Higgs differential cross-sections and CP Higgs couplings results with the ATLAS experiment

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The Higgs Boson!

- Characterised in multiple decay channels by the ATLAS and the CMS experiments.
- A major goal of Run 2 is to measure its properties and provide constraints on Beyond Standard Model effects to which Higgs boson’s production and decays are sensitive.
INTRODUCTION

Motivation

- **Differential Cross Section Measurements** -
  - Measured in the “fiducial” region: Limited phase space defined by the detector acceptance. Minimal physics assumption needed for extrapolation.
  - Minimal model dependence.
  - Shapes of different observable sensitive to different BSM phenomena which might not be apparent in the inclusive yield.

- **CP (Charge Parity) Measurements** -
  - SM Predicts a CP-even Higgs boson $\rightarrow$ CP-odd contribution out of purely BSM effects.
  - New source of CP violation could partly explain matter-antimatter asymmetry in the universe.
Differential XS Measurements

[1.] Define measurement phase space and “fit” observable. Extract signal yield in each bin.

Resonant Signal

Multivariate Approach

\[ \sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times C} \]

“Migration Matrix” accounts for detector effects. In-likelihood unfolding done for all diff XS results shown in this talk.

\[ \mu_s = \sum_j^N \text{fid. bins} \mathcal{L} \cdot A_{i,j} \cdot C_{i,j} \cdot \sigma_{\text{fid},j} + f_i \cdot \mathcal{L} \cdot \sigma_{\text{fid}} \]
Analysis Strategy

- Additional result based on resolved $VH(b\bar{b})$ [Eur. Phys. J. C 81 (2021) 178]
- $H \rightarrow b\bar{b}$ most probable decay (60%) for Higgs boson,
  - Difficult to isolate: very large multi-jet background,
  - Suppressed using the associated $V$ boson decay to leptons for triggering ($E_T^{miss}$ in this case).

- Targets the 0-lepton channel in $VH$ production channel.

- Uses the other channels to constrain background -
  - 2 lepton channel to constrain $Z +$ jets,
  - 1 lepton channel to constrain $W +$ jets and $t\bar{t}$.
  - CRs based on $\Delta R$ b/w b-jets to constrain $t\bar{t}$ and $V+$jets.

Fig: Post fit $m_{bb}$ in the 2 jets category with $E_T^{miss} \geq 250$ GeV
Results

- Cross section measurements agree with the standard model prediction.

- Hadronic jet measurement dominant experimental uncertainty in both bins, followed by flavour tagging.

- $t\bar{t}$ modelling dominates the background modelling uncertainty in the first bin, and $Z+\text{jets}$ in the second.
**Analysis Strategy**

- $H \rightarrow \gamma \gamma$ decay has a very small BR (~0.002),
  - High photon reconstruction efficiency in ATLAS,
  - Sharp resonant peak above the background.

- Distinct signal signature allows a very inclusive phase space (mostly ggF) sub-divided into more regions.

- Main bkg - (non resonant $\gamma$ and mis-ID jets) estimated from $m_{\gamma\gamma}$ sidebands.

- Background modelled analytically with functional parameters estimated from the fit. Choice between functions based on bias tests and goodness of fits.

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Massive and separated jets

BSM Sensitive

High jet multiplicity + leptons

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arXiv:2202.00487
Results

- 5 fiducial, 20 differential, and 4 double differential cross sections were measured, including di-photon and di-jet masses, momenta, angular separations, etc.

- Statistical uncertainty dominates followed by background modelling and photon reconstruction.

- Results consistent with SM prediction.
Strategy and Results

- The measurement can be improved by combining multiple channels.
- The combination uses similar fiducial phase space definitions as in individual measurements.
- Extrapolation from fiducial phase space to full phase space done using MC (inclusive acceptance factor ~50% for both channels).
- Higgs boson kinematic variables computed from the simulated Higgs boson instead of decay products in the total phase space.
- Measurements dominated by statistical uncertainties.
- Good agreement with SM.

- \( H \rightarrow ZZ^* \rightarrow 4\ell \) differential XS [arXiv:2004.03969]
- Yukawa couplings interpretation in Philipp Windischhofer’s talk [link].
Interpretation - Yukawa Couplings

- ggF production dominated by t-quark has negative but small interference from the b- and c-quark loops.
- $p_T^H$ spectrum is sensitive to Yukawa couplings of the Higgs boson to the b- and c-quarks.

Bishara et al [PRL 118, 121801]
Interpretation - Yukawa Couplings

- Two fits with increasing model dependency -
  - only shape of the spectrum considered,
  - Shape+norm along with the partial decay width considered.

- Direct search status -
  - $\kappa_b$ - 20% uncertainty at 68% CL,
  - $|\kappa_c| < 8.5$ at 95% CL.

- See Philipp’s talk for more details.
SM predicts a scalar Higgs boson, but the presence of a pseudoscalar admixture has not yet been excluded!

Two main ways CP violation in the Higgs boson sector manifests -

- CP-odd $V$ to $H$ BSM couplings: naturally suppressed by BSM scale,
- CP-odd fermion to $H$ BSM Yukawa couplings: possibly significant at tree level (in this talk!).

\[ \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} \]

Suppressed higher order terms

CP mixing angle \((SM : \alpha = 0^\circ)\)

Top Yukawa coupling parameter

\[ \mathcal{L} = -\frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha) \gamma_5 \right] \psi_t \right\} H \]

\[ \sigma \sim C_{P_{even}}^2 + C_{P_{odd}}^2 \]
**CP Measurement**

- Analysis targets $tH$ and $t\bar{t}H$ production modes.
- Tree level production: Less susceptible to assumptions embedded in loop-induced $t$-$H$ coupling.
- Attempts to reconstruct $t$ and $H$, used to build CP sensitive observables.
- Bkg dominated by $t\bar{t} + b\bar{b}$. Shape from MC, norm from data.
- $t\bar{t} + \geq 1b$ modelling uncertainty dominates with sub-leading experimental uncertainties.

\[
\mathcal{L} = -\frac{m_t}{\nu} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha)\gamma_5 \right] \psi_t \right\} H
\]

- Best fit $\alpha = 11^\circ +55^\circ_{-77}^{+55}$ and $\kappa_t = 0.83^{+0.30}_{-0.46}$.
- $\alpha = 90^\circ$ excluded at 1.2$\sigma$.
- Systematic uncertainties dominate.

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CP Measurement

- Analysis targets $tH$ and $t\bar{t}H$ production modes.
- The CP-odd contribution introduces a second coupling to the top quark, which modifies the $H \to \gamma\gamma$ decay rate.

"Lep" region
- Targets leptonic final state
- $\geq 1$ isolated lepton

"Had" region
- Targets hadronic final state
- $\geq 2$ additional jets and no leptons

- Without prior constraints on $\kappa_t''$,
  $|\alpha| > 43^\circ (63^\circ \text{expected})$ is excluded at 95% CL.
- $\alpha = 90^\circ$ excluded at $3.9\sigma$.
- Systematic uncertainties negligible.

\[
\mathcal{L} = -\frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left( \cos(\alpha) + i \sin(\alpha) \gamma_5 \right) \psi_t \right\} H
\]
Analysis Strategy

- $H \rightarrow WW^*$ has a high BR (0.2) but difficult to isolate signal. Measurement sensitive to $V-H$ interaction and EWSB structure.

- Analysis targets ggF production mode.

- The CP-odd contribution to the top coupling also affects the $ggH$ effective coupling.

- Interference between CP-even and CP-odd contributions affect the shape of the $\Delta \Phi_{jj}$ distribution.
Results

- Three different fits are performed -
  - 1. Only $\tan(\alpha)$ is scanned -
    - 1A. Only shape effects are considered,
    - 1B. Shape+normalization effects are considered,
    \[ \tan(\alpha) = 0.0 \pm 0.4\text{(stat.)} \pm 0.3\text{(sys.)} \]
  - 2. Simultaneous fit of $\kappa_g \cos(\alpha)$ and $\kappa_g \sin(\alpha)$ using both shape and normalisation effects.

- Measurement of $\tan(\alpha)$ is dominated by statistical uncertainty in the SR followed by b-tagging and signal modelling.

- Results consistent with SM prediction.
Conclusion and Outlook

- Presented 6 exciting measurements done with the ATLAS Experiment using Run 2 LHC data.
- Most results limited by statistical uncertainty, so Run 3 presents a promising opportunity to improve on current limits!
- All results currently compatible with the standard model but scope for improving the precision.
- 10 years after the Higgs boson discovery, we have made significant progress in understanding its characteristics, and there’s more to come!
INTRODUCTION

Results shown in this talk


- CP Properties of Higgs Boson Interactions with Top Quarks in the $t\bar{t}H$ and $tH$ Processes using $H \to \gamma\gamma$ with the ATLAS detector. [Phys. Rev. Lett. 125, 061802 (2020)]

- Combined measurement of the total and differential cross sections in the $H \to \gamma\gamma$ and the $H \to ZZ^* \to 4\ell$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS detector. [ATLAS-CONF-2022-002]

- Constraints on Higgs boson properties using $WW^*(\to e\nu\mu\nu)jj$ production in 36.1 fb$^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector. [arXiv:2109.13808 – submitted to Eur. Phys. J. C]

- Probing the CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ and $tH$ events with $H \to bb$ using the ATLAS detector at the LHC [ATLAS-CONF-2022-016]
Analysis Strategy

- Particle level categories -
  - $T_i$ - Pass particle selection in bin $i$ of $E_{T}^{\text{miss}}$.
  - $O_i$ - Off fiducial but in bin $i$ of $E_{T}^{\text{miss}}$.

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Signal and Background Modelling

- Signal Modelling - Double sided Crystal Ball function. Gaussian peak with exponential tails due to photon to electron conversions with electrons losing energy from Bremsstrahlung.

- Background Modelling - Main bkg are $\gamma\gamma$, $\gamma j$, and $jj$ with jets mis-ID as leptons. Templates estimated from CRs by inverting isolation requirements on jets. Several functions considered - polynomials, power law, Bernstein polynomials.
Interpretation - SMEFT

- $\Delta \Phi_j$, observable is sensitive to CP-odd coefficients when only interference terms are considered.

Affect ggF

Affect VBF+VH
Introduction

- $ZZ^*$ decay has a very small BR (~0.03), yet $4\ell$ final state very clean due to high S/B.
- Non resonant $ZZ^*$ constitutes the major bkg.
- Bkg normalisation estimated from $m_{4\ell}$ sidebands for the first time.

![Higgs decay distribution](image)

Results

- 5 inclusive, 20 differential, and 8 double differential cross sections measured, including di-lepton and di-jet masses, momenta, angular separations, etc.

- Statistical uncertainty dominates followed by background modelling and lepton measurements.

- Results consistent with SM prediction.

\[ H \rightarrow ZZ^* \rightarrow 4\ell \]

\[ H \rightarrow ZZ^* \rightarrow 4\ell \]

Different Z decay combinations

Combined measurement

CP Measurement

\[ \mathcal{L} = - \frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha) \gamma_5 \right] \psi_t \right\} H \]

\[ b_2 = \frac{\left( \vec{p}_1 \times \hat{n} \right) \cdot \left( \vec{p}_2 \times \hat{n} \right)}{\left| \vec{p}_1 \right| \left| \vec{p}_2 \right|} \]

\[ b_4 = \frac{\vec{p}_1 \cdot \vec{p}_2}{\left| \vec{p}_1 \right| \left| \vec{p}_2 \right|} \]

"Lep" region
- Targets leptonic final state
- \( \geq 1 \) isolated lepton
$tH$ & $t\bar{t}H$ ($H \rightarrow \gamma\gamma$)

### CP Measurement

$$\mathcal{L} = -\frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha) \gamma_5 \right] \psi_t \right\} H$$

- **CP mixing angle**
- **top Yukawa coupling parameter**

![Diagram with Feynman diagrams showing $tH$ and $t\bar{t}H$ interactions](image)

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**ATLAS**

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- Fraction of Events
- Hadronic Bkg. Rej. Discriminant
- Hadronic CP Discriminant

**ATLAS**

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- Sum of Weights [2.5 GeV]
- Sum of Weights [10 GeV]
- Reconstructed Primary Top Quark Mass [GeV]
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**Analysis Strategy**

\[
\mathcal{L} = -\frac{g_{Hgg}}{4} (\kappa_{gg} \cos(\alpha) G^{\alpha}_{\mu \nu} G^{a,\mu \nu} + \kappa_{gg} \sin(\alpha) G_{\mu \nu} \tilde{G}^{a,\mu \nu}) H
\]

**Effective Higgs gluon coupling parameter**

**CP mixing angle**

**WW* (\rightarrow e\nu\mu\nu)jj**

\[\text{\textbf{ATLAS}}\]
\[\sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1}\]

\[H \rightarrow WW^* \rightarrow e\nu\mu\nu\]

\[\text{ggF + 2 jets SR}\]

\[\text{Data / pred.}\]

\[\Delta \Phi_{jj}\]