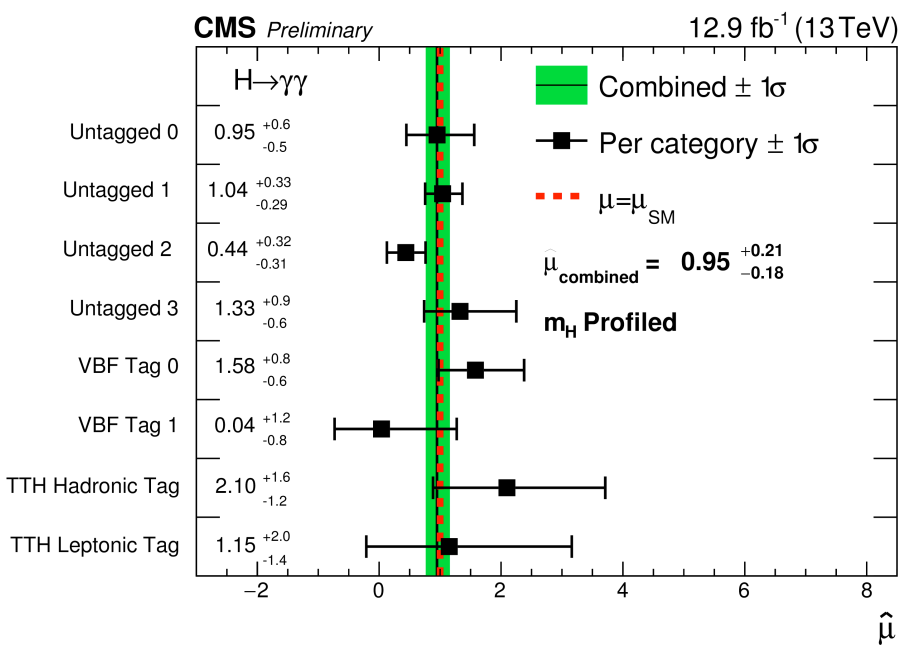


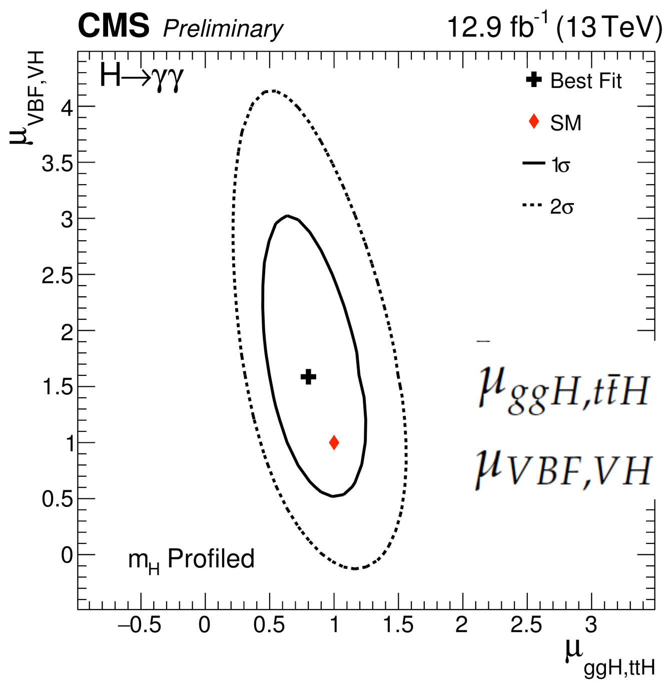
H→γγ results HIG-16-020



- Significance @ 125.09 GeV: 5.6σ observed (6.2σ expected)
- Maximum observed significance is 6.1σ at 126.0 GeV
- Best-fit signal strength @ 125.09 GeV:

$$\sigma_{obs}/\sigma_{SM} = 0.91 \pm 0.20 = 0.91 \pm 0.17\,(\text{stat.})\,^{+0.09}_{-0.07}\,(\text{syst.})\,^{+0.08}_{-0.05}\,(\text{theo.})$$



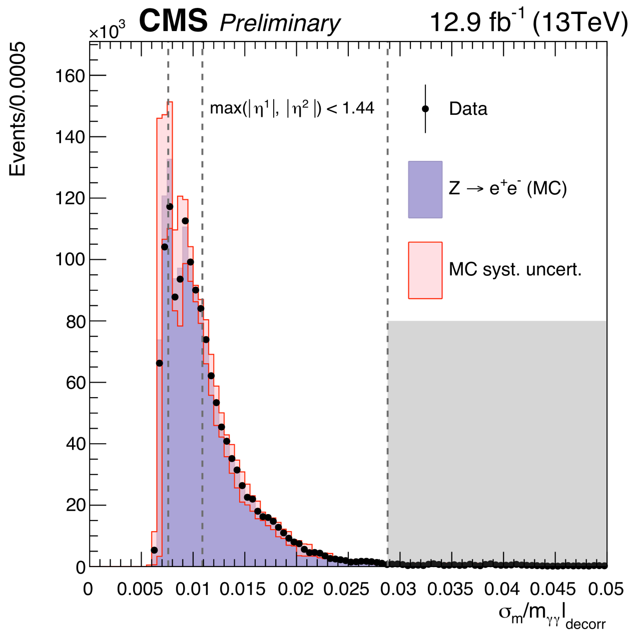


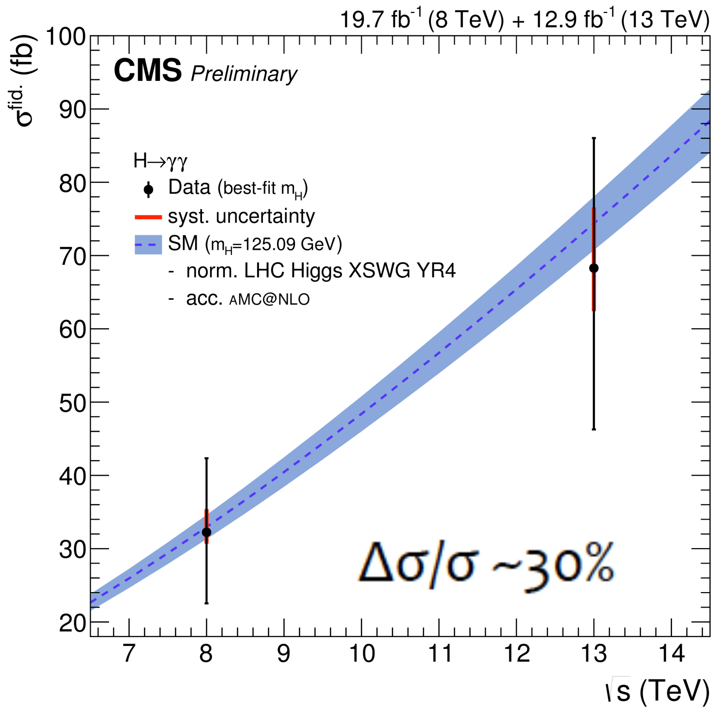
$$\mu_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18}$$

$$\mu_{VBF,VH} = 1.59^{+0.73}_{-0.45}$$

H→γγ fiducial cross-section HIG-16-020

- Different event categorization: 3 mass resolution categories.
- Event yields corrected for detector inefficiency and resolution
  - Minimal dependence on theoretical modeling





- Fiducial cross section measured profiling m_H

$$\hat{\sigma}_{fid} = 69^{+18}_{-22}\text{fb} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

- Theoretical prediction for m_H=125.09 GeV

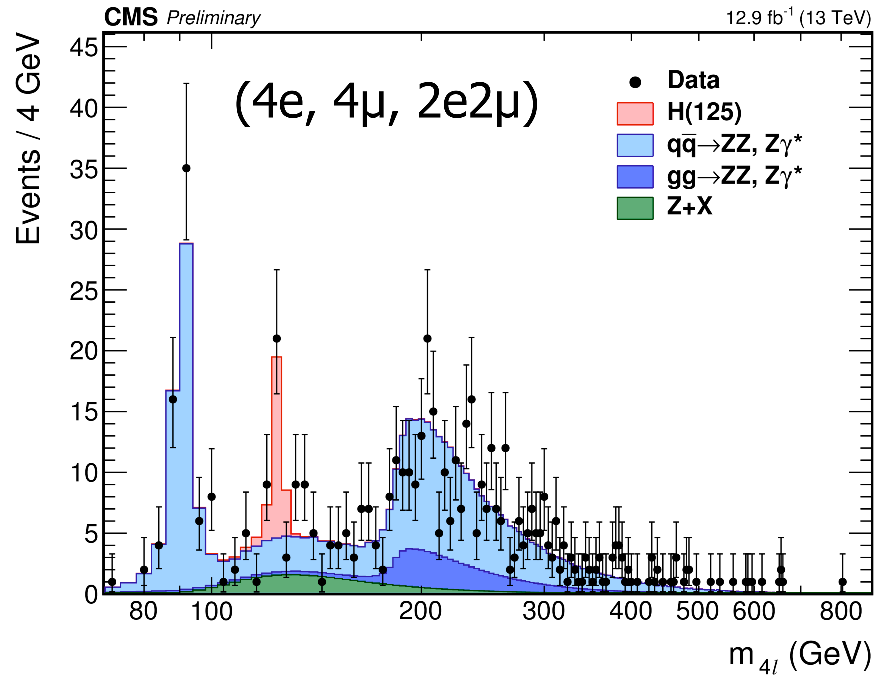
$$\hat{\sigma}_{fid} = 73.8 \pm 3.8 \text{ fb}$$

