BSM theory

HCPSS '24
A. Martin

Why should there be physics BSM?

empirical: we see phenomena it doesn't contain:
ν masses, DM [baryon asymm]

theoretical: . why not? reductionism has been a triumph!
. why are scales so different? v vs. M_{Pl}? m_t vs. m_e
. why are quantum # how the pattern they do?

If we want to extend SM, should remember it's rules

. defined by symmetries: $\underbrace{\text{Lorentz}}_{\text{spacetime}} \otimes \underbrace{SU(3) \otimes SU(2) \otimes U(1)}_{\text{internal}}$

internal: local / gauge $\therefore$ need massless spin-1 for each

. Particles defined by charges under groups.

i.e. Q_L = spin-1/2, $(\frac{1}{2}, 0)$ $(3, 2)_{1/6}$ $\{ Q_L^{\dagger}$ = spin-1/2 $(0, \frac{1}{2})$, $(\bar{3}, 2)_{-1/6}$

- importantly, fermions are chiral: LH fermions have different internal charges than RH

$\therefore$ can't write $\psi_L^{\dagger} \psi_R$. although Lorentz works, internal charges don't

"chiral symmetry" prevents fermion mass.

. SSB: $SU(2)_w \otimes U(1)_Y$ by vev of single Higgs $(0, 2)_{1/2}$

. gives $W^{\pm}, Z$ mass as $|D_\mu H|^2 \xrightarrow{\langle h \rangle = v/\sqrt{2}} \underbrace{\frac{g^2 v^2}{4}}_{m_W^2} W_\mu^+ W_\mu^- + \underbrace{\frac{g^2 v^2}{8 \cos^2\theta_w}}_{m_Z^2} Z_\mu^2$

(only way to give spin-1 mass valid to arbitrary energy)

- Also gives chiral fermion mass via Yukawa interaction

$$y_d \, \overline{Q}_L^{\dagger} H d_R + h.c. \xrightarrow[\langle h\rangle \neq 0]{} \underbrace{\frac{y_d v}{\sqrt{2}}}_{m_d} d_L^{\dagger} d_R + h.c$$

if $y_d = 0$ Q_L, d_R wouldn't talk, interaction would never be generated perturbatively (chiral symm at work)

- Mass for Higgs itself: part of scalar potential

$-\mu^2 H^{\dagger} H$: different term compared to fermion mass, can't be forbidden by any symm consistent w/ SM

- Given those ingredients, add everything (all interactions) up to mass dim-4

[Quick reminder of mass dim: work in units where only unit is mass (energy): $[x] = E^{-1}$, $[p] = E$, etc.

$S = \int d^4x \, \mathcal{L}$ is dimensionless (we exponentiate it), so

$[\mathcal{L}] = E^4$. Using $\left[\frac{\partial}{\partial x_\mu}\right] = E$, can work out

$[\phi] = [A_\mu] = E$, $[\psi] = E^{3/2}$

classify operator by sum of dim of fields it contains:

$[\phi^2] = E^2$ .. mass dim 2

$[\bar{\psi} \not{\partial} \psi] = E^4$ .. " " 4

so $\phi \bar{\psi} \psi$ is an interaction w/ mass dim 4

$(\bar\psi\psi)^2$ " " " dim 6 > 4 ✓

Extend the SM:

- pick some charges, add everything!

Ex.) ν mass a missing piece, lets add in RH neutrino

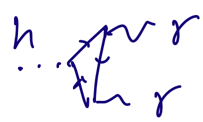
$y_\nu L H N$ + h.c. .. tells us $N \sim (0,0)_0$ SM neutral (also an option!!)

... but we need to add everything, must add

$M_N N N$

- Additional rules of thumb: Say you want new fermions w/ SU(2), U(1) Q# ...

  * chiral fermion mass: came from $\langle h \rangle = v$ $\qquad m_{new} = \frac{y_{new}\, v}{\sqrt{2}}$,

    v fixed, so only way to explain why we havent seen them is to take y_{new} big, but yukawa charges, would means new stuff has SU(2), U(1) shows up in  ! $\qquad$ 4th gen = ruled out. partial gen = tricky

  Headache-free new fermions, have to give L and R same quantum #. "vector-like" fermions (now $M_{new}\, \bar\psi_L \psi_R$ now allowed)

  * Only ways to consistently have massive spin-1: Composite, or via Higgs mechanism = gauge symmetry + SSB.

    So if I add a new Z', also need to add whatever other particles (typically just another scalar) do the SSB.
    w/ similar mass

  * Go nuts... Extra Higgs multiplets, new vector-like fermions, Z' ...

phenomenology will be set by how particles are <u>produced</u> (do they talk to quarks? gluons?)

& if / how they <u>decay</u> (what particles actually show up in the detector?)

All traced back to particles charges. Usually each particle we add introduces many free parameters...

Can start crossing these off, search for each combo of particle & parameters ... } How do you pick? Connection w/ big questions?

I could tell you some faves, but let's go a different direction

<u>Revisit assumption of dim ≤ 4</u>: Let's not add new stuff, but add "higher dim" operators, meaning $d > 4$.

Ex: $\dfrac{(LH)^2}{\Lambda}$, $\dfrac{(Q_i^\dagger \bar{\sigma}^\mu Q_i)^2}{\Lambda^2}$, $\dfrac{u_R^\dagger \sigma^\mu u_R \, i H^\dagger \overleftrightarrow{D}^\mu H}{\Lambda^2}$. $\dfrac{Q_L^\dagger H \sigma^{\mu\nu} d_R B^{\mu\nu}}{\Lambda^2}$

dim: 5 dim: 6

All terms in $\mathcal{L}$ must have $[\mathcal{O}] = E^4$, so if $\sum_i$ fields dim > 4, we need to introduce a dimensionful parameter Λ to compensate.

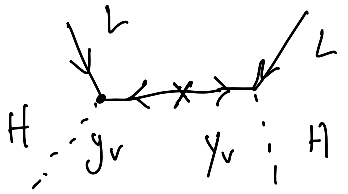
All terms have same Λ? Would be weird, so tend to accommodate different Λ by $\frac{1}{\Lambda} \to \frac{c_i}{\Lambda}$ ← dimensionless "Wilson coefficient"

Where are all the new particles?

We get higher dim ops by "integrating out" BSM stuff that's too heavy.

