Search for rare decays of the observed Higgs boson and additional Higgs bosons with the ATLAS detector

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Introduction

Higgs couplings to pairs of EW bosons or 3rd-generation fermions were observed and they indicate good agreement with the Standard Model (SM).

- Study of the couplings to 2nd-generation fermions is a next major step.

SM cannot address several issues (dark matter, fine-tuning problem, …) and thus we search for the physics beyond the SM (BSM):

- Search in the rare decays through loop of the observed Higgs boson
- Searches for additional Higgs bosons predicted by several BSM scenarios

The large Run-2 dataset (139 fb^{-1}) provides high sensitivities for the above studies.

Searches covered in this presentation

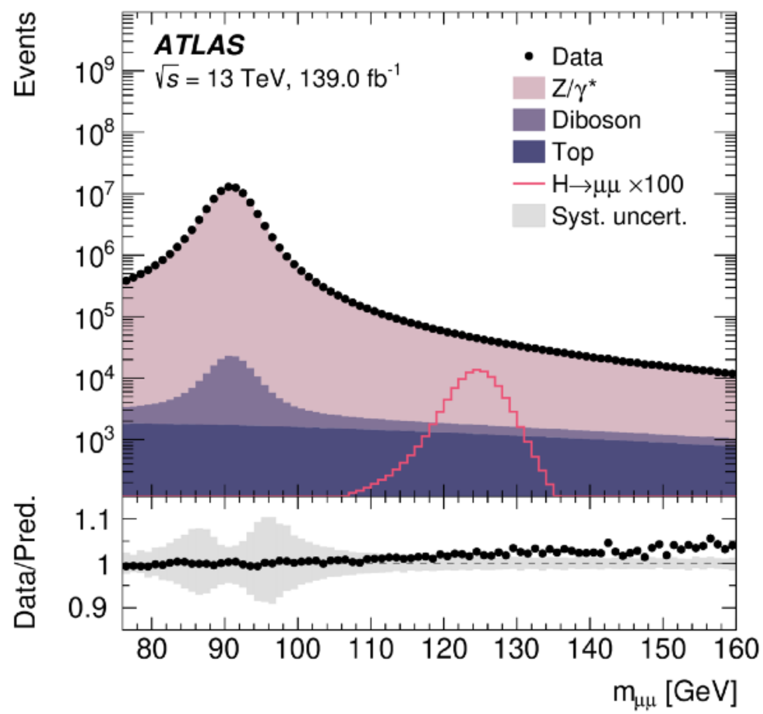
- **Search for Higgs rare decay into 2nd-generation fermions:**
  - $H\rightarrow\mu\mu$ (139 fb^{-1}): arXiv:2007.07830
- **Search for Higgs rare decay through loop:**
  - $H\rightarrow Z\gamma$ (139 fb^{-1}): arXiv:2005.05382
- **Searches for additional heavy Higgs bosons:**
  - Heavy γγ resonance (139 fb^{-1}): ATLAS-CONF-2020-037
  - Heavy $ZZ\rightarrow 4l/ll\nu\nu$ resonance (139 fb^{-1}): ATLAS-CONF-2020-032
    → Theodota's talk

These are all new results obtained in 2020.

H→$\mu\mu$ rare decay search

- The H→$\mu\mu$ rare decay offers the best possibility to measure the Higgs coupling to a 2nd-generation fermion.

- Very clean final state, but typical S/B=0.2% for $m_{\mu\mu}$: 120-130 GeV.
  - BR(SM H→$\mu\mu$) = 2.17×10^{-4}
  - Large irreducible background dominated by Drell-Yan

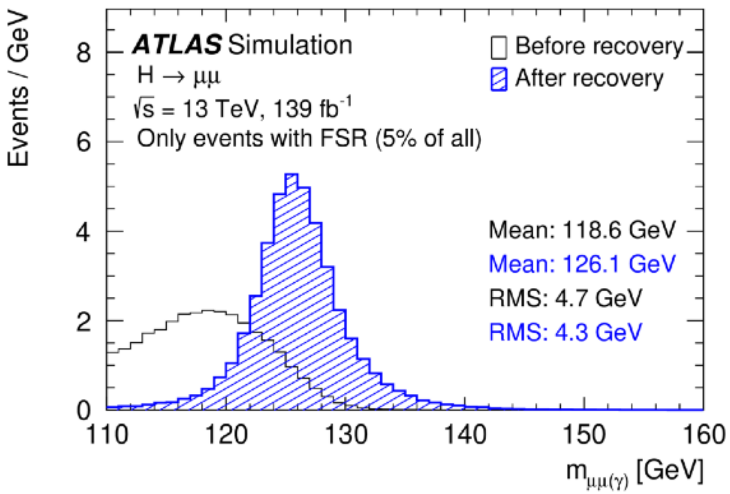


H→$\mu\mu$ search: Analysis strategy

- Two opposite-charge, isolated muons are required
  - $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 10$ GeV

- To improve the sensitivity by isolating regions of higher S/B, events are classified into 20 categories using production-driven BDT categorization.
  - Targeting production modes in the following order:
    ttH → VH(3L, 4L) → VBF → ggF

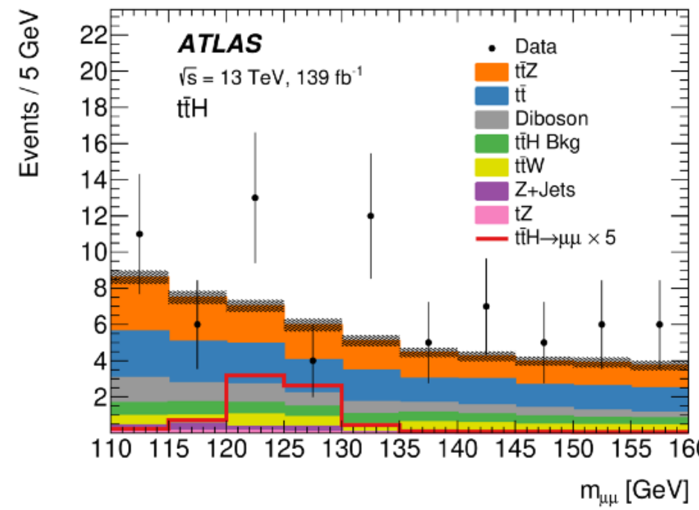
- Add final state radiation γ to $m_{\mu\mu}$ calculation to improve $m_{\mu\mu}$ resolution
  (only in ggF and VBF categories).



