

Highlights on Higgs Physics with ATLAS

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on behalf of the ATLAS Experiment Collaboration



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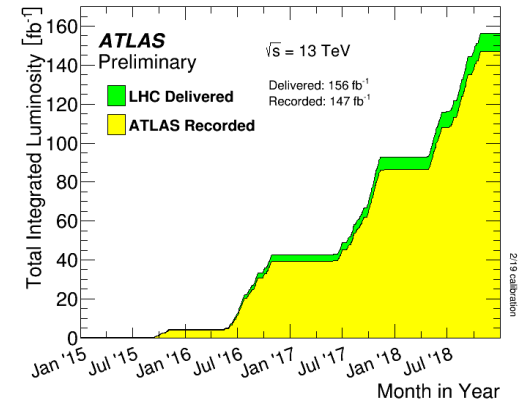
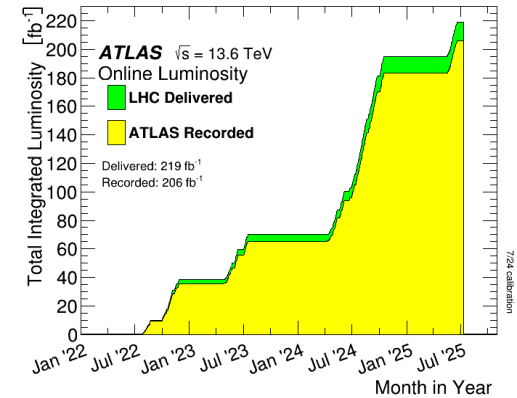
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Introduction

- Excellent data-taking efficiency in both Run 2 and Run 3
- ATLAS recorded **147 fb⁻¹ in Run 2**
- Already **200+ fb⁻¹ in Run 3...** and counting...
- Run-3: **4 Higgs-physics papers** so far (vs 145 in Run-2).
- Many analyses ongoing, exploiting higher energy and luminosity.

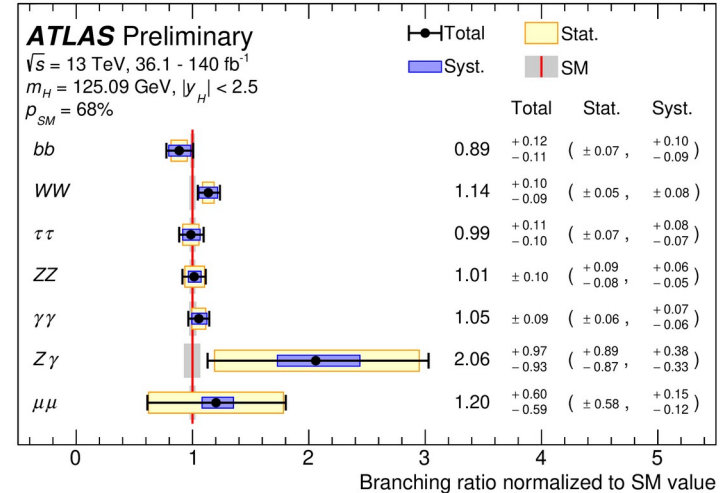
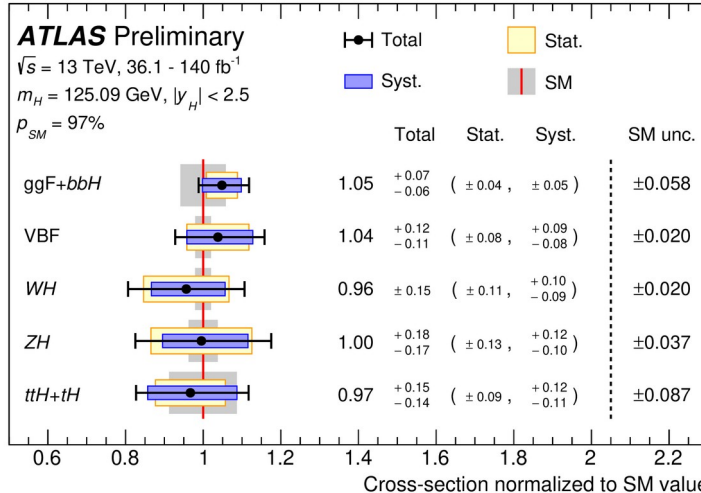
In This Talk:

- Rare modes: $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$.
- Precision measurements of Higgs production and decay rates.
- CP studies via angular observables & EFT fits.
- Searches for di-Higgs production and self-coupling.



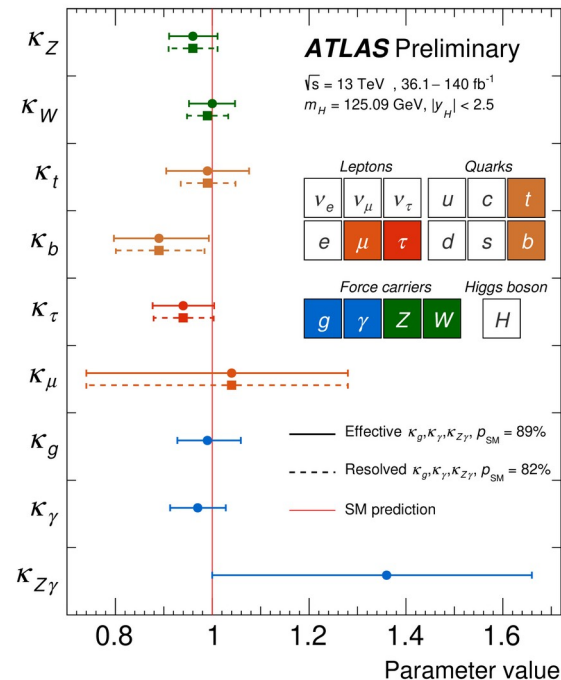
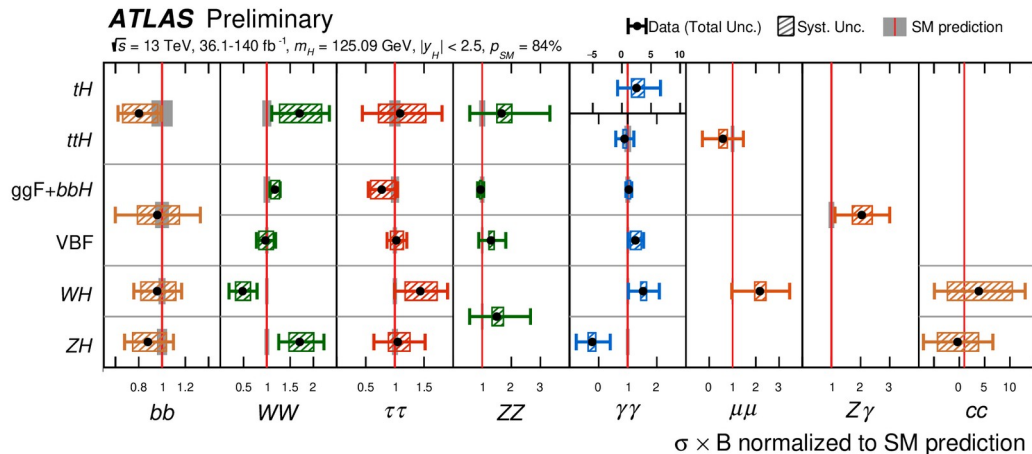
ATLAS Run-2 combination

