Search for the Higgs Boson Decay $H \rightarrow Z\gamma$ with the CMS Experiment

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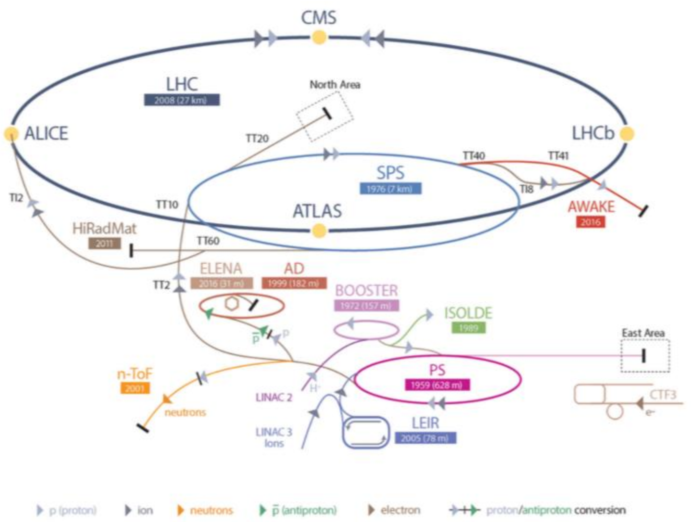
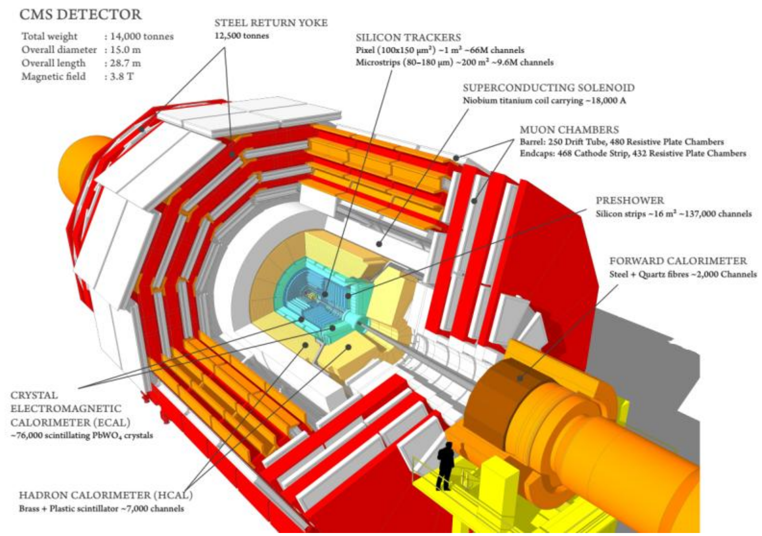
Large Hadron Collider and CMS Experiment

- The Large Hadron Collider (LHC) is the largest circular particle accelerator.
  - Located at CERN, Geneva, Switzerland
  - 27 km circumference, ~100 m underground
  - Colliding protons or heavy ions

- The Compact Muon Solenoid (CMS) is a general-purpose detector at LHC.
  - 14000 tons and 15×29 m
  - Cylindrical design with 4π solid angle coverage
- About 40M collisions recorded per second
  - Trigger system reduces the to ~1kHz
- Data processed by data centers worldwide.
  - ~20PB data annually



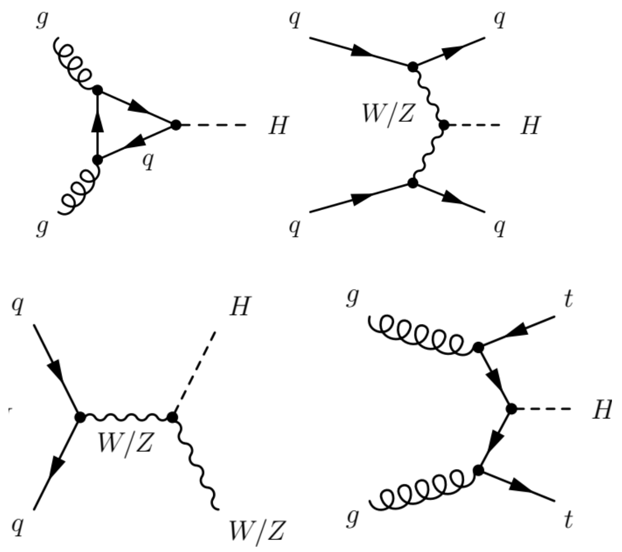
CERN accelerator complex



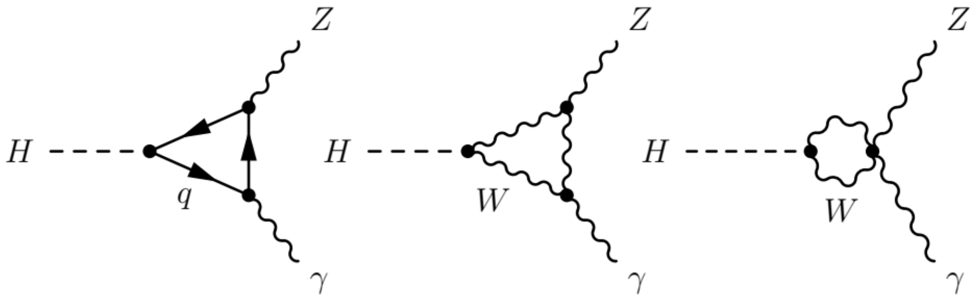
Schematic of CMS detector

H → Zγ Process

- H → Zγ → $e^+e^-\gamma/\mu^+\mu^-\gamma$ is a rare Higgs decay with SM BR(H→Zγ) ≈ 1.54×10^{-3}
  - All major Higgs production modes are considered
- Any deviation from SM prediction can hint for new physics beyond SM.
  - Higgs imposter, new fields that couple to Higgs, composite Higgs, etc.
- This analysis uses data collected in Run 2 (2016 – 2018) and early Run 3 (2022 and 2023)
  - 10M Higgs bosons produced
  - Expect about 15k events



Higgs boson production modes



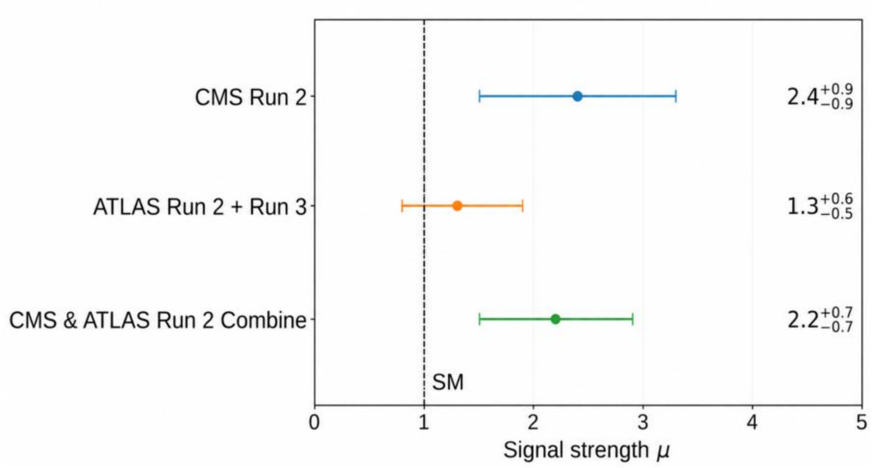
SM H → Zγ Feynman diagrams

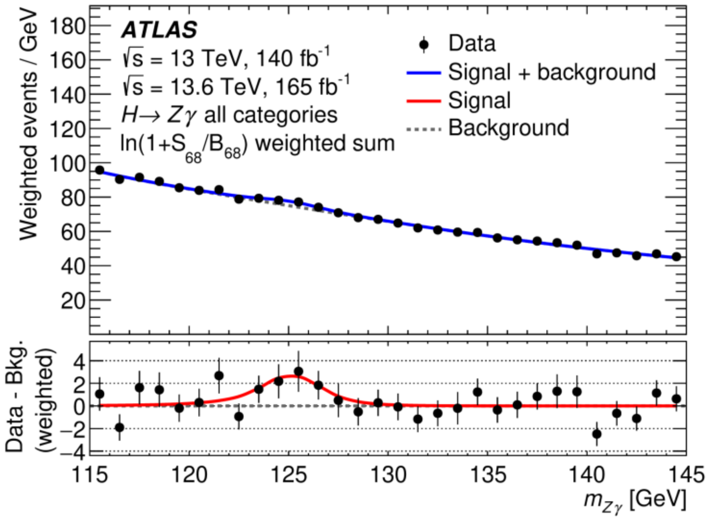
Results from CMS and ATLAS

- CMS Run 2 [1]: signal strength $\mu = 2.4^{+0.9}_{-0.9}$
- CMS + ATLAS (Run 2) [2]: $\mu = 2.2^{+0.7}_{-0.7}$
  - 1.9 s.d. consistency w/ SM
- ATLAS Run 2 + 2022-2024 [3]: $\mu = 1.3^{+0.6}_{-0.5}$ (305 fb^{-1})

- Signal strength: observed signal yield/expected signal yield

- Main challenges:
  - Tiny signal
  - Large backgrounds from non-resonant Z with photon
  - Avoid bias in the signal extraction procedure



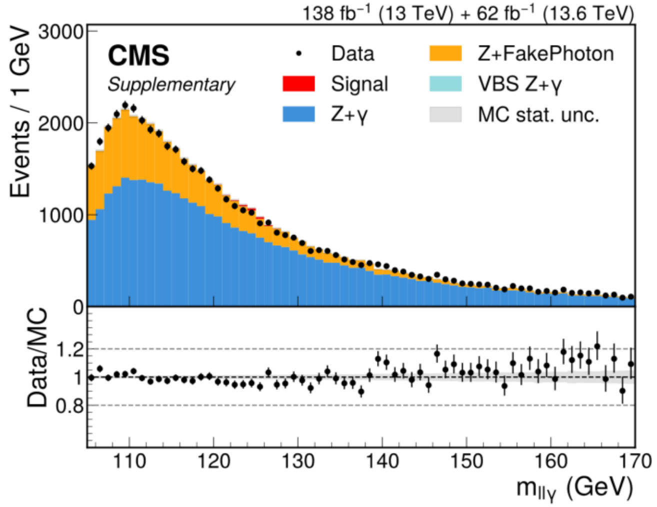


ATLAS weighted post-fit plot [3]

[1] JHEP 05 (2023) 233， [2] Phys.Rev.Lett. 132 (2024) 021803, 2024.
[3] HIGP-2024-19

Analysis Strategy

- Signal extracted from the distributions of the invariant mass of Higgs candidates, $m_{ll\gamma}$
- Data collected using single and dilepton triggers
- MC simulated samples are used to study background and signal
  - Two major non-resonant backgrounds are Z+γ and Z+fake photon
- Physics object selection and baseline selection to improve sensitivity
- Events are categorized into various categories based on Higgs production modes
  - Boosted Decision Tree (BDT) and kinematic variable selections
- Parametric models are used to fit the $m_{ll\gamma}$ distributions
- A sequence of tests is developed to ensure the parametric models can describe the shape with minimal bias



Data vs. MC shape comparison in one of the ggF categories

Event Categorization

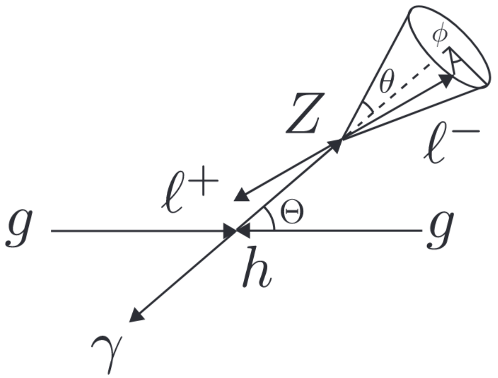
- After baseline selection, events are sorted into inclusive & non-overlapping categories
- Use object multiplicity and other basic event features to target all major Higgs production modes

