University of Massachusetts Amherst

An introduction to Higgs measurements

Rafael Coelho Lopes de Sa

July 30th, 2024

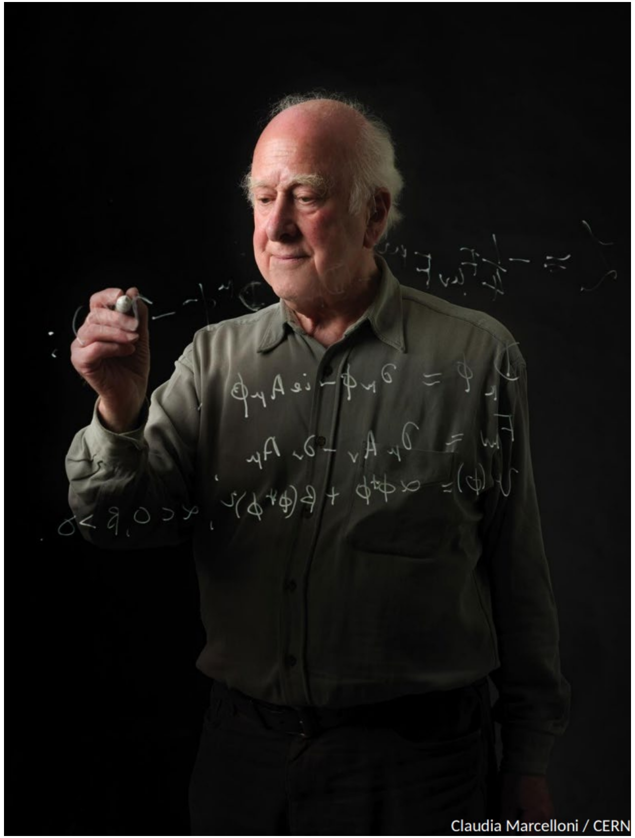
In memoriam

Peter Higgs (1929 - 2024)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)



Slide from N. Berger at ICHEP 2024

In memoriam

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

122

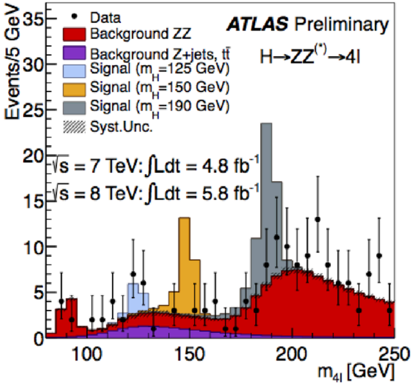
Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

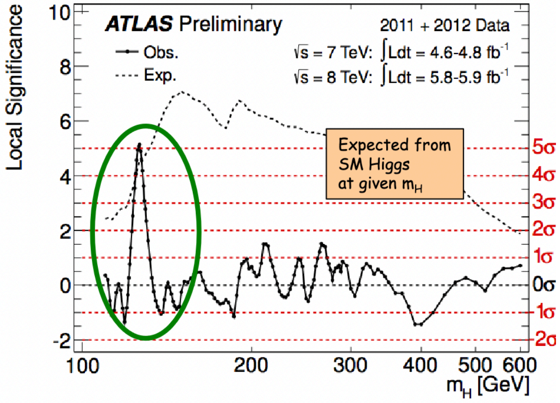
By Dennis Overbye

July 4, 2012

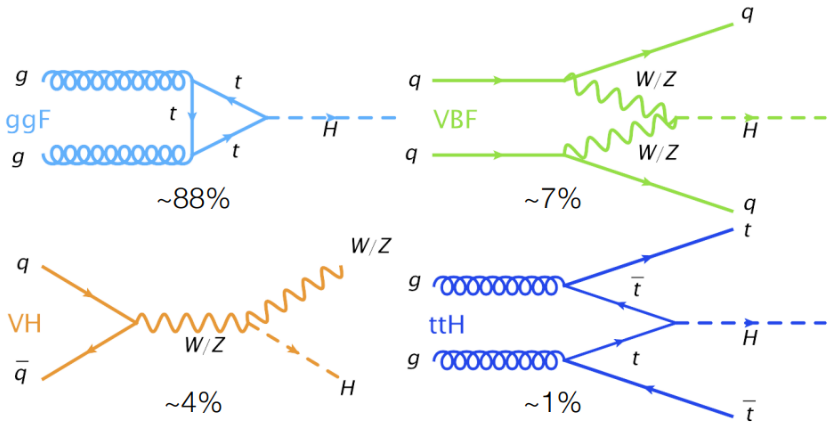
ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said

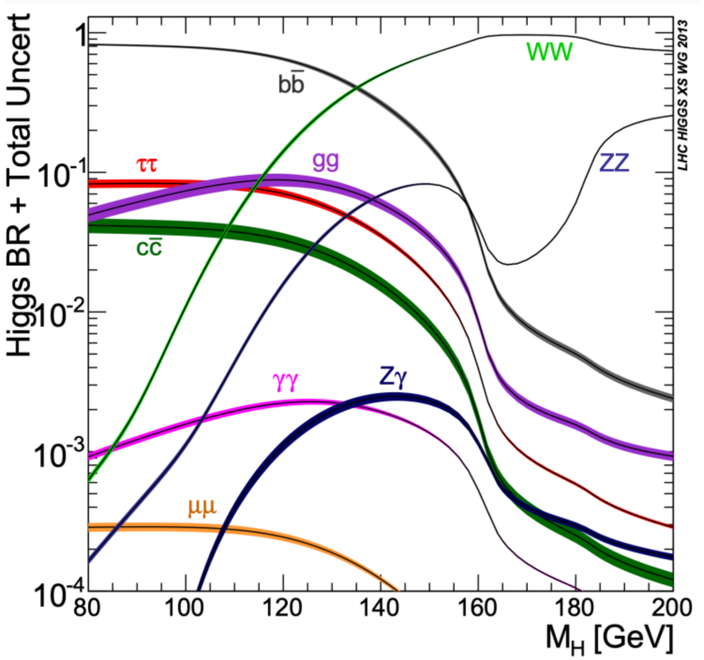
Physics Nobel Prize 2013





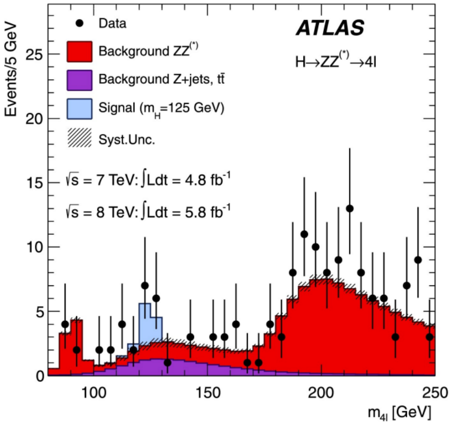
The LHC is a Higgs machine

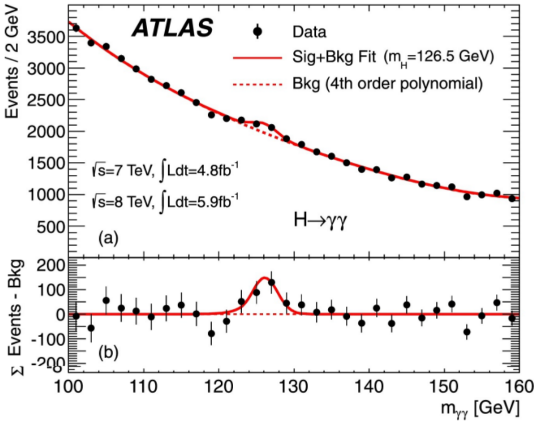


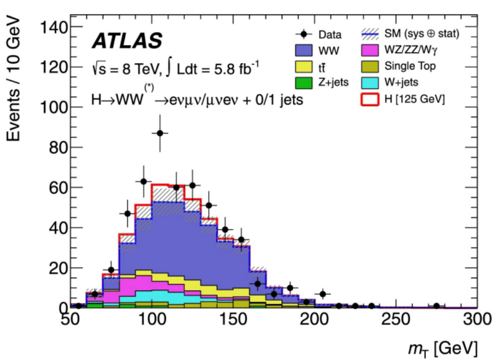


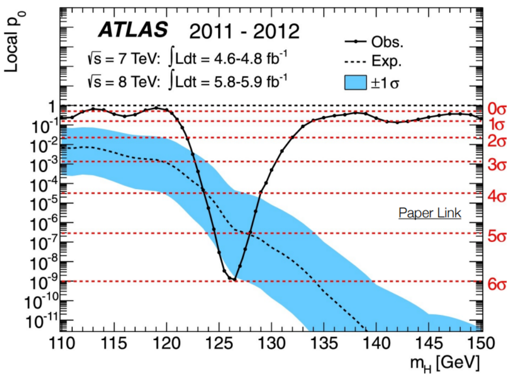
The inclusive Higgs cross section at 13 TeV is approximately 50pb, which means that the LHC produces approximately one Higgs boson per second inside ATLAS or CMS.

Higgs search circa 2012









- It took approximately $10\ \mathrm{fb}^{-1}$ to have an observation of the Higgs boson.
- We now have almost $300\ \mathrm{fb}^{-1}$ of data accumulated by ATLAS and CMS.
- What else did we do? What else can we do?

References to learn more:

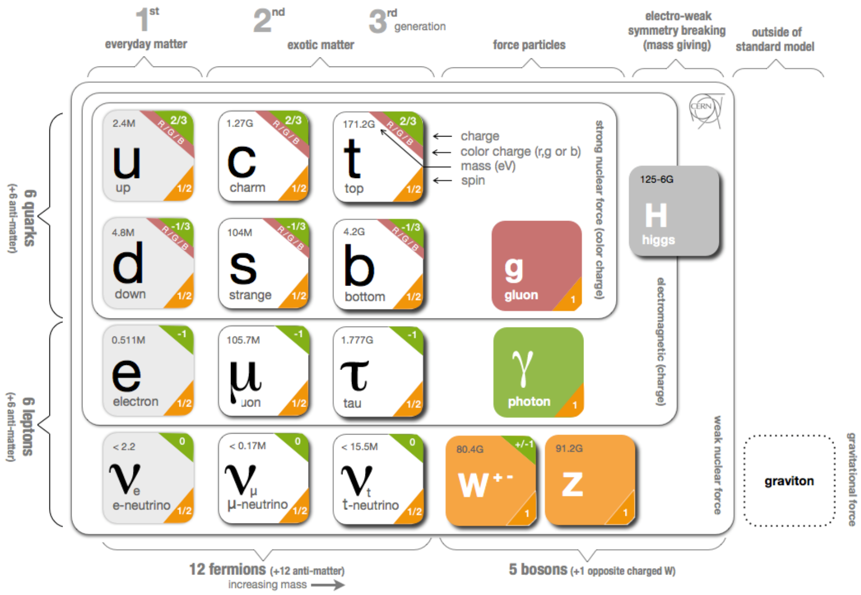
ATLAS collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

CMS collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

Contents

- Higgs spin and parity
- CP violation in the Higgs sector
- Higgs couplings
- Simplified Template Cross Section (STXS)
- Differential cross sections
- Higgs mass
- Higgs width/lifetime
- Higgs potential

The Higgs is a very special particle. The only fundamental scalar in the SM.



Open questions

What is the origin of quark and lepton masses ?

- Fermion flavor violating Higgs boson decays ?
- Are there modified Higgs couplings to other particles ?

Why is the EW interaction much stronger than gravity ?

- Are there anomalies in HVV interactions ?
- New particles at the TeV scale
- Is the Higgs boson elementary?

Why is there more matter than antimatter ?

- Higgs boson self-coupling strong first-order EWPT ?
- Are there multiple Higgs sectors?
- Are there CP-violating Higgs boson decays

What is dark matter?

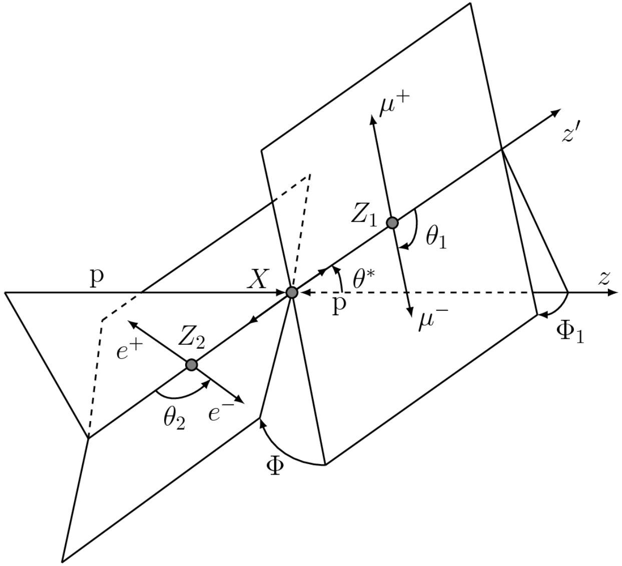
- Can the Higgs boson provide a portal to dark matter ?
- New decay modes of the Higgs boson ?
- Higgs lifetime consistent with the SM ?

Adapted from G. Salam et al, Nature volume 607, pages 41–47 (2022)

Initial disclaimers

- You will notice that most examples that I will give are from the ATLAS experiment. This is just for convenience. ATLAS and CMS perform almost the same Higgs measurements and, when relevant, I will add both links.
- The field of Higgs Measurements is very vast. There is no way I can cover everything in 2 hours. I will give you a walkthrough, highlighting some of the important techniques we use to characterize the Higgs boson. But I will also add references so that you can learn more.
- Perhaps the most useful references to learn about Higgs measurements are the following CERN Yellow Reports:
  - Inclusive Observables
  - Differential Distributions
  - Higgs Properties
  - Deciphering the Nature of the Higgs Sector
- (and for some light reading) The Higgs boson turns ten

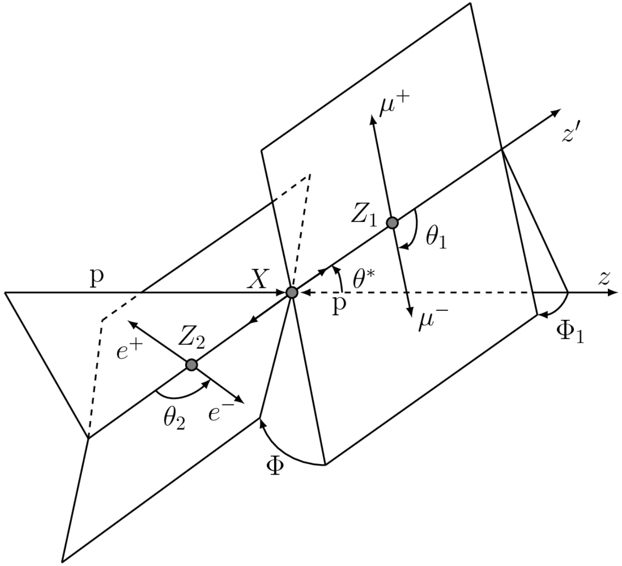
Higgs boson spin and parity



- The determination of the spin and parity of the Higgs boson was one of the first tasks completed at the LHC.
- The basic idea of the measurement is to test each alternative hypothesis, i.e. different spin-parity values (0^+, 0^-, 2^+, …), by using a dedicated observable.
- The diagram shows the angular parametrization to study Higgs decays, where the angles and planes are defined in the decaying particle rest frame.

Diagram and figures from Gao et al. Spin determination of single-produced resonances at hadron colliders

Higgs boson spin and parity



- The spin of the Higgs boson can be determined by the angular distribution of the decay product in the rest frame.
- Spin 1 can be excluded from the existence of $H \to \gamma\gamma$ (Laudau-Yang theorem)
- That has been done in $H \to ZZ$, $H \to WW$, and $H \to \gamma\gamma$ decay channels.
- Different parity creates different spin correlations in the decay products, so it requires particles that subsequently decay (like $H \to ZZ$ or $H \to WW$)

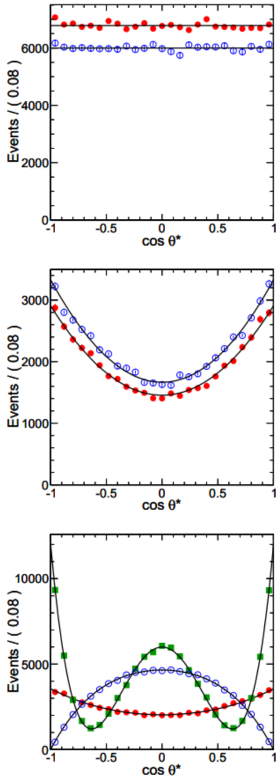
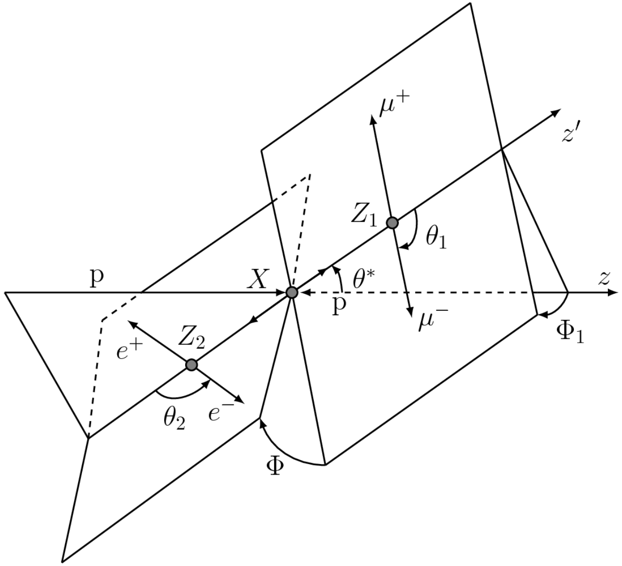
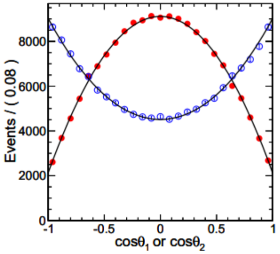


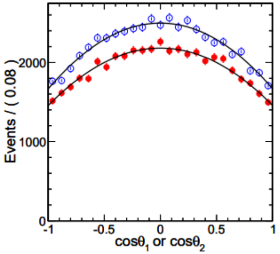
Diagram and figures from Gao et al. [Spin determination of single-produced resonances at hadron colliders]

Higgs boson spin and parity



- The spin of the Higgs boson can be determined by the angular distribution of the decay product in the rest frame.
- Spin 1 can be excluded from the existence of $H \to \gamma\gamma$ (Laudau-Yang theorem)
- That has been done in $H \to ZZ$, $H \to WW$, and $H \to \gamma\gamma$ decay channels.
- Different parity creates different spin correlations in the decay products, so it requires particles that subsequently decay (like $H \to ZZ$ or $H \to WW$)





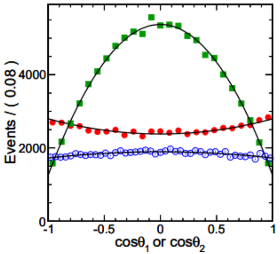
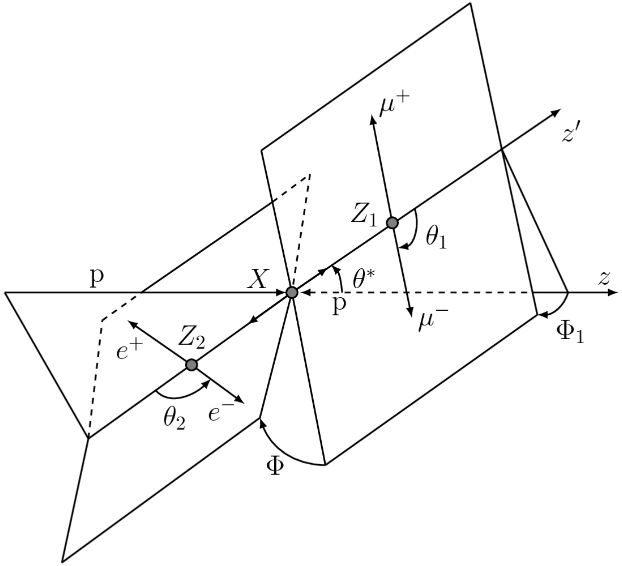


