中国科学院高能物理研究所
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ATLAS EXPERIMENT

Partial Run3 search for the Higgs boson decay to $Z\gamma$ with ATLAS detector

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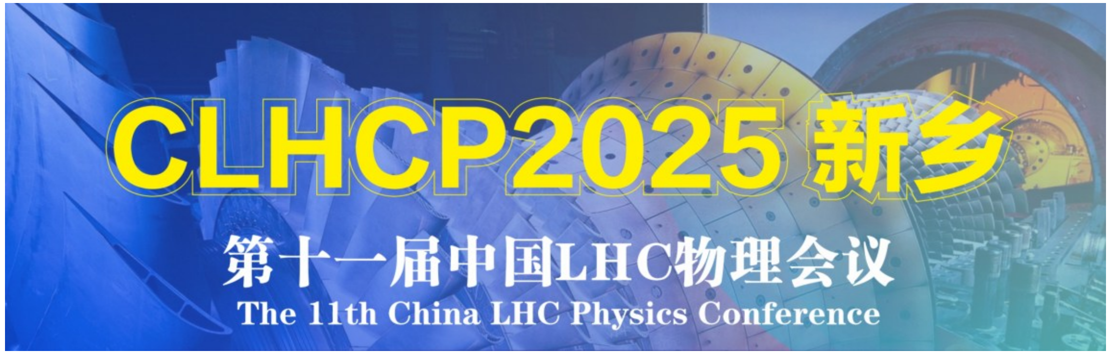
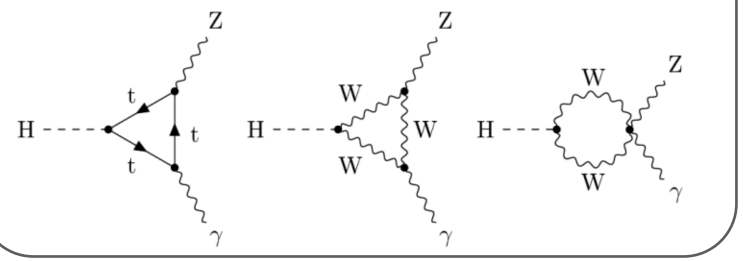


Link to plots and paper

Introduction

loop-induced processes



- Within the SM, the Higgs boson decay to a Z boson and a photon ($\boldsymbol{H \rightarrow Z\gamma}$) proceeds via loop-induced processes
  - Predict branching ratio: $BR(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ for mH = 125.09 GeV
- Precise measurements of this rare decay provide a sensitive probe for the SM and its extensions
- Previous analysis: evidence of Higgs decay to a Z boson and a photon in LHC
  - Combining ATLAS and CMS datasets (139 and 138 fb^{-1})
  - $3.4\sigma/1.6\sigma$ observed/expected significance
- **Partial Run3** analysis with $\boldsymbol{165\ fb^{-1}}$ data collected by ATLAS during **2022-2024**
  - Validate SM $H \rightarrow Z\gamma$ with > 2x statistics than Run 2 ATLAS analysis

