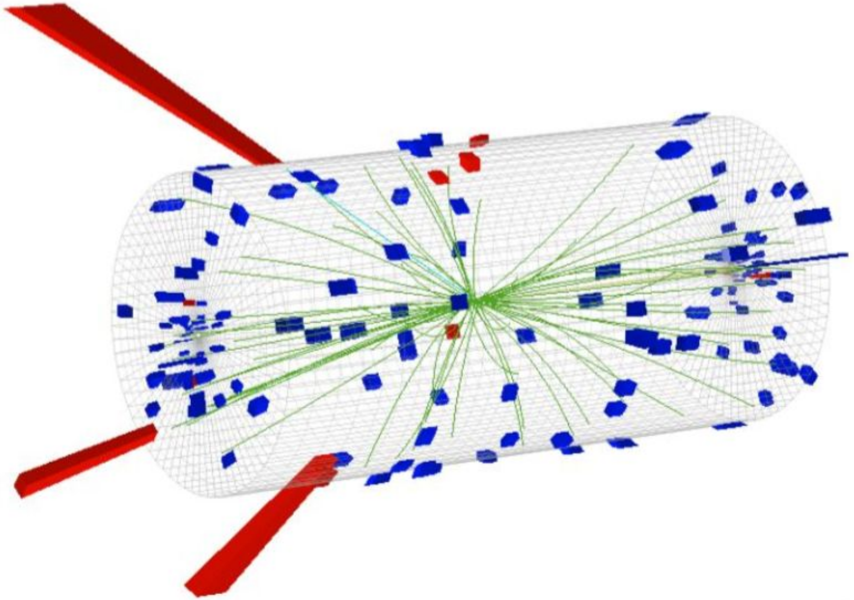
Search for the Rare Higgs Boson Decay $H \rightarrow Z\gamma$ with Run 2 and Early Run 3 CMS Data



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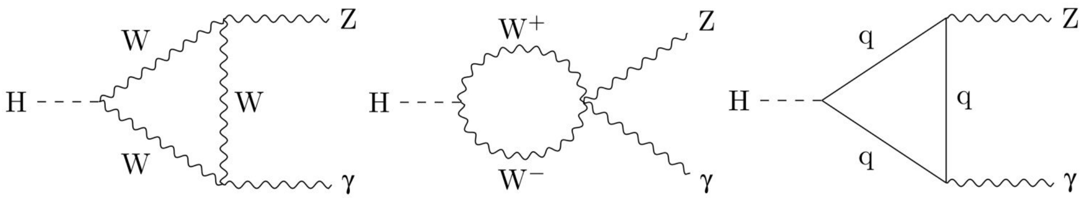
Introduction: H → Zγ

- Rare loop-induced Higgs decay.
- $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (1.5 \pm 0.1) \times 10^{-3}$
  - Z→e+e-/μ+μ-



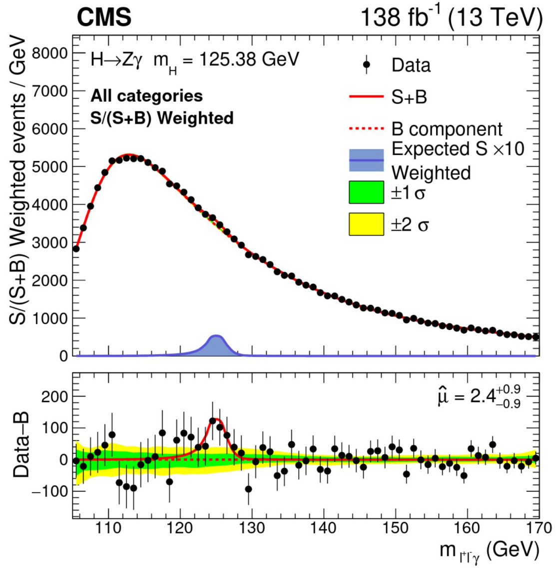
W loop | Associated-type | Top/quark loop

Why interesting?

- Loop-induced ⇨ Large relative senstivity to new physics.
- Particularly sensitive to scenarios such as composite Higgs models.

