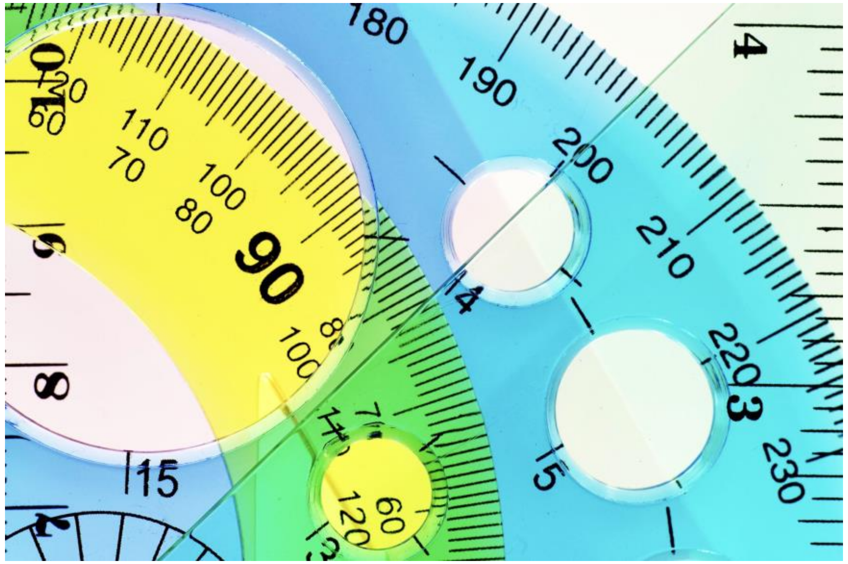
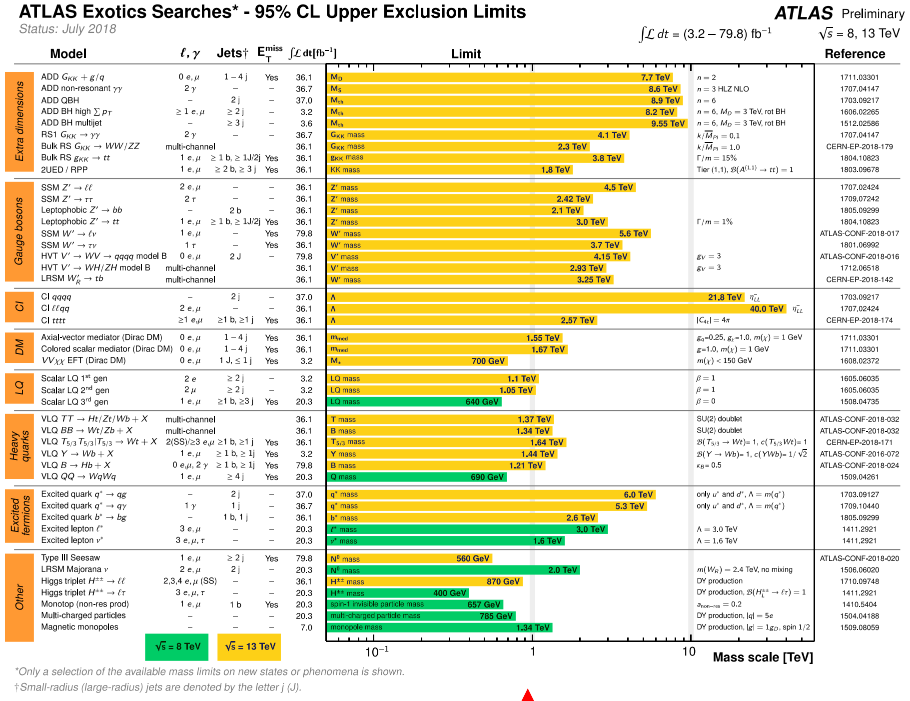


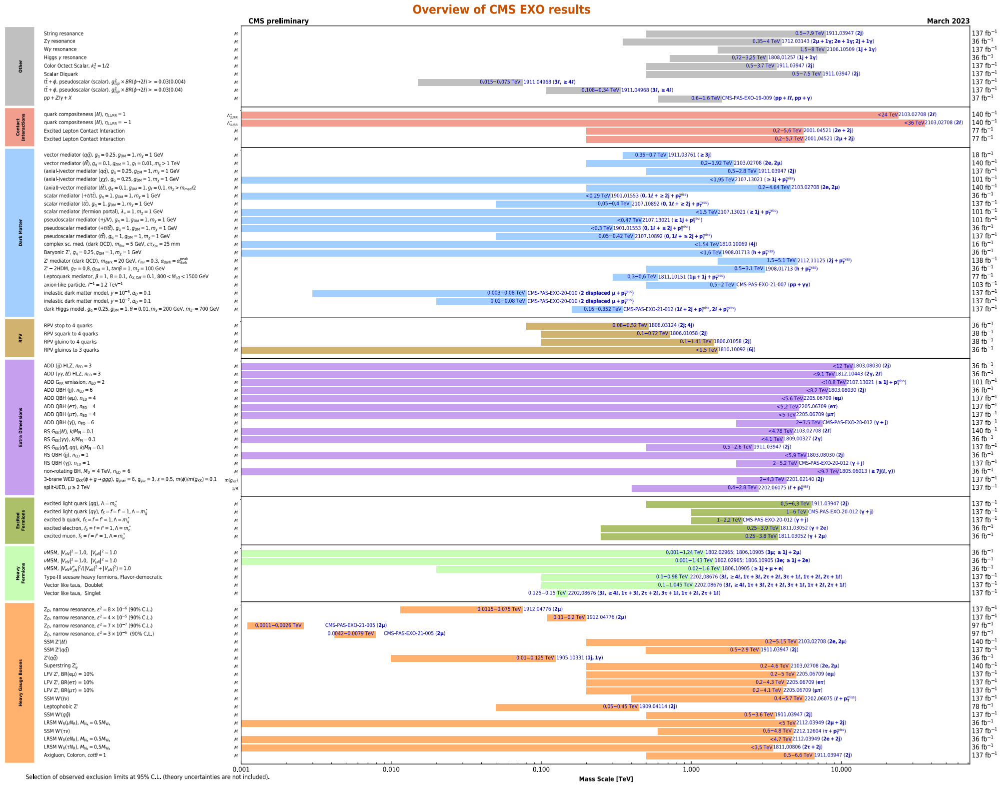
The Search for New Physics through precision measurements

