Higgs boson measurements in the decays into bosons with ATLAS experiment

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on behalf of the ATLAS collaboration

Higgs measurements with H→VV

H^0

$J^{CP}=0^{++}$

Mass：$124.92^{+0.21}_{-0.20}$ GeV

Width: < 14.4 MeV

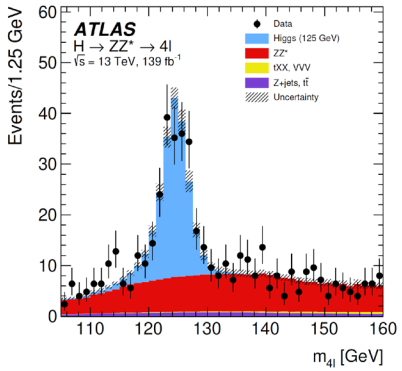
(Expected 4.2 MeV)

Indirect: 15.2 MeV

H→ZZ*

Small Br

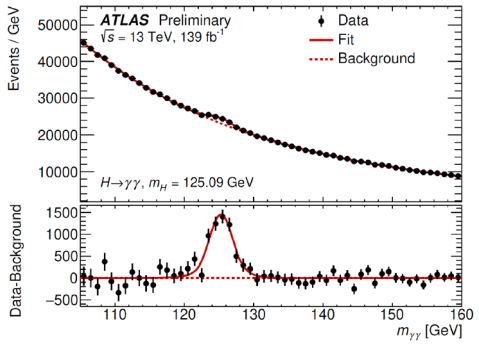
Clean signature



H→γγ

Larger BG

sharp peak

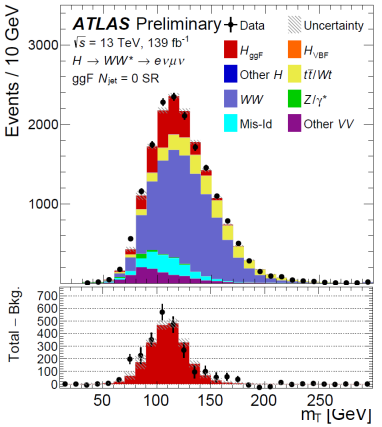


H→WW*

Large signal

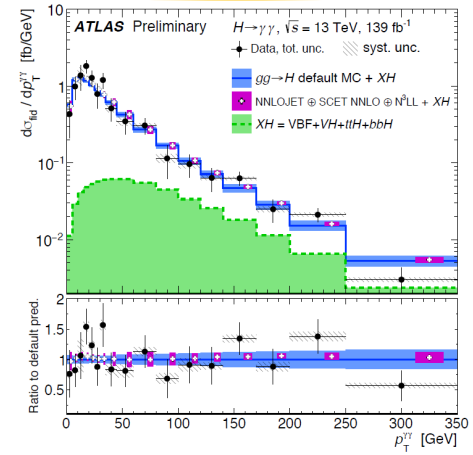
Large BG

No clear peak

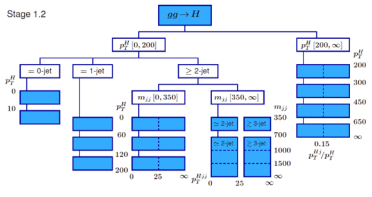


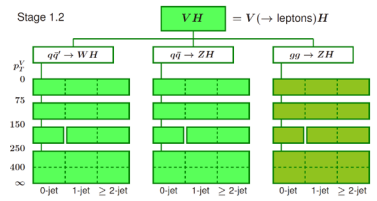
Two approaches to probe physics beyond the standard model

Fiducial Differential Measurements



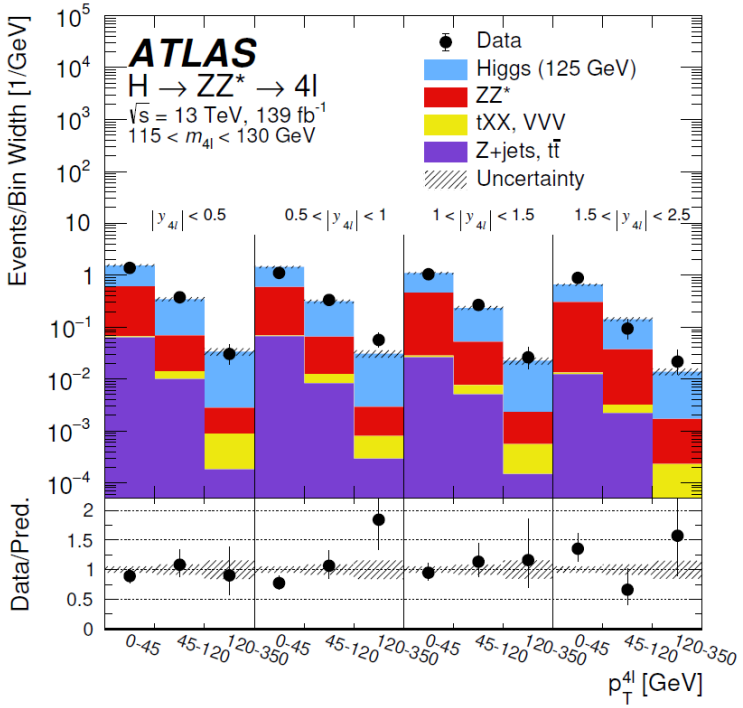
Simplified Template Cross section (STXS)





Differential cross section measurement

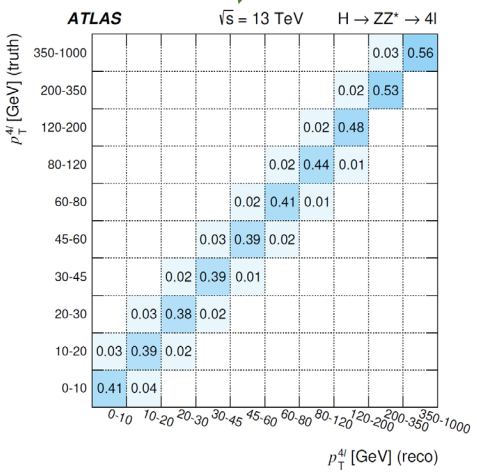
1. Selection
   - object selection
   - Higgs boson reconstruction
2. Define distribution
   - observable
   - # of bins

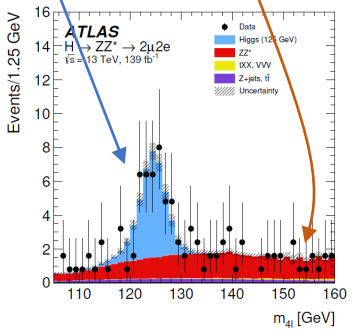


3. Perform fit to subtract background and unfold to particle-level fiducial phase space
   - **response matrices**
   - **signal shape**
   - **background estimate pre-fit**

$$\sigma_j^{\text{fid}} = \sigma_j \cdot A_j \cdot \mathcal{B}$$

$$N_i(m_{4\ell}) = \sum_j r_{ij} \cdot \sigma_j^{\text{fid}} \cdot \mathcal{P}_i(m_{4\ell}) \cdot \mathcal{L} + N_i^{\text{bkg}}(m_{4\ell})$$





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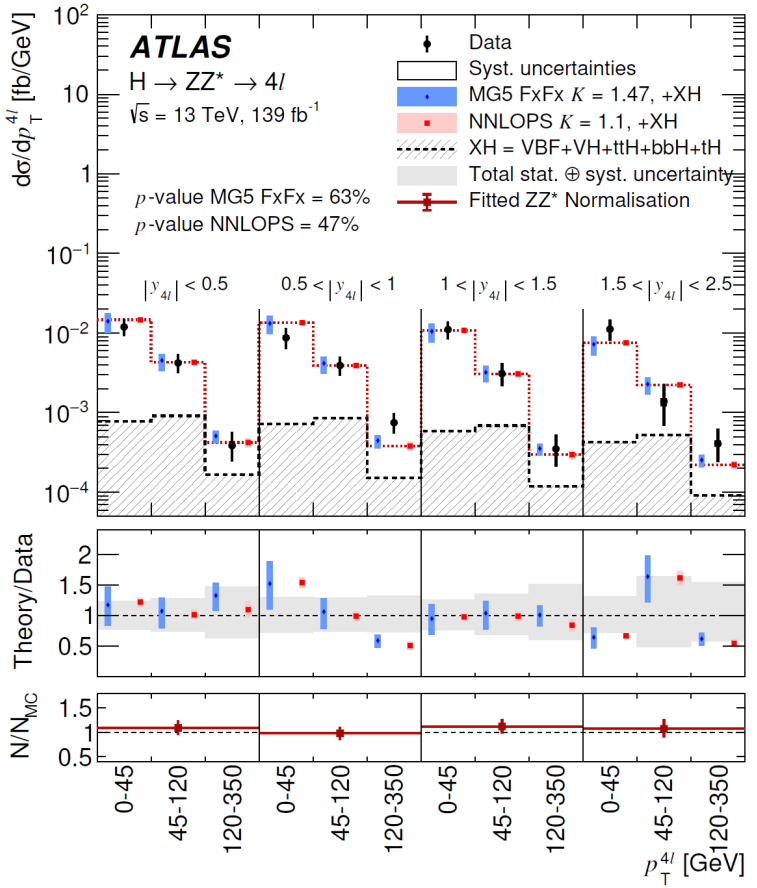
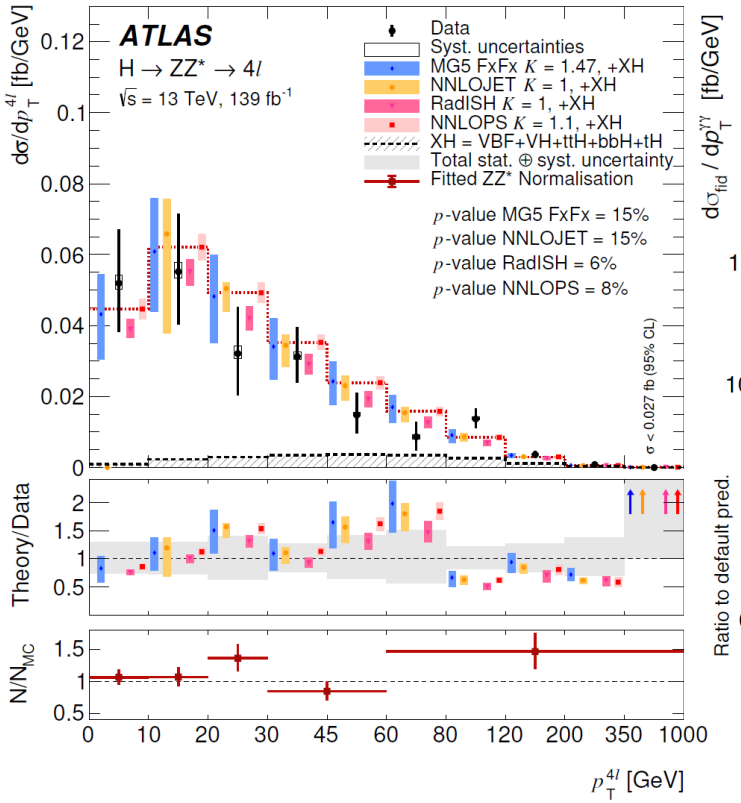
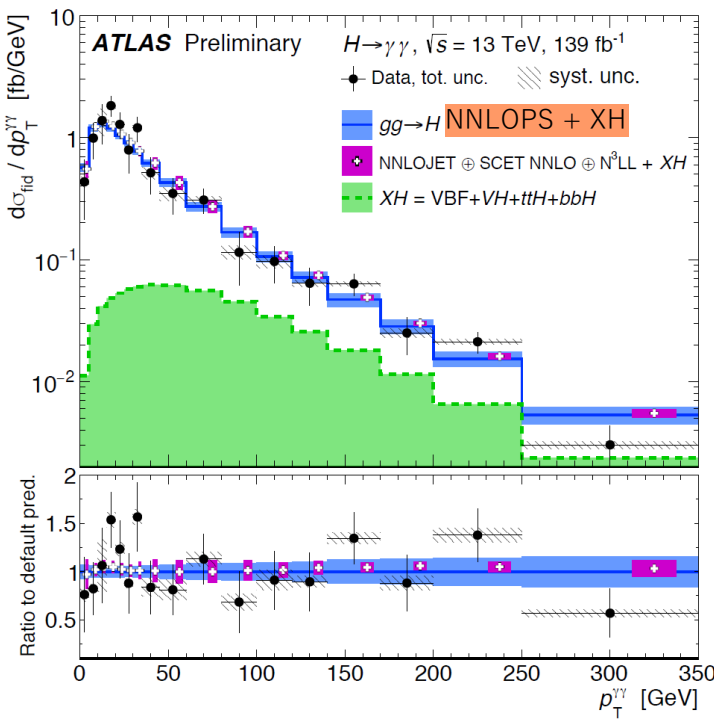
4. Compare results with theory prediction
   → generators, BSM effects..

