Higgs Coupling Precision & New Physics Scales @ CEPC

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SFG, Hong-Jian He, Rui-Qing Xiao, **arXiv:1603.03385**

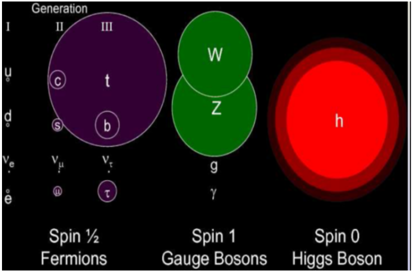
CEPC preCDR

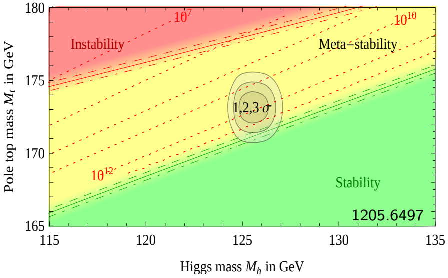
Higgs discovery is not just about H particle

- **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]
  - **Higgs Self-Interaction Forces** – $\mathbf{h^3}$ & $\mathbf{h^4}$ (concerns spontaneous EWSB and providing masses to all particles).
    True Self-Interactions – **Exactly the Same Quantum # (Spin & Charge**
  - **hWW**, **hZZ**, $\mathbf{h\gamma\gamma}$ & $\mathbf{hZ\gamma}$
- 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!**

Standard Model is Incomplete!

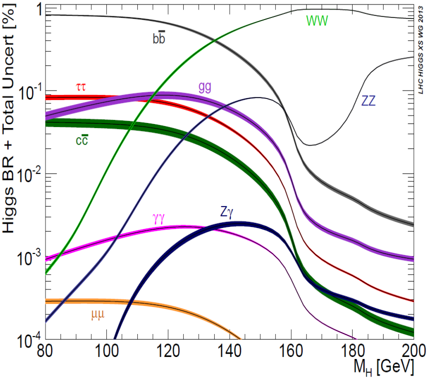
- **Mass Generation**
  - Yukawa force is **Flavor-Dependent** & **Hierarchically Unnatural**
  - Higgs mass itself is **Radiatively Unnatural**
- **Neutrino Oscillation**
- **Dark Matter**
- **Matter-Antimatter Asymmetry**
- **Vacuum Stability**
- **Vacuum Energy** & **Inflation**

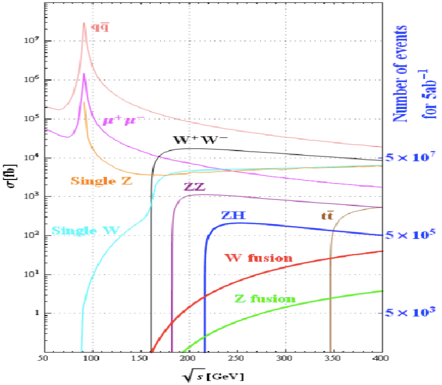




Higgs Factory @ 250 GeV

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





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

Inputs: Event Rate $\rightarrow$ Cross Section & BR

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

Decay Mode	$\sigma(Zh) \times \mathrm{Br}$	Br
$h \rightarrow bb$	**0.21%**	0.54%
$h \rightarrow cc$	2.5%	2.5%
$h \rightarrow gg$	1.7%	1.8%
$h \rightarrow \tau\tau$	1.2%	1.3%
$h \rightarrow WW$	**1.4%**	1.5%
$h \rightarrow ZZ$	**4.3%**	4.3%
$h \rightarrow \gamma\gamma$	**9.0%**	9.0%
$h \rightarrow \mu\mu$	17%	17%
$h \rightarrow \mathrm{invisible}$	–	0.14%

latest 1σ uncertainty
Software WS, March 26

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**

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

- **Cross Section**

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

- **Decay Width**

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

- **Branching Ratio**

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

with **coefficients**,

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

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})**.

