BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY
ATLAS EXPERIMENT

Measurements of the Higgs boson couplings / cross sections and their interpretations at the ATLAS experiment

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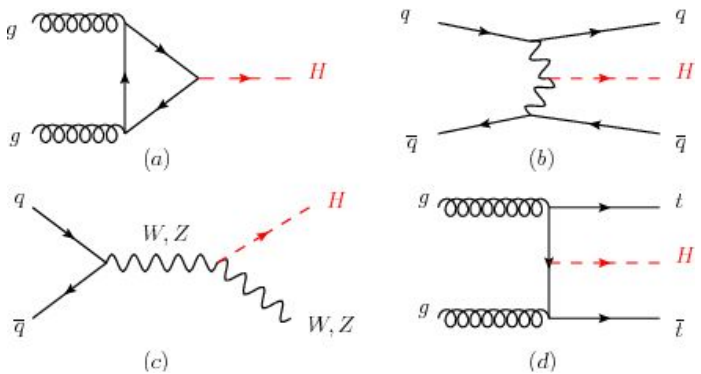
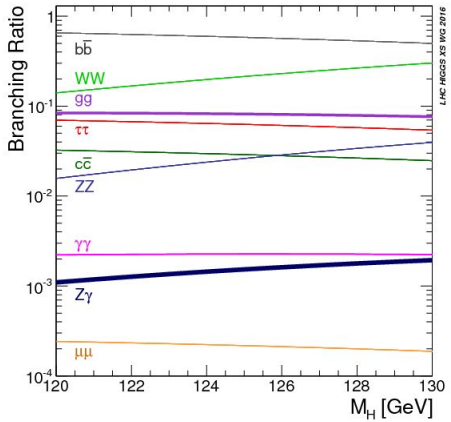
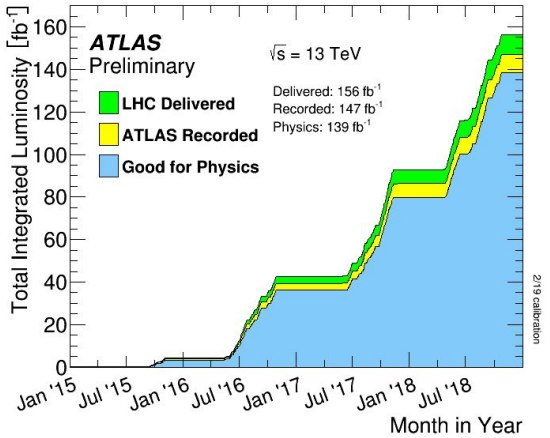
Introduction

- The Higgs boson in the Standard Model (SM) are produced with several major production modes at LHC, where ggF, VBF, WH, ZH, ttH+tH have higher signal sensitivities.
- Higgs boson decays to various final states with different branching ratios.
- Measurements are based on the full LHC Run 2 dataset with the ATLAS detector
  - It records 139 fb^{-1} of good pp collision data at 13 TeV, with about 8 million Higgs bosons







Outline

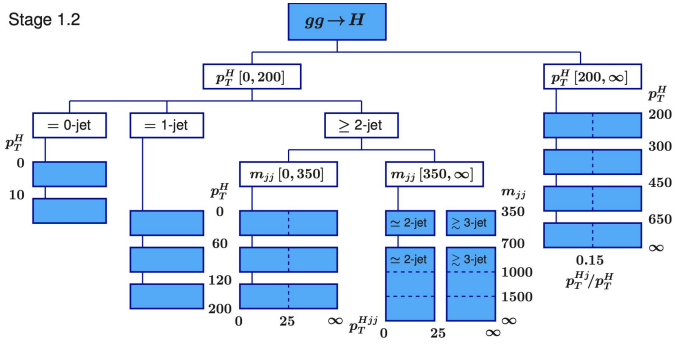
- This talk presents the measurements of the Higgs boson couplings / cross sections and their interpretations at the ATLAS experiment
- Presenting the Higgs coupling measurements in the following individual channels:
  - Higgs to $\gamma\gamma$: CERN-EP-2022-094
  - Higgs to ZZ* to 4 leptons: EPJC 80 (2020) 957
  - ggF and VBF, Higgs to WW* to $e\nu\mu\nu$: CERN-EP-2022-078
  - WH and ZH, Higgs to bb: EPJC 81(2021)178, boosted Higgs to bb PLB 816(2021)136204
  - Higgs to $\tau\tau$: CERN-EP-2021-217
- These and a few other measurements are included in combined measurement: Nature 607 (2022) 52-59
- Presenting the following interpretation results
  - Interpretation in terms of Higgs coupling strengths: Nature 607 (2022) 52-59
  - Interpretation within the SM effective field theory: ATLAS-CONF-2021-053

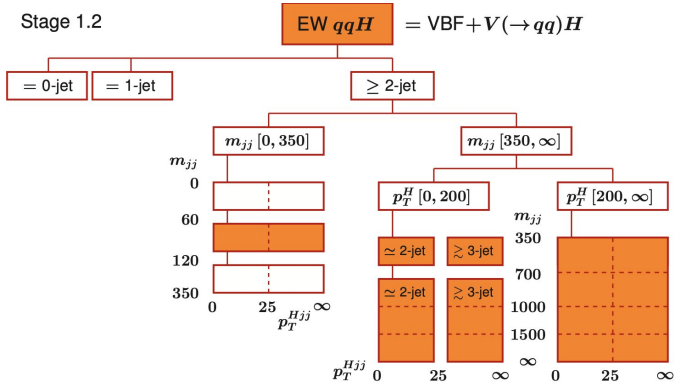
- Note: The Higgs fiducial / differential cross-section measurements are summarized in CERN-EP-2022-143
- There are other measurements and important Higgs decay searches used in the combination. (H→μμ, H→Zγ, H→cc)

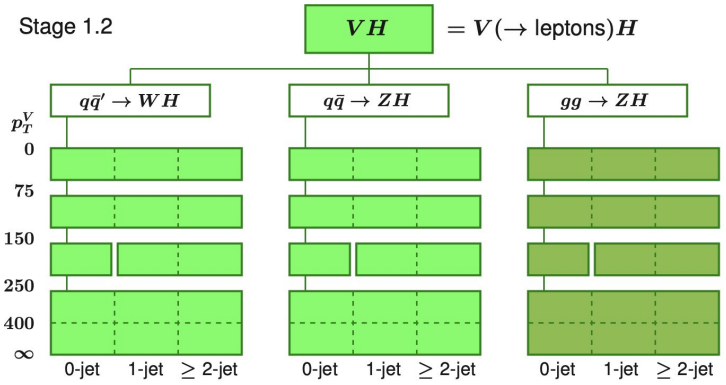
The Simplified Template Cross Sections (STXS)

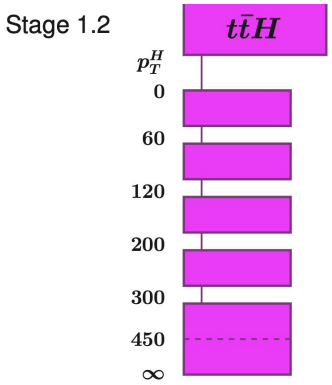
- The simplified template cross section (STXS) framework introduces the **Higgs cross section measurements in various kinematic regions** in an optimized way matching the following requirements:
  - **Fine-grained measurements** for individual Higgs production modes in various kinematic regions
  - **Reduced theoretical uncertainties** that are directly folded into the measurements.
  - Allowing the **combination of measurements** in different decay channels and eventually between experiments.

