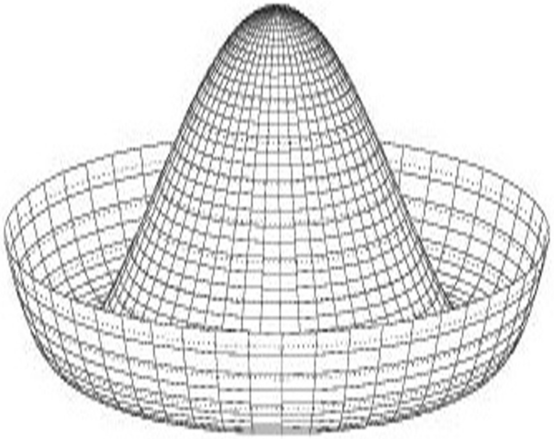
INTRODUCTION TO SMEFT

S. Dawson, BNL

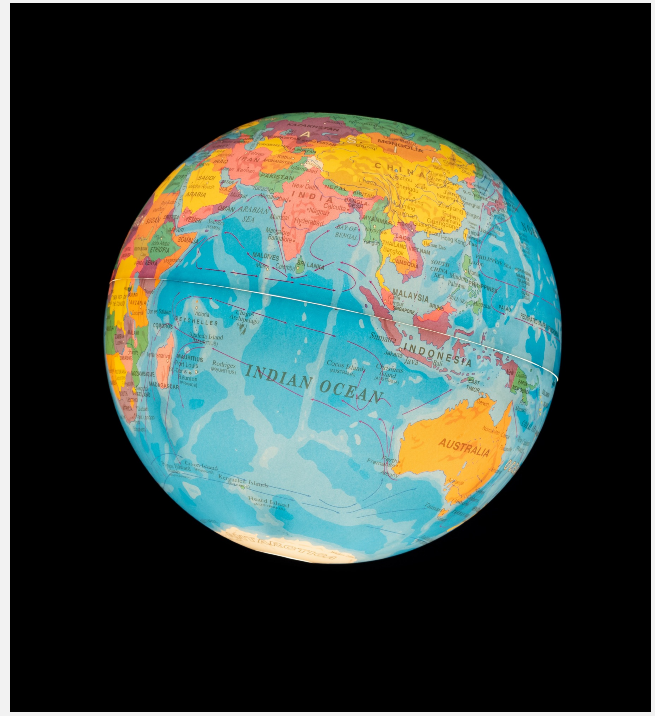
CTEQ, 2023

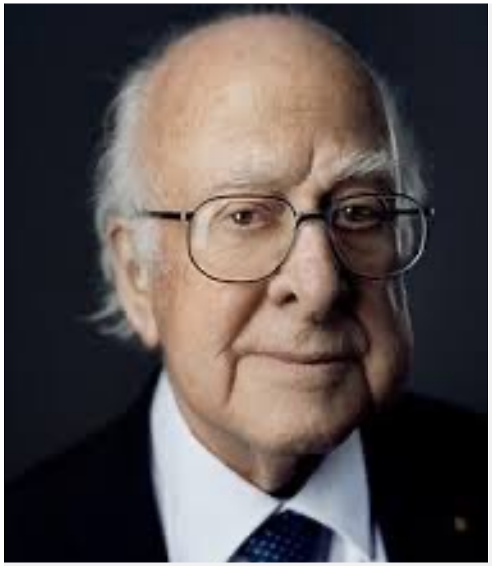


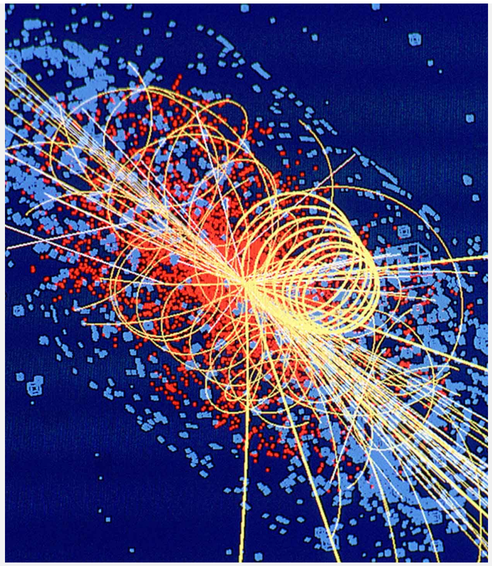
Complaints, suggestions to dawson@bnl.gov

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 11 YEARS....

