W-Boson Mass, Electroweak Precision Tests and SMEFT

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Based on arXiv: [2204.04805](https://arxiv.org/abs/2204.04805),
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W mass discussion

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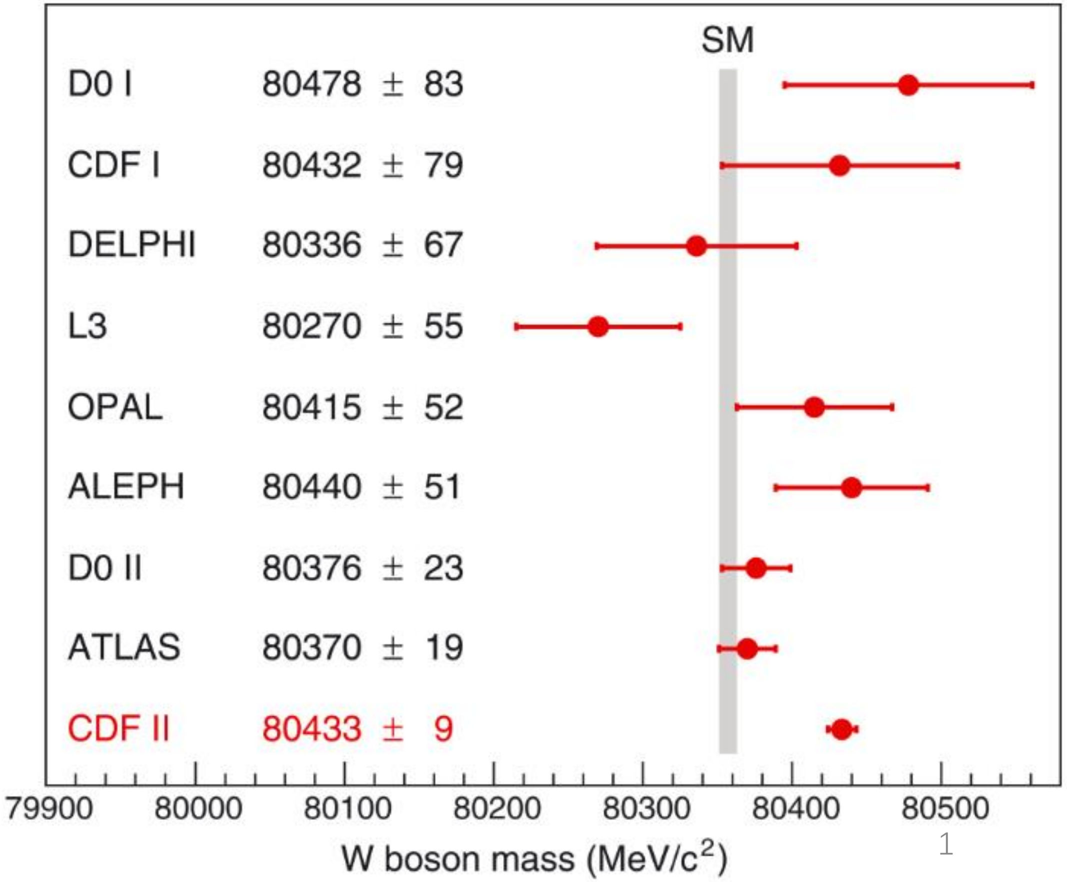


In total six Dim-6 SMEFT operators that are "self-contained": restrictions power comes from EWPO (except O_{WB}):

