Higgs Boson Property Measurements at the ATLAS Experiment

DISCRETE2024
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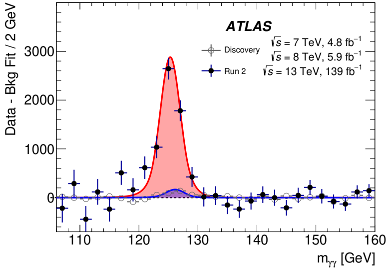
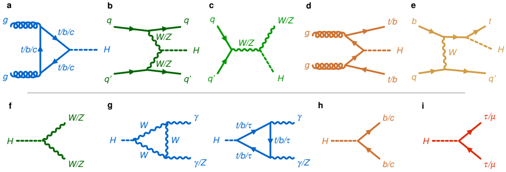
On behalf of the ATLAS collaboration

The Higgs Boson

Discovered over 10 years ago. The LHC experiments have accumulated 140 fb^{-1} in Run 2 ($\sqrt{s} = 13$ TeV p–p collisions) and recorded 180 fb^{-1} in Run 3 ($\sqrt{s} = 13.6$ TeV p–p)

Nature 607 52 (2022)





Search for and constrain physics beyond the standard model by making precise measurements of the fundamental properties of the Higgs boson:

- Measurements of single Higgs bosons:
  - mass, width, spin/CP
  - production cross sections
  - Coupling strengths to other particles
- Searches for multi-Higgs production
  - self-coupling
  - higher order couplings HHVV
- Searches for additional Higgs bosons
  - Motivated by models that solve SM's problems
  - Modify baryogenesis, provide DM candidate, solve strong CP problem, ...

Higgs Properties Highlights

Only time to cover a selection of results with a focus on the most recent preliminary and final ATLAS results

- Single Higgs boson measurements
  - Final result on VH production with $H \to b\bar{b}$ or $H \to c\bar{c}$ arXiv:2410.19611
  - Final result on $H \to \tau\tau$ arXiv:2407.16320
  - Preliminary off-shell measurement ATLAS-CONF-2024-016
- Search for additional Higgs bosons
  - Final result on search for $HHH \to 6b$ arXiv:2411.02040
- First results from early Run 3 measurements
  - $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ at $\sqrt{s} = 13.6$ TeV Eur. Phys. J. C 84 (2024) 78

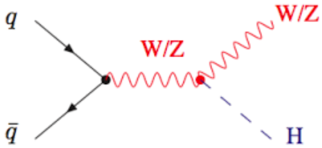
And slightly older results, which do not have time to cover here but, relevant to the conference

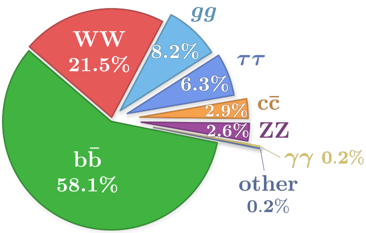
- Higgs boson production in association with a top-quark pair and $H \to bb$ arXiv:2407.10904
- $H(125)$ CP $H \to 4\ell$ JHEP05(2024)105
- Study of top-Higgs CP properties with ttH and tH events with $H \to bb$ decays Phys. Lett B 849 (2024) 138469

VH with $H \to b\bar{b}$ or $H \to c\bar{c}$

Overview

- VH has the third highest production cross section
- Decay to $b\bar{b}$ is important as it has highest BR
  - Strong effect on Higgs decay width, need precise knowledge for general interpretations
- Can easily tag VH ($V \to$ leptons).
- Ideal production mode to study $H \to q\bar{q}$



