CEPC Higgs Physics

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On Behalf of the Higgs Working Group

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

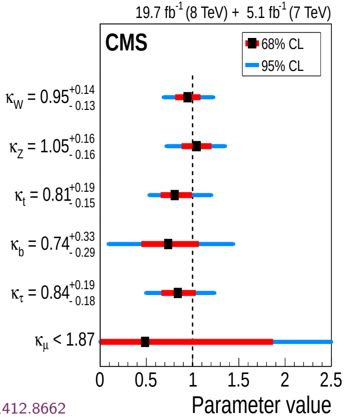
- Deep understanding of **Mass Generation**
  - **Yukawa Forces** – **Hierarchy** & **Mixing** (**Flavor Symmetries?**)
    - Discrete v.s. Continuous
    - Full v.s. Residual [1104.0602, 1108.0964, 1308.6522]
  - **Higgs Self-Interaction Forces** – $\mathbf{h^3}$ & $\mathbf{h^4}$ (concerns spontaneous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

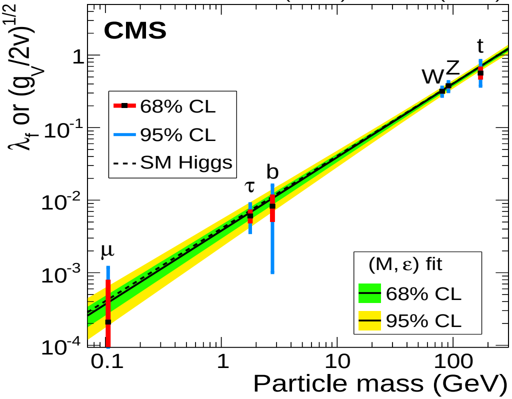
- **True Self-Interactions** – **Exactly the Sample Quantum #**
  - Spin
  - Charge

- 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% $\sim$ 30%**.
  - LHC cannot probe other Yukawa Couplings!
- **Higgs Self-Interaction** is also difficult @ LHC **Run-I**.

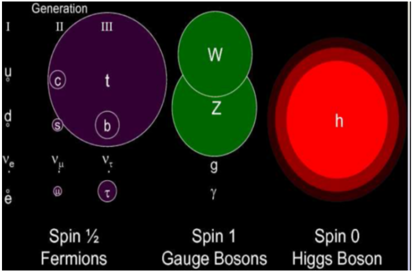


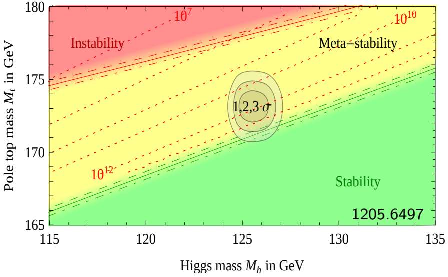


1412.8662

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**



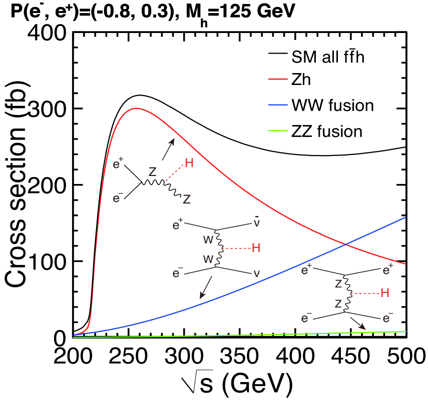


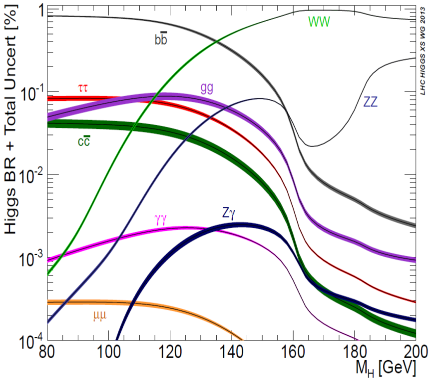
Beyond SM?

