EFT interpretation with Higgs combination analysis

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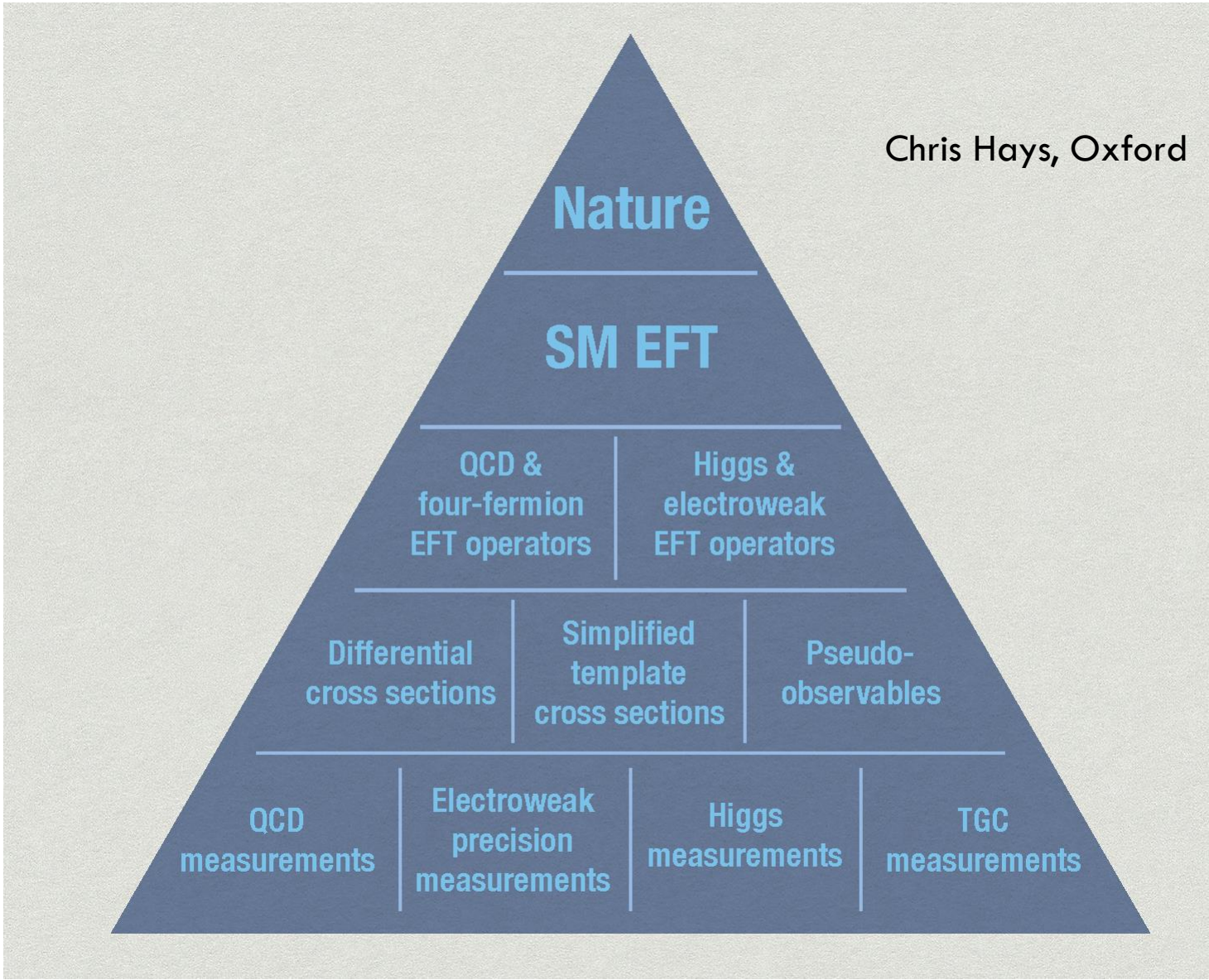
CEPC Theory Group Workshop

From measurements to EFT



EFT operator basis

- The SM EFT is a basis with 59 dimension-6 Wilson coefficients
  - assuming flavour-diagonal couplings and no baryon-number violation
  - combine all sensitive Higgs, electroweak, QCD, four-fermion measurements

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_{i=1}^{59} \alpha_i \mathcal{O}_i$$

arXiv:1008.4884

- Only a subset of these operators contribute to the $e^+e^- \to ZH$ process, and of these many may be exchanged via field redefinitions or equations of motion.

arXiv:1406.1361

$\Phi^4\, D^2$	$X^2\, \Phi^2$	$\psi^2\, \Phi^2\, D$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{\ell}\gamma^\mu\ell)$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{\ell}\gamma^\mu\tau^I\ell)$
	$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
	$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	

Observable parameterization

- Reparameterize observables in terms of functions of EFT coefficiencies and SM parameters
  - mass, cross section, branching ratios, angular observables etc.

$$\sigma(s) = \frac{32\pi}{9}\frac{1}{2^{10}(2\pi)^3}\frac{1}{\sqrt{r}\gamma_Z}\frac{\sqrt{\lambda(1,s,r)}}{s^2}\frac{1}{m_h^2}(4J_1+J_2)\,.$$

arXiv:1603.03385
Shao-Feng Ge, Hong-Jian He, Rui-Qing Xiao

angular observables $\mathcal{A}_i$, normalized to σ:

$$\begin{aligned}
\mathcal{A}_{\theta_1} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos(2\theta_1))\,\frac{d\sigma}{d\cos\theta_1} \\
&= 1-\frac{5}{2\sqrt{2}}+\frac{3J_1}{\sqrt{2}(4J_1+J_2)} \\
\mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin\phi)\,\frac{d\sigma}{d\phi} = \frac{9\pi}{32}\frac{J_4}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin(2\phi))\,\frac{d\sigma}{d\phi} = \frac{2}{\pi}\frac{J_8}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos\phi)\,\frac{d\sigma}{d\phi} = \frac{9\pi}{32}\frac{J_6}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos(2\phi))\,\frac{d\sigma}{d\phi} = \frac{2}{\pi}\frac{J_9}{4J_1+J_2}
\end{aligned}$$

arXiv:1512.06877
Nathaniel Craig, Jiayin Gu, Zhen Liu, Kechen Wang

the forward-backward asymmetry

$$\begin{aligned}
\mathcal{A}_{c\theta_1,c\theta_2} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} \\
&= \frac{9}{16}\frac{J_3}{4J_1+J_2}.
\end{aligned}$$

Observable precision to EFT constraints

- Use analytical χ^2 fit to get constraints on EFT operator coefficiencies

arXiv:1603.03385

New physics scales $\Lambda/\sqrt{|c_j|}$ (in TeV) which can be probed by combining the current electroweak precision tests on (α, G_F, M_Z, M_W) [36] and the future Higgs measurements on $(\sigma(Zh)$, $\sigma(\nu\bar{\nu}h)$, and branching fractions) at the Higgs factory CEPC (250 GeV) [13] with a projected luminosity of $5\,\mathrm{ab}^{-1}$. The sensitivities are presented as the 95% exclusions (first row) and the $5\,\sigma$ discoveries (second row), respectively.

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_{L}^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
2.5	10.6	6.38	5.78	6.53	2.12	0.604	8.23	12.1	10.2	8.78	2.06	0.568	0.393	0.339	43.8
1.57	6.65	4.00	3.62	4.09	1.33	0.378	5.15	7.57	6.39	5.49	1.29	0.356	0.246	0.212	27.4

- including the existing EWPO together with future Higgs measurements can probe the new physics scales up to 10TeV
- including the CEPC precision measurements can further lift the reach up to 35TeV
  - motivates a longer Z-pole running
- the CEPC precision tests of Higgs couplings can probe the new physics scales with Yukawa type operators up to (13-25)TeV

Observable precision to EFT constraints

- Use appropriately-constructed angular asymmetries to probe non-standard tensor structures arising from BSM physics.
  - angular measurements provide complementary sensitivity to rate measurements

arXiv:1512.06877

1σ uncertainties for individual Wilson coefficients, with the assumption that all other coefficients are zero. The second row shows the constraints from the rate measurements only, the third row shows the constraints from measurements of angular observables (combined) only, and the last row shows the total combined constraints from both rate and angular measurements. If no constraint could be derived within our procedure, a ∞ is shown.

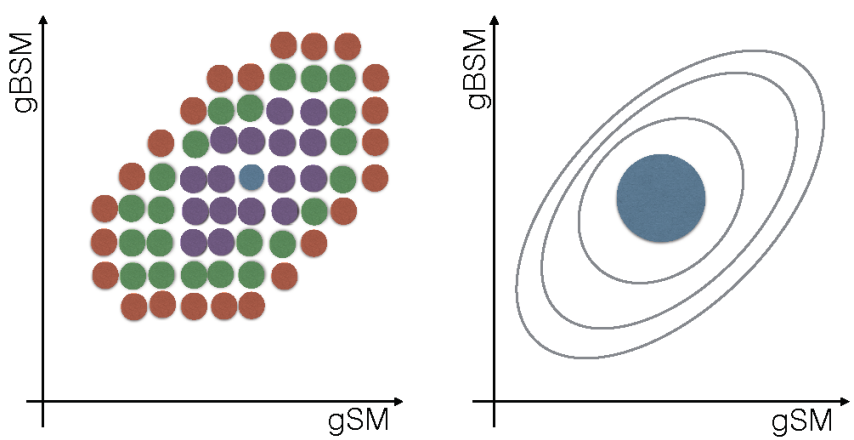
	$\widehat{\alpha}_{ZZ}$	$\widehat{\alpha}^{(1)}_{ZZ}$	$\widehat{\alpha}^{V}_{\Phi\ell}$	$\widehat{\alpha}^{A}_{\Phi\ell}$	$\widehat{\alpha}_{AZ}$	δg_V	δg_A	$\widehat{\alpha}_{Z\tilde{Z}}$	$\widehat{\alpha}_{A\tilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	∞	∞
angles	0.016	∞	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	0.0047	0.00059	0.0070	0.014	0.0018	0.012	0.036

- Including additional channels would help to determine the maximum possible sensitivity of angular asymmetries
- Need detailed estimate of current and projected theory uncertainties in the Standard Model prediction for Higgsstrahlung differential distributions

Work with distributions? morphing

- **Analytical morphing** is a method to construct a **continuous signal model** describing Higgs boson couplings in **effective field theories** with BSM couplings.

