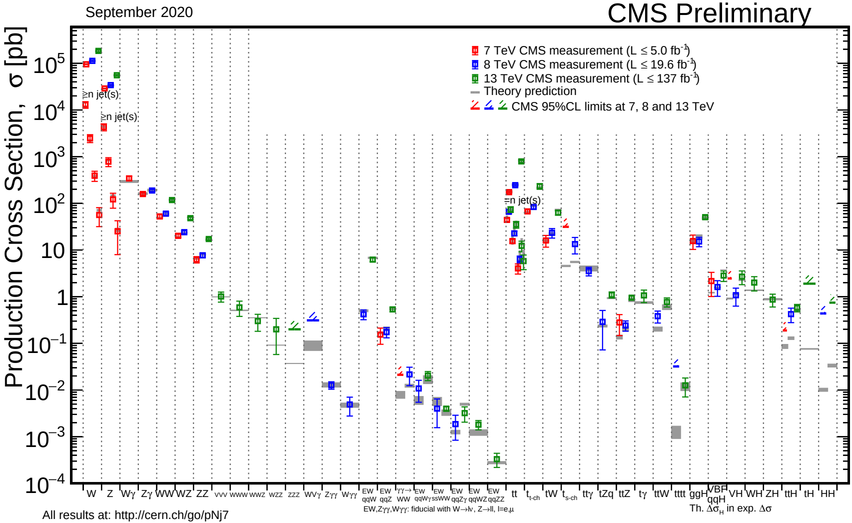
Higgs boson measurements and their EFT interpretations

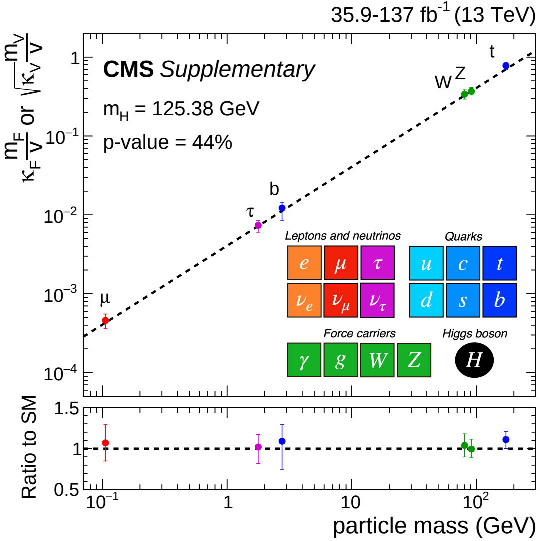
Dermot Moran (CIEMAT)

Triumph of the SM at the LHC



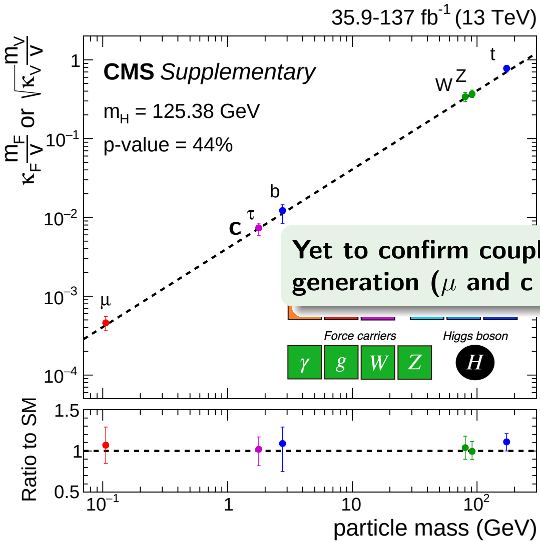
Predictions and measurements agree over **many orders of magnitude**

SM picture of EWSB established



Observed Higgs coupling to **heavy fermions and vector bosons**

SM picture of EWSB established..



Yet to confirm coupling to 2nd generation (μ and c quark?)

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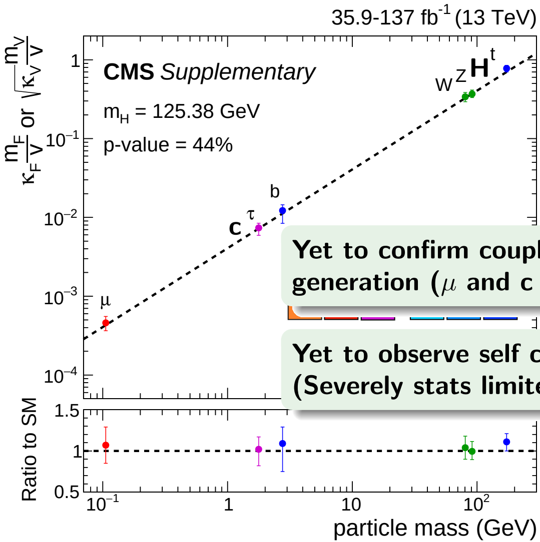

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Yet to observe self coupling of Higgs (Severely stats limited at LHC!)

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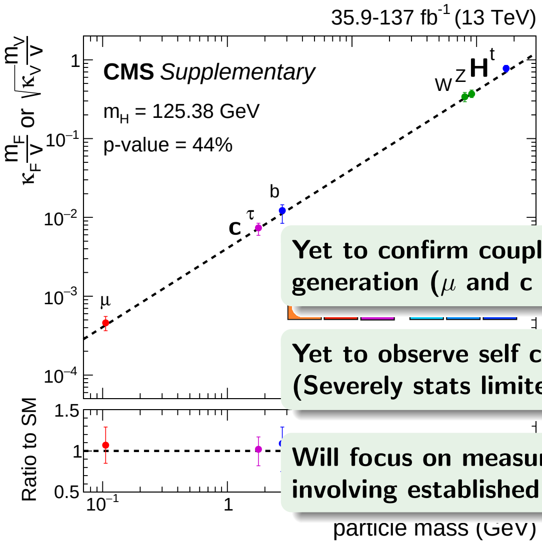


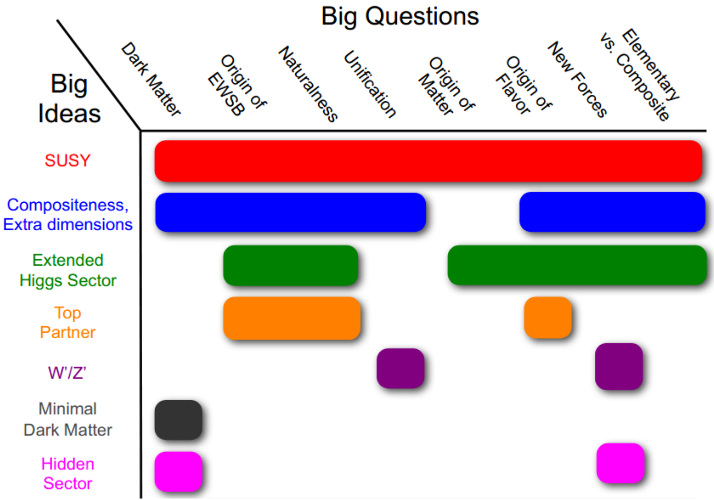
Yet to confirm coupling to 2nd generation (μ and c quark?)

Yet to observe self coupling of Higgs (Severely stats limited at LHC!)

Will focus on measurements involving established couplings

Observed Higgs coupling to **heavy fermions and vector bosons**

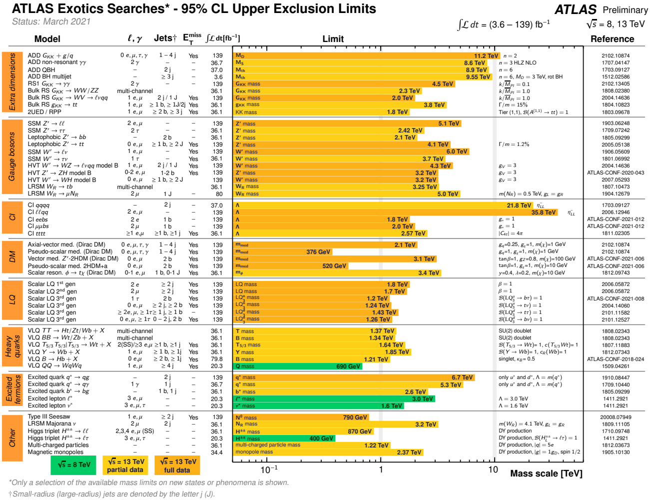
Big questions remain



Big ideas for what lies beyond the SM

→ Generally predict **new particles at the TeV scale**

Direct searches at LHC find no new particles

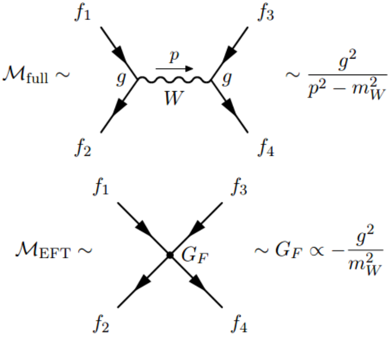


Suggests **energy gap** between SM and New Physics (NP)

Energy scale hierarchy motivates use of **Effective Field Theory (EFT)**

Different physics at different Energy scales

Fermi Theory : Low energy EFT of the SM (Full underlying theory)



W propagator $\rightarrow$ contact interaction

Correctly describes physics if $p^2 << m_W^2$

In turn can **treat SM as low energy EFT** of some unknown underlying theory

Recipe for a SM EFT

Don't know underlying theory so take a **"bottom-up"** approach :

- **1) Particles :** Include **all particles with m** $<< \Lambda \rightarrow$ Operators ($\mathcal{O}_i$) built from combinations of SM Fields and derivatives
- **2) Symmetries :** Require $\mathcal{O}_i$ obey **SM symmetries** (Gauge, Lorentz)
- **3) Dimension Counting :** Split coupling in front of $\mathcal{O}_i$ into constant c_i and some power of $\Lambda \rightarrow$ Organize $\mathcal{O}_i$ with respect to their mass dimension D

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

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$\mathcal{O}_i^5$ violate lepton number and $\mathcal{O}_i^7$ violate Lepton or Baryon number

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$\mathcal{O}_i^5$ violate lepton number and $\mathcal{O}_i^7$ violate Lepton or Baryon number

$\mathcal{O}_i^8$ suppressed by $1/\Lambda^4 \rightarrow$ Typically neglected

A SM EFT

$$\boxed{\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}.}$$

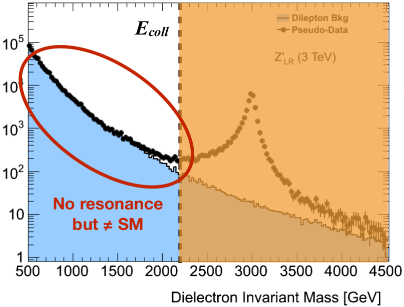
Effects of heavy **NP mapped onto** $\mathcal{O}_i^6$

c_i **(Wilson coefficient)** specify the strength of the new interactions

Contribution of $\mathcal{O}_i^6$ scale as $(E/\Lambda)^2 \rightarrow$ Can induce growth with $\sqrt{s}$

EFT only **valid at** $E < \Lambda$

For example : Effect of Z' on dielectron mass when E $< m_{Z'}$



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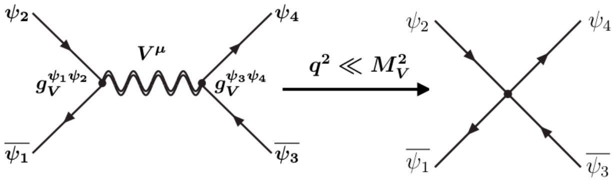


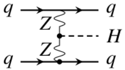
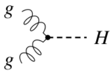
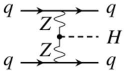
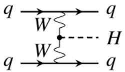
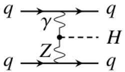
Deformation in dielectron mass described by $\mathcal{O}_i^6$ effective interaction

Basis of Dimension 6 Operators

Warsaw basis : First complete and non-redundant set of operators (59)

Popular SMEFT basis in the theoretical community

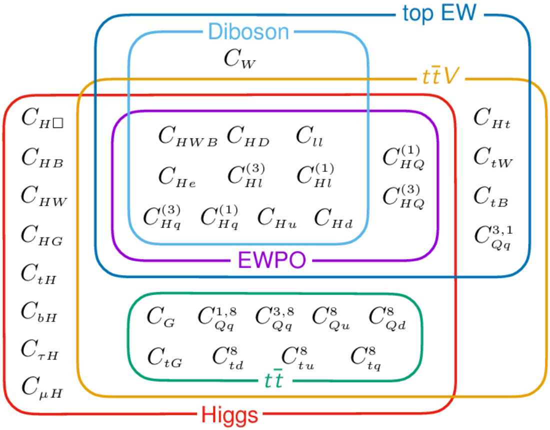
Most relevant for HVV interactions (V = Gauge boson) :

Coefficient	Operator	Example process
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	
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}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	

+ corresponding CP−Odd operators $\tilde{\mathcal{O}}_{HG}$, $\tilde{\mathcal{O}}_{HB}$,$\tilde{\mathcal{O}}_{HW}$, $\tilde{\mathcal{O}}_{HWB}$

Basis of Dimension 6 Operators

Operators may contribute to **several classes of measurements**



Long term goal : ATLAS and CMS combination (**Global Fit**) of EW+Higgs+Top measurements to detect SM deformations

Basis of Dimension 6 Operators

Higgs basis : Convenient (experimentally) to express EFT in terms of **mass eigenstates after EWSB** :

$$\begin{aligned}\mathcal{L}_{\rm hvv} = \quad & \frac{h}{v}\left[(1+\delta c_z)\,\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu \partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}\right.\\ & + (1+\delta c_w)\,\frac{g^2v^2}{2}W^+_\mu W^-_\mu + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + c_{w\Box}g^2\left(W^-_\mu \partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}\\ & + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}\\ & \left. + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\right],\end{aligned}$$

More transparent connection to measurable quantities

SILH basis : Strongly-Interacting Light Higgs "**top-down**" EFT

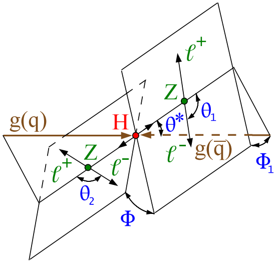
More direct mapping to some BSM scenarios (Composite Higgs)

Both related to Warsaw basis through linear transformations

So how are Higgs related EFT coefficients measured?

Dedicated (detector-level) measurements :

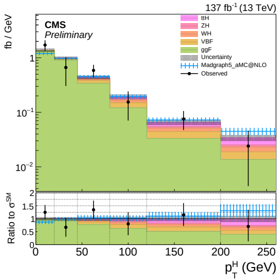
Use **dedicated discriminants** and **full simulation** of Signal PDFs



Interpretations of other measurements :

2 types : Differential fiducial σ and simplified template σ (STXS)

Signal **parameterised in gen-level** fiducial bins



Pros and cons for all approaches

Instructive to go through some recent examples from Run 2!

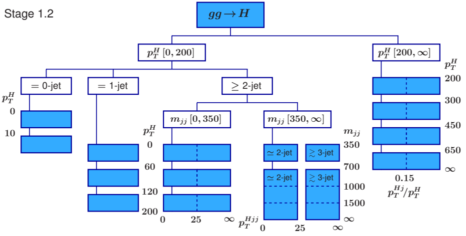
STXS measurements

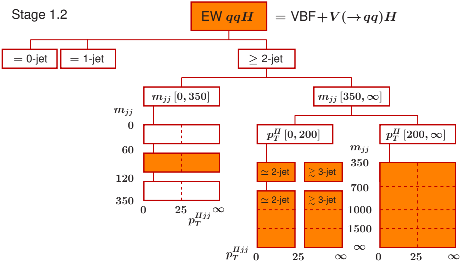
Measure σ in **pre-defined kinematic bins per production mode**

Aim to **minimize theory dependence** while
maximizing sensitivity to BSM effects

No fiducial phase space (except for $|y_H|$ <2.5)

Can combine decay channels but significant model dependence





ATLAS STXS interpretations with Warsaw basis

Using $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ$ and V(lep)$H\rightarrow bb$

SMEFT σ parameterisation :

$$\sigma \propto |\mathcal{M}_{SM} + \sum_i \bar{c}_i \mathcal{M}_i|^2$$

$$\sigma = \sigma_{SM} + \sigma_{Int} + \sigma_{BSM}$$

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$

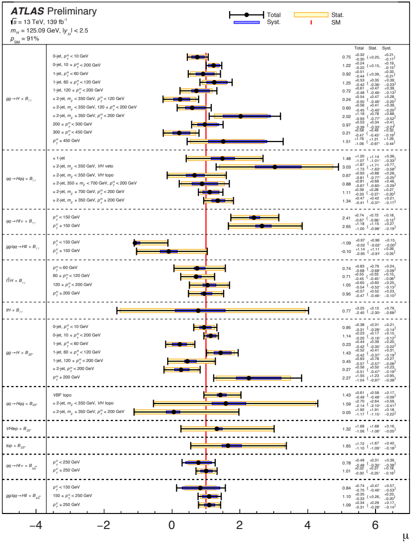
Remember $\bar{c}_i = c_i/\Lambda^2$ so we have :

Linear ($\bar{c}_i$) term suppressed by $1/\Lambda^2$

Quadratic ($\bar{c}_i \bar{c}_j$) term suppressed by $1/\Lambda^4$

A_i and B_{ij} are extracted from simulation

(Same procedure for decay param)

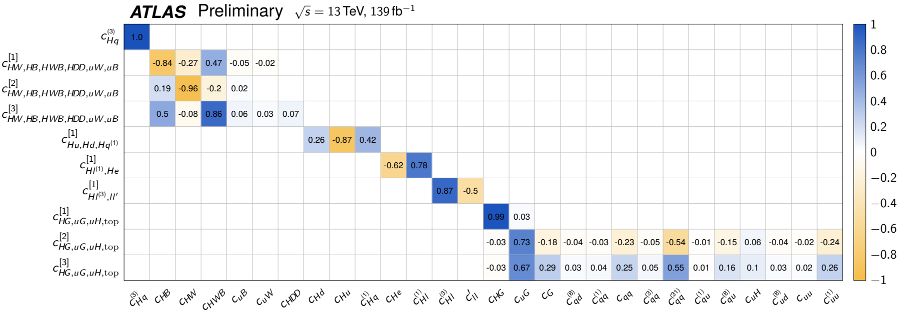


A modified Warsaw basis

Consider **all CP-Even** $\mathcal{O}_i^6$ - Insufficient info to constrain all c_i simultaneously

Use Fisher information and find eigenvectors
$\rightarrow$ **Sensitive directions** in $\mathcal{O}_i$ space

Set constraints on linear combinations of c_i (Modified basis)



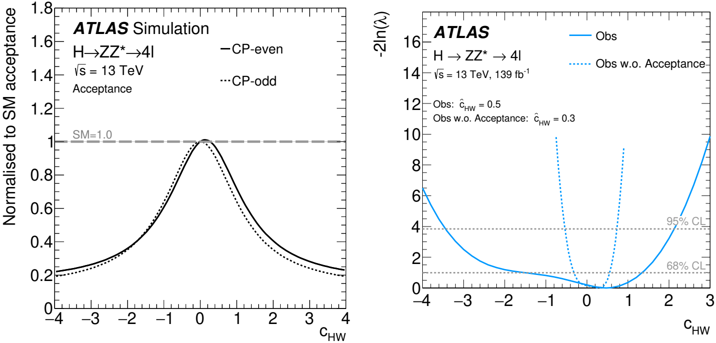
Degeneracy broken with info from other measurements? (VV, top, ...)

Acceptance effects

Possibility of **acceptance changes** induced by operators

H$\rightarrow$ZZ$\rightarrow$4ℓ is significantly impacted
(Particularly due to m_{Z_2} requirements in the analysis)

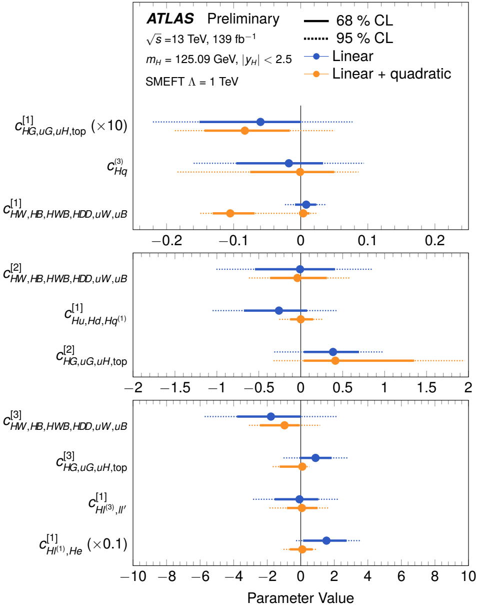
Ad-hoc correction derived and applied to ZZ decay parameterisation



For all other H decays acceptance effects are neglected

***Effect could be significant for HWW also**

ATLAS STXS interpretations with Warsaw basis



CMS STXS interpretations with SILH basis

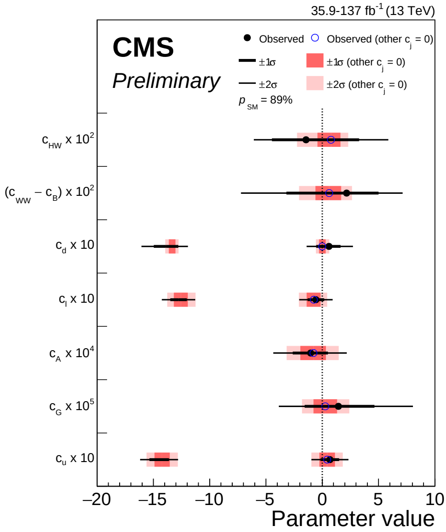
Using H decays to ZZ, $\gamma\gamma$, WW, bb and $\tau\tau$

Considered **8 leading CP-even operators**

Linear + Quadratic terms considered

For full run 2 analysis **moving to Warsaw basis**

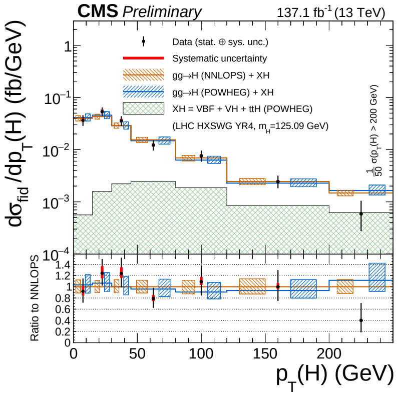
Also **acceptance effects to be included!**

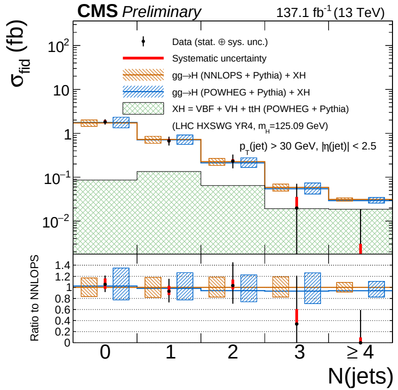


Fiducial Differential measurements

Fiducial : Target phase-space region matching experimental selection (Minimize model dependence)

Differential : In bins of a variable (p_T^H, N_{Jets},...) (generally 1 or 2 dimensions)





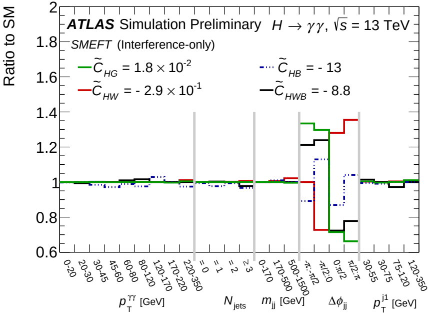
Fiducial depends on final state → Not trivial to combine different modes

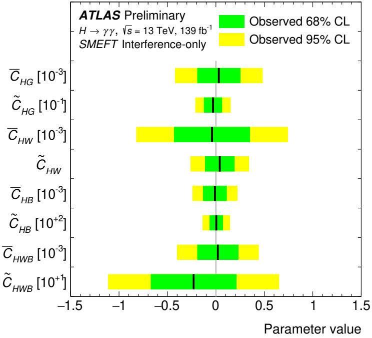
ATLAS H$\to \gamma\gamma$ interpretation with Warsaw basis

Several 1D measurements : $p_T^{\gamma\gamma}, N_{Jets}, m_{jj}, \Delta\Phi_{jj}$ and p_T^{j1}

Correlations between bins in different distributions calculated using bootstrapping
$\to$ Use all variables in interpretation

Target **8 leading CP-Even and Odd** (Sensitivity from $\Delta\Phi_{jj}$) $\mathcal{O}_i^6$
$\to$ Constraining one at a time





Constraints much greater when including quadratic terms for CP-odd $\mathcal{O}_i^6$

Dedicated HZZ EFT measurements at CMS

General Lorentz invariant form of **HVV scattering amplitude :**

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

SU(2)xU(1) enforces relations between ZZ,WW,$\gamma\gamma$ and Zγ couplings :

$$\begin{aligned}
a_1^{\mathrm{WW}} &= a_1^{\mathrm{ZZ}}, \\
a_2^{\mathrm{WW}} &= c_w^2 a_2^{\mathrm{ZZ}} + s_w^2 a_2^{\gamma\gamma} + 2 s_w c_w a_2^{\mathrm{Z}\gamma}, \\
a_3^{\mathrm{WW}} &= c_w^2 a_3^{\mathrm{ZZ}} + s_w^2 a_3^{\gamma\gamma} + 2 s_w c_w a_3^{\mathrm{Z}\gamma}, \\
\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_w^2 \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2}, \\
\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2}\right) + 2(c_w^2 - s_w^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2}
\end{aligned}$$

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$$+ \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

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\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{\cancel{a_2^{\gamma\gamma}} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2}\right) + 2(c_w^2 - s_w^2) \frac{\cancel{a_2^{\mathrm{Z}\gamma}}}{m_{\mathrm{Z}}^2}
\end{aligned}$$

Assume $a^{\gamma\gamma}$ and $a^{Z\gamma}$ constrained by H$\rightarrow \gamma\gamma$ and H$\rightarrow$Zγ measurements

4 independent couplings : a_1 (SM), a_2, a_3 (CP-Odd), k_1

Dedicated HZZ EFT measurements at CMS

Amplitude a_i map directly to **Higgs basis EFT couplings :**

$$\delta c_z = \frac{1}{2} a_1 - 1 \,,$$
$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1}{(\Lambda_1)^2} \,,$$
$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2 \,,$$
$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3 \,.$$

Full detector simulation of corresponding HZZ states

For 1 HVV vertex $\sigma \propto |a_1 \mathcal{M}_1 + a_2 \mathcal{M}_2 + a_3 \mathcal{M}_3 + k_1 \mathcal{M}_{k1}|^2$

Many interference terms!

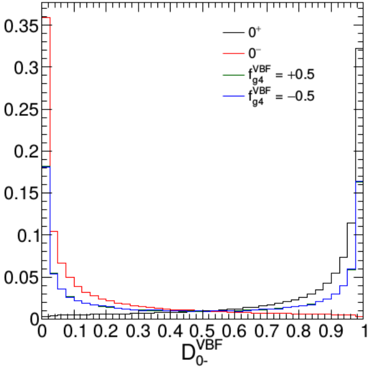
Use reweighting rather than simulate all required terms

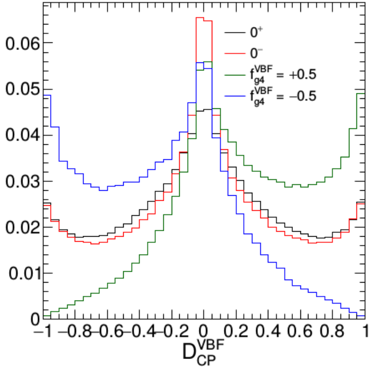
Dedicated Observables

Exploit full production (ggF,VBF,VH) and decay info ($ZZ \rightarrow 4\ell$)
with **ME based discriminants**

Can target **production mode**, **Higgs coupling model** and **interference**

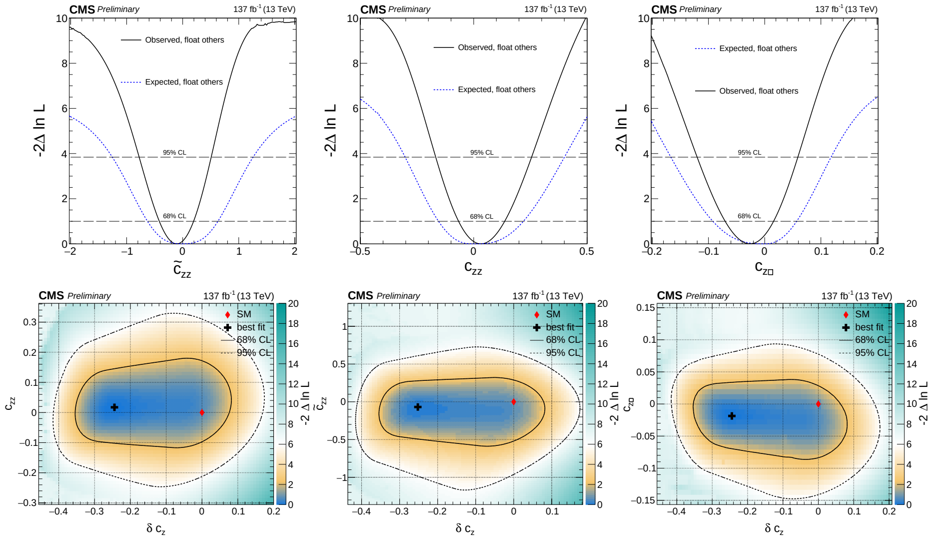
For example to study a_3(CP-Odd) in VBF HZZ can use :





Dedicated studies of **other Higgs vertices** include ggH, ttH, $H\tau\tau$

Scans of Higgs basis EFT couplings



Can **rotate to warsaw basis** → In principle could include in **global fits**

Dedicated HWW analysis also under development

Some Lessons going forward

STXS/Differential approach promising for EFT global fits but.....

1) Carefull when **extrapolating to "fiducial regions"**
Often relying on SM templates to determine efficiencies/acceptances

2) **Higgs decay** information not included
Angular info of decay (e.g HZZ 4l) sensitive to BSM effects

3) STXS not sensitive to **CP-Odd** operators

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Dedicated analysis also promising and avoids these issues but....

1) Lacks **re-interpretation flexibility** of STXS/Differential
Necessary to redo analysis for any change in theory

2) Limited to a **smaller set of operators**

3) **Time-consuming and computer-intensive** to implement

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And finally for all approaches we are neglecting **effect of operators on backgrounds**....

Global fits from Theorists

Several theorists already use LHC measurements in their **global EFT fits**

Several fitting frameworks available
(different statistical interpretations, Linear/Quadratic, LO/NLO...)

EFTfitter   Fitmaker   HEPfit

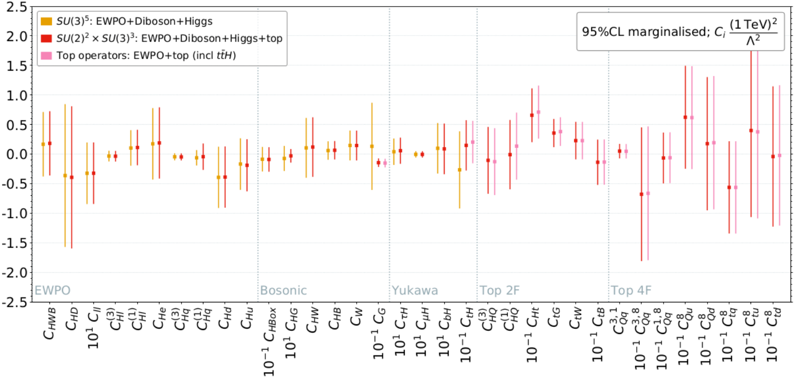
SFitter   SMEFiT

Combining **statistically independent measurements**
(include correlation info using published covariance matrices)

Combination with non-LHC constraints (LEP, Tevatron, etc)

Global fit with FitMaker

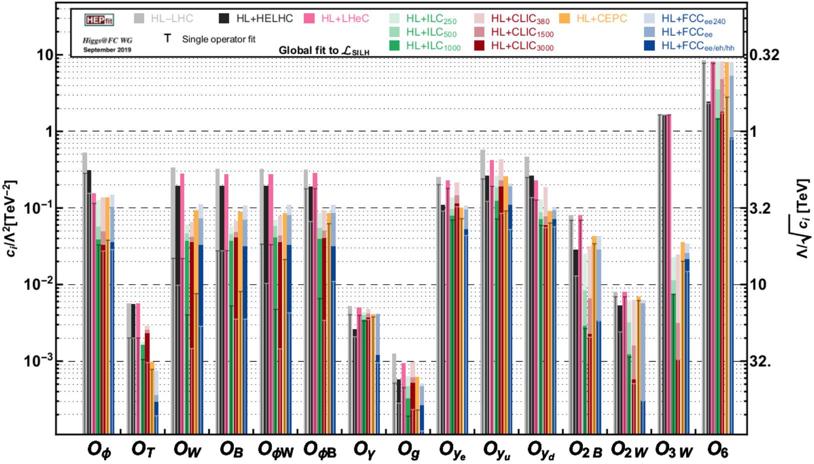
Top, Higgs, diboson and EWK fit with **warsaw basis**
(Neglecting quadratic $\mathcal{O}_i^6$ contributions)



Input from Higgs : Run 1 μ + Run 2 STXS + (CMS) HWW Differential

Global fit projections with HEPFit

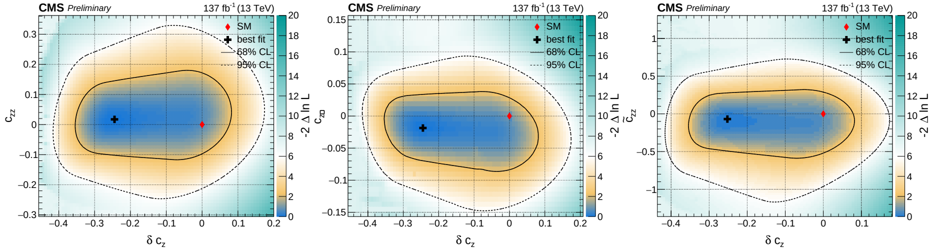
Projected Higgs (μ), diboson and EWK fit with **SILH basis**
(Neglecting quadratic $\mathcal{O}_i^6$ contributions)



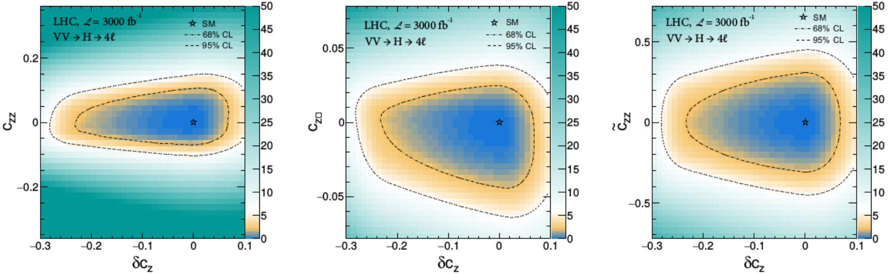
Large difference between global and single operator fit → large correlations

Projections for dedicated HZZ studies at CMS

Run 2 :



HL-LHC :



SUMMARY

- Given apparent energy gap between SM and new physics an EFT approach is well motivated at the LHC
- Long term goal would be ATLAS and CMS global fit of EW+Higgs+Top measurements to detect SM deformations
- Within Higgs groups there are a number of types of measurements that could be exploited in a global fit :

  STXS
  Fiducial Differential
  Dedicated (detector-level) analysis

- Pros and cons of each and many recent developments discussed
- Exciting and fast moving area so watch this space!!