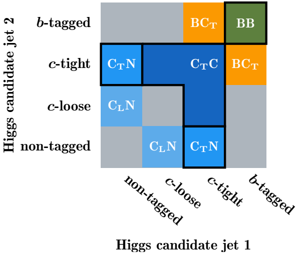


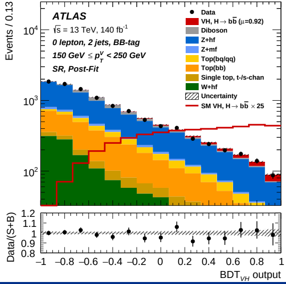
- H $\to c\bar{c}$ decay, like all other 2nd gen. fermions, not yet observed:
- Much lower branching ratio than $b\bar{b}$
- Difficult experimentally to identify c-initiated jets
- Large $Z + c$ background

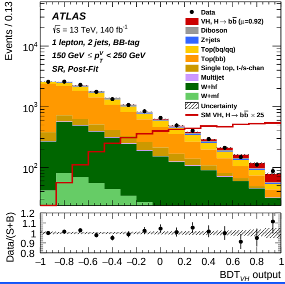
VH with $H \to b\bar{b}$ or $H \to c\bar{c}$

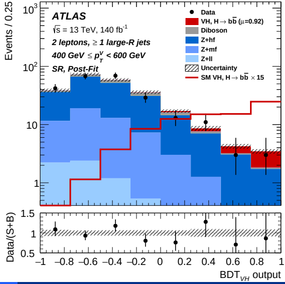
Analysis approach

- Analysis of Run 2 dataset arXiv:2410.19611, supercedes previous
- 2D jet flavour tagging setup to separate c and b jet
- To better control fake b/c -jet contributions, include mixed-tag regions
- Split events by number of charged leptons produced by decay: 0, 1 or 2
- BDT per lepton, p_T^V region (jets with R=0.4/1.0)





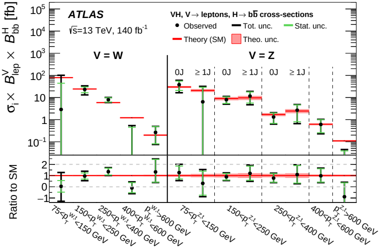


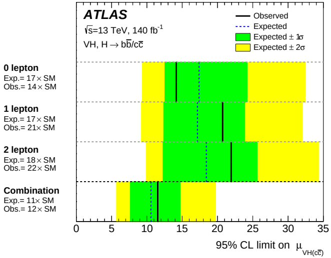


VH with $H \to b\bar{b}$ or $H \to c\bar{c}$

Selection of results

- Big improvements over results in previous analysis
- 23% (10%) better precision on total WH (ZH), $H \to b\bar{b}$ signal strength
- First 5σ observation of WH, $H \to b\bar{b}$ process
- Additional simplified template cross section (STXS) bins at lowest/highest p_T^V plus N_{jets}



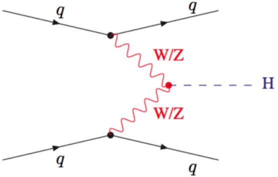


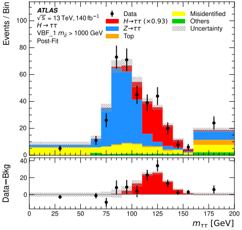
- Limit on $H \to c\bar{c}$ signal strength improved by a factor of 3 wrt first full Run 2 result
- Similar improvement on constraint of modified coupling strength κ_c

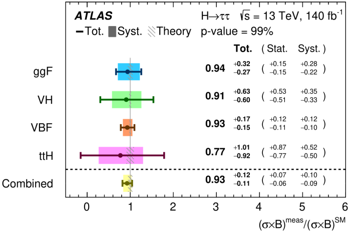
$H \to \tau\tau$ Measurement

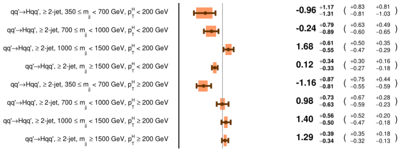
Overview

- Final Run 2 data arXiv:2407.16320, supercedes JHEP 08 (2022) 175
- $H \to \tau\tau$ decay has largest BR of all leptonic H decays
- Most significant decay mode for VBF STXS ($+\simeq 15\%$ wrt previous)
- Now VBF measurement in 8 kinematic regions including first for $p_T^H > 200$ GeV
- Analysis uses BDT e.g. to distinguish ggF from VBF



