INTRODUCTION TO SMEFT

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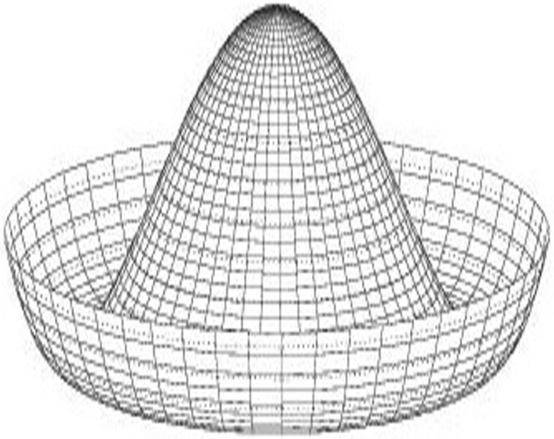
CTEQ, 2023

Lecture 2



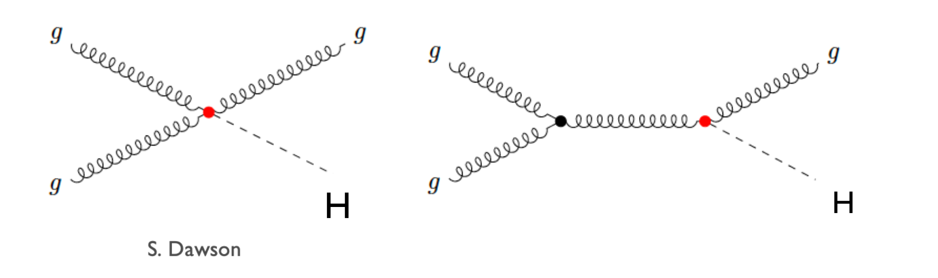
Complaints, suggestions to dawson@bnl.gov

MOMENTUM DEPENDENT OPERATORS CHANGE KINEMATIC DISTRIBUTIONS

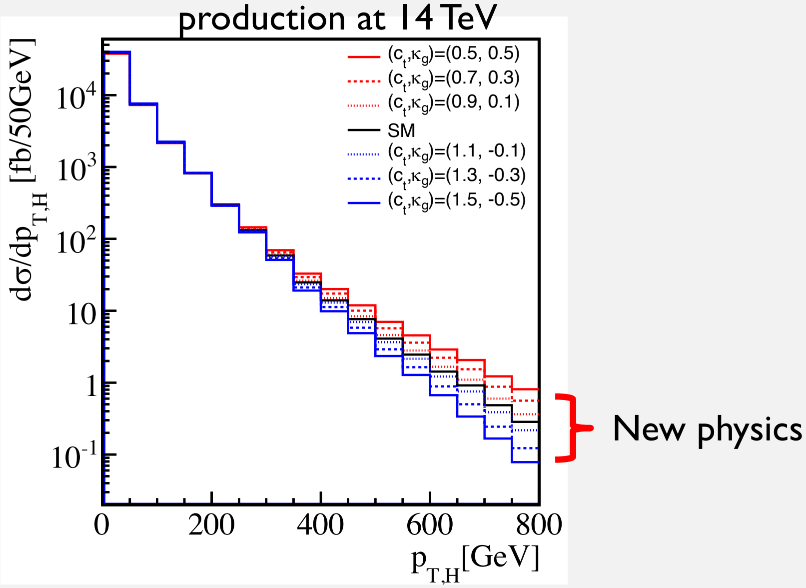
- Typically quite small effects:

$$\mathcal{O}\left(\frac{p_T^2}{\Lambda^2}\right)$$

- Couplings constrained to give correct rate for ggH
- Look in tails of distributions (Is theory valid?)



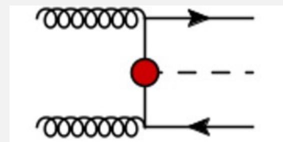
Higgs plus jet production at 14 TeV

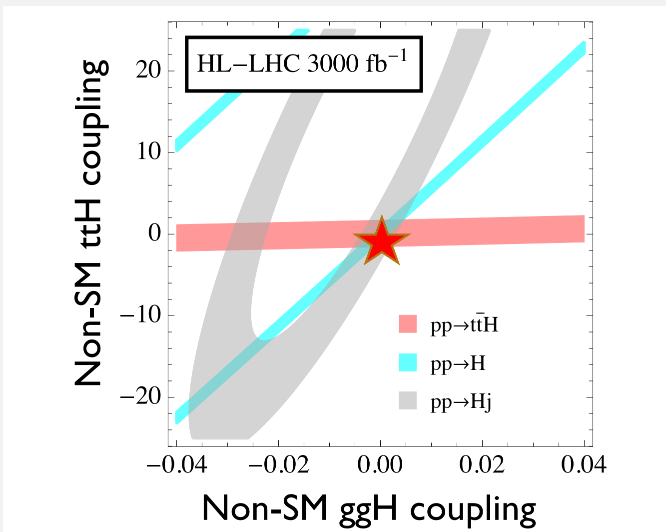


Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, arxiv:1405.4295

IDENTIFY SMEFT COEFFICIENTS

- Is the ttH coupling the Standard Model coupling?
- Non-SM contributions change rate/distributions





- Observation of gluon fusion production of Higgs at expected rate doesn't mean Higgs has SM ttH coupling
- Need ttH production
- High luminosity will pin down coupling

*tH production is sensitive to the sign of the coupling

Maltoni, Vryonidou, Zhang, [Arxiv:1607.05330](https://arxiv.org/abs/1607.05330)

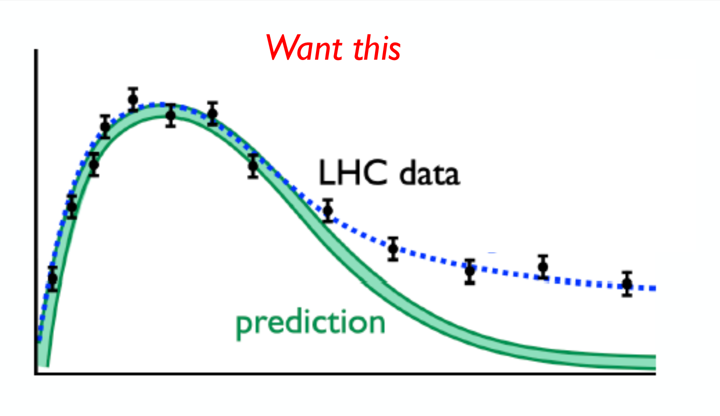
LEARNING FROM SMEFT

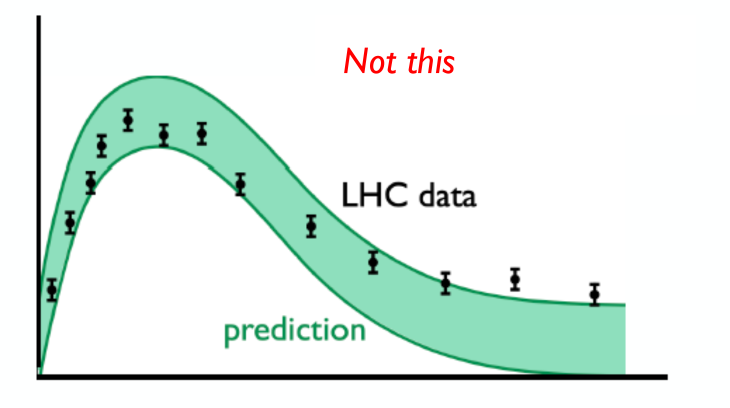
$$\text{Experiment} = \text{Theory}_{\text{SM}} + \sum \frac{x_i C_i^6}{\Lambda^2} + \ldots$$