Current result:

- Run 2 pre-UL CMS result: signal strength μ = 2.4 ± 0.9
- ATLAS Run2+22–24: μ = 1.3 +0.6/-0.5



Why challenging?

- Tiny signal and irreducible background from Z+γ/fake γ.

Analysis Strategy

Analysis chain:

Run2 UL + 2022-23 Data/MC 200fb^{-1} → **Z(ll)+γ selections** → **Z mass constrain reconstruction** 10-20% better on resolution → **Procution mode categorization** cut-based on VH/ttH mode → **BDT categorization** ggF: 4 bins VBF: 4 bins → **Simultaneous $m_{ll\gamma}$ fit** 13 categories data-driven background

Improvement in three directions:

More signal
- single + dilepton triggers
  Improve ~10% trigger efficiency
- optimized selection for higher efficiency and sensitivity

Better separation
- Better signal resolution.
- Target on all production mode
- ggF/VBF BDT modification

Robust extraction
- Sequence of fitting tests
- High statistics bias test based on simulation

Expected sensitivity: ~50% expected sensitivity improvement

Recover signal and Sharpen the Higgs peak

Trigger:

- OR of single and double lepton trigger
  - Efficiency 80%→93% in electron channel
  - Efficiency 87%→97% in muon channel
- +15% / +12% trigger efficiency

– Dilepton OR single lepton triggers

– Dilepton triggers only

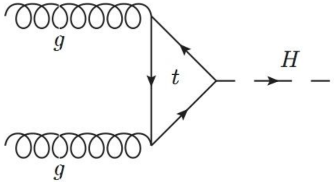
Z-constraint fit:

- Use maximum likelihood estimation with fit of MC truth m_Z line shape
  - Incorporate FSR photon recovery for muons
- Improve $m_{ee\gamma}$ resolution ~20% and $m_{\mu\mu\gamma}$ resolution ~10%
  - Signal resolution: e: 1.4-1.8 GeV; μ: 1.2-1.5 GeV

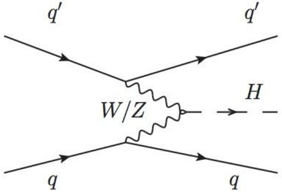
Categorization maximizes sensitivity

- Optimize categorization for all production mode. (4 ggF + 4 VBF + 2 VH + 2 ttH + untagged)
- Cut based for VH and ttH and BDT sub-categorization for ggF and VBF.

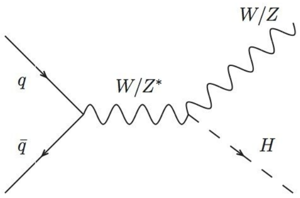
N_{sig} passing baseline:

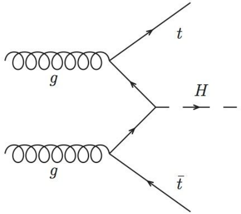


ggF: 280



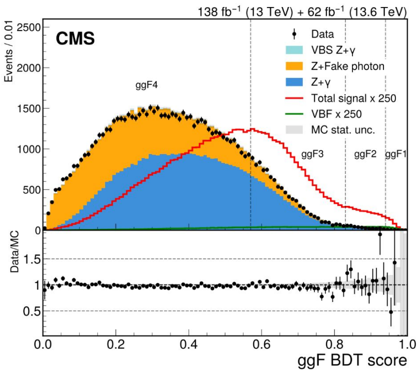
VBF: 23



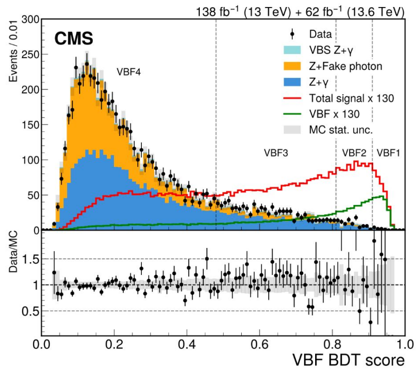


Associated production mode: 14

- ~80% signal enters ggF-targeted category
- VBF category provides the largest individual sensitivity
- BDT variables chosen for S/B discrimination while avoiding $m_{ll\gamma}$ sculpting
- 4-fold training/validation



ggF BDT



VBF BDT

Substantial Sensitivity Improvement

Improvement breakdown:

- Selection improvement:
  - single-lepton trigger
  - looser min $\Delta R(l,\gamma)$, etc.
- Binning optimization:
  - with fit robustness check
- Improved BDT:
  - XGBoost
  - better variables choice
  - train in Higgs mass peak
- Extended MC:
  - high-statistic fake-photon samples

Z-constraint fit:

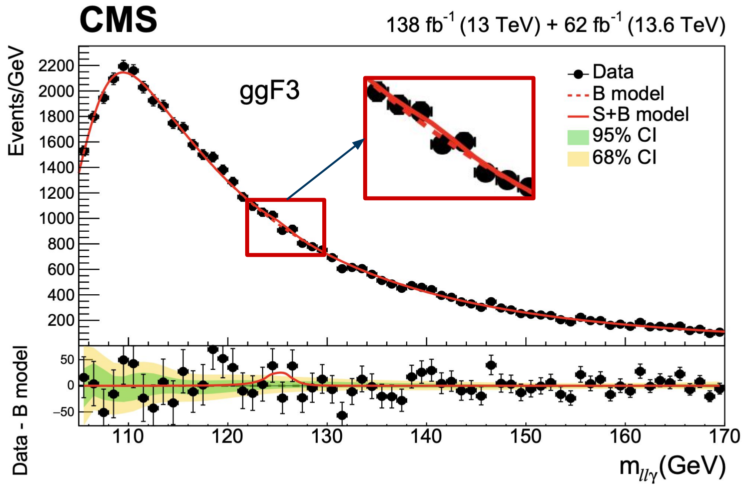
- Use maximum likelihood estimation with fit of MC truth m_Z line shape
  - Incorporate FSR photon recovery for muons
- 10–20% improvement in $m_{ll\gamma}$ resolution
  - resolution: e: 1.4-1.8 GeV; μ: 1.2-1.5 GeV

Category	ggF1	ggF2	ggF3	ggF4	VBF1	VBF2	VBF3	VBF4
$\sigma_{\text{eff}}(e^+e^-\gamma)$ (GeV)	1.47	1.59	1.65	1.83	1.45	1.53	1.63	1.80
$\sigma_{\text{eff}}(\mu^+\mu^-\gamma)$ (GeV)	1.23	1.26	1.29	1.50	1.29	1.32	1.36	1.50

Category	VH $N_\ell \geq 3$	VH p_T^{miss}	$t\bar{t}$H had.	$t\bar{t}$H lep.	Untag.
$\sigma_{\text{eff}}(e^+e^-\gamma)$ (GeV)	1.70	1.70	1.56	1.62	1.69
$\sigma_{\text{eff}}(\mu^+\mu^-\gamma)$ (GeV)	1.47	1.34	1.34	1.38	1.42

A Robust Background Model is Essential

- Simultaneous binned maximum-likelihood fit to $m_{ll\gamma}$ distribution in data in 13 categories.
- **Chanllenge:** extract small signal over large background without bias.
- A bunch of test on the background.



