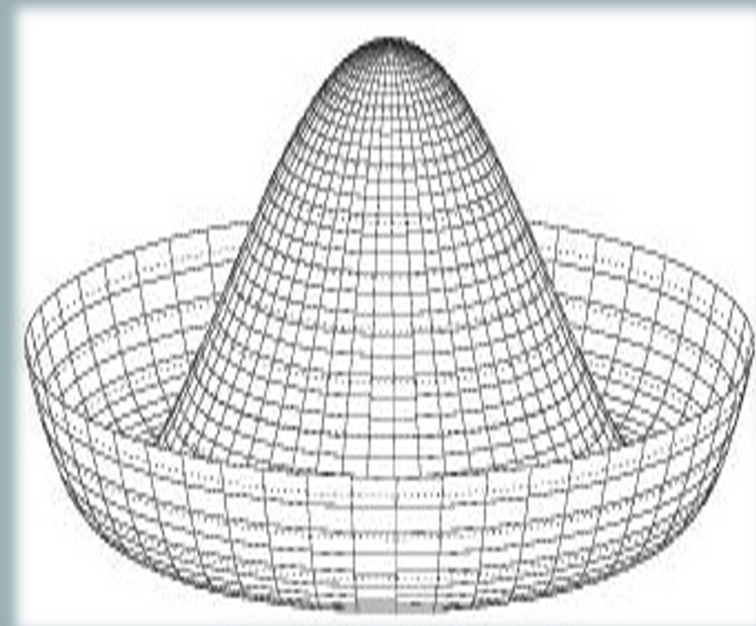
EFTS FOR HIGGS PHYSICS

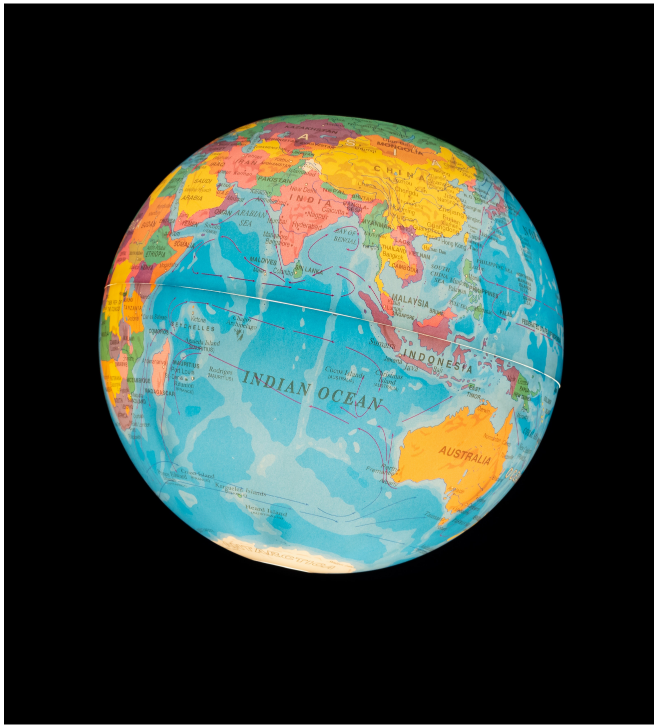
EFFECTIVE PATHWAYS TO NEW PHYSICS WORKSHOP

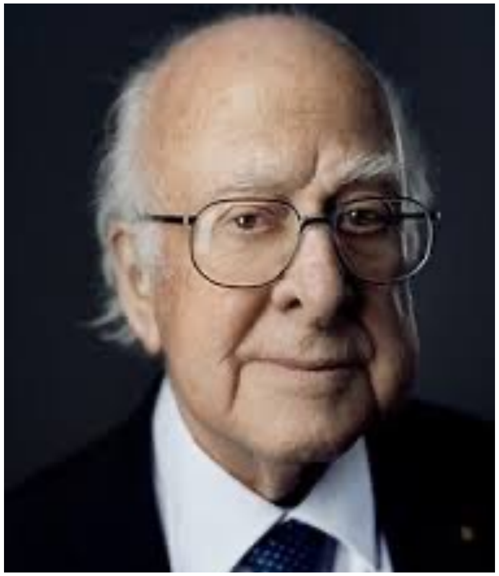
S. DAWSON, BNL, 2022

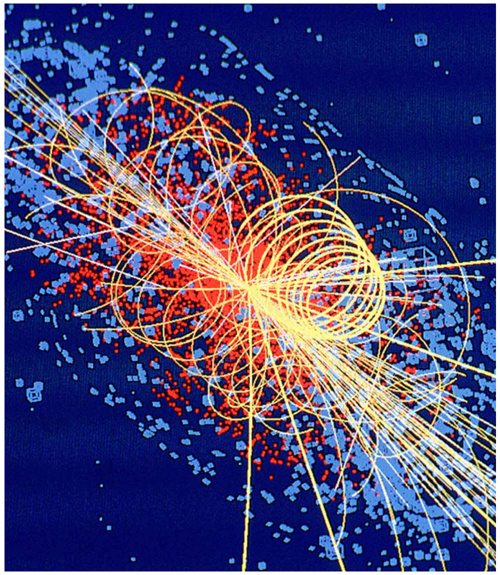


THE PARTICLE PHYSICS WORLD HAS CHANGED DRAMATICALLY IN THE LAST DECADE

- The triumph of the Standard Model
- European Strategy Study and Snowmass Study inspire us to think about the future
- What is missing from our knowledge of the Higgs?







IN THE LAST 10 YEARS….

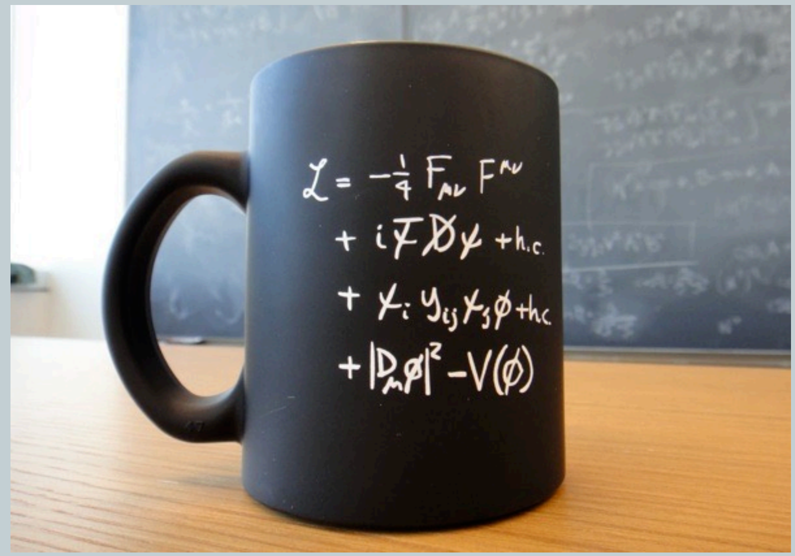
2012: LHC discovered a Higgs boson; it appears to have predicted properties

THE SM IS SIMPLE AND PREDICTIVE

- SU(3) x SU(2) x U(1)
- Electroweak sector described in terms of masses and 3 inputs
  - Typically G_F, α, M_Z
- Particle couplings fixed

Only unknown parameter is Higgs mass

Testable model !



REVIEW OF HIGGS COUPLINGS

- Couplings to fermions proportional to mass: $\frac{m_f}{v} h \overline{f} f$
- Couplings to massive gauge bosons proportional to (mass)^2 :

$$2M_W^2 \frac{h}{v} W_\mu^+ W^{-\mu} + M_Z^2 \frac{h}{v} Z_\mu Z^\mu$$

- Couplings to massless gauge bosons at 1-loop:*

$$F(m_f) \frac{\alpha_s}{12\pi} \frac{h}{v} G^A_{\mu\nu} G^{A,\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi s_W} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu}$$