Software WS, March 26

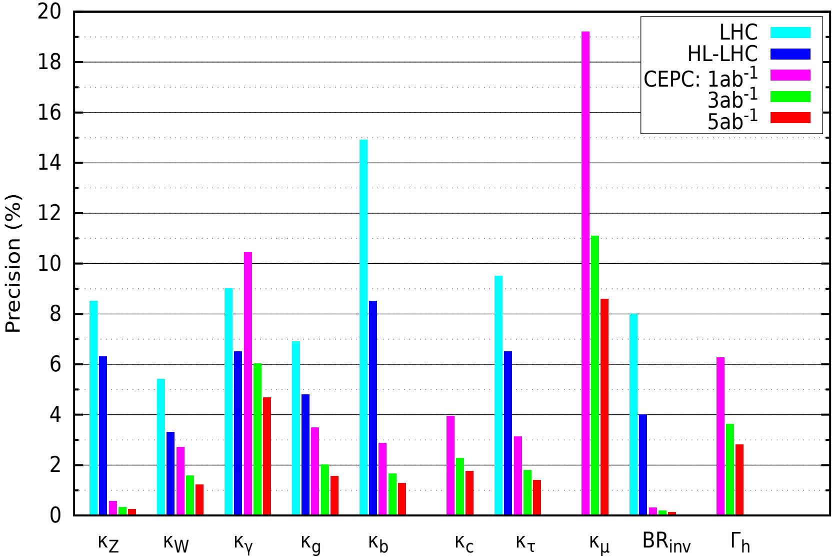
Precision (%)	CEPC		LHC	HL-LHC	ILC-250+500
κ_Z	0.249	0.249	8.5	6.3	0.50
κ_W	1.21	1.21	5.4	3.3	0.46
κ_γ	4.67	4.67	9.0	6.5	8.6
κ_g	1.55	1.55	6.9	4.8	2.0
κ_b	1.28	1.28	14.9	8.5	0.97
κ_c	1.76	1.76	–	–	2.6
κ_τ	1.39	1.39	9.5	6.5	2.0
κ_μ	–	8.59	–	–	–
$\mathrm{Br}_{\mathrm{inv}}$	0.135	0.135	8.0	4.0	0.52
Γ_h	2.8	2.8	–	–	–

LHC & ILC from Peskin 1312.4974

SM Predictions

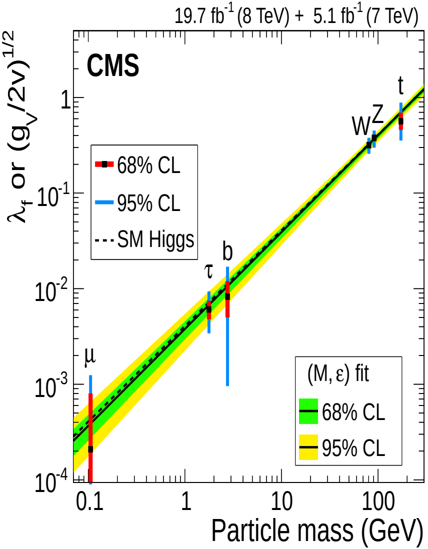
$\mathrm{Br}(b\bar{b})$	$\mathrm{Br}(c\bar{c})$	$\mathrm{Br}(gg)$	$\mathrm{Br}(\tau\bar{\tau})$	$\mathrm{Br}(WW)$	$\mathrm{Br}(ZZ)$	$\mathrm{Br}(\gamma\gamma)$	$\mathrm{Br}(\mu\bar{\mu})$	$\mathrm{Br}(\mathrm{inv})$
58.1%	2.10%	7.40%	6.64%	22.5%	2.77%	0.243%	0.023%	0

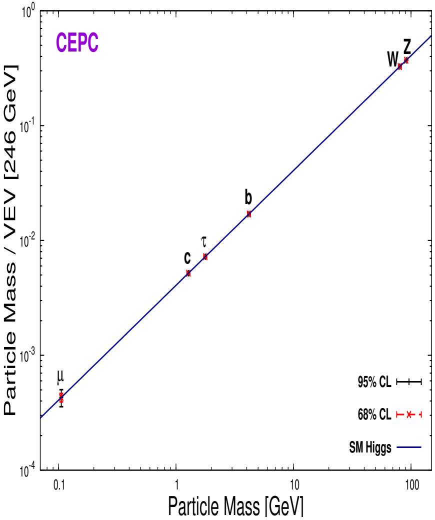
Combined Higgs Coupling Precision Ge, He, Xiao, 1603.03385; preCDR