- $\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$
- Total Higgs signal strength: $\mu = 1.023^{+0.056}_{-0.053} = 1.023 \pm 0.028 \text{ (stat)}^{+0.026}_{-0.025} \text{ (exp)}^{+0.039}_{-0.036} \text{ (sig)} \pm 0.012 \text{ (bg)}$
- Cross sections and BRs: **good agreement with SM**
- Improved precision: **~10–20% vs previous combination**



ATLAS Run-2 combination

- **29 $\sigma \times \text{BR}$ combinations** measured across production and decay modes
- Most channels within **1 σ of SM**; uncertainties **10–40%**
- **Coupling modifiers (κ)** extracted assuming only SM decays
- $\kappa_{W,Z}$, $\kappa_{t,b,\tau}$ at **5–12%**, κ_{μ} **~25%**, κ_C weakly constrained



Run-3 Higgs Physics Prospects

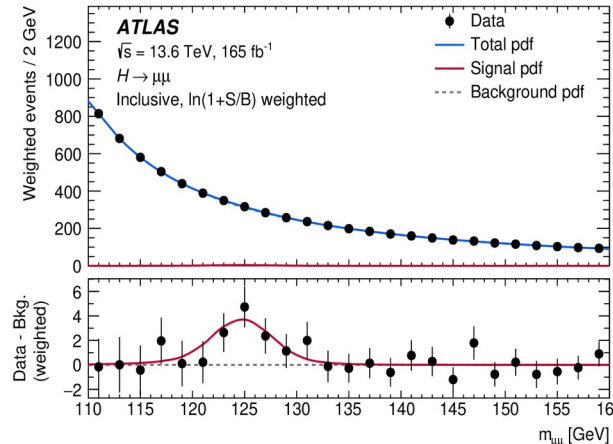
Selected Key Points (13.6 TeV, $\sim 250 \text{ fb}^{-1}$)

- **Coupling precision:** improve by 20–30% in $\gamma\gamma$, WW , ZZ , $\tau\tau$, $b\bar{b}$.
- **2nd gen couplings:** $H \rightarrow \mu\mu$ discovery; Higgs–charm benchmark with boosted & charm tagging.
- **Rare decays:** Single-exp. $H \rightarrow Z\gamma$ observation; $\sim 3.2\sigma$ evidence $H \rightarrow \gamma^*\gamma$ (nearing combined observation).
- **Higgs Width (Γ_H):** Investigate $H \rightarrow \gamma\gamma$ and $H \rightarrow WW$, alongside $H \rightarrow ZZ$.
- **Di-Higgs:** $\sim 2\sigma$ combined sensitivity; $\sigma(\text{HH}) < 2.4 \times \text{SM}$ (95% CL); $\kappa_\lambda \in [-0.4, 6.3]$ at 95% CL (driven by innovative analyses and machine learning techniques).
- **Indirect BSM search:** SMEFT global fits; constrain c_{HW} , c_{HG} and CP-violating terms (e.g., c_{HW})

Search for $H \rightarrow \mu\mu$ decay

Test Yukawa sector on 2nd Fermion Generation

- Rare decay, branching ratio $\sim 0.02\%$
 - Run-2 observed (expected) signal significance: 2.0σ (1.7σ).
-
- Using 165 fb^{-1} Run-3 data at 13.6 TeV + 139 fb^{-1} Run-2 data at 13 TeV – **x2 statistics of previous result.**
 - Signature: 2 opposite-charge isolated muons.
 - 23 event categories by Higgs production mode (ggF, VBF, VH, $t\bar{t}H$) + BDT scores within, to enhance S/B.
 - Fit discriminant: $m_{\mu\mu}$.



Dimuon invariant mass spectrum in all the categories observed in Run-3 (error bars represent statistical uncertainties)

Search for $H \rightarrow \mu\mu$ decay

Main Improvements:

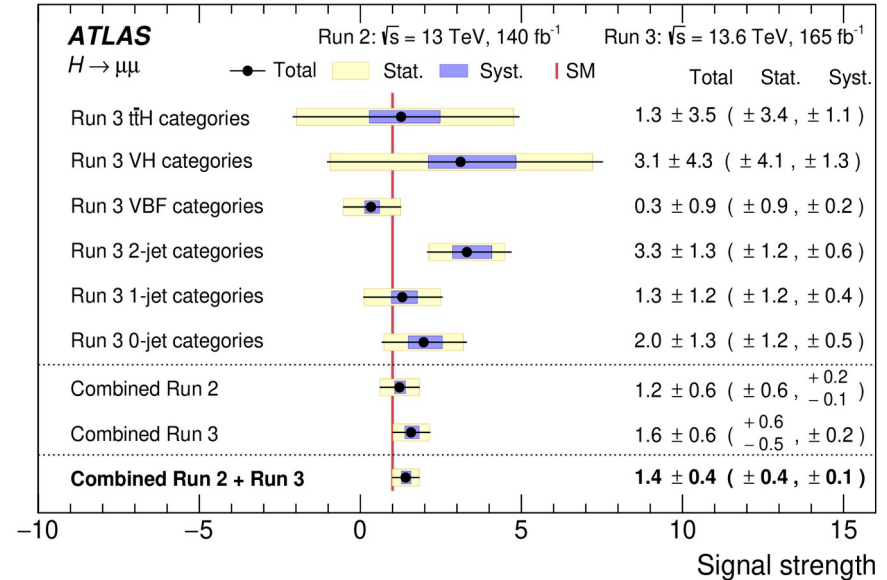
- Increased statistics with the inclusion of Run-3 data.
- Huge Drell-Yan sample (5B events) to study BG modeling.
- Precise calibration of physics objects.
- Refined categorization.
- Improved reconstruction (μ -vertex refit)

Results:

- **Run-3:** $\mu = 1.6^{+0.6}_{-0.5}(\text{stat}) \pm 0.2(\text{syst})$
Observed (expected) significance: **2.8σ** (1.8σ)
- **Run-3 + Run-2:** $\mu = 1.4 \pm 0.4(\text{stat}) \pm 0.1(\text{syst})$
Observed (expected) significance: **3.4σ** (2.5σ)

Evidence for $H \rightarrow \mu\mu$ -- in agreement with SM.

