Recent results of searches for rare Higgs Boson decays with the ATLAS detector

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on behalf of the ATLAS Collaboration

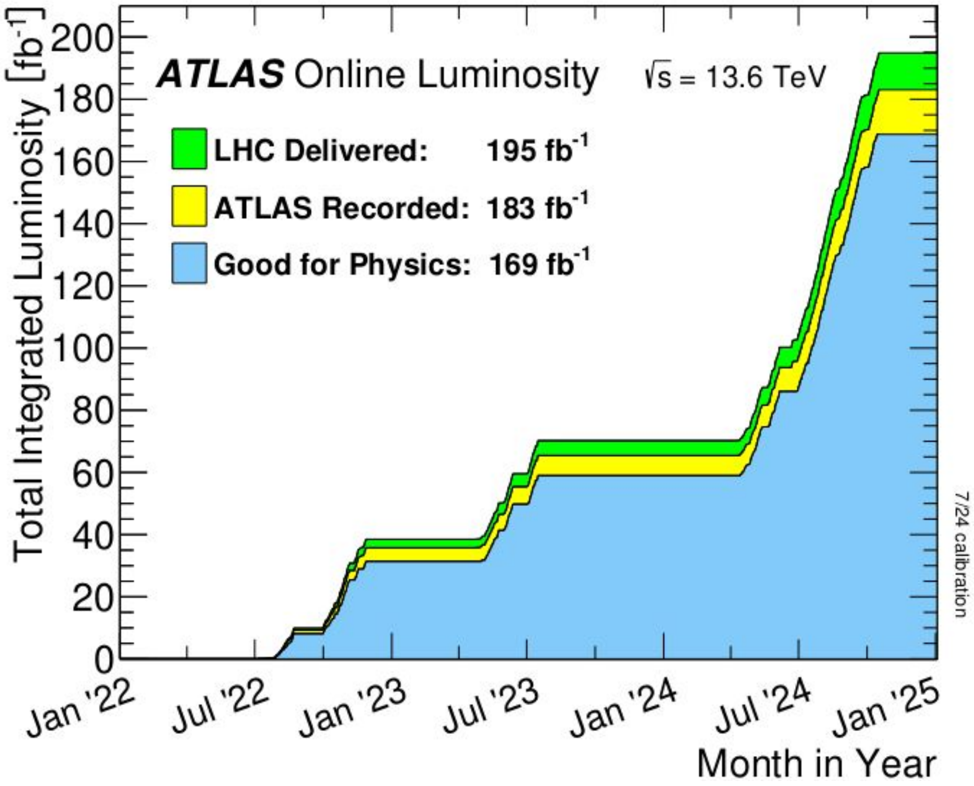
Higgs Hunting 2025

17th July 2025, Paris

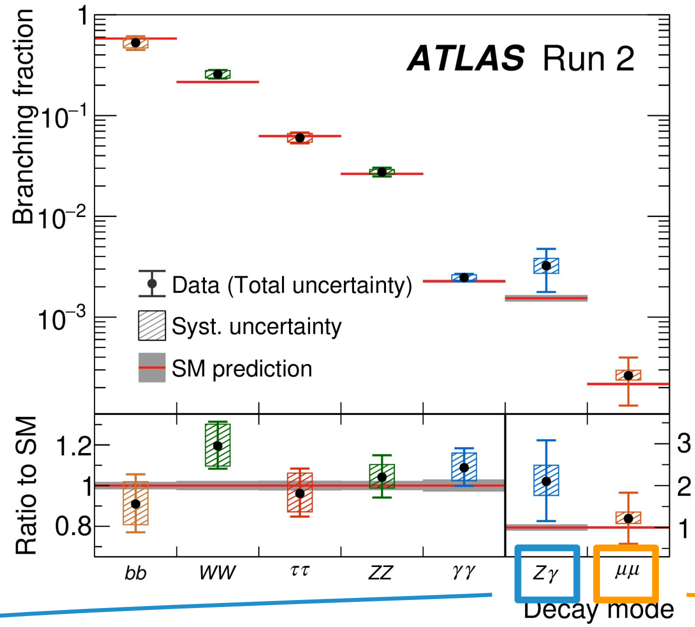
Introduction

Large amount of data available for Physics in Run 3 at sqrt(s)=13.6 TeV

- 2024 record data taking year
- from 2022 to 2024, the collected luminosity has already surpassed that of Run 2
- almost **90% of luminosity delivered by LHC is ready for ATLAS data analysis**

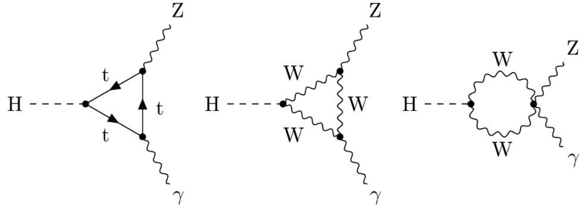


Introduction: open question from Run 2, a new quest in Run 3



H→Zγ search L=165 fb^{-1} at 13.6 TeV

CERN-EP-2025-155

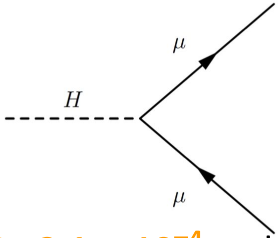


Rare decay loop suppressed **BR= 1.5 × 10^{-3}**

-> potentially sensitive to BSM

H→μμ search L=165 fb^{-1} at 13.6 TeV

arXiv:2507.03595



Rare decay **BR= 2.1 × 10^{-4}** and direct probe of Higgs coupling to second fermion generation

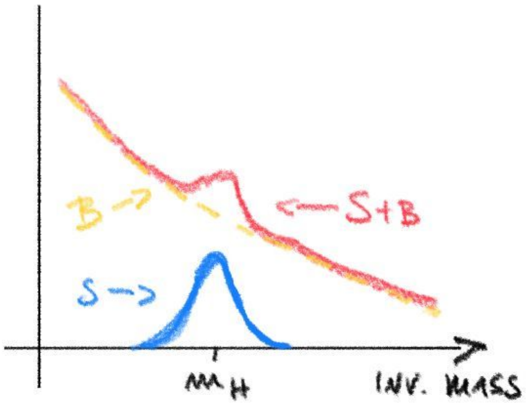
New analysis based on 2022-2024 data and combined with Run 2

$H \rightarrow Z\gamma$

H⟶Zγ

Phys. Rev. Lett. 132 (2024) 021803

- The H⟶Zγ ⟶ **ℓℓγ(ℓ=e,μ)** final state, additional rate reductio **BR(Z ⟶ ℓℓ)= 7%**
  - Fully reconstructable with excellent mass resolution
  - High trigger efficiency using electron and muon triggers
- Main background continuous Zγ and Z+jets production

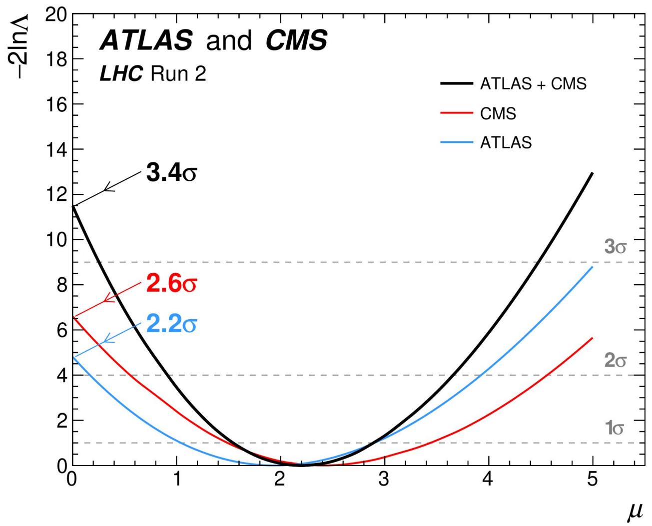


Full Run 2 H⟶Zγ

- Based on 5 categories (VBF, High/LowRelPt)
- **Obs (Exp.) significance 2.2 (1.2) σ**
- **$\mu = 2.0^{+1.0}_{-0.9}$ (1.0 ± 0.9)**

Combination with CMS -> Evidence!

- **Obs (Exp.) significance 3.4 (1.6) σ**
- **μ = 2.2 ± 0.7 (1.0 ± 0.6)**

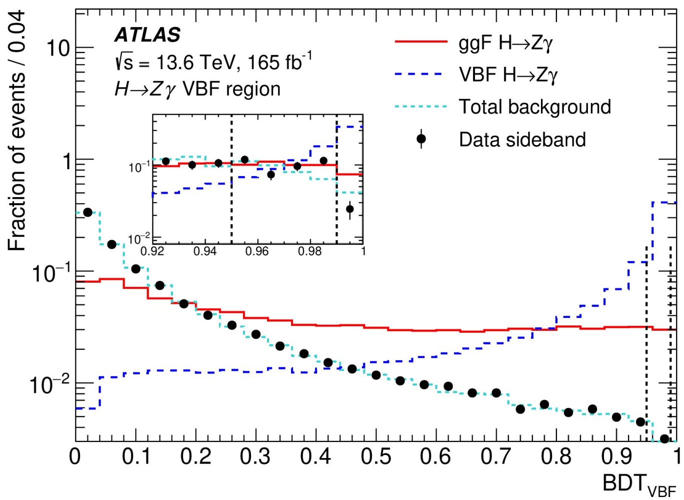


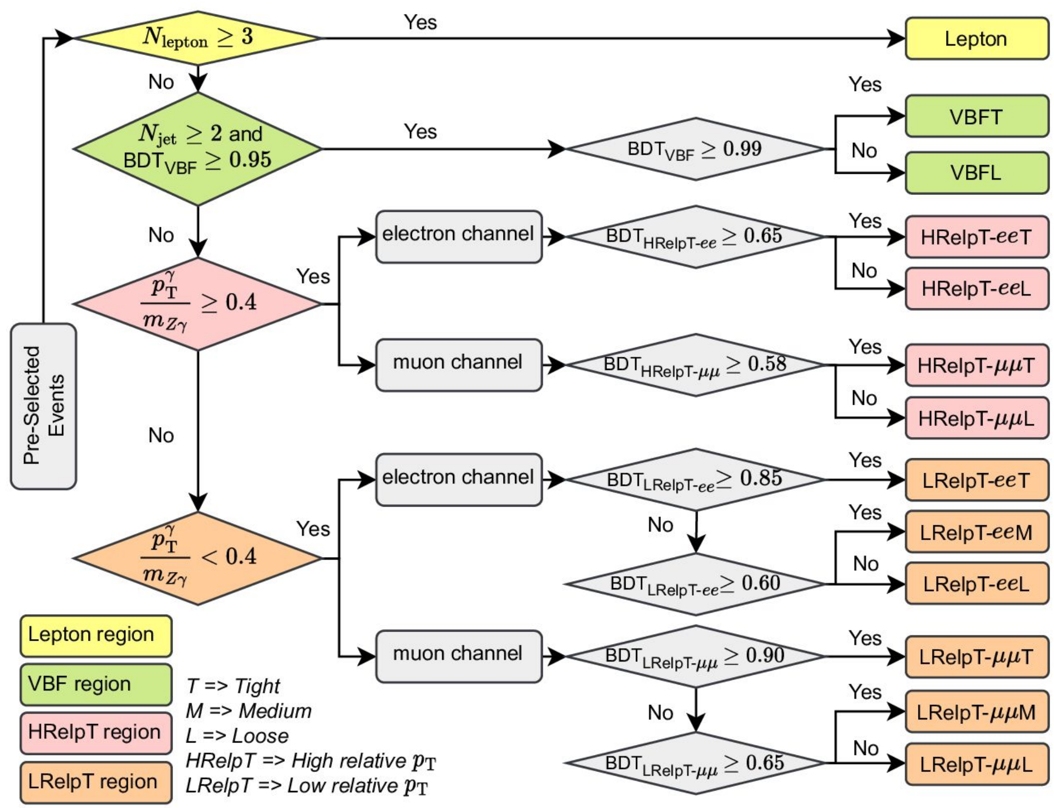
Run 3 H→Zγ: Event selection and categorization

