10th International Conference on New Frontiers in Physics (ICNFP 2021)

Searches for high-mass Higgs-like resonances with the ATLAS detector

09.2nd,2021

Wanyun Su (Tsung-Dao Lee Institute)

On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

TDLI 李政道研究所

Introduction

- Huge success of the discovery of Higgs Boson predicted by Standard Model (SM).

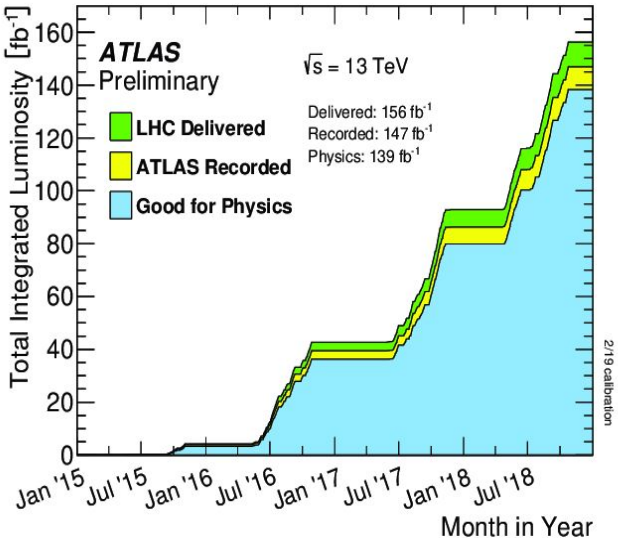
4 July 2012,
The discovery of the Higgs boson was announced at CERN

Questions: Is the 125 GeV Higgs the only one?

- Many models of Beyond SM (BSM) include extensions to the Higgs sector.
- All allow for SM-like Higgs phenomenology with smaller or larger coupling modification.

Introduction

- Focuses on the explicit searches for high-mass Higgs-like resonances.
- What next when no significant deviation from the SM is observed?
  - How much of the BSM scenarios can current data exclude?
- Shows results based on full Run-2 data (139 fb^{-1})

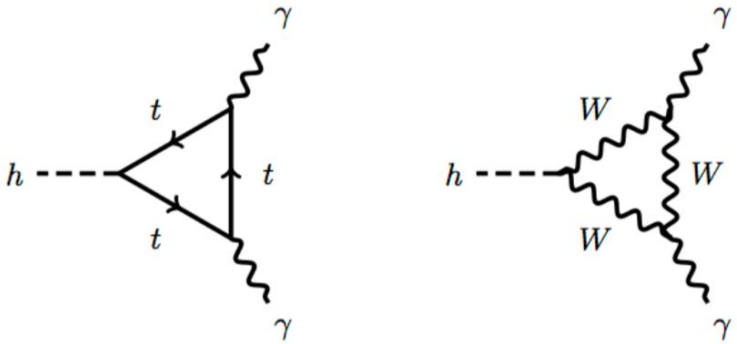


- **Outline**
  - **H→ $\gamma\gamma$ high-mass search**
  - **H→ZZ high-mass search**

H-> $\gamma\gamma$ high-mass search

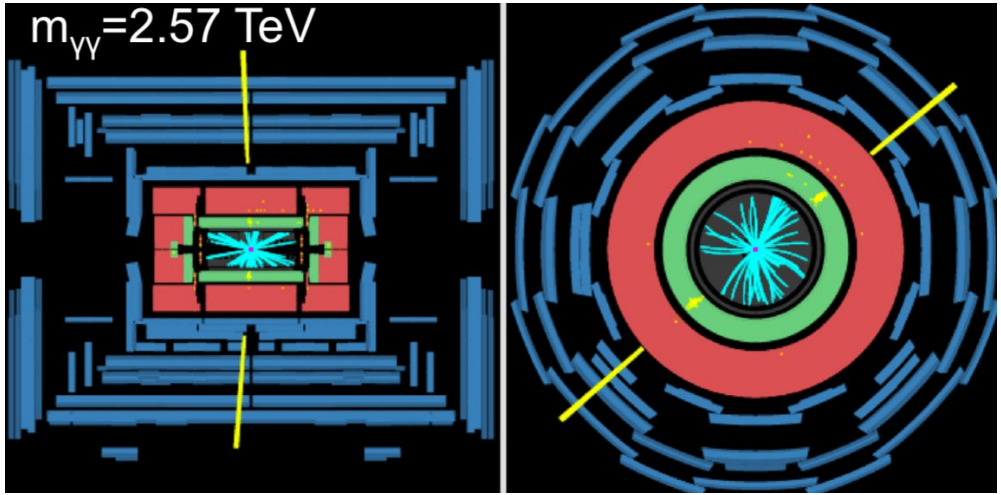
ANA-HIGG-2018-27

- Searches for $\gamma\gamma$ resonances in high mass spectrum ($m_{\gamma\gamma}$ >160 GeV) using full Run-2 data (139.0 ± 2.4 fb^{-1}).
  - Spin-0 as predicted by theories with an extended Higgs sector.
    - For spin-0, search on narrow-width (NW) and large-width (LW) resonances.
  - Spin-2 graviton benchmark is also considered (not covered in this talk).
- Final state provides excellent invariant mass resolution and smoothly falling background.
- The mass range of the search has reached 3 TeV.