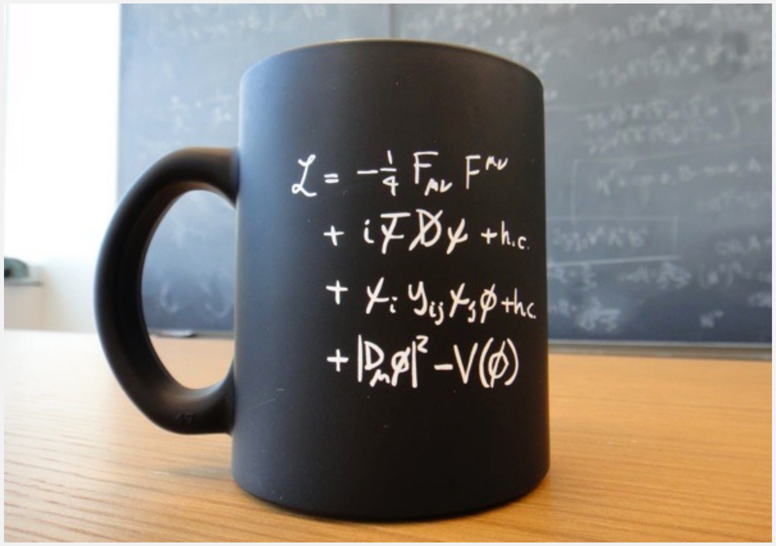
2012: LHC discovered a Higgs boson; it appears to have predicted properties

THE SM IS SIMPLE AND PREDICTIVE

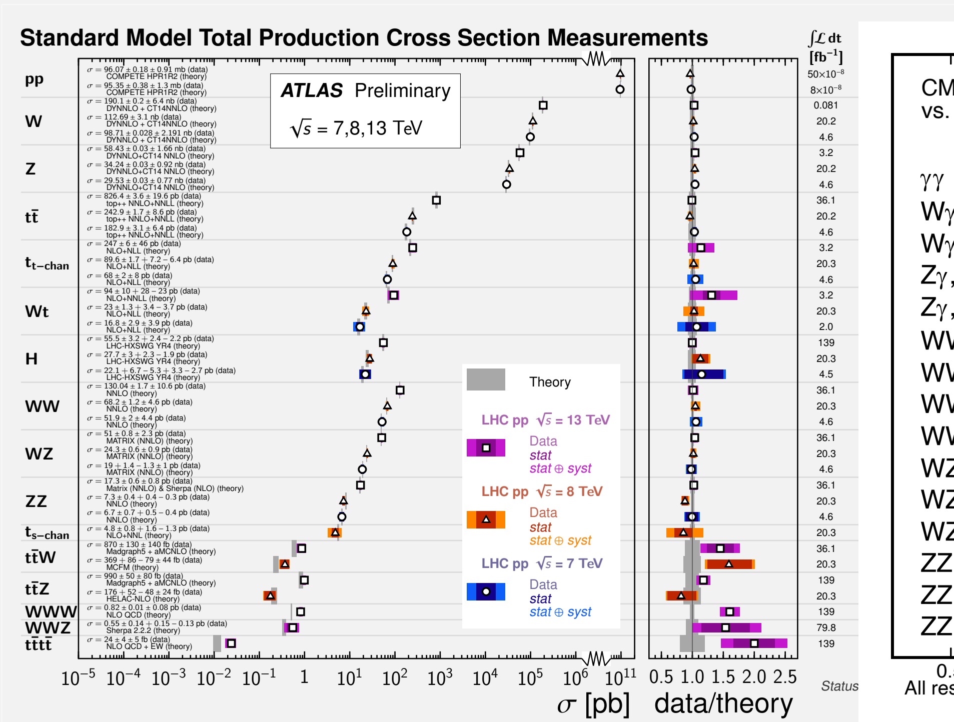
- SU(3) x SU(2) x U(1)
- Electroweak sector described in terms of masses and 3 inputs
  - Typically G_F, α, M_Z
- Particle couplings fixed

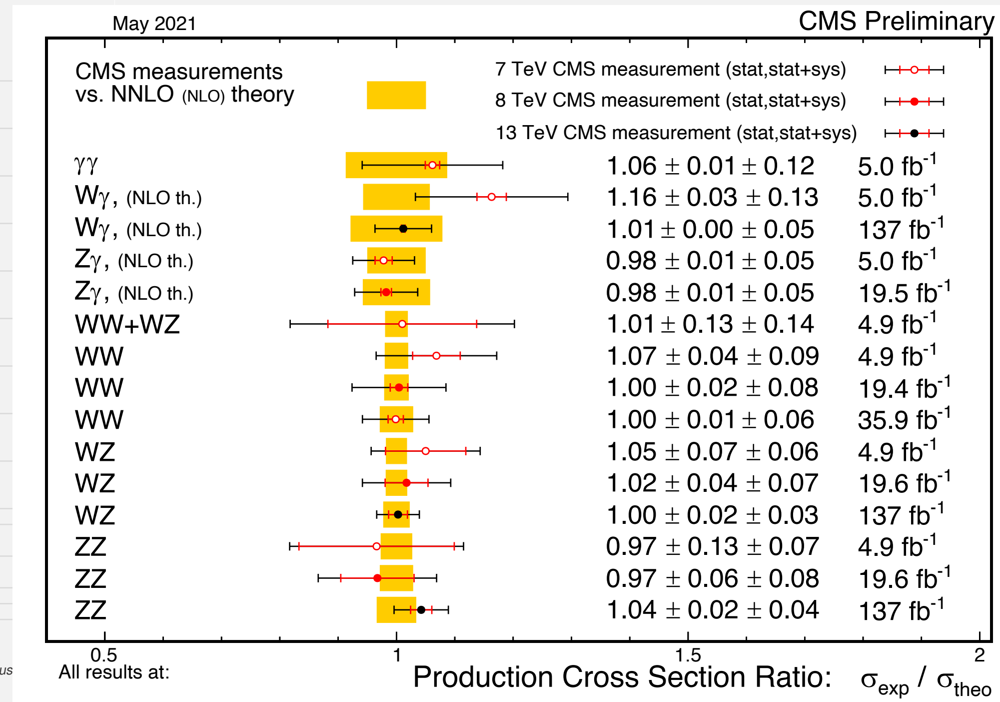
Only unknown parameter is Higgs mass

Testable model !