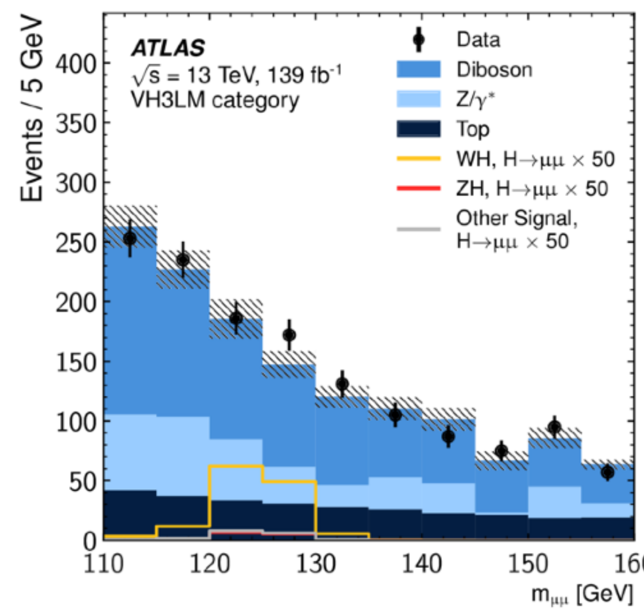
- Simultaneous S+B fit to $m_{\mu\mu}$ spectrum in each category to extract signal.
  Fit functions are parametric. Several parameters for background are free in fit to data.

H→$\mu\mu$ search: ttH/VH categorization

- **ttH production mode:**
  - Target: the dileptonic or semileptonic decay of the $t\bar{t}$ system.
  - At least one additional lepton (e or μ) and at least one b-tagged jet
  - Use BDT discriminant to separate from background (dominated by $t\bar{t}Z$ and $t\bar{t}$)



- **VH production mode:**
  - Target: W→lν (VH3L) or Z→ll (VH4L)
  - At least one additional lepton, no b-jets
  - Events are classified into 3 categories using 2 BDTs separately trained in VH3L and VH4L (2 categories for VH3L, 1 category for VH4L)



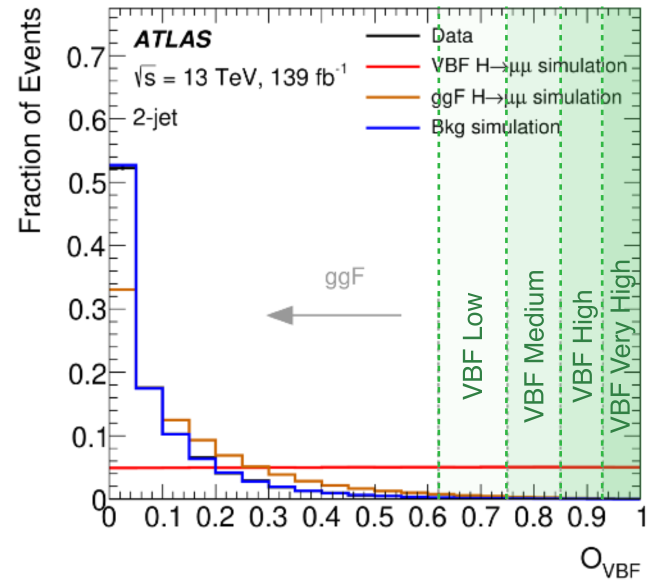
Two muons are selected by minimum χ^2 for $m_{\mu\mu}$.

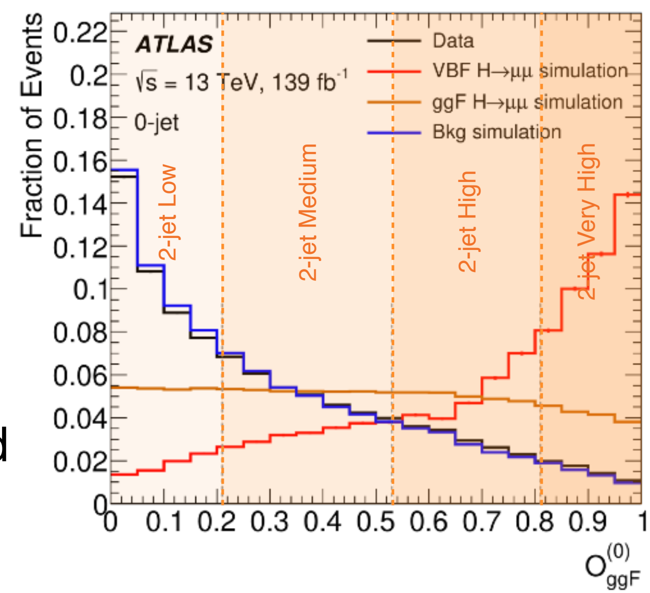
H→$\mu\mu$ search: ggF/VBF categorization

- Exactly two opposite-charge muons, no b-jets
- Events divided into 0-jet, 1-jet and ≥ 2-jet regions
- BDTs are trained in each jet multiplicity
  to fully exploit differences between S and B.
- Events are classified based on
  dedicated BDT output in each jet multiplicity.