Event selection:

- Events selected using single and di-electron/muon triggers
- At least 2 opposite charged leptons + one photon, **with pT > 5(μ)/10(e,γ) GeV**
- Overlap removal between leptons, photon and jets
- Z mass requirement: |mll-mZ|< 10 GeV
- Photon relative pT cut: **pTγ/mZγ > 0.09**

After event selection S/B~0.4%

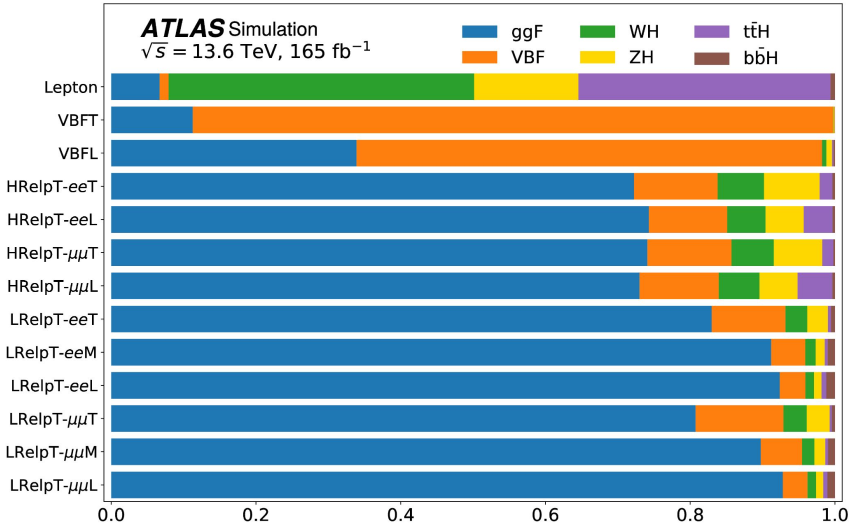




Events are classified into 13 categories:

- 1 VH+ttH lepton category
- 2 VBF categories
- 10 ggF categories (separated by ee/μμ final states)

Run 3 H→Zγ: Event selection and categorization



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	76.3	78	4.4	0.17
VBFT	1.5	1.2	3	3.8	0.91
VBFL	2.8	27.6	23	4.0	0.51
HRelpT-eeT	1.2	6.6	11	3.1	0.43
HRelpT-eeL	3.0	54.1	77	4.0	0.40
HRelpT-$\mu\mu$T	2.4	20.3	33	3.9	0.50
HRelpT-$\mu\mu$L	2.4	56.5	72	4.1	0.31
LRelpT-eeT	8.9	233.6	251	3.8	0.57
LRelpT-eeM	28.7	2 590.9	3 806	4.1	0.56
LRelpT-eeL	23.9	13 261.0	17 435	4.5	0.21
LRelpT-$\mu\mu$T	4.9	95.7	127	3.9	0.49
LRelpT-$\mu\mu$M	34.1	2 544.6	3 133	4.1	0.67
LRelpT-$\mu\mu$L	36.5	16 961.3	19 331	4.4	0.28

- **Best sensitivity from VBF categories** and low relative pT categories
- The categorization enhances the overall sensitivity of the analysis by a **factor of 2 compared to the inclusive selection.**

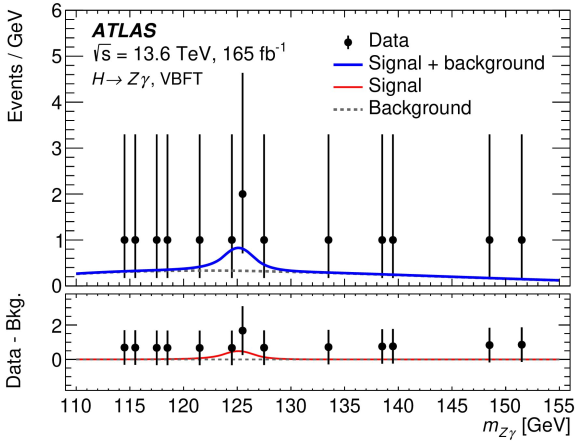
Run 3 H→Zγ: Signal and Background modeling

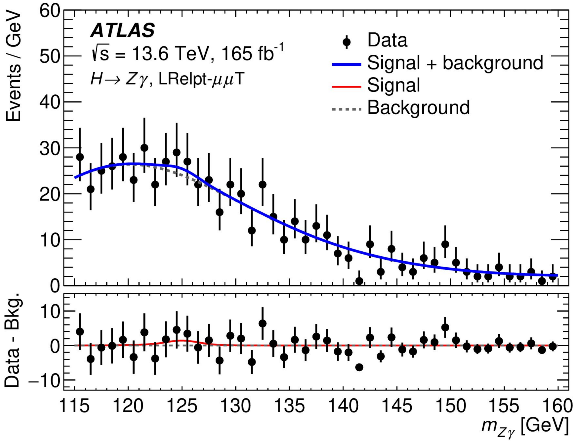
- Signal $m_{Z\gamma}$ invariant mass is modeled by a double-sided Crystal Ball (DSCB) function in each category using MC simulation
- Mass resolution **improved by 17% (11%) for e (μ) channel**
  - **Z-mass constraint:** kinematic fit to correct lepton 4-momentum
  - **FSR photon correction** (dR<0.15) for corresponding muons
- Residual H→μμ(γ) contamination (up to 3.8%) is modeled with another DSCB

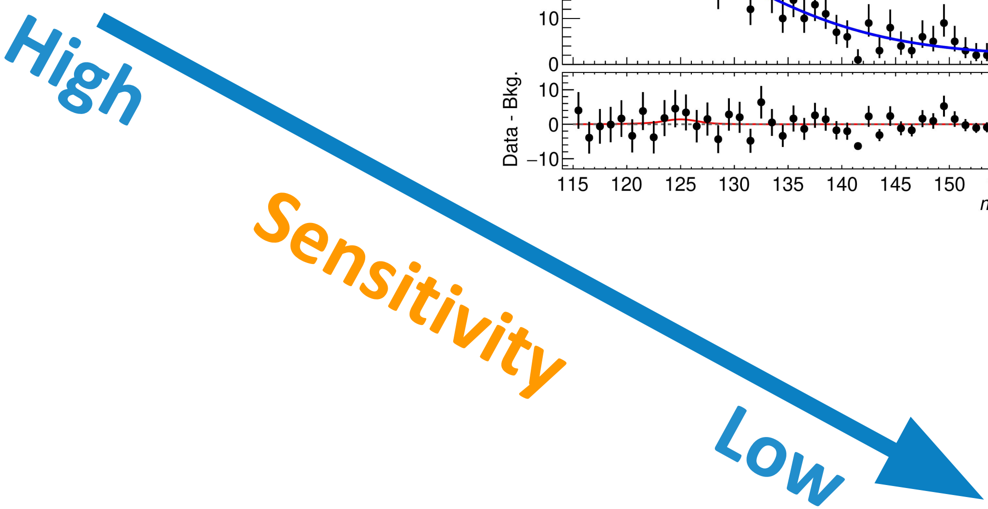
- **Main Backgrounds:** Non-resonant Zγ, Z+jets, and diboson processes
- **Background Modeling:** select analytical functions tested on high-statistics background-only templates. **Function Selection Criteria:**
  - Minimal induced signal bias (i.e. Spurious Signal) and simpler function
  - χ^2 p-value > 0.01 on bkg template
  - Wald test on data $m_{ll\gamma}$ in [110,120 GeV] and [130,160 GeV] to avoid overfitting
- **Fit Range:** optimized within 110–160 GeV to minimize the spurious signal

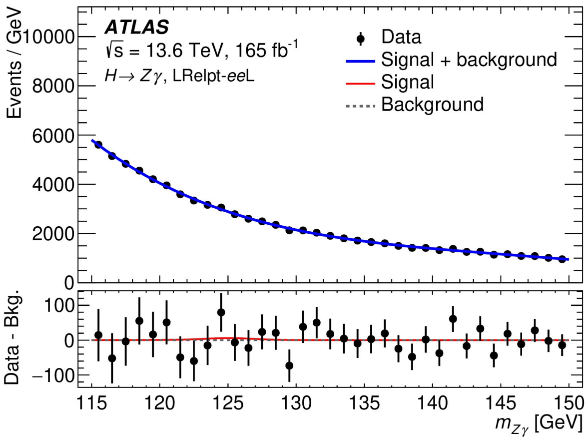
After the choice of the function-range the spurious signal is re-evaluated on smoothed template through **Gaussian Process Regression** to further reduce the final bkg modeling uncertainty

