New Physics Scales to be Probed @ Lepton Colliders (CEPC)

Shao-Feng Ge

(gesf02@gmail.com)

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

2016-1-11

Contribution to **CEPC preCDR & CDR**

Collaboration with **Hong-Jian He** & **Rui-Qing Xiao**

arXiv:1603.03385

LHC Discovery @ 2012

Higgs Boson (125GeV) — God Particle?

(Nobel 2013)

HEP at a New Historical Turning Point posing :

New Opportunities + New Questions + New Challenges

Hong-Jian He's talk on Feb.28 2015

Higgs discovery is not just about H particle

- **Force Mediators**
  - **Gauge Forces** – Spin-**1** Gauge Bosons
  - **Gravity** – Spin-**2** Graviton (?)
  - **New Force** – Spin-**0** Higgs Boson

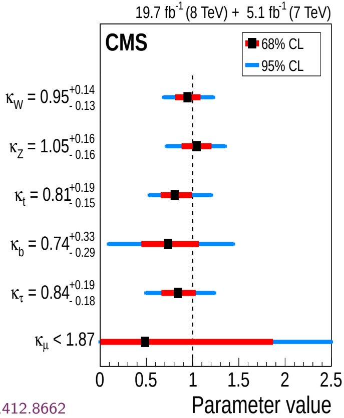
- Deep understanding of **Mass Generation**
  - **Yukawa Forces** – **Hierarchy** & **Mixing** (**Flavor Symmetries?**)
    - Discrete v.s. Continuous
    - Full v.s. Residual [1104.0602, 1108.0964, 1308.6522]
  - **Higgs Self-Interaction Forces** – $\mathbf{h^3}$ & $\mathbf{h^4}$ (concerns spontaneous EWSB and providing masses to all particles).

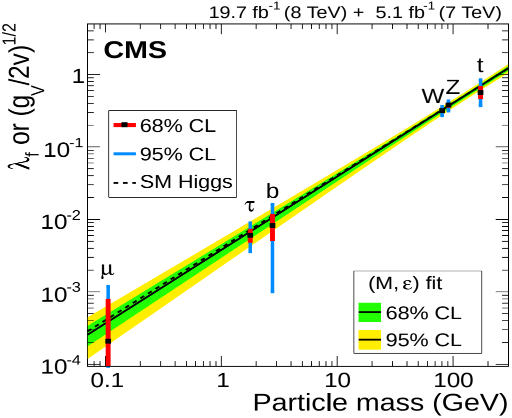
- **True Self-Interactions** – **Exactly the Same Quantum #**
  - Spin
  - Charge

- Both **Yukawa** & **Self-Interaction** forces associated with spin-0 Higgs were **Never Seen Before**. Needs to be directly tested.

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**.

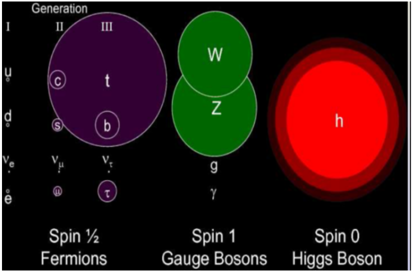


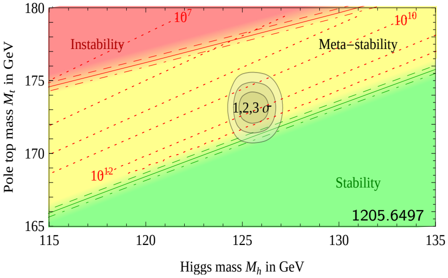


1412.8662

Standard Model is Incomplete!

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



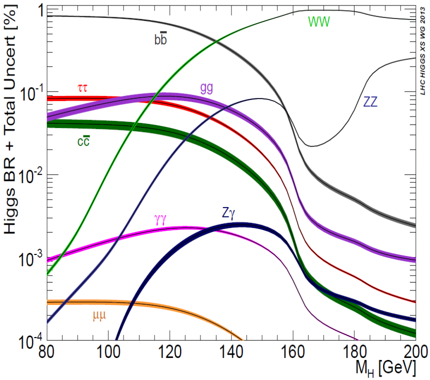


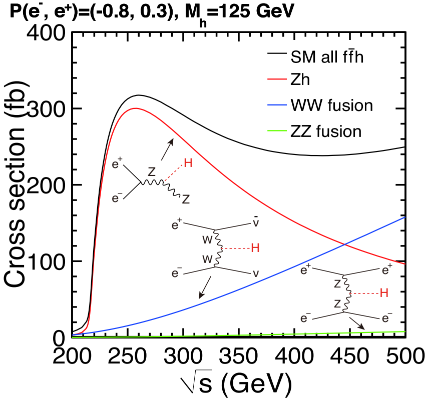
Beyond SM?