The Simplified Template Cross Sections (STXS)







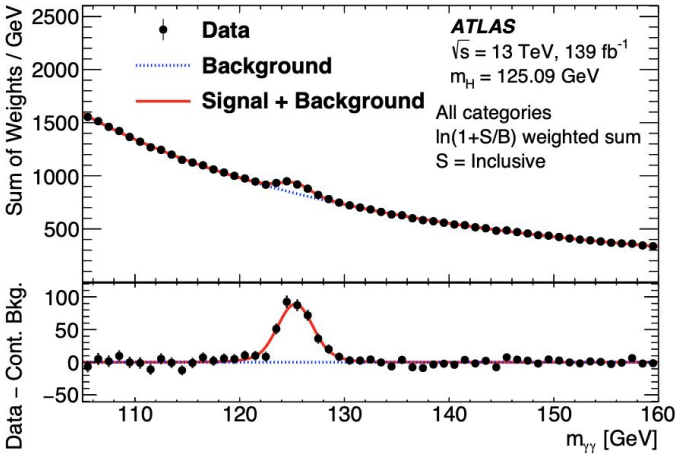


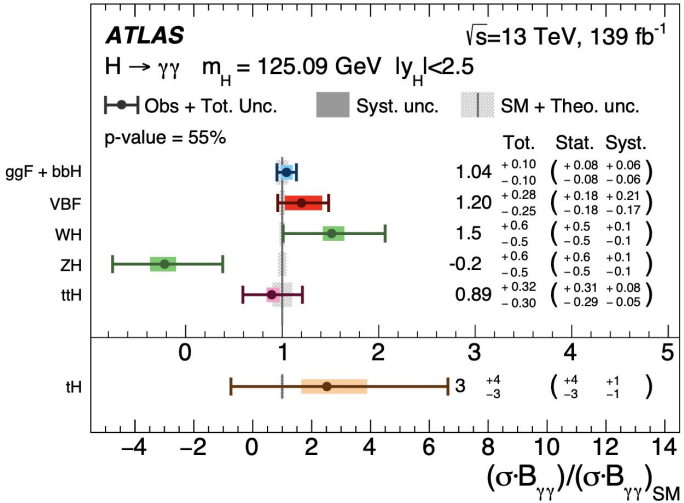
Variables: production modes, Higgs pT, Higgs+jet pT or Higgs+dijet pT, number of jets, mass of di-jet, vector boson pT

Higgs to γγ

- The analysis selects **two isolated photons**, then it defines **orthogonal multi-class MVA categories** targeting different STXS truth regions.
- Main background: non-resonant γγ, γ-jet, dijet, Vγγ, ttγγ
- An unbinned simultaneous S+B fit is performed on **m(γγ)**

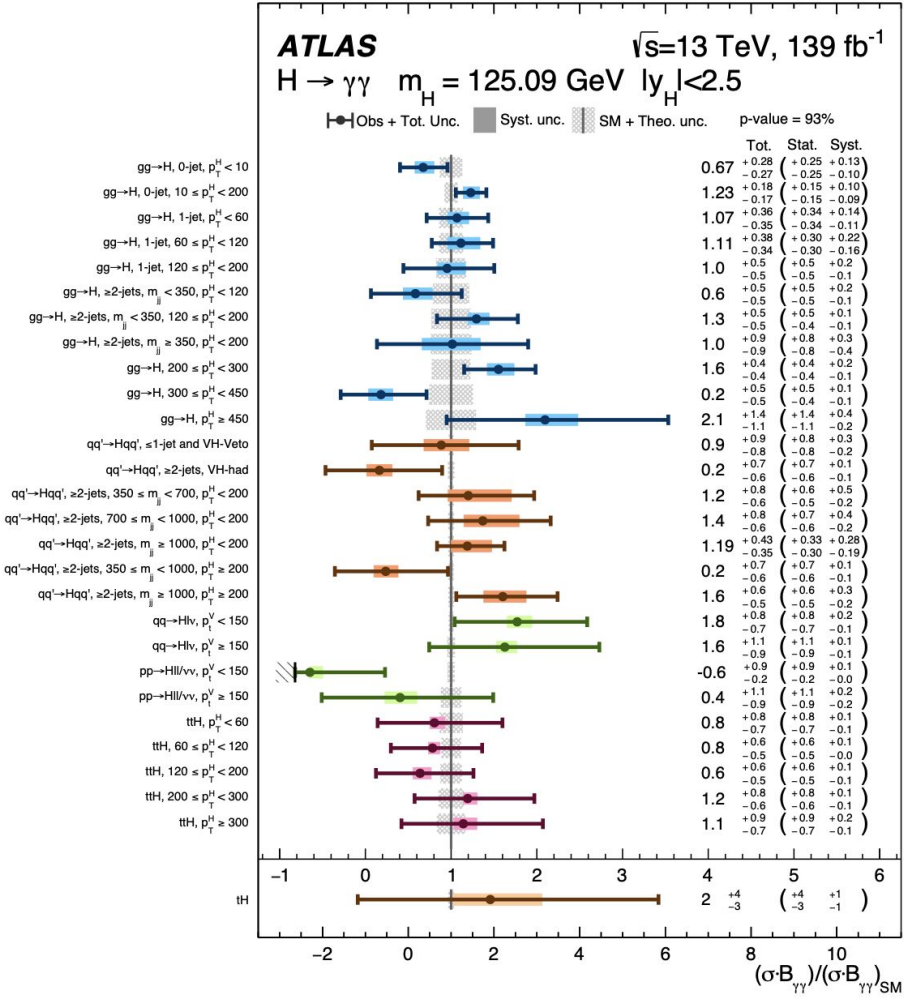
$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.}).$$