Best-fit values of the signal-strength parameters



Search for $H \rightarrow Z(\rightarrow ll)\gamma$ decay

Last unobserved decay to gauge bosons ($\gamma\gamma$, ZZ^* , WW^*)

- Rare (loop-suppressed) decay – Branching ratio $\sim 0.15\%$
- Run 2 observed (expected) signal significance: 2.2σ (1.2σ) – **combined with CMS: 3.4σ (1.6σ) \rightarrow evidence.**

- Using 165 fb^{-1} Run-3 data at 13.6 TeV + 139 fb^{-1} Run-2 data at 13 TeV.
- Signature: isolated photon + 2 same-flavor, opposite-charge isolated leptons.
- 13 categories: ≥ 3 leptons (VH/ttH), VBF, high/low relative photon p_T (ggF-dominated).
- BDTs in VBF and p_T categories to enhance signal/BG separation.
- Fit discriminant: $m_{Z\gamma}$.

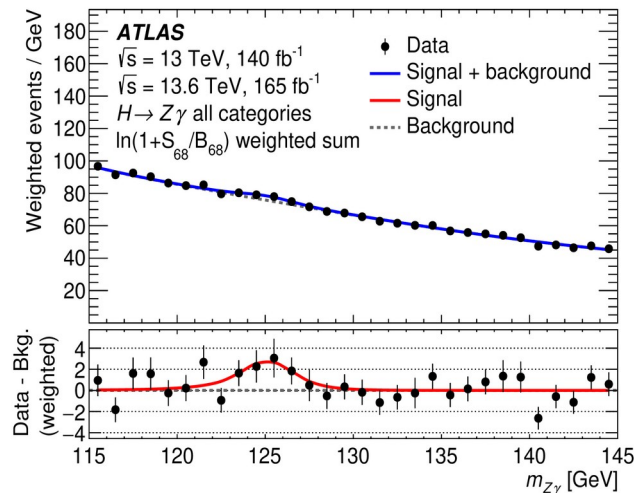
Run- 3: $\mu = 0.9^{+0.7}_{-0.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$

Observed (expected) significance: **1.4σ (1.5σ)**

Run-3 + Run-2: $\mu = 1.3 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})$

Observed (expected) significance: **2.5σ (1.9σ)**

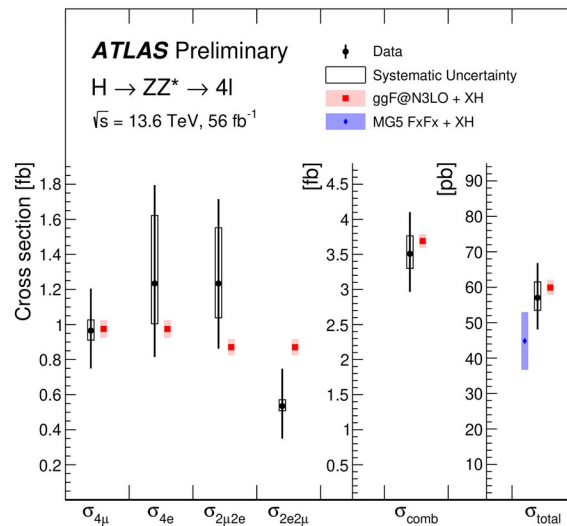
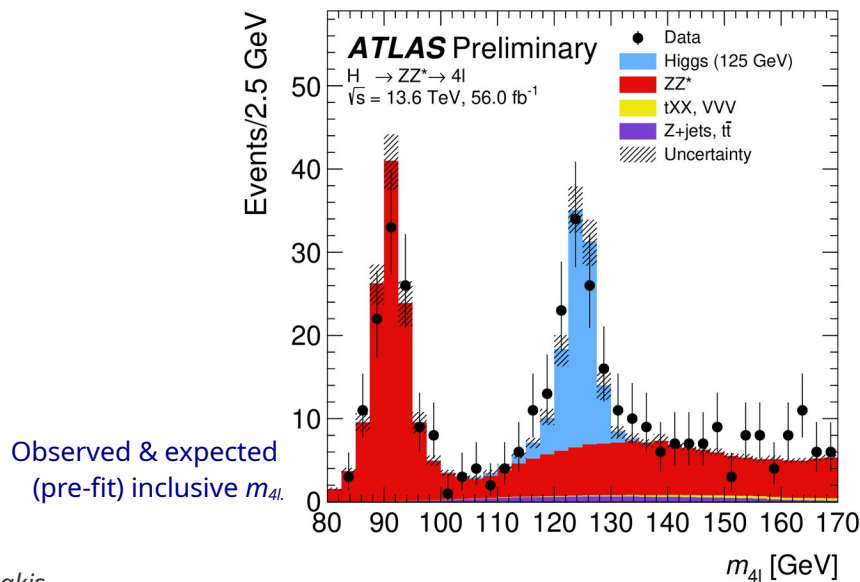
Most stringent expected sensitivity to date



