



Rare Higgs Decays at CMS

Featuring Run 2 $H \rightarrow Z\gamma$ Results

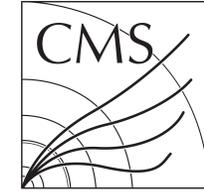
James Bueghly

On behalf of the CMS Collaboration

Higgs 2021 conference

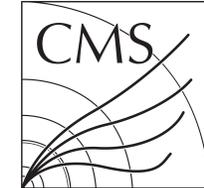
October 18-22, 2021

Introduction

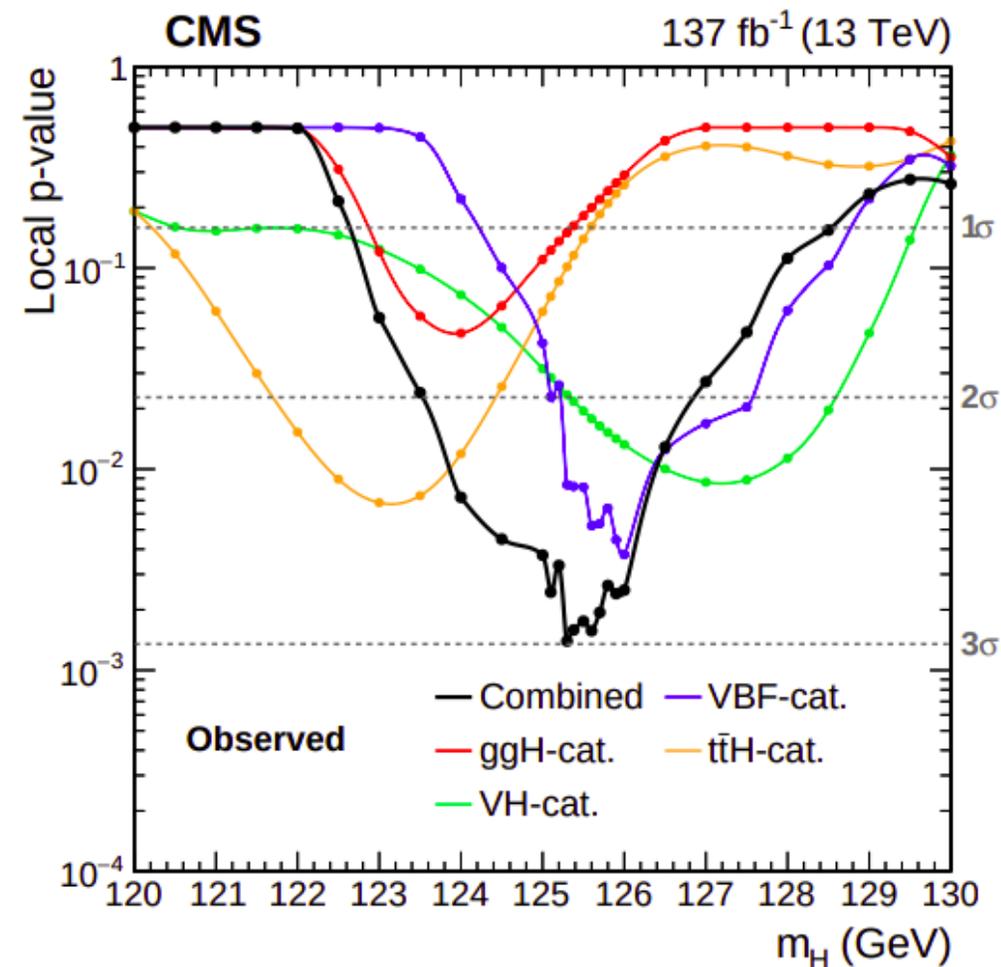


- The search for rare Higgs decays is an ongoing effort within the CMS Higgs physics program.
- Some relatively recent CMS rare Higgs decay results:
 - Full Run 2: $H \rightarrow \mu^+ \mu^-$
 - Full Run 2: first limits on $H \rightarrow Z\rho$ and $H \rightarrow Z\phi$
 - 2017 data: $H \rightarrow J/\psi J/\psi$ and $H \rightarrow \Upsilon\Upsilon$
- **This talk features new CMS Run 2 results for $H \rightarrow Z\gamma$, with $Z \rightarrow e^+ e^-$ or $\mu^+ \mu^-$.**

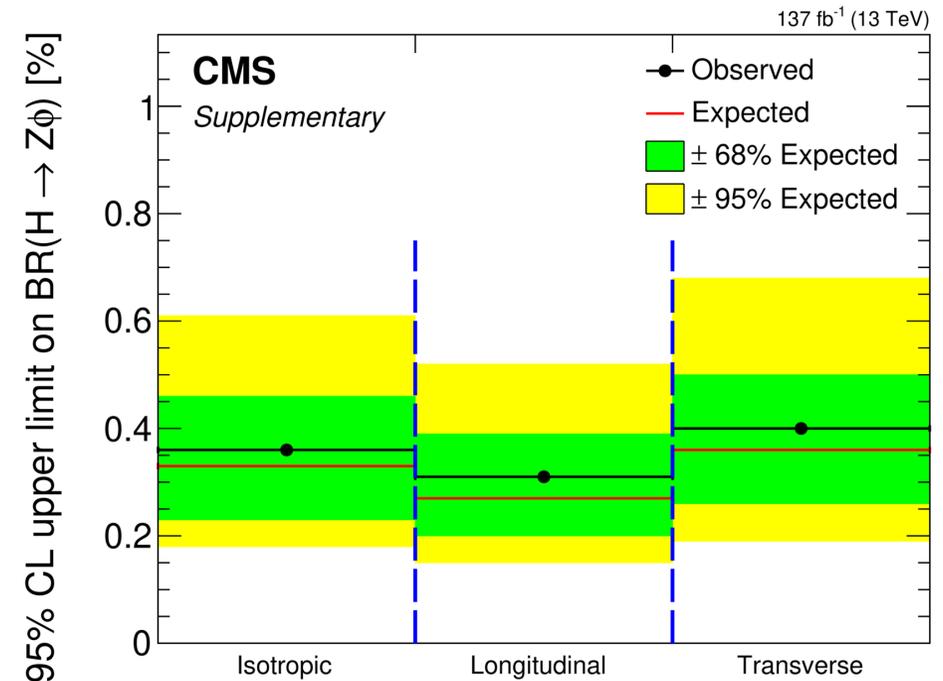
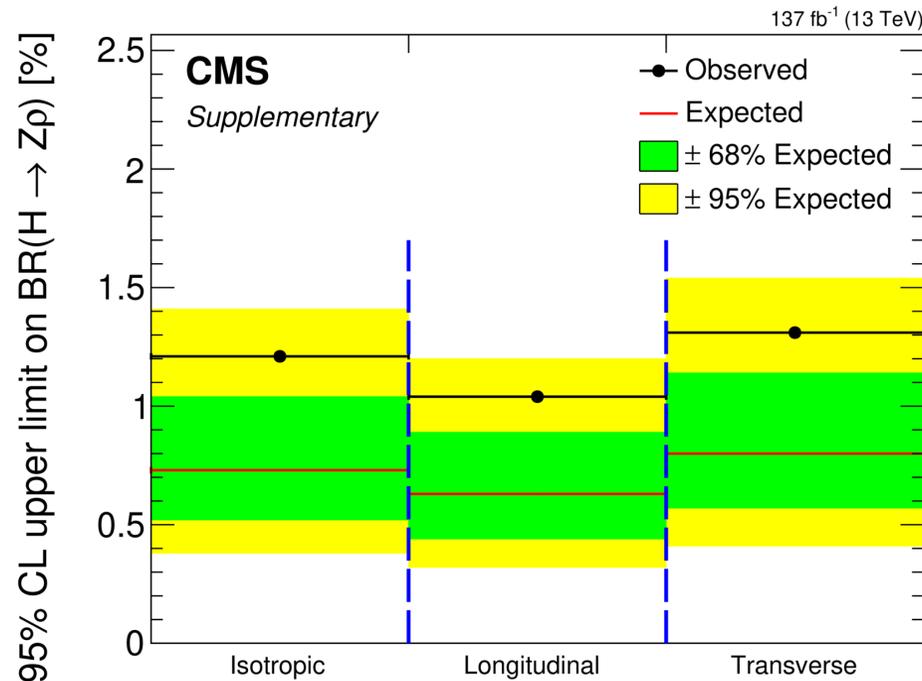
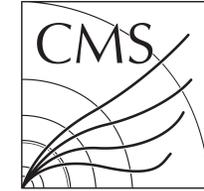
$H \rightarrow \mu^+ \mu^-$ (full Run 2)