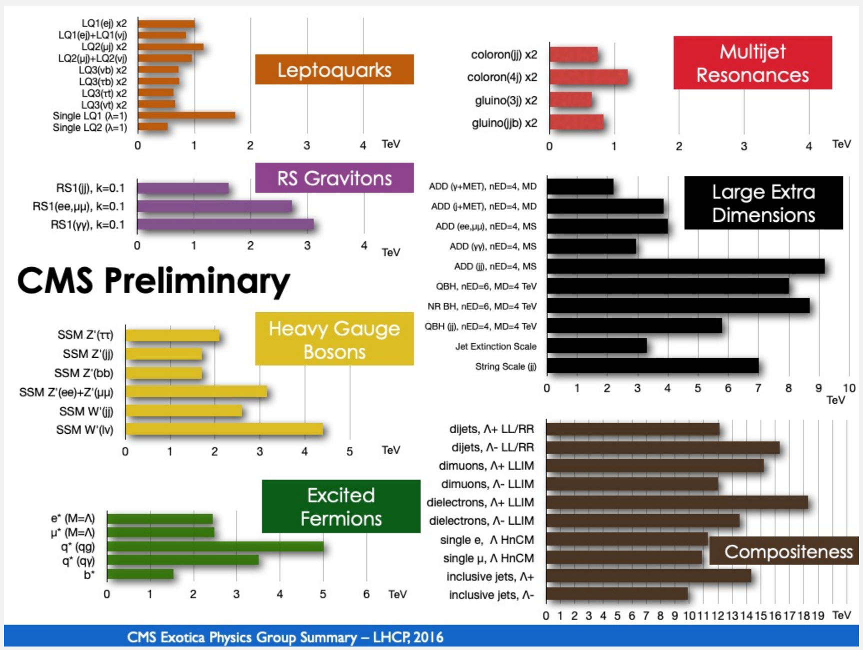


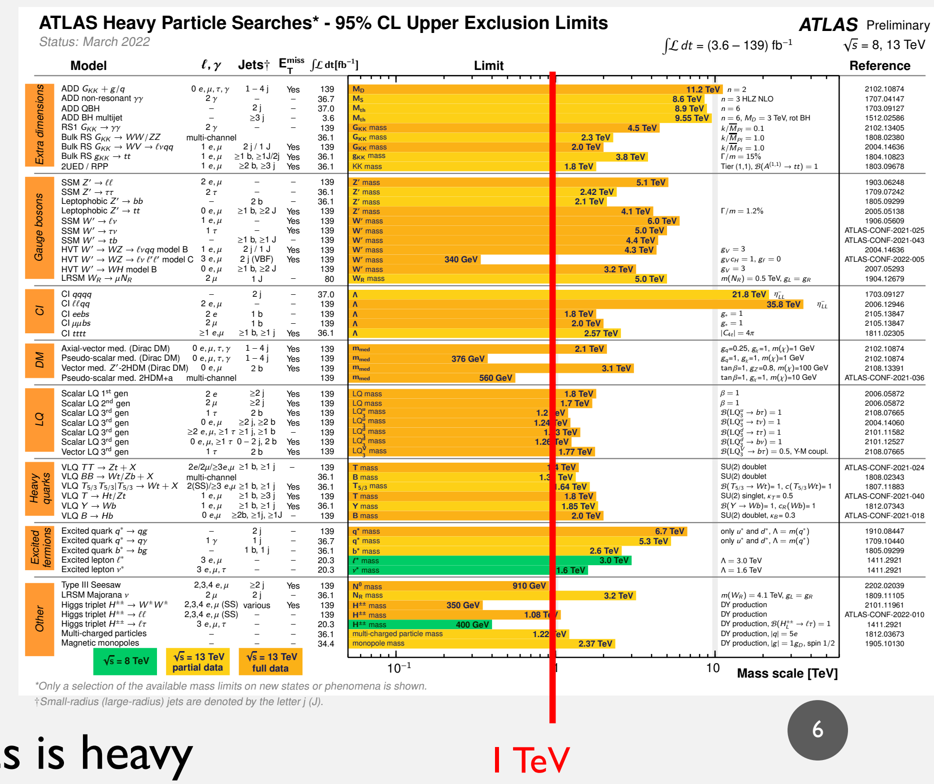
SM PROCESSES APPEAR TO HAVE PREDICTED RATES