Category name	Lepton, jet, and $p_{\mathrm{T}}^{\mathrm{miss}}$ requirements				Optimization selections		
	N_ℓ	N_{jet}	$N_{\mathrm{b,med.}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$m_{\ell\ell}$ [GeV]	$p_{\mathrm{T}}(\ell\ell\gamma)/m_{\ell\ell\gamma}$	I_{mini}
ggF	$= 2$	≤ 1		< 90	Further binned by BDT		
VBF	$= 2$	≥ 2	$= 0$		Further binned by BDT		
$\mathrm{t\bar{t}H}$ leptonic	$= 3$	≥ 3	≥ 1				< 0.1
	≥ 4	≥ 1	≥ 1				
VH $N_\ell \geq 3$	≥ 3		$= 0$	> 30		> 0.3	< 0.15
$\mathrm{t\bar{t}H}$ hadronic	$= 2$	≥ 5	≥ 1		[85,95]		
VH $p_{\mathrm{T}}^{\mathrm{miss}}$	$= 2$	≤ 1		> 90		> 0.4	
Untagged	Events passing baseline selection not in another category						

(HIG-25-010)

ggF and VBF BDT

- Kinematic variables selection optimized by signal and background separation and no correlation with $m_{ll\gamma}$
  - Higgs variables and jet variables
  - Used as BDT input variables
- Good data vs MC agreement

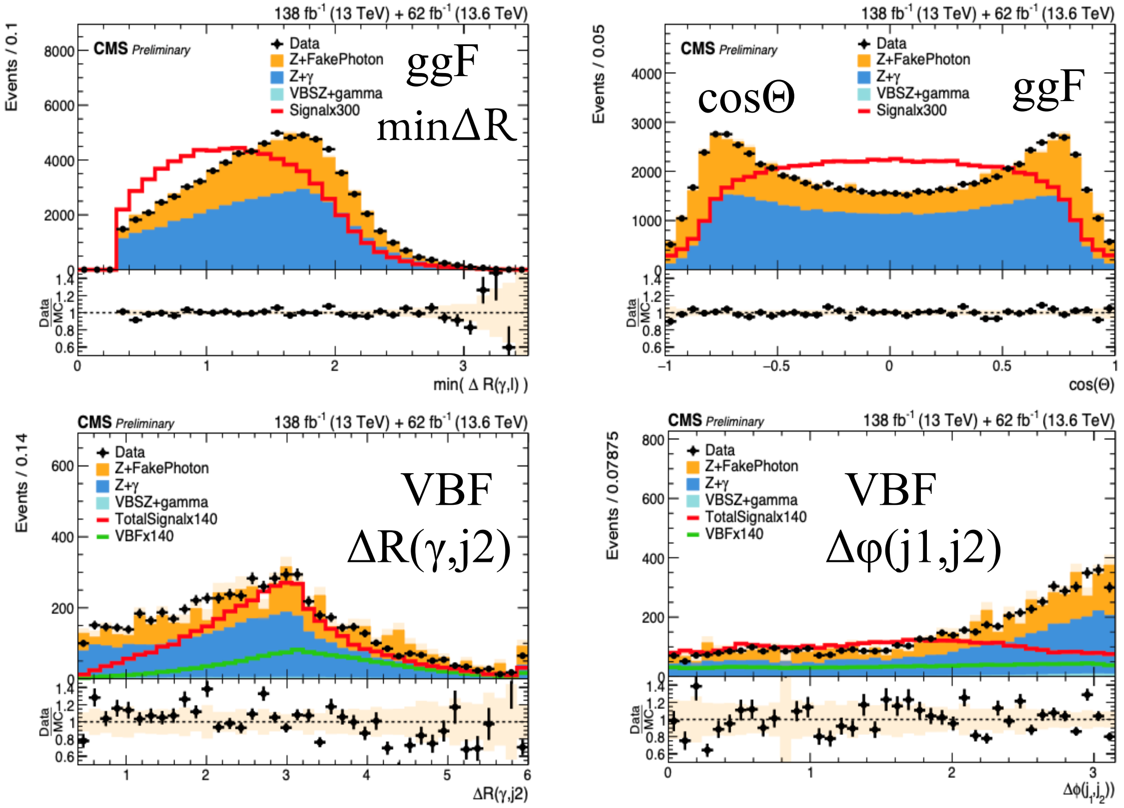


ggF BDT inputs:

Type	Variables
Boosted Higgs	$p_{T}^{ll\gamma}/m_{ll\gamma}$
Photon Quality	photon ID MVA
	σ_γ/E_γ
Angles Between Final State Particles	min $\Delta R(l,\gamma)$
	max $\Delta R(l,\gamma)$
	$\cos\Theta$
	$\cos\theta$
	ϕ
	$\lvert\eta_\gamma-\eta_{j1}\rvert$
	$\Delta R(j_1,\gamma)$
Angles Of Final State Particles	$\eta(l_1)$
	$\eta(l_2)$
	$\eta(\gamma)$
	$\eta(j_1)$
Jet Kinematics	j_1 m
	j_1 p_T
	N_{jets}
System Balance	system p_T balance
	$\Delta\phi(H^{miss}_T,\gamma)$
	$\Delta\phi(ll\gamma,j_1)$

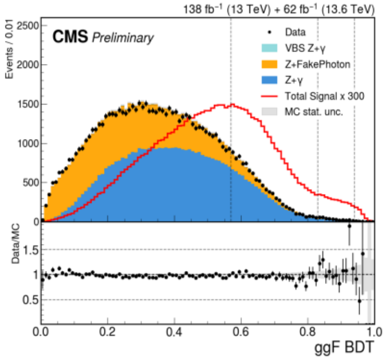
VBF BDT inputs:

Type	Variables
Boosted Higgs	$p_{T}^{ll\gamma}/m_{ll\gamma}$
Photon Quality	photon ID MVA
	σ_γ/E_γ
Angles Between Final State Particles	min $\Delta R(l,\gamma)$
	max $\Delta R(l,\gamma)$
	$\cos\Theta$
	$\cos\theta$
	ϕ
	photon zeppenfeld
	$\Delta R(j_1,\gamma)$
	$\Delta R(j_2,\gamma)$
Angles Of Final State Particles	$\eta(l_1)$
	$\eta(l_2)$
	$\eta(\gamma)$
Jet Kinematics	$m(j_1,j_2)$
	$\Delta\eta(j_1,j_2)$
	$\Delta\phi(j_1,j_2)$
	j_1 p_T
	j_2 p_T
	N_{jets}
System Balance	system p_T balance
	$\Delta\phi(H^{miss}_T,\gamma)$
	$\Delta\phi(ll\gamma,jj)$

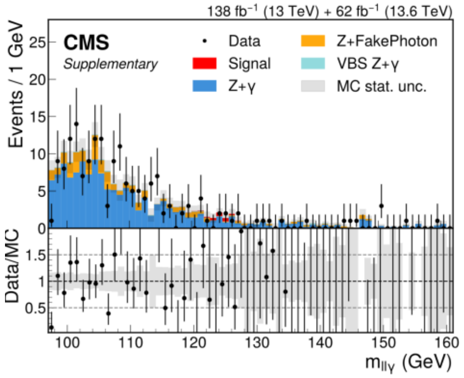


ggF and VBF Categories

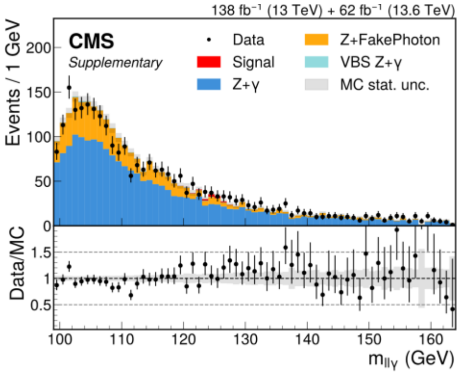
- Divide selected events into 4 categories based on their BDT scores.
  - Maximize cut-and-count significance in 120-130 GeV window: $Z_{cc} = \sqrt{2[(N_S + N_B) \cdot \ln(1 + N_S/N_B) - N_S]}$
- Two major backgrounds: Z+γ, Z + fake photon