Study of $H \rightarrow ZZ^* \rightarrow 4l$

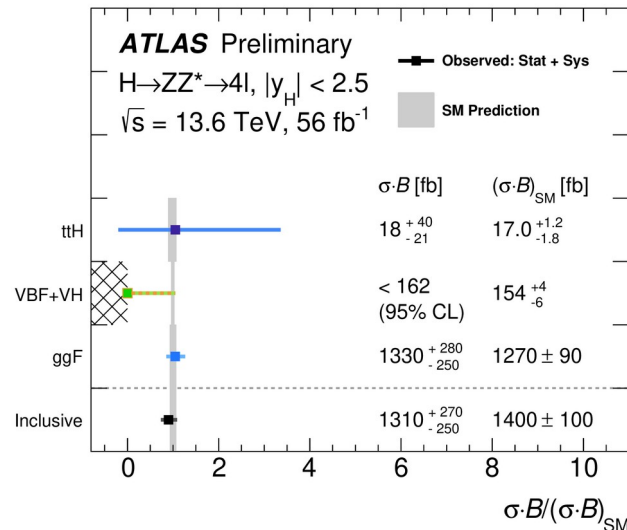
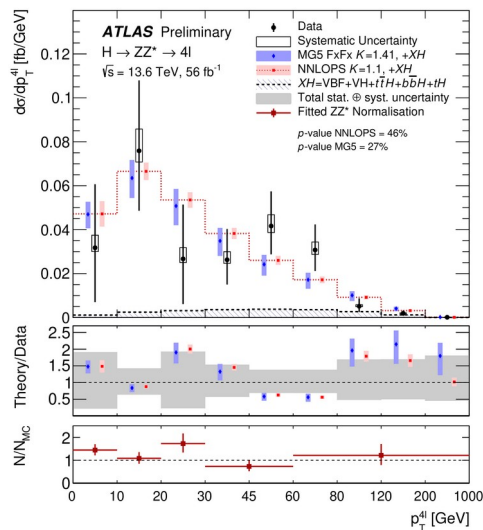
First detailed Run 3 study of $H \rightarrow 4l$: production modes, couplings, EFT, CP...

- Based on 56 fb^{-1} Run-3 data (2022-23)
- Analysis channels: 4μ , $2e2\mu$, $2\mu2e$, $4e$
- Measurement of differential fiducial XS vs key observables: $|y_{4l}|$, $p_{T,4l}$, N_{jets} , m_{34}
- Total XS (acceptance corrected using MC)



Study of $H \rightarrow ZZ^* \rightarrow 4l$

- Production-mode XS (ggF, VBF, VH, $t\bar{t}H$) enabling future precision measurements.
- XS interpreted with universal κ_f, κ_V ; Run 3 + Run 2 combined.
- Differential XS vs. m_{34} sets limits on CP-even and CP-odd EFT operators.
- **No significant deviations from SM observed**
- **Run 2 + Run 3 combination reduces uncertainties, with central values consistent with Run 2**



Study of $H \rightarrow WW^* \rightarrow l\nu l\nu$

Measurements of the ggF and VBF production cross-sections.

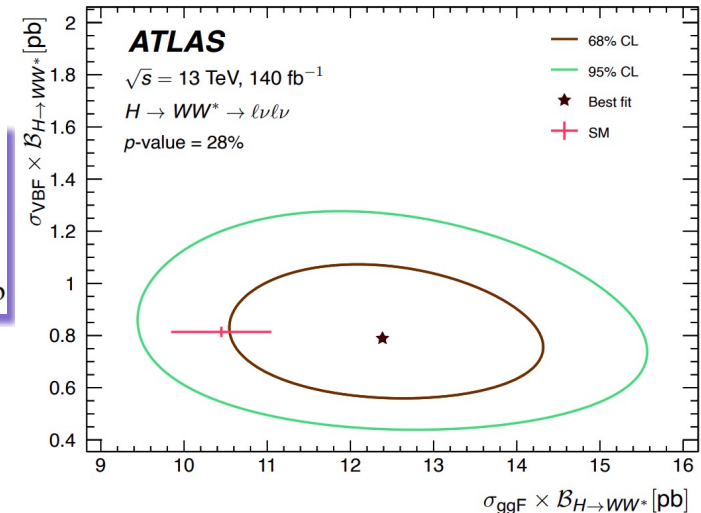
- Based on 140 fb^{-1} Run-2 data at 13 TeV.
- Signature: 2 opposite-charge leptons + $E_{T,\text{miss}}$.
- Improvements w.r.t. previous results: Inclusion of same-flavour final state, improved background rejection (NNs), and method upgrades.
- Analysis channels by (a) Njets: 0, 1, ≥ 2 and (b) lepton flavour (SF, DF)
- Discriminant: DNN score.

ggF/VBF Inclusive Cross-Section:

$$\begin{aligned}\sigma_{\text{ggF}} \times \mathcal{B}_{H \rightarrow WW^*} &= 12.4^{+1.3}_{-1.2} \text{ pb} \\ &= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp. syst.)} \pm 0.3 \text{ (sig. theo.)}^{+0.6}_{-0.5} \text{ (bkg. theo.) pb,}\end{aligned}$$

$$\begin{aligned}\sigma_{\text{VBF}} \times \mathcal{B}_{H \rightarrow WW^*} &= 0.79^{+0.18}_{-0.16} \text{ pb} \\ &= 0.79 \pm 0.11 \text{ (stat.)}^{+0.07}_{-0.06} \text{ (exp. syst.)}^{+0.12}_{-0.09} \text{ (sig. theo.)} \pm 0.05 \text{ (bkg. theo.) pb}\end{aligned}$$

11% precision improvement w.r.t. previous analysis results.



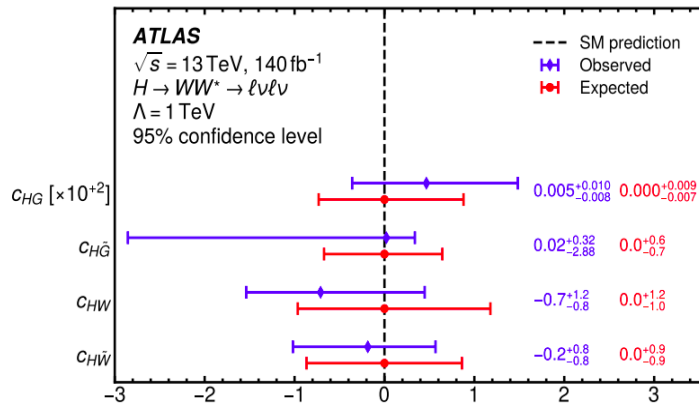
Study of $H \rightarrow WW^* \rightarrow l\nu l\nu$

STXS measurements:

