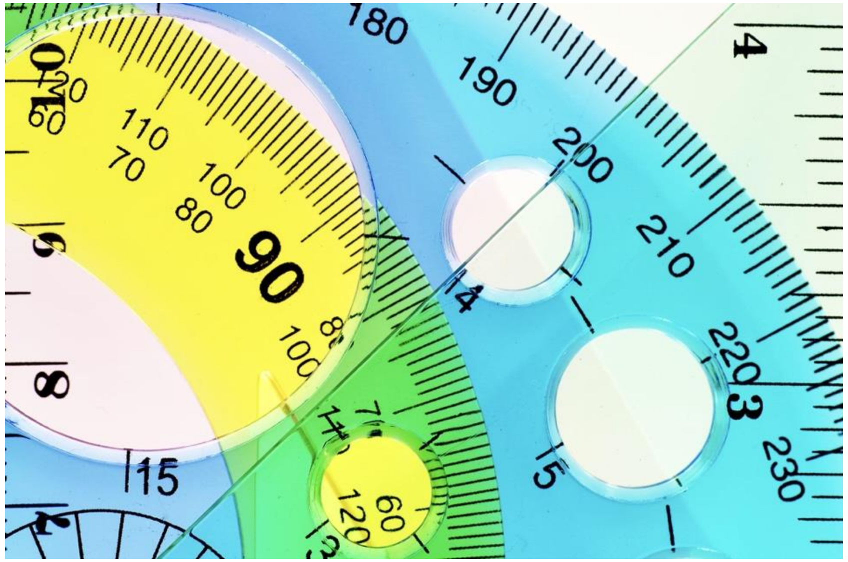


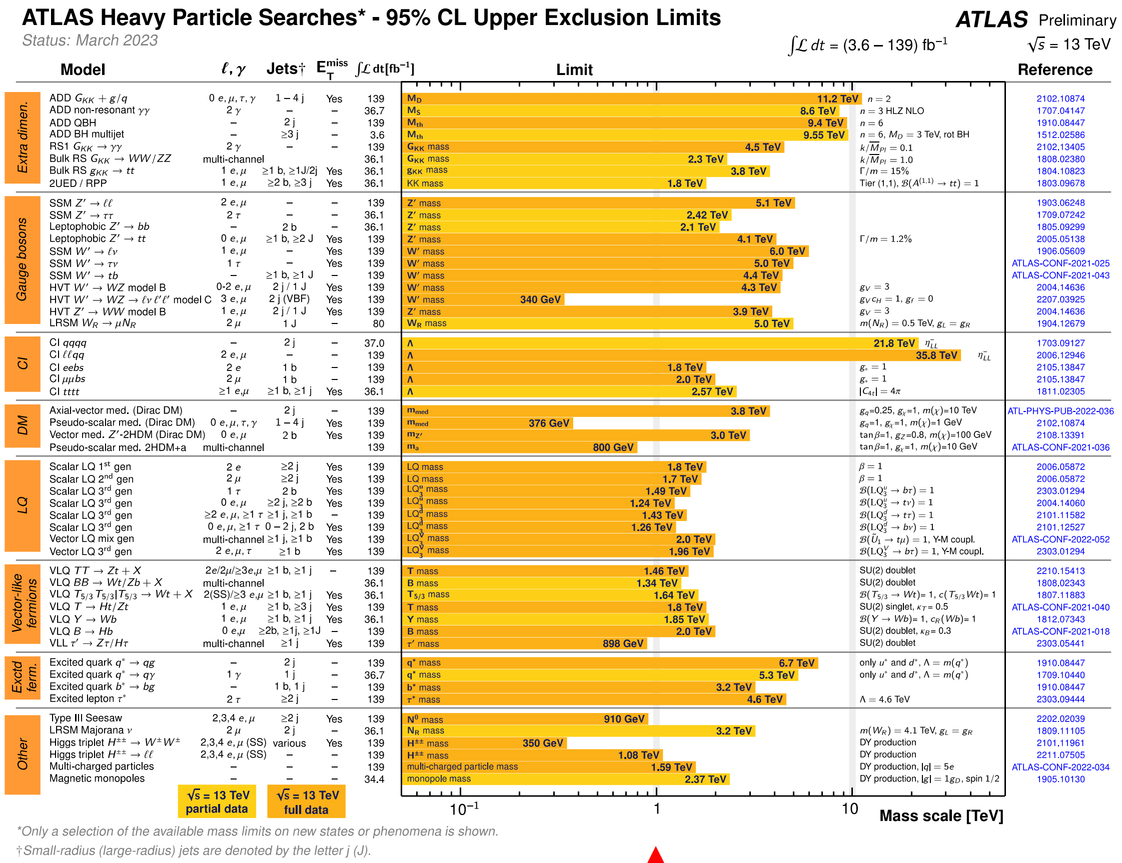
Effective Lagrangians and The Search for New Physics

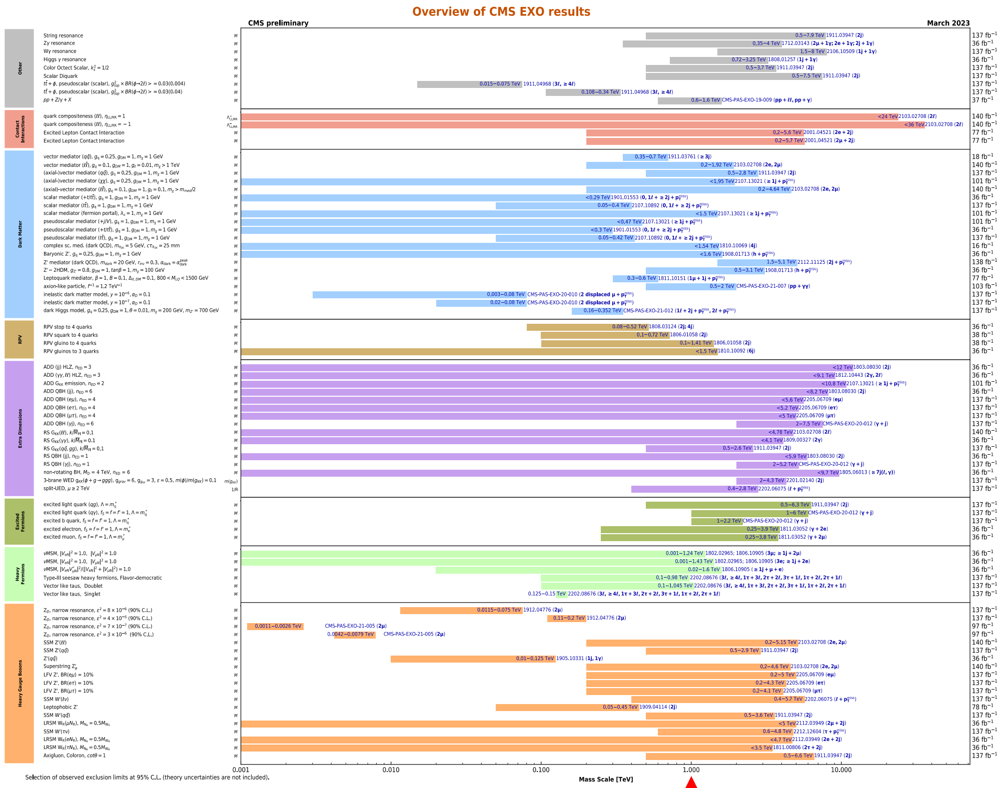
New Opportunities for BSM Searches at the EIC

SBU

S. Dawson, BNL, July 21, 2025

No new particles discovered *(yet?)*

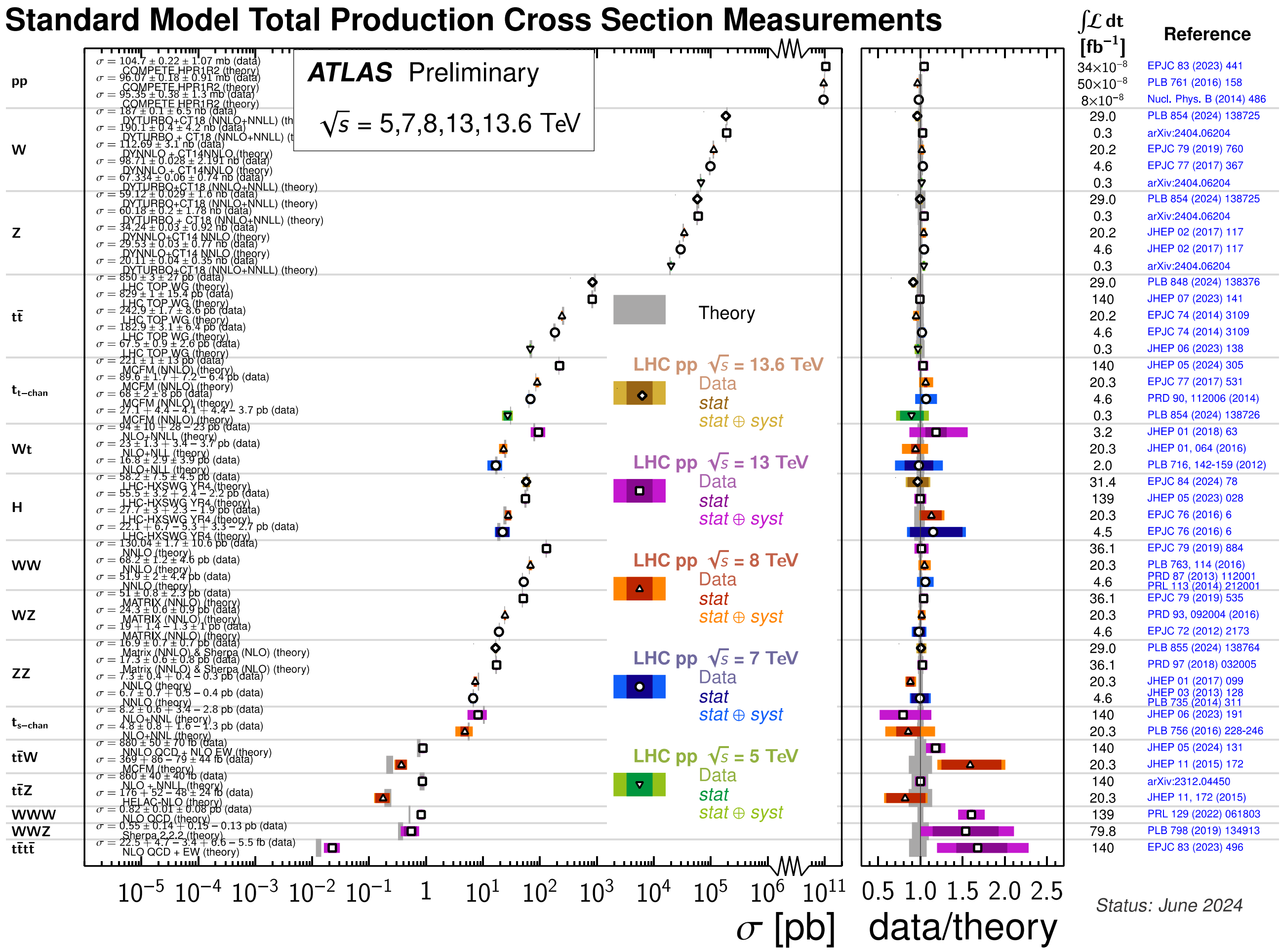




Many limits exceed 1 TeV

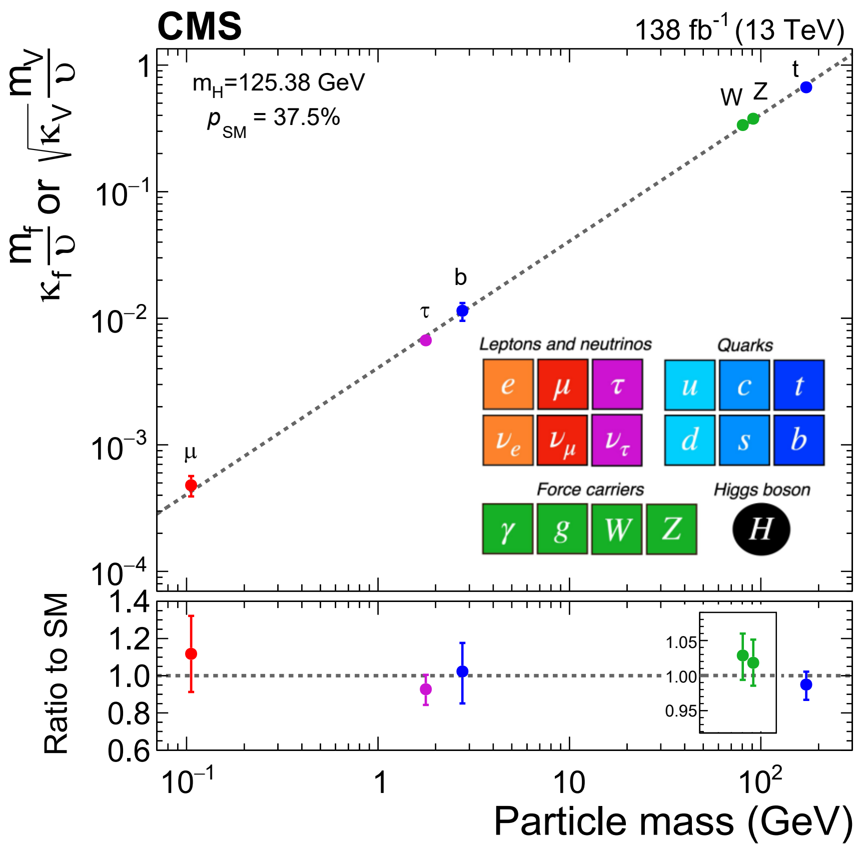
*note holes for light stuff

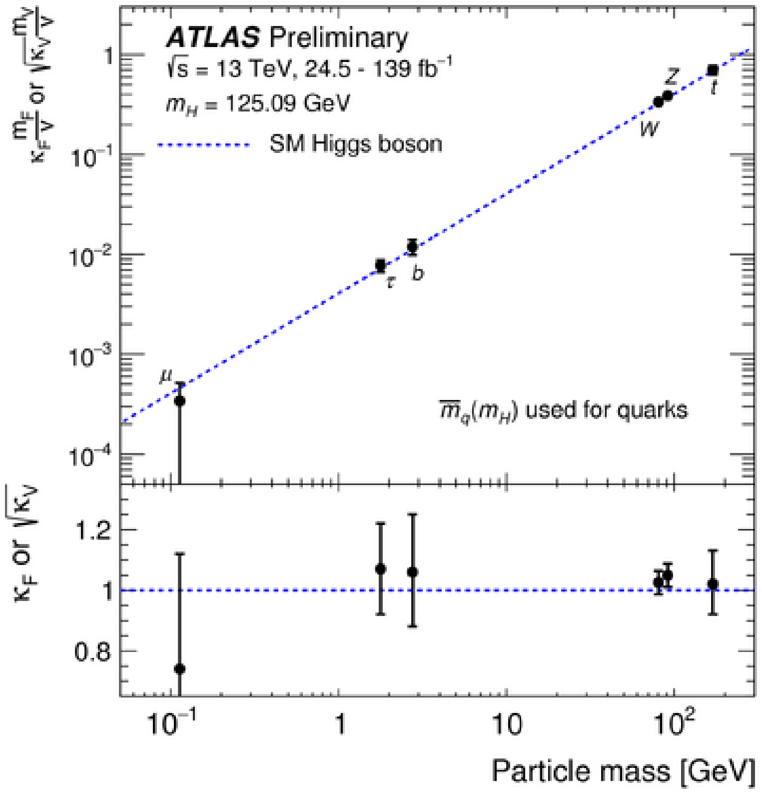
LHC measurements look "SM-like"



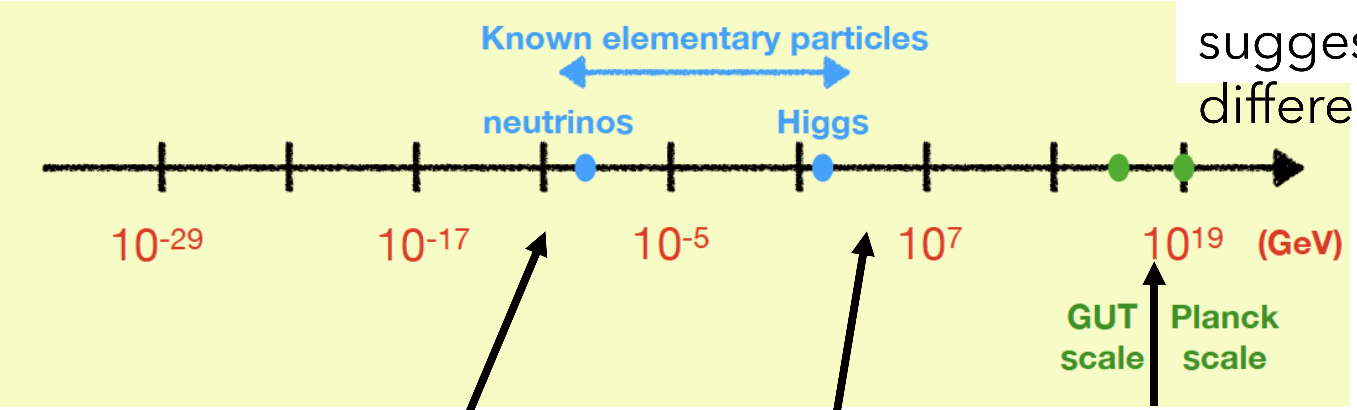
Impressive theory/experiment agreement over many orders of magnitude and in many varied processes

Higgs couplings look “SM-like”





No free parameters in plots



Different questions suggest searching at different scales

Dark matter?

Hierarchy problem?

Neutrino masses?

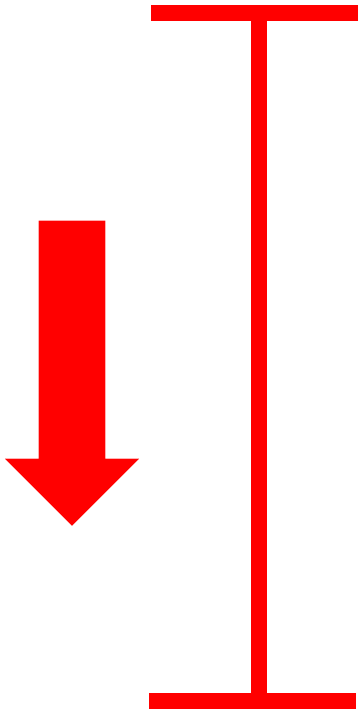
WHERE TO LOOK for new physics?

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

S. Dawson, BNL

Consider 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

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

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

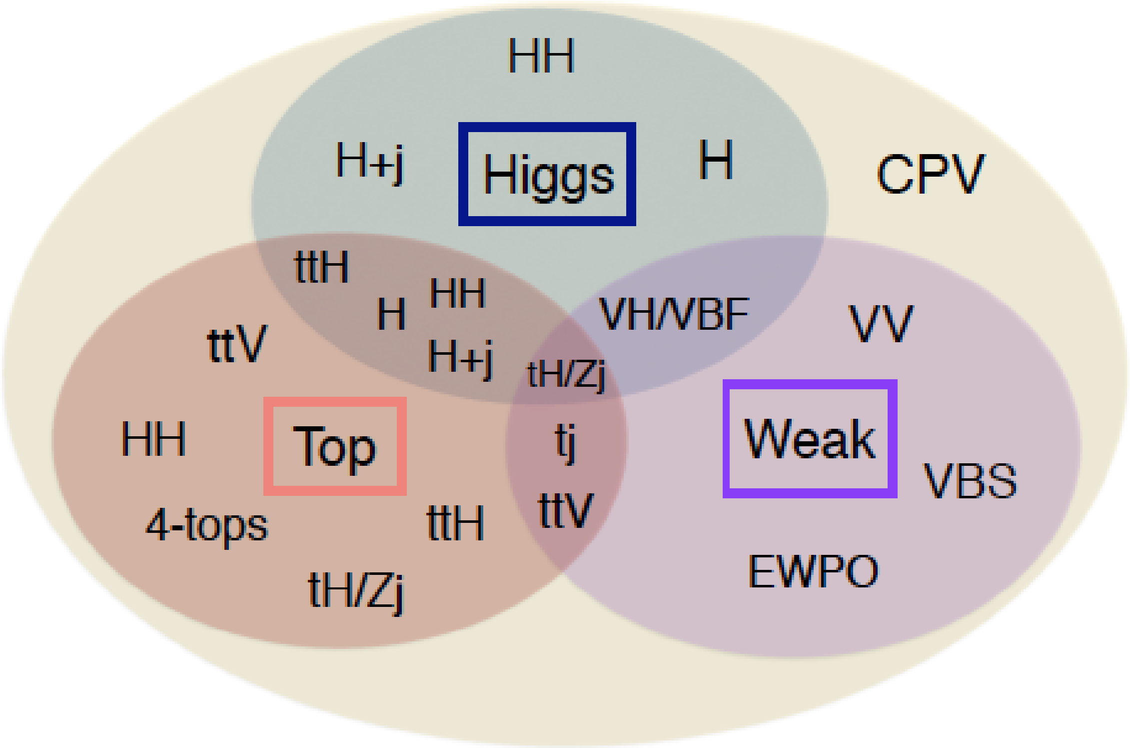
BSM Effects SM Particles

Typically stop at dimension-6

- Many (~2500) possible operators, must choose relevant set (typically ~20-30 in current fits)
- Power of SMEFT is that it connects top, Higgs, EW physics processes

SMEFT limits

- It's all connected
- Plus Drell-Yan, Z-pole, EIC



Adapted from K. Mimasu

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
  - Can calculate loops at each order in $1/\Lambda$
- At this level, SMEFT calculations are model independent
- Measurements interpreted in terms of SMEFT coefficients
- Can compare very different classes of measurements

Learning from SMEFT

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

Precise experimental measurements

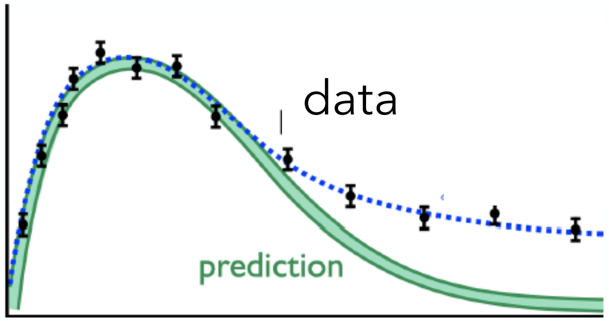
Precise SM calculations

Precise SMEFT calculations

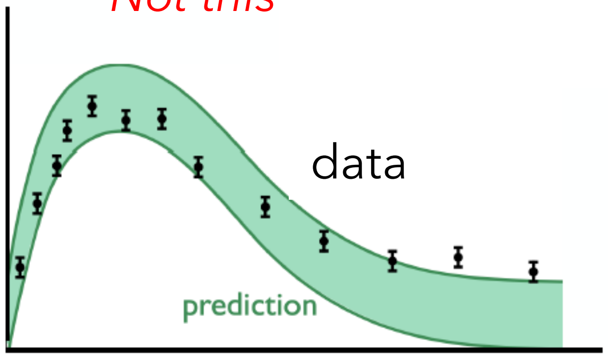
- Understanding uncertainties in SMEFT interpretations of data is a work in progress…. No theoretical consensus

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

Want this



Not this



A tower of EFTs

Heavy physics decouples and leaves interactions with d>4

↓ SMEFT operators and coefficients depend on SM fields and parameters

$$L_{SMEFT} = L_{SM} + \Sigma_{i,d} \frac{C_i^d}{\Lambda^{d-4}} O_i^d$$

↓ LEFT operators and coefficients don't depend on M_W, M_Z, M_t, M_H

$$L_{LEFT} = L_{QED+QCD} + \Sigma_{i,d} \frac{\hat{C}_i^d}{\Lambda^{d-4}} \hat{O}_i^d$$

- Going beyond tree level predictions
- When does it matter?
- When is it essential?

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

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

- 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 $O(v^2/\Lambda^2)$, which means there is some maximum energy for which the expansion 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 $g_{SM} \sim g_{BSM}$

(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 to get an estimate of uncertainties, ie is the expansion converging?

Where do limits come from?

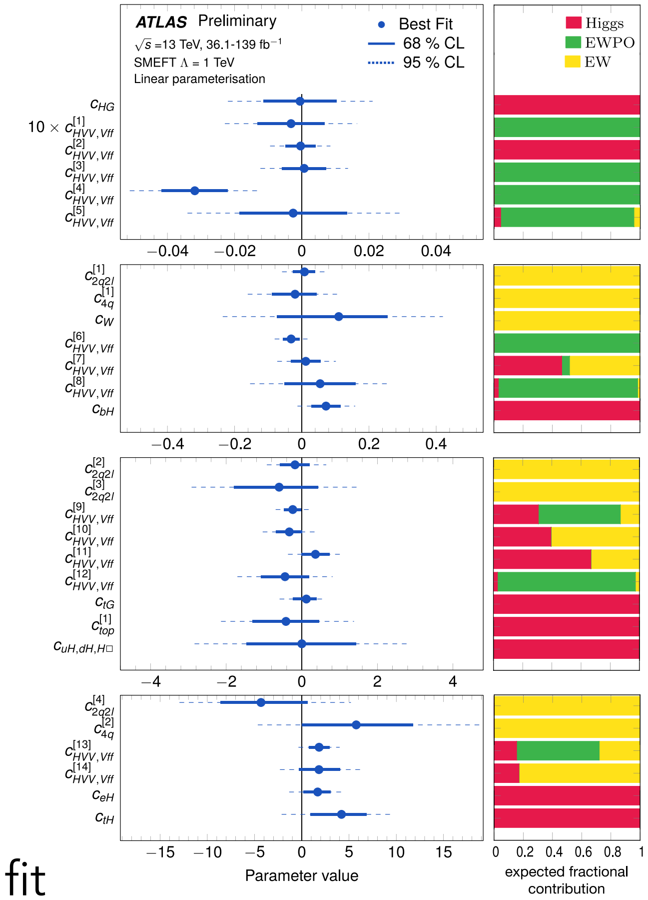
- Electroweak precision observables:

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

- LHC Higgs data
- LHC and LEPII W^+W^- data

Often, multiple measurements contribute to limits

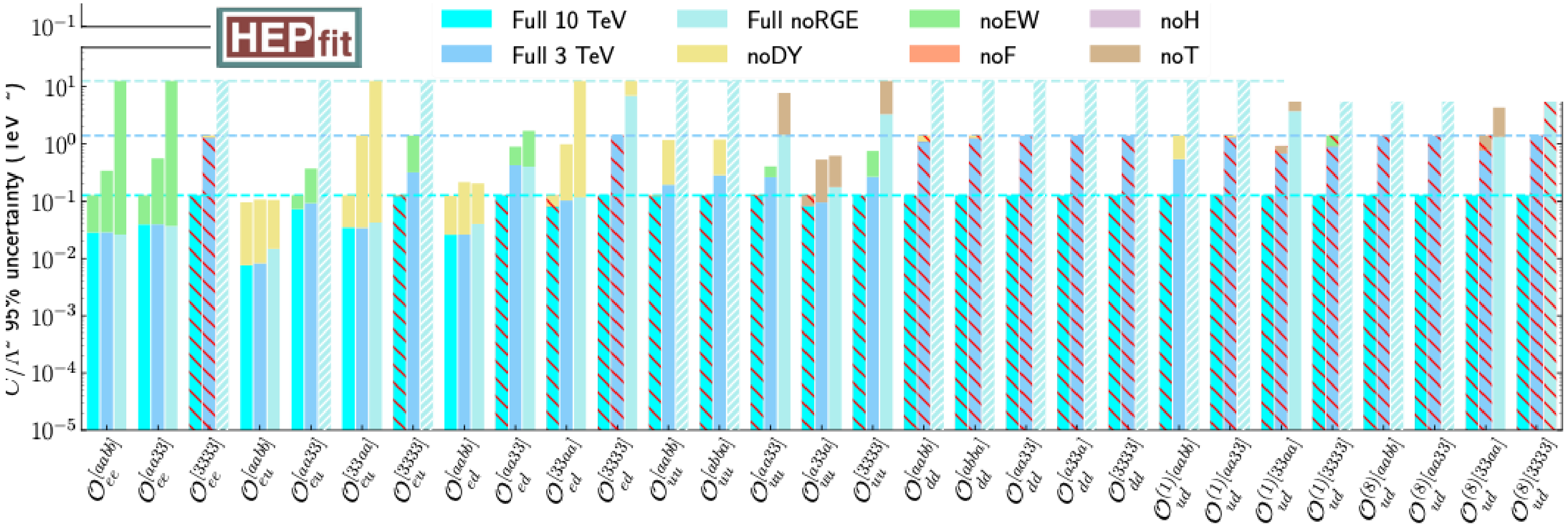
ATLAS fit to Higgs, VV, EWPO data



* Linear fit

Many global fits

- Fits to anomalous interactions (Include Drell-Yan, EWPO, Higgs, top, B)
- Top measurements play an important role in constraining effective 4-fermion operators



2507.06191

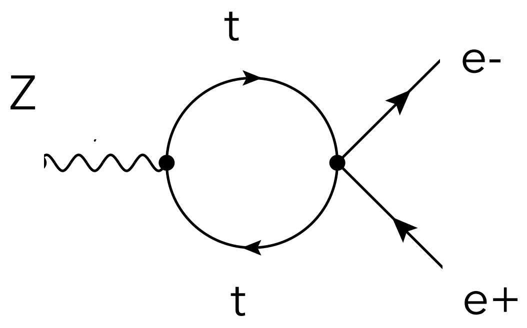
Fit includes NLO QCD, but is tree level electroweak

Go beyond tree level

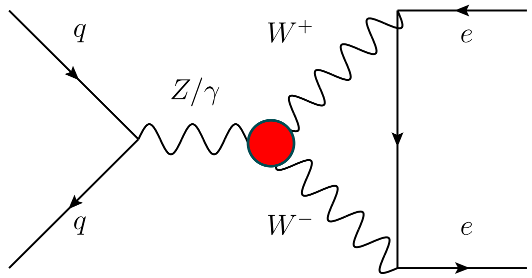
- NLO QCD is automated for dimension-6 SMEFT
- Electroweak NLO SMEFT must be done on a case-by-case basis
  - NLO EW has complicated momentum structures, lots of γ_5's
- NLO EW corrections typically introduce a dependence on many new operators
  - Typically, LO limits are weakened at NLO
- Program of systematically computing relevant processes at NLO EW in SMEFT
- Start with Z pole physics, then do Drell Yan, Higgstrahlung, Higgs decays, DIS…
- Goal is a global fit that is accurate to NLO EW

The power of loops

- SMEFT is consistent field theory: renormalizable at each order in $1/\Lambda^2$
- Can calculate to NLO (one loop) using standard techniques to improve predictions
- Many interesting effects: typically gain sensitivity to new interactions at loop level
- Tree level predictions are often misleading



eett vertex poorly constrained



Drell Yan sensitive to ZWW vertex

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 completely known at 1 loop for dimension-6 operators
  - Partial dimension-8 results exist
- Are logs a good approximation to complete results? [They are easy to get and implement in codes]
  - *A priori* this is not known
- Compute in a hybrid scheme: M_W, M_Z on-shell, Coefficients in $\overline{\mathrm{MS}}$

W and Z pole observables

- Fit to 24 data points–inputs are G_μ, M_Z, α

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

- Tree level expressions depend on (in Warsaw basis)

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

- Tree level observables depend on 8 combinations of operators parameterized as:

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

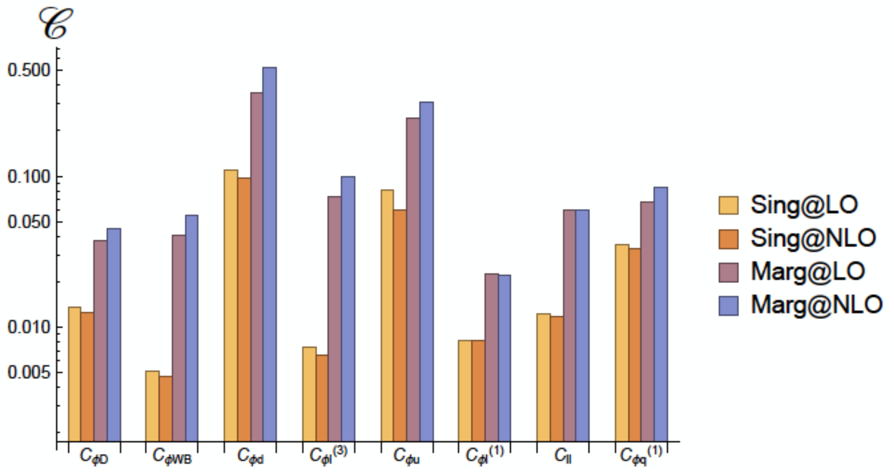
⇒ 2 blind directions (resolved by other measurements)

Fits are straightforward

- Compute observables in SMEFT including all NLO QCD and EW contributions:

$$O_i = O_{i,SM} + \delta O_{i,SMEFT}$$

- Use most accurate SM theory
- Do χ^2 fit to data
- Operators contributing to EWPOs at tree level strongly restricted
- At NLO, many new operators contribute



NLO results for Z-pole are public—have been widely used by SMEFT global fitters

Coefficients constrained at tree level

* This is log plot, NLO effects significant

Dawson, Giardino 2201.09887

Large effects at NLO

Fit to EPWO using LEP; NLO operators are put to 0

$\Lambda = 1$ TeV

Single parameter fits at 95% CL

Coefficient	LO	NLO
$\mathcal{C}_{ll}$	$[-0.0039, 0.021]$	$[-0.0044, 0.019]$
$\mathcal{C}_{\phi WB}$	$[-0.0088, 0.0013]$	$[-0.0079, 0.0016]$
$\mathcal{C}_{\phi u}$	$[-0.072, 0.091]$	$[-0.035, 0.084]$
$\mathcal{C}_{\phi q}^{(3)}$	$[-0.011, 0.014]$	$[-0.010, 0.014]$
$\mathcal{C}_{\phi q}^{(1)}$	$[-0.027, 0.043]$	$[-0.031, 0.036]$
$\mathcal{C}_{\phi l}^{(3)}$	$[-0.012, 0.0029]$	$[-0.010, 0.0028]$
$\mathcal{C}_{\phi l}^{(1)}$	$[-0.0043, 0.012]$	$[-0.0047, 0.012]$
$\mathcal{C}_{\phi e}$	$[-0.013, 0.0094]$	$[-0.013, 0.0080]$
$\mathcal{C}_{\phi D}$	$[-0.025, 0.0019]$	$[-0.023, 0.0023]$
$\mathcal{C}_{\phi d}$	$[-0.16, 0.060]$	$[-0.13, 0.063]$

Marginalized fits at 95% CL

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

Include Flavor Structure

- Consider CKM diagonal, which implies specific flavor structures
- In Warsaw basis:
  - 4-fermion operators

$$(\bar{f}_i\gamma^\mu f_j)(\bar{f}_k\gamma_\mu f_l)$$

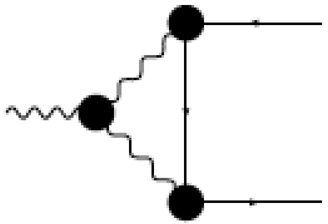
  - 2-fermion operators

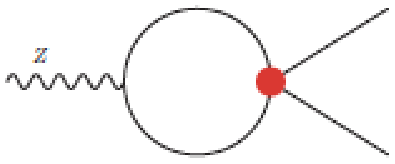
$$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j) \to C_X[ij] = E_X\delta_{ij}$$

  - Bosonic operators

Not all combinations of flavor indices arise in EWPOs

- Most general case: NLO EWPO calculation involves 178 independent coefficients (6 from bosonic, 23 from 2-fermion, 149 from 4-fermion)





Enhancement of diagrams with internal top quarks

* Only 1 insertion of SMEFT operator

What about flavor assumptions?

- Global fits often done assuming flavor universality
- SM has $U(3)^5$ global symmetry that is broken only by Yukawas

$$(q_L)^T = (u_L, d_L),\ (l_L)^T = (\nu_L, e_L),\ u_R,\ d_R,\ e_R$$

- 3rd generation is different
  - Do fits with $U(2)^5$ global symmetry
- MFV assumption assumes top Yukawa is only source breaking $U(3)^5$ symmetry (since we assume all other fermions are massless)
- Do fits assuming new physics only couples to 3rd generation
- Do fits assuming new physics doesn't couple to 3rd generation

Do flavor assumptions make significant differences to SMEFT fits?

Flavor assumptions reduce possibilities

Operators that contribute to EWPO at NLO

Operator	$U(3)^5$	MFV	$U(2)^5$	3^{rd} gen specific	3^{rd} gen phobic	3^{rd} gen phobic + $U(2)^5$	Flavorless
Class A	7	12	16	9	14	7	9
Class B	11	17	27	5	23	11	6
Class C	11	21	44	11	44	11	11
Total	29	50	87	25	81	29	26

2-fermion → Class A

4-fermion with identical representations → Class B

Remaining 4-fermion → Class C

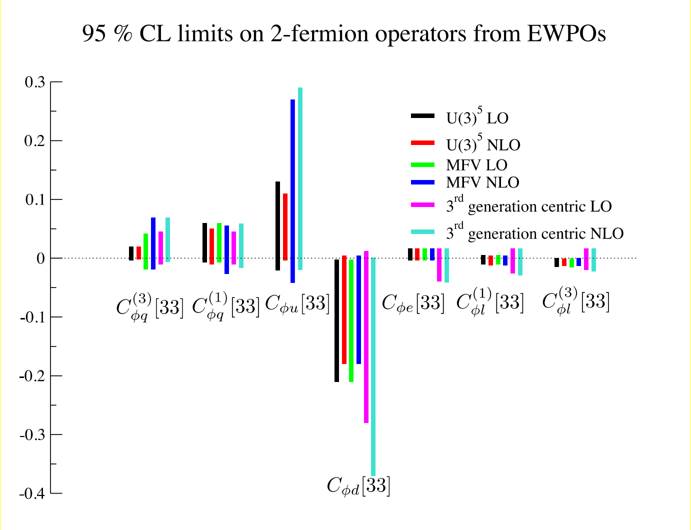
- NLO SMEFT EW fits done with coefficients evaluated at M_Z
- Input parameter dependence? Results use G_F, M_Z, α [Could use G_F, M_Z, M_W]
- After separating out dominant scheme independent contributions, residual scheme dependent contributions similar in commonly used schemes [Biekotter, Pecjak, Scott, Smith, 2305.03763]

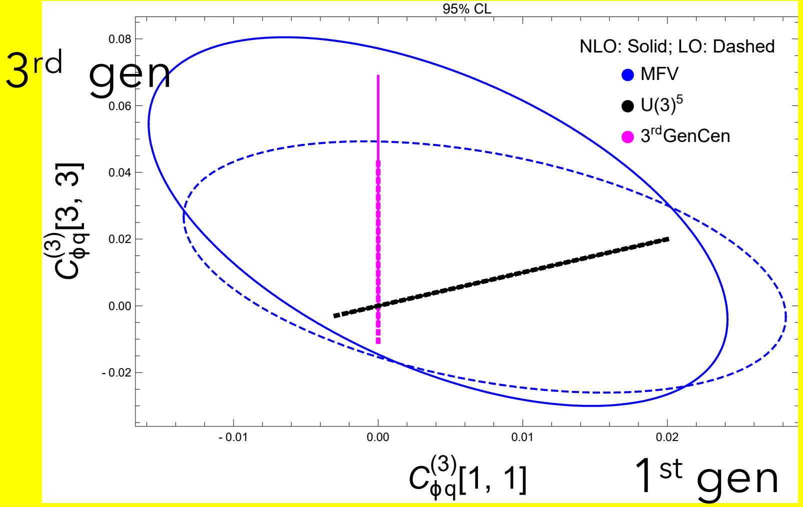
Flavor matters!

- Neglecting flavor gives overly aggressive limits
- Strong correlations in flavor space
- NLO EW can have large effects

Fits to Z pole observables in different flavor scenarios

2-fermion operators





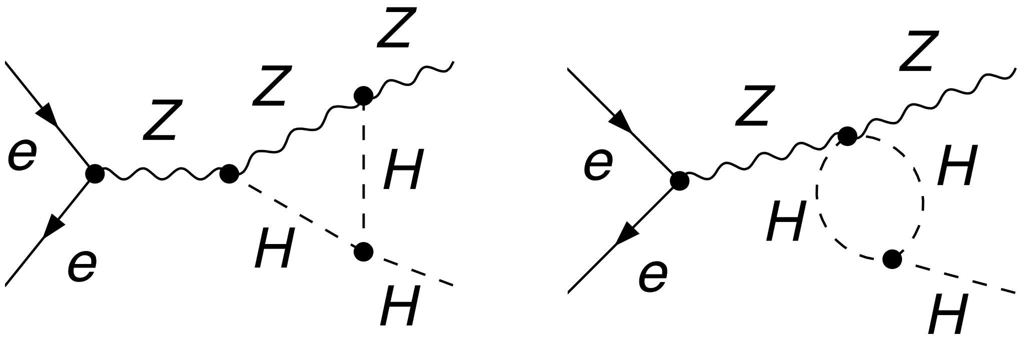
Note difference in NLO/LO shapes in MFV scenario

* Coefficients are related by flavor assumptions

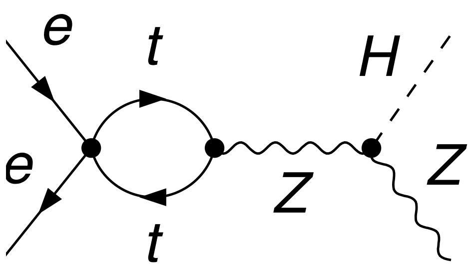
Bellafronte, Dawson, Giardino, 2304.00029

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators
  - (~70 SMEFT operators contribute in ~ 35 combinations)
- Sensitive to poorly constrained interactions that first arise at NLO



Higgs tri-linear coupling, C_ϕ



+ many more

4-fermion operators, $C_{eu}[1133]$

* Complete results at
https://gitlab.com/smeft/eehz

Note complementarity with Z-pole results:
2304.00029 , 2201.09887 , 2412.14241

Higgstrahlung

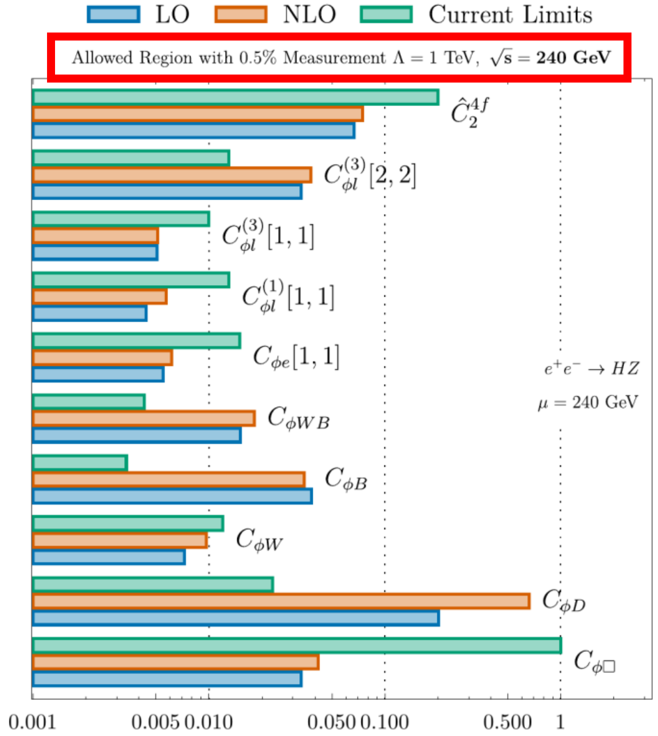
- Combine virtual diagrams with real photon emission
- IR poles from real photons controlled using EW dipole subtraction (Just like dipole subtraction in QCD)
- Pure QED corrections are large (and negative)

$$\sigma_{\rm NLO} = \sigma^{W}_{\rm SM,NLO}\left(1 + \delta_{SM,QED} + \frac{1}{\Lambda^2}\sum_i \mathscr{C}_i(\mu)\left\{\Delta^{\rm (NLO)}_{i,\rm weak} + \bar{\Delta}_i \log\frac{\mu^2}{s} + \Delta_{i,\rm QED}\right\}\right)$$

SMEFT Operators Present at LO

- Consider future measurements at:
  - $\sqrt{s}$=240 GeV with a precision of 0.5% on total rate
  - $\sqrt{s}$=365 and 500 GeV with a precision of 1%
- Single parameter bounds in general slightly weakened at NLO
- For most operators, FCC-ee significantly improves bounds

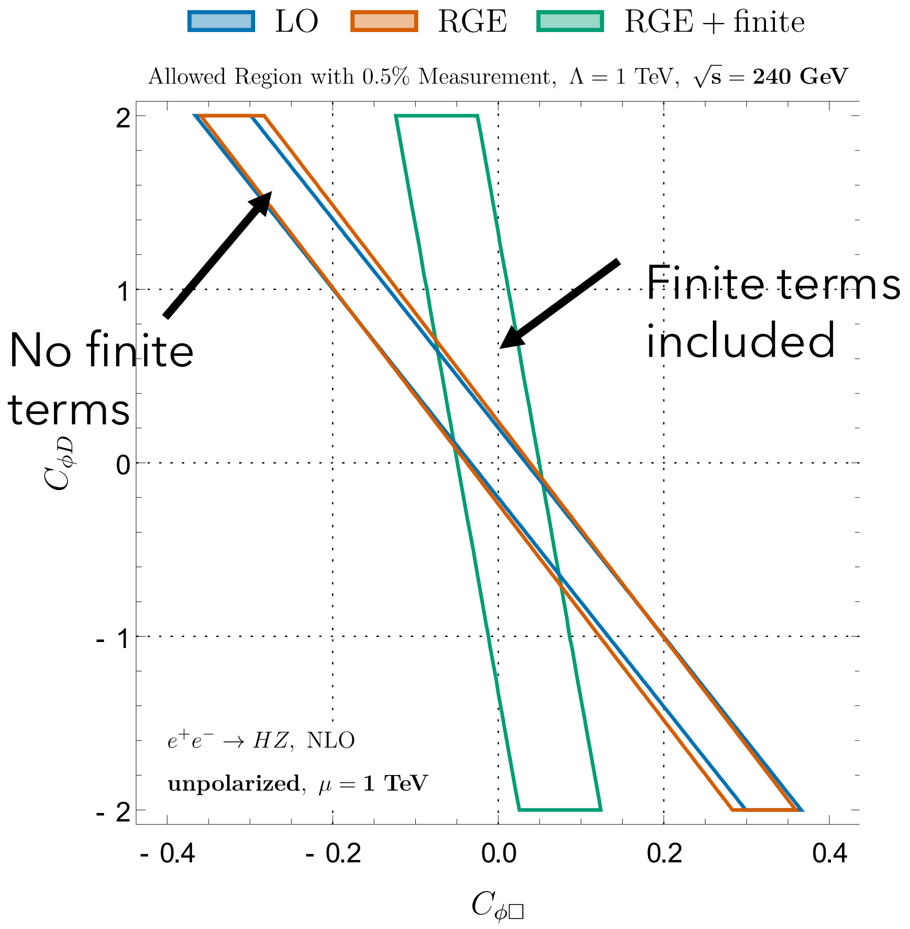
Single Parameter Fits



Global single parameter fit limits from 2012.02779

Finite Contributions Matter

- Logarithmic contributions can be found from renormalization group evolution (RGE)
- Finite contributions require complete NLO calculation
- Finite pieces sometimes larger than logarithms
- *A priori*, we don't know if finite pieces or logs will dominate



Sensitivity at FCC-ee

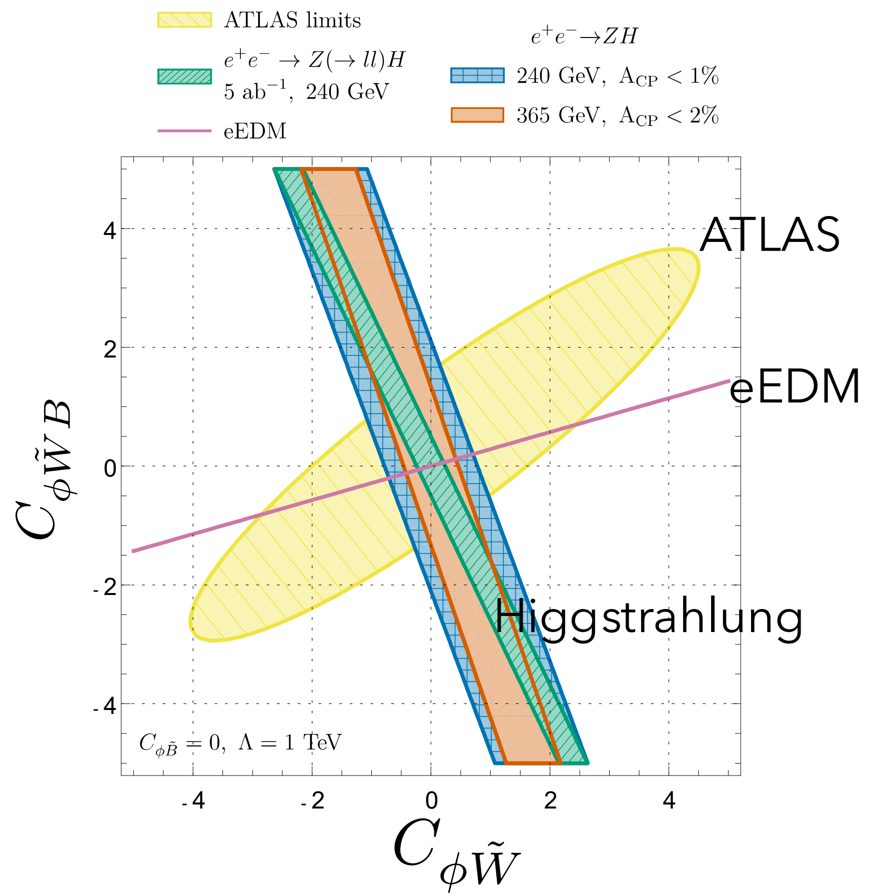
CP violation at future e^+e^- colliders

- 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 limited by eEDMs
    - eEDM depends on SMEFT coefficients
- Limits from angular observables at LHC from H→ 4 lepton

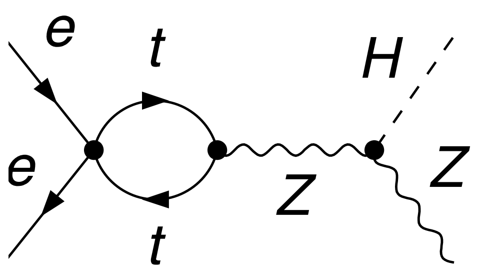
eEDM, LHC, e^+e^- probes of CP violation are complementary

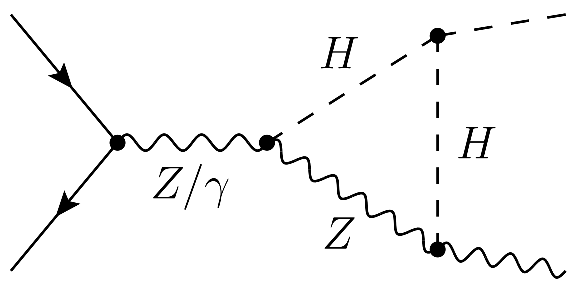


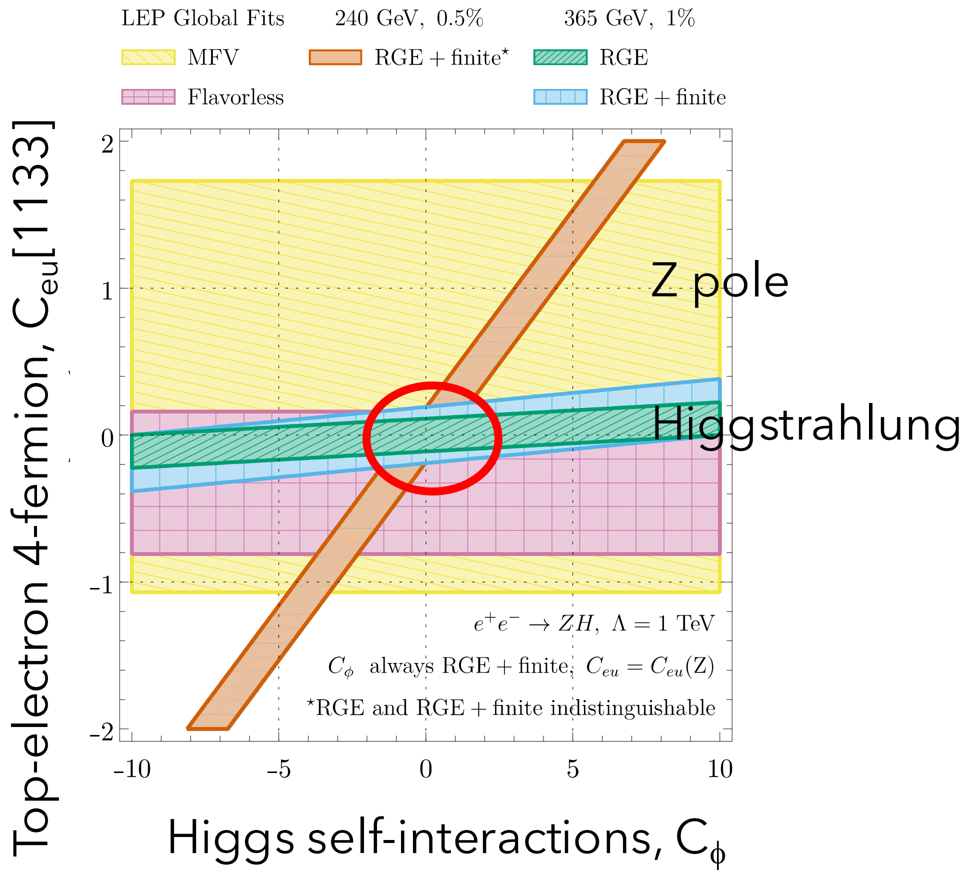
eEDM: 2109.15085, 1810.09413

2406.03557

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







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

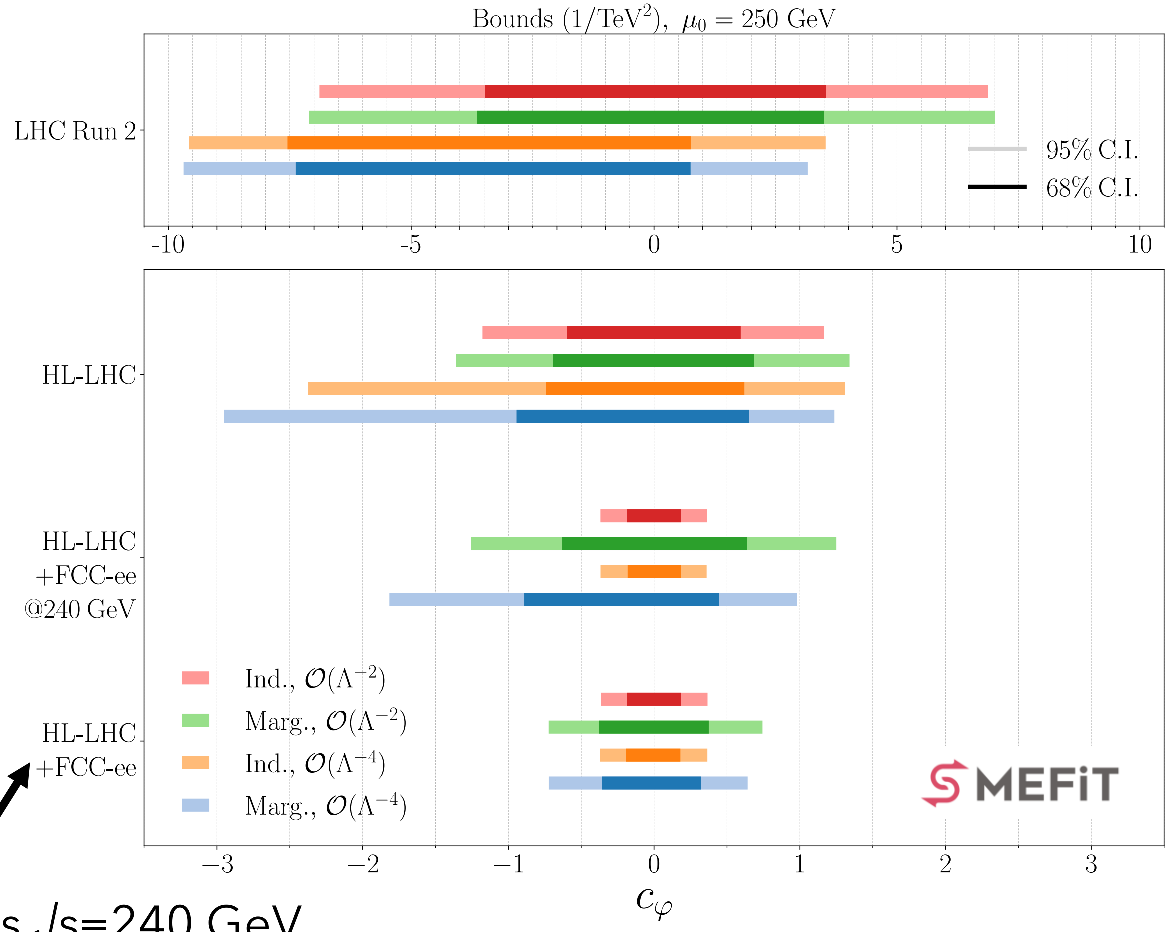
Note: Z pole limits depend on flavor assumptions

Need running at $\sqrt{s}$=365 GeV to really nail down Higgs tri-linear

2406.03557

Global fit

- Include top, H, VV, HH in LHC projections
  - HL-LHC limits largely independent of contamination from other operators, (ie single parameter and marginalized fits very similar)
- Include EW loops in FCC-ee fits (don't have NLO for other pieces)
  - FCC-ee marginalized limits differ from single parameter limits
- Need √s=365 GeV @FCC-ee to improve on HL-LHC limits
- (Results depend on flavor assumptions)



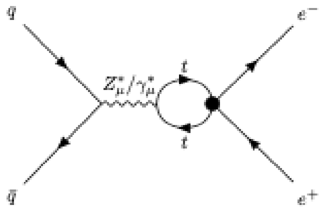
Includes √s=240 GeV + √s=365 GeV running

Higgs tri-linear

2504.05974

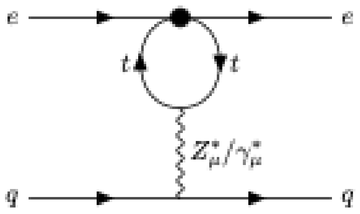
Example fit

- Z decays at FCC-ee, Drell-Yan at HL-LHC, DIS at EIC all closely related
- Consider all 4-fermion operators involving electrons and top

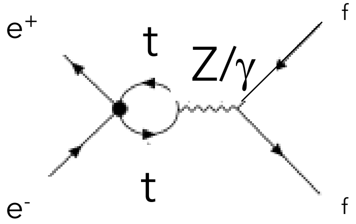


DY @ HL-LHC

$s \leftrightarrow t$



DIS @ EIC



FCC-ee : $e^+e^- \rightarrow b\bar{b}$

$$\mathcal{O}_{\ell q}^{(3),1133} = (\bar{\ell}_L \gamma_\mu \tau^I \ell_L)(\bar{Q}_L \gamma^\mu \tau^I Q_L)$$

$$\mathcal{O}_{\ell q}^{(1),1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{Q}_L \gamma^\mu Q_L)$$

$$\mathcal{O}_{\ell u}^{1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{t}_R \gamma^\mu t_R)$$

$$\mathcal{O}_{qe}^{3311} = (\bar{e}_R \gamma_\mu e_R)(\bar{Q}_L \gamma^\mu Q_L)$$

$$\mathcal{O}_{eu}^{1133} = (\bar{e}_R \gamma_\mu e_R)(\bar{t}_R \gamma^\mu t_R)$$

Work to $1/(16\pi^2\Lambda^2)$, so only operators that interfere with SM

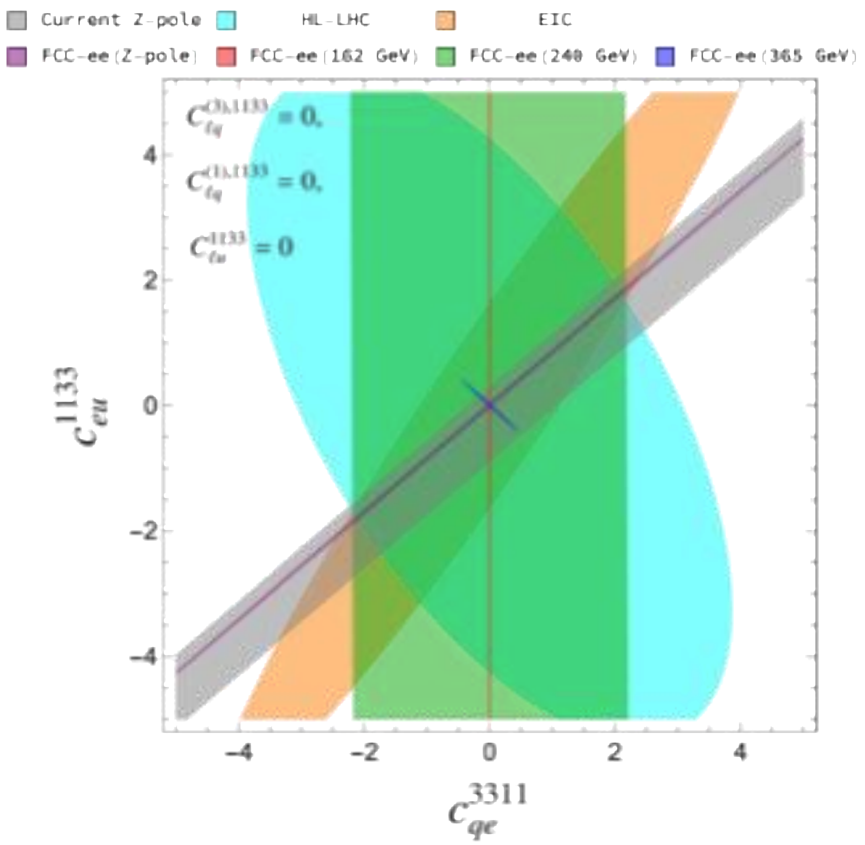
Example fit, #2

- Tree level contributions to $b\bar{b} \to e^+e^-$ (Drell-Yan), $e^+e^- \to b\bar{b}$ (FCC-ee), $e^+e^- \to t\bar{t}$ (FCC-ee @365)
- Calculations include all NLO EW and QCD contributions. [This is unique]
- DY projections for 3 ab^{-1} plus $pp \to t\bar{t}e^+e^-$ projections (restrict DY to $m_{ll} < 800$ GeV to ensure validity of EFT)
- EIC projections: Assume $\sqrt{s}$=140 GeV, P_e=70%, 1% systematic uncertainty
  - Take advantage of polarization to reduce large SM photon contribution

$$A_{LR} \equiv \frac{(\tilde{\sigma}_L - \tilde{\sigma}_R)}{(\tilde{\sigma}_L + \tilde{\sigma}_R)}, \quad \tilde{\sigma}_{L,R} \equiv P_e \sigma_{L,R} + (1 - P_e)\sigma_{R,L}$$

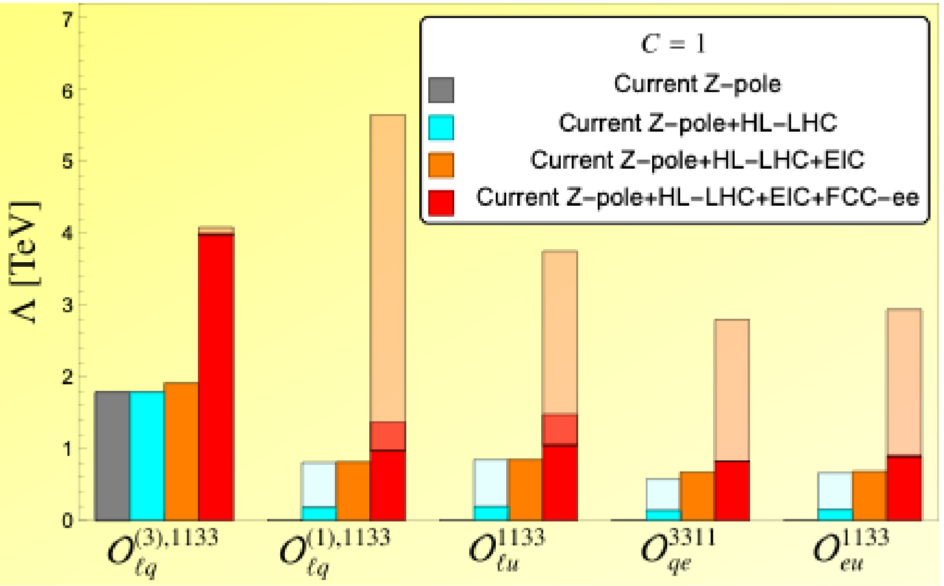
Example fit, #3

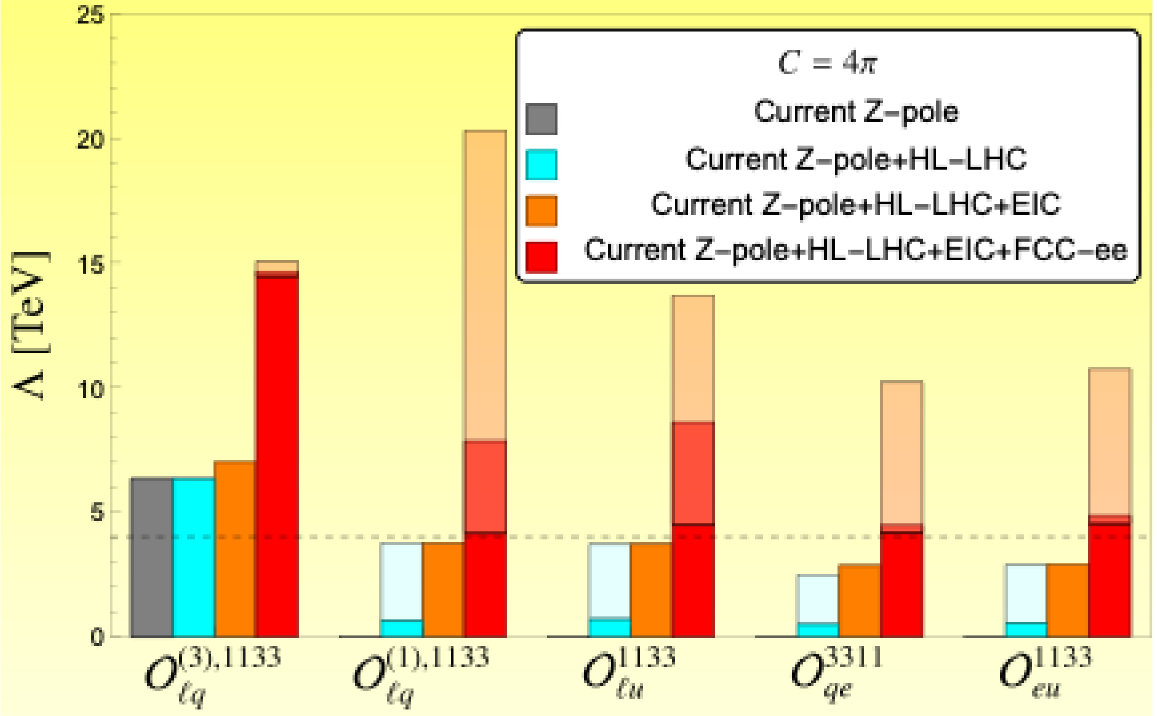
- FCC-ee program: Z pole → WW threshold → tt threshold



Example fit, #4

- Future colliders probe top-electron 4-fermion interactions





Marginalized fits

2507.02039

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 to find heavy new physics
  - NLO EW corrections give new insights, but must be included consistently

➢ Working towards a global fit that is accurate at NLO EW order
➢ Still many missing pieces….