Run 3 H⟶Zγ: Fit on data



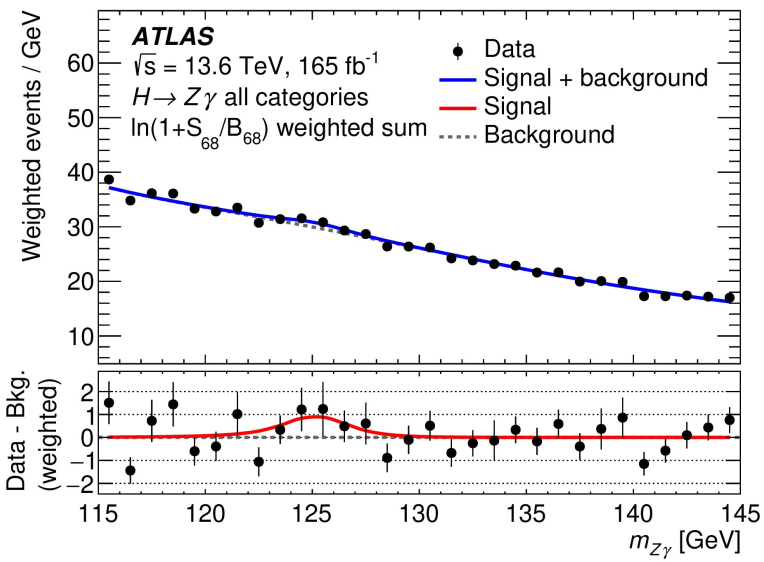


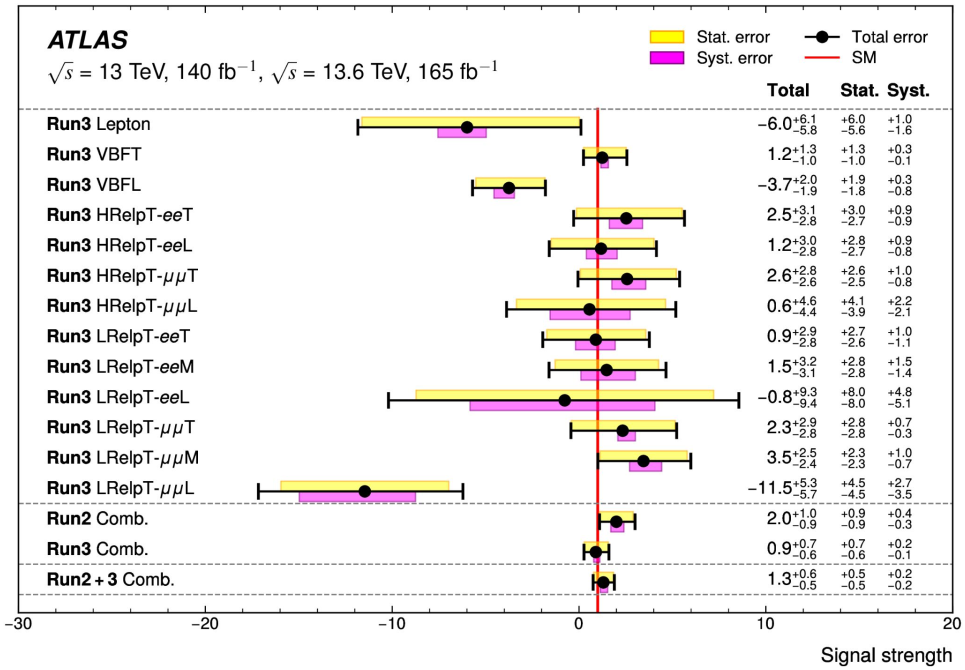




Run 3 H→Zγ: Results

- **Observed μ = 0.9 ± 0.6(stat.) $^{+0.2}_{-0.1}$ (syst.) = 0.9 $^{+0.7}_{-0.6}$**
- Expected μ = 1.0 ± 0.7(stat.) $^{+0.2}_{-0.1}$ (syst.) = 1.0 ± 0.7
  - Dominant systematic uncertainties: background modelling (11%) and theory unc (12%)
- **Obs (Exp.) significance 1.4 (1.5) σ**





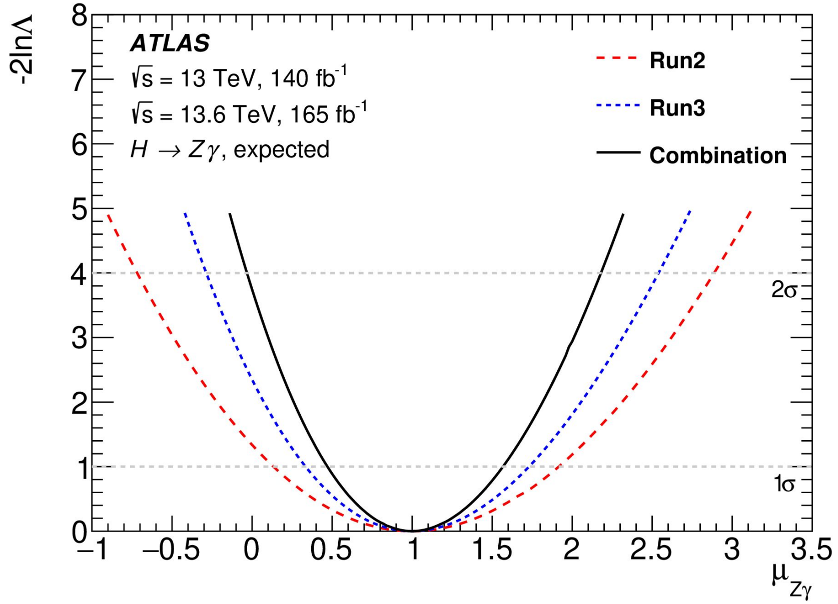
Run 3 significance improves by 28% wrt Run2:

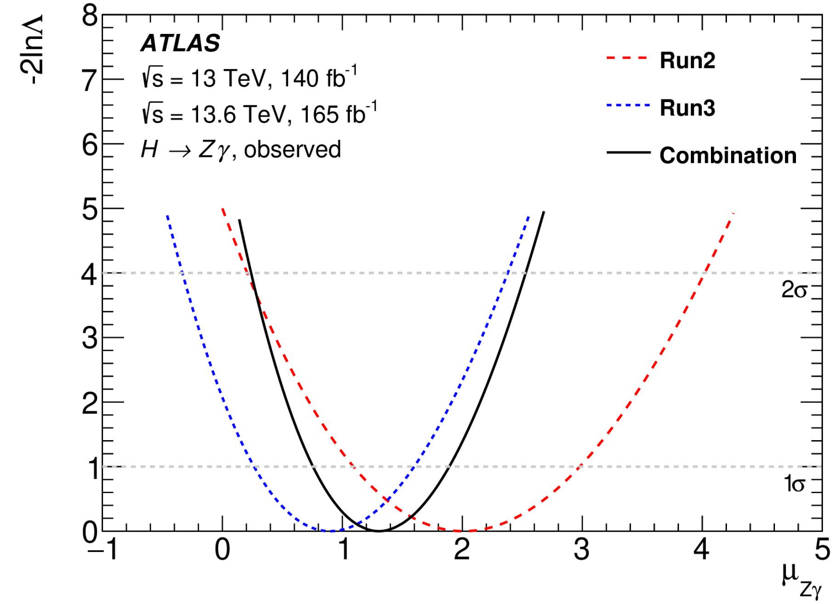
- 15% event selection and categorization
- 11% increased integrated luminosity and cross section scaling

The measurement of **signal strengths across individual categories** is consistent with the overall signal strength result, corresponding to a **p-value of 0.37**.

Run 2 + Run 3 H→Zγ: Results based on 305 fb^{-1}

- **Observed μ = 1.3 ± 0.5(stat.) ± 0.2 (syst.) = $1.3^{+0.6}_{-0.5}$**
- Expected μ = 1.0 ± 0.5(stat.) $^{+0.2}_{-0.1}$ (syst.) = $1.0^{+0.6}_{-0.5}$
- **BR(H→Zγ) = $2.0^{+0.9}_{-0.8} \times 10^{-3}$** ($1.5^{+0.9}_{-0.8} \times 10^{-3}$) compare to SM = $1.5^{+0.10}_{-0.11} \times 10^{-3}$
- **Obs (Exp.) significance 2.5 (1.9) σ**





- Combination improves Run 2 by 61%
- ATLAS results 19% better than ATLAS+CMS

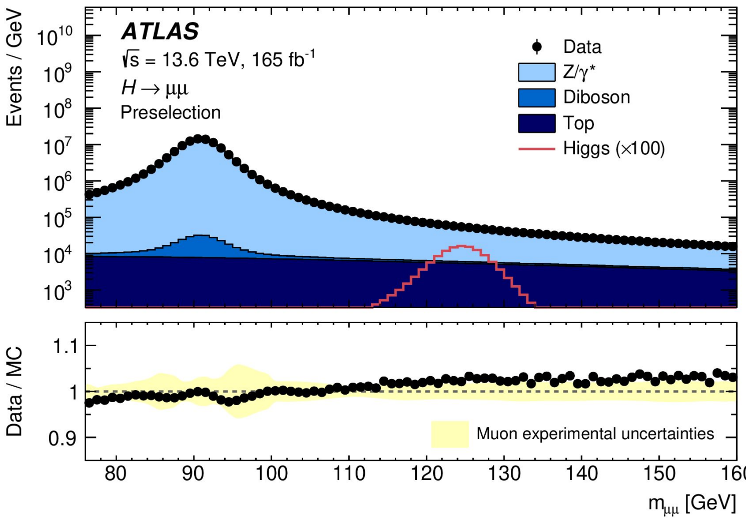
-> Most precise measurements to date

The Run 2 and Run 3 measurements are compatible, with a ***p*-value of 0.33**.

$H \rightarrow \mu\mu$

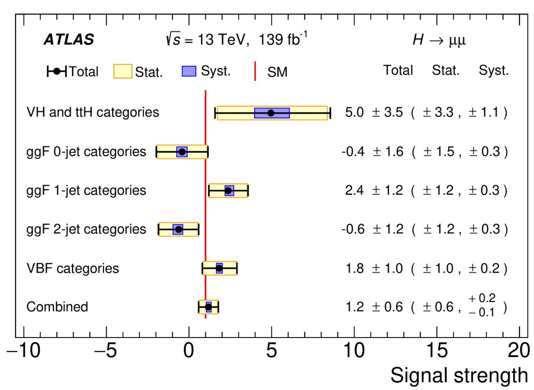
H→μμ Run 2 results

- Fully reconstructable signal
- Huge background contribution from Drell-Yan
  - **~0.2% signal-to-background ratio**



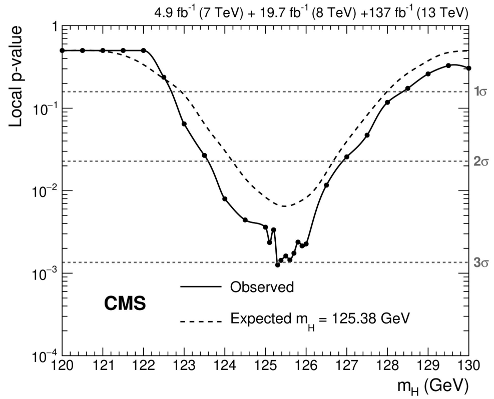
<u>Full Run 2 H→μμ</u>

- Based on 20 categories targeting main production modes
- **Obs (Exp.) significance 2.0 (1.7) σ**
- **μ = 1.2 ± 0.6**



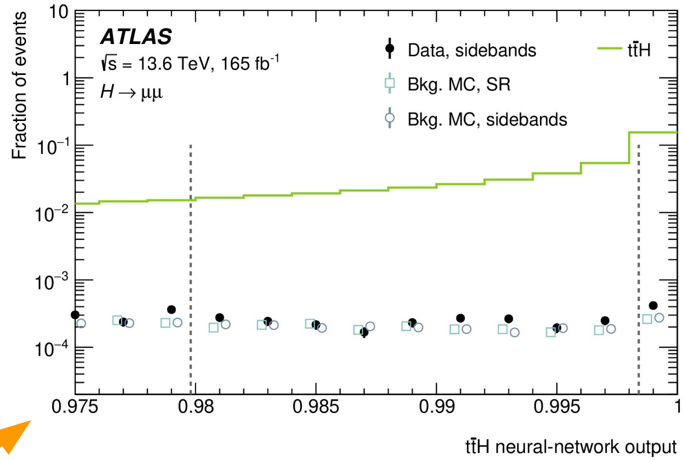
<u>CMS Run 1 + Run 2:</u>

- **Obs (Exp.) significance 3.0 (2.5) σ**
- **$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})\ ^{+0.15}_{-0.14}(\text{syst})$**
- **First single experiment evidence**