Analysis overview

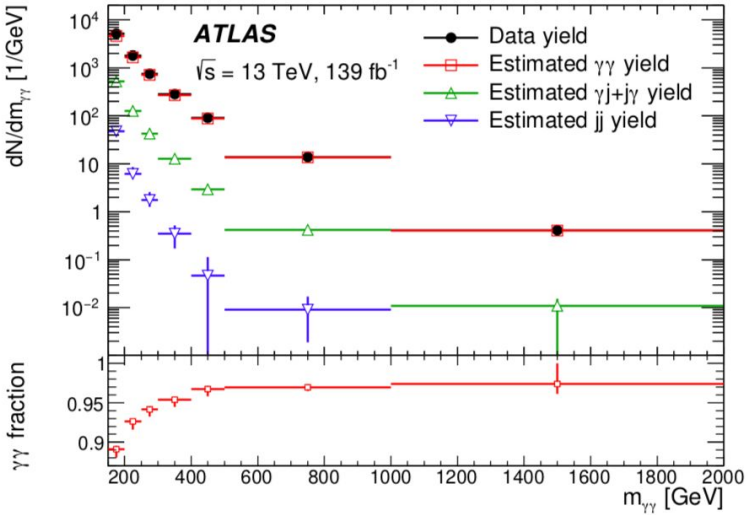
- **Event selections**
  - at least two photon candidates with E_T > 22 GeV and $|\eta|$ < 2.37.
  - $E_T(\gamma 1)/m_{\gamma\gamma}$ > 0.3, $E_T(\gamma 2)/m_{\gamma\gamma}$ > 0.25



- **Signal modelling:**
  - Double-sided Crystal Ball function (DSCB) convolved with relativistic Breit-Wigner function and mass-dependent factors which are derived from the simulation.

Analysis overview

- **Background modelling:**
  - Analytic function which determined by fitting a template built from simulated Monte Carlo $\gamma\gamma$ events and γj events.



- The overall $\gamma\gamma$ purity of the selected events increases with $m_{\gamma\gamma}$ from ~ 89% (150–200 GeV) to ~ 97% (> 400 GeV).

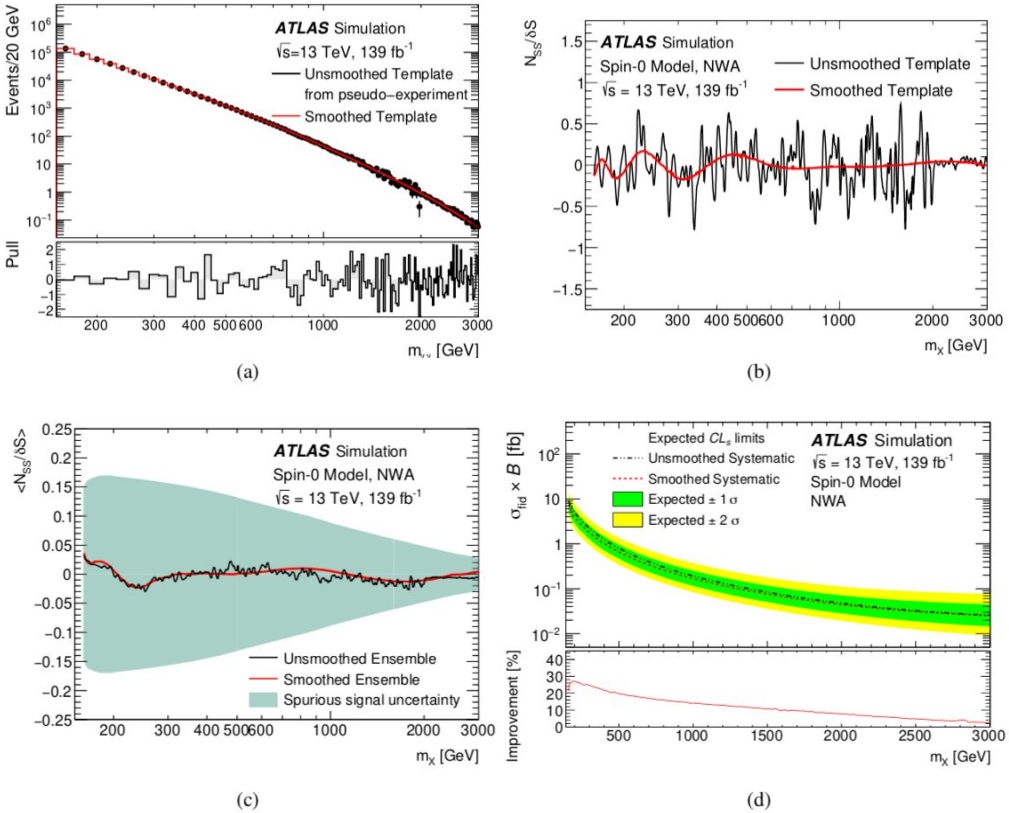
- The search region for a resonant signal covers the region 160–3000 GeV (NW signal) and 400–2800 GeV (LW signal).

