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ATLAS EXPERIMENT

Latest search for the Higgs boson decay to $Z\gamma$ with the ATLAS detector

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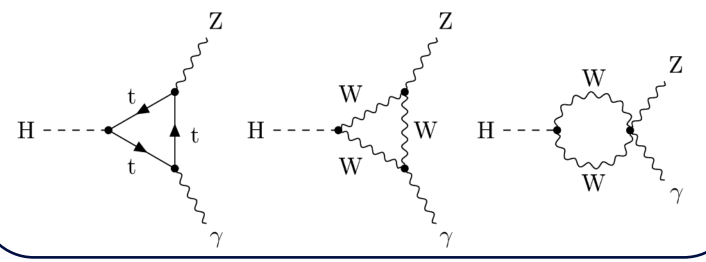
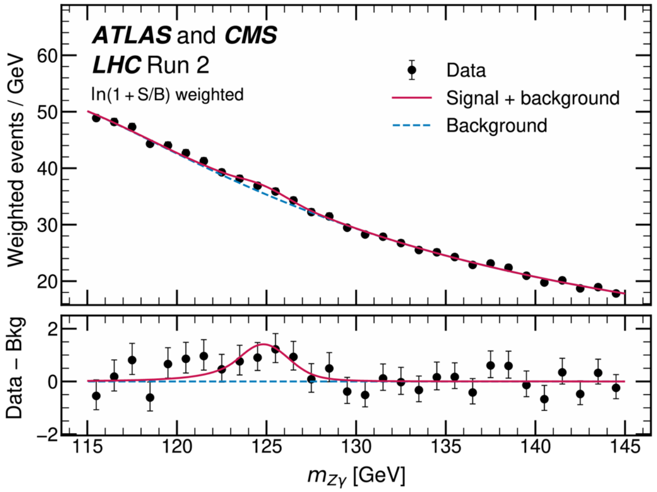
Introduction

- $\boldsymbol{H \rightarrow Z\gamma}$: **Rare loop-induced Higgs decay**
  - Predicted branching ratio: $(1.54^{+0.10}_{-0.11})\times10^{-3}$
- **Sensitive probe** for the SM and its extensions through loop contributions
- Run-2 ATLAS+CMS: **obs. (exp.)** significance is $\boldsymbol{3.4\sigma(1.6\sigma)}$
- **This study:** Search $H \rightarrow Z\gamma$ with $\boldsymbol{165\ fb^{-1}}$ data collected by **ATLAS during 2022-2024**
  - then combined with Full Run-2 $(140\ fb^{-1})$

loop-induced processes



Phys. Rev. Lett. 132, 021803



Analysis strategy

- **Leptonic final state:** $H \rightarrow Z\gamma \rightarrow ll\gamma(e,\mu)$
  - efficient **triggers**, **full kinematic reconstruction**, excellent mass **resolution**
- Object and event selection
- Dedicated event **categorization** to **enhance the sensitivity**
  - 13 mutually exclusive categories targeting different Higgs production modes
- Data-driven and MC-based **background estimation**
- **Signal extraction**
  - Signal and background described by analytic functions
  - Simultaneous fit to the reconstructed $m_{ll\gamma}$ spectra across all categories
- Combined with Run-2 analysis

Event selection and reconstruction

- **Preselection**
  - Single-/di- lepton triggers
  - Object selection(backup)
  - Optimized overlap removal to improve the photon efficiency

↓

- **Z boson candidate reconstruction**
  - **FSR recovery**(μ channel)
  - **Kinematic fit constrains** to the known Z mass
  - $|m_{ll} - m_Z| < 10$ GeV

↓

- **Higgs boson candidate reconstruction**
  - selected Z boson and the highest p_T photon
  - $p_T^{\gamma}/m_{Z\gamma}$ **> 0.09**
  - $110 < m_{Z\gamma} < 160$ GeV