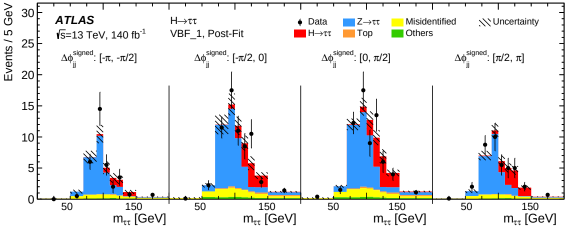


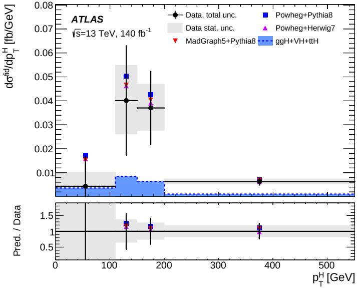




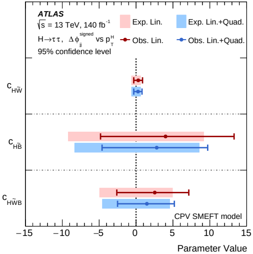
$H \to \tau\tau$ measurement

Cross section measurements

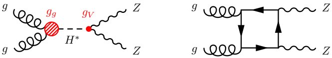




- Also measured unfolded differential fiducial cross sections in VBF enhanced regions
- Split events into four bins of e.g. $\Delta\phi_{jj}^{\text{signed}}$ or p_T^H, fit $m_{\tau\tau}$
- Overall good agreement with different generators
- Standard Model Effective Field Theory (SMEFT) interpretation based on differential cross section measurements
- Most stringent constraint to date on CP-odd dim-6 operator $H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$ ($c_{H\tilde{W}}$) from shape of $\Delta\phi_{jj}^{\text{signed}}$

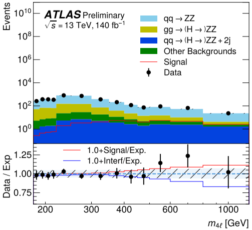


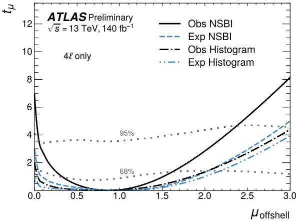
$H^* \to ZZ \to 4\ell$ measurement

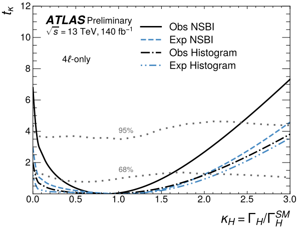


New measurement of the Higgs boson decay width

- Update of off-shell Higgs boson production analysis in 4ℓ final state: ATLAS-CONF-2024-016
- Off-shell large destructive interference between signal and background
- Event kinematics described by 14 variables from 4 leptons and any jets
- Using Neural Simulation-Based Inference (NSBI) method which uses unbinned nature to maximise statistical power of Run 2 dataset (+ 20%)
- Indirect measurement of Higgs boson decay width, assuming equal modifications to on-/off-shell couplings



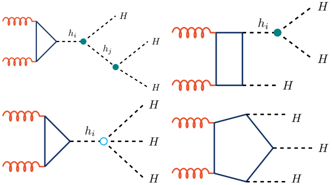


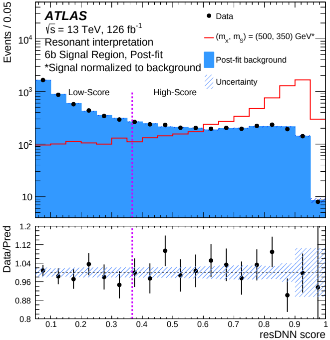


Search for $HHH \to 6b$

Triple Higgs boson production

- HHH production is sensitive to self-coupling modifiers $\kappa_3(\kappa_\lambda)$ and, uniquely, to κ_4
- But: $\frac{\sigma^{SM}_{HH}}{\sigma^{SM}_{HHH}} \simeq 400$, and HH is not yet observed either
- But BSM physics can still produce a signal within reach of LHC (e.g. "Two Real Scalar Model" TRSM)