COMETA Colloquium

S. Dawson, BNL, Sept. 16, 2024

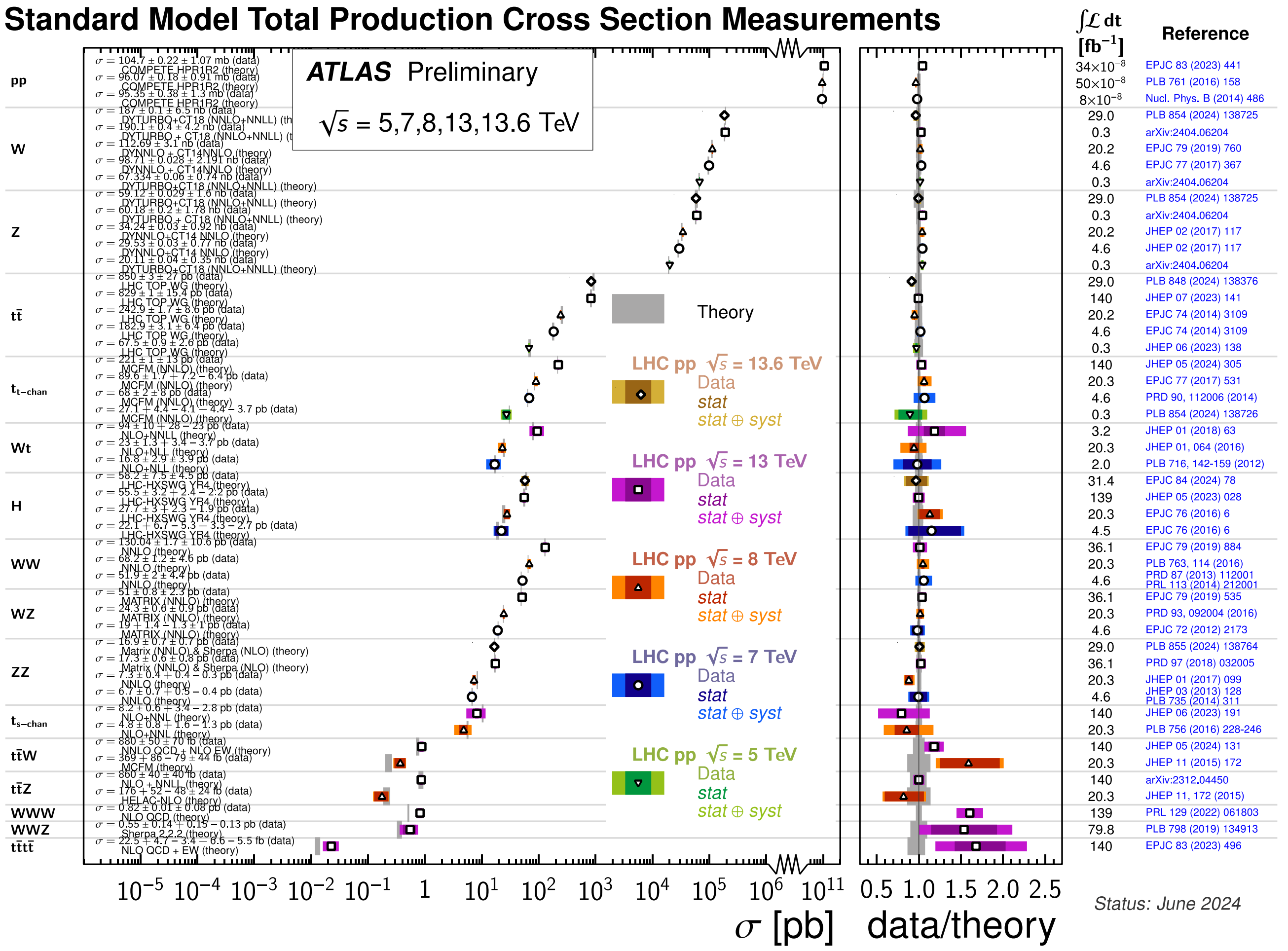
No new particles discovered *(yet?)*





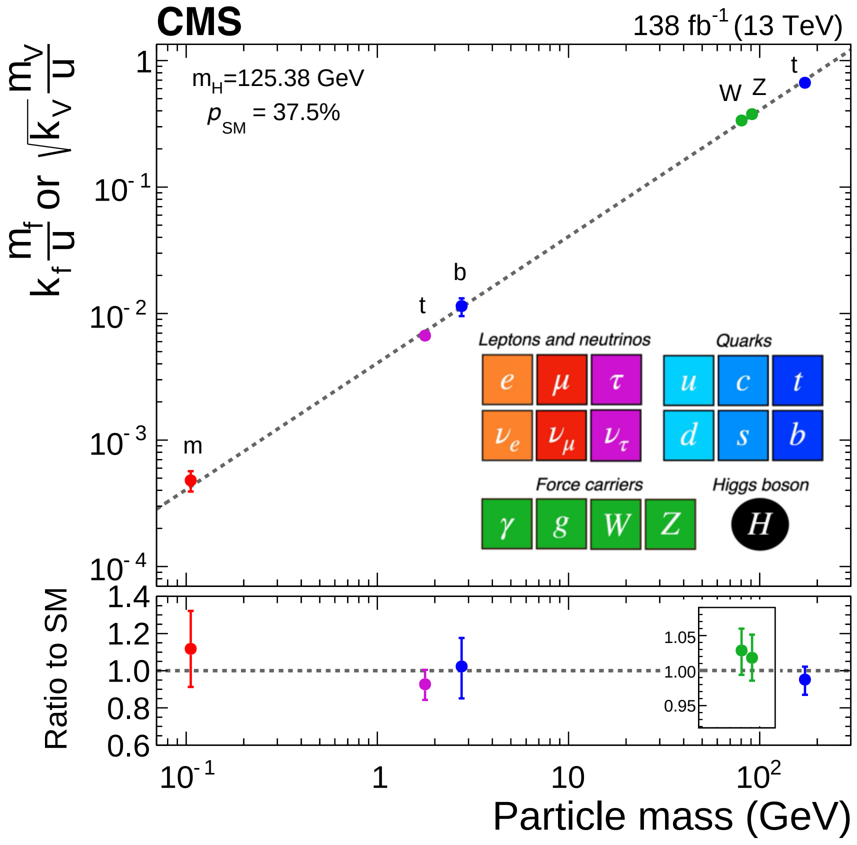
Many limits exceed 1 TeV

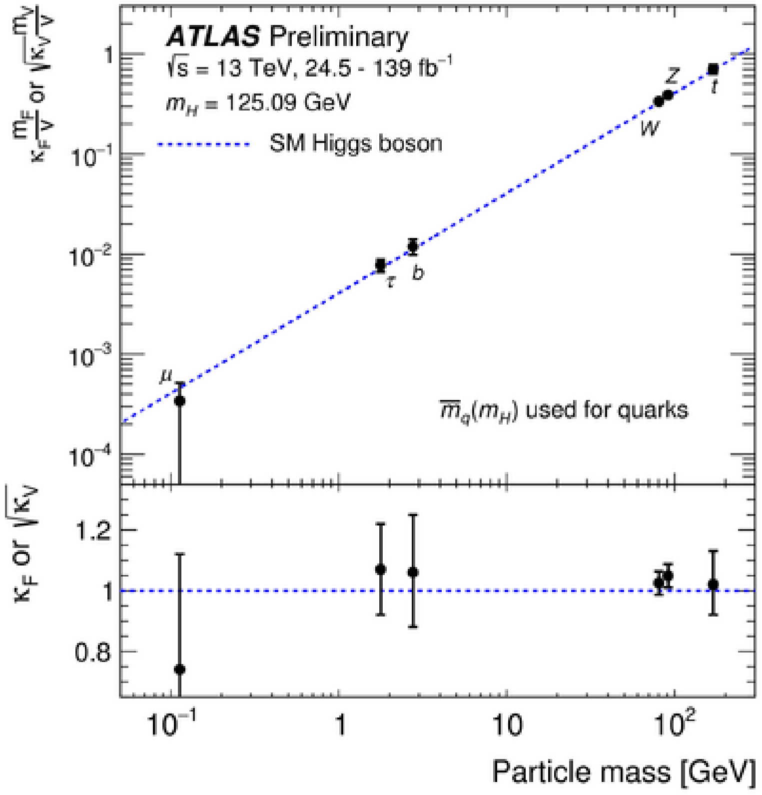
LHC measurements look "SM-like"



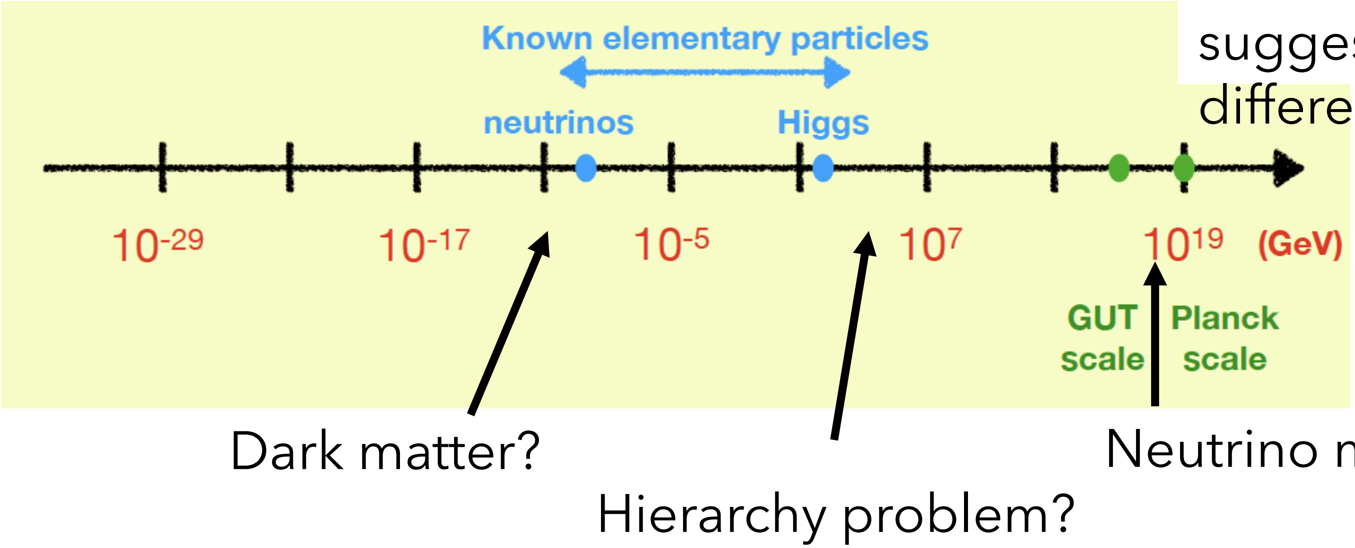
Impressive theory/experiment agreement over many orders of magnitude and in many varied processes

Higgs couplings look "SM-like"





No free parameters in plots



Different questions suggest searching at different scales

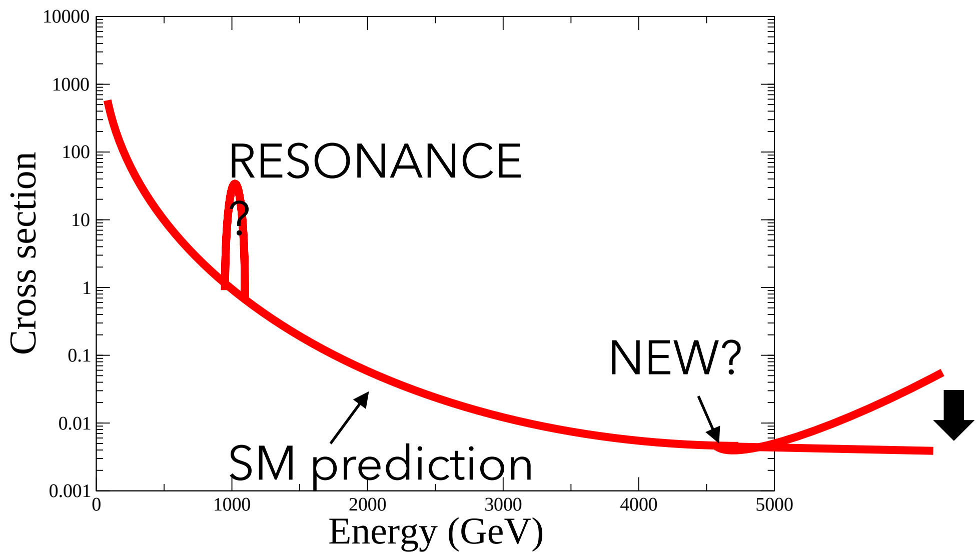
WHERE TO LOOK for new physics?