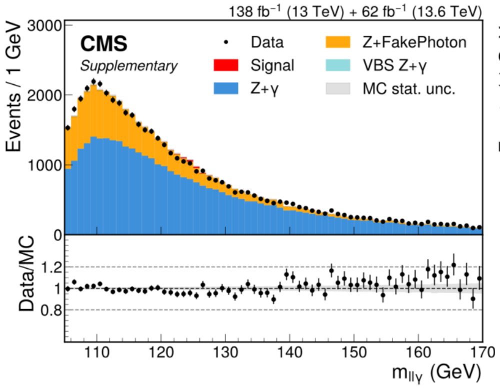
ggF BDT



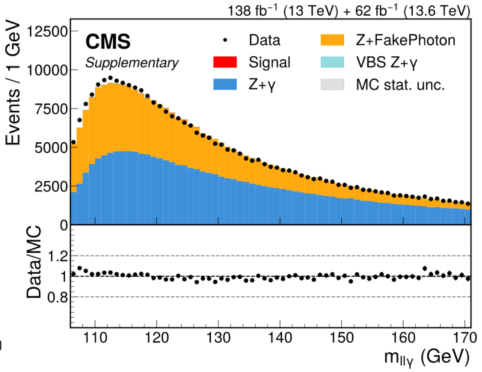
ggF1



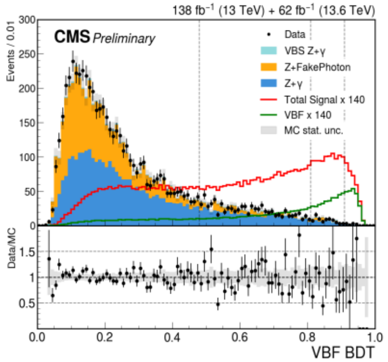
ggF2



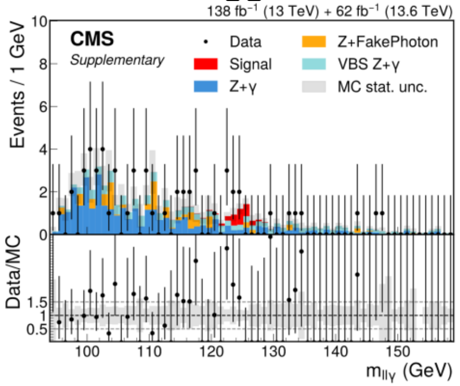
ggF3



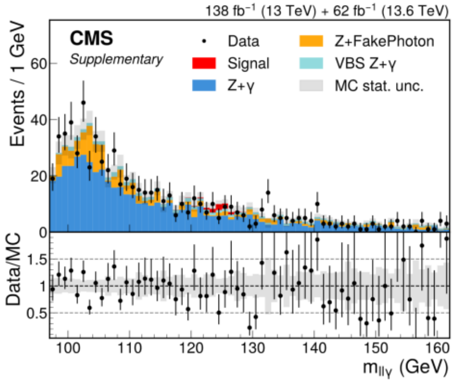
ggF4



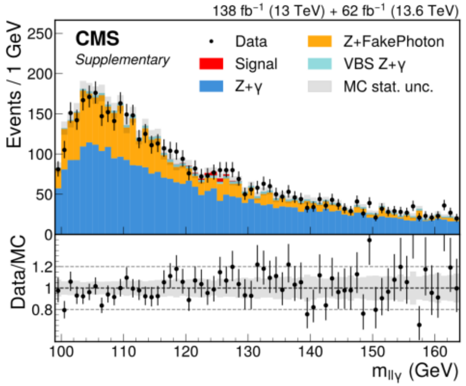
VBF BDT



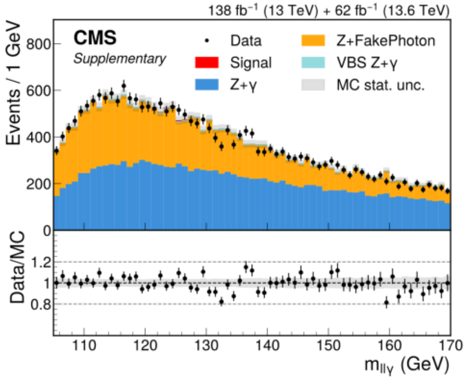
VBF1



VBF2



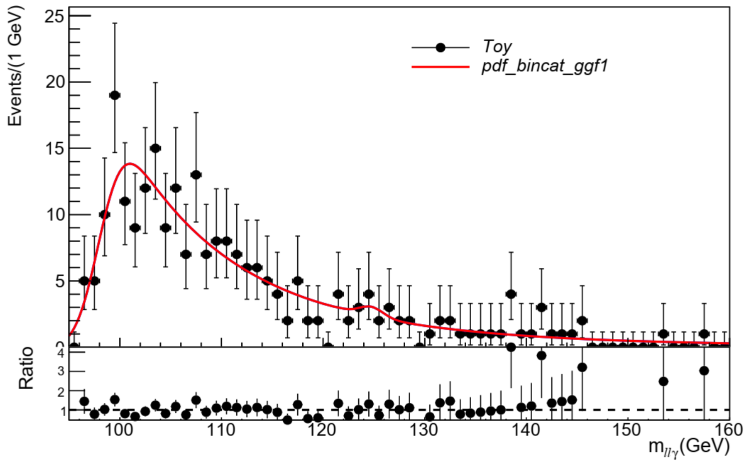
VBF3



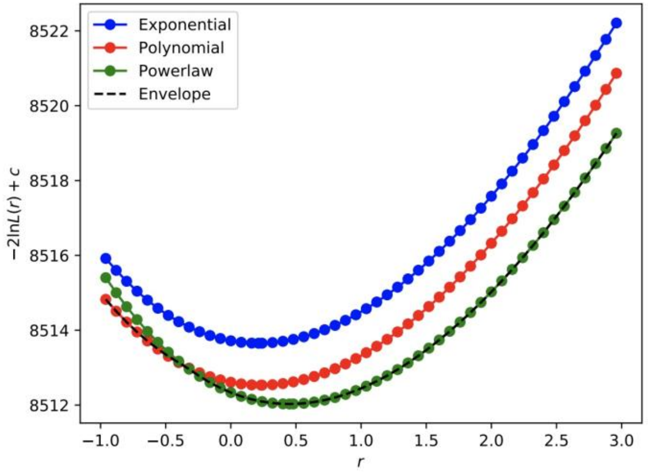
VBF4

Fit Strategy

- Parametric binned maximum likelihood fit to $m_{ll\gamma}$ distribution in data (ROOT/RooFit)
- For each category, fit over one $m_{ll\gamma}$ distribution summing Run 2+Run 3 and lepton flavors
    - Thirteen category simultaneous fit
- Background model using discrete profiling method where the fit can pick a model from a validated envelope
    - Discrete profiling method: The best-fit model is selected from a group of functional models, referred to as **envelope**. A discrete parameter, index, is floating for the choice of models.



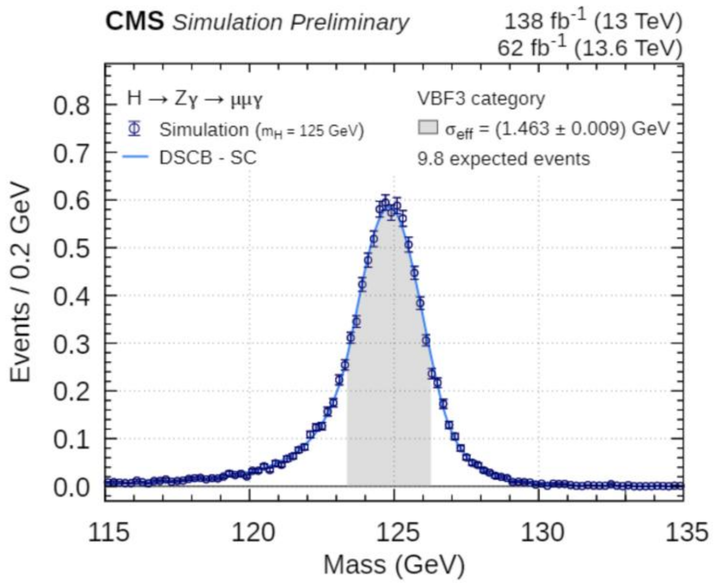
Toy data from one category showing what S+B fit looks like



Discrete profiling (CMS Combine)

Signal Model

- Double-Sided Crystal Ball (DSCB) with symmetric core as the signal model.
- Model parameters are determined by fits to signal MC samples
  - MC samples available at m_H = 120, 125, and 130 GeV.
  - Model mean and sigma values at m_H = 125.38 GeV are extrapolated from linear fit to results at three mass points.
- Model parameters are fixed for final fit, but nuisance parameters are floating to account for scale/resolution uncertainties.
- In each category, the signal model is an addition of two DSCB, one for each lepton flavor.
  - Years and production modes are not separated.
- Same model from the 125 GeV simulation for the small resonant background from $H\to\mu\mu+\gamma_{FSR}$



Signal model fit to VBF3 MC muon channel at m_H = 125 GeV

Background Model

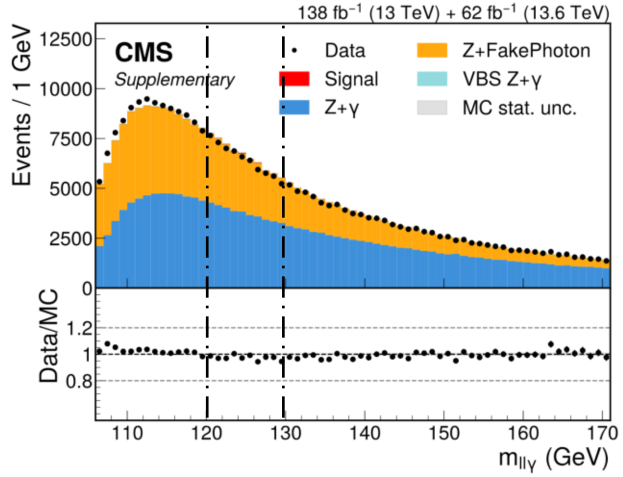
- With the selection, the background in general has a peak below the signal window and a falling region over the signal window.
  - Signal window: 120 – 130 GeV
- The convolution model is defined as

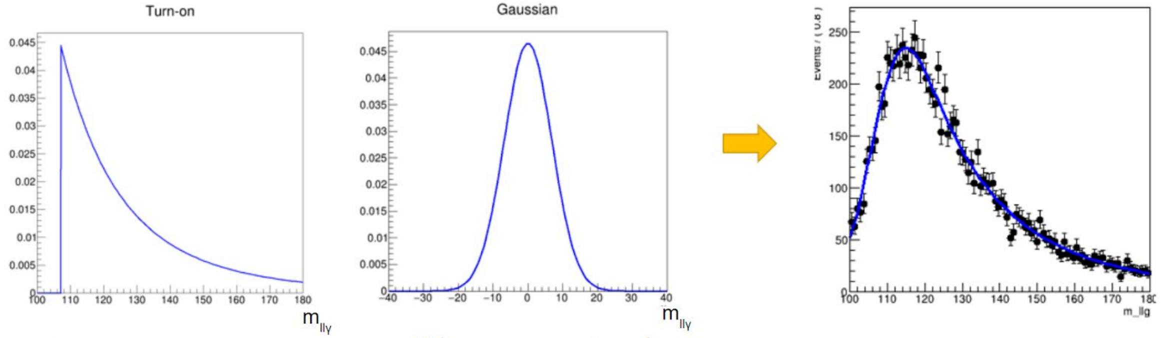
$$\mathcal{F}(m_{\ell\ell\gamma};\mu_G,\sigma_G,s,\vec{\alpha}) \equiv \int_{-\infty}^{\infty} \mathcal{N}(m_{\ell\ell\gamma}-t;\mu_G,\sigma_G)\Theta(t;s)f(t;\vec{\alpha})dt$$

where N is the Gaussian with $\mu_G = 0$, Θ is the step function at s and f is an empirical function.

- Different families of functions are used

- Asymmetric Gaussian variants
  - Modify the mean and sigma so that they are $m_{ll\gamma}$ dependent





$\Theta(m_{llg},s)f(m_{llg},\vec{\alpha})$ $N(m_{llg},\mu_G=0,\sigma_G)$

Convolution of an empirical function with a Gaussian

Fit Test Sequence

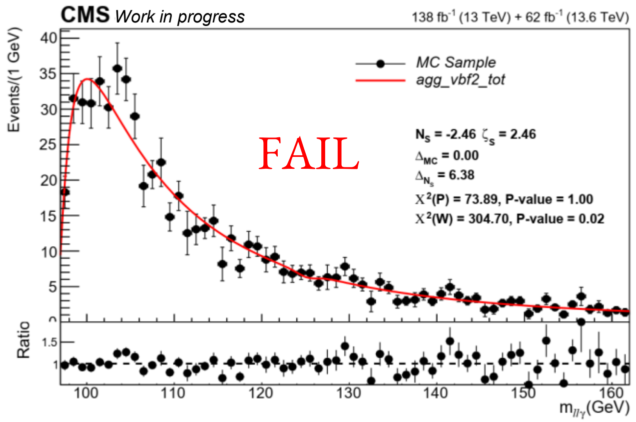
- To ensure the robustness and reliability of the final fit, background models must go through a sequence of tests
  - Good flexibility and with small fit bias
- A validated final background envelope is created for discrete profiling at the end of the sequence.

Signal model + initial bkg envelope → Goodness-of- fit test: $m_{ll\gamma}$ data sideband → Spurious signal: High-stats bkg MC → Fisher test: $m_{ll\gamma}$ data sideband

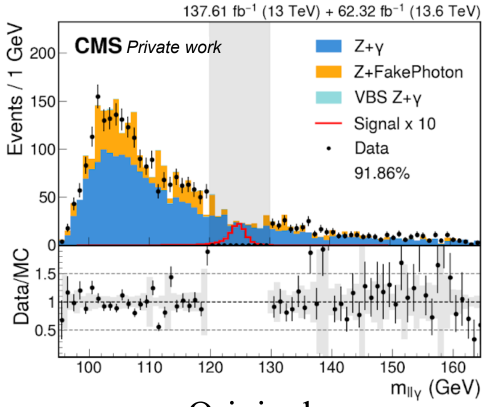
→ Profile bias test: Toy samples → Signal injection test: Toy samples → (Final bkg envelope) → Multi-category fit for expected significance (Discrete profiling) → Unblinding (Discrete profiling)

Spurious Signal Test and Low MC Statistics Challenge

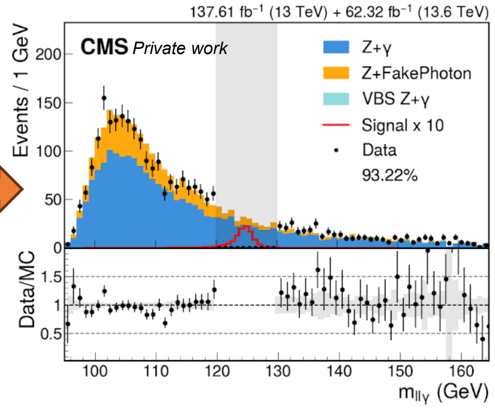
- Use the **background-only high statistics simulation** to test whether the S+B fit with a given background model would bias the signal measurement, giving “spurious signal”
- Central produced Drell-Yan MC sample has too low statistics.
  - Large fluctuation in Z + fake photon
- We study the physics of Drell-Yan process and generate more events with different methods, depending on the sources.
  - Events whose photon from pile-up: event mixing method
  - Events whose photon from jets: private MC with gen-level filter
- The high-stat Z + fake photon sample is used only in the BDT training and spurious signal test.



S+B fit of Exp1 bkg model over the high-stat MC of VBF2. This model fails the test with high spurious signal.