Main goal: Develop a signal model covering a wide range of values of EFT parameters.



(K. Ecker, HZZ Workshop, 25/04/16)

- prediction of kinematic distributions and cross-sections at every parameter point
- continuous description of distributions in terms of mixing parameters

Morphing: a simple example

Suppose we want to **describe an observable T_{Out}** defined by an interaction vertex affected by a **Standard Model** coupling (denoted g_{SM}) plus a **Beyond Standard Model** (BSM) coupling (denoted g_{BSM}) …

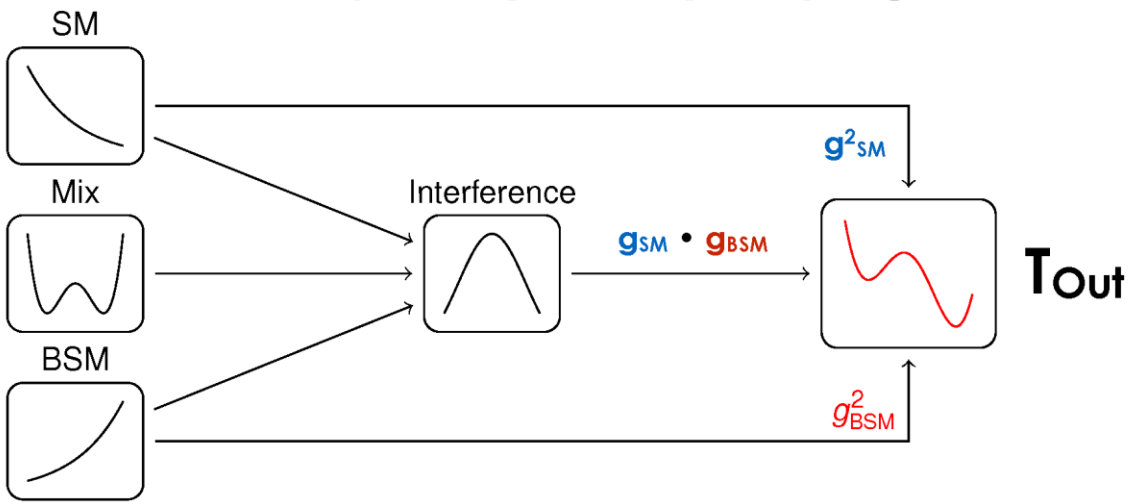
We can express the output distribution T_{Out} as a **weighted sum** of the same observable with different **"template" (or base) couplings**:

David Di Valentino

$w_1 \cdot T_1(1, 0)$

$w_2 \cdot T_2(1, 1)$

$w_3 \cdot T_3(0, 1)$



For an **arbitrary choice** of $g_{Target} = (g_{SM}, g_{BSM})$, then we can write,

$$T_{\mathrm{Out}}(\vec{g}_{\mathrm{Target}}) = \sum_{i=1}^{N_{\mathrm{Input}}} w_i(\vec{g}_{\mathrm{Target}}; \vec{g}_i) \cdot T_i(\vec{g}_i)$$

Higgs EFT or SM EFT?

- **1. Higgs and TGC measurements** (11 CP-even operators, 4 CP-odd operators)
- **2. Electroweak precision measurements** (10 CP-even operators)
- **3. QCD & four-fermion measurements** (34 operators)

- **Benefits of using SM EFT**
  - Extracts the maximum sensitivity from the input datasets
  - More complete predictions in the event of a deviation
  - Connects results from many experiments and allows comparison of sensitivity
  - Straightforward to compare to models, continual improvements possible
  - Experiments can learn subtleties in performing fits
    - more likely to produce optimal measurements for constraining coefficients
- **Challenges**
  - Less distinction between “signal” and “background”
  - Large number of required measurements

More EFT discussion toward CEPC CDR

- Manpower on EFT interpretation for CEPC CDR
  - invite current authors to contribute or perform additional independent study
- Choice of EFT basis
  - Higgs, SILH etc.
  - should be flexible to be mapped to other basis
- Choice of observables
  - rates, masses, width, angular, EWPO
- Statistical methods
  - fit with EFT coefficiency parameterization or scan of the signal model distributions
- Presentation of the results
  - parameters + correlation matrix
- Test models with dimension-8 operators?
  - special symmetries that kill dim-6 and make dim-8 the most important