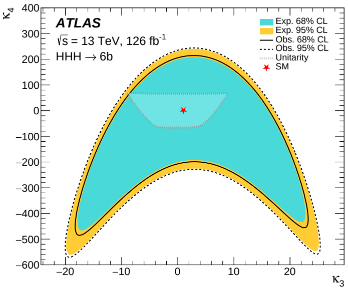


- First search for HHH at LHC, using $6b$ final state: arXiv:2411.02040
- Searching for events with 6 b-tagged jets, 3 pairs with $m_{jj} \simeq m_H$
- Consider following model scenarios:
  - SM-like HHH production ("non-resonant")
  - TRSM benchmark $h_i = X, h_j = S$ ("resonant")
  - Generic spin-0, ggF only, $m_X > m_S$ ("heavy resonant")
- Different Deep NNs trained to identify HHH events depending on signal hypothesis

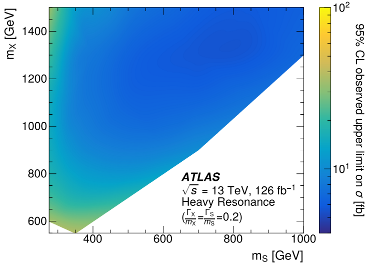
Search for $HHH \to 6b$

Results

- No excess over background found
- 95% CL upper limit on $\frac{\sigma_{HHH}}{\sigma^{SM}_{HHH}}$ is $\simeq 750$
- First direct limits set on limits set on κ_4



- Considered TRSM benchmark model for $X \to SH \to HHH$
- Set limits on large range of masses, up to $(m_X, m_S) = (1500, 1000)$ GeV
- Example, wide-width heavy resonance signals upper limits in range $6.3 - 39$ fb



$H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ at $\sqrt{s} = 13.6$ TeV

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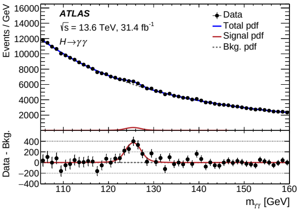
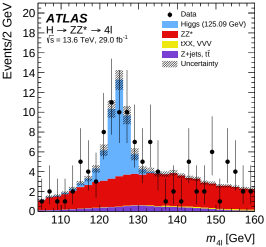
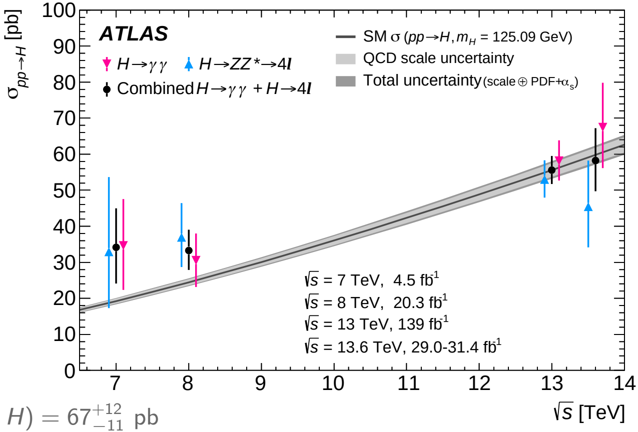
- The data from the first year of Run 3 (2022) has been analysed:
  - $31.4~\text{fb}^{-1}$ for the $H \rightarrow \gamma\gamma$ channel
  - $29.0~\text{fb}^{-1}$ for the $H \rightarrow ZZ \rightarrow 4\ell$ channel
- The expected peaks in the invariant mass spectra are clearly visible
- Cross sections are measured in the fiducial region and extrapolated to inclusive cross sections assuming SM BRs and acceptance, allowing combination
- Statistical uncertainties dominate both cross section measurements