- Higgs self-couplings proportional to M_h^2:

$$\frac{m_h^2}{2} h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4$$

Only unpredicted parameter is M_h

* Normalization is such that F→1 for m_t, $M_W \to \infty$

HIGGS PRODUCTION AT A HADRON COLLIDER

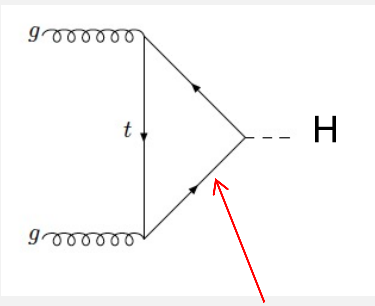
Most important processes:

$$gg \to H$$

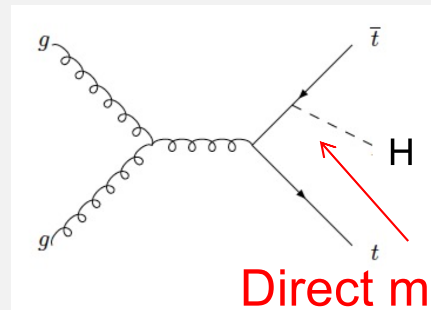
$$q\bar{q} \to q\bar{q}H$$

$$q\bar{q} \to VH$$

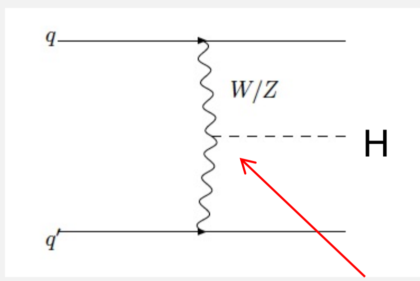
$$q\bar{q}, gg \to t\bar{t}H$$

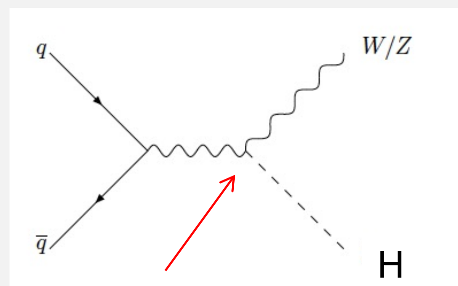


Depends on new physics in loop



Direct measurement of tth Yukawa



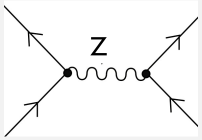


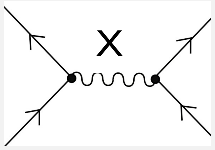
Vanishes if v=0: Fundamental test of EWSB mechanism

IS THERE MORE?

- How do we know if the SM with the Higgs is just the low energy manifestation of some more complete model that exists at high scales?

HIGH SCALE DECOUPLING

- Suppose there is a new particle X, with mass $M_X >> M_W$
- SM scattering: 

$A_{SM} \sim \frac{g^2}{M_Z^2}$
- Contribution from X: 

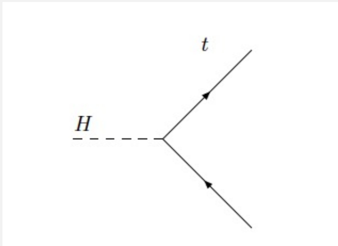
$A_X \sim \frac{g_X^2}{M_X^2}$
- Scattering rate: $\sigma \sim \sigma_{SM} + \frac{g^2 g_X^2}{M_X^2} \rightarrow \sigma_{SM}$

Effects of X vanish as $1/M_X^2$ for ***weak coupling***

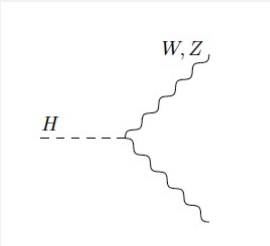
Applequist-Carrazone decoupling theorem

THE HIGGS IS DIFFERENT

- Particles whose couplings are proportional to mass don't decouple



$$-i\frac{m_f}{v}$$



$$-2i\frac{M_V^2}{v}g^{\mu\nu} \qquad \epsilon_L(p_V) \sim \frac{p_V}{M_V}$$

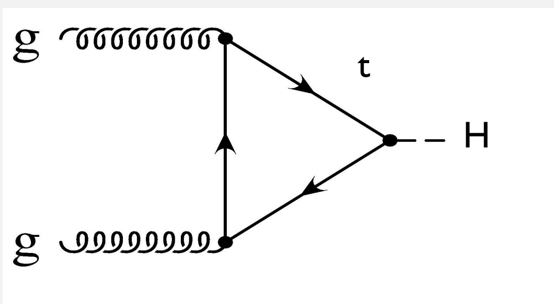
See non-decoupling effect in gg→H:
Rate is independent of m_t for $M_H << m_t$

Longitudinal polarizations also change counting (growth with energy)

Suggests that Higgs sector is good place to look for new physics

COUNTER-EXAMPLE OF NON-DECOUPLING

- Most familiar example of non-decoupling is gluon fusion with heavy chiral fermion:



$$\sigma_{gg\to H} = \frac{\alpha_s}{1024\pi v^2} \mid \Sigma_q F_q\left(\frac{M_H^2}{4m_t^2}\right) \mid^2 \delta\left(1-\frac{M_H^2}{s}\right)$$

$$\to \frac{9\alpha_s^2}{64\pi v^2}\delta\left(1-\frac{M_H^2}{s}\right)$$

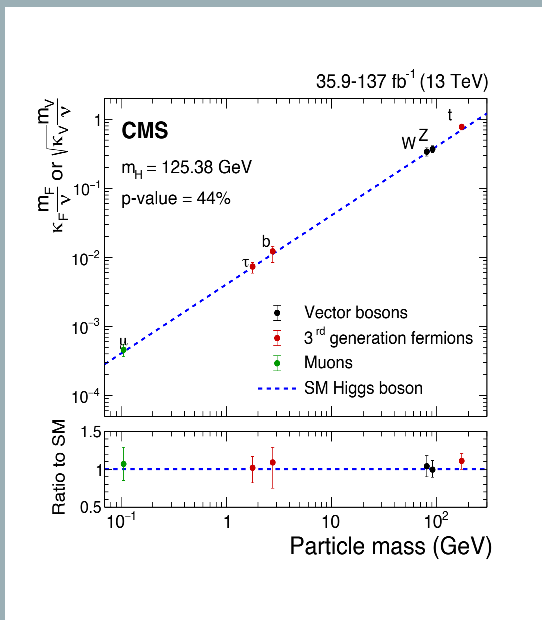
- For heavy chiral fermion, $F_{1/2} \to -4/3$, independent of mass
- This result can be derived from the effective Lagrangian

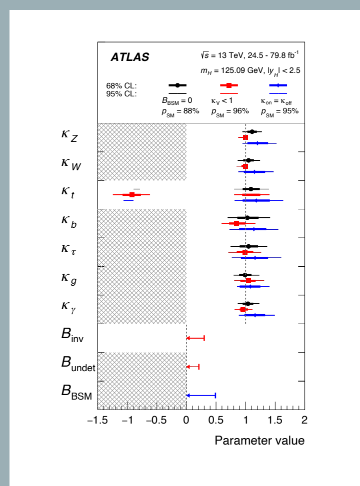
$$L_{EFT} = \frac{\alpha_s}{12\pi v^2} \mid \phi \mid^2 G^A_{\mu\nu} G^{A,\mu\nu}$$

$$\phi^0 \to \frac{H+v}{\sqrt{2}}$$

κ RESCALING OF HIGGS COUPLINGS

- κ_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)
- Problems:
  - Gauge invariance requires κ=1
    - Higgs couplings not free parameters in SM
  - Not a consistent field theory → no higher order corrections
    - EW corrections don't factorize (can't be included)
  - No kinematic information
  - Higgs coupling measurements cannot be combined with other measurements





Higgs couplings to fermions and gauge bosons *fixed in SM*

HIGGS COUPLINGS CLOSE TO SM

- *Couplings proportional to mass*
- *A deviation from this pattern signals new physics!*

Need to go beyond κ framework

NEW PHYSICS

Use precision measurements and effective field theory

Can we determine source of new physics?

No resonance or light resonance or new signatures

No need for EFT in this scenario

Find resonance!

Current limits will be strengthened at HL-LHC

ASSUME A HIERARCHY OF SCALES

$\Lambda >> M_W$ where complete theory exists

- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed

This is sad scenario where there is no intermediate scale physics

M_W Only SM particles in theory at low scales

Learn about high scale physics by measuring coefficients of effective operators with global fits

SMEFT: SM EFFECTIVE FIELD THEORY

- Assumptions: New physics decouples Λ >> v, E
- At the weak scale: SM SU(3) x SU(2) x U(1) symmetry and SM particles only
- New physics described by

$$L_{SMEFT} = L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \frac{L_7}{\Lambda^3} + \frac{L_8}{\Lambda^4}$$

$$L_n = \Sigma_i C_i^n O_i^n$$

Assume Higgs is in an SU(2) doublet

- New physics contributions contained in coefficients C
- Operators form a complete basis (not unique)
- L_5 and L_7 are lepton number violating

ADVANTAGES OF SMEFT APPROACH

- Quantum field theory where calculations done order by order i
  - Compute cross sections without knowing high scale (UV) physics
- Systematically improvable
- At this level, SMEFT calculations are model independent
- Measurements interpreted in terms of SMEFT coefficients
- Can compare very different classes of measurements

Sounds good, but how does this work in practice?

And even more important, how model independent is this?