Higgs to γγ

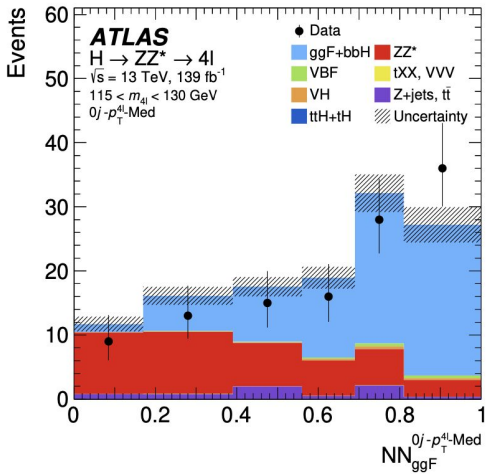
- This page shows the STXS results.
- The γγ channel has good signal sensitivity in high Higgs boson transverse momenta and ttH/tH regions

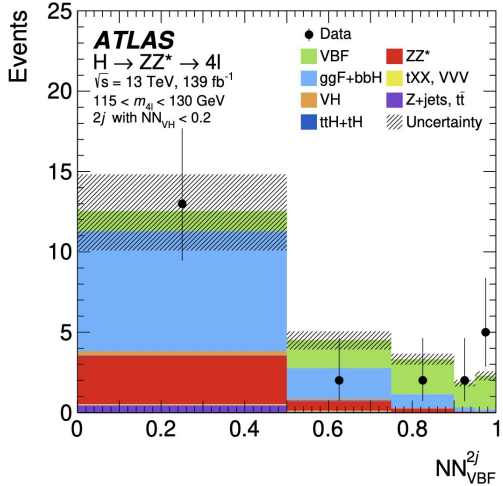


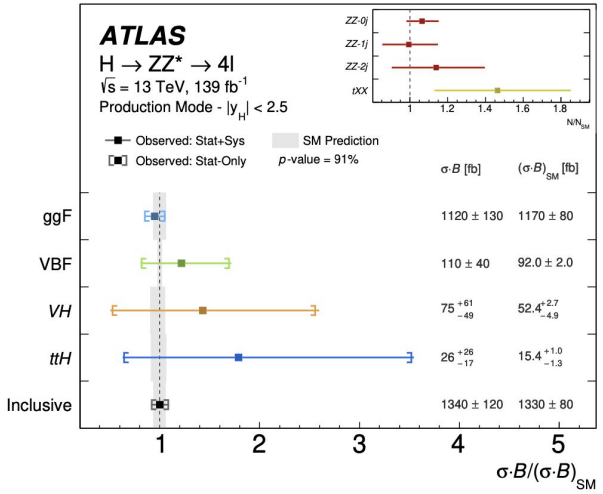
Higgs to ZZ* to 4l

- Selecting **4 leptons**, with a leading lepton pair in the **Z mass window** and m4l in the **Higgs mass window**. Cut-based categories targeting STXS regions.
- Main background: SM ZZ*, tt, Z+jets
- A binned S+B fit is performed on the **NN scores** for different production modes

xs/xs_SM = 1.01±0.08(stat)±0.03(exp)±0.02(th)