- **NO particle beyond SM** discovered @ **LHC** yet!
  - **1.9TeV di-boson?**
  - **750GeV di-photon?**
- **Full/Precise Picture** of **New Physics** @ Higher Energy?
- **Even within SM, we are strongly motivated to quantitatively test Yukawa and Higgs Self-Interaction Forces!**
- **Precision Measurement + Discovery Machine**:
  - **SLAC? + S$p\bar{p}$S [W/Z Masses]**
  - **LEP + (Tevatron [t] + LHC [h])**
  - **Go beyond!**
    - **CEPC (e^+e^-, 250 GeV)**
    - **SppC (pp, 50-100 TeV)**

Higgs Factory @ 250 GeV

- **LHC** tells us: $h(125)$ is **SM-like** $\rightarrow$ **Dream Case for Experiments!**
- **CEPC** produces $h(125)$ via $e^+e^- \rightarrow$ **Zh**, $\boldsymbol{\nu\bar{\nu}}$**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** $\sim \mathbf{10^{-3}}$.





Production & Background Processes

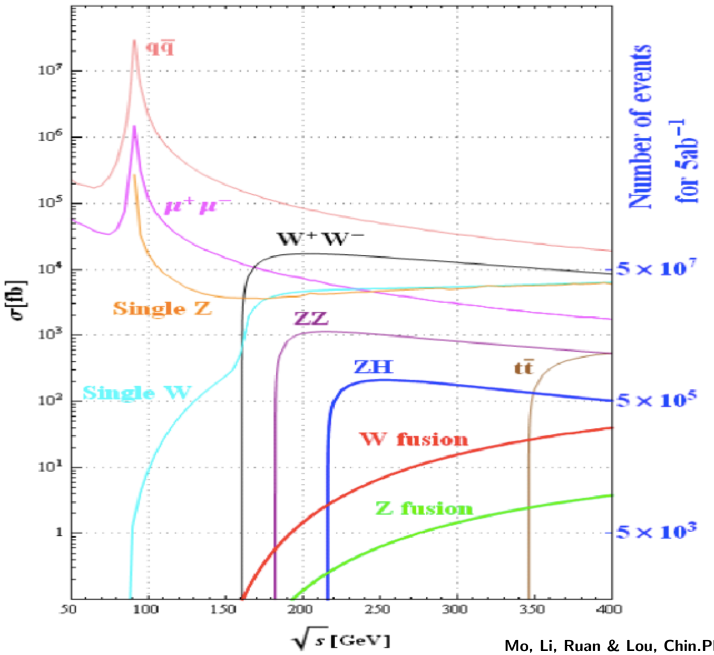
- **Large Statistics – 10^6 Higgs → Relative Error $\sim 10^{-3}$.**

Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

- **Clean Background**

Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to qq$	50.2	2.5×10^8
$e^+e^- \to \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to eeZ$	4.73	2.4×10^7
$e^+e^- \to e\nu W$	5.14	2.6×10^7

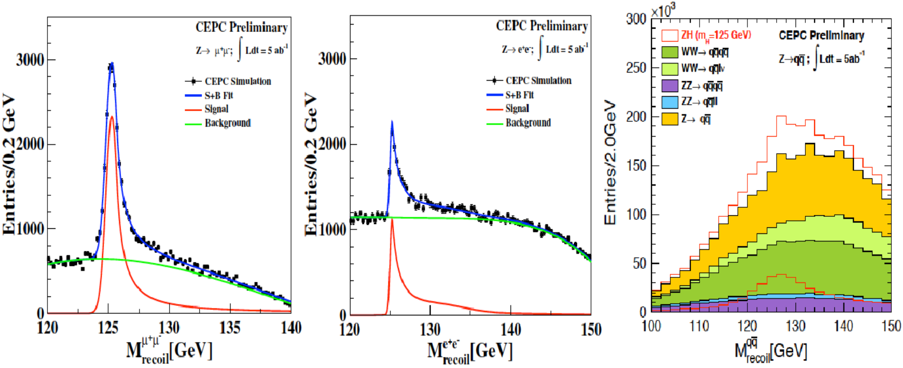
- **Easy for Simulation [Loop Calculation]**
- **Polarization**



