Higgs Couplings & NP Scales @ Lepton Colliders

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SFG, Hong-Jian He, Rui-Qing Xiao, JHEP 1610 (2016) 007 [arXiv:1603.03385]

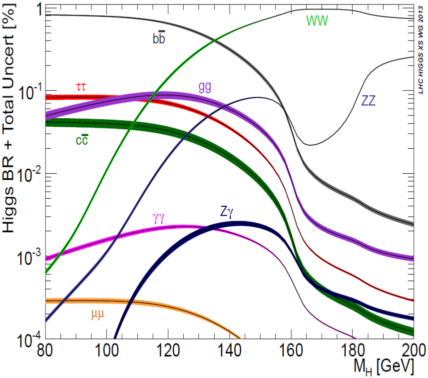
CEPC preCDR

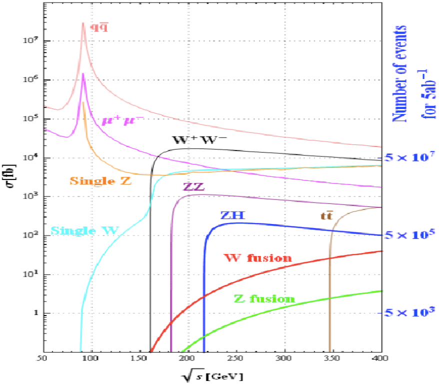
Higgs discovery is not just about *H* particle

- **Force Mediators**
  - **Gauge Forces** – Spin-1 Gauge Bosons
  - **Gravity** – Spin-2 Graviton (Planck Scale?)
  - **New Force** – Spin-0 Higgs Boson
- Deep understanding of **Mass Generation**
  - **Yukawa Forces** – **Hierarchy** & **Mixing** (**Flavor Symmetries?**)
    - Discrete v.s. Continuous
    - Full v.s. Residual [1001.0940, 1104.0602, 1108.0964, 1308.6522]
  - **hWW**, **hZZ**, **h$\gamma\gamma$** & **hZγ**
  - **Higgs Self-Interaction Forces** – **h^3** & **h^4** (concerns spontaneous EWSB and providing masses to all particles). **True Self-Interactions** – **Exactly the Same Quantum # (Spin & Charge**
- These new forces associated with spin-0 Higgs were **Never Seen Before**. Needs to test directly.
- **Even within SM, we are strongly motivated to quantitatively test Higgs Couplings!**

Higgs Factory @ 250 GeV

- **LHC** tells us: $h(125)$ is **SM-like** → **Dream Case for Experiments!**
- **ILC250 & CEPC** produces $h(125)$ via $e^+e^- \to \mathbf{Zh}, \nu\bar{\nu}\mathbf{h}, \mathbf{e^+e^-h}$
- **Indirect Probe** to **New Physics**. **5/ab** with 2 detectors in 10y → $\mathbf{10^6}$ Higgs → **Relative Error** $\sim \mathbf{10^{-3}}$.





Mo, Li, Ruan & Lou, Chin.Phys.C 2015

Inputs: Event Rate → Cross Section & BR

ΔM_h	Γ_h	$\boxed{\sigma(Zh)}$	$\boxed{\sigma(\nu\bar{\nu}h) \times \mathrm{Br}(h \to bb)}$
5.0 MeV	2.6%	**0.5%**	2.8%

Decay Mode	$\boxed{\sigma(Zh) \times \mathrm{Br}}$	Br
$h \to bb$	**0.21%**	0.54%
$h \to cc$	2.5%	2.5%
$h \to gg$	1.3%	1.4%
$h \to \tau\tau$	1.0%	1.1%
$h \to WW$	**1.1%**	1.2%
$h \to ZZ$	**4.3%**	4.3%
$h \to \gamma\gamma$	**9.0%**	9.0%
$h \to \mu\mu$	17%	17%
$h \to \mathrm{invisible}$	–	0.14%

latest 1σ uncertainty
KITPC WS, July 28, 2016

SM Predictions

$\mathrm{Br}(b\bar{b})$	$\mathrm{Br}(c\bar{c})$	$\mathrm{Br}(gg)$	$\mathrm{Br}(\tau\bar{\tau})$	$\mathrm{Br}(WW)$	$\mathrm{Br}(ZZ)$	$\mathrm{Br}(\gamma\gamma)$	$\mathrm{Br}(\mu\bar{\mu})$	$\mathrm{Br}(\mathrm{inv})$
58.1%	2.10%	7.40%	6.64%	22.5%	2.77%	0.243%	0.023%	0

Deviation from SM by Scaling

Ge, He, Xiao,1603.03385; preCDR

- **Coupling**

$$\frac{g_{hii}}{g_{hii}^{\rm sm}} \equiv \boldsymbol{\kappa_{\rm i}} \equiv 1 + \boldsymbol{\delta\kappa_{\rm i}}\,.$$

- **Cross Section**

$$\frac{\delta\sigma(Zh)}{\sigma(Zh)} \simeq 2\boldsymbol{\delta\kappa_{\rm Z}}\,, \qquad \frac{\delta\sigma(\nu\bar{\nu}h)}{\sigma(\nu\bar{\nu}h)} \simeq 2\boldsymbol{\delta\kappa_{\rm W}}\,.$$

- **Decay Width**

$$\frac{\Gamma_{hii}}{\Gamma_{hii}^{\rm sm}} = \boldsymbol{\kappa_{\rm i}^2}\,, \qquad \frac{\Gamma_{\rm inv}}{\Gamma_{\rm tot}^{\rm sm}} = {\rm Br(inv)} \equiv \boldsymbol{\delta\kappa_{\rm inv}}\,.$$