- Search for resonance in dimuon mass spectrum
- Tag events to target Higgs production modes
 - ttH tag, VH tag, VBF tag, ggH tag
- Use MVA methods to discriminate signal from background and define subcategories
- Results for $m_H = 125.38$ GeV:
 - Best fit signal strength: $1.19^{+0.44}_{-0.42}$
 - Observed (expected) significance: **3.0 (2.5) σ**
 - **Evidence** for this decay

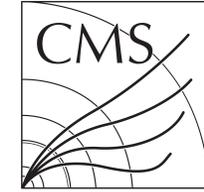


$H \rightarrow Z\rho$ and $H \rightarrow Z\phi$ (full Run 2)

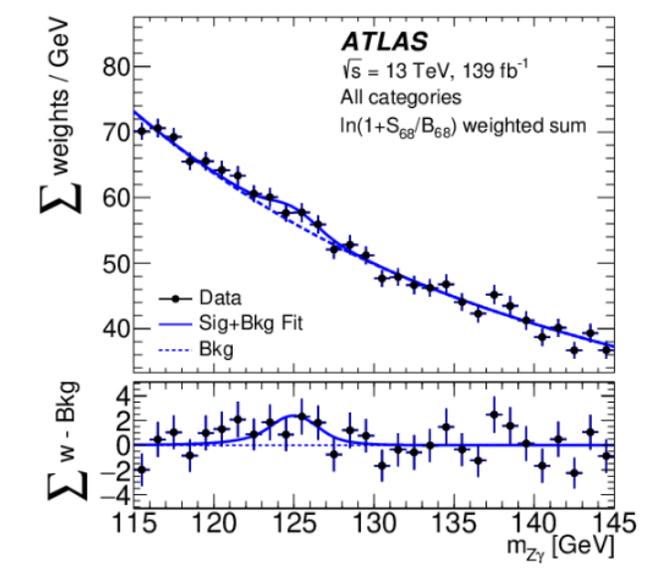
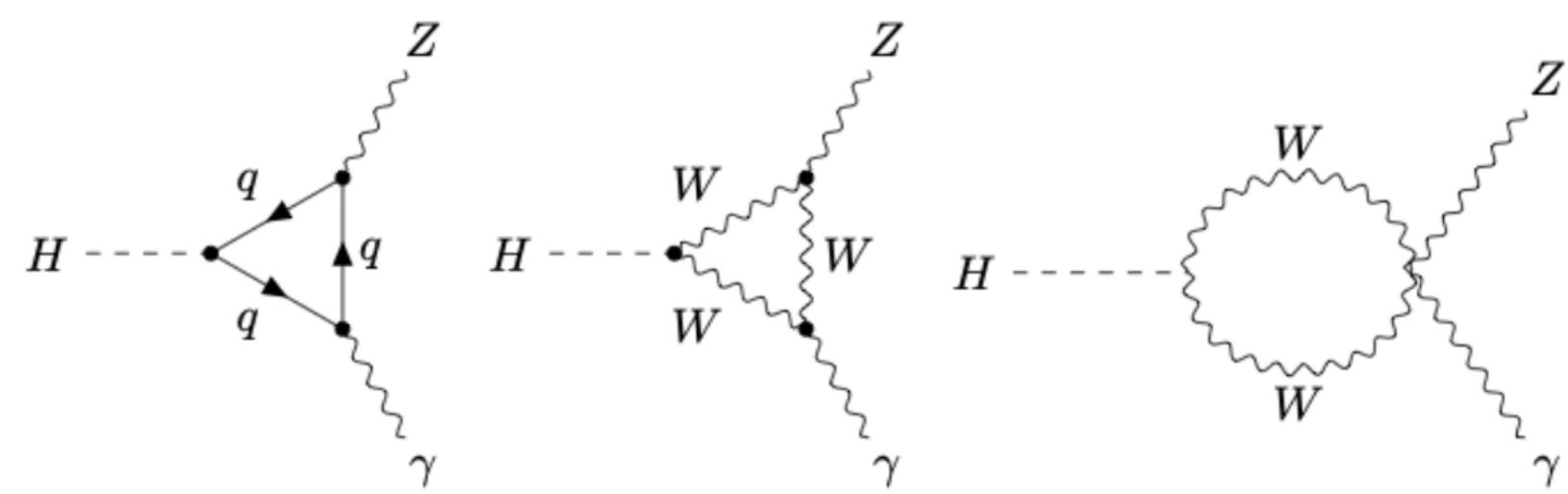
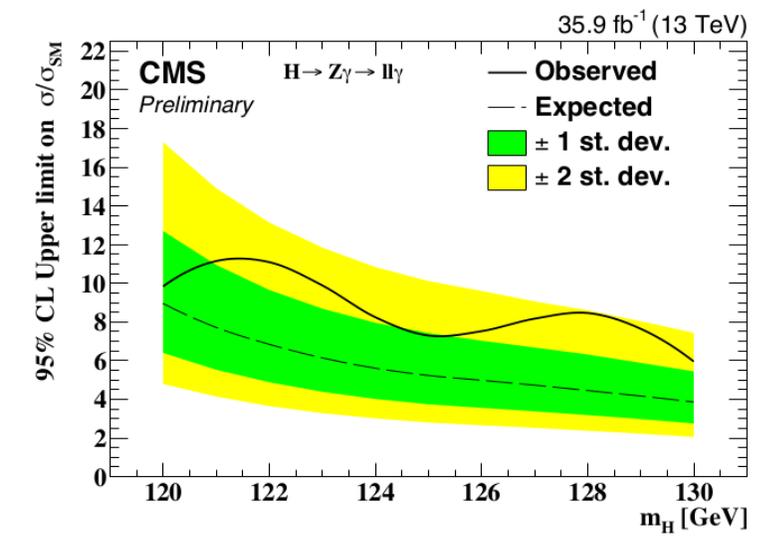


- Search for resonances in $m_{\ell^+\ell^-\kappa^+\kappa^-}$ and $m_{\ell^+\ell^-\pi^+\pi^-}$ where $\ell = e, \mu$
- Exploit track information to separate signal from background
- First experimental limits on branching fraction for $m_H = 125$ GeV:
 - $H \rightarrow Z\rho$: 1.04-1.31% (740-940 times SM)
 - $H \rightarrow Z\phi$: 0.31-0.41% (730-950 times SM)

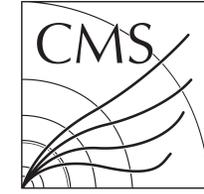
$H \rightarrow Z\gamma$ (full Run 2)



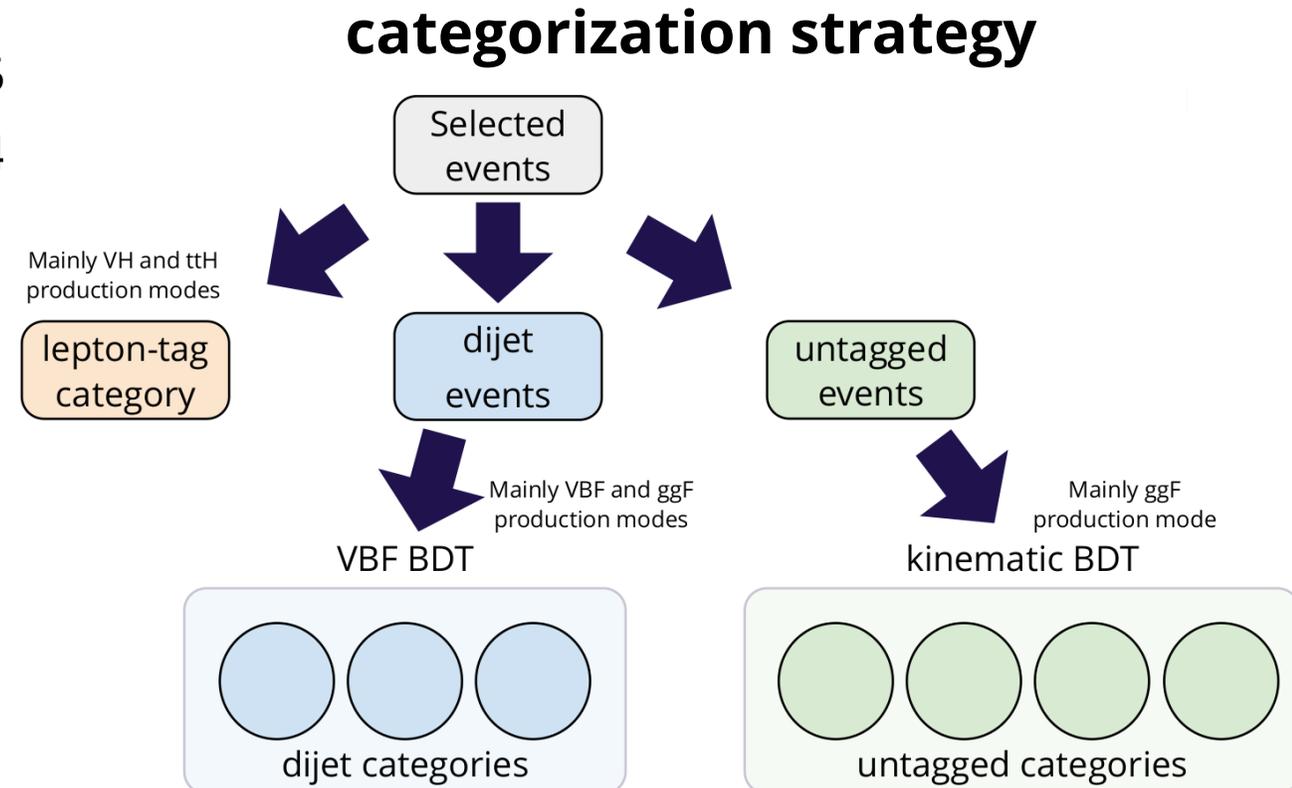
- $H \rightarrow Z\gamma$ is one of the remaining undiscovered Higgs decay modes.
- Loop nature makes it sensitive to potential BSM physics models
- Ratio $B(H \rightarrow Z\gamma)/B(H \rightarrow \gamma\gamma)$ a good BSM probe
 - BSM effects can shift $B(H \rightarrow Z\gamma)$ and $B(H \rightarrow \gamma\gamma)$ differently
- Existing results
 - CMS 2016: 7.4 (5.3) observed (expected) limit at 125 GeV
 - ATLAS Run 2: 3.6 (1.7) observed (expected) limit at 125.09 GeV
 - Observed (expected) significance 2.2 (1.2) σ