- Interference effects between the resonant signal and all background processes are expected to be small for a NW signal and are neglected in this analysis.

Largest background (97% above 400 GeV) comes from non-resonant production of QCD photon pairs ($\gamma\gamma$ events) .

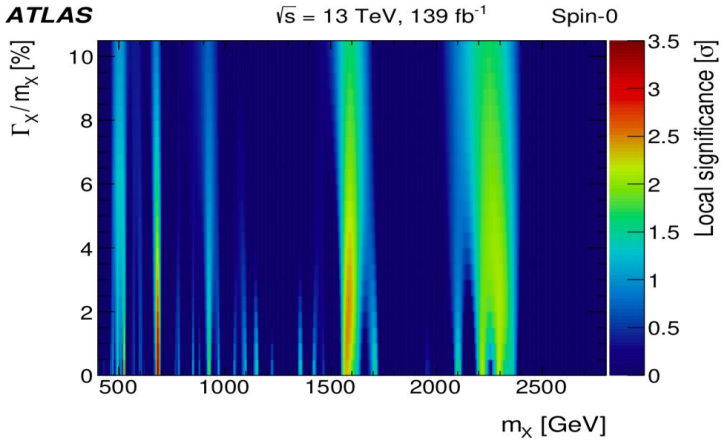
Analysis overview

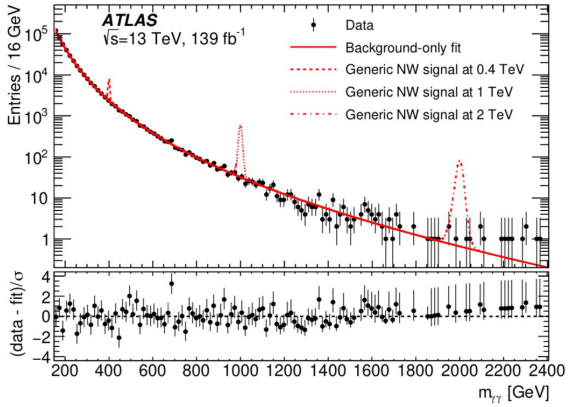
- **Background modelling:**
  - To suppress the statistical fluctuations, **a smoothing process** is employed:
    - **a).** fit the pseudo-experiment, resulting in a smoothed template.
    - **b).** estimate spurious signal by fitting the smoothed template with the signal-plus-background model.
    - **c).** repeat the process and take mean value.
    - **d).**the use of smoothed templates leads to a limit improvement of 2–28%.

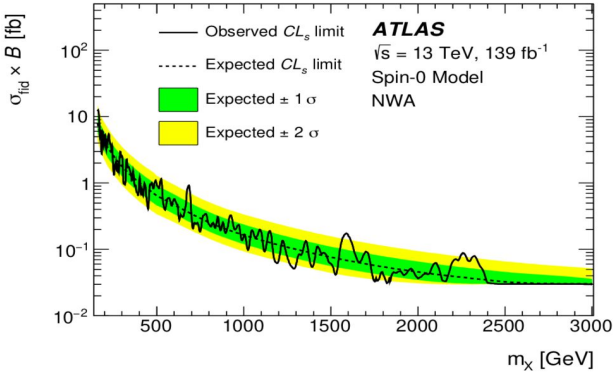


Results

- No significant excess observed.
  - limits are placed on the production cross-section times branching ratio, $\sigma \times B(X \rightarrow \gamma\gamma)$.
- The most significant excess for the spin-0 NWA model is 3.29 σ (local), 1.30 σ (global) at $m_X \simeq 684$ GeV.







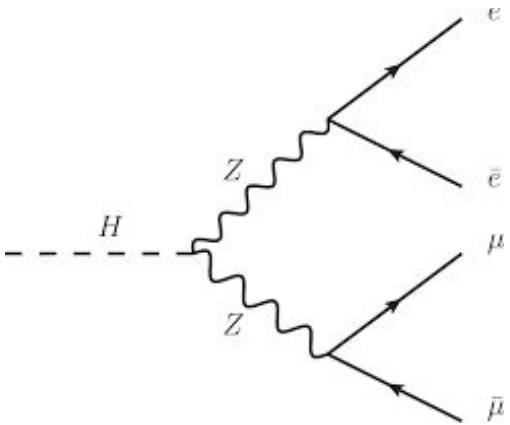
Observed upper limits at 95% CL on NWA : 12.5 fb (160 GeV) to 0.03 fb (2800 GeV)

H->ZZ high-mass search

Eur. Phys. J. C 81 (2021) 332

- Searches for heavy resonances in high mass spectrum using full Run-2 data.
  - $ZZ \rightarrow 4l$:good mass resolution.
  - $ZZ \rightarrow ll\nu\nu$ ($l=e,\mu$) :large branching ratio.
- Combination of $4l$ and $ll\nu\nu$ final states improve overall sensitivity.
- Interpretation of results in terms of Narrow Width (NW) and Large Width (LW) heavy Higgs for spin-0 resonance.
- Covering mass range 200 GeV to 2 TeV.
- Look for an excess in m_{4l} ($4l$) and m_T ($ll\nu\nu$).