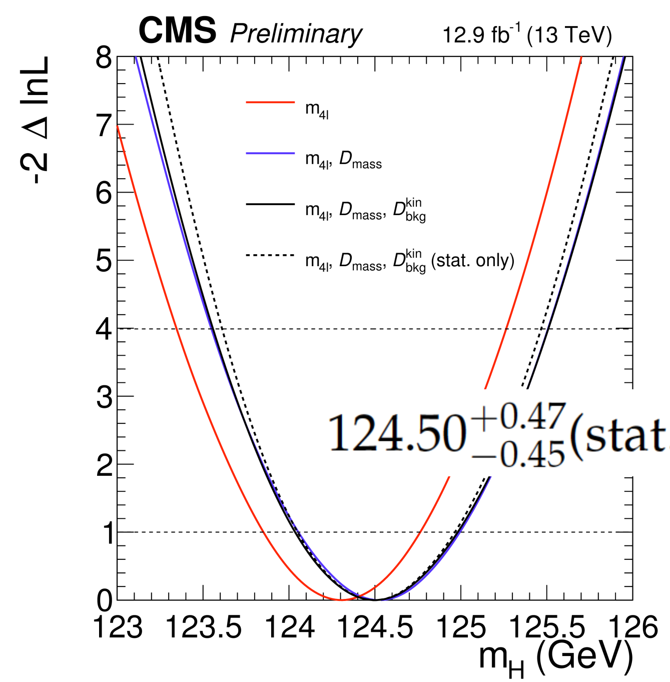
H→ZZ HIG-16-033

- Clean signature under a small background, but tiny signal yield (S/B>>1)
- Signature: two pairs of same flavor, opposite sign, isolated leptons: 4e, 2e2μ, 2μ2e, 4μ
- All production modes included ggH, VBF,VH and ttH events
- Very small background from irreducible ZZ and reducible Z+X

- Analysis strategy:
  - Kinematic discriminant: MZ1, MZ2, 5 angles from decay chain, matrix element, used to enhance the signal purity of different production modes
  - Extraction of signal through 2D fit of m4l and the discriminant gg/qq (D^{kin}_{bkg})

- Dominant systematic uncertainty: luminosity and lepton SF



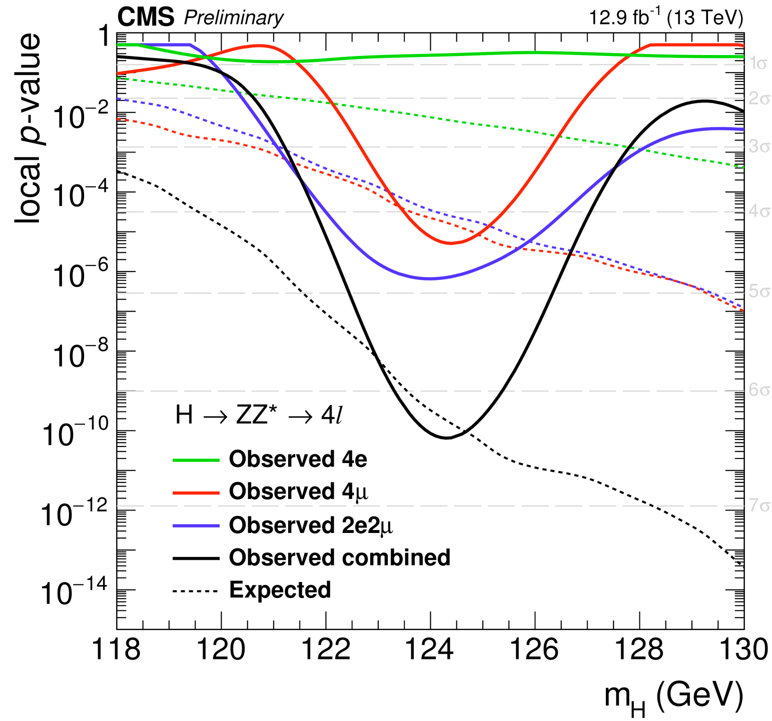


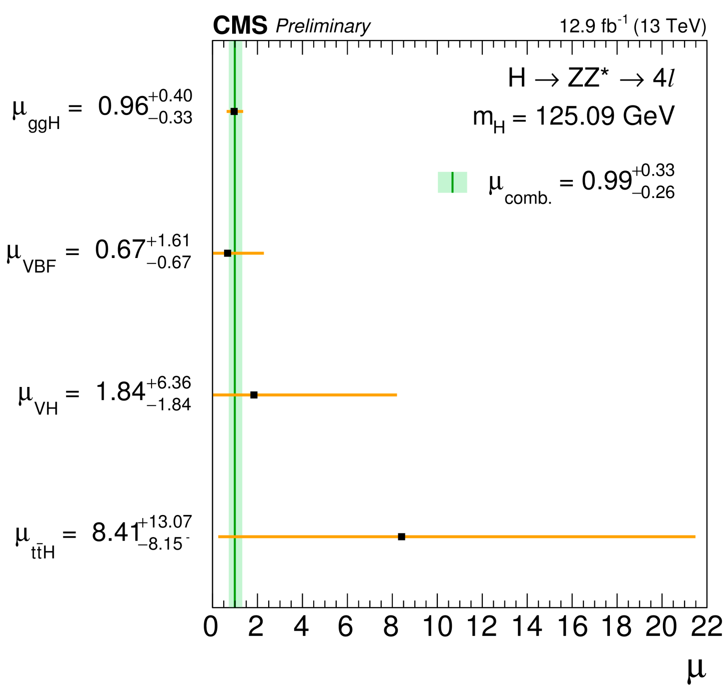
$$124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$$

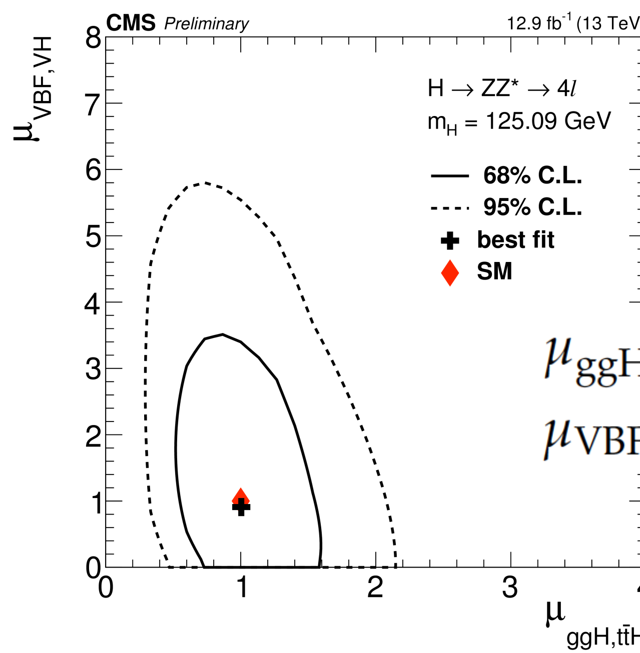
H→ZZ results HIG-16-033

- Extract p-values and signal strength from simultaneous fit of the 2D likelihood in 3 final states x 6 categories.
- Significance @ 125.09 GeV (Run I LHC comb.): 6.2σ observed (6.5σ expected)
- Maximum observed significance is 6.4σ at 124.3 GeV
- Best-fit signal strength @ 125.09 GeV:

$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$







$$\mu_{\mathrm{ggH,t\bar{t}H}} = 1.00^{+0.39}_{-0.32}$$

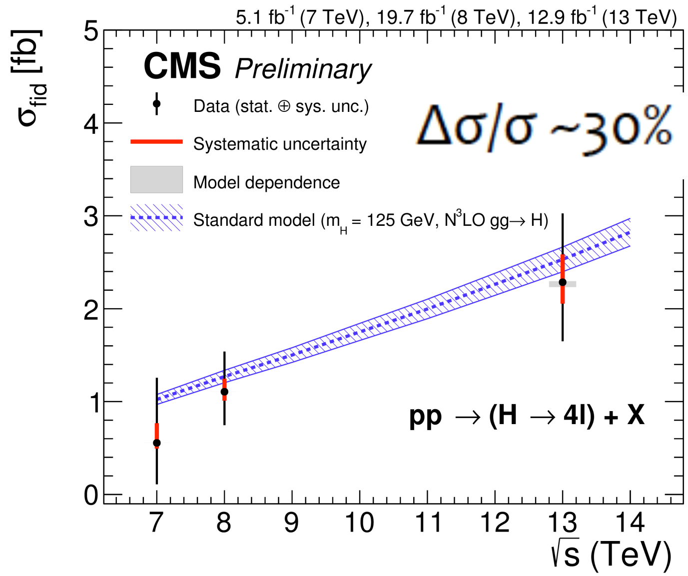
$$\mu_{\mathrm{VBF,VH}} = 0.91^{+1.56}_{-0.91}$$

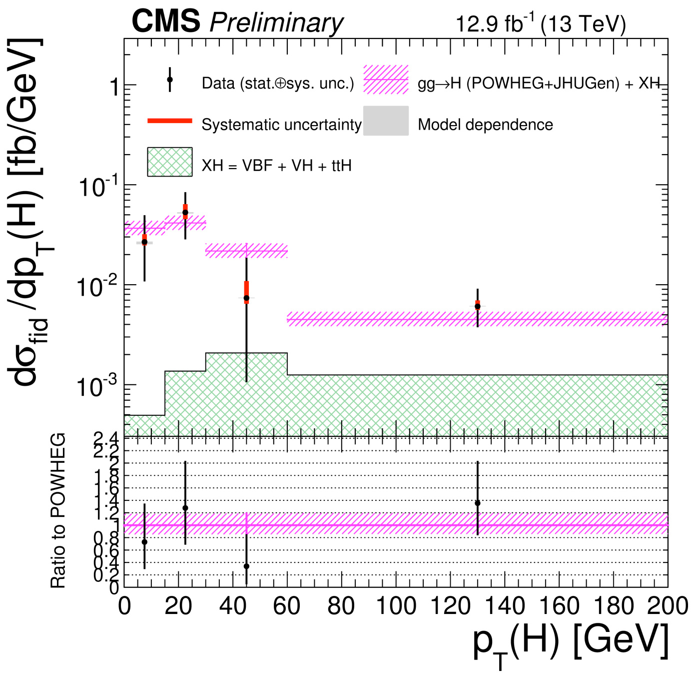
H→ZZ fiducial cross-section HIG-16-033

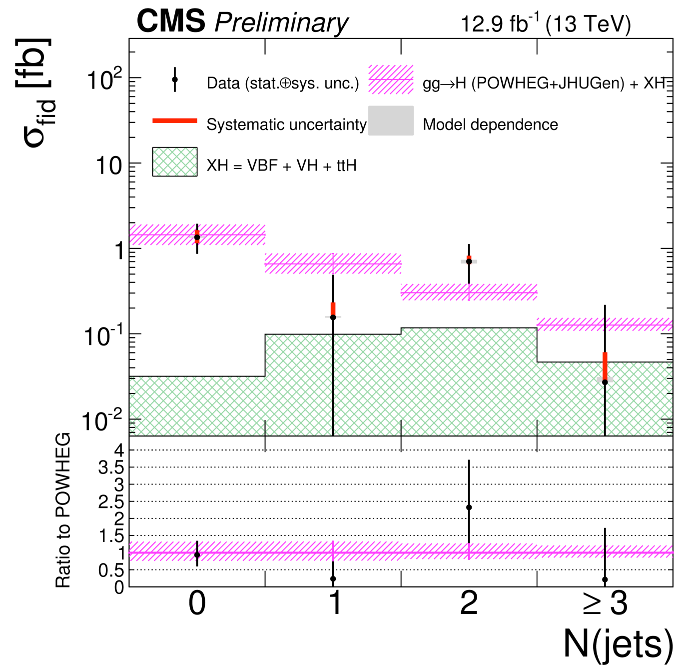
- Fiducial volume closely matches reconstruction level
  - Minimal dependence on theoretical modeling
- Maximum likelihood fit to the uncategorized m_{4l} distribution, assuming m_H = 125.0 GeV

$$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$$

SM prediction: $\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13\ \text{fb}$