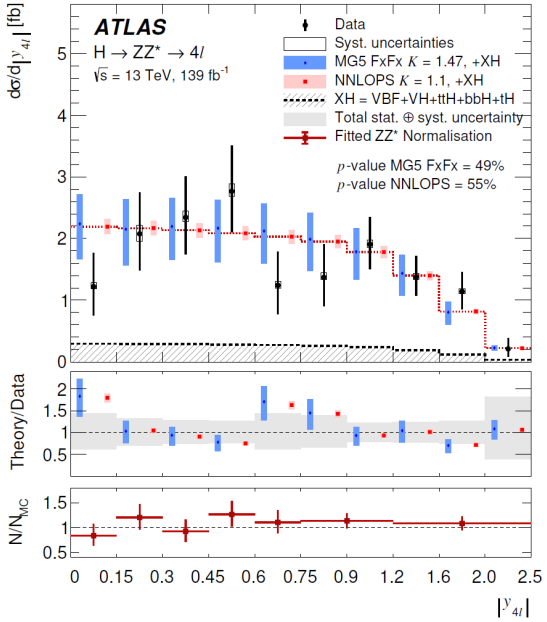


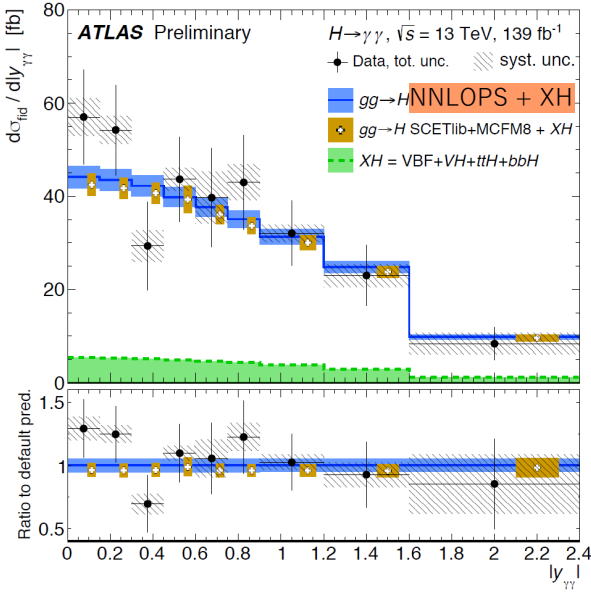
Unfolded distribution from H→ZZ and H→γγ

Eur. Phys. J. C 80 (2020) 957 ATLAS-CONF-2019-029





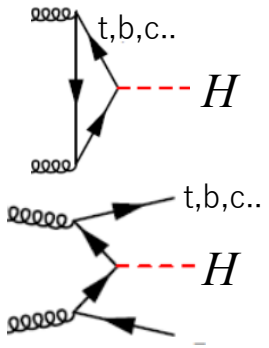


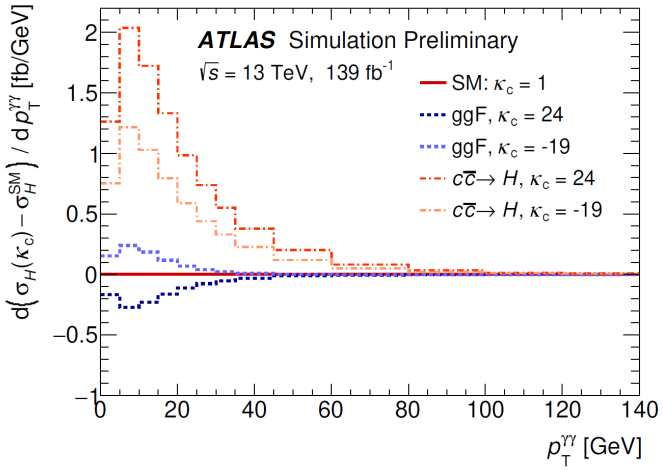


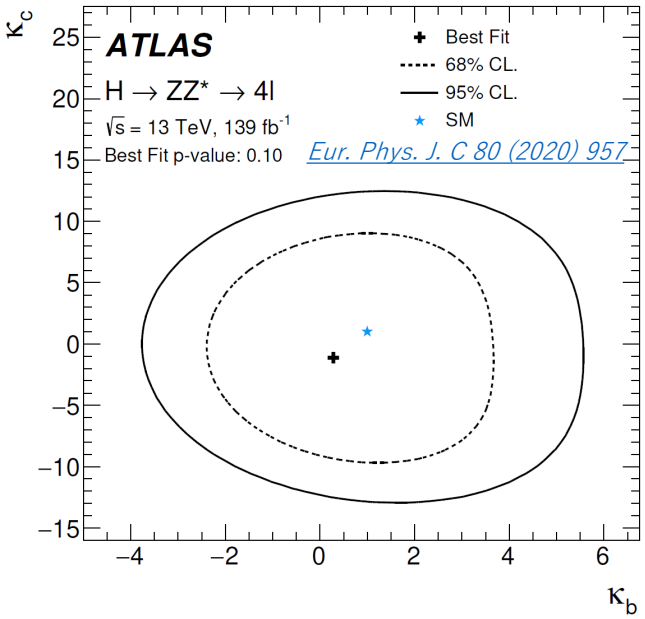
- Differential cross section of ggH + XH (VBF+VH+ttH+bbH).
- Unfolded Higgs pT and rapidity distributions are described well with current statistics
  - Consistent results between H→ZZ and H→γγ

Differential to Coupling

- Constrain on Yukawa







Limit on κ_c :

-11.7 <κ_c< 10.5 @ 95% CL

→ use only pT shape.

Tighter constrain can be set with assumptions (width and Br.)

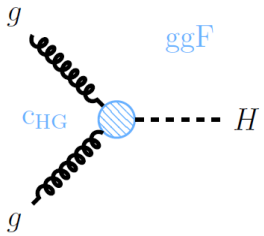
Comparable to direct search

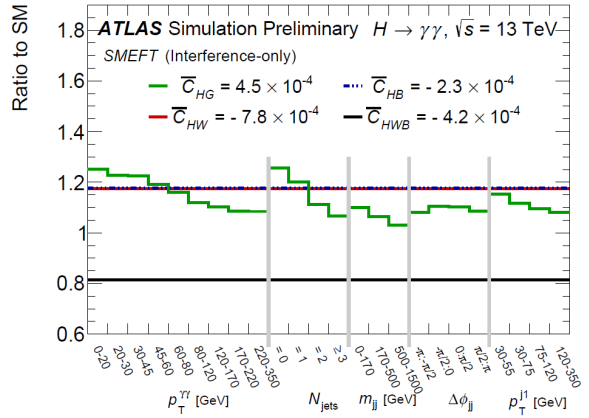
VH H→cc : $|\kappa_c|$<8.4 (12.4)@ 95% CL obs (exp)