Precise experimental measurements

Precise SM calculations

Precise SMEFT calculations





HIGGS DECAYS

- Example: H→bb

$$\frac{\Gamma(H\to b\bar{b})}{\Gamma(H\to b\bar{b})\,|_{SM}} = (1+\Delta\kappa_b)^2$$

$$\Delta\kappa_b = \frac{1}{\sqrt{2}G_F\Lambda^2}\left(\underbrace{C_{H\Box} - \frac{C_{HD}}{4}}_{\text{From normalizing H kinetic energy}} \underbrace{- C_{Hl}^{(3)} + \frac{C_{ll}^{1}}{2}}_{\text{From change in relation between } G_F \text{ and v}} \underbrace{- \frac{C_{dH}}{2^{3/4} m_b \sqrt{G_F}}}_{\text{New dimension-6 operator}}\right)$$

- ***Is this just a fancy way of writing the κ's?***

$$O_{dH} = Y_d(\phi^\dagger\phi)\bar{q}_L\phi d_R$$

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Feynman rules: [1704.03888](1704.03888)

CONSIDER H→ZZ

- H→Zff

$$\frac{\Gamma(H\rightarrow Zf\overline{f})}{\Gamma(H\rightarrow Zf\overline{f})\mid_{SM}}=1+\frac{1}{\sqrt{2}G_F\Lambda^2}\left[c_k-.97c_{ZZ}\right]$$

c_{ZZ} generate momentum dependent contributions

- EFT can capture off-shell effects (not just a κ)

$$c_k=\frac{C_{HD}}{2}+2C_{H\Box}+C_{ll}-2C^{(3)}_{Hl}$$

$$c_{ZZ}=\frac{M_W^2}{M_Z^2}C_{HW}+(1-\frac{M_W^2}{M_Z^2})C_{HB}+\frac{M_W}{M_Z}\sqrt{1-\frac{M_W^2}{M_Z^2}}C_{HWB}$$

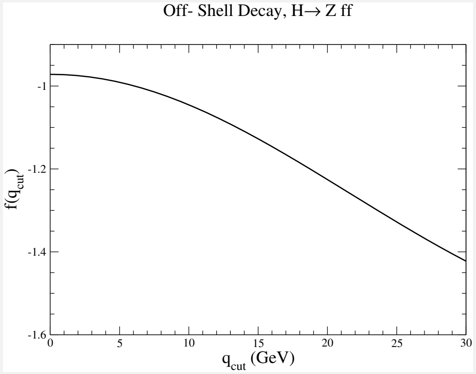
These operators have derivatives

H→Zff

- EFT has more information than total rate
  - q^2 is fermion pair invariant mass squared

$$\frac{d\Gamma}{dq^2}\Big|_{EFT}=\frac{d\Gamma}{dq^2}\Big|_{SM}\left[1+\frac{1}{\sqrt{2}G_F\Lambda^2}c_k\right]+\frac{G_Fq^2}{\Lambda^2}c_{ZZ}(\ldots)$$

  - Integrate up to q_{cut}
  - $(G_Fq^2/\Lambda^2)f(q_{cut})$ is coefficient of c_{ZZ}



κ formalism does not capture this momentum dependence present in the SMEFT

CONNECTING HZZ SMEFT WITH HZZ κ CALCULATIONS

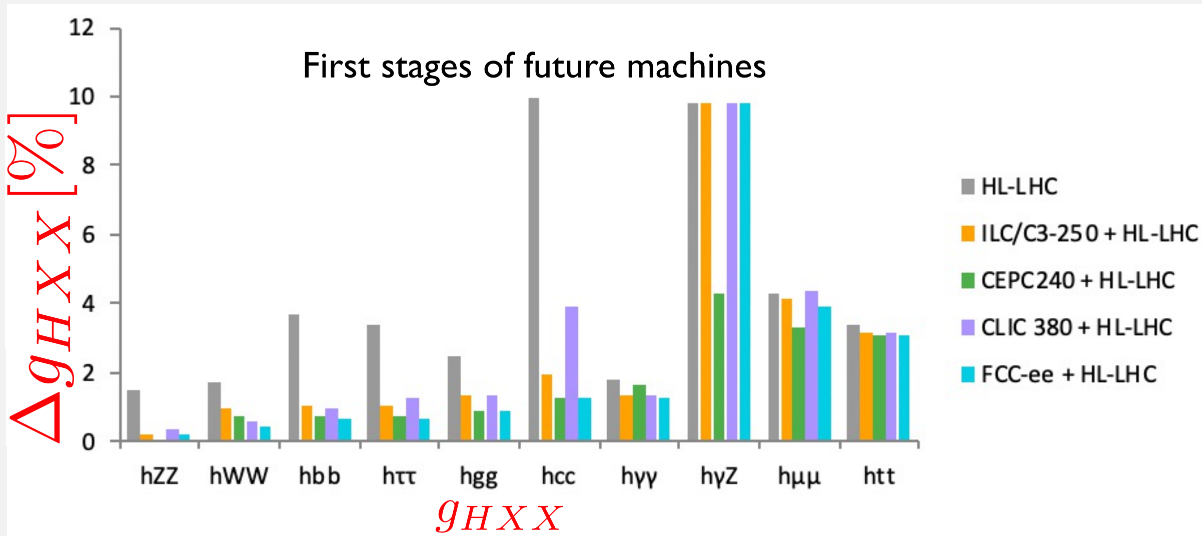
- Define an **effective** g_{HZZ} coupling such that

$$\frac{\Gamma(H\to ZZ)\mid_{SMEFT}}{\Gamma(H\to ZZ)\mid_{SM}} = (1+\Delta g_{HZZ})^2 \sim 1+2\Delta g_{HZZ}$$