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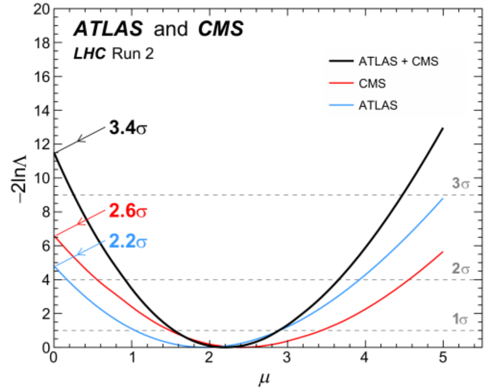
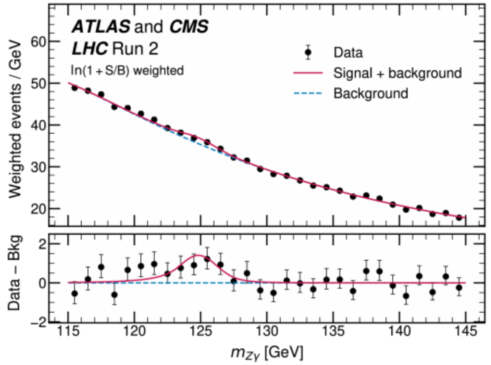
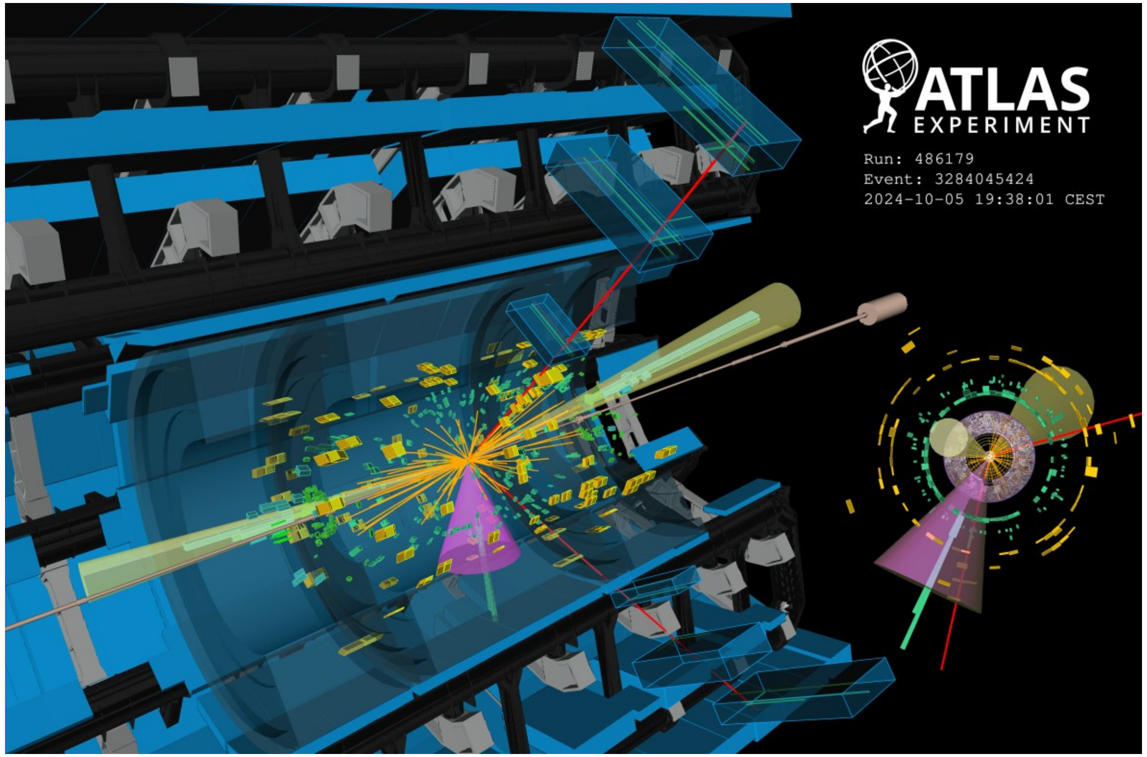




Analysis Strategy

- **$Z(\to ll)\gamma$ final states ($l = e, \mu$)**, low BR, but offer the best sensitivity to the $H \to Z\gamma$ search
  - **Efficient trigger** on leptons w.r.t Z hadronic/invisible decay
  - Benefit from full kinematic **reconstruction** and excellent invariant mass **resolution**
- Partial Run3 combine with Run2
  - We don't reanalysis the Run2 dataset
  - Combine with Run2 workspace
  - Total luminosity: $305\ fb^{-1}$



Event display, $VBFH \to Z\gamma \to \mu\mu\gamma$ event candidates
red tracks represent the muon,
purple cone represents the photon
yellow cones represent the VBF associated jets