STANDARD MODEL WORKS





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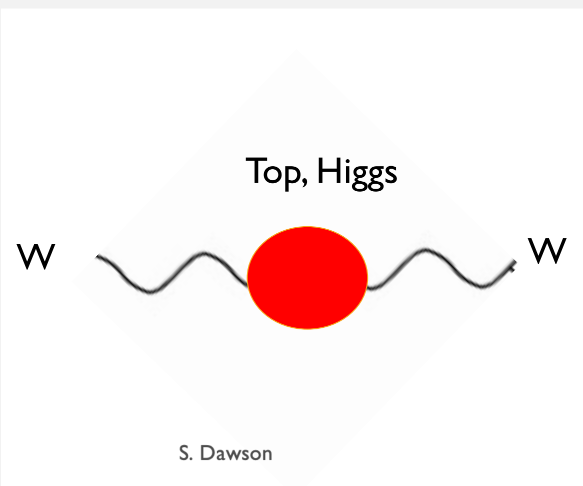
New physics is heavy

CONSISTENCY AT THE QUANTUM LEVEL

- W boson mass is a prediction of the theory
- At the quantum level contributions from the top quark and the Higgs boson



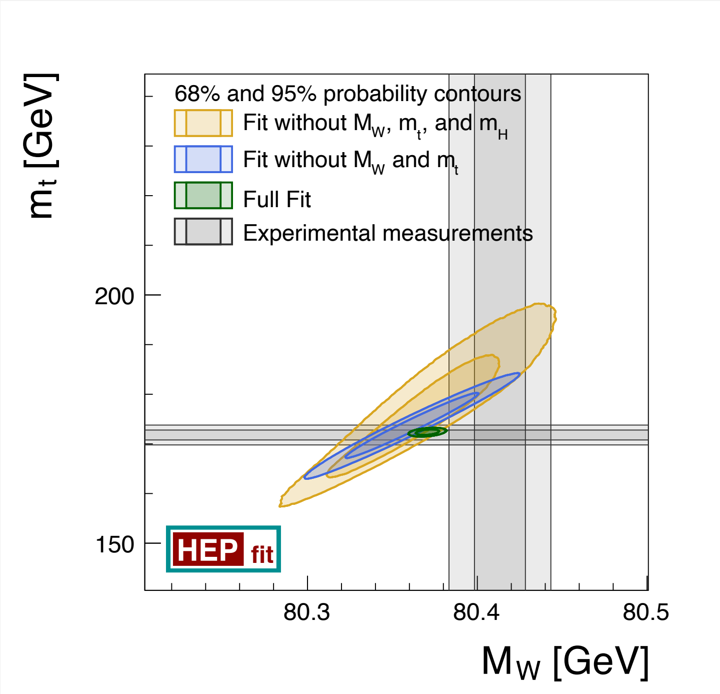
$$M_W \sim 80.94\ GeV + (\ldots)\frac{M_t^2}{(246\ GeV)^2} + (\ldots)\log(M_H^2) + \ldots$$

calculable

* Infinite without Higgs boson

AND EVERYTHING IS REASONABLY CONSISTENT WITH ELECTROWEAK PRECISION….

- SM works at the quantum level
- M_W is a predicted quantity



De Blas, Pierini, Reini, Silvestrini, 2204.04204

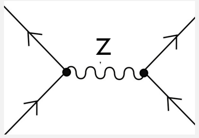
ALL DATA SO FAR CONSISTENT WITH....

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?

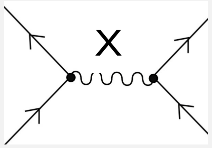
HIGH SCALE DECOUPLING

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



$$A_{SM} \sim \frac{g^2}{M_Z^2}$$

- Contribution from X:



$$A_X \sim \frac{g_X^2}{M_X^2}$$

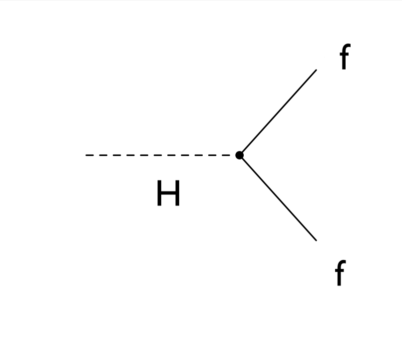
- Scattering rate:

$$\sigma \sim \sigma_{SM} + \frac{g^2 g_X^2}{M_X^2} \to \sigma_{SM}$$

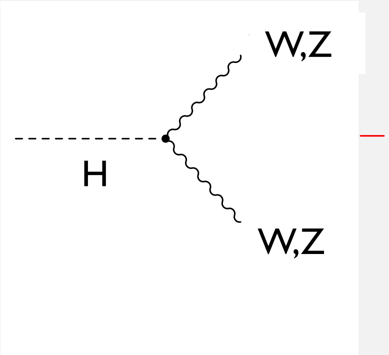
Effects of X vanish as $1/M_X^2$ for ***weak coupling***

THE HIGGS IS DIFFERENT

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



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



$$-2i\frac{M_V^2}{v}g^{\mu\nu}$$

- Longitudinal polarizations also change counting

> This suggests that the Higgs sector is a good place to begin our search for new physics