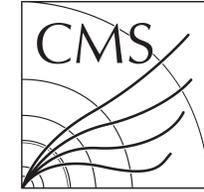
Analysis strategy



- Search for a resonance at $m_{\ell^+\ell^-\gamma} = 125.38$ GeV in the $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ final states
- Main backgrounds: SM $Z\gamma$ production and Z+jets (jet fakes a photon)
- Baseline event selection:
 - double electron and double muon triggers
 - leading (subleading) $p_T^e > 25$ (15) GeV; $|\eta| < 2.5$
 - leading (subleading) $p_T^\mu > 20$ (10) GeV; $|\eta| < 2.4$
 - photon $p_T^\gamma > 15$ GeV; $|\eta| < 2.5$
 - $m_{\ell^+\ell^-} > 50$ GeV; 105 GeV $< m_{\ell^+\ell^-\gamma} < 170$ GeV
 - $m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 185$ GeV; $p_T^\gamma/m_{\ell^+\ell^-\gamma} > 15/110$
- FSR photon recovery for muon momentum
- Kinematic fit to improve mass resolution
- BDT-based categorization
- Simultaneous $m_{\ell^+\ell^-\gamma}$ fit in each category
- Measurement of $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma)$



Kinematic Fit



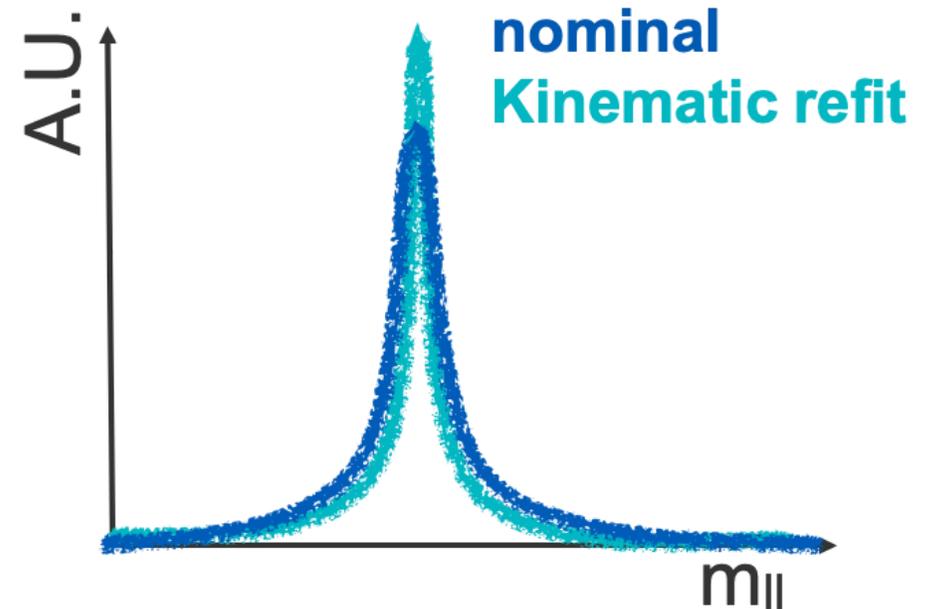
- Use known kinematic information in a fit to constrain measured lepton momenta
- Information taken into account in the fit:
 - The true Z boson lineshape, obtained from $H \rightarrow Z\gamma$ signal simulation at GEN level
 - The nominal measured p_T of each lepton
 - The p_T resolution of each lepton

$$\mathcal{L}(p_T^{(1)}, p_T^{(2)} | p_T^{reco(1)}, \sigma_{p_T^{(1)}}, p_T^{reco(2)}, \sigma_{p_T^{(2)}}) = \mathcal{N}(p_T^{reco(1)} | p_T^{(1)}, \sigma_{p_T^{(1)}}) \mathcal{N}(p_T^{reco(2)} | p_T^{(2)}, \sigma_{p_T^{(2)}}) \mathcal{L}(m_{12} | m_Z, \Gamma_Z)$$

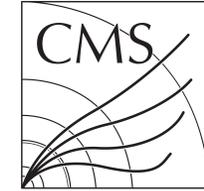
- $p_T^{(1)}$ $p_T^{(2)}$ the parameters to optimize
- $\mathcal{L}(m_{12} | m_Z, \Gamma_Z)$ is the likelihood given the true Z lineshape

Improvement in $m_{\ell^+\ell^-\gamma}$ resolution

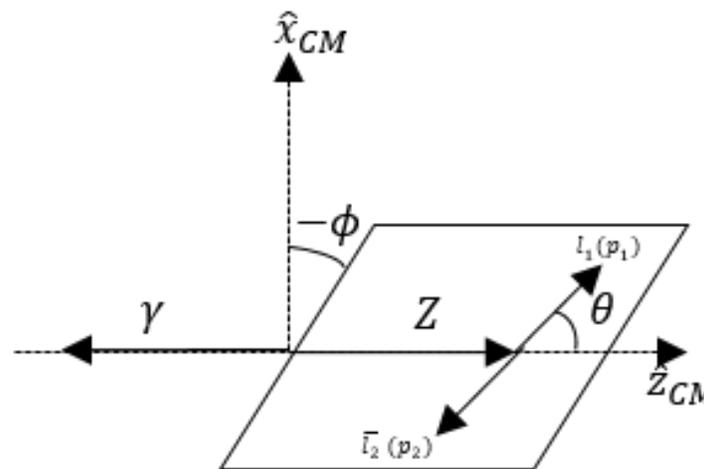
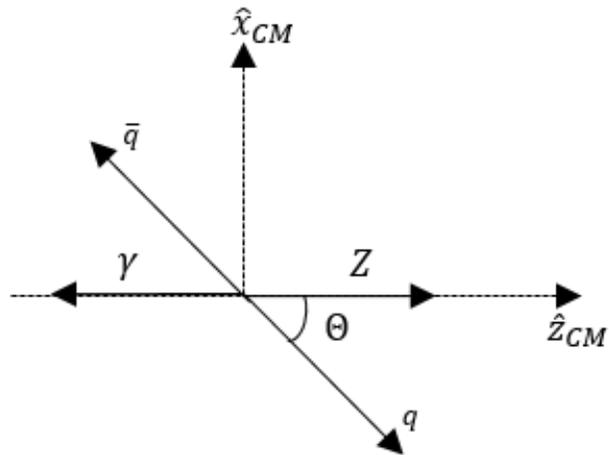
- 20 - 27% in the electron channel
- 10 - 12% in the muon channel



Kinematic BDT training



- Discriminate $H \rightarrow Z\gamma$ signal from backgrounds based on kinematics
- Events must pass the full selection.
- Signal: ggF, VBF, VH, and ttH $H \rightarrow Z\gamma$
- Background: Z+jets, QCD $Z\gamma$, $t\bar{t}$