VBF classifier:
- 4 categories in 2-jet region
- Trained to disentangle VBF vs background
- BDT output: O_{VBF}

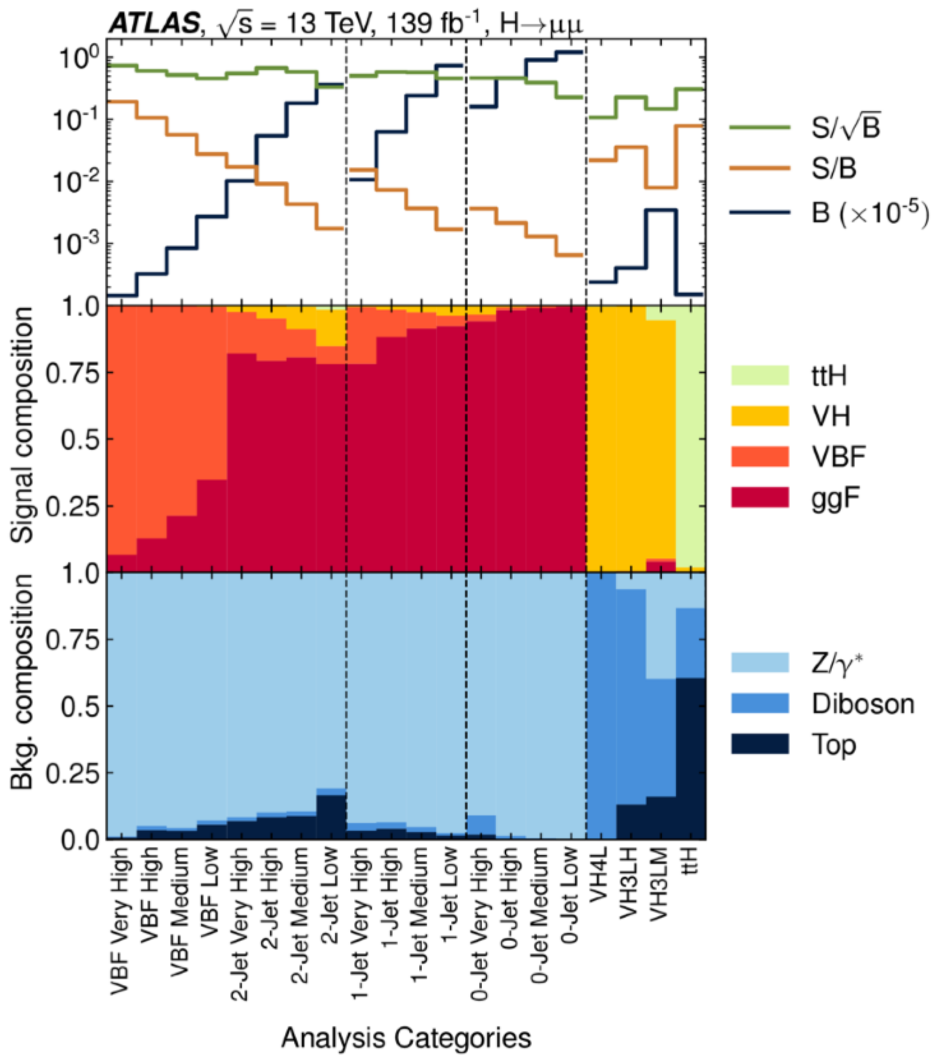
ggF classifier:
- 4 categories in each 2/1/0-jet region
- Trained to disentangle ggF+VBF vs background
- BDT output of N-jet region: $O_{\mathrm{ggF}}^{(N)}$





H→μμ search: Categorization summary

Signal and background composition in 20 categories in $m_{\mu\mu}$=120-130 GeV



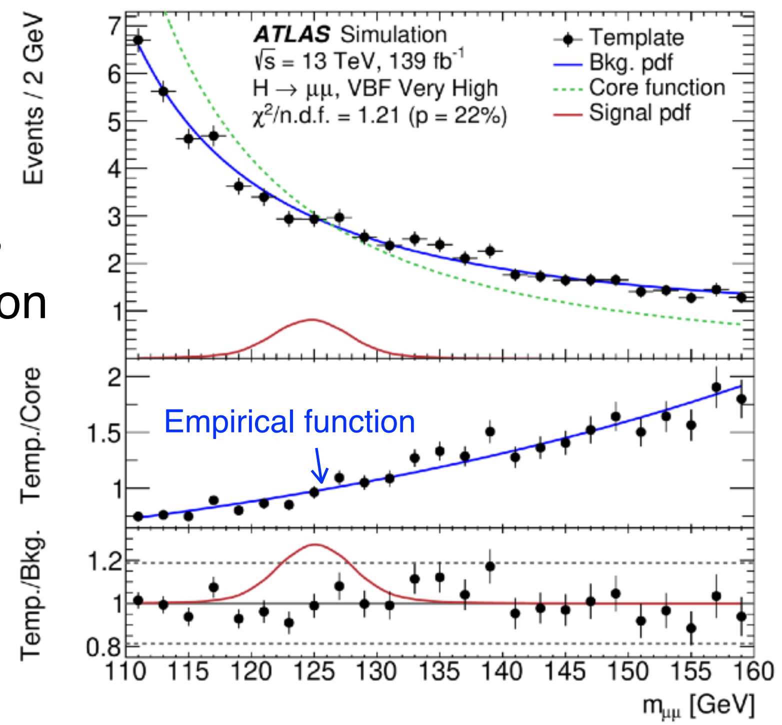
- S/B is quite different between categories. Wide range from 0.1% to 20%.
- Very good separation of production modes.