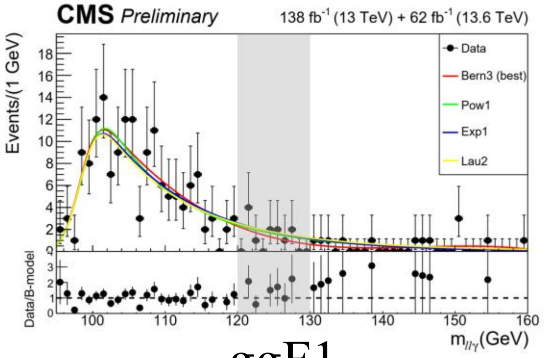
Original



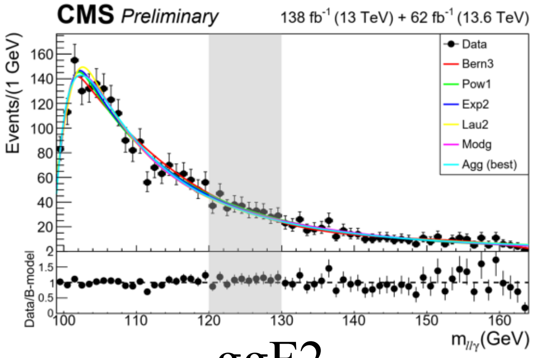
Extended

Final Background Envelopes

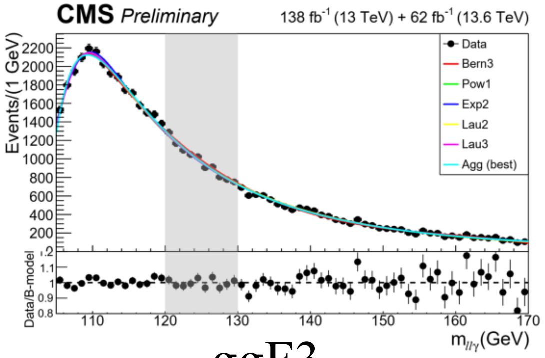
- Envelope functions are from data sideband fits.
- Scope of background functions restricted by the test sequence.



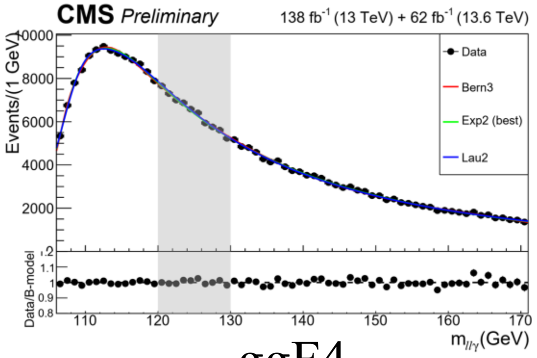
ggF1



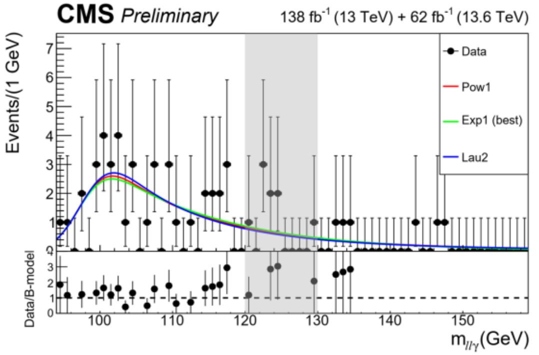
ggF2



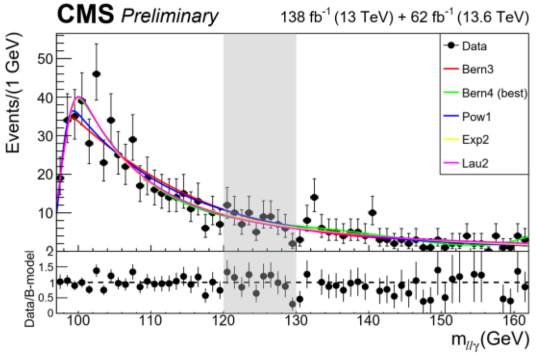
ggF3



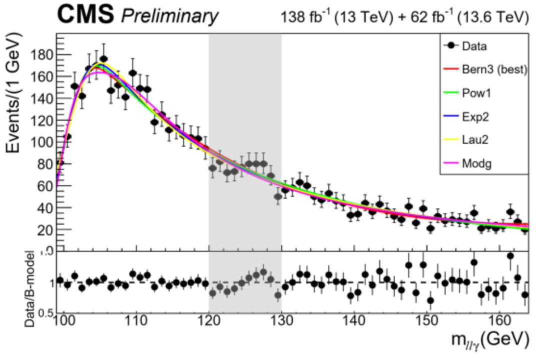
ggF4



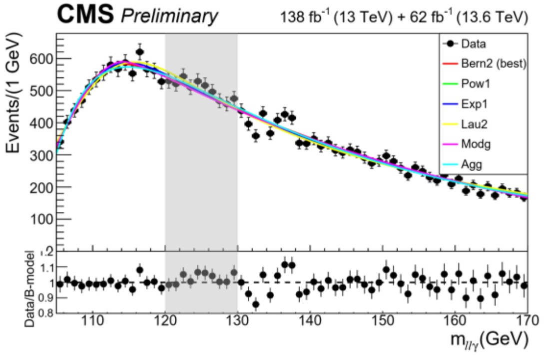
VBF1



VBF2



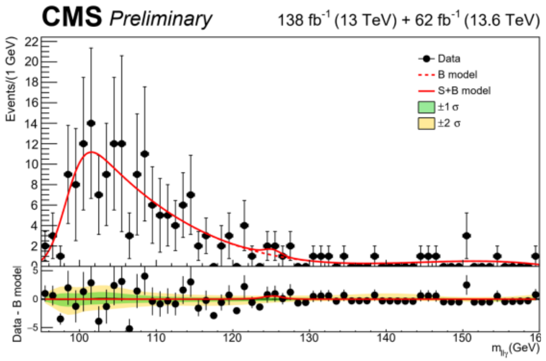
VBF3



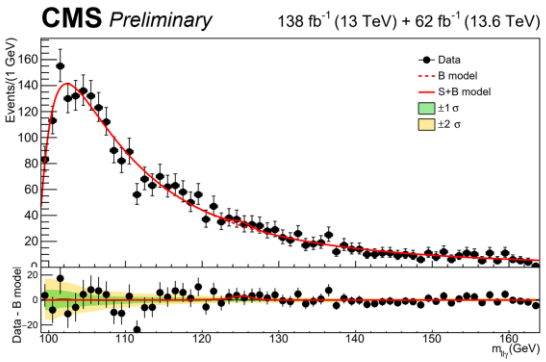
VBF4

Analysis Results - ggF and VBF Categories

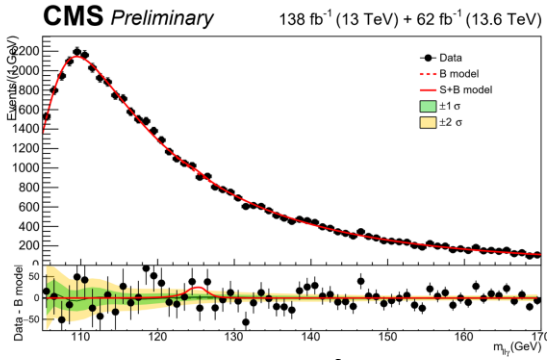
- S+B from simultaneous fit
- Fit provides good description of the data



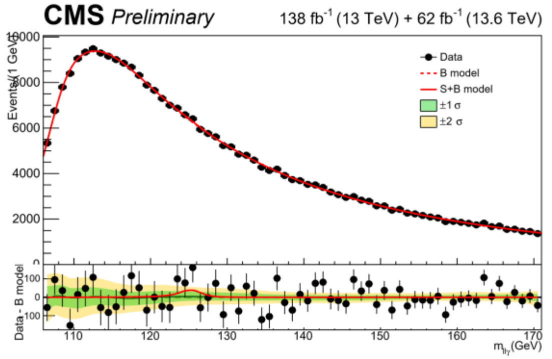
ggF1



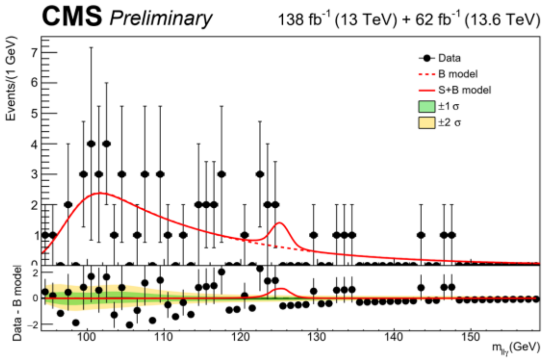
ggF2



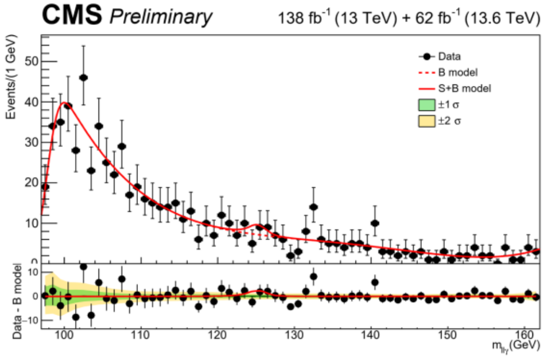
ggF3



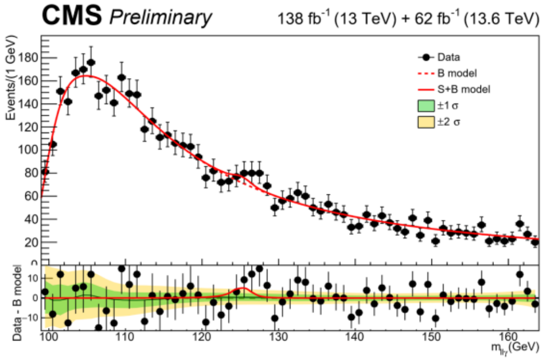
ggF4



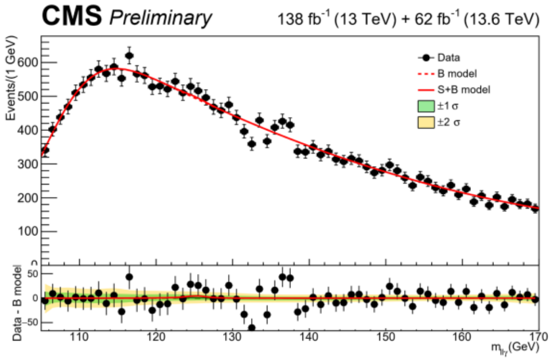
VBF1



VBF2



VBF3



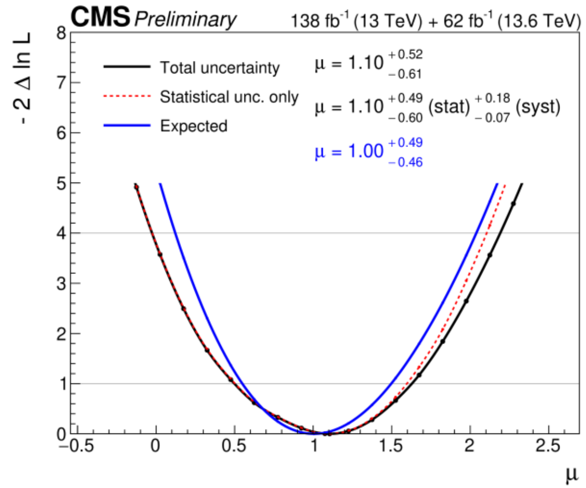
VBF4

([HIG-25-010])