Fit for one category (ggF3) showing what S+B fit might look like

1.Goodness of fit on data sidebands

⭐ 2.Spurious signal with **high stats MC bkg**

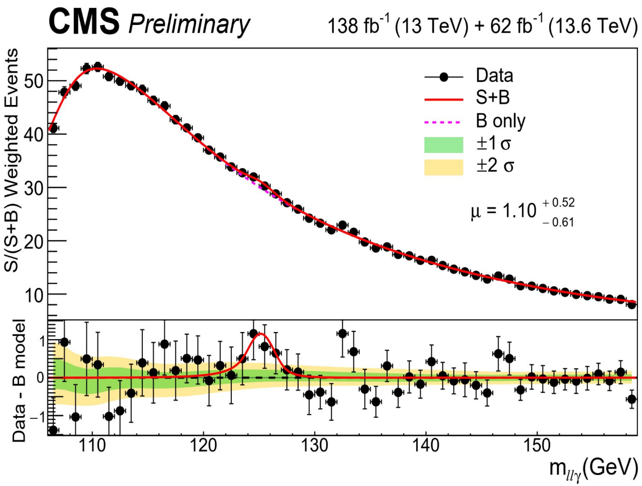
3.Fisher (F) on data sidebands

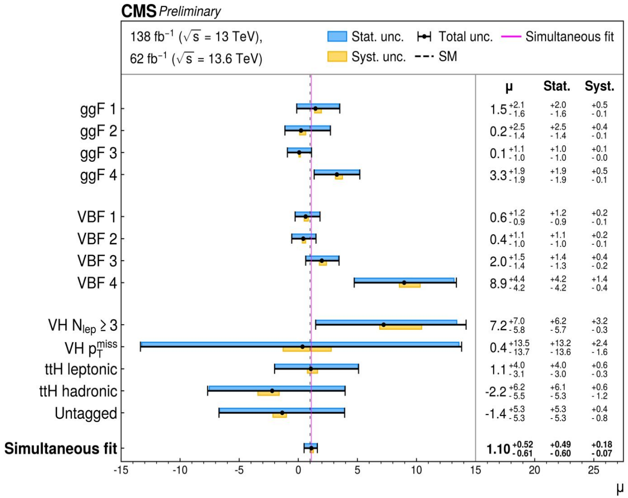
4.Bias (0 or different signal strength injected)

Validated function envelope:
chosen dynamically through discrete profiling

Result

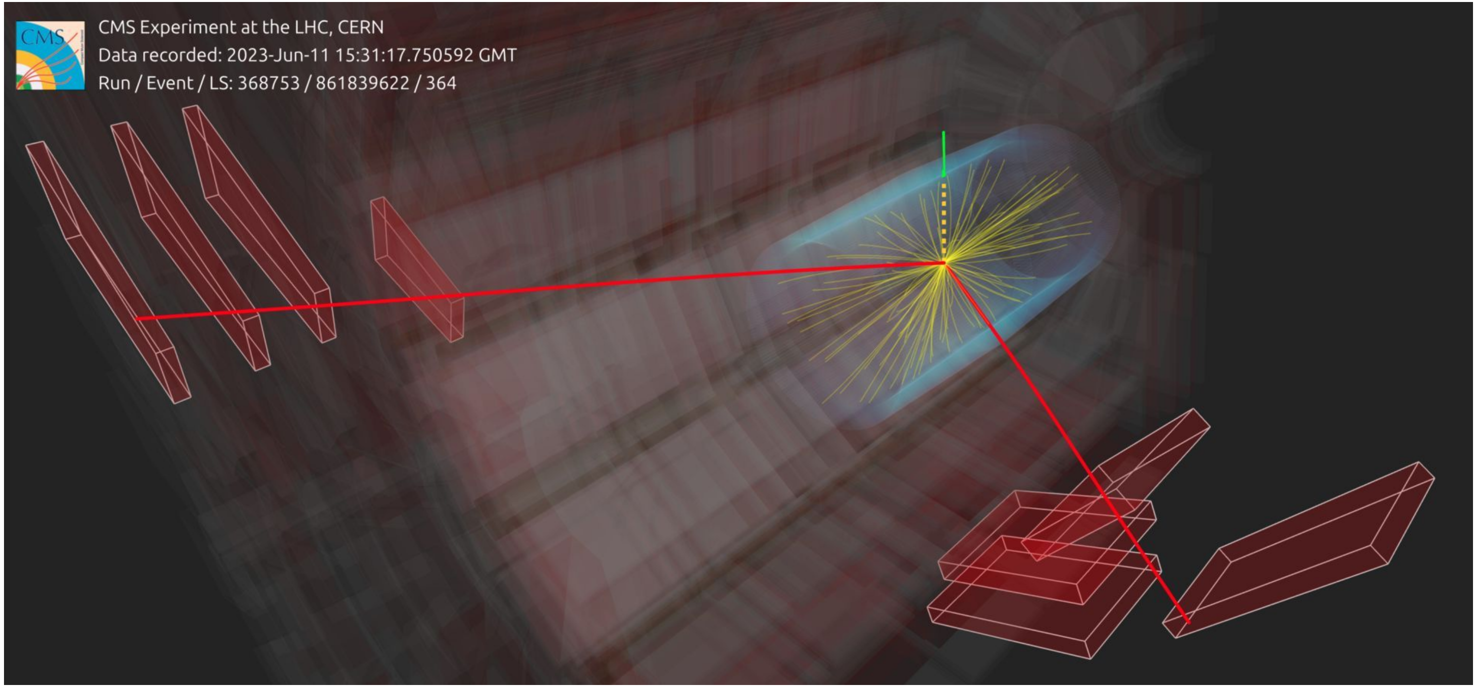
- A simultaneous fit to the $m_{ll\gamma}$ spectra is performed in 13 categories.
- An excess compatible with a Higgs boson signal is observed near 125 GeV.
- Observed significance: 1.9σ (expected: 2.3σ post-fit).
- Best-fit signal strength: μ = 1.10+0.52/-0.61, consistent with the SM.
- Channel Comparibility: p = 0.75.