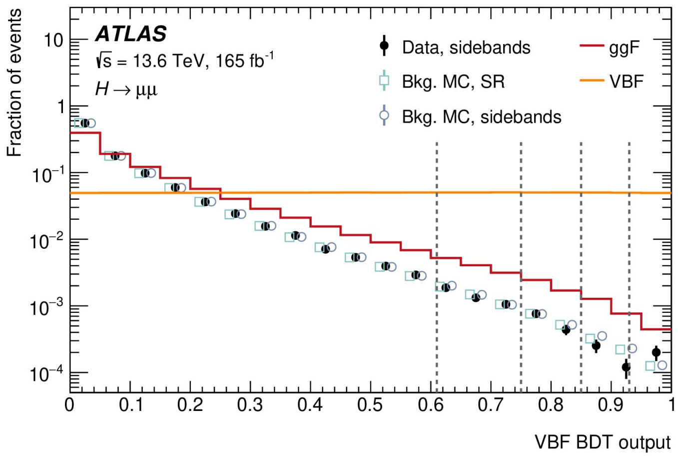
H→μμ: Event selection and categorization

	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\lvert\eta\rvert < 2.5$, $p_T^{\text{lead}} > 27$ GeV, $p_T^{\text{sublead}} > 15$ GeV
Fit region	$m_{\mu\mu} = 110 - 160$ GeV
Jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_T > 30$ GeV and $2.4 < \lvert\eta\rvert < 4.5$
b-tagged jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_T > 30$ GeV and $2.4 < \lvert\eta\rvert < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b-jet
VH 4-lepton category	Exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b-jets
VH 3-lepton categories	Exactly one additional e or μ with $p_T > 15$ GeV, no b-jets
VH 2-lepton categories	No additional lepton, no b-jets, $E_T^{\text{miss}} > 120$ GeV
VBF and ggF categories	No additional lepton, no b-jets, $E_T^{\text{miss}} < 120$ GeV



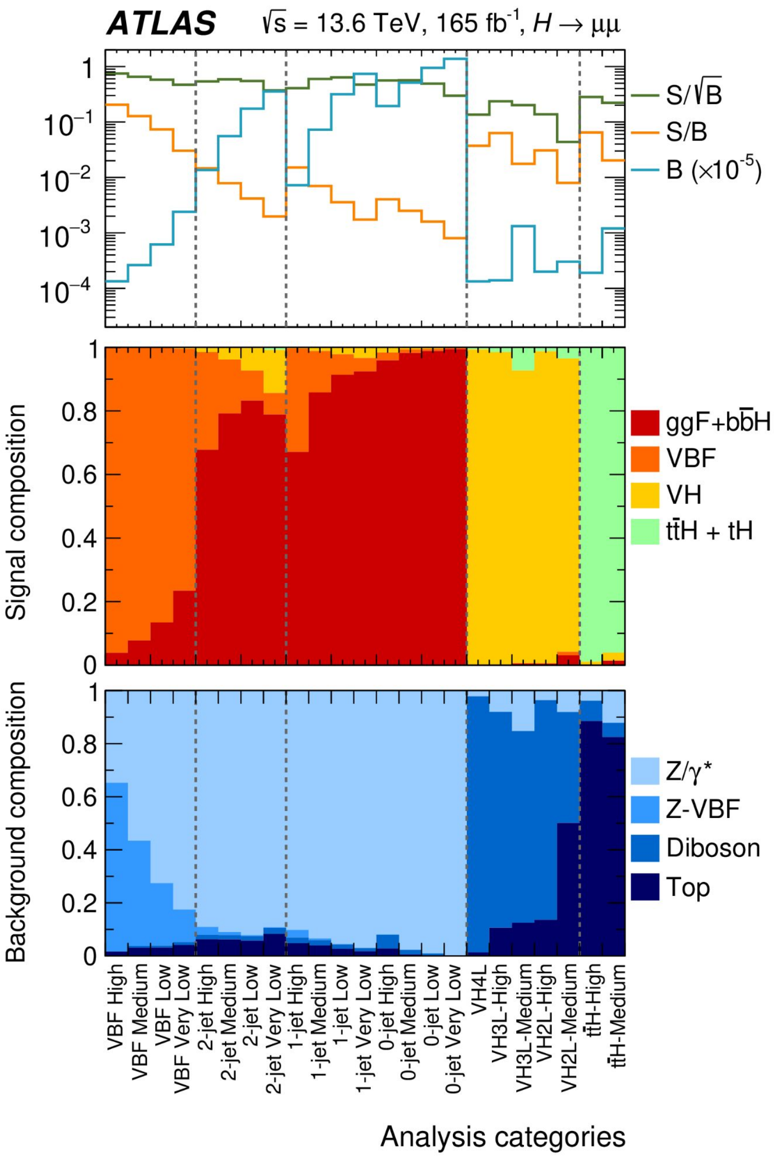
Events with a neural-network output below ~0.98 are not included in the tt̄H categories

- Events are categorized in **23 categories:**
  - Defined sequentially **ttH->VH->VBF->ggH**
  - Within each topology NN/BDT trained to separate sig vs bkg (and other production modes)
  - 2 ttH categories, 3 ZH categories, 2 WH categories, 4 VBF categories, and 12 ggF categories



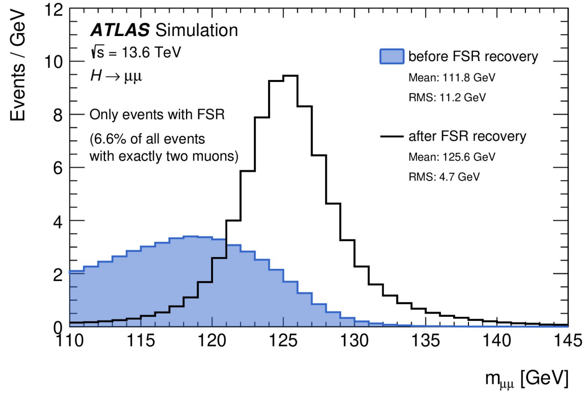
H→μμ: Event selection and categorization

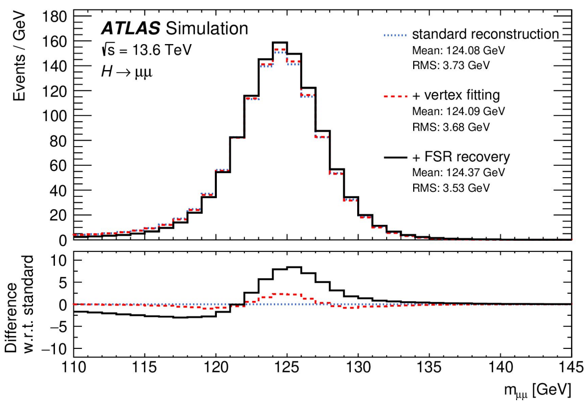
Category	Data	S	B	$S/\sqrt{B}$	S/B [%]
$t\bar{t}H$-High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$-Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very Low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1 399	31 ± 12	$1\,367 \pm 25$	0.84	2.3
2-jet Medium	5 657	69 ± 26	$5\,560 \pm 50$	0.92	1.2
2-jet Low	17 684	110 ± 40	$17\,300 \pm 70$	0.87	0.7
2-jet Very Low	35 147	110 ± 40	$35\,160 \pm 140$	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7 166	80 ± 30	$7\,140 \pm 70$	0.95	1.1
1-jet Low	31 761	180 ± 70	$31\,510 \pm 120$	1.00	0.6
1-jet Very Low	73 578	200 ± 80	$73\,330 \pm 200$	0.75	0.3
0-jet High	19 445	120 ± 50	$19\,260 \pm 90$	0.89	0.6
0-jet Medium	50 742	200 ± 80	$50\,830 \pm 190$	0.90	0.4
0-jet Low	94 032	240 ± 90	$93\,770 \pm 210$	0.78	0.3
0-jet Very Low	136 762	170 ± 60	$136\,510 \pm 290$	0.47	0.1

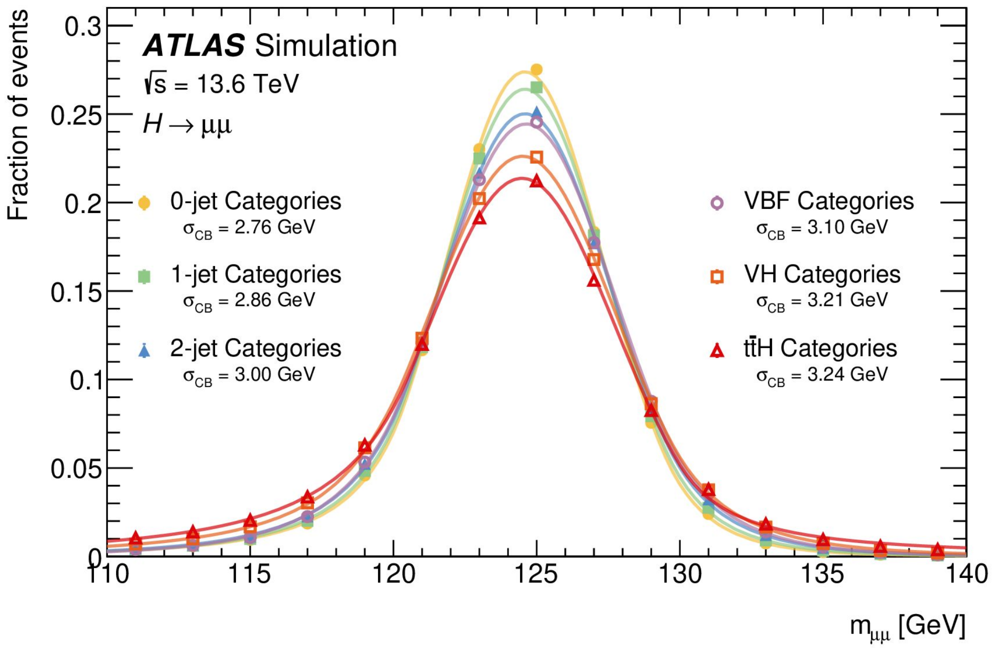


H→μμ: Signal modeling

- Signal mμμ invariant mass is modeled by a DSCB function in each category using MC
  - **Fitting decay vertex of dimuon system:** 2% improvement on resolution
  - **FSR recovery** (5% of total events): 3% improvement on resolution