- Hides SMEFT complications, but they are still there

EXTRACTION OF HIGGS COUPLINGS AT FUTURE COLLIDERS

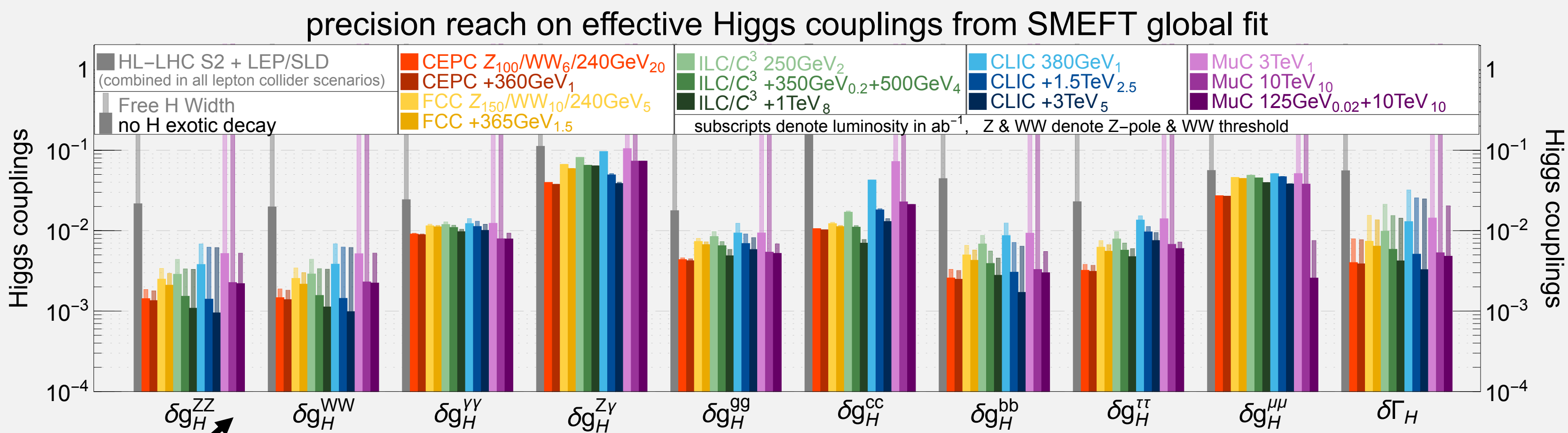
- Plot assumes no BSM
  (ie. Higgs width is sum of SM decay widths)
- Significant improvements at future colliders
- Differences between e^+e^- colliders due to different L assumptions



Snowmass Higgs report, 2209.07510

*Next include electroweak precision observables and diboson production in SMEFT framework

MANY POSSIBILITIES



Order of magnitude improvement in HWW/HZZ couplings at future machines

Solid: no BSM decays
Light: width floats
(invisible/BSM allowed)

Order of magnitude improvement in unconstrained Γ_H at future machines

Off-shell@HL-LHC, $\delta\Gamma_H$~17%
Recoil@full FCC-ee, $\delta\Gamma_H$~1%

2209.08078

CALCULATE AT ONE LOOP IN SMEFT

- Theory is renormalizable order by order in $1/\Lambda^2$ expansion
  - Drop terms of $O(1/\Lambda^4)$
- Wilson coefficients renormalized in $\overline{MS}$: $C_i(\mu) = C_i^0 - \frac{1}{32\pi^2\epsilon}\gamma_{ij}C_j$
  - Tree level relationships changed from SM
  - Renormalization counterterms have $1/\Lambda^2$ contributions

$$G_\mu = \frac{1}{\sqrt{2}\Lambda^2}\left(2C_{Hl}^3 - C_{ll}\right) + \frac{1}{\sqrt{2}v_0^2}(1+\Delta r)$$

* Δr in SMEFT different from SM

- Idea is that including SMEFT@NLO gives a window into the dependence on operators that don't contribute at tree level

NLO RESULTS FOR H$\rightarrow \gamma\gamma$

- Use α, M_Z, G_μ as input parameters
  - Using M_W, M_Z, G_μ as inputs changes coefficients of C_{ll}, $C_{Hl}^{(3)}$, C_{HD}

$$\mu_{\gamma\gamma} = 1 + \left[-40C_{HB} - 13C_{HW} + 22C_{HWB}\right]$$ ~5% shifts from tree level values

$$\left[-.9C_W + .12C_{H\Box} - .2C_{HD}\right]$$ Limited from VV production

New $$+ .03C_{uH} - 1.2C_{uW} - 2C_{uB}$$

$$\left[-.36C_{Hl}^{(3)} + .18C_{ll}\right]$$ G_μ

Note NLO results involve many coefficients

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*Coefficients evaluated at scale Λ=1 TeV

NON-SM COUPLINGS IN EFFECTIVE COUPLING LANGUAGE

- Effective Z/W-fermion couplings
- (neglect RH W couplings and RH υ couplings since they don't interfere with the SM)

$$L = 2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\Big\{\Big[g_L^{Zu}+\boxed{\delta g_L^{Zu}}\Big]\overline{u}_L\gamma_\mu u_L+\Big[g_L^{Zd}+\boxed{\delta g_L^{Zd}}\Big]\overline{d}_L\gamma_\mu d_L+\Big[g_R^{Zu}+\boxed{\delta g_R^{Zu}}\Big]\overline{u}_R\gamma_\mu u_R$$
$$+\Big[g_R^{Zd}+\boxed{\delta g_R^{Zd}}\Big]\overline{d}_R\gamma_\mu d_R+\Big[g_L^{Ze}+\boxed{\delta g_L^{Ze}}\Big]\overline{e}_L\gamma_\mu e_L+\Big[g_L^{Z\nu}+\boxed{\delta g_L^{Z\nu}}\Big]\overline{\nu}_L\gamma_\mu\nu_L$$
$$+\Big[g_R^{Ze}+\boxed{\delta g_R^{Ze}}\Big]\overline{e}_R\gamma_\mu e_R\Big\}+\frac{\overline{g}_2}{\sqrt{2}}\Big\{W_\mu\Big[(1+\delta g_L^{Wq})\overline{u}_L\gamma_\mu d_L\Big]+W_\mu\Big[(1+\delta g_L^{Wl})\overline{\nu}_L\gamma_\mu e_L\Big]+h.c.\Big\}$$

- SU(2) invariance requires

$$\delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$$
$$\delta g_L^{Wl} = \delta g_L^{Z\nu} - \delta g_L^{Ze}$$

