Standard Model Effective Field Theory for H/EW/tt

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 \blacktriangleright Build large colliders \rightarrow go to high energy \rightarrow discover new particles!

Higgs and nothing else?



- What's next?
 - Build an even larger collider (~ 100 TeV)?
 - No guaranteed discovery!

■ Build large colliders → go to high energy → discover new particles!

do precision measurements \rightarrow discover new physics indirectly!

Higgs and nothing else?



LHC will definitely find new physics!

- What's next?
 - Build an even larger collider ($\sim 100 \,\text{TeV}$)?
 - No guaranteed discovery!
 - Higgs factory! (A lepton collider at $\sqrt{s} \sim 240-250 \,\text{GeV}$ or above.)
 - More than just a Higgs factory! (Z, W, top, ...)
 - Standard Model Effective Field Theory (model independent approach)

Precision is the key!



"Our future discoveries must be looked for in the sixth place of decimals."

- Albert A. Michelson

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The Standard Model Effective Field Theory



- $[\mathcal{L}_{sm}] \leq 4$. Why?
 - Bad things happen when we have non-renormalizable operators!
 - Everything is fine as long as we are happy with finite precision in perturbative calculation.
- ► **d=5:** $\frac{c}{\Lambda}LLHH \sim \frac{cv^2}{\Lambda}\nu\nu$, Majorana neutrino mass.
- Assuming Baryon and Lepton numbers are conserved,

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{\boldsymbol{c}_{i}^{(6)}}{\Lambda^{2}} \mathcal{O}_{i}^{(6)} + \sum_{j} \frac{\boldsymbol{c}_{j}^{(8)}}{\Lambda^{4}} \mathcal{O}_{j}^{(8)} + \cdots$$

If Λ ≫ v, E, then SM + dimension-6 operators are sufficient to parameterize the physics around the electroweak scale.

C	$\begin{split} \chi &= -\frac{1}{4} \int_{\infty}^{\infty} F^{*} \\ &+ i \mathcal{F} \mathcal{D} \mathcal{J} + * k_{c} \\ &+ \mathcal{J}_{c} \cdot y_{ij} \mathcal{J}_{j} \mathcal{J} + k_{c} \\ &+ \left \mathbf{P}_{ij} \right ^{2} - V(\mathcal{D}) \end{split}$	+
C	+ Þ.ø ² -V(ø)	ĺ

	X^3		φ^4 and $\varphi^4 D^2$		$\psi^2 \varphi^3$		(LL)(LL)		$(\bar{R}R)(\bar{R}R)$		(LL)(RR)
Qa	$f^{ABC}G^{A\nu}_{\nu}G^{S\mu}_{\nu}G^{C\mu}_{\nu}$	9,	(φ [†] φ) ³	9.4	$(\varphi^{\dagger}\varphi)(\overline{l_{p}e_{r}}\varphi)$	Q_{k}	$(\bar{l}_t \gamma_t \bar{l}_t)(\bar{l}_t \gamma^{\mu} l_t)$	Q_{ee}	$(\tilde{e}_{\mu}\gamma_{\mu}e_{\tau})(\tilde{e}_{\nu}\gamma^{*}e_{\ell})$	Q_{1c}	$(\tilde{l}_{\mu}\gamma_{\mu}l_{\nu})(\tilde{e}_{\mu}\gamma^{\mu}e_{\mu})$
90	1 ABC GA GA GA GC	20	$(\varphi^{\dagger}\varphi) \Box (\varphi^{\dagger}\varphi)$	9	$(\varphi^{\dagger}\varphi)(\bar{q}_{\mu}u_{\mu}\bar{\varphi})$	$Q_{m}^{(1)}$	$(\bar{q}_{\mu}\gamma_{\mu}q_{\nu})(\bar{q}_{\nu}\gamma^{\mu}q_{\nu})$	Q_{in}	$(\hat{u}_{\mu}\gamma_{\mu}v_{\nu})(\hat{u}_{e}\gamma^{\mu}s_{i})$	Q_{he}	$(\tilde{l}_p \gamma_p \tilde{l}_r)(\hat{u}_s \gamma^\mu u_t)$
Qu	SIJKWDWJeWKE	Que	$(\varphi^{\dagger}D^{\mu}\varphi)^{\dagger}(\varphi^{\dagger}D_{\mu}\varphi)$	Q.	$(\varphi^{\dagger}\varphi)(\bar{q}_{s}d_{s}\varphi)$	$Q_{ii}^{(l)}$	$(\bar{q}_{\mu}\gamma_{\mu}\tau^{I}q_{\nu})(\bar{q}_{\mu}\gamma^{\mu}\tau^{I}q_{\ell})$	Q_{M}	$(\tilde{d}_{\mu}\gamma_{\mu}d_{r})(\tilde{d}_{e}\gamma^{\mu}d_{l})$	Q_{1d}	$(\bar{l}_{\mu}\gamma_{\mu}l_{\tau})(\bar{d}_{e}\gamma^{\mu}d_{l})$
0.0	LIKWINW JOWKY					$Q_{lg}^{(1)}$	$(\tilde{l}_p \gamma_p l_r)(\tilde{q}_i \gamma^\mu q_i)$	Q_{ci}	$(\tilde{e}_{\mu}\gamma_{\mu}e_{\tau})(\tilde{a}_{\mu}\gamma^{\mu}u_{\ell})$	$Q_{\ell^{\mathrm{H}}}$	$(\bar{q}_j \gamma_{j\ell} q_{\ell})(\bar{e}_i \gamma^{\mu} e_l)$
	12.2	-	d ² Y.c	-	±2.20	$Q_{iq}^{(3)}$	$(\bar{l}_{p}\gamma_{\mu}\tau^{I}l_{r})(\bar{q}_{i}\gamma^{\mu}\tau^{I}q_{i})$	Q_{et}	$(\bar{e}_y \gamma_p e_r)(\bar{d}_s \gamma^s d_b)$	$Q_{qu}^{(1)}$	$(\bar{q}_t \gamma_p q_r)(\bar{u}_s \gamma^\mu u_t)$
-	A V		V AV	*00	V V V			$Q_{ad}^{(1)}$	$(\hat{u}_{\mu}\gamma_{\mu}u_{r})(\tilde{d}_{e}\gamma^{\mu}d_{l})$	$Q_{q_1}^{(k)}$	$(\bar{q}_{g}\gamma_{\mu}T^{A}q_{r})(\bar{u}_{e}\gamma^{\mu}T^{A}u_{l})$
9,0	$\varphi^{i}\varphi G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu}$	Q _{eff} .	$(l_p \sigma^{\mu\nu} e_r) \tau^{\nu} \varphi W^{\prime}_{\mu\nu}$	$Q_{q\bar{q}}$	$(\varphi^{\dagger}(D_{\mu}\varphi)(l_{p}\gamma^{*}l_{r})$			22	$(\bar{a}_s \gamma_s T^A u_s)(\bar{d}_s \gamma^{\mu} T^A d_t)$	Q(1)	(4.2.4.)(d.2*d)
$Q_{\mu\bar{\Omega}}$	$\varphi^{\dagger} \varphi \widetilde{G}^{A}_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_{\rho}\sigma^{\mu\nu}c_{r})\varphi B_{\mu\nu}$	$Q_{gl}^{(3)}$	$(\varphi^{\dagger}i\hat{D}^{I}_{\mu}\varphi)(\hat{l}_{\mu}\tau^{I}\gamma^{\mu}l_{r})$					92	$(\bar{q}_t\gamma_tT^Aq_t)(\bar{d}_t\gamma^sT^Ad_t)$
Q_{qW}	$\varphi^{\dagger}\varphi W^{I}_{\mu\nu}W^{I}\mu\nu$	Q_{uG}	$(\bar{q}_{p}\sigma^{\mu\nu}T^{A}u_{r})\widetilde{\varphi}G^{A}_{\mu\nu}$	Q_{ee}	$(\varphi^{\dagger}i \vec{D}_{\mu} \varphi)(\vec{e}_{\mu} \gamma^{\mu} e_{\nu})$	(LR	(RL) and (LR)(LR)	-	B-rio	ating	
$Q_{\sqrt{N}}$	$\varphi^{\dagger}\varphi W^{\dagger}_{\mu\nu}W^{\dagger}\omega$	Q_{eW}	$(\bar{q}_{\mu}\sigma^{\mu\nu}u_{\nu})\tau^{I}\tilde{\varphi}W^{I}_{\mu\nu}$	$Q_{q\bar{q}}^{(1)}$	$(\varphi^{\dagger}iD_{\mu}\varphi)(\bar{q}_{\rho}\gamma^{\mu}q_{\nu})$	Quela	$(\bar{l}_{s}^{i}e_{r})(\bar{d}_{s}q_{s}^{i})$	Que	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_{\pi}^{\alpha})\right]$	TCu!	$[\langle q_i^{cj} \rangle^T C l_i^k]$
9,08	$\varphi^{\dagger}\varphi B_{\mu\nu}B^{\mu\nu}$	Q_{vS}	$(\bar{q}_{p}\sigma^{\mu\nu}u_{r})\overline{\varphi} B_{\rho\nu}$	$Q_{H_{1}}^{(3)}$	$(\varphi^{\dagger}i \widetilde{D}^{I}_{\mu} \varphi)(q_{\nu}\tau^{I}\gamma^{\mu}q_{\nu})$	Q(1)	$(\bar{q}_{s}^{i}u_{r})e_{jk}(\bar{q}_{s}^{k}\mathbf{d}_{l})$	900	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_k^{\alpha j})\right]$	TCg ^{il}	$[(\mathbf{s}_i)^T C \mathbf{e}_i]$
$Q_{\mu\bar{N}}$	$\varphi^{\dagger}\varphi \overline{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_{\mu}\sigma^{\mu\nu}T^Ad_{\sigma})\varphi G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^{\dagger}iD_{\mu}\varphi)(\bar{u}_{\rho}\gamma^{\mu}u_{r})$	Q ^{HI}	$\langle q_t^{c}T^{cl}v_r \rangle e_{jk} \langle q_s^{b}T^{cl}d_l \rangle$	$Q_{\rm eff}^{(1)}$	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\epsilon_{mn} [(q_p^{\alpha}$	i)TOW	$[k] [(q_{i}^{m})^{T} C Q_{i}^{n}]$
Q_{gWB}	$\varphi^{\dagger}\tau^{J}\varphi W^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(q_p\sigma^{\mu\nu}d_r)\tau^J\varphiW^J_{\mu\nu}$	Q_{qd}	$(\varphi^{\dagger}i \overrightarrow{D}_{\mu} \varphi)(\widetilde{d}_{p} \gamma^{\mu} d_{r})$	$Q_{logs}^{(0)}$	$(\tilde{l}_{s}^{i}c_{s})c_{jk}(\tilde{q}_{s}^{k}a_{t})$	$Q_{\rm HH}^{\rm IS}$	$\varepsilon^{\chi g_7}(\tau^I \varepsilon)_{\mu}(\tau^I \varepsilon)_{en}$	$[(q_{F}^{c_{3}})^{3}$	$Cq_{\tau}^{(k)}$ [($q_{\tau}^{(m)}$) ^T $CQ_{\tau}^{(m)}$]
$Q_{\sqrt{K}B}$	$\varphi^{\dagger}\tau^{J}\varphi \widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{d3}	$(\bar{q}_{\mu}\sigma^{\mu\sigma}d_{\tau})\varphi B_{\mu\nu}$	Q_{pol}	$i(\hat{\varphi}^{\dagger}D_{\mu}\varphi)(\hat{u}_{\mu}\gamma^{\mu}d_{\ell})$	$Q_{logu}^{(3)}$	$(\bar{p}_{\rho}\sigma_{\mu\nu}e_{\nu})e_{\mu}(\bar{q}_{\mu}^{k}\sigma^{\mu\nu}u_{l})$	Qen	$\varepsilon^{\alpha\beta\gamma} [(d^a_{\mu})^3$	Cu_{r}^{β}	$[(u_i^*)^T C e_i]$

- Write down all possible (non-redundant) dimension-6 operators ...
- 59 operators (76 parameters) for 1 generation, or 2499 parameters for 3 generations. [arXiv:1008.4884] Grzadkowski, Iskrzyński, Misiak, Rosiek, [arXiv:1312.2014] Alonso, Jenkins, Manohar, Trott.
- A full global fit with all measurements to all operator coefficients?
 - ▶ We usually only need to deal with a subset of them, *e.g.* ~ 20-30 parameters for **Higgs and electroweak** measurements.
- Do a global fit and present the results with some fancy bar plots!

Higgs + EW, Results from the Snowmass 2021 (2022) study

[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou



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6



- Without good Z-pole measurements, the *eeZh* contact interaction may have a significant impact on the Higgs coupling determination.
- Current (LEP) Z-pole measurements are not good enough for CEPC/FCC-ee Higgs measurements!
 - A future Z-pole run is important!
- Linear colliders suffer less from the lack of a Z-pole run. (Win Win!)



- 28-parameter fit projected on Higgs couplings and anomalous triple gauge couplings.
- ► $\delta g_H^{ZZ} \approx \delta g_H^{WW}$ from theoretical constraints (gauge invariance & custodial symmetry) and EW measurements.
- ▶ Non-negligible improvement from the 360 GeV run.

8

SMEFT global fit (reach on new physics scale)



95% CL reach from SMEFT fit

 20-parameter fit (assuming flavor universality in gauge-fermion couplings).

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9

$$\begin{array}{l} O^1_{\varphi q} \equiv \frac{y_2^2}{2} ~~\bar{q} \gamma^\mu q ~~ \varphi^{\dagger} i \overrightarrow{D}_{\mu} \varphi, ~~ O_{uG} \equiv y_t g_s ~~\bar{q} T^A \sigma^{\mu\nu} u ~\epsilon \varphi^* G^A_{\mu\nu}, \\ O^3_{\varphi q} \equiv \frac{y_2}{2} ~~\bar{q} \tau^I \gamma^\mu q ~~ \varphi^{\dagger} i \overrightarrow{D}_{\mu} \varphi, ~~ O_{uW} \equiv y_t g_W ~~\bar{q} \tau^I \sigma^{\mu\nu} u ~\epsilon \varphi^* W^I_{\mu\nu}, \\ O_{\varphi u} \equiv \frac{y_2^2}{2} ~~\bar{u} \gamma^\mu u ~~ \varphi^{\dagger} i \overrightarrow{D}_{\mu} \varphi, ~~ O_{dW} \equiv y_t g_W ~~\bar{q} \tau^I \sigma^{\mu\nu} d ~\epsilon \varphi^* W^I_{\mu\nu}, \\ O_{\varphi u d} \equiv \frac{y_2}{2} ~~\bar{u} \gamma^\mu d ~~ \varphi^T \epsilon ~i D_\mu \varphi, ~~ O_{uB} \equiv y_t g_Y ~~\bar{q} \sigma^{\mu\nu} u ~~ \epsilon \varphi^* B_{\mu\nu}, \\ O^1_{iq} \equiv \frac{1}{2} ~~\bar{q} \tau^I \gamma_\mu q ~~\bar{l} \tau^I \gamma^\mu l, \\ O^1_{iq} \equiv \frac{1}{2} ~~\bar{q} \tau_\mu \gamma_\mu ~~\bar{l} \tau^I \gamma^\mu l, \\ O_{eq} \equiv \frac{1}{2} ~~\bar{q} \gamma_\mu q ~~\bar{l} \gamma^\mu e, \\ O_{eu} \equiv \frac{1}{2} ~~\bar{u} \gamma_\mu u ~~\bar{e} \gamma^\mu e, \end{array}$$

- Also need to include top dipole interactions and *eett* contact interactions!
- Hard to resolve the top couplings from 4f interactions with just the 365 GeV run.
 - Can't really separate $e^+e^- \rightarrow Z/\gamma \rightarrow t\bar{t}$ from

$$e^+e^-
ightarrow Z'
ightarrow tt$$
 .

Is that a big deal?



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Results from the recent snowmass study

[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou



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11

Top operators in loops (Higgs processes) [1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang



- $O_{tB} = (\bar{Q}\sigma^{\mu\nu}t) \tilde{\varphi}B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling \Rightarrow run at $\sim 365 \text{ GeV}$ to confirm?



Top operators in loops (current EW processes)

[2205.05655] Y. Liu, Y. Wang, C. Zhang, L. Zhang, JG

	Experiment	Observables				
Low Energy	CHARM/CDHS/ CCFR/NuTeV/ APV/QWEAK/ PVDIS	Effective Couplings				
Z-pole		Total decay width Γ_Z				
		Hadronic cross-section σ_{had}				
	LEP/SLC	Ratio of decay width R_f				
		Forward-Backward Asymmetry A_{FB}^{f}				
		Polarized Asymmetry A_f				
W-pole	LHC/Temptage /	Total decay width Γ_W				
	LEP/SLC	W branching ratios $Br(W \rightarrow lv_l)$				
		Mass of W Boson M_W				
$ee \rightarrow qq$		Hadronic cross-section σ_{had}				
	LEP/TRISTAN	Ratio of cross-section R_f				
		Forward-Backward Asymmetry for $b/c A_{FB}^{f}$				
$ee \rightarrow ll$		cross-section σ_f				
	LEP	Forward-Backward Asymmetry A_{FB}^{f}				
		Differential cross-section $\frac{d\sigma_f}{dcos\theta}$				
$ee \rightarrow WW$	LED	cross-section σ_{WW}				
	LEF	Differential cross-section $\frac{d\sigma_{WW}}{dcos\theta}$				

- Top operators (1-loop) + EW operators (tree, including bottom dipole operators)
- $e^+e^- \rightarrow f\bar{f}$ at different energies, $e^+e^- \rightarrow WW$.

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Top operators in loops (current EW processes)



Good sensitivities, but too many parameters for a global fit...

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Top operators in loops (future EW processes)



- Good sensitivities, but too many parameters for a global fit...
- It shows the importance of directly measuring $e^+e^- \rightarrow t\bar{t}$.

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Machine learning is not physics!





past

now

- ▶ Current work with Shengdu Chai (柴声都), Lingfeng Li (李凌风) on $e^+e^- \rightarrow WW$.
- ▶ Current work with Yifan Fei (费昳帆), Tong Shen (沈同) and Kerun Yu (余柯润) on *e*⁺*e*⁻ → *tt*.

16

Why Machine learning?

- In many cases, the new physics contributions are sensitive to the differential distributions.
 - $e^+e^- \rightarrow WW \rightarrow 4f \Rightarrow 5$ angles
 - ► $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow 6f$ \Rightarrow 9 angles
 - How to extract information from the differential distribution?
 - ► If we have the full knowledge of $\frac{d\sigma}{d\Omega} \Rightarrow$ matrix-element method, optimal observables...
- The ideal $\frac{d\sigma}{d\Omega}$ we can calculate is not the $\frac{d\sigma}{d\Omega}$ that we actually measure!
 - detector acceptance, measurement uncertainties, ISR/beamstrahlung ...
 - In practice we only have MC samples, not analytic expressions, for do/do.





The "inverse problem"



- ► Forward: From model parameters we can calculate the ideal $\frac{d\sigma}{d\Omega}$, simulate complicated effects and produce MC samples.
- Inverse: From data / MC samples, how do we know the model parameters?
- ► With Neural Network we can (in principle) reconstruct $\frac{d\sigma}{d\Omega}$ (or likelihood ratios) from MC samples.

Particle physics structure

• One could make use of latent variable "*z*" (the parton level analytic result for $\frac{d\sigma}{d\Omega}$) to increase the performance of ML.

[1805.00013, 1805.00020] Brehmer, Cranmer, Louppe, Pavez



• Assuming linear dependences $\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i} c_i$, there is a method

called SALLY (Score approximates likelihood locally).

- ► In this case, for each parameter we only need to train once to obtain $\alpha_i \equiv \frac{S_{1,i}}{S_0}$. (It is basically the ML version of Optimal Observables.)
- We can calculate the "ideal" $\alpha(z)$ which will help us train the actual $\alpha(x)$.

$$L[\hat{\alpha}(\mathbf{x})] = \sum_{\mathbf{x}_i, \mathbf{z}_i \sim \mathrm{SM}} |\alpha(\mathbf{z}_i) - \hat{\alpha}(\mathbf{x}_i)|^2.$$

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19

Machine Learning in $e^+e^- o WW$ (preliminary results, Shengdu Chai, JG, Lingfeng Li)



 Left: truth level. Middle: detector level. Right: detector level with backgrounds.

- ▶ 3-aTGC fit, scaled to 10⁴ events.
- Training sample: 2×10^6 events. Validation sample: 5×10^5 events.
- Naively applying truth-level optimal observables could lead to a large bias!
- It's easier for machine learning to take care of systematics!

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Machine learning



When will Machine take over?

Before or after a future lepton collider is built?

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Standard Model Effective Field Theory for H/EW/tt

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We have no idea what is the new physics beyond the Standard Model.

- One important direction to move forward is to do precision measurements of the Standard Model processes.
 - A future lepton collider is an ideal machine for that.
 - SMEFT is a good theory framework (but is not everything).
 - Expanding the theory framework?
 - Loop contributions, dimension-8 operators, HEFT ...
- Machine learning is (likely to be) the future!

Conclusion



Waiting for the CEPC to be built...

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Probing dimension-8 operators?

- The dimension-8 contribution has a large energy enhancement (~ E⁴/Λ⁴)!
- It is difficult for LHC to probe these bounds.
 - Low statistics in the high energy bins.
 - Example: Vector boson scattering.
 - Λ ≤ √s, the EFT expansion breaks down!
- Can we separate the dim-8 and dim-6 effects?
 - Precision measurements at several different √s?

(A very high energy lepton collider?)

Or find some special process where dim-8 gives the leading new physics contribution?



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The diphoton channel [arXiv:2011.03055] Phys.Rev.Lett. 129, 011805, JG, Lian-Tao Wang, Cen Zhang

- $e^+e^- \rightarrow \gamma\gamma$ (or $\mu^+\mu^- \rightarrow \gamma\gamma$), SM, non-resonant.
- ► Leading order contribution: dimension-8 contact interaction. $(f^+f^- \rightarrow \bar{e}_L e_L \text{ or } e_R \bar{e}_R)$

$$\mathcal{A}(f^+f^-\gamma^+\gamma^-)_{\rm SM+d8} = 2e^2 \frac{\langle 24\rangle^2}{\langle 13\rangle\langle 23\rangle} + \frac{a}{v^4} [13][23]\langle 24\rangle^2 \,.$$

Can probe dim-8 operators (and their positivity bounds) at a Higgs factory (~ 240 GeV)!



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A rough sketch

- We have a theory (SMEFT) that gives a differential cross section $\frac{d\sigma}{d\Omega}$ which is a function of the parameters of interest c (Wilson coefficients).
 - For simplicity, let's ignore the total rate and focus on $\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \equiv \mathbf{p}(\mathbf{x}|\mathbf{c}), i.e.$ it's a probability density function of the observables \mathbf{x} .
 - ► Define the likelihood function $\mathcal{L}(\mathbf{c}|\mathbf{x}) \equiv p(\mathbf{x}|\mathbf{c})$. For a sample of *N* events, maximizing the joint likelihood $\prod_{i=1}^{N} \mathcal{L}(\mathbf{c}|\mathbf{x}_i)$ (or the log likelihood) gives the best estimator for **c**. (matrix-element method)
- Suppose we have two equal-size samples $\{\mathbf{x}_{i,\mathbf{c}_{0}}\} \sim p(\mathbf{x}|\mathbf{c}_{0})$ and $\{\mathbf{x}_{i,\mathbf{c}_{1}}\} \sim p(\mathbf{x}|\mathbf{c}_{1})$, one could define the cross-entropy loss function(al)

$$L(\hat{s}) = -\sum_{i=1}^{N} \log \hat{s}(\mathbf{x}_{i,c_1}) - \sum_{i=1}^{N} \log (1 - \hat{s}(\mathbf{x}_{i,c_0})) ,$$

which is minimized by the optimal decision function

$$oldsymbol{s}(\mathbf{x}|\mathbf{c}_0,\mathbf{c}_1) = rac{oldsymbol{
ho}(\mathbf{x}|\mathbf{c}_1)}{oldsymbol{
ho}(\mathbf{x}|\mathbf{c}_0) + oldsymbol{
ho}(\mathbf{x}|\mathbf{c}_1)}\,.$$

A rough sketch



From neural network we can construct a function ŝ(x). By minimizing L(ŝ) with respect to ŝ(x) we can obtain an estimator for the likelihood ratio

$$\hat{r}(\mathbf{x}|\mathbf{c}_0,\mathbf{c}_1) = rac{1-\hat{s}(\mathbf{x}|\mathbf{c}_0,\mathbf{c}_1)}{\hat{s}(\mathbf{x}|\mathbf{c}_0,\mathbf{c}_1)} = rac{\hat{p}(\mathbf{x}|\mathbf{c}_0)}{\hat{p}(\mathbf{x}|\mathbf{c}_1)},$$

which is the same as the true likelihood ratio in the ideal limit (large sample, perfect training).

- There are many other ways to construct a loss function(al)....
- ► With additional assumptions on how $\frac{d\sigma}{d\Omega}$ depends on **c** (*i.e.*, a quadratic relation), we only need to train a finite number of times to know how the likelihood ratio depend on **c**.

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Machine Learning in $e^+e^- ightarrow WW$ (preliminary results, Shengdu Chai, JG, Lingfeng Li)



 Semileptonic channel, MadGraph/Pythia/Delphes (CEPC detector card), with ZZ backgrounds.

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• $e^+e^-
ightarrow t ar{t}$, 3 different channels (no background yet)

• Left: $\sqrt{s} = 1$ TeV, Right: $\sqrt{s} = 360$ GeV

$\mathcal{O}_{H} = \frac{1}{2} (\partial_{\mu} H^{2})^{2}$	$\mathcal{O}_{GG}=g_{s}^{2} \mathcal{H} ^{2}G_{\mu u}^{A}G^{A,\mu u}$
$\mathcal{O}_{WW}=g^2 \mathcal{H} ^2 W^a_{\mu u} W^{a,\mu u}$	$\mathcal{O}_{y_u} = y_u H ^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} (u \to t, c)$
$\mathcal{O}_{BB}=g^{\prime2} H ^2B_{\mu u}B^{\mu u}$	$\mathcal{O}_{y_d} = y_d H ^2 \bar{q}_L H d_R + \text{h.c.} (d \to b)$
$\mathcal{O}_{HW} = ig(D^{\mu}H)^{\dagger}\sigma^{a}(D^{\nu}H)W^{a}_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e H ^2 \overline{l}_L He_R + \text{h.c.} (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^{\mu}H)^{\dagger}(D^{\nu}H)B_{\mu\nu}$	$\mathcal{O}_{3W}=rac{1}{3!}g\epsilon_{abc}W^{a u}_{\mu}W^{b}_{ u ho}W^{c ho\mu}$
$\mathcal{O}_{W} = \frac{ig}{2} (H^{\dagger} \sigma^{a} \overleftrightarrow{D_{\mu}} H) D^{\nu} W^{a}_{\mu\nu}$	$\mathcal{O}_{B} = \frac{ig'}{2} (H^{\dagger} \overleftarrow{D_{\mu}} H) \partial^{\nu} B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^{\dagger}_{\mu\nu} \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^{\dagger} \overleftrightarrow{D_{\mu}} H \bar{\ell}_L \gamma^{\mu} \ell_L$
$\mathcal{O}_{T} = \frac{1}{2} (H^{\dagger} \overrightarrow{D_{\mu}} H)^{2}$	$\mathcal{O}'_{H\ell} = iH^{\dagger}\sigma^{a}\widetilde{D_{\mu}}H\bar{\ell}_{L}\sigma^{a}\gamma^{\mu}\ell_{L}$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu_\ell \ell_L) (\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = i H^{\dagger} \overleftarrow{D_{\mu}} H \overline{e}_R \gamma^{\mu} e_R$
$\mathcal{O}_{Hq} = i H^{\dagger} \overleftrightarrow{D_{\mu}} H \overline{q}_L \gamma^{\mu} q_L$	$\mathcal{O}_{Hu} = iH^{\dagger} \overleftrightarrow{D_{\mu}} H \overline{u}_R \gamma^{\mu} u_R$
$\mathcal{O}_{Hq}^{\prime} = i H^{\dagger} \sigma^{a} \overrightarrow{D_{\mu}} H \overline{q}_{L} \sigma^{a} \gamma^{\mu} q_{L}$	$\mathcal{O}_{Hd} = i H^{\dagger} \widetilde{D_{\mu}'} H \overline{d}_R \gamma^{\mu} d_R$

- ▶ SILH' basis (eliminate \mathcal{O}_{WW} , \mathcal{O}_{WB} , $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate \mathcal{O}_W , \mathcal{O}_B , $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate \mathcal{O}_W , \mathcal{O}_B , \mathcal{O}_{HW} and \mathcal{O}_{HB})

$e^+e^- ightarrow WW$ with Optimal Observables

- TGCs (and additional EFT parameters) are sensitive to the differential distributions!
 - One could do a fit to the binned distributions of all angles.
 - Not the most efficient way of extracting information.
 - Correlations among angles are sometimes ignored.
- What are optimal observables?

(See e.g. Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

In the limit of large statistics (everything is Gaussian) and small parameters (linear contribution dominates), the best possible reaches can be derived analytically!

$$rac{d\sigma}{d\Omega} = oldsymbol{S}_0 + \sum_i oldsymbol{S}_{1,i} oldsymbol{g}_i, \qquad oldsymbol{c}_{ij}^{-1} = \int d\Omega rac{oldsymbol{S}_{1,i} oldsymbol{S}_{1,j}}{oldsymbol{S}_0} \cdot \mathcal{L}$$

The optimal observables are given by O_i = S_{1,i}/S₀, and are functions of the 5 angles.







[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

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Jiayin Gu (顾嘉荫)

Top operators in loops (EW processes) [2205.05655] Y. Liu, Y. Wang, C. Zhang, L. Zhang, JG



- Top operators (1-loop) + EW operators (tree, including bottom dipole operators)
- Good sensitivities, but too many parameters for a global fit...
- It shows the importance of directly measuring $e^+e^-
 ightarrow tar{t}$.

Jiayin Gu (顾嘉荫)

We know very little about the Higgs potential!



- To know more about the Higgs potential, we need to measure the Higgs self-couplings (hhh and hhhh couplings).
- The $(H^{\dagger}H)^3$ operator can modify the Higgs self-couplings.
- Probing the *hhh* coupling at Hadron colliders.
 - ▶ $gg \rightarrow hh$
 - ▶ $\lesssim 50\%$ at HL-LHC.
 - $\lesssim 5\%$ at a 100 TeV collider.



Triple Higgs coupling at one-loop order

[arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, Vantalon





$$\begin{split} \kappa_{\lambda} &\equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}},\\ \delta\kappa_{\lambda} &\equiv \kappa_{\lambda} - 1 = \mathcal{C}_{6} - \frac{3}{2}\mathcal{C}_{H},\\ \text{with } \mathcal{L} &\supset -\frac{c_{6}\lambda}{v^{2}}(H^{\dagger}H)^{3}. \end{split}$$

- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: hZ near threshold (more sensitive to δκ_λ)
- ▶ at 350-365 GeV:
 - WW fusion
 - hZ at a different energy
- h → WW*/ZZ* also have some discriminating power (but turned out to be not enough).

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Triple Higgs coupling from EFT global fits



Runs at two different energies (240 GeV and 350/365 GeV) are needed to obtain good constraints on the triple Higgs coupling in a global fit!

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Triple Higgs coupling from global fits [arXiv:1711.03978]

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39

- 240, 365 GeV are better than 250, 350 GeV.
- ▶ Impacts of Z-pole measurements are not negligible. (eeZ(h) contact interaction enters $e^+e^- \rightarrow hZ$.)

Standard Model Effective Field Theory for H/EW/tt

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Updates on the WW analysis with Optimal Observables

- How well can we do it in practice?
 - detector acceptance, measurement uncertainties, ...
- What we have done (current work for the snowmass study)
 - detector acceptance
 (|cos θ| < 0.9 for jets, < 0.95 for leptons)
 - some smearing (production polar angle only, $\Delta = 0.1$)
 - ILC: marginalizing over total rate (δN) and effective beam polarization (δP_{eff})
- Constructing full EFT likelihood and feed it to the global fit. (For illustration, only showing the 3-aTGC fit results here.)
- Further verifications (by experimentalists) are needed.

Reach on the scale of new physics

95% CL reach from the full EFT fit

- Reach on the scale of new physics Λ .
- Note: reach depends on the couplings c_i!

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Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

- Higgs precision measurements have sensitivity to the top operators in the loops.
 - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

Jiayin Gu (顾嘉荫)

You can't really separate Higgs from the EW gauge bosons!

 $\begin{array}{l} \bullet \quad \mathcal{O}_{H\ell} = iH^{\dagger} \overrightarrow{D_{\mu}} H \overline{\ell}_{L} \gamma^{\mu} \ell_{L}, \\ \mathcal{O}_{H\ell}' = iH^{\dagger} \sigma^{a} \overrightarrow{D_{\mu}} H \overline{\ell}_{L} \sigma^{a} \gamma^{\mu} \ell_{L}, \\ \mathcal{O}_{He} = iH^{\dagger} \overrightarrow{D_{\mu}} H \overline{e}_{R} \gamma^{\mu} e_{R} \end{array}$

(or the ones with quarks)

- modifies gauge couplings of fermions,
- also generates hVff type contact interaction.

- $\mathcal{O}_{HW} = ig(D^{\mu}H)^{\dagger}\sigma^{a}(D^{\nu}H)W^{a}_{\mu\nu}, \\ \mathcal{O}_{HB} = ig'(D^{\mu}H)^{\dagger}(D^{\nu}H)B_{\mu\nu}$
 - generate **aTGCs** $\delta g_{1,Z}$ and $\delta \kappa_{\gamma}$,
 - also generates *HVV* anomalous couplings such as hZ_μ∂_νZ^{μν}.

Jiayin Gu (顾嘉荫)

You also have to measure the Higgs!

- Some operators can only be probed with the Higgs particle.
- $|H|^2 W_{\mu\nu} W^{\mu\nu} \text{ and } |H|^2 B_{\mu\nu} B^{\mu\nu}$
 - $H \rightarrow v/\sqrt{2}$, corrections to gauge couplings?
 - Can be absorbed by field redefinition! This applies to any operators in the form |*H*|²𝔅_{SM}.

$$c_{\rm SM} \mathcal{O}_{\rm SM}$$
 vs. $c_{\rm SM} \mathcal{O}_{\rm SM} + \frac{c}{\Lambda^2} |H|^2 \mathcal{O}_{\rm SM}$
= $(c_{\rm SM} + \frac{c}{2} \frac{v^2}{\Lambda^2}) \mathcal{O}_{\rm SM}$ + terms with h
= $c'_{\rm SM} \mathcal{O}_{\rm SM}$ + terms with h

- probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the *hWW* and *hZZ* anomalous couplings.
- or Higgs in the loop (different story...)
- Yukawa couplings, Higgs self couplings, ...

EFT is good for lepton colliders.

 A systematic parameterization of Higgs (and other) couplings.

Lepton colliders are also good for EFT!

- High precision $\Rightarrow E \ll \Lambda$ Ideal for EFT studies!
- LHC is built for discovery, but

- EFT is good for lepton colliders.
 - A systematic parameterization of Higgs (and other) couplings.
- Lepton colliders are also good for EFT!
 - High precision $\Rightarrow E \ll \Lambda$ Ideal for EFT studies!
 - LHC is built for discovery, but
- Energy vs. Precision
 - Poor measurements at the high energy tails lead to problems in the interpretation of EFT...

But you are ignoring the dim-8 effects which are at the same order

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Jiayin Gu (顾嘉荫)

A lesson from history

- In 1875, a young Max Planck was told by his advisor Philipp von Jolly not to study physics, since there was nothing left to be discovered.
 - Planck did not listen.

- In 1887, Michelson and Morley tried to find ether, the postulated medium for the propagation of light that was widely believed to exist.
 - They didn't find it.

 "Our future discoveries must be looked for in the sixth place of decimals." — Albert A. Michelson

Jiayin Gu (顾嘉荫)

A lesson from Christopher Columbus (哥伦布发现美洲大陆)

- You need to have a theory.
 - The earth is round, India is in the east...
- Your theory can be wrong!
 - Columbus did not find India, but found America instead...
- You need to ask money from the government!
 - Columbus convinced the monarchs of Spain to sponsor him.

Will we discover the new world?