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:*

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

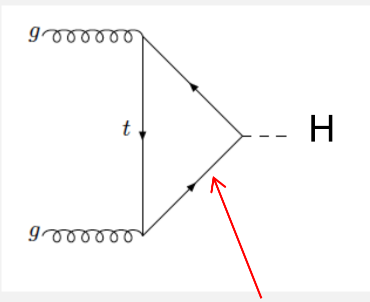
- Higgs self-couplings proportional to $M_H{}^2$:

$$\frac{M_H^2}{2}H^2 + \frac{M_h^2}{2v}H^3 + \frac{M_h^2}{8v^2}H^4$$

Only unpredicted parameter is M_H

* Normalization is such that F→1 for M_t, M_W→ ∞

HIGGS PRODUCTION AT A HADRON COLLIDER



Depends on new physics in loop

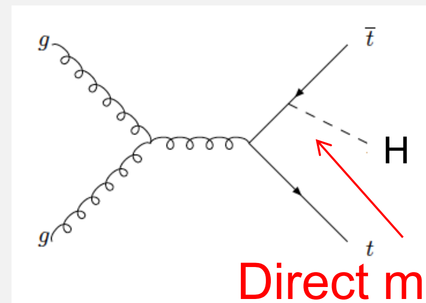
Most important processes:

$$gg \to H$$

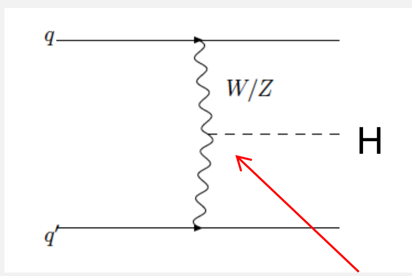
$$q\bar{q} \to q\bar{q}H$$

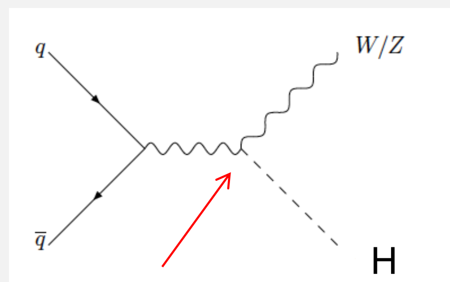
$$q\bar{q} \to VH$$

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



Direct measurement of tth Yukawa





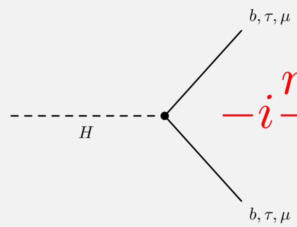
Vanishes if v=0: Fundamental test of EWSB mechanism

TESTING HIGGS COUPLINGS: κ APPROACH

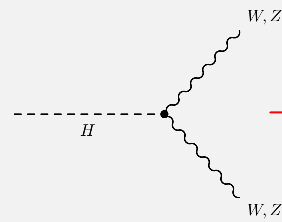
- Assume no new resonances/zero width approx/no new tensor structures

$$\sigma \cdot BR(ii \to H \to jj) = \frac{\sigma_{ii}\Gamma_{jj}}{\Gamma_H}$$

- Define scaling factors κ



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



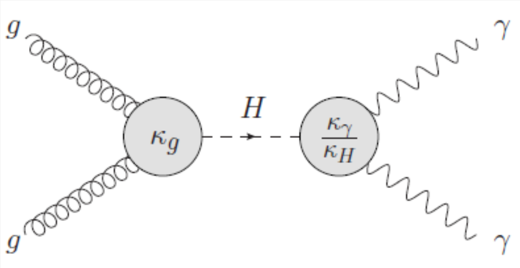
$$-2i\frac{M_V^2}{v}g^{\mu\nu}\kappa_V$$

SM gauge invariance requires κ=1

Doing this spoils unitarity cancellations, gauge invariance….

HIGGS COUPLINGS: κ FRAMEWORK

Example:
$gg \rightarrow H \rightarrow \gamma\gamma$



$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \left[\sigma(gg \rightarrow H) \cdot BR(H \rightarrow \gamma\gamma)\right]_{SM} \times \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

κ_H^2 is the scale factor to the total Higgs decay width

$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \rightarrow xx) \xrightarrow{\text{No BSM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \rightarrow xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \rightarrow xx)}{1 - BR_{BSM}}$$

Note dependence on total width

Fits typically done under both assumptions
(Crucial to read the fine print!)