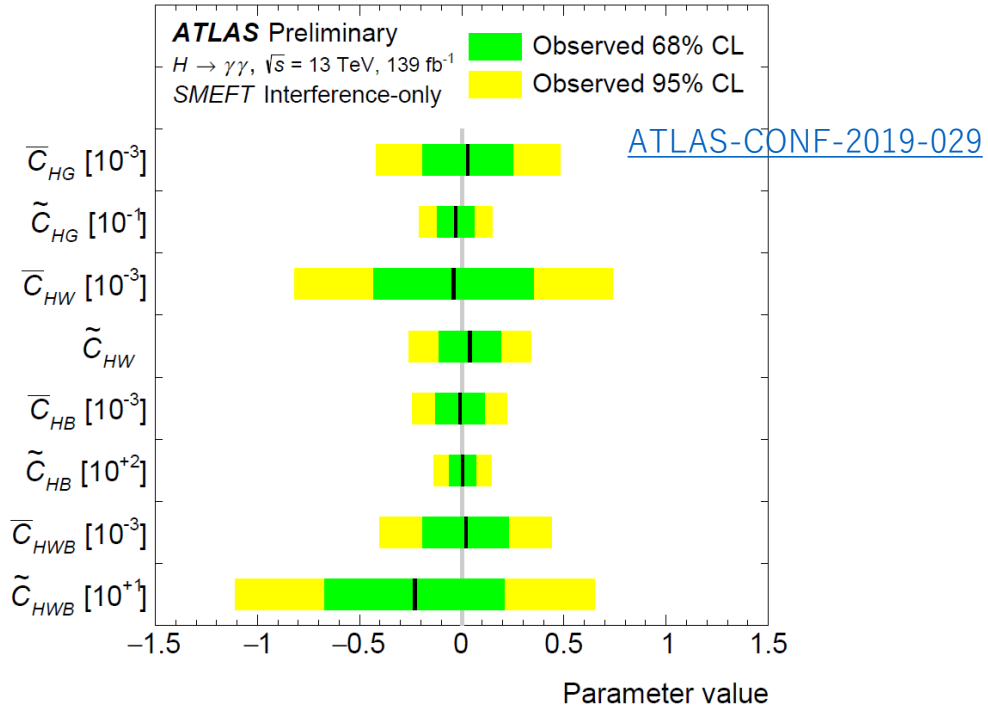
ATLAS-CONF-2021-021

- Constrain on Wilson coefficient

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





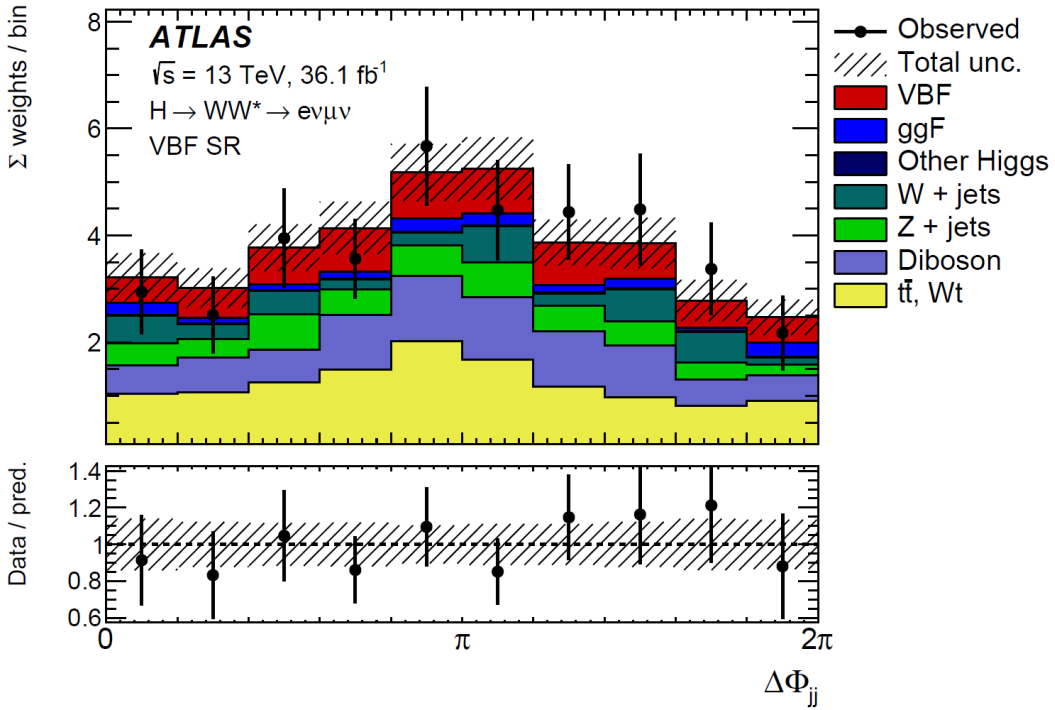


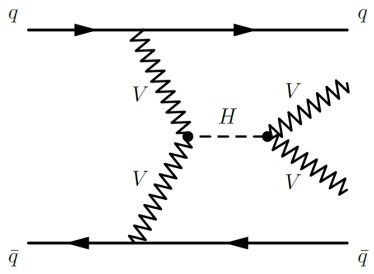
ATLAS-CONF-2019-029

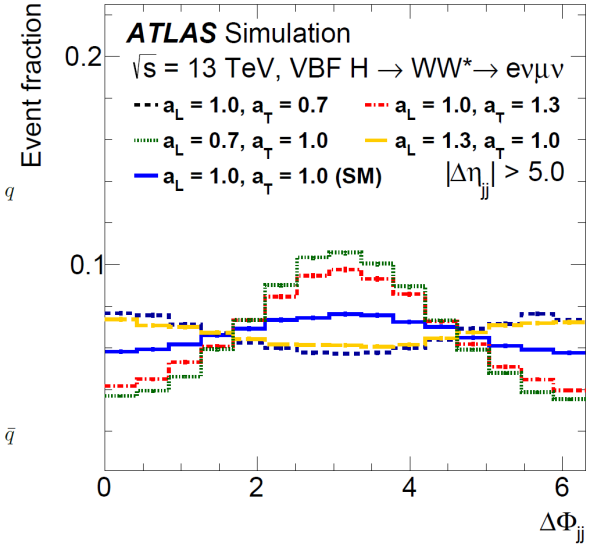
Constrain on Polarization(H→WW + 2jets)

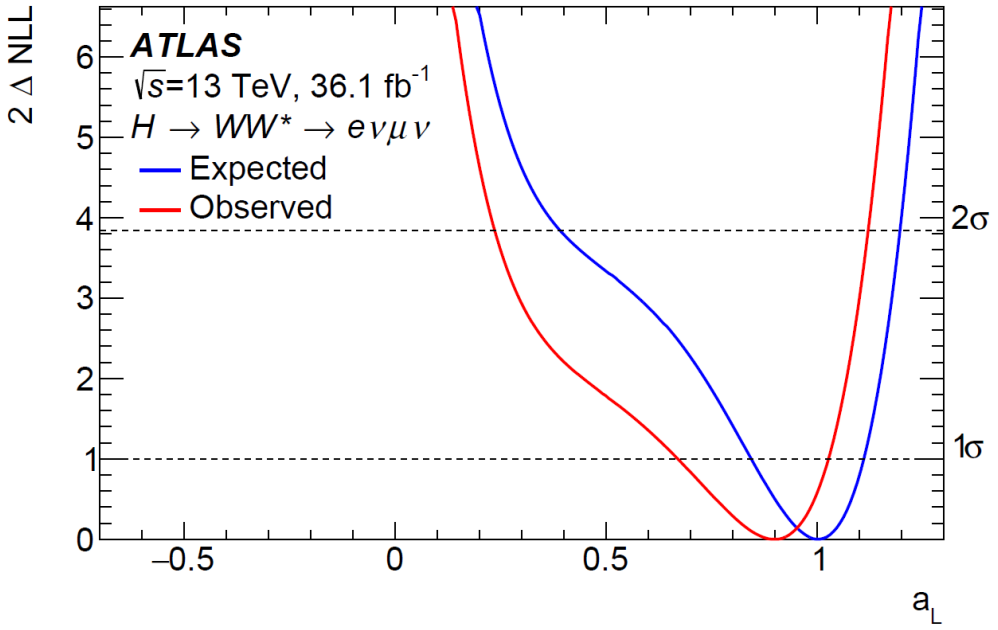
arXiv:2109.13808

- Higgs coupling form factor to polarized W and Z bosons.
- Probed on $\Delta\phi$ of two jets in Higgs VBF production.
  - ggH and VBF categories defined with BDT.









Fit on shape and rate:

Polar. Param:

(expected: $a_{L/T}$ =1.0)

$$a_{\mathrm{L}} = 0.91^{+0.10}_{-0.18}(\mathrm{stat.})^{+0.09}_{-0.17}(\mathrm{syst.})$$

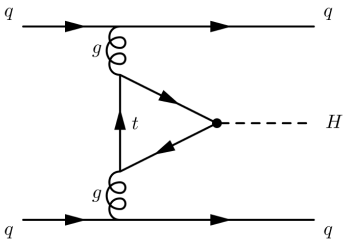
$$a_{\mathrm{T}} = 1.2 \pm 0.4(\mathrm{stat.})^{+0.2}_{-0.3}(\mathrm{syst.})$$

Constrain on CP (H→WW and ttH H→γγ)

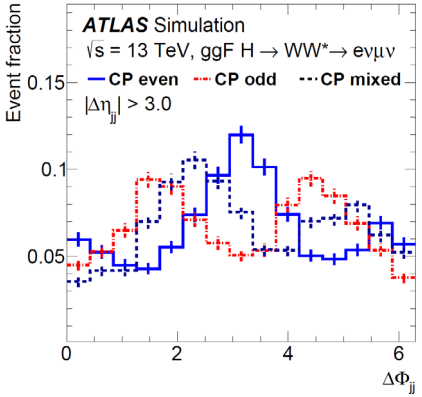
arXiv:2109.13808,
PRL 125 (2020) 061802

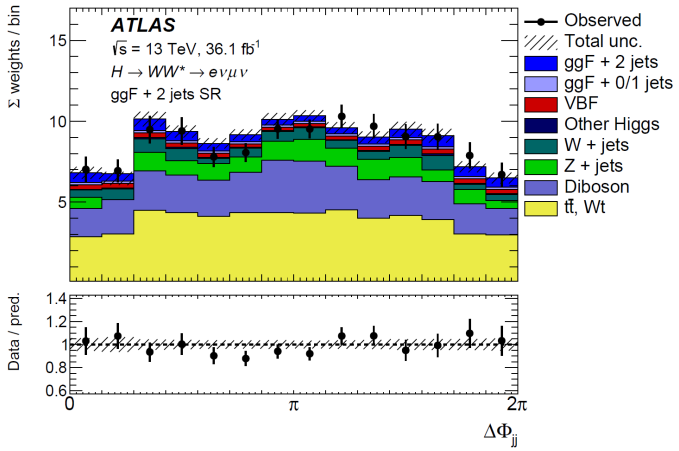
- CPV Higgs coupling inherited by Yukawa coupling.
  - Higgs-gluon vertex could have CPV.

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



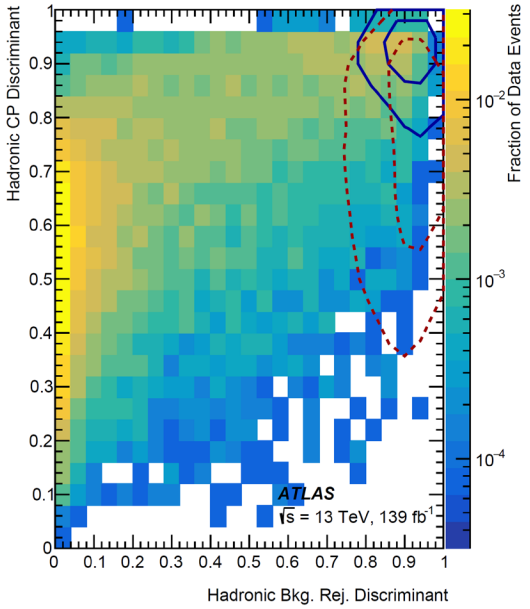
H→WW analysis

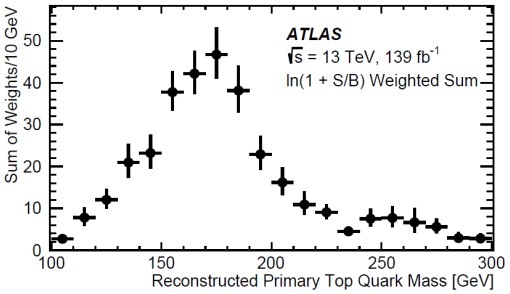


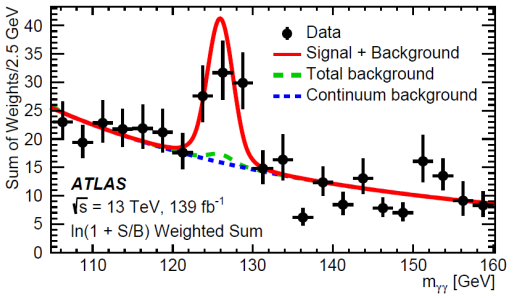


ggH category based on BDT
$\Delta\phi$ of two jets is sensitive to CP.

ttH analysis







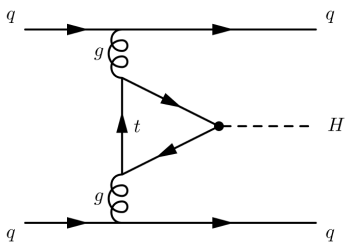
Based on ttH observation analysis
BDT for categorization and CP-even/odd separation

Constrain on CP (H→WW and ttH H→γγ)

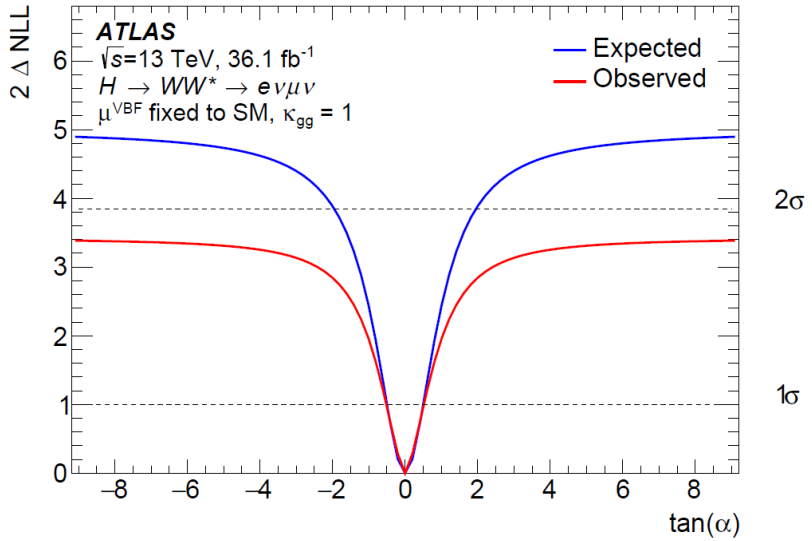
arXiv:2109.13808,
PRL 125 (2020) 061802

- CPV Higgs coupling inherited by Yukawa coupling.
  - Higgs-gluon vertex could have CPV.