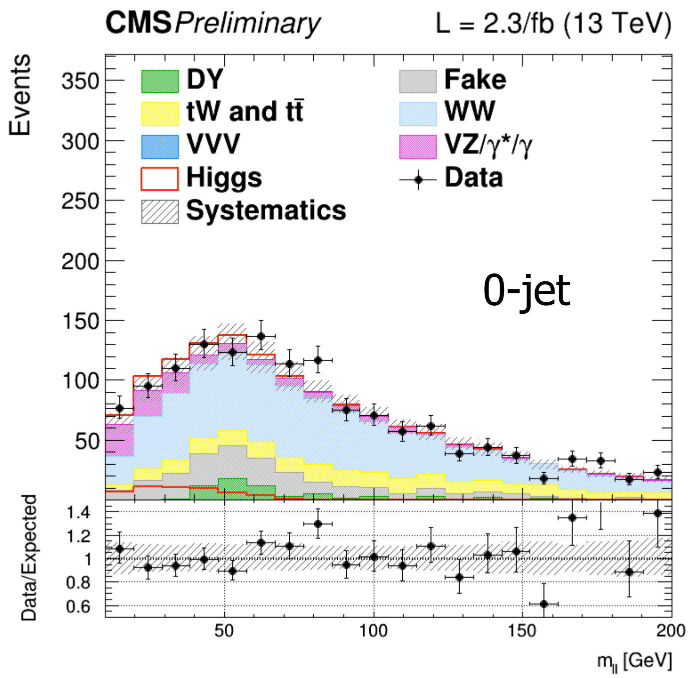


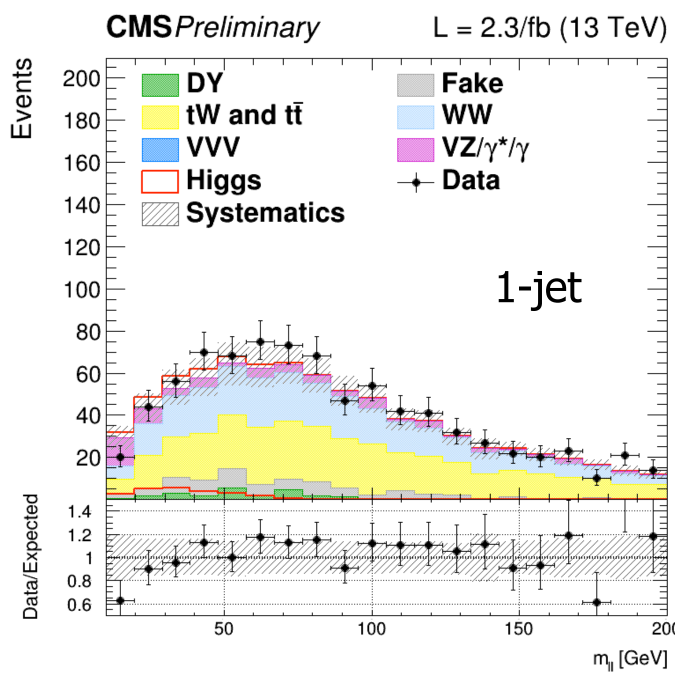
H→WW HIG-15-003

- Large BR and a reasonable clean final state (S/B<1)
- Signature: two high pT isolated leptons and moderate MET (only eμ channel considered)
- No mass peak is the main drawback
- Controlling the background is the key
- Analysis strategy:
  - Using 0-jet and 1-jet categories only for now (2.3/fb 2015 dataset)
  - Perform a 2D fit: mll vs. mT

➢ **Results with 2015 data:**

- Significance @ 125 GeV: 0.7σ observed (2.0σ expected)
- Best-fit signal strength @ 125 GeV: 0.3 ± 0.5





- Working on including 2016 dataset

H→WW differencial cross-section arXiv:1606.01522

- Differential measurement of Higgs transverse momentum
  - with MET resolution, but still p_T^H good observable

$$\vec{p}_T^{\,H} = \vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}$$

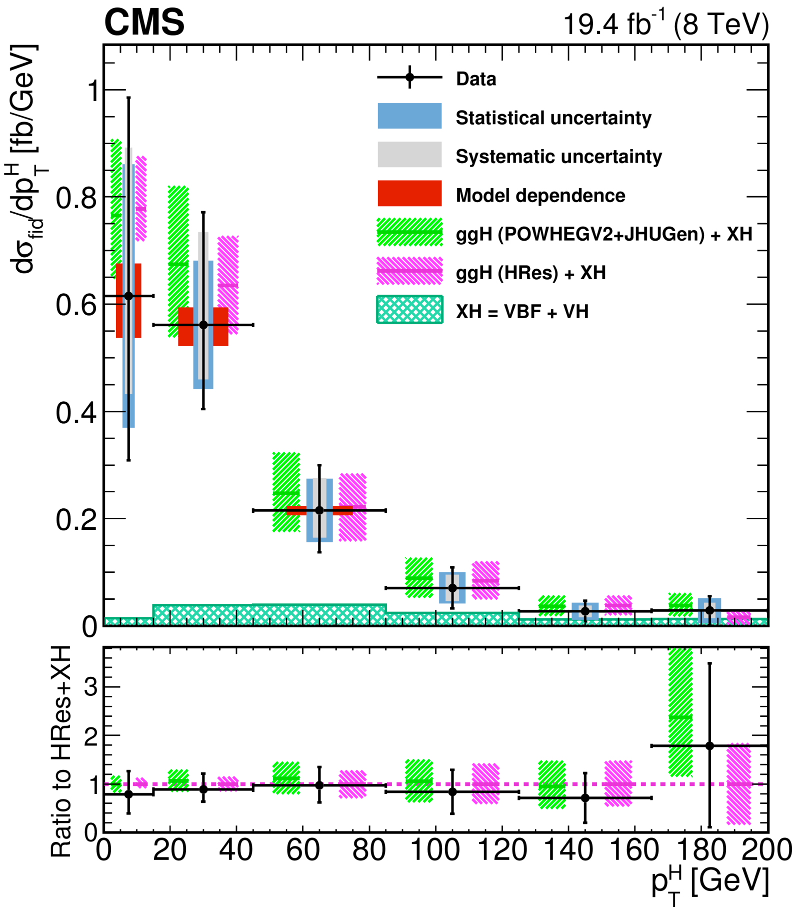
- Inclusive in jet multiplicity
- Inputs: measure the Higgs cross section in bins of **p_T^{llMET}**
- Result unfolded at generation level in fiducial phase space

- Fiducial cross section for ggH+XH:

$$\sigma_{\rm fid} = 39 \pm 8\,({\rm stat}) \pm 9\,({\rm syst})\,{\rm fb}$$

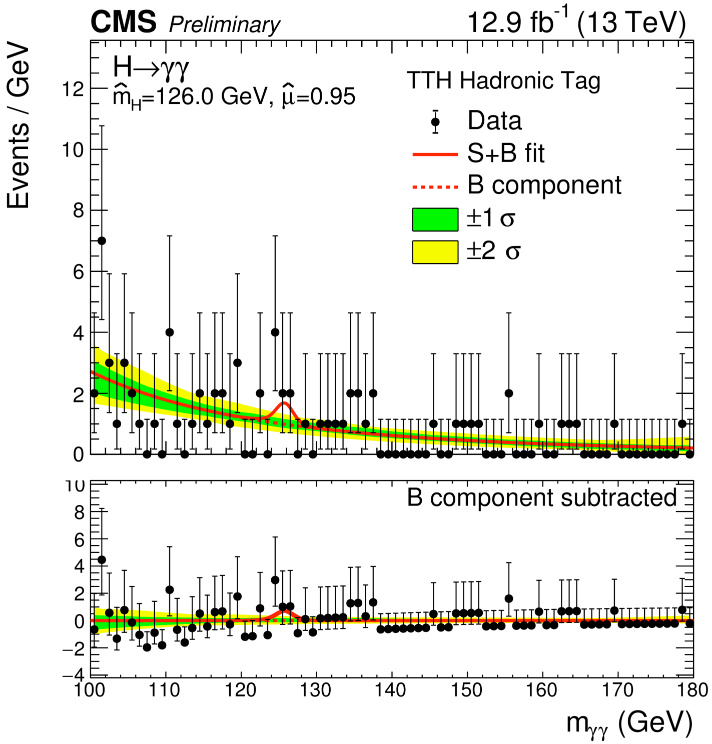
SM prediction: $\sigma_{\rm fid}^{SM} = 48 \pm 8\,{\rm fb}$