κ RESCALING OF HIGGS COUPLINGS

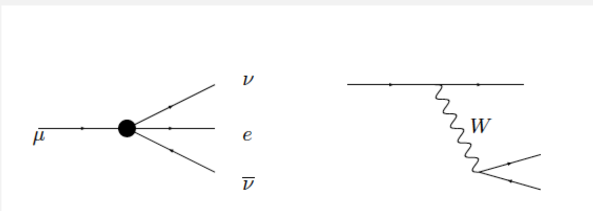
- Problems:
  - Gauge invariance requires $\kappa=1$
    - Higgs couplings not free parameters in SM
  - Not a consistent field theory $\rightarrow$ no higher order corrections
    - EW corrections don't factorize (can't be included)
  - No kinematic information
  - Higgs coupling measurements cannot be combined with other measurements

EFFECTIVE FIELD THEORY

- Assume all new physics is at a higher scale than current measurements
- See what we can learn by looking at corrections to SM predictions from unknown higher scale physics
- Can connect data from different sectors (Higgs, top, electroweak) for more information
- Effective field theories are consistent theories where corrections can be calculated in terms of some expansion parameter

FAMILIAR EXAMPLE OF EFFECTIVE THEORY

- μ decay: Gives very precisely measured $G_F \sim 10^{-5}$ GeV^{-2}



$$A_{\text{low energy}} = -\frac{G_F}{\sqrt{2}}(\overline{\psi}\gamma^\mu(1-\gamma_5)\psi)(\overline{\psi}\gamma_\mu(1-\gamma_5)\psi)$$

- 4 fermion interaction rate grows with energy ~ G_F^2 (Energy)^2
- Theory only makes sense for Energy < 600 GeV

- In the SM:

$$A_{\text{high energy}} = \frac{g^2}{2}(\overline{\psi}\gamma^\mu P_L\psi)(\overline{\psi}\gamma_\mu P_L\psi)\left(\frac{1}{q^2 - M_W^2}\right)$$

- Match at low q^2

$$q^2 << M_W^2 \rightarrow \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

Predict coefficients of low energy effective theory in terms of UV physics

EFFECTIVE FIELD THEORY FRAMEWORK

- Assume SU(3) x SU(2) x U(1) gauge theory with no new light particles
- Assume Higgs particle is part of SU(2) doublet (defines SMEFT)
- SM is low energy limit of effective field theory with towers of higher dimension operators

$$L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \Sigma \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots$$

BSM Effects SM Particles

- Many possible operators, must choose relevant set (typically ~20-30 in current fits)
- Power of SMEFT is that it connects top, Higgs, EW physics processes

COUNTING DIMENSIONS

- $[\psi]\sim 3/2$
- $[\phi]\sim 1$
- $[W]\sim 1$
- $[D_\mu]\sim 1$

SM is dimension 4 $[\overline{\psi}\gamma^\mu D_\mu \psi] \sim 4$

Only 1 dim-5 operator(for 1 generation) and it violates lepton number conservation

$$(\tilde{\phi}^\dagger L_L)^T C(\tilde{\phi}^\dagger L_L) \qquad \tilde{\phi} = i\sigma_2\phi$$

Usually start our EFT at dimension-6

EXAMPLE OF CONSTRUCTING OPERATORS

- Take any SM interaction, say $L \sim -ig_s \bar{t}\gamma^\mu T^A t G^a_\mu$
- Tack on $\phi^\dagger \phi$

$$L \sim \left[-ig_s \bar{t}\gamma^\mu T^A t G^a_\mu\right] c_{tg} \left(\frac{\phi^\dagger \phi}{\Lambda^2}\right)$$

- Generate redefinition of SM terms plus Higgs couplings from

$$\phi^\dagger \phi = \frac{(H+v)^2}{2} \qquad L \sim \left[-ig_s \bar{t}\gamma^\mu T^A t G^A_\mu\right] c_{tg} \left(\frac{v^2 + 2vH + H^2}{2\Lambda^2}\right)$$

- First term redefines α_s $\quad \alpha_s \rightarrow \alpha_s^{SM}\left(1 + \frac{c_{tg} v^2}{\Lambda^2}\right)$

Change SM interactions in gauge invariant manner

*ttGH and ttGH are correlated!

CONSTRUCT SMEFT FOR GAUGE INTERACTIONS

Change definitions of input parameters

g_s	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{\mu\nu,A}$	$O_{HG}: gg\rightarrow H$
g_1	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$O_{HB}: H\rightarrow \gamma\gamma$
g_2	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{\mu\nu^a}$	$O_{HW}: H\rightarrow Z\gamma$

Warsaw basis operator — Example effects

Take SM operators and add $\phi^\dagger\phi=\frac{1}{2}(H+v)^2$

Gauge fields not canonically normalized

Also mixed contribution: $O_{HWB}=(\phi^\dagger\sigma^a\phi)W^a_{\mu\nu}B^{\mu\nu}$

O_{HWB} ~ S parameter

NO UNIQUE BASIS FOR OPERATORS

- Write down an operator
- Use equations of motion to generate new operator
- Need to find an independent set of operators
- Most commonly used basis is called Warsaw Basis

Example:

$$(D^\nu G^A_{\mu\nu})^2 \longrightarrow J^{A,\mu}_G J^A_{G,\mu} \qquad\qquad J^{A,\mu}_G = g_s \Sigma_{f=q,u,d}(\overline{f}\gamma^\mu T^A f)$$