H→$\mu\mu$ search: Signal and background modelling

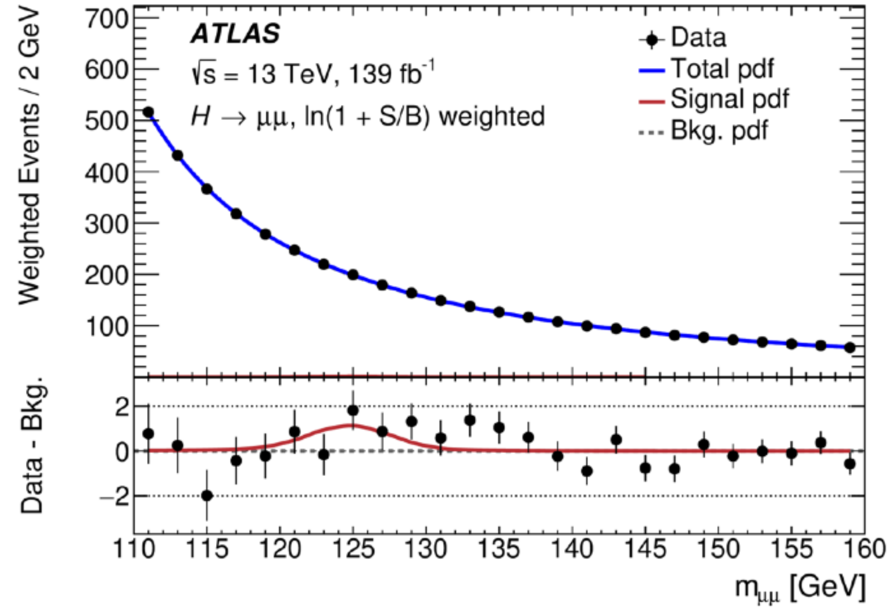
- **Signal:** Double-sided Crystal Ball with shape parameters fixed in each category from fit to MC

- **Background:** product of core and empirical functions
  - Core: LO Drell-Yan analytic line shape smeared with Gaussian for mass resolution.
  - Empirical: **PowerN or EpolyN** depending on categories to correct for distortions of the mass shape due the event selection and categorization and other smaller background contributions. Function was selected so that **the systematic uncertainty due to the mismodeling is less than 20% of the data statistical uncertainty.**

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\ldots+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \ldots + a_N m_{\mu\mu}^N)$



H→$\mu\mu$ search: Results



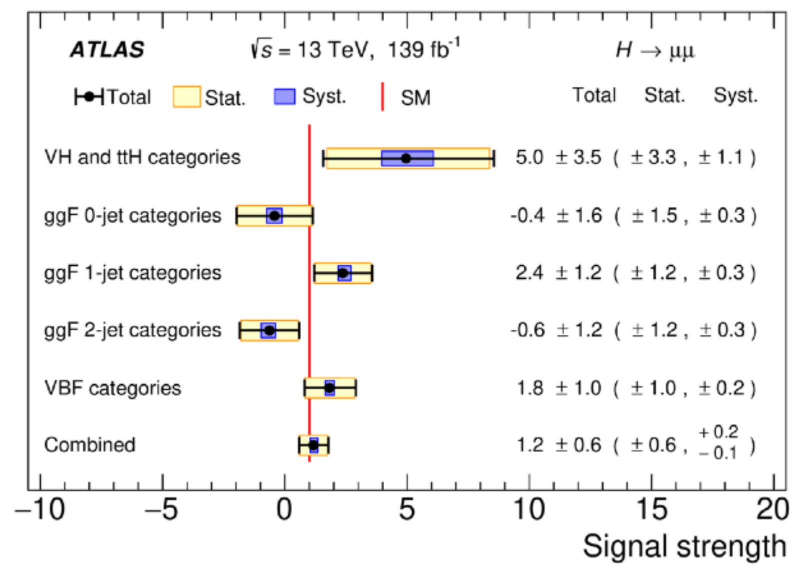
- Observed (expected) significance:
  2.0σ (1.7σ)

- Signal strength ***μ* = 1.2 ± 0.6**

- Total uncertainty is dominated by statistical uncertainty of data.

- Observed (expected) upper limit on *μ* at 95% CL:
  2.2 (1.1 for no H→*μμ*)

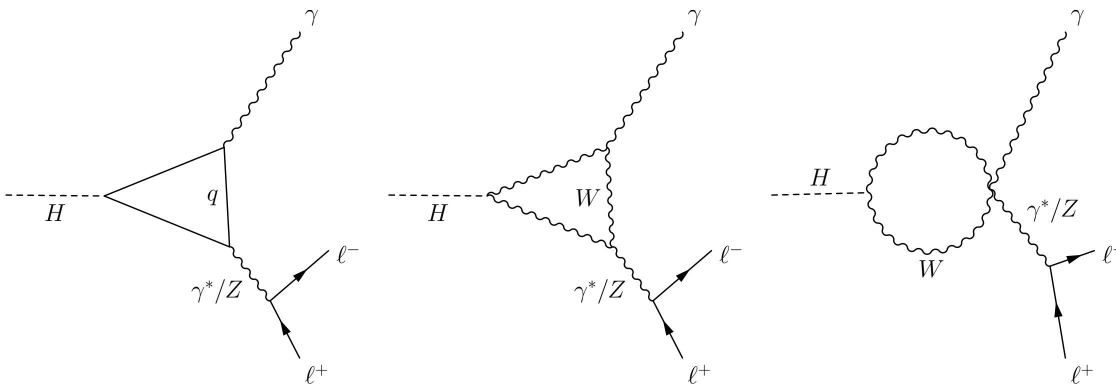
- Observed limit on branching ratio at 95% CL:
  BR(H→*μμ*) < 4.7x10^{-4}
  assuming SM σ



We got closer to understanding the origin of particle mass for 2nd-generation!

H→Zγ rare decay search

- H→Zγ rare decay is important to understand Higgs loop interaction.



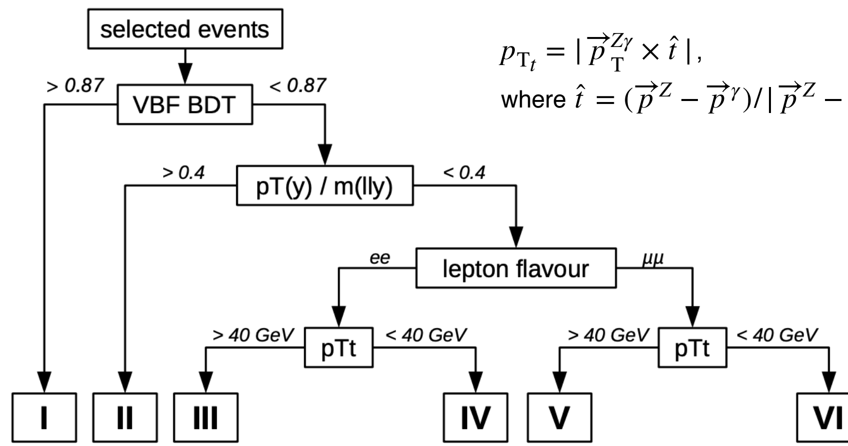
  - BR(H→Zγ)=$(1.54\pm0.09)\times10^{-3}$ @m_H=125.09 GeV
    In several scenarios beyond SM, BR can differ from BR of SM.

- Z→ee/$\mu\mu$ decays provide good invariant mass resolution and relatively small backgrounds.

- Analysis strategy:
  - Events are classified into 6 categories for higher sensitivity.
  - Simultaneous fit to $m_{Z\gamma}$ in all the categories for signal extraction.

H→Zγ search: Analysis overview

- Events with two same-flavour opposite-charge leptons and at least one γ
- For $m_{Z\gamma}$ resolution correction,
  - Final state radiation γ is added to $m_{Z\gamma}$ calculation in $\mu\mu$ channel,
  - Z-mass constrained kinematic fit in both channels
- Event classification into 6 categories, based on:
  - BDT to tag VBF-like events
  - lepton flavour and event kinematics in untagged events

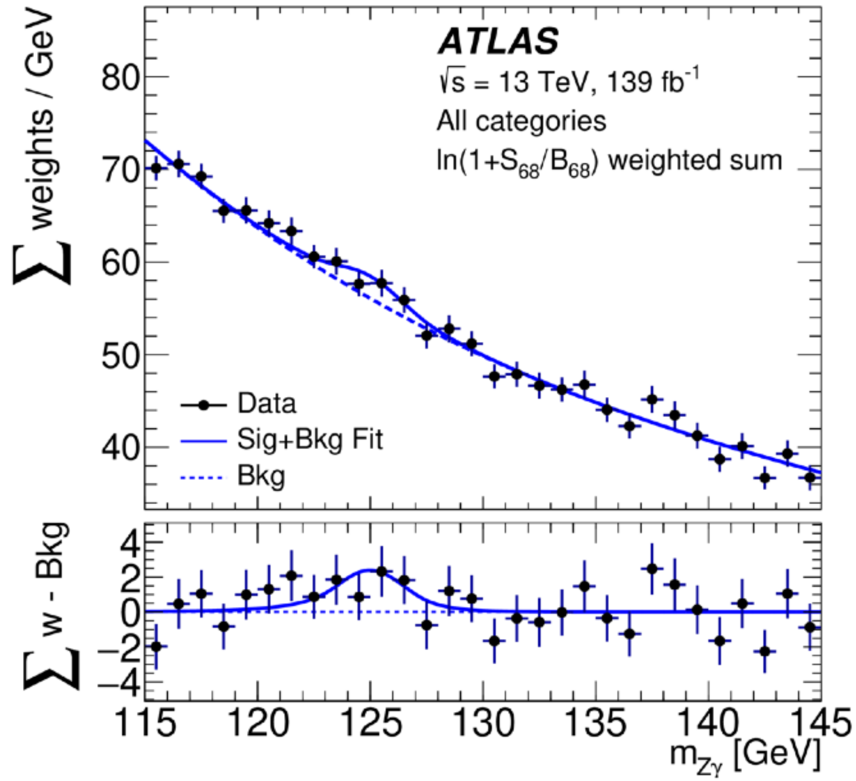


$p_{T_t} = |\vec{p}_T^{Z\gamma} \times \hat{t}|$,
where $\hat{t} = (\vec{p}^{Z} - \vec{p}^{\gamma})/|\vec{p}^{Z} - \vec{p}^{\gamma}|$

- Signal and background modeling:
  - Signal: Double-sided Crystal Ball function
  - Background: Analytical function with floating parameters, shape and uncertainty determined using background templates from Zγ MC simulation and Z+jets data control region

H→Zγ rare decay: Results

- Observed (expected) significance:
  2.2σ (1.2σ)
- Signal strength ***μ* = 2.0 $^{+1.0}_{-0.9}$**
- The total uncertainty is dominated by the statistical uncertainty of data.
- Observed (expected) upper limit on *μ* at 95% CL:
  3.6 (1.7 for no H→Zγ)
- Observed upper limit at 95% CL:
  - **σ(pp→H)·BR(H→Zγ) < 305 fb**
  - **BR(H→Zγ) < 0.55%** assuming SM σ



Observed upper limit on BR is close to SM BR.
Search for BSM physics in loop using larger dataset is important!