- **Branching Ratio**

$$\mathrm{Br}_i \equiv \frac{\Gamma_i}{\Gamma_{tot}} \simeq \mathbf{Br}_{\mathbf{i}}^{\rm sm}\left(1 + \sum_j \mathbf{A}_{\mathbf{ij}}\boldsymbol{\delta\kappa_{\rm j}}\right)\,, \qquad \mathrm{Br}_{\rm inv} \simeq \boldsymbol{\delta\kappa_{\rm inv}}\,.$$

with **coefficients**,

$$\mathbf{A}_{\mathbf{ij}} = 2(\delta_{ij} - \mathbf{Br}_{\mathbf{j}}^{\rm sm})\,, \quad \mathbf{A}_{\mathbf{i,inv}} = -1\,, \quad \mathbf{A}_{\mathbf{inv,i}} = 0\,, \quad \mathbf{A}_{\mathbf{inv,inv}} = 1\,.$$

Combined Higgs Coupling Precision

Ge, He, Xiao, 1603.03385; preCDR

Table: Precisions on measuring Higgs couplings at **CEPC (250GeV, 5ab^{-1})**, in comparison with **LHC (14TeV, 300fb^{-1})**, **HL-LHC (14TeV, 3ab^{-1})** and **ILC (250GeV, 250fb^{-1})+(500GeV, 500fb^{-1})**.

KITPC WS, July 28

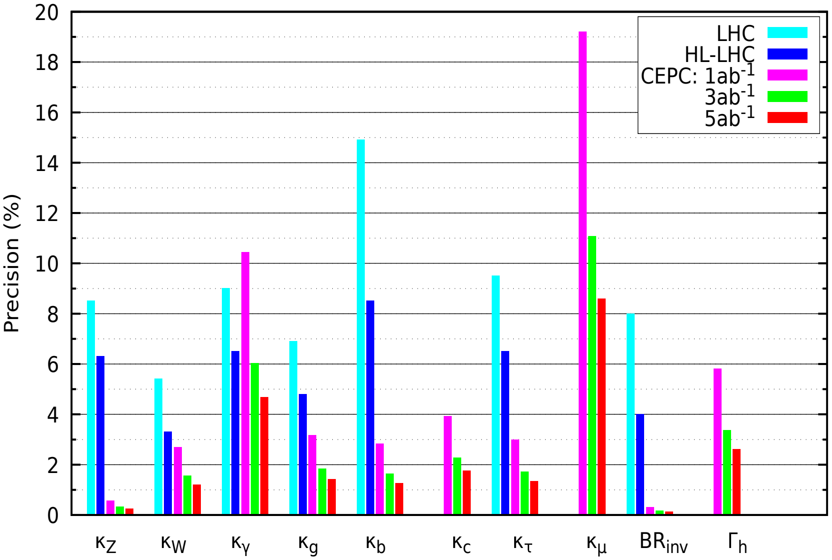
Precision (%)	CEPC		LHC	HL-LHC	ILC-250+500
κ_Z	0.249	0.249	8.5	6.3	0.50
κ_W	1.20	1.20	5.4	3.3	0.46
κ_γ	4.67	4.67	9.0	6.5	8.6
κ_g	1.42	1.42	6.9	4.8	2.0
κ_b	1.27	1.27	14.9	8.5	0.97
κ_c	1.75	1.75	–	–	2.6
κ_τ	1.33	1.33	9.5	6.5	2.0
κ_μ	–	8.59	–	–	–
$\mathrm{Br}_{\mathrm{inv}}$	0.134	0.134	8.0	4.0	0.52
Γ_h	2.6	2.6	–	–	–

LHC & ILC from Peskin 1312.4974

SM Predictions

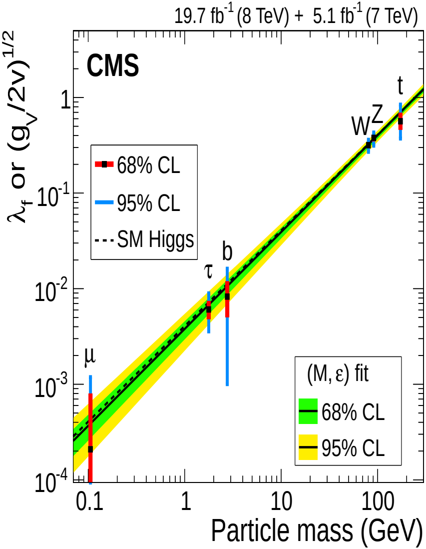
$\mathrm{Br}(b\bar{b})$	$\mathrm{Br}(c\bar{c})$	$\mathrm{Br}(gg)$	$\mathrm{Br}(\tau\bar{\tau})$	$\mathrm{Br}(WW)$	$\mathrm{Br}(ZZ)$	$\mathrm{Br}(\gamma\gamma)$	$\mathrm{Br}(\mu\bar{\mu})$	$\mathrm{Br}(\mathrm{inv})$
58.1%	2.10%	7.40%	6.64%	22.5%	2.77%	0.243%	0.023%	0

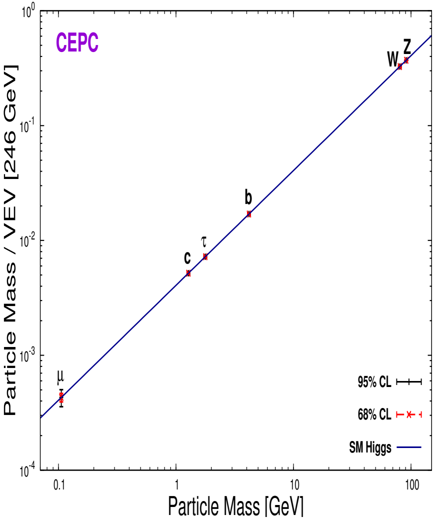
Combined Higgs Coupling Precision Ge, He, Xiao,1603.03385; preCDR