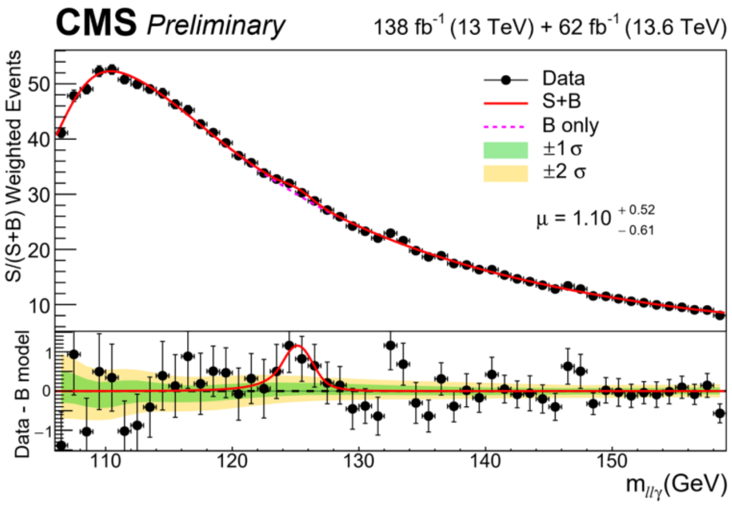
Analysis Results – Signal Strength and Significance

(HIG-25-010)

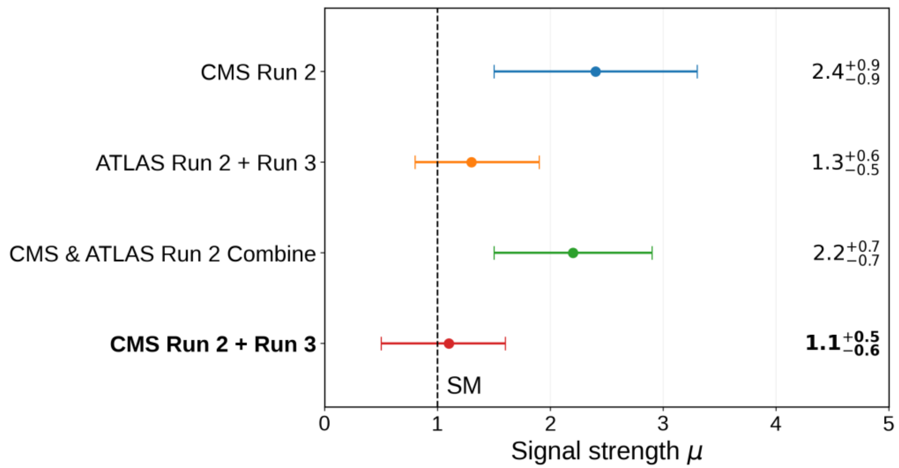
- Observed signal strength: $\mu = 1.10^{+0.52}_{-0.61}$
- Observed (expected) significance: **1.9σ (2.3σ)**
- Weighted final fit plot over the common range of 13 categories
  - Categories weighted by expected S/(S+B) in 120 – 130 GeV window and combined
- Channel Compatibility: p-value = 0.75



NLL scan



Weighted final fit plot



Summary

- I present the search for $H \to Z\gamma$ with Run 2 and 2022 + 2023 data at the CMS experiment.

- Highlights of the analysis:
    - Thorough trigger study and refined event selection
    - Robust BDT performance and categorization
    - A sequence of fit tests with extra care of bias
    - New method to extend MC statistics of Drell-Yan process

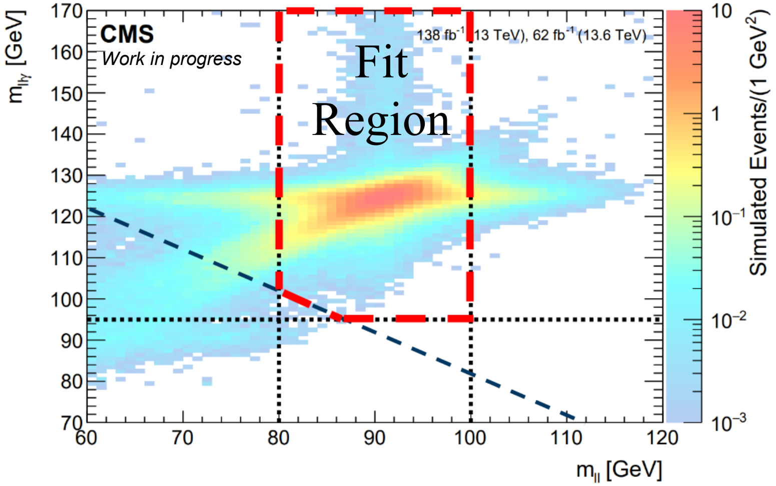
- With the observed signal strength $\mu = 1.10^{+0.52}_{-0.61}$, the result is consistent with the SM within 0.2σ.

- Thank you for your attention!

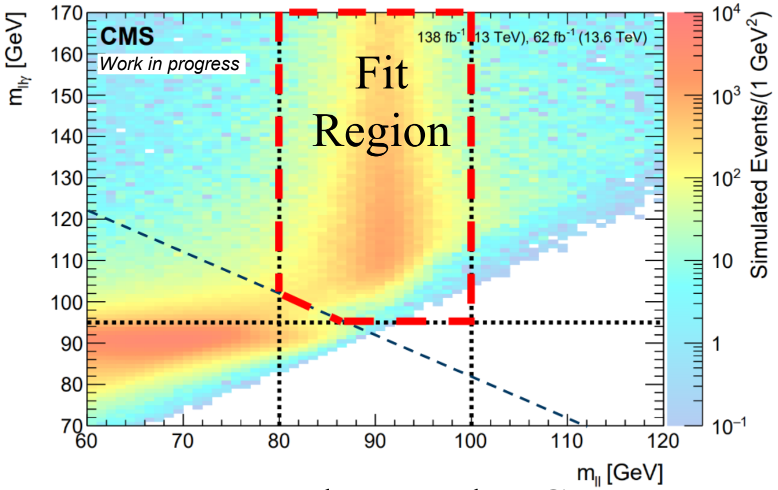
BACKUP

Event Selection

- Object selections
  - Photons: p_T >15 GeV, $|\eta|$ <2.5, $\Delta R_{min}(l,\gamma) > 0.3$, etc.
  - Electrons: p_T>7 GeV, $|\eta|$ <2.5, di-electron or single-electron trigger, etc.
  - Muons: p_T>5 GeV, $|\eta|$ <2.4, di-muon or single-muon trigger, etc.
  - Jets: p_T >30 GeV, $|\eta|$ <4.7, tight jet ID, etc.
- Baseline selection
  - $N_\gamma \geq 1$, $N_e \geq 2$ or $N_\mu \geq 2$
  - 80 GeV < m_{ll} <100 GeV, $p_T(\gamma)/m_{ll\gamma}$ > 15/110, m_{ll}+ $m_{ll\gamma}$ >185 GeV



Signal MC



Background MC

- Event selection mainly rejects Z + FSR γ and soft γ background
- Optimized for max background rejection while maintaining background shape and signal efficiency

ggF and VBF Categorization Strategy

- ggF: 90% of signal events are in this category.
- VBF: category with highest significance
- Extensive studies gone into studying the separation of these two categories
  - Optimized for highest overall sensitivity and simplicity
  - BDTs are used to further divide them into sub-categories
- BDT training strategy:
  - Use MC samples ($120<m_{ll\gamma}<130$ GeV) in training:
    - Background: Z+γ, high statistics Z+fake γ samples, VBS Z+γ
    - Signal: ggF, VBF
  - Train Run 2 + early Run 3 (2022+2023) combined
  - Four-fold training & validation method
    - Divide MC samples into 3 parts (50% training, 25% validation, 25% testing)
    - More stable BDT performance and better usage of simulated samples

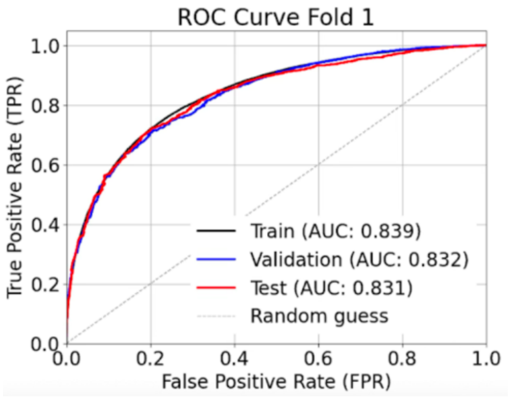
	25%	25%	25%	25%
1st fold	Training set		Validation set	Test set
2nd fold	Test set	Training set		Validation set
3rd fold	Validation set	Test set	Training set	
4th fold	Training set	Validation set	Test set	Training set

Systematics

- Incorporated by allowing signal model to vary in shape and normalization
- Analysis statistically limited
  - Statistical uncertainty +0.49/-0.60
  - Overall systematic uncertainty +0.18/-0.07
- Summary of the uncertainty sources:

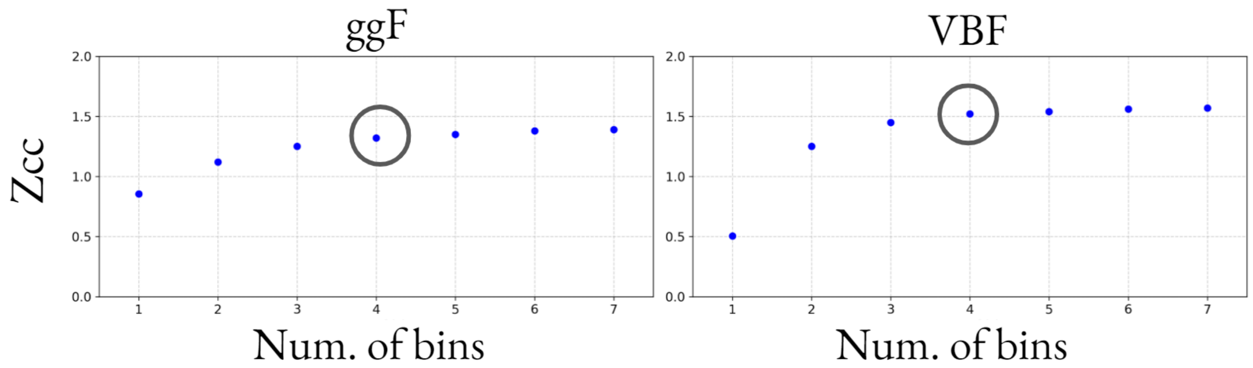
Uncertainty source	Impact on μ
Statistical uncertainty	$+0.50, -0.60$
Background shape	$+0.08, -0.36$
Signal systematic uncertainty	0.11
Fixed-order calculations	0.09
Lepton and photon energy scale and resolution	0.04
Photon quality	0.04
PDFs, α_S, and m_q	0.03
Lepton and photon reconstruction, identification, and trigger efficiency	0.02
Luminosity and pileup	0.01
Underlying event and parton shower	0.01
Jet and p_T^{miss} energy, b tagging, simulation statistics	< 0.01

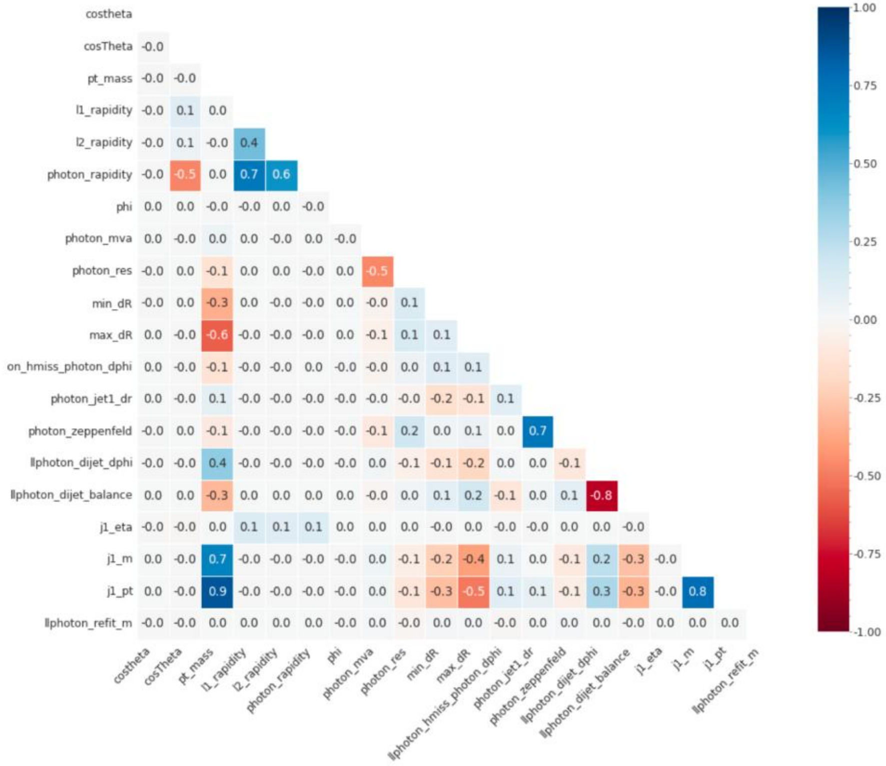
ggF & VBF BDT Optimization



- Input variables selection optimized by S vs B separation power & correlation with $m_{ll\gamma}$
- Hyperparameters optimized to minimize overtraining (validation vs training) and to ensure consistent behavior among folds
- Number of bins optimized by