8 TeV

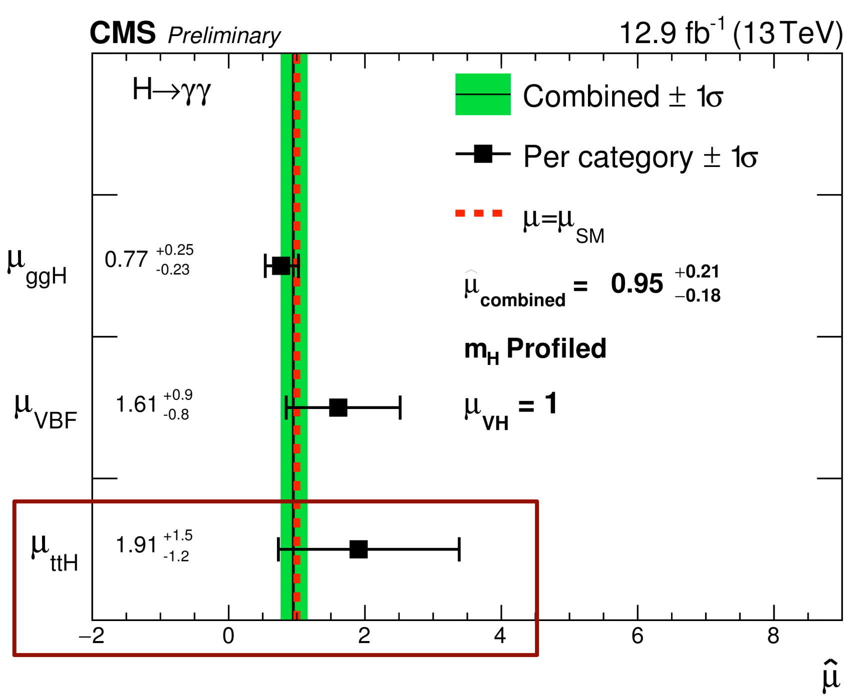


ttH production HIG-16-022, HIG-16-020

- Cross-section at 13 TeV ~4 times that at 8 TeV
- Sensitivity approaching Run 1: challenging due to the presence of additional jets and leptons from top decays
- ttH(γγ), through H→γγ event categorisation
  - small branching ratio, but very clean final state (small systematic uncertainty)
  - tagged H→γγ categories selecting hadronic and leptonic top decays

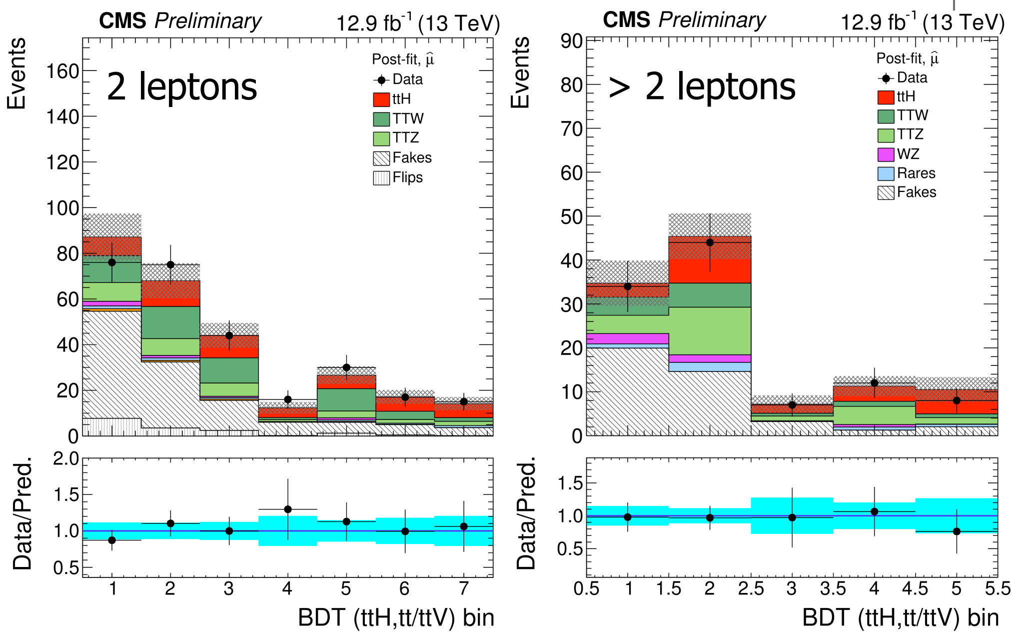


μ = 1.9 $^{+1.5}_{-1.2}$ (2016 dataset)



ttH production HIG-16-022, HIG-16-020

- ttH(multileptons) targeting Higgs decays to WW*, ZZ*, $\tau\tau$
  - lower rate, low background multi-lepton final state
- Further categorization based on lepton flavor, presence of b-jets, hadronically-decaying τ, lepton charge:
- The signal is extracted via a 2-D fit to the BDT discriminators.
- Dominant systematic uncertainty: non-prompt background estimates in some channels.



➢ Observed and expected asymptotic 95% CL upper limits on and best value of the signal strength (2015+2016 datasets)

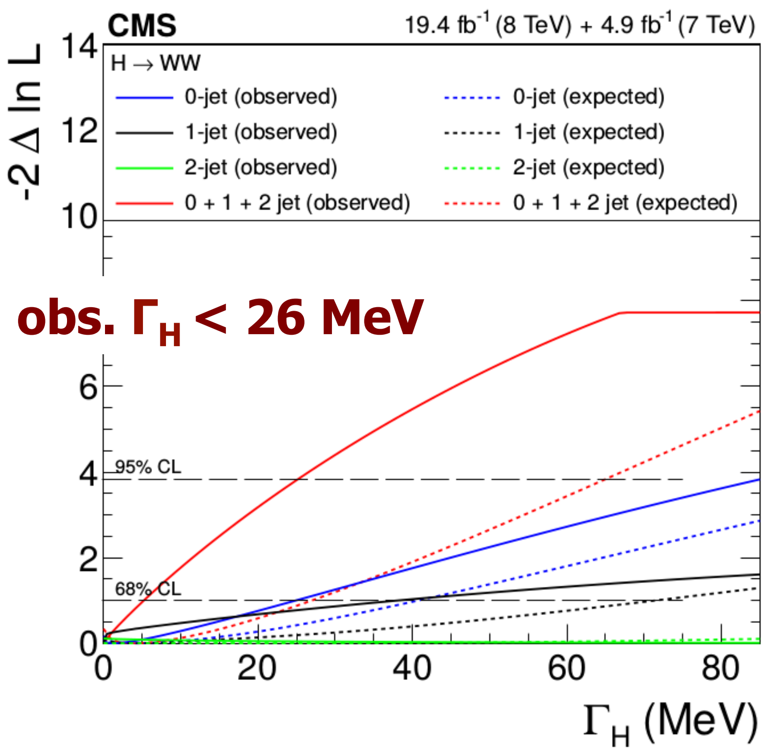
Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

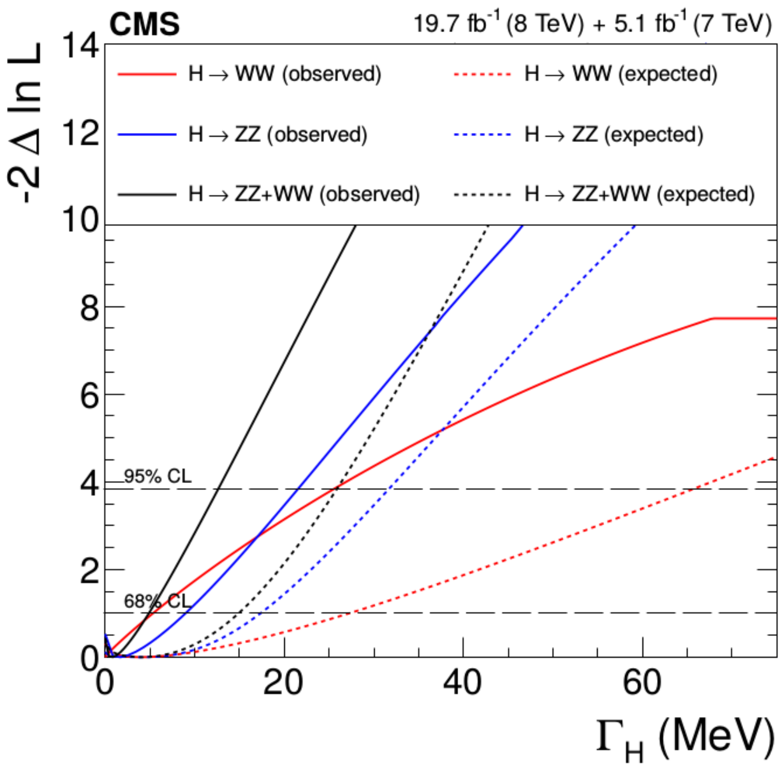
Higgs width in Run I arXiv:1605.02329

- Ratio of on-shell to off-shell cross section is very sensitive to the width; modest model-dependence.

$$\frac{\sigma^{\text{off-peak}}_{gg\to H\to VV}}{\sigma^{\text{on-peak}}_{gg\to H\to VV}} = \Gamma_H$$

- Signal parameterization includes interference.
- First measurement of the Higgs width in the HWW channel (mll<70 & mll>70)
- Final combination of WW and ZZ final states: **obs. $\Gamma_H < 13$ MeV**



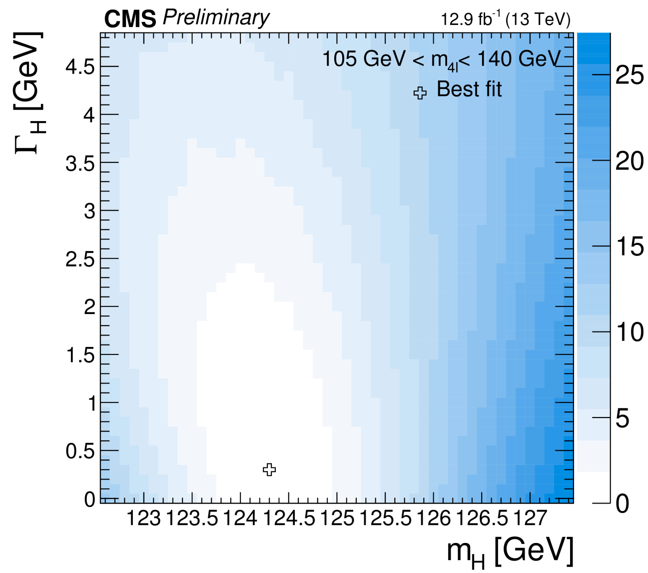


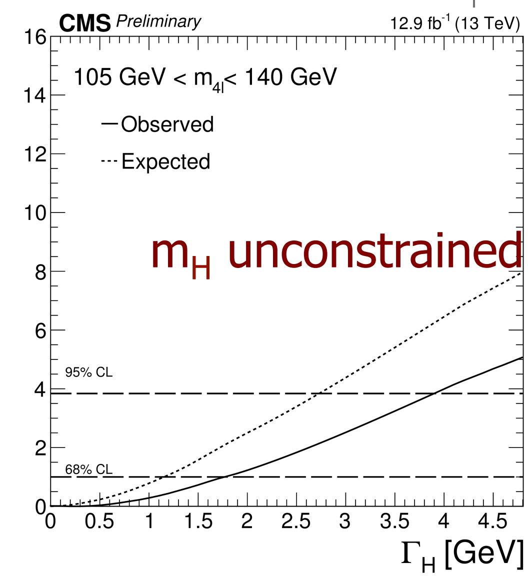
Run II H→ZZ combined mass-width HIG-16-033