$O_{WB} \approx 1/3$ S

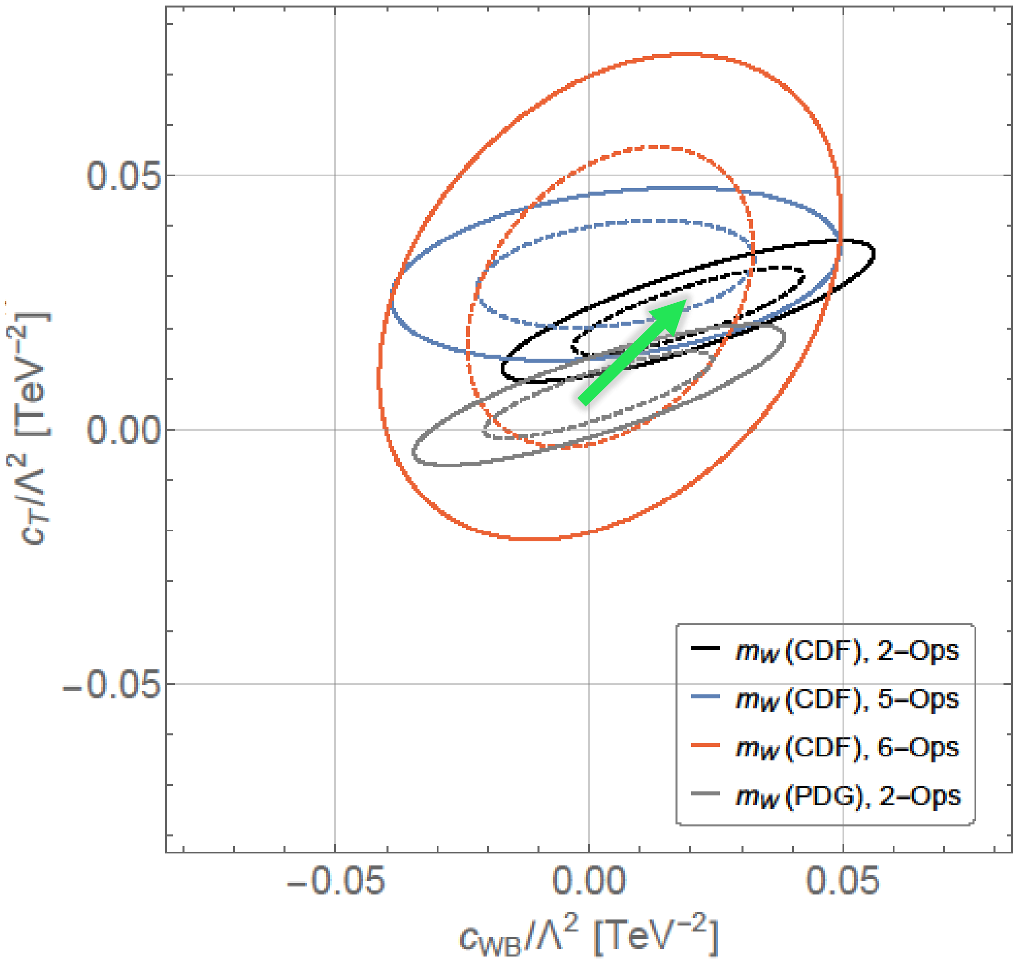
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu},$$

$O_T \approx 1/8$ T

$$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2\,,$$

$$\mathcal{O}_L^{(3)l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L), \qquad \mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$$

$$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L), \qquad \mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}_R \gamma^\mu l_R)\,.$$



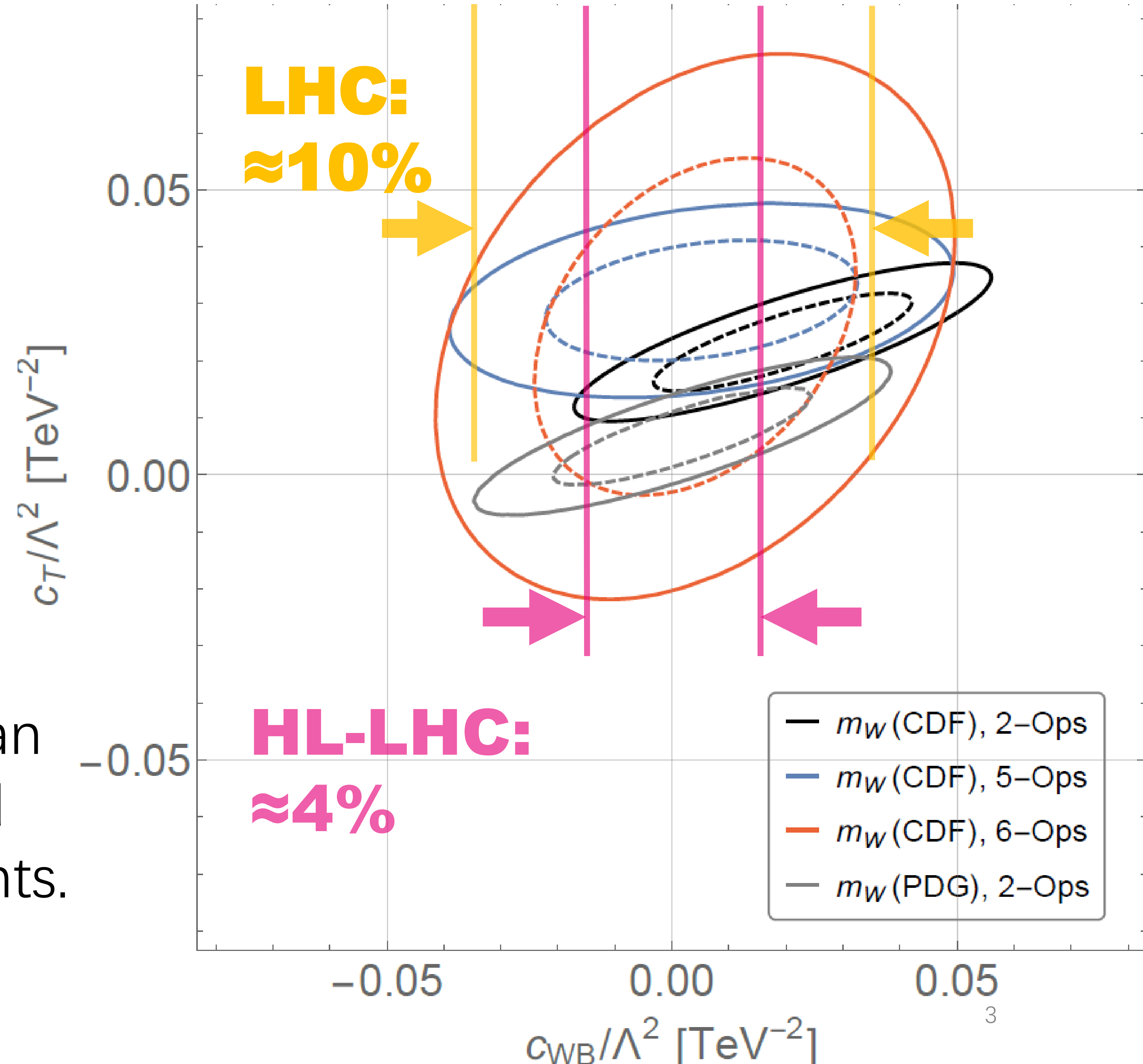
Fit with basic EWPO constraints with a theoretical W mass: 80354 ± 6 MeV:

$$R_b = \frac{\Gamma_b}{\Gamma_{\rm had}}, \quad R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_\ell}, \quad A_f, \quad A_{FB}^f = \frac{3}{4} A_e A_f \quad (f = b, \ell),$$

$$\sin^2\theta_{\rm eff}^{\rm lep} = \frac{1}{4}\left(1 - \frac{g_V^l}{g_A^l}\right), \quad \Gamma_Z, \quad \sigma_{\rm had}^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_e \Gamma_{\rm had}}{\Gamma_Z^2}, \quad \Gamma_W, \quad {\rm BR}_{W\to {\rm had}}$$

Also include the Higgs to γγ signal strength: $\mu_{ggh}^{\gamma\gamma}/\mu_{\rm SM}$ to constrain O_{WB}

Other Higgs signal strengths, especially Zγ, ZZ, and WW can further help pinning O_{WB} and O_T, but with weaker constraints.



Three different scenarios are considered:

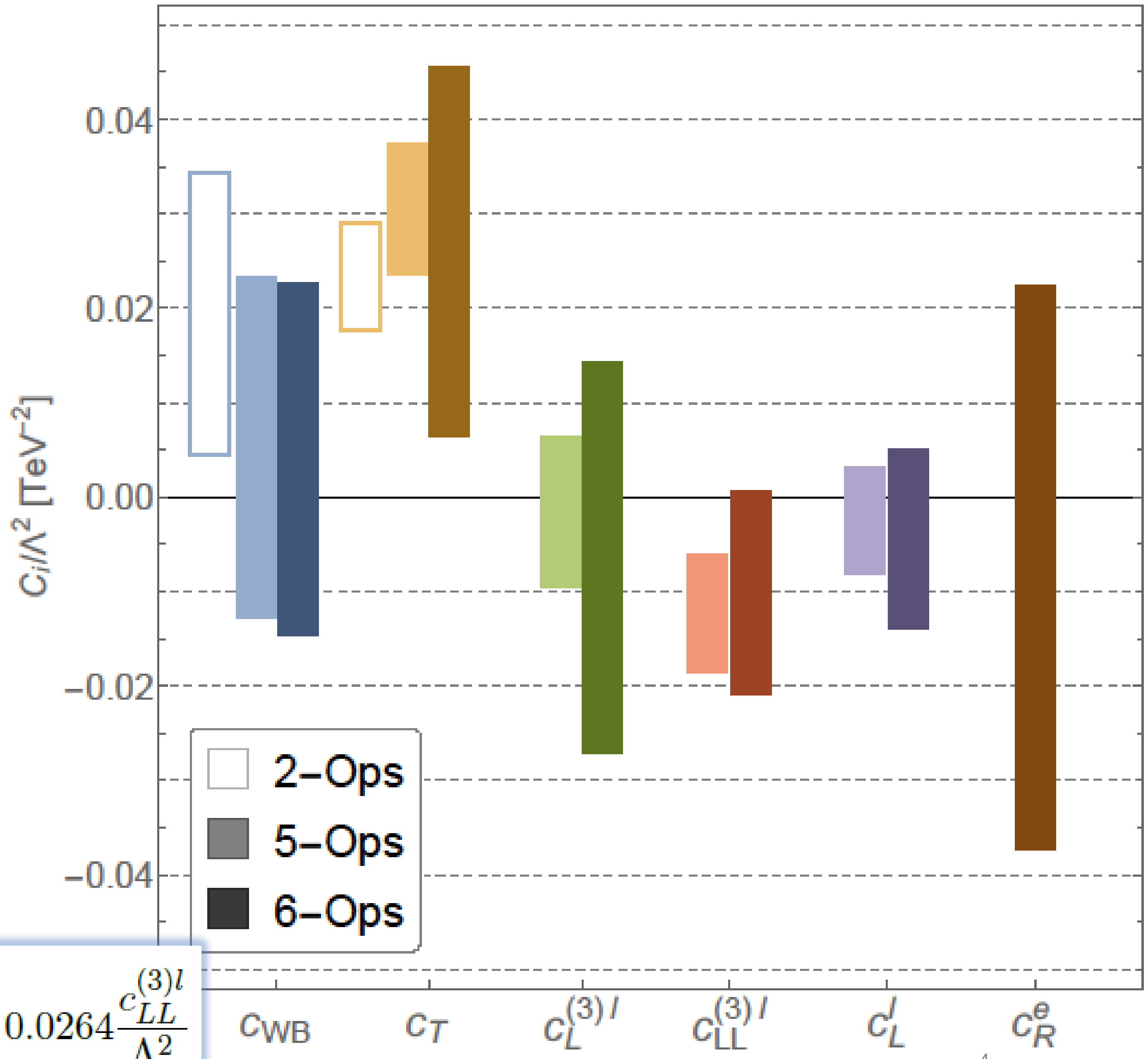
1. Only $\mathcal{O}_{WB}$ and $\mathcal{O}_T$ operators are turned on, corresponding to an S-T fit.

2. Five operators (except $\mathcal{O}_R^e$) are turned on.

3. All six opeartors are turned on.

$c_T(\mathrm{TeV}/\Lambda)^2 \gtrsim 0.01$ in all scenarios

$$\frac{\Delta m_W}{m_W} = -0.0111\frac{c_{WB}}{\Lambda^2} + 0.0433\frac{c_T}{\Lambda^2} - 0.0264\frac{c_L^{(3)l}}{\Lambda^2} + 0.0264\frac{c_{LL}^{(3)l}}{\Lambda^2}$$



W mass can (always) be satisfied, driving the whole fit away.

W width is also larger, coincide with the CDF W mass if $\Gamma_W \propto m_W$^3

The fit quality doesn't improve by including more operators.

Observables	Case (1)	Case (2)	Case (3)	Experimental Measurement
m_W(GeV)	80.4182	80.4335	80.4335	80.4335 ± 0.0094 [21]
A_b	0.934895	0.93481	0.934944	0.923 ± 0.020 [5, 19]
A_ℓ (P_τ)	0.14889	0.14744	0.14736	0.1465 ± 0.0033 [5, 19]
A_ℓ (SLD)	0.14889	0.14744	0.14736	0.1513 ± 0.0021 [5, 19]
R_b	0.21587	0.21588	0.21587	0.21629 ± 0.00066 [5, 19]
R_ℓ	20.7510	20.7592	20.7634	20.767 ± 0.025 [5, 19]
$A^b_{\rm FB}$	0.10448	0.10340	0.10335	0.0996 ± 0.0016 [5, 19]
$A^\ell_{\rm FB}$	0.01657	0.01629	0.01627	0.0171 ± 0.0010 [5, 19]
Γ_Z(GeV)	2.49818	2.49515	2.49537	2.4955 ± 0.0023 [5]
$\sigma^0_{\rm had}$(nb)	41.4915	41.4729	41.4771	41.480 ± 0.033 [22]
Γ_W(GeV)	2.09262	2.09109	2.09261	2.085 ± 0.042 [5]
${\rm BR}_{W\to{\rm had}}$	0.6748	0.6748	0.6749	0.6741 ± 0.0021 [5]
$\sin^2\theta^{\rm lep}_{\rm eff}(10^{-5})$	23127.7	23146.6	23147.7	(23143 ± 25) [6]
$\mu^{\gamma\gamma}_{ggh}/\mu_{\rm SM}$	1.11	1.03	1.02	1.02 ± 0.11 [23]
χ^2/D.O.F	1.38	1.20	1.34	

Implications of New Physics

A hypercharge-free triplet (Σ) with SU(3) ×SU(2) ×U(1) = (1,3,0) :

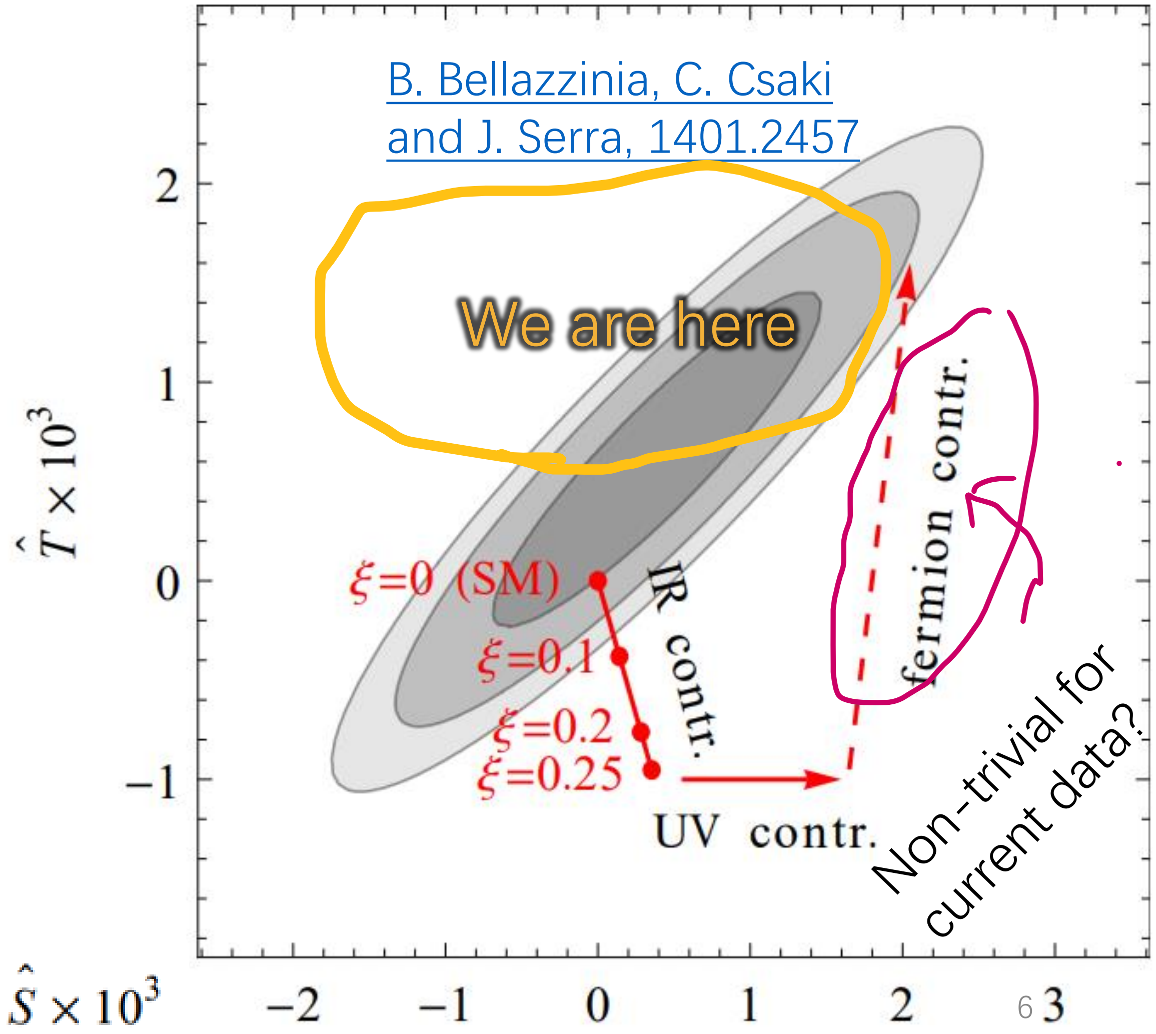
$$\mathcal{L} \supset -\lambda H^\dagger \Sigma H \ - \frac{\lambda_3}{2}(H^\dagger H)\Sigma\Sigma, \ \Rightarrow \ T \simeq \frac{1}{\alpha}\frac{2\langle\Sigma\rangle^2}{v^2}$$

Found in many references, see e.g:

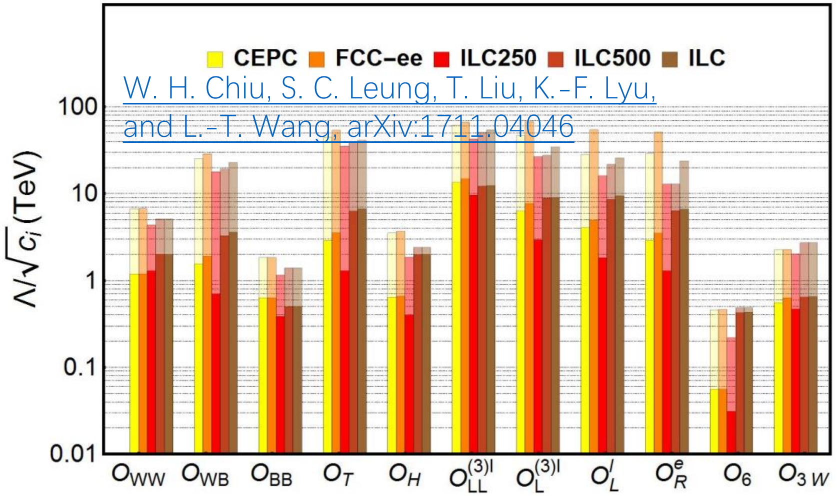
Z. U. Khandker, D. Li, and W. Skiba, 1201.4383

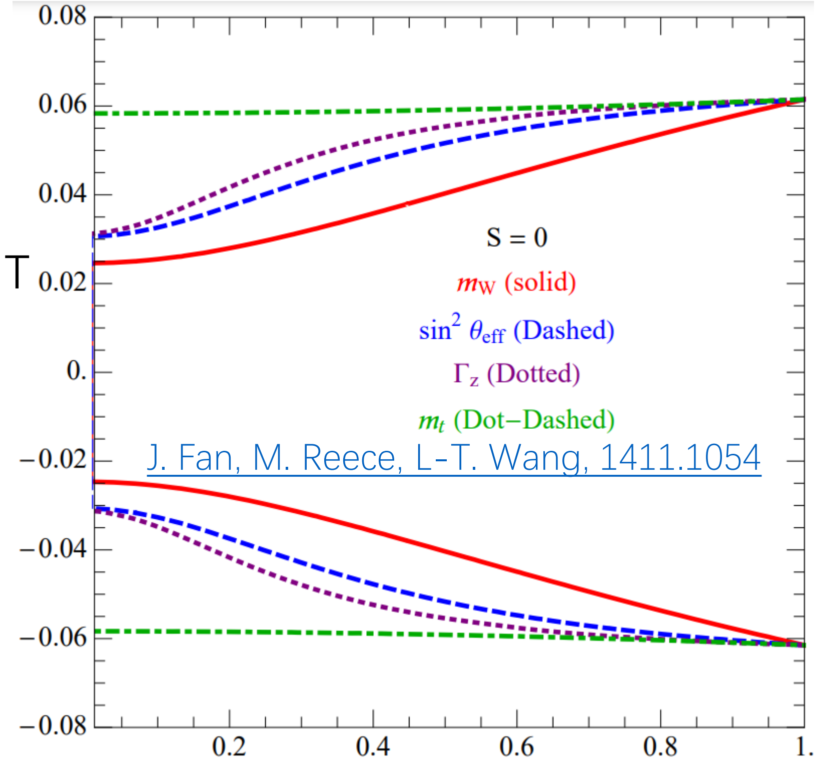
Mass raised to multi-TeV range with large couplings, not guaranteed at HL-LHC.

Composite Higgs models: not in a good shape?



CEPC Wishlist





Could future ee colliders like CEPC bring us the best experimental precision on bread and butter for EWPO: m_W, m_Z, Γ_Z, m_t, $\sin\theta_w$, etc.?

- YES! Powerful runs at the Z pole, WW threshold(!), Higgs factory mode and tt threshold after upgrades.
- Key numbers from the preliminary CEPC white paper and other ref.: $\delta m_W \approx 0.5$-1 MeV, $\delta m_Z \approx 0.1$ MeV, $\delta m_t \lesssim 100$ MeV, $\delta \sin\theta_w \lesssim 10^{-5}$: experiment is no longer the most limiting factor.
- Possible to bring the current EW precision up by an order of magnitude.

Could the theory interpretation of m_W catch-up with the experiment by the time of CEPC runs? (More discussions in J. Fan, M. Reece, L-T. Wang, 1411.1054 & A. Freitas, S. Heinemeyer et al. 1906.05379)

- "parametric uncertainties" bottle necks: currently from m_t (0.5 → <0.1 GeV). At CEPC era: $\Delta\alpha_{\rm had}^{(5)}$ (4×10^{-4} → ~5×10^{-5}) → δm_W(th) ≲1 MeV.
- "Intrinsic uncertainties": on m_W itself needs to go beyond two-loops (4 → 1 MeV). QED radiation & σ(WW → 4f) will contribute δm_W(th) ≲ 0.6 MeV.

Could CEPC figure out the nature of new physics?

- O(20) EW (pseudo)observables and similarly many Higgs ones: greatly narrow down the candidate theory space.

Hope for CEPC to DISCOVER the new physics DIRECTLY?