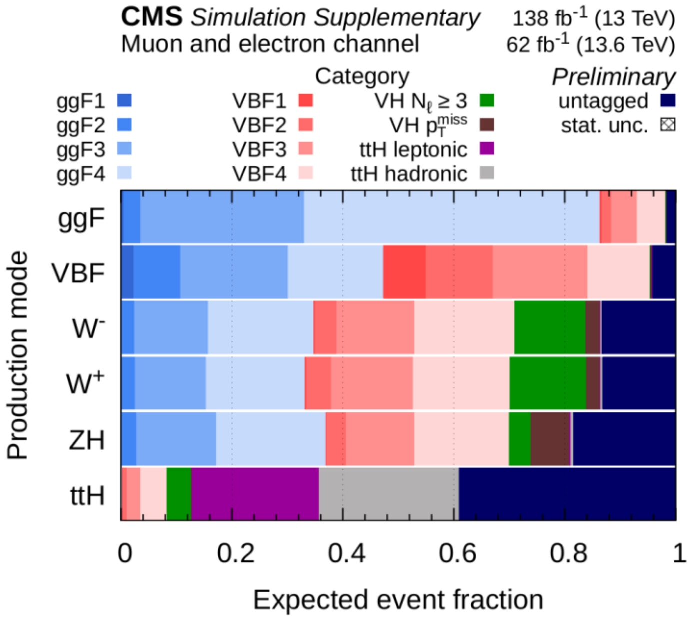
$$Z_{cc} = \sqrt{2[(N_S + N_B) \cdot \ln(1 + N_S/N_B) - N_S]}$$

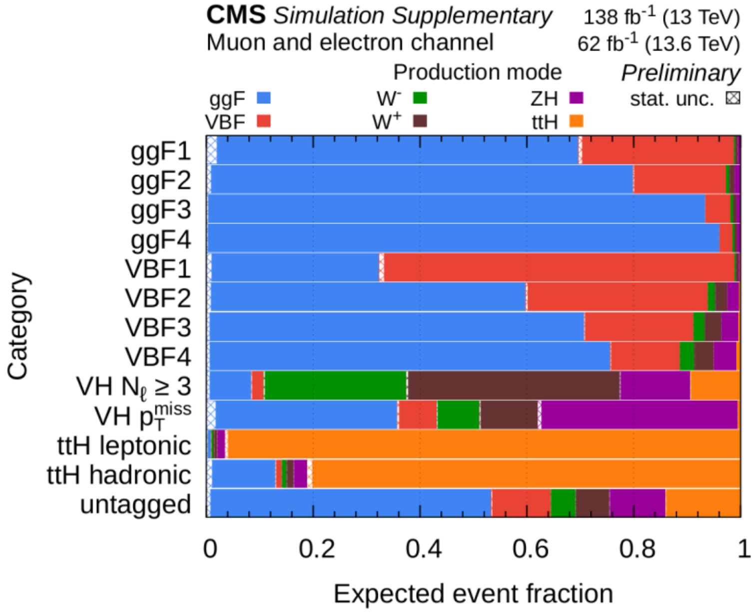


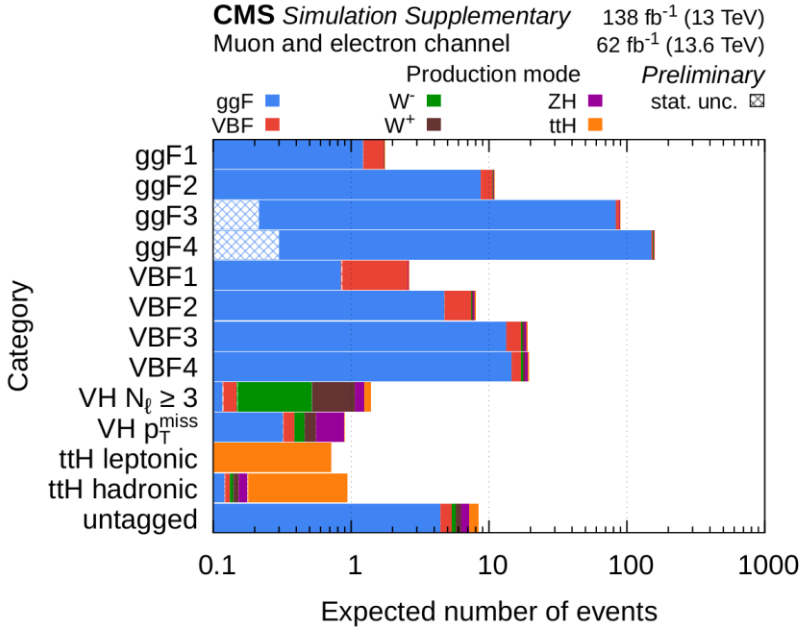


Categorization Output

- ggF & VBF categories have comparable cut and count significance (Zcc)
- VBF highest bin: 70% VBF production
- Associated production enriched in corresponding categories

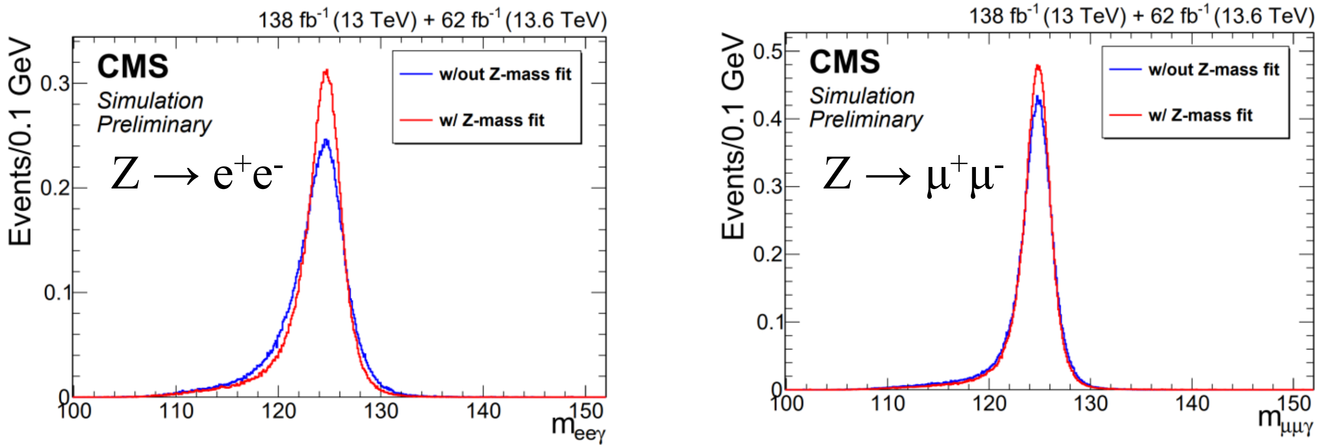






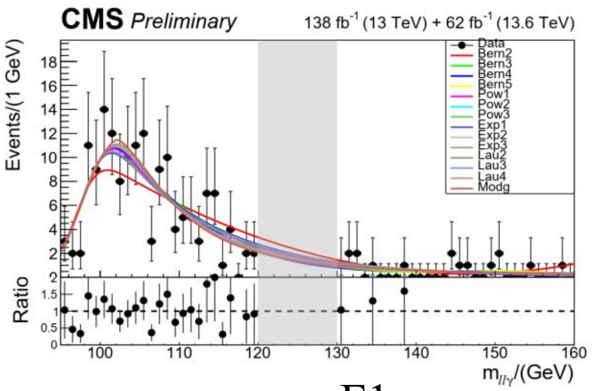
Z-Line Shape Constraint Fit

- Use maximum likelihood estimation with fit of MC truth m_Z line shape
  - Incorporate FSR photon recovery for muons

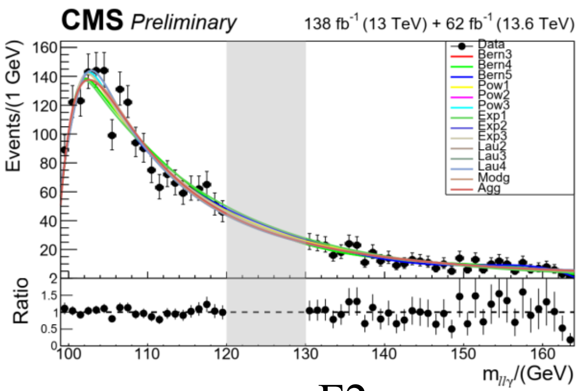


- Improve $m_{ee\gamma}$ resolution ~20% and $m_{\mu\mu\gamma}$ resolution ~10%
  - Signal resolution: e: 1.4-1.8 GeV μ:1.2-1.5 GeV
- No shift in background $m_{ll\gamma}$ shape

