Measurement of Higgs boson Differential and Fiducial Cross Sections with the ATLAS Detector

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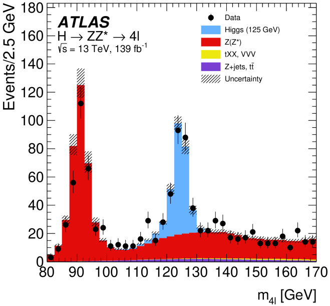
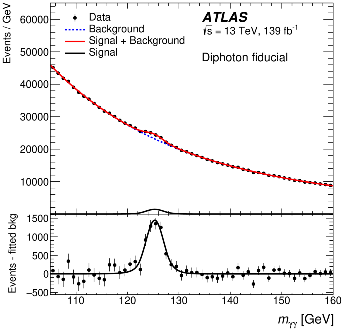
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Probing the Standard Model with Higgs Boson Events

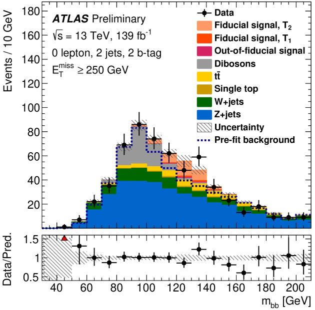
1. Common Higgs production and **complex 4-body decay**
$H \to ZZ^* \to 4\ell$ ▸ EPJC 80 (2020) 942



2. Expand to **less common production** processes
$H \to \gamma\gamma$ ▸ arXiv:2202.00487



4. Rare *ZH* or *WH* processes with $E_T^{miss} > 150$ GeV
$H \to bb$ ▸ ATLAS-CONF-2022-015



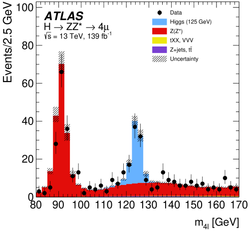
3. $H \to ZZ$ plus $H \to \gamma\gamma$ **combination** ▸ ATLAS-CONF-2022-002

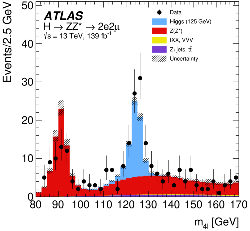
Full Run 2 dataset utilized for all these measurements

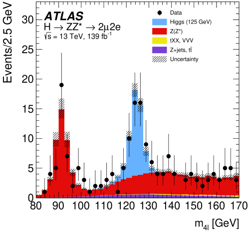
STXS at ATLAS ▸ Carolyn Gee's talk

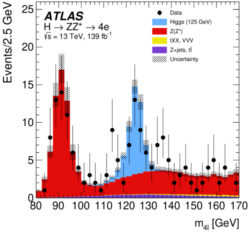
$H \to ZZ^* \to 4\ell$ Fiducial ▸ EPJC 80 (2020) 942

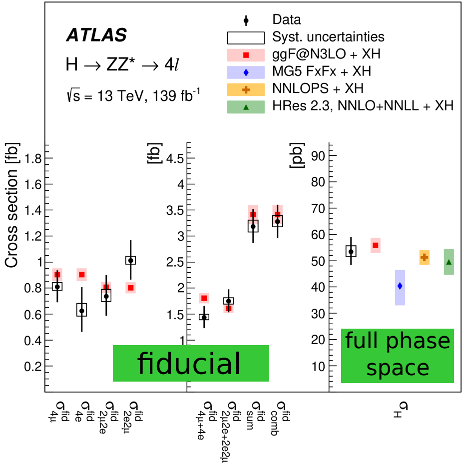
- Select $\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp}$ (with $\ell, \ell' = e, \mu$) **as inclusive as feasible** $\to$ cuts in backup
- **Binned fit of $m_{4\ell}$** in 105–160 GeV window per final state
- **Main backgrounds normalized from data** (ZZ^* continuum; reducible i.e. Z+jets, $t\bar{t}$)











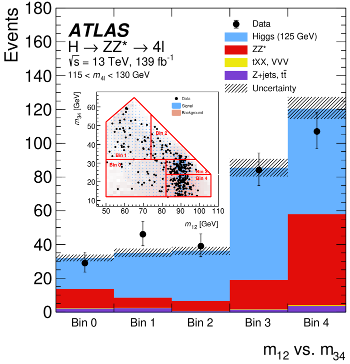
$H \to 4\ell$ Differential

EPJC 80 (2020) 942

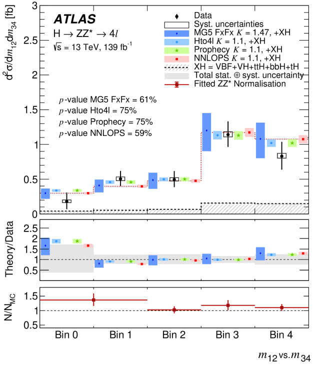
- Fit $m_{4\ell}$ per differential (1D or 2D) bin. **In-likelihood unfolding**, i.e. correction for detector effects via the detector response matrix is embedded in likelihood fit
- **No regularization**, bias would counterbalance reduction of fluctuations