Software WS, March 26

Precision on Higgs Couplings





New Physics Scales

Ge, He, Xiao, 1603.03385

- New physics appears @ high energy scale & can only be probed **Indirectly**

$$\mathcal{L} = \mathcal{L}_{\mathbf{SM}} + \sum_{ij} \frac{\mathbf{y_{ij}} \sim \mathcal{O}(1)}{\boldsymbol{\Lambda} \sim 10^{14}\,\mathrm{GeV}} (\overline{L}_i \tilde{\mathbf{H}})(\tilde{\mathbf{H}}^\dagger L_j) + \sum_i \frac{\mathbf{c_i}}{\boldsymbol{\Lambda}^2} \mathcal{O}_{\mathbf{i}} \,.$$

- **SM Gauge Invariance** is respected

Higgs	EW Gauge Bosons	Fermions
$\mathcal{O}_{\mathbf{H}} = \frac{1}{2}(\partial_\mu \lvert\mathbf{H}\rvert^2)^2$	$\mathcal{O}_{\mathbf{WW}} = g^2 \lvert\mathbf{H}\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}^{(3)}_{\mathbf{LL}} = (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
$\mathcal{O}_{\mathbf{T}} = \frac{1}{2}(\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})^2$	$\mathcal{O}_{\mathbf{BB}} = g^2 \lvert\mathbf{H}\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\mathbf{L}} = (i\mathbf{H}^\dagger \sigma^a \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
	$\mathcal{O}_{\mathbf{WB}} = gg' \mathbf{H}^\dagger \sigma^a \mathbf{H} W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\mathbf{L}} = (i\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\Psi}_L \gamma^\mu \Psi_L)$
Gluon	$\mathcal{O}_{\mathbf{HW}} = ig(D^\mu \mathbf{H})^\dagger \sigma^a (D^\nu \mathbf{H}) W^a_{\mu\nu}$	$\mathcal{O}_{\mathbf{R}} = (i\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_{\mathbf{g}} = g_s^2 \lvert\mathbf{H}\rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{\mathbf{HB}} = ig'(D^\mu \mathbf{H})^\dagger (D^\nu \mathbf{H}) B_{\mu\nu}$	$\mathcal{O}_{\mathbf{f}} = \lvert\mathbf{H}\rvert^2 \overline{F}_L H f$

Existing EWPO & Future HO

- **Observables**: **EWPO** (PDG14) + **HO** (preCDR)

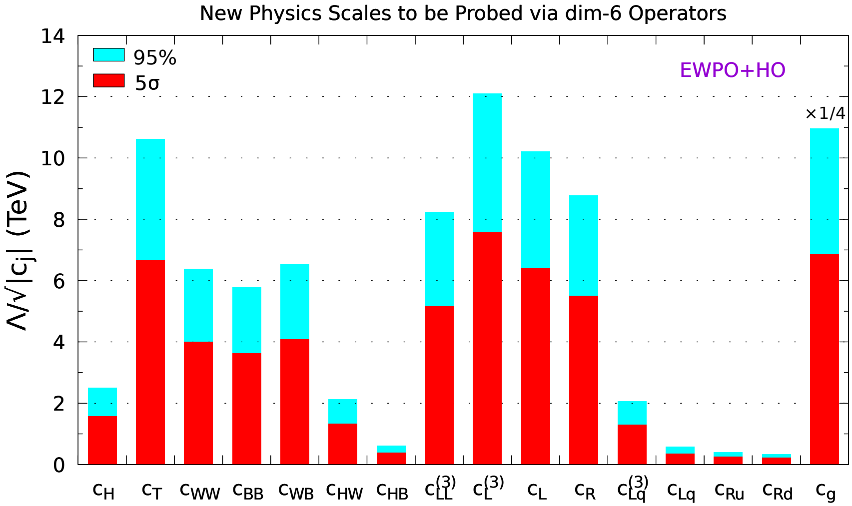
Observables	Central Value	Relative Error	SM Prediction
α	$7.2973525698 \times 10^{-3}$	3.29×10^{-10}	–
G_F	$1.1663787 \times 10^{-5}\text{GeV}^{-2}$	5.14×10^{-7}	–
M_Z	91.1876GeV	2.3×10^{-5}	–
M_W	80.385GeV	1.87×10^{-4}	–
$\sigma[Zh]$	–	0.50%	–
$\sigma[\nu\bar{\nu}h]$	–	2.86%	–
$\sigma[\nu\bar{\nu}h]_{350\text{GeV}}$	–	0.75%	–
$\text{Br}[WW]$	–	1.2%	22.5%
$\text{Br}[ZZ]$	–	4.3%	2.77%
$\text{Br}[bb]$	–	0.54%	58.1%
$\text{Br}[cc]$	–	2.5%	2.10%
$\text{Br}[gg]$	–	1.4%	7.40%
$\text{Br}[\tau\tau]$	–	1.1%	6.64%
$\text{Br}[\gamma\gamma]$	–	9.0%	0.243%
$\text{Br}[\mu\mu]$	–	17%	0.023%

- **Exclusion (95%) & Discovery (5σ) Reach**

Ge, He, Xiao,1603.03385

	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}^{(3)}_{LL}$	$\mathcal{O}^{(3)}_{L}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}^{(3)}_{L,q}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
95%	2.50	**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**
5σ	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

Sensitivities from Existing EWPO & Future HO



Ge, He, Xiao, **1603.03385**

Enhancement from M_Z & M_W @ CEPC

Observables	Relative Error	
	Current	**CEPC**
M_Z	2.3×10^{-5}	$5.5 \times 10^{-6} \sim 1.1 \times 10^{-5}$
M_W	1.9×10^{-4}	$\mathbf{3.7 \times 10^{-5}} \sim 6.2 \times 10^{-5}$

Table: The M_Z & M_W @ CEPC [Z.Liang, "Z & W Physics @ CEPC" & preCDR].

