EFT Mapping to UV Models

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Top Down or Bottoms up approach?

- Bottoms up: $L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \Sigma \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots$

All BSM physics is in coefficient functions

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}'^j_p e'_r)(\bar{d}'_s q'^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(q'^{\gamma j}_s)^T C l'^k_t\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}'^j_p u'_r)\varepsilon_{jk}(\bar{q}'^k_s d'_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}'^j_p T^A u'_r)\varepsilon_{jk}(\bar{q}'^k_s T^A d'_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(q'^{\gamma m}_s)^T C l'^n_t\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}'^j_p e'_r)\varepsilon_{jk}(\bar{q}'^k_s u'_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}'^j_p \sigma_{\mu\nu} e'_r)\varepsilon_{jk}(\bar{q}'^k_s \sigma^{\mu\nu} u'_t)$		

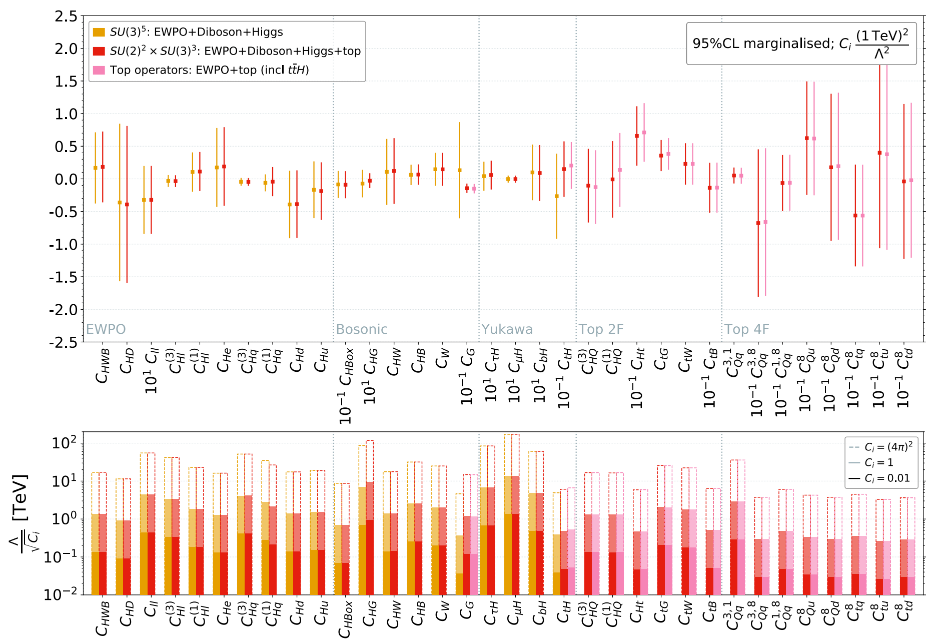
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}'_p e'_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}'_p u'_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^* (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}'_p d'_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar{q}'_p\sigma^{\mu\nu} d'_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}'_p\gamma^\mu d'_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}'_p\sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}'_p\gamma^\mu d'_r)$

In general,
2499 operators
at dimension-6

Many new fits (apologies to fit makers…)

- Fits have different assumptions, different sets of data included
- Probing TeV scale new physics



Fit includes top, Higgs, EWPO, diboson

Compare results with and without top data

C~1: New physics generated at tree level

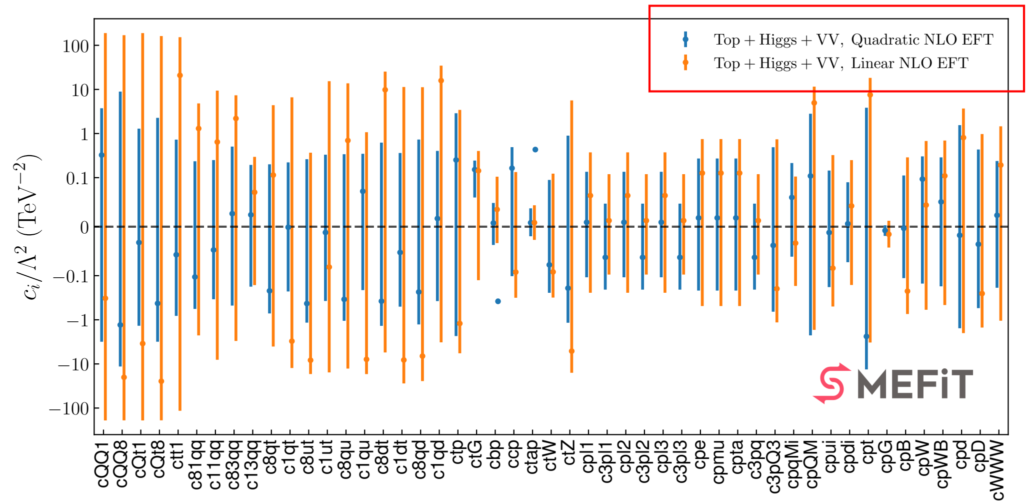
C~1/$(4\pi)^2$: New physics generated at loop level