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	

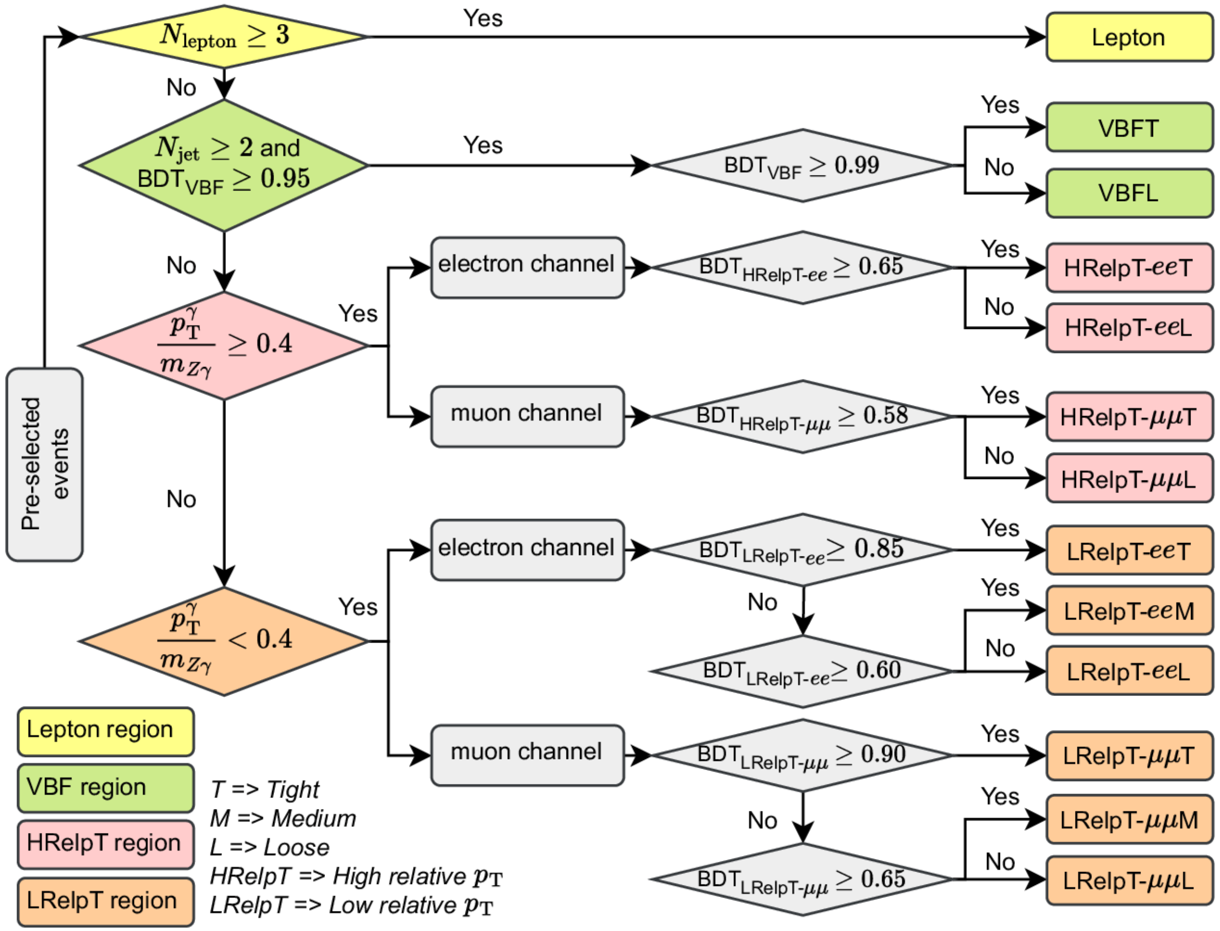
- Triggers: **single-/di - lepton triggers**
- **Overlap removal**:
  - Specially, overlap removal of photon is only preformed with the two selected leptons to improve the photon efficiency

- Z boson candidates reconstruction
  - **FSR correction**: FSR photons (ΔR < 0.15) are added to muon pairs
  - **Kinematic fit constrains** to the know Z mass
- Select the Z candidates by closest to Z mass
  - And Z mass window: $|m_{ll} - m_Z| < 10\ GeV$

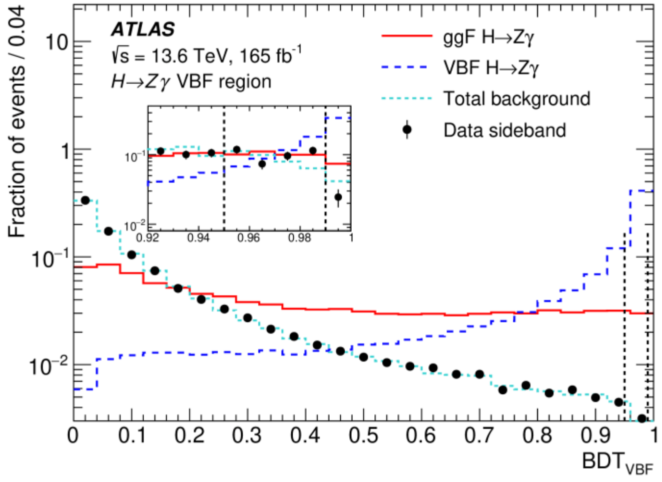
- Higgs boson candidate reconstruction
  - Combine the selected Z boson and the highest pT photon
  - $m_{Z\gamma}$ in 110-160 GeV
  - $\boldsymbol{p_T^{\gamma}/m_{Z\gamma}}$ **> 0.09** to further reduce background while **avoiding a sharp "turn-on"** in the $m_{Z\gamma}$ spectrum

Categorization

- Events are classified into four regions:
  - Lepton, VBF ,high relative p_T , low relative p_T
- **BDTs** and **Z decay modes** are used to split events
  - Lepton category: lepton number
  - VBF category: 2 jets and BDT_{VBF}
  - Photon Relative pT category: lepton flavor and BDTs
  - In total, 13 event categories are defined