Current data doesn't really give us any hints

I will focus on scenario where new physics is heavy (ie, much larger than weak scale

NO sign of more Higgs-like particles

- No shortage of models predicting more Higgs particles (or any other particle)
  - But no evidence yet….
- Look for new physics in tails of distributions
  - Requires precision calculations of SM predictions for comparison
  - This is much harder than looking for resonances



Hierarchy of scales

$\Lambda >> M_W$ where complete theory exists

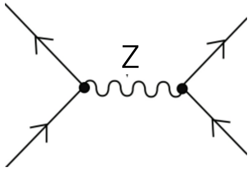
- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed

This is sad scenario where there is no intermediate scale physics

M_W Only SM particles in theory at low scales

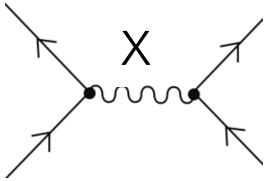
High scale decoupling

- 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:



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

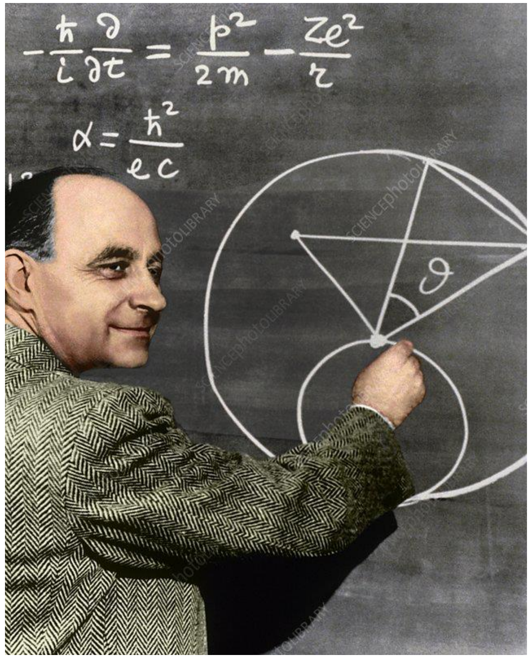
- Scattering rate:

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

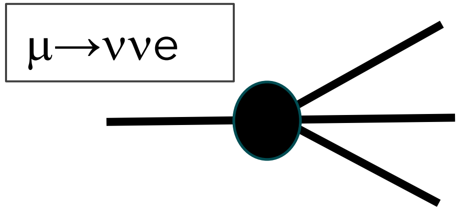
Effects of X vanish as $1/M_X^2$ for ***weak coupling***

This is implicit assumption as we construct SMEFT

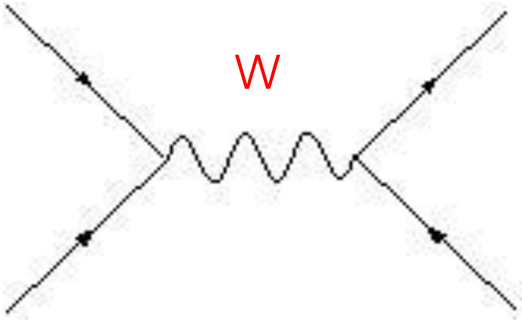
Indirectly discover new physics



- Fermi theory (μ→ννe) becomes non-perturbative at E ~ 600 GeV
- W boson saves the day



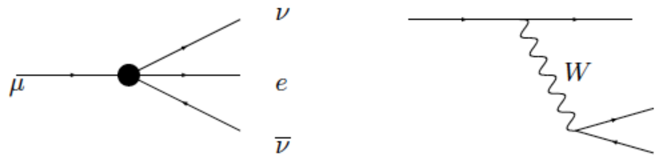
$G_F E^2 \rightarrow G_F M_W^2$



Indirectly discover new physics
Goal is to apply this lesson to TeV scale physics

Constructing the EFT

- Full theory is SM: Renormalizable, consistent dimension-4 theory



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

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

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

Predict coefficients of low energy effective theory (G_F) in terms of UV physics (g, M_W)

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

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

BSM Effects → $\frac{C_i}{\Lambda^2}$ SM Particles → $O_i^{d=6}$

- 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

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

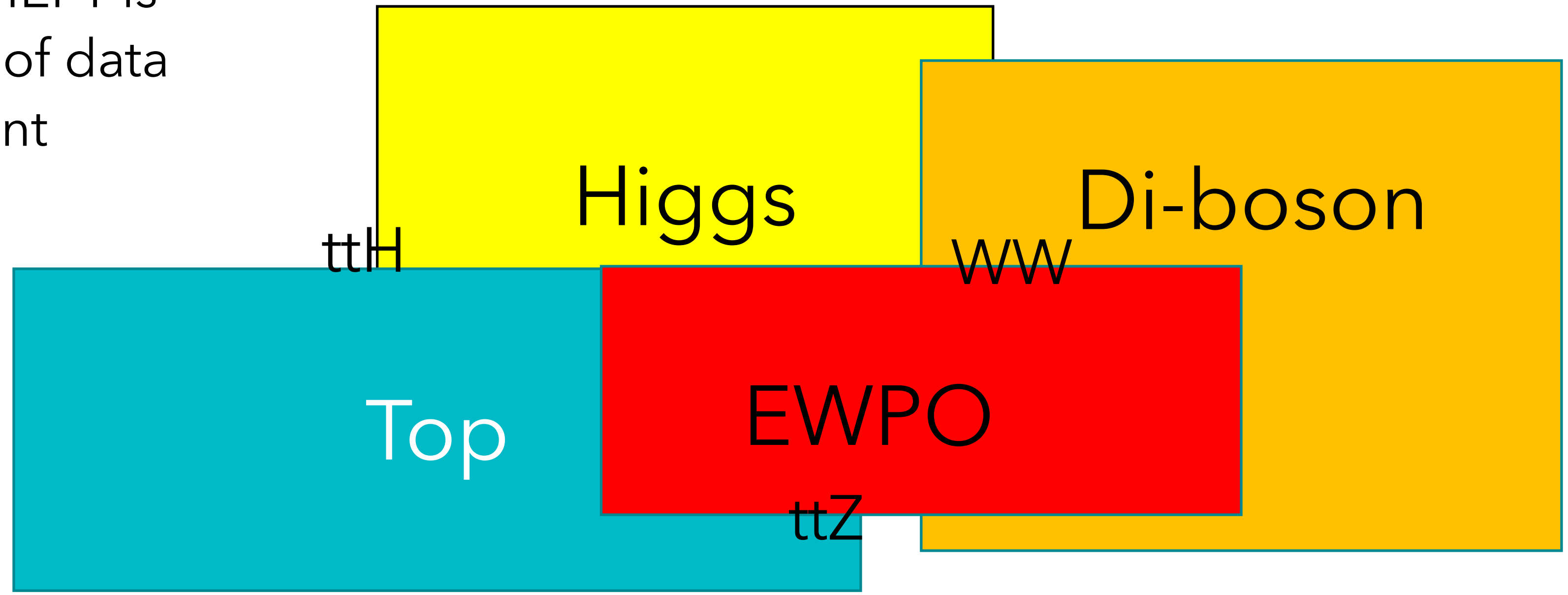
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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 (effects not in the κ formalism)
- Derivative operators introduce new structures into kinematic distributions
- Most of 2499 operators come from flavor permutations

Complicated

- Power of SMEFT is connection of data from different processes



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?

Learning from SMEFT

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

Precise experimental measurements

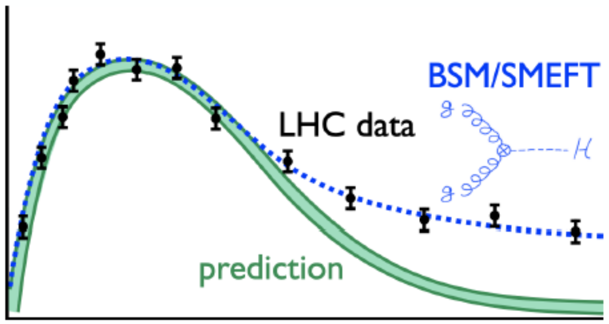
Precise SM calculations

Precise SMEFT calculations

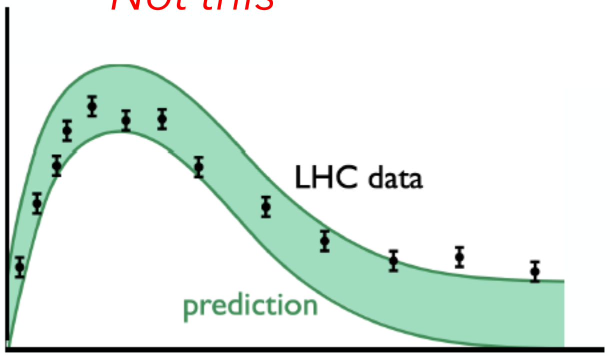
- Understanding uncertainties in SMEFT interpretations of data is a work in progress…. No theoretical consensus

- Interpreting a pattern of non-zero SMEFT coefficients gives information about UV models

Want this



Not this

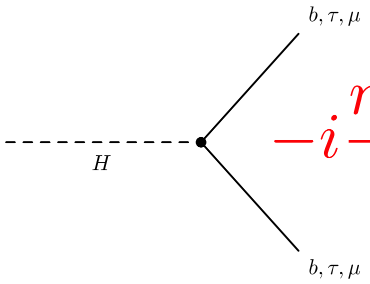


Testing Higgs Couplings: κ

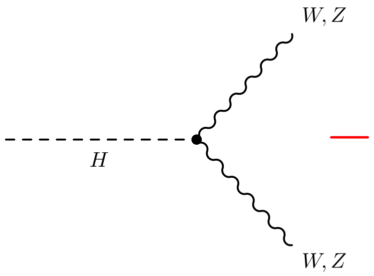
- Assume no new resonances/zero width approx/no new tensor structures