Nice review: arXiv:1706.08945

FIND A BASIS OF OPERATORS

- Start with dimension-6 operators: with no assumptions, 2499 possibilities
- Most popular basis is "WARSAW BASIS"
- Work to tree level with one occurrence of dimension-6 operator
- Consider contributions to processes dominated by H/Z/W resonances, and interference with SM only (linear in EFT) (REASONABLE ASSUMPTION)

	Total	Not resonance suppressed
General	2499	46
MFV	108	30
$U(3)^5$	70	24

Brivio, Jiang, Trott, 1709.06492

Useful source of Feynman rules: arXiv:1704.03888.pdf

WARSAW BASIS

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

+…..

- The interesting operators are those with derivatives
- Derivative operators introduce new structures into kinematic distributions
- Most of 2499 operators come from flavor permutations

HIGGS MECHANISM IN SMEFT

- Higgs mechanism as usual, but with extra terms

$$L_H = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 + \frac{C_6}{\Lambda^2}(\phi^\dagger \phi)^3 + \frac{C_{H\Box}}{\Lambda^2}(\phi^\dagger \phi)\Box(\phi^\dagger \phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu \phi)^*(\phi^\dagger D^\mu \phi)$$

$$\phi = \begin{pmatrix} \phi_0^+ \\ \frac{1}{\sqrt{2}}(v + H_0 + i\phi_0^0) \end{pmatrix}$$

*subscript 0 indicates field before shift of field to get canonical normalization

- Minimize potential (keeping only terms up to $1/\Lambda^2$):

$$v = \sqrt{\frac{\mu^2}{\lambda} + \frac{3\mu^3}{8\lambda^{5/2}} \frac{C_6}{\Lambda^2}}$$

*This is Warsaw basis

HIGGS MECHANISM IN SMEFT, #2

- Higgs field is not canonically normalized:

$$L_H \sim \frac{1}{2}\left[1+\frac{v^2}{2\Lambda^2}C_{HD}-\frac{2v^2}{\Lambda^2}C_{H\Box}\right](\partial_\mu H_0)^2$$
$$+\frac{1}{2}\left[\mu^2-3\lambda v^2+\frac{15v^4}{4\Lambda^2}C_6\right]H_0^2+\text{Goldstones...}$$

- Canonical normalization recovered: $H=Z_h H_0$
- All Higgs interactions shifted $Z_h=1+\frac{v^2}{4\Lambda^2}C_{HD}-\frac{v^2}{\Lambda^2}C_{H\Box}$

Other possible purely scalar operators can be eliminated by integration by parts, or by use of the equations of motion

SMEFT GAUGE SECTOR

- Shift fields so that gauge fields have canonical forms
- Find mass eigenstates as usual:

$$M_W = \frac{\overline{g}_2 v}{2}$$

$$M_Z = \frac{v}{2}\sqrt{(\overline{g}_1)^2 + (\overline{g}_2)^2}\left(1 + \frac{\overline{g}_1\overline{g}_2}{(\overline{g}_1)^2 + (\overline{g}_1)^2}\frac{v^2}{\Lambda^2}C_{HWB} + \frac{v^2}{4\Lambda^2}C_{HD}\right)$$

- SM relationships among parameters altered (barred fields remind us of this)

HIGGS DECAYS

- Example: H→bb

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

$$\Delta\kappa_b = \frac{1}{\sqrt{2}G_F\Lambda^2}\left(C_{H\Box} - \frac{C_{HD}}{4} - C_{Hl}^{(3)} + \frac{C_{ll}^1}{2} - \frac{C_{dH}}{2^{3/4}m_b\sqrt{G_F}}\right)$$

From normalizing H kinetic energy

From change in relation between G_F and v

New dimension-6 operator

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

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

CONSIDER H→ZZ

- Compare H→ZZ (on-shell) to H→Zff

$$\frac{\Gamma(H\rightarrow ZZ)}{\Gamma(H\rightarrow ZZ)\mid_{SM}} = 1+\frac{1}{\sqrt{2}G_F\Lambda^2}\left[c_k - .4c_{ZZ}\right]$$

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

c_{ZZ} are momentum dependent operators

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

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

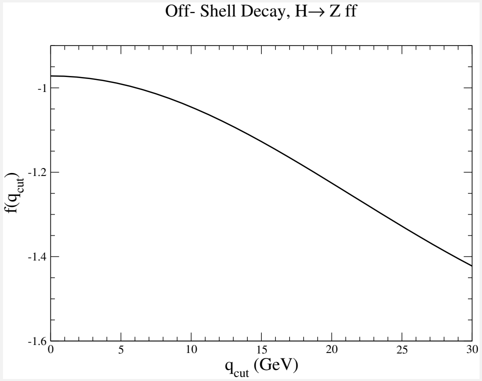
$$c_{ZZ} = \frac{M_W^2}{M_Z^2}C_{HW} + (1-\frac{M_W^2}{M_Z^2})C_{HB} + \frac{M_W}{M_Z}\sqrt{1-\frac{M_W^2}{M_Z^2}}C_{HWB}$$

H→Zff

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

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

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



GLUON FUSION

$$L = L_{SM} + \frac{C_{HG}}{\Lambda^2} O_{HG} + \frac{C_{tH}}{\Lambda^2} O_{tH}$$
$$\sim \left[-Y_t \overline{q}_L \tilde{\phi} t_R + \frac{C_{tH}}{\Lambda^2} \phi^\dagger \phi \overline{q}_L \tilde{\phi} t_R + hc \right] + \frac{C_{HG}}{\Lambda^2} (\phi^\dagger \phi) G^A_{\mu\nu} G^{A,\mu\nu}$$

- Changes relationship between top mass and SM Yukawa, Y_t:

$$m_t = \frac{v}{\sqrt{2}} \left[-Y_t + \frac{v^2}{2\Lambda^2} C_{tH} \right]$$

- Changes ttH coupling:

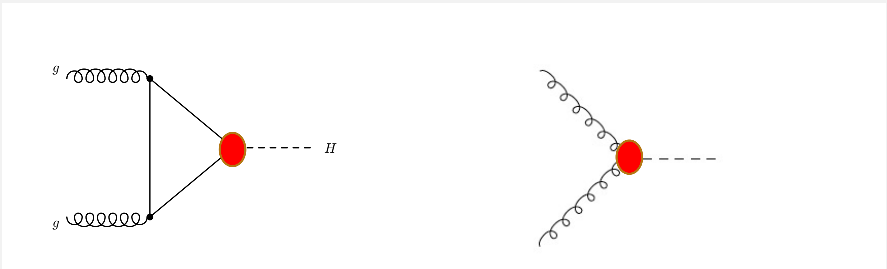
$$\frac{m_t}{v} \left[1 - \frac{v^2}{\Lambda^2} \frac{C_{tH}}{Y_t} \right]$$

$$\phi^0 = \frac{H + v}{\sqrt{2}}$$

WHAT DOES GLUON FUSION MEASURE?

- $gg \to H$ cannot distinguish C_{HG} from C_{tH} in the large m_t limit
- Flat directions like this are common in SMEFT

$$A(gg \to H) \sim A_{SM}\left[1 + \frac{v^2}{\Lambda^2}\left(\frac{12\pi C_{HG}}{\alpha_s} - \frac{C_{tH}}{Y_t}\right)\right]$$



Only sensitive to C/Λ^2

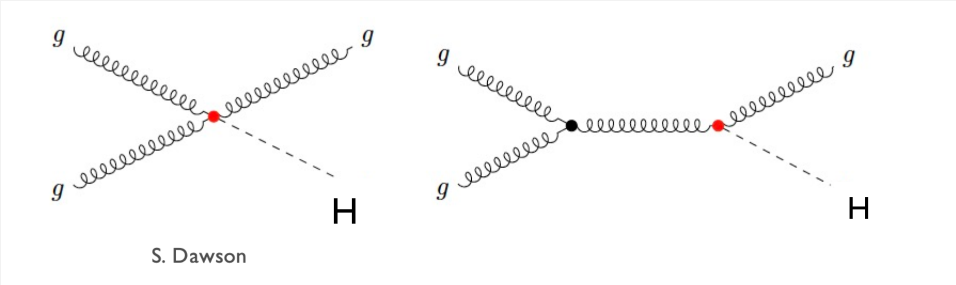
MOMENTUM DEPENDENT OPERATORS CHANGE KINEMATIC DISTRIBUTIONS

- Typically quite small effects:

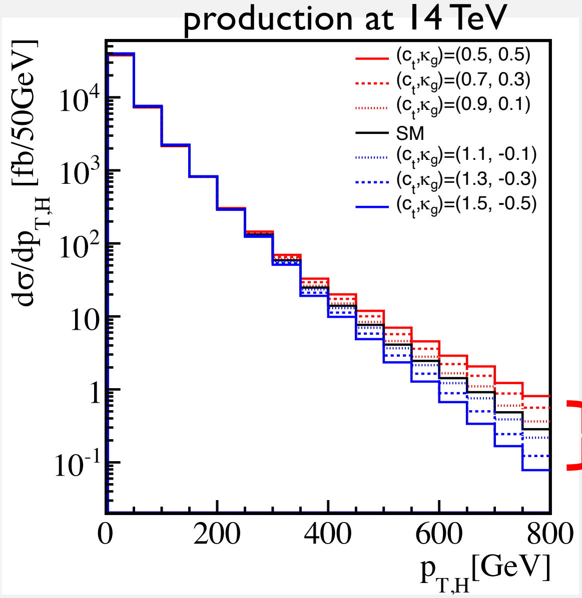
$$\mathcal{O}\left(\frac{p_T^2}{\Lambda^2}\right)$$

- Couplings contrained to give correct rate for ggH

- Look in tails of distributions



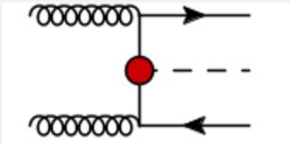
Higgs plus jet production at 14 TeV

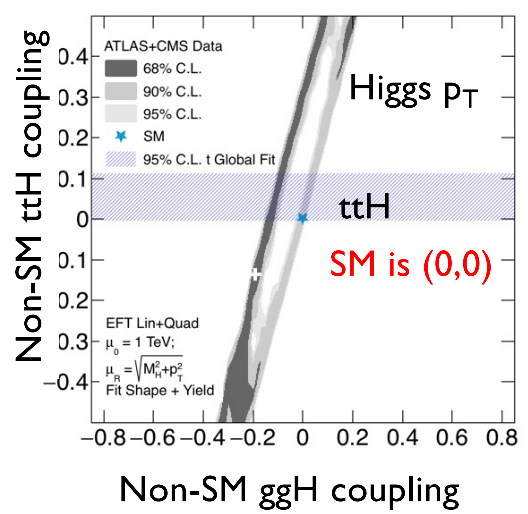


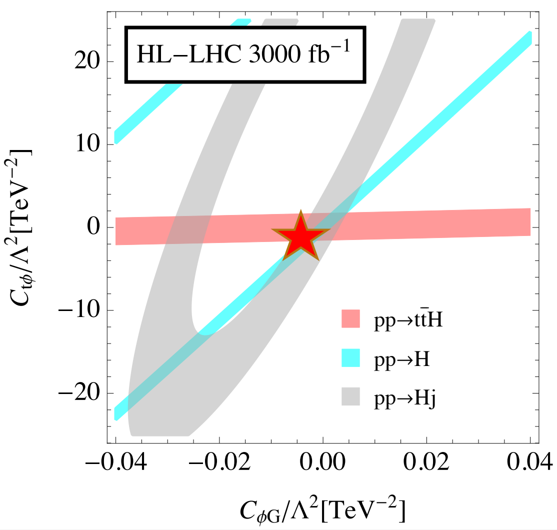
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, arxiv:1405.4295

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

Battaglia, Grazzini, Spira, Wiesemann, Arxiv:2109.02987

Maltoni, Vryonidou, Zhang, Arxiv:1607.05330

WHEN IS EFT VALID?

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

- SMEFT

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

- Problem is that $(A_6)^2$ terms are the same order as A_8 terms that we have dropped when counting in $1/\Lambda$
- If we only keep A_6/Λ^2 terms and drop $(A_6/\Lambda^2)^2$, the cross section is not guaranteed to be finite
- Corrections are $O(s/\Lambda^2)$ or $O(v^2/\Lambda^2)$

Leads to idea that there is a maximum energy scale where SMEFT is valid

COUNTING LORE

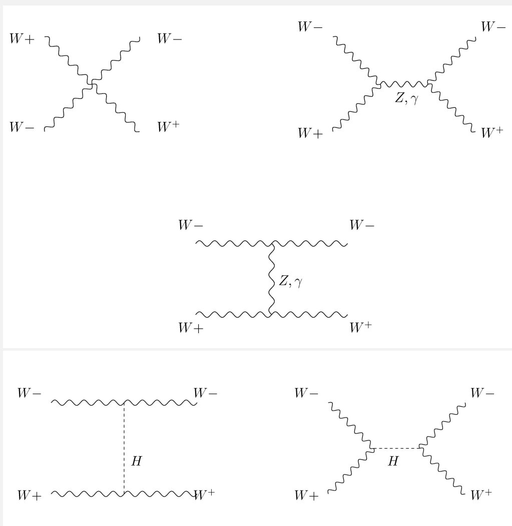
$$\sigma \sim g_{SM}^2 (A_{SM})^2 + g_{SM} g_{BSM} A_{SM} A_6 \frac{s}{\Lambda^2}$$
$$+ g_{BSM}^2 (A_6)^2 \frac{s^2}{\Lambda^4} + g_{SM} g_{BSM} A_{SM} A_8 \frac{s^2}{\Lambda^4}$$

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

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

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

SM IS SPECIAL AT HIGH ENERGY



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

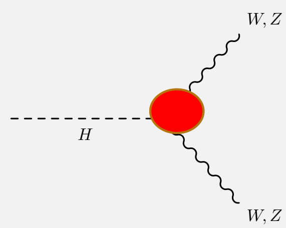
Terms which grow with energy cancel for E >> M_H

SM particles have just the right couplings so amplitudes don’t grow with energy

*measure WW scattering in VBF

HIGGS COUPLINGS TO GAUGE BOSONS

Operators that contribute to VVV vertices and Higgs-VV vertices



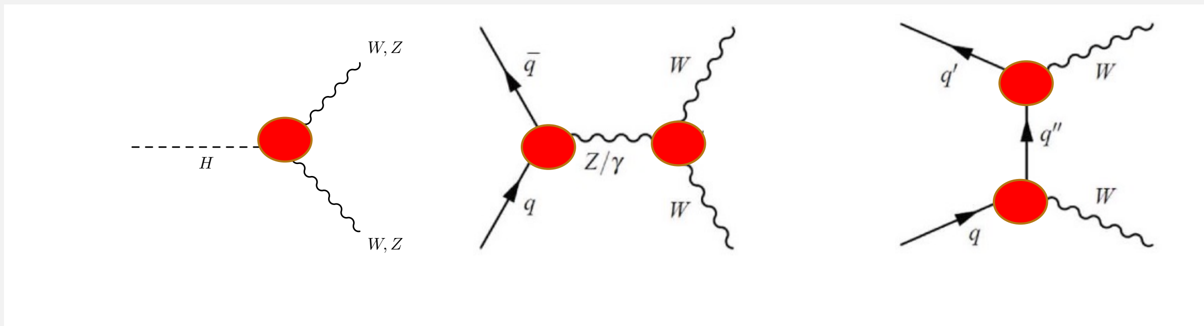
$$O_W = (D_\mu \phi)^\dagger W^{\mu\nu} (D_\nu \phi)$$
$$O_B = (D_\mu \phi)^\dagger B^{\mu\nu} (D_\phi)$$
$$O_{WW} = Tr(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu)$$

- Effective Field Theory effects enhanced at high energy, high p_T

Derivative interactions change kinematic shapes

CAN'T JUST FIT HIGGS COUPLINGS

Operators that contribute to VVV vertices and Higgs-VV vertices



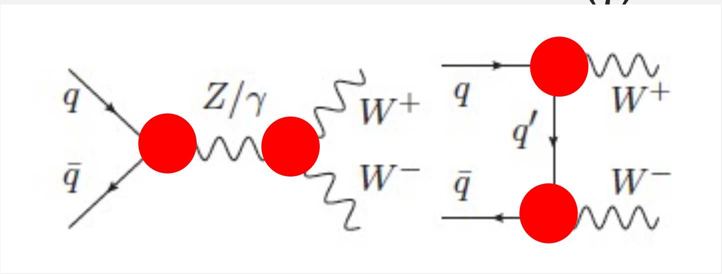
Anomalous qqZ vertices too!