Summary

- H→Zγ is a rare and sensitive Higgs probe
- New reconstruction and categorization significantly improve sensitivity
    - expected significance: about 50% improvement.
- Data are consistent with the SM
    - $\mu = 1.10^{+0.52}_{-0.61}$, observed **1.9σ**
- The analysis is still statistics limited
    - The full Run 3 dataset should provide a substantial improvement



Thanks for your attention!

Back Up

Extended MC sample for Z+fake photon

- Limited MC statistics in Z+fake photon sample an issue for spurious signal test
- Extend MC used for BDT training and spurious signal (bias) test based on sources of fake photons

"Pile-up" (non-PV) photon
No PV particle nearby

"Jet" (PV) photon
PV (nonprompt) photon nearby

Other particles
Other PV particle nearby

Extend sample by mixing photons and Z bosons from different events (~45%)

Extend sample by generating MC with filter to select (nonprompt) photons (~50%)

Mix of coincidences and and other misID'd jets: extend with combination of other two methods (~5%)

(Percentages based on 2017 UL MC)

Physics Object Definitions

Photon selection

p_T >15 GeV ⟶ **custom SF**
$\lvert\eta_{sc}\rvert$<2.5 and not gap
$\Delta R_{min}(l,\gamma)$>0.3 (looser, better ε_S)
Conversion-safe electron veto, [γ/e cleaning requirement]
Fall17v2 (run 2)/Winter22 ID (run 3) w/ ISO, WP80 (tighter & standardized)

Electron selection

p_T>7 GeV (trigger pT threshold higher)
$\lvert\eta_{sc}\rvert$<2.5
$\lvert d_z\rvert$<1.0 cm, $\lvert d_{xy}\rvert$<0.5 cm
Fall17v2 ID WPL (run 2) HToZZ(2018) ID with 2022 WP (run 3)

Muon selection

p_T>5 GeV (trigger pT threshold higher)
$\lvert\eta\rvert$<2.4
$\lvert d_z\rvert$<1.0 cm, $\lvert d_{xy}\rvert$<0.5 cm, SIP3D<4
Loose ID
I_{rel}<0.35

Jet selection

p_T >30 GeV
$\lvert\eta\rvert$<4.7
Tight jetID, loose PUID
Jet veto (run 3), HEM veto, horn veto

b-tagging with deepJET
p_T^{miss} filters + set p_T^{miss} to 0 in events with jets failing veto

