HEFT2024
Bologna, Italy

- WHY USE SMEFT?
- (What can we learn?)
- (What are the consequences of the assumptions we make?)

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Searching for discoveries

- High energy or low energy?
- Hope to see new particles….anywhere….
- But if we don't EFTs are the tools for precision physics

$$L_{SMEFT} = L_{SM} + \Sigma_i \frac{C_i}{\Lambda^2} O_i + \frac{C_i^8}{\Lambda^4} O_i^8 + ...$$

- Many assumptions in SMEFT interpretations of data
  - Flavor structure of operators
  - Loop expansion
  - Dimension-6 versus dimension-8 expansion

I will give a summary of some recent work on these questions related to NLO EW SMEFT calculations

Part I: Fits to Z-pole observables with flavor Structure

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

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

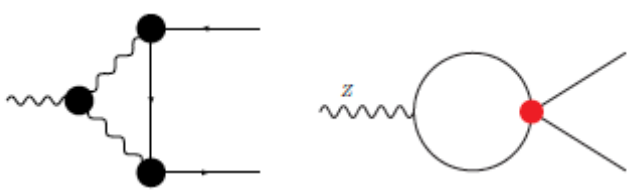
  - 2-fermion operators

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

  - 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)



Z pole SMEFT NLO: 2304.00029, 2201.09887

Flavor assumptions reduce possibilities

Operators that contribute to EWPO at NLO

2-fermion → Class A
4-fermion with identical representations → Class B
Remaining 4-fermion → Class C

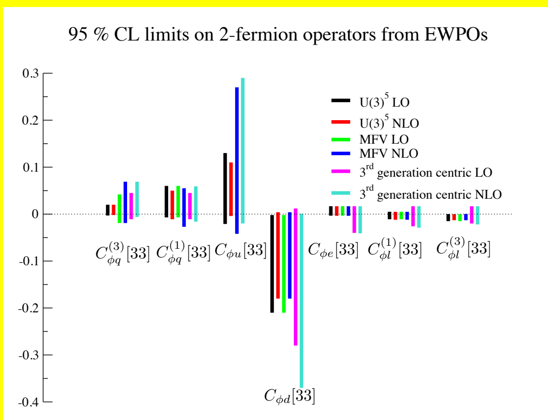
Operator	$U(3)^5$	MFV	$U(2)^5$	3^{rd} gen specific	3^{rd} gen phobic	3^{rd} gen phobic + $U(2)^5$	Flavorless
Class A	7	12	16	9	14	7	9
Class B	11	17	27	5	23	11	6
Class C	11	21	44	11	44	11	11
Total	29	50	87	25	81	29	26

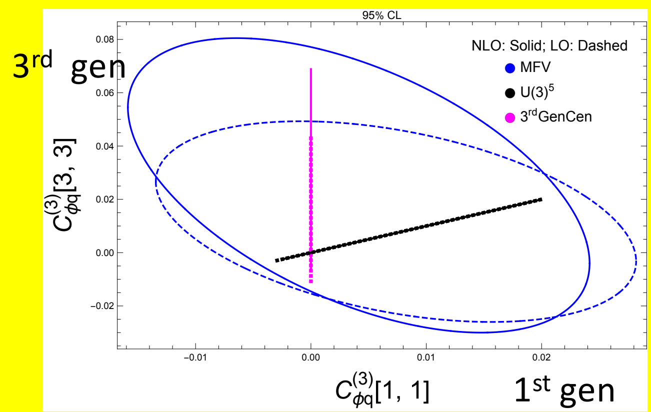
- Compare Z pole global fit results with $U(3)^5$, $U(2)^5$, MFV, only 3^{rd} generation operators, no flavor structure

Flavor matters!

- Take-away: Neglecting flavor in Z pole fits gives overly aggressive limits
- Strong correlations in flavor space
- NLO can have large effects

2-fermion operators



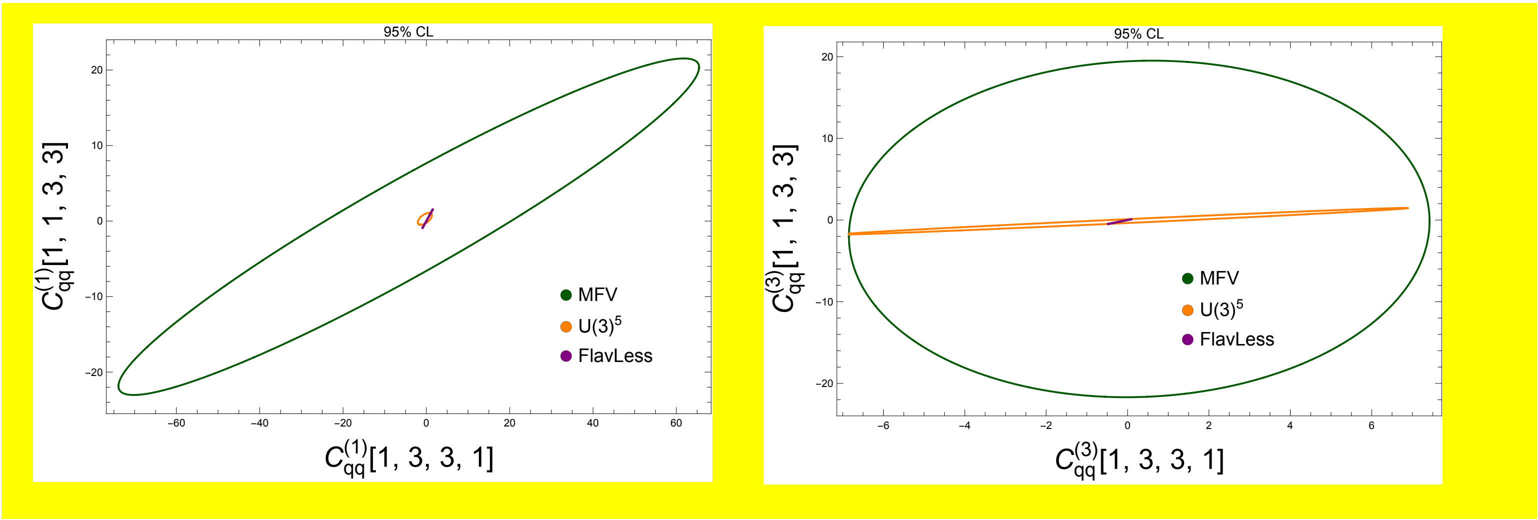


Note difference in NLO/LO shapes in MFV scenario

* Coefficients are related by flavor assumptions

Flavor matters!

4-fermion operators



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

Part II: NLO Electroweak SMEFT

- Broad program of computing Higgs decays at NLO in SMEFT, Z decays at NLO in SMEFT
  - $H \to \gamma\gamma$, $H \to \gamma Z$, $H \to VV$, $H \to bb$, $Z \to ff$
- Results can be expressed similarly to (plus tree level EFT if applicable):

$$A_{\mu\nu}(H \to \gamma Z) = \mathcal{A}\left(g_{\mu\nu} - \frac{p^\nu q^\mu}{p \cdot q}\right)$$

$$\mathcal{A} \sim \frac{a_{sm}}{16\pi^2} + \Sigma_i \frac{C_i}{\Lambda^2}\left[A_{EFT,i} + \frac{B_{EFT,i}}{16\pi^2} + \frac{C_{EFT,i}}{16\pi^2}\log\left(\frac{\Lambda^2}{M_Z^2}\right)\right] + \ldots.$$

- C_{EFT} can be found from RGE running
- B_{EFT} requires complete NLO calculation
- For $H \to \gamma\gamma$ and $H \to \gamma Z$, B_{EFT} and C_{EFT} are of similar numerical size

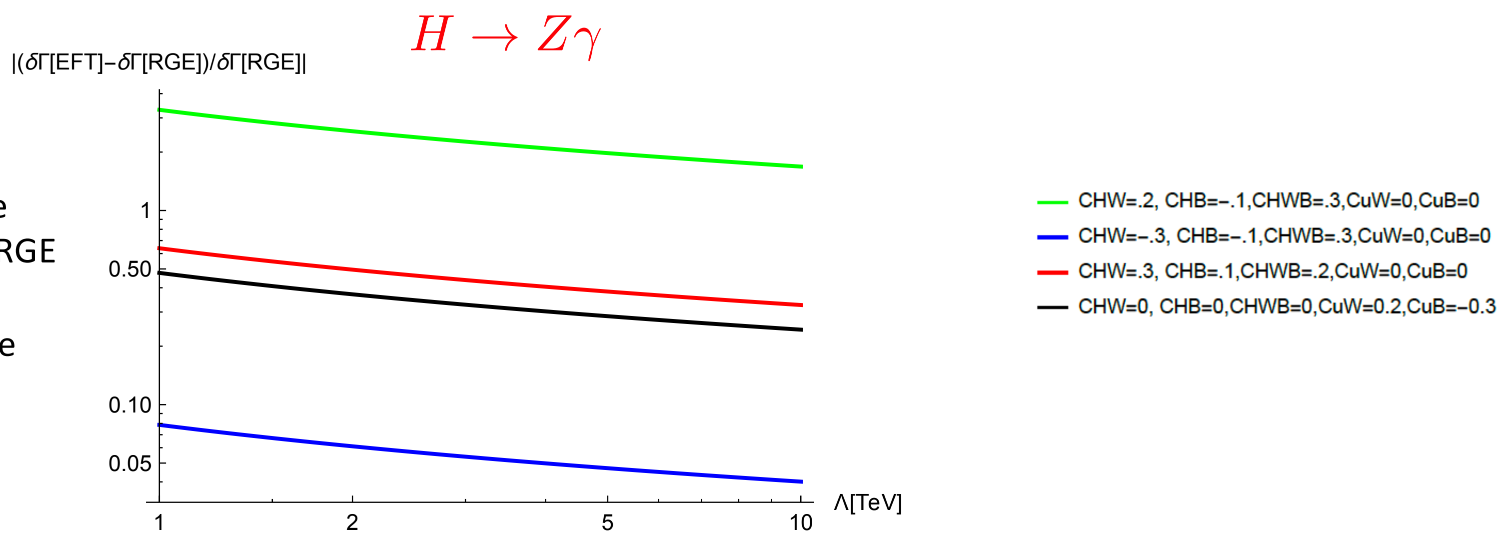
$\gamma\gamma$: 1807.11504, 1805.00302 γZ: 1801.01136, 1903.12046 $Z \to ff$: 1909.02000 $H \to bb$: 2007.15238, 1904.06358

NLO Electroweak SMEFT: Constants matter

- Example: H→Zγ
  - Λ~ 1 TeV, constants can give large effects (very dependent on specific values of coefficients)

δΓ[EFT]=Include loop constant +RGE

δΓ[RGE]=Include only RGE

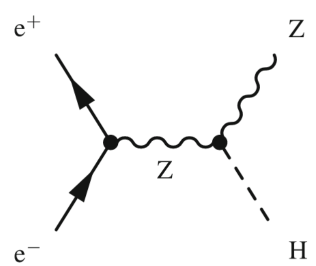


1801.01136, 1903.12046

* Similar conclusions for H→γγ

Precision Measurements at future e+e- colliders

- Model independent Higgs couplings and Higgs width at e^+e^- colliders
- Total Higgs width is window into light new physics
  - Perhaps H-> dark matter, new light scalars?



- Measure recoil mass from $Z\rightarrow l^+l^-$ to get σ_{ZH} and absolute measurement of g_{HZZ}

- Exclusive Higgs decays to xx give g_{Hxx}

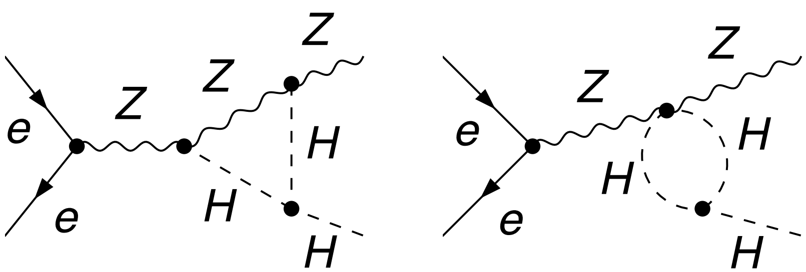
$$\sigma_{HZ}\frac{\Gamma(H\rightarrow ZZ)}{\Gamma_H}\sim\frac{g_{HZZ}^4}{\Gamma_H}$$

- Strong constraints on SMEFT coefficients that contribute at tree level from future e^+e^- colliders

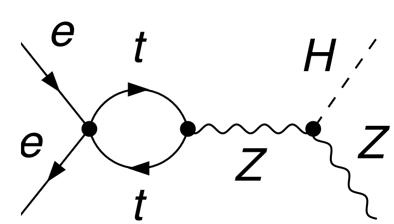
Projections: 2404.12809

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators
  - (~80 SMEFT operators contribute)
- Sensitive to poorly constrained interactions that first arise at NLO
- One-loop virtual + tree level real photon emission
  - Generate with FeynArts → FeynCalc → Package-X
  - Renormalize on-shell for M_W, M_Z, $\overline{\mathrm{MS}}$ for Wilson Coefficients, $C_i(\mu)$



Higgs tri-linear coupling, C_ϕ

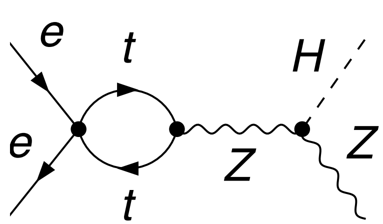


4-fermion operators, $C_{eu}[1133]$

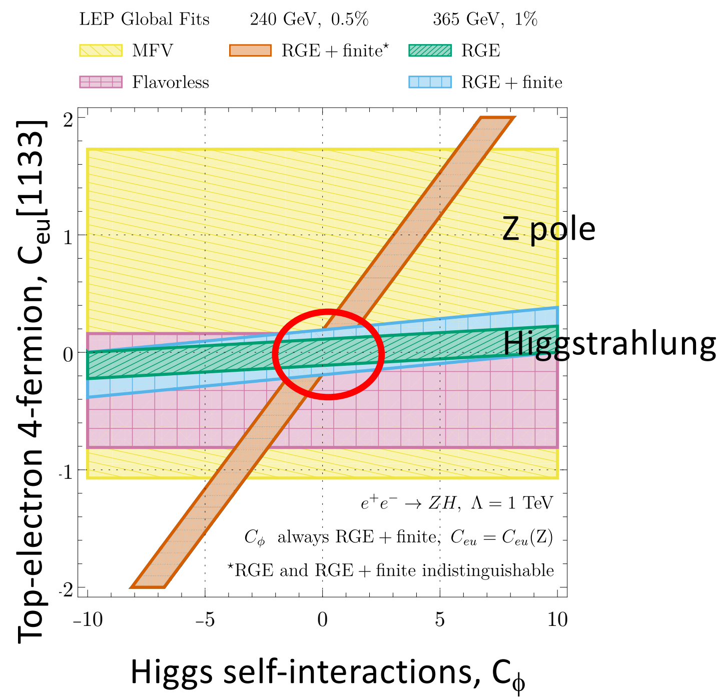
+ many more

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

- Sensitivity to Higgs tri-linear correlated with other contributions
  - Calculate to $1/\Lambda^2$ so results are linear bands
- How do future constraints compare with existing information?
  - Assume .5% accuracy on total cross section measurement at $\sqrt{s}$=240 GeV, 1% at $\sqrt{s}$=365 GeV
- Limits from Z-pole depend on flavor assumptions
  - Compare with global fits using MFV and flavor-blind operators



Observables at different scales: Z pole observables at M_Z, Higgstrahlung at $\sqrt{s}$



Power of measurement at 2 different energies

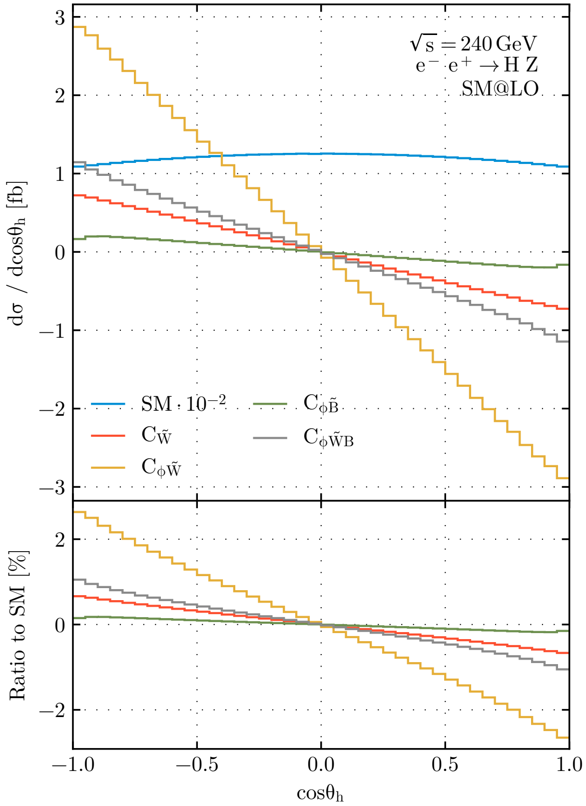
2406.03557

* C's in plots evaluated at $\mu = M_Z$

Sensitivity to CP violation

- Higgstrahlung at e^+e^- colliders is sensitive to CP violation in the gauge sector at NLO
- At tree level and to $O(1/\Lambda^2)$, CP violating dimension-6 operators do not interfere with the SM contribution from $e^+e^- \to ZH$ (since SM contribution is real and CP violating piece is imaginary)
- At one-loop, there is a contribution from imaginary part of loop integrals

$$
\begin{aligned}
O_{\tilde{W}} &= \epsilon_{abc} \tilde{W}_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{c,\mu} \\
O_{\phi\tilde{W}} &= \tilde{W}_{\mu\nu}^{a} W^{\mu\nu b} (\phi^\dagger \phi) \\
O_{\phi\tilde{B}} &= \tilde{B}_{\mu\nu} B^{\mu\nu} (\phi^\dagger \phi) \\
O_{\phi\tilde{W}B} &= \tilde{W}_{\mu\nu}^{a} B^{\mu\nu} (\phi^\dagger \sigma^a \phi)
\end{aligned}
$$



CP violation at future e^+e^- colliders

- Define CP violating asymmetry

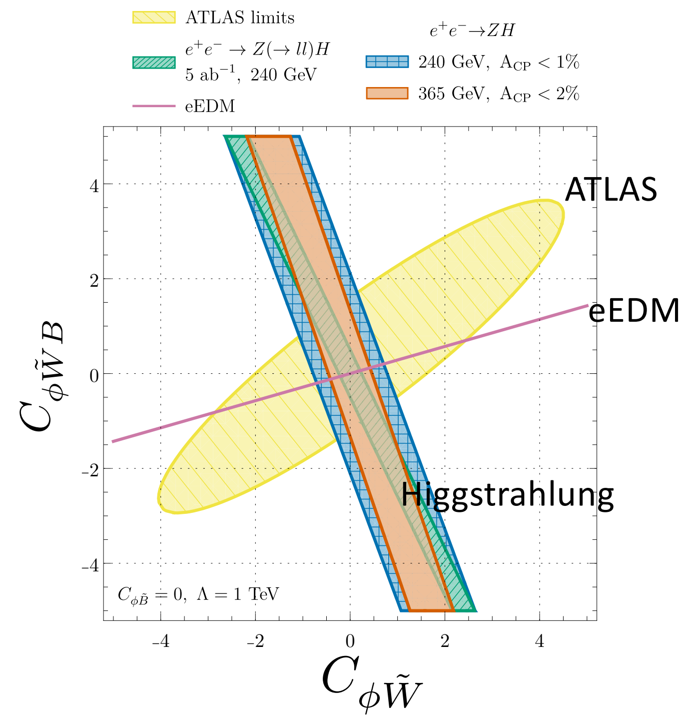
$$A_{CP} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

- 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

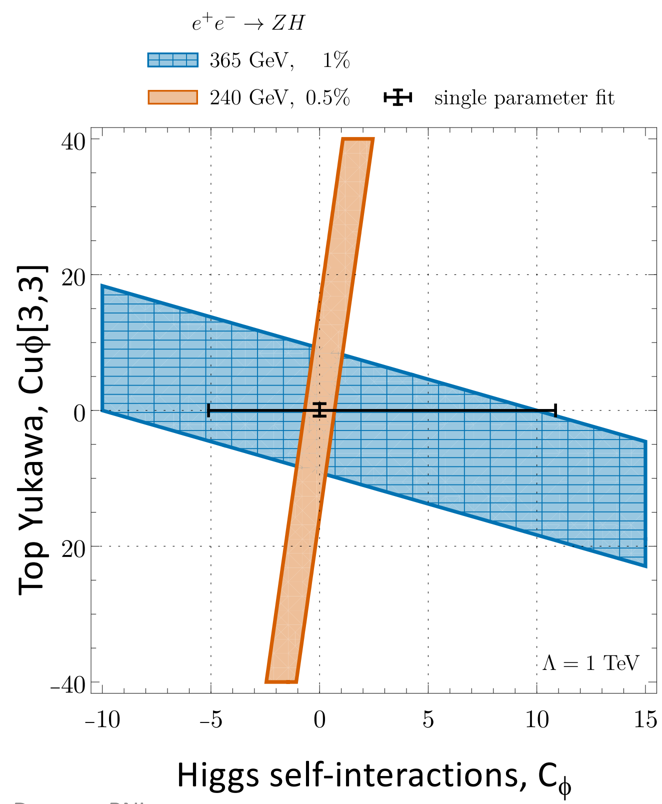


eEDM: 2109.15085, 1810.09413

2406.03557

Sensitivity to top operators in $e^+e^- \to ZH$

Combination of measurements at different energies can pin down coefficients very precisely



Global fits: 2012.02779, 2404.12809

Part III: When is Dimension-8 relevant?

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

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

- Generically, $1/\Lambda^4$ terms from $(\text{dim-6})^2$ and dim-8 are of the same order of magnitude
- Insight from case studies: scalar singlet, 2HDM, Z', and top partner models
- (Note these are all weakly coupled models)

Z' models

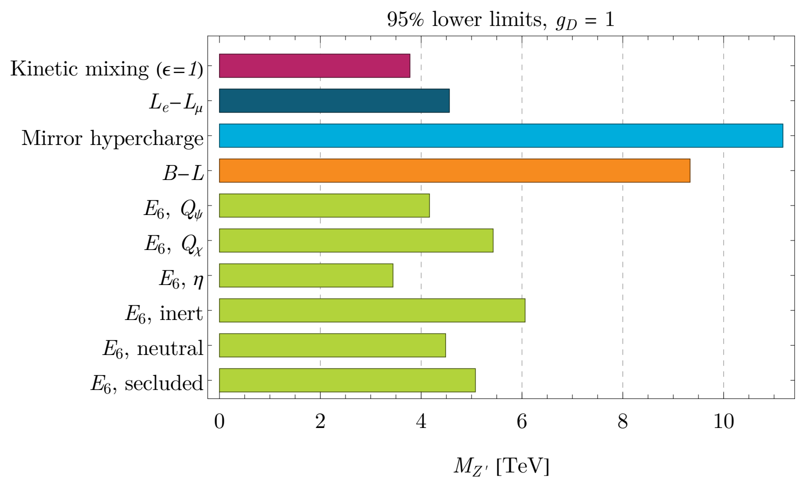
- Consider real spin-1 Z' that is a singlet under all SM gauge groups
- Most general gauge invariant Lagrangian

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu - \frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu} + (g_{H,2})^2 Z'_\mu Z'^\mu |H^\dagger H| - Z'_\mu \mathcal{J}^\mu,$$
$$\mathcal{J}^\mu = (i g_H) \left(H^\dagger \overleftrightarrow{D}^\mu H \right) + \sum_f \left(g_{ij}^{fL} \bar{f}_L^i \gamma^\mu f_L^j + g_{ij}^{fR} \bar{f}_R^i \gamma^\mu f_R^j \right),$$

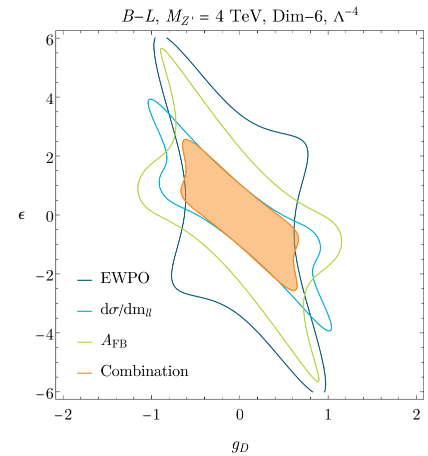
- Integrate Z' out of theory using standard techniques for tree level matching
- Match coefficients to dimension-8 for many popular Z' models
- Generates 2-fermion and 4-fermion operators, along with isospin violating operators
- Find limits from Drell-Yan (FB asymmetry and $d\sigma/dm_{ll}$) and from Z pole observables at NLO

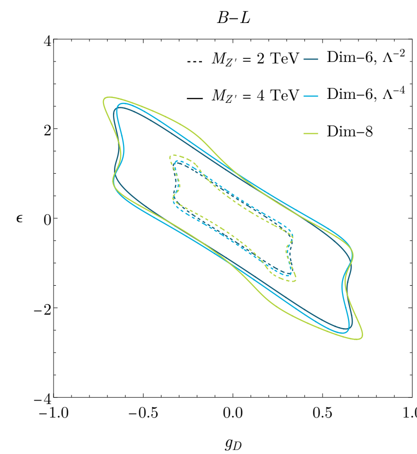
Z’ Models

- Limits are model dependent
- g_D defined in terms of parameters of specific models



2404.01375

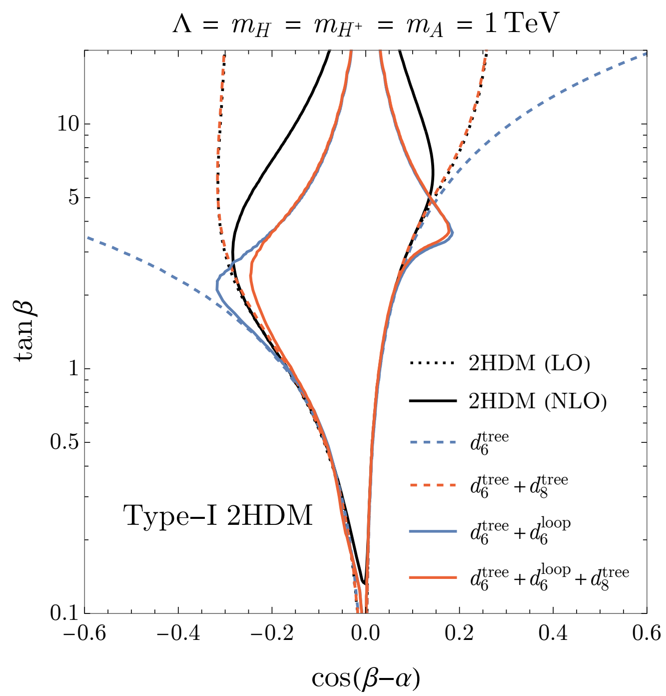




- In the B-L model: $d\sigma/dm_{ll}$ more constraining than A_{FB}
- Dim-8 contribution irrelevant

- Many generic dimension-8 operators are more constrained from A_{FB} than from $d\sigma/dm_{ll}$ 2303.08257

More complicated models: 2HDM



- Dim-8 relevant because H→VV first appears at dim-8 in the 2HDM
- Note importance of loop matching

- See also Higgs singlet to dimension-8: 2304.06663
- At dim-8, sensitivity to more parameters of scalar sector than at dim-6
- (This model has dimensionful cubic couplings)

2HDM: 2401.12279, 2205.01561

Conclusions

- Systematic study of SMEFT predictions with dependence on:
  - Flavor assumptions: They matter
  - Loop expansion: Need complete calculations including constant terms
  - $1/\Lambda^2$ expansion: Importance of dim-8 appears to be very model dependent
- Much work left to be done!
  - All of this can help to understand uncertainties on SMEFT predictions

All results are posted as auxiliary files, so you can do your own fits including your favorite assumptions