Electroweak precision data and Higgs physics

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HEFT 2017

1. **Overview of electroweak precision tests**

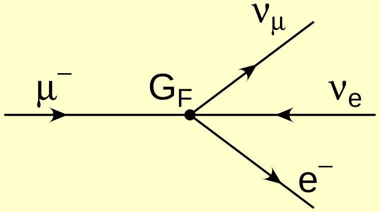
2. **Effective operator description**

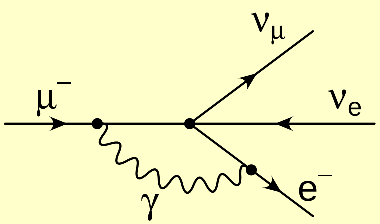
3. **Connection between EWPO and HEFT**

Overview of electroweak precision tests

W mass

μ decay in Fermi Model



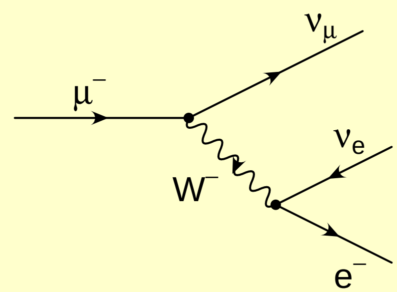


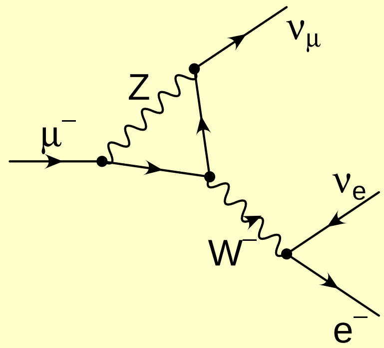
← QED corr. (2-loop)

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)(1 + \Delta q)$$

Ritbergen, Stuart '98
Pak, Czarnecki '08

μ decay in Standard Model





$$\frac{G_F^2}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}(1 + \Delta r)$$

electroweak corrections

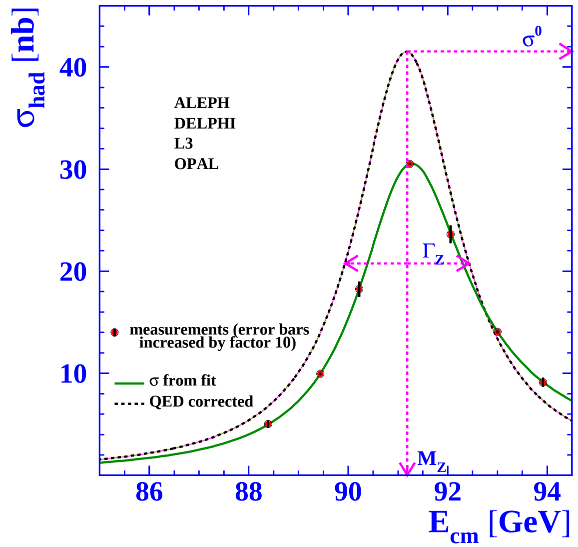
Z-pole observables

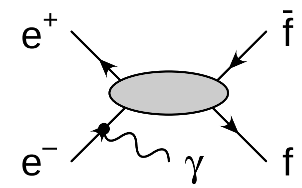
- Deconvolution of initial-state QED radiation:

$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\text{ini}}(s,s') \otimes \sigma_{\text{hard}}(s')$$

Kureav, Fadin '85
Berends, Burgers, v. Neerven '88
Kniehl, Krawczyk, Kühn, Stuart '88
Beenakker, Berends, v. Neerven '89
Skrzypek '92
Montagna, Nicrosini, Piccinini '97

LEP EWWG '05





Z-pole observables

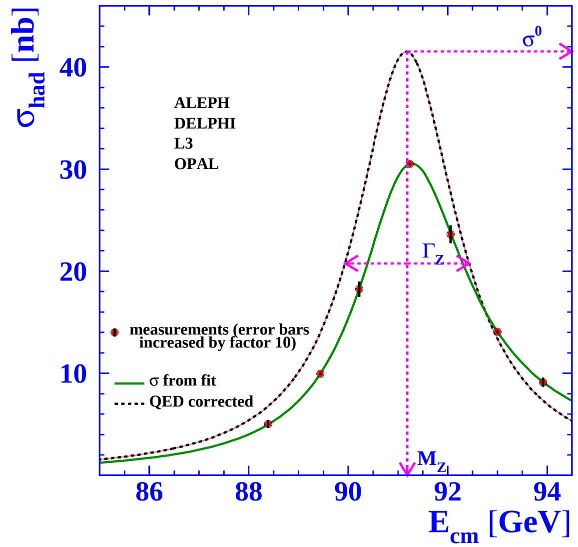
- Deconvolution of initial-state QED radiation:

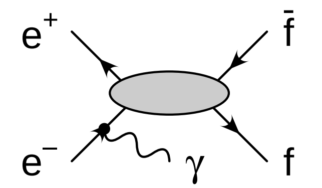
$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\text{ini}}(s,s') \otimes \sigma_{\text{hard}}(s')$$

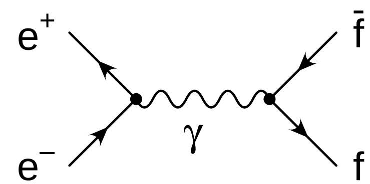
- Subtraction of γ-exchange, γ–Z interference, box contributions:

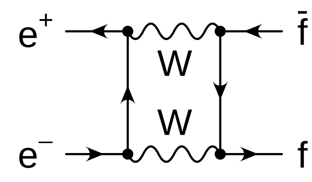
$$\sigma_{\text{hard}} = \sigma_Z + \sigma_\gamma + \sigma_{\gamma Z} + \sigma_{\text{box}}$$

LEP EWWG '05









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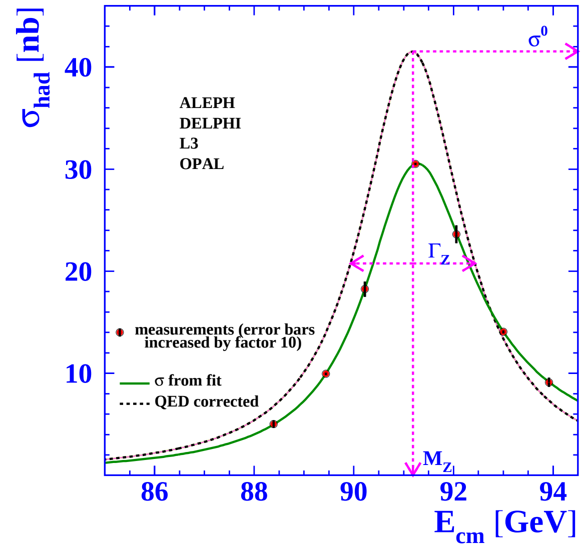
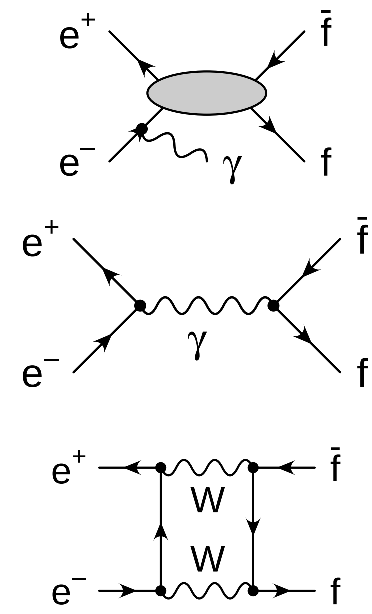
- Z-pole contribution:

$$\sigma_{\text{Z}} = \frac{R}{(s - \overline{M}_{\text{Z}}^2)^2 + \overline{M}_{\text{Z}}^2\overline{\Gamma}_{\text{Z}}^2} + \sigma_{\text{non-res}}$$