Ex.) $\mathcal{L} = \mathcal{L}_{SM} + N^\dagger i \bar{\partial} N - M_N NN - y_\nu LHN + h.c.$

[diagrammatically, shrink to point

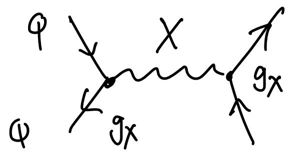


$$\sim \quad (y_\nu)^2 \frac{L M_N L}{p^2 - M_N} H^2$$

$$\text{if } M_N \gg p \quad \sim -y_\nu^2 \frac{(LH)^2}{M_N} + \ldots \quad \mathcal{O}(p^2/M^2)$$

identical to example, but w/ $\frac{1}{\Lambda} = -\frac{y_\nu^2}{M_N}$ [or $c_i = y_\nu^2$, $\Lambda = M_N$]
at dim-5

Ex.) $\mathcal{L} = \mathcal{L}_{SM} + g_X \varphi^\dagger \bar{\sigma}^\mu \varphi X^\mu + \frac{M_X^2}{2} X_\mu X^\mu + \ldots$



$$\sim \quad g_X^2 \frac{(\varphi^\dagger \bar{\sigma}^\mu \varphi)^2}{p^2 - M_X^2} \quad . \quad \text{if } p^2 \ll M_X^2$$

$$-\frac{g_X^2}{M_X^2} (\varphi^\dagger \bar{\sigma}^\mu \varphi)^2 + \mathcal{O}(p^2/M_X^2)$$

matches example! $\frac{c}{\Lambda^2} = \frac{-g_X^2}{M_X^2}$

Moral: SM + new, heavy stuff ($\gg E$) $=$ SM + higher dim operators.
up to corrections $\mathcal{O}((p^2/\Lambda^2)^{\#})$

N.B. Λ is not a cutoff in some loop integral, its a scale of heavy new physics.

(no other light stuff: DM / axion...)

Why do this?

- Any BSM w/ all new particles $\gg$ SM (+ single source of EWSB) can be mapped into collection of higher dim ops.

$\therefore$ By phrasing LHC searches in terms of higher dim ops, can cover many different BSM scenarios at once.

- Working only w/ relevant degrees of freedom is philosophy of effective field theory (EFT)

$\therefore$ applied to SM, it's the SMEFT.

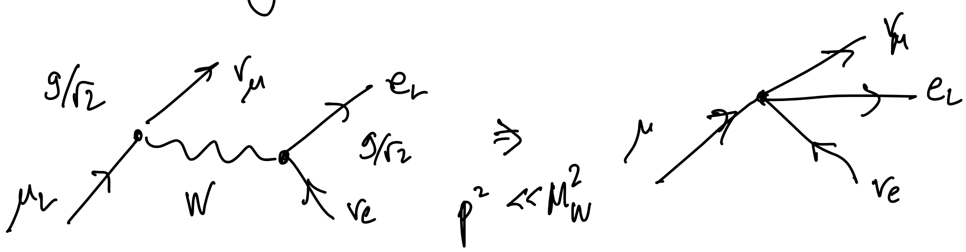
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \sum_{i=1}^{n} \frac{C_i^{(d)} \mathcal{O}_i^{(d)}(Q, u, d, L, e, H, D_\mu, F, G, W)}{\Lambda^{d-4}}$$

mass dimension starting w/ 5

may be multiple ops at same dimension

ingredients in ops are just SM stuff.

You've been doing this forever! Take SM, $E \ll M_W$

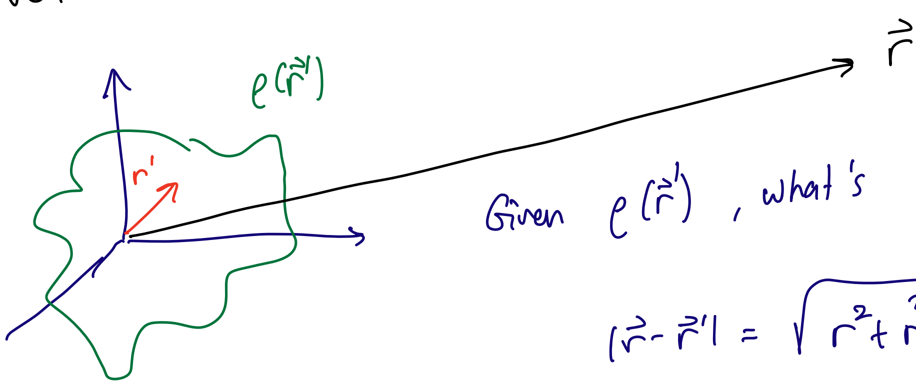


$$\sim \frac{g^2}{8M_W^2} (\nu_\mu^\dagger \bar{\sigma}^\mu \mu_L)(e_L^\dagger \bar{\sigma}_\mu \nu_e) = \frac{G_F}{\sqrt{2}} (\nu_\mu^\dagger \bar{\sigma}^\mu \mu_L)(e_L^\dagger \bar{\sigma}_\mu \nu_e)$$

$$+ \mathcal{O}(p^2/M_W^2)$$

Fermi theory: poster child, and useful calculationally as, now we don't have to drag around M_W if we're doing experiments @ much lower scales

Even earlier! Multipole expansion (E&M)



Given $\rho(\vec{r}')$, what's $V(\vec{r})$, $\vec{r} \gg \vec{r}'$

$$|\vec{r} - \vec{r}'| = \sqrt{r^2 + r'^2 - 2\vec{r}\cdot\vec{r}'}, \text{ so}$$

$$V(\vec{r}) = \int d^3\vec{r}' \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} \qquad \frac{1}{|\vec{r} - \vec{r}'|} = \frac{1}{r} + \frac{\vec{r}\cdot\vec{r}'}{r^3} + \frac{1}{r}\mathcal{O}\left(\left(\frac{r'}{r}\right)^2\right) \dots$$

$$V(\vec r) = \int d^3\vec r\,' \rho(\vec r\,')\left(\frac{1}{r} + \frac{\vec r\cdot\vec r\,'}{r^3} + \cdots\right)$$

$$= \frac{1}{r}\underbrace{\int d^3 r'\rho(\vec r\,')}_{Q_{tot}} + \frac{\vec r}{r^3}\cdot\underbrace{\int d^3r'\,\vec r\,'\rho(\vec r\,')}_{\text{dipole moment}} + \cdots$$

quadrupole
octopole ..

At longest distance, all we see is total charge Q

shape of charge, dipole-ness, etc. expressed as higher orders in r'/r

Analogy w/ SMEFT : $\frac{r'}{r} \to \frac{E}{\Lambda}$

$Q_{tot} \to \mathcal{L}_{SM}$

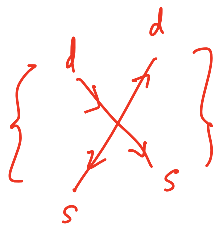
Higher dim ops show up as new 'texture' to interactions of SM.

If $E \ll \Lambda$, only need SM.. but to see detail, or as E bigger, need more.

OK, grab this idea & run with it ...

$$\mathcal{L}_{SMEFT} \supset \frac{(\bar s d)(\bar s d)}{M_H^2}$$

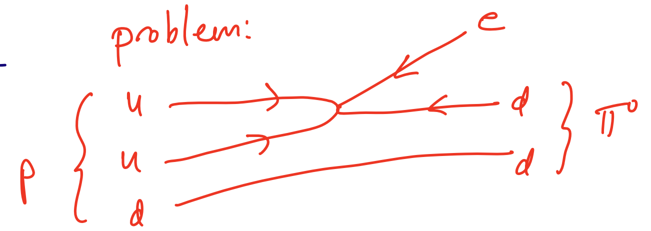
problem: K^0 { } $\overline{K^0}$



if $M_H \sim$ LHC energy, totally excluded by $K^0-\overline{K^0}$ mixing. Need $\Lambda \sim 1000$ TeV

$$\supset \frac{QQQL}{M_H^2}$$

problem:



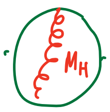
Proton decay! Totally ruled out unless $M_H > 10^{16}$ GeV

Scale $M_{\not{4}}$ needs to be $\gg$ LHC energy

- bad as we'll never see anything at LHC

- problematic, as we know $\exists$ loops, and at loop level

Higgs mass param (no symm.) gets corrected additively

$\delta\mu^2 = \ldots$  $\ldots \propto M_H^2$

has to be, it's the only dimensionful param around!!

But then, why is measured

$\mu^2 \sim \mathcal{O}\left(\frac{100}{\text{GeV}}\right) \ll M_H^2$

This is the hierarchy problem...

[for Higgs, but also for any other scalar we add!]

OR

Need to add more requirements = symmetry!

Say impose $U(1)_B$, where

$Q \to e^{i\theta_q} Q$, same for u, d.

then $QQQL \to e^{i3\theta_q} QQQL$, not allowed.

But! Now paradigm has changed!

No longer just "write everything consistent w/ Lorentz & gauge invariance"

Now have to impose new symm.

Given correspondence we brought up earlier, new symm on higher dim ops = new symmetries on heavy BSM

Don't abandon SMEFT, repurpose it: Now, goal is to discover what additional symm are consistent w/ $M_H \sim$ LHC & look for effects consistent w/ these scenarios.

- for starters, let's impose B, L $\to$ eliminates all odd dim operators. (now no proton decay)

- Also can impose CP conservation (very small in SM)

0-fermion and 2-fermion operators in “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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$\cancel{f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\cancel{\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\cancel{\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\cancel{\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\cancel{\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

Here, $\varphi = H$; $p, r, \cdots =$ flavor indices (so $p = r$ -> flavor universal)

4-fermion operators in “Warsaw basis”

• Just leading effects,
∃ higher order corrections at dim-8,
-10
⋮

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Implemented in MadGraph UFO models via SMEFTsim, SMEFT@NLO

- flavor symmetry, i.e. "flavor universal", avoids $K^0 - \bar{K}^0$, etc. flavor issues

- with these assumptions, narrowed down dim-6 stuff (encapsulating bunch of BSM models) into 59 operators (25 just 4-fermi)

- New vertices (no SM analog), can be turned into Feynman rules w/ usual tricks [& fully implemented into MC tools like MadGraph...]

So let's go!!

- top down: have some BSM model in mind, makes a subset of ops, turn those on & look at LHC pheno...

- bottom up: turn on all operators, find constraints. Map any model into them. Need enough measurements to break degeneracies (linear combos of ops that appear)

Before we dive in, important to point out some differences of field theory / pheno done w/ SM (EFT) vs. SM, or even SM + new particles

- We use the term "basis" for set of ops. What does that mean? Want to cover any possible effect... When we stop & think, this raises questions...

Ex.) Focus on ops w/ 2 deriv, $2H$, $2H^\dagger$. Make all terms...

[dropping overall $\frac{1}{\Lambda^2}$]

$D_\mu H^\dagger D^\mu H \; H^\dagger H$ $\qquad$ $D_\mu H \tau^A D^\mu H \; H^\dagger \tau^A H^\dagger + h.c.$

$D_\mu H^\dagger \tau^A D_\mu H \; H^\dagger \tau^A H$ $\qquad$ $(\Box H) \tau^A H \; H^\dagger \tau^A H^\dagger + h.c.$

[τ^A .. forms triplets. H are EW doublets so product of two = triplet + singlet]

= 4 terms, not 2...

But we want independent ops, $\exists$ field theory tricks can use to relate ops. that don't really show up when only do $d \leq 4$ physics

① IBP: can shuffle derivs around, drop total derivs..

$$D_\mu H^\dagger T_A D^\mu H^\dagger H T^A H = -H^\dagger T_A \Box H^\dagger (H T^A H) - 2 H^\dagger T^A D^\mu H^\dagger D_\mu H T^A H$$

relates one op to linear combo of others; no longer indep.

② Field redefinitions: Path integral, fields are just integration variables

$$\langle \mathcal{O} \rangle = \int \mathcal{D}\text{fields}\ \mathcal{O}\ e^{iS(\text{fields})}$$

Just as we can change integration variables w/out affecting integral can change/redefine fields w/out affecting physical qty [S-matrix elements]

Imagine a simpler theory, single scalar

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{m^2}{2}\phi^2 - \frac{\phi^3 \Box \phi}{\Lambda^2}$$

["free" EOM $(\Box + m^2)\phi = 0$]

Now redefine $\phi \to \phi - \frac{\phi^3}{\Lambda^2}$ ...

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - 3\frac{\phi^2 \partial\phi\partial\phi}{\Lambda^2} - \frac{m^2}{2}\phi^2 - \frac{m^2\phi^4}{\Lambda^2} - \frac{\phi^3 \Box\phi}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

IBP

$$= \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \cancel{\frac{\phi^3\Box\phi}{\Lambda^2}} - \frac{m^2\phi^4}{\Lambda^2} - \cancel{\frac{\phi^3\Box\phi}{\Lambda^2}} + \mathcal{O}(1/\Lambda^4)$$

$$= \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{m^2\phi^4}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

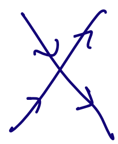
Net effect: looks as we've just used free EOM to swap $\Box\phi \to -m^2\phi$ up to higher corrections [same math works for fermions, gauge fields...] [as involves juggling effects to higher $1/n$ order, not something we see at dim-4 level]

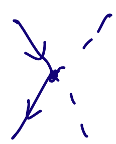
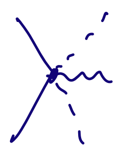
Back to SMEFT $\mathcal{O}(D^2H^4)$, means

$$\frac{1}{\Lambda^2}\,\Box H H H^\dagger H^\dagger \;\to\; \frac{\mu^2}{\Lambda^2}(H^\dagger H)^2$$ changing Higgs quartic has same effect...

So: basis means complete, independent, set. Have to watch out when comparing in literature. If you want to be sure you've covered all possible deviations from SM [w/ symmetry assumptions], need a complete basis. [Remember operators $\neq$ observables...]

OK, explained basis, what manipulations that allows. Let's go...

Ex.) $$\frac{(Q^\dagger \bar\sigma^\mu Q)^2}{\Lambda^2}$$  ∴ should show up in $pp \to jj$

$$\frac{(Q^\dagger \bar\sigma^\mu Q)(iH^\dagger \overleftrightarrow{D}_\mu H)}{\Lambda^2}$$  ,  $pp \to hh$, $pp \to hhV$!

Using Feynman rules, we'd calculate amplitude...

$$A = \underbrace{A_{SM} + \frac{1}{\Lambda^2} A_{dim\text{-}6}}_{} + \cdots$$

$\bar u, v$ spinors, polarizations, couplings, Wilson coefficients all buried in here

Now you square:

$$|A|^2 = |A_{SM}|^2 + \frac{2}{\Lambda^2}\mathrm{Re}(A_{SM}^* A_{dim\text{-}6}) + \frac{1}{\Lambda^4}|A_{dim\text{-}6}|^2 + \cdots$$

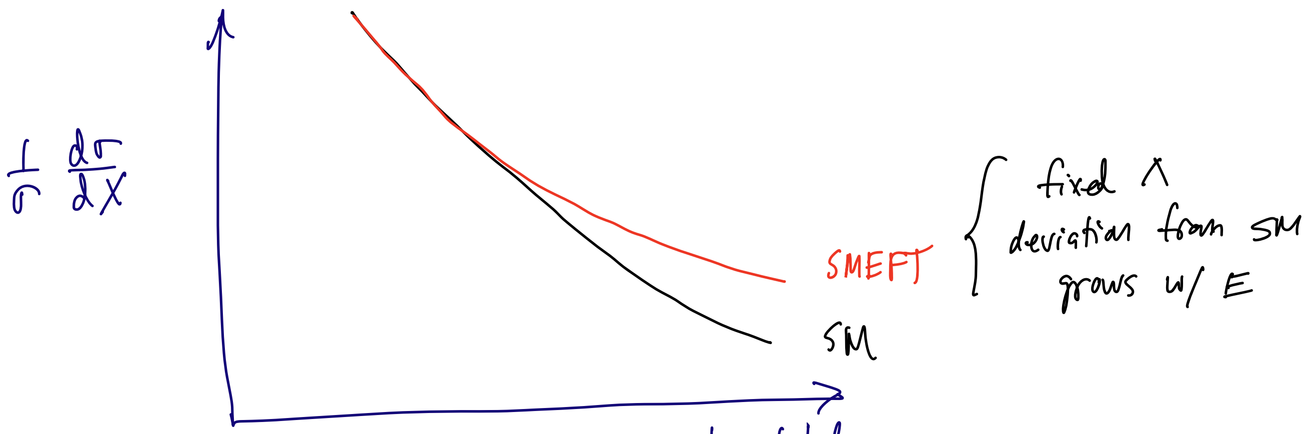
$$= |A_{SM}|^2\left(1 + \frac{2}{\Lambda^2}\frac{\mathrm{Re}(A_{SM}^* A_{dim\text{-}6})}{|A_{SM}|^2} + \frac{1}{\Lambda^4}\frac{|A_{dim\text{-}6}|^2}{|A_{SM}|^2} + \cdots\right)$$

All dimensionless.. so something has to compensate for Λ $\longrightarrow$ only thing around is E = energy of collision. [$\sqrt{\hat{s}}$, not $\sqrt{s}$!!]

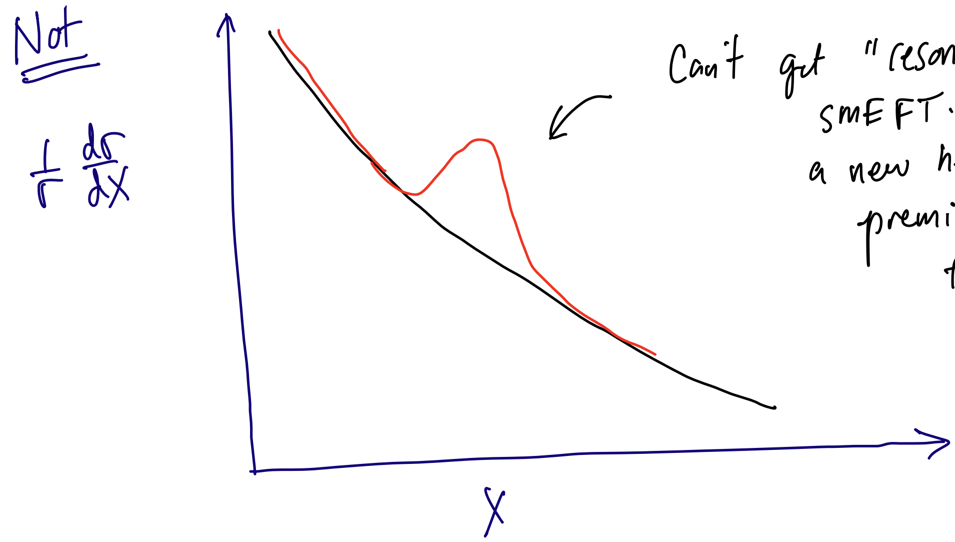
So first term is $\left(\frac{E}{\Lambda}\right)^2$ smaller than SM,
next piece $\left(\frac{E}{\Lambda}\right)^4$...

Knew $\frac{E}{\Lambda}$ was our SMEFT expansion param, this is how we see it in observables.

what does this look like?



Not



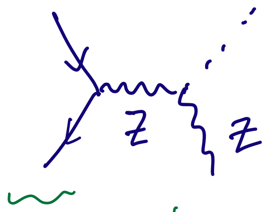
Can't get "resonance" type signal in SMEFT. Resonance = you made a new heavy particle, while whole premise of SMEFT is that new stuff is too heavy.

SMEFT type signal is trickier, as it means you really gotta know your SM prediction.

* as vague as above is, still assumed that SM & dimension-6 interfere. This means they have same initial & final states, where same = helicity / color / polarization ... . Not always the case!

Ex.) $q\bar{q} \to hZ$:

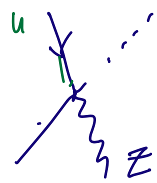
SM



$\varphi^\dagger \bar{\sigma}^\mu \varphi$, or $u_R^\dagger \bar{\sigma}^\mu u_R$
$d_R \bar{\sigma}^\mu d_R$

Same helicity
(LH in, out or RH in, out)

$\varphi^\dagger \sigma_{\mu\nu} T_A u_R H W^{A\mu\nu}$



RH in LH out

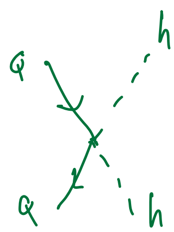
Helicity doesn't match, no interference!

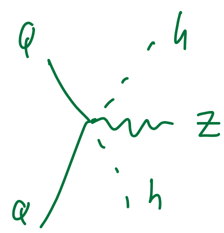
first place this op shows up is in $|A_{dim-6}|^2$ term...

* Above argument made it look like way to find SMEFT ⇒ look at tails of kinematic distributions... Came from E/Λ argument. But, ∃ another scale = v! So SMEFT really a double expansion in v/Λ, E/Λ.

Because $\langle H \rangle \neq 0$, what appear to be higher dim operators can trickle down into lower dimension.

Ex.) $\frac{C_{HQ}}{\Lambda^2} (Q^\dagger \bar{\sigma}^\mu Q)\, i\, (H^\dagger \overleftrightarrow{D}_\mu H)$





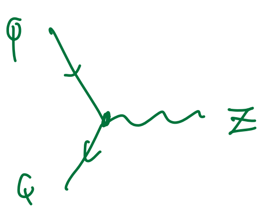
$[g_Z = \frac{g}{\cos\theta}]$

$$D_\mu H = \partial_\mu H + i g \vec{T} \cdot \vec{W}_\mu H + i\frac{g'}{2} B_\mu H \xrightarrow{H \to v+h} \partial_\mu h + i g_Z (v+h) Z_\mu$$

$H^\dagger = v+h$

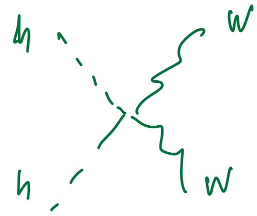
$$\supset -\frac{g_Z}{2\Lambda^2} (Q^\dagger \bar{\sigma}^\mu Q Z_\mu) \;..$$

Contains a shift in SM coupling between fermions (here Q_L) on Z_μ



Means we can/should be looking for SMEFT effects in SM $f\bar{f}V$ couplings! These (esp. Z) quite constrained by LEP experiment $e^+e^- \to$ stuff, in particular $e^+e^- \to f\bar{f}$ at Z-pole

Ex) $\frac{C_{HW}}{\Lambda^2} H^\dagger H W^I_{\mu\nu} W^I_{\mu\nu}$



new h^2W^2 interaction, but take $\langle H \rangle \neq 0$

$\downarrow$

$+\frac{C_{HW}}{2} \frac{v^2}{\Lambda^2} W_{\mu\nu} W_{\mu\nu}$ .. looks like W kinetic term.

$$\mathcal{L} \supset -\frac{1}{4} W^I_{\mu\nu} W^{I\mu\nu} + \frac{C_{HW}}{2} \frac{v^2}{\Lambda^2} W^I_{\mu\nu} W^{I\mu\nu} = -\frac{1}{4}\left(1 + 2C_{HW}\frac{v^2}{\Lambda^2}\right) W_{\mu\nu} W^{\mu\nu}$$

Redefine $W_{\mu\nu} = \frac{\hat{W}^I_{\mu\nu}}{\sqrt{1 + 2C_{HW}\frac{v^2}{\Lambda^2}}}$ to get back to usual normalization.. But, we have to do that everywhere consistently

In particular; $W/Z/A$ mass matrix

$$|D_\mu H|^2 \supset \frac{v^2}{2} \begin{pmatrix} W_{3\mu} & B_\mu \end{pmatrix} \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W_{3\mu} \\ B_\mu \end{pmatrix} \Rightarrow$$

diagonalize to get Z_μ, A_μ. We define couplings like e_{em}, $\sin\theta_W$ by how they talk to mass eigenstates

w/ normalization change:

$$\frac{v^2}{2} \begin{pmatrix} \hat{W}_{3\mu} & B_\mu \end{pmatrix} \begin{pmatrix} \frac{g^2}{1 + 2C_{HW}\frac{v^2}{\Lambda^2}} & \frac{-gg'}{\sqrt{1 + 2C_{HW}v^2/\Lambda^2}} \\ \frac{-gg'}{\sqrt{1 + 2C_{HW}\frac{v^2}{\Lambda^2}}} & -g'^2 \end{pmatrix} \begin{pmatrix} \hat{W}_{3\mu} \\ B_\mu \end{pmatrix}$$

mixing (how you go from gauge → mass basis) now depends on C_{HW} : $\sin\hat{\theta}_W = \frac{g'}{\sqrt{g^2+g'^2}} + \mathcal{O}(C_{HW})$

Since mass eigenstates depend on C_{HW} & couplings depend on mass eigenstates, mean qty like e_{em} also depend on C_{HW}!

<u>Net result:</u> SMEFT operators enter in subtle ways & in multiple processes.

(1.) Hard in that no "bump hunt".

(2.) Good in that lots of cross checks.. i.e. if you see a deviation in e.g. $\bar{u}_L u_L Z$, if it's from $(q_L^\dagger \sigma^\mu q_L) i H^\dagger \overleftrightarrow{D}_\mu H$ you better see something in $\bar{u}_L u_L Z h$, $\bar{u}_L u_L Z h^2$ too! and $\bar{d}_L d_L Z$, etc. [SU(2)]

For any observable (cross section, differential cross sect, etc.)

$$\sigma_{tot} = \sigma_{SM} + \sum_i \frac{C_i}{\Lambda^2}\,\underbrace{\sigma_{SM-dim-6}}_{\text{interference}} + \overbrace{\left\{ \sum_{i,j} \frac{C_i C_j}{\Lambda^4}\,\sigma_{(dim-6)^2} + \cdots \right\}}^{\text{higher order}}$$

just #, from integrating $|A|^2$ over phase space.. (before we pulled out factors of E, v. Now these are folded in)

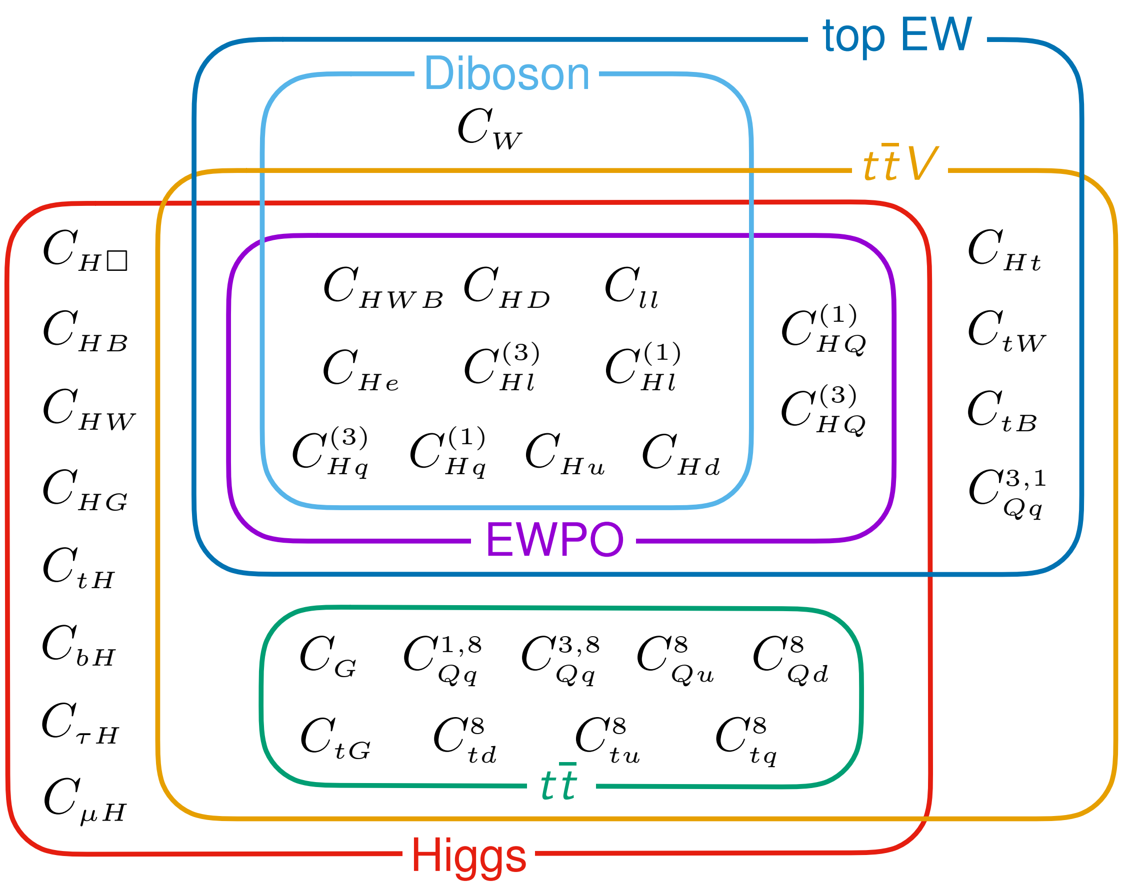
$= \text{function of } \frac{C_i}{\Lambda}$

Comparing σ_{tot} w/ whats observed → can constrain C_i/Λ

Multiple observables? Combine obs. vs. σ_{tot} into giant χ^2

SMEFT approach is a global approach

$$\sigma_{tot} = \sigma_{SM} + \sum_{i} \frac{c_i}{\Lambda^2}\sigma_{SM*dim-6} + \sum_{i,j} \frac{c_i\, c_j}{\Lambda^4}\sigma_{(dim-6)^2}$$



Operators impact multiple processes: Global approach needed

LHC SMEFT analysis goal:

from pattern in deviations, **determine Λ**

SMEFT approach is a global approach

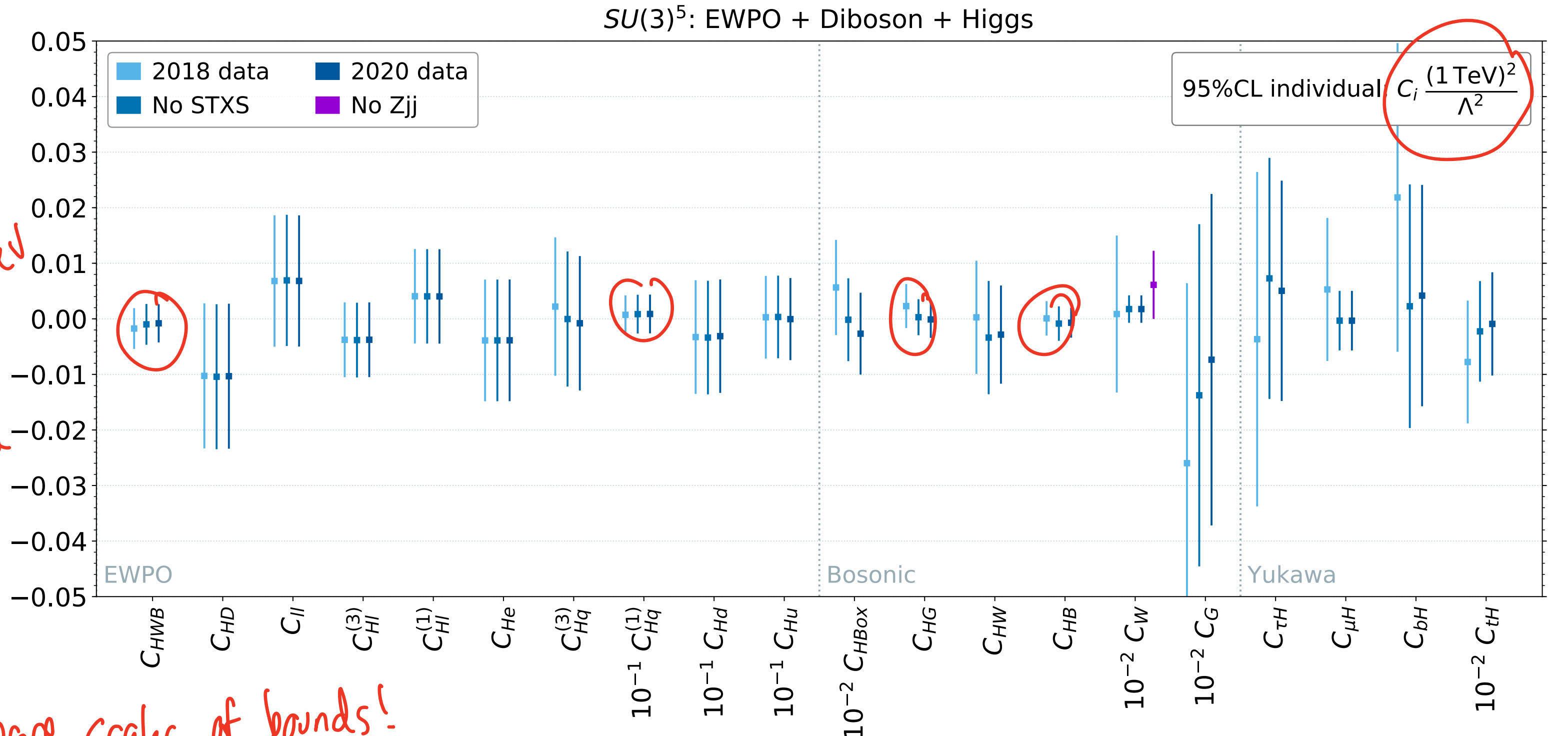
• can analyze χ^2 turning only one operator on ....

or "marginalizing" over others

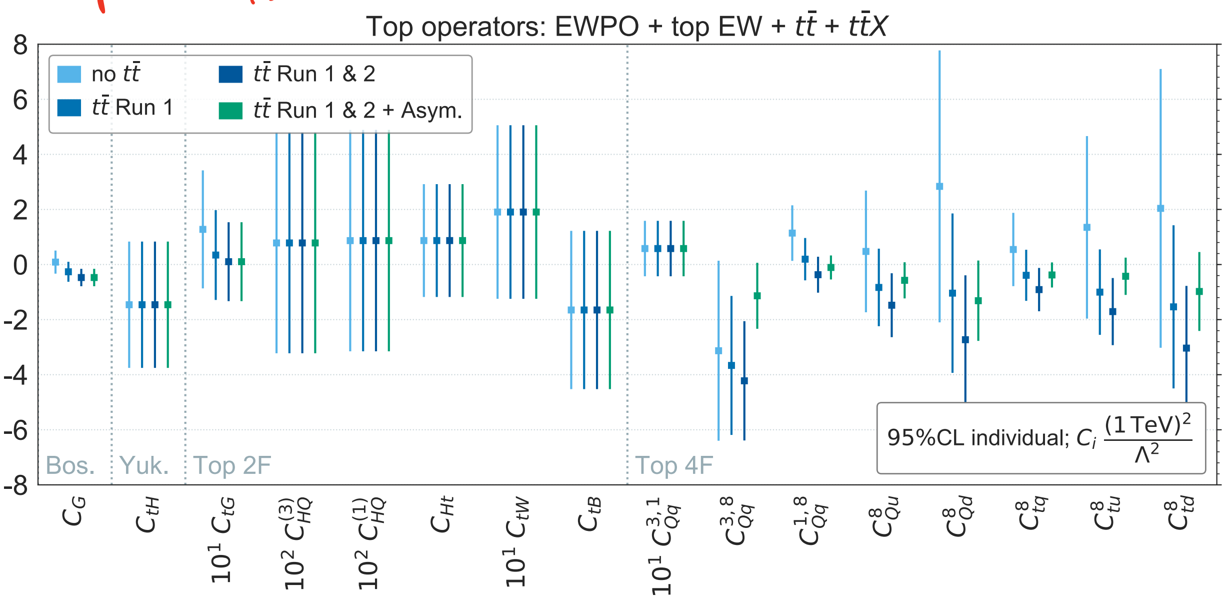
[in " " as $\exists$ multiple interpretations of how to marginalize]

size of C_i if $\Lambda = 1$ TeV

smaller = more constrained



compare scales of bounds!

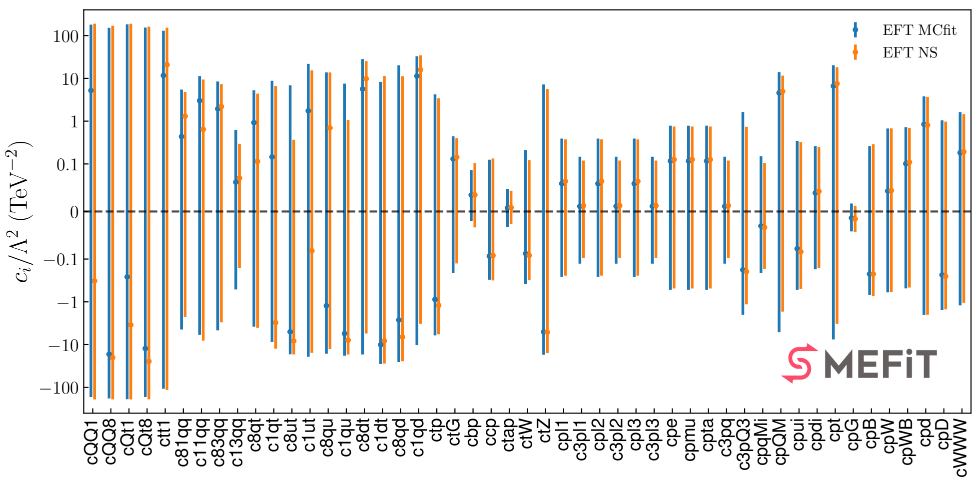


Lots of work in the area! Tightest constraints on operators that affect $\bar{f}fV$ couplings or $h \rightarrow \gamma\gamma$

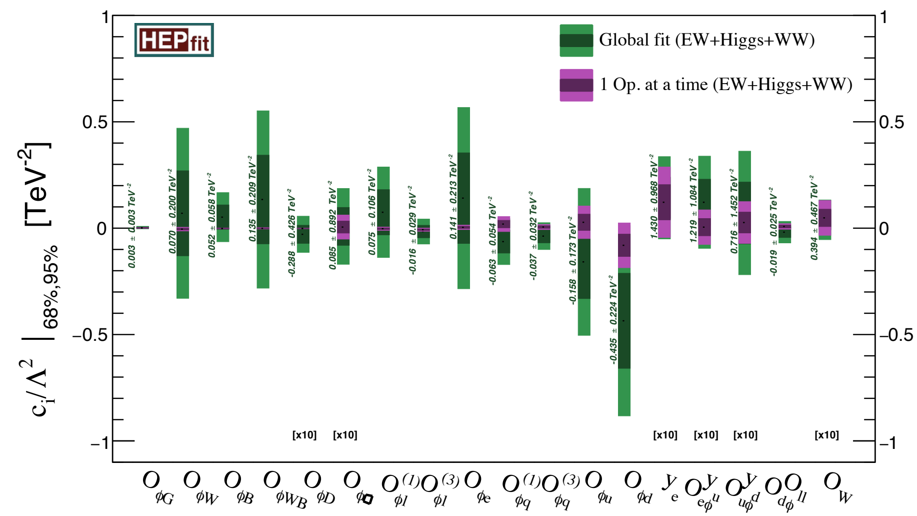
[Ellis et al 2012.02779]

SMEFT approach is a global approach

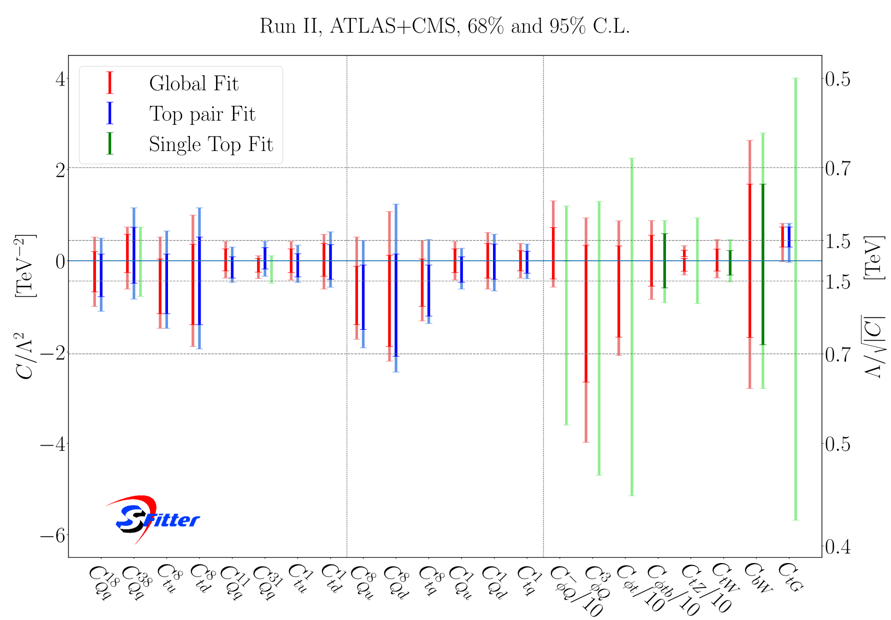
• weak constraints on ops w/ multiple 3rd gen fermions.



[2105.00006]



[1910.14012]



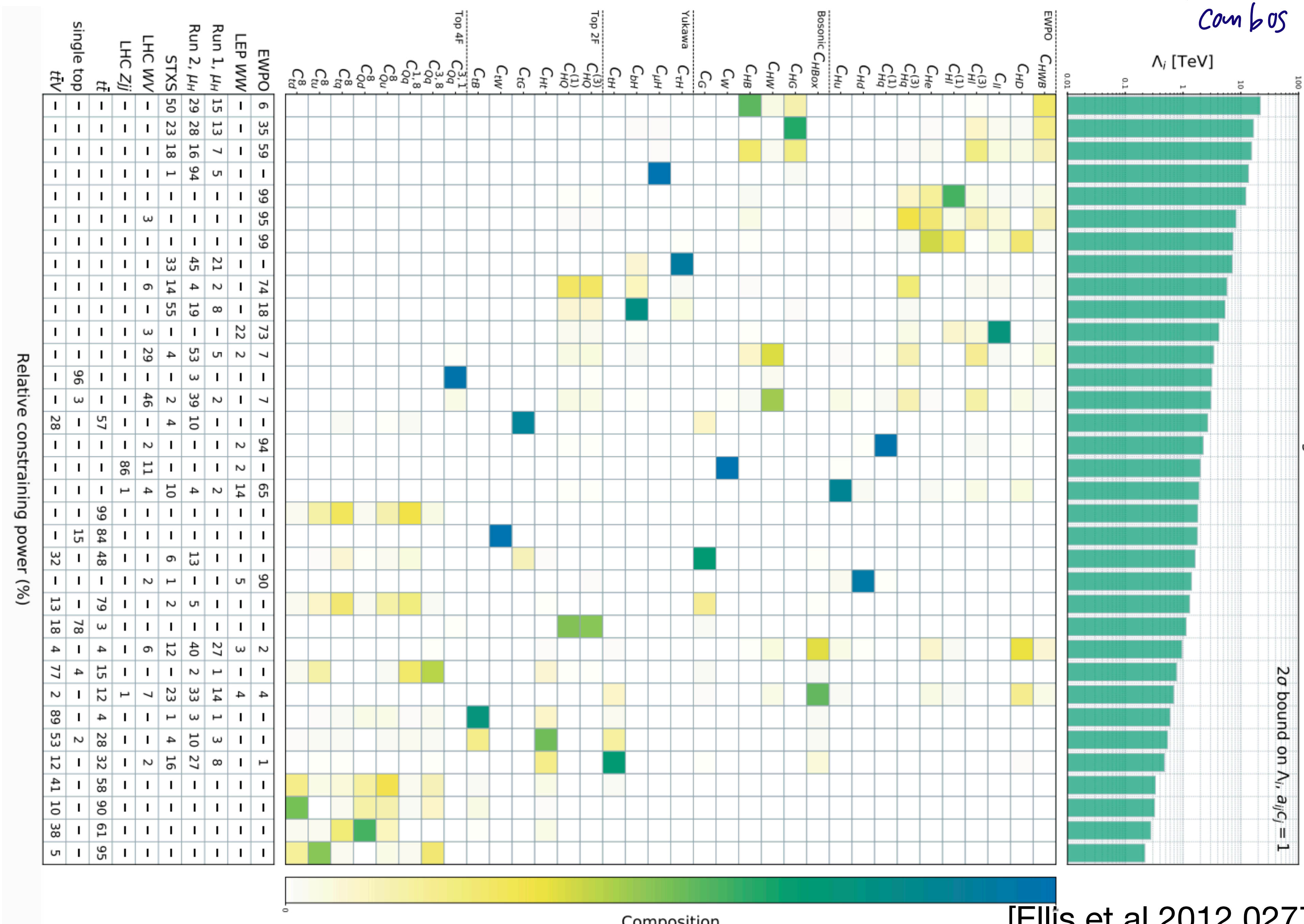
[1910.03606]

Watch for different assumptions (flavor/CP), coefficient conventions, linear vs. quadratic SMEFT, NLO vs. LO

only $1/\Lambda^2$ or $1/\Lambda^2$ and $1/\Lambda^4$

SMEFT approach is a global approach

- View χ^2 as giant matrix
  look for tighter/weaker
  constrained combos



[Ellis et al 2012.02779]

OK great, what's left to do?

New analyses (different final states, different kinematic regions) expand list of coefficients, improve constraints e.g. by lifting a "flat direction" = linear combo. of operators that's poorly constrained.,

also can help spot inconsistencies.

→ $t\bar{t}$, $t\bar{t}+X$, VVV (though I wish we'd revisit VV), HH are all beginning to be explored w/ SMEFT lens, room for new energy & ideas!

Final word of caution: recall SMEFT is an expansion in $\left(\frac{v}{\Lambda}\right)^n$ or $\left(\frac{E}{\Lambda}\right)^n$

current processes that dominate global fit are v^2/Λ^2 .. they come from operators trickling down to ffV, ggh, $h\gamma\gamma$ by setting $\langle H \rangle \neq 0$.

Most processes aren't in this category, so SMEFT effects

any thing except 2 → resonance → 2

$$\sim c_i^{(6)} \frac{E^2}{\Lambda^2}$$ ← set by cuts

Tempting to go look at highest E possible ... BuT, remember we're doing an expansion! Higher order corrections (operators at dim 8, 10 ...) come in as

$$c_i^{(8)} \frac{E^4}{\Lambda^4}, \quad c_i^{(10)} \frac{E^6}{\Lambda^6}, \text{ etc.}$$

{ # operators explodes w/ dim.

at dim-8 → 993 even w/ flavor / CP assumptions }

- If $c_i^{(6)} \frac{E^2}{\Lambda^2} > 1$, perturbation theory breaks down.. no sense in which dim-6 stuff captures full effect

- Even if $C_i^{(6)} \frac{E^2}{\Lambda^2} < 1$, the larger it is, the larger higher order corrections are.

e.g. if $\frac{E^2}{\Lambda^2} = 0.5$, bound on Λ come w/ 25% uncertainty

if $\frac{E^2}{\Lambda^2} = 0.1$ " " " " 5% uncertainty.

[Λ is where you build the next collider, don't wan't to be wrong about that...]

How to include / estimate / handle uncertainty from higher order (in $\frac{E}{\Lambda}$) SMEFT is an active area of research, both theory & experiment.