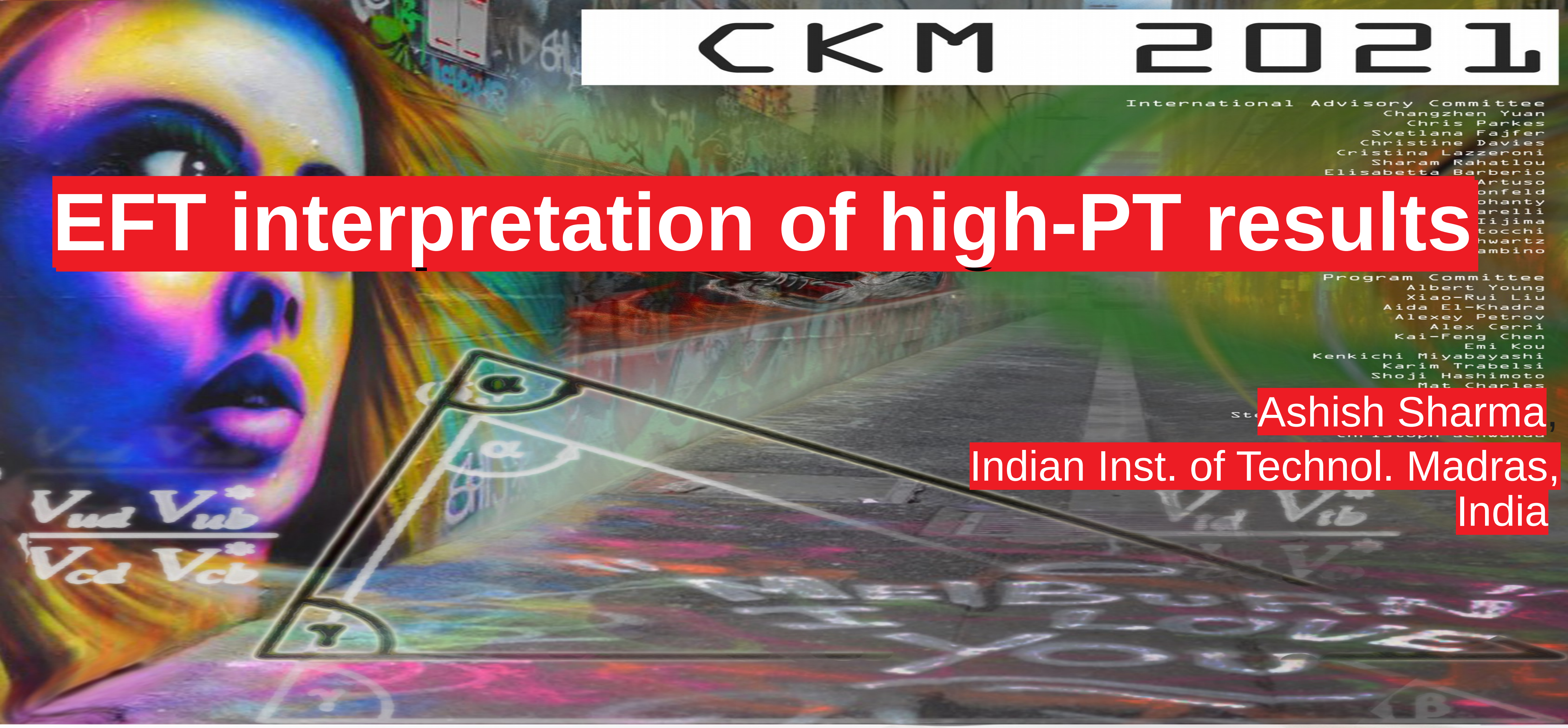

EFT interpretation of high-PT results

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Outline

- **Introduction**
- **Motivation**
- **Combined measurements of Higgs boson production and decay with the ATLAS experiment.** [ATLAS-CONF-2021-053]
  - Effective Field Theory (EFT) interpretation of differential cross-section.
- **Combine measurements of Higgs boson coupling with CMS detector.** [CMS- HIG-19-005]
  - EFT interpretation of differential cross-section.
- **Summary**

NOTE

- High p_T can be referred to as p_T of any physics process which is above flavour physics.
- There are many high p_T physics processes, e.g., Higgs, top, W/Z productions, which set constraints on EFT parameters.
- Several Higgs results are interpreted in EFT framework, I will discuss EFT interpretation of some recent Higgs physics results.
- Differential cross-section of various Higgs productions can be interpreted in the EFT framework with the CMS and ATLAS experiments.

Motivation

- **No new physics discovered so far….**
- **Deviations from SM predictions may be a sign of new physics beyond SM.**

Why EFT ?

- **Effective Field Theory(EFT) parametrizes unknown interactions in a model-independent way.**
- **Gauge-invariant.**
- **Provides guidance to new physics. Leading effects are parametrized by large no. of dimension-six operators.**
- **For Higher dimensions, EFT effects become negligible as**

$1/\Lambda^2 > 1/\Lambda^4 > 1/\Lambda^8$

Lagrangian of effective field theory is -

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Violate the lepton number **Violate baryon and lepton number**

- EFT is one way to search 'Beyond Standard Model'.
- In SM, values of all coefficients(C_i) are zero.
- Impact of higher-dimensional operators is expected to be suppressed by more powers of the cutoff scale Λ.
- only dim-6 operators are considered in the following, neglecting all higher-order operators.
- Several operator bases can be defined using the Warsaw (in ATLAS) and the HEL basis (in CMS) in this talk.

C_i ; Wilson coefficients

O_i ; operators with dimensions

Λ ; energy scale of new physics

Operator baisis

- The Warsaw and SILH basis are both defined with operators containing SM fields before the electroweak symmetry breaking. The differences between the two come from the slightly different definitions of operators.