LEP EWWG '05





Z-pole observables

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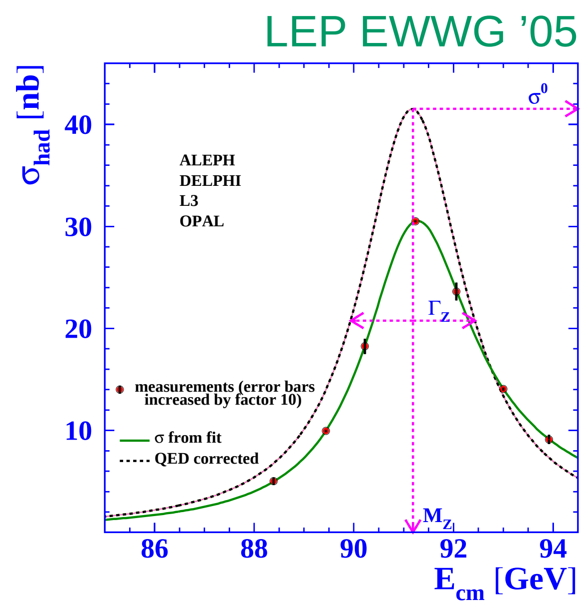
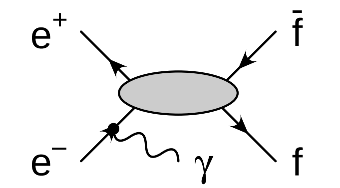
- In experimental analyses:

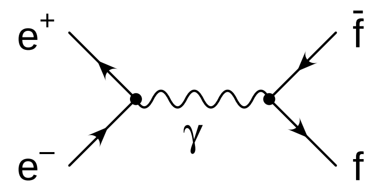
$$\sigma \sim \frac{1}{(s-M_{\text{Z}}^2)^2 + s^2\Gamma_{\text{Z}}^2/M_{\text{Z}}^2}$$

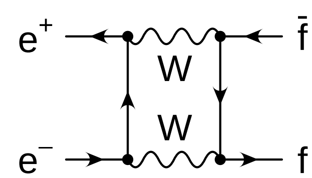
$$\overline{M}_{\text{Z}} = M_{\text{Z}}\Big/\sqrt{1+\Gamma_{\text{Z}}^2/M_{\text{Z}}^2} \approx M_{\text{Z}} - 34\text{ MeV}$$

$$\overline{\Gamma}_{\text{Z}} = \Gamma_{\text{Z}}\Big/\sqrt{1+\Gamma_{\text{Z}}^2/M_{\text{Z}}^2} \approx \Gamma_{\text{Z}} - 0.9\text{ MeV}$$









Z-pole observables

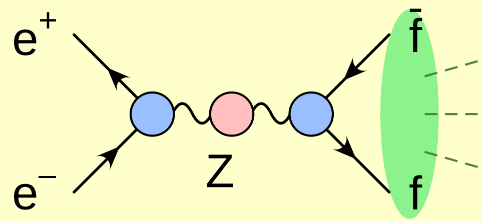
Total and partial Z widths:

$$\overline{\Gamma}_f = \Gamma[Z \to f\bar{f}]_{s=\overline{M}_Z^2} \qquad \overline{\Gamma}_Z = \sum_f \overline{\Gamma}_f$$

$$\overline{\Gamma}_f \approx \frac{N_c \overline{M}_Z}{12\pi}\left[\left(\mathcal{R}_V^f |g_V^f|^2 + \mathcal{R}_A^f |g_A^f|^2\right)\frac{1}{1+\text{Re}\,\Sigma'_Z}\right]_{s=\overline{M}_Z^2}$$

$\mathcal{R}_V^f, \mathcal{R}_A^f$: Final-state QED/QCD radiation;

g_V^f, g_A^f, Σ'_Z: Electroweak corrections



Branching ratios:

$R_q = \overline{\Gamma}_q / \overline{\Gamma}_{\text{had}}$ ($q = b, c$, probes heavy quark generations)

$R_\ell = \overline{\Gamma}_{\text{had}} / \overline{\Gamma}_\ell$ ($\ell = e, \mu, \tau$)

Z-pole observables

Peak cross section:

$$\sigma^0_{\text{had}} = \sigma_Z(s = \overline{M}^2_Z) = \frac{12\pi}{\overline{M}^2_Z} \sum_q \frac{\overline{\Gamma}_e \overline{\Gamma}_q}{\overline{\Gamma}^2_Z}(1 + \delta X)$$

↳ NNLO correction term

Z-pole asymmetries / effective weak mixing angle:

$$A^f_{\text{FB}} \equiv \frac{\sigma(\theta < \frac{\pi}{2}) - \sigma(\theta > \frac{\pi}{2})}{\sigma(\theta < \frac{\pi}{2}) + \sigma(\theta > \frac{\pi}{2})} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$A_{\text{LR}} \equiv \frac{\sigma(\mathcal{P}_e > 0) - \sigma(\mathcal{P}_e < 0)}{\sigma(\mathcal{P}_e > 0) + \sigma(\mathcal{P}_e < 0)} = \mathcal{A}_e$$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2} = \frac{1 - 4|Q_f| \sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2}$$

Most precisely measured for $f = \ell$ (also $f = b, c$)

Current uncertainties

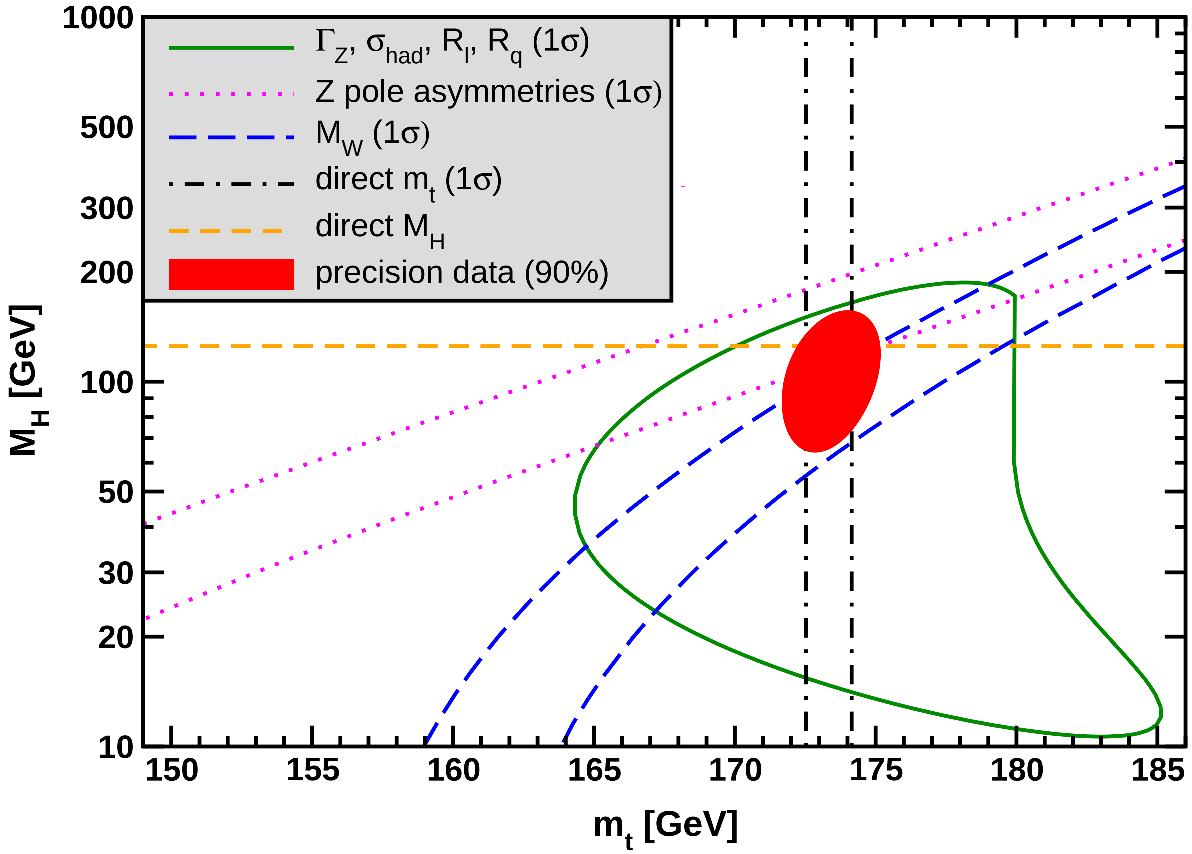
	Experiment	Theory error	Main source
M_W	80385 ± 15 MeV	4 MeV	α^3, $\alpha^2\alpha_\mathrm{s}$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$, $\alpha\alpha^2_\mathrm{s}$
σ^0_had	41540 ± 37 pb	6 pb	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$
R_b	0.21629 ± 0.00066	0.00015	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$
$\sin^2\theta^\ell_\mathrm{eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_\mathrm{s}$

Impact on Higgs physics

Standard Model:

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables

Erler '16



Direct measurements:

$M_H = 125.09 \pm 0.24$ GeV

$m_t = 173.34 \pm 0.81$ GeV

Indirect prediction:

$M_H = 126.1 \pm 1.9$ GeV (with LHC BRs)

$M_H = 96^{+22}_{-19}$ GeV (w/o LHC data)

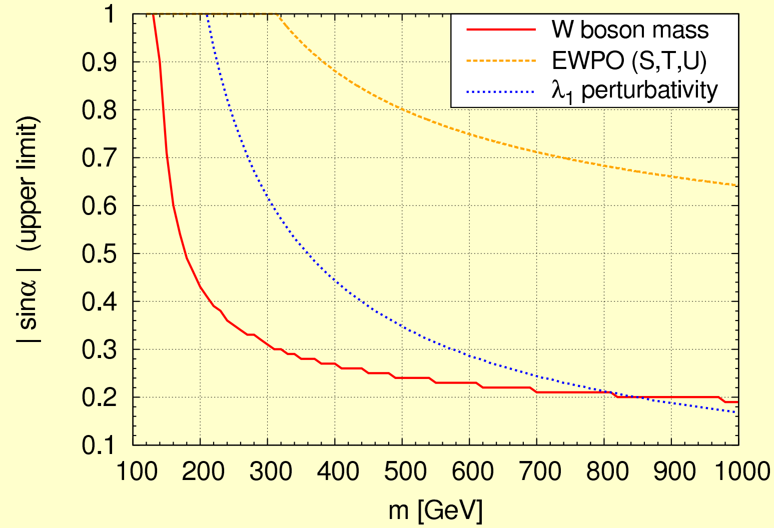
$m_t = 176.7 \pm 2.1$ GeV

Impact on Higgs physics

Higgs singlet extension:

Robens, Stefaniak '13

Constraints on singlet mass and mixing angle



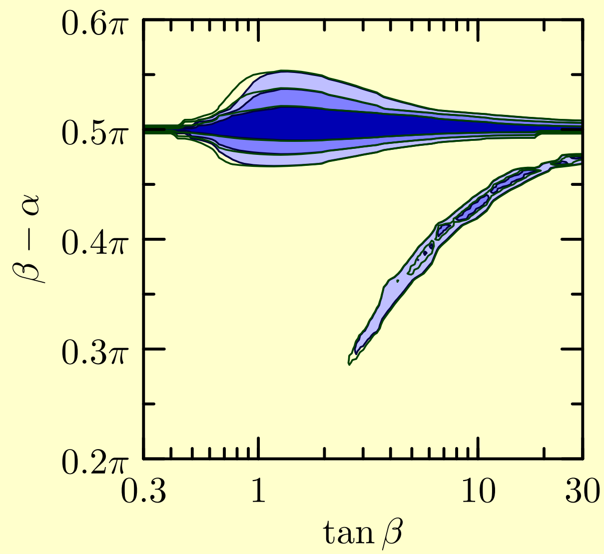
Two-Higgs-Doublet Model:

Eberhardt, Nierste, Wiebusch '13

Constraints on couplings of SM-like Higgs

$$\left|\frac{g_{hVV}^{\text{THDM}}}{g_{hVV}^{\text{SM}}}\right| = \sin(\beta - \alpha),$$

$$\left|\frac{g_{hff}^{\text{THDM}}}{g_{hff}^{\text{SM}}}\right| = \frac{\cos\alpha}{\sin\alpha} \text{ or } \frac{\sin\alpha}{\cos\alpha}$$



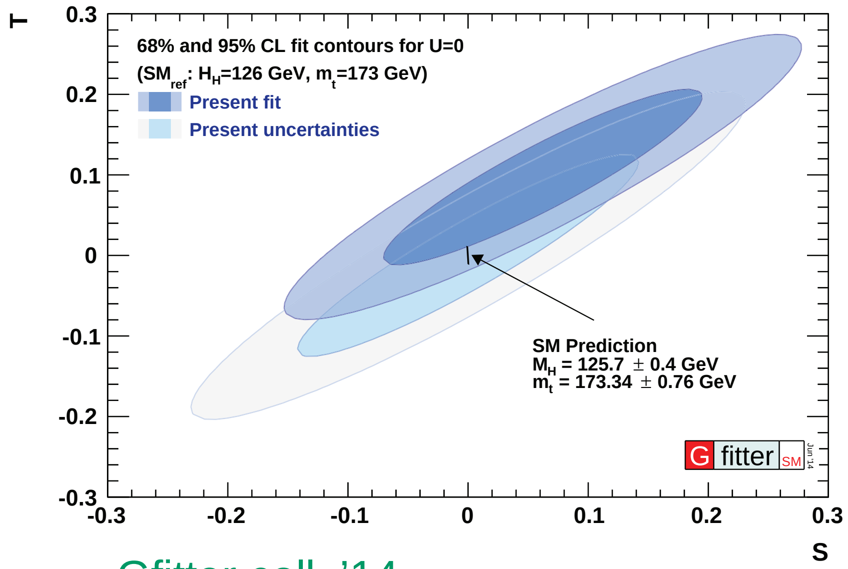
Impact on Higgs physics

Oblique parameters:

$$\alpha T = \frac{\Sigma_{WW}(0)}{M_W} - \frac{\Sigma_{ZZ}(0)}{M_Z}$$

$$\frac{\alpha}{4s^2c^2} S = \frac{\Sigma_{ZZ}(M_Z^2) - \Sigma_{ZZ}(0)}{M_Z}$$

$$+ \frac{s^2 - c^2}{sc} \frac{\Sigma_{Z\gamma}(M_Z^2)}{M_Z} - \frac{\Sigma_{\gamma\gamma}(M_Z^2)}{M_Z}$$



Gfitter coll. ’14

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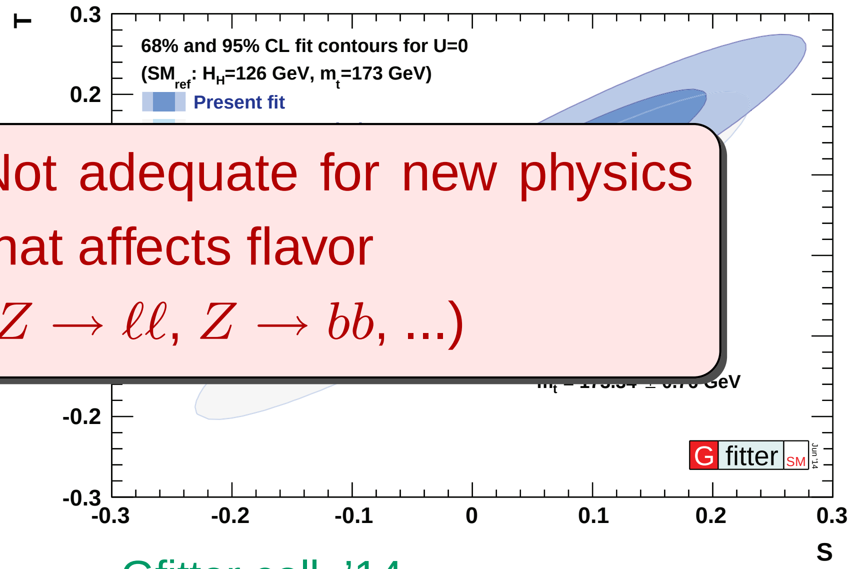


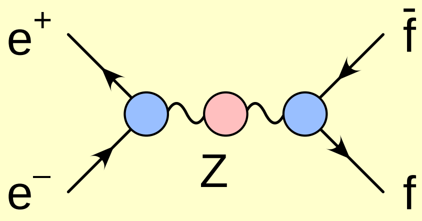
Not adequate for new physics that affects flavor ($Z \to \ell\ell$, $Z \to bb$, ...)

Gfitter coll. '14

Effective operator description

Effective field theory: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3})$ $(\Lambda \gg M_Z)$

Contributions at tree-level:



$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi \, \Phi^\dagger (D^\mu \Phi)$$

$$\mathcal{O}_{BW} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi$$

$$O_{LL}^{(3)e} = (\bar{L}_L^e \sigma^a \gamma_\mu L_L^e)(\bar{L}_L^e \sigma^a \gamma^\mu L_L^e)$$

$$O_R^f = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{f}_R \gamma^\mu f_R) \qquad f = e, \mu\, \tau, b, lq$$

$$O_L^F = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{F}_L \gamma^\mu F_L) \qquad F = \begin{pmatrix}\nu_e \\ e\end{pmatrix}, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}, \begin{pmatrix}u, c \\ d, s\end{pmatrix}, \begin{pmatrix}t \\ b\end{pmatrix}$$

$$O_L^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}_\mu^a \Phi)(\bar{F}_L \sigma_a \gamma^\mu F_L)$$

Effective operator description

Effective field theory: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3}) \qquad (\Lambda \gg M_\mathrm{Z})$

Contributions at tree-level:

$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi \, \Phi^\dagger (D^\mu \Phi) \qquad \alpha \Delta T = -\frac{v^2}{2}\frac{c_{\phi 1}}{\Lambda^2}$$

$$\mathcal{O}_\mathrm{BW} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi \qquad \alpha \Delta S = -e^2 v^2 \frac{c_\mathrm{BW}}{\Lambda^2}$$

$$O_\mathrm{LL}^{(3)e} = (\bar{L}_\mathrm{L}^e \sigma^a \gamma_\mu L_\mathrm{L}^e)(\bar{L}_\mathrm{L}^e \sigma^a \gamma^\mu L_\mathrm{L}^e) \qquad \Delta G_F = -\sqrt{2}\frac{c_\mathrm{LL}^{(3)e}}{\Lambda^2}$$

$$\left.\begin{aligned} O_\mathrm{R}^f &= i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{f}_\mathrm{R} \gamma^\mu f_\mathrm{R}) \\ O_\mathrm{L}^F &= i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{F}_\mathrm{L} \gamma^\mu F_\mathrm{L}) \\ O_\mathrm{L}^{(3)F} &= i(\Phi^\dagger \overleftrightarrow{D}_\mu^a \Phi)(\bar{F}_\mathrm{L} \sigma_a \gamma^\mu F_\mathrm{L}) \end{aligned}\right\} \text{effect on } Z \to f\bar{f}$$

Effective operator description

Effective field theory: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3}) \qquad (\Lambda \gg M_\mathrm{Z})$

Contributions at tree-level:

$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi\, \Phi^\dagger (D^\mu \Phi)$$

$$\mathcal{O}_\mathrm{BW} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi$$

} relevant for Higgs physics, but strongly bounded from EWPO

$$O_\mathrm{LL}^{(3)e} = (\bar{L}^e_\mathrm{L} \sigma^a \gamma_\mu L^e_\mathrm{L})(\bar{L}^e_\mathrm{L} \sigma^a \gamma^\mu L^e_\mathrm{L})$$

$$O_\mathrm{R}^f = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{f}_\mathrm{R} \gamma^\mu f_\mathrm{R})$$

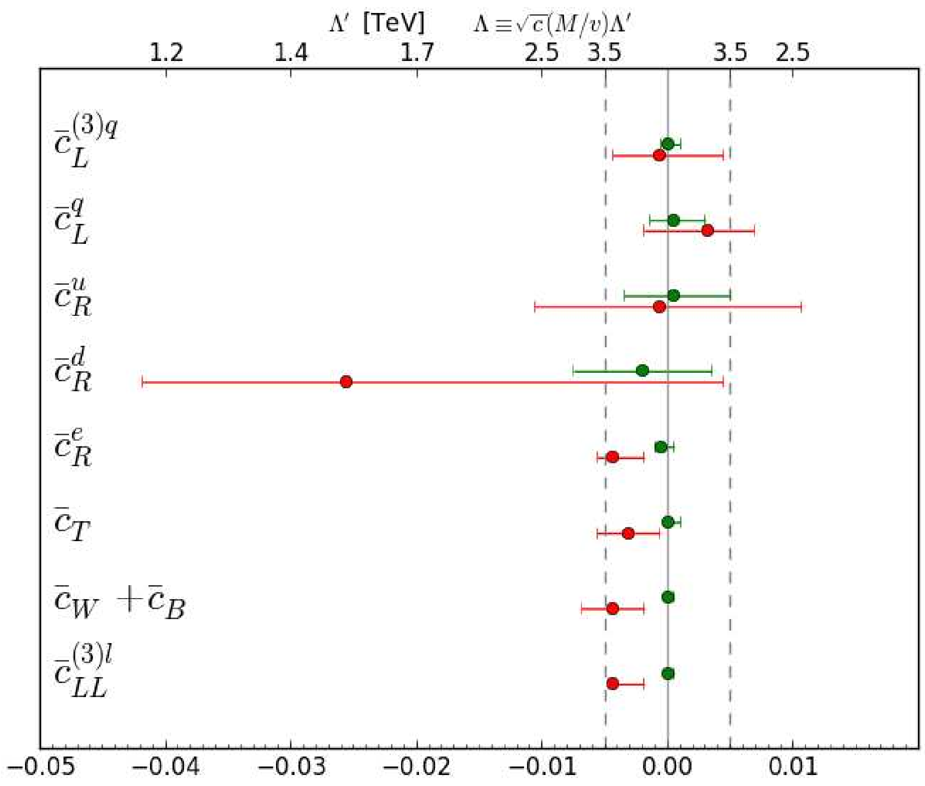
$$O_\mathrm{L}^F = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{F}_\mathrm{L} \gamma^\mu F_\mathrm{L})$$

$$O_\mathrm{L}^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}^a_\mu \Phi)(\bar{F}_\mathrm{L} \sigma_a \gamma^\mu F_\mathrm{L})$$

} irrelevant for Higgs physics

Current constraints on some dim-6 operators

Assuming flavor universality:

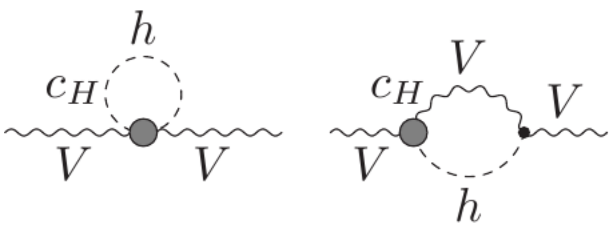


Significant correlation/ degeneracy between different operators

Pomaral, Riva ’13
Ellis, Sanz, You ’14

Effective operator description

Contributions at 1-loop-level:



$$\mathcal{O}_{\mathrm{H}} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\,\partial^\mu(\Phi^\dagger\Phi)$$

$$\mathcal{O}_{\mathrm{B}} = i(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\mathrm{W}} = i(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\mathrm{BB}} = -\Phi^\dagger B^{\mu\nu}B_{\mu\nu}\Phi$$

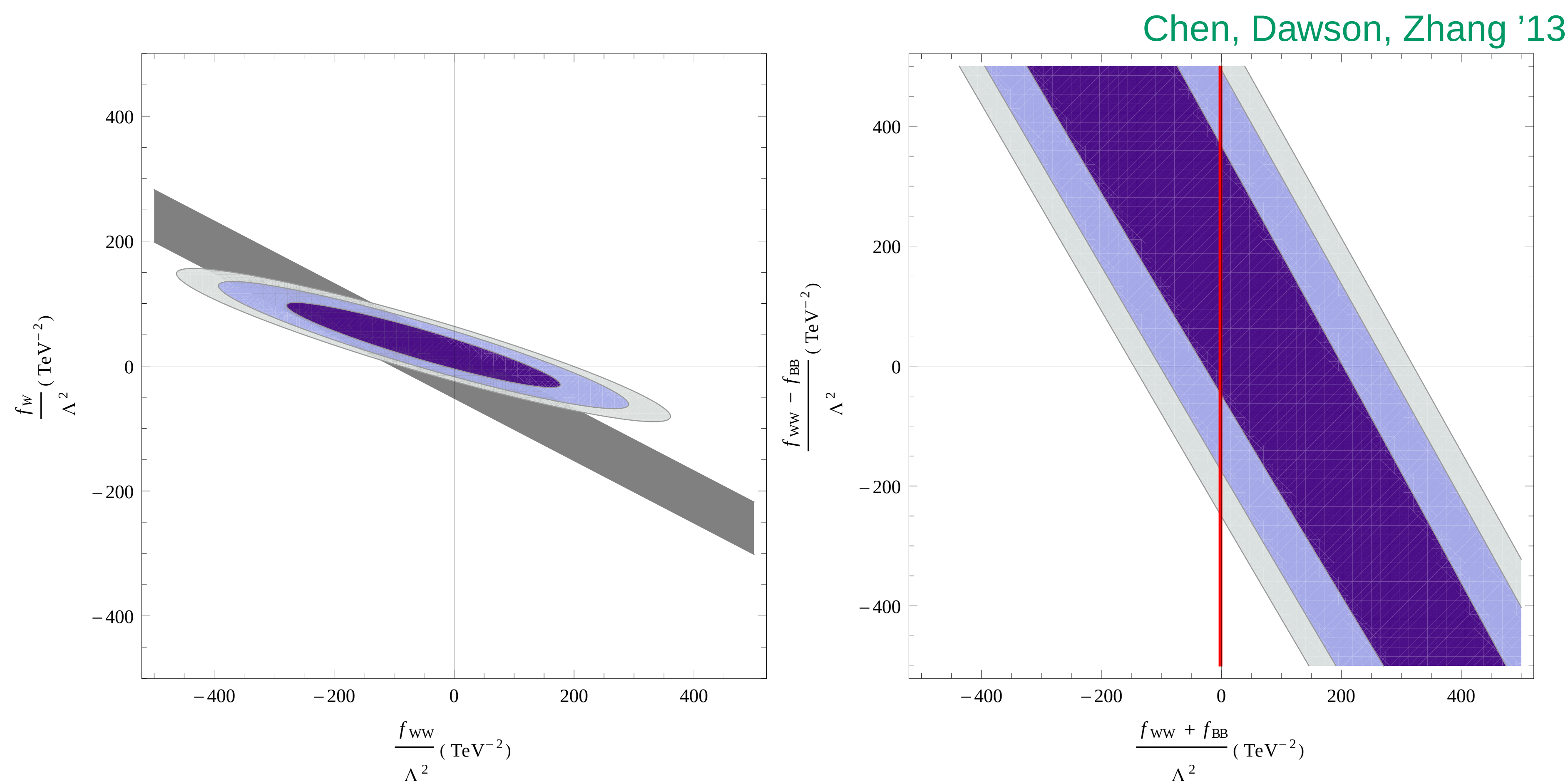
$$\mathcal{O}_{\mathrm{WW}} = -\Phi^\dagger W^{\mu\nu}W_{\mu\nu}\Phi$$

+ few more

$\longrightarrow$ Direct correlation with Higgs production and decay rates

Chen, Dawson, Zhang '13
Hartmann, Shephard, Trott '16

Impact of one-loop operator insertions



Assumptions:

- Tree-level EWPO operators are zero
- Loop contributions are UV-divergent ⟶ must choose renormalization scheme

Connection between EWPO and HEFT

- Competetive and complementary senstivity to HEFT operators from Higgs physics and EWPO @ NLO
- SMEFT @ NLO requires (model-dependent) assumptions

More operators than EWPOs

a) 1-loop contributions from $\mathcal{O}_{\rm H}$, $\mathcal{O}_{\rm B}$, $\mathcal{O}_{\rm W}$, $\mathcal{O}_{\rm BB}$, $\mathcal{O}_{\rm WW}$ can be absorbed into tree-level contributions from $\mathcal{O}_{\phi 1}$, $\mathcal{O}_{\rm BW}$, ...

$\longrightarrow$ No sensitivity on $\mathcal{O}_{\rm H}$, $\mathcal{O}_{\rm B}$, ... since $\mathcal{O}_{\phi 1}$, $\mathcal{O}_{\rm BW}$, ... dominate

b) Assume some operators ($\mathcal{O}_{\phi 1}$, $\mathcal{O}_{\rm BW}$, ...) vanish

$\longrightarrow$ Depends on renormalization scheme and scale

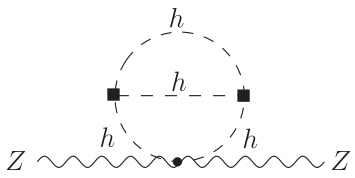
$\longrightarrow$ Compatible with some UV-completions, but not all

Connection between EWPO and HEFT

Renormalization

- Loop diagrams with HEFT operator insertions are in general UV-divergent

  [Exceptions e.g. $\mathcal{O}_6 = (\Phi^\dagger\Phi)^3$ in 2-loop diagrams
  Kribs, Maier, Rzehak, Spannowsky, Waite '17]



- Divergencies absorbed in oparators entering at tree-level ($\mathcal{O}_{\phi 1}$, $\mathcal{O}_{\mathrm{BW}}$, ...)
  - Ambiguity due to choice of renormalization ($\overline{\mathrm{MS}}$, $\overline{\mathrm{MS}}$ with BFM, ...) Mebane, Greiner, Zhang, Willenbrock '13 Hartmann, Trott '15
  - Ambiguity due to choice of scale: $\mathcal{O}_{\phi 1}$, $\mathcal{O}_{\mathrm{BW}}$, ... can only be zero at one scale μ_0

RG running and mixing

- Operators in loops and renormalization can be treated through RG evolution (as well as resummation of $\log \frac{\Lambda}{\mu}$ terms)

Shiftman, Vainshtein, Zakharov ’77; Floratos, Ross, Sachrajda ’77; Gilman, Wise ’79
Morozov ’84; Hagiwara, Ishihara, Szalapski, Zeppenfeld ’93; Han, Skiba ’04
Grojean, Jenkins, Manohar, Trott ’13; Jenkins, Manohar, Trott ’13
Alonso, Jenkins, Manohar, Trott ’13; Elias-Miro, Espinosa, Masso, Pomarol ’13
...

- Currently only leading-log (LL) approximation known; for Higgs physics today $\Lambda/\mu < 10$ Englert et al. ’14

Example: Higgs singlet extension

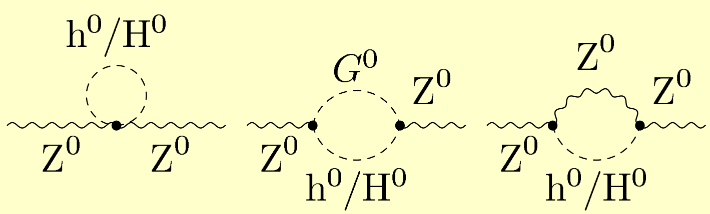
SM + singlet scalar S

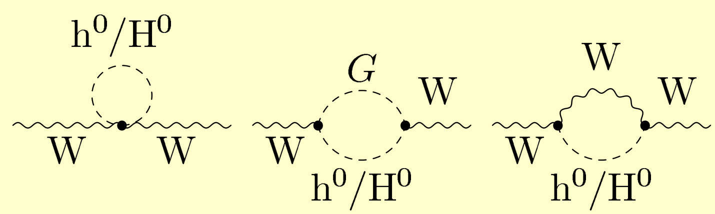
$$V(\Phi, S) = \mu_1^2 \Phi^\dagger \Phi + \lambda_1 (\Phi^\dagger \Phi)^2 + \mu_2^2 S^2 + \lambda_2 S^4 + \lambda_3 (\Phi^\dagger \Phi) S^2$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & v \end{pmatrix}^\top \qquad \langle S \rangle = v_s / \sqrt{2}$$

For $v_s \gg v$: $\quad m_H^2 \approx \Lambda^2 \equiv 2\lambda_2 v_s^2 \qquad \sin^2 \alpha \approx \frac{\lambda_3^2}{2\lambda_2} \frac{v^2}{\Lambda^2}$

Oblique parameters:

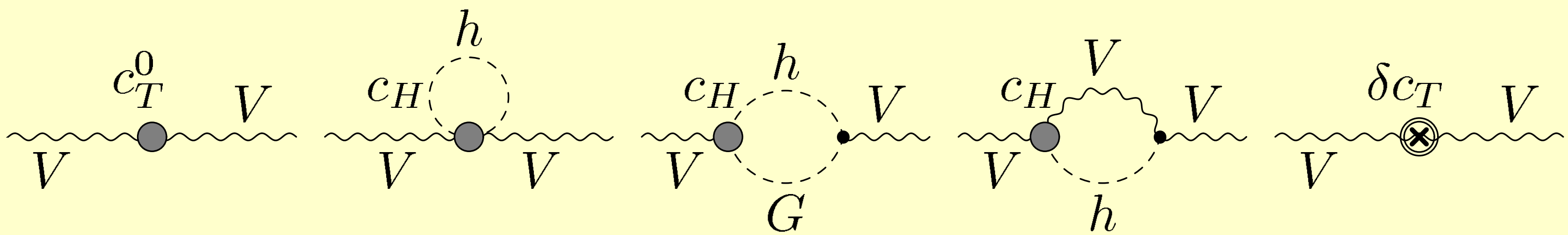




$$S \approx \frac{\lambda_3^2}{24\pi\lambda_2} \frac{v^2}{m_H^2} \ln \frac{m_H^2}{m_h^2} + \dots \qquad T \approx -\frac{3\lambda_3^2}{32\pi c_\text{w}^2 \lambda_2} \frac{v^2}{m_H^2} \ln \frac{m_H^2}{m_h^2} + \dots$$

Example: Higgs singlet extension

EFT description:



LO: $$\alpha T = -c_{\phi 1}\frac{v^2}{\Lambda^2}$$

$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi \, \Phi^\dagger (D^\mu \Phi)$$

NLO: $$\alpha T = \frac{3\alpha c_H}{16\pi s_\mathrm{w}^2 M_\mathrm{W}^2}\frac{v^2}{\Lambda^2}\left[\left\{\frac{M_\mathrm{Z}^2 m_h^2}{m_h^2 - M_\mathrm{Z}^2}\ln\frac{m_h^2}{M_\mathrm{Z}^2}\right\} - \{M_\mathrm{Z} \leftrightarrow M_\mathrm{W}\}\right]$$

$$\mathcal{O}_\mathrm{H} = \tfrac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\,\partial^\mu(\Phi^\dagger\Phi)$$

Note: NLO contribution is finite, so cannot be obtained through RG mixing

Example: Higgs singlet extension

Matching: $(\mu = M_\mathrm{W})$

Freitas, Lopez-Val, Plehn '16

LL-L: $c_{\phi 1} = \dfrac{3\alpha s_\mathrm{w}^2 \lambda_3^2}{32\pi c_\mathrm{w}^2 \lambda_2} \ln \dfrac{\Lambda^2}{\mu^2}$ $\quad c_H = 0$

LL-TL: $c_{\phi 1} = \dfrac{3\alpha s_\mathrm{w}^2 \lambda_3^2}{32\pi c_\mathrm{w}^2 \lambda_2} \ln \dfrac{\Lambda^2}{\mu^2}$ $\quad c_H = \lambda_3^2/(2\lambda_2)$

BP-TL: $c_{\phi 1} = \dfrac{\alpha s_\mathrm{w}^2 \lambda_3^2}{32\pi c_\mathrm{w}^2 \lambda_2} \left(3 \ln \dfrac{\Lambda^2}{\mu^2} - \dfrac{5}{2} \right)$ $\quad c_H = \lambda_3^2/(2\lambda_2)$

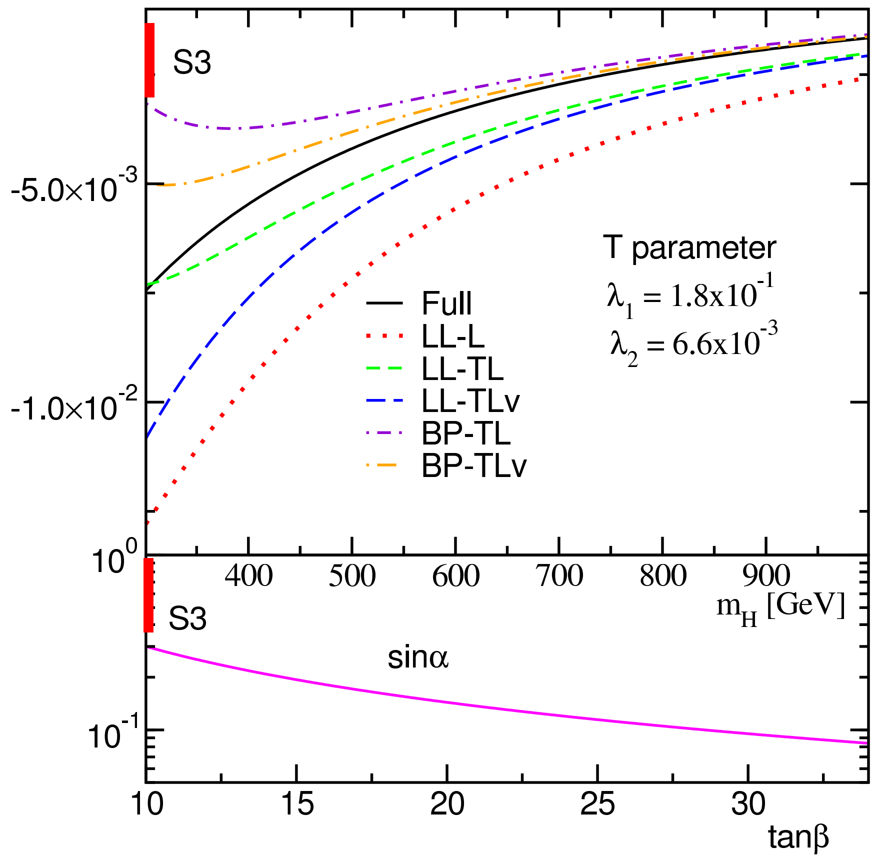
v-improv.: $\Lambda \to m_H, \quad \dfrac{\lambda_3^2}{2\lambda_2} \to \sin^2 \alpha \, \dfrac{\Lambda^2}{v^2}$

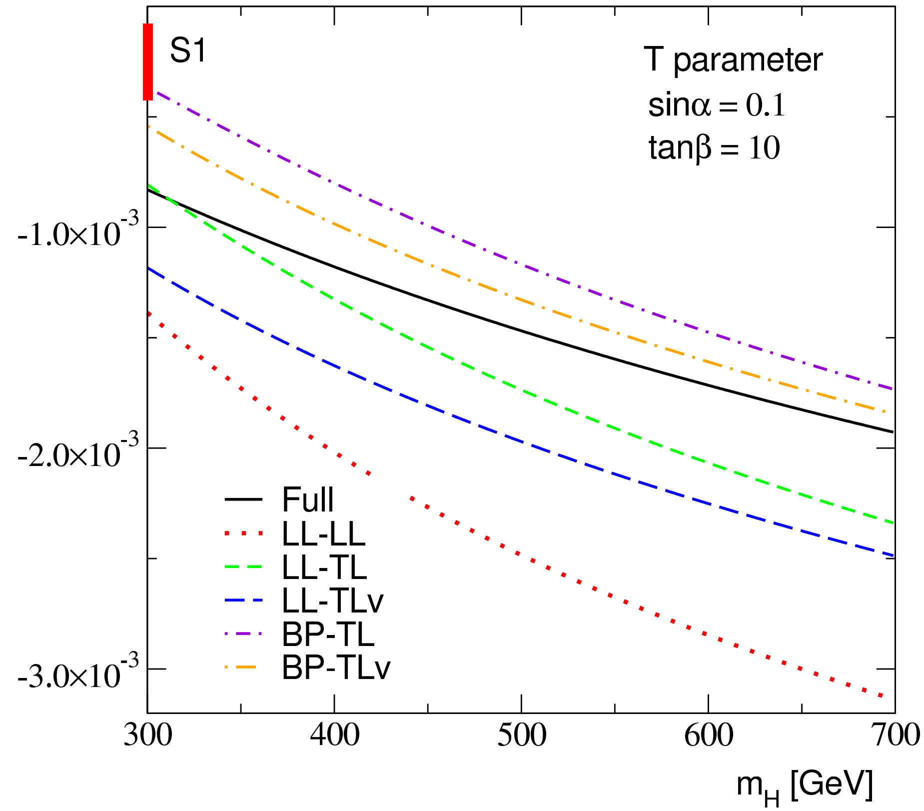
Brehmer, Freitas, Lopez-Val, Plehn '15

Example: Higgs singlet extension

Sample benchmarks:

Freitas, Lopez-Val, Plehn '16





- LL approximation not adequate
- Full 1-loop matching (with v-induced terms) necessary to relate EWPO–HEFT
- "Phenomenological" operators to be defined at weak scale

Conclusions

- **Electroweak precision tests** can probe Higgs physics beyond the Standard Model
- Model independent description of new physics through **dim-6 operators**
- Sensitivity of EWPO to HEFT operators mostly through **loop contributions**
  $\longrightarrow$ Analysis depends on (model-dependent) assumptions
- Full **1-loop matching** important for connecting HEFT to UV-complete models

Conclusions

- **Electroweak precision tests** can probe Higgs physics beyond the Standard Model

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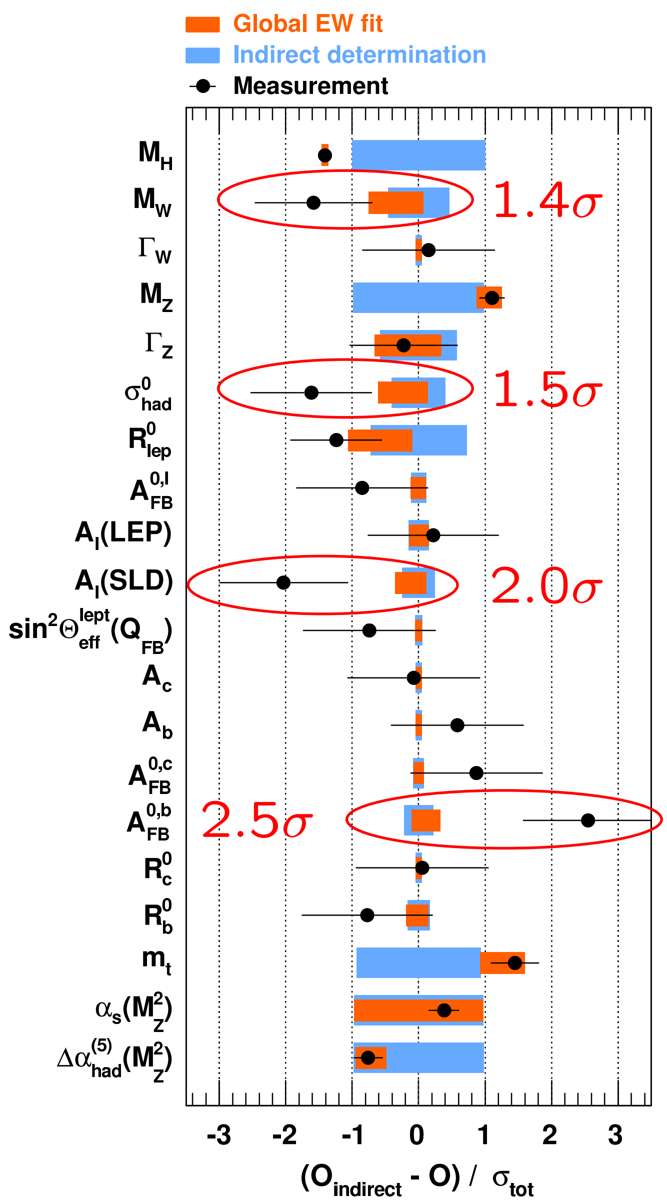
Backup slides

Current status of electroweak precision tests



Surprisingly good agreement:
$\chi^2/\text{d.o.f.} = 18.1/14$ ($p = 20\%$)

Most quantities measured with 1%–0.1% precision

A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

GFitter coll. ’14

Future projections

ILC: High-energy e^+e^- linear collider, running at $\sqrt{s} \approx M_\mathrm{Z}$ with 30 fb^{-1}

CEPC: Circular e^+e^- collider, running at $\sqrt{s} \approx M_\mathrm{Z}$ with 2×150 fb^{-1}

FCC-ee: Circular e^+e^- collider, running at $\sqrt{s} \approx M_\mathrm{Z}$ with 4×3000 fb^{-1}

	Current exp.	ILC	CEPC	FCC-ee	Current perturb.
M_W [MeV]	15	3–4	3	1	4
Γ_Z [MeV]	2.3	0.8	0.5	0.1	0.5
R_b [10^{-5}]	66	14	17	6	15
$\sin^2\theta^\ell_\mathrm{eff}$ [10^{-5}]	16	1	2.3	0.6	4.5

→ Existing theoretical calculations adequate for LEP/SLC/LHC, but not ILC/CEPC/FCC-ee!

Theory and parametric uncertainties

	ILC	CEPC	perturb. error with 3-loop†	Param. error ILC*	Param. error CEPC**
M_{W} [MeV]	3–4	3	1	2.6	2.1
Γ_Z [MeV]	0.8	0.5	$\lesssim 0.2$	0.5	0.15
R_b [10^{-5}]	14	17	5–10	< 1	< 1
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ [10^{-5}]	1	2.3	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_{\mathrm{s}}^2)$, $\mathcal{O}(N_f\alpha^2\alpha_{\mathrm{s}})$, $\mathcal{O}(N_f^2\alpha^2\alpha_{\mathrm{s}})$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_{\mathrm{s}} = 0.001$, $\delta M_{\mathrm{Z}} = 2.1$ MeV

****CEPC:** $\delta m_t = 600$ MeV, $\delta\alpha_{\mathrm{s}} = 0.0002$, $\delta M_{\mathrm{Z}} = 0.5$ MeV

also: $\delta(\Delta\alpha) = 5 \times 10^{-5}$

Theory uncertainties in extraction of pseudo-observables

- Subtraction of QED radiation contributions

  $\longrightarrow$ Known to $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3 L^3)$ for **ISR**, $\mathcal{O}(\alpha^2)$ for **FSR** and $\mathcal{O}(\alpha^2 L^2)$ for **A$_{\mathbf{FB}}$**

  $(L = \log \frac{s}{m_e^2})$

  Berends, Burgers, v.Neerven '88
  Kniehl, Krawczyk, Kühn, Stuart '88
  Beenakker, Berends, v.Neerven '89
  Skrzypek '92; Montagna, Nicrosini, Piccinini '97

  $\longrightarrow$ $\mathcal{O}(0.1\%)$ uncertainty on σ_Z, A_{FB}

  $\longrightarrow$ Improvement needed for ILC/CEPC/FCC-ee

- Subtaction of non-resonant γ-exchange, γ–Z interf., box contributions, Bhabha scattering

  see, e.g., Bardin, Grünewald, Passarino '99

  $\longrightarrow$ $\mathcal{O}(0.01\%)$ uncertainty within SM (improvements may be needed)

  $\longrightarrow$ Sensitivity to some NP beyond EWPO

LEP EWWG '05