Measurements and Interpretations of Simplified Template Cross-Sections, differential and fiducial cross sections in $H \rightarrow \gamma\gamma$ decays with the ATLAS detector

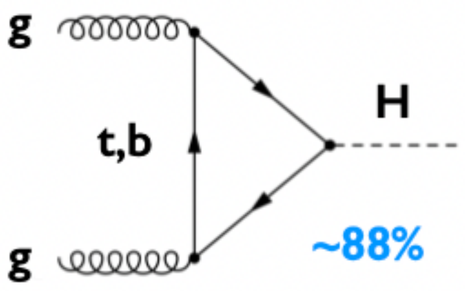
Tom Schwarz
University of Michigan

On behalf of the ATLAS Collaboration

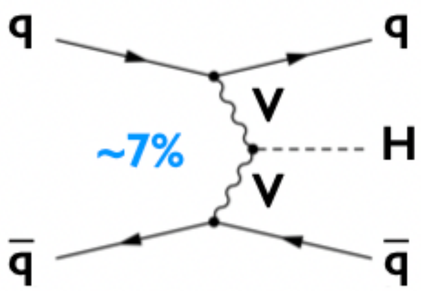
Nov 10th, 2022
Higgs 2022
Pisa, Italy

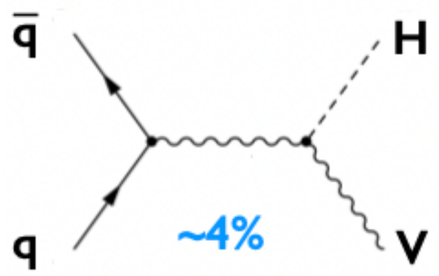
SM Higgs Production and Decay

Gluon-gluon fusion

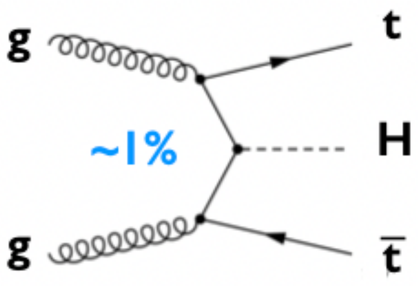


Vector-boson fusion



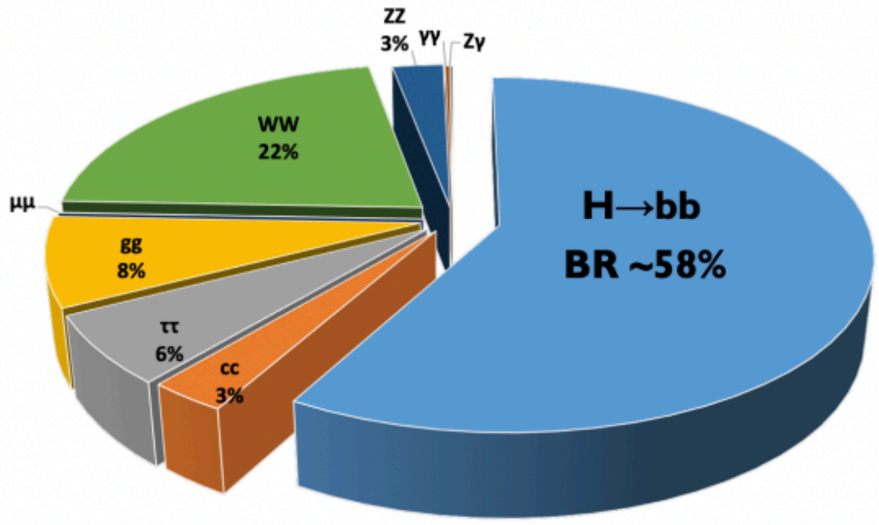


Associated production with vector boson (VH)



Associated production with top quark pair (ttH)

Decay modes:



Observed (5σ) production modes:

- Gluon gluon fusion, VBF (Run-1)
- ttH, VH (Run-2)

Observed (5σ) decay modes:

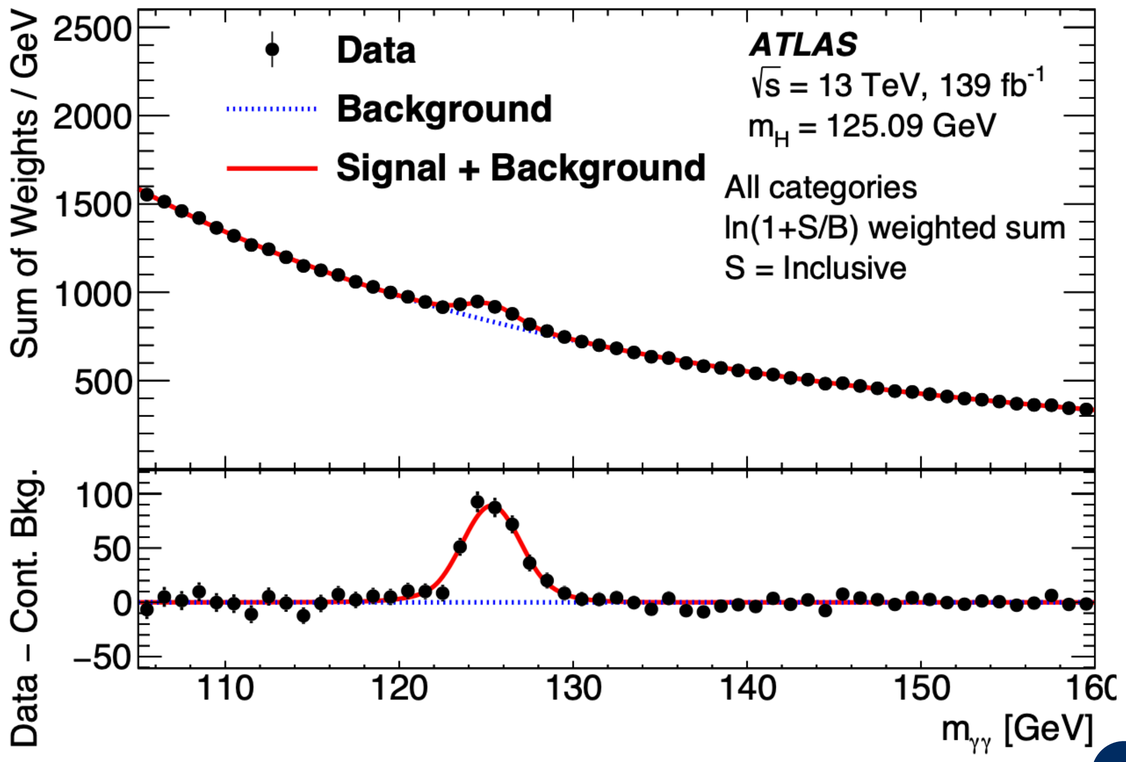
- To bosons: H→ZZ, H→WW, H→$\gamma\gamma$
- To fermions: H→$\tau\tau$, H→bb

Showing Full Run 2 Results in this Talk!

$H \rightarrow \gamma\gamma$ STXS Measurements

ARXIV: 2207.00348
Submitted to JHEP

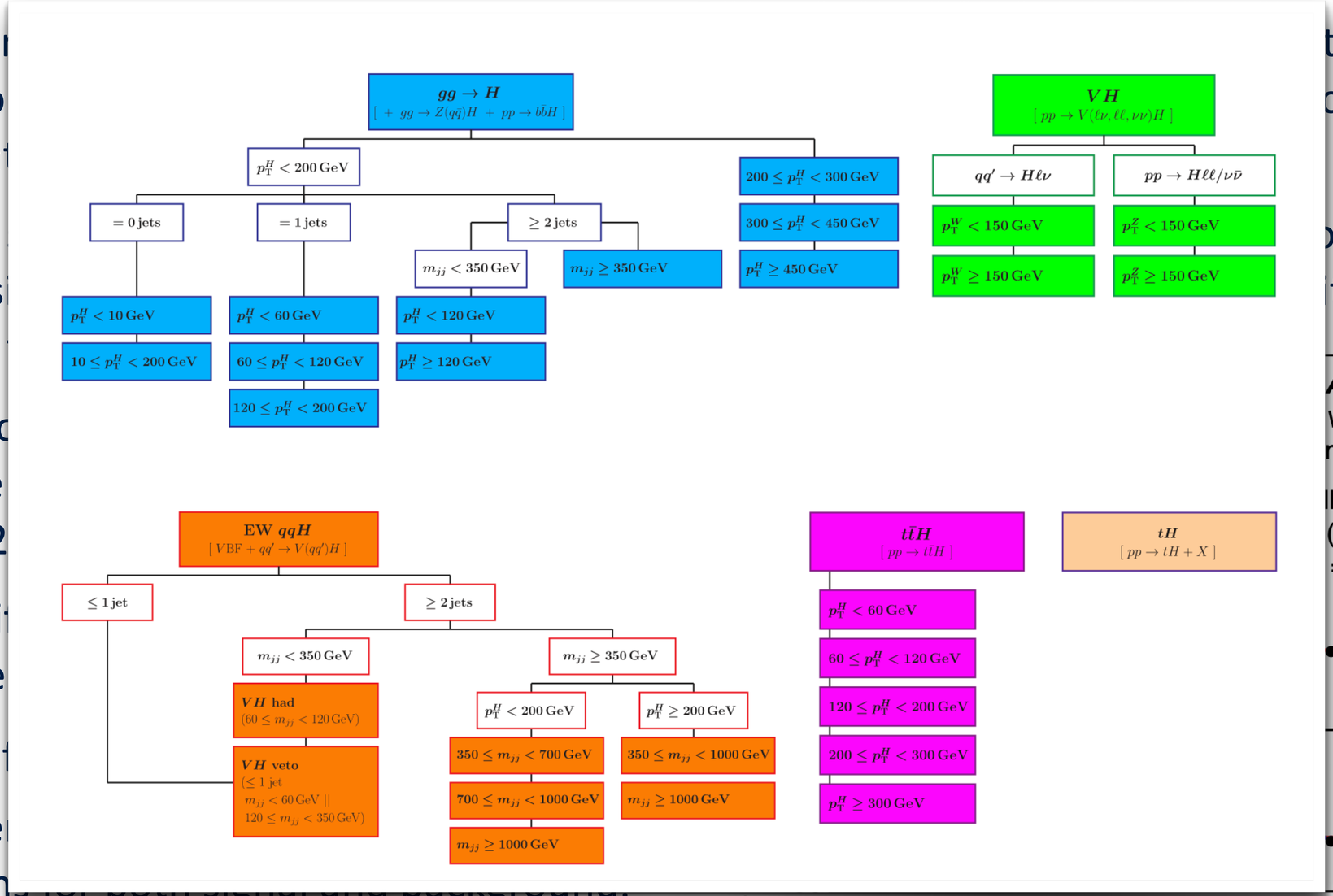
- Analysis measures production cross-sections in the Simplified Template Cross-Sections (STXS) framework, in which Higgs production phase space is partitioned by production process, kinematics, and event properties.
- Provides strong sensitivity to the cross-sections of primary Higgs boson production modes: gluon-gluon fusion (ggF), vector-boson fusion (VBF), and associated production with a vector boson or top quark (VH or ttH).
- Events split into classes targeting 45 STXS regions (based on Stage 1.2 binning) using a multi class BDT. Only report on 28 regions.
- Additional classifier (BDT/NN) trained in each class to further separate events into 101 categories.
- A simultaneous fit to $M_{\gamma\gamma}$ is performed in each of the categories, where the distribution is modeled with analytic functions for both signal and background.