Leads to concept of global fits

- Changing ZWW, γWW vertices spoils high energy cancellations between contributions

DIBOSON PRODUCTION

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



No growth with energy in SM

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

Changing gauge or fermion couplings spoils cancellation

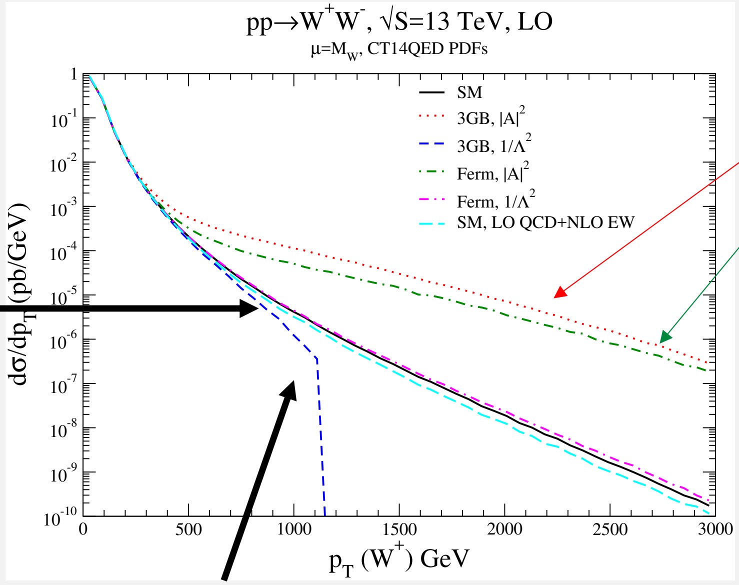
Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB482 (1987)

OBVIOUS PROBLEM

- One proposal for dealing with this issue is to put a cut on the maximum energy where the SMEFT is assumed to be valid, [1604.06444](1604.06444)

Linear expansion

Cannot ignore negative cross section region



….Anomalous 3 gauge boson couplings

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

Baglio, Dawson, Lewis , arXiv:1708.03332

* σ goes negative, expansion not valid

NLO CORRECTIONS IN SMEFT

- Compute NLO corrections to $O(v^2/\Lambda^2)$ (ie linear in EFT coefficients)
- SMEFT is a new theory; calculate consistently to one-loop QCD and EW
- One-loop SMEFT QCD corrections automated in SMEFT@NLO, 2008.11743
- One-loop SMEFT EW corrections done on case by case basis
- Coefficient functions renormalized in $\overline{MS}$
  - Solved problem at one-loop

$$C_i(\mu) = C_i^0 - \frac{1}{32\pi^2\hat{\epsilon}}\gamma_{ij}C_j$$

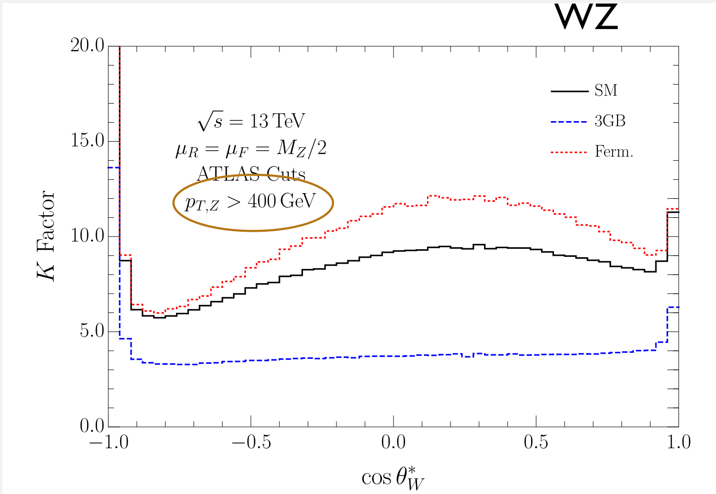
EW SMEFT corrections done on individual basis at present

Alonso, Jenkins, Manohar, Trott, arxiv:1312.2014;
Jenkins, Manohar, Trott, arxiv:1310.4838, 1309.0819

QCD MATTERS

- K factors aren't the same as in SM
- Effect is enhanced for large momenta

WZ

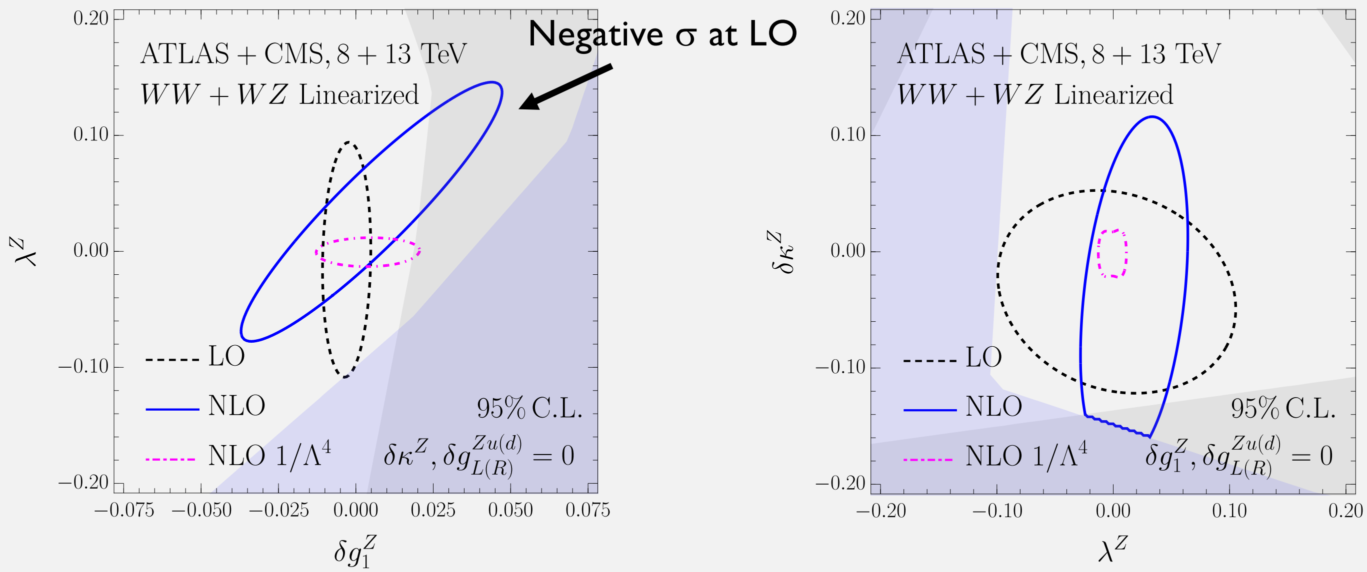


SMEFT is a new theory: can consistently calculate loop corrections

Baglio, Dawson, Homiller, [1909.11576]

FIT TO LINEARIZED RATES

- Drop all coefficients where cross section is negative
- Linearized limits significantly weaker than $1/\Lambda^4$ limits (can cancel terms)

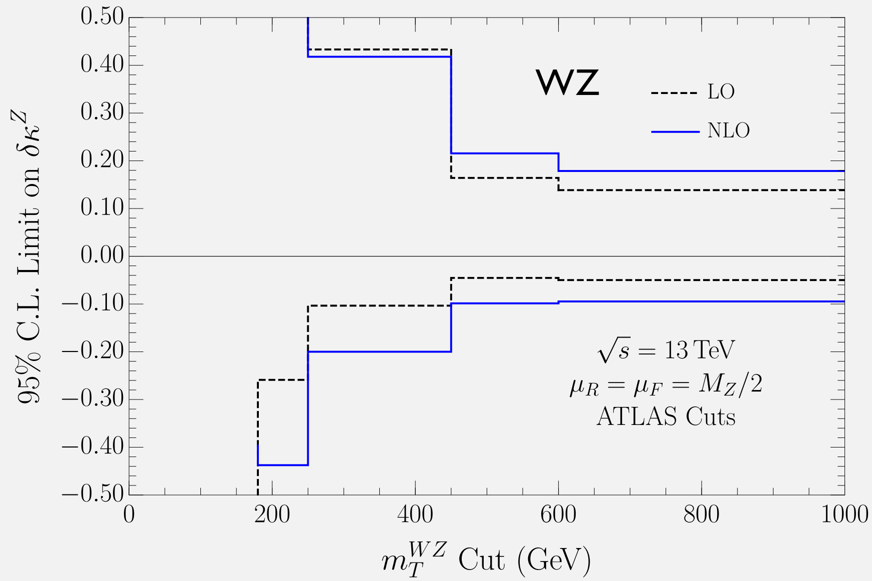


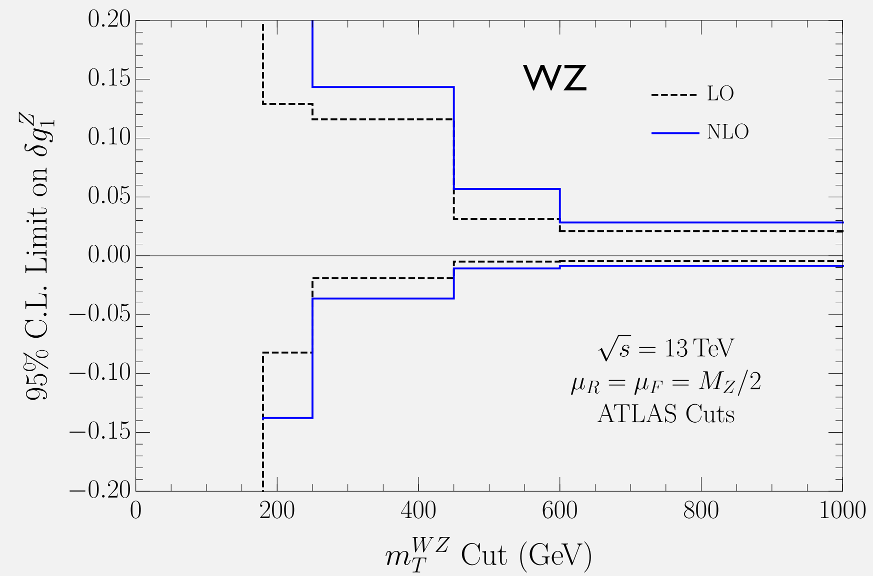
Negative σ at NLO (blue), negative at LO (gray)

1909.11576

IS IT ALL THE LAST BIN?