- Using on-shell only
  (105 < m4l < 140 GeV)

$\Gamma_H = 0.3^{+1.4}_{-0.0}$ GeV (68% CL)

Γ_H < 3.9 GeV (95% CL)



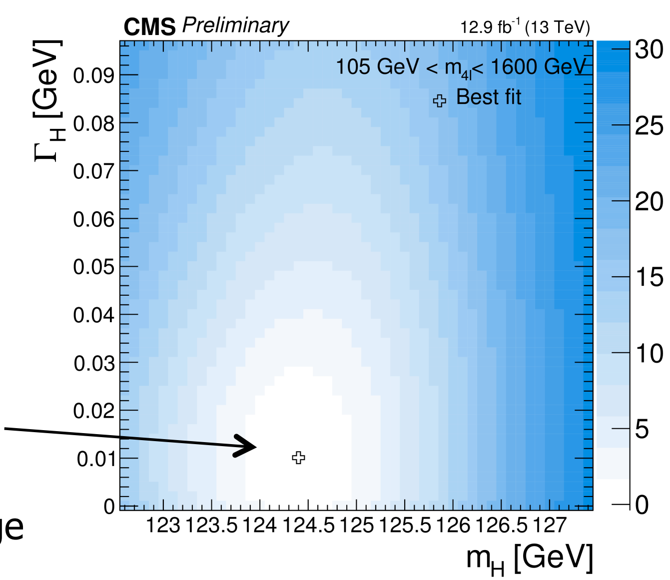


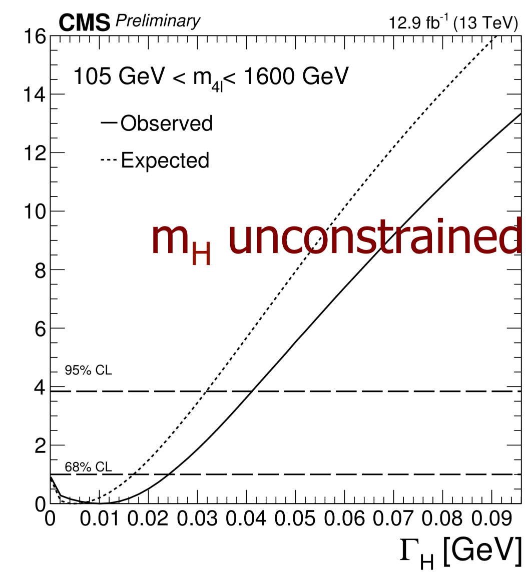
- Using on-shell & off-shell
  (100 < m4l < 1600 GeV)

$\Gamma_H = 0.010^{+0.014}_{-0.010}$ GeV (68% CL)

Γ_H < 41 MeV (95% CL)

Mass fit not dependent on the mass range





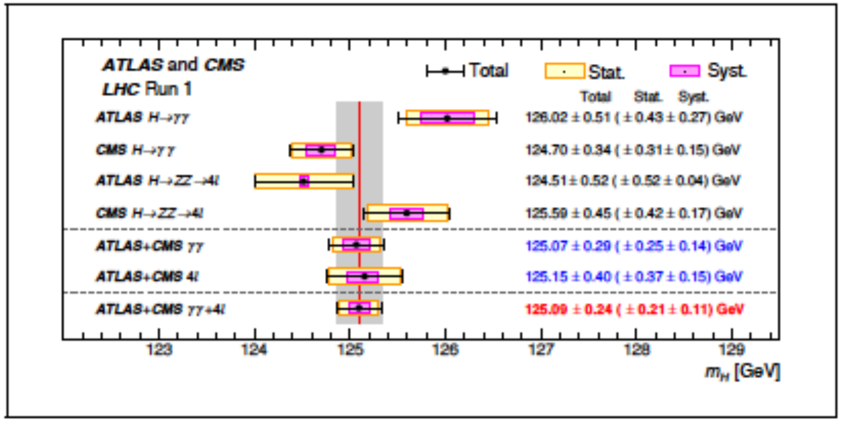
Summary

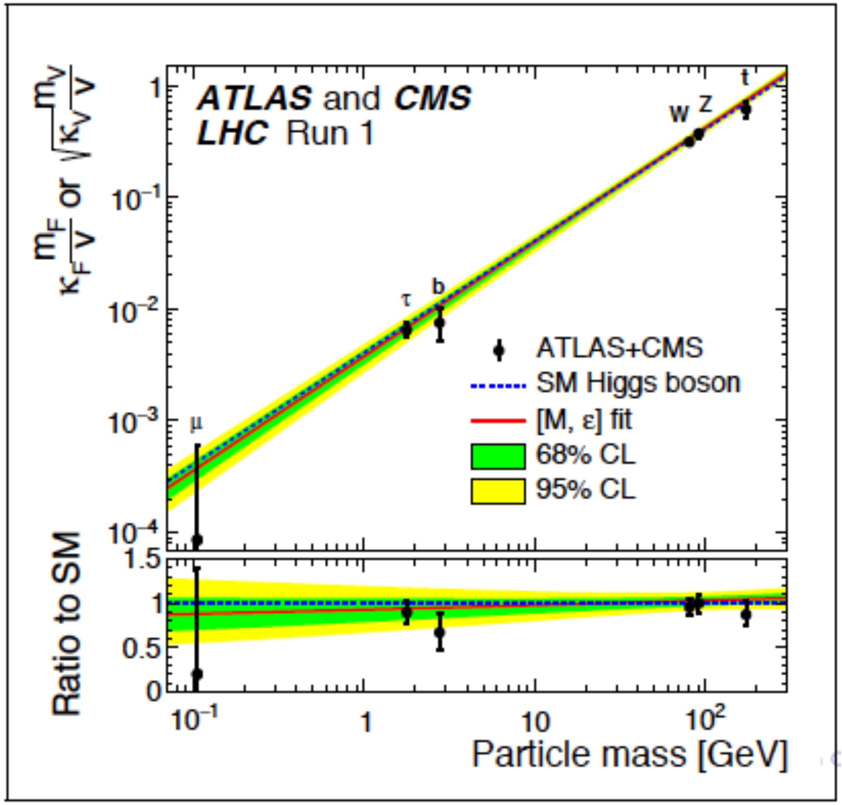
- Exploration of the new energy regime of 13 TeV has just started
- New era in Higgs re-discovered, Higgs precision physics, ttH
- So far…
  - Higgs re-discovery: $\gamma\gamma$ (obs. 5.5σ); ZZ (6.2σ);
  - Direct study of production mechanisms: measurements of μ_{ggH}, μ_{VBF}, μ_{VH}, and μ_{ttH}
  - Precision reaching Run I results. Everything compatible with SM predictions.
  - Increase sensitivity in the ttH production mode channel.
    - Combination of 2015 results is in agreement with the SM expectation.
  - Fiducial and differential cross sections still statistically limited
- 10x more data to come by end of 2018. It will allow to reach precision measurements on Higgs properties: cross sections, width, couplings… observe any deviation?

Additional material

Summary of Run-I Higgs Results

- Run-1: **Discovery**!
  - **Its mass has been measured with high precision (±0.2%)** Phys. Rev. Lett. 114, 191803
  - Its spin-parity: a scalar, beyond "reasonable" doubts
  - Production via gluon-fusion, vector-boson fusion, and associated with a W or Z, arXiv: 1606.02266
  - decays to γγ, WW, ZZ, and the fermionic decay to ττ
- Higgs signal strength ~1, determined to 10%
- Couplings consistent with Standard Model (SM) Higgs boson
- No additional Higgs bosons found so far





The Higgs Boson width

- It is impossible to extract he coupling and the Higgs width separately from the on-shell cross section measurement.

$$\sigma^{on-shell}_{i \to H \to f}(SM) \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

- LHC is insensitive to the direct Higgs width measurement (Γ_{SM} ~ 4.2 MeV, which is too small for the detector resolution.

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg \to H^* \to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg \to H^* \to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

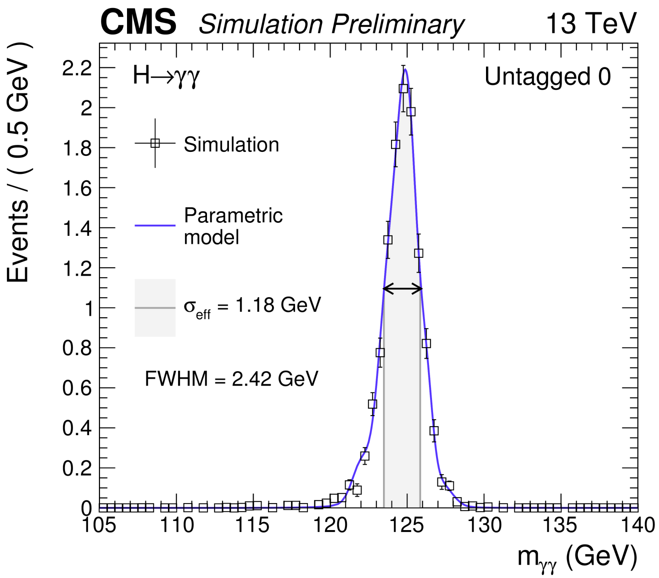
$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg \to H \to VV}_{\text{on-shell}}}{\sigma^{gg \to H \to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H / \Gamma_H^{SM}}$$

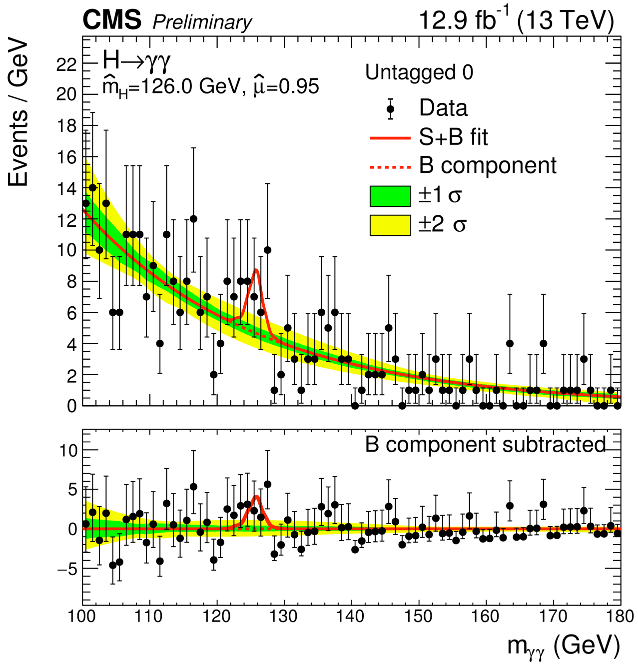
$$\mu_{offshell} = \mu_{onshell} \times \Gamma_H / \Gamma_H(SM)$$

- We can perform indirect Higgs width measurement with the combination between on-shell and off-shell analysis under the following assumptions:
  - $\mu_{\text{off-shell}} = \mu_{\text{on-shell}}$
  - No BSM particle or interactions affect the Higgs coupling and SM background expectation.