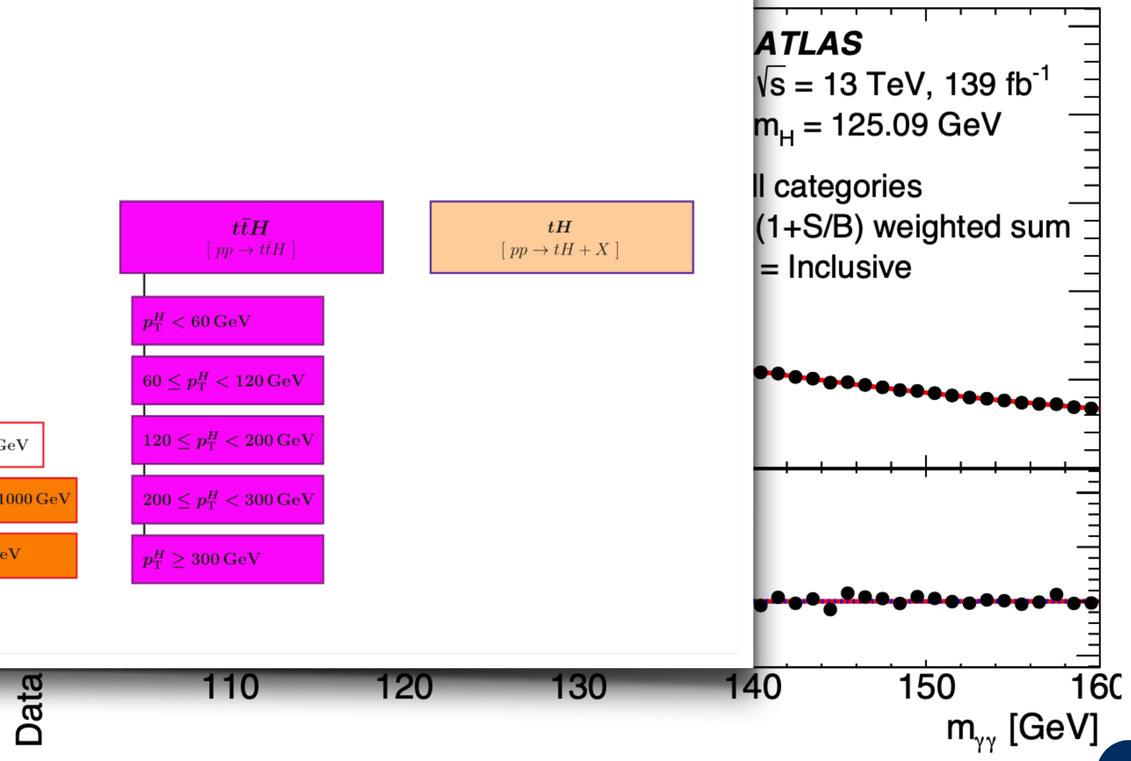


$H \to \gamma\gamma$ STXS Measurements

ARXIV: 2207.00348
Submitted to JHEP

- Analysis measu… …tions (STXS) framewo… …ction process, kinemat…
- Provides strong … …odes: gluon-gluon fus… …th a vector boson or …
- Events split into … (based on Stage … Only report on 2…
- Additional classi… further separate…
- A simultaneous … categories, whe… analytic function…

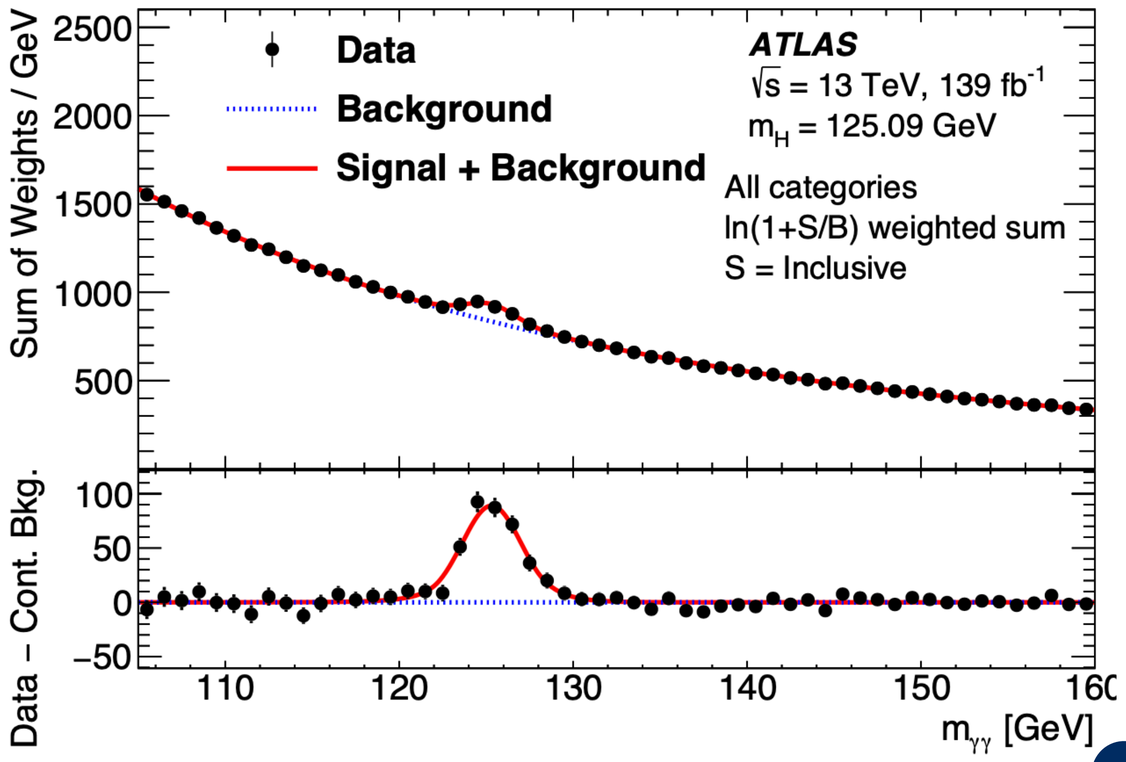




$H \rightarrow \gamma\gamma$ STXS Measurements

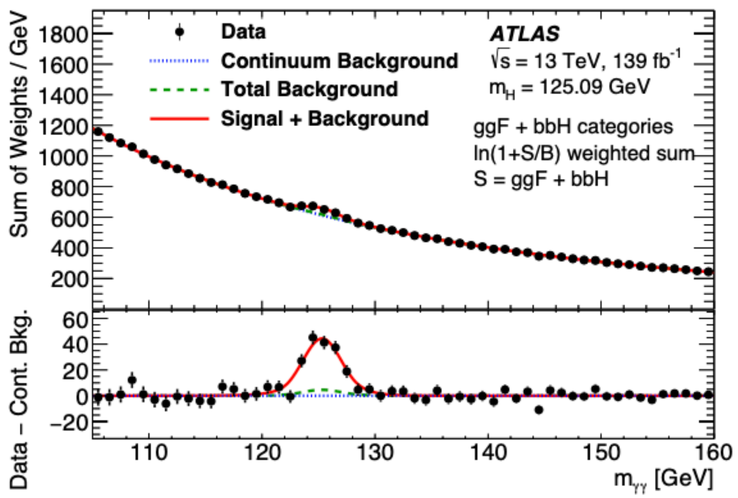
ARXIV: 2207.00348
Submitted to JHEP

- Analysis measures production cross-sections in the Simplified Template Cross-Sections (STXS) framework, in which Higgs production phase space is partitioned by production process, kinematics, and event properties.
- Provides strong sensitivity to the cross-sections of primary Higgs boson production modes: gluon-gluon fusion (ggF), vector-boson fusion (VBF), and associated production with a vector boson or top quark (VH or ttH).
- Events split into classes targeting 45 STXS regions (based on Stage 1.2 binning) using a multi class BDT. Only report on 28 regions.
- Additional classifier (BDT/NN) trained in each class to further separate events into 101 categories.
- A simultaneous fit to $M_{\gamma\gamma}$ is performed in each of the categories, where the distribution is modeled with analytic functions for both signal and background.