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



H→WW analysis

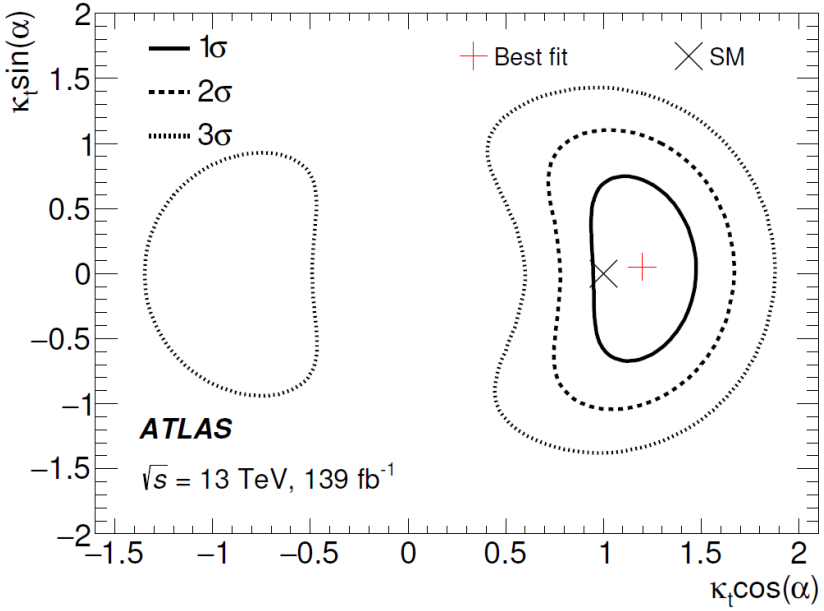


CP-mix angle α:
(expected: tan(α)=0.0)

$$\tan(\alpha) = 0.0 \pm 0.4(\mathrm{stat.}) \pm 0.3(\mathrm{syst.})$$

Similar level sensitivity

ttH analysis

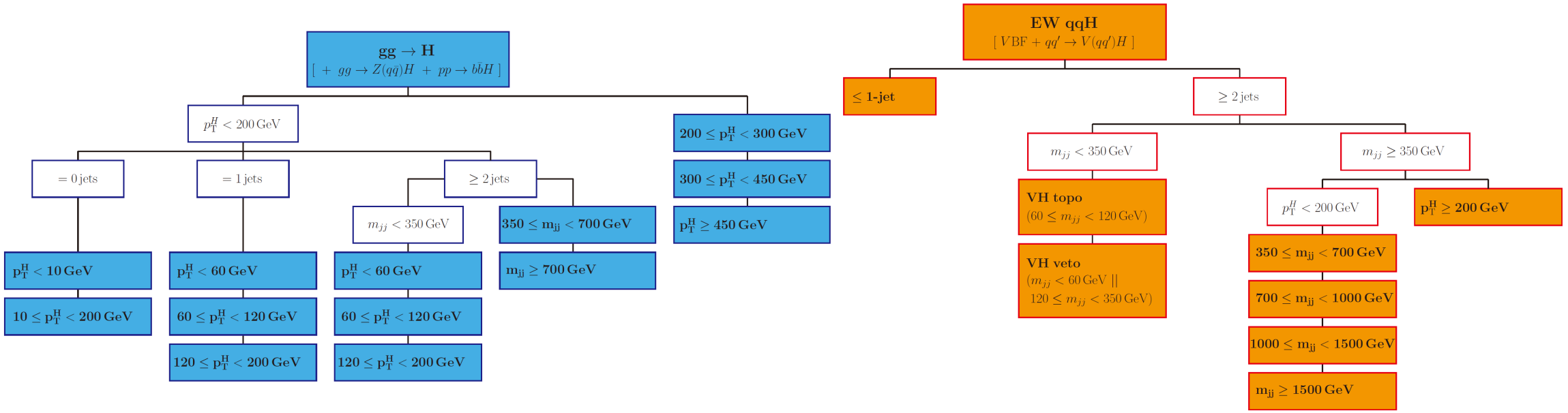


A pure CP-odd coupling is excluded at 3.9 σ
|α|<43 degree at 95%CL.

Simplified Template Cross section (STXS)

LHC Higgs WG

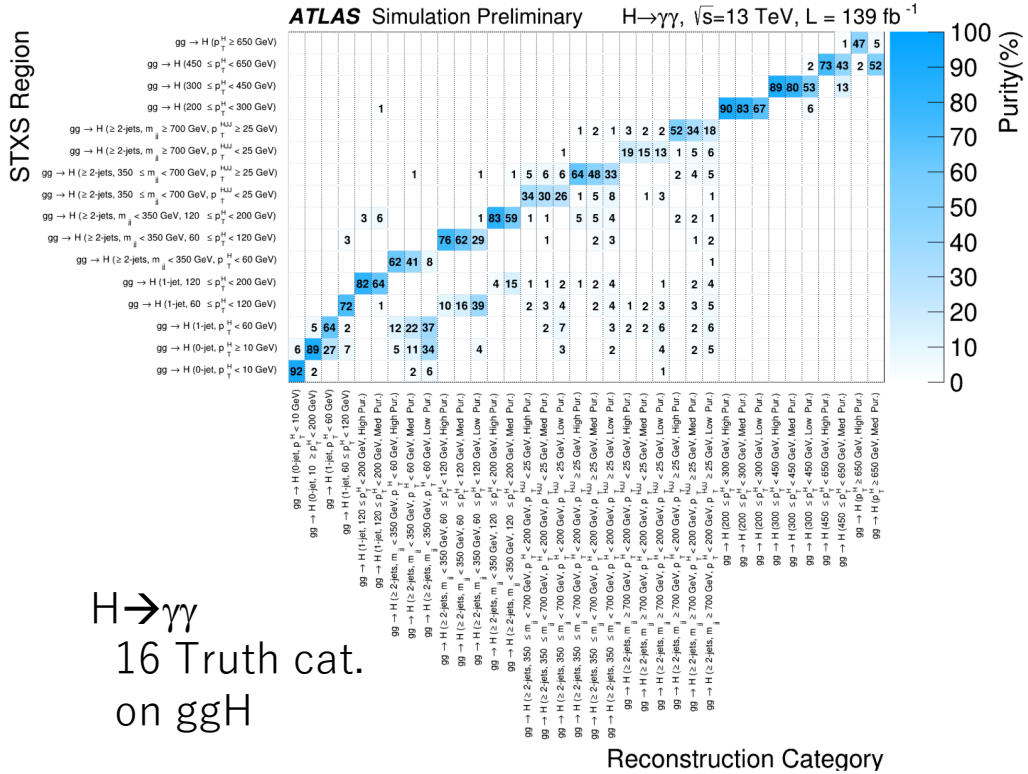
- Pre-defined truth category for **combination**
  - In order to maximize sensitivity to BSM couplings
  - Separate production processes and pT of Higgs
  - A lot of effort to reduce theory uncertainties
- Staged implementation according to statistics
  - Started with Stage-0 (kappa), now upto Stage 1.2
  - Optimize analysis in each category → maximize sensitivity



STXS analyses

	H→ZZ→4l EPJ C 80 (2020) 957	H→WW ATLAS-CONF-2021-014	H→γγ ATLAS-CONF-2020-026
STXS stage	Stage 1.1	Stage 1.2	Stage 1.2
Int. Lumi	139 fb^{-1}	139 fb^{-1}	139 fb^{-1}
# of Truth Cat	12	11	44
# of Reco Cat	12	11	88

- Ideal categorization:
  100% correlation between truth and reconstructed categories with good S/N.
- Define production processes by topology
  - Ex. Njets >=2 with b-tag→ ttH, leptonic or hadronic.
  - ggH production is divided by Njets and Higgs pT
- Use multivariate technique for categorization
  - Two step categorization in H→γγ analysis
    - Multi-class BDT to classify into STXS truth category
    - Categorize more in each class based on Signal to background



H→γγ
16 Truth cat.
on ggH

STXS results (ggH categories*)

*This is partial result.
Full set of results is available in backup

	H→ZZ→4l EPJ C 80 (2020) 957	H→WW ATLAS-CONF-2021-014	H→γγ ATLAS-CONF-2020-026
STXS stage	Stage 1.1	Stage 1.2	Stage 1.2
Int. Lumi	139 fb^{-1}	139 fb^{-1}	139 fb^{-1}
# of Truth Cat	12	11	44
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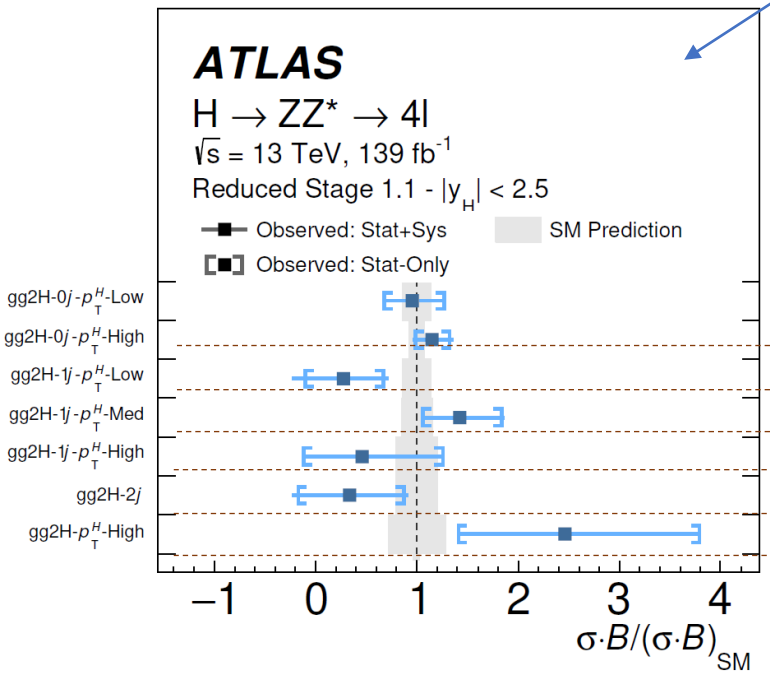
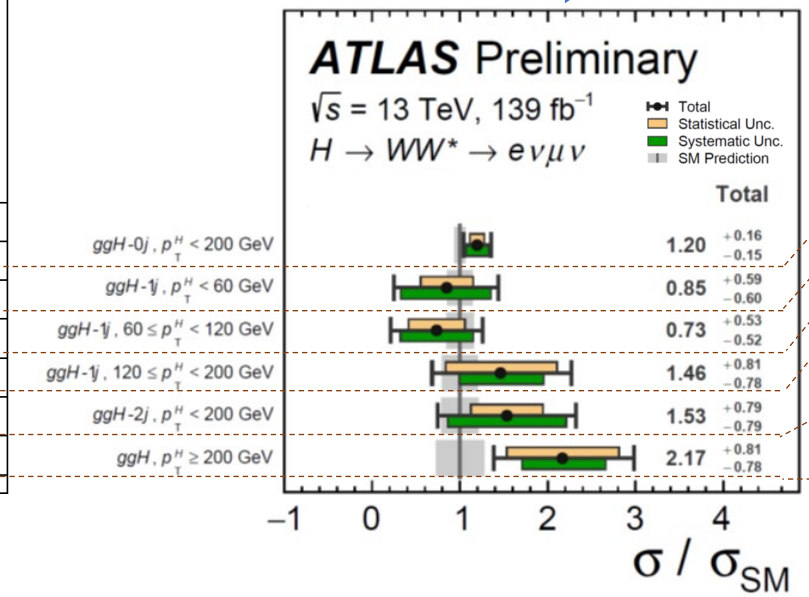
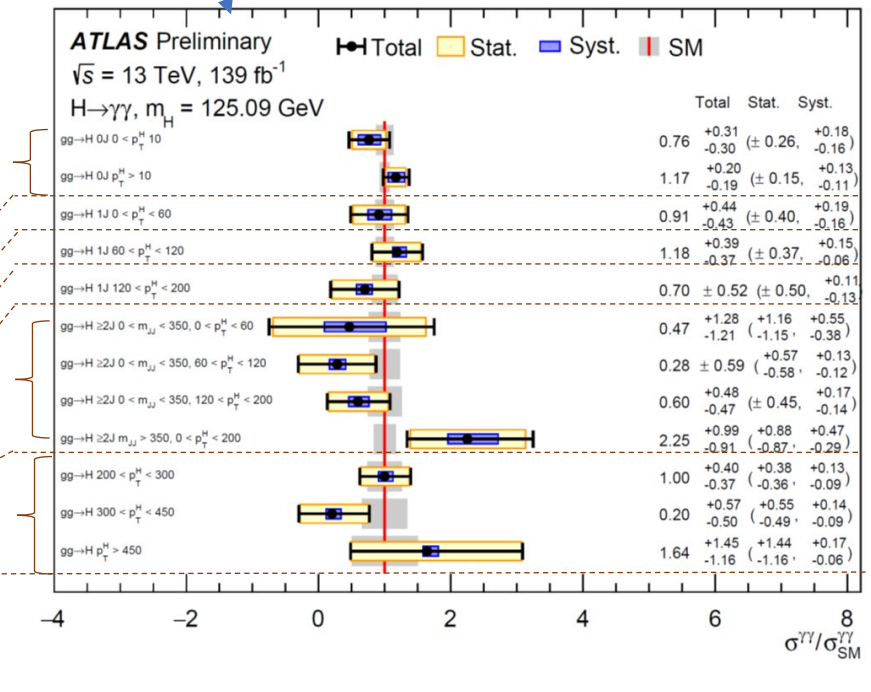