Diagram and figures from Gao et al. Spin determination of single-produced resonances at hadron colliders

Higgs boson spin and parity



- Observables based on "matrix element" calculation since production and decay decouple

$$\frac{128\pi\, d\Gamma_{J=0}}{9\,\Gamma\, d\cos\theta_1 d\cos\theta_2 d\Phi} = 4\,(1-f_{++}-f_{--})\,\sin^2\theta_1\sin^2\theta_2$$
$$+(f_{++}+f_{--})\left((1+\cos^2\theta_1)(1+\cos^2\theta_2)+4R_1R_2\cos\theta_1\cos\theta_2\right)$$
$$-2\,(f_{++}-f_{--})\left(R_1\cos\theta_1(1+\cos^2\theta_2)+R_2(1+\cos^2\theta_1)\cos\theta_2\right)$$
$$+4\sqrt{f_{++}(1-f_{++}-f_{--})}\,(R_1-\cos\theta_1)\sin\theta_1(R_2-\cos\theta_2)\sin\theta_2\cos(\Phi+\phi_{++})$$
$$+4\sqrt{f_{--}(1-f_{++}-f_{--})}\,(R_1+\cos\theta_1)\sin\theta_1(R_2+\cos\theta_2)\sin\theta_2\cos(\Phi-\phi_{--})$$
$$+2\sqrt{f_{++}f_{--}}\sin^2\theta_1\sin^2\theta_2\cos(2\Phi+\phi_{++}-\phi_{--})\,.$$

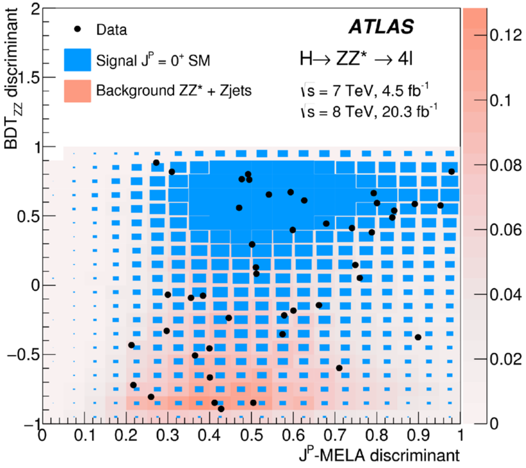
- In practice, this is calculated with reconstructed variables, but this is a good approximation when the final state particles have very high resolutions (electrons, muons, photons, …)
- Create an approximation to an optimal observable (Neyman-Person lemma):

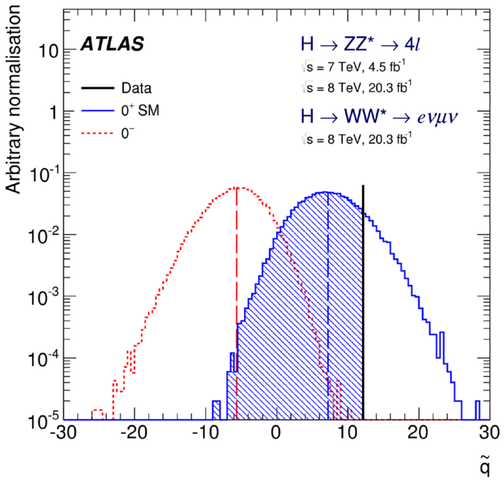
$$OO(0^- \text{ vs } 0^+) = \frac{\mathcal{P}(0^-)}{\mathcal{P}(0^+)}$$

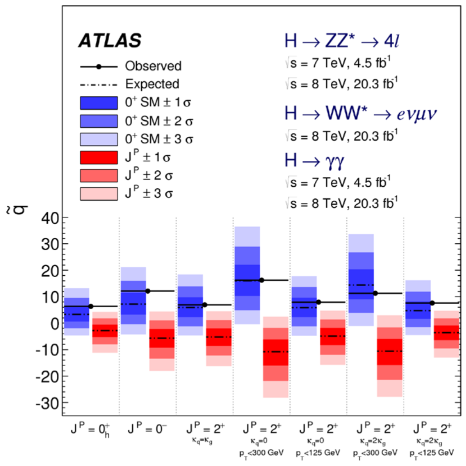
Diagram and figures from Gao et al. Spin determination of single-produced resonances at hadron colliders

Higgs boson spin and parity

- In practice, one has to add another dimension to reject background.
- This can be done with another "matrix element" discriminator or with ML discriminator
  - For $q\bar{q}ZZ$ it is a bit more complicated to obtain the "matrix element" because production and decay do not decouple, and explicit calculations usually rely on automated matrix elements generators (like Madgraph and others)







CP violation

- The early Run 1 measurements excluded pure states with different spin-parity values.
- However, one can still imagine scenarios where the Higgs have a mix of CP-even and CP-odd interactions, which would imply CP violation.
- Additional sources of CP violation in the SM are expected to explain cosmological Baryon Asymmetry in the early universe.

- Sakharov's Conditions for Baryon Asymmetry in the Universe:
  - Baryon Number (B) Violation
  - C and CP Violation
  - Departure from thermal equilibrium
- Challenges:
  - $\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-10}$, 8 orders larger than standard cosmological model prediction
  - What else is out there?

UMassAmherst

CP violation

- The search for CP violation in Higgs couplings to bosons and to fermions is very different

Coupling to bosons

$(\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma})$

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

Coupling to fermions

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H,$$

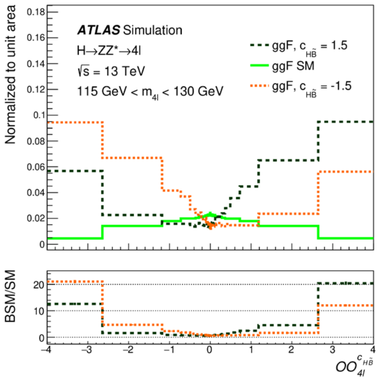
- CP-violating couplings to vector bosons require dimension-6 operators
  - Suppressed by high-mass scale
- CP-violating couplings to fermions can be written with dimension 4 operators
  - Not suppressed

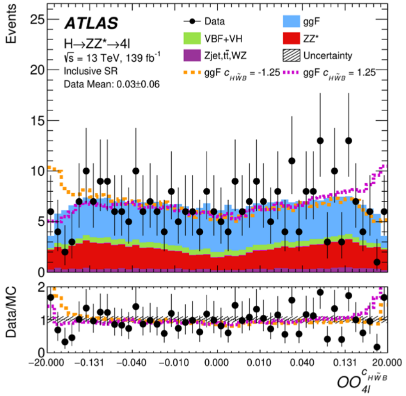
CP violation in HVV couplings

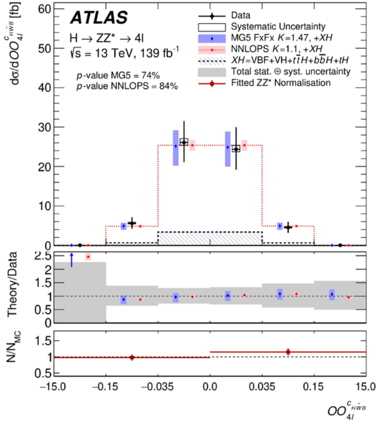
- It uses a very similar strategy as the spin-parity couplings, with an approximation to optimal observable built from “matrix elements”

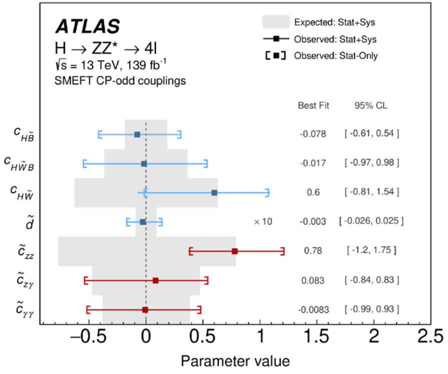
$$OO = 2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP-odd}})/|\mathcal{M}_{\mathrm{SM}}|^2$$

- The VBF channels are particularly sensitive, since we can HVV couplings in both production and decay.
- Dedicated selection (often ML-based) can be used to select VBF events and reject background.









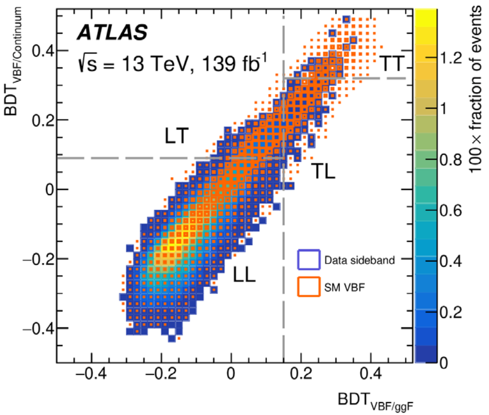
Plots from ATLAS collaboration, [Test of CP-invariance of the Higgs boson in vector-boson fusion production and its decay into four leptons]

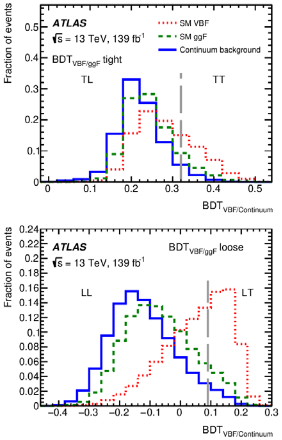
CP violation in HVV couplings

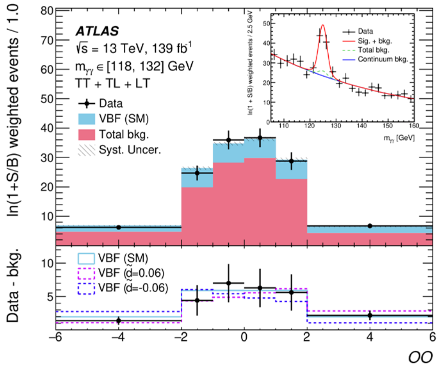
- It uses a very similar strategy as the spin-parity couplings, with an approximation to optimal observable built from "matrix elements"

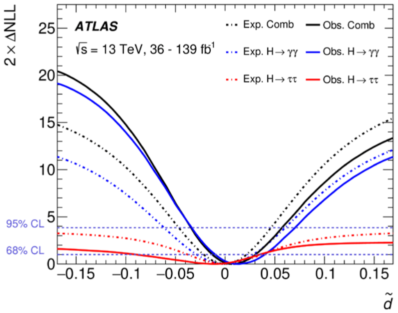
$$OO = 2\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})/|\mathcal{M}_{SM}|^2$$

- The VBF channels are particularly sensitive, since we can HVV couplings in both production and decay.
- Dedicated selection (often ML-based) can be used to select VBF events and reject background.
- Sometimes even the same experiment can't use the same conventions…





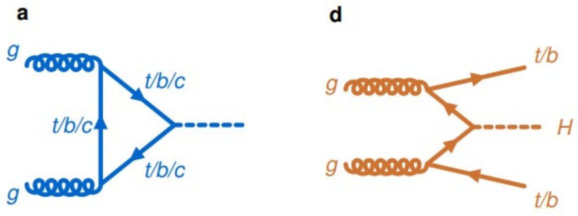


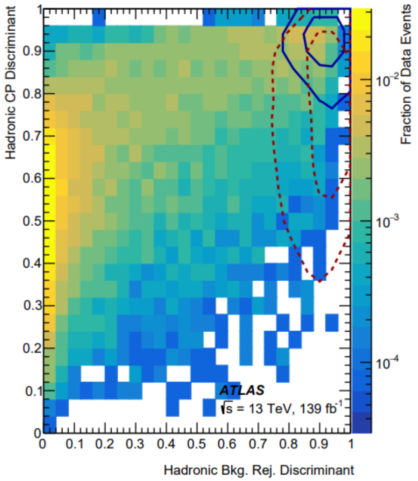


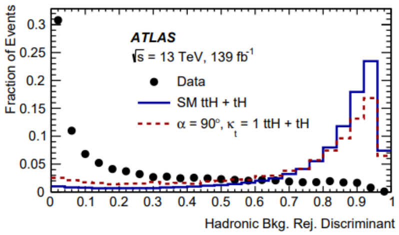
Plots from ATLAS collaboration, [Study of the CP property of the Higgs boson to electroweak boson coupling in the VBF H→γγ channel with the ATLAS detector]

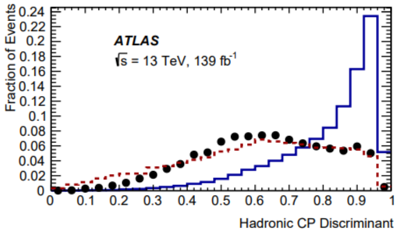
CP violation in $Hf\bar{f}$

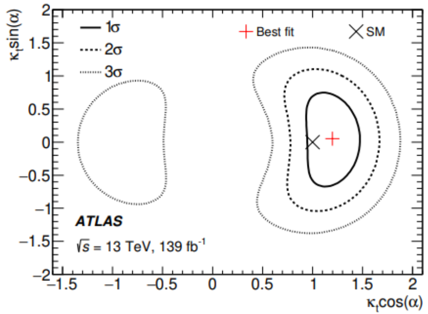
- The idea here is very similar: one builds a CP-sensitive observable, either from explicit matrix element calculations or from ML-based methods.
- In this case, it is better to target production channels with fermion couplings: ggF and $t\bar{t}H$
- The tests using $t\bar{t}H$ provide a test of CP invariance without the influence of possible new particles in the ggF loop











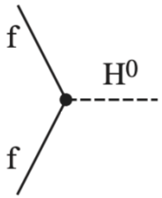
Plots from ATLAS collaboration, CP Properties of Higgs Boson Interactions with Top Quarks in the ttH and tH Processes Using H → γγ with the ATLAS Detector

References to learn more

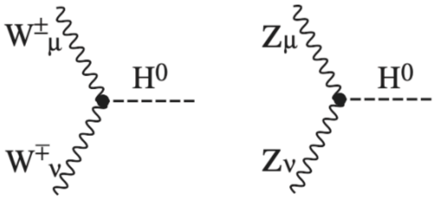
- Higgs properties
- Gao, Y et al. Spin determination of single-produced resonances at hadron colliders
- CMS collaboration, Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs
- ATLAS collaboration, Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector
- ATLAS collaboration, CP Properties of Higgs Boson Interactions with Top Quarks in the ttH and tH Processes Using H → γγ with the ATLAS Detector
- ATLAS collaboration, Test of CP-invariance of the Higgs boson in vector-boson fusion production and its decay into four leptons
- ATLAS collaboration, Study of the CP property of the Higgs boson to electroweak boson coupling in the VBF H→γγ channel with the ATLAS detector

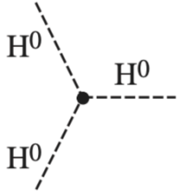
Higgs couplings

Higgs - fermion coupling

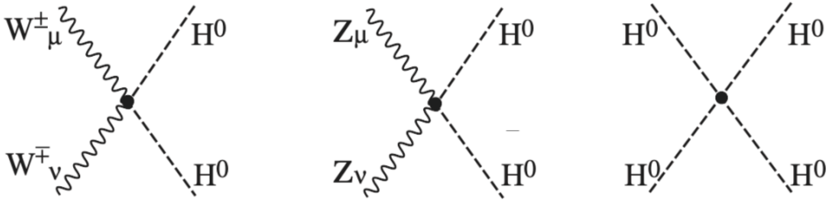


Higgs - vector boson coupling





Higgs - self coupling



Multi-higgs + boson coupling

Slide from H. Abidi at ATLAS Lecture Series

Couplings measurements

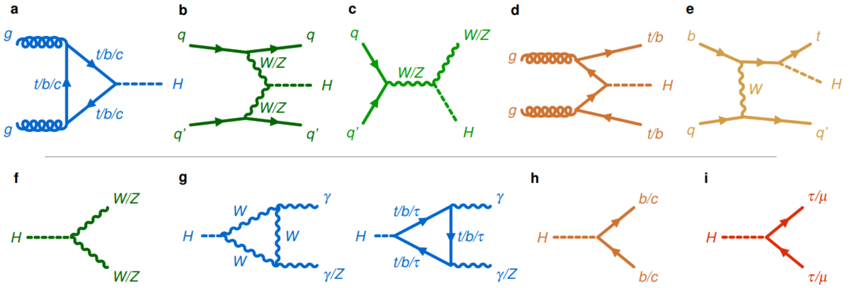
- The basic input for any couplings measurements are **signal strengths**

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

which can be decomposed into production and decay

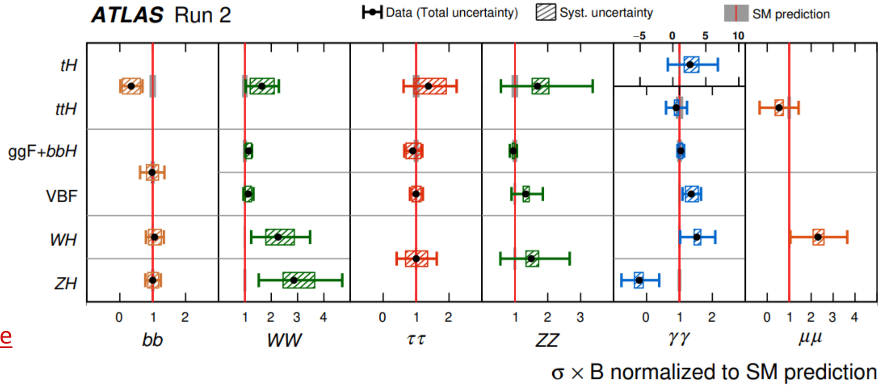
$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with} \quad \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$



Plots from ATLAS collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

- In practice, today, all the analyses are extremely complex.
- The number of channels c can be very large to enhance the signal significance and to provide data-driven estimates of the backgrounds.
- Even "simple" channels like $H \to ZZ$ use ML-based observables to define channels.