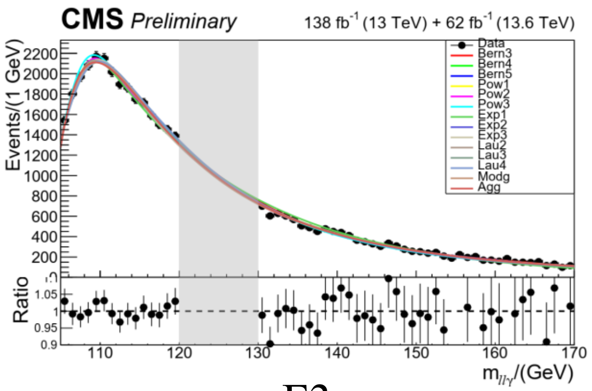
Data Sideband Goodness-of-fit Test



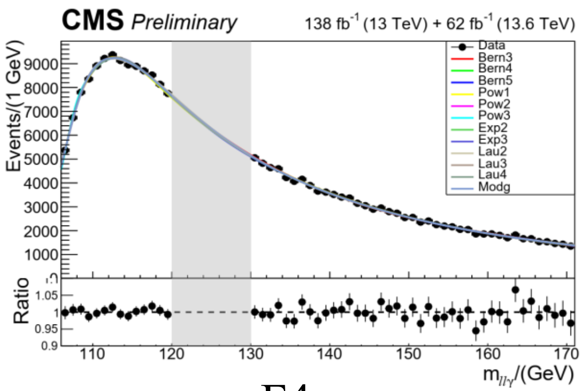
ggF1



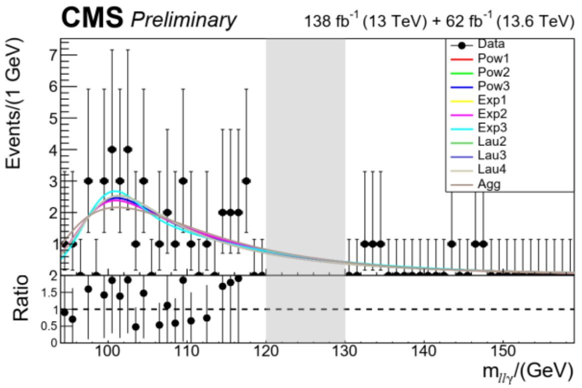
ggF2



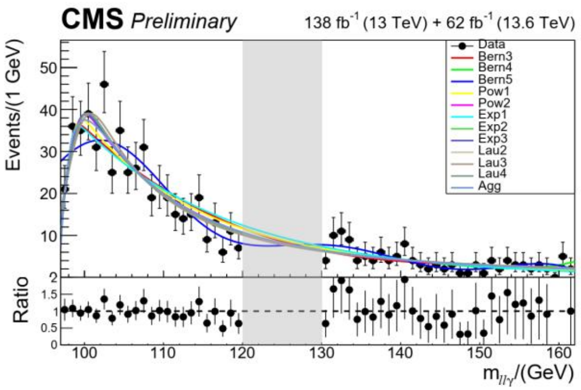
ggF3



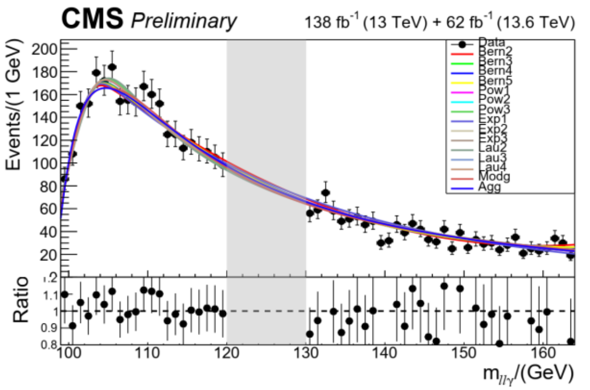
ggF4



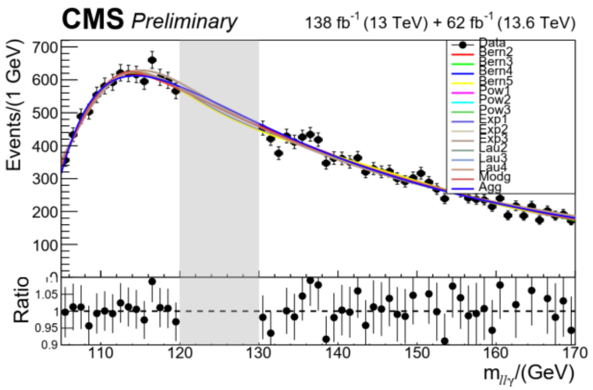
VBF1



VBF2



VBF3



VBF4

- Basic test to ensure the selected background models can fit the data sideband.
- χ^2 binned fit and Kolmogorov–Smirnov (KS) test as criteria.
- Models passing this initial test form an initial envelope to be optimized in the following tests.

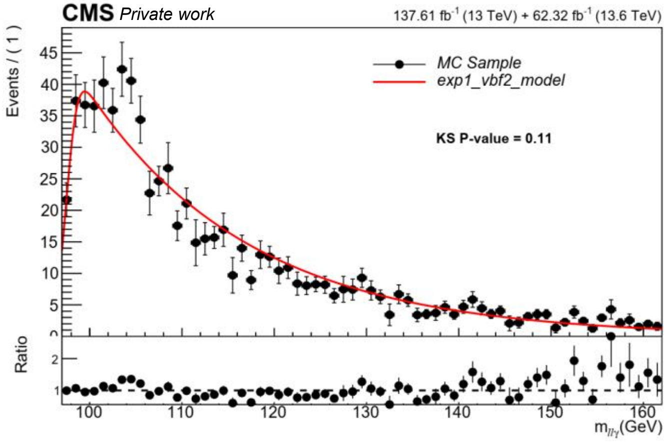
Spurious Signal Test

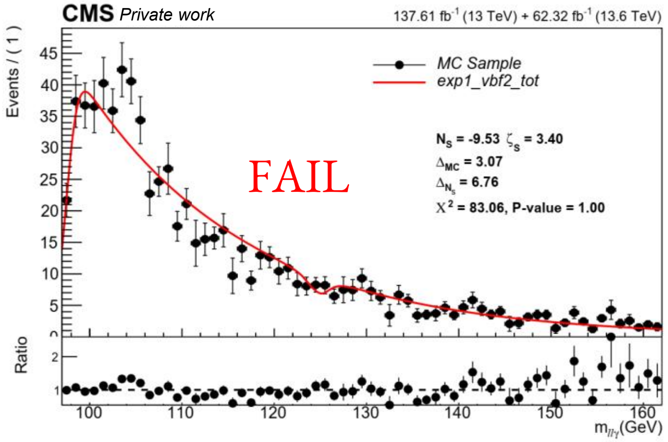
- Use the **background-only high statistics simulation** to test whether the S+B fit with a given background model would bias the signal measurement, giving “spurious signal”
  - Use the **extended DY** introduced before.

- The spurious signal is defined as $|\zeta_s| = \max(0, |N_s| - 2\Delta_{MC})$
  - N_s is the signal yield from the fit
  - Δ_{MC} is the error of the signal yield representing the statistical uncertainty of the MC sample
  - ΔN_s is also the error of the signal yield but representing the expected uncertainty of the data

- To pass the test, on top of a good fit (χ^2 p-value > 0.05),

$$|\zeta_s| < 20\% \times \Delta N_s \quad \text{or} \quad |\zeta_s| < 10\% \times N_{\text{exp signal}}$$





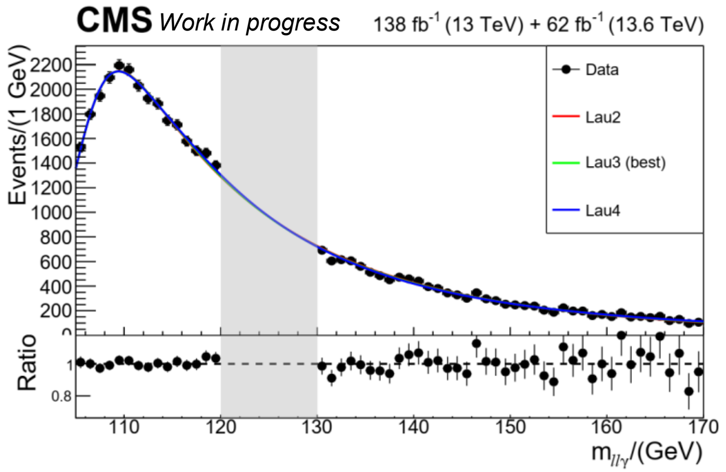
B-only fit and S+B fit of Exp1 bkg model over the high-stat MC of VBF2. Exp1 fails the test with $\zeta = 3.40$

Fisher Test

- To decide # degrees of freedom (DoF) to use: Fisher test probes marginal improvement that extra DoFs can bring to the background function.
- Data sideband negative log-likelihood (NLL) fit of the background functions from the same family, use the difference between NLL to select functions
- Quantity F follows the χ^2 (k = Δn) distribution where Δn is the difference of DoF of two models in the same family. P-value of the test is:

$$p = P(F > 2(NLL(n) - NLL(n + \Delta n)) | \chi^2(\Delta n))$$

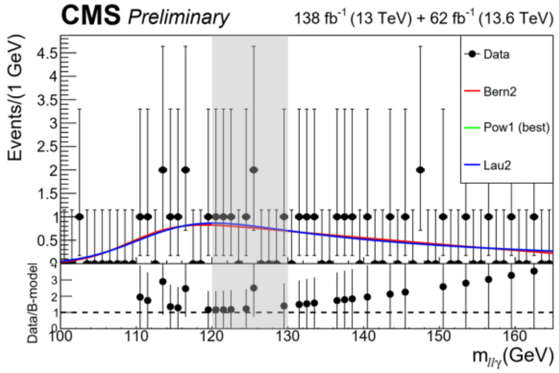
- If p-value < 0.05, the model with the higher DoF is preferred, otherwise only the lower DoF model is kept in the envelope.



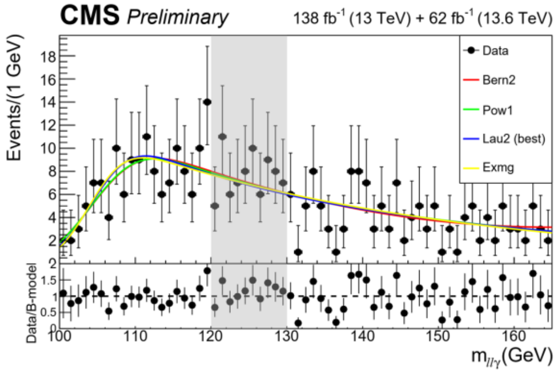
F test in the Laurent series family in ggF3 category. Lau4 has no noticeable improvement over Lau3, thus being removed.

Final Background Envelopes

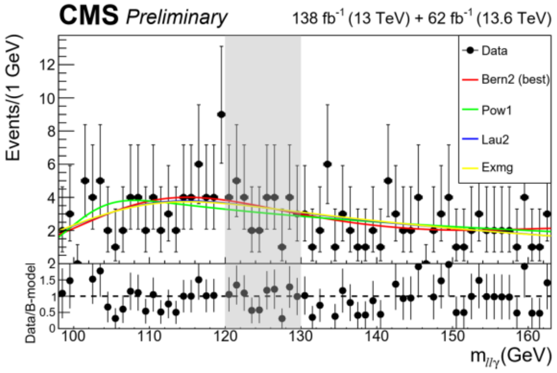
- Envelope functions are from data sideband fits.
- No spurious signal test for these categories due to lack of statistics.



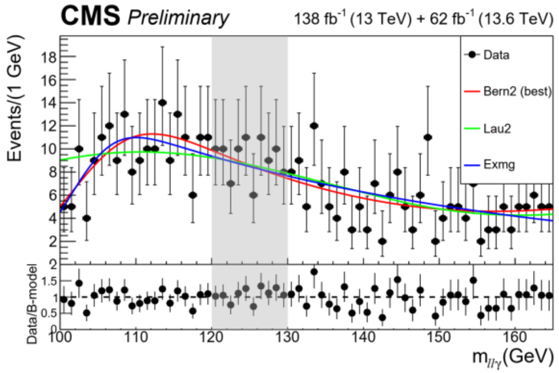
ttH leptonic



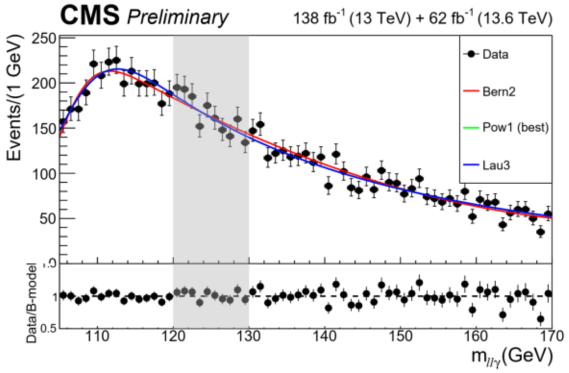
VH $N_{lep} \geq 3$



ttH hadronic



VH p_T^{miss}



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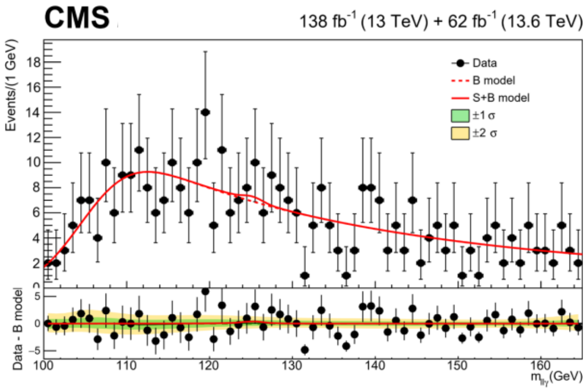
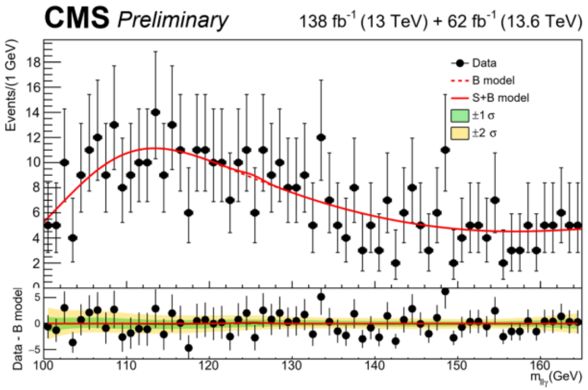
Analysis Results - VH and ttH Categories