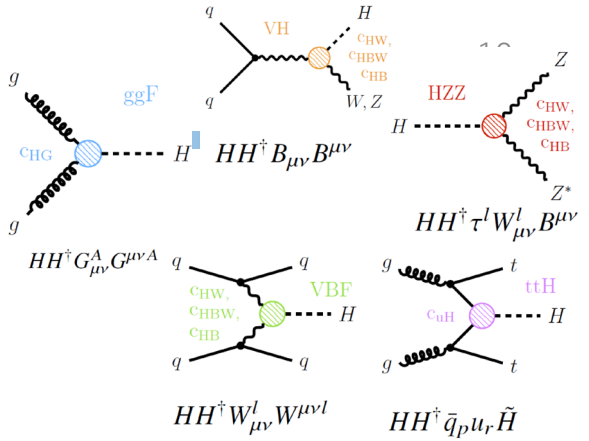




Interpretation with EFT

- Constrain on Wilson coefficients
- Result for H→ZZ→4lepton
  - Sensitive on couplings related to ggH and HZZ.
  - 2-D scans are also performed.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$



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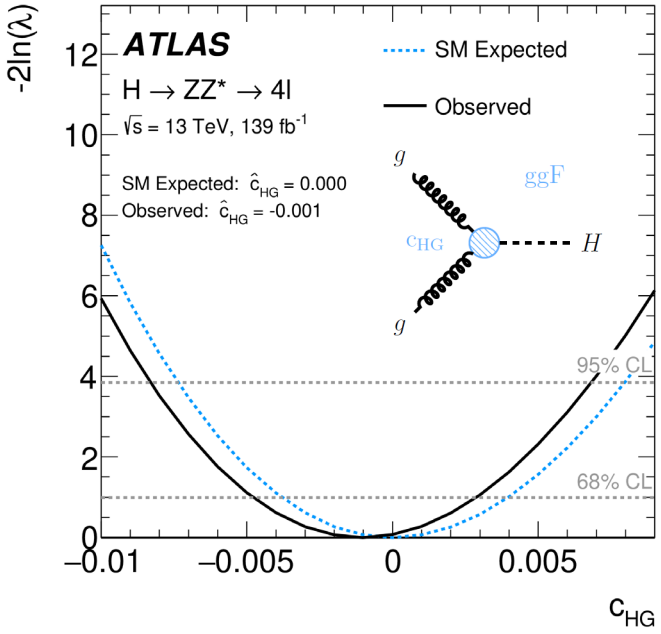
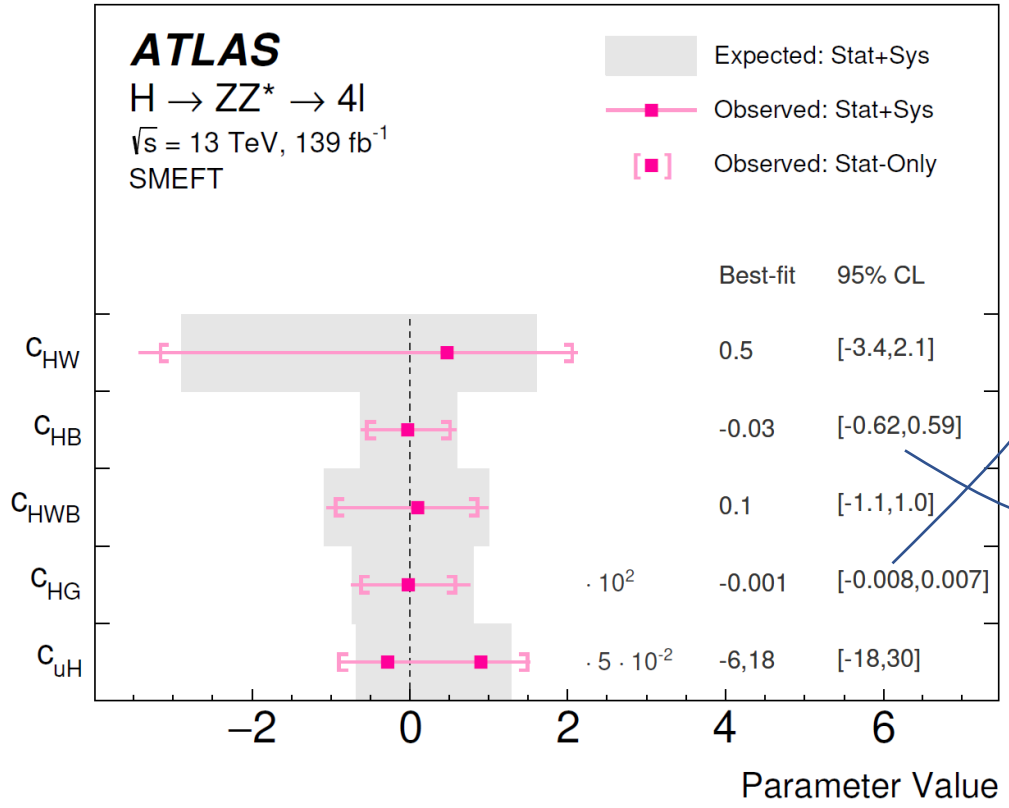
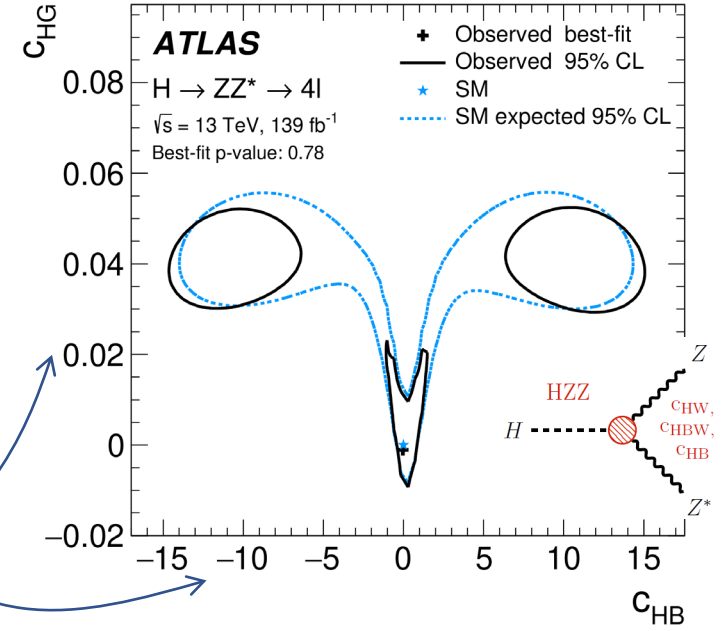






Correlation due to
- ggF amplitude and decay Br.
- VBF is also sensitive on c_{HB}

More results to come soon on H→γγ and H→WW. For combined result, see Hannes' talk.

Summary

- Measurements with H→VV from ATLAS experiment
  - **Fiducial differential cross section measurements**
  - **Simplified Template cross section measurements**

- Sensitive to various **SM and BSM couplings**:
  - Probing Yukawa coupling via top loop or ttH
  - Proving polarized coupling, CP-odd and CP-even couplings
  - Making constrain to Wilson coefficients

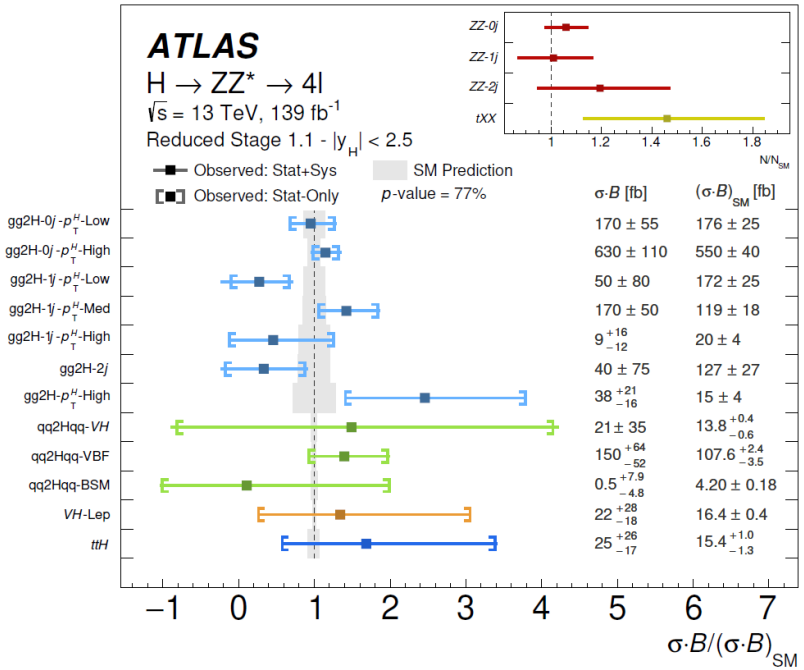
- Most of the measurements are statistically dominated.
  - Large statistics will open new and interesting phase space
  - New analysis technique / methods are being developed.

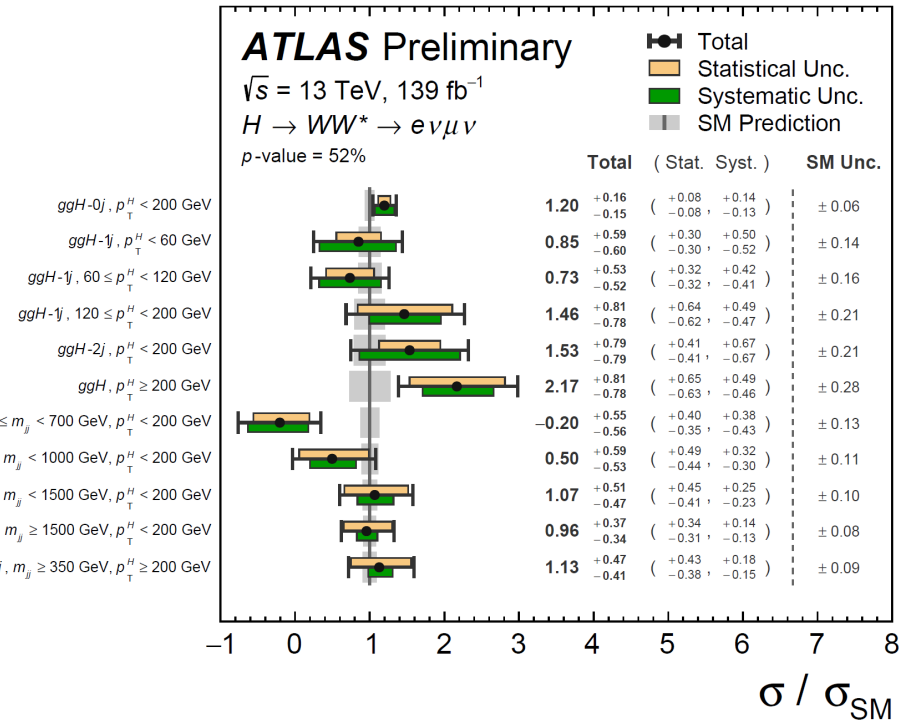
We have only 5% of full data set of 3000 fb^{-1}. Stay tuned!