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

- Define scaling factors κ



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



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

- In SM, gauge invariance requires κ=1
- κ framework isn't consistent in QFT

Higgs decays

- Example: H→bb

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

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

From normalizing H kinetic energy

From change in relation between G_F and v

New dimension-6 operator affecting Yukawa

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

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

1704.03888

Consider H→Z*Z→Z f f

- Consider H→Zff

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

c_{ZZ} are momentum dependent operators

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

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

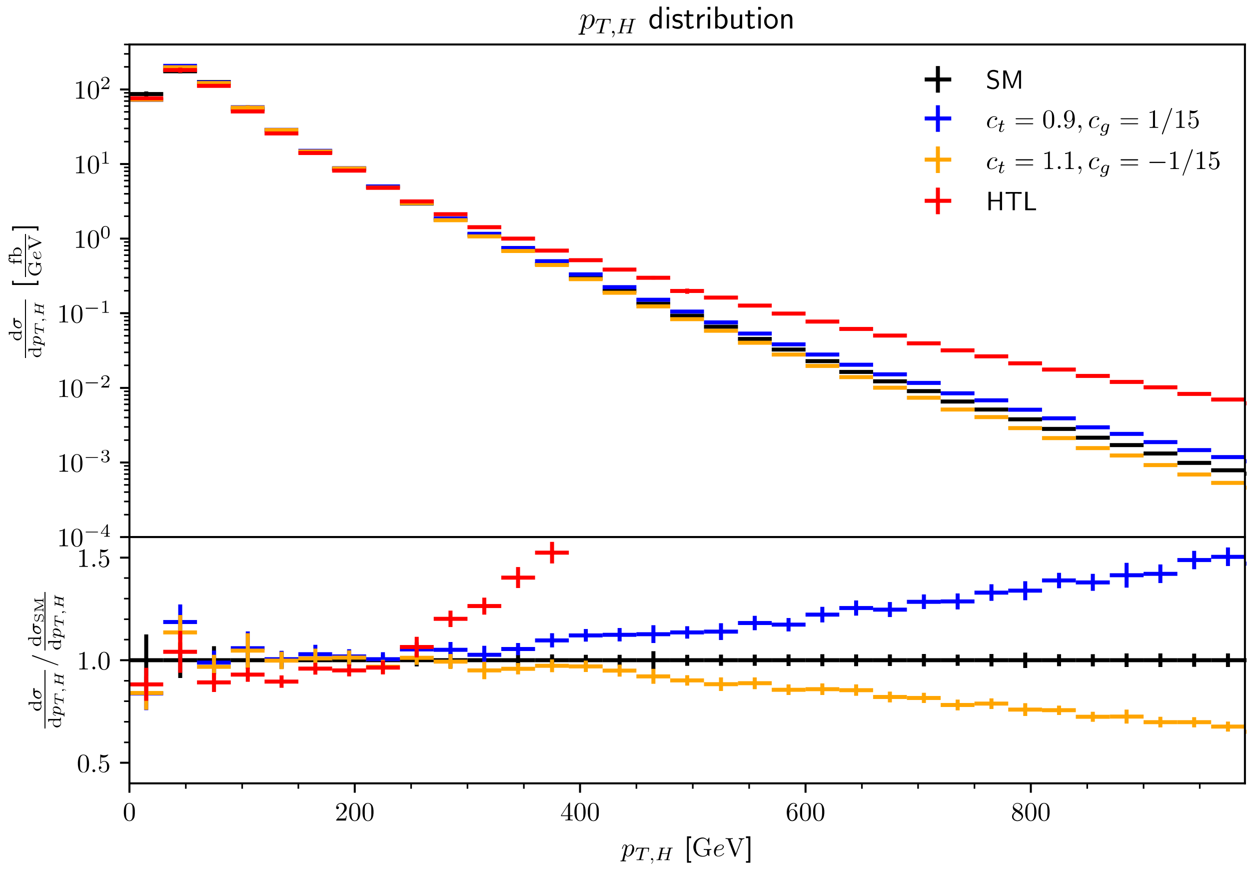
$$c_{ZZ} = \frac{M_W^2}{M_Z^2}C_{HW} + \left(1 - \frac{M_W^2}{M_Z^2}\right)C_{HB} + \frac{M_W}{M_Z}\sqrt{1 - \frac{M_W^2}{M_Z^2}}C_{HWB}$$

These operators have derivatives

Recap

- Momentum dependent operators change shapes of distributions
- Effects largest at high p_T

Higgs + jet production at NLO



2409.05728

When is eft valid?

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

- SMEFT

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

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

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 $g_{SM} \sim g_{BSM}$

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

Assumptions are creeping in

State of the art fits typically use dimension-6 operators and compare linear and quadratic fits

Where do limits come from?

- Electroweak precision observables:

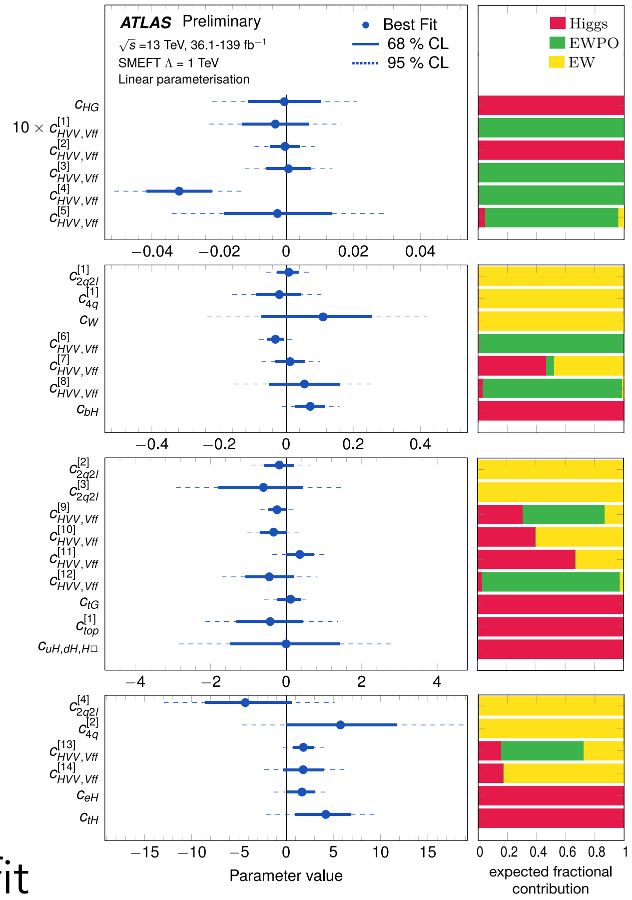
$$M_W, \Gamma_W, \Gamma_Z, \sigma_h, A_{l,FB}, A_{b,FB}$$

$$A_{c,FB}, A_b, A_c, A_l, R_l, R_b, R_c$$

- LHC Higgs data
- LHC and LEPII W^+W^- data
- (Top data)

Often, multiple measurements contribute to limits

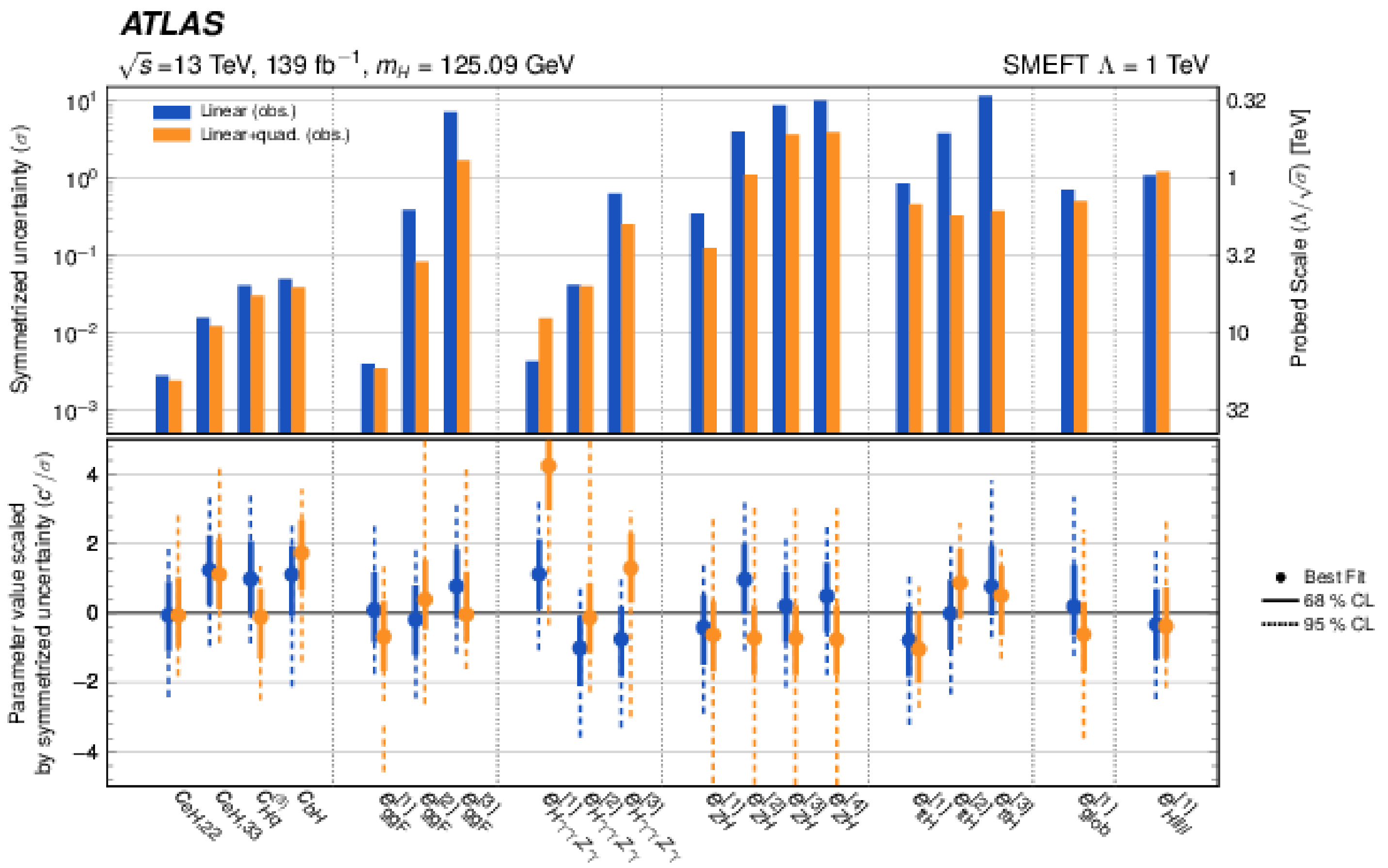
ATLAS fit to Higgs, VV, EWPO data



* Linear fit

Global fit to Higgs

- ATLAS fit to Higgs data
- ***Comparison of linear and quadratic fits***
- Not huge difference between them (the better the limit is, the closer they are)
- Typically probe 1-10 TeV scale ***(with C=1)***



ATLAS, [2402.05742](2402.05742)