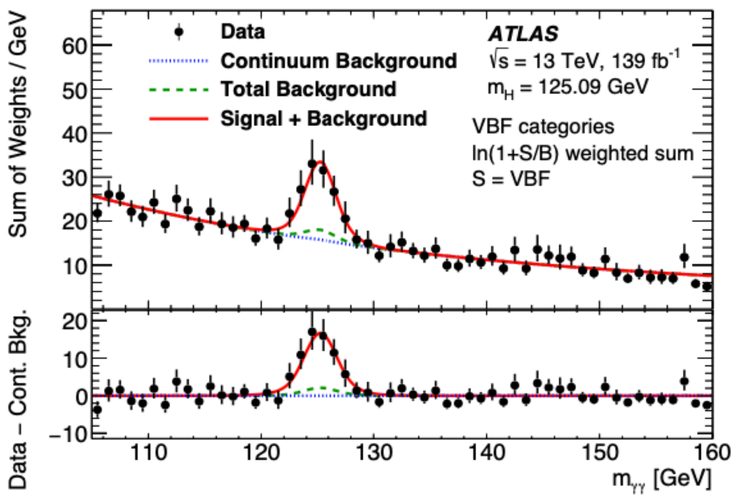


$H \to \gamma\gamma$ STXS Measurements

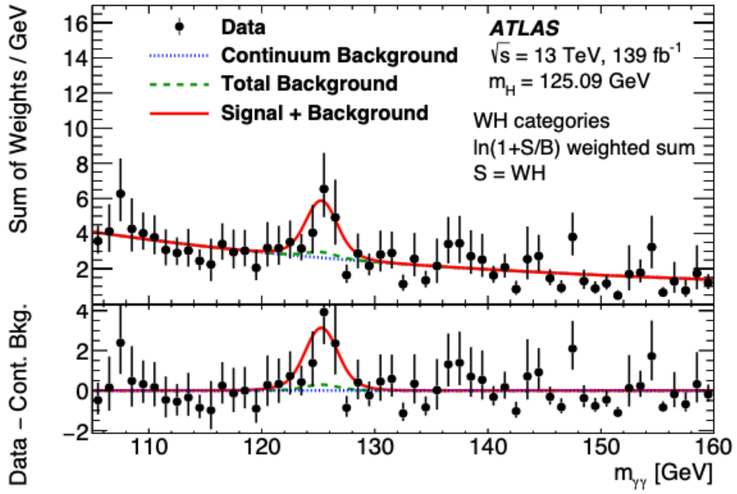
- Analysis measures produ
(STXS) framework, in whi
process, kinematics, and e
- Provides strong sensitivity
gluon-gluon fusion (ggF),
vector boson or top quark
- Events split into classes
(based on Stage 1.2 binnir
Only report on 28 regions.
- Additional classifier (BDT/N
further separate events int
- A simultaneous fit to $M_{\gamma\gamma}$ i
categories, where the dis
analytic functions for both



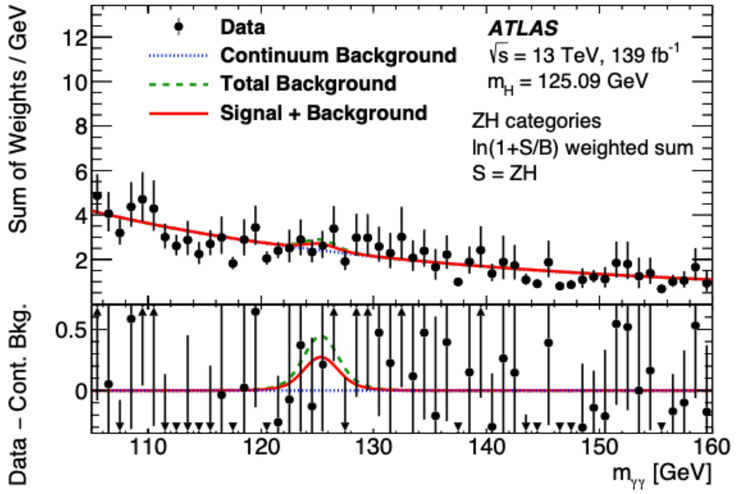
(a) ggF+ $b\bar{b}H$



(b) VBF



(c) WH



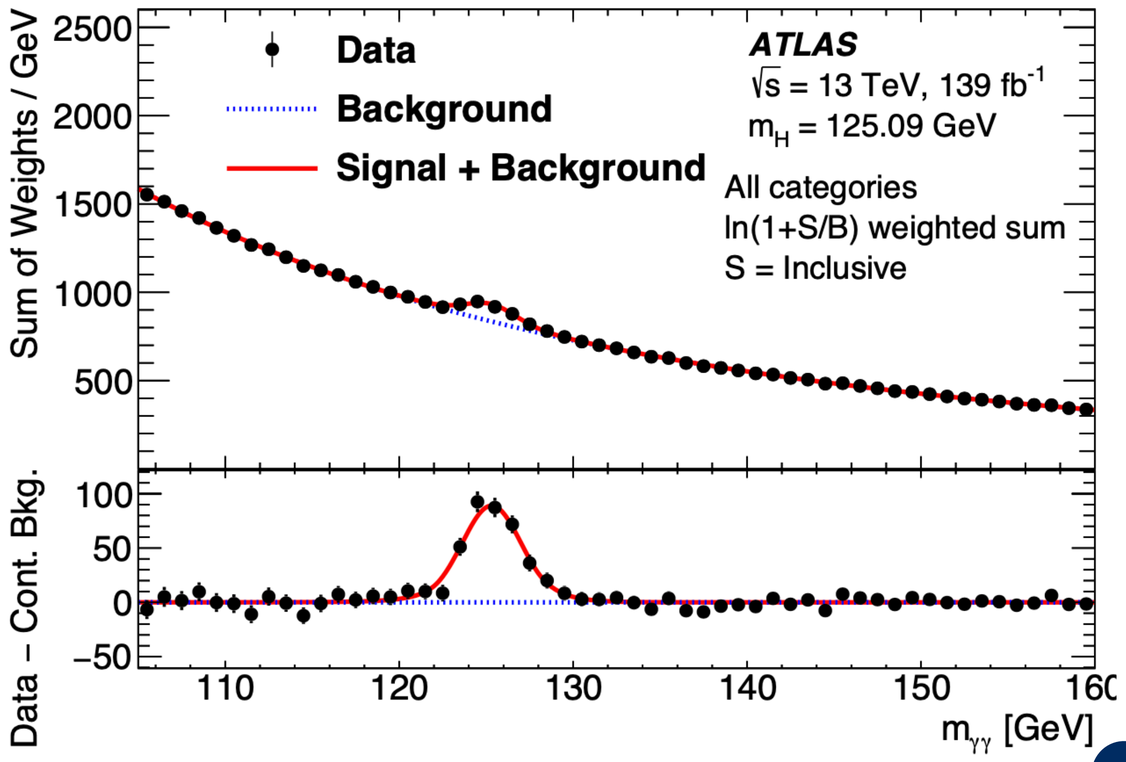
(d) ZH

.00348
o JHEP

$H \rightarrow \gamma\gamma$ STXS Measurements

ARXIV: 2207.00348
Submitted to JHEP

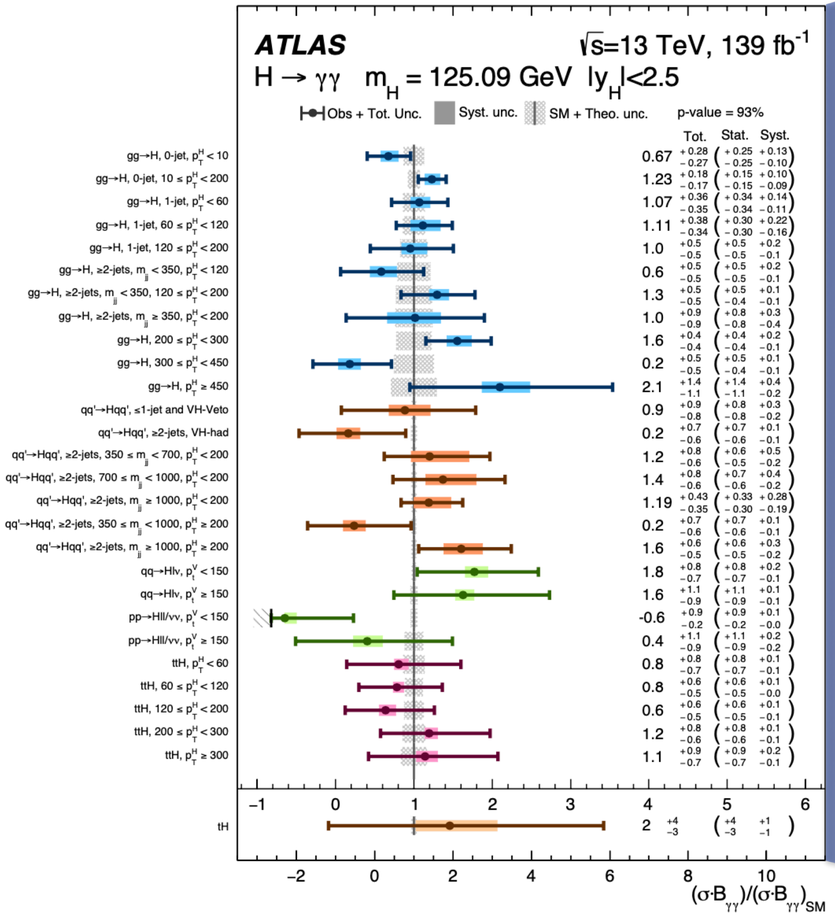
- Analysis measures production cross-sections in the Simplified Template Cross-Sections (STXS) framework, in which Higgs production phase space is partitioned by production process, kinematics, and event properties.
- Provides strong sensitivity to the cross-sections of primary Higgs boson production modes: gluon-gluon fusion (ggF), vector-boson fusion (VBF), and associated production with a vector boson or top quark (VH or ttH).
- Events split into classes targeting 45 STXS regions (based on Stage 1.2 binning) using a multi class BDT. Only report on 28 regions.
- Additional classifier (BDT/NN) trained in each class to further separate events into 101 categories.
- A simultaneous fit to $M_{\gamma\gamma}$ is performed in each of the categories, where the distribution is modeled with analytic functions for both signal and background.