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

$e^+e^- \to Zh$

- **Recoil Mass Distribution**: $m^2_{rec} \equiv (\sqrt{s} - E_{ff})^2 - p^2_{ff}$
  - **Cross Section**: $\sigma(Zh) \quad \Rightarrow \quad \Gamma(h \to ZZ)$
  - **Higgs Mass**: m_h
  - **Higgs Width**: Γ_h
  - **Branching Ratios**: **Model-Independent**
  - **Invisible Decay**



Combination of Various Channels

- $\sigma(\mathrm{Zh})$ [**0.51%**]

Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	13	2.1%	
$\mu\mu$	6.6	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
qq		0.65%	0.32%
$ee+\mu\mu+qq$		0.51%	0.25%

- $h \to \mathrm{bb}$ [**0.28%**], cc [**2.2%**], gg [**1.6%**]

Channel		$H \to bb$	$H \to cc$	$H \to gg$
$\mu\mu H$	signal	11067	561	1808
	background	467	746	1838
	$\Delta(\sigma \times \mathrm{BR})/\sigma \times \mathrm{BR}$	0.9%	12.6%	3.8%
eeH	signal	11033	544	1914
	background	732	1369	3137
	$\Delta(\sigma \times \mathrm{BR})/\sigma \times \mathrm{BR}$	1.1%	14.6%	5.6%
$\nu\nu H$	$\Delta(\sigma \times \mathrm{BR})/\sigma \times \mathrm{BR}$	0.45%	3.2%	2.8%
qqH	$\Delta(\sigma \times \mathrm{BR})/\sigma \times \mathrm{BR}$	0.4%	3.0%	2.6%
Combined	$\Delta(\sigma \times \mathrm{BR})/\sigma \times \mathrm{BR}$	0.28%	2.2%	1.6%

Combination of Various Channels

- h → ZZ [4.3%]

Channel	Precision	Comment
$\sigma(Z(\nu\nu)H + \nu\nu H) \times \mathrm{BR}(H \to ZZ)$	6.9%	CEPC Fast Simulation
$\mathrm{BR}(H \to ZZ^*)$	4.3%	Extrapolation from FCC-ee [29]

- h → WW [1.5%]

Channel	Precision	Comment
$Z \to \mu\mu, H \to WW^* \to \ell\nu qq, \ell\ell\nu\nu$	4.9%	CEPC Full Simulation
$Z \to ee, H \to WW^* \to \ell\nu qq,\ \ell\ell\nu\nu$	7.0%	Estimated
$Z \to \nu\nu, H \to WW^* \to qqqq$	2.3%	Extrapolated from ILC result
$Z \to qq, H \to WW^* \to \ell\nu qq$	2.2%	Extrapolated from ILC result
Combined	1.5%	

- h → $\tau\tau$ [1.2%]
- h → $\gamma\gamma$ [9.0%]
- h → $\mu\mu$ [17%]
- h → invisible [0.14%]

CEPC: http://cepc.ihep.ac.cn/

Extracting the Physics Potential

- **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**,

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

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

ΔM_h	Γ_h	$\sigma(Zh)$	$\sigma(\nu\bar{\nu}h) \times \mathrm{Br}(h \to bb)$
5.9 MeV	2.8%	0.51%	2.8%

Decay Mode	$\sigma(Zh) \times \mathrm{Br}$	Br
$h \to bb$	0.28%	0.57%
$h \to cc$	2.2%	2.3%
$h \to gg$	1.6%	1.7%
$h \to \tau\tau$	1.2%	1.3%
$h \to WW$	1.5%	1.6%
$h \to ZZ$	4.3%	4.3%
$h \to \gamma\gamma$	9.0%	9.0%
$h \to \mu\mu$	17%	17%
$h \to \mathrm{invisible}$	–	0.14%