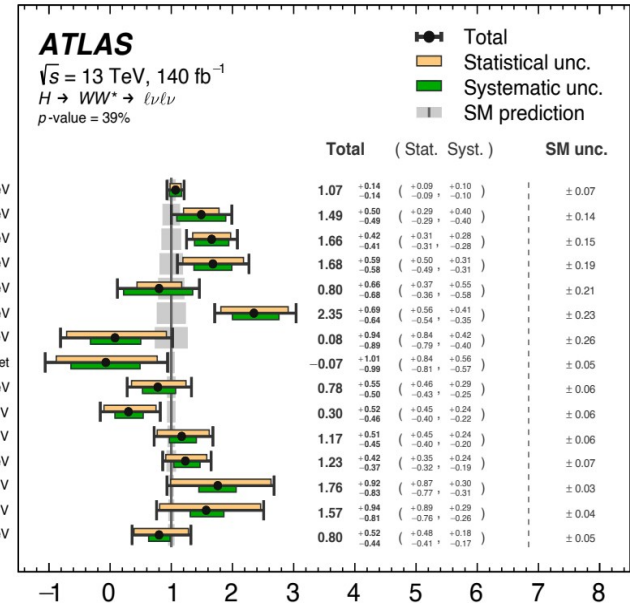
- 15 categories - further categorization by m_{jj} , $p_{T,H}$.
- Improvement in precision up to 36%.

CP-sensitive measurements:

- **New:** $\Delta\phi_{jj}$ - based categorization in ≥ 2 -jet events (qqH phase space)
- Interpretation in EFT using dim.-6 operators in the Warsaw basis
- CP-even (C_{HW} , C_{HG}) and CP-odd ($C_{H\bar{W}}$, $C_{H\bar{G}}$) effective $\ell\nu\ell\nu$ couplings constrained



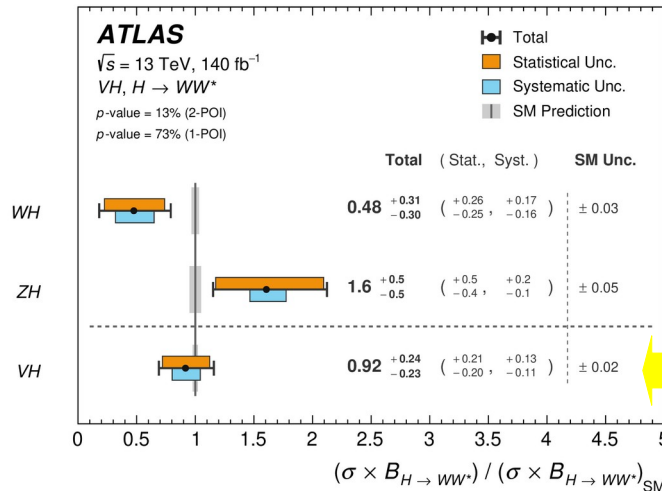
ggH 0-jet, $p_T^H < 200 \text{ GeV}$	1.07	$+0.14$	-0.14	-0.09	-0.10	± 0.07
ggH 1-jet, $p_T^H < 60 \text{ GeV}$	1.49	$+0.50$	$+0.29$	$+0.40$	-0.40	± 0.14
ggH 1-jet, $60 \leq p_T^H < 120 \text{ GeV}$	1.66	$+0.42$	$+0.31$	$+0.28$	-0.28	± 0.15
ggH 1-jet, $120 \leq p_T^H < 200 \text{ GeV}$	1.68	$+0.59$	$+0.50$	$+0.31$	-0.31	± 0.19
ggH 2-jet, $p_T^H < 200 \text{ GeV}$	0.80	$+0.66$	$+0.37$	$+0.55$	-0.55	± 0.21
ggH , $200 \leq p_T^H < 300 \text{ GeV}$	2.35	$+0.68$	$+0.56$	$+0.41$	-0.41	± 0.23
ggH , $p_T^H \geq 300 \text{ GeV}$	0.08	$+0.84$	$+0.84$	$+0.42$	-0.40	± 0.26
EW qqH 1-jet	-0.07	-1.01	$+0.84$	-0.56	-0.57	± 0.05
EW qqH 2-jet, $p_T^H < 200 \text{ GeV}, 350 \leq m_{jj} < 700 \text{ GeV}$	0.78	$+0.55$	$+0.46$	$+0.29$	-0.25	± 0.06
EW qqH 2-jet, $p_T^H < 200 \text{ GeV}, 700 \leq m_{jj} < 1000 \text{ GeV}$	0.30	$+0.52$	$+0.45$	$+0.24$	-0.24	± 0.06
EW qqH 2-jet, $p_T^H < 200 \text{ GeV}, 1000 \leq m_{jj} < 1500 \text{ GeV}$	1.17	$+0.51$	$+0.45$	$+0.24$	-0.20	± 0.06
EW qqH 2-jet, $p_T^H < 200 \text{ GeV}, m_{jj} \geq 1500 \text{ GeV}$	1.23	$+0.42$	$+0.35$	$+0.24$	-0.22	± 0.07
EW qqH 2-jet, $p_T^H \geq 200 \text{ GeV}, 350 \leq m_{jj} < 1000 \text{ GeV}$	1.76	$+0.82$	$+0.87$	$+0.30$	-0.31	± 0.03
EW qqH 2-jet, $p_T^H \geq 200 \text{ GeV}, 1000 \leq m_{jj} < 1500 \text{ GeV}$	1.57	$+0.94$	$+0.89$	$+0.29$	-0.29	± 0.04
EW qqH 2-jet, $p_T^H \geq 200 \text{ GeV}, m_{jj} \geq 1500 \text{ GeV}$	0.80	$+0.81$	$+0.76$	$+0.26$	-0.26	± 0.05



VH($\rightarrow WW^*$) associated production cross-section

Probes Higgs coupling to vector-bosons both at production and decay vertex.