H→γγ signal and background models

- Fully parametric signal model from simulation
  - continuous model in m_H
  - physical nuisances allowed to float
  - corrections and data/MC efficiency scale factors applied
- Background model data driven:
  - background functional form treated as discrete nuisance parameter
  - for each category, use different functional forms (sums of exponentials, sums of power law terms, Laurent series and polynomials)





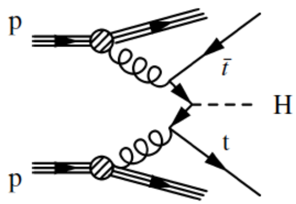
H→γγ event yields

ttH tags

ttH leptonic tag

$t\bar{t} \rightarrow bl\nu_l \bar{b}q\bar{q}^{'}$ $t\bar{t} \rightarrow bl\nu_l \bar{b}l^{'}\nu_{l^{'}}$

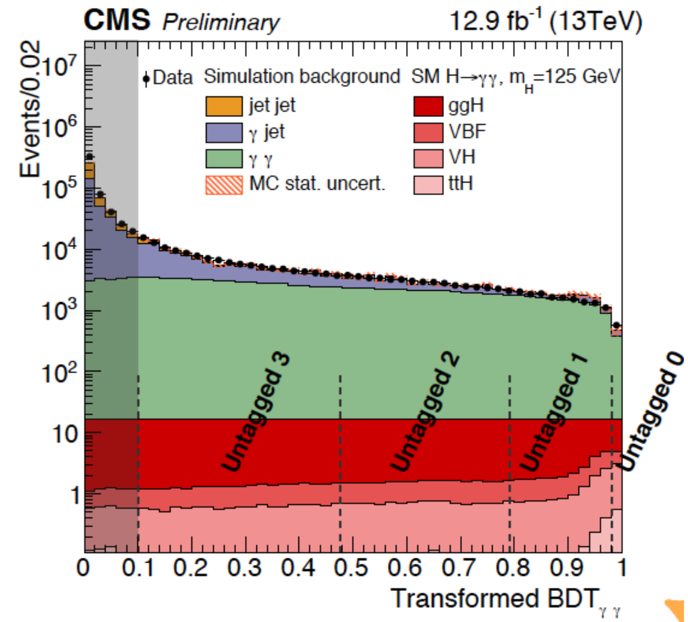
- (sub)lead pT/$m_{\gamma\gamma}$ > 1/2(1/4)
- at least one lepton (ℓ=e,μ), away from Z peak
- ≥ 2 jets
- ≥ 1 b-jet



ttH hadronic tag

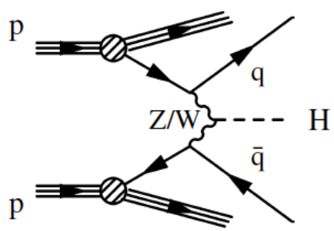
$t\bar{t} \rightarrow bq\bar{q}^{'}\bar{b}q\bar{q}^{'}$

- (sub)lead pT/mγγ > 1/2(1/
- 0 leptons
- ≥ 5 jets
- ≥ 1 b-jet



VBF tags

- Identify events with **2 jets** through a MVA
  - inputs: pT/$m_{\gamma\gamma}$ of both photons, pT of both jets, m_{jj}, $\Delta\eta_{jj}$, Zeppenfeld variable, $\Delta\phi_{\gamma\gamma jj}$
- 2 jets with p_{T1} > 30GeV, p_{T2} >20 GeV, |η| < 4.7, m_{jj} >250 GeV
- **VBF Classification** BDT combines di-jet and diphoton BDT: 2 data categories (**VBF tag 0-1**)



Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV^{-1})
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

H→γγ fiducial region

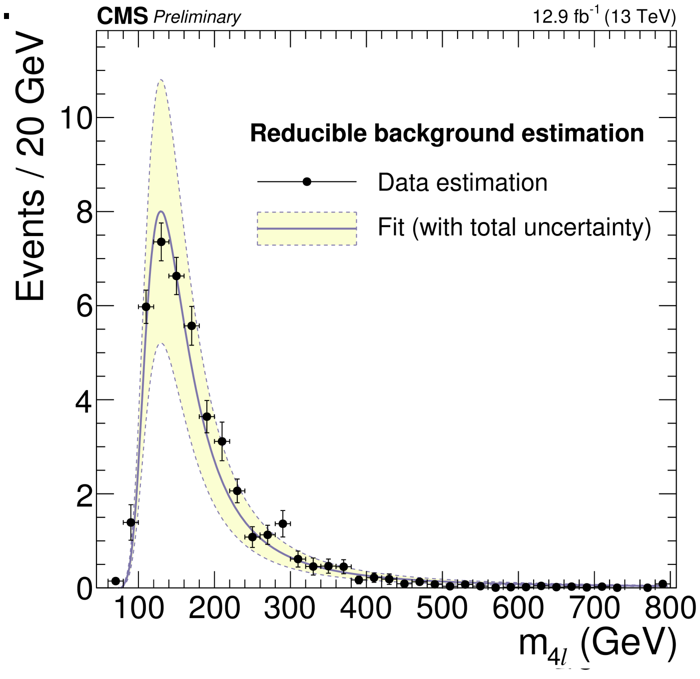
- The fiducial region is defined at generator-level with the following requirements:

- $\frac{p_{T,gen}^{\gamma_{1,(2)}}}{m_{\gamma\gamma}} > \frac{1}{3}(\frac{1}{4})$ for the generator-level transverse momentum of the leading (subleading) photon,
- $|\eta_{gen}^{\gamma}| < 2.5$ for the generator-level pseudorapidities of both photon
- the generator-level isolation of the photons, calculated as the sum of the transverse momenta of all stable particles inside a cone of aperture $R = 0.3$ around the photon, is required to be smaller than 10 GeV.

H→ZZ analysis strategy

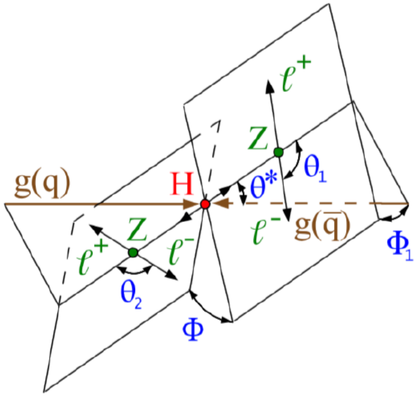
- Theoretical cross section: ggH N^3LO computation (arXiv:1602.00695)
- Analysis relies on $(\text{efficiency})^4$ of selecting leptons!
  - electron (muons) reconstructed down to 7 (5) GeV
  - reoptimized isolation, electron MVA ID & FSR recovery algorithm
  - thorough corrections for efficiencies in data, measured by Tag&Probe.
- Time-dependent lepton momentum calibrations
- Improved ZZ candidate arbitration
  - choose best value of kinematic discriminant.

- Background estimation:
  - Main background = non-resonant qq→ZZ and gg→ZZ. Apply NNLO/NLO (resp. NNLO/LO) QCD k-factors as a function of m_{ZZ}.
  - Reducible background (Z+X): data-driven estimation from control regions, 2 independent methods



H→ZZ observables

- To further reduce background: encode angular information in matrix-element based discriminants (calculated with MELA, based on JHUGen and MCFM)
- Discriminant sensitive to qq/gg → 4l kinematics:



$$\mathcal{D}^{\rm kin}_{\rm bkg} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\rm bkg}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\rm sig}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}\right]^{-1}$$

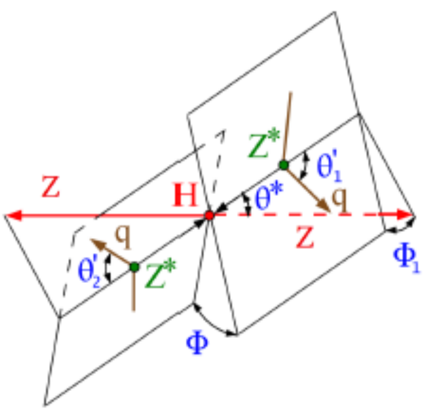
- New discriminants for production mode topology: D_{2jet} & D_{1jet} (for VBF), D_{WH}, DZH

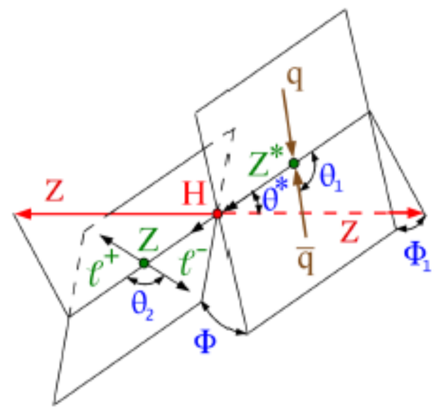
$$\mathcal{D}_{\rm 2jet} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm 1jet} = \left[1 + \frac{\mathcal{P}_{\rm HJ}(\vec{\Omega}^{\rm H+J}|m_{4\ell})}{\int d\eta_{\rm J}\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm WH} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm ZH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm ZH} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm WH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