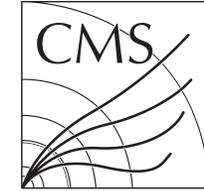


Angle definitions

Training variables

- **Angular variables**
 - $\Delta R(\ell, \gamma)$
 - $\cos(\Theta)$
 - ϕ
 - $\cos(\theta)$
- **Final state kinematics**
 - η_γ
 - η_ℓ
 - $p_T^{\ell^+\ell^-\gamma} / m^{\ell^+\ell^-\gamma}$
- **Photon quality**
 - photon MVA score
 - $\sigma_{E\gamma} / E_\gamma$

VBF BDT training

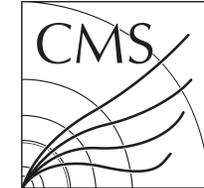


- Discriminate $H \rightarrow Z\gamma$ VBF signal from ggF signal and backgrounds in dijet events
- Events must pass the full selection and have a dijet pair
 - $p_T^j > 30 \text{ GeV}$; $|\eta_j| < 4.7$; separated from leptons and photon
- Signal: VBF $H \rightarrow Z\gamma$
 - Signal VBF jets matched to truth-level partons
- Background: Z+jets, QCD $Z\gamma$, EWK $Z\gamma$, $t\bar{t}$, ggF $H \rightarrow Z\gamma$

Training variables

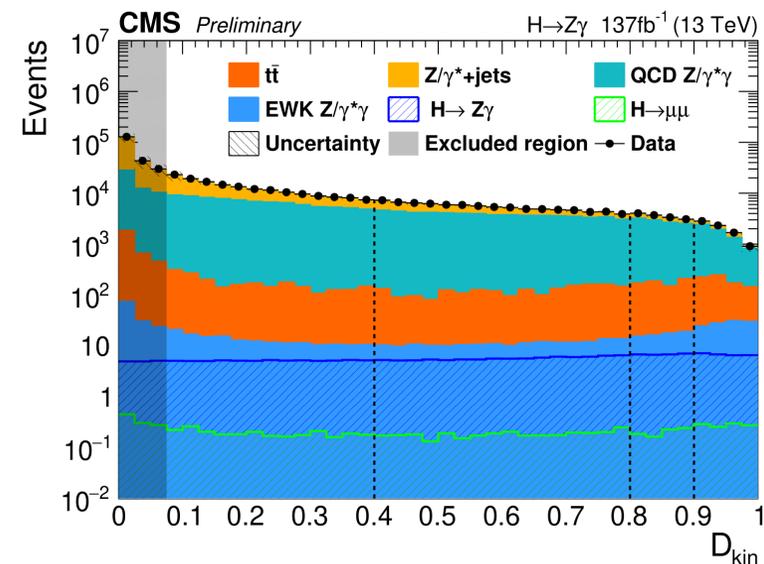
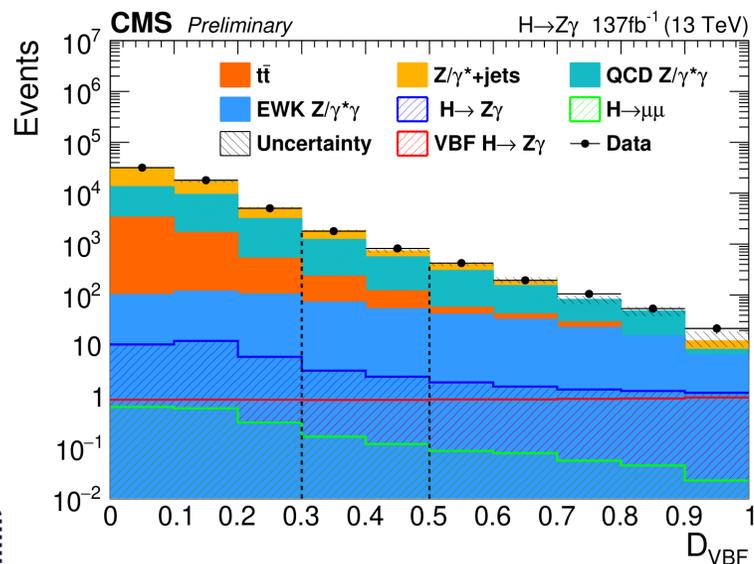
- $|\Delta\phi(Z\gamma, jj)|$
- $\Delta R(\gamma, j)$
- $|\Delta\eta(j, j)|$
- $|\Delta\phi(j, j)|$
- p_T^j
- $|\eta_\gamma - (\eta_j^{(1)} + \eta_j^{(2)})/2|$
- $|\sum_{Z,\gamma,j^{(1)},j^{(2)}} \vec{p}_T / \sum_{Z,\gamma,j^{(1)},j^{(2)}} p_T|$
- $p_T^t = \frac{(2|p_T^Z(x)p_T^\gamma(y) - p_T^Z(y)p_T^\gamma(x)|)}{p_T^H}$
- Kinematic BDT score

Category Definitions



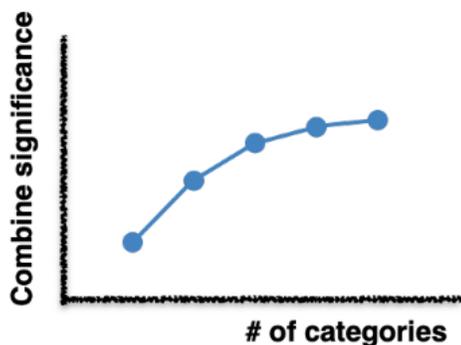
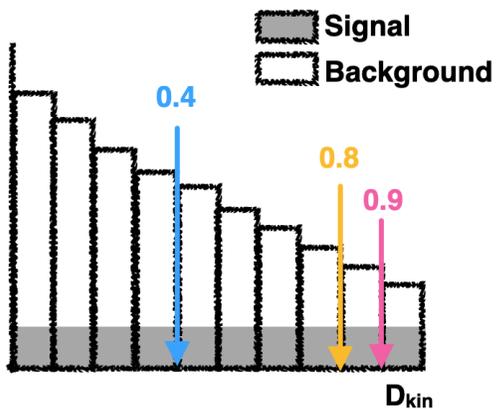
Category Optimization

- Subdivide dijet and untagged events into categories using BDT score regions
- Optimize number of categories and locations of the category boundaries based on combined significance

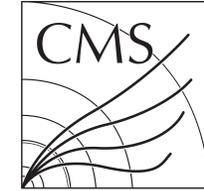


$$\text{combined significance} = \sqrt{\sum_i^n S_i^2 / B_i}$$

Lepton	Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
$\geq 1 e, \mu$		\mathcal{D}_{VBF}			\mathcal{D}_{kin}		
-	0.5–1.0	0.3–0.5	0.0–0.3	0.9–1.0	0.8–0.9	0.4–0.8	0.1–0.4



Signal and background modeling



Signal modeling

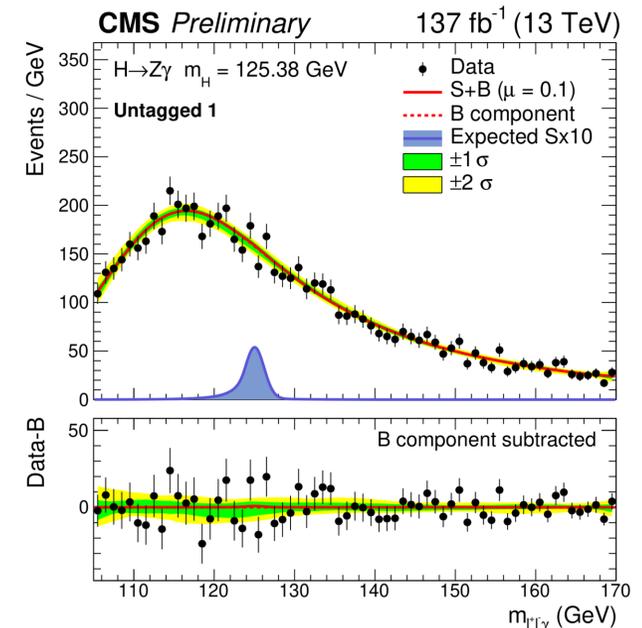
- Model signal with a Crystal Ball function plus a Gaussian function
- Account for differences in mass resolution for different years and channels