7 new parameters + M_W

RH W couplings do not interfere with SM

CHANGES TO FERMION-GAUGE COUPLINGS

	Warsaw Basis
δg_L^{Zu}	$-\frac{v^2}{2\Lambda^2}\left(\mathcal{C}_{Hq}^{(1)}-\mathcal{C}_{Hq}^{(3)}\right)+\frac{1}{2}\delta g_Z+\frac{2}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_L^{Zd}	$-\frac{v^2}{2\Lambda^2}\left(\mathcal{C}_{Hq}^{(1)}+\mathcal{C}_{Hq}^{(3)}\right)-\frac{1}{2}\delta g_Z-\frac{1}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
$\delta g_L^{Z\nu}$	$-\frac{v^2}{2\Lambda^2}\left(\mathcal{C}_{Hl}^{(1)}-\mathcal{C}_{Hl}^{(3)}\right)+\frac{1}{2}\delta g_Z$
δg_L^{Ze}	$-\frac{v^2}{2\Lambda^2}\left(\mathcal{C}_{Hl}^{(1)}+\mathcal{C}_{Hl}^{(3)}\right)-\frac{1}{2}\delta g_Z-\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Zu}	$-\frac{v^2}{2\Lambda^2}\mathcal{C}_{Hu}+\frac{2}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Zd}	$-\frac{v^2}{2\Lambda^2}\mathcal{C}_{Hd}-\frac{1}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Ze}	$-\frac{v^2}{2\Lambda^2}\mathcal{C}_{He}-\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_L^{Wq}	$\frac{v^2}{\Lambda^2}\mathcal{C}_{Hq}^{(3)}+c_W^2\delta g_Z+\delta s_W^2$
δg_L^{Wl}	$\frac{v^2}{\Lambda^2}\mathcal{C}_{Hl}^{(3)}+c_W^2\delta g_Z+\delta s_W^2$
δg_Z	$-\frac{v^2}{\Lambda^2}\left(\delta v+\frac{1}{4}\mathcal{C}_{HD}\right)$
δv	$\mathcal{C}_{Hl}^{(3)}-\frac{1}{2}\mathcal{C}_{ll}$
δs_W^2	$-\frac{v^2}{\Lambda^2}\frac{s_W c_W}{c_W^2-s_W^2}\left[2s_W c_W\left(\delta v+\frac{1}{4}\mathcal{C}_{HD}\right)+\mathcal{C}_{HWB}\right]$

Expansion in v^2/Λ^2

Scale is fixed to M_Z

Change in relationship between input parameters: $g_Z=G_F M_Z$

Change in relationship between v and G_F

W AND Z POLE OBSERVABLES

- Fit to 14 data points—inputs are G_μ, M_Z, α

$$M_W, \Gamma_W, \Gamma_Z, \sigma_h, A_{l,FB}, A_{b,FB}, A_{c,FB}, A_b, A_c, A_l, R_l, R_b, R_c$$

- Tree level expressions depend on (in Warsaw basis)

$$C_{ll}, C_{HWB}, C_{Hu}, C_{Hq}^{(3)}, C_{Hq}^{(1)}, C_{Hl}^{(3)}, C_{Hl}^{(1)}, C_{He}, C_{HD}, C_{Hd}$$

- Tree level observables depend on 8 combinations of operators

$$M_W, \delta g_L^{Zu}, \delta g_L^{Zd}, \delta g_L^{Z\nu}, \delta g_L^{Ze}, \delta g_R^{Zu}, \delta g_R^{Zd}, \delta g_R^{Ze}$$

$\Rightarrow$ 2 blind directions (resolved by other measurements)

FITS ARE STRAIGHTFORWARD

- Compute observables in SMEFT: $O_i = O_i^{SM} + \delta O_i$
- Use most accurate SM theory
- Do χ^2 fit to data
- Operators contributing to LEP observables strongly restricted

Measurement	Experiment	"Best" theory
Γ_Z(GeV)	2.4952 ± 0.0023	2.4945 ± 0.0006
σ_h(nb)	41.540 ± 0.037	41.491 ± 0.008
R_l	20.767 ± 0.025	20.749 ± 0.009
R_b	0.21629 ± 0.00066	0.21586 ± 0.0001
R_c	0.1721 ± 0.0030	0.17221 ± 0.00005
A_l	0.1465 ± 0.0033	0.1472 ± 0.0004
A_c	0.670 ± 0.027	0.6679 ± 0.0002
A_b	0.923 ± 0.020	0.92699 ± 0.00006
$A_{l,FB}$	0.0171 ± 0.0010	0.0162 ± 0.0001
$A_{b,FB}$	0.0992 ± 0.0016	0.1023 ± 0.0003
$A_{c,FB}$	0.0707 ± 0.0035	0.0737 ± 0.0003
$A_l(SLD)$	0.1513 ± 0.0021	0.1472 ± 0.0004
$\sin^2\theta_{l,eff}$	0.23179 ± 0.00035	0.23150 ± 0.00006
M_W(GeV)	80.379 ± 0.012	80.359 ± 0.006
Γ_W(GeV)	2.085 ± 0.042	2.0904 ± 0.0003

LEP FITS

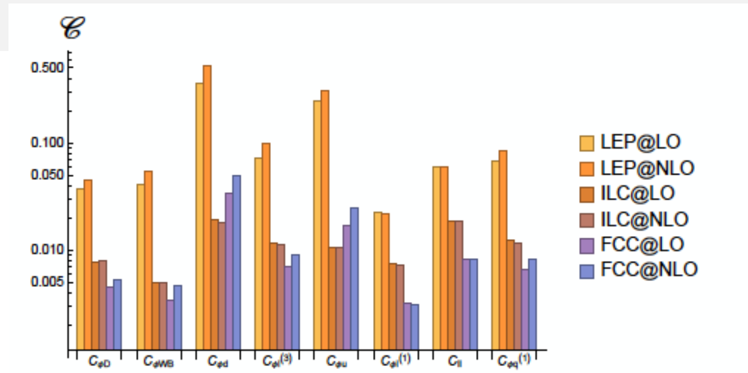
- Strong cancellations possible
- Can't just fit to one operator
- Contributions from different operators vary greatly
- At NLO, dependence on many operators

$$
\begin{aligned}
\delta M_W^{LO} &= \frac{v^2}{\Lambda^2}\Big\{-29.827\mathcal{C}_{Hl}^{(3)} + 14.914\mathcal{C}_{ll} - 27.691\mathcal{C}_{HD} - 57.479\mathcal{C}_{HWB}\Big\} \\
\delta\Gamma(Z \to b\bar{b})^{LO} &= \frac{v^2}{\Lambda^2}\Big\{-0.1400\mathcal{C}_{Hd} - 1.0242\mathcal{C}_{Hl}^{(3)} + 0.8498\mathcal{C}_{Hq}^{(1)} + 0.8498\mathcal{C}_{Hq}^{(3)} + 0.5121\mathcal{C}_{ll} \\
&\quad -0.2561\mathcal{C}_{HD} - 0.3361\mathcal{C}_{HWB}\Big\} \\
\delta R_l^{LO} &= \frac{v^2}{\Lambda^2}\Big\{-4.978\mathcal{C}_{Hd} + 33.673\mathcal{C}_{He} - 45.688\mathcal{C}_{Hl}^{(1)} - 49.393\mathcal{C}_{Hl}^{(3)} + 13.39\mathcal{C}_{Hq}^{(1)} + 47.041\mathcal{C}_{Hq}^{(3)} \\
&\quad +6.637\mathcal{C}_{Hu} + 1.853\mathcal{C}_{ll} - 0.926\mathcal{C}_{HD} - 4.532\mathcal{C}_{HWB}\Big\}
\end{aligned}
$$