HEL basis

$$\mathcal{O}_g = |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\tilde{\mathcal{O}}_g = |H|^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$
$$\mathcal{O}_\gamma = |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\tilde{\mathcal{O}}_\gamma = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$
$$\mathcal{O}_u = y_u |H|^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$$
$$\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R + \text{h.c.}$$
$$\mathcal{O}_\ell = y_\ell |H|^2 \bar{L}_L H \ell_R + \text{h.c.}$$
$$\mathcal{O}_H = \left(\partial^\mu |H|^2\right)^2$$
$$\mathcal{O}_6 = \left(H^\dagger H\right)^3$$
$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$$
$$\mathcal{O}_W = i\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = i\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

Warsaw basis

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p \gamma_\mu l_t)(\bar{l}_r \gamma^\mu l_s)$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r \widetilde{H})$	c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	c_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

EFT interpretation of Higgs measurements

- For the interpretation of Higgs boson measurement in EFT framewrk, STXS measurements is possible input to interpret it.
  - STXS measurements allow straight forward combination of different Higgs analysis results, therefore increasing the number of EFT parameters that can be fitted simultaneously.
  - STXS bins are defined in different stages such as STXS stage 1.1 [Ref.] and STXS stage 1.2 [Ref.]
  - **The cross section in bin 'i' of the STXS framework**

$$\sigma^{EFT}_i = \sigma^{SM}_i + \sigma^{int}_i + \sigma^{BSM}_i$$

  - **Branching ratio parametrization is given** $\sigma \times B$
  - **Scaling functions:** $\mu_i(C_j) = \sigma^{EFT}_i / \sigma^{SM}$

$$\mu_i(C_j) = 1 + \sum_j A_j C_j + \sum_{jk} B_{jk} C_j C_k$$

linear terms from the SM-BSM interference

quadratic term from purely BSM effect

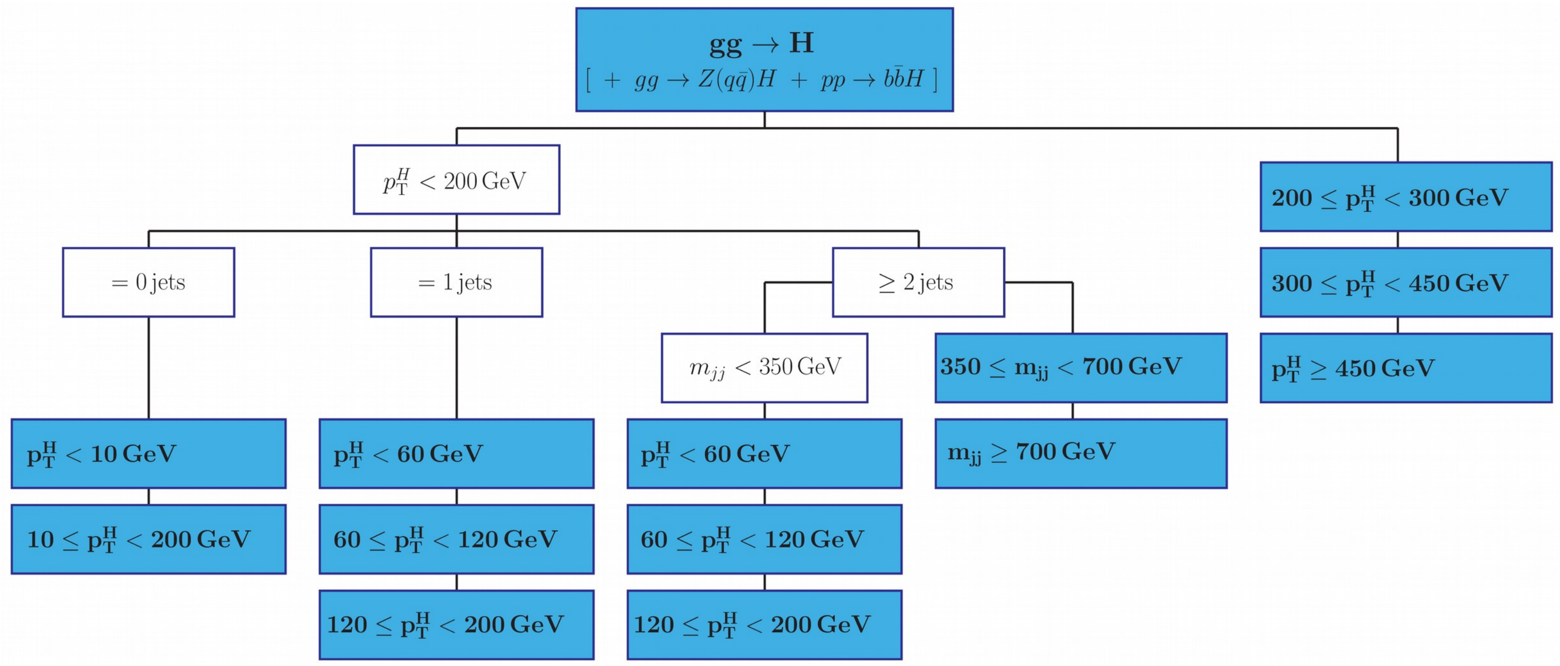
$$\sigma \propto |\mathcal{M}_{\rm SMEFT}|^2 = \left| \mathcal{M}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{M}_i \right|^2$$
$$= |\mathcal{M}_{\rm SM}|^2 + \sum_i 2Re\left(\mathcal{M}^*_{\rm SM} \mathcal{M}_i\right) \frac{C_i}{\Lambda^2}$$
$$+ \sum_{ij} 2Re\left(\mathcal{M}^*_i \mathcal{M}_j\right) \frac{C_i C_j}{\Lambda^4},$$

