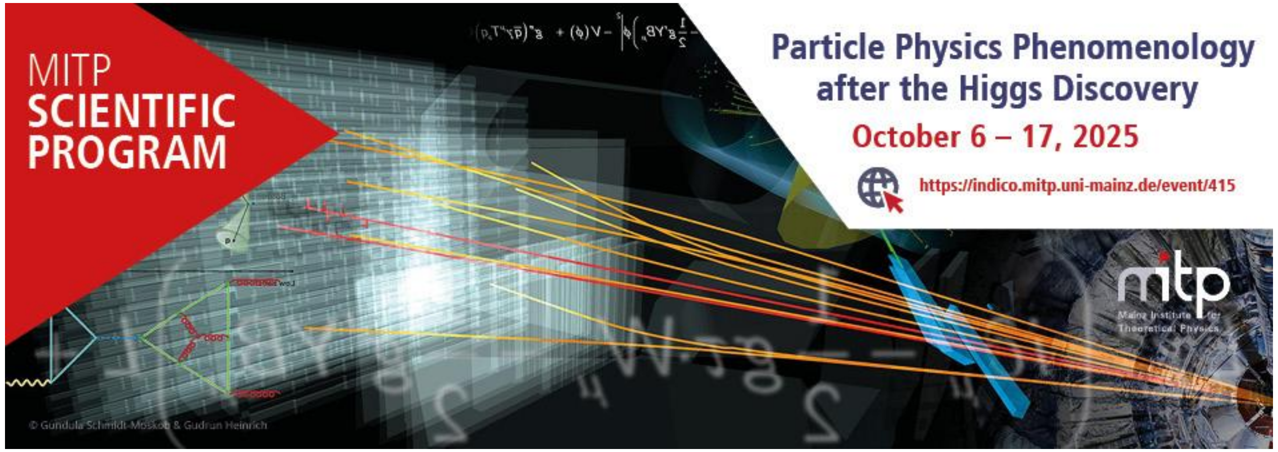
Why is SMEFT/HEFT the right approach to BSM physics and what can we expect from it?

S. Dawson, BNL

Oct. 6, 2025

MITP



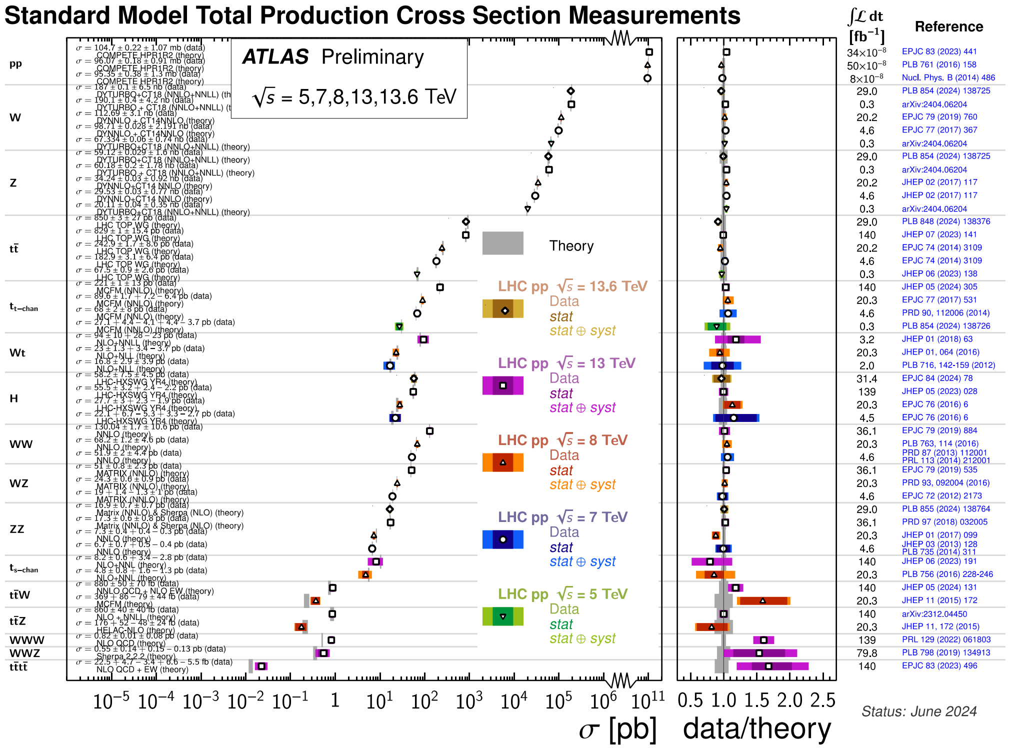
Questions for discussion at this workshop

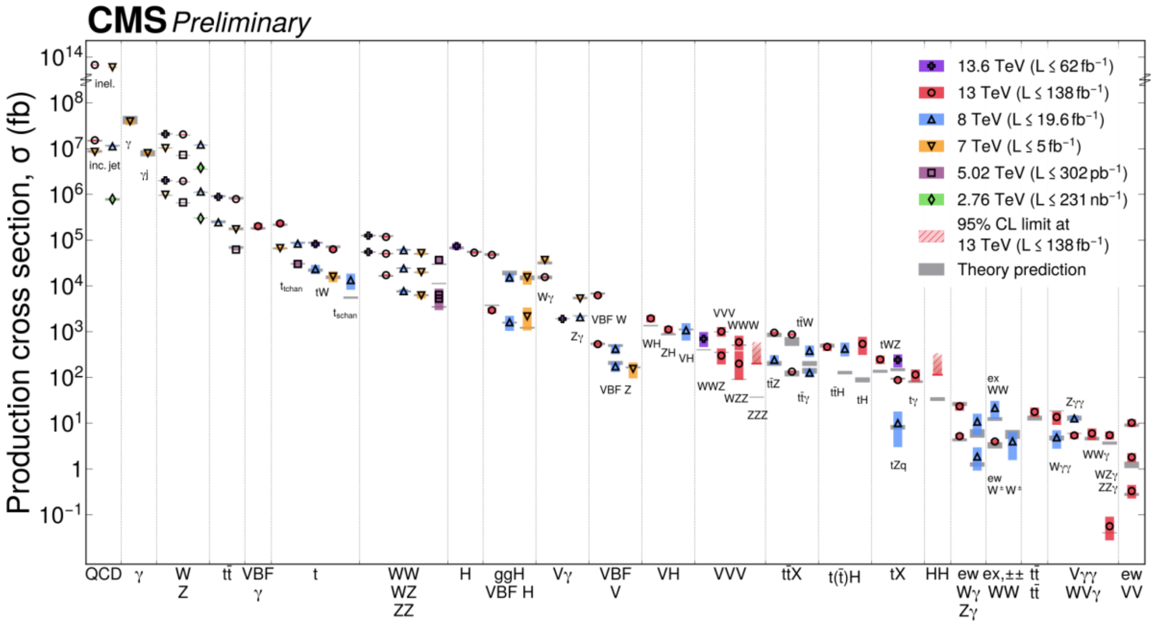
- What has been achieved in the field after the Higgs discovery?
- What are the perspectives of the field?
- What needs to be developed to create further advances
- … regarding HL-LHC?
- … regarding future collider projects?

- Questions posed by the organizers….
- Feel free to stop me for discussion

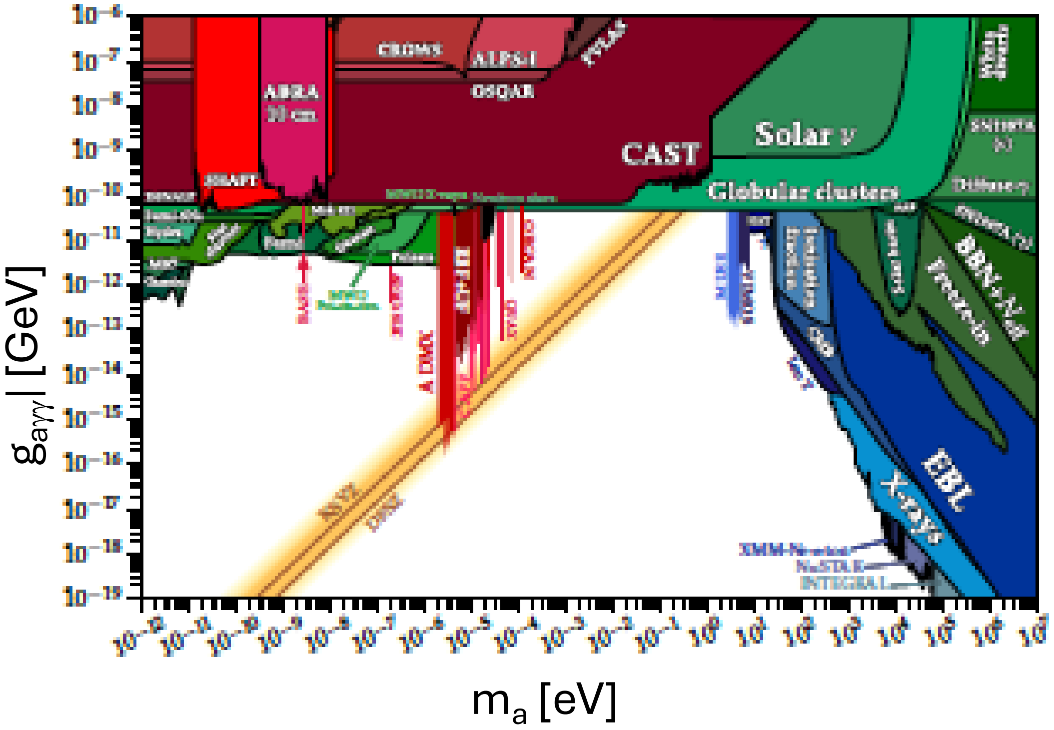
Where are we now?

- LHC results are very, very similar to our best SM predictions over many orders of magnitude and for many processes

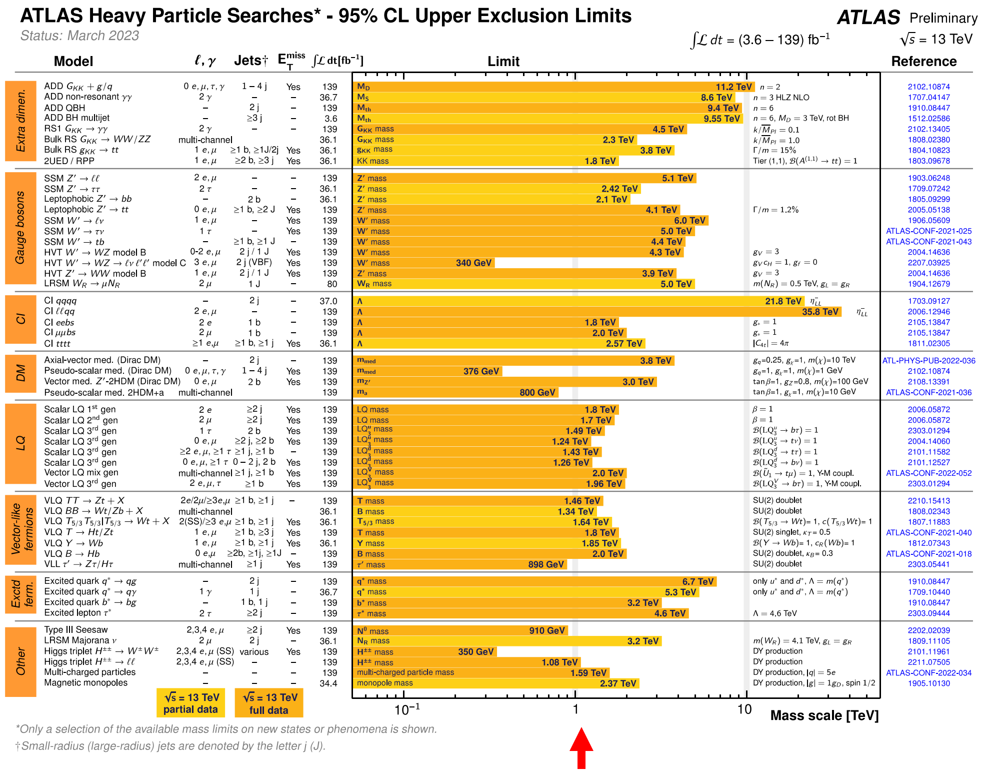




Searches for new physics find no hints



No evidence for light ALPs (PDG)



1 TeV

Where to look?

Limits on many types of new physics exceed 1 TeV

Not obvious how to search for new physics: EFTs are one technique

$\Lambda >> M_W$ where complete theory exists

- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed *(decoupling!)*

This is sad scenario where there is no intermediate scale physics

M_W

Only SM particles in theory at low scales

- Learn about high scale physics by measuring interactions of effective low energy theory
- ***We don't need to know the complete theory***

M_b

SMEFT: SM Effective Field theory

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

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

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

Assume Higgs is in an SU(2) doublet

This is the big assumption

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

*Warsaw basis commonly used

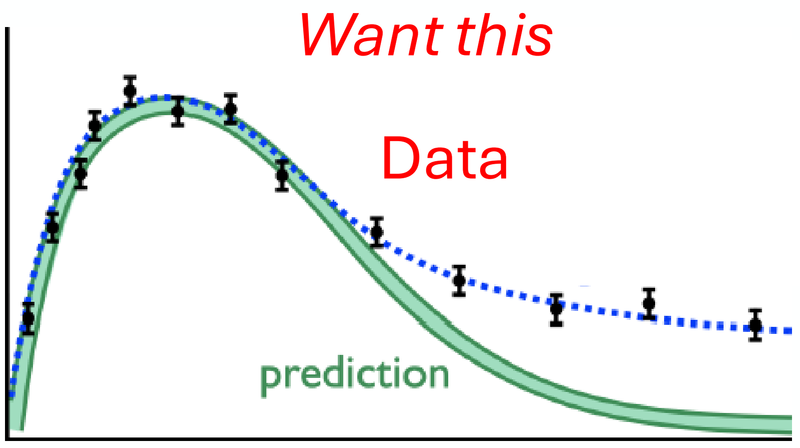
What needs to be developed to create further advances?

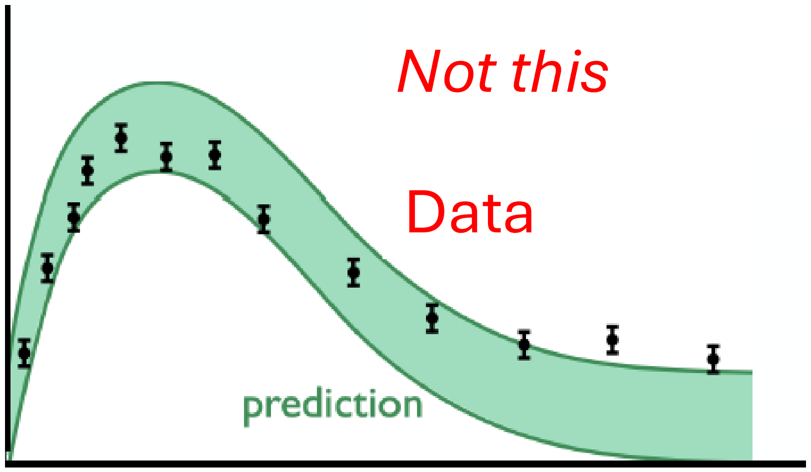
$$\text{Experiment} = \text{Theory}_{SM} + \sum \frac{x_i C_i^6}{\Lambda^2} + \ldots$$

Precise experimental measurements

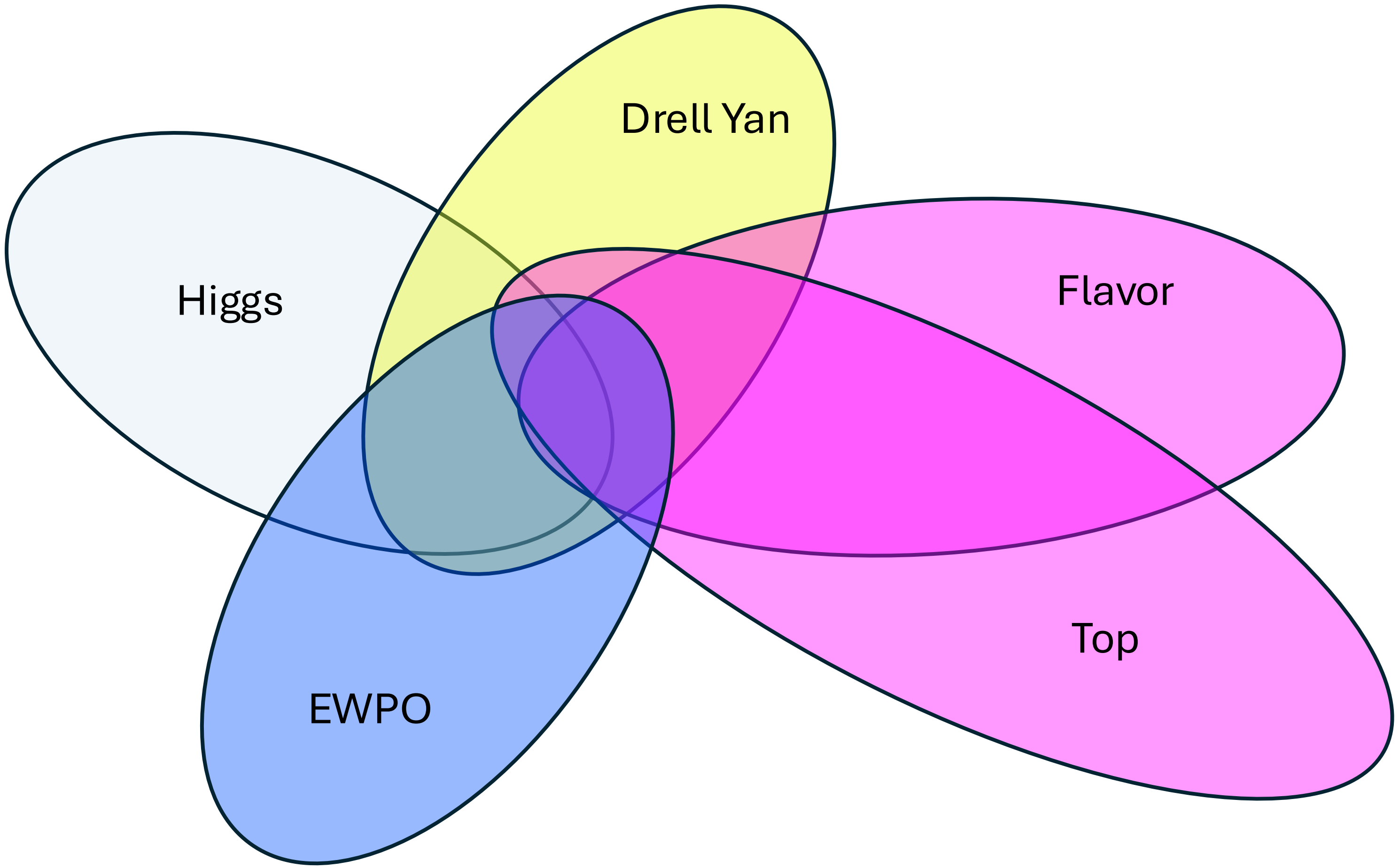
Precise SM calculations

Precise SMEFT calculations





Power of SMEFT is information from many observables



- SMEFT operators contribute to different types of observables
- Leads to concept of global fits

* Picture is not exhaustive

What needs to be developed to create further advances?

- Understanding of theory uncertainties on SMEFT calculations
- Can new techniques (AI/ML) improve global fits?
- Precise SMEFT calculations beyond LO
- Understanding of interpretation of SMEFT calculations
  - Do they really tell us about UV models?

Precise SMEFT calculations

- Compute an amplitude at tree level

$$A \sim A_{SM} + \frac{A_6}{\Lambda^2} + \frac{A_8}{\Lambda^4} + \ldots$$

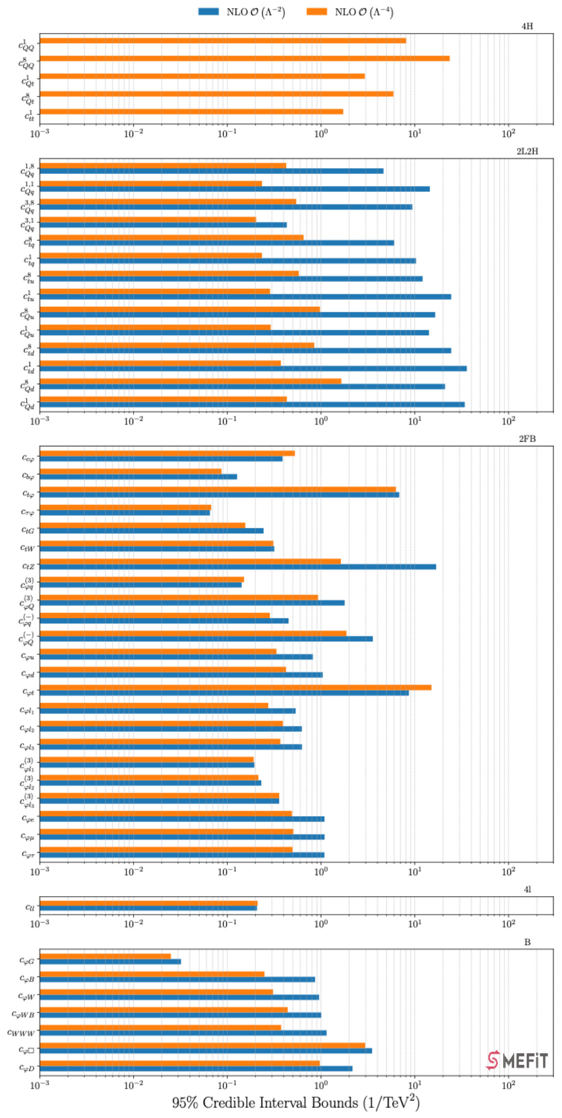
- Various possibilities for defining observables

$$O \sim O_{SM} + \underbrace{\frac{A_6 A_{SM}}{\Lambda^2}}_{\text{Linear}} + \underbrace{\left(\frac{A_6}{\Lambda^2}\right)^2}_{\text{Quadratic}} + \frac{A_{SM} A_8}{\Lambda^4} + \ldots$$

- Where to truncate?

When is expansion valid?

- Expansion is both in $1/\Lambda^2$ and in loops
- Compare tree level $1/\Lambda^2$ with $1/\Lambda^4$ fits using just dimension-6 operators and including QCD@NLO
- In general, $1/\Lambda^4$ contributions change limits significantly
- (less so for observables contributing to EWPO, which are well measured)
- Is the difference useful as a handle on the theoretical uncertainty?

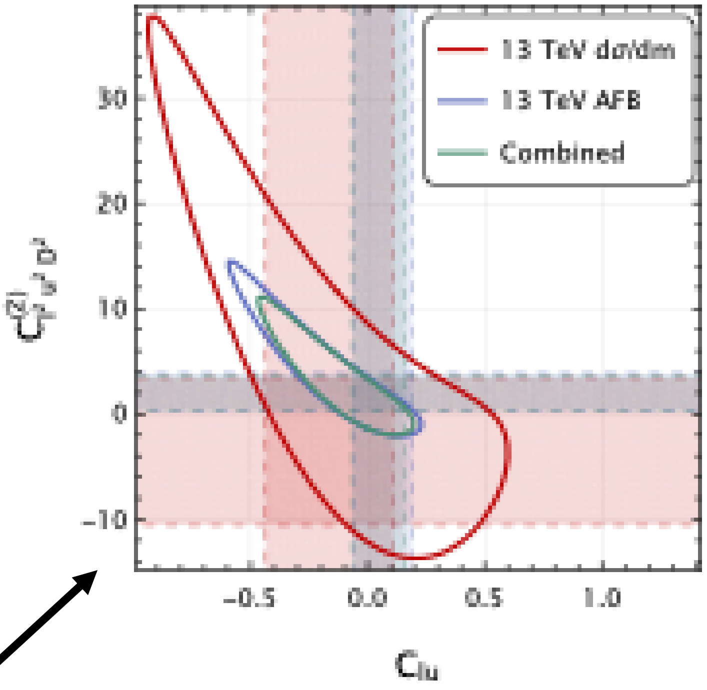


SMEFTFiT, 2404.12809

When does dimension-8 matter?

- Dimension-8 operators are $1/\Lambda^4$
- Some studies on a case- by- case basis, but no general conclusions
- Model independent approach: Drell Yan as case study
  - Precise SM and SMEFT calculations exist
  - 7 dim-6, 14 dim-8 operators. Potentially a general study could be possible?
  - Example: Left-handed lepton coupling to right-handed quark (4-quark interaction)

LHC

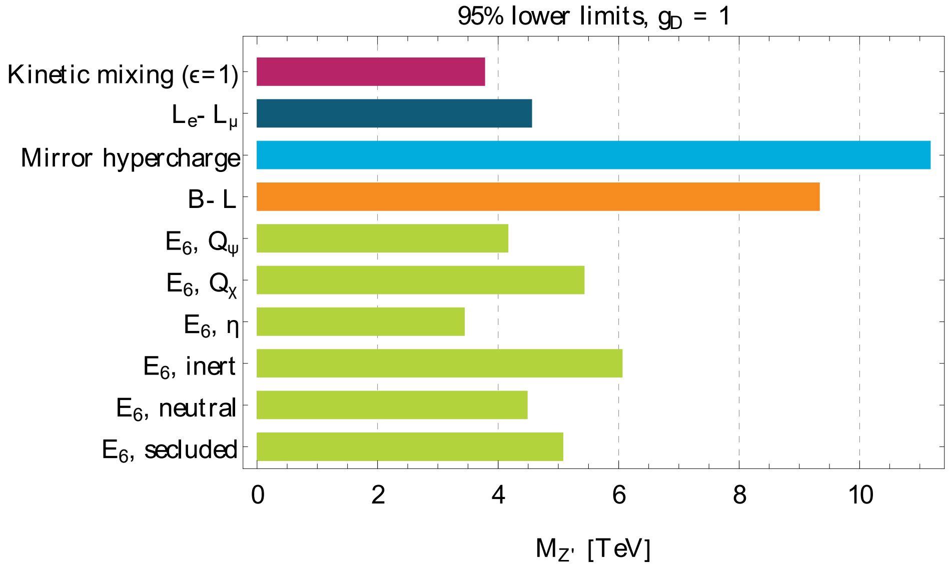


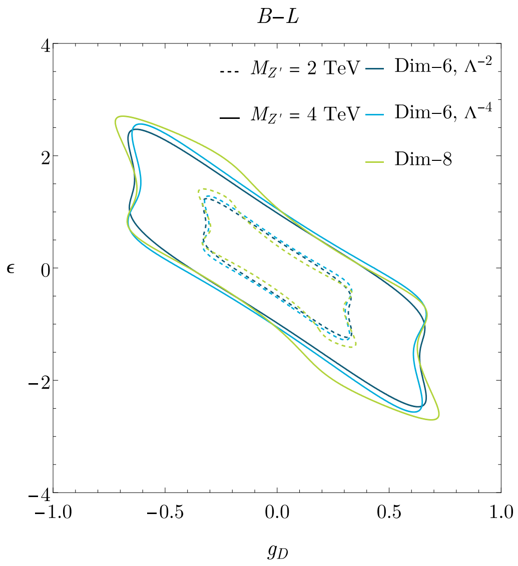
dim-8 changes conclusions

2303.08257

When does dimension-8 matter?

- Model dependent studies: Z’ models





Match models to dim-6 and dim-8 SMEFT operators

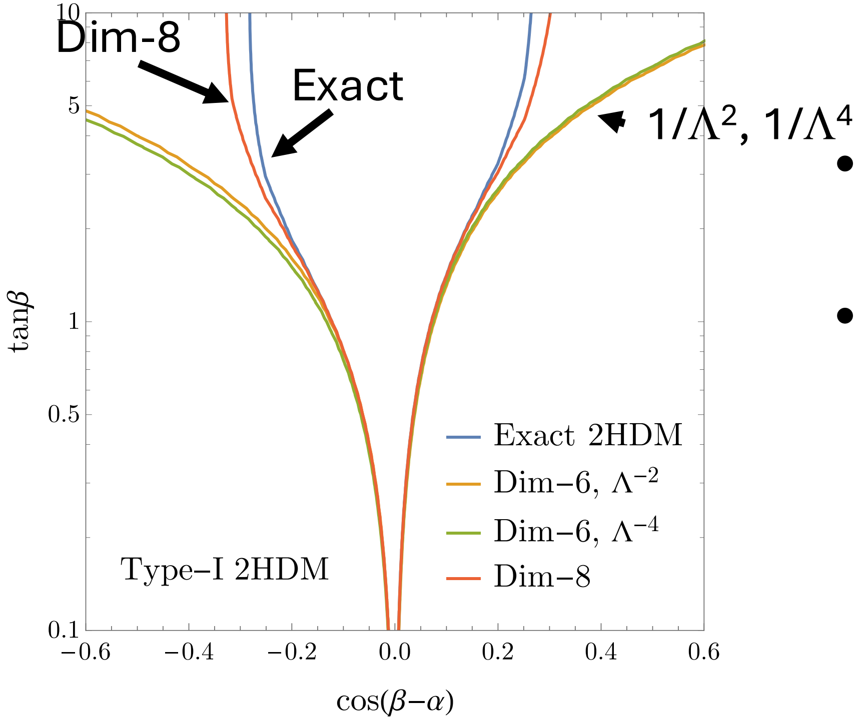
$$\frac{C}{\Lambda^2} \sim \frac{g_D(..)}{M_Z^2}$$

Dimension-8 effects small: Fit to EWPO and DY m_{ll} at LHC

2404.01375

When does dimension-8 matter?

- Model dependent studies: 2HDM as case study



- VVH interactions don't occur at dimension-6 in Type-I 2HDM
- Need dimension-8 to get physics right

More case studies of the impact of dim-8 would be useful

2205.01561

Going beyond Tree Level

$$\mathcal{A} \sim a^0_{sm} + \frac{a^1_{sm}}{16\pi^2} + \Sigma_i \frac{C^6_i}{\Lambda^2}\left[A^0_{EFT,i} + \frac{B^1_{EFT,i}}{16\pi^2} + \frac{D^1_{EFT,i}}{16\pi^2}\log(\frac{\Lambda^2}{M_Z^2})\right] + \Sigma_i \frac{C^8_i}{\Lambda^4} F^0_{EFT,i} + ...$$

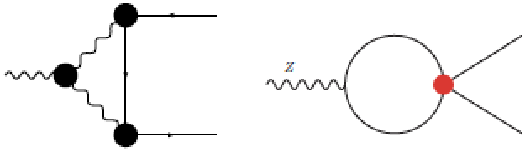
- NLO QCD is automated, but NLO EW corrections done on a case- by -case basis
- At NLO, new operators contribute
  - In general, effect of more operators is to weaken many limits
- Logarithms come for free from RGE. Do they dominate?

$$C_i(\mu) = \gamma_{ij} C_j \log\left(\frac{\mu}{\Lambda}\right)$$

We'd really like this to be the case!

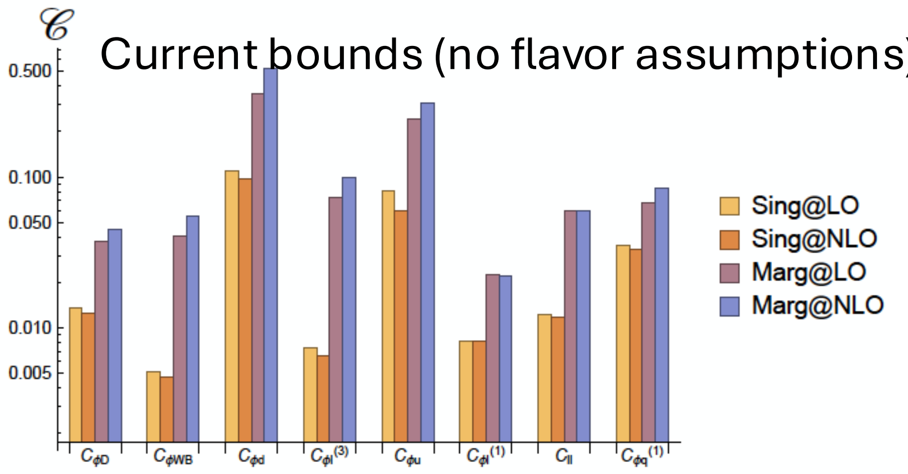
Not diagonal

Example of loop effects



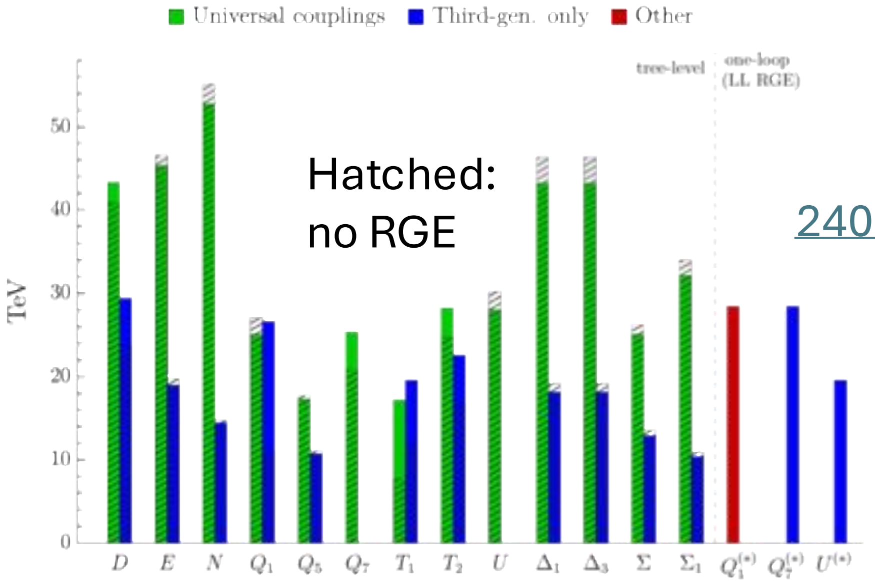
- Z pole observables (without flavor for now)
  - At tree level, dependence on 10 operators (2 blind directions)
  - At NLO, dependence on 32 operators (new contributions especially from 4-fermion operators)

Current bounds (no flavor assumptions)



Public results for complete NLO EW Z pole SMEFT observables, 2304.00029 , 2503.07724

Tera-Z: Single parameter models



Hatched: no RGE

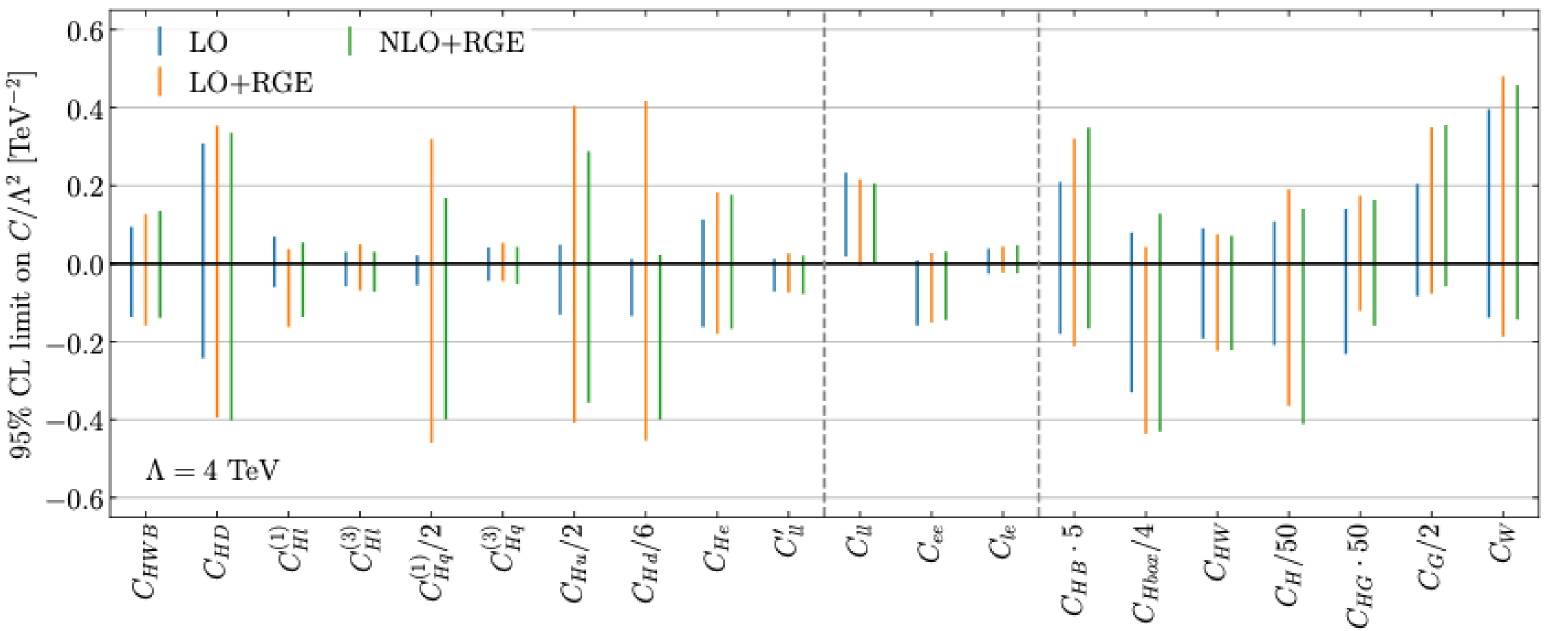
Heavy fermions

2408.03992 , 2412.01759

RGE and flavor change conclusions

Including RGE in global fits is state of the art

- RGE effects can be large
- RGE effects generate dependence on new operators



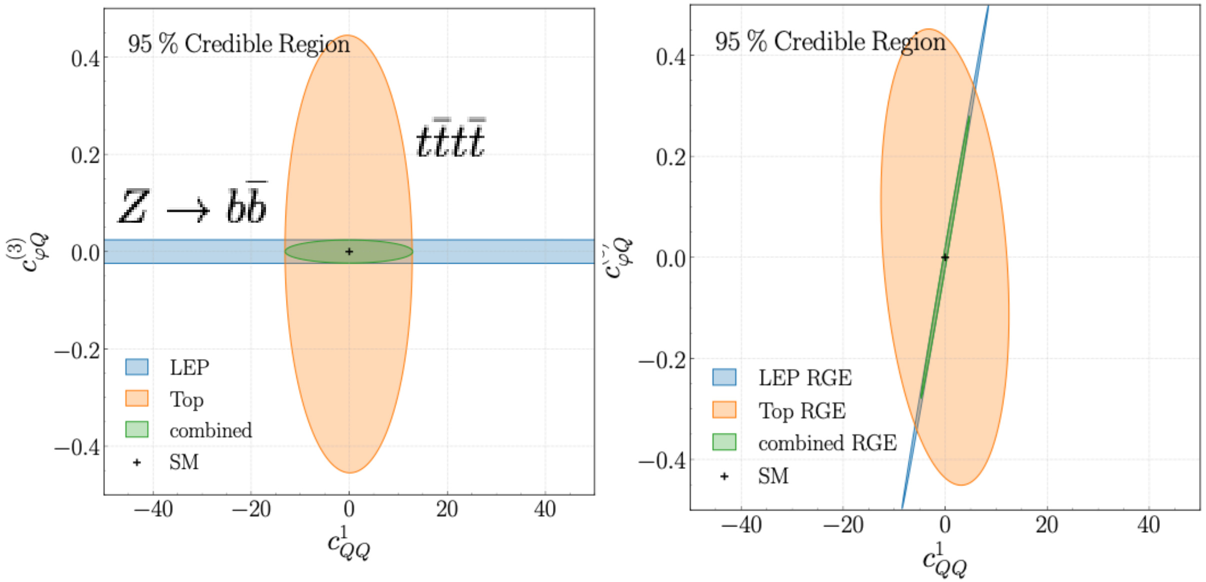
These are observables contributing to EWPOs

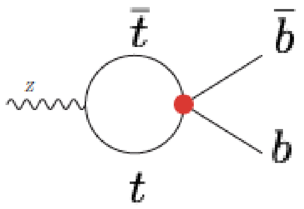
2412.09674

See also, 2502.20453 2507.06191

Including RGE in global fits is state of the art

- RGE has large effects on 4-fermion heavy quark operators
  - They are poorly unconstrained at LHC
  - RGEs mix these operators with operators that contribute to well measured observables at Z pole (Z→bb)





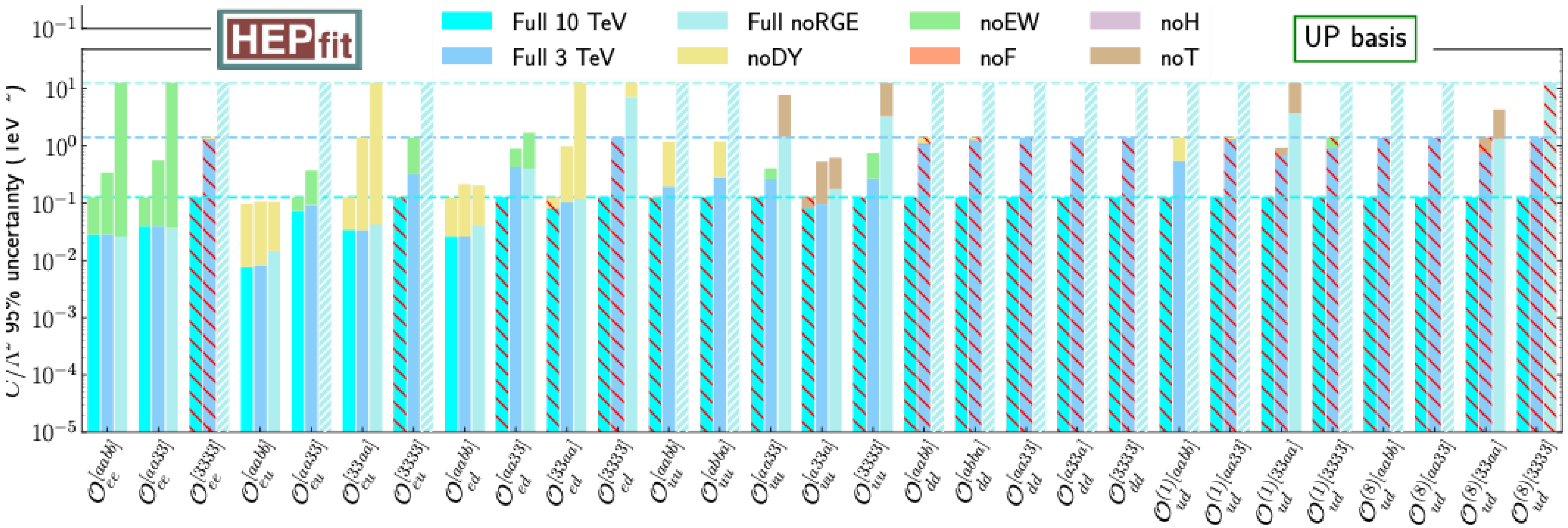
2502.20453 , 2507.01137 , 2410.13304

O_{QQ}^1 is 4-quark (LL)(LL) operator with (t,b) doublet
$O_{\phi Q}^3$ is 2-quark LL operator with 2 fermion fields

Many global fits with different data sets

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

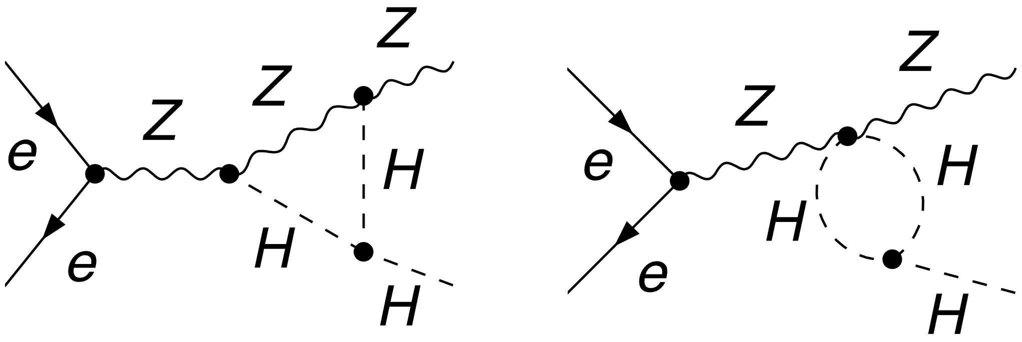
2507.06191



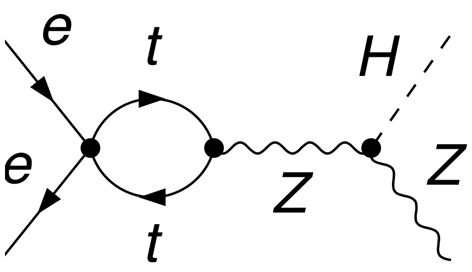
Fit includes NLO QCD, but is tree level electroweak

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators and no flavor assumptions
  - (~70 SMEFT operators contribute in ~ 35 combinations)
- Sensitive to poorly constrained interactions that first arise at NLO



Higgs tri-linear coupling, C_ϕ



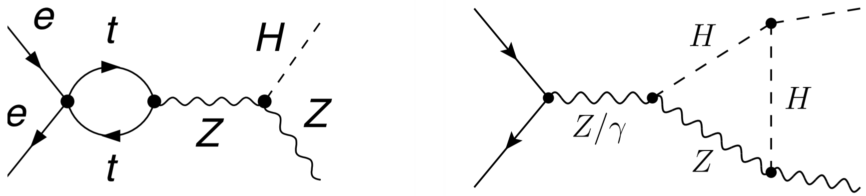
+ many more

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

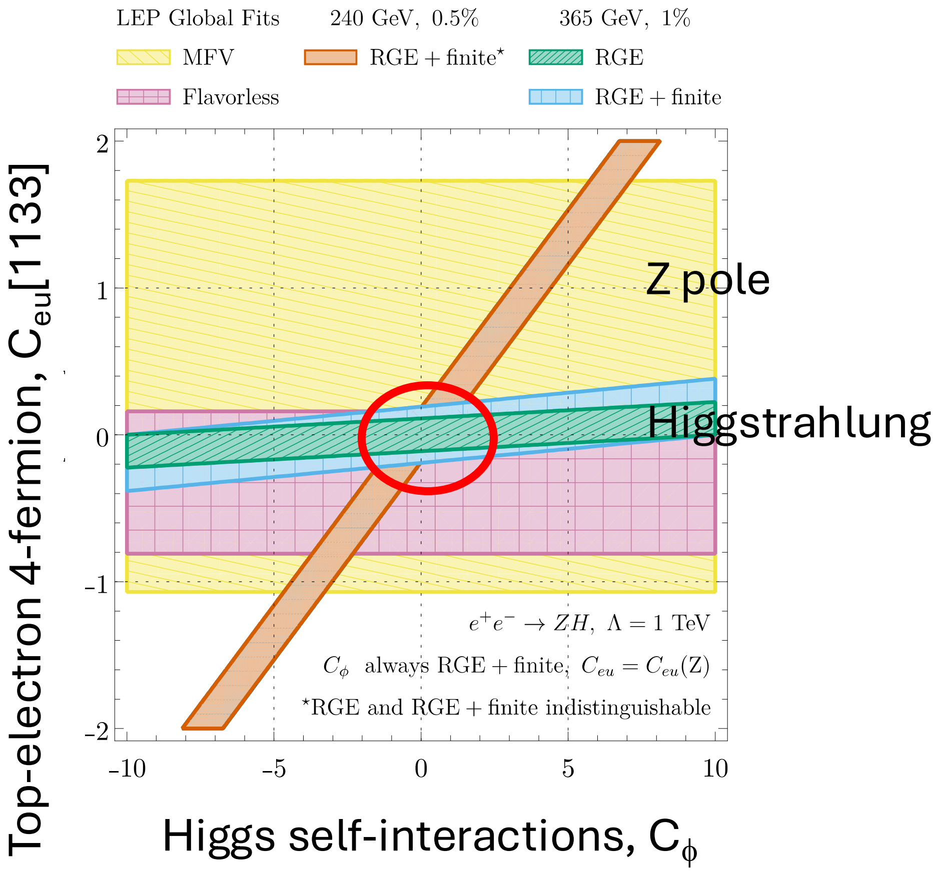
$e^+e^- \to ZH$ is window to many new interactions



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

Note: Z pole limits depend on flavor assumptions

2406.03557

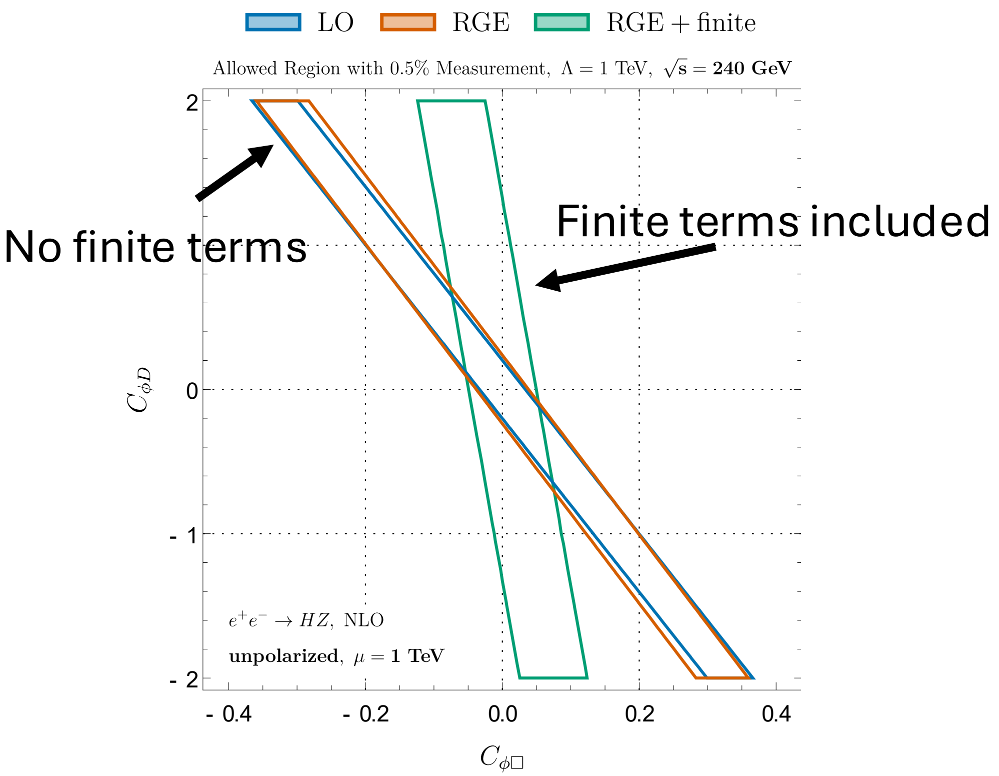


Need running at $\sqrt{s}$=365 GeV to really nail down Higgs tri-linear

NLO EW corrections in dim-6 SMEFT

- EWPOs, Drell-Yan, Higgs decays known at 1-loop EW dim-6 SMEFT
- Can test when RGE logs dominate
  - No general conclusion
- Complete set of 1-loop corrections needed for global fits that is accurate to NLO EW not available

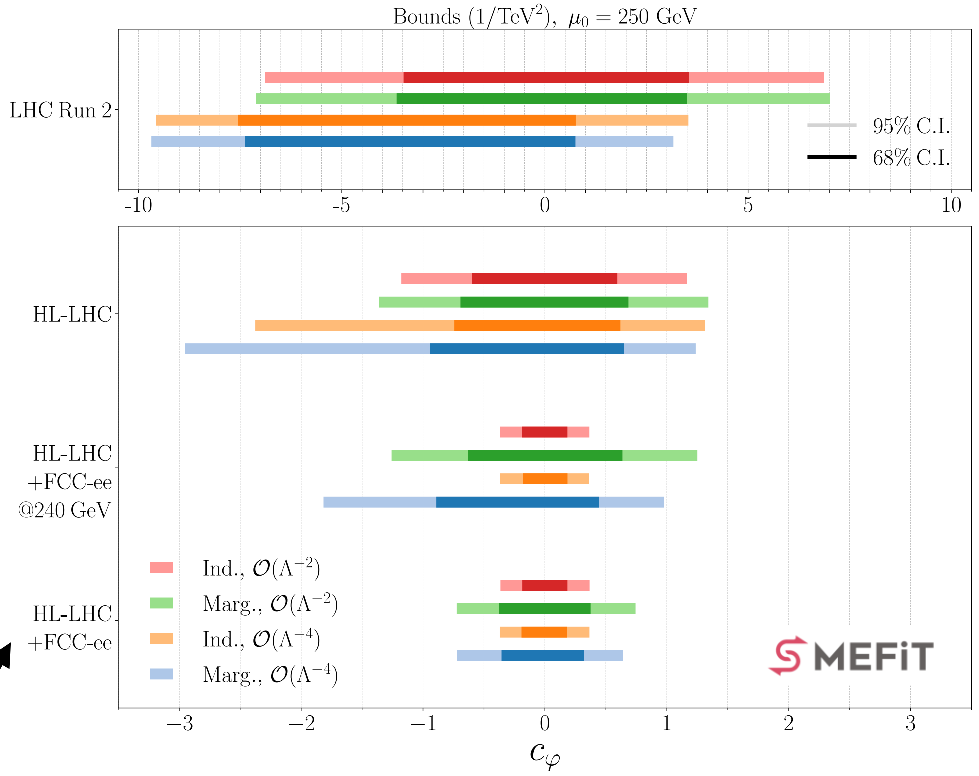
Sensitivity at FCC-ee from $e^+e^-\to ZH$



2409.11466

Global fit for Higgs tri-linear

- 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 marginalized HL-LHC limits



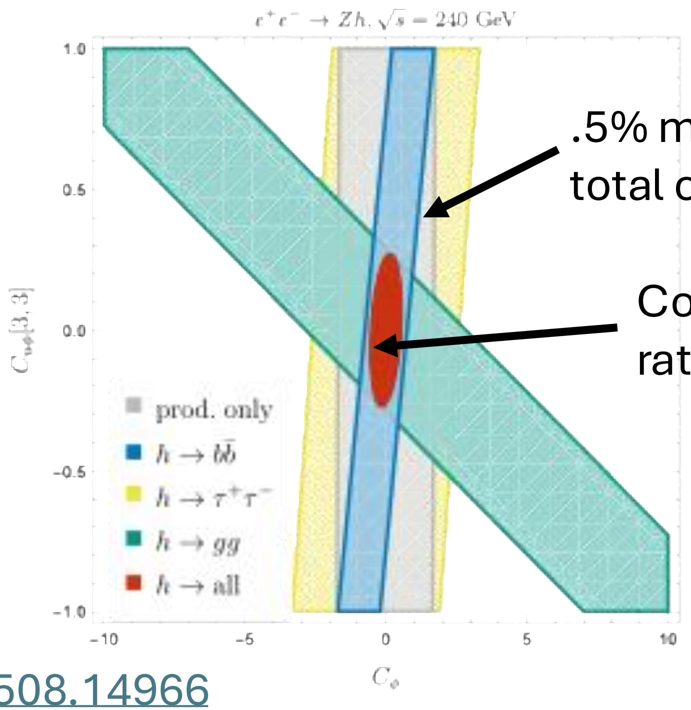
Includes √s=240 GeV + √s=365 GeV running

Higgs tri-linear

2504.05974

End-to-end NLO EW fit

- Example case: $e^+e^- \rightarrow ZH$, $H \rightarrow XX$
- Use NWA and include full NLO corrections to $e^+e^- \rightarrow ZH$, $Z \rightarrow ff$, $H \rightarrow XX$
- Significantly more information when decays are included



.5% measurement of total cross section

Combining total rate with decays

These are coefficients that don't contribute at LO

FCC-ee, Tera-Z

	$\sqrt{s} = 240$ GeV	$\sqrt{s} = 365$ GeV
$b\bar{b}$	0.21	0.38
$c\bar{c}$	1.6	2.9
$s\bar{s}$	120	350
gg	0.8	2.1
$\tau^+\tau^-$	0.58	1.2
$\mu^+\mu^-$	11	25
WW^*	0.8	1.8
ZZ^*	2.5	8.3
$\gamma\gamma$	3.6	13
$Z\gamma$	11.8	22

2508.14966

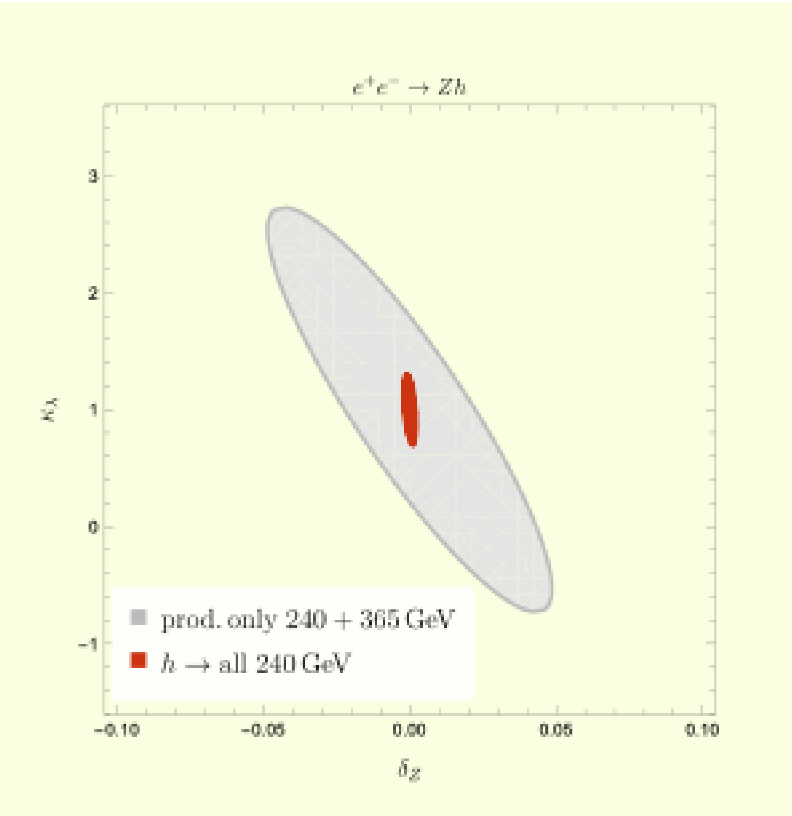
End-to-end NLO EW fit

- Translate to κ formalism

$$\delta_Z = \frac{1}{4}\frac{v^2}{\Lambda^2}\left(C_{\phi D} + 4C_{\phi\Box}\right)$$

$$\kappa_\lambda = 1 + \frac{v^2}{\Lambda^2}\left(3\left[\frac{C_{\phi D}}{4} - C_{\phi\Box}\right] - 2\frac{v^2}{m_H^2}C_\phi\right)$$

- Decays provide new information



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$* \; C_{\phi\Box} = 0$

Missing pieces for end-to-end NLO EW fit at LHC

- Very few of the production processes are known to NLO EW order

- Coming soon (!): public code NEWISH
  - Differential rates for ALL 2- and 3-body Higgs decays using dimension-6 SMEFT that is accurate to NLO in QCD and EW interactions
  - NWA results for ALL 4-body decays dimension-6 SMEFT that is accurate to NLO in QCD and EW interactions
  - Tree level 4-body dimension-6 SMEFT Higgs decays

→ Towards a global fit that is accurate to NLO QCD and EW

What about flavor?

- Much of the complexity of SMEFT studies comes from 4-fermion operators
- SM has $U(3)^5$ flavor symmetry:

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \, X \, U(3)_e$$

- Top Yukawa breaks this to:

$$U(2)^2 \times U(1) \times U(3)_d \times U(3)_l \, X \, U(3)_e$$

- Various assumptions in the literature
  - New physics is flavor independent
  - New physics only couples to 3rd generation
  - New physics obeys a U(3)^5 or U(2)^5 symmetry
  - New physics only arises from Yukawa interactions
  - ….

From a global fitting point of view, these assumptions matter

Flavor assumptions reduce possibilities

Operators that contribute to EWPO at NLO

2-fermion

4-fermion with identical representations

Remaining 4-fermion

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

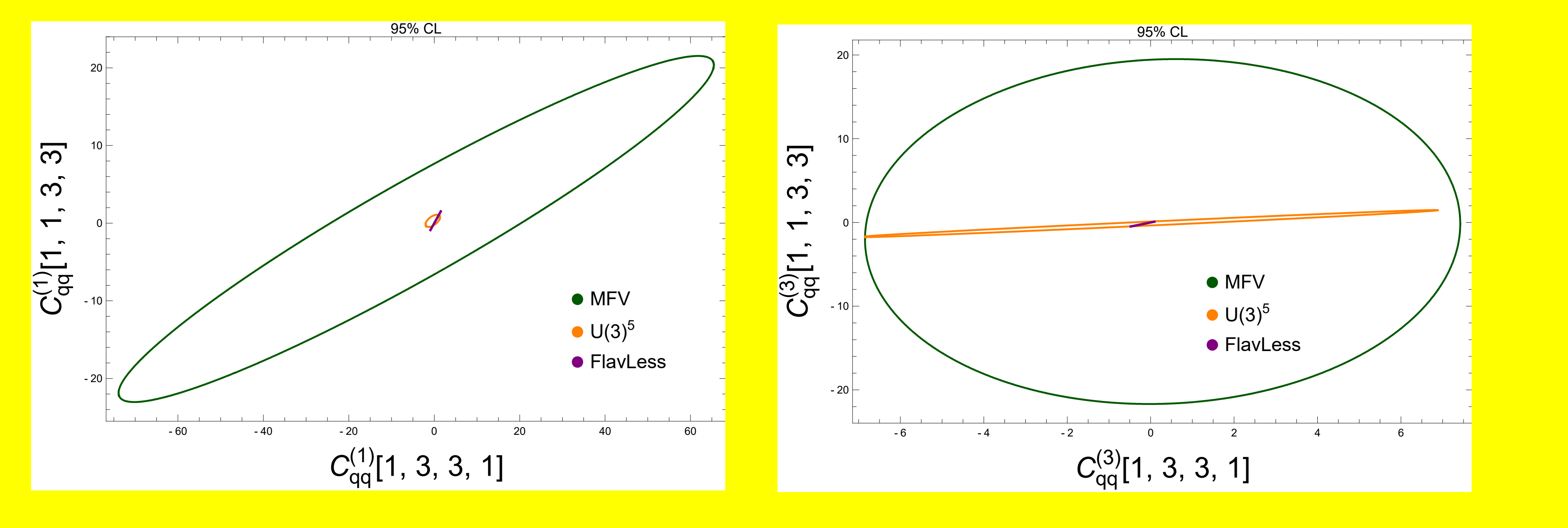
- Compare Z pole global fit results with $U(3)^5$, $U(2)^5$, MFV, only 3^{rd} generation operators, no flavor structure

Much work to be done understanding flavor in SMEFT global fits

* In all generality, 168 operators contribute to EWPO with no flavor assumptions

Flavor matters!

Current Z pole limits on 4-fermion operators



Consider 1 operator type at a time and marginalize over flavor structures not shown

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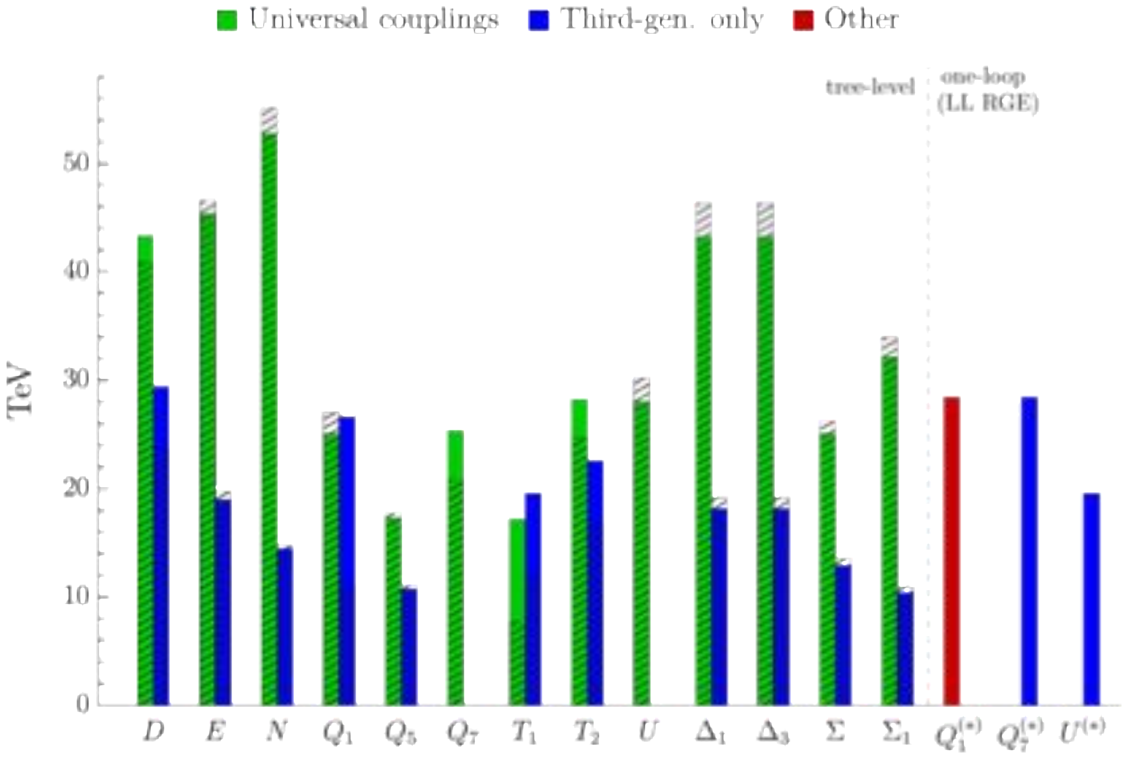
Flavor matters

Tera-Z sensitivity to heavy fermions



[2408.03992](2408.03992)

RGE operator mixing leads to new flavor structures

- Assume all (non-SM) couplings=1, and all dimensionful parameters=M
- This "dictionary" type of analysis is perhaps oversimplified

What needs to be developed to create further advances?

- Understanding of theory uncertainties on SMEFT calculations
  - When do we need dimension-8?
  - Truncating dimension-6 at $1/\Lambda^2$ vs $1/\Lambda^4$?
  - Flavor assumptions—when are they crucial?
  - Validity of expansion
  - The most straightforward--including input scheme, scale and parametric uncertainties

Input scheme matters

$h \to b\bar{b}$		SM	$C_{H\Box}$	C_{HD}	$C_{\substack{dH \\ 33}}$	C_{HWB}	$C^{(3)}_{\substack{Hl \\ jj}}$	$C_{\substack{ll \\ 1221}}$
α	NLO QCD	20.3%	20.3%	20.3%	20.3%	20.3%	-	-
	NLO EW	-5.2 %	2.1%	-11.0%	4.2%	-6.7%	-	-
	NLO correction	15.1%	22.4%	9.3%	24.5%	13.6%	-	-
α_μ	NLO QCD	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	NLO EW	-0.8 %	2.1%	2.0%	1.9%	-	0.9%	-0.8%
	NLO correction	19.5%	22.4%	22.3%	22.2%	-	21.2%	19.5%
LEP	NLO QCD	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	NLO EW	-0.7 %	2.1%	1.6%	1.9%	-	0.7%	-0.9%
	NLO correction	19.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

2305.03763, 2312.08446

α: (α, M_W, M_Z), α_μ: (G_F, M_W,M_Z), LEP: (α, G_F,MZ)

HEFT vs SMEFT

- HEFT has Higgs (h) as a singlet, SMEFT has Higgs (H) as a doublet
- Different expansions (derivative vs 1/Λ)

$$L_{HEFT} \sim \frac{v^2}{4}\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + ...\right] Tr\left\{D_\mu U^\dagger D_\mu U\right\} + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

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

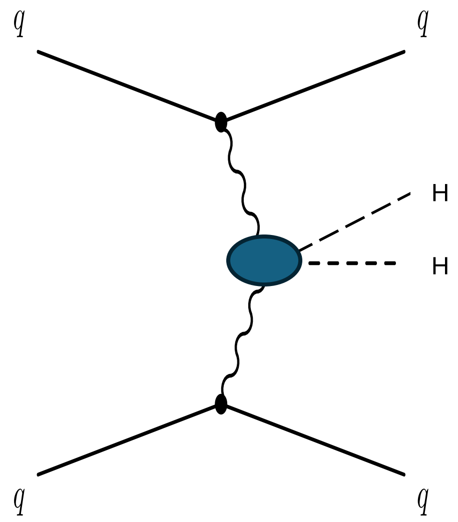
$$D_\mu U = \partial_\mu U + igW_\mu^a \frac{\sigma^a}{2} U - ig' U \frac{\sigma^3}{2} B_\mu$$

- Unitary gauge U=1, suggests WW→hh is good probe of HEFT vs SMEFT
- SM: a=b=κ_3=κ_4=1 SMEFT: $b - a = \frac{3C_{H\Box}v^2}{\Lambda^2}$

⇨ Correlations

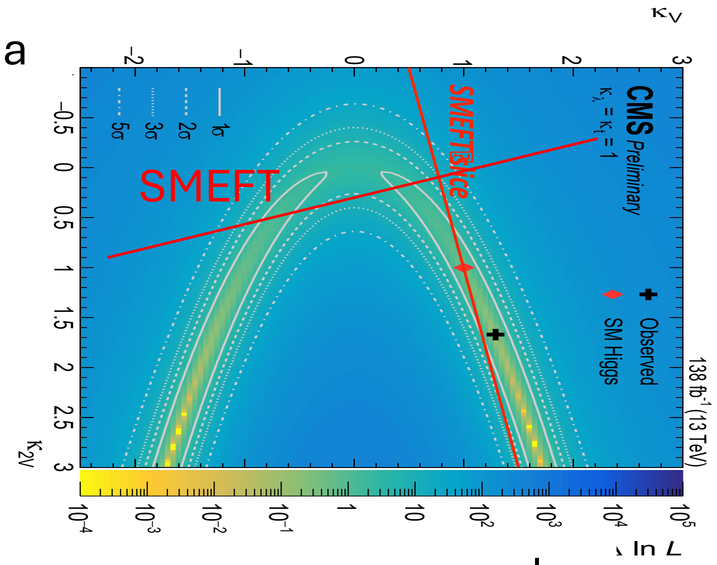
SMEFT vs HEFT

HH production via VBS can potentially distinguish SMEFT from HEFT



LHC

a



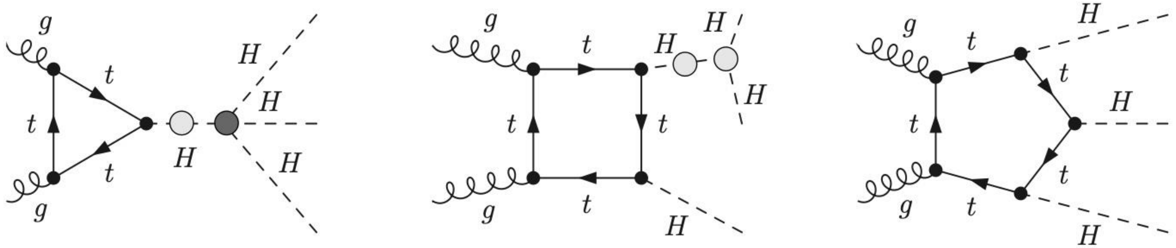
b

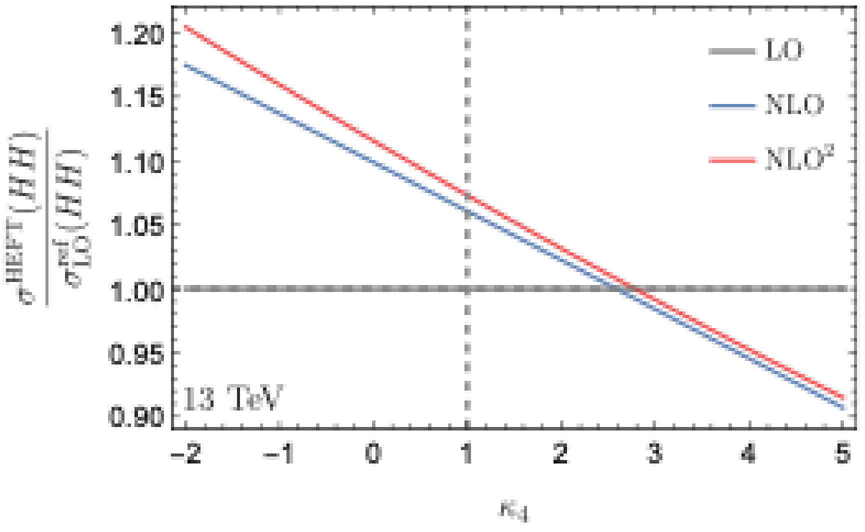
Is the Higgs in an SU(2) doublet?

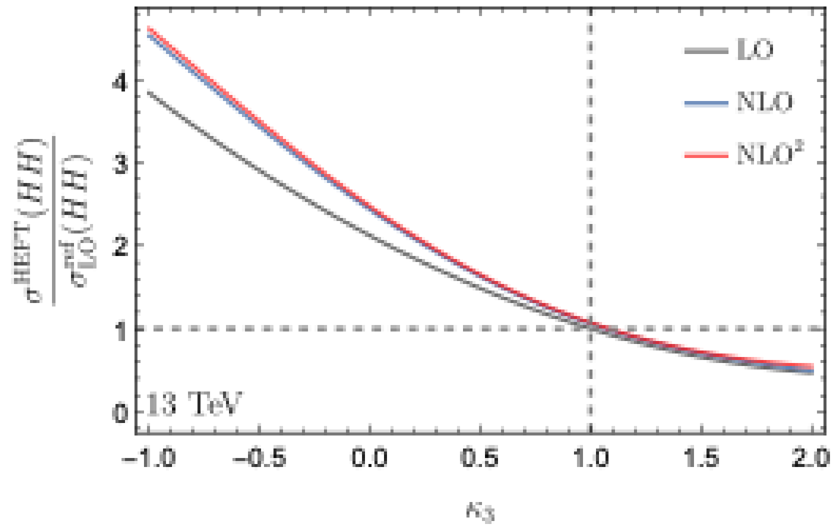
2211.09605

$$L_{HEFT} \sim \frac{v^2}{4}\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + ...\right] Tr\left\{D_\mu U^\dagger D_\mu U\right\}$$

HEFT HHH vs HH







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Conclusions

- Much interesting work for theorists to make SMEFT useful for experiment
  - Theory uncertainties?
  - New AI/ML tools for global fits?
  - More understanding of HEFT vs SMEFT correlations
- At the top of my personal list are more dimension-8 studies and completion of NLO EW dimension-6 calculations
- Much progress that I didn't cover (in particular automated tools for 1 loop matching, progress in 2-loop SMEFT RGEs)