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{miss})^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2},$$



Analysis overview ($ZZ \rightarrow 4l$)

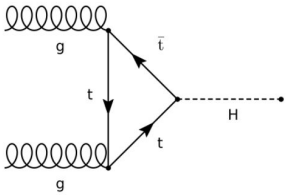
- Event selections
  - Lepton-quadruplet: two same-flavour, opposite-charge lepton pairs (4μ, 2e2μ, 4e)
  - e(μ) p_T >7 (5 GeV), |η|<2.5 (2.7)
  - p_T(Lep1th)>20 GeV, p_T(Lep2nd)>15 GeV, p_T(Lep3rd)>10 GeV.
  - lepton pair closest to Z mass
    - 50 GeV < m_{12} (leading pair) < 106 GeV
    - 50 GeV < m_{34} (subleading pair) < 115 GeV
  - Leptons cut: impact-parameter requirements & track- and calorimeter-based isolation to reduce the Z+jets and ttbar background contributions.

H->ZZ high-mass search

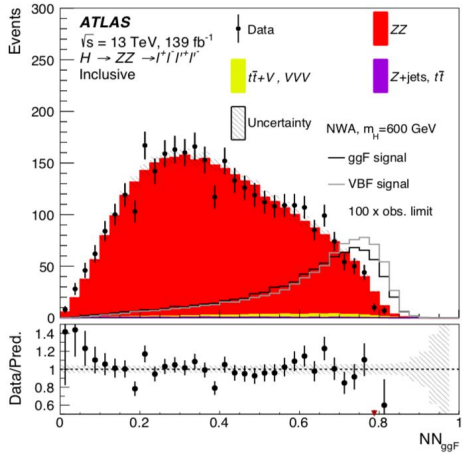
Eur. Phys. J. C 81 (2021) 332

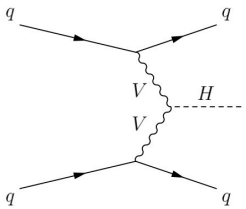
Analysis overview (ZZ→ 4l)

- Event categorization
  - NWA signal :
    - multivariate analysis (MVA)
      - VBF classifier (flavor inclusive)
      - ggF classifier (channels: 4μ, 2e2μ, 4e)
    - cut-based analysis (CBA)
      - VBF , when two or more jets p_T > 30 GeV, m_{jj} > 400 GeV, $\Delta\eta_{jj}$ > 3.3 (flavor inclusive)
      - ggF, otherwise (channels: 4μ, 2e2μ, 4e)
  - LWA signal:
    - ggF-enriched CBA

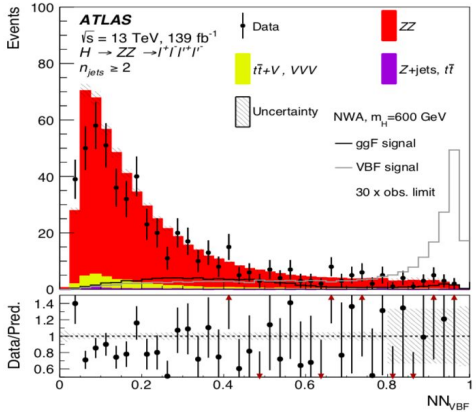


ggF





VBF

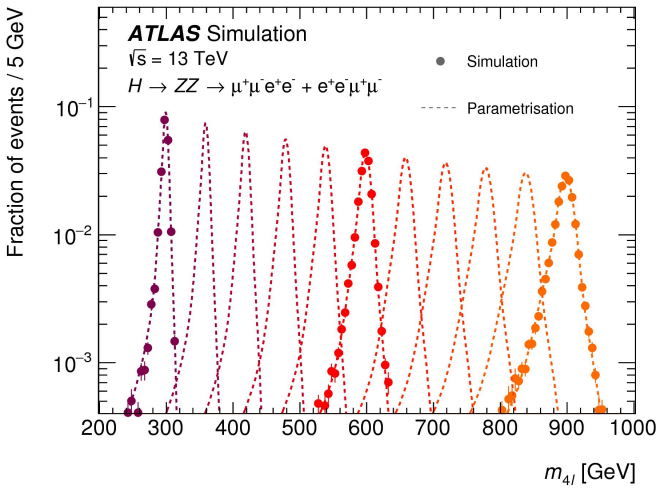


Eur. Phys. J. C 81 (2021) 332

Analysis overview (ZZ→ 4ℓ)

- Signal and background modelling
  - NWA Signal : detector resolution modelled by the sum of a Crystal Ball function and a Gaussian function.
  - LWA Signal: theoretical calculation convolved with the detector resolution.
  - Background:
    - 97% comes from non-resonant SM ZZ production (qq/gg→ZZ (96%) or EW vector-boson scattering (1%)): Parameterised with analytic functions estimated from MC.
    - Z+jets, ttbar: Data-driven estimate.
    - ttbarV,VVV: MC simulation.