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

Precision on Higgs Couplings

CEPC preCDR

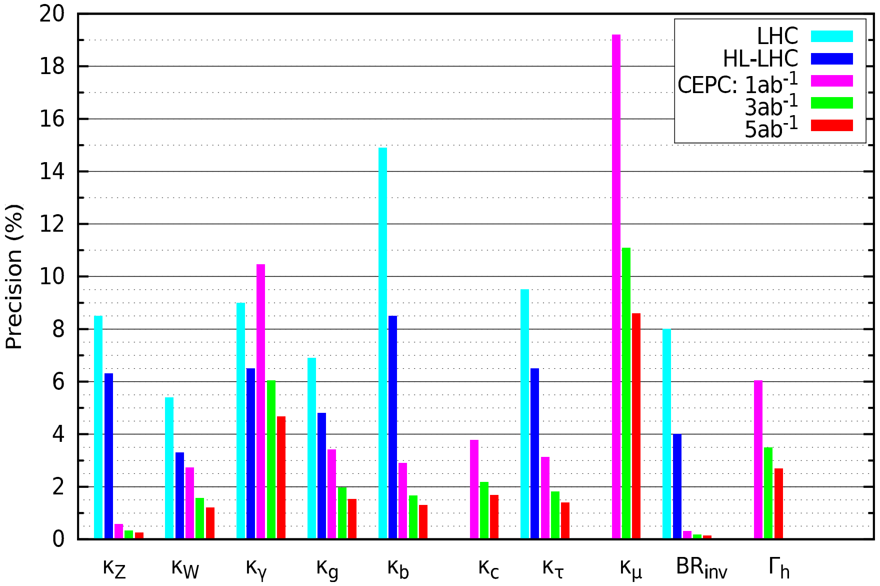
Table: Precisions on measuring Higgs couplings at **CEPC (250GeV, 5ab^{-1})**, in comparison with **LHC (14TeV, 300fb^{-1})**, **HL-LHC (14TeV, 3ab^{-1})** and **ILC (250GeV, 250fb^{-1})+(500GeV, 500fb^{-1})**.

Precision (%)	CEPC		LHC	HL-LHC	ILC-250+500
κ_Z	0.254	0.254	8.5	6.3	0.50
κ_W	1.22	1.22	5.4	3.3	0.46
κ_γ	4.67	4.67	9.0	6.5	8.6
κ_g	1.52	1.52	6.9	4.8	2.0
κ_b	1.29	1.29	14.9	8.5	0.97
κ_c	1.69	1.69	–	–	2.6
κ_τ	1.40	1.40	9.5	6.5	2.0
κ_μ	–	8.59	–	–	–
$\mathrm{Br}_{\mathrm{inv}}$	0.138	0.138	8.0	4.0	0.52
Γ_h	2.8	2.8	–	–	–

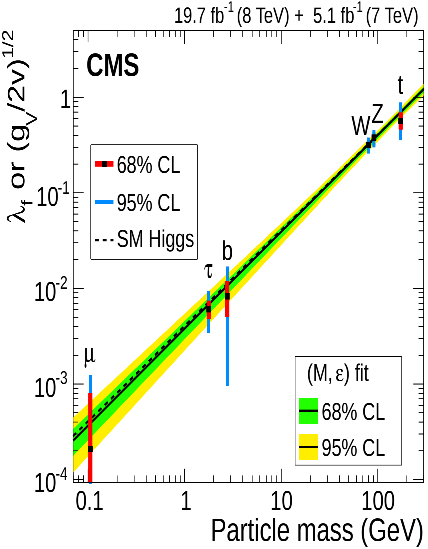
LHC & ILC from 1312.4974

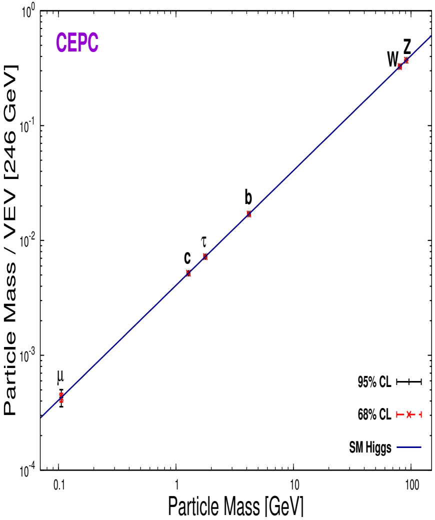
Precision on Higgs Couplings

CEPC preCDR



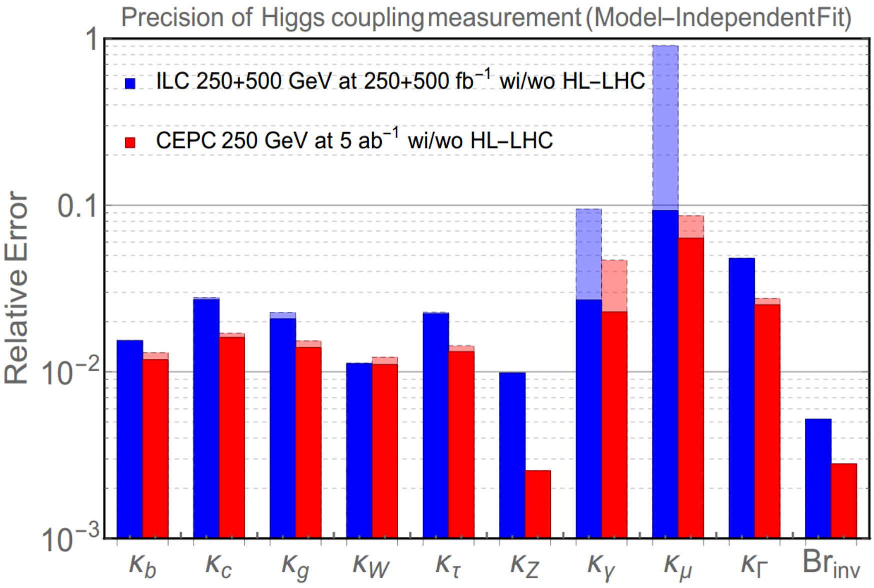
Precision on Higgs Couplings





Precision on Higgs Couplings

CEPC preCDR

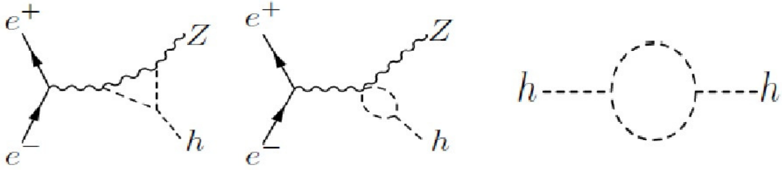


Higgs Self-Coupling

- Rescaling of the trilinear term h^3

$$\Delta\mathcal{L} = -\frac{1}{3!}\boldsymbol{\delta\kappa_{h3}}\lambda^{sm}_{hhh}h^3\,.$$

- Affect $\boldsymbol{\sigma}(\mathbf{Zh})$ via **Loop Correction**



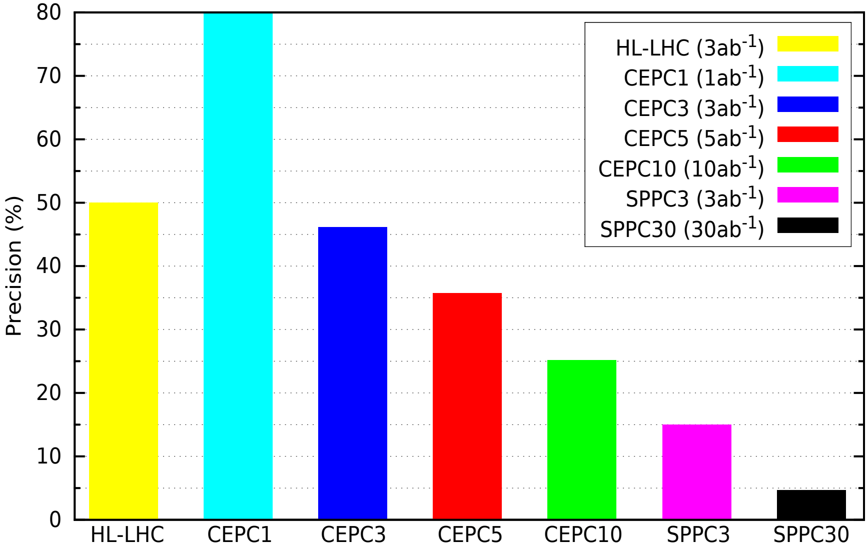
- Constrained by $\boldsymbol{\sigma}(\mathbf{Zh})$ meansurement

$$\frac{\delta\sigma(Zh)}{\sigma(Zh)} \approx \mathbf{2} \times \delta\kappa_Z + \mathbf{0.014} \times \boldsymbol{\delta\kappa_{h3}}\,.$$

1312.3322

Higgs Self-Coupling

CEPC preCDR



CEPC Test of Higgs CP Violation

1308.1094

- **LHC**: **h** $\rightarrow$ **ZZ**, $\tau\tau$
- **CEPC**: **h** $\rightarrow \tau\tau$

$$\mathcal{L}_{h\tau\tau} \propto \frac{y_\tau}{\sqrt{2}} h\bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau\,.$$

- Complex enough to retain info about the τ spin.

$$\begin{aligned} h &\rightarrow \tau^+ + \tau^- \\ &\rightarrow \rho^+\bar{\nu}_\tau + \rho^-\nu_\tau \\ &\rightarrow \pi^+\pi^0\bar{\nu}_\tau + \pi^-\pi^0\nu_\tau\,. \end{aligned}$$

CP-even part ($\cos\Delta$) in **p-wave** & **CP-odd** ($\sin\Delta$) in **s-wave**.

- **Precision Measurement @ CEPC**

Higgs Report

Colliders	LHC	HL-LHC	CEPC1	CEPC5	CEPC10
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Effective Field Approach – Unitarity

see also 1411.0676

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

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

- **SM Gauge Invariance** is respected

$$\mathcal{O}_{\mathbf{H}} \equiv \frac{1}{2}(\partial_\mu |\mathbf{H}|^2)^2 \,, \qquad \mathcal{O}_{\mathbf{T}} \equiv \frac{1}{2}(\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})^2 \,,$$

$$\mathcal{O}_{WW} \equiv g^2 |\mathbf{H}|^2 W^a_{\mu\nu} W^{a,\mu\nu} \,, \qquad \mathcal{O}_{BB} \equiv g'^2 |\mathbf{H}|^2 B_{\mu\nu} B^{\mu\nu} \,,$$

$$\mathcal{O}_{WB} \equiv g g' \mathbf{H}^\dagger \sigma^a \mathbf{H} W^a_{\mu\nu} B^{\mu\nu} \,, \qquad \mathcal{O}_{HB} \equiv i g' (D^\mu \mathbf{H})^\dagger (D^\nu \mathbf{H}) B_{\mu\nu} \,,$$

$$\mathcal{O}_{HW} \equiv i g (D^\mu \mathbf{H})^\dagger \sigma^a (D^\nu \mathbf{H}) W^a_{\mu\nu} \,, \qquad \mathcal{O}^{(3)}_{\mathbf{L}} \equiv (i \mathbf{H}^\dagger \sigma^a \overleftrightarrow{D}_\mu \mathbf{H})(\bar{\Psi}_L \gamma^\mu \sigma^a \Psi_L) \,,$$

$$\mathcal{O}^{(3)}_{LL} \equiv (\bar{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\bar{\Psi}_L \gamma^\mu \sigma^a \Psi_L) \,, \qquad \mathcal{O}_{\mathbf{L}} \equiv (i \mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\bar{\Psi}_L \gamma^\mu \Psi_L) \,,$$

$$\mathcal{O}_{\mathbf{g}} \equiv g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu} \,, \qquad \mathcal{O}_{\mathbf{R}} \equiv (i \mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\bar{\psi}_R \gamma^\mu \psi_R) \,.$$