Not considered ($\sim 1/\Lambda^4$)

Simplified Template Cross Sections (STXS)

- STXS can be built different productions of Higgs boson e.g. ggH(right).
- In fig, Bins are based on multiplicity of particle-level jets, the Higgs boson transverse momentum p^H_T and the invariant mass m_{jj} of the two jets.
- Fit parameter is

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \frac{B_f}{B_{ZZ}}$$



Ref : https://cds.cern.ch/record/2789544/files/ATLAS-CONF-2021-053.pdf

EFT interpretation of Higgs measurements

- There are some other Higgs measurements, such as differential distributions, which are also sensitive to EFT effects. Some results are.
  - Measurements and interpretations of Higgs-boson fiducial cross sections in the diphoton decay channel using 139 fb^{-1} of p p collision data at $\sqrt{s}$ =13 TeV with the ATLAS detector. [ATLAS-CONF-2019-029]
  - Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state.[CMS-HIG-19-009]
- These topics are not covered in this presentation because of time constraints.

Combined measurements of Higgs boson production and decay using up ATLAS experiment

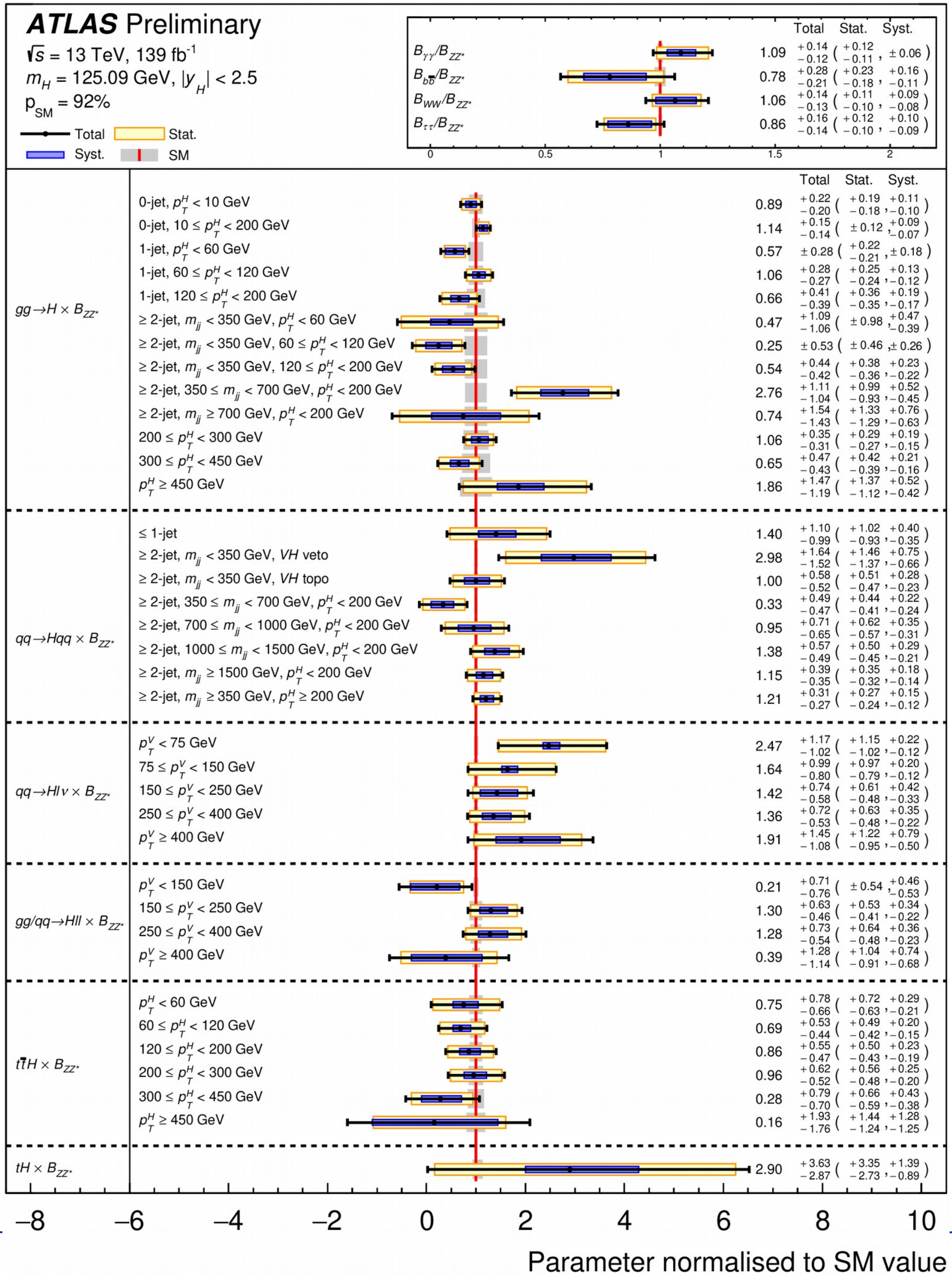
Reference

- **H → γγ, ZZ*, WW*, ττ, $b\bar{b}$ decay modes are combined.**
- **Combined cross-sections are measured in gluon–gluon fusion (ggF) and vector-boson fusion (VBF) processes, and for associated production with vector bosons (VH) or top-quarks ($t\bar{t}H$).**
- **Measurements in kinematic regions are defined within the simplified template cross section stage 1.2 framework.**
- **STXS 1.2 results are interpreted in EFT framework.**
- **The constraints on the Wilson coefficients can be derived by comparing the expected with the measured simplified template cross-sections.**
- **All individual analyses are done with full Run 2 data.**
- **Combined Result was published only one month ago.**

STXS results

- STXS are built for ggH(slide 9), qqH, VH, ttH(in backup) .

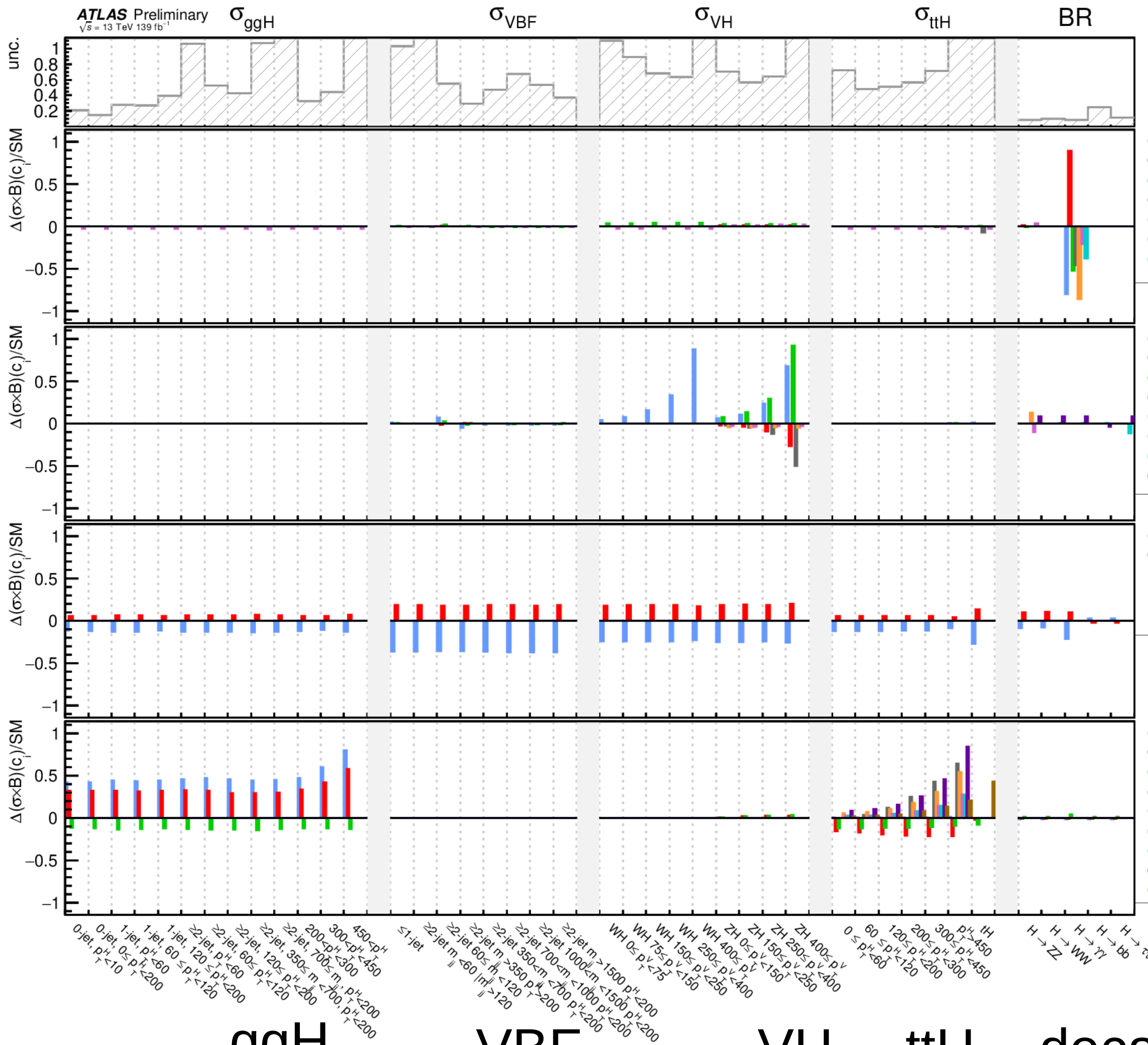
Ref : https://cds.cern.ch/record/2789544/files/ATLAS-CONF-2021-053.pdf



Impact on STXS

- SMEFT operators are defined within the Warsaw basis.

  boson couplings to quarks and leptons.
- EFT parametrization takes into account only the linear EFT terms, i.e. only the interference between SM and BSM
- A set of mutually orthogonal linear combinations of Wilson coefficients is fitted simultaneously to data
- Sensitivity of some operators is increasing with high Higgs p_T(bins are ordered in increasing manner).



Coupling to Vector bosn

boson couplings to quarks and leptons

Higgs couplings to leptons, four-lepton couplings

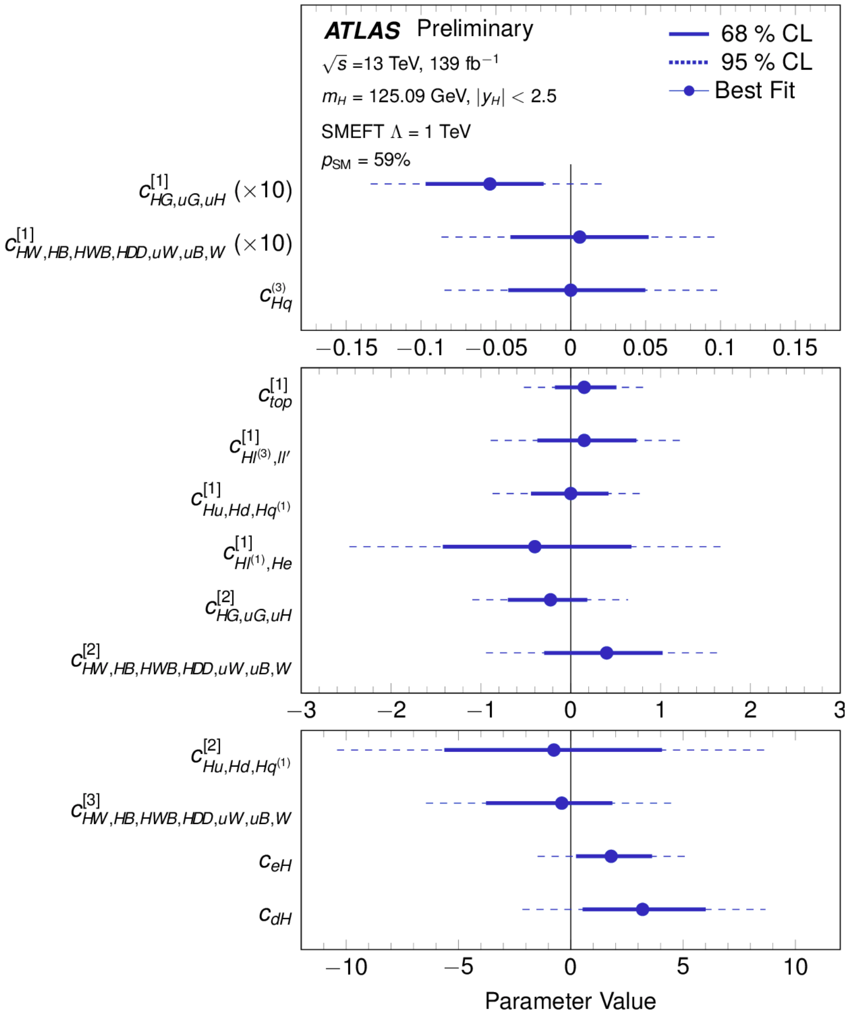
Higgs couplings to gluons and quarks, four-quark couplings

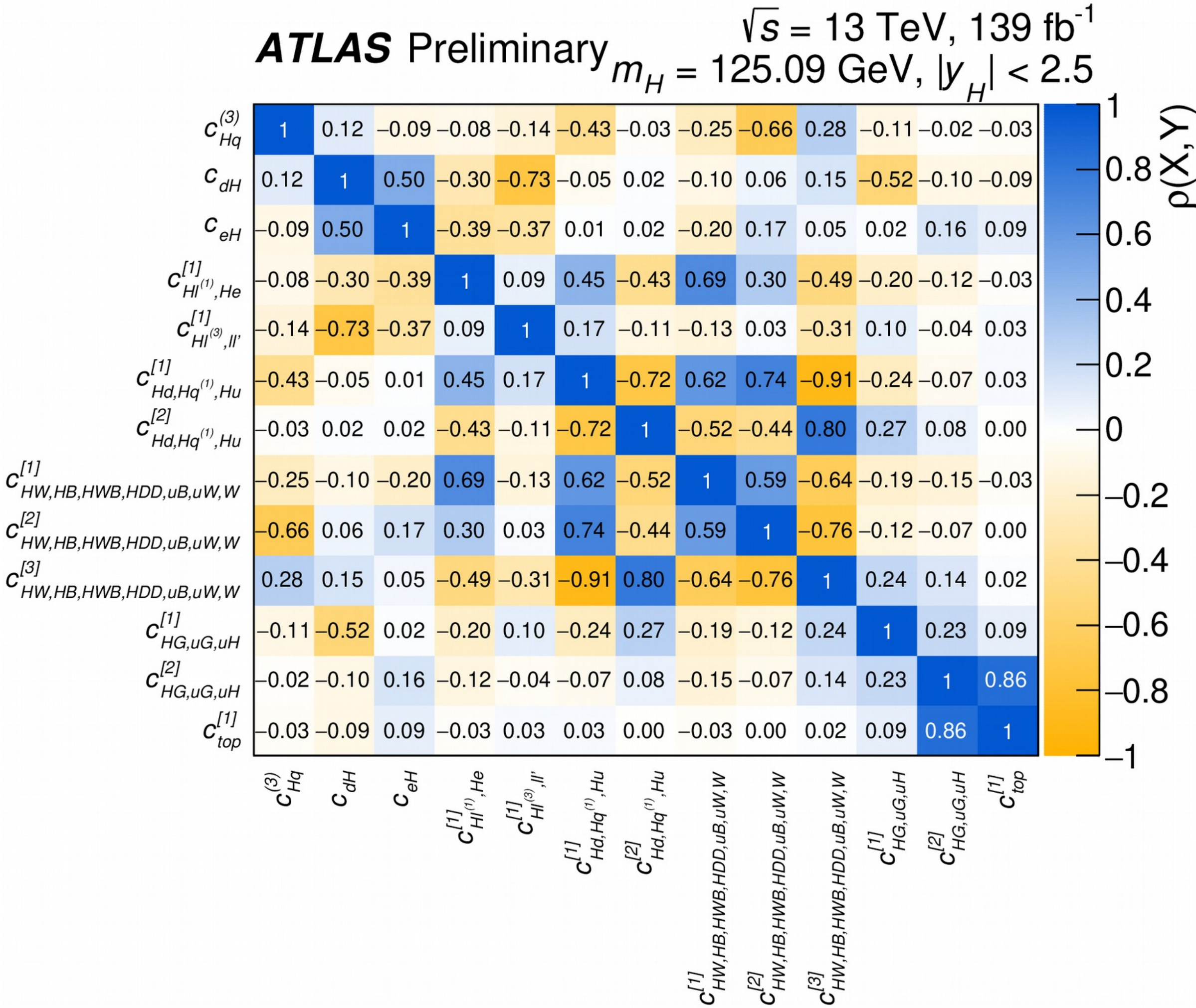
ggH VBF VH ttH decays

Impact of the most relevant SMEFT operators on the STXS regions and decay modes.

Results

Reference





- Signal acceptance is parametrized in terms of Wilson coefficients and this correction is then applied on top of the sigmaxBR parametrization.
- Obtained exclusion limits improved by up to 70% compared to the ATLAS EFT interpretation of previous combined Higgs STXS measurements.

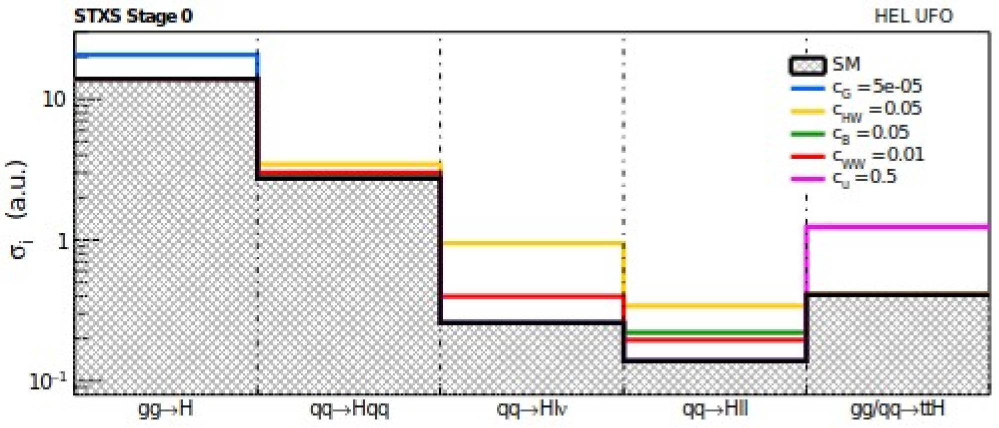
Combined measurements of the Higgs boson couplings at 13 TeV in the CMS experiment

- **Analyses included in the combination**
- **The Higgs boson production modes and decays are considered as signal.**
- **After combination, STXS measurements are interpreted in EFT framework.**

CADI	Channel	Dataset
HIG-19-001	H→ZZ (STXS 1.1)	2016+2017+2018
HIG-18-029	H→γγ (STXS 1.0)	2016+2017
HIG-16-042	H→WW	2016
HIG-18-032	H→ττ	2016+2017
HIG-17-019	H→μμ	2016
HIG-17-010	H→bb boosted	2016
HIG-18-018	ttH H→γγ	2016+2017
HIG-18-019	ttH H→lep	2017
HIG-17-018	ttH H→lep	2016
HIG-18-030	ttH H→bb	2016+2017
HIG-18-016	VH H→bb	2017
HIG-16-044	VH H→bb	2016
HIG-18-007	VH H→ττ	2016

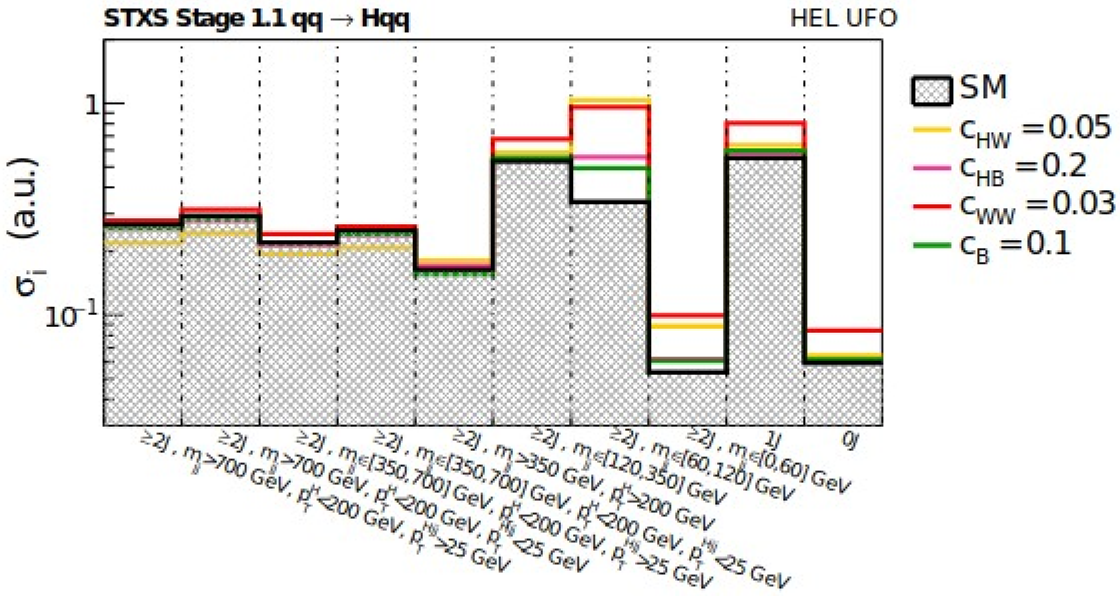
https://cds.cern.ch/record/2706103/files/HIG-19-005-pas.pdf

Effective field theory couplings: STXS re-interpretation



- **HIG-19-005: combination of STXS stage 0, 1 & 1.1 processes.**

- **Modifications to the acceptance due to EFT operators are ignored.**

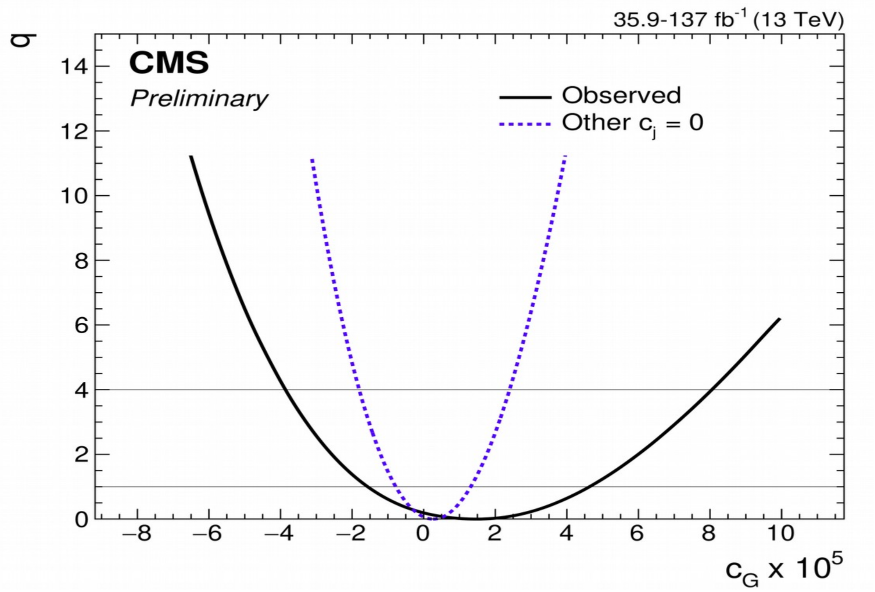


- **Introduces 39 flavor independent dim-6 operators consider eight of these(CP even) in HEL.**

- **New physics: deviations from 0 in HEL coefficients.**

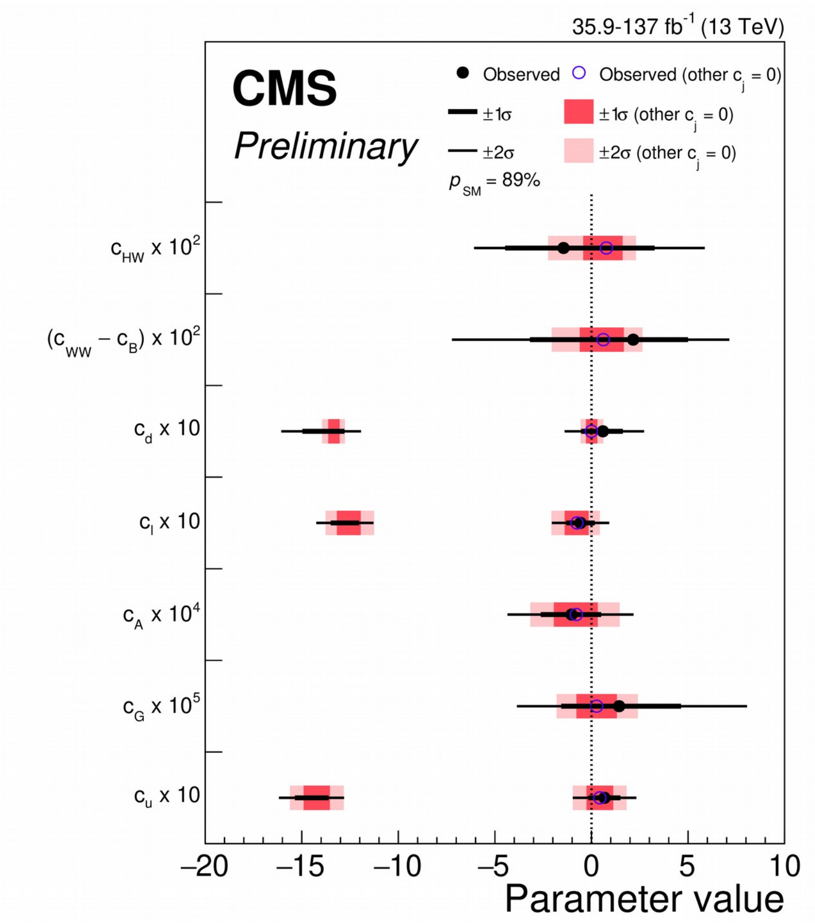
HEL parameters

- **7 parameters of 15 dim- 6 operators affecting Higgs physics are:**
  - c_G , c_A , c_u , c_d , c_l , c_{HW} , $c_{WW} - c_B$
- **Signal scales according to product of STXS & decay parametrization**
  - take decay parametrization directly from [LHCHXSWG-2019-004]
- **EFT fit**
  - Two likelihood scans for each POI
  - fix other parameters to SM, $c_j = 0$ (blue dashed)
  - profile other parameters during minimization (solid black)



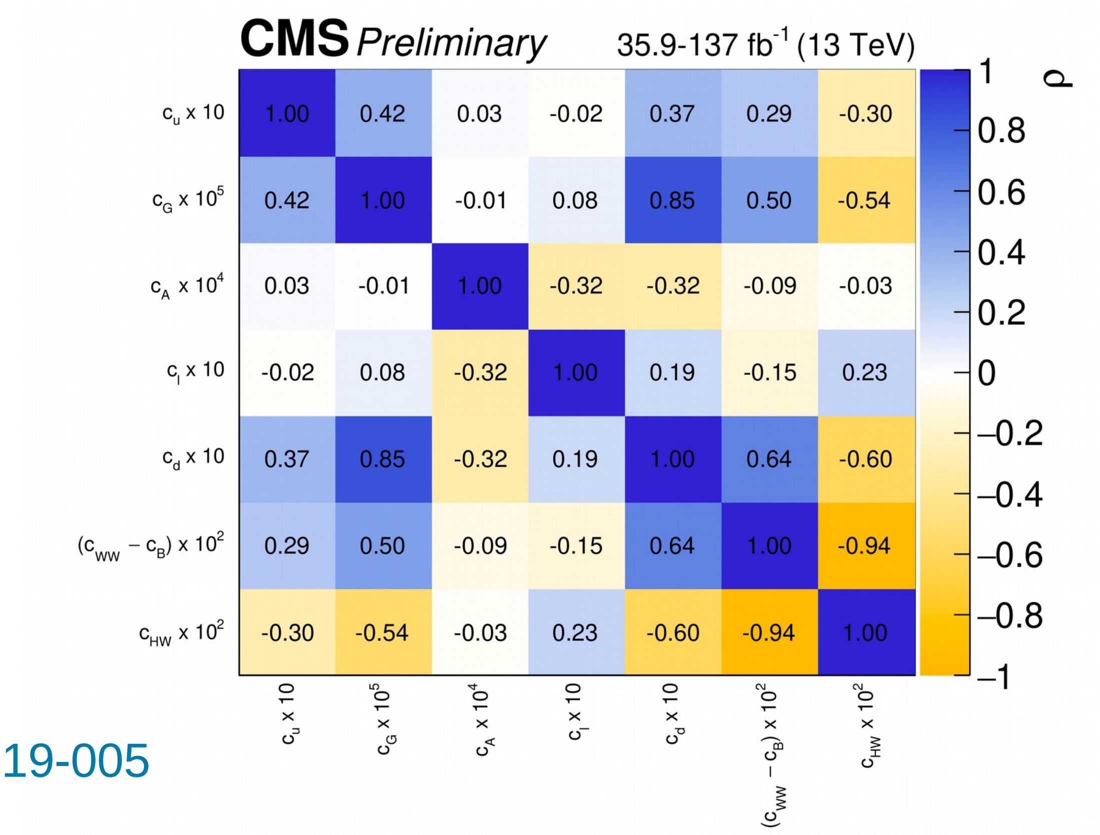
Reference : HIG-19-005

Results : Summary plot and correlation matrix



Summary plot for the HEL parameter scans. The best fit values when profiling (fixing) the other parameters are shown by the solid black (hollow blue) points.

Reference : HIG-19-005



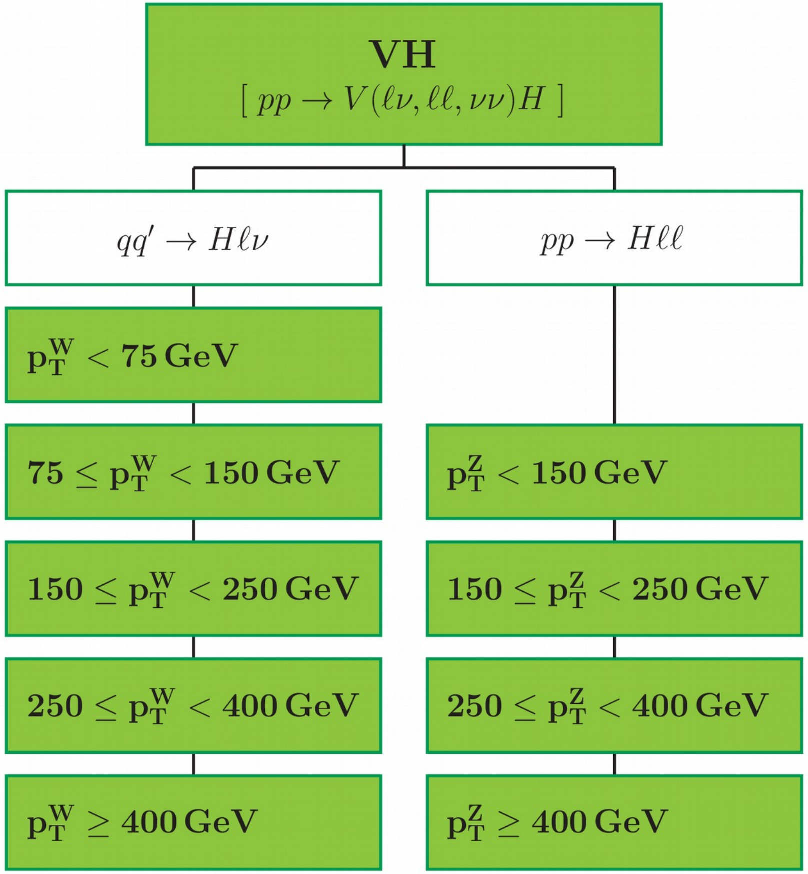
Observed correlations in the HEL parameters. The size of the correlation is given by the colour scale with positive (negative) correlation represented by blue (yellow).

Summary

- **EFT is a very promising and model-independent way to search for new BSM physics, especially in the absence of new particle detection..**
- **Higgs boson measurement results can be interpreted using EFT approach.**
- **Higgs STXS cross sections are measured in ATLAS and CMS experiments.**
  - **Combined measurements of Higgs boson production and decay with the ATLAS experiment, doi: https://doi.org/10.1140/epjc/s10052-020-8227-9**
  - **Combine measurements of Higgs boson couplings in CMS experiment, doi: https://cds.cern.ch/record/2706103/files/HIG-19-005-pas.pdf**
- **STXS results are in good agreement with SM theoretical predictions.**
- **STXS measurements used to set constraints on several EFT parameters related to the Higgs couplings.**


Thank you!

Simplified Template Cross Sections (STXS)



Ref :
https://arxiv.org/pdf/21
pdf