Couplings measurements

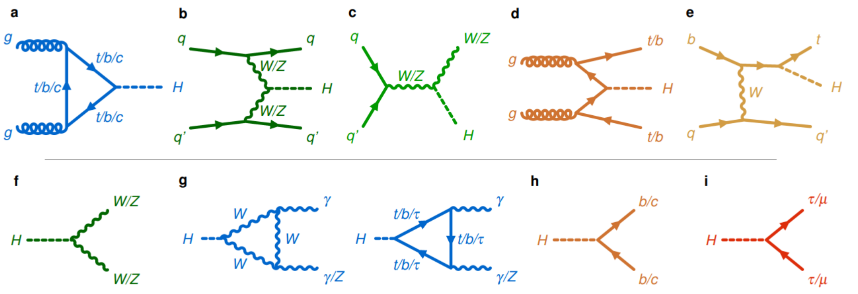
- The basic input for any couplings measurements are **signal strengths**

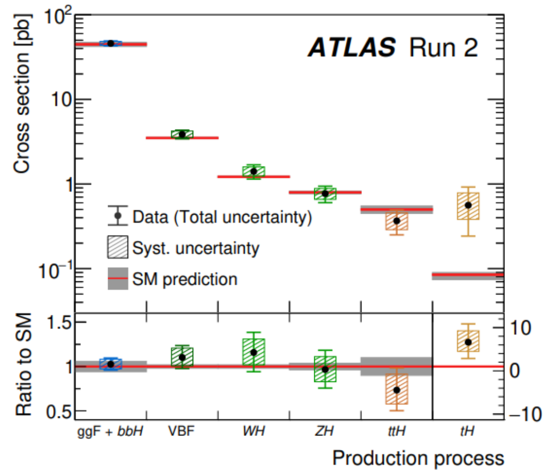
$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

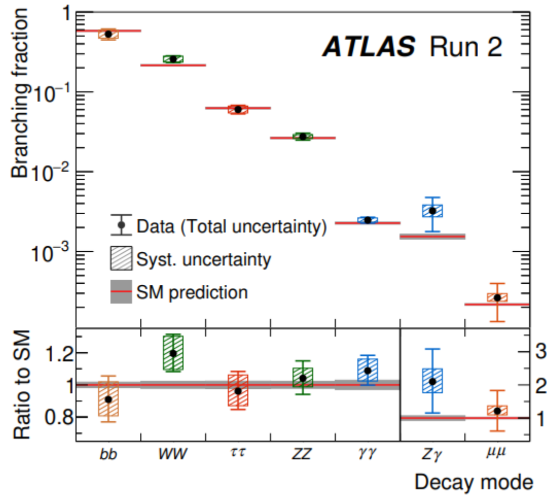
which can be decomposed into production and decay

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with} \quad \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$







Plots from ATLAS collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

κ-framework

- During Run 1 (and still done at Run 2), the main framework to understand what the signal strength measurements mean is the κ-framework.
- κ are modifiers of the Higgs coupling to one particle (or to a group of particles). The idea is that the same couplings can be present in production and decays.

$$\kappa_p^2 = \frac{\sigma_p}{\sigma_p^{SM}} \qquad \kappa_p^2 = \frac{\Gamma_p}{\Gamma_p^{SM}}$$

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$\Gamma_H(\kappa_j) = \kappa_H^2(\kappa_j)\Gamma_H^{SM}$$

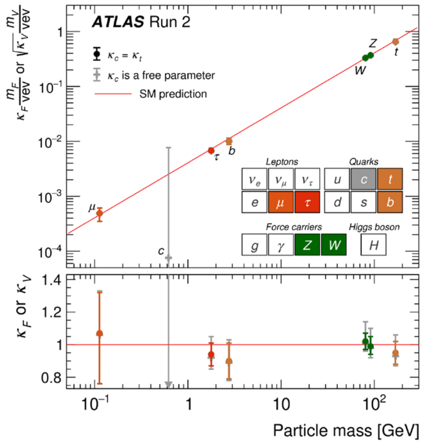
Production	Loops	Interference	Expression in fundamental coupling-strength scale factors	
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	-	W–t	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	W–t	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim$	$1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

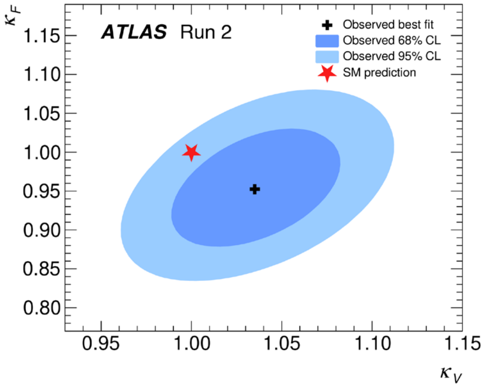
Different hypotheses

- We don’t need to resolve all κ-factors at the same time. For instance, we can test all the couplings to fermions and bosons at the same time.
- If we assume that there are BSM contributions to the Higgs total width, then there are degeneracies in the determination

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}.$$

- You can’t differentiate between a change in $\mathrm{BR}_{\mathrm{i,u}}$ and κ_H.
  - Additional hypothesis $\kappa_V \leq 1$ is required
- When assuming BSM contributions, we do not resolve κ_g, κ_γ, and $\kappa_{Z\gamma}$, since the BSM contributions can alter the loop calculation.





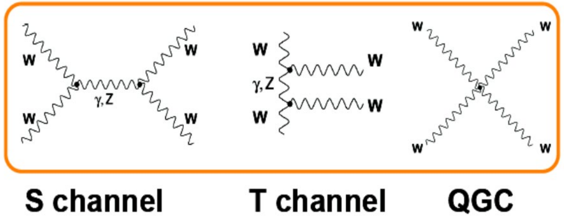
Plots from ATLAS collaboration, [A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery]

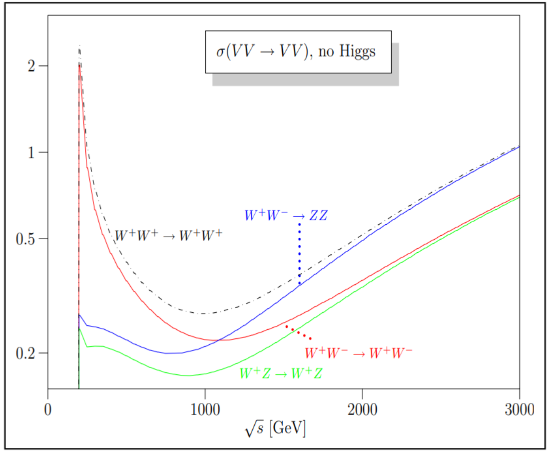
Different hypotheses

- We don't need to resolve all κ-factors at the same time. For instance, we can test all the couplings to fermions and bosons at the same time.
- If we assume that there are BSM contributions to the Higgs total width, then there are degeneracies in the determination

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1-\mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}.$$

- You can't differentiate between a change in $\mathrm{BR}_{\mathrm{i,u}}$ and κ_H.
  - Additional hypothesis $\kappa_V \leq 1$ is required
- When assuming BSM contributions, we do not resolve κ_g, κ_γ, and $\kappa_{Z\gamma}$, since the BSM contributions can alter the loop calculation.





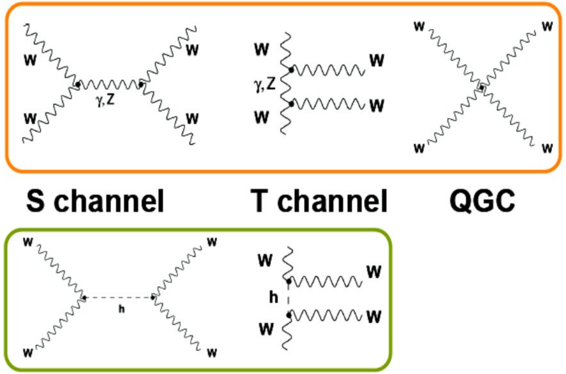
Plots from Alboteanu, A. et al. Resonances and Unitarity in Weak Boson Scattering at the LHC

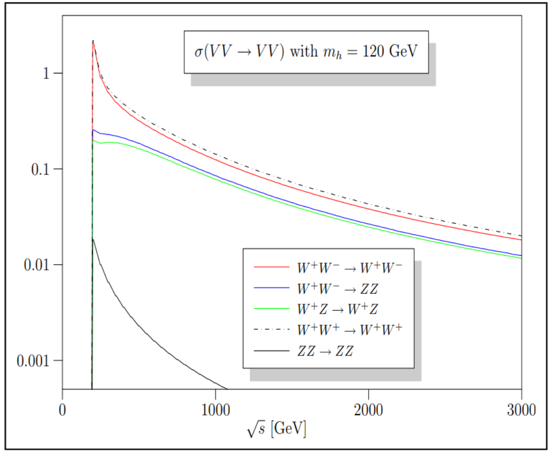
Different hypotheses

- We don't need to resolve all κ-factors at the same time. For instance, we can test all the couplings to fermions and bosons at the same time.
- If we assume that there are BSM contributions to the Higgs total width, then there are degeneracies in the determination

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1-\mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}.$$

- You can't differentiate between a change in $\mathrm{BR}_{\mathrm{i,u}}$ and κ_H.
  - Additional hypothesis $\kappa_V \leq 1$ is required
- When assuming BSM contributions, we do not resolve κ_g, κ_γ, and $\kappa_{Z\gamma}$, since the BSM contributions can alter the loop calculation.





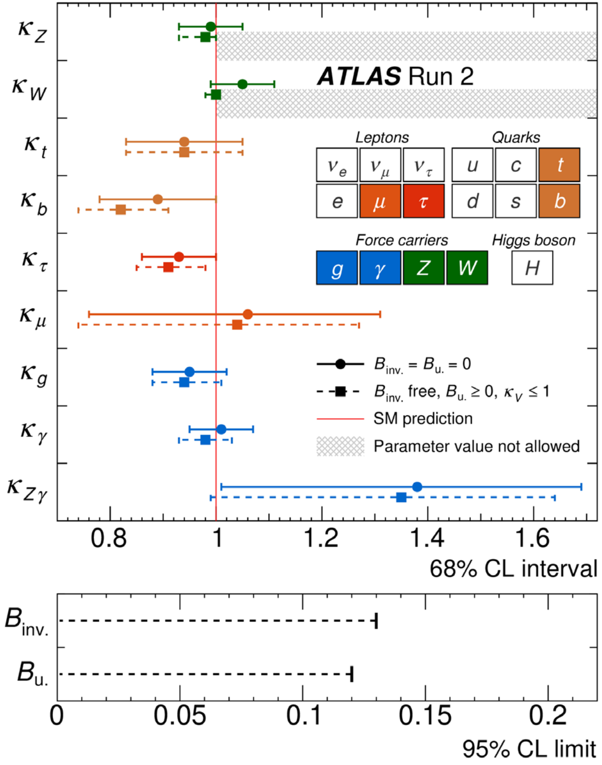
Plots from Alboteanu, A. et al. Resonances and Unitarity in Weak Boson Scattering at the LHC

Different hypotheses

- We don't need to resolve all κ-factors at the same time. For instance, we can test all the couplings to fermions and bosons at the same time.
- If we assume that there are BSM contributions to the Higgs total width, then there are degeneracies in the determination

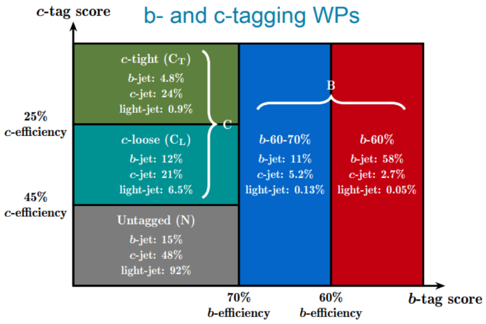
$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1-\mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}.$$

- You can't differentiate between a change in $\mathrm{BR}_{\mathrm{i,u}}$ and κ_H.
  - Additional hypothesis $\kappa_V \leq 1$ is required
- When assuming BSM contributions, we do not resolve κ_g, κ_γ, and $\kappa_{Z\gamma}$, since the BSM contributions can alter the loop calculation.

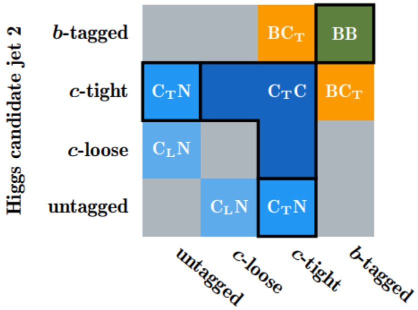


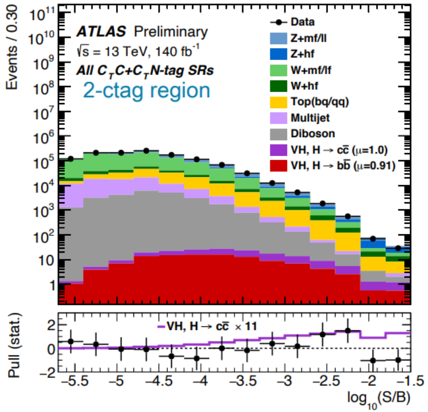
Plots from ATLAS collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

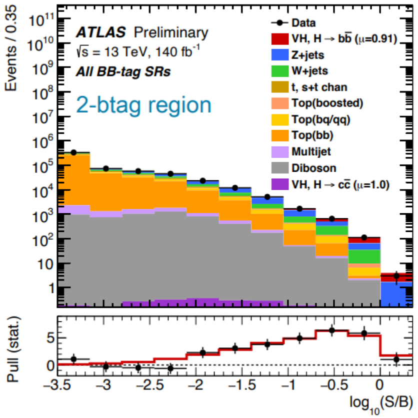
Intermezzo: the $Hc\bar{c}$ coupling

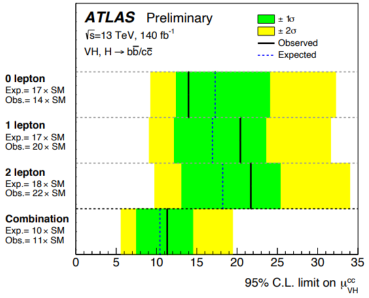


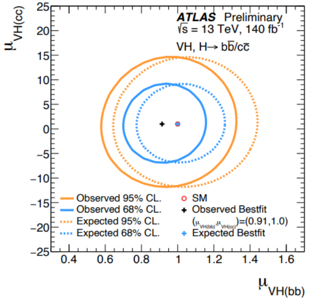
NB: Example, used for the VH analysis



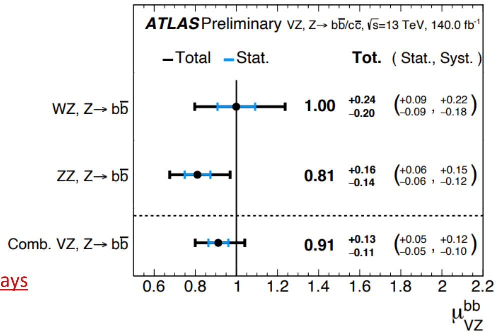




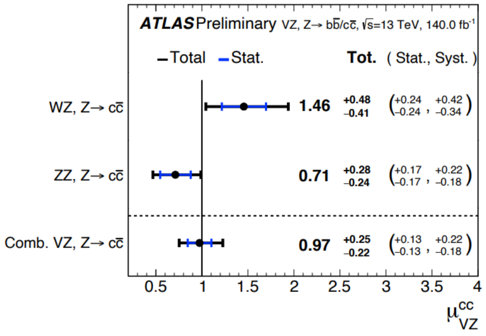




Z -> bb



Z -> cc



Plots from ATLAS collaboration, Measurements of WH and ZH Higgs production with decays into bottom quarks and direct constraints on the charm Yukawa coupling with 13 TeV collisions in the ATLAS detector.

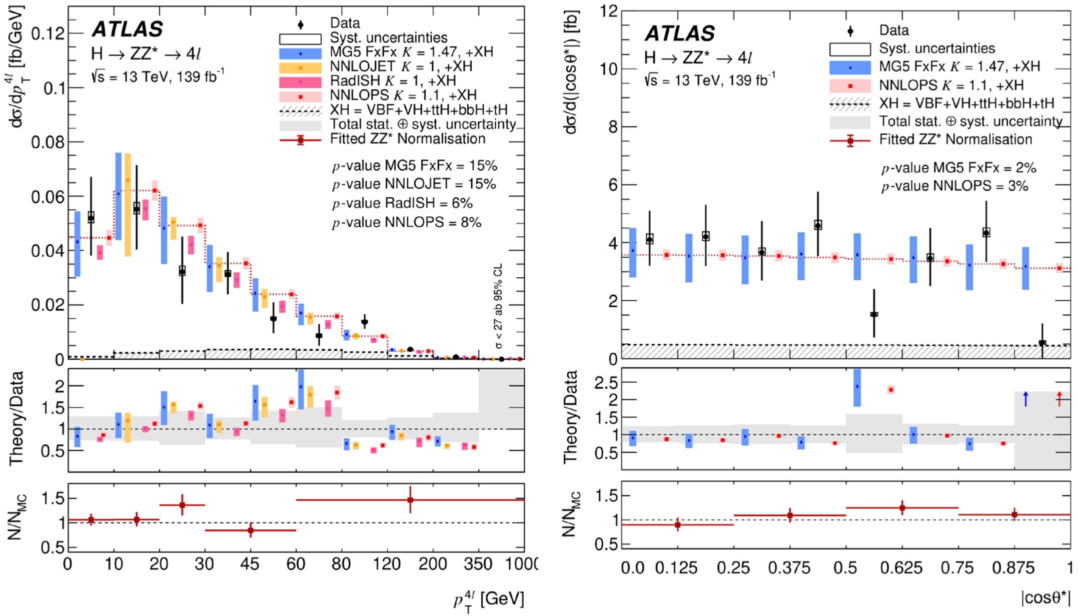
UMassAmherst

References to learn more

- Inclusive Observables
- ATLAS collaboration, A detailed map of Higgs boson interactions ten years after the discovery
- ATLAS collaboration, Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at √s=7 and 8 TeV in the ATLAS experiment
- ATLAS and CMS collaborations, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at s√= 7 and 8 TeV

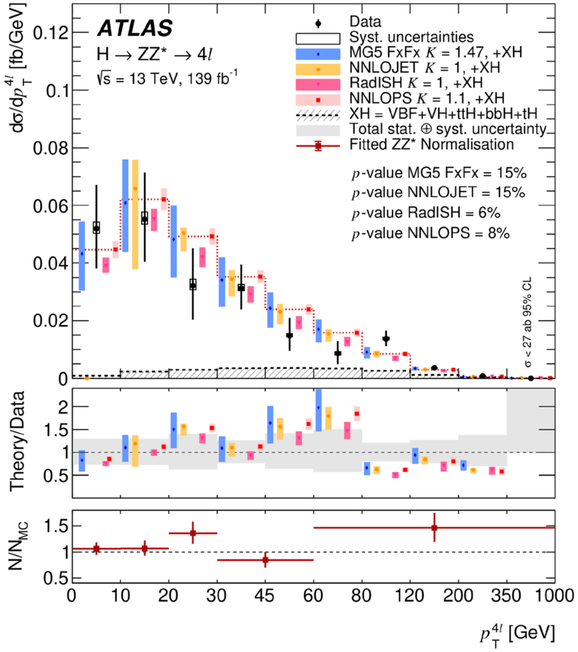
Differential cross sections

- Differential cross sections provide tests of Higgs physics without model and theory dependence (as long as you don't extrapolate).
- In final states with high-resolution particles ($H \to ZZ \to 4\ell$, $H \to \gamma\gamma$, …) unfolding by simple matrix inversion works.
- Lately, profile likelihood unfolding has become very popular in these cases, since there is a well established way to account for uncertainties.
- For variables like N_{jets}, associated jet p_T, … regularization can be used. For instance, Tikhonov regularization is easy to implement in this formalism.



Plots from ATLAS collaboration, Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at √s = 13 TeV

What kind of tests?