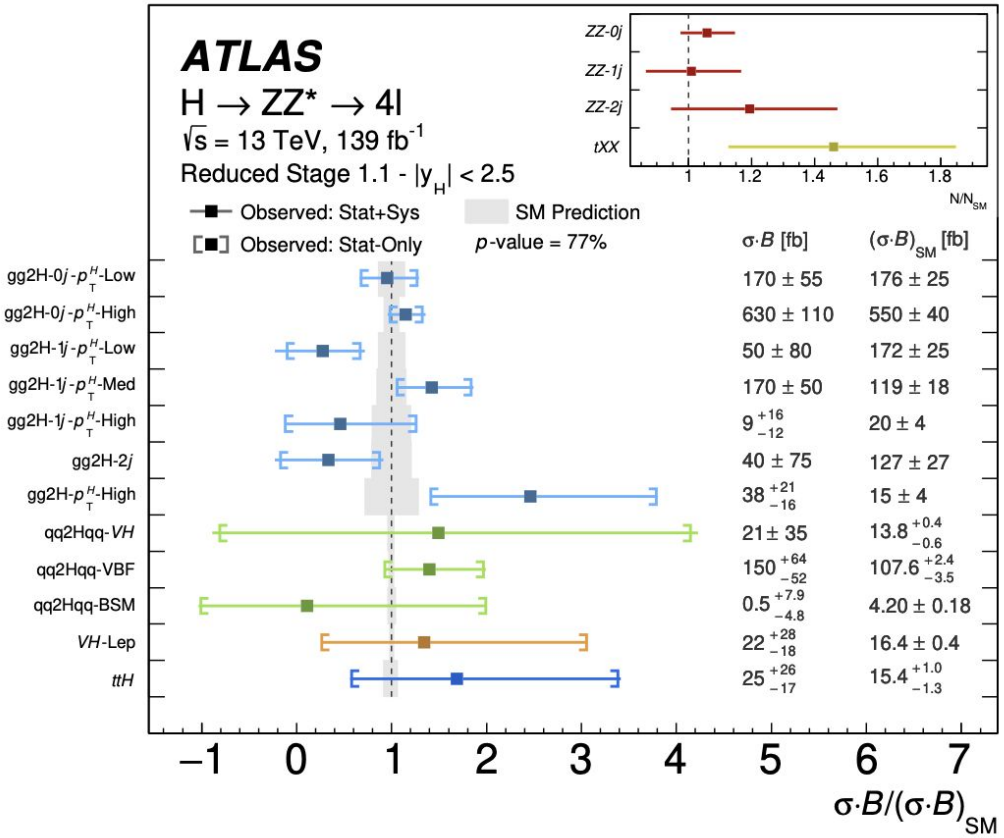






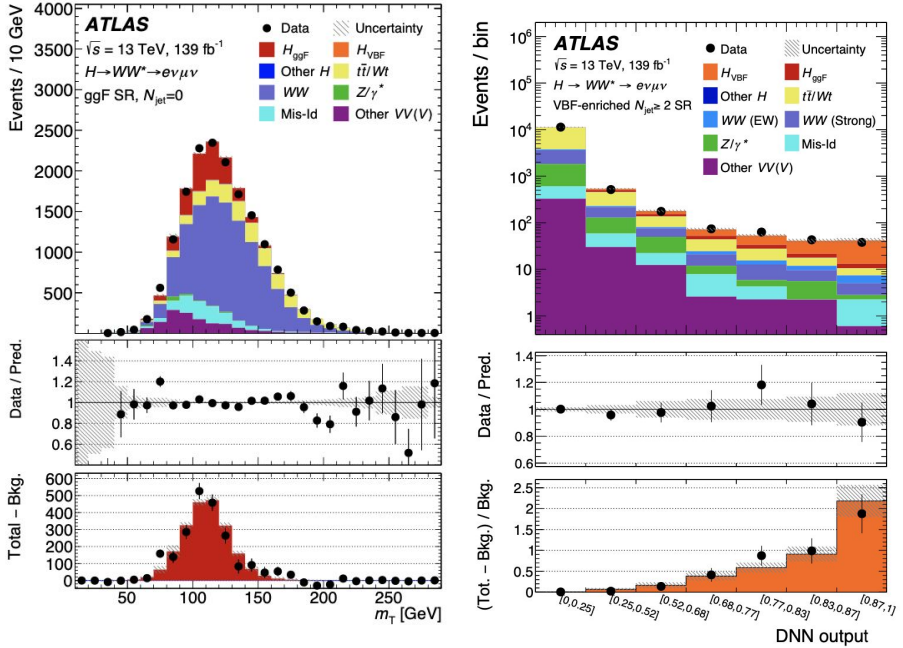
Higgs to ZZ* to 4l

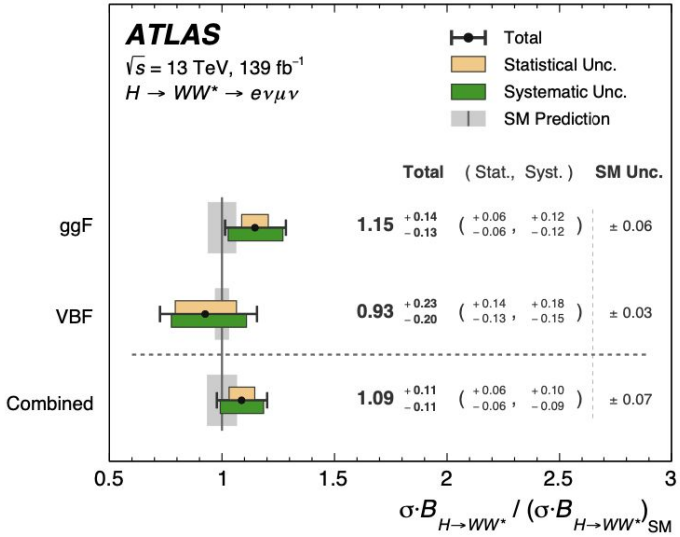
- This page shows the STXS results.
- The Higgs to ZZ channel has good signal sensitivities in the truth regions targeting ggH - 0 jet and VBF.



ggF/VBF, Higgs to WW* to $e\nu\mu\nu$

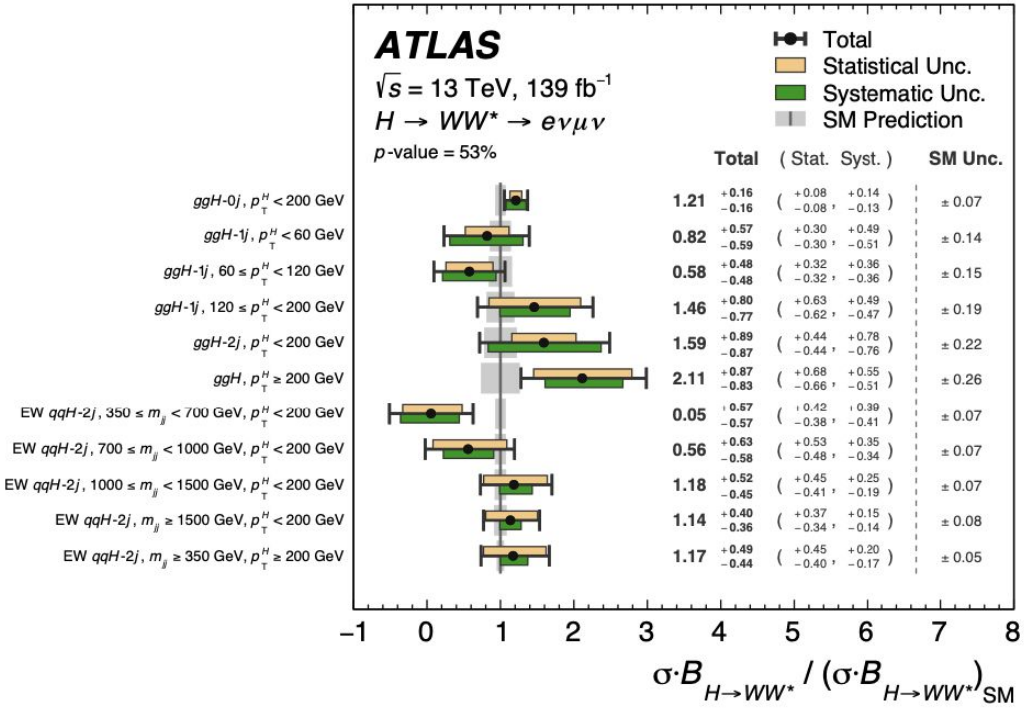
- Selecting events with **2 different-flavour, opposite-sign leptons** and missing transverse energy (MET). **Cut-based categories** target different STXS regions.
- Main background: SM WW*, ttbar/tW, $Z\tau\tau$ + jets, W+jets, VV
- A binned S+B fit is performed on **m_T** for ggF, and on **DNN scores** for VBF
- Note: H→WW measurement targeting the WH/ZH production modes is also performed [PLB 798 (2019) 134949]





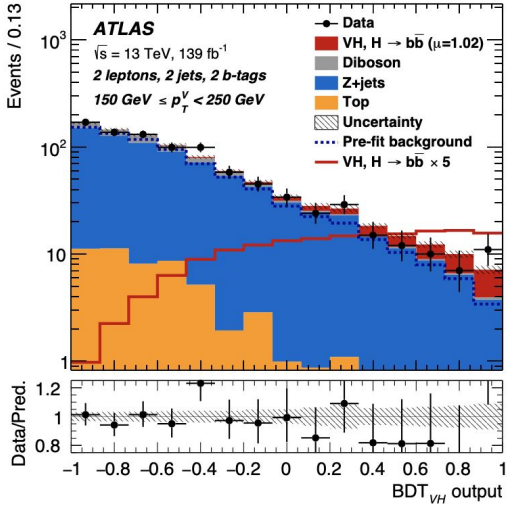
ggF/VBF, Higgs to WW* to $e\nu\mu\nu$

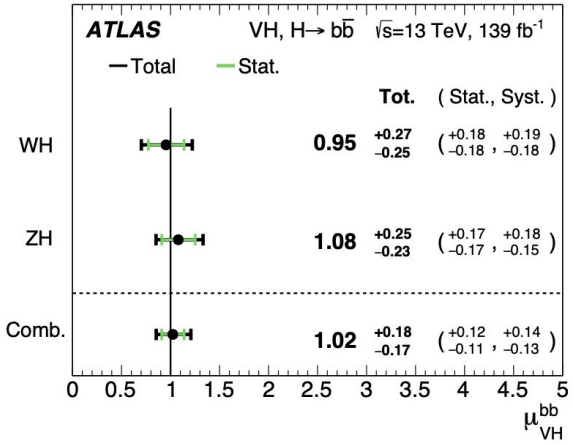
- This page shows the STXS results in the ggF/VBF regions
- It has good sensitivity in the low Higgs pT bin for ggF