Background modeling

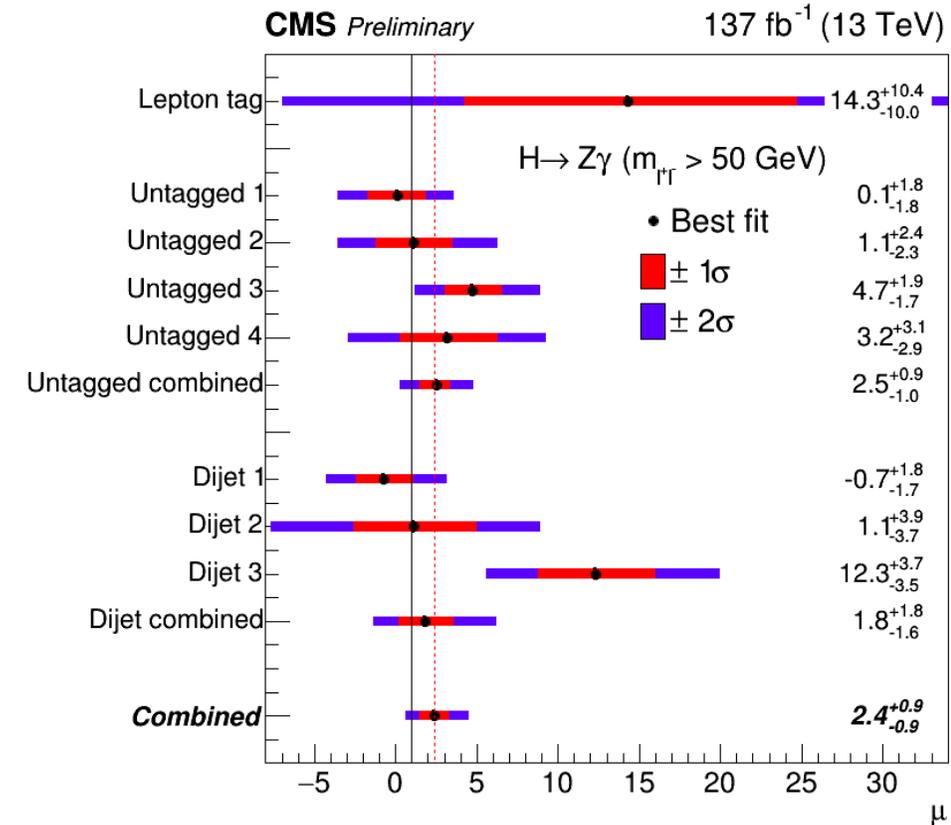
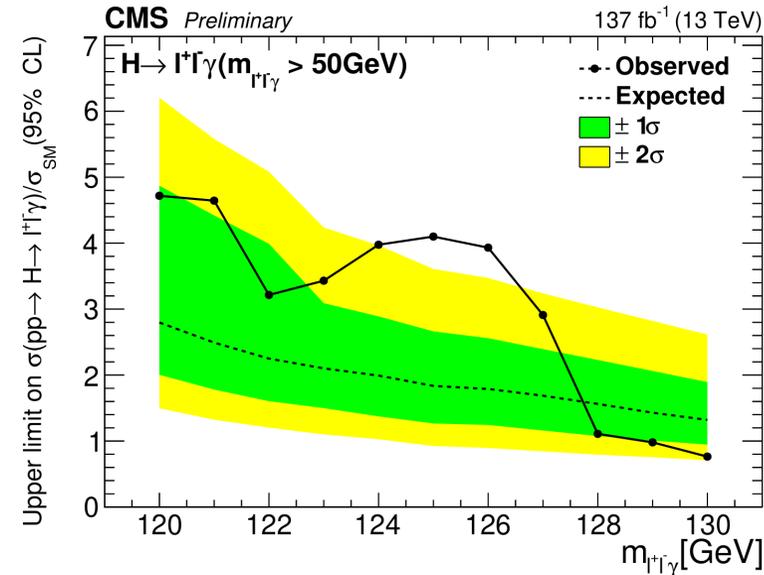
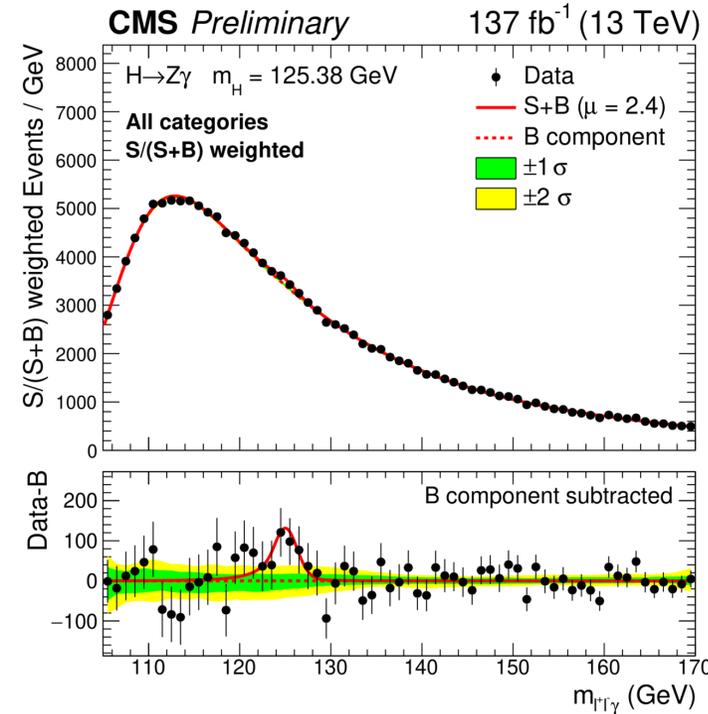
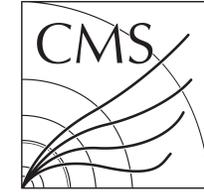
- Background model obtained from analytic fit to the $m_{\ell^+\ell^-\gamma}$ data in each category
- Background function choice determined using [discrete profiling method](#)

$$\mathcal{F}(m_{\ell^+\ell^-\gamma}; \mu, \sigma, s, \vec{\alpha}) = \int_{105}^{170} \mathcal{N}(m_{\ell^+\ell^-\gamma} - t; \mu, \sigma) f(t; \vec{\alpha}) \Theta(t; s) dt$$

- \mathcal{F} is the general functional form considered.
- Gaussian component models the low-mass turn-on
- $f(t; \vec{\alpha})$ is a falling spectrum component

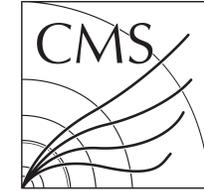


Results



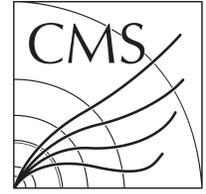
- All results shown are for mass hypothesis m_H = 125.38 GeV
- Best fit signal strength: $\mu = 2.4_{-0.9}^{+0.8}(\text{stat})_{-0.2}^{+0.3}(\text{syst}) = 2.4 \pm 0.9(\text{tot})$
- Measured $\sigma(\text{pp} \rightarrow \text{H}) \times \mathcal{B}(\text{H} \rightarrow \text{Z}\gamma) = 0.21 \pm 0.08 \text{ pb}$, consistent with SM prediction at 1.6σ level
- Local significance under background-only hypothesis: **2.7 (1.2)σ** observed (expected)
- 95% CL upper limit on $\sigma(\text{pp} \rightarrow \text{H}) \times \mathcal{B}(\text{H} \rightarrow \text{Z}\gamma)$ under background-only hypothesis: 4.1 (1.8) observed (expected)
- $\mathcal{B}(\text{H} \rightarrow \text{Z}\gamma)/\mathcal{B}(\text{H} \rightarrow \gamma\gamma) = 1.54_{-0.58}^{+0.65}$, compatible with SM at the 1.5σ level

Summary

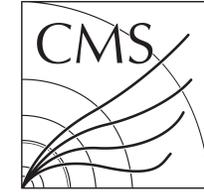


- CMS continues to search for rare Higgs decays.
- Some relatively recent results:
 - Full Run 2 $H \rightarrow \mu^+ \mu^-$: evidence for the decay (3.0σ significance)
 - Full Run 2: first limits on $H \rightarrow Z\rho$ and $H \rightarrow Z\phi$
 - 2017 data: $H \rightarrow J/\psi J/\psi$ and $H \rightarrow \Upsilon\Upsilon$
- Presented new results for the CMS full Run 2 search for $H \rightarrow Z\gamma$
- Observe an excess in the data near the Higgs boson mass ($m_H = 125.38$ GeV)
 - Best fit signal strength: $\mu = 2.4 \pm 0.9$
 - Measured $\sigma(pp \rightarrow H) \times \mathcal{B}(H \rightarrow Z\gamma) = 0.21 \pm 0.08 \text{ pb}$
 - consistent with SM prediction at 1.6σ level
 - Observed local significance under background-only hypothesis: 2.7σ
- Used a combined fit with $H \rightarrow \gamma\gamma$ to measure $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma) = 1.54^{+0.65}_{-0.58}$
 - Consistent with SM value at the 1.5σ level