Primary Event Categorization

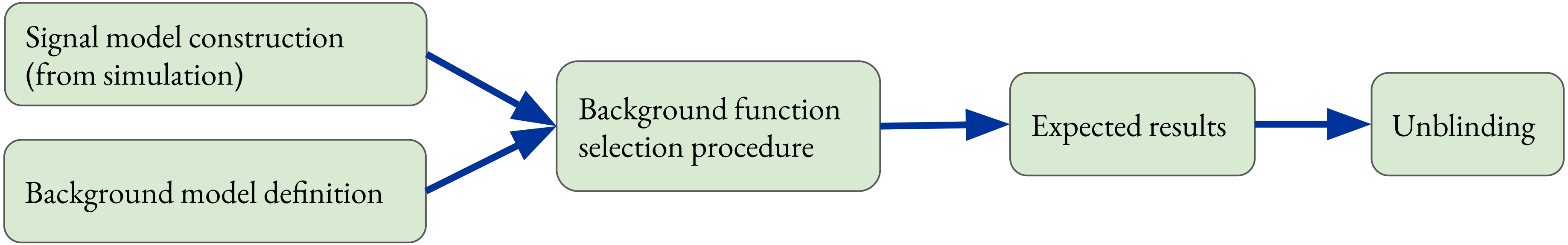
Category	Lepton, jet, and $p_{\mathrm{T}}^{\mathrm{miss}}$ requirements				Binning/optimization selections		
	N_{ℓ}	N_{jet}	N_{b}	$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	$m_{\ell\ell}$ (GeV)	$p_{\mathrm{T},\ell\ell\gamma}/m_{\ell\ell\gamma}$	I_{mini}
ggF	$=2$	≤ 1		<90	[Binned by ggF BDT (4 bins)]		
VBF	$=2$	≥ 2	$=0$		[Binned by VBF BDT (4 bins)]		
VH $N_{\ell} \geq 3$	≥ 3		$=0$	>30		>0.3	<0.15
VH $p_{\mathrm{T}}^{\mathrm{miss}}$	$=2$	≤ 1		>90		>0.4	
$\mathrm{t\bar{t}H}$ leptonic	$=3$ ≥ 4	≥ 3 ≥ 1	≥ 1 ≥ 1				<0.1
$\mathrm{t\bar{t}H}$ hadronic	$=2$	≥ 5	≥ 1		(85, 95)		
Untagged	Events passing baseline selection not assigned to any other category						

BDT Input Variables

Input variable	Description	ggF	VBF
	Higgs boson kinematic variables		
$p_{\mathrm{T},\ell\ell\gamma}/m_{\ell\ell\gamma}$	Higgs boson candidate p_{T} relative to its mass	✓	✓
	Photon quality indicators		
γ IDMVA	Photon identification MVA score	✓	✓
$\sigma_E(\gamma)/E(\gamma)$	Photon energy resolution	✓	✓
	Angular variables of final state particles from Higgs boson candidate		
$\eta(\ell_1), \eta(\ell_2), \eta(\gamma)$	Pseudorapidity of leptons and photon	✓	✓
$\Delta R_{\mathrm{min}}(\gamma,\ell)$ and $\Delta R_{\mathrm{max}}(\gamma,\ell)$	Separation between photon and leptons	✓	✓
$\cos\Theta$	Z boson production angle	✓	✓
$\cos\theta$	Z boson decay polar angle	✓	✓
ϕ	Z boson decay azimuthal angle	✓	✓
	Jet variables		
$\eta(\mathrm{j})$	Jet pseudorapidity	✓	
$p_{\mathrm{T}}(\mathrm{j}_{1,2})$	Jet transverse momenta	✓	✓
$\Delta\eta(\mathrm{j}_1,\mathrm{j}_2)$	Dijet pseudorapidity separation		✓
$\Delta\phi(\mathrm{j}_1,\mathrm{j}_2)$	Dijet azimuthal angular separation		✓
$\Delta R(\mathrm{j}_{1,2},\gamma)$	Jet separation from photon	✓	✓
$m_{\mathrm{j}}, m_{\mathrm{jj}}$	Jet/dijet system invariant mass	✓	✓
N_{jet}	Number of jets	✓	✓
	System balance indicators		
$\Delta\phi(\ell^+\ell^-\gamma,\mathrm{j}), \Delta\phi(\ell^+\ell^-\gamma,\mathrm{jj})$	Azimuthal separation between jet/dijet and $\ell^+\ell^-\gamma$	✓	✓
$\lvert\sum_{\ell\ell,\gamma,\mathrm{jets}} \vec{p}^{\,i}_{\mathrm{T}}\rvert / \sum_{\ell\ell,\gamma,\mathrm{jets}} p^i_{\mathrm{T}}$	System p_{T} balance	✓	✓
$\lvert\eta(\gamma)-\eta(\mathrm{j})\rvert, \lvert\eta_\gamma - \frac{\eta_{j_1}+\eta_{j_2}}{2}\rvert$	Pseudorapidity separation between photon and jet(s)	✓	✓
$\Delta\phi(\gamma,\vec{S}^{\mathrm{miss}}_{\mathrm{T}})$	Azimuthal angular separation between photon and $\vec{S}^{\mathrm{miss}}_{\mathrm{T}}$	✓	✓