Z AND W POLE OBSERVABLES

- 10 operators contribute at tree level

$\mathcal{O}_{ll}$	$(\bar{l}_L\gamma_\mu l_L)(\bar{l}_L\gamma^\mu l_L)$	$\mathcal{O}_{HWB}$	$(H^\dagger\tau^a H)\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^*\,(H^\dagger D_\mu H)$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}^{(3)}_{\phi q}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{q}_L\tau^a\gamma^\mu q_L)$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_L\tau^a\gamma^\mu q_L)$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{l}_L\tau^a\gamma^\mu l_L)$
$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_L\tau^a\gamma^\mu l_L)$				



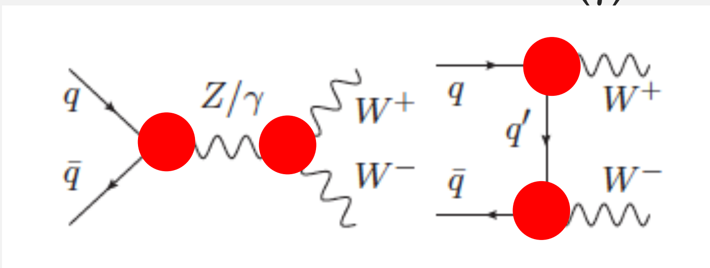
$$\alpha\Delta S = 4 c_W s_W \frac{v^2}{\Lambda^2} C_{HWB}$$

$$\alpha\Delta T = -\frac{v^2}{2\Lambda^2} C_{HD}$$

Improving these fits is a major motivation for future e+e- colliders

DIBOSON PRODUCTION IS OLD STORY

- Sensitive to variations of Zff and Z(γ)WW couplings



No growth with energy in SM

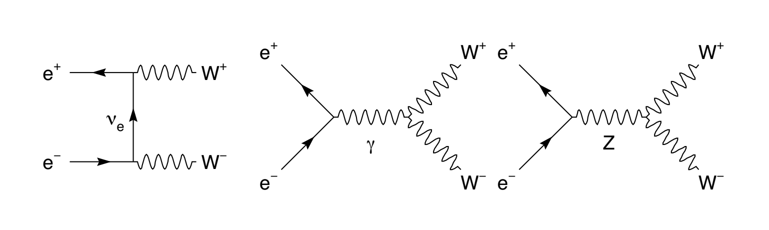
- Individual contributions grow with energy
- Cancellations keep amplitudes from growing at high energy in SM

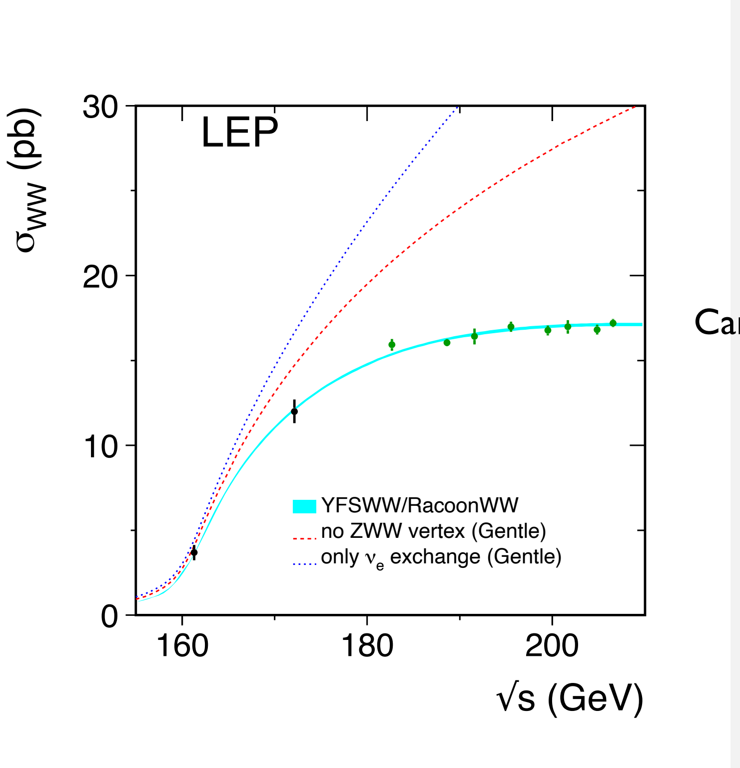
Changing gauge or fermion couplings spoils cancellation

Question: Who cares if cross sections grow with energy?

REAL WORLD CONSEQUENCES

- *Probing the Weak Boson Sector in $e^+e^- \to W^+W$* (Hagiwara, Peccei, Zeppenfeld, Hikasa, 1987)
- At that time the structure of the 3 gauge boson interactions had not been verified experimentally



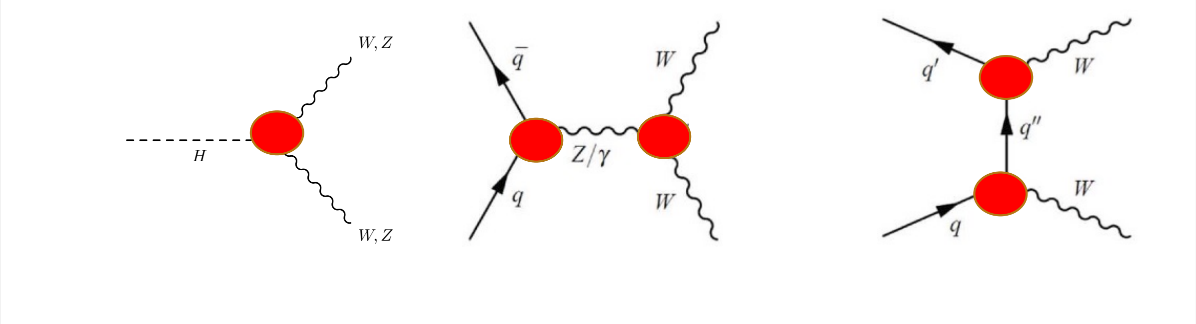


Cancellations

SMEFT CONTRIBUTIONS SPOIL THIS CANCELLATION!