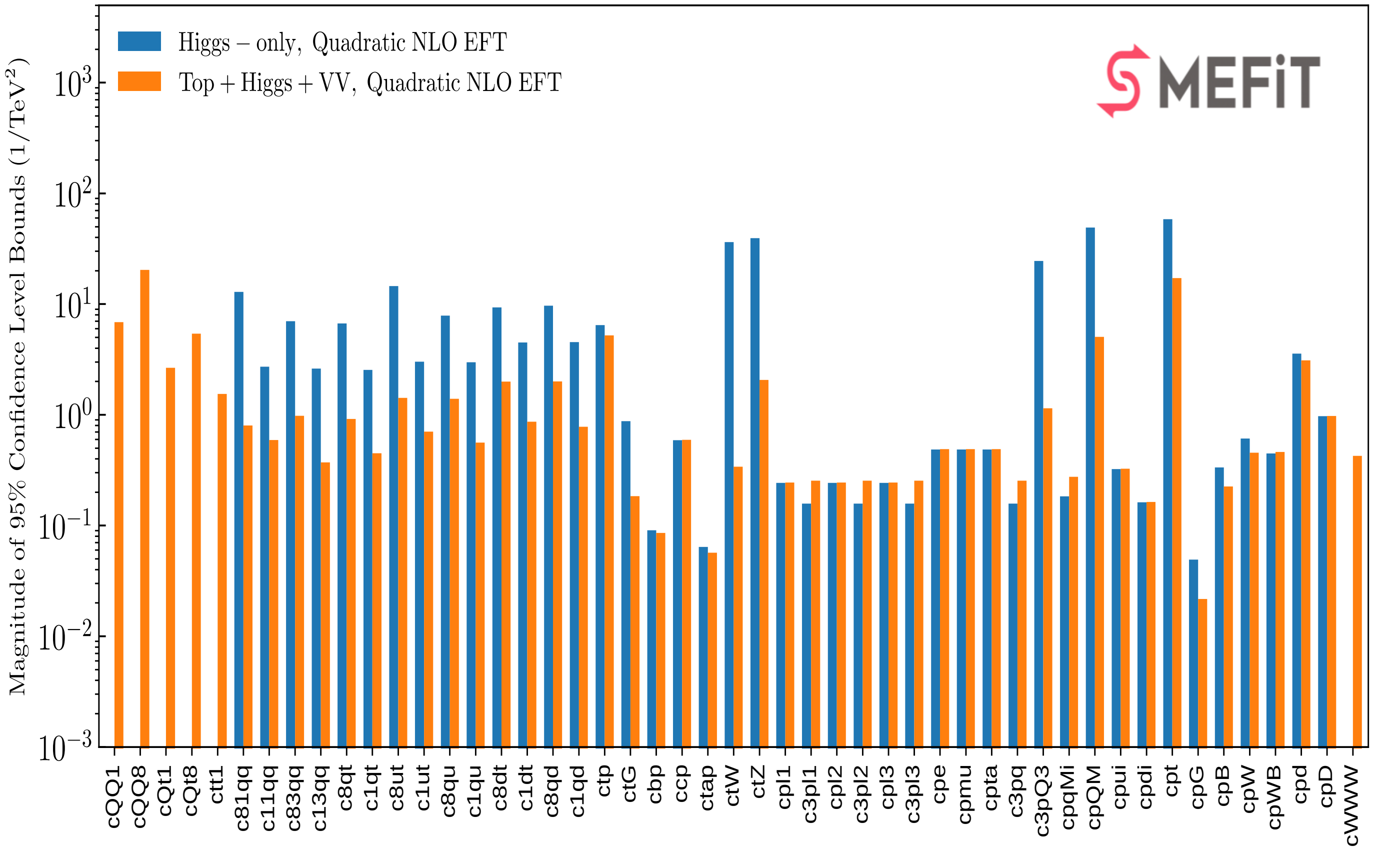
Many global fits

- ***Include top, Higgs, VV***

$$A \sim A_{SM} + a_i \frac{C_{6i}}{\Lambda^2} + a_{ij} \frac{C_{6i} C_{6j}}{\Lambda^4}$$

- Blue: Higgs only observables calculated to $1/\Lambda^4$ at dimension-6
- Red: Higgs + top+VV observables calculated to $1/\Lambda^4$ at dimension-6

Including top can make a big difference



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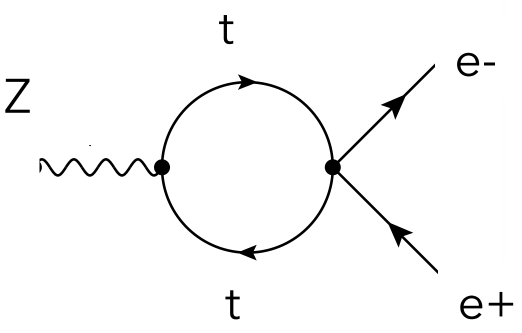
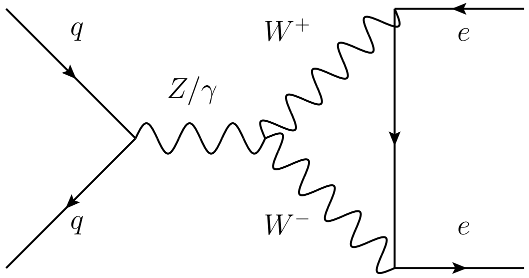
The power of loops

- SMEFT is consistent field theory
- Can calculate to NLO (one loop) using standard techniques to improve predictions
- Many interesting effects: typically gain sensitivity to new interactions at loop level

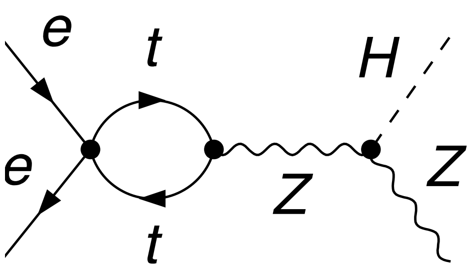


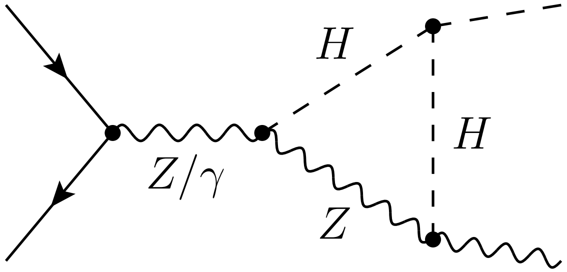
eett vertex poorly constrained



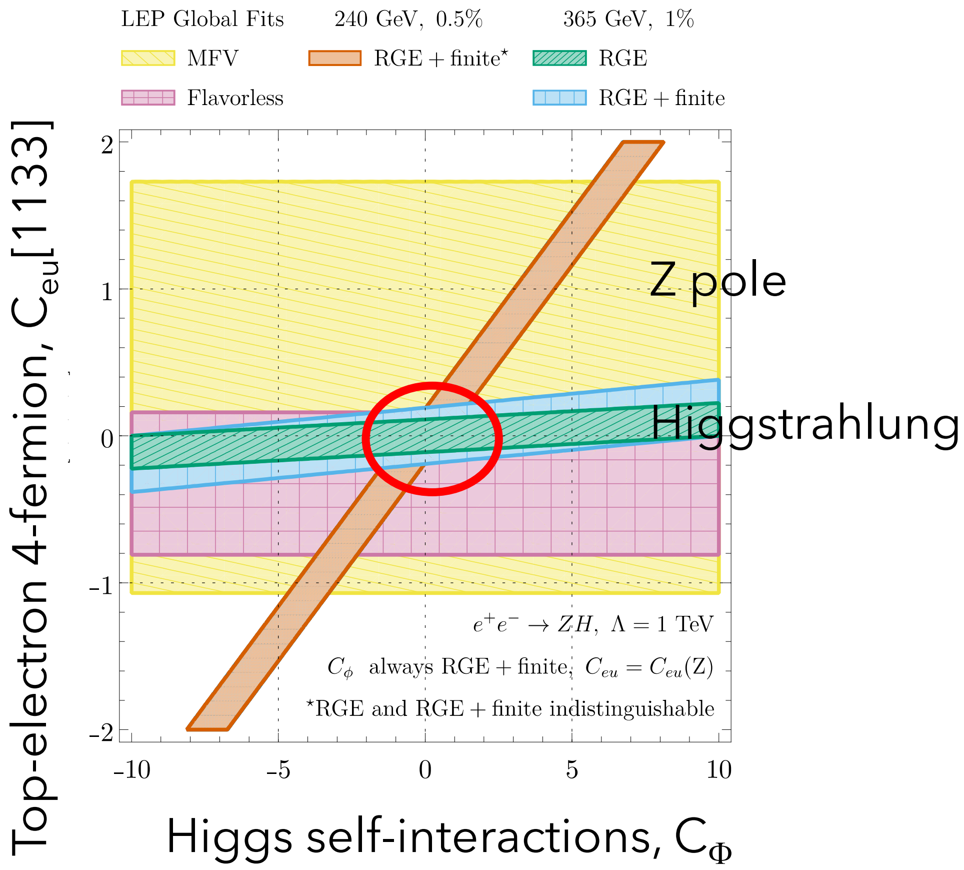
Drell Yan sensitive to ZWW vertex

$e^+e^- \rightarrow ZH$ is window to many new interactions





- Effects of different operators is correlated
- Power of measurement at 2 different energies



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CP violation at future e^+e^- colliders

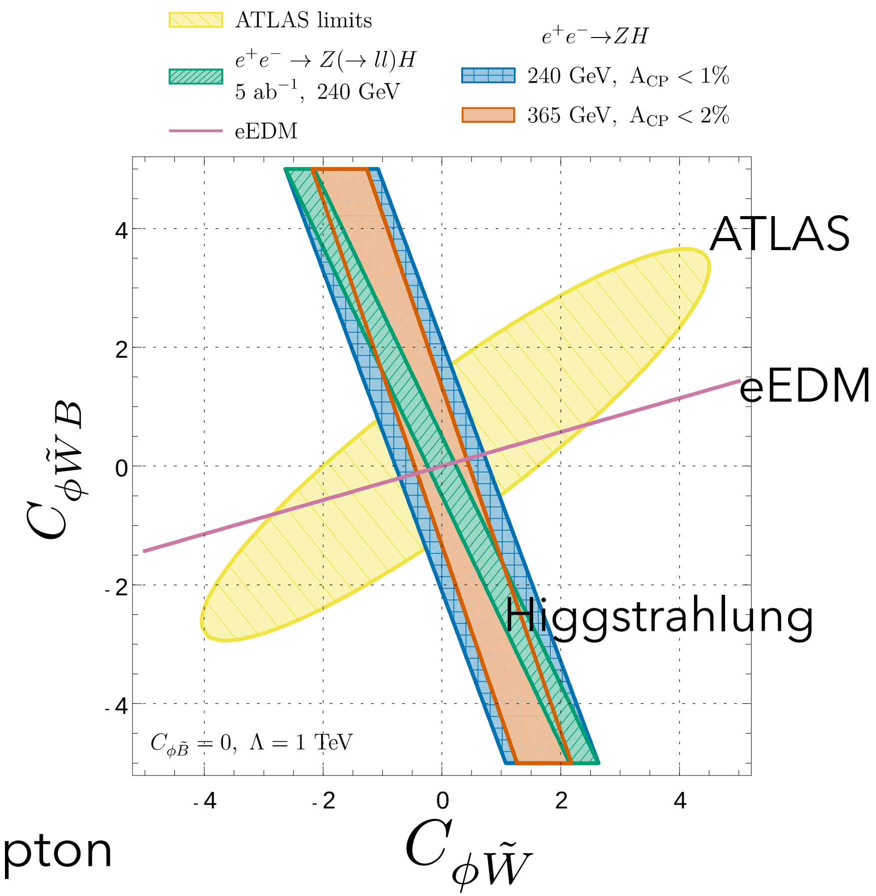
- Define CP violating asymmetry

$$A_{CP} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

- CP violation in the gauge sector is strongly limited by eEDMs
  - eEDM depends on SMEFT coefficients

$$d_e = \sqrt{2} v Im\left\{\sin\theta_W \frac{C_{eW}}{\Lambda^2} - \cos\theta_W \frac{C_{eB}}{\Lambda^2}\right\}$$