Eur. Phys. J. C 78 (2018) 293



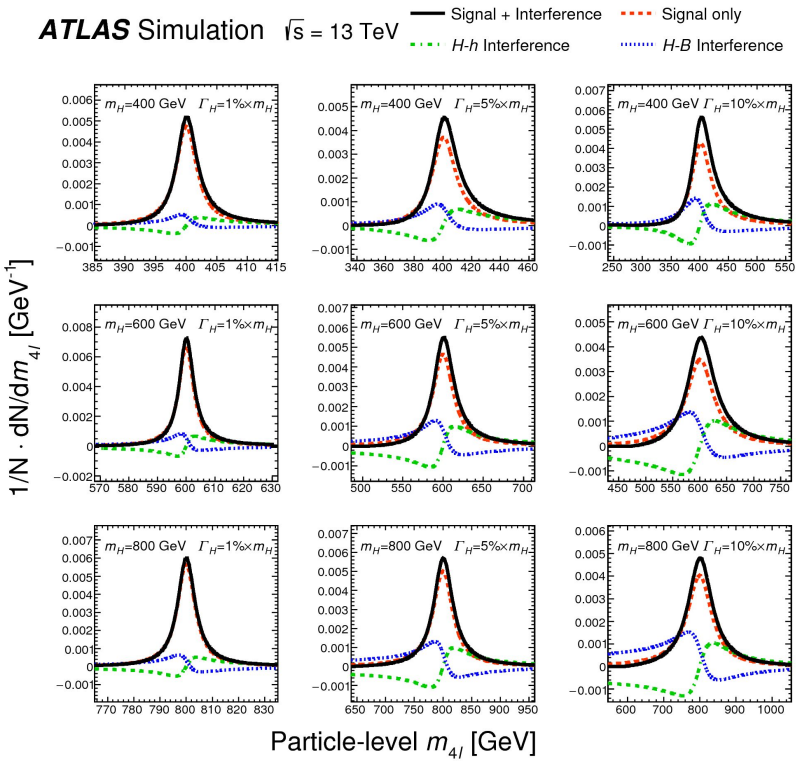
Parameterisation of signal in $m_{4\ell}$ spectrum (NWA)

Eur. Phys. J. C 81 (2021) 332

Analysis overview (ZZ→ 4*l*)

Eur. Phys. J. C 78 (2018) 293

- Interference modelling
  - The gluon-initiated production of a heavy scalar ***H***, the SM Higgs ***h*** and the gg → ZZ continuum background ***B*** all share the same initial and final state.
  - The effect could modify the integrated cross section by up to O(10%), and would be enhanced as the width of the heavy scalar increases.
  - Therefore, search in LWA must take them into account.
    - *H–h* interference: reweighting function.
    - *H-B* interference: empirical function fit to MC.

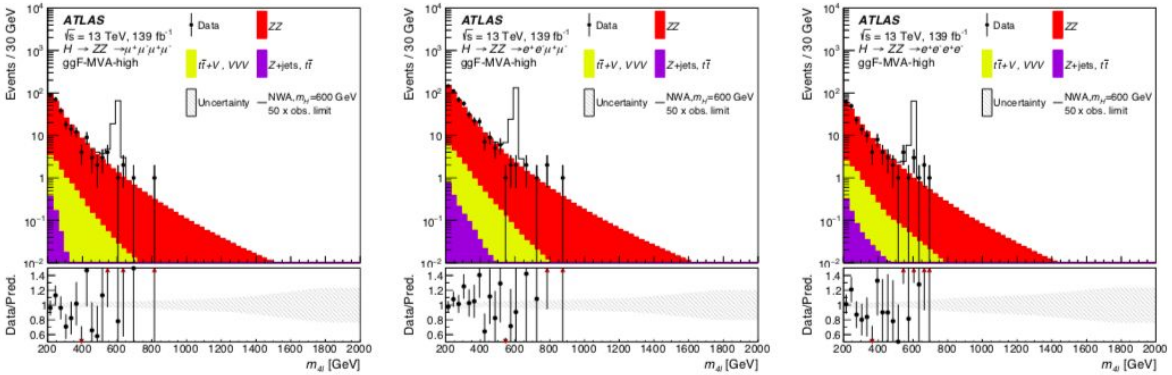


H->ZZ high-mass search

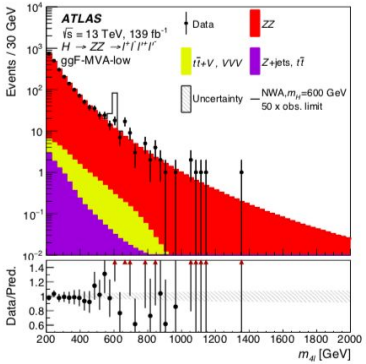
Eur. Phys. J. C 81 (2021) 332

Analysis overview (ZZ→ 4l)