CAN'T JUST FIT HIGGS COUPLINGS

Operators that contribute to VVV vertices and Higgs-VV vertices



Leads to concept of global fits

PRACTICAL PROBLEMS

$$L \to L_{SM} + \Sigma_i \frac{C_{6i}}{\Lambda^2} O_{6i} + \Sigma_i \frac{C_{8i}}{\Lambda^4} O_{8i} + \ldots$$

- SMEFT

$$A^2 \sim \mid A_{SM} + \frac{A_6}{\Lambda^2} + \ldots \mid^2 \sim A_{SM}^2 + \frac{A_{SM} A_6}{\Lambda^2} + \frac{A_6^2}{\Lambda^4} + \ldots.$$

- Problem is that $(A_6)^2$ terms are the same order as A_8 terms that we have dropped
- If I only keep A_6/Λ^2 terms and drop $(A_6/\Lambda^2)^2$, the cross section is not guaranteed to be positive
- Corrections are $O(s/\Lambda^2)$ or $O(v^2/\Lambda^2)$
- Information from distributions

COUNTING LORE

$$\sigma \sim g_{SM}^2 (A_{SM})^2 + g_{SM} g_{BSM} A_{SM} A_6 \frac{s}{\Lambda^2}$$
$$+ \underbrace{g_{BSM}^2 (A_6)^2 \frac{s^2}{\Lambda^4} + g_{SM} g_{BSM} A_{SM}}A_8 \frac{s^2}{\Lambda^4}$$

Same order of magnitude if $g_{SM} \sim g_{BSM}$

(Dim-6)^2 could dominate if $g_{BSM} >> g_{SM}$

Dimension-6 quadratic expansion can be valid for strongly interacting theory

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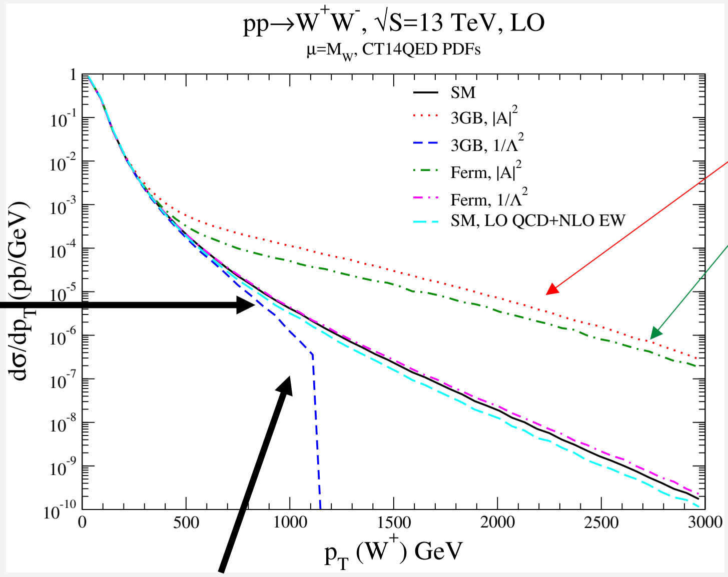
OBVIOUS PROBLEM WHEN TRUNCATING THE SERIES WITH THE INTERFERENCE PIECE

- One proposal for dealing with this issue is to put a cut on the maximum energy where the SMEFT is assumed to be valid

Linear expansion

How to interpret negative cross section region?



....Anomalous 3 gauge boson couplings

----Anomalous Z-fermion couplings allowed by LEP measurements

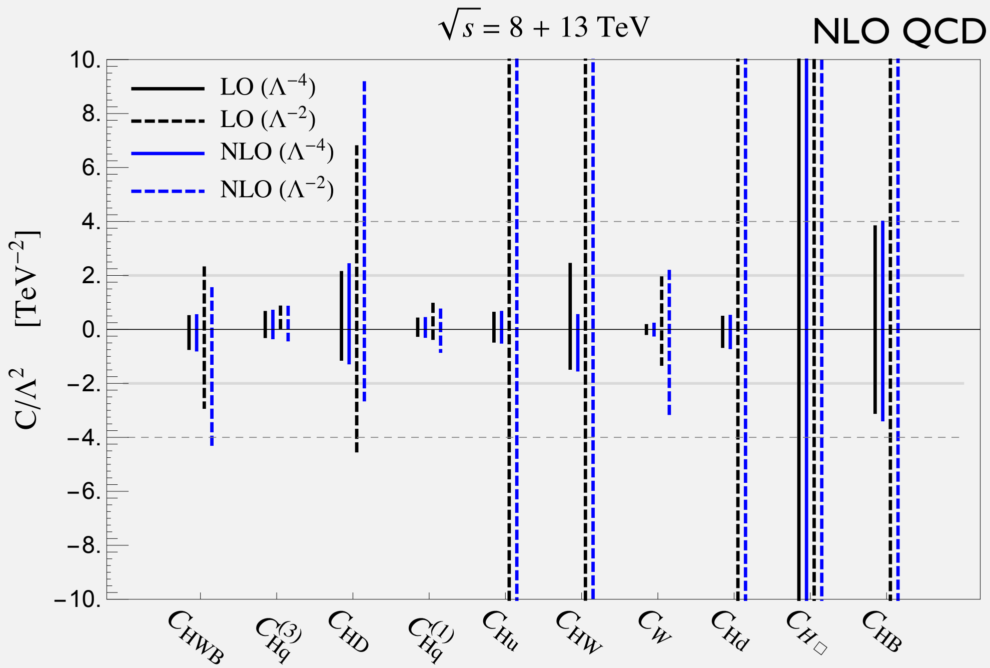
Do such large effects make any sense?

Baglio, Dawson, Lewis , arXiv:1708.03332

* σ goes negative, expansion not valid

ASSUMPTIONS CREEPING IN

- Single parameter fit to WW/WZ/WH/ZH
- For linear fit, throw out points with negative cross section
- Fit assumes SM efficiencies in each bin (not necessarily true)
- Fit ignores flavor