- Fit results depend on cut on maximum energy

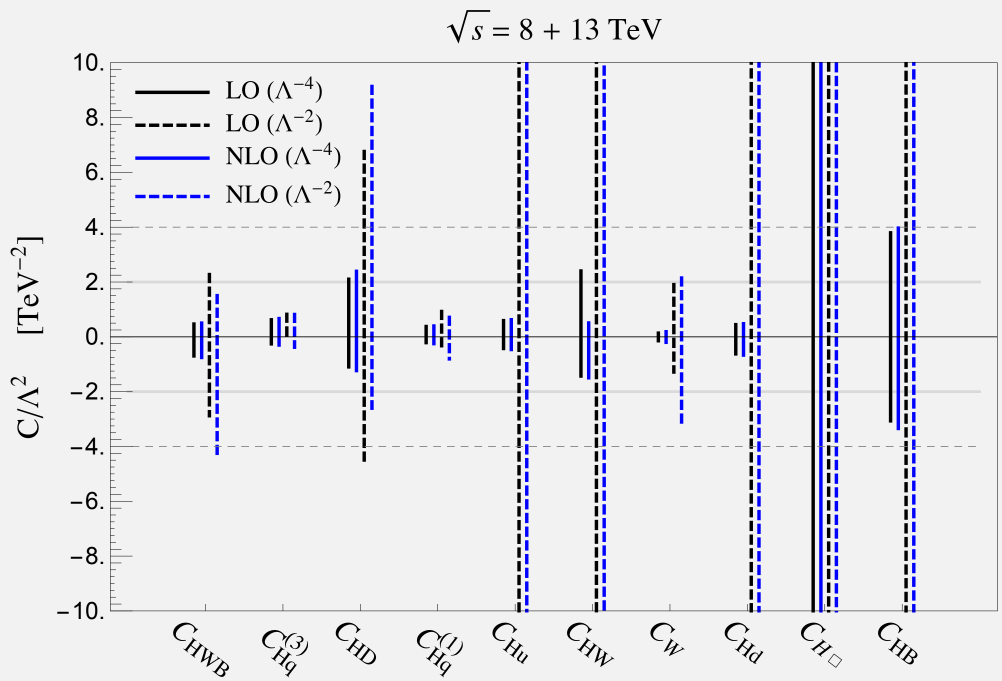




Plots successively remove high m_T bins

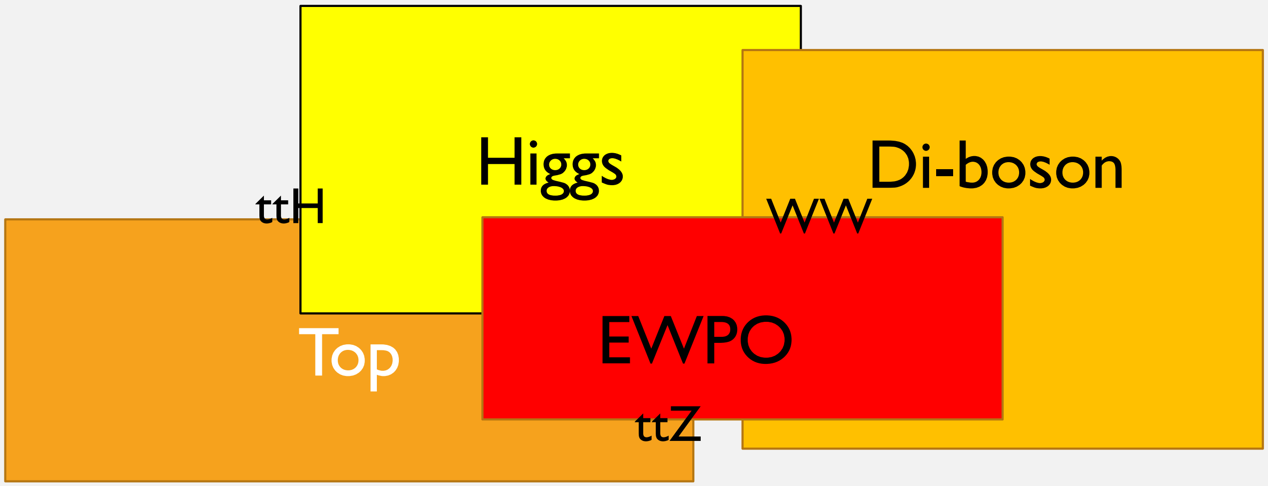
ASSUMPTIONS CREEPING IN

- 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

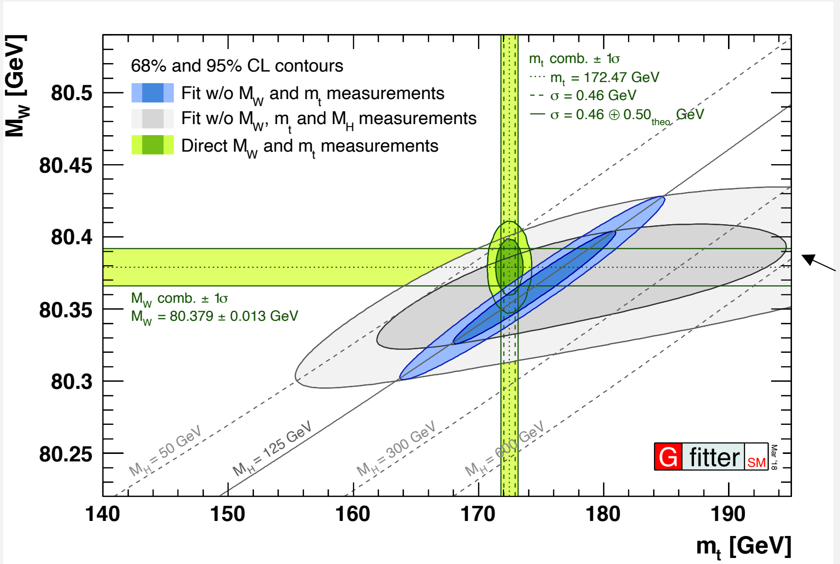


2003.07862

SMEFT CONNECTS PROCESSES



EWPO



Fit without M_W, M_t, M_H

This assumes SM

Gfitter, 1803.01853

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) assuming flavor independence

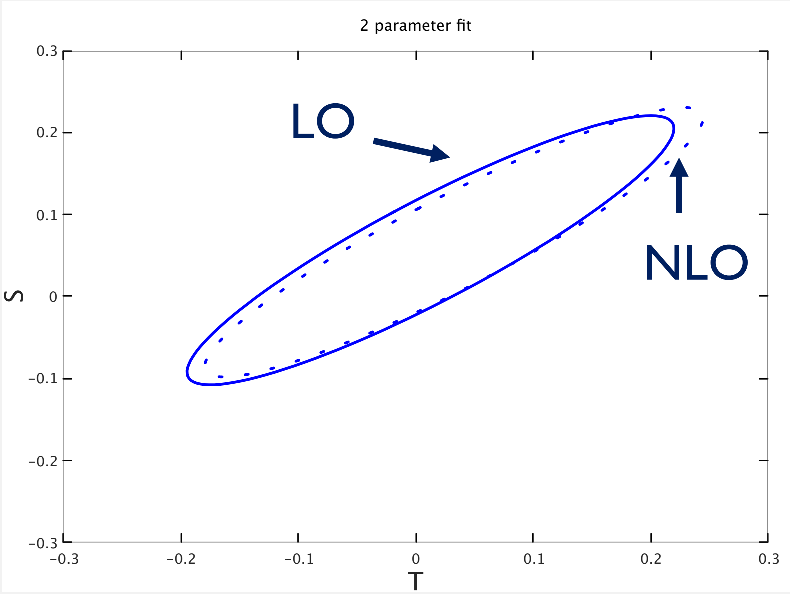
$$C_{ll}, C_{\phi WB}, C_{\phi u}, C_{\phi q}^{(3)}, C_{\phi q}^{(1)}, C_{\phi l}^{(3)}, C_{\phi l}^{(1)}, C_{\phi e}, C_{\phi D}, C_{\phi d}$$