Backup



Datasets and simulation



• Data

- 2016 legacy (35.9 fb⁻¹)
 - 17Jul2018 GT: 94X_dataRun2_v10
 - DoubleMuon and DoubleEG, runs B-H
- 2017 rereco (41.8 fb⁻¹)
 - 31Mar2018 GT: 94X_dataRun2_v11
 - DoubleMuon and DoubleEG, runs B-F
- 2018 rereco (ABC) plus prompt (D) (58.8 fb⁻¹)
 - 17Sep2018 GT: 102X_dataRun2_Sep2018ABC_v2, 102X_dataRun2_Prompt_v13
 - DoubleMuon and EGamma, runs A-D

• Triggers

- 2016
 - Double electron: HLT_Ele23_Ele12_CalIdL_TrackIdL_IsoVL_(DZ)_v
 - Double muon: HLT_Mu17_TrkIsoVVL_(Tk)Mu8_TrkIsoVVL_DZ
- 2017
 - Double electron: Ele23Ele12CalIdLTrackIdLIsoVLTrackIso
 - Double muon: HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8(8)
- 2018
 - Double electron: Ele23Ele12CalIdLTrackIdLIsoVLTrackIso
 - Double muon: HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8 v

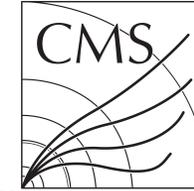
• Signal

- $H \rightarrow Z\gamma \rightarrow \ell^+\ell^-\gamma$, $m_H = 120, 125, 130$ GeV
 - ggF, VBF, ZH, W⁺H, W⁻H, ttH
 - POWHEG v2.0
 - 2016 (2017 and 2018):
 - Pythia v8.226 (v8.230)
 - CUETP8M1 (CP5) UE tune
 - NNPDF3.0 (NNPDF3.1)

• Background

- QCD ($Z/\gamma^* + \gamma$) $\rightarrow \ell^+\ell^-\gamma$ MADGRAPH5_aMC@NLO
- $Z/\gamma^* \rightarrow \ell^+\ell^- + \text{jets}$ MADGRAPH5_aMC@NLO
- $t\bar{t}$ POWHEG v2.0
- EWK ($Z/\gamma^* + \gamma$) $\rightarrow \ell^+\ell^-\gamma$
- $H \rightarrow \mu^+\mu^-$, $m_H = 120, 125, 130$ GeV
 - ggF, VBF, ZH, W⁺H, W⁻H, ttH
- 2016 (2017 and 2018):
 - Pythia v8.226 (v8.230)
 - CUETP8M1 (CP5) UE tune
 - NNPDF3.0 (NNPDF3.1)

Object and event selection



Vertex selection: ≥ 1 PV $|d_z| < 24$ cm, $|d_{xy}| < 2$ cm NDF > 4

Electron selection:

- $p_{T1} > 25$ GeV, $p_{T2} > 15$ GeV
- $|\eta_{sc}| < 2.5$
- $|d_z| < 1$ cm, $|d_{xy}| < 0.5$ cm
- Loose MVA electron ID (Fall17V2Iso)

Muon selection:

- $p_{T1} > 20$ GeV, $p_{T2} > 10$ GeV
- $|\eta| < 2.4$
- $|d_z| < 1$ cm, $|d_{xy}| < 0.5$ cm, SIP < 4
- H \rightarrow ZZ cut-based muon ID

Photon selection: $p_T > 15$ GeV $|\eta_{sc}| < 2.5$ (exclude $1.4442 < |\eta_{sc}| < 1.566$) $\Delta R(\gamma, \ell) > 0.4$ MVA photon ID Fall17V2Iso*

Event selection: $m_{\ell\ell} > 50$ GeV $p_T^\gamma / m_{\ell\ell-\gamma} > 15/110$ $m_{\ell\ell} + m_{\ell\ell-\gamma} > 185$ GeV $105 < m_{\ell\ell-\gamma} < 170$ GeV

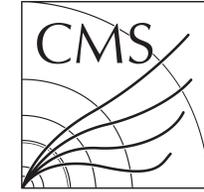
Additional lepton selection (for categorization): $p_T > 7$ (5) GeV for additional electron (muon), same ID requirements

Dijet selection (for categorization):

- $p_T > 30$ GeV, $|\eta| < 4.7$, $\Delta R(\gamma/\ell, j) > 0.4$
- Pass loose (tight) jet ID for 2016 (2017 and 2018)
- Veto EE-noise jets in 2017
- If multiple jet pairs, take the highest p_T jets

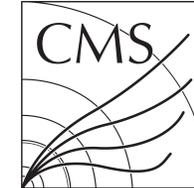
* Shower shape corrections applied, and WP determined for H \rightarrow Z γ

FSR photon recovery



- Add back the momentum of FSR photons to radiating muons
- FSR photon selection (inspired by $H \rightarrow ZZ$) applied to particle flow photon collection:
 - $p_T > 2 \text{ GeV}, |\eta| < 2.4$
 - Relative PF isolation less than 1.8
 - $\Delta R(\gamma, \mu)/p_{T\gamma}^2 < 0.012 \text{ GeV}^{-2}$
 - $\Delta R(\gamma, \mu) < 0.4$
- If multiple PF photons pass the selection, choose the photon with smallest $\Delta R(\gamma, \mu)/p_{T\gamma}^2$
- Selected reconstructed signal FSR photons match generator level FSR photons 93% of the time.
- Overall, 1% improvement of $m_{\ell^+\ell^-\gamma}$ resolution in the muon channel

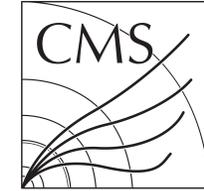
Yields, resolution, sensitivity



	Lepton		Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
Signal yield									
ggF	0.51	ee	1.10	1.62	9.44	6.89	7.35	29.8	22.5
		$\mu\mu$	1.41	2.05	12.1	8.52	9.17	38.0	29.0
VBF	0.09	ee	1.94	0.76	1.13	0.71	0.35	0.92	0.51
		$\mu\mu$	2.40	0.97	1.43	0.89	0.43	1.18	0.65
VH + t \bar{t} H	1.84	ee	0.04	0.13	1.89	0.31	0.17	0.45	0.27
		$\mu\mu$	0.05	0.16	2.36	0.39	0.21	0.57	0.33
Resonant background									
H \rightarrow $\mu\mu$	0.14	$\mu\mu$	0.27	0.27	0.43	0.62	0.49	2.02	1.78
Mass resolution (GeV)	2.12	ee	1.91	2.06	2.15	1.80	1.97	2.12	2.33
		$\mu\mu$	1.52	1.61	1.72	1.37	1.42	1.62	1.83
Data yield	1485		168	589	11596	1485	1541	2559	17608
S/\sqrt{B}	0.06		0.54	0.24	0.26	0.45	0.35	0.53	0.30

- Yields defined in narrowest mass window containing 95% of signal
- Resolution defined in narrowest mass window containing 68% of signal

Signal and background modeling



Signal modeling

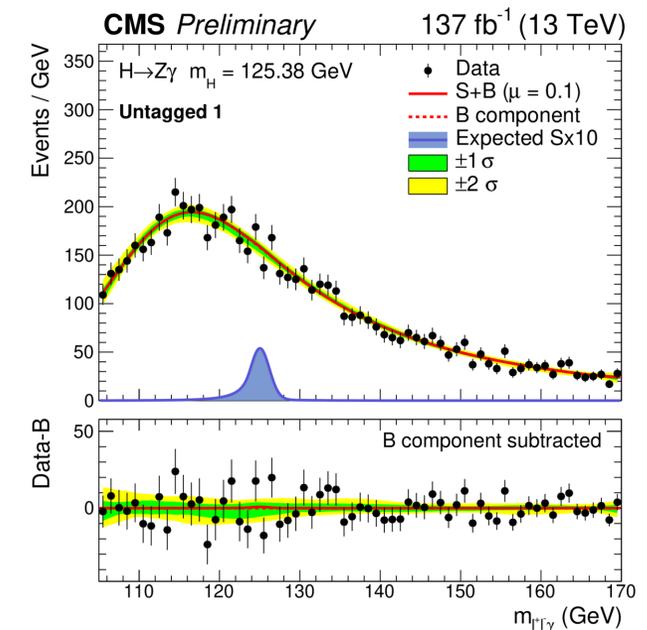
- Model signal with a Crystal Ball function plus a Gaussian function
- Account for differences in mass resolution for different years and channels
- Shape parameters obtained from MC are held fixed during the final fit to data.