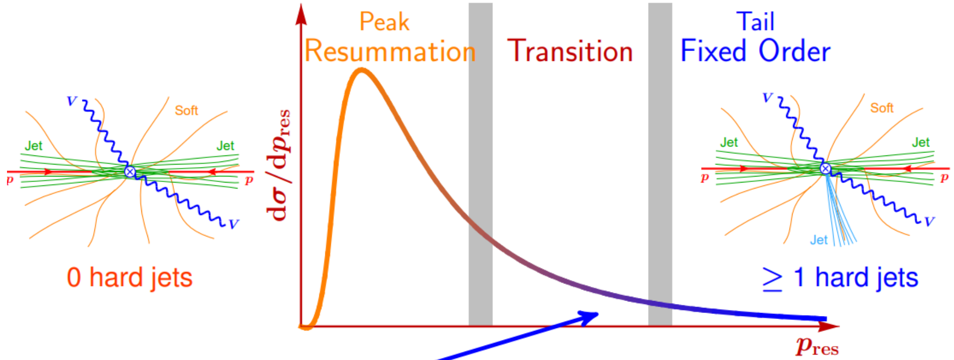
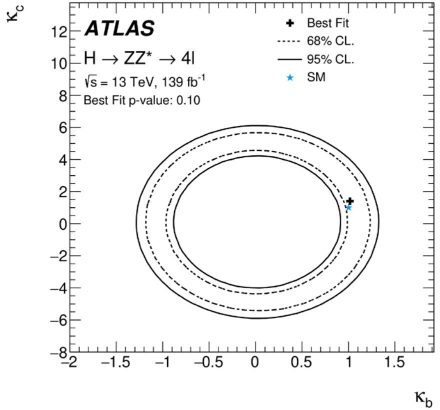


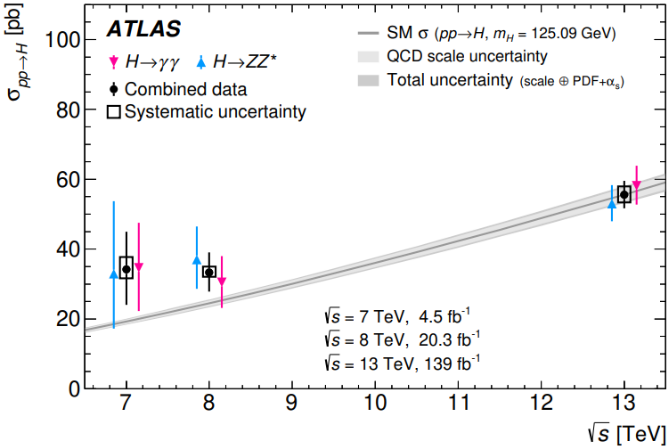
Diagram from F. Tackman

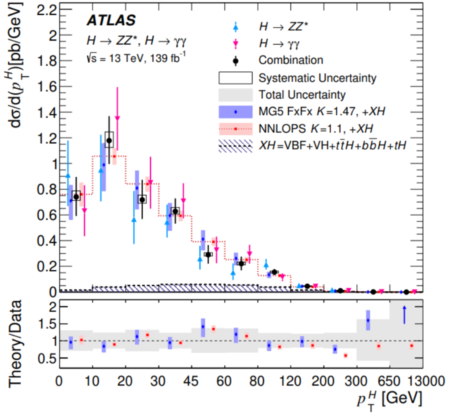
- Differential cross sections can test predictions of Higgs production in different QCD regimes (fixed order, resummation, …)
- Balance between gluon and quark-initiated production allows one to set limits on κ_b and κ_c

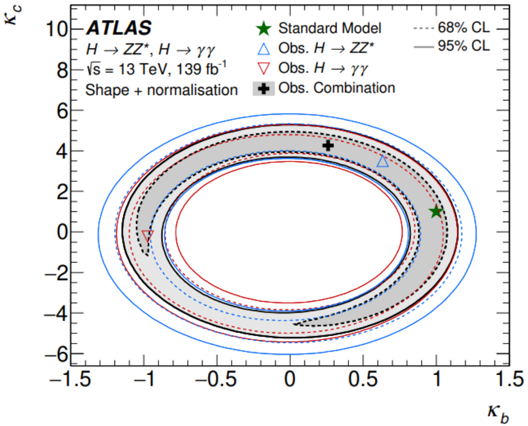


Extrapolations and combinations

- Differential cross sections can't be combined across channels without re-introducing some degree of theory dependency.
- The extrapolation can be kept under control if the acceptance of the fiducial region used is large (in practice it is approximately 50%)







Plots from ATLAS collaboration, Measurement of the total and differential Higgs boson production cross-sections at √s=13 TeV with the ATLAS detector by combining the H→ZZ∗→4ℓ and H→γγ decay channels

References to learn more

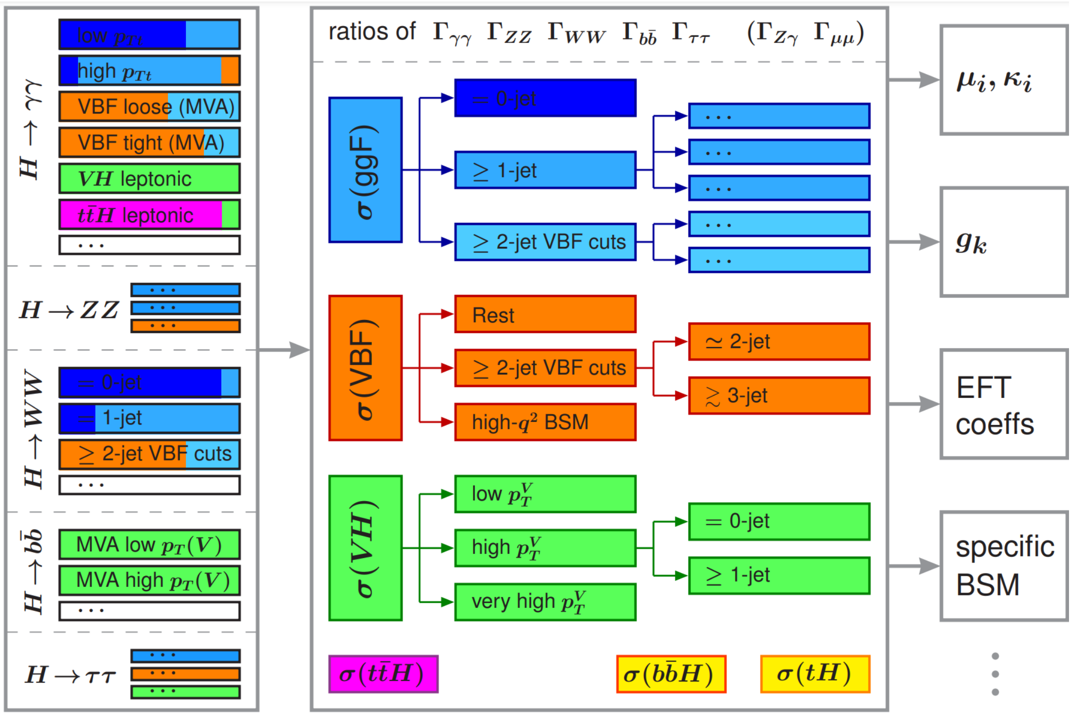
- Differential Distributions
- ATLAS collaboration, Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s}$=13 TeV
- ATLAS collaboration, Measurement of the total and differential Higgs boson production cross-sections at $\sqrt{s}$=13 TeV with the ATLAS detector by combining the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels

Simplified Template Cross Sections

- Direct measurements (κ-framework, CP violation OO, ...)
  - Maximum sensitivity
  - Theory model, uncertainties and predictions are part of the measurement.
  - If these change, you have to redo measurement
- Differential fiducial measurements
  - Best model and theory independence
  - Less sensitive: measurements use simple cuts and avoid selections with a strong production model/signal dependence
- Simplified Template cross Section (STXS) is a compromise
  - Use “most sensitive analysis” to separate between Higgs production modes and against backgrounds
  - Extrapolate to coarse kinematic regions for each Higgs production mode
  - Good sensitivity while keeping reduced theory dependence

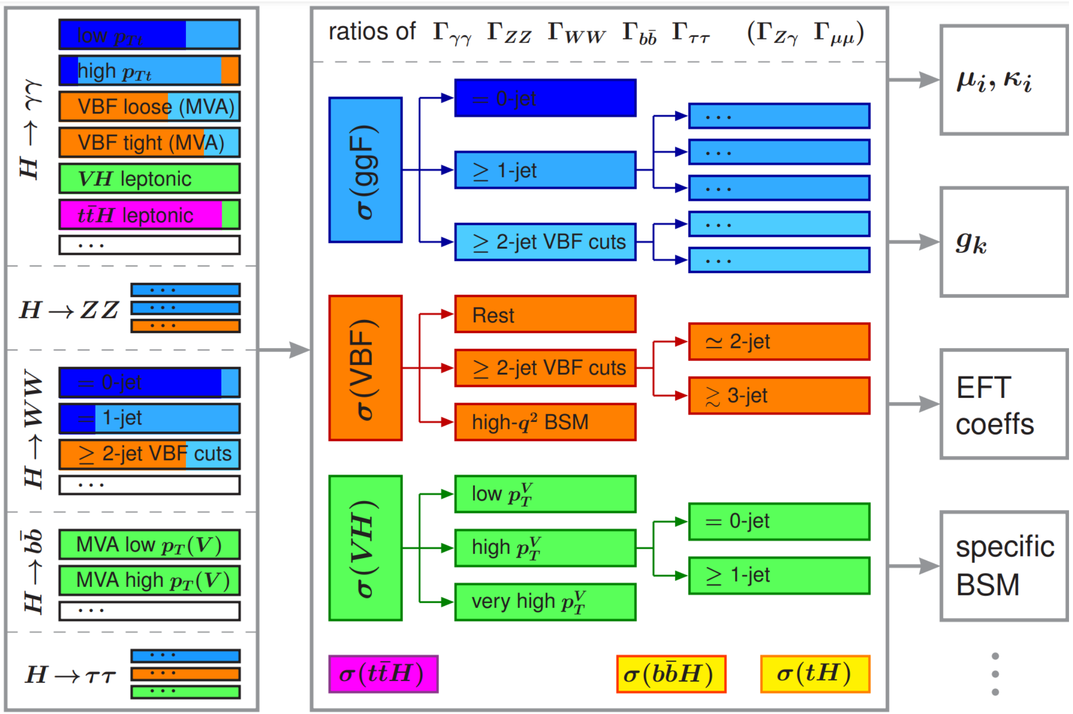
What is STXS?

- Measure cross sections in predefined kinematic bins per production mode template with the goal of
  - Minimizing theory dependence
  - Maximizing experimental sensitivity
  - Possible to isolate out and probe certain classes of BSM effects
- No fiducial phase space (except for $|y_H| < 2.5$)
- STXS is designed for the combination of all Higgs measurements.
  - Across channels and across experiments.



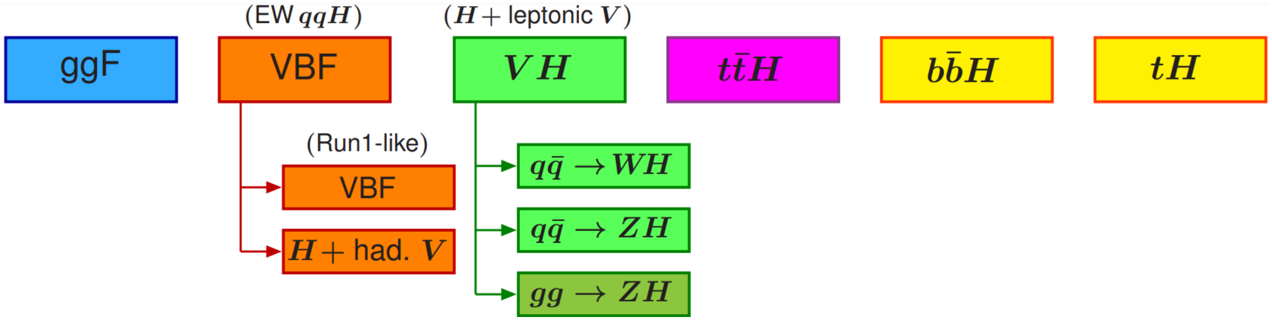
How is it done?

- The measurements should avoid large extrapolations from experimental selections to STXS bins.
- Each decay channels should be able to define experimental selections which approximately reproduce the STXS bin.
- This should work for approximately all Higgs decay channels.
- For each Higgs production mode, use the SM process as kinematic template (profile likelihood unfolding)
- Different channels may merge bins if there is no sensitivity.



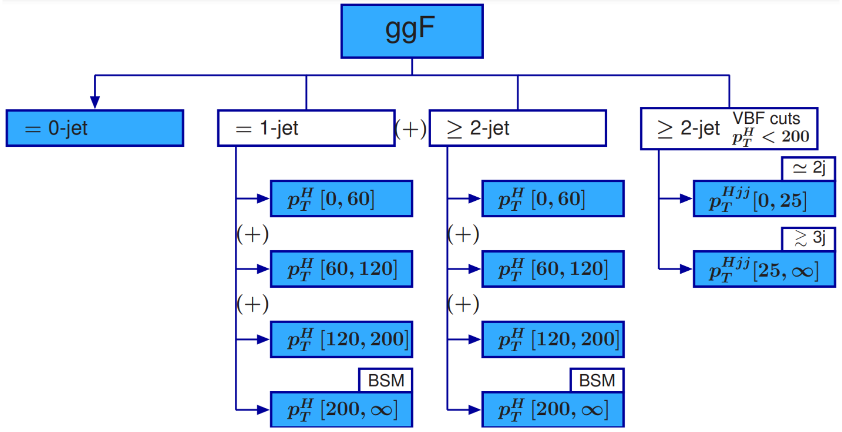
STXS stage 0

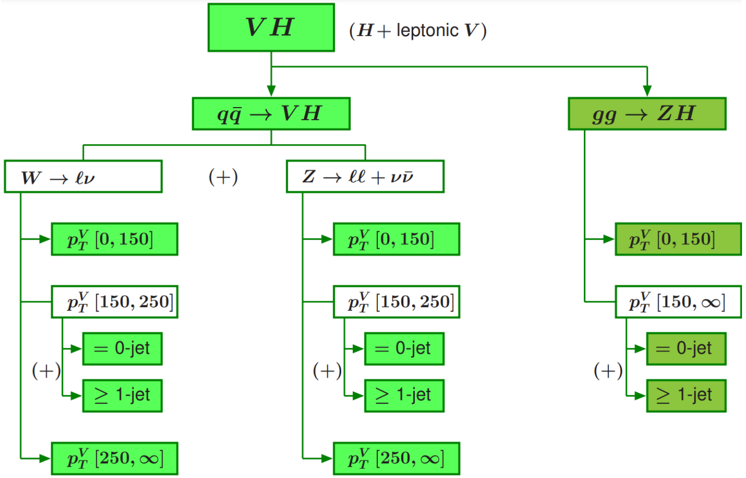
- It is essentially the same as the production signal strength measured in Run 1 (with the $|y_H| < 2.5$ condition).
- Replaces the μ-combinations done in Run 1.

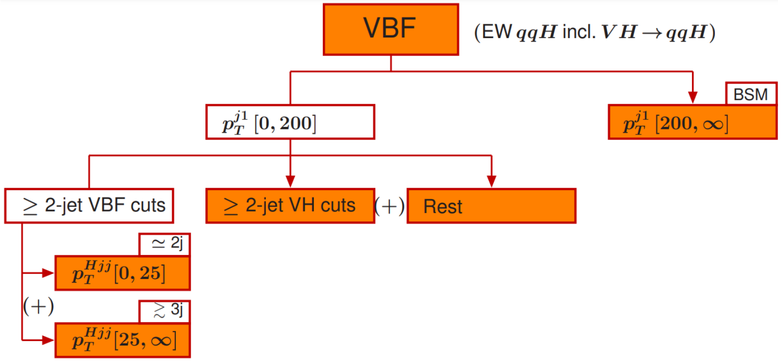


STXS stage 1

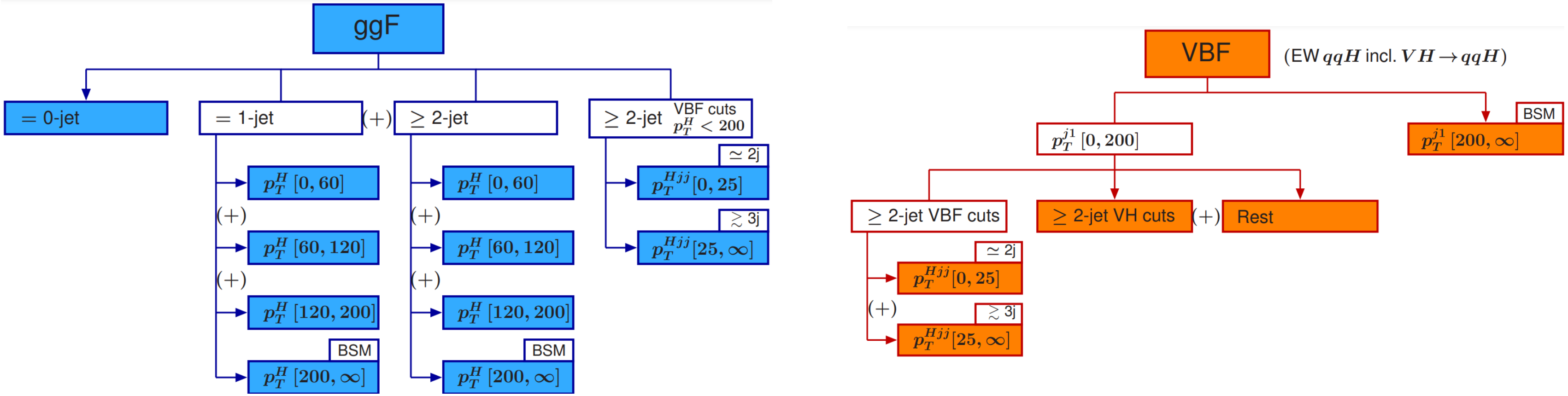
- First attempt to measure the Higgs boson production in bins.
- Used for the early Run 2 measurements.
- Some poor choices: complicated VBF cuts/rest, large correlations (p_T^H, $p_T^{j_1}$, …)







Example of problems with stage 1



- Problem in BSM regions: it is very difficult to create experimental channels with large separation between ggF at large p_T^H and VBF at large $p_T^{j_1}$.
- Example of proposed (and actually implemented) modification: use p_T^H for VBF too.

Stages 1.1 and 1.2

- Used for full Run 2 measurements
- Careful evaluation of theory uncertainties. Simple scale variations tend to be artificially small in the bins.
- Uncertainties are estimated via a Stewart-Tackman procedure

$$C(\{\sigma_0, \sigma_{\geq 1}\}) = \begin{pmatrix} (\Delta_0^{\mathrm{y}})^2 & \Delta_0^{\mathrm{y}} \Delta_{\geq 1}^{\mathrm{y}} \\ \Delta_0^{\mathrm{y}} \Delta_{\geq 1}^{\mathrm{y}} & (\Delta_{\geq 1}^{\mathrm{y}})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\mathrm{cut}}^2 & -\Delta_{\mathrm{cut}}^2 \\ -\Delta_{\mathrm{cut}}^2 & \Delta_{\mathrm{cut}}^2 \end{pmatrix}$$

$$\mathrm{ST}: \quad \Delta_0^{\mathrm{y}} = \Delta_{\geq 0}^{\mathrm{y}} = \Delta_{\geq 0}^{\mathrm{FO}}, \quad \Delta_{\geq 1}^{\mathrm{y}} = 0, \quad \Delta_{\mathrm{cut}} = \Delta_{\geq 1}^{\mathrm{FO}}$$

$$\mathrm{ST}(\rho): \quad \Delta_0^{\mathrm{y}} = \Delta_{\geq 0}^{\mathrm{FO}}, \quad \Delta_{\geq 1}^{\mathrm{y}} = \rho\, \Delta_{\geq 1}^{\mathrm{FO}}, \quad \Delta_{\mathrm{cut}} = \sqrt{1-\rho^2}\, \Delta_{\geq 1}^{\mathrm{FO}}$$

- Bins are chosen to keep theoretical uncertainties under control.
- Bins can be merged if separation cannot be achieved experimentally.

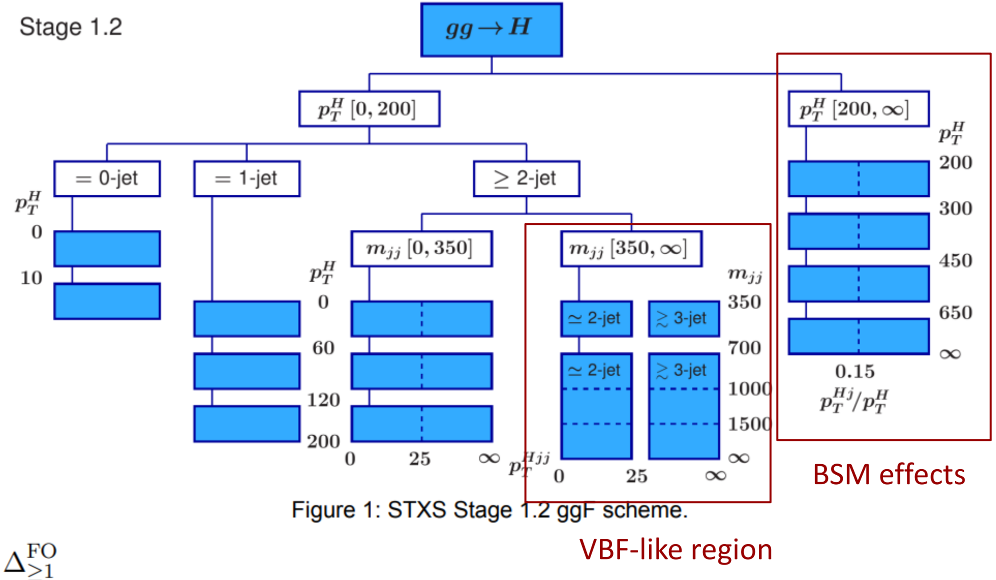


Figure 1: STXS Stage 1.2 ggF scheme.

