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EFTs: What are they and how do we use them to constrain BSM physics

Hongtao Yang (LBNL)

Berkeley graduate student seminar

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Introduction

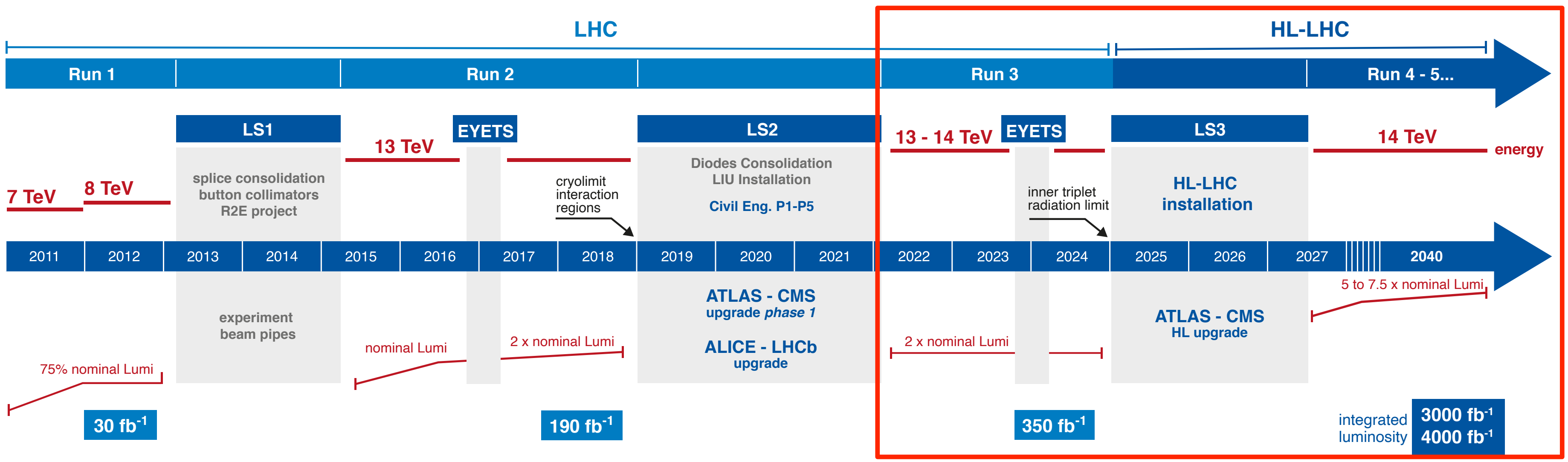
- Goal of particle physics experiments
  - Refine knowledge on SM (e.g. W boson mass)
  - Make discoveries
    - Search for particles predicted by SM: chapter closed
    - Look for new physics, ideally new particles as predicted by BSM models (SUSY, 2HDM…)

Fish discovered water

F. Wilczek

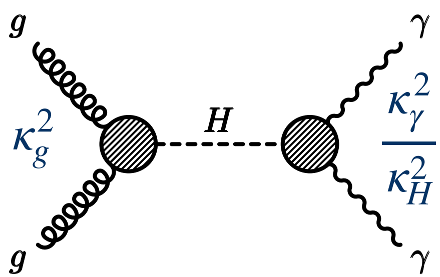
Search for new physics at LHC

- While new physics must exist (e.g. neutrino mass, dark energy/dark matter), there are unfortunately no theories that could provide as solid guide as SM to experiments
- **We will not have another significant increase of center-of-mass energy in the coming decades**
  - If energy scale of new physics is beyond the reach of LHC, then it can only be inferred **indirectly** through **deviations** in precision measurements



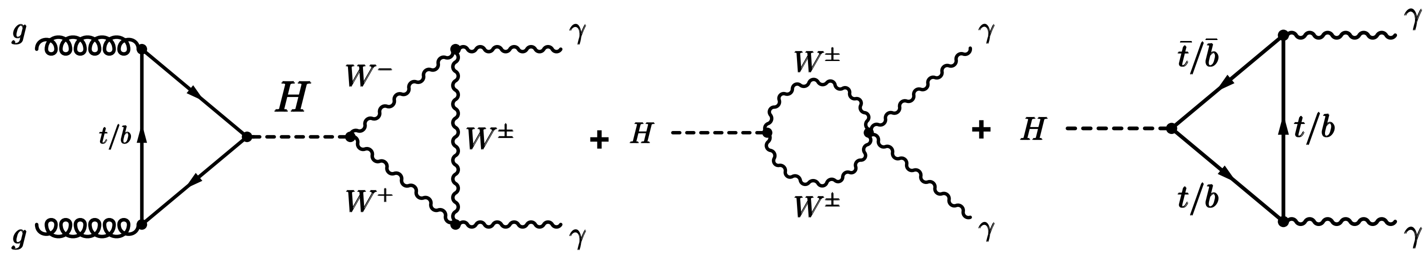
Interpretation example: kappa framework

- 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)



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

Assume only SM particles contribute

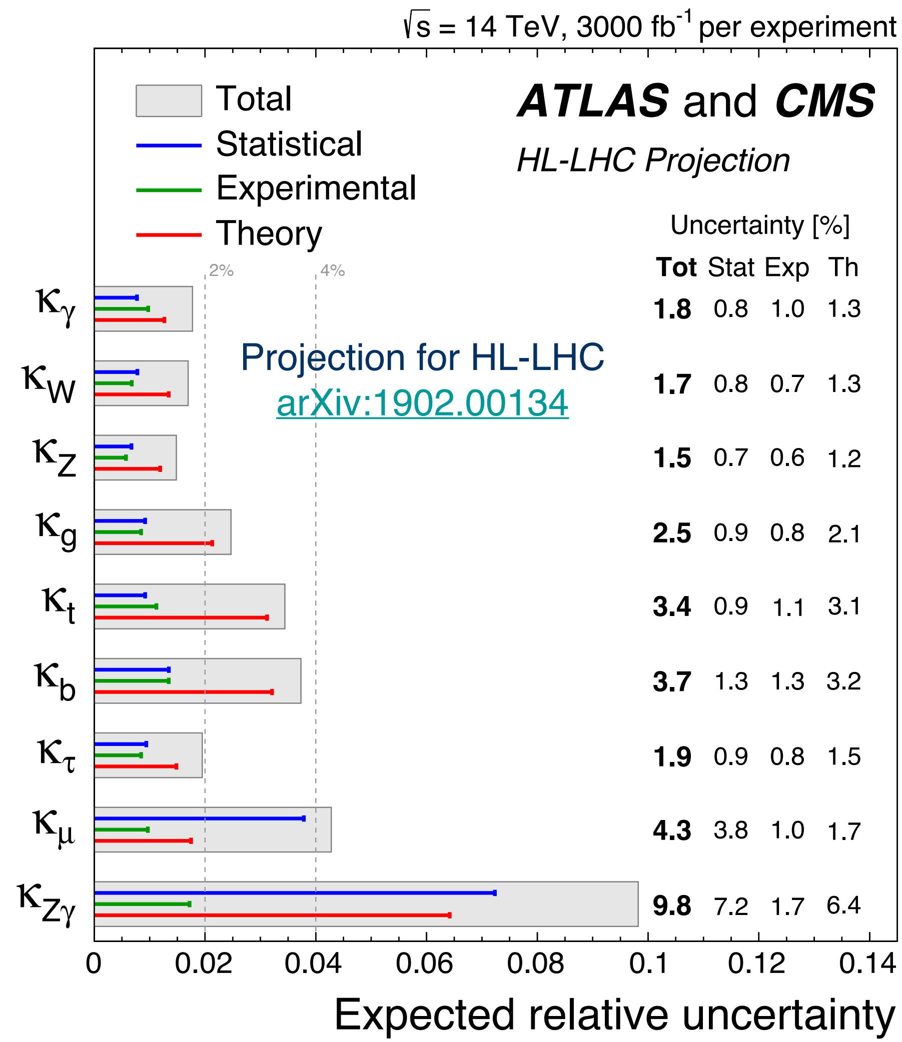


$$\sigma \times BR(gg \rightarrow H \rightarrow \gamma\gamma) \propto \underbrace{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b)}_{\kappa_g^2} \underbrace{\frac{1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_\tau, \ldots)}}_{\kappa_\gamma^2/\kappa_H^2}$$

Yellow Report 3

Limitation of kappa framework

- Kappa framework is intrinsically LO, designed to probe deviations
    - If everything is SM, the results are straightforward to interpret
    - **If deviations are observed, however, this framework by itself cannot provide clear physics guidance**
- Kappa framework is based on inclusive production and decay rates. **It is, therefore, blind to tension in diff. distributions**



Current dataset only 5% of expected LHC total!

A better option: EFT

- **SMEFT**: only use SM fields and respect SM symmetries, expand SM Lagrangian to include higher dimension terms that are suppressed by cut-off scale Λ

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

* Dimension 5 and 7 operators excluded as they introduce violation to lepton/baryon number conservations

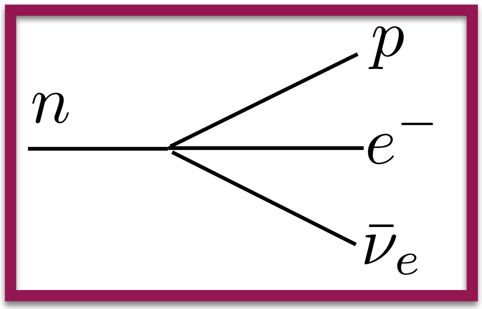
- Using above Lagrangian to calculate cross section of a process, the BSM part should include
    - **Leading order ($1/\Lambda^2$)**: inference between SM and d6 EFT
    - **Next leading order ($1/\Lambda^4$)**: pure d6 EFT + interference between SM and d8 EFT

Does the effective theory work?

Eleni Vryonidou's lecture

An example of a successful EFT:

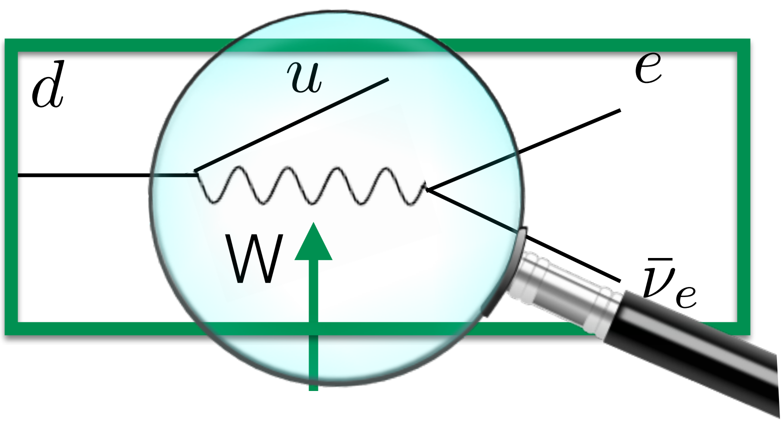
$$n \to p + e^- + \bar{\nu}_e$$



Fermi formulated his theory in the 1930's

It described β-decay data very well
Energy of β-decay: ~MeV

But this is not the full theory: cross-section rising with energy, violating unitarity



1983 Discovery of W-boson at CERN UA1 and UA2
M_W=80 GeV >> Q_β

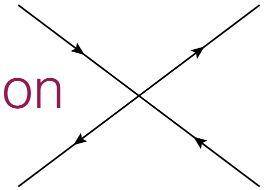
Energy borrowed from the vacuum
A virtual W-boson exchange

EFT for New Physics

Eleni Vryonidou's lecture

Low Energy Effective Theory without the Z'

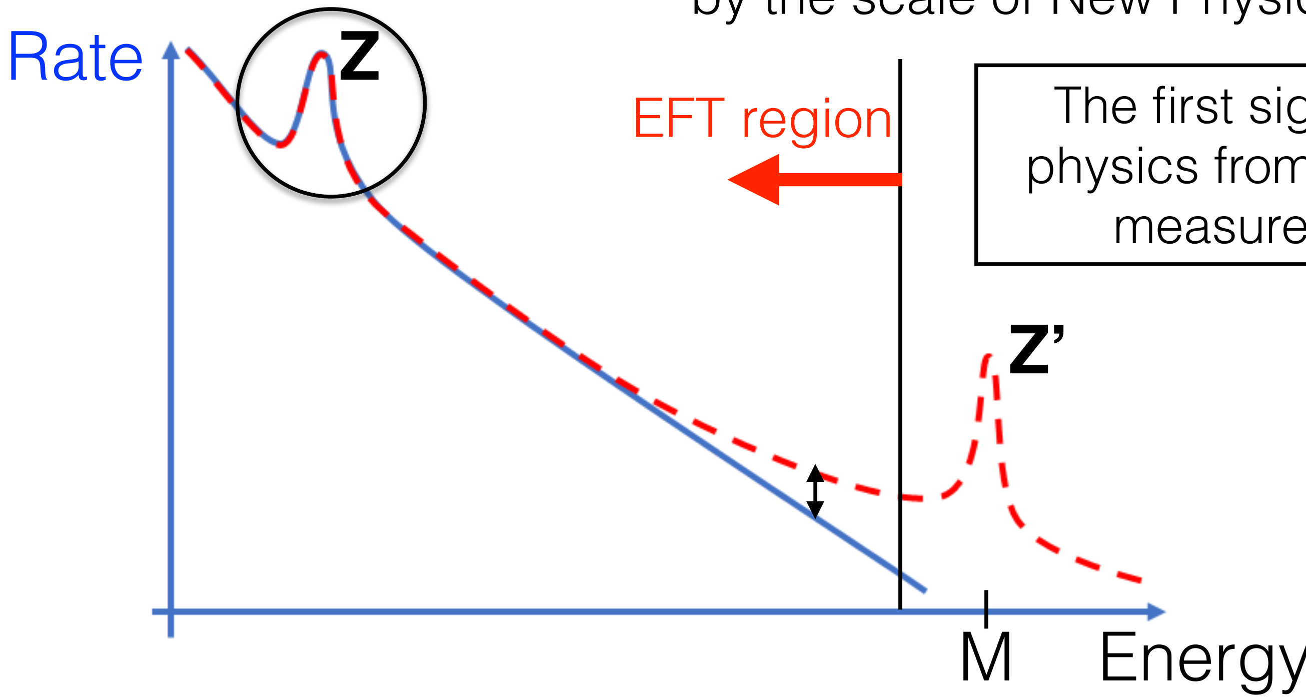
New Interaction



$\frac{1}{-M^2}$

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

Modified interactions suppressed by the scale of New Physics



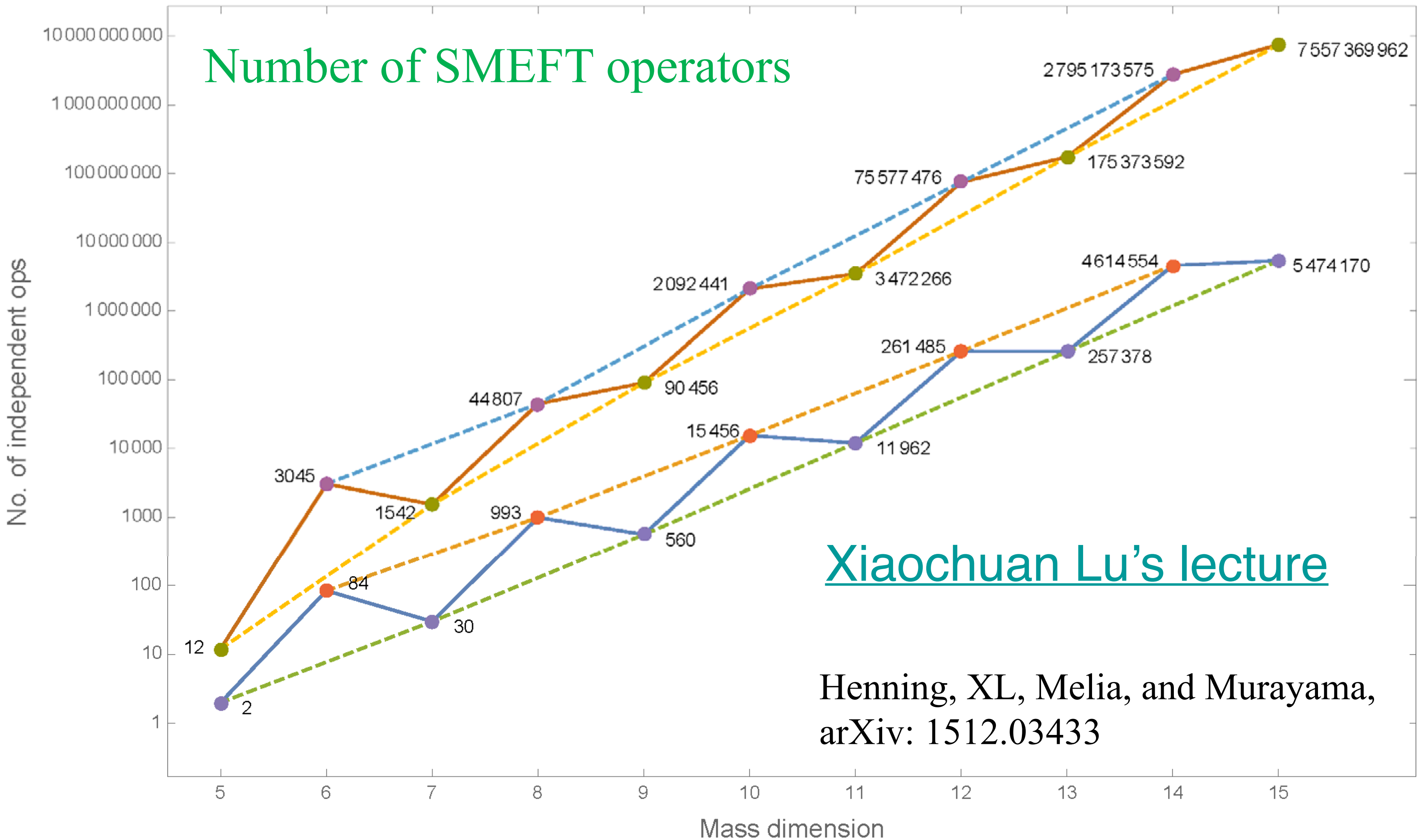
The first sign of new physics from precision measurements

The way to probe New Physics in the absence of light states

Challenges of EFT interpretations

- Large amount of operators to be taken into account. Fortunately, many are well-constrained by precision measurements e.g. from LEP. But there are still many left
- Same physics processes can be modified by multiple operators, and same operator can modify multiple processes
  - Large correlation between difference Wilson coefficients in experimental measurements (degeneracy)
- Operators modify rate and kinematics of physics processes
  - Ideally the EFT MC should be processed with the full analysis chain to consider acceptance effects
- Operators modify both “signal” and “background” processes
  - Greater overhead for MC production and also analyses. Difficult to combine multiple channels

General Principles of Building EFTs



[Xiaochuan Lu's lecture]()

Henning, XL, Melia, and Murayama, arXiv: 1512.03433

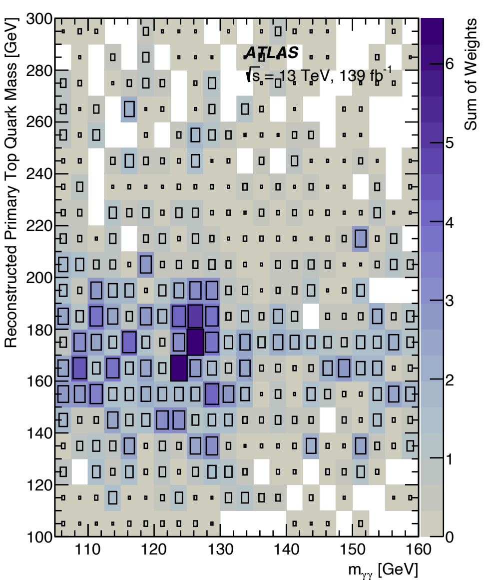
Example of EFT interpretations in Higgs analyses

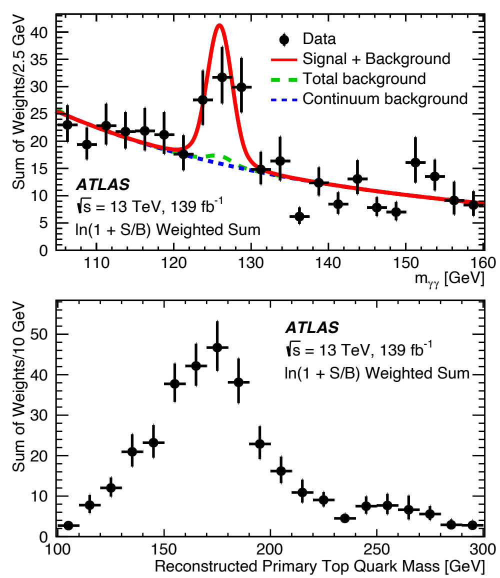
Dedicated analyses

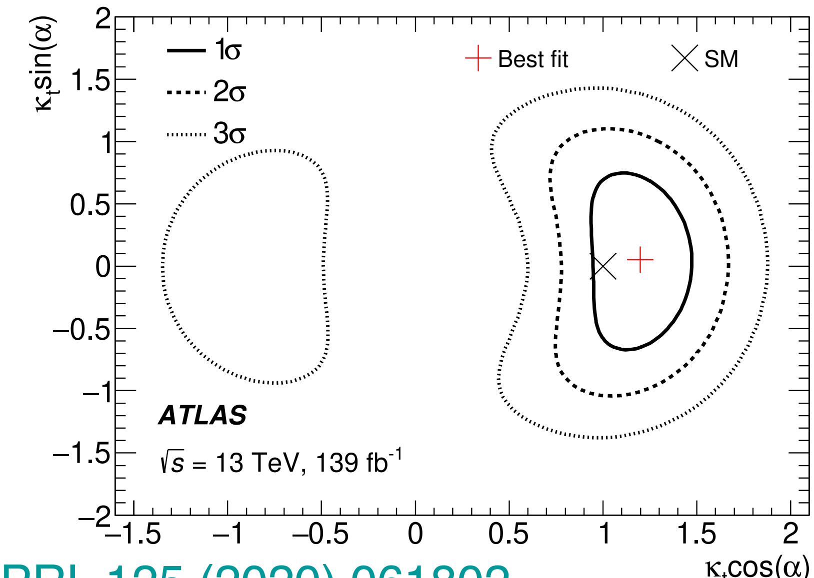
- Dedicated analyses optimized to probe one property (e.g. CP mixing angle)
  - Optimal sensitivity, but also very model dependent. Not for generic interpretations

$$\mathcal{L}^{\mathrm{SMEFT}}_{\text{top-Yuk}} = \frac{1}{\sqrt{2}} H \bar{t}_L \left[\frac{y_t^{\mathrm{SM}}}{\sqrt{2}} \left(1 - \frac{1}{4} c_{\varphi D} \frac{v^2}{\Lambda^2} + c_{\varphi \Box} \frac{v^2}{\Lambda^2} \right) - \frac{v^2}{\sqrt{2}\Lambda^2} \mathrm{Re}(c_{t\varphi}) - i\gamma_5 \frac{v^2}{\sqrt{2}\Lambda^2} \mathrm{Im}(c_{t\varphi}) \right] t_R$$

$$\mathscr{L}_t = -\frac{m}{v} \kappa_t (\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t) H, \; \kappa_t > 0, \; \alpha \in [-\pi, \pi]$$







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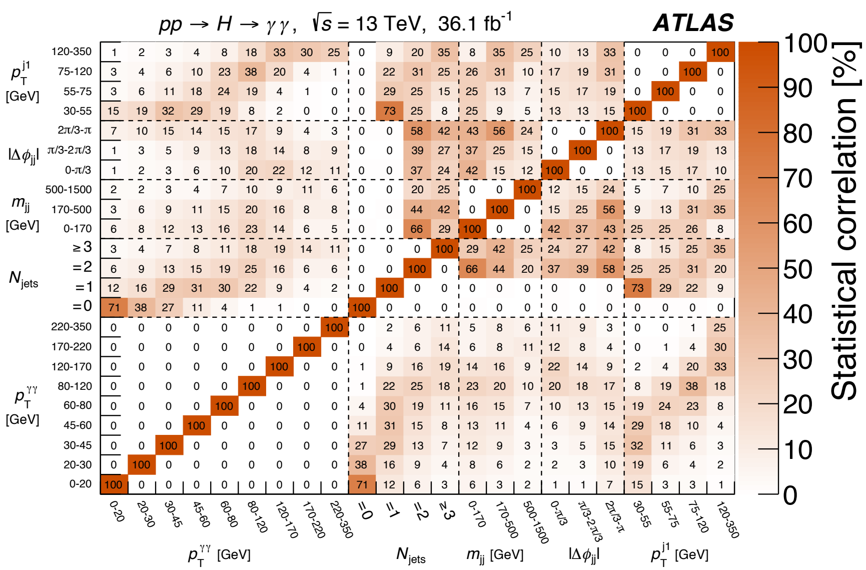
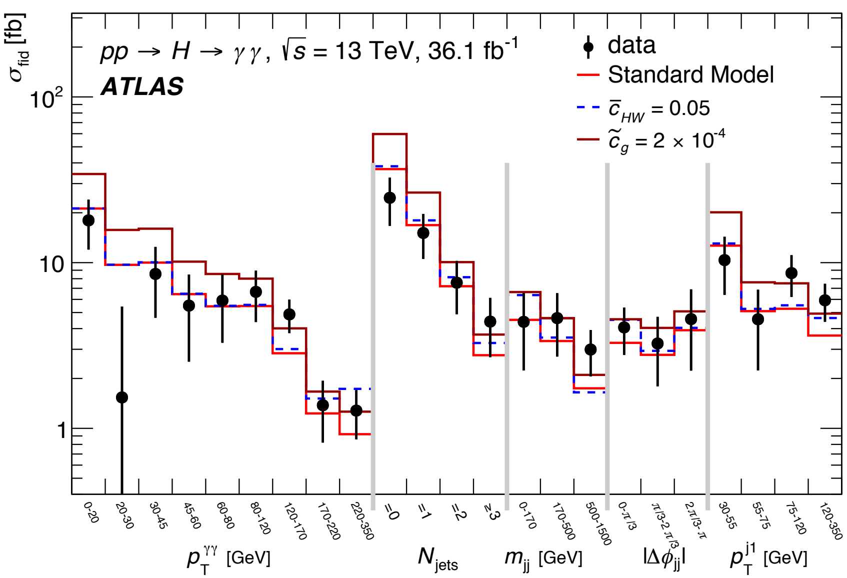
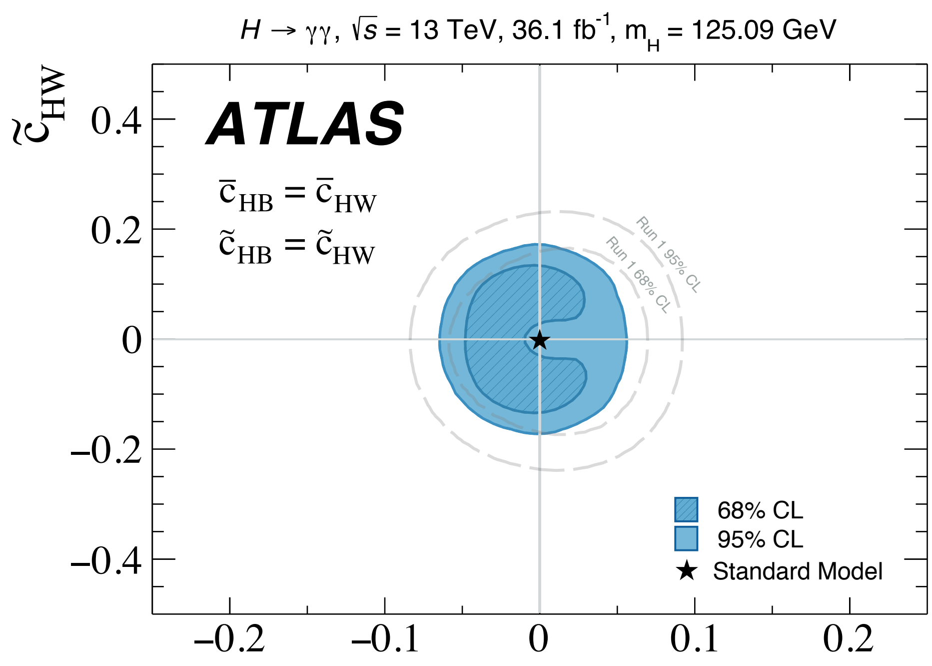
Interpret differential cross-section measurements





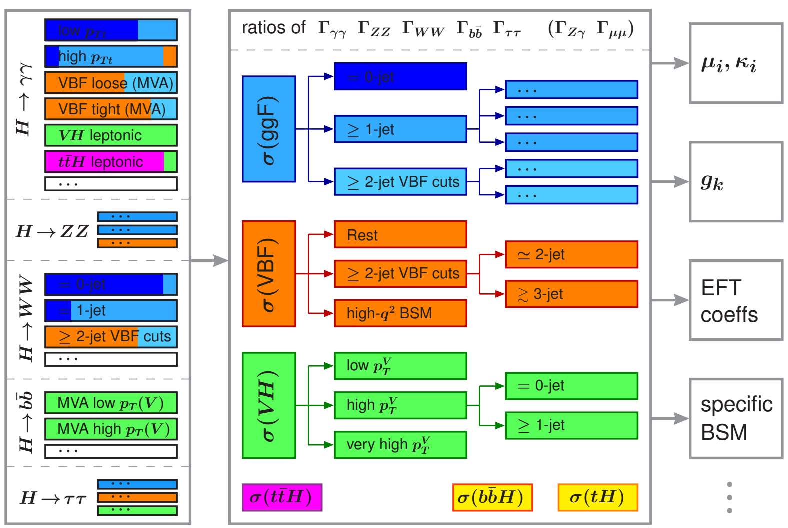
- Interpret differential cross-section measurement results
  - Minimal model dependence
  - Not trivial to combine multiple distributions within a channel, or combine multiple decay channels

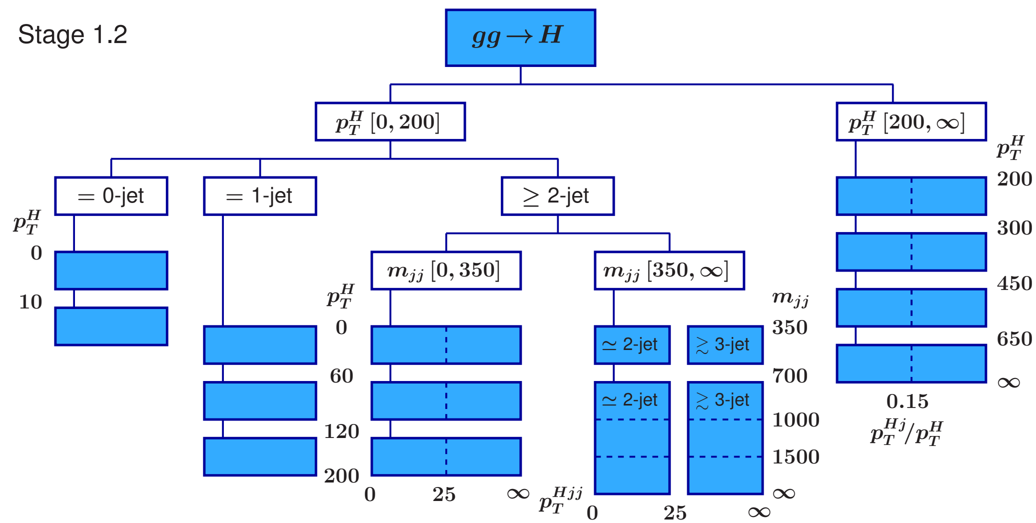


PRD 98 (2018) 052005

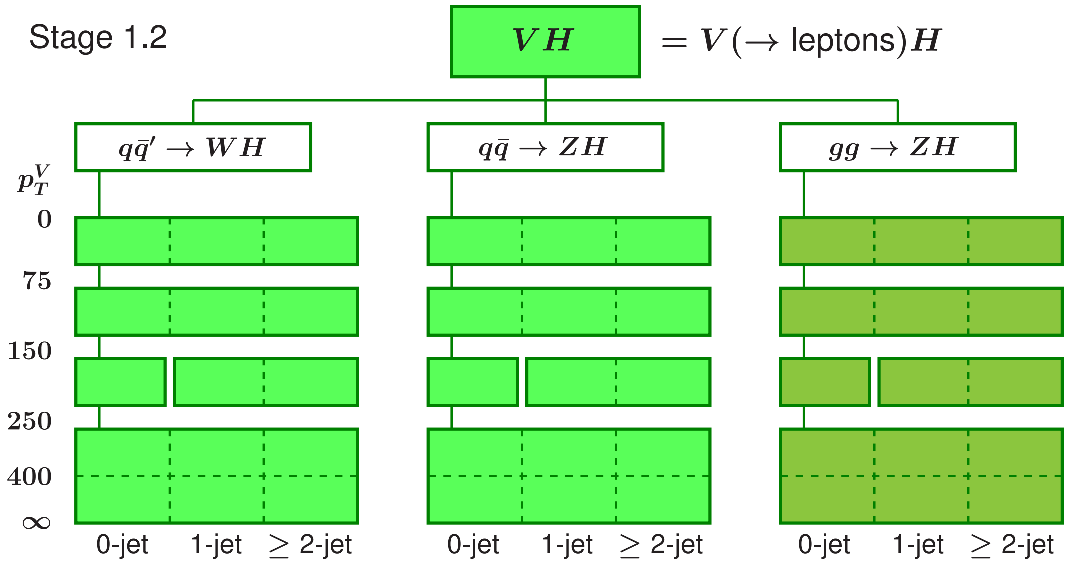
Rate analysis + STXS framework

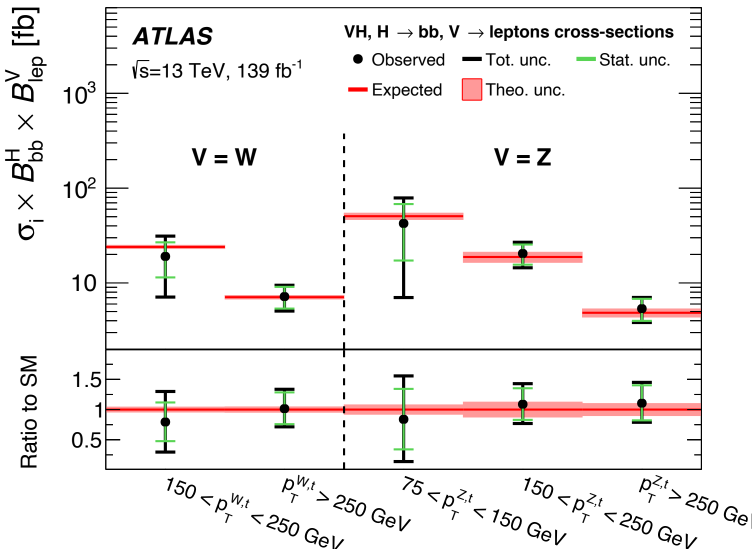
- **Simplified template cross-section (STXS) framework:** measure cross-section per production mode in different phase-space regions
  - Decay is inclusive so far. No kinematic bins introduced yet
- STXS is ideal for EFT interpretation
  - Provide differential cross-section measurements while allow experimentalists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





STXS bins for V(lep)H





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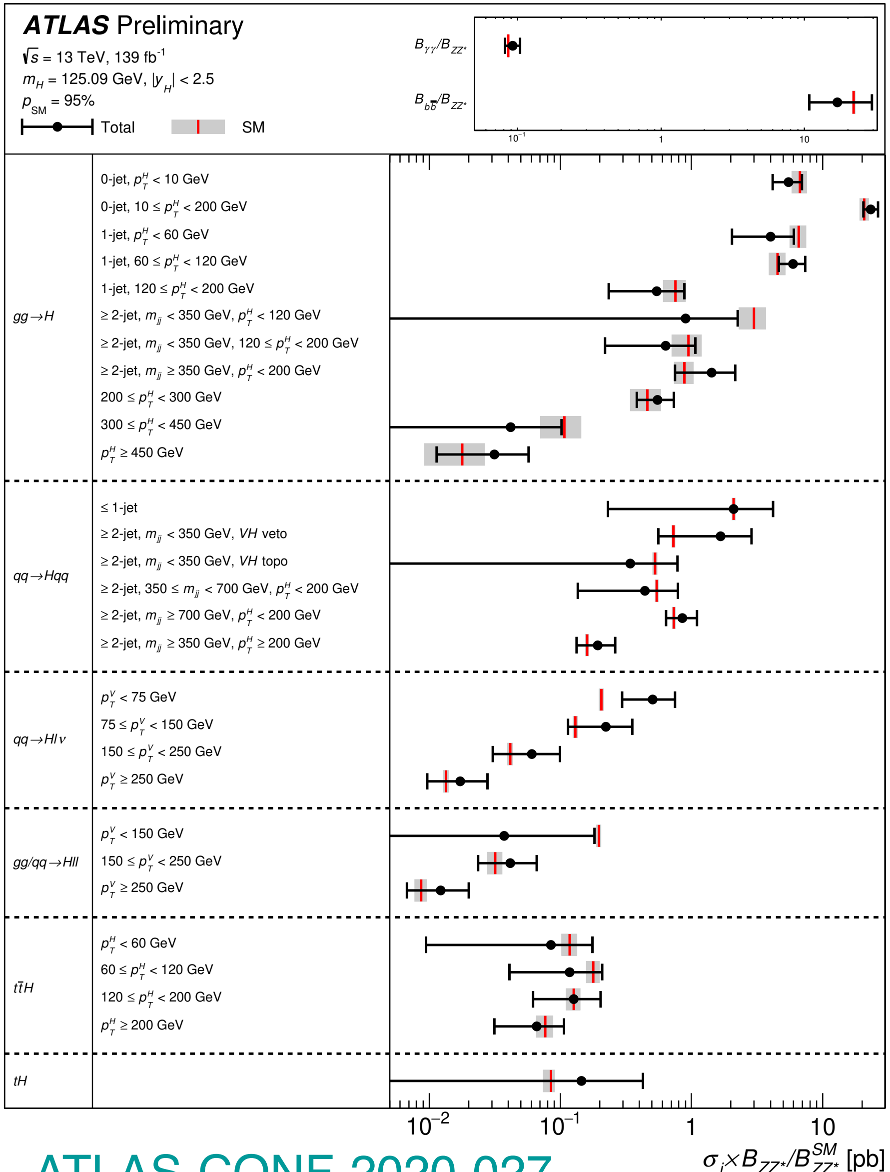
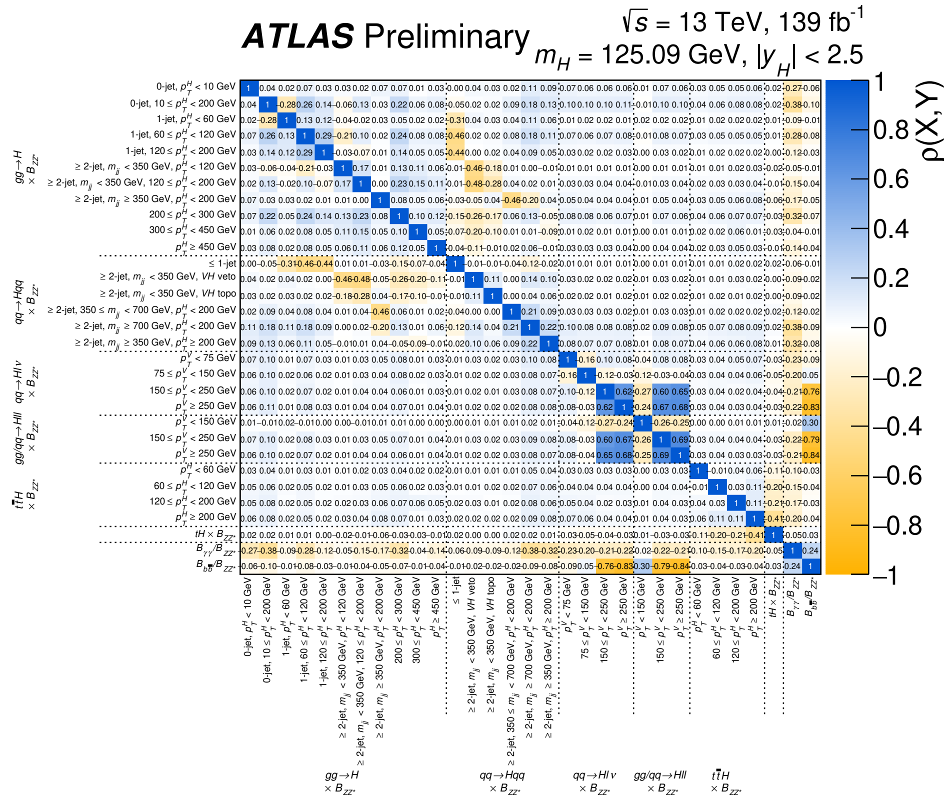
- STXS framework is designed to find balance between experimental and theory demand
- Definition of V(lep)H STXS bins is driven by selection used in V(lep)H, H→bb analyses at LHC
  - Separate different N(lepton) and N(jet) regions
  - Categorize analysis using vector boson p_T

STXS measurements





[ATLAS-CONF-2020-027]

- So far including H→γγ, H→ZZ, and VH, H→bb
- Ratio of branching ratio is a free parameter determined by data

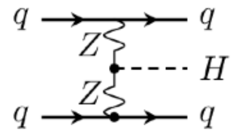
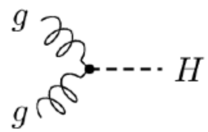
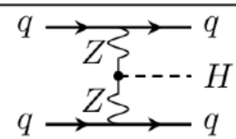
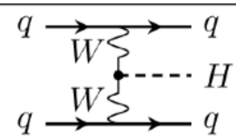
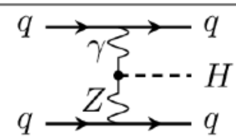
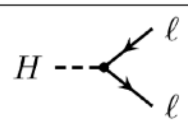
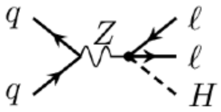
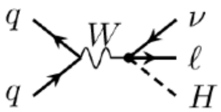
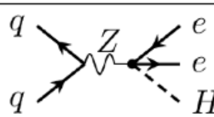
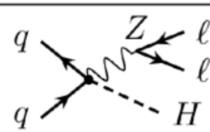
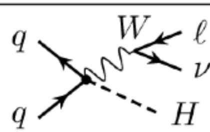
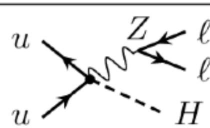
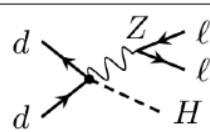
EFT parameterization of STXS production x-section

- 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 ($1/\Lambda^4$)
    - Interference between d8 and SM is not calculated yet
  - σ_{SM} in the front will be replaced by state-of-art calculation
  - Ratios will be replaced by parameterization derived from MadGraph_aMC@NLO
    - 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

Example operators considered

Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

- EFT operators can be presented in different bases
- Warsaw basis is now widely used in ATLAS

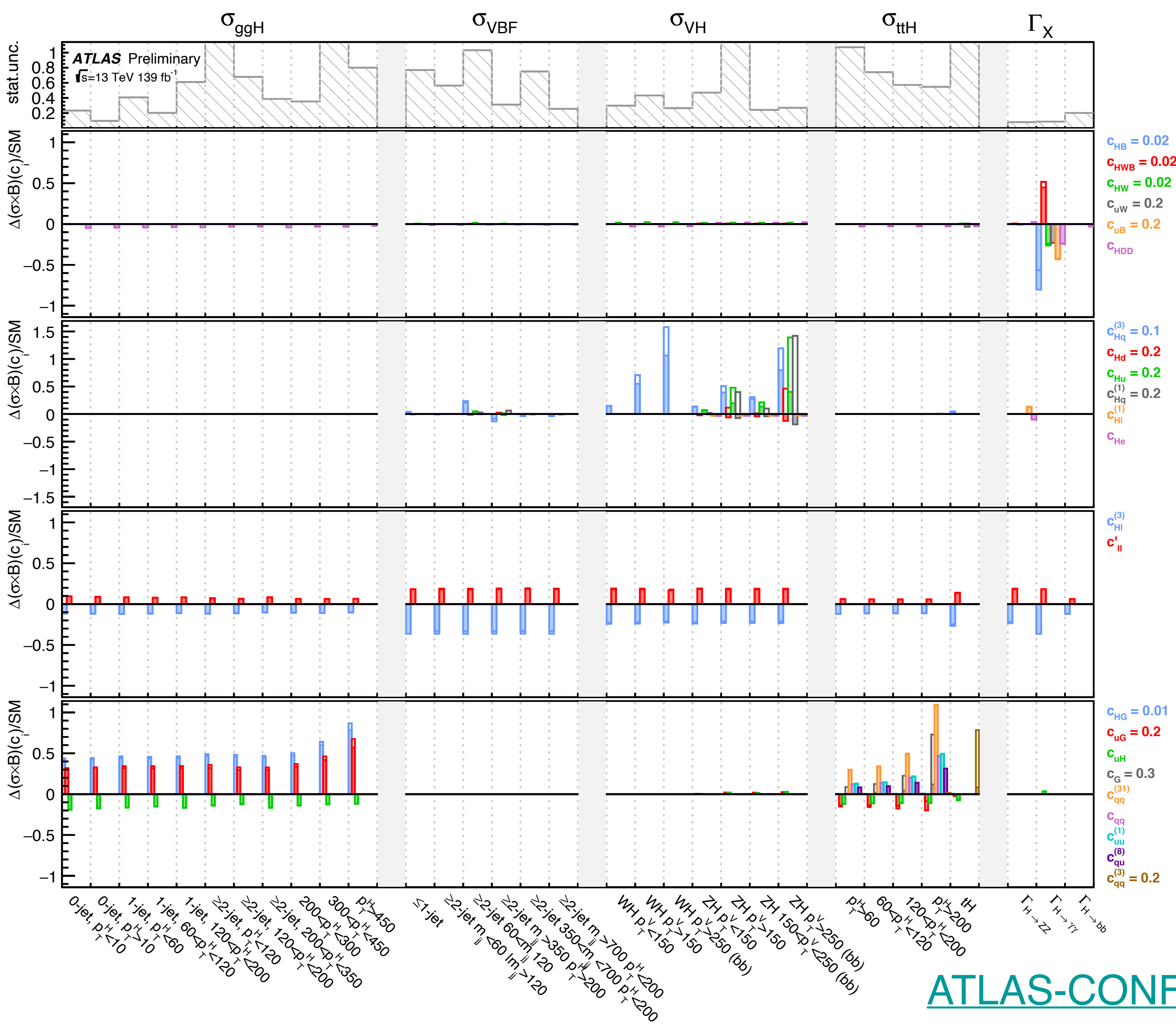
Parameterization of decay

- 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
- For both production cross-sections and decay branching ratios, two interpretation scenarios considered
  - **Linear**: only contains 1st order Wilson coefficients
  - (Linear +)**Quadratic**: also contains 2nd order terms to estimate the potential effect from higher order (incomplete)

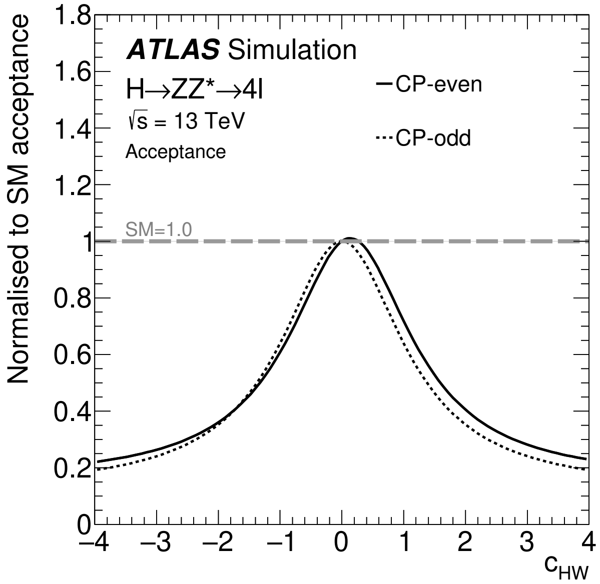
Linear (solid) vs. linear+quadratic (hollow)

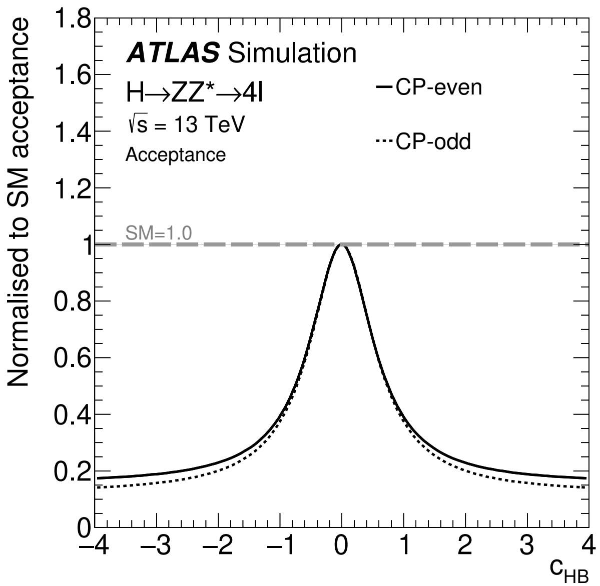


ATLAS-CONF-2020-053

Acceptance effect

- **Production**: (partially) handled by phase-space partitions within the STXS framework
  - Analyses selections are usually aligned with STXS bin definitions
  - Acceptance effect within each STXS bin is neglected
- **Decay**: non-trivial effect in channels such as H→ZZ. Needs to take into account if possible
  - Plan to introduce STXS bins to decay





Physics (Warsaw) basis → fit basis

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

ATLAS-CONF-2020-053

#	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}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	$c_{ll}^{(1)}$	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			

- Warsaw basis cannot be used out of box due to **large correlations**
- Considering only linear terms. Calculate eigenvectors and eigenvalues of hesse matrix (= (covariance)$^{-1}$) from fitting to data
- Focus on eigenvectors with eigenvalue > 0.01

How to get fit basis (cont'd)

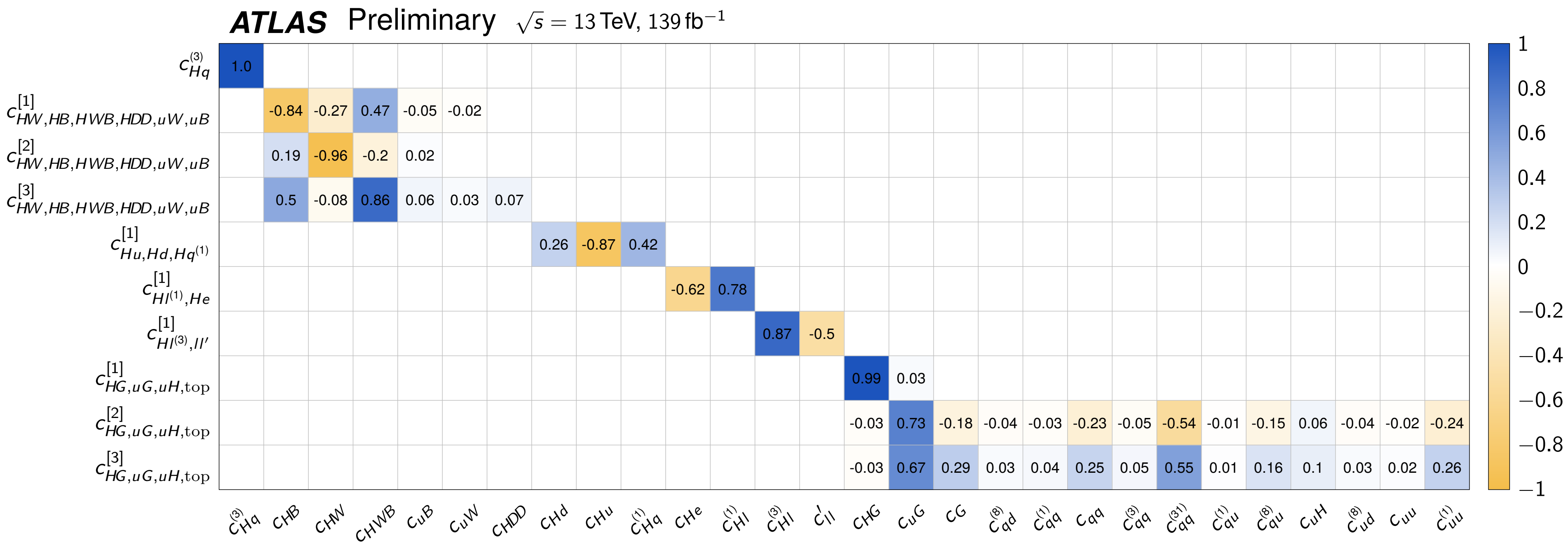
ATLAS Preliminary $\sqrt{s}=13$ TeV, 139 fb^{-1}

#	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}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	$c_{ll}^{(1)}$	c_{HG}	c_{uG}
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
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
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
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
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
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
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01

#	λ	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															-0.02	
2	121830																
3	1960																
4	38									0.02				0.03			
5	19	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				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-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	0.03								0.06				0.06	-0.11	-0.01	
10	0.16	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036	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	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

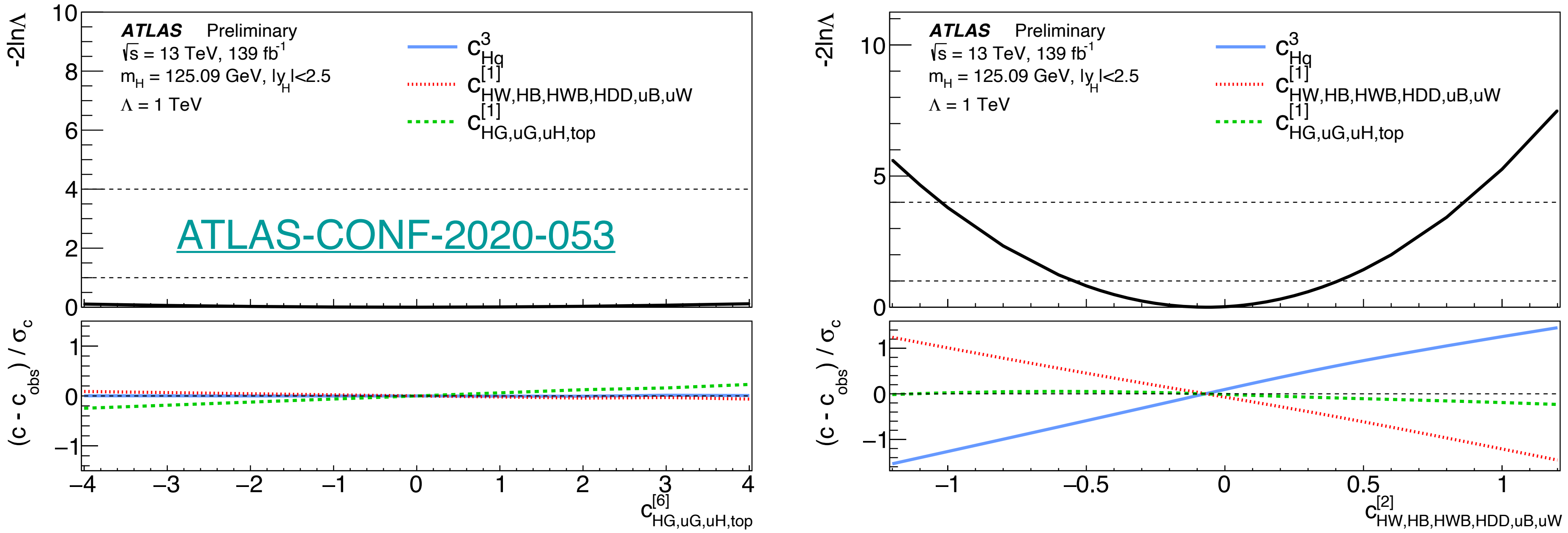
- Fix coefficients that only scale the overall normalization ($c_{H\Box}$, c_{dH}, c_{eH}) to zero (degenerate with other coefficients)
- Regroup remaining parameters with physics judgement, and re-diagonalize within each group

Final “fit basis” choice



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

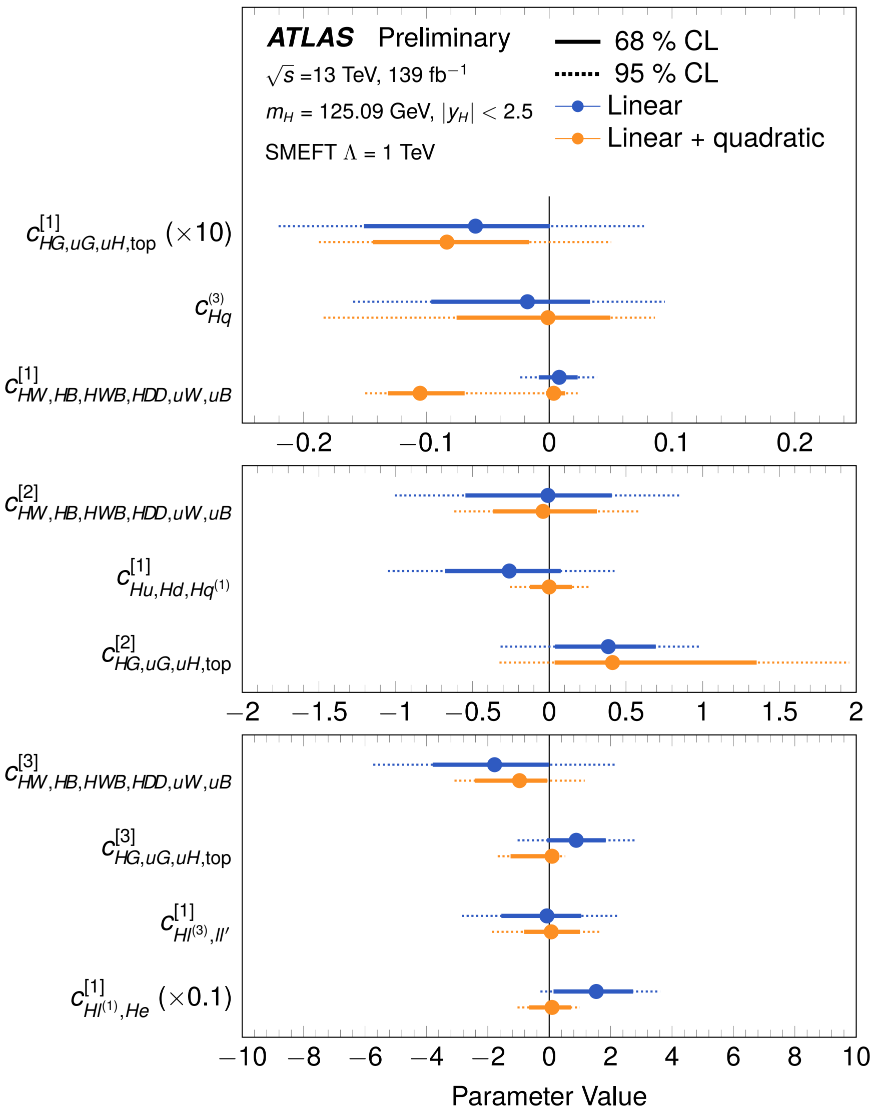
Identify flat directions

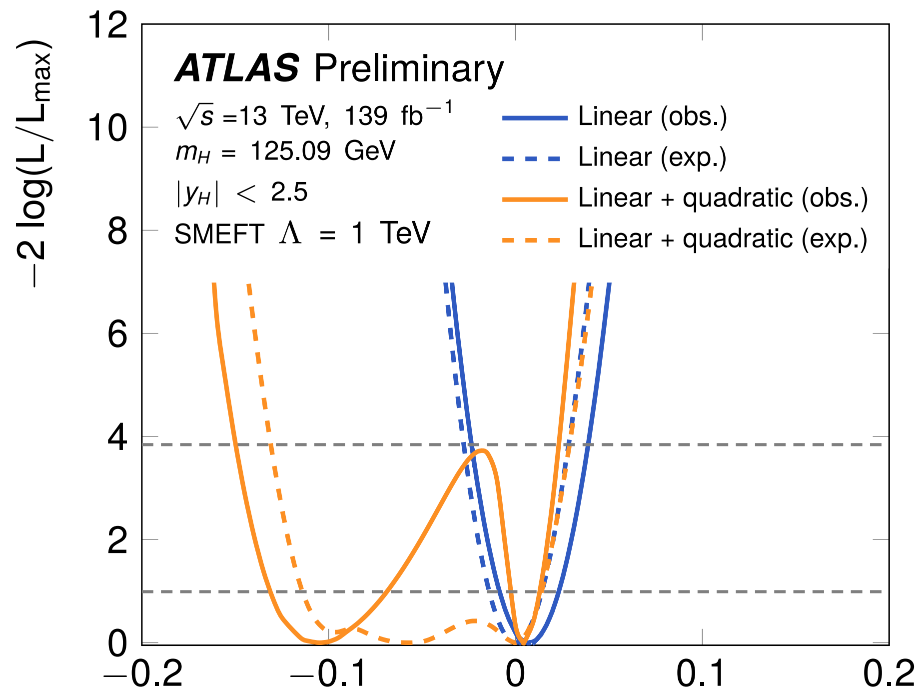


✗ A flat direction: fixed to 0 ✓ A well-constrained eigenvector

- 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

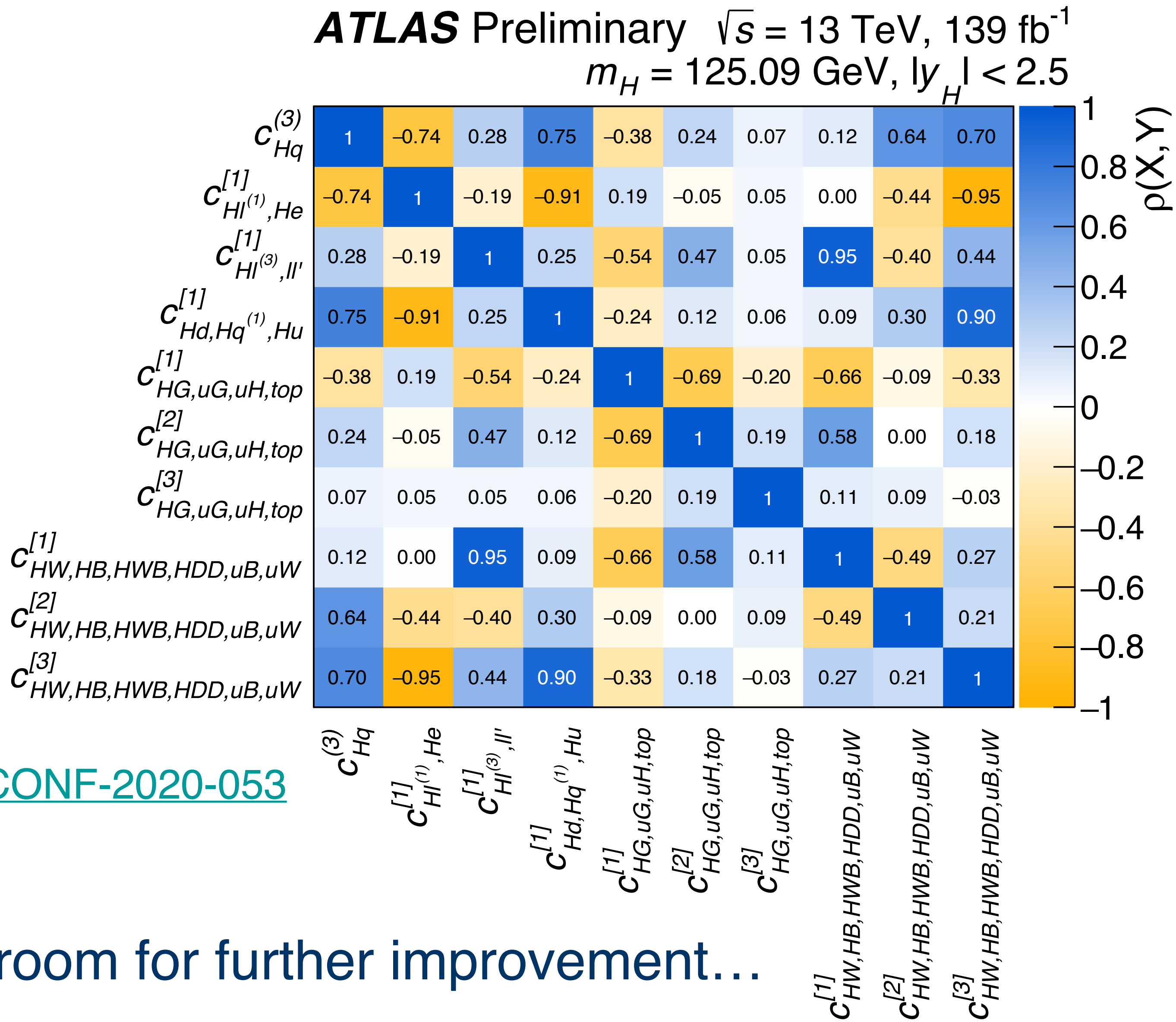




ATLAS-CONF-2020-053 $c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$

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

Correlation matrix



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- Large room for further improvement…

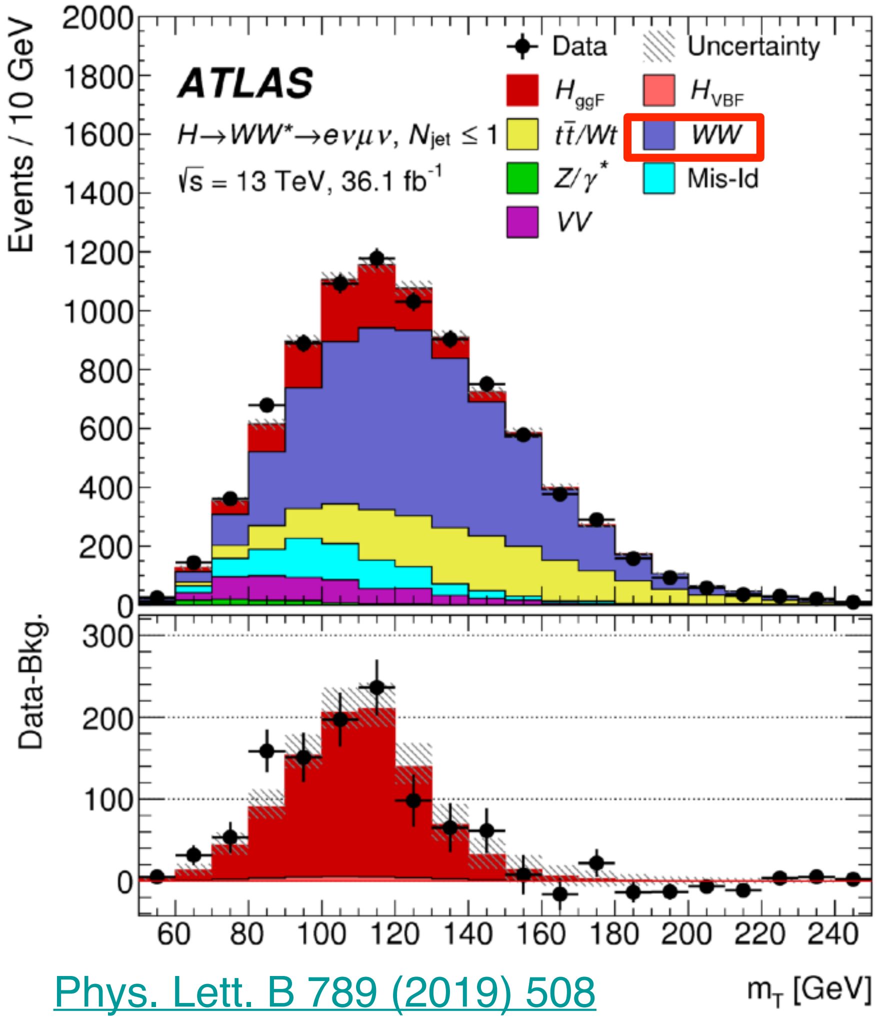
Towards the grand EFT combination

ATL-PHYS-PUB-2021-010

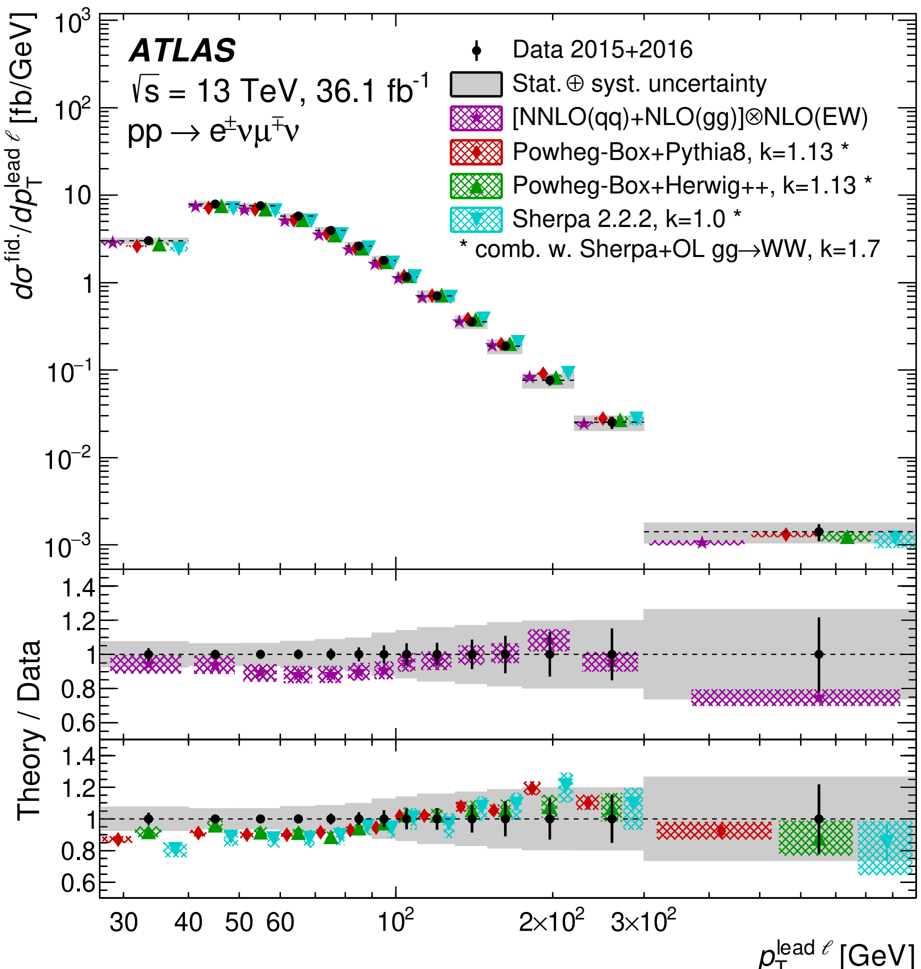
Everything can be signal

- 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: $H \rightarrow WW$ and SM WW

Inputs



Phys. Lett. B 789 (2019) 508



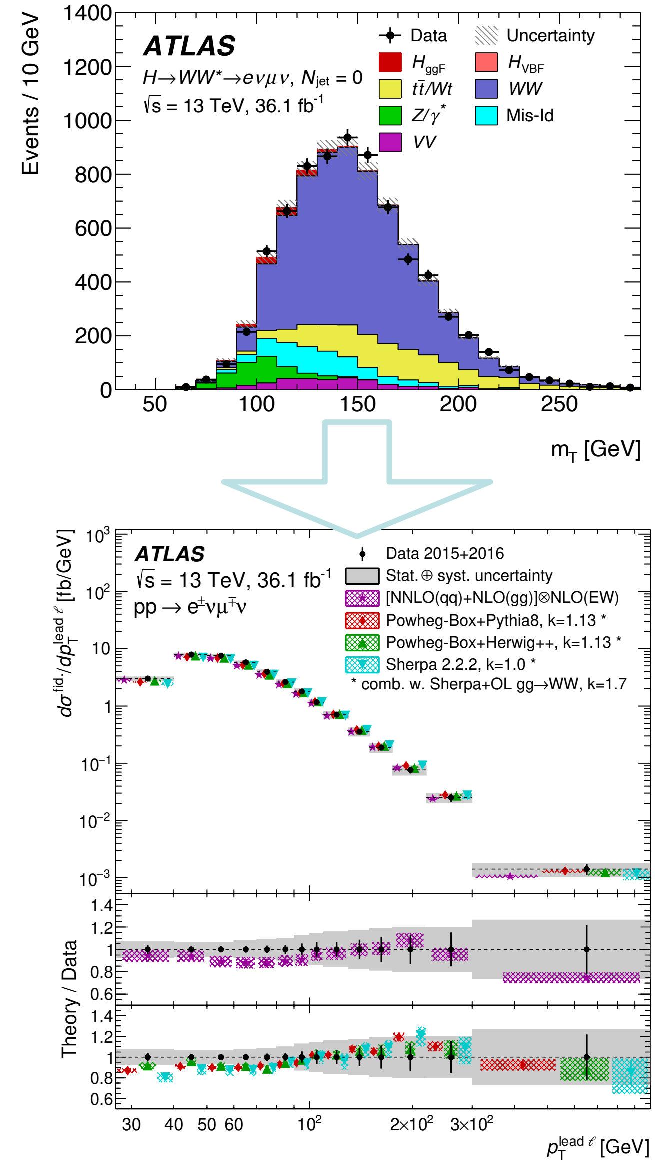
Eur. Phys. J. C 79 (2019) 884

H→WW: inclusive ggF and VBF rate measurements

SM WW: differential xs measurement in leading lepton p_T bins

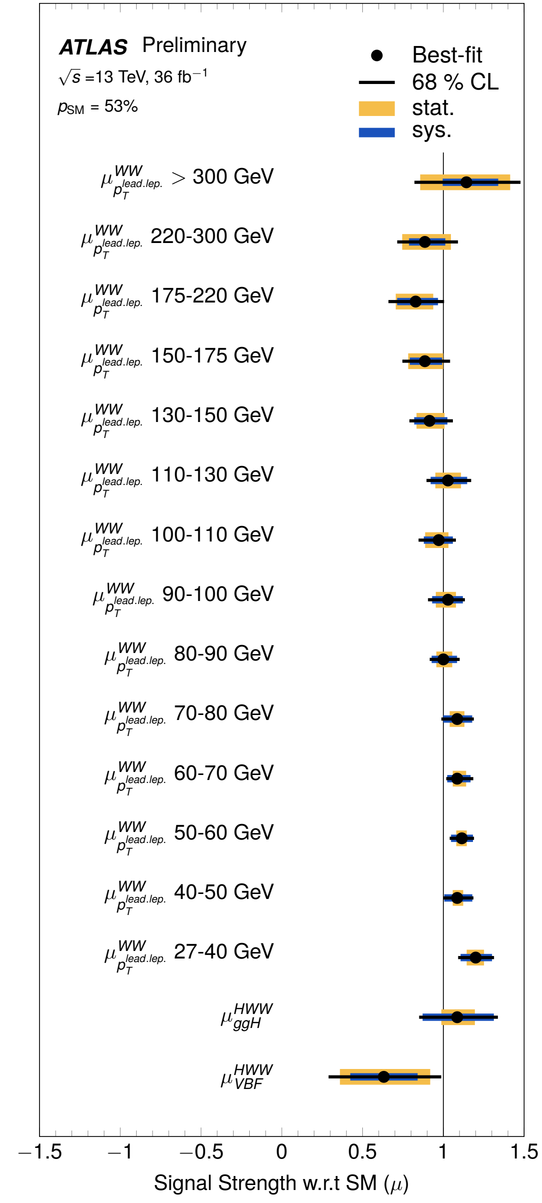
Challenges: overlap

- 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%

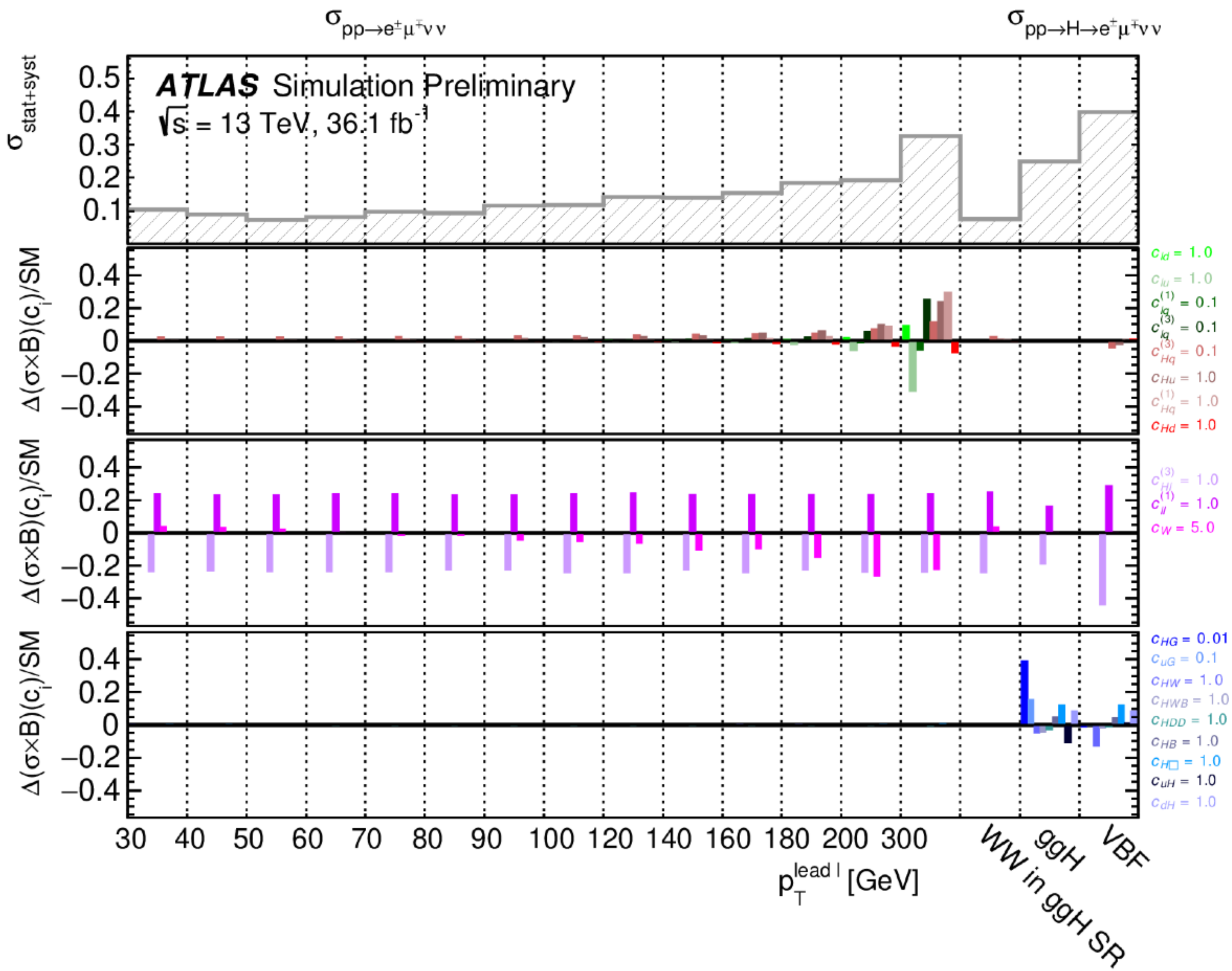


Challenges: different analysis techniques

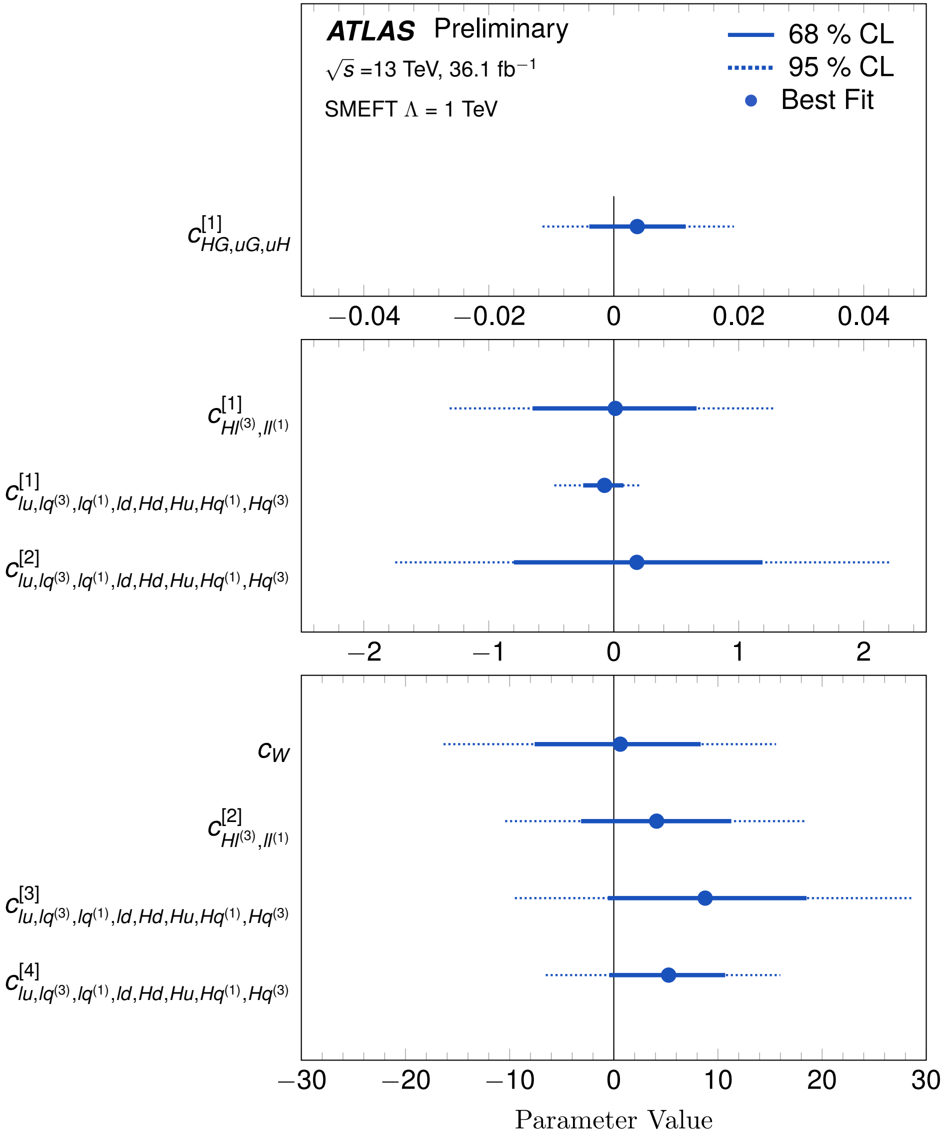
- SM analysis provides an unfolded distribution, while Higgs analysis has full likelihood function
  - Construct a multi-Gaussian from SM diff. xs measurement. Introduce constrained nuisance parameters for systematics
  - Combine multi-Gaussian with Poisson likelihood function from Higgs analysis

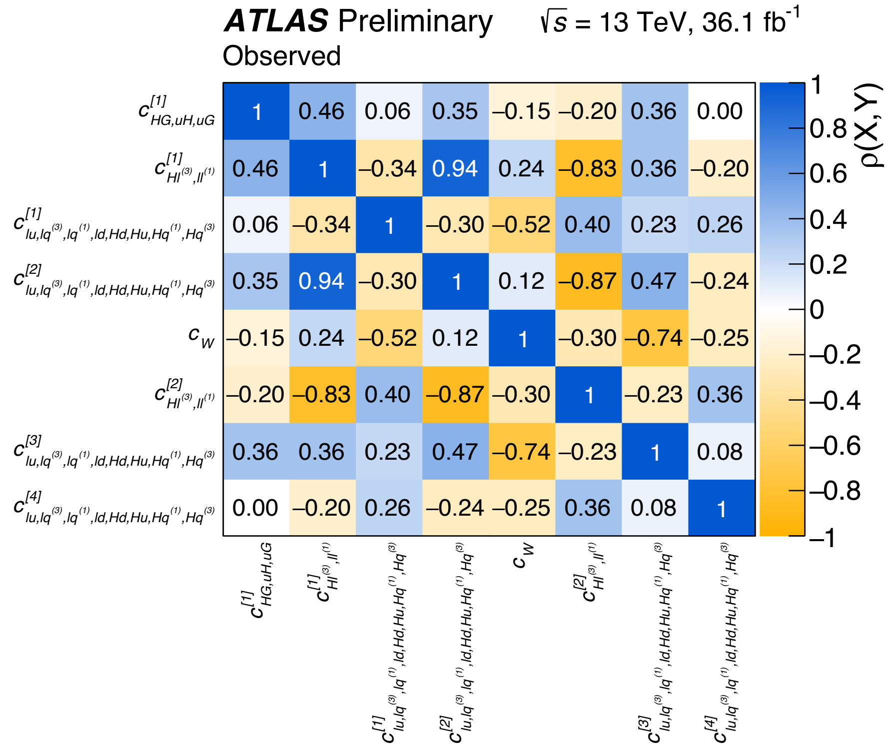


Impact of Wilson coefficients



Results





- Construct “fit basis” using similar techniques just discussed

Conclusions

- LHC experiments are making good progress implementing EFT interpretations facilitated by the STXS framework
  - Many results based on Run 2 data are available
  - "Grand combination" covering Higgs, EW, and top measurements under preparation
- For longer term, EFT results will probably be an important legacy of LHC. This direction is worth pursuing further
  - Although we also need to be pragmatic and conscious with limitation of resource and person-power
- **Finally, EFT ≠ everything! For new physics reachable by LHC, better to directly search for them**