Background Modeling

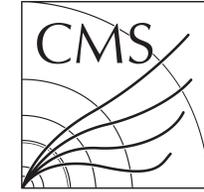
- Background model obtained from analytic fit to the $m_{\ell^+\ell^-\gamma}$ data in each category
 - Fit range is $105 < m_{\ell^+\ell^-\gamma} < 170$ GeV, which includes turn-on
 - Background function choice determined by envelope method, which treats the choice of function as a discrete nuisance parameter

$$\mathcal{F}(m_{\ell^+\ell^-\gamma}; \mu, \sigma, s, \vec{\alpha}) = \int_{105}^{170} \mathcal{N}(m_{\ell^+\ell^-\gamma} - t; \mu, \sigma) f(t; \vec{\alpha}) \Theta(t; s) dt$$

- \mathcal{F} is the general functional form considered.
- Gaussian component models the low-mass turn-on
- $f(t; \vec{\alpha})$ is a falling spectrum component profiled by envelope method
 - Families: exponential, power law, Laurent, Bernstein polynomial

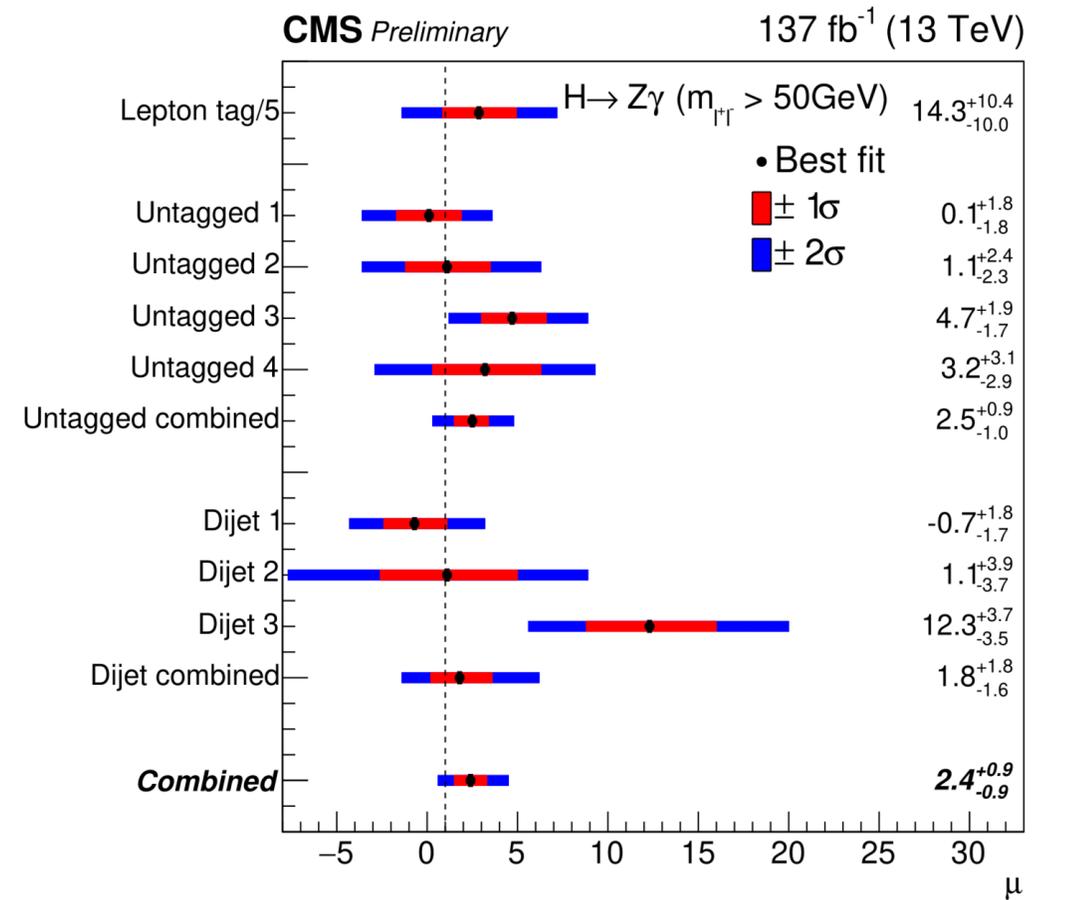
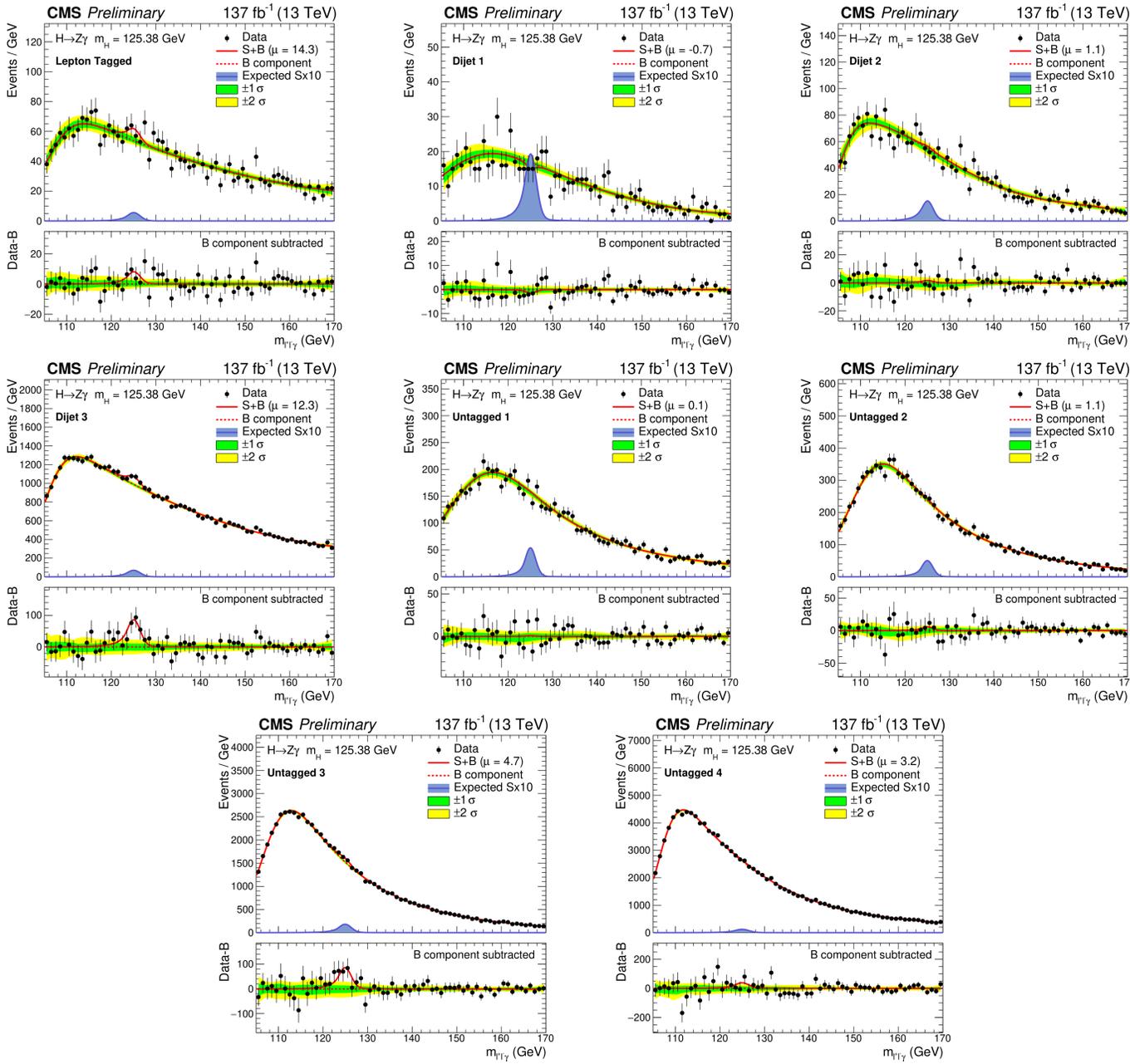
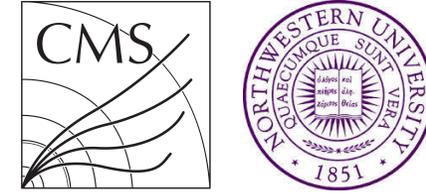


Systematic uncertainties



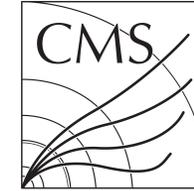
- Systematic uncertainty due to the choice of background function is taken into account by the envelope method in the fit to data
- Uncertainty in background normalization taken from fit to data
- Uncertainties related to signal
 1. Signal yield
 - Theory
 - Luminosity
 - Event weights and corrections
 - BDT uncertainties
 2. Signal shape
 - Lepton energy scale and resolution
 - Photon energy scale and resolution
- Impact of systematic uncertainties on the final results is roughly 5%.
 - Statistical uncertainties dominate in this search.