Software WS, March 26

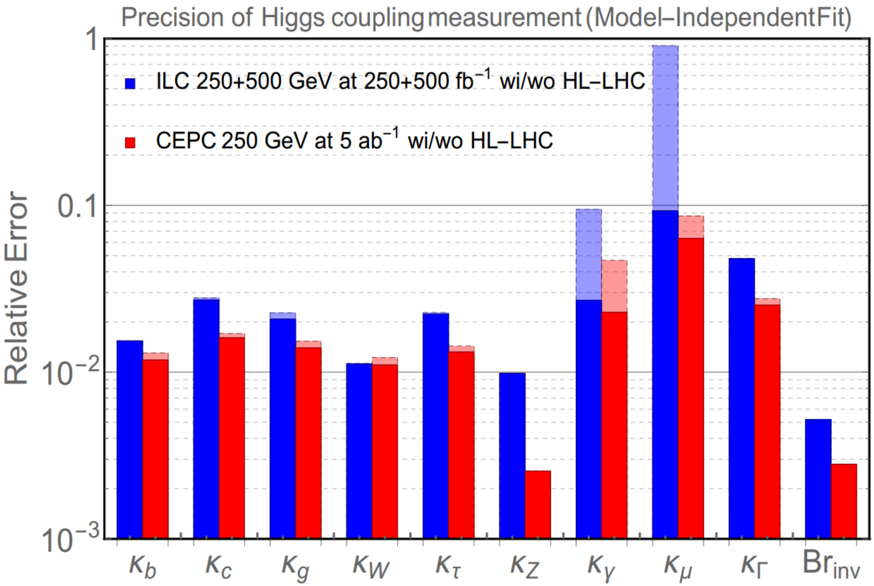
Precision on Higgs Couplings





Precision on Higgs Couplings

preCDR



New Physics Scales

Ge, He, Xiao, 1603.03385

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

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

- **SM Gauge Invariance** is respected

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

Scheme-Independent Analysis

Ge, He, Xiao, 1603.03385

EW Parameters:

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

which can be denoted as

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

Observables:

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

Analytical χ^2 Fit:

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

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

$$\frac{\widetilde{\delta M_Z}}{M_Z} \simeq \frac{\delta M_Z}{M_Z} - 0.0303\frac{c_T}{\Lambda^2_{\rm TeV}} + 0.0206\frac{c_{WW}}{\Lambda^2_{\rm TeV}} + 0.00149\frac{c_{BB}}{\Lambda^2_{\rm TeV}} + 0.00555\frac{c_{WB}}{\Lambda^2_{\rm TeV}},$$

$$\frac{\widetilde{\delta M_W}}{M_W} \simeq 0.184\frac{\delta G_F}{G_F} + 1.37\frac{\delta M_Z}{M_Z} - 0.184\frac{\delta\alpha}{\alpha} + 0.0262\frac{c_{WW}}{\Lambda^2_{\rm TeV}},$$

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

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

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

$$Z^\mu \to \left[1 + \frac{v^2}{\Lambda^2}\left(c_w^2 g^2 c_{WW} + c_w s_w g g' c_{WB} + s_w^2 g'^2 c_{BB}\right)\right] Z^\mu \equiv Z_Z Z^\mu ,$$

$$A^\mu \to \left[1 + \frac{v^2}{\Lambda^2}\left(s_w^2 g^2 c_{WW} - c_w s_w g g' c_{WB} + c_w^2 g'^2 c_{BB}\right)\right] A^\mu$$

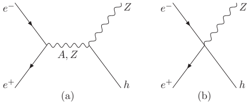
$$+ \quad 2\frac{v^2}{\Lambda^2}\left[c_w s_w g^2 c_{WW} - \frac{1}{2}(c_w^2 - s_w^2) g g' c_{WB} - c_w s_w g'^2 c_{BB}\right] Z^\mu \equiv Z_A A^\mu + \delta Z_X Z^\mu .$$

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

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

Ge, He, Xiao, 1603.03385

Vertex



ZZh

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

$\mathbf{Ze^+e^-}$

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

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

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

AZh

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

$\mathbf{Zhe^+e^-}$

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

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}	–
$\sigma[Zh]$	–	0.51%	–
$\sigma[\nu\bar{\nu}h]$	–	2.86%	–
$\sigma[\nu\bar{\nu}h]_{350\text{GeV}}$	–	0.75%	–
$\text{Br}[WW]$	–	1.6%	22.5%
$\text{Br}[ZZ]$	–	4.3%	2.77%
$\text{Br}[bb]$	–	0.57%	58.1%
$\text{Br}[cc]$	–	2.3%	2.10%
$\text{Br}[gg]$	–	1.7%	7.40%
$\text{Br}[\tau\tau]$	–	1.3%	6.64%
$\text{Br}[\gamma\gamma]$	–	9.0%	0.243%
$\text{Br}[\mu\mu]$	–	17%	0.023%