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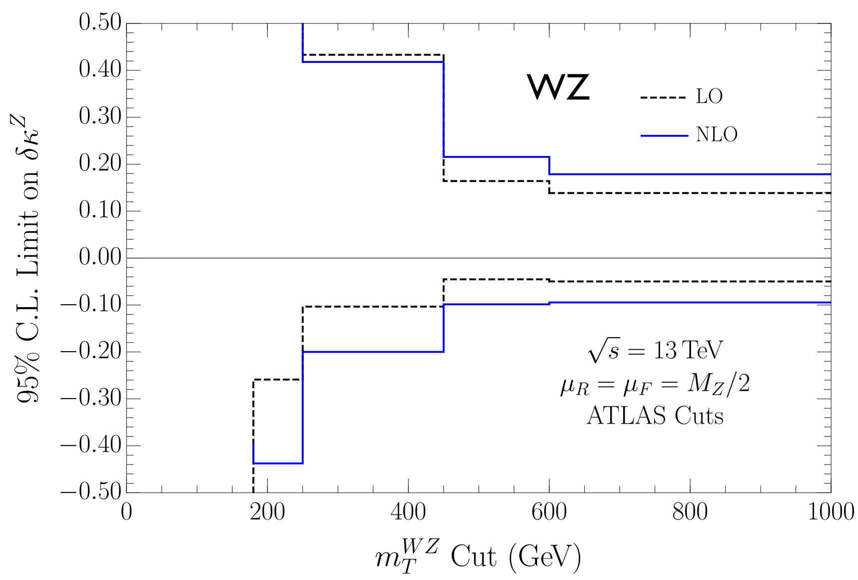
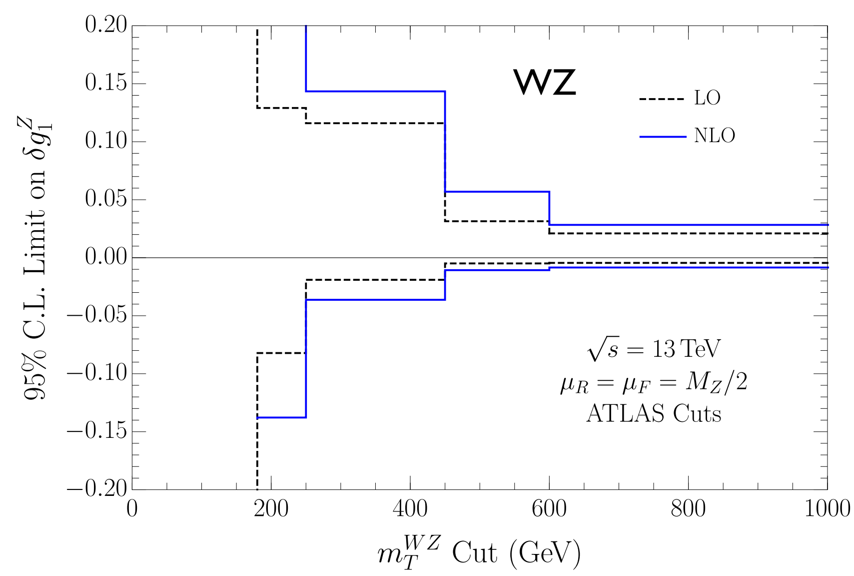
IS IT ALL THE LAST BIN?

- Fit results depend on cut on maximum energy





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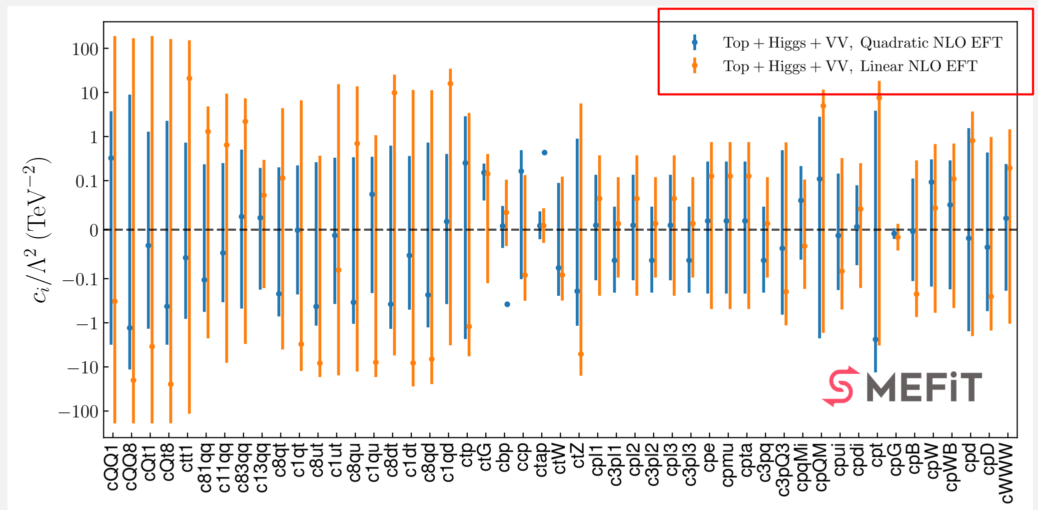
Plots successively remove high m_T bins

MANY GLOBAL FITS TO DATA

Take home message:

- Precision on operators varies over many order of magnitude
- Exact values of couplings sensitive to assumptions
- Rates (with QCD) can be generated automatically
- Compare linear and quadratic contributions



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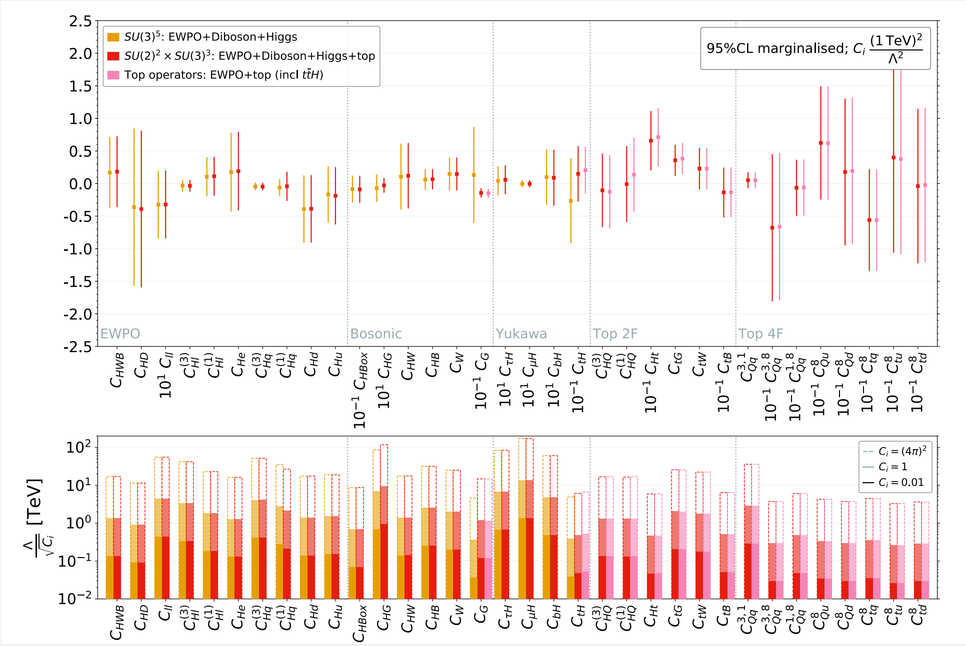
Challenge to experimental collaborations to include data outside of Higgs sector

MANY NEW FITS

- Fits have different assumptions, different sets of data included
- Probing TeV scale new physics