m_Z vs. m_{Z^*}

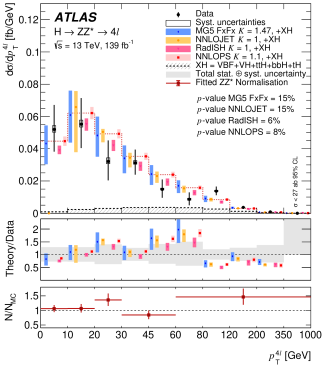
Data and pre-fit expected



Unfolded



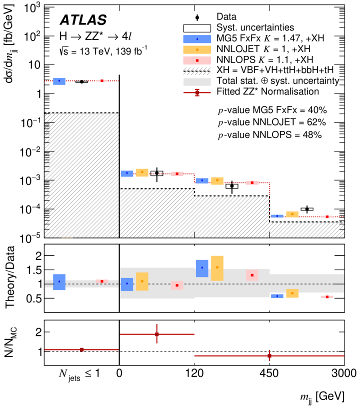
Higgs p_T unfolded



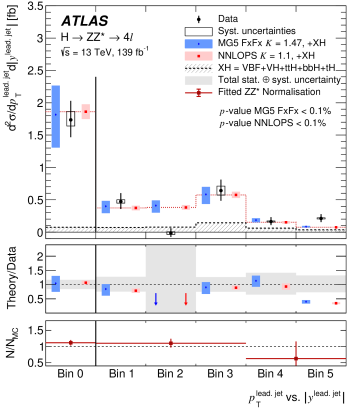
$H \to 4\ell$ Differential

▸ further distributions in EPJC 80 (2020) 942

Di-jet mass spectrum



p_T vs $|y|$ for leading jet



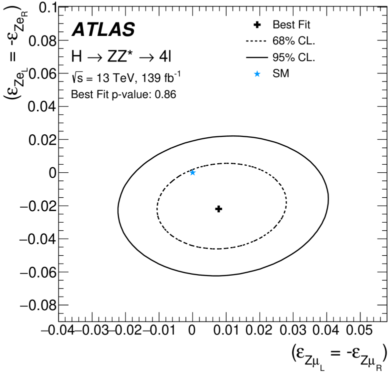
- Production modes are combined. However, e.g. VBF enhanced for large m_{jj}
- Some features (largest on right) but overall data are consistent with Standard Model

Interpretation of $H \to 4\ell$ Differential

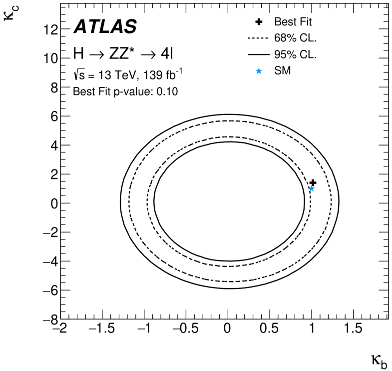
▸ EPJC 80 (2020) 942

- Probe 4 scenarios with **BSM contact interactions** from ▸ JHEP 10 (2018) 073 via m_Z vs. m_{Z^*}
- Constrain **Yukawa couplings** to *b*- and *c*-quarks via Higgs p_T

Limits for BSM flavour non-universal axial-vector contact terms



Utilize changes of Higgs p_T differential cross section and branching ratios



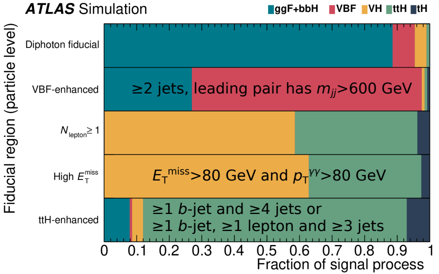
$H \to 4\ell$ results limited by data stat. or data-limited syst. (background normalization/closure)

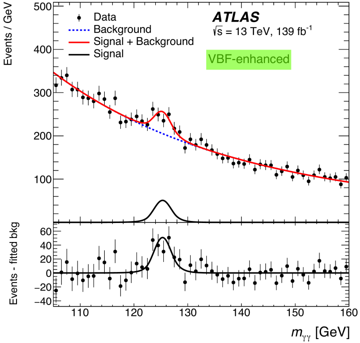
$H \to \gamma\gamma$ Fiducial

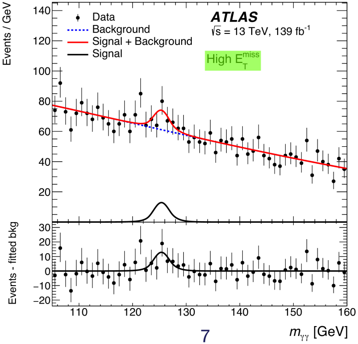
arXiv:2202.00487

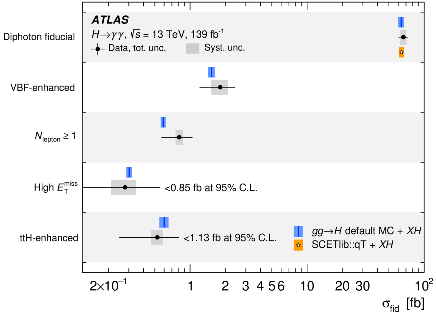
- Select γ**-pairs within precision region of EM calo** with $E_T^{\gamma\ \text{lead}}/m_{\gamma\gamma} > 0.35$ and $E_T^{\gamma\ \text{sublead}}/m_{\gamma\gamma} > 0.25$
- **Sub-regions** enhanced in VBF, VH, or top+H
- **Unbinned** $m_{\gamma\gamma}$ **fit** within 105–160 GeV per region

Incl. diphoton: stat $\simeq$ syst (largest: spurious signal, E^γ resolution)







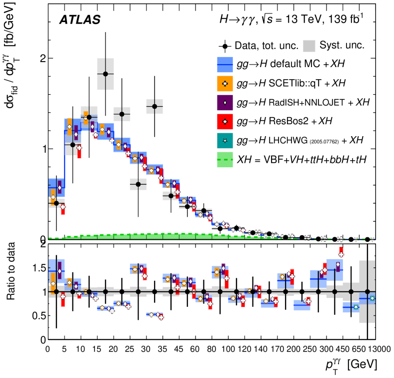


$H \to \gamma\gamma$ Differential arXiv:2202.00487

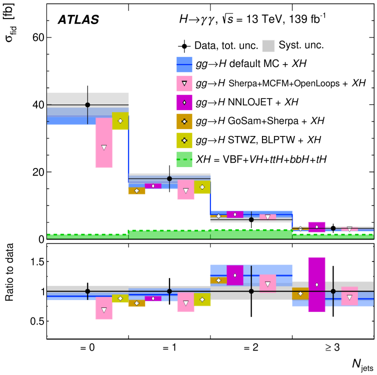
- Measure differentially for **inclusive diphoton** and **VBF fiducial regions**
- Fit $m_{\gamma\gamma}$ per bin with in-likelihood unfolding and without regularization

Observed spectra are limited by stat. uncertainties and consistent with predictions

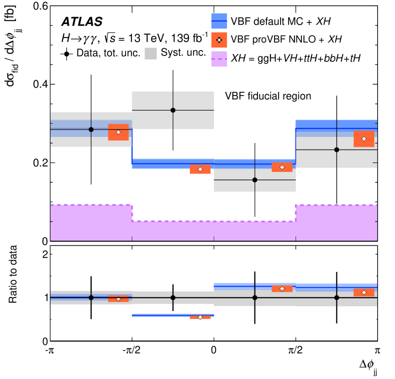
Higgs p_T



Jet multiplicity



Signed $\Delta\phi_{jj}$ for VBF fiducial region



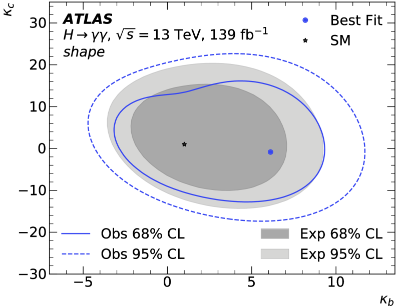
Interpretation of $H \to \gamma\gamma$ Differential

arXiv:2202.00487

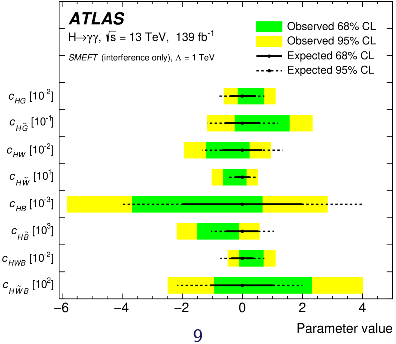
- Constrain **Yukawa couplings** to *b*- and *c*-quarks via Higgs p_T
- Constrain **SMEFT** dimension-6 **operators** in Warsaw basis
  - measure one Wilson coefficient at a time setting all others to 0
  - employ simultaneous fit of p_T^H, N_{jets}, m_{jj}, $\Delta\phi_{jj}$, $p_T^{j_1}$ distributions
  - strong limits for CP-even operators, loose limits for some CP-odd. *Mind* 10^X *scaling in plots*

Results agree with Standard Model predictions

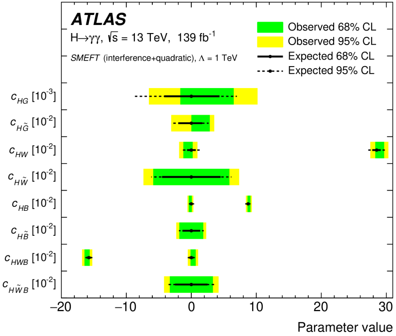
use change of Higgs p_T shape only



use c_i/Λ^2 terms only



use c_i/Λ^2 and c_i^2/Λ^4 terms

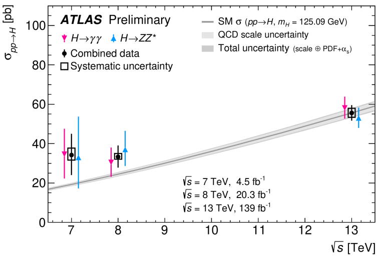


Combination of $H \to \gamma\gamma$ and $H \to 4\ell$ ▸ ATLAS-CONF-2022-002

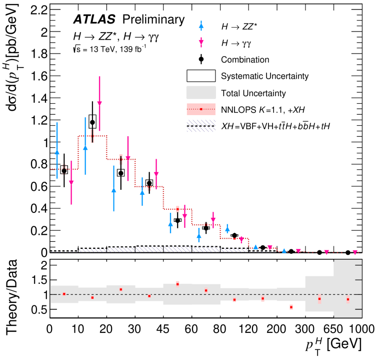
- Measure p_T^H, y^H, N_j, $p_T^{j_1}$ spectra after extrapolating individual results to **full phase space**. Extrapolate assuming SM considering theory syst. Acceptance $\sim$50% for both channels
- $\sim$20 – 40% more accurate than individually despite larger extrapolation uncertainties

Results agree with Standard Model predictions and are primarily stat limited

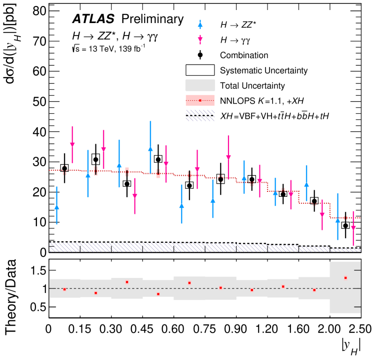
Total Higgs cross section



Higgs p_T

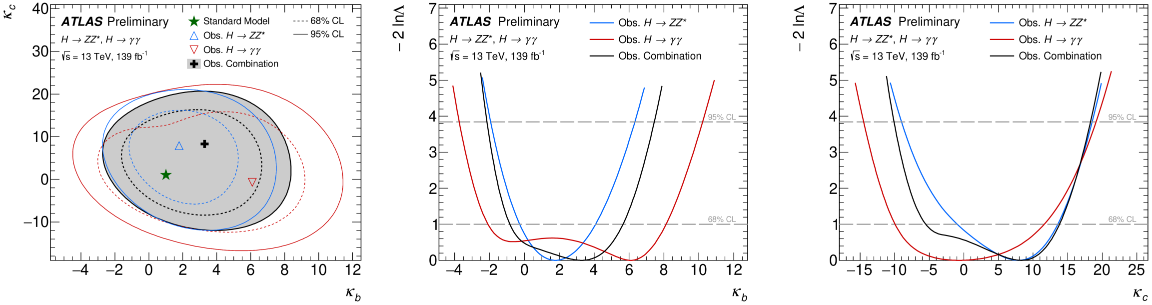


Higgs rapidity



Combination of $H \to \gamma\gamma$ and $H \to 4\ell$ ATLAS-CONF-2022-002

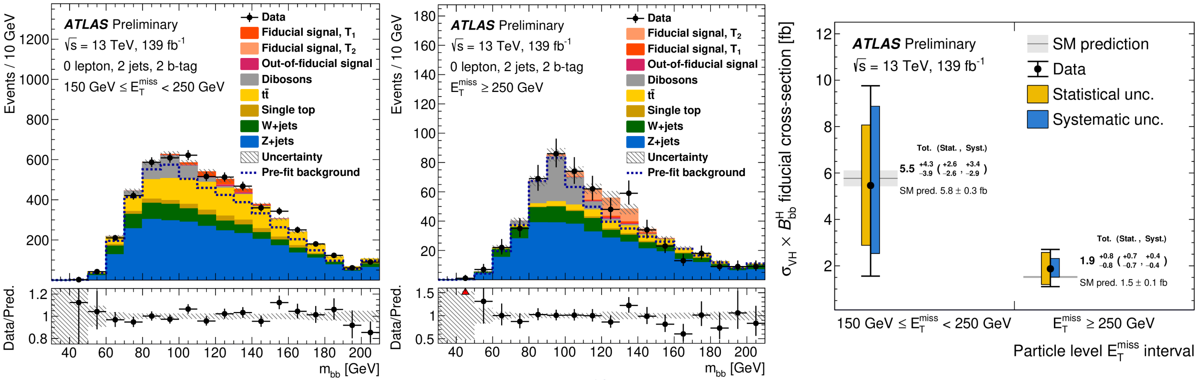
- Constrain b- and c-**Yukawa couplings** via p_T^H using the shape of the distribution only
- Observed constraints are looser for combination than $H \to 4\ell$
  - Reason: quadratic dependency of differential cross-section creates double local minimum for $H \to \gamma\gamma$



Measurement of $H \to bb$ with large E_T^{miss}

ATLAS-CONF-2022-015

- Measure ZH and WH in fiducial regions with $150 \leq E_T^{miss} < 250$ GeV and $E_T^{miss} \geq 250$ GeV
- Based on resolved $VH(bb)$ analysis EPJC 81 (2021) 178 SR is 0ℓ channel, $1/2\ell$ channels used as CRs to normalize Z+HF, W+HF and ttbar
- Fit m_{bb} with in-likelihood unfolding. Have separate reco-level SRs and CRs for 2/3 jets
- Largest systematics: background theory, hadronic jets measurements, out-of-fiducial signal



Conclusions

- Fiducial and differential Higgs measurements reach up to $\mathcal{O}(10\%)$ precision and reach to sparsely populated regions of phase space
- Powerful tests of Standard Model and constraints for BSM physics (EFT, κ_b and κ_c, contact interactions)
- Measurements are generally stat limited, can expect large improvements with Run 3 data. Stay tuned!

Backup: Selection for $H \to ZZ^* \to 4\ell$

Detector-level selection

Leptons and jets	
Muons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Electrons	$E_T > 7$ GeV, $\|\eta\| < 2.47$
Jets	$p_T > 30$ GeV, $\|\eta\| < 4.5$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and $m_{\text{threshold}} < m_{34} <$ 115 GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\mu_i(e_i), \text{jet}) > 0.1(0.2)$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$\|d_0\|/\sigma(d_0)$ ¡ 5 (3) for electrons (muons)
Mass window	105 $GeV < m_{4\ell} <$ 160 GeV
Vertex selection:	χ^2/N_{dof} ¡ 6 (9) for 4μ (other channels)
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element (ME) value

Fiducial region

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_T > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

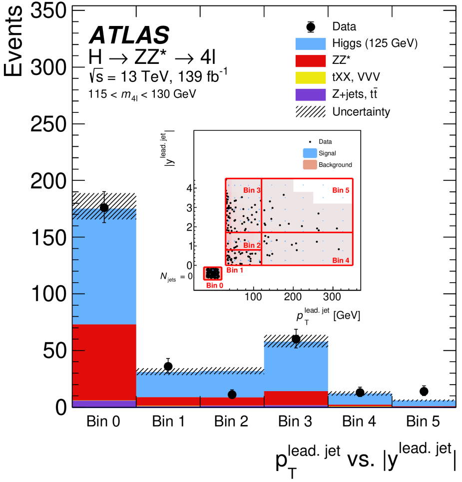
- 49% of $H \to 4\ell$ events lie in fiducial region
- 45% of events in fiducial region pass detector-level selection
- 1.6% of events passing detector-level selection lie outside fiducial region

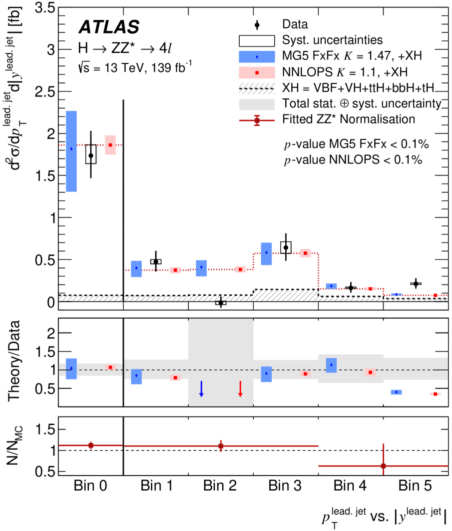
Backup: Differential Observables in $H \to 4\ell$ Analysis

Higgs boson kinematic-related variables	
$p_T^{4\ell}$, $\lvert y_{4\ell}\rvert$	Transverse momentum and rapidity of the four-lepton system
m_{12}, m_{34}	Invariant mass of the leading and subleading lepton pair
$\lvert\cos\theta^*\rvert$	Magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame relative to the beam axis
$\cos\theta_1$, $\cos\theta_2$	Production angles of the anti-leptons from the two Z bosons, where the angle is relative to the Z vector.
ϕ, ϕ_1	Two azimuthal angles between the three planes constructed from the Z bosons and leptons in the Higgs boson rest frame.
Jet-related variables	
N_{jets}, $N_{b\text{-jets}}$	Jet and b-jet multiplicity
$p_T^{\text{lead. jet}}$, $p_T^{\text{sublead. jet}}$	Transverse momentum of the leading and subleading jet, for events with at least one and two jets, respectively. Here, the leading jet refers to the jet with the highest p_T in the event, while subleading refers to the jet with the second-highest p_T.
m_{jj}, $\lvert\Delta\eta_{jj}\rvert$, $\Delta\phi_{jj}$	Invariant mass, difference in pseudorapidity, and signed difference in ϕ of the leading and subleading jets for events with at least two jets
Higgs boson and jet-related variables	
$p_T^{4\ell\text{j}}$, $m_{4\ell j}$	Transverse momentum and invariant mass of the four-lepton system and leading jet, for events with at least one jet
$p_T^{4\ell\text{jj}}$, $m_{4\ell jj}$	Transverse momentum and invariant mass of the four-lepton system and leading and subleading jets, for events with at least two jets

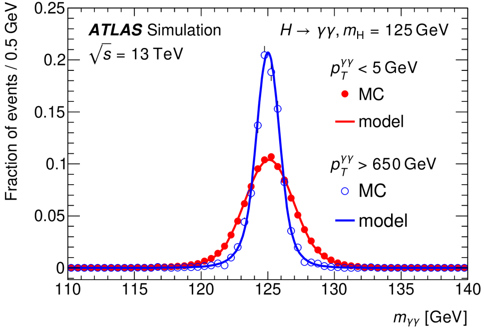
Additionally 2D measurements for various combinations of these

Backup: Closer Look at Observable with Feature for $H \to 4\ell$





Backup: Signal and Background Models for $H \to \gamma\gamma$



Signal:

- Fit double-sided Crystal Ball to MC for each category or differential bin
- MC has $m_H = 125.00$ GeV instead of $m_H = 125.09$ GeV, so shift Gaussian mean by 90 MeV

Background:

- Alter photon ID/iso to measure $\gamma\gamma$, γj, and jj fractions per category. It is 66–92% for $\gamma\gamma$
- Parametrise $\gamma\gamma$ from MC and γj from data with looser photon ID. Use γj template for jj
- Select function based on goodness of fit and spurious signal tests. Mitigate fluctuations via gaussian process regression for spurious signal tests

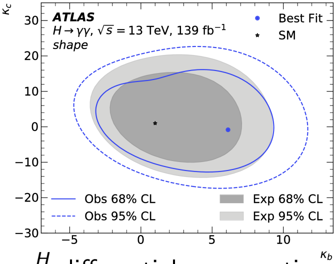
Backup: Differential Variables and Binning for $H \to \gamma\gamma$

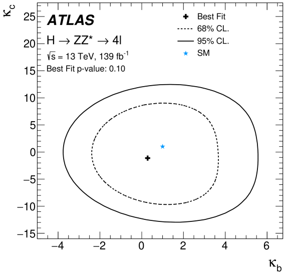
Variable	Bin Edges	N_{bins}
$p_{\text{T}}^{\gamma\gamma}$	0, 5, 10, 15, 20, 25, 30, 35, 45, 60, 80, 100, 120, 140, 170, 200, 250, 300, 450, 650, 13000	20
$\|y_{\gamma\gamma}\|$	0, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.2, 1.6, 2.0, 2.5	10
$p_{\text{T}}^{\gamma 1}/m_{\gamma\gamma}$	0.35, 0.45, 0.5, 0.55, 0.6, 0.65, 0.75, 0.85, 0.95, 10	9
$p_{\text{T}}^{\gamma 2}/m_{\gamma\gamma}$	0.25, 0.35, 0.4, 0.45, 0.5, 0.55, 0.65, 0.75, 0.85, 10	9
N_{jets}	0, 1, 2, $\geq$3	4
$N_{b\text{-jets}}$	$N_{\text{jets}}^{\text{central}} = 0$ or $N_{\text{lep}} > 0$, $N_{b\text{-jets}} = 0, \geq 1$	3
$p_{\text{T}}^{j_1}$	30, 60, 90, 120, 350, 13000	5
H_{T}	30, 60, 140, 200, 500, 13000	5
$p_{\text{T}}^{\gamma\gamma j}$	0, 30, 60, 120, 13000	4
$m_{\gamma\gamma j}$	120, 220, 300, 400, 600, 900, 13000	6
$\tau_{C,j1}$	0, 5, 15, 25, 40, 13000	5
$\sum \tau_{C,j}$	5, 15, 25, 40, 80, 13000	5
$p_{\text{T}}^{\gamma\gamma,\text{ jet veto 30 GeV}}$	0, 5, 10, 15, 20, 30, 40, 50, 100, 13000	9
$p_{\text{T}}^{\gamma\gamma,\text{ jet veto 40 GeV}}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 100, 13000	10
$p_{\text{T}}^{\gamma\gamma,\text{ jet veto 50 GeV}}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 100, 13000	11
$p_{\text{T}}^{\gamma\gamma,\text{ jet veto 60 GeV}}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 13000	12
m_{jj}	0, 120, 450, 3000, 13000	4
$\Delta\phi_{jj}$	$-\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi$	4
$\pi - \|\Delta\phi_{\gamma\gamma,jj}\|$	0, 0.15, 0.65, π	3
$p_{\text{T},\gamma\gamma jj}$	0, 30, 60, 120, 13000	4
VBF-enhanced: $p_{\text{T}}^{j_1}$	30, 120, 13000	2
VBF-enhanced: $\Delta\phi_{jj}$	$-\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi$	4
VBF-enhanced: $\|\eta^*\|$	0, 1, 2, 10	3
VBF-enhanced: $p_{\text{T},\gamma\gamma jj}$	0, 30, 13000	2

Additionally 2D measurements for various combinations of these

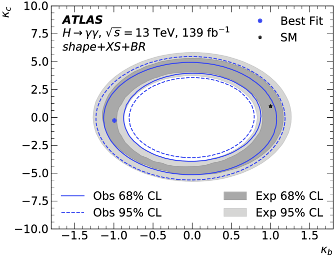
Comparison of $H \to 4\ell$ and $H \to \gamma\gamma$ limits for κ_b and κ_c

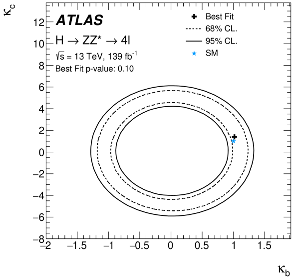
Only use change of Higgs p_T shape



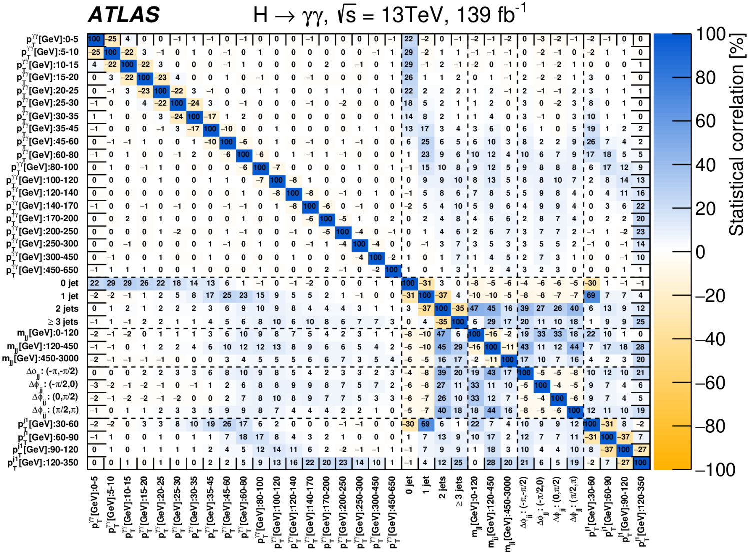


Consider p_T^H differential cross section and branching ratios



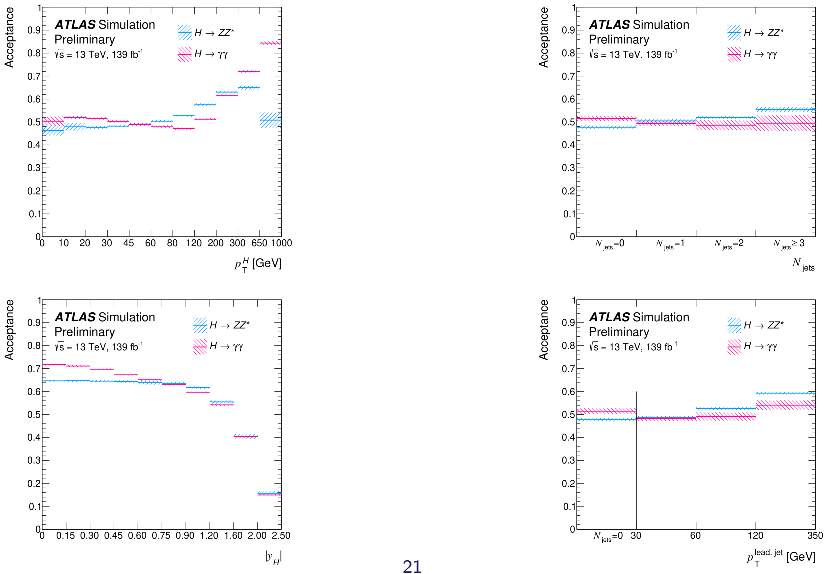


Backup: Bin Correlations for $H \to \gamma\gamma$ EFT Measurement (Bootstrapping)

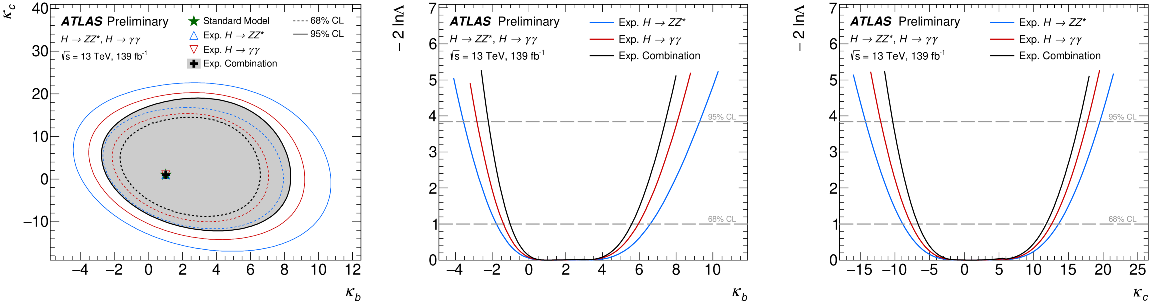


Acceptance wrt full phase space $H \to \gamma\gamma$ and $H \to 4\ell$

ATLAS-CONF-2022-002



Expected κ_b vs. κ_c limits for $H \to \gamma\gamma$ and $H \to 4\ell$ ATLAS-CONF-2022-002

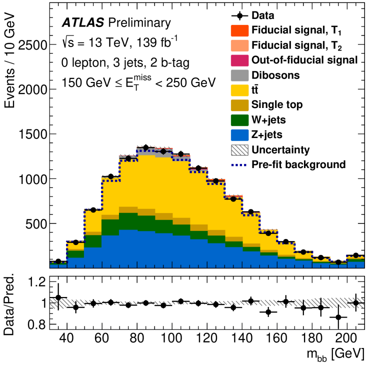


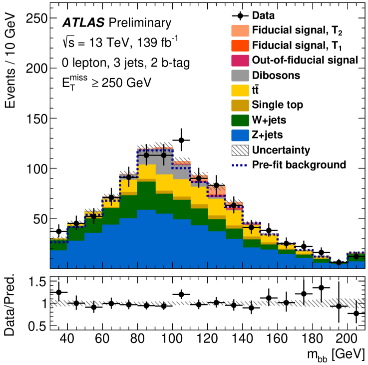
Here the combination outperforms both channels as is to be assumed

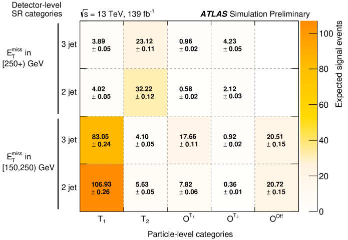
Backup: Selection for $H \to bb$ with large E_T^{miss}

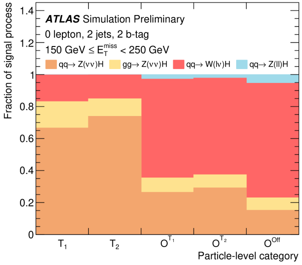
Selection	Detector-level	Particle-level
Leptons	No electrons or muons $p_T > 7$ GeV Electrons: $\lvert\eta\rvert < 2.47$, LooseLH, $\lvert d_0/\sigma_{d_0}\rvert < 5$, $\lvert z_0 \sin\theta\rvert < 0.5$ mm Muons: $\lvert\eta\rvert < 2.7$, Loose, $\lvert d_0/\sigma_{d_0}\rvert < 3$, $\lvert z_0 \sin\theta\rvert < 0.5$ mm Loose track-isolation	No electrons or muons $p_T > 7$ GeV Electrons: $\lvert\eta\rvert < 2.47$ Muons: $\lvert\eta\rvert < 2.7$
Hadronic τ	$p_T > 20$ GeV $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$ Medium	τ-labelled central jets
Anti-k_t $R = 0.4$ Jets	From topological clusters ≥ 2 central jets Central: $p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$ Forward: $p_T > 30$ GeV, $2.5 < \lvert\eta\rvert < 4.5$	From collider-stable particles ≥ 2 central jets Central: $p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$ Forward: $p_T > 30$ GeV, $2.5 < \lvert\eta\rvert < 4.5$
b-jets	2 b-tagged central jets, MV2 (70% efficiency) At least one b-jet with $p_T > 45$ GeV	2 b-labelled central jets At least one b-labelled jet with $p_T > 45$ GeV
Jet categories	Two, with exactly 2 and 3 jets	One, with 2 or 3 jets
Overlap removal	Between e, μ, τ and jets	Remove e/μ within $\Delta R = 0.4$ of a jet, remove τ-labelled jets
E_T^{miss}	Negative vectorial sum of p_T of jets, leptons, taus and photons plus a track-based soft term > 150 GeV	Negative vectorial sum of p_T of all stable interacting particles with $\lvert\eta\rvert < 5$, including muons with $p_T > 6$ GeV > 150 GeV
H_T	> 120 GeV (2 jets), > 150 GeV (3 jets)	> 120 GeV (2 jets), > 150 GeV (3 jets)
$\min \Delta\phi(\vec{E}_T^{miss}, \vec{j})$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)
$\Delta\phi(\vec{E}_T^{miss}, \vec{b}_1 + \vec{b}_2)$	$> 120^\circ$	$> 120^\circ$
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	$< 140^\circ$
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< 90^\circ$	–
E_T^{miss} regions	$150\ \text{GeV} \leq E_T^{miss} < 250$ GeV $E_T^{miss} \geq 250$ GeV	$150\ \text{GeV} \leq E_T^{miss} < 250$ GeV $E_T^{miss} \geq 250$ GeV

Backup: Additional SRs and Signal Composition for $V + (H \to bb)$









- $T_{1/2}$: fiducial signal with true E_T^{miss} 150–250/$\geq$ 250 GeV
- $O^{off}/T^{1/2}$: non-fiducial with $E_T^{miss} < 150$ GeV/150–250/$\geq$ 250 GeV