Scheme-Independent Analysis

$\frac{\Lambda}{\sqrt{c_i}}$ [TeV]	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}^{(3)}_{LL}$	$\mathcal{O}^{(3)}_{L}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}^{(3)}_{L,q}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
HO+EWPO	2.74	10.6	6.38	5.78	6.53	2.16	0.604	8.58	12.1	10.2	8.78	2.06	0.568	0.393	0.339	43.8
+$\mathbf{M_Z}$	2.74	**10.7**	6.38	5.78	**6.54**	2.16	0.604	**8.62**	12.1	10.2	8.78	2.06	0.568	0.393	0.339	43.8
+$\mathbf{M_W}$	2.74	**21.0**	6.38	5.78	**10.4**	2.16	0.604	**15.5**	**16.4**	10.2	8.78	2.06	0.568	0.393	0.339	43.8
+$\mathbf{M_{Z,W}}$	2.74	**23.7**	6.38	5.78	**11.6**	2.16	0.604	**17.4**	**18.1**	10.2	8.78	2.06	0.568	0.393	0.339	43.8

Table: Impacts of the projected M_Z and M_W measurements at CEPC on the reach of new physics scale $\Lambda/\sqrt{|c_j|}$ (in TeV) at 95% C.L. The Higgs observables (including $\sigma(\nu\bar{\nu}h)$ at 350 GeV) and the existing electroweak precision observables are always included in each row. The differences among the four rows arise from whether taking into account the measurements of M_Z and M_W or not. The second (third) row contains the measurement of M_Z (M_W) alone, while the first (last) row contains none (both) of them. We mark the entries of the most significant improvements from M_Z/M_W measurements in red color.

Ge, He, Xiao, **1603.03385**

Enhancement from Z-Pole Observables @ CEPC

N_ν	$A_{FB}(b)$	R^b	R^μ	R^τ	$\sin^2\theta_w$
1.8×10^{-3}	1.5×10^{-3}	8×10^{-4}	5×10^{-4}	5×10^{-4}	1×10^{-4}

Table: The Z-pole measurements at CEPC [Z.Liang, “Z & W Physics @ CEPC” & preCDR].

Ge, He, Xiao, **1603.03385**

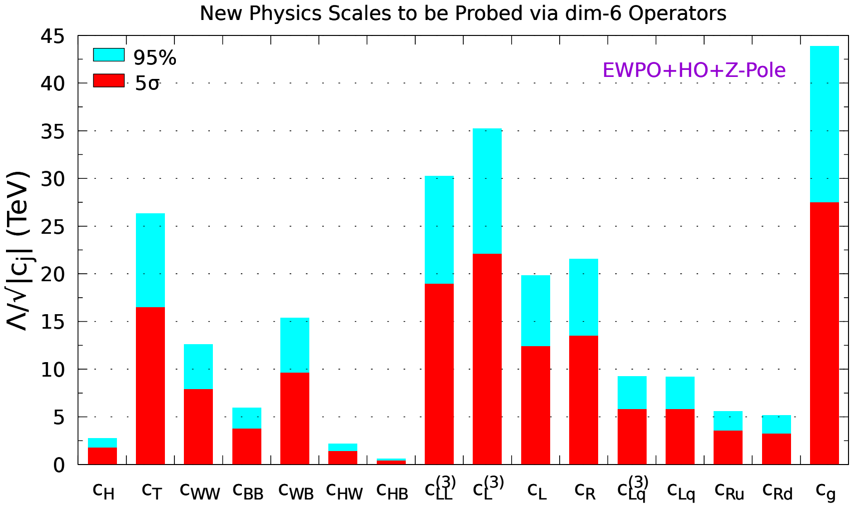
Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_L^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
2.74	23.7	6.38	5.78	11.6	2.16	0.604	17.4	18.1	10.2	8.78	2.06	0.568	0.393	0.339	43.8
2.74	23.7	6.38	5.78	11.6	2.16	0.604	**17.5**	**18.3**	**10.5**	8.78	2.06	0.568	0.393	0.339	43.8
2.74	24.0	**8.32**	5.80	**12.2**	2.16	0.604	**20.7**	**23.0**	**12.5**	**13.0**	2.23	**1.62**	0.393	**3.97**	43.8
2.74	24.0	8.33	5.80	12.2	2.16	0.604	20.7	23.0	12.5	13.0	**7.90**	**7.89**	**3.55**	4.05	43.8
2.74	24.0	8.54	5.80	12.2	2.16	0.604	20.7	23.4	**14.4**	**14.0**	8.63	8.62	4.88	**4.71**	43.8
2.74	24.0	8.75	5.81	12.3	2.16	0.604	20.7	23.7	15.8	14.9	**9.21**	**9.21**	5.59	5.17	43.8
2.74	**26.3**	**12.6**	**5.93**	**15.3**	2.16	0.604	**30.2**	**35.2**	**19.8**	**21.6**	9.21	9.21	5.59	5.17	43.8

Table: Impacts of the projected Z-pole measurements at the CEPC on the reach of new physics scale $\Lambda/\sqrt{|c_j|}$ (in TeV) at 95% C.L. For comparison, the first row of this table repeats the last row of Table **??**, as our starting point of this table. For the $(n+1)$-th row, the first n observables are taken into account. In addition, the estimated M_Z and M_W measurements at the CEPC, the Higgs observables (HO), and the existing electroweak precision observables (EWPO) are always included for each row. The entries with major enhancements of the new physics scale limit are marked in red color.

