Precise Measurements of the Higgs Boson

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On behalf of ATLAS and CMS Collaborations

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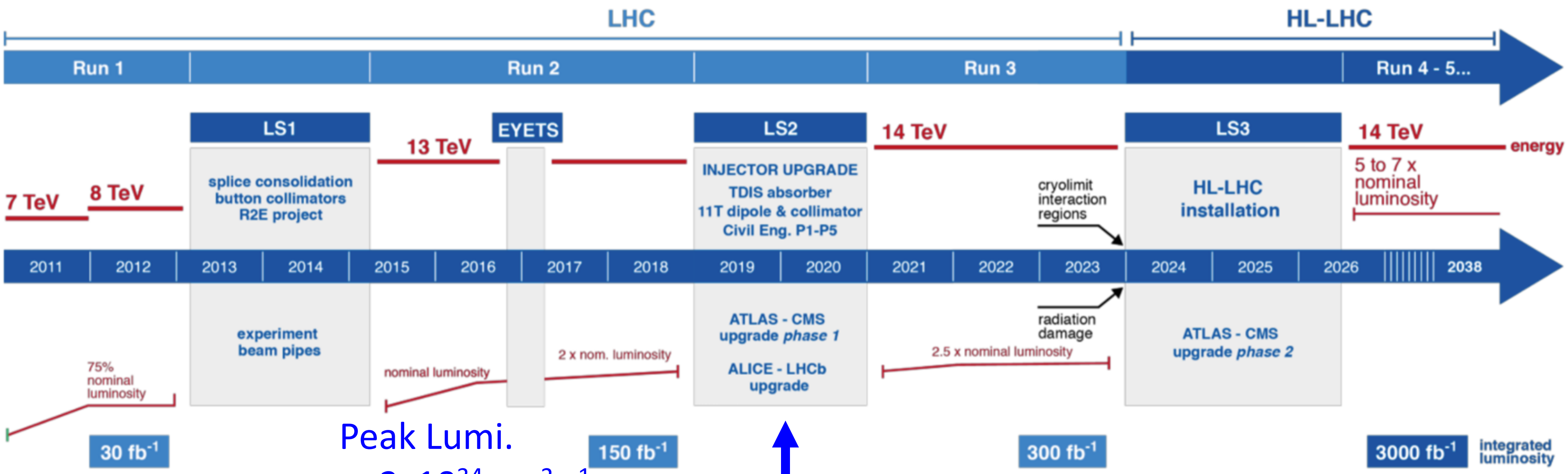
The Higgs Boson

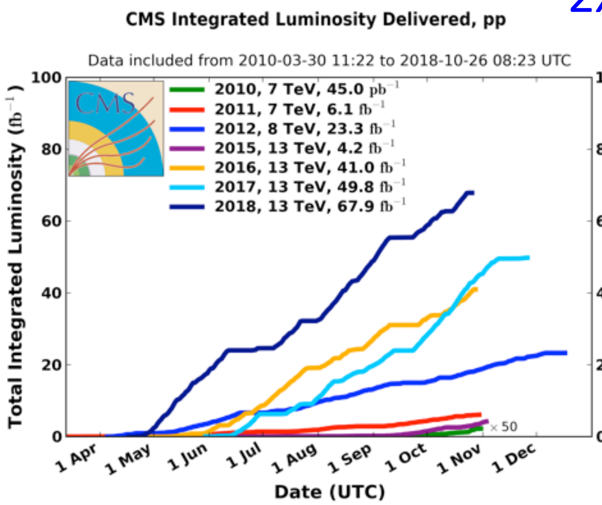
- The Higgs boson, discovered in 2012 by ATLAS and CMS, “completes” the Standard Model of particle physics
  - It’s the quantum of the Higgs field , whose spontaneous symmetry breaking is responsible for generating particle masses
- The SM model still does not explain many of the phenomena of our physical universe
  - Neutrino masses, baryon asymmetry of the universe, dark matter .....
- The discovery of the Higgs boson opens a new window for us to understand the universe
  - First fundamental scalar particle (also the only one in SM) found so far
  - Looking for deviations from the SM predictions by studying its properties......

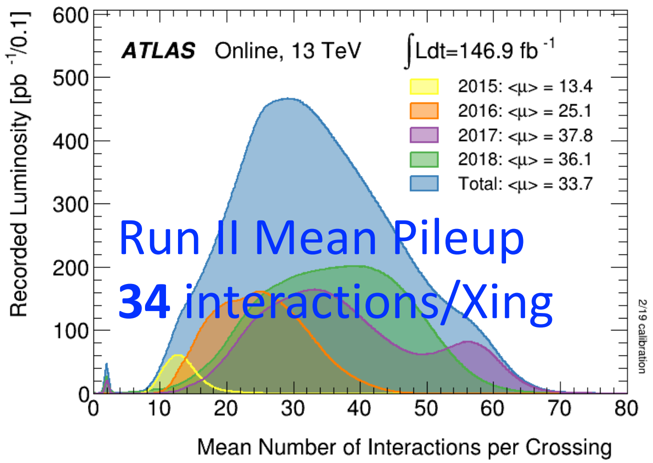
Where do we stand ?



Peak Lumi.

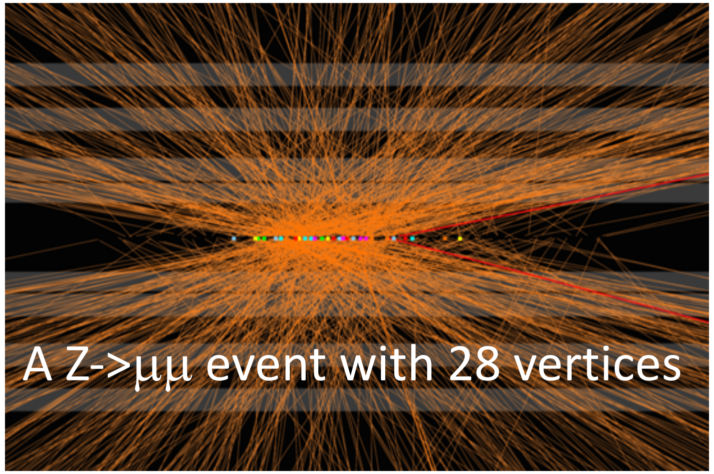
～$2x10^{34}cm^{-2}s^{-1}$





Run II Mean Pileup

34 interactions/Xing

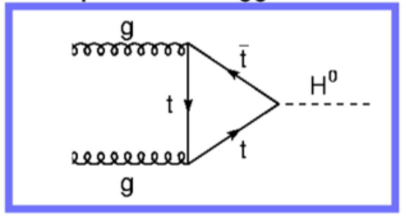


A Z->μμ event with 28 vertices

Higgs @ LHC

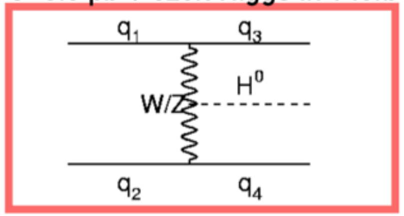
σ=49 pb / 6.9M Higgs in 140fb^{-1}

~88%



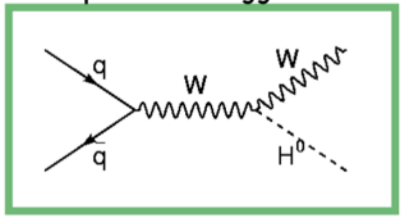
σ=3.8 pb / 520k Higgs in 140fb^{-1}

~7%



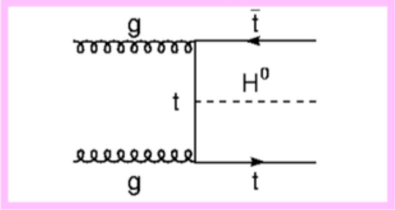
σ=2.3 pb / 320k Higgs in 140fb^{-1}

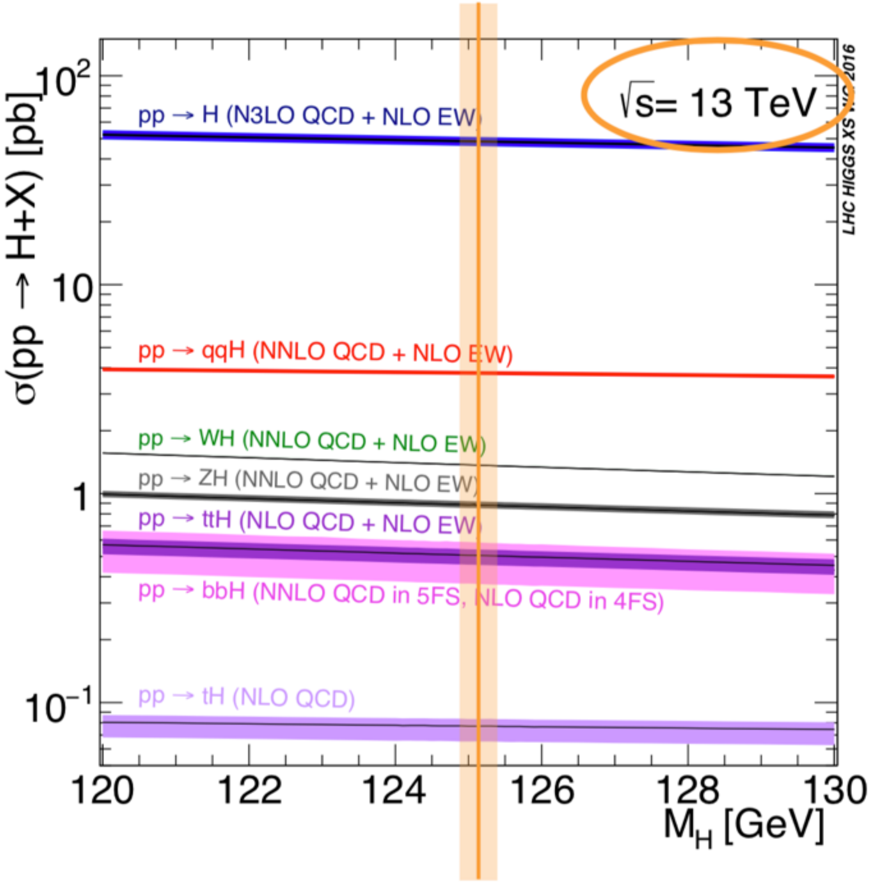
~4%



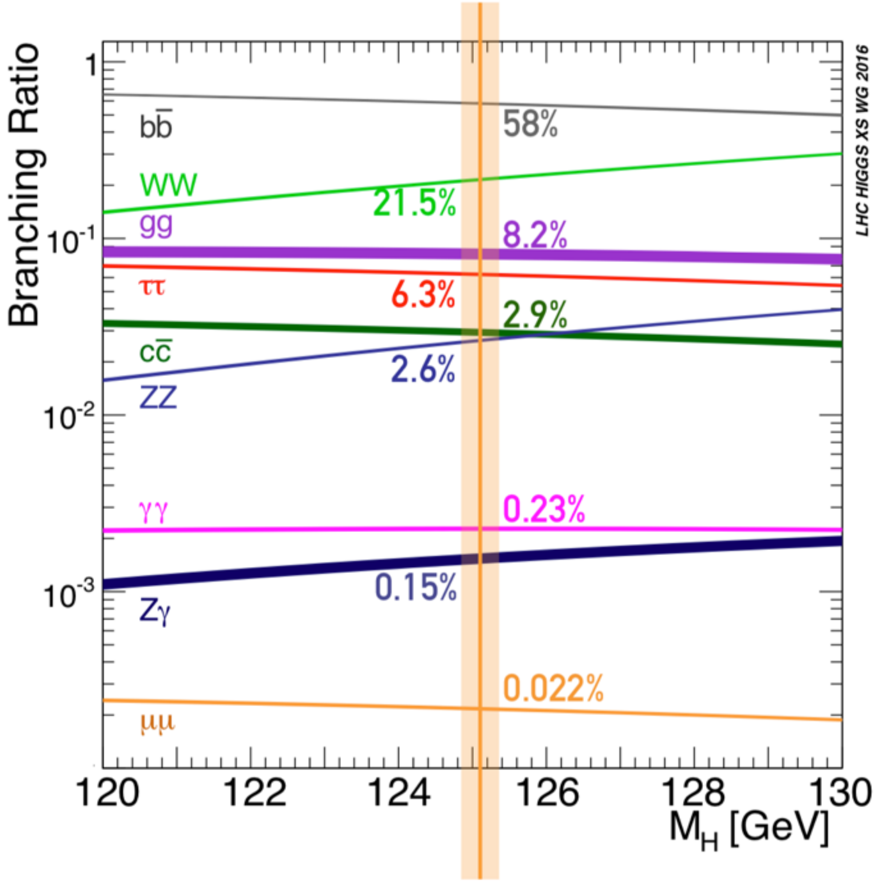
σ=0.5 pb / 70k Higgs in 140fb^{-1}

~1%





125.09 ± 0.24 GeV
LHC Run1 measurement



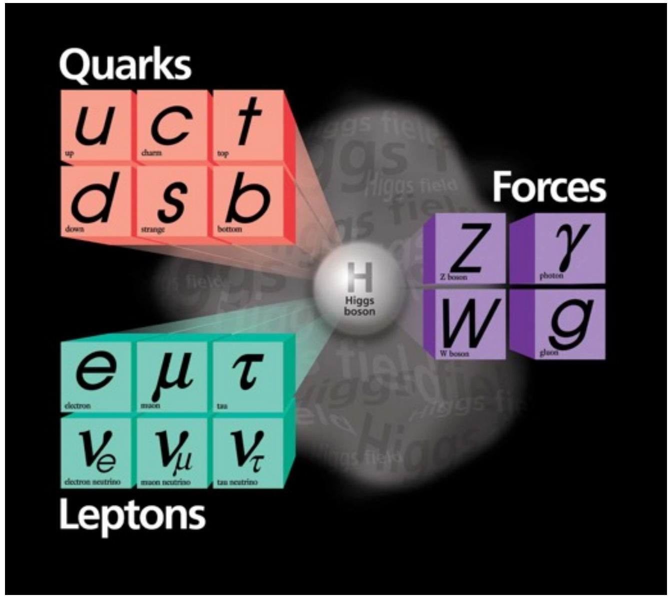
125.09 ± 0.24 GeV
LHC Run1 measurement

Thanks to its mass ~ 125 GeV, the Higgs physics program at LHC is very rich.
All the main production and decay modes are under scrutiny by ATLAS and CMS.

Outline

- **Higgs – bosonic channels**
  - Mass, width
  - Inclusive/differential cross sections
  - Coupling properties
- **Higgs - Yukawa interactions**
  - Higgs to 3rd – generation fermion couplings
  - Higgs to 2nd – generation fermion couplings
- **Combinations**
- **Higgs – self-couplings**
- **BSM Higgs**

See Stefania's talk



Disclaimer: only a few selected recent updates among all results from ATLAS and CMS

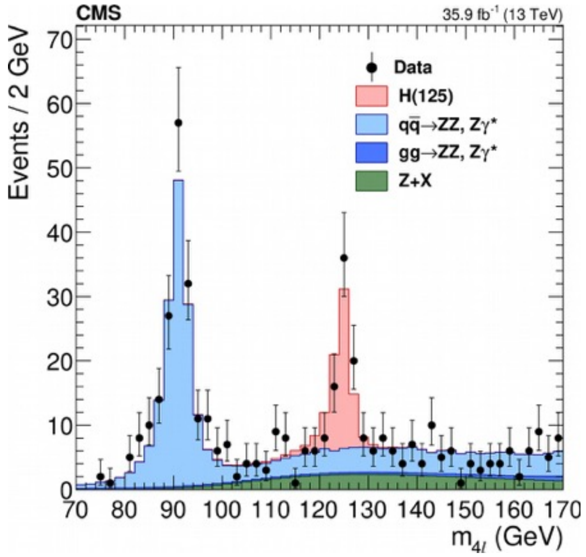
Higgs Boson Mass

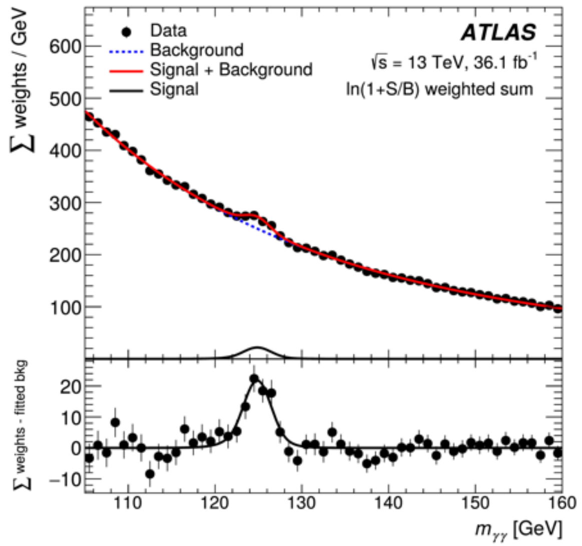
JHEP 11 (2017) 047
PLB 784 (2018) 345

- **The only free fundamental parameter of the Higgs sector in SM**
  - **Completely determined the SM Higgs properties**
- **Measured from the mass peaks in the two high resolution channels: 4l and $\gamma\gamma$**

	m_H ± tot (± stat ± syst)
$4\ell+\gamma\gamma$ (Run1+ 36/fb Run2)	124.97 ± 0.24 (± 0.16 ± 0.18) GeV
4ℓ (36/fb Run2)	125.26 ± 0.21 (± 0.20 ± 0.08) GeV
LHC $4\ell+\gamma\gamma$ (Run1)	125.09 ± 0.24 (± 0.21 ± 0.11) GeV

- **Already < 0.2% precision (~200 MeV)**
  - **Among the most precise EWK parameters**

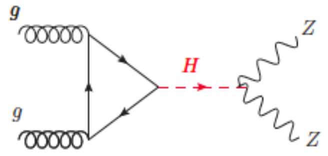




Higgs Boson Width

- **SM prediction Γ_H = 4.1 MeV, crucial for BSM searches**
  - direct measurement limited by detector resolutions
  - **indirect measurement from off-shell production**

Breit-Wigner production pp $\rightarrow H \rightarrow ZZ$

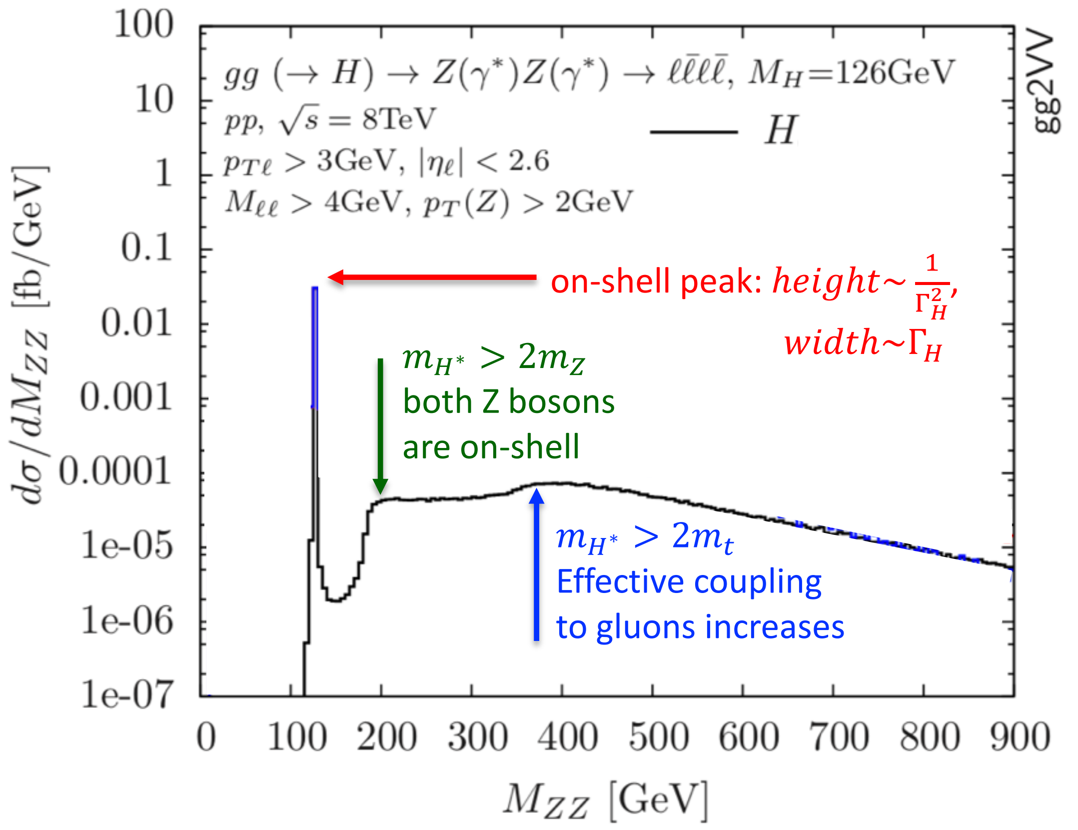


$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-peak cross sections: $\sigma^{\text{on-shell}} = \int_{|m - m_H| \leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$