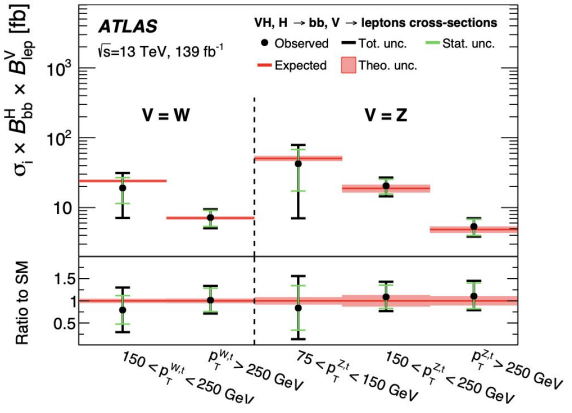


VH, Higgs to bb (resolved)

- **3 lepton channels** targeting $ZH \to \nu\nu bb$, $WH \to l\nu bb$ and $ZH \to llbb$ via MET or Z→ll selections. Requiring **2 or 3 jets** in the final state, with exactly **2 b-jets**. **Cut-based categories** targeting different STXS regions.
- Main background: ttbar, W+jets, Z+jets, VV, single top, multi-jets.
- A binned S+B fit is performed on the **BDT scores** in different lepton channels. The m(bb) observable is included as the input to the BDT algorithm.

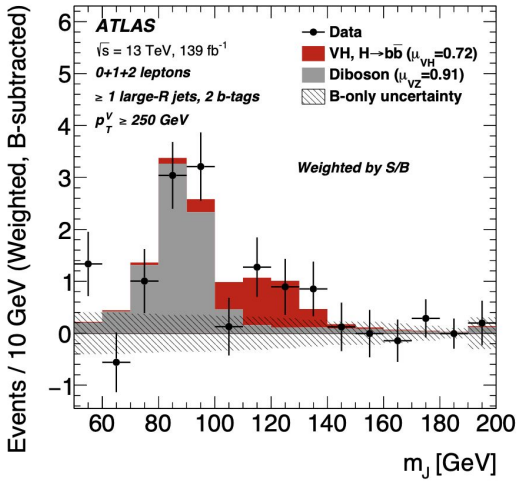






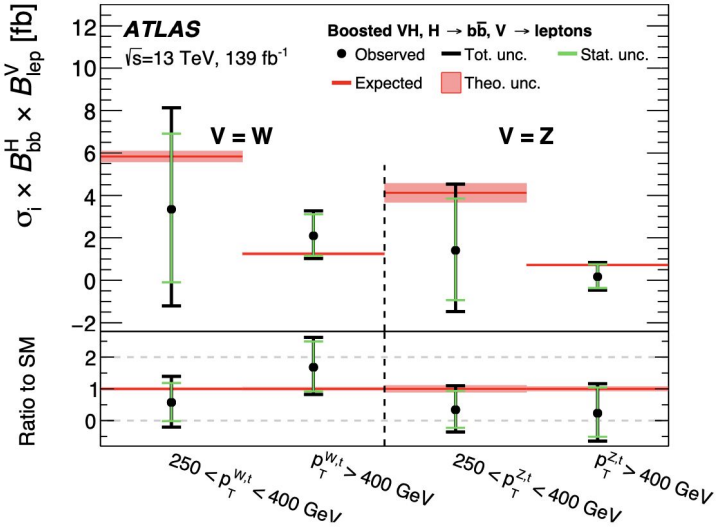
VH, Higgs to bb (boosted)

- **3 lepton channels** as before, but the jet requirements are replaced by the requirement of a **large-radius jet** containing two b-jets. **Cut-based** categories targeting different STXS regions
- Main background: ttbar, W+jets, Z+jets, VV, single top, multi-jets.
- A binned S+B fit is performed on the **mass of the large radius jet**, fitting simultaneously on the VH and VZ signal strengths
- Note: H→bb measurement targeting VBF (EPJC 81 (2020) 537) and ttH (JHEP 06 (2022) 097) are also performed
- The inclusive boosted H→bb measurement is presented in PRD 105(20



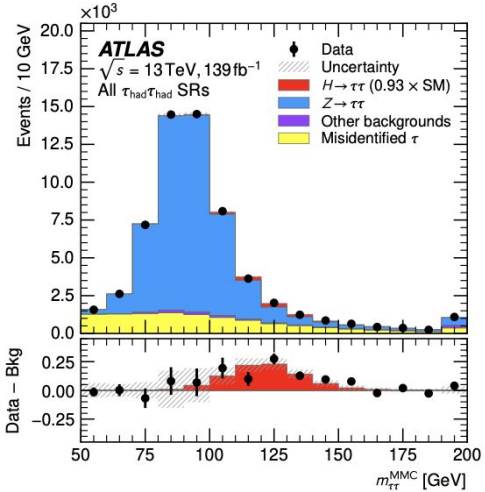
$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}).$$

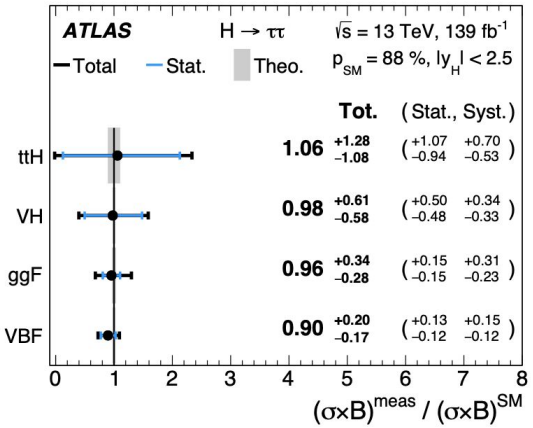
$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.24}_{-0.17}(\text{syst.}),$$