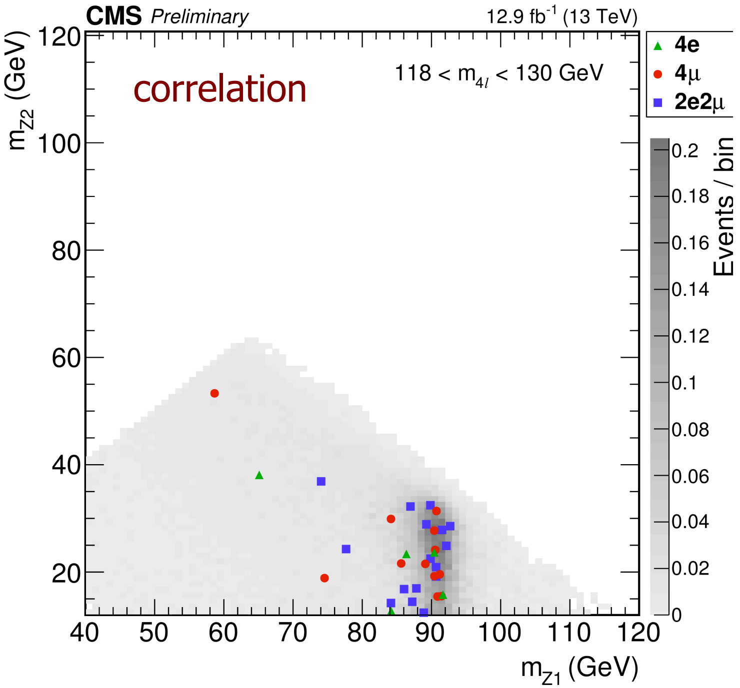


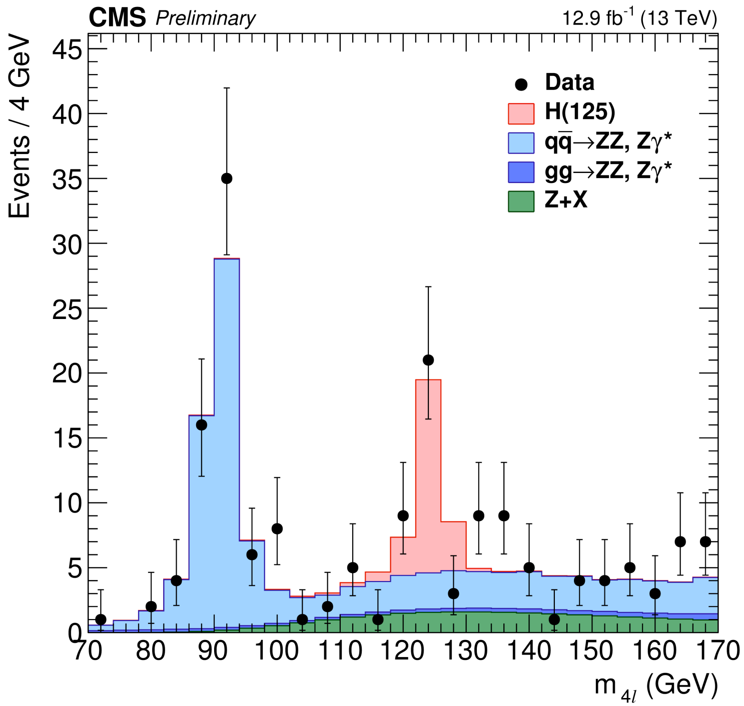


H→ZZ event yields

118 < m4l < 130 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	$1.37^{+0.16}_{-0.15}$	$3.09^{+0.27}_{-0.27}$	$3.90^{+0.46}_{-0.43}$	$8.36^{+0.81}_{-0.79}$
$gg \to ZZ$	$0.16^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$	$0.30^{+0.05}_{-0.05}$	$0.77^{+0.12}_{-0.12}$
Z + X	$0.90^{+0.38}_{-0.37}$	$1.40^{+0.52}_{-0.51}$	$2.34^{+0.91}_{-0.89}$	$4.64^{+1.11}_{-1.09}$
Sum of backgrounds	$2.42^{+0.42}_{-0.40}$	$4.81^{+0.59}_{-0.59}$	$6.54^{+1.03}_{-1.00}$	$13.77^{+1.41}_{-1.38}$
Signal ($m_H = 125$ GeV)	$3.90^{+0.53}_{-0.54}$	$7.92^{+0.88}_{-0.93}$	$9.80^{+1.34}_{-1.36}$	$21.61^{+2.63}_{-2.71}$
Total expected	$6.32^{+0.78}_{-0.76}$	$12.73^{+1.21}_{-1.24}$	$16.34^{+1.92}_{-1.90}$	$35.38^{+3.43}_{-3.45}$
Observed	5	12	16	33

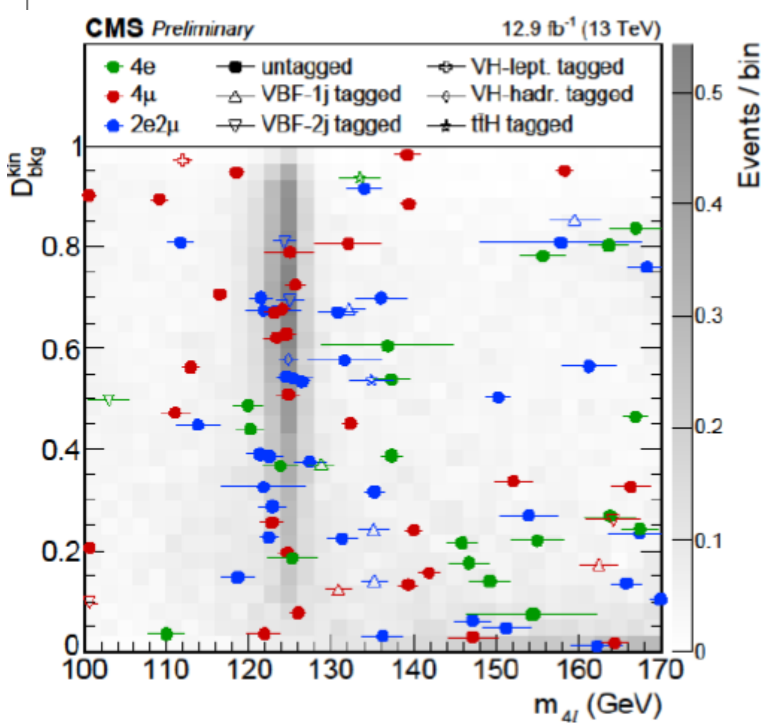


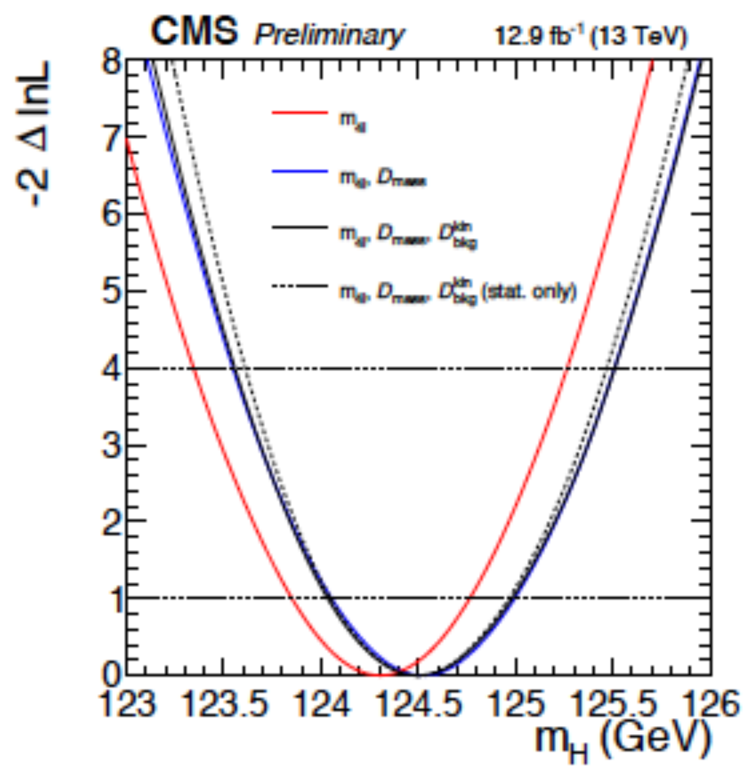


H→ZZ mass measurement

- Exploit event-by-event mass resolution:
  - Defined by propagating per-lepton momentum error to the 4-lepton candidate; corrected in data and MC using Z events
- 3D fit based on $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$ brings 8% exp. improvement

$$m_{\text{H}} = 124.50^{+0.48}_{-0.46}\ \text{GeV} = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})\ \text{GeV}$$





H→ZZ fiducial region

- "dressed" leptons are used → 4-momenta of photons in a cone of radius ΔR<0.4 are summed to the bare lepton momentum

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_T$ ←
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\text{GeV} < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12\,\text{GeV} < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$

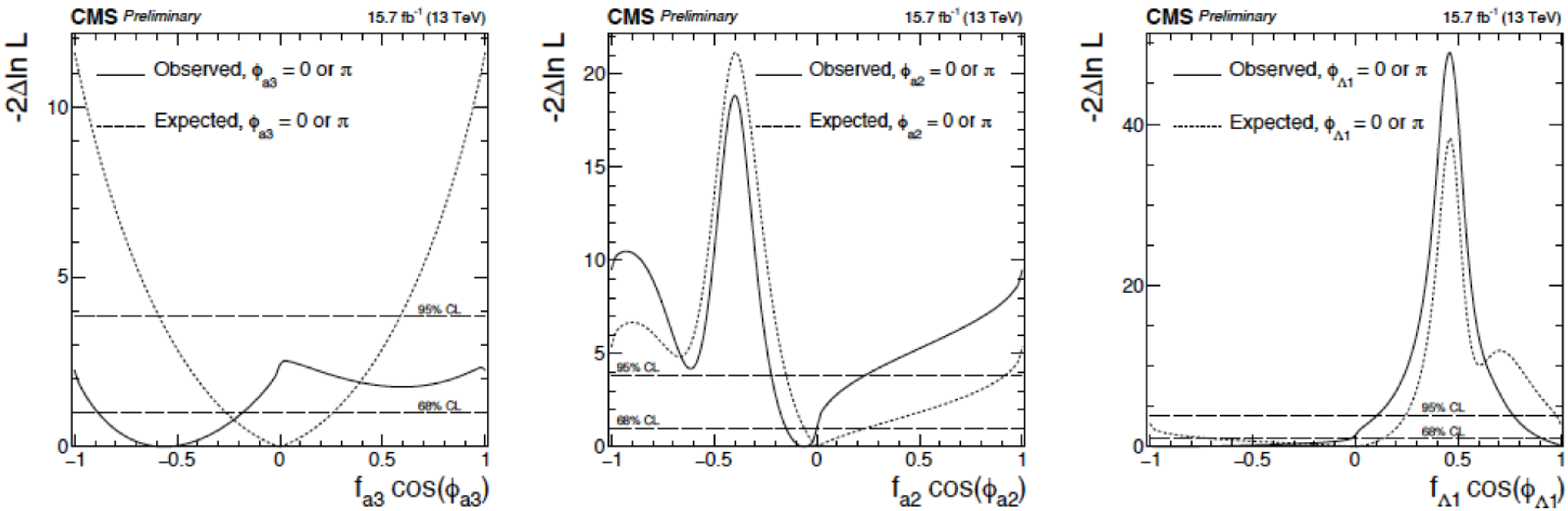
- Performing a maximum likelihood fit of the signal and background parameterizations to the observed 4l mass distribution.
- The fiducial cross section is directly extracted from the fit.
- Keep the model dependence minimal, the fit is done inclusively (i.e. without any event categorization)