Stages 1.1 and 1.2

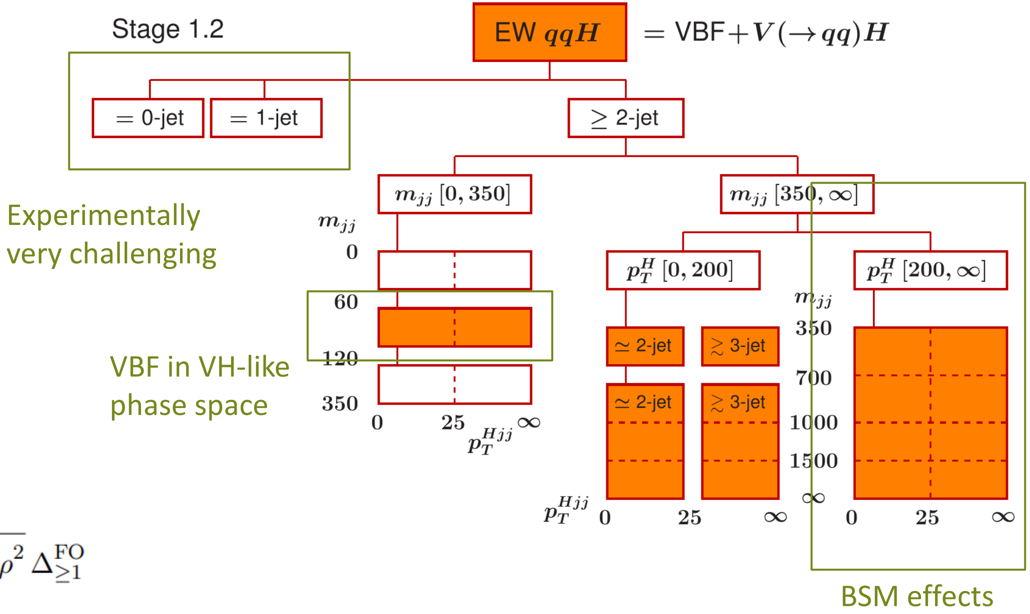
- Used for full Run 2 measurements
- Careful evaluation of theory uncertainties. Simple scale variations tend to be artificially small in the bins.
- Uncertainties are estimated via a Stewart-Tackman procedure

$$C(\{\sigma_0, \sigma_{\geq 1}\}) = \begin{pmatrix} (\Delta_0^{y})^2 & \Delta_0^{y}\,\Delta_{\geq 1}^{y} \\ \Delta_0^{y}\,\Delta_{\geq 1}^{y} & (\Delta_{\geq 1}^{y})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm cut}^2 & -\Delta_{\rm cut}^2 \\ -\Delta_{\rm cut}^2 & \Delta_{\rm cut}^2 \end{pmatrix}$$

$$\text{ST}: \quad \Delta_0^{y} = \Delta_{\geq 0}^{y} = \Delta_{\geq 0}^{\rm FO}\,, \quad \Delta_{\geq 1}^{y} = 0\,, \quad \Delta_{\rm cut} = \Delta_{\geq 1}^{\rm FO}$$

$$\text{ST}(\rho): \quad \Delta_0^{y} = \Delta_{\geq 0}^{\rm FO}\,, \quad \Delta_{\geq 1}^{y} = \rho\,\Delta_{\geq 1}^{\rm FO}\,, \quad \Delta_{\rm cut} = \sqrt{1-\rho^2}\,\Delta_{\geq 1}^{\rm FO}$$

- Bins are chosen to keep theoretical uncertainties under control.
- Bins can be merged if separation cannot be achieved experimentally.



Stages 1.1 and 1.2

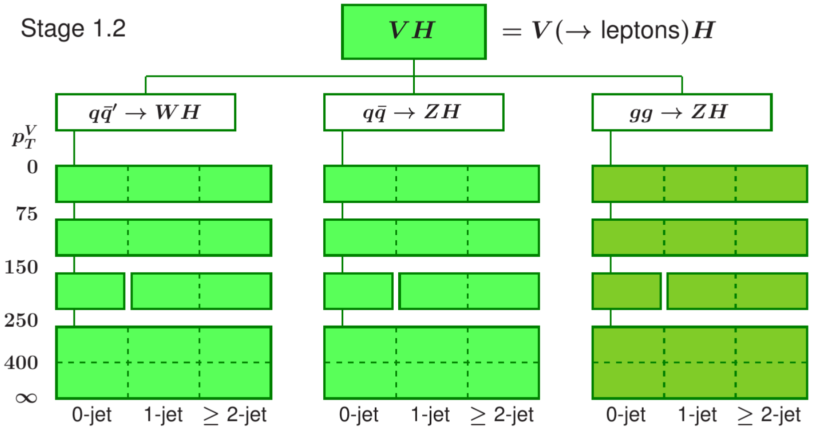
- Used for full Run 2 measurements
- Careful evaluation of theory uncertainties. Simple scale variations tend to be artificially small in the bins.
- Uncertainties are estimated via a Stewart-Tackman procedure

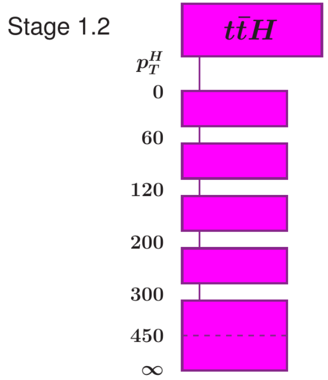
$$C(\{\sigma_0, \sigma_{\geq 1}\}) = \begin{pmatrix} (\Delta_0^y)^2 & \Delta_0^y \Delta_{\geq 1}^y \\ \Delta_0^y \Delta_{\geq 1}^y & (\Delta_{\geq 1}^y)^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm cut}^2 & -\Delta_{\rm cut}^2 \\ -\Delta_{\rm cut}^2 & \Delta_{\rm cut}^2 \end{pmatrix}$$

$$\text{ST}: \quad \Delta_0^y = \Delta_{\geq 0}^y = \Delta_{\geq 0}^{\rm FO}\,, \quad \Delta_{\geq 1}^y = 0\,, \quad \Delta_{\rm cut} = \Delta_{\geq 1}^{\rm FO}$$

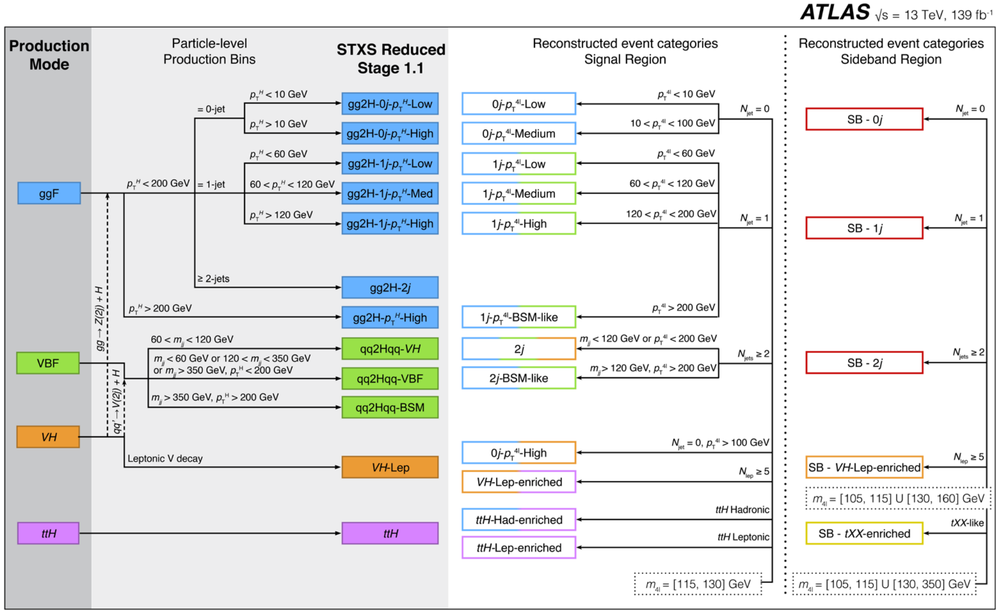
$$\text{ST}(\rho): \quad \Delta_0^y = \Delta_{\geq 0}^{\rm FO}\,, \quad \Delta_{\geq 1}^y = \rho\,\Delta_{\geq 1}^{\rm FO}\,, \quad \Delta_{\rm cut} = \sqrt{1-\rho^2}\,\Delta_{\geq 1}^{\rm FO}$$

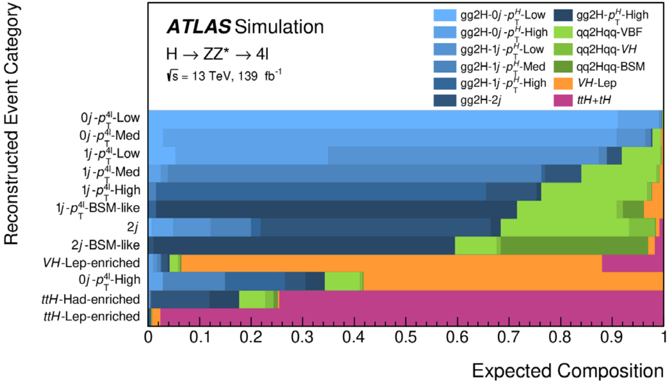
- Bins are chosen to keep theoretical uncertainties under control.
- Bins can be merged if separation cannot be achieved experimentally.

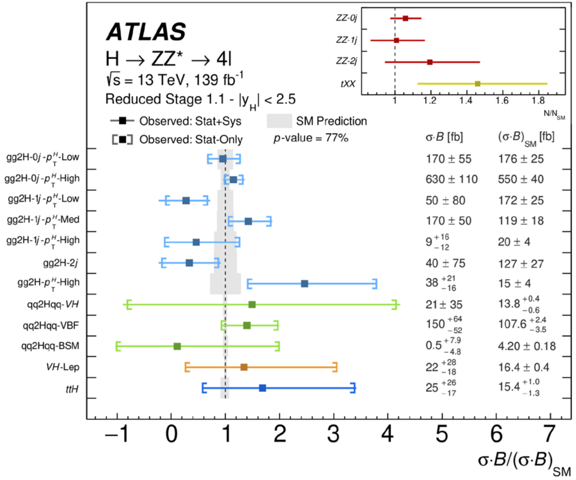




Experimental methods

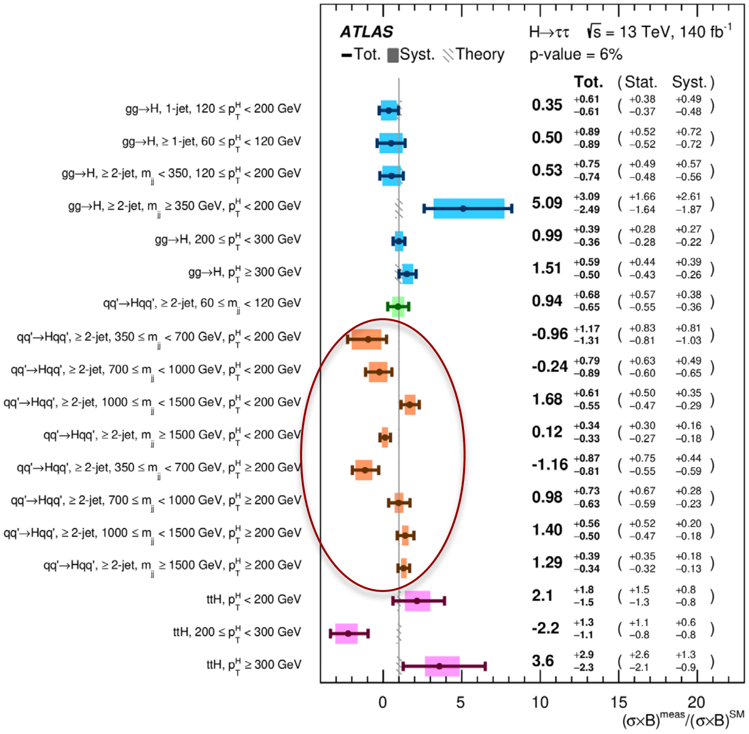


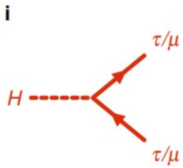


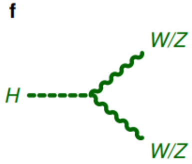


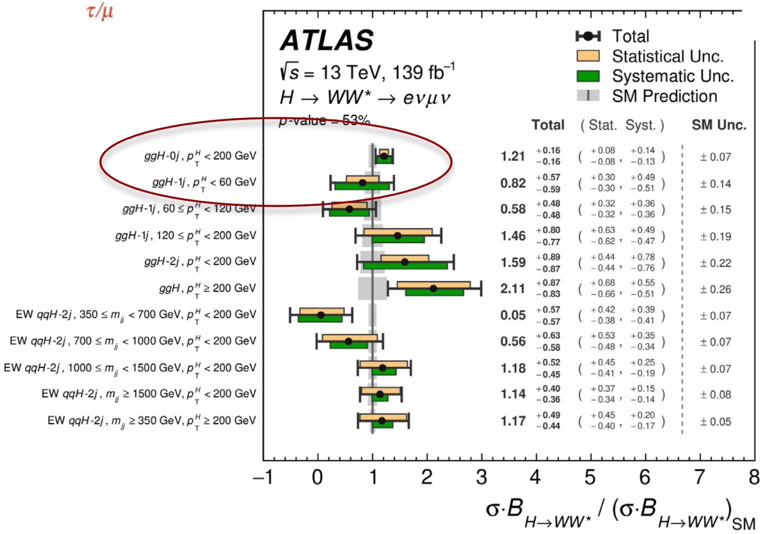
Plots from ATLAS collaboration, [Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at √s = 13 TeV with the ATLAS detector]

More experimental results



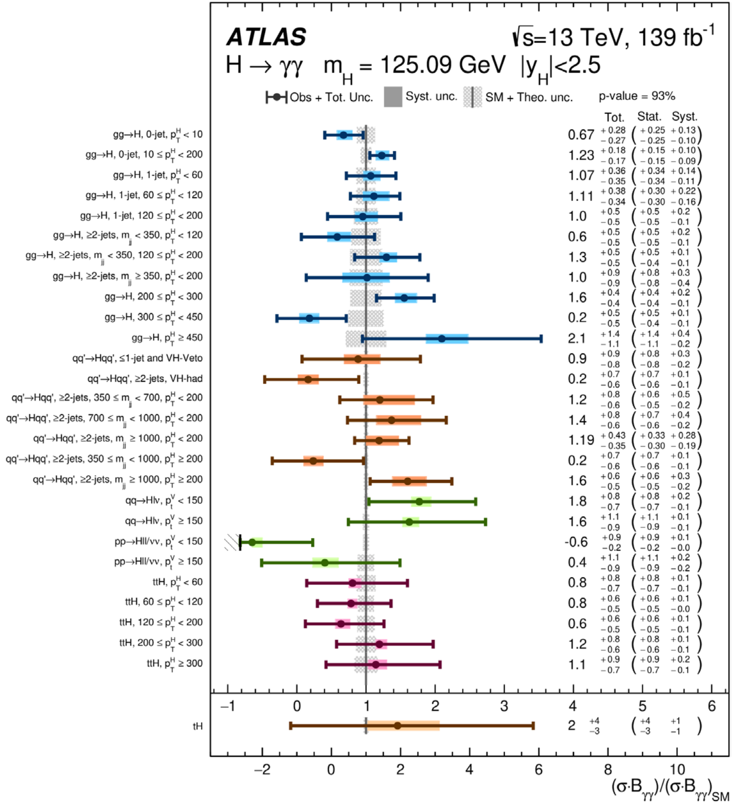




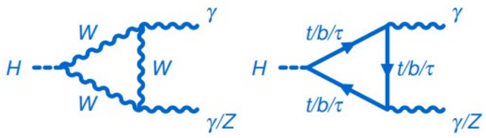


See references in the next slides

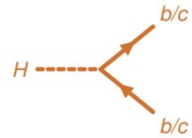
More experimental results

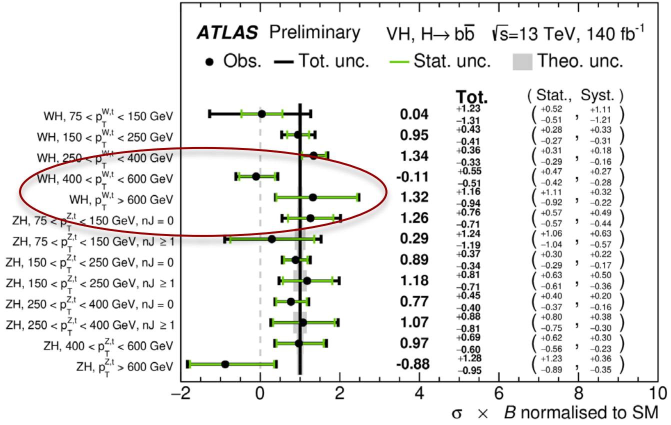


g



h





See references in the next slides

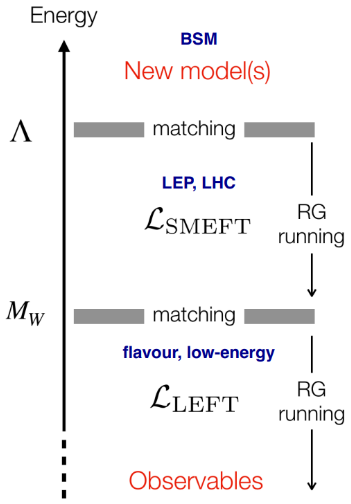
References to learn more

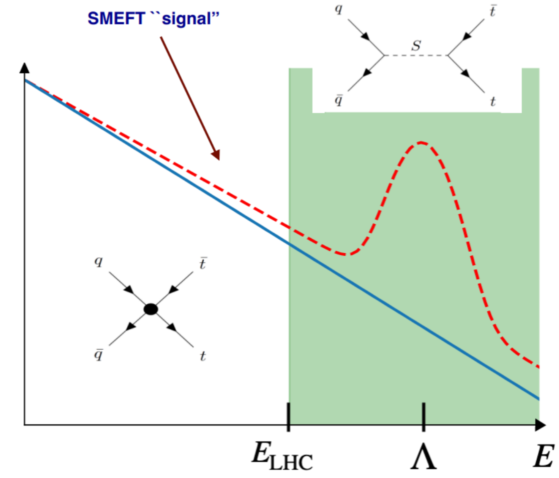
- Simplified Template Cross Sections – Stage 1.1
- Summary of recommended ggF STXS Stage 1.2 uncertainty scheme after discussion between ATLAS, CMS, and theorists
- Deciphering the nature of the Higgs sector
- Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report
- Les Houches 2019: Physics at TeV Colliders: Standard Model Working Group Report
- ATLAS collaboration, Evaluation of QCD uncertainties for Higgs boson production through gluon fusion and in association with two top quarks for simplified template cross-section measurements
- Gangal, S. and Tackman, F., NLO Uncertainties in Higgs + 2 Jets From Gluon Fusion
- LHC Higgs Working Group: Fiducial and STXS
- Simplified template cross sections for Higgs boson decays

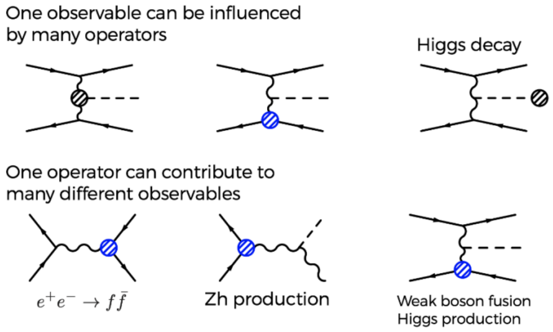
References to learn more

- ATLAS collaboration, Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at √s = 13 TeV with the ATLAS detector
- ATLAS collaboration, Measurement of the associated production of a top-antitop-quark pair and a Higgs boson decaying into a bb pair in pp collisions at √s=13 TeV using the ATLAS detector at the LHC
- ATLAS collaboration, Measurement of the properties of Higgs boson production at √s=13 TeV in the $H\to\gamma\gamma$ channel using 139 fb−1 of pp collision data with the ATLAS experiment
- ATLAS collaboration, Measurements of WH and ZH Higgs production with decays into bottom quarks and direct constraints on the charm Yukawa coupling with 13 TeV collisions in the ATLAS detector.
- ATLAS collaboration, Measurements of Higgs boson production by gluon-gluon fusion and vector-boson fusion using $H\to WW^*\to e\nu\mu\nu$ decays in pp collisions at √s=13 TeV with the ATLAS detector
- ATLAS collaboration, Differential cross-section measurements of Higgs boson production in the $H\to\tau^+\tau^-$ decay channel in pp collisions at s√=13 TeV with the ATLAS detector