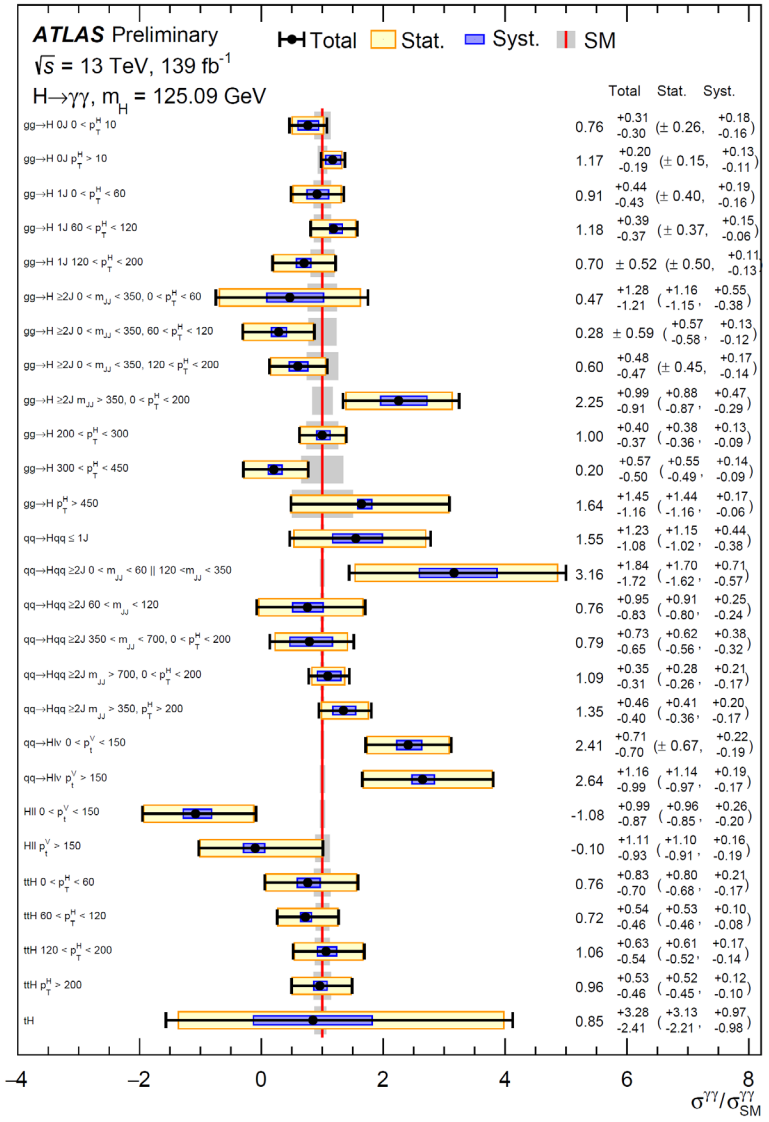
Extra materials

STXS result

H→ZZ→4l	H→WW	H→γγ
EPJ C 80 (2020) 957	ATLAS-CONF-2021-014	ATLAS-CONF-2020-026







Constrain on Yukawa Coupling

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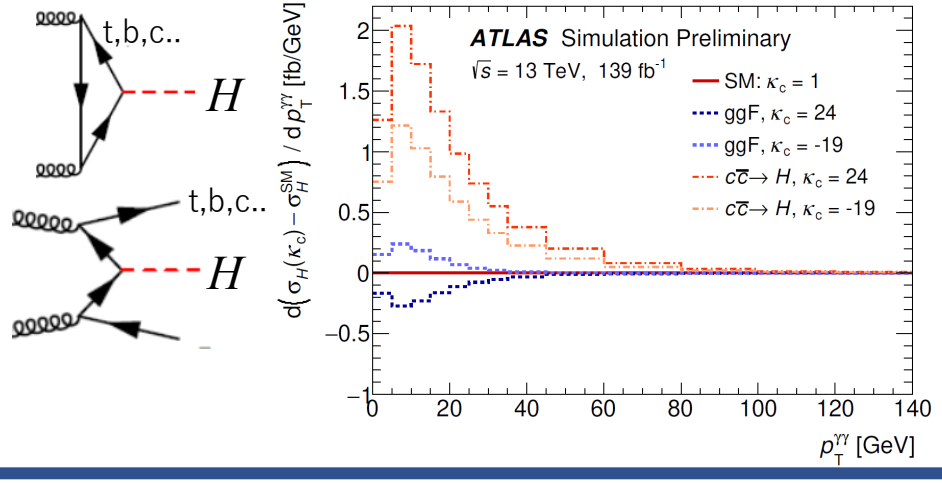
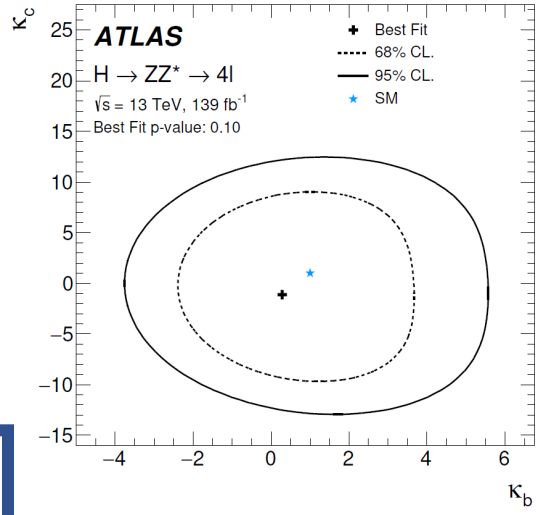
- H→ZZ→4 leptons



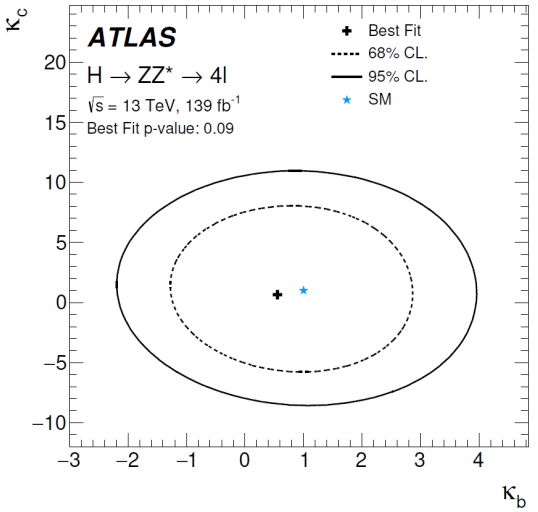
Use only pT shape:

$-11.7<\kappa_c<10.5$



Use rate and pT shape:

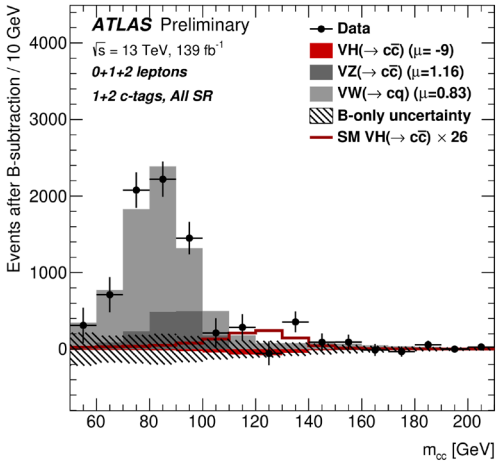
$-7.46<\kappa_c<9.27$



Direct search

VH H→cc : $|\kappa_c|<8.4\ (12.4)$ @ 95% CL obs (exp)

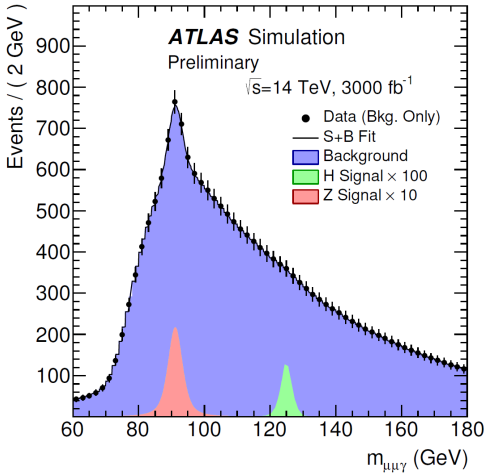
ATLAS-CONF-2021-021

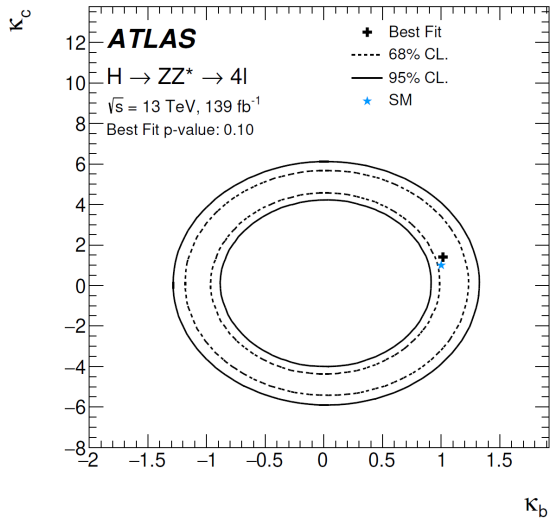


H→J/ψγ : Upper limit @95% CL

SMx15 @3000 fb-1

ATL-PHYS-PUB-2015-043





Use SM prediction on pT diff. cross section and branching ratio due to κ_c and κ_b modifications.

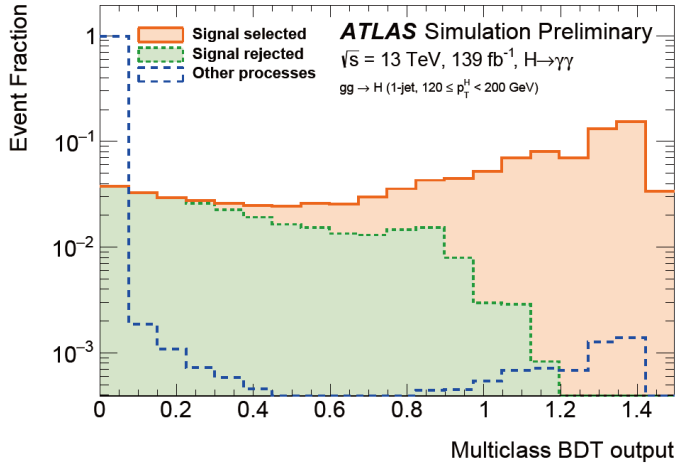
STXS categorization in H→γγ

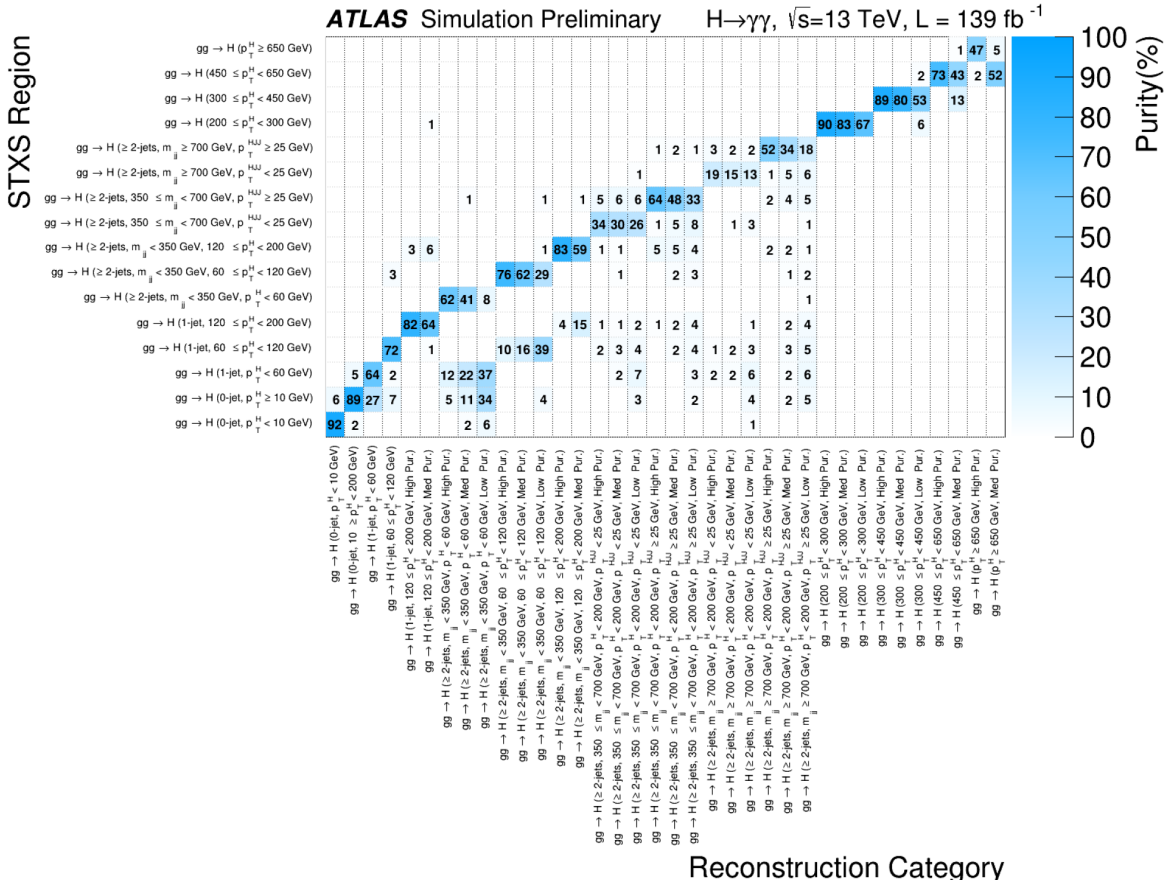
ATLAS-CONF-2020-026

- Ideal case: 100% correlation between truth and reconstructed categories and good S/N.