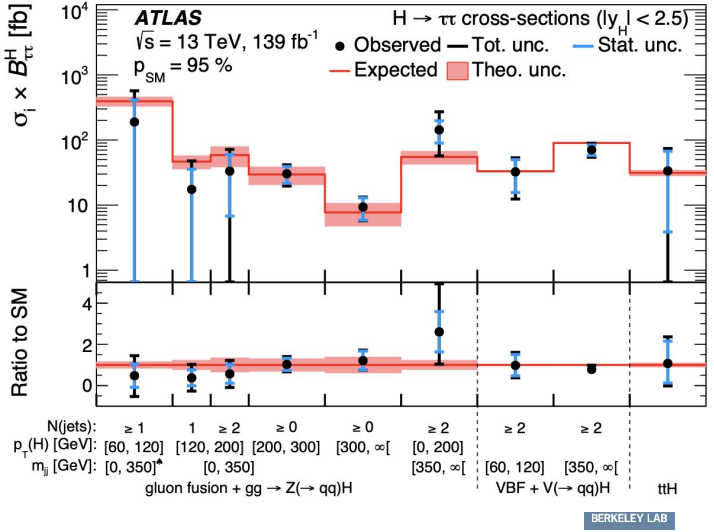


Higgs to $\tau\tau$

- 3 different channels with two opposite-sign tau-candidates in the final state: τ(e)τ(mu), τ(lep) τ(had), τ(had)τ(had). **Cut-based and BDT-tagged (VBF, VH, ttH)** categories used to target different STXS regions.
- Main background: Z to $\tau\tau$, mis-identified τ, top quark processes
- A binned S+B fit will be performed on the **m$\tau\tau$ mass** in different categories.



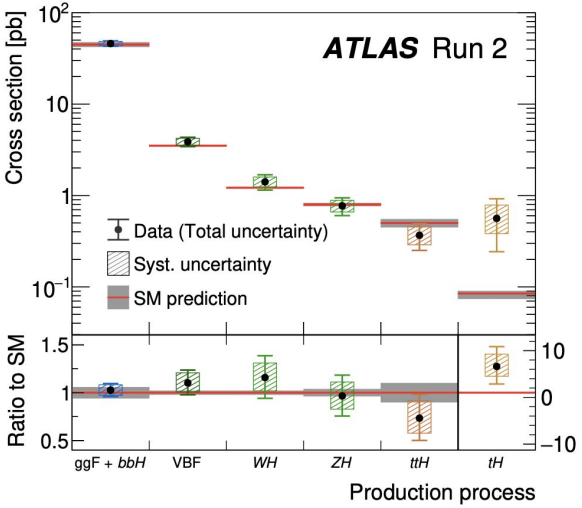


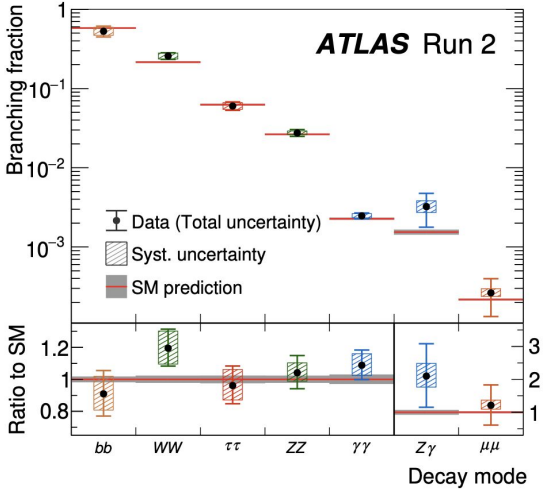


The combined measurement

- A combined measurement on the Higgs coupling properties was published for the 10 year anniversary of the Higgs boson discovery
- The result includes the input measurements from $\gamma\gamma$, **ZZ*, WW*, bb and $\tau\tau$ channels**, as well as the **searches for the μμ, Zγ and cc decays**.
- The combined results are in good agreement with the SM predictions. The measurement precision is improved by about 30% compared to the previous combination with a partial Run 2 datase

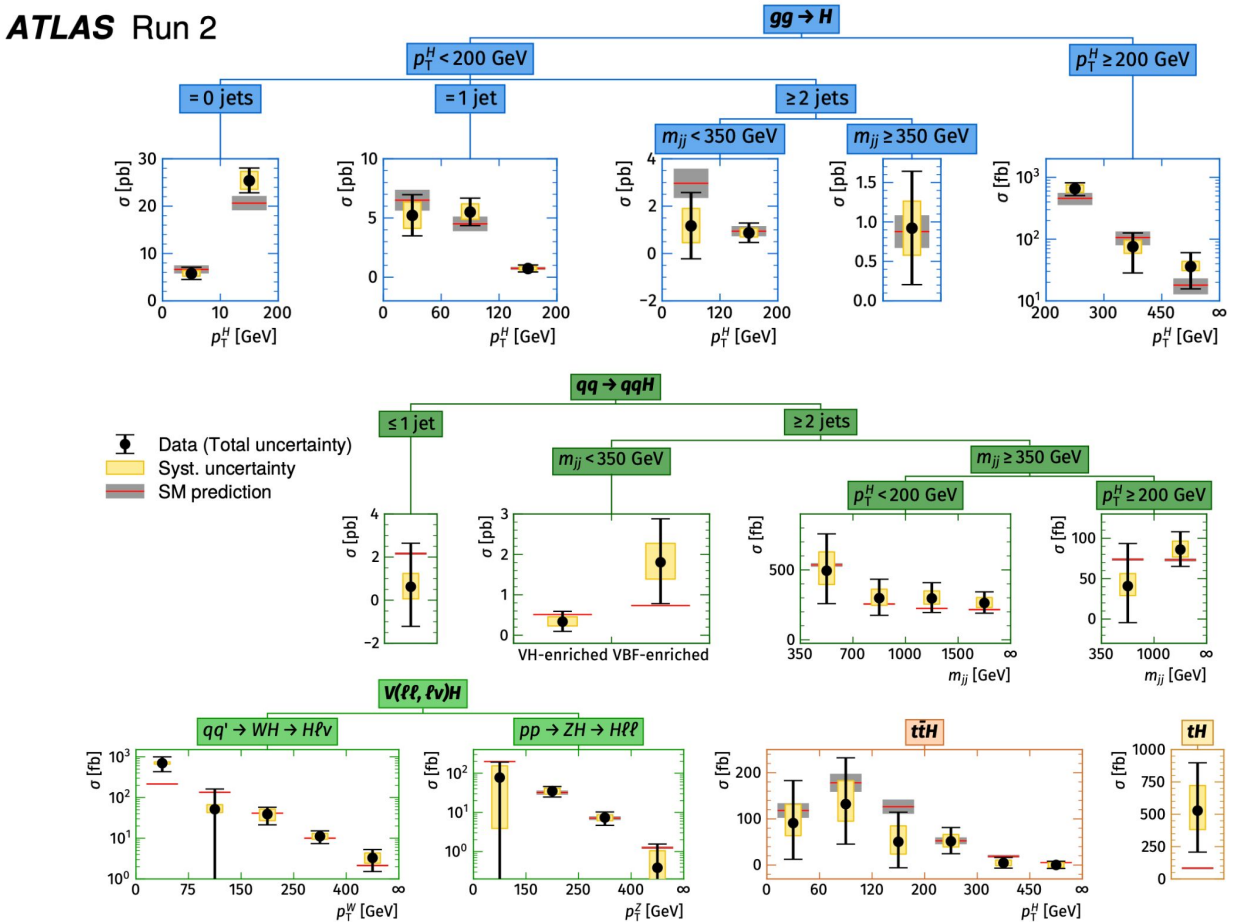
$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$