- Tree level SMEFT expressions depend on 8 combinations of operators

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

OBLIQUE PARAMETERS

- Arbitrarily set all parameters except $C_{\phi WB}$ and $C_{\phi D}$=0



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

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

You get quite different results when you allow all coefficients to vary. Picking specific non-zero coefficients involves assumptions about underlying model

EWPO and SMEFT, Dawson, Giardino arXiv:1909.02000

COMPUTE EACH OBSERVABLE TO NLO IN SMEFT

- Example $M_W = M_W^{SM} + \delta M_W$ ⟵ All SMEFT effects here
- Dependence on many coefficients at NLO (QCD + EW)
- Always use "best" SM prediction for fits

$$\delta M_W^{LO} = \frac{v^2}{\Lambda^2}\left\{-30C_{\phi l}^{(3)} + 15C_{ll} - 28C_{\phi D} - 57C_{\phi WB}\right\}$$

$$\delta M_W^{NLO} = \frac{v^2}{\Lambda^2}\left\{-36C_{\phi l}^{(3)} + 17C_{ll} - 30C_{\phi D} - 64C_{\phi WB}\right.$$
$$- 0.1C_{\phi d} - 0.1C_{\phi e} - 0.2C_{\phi l}^{(1)} - 2C_{\phi q}^{(1)} + C_{\phi q}^{(3)} + 3C_{\phi u} + 0.4C_{lq}^{(3)}$$
$$\left. - 0.03C_{\phi B} - 0.03C_{\phi \Box} - 0.04C_{\phi W} - 0.9C_{uB} - 0.2C_{uW} - 0.2C_W \right\}$$

α, G_μ, M_Z scheme

NLO SMEFT EFFECTS ON POLE OBSERVABLES

- Fits marginalizing over other coefficients

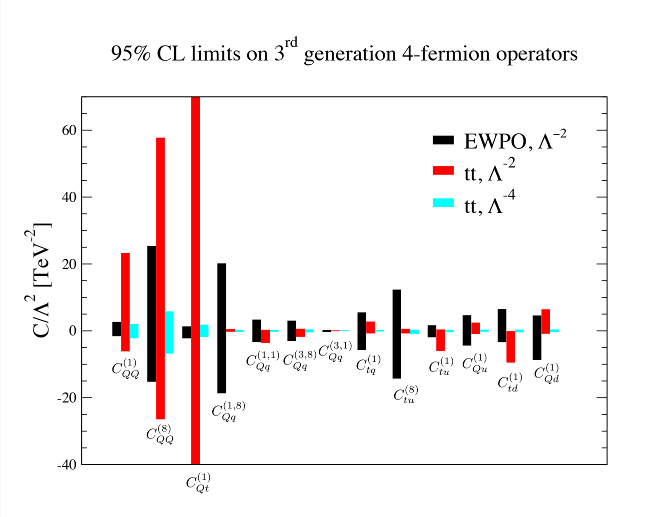
Coefficient	LO	NLO
$\mathcal{C}_{\phi D}$	$[-0.034, 0.041]$	[-0.039,0.051]
$\mathcal{C}_{\phi WB}$	$[-0.080, 0.0021]$	$[-0.098, 0.012]$
$\mathcal{C}_{\phi d}$	$[-0.81, -0.093]$	$[-1.07, -0.03]$
$\mathcal{C}_{\phi l}^{(3)}$	$[-0.025, 0.12]$	$[-0.039, 0.16]$
$\mathcal{C}_{\phi u}$	$[-0.12, 0.37]$	$[-0.21, 0.41]$
$\mathcal{C}_{\phi l}^{(1)}$	$[-0.0086, 0.036]$	$[-0.0072, 0.037]$
$\mathcal{C}_{ll}$	$[-0.085, 0.035]$	$[-0.087, 0.033]$
$\mathcal{C}_{\phi q}^{(1)}$	$[-0.060, 0.076]$	$[-0.095, 0.075]$

- Neglect flavor effects
- Contribution from top loops

NLO effects can be important

EWPO WITH FLAVOR

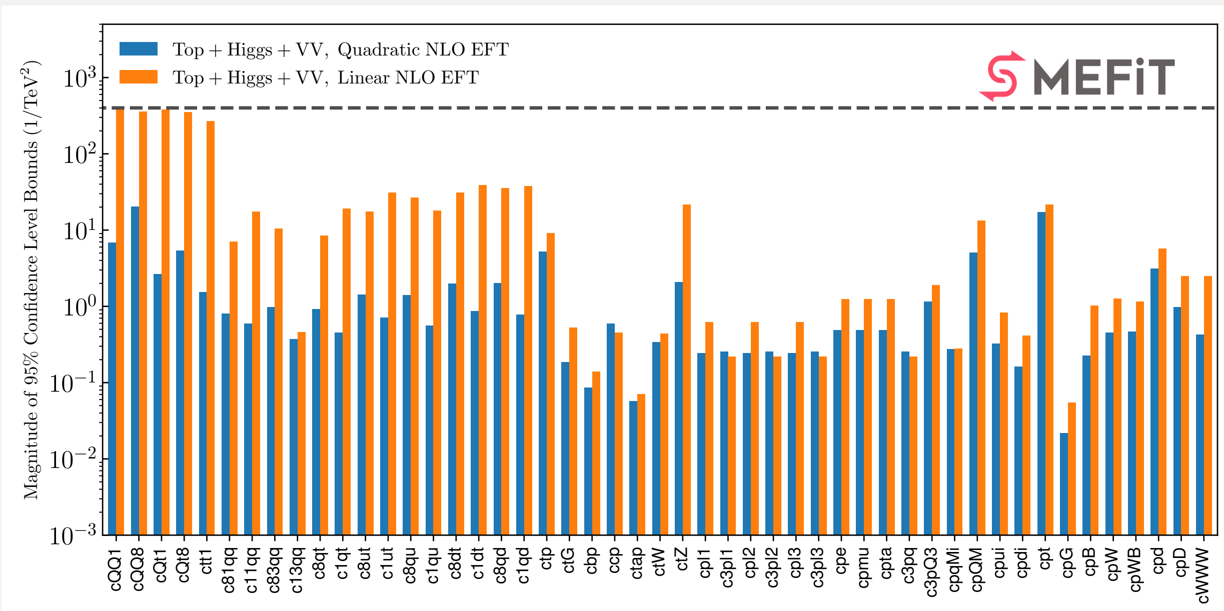
- Allow coefficients to have flavor dependence
- Consider operators that contribute both to top pair production at the LHC and to EWPO at 1-loop
- For some operators, similar sensitivity



SMEFT message: CONNECTIONS between data sets

Dawson, Giardino: arXiv:2201.09887

EXAMPLE OF GLOBAL FIT

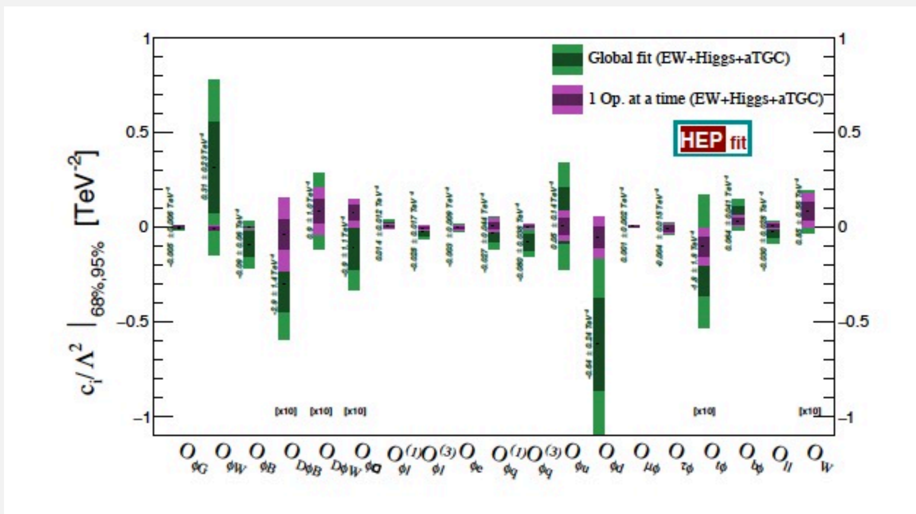


- Precision of limits very different for different operators
- Orange and blue are different approaches to expansion in $1/\Lambda^2$