At dim-6 only sensitive to C/Λ^2

See Madigan talk, 2012.02779

Many global fits to data

- Precision on operators varies over many order of magnitude
- Exact values of couplings sensitive to assumptions
- Compare effects of $1/\Lambda^2$ expansion



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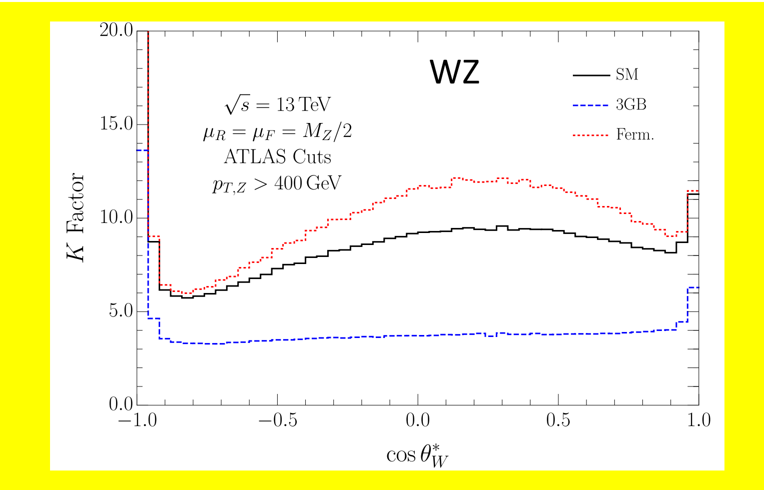
Understanding uncertainties in UV matching

- The order of the expansion in $1/\Lambda^2$
- Radiative corrections
- The order of the UV matching (tree or loop)
- RGE effects

Study a few models as an example

Radiative corrections matter

- QCD is automated for SMEFT fits
- EW is case by case basis
  - Problem with EW corrections is that they typically introduce a dependence on many new operators beyond that of LO fits



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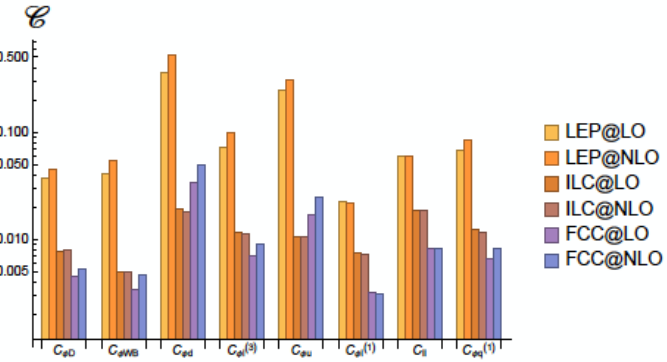

Simple examples

- When there is only 1 new high scale particle, finding the operators generated at tree and loop level is a solved problem at dimension-6
- Examples:
  - Scalar singlet S
  - Scalar Y=0 triplet ζ
  - U(1) Z', B
  - Gauge vector triplet, W
  - Top partner, T
  - Lepton Y=-1/2 doublet fermions (N,E)

* Table on next page includes possible contributions generated from dim-5 operators

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Patterns (table is incomplete!)