$H \to ZZ^* \to 4\ell$ at $\sqrt{s} = 13.6$ TeV

The plot with Higgs boson cross sections as a function of collision energy has been updated to incorporate measurements at the new centre-of-mass energy



13.6 TeV:

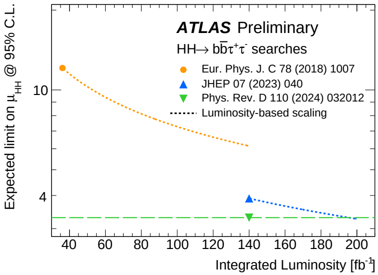
$H \to \gamma\gamma$: $\sigma(pp \to H) = 67^{+12}_{-11}$ pb

$H \to ZZ^* \to 4\ell$: $\sigma(pp \to H) = 46 \pm 12$ pb

Combined $\sigma(pp \to H) = 58.2 \pm 8.7$ pb, in agreement with SM $\sigma(pp \to H)_{\rm SM} = 59.9 \pm 2.6$ pb

Summary

- Presented a snapshot of ATLAS results on Higgs properties from precision measurements to searches
- Updates of Run 2 data analyses has led to significant improvements in precision
- First results from the Run 3 at a centre-of-mass energy of 13.6 TeV. The integrated luminosity of Run 3 exceeded that of Run 2 during this year's running (1.5 years to go)
- We continue to evolve the experimental and analysis techniques e.g. evolution of μ_{HH} limits in $HH \rightarrow bb\tau\tau$ as shown in recent High Luminosity LHC projection update
- Stay tuned for new ATLAS Higgs results along this exciting journey . . .



ATL-PHYS-PUB-2024-016

Backup

VH with $H \to b\bar{b}$ or $H \to c\bar{c}$

	Resolved VH, $H \to b\bar{b}, c\bar{c}$			Boosted VH, $H \to b\bar{b}$		
Variable	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
m_H	✓	✓	✓	✓	✓	✓
$m_{j_1 j_2 j_3}$	✓	✓	✓			
$p_T^{j_1}$	✓	✓	✓	✓	✓	✓
$p_T^{j_2}$	✓	✓	✓	✓	✓	✓
$p_T^{j_3}$				✓	✓	✓
$\sum p_T^{j_i}, i > 2$	✓	✓	✓			
$\text{bin}_{D_{\text{DL1r}}}(j_1)$	✓	✓	✓	✓	✓	✓
$\text{bin}_{D_{\text{DL1r}}}(j_2)$	✓	✓	✓	✓	✓	✓
p_T^V	$\equiv E_T^{\text{miss}}$	✓	✓	$\equiv E_T^{\text{miss}}$	✓	✓
E_T^{miss}	✓	✓		✓	✓	
$E_T^{\text{miss}}/\sqrt{S_T}$			✓			
$\lvert\Delta\phi(\boldsymbol{V}, \boldsymbol{H})\rvert$	✓	✓	✓	✓	✓	✓
$\lvert\Delta y(\boldsymbol{V}, \boldsymbol{H})\rvert$		✓	✓		✓	✓
$\Delta R(\boldsymbol{j_1}, \boldsymbol{j_2})$	✓	✓	✓	✓	✓	✓
$\min[\Delta R(\boldsymbol{j_i}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})], i > 2$	✓	✓				
N(track-jets in J)				✓	✓	✓
N(add. small-R jets)				✓	✓	✓
colour ring				✓	✓	✓
$\lvert\Delta\eta(\boldsymbol{j_1}, \boldsymbol{j_2})\rvert$	✓					
$H_T + E_T^{\text{miss}}$	✓					
m_T^W		✓				
m_{top}		✓				
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})]$		✓				
p_T^{ℓ}					✓	
$(p_T^{\ell} - E_T^{\text{miss}})/p_T^V$					✓	
$m_{\ell\ell}$			✓			
$\cos\theta^*(\boldsymbol{\ell}^-, \boldsymbol{V})$			✓			✓