  - RGE evolution generates $C_{\phi\tilde{W}B}, C_{\phi\tilde{W}}, C_{\phi\tilde{B}}$
- Limits from angular observables at LHC from H⟶ 4 lepton



eEDM, LHC, e^+e^- probes of CP violation are complementary

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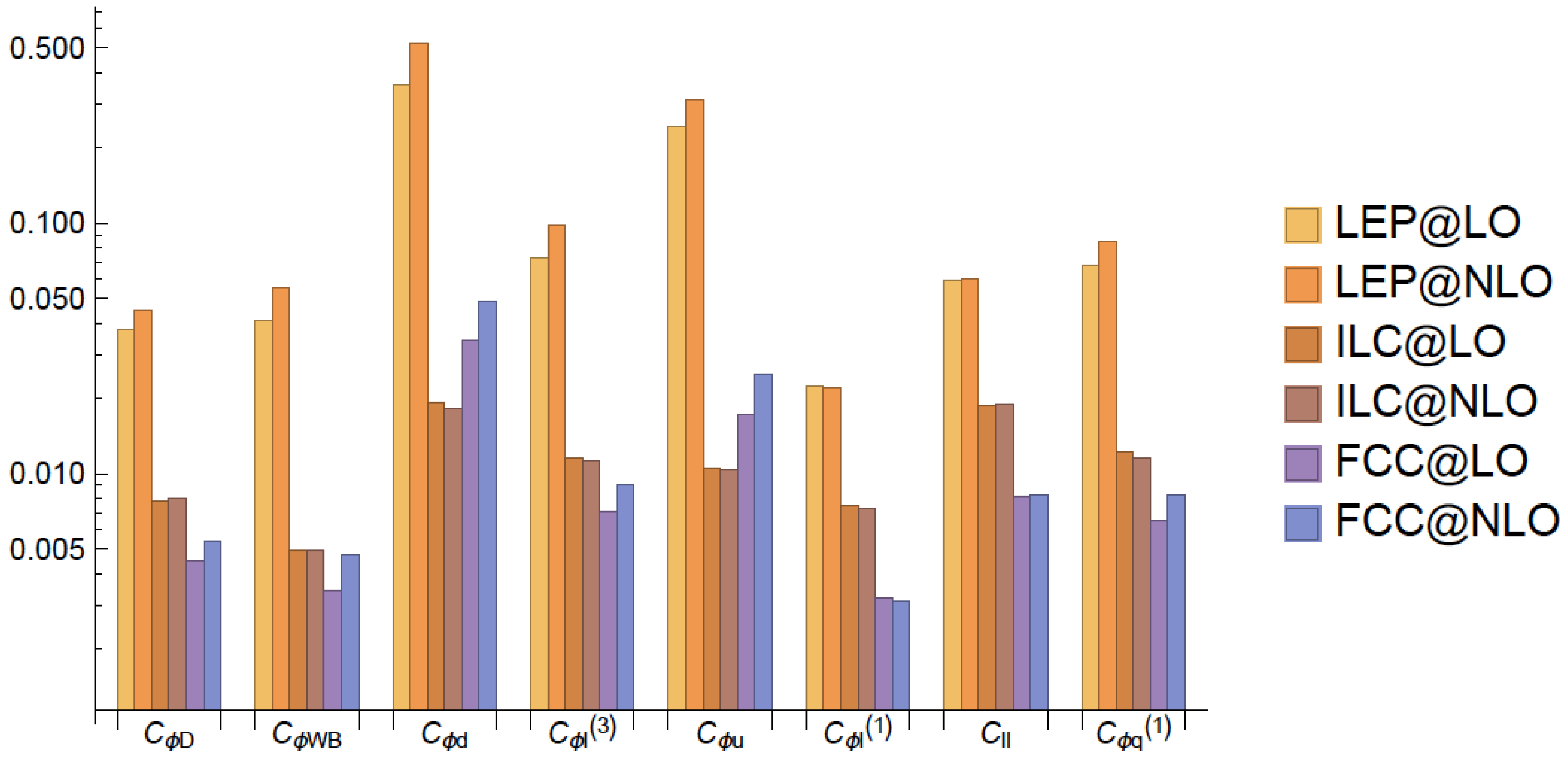
Future colloders need NLO SMEFT



NLO corrections

- Loop corrections include logarithms which can be found from renormalization group running (RGEs) and constant pieces

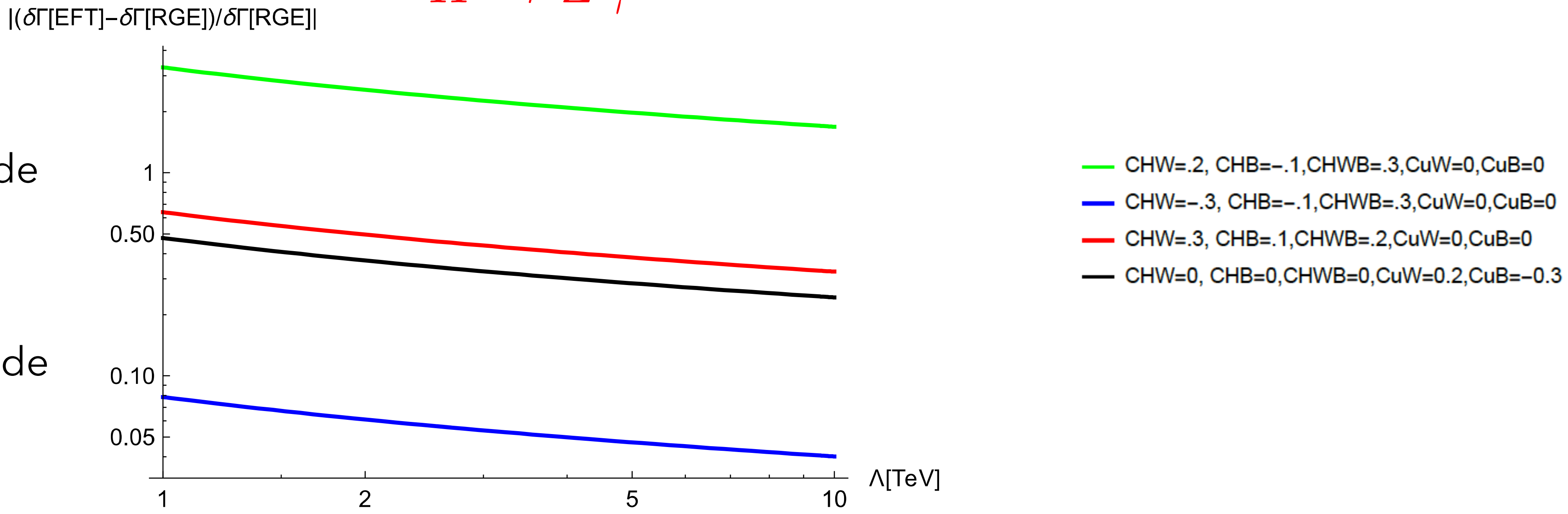
$$\sigma \sim (\ldots) \log\left(\frac{M_Z^2}{\Lambda^2}\right) + (\ldots)$$

- RGEs known at 1 loop for dimension-6 operators
  - Partial dimension-8 results exist
- NLO QCD SMEFT corrections automated
- NLO EW SMEFT corrections not automated and must be done on ***case by case*** basis

NLO Electroweak SMEFT: constants matter

- Example: $H \to Z\gamma$
  - $\Lambda \sim$ 1 TeV, constants can give large effects (very dependent on specific values of coefficients)

$$H \to Z\gamma$$



$\delta\Gamma$[EFT]=Include loop constant +RGE

$\delta\Gamma$[RGE]=Include only RGE

* Similar conclusions for $H \to \gamma\gamma$

Recap

- NLO corrections open window to new interactions
- Logarithms from RGEs may not tell the whole story

What does it mean?

- I don't particularly care about the numerical value of some coefficient
- But… an unambiguously non-zero value of a Wilson coefficient is a clear sign of new physics.
- Power of EFTs is that coefficients can be matched to high scale models of underlying UV physics

Different BSM models will have different (calculable) patterns of coefficients

Patterns

- Only a small number of operators generated in specific models
- Coefficients can be computed in terms of BSM inputs

	Singlet$_{\not Z_2}$	Singlet$_{Z_2}$	2HDM	T VLQ	(TB) VLQ	s
C_H						
$C_{H\Box}$						
C_{bH}						
C_{tH}						
$C_{\tau H}$						
$C^1_{Hq}[tt]$						
$C^3_{Hq}[tt]$						
C_{Hb}						
C_{Ht}						
C_{Htb}						
C_{Hg}						

The Inverse Problem?