Step-1: multi-class BDT for STXS bin

- LightGBM package + optimization
- input var: pT, η, angles of γ, jets, leptons, E_T^{miss}, etc

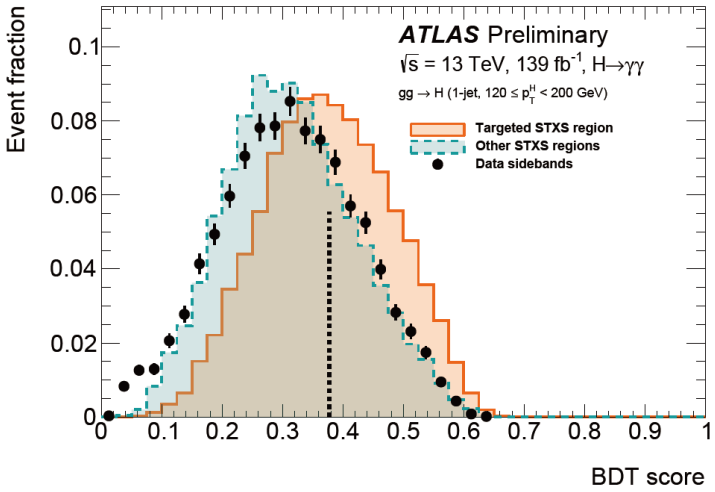




Step-2: binary BDT to categorize more based on S/N

Training: signal = target Higgs process

BG = other Higgs + SM BG



Upto three categories

In total:

- 44 truth categories
- 88 reco. categories

In each category, perform un-binned fit on $m_{\gamma\gamma}$ distribution.

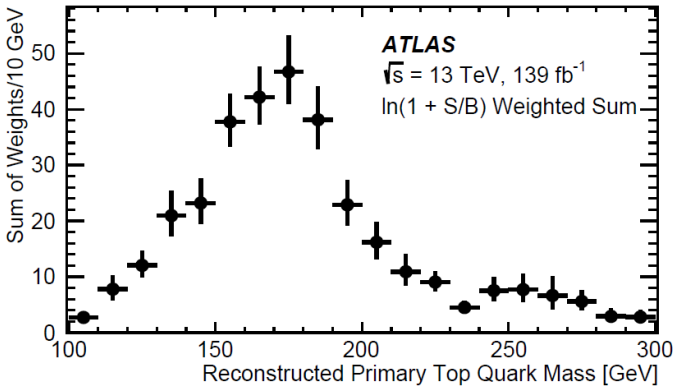
ttH H→γγ CP analysis

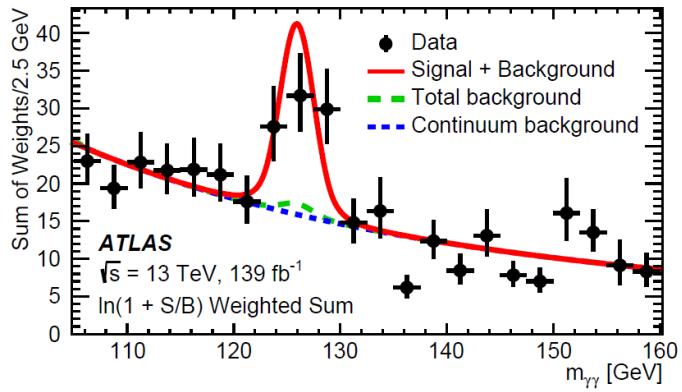
[Phys. Rev. Lett. 125 (2020) 061802]

- CPV term in Yukawa coupling are not suppressed.

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

- Based on ttH observation analysis



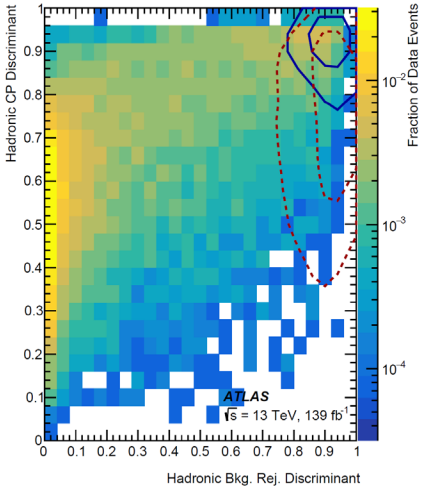


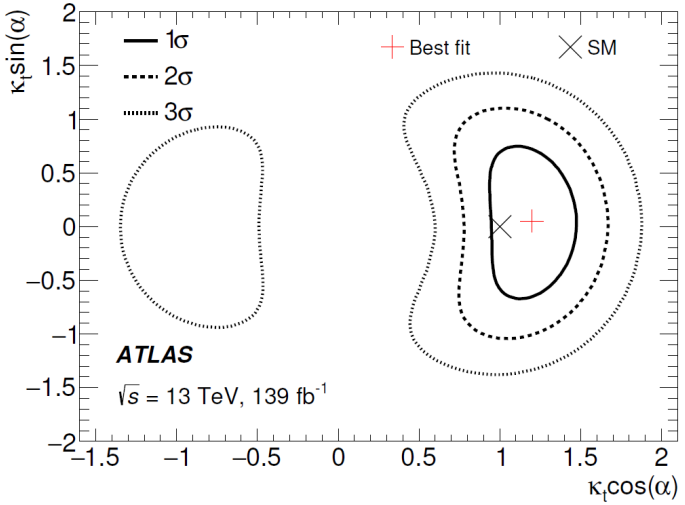
Top reconstruction
- leptonic and hadronic channels
- BDT to obtain best combination

Two BDTs for event categorization
- BG suppression
  - H→γγ vs γ+jet, tt+γγ
- CP discriminant
  - CP-even vs CP-odd

→ 12 categories for Had modes
8 categories for Lep modes

Final discriminant: $m_{\gamma\gamma}$
Make simultaneous fit.



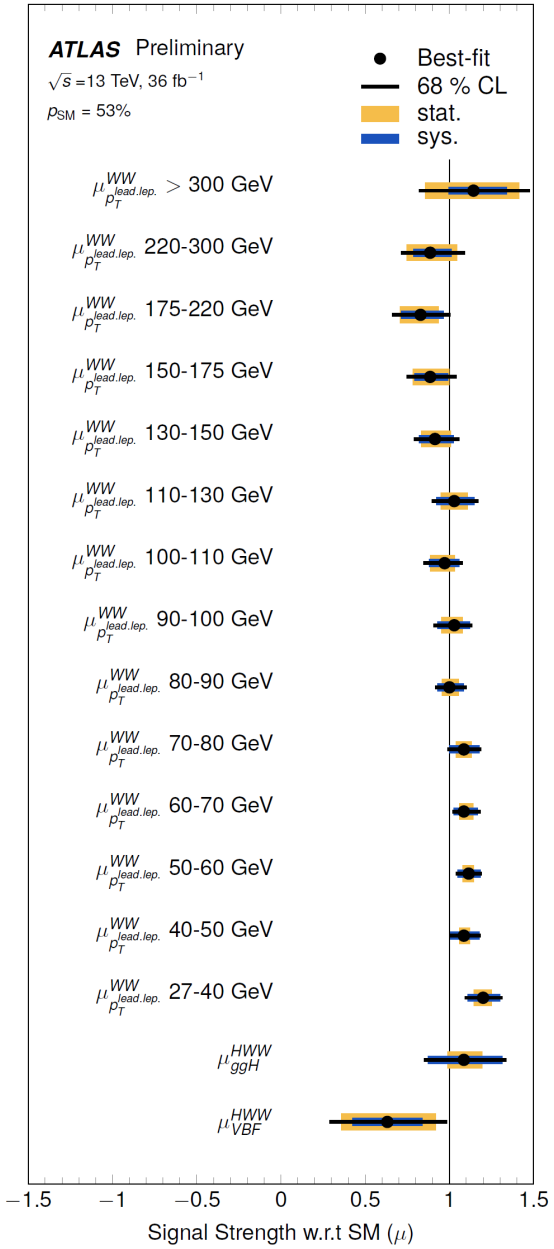


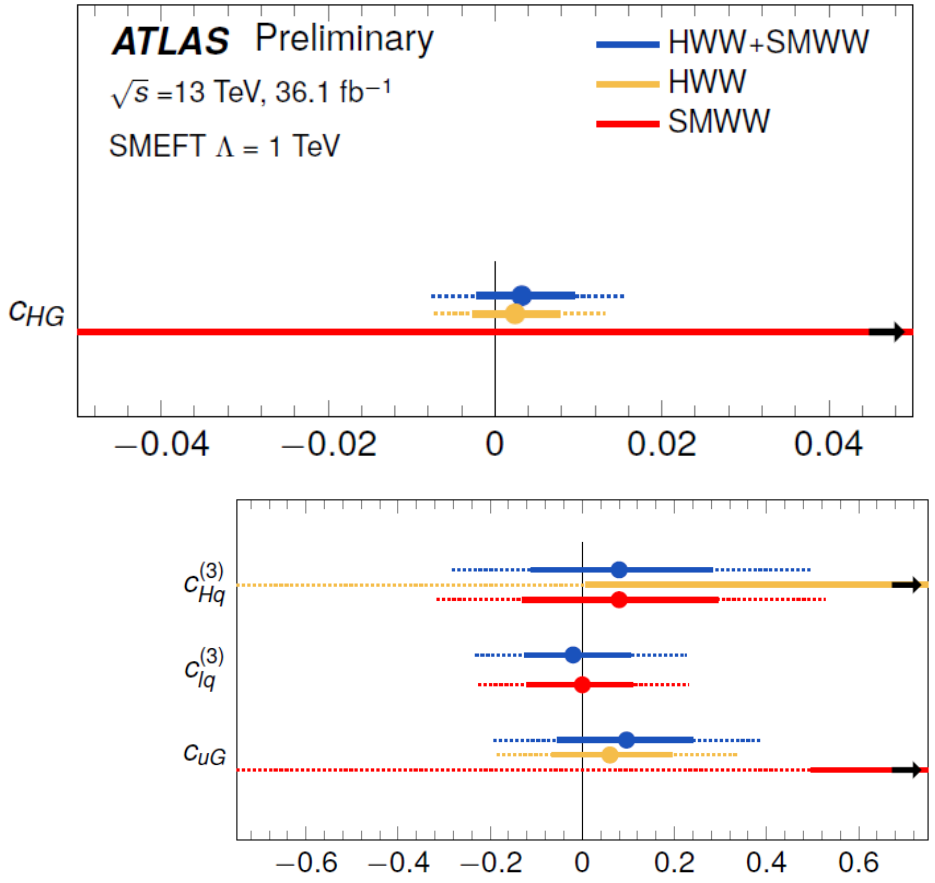
A pure CP-odd coupling is excluded at 3.9 σ
$|\alpha|<43$ degree at 95%CL.