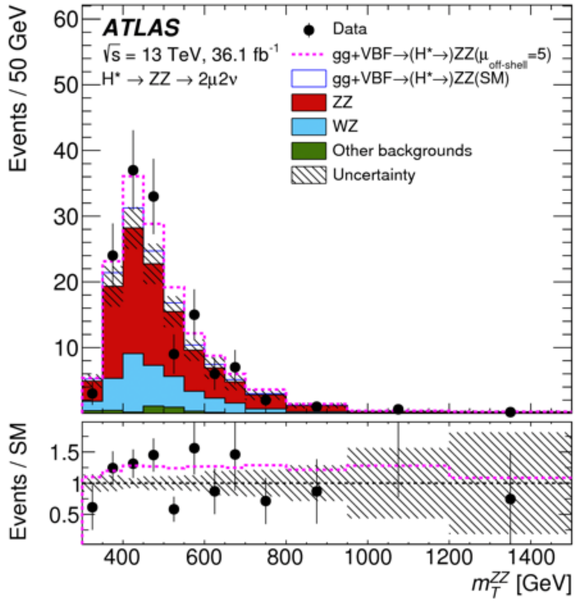
Off-peak cross sections: $\sigma^{\text{off-shell}} = \int_{m - m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$

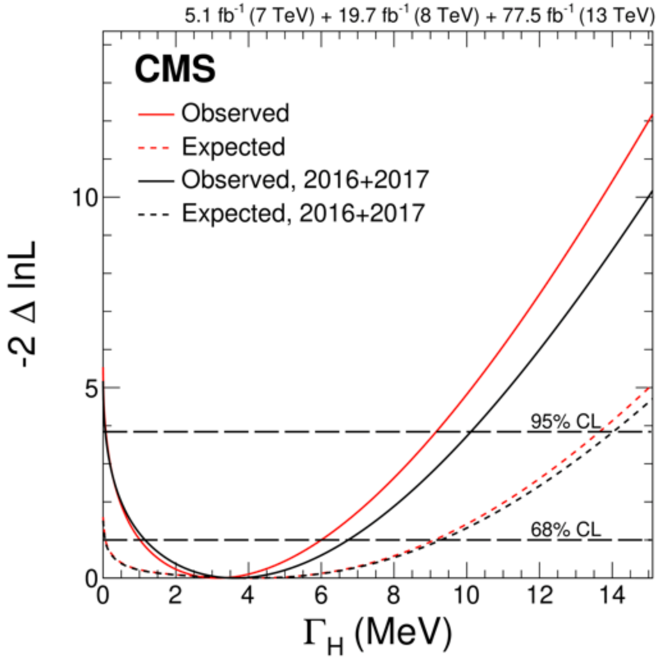
Off-peak to on-peak ratio $\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$



Higgs Boson Width

PRD 99 (2019) 112003
PLB 786 (2018) 223

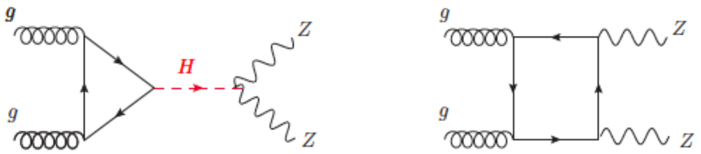


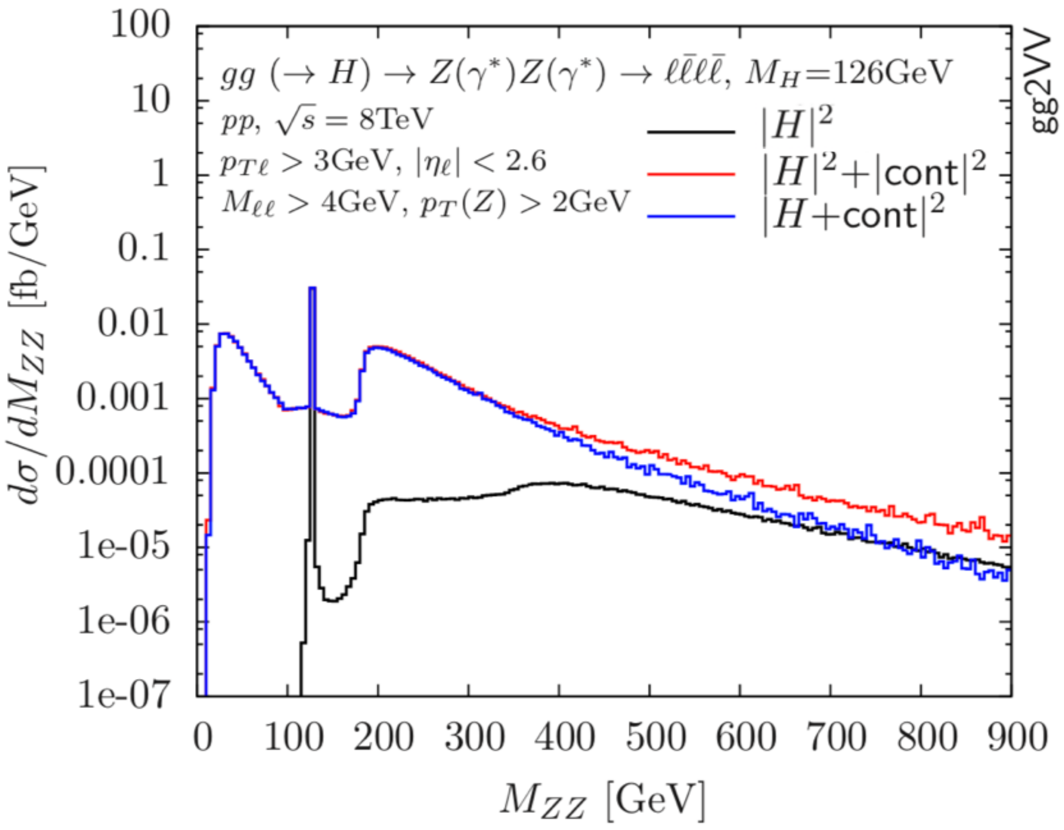


	obs. 95% CL on Γ_H
ATLAS $4\ell+2\ell2\nu$ (36/fb Run2)	Γ_H < 14.4 MeV
CMS 4ℓ (Run1 + 77/fb Run2)	0.08 < Γ_H < 9.16 MeV

Start to place a lower bound on Γ_H

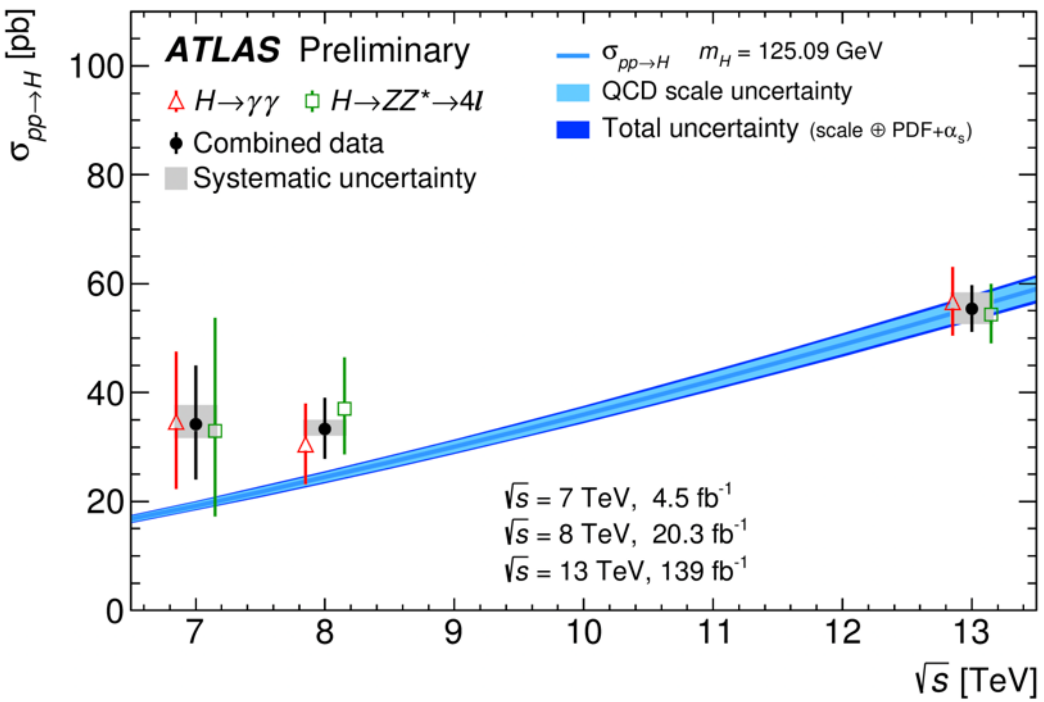
Negative interference with non-resonant gg->ZZ

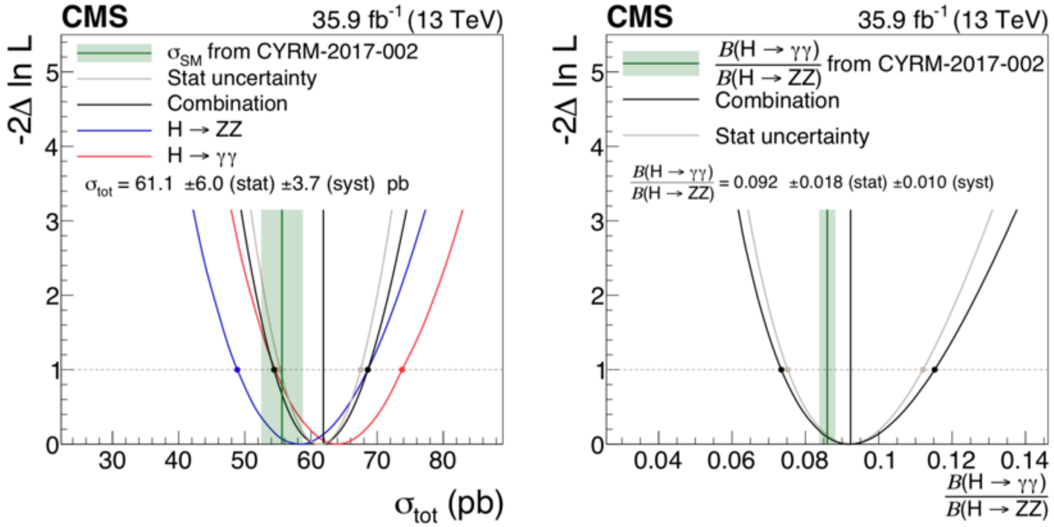




Higgs Cross Sections

- **Inclusive X-section measurements in $\gamma\gamma$ and ZZ channels at 7, 8 and 13 TeV**
  - **The ratio of BRs for the two decay channels is also measured**





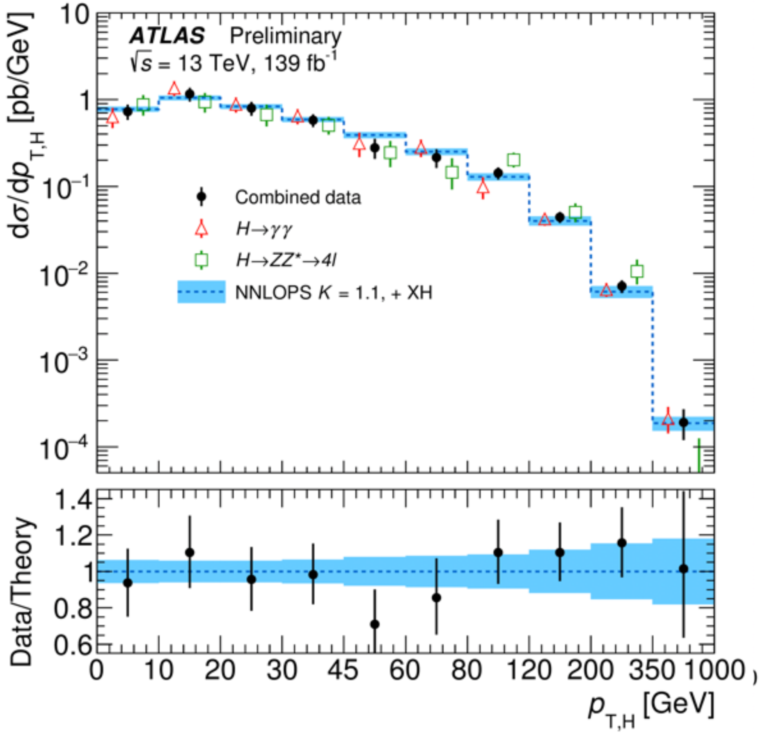
	Total H production xsec
$\gamma\gamma$ (full Run2)	$56.7^{+6.4}_{-6.2}$ pb
4ℓ (full Run2)	$54.4^{+5.6}_{-5.4}$ pb
Combination	$55.4\ ^{+3.1}_{-3.1}$ (stat) $^{+3.0}_{-2.8}$ (syst) pb
$\gamma\gamma$ (36/fb Run2)	$64.4^{+9.6}_{-9.6}$ pb
4ℓ (36/fb Run2)	$58.2^{+9.8}_{-9.8}$ pb
Combination	$61.1\ ^{+6.0}_{-6.0}$ (stat) $^{+3.7}_{-3.7}$ (syst) pb
SM prediction	55.6 ± 2.5 pb

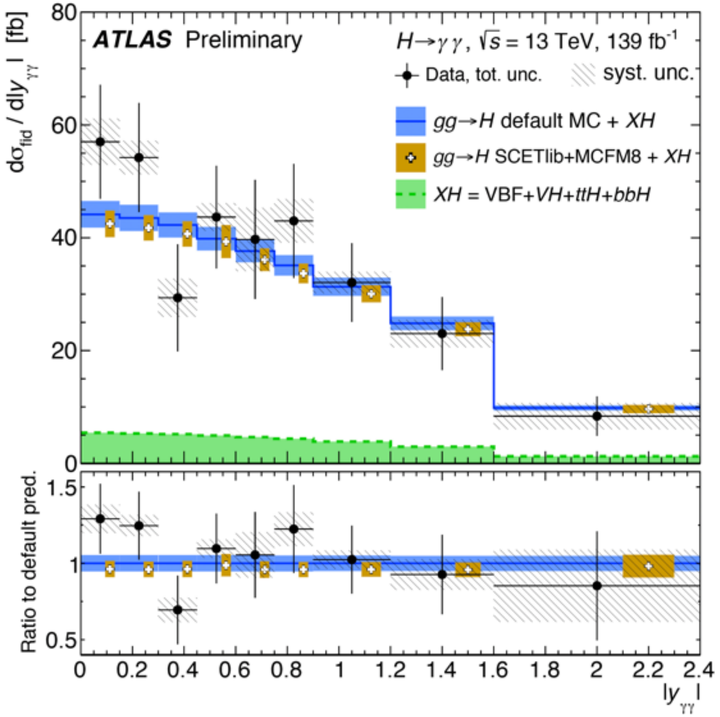
- In good agreement with the SM prediction
- Comparable uncertainties from statistics, experimental systematics and theory sources

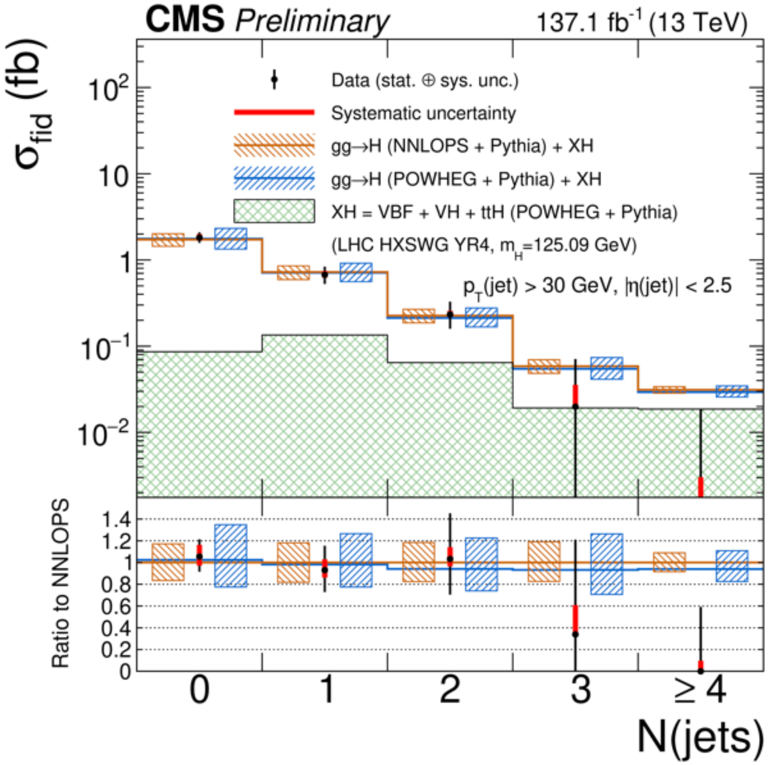
Differential Cross Sections

CMS-PAS-HIG-19-001
ATLAS-CONF-2019-029
ATLAS-CONF-2019-032

- **Fiducial and differential cross sections**
  - **Measure the rate of Higgs boson production in a certain region(s) of phase space, e.g. in different regions of Higgs boson p_T, rapidity, and N_{jets}, p_T^{jet1}, m_{jj}, $\Delta\phi_{jj}$, ...**
  - **Compare with various predictions**

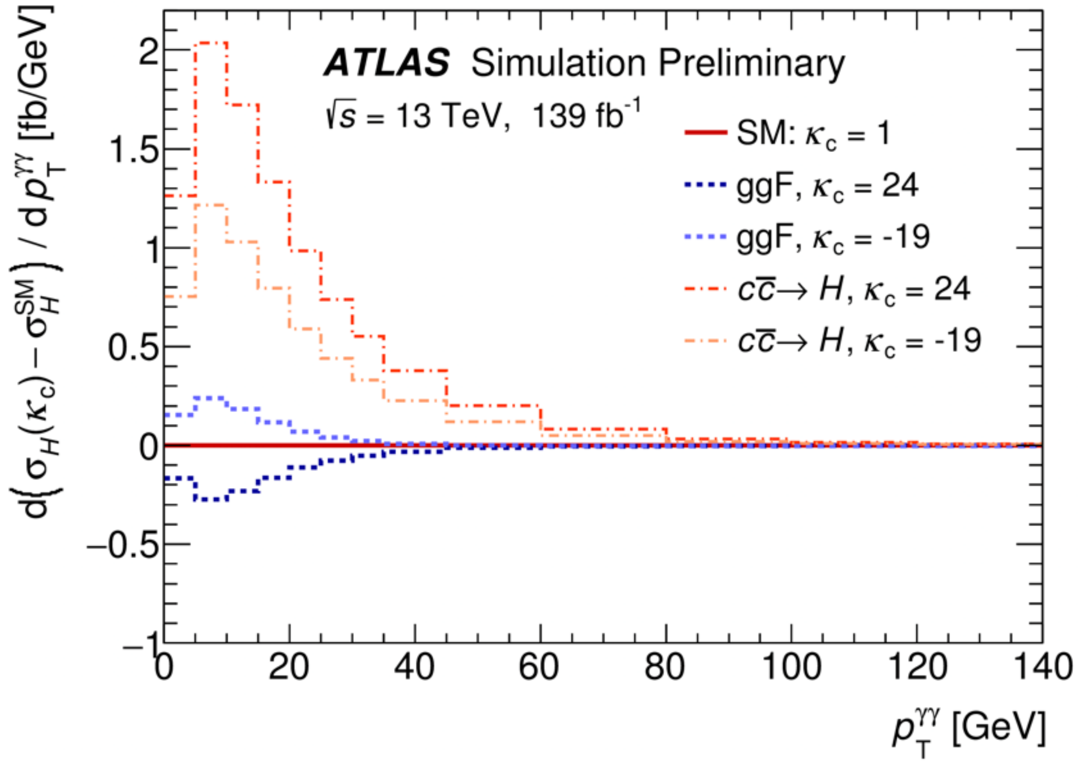


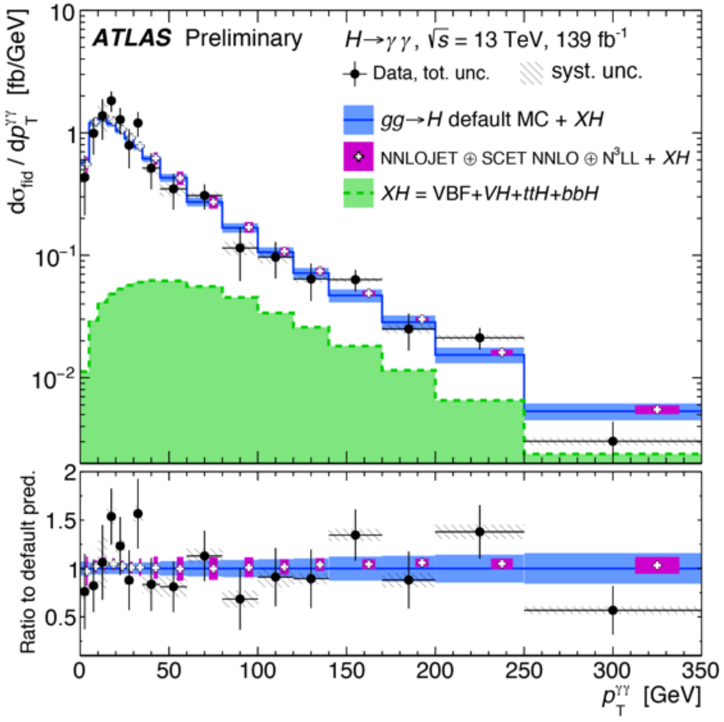




Differential Cross Sections -> constrain c-H coupling

- **Higgs differential X-section at low p_T is sensitive to Charm Yukawa coupling -> constrain charm-H coupling (not directly accessible)**

