Higgs Hunting '19

Measurement of $H \to \gamma\gamma$ Differential Cross Sections and Charm Yukawa Coupling Interpretation with ATLAS

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on behalf of the ATLAS collaboration

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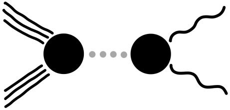
Introduction



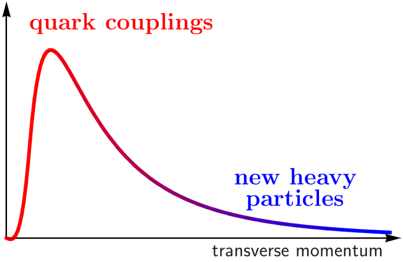
- Big picture: Study Higgs boson properties – match SM predictions?
- A way to do this:

  Measure Higgs production cross section in fiducial volume
  - inclusively
  - differentially
- $H \to \gamma\gamma$ well suited decay channel for this:
  - Good mass resolution $\to$ Robust subtraction of background
  - Good final state selection efficiency
  - But: Rather small S/B
- Note ATLAS-CONF-2019-029: `http://cdsweb.cern.ch/record/2682800`

Motivation

What are differential cross sections sensitive to?

- Focus: p_{T}^{H}:
  - QCD calcluation, especially for $gg \to H$
  - Low p_{T}^{H}: Yukawa couplings to lighter quarks such as b, c
  - High p_{T}^{H}: Couplings to heavy NP particles, m_t treatment
- y^{H}, p_{T}^{j1}, $\Delta\phi_{jj}$, m_{jj}, N_j: PDF, Spin and CP property of Higgs, production mode contributions, ...

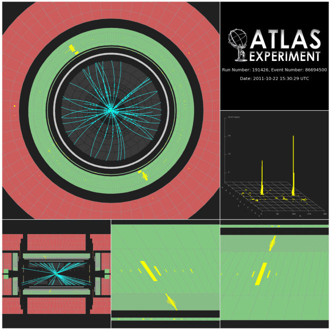


Fiducial Selection

- Detector has limited acceptance and $H \to \gamma\gamma$ events have certain kinematic features $\to$ Design selection criteria accordingly.
- To require minimal extrapolation in correction for detector effects as possible: Make fiducial selection on theory level as similar as possible.
  $\to$ Measurement almost model-independent

Objects	Fiducial definition
Photons	$\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$), $\sum p_{\mathrm{T}}^{i}/p_{\mathrm{T}}^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_{\mathrm{T}} > 30$ GeV, $\|y\| < 4.4$
Diphoton	$N_{\gamma} \geq 2$, $105\,GeV < m_{\gamma\gamma} < 160\,GeV$, $p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma} > 0.35$, $p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma} > 0.25$

- What needs to be done to measure these cross sections?
  - Object reconstruction, diphoton event selection
  - Signal yield extraction by fit to $m_{\gamma\gamma}$ spectrum
  - Correct signal yield for detector effects to make it comparable to theory prediction

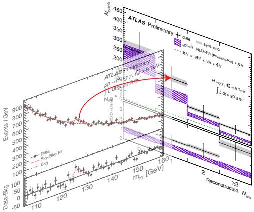


Event with diphoton candidate

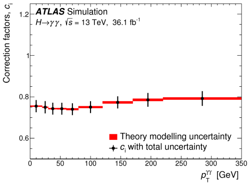
https://cds.cern.ch/record/1406055?ln=en

Signal Extraction and Unfolding

- Signal extraction with Maximum-Likelihood method
  - Simulatenous fit of several regions of phase-space
- Correction for Detector Effects
  - To make measurement comparable with theory predictions:
    Correct cross section for detector resolution and inefficiencies.
  - Method used for the presented results:
    - Bin-by-bin unfolding: $\sigma_i = \frac{\nu_{\mathrm{sig}}}{c_i} \cdot \frac{1}{\mathcal{L}}$,
      with $c_i = \frac{N_i^{\mathrm{det}}}{N_i^{\mathrm{ptcl}}}$
      (Only suitable if measurement is dominated by statistical uncertainty and migration between bins is small enough)



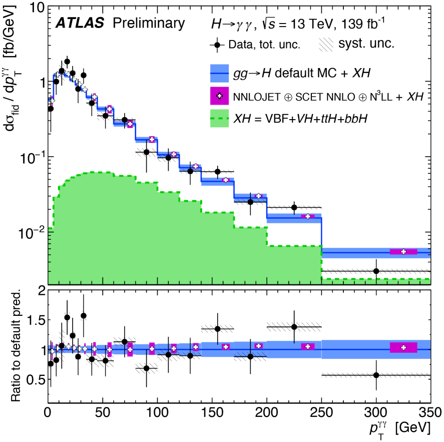
Bin-by-bin signal extraction. [Figure from Florian Bernlochner]



Correction factors. [Phys. Rev. D 98 (2018) 052005]

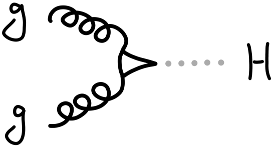
Result: p_T^H

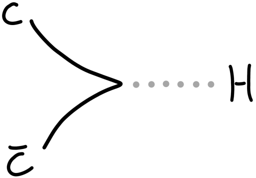
- Unfolded p_T^H spectrum compared to theory predictions
- 5 additional differential distributions measured, shown in presentation of Lailin Xu



- Shape and normalization of the differential Higgs cross section in p_T depend slightly on the Charm Yukawa coupling

  $\rightarrow$ Measured p_T spectrum can be used to extract limits on $\kappa_c = y_c/y_c^{\mathrm{SM}}$
- Which Higgs production modes depend on κ_c?
  - $gg \rightarrow H$
  - $c\bar{c} \rightarrow H$

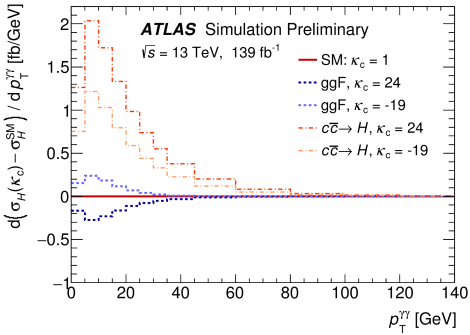




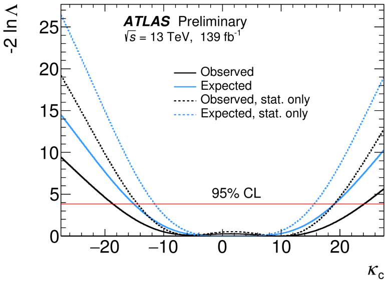
- $gg \rightarrow H$ dependence on κ_c from NNLO RadISH, $c\bar{c} \rightarrow H$ from MG5_NLO

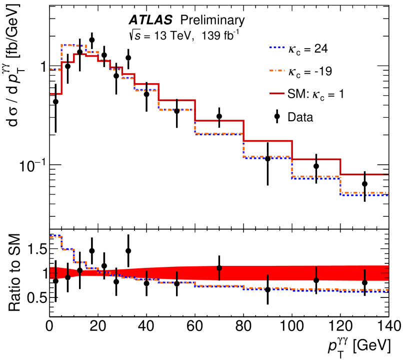
κ_c-dependendence of $gg \to H$ and $c\bar{c} \to H$

- $gg \to H$
  - Largest change in from top-loop interference with charm-loop
  - Can be positive or negative
- $c\bar{c} \to H$
  - Cross section simply scaled by κ_c^2 in each bin
  - Has stronger contribution to sensitivity



- Shape-only fit → reduce model-dependence (Normalization depends on NP modifications to Higgs decay width)
- Measurement statistically limited





Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$

Conclusions

- Measurement of inclusive and differential cross sections performed on full Run-2 dataset in $H \to \gamma\gamma$ decay channel
- Measured Higgs differential distributions agree very well with SM prediction
- p_{T} spectrum can be used to extract limits on κ_c

$$\to \kappa_c \in [-19, 24] \text{ @ } 95\,\% \text{ CL}$$

The
end

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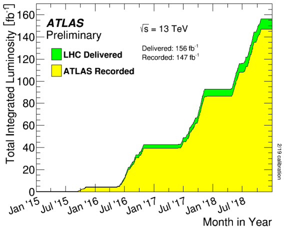
Data and Simulation

- Combined Run-2 dataset
  (139 fb^{-1}, $\sqrt{s}$ = 13 TeV)
- Diphoton trigger: ID, isolation cuts on photon candidates

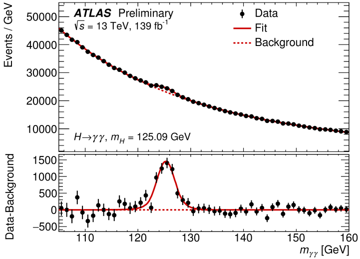


[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2]

- MC used to model signal peak in $m_{\gamma\gamma}$ and to correct for detector effects
  - Gluon fusion (*ggF*): `POWHEG NNLOPS`, normalized to $\mathrm{N^3LO\,(QCD)}$
  - *VBF*, *VH*, *ttH*, *bbH*: `POWHEG-BOX`, normalized to (approx.) NNLO or NLO
  - For each: `PDF4LHC15` PDF set

Signal and Background Parametrization

- Signal:
  - Width of signal peak essentially determined by detector resolution → Double-sided Crystal Ball function:
    Gaussian core and power-law tails
- Background:
  - Non-resonant, falling QCD background to Higgs peak ($\gamma\gamma$, γj, jj)
  - Irreducible $\gamma\gamma$ (75 %) and reducible γj (22 %) + jj (3 %)
    ($\geq$ 1 jets falsely identified as photon)
  - BG shape described by empirically chosen function:
    Smallest number of free parameters with sufficienctly small bias in signal extraction



Diphoton mass spectrum for the fiducial event selection in data

Signal Parametrization

- Fitted to simulation with $m_H = 125\,\mathrm{GeV}$ for each phase-space region corresponding to bin in differential distribution
- In fit to $m_{\gamma\gamma}$ spectrum m_H is fixed, but uncertainty on m_H of 0.24 GeV enters as nuisance parameters

Signal extraction

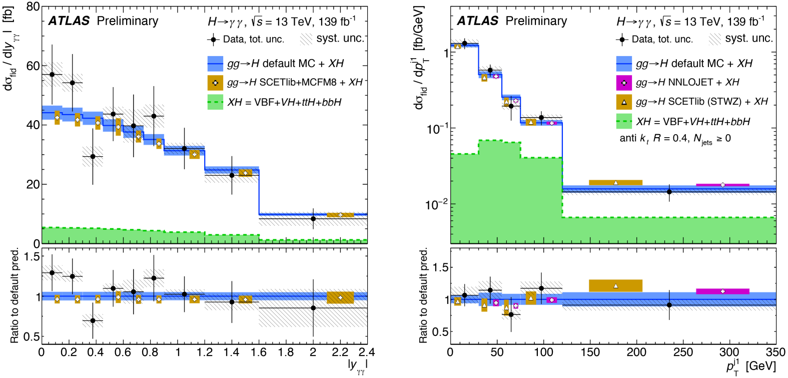
- Signal extraction with Maximum-Likelihood method, assuming Poisson distribution of number of events per bin
- Compute Likelihood for each bin of differential distribution and maximize simultaneously
- For every bin compute:
  $$\mathcal{L} = \frac{e^{-\nu}}{n!} \prod_{i}^{n} [\nu_{\mathrm{sig}} \cdot \mathcal{S}(m^{i}_{\gamma\gamma}|\theta_k) + \nu_{\mathrm{bkg}} \cdot \mathcal{B}(m^{i}_{\gamma\gamma})] \cdot \prod_{k} G(\theta_k|0,1)$$
  With: $\nu = \nu_{\mathrm{sig}} + \nu_{\mathrm{bkg}}$, n: Number of events, $\mathcal{S}$: Signal distribution, $\mathcal{B}$: Background distribution, θ_k: Nuisance parameters distributed with Gaussian $G(\theta_k|0,1)$ in most cases
- Fitted quantities: ν_{sig}, ν_{bkg}, θ_k
- Likelihood maximized for all bins of differential distribution simultaneously

Correction for Detector Effects: Unfolding

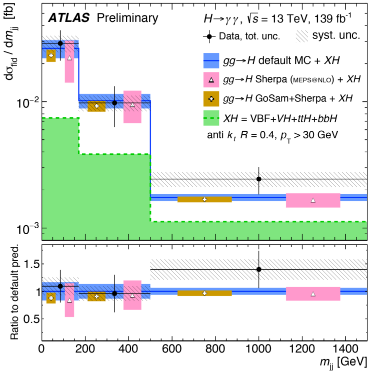
- Unfolded cross section: $\sigma_i = \frac{\nu_{\mathrm{sig}}}{c_i} \cdot \frac{1}{\mathcal{L}}$, with $c_i = \frac{N_i^{\mathrm{det}}}{N_i^{\mathrm{ptcl}}}$
- N_i^{det}: Number of events reconstructed in bin i of differential distribution
- N_i^{ptcl}: Number of events on truth level in bin i of differential distribution

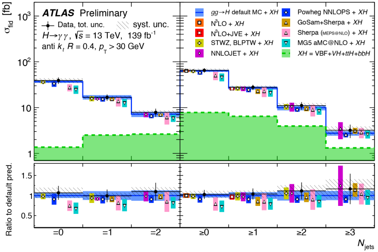
Result: y_H & p_{T}^{j1}

- Unfolded p_{T}^{H} spectrum compared to theory predictions

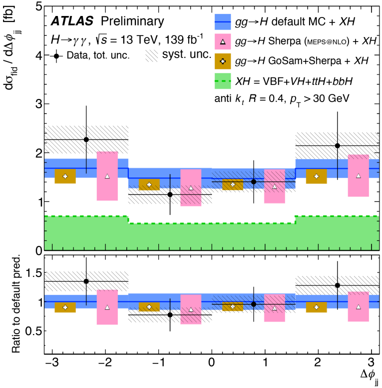


Result: m_{jj} & N_{jets}





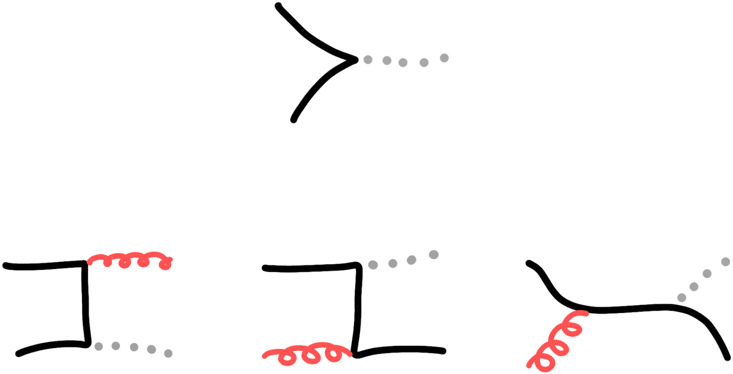
Result: $\Delta\phi_{jj}$



Uncertainty decomposition for inclusive cross section

Source	Uncertainty (%)
Statistics	6.9
Signal extraction syst.	7.9
Photon energy scale & resolution	4.6
Background modelling (spurious signal)	6.4
Correction factor	2.6
Pile-up modelling	2.0
Photon identification efficiency	1.2
Photon isolation efficiency	1.1
Trigger efficiency	0.5
Theoretical modelling	0.5
Photon energy scale & resolution	0.1
Luminosity	1.7
Total	11.0

LO and NLO Diagrams for ccH process



Uncertainty decomposition for κ_c (68% CL)

Source	$\delta\kappa_c$ $\left(^{+\mathrm{up}}_{-\mathrm{down}}\right)$
Stat.	$^{+10.1}_{-8.2}$
Exp. syst.	$^{+3.0}_{-2.7}$
QCD scale (ggF)	$^{+5.4}_{-5.4}$
QCD scale ($c\bar{c} \to H$ & $b\bar{b} \to H$)	$^{+0.8}_{-0.4}$
PDF (ggF)	$^{+0.5}_{-0.5}$
PDF ($c\bar{c} \to H$ & $b\bar{b} \to H$)	$^{+0.3}_{-0.1}$
Parton shower ($c\bar{c} \to H$ & $b\bar{b} \to H$)	$^{+1.4}_{-0.7}$
Total	$^{+12.1}_{-10.3}$

Caveats for κ_c measurement

- $gg \rightarrow H$ prediction relies on top-bottom interference for gluon fusion loop, which is theoretically not well understodd
- It is assumed that gluon fusion acceptance for fiducial region is not depending on κ_c
- All other quark Yukawa couplings are set to SM value

Comparisons with direct $H \to c\bar{c}$ measurements

- Both CMS and ATLAS have a $H \to c\bar{c}$ measurement based on the $pp \to ZH$ production mode, based on $36\,\mathrm{fb}^{-1}$
- Assuming SM value for Z-H coupling:
  - CMS: $|\kappa_c| < 8.4$ (https://cds.cern.ch/record/2682638)
  - ATLAS: $|\kappa_c| < 10.5$ (https://cds.cern.ch/record/2304413/)