Improve $ll\gamma$ **mass resolution**
17% for e channel, **11%** for μ channel

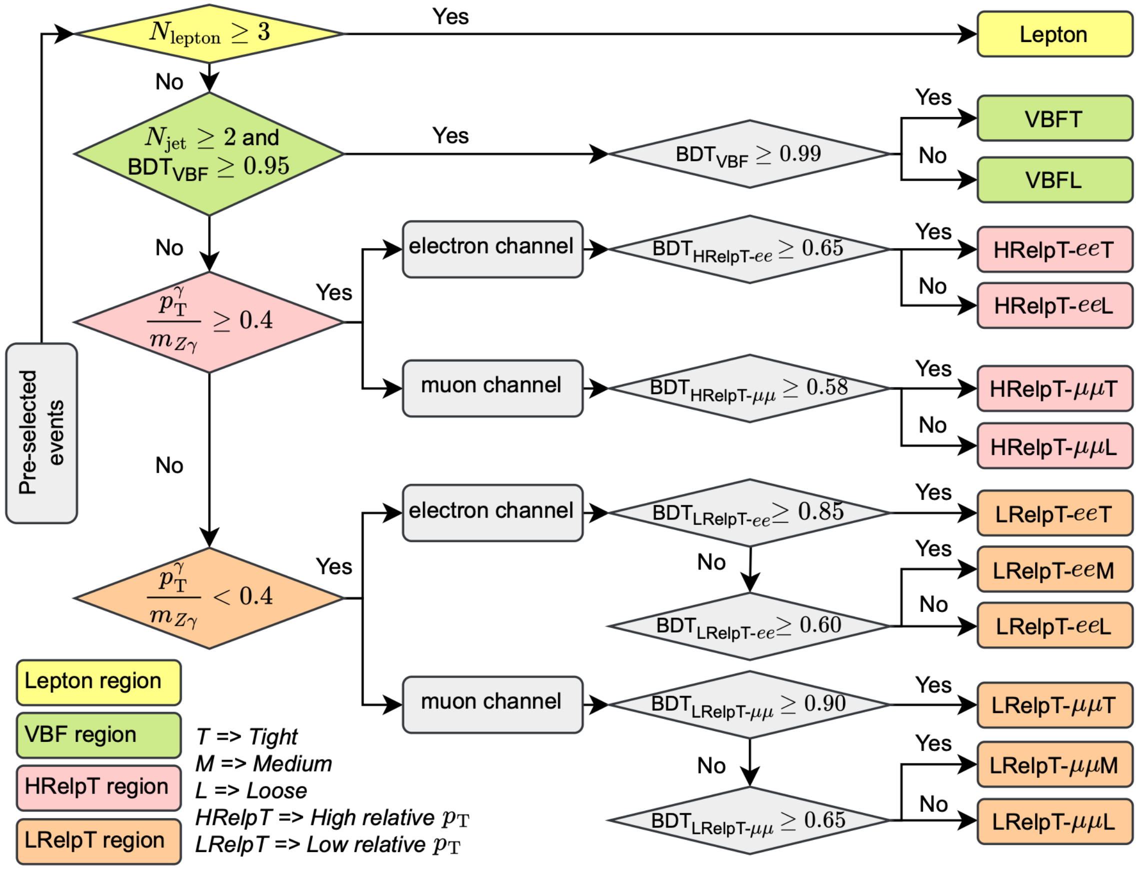
further **reduce background** while **not sculpting** in the $m_{Z\gamma}$ spectrum

Categorization

- **events are classified into four regions :**
  - **Lepton**, **VBF** ,**high relative p_T** , **low relative p_T**
- Cut-based selections and BDT classifiers are used to split events

Category	S_{68}^{exp}	B_{68}^{exp}	N_{68}	w_{68} [GeV]	$S_{68}^{exp}/\sqrt{S_{68}^{exp}+B_{68}^{exp}}$
Lepton	1.5 ± 1.1	75.4 ± 2.8	70	4.4	0.17
VBFT	1.5 ± 1.1	1.3 ± 0.4	3	3.8	0.92
VBFL	2.8 ± 2.0	27.2 ± 1.8	18	4.0	0.52
HRelpT-eeT	1.2 ± 0.8	6.6 ± 0.9	9	3.2	0.43
HRelpT-eeL	2.9 ± 2.1	53.9 ± 1.8	61	4.0	0.39
HRelpT-$\mu\mu$T	2.4 ± 1.7	20.3 ± 1.7	25	3.9	0.51
HRelpT-$\mu\mu$L	2.4 ± 1.7	56.5 ± 1.7	61	4.1	0.32
LRelpT-eeT	8.9 ± 6.2	231 ± 6	240	3.8	0.57
LRelpT-eeM	29 ± 20	2 562 ± 19	2 587	4.1	0.56
LRelpT-eeL	24 ± 17	13 122 ± 50	13 074	4.5	0.21
LRelpT-$\mu\mu$T	4.9 ± 3.4	95 ± 4	107	3.9	0.49
LRelpT-$\mu\mu$M	34 ± 24	2 527 ± 19	2 583	4.1	0.67
LRelpT-$\mu\mu$L	36 ± 25	16 844 ± 40	16 642	4.4	0.28
Inclusive	150 ± 110	35 625 ± 70	35 480	4.0	1.81

S, B in 68% signal region for each category



Schematic of the event categorization

Signal and background modeling

- **Signal model: Double-sided Crystal Ball function**
  - Describes the Higgs signal peak including $H \to \mu\mu$ contamination