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

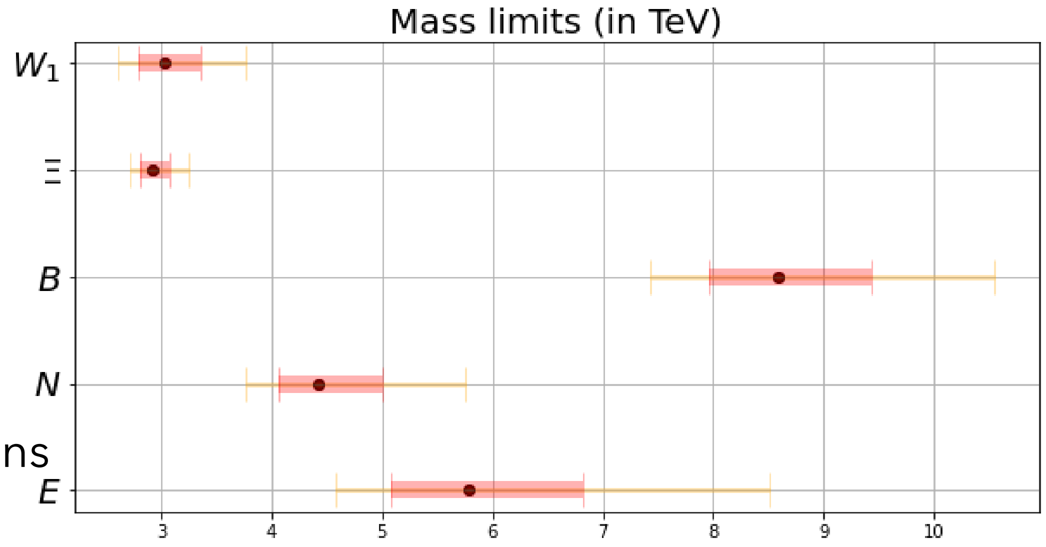
Global fit with C=1

SU(2) triplet gauge boson

SU(2) triplet scalar, Y=0

Neutral gauge boson

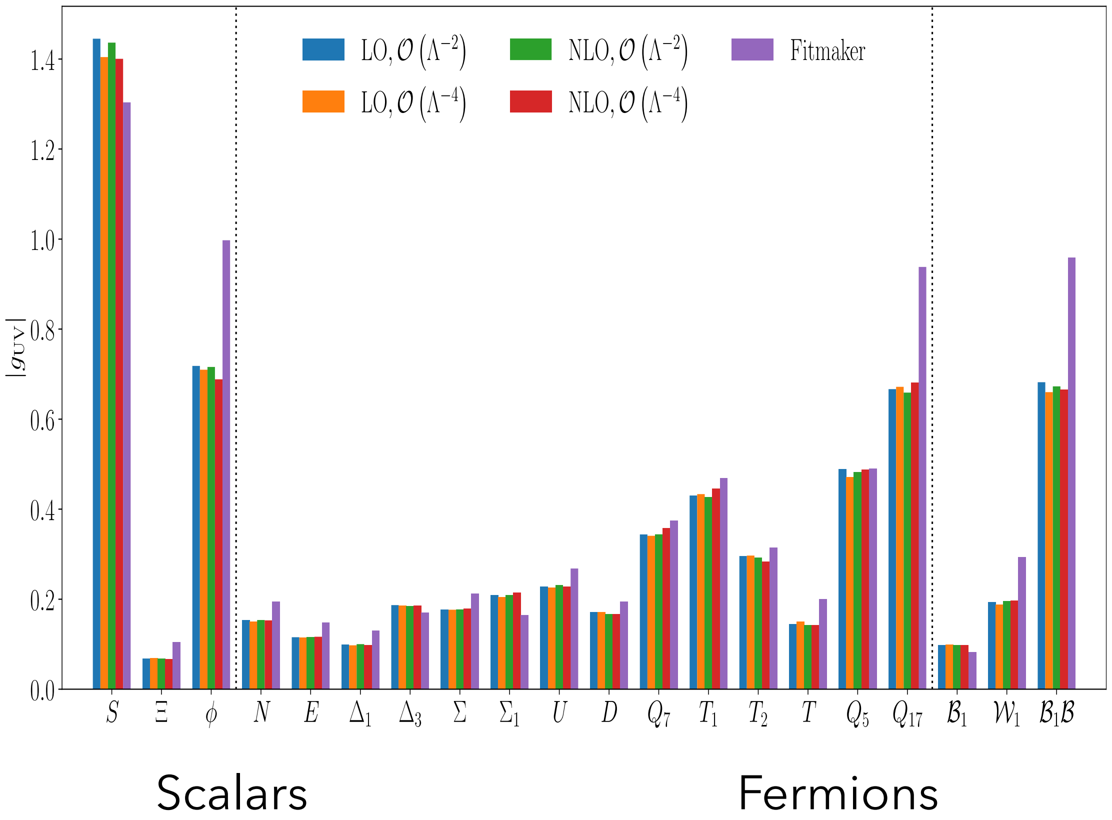
Charge 0 and charge 1 fermions



2204.05260

Even better

- Can probe simple models with 1-loop matching at high scale
- Assume Λ=1 TeV and vary coupling
- NLO is one-loop matching, with automated coded MATCH2FIT
- For most models, loop matching effects are small
- Limits from EWPOs and LHC data



2309.04523

Coefficients have scale

- SMEFT coefficients defined at high scale, Λ
- Measurements at weak scale
- Running is solved problem

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

- Running of UV scale coefficients of poorly constrained operators may generate operators that are tightly limited at weak scale.
- Ex: matching to scalar singlet model generates $C_{H\Box}, C_H$

$$C_{H\Box}(M_W) = C_{H\Box}(\Lambda) + \frac{10e^2}{3c_W^2}C_{HD}\log\left(\frac{M_W^2}{\Lambda^2}\right)$$

$C_{HD} \sim \Delta T$ highly constrained

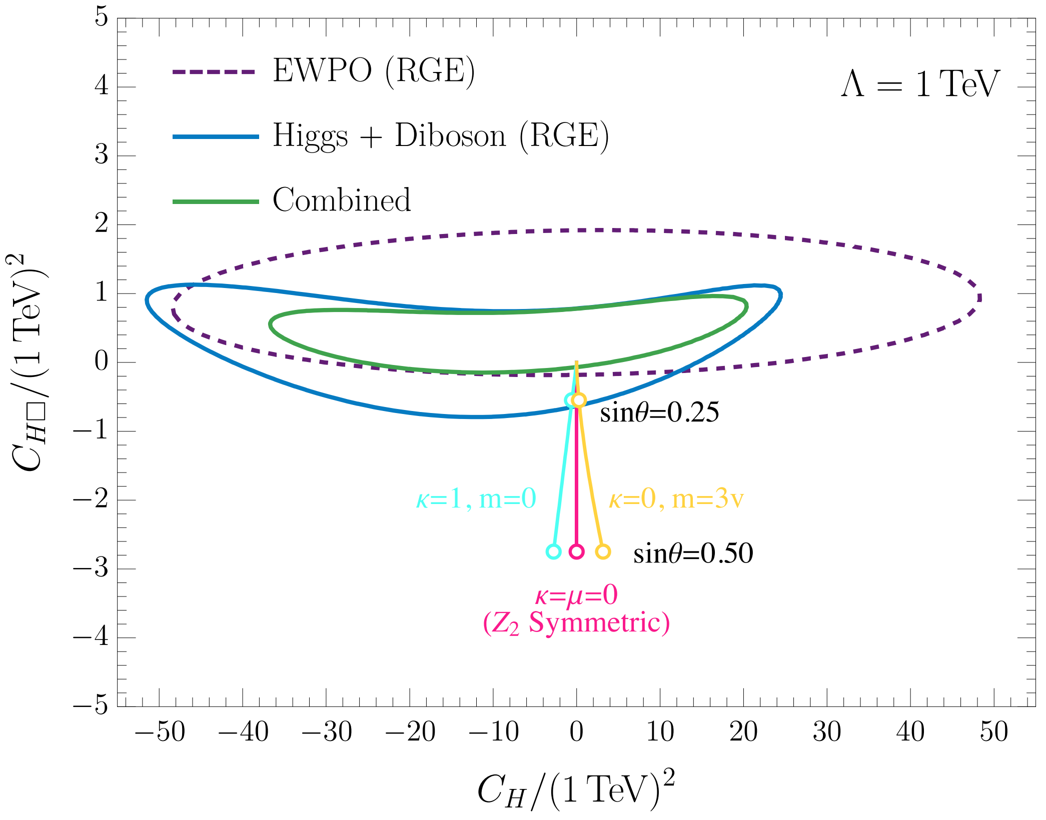
Running gives new effects

1312.2014, 1310.4838, 1309.0819

Coefficients have scale

- Match SMEFT to model at high scale
- RGE evolve coefficients to M_Z to extract limits
- Singlet model corresponds to point in parameter space

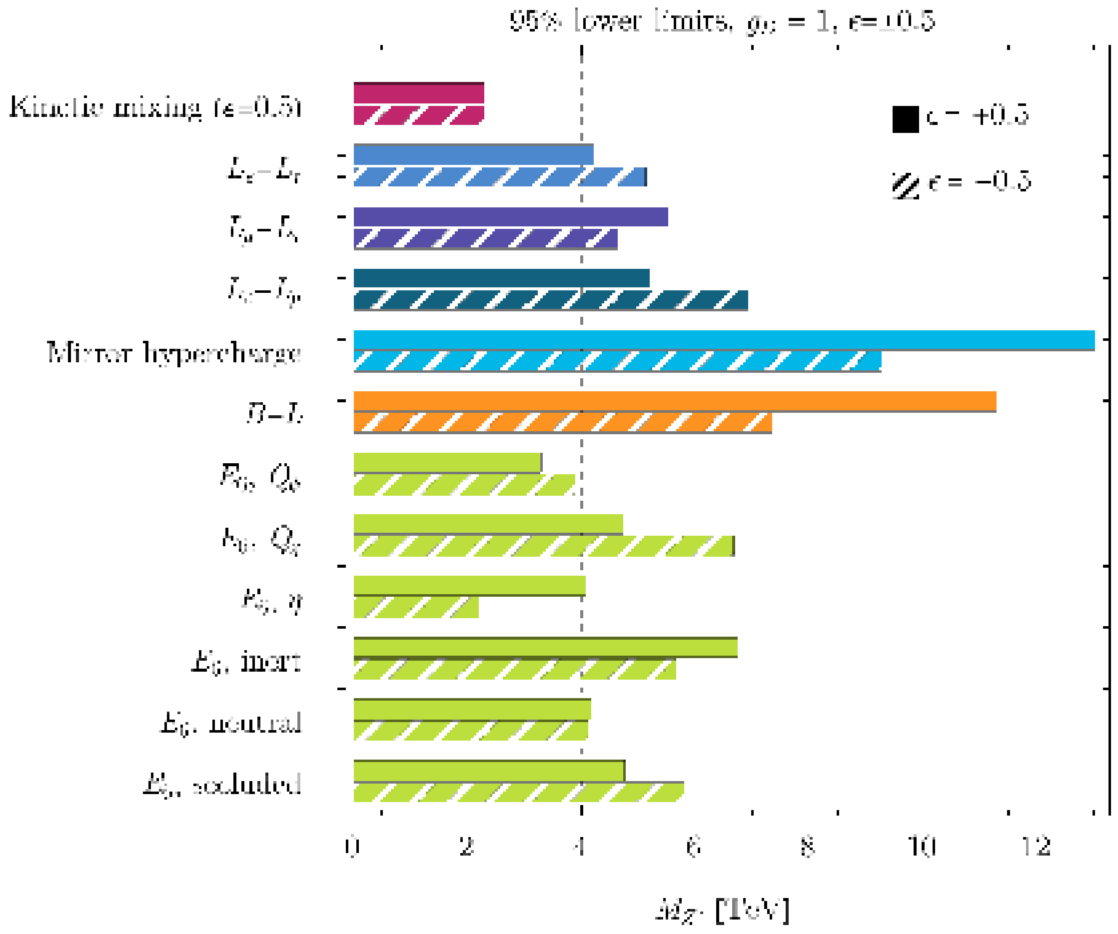
Global fit to Scalar singlet model



2007.01296

Look for heavy Z′s

- Many types of Z′s: Interpretations model dependent
- Can match predictions to dimension-8 operators (ie include C/Λ^4 operators)
- Generate (many) 2- and 4-fermion operators
- Calculate coefficients in terms of model parameters
- In this example, the dimension-8 operators give a very small contribution



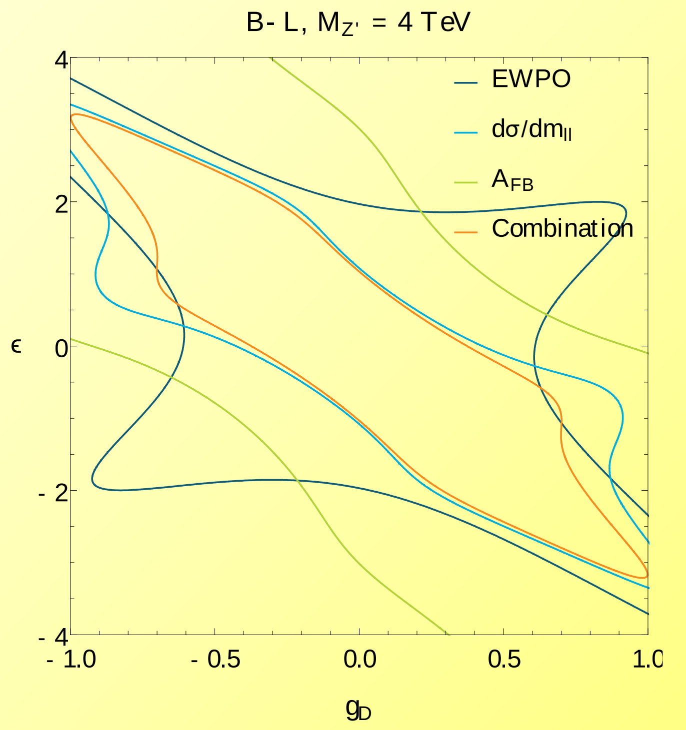
2404.01375

Information from many places

- Primarily from LHC and Z pole measurements
- At LHC, info from Drell-Yan FB asymmetries and from $d\sigma/dm_{ll}$ measurements
- Measurements complementary

Current information

Kinetic mixing



Gauge coupling

[2404.01375](https://arxiv.org/abs/2404.01375), [2303.08257](https://arxiv.org/abs/2303.08257)

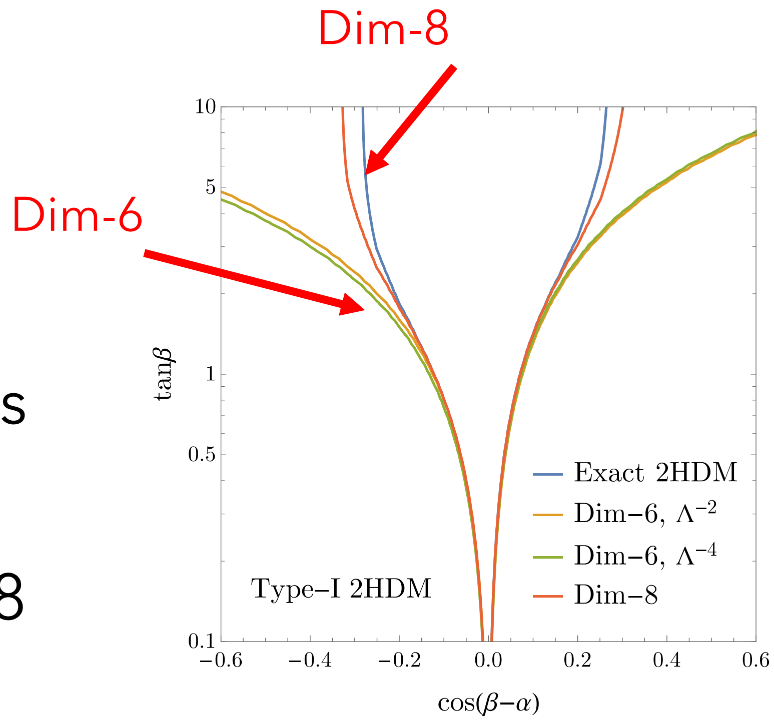
2HDM more interesting

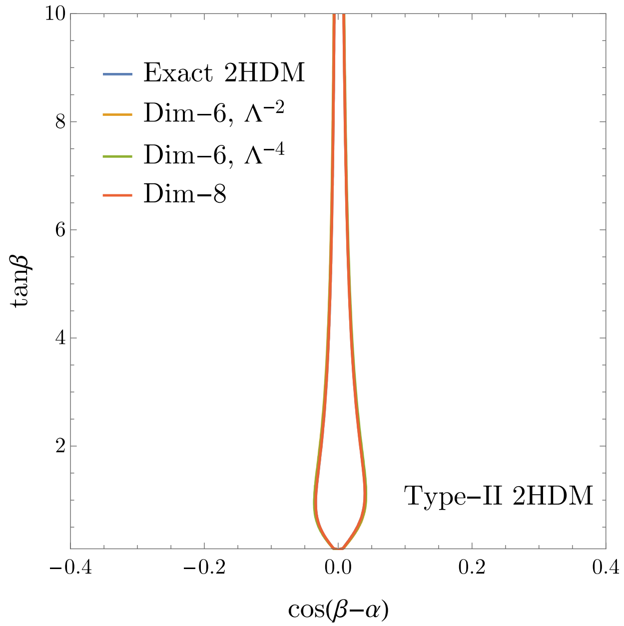
- Model has 2 Higgs doublets with vevs, v_1 and v_2, $\tan\beta = v_2/v_1$
- 5 physical Higgs bosons: h, H (neutral), A (pseudoscalar), $H^{\pm}$
- Diagonalize neutral Higgs mass matrix with angle α
- Take M_H, M_A, M_{H+} $\rightarrow\infty$
- In this limit $\cos(\alpha-\beta) \sim v^2/M^2$
- So: dimension-6 coefficients are proportional to $\cos(\beta-\alpha)$
- Gauge couplings are dimension 8 since they are proportional to $\sin(\beta-\alpha)$

Example of model where you need to go to dimension-8 to capture the physics

2HDM

- Global fit to Higgs data
- Include dim-6 squared terms [O(1/Λ^4)] and dim-8 O(1/Λ^4) matched to 2HDM
- Dim-6 fails to capture the physics of the 2HDM, type I model
- HVV couplings first arise at dim-8 in 2HDM





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What if it's not SMEFT?

- What if Higgs is not part of an SU(2) doublet? $\rightarrow$ HEFT (Higgs Effective Field Theory)
- Expansion is different from SMEFT

$$V(h) = \frac{1}{2} m_h^2 h^2 \left(1 + \kappa_3 \frac{h}{v} + \frac{\kappa_4}{4} \frac{h^2}{v^2} + \ldots\right)$$

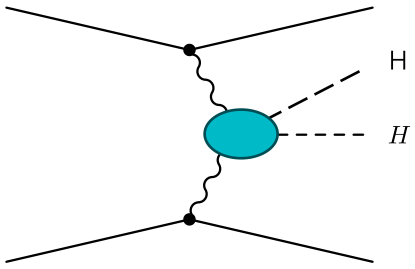
h is physical Higgs

- SM: $\kappa_3 = \kappa_4 = 1$
- Suggests that hh→hh, WW→hh can distinguish between SMEFT and HEFT

SMEFT can always be written as HEFT

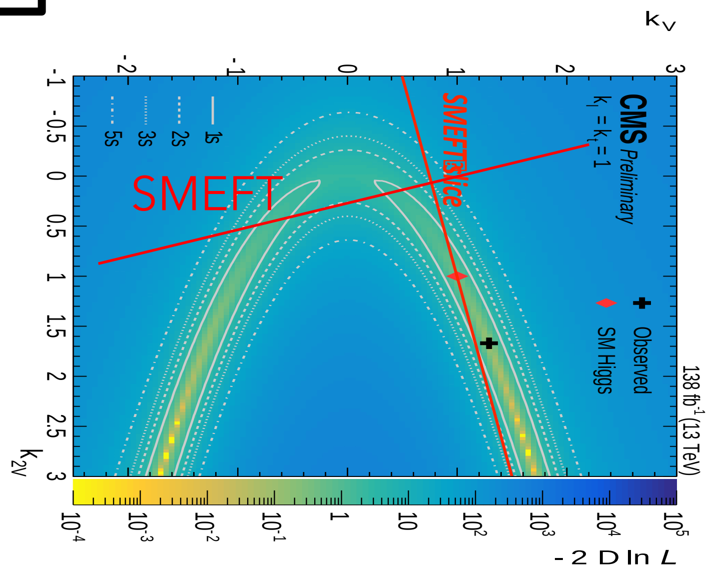
HH production

HH production via VBS can potentially distinguish SMEFT from HEFT



If the theory is SMEFT, results must lie on red line

LHC



2211.09605

Conclusion

- SMEFT approach may be able to extract insights about new physics even if new physics is very heavy
  - It could be the only tool we have
- Experiments have begun to produce SMEFT results combining input from different types of physics
  - Really want these studies to be done consistently by experimentalists
- Most pressing theoretical need is to understand uncertainties