SMEFT and Higgs physics







Plots from J. Fuentes-Martin, J. Rojo and A. Biekötter

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathscr{O}_i^{(d=5)} + \sum_j \frac{c_j^{(6)}}{\Lambda^2}\mathscr{O}_j^{(d=6)} + \sum_k \frac{c_j^{(7)}}{\Lambda^3}\mathscr{O}_k^{(d=7)} \ldots$$

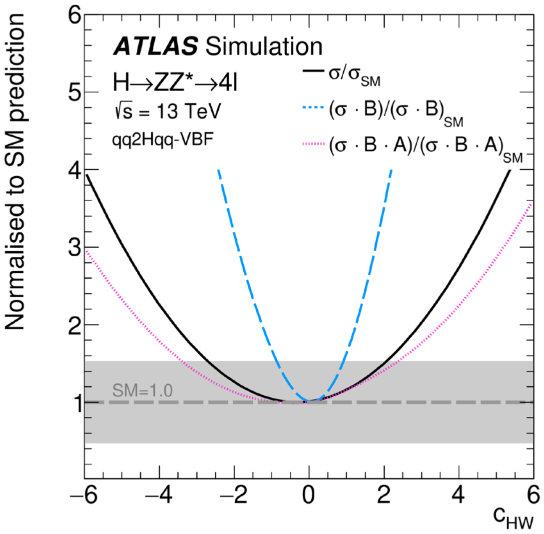
Wilson coefficients

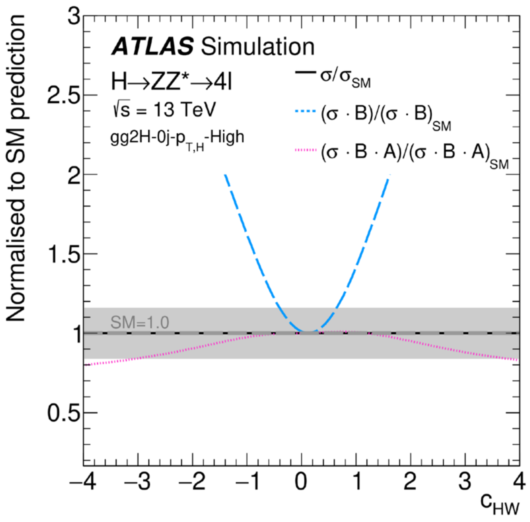
cutoff (BSM) scale

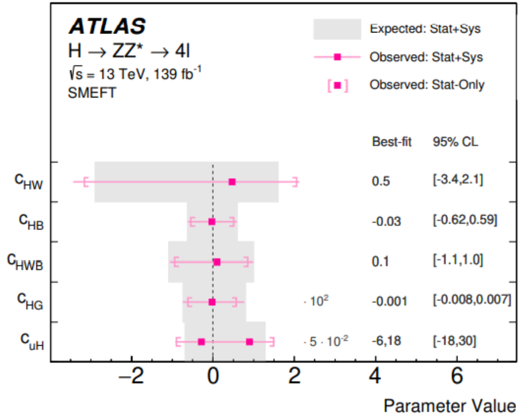
all possible operators consistent with these requirements

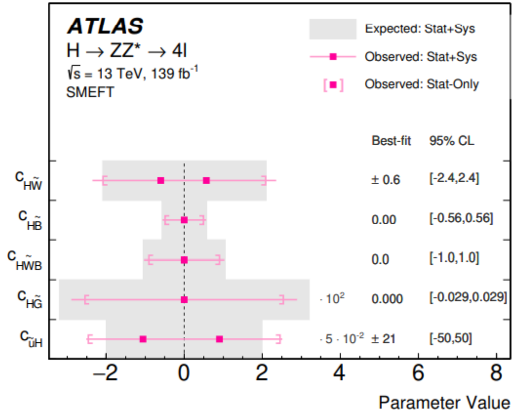
- SMEFT provides a systematic way to study deviations in the SM.
- Blur distinctions between measurements and searches.
- Sometimes it is difficult to ensure that measurements are within the EFT validity range.
- An s-channel Higgs production provides a natural energy scale for the process.

SMEFT interpretation



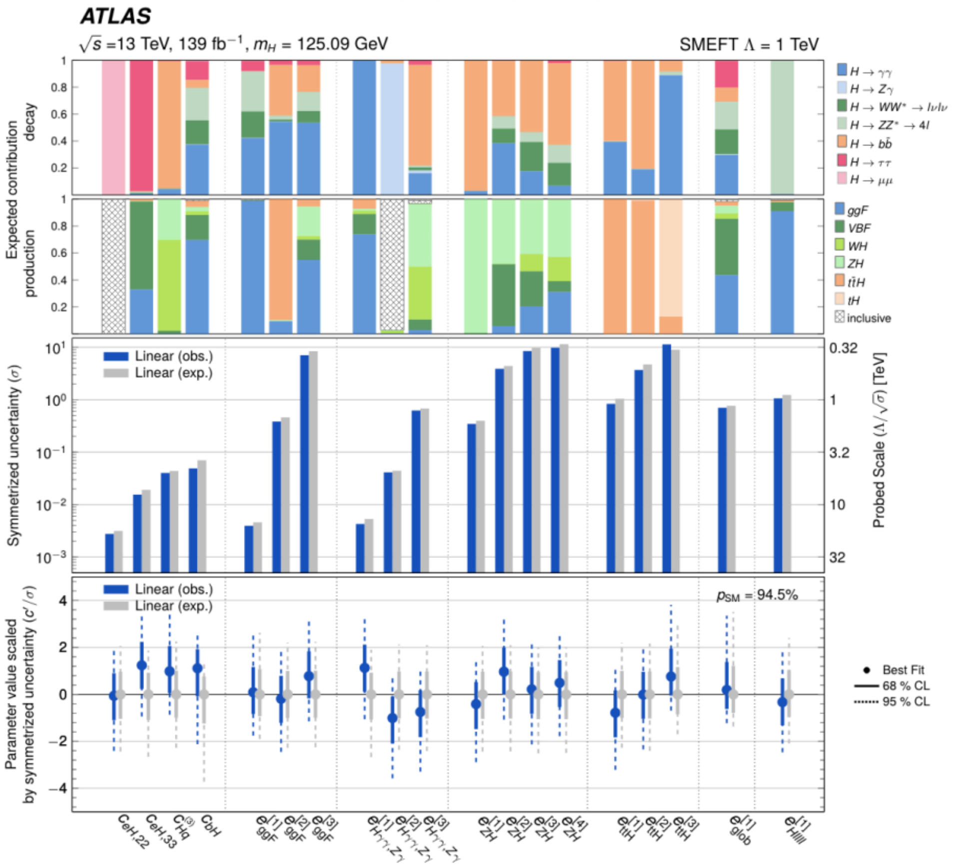






$$\mu^p(\vec{c}) = \frac{\sigma^p(\vec{c})}{\sigma_{\text{SM}}} \cdot \frac{\mathcal{B}^{4\ell}(\vec{c})}{\mathcal{B}^{4\ell}_{\text{SM}}} \cdot \frac{A(\vec{c})}{A_{\text{SM}}}.$$

SMEFT and Higgs physics



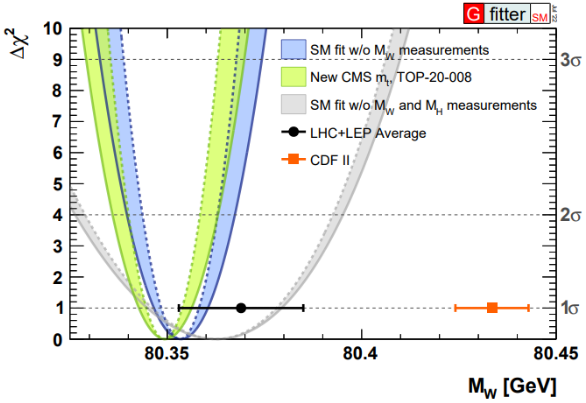
Plot from ATLAS collaboration, Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables

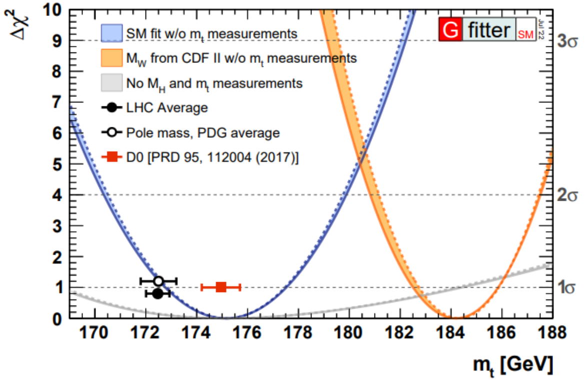
Higgs mass

- The Higgs mass is a fundamental parameter of the SM → needs to be measured
- But the electroweak sector of the SM is over constrained.

$$M_W^2 = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2} G_\mu M_Z^2} \left[1 + \Delta r(M_W, M_Z, M_H, m_t, \ldots) \right]} \right\}$$

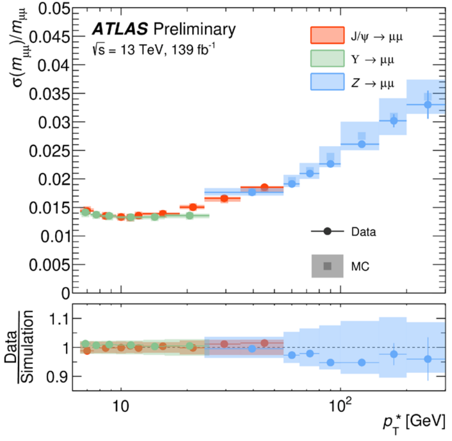
- The uncertainties in this formula are largely dominated by M_W, m_t, and the light quark evolution contribution to α.
- Measuring M_H as one of the most important results in Run 1, but it has reduced importance these days.
- May be an important input for future lepton collider scans if we can reach $\mathcal{O}(10 - 40)$ MeV uncertainty.

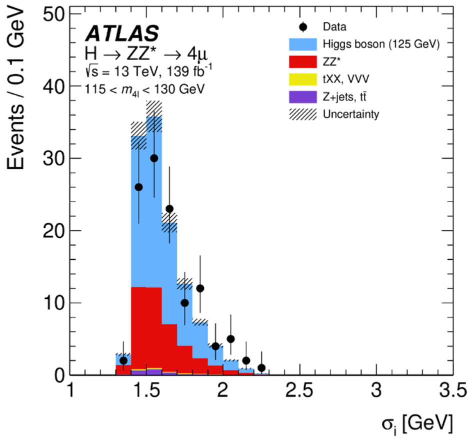


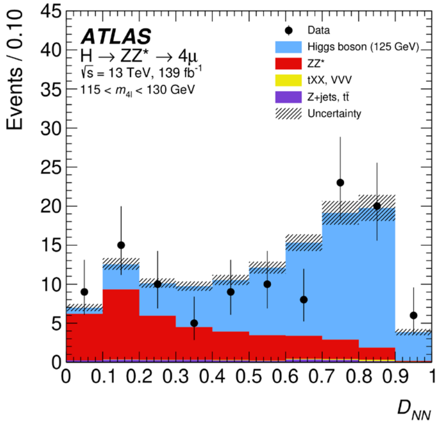


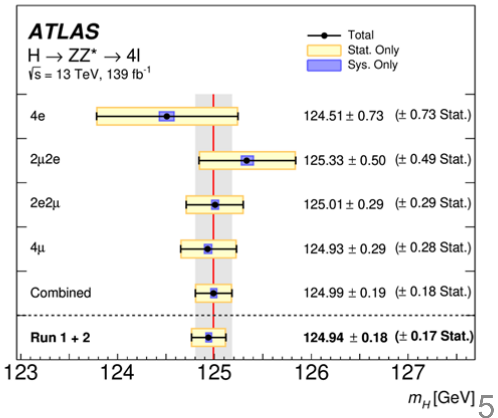
m_H measurements

- Mass measurements are all about knowing the momentum scale of the final-state particles with ultimate precision.
- A lot of effort goes into electron energy scale, muon momentum scale, and photon energy scale calibration.
- On analysis level, the signal probability model is estimate through a mix of ML-methods and mass peak parameterization.
- What you really don't want is to mix events with good and bad mass resolution.
- Possible to train a quantile NN to regress per-event reconstructed m_{reco} resolution



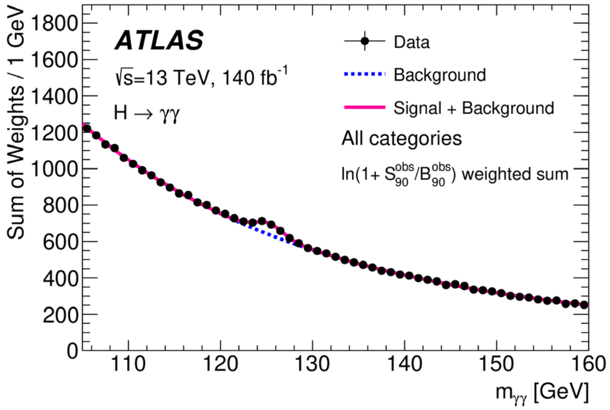


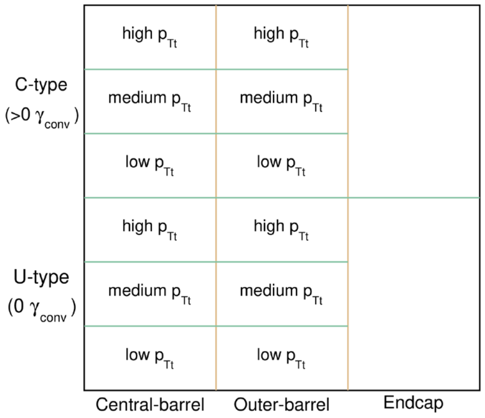


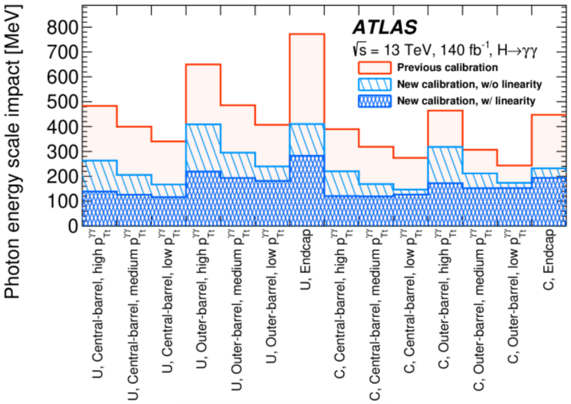


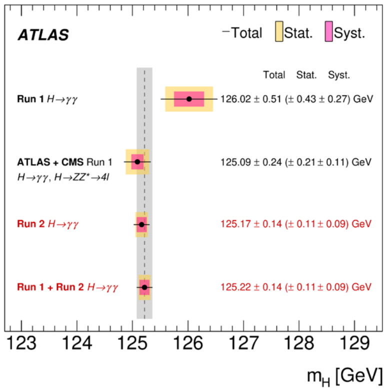
m_H measurements

- Mass measurements are all about knowing the momentum scale of the final-state particles with ultimate precision.
- A lot of effort goes into electron energy scale, muon momentum scale, and photon energy scale calibration.
- On analysis level, the signal probability model is estimate through a mix of ML-methods and mass peak parameterization.
- What you really don't want is to mix events with good and bad mass resolution.
- Possible to train a quantile NN to regress per-event reconstructed m_{reco} resolution



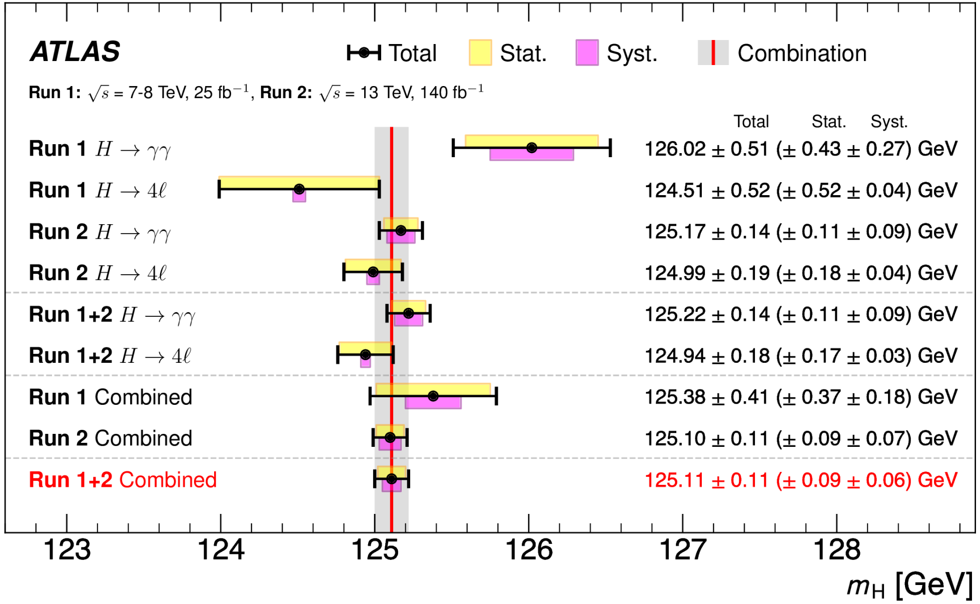






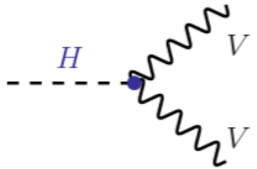
m_H measurements

- Mass measurements are all about knowing the momentum scale of the final-state particles with ultimate precision.
- A lot of effort goes into electron energy scale, muon momentum scale, and photon energy scale calibration.
- On analysis level, the signal probability model is estimate through a mix of ML-methods and mass peak parameterization.
- What you really don't want is to mix events with good and bad mass resolution.
- Possible to train a quantile NN to regress per-event reconstructed m_{reco} resolution

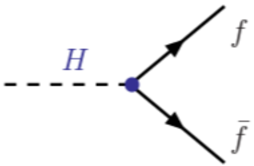


The Higgs width

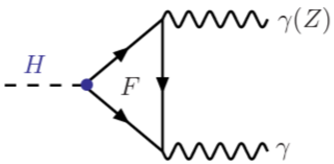
The decay widths of the Higgs boson in the Standard Model are small compared to its mass



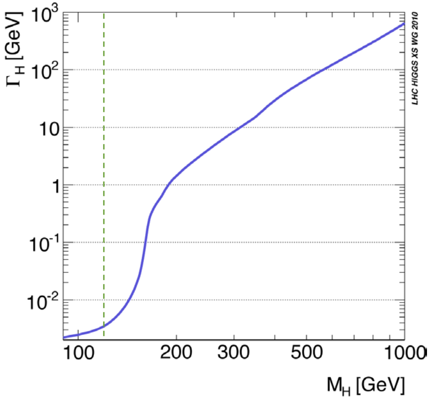
decay to off-shell weak bosons
$H \to VV^*$



small Yukawa coupling
$H \to ff$ (not the top quark)



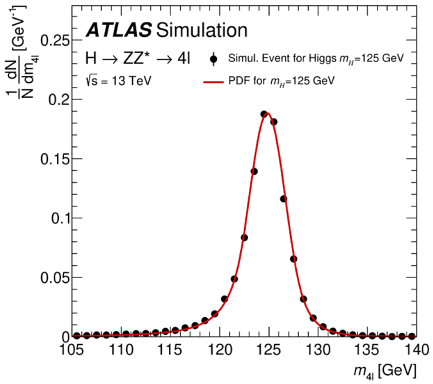
loop-suppressed
$H \to \gamma\gamma$ and $H \to Z\gamma$

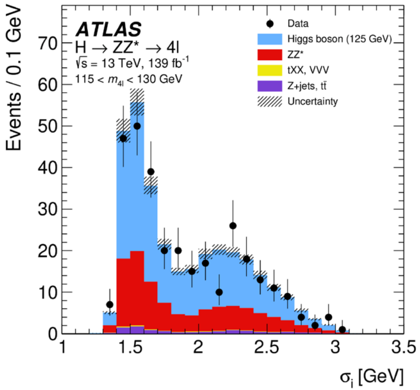


The best estimate of the Higgs boson total width is:

$$\Gamma_H^{SM} = 4.07 \text{ MeV}$$

3 orders of magnitude smaller than our mass resolution





Direct measurements of the width using the Higgs line shape (CMS-PAS-HIG-21-019):

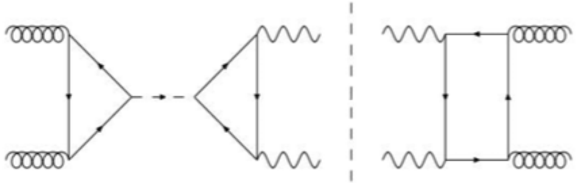
$$\Gamma_H < 60 \text{ MeV @ } 68\% \text{ CL.}$$

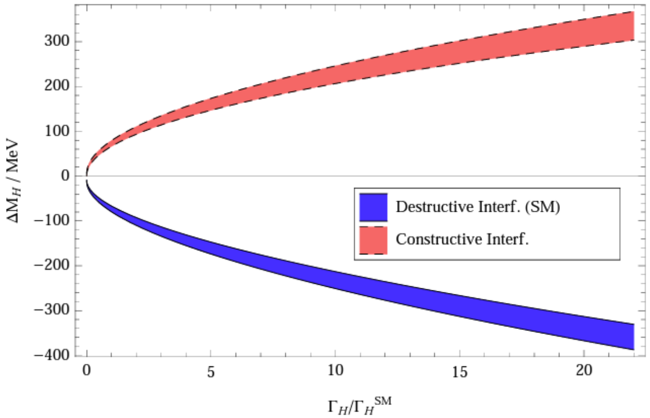
Measurements of the lifetime (CMS, Run 1):

$$\Gamma_H > 3.5 \times 10^{-9} \text{ MeV @ } 95\% \text{ CL.}$$

Intermezzo: on-shell interference

In 2013, L. Dixon and Y. Li pointed out there is a large interference between $H \to \gamma\gamma$ and the continuous $\gamma\gamma$ that can be used to probe the Higgs boson width Γ_H





The interference creates a shift in the $m_{\gamma\gamma}$ peak with respect to m_H.