- **NO particle beyond SM** discovered @ **LHC** yet!
- **New Physics** @ Higher Energy?
- **Even within SM, we are strongly motivated to quantitatively test Yukawa and Higgs Self-Interaction Forces!**
- **Precision Measurement + Discovery Machine**:
  - **LEP + LHC**
  - **Go beyond!**
    - **CEPC (ee, 250 GeV)**
    - **SppC (pp, 50-100 TeV)**

Higgs Factory @ 250 GeV

- **LHC** tells us: $h(125)$ is **SM-like** $\rightarrow$ **Precision test is possible!**
- **CEPC** produces $h(125)$ via $e^+e^- \rightarrow \mathbf{Zh}, \nu\nu\mathbf{h}, \mathbf{e^+e^-h}$
- **Indirect Probe** to **New Physics**. **5/ab** with 2 detectors in 10y $\rightarrow$ $\mathbf{10^6}$ Higgs





Production & Background Processes

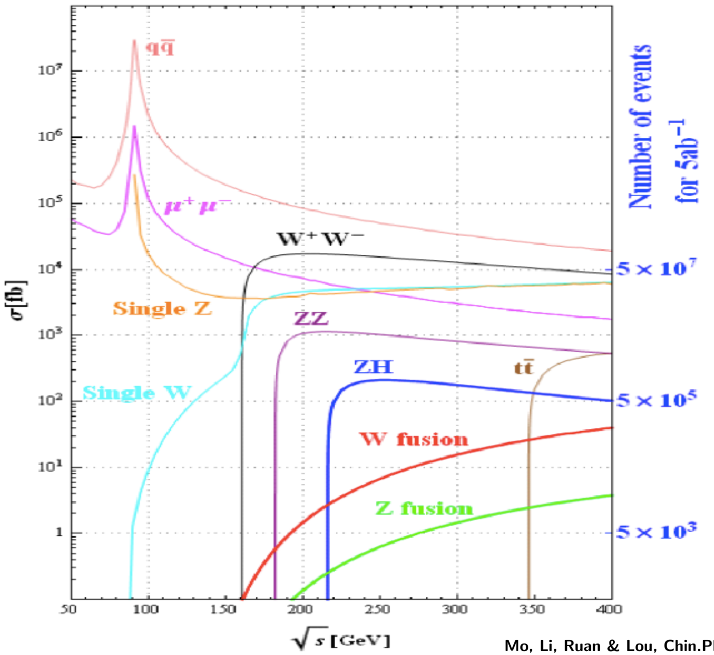
- Large Statistics – 10^6 Higgs

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

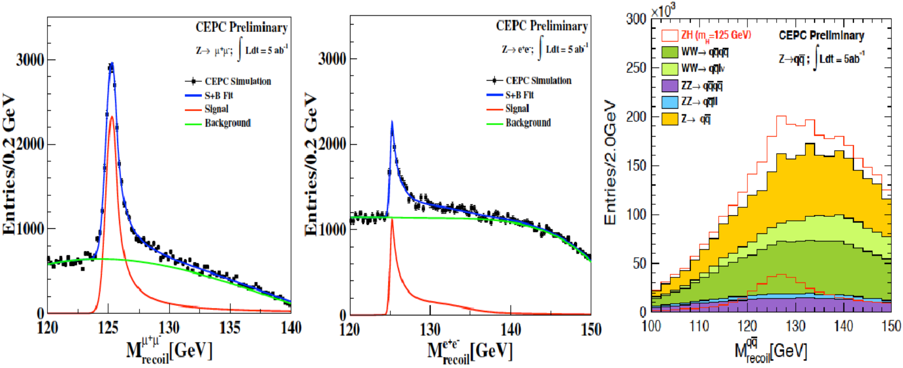
- Easy for Simulation [Loop Calculation]
- Polarization



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

- $\sigma(Zh)$ [**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 $\to$ 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 → 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 → 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 → $\tau\tau$ [1.2%]
- h → $\gamma\gamma$ [9.0%]
- h → $\mu\mu$ [17%]
- h → invisible [0.14%]

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 → Cross Section & BR

ΔM_h	Γ_h	$\sigma(Zh)$	$\sigma(\nu\nu h) \times \mathrm{Br}(h \to bb)$
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%
$h \to$ invisible	–	0.14%

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

Analytical Linear χ^2 Fit – Definition

- **Observable Basis**:

$$\chi^2 = (\mathcal{O}^{th,0} + \mathcal{A}\delta\kappa - \mathcal{O}^{exp})^T \overline{\Sigma}^{-1} (\mathcal{O}^{th,0} + \mathcal{A}\delta\kappa - \mathcal{O}^{exp}) \,,$$

where the **error matrix** $\overline{\Sigma}^{-1}$ of measurements is diagonal,

$$\overline{\Sigma}^{-1} = \text{diag}\left\{ \frac{1}{(\Delta\mathcal{O}_1)^2}, \frac{1}{(\Delta\mathcal{O}_2)^2}, \cdots, \frac{1}{(\Delta\mathcal{O}_n)^2} \right\} .$$

- **Fitting Basis**:

$$\chi^2 \equiv \chi^2_{\text{min}} + \delta\kappa^T \Sigma^{-1} \delta\kappa \,,$$

can be obtained by a simple **matrix manipulation**,

$$\Sigma^{-1} = \mathcal{A}^T \overline{\Sigma}^{-1} \mathcal{A} \,.$$

- **No Data yet**

$$\mathcal{O}^{th,0} = \mathcal{O}^{exp} \quad \Longrightarrow \quad \chi^2_{\text{min}} = 0 \,.$$

This assumption affects only χ^2_{min}, not **error matrix** Σ^{-1}.

Analytical Linear χ^2 Fit – Marginalization

Marginalization

When talking about the uncertainty of a specific fitting parameter, the number quoted should be independent of any other parameters.

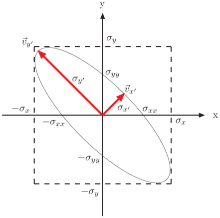
$$\mathbb{P}(\delta\kappa_1 \cdots \hat{\delta\kappa_k} \cdots \delta\kappa_n) = \int_{-\infty}^{+\infty} \mathbb{P}(\delta\kappa_1 \cdots \delta\kappa_k \cdots \delta\kappa_n)\, d\delta\kappa_k \,.$$

Keep doing this until only one parameter is left.

Matrix Manipulation

For linear χ^2 fit, Gaussian-type integration can be replaced by matrix manipulation.

$$\widetilde{\Sigma}^{-1}_{ij} = \Sigma^{-1}_{ij} - \frac{\Sigma^{-1}_{ik}\Sigma^{-1}_{jk}}{\Sigma^{-1}_{kk}} \,.$$



Uncertainty

$$\Delta(\delta\kappa_l) = \sqrt{\widetilde{\Sigma}_{ll}} \,.$$

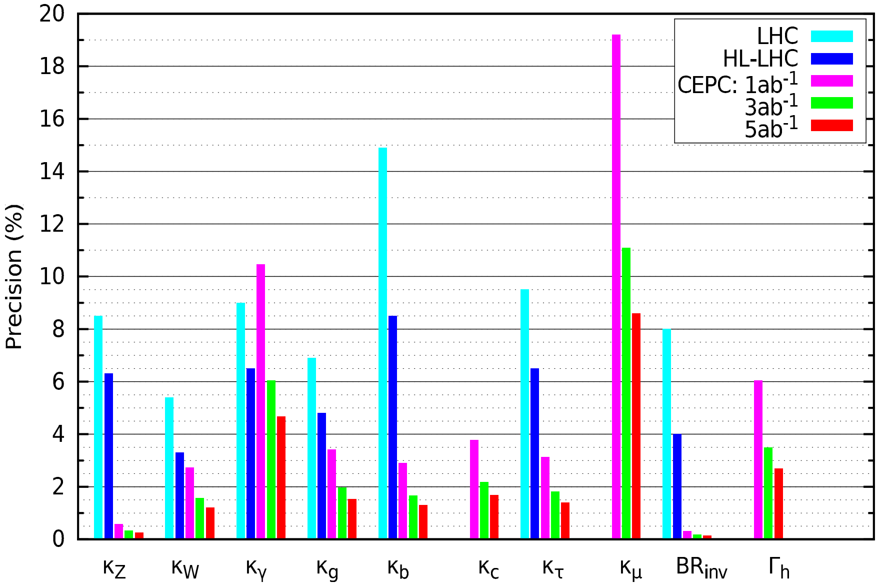
Precision on Higgs Couplings

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})**.

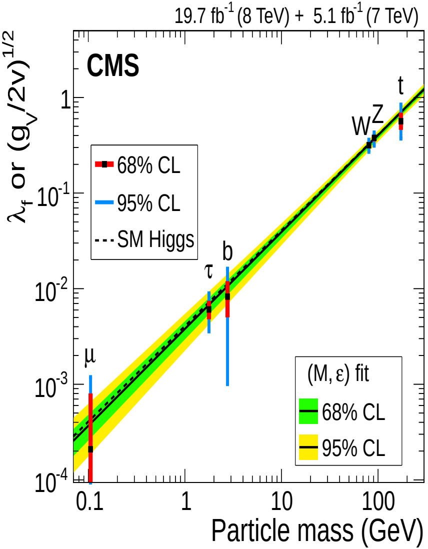
Precision (%)	CEPC		LHC	HL-LHC	ILC-250+500
κ_Z	0.254	0.254	8.5	6.3	0.50
κ_W	1.22	1.22	5.4	3.3	0.46
κ_γ	4.67	4.67	9.0	6.5	8.6
κ_g	1.52	1.52	6.9	4.8	2.0
κ_b	1.29	1.29	14.9	8.5	0.97
κ_c	1.69	1.69	–	–	2.6
κ_τ	1.40	1.40	9.5	6.5	2.0
κ_μ	–	8.59	–	–	–
$\mathrm{Br}_{\mathrm{inv}}$	0.138	0.138	8.0	4.0	0.52
Γ_h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

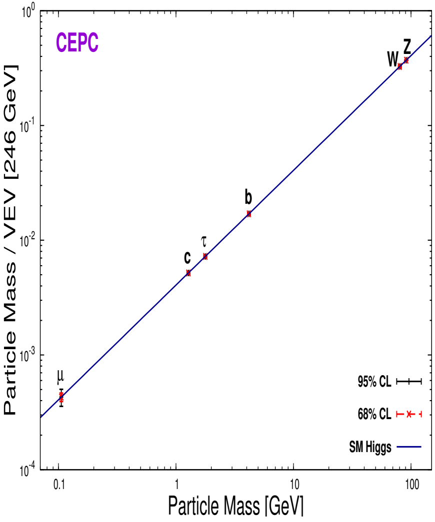
LHC & ILC from 1312.4974

Precision on Higgs Couplings

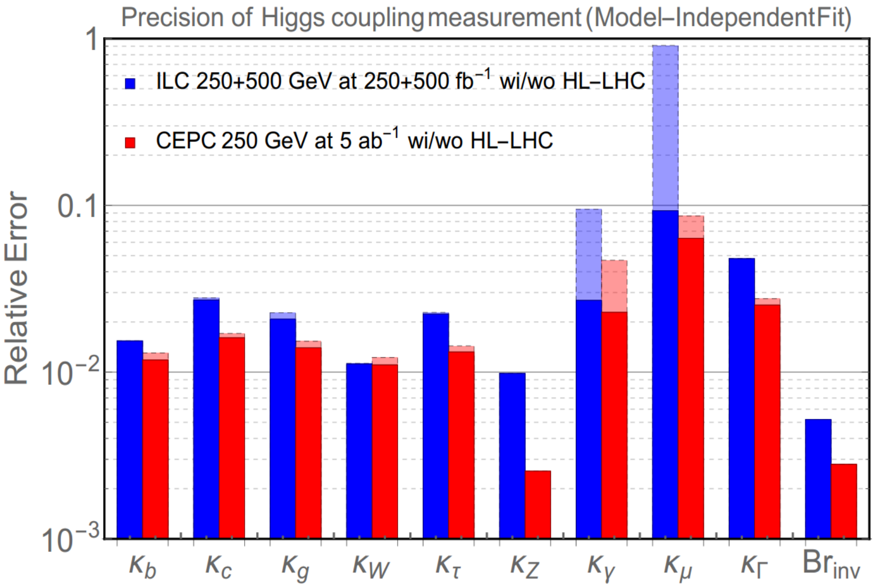


Precision on Higgs Couplings





Precision on Higgs Couplings



Effective Field Approach

see also 1411.0676

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

$$\mathcal{L} = \mathcal{L}_{\mathbf{SM}} + \sum_i \frac{\mathbf{c_i}}{\Lambda^2} \mathcal{O}_{\mathbf{i}} \,.$$

- **SM Gauge Invariance** is respected

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

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

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

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

$$\mathcal{O}^{(3)}_{LL} \equiv (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L) \,, \qquad \mathcal{O}_{\mathbf{H}} \equiv (\mathbf{H}^\dagger \mathbf{H}) \overline{\Psi}_L \mathbf{H} \psi_R \,,$$

$$\mathcal{O}_{\mathbf{L}} \equiv (i \mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\Psi}_L \gamma^\mu \Psi_L) \,, \qquad \mathcal{O}_{\mathbf{R}} \equiv (i \mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\psi}_R \gamma^\mu \psi_R) \,.$$

Effective Field Approach

see also 1411.0676

- **Z-Scheme** to fix free parameters in EW sector

$$(\alpha, \mathbf{G_F}, \mathbf{M_Z}) \Longleftrightarrow (\mathbf{g}, \mathbf{g}', \mathbf{v})$$

- **Zeroth-Order Correlation**

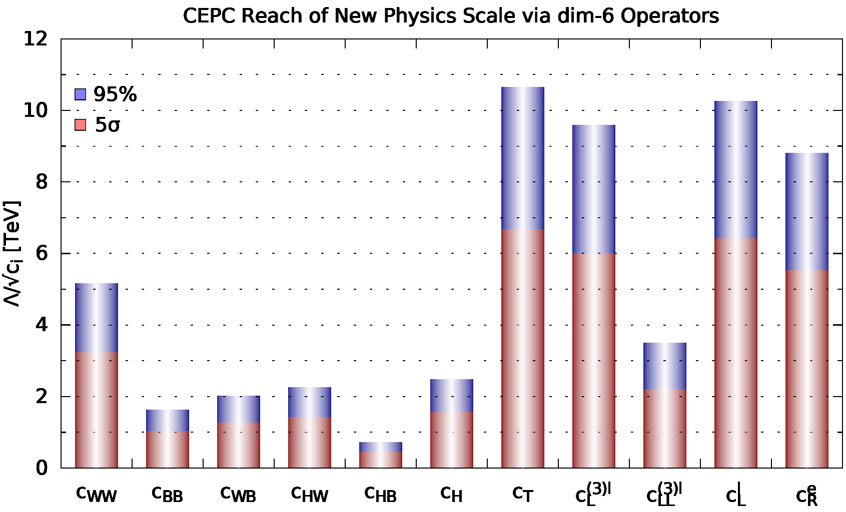
$$\sin 2\theta_w^{(0)} \equiv \sqrt{\frac{4\pi\alpha^{(0)}}{\sqrt{2}\mathbf{G_F^{(0)}}\left(\mathbf{M_Z^{(0)}}\right)^2}}\,.$$

- **Inputs**

$$\frac{\delta\sigma(Zh)}{\sigma(Zh)} = \mathbf{0.51\%} \text{ @ } \mathbf{CEPC}\,,$$

$$\mathbf{M_W} = \mathbf{80.835} \pm \mathbf{0.015}\,\text{GeV}\,.$$

Effective Field Approach



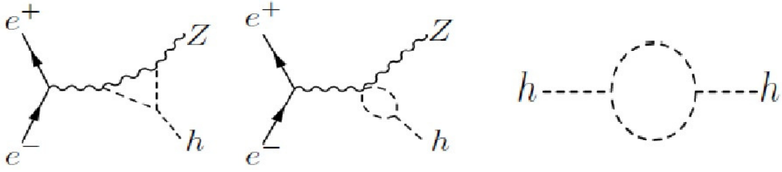
See also Craig & McCullough's talks [1411.0676]

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**