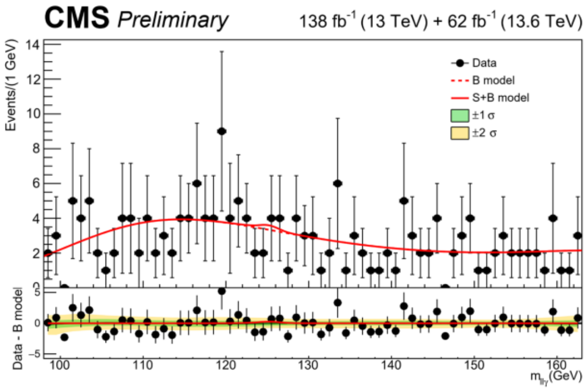
- S+B from simultaneous fit
- Fit provides good description of the data



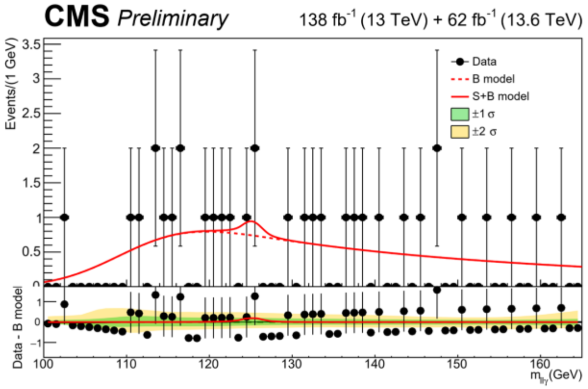
VH $N_l \geq 3$



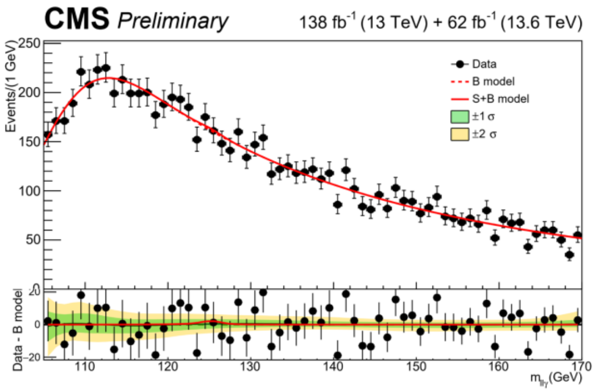
VH p_T^{miss}



ttH hadronic



ttH leptonic



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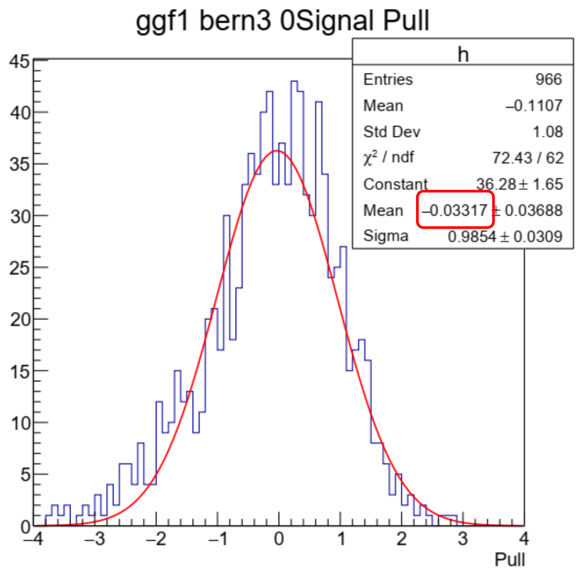
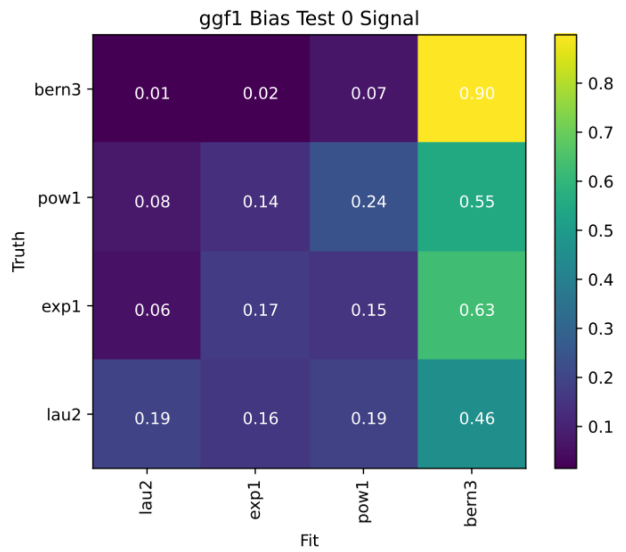
(HIG-25-010)

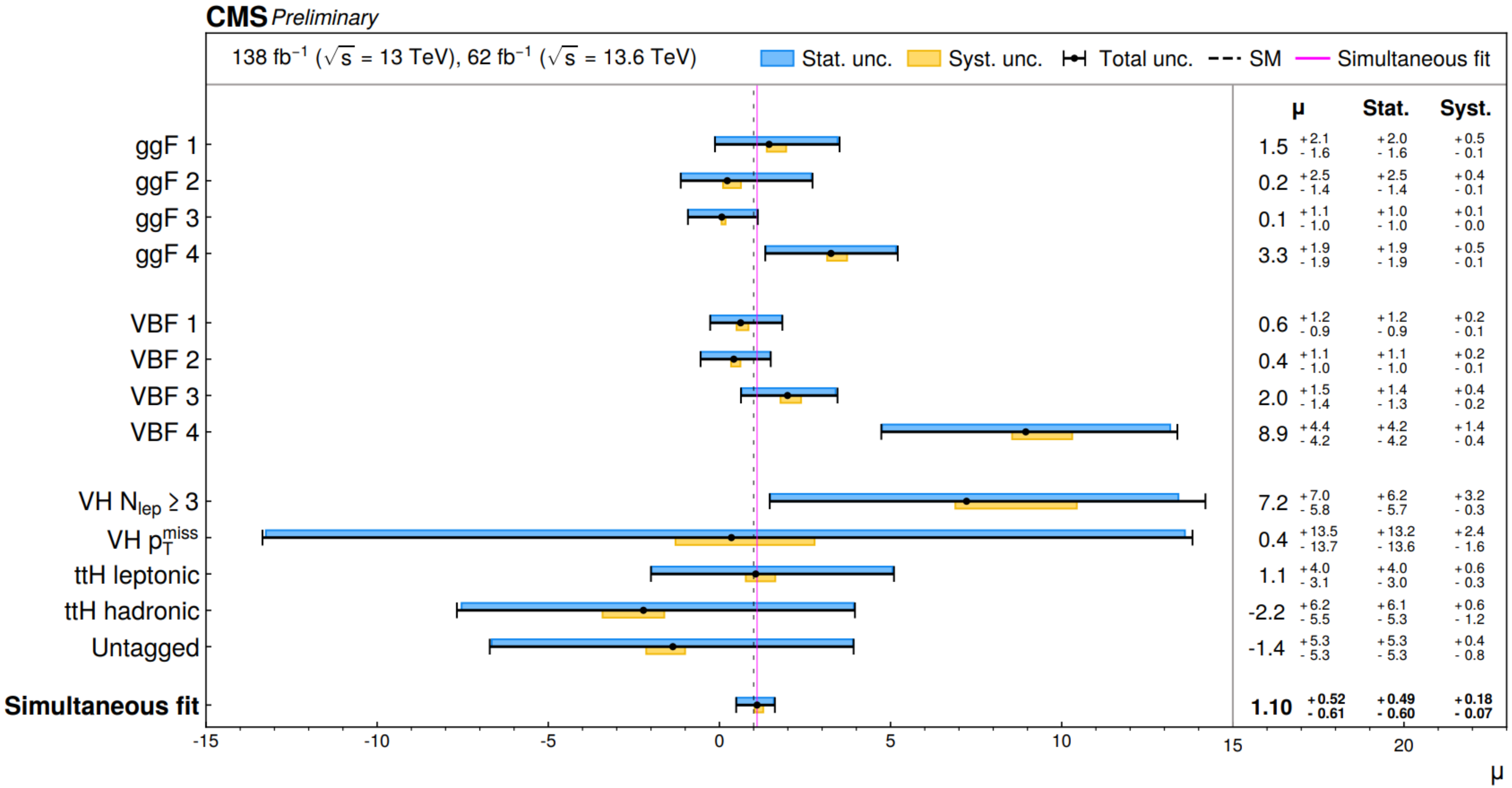
Profile Bias and Signal Injection Test

- In the **profile bias test**, we generate 1000 background-only toys for each model in the envelope and estimate the envelope bias by performing a S+B fits on the toys
    - Toys fit with **the envelope**
    - The pull = $(N_{\text{sig fit}} - N_{\text{sig exp}})/\sigma_{\text{sig fit}}$ should form a Gaussian whose mean is an estimate of the bias for the envelope
- To pass the test, all the members of the envelope should have bias smaller than 0.2
    - In cases with high bias, a heat map is used to determine the functions responsible for the biased fits
- **Signal injection test**, in principle, is the same test as the profile bias test, but where the toys are generating assuming 1× or 5× the nominal signal





Analysis Results Per Category



Category	μ	Stat.	Syst.
ggF 1	$1.5^{+2.1}_{-1.6}$	$^{+2.0}_{-1.6}$	$^{+0.5}_{-0.1}$
ggF 2	$0.2^{+2.5}_{-1.4}$	$^{+2.5}_{-1.4}$	$^{+0.4}_{-0.1}$
ggF 3	$0.1^{+1.1}_{-1.0}$	$^{+1.0}_{-1.0}$	$^{+0.1}_{-0.0}$
ggF 4	$3.3^{+1.9}_{-1.9}$	$^{+1.9}_{-1.9}$	$^{+0.5}_{-0.1}$
VBF 1	$0.6^{+1.2}_{-0.9}$	$^{+1.2}_{-0.9}$	$^{+0.2}_{-0.1}$
VBF 2	$0.4^{+1.1}_{-1.0}$	$^{+1.1}_{-1.0}$	$^{+0.2}_{-0.1}$
VBF 3	$2.0^{+1.5}_{-1.4}$	$^{+1.4}_{-1.3}$	$^{+0.4}_{-0.2}$
VBF 4	$8.9^{+4.4}_{-4.2}$	$^{+4.2}_{-4.2}$	$^{+1.4}_{-0.4}$
VH $N_{lep} \geq 3$	$7.2^{+7.0}_{-5.8}$	$^{+6.2}_{-5.7}$	$^{+3.2}_{-0.3}$
VH p_T^{miss}	$0.4^{+13.5}_{-13.7}$	$^{+13.2}_{-13.6}$	$^{+2.4}_{-1.6}$
ttH leptonic	$1.1^{+4.0}_{-3.1}$	$^{+4.0}_{-3.0}$	$^{+0.6}_{-0.3}$
ttH hadronic	$-2.2^{+6.2}_{-5.5}$	$^{+6.1}_{-5.3}$	$^{+0.6}_{-1.2}$
Untagged	$-1.4^{+5.3}_{-5.3}$	$^{+5.3}_{-5.3}$	$^{+0.4}_{-0.8}$
Simultaneous fit	$\mathbf{1.10^{+0.52}_{-0.61}}$	$\mathbf{^{+0.49}_{-0.60}}$	$\mathbf{^{+0.18}_{-0.07}}$