Category Results



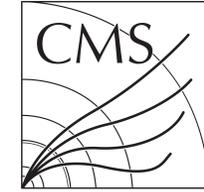
Channel compatibility p-value: 0.02 (2.3σ)

Measurement of $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma)$

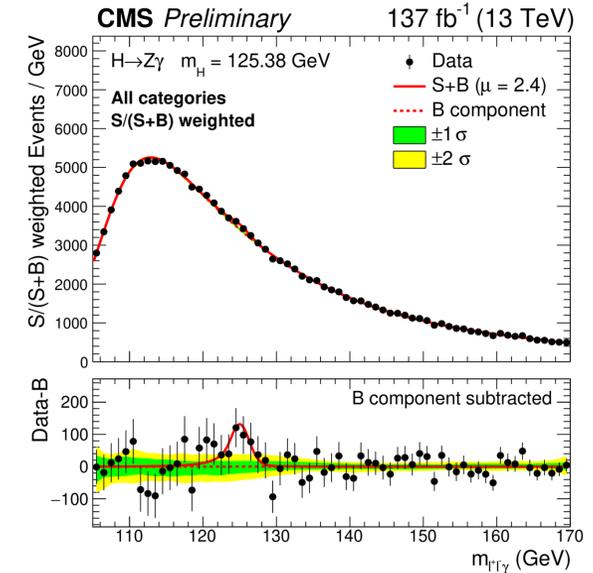
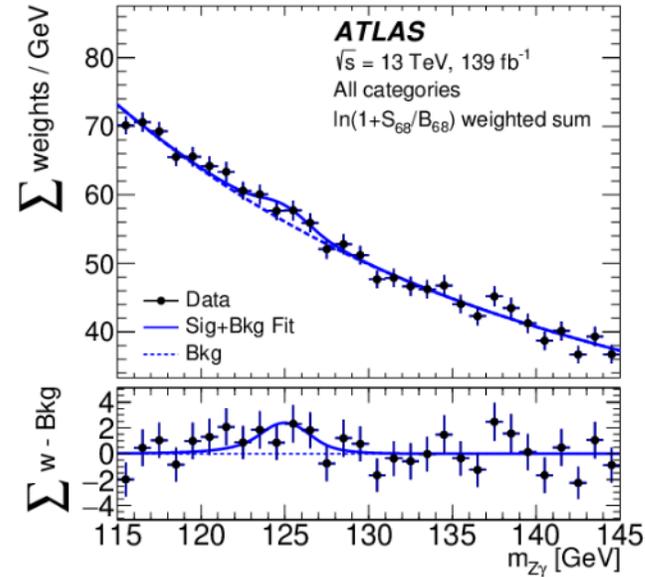


- Measurement of $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma)$ theoretically interesting, as it is sensitive to potential BSM physics
 - SM prediction: 0.69 ± 0.04
- Perform a combined fit with the $H \rightarrow \gamma\gamma$ analysis
 - Two parameters of interest: $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}/\mu_{\gamma\gamma}$
 - Common systematic uncertainties correlated in the fit
 - Higgs mass hypothesis is $m_H = 125.38$ GeV
- Scale $\mu_{Z\gamma}/\mu_{\gamma\gamma}$ to the ratio $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma)$
- Result: $\mathcal{B}(H \rightarrow Z\gamma)/\mathcal{B}(H \rightarrow \gamma\gamma) = 1.54^{+0.65}_{-0.58}$
 - Agrees with SM at the 1.5σ level

Comparison with ATLAS

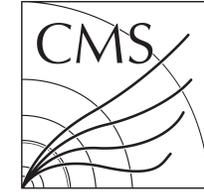


- Theoretical inputs are similar
- Expected sensitivity is similar
- Measured results are compatible



		ATLAS	CMS
Theoretical input	$\mathcal{B}(H \rightarrow Z\gamma)$	$1.54 \pm 0.09 \times 10^{-3}$	$1.567 \pm 0.09 \times 10^{-3}$
	m_H	125.09 GeV	125.38 GeV
Measurement	Signal strength	$2.0^{+1.0}_{-0.9}$	$2.4^{+0.9}_{-0.9}$
	Observed significance	2.2σ	2.7σ
	Expected significance	1.2σ	1.2σ
	95% CL observed (expected) limit	3.6 (1.7)	4.1 (1.8)
	$\sigma(\text{pp} \rightarrow H) \times \mathcal{B}(H \rightarrow Z\gamma)$	305 fb (95% CL UL)	352 fb (95% CL UL), 210 ± 80 fb (measured)
	Mass resolution	4.0 GeV	3.7 GeV

Comparison of analysis techniques



		ATLAS (Run 2)	HIG-17-007 (2016)	HIG-19-014 (Run 2)
FSR photon recovery		Yes	No	Yes
Kinematic fit		Yes	No	Yes
Categorization	Lepton tag	No	Yes	Yes
	Dijet	VBF BDT	Cut-based	VBF BDT
	Untagged	p_T^t	R_9^γ, η_γ	Kinematic BDT
	Boosted	p_T^t	p_T^H	Not needed

Mass contributions

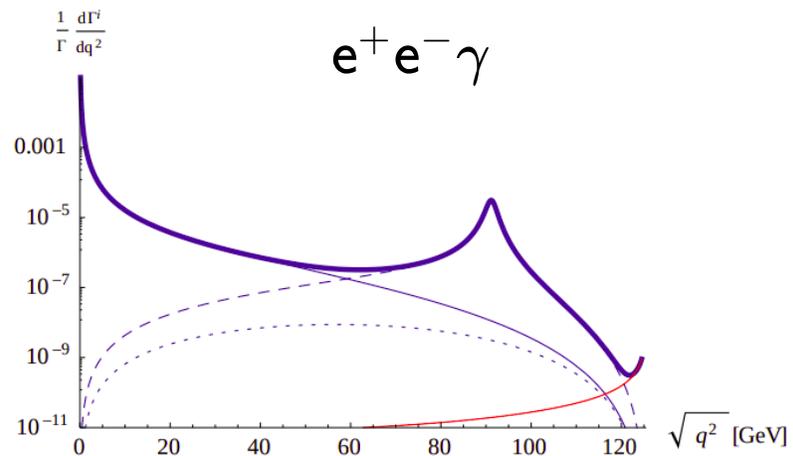
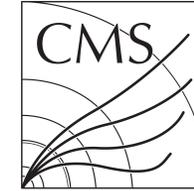


Figure 4: The invariant mass distributions of $h \rightarrow \gamma e^+ e^-$ normalized by $\Gamma(h \rightarrow \gamma\gamma)$. The red line denotes the contribution of the tree diagrams, the thin solid line denotes the contribution from the γ^* pole diagrams, and the dashed line the contribution from the Z^* pole diagrams while the thick line gives the total contributions. The dotted line denotes the contribution from the four-point box diagrams.

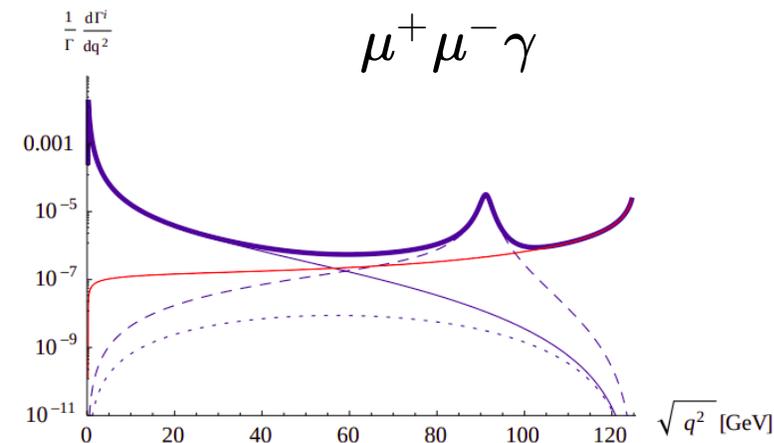


Figure 5: The invariant mass distribution of $h \rightarrow \gamma \mu^+ \mu^-$ normalized by $\Gamma(h \rightarrow \gamma\gamma)$. The red line denotes the contribution of the tree diagrams, the thin solid line denotes the contribution from the γ^* pole diagrams, and the dashed line the contribution from the Z^* pole diagrams while the thick line gives the total contributions. The dotted line denotes the contribution from the four-point box diagrams.

Sun, Chang, Gao, 2013