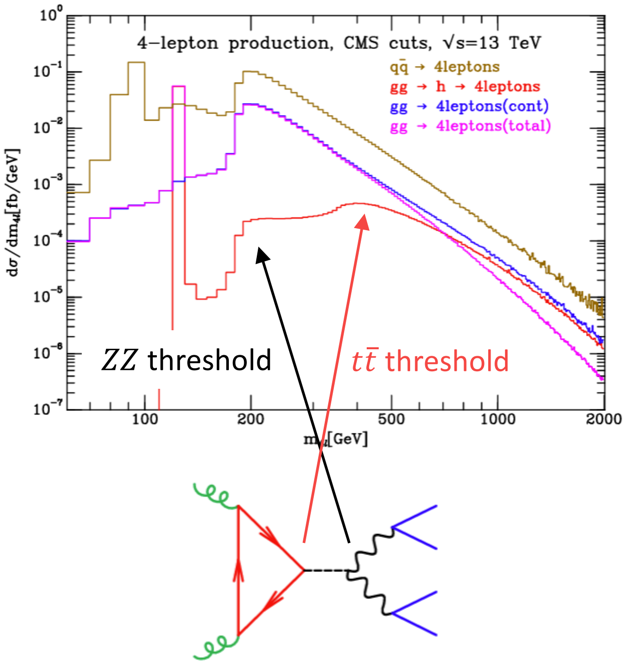
The shift can be used probe Γ_H experimentally by comparing the $m_{\gamma\gamma}$ and $m_{4\ell}$ peaks.

More discussion in ATLAS collaboration, Estimate of the mH shift due to interference between signal and background processes in the H → γγ channel, for the √s = 8 TeV dataset recorded by ATLAS

This method should be able to constrain

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} < \sim 100\text{MeV}$$

Width via off-shell Higgs production



- On-shell production analyses are measurements of Higgs couplings divided by the total width.
- Off-shell production analyses are measurements of Higgs couplings without the influence of the total width.
- A comparison of the two results yields an indirect measurement of the Higgs width

$$\frac{d\sigma^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

on-shell:

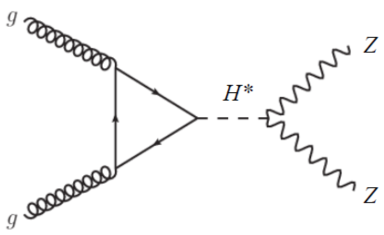
$$\sigma_{\text{on-shell}}^{pp\to H\to ZZ} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H\Gamma_H}$$

off-shell:

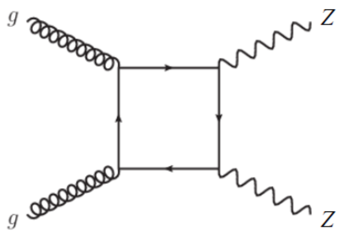
$$\frac{d\sigma_{\text{off-shell}}^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2}$$

Plot from Campbell, J. et al., Bounding the Higgs width at the LHC using full analytic results for gg -> 2e 2μ

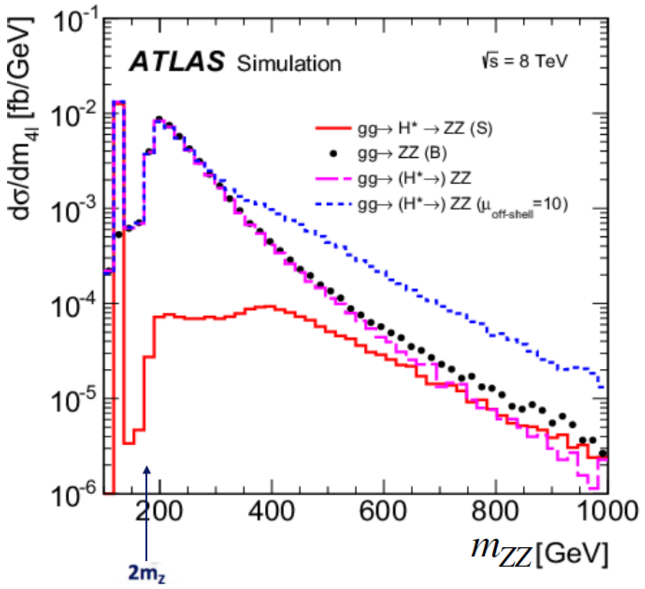
Off-shell $H \to ZZ$ production



signal (S)
$gg \to H^* \to ZZ$



background (B)
$gg \to ZZ$

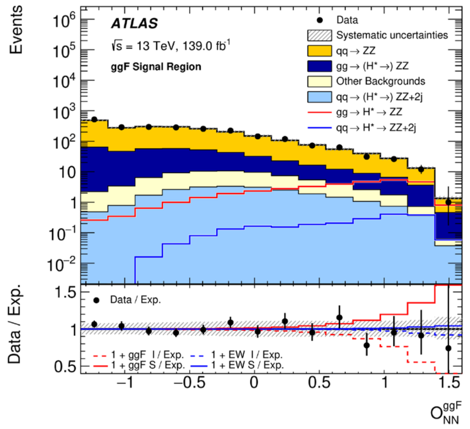


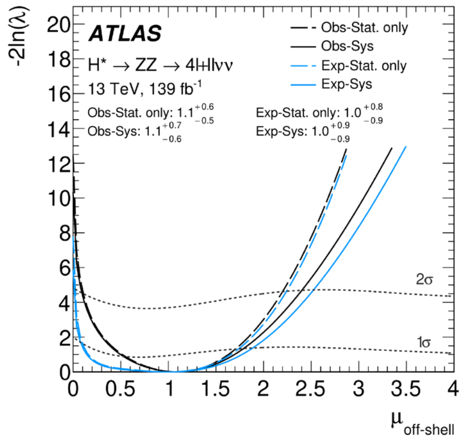
In the off-shell region, the interference (I) between the two components S and B is large and destructive

The interference is negative to preserve unitarity at high energies.

Off-shell $H \to ZZ$ production

- The basic method of the measurements is the same as for the on-shell measurements.
- Most measurements use either a "matrix element" approximation of an "optimal observable" or a ML-based discriminator.
- The interference here is the problem. A single discriminator does not work signal and interference and higher-dimension solutions have to be used.
- The statistics in the off-shell region is still small, so in many ways we are still in the same "stage" as we were with on-shell Higgs in Run 1.

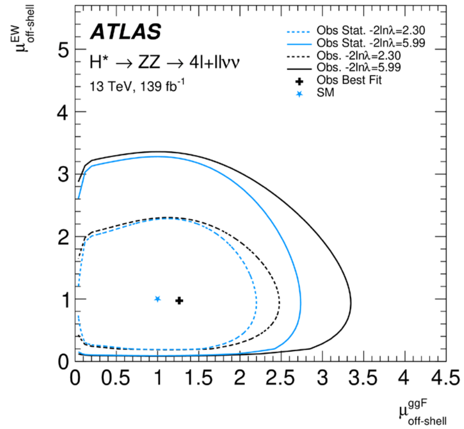


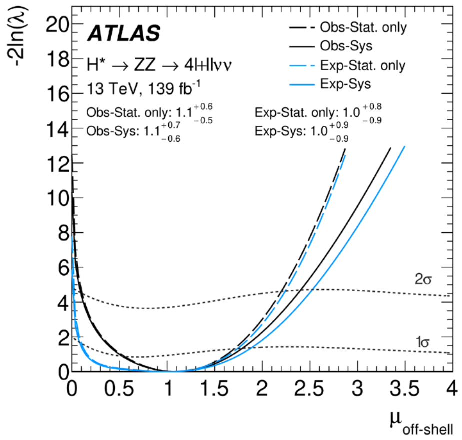


Plots from ATLAS collaboration, Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector

Off-shell $H \rightarrow ZZ$ production

- The basic method of the measurements is the same as for the on-shell measurements.
- Most measurements use either a “matrix element” approximation of an “optimal observable” or a ML-based discriminator.
- The interference here is the problem. A single discriminator does not work signal and interference and higher-dimension solutions have to be used.
- The statistics in the off-shell region is still small, so in many ways we are still in the same “stage” as we were with on-shell Higgs in Run 1.
  - Signal strength measurements, κ-framework, dedicated OO measurements.

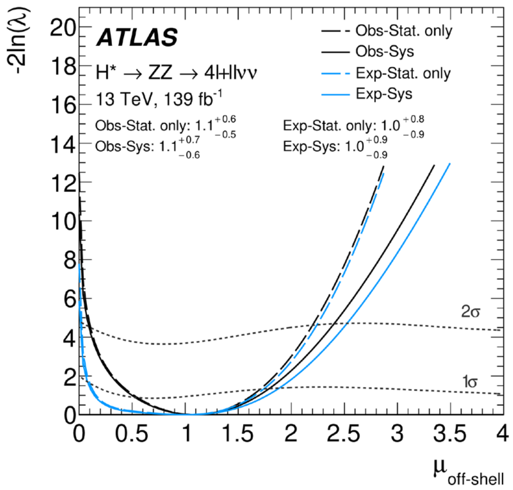


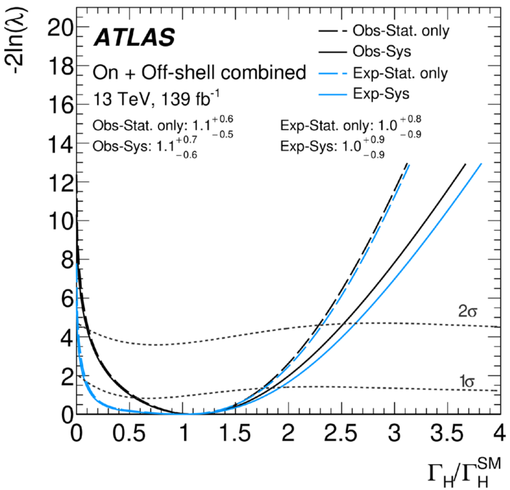


Plots from ATLAS collaboration, Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector

Higgs width from $H \to ZZ$

- Simultaneously fit signal strength and background normalization factors in all signal regions and control regions
- Direct measurement of off-shell signal strength $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$ with significance off-shell production 3.3 (2.2)σ
- Combination with on-shell STXS $H \to ZZ \to 4\ell$ measurement yields $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV and $0.5\ (0.1) < \Gamma_H < 10.5\ (10.9)$ MeV @ 95% C.L.



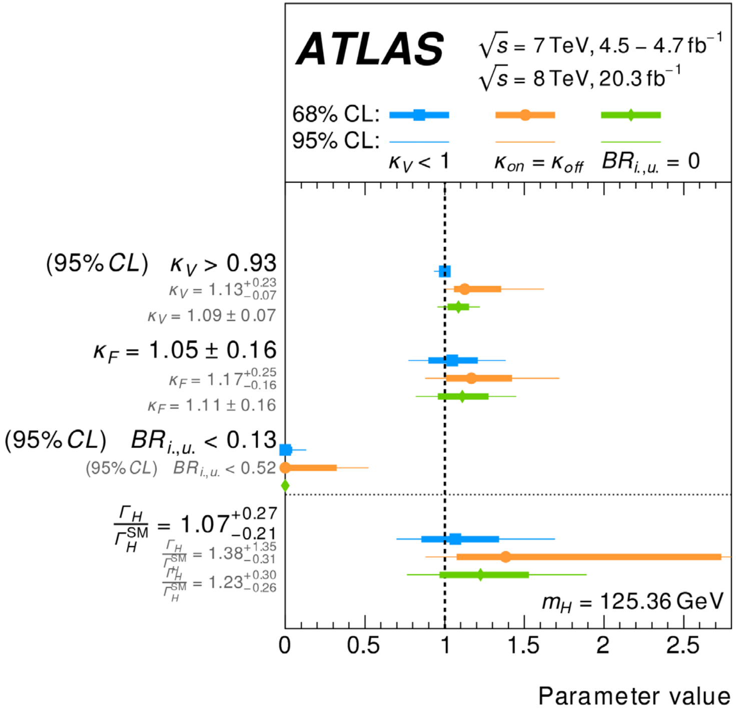


Run 2 $H \to ZZ$ result:

$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \text{MeV}$$

Plots from ATLAS collaboration, Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector

Off-shell and Higgs couplings



$$\Gamma_H = \Gamma_H^{SM} \frac{\sum_j B_j^{SM} \kappa_j^2}{(1 - B_{i,u})}$$

With an off-shell measurement we can discuss again the issue of a possible invisible or undetected Higgs decays when studying Higgs couplings.

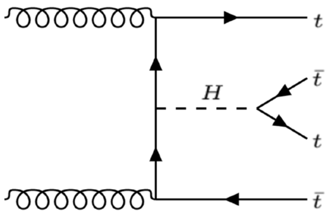
The off-shell measurement, which does not depend on Γ_H allows us to constrain this component without the κ_V hypothesis.

This has been used in Run 1 when studying Higgs couplings.

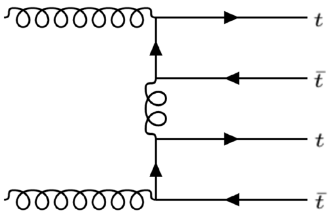
Plots from ATLAS collaboration, Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at √ s = 7 and 8 TeV in the ATLAS experiment

Intermezzo: $H \to t\bar{t}$ production

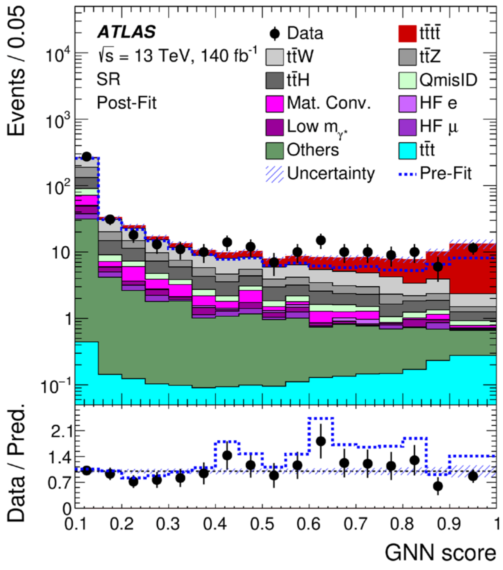
- Four-top production measured with $2\ell SS$ and multi-lepton ($> 3\ell$) events
- GNN discriminator trained with all events to discriminate $t\bar{t}t\bar{t}$ events from other sources of background.
- Interpretation of $t\bar{t}t\bar{t}$ measurement. No attempt to discriminate (Higgs) S and B.



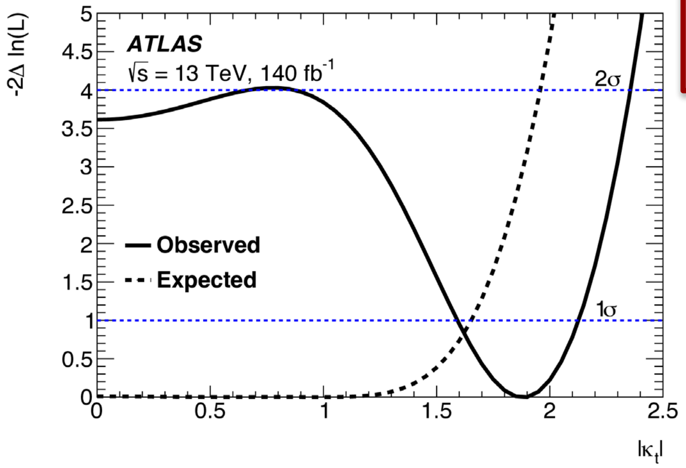
signal (S)



background (B)



$$\mu_{\text{off-shell}} = |\kappa_t|^4$$



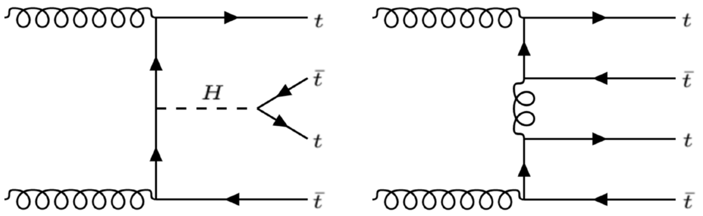
Probing only the **off-shell Higgs contribution to the $t\bar{t}t\bar{t}$ events**, and **a pure CP-even κ_t**, then the observed (expected) limits are:

$$\kappa_t < 2.3 \text{ @ 95\% C.L.}$$

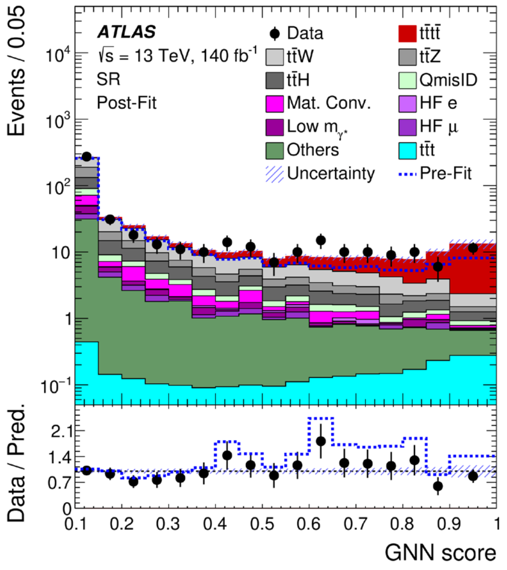
Plots from ATLAS collaboration, Constraint on the total width of the Higgs boson from Higgs boson and four-top-quark measurements in pp collisions at √s = 13 TeV with the ATLAS detector

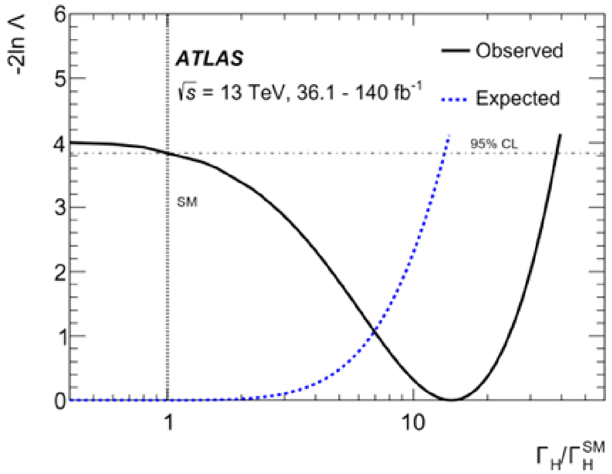
Intermezzo: $H \rightarrow t\bar{t}$ production