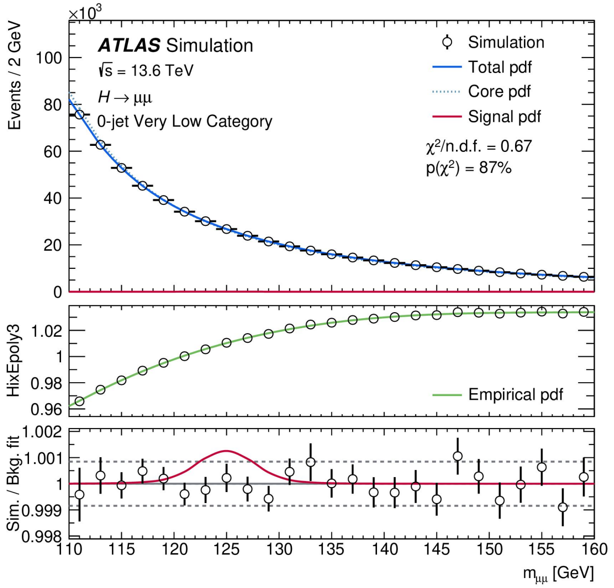


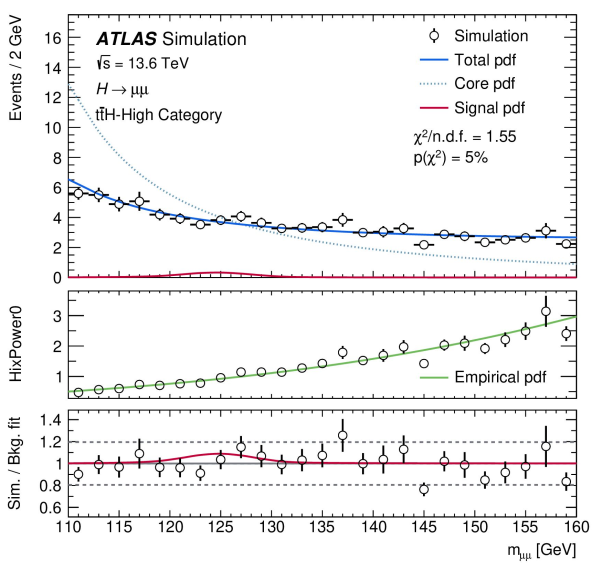


H→μμ: Background modeling

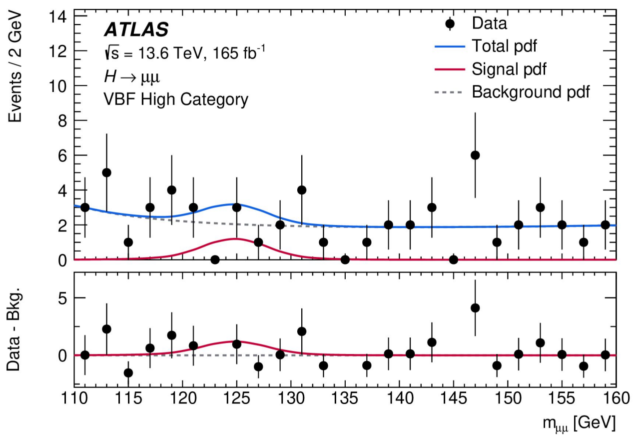
- Background modeling:
  Core function ⊗ empirical function
- **Core function:**
  - LO Drell-Yan line-shape smeared with a Gaussian distribution
  - No free parameters and same for all the category
- **Empirical functions:**
  - account for distortions of the mass shape and different background contribution
- **Function Selection Criteria:**
  - χ^2 p-value > 0.01 on bkg template and data
  - SS/δS < 20%
  - Smallest degree of freedom and smallest SS
- Spurious Signal ranging 5-40% of $\delta\mathrm{stat}_{\mathrm{signal}}$

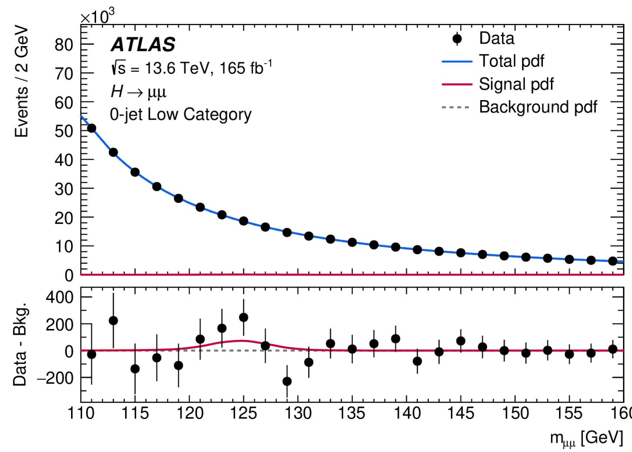
Improved SS treatment thanks to DY **full-simulation MC sample with 5 billions** of events

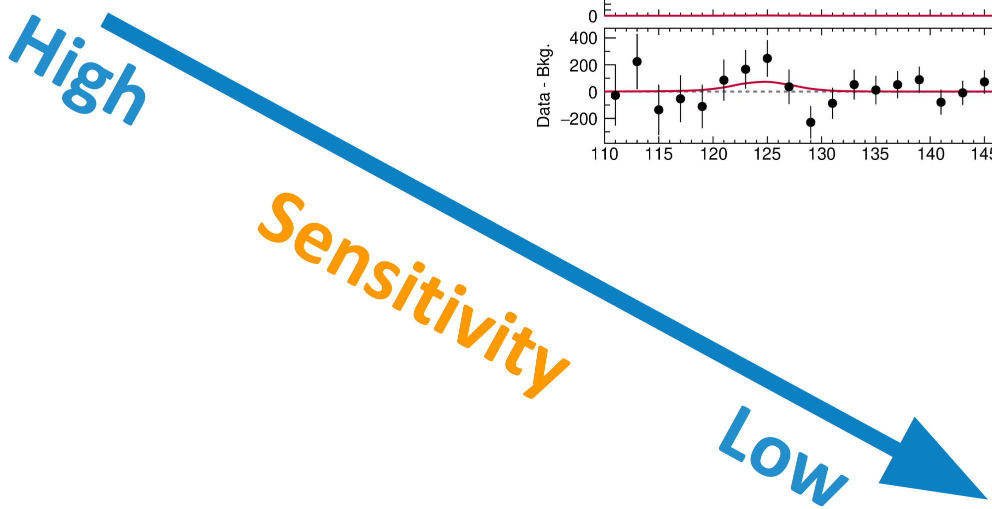


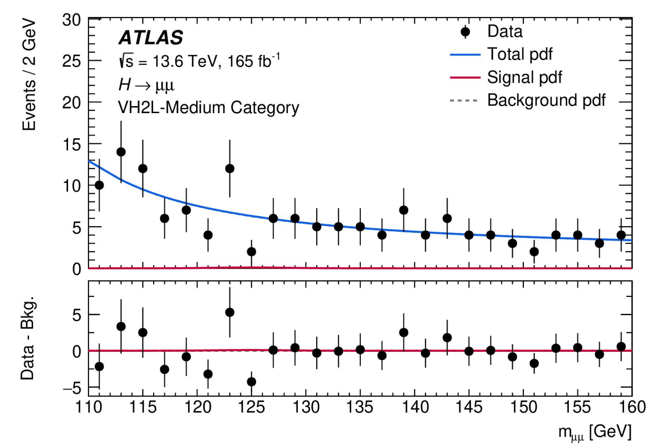


H⟶μμ: Fit on data



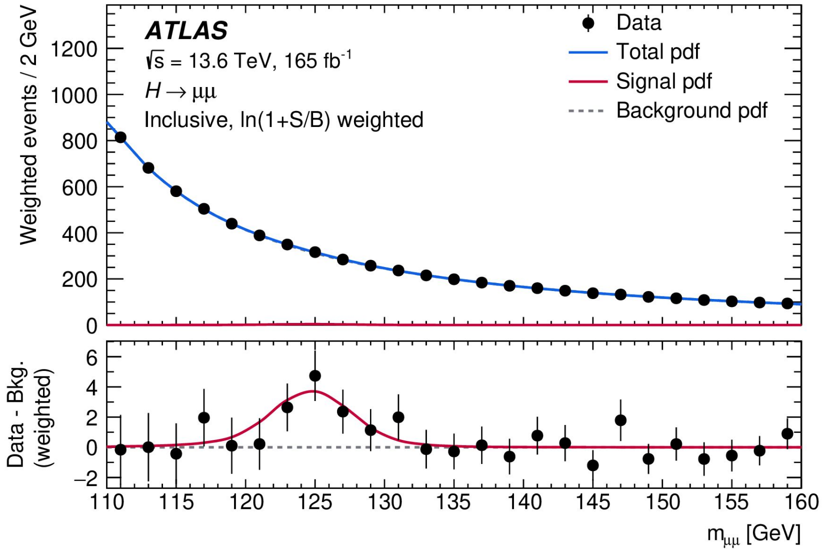


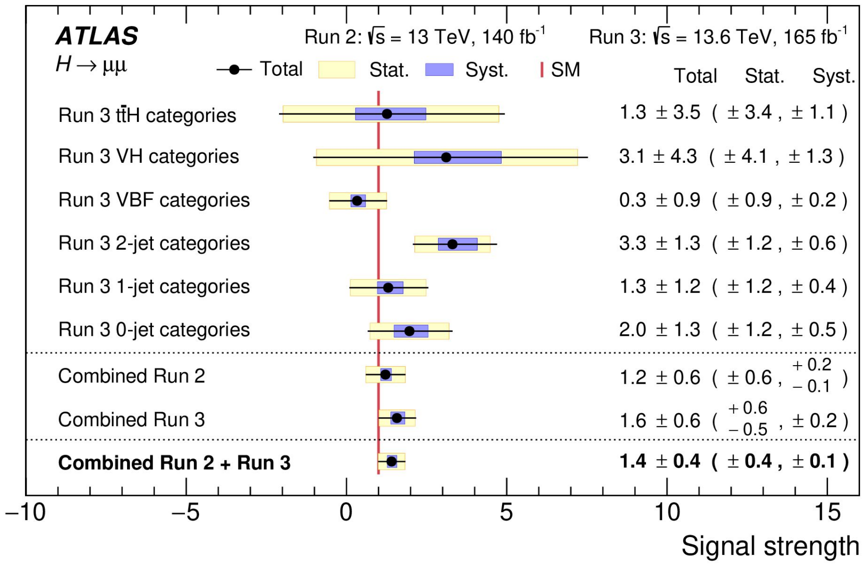




H⟶μμ: Run 3 results

- **Observed μ = 1.6 ± 0.6**
  - Dominant systematic uncertainties: background modelling (9%) and theory unc (9%)
- **Obs (Exp.) significance 2.8 (1.8) σ**