↑

Equations of motion take derivative operator to 4-fermion operator

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

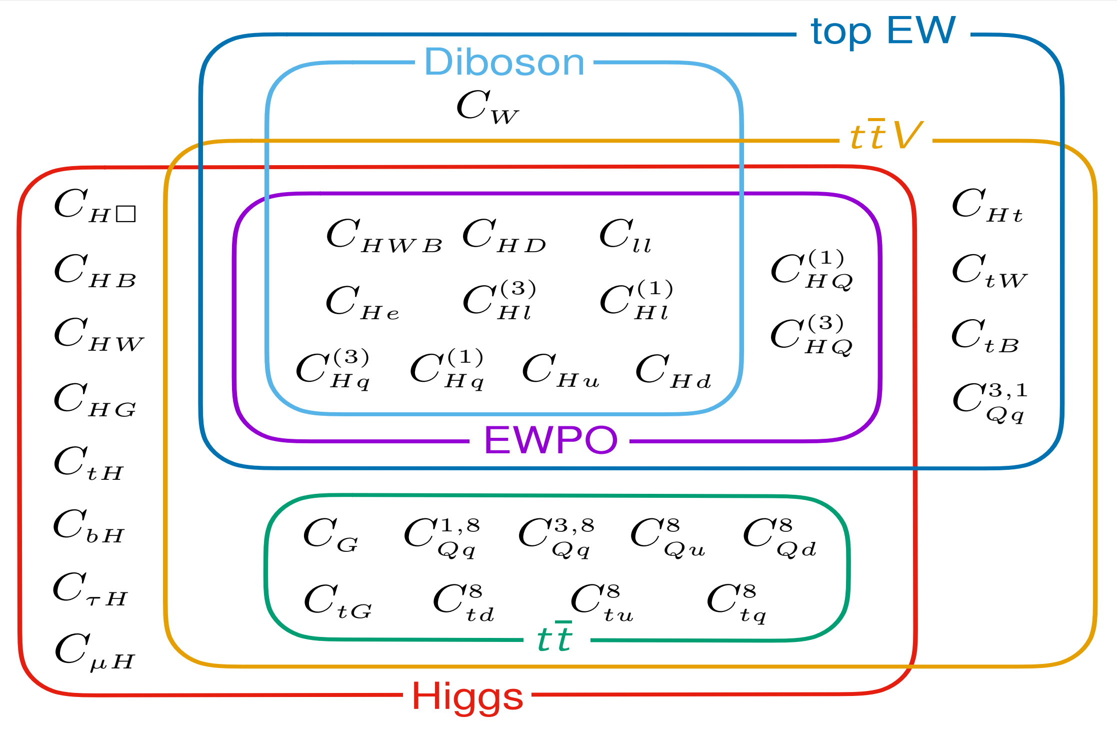
+…..

- Start from SM Lagrangian and add $(\phi^+\phi)$ to all terms
- The interesting operators are those with derivatives
- Derivative operators introduce new structures into kinematic distributions
- Most of 2499 operators come from flavor permutations

S. Dawson

COMPLICATED

- Power of SMEFT is connection of data from different processes
- Eventually, EIC will contribute to this picture



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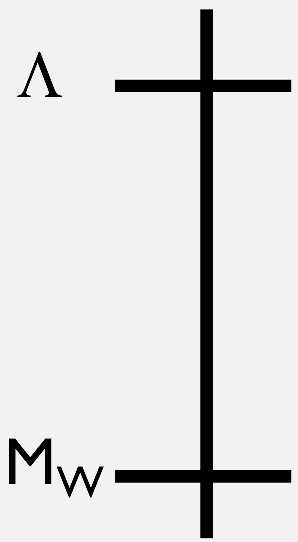
SCALES AND THE EFT



UV Model $\longrightarrow$ C(Λ) **Matching**

$$\frac{dC_i(\mu)}{d\log\mu} = \Sigma_j \frac{1}{16\pi^2}\gamma_{ij}C_j$$ **Running**

EFT$\longrightarrow$ C(M_W) **Precision**

Assume large separation of scales

ADVANTAGES OF SMEFT APPROACH

- Quantum field theory where calculations done order by order in $1/\Lambda$
  - 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

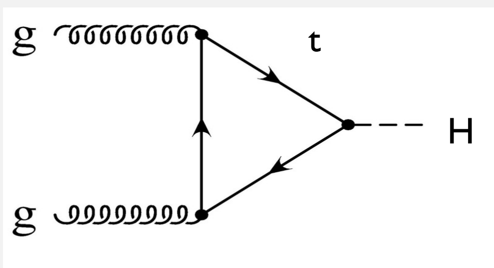
Sounds good, but how does this work in practice?

And even more important, how model independent is this?

HIGGS COUPLINGS TO GLUONS

- Largest contribution in SM is from top quarks
- (Hff coupling ~ m_f/v)
- Not a direct measurement of ttH coupling since there could be new particles in loop

Contribution of b quark ~ -4%

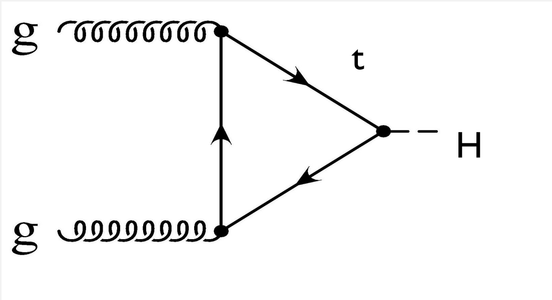


No direct ggH , $\gamma\gamma\mathrm{H}$ couplings since Higgs couples to mass

HEAVY MASS STATES AND SM

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

$$\hat{\sigma}_{gg\to h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2 \delta(1-\frac{M_h^2}{\hat{s}})$$



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

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

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

Question: Why does this logic show that there can't be a SM-like 4th generation?