Another factor of 2 enhancement from Z-Pole Observables

Sensitivity from EWPO+HO+Z-Pole



Ge, He, Xiao, **1603.03385**

Yukawa-like Operators

- **Dim-6 Yukawa-like Operators**

$$\mathcal{O}_f \equiv |H|^2 \overline{F}_L H f_R$$

- **Shifting Yukawa Couplings**

$$y_f \to y_f + \frac{3 c_f v^2}{2\Lambda^2} = \frac{\sqrt{2} m_f}{v} + \frac{c_f v^3}{\sqrt{2} m_f \Lambda^2}$$

- **Constraining New Physics Scales**

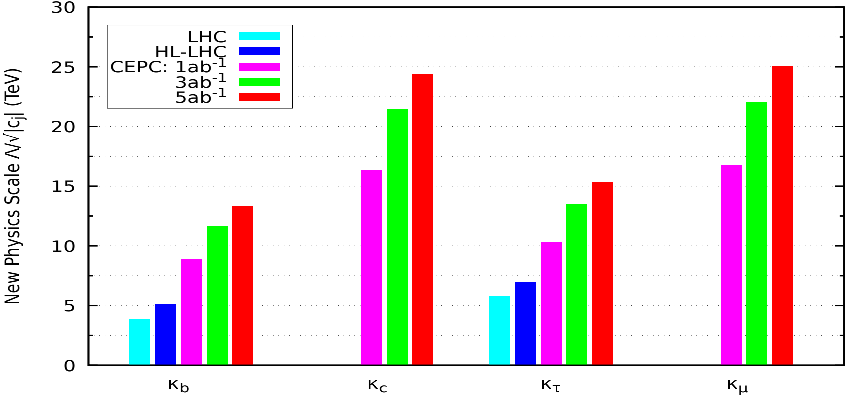
$$\frac{\Lambda}{\sqrt{c_f}} \leq \sqrt{\frac{v^3}{\sqrt{2} m_f \Delta\kappa_f}} .$$

Naive Expectations

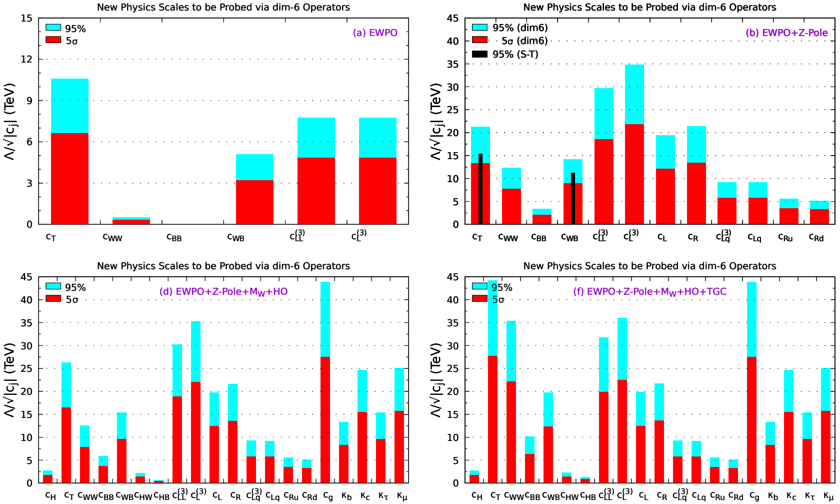
$$N_f \propto y_f^2 \quad \Rightarrow \quad \Delta\kappa_f \propto y_f^{-1} \quad \Rightarrow \quad \Lambda \propto y_f^0$$

New Physics Scale via Yukawa-like Operators

$\Lambda/\sqrt{\lvert c_j \rvert}$(TeV)	σ	CEPC	LHC	HL-LHC	ILC-250	ILC-500
b quark	**1.27%**	**13.2**	3.87	5.12	6.89	15.2
τ lepton	**1.33%**	**15.4**	5.74	6.95	12.8	20.0
c quark	**1.75%**	**24.4**	–	–	7.76	12.5
μ lepton	**8.59%**	**25.1**	–	–	–	–



TGC Constraints



$$\frac{\delta\sigma_{WW}}{\sigma_{WW}} = 1.94\frac{\delta G_F}{G_F} + 20.8\frac{\delta M_Z}{M_Z} + 0.246\frac{\delta\alpha}{\alpha} + 0.0956\frac{c_T}{\Lambda^2_{\rm TeV}} - 0.0214\frac{c_{WB}}{\Lambda^2_{\rm TeV}} + 0.000922\frac{c_{HW}}{\Lambda^2_{\rm TeV}} + 0.000611\frac{c_{HB}}{\Lambda^2_{\rm TeV}}$$

Summary

- **Higgs Discovery** is not just **New Particle**, but also **New Force**!
  - **Yukawa Force**: **Non-Trivial Mixing** & **Hierarchically Unnatural**
  - **Higgs Self-Interaction Force**: **Radiatively Unnatural**