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

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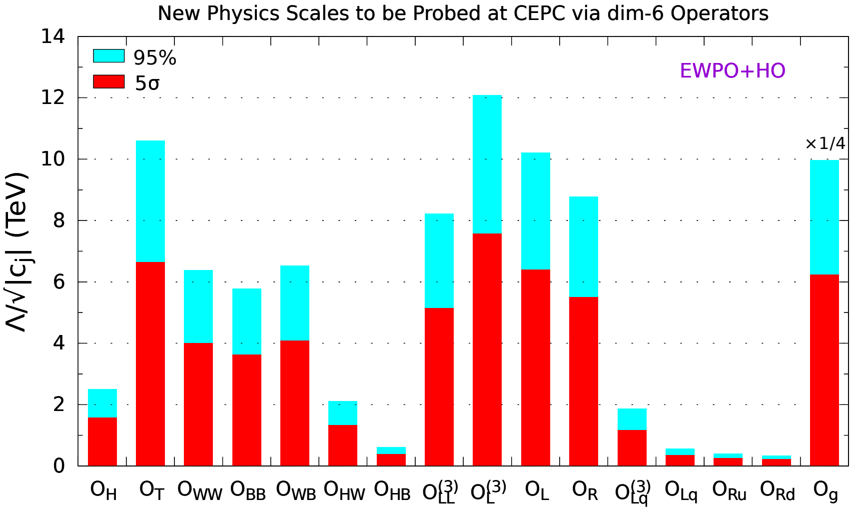
	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}^{(3)}_{LL}$	$\mathcal{O}^{(3)}_{L}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}^{(3)}_{L,q}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
95%	2.50	**10.6**	**6.38**	**5.78**	**6.52**	2.11	0.603	**8.21**	**12.1**	**10.2**	**8.78**	1.85	0.565	0.391	0.337	**39.8**
$\boldsymbol{5\sigma}$	1.57	6.64	3.99	3.62	4.08	1.32	0.378	5.14	7.57	6.39	5.49	1.16	0.354	0.245	0.211	24.9

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]	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_{L}^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
HO+EWPO	2.74	10.6	6.38	5.78	6.53	2.15	0.603	8.57	12.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
+M_Z	2.74	**10.7**	6.38	5.78	**6.54**	2.15	0.603	**8.61**	12.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
+M_W	2.74	**21.0**	6.38	5.78	**10.4**	2.15	0.603	**15.5**	**16.4**	10.2	8.78	1.85	0.565	0.391	0.337	39.8
+$M_{Z,W}$	2.74	**23.7**	6.38	5.78	**11.6**	2.15	0.603	**17.4**	**18.1**	10.2	8.78	1.85	0.565	0.391	0.337	39.8

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**

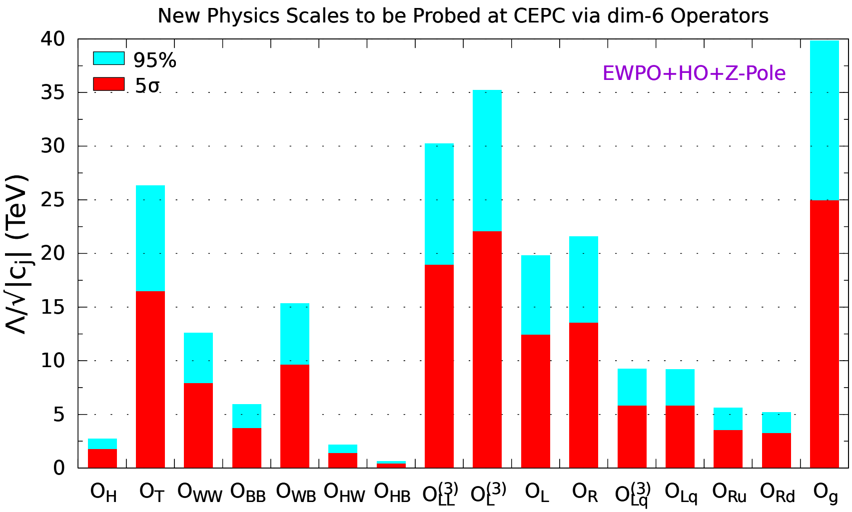
Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_L^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
2.74	23.7	6.38	5.78	11.6	2.15	0.603	17.4	18.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
2.74	23.7	6.38	5.78	11.6	2.15	0.603	**17.5**	**18.3**	**10.5**	8.78	1.85	0.565	0.391	0.337	39.8
2.74	24.0	**8.32**	5.80	**12.2**	2.15	0.603	**20.7**	**23.0**	**12.5**	**13.0**	2.08	**1.62**	0.391	**3.97**	39.8
2.74	24.0	8.33	5.80	12.2	2.15	0.603	20.7	23.0	12.5	13.0	**7.90**	**7.89**	**3.55**	4.05	39.8
2.74	24.0	8.54	5.80	12.2	2.15	0.603	20.7	23.4	**14.4**	**14.0**	8.63	8.62	4.88	**4.71**	39.8
2.74	24.0	8.75	5.80	12.3	2.15	0.603	20.7	23.7	15.8	14.9	**9.21**	**9.21**	5.59	5.17	39.8
2.74	**26.3**	**12.6**	**5.93**	**15.3**	2.15	0.603	**30.2**	**35.2**	**19.8**	**21.6**	9.21	9.21	5.59	5.17	39.8

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**

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** (**40 TeV** for $\mathcal{O}_g$) from **EWPO+HO**
    - **35 TeV** **@ Z-Pole**

- **CEPC** $\Rightarrow$ **SPPC**

Thank You!