Heavy γγ resonance search

- Search for γγ resonance in high-mass spectrum ($m_{\gamma\gamma}$>160 GeV).
- Spin-0 resonant state (X) predicted by theories with extended Higgs sector (additional heavy Higgs).
  - Spin-2 graviton benchmark is also considered (not covered in this talk).
- γγ final state provides excellent invariant mass resolution and smoothly falling background.
- Analysis strategy:
  - For spin-0, search for a narrow or large width (NW or LW) resonances, up to Γ_X/m_X=10%.
  - Fit $m_{\gamma\gamma}$ with analytical functions that model bkg. and signal shape.

Heavy γγ resonance: Analysis overview

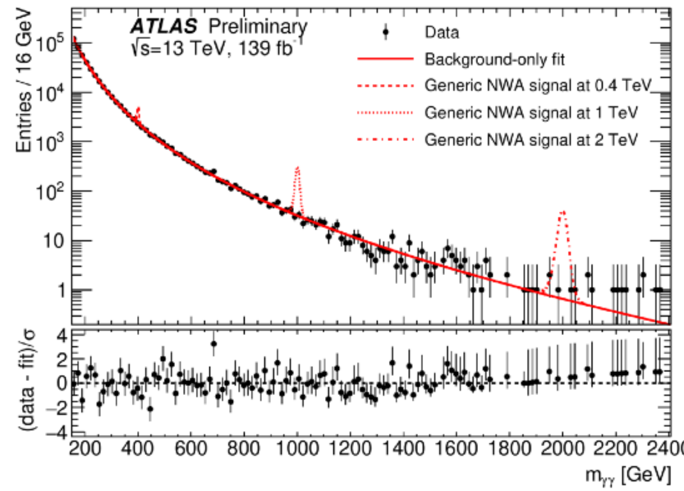
- Common event selection is used for spin-0/2:
  - At least two photon candidates
  - $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.3$, $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.25$
  - $|\eta| < 2.37$

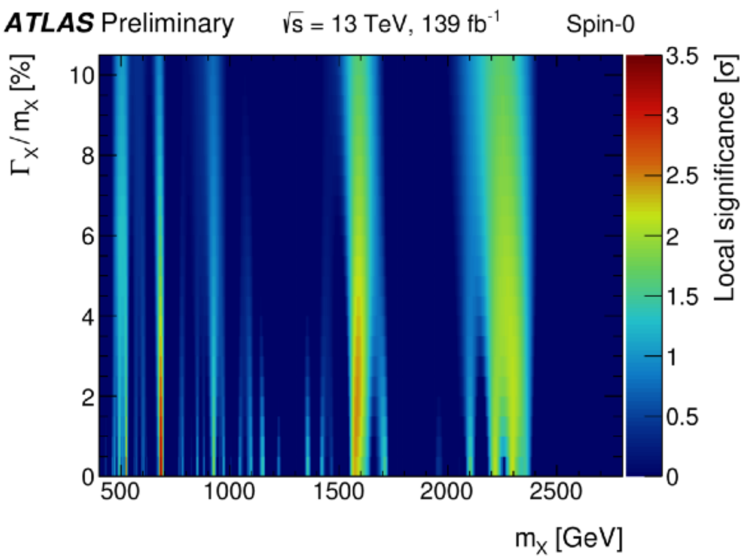
- Signal modelling:
  - NW: Double-sided Crystal Ball function (DSCB)
  - LW: DSCB $\otimes$ relativistic Breit-Wigner function for spin-0

- Background modelling:
  Analytical function with floating parameters, shape and uncertainty determined using background templates from γγ MC simulation and γ+jet data control region

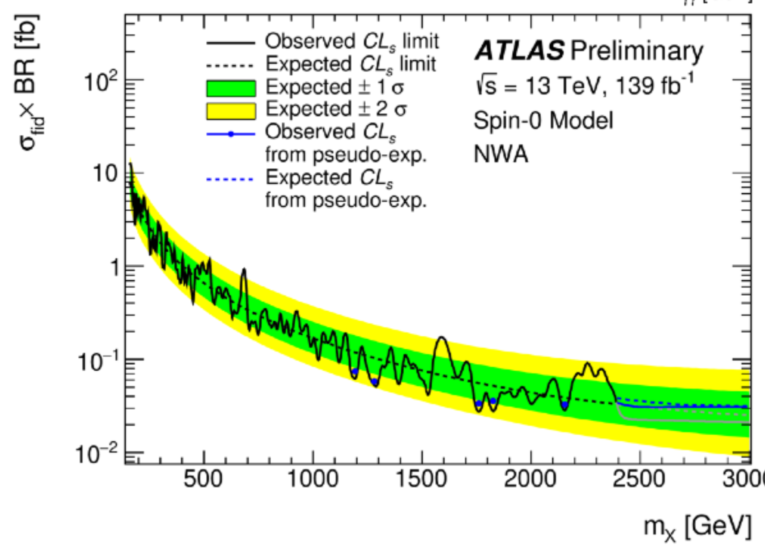
Heavy γγ resonance: Results

- Highest m_X candidate selected in data has a mass of 2.36 TeV.
- No significant deviation from the SM is observed.
- Largest deviation for NWA model: 3.29σ (local), 1.30σ (global) at m_X = 684 GeV





Local significance obtained for $\Gamma_X/m_X < 10\%$.