Fit includes top, Higgs, EWPO, diboson

Compare results with and without top data

C~1: New physics generated at tree level

C~1/(4π)^2: New physics generated at loop level

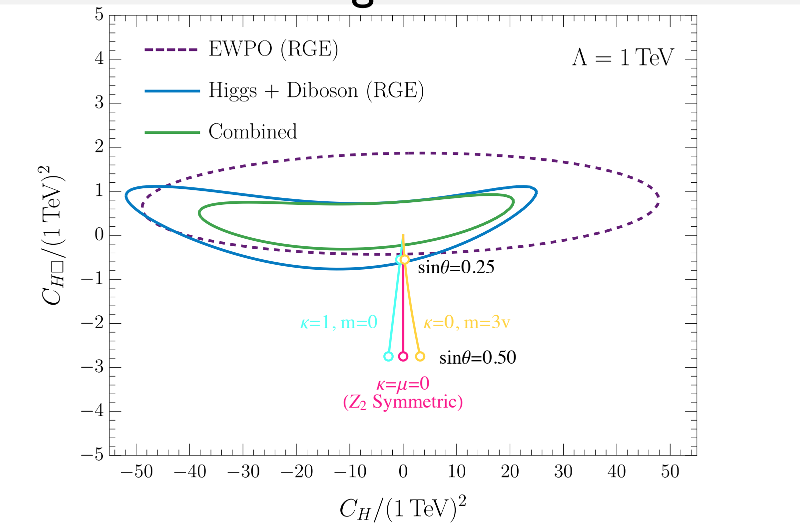
At dim-6 only sensitive to C/Λ^2

Ellis, Madigan, Mimasu, Sanz, You, [2012.02779]

DREAM OF SMEFT FITTERS

- Fit to data ➜ non-zero coefficients
- Pattern of coefficients ➜ UV model
- Lots of theory holes to fill in this program

Fit to coefficients occurring in scalar singlet model



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THE HIGGS INVERSE PROBLEM

- If we measure non-zero SMEFT coefficients, can we determine the high scale model?
- In simple models (ie 1 new massive particle, whose interactions are described in terms of a single parameter) the particles that can contribute to dimension-6 operators have been categorized long ago 1711.10391
- Dimension-6 contributions only sensitive to C/Λ^2

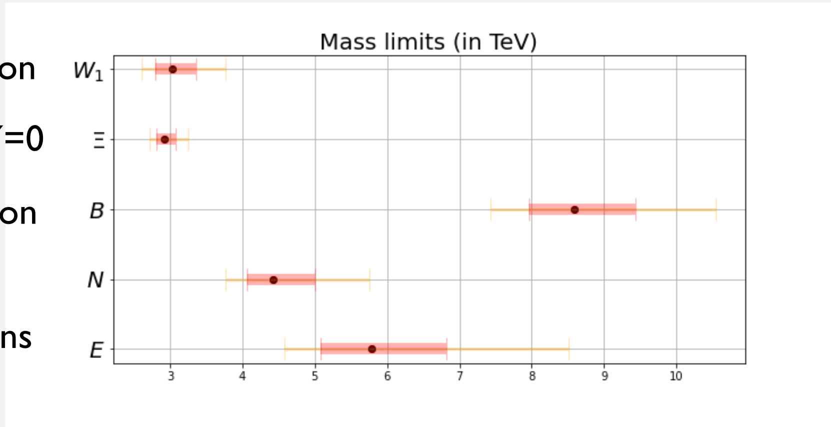
Global fit with C=1

SU(2) triplet gauge boson

SU(2) triplet scalar, Y=0

Neutral gauge boson

Charge 0 and
charge 1 fermions



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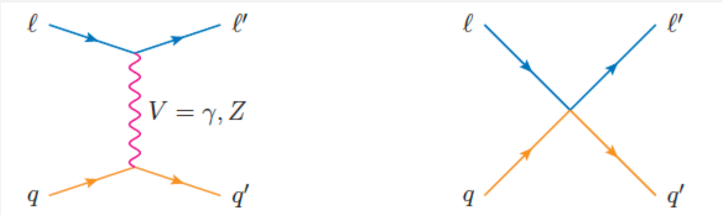
NUCLEAR PHYSICS AND SMEFT



	Joint EIC	Joint LHeC	Joint FCCeh	EW diboson, Higgs, and top data
$C_{\varphi D}$	[−3.8, 3.8]	[−0.019, 0.019]	[−0.013, 0.013]	[−1.6, 0.81]
$\frac{\Lambda}{\sqrt{C_{\varphi D}}}$	0.51	7.2	8.8	0.91
$C_{\varphi WB}$	[−9.9, 9.9]	[−0.098, 0.098]	[−0.034, 0.034]	[−0.36, 0.73]
$\frac{\Lambda}{\sqrt{C_{\varphi WB}}}$	0.32	3.2	5.4	1.4
$C_{\varphi q}^{(1)}$	[−38., 38.]	[−0.40, 0.40]	[−0.39, 0.39]	[−0.27, 0.18]
$\frac{\Lambda}{\sqrt{C_{\varphi q}^{(1)}}}$	0.16	1.6	1.6	2.1
$C_{\varphi q}^{(3)}$	[−4.1, 4.1]	[−0.11, 0.11]	[−0.031, 0.031]	[−0.11, 0.012]
$\frac{\Lambda}{\sqrt{C_{\varphi q}^{(3)}}}$	0.49	3.1	5.7	4.1
$C_{\varphi u}$	[−38., 38.]	[−0.51, 0.51]	[−0.45, 0.45]	[−0.63, 0.25]
$\frac{\Lambda}{\sqrt{C_{\varphi u}}}$	0.16	1.4	1.5	1.5
$C_{\varphi d}$	[−84., 84.]	[−0.82, 0.82]	[−0.71, 0.71]	[−0.91, 0.13]
$\frac{\Lambda}{\sqrt{C_{\varphi d}}}$	0.11	1.1	1.2	1.4
$C_{\varphi \ell}^{(1)}$	[−18., 18.]	[−0.094, 0.094]	[−0.060, 0.060]	[−0.19, 0.41]
$\frac{\Lambda}{\sqrt{C_{\varphi \ell}^{(1)}}}$	0.23	3.3	4.1	1.8
$C_{\varphi \ell}^{(3)}$	[−4.1, 4.1]	[−0.060, 0.060]	[−0.022, 0.022]	[−0.13, 0.055]
$\frac{\Lambda}{\sqrt{C_{\varphi \ell}^{(3)}}}$	0.49	4.1	6.7	3.3
$C_{\varphi e}$	[−5.7, 5.7]	[−0.16, 0.16]	[−0.046, 0.046]	[−0.41, 0.79]
$\frac{\Lambda}{\sqrt{C_{\varphi e}}}$	0.42	2.5	4.6	1.3
$C_{\ell t}$	[−7.7, 7.7]	[−0.039, 0.039]	[−0.026, 0.026]	[−0.084, 0.02]
$\frac{\Lambda}{\sqrt{C_{\ell t}}}$	0.36	5.1	6.2	4.4

- Familiar SMEFT modification of Z vertices and introduction of 4-fermion operators
- All the same issues as Higgs physics!

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