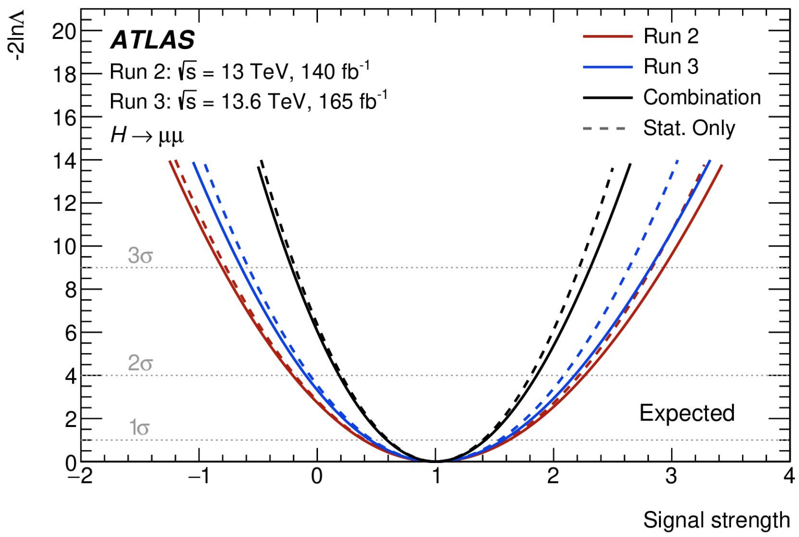


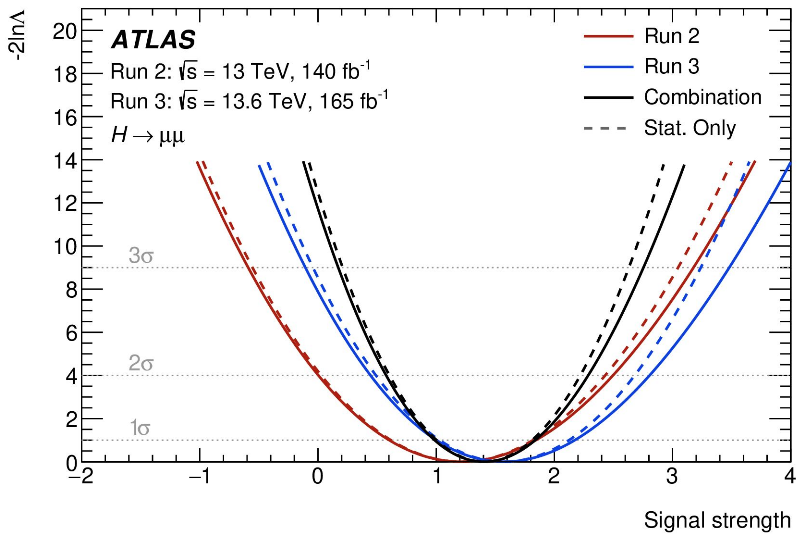


The measurement of **signal strengths across individual categories** is consistent with the overall signal strength result, corresponding to a **p-value of 0.68 (0.54 if considering six groups)** .

H⟶μμ: Run 2 + Run 3

- **Observed μ = 1.4 ± 0.4**
- **BR(H⟶Zγ) = 3.0 ± 0.9 × 10^{-4}**
- **Obs (Exp.) significance 3.4 (2.5) σ ⟶Evidence from ATLAS experiment**



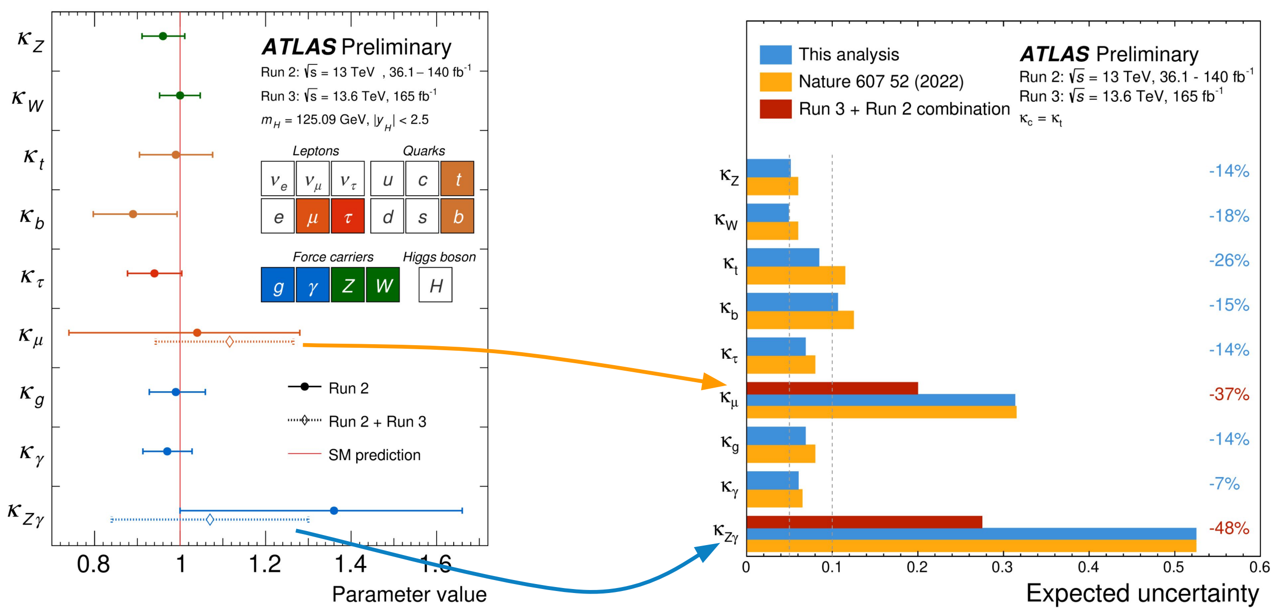


Combination improves Run 2 results by 50%

The Run 2 and Run 3 measurements are compatible, with a ***p*-value greater than 0.68**.

Conclusion

- ATLAS reported two new searches for rare Higgs boson decays using Run 3 data (2022–2024), corresponding to an **integrated luminosity of 165 fb^{-1}**
  - Significant effort enabled the analysis of a new dataset under updated experimental conditions, including improved reconstruction, updated object calibration, and Monte Carlo simulation
- After combining the new results with the analyses performed in Run 2 we obtained:
  - **Single experiment evidence for $H\to\mu\mu$: Obs (Exp.) significance 3.4 (2.5) σ**
  - **The most sensitive measurement of $H\to Z\gamma$ to date: $\mu = 1.3^{+0.6}_{-0.5}$ $(1.0^{+0.6}_{-0.5})$**

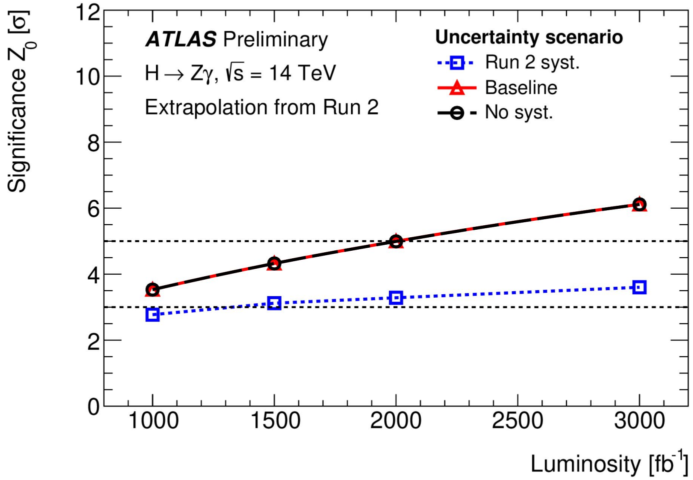


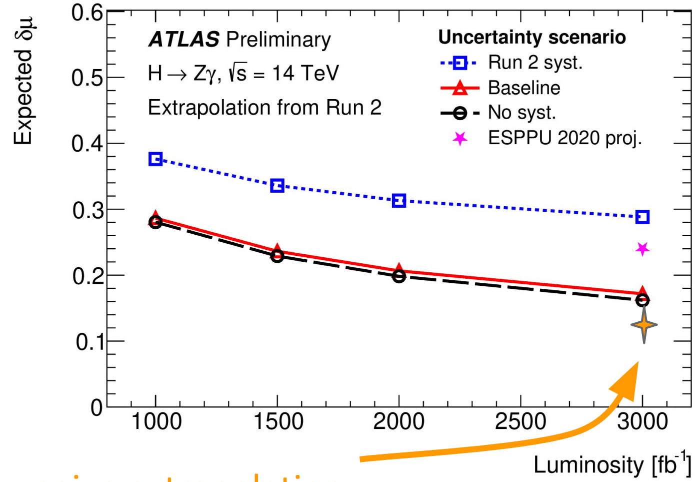
Bonus slides

HL-LHC projections

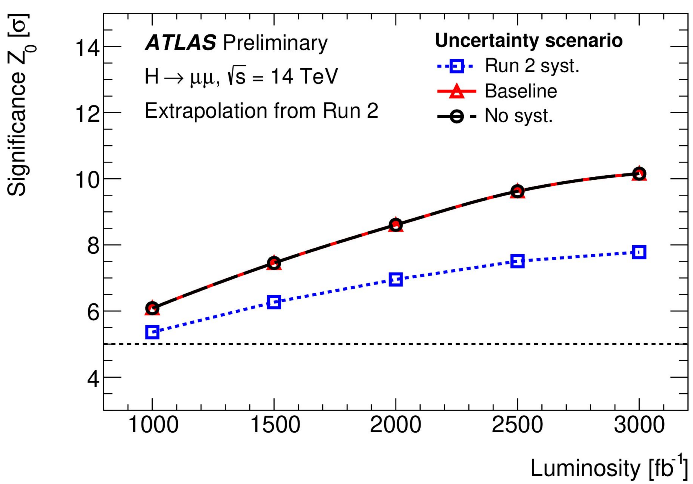
ATL-PHYS-PUB-2025-014

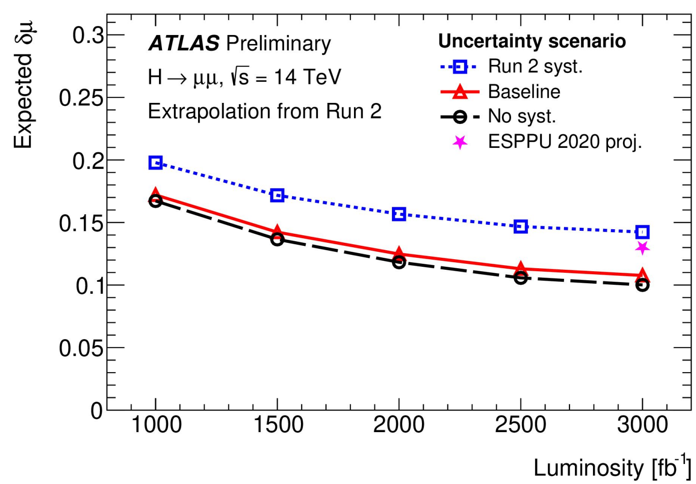
New projections based on Run 2 - 139fb^{-1} analyses