- **New Physics** motivates precision measurement of Higgs couplings

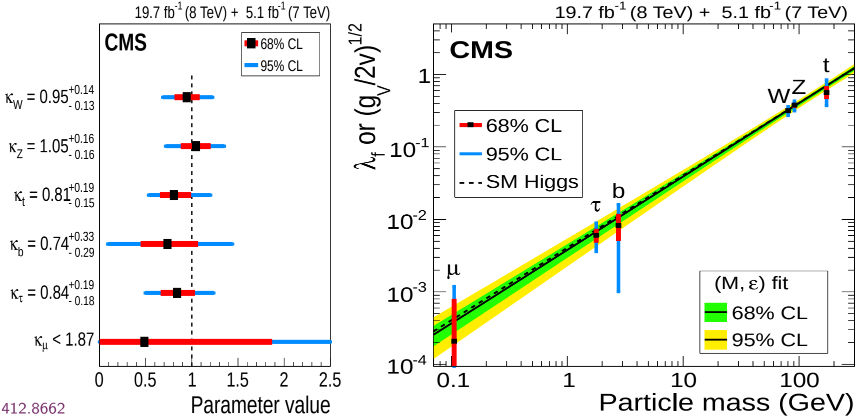
- **CEPC** – $\mathbf{10^6}$ Higgs
  - **Precision Measurement**
    - Higgs Coupling $\sim \mathcal{O}(1\%)$ Level
    - Higgs Self-Coupling $\sim$ **30%** (?)
  - **New Physics Scales**
    - Probe indirectly to **10 TeV** (**43 TeV** for $\mathcal{O}_g$) from **EWPO+HO**
    - **35 TeV @ Z-Pole**
    - **25 TeV for Yukawa-like Operators**

- **CEPC ⇒ SPPC**

Thank You!

Current Status

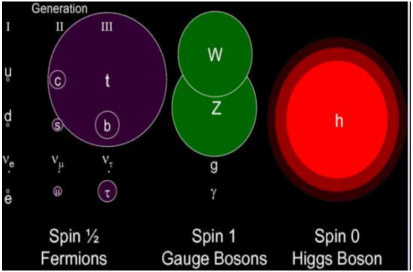
- **LEP/Tevatron/LHC** have **good tests only on gauge forces**.
- **Higgs Yukawa Force** is **Flavor-Dependent** + **Huge Hierarchy**.
  - LHC has limited sensitivity to Yukawa couplings of **htt**, **hbb**, **h$\tau\tau$** @ the order of **15% ∼ 30%**.
  - LHC cannot probe other Yukawa Couplings!
- **Higgs Self-Interaction** is also difficult @ LHC **Run-I**.

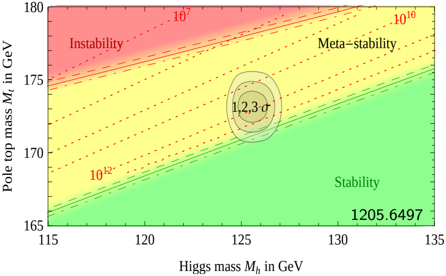


1412.8662

Standard Model is NOT Enough!

- **Mass Generation**
  - Yukawa force is **Flavor-Dependent** & **Hierarchically Unnatural**
  - Higgs mass itself is **Radiatively Unnatural**
- **Neutrino Oscillation**
- **Dark Matter**
- **Matter-Antimatter Asymmetry**
- **Vacuum Stability**
- **Vacuum Energy** & **Inflation**





Scheme-Independent Analysis

Ge, He, Xiao, 1603.03385

- **EW Parameters:**

$$\mathbf{M_Z^{(SM)}} = \mathbf{M_Z^{(r)}} \left(1 + \frac{\boldsymbol{\delta} \mathbf{M_Z}}{M_Z}\right), \quad \mathbf{G_F^{(SM)}} = \mathbf{G_F^{(r)}} \left(1 + \frac{\boldsymbol{\delta} \mathbf{G_F}}{G_F}\right), \quad \boldsymbol{\alpha}^{(SM)} = \boldsymbol{\alpha}^{(r)} \left(1 + \frac{\boldsymbol{\delta\alpha}}{\alpha}\right).$$

which can be denoted as

$$\mathbf{f}^{(\mathbf{SM})} \equiv \mathbf{f}^{(\mathbf{r})} + \boldsymbol{\delta}\mathbf{f} \simeq \mathbf{f}^{(\mathbf{r})} \left(1 + \frac{\boldsymbol{\delta}\mathbf{f}}{f}\right)$$

- **Observables:**

$$\mathcal{O} \equiv \mathcal{O}(\mathbf{f}^{(\mathbf{SM})}) + \overline{\delta\mathcal{O}} = \mathcal{O}(\mathbf{f}^{(\mathbf{r})}) + \mathcal{O}'(f)\boldsymbol{\delta}\mathbf{f} + \overline{\delta\mathcal{O}}$$

- **Analytical χ^2 Fit:**

$$\chi^2\left(\boldsymbol{\delta}\mathbf{M_Z}, \boldsymbol{\delta}\mathbf{G_F}, \boldsymbol{\delta\alpha}, \frac{\mathbf{c_i}}{\Lambda^2}\right) = \sum_j \left[\frac{\mathcal{O}_j^{\mathbf{th}}\left(\boldsymbol{\delta}\mathbf{M_Z}, \boldsymbol{\delta}\mathbf{G_F}, \boldsymbol{\delta\alpha}, \frac{\mathbf{c_i}}{\Lambda^2}\right) - \mathcal{O}_j^{\mathbf{exp}}}{\Delta\mathcal{O}_j}\right]^2,$$

Correction of Dim-6 $\mathcal{O}_i$ to EWPO

Ge, He, Xiao, 1603.03385

- **Fine-Structure Constant**

$$\frac{\widetilde{\delta\alpha}}{\alpha} \simeq \frac{\delta\alpha}{\alpha} + 0.0111\left(\frac{c_{WW}}{\Lambda^2_{\rm TeV}} - \frac{c_{WB}}{\Lambda^2_{\rm TeV}} + \frac{c_{BB}}{\Lambda^2_{\rm TeV}}\right)$$

- **Fermi Constant**

$$\frac{\widetilde{\delta G_F}}{G_F} \simeq \frac{\delta G_F}{G_F} + 0.121\left(\frac{c^{(3)}_{LL}}{\Lambda^2_{\rm TeV}} - \frac{c^{(3)}_{L}}{\Lambda^2_{\rm TeV}}\right).$$

- **M_Z & M_W**

$$\begin{aligned}\frac{\widetilde{\delta M_Z}}{M_Z} &\simeq \frac{\delta M_Z}{M_Z} - 0.0303\frac{c_T}{\Lambda^2_{\rm TeV}} + 0.0206\frac{c_{WW}}{\Lambda^2_{\rm TeV}} + 0.00149\frac{c_{BB}}{\Lambda^2_{\rm TeV}} + 0.00555\frac{c_{WB}}{\Lambda^2_{\rm TeV}},\\ \frac{\widetilde{\delta M_W}}{M_W} &\simeq 0.184\frac{\delta G_F}{G_F} + 1.37\frac{\delta M_Z}{M_Z} - 0.184\frac{\delta\alpha}{\alpha} + 0.0262\frac{c_{WW}}{\Lambda^2_{\rm TeV}},\end{aligned}$$

$$M_W^{\rm sm} = M_W^{(r)}\left\{1 + \frac{1}{\cos 2\theta_w}\left[c_w^2\frac{\delta M_Z}{M_Z} + \frac{s_w^2}{2}\left(\frac{\delta G_F}{G_F} - \frac{\delta\alpha}{\alpha}\right) - \frac{s_w^2}{2}\Delta r - \frac{s_w^4(5c_w^2 - s_w^2)}{8(c_w^2 - s_w^2)^2}\Delta r_1^2\right]\right\}.$$

Correction of Dim-6 $\mathcal{O}_{\mathbf{i}}$ to HO (1)

Ge, He, Xiao, 1603.03385

- **Mass:** M_Z & M_W
- **Parameter Shifts**

$$(m_Z, G_F, \alpha) \quad : \quad \sin 2\theta_w^{(0)} \equiv \sqrt{\frac{4\pi\alpha^{(0)}}{\sqrt{2} G_F^{(0)} \left(m_Z^{(0)}\right)^2}}$$

- **Field Redefinition & Kinetic Mixing**

$$h \to \left(1 - \frac{1}{2}\frac{v^2}{\Lambda^2} \mathbf{c_H}\right) h \equiv \mathbf{Z_h} h, \qquad W^\pm \to \left(1 + \frac{v^2}{\Lambda^2} g^2 \mathbf{c_{WW}}\right) W^\pm \equiv \mathbf{Z_W} W^\pm.$$

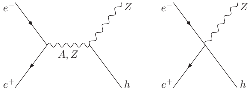
$$\begin{aligned}
Z^\mu &\to \left[1 + \frac{v^2}{\Lambda^2}\left(c_w^2 g^2 \mathbf{c_{WW}} + c_w s_w g g' \mathbf{c_{WB}} + s_w^2 g'^2 \mathbf{c_{BB}}\right)\right] Z^\mu \equiv \mathbf{Z_Z} Z^\mu, \\
A^\mu &\to \left[1 + \frac{v^2}{\Lambda^2}\left(s_w^2 g^2 \mathbf{c_{WW}} - c_w s_w g g' \mathbf{c_{WB}} + c_w^2 g'^2 \mathbf{c_{BB}}\right)\right] A^\mu \\
&+ \quad 2\frac{v^2}{\Lambda^2}\left[c_w s_w g^2 \mathbf{c_{WW}} - \frac{1}{2}(c_w^2 - s_w^2) g g' \mathbf{c_{WB}} - c_w s_w g'^2 \mathbf{c_{BB}}\right] Z^\mu \equiv \mathbf{Z_A} A^\mu + \delta \mathbf{Z_X} Z^\mu.
\end{aligned}$$

$$G_\mu^a \to \left(1 + \frac{v^2}{\Lambda^2} g_s^2 \mathbf{c_g}\right) G_\mu^a \equiv \mathbf{Z_G} G_\mu^a\,,$$

Correction of Dim-6 $\mathcal{O}_\mathrm{i}$ to HO (2)

Ge, He, Xiao, 1603.03385

- **Vertex**



(a) (b)

  - **ZZh**

$$-\frac{g^2 v}{2c_w^2}\frac{v^2}{\Lambda^2}\mathbf{c_T} h Z_\mu Z^\mu + (\mathbf{Z_Z} - 1) h \mathcal{Z}_{\mu\nu}\mathcal{Z}^{\mu\nu} + \frac{g}{2}\frac{v\partial_\mu h}{\Lambda^2}\left[g\mathbf{c_{HW}} + \frac{s_w}{c_w} g' \mathbf{c_{HB}}\right] Z_\nu \mathcal{Z}^{\mu\nu},$$

  - **Ze$^+$e$^-$**

$$\begin{aligned}\widetilde{\delta g_L} &\equiv -\left[\frac{1}{2\cos 2\theta_w}\left(\frac{\boldsymbol{\delta}\mathbf{M_Z}}{M_Z} + \frac{1}{2}\frac{\boldsymbol{\delta}\mathbf{G_F}}{G_F}\right) - \frac{c_w^2 s_w^2}{\cos 2\theta_w}\frac{\boldsymbol{\delta\alpha}}{\alpha}\right] g_z - \frac{g_z v^2}{2\Lambda^2}\left(\mathbf{c_L^{(3)}} + \mathbf{c_L}\right) + \boldsymbol{\delta}\mathbf{g_L^*}, \\ \widetilde{\delta g_R} &\equiv -\left[\frac{s_w^2}{\cos 2\theta_w}\left(\frac{\boldsymbol{\delta}\mathbf{M_Z}}{M_Z} + \frac{1}{2}\frac{\boldsymbol{\delta}\mathbf{G_F}}{G_F}\right) - \frac{c_w^2 s_w^2}{\cos 2\theta_w}\frac{\boldsymbol{\delta\alpha}}{\alpha}\right] g_z - \frac{g_z v^2}{2\Lambda^2}\mathbf{c_R} + \boldsymbol{\delta}\mathbf{g_R^*},\end{aligned}$$

where $\boldsymbol{\delta}\mathbf{g_L^*} \equiv Q g_z c_w s_w \boldsymbol{\delta}\mathbf{Z_X} + g_z(T_3 - s_w^2 Q)(\mathbf{Z_Z} - 1)$, $\boldsymbol{\delta}\mathbf{g_R^*} \equiv Q\, g_z c_w s_w \boldsymbol{\delta}\mathbf{Z_X} - g_z s_w^2 Q(\mathbf{Z_Z} - 1)$.

  - **AZh**

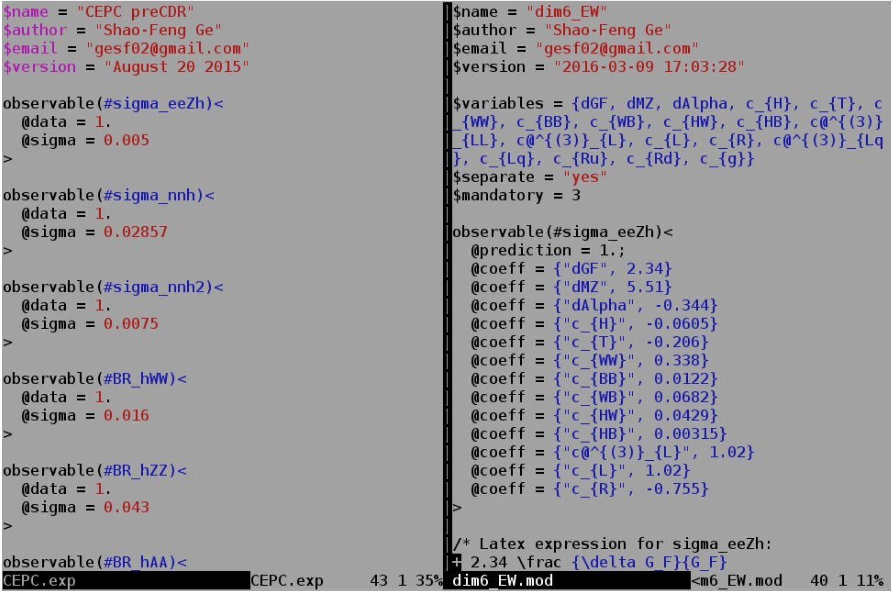
$$2\frac{\boldsymbol{\delta}\mathbf{Z_X}}{v} h\mathcal{Z}_{\mu\nu}F^{\mu\nu} + \frac{s_w g^2 v}{2c_w\Lambda^2}\left(\mathbf{c_{HW}} - \mathbf{c_{HB}}\right)\partial_\mu h Z_\nu F^{\mu\nu},$$

  - **Zhe$^+$e$^-$**

$$\frac{g_z v}{\Lambda^2}\left[\left(\mathbf{c_L^{(3)}} - \mathbf{c_L}\right) Z_\mu \bar{u}_L\gamma^\mu u_L - \left(\mathbf{c_L^{(3)}} + \mathbf{c_L}\right) Z_\mu \bar{d}_L\gamma^\mu d_L - \mathbf{c_R^\psi}\bar{\psi}_R\gamma^\mu\psi_R\right] h.$$

Beyond SM Fitter (BSMfitter)

http://bsmfitter.hepforge.org



```
$name = "CEPC preCDR"
$author = "Shao-Feng Ge"
$email = "gesf02@gmail.com"
$version = "August 20 2015"

observable(#sigma_eeZh)<
  @data = 1.
  @sigma = 0.005
>

observable(#sigma_nnh)<
  @data = 1.
  @sigma = 0.02857
>

observable(#sigma_nnh2)<
  @data = 1.
  @sigma = 0.0075
>

observable(#BR_hWW)<
  @data = 1.
  @sigma = 0.016
>

observable(#BR_hZZ)<
  @data = 1.
  @sigma = 0.043
>

observable(#BR_hAA)<
CEPC.exp                           CEPC.exp       43 1 35%
```

```
$name = "dim6_EW"
$author = "Shao-Feng Ge"
$email = "gesf02@gmail.com"
$version = "2016-03-09 17:03:28"

$variables = {dGF, dMZ, dAlpha, c_{H}, c_{T}, c
_{WW}, c_{BB}, c_{WB}, c_{HW}, c_{HB}, c@^{(3)}
_{LL}, c@^{(3)}_{L}, c_{L}, c_{R}, c@^{(3)}_{Lq
}, c_{Lq}, c_{Ru}, c_{Rd}, c_{g}}
$separate = "yes"
$mandatory = 3

observable(#sigma_eeZh)<
  @prediction = 1.;
  @coeff = {"dGF", 2.34}
  @coeff = {"dMZ", 5.51}
  @coeff = {"dAlpha", -0.344}
  @coeff = {"c_{H}", -0.0605}
  @coeff = {"c_{T}", -0.206}
  @coeff = {"c_{WW}", 0.338}
  @coeff = {"c_{BB}", 0.0122}
  @coeff = {"c_{WB}", 0.0682}
  @coeff = {"c_{HW}", 0.0429}
  @coeff = {"c_{HB}", 0.00315}
  @coeff = {"c@^{(3)}_{L}", 1.02}
  @coeff = {"c_{L}", 1.02}
  @coeff = {"c_{R}", -0.755}
>

/* Latex expression for sigma_eeZh:
+ 2.34 \frac {\delta G_F}{G_F}
dim6_EW.mod                  <m6_EW.mod    40 1 11%
```