- Hope: Measuring a pattern of coefficients will give information about UV model

	$O_{\phi D}$	$O_{\phi \Box}$	$O_{\phi W}$	$O_{\phi B}$	$O_{\phi WB}$	$O_{d\phi}$	$O_{u\phi}$	$O_{e\phi}$	$O_{qq}^{(1)}$	$O_{qq}^{(3)}$
S		✓	✓	✓		✓	✓	✓		
ζ	✓	✓			✓	✓	✓	✓		
Z’	✓	✓				✓	✓	✓	✓	
W	✓	✓				✓	✓	✓		✓
T							✓			
(N,E)								✓		

Example: Spontaneously broken Higgs singlet model without Z_2 Symmetry

$$V(\phi, S) = V_{SM}(\phi) + V_{\phi S}(\phi, S) + V_S(S)$$

$$V_{\phi S}(\phi, S) = \frac{a_1}{2}(\phi^\dagger \phi) S + \frac{a_2}{2}(\phi^\dagger \phi) S^2$$

$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

- Models without Z_2 symmetry motived by desire to explain electroweak baryogenesis
- (They typically prefer negative a_1, b_3 and lighter H)
- Can set tan β=0 in this case (because we have included all possible terms: this just amounts to redefining parameters)

Can be studied in terms of mass of H, coupling of h to SM fermions (cos θ), coupling of Hhh, b_3, b_4

Singlet continued

- Tree level matching:

$$\frac{v^2}{\Lambda^2} C_{\phi\Box} = -\frac{1}{2}\tan^2\theta$$

$$C_\phi = -C_{\phi\Box}(\tan\theta\frac{b_3}{3v} - b_2)$$

$$\delta\lambda = -\frac{a_1^2}{b_2}$$

$$O_{\phi\Box} = (\phi^\dagger\phi)\partial^2(\phi^\dagger\phi)$$

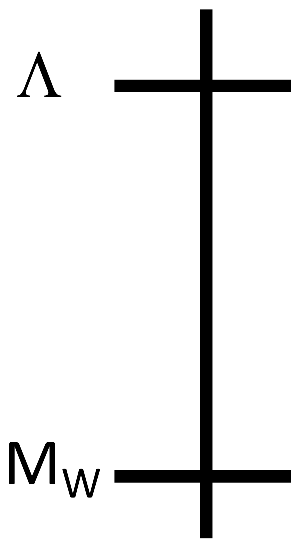
$$O_\phi = (\phi^\dagger\phi)^3$$

Coefficients predicted in terms of
UV model parameters

Scales and the EFT

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

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



UV Model → $C(\Lambda)$ — **Matching**

$$\frac{dC_i(\mu)}{d\log\mu} = \Sigma_j \frac{1}{16\pi^2}\gamma_{ij}C_j$$

Running — Note that γ_{ij} is not diagonal in general

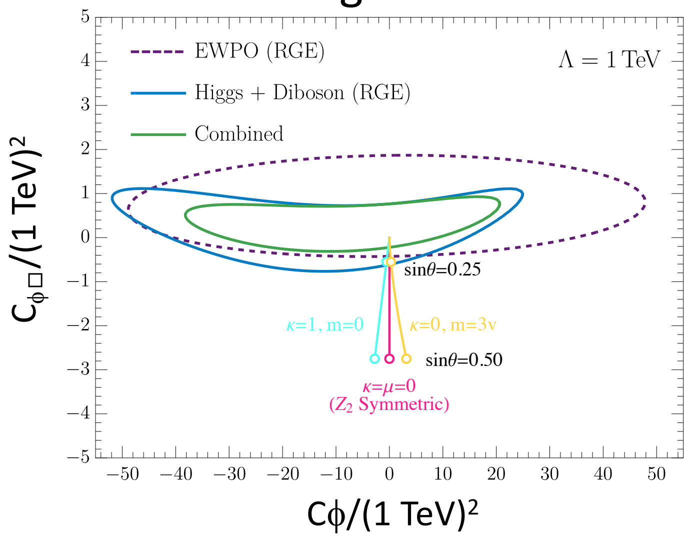
EFT→ $C(M_W)$ — **Precision**

Assume large separation of scales

Information about Singlet model from fits

- Including RGE running has significant effect on numerical fits
- Fit is done to arbitrary C_ϕ and $C_{\phi\Box}$, but model points lie on colored lines
- Uncertainty in combining C_ϕ and $C_{\phi\Box}$