my naive extrapolation

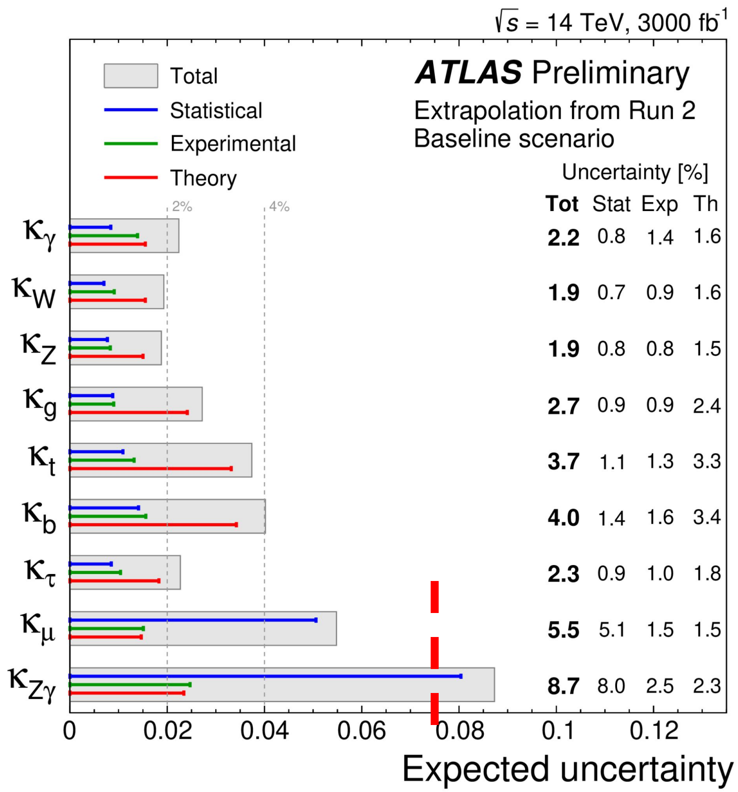


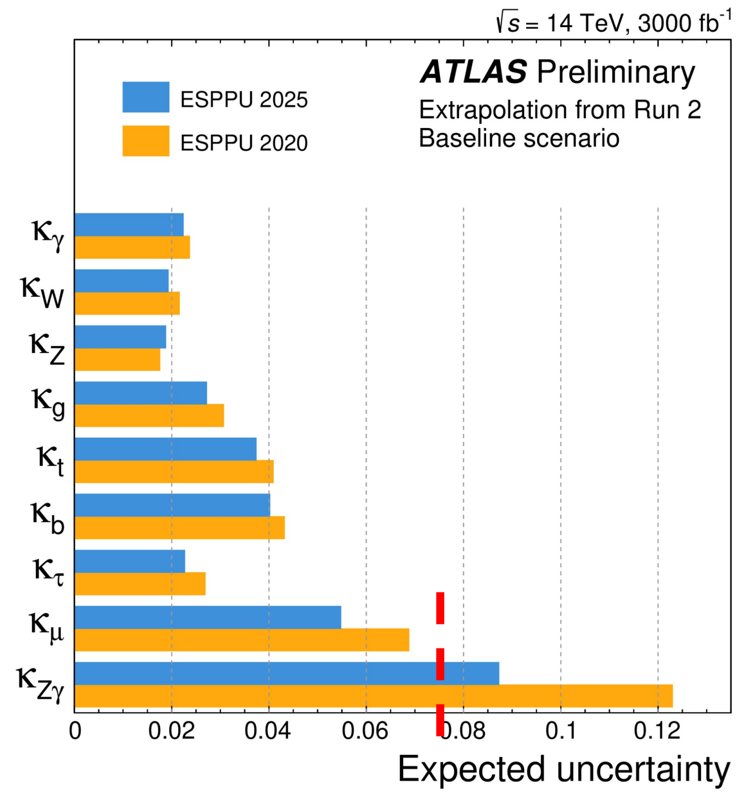


HL-LHC projections

ATL-PHYS-PUB-2025-014

New projections based on Run 2 - 139fb^{-1} analyses





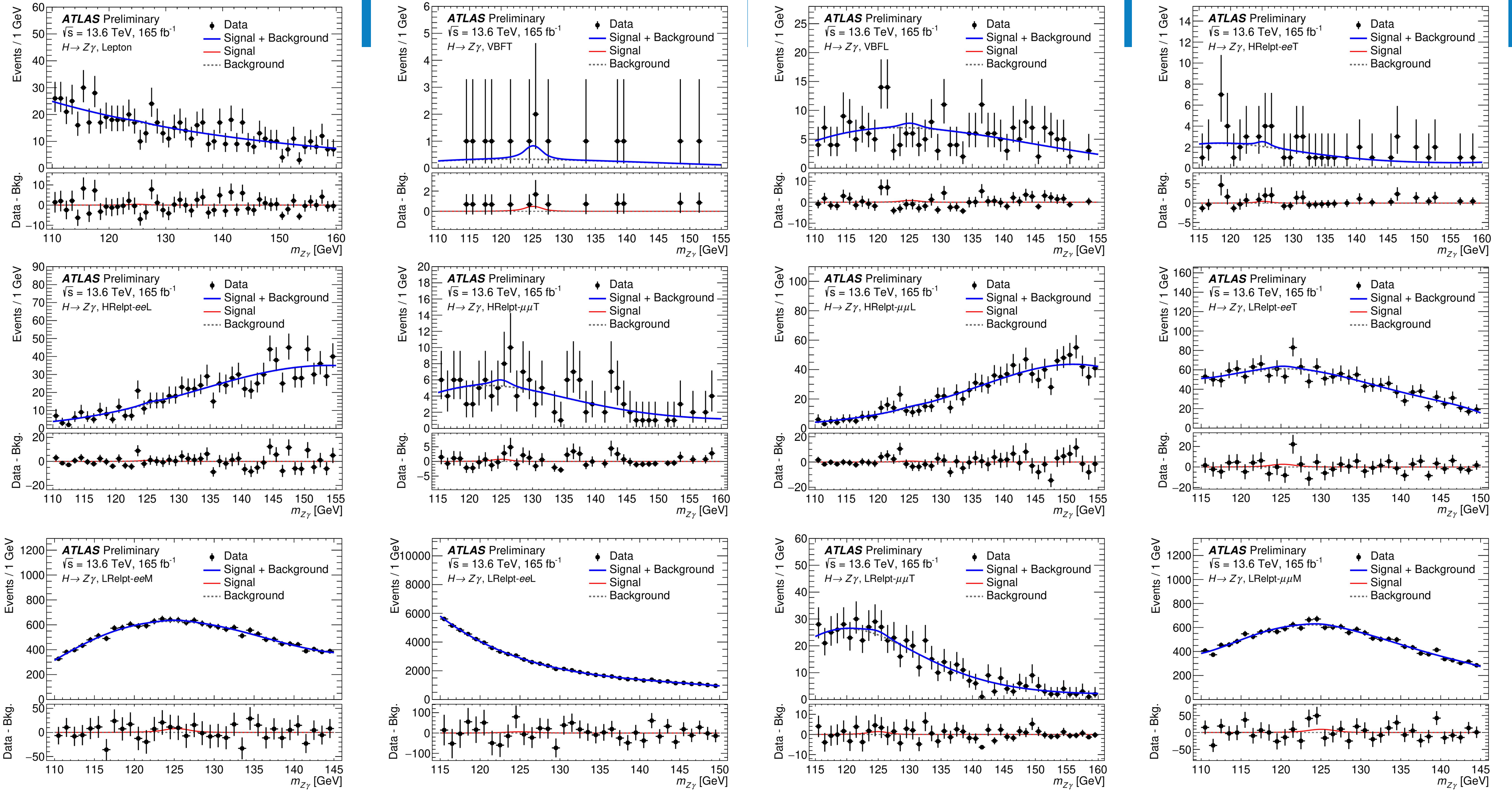
-> projection/results on stat-dominated process can be significantly improve over time

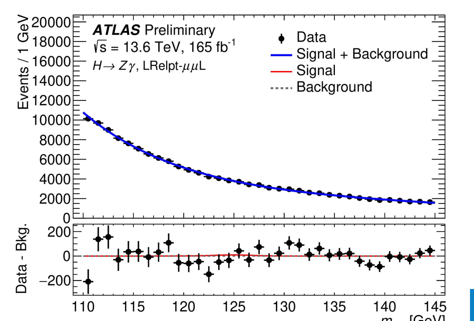
Back-up

Run 3 H→Zγ: Background modeling

Category	Function Type	Fit range [GeV]
Lepton	Exponential	110-160
VBFT	FK0	110-155
VBFL	FK0	110-155
HRelpT-eeT	Third-order exponential polynomial	115-160
HRelpT-eeL	Second-order exponential polynomial	110-155
HRelpT-$\mu\mu$T	Third-order exponential polynomial	115-160
HRelpT-$\mu\mu$L	Third-order exponential polynomial	110-155
LRelpT-eeT	Fifth-order Bernstein polynomial	115-150
LRelpT-eeM	Fifth-order Bernstein polynomial	110-145
LRelpT-eeL	Fourth-order Bernstein polynomial	115-150
LRelpT-$\mu\mu$T	Third-order exponential polynomial	115-160
LRelpT-$\mu\mu$M	Fifth-order Bernstein polynomial	110-145
LRelpT-$\mu\mu$L	Fourth-order exponential polynomial	110-145

Run 3 H→Zγ: data fit





H→Zγ: Uncertainty break down

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 ($H \to Z\gamma$)	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

H→μμ: category composition

Category	$ggF + b\bar{b}H$	VBF	WH	ZH	$t\bar{t}H + tH$
$t\bar{t}H$-High	0.1%	0.0%	0.5%	0.5%	98.9%
$t\bar{t}H$-Medium	1.4%	0.1%	1.2%	1.3%	96.0%
VH4L	0.0%	0.0%	0.0%	99.3%	0.7%
VH3L-High	0.1%	0.0%	95.1%	3.3%	1.5%
VH3L-Medium	0.5%	0.2%	83.7%	8.3%	7.3%
VH2L-High	0.4%	0.1%	26.1%	72.0%	1.3%
VH2L-Medium	3.1%	1.1%	29.7%	62.5%	3.5%
VBF High	3.9%	96.1%	0.0%	0.0%	0.0%
VBF Medium	7.7%	92.2%	0.0%	0.0%	0.0%
VBF Low	13.4%	86.4%	0.0%	0.1%	0.1%
VBF Very Low	23.4%	76.2%	0.1%	0.1%	0.2%
2-jet High	67.8%	30.7%	0.7%	0.6%	0.2%
2-jet Medium	79.2%	16.9%	2.2%	1.5%	0.2%
2-jet Low	83.2%	9.4%	4.4%	2.7%	0.3%
2-jet Very Low	78.9%	6.7%	8.4%	5.2%	0.8%
1-jet High	67.1%	32.5%	0.2%	0.2%	0.0%
1-jet Medium	85.8%	13.0%	0.7%	0.5%	0.0%
1-jet Low	91.3%	6.5%	1.4%	0.8%	0.0%
1-jet Very Low	92.4%	4.2%	2.2%	1.1%	0.0%
0-jet High	95.9%	2.5%	0.7%	0.9%	0.0%
0-jet Medium	98.3%	1.1%	0.3%	0.3%	0.0%
0-jet Low	98.8%	0.7%	0.2%	0.3%	0.0%
0-jet Very Low	99.5%	0.3%	0.1%	0.1%	0.0%

H⟶μμ: DY lineshape

Phys. Lett. B 812 (2021) 135980

A Expression for the leading-order Drell–Yan lineshape

The core component of the background function is based on a LO DY line-shape (see e.g. Ref. [116]):

$$DY(m_{\mu\mu}) = \sum_q \mathcal{L}_{q\bar{q}}(m_{\mu\mu}) \cdot \sigma_{q\bar{q}}(m_{\mu\mu}) \ , \ q = u, \ s, \ d \, .$$

New ccbar and bbar contribution in Run-3

The parton luminosity contribution $\mathcal{L}_{q\bar{q}}$ is derived from the PDF4LHC15 PDF set as a function of $\hat{s} = m^2_{\mu\mu}$ using APFEL [140] interfaced to LHAPDF [141] and parameterised using a 6th order polynomial. The matrix element component $\sigma_{q\bar{q}}(\hat{s}) = \sigma_{q\bar{q}}(m_{\mu\mu})/(2m_{\mu\mu})$ can be expressed as

$$\sigma_{q\bar{q}}(\hat{s}) = \frac{4\pi\alpha^2}{3\hat{s}N_c}[Q_q^2 - 2Q_q V_\ell V_q \chi_{Z\gamma}(\hat{s}) + (A_\ell^2 + V_\ell^2)(A_q^2 + V_q^2)\chi_Z(\hat{s})] \, ,$$

where

$$\chi_{Z\gamma}(\hat{s}) = \kappa \frac{\hat{s}(\hat{s} - m_Z^2)}{(\hat{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \, ,$$

$$\chi_Z(\hat{s}) = \kappa^2 \frac{\hat{s}^2}{(\hat{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \, ,$$

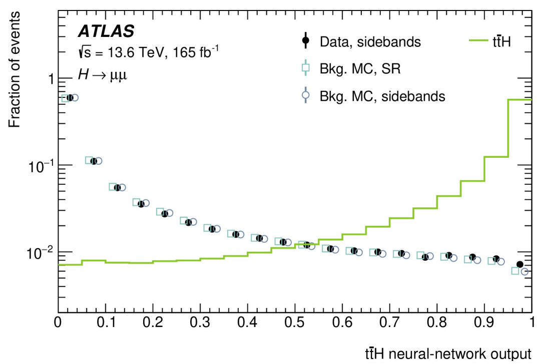
$$\kappa = \frac{\sqrt{2} G_F m_Z^2}{4\pi\alpha} \, .$$

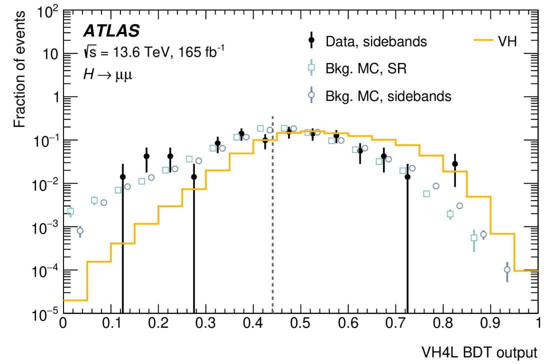
Here Q, V, A denote the electric charges, vector and axial-vector couplings of the fermions, α, G_F the electroweak couplings, m_Z, Γ_Z the mass and width of the Z-boson using values from Ref. [142] and $N_c = 3$ the number of QCD colour charges. The DY function described above is then convolved with a Gaussian function with a mass-dependent resolution derived from the simulation.

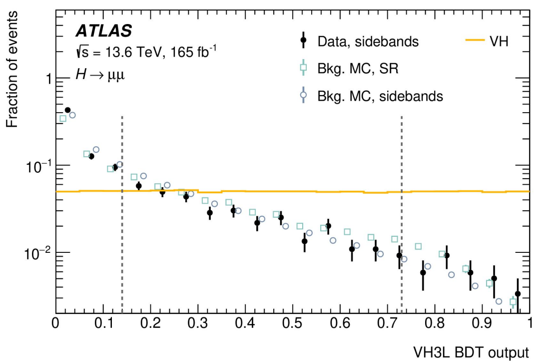
H⟶μμ: Uncertainty break down

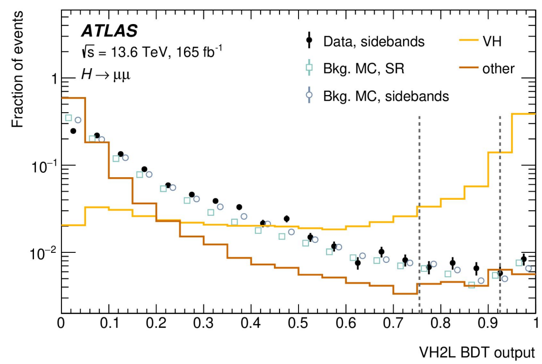
Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.55	+0.55
Systematic uncertainty	-0.18	+0.24
Spurious signal	-0.14	+0.15
Theory	-0.08	+0.13
Luminosity	-0.04	+0.08
Muon	-0.03	+0.07
Jets, flavor tagging	-0.02	+0.03
Other	-0.04	+0.07
Total	-0.57	+0.60

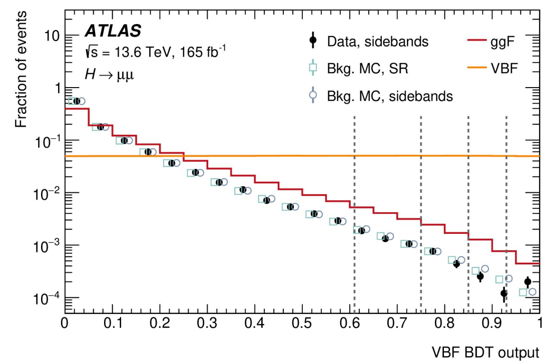
BDT/NN output for categorization

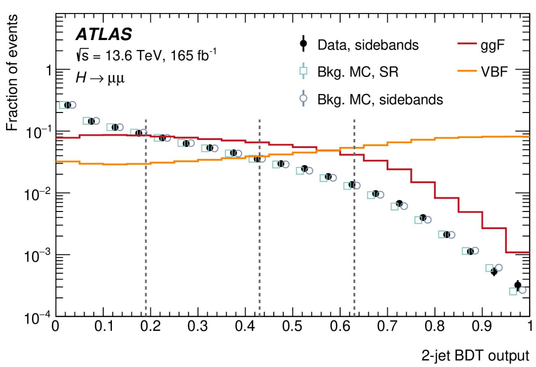


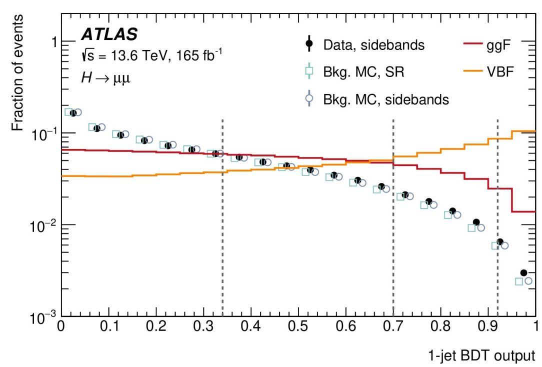


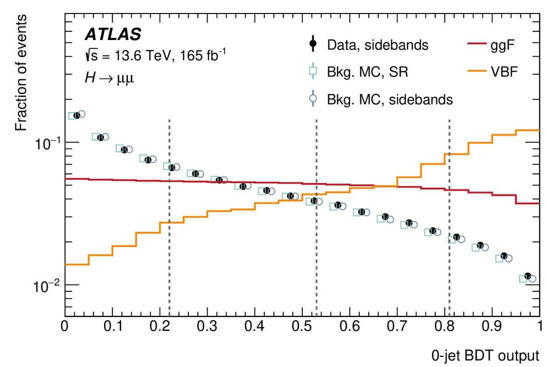








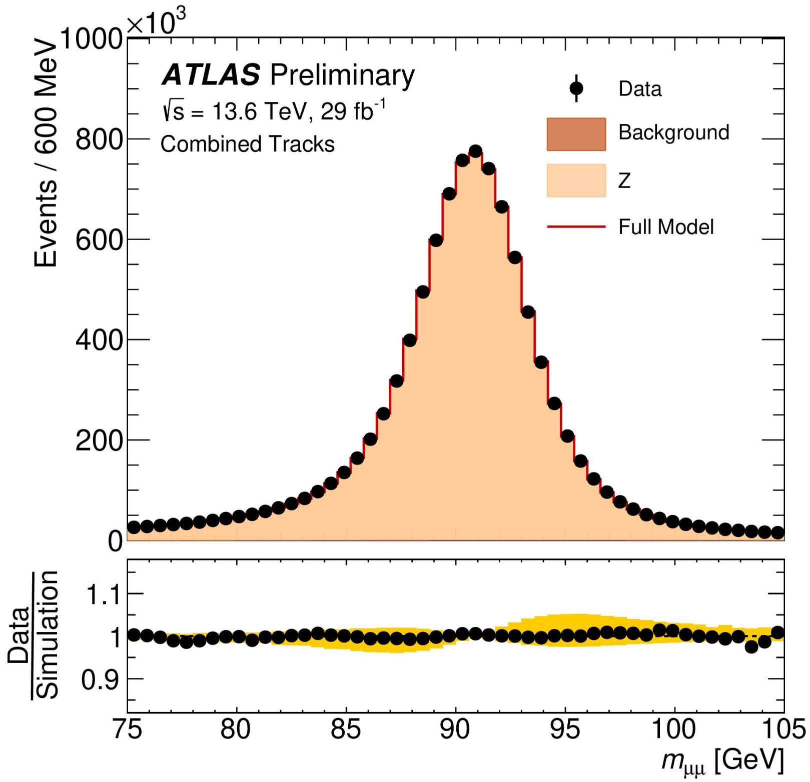


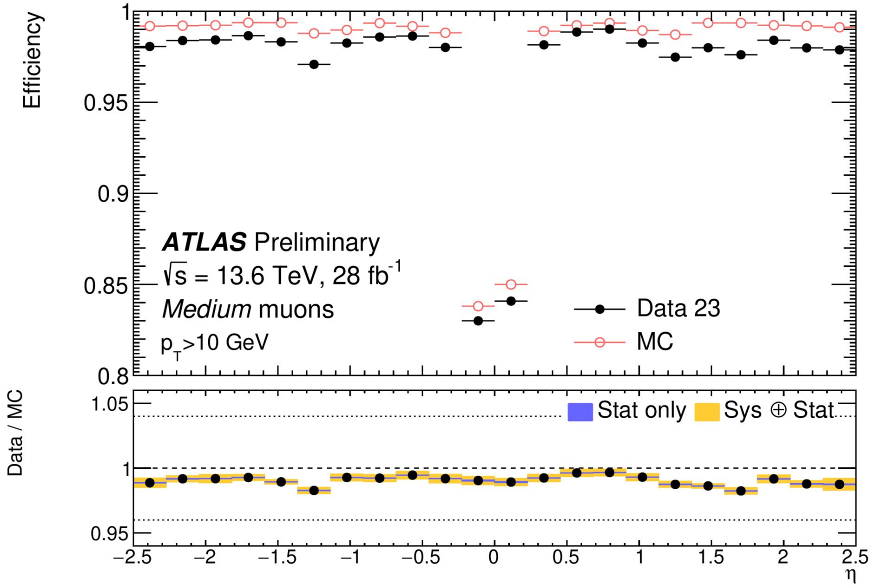


Muon calibration and identification

MUON-2023-02

- Muons energy calibration: muons from Z→μμ process with 29 fb-1, < 5% uncertainty vs mμμ
- Muons from Z→μμ process, > 95% reconstructing+identifying muon with Medium working point





Electron/photon calibration and identification

- Photon and electron energy calibration using electrons from Z→ee process, < 3% uncertainty vs mee
- Photons from radiative Z decays, ~ 50-95% efficiency and pT down to 10 GeV
- Electrons from Z→ee process, Medium working point of 75-95% efficiency and pT down to 15 GeV