- Four-top production measured with $2\ell SS$ and multi-lepton ($> 3\ell$) events
- GNN discriminator trained with all events to discriminate $t\bar{t}t\bar{t}$ events from other sources of background.
- Interpretation of $t\bar{t}t\bar{t}$ measurement. No attempt to discriminate (Higgs) S and B.



signal (S) background (B)





First Γ_H result with off-shell $H \rightarrow t\bar{t}$ production:

$$\Gamma_H < 445\ (75)\ \text{MeV @ 95\% C.L.}$$

Assuming only SM particles in $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loop-induced production:

$$\Gamma_H < 157\ (55)\ \text{MeV @ 95\% C.L.}$$

Plots from ATLAS collaboration, Constraint on the total width of the Higgs boson from Higgs boson and four-top-quark measurements in pp collisions at √s = 13 TeV with the ATLAS detector

References to learn more

- Kauer, N. and Passarino, G., Inadequacy of zero-width approximation for a light Higgs boson signal
- Caola, F. and Melnikov, K., Constraining the Higgs boson width with ZZ production at the LHC
- Campbell, J. et al., Bounding the Higgs width at the LHC using full analytic results for gg -> 2e 2μ
- Dixon, L. and Li, Y., Bounding the Higgs Boson Width Through Interferometry
- ATLAS collaboration, Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector
- ATLAS collaboration, Effective field theory interpretation of the measurement of off-shell Higgs boson production from $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ decay channels with the ATLAS detector
- CMS collaboration, Measurement of the Higgs boson mass and width using the four leptons final state
- CMS collaboration, Limits on the Higgs boson lifetime and width from its decay to four charged leptons
- ATLAS collaboration, Constraint on the total width of the Higgs boson from Higgs boson and four-top-quark measurements in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector
- ATLAS collaboration, Estimate of the mH shift due to interference between signal and background processes in the $H \to \gamma\gamma$ channel, for the $\sqrt{s}$ = 8 TeV dataset recorded by ATLAS

The Higgs potential

- Reconstructing the electroweak symmetry breaking potential
- Probing the Higgs self-interaction
- Assessing the doublet nature of the Higgs by means of the HHVV coupling

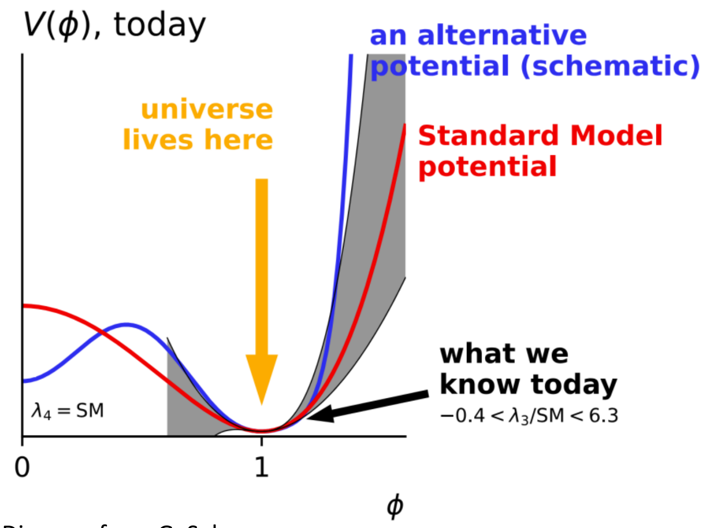
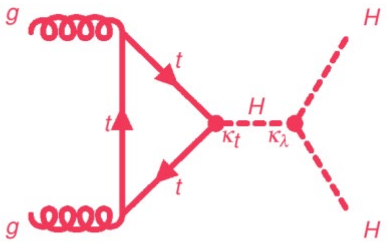


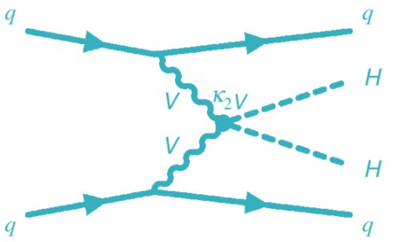
Diagram from G. Salam

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

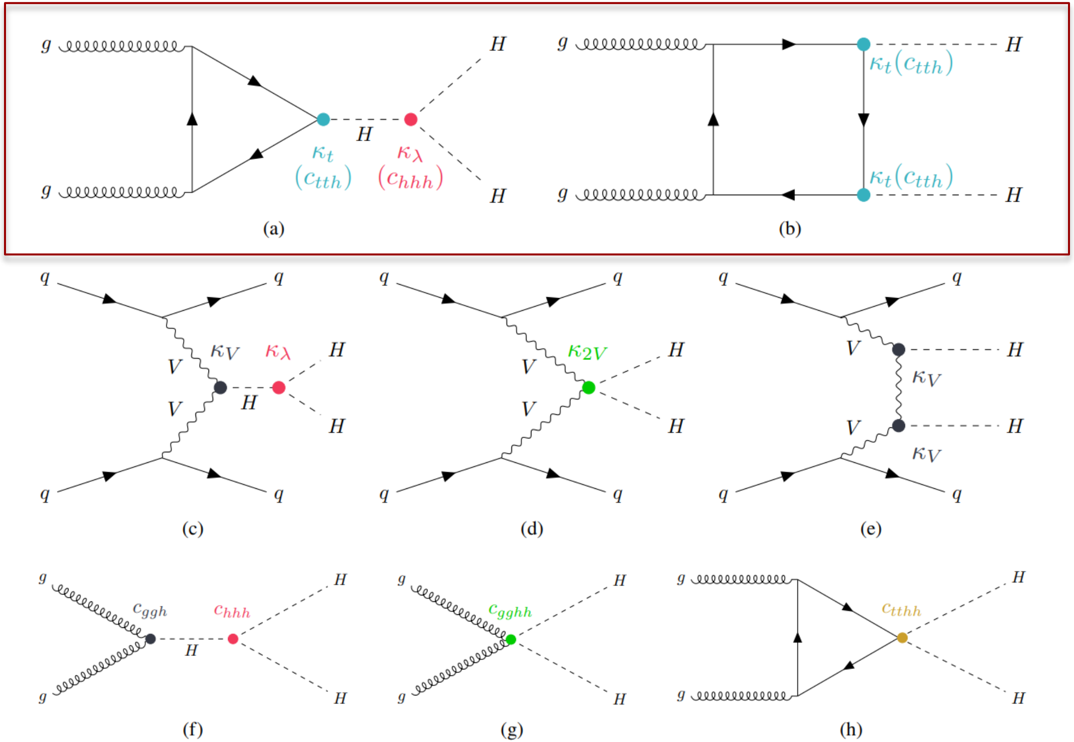
In the SM, specified by
v ~ 246 GeV (from G_F)
and **m_H ~ 125 GeV**

$$\lambda_3 = \lambda_4 = \frac{m_H^2}{2 v^2}$$



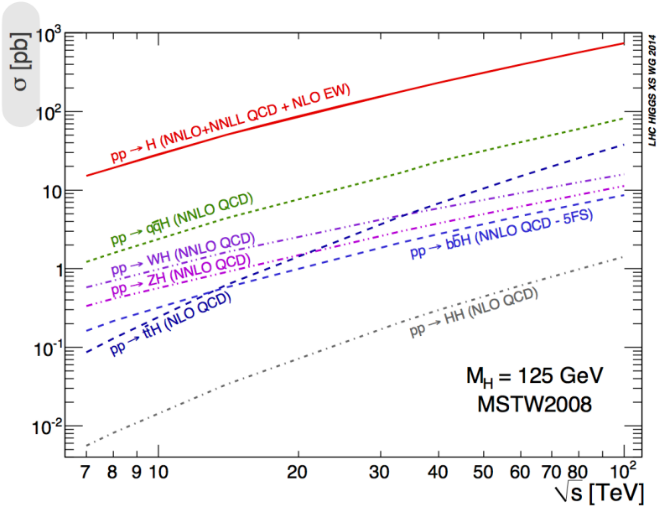


Higgs pair production

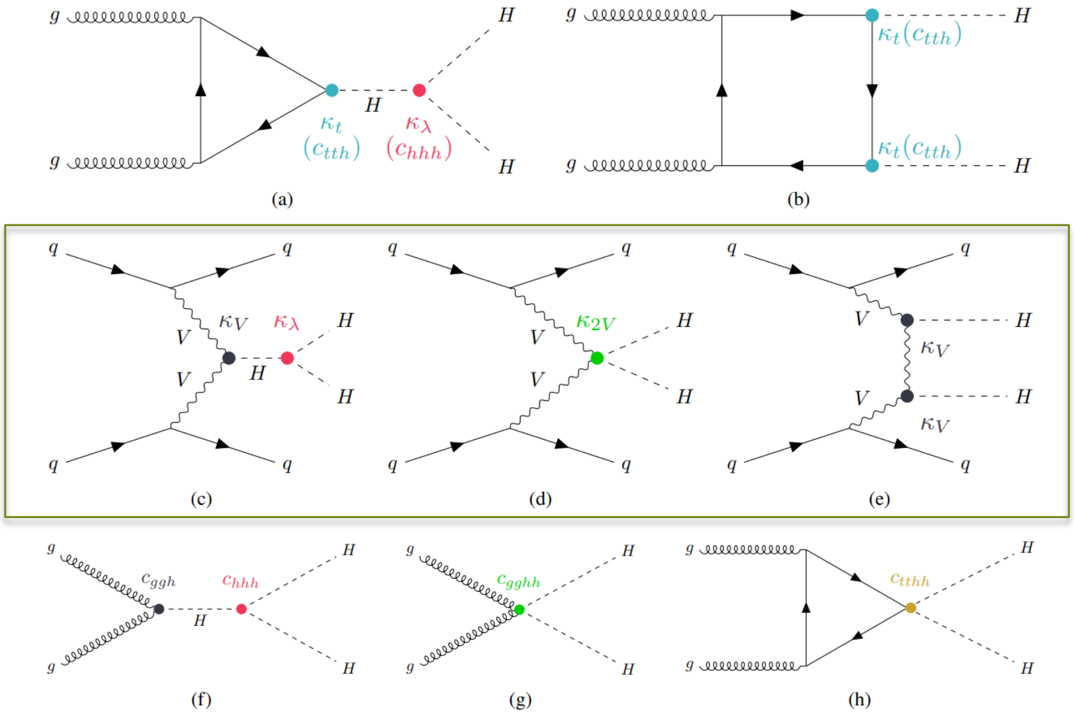


Large destructive interference (unitarity restoration again!)

Di-higgs cross section 1000x smaller than single Higgs



Higgs pair production



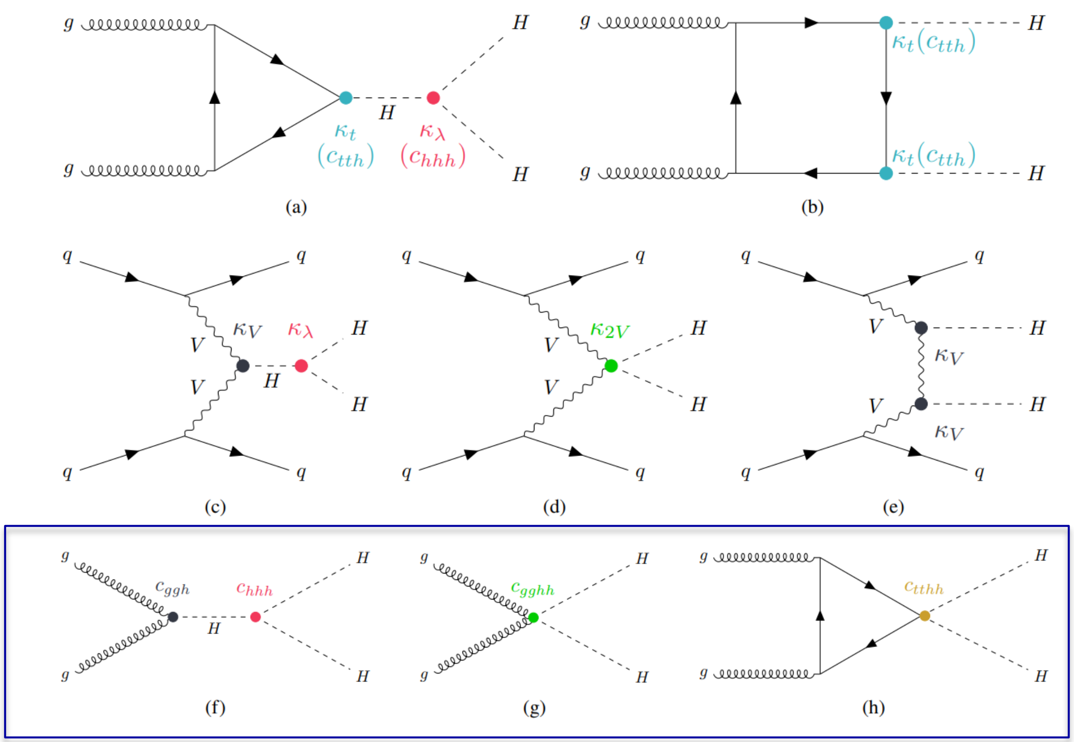
VBF di-Higgs searches can be used to test the doublet nature of the Higgs boson in the SM

In the SM ($c_V^2 = c_{2V}$), and there are exact cancellations at high energies

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

If the Higgs boson is not a doublet, this can lead to striking signatures at the (HL-)LHC

Higgs pair production

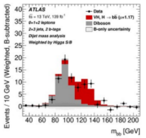


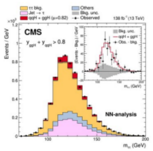
Modifications of the Higgs potential can be probed via effective field theories

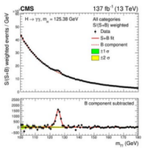
SMEFT – assumes the Higgs is a doublet

HEFT – relaxes this assumption

Higgs pair production

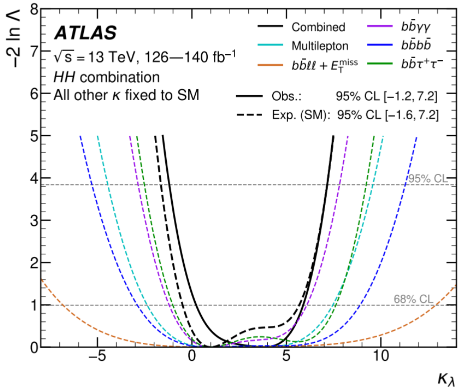




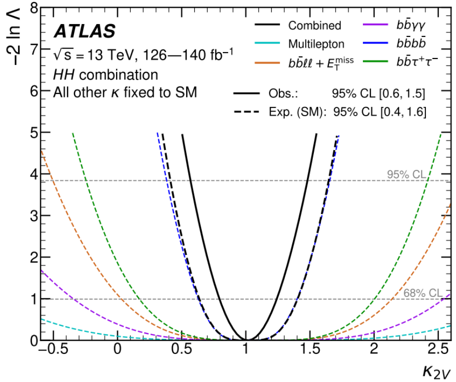


	H→bb	ττ	γγ	Others
H→bb (58%)	**HH→bbbb (34%)** μ < 3.9 (7.8) [C,R] μ < 9.9(5.1) [C,B] μ < 5.3 (8.1) [A]		**HH→multileptons** μ < 21 (19) [C] μ < 17 (11) [A]	
H→ττ (6.3%)	**HH→bbττ (7.3%)** μ < 3.3 (5.2) [C] μ < 5.9 (3.3) [A]	HH→ττττ		
H→γγ (0.23%)	**HH→bbγγ (0.26%)** μ < 7.7 (5.2) [C] μ < 4.0 (5.0) [A]	HH→γγττ	HH→γγγγ	
Others	**HH→bbWW** (25%) μ < 14 (18) [C] μ < 10 (14) [A,bbll]	HH→VVττ	HH→VVγγ	HH→VVVV

Plots from ATLAS collaboration, Combination of searches for Higgs boson pair production in pp collisions at √s=13 TeV with the ATLAS detector

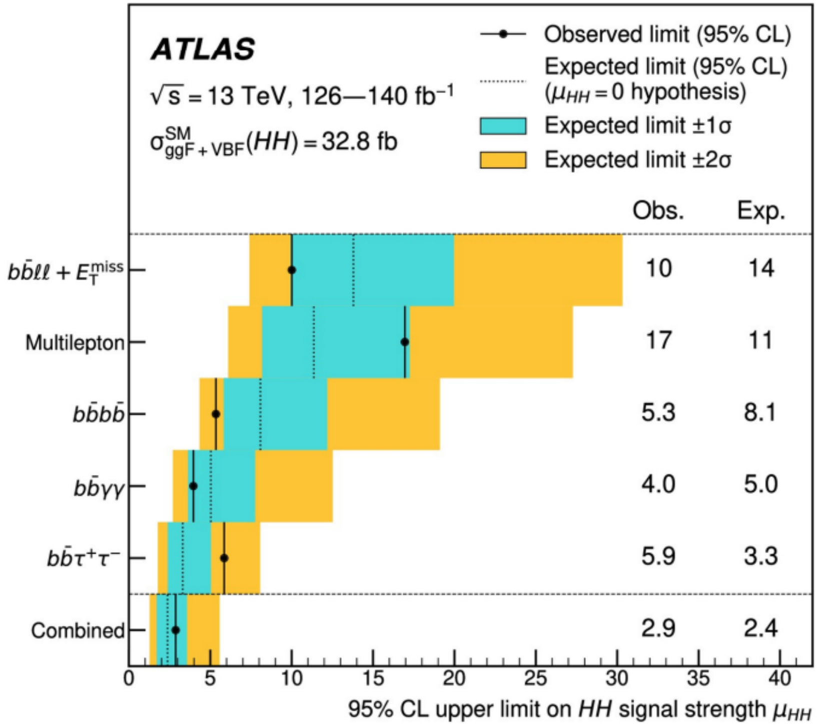


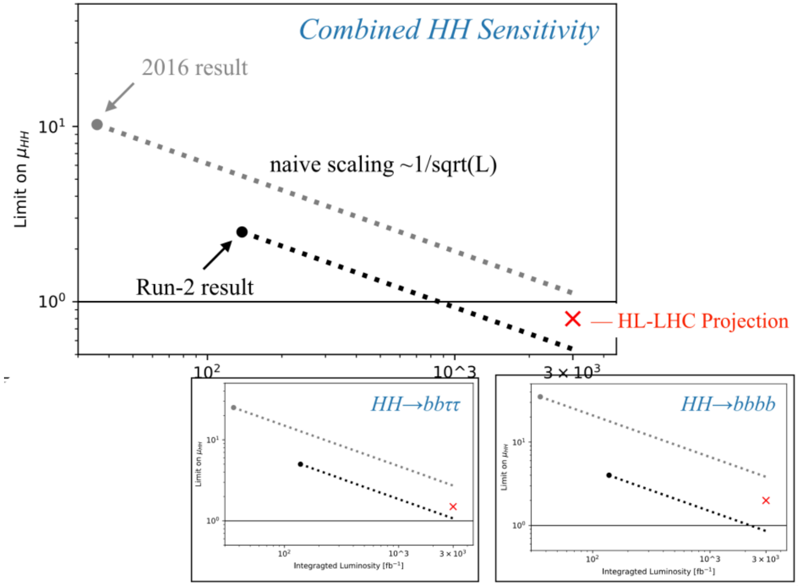
(a)



(b)

Looking ahead





Plots by J. Allison

We are improving much fast than $\sqrt{L}$ because of the huge investment in algorithms, calibration, and analysis techniques.

UMassAmherst

Reference to learn more

- ATLAS collaboration, Combination of searches for Higgs boson pair production in pp collisions at √s=13 TeV with the ATLAS detector
- ATLAS collaboration, Search for pair production of boosted Higgs bosons via vector-boson fusion in the bbbb final state using pp collisions at √s=13 TeV with the ATLAS detector
- CMS collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery