towards NLO SMEFT global fit at e+e-: RG Mixing between Higgs & Top operators

ongoing work with
Sunghoon Jung, Junghwan Lee (Seoul National U.),
Martin Perello, Marcel Vos (Valencia U.)

Junping Tian (U. Tokyo)

the 27th Meeting of New Higgs Working Group,
Dec. 13-14, 2019 @ Osaka U.

introduction: SM Effective Field Theory @ future e+e-

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}$$

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

- (background) kappa formalism not suitable for precision Higgs coupling determination @ future e+e-: model-dependent; radiative corrections
- SMEFT provides a more model independent formalism
- most general effects from BSM represented by higher dimensional ops.
- respect SU(3)xSU(2)xU(1) gauge symmetries
- consistently relate BSM effects in Higgs, W/Z, top, 2-fermion physics: provide a global view of roles of various measurements @ future e+e-

SMEFT @ future e+e-: some assumptions & simplifications

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}$$

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

assume **Λ >> v** : suggested by new particle searches at LHC Run 2

justify the analysis at dimension-**6** operators

there are ***84*** of such operators for **1** fermion generation

assuming B & L number conservation, there are ***59***

- there exists a smaller but complete set relevant to Higgs couplings determination at e+e-

SMEFT global fit @ e+e-

(Barklow et al, arXiv:1708.09079, 1708.08912; + many papers by other groups)

$$\begin{aligned}\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ &+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}$$

Φ: higgs field
W, B: SU(2), U(1) gauge
L, e: left/right electron

- in total 23 parameters: 17 D-6 operators
  + 4 SM parameters (g, g', v, λ) + 2 for Higgs exotic decays

a complete subset (**@LO**) for Higgs physics at e+e-

SMEFT global fit: important implications for future Higgs factories in particular at their initial stages

ILC250: 2 ab^{-1} **FCCee240: 5 ab^{-1}**

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

(arXiv:1903.01629)

(arXiv:1908.11299)

see recent discussions for European Strategy Update: 1905.03764; 1910.11775

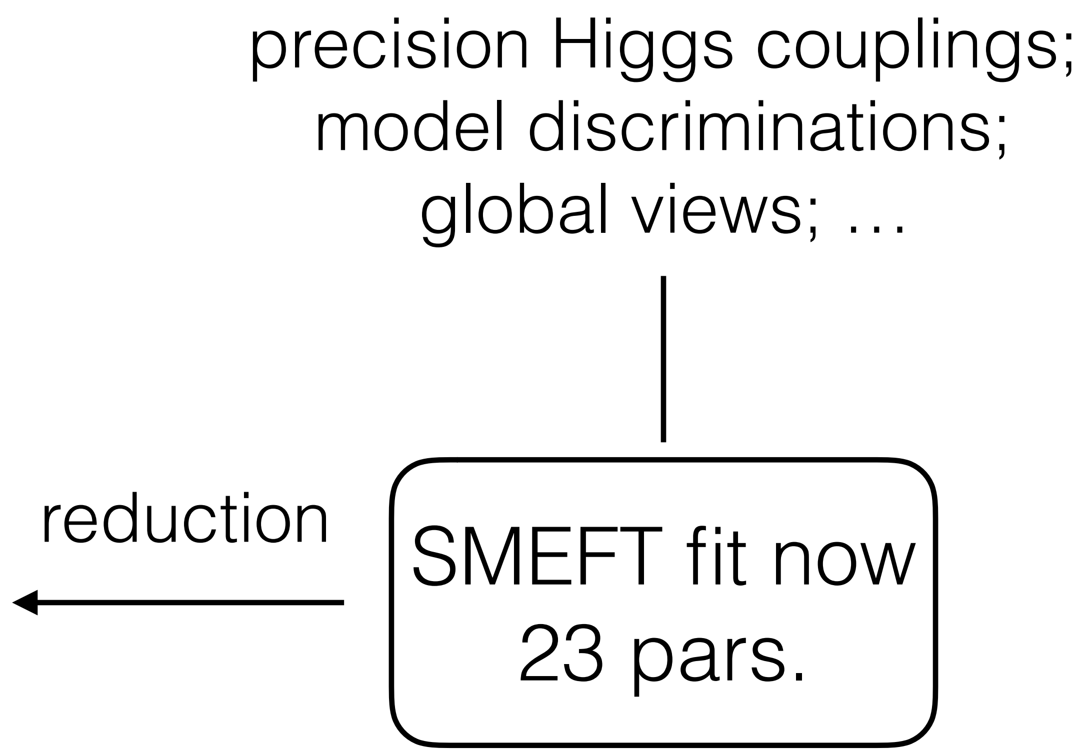
what's next (an experimenter's view)

what's next (an experimenter's view)

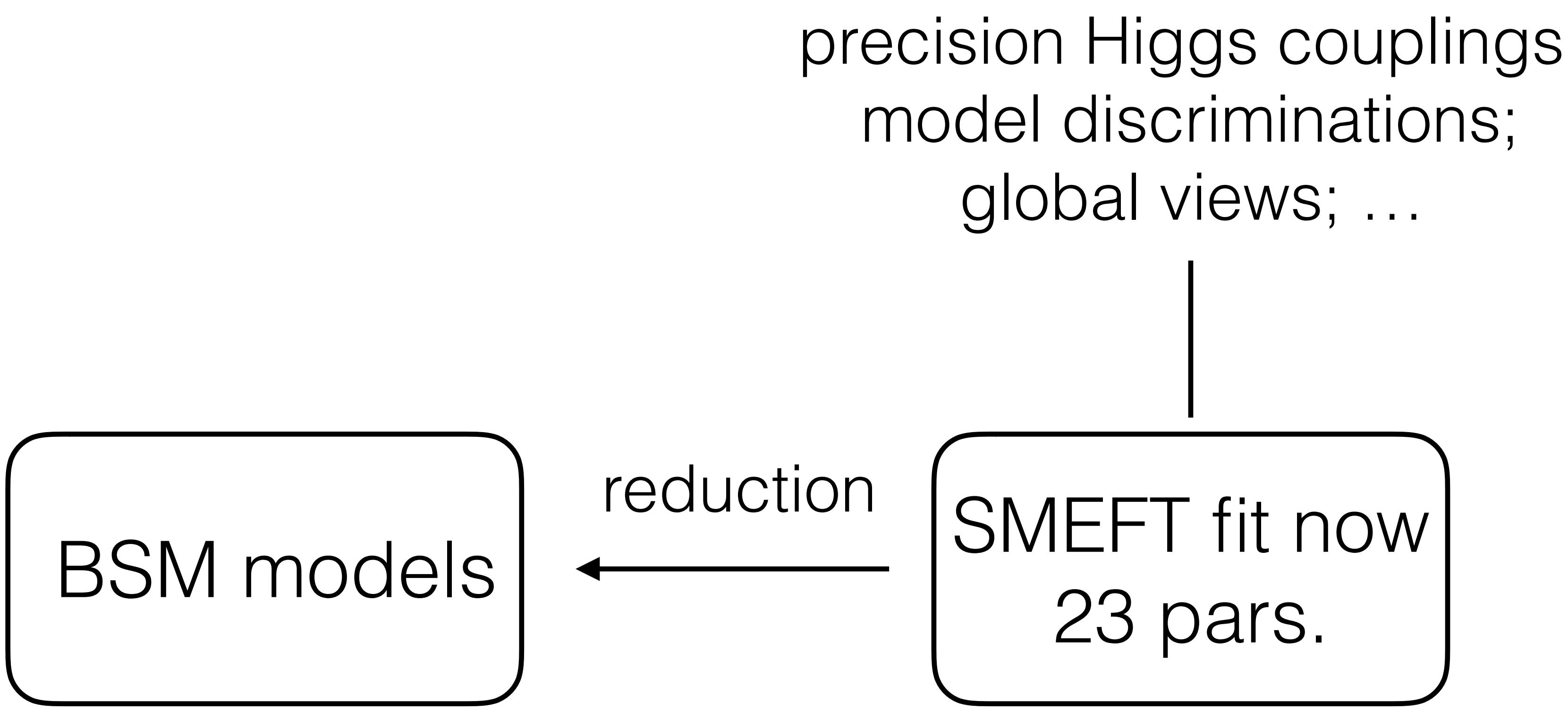
precision Higgs couplings;
model discriminations;
global views; …

SMEFT fit now
23 pars.

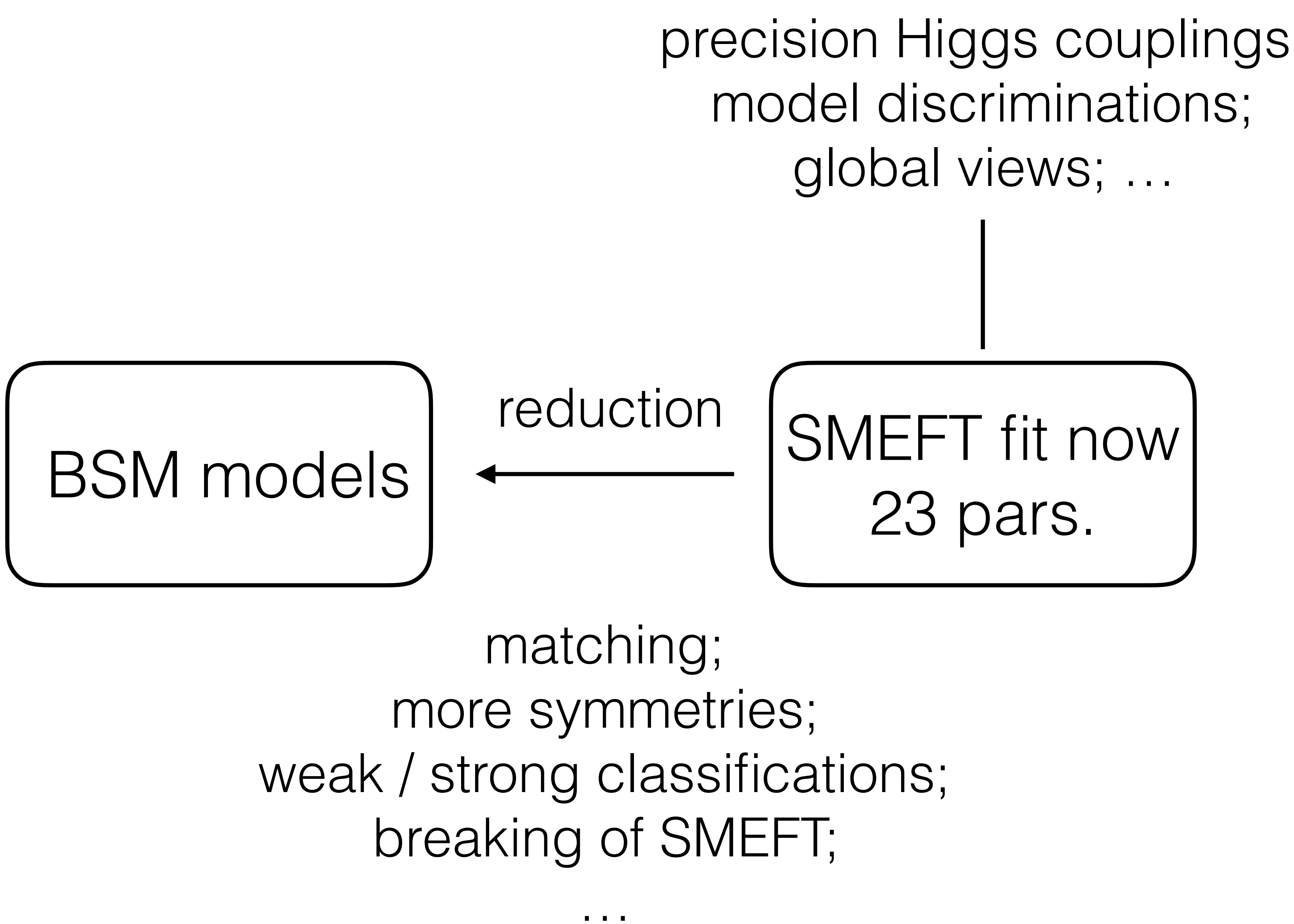
what’s next (an experimenter’s view)



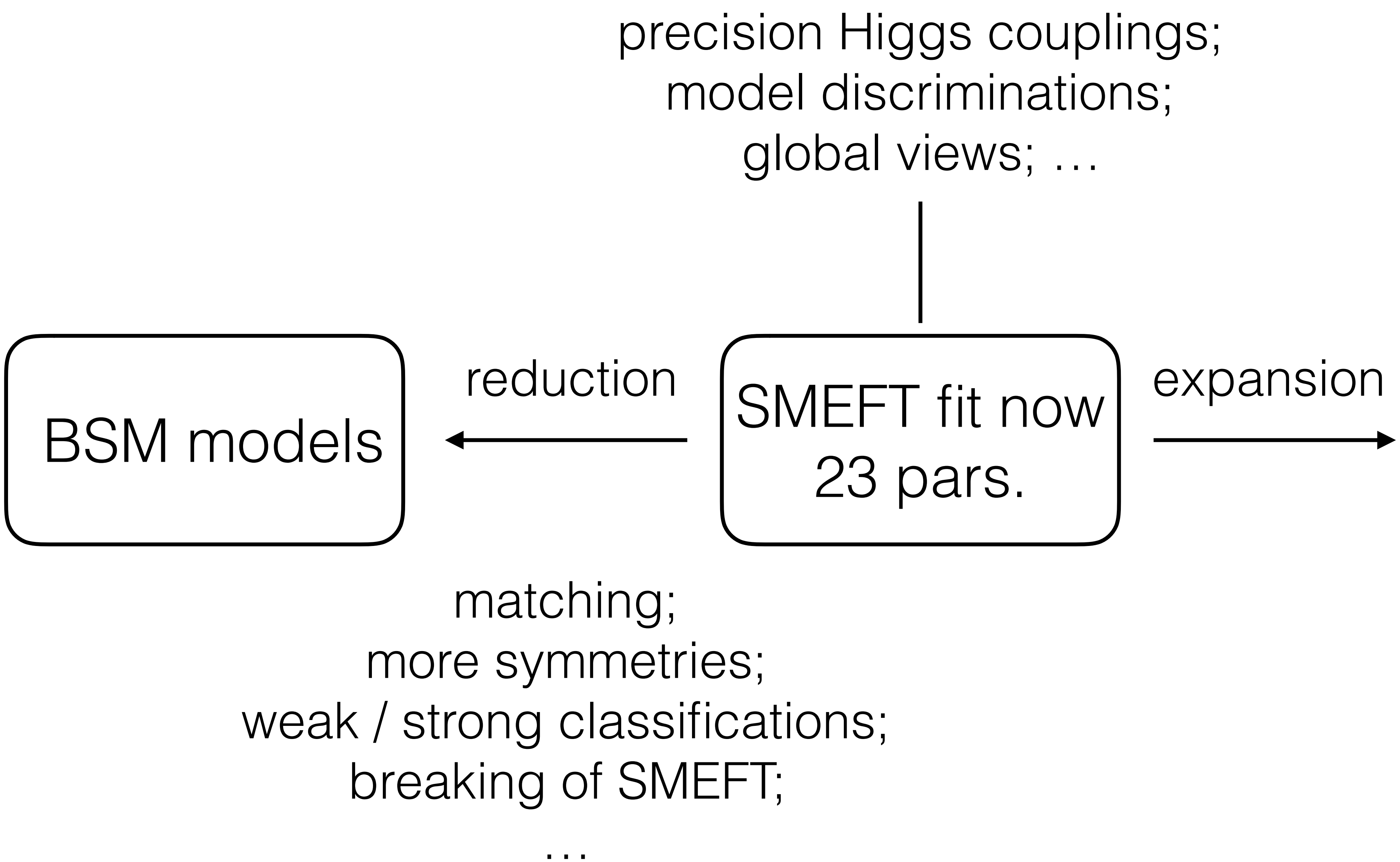
what's next (an experimenter's view)



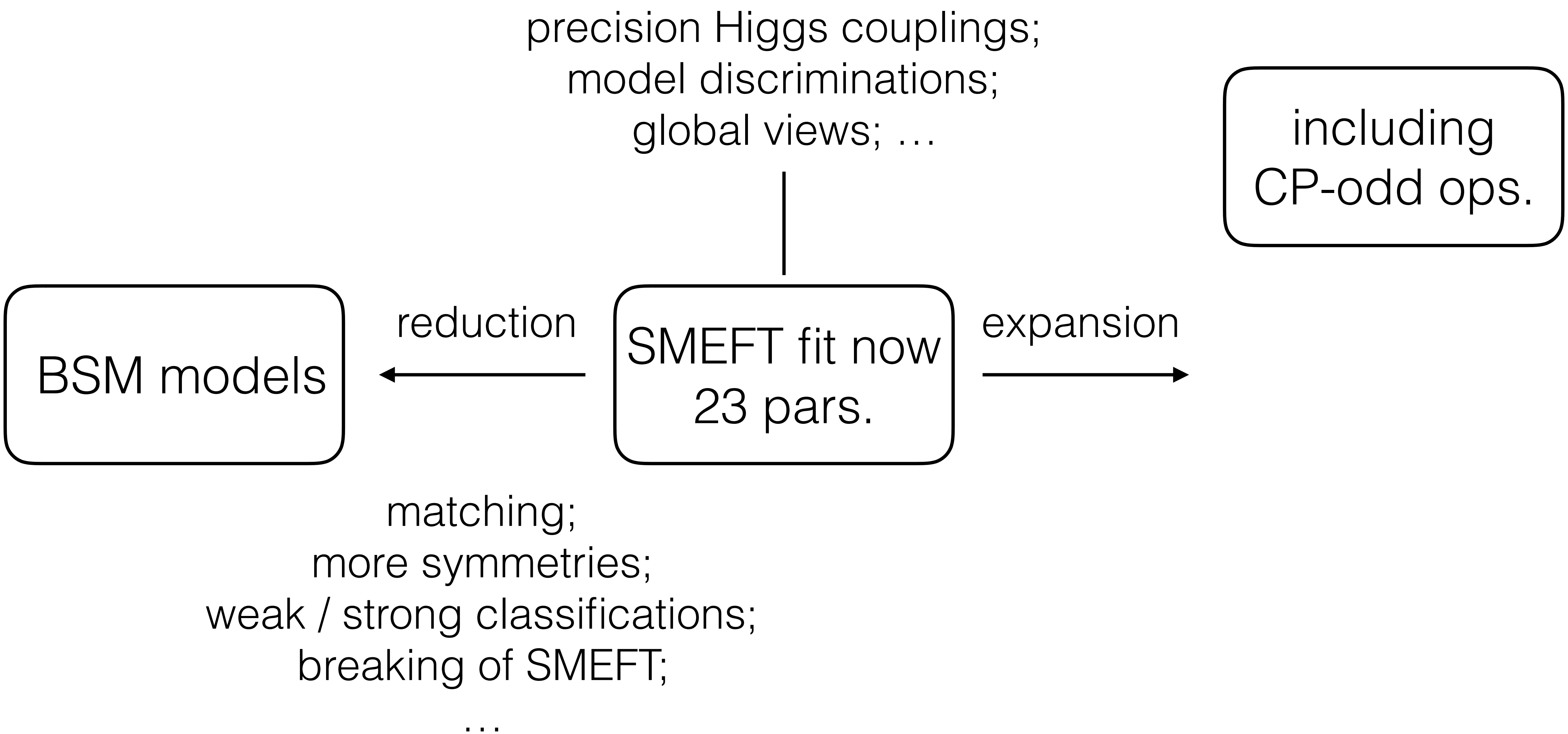
what's next (an experimenter's view)



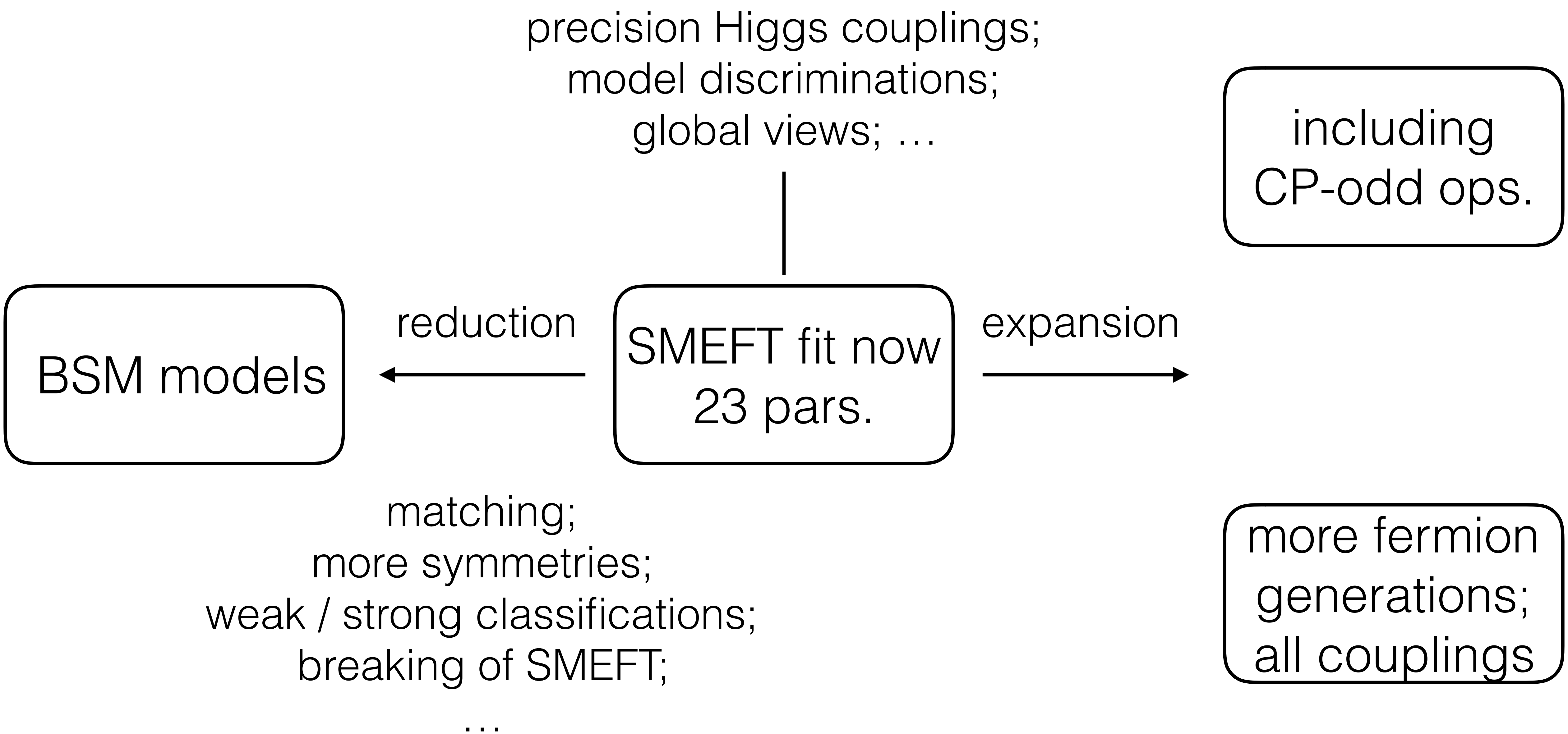
what's next (an experimenter's view)



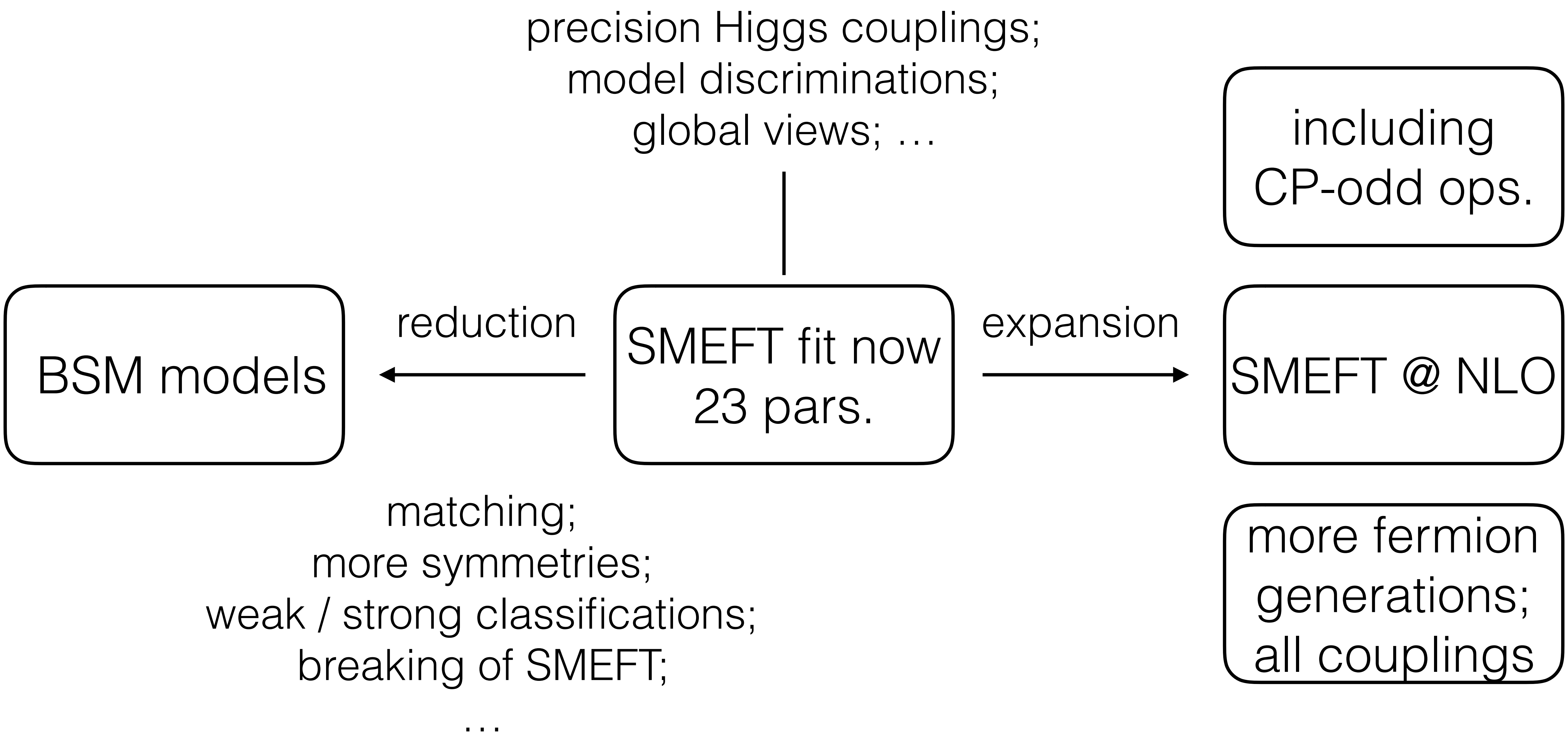
what’s next (an experimenter’s view)



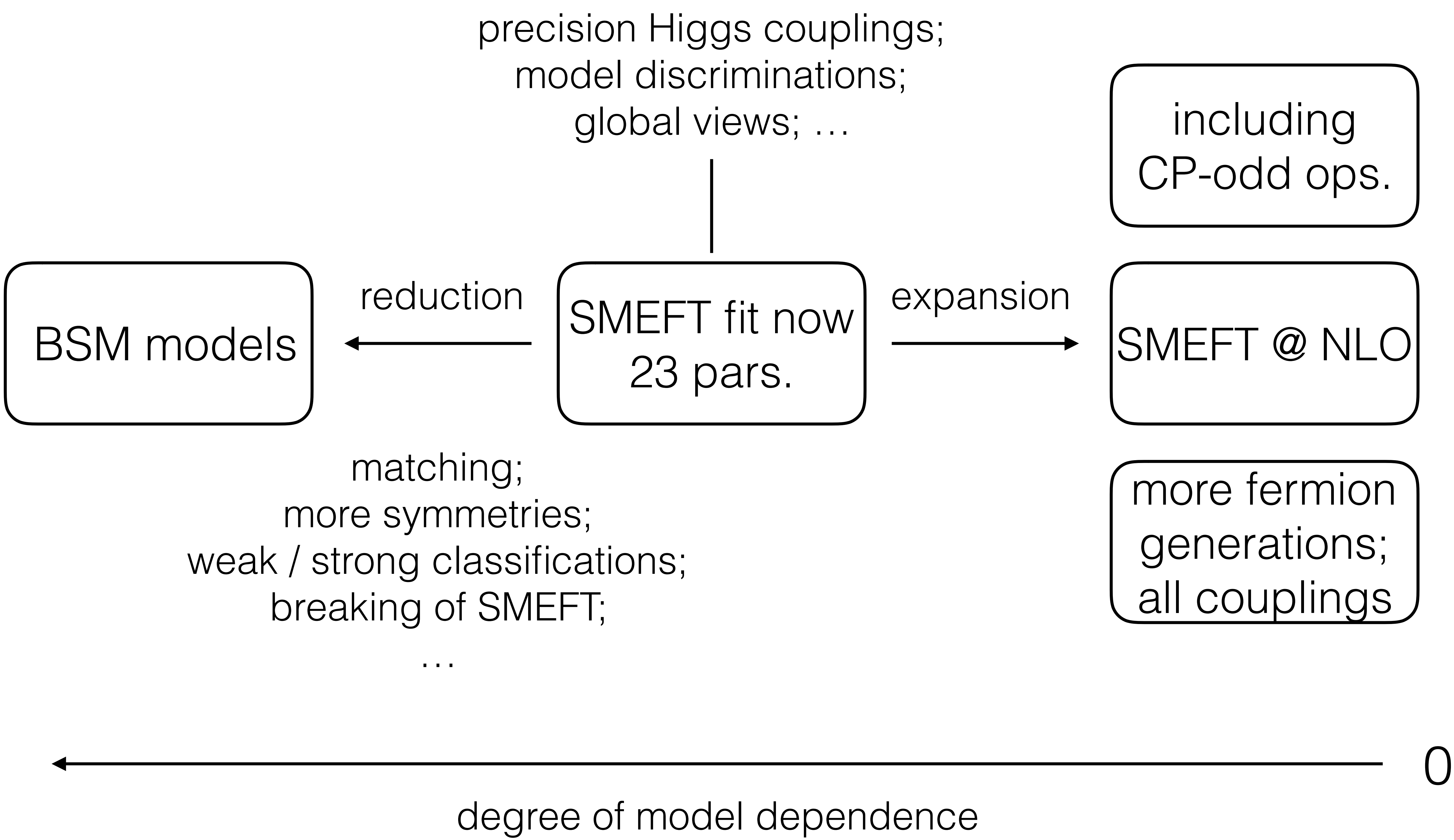
what's next (an experimenter's view)



what's next (an experimenter's view)



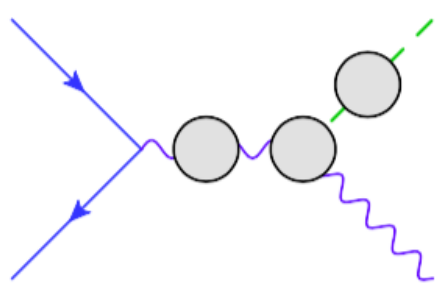
what's next (an experimenter's view)



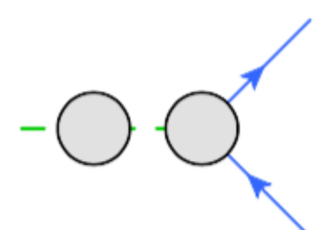
what happens at next leading order for SMEFT

- at e+e-, NLO ~ O(α), 1% level
- for NLO from W/Z/γ/H, operators constrained to ~<0.01, overall effect will be < 0.1%

- for NLO from top, operators would be much less constrained, currently ~ O(1) -> overall effect 1% -> potential impact in global fit on Higgs coupling precision



WH,ZH



H→bb

Zhang, et al, arXiv:1804.09766, 1807.02121

Jung, Vos, JT, et al, work in progress

our approach to include NLO top effects

- we didn't try to include full NLO effects for all observables
- instead, include NLO effects that are log-enhanced
- captured by Renormalization Group Evolution (mixing)

$$\dot{c}_i \equiv 16\pi^2 \frac{\mathrm{d}c_i}{\mathrm{d}\ln\mu} = \gamma_{ij} c_j$$

- c_i: Higgs operators; c_j: Top operators
- no worry to ignore Higgs operators in c_j, as explained last slide
- in this way, we can consistently apply power-counting to all observables, e.g. EWPOs (major difference with earlier work)

new operators (to previous SMEFT fit)

$$\mathcal{O}_{tH} = (\Phi^\dagger\Phi)(\bar{Q}t\tilde{\Phi}), \qquad \mathcal{O}_{Hq}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}\gamma^\mu Q),$$

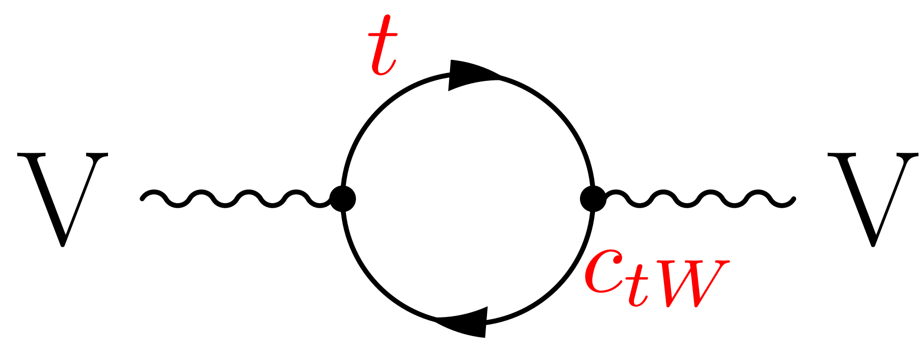
$$\mathcal{O}_{Hq}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}\gamma^\mu\tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{t}\gamma^\mu t),$$

$$\mathcal{O}_{Htb} = i(\tilde{\Phi}^\dagger D_\mu\Phi)(\bar{t}\gamma^\mu b),$$

$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}t)\tau^a\tilde{\Phi}W^a_{\mu\nu}, \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{\Phi}B_{\mu\nu},$$

$$\Delta\mathcal{L}_{\rm top} = y_t\frac{c_{tH}}{v^2}\mathcal{O}_{tH} + \frac{c_{Hq}^{(1)}}{v^2}\mathcal{O}_{Hq}^{(1)} + \frac{c_{Hq}^{(3)}}{v^2}\mathcal{O}_{Hq}^{(3)} + \frac{c_{Ht}}{v^2}\mathcal{O}_{Ht} + \frac{c_{Htb}}{v^2}\mathcal{O}_{Htb} + \frac{c_{tW}}{v^2}\mathcal{O}_{tW} + \frac{c_{tB}}{v^2}\mathcal{O}_{tB}$$

effect of top operators: example



log-enhanced

higgs operator

$$\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu}$$

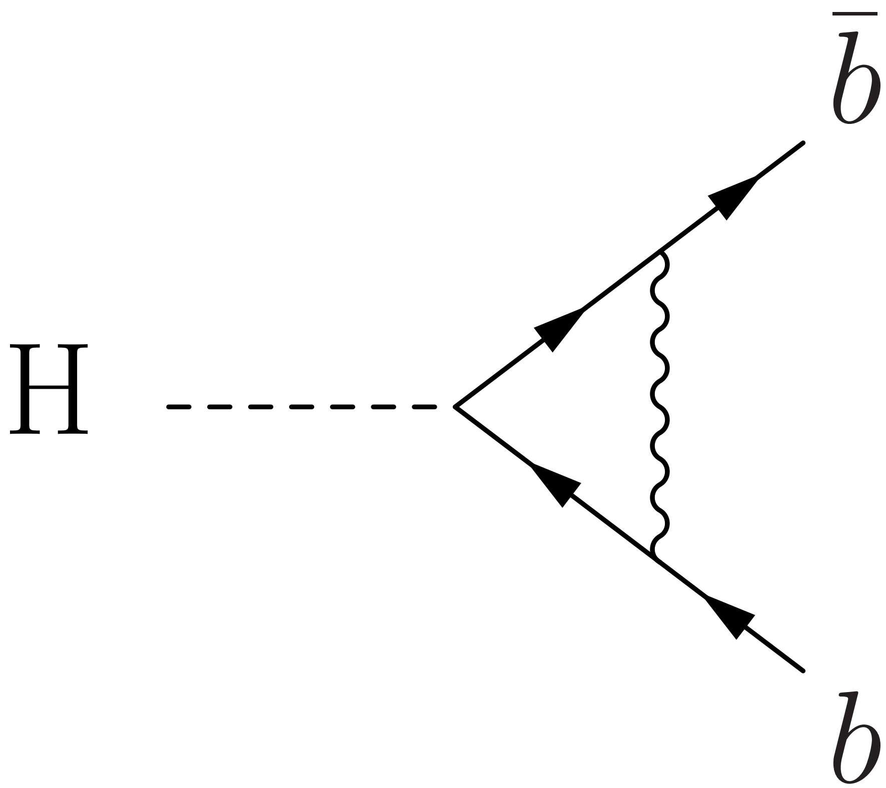
top operator

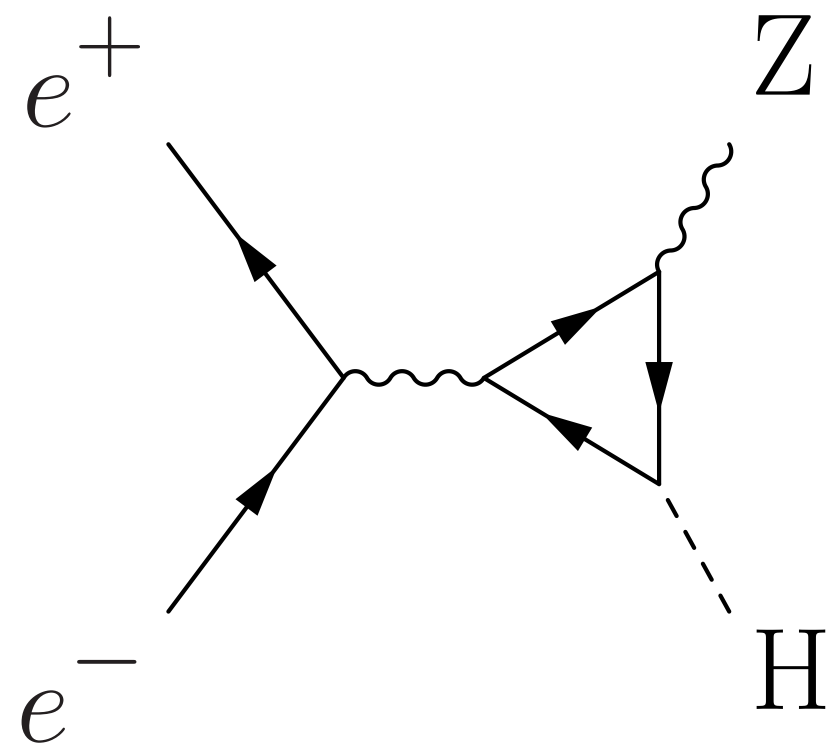
$$\frac{c_{tW}}{v^2}(\bar{Q}\sigma^{\mu\nu} t)\tau^a \tilde{\Phi} W^a_{\mu\nu}$$

$$\dot{c}_{WW} = \frac{1}{4}(-2 g y_t N_c \underline{c_{tW}})$$

effect of top operators: example

not log-enhanced, hence not captured in our approach





power counting

	Higgs loop decays	other Higgs/EW observables	top productions
SM	finite one-loop	tree-level	tree-level
Higgs operators	tree-level	tree-level	-
top operators	finite one-loop	log-enhanced one-loop	tree-level

effect of top operators: example

RG evolution

$$\dot{c}_H = (12y_t^2 N_c - 4g^2 N_c)\underline{c_{Hq}^{(3)}} - 12y_t y_b N_c \underline{c_{Htb}}$$

$$\dot{c}_{BB} = \frac{1}{4t_W^2}(-4g' y_t (Y_q + Y_u) N_c \underline{c_{tB}})$$

$$\dot{c}_{HL} = \frac{1}{2} Y_l g'^2 \left(\frac{16}{3} Y_q N_c \underline{c_{Hq}^{(1)}} + \frac{8}{3} Y_u N_c \underline{c_{Ht}} \right)$$

$$\ldots$$

LO: without top-op

$$\delta\Gamma(h \to WW^*) = -24c_{WW} - 7.8c_H$$

NLO: with top-op

$$\delta\Gamma(h \to WW^*) += 3.1c_{HQ}^{(3)} - 0.09c_{Htb} - 0.36c_{tW}$$

Q scale for various observables

$$c_i(Q) \simeq c_i(Q') + \frac{1}{16\pi^2}\gamma_{ij}c_j(Q')\ln\frac{Q}{Q'}$$

	G_F	EWPO	$\delta m_{W,Z,h}$	$\delta\Gamma(h)$	W^-W^+	$\sigma(\nu\bar{\nu}h)$	$\sigma(Zh)$	$\sigma(Zhh)$
scale Q [GeV]	m_μ	m_Z, m_W	$m_{W,Z,h}$	m_h	250, 500	250, 500	250, 500	500

some at multiple scales:

$$\delta\sigma(Zh \to Zb\bar{b})(Q = 250) = \quad (2.25)$$
$$\delta\sigma(Zh)(Q = 250) + \delta\Gamma(b\bar{b})(Q = m_h) - \delta\Gamma_{\rm tot}(Q = m_h).$$

results

still very preliminary; I will only show a few

see more results in talk by S. Jung @ LCWS2019

paper on arXiv soon

results (I): $\sqrt{s}$ = 250 GeV e+e-

- with the same set of observables, at 250 GeV running only, the global fit will not converge at any of the Higgs factories
- e.g. Higgs couplings could not be determined unambiguously

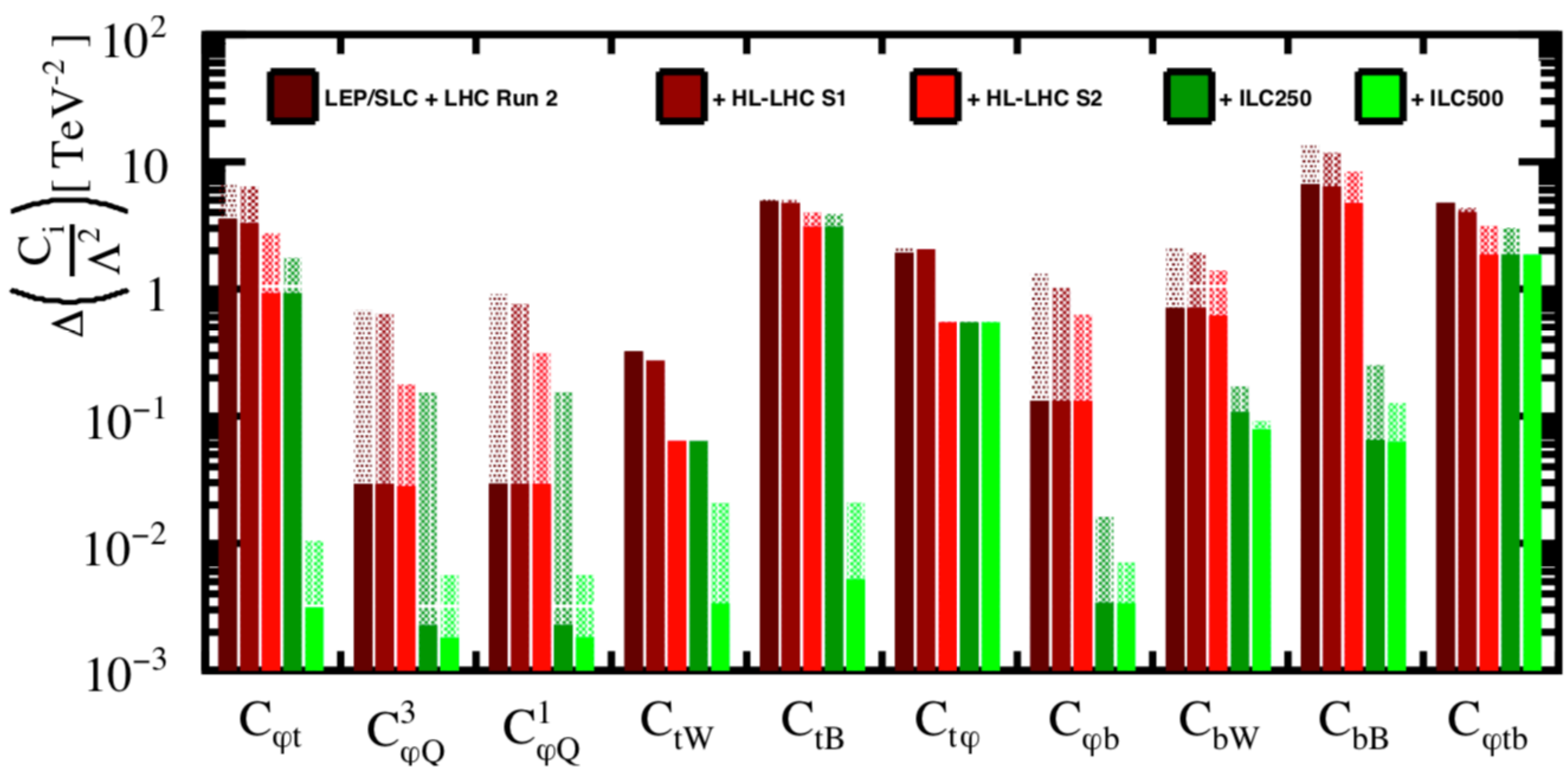
not surprising, but don't worry

results (II): ILC250 + LHC

- LHC will provide us valuable top data sets, such as

$$pp \to t\bar{t} + Z/W/\gamma \qquad t \to Wb$$

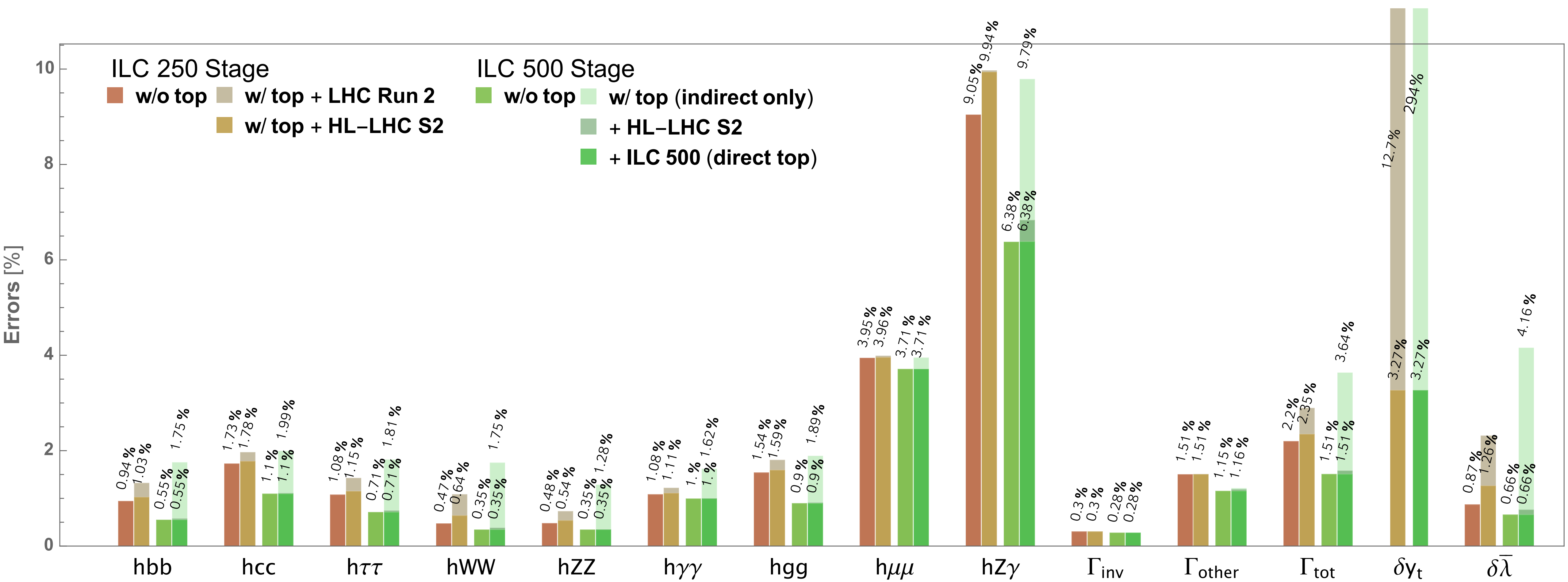
- top operators will be constrained to some extent at (HL-)LHC



(Durieux, et al, arXiv:1907.10619)

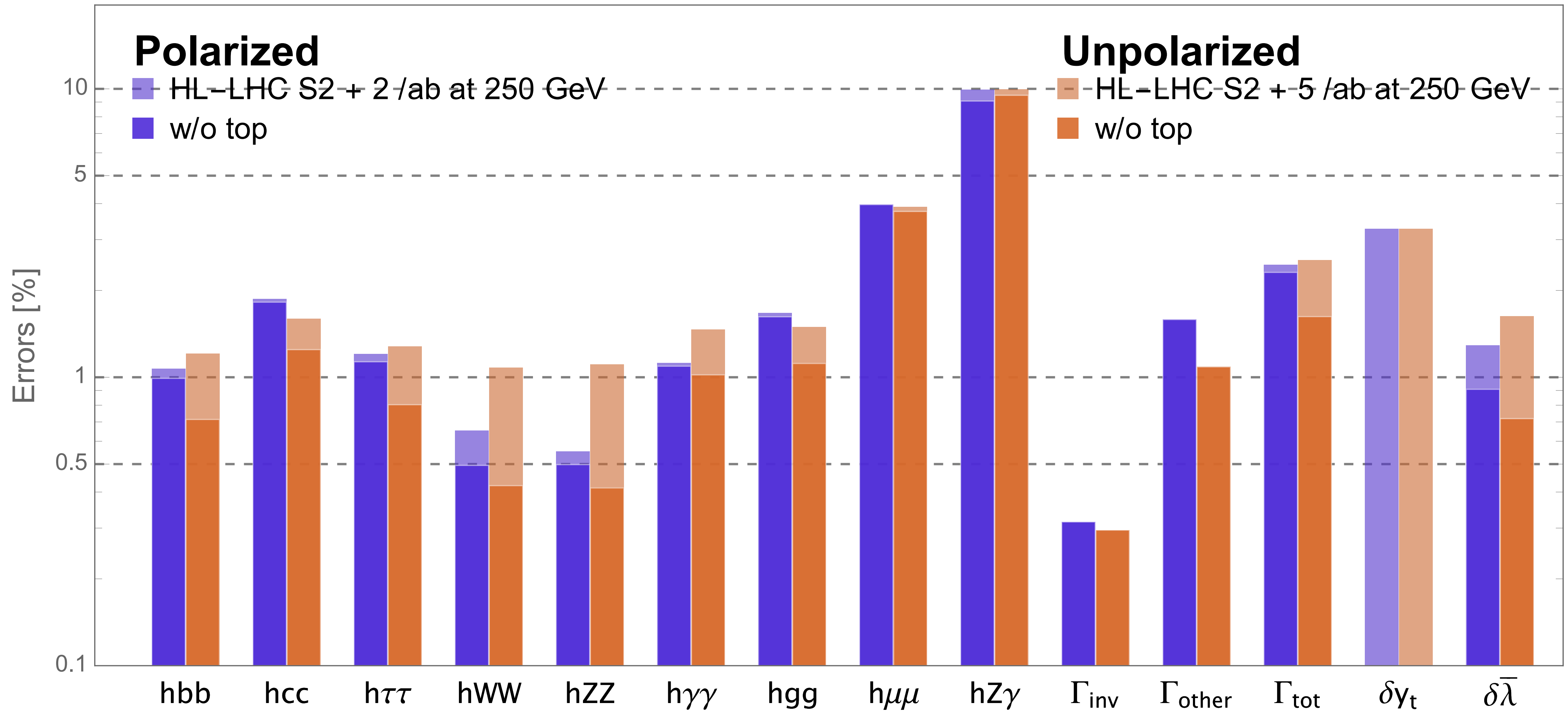
results (II): ILC250 + LHC

- with the help of LHC top data, Higgs coupling precisions @ ILC250 are almost restored
- note: top data from LHC Run 2 is not constraining enough



results (III): polarized vs unpolarized

- polarization now shows its important role
- w/o beam polarizations, even with the help of HL-LHC top data, Higgs coupling precisions @ e+e-250 will suffer a lot



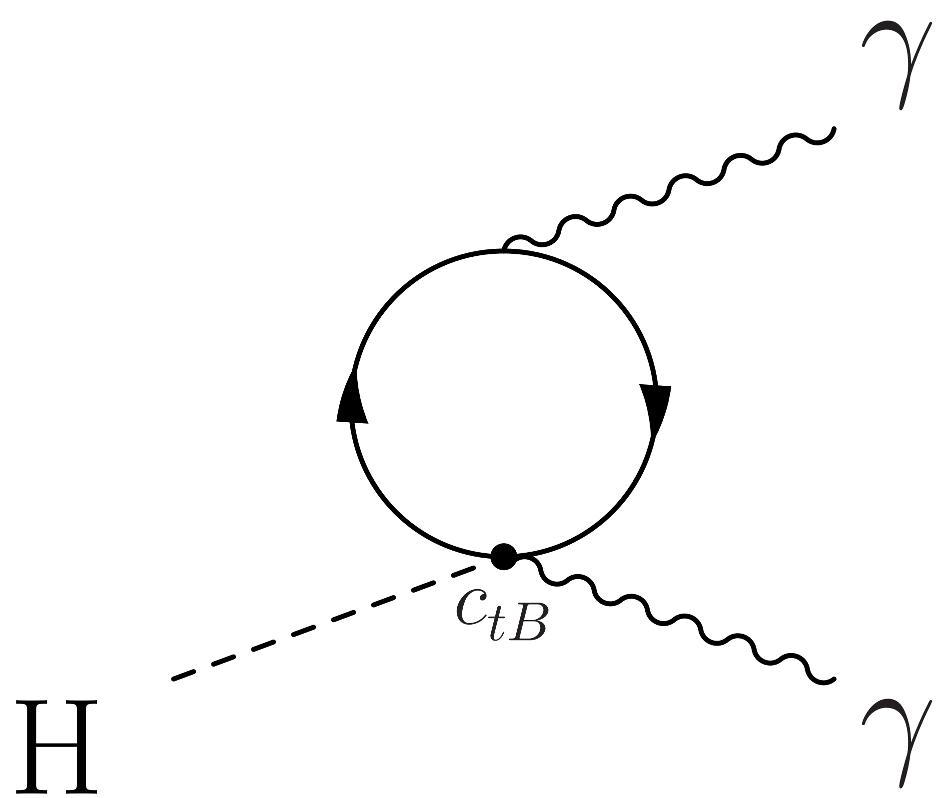
results (IV): $\sqrt{s}$ >= 350 GeV e+e-

- once e+e- -> t t-bar becomes accessible, effects of top operators on the Higgs coupling determination will be well under-control

some detailed understandings

$$\delta\Gamma(h \to \gamma\gamma) : + = -0.56c_{tH} + 1.2c_{HQ}^{(3)} - 0.04c_{Htb} + 33c_{tW} + 61c_{tB}$$

HL-LHC~600%

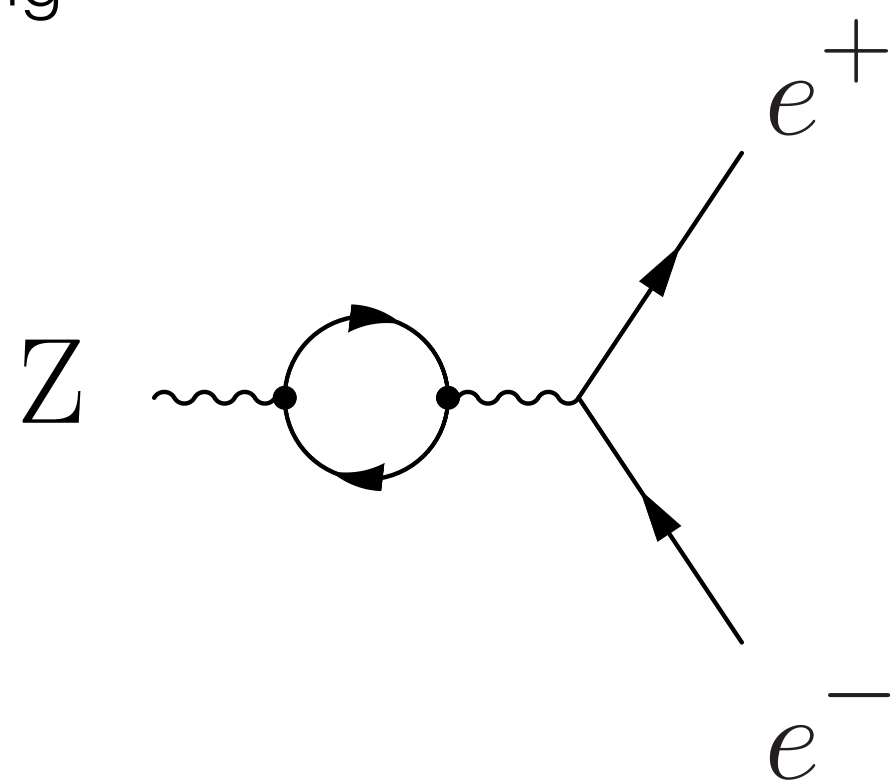


some detailed understandings

$$\delta A_l : + = 0.05 c_{HQ}^{(1)} - 0.2 c_{HQ}^{(3)} + 0.1 c_{Ht} + 1.8 c_{tW} - 0.3 c_{tB}$$

~1%

A_{LR}: left-right asymmetry
in Z-e-e coupling



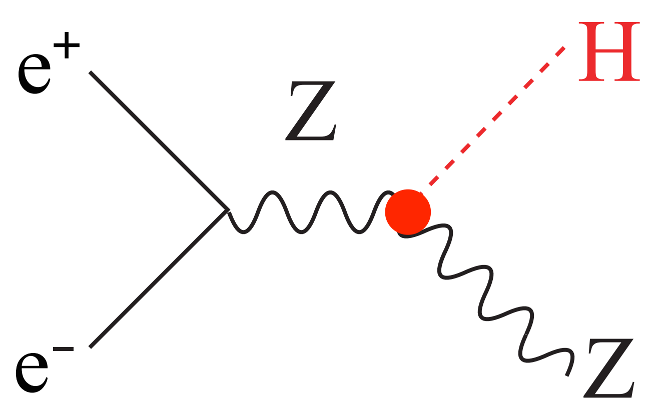
summary

- the capabilities of a e+e- are best represented in SMEFT formalism
- NLO effects from top operators are important for Higgs coupling determination at future Higgs factories by SMEFT fit
- LHC measurements for top processes are important for future Higgs factories
- Higgs coupling precisions at ILC250 will be more or less restored at NLO thanks to the more degrees of freedom provided by beam polarizations

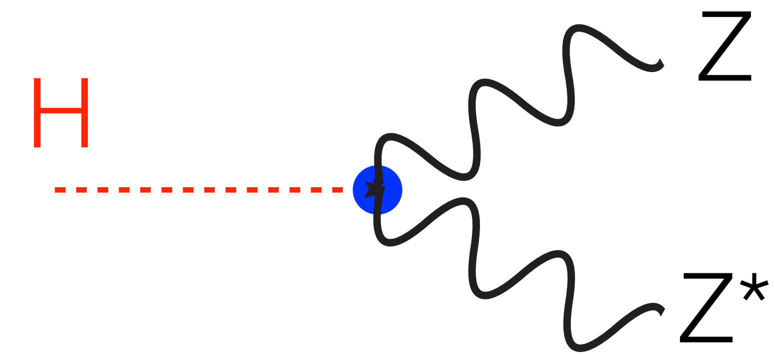
backup

one question in kappa formalism:

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad \textbf{?}$$



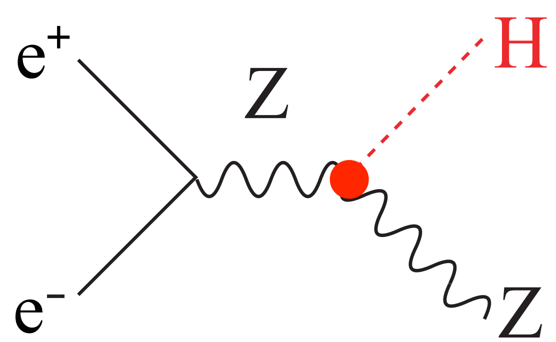
$\propto \quad \kappa_Z^2 \, ? \quad \propto$

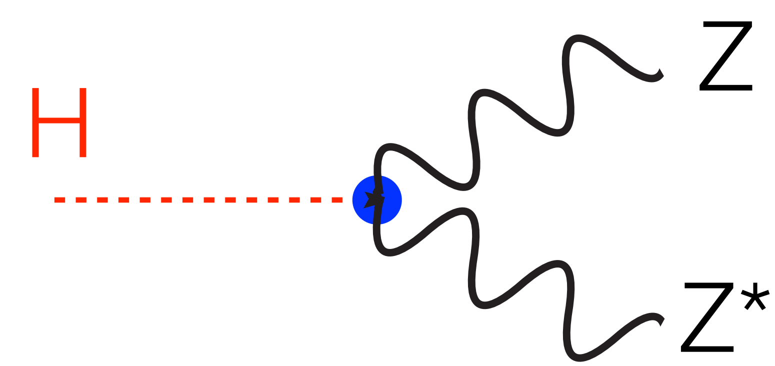


BSM territory: can deviations be represented by single κ_Z?

the answer is model dependent

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$





$$\sigma(e^+e^- \to Zh) = (SM) \cdot (1 + 2\eta_Z + (5.5)\zeta_Z) \neq \Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z)$$

- BSM can induce new Lorentz structures in hZZ
- need a better, more theoretical sound framework