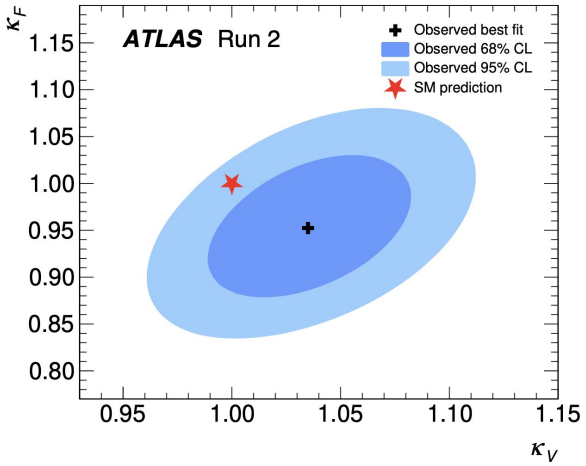
The combined measurement

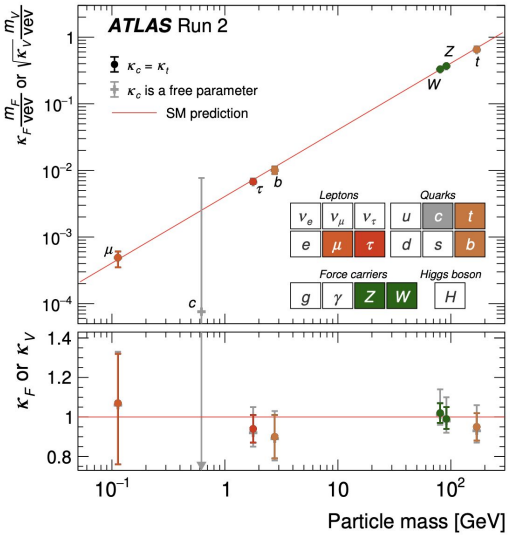
- This page shows the combined STXS results.
- A large number of kinematic regions are probed, particularly at high Higgs boson transverse momenta (where in many cases the sensitivity to BSM physics is expected to be enhanced)

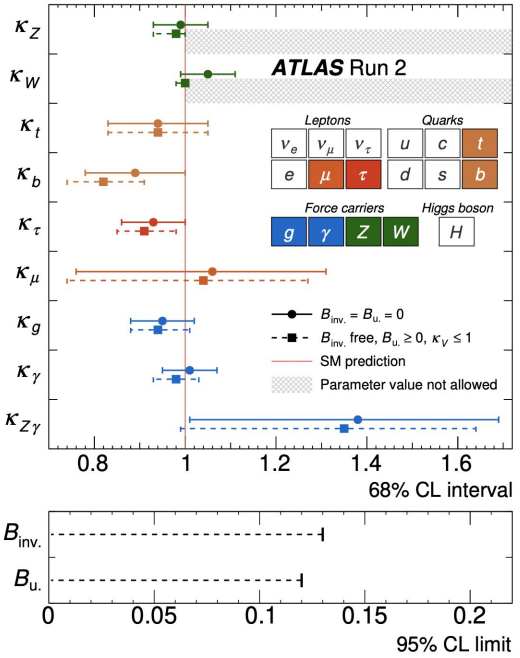


Interpretation: κ-framework

- Event rates for Higgs production and decay processes can be expressed in terms of coupling modifiers (κ) multiplying the SM Higgs coupling strengths to other particles.
- Combined measurement of production cross-section times decay rates is interpreted in terms of the κ-modifiers.
- The kappa-framework results are compatible with SM.





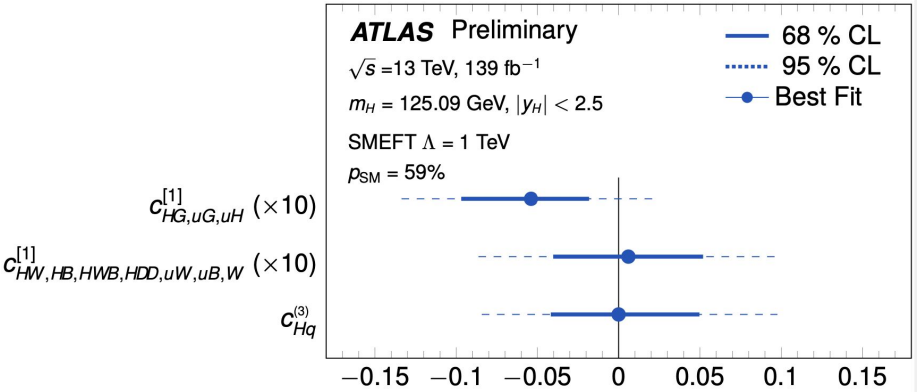


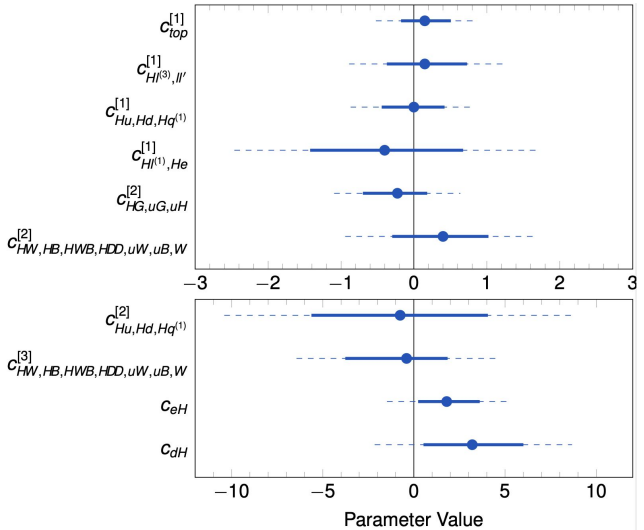
Interpretation: effective field theory

- The Standard Model Effective Field Theory (SMEFT, ref) describes the deviations from SM predictions in terms of new effective interactions caused by new BSM physics at very large energy scales.
- New interactions are scaled by Wilson coefficients which are free parameters of the theory.
- Limits are set on the selected linear combinations of Wilson coefficients (eigenvectors) in a simultaneous fit of all relevant coefficients, using a combined STXS measurement as an input.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots,$$

$$\mathcal{L}^{(\text{d})} = \sum \frac{C_i^{(\text{d})}}{\Lambda^{\text{d}-4}} \mathcal{Q}_i^{(\text{d})} \text{ for d} > 4.$$