GLUON FUSION IN THE SMEFT

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

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

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

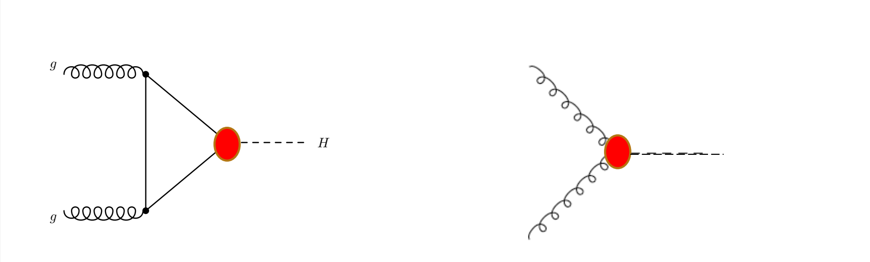
- Changes ttH coupling: $\frac{m_t}{v} \left[1 - \frac{v^2}{\Lambda^2} \frac{C_{tH}}{Y_t} \right]$

WHAT DOES GLUON FUSION MEASURE?

- gg →H cannot distinguish effective ggH coupling from modification to Yukawa coupling 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
Assumptions about scale require assumptions about C



Need to combine measurements to get limits on SMEFT parameters

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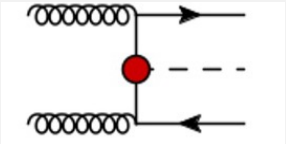
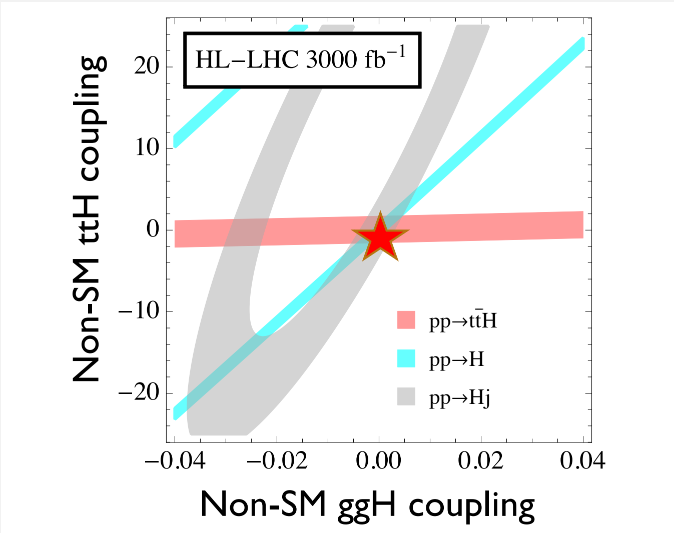
*A_{SM} approximated by $m_t \to \infty$ limit

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

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

$$\Box = \partial_\mu\partial^\mu$$

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 (ok with dim-6 operators) or by field redefinitions

SMEFT GAUGE SECTOR

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

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

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

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

$$O_{HWB} = \phi^\dagger \sigma^a \phi W^a_{\mu\nu} B^{\mu\nu}$$

$$O_{HD} = (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi)$$

$$\frac{v^2}{\Lambda^2}C_{HWB} = \frac{\overline{g}\overline{g}'}{16\pi}\Delta S$$

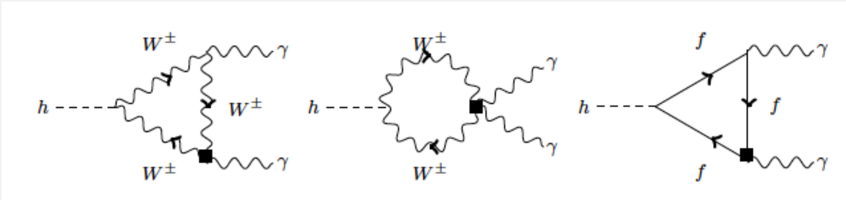
$$\frac{v^2}{\Lambda^2}C_{H\Box} = -\frac{\overline{g}\overline{g}'}{2\pi(\overline{g} + \overline{g}')}\Delta T$$

S. Dawson

H→γγ

- What do we learn from precision Higgs decays?
- Some operators are constrained at tree level in γγ [C_{HB}, C_{HW}, C_{HWB}]

$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(H \to \gamma\gamma)_{SMEFT}}{\Gamma(H \to \gamma\gamma)_{SM}}$$



- EFT confuses loop and tree expansion of SM
- Consider effects of EFT operators in loops (since it is a consistent field theory)