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Higgs measurements and EFT interpretations

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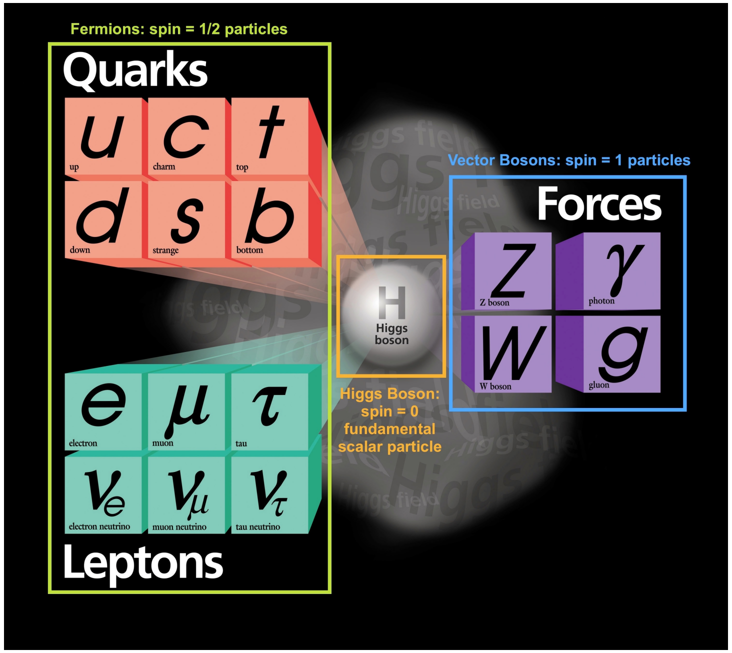
Before I start

- This lecture will focus on **Higgs physics** and mainly discuss **experimental aspects**
- I will use Run 2 results from **ATLAS experiment** (where I came from) to explain how the measurements on Higgs boson properties are performed, and how we interpret the measurements using EFT framework
  - The methods discussed are general (instead of experiment-specific). Most ATLAS results discussed here have their counterparts from CMS experiment

The Standard Model Higgs boson

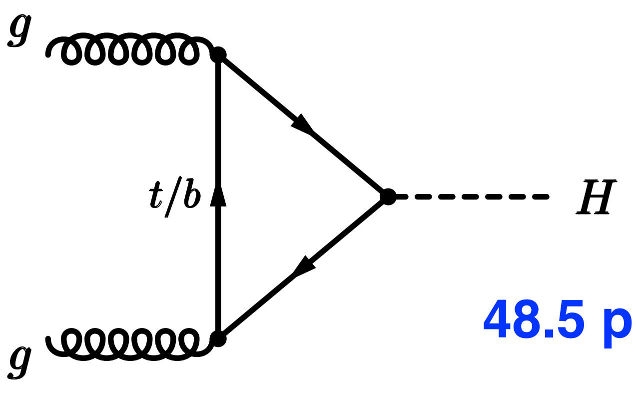
- In the Standard Model (SM), the Brout-Englert-Higgs (BEH) mechanism provides masses to elementary particles
- It predicts a CP-even scalar particle: **the Higgs boson**
- Couplings of fermions (bosons) to Higgs boson proportional to $m_{fermion}$ (m^2_{boson})



Fish discovered water

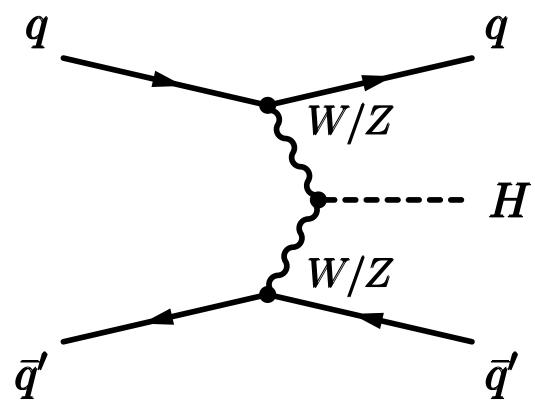
F. Wilczek

Major SM Higgs boson production modes at LHC



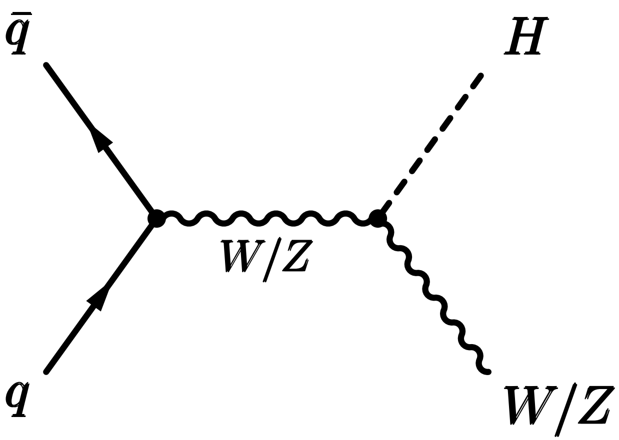
48.5 pb

Gluon-fusion (ggF): ~87%

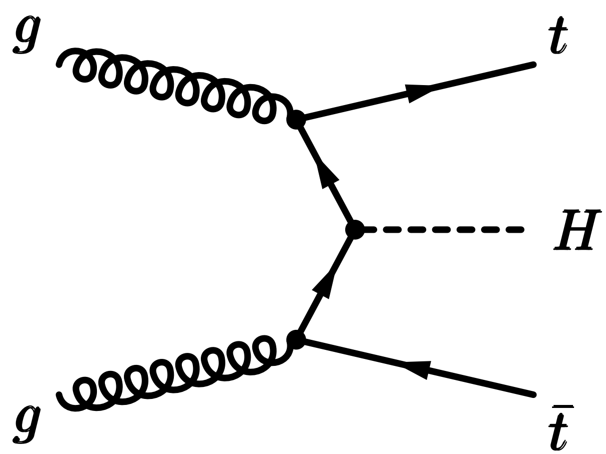


3.78 pb

Vector boson fusion (VBF): ~7%



VH (~4%) 2.25 pb

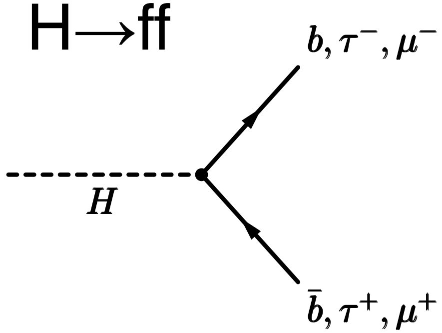


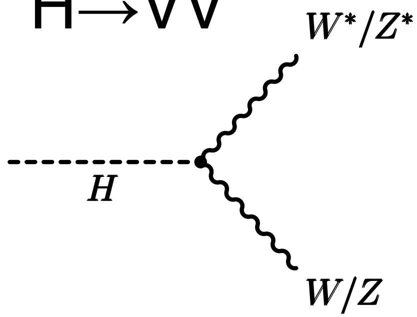
ttH (~1%) 0.51 pb

* Cross-sections are for $\sqrt{s} = 13$ TeV

SM Higgs boson decays

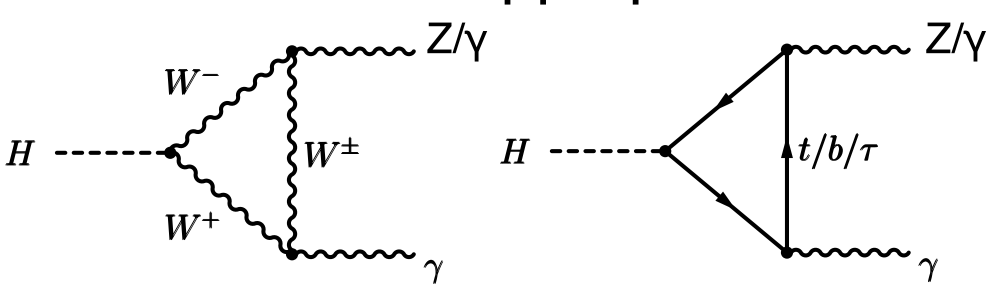
- **“Big five” at LHC: γγ, ZZ, WW, ττ, bb**
  - γγ and ZZ→4l have best precision due to excellent detector resolution and high S/B
- Less sensitive (but still important) channels: μμ, Zγ, cc, …

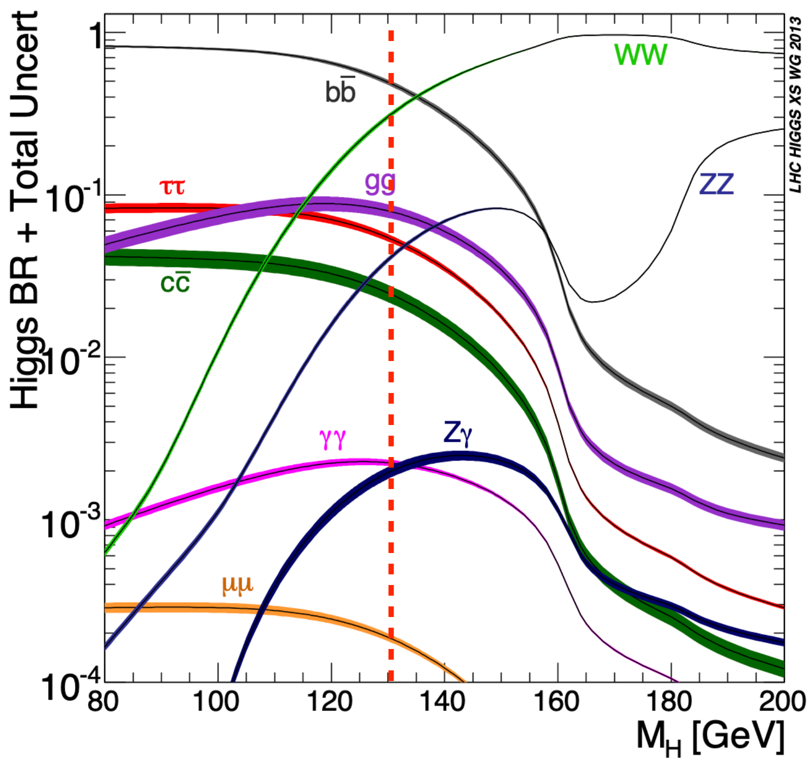




H→γγ/Zγ

Yellow Report 4

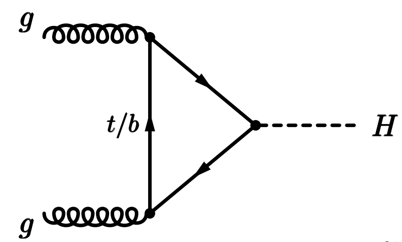




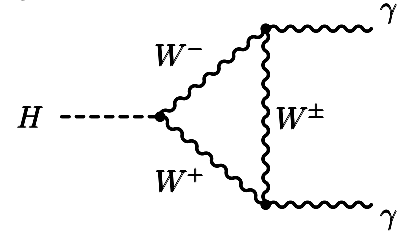
Where to look for new physics in measurements

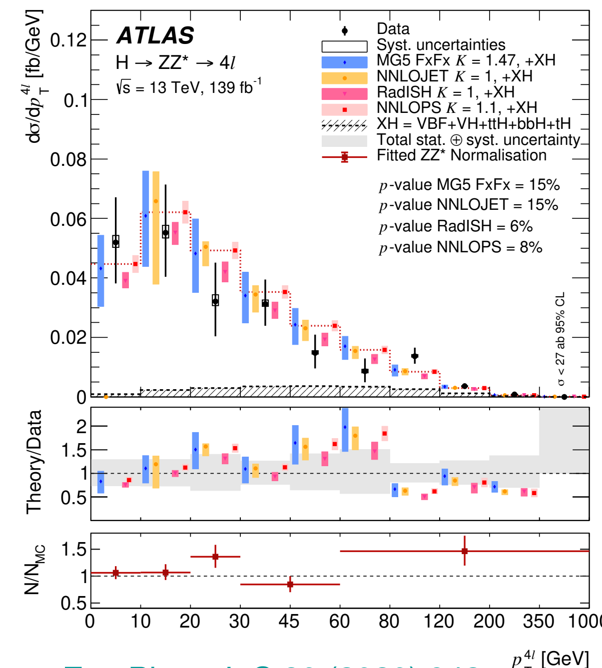
- Experimental measurements of Higgs boson properties serve as **a test bench for the SM** and **a portal to look for possible new physics**
  - Measurements of inclusive production and decay rates
    - Loop-induced **ggF** and **H→γγ** rates are particularly interesting
  - Exploit differential distributions
    - E.g. Very low/high p_T(H) regime sensitive to physics in ggF loop
  - Search for rare processes: H→Zγ, μμ etc.

ggF:



H→γγ:





Eur. Phys. J. C 80 (2020) 942

Combined measurements of Higgs boson couplings

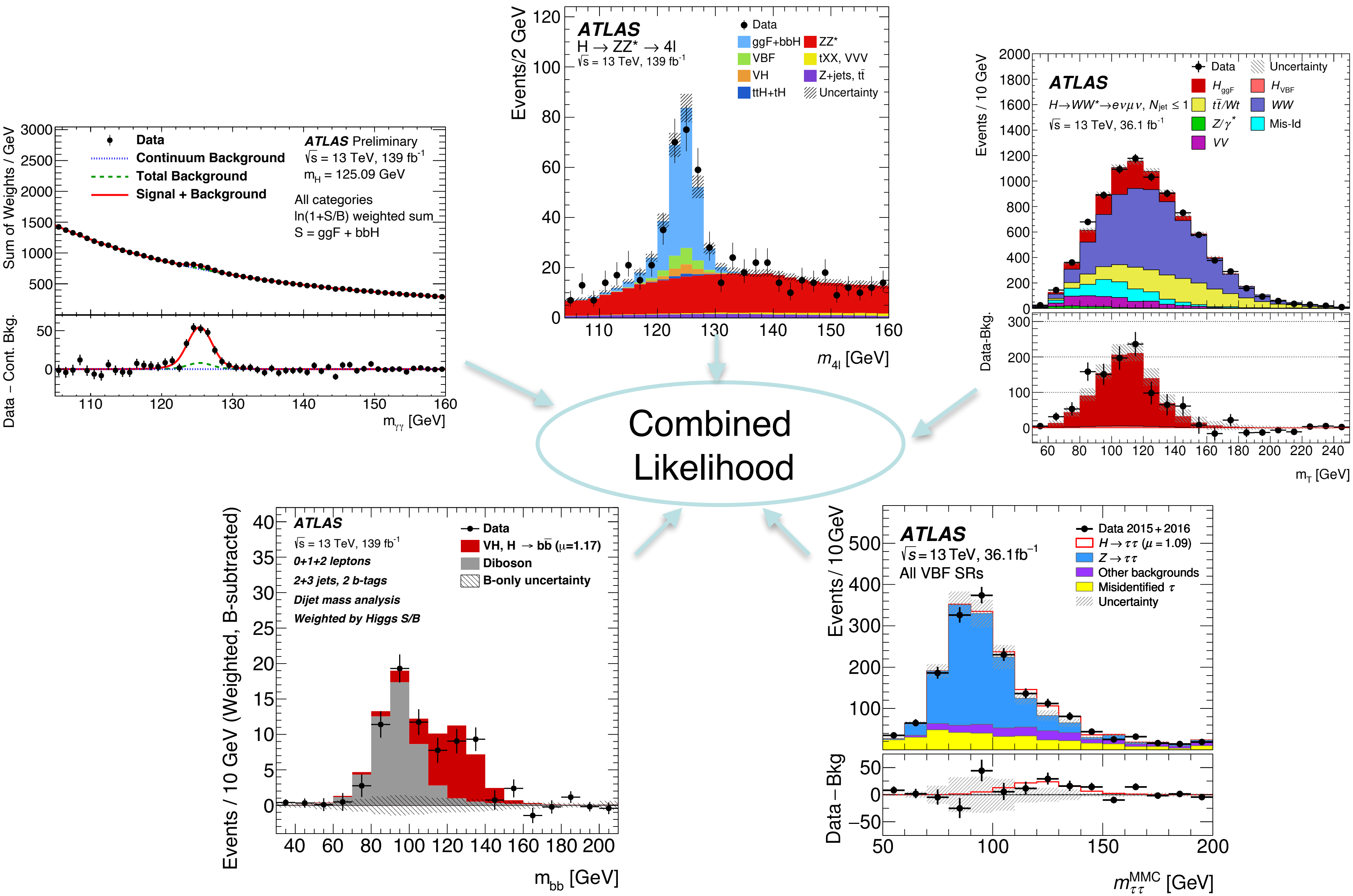
ATLAS-CONF-2020-027

With up to 139 fb^{-1} of 13 TeV data

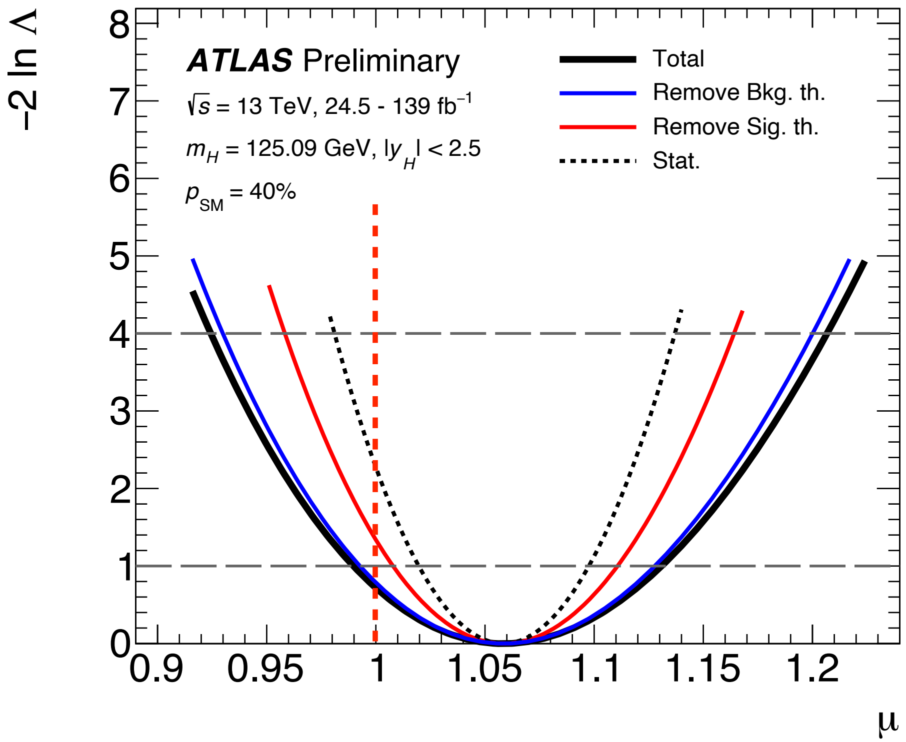
Channel	ggF	VBF	VH	ttH
$H \to \gamma\gamma$ (139 fb^{-1})	✔	✔	✔	✔
$H \to ZZ$ (139 fb^{-1})	✔	✔	✔	✔
$H \to WW$ (36 fb^{-1})	✔	✔	✔ (blue)	✔
$H \to \tau\tau$ (36 fb^{-1})	✔	✔	✔ (blue)	✔
$H \to bb$ (VH 139 fb^{-1}, others 36 fb^{-1})	✔ (blue)	✔	✔	✔
$H \to \mu\mu$ (139 fb^{-1})	✔	✔	✔	✔
$H \to$ inv. (139 fb^{-1})	✔ (blue)	✔	✔ (blue)	✔ (blue)

✔ (red): channel included in the combination
✔ (blue): channel available but not included in combination

How the combination is performed



Inclusive signal strength



Signal strength: **μ = N$_{signal}$(obs.)/N$_{signal}$(exp.)**

Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavor tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7

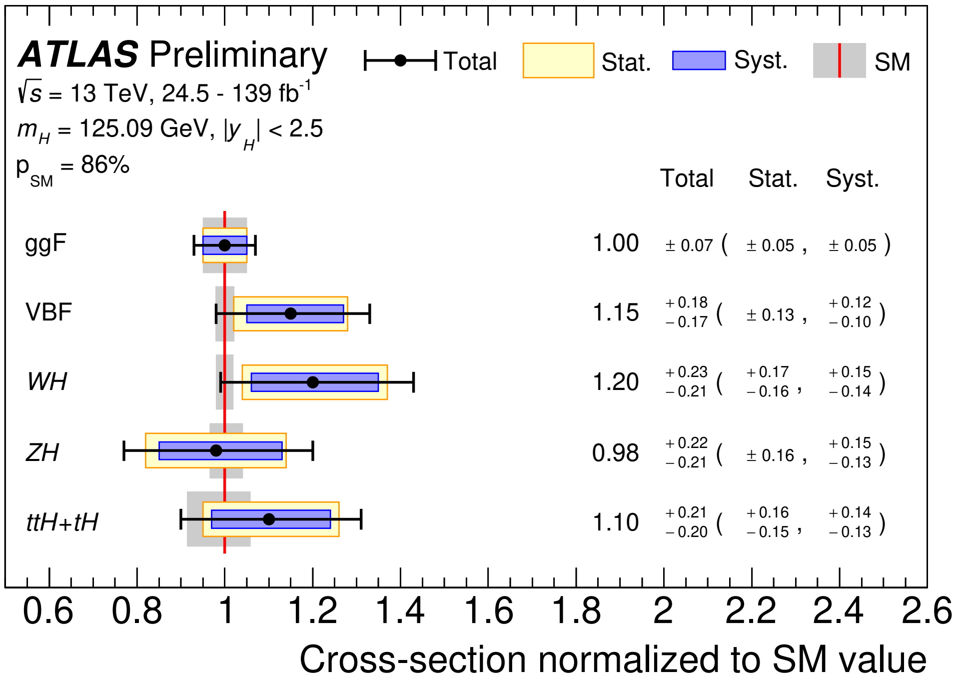
Overall cross-section uncertainty

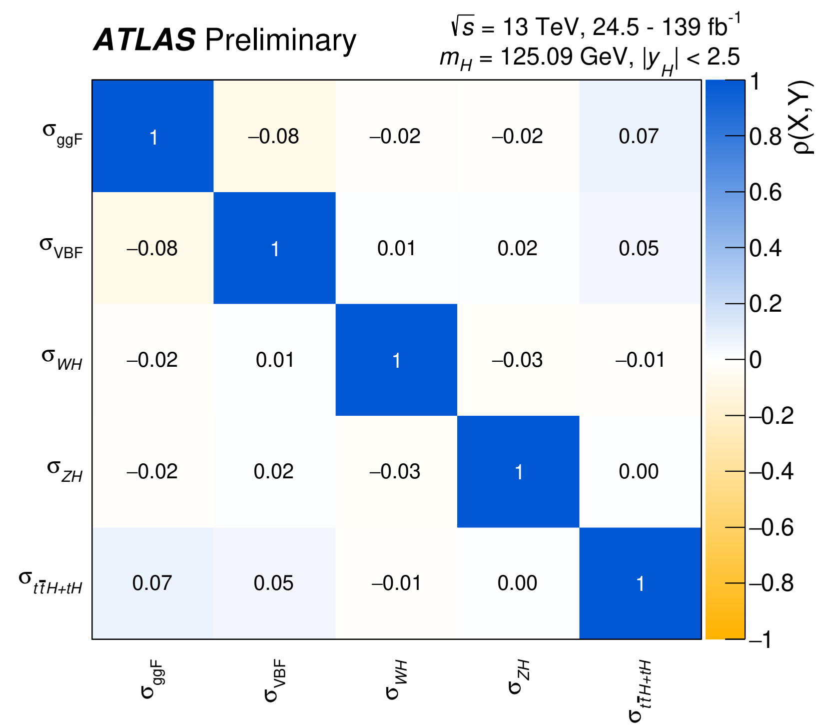
*All numbers are in percentage. Table is obsolete

$$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$$

- Reaching 8% precision. Good agreement with SM

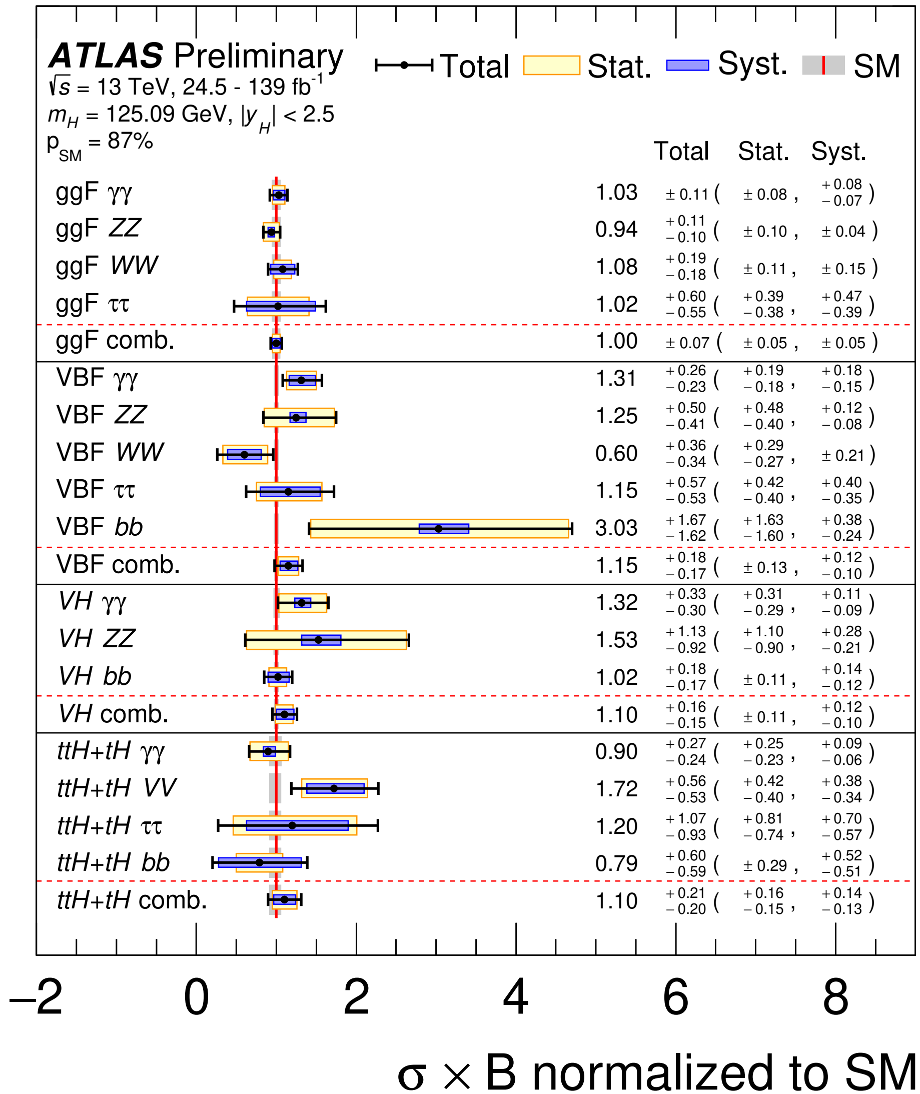
Production mode cross-sections (assuming the SM BRs)

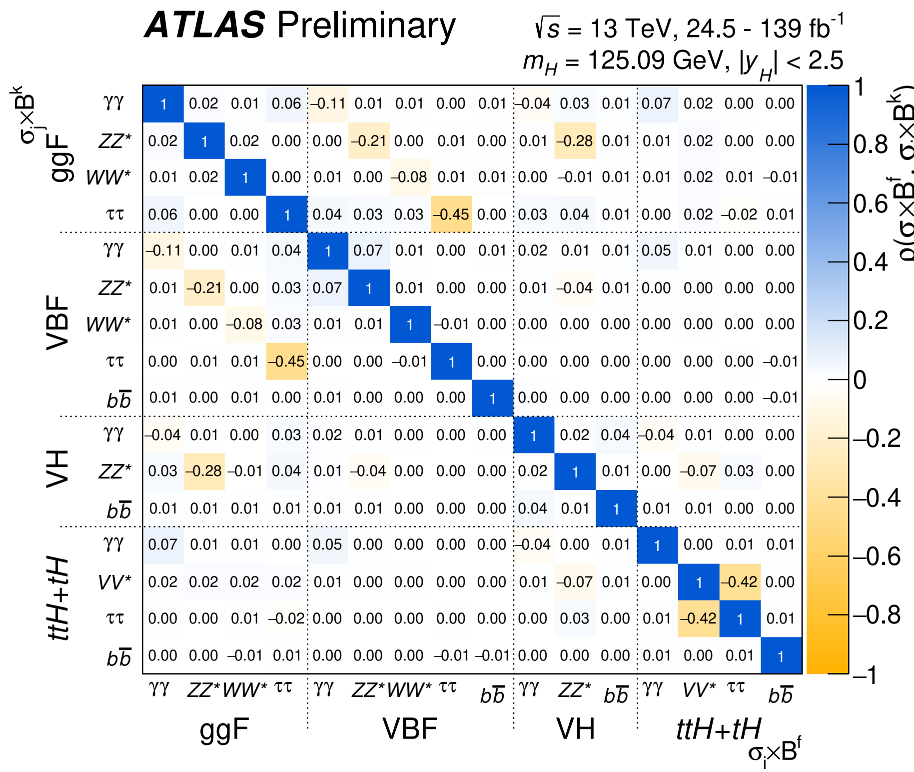




- **ggF cross-section measured with precision of 7%, close to 5% uncertainty on the N³LO cross section prediction**
- **All production modes observed with significance >5σ**
- Small correlations between different production modes

Production cross-section measured in each decay channel

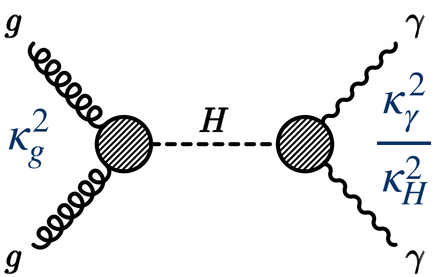




- Good compatibility among decay channels and also with the SM
- Results commonly used for theory interpretations

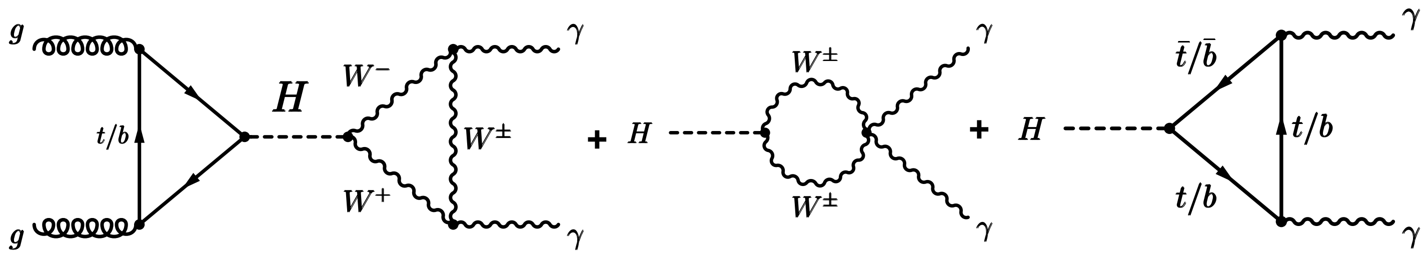
Interpretation using kappa framework

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_Z, κ_t…) and total width (κ_H)



$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2}$$

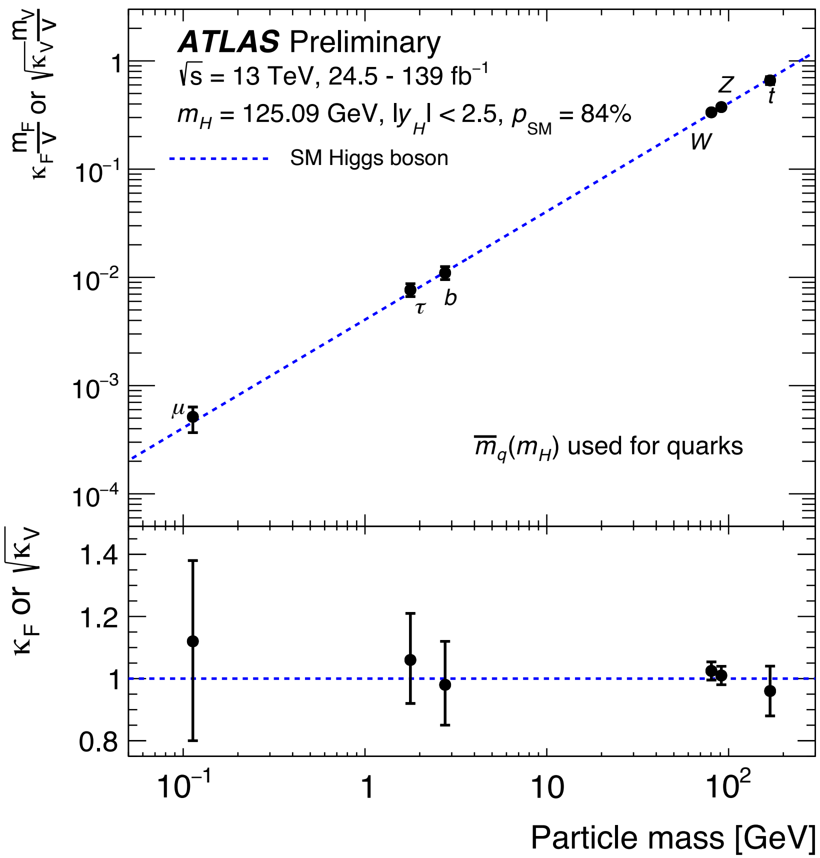
Assume only SM particles contribute

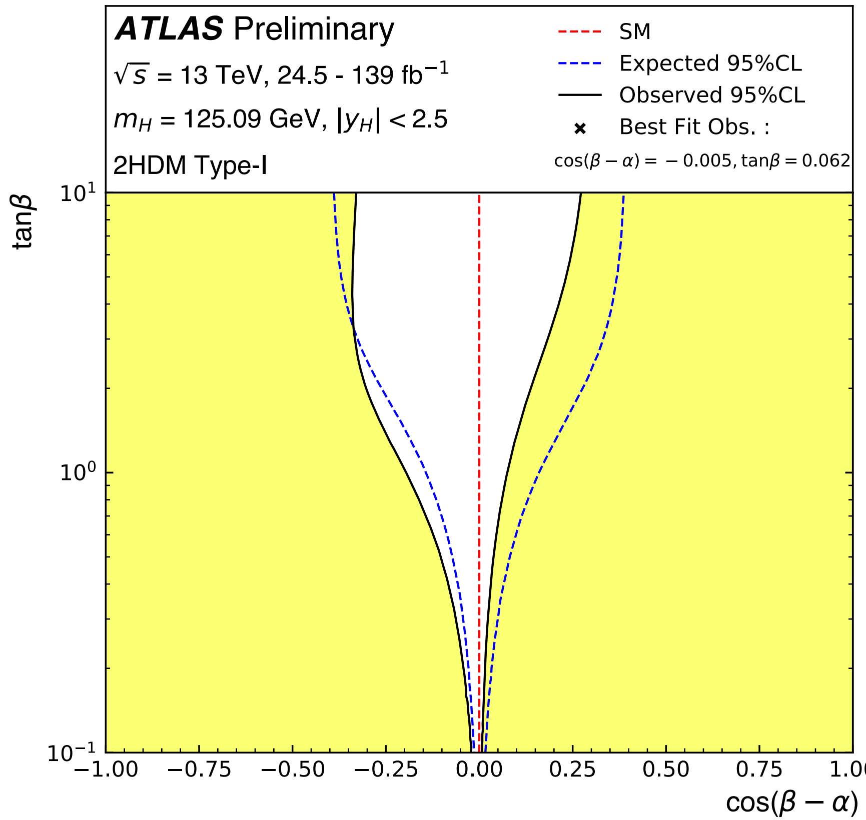


$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \underbrace{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b)}_{\kappa_g^2} \underbrace{\frac{1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_\tau, \ldots)}}_{\kappa_\gamma^2/\kappa_H^2}$$

Yellow Report 3

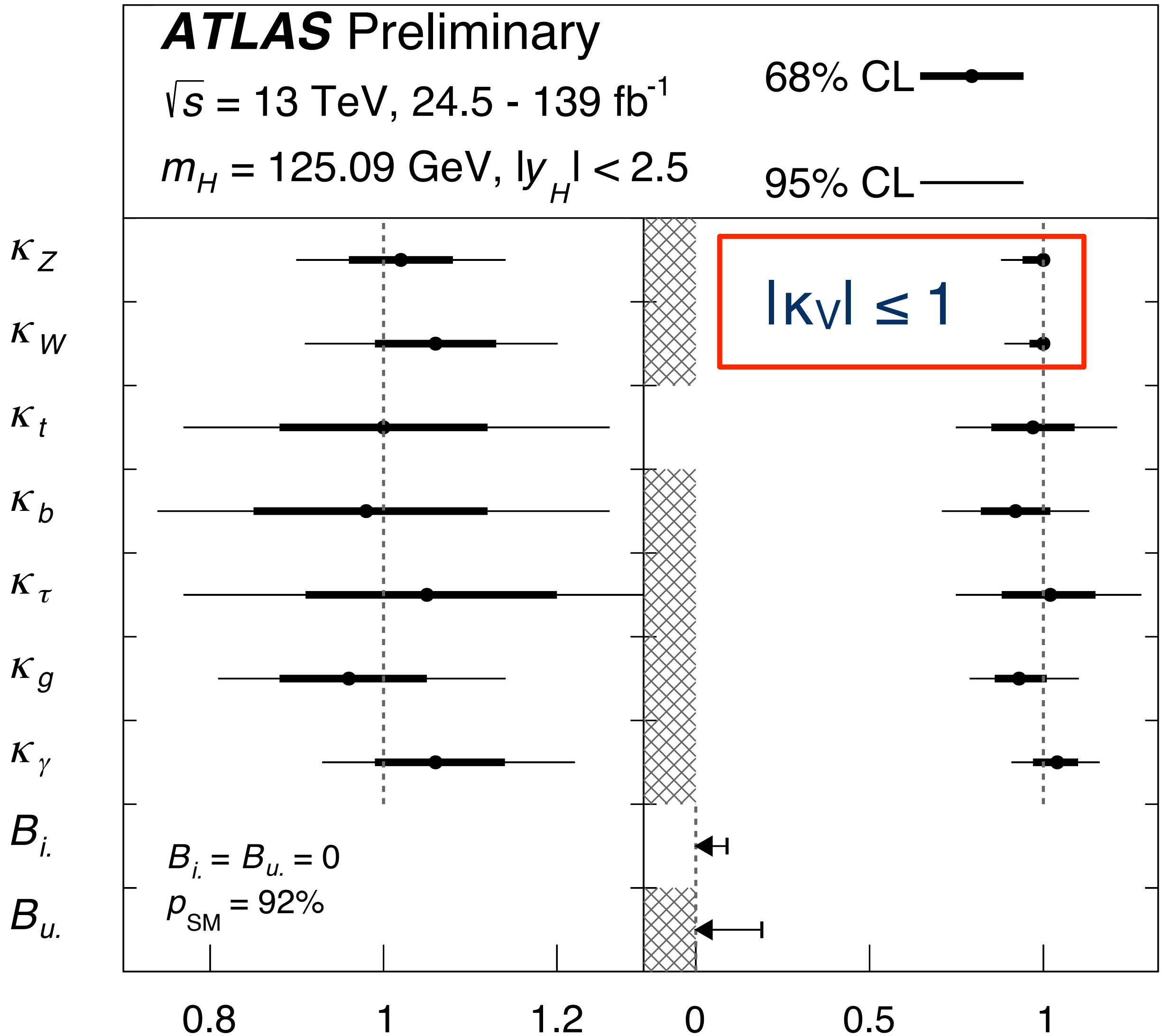
Coupling modifier vs. particle mass





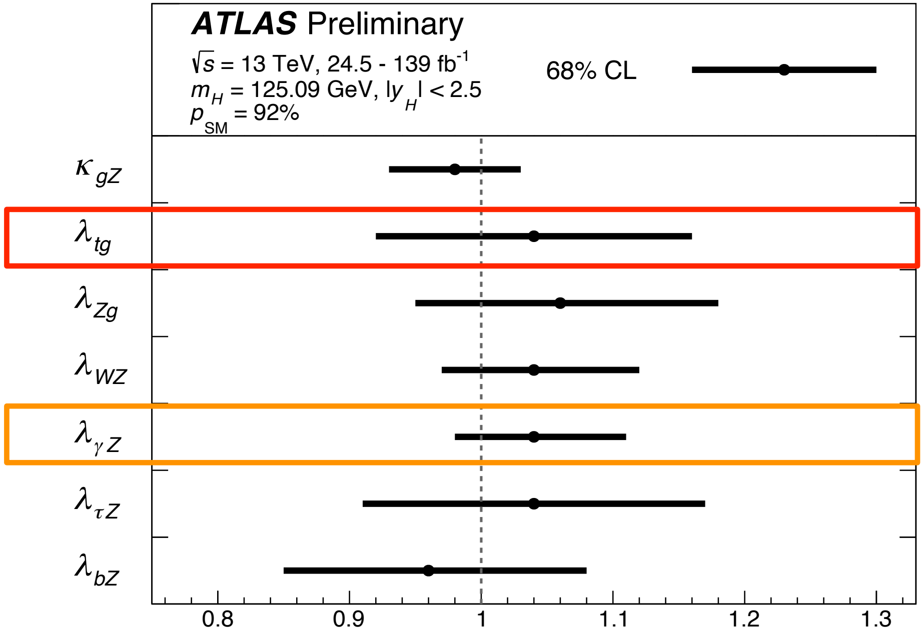
- **Good agreement with the SM within uncertainties across three orders of magnitude in particle mass!**
- Can be used to constrain Beyond SM (BSM) scenarios like Two-Higgs-doublet model

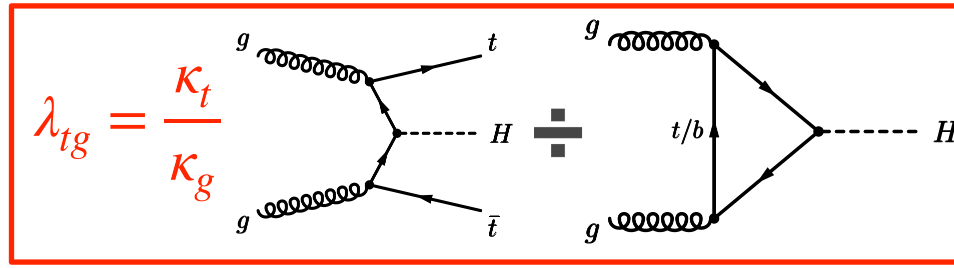
Generic model

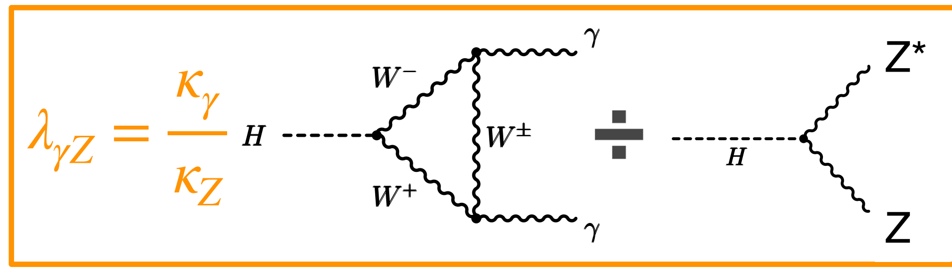


- LHC experiments do not have sensitivity to directly constrain Higgs boson total width
  - $\Gamma_{SM}(H)$ = 4 MeV. Far below detector resolution (~1 GeV)
- So we need additional assumptions to constrain undetected BR (= BSM final state + deviation in SM final state that is not included in combination, e.g. H→cc)

Ratios of coupling strength modifiers



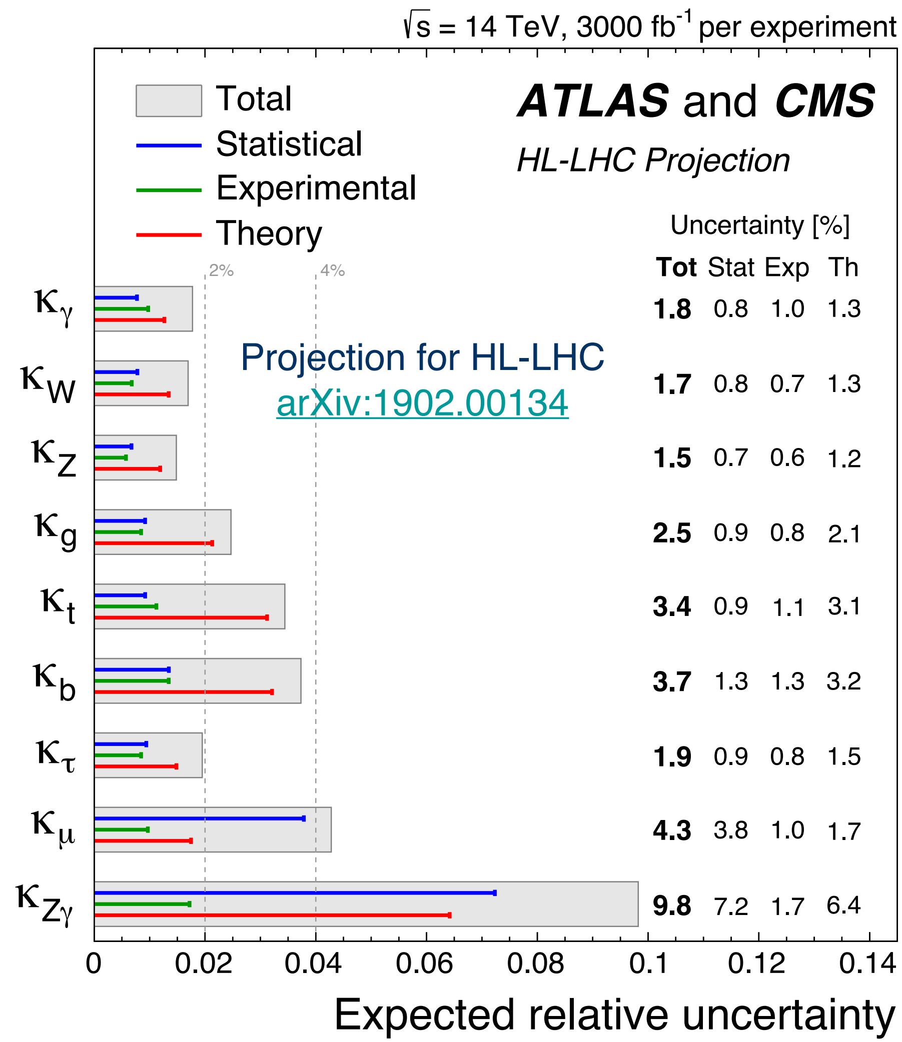




- Ratios are what we can measure best at LHC: less model assumptions; common systematic uncertainties cancel out
  - **λ_{tg}**: compare the direct determination of the top coupling through ttH production (κ_t) to the indirect determination in the ggF loop (κ_g)
  - **$\lambda_{\gamma Z}$**: probe new physics in $H\to\gamma\gamma$ process by comparing with $H\to ZZ$

Limitation of kappa framework

- Kappa framework is intrinsically LO, designed to probe deviations
  - Higher order QCD/EW corrections only valid at SM
  - If a deviation is established, the framework cannot be used for interpretations
- Kappa interpretation is based on inclusive production and decay rates. It is blind to tension in diff. distributions

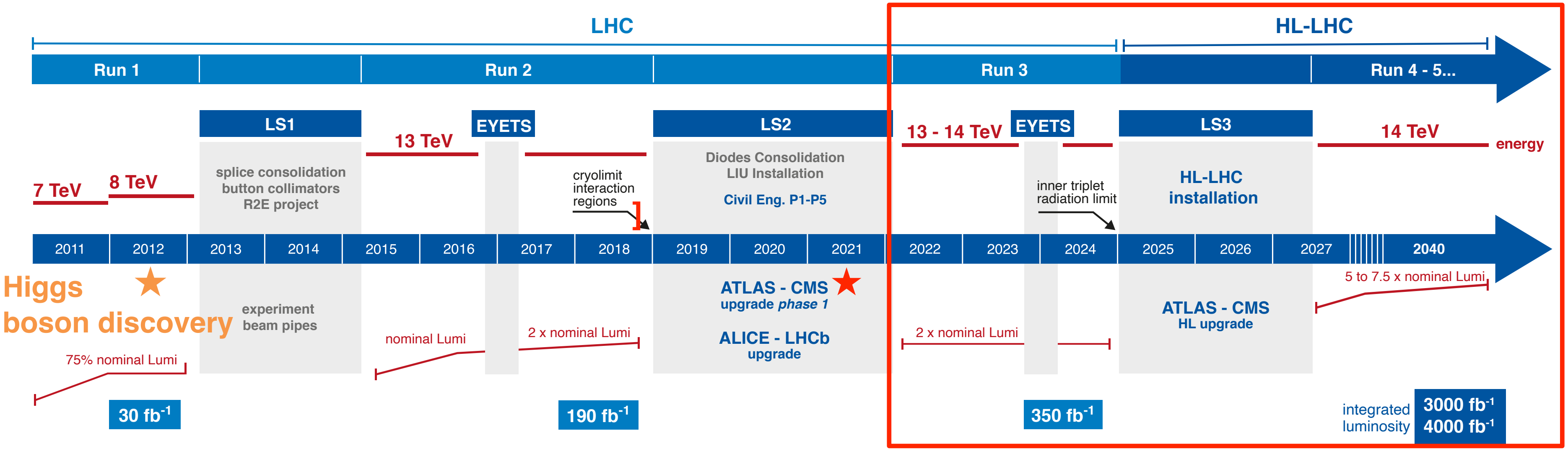


Projection for HL-LHC
arXiv:1902.00134

Current dataset only 5% of expected LHC total!

A better option: EFT

- Direct discovery usually enabled by boost of center-of-mass energy
  - (HL-)LHC's center-of-mass energy will not increase dramatically from now on
- On the other hand, much higher data statistics will be available → measurements will reach very high precision
  - **The hint of new physics is likely to show up as deviations from SM in the future precision measurements**
  - EFT framework is ideal to interpret such deviations

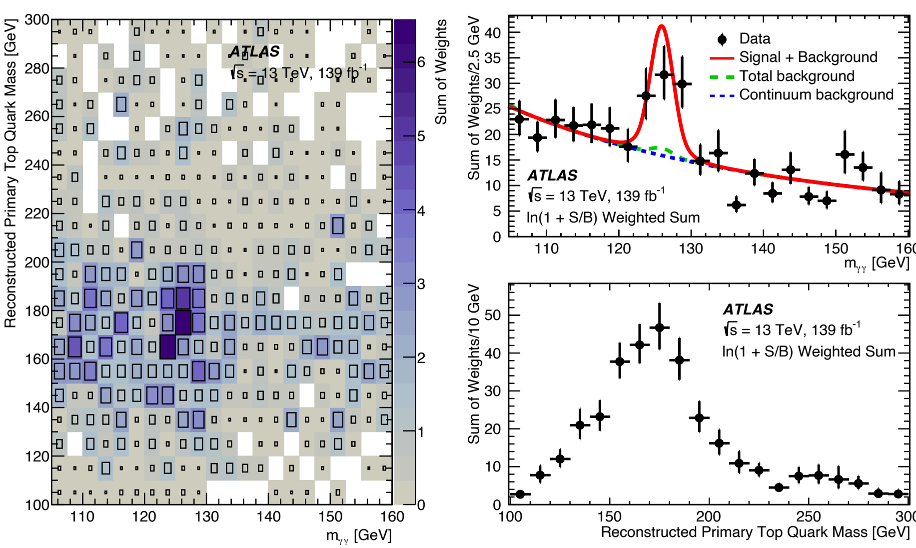


Options to apply EFT framework on data

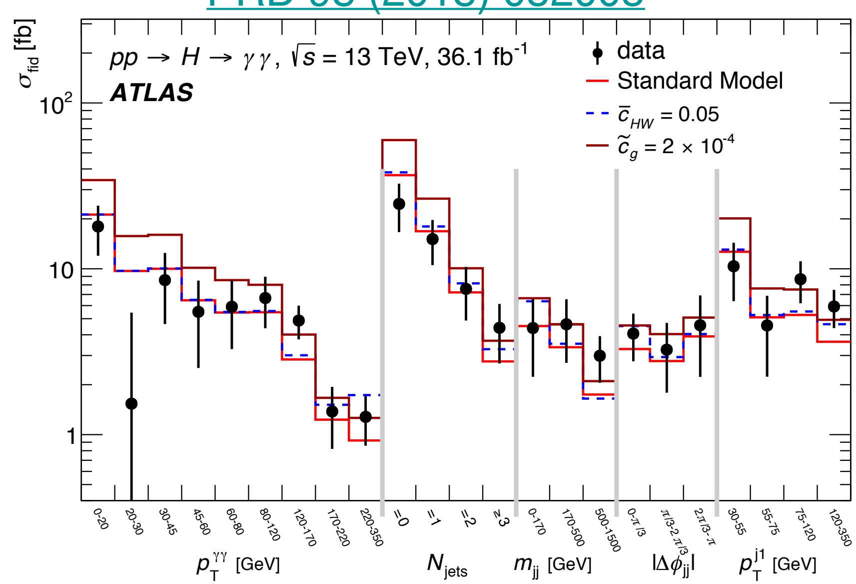
- Build dedicated analysis optimized to probe one property (e.g. CP mixing angle)
  - Optimal sensitivity, but also very model dependent
  - Not for generic interpretations

- Use fiducial differential cross-section measurements
  - No restriction on interpretations
  - Cannot easily combine multiple decay channels, or multiple distributions within a channel

PRL 125 (2020) 061802

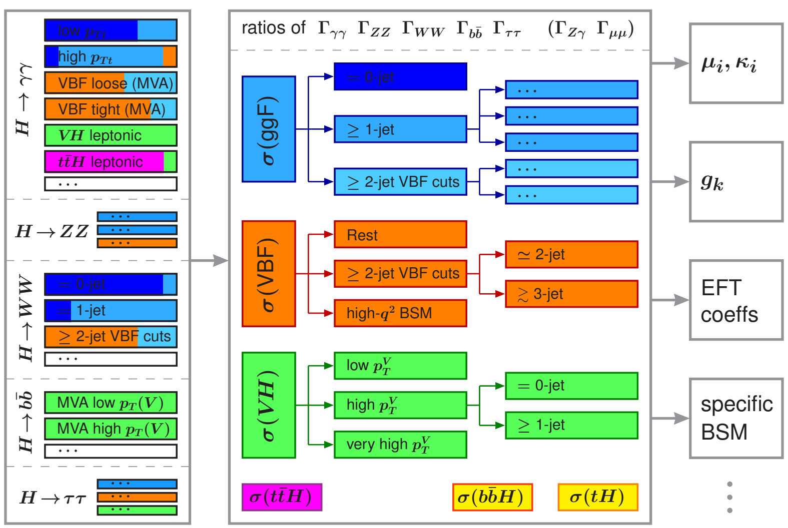


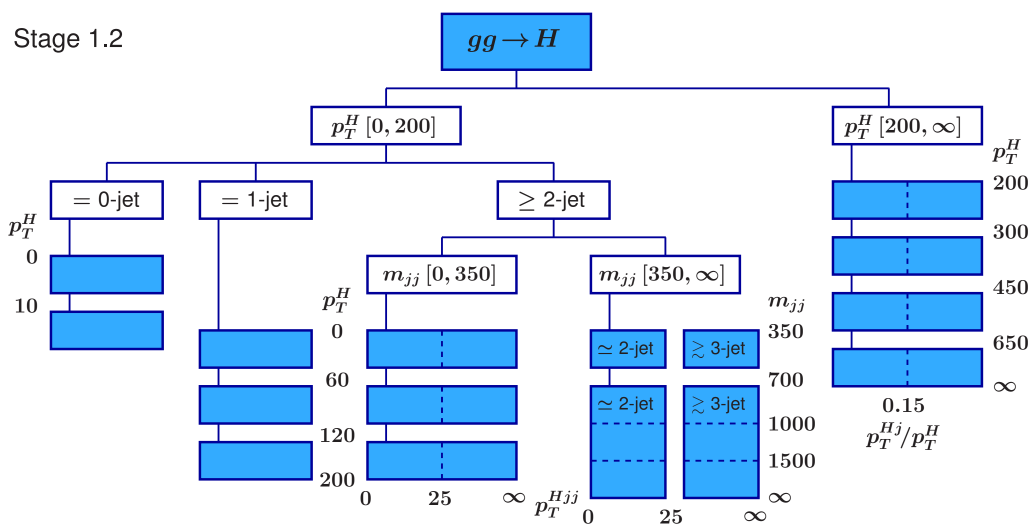
PRD 98 (2018) 052005



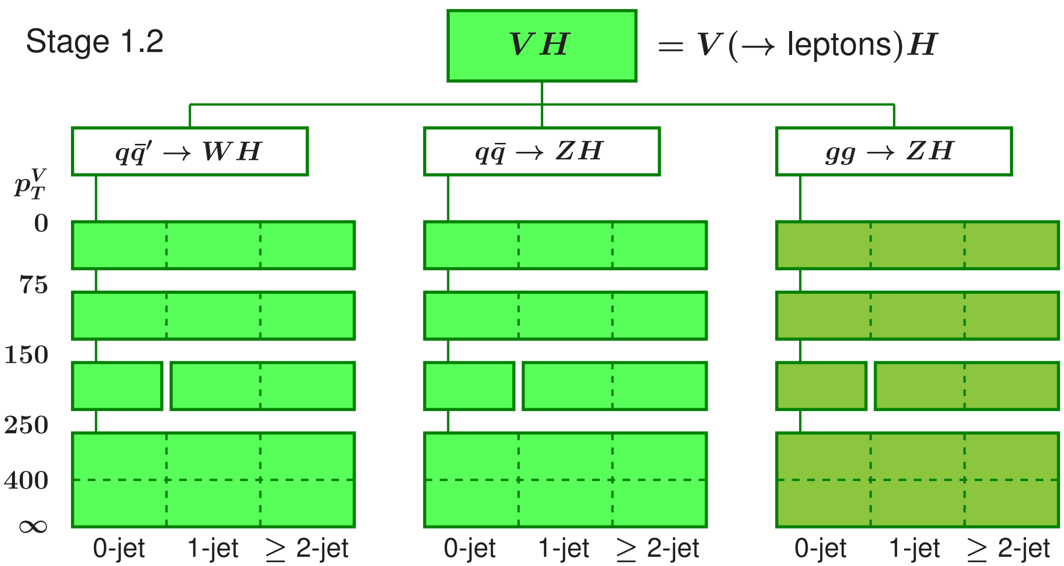
STXS framework

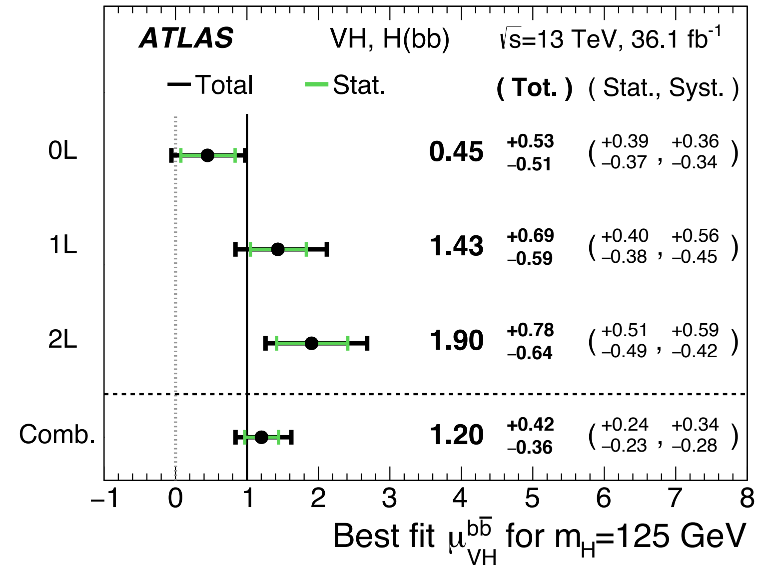
- **Simplified template cross-section (STXS) framework:** measure cross-section per production mode in different phase-space regions
  - Decay is inclusive so far. No kinematic bins introduced yet
- STXS is ideal for EFT interpretation
  - Provide differential cross-section measurements while allow experimentalists to apply aggressive analysis techniques
  - Easy to combine multiple production & decay channels





STXS bins for V(lep)H

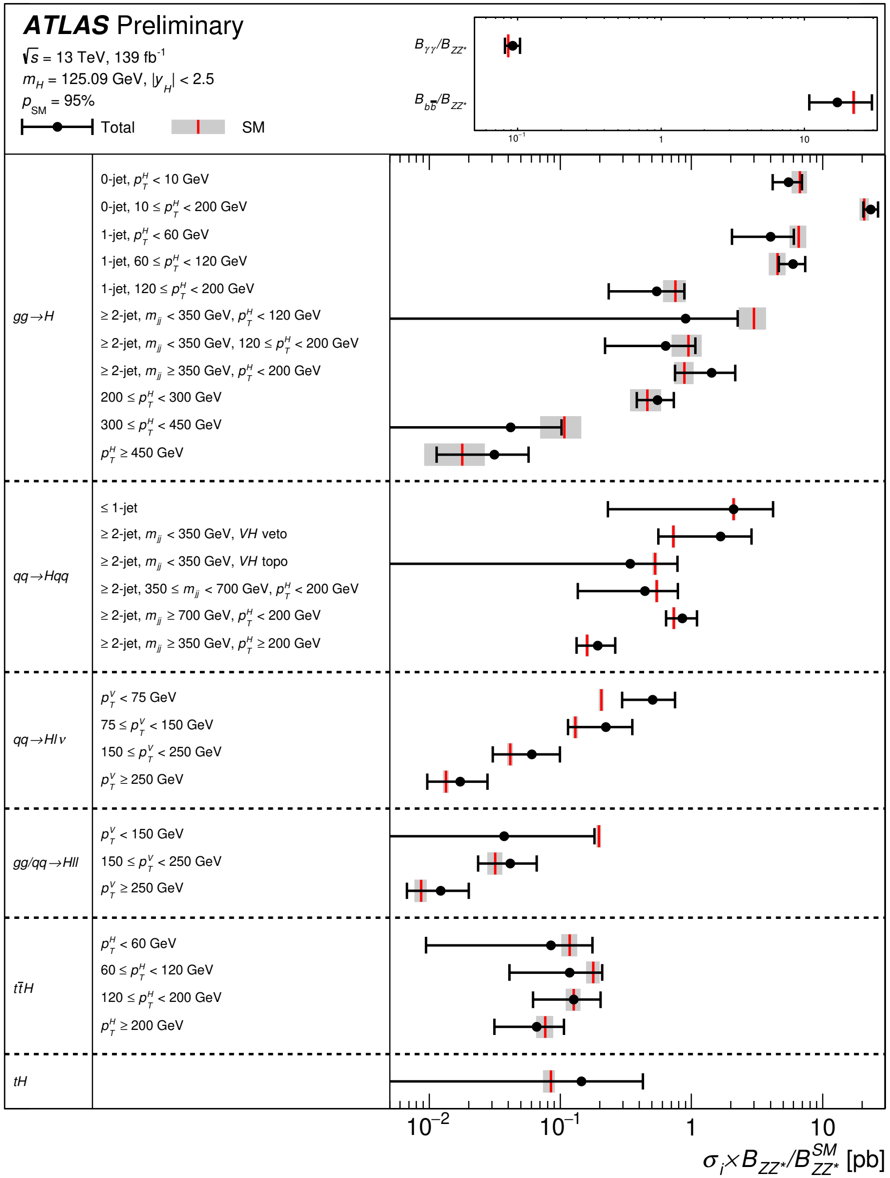


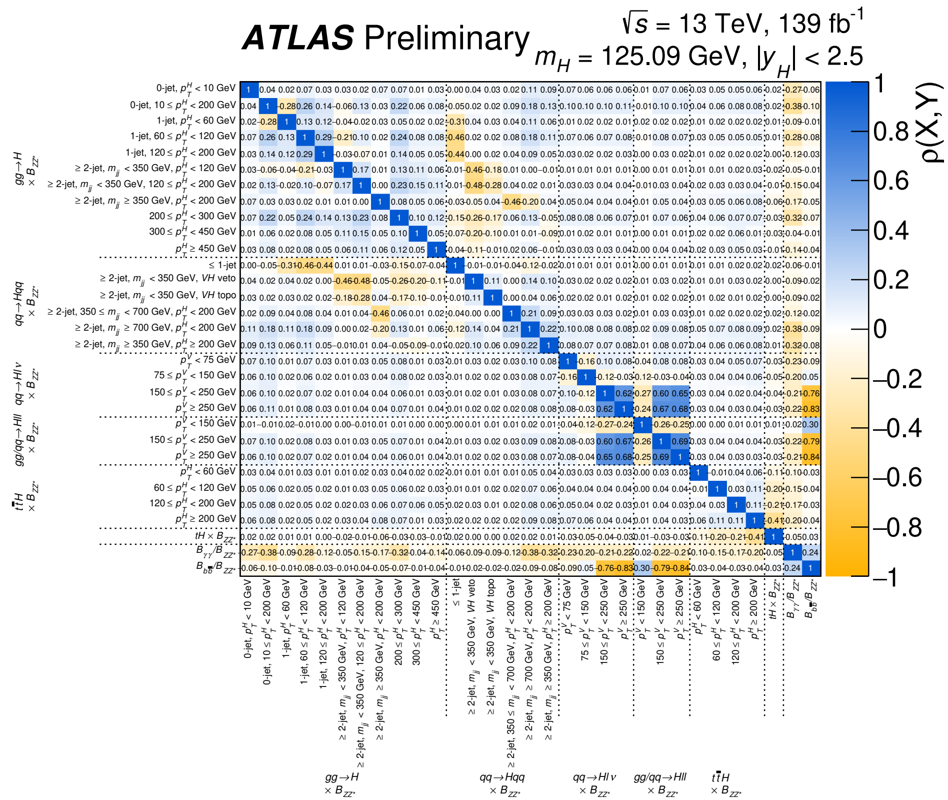


JHEP 12 (2017) 024

- STXS framework is designed to find balance between experimental and theory demand
- Definition of V(lep)H STXS bins is driven by selection used in V(lep)H, H→bb analyses
  - Separate different N(lepton) and N(jet) regions
  - Categorize analysis using vector boson p_T

STXS measurements





- Including H→γγ, H→ZZ, and H→bb
- Ratio of branching ratio is a free parameter determined by data

EFT interpretation of STXS measurements

ATLAS-CONF-2020-053

SMEFT framework

- Use SMEFT framework (Warsaw basis), consider only dimension 6 (d6) and d8 operators

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

- **Leading order ($1/\Lambda^2$)**: inference between SM and d6 EFT
- **Next leading order ($1/\Lambda^4$)**: pure d6 EFT + interference between SM and d8 EFT
  - Calculation involving d8 operators is not available yet, so only pure d6 operator contribution will be considered

EFT parameterization of STXS production x-section

- Production cross-section in any STXS bin can be written as

$$\sigma_{STXS} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM} = \sigma_{SM}(1 + \frac{\sigma_{int}}{\sigma_{SM}} + \frac{\sigma_{BSM}}{\sigma_{SM}})$$

  - Here σ_{int} is the interference between SM and d6 EFT ($1/\Lambda^2$), and σ_{BSM} is pure d6 EFT contribution ($1/\Lambda^4$)
  - σ_{SM} in the front will be replaced by state-of-art calculation
  - Ratios such as σ_{int}/σ_{SM} will be replaced by parameterization derived from UFO model with MG_aMC
    - σ_{int}/σ_{SM} will be a linear function of Wilson coefficient c_i
    - σ_{BSM}/σ_{SM} will be a 2nd order polynomial of c_i

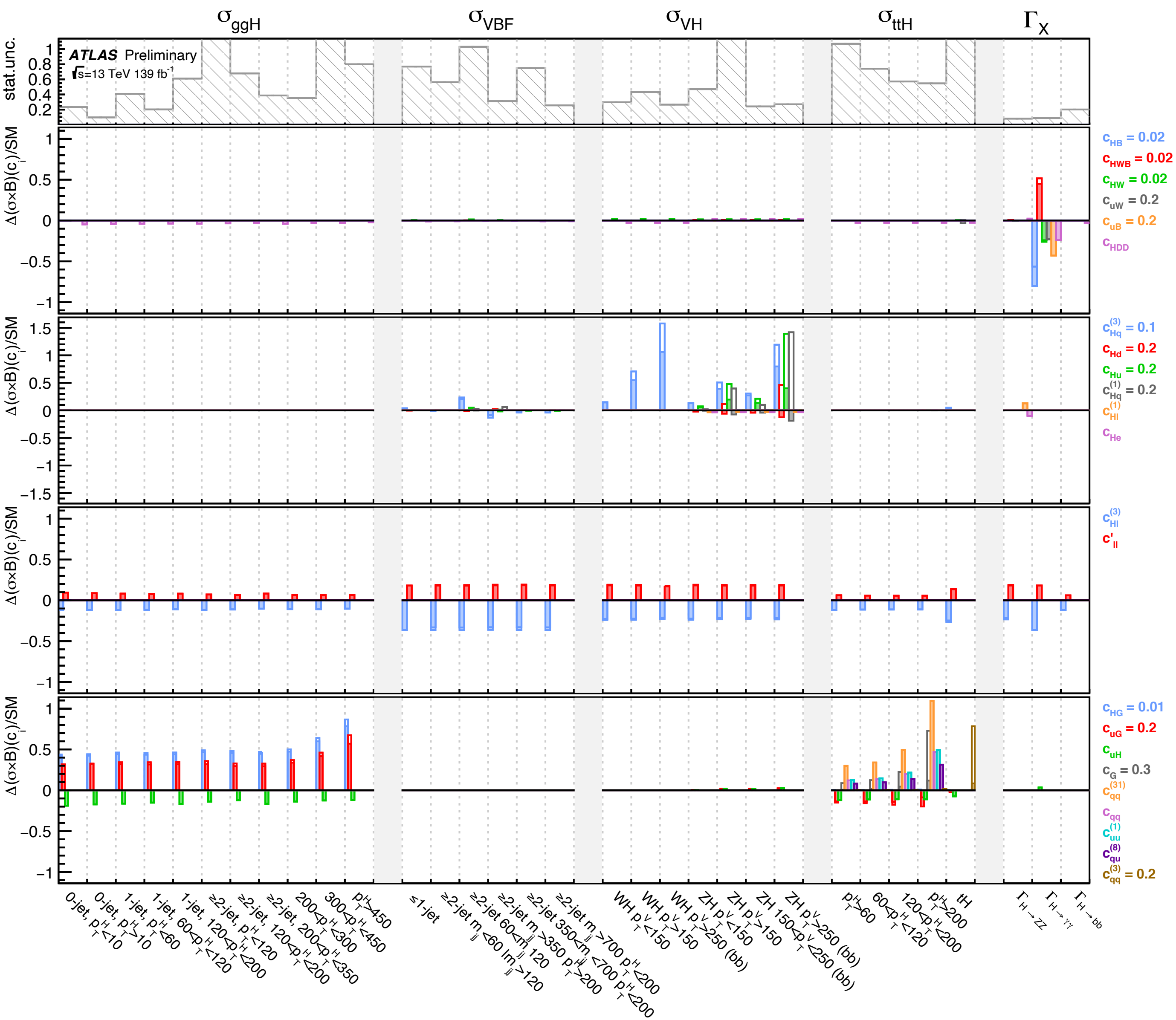
Parameterization of decay

- Use narrow-width approximation, production and decay of Higgs boson can be factorized

$$(\sigma \times B)^{i,H\to X} = (\sigma \times B)^{i,H\to X}_{SM}\left(1 + \frac{\sigma^i_{int}}{\sigma^i_{SM}} + \ldots\right)\frac{\left(1 + \frac{\Gamma^{H\to X}_{int}}{\Gamma^{H\to X}_{SM}} + \ldots\right)}{\left(1 + \frac{\Gamma^{H}_{int}}{\Gamma^{H}_{SM}} + \ldots\right)}$$

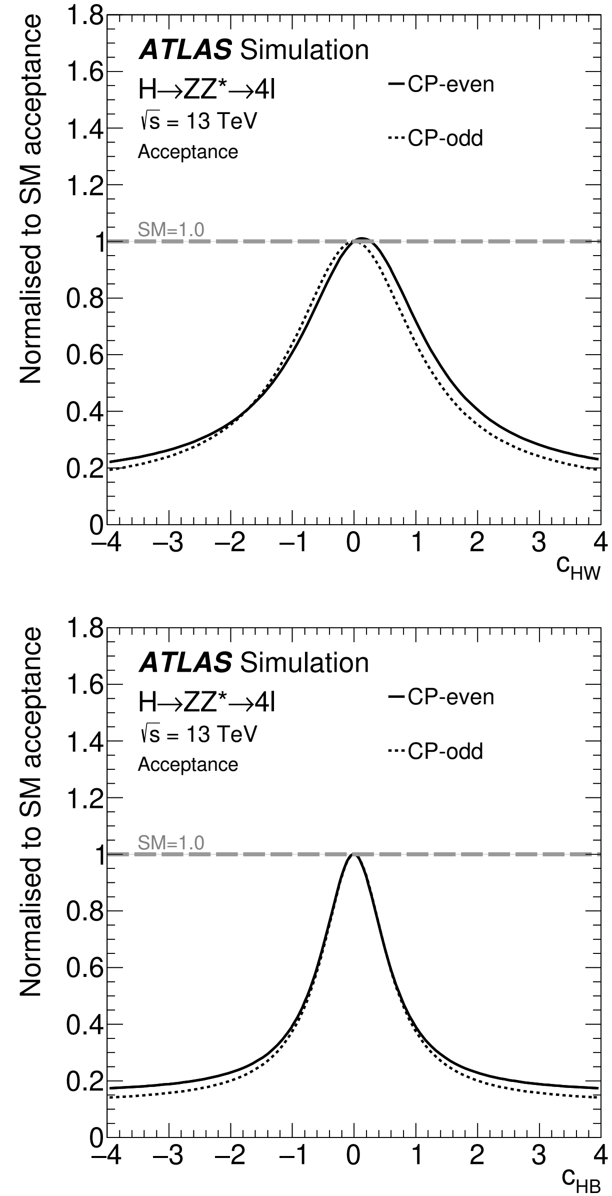
- Again the ratios can be expressed as 1st (interference) or 2nd (BSM) order polynomial of Wilson coefficients
- Two interpretation scenarios
  - **Linear**: only contains 1st order Wilson coefficients
  - (Linear +)**Quadratic**: also contains 2nd order terms to estimate the potential effect from higher order (incomplete)

Linear (solid) vs. linear+quadratic (hollow)



Acceptance effect

- One nice and also tricky thing about EFT is that it modifies event topo. and kinematics
- **Production**: (partially) handled by phase-space partitions in STXS framework
  - Analyses selections are usually aligned with STXS bin definitions
  - Acceptance effect within each STXS bin is neglected (can be amended with further splitting in the future)
- **Decay**: non-trivial effect channels such as H→ZZ. Needs to take into account if possible
  - Plan to introduce STXS bins to decay



Handle large autocorrelations in EFT

- Another nice and also tricky thing about EFT is that there is in general no one-to-one matching between operators and physics processes: large entanglement among operators
  - In addition, STXS measurements usually contain non-trivial autocorrelations
- As a result, if we measure Wilson coefficients as in Warsaw basis, there will be **large correlations**
  - Need to figure out "flat directions" that data cannot constrain: convert **Warsaw basis** into "**fit basis**"

How to get fit basis

ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1}

#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{ll}	c_{HG}	c_{uG}	c_G
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03	
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02			
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08	
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04	
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05

#	λ	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_W	c_{eH}
1	299310														-0.02	
2	121830															
3	1960															
4	38								0.02				0.03			
5	19	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10			0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3								0.06				0.06	-0.11	-0.01	
10	0.16				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

- Use linear model. Calculate eigenvectors and eigenvalues of hesse matrix (=1/Covar) from fitting to data
- Focus on eigenvectors with eigenvalue > 0.01

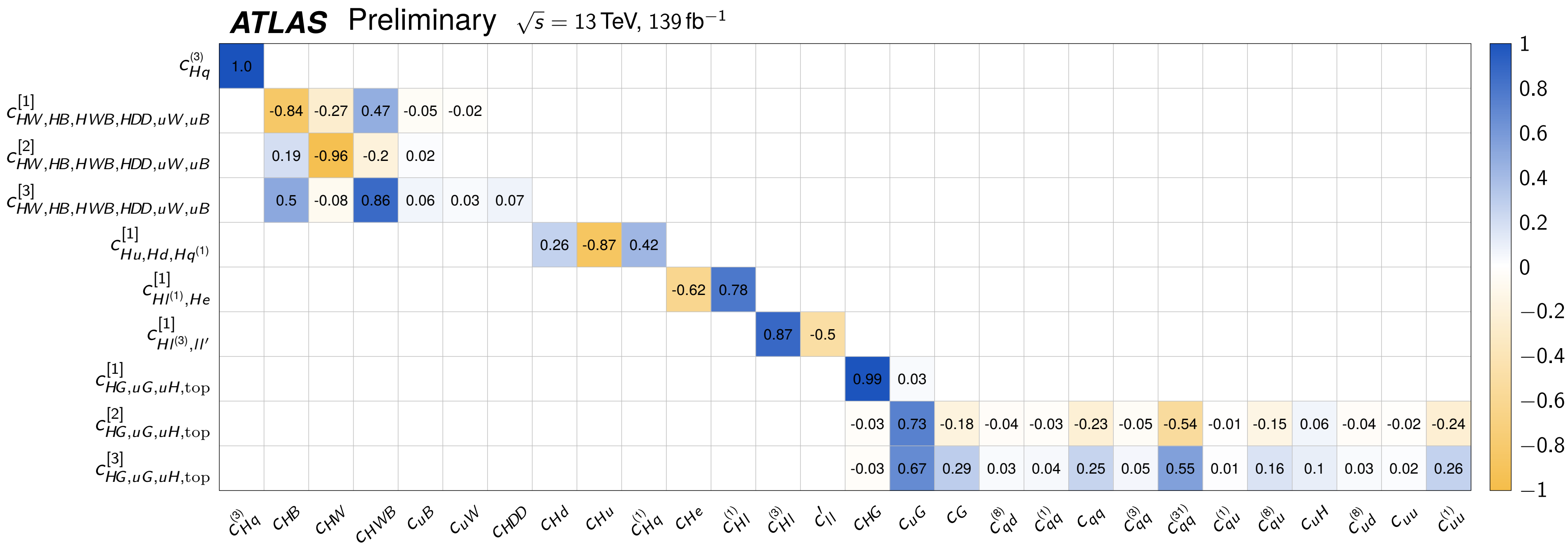
How to get fit basis (cont'd)

ATLAS Preliminary $\sqrt{s}$ =13 TeV, 139 fb^{-1}

#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c'_{ll}	c_{HG}	c_{uG}	c_G	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_W	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03																
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02																		
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08									0.02				0.03			
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

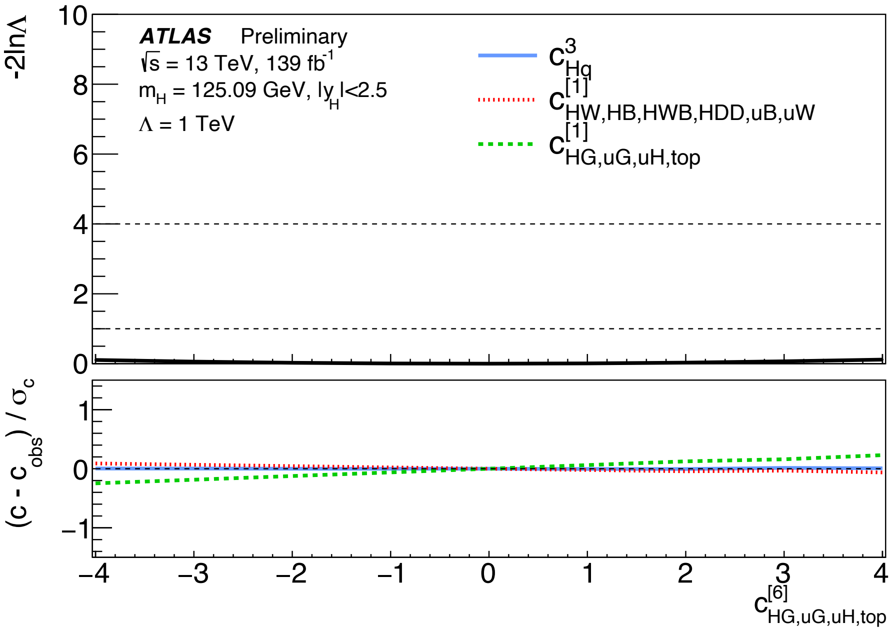
- Fix coefficients that only scale the overall normalization ($c_{H\Box}$, c_{dH}, c_{eH}) to zero (degenerate with other coefficients)
- Regroup remaining parameters with physics judgement, and re-diagonalize within each group

Final “fit basis” choice

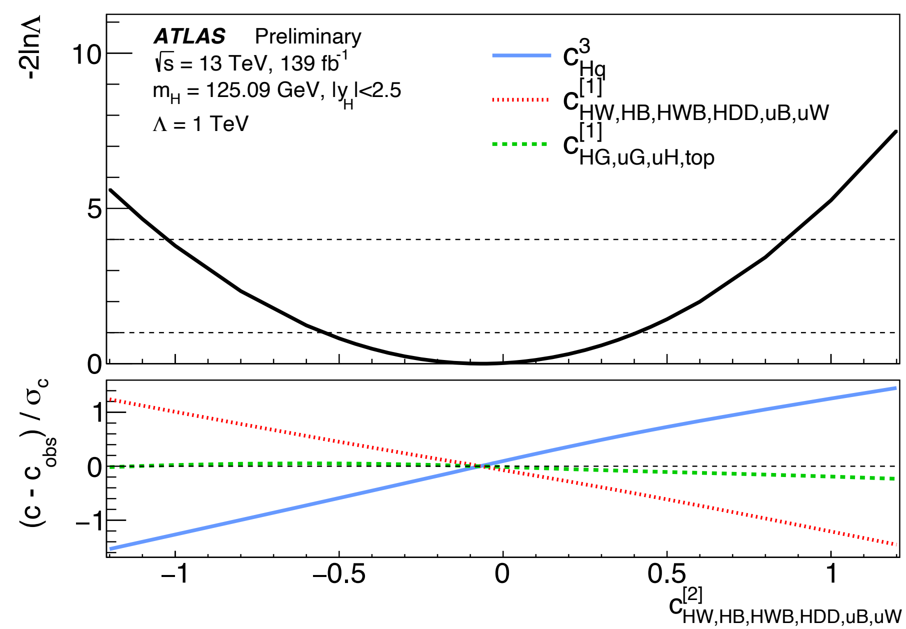


$$
\begin{aligned}
\{c_i\} \quad = \quad & \{c_{Hq}^{(3)}\} \times \\
& \{c_{HG}, c_{uG}, c_{uH}, c_{qq}^{(1)}, c_{qq}, c_{qq}^{(3)}, c_{qq}^{(31)}, c_{uu}, c_{uu}^{(1)}, c_{ud}^{(8)}, c_{qu}^{(1)}, c_{qu}^{(8)}, c_{qd}^{(8)}, c_G\} \times \\
& \{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB}, \} \times \\
& \{c_{Hl}^{(1)}, c_{He}\} \times \\
& \{c_{Hl}^{(3)}, c'_{ll}\} \times \\
& \{c_{Hu}, c_{Hd}, c_{Hq}^{(1)}\}.
\end{aligned}
$$

Identify flat directions



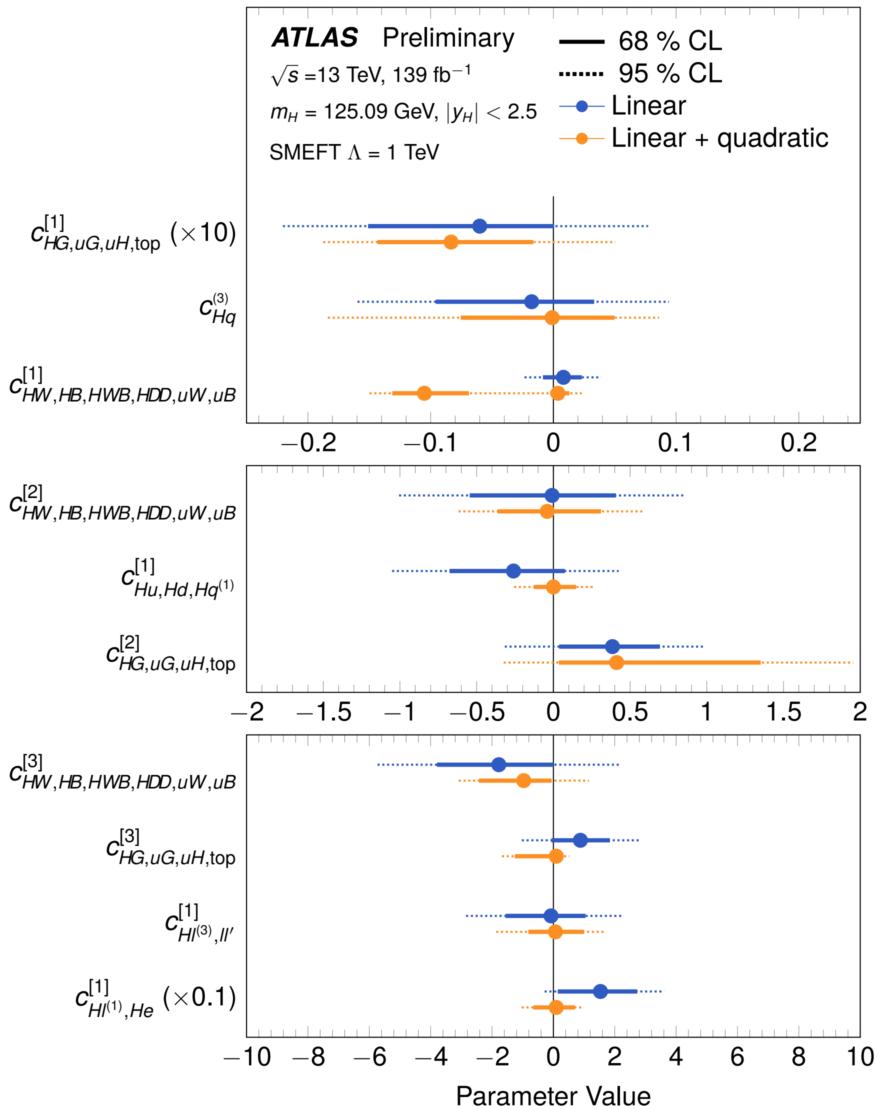
✗ A flat direction: fixed to 0

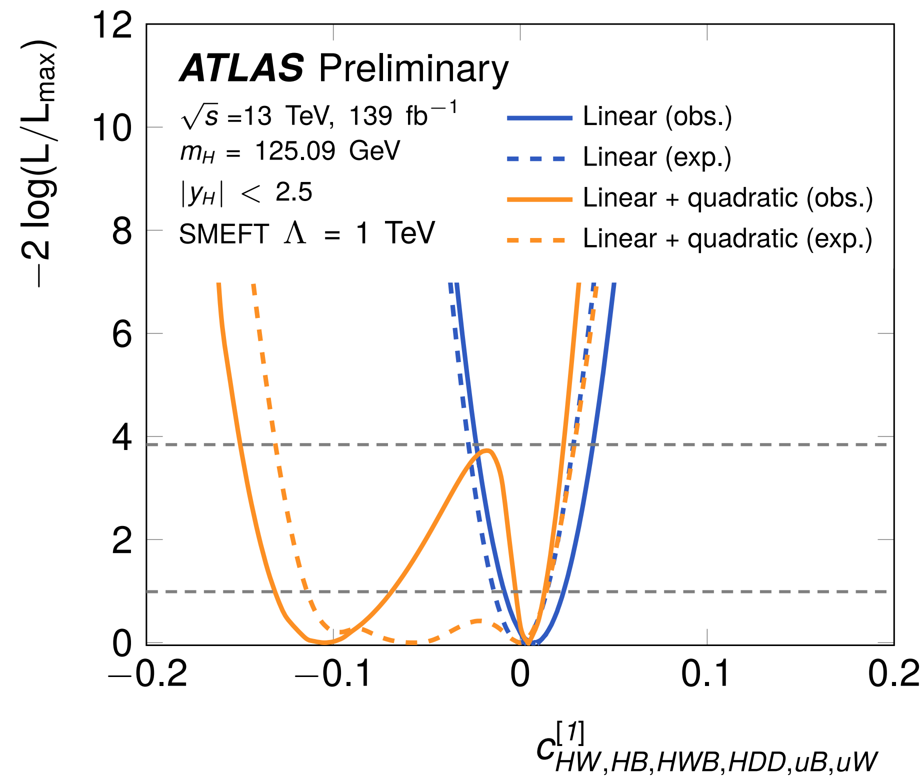


✓ A well-constrained eigenvector

- After transforming Wilson coefficients into fit basis, identify flat directions and fix them to 0 in the fit
- We are finally ready for getting the results!

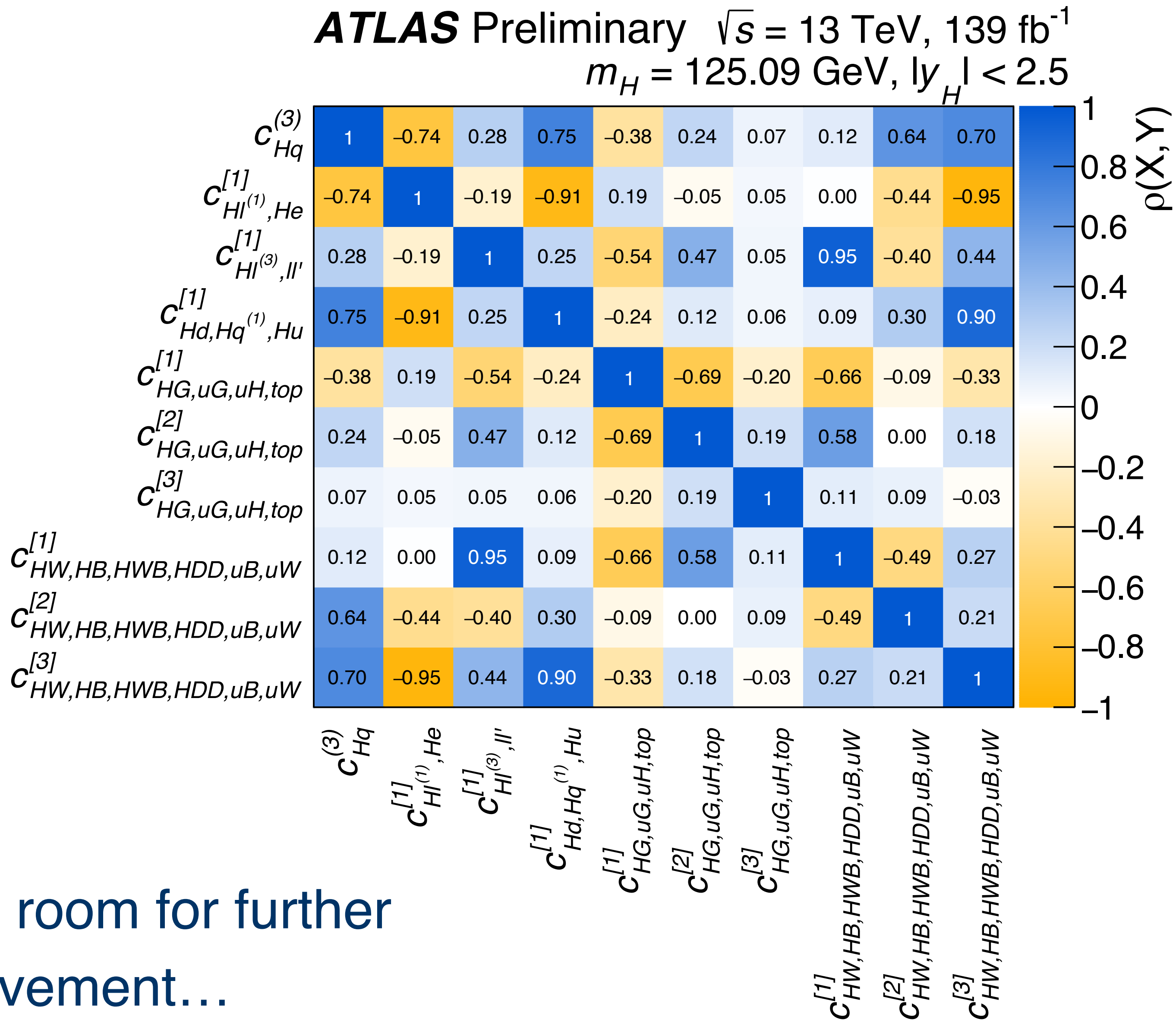
Constraints of Wilson coefficients





- Impact from quadratic terms not small, resulting in tighter constraint in most cases

Correlation matrix



- Large room for further improvement…

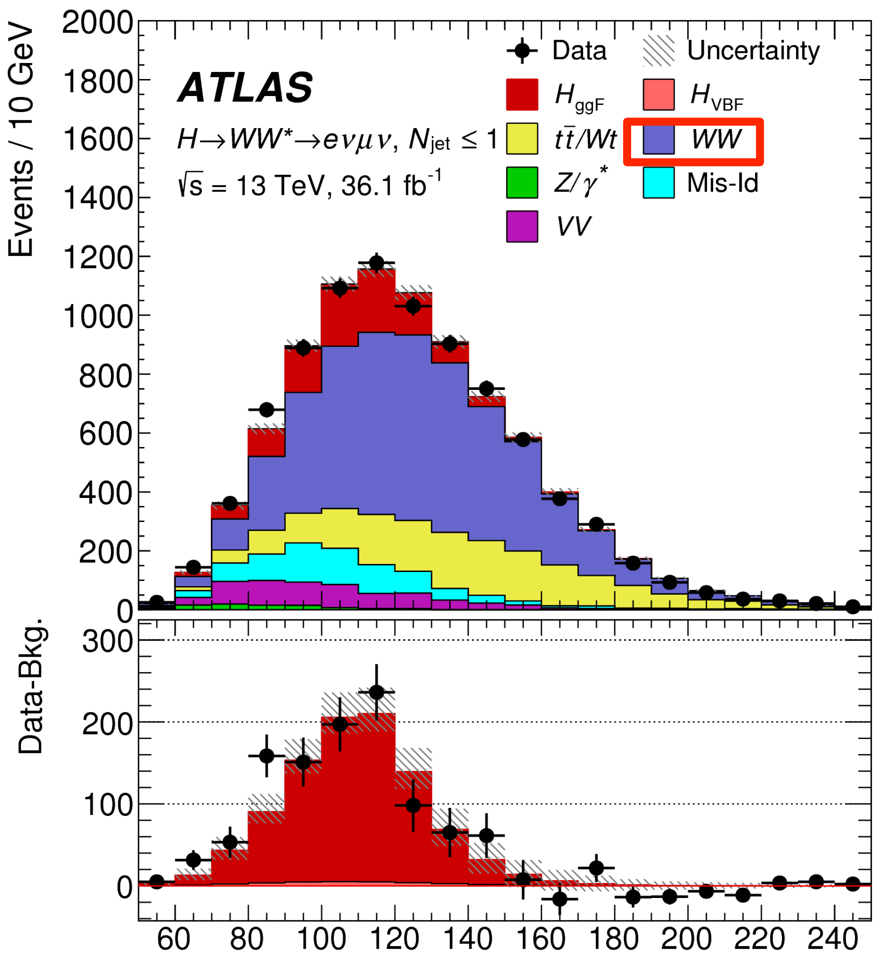
Towards the grand EFT combination

ATL-PHYS-PUB-2021-010

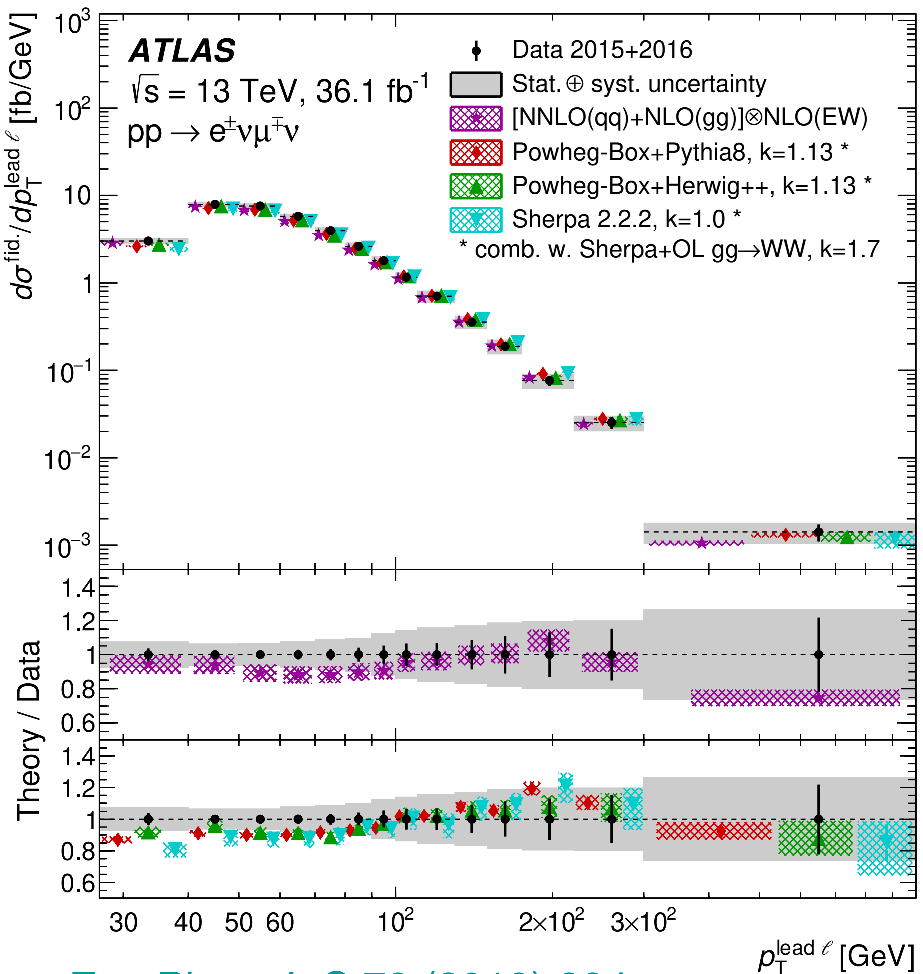
Everything can be signal

- So far we have only exercised EFT on Higgs boson production and decay measurements
  - In fact, the EFT operators modify not only Higgs, but also other SM processes measured at LHC
- The ultimate goal is to have **a grand EFT combination** including all relevant measurements
  - Very ambitious goal. Possibly a logistic nightmare
  - Study feasibility by combining two closely related processes: $H \to WW$ and SM WW

Inputs



[Phys. Lett. B 789 (2019) 508]



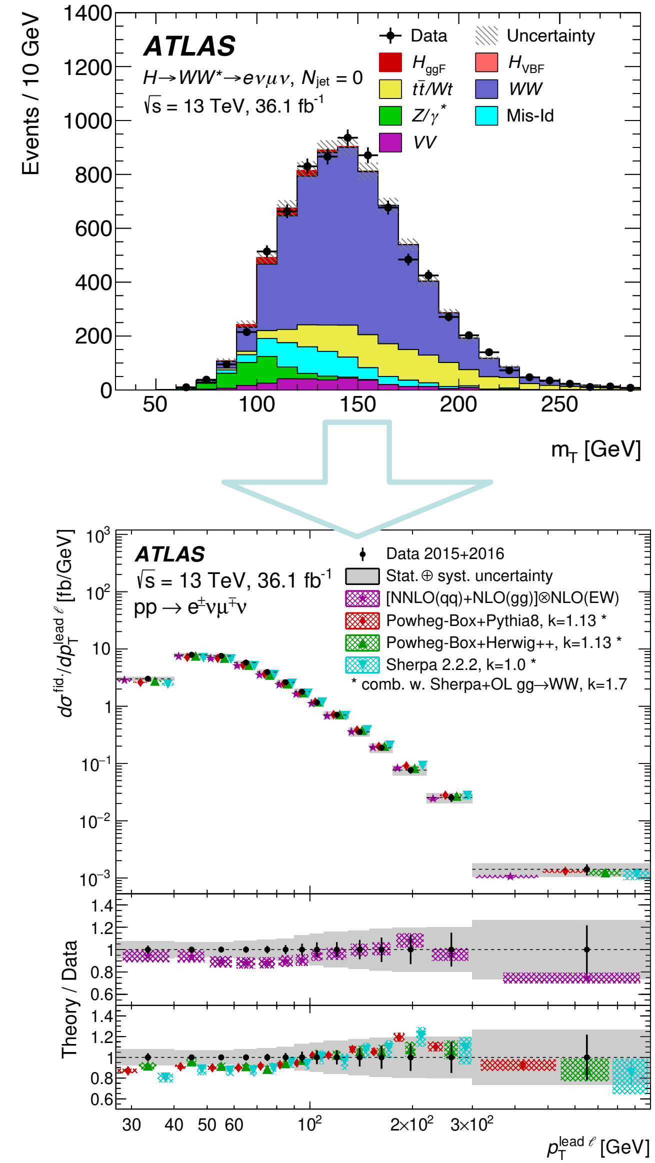
[Eur. Phys. J. C 79 (2019) 884]

H→WW: inclusive ggF and VBF rate measurements

SM WW: differential xs measurement in leading lepton p_T bins

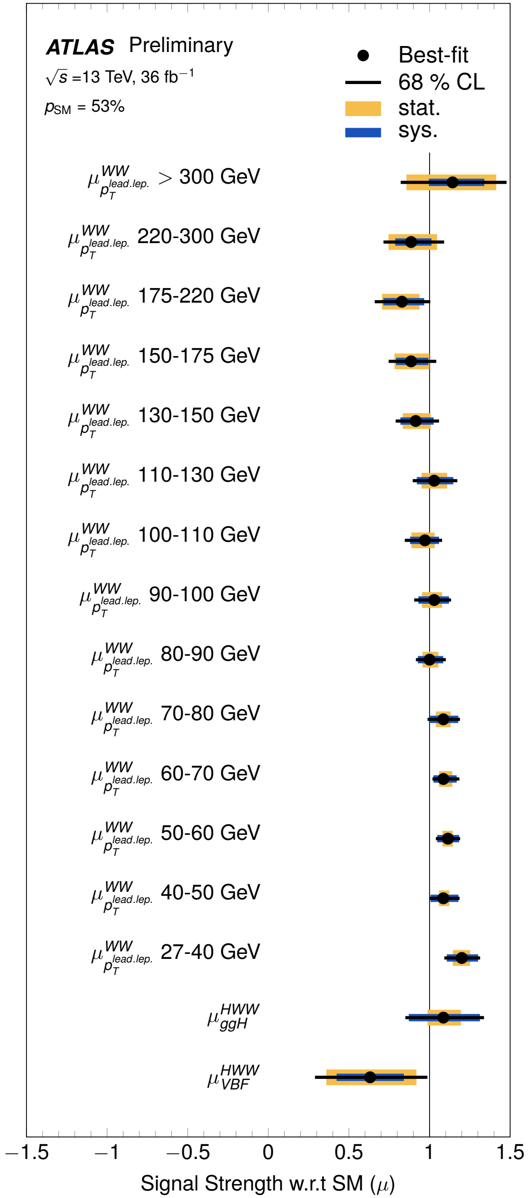
Challenges: overlap

- Higgs analysis signal region is orthogonal with SM analysis
- But Higgs analysis WW background control region overlaps with SM analysis
- **Solution: use SM analysis as control region for Higgs analysis**
  - Worsening ggF signal strength precision by 10%

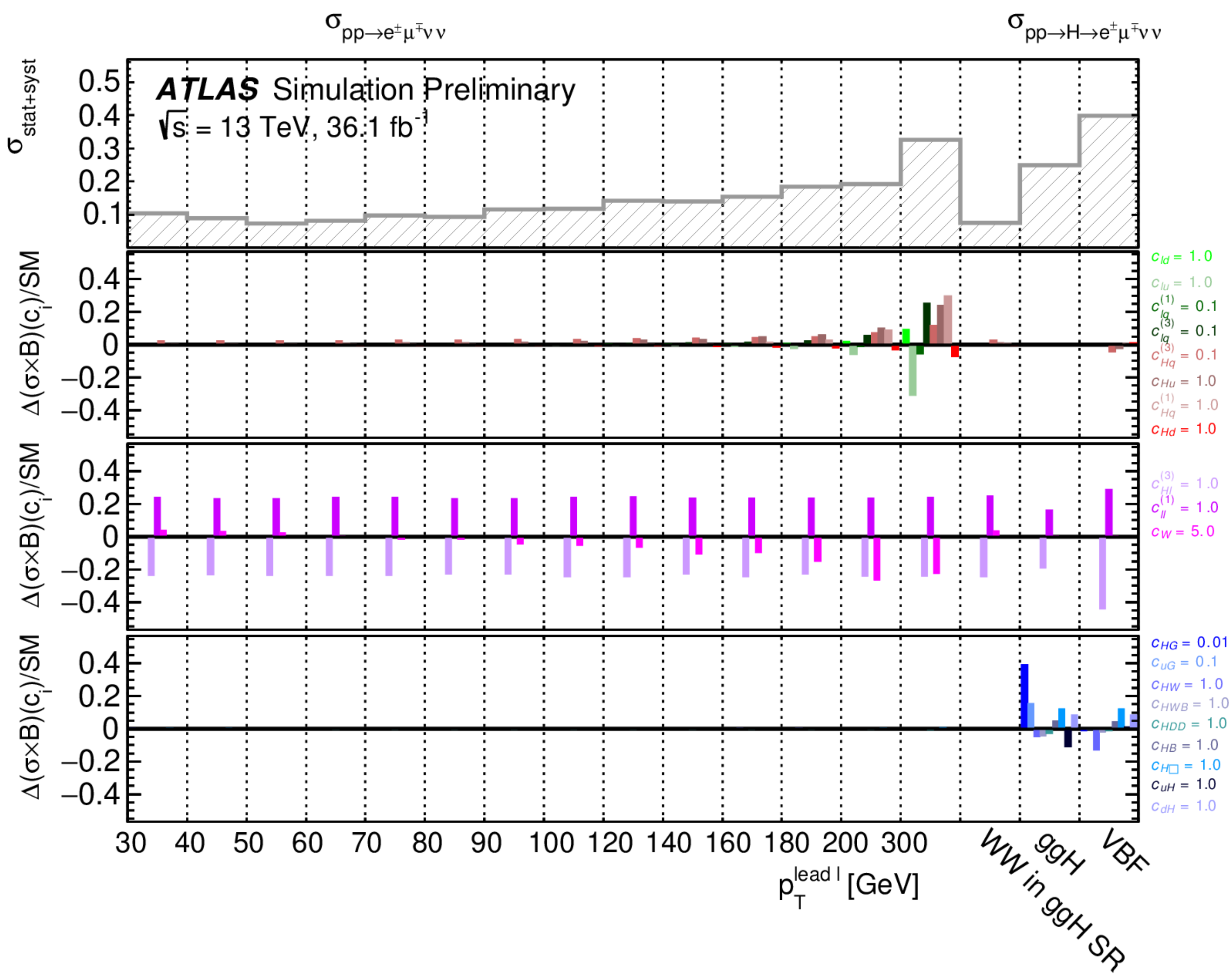


Challenges: different analysis techniques

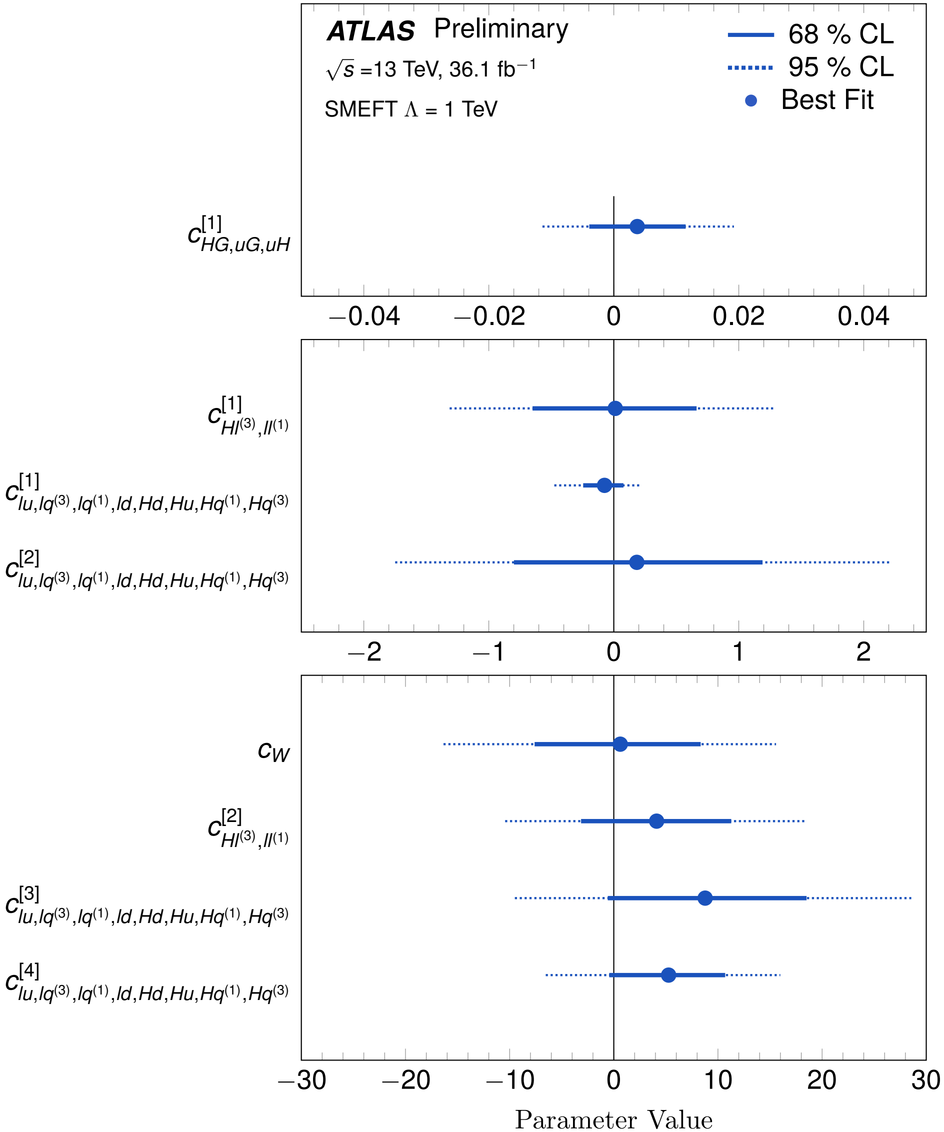
- SM analysis provides an unfolded distribution, while Higgs analysis has full likelihood function
  - Construct a multi-Gaussian from SM diff. xs measurement. Introduce constrained nuisance parameters for systematics
  - Combine multi-Gaussian with Poisson likelihood function from Higgs analysis

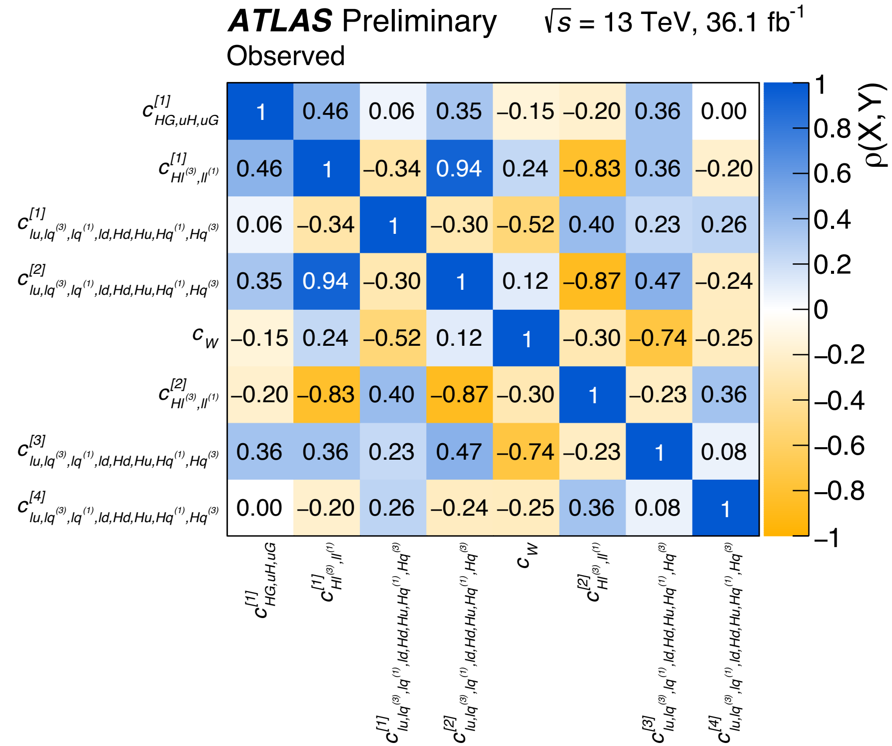


Impact of Wilson coefficients



Results





- Construct "fit basis" using similar techniques just discussed

Conclusions

- LHC experiments are making good progress implementing EFT interpretations of Higgs measurements, with the support of STXS framework
    - Many other results based on Run 2 data are already available or under preparation
    - Start investigating combination between Higgs and SM measurements
- For longer term, EFT interpretation could be a significant legacy from LHC. It is worth investigating effort to pursue this direction further