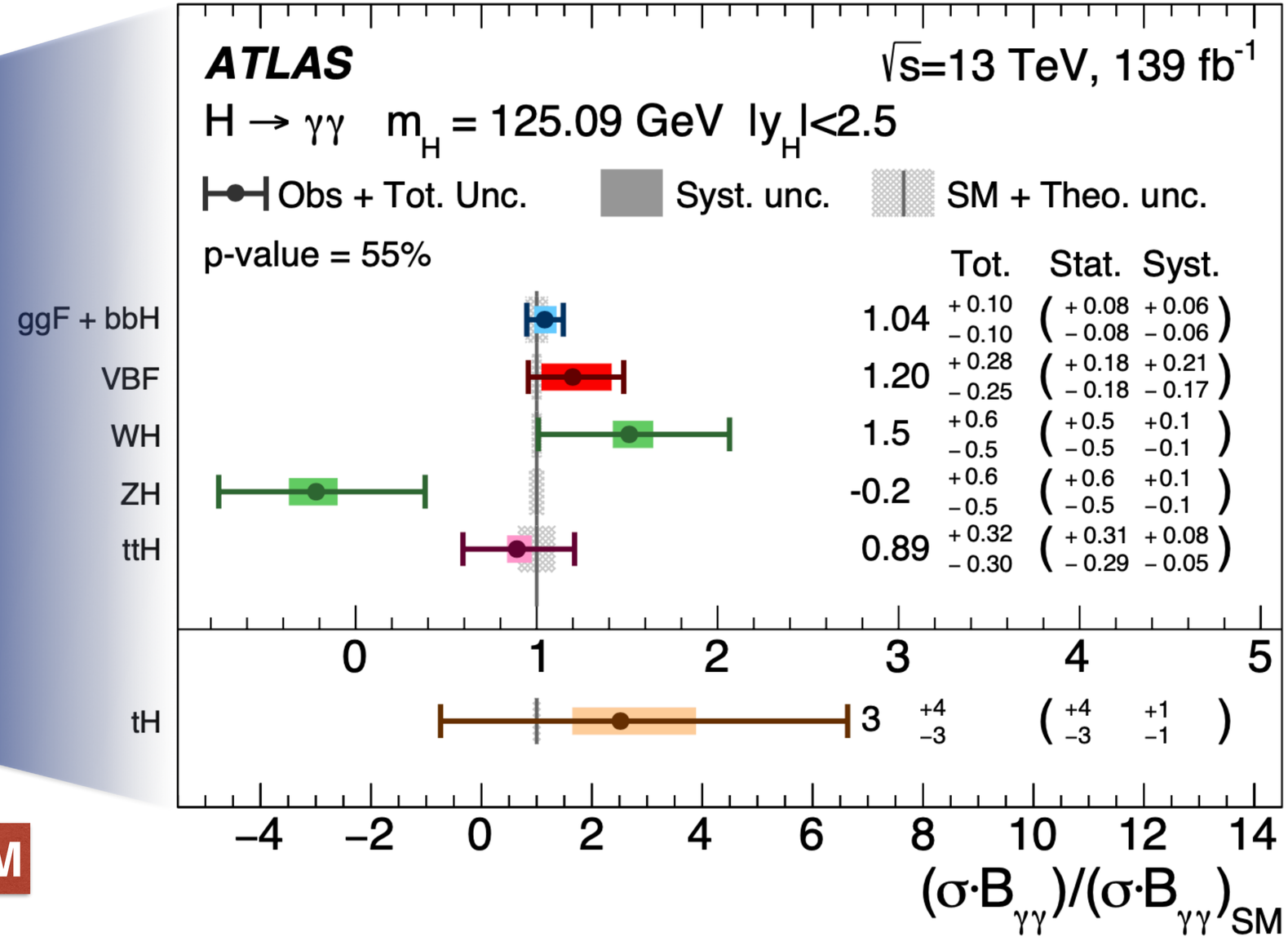
$H \rightarrow \gamma\gamma$ STXS Measurements

ARXIV: 2207.00348
Submitted to JHEP

28 STXS Categories

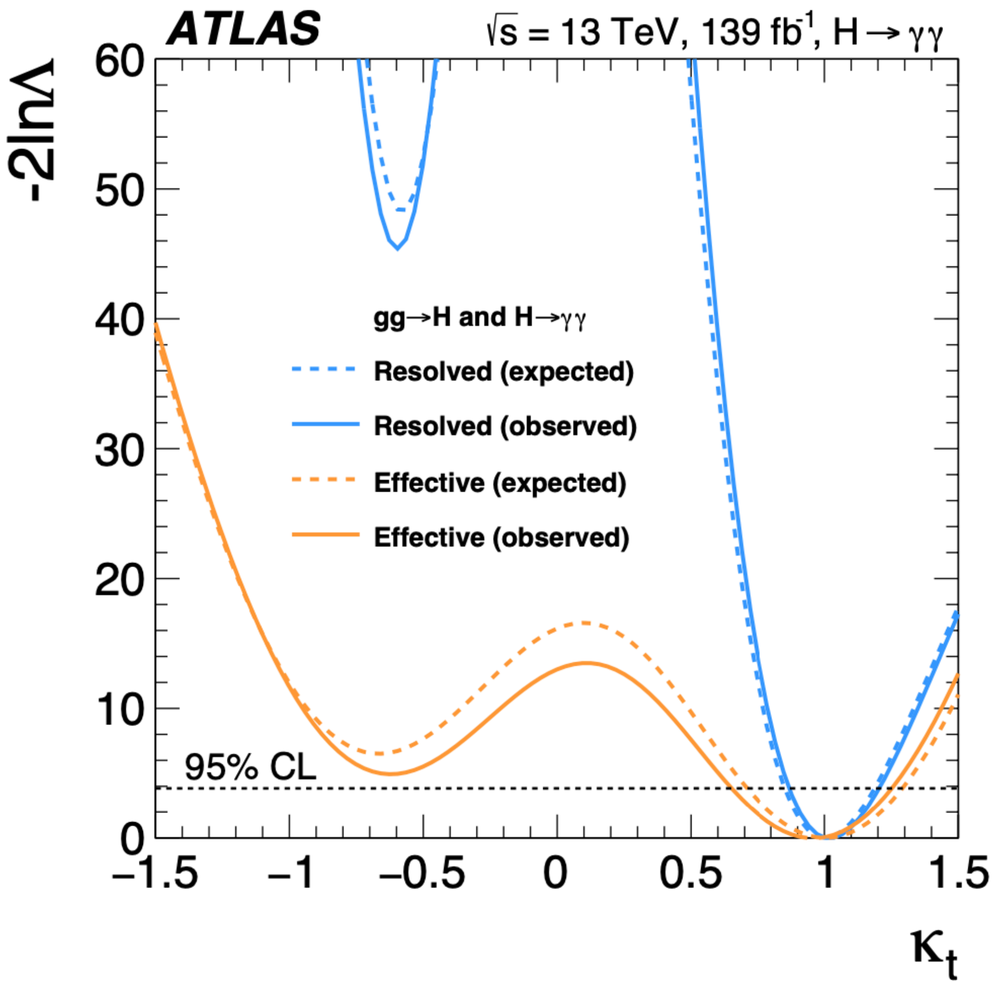


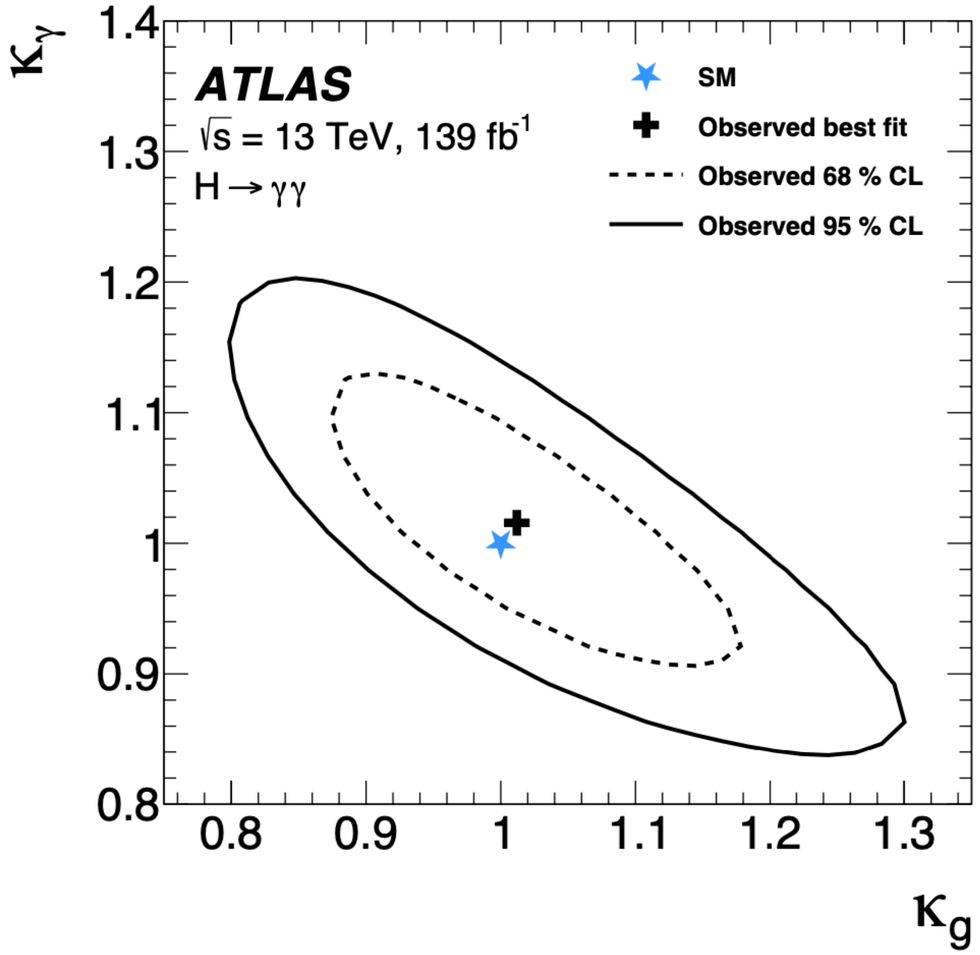
93% Compatibility with SM



Interpretation of the STXS Results (κ Framework)

ARXIV: 2207.00348
Submitted to JHEP





Note: tHjb category sensitive to negative Kt

Interpretation of the STXS Results (SM EFT)

ATLAS EXPERIMENT

ARXIV: 2207.00348
Submitted to JHEP

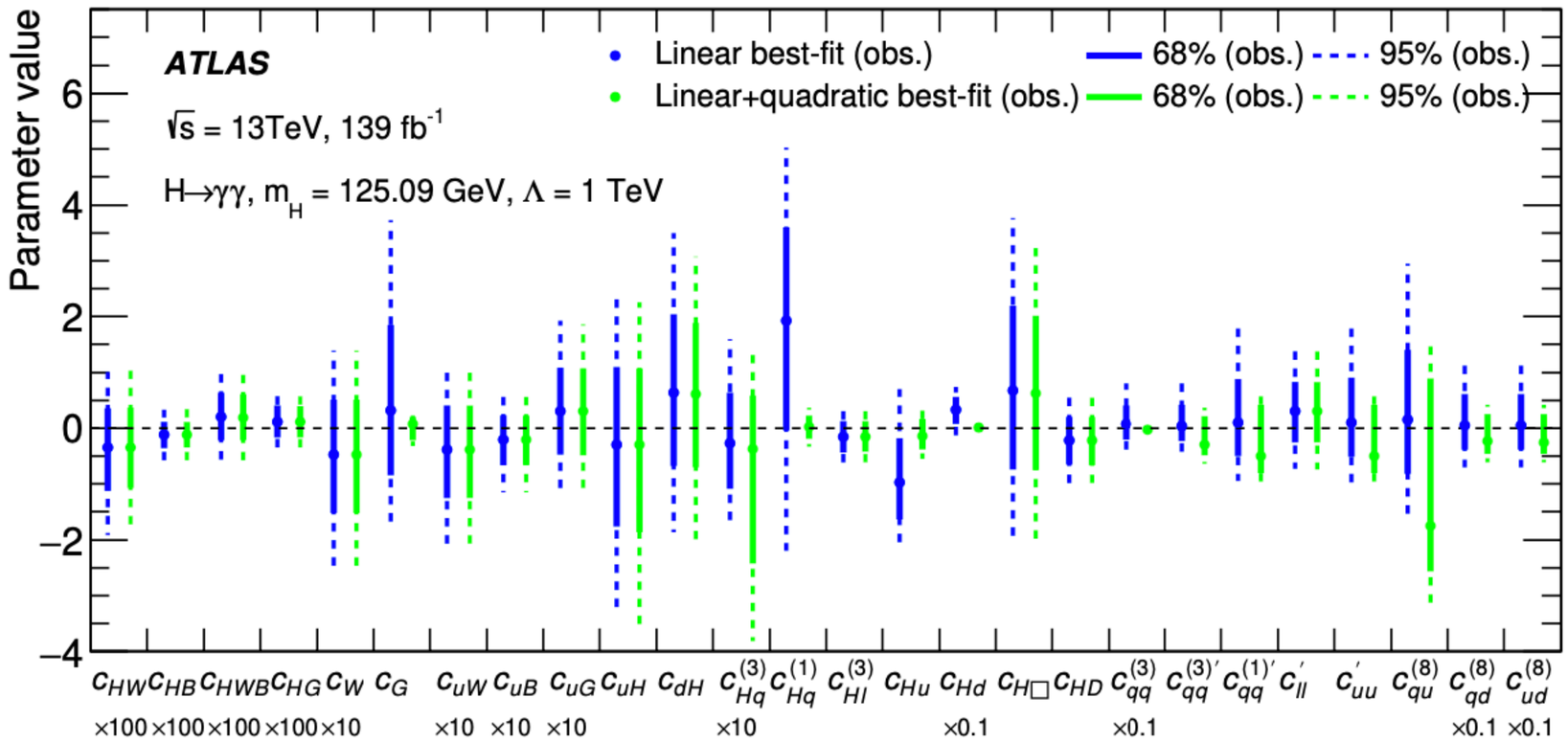
- Interpretation in SMEFT used to set constraints on possible new physics.
- Using STXS results, individual Wilson coefficients (c_k) are measured while fixing others to zero.
- A simultaneous measurement of all SMEFT parameters is also performed (see paper).
  - ➡ *A principal component analysis is being performed to identify sensitive directions for the simultaneous measurement.*

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_k \frac{c_k}{\Lambda^2} O_k$$

Coeff.	Operator	Incl.	Coeff.	Operator	Incl.
c_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	✓	$c_{qq}^{(3)}$	$(\bar{q}_r \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_s)$	✓
c_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	✓	$c_{qq}^{(3)\prime}$	$(\bar{q}_r \gamma_\mu \tau^I q_s)(\bar{q}_s \gamma^\mu \tau^I q_r)$	✓
c_H	$(H^\dagger H)^3$		$c_{qq}^{(1)}$	$(\bar{q}_r \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_s)$	✓
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	✓	$c_{qq}^{(1)\prime}$	$(\bar{q}_r \gamma_\mu q_s)(\bar{q}_s \gamma^\mu q_r)$	✓
c_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	✓	$c_{lq}^{(3)}$	$(\bar{l}_r \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_s)$	
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	✓	$c_{lq}^{(1)}$	$(\bar{l}_r \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_s)$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	✓	c_{ee}	$(\bar{e}_r \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_s)$	
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	✓	c_{eu}	$(\bar{e}_r \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_s)$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	✓	c_{ed}	$(\bar{e}_r \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_s)$	
c_{eH}	$(H^\dagger H)(\bar{l}_p [Y_e^\dagger]_{pq} e_q H)$	✓	c_{uu}	$(\bar{u}_r \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_s)$	✓
c_{uH}	$(H^\dagger H)(\bar{q}_p [Y_u^\dagger]_{pq} u_q \widetilde{H})$	✓	c_{uu}'	$(\bar{u}_r \gamma_\mu u_s)(\bar{u}_s \gamma^\mu u_r)$	✓
c_{dH}	$(H^\dagger H)(\bar{q}_p [Y_d^\dagger]_{pq} d_q H)$	✓	c_{dd}	$(\bar{d}_r \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_s)$	
c_{eW}	$(\bar{l}_p \sigma^{\mu\nu} [Y_e^\dagger]_{pq} e_q) \tau^I H W_{\mu\nu}^I$		c_{dd}'	$(\bar{d}_r \gamma_\mu d_s)(\bar{d}_s \gamma^\mu d_r)$	
c_{eB}	$(\bar{l}_p \sigma^{\mu\nu} [Y_e^\dagger]_{pq} e_q) H B_{\mu\nu}$		$c_{ud}^{(1)}$	$(\bar{u}_r \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_s)$	✓
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A [Y_u^\dagger]_{pq} u_q) \widetilde{H} G_{\mu\nu}^A$	✓	$c_{ud}^{(8)}$	$(\bar{u}_r \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_s)$	✓
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} [Y_u^\dagger]_{pq} u_q) \tau^I \widetilde{H} W_{\mu\nu}^I$	✓	c_{le}	$(\bar{l}_r \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_s)$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} [Y_u^\dagger]_{pq} u_q) \widetilde{H} B_{\mu\nu}$	✓	c_{lu}	$(\bar{l}_r \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_s)$	
c_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A [Y_d^\dagger]_{pq} d_q) H G_{\mu\nu}^A$		c_{ld}	$(\bar{l}_r \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_s)$	
c_{dW}	$(\bar{q}_p \sigma^{\mu\nu} [Y_d^\dagger]_{pq} d_q) \tau^I H W_{\mu\nu}^I$		c_{qe}	$(\bar{q}_r \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_s)$	
c_{dB}	$(\bar{q}_p \sigma^{\mu\nu} [Y_d^\dagger]_{pq} d_q) H B_{\mu\nu}$		$c_{qu}^{(1)}$	$(\bar{q}_r \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_s)$	✓
$c_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_r \tau^I \gamma^\mu l_r)$	✓	$c_{qu}^{(8)}$	$(\bar{q}_r \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_s)$	✓
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_r \gamma^\mu l_r)$	✓	$c_{qd}^{(1)}$	$(\bar{q}_r \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_s)$	✓
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_r \gamma^\mu e_r)$	✓	$c_{qd}^{(8)}$	$(\bar{q}_r \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_s)$	✓
$c_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_r \tau^I \gamma^\mu q_r)$	✓	c_{ledq}	$(\bar{l}_p^j [Y_l^\dagger]_{pq} e_q)(\bar{d}_r [Y_d]_{rs} q_s^j)$	
$c_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_r \gamma^\mu q_r)$	✓	$c_{quqd}^{(1)}$	$(\bar{q}_p^j [Y_u^\dagger]_{pq} u_q) \epsilon_{jk} (\bar{q}_r^k [Y_d^\dagger]_{rs} d_s)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_r)$	✓	$c_{quqd}^{(1)\prime}$	$(\bar{q}_p^j [Y_d^\dagger]_{ps} u_q) \epsilon_{jk} (\bar{q}_r^k [Y_u^\dagger]_{rq} d_s)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_r \gamma^\mu d_r)$	✓	$c_{quqd}^{(8)}$	$(\bar{q}_p^j T^A [Y_u^\dagger]_{pq} u_q) \epsilon_{jk} (\bar{q}_r^k T^A [Y_d^\dagger]_{rs} d_s)$	
c_{Hud}	$(H^\dagger i D_\mu H)(\bar{u}_p \gamma^\mu [Y_u Y_d^\dagger]_{pq} d_q)$		$c_{quqd}^{(8)\prime}$	$(\bar{q}_p^j T^A [Y_d^\dagger]_{ps} u_q) \epsilon_{jk} (\bar{q}_r^k T^A [Y_u^\dagger]_{rq} d_s)$	
c_{ll}	$(\bar{l}_r \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_s)$		$c_{lequ}^{(1)}$	$(\bar{l}_p^j [Y_e^\dagger]_{pq} e_q) \epsilon_{jk} (\bar{q}_r^k [Y_u^\dagger]_{rs} u_s)$	
c_{ll}'	$(\bar{l}_r \gamma_\mu l_s)(\bar{l}_s \gamma^\mu l_r)$	✓	$c_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma^{\mu\nu} [Y_e^\dagger]_{ps} e_q) \epsilon_{jk} (\bar{q}_r^k \sigma_{\mu\nu} [Y_u^\dagger]_{rq} u_s)$	