Scheme-Independent Analysis

- **EW Parameters:**

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

which can be denoted as

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

- **Observables:**

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

- **Analytical Fit:**

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

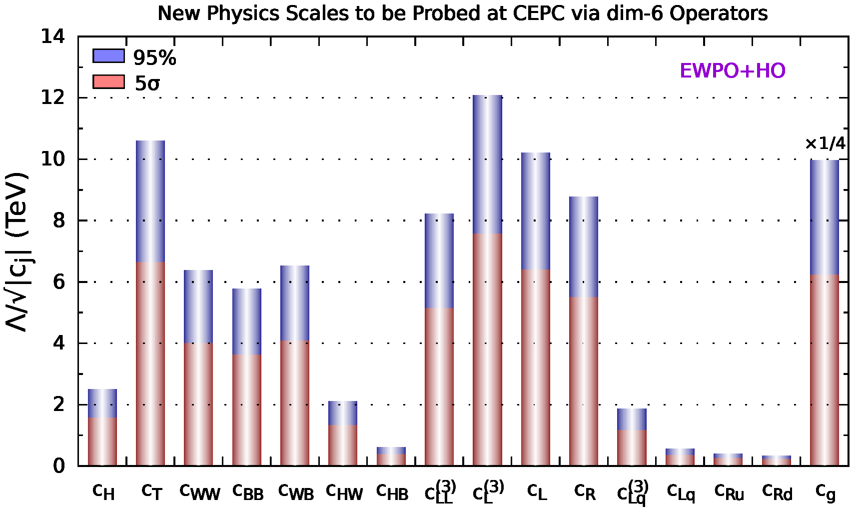
Scheme-Independent Analysis

- **Observables**: **EWPO** + **HO**

Observables	Central Value	Relative Error	SM Prediction
M_Z	91.1876GeV	2.3×10^{-5}	–
M_W	80.385GeV	1.87×10^{-4}	–
G_F	1.1663787×10^{-5}GeV^{-2}	5.14×10^{-7}	–
α	$7.2973525698 \times 10^{-3}$	3.29×10^{-10}	–
$\sigma[Zh]$	–	0.51%	–
$\sigma[\nu\bar{\nu}h]$	–	2.86%	–
$\sigma[\nu\bar{\nu}h]_{350\text{GeV}}$	–	0.75%	–
Br$[WW]$	–	1.6%	22.5%
Br$[ZZ]$	–	4.3%	2.77%
Br$[bb]$	–	0.57%	58.1%
Br$[cc]$	–	2.3%	2.10%
Br$[gg]$	–	1.7%	7.40%
Br$[\tau\tau]$	–	1.3%	6.64%
Br$[\gamma\gamma]$	–	9.0%	0.243%
Br$[\mu\mu]$	–	17%	0.023%

- **Fitting Parameters:**
  - **EW:** $M_Z^{(\text{SM})} = M_Z^{(r)} \left(1 + \frac{\delta M_Z}{M_Z}\right), \; G_F^{(\text{SM})} = G_F^{(r)} \left(1 + \frac{\delta G_F}{G_F}\right), \; \alpha^{(\text{SM})} = \alpha^{(r)} \left(1 + \frac{\delta\alpha}{\alpha}\right).$
  - **dim-6 Higgs Operators:** c_i

Sensitivities from Existing EWPO & Future HO



1603.03385

Enhancement from M_Z & M_W @ CEPC

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

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

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
$+\mathbf{M_Z}$	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
$+\mathbf{M_W}$	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
$+\mathbf{M_{Z,W}}$	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.

SFG, Hong-Jian He, Rui-Qing 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"].

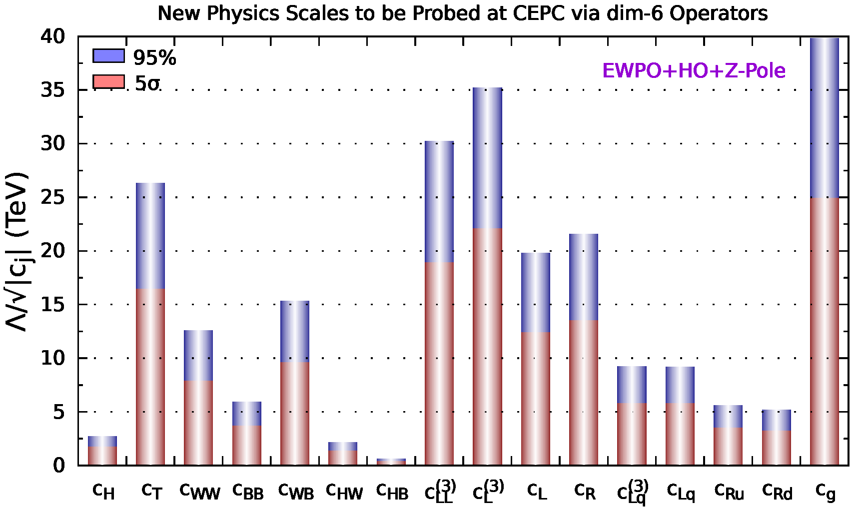
Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

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

A factor of 2 enhancement from Z-Pole Observables

Sensitivity from EWPO+HO+Z-Pole



1603.03385

Summary

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

- **New Physics**
  - Neutrino Oscillation
  - Dark Matter
  - Matter-Antimatter Asymmetry
  - Vacuum Energy & Inflation

- **LHC** – Discovery Machine vs Poor sensitivity

- **CEPC** – $\mathbf{10^6}$ Higgs
  - Higgs Coupling $\sim \mathcal{O}(1\%)$ Level
  - Higgs Self-Coupling $\sim$ **30%**
  - Precise measurement of CP $\sim$ **2.5°**
  - Probe new physics to **10 TeV** (**40 TeV** for $\mathcal{O}_g$) **[35 TeV @ Z-Pole]**

Thank You!