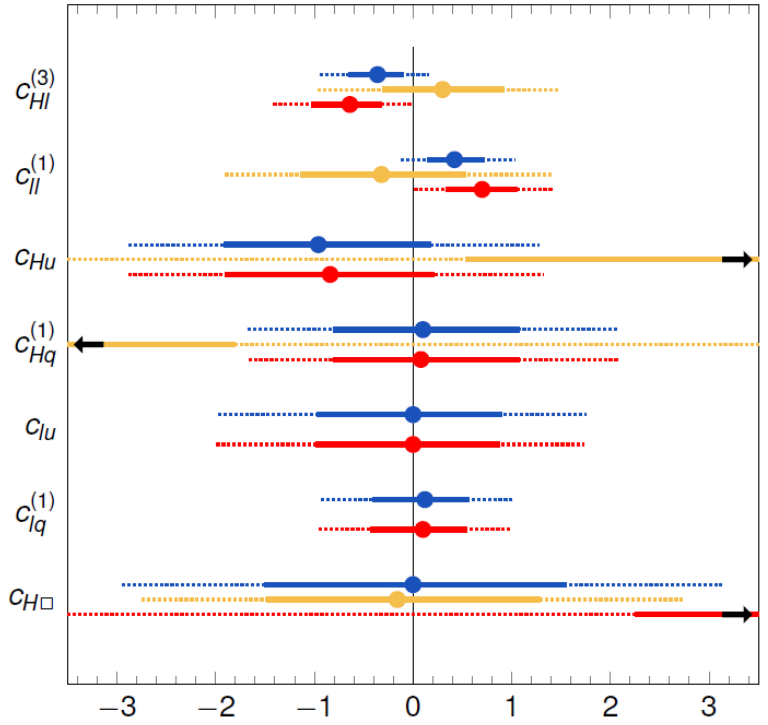
Differential to EFT result with H→WW

- Include interference between H→WW and WW

ATL-PHYS-PUB-2021-010



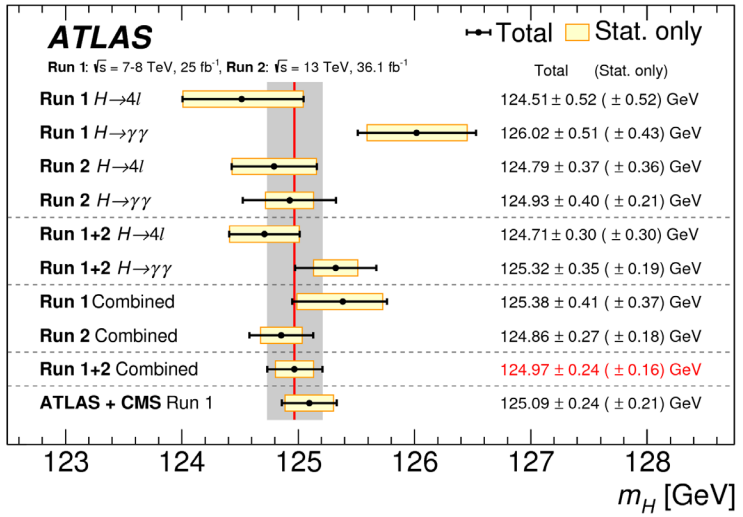




Higgs Mass measurement

- HZZ and Hγγ 36 fb-1

[Phys. Lett. B 784 (2018) 345]

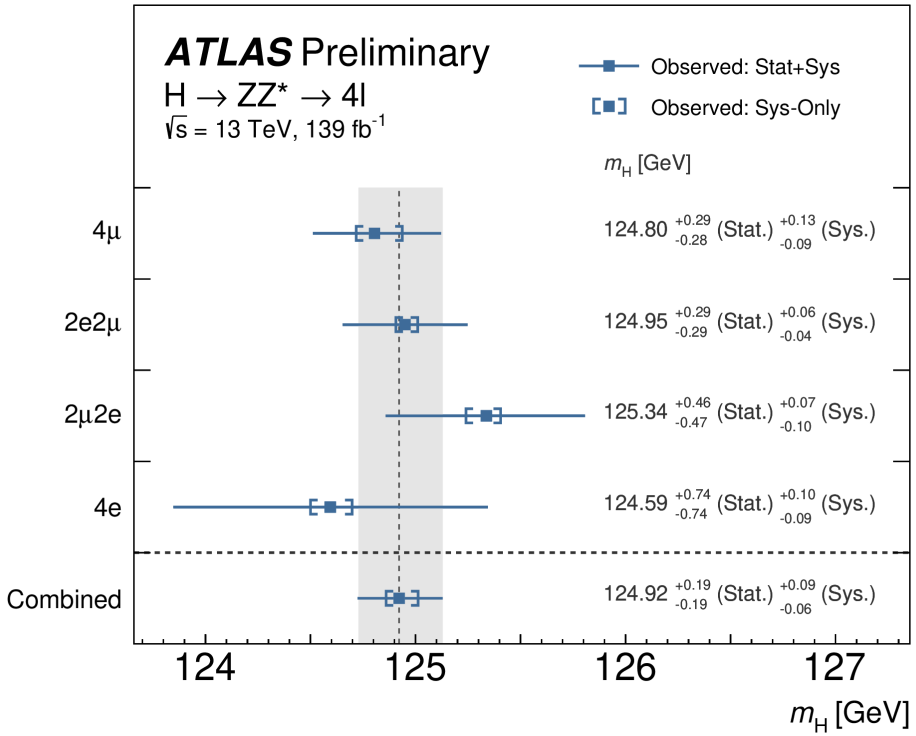


- HZZ 139 fb-1

[ATLAS-CONF-2020-005]

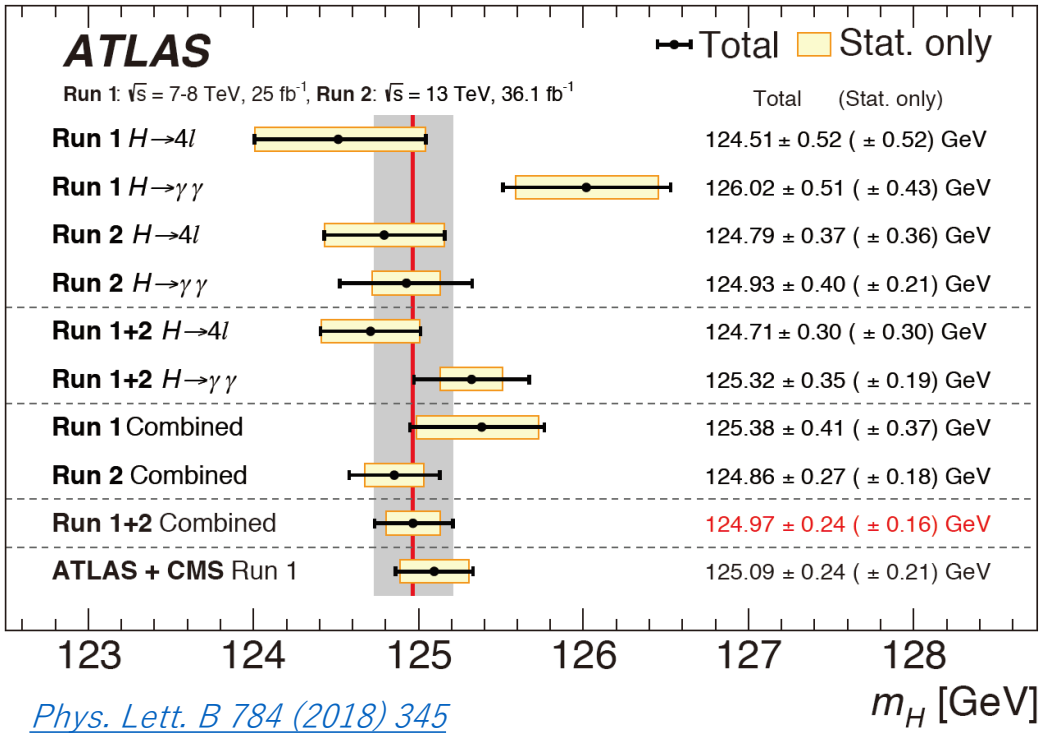
- Combined is the best.

Systematic Uncertainty	Impact (GeV)
Muon momentum scale	+0.08,−0.06
Electron energy scale	±0.02
Muon momentum resolution	±0.01
Muon sagitta bias correction	±0.01

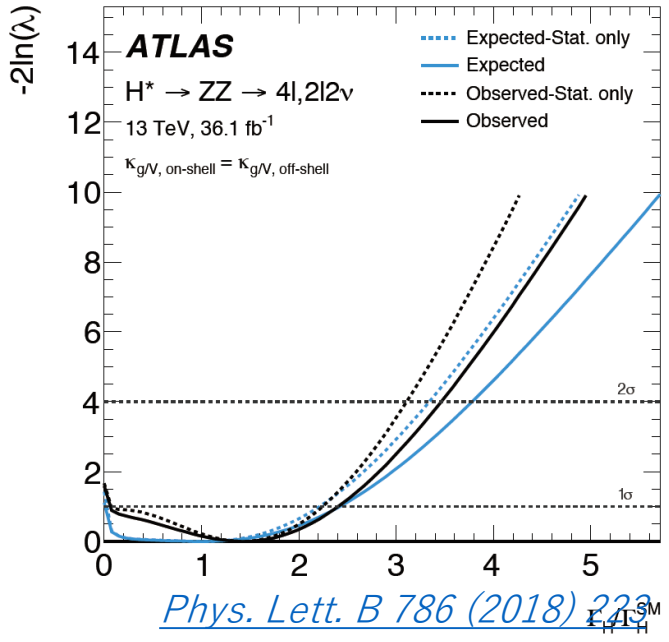


Higgs Properties

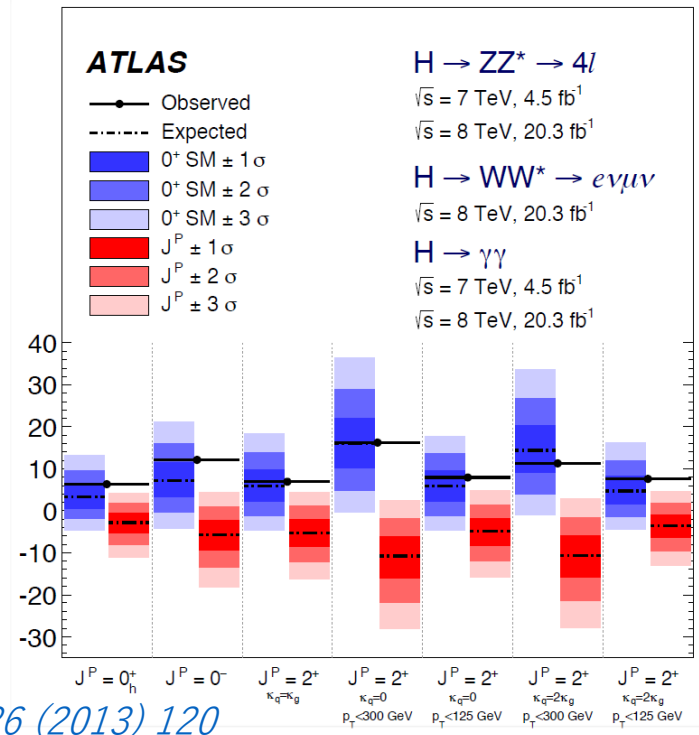
- Mass： 124.97 ± 0.24 GeV
- Width: < 14.4 MeV (Expected 4.2 MeV)
  - Indirect: 15.2 MeV
- Spin-parity: $J^{PC} = 0^{++}$



Phys. Lett. B 784 (2018) 345



Phys. Lett. B 786 (2018) 223



Phys. Lett. B 726 (2013) 120