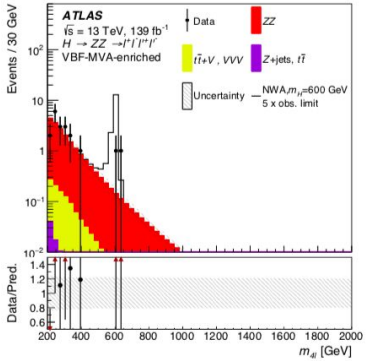
- 4l Results
  - Simulated m_H = 600 GeV signal is normalised to a cross section corresponding to 50 (5) times the obs. limit.
  - The error bars on the data points indicate the statistical uncertainty.
  - The lower panels show the ratio of data to prediction.



ggF-MVA-high categories



ggF-MVA-low category



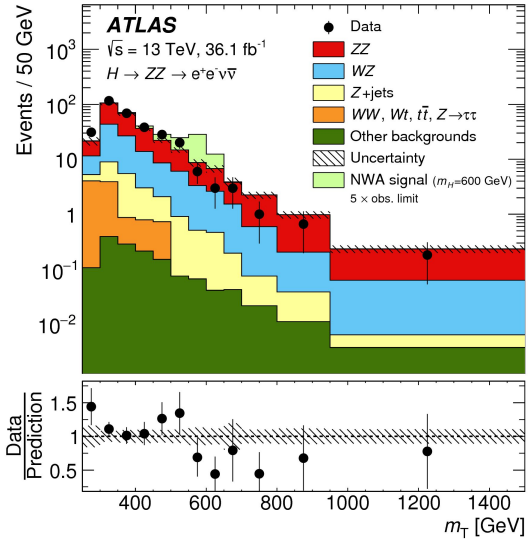
VBF-MVA-enriched category

H->ZZ high-mass search

Eur. Phys. J. C 81 (2021) 332

Analysis overview ($ZZ \to ll\nu\nu$)

- Event selections
  - Two same flavor leptons with opposite charges
  - $E_T^{miss} > 120$ GeV
  - 76 GeV < m_{ll} < 106 GeV
- Cut-based categorization
  - VBF: at least two selected jets with $p_T > 30$ GeV, $m_{jj} > 550$ GeV and $\Delta\eta_{jj} > 4.4$
  - ggF: otherwise
  - Both with channels: ee and μμ
- Backgrounds modelling:
  - Mainly ZZ (60%) and WZ (30%)
  - Smaller comes from non-resonant ll (5%), Z+jets(4%),VVV and ttbarV (< 1%)
  - Data-driven estimate



Eur. Phys. J. C 78 (2018) 293

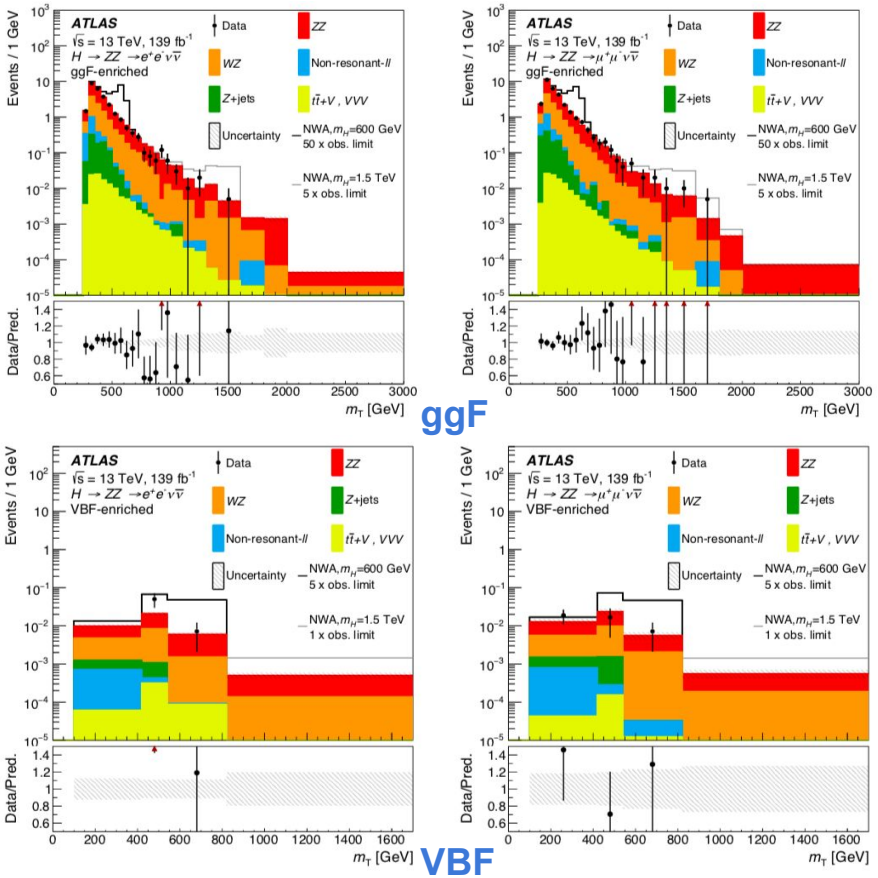
H->ZZ high-mass search

Eur. Phys. J. C 81 (2021) 332

Analysis overview (ZZ→*ll*νν)