Fit to coefficients occurring in scalar singlet model



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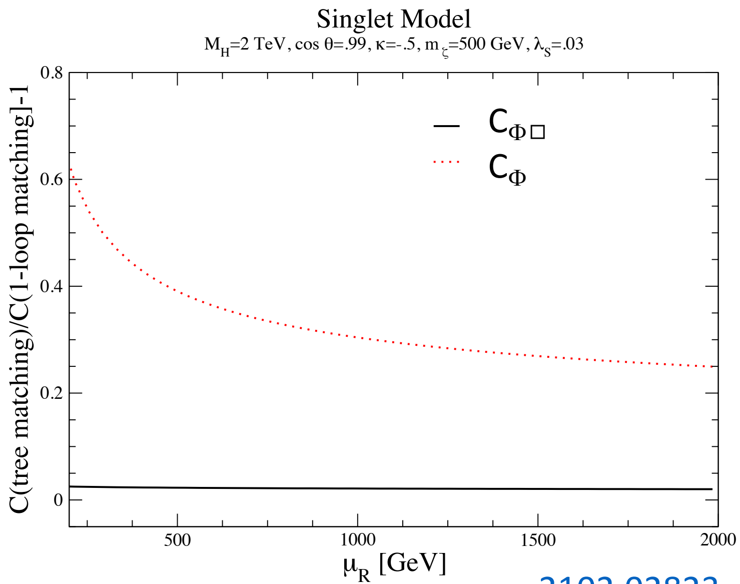
Singlet One-loop matching

- Does it matter for interpretation?
- Many more coefficients generated at 1-loop
  - Most of them are proportional to tree level $C_{\Phi\Box}$
  - 1-loop contributions to C_{Φ} and $C_{\Phi\Box}$ complicated



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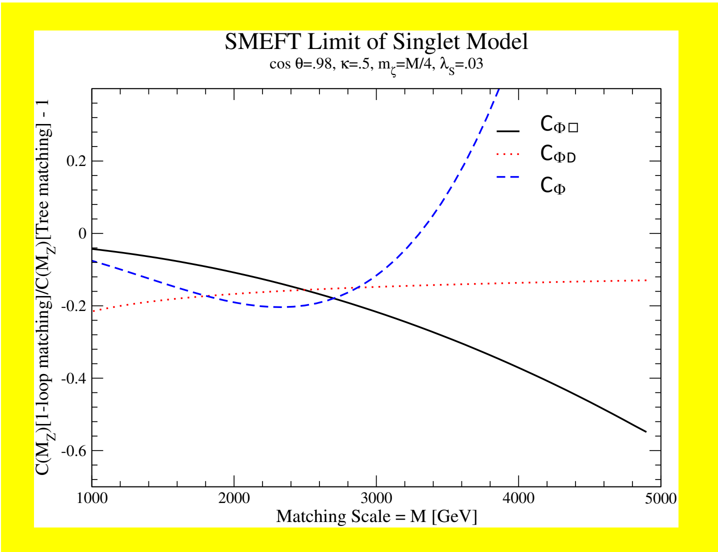
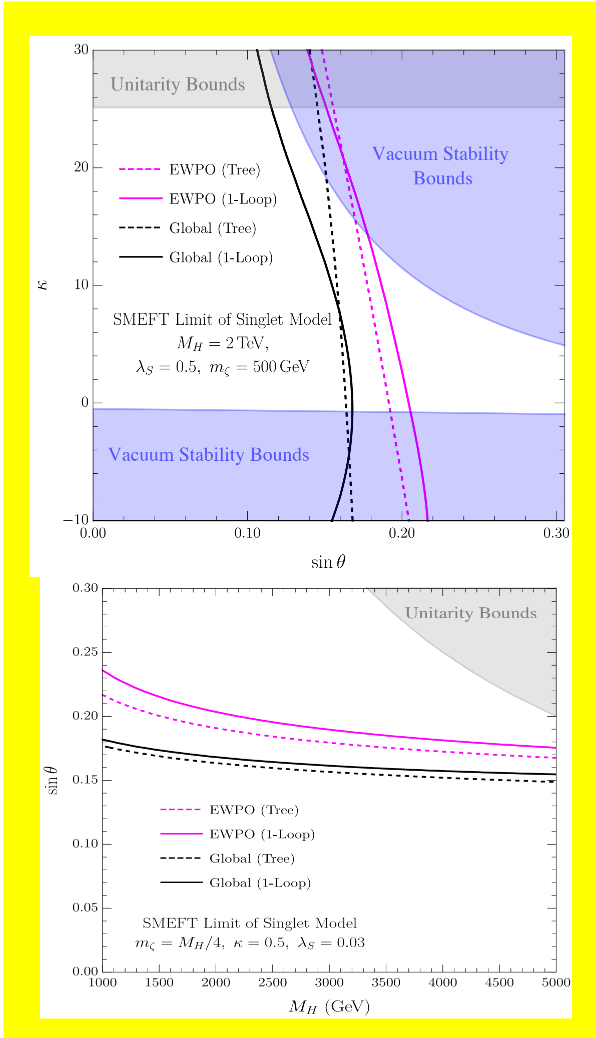
$$V(\Phi, S) \sim \frac{m_\xi}{2}\Phi^\dagger\Phi S + \frac{\kappa}{2}\Phi^\dagger\Phi S^2 + t_S S + \frac{M^2}{2}S^2 + \frac{m_\zeta}{3}S^3 + \frac{\lambda_S}{4}S^4$$

Singlet one-loop matching



In principle, one loop matching requires 2-loop RGEs

$$V(\Phi,S) \sim \frac{m_\xi}{2}\Phi^\dagger\Phi S + \frac{\kappa}{2}\Phi^\dagger\Phi S^2 + t_S S + \frac{M^2}{2}S^2 + \frac{m_\zeta}{3}S^3 + \frac{\lambda_S}{4}S^4$$



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Uncertainties at dimension-8?

$$A \sim A_{SM} + \frac{C_6}{\Lambda^2} A_6 + \frac{C_8}{\Lambda^4} A_8$$

$$d\sigma \sim |A_{SM}|^2 + 2Re(A_{SM} A_6^*) \frac{C_6}{\Lambda^2} + \left(\frac{C_6^2}{\Lambda^4} \mid A_6 \mid^2 + 2Re(A_{SM} A_8^*) \frac{C_8}{\Lambda^4} \right)$$

- Expanding a dimension-6 amplitude to O($1/\Lambda^2$) and squaring amplitude generates $1/\Lambda^4$ terms
- The interference of the SM with the dimension-8 amplitude also gives $1/\Lambda^4$ terms
- Agnostic approach, look at effects of generic dimension-8 operators
- Model specific approach, consider effects in typical models

T VLQ model

- Model is simple: add charge 2/3 vector-like Top partner T_L, T_R

$$L \sim -\lambda_t \overline{q}_L \tilde{H} t_R - \lambda_T \overline{q}_L \tilde{H} T_R - m_T \overline{T}_L \tilde{H} T_R + h.c.$$

- At tree level, generate 3 operators

$$Y_t C_{t\phi} = 2C^{(1)}_{\phi q,33} = -2C^{(3)}_{\phi q,33}$$

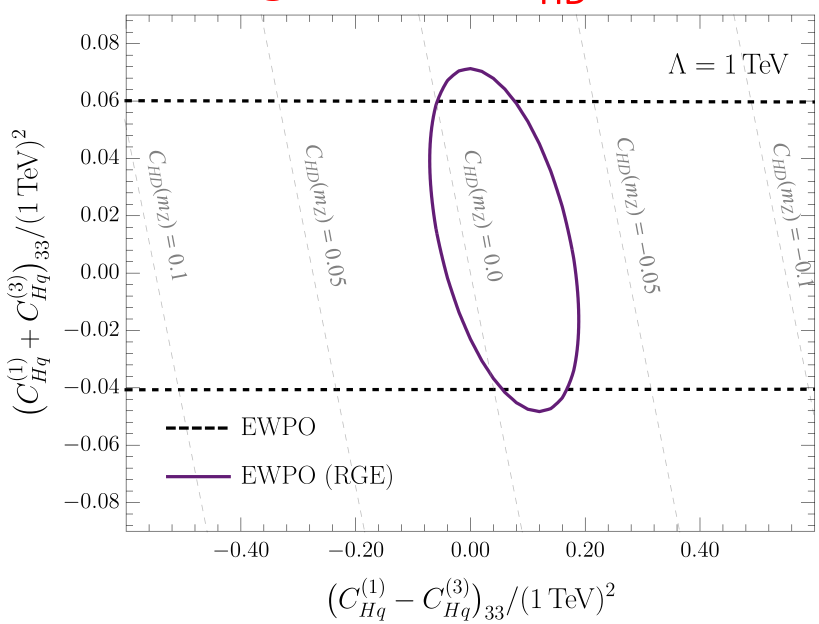
Note blind direction

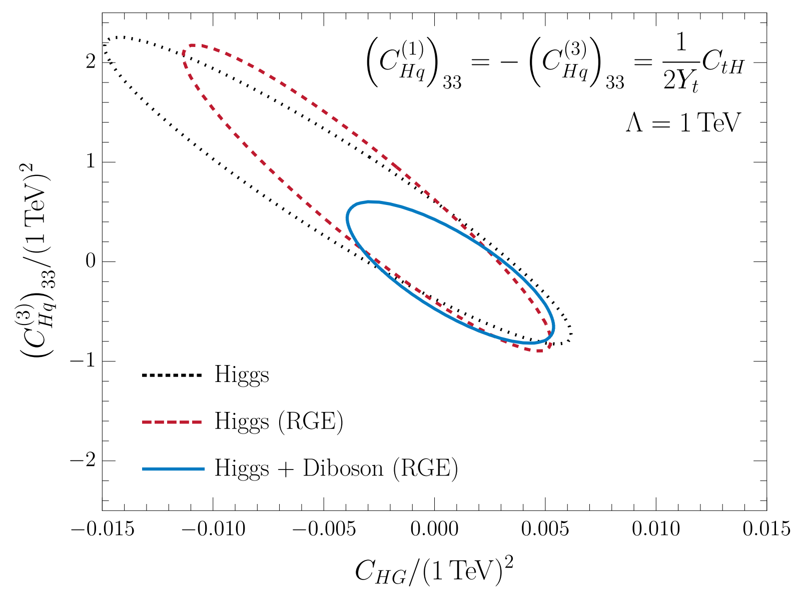
$$\frac{v^2}{\Lambda^2} C^{(1)}_{\phi q} = \frac{1}{2}(\sin\theta_L)^2$$

- At 1-loop, generate (among others) $O_{\Phi G}$ (effective ggH vertex)

TVLQ at dimension-6

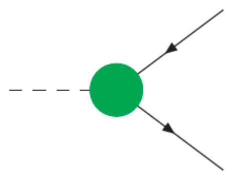
RGE generates C_{HD}



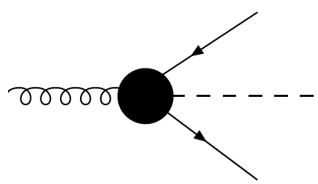


TVLQ at dimension-8

- At dimension-8, generate corrections to top Yukawa, but also momentum dependent contributions
- Can we see these effects in tails of distributions?

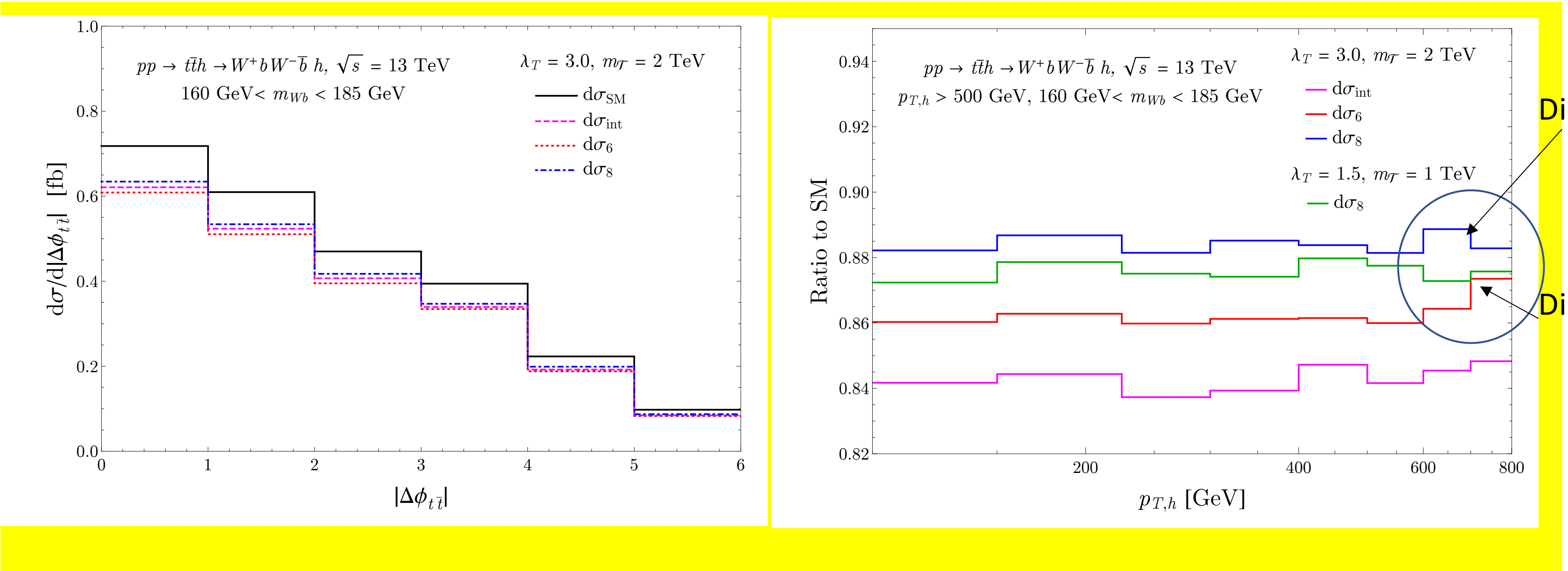


$$+\frac{i\lambda_T^2 v m_t}{4m_T^4}(p_1 - p_2)\cdot p_H (P_R - P_L)$$



$$\frac{m_t}{\iota_T^4} p_h^\mu T^A (P_R - P_L)$$

TVLQ at dimension-8 (ttH production)



Dimension-8 effects very small in this example

2HDM at dimension-8

- Add 2 Higgs doublets, Φ_1 and Φ_2, with VEVs v_1 and v_2
- Rotate to Higgs basis (H_1 and H_2) where only H_1 has VEV
- Consider usual fermion couplings to H_1 and H_2
- Assume H_2 is heavy and integrate it out using covariant derivative expansion
- At dimension-6 generate corrections to Yukawa-like interactions, $O_{\phi f,}$ and to Higgs self coupling, C_Φ

$$L_6 = \frac{C_H}{M^2}(H^\dagger H)^3 + \left[\frac{C_{dH}}{M^2}(H^\dagger H)\bar{q}_L H d_R + \frac{C_{uH}}{M^2}(H^\dagger H)\bar{q}_L \tilde{H} u_R + hc\right]$$

New operators at dim-6 change Higgs-fermion Yukawas and Higgs tri-linear, but don't generate momentum dependence

2HDM to dim-8

- At dim-8, new coefficients generate hVV interactions along with momentum dependent operators contributing to hh, VV production

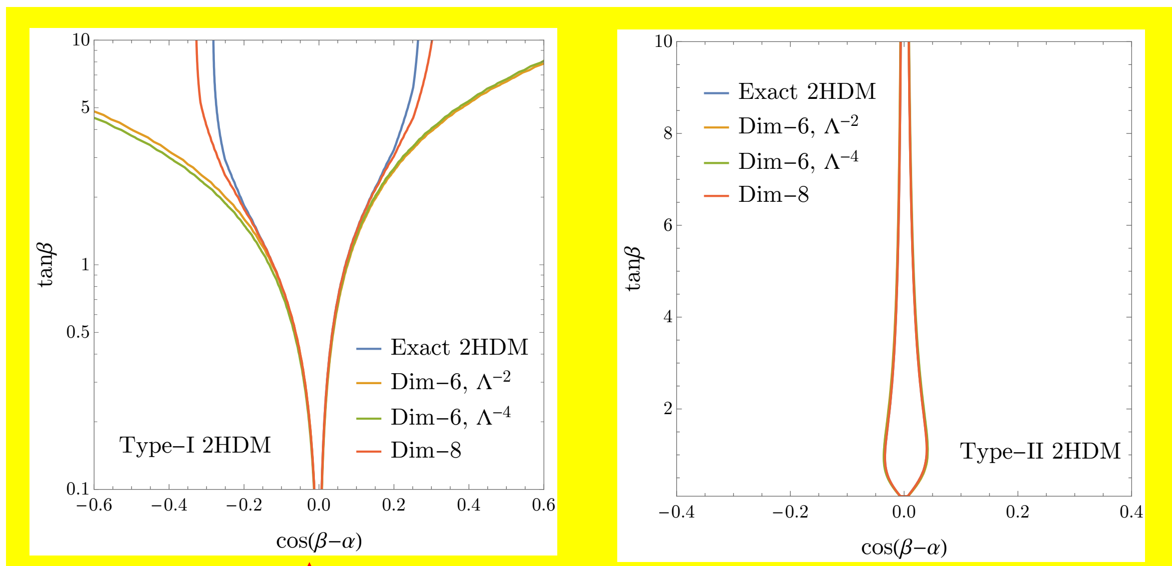
$$Y_f^{(2)} = \frac{\eta_f}{\tan\beta}\frac{\sqrt{2}m_f}{v}$$

	Type-I	Type-II
η_u	1	1
η_d	1	$-\tan^2\beta$
η_l	1	$-\tan^2\beta$

$$hVV \sim \sin(\beta-\alpha)$$

$$\cos(\beta-\alpha) \sim \frac{v^2}{M^2}$$

New physics at dim-8

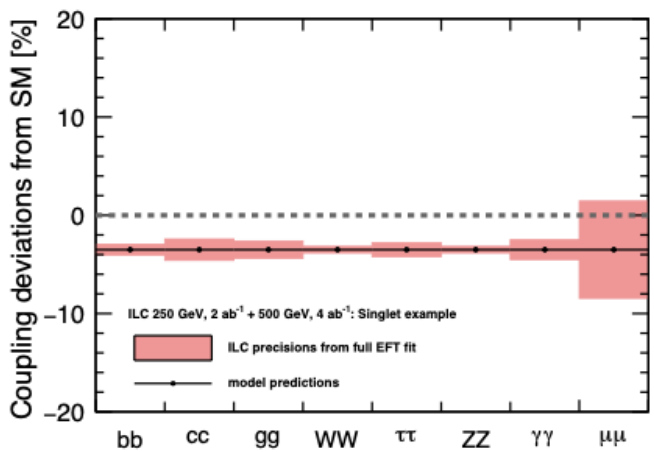


SM

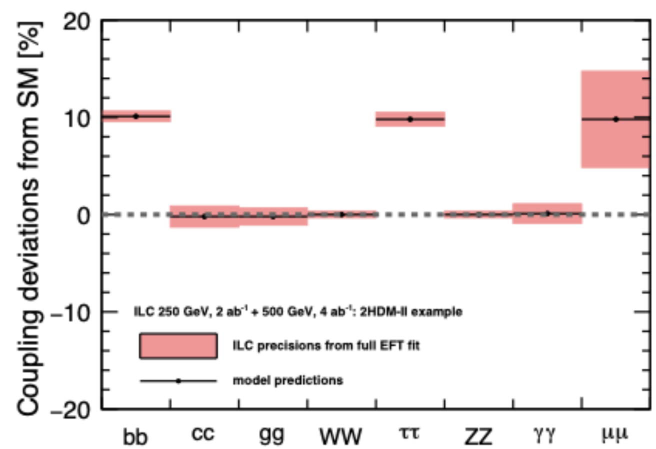
SD, D. Fontes, S. Homiller, and M. Sullivan, 2205.01561

Higgs Inverse problem from an e^+e^- perspective

- Take precision expected on SMEFT couplings at ILC



Singlet model with M_S=2.8 TeV



Type-II 2HDM with M_H=600 GeV, tan β=7

Uncertainties in UV matching to SMEFT

- Radiative corrections
  - QCD automatized
  - EW still on a case by case basis
- RGE running has significant effect on interpretations
- 1-loop matching automatized
  - But need 2-loop RGE for consistency
- Dimension-8 effects
  - Jury is still out