- **Background estimation**
  - non-resonant $Z\gamma$(MC) and Z +jets with misidentified photon (data-driven)
  - Other minor backgrounds from MC

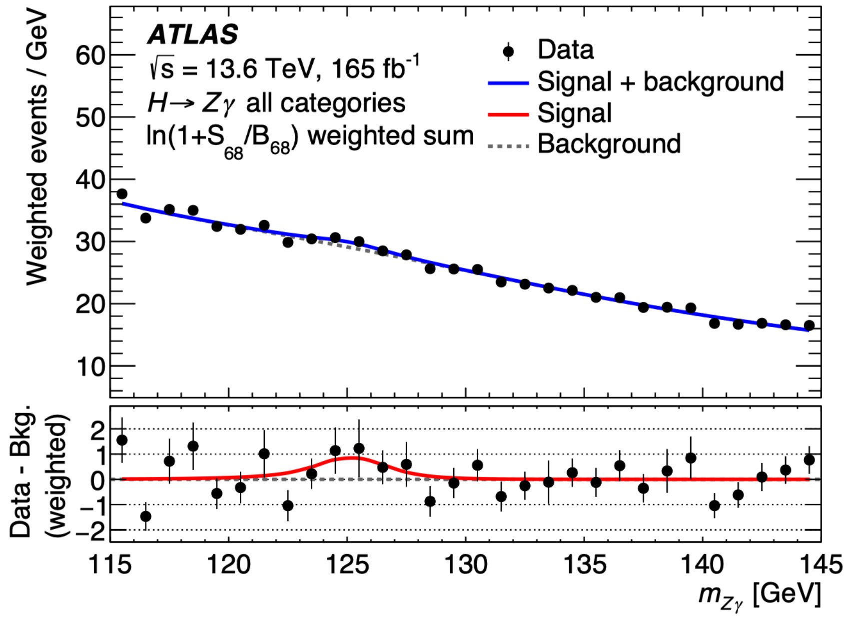
- **Background modeling**
  - Estimate the relative $Z\gamma$ and Z + jets fractions using **ABCD method**
  - Construct background templates with smoothed Z+jets to $Z\gamma$ shapes ratio
  - **Analytical function** to model the background is determined by **spurious signal study**

Backup: Introduction of ABCD methods, R

Results of Run-3 analysis

- Measured signal strength
  - $\mu = 0.9 \pm 0.6(stat)^{+0.2}_{-0.1}(syst) = 0.9^{+0.7}_{-0.6}$
- Expected (SM) signal strength
  - $\mu_{exp} = 1.0 \pm 0.7(stat)^{+0.2}_{-0.1}(syst) = 1.0^{+0.7}_{-0.7}$
  - **Statistically limited!**
- **Obs. significance** (background-only hypothesis): **1.4** σ
- **Exp. significance: 1.5** σ
- Measurement is statistically **consistent with SM** expectation

$Z\gamma$ invariant mass distributions of weighted data



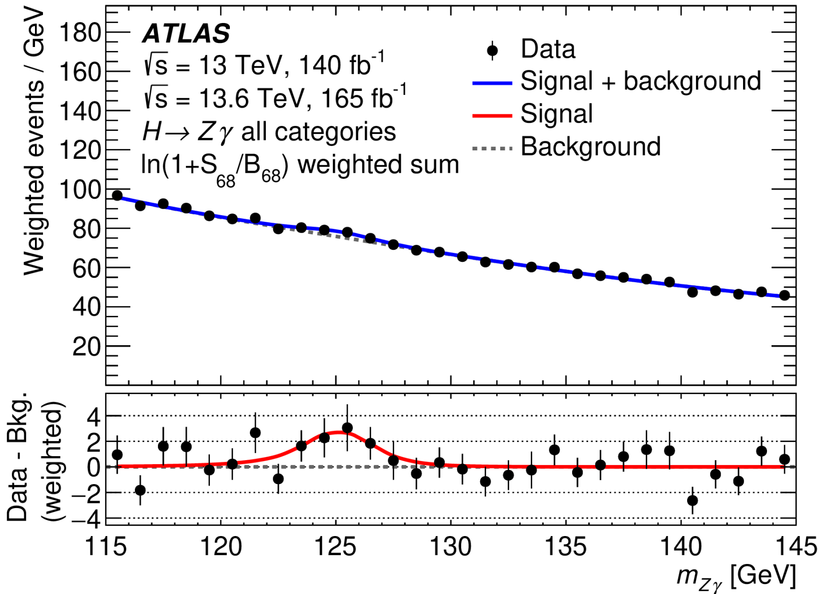
Expected significance improves for 28% relative to the previous Run-2 ATLAS result

- **11%** from increased integrated **luminosity and cross section scaling**
- **15%** from the advanced event **selection and categorization** (after scaling luminosity and XS)

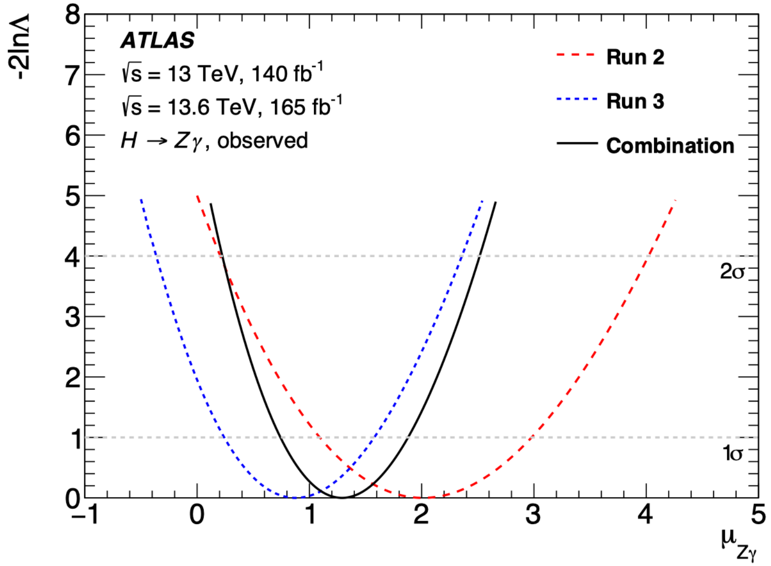
Results of Run-2 + Run-3

- The combined best-fit **signal strength**:
  - $\mu = 1.3 \pm 0.5(stat) \pm 0.2(syst) = 1.3^{+0.6}_{-0.5}$
- SM **expected** value:
  - $\mu = 1.0 \pm 0.5(stat)^{+0.2}_{-0.1}(syst) = 1.0^{+0.6}_{-0.5}$
- **Obs. (exp.) significance** is **2.5σ** (**1.9σ**)
  - Combination improves Run-2 by 61%
  - Current ATLAS expected results 19% better than previous ATLAS+CMS
- Assuming the SM cross-section, the observed branching ratio is $BR(H \to Z\gamma) = (2.0^{+0.9}_{-0.8})\times10^{-3}$, expected $(1.5^{+0.9}_{-0.8})\times10^{-3}$

$Z\gamma$ invariant mass distributions of weighted data



Profiled likelihood scan of the signal strength



Summary & Outlook

- **ATLAS search for $H \to Z\gamma$ @13.6TeV using $165\ fb^{-1}$ data(2022-2024)**
- The obs. (exp.) signal yield normalized to the SM prediction
  - $\mu_{obs} = 0.9^{+0.7}_{-0.6}(\mu_{exp} = 1.0 \pm 0.7)$
  - with a significance of **1.4 (1.5)σ**
  - Compared to Run2 ATLAS results, the expected significance improved by **28%**
- **Combined** with the Run-2 results
  - Obs.(exp.) signal strength and significance: $\mu_{obs} = 1.3^{+0.6}_{-0.5}(\mu_{exp} = 1.0^{+0.6}_{-0.5})$, **2.5 (1.9)$\sigma$**
  - Current ATLAS expected results **19%** better than previous ATLAS+CMS
- **Full Run-3 analysis** on-going
  - with larger datasets and further analysis improvements expected

Thank you!

Backup

Detailed event selection and reconstruction

- **Object definition**

Cut	Electron	Muon	Photon	Jet
p_T	> 10 GeV	> 5 GeV	> 10 GeV	> 25 GeV
$\lvert\eta\rvert$	$\lvert\eta\rvert$ < 2.47 exclude [1.37, 1.52]	$\lvert\eta\rvert$ < 2.5	$\lvert\eta\rvert$ < 2.37 exclude [1.37, 1.52]	$\lvert y\rvert$ < 4.4
d_0 significance	< 5	< 3		
$\lvert\Delta z_0 \sin\theta\rvert$	< 0.5 mm	< 0.5 mm		
ID / JVT (fJVT)	Loose	Medium	Tight	FixedEffPt (Loose)
ISO	Loose	Loose	FCLoose	

- Triggers: **single-/di - lepton triggers**
- **Overlap removal**:
  - Specially, overlap removal of photon is only preformed with the two selected leptons to **improve the photon efficiency**

- Z boson candidates reconstruction
  - **FSR correction**: final state radiation(photons or electrons) recovered to the closest muons
  - **Kinematic fit constrains** to the known Z mass
- Select the Z candidates by closest to Z mass
- $|m_{ll} - m_Z| < 10$ GeV

- Higgs boson candidate reconstruction
  - Combine the selected Z boson and the highest p_T photon
  - $m_{Z\gamma}$ in 110-160 GeV
  - **$p_T^\gamma / m_{Z\gamma}$ > 0.09** to further reduce background while **avoiding a sharp "turn-on"** in the $m_{Z\gamma}$ spectrum

BDT training strategy

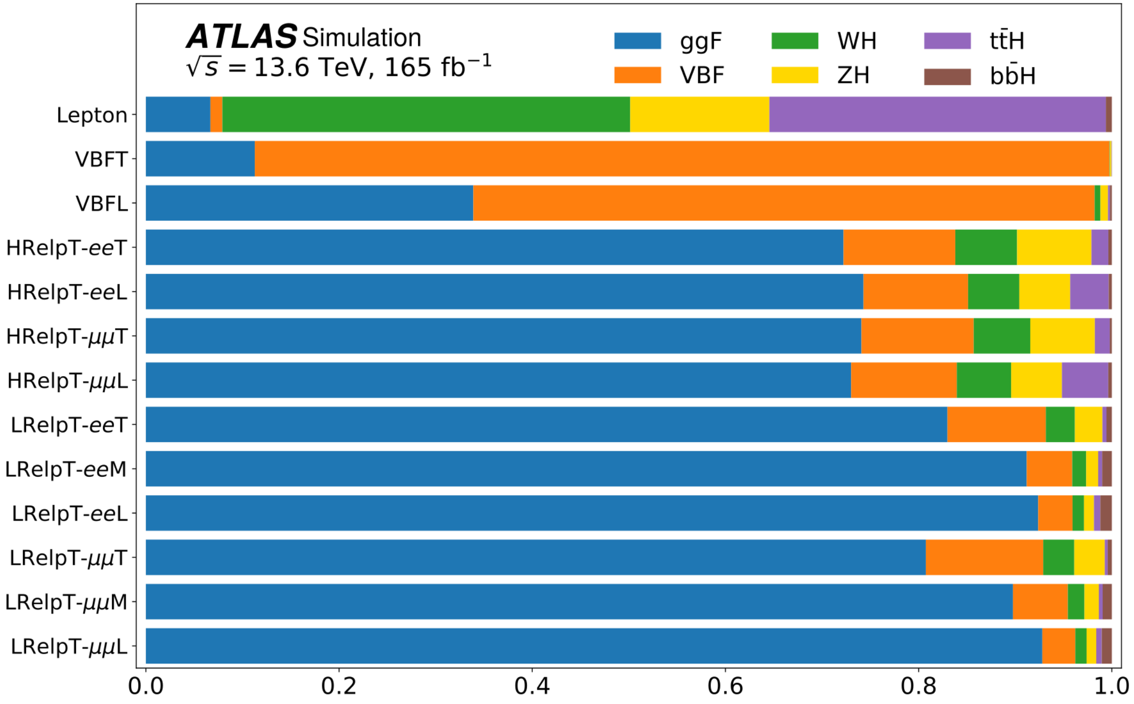
- **Optimization target: maximizes the combined number counting significance**
  - Requires at least two background events(MC) in the signal region ([120, 130] GeV) of each category
- **VBF BDT**
  - VBFH as signal and ggFH+Zy as backgrounds
- **High/Low relative photon p_T BDT**
  - Separated by lepton flavor
  - ggH as signal and Zy+Zjets as backgrounds

Input variable	Description	VBF	relative photon p_T
N_{jet}	Number of jets	✓	✓
$p_T^{j_1}, \eta_{j_1}$	p_T, and η of the leading jet (j_1)	✓	✓
m_{j_1}	Mass of the leading jet	✓	
ϕ_{j_1}	Azimuthal angle of the leading jet		✓
$m_{j_2}, p_T^{j_2}, \eta_{j_2}$	Mass, p_T, and η of the subleading jet (j_2)	✓	
$m_{j_1 j_2}, p_T^{j_1 j_2}, \Delta\eta_{j_1 j_2}$	Dijet invariant mass, p_T, and η separation	✓	
η_γ	Pseudorapidity of the photon	✓	✓
p_T^γ	Transverse momentum of the photon	✓	
$p_T^{\ell\ell}$	Transverse momentum of the dilepton system	✓	
$\eta_{\ell\ell}, \eta_{\ell\ell\gamma}$	Pseudorapidity of the dilepton and $\ell\ell\gamma$ systems	✓	✓
$p_T^{\ell\ell\gamma}$	Transverse momentum of the $\ell\ell\gamma$ system	✓	
$p_T^{\ell\ell\gamma}/m_{\ell\ell\gamma}, p_T^\gamma/m_{\ell\ell\gamma}$	Relative p_T of the $\ell\ell\gamma$ and the photon		✓
$p_T^{\ell\ell}/m_{\ell\ell\gamma}$	Relative p_T of the dilepton system		✓
p_T^t	Component of $\vec{p}_T^{\,\ell\ell\gamma}$ perpendicular to the difference between $\vec{p}_T^{\,\ell\ell}$ and $\vec{p}_T^{\,\gamma}$ ($p_T^t = \lvert\vec{p}_T^{\,\ell\ell\gamma} \times \hat{t}\rvert$, with $\hat{t} \propto \vec{p}_T^{\,\ell\ell} - \vec{p}_T^{\,\gamma}$)	✓	✓
$\Delta\phi_{\ell\ell,\gamma}$	Azimuthal separation between the $\ell\ell$ system and the photon	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1}$	Azimuthal separation between the $\ell\ell\gamma$ system and the leading jet	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1 j_2}$	Azimuthal separation between the $\ell\ell\gamma$ system and the dijet system	✓	
$\Delta\eta_{\ell\ell,\gamma}$	Pseudorapidity separation of the dilepton and the photon	✓	✓
$\Delta R^{\text{min}}_{\gamma \text{ or } \ell\ell, j}$	Minimum ΔR to j_1/j_2 from the photon or the dilepton system	✓	✓
$\cos\theta^*(\ell^+)$	Cosine of the polar angle of the ℓ^+ in the $\ell\ell$ rest frame	✓	✓
$\cos\theta(\ell\ell)$ in $\ell\ell\gamma$	Cosine of the polar angle of the $\ell\ell$ in the $\ell\ell\gamma$ rest frame	✓	✓
$\eta^{\text{Zeppenfeld}}$	Pseudorapidity difference between the $\ell\ell\gamma$ system and the dijet system, defined as $\lvert\eta_{\ell\ell\gamma} - (\eta_{j_1} + \eta_{j_2})/2\rvert$	✓	

Signal/background after categorization

➢ **Lepton and VBF categories show good classifications of VH, ttH and VBF signal events**

Signal decomposition in each category



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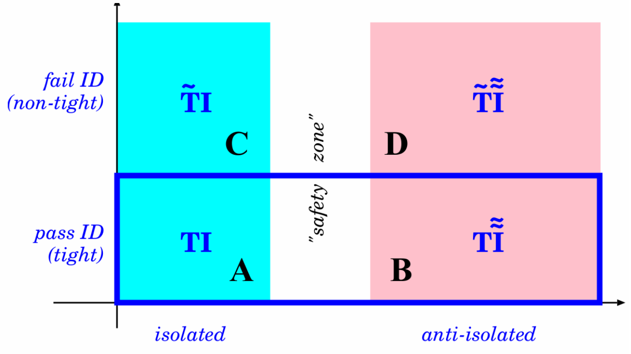
Two-dimensional sideband method

ABCD method (ID/ISO) for the background decomposition:

- **Signal leakage $c_k \equiv N_K^{Z\gamma}/N_A^{Z\gamma}$: assume it can be well described in MC**

$$N_A^{Z\gamma} = N_A^{data} - \left(N_B^{data} - c_B N_A^{Z\gamma}\right)\times\frac{\left(N_C^{data} - c_C N_A^{Z\gamma}\right)}{\left(N_D^{data} - c_D N_A^{Z\gamma}\right)}R$$

- The key point is to estimate the correlation of Zjets, $R \equiv \frac{N_A^{Zj} N_D^{Zj}}{N_B^{Zj} N_C^{Zj}}$



Three methods of the R value calculation for the purity estimation:

- A'B'C'D' method: fail track ISO

C':LP4 & $E_T^{iso} < 0.065 \times P_T, P_T^{iso} > 0.05 \times P_T$	D': LP4 & $E_T^{iso} < 0.065 \times P_T + 2\text{GeV}, P_T^{iso} > 0.05 \times P_T$
A':Tight ID & $E_T^{iso} < 0.065 \times P_T, P_T^{iso} > 0.05 \times P_T$	B': Tight ID & $E_T^{iso} < 0.065 \times P_T + 2\text{GeV}, P_T^{iso} > 0.05 \times P_T$

- BDEF method: split BD region by calo ISO

D-F: LP4 &$E_T^{iso} - 0.065 \times P_T \in [2, 3.5]\text{GeV}, P_T^{iso} < 0.05 \times P_T$	F: LP4 &$E_T^{iso} - 0.065 \times P_T > 3.5\text{GeV}, P_T^{iso} < 0.05 \times P_T$
B-E: Tight ID &$E_T^{iso} - 0.065 \times P_T \in [2, 3.5]\text{GeV}, P_T^{iso} < 0.05 \times P_T$	E: Tight ID &$E_T^{iso} - 0.065 \times P_T > 3.5\text{GeV}, P_T^{iso} < 0.05 \times P_T$

- Use Z+jets simulated sample:
  - Calculate in ABCD region

Background templates

- Background templates are built by combining $Z\gamma$ and Z + jets components
- Inclusive purity of $Z\gamma$ is extrapolated to each event category
  - Using efficiencies from the $Z\gamma$ fast-simulation MC and data-driven Z + jets samples
- Ratio of Z + jets to $Z\gamma$ shapes of $m_{Z\gamma}$ is smoothed by fitting
  - To reduce statistical fluctuations in the control region(Data Driven Z+jets)
- Specially:
  - VBF categories: high-statistics EW $Z\gamma jj$ simulation added
  - Lepton category: Di-boson backgrounds added
- Last, Spurious signal (SS) study is performed to choose the analysis function
  - Fit range is optimized in the SS study, then Wald test is applied to compare functions in each family, last Gaussian Process Regression smoothing is applied to increase effective statistics

Background function decision strategy

Selection criteria: $S/\Delta S$ <20%, $P_{(\chi^2)} > 0.01,\ S \pm 1\zeta/\Delta S < 20\%$

Fit range optimization:

1. Starting from 110-160 GeV, 115-150 GeV, and 110-155 GeV
   - Put **high priority on lowest function DOF**, then lowest SS with same DOF
2. IF step-1 failed to pass the criteria, test narrower mass regions: 110-150 and 115-155 GeV
3. IF all failed, select the function with lowest SS and mass region ≥35GeV

A Wald test is then applied to data sidebands to compare nested functions:

- If a lower-degree function is statistically compatible without significantly increasing SS
- It replaces the nominal model to guard **against over-fitting**

Re-evaluate SS with a smoothing technique based on Gaussian Process Regression on the background templates

- Reduces the effect of residual statistical fluctuations without introducing any shape bias
- Does not affect the choice of any function–range combination in any categories

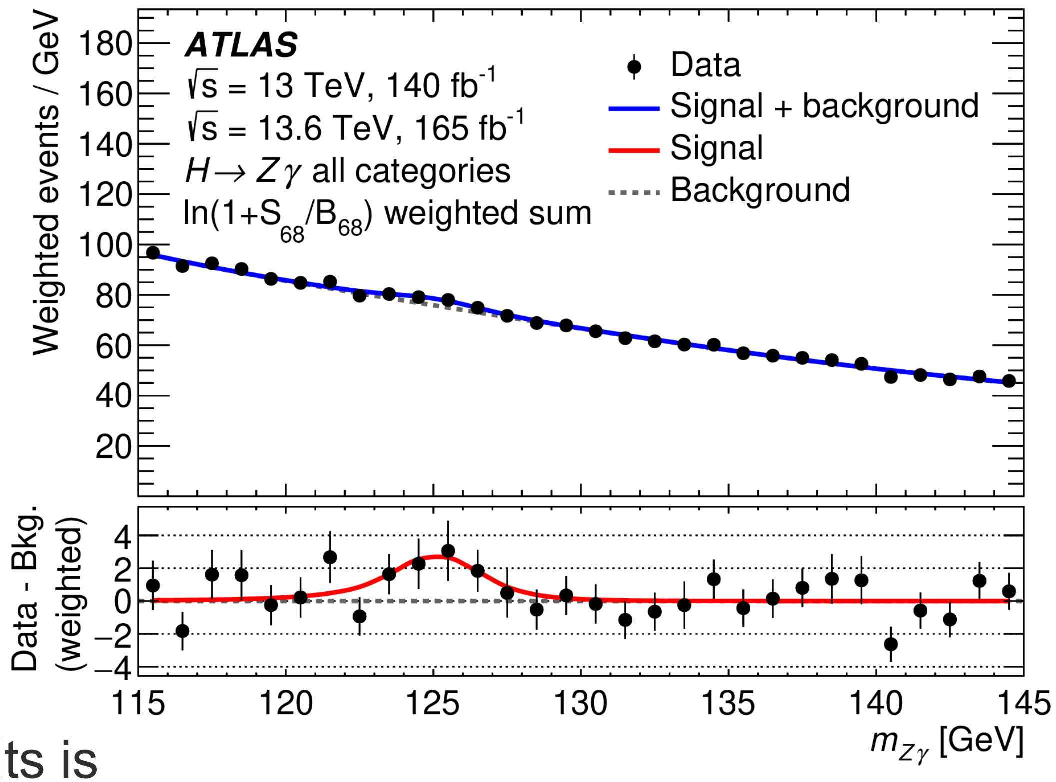
To account for uncertainties in the relative $Z\gamma$ and Z +jets fractions

- Templates with **±1σ variation** are built and repeat the SS study, the maximum |SS| is assigned as the final uncertainty

Run 2 & Run 3 combination

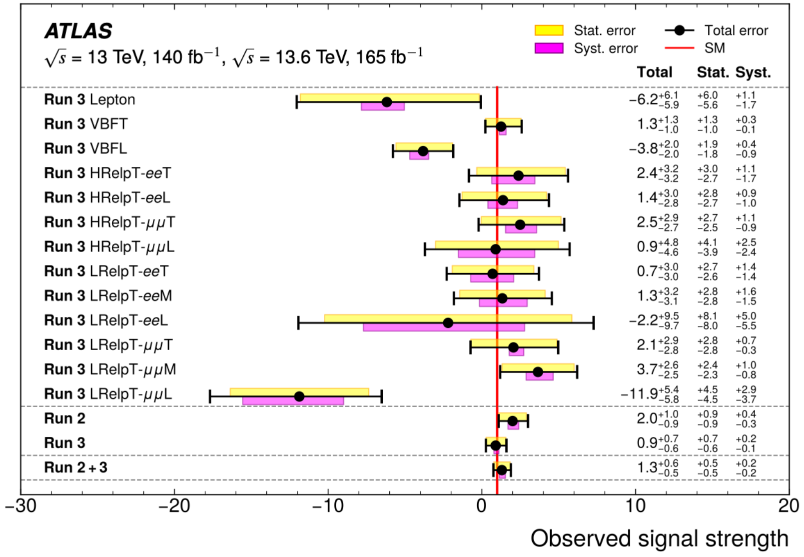
- ➢ Uncertainty Correlation Strategy
- ➢ **Fully correlated:**
  - Theoretical uncertainties: Branching ratio, QCD scale, α_s
- ➢ **Uncorrelated:**
  - PDF uncertainties (different sets used in Run 2 vs. Run 3)
  - Most experimental uncertainties:
    - due to distinct data-taking conditions
    - Trigger, luminosity, electron, photon, spurious signal
- ➢ Partially correlated:
  - Muon and jet uncertainties are partial correlated
- ➢ The **impact of the correlation** scheme on final results is **negligible**
  - Total uncertainty remains dominated by statistical contribution

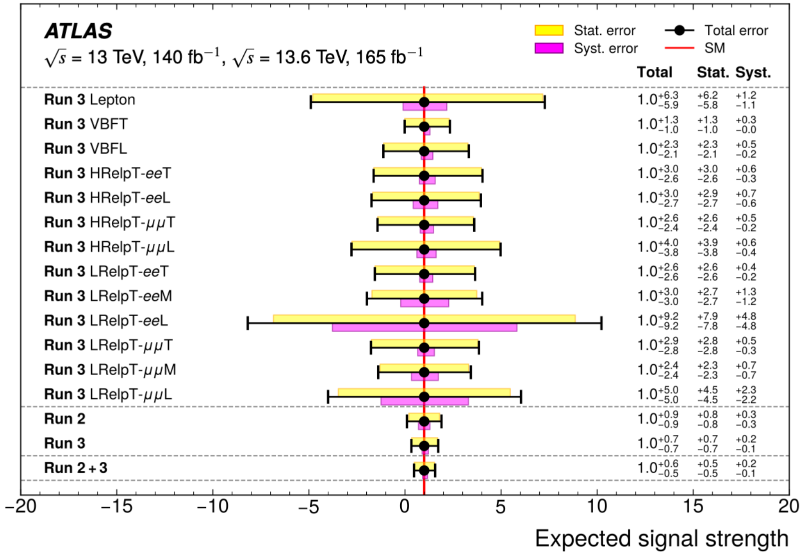
$Z\gamma$ invariant mass distributions of weighted data



Compatibility check

- **For Run 3 analysis:**
  - Using individual signal strengths for each category in the measurement
  - **Consistent with results from global signal strength**: p-value = 0.37
- **Run 2 and Run 3 measurements are statistically compatible: p-value = 0.33**





Run2/Run3 difference

Expected significance improves for 28% relative to the previous Run 2 ATLAS result
- **11%** from increased integrated **luminosity and cross section scaling**
- **15%** from the advanced event **selection and categorization** (after scaling luminosity and XS)

11% is calculated by scaling luminosity and XS in Run2 WS to Run3 and then refit with the scaled WS

Selection difference

Muon pT threshold is decreased from 10 GeV (Run 2) to 5 GeV

Photon pT threshold is decreased from 15 GeV (Run 2) to 10 GeV

Photon relative pT cut is decrease from 0.12 (Run2) to 0.09

Run2 categorization