2105.00006

GLOBAL FITS CONSTRAIN EFT COEFFICIENTS

- Very different results when only a single operator is constrained



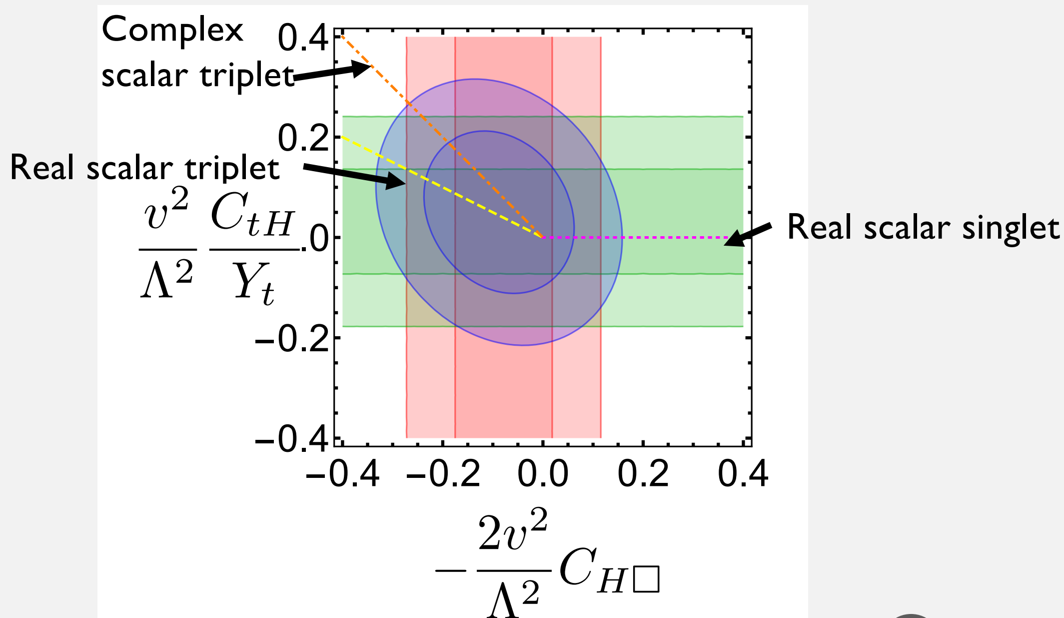
Reina, LHCP, 2019

WHAT DO WE LEARN BY FITTING EFT COUPLINGS?

- In any given high scale model, coefficients of EFT predicted in terms of small number of parameters
- Different operators are generated in different models
- By measuring the pattern of coefficients, information is gleaned about high scale physics

Example with new scalars at very high mass scales

Fit to Higgs data



Dawson, Murphy: arXv:1704.07851

HOW TO MATCH UV THEORY TO SMEFT

- Consider model with gauge singlet scalar, S, that only couples to SM Higgs

$$L \sim \frac{1}{2}(\partial_\mu S)^2 - V(S,\phi) = -\frac{1}{2} S \Box S - V(S,\phi)$$

$$V = \frac{m_s^2}{2} S^2 + A \mid \phi \mid^2 S + \frac{\kappa}{2} \mid \phi \mid^2 S^2 + \frac{m}{6} S^3 + \frac{\lambda_S}{24} S^4$$

- Find classical solution

$$\frac{\delta L}{\delta S} \mid_{S_c=0} \longrightarrow S_c = \frac{A \mid \phi \mid^2}{\partial^2 + m_s^2 + \kappa \phi^2}$$

Covariant Derivative Expansion, arXiv:1412.1837

CAN WE UNCOVER UV MODEL?

- Plug Sc into original Lagrantian and expand consistently in powers of $1/m_s^2$
- Generates $O_{H\Box}$ and O_H with coefficients predicted in terms of parameters of UV model

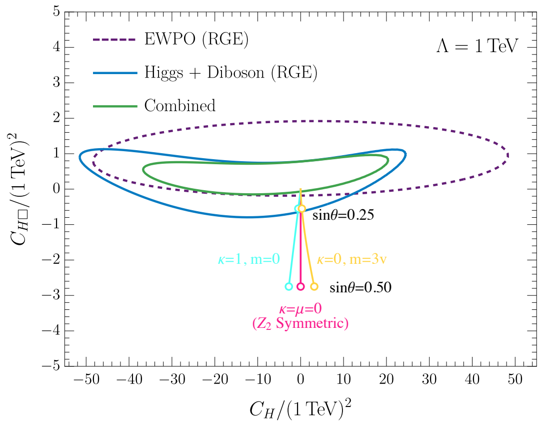
$$O_{H\Box} = (\phi^\dagger \phi)\Box(\phi^\dagger \phi) \qquad \frac{v^2 C_{H\Box}}{\Lambda^2} = -\frac{1}{2}\tan^2\theta$$

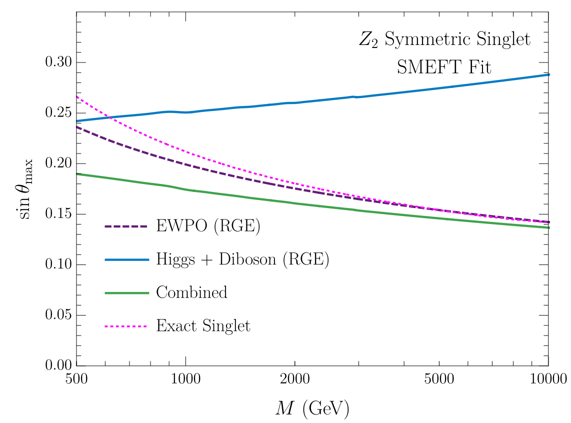
$$O_H = (\phi^\dagger \phi)^3 \qquad \frac{v^2 C_H}{\Lambda^2} = \frac{\tan^2\theta}{2}\left(\tan\theta \frac{m}{3v} - \kappa\right)$$

Dawson, Homiller, Lane: Arxiv:2007.01296

* $\tan\theta = Av/M_S^2$

DO FITS TO SUBSETS OF OPERATORS

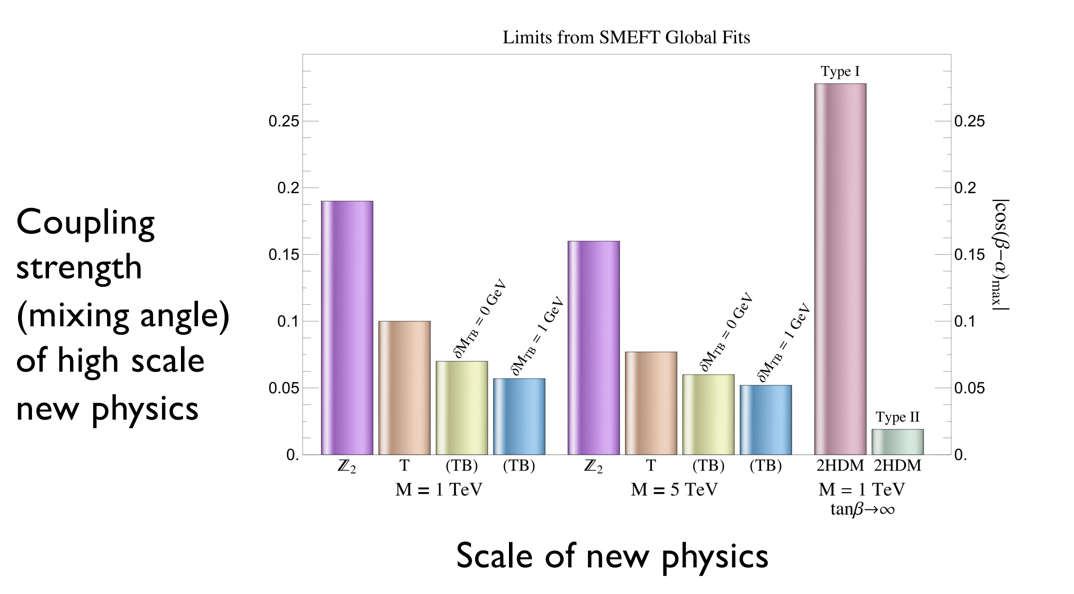




Interpret fit results in terms of model parameters
Information from RGE running of coefficients from Λ to M_Z

PATTERNS OF COEFFICIENTS

- Compare models with new scalars or new heavy top/bottom quarks at the high energy scale
- Do global fits to just the sets of operators generated in these models
- Fits can restrict high scale models



2007.01296

*These are particularly simple toy models

POWER OF SMEFT

- Higgs decays, top quark interactions, diboson production, LEP physics all described by overlapping sets of operators
- Coefficients can be predicted in UV complete theories
- Since SMEFT is a consistent field theory, it can be systematically improved by including loop corrections
- Cons: Too many operators; difficult to define consistent criteria for range of validity; what about higher dimension operators?