BDT distribution for VBF category



BDT training strategy

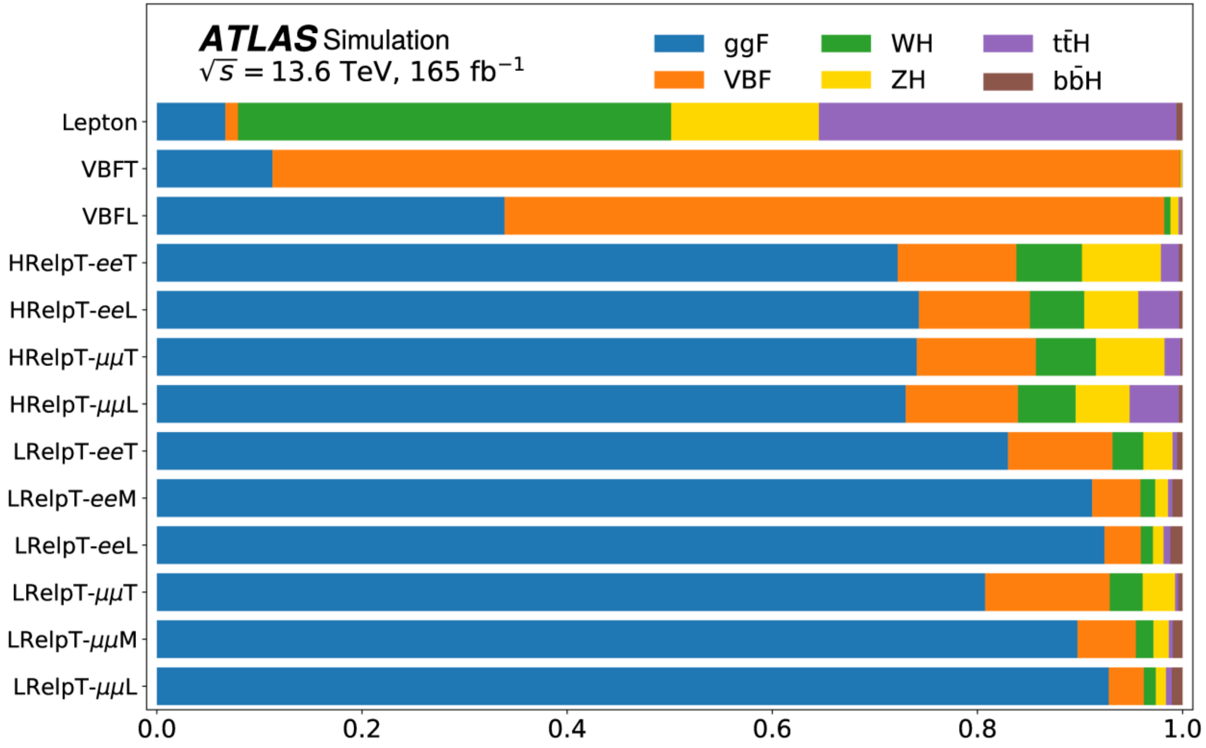
- Optimization target: maximizes the combined number counting significance
  - Requires at least two background events(MC) in the signal region ([120, 130] GeV) of each category
- VBF BDT
  - VBFH as signal and ggFH+Zy as backgrounds
- High/Low relative photon pT BDT
  - Separated by lepton flavor
 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

Input variable	Description	VBF	relative photon p_{T}
N_{jet}	Number of jets	✓	✓
$p_{\mathrm{T}}^{j_1}, \eta_{j_1}$	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		✓
$m_{j_2}, p_{\mathrm{T}}^{j_2}, \eta_{j_2}$	Mass, p_{T}, and η of the subleading jet (j_2)	✓	
$m_{j_1 j_2}, p_{\mathrm{T}}^{j_1 j_2}, \Delta\eta_{j_1 j_2}$	Dijet invariant mass, p_{T}, and η separation	✓	
η_{γ}	Pseudorapidity of the photon	✓	✓
p_{T}^{γ}	Transverse momentum of the photon	✓	
$p_{\mathrm{T}}^{\ell\ell}$	Transverse momentum of the dilepton system	✓	
$\eta_{\ell\ell}, \eta_{\ell\ell\gamma}$	Pseudorapidity of the dilepton and $\ell\ell\gamma$ systems	✓	✓
$p_{\mathrm{T}}^{\ell\ell\gamma}$	Transverse momentum of the $\ell\ell\gamma$ system	✓	
$p_{\mathrm{T}}^{\ell\ell\gamma}/m_{\ell\ell\gamma}, p_{\mathrm{T}}^{\gamma}/m_{\ell\ell\gamma}$	Relative p_{T} of the $\ell\ell\gamma$ and the photon		✓
$p_{\mathrm{T}}^{\ell\ell}/m_{\ell\ell\gamma}$	Relative p_{T} of the dilepton system		✓
p_{T}^{t}	Component of $\vec{p}_{\mathrm{T}}^{\,\ell\ell\gamma}$ perpendicular to the difference between $\vec{p}_{\mathrm{T}}^{\,\ell\ell}$ and $\vec{p}_{\mathrm{T}}^{\,\gamma}$ ($p_{\mathrm{T}}^{t} = \lvert\vec{p}_{\mathrm{T}}^{\,\ell\ell\gamma} \times \hat{t}\rvert$, with $\hat{t} \propto \vec{p}_{\mathrm{T}}^{\,\ell\ell} - \vec{p}_{\mathrm{T}}^{\,\gamma}$)	✓	✓
$\Delta\phi_{\ell\ell,\gamma}$	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	✓	✓
$\Delta R^{\mathrm{min}}_{\gamma \text{ or } \ell\ell, j}$	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	✓	✓
$\eta^{\mathrm{Zeppenfeld}}$	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