Interpretation of the STXS Results (SM EFT)

ARXIV: 2207.00348
Submitted to JHEP



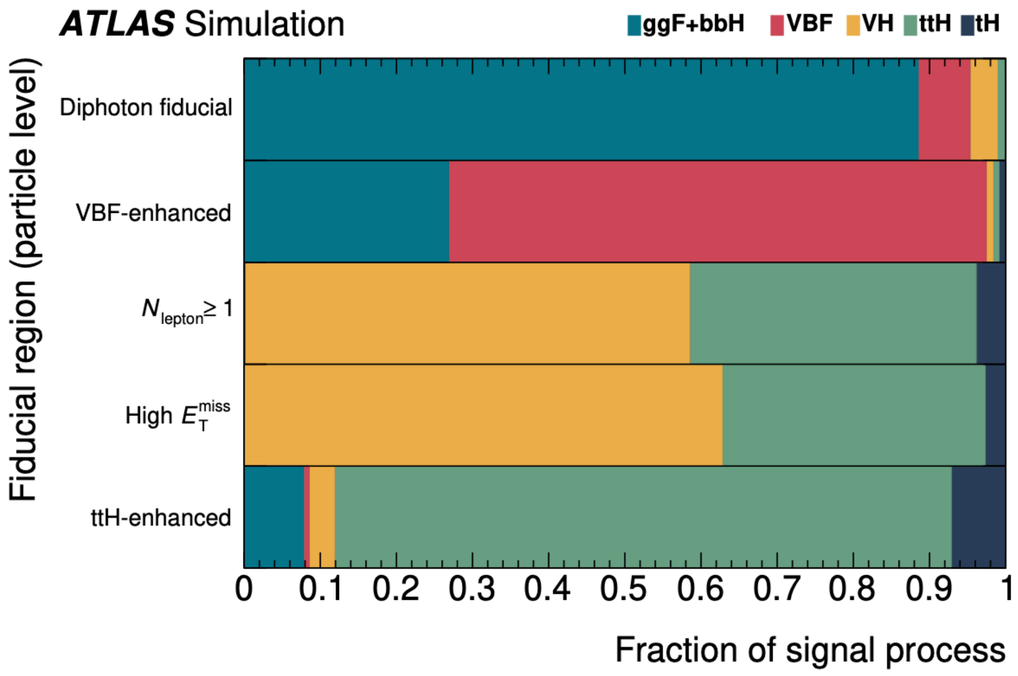
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_k \frac{c_k}{\Lambda^2} O_k$$

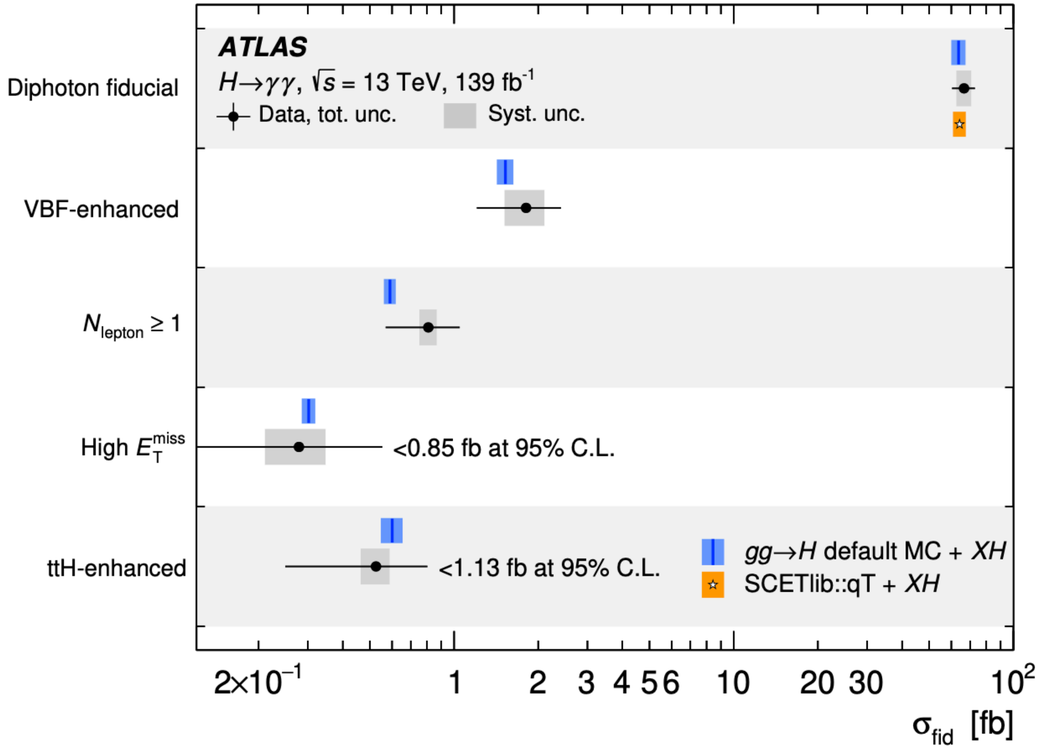
0 means SM

Fiducial Cross-Sections

ARXIV: 2202.00487
JHEP 08 (2022) 027

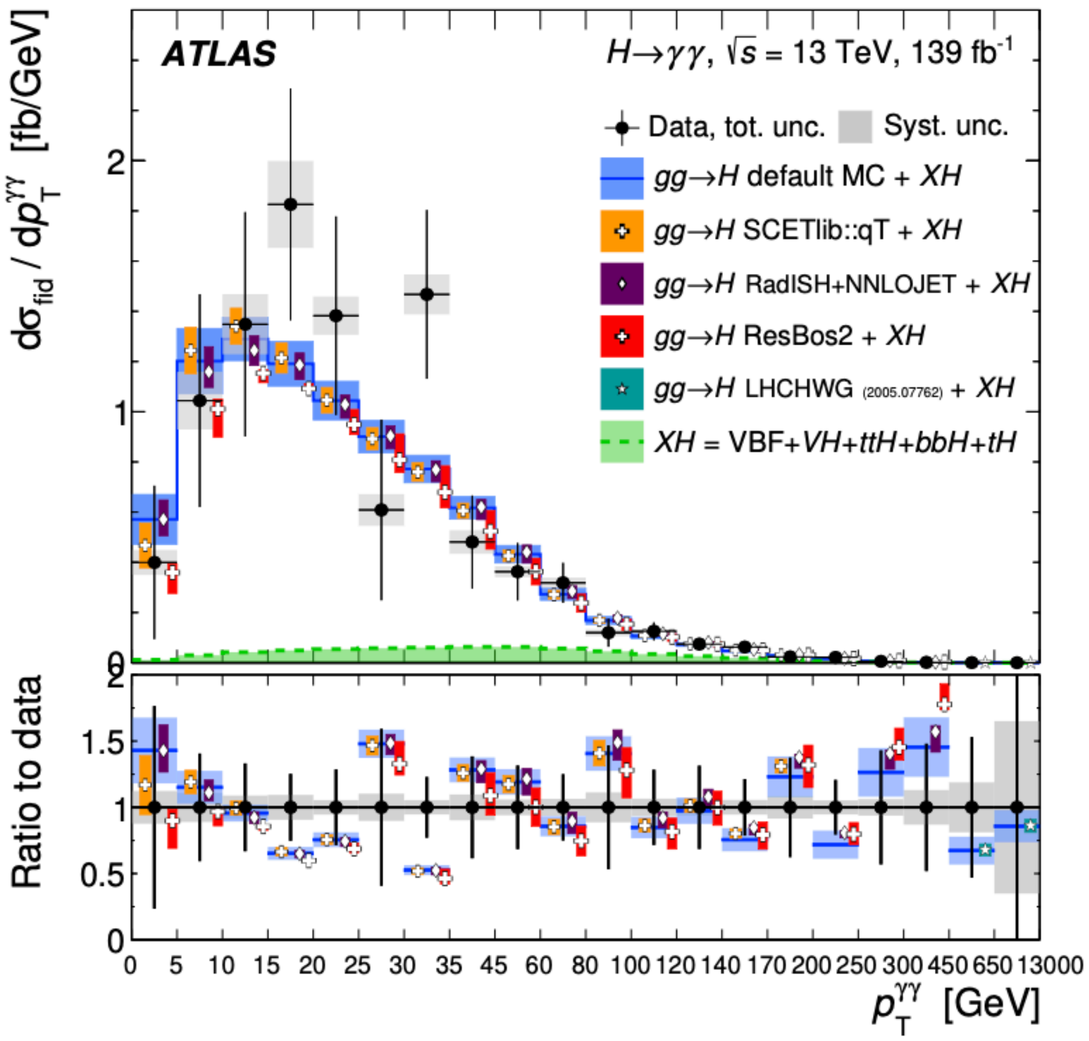
- Fiducial measurements of $H \rightarrow \gamma\gamma$ observables allow for a more model independent comparison with predictions by measuring fiducial phase space that closely matches the available analysis phase space - minimizing extrapolations.
- Results can constrain couplings not directly accessible (such as c_H) and can be applied to Wilson coefficient in SM EFT