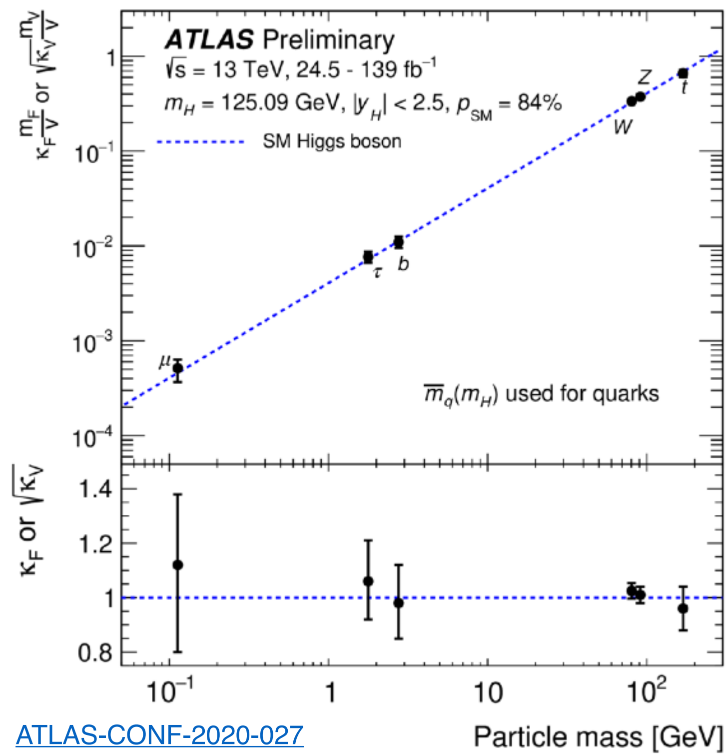
Observed upper limits for NWA at 95% CL: 12.5 fb (160 GeV) to 0.03 fb (2800 GeV)

The mass range of the search has reached 3 TeV.

Conclusion

Rare decays of the observed Higgs boson and additional Higgs bosons were searched for with full Run-2 dataset (139 fb^{-1}).

- $H \to \mu\mu$ search:
  - Signal strength: 1.2±0.6
  - Observed significance: 2.0σ
- $H \to Z\gamma$ search:
  - Signal strength: $2.0^{+1.0}_{-0.9}$
  - Observed significance: 2.2σ
- Heavy γγ resonance search:
  - The mass range of the search has reached 3 TeV.
  - No significant deviation from the SM is observed.



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We gained a deeper understanding of the Higgs sector.
We expect higher sensitivities with Run-3 dataset and the beyond.

Backup

$H \to \mu\mu$ search: BDT input variables (ttH/VH)

ttH categorization

- Lepton related: $p_T^{\mu\mu}$, $\cos\theta^*$, p_T^{l3}, p_T^{l4}, m_{l3l4}, $m_{\mu\mu}^{subleading}$
- Additional invariant mass: $m_{Lep\text{-}Top}$, $m_{Lep\text{-}W}$, $m_{Had\text{-}Top}$
- Jet related: $N_{jet(central)}$, $N_{b\text{-}jet}$, H_T

$\cos\theta^*$: value of the cosine of the lepton decay angle in the Collins–Soper frame
$m_{Lep\text{-}Top}$: transverse mass of l3 + MET + b-jet
$m_{Lep\text{-}W}$: transverse mass of l3 + MET
$m_{Had\text{-}Top}$: mass of 2jets + b-jet
$N_{jet(central)}$: multiplicity of central jets with $|\eta| < 2.5$

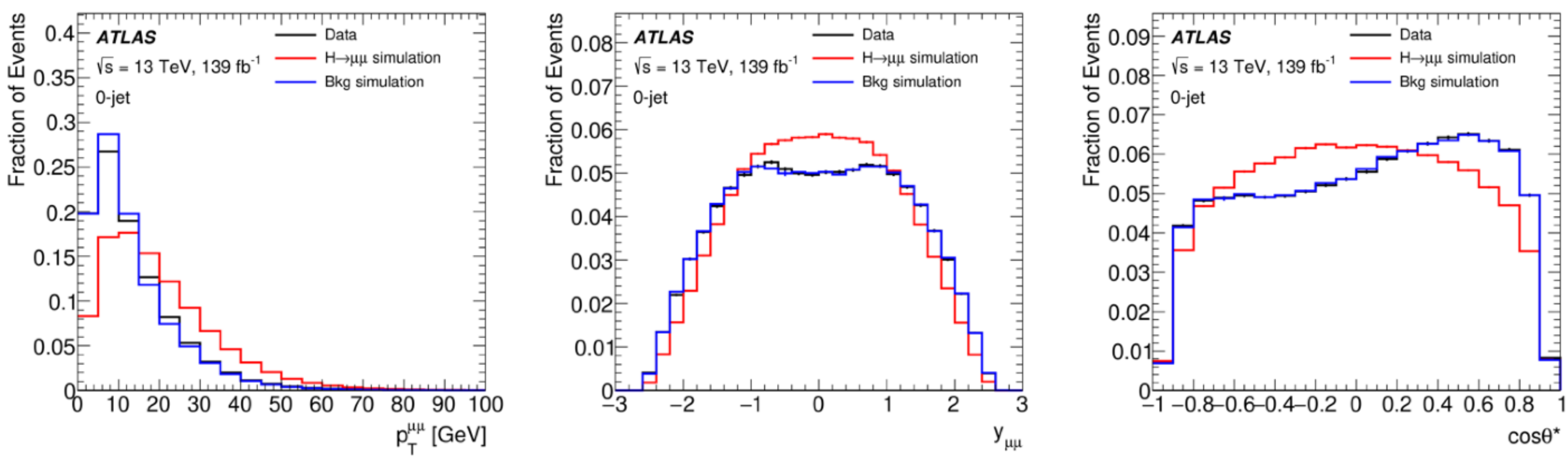
VH categorization

- VH3L: $m_{Lep\text{-}Top}$, p_T^{l3}, $\Delta\eta_{l3,\mu\mu}$, $\Delta\phi_{l3,\mu\mu}$, p_T^{j1}, MET, $\Delta\phi_{MET,\mu\mu}$, N_{jet}
- VH4L: $\Delta\phi_{l3,l4}$, m_{l3l4}, $\Delta\eta_{l3,\mu\mu}$, $\Delta\phi_{l3l4,\mu\mu}$, p_T^{j1}, p_T^{j2}, N_{jet}