Fit strategy

- Challenge: fit large background without bias to small signal
- Binned maximum-likelihood fit to $m_{ll\gamma}$ distribution in data
  - Simultaneous fit in 13 categories with single signal strength
  - Mass constrained to 125.38 GeV (+- nuisance)
- Each category is the sum Run 2+Run 3 (‘22, ‘23) and electron+muon events
  - Separate signal models for electron and muons, one single background model
  - Difference in signal width and background shape not enough to provide gain in significance if lepton flavors were separated (details)
  - $H\rightarrow\mu\mu+\gamma_{FSR}$ contribution (~3%) fixed to SM expectation
- Data-driven background determination (sidebands)



Signal model

- Model: double-sided Crystal Ball with symmetric core
- Available simulation at 120 GeV, 125 GeV and 130 GeV
- Due to low amount of simulated events:
  - Sum all production modes and campaigns, independent model for each combination of category and lepton flavour
  - Fix tails parameters of 120 GeV and 130 GeV fits to values of 125 GeV
- Parametric model as a function of the mass
  - Linear fit between of 120, 125 and 130 GeV to extrapolate model at 125.38 GeV
  - In the final fit, all the parameters are fixed or function of mH (fixed)
  - Nuisances on mean and sigma to account for MC scale/resolution uncertainties
- Same model from the 125 GeV simulation for the small resonant background from $H \rightarrow \mu\mu + \gamma_{FSR}$

Background model

- Model: “envelope” of functions, discrete profiling method (details)
  - One envelope per category since background turn-on at different locations
- Two kind of function families

$$\mathcal{F}(m_{\ell\ell\gamma};\mu_G,\sigma_G,s,\vec{\alpha}) \equiv \int_{-\infty}^{\infty} \mathcal{N}(m_{\ell\ell\gamma}-t;\mu_G,\sigma_G)\Theta(t;s)f(t;\vec{\alpha})dt,$$

  - Convolution models

    where N is the Gaussian function and f is a function from selected families (Bernstein polynomials, power laws, exponentials and Laurent series)
  - Asymmetric gaussian variants
- Emphasis on the robustness and reliability of the fit, multiple tests to select functions:

Goodness of fit on data sidebands → Spurious signal with **high stats MC bkg** → Fisher (F) on data sidebands → Bias (0 or different signal strength injected)

Spurious signal with **high stats MC bkg**, Bias (0 or different signal strength injected) } Final envelope

Comparison to ATLAS and HIG-19-014

- One coherent analysis over Run 2 + Run3 ('22, '23) searching for H→ Zγ with a total of
  - Improved analysis sensitivity 2.3
  - Focused on robustness and validation

Experiment	Dataset	$\mathscr{L}$ (fb^{-1})	Results
CMS	Run2 + '22, '23	200	$\mu = 1.10^{+0.52}_{-0.61} = 1.10^{+0.49}_{-0.60}\,(\text{stat})\,^{+0.18}_{-0.07}\,(\text{syst})$
			significance: 1.9 (2.3) σ
	Run2 HIG-19-014	138	$\mu = 2.4 \pm 0.9 = 2.4^{+0.8}_{-0.9}\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})$
			significance: 2.7 (1.2) σ
ATLAS	Run2 + '22, '23, '24 ATLAS	305	$\mu = 1.3^{+0.6}_{-0.5} = 1.3 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst})$
			significance: 2.5 (1.9) σ