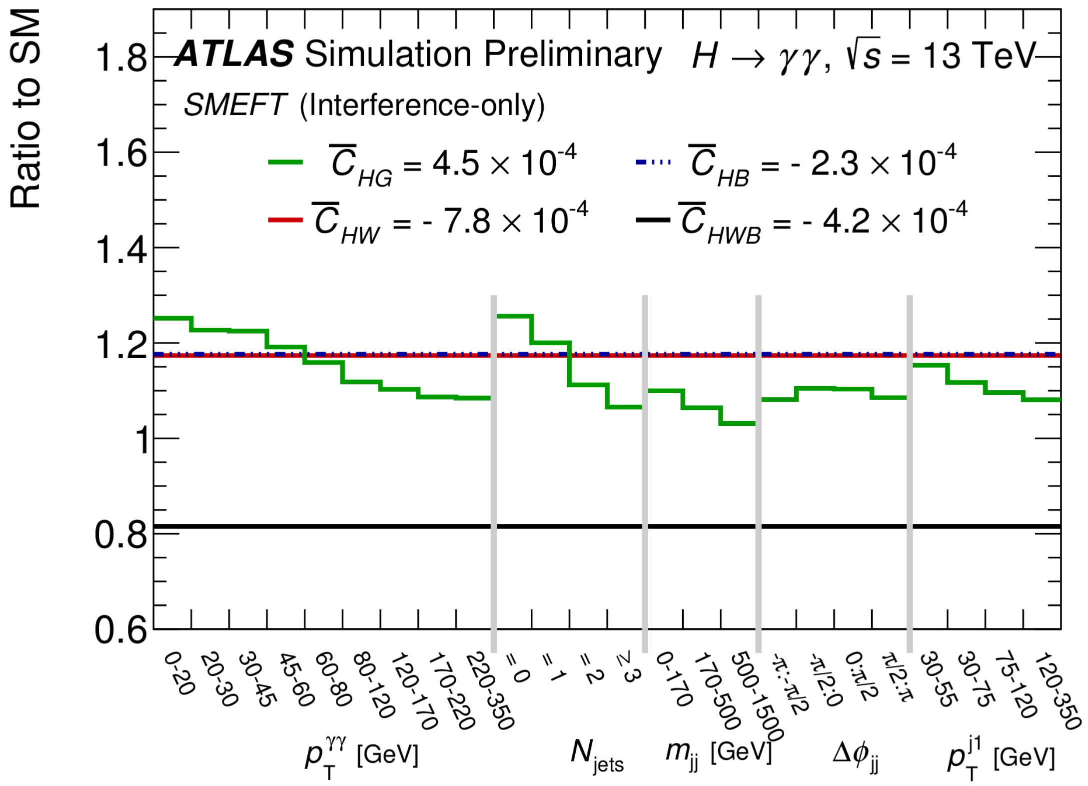




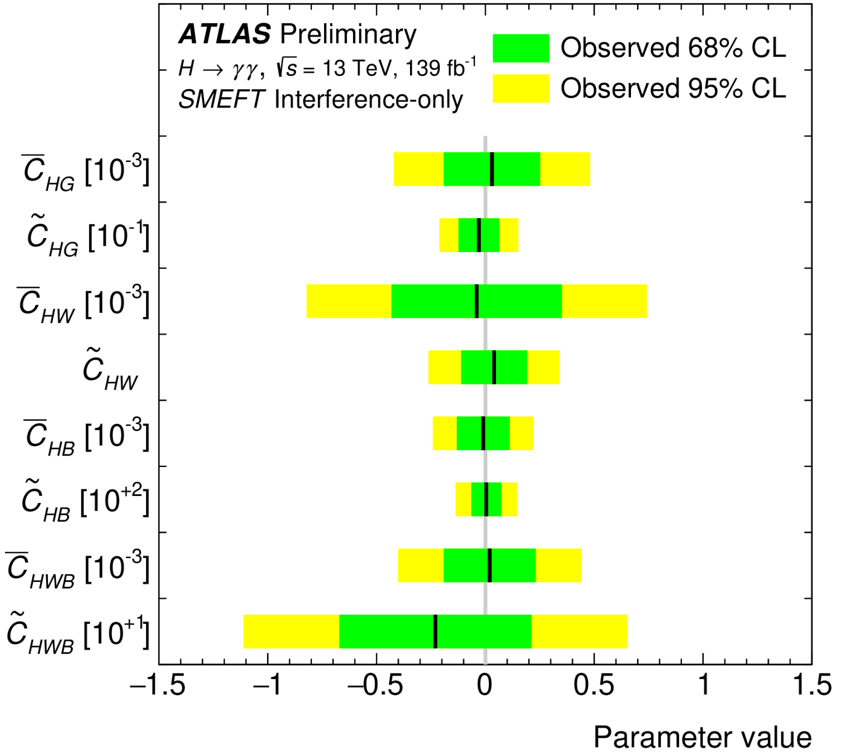
$$\kappa_c(y_c/y_c^{SM}) \in [-19,24]$$
@ 95% C.L.

Differential Cross Sections -> constrain Wilson Coefficients

- **Use the 5 differential distributions ($p_T^{\gamma\gamma}$, N_{jets}, p_T^{jet1}, m_{jj}, $\Delta\phi_{jj}$) measured in the H->γγ analysis to constraint Wilson Coefficients in SILH and SMEFT bases**



The effect on differential distributions of the four CP-even coefficients in the SMEFT basis.

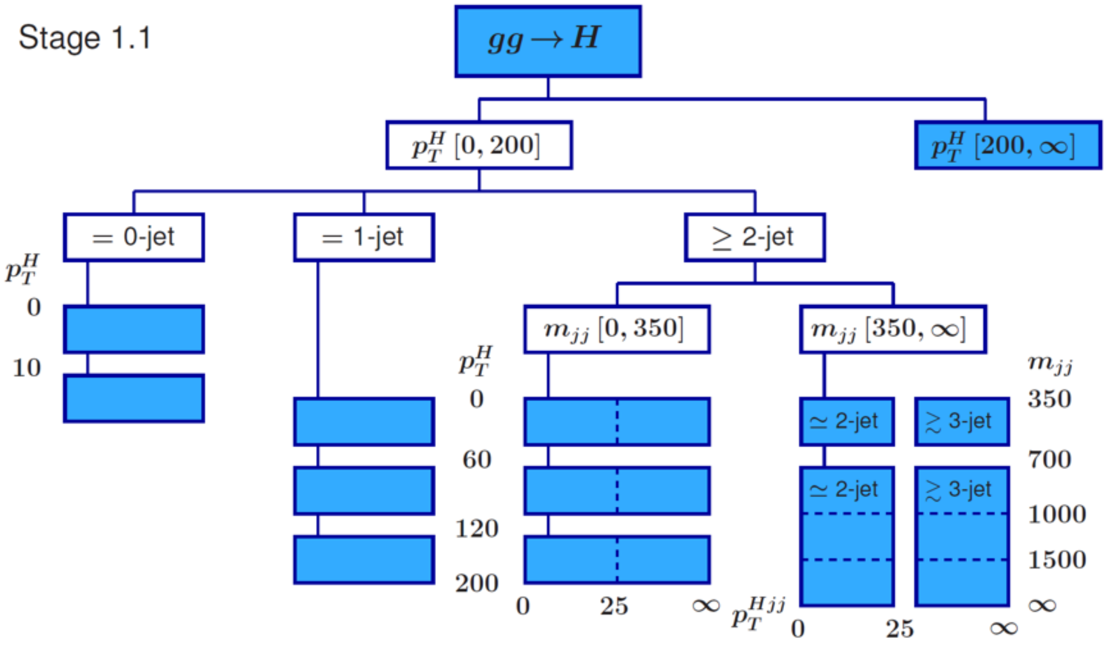


Limits are derived fitting one Wilson coefficient at a time while setting the other coefficients to zero.

Simplified Template Cross Sections

- **Simplified Template Cross Sections (STXS). Dividing phase space into bins:**
  - **According to *production mode*, and kinematic distributions like number of jets, p_T(H), and m_{jj} (where applicable).**
  - **Designed to reduce impact of theoretical uncertainties on the results.**
  - **Approximately to match experimental selections so as to minimize model-dependent extrapolations.**
  - **Bins are merged if lack of statistics, called different "stages" of STXS.**

Example: STXS stage 1.1 for ggF production

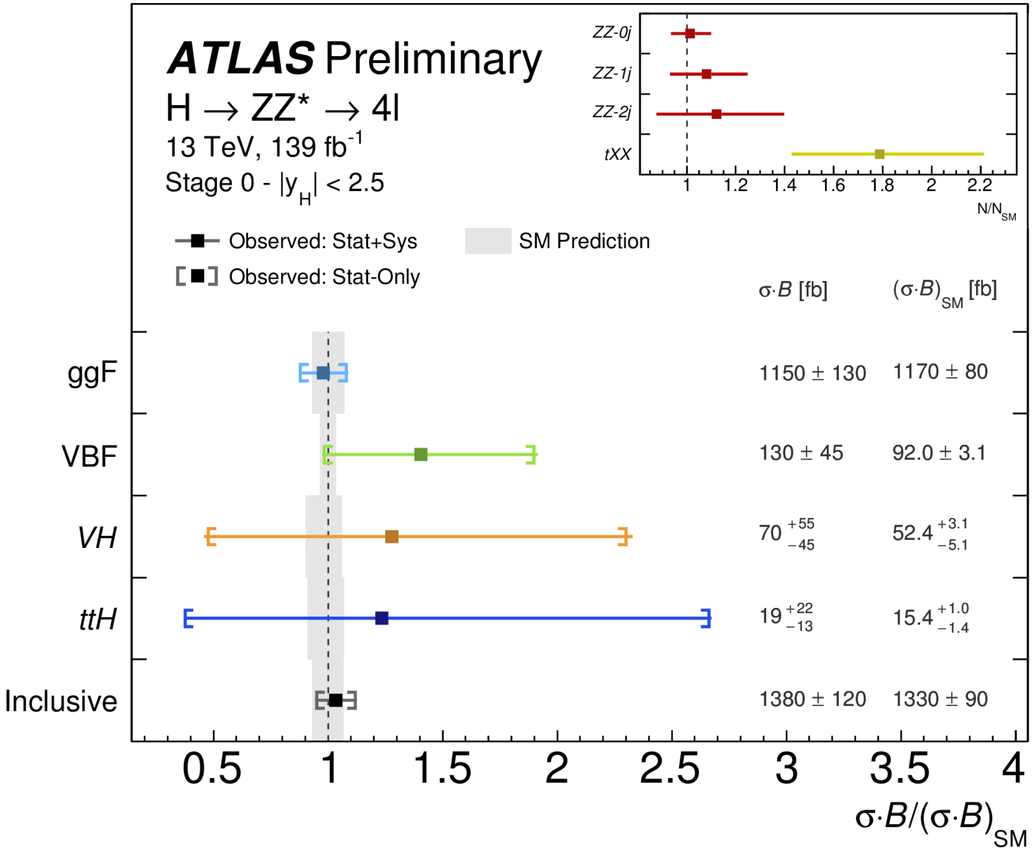


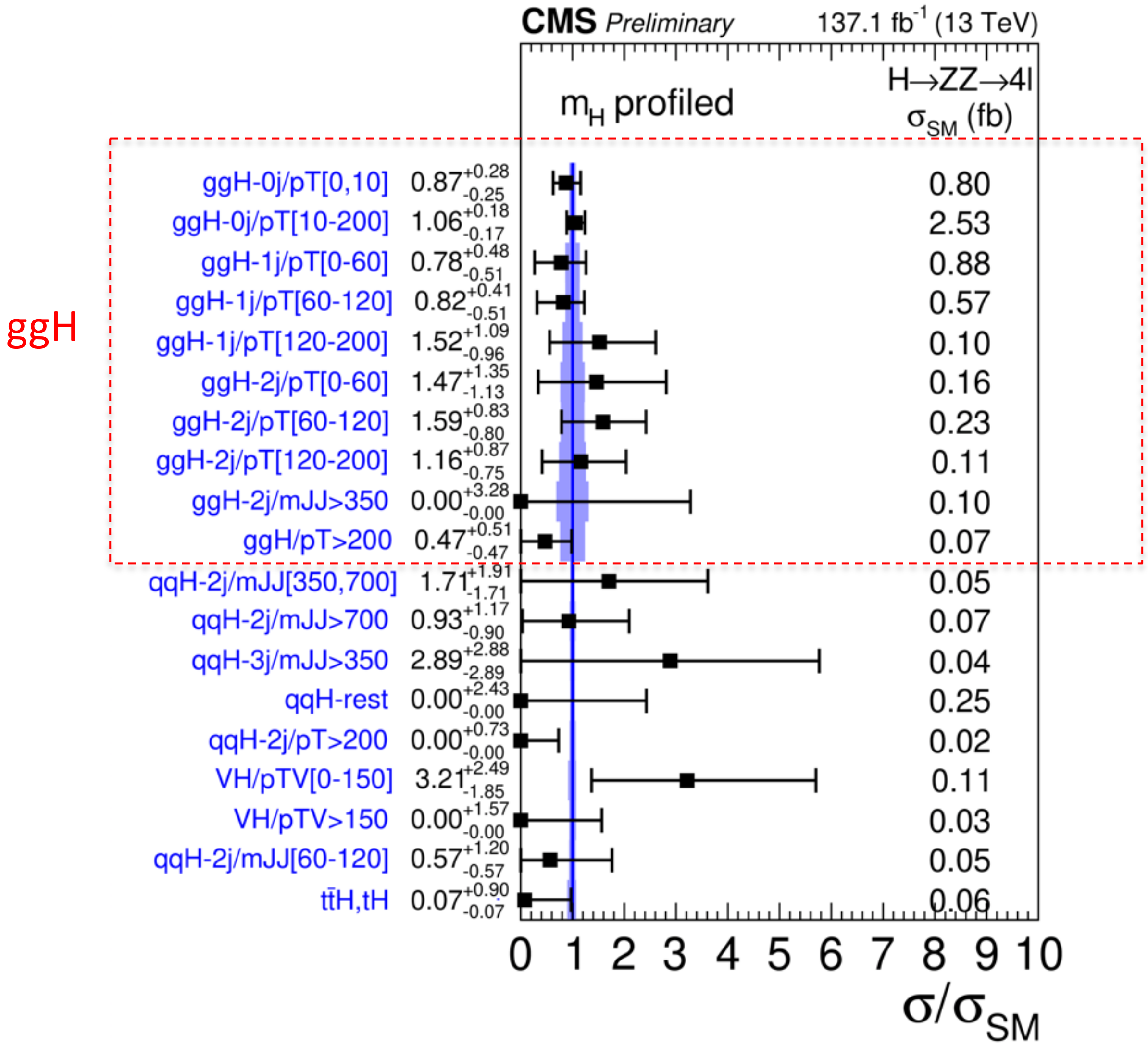
Simplified Template Cross Sections

CMS-PAS-HIG-19-001
ATLAS-CONF-2019-025

From "Stage 0" just Higgs boson production bins …

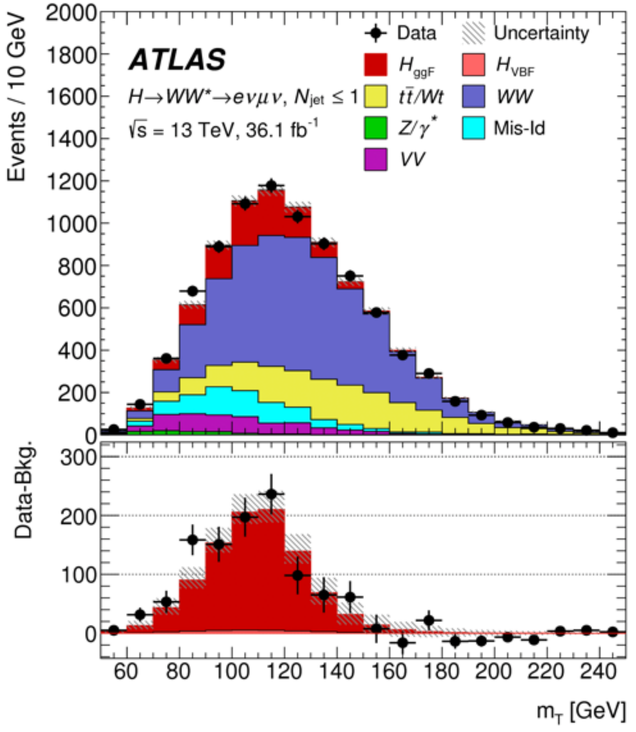
… to "Stage 1.1" bins with finer split of kinematics regions

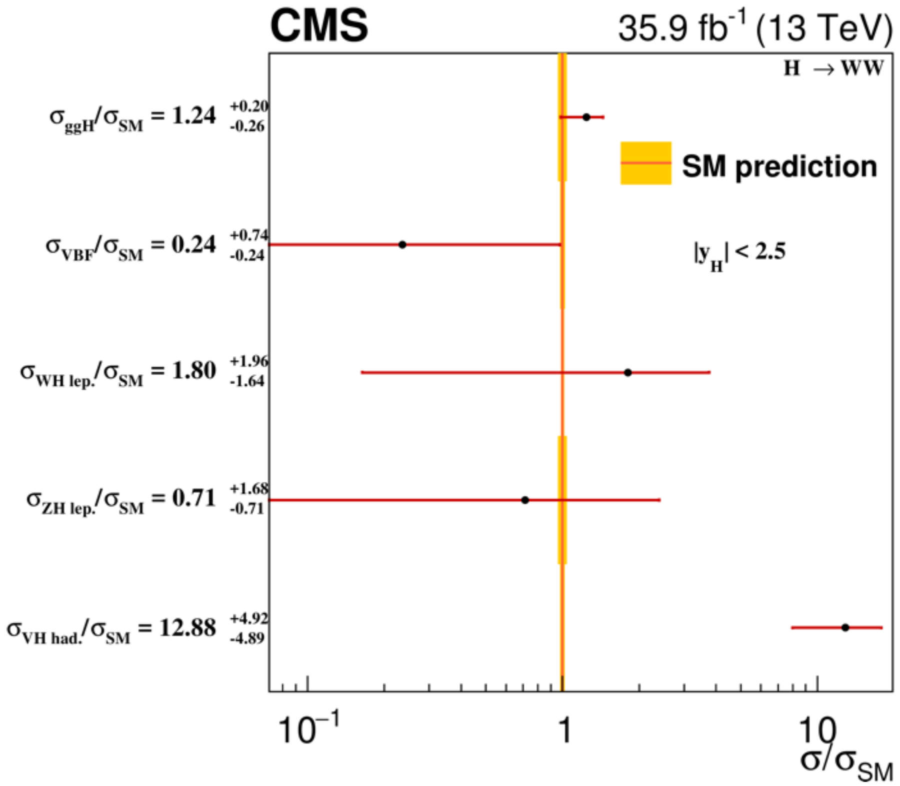


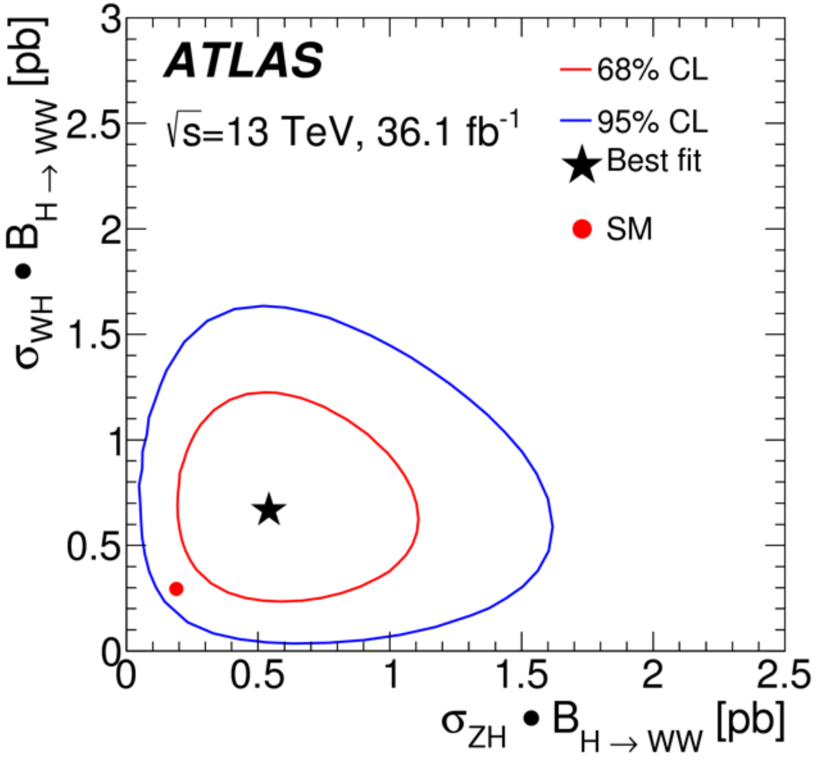


Cross Sections in H→WW

- **With second Highest B.R. for Higgs at 125 GeV, H→WW is an important channel for measurement of Higgs boson properties**
  - **Cross sections measured with 36 fb^{-1} in the H→WW→lνl'ν' channel**



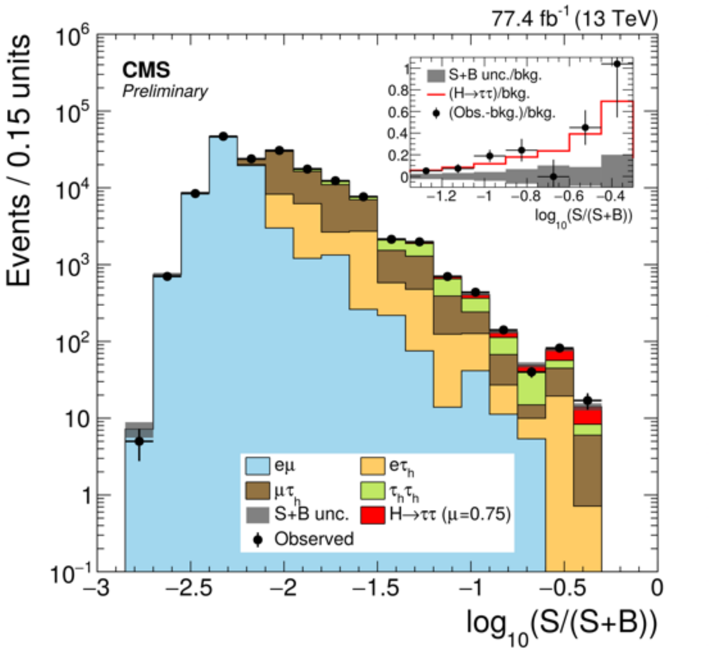


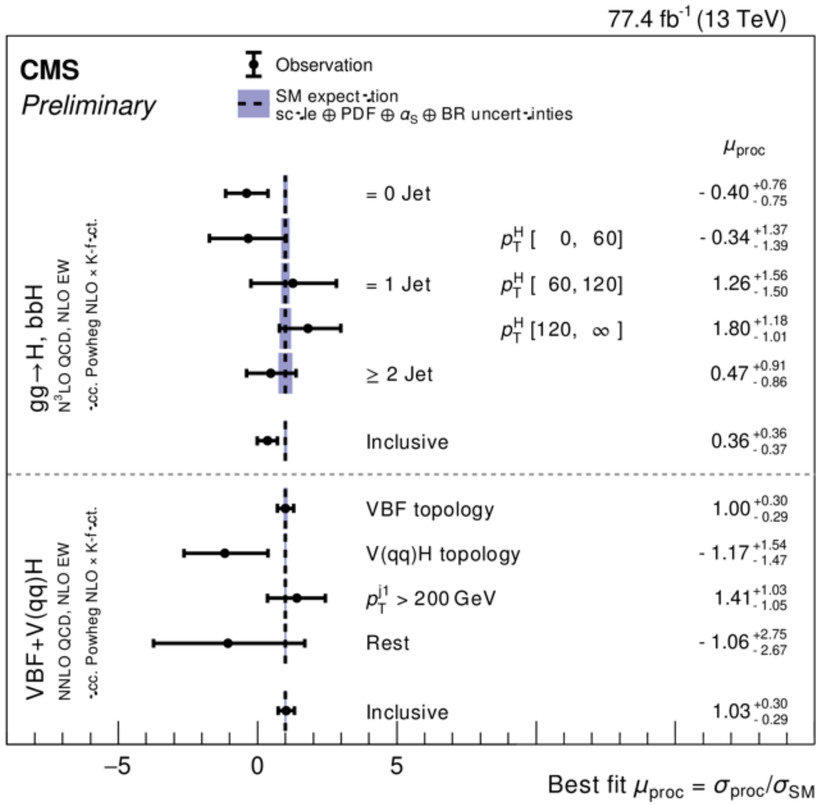


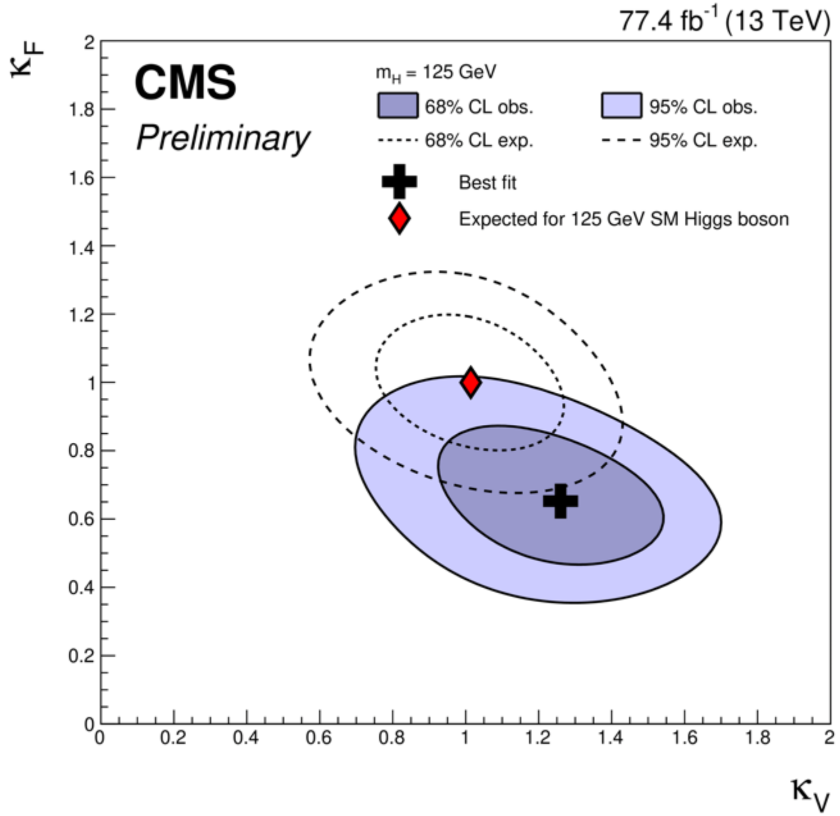
Higgs – Yukawa interactions

3rd-generation fermion coupling: H→ττ

- **After observed independently with more than 5σ significance by both experiments**
  - **Measurements in STXS bins, results split by production mode and limits are placed on the κ_V and κ_F coupling modifiers**





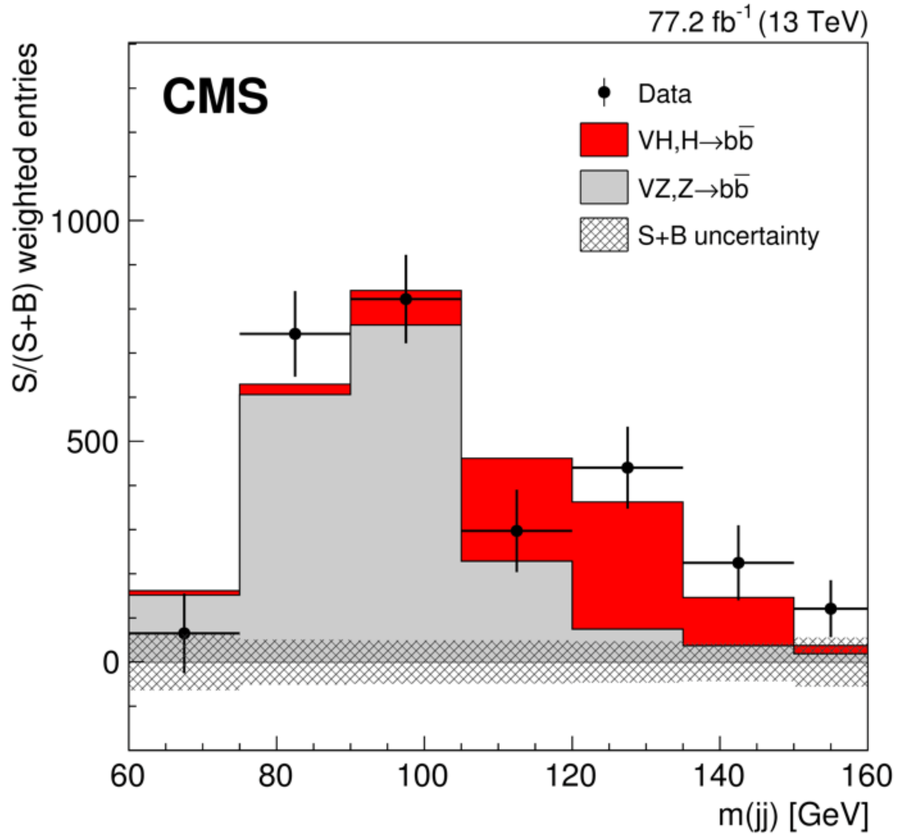


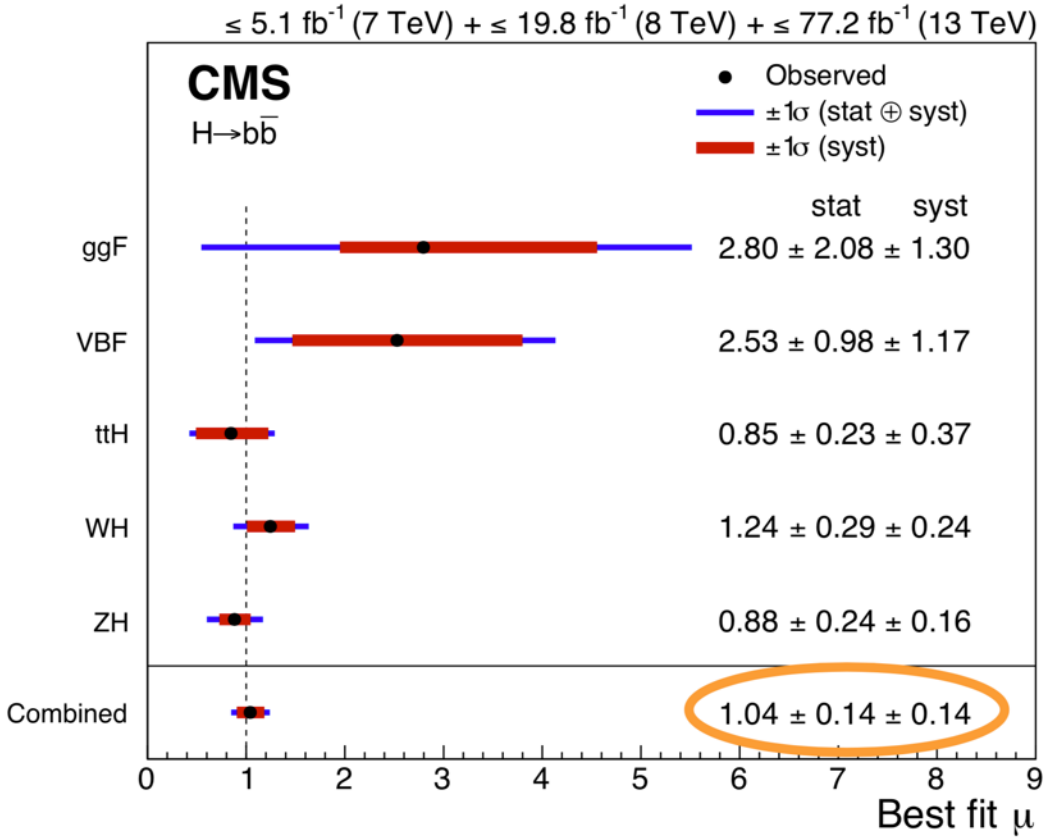
Improvements in the CMS 77/fb analysis: Machine learning for categorization, 90% of backgrounds with data-driven methods

3^{rd}-generation fermion coupling: H→bb

PRL 121 (2018) 121801
JHEP 05 (2019) 141

- Difficult channel despite large BR (58%) due to large bkg
- VH most sensitive but ggF, VBF and ttH play a role
- Established with a significance >5σ

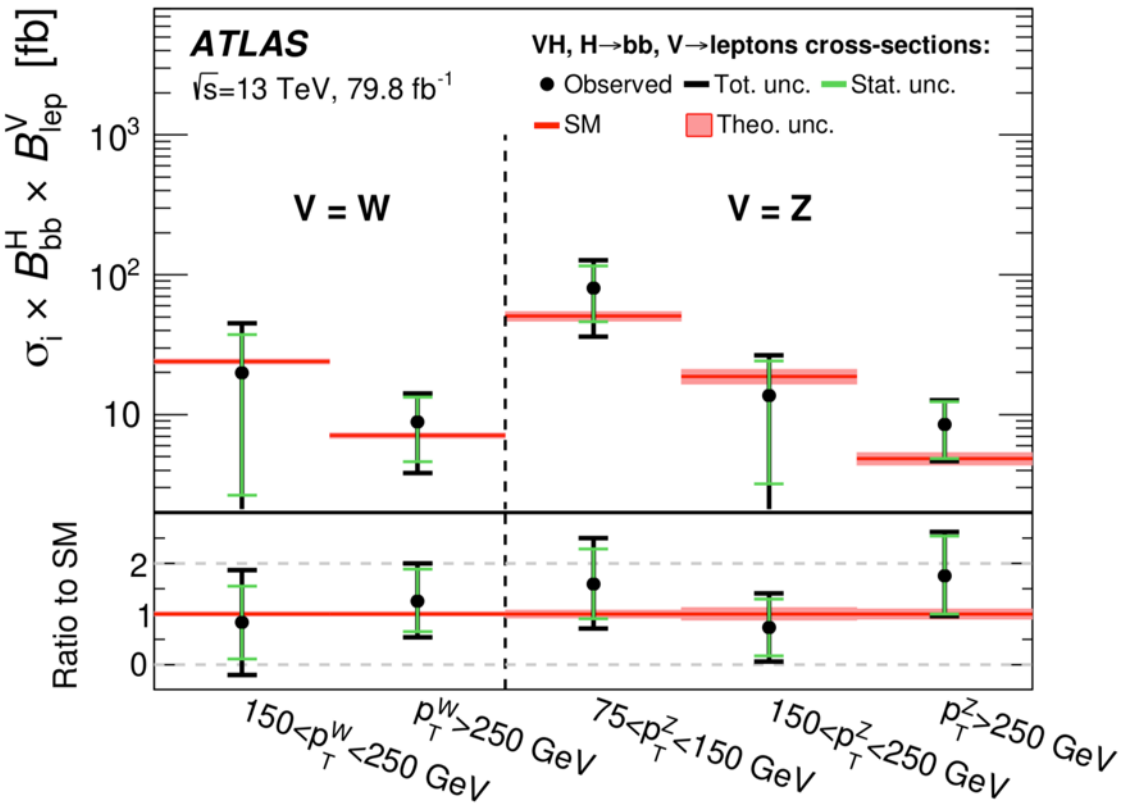


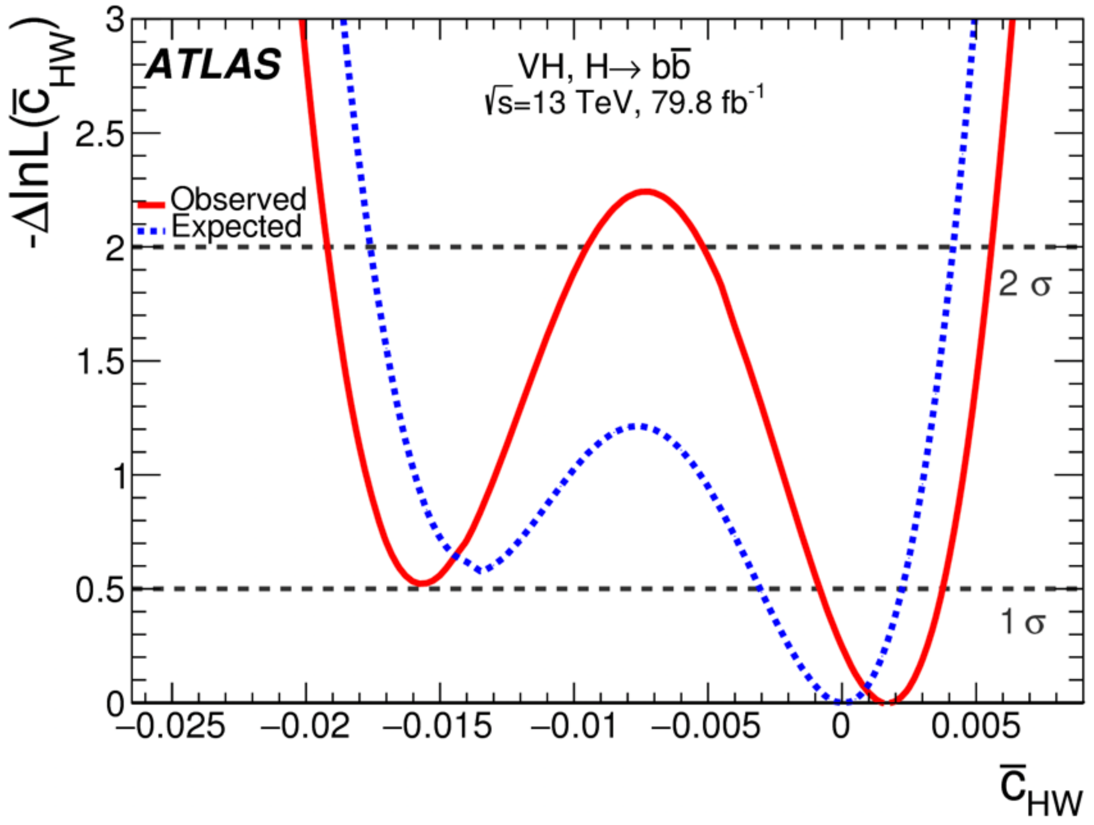


3^{rd}-generation fermion coupling: H→bb

PRL 121 (2018) 121801
JHEP 05 (2019) 141

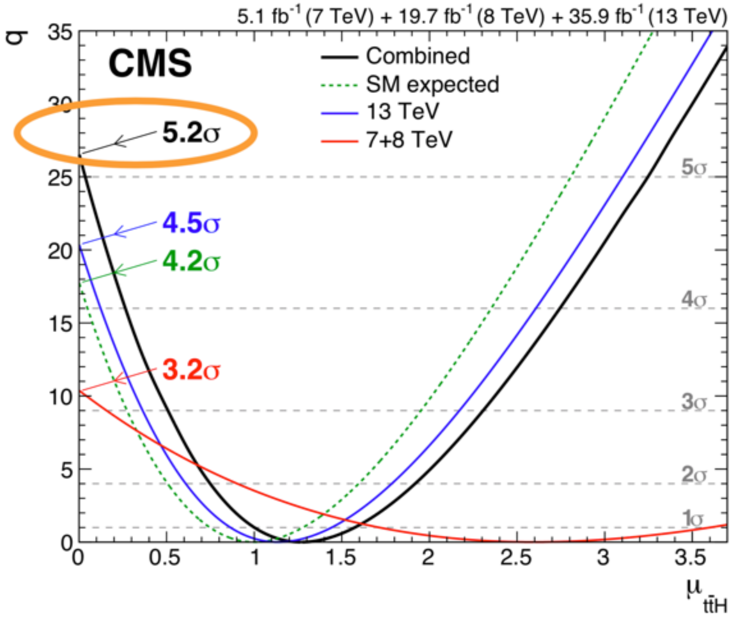
- **Differential cross section measurement for VH production has sensitivity to p_T^V**
- **Results interpreted in EFT, limits placed on new H-W interaction coefficient c_{HW}**

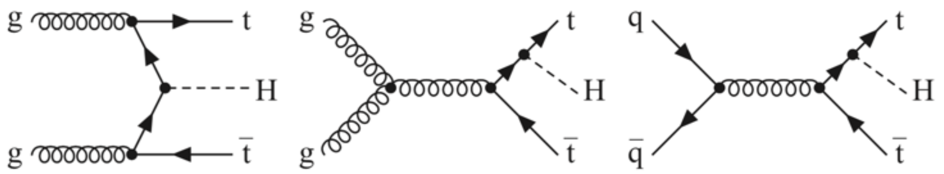




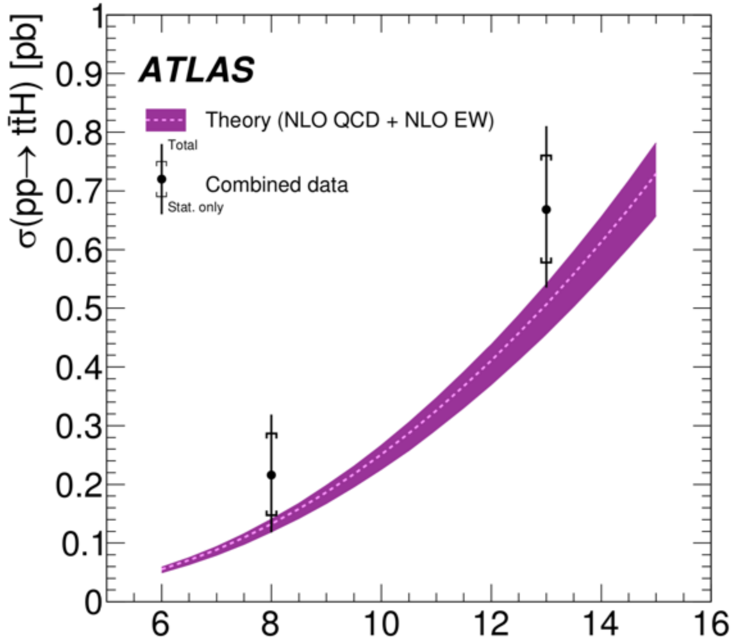
3rd-generation fermion coupling: ttH

- **The H-top coupling can only be directly probed in the Higgs boson production.**
  - **Top quark too heavy for the H→tt decay.**
- **> 5σ observation established using the H→bb, WW, $\tau\tau$, γγ, ZZ decays.**





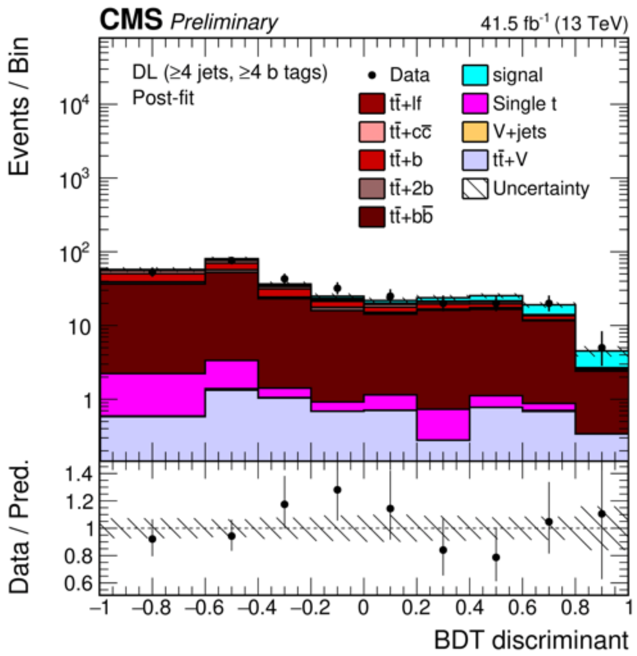
	signal strength
ttH comb (Run1+80/fbRun2)	$1.32^{+0.28}_{-0.26}$
ttH comb (Run1+36/fbRun2)	$1.26^{+0.31}_{-0.26}$

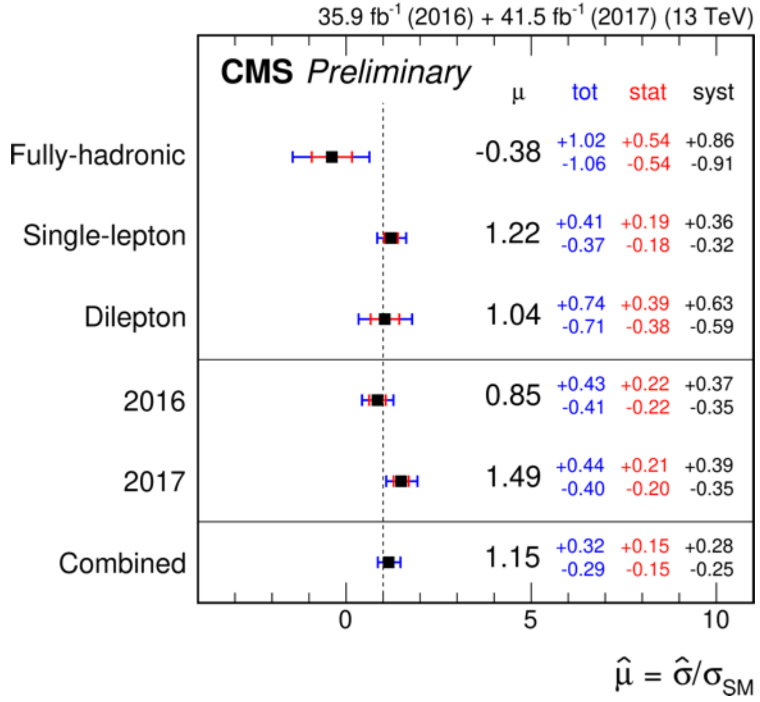


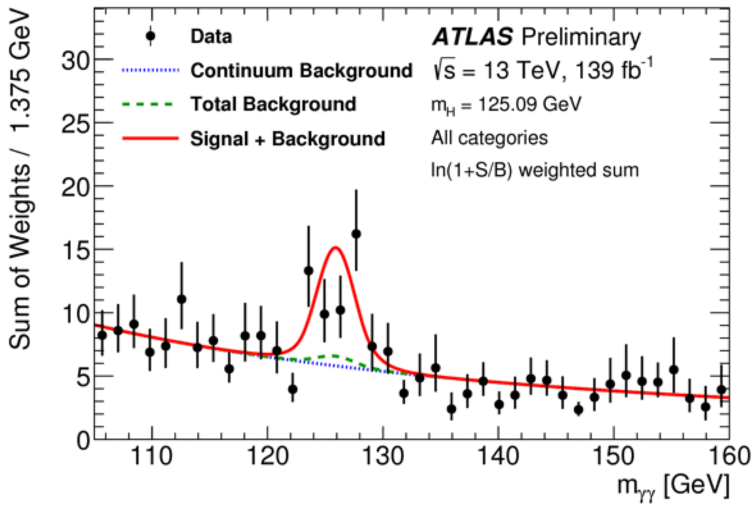
3rd-generation fermion coupling: ttH

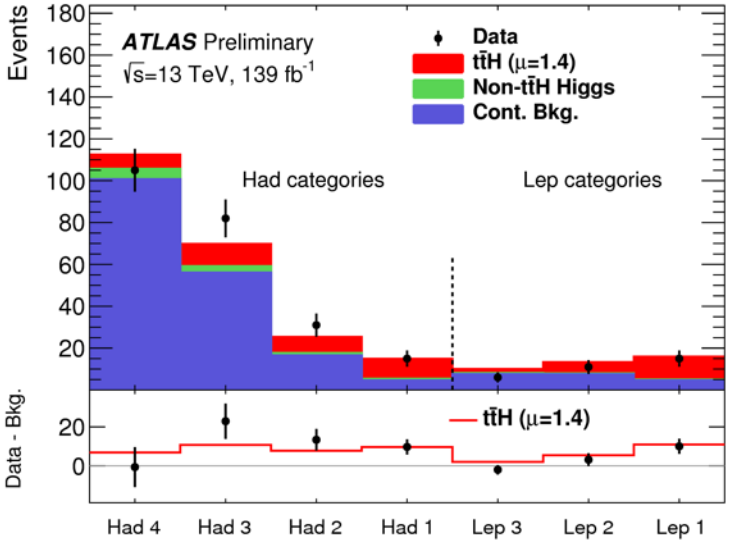
CMS-PAS-HIG-18-030
ATLAS-CONF-2019-004

- **With more data and improved analyses (usage of sophisticated methods for signal identification)**
  - **With full Run 2 luminosity, ATLAS ttH(H->$\gamma\gamma$) has 4.9σ observed significance**
  - **With 2016+2017 data, CMS ttH(H->bb) obs.(exp.) significance is 3.7σ (2.6σ) → Evidence for ttH(H->bb) channel**





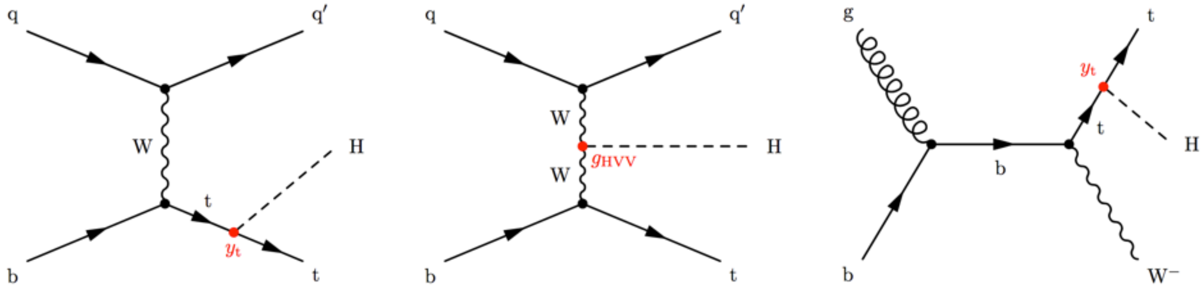




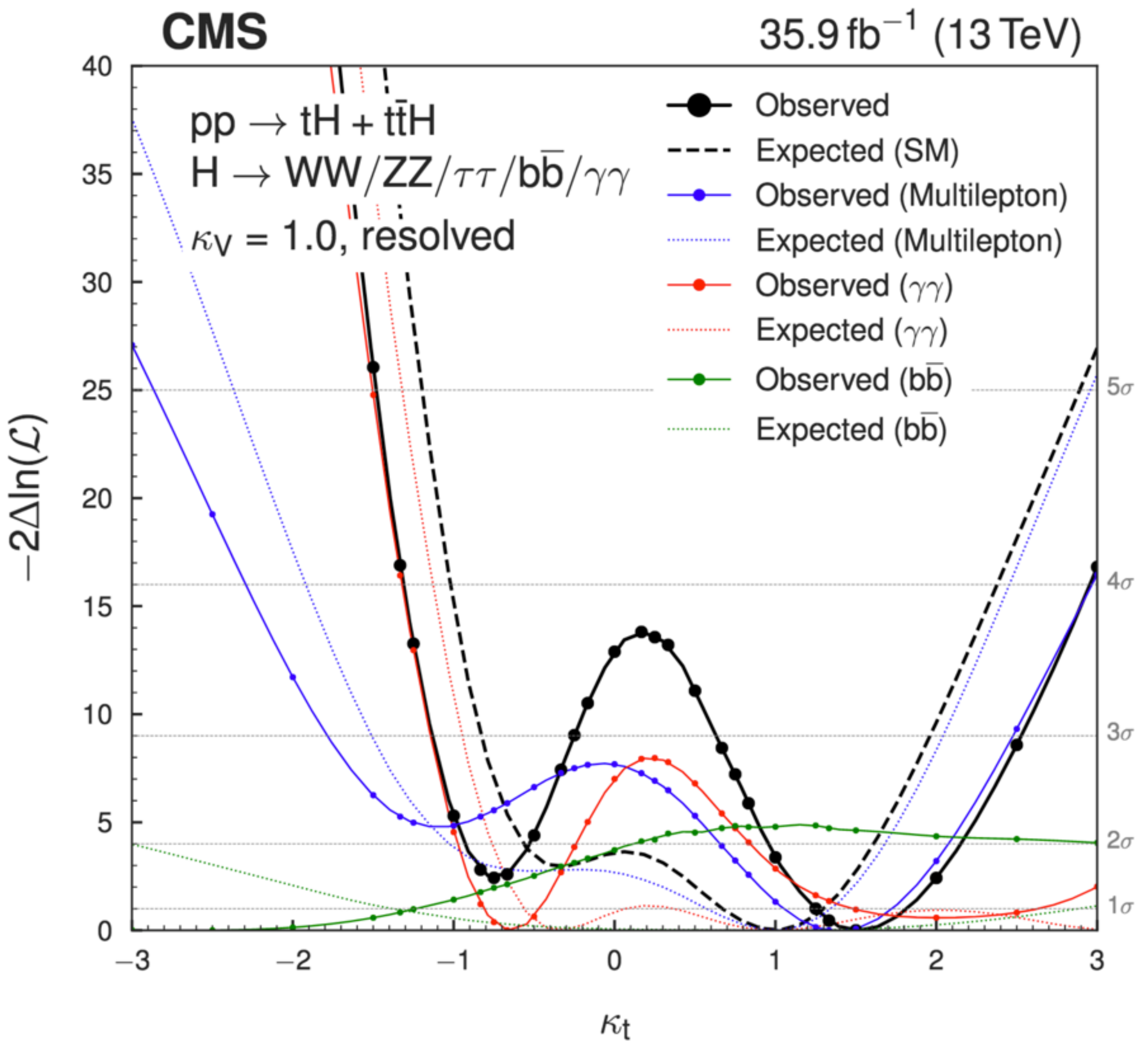
3^{rd}-generation fermion coupling: tH

PRD 99 (2019) 092005

- **SM tH production XS is only ~90 fb, but it is sensitive to Higgs-top Yukawa coupling sign because of the interference**

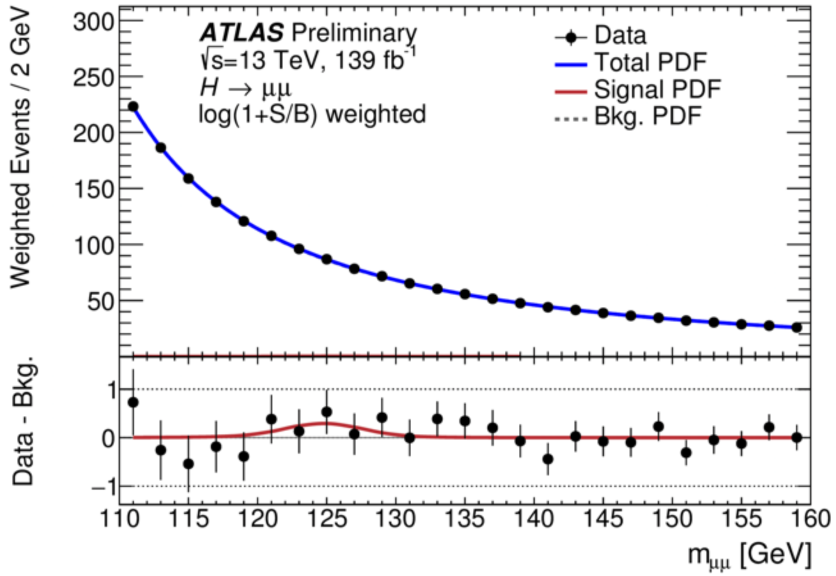


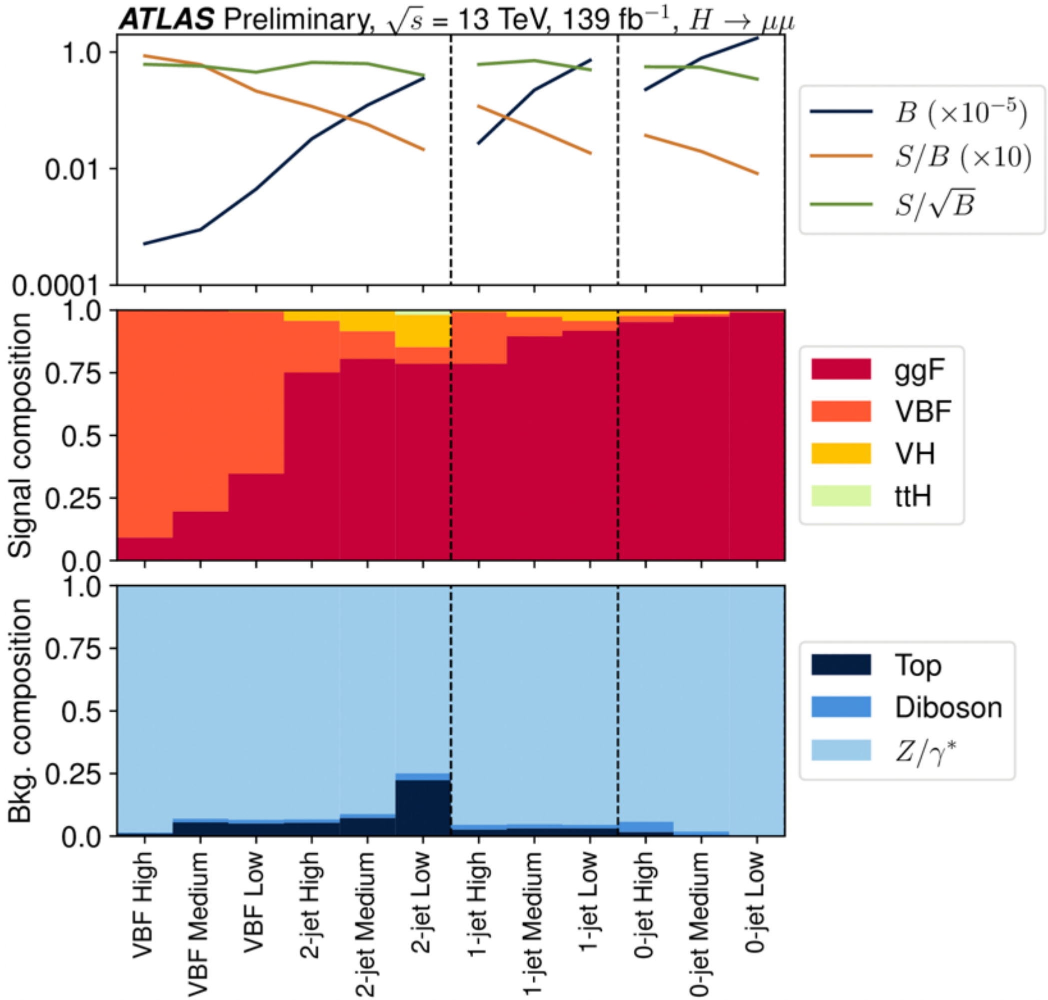
- **CMS analysis combines H->bb, γγ and multi-lepton channels**
- **95% C.L. upper limit on SM-like tH signal strength: 25 (12) obs.(exp.)**
- **ttH+tH combination favors positive κ_t over negative by ~1.5σ (expected to favor κ_t=1.0 over κ_t=−1.0 by 4σ)**



2nd-generation fermion coupling: H→$\mu\mu$

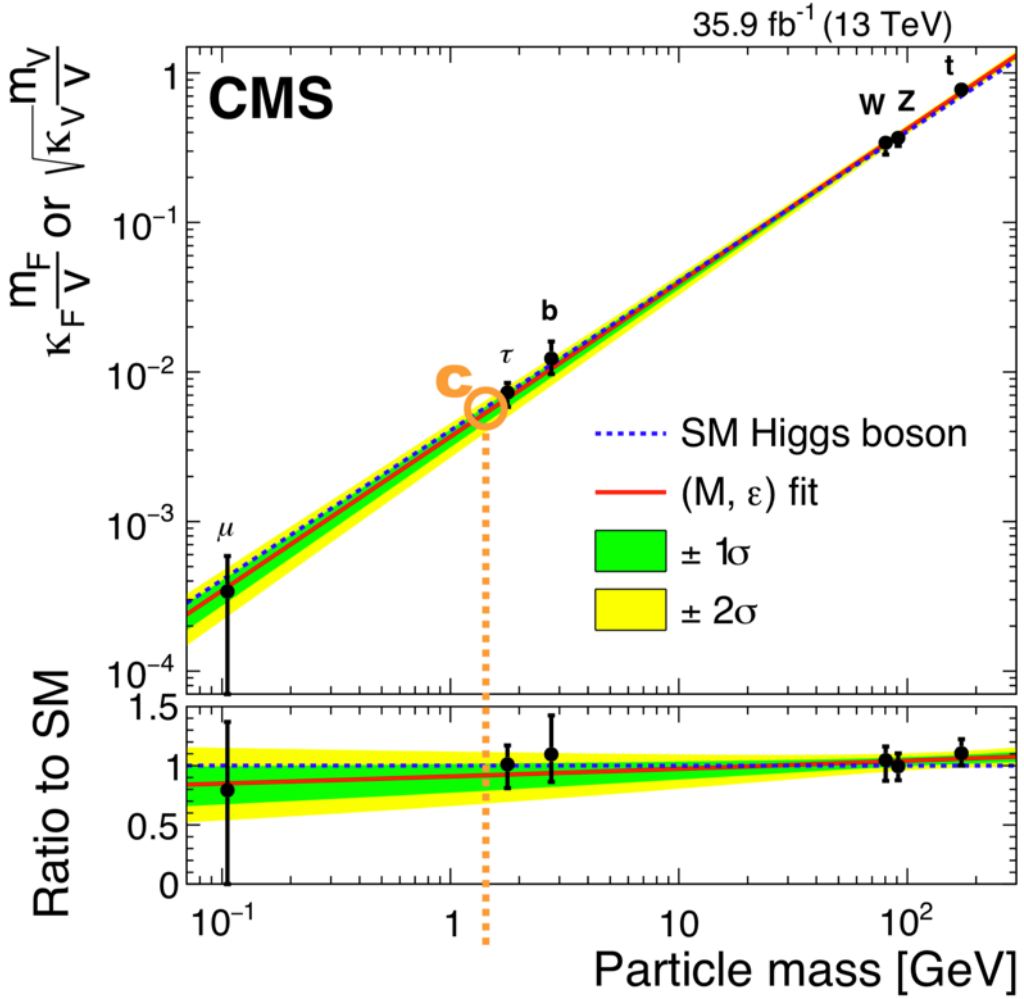
- **Challenging channel**
  - **Small BR(H→$\mu\mu$) ≈ $2\cdot10^{-4}$**
  - **Large irreducible background**
- **Needs excellent muon resolution and sophisticated techniques for good categorization of events (BDTs, FSR Recovery, pile-up jet rejection, etc), and then look for peak in the $m_{\mu\mu}$ spectrum.**
- **Upper limit set on μ < 1.7 using the full Run 2 dataset**
  - **Observed μ = 0.5 ± 0.7.**
  - **Significance of the signal 0.8σ (expected 1.5σ).**





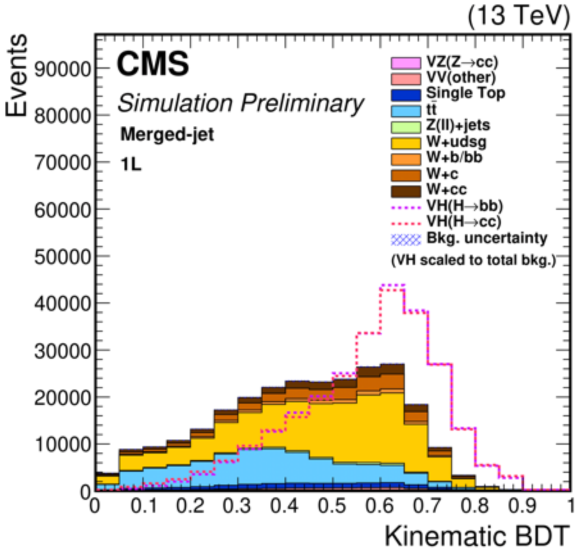
2^{nd}-generation fermion coupling: charm-H

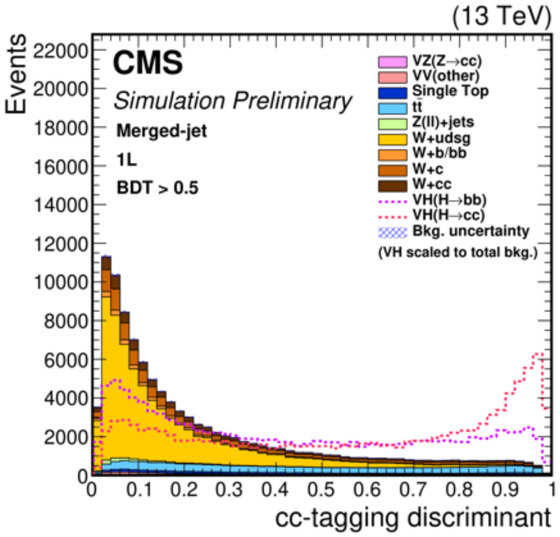
- **The BR(H→cc) is 2.9%, similar to BR(H->ττ), but way harder to probe**
  - **Very hard to separate the signal from the overwhelming background at a hadron collider (H->bb is background, 20 times more)**
  - **Charm jet ID is highly challenging**
- **Complementary approaches exist :**
  - **Direct search for H→cc decay**
  - Searches for charmonium decays: H→J/Ψγ
  - Extract constraints on λ_c from kinematics
  - Total width / global analysis

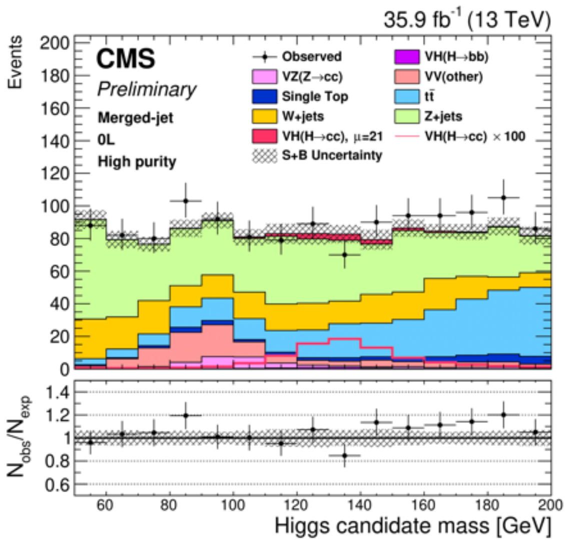


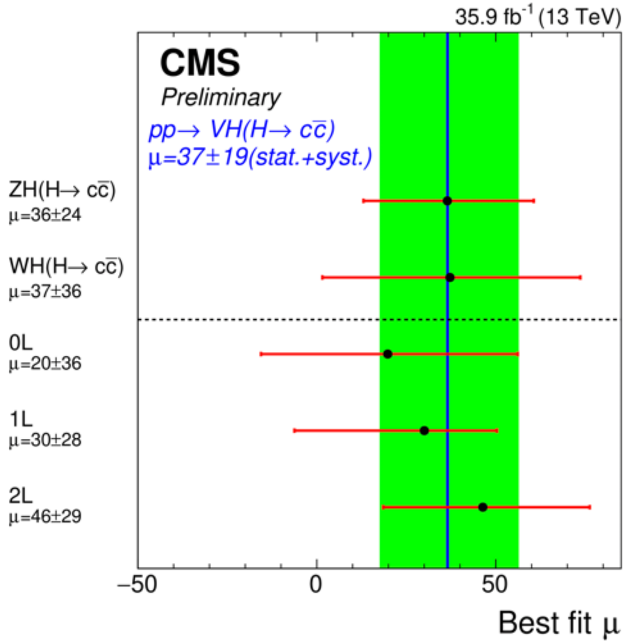
2^{nd}-generation fermion coupling: H→cc

- **CMS has searched for H→cc in VH production.**
  - **Analysis separated according to number of leptons, and depending on whether the c-quarks are reconstructed as one or two jets.**
  - **Apply novel c-tagging techniques.**
- **Limit placed on μ < 70 (μ < 36^{+16}_{-11} expected).**





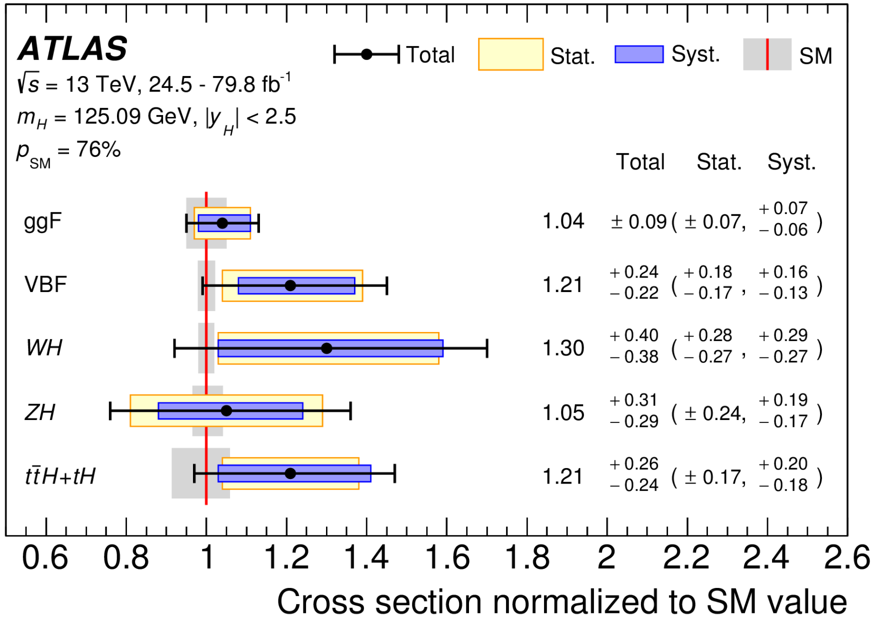


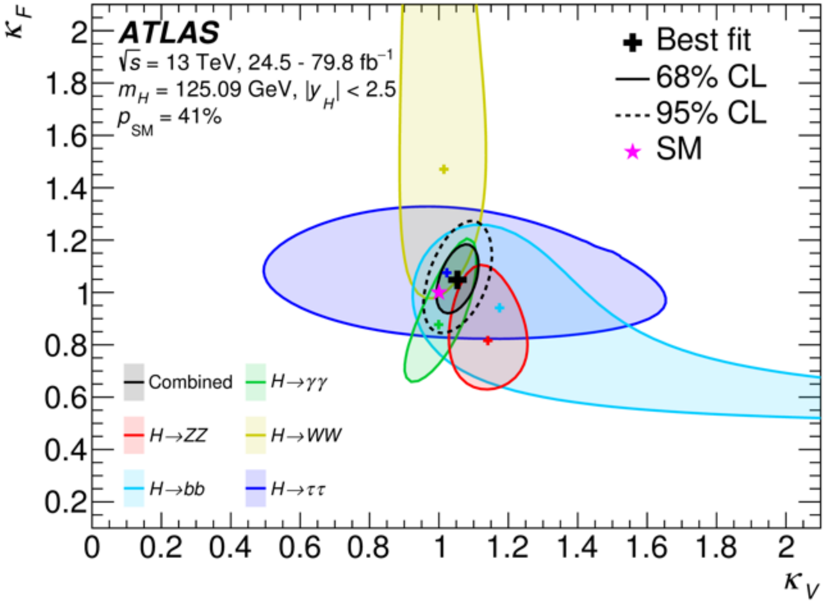


Combinations

Higgs Coupling from Combination

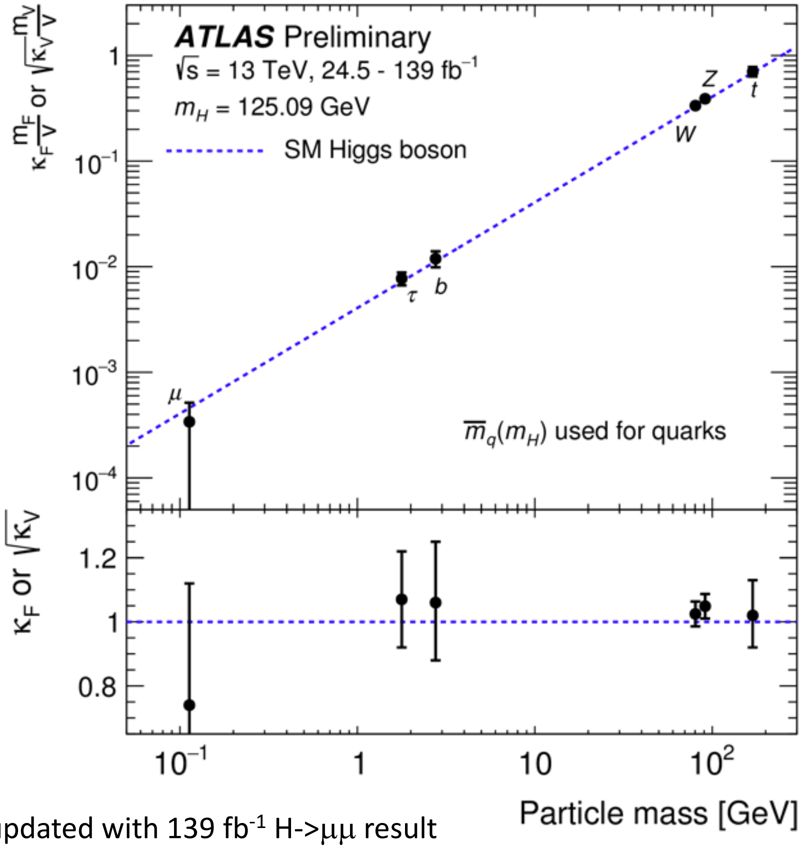
- **Combination of the H→γγ, ZZ, WW, $\tau\tau$, bb and $\mu\mu$ channels using up to 79.8 fb^{-1} has been used to:**
  - **Measure production mode cross sections.**
  - **Measure Higgs boson couplings.**
  - **Place limits on coupling scaling factors, for example on overall scaling factors for couplings to vector bosons, κ_V, and to fermions, κ_F**

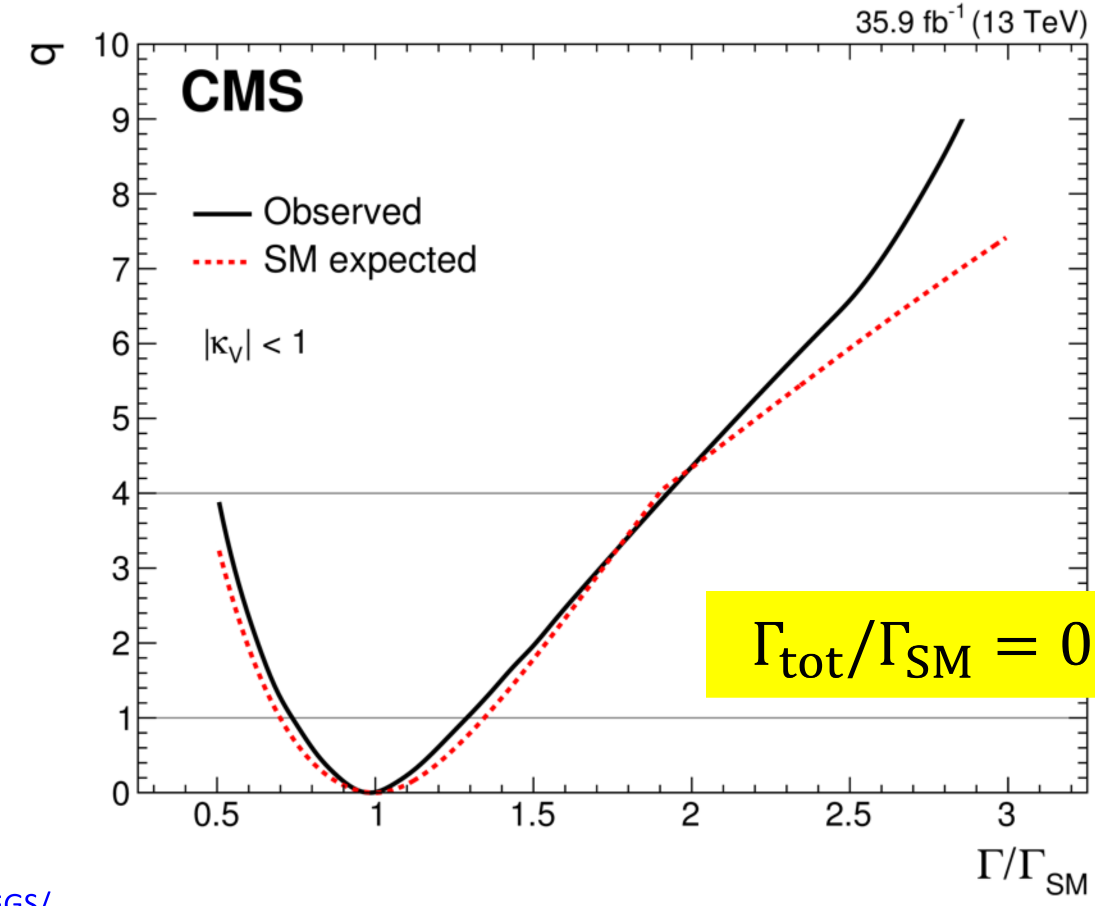




Higgs Coupling from Combination

- ~10% uncertainty on Higgs to W/Z boson couplings
- ~10-20% uncertainty on Higgs to the 3rd generation fermion couplings
- ~30% uncertainty on the total width constraint derived from coupling fit

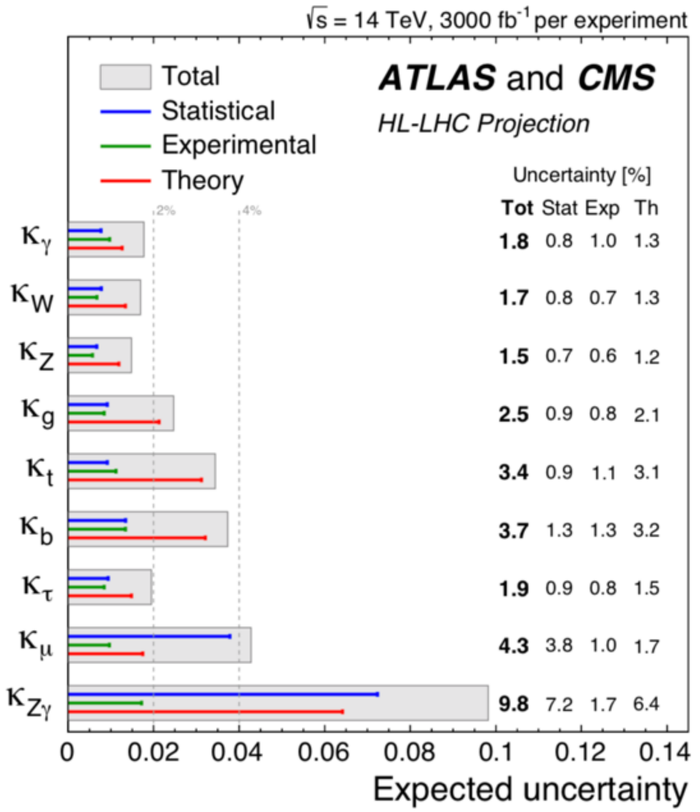


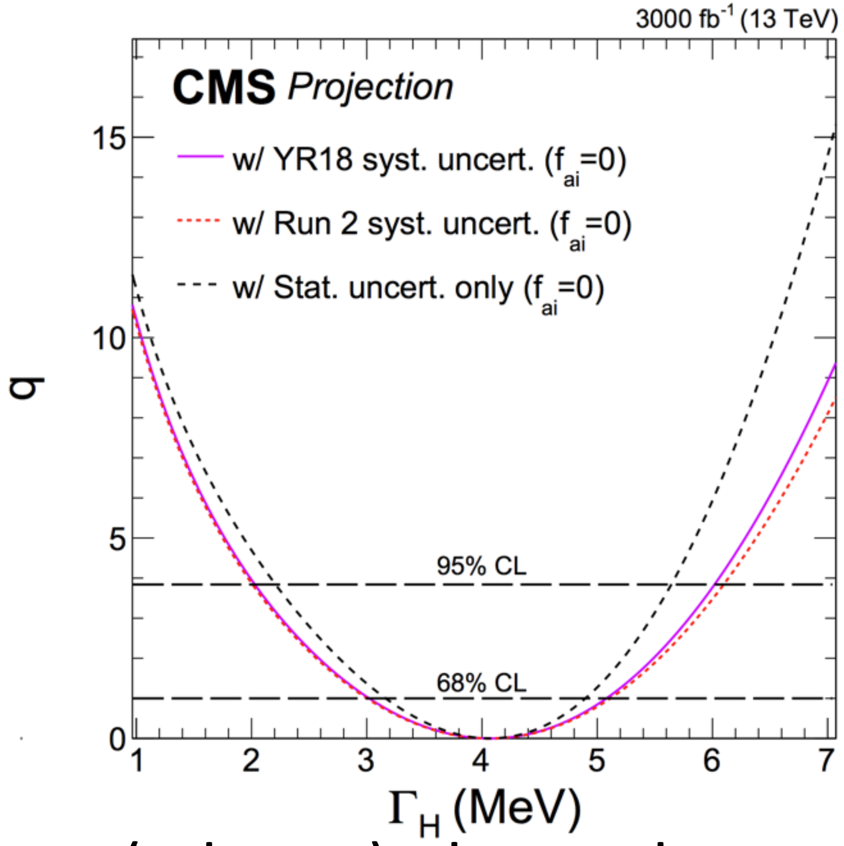


$$\Gamma_{tot}/\Gamma_{SM} = 0.98^{+0.31}_{-0.25}$$

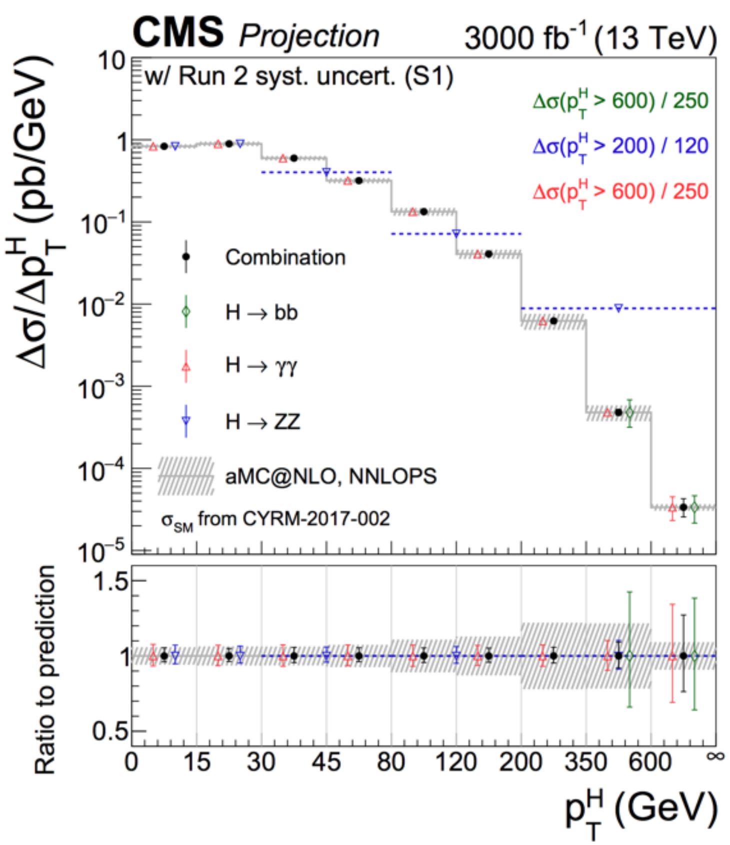
* Plot updated with 139 fb^{-1} H->$\mu\mu$ result
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

Towards HL-LHC





Uncertainties in the high Higgs pT region can reach 20-30%



A substantial amount of parameter space (and masses) to be covered

- 2-4 % precision of Higgs couplings to W/Z, 3rd gen. fermions, γ/g and muon
- Discovery for H->μμ and H->Zγ decays
- H→cc : $\sigma/\sigma_{SM} < 6.3$ from ATLAS Run 2 result extrapolation
- Γ_H can be measured in CMS = $4.1^{+1.0}_{-1.1}$ MeV

Summary

- The Higgs Boson is "really" new physics
  - Higgs boson is the most recent fundamental (?) particle discovered
  - It has a very special role in the SM
- Higgs measurements have entered a precision era at LHC
  - Higgs boson mass is measured with better than 0.2% accuracy
  - All main decay modes (ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb) and production modes (ggF, VBF, VH, ttH) are established
    - Many differential cross sections/STXS measurements already started
- No deviations from SM have been observed
- A broad Higgs physics program is ongoing within ATLAS and CMS using the LHC Run2 dataset (<5% of the final HL-LHC integrate luminosity)
  - Stay tuned!

Thanks for your attentions

More references at

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Backup

Observations of 3rd generation fermion couplings

Run 2 Higgs Physics Milestones Already Reached

Third Generation (Charged) Completed!

Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

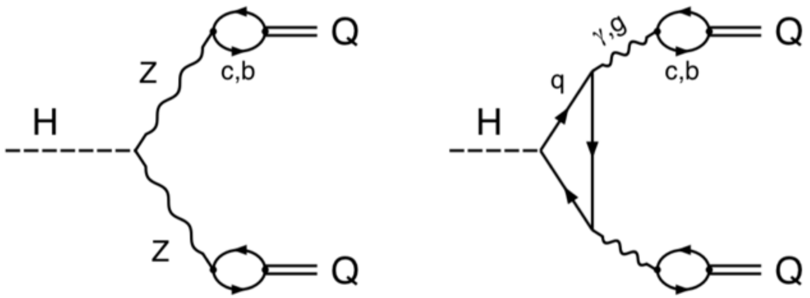
* 13 TeV only derived from cross section measurements

** Lower uncertainty (upper uncertainty 31)

H→J/Ψ J/Ψ AND H→ΥΥ

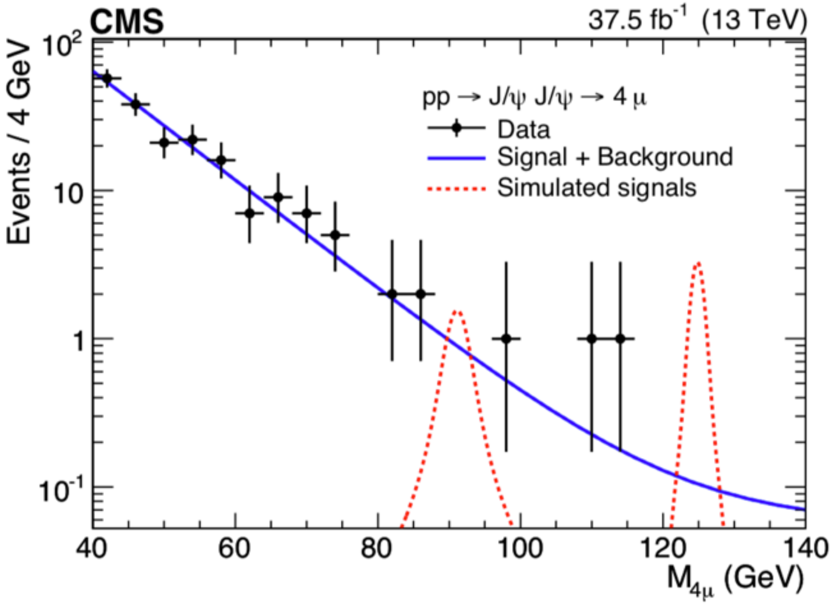
arXiv:1905.10408

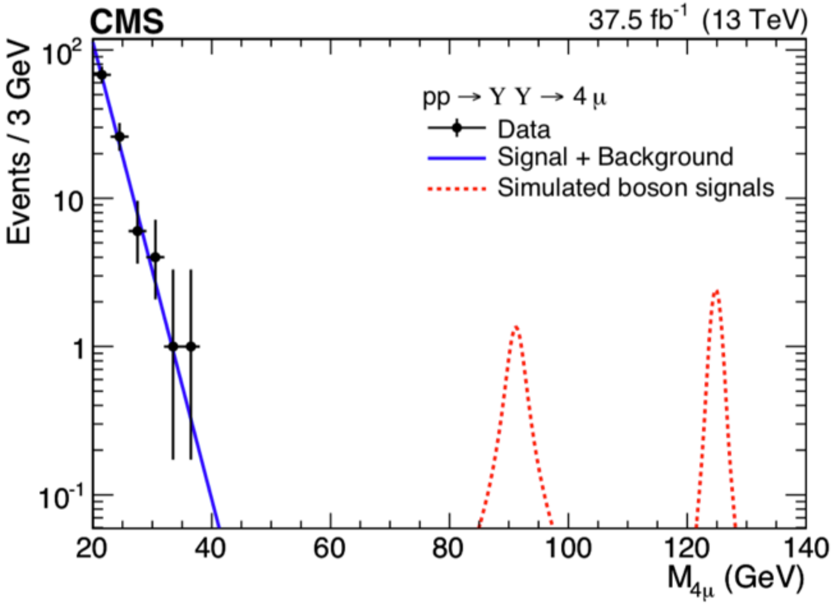
SM BRs inaccessible by many orders of magnitude.



Four-muon final state

- Experimentally clean with very small SM backgrounds
- Excess at H or Z mass would be sign of BSM physics



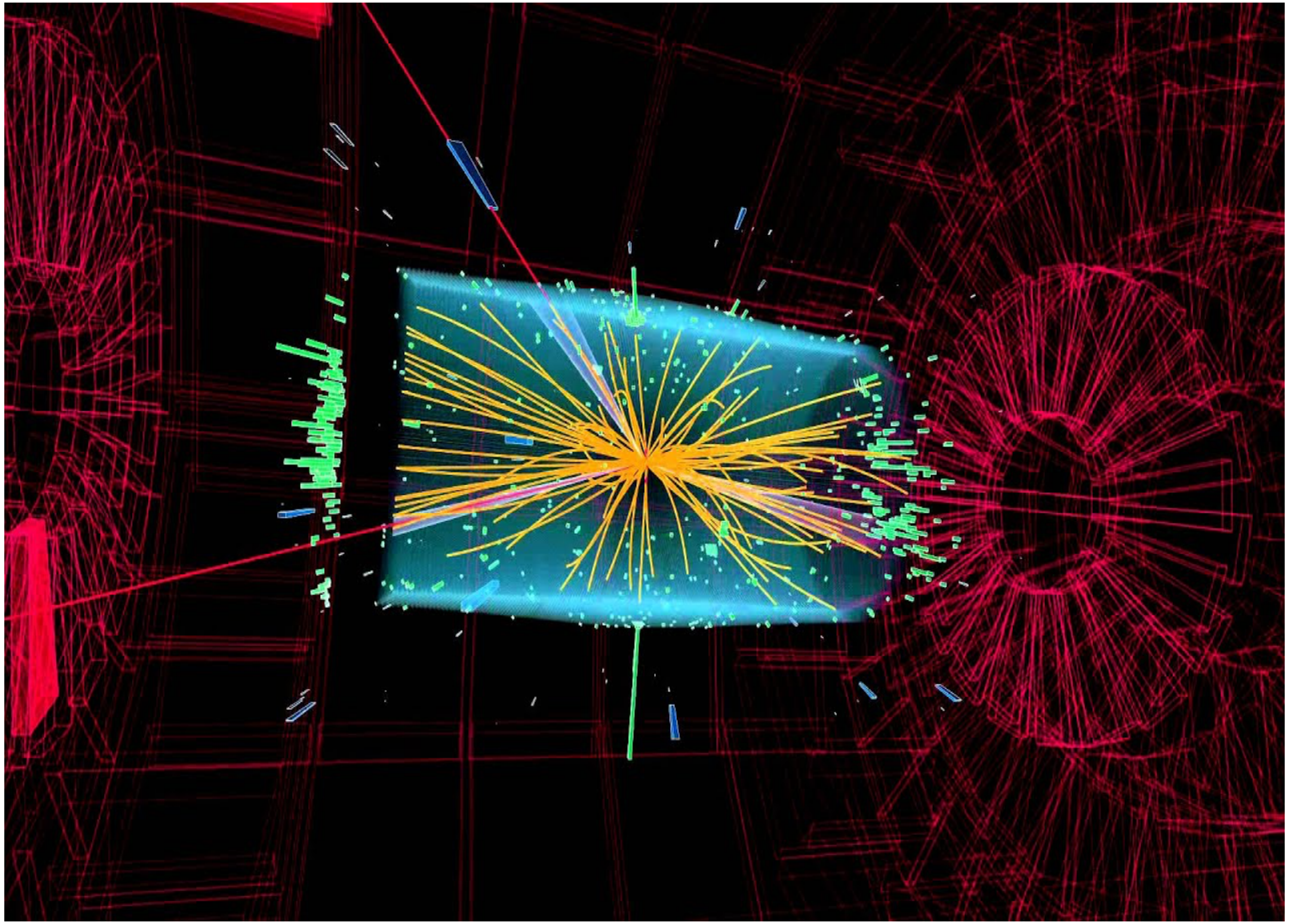


95% CL Upper Limits

Process	Observed	Expected
$\mathcal{B}(H \to J/\psi J/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(H \to \Upsilon\Upsilon)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(Z \to J/\psi J/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(Z \to \Upsilon\Upsilon)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

$H \to ZZ^* \to 4\ell$

Run 2: σ×B×L = 850 events



Analysis features to note:

- **low event yield: 850**
- **best final S/B-ratio, better than 2:1**
- **good mass resolution = 1-2%**

- **Best channel to observe Higgs at 125 GeV**
  (due to excellent S/B ratio, despite of low yield)

- **Best for Higgs mass measurement**
  (very small systematics for muons)

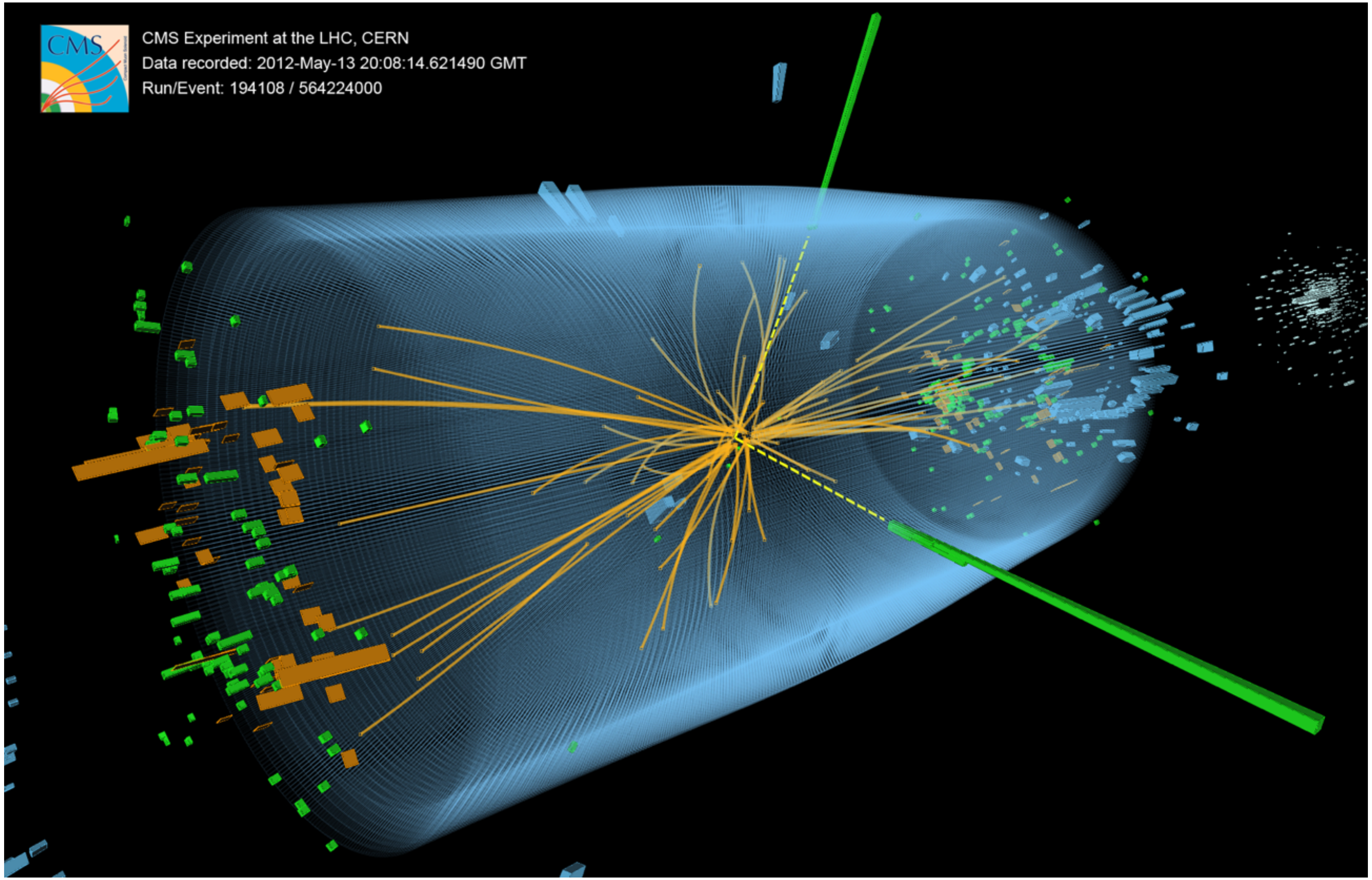
- **Best for studying Higgs J^P properties**
  (fully reconstructed four-body final state)

- **Best for studying Higgs width** via ratio of off-shell to on-shell production rates

- **Second-best for measuring cross sections**
  (after the diphoton channel)

$H \rightarrow \gamma\gamma$

Run 2: σ×B×L = 16K events



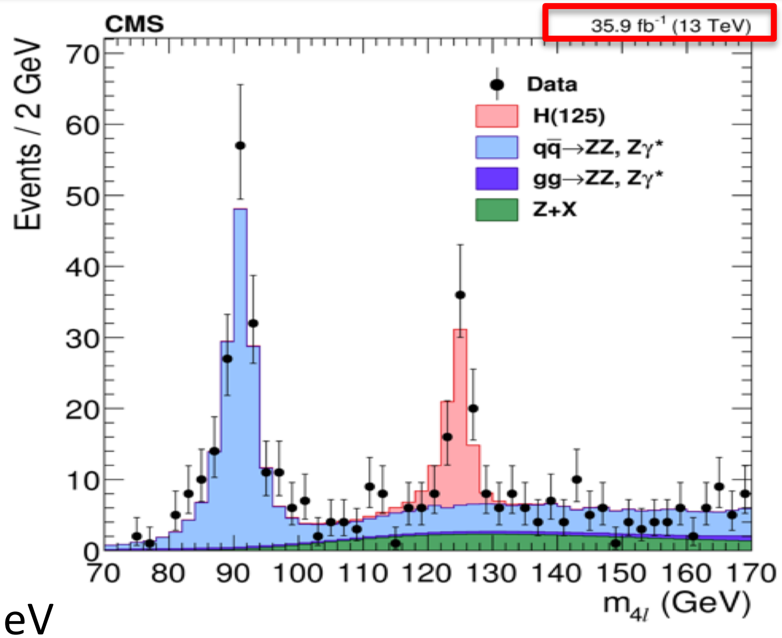
Analysis features to note:

- **fairly high event yield:**
  $20 \times (H \rightarrow ZZ^* \rightarrow 4\ell)$
- **good mass resolution: 1-2%**
- **fair final S/B-ratio: 1:20**
- **Excludes J=1** (Landau-Yan theorem)
- **Best for measuring cross sections**
  (comb. of high yield and fair S/B ratio)
- **Good for Higgs mass measurement**
  but not the best due to systematics
- **Decay is via loop:** look for BSM contributions!

$H \rightarrow ZZ^* \rightarrow 4\ell$: Higgs mass measurement

Mass measurement:

- Three event categories: $4\mu, 2e2\mu, 4e$
- Momenta of two leptons forming Z_1 are refit using $\boldsymbol{pdf_{Z1}(m_{ll})}$
- Fit is performed for m_H in 3D space: $\boldsymbol{pdf\left(m_{4l}, D_{bkg}^{kin}, \sigma_{m_{4l}} \middle| m_H\right)}$
- With respect to using just mass distribution
  - Z_1-refit improves m_H measurement by **10%**
  - per-event four-lepton uncertainties -- by **8%**
  - ME-based discriminant (signal-vs-background) -- by **3%**



Run 2, 2016 result: $\boldsymbol{m_H = 125.26 \pm 0.21 = 125.26 \pm 0.20(stat) \pm 0.08(syst)}$ GeV

This is the best Higgs boson mass measurement at the moment

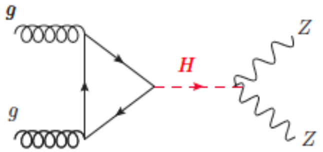
Run 1	
ATLAS+CMS	**ZZ+$\gamma\gamma$ combination**
125.09 $\pm$ 0.24 GeV	

2016 dataset	H->ZZ->4l	H->$\gamma\gamma$	Combination
ATLAS	124.79 $\pm$ 0.37	124.93 $\pm$ 0.40	124.97 $\pm$ 0.24
CMS	**125.26 $\pm$ 0.21**	125.4 $\pm$ 0.3	

Awaiting updates with full Run 2 dataset (stat errors are expected to improve by a factor of 2: $\pm$ 0.10)

HL-LHC: stat error will improve by a factor of 10: ~20 MeV
One needs to improve systematics proportionally to about 10 MeV, or 0.01% – huge challenge!

$H \rightarrow ZZ$: Γ_H from off-shell to on-shell production



$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

F(m) depends on:

- **<u>huge boost</u> for $m_{H^*} > 2m_Z$ (both Z bosons are now on-shell)**
- Hgg coupling g_g^2 evolution (notice the bump for $m_{H^*} > 2m_t$)
- partonic gg-luminosity drives F(m) down
- tensor structure Hgg coupling (non-SM couplings tend to give a large boost to off-shell production)

Assumptions:

- The coupling modifiers are identical for on-shell and off-shell production;
- The coupling modifiers are independent of the momentum transfer of the Higgs boson production mechanism considered in the analysis;
- Any new physics which modifies the off-shell signal strength and the off-shell couplings does not modify the relative phase of the interfering signal and background processes;
- There are no sizable modifications to the off-shell signal region unrelated to an enhanced off-shell signal strength

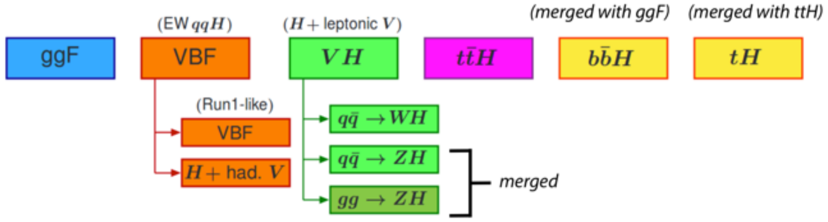
Simplified Template Cross Sections

To measure as precisely as possible individual production processes (ggF, VBF, VH and ttH) in different regions of phase space

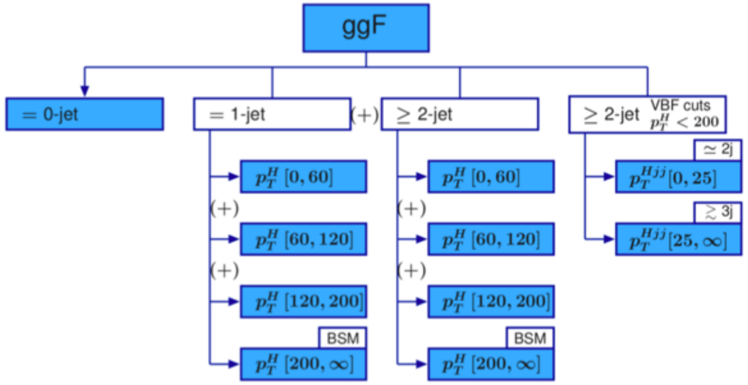
- **Integrate over the decay products of the Higgs.**
- **Define fiducial cuts at truth particle level on the Higgs production (eta, pT, number and kinematics of the additional jets or leptons in the events).**
- **Define (as much as possible) reconstruction level cuts corresponding to the fiducial volume of interest (as much as possible).**
- **Fit the defined partially fiducial defined cross sections in all regions simultaneously.**

Advantage possibility to combine decay channels and use multivariate techniques in specific channels -- Compromise as both aspects increase the extrapolation.

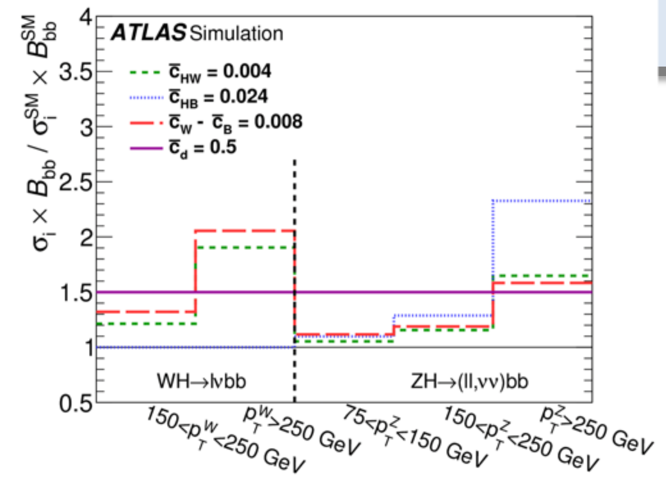
Stage 0



Stage 1 - ggF



Interpretation in EFT with STXS



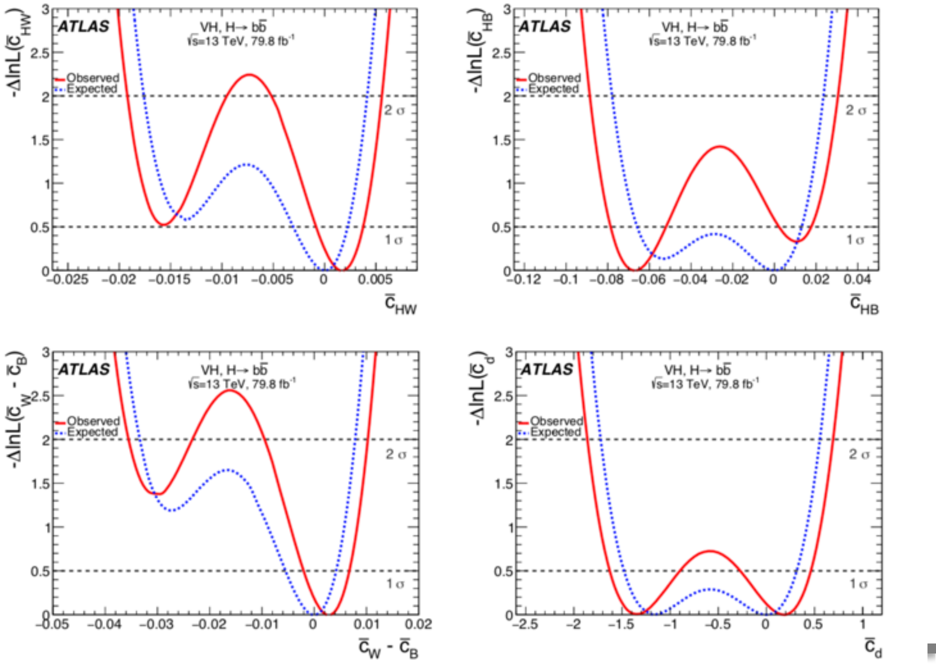
Interpretation of ATLAS VH(bb) STXSs in an EFT framework, in this case the high energy parametrization is important

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

- Reduction of the (2499 baryon number preserving dim-6 Wilson coefficients) keeping only universal and CP- invariant operators reduces to 8 Higgs production operators and 9 operators affecting EW observables.
- **SILH**: Strongly interacting light Higgs basis, with universal couplings in which new physics couples only to the Higgs captures best the low energy effects.

$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2}, \quad \bar{c}_d = v^2\frac{c_d}{\Lambda^2}$$

- $O_{HW} = i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu},$
- $O_{HB} = i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu},$
- $O_W = \frac{i}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu},$
- $O_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}.$



Linear terms for SM-BSM interference and quadratic terms taken into account.

Combination of all Higgs boson analyses

	gg->H	VBF	VH	ttH
WW				
ZZ				
bb				
ττ				
γγ				
μμ				
invisible				

$$\sigma(xx \to H) \cdot BR(H \to yy) \propto \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{TOT}}}$$

One needs **11 independent parameters** to describe all currently relevant production & decay mechanisms:

Γ_{gg} **(loop induced: t and some b)**

Γ_{WW}

Γ_{ZZ}

Γ_{tt}

Γ_{bb}

$\Gamma_{\tau\tau}$

$\Gamma_{\gamma\gamma}$ **(loop induced: W and t)**

$\Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + Γ_{BSM}

decay modes not studied or, perhaps, studied, but not included in combination

Global Signal Strength

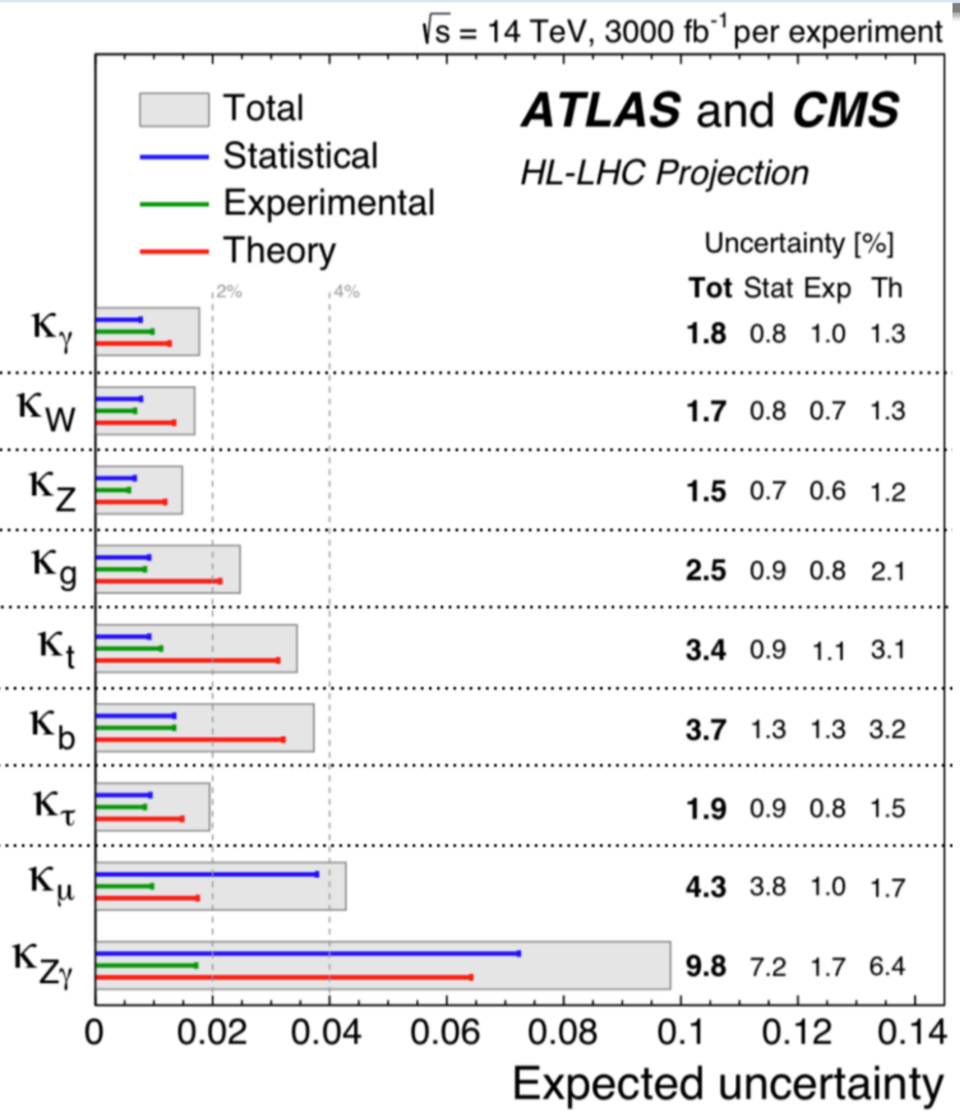
EPJC 79 (2019) 421
ATLAS-CONF-2019-005

- **Inclusive Higgs signal strength from combination of all analysis channels:**
  - **ATLAS Run 2 (80 fb^{-1}):** $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$
  - **CMS Run 2 (36 fb^{-1}):** $\mu = 1.17 \pm 0.10 = 1.17 \pm 0.06\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{sig theo}) \pm 0.06\,(\text{other syst})$

Comparable uncertainties from statistics, experimental systematics and theory sources

Towards HL-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2	HL-LHC
κ_γ	13%	9%	1.8%
κ_W	11%	8.6%	1.7%
κ_Z	11%	7.2%	1.5%
κ_g	14%	11%	2.5%
κ_t	30%	14%	3.4%
κ_b	26%	18%	3.7%
κ_τ	15%	14%	1.9%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134



"YR18 systematic uncertainties" scenario (S2): Theoretical uncertainties are scaled down by a factor of two, while experimental systematic uncertainties are scaled down with the square root of the integrated luminosity until they reach a defined minimum value based on estimates of the achievable accuracy with the upgraded detector

Statistics

Workhorse of the combination is the profile likelihood ratio, Λ

$\vec{\alpha}$ = Set of POIs at some fixed values to be tested

$\vec{\theta}$ = Nuisance parameters

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

Values of $\vec{\theta}$ that maximise the likelihood given the fixed values of $\vec{\alpha}$ being tested (conditional estimate)

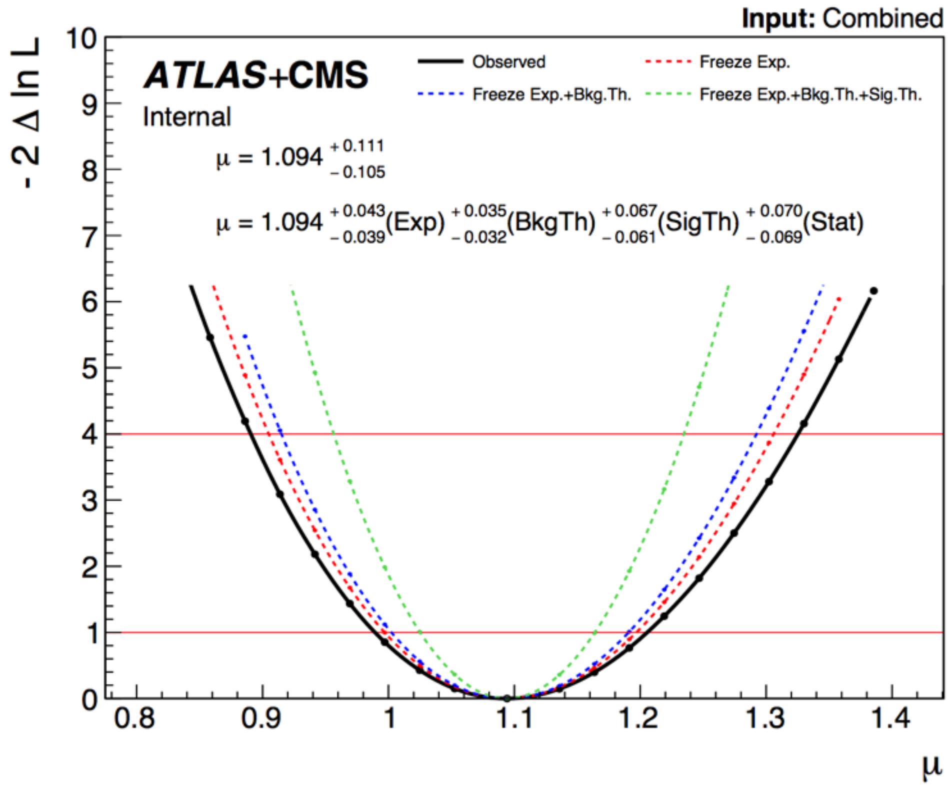
Values of $\vec{\alpha}$ and $\vec{\theta}$ that globally maximise the likelihood (unconditional estimate)

Exploit the asymptotic limit:

- Test statistics $q(\vec{\alpha}) = -2 \ln (\Lambda(\vec{\alpha}))$ is assumed to follow a χ^2 distribution with $\vec{\alpha}$ degrees of freedom
- To determine a confidence-level (CL) interval for a single parameter α, we only need to find the values of α where $q(\alpha)$ = the χ^2 critical value for that CL, e.g. 1D 68% CL at $q(\alpha) = 1.00$

An example of breaking down of uncertainties

- For this, and other key measurements, break uncertainty down into 4 components:
  - statistical, experimental, background theory, signal theory
- All ~4300 NPs assigned to one of these groups
- Each component determined by fixing successive group of NPs to best-fit values $\hat{\theta}$ and repeating NLL scan



Higgs rates & couplings

Signal parameterization

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{BR^f}{BR^f_{SM}}.$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$$

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{SM}$$

$$\sigma_i \cdot BR^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

Total width determined as

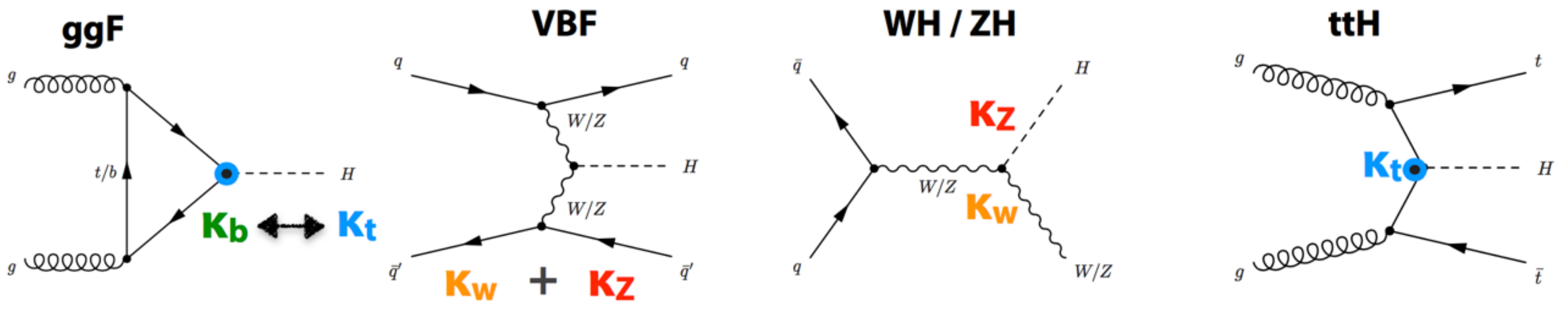
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

Where

$$\kappa_H^2 = \sum_j BR_{SM}^j \kappa_j^2$$

Higgs production processes

Usual suspects:



- Rare processes: