Top and Higgs in SMEFT and the LHC

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The University of Manchester

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Where Does This Talk Stand?

Theory

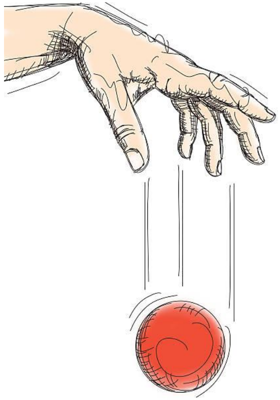
``I did some math, there is gravity''

Phenomenology

``If there is gravity, then things should fall''

Experiment

``Things fall, Newton is correct''



What Is The Goal of This Talk?

The goal is **not to go** through the intricate details of the Standard Model (SM) nor the SM Effective Field Theory (SMEFT)

nor it is to summarise the LHC measurements, theory predictions, or to discuss a particular LHC process

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The goal **is to remind you of the fundamental problem** we are here for,

and **what is it we can do about it;** with real practical examples

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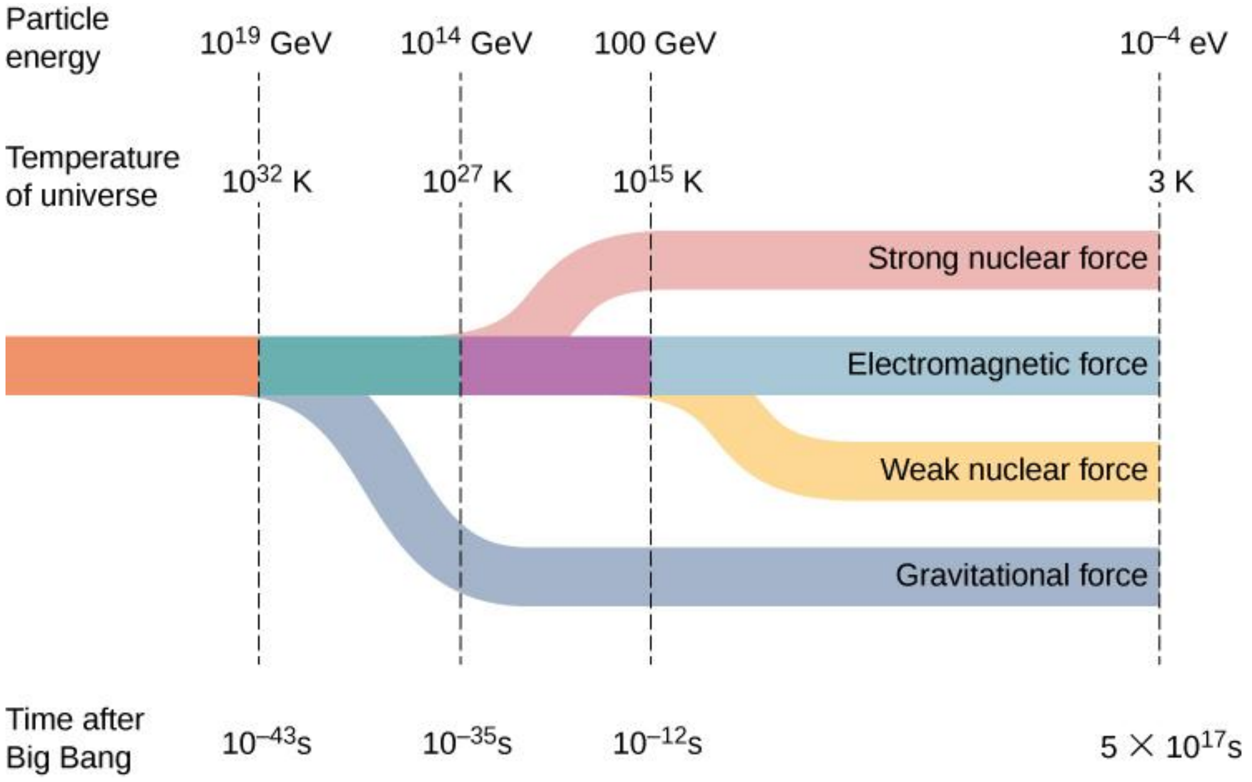
Universe Timeline



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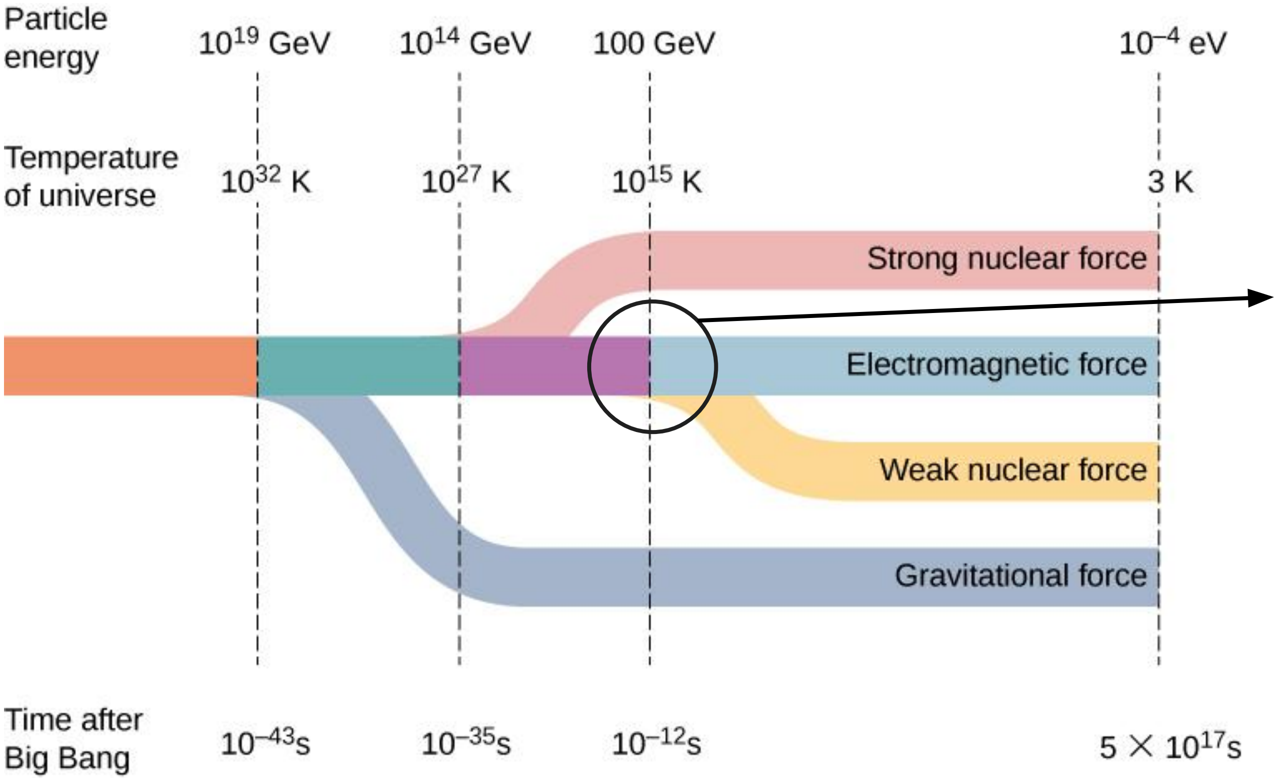
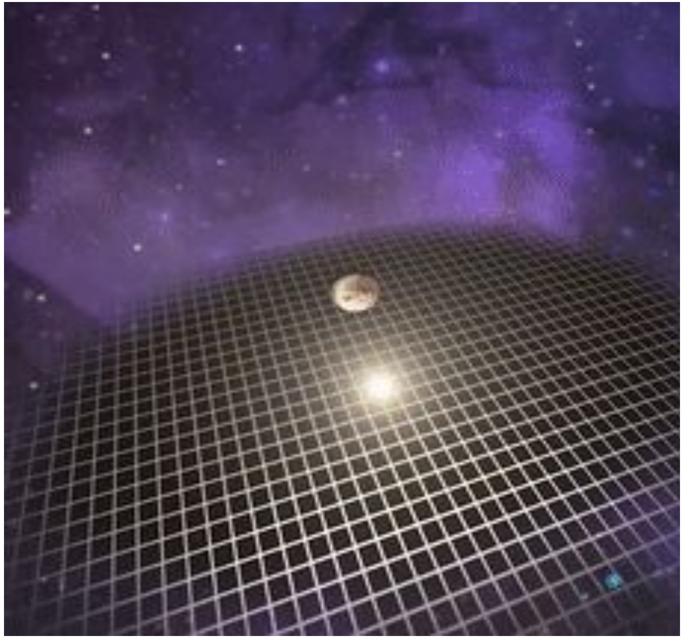


Do we really understand what is going on here?

Intermission: Symmetry



How the Higgs Mechanism Give Things Mass PBS Space Time

Physics does not change under change of coordinates; **dynamics of the system are symmetric under certain transformations described by some symmetry**

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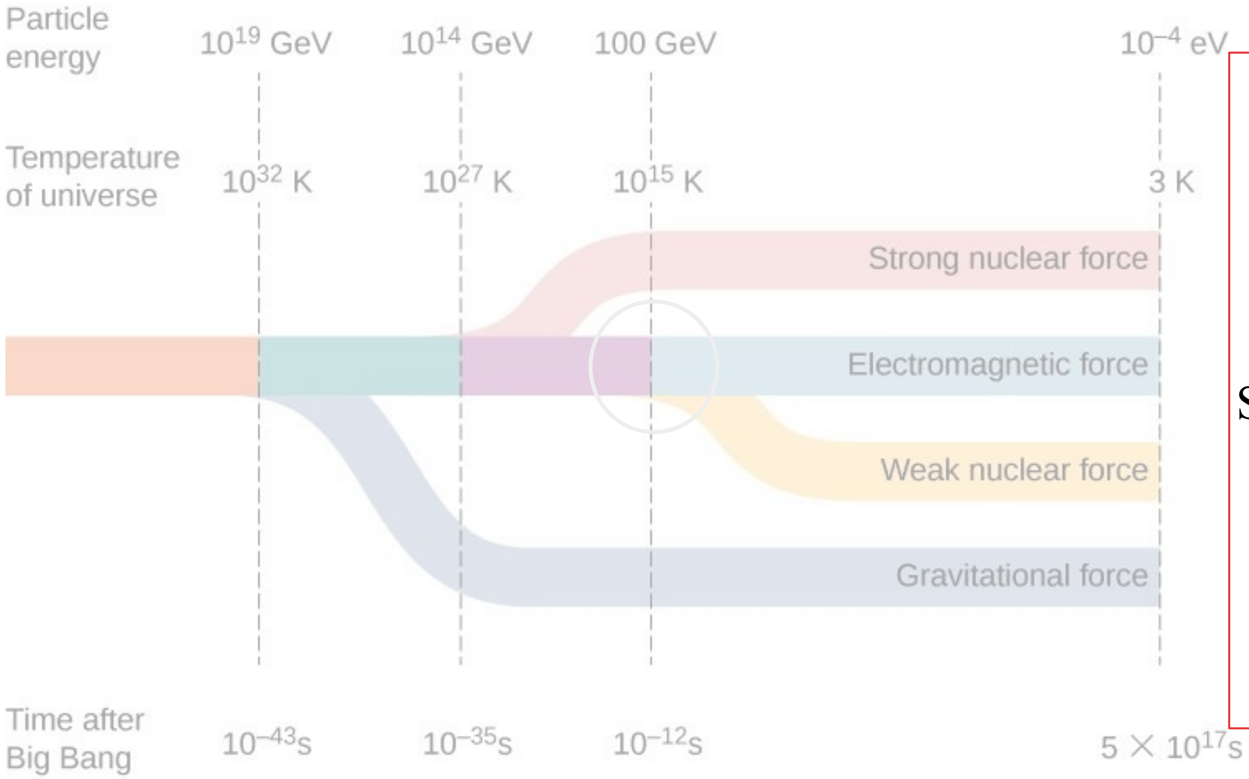
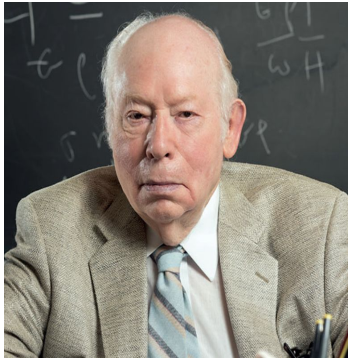


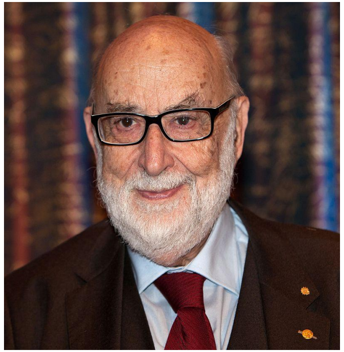
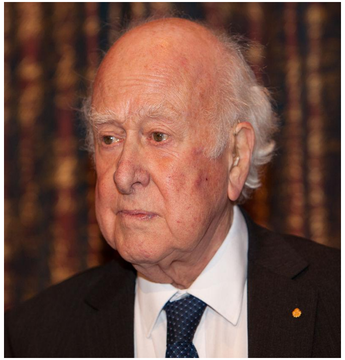
The SM is a gauge symmetry; $SU(3)_C \times SU(2)_L \times U(1)_Y$

$SU(2)_L \times U(1)_Y$ Electroweak (EW) symmetry dictates massless gauge bosons, but we know the weak bosons are massive..

Through an Intertwined History, A Symmetry is Understood and Broken!





and After Some Time..

ABOUT NEWS

ATLAS and CMS publish observations of a new particle

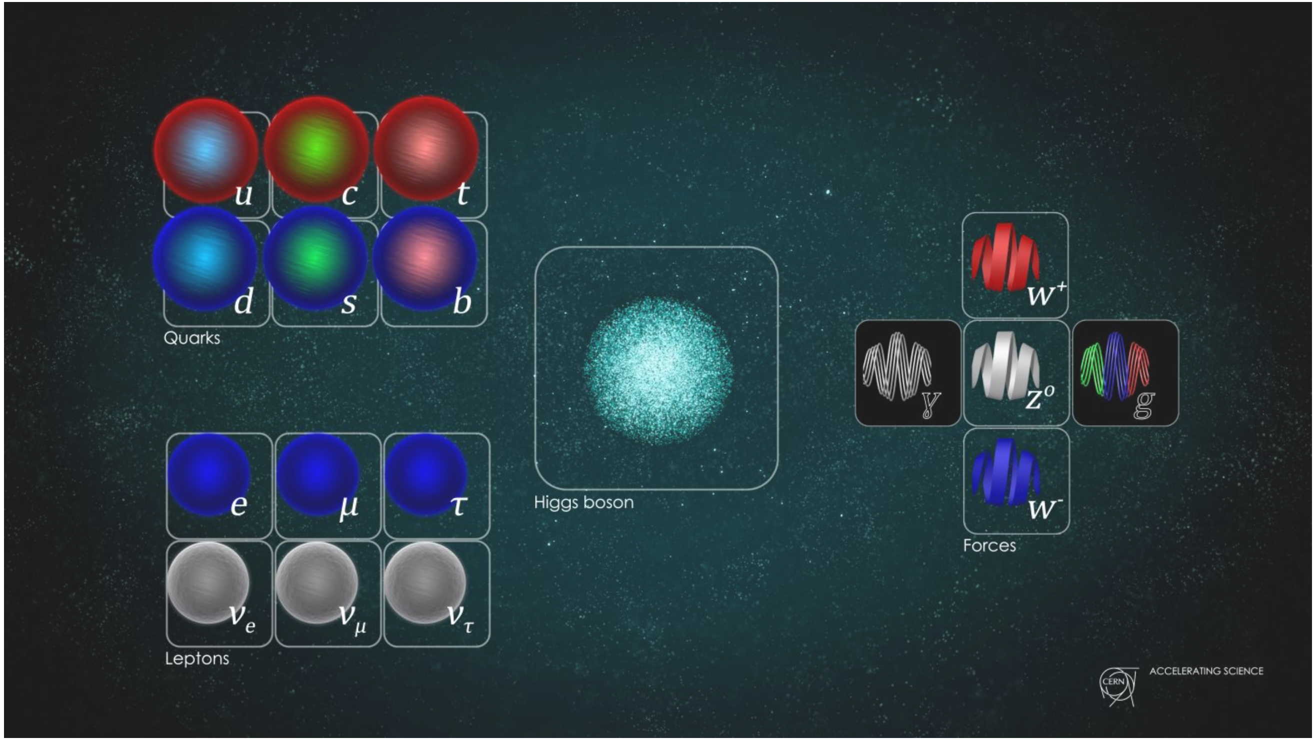
The collaborations published the latest in the search for the Standard Model Higgs boson in the journal Physics Letters B

10 SEPTEMBER, 2012

The ATLAS and CMS experiments at CERN today published observations of a new particle in the search for the Higgs boson in the journal *Physics Letters B*.

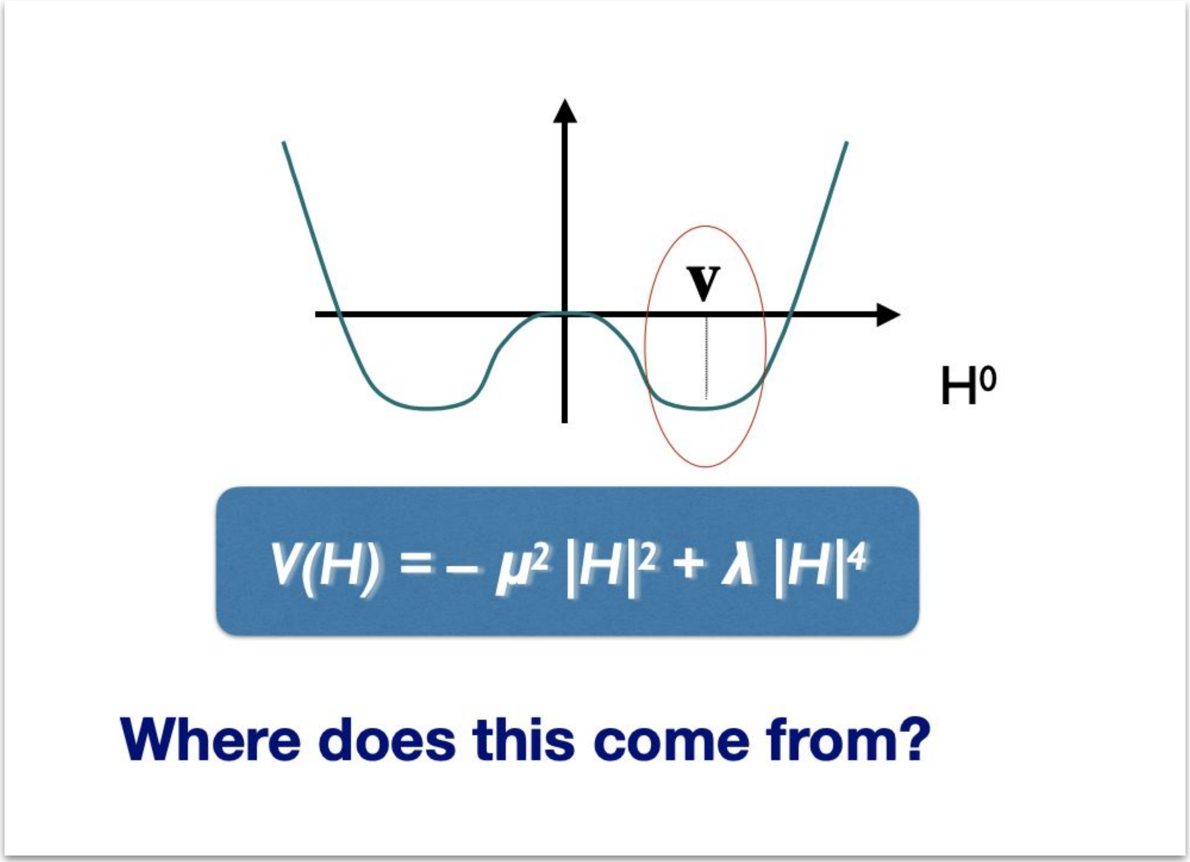
The papers: "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC" and "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC" are freely available online on ScienceDirect.

The Picture Became ‘Complete’



All Good, But..

Slide by Michelangelo L. Mangano
https://indico.cern.ch/event/1240244/contributions/5474414/



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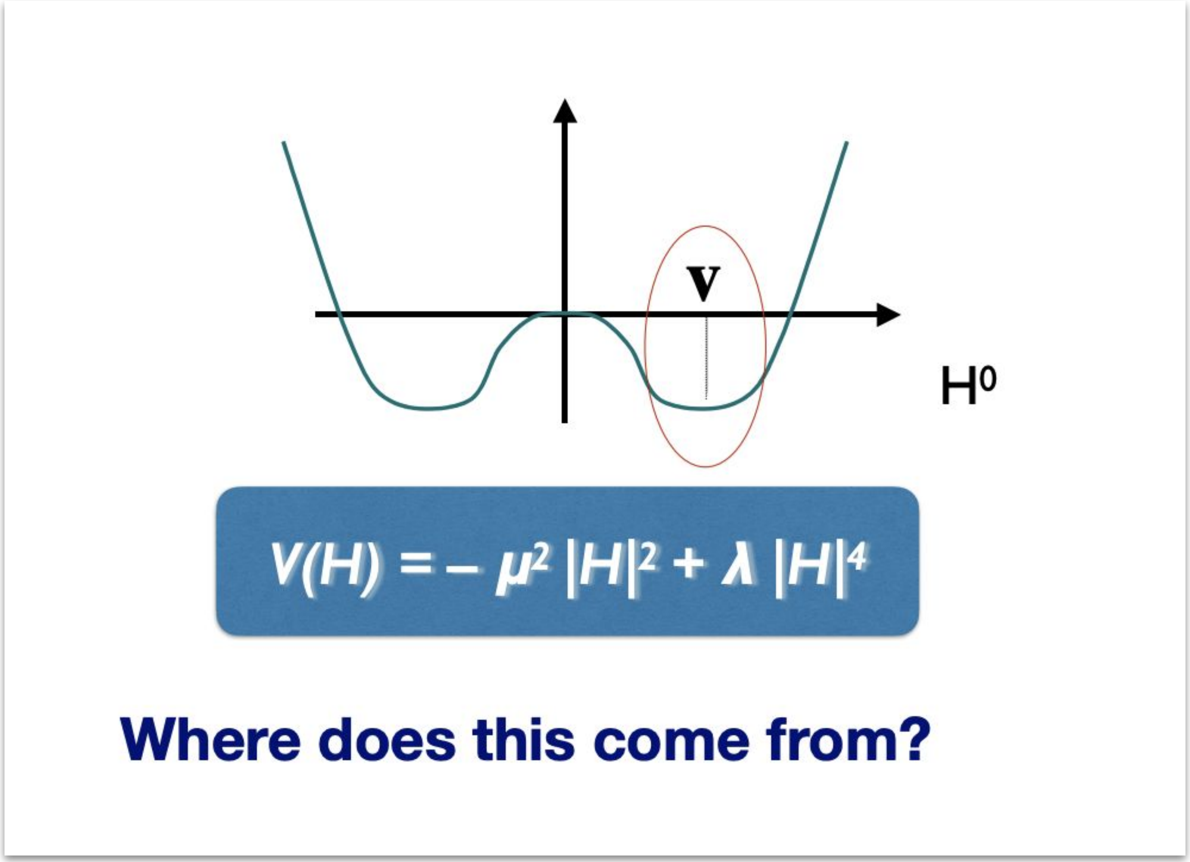
This is a problem!



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The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

How do we calculate m_H?

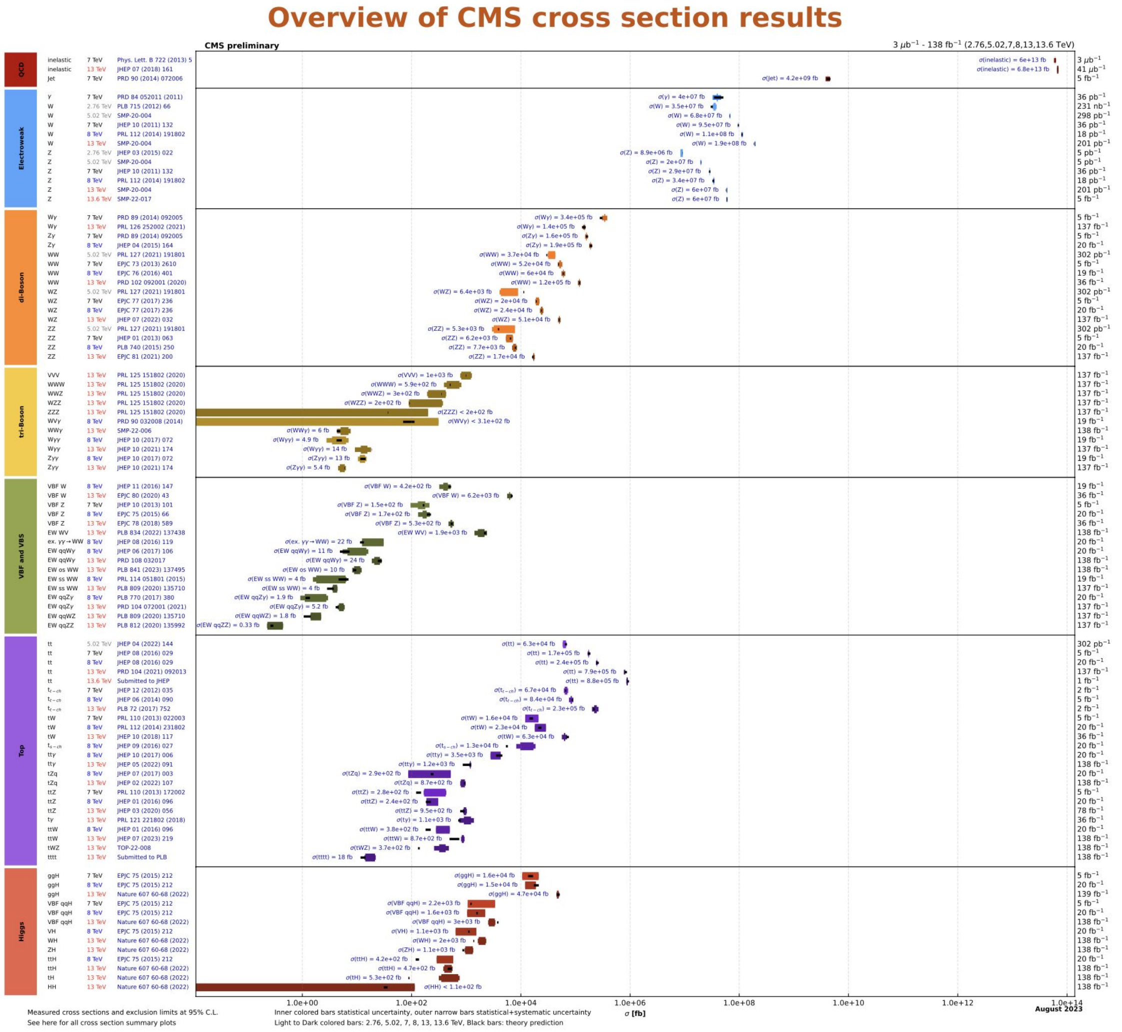
and the SM does not have all the answers

What Are We Doing About It?

Test the SM; i.e. accurate and precise predictions and measurements

and

Search for and constrain potential new physics scenarios



Any Conclusions?

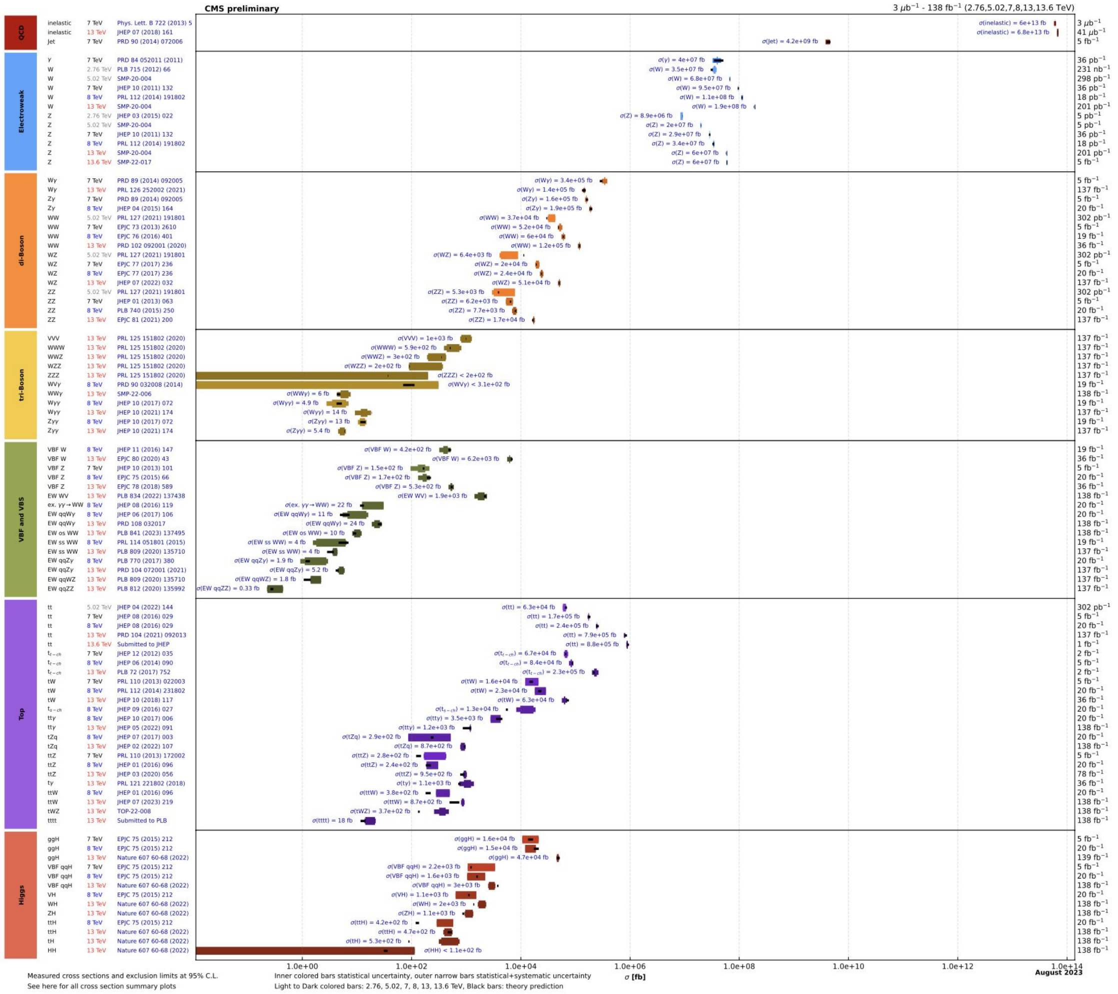
So far,

SM is robust

and

No direct signs of new physics

Overview of CMS cross section results

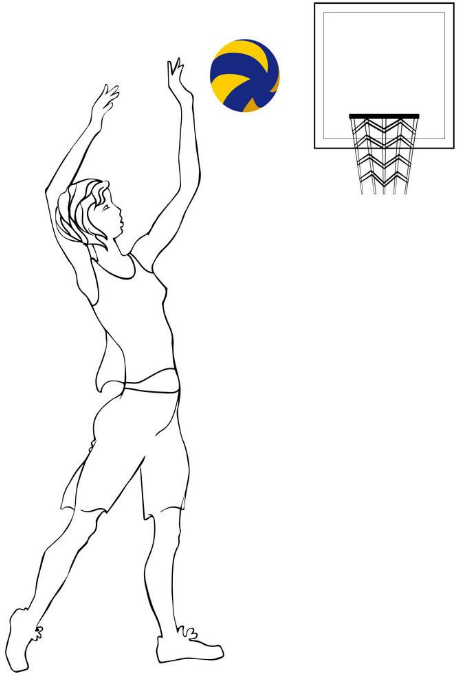


Let's Go The Other Way Around

- Assume the SM (gauge symmetries and field content)
- Keep measuring and predicting to the best of our abilities
- Deviation found can be parameterised as new physics (NP) contributions

→ **Standard Model Effective Field Theory**

[see introduction by A. Manohar [1804.05863]



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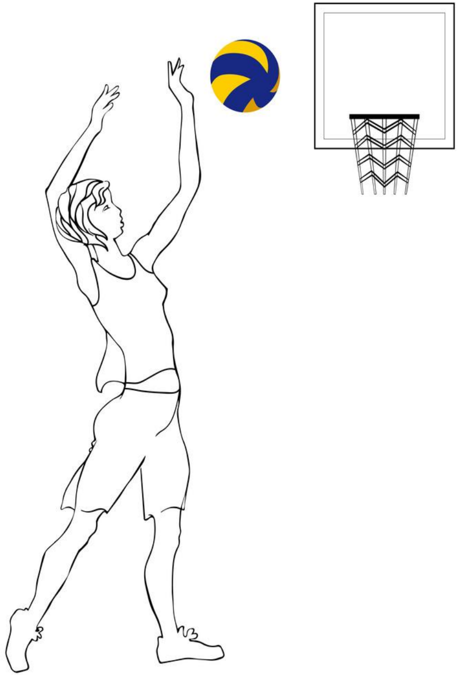


SMEFT can guide us to where NP might be, but it can not tell us what it is!

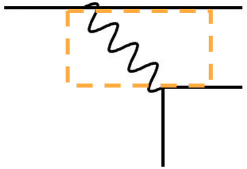
Into Effective Field Theories and SMEFT

EFT in a Nutshell

Energy

SM

$$\mathcal{A} = \frac{g_L^2}{2}\bar{x}(k_3)\sigma_\rho x(p)\frac{1}{q^2 - m_W^2}\bar{x}(k_1)\sigma_\rho y(k_2)$$



Low Energy

EFT in a Nutshell

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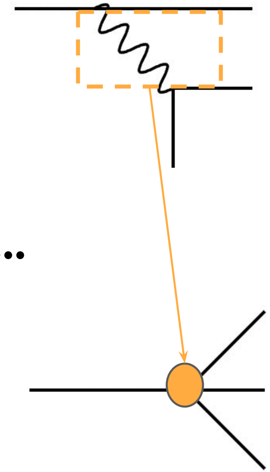
$$\mathcal{A} = \frac{g_L^2}{2}\overline{x}(k_3)\sigma_\rho x(p)\frac{1}{q^2 - m_W^2}\overline{x}(k_1)\sigma_\rho y(k_2)$$

Assume W-boson mass is larger than all other scales...

Low Energy

$$\mathcal{A} \approx -\frac{g_L^2}{2m_W^2}[\overline{x}(k_3)\sigma_\rho x(p)\overline{x}(k_1)\sigma_\rho y(k_2)][1 + \mathcal{O}(q^2/m_W^2)]$$



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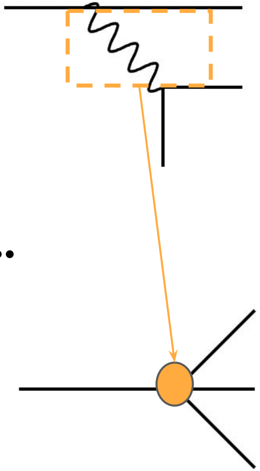


EFT in a Nutshell

'I have no idea what is going on here. I will call it v.'

$v = 2m_W/g_L$

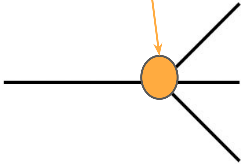
Energy

SM

Low Energy

Assume W-boson mass is larger than all other scales...

$$\mathcal{A} \approx -\frac{g_L^2}{2m_W^2}[\bar{x}(k_3)\sigma_\rho x(p)\bar{x}(k_1)\sigma_\rho y(k_2)][1+\mathcal{O}(q^2/m_W^2)]$$



SMEFT in a Nutshell

Energy

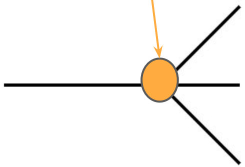
UV

Λ

Assume new physics is larger than all other scales...

SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} Q_i^{dim-6} + \dots$$



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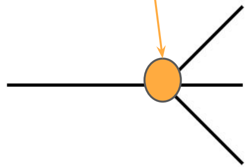

UV physics projected onto the low-energy dynamics

SMEFT in a Nutshell

'We have no idea what is going on here. We will call it c/Λ^2.'

Energy

UV

Λ

Assume new

SMEFT

$\mathcal{L}_{SM}$

But It is Not One Dim-6 Operator..

In the so-called Warsaw basis and under flavour universality, there are 59-operators at dimension-six augmenting the SM

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653; Grzadkowski et al 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
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$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
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$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

But It is Not One Dim-6 Operator..

How to find those operators is a whole story by itself..

In the so-called Warsaw basis and under flavour universality, there are 59-operators at dimension-six augmenting the SM

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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
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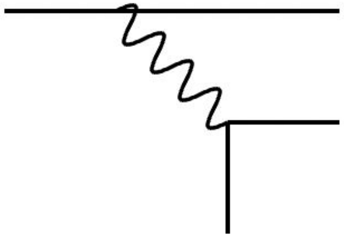
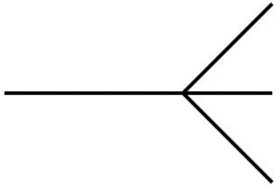
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

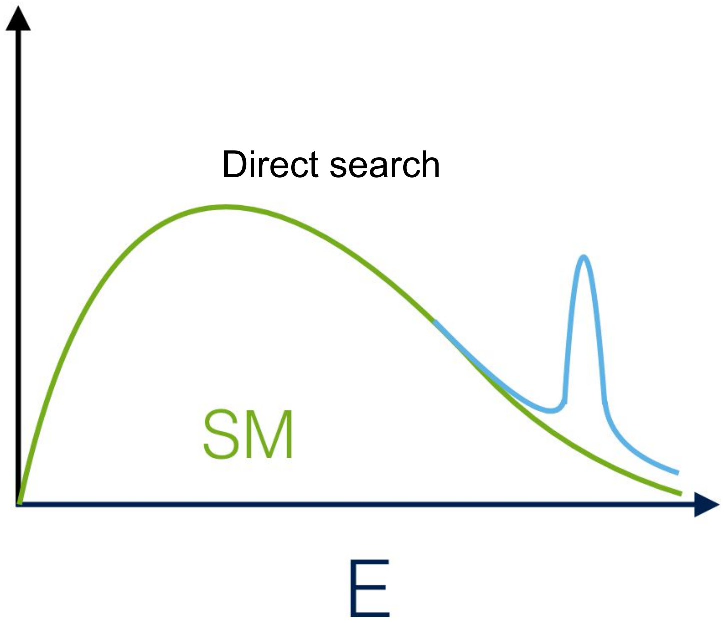
At the End, Theorists Compute Cross-Sections

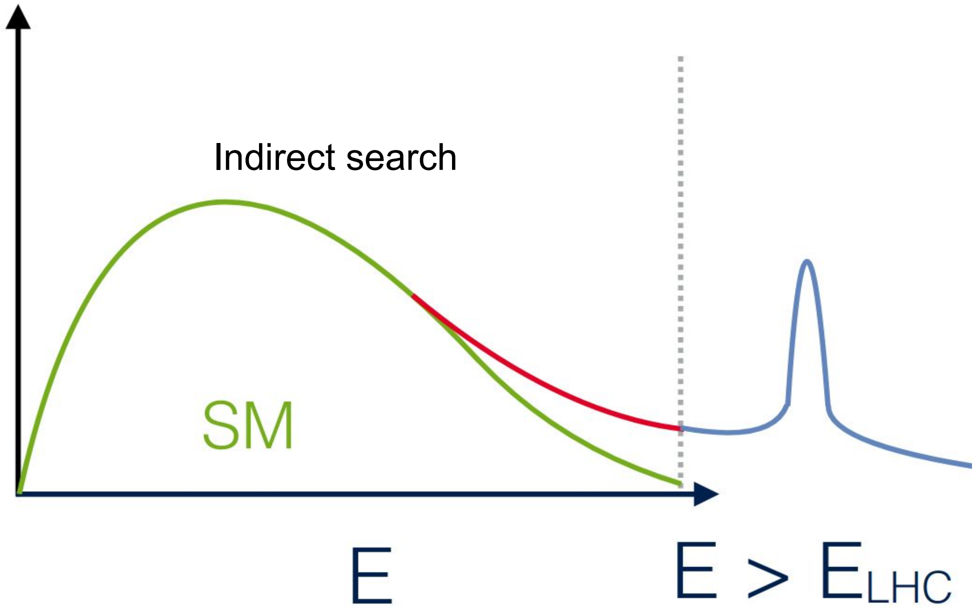




$$\sigma \simeq \begin{cases} \sigma_{\mathrm{SM}} + \sigma_{\mathrm{SM}\times\mathrm{dim6}} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} + \sigma_{\mathrm{SM}\times\mathrm{dim6}^2} \\ \sigma_{\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)\times\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)} \end{cases}$$

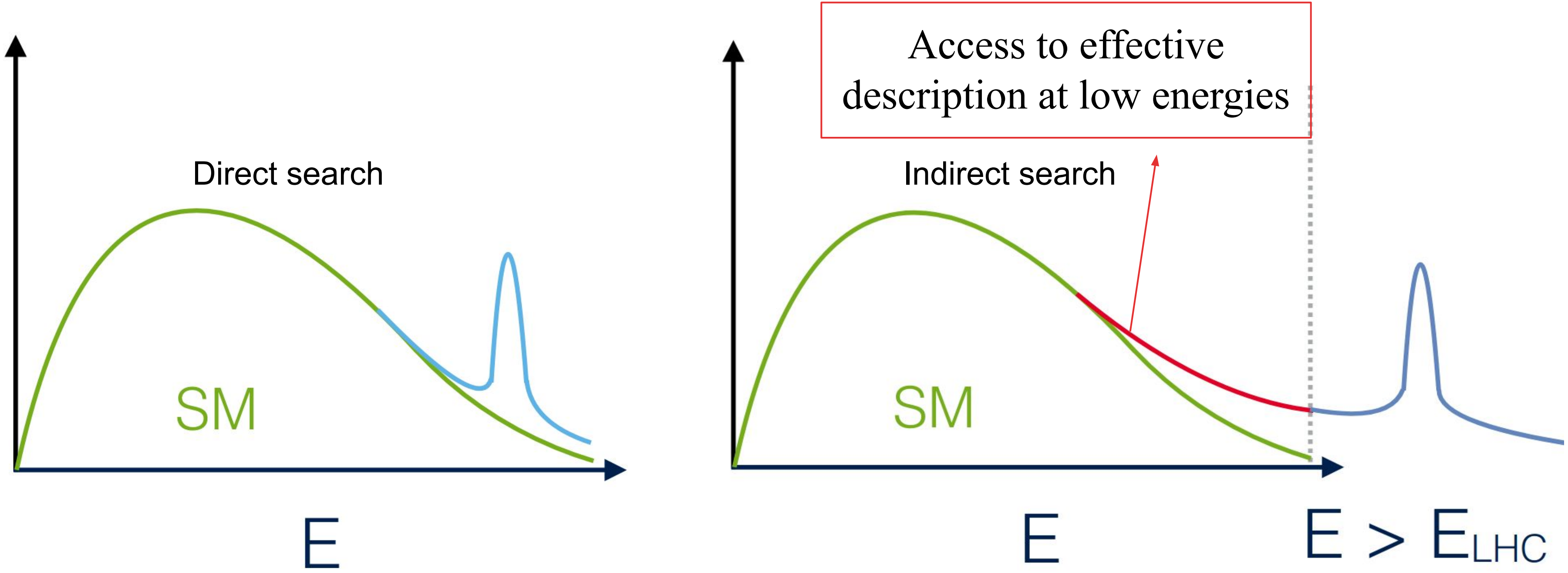
And Experimentalists Measure Cross-Sections





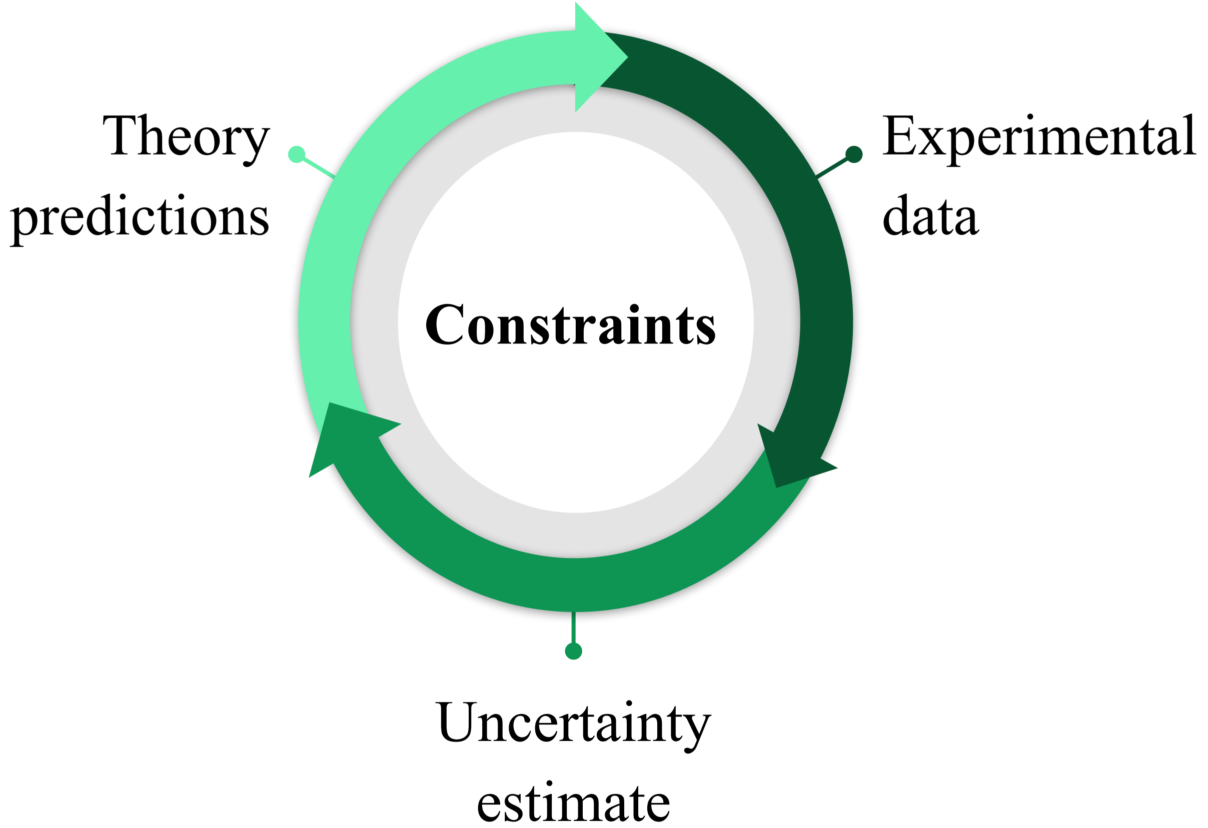
Images by Ken Mimasu

And Experimentalists Measure Cross-Sections



Images by Ken Mimasu

And Both Obtain Constraints Through Fits



Fits: Introduction

The ultimate motivation for doing SMEFT is to constrain new physics

It is complicated; high-dimensional parameter space leading from a few to hundreds of coefficients to be constrained

Fits: Tools [non-exhaustive]

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

Fitmaker

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

[a] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK*

[b] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

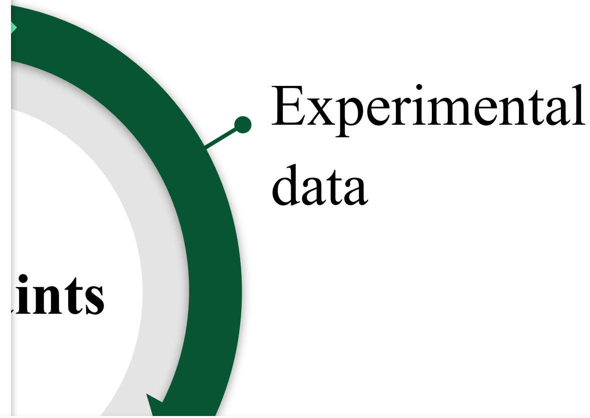
[c] *National Institute of Chemical Physics & Biophysics, Rävala 10, 10143 Tallinn, Estonia*

[d] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*

[e] *Instituto de Física Corpuscular (IFIC), Universidad de Valencia-CSIC, E-46980 Valencia, Spain*

[f] *Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*

[g] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK*



SMEFiT

Project description

SMEFiT is a Python package for global analyses of particle physics data in the framework of the Standard Model Effective Field Theory (SMEFT). The SMEFT represents a powerful model-independent framework to constrain, identify, and parametrize potential deviations with respect to the predictions of the Standard Model (SM). A particularly attractive feature of the SMEFT is its capability to systematically correlate deviations from the SM between different processes. The full exploitation of the SMEFT potential for indirect New Physics searches from precision measurements requires combining the information provided by the broadest possible dataset, namely carrying out extensive global analysis which is the main purpose of SMEFiT.

What If We Find Strong Deviations From the SM?

- At face value, this **hints to interactions or particles not account for in the SM**
- The **size of deviation** can hint to the energy scale of the potential new physics
- **Character of new interactions;** if deviations are found in coefficients closely connected to EW symmetry breaking (EWSB), then perhaps new dynamics in the Higgs sector
- **Theorist would focus on UV-complete models** relevant to such deviations, **experimentalist would focus on processes, decay channels, etc.** which are sensitive to those coefficients

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- Are the deviations consistent across different processes and observables?
- Do we have our systematic, statistical and theory uncertainties under control?
- Do we need to look back to what assumptions we have made in the SMEFT expansion?

This is just my own thought process

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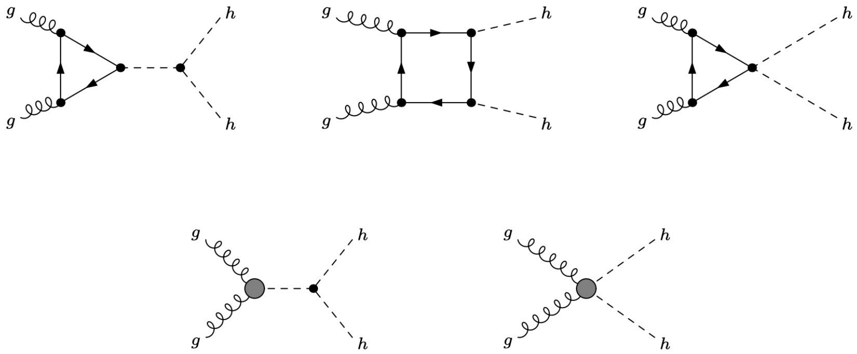
Higgs Pair Production (HH)



Brief History of HH Predictions in the SM

→ NLO real emissions;
F. Maltoni, E. Vryonidou and M. Zaro [1408.6542]
→ Numerical virtual corrections;
S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert and T. Zirke[1604.06447]
S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk and T. Zirke [1608.04798]
J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, M. Spira and J. Streicher [1811.05692]
→ Numerical Two loop integrals (for gg→ZZ; gg→ZH; gg→WW as well);
B. Agarwal, S. P. Jones and A. von Manteuffel[2011.15113]
L. Chen, G. Heinrich, S. P. Jones, M. Kerner, J. Klappert and J. Schlenk [2011.12325]
C. Brønnum-Hansen and C. Y. Wang [2101.12095]
→ To avoid numerical disadvantages, analytical approximations has been made for gg→HH;
Dawson et al. [9805244], Grigo et al. [1305.7340], Degrassi et al. [1603.00385]; **large top quark mass expansions**
Davies et al. [1801.09696],[1811.05489]; **high energy expansions**
Bonciani et al. [1806.11564]; **small transverse momenta expansions**
Grober et al. [1709.07799]; **expansions around the top quark threshold**
Xu et al. [1810.12002],Wang et al. [2010.15649]; **small higgs mass expansion with subsequent numerical approach**
→ A combination of different phase space approaches;
Bellafronte et al. [2202.12157] and Degrassi et al. [2205.02769] **combined analytic small pT expansion with high energy ones**

And in the SMEFT

R. Gröber, M. Mühlleitner, M. Spira and J. Streicher, *NLO QCD Corrections to Higgs Pair Production including Dimension-6 Operators*, JHEP **09** (2015) 092 [1504.06577].

R. Gröber, M. Mühlleitner and M. Spira, *Higgs Pair Production at NLO QCD for CP-violating Higgs Sectors*, Nucl. Phys. B **925** (2017) 1 [1705.05314].

G. Buchalla, M. Capozi, A. Celis, G. Heinrich and L. Scyboz, *Higgs boson pair production in non-linear Effective Field Theory with full m_t-dependence at NLO QCD*, JHEP **09** (2018) 057 [1806.05162].

D. de Florian, I. Fabre and J. Mazzitelli, *Higgs boson pair production at NNLO in QCD including dimension 6 operators*, JHEP **10** (2017) 215 [1704.05700].

D. de Florian, I. Fabre, G. Heinrich, J. Mazzitelli and L. Scyboz, *Anomalous couplings in Higgs-boson pair production at approximate NNLO QCD*, JHEP **09** (2021) 161 [2106.14050].

Refs list is from the recent computation of HH in SMEFT at full NLO QCD [2204.13045]

All to say that it is complicated, but people care..

Why Do We Care About HH?

Higgs potential after EWSB ⟶ $V(H) = \frac{1}{2}{m_H}^2H^2 + \lambda v H^3 + \lambda H^4$

The mass of the Higgs boson ⟶ $m_H = \sqrt{2\lambda} v$

The Higgs mass was measured at the sub-percent level and the *vev* is precisely determined through EW precision tests of Fermi theory

So, if the Higgs potential that induces EWSB is that of the SM then

$$\boxed{\lambda \approx 0.13}$$

Why Do We Care About HH?