S, B in 68% signal region for each category

Category	S_{68}^{exp}	B_{68}^{exp}	N_{68}	w_{68} [GeV]	$S_{68}^{\text{exp}}/\sqrt{S_{68}^{\text{exp}}+B_{68}^{\text{exp}}}$
Lepton	1.5 ± 1.1	76.3 ± 2.8	78	4.4	0.17
VBFT	1.5 ± 1.1	1.2 ± 0.4	3	3.8	0.91
VBFL	2.8 ± 2.0	27.6 ± 1.8	23	4.0	0.51
HRelpT-eeT	1.2 ± 0.8	6.6 ± 0.9	11	3.1	0.43
HRelpT-eeL	3.0 ± 2.1	54.10 ± 1.8	77	4.0	0.40
HRelpT-$\mu\mu$T	2.4 ± 1.7	20.3 ± 1.7	33	3.9	0.50
HRelpT-$\mu\mu$L	2.4 ± 1.7	56.5 ± 1.7	72	4.1	0.31
LRelpT-eeT	9 ± 6	234 ± 6	251	3.8	0.57
LRelpT-eeM	29 ± 20	2 591 ± 19	3 806	4.1	0.56
LRelpT-eeL	24 ± 17	13 260 ± 50	17 435	4.5	0.21
LRelpT-$\mu\mu$T	4.9 ± 3.4	96 ± 4	127	3.9	0.49
LRelpT-$\mu\mu$M	34 ± 24	2 545 ± 19	3 133	4.1	0.67
LRelpT-$\mu\mu$L	37 ± 26	16 960 ± 40	19 331	4.4	0.28
Inclusive	150 ± 110	35 930 ± 70	44 380	4.0	1.81

Signal modeling and background estimation

- **Signal model**: DSCB function
  - Combine all production modes with SM XS
  - Contribution from $H \to \mu\mu$ decays (up to 3.8% in category, 1.8% inclusively) is modeled with its own DSCB template and fixed to the predicted fraction
- **Background estimation**
  - Main backgrounds: **Irreducible non-resonant $Z\gamma$** production and **Z + jets** events in which a jet is misidentified as a photon
    - Diboson background: constitutes 35% in **lepton category**, 0.2% inclusively
  - The relative fractions of $Z\gamma$ and Z + jets components are determined inclusively via a two-dimensional sideband method
  - $Z\gamma$ purity is estimated to be $0.49^{+0.05}_{-0.10}$, uncertainty is from different R estimation methods

Backup: Introduction of 2D sideband methods, R

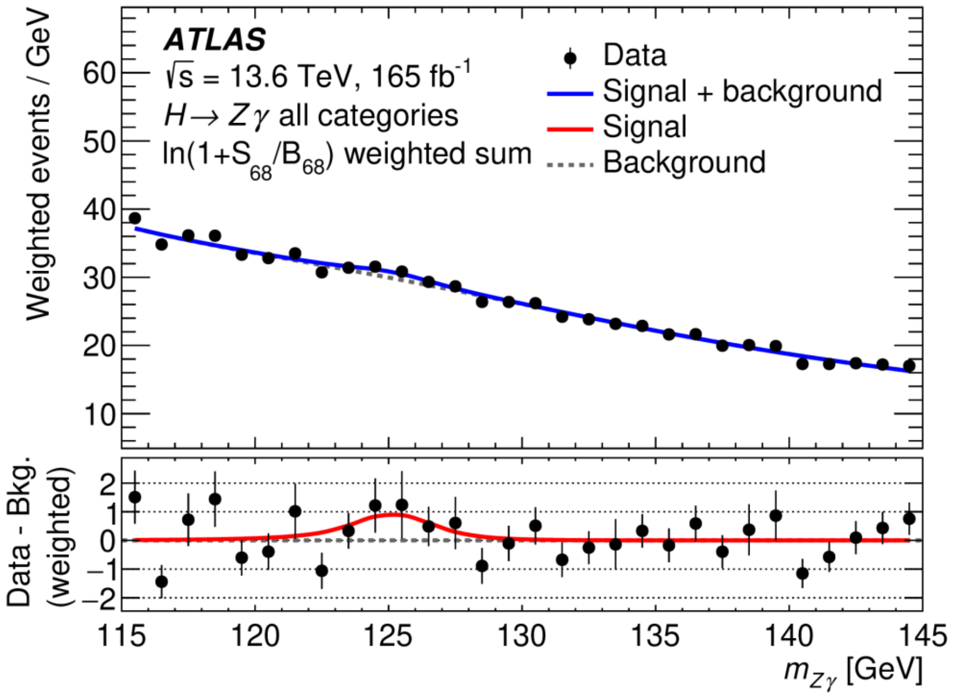
Background templates

- 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, details workflow in backup

Results of Run 3 analysis

- **Profiled Likelihood Ratio test**
  - Un-binned maximum-likelihood fit
- **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**
  - $\mu_{exp} = 1.0 \pm 0.7(stat)^{+0.2}_{-0.1}(syst) = 1.0^{+0.7}_{-0.7}$
  - **Statistical uncertainty dominant!**
- **Observed significance** (background-only hypothesis): 1.4 σ
- **Expected significance**: 1.5 σ
- **Measurement is statistically consistent with SM expectation**

$Z\gamma$ invariant mass distributions of weighted data

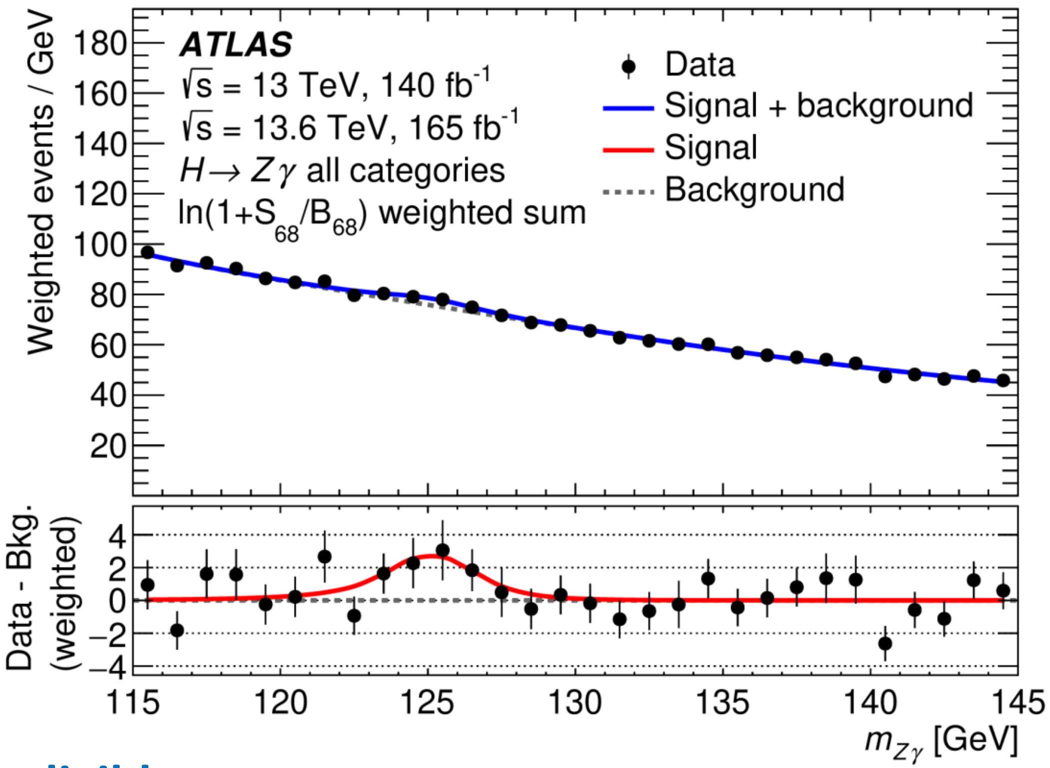


Expected significance improves for 28% relative to the previous Run 2 ATLAS result
- **11%** from increased integrated **luminosity and cross section scaling**
- **15%** from the advanced event **selection and categorization** (after scaling luminosity and XS)

Run 2 & Run 3 combination

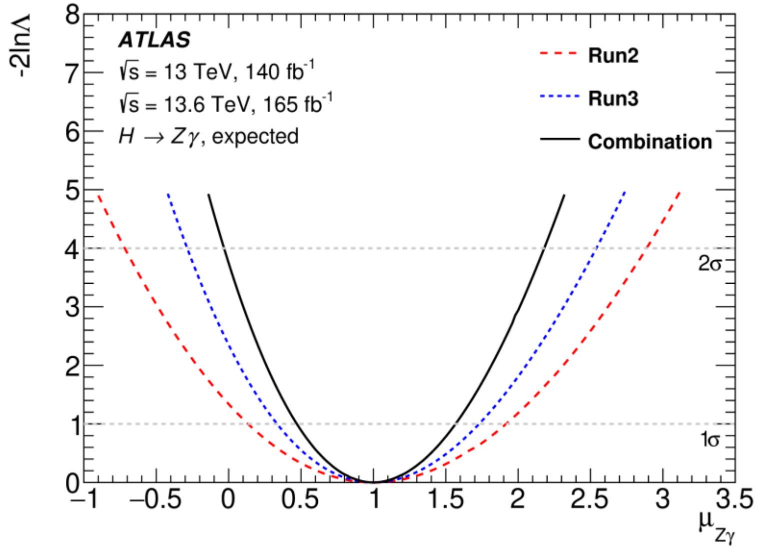
- ➢ Uncertainty Correlation Strategy
- ➢ **Fully correlated:**
  - Theoretical uncertainties: Branching ratio, QCD scale, α_s
- ➢ **Uncorrelated**:
  - PDF uncertainties (different sets used in Run 2 vs. Run 3)
  - Most experimental uncertainties:
    - due to distinct data-taking conditions
    - Trigger, 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

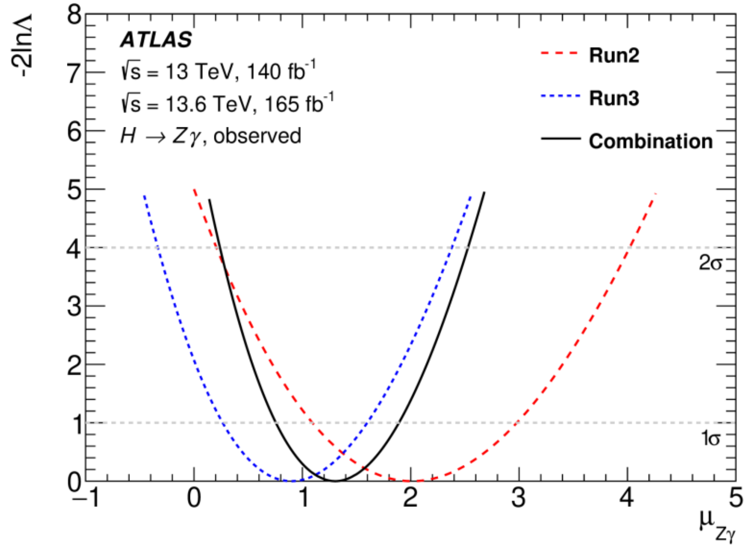
$Z\gamma$ invariant mass distributions of weighted data



Results of Run 2 + Run 3

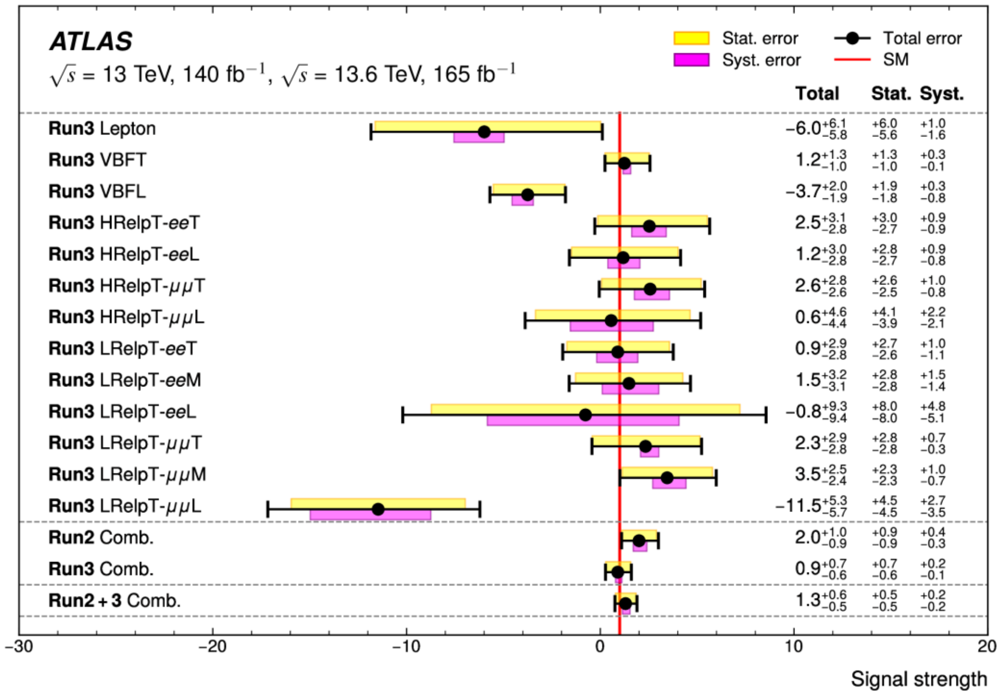
- The combined best-fit signal strength:
  - $\boldsymbol{\mu = 1.3 \pm 0.5(stat) \pm 0.2(syst) = 1.3^{+0.6}_{-0.5}}$
- SM expected value:
  - $\boldsymbol{\mu = 1.0 \pm 0.5(stat)^{+0.2}_{-0.1}(syst) = 1.0^{+0.6}_{-0.5}}$
- The observed (expected) significance is **2.5σ** (**1.9σ**)
  - Combination improves Run2 by 61%
  - Current ATLAS expected results 19% better than previous ATLAS+CMS
- Assuming the SM cross-section, the observed branching ratio is $BR(H \rightarrow Z\gamma) = (2.0^{+0.9}_{-0.8}) \times 10^{-3}$, expected $(1.5^{+0.9}_{-0.8}) \times 10^{-3}$
- This combination provides the **highest expected significance** to date for the $H \rightarrow Z\gamma$ mearesurement

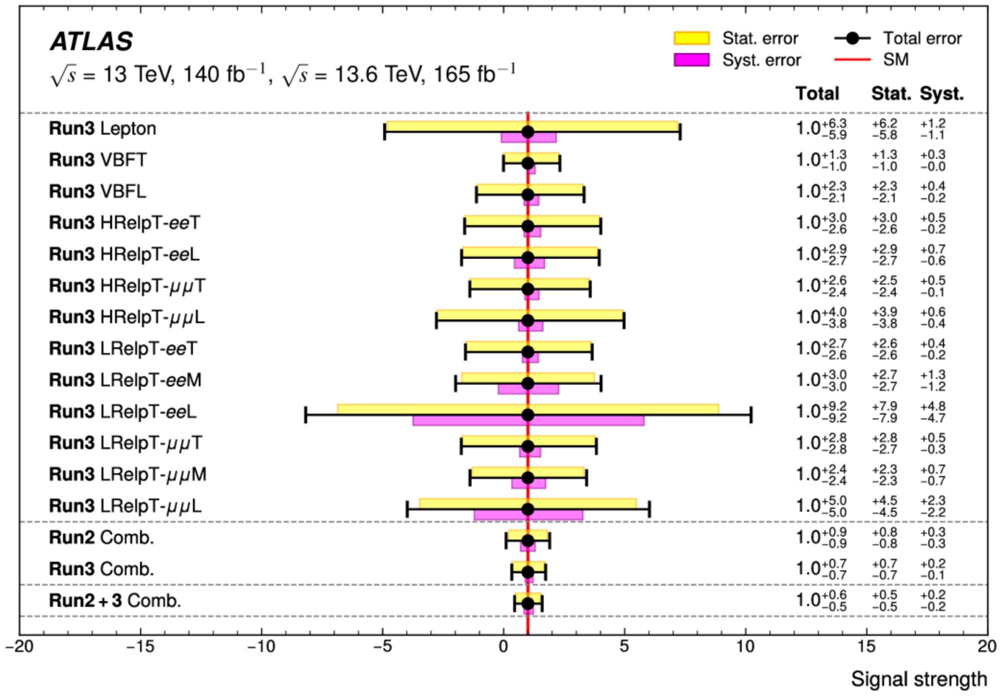




Compatibility check

- **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**





Summary

- The search for the Higgs boson decay to $Z\gamma$ was conducted with the ATLAS detector at an energy of √s = 13.6 TeV at the integrated luminosity of $165\ fb^{-1}$
- The observed (expected) 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) standard deviations
  - Compared to Run2 ATLAS results, the expected significance improved by 28%
- Combined with the Run 2 results
  - Observed (expected) signal strength and significance:$\mu_{obs} = 1.3^{+0.6}_{-0.5} (\mu_{exp} = 1.0^{+0.6}_{-0.5})$, 2.5 (1.9) standard deviations
  - Current ATLAS expected results 19% better than previous ATLAS+CMS
- The findings are consistent with the SM expectations
- Provides the highest expected significance to date for the $H \to Z\gamma$ mearesurement

Plots link, Arxiv link

Additional slides

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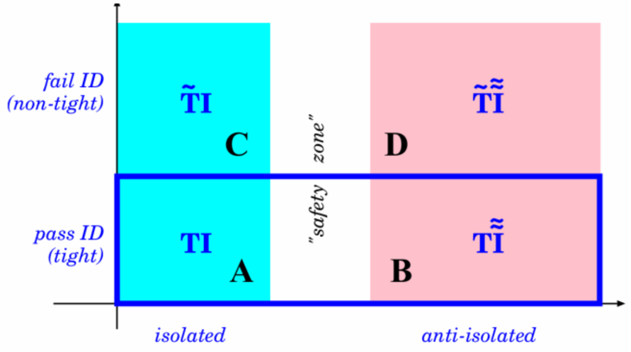
Two-dimensional sideband method

- ABCD method (ID/ISO) for the background decomposition:
  - **Signal leakage $c_k \equiv \mathrm{N}_{\mathrm{K}}^{Z\gamma}/\mathrm{N}_{\mathrm{A}}^{Z\gamma}$: assume it can be well described in MC.**

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

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

  - BDEF method: split BD region by calo ISO

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

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

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

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