$H\to\mu\mu$ search: BDT input variables (ggF/VBF)

jet channel	Training variables
0-jet	$p_T^{\mu\mu}$, $Y_{\mu\mu}$, $\cos\theta^*$
1-jet	0-jet variables + p_T^{j1}, η_{j1}, $\Delta\phi_{j1,\mu\mu}$, N^{j1}_{track}
≥ 2-jet	1-jet variables + p_T^{j2}, η_{j2}, $\Delta\phi_{j2,\mu\mu}$, N^{j2}_{track}, p_T^{jj}, η_{jj}, $\Delta\phi_{jj,\mu\mu}$, m_{jj}, MET, H_T

N^{ji}_{track}: multiplicity of ID tracks with $p_T > 0.5$ GeV associated with each of the two leading jets



H→$\mu\mu$ search: Criteria to select empirical function

- The empirical function was selected so that the systematic uncertainty due to the mismodeling is less than 20% of the data statistical uncertainty.

- The systematic uncertainty was evaluated with fitting the $m_{\mu\mu}$ distributions of the following MC template in each categories.
  - **ggF/VBF categories**: High stats (~50 ab^{-1}) fast simulation for Drell-Yan background reweighted using $m_{\mu\mu}$ data sidebands
    - Sherpa Z/γ* + 0-3 partons, LO, showered with Pythia
  - **VH/ttH categories**: Full MC simulation of background reweighted using $m_{\mu\mu}$ data sidebands

- Among the functions that pass the requirement, those with the smallest number of degrees of freedom are selected to minimize the statistical uncertainty that dominates in this search.

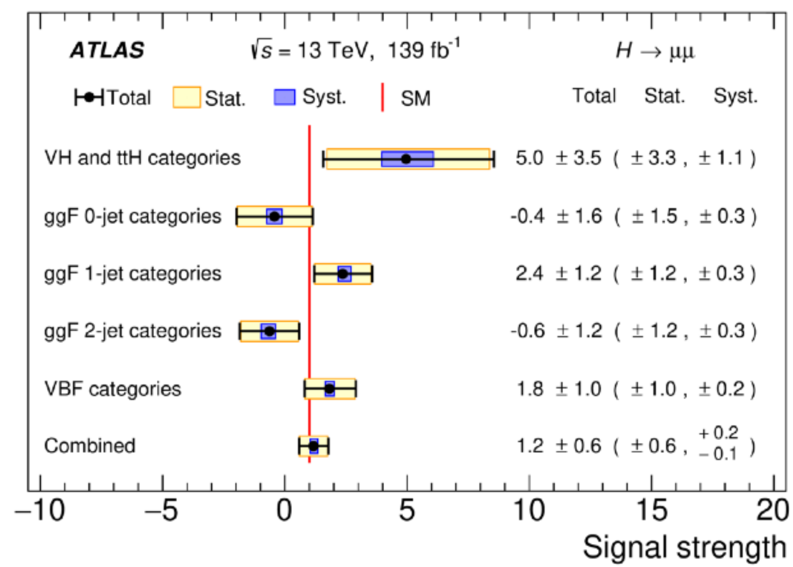
H→$\mu\mu$ search: Number of events observed in $m_{\mu\mu}$ = 120–130 GeV

Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0
2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0
2-jet Medium	18 311	79 ± 15	90 ± 50	$18\,320 \pm 90$	0.66	0.5
2-jet Low	36 409	63 ± 17	70 ± 40	$36\,340 \pm 140$	0.37	0.2
1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8
1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9
1-jet Medium	24 576	90 ± 11	100 ± 50	$24\,290 \pm 100$	0.67	0.4
1-jet Low	73 459	125 ± 17	150 ± 70	$73\,480 \pm 190$	0.53	0.2
0-jet Very High	15 986	59 ± 11	70 ± 40	$16\,090 \pm 90$	0.55	0.4
0-jet High	46 523	99 ± 13	120 ± 60	$46\,190 \pm 150$	0.54	0.3
0-jet Medium	91 392	119 ± 14	140 ± 70	$91\,310 \pm 210$	0.46	0.2
0-jet Low	121 354	79 ± 10	90 ± 50	$121\,310 \pm 280$	0.26	0.1
VH4L	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6
VH3LH	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2
VH3LM	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2

H→$\mu\mu$ search: Compatibility between categories

- Compatibility of measured signal strengths between 20 categories is tested by repeating the fit after allowing each category to have its own signal strength parameter.
  - Compatibility is evaluated to be 2%.
  - VBF Medium, 0-jet Very High, and VH4L categories have 2σ level deviations from mean value.

- Compatibility between 5 groups of categories is also tested with the same method.
  - Compatibility is evaluated to be 20%



H→$\mu\mu$ search: Compatibility with preliminary result

- Preliminary result using the same dataset is presented in ATLAS-CONF-2019-028.
    - Preliminary signal strength $\boldsymbol{\mu}$ **= 0.5 ± 0.7**
    - New signal strength $\boldsymbol{\mu}$ **= 1.2 ± 0.6**

- Compatibility between the two signal strength measurements was checked using the following bootstrap technique.
    - Prepare dataset including events passing either preliminary or new analysis.
    - Assign random Poisson(1) weight to each event and then extract signal strengths from the two analyses.
    - Repeat the above steps to get a distribution for evaluating compatibility.

- Results of the check:
    - Compatibility: 1.4σ
    - Correlation: 75%

$H\rightarrow Z\gamma$ search: BDT input variables

$\Delta\eta_{j,j}$, $\Delta R^{min}_{\gamma orZ,j}$, mjj, $|\eta_{Z\gamma}-(\eta_{j1}+\eta_{j2})/2|$, $\Delta\Phi_{Z\gamma,jj}$, $\Delta\Phi_{Z,\gamma}$, p_{Tt}