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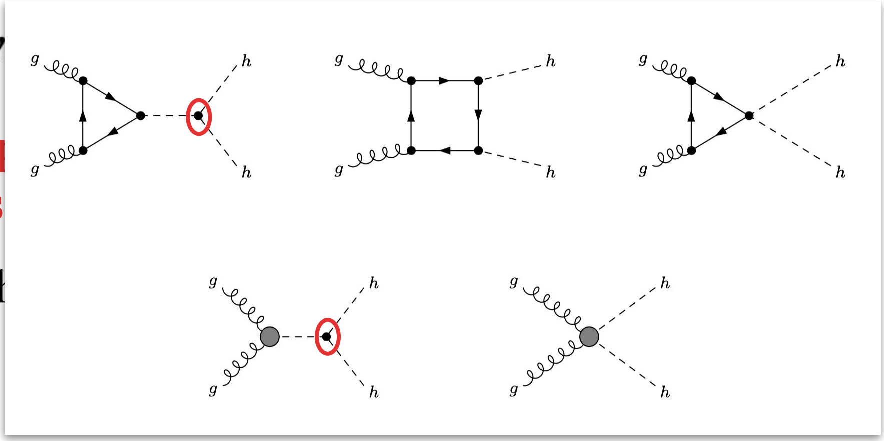

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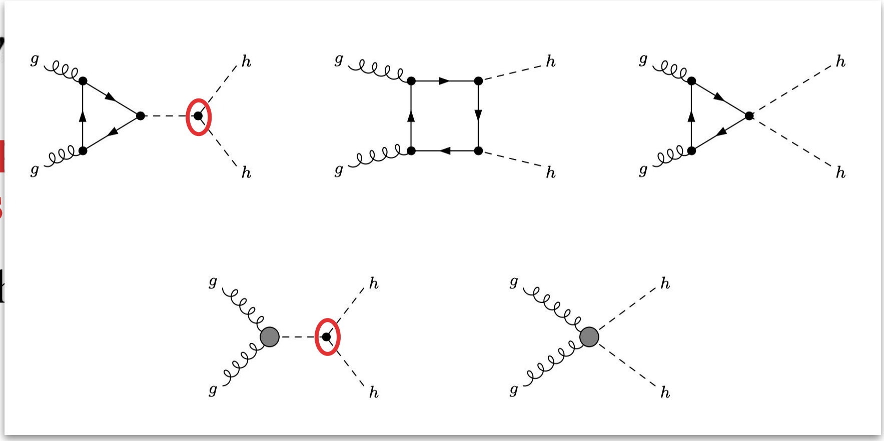

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determined through EW precis

So, if the Higgs potential that induces EWSB is th

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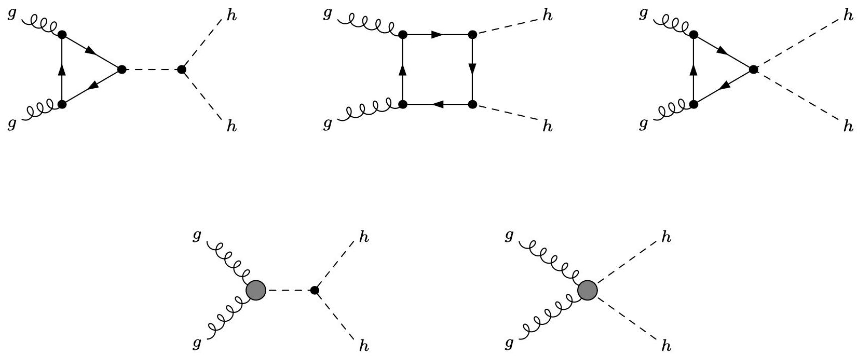
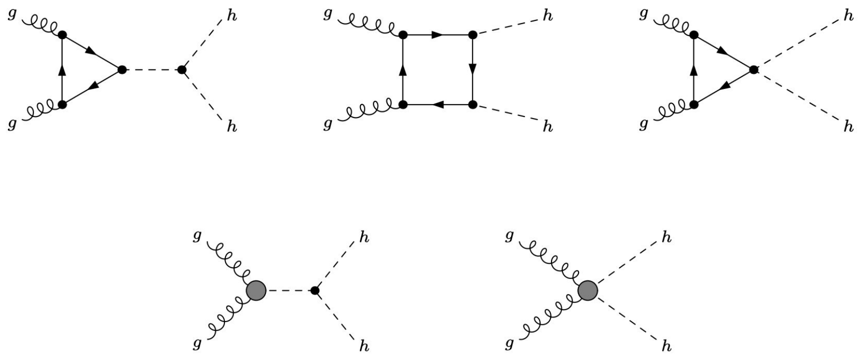
To examine the structure of the SM Higgs potential, the Higgs self-coupling must be measured directly. SMEFT coefficients sensitive to HHH vertex can encapsulate deviations as Dim6 contributions.

gg→ HH Amplitudes



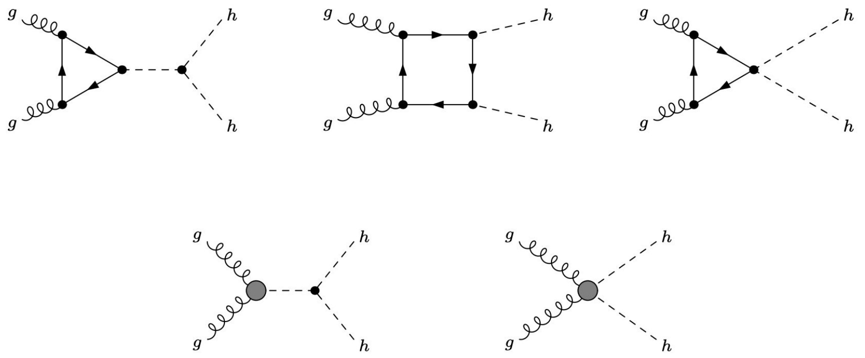
gg→ HH Amplitudes

The translation from HEFT to Warsaw basis and truncation effects have been studied in [2204.13045]



HEFT	Warsaw
c_{hhh}	$1-2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H+3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1+\frac{v^2}{\Lambda^2}C_{H,\text{kin}}-\frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH}+\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

gg→ HH Amplitudes



$\lambda_{g_1}, \lambda_{g_2}, \lambda_{H_1}, \lambda_{H_2}$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tG}$	$\mathcal{O}_{d\varphi}$	$\mathcal{O}_{\varphi G}$
$+,+,0,0$	s^0	$\frac{3\, m_t\, v\, g_s^2}{32\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$s\, \frac{m_t\, g_s^2}{4\pi^2 v}\left[\log\left(\frac{s}{\mu_{EFT}^2}\frac{\sqrt{1-c\theta^2}}{2}\right) - 2\right]$	$\frac{m_t^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$s\,\sqrt{2}$
$+,-,0,0$	s^0	–	$s\,\frac{m_t\, g_s^2}{8\pi^2\, v}$	–	⁄

Table 2: High energy behaviour of the $gg \to HH$ helicity amplitudes in the SM and modified by SMEFT operators. The "–" and "⁄" denote when a helicity amplitude is not growing or is equal to 0 respectively. $\lambda_{g_1}, \lambda_{g_2}, \lambda_{H_1}, \lambda_{H_2}$ represent the polarisation of the two incoming gluons and the two outgoing Higgs bosons and $c\theta$ stands for the cosine of the collision angle in the centre of mass frame. We also keep implicit the overall colour factor δ^{ab}, where a, b are the colours of the incoming gluons, as well as the overall dependence on the WCs and Λ^2.

The translation from HEFT to Warsaw basis and truncation effects have been studied in [2204.13045]

HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

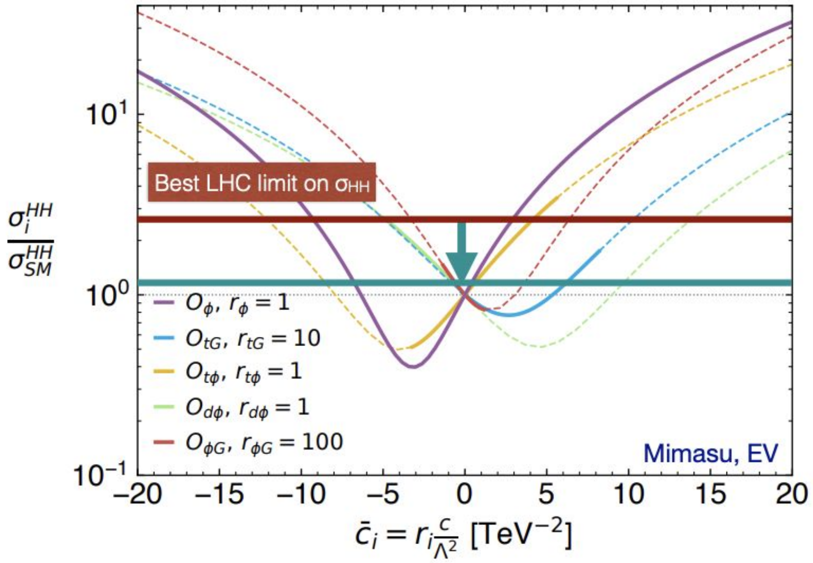
The high-energy behaviour of the *gg→HH* helicity amplitudes has been studied in [2306.09963]

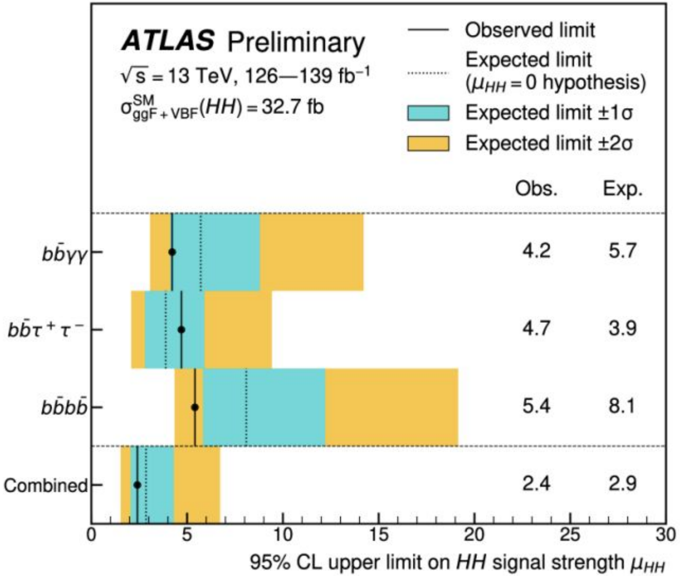
How to Constrain Coefficients in HH?

➡ $\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G_A^{\mu\nu}\, G_{\mu\nu}^A$	➡	**ttH, H+j**
➡ $\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	➡	**ttH, H+j**
➡ $\mathcal{O}_{tG}$	ctG	$igs\, (\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\varphi}\, G_{\mu\nu}^A + \text{h.c.}$	➡	**ttH, ttV, ..**
➡ $\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$	➡	**All Higgs Couplings**
➡ $\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$	➡	**HH and H at NLO**

See recent analysis by ATLAS [2301.03212] of HH in bbbb final state

How to extract the self-coupling from HH?



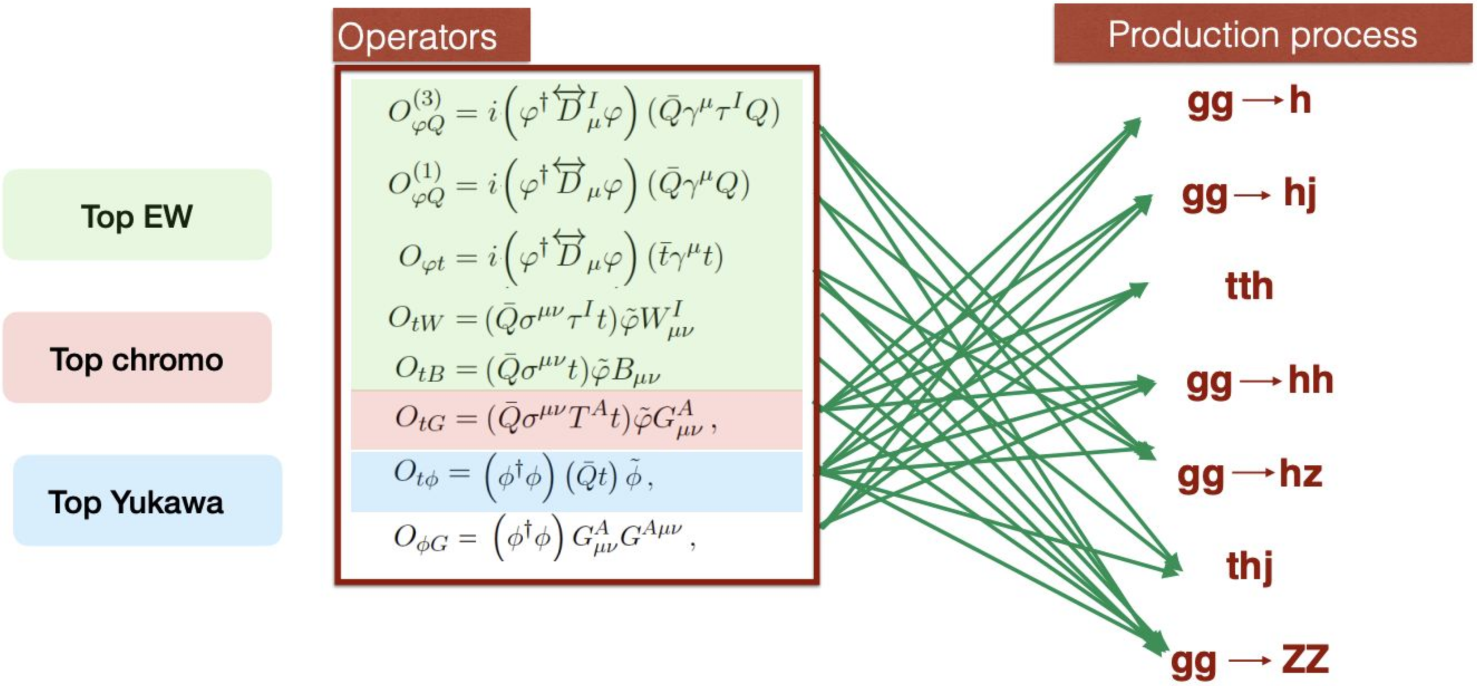


The future

Precise knowledge of all Wilson coefficients will be needed to bound λ as we get closer to SM
Differential distributions will also be necessary

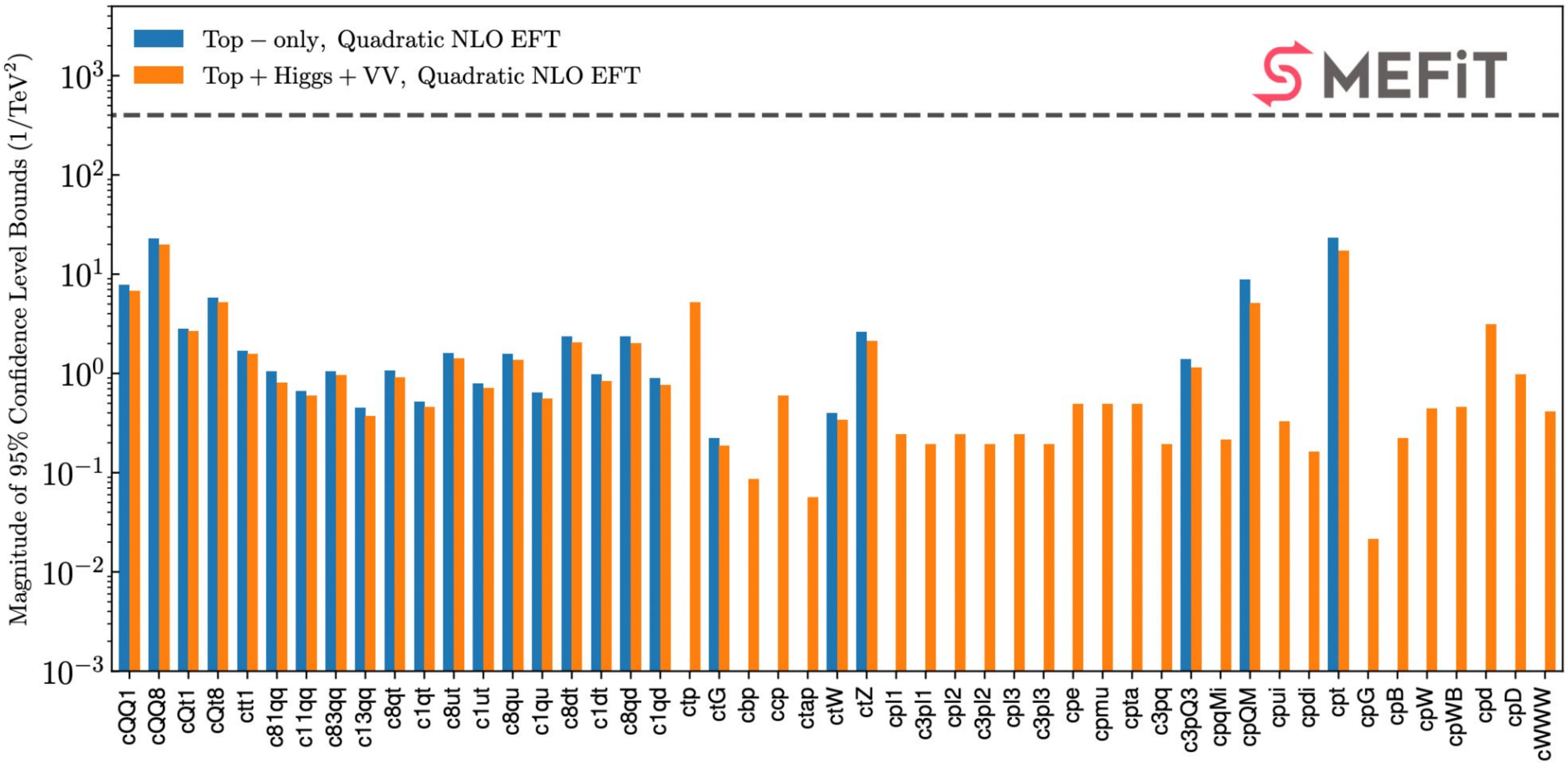
Slide by Eleni Vryonidou, Higgs2022 https://indico.cern.ch/event/1086716/contributions/4968418/attachments/2543978/4380494/Vryonidou_Higgs.pdf

Broader Higgs-top interplay



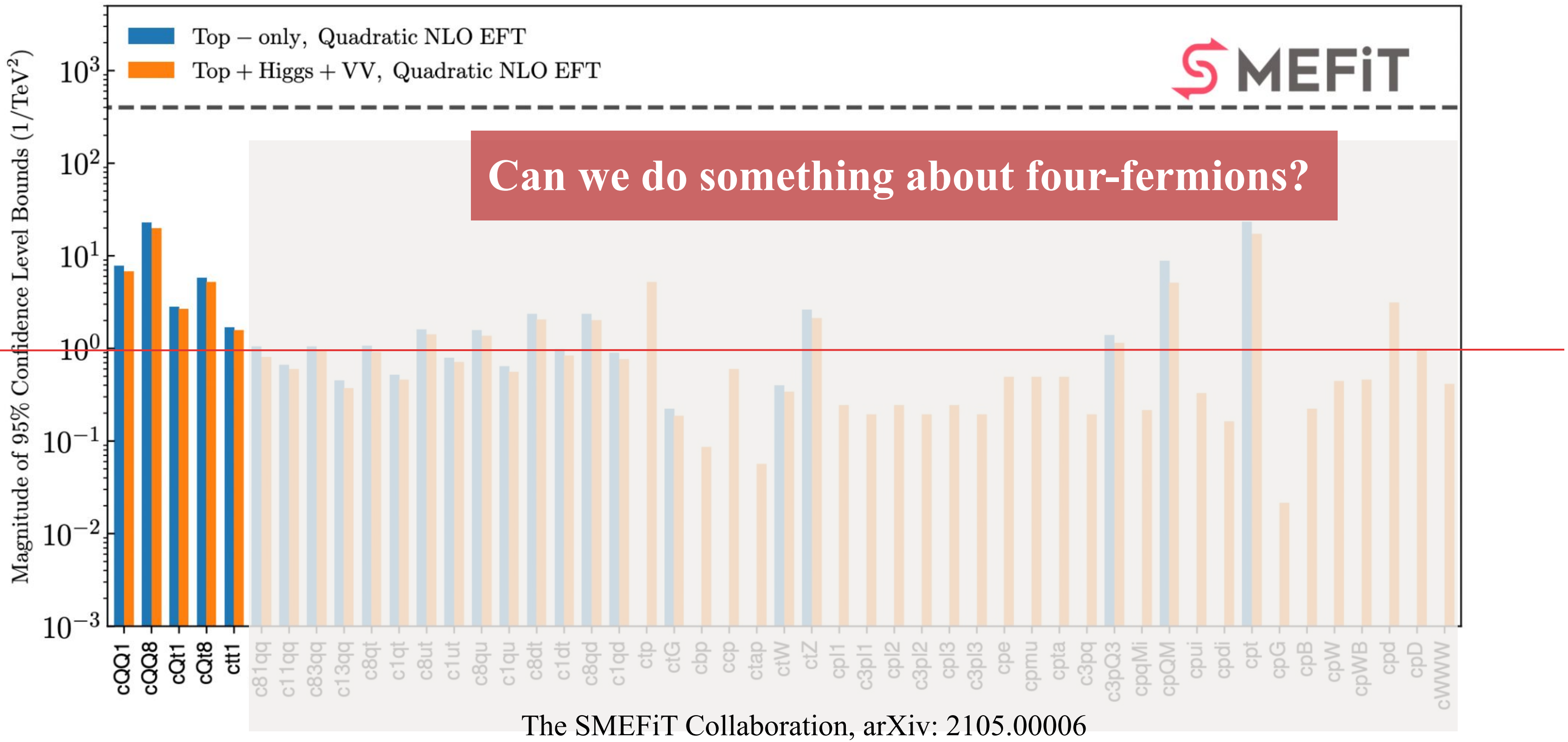
Top-Higgs are deeply connected

Bounds on Coefficients From Global Fits



The SMEFiT Collaboration, arXiv: 2105.00006

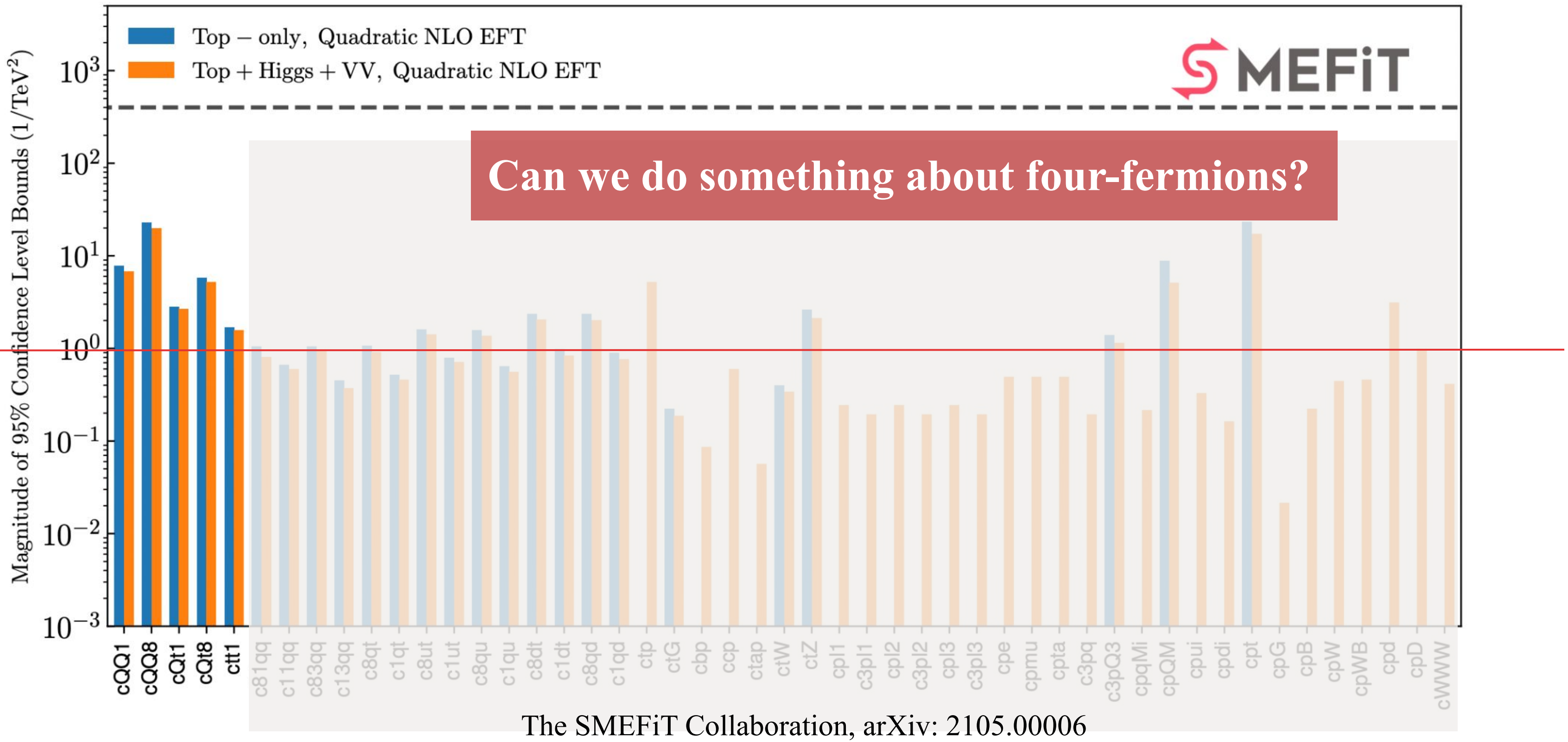
Bounds on Coefficients From Global Fits



The SMEFiT Collaboration, arXiv: 2105.00006

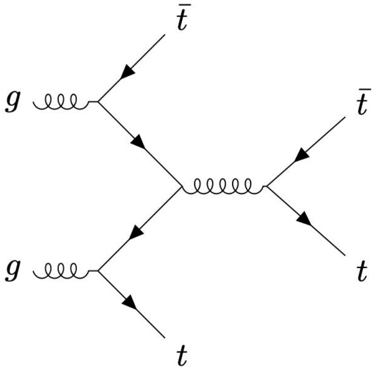
See very recent results by the SMEFit collaboration in [2404.12809]

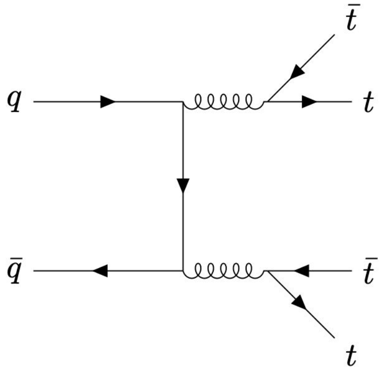
Bounds on Coefficients From Global Fits



The SMEFiT Collaboration, arXiv: 2105.00006

Four Top Quarks Production



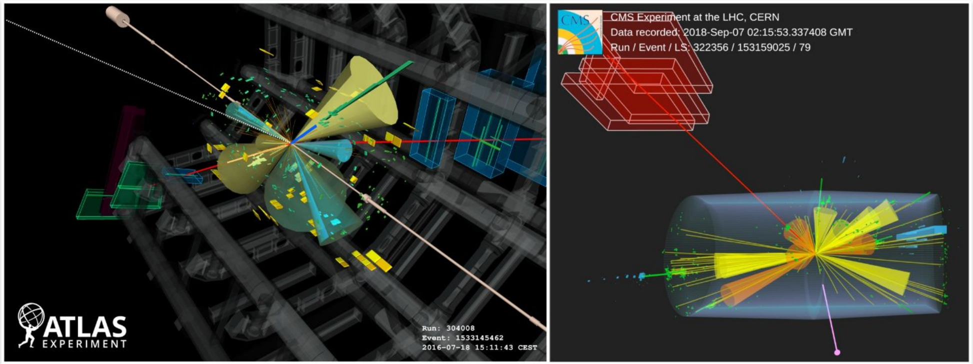


Four Tops Finally Observed!

ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

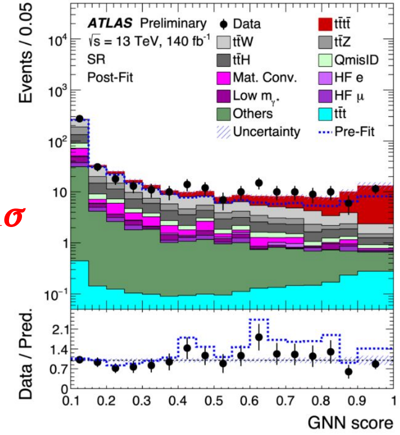
24 MARCH, 2023 | By Naomi Dinmore



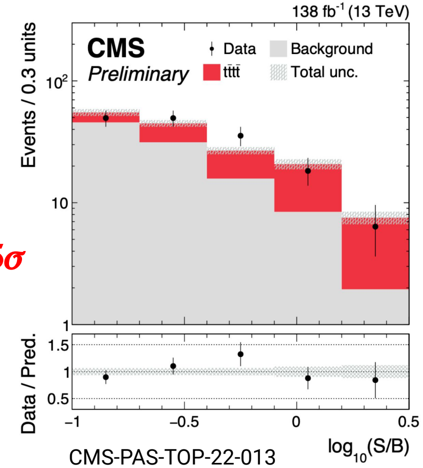
Event displays of four-top-quark production from ATLAS (left) and CMS (right).

arXiv:2303.15061

6.1σ



5.5σ



CMS-PAS-TOP-22-013

Be Careful When Doing Four Tops

- Cao, Chen, Liu, arXiv: 1602.01934
  ".. be careful at LO SM"

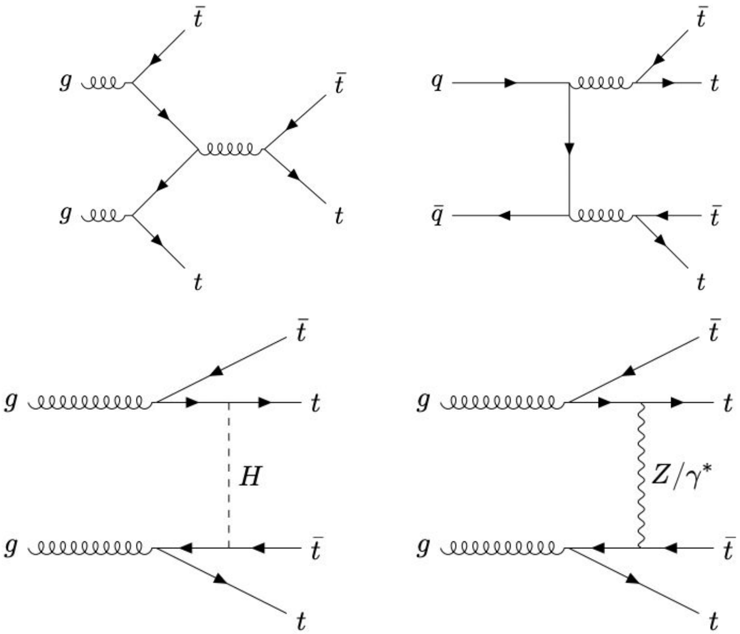
- Frederix, Pagani, Zaro, arXiv: 1711.02116
  ".. be careful at NLO SM"

- Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743
  ".. be careful at SMEFT for some operators"

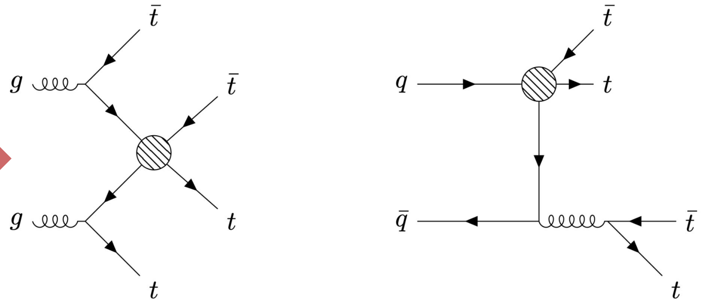
- Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962
  "..we are being careful at SMEFT for all operators"

And a lot of other work considering four-fermion operators/ four tops in SMEFT [arXiv:1010.6304, 1708.05928, 1903.07725, 2010.05915, 2104.09512, ..]

Four Tops in SMEFT: Interference



Interference



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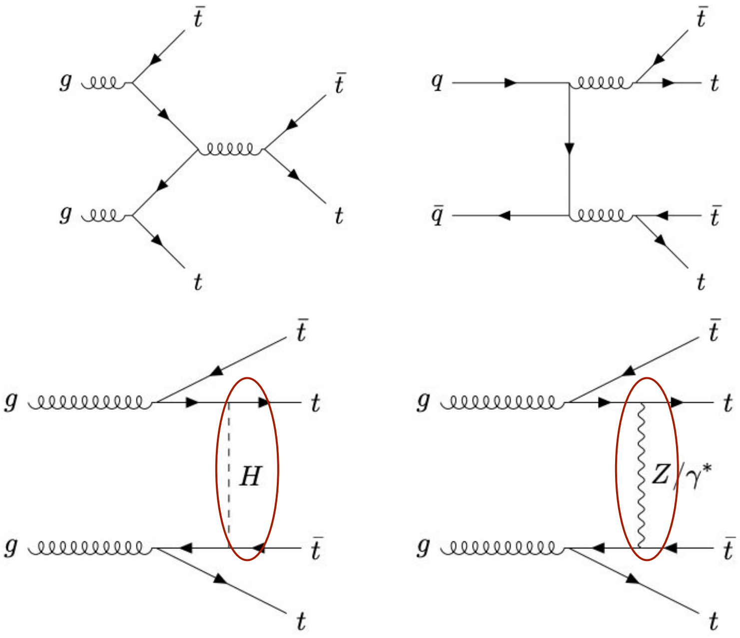
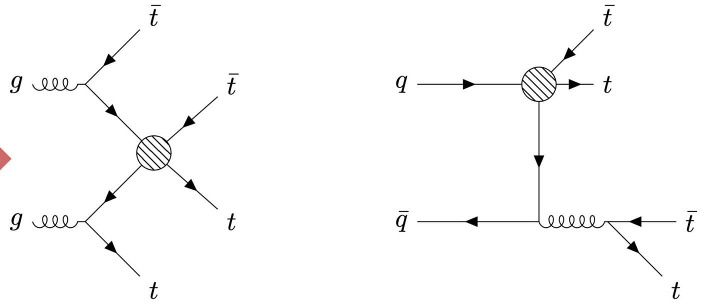


Interference



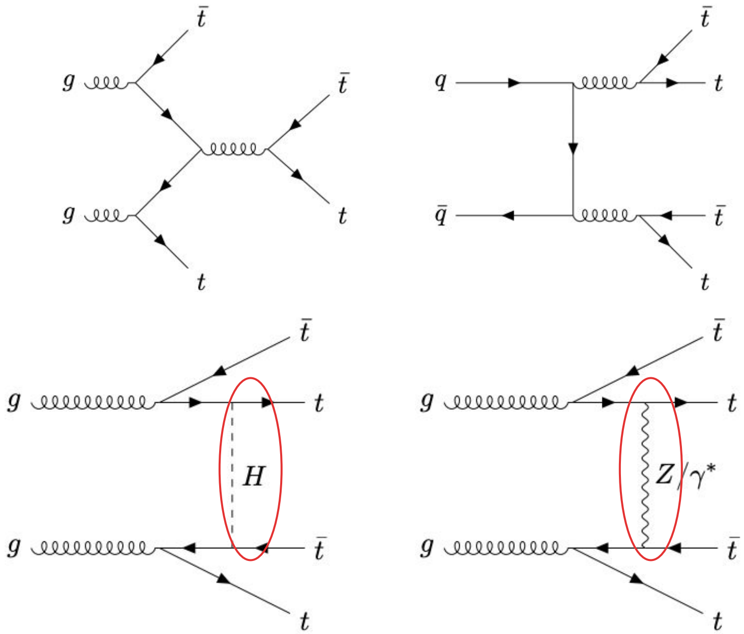
$t\bar{t}$ production, noted above. Table II also provides the LO interferences with subleading SM amplitudes of order $\alpha_S\alpha_{\rm EW}$ and $\alpha_S y_t^2$ which are actually larger than with the leading QCD ones. Note they also have opposite signs. At the quadratic level, the NLO enhance-

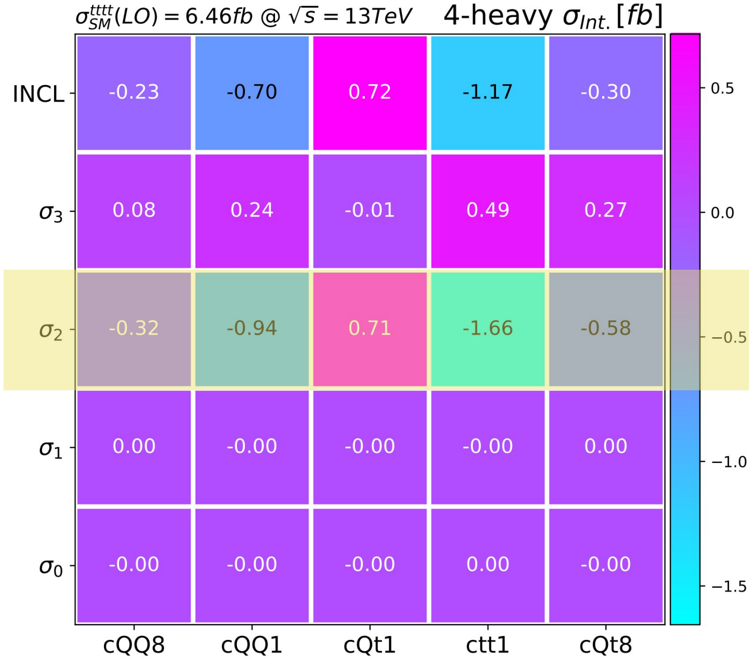
Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743

Four Tops in SMEFT

4-heavy

$\mathcal{O}^1_{QQ}$	cQQ1	$2[C^{(1)}_{qq}]^{3333} - \frac{2}{3}[C^{(3)}_{qq}]^{3333}$	$\mathcal{O}^8_{QQ}$	cQQ8	$8[C^{(3)}_{qq}]^{3333}$
$\mathcal{O}^1_{Qt}$	cQt1	$[C^{(1)}_{qu}]^{3333}$	$\mathcal{O}^8_{Qt}$	cQt8	$[C^{(8)}_{qu}]^{3333}$
$\mathcal{O}^1_{tt}$	ctt1	$[C^{(1)}_{uu}]^{3333}$			





Electroweak contributions are important

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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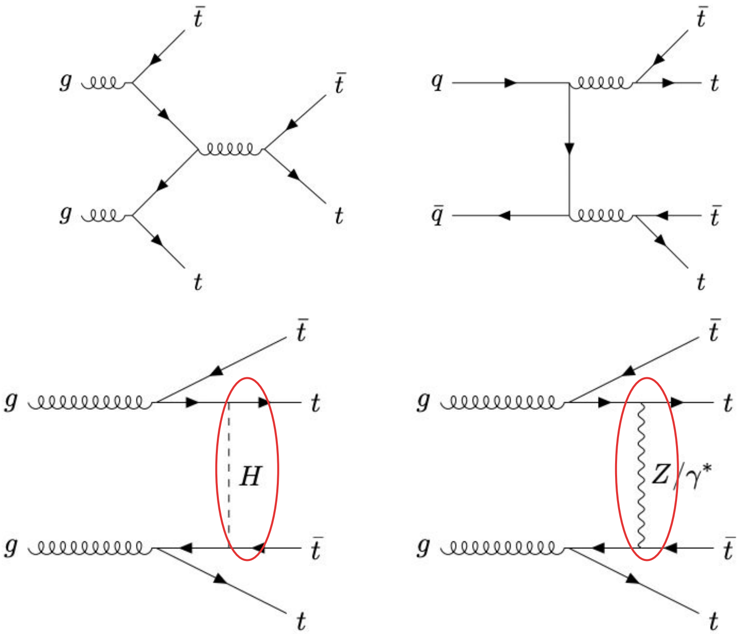

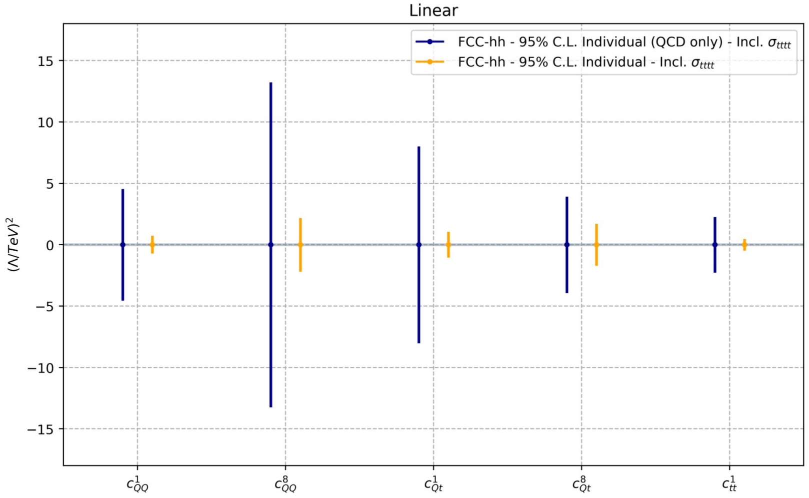

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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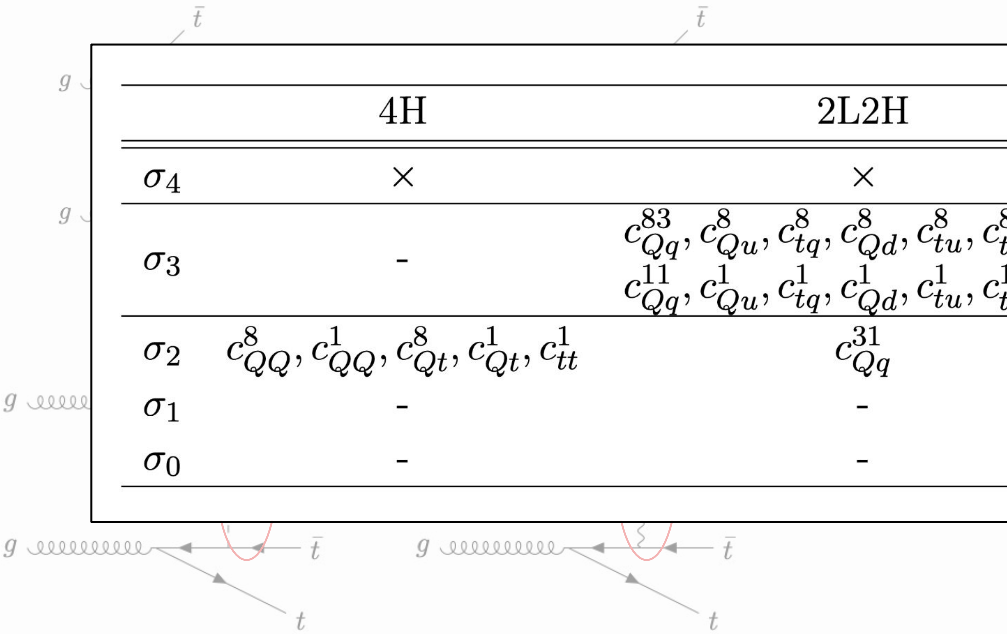
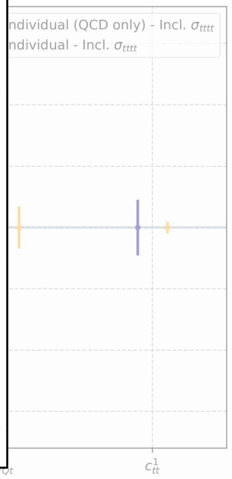
	4H	2L2H	2F	0F
σ_4	×	×	c_{tG}	c_G
σ_3	-	$c^{83}_{Qq}, c^{8}_{Qu}, c^{8}_{tq}, c^{8}_{Qd}, c^{8}_{tu}, c^{8}_{td}, c^{81}_{Qq}$ $c^{11}_{Qq}, c^{1}_{Qu}, c^{1}_{tq}, c^{1}_{Qd}, c^{1}_{tu}, c^{1}_{td}$	$c_{t\varphi}, c_{tZ}, c_{tW}$	-
σ_2	$c^8_{QQ}, c^1_{QQ}, c^8_{Qt}, c^1_{Qt}, c^1_{tt}$	c^{31}_{Qq}	$c_{\varphi t}, c^{(-)}_{\varphi Q}$	-
σ_1	-	-	-	$c_{\varphi G}$
σ_0	-	-	-	-





Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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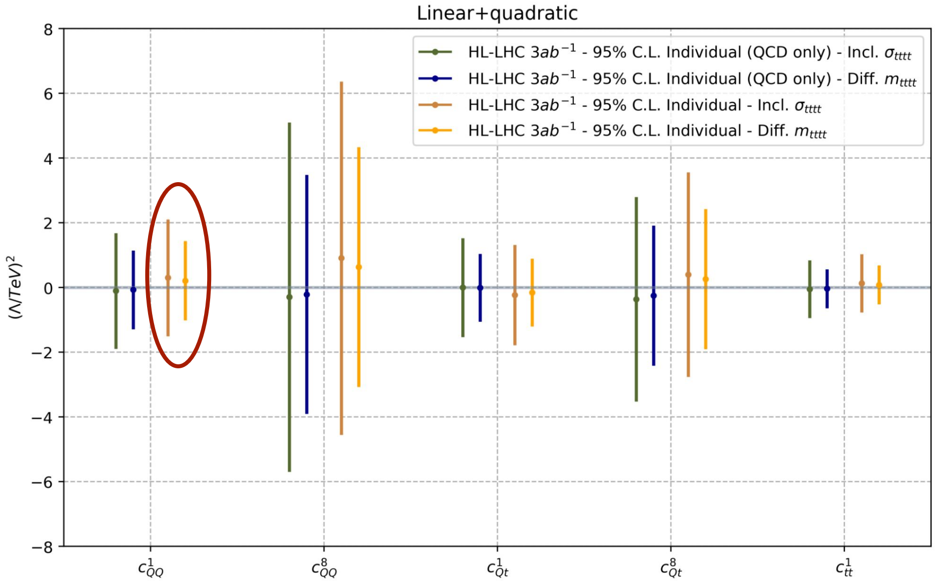

Differential information is important

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Four Tops in SMEFT

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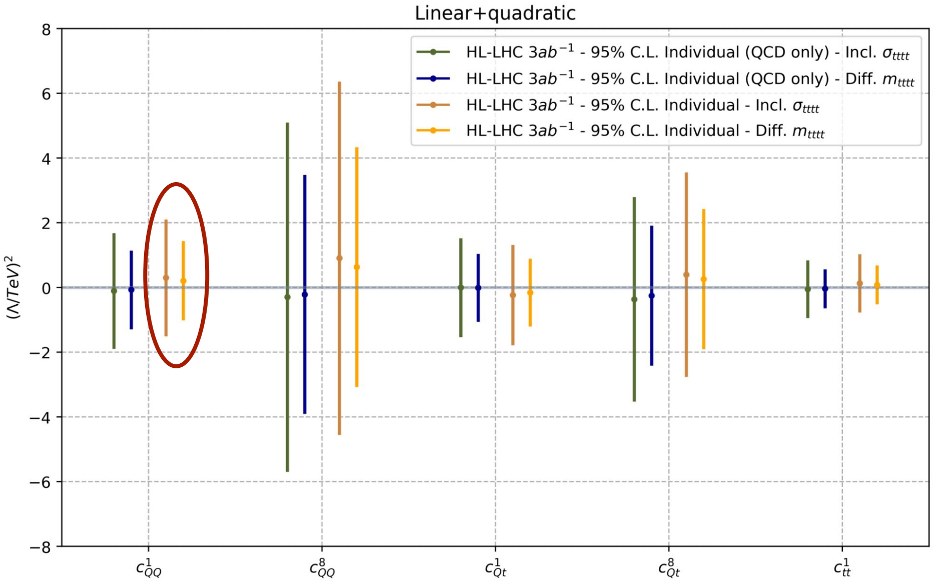
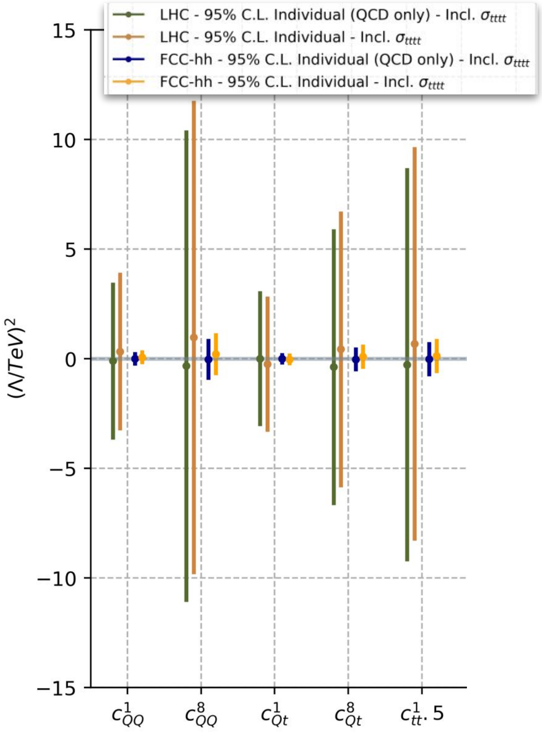
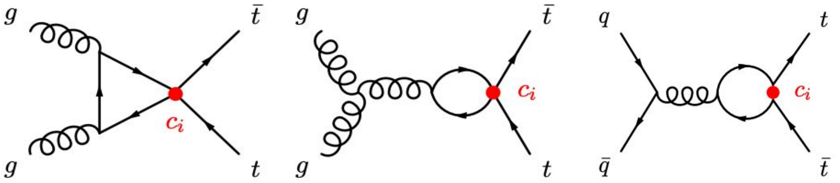




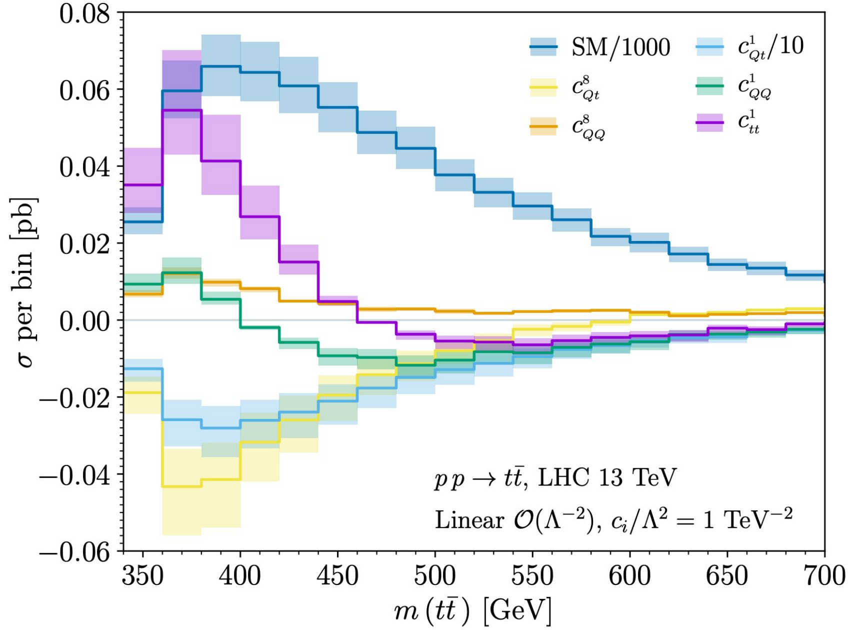
Differential information is important
FCC-hh provides a good handle

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Four-fermion in SMEFT: One loop in Top Pair

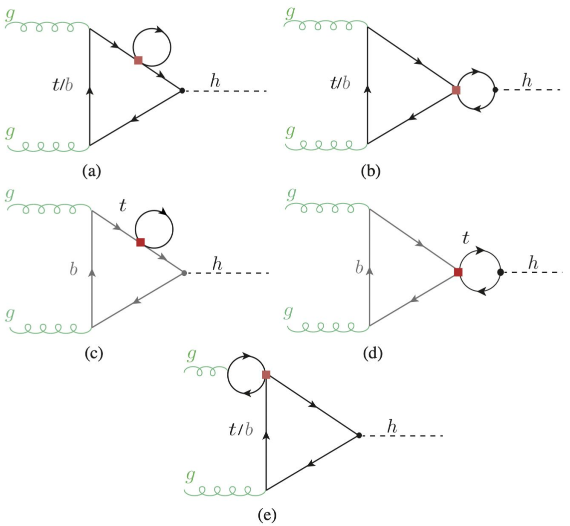


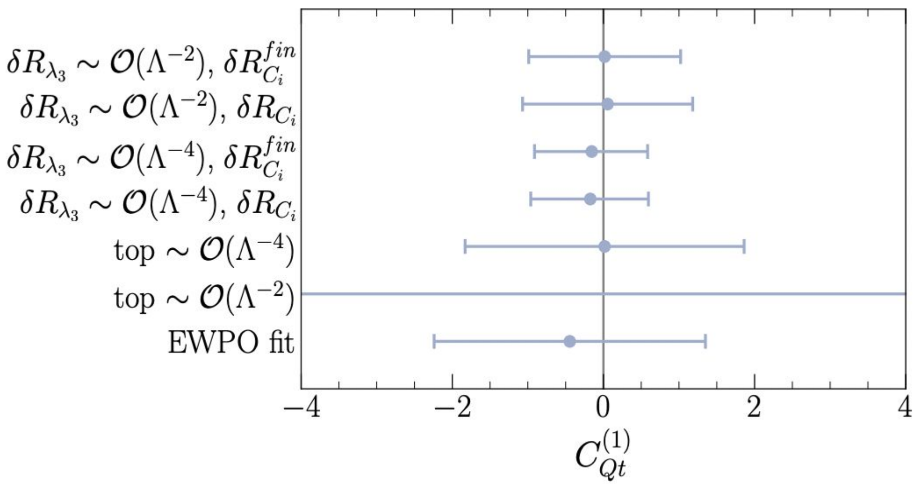
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×



Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743

Four-fermion in SMEFT: One loop in Single H





$\langle C_{Qt}^{(1)} \rangle$	95% CI
0.0	[-1.0, 1.0]
0.1	[-1.1, 1.2]
-0.2	[-0.9, 0.6]
-0.2	[-1.0, 0.6]
0.0	[-1.8, 1.9]
-18.0	[-195.0, 159.0]
-0.4	[-2.2, 1.4]

Alasfar, Blas, Gröber, arXiv:2202.02333

Higgs data bounds are competitive with ones from top quark data

Final words

My personal opinion

What Should We Keep In Mind?

- **Precise experimental measurements and predictions (SM and EFT)**
- **EFT predictions with higher-level of accuracy:**
  - QCD and EW corrections
  - Higher order in EFT, e.g. squared dim-6, double insertions of dim-6, dim-8
  - Including Renormalisation Group Equations (RGE) effects
- **More SMEFT operators, e.g. different flavour assumptions**
- **More observables, e.g. spin correlations, etc.**

EFT Including RGE Effects

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} \boxed{a_{n,i}^6(\mu)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- Observables are typically associated to specific energy scales
- RGE account for different natural scales of different processes

$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

→ **RG evolution is known at dim-6**

[Jenkins et al., arXiv:1308.2627, 1310.4838] [Alonso et al., arXiv: 1312.2014]

Recently implemented in MG5

[Aoude, Maltoni, Mattelaer, Severi, Vryonidou, arXiv:2212.05067]

SMEFT Computations In Practice

Tree-level (`SMEFTsim`); https://smeftsim.github.io/

[Brivio, 2012.11343]

NLO in QCD (`SMEFT@NLO`);
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

[Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, 2008.11743]

NLO in EW; Sudakov EW approximation in SMEFT

[HF, Mimasu, Pagani, Severi, Vryonidou, Zaro, *WIP*]

Summary and Conclusions

- SMEFT is a powerful and robust, model-independent approach to parameterise potential new physics
- Conducting global fits to constrain SMEFT coefficients is the ultimate goal
- Higgs and Top are feature a strong interplay within SMEFT framework
- Higgs pair production in SMEFT can shed some light on the trilinear Higgs coupling
- Precise experimental measurements and theoretical predictions are key to better constraining SMEFT coefficients