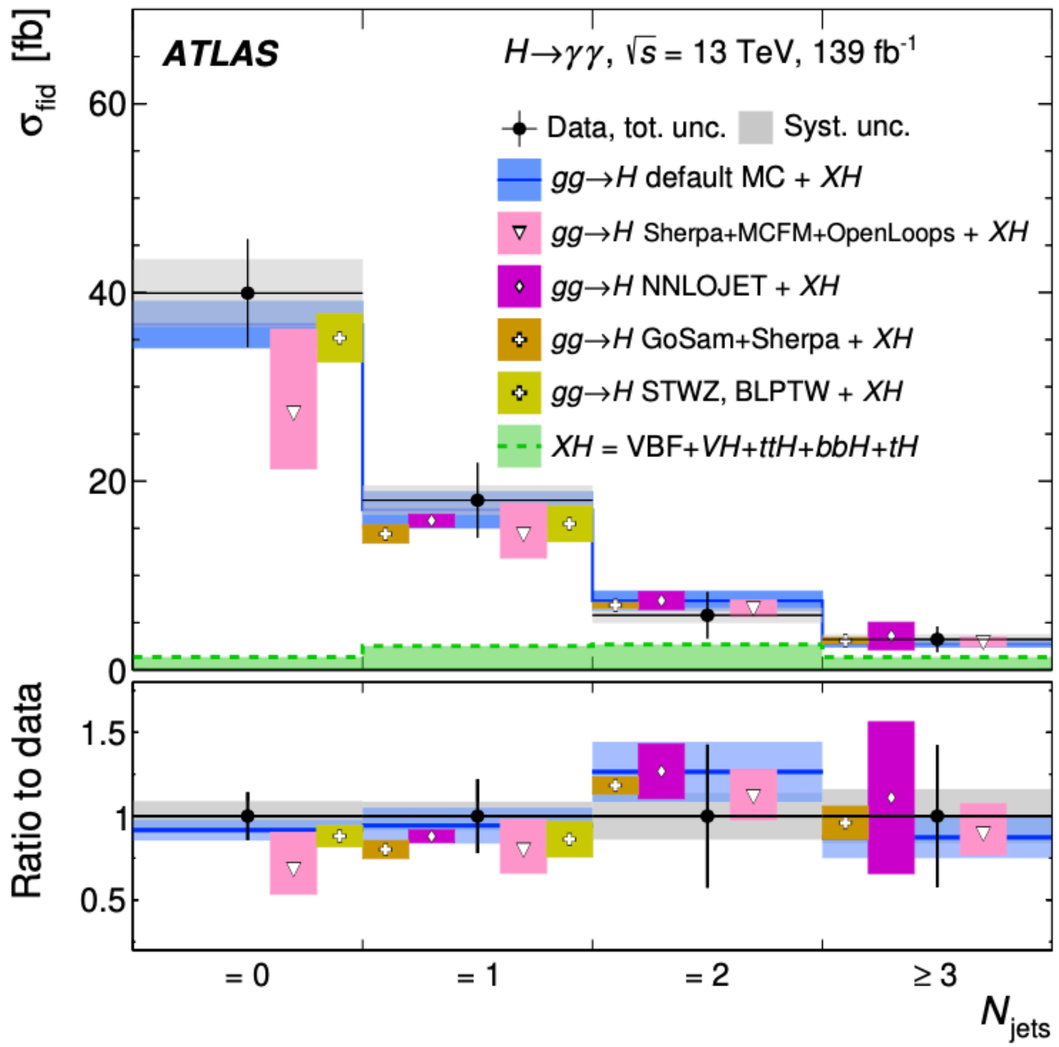




Differential Fiducial Cross-Sections

ARXIV: 2202.00487
JHEP 08 (2022) 027

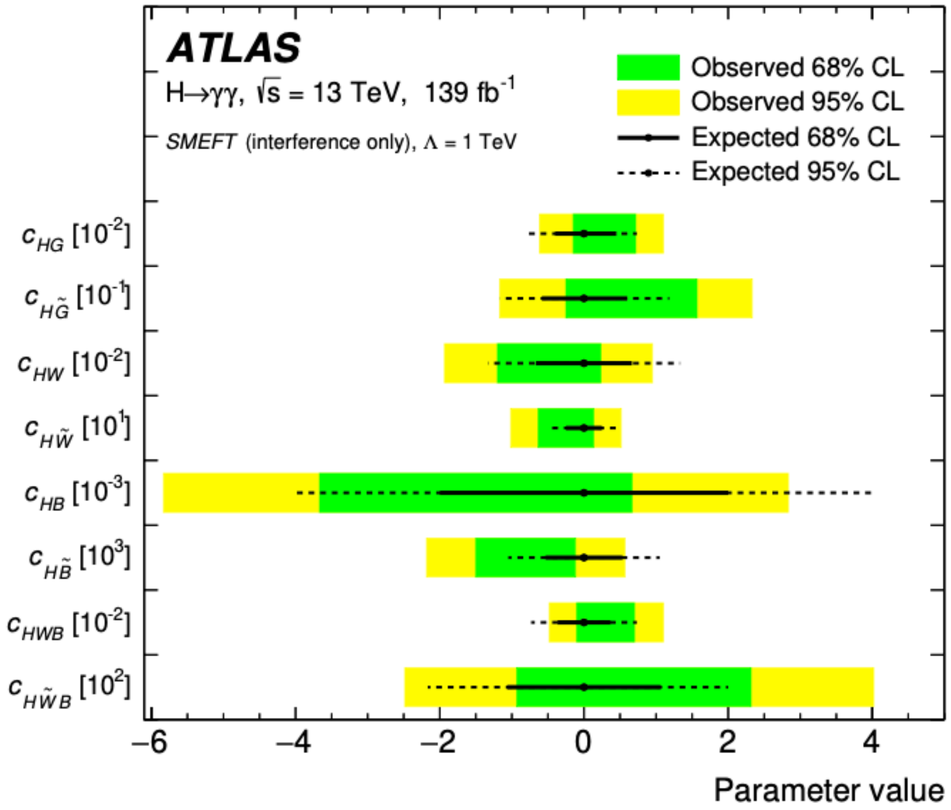


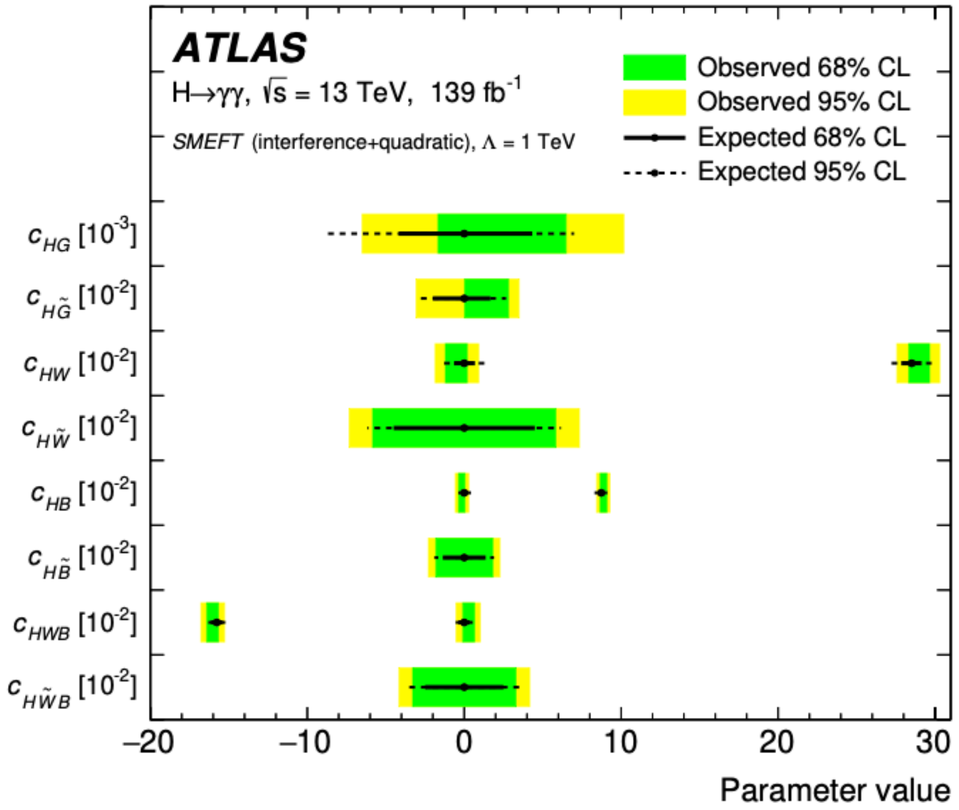


Fiducial Cross-Sections

ARXIV: 2202.00487
JHEP 08 (2022) 027

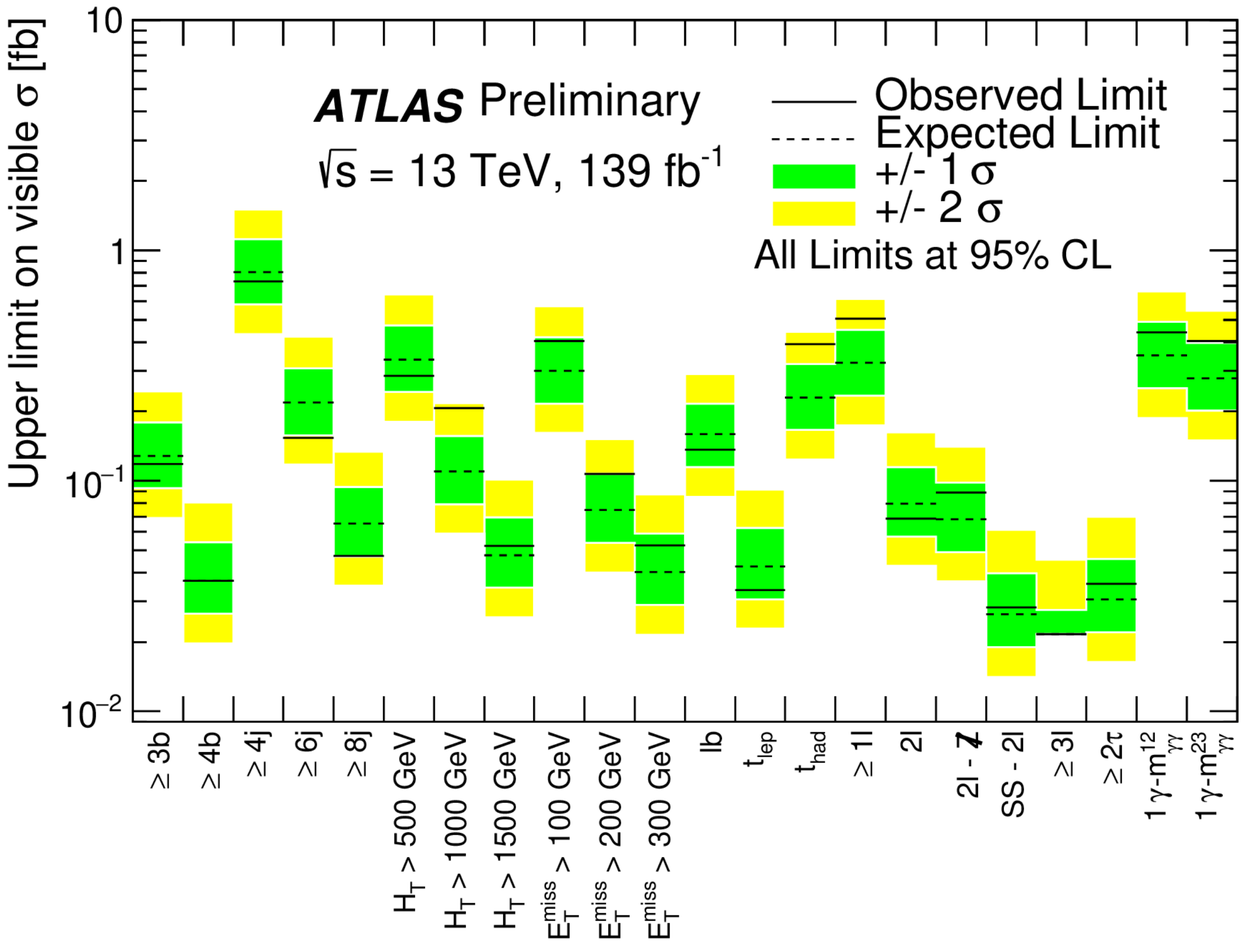
- Interpretation in SMEFT used to set constraints on possible new physics.
- Using fiducial differential results, individual Wilson coefficients (c_k) are measured while fixing others to zero.





Model-independent Search in $H \rightarrow \gamma\gamma$

- A model independent search for new physics examines 22 final states categorized by objects produced in association with $H \rightarrow \gamma\gamma$.
- Signal regions can roughly be classified into six groups: events with heavy flavor jets; events with high jet multiplicity or larger H_T; events with large E_T^{miss}; events with leptons; events with additional photons; and events with top quarks.
- No significant excess above SM observed and limits on production cross-sections placed at 95% CL.
- Detector efficiencies are reported for all 22 signal regions which are used to convert detector-level cross section limits to particle-level cross-section constraints.



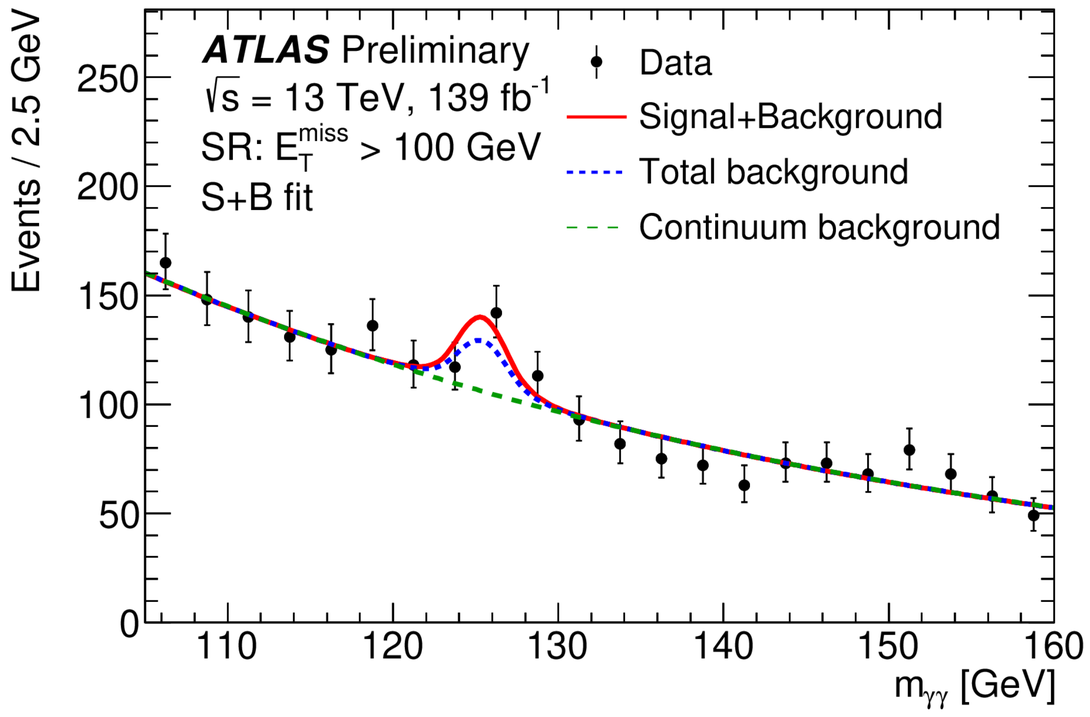
Model-independent Search in $H \rightarrow \gamma\gamma$

- An example using an Ewk SUSY production model to demonstrate how to derive constraints on a given BSM model

- In this process, a chargino and neutralino pair decay to a final state W boson, Higgs, and two undetectable neutralinos (so large E_T^{miss}).

- The E_T^{miss} > 100 GeV signal region for this analysis placed a 95% CL limit at the detector level of 0.4 fb.

- Accounting for detector efficiency (0.68 reported in paper), the particle level limit on the BSM cross-section is 0.59 fb at 95% CL, which would exclude the considered SUSY model ($\sigma = 1.05\ fb$ at particle level).



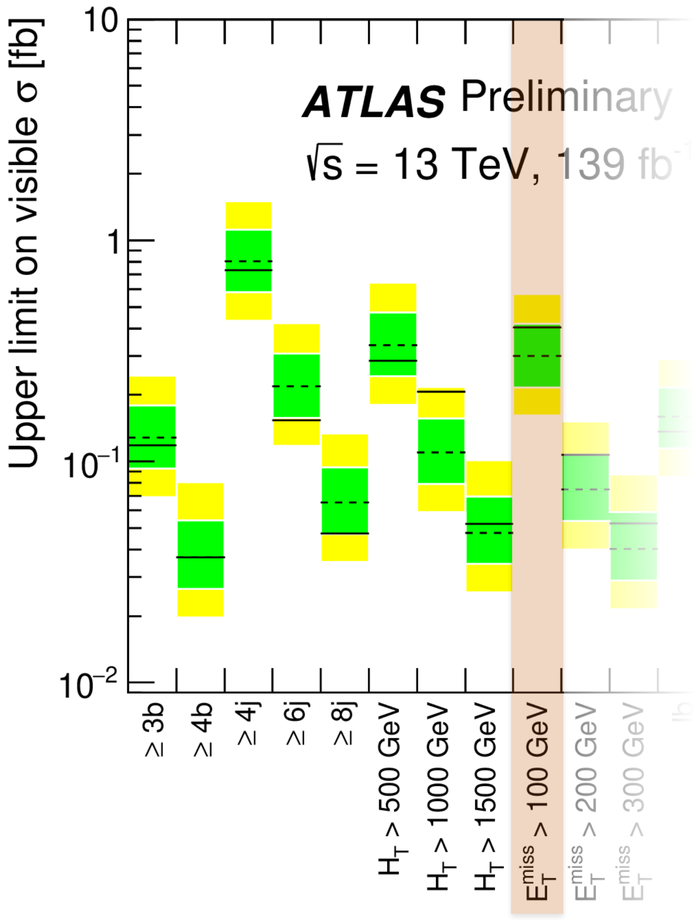
Model-independent Search in $H \rightarrow \gamma\gamma$

- An example using an Ewk SUSY production model to demonstrate how to derive constraints on a given BSM model

- In this process, a chargino and neutralino pair decay to a final state W boson, Higgs, and two undetectable neutralinos (so large E_T^{miss}).

- The E_T^{miss} > 100 GeV signal region for this analysis placed a 95% CL limit at the detector level of 0.4 fb.

- Accounting for detector efficiency (0.68 reported in paper), the particle level limit on the BSM cross-section is 0.59 fb at 95% CL, which would exclude the considered SUSY model ($\sigma = 1.05\ fb$ at particle level).



Conclusions

- SM Higgs physics in the $H \rightarrow \gamma\gamma$ channel have been probed in a variety of ways - simplified template cross sections, fiducial measurements, full phase space differential measurements.
- Interpretations of the results have been performed in the κ framework and in SM Effective Field Theory.
- All measurements/interpretations are consistent with the SM.
- However, the results are mostly dominated by statistical uncertainties, so future runs will probe deeper into Higgs properties.