Summary

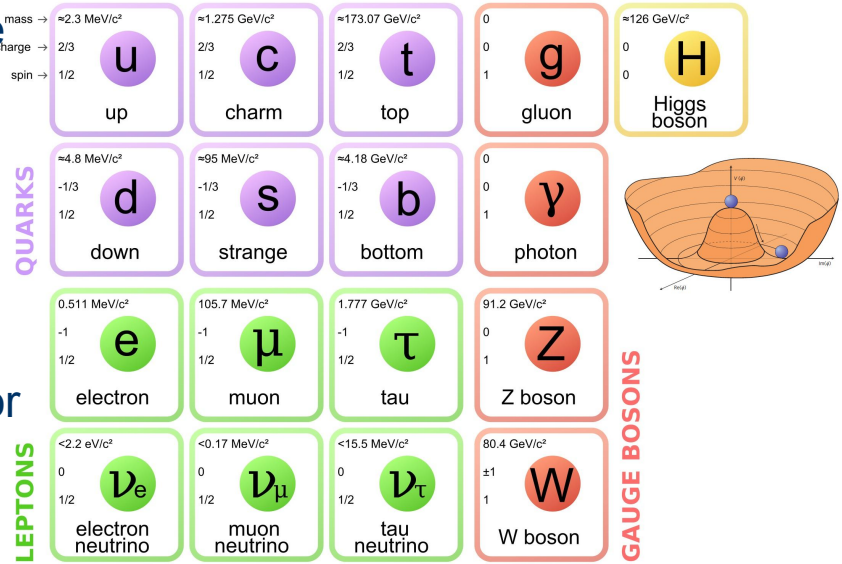
- Measurement of the Higgs boson properties is one of the most important tasks for the high energy physics.
- Precise measurements are performed in many Higgs boson decay modes, targeting different Higgs production processes, and in an increasingly large number of different kinematic regions.
- Recent combined measurement of the Higgs boson cross sections and couplings substantially improves on the previous results.
- The measurements are interpreted in terms of the coupling strengths in the kappa-framework and within an effective field theory framework.
- All measurements are in a good agreement with the predictions of the Standard Model,

Backup

The Standard Model of particle physics

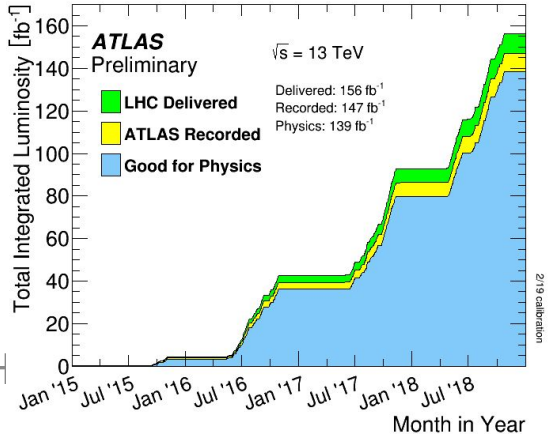
- The Standard Model (SM) of particle physics is a successful and effective theory for most of the observations in the experimental physics researches, it describes 3 out of 4 fundamental interactions in the universe with a high precision.

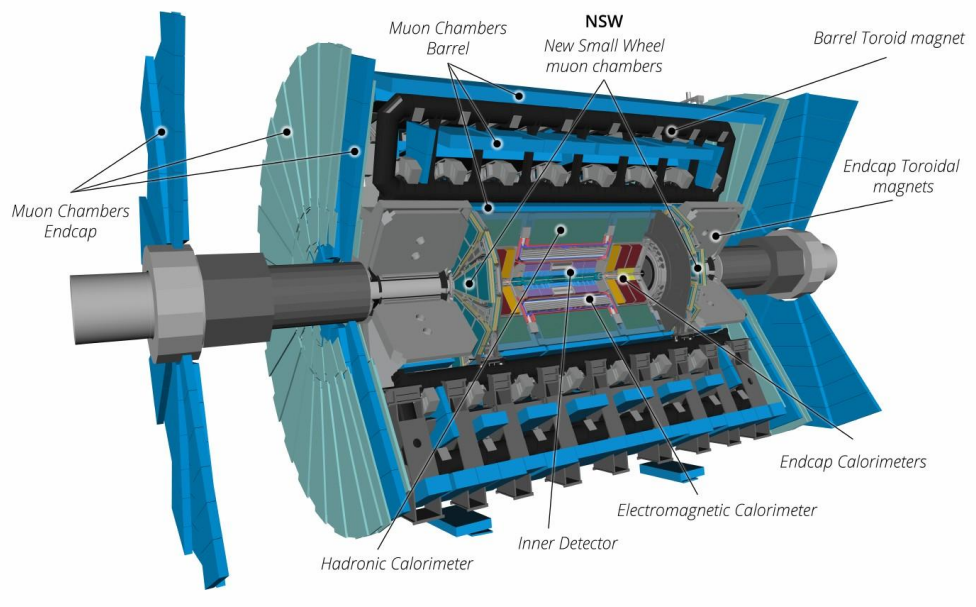
- The Higgs boson is an elementary particle in the SM, the Higgs mechanism explains the mass of the gauge boson and fermions.
- The Higgs properties, including production cross-sections, decay branching ratios, Higgs-fermion coupling strength, self coupling strength, mass etc. are important SM features for precise measurement at the LHC.



The ATLAS detector

- ATLAS is one of the largest, general-purpose particle detector experiment at the LHC
- ATLAS has the capability to reconstruct photons, charged leptons, jets and missing transverse energy from the physics processes of pp collisions
- During the 2015-2018 LHC Run-2 data taking. ATLAS has recorded 139 fb-1 of good pp collision data at 13 TeV





Higgs to γγ - interpretations

- The BSM interpretations are done with the κ-framework and the Standard Model effective field theory
- Parameterizations are based on the measurement on the STXS
- The results are compatible with the SM for both interpretations

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots,$$

$$\mathcal{L}^{(\mathrm{d})} = \sum_i \frac{C_i^{(\mathrm{d})}}{\Lambda^{\mathrm{d}-4}} \mathcal{Q}_i^{(\mathrm{d})} \text{ for } \mathrm{d} > 4.$$