- *llνν* Results
  - Simulated m_H = 600 GeV (1.5 TeV) signals are normalised to a cross section corresponding to
    - 50 (5) times the obs. Limit in ggF
    - 5 (1) times the obs. limit in VBF

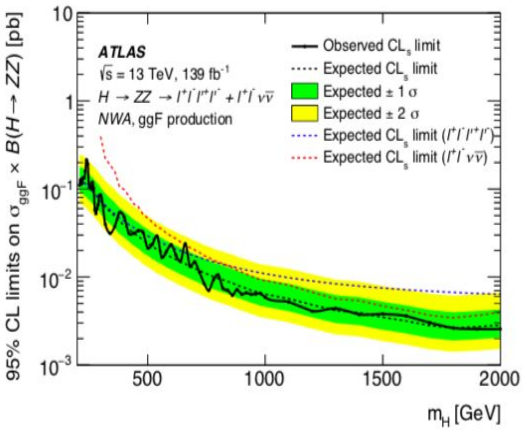
    (the two mass points were selected for demonstration purpose only)
  - The error bars on the data points indicate the statistical uncertainty.
  - The lower panels show the ratio of data to prediction.



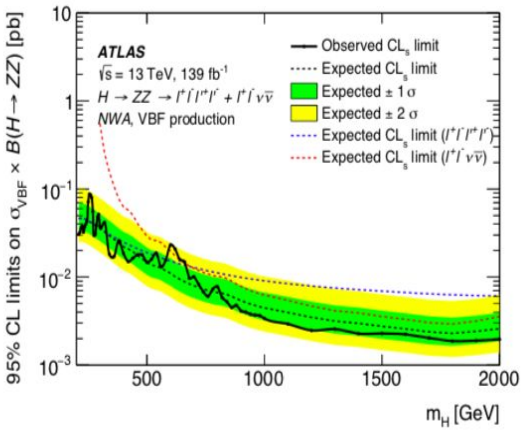
Eur. Phys. J. C 81 (2021) 332

Combined Results

- No significant excess observed
- upper limits are set on Spin-0 resonances with NWA
  - fits for the ggF and VBF processes are done separately.
    - the ratio of the two production mechanisms unknown



ggF



VBF

200 fb (240 GeV) to 2.6 fb (2000 GeV)

The most significant excess is 2.1 σ (local), 0.5 σ (global) at a mass of ≈ 240 GeV.

87 fb (250 GeV) to 1.9 fb (1800 GeV)

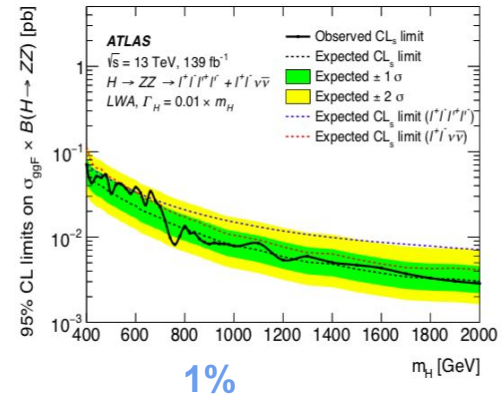
The most significant excess is 2.6 σ (local), 1.2 σ (global) at a mass of ≈ 660 GeV.

H->ZZ high-mass search

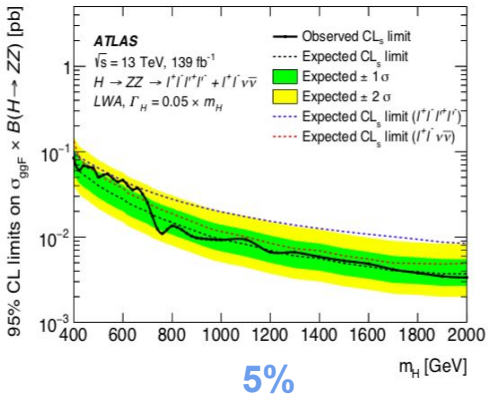
Eur. Phys. J. C 81 (2021) 332

Combined Results

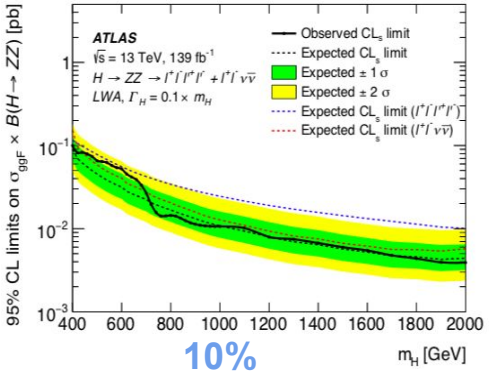
- No significant excess observed
- upper limits are set on Spin-0 resonances with LWA
  - Only ggF process is considered.
  - The limits are set for masses of m_H > 400 GeV.
  - Interference effects taken into account.



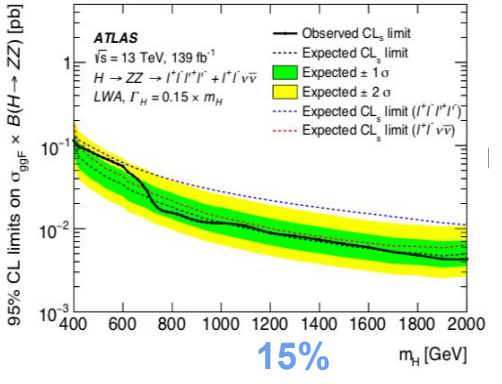
1%



5%



10%

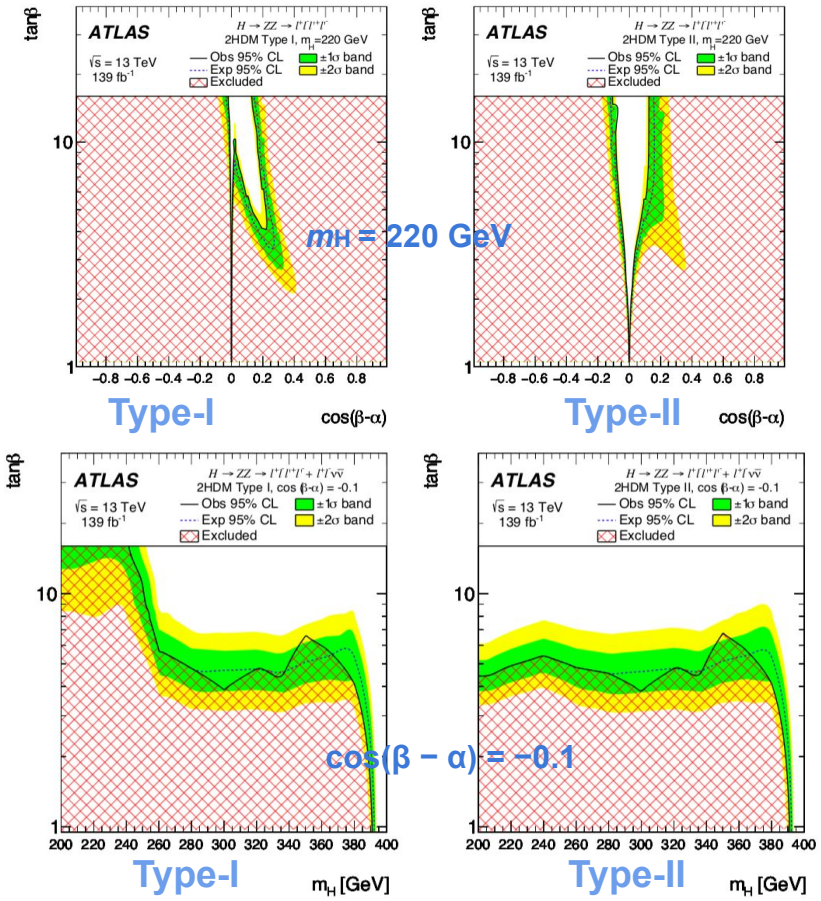


15%

Eur. Phys. J. C 81 (2021) 332

Combined Results

- No significant excess observed
- upper limits are set on Two-Higgs-doublet model
  - **Type-I**: Second Higgs doublet (Φ2) couples to all quarks and leptons.
  - **Type-II**: Φ1 couples to down-type quarks and leptons and Φ2 couples to up-type quarks.
  - **tan β**: the ratio of the vacuum expectation values of the two Higgs doublets.
  - **cos(β − α)** ~ the coupling of the heavier CP-even Higgs boson to vector bosons.



Conclusion

- Search for heavy Higgs-like resonances with ATLAS Run-2 data of 139 fb^{-1}
  - Several models studied:
    - Narrow-width spin-0 resonance.
    - Large-width spin-0 resonance with widths of 1, 5, 10, 15% of signal mass.
    - Type-I and Type-II 2HDM models on the assumption of NW signal.
- No evidence for BSM phenomena in the scalar sector.
  - Analyses managed to place exclusion limits on various BSM scenarios
- The mass range of the search has reached 3 TeV ($H \rightarrow \gamma\gamma$) and 2 TeV ($H \rightarrow ZZ$).
- Upper limits of production cross section of heavy resonances improved by up to 60% since previous paper.
- Expect higher sensitivities with Run-3 dataset and the beyond.

Thank you

Back up