- Based on 140 fb⁻¹ Run-2 data at 13 TeV -- Update from previous result (36.1 fb⁻¹).
- 4 analysis regions (mutually exclusive) based on lepton multiplicity and charge 2LSS / 2LOS / 3L / 4L.
- Signal regions further defined by kinematic selections
- MVA discriminants optimized per region to separate signal from background
- Measures total and differential WH and ZH production cross section
- **Results agree with the Standard Model.**



Best-fit values of the total WH, ZH, and VH cross-sections times the $H \rightarrow WW^*$ branching ratio.

corresponds to a 4.5 significance over the background-only hypothesis

$H \rightarrow WW$ off-shell production

- Based on 140 fb^{-1} Run-2 data at 13 TeV.
- Signature: 2 opposite-charge leptons + $E_{T,\text{miss}}$.
- 6 analysis regions by lepton flavor (DF/SF) and $N_{\text{jets}} = 0, 1, \geq 2$ (inc. VBF)
- Selection: 0 b -tagged jets, $|m_{\ell\ell} - m_Z| > 15 \text{ GeV}$ + lepton angular separation (orthog. to $H \rightarrow ZZ$ & on-shell $H \rightarrow WW$)
- DNN to separate signal (and signal-BG interf.) from background, and define control regions.
- Fit discriminant: Combination of $m_{\ell\ell}$ and $m_{T,WW}$

$$\mu_{\text{on-shell}} = K_{\text{prod,on-shell}}^2 \cdot K_{\text{decay,on-shell}}^2 \cdot \frac{1}{K_H} \quad K_{i,\text{off-shell}}^2 \sim K_{i,\text{on-shell}}^2 \quad \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} \sim \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

$$\mu_{\text{off-shell}} = K_{\text{prod,off-shell}}^2 \cdot K_{\text{decay,off-shell}}^2$$

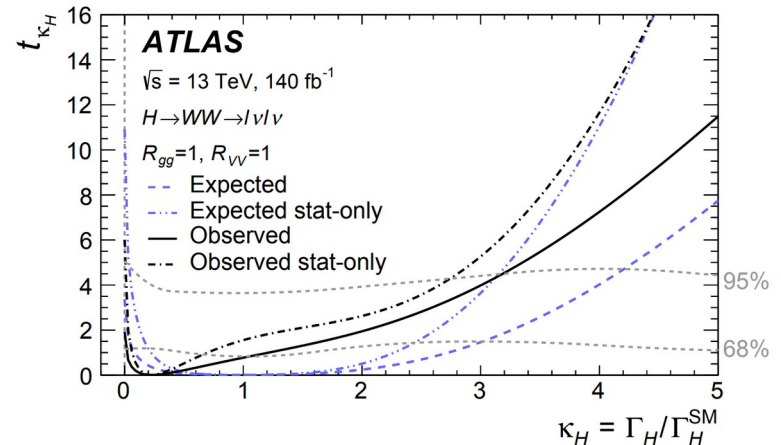
Signal Strength (yield w.r.t. SM):

- Observed (expected) $\mu_{\text{off-shell}} = 0.3^{+0.9}_{-0.3} (1.0^{+2.3}_{-1.0})$
- Observed (expected) 95% CL upper limit: **3.4 (4.4)**

Substantial improvement w.r.t. previous limits of 17.2 (21.3) using 20.3 fb^{-1} Run-2 data.

Higgs Decay Width:

- Observed (expected) $\Gamma_H = 0.9^{+3.4}_{-0.9} (4.1^{+8.3}_{-3.8}) \text{ MeV}$
- Observed (expected) 95% CL upper limit: **13.1 (17.3) MeV**

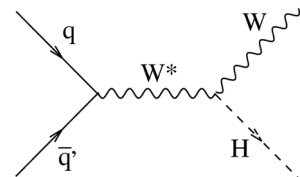


Study of CP-violation in WH production

Test CP-violating effects in Higgs- W interactions

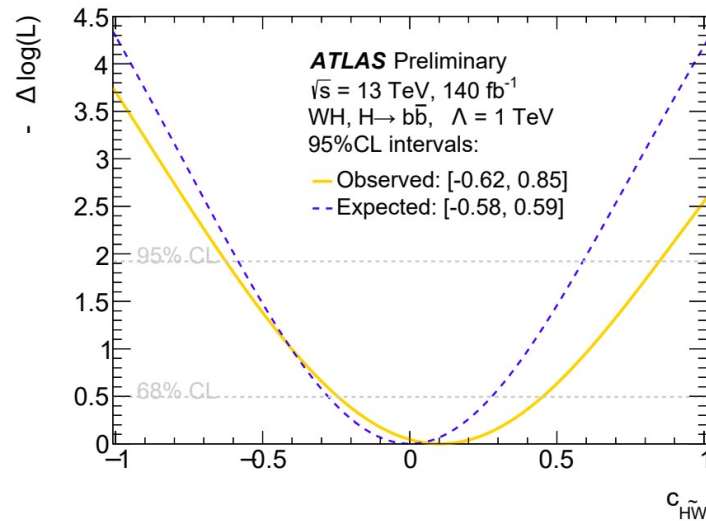
via angular observable $Q_\ell \cos \delta^+$, sensitive to SMEFT operator O_{HW} with Wilson coefficient c_{HW} .

$$\cos \delta^+ = \frac{\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$$



- Based on 140 fb^{-1} Run-2 data at 13 TeV.
- WH production with $W \rightarrow l\nu$, $H \rightarrow b\bar{b}$
- Events categorized by jet multiplicity (resolved/boosted) and bins $Q_\ell \cos \delta^+$.
- Fit Discriminant: Score of BDT trained separately in each SR and CR.

- **Signal strength** $\mu_{WH}^{bb} = 0.93_{-0.21}^{+0.22} = 0.93_{-0.15}^{+0.15}(\text{stat.})_{-0.15}^{+0.16}(\text{syst.})$
consistent with SM; 4.7σ (5.0σ) observed (expected significance)
- **Observed (expected) 95% CL limits on the CP-odd coupling:**
 c_{HW} are $[-0.62, 0.85]$ ($[-0.58, 0.59]$) computed with $\Lambda = 1 \text{ TeV}$
competitive with most stringent ATLAS limits to date