Summary of different SM signal models

Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg→H	0.371	0.608 ± 0.001	0.121 ± 0.001	0.682 ± 0.002
VBF	0.422	0.614 ± 0.002	0.089 ± 0.001	0.669 ± 0.002
WH	0.283	0.587 ± 0.002	0.241 ± 0.003	0.729 ± 0.003
ZH	0.307	0.611 ± 0.003	0.207 ± 0.004	0.738 ± 0.005
ttH	0.238	0.573 ± 0.004	0.593 ± 0.011	0.914 ± 0.009

H→ZZ anomalous couplings

- Anomalous contributions to the tensor structure of HZZ interactions characterized by coef. a2, a3, & Λ1.
- Described with effective on-shell fractional cross sections & phases (f_{a3} $\cos(\phi_{a3})$, f_{a2} $\cos(\phi_{a2})$, $f_{\Lambda 1}$ $\cos(\phi_{\Lambda 1})$)



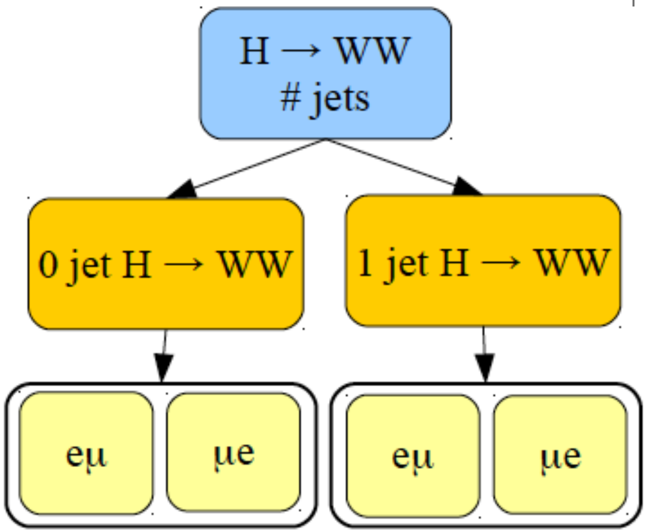
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.56^{+0.38}_{-0.32}$ $[-1.00, 1.00]$	$0.00^{+0.26}_{-0.26}$ $[-0.59, 0.59]$
$f_{a2}\cos(\phi_{a2})$	$-0.06^{+0.06}_{-0.09}$ $[-0.22, 0.24]$	$0.00^{+0.24}_{-0.06}$ $[-0.15, 0.92]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$-0.93^{+0.90}_{-0.16}$ $[-1.00, 0.10] \cup [0.77, 1.00]$	$0.00^{+0.13}_{-0.69}$ $[-1.00, 0.24] \cup [0.98, 1.00]$

H→WW analysis strategy

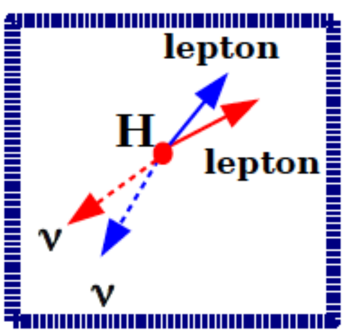
- **Neutrinos** → impossible reconstruct an invariant mass spectrum
- In transverse plane momentum conservation
  - Build a **transverse mass** variable:
    - 2 neutrinos → more complicated than in simple W → lν decay
    - Di-lepton and MET system considered

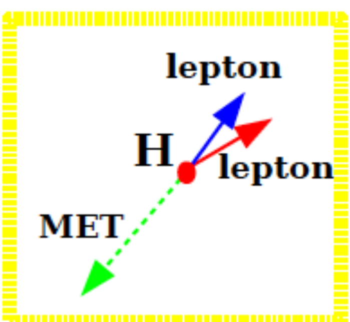
$$m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - cos\Delta\phi_{\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}}\right)}$$

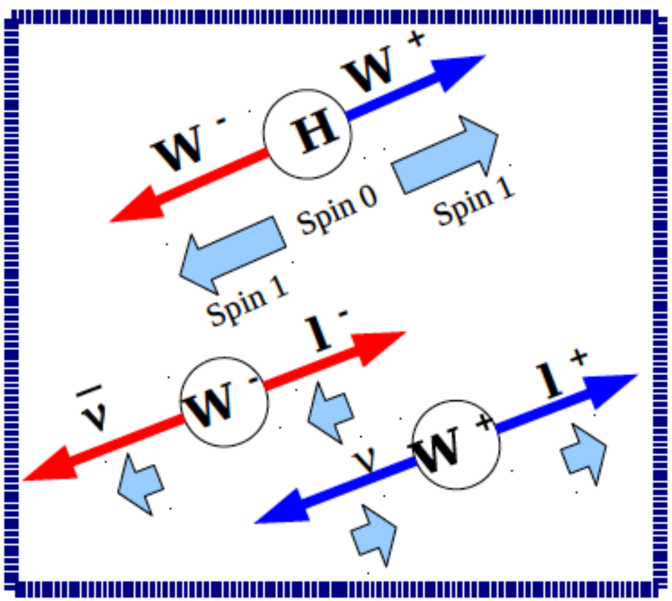
- Δφ (ll,MET) = angle between di-lepton system and MET
- p_T^{ll} = momentum of di-lepton system



- 2D template fit based on $m_{ll}/m_T^{ll\,MET}$ as in Run 1
  - **0 jet** and **1 jet** to have different background contamination
  - eμ and μe p_T ordered leptons, to exploit different fake rate for electrons and muons





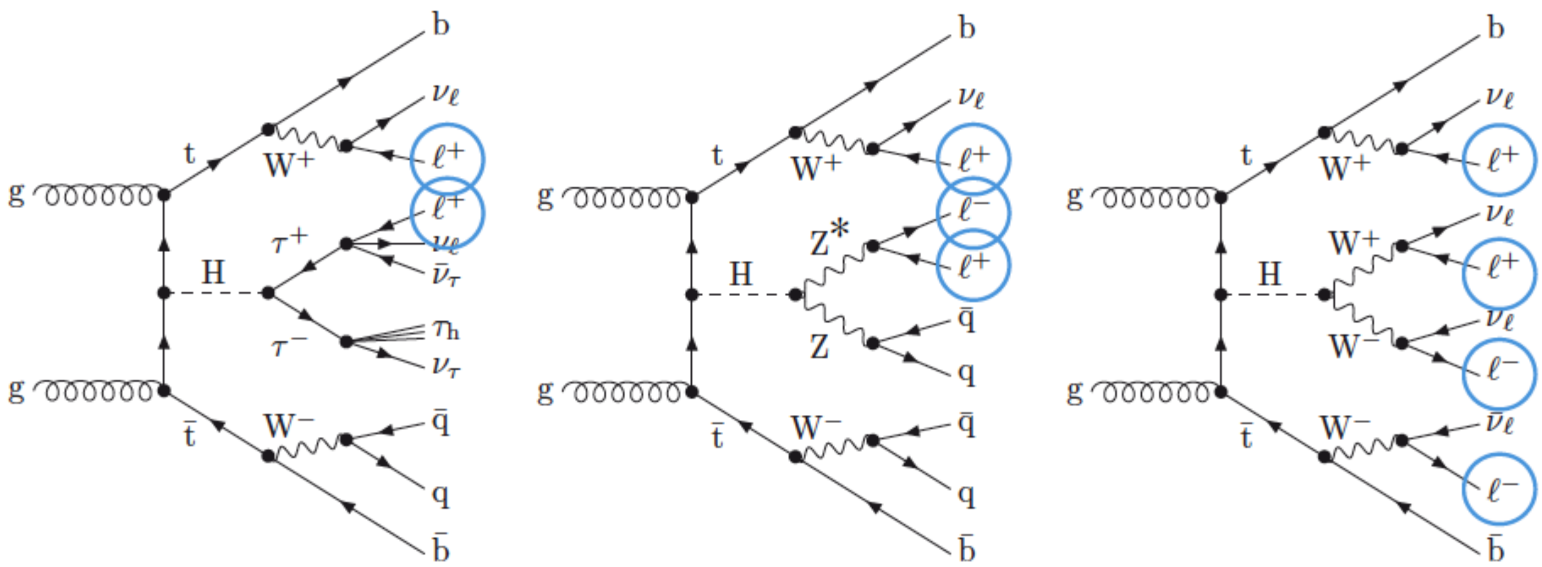


H→WW fiducial definition

- Born-level leptons (effect of using "dressed" leptons is negligible, 5%)
- use regularized unfolding techniques: singular value decomposition with Tikkhonov regularization

Physics quantity	Requirement
Leading lepton p_T	$p_T > 20\,\mathrm{GeV}$
Subleading lepton p_T	$p_T > 10\,\mathrm{GeV}$
Pseudorapidity of electrons and muons	$\lvert\eta\rvert < 2.5$
Invariant mass of the two charged leptons	$m_{\ell\ell} > 12\,\mathrm{GeV}$
Charged lepton pair p_T	$p_T^{\ell\ell} > 30\,\mathrm{GeV}$
Invariant mass of the leptonic system in the transverse plane	$m_T^{\ell\ell\nu\nu} > 50\,\mathrm{GeV}$
E_T^{miss}	$E_T^{miss} > 0$

ttH (multileptons) categories HIG-16-022



- Target multi-lepton final states from Higgs decays to WW*, ZZ*, $\tau\tau$
- Channels:
  - two same-sign leptons + 4 jets
  - at least three leptons (with Z veto) + 2 jets
- At least 2 loose or 1 medium b-tagged jets

ttH (multileptons) yields HIG-16-022

12.9 fb^{-1}, stat. unc. only

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105