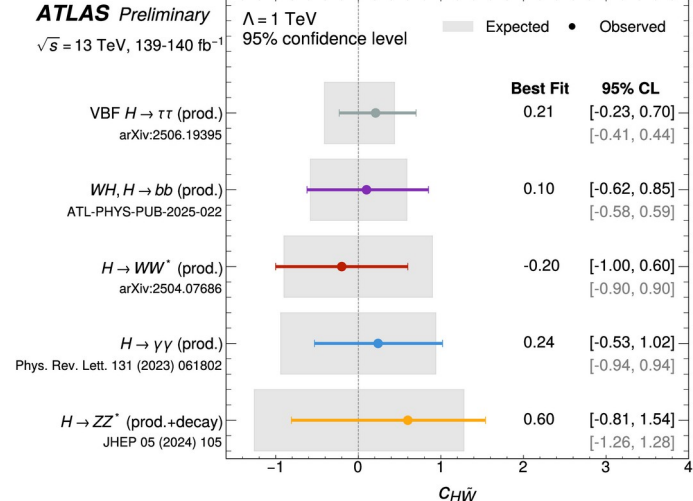
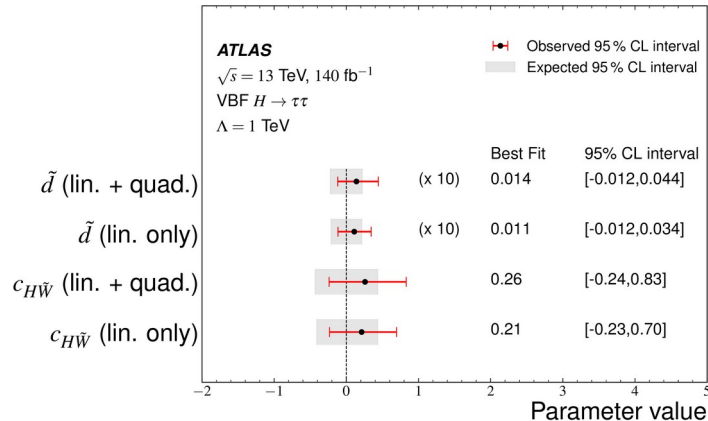
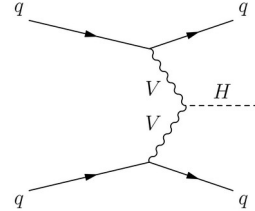


Study of CP-violation in $H \rightarrow \tau\tau$

Probe CP-violating effects in VBF Higgs production using $H \rightarrow \tau\tau$ decays.

- Based on 140 fb⁻¹ Run-2 data at 13 TeV.
- Optimal Observable (OO) combining Higgs + VBF jet kinematics.
- Constraints set in HISZ (parameter \tilde{d}) and Warsaw (e.g., $c_{H\tilde{W}}$) bases.
- Event selection: 3 final states ($\tau_{\text{had}}\tau_{\text{had}} / \tau_{\text{had}}\tau_{\text{lep}} / \tau_{\text{lep}}\tau_{\text{lep}}$) + $E_{T,\text{miss}} (> 20 \text{ GeV})$ + 2 jets (VBF).
- NN-based discrimination of the SM signal Vs background in each region.
- Fit Discriminant: OO distribution.
- **No deviation from SM observed.**

$$OO = \frac{2\Re(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$



Search for $HH \rightarrow b\bar{b}\gamma\gamma$

Targets non-resonant HH production to probe the trilinear self-coupling κ_λ and quartic κ_{2V} .

- Based on 140 fb^{-1} Run 2 data at 13 TeV + 168 fb^{-1} Run 3 data at 13.6 TeV – **x2 statistics of previous result.**
- Sensitive channel near threshold despite low BR (0.26%) due to excellent $m_{\gamma\gamma}$ resolution.
- m_{bb} resolution enhanced via jet corrections and kinematic fit.
- Categorization in 2 regions of $m_{b\bar{b}\gamma\gamma}$ sensitive to κ_λ (low mass) or κ_{2V} (high mass); further categorised using BDTs optimised for signal purity.
- Simultaneous fit to $m_{\gamma\gamma}$ in 14 signal regions (7 per Run); background shapes constrained from sidebands.

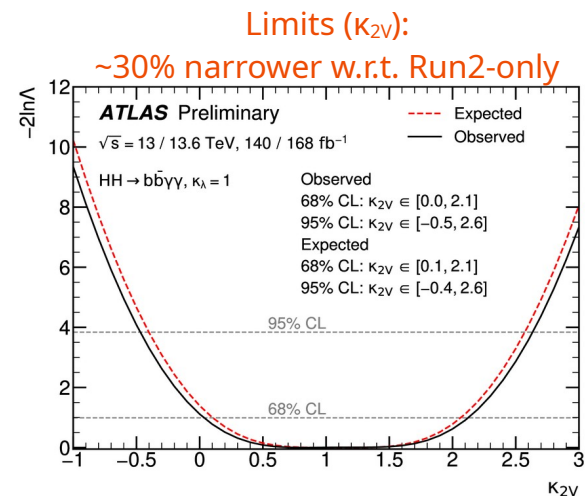
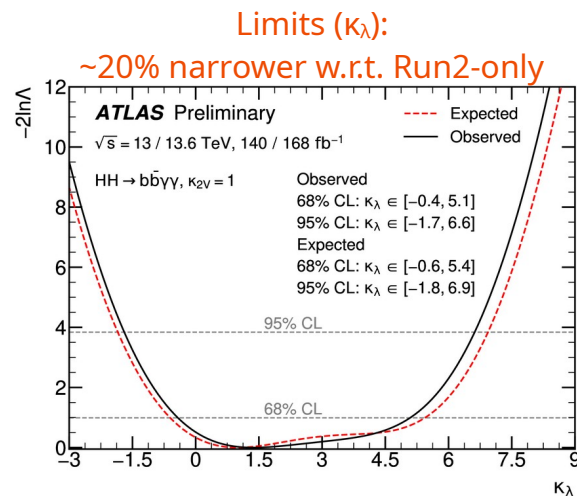
Observed signal strength:

$$\mu_{HH} = 0.9^{+1.3}_{-1.0} \text{ (stat)} \quad {}^{+0.6}_{-0.5} \text{ (syst)}$$

No significant excess

95% CL observed limit: $\mu_{HH} < 3.8$;

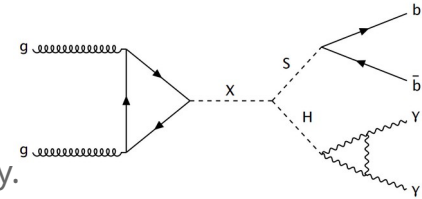
**Expected limit improved by
~2x vs previous analysis**



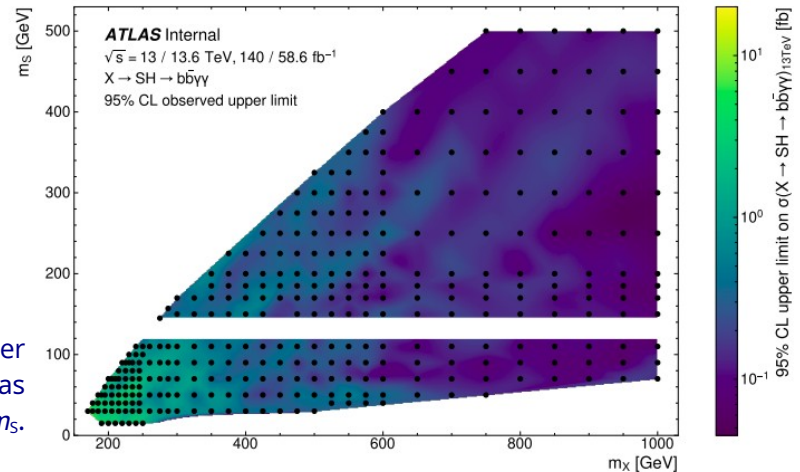
Search for $X \rightarrow SH \rightarrow b\bar{b}\gamma\gamma$

Targets resonant production: Scalar boson X decays to scalar S ($\rightarrow b\bar{b}$) and SM H ($\rightarrow \gamma\gamma$).

- Uses 140 fb^{-1} Run 2 + 58.6 fb^{-1} Run 3 data -- update of previous (Run-2) ATLAS result.
- Events categorized by 1 or 2 b -tagged jets; multivariate PNN discriminants trained per (m_X, m_S) hypothesis.
- Signal Regions defined by photon invariant mass (122.5–127.5 GeV) and b -jet multiplicity.
- Simultaneous binned maximum-likelihood fit on PNN outputs in signal and control regions.
- 95% CL upper limits on $\sigma(X \rightarrow SH)$ span 9 fb (low mass) to 0.06 fb (high mass).
- **No significant deviation from Standard Model observed.**
- **Sensitivity improved 15–73% vs previous Run 2-only search, driven by Run-3 data, improved selections, retrained PNNs.**



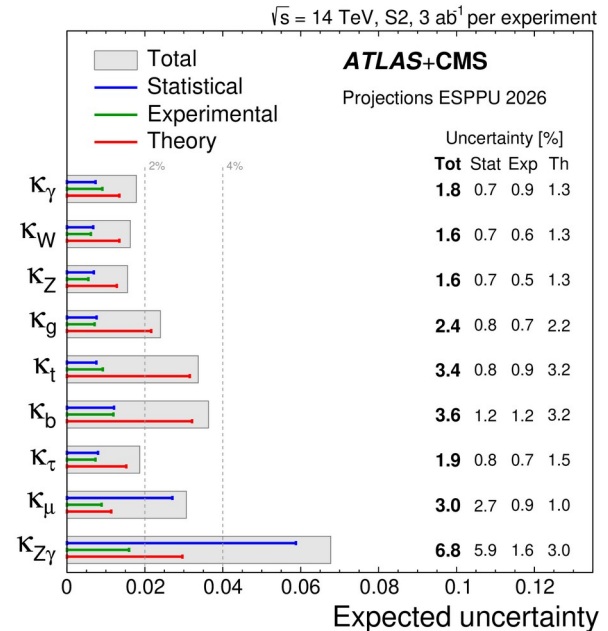
Observed 95% CL_s upper limits on $X \rightarrow SH \rightarrow b\bar{b}\gamma\gamma$ as a function of m_X and m_S .



Conclusions

- Full Run 2 and Run 3 data already improving sensitivity in multiple channels.
- No significant deviations from the Standard Model observed.
- Couplings, CP structure, and rare decays increasing precision.
- Analyses such as di-Higgs production are maturing — laying the foundation for HL-LHC.
- HL-LHC will increase data ($\times 10$), enabling (e.g.):
 - Improved constraints on Higgs self-coupling,
 - Coupling precisions at few-percent, \longrightarrow
 - EFT constraints at the 10–20% level in global fits.

Projected uncertainty in the combined coupling signal strength modifiers



Backup Slides

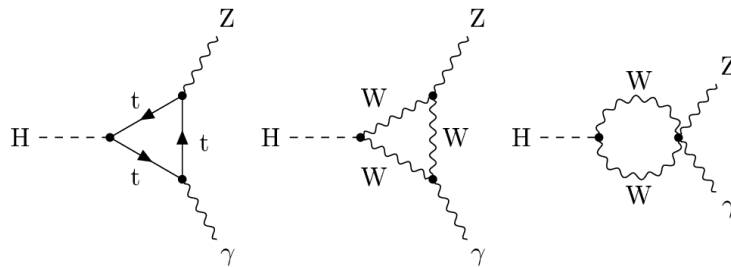
Search for $H \rightarrow \mu\mu$ decay

Ranking of uncertainties according to impact on the measured signal strength ($\Delta\mu$) in the combination of the Run-2 and Run-3 datasets.

Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.40	+0.41
Systematic uncertainty	-0.12	+0.15
Spurious signal	-0.09	+0.09
Theory	-0.07	+0.10
Luminosity	-0.02	+0.04
Muon	-0.02	+0.04
Jets, flavor tagging	-0.01	+0.01
Other	-0.02	+0.03
Total	-0.42	+0.43

Search for $H \rightarrow Z(\rightarrow ll)\gamma$ decay

Examples of Feynman diagrams for $H \rightarrow Z\gamma$ decay.



Ranking of uncertainties according to impact on the measured signal strength ($\Delta\mu$) in the combination of the Run-2 and Run-3 datasets.

Uncertainty source	$\Delta\mu$	
	Expected	Observed
Statistical uncertainty	0.70	0.64
Systematic uncertainty	0.17	0.17
Spurious signal (background modelling)	0.11	0.10
QCD scale, PDF+ α_S , parton shower	0.09	0.06
Branching ratio ($H \rightarrow Z\gamma$)	0.08	0.05
Luminosity	0.05	0.03
Photon efficiency	0.05	0.03
Jet	0.04	0.07
Electron and photon energy scale and resolution	0.02	0.02
Electron efficiency	0.02	0.02
Muon	0.02	< 0.01
Trigger	0.02	< 0.01
Total	0.72	0.67

Search for $H \rightarrow Z(\rightarrow ll)\gamma$ decay

Expected (left) and observed (right) best-fit signal strengths and corresponding uncertainties in each category of the Run-3 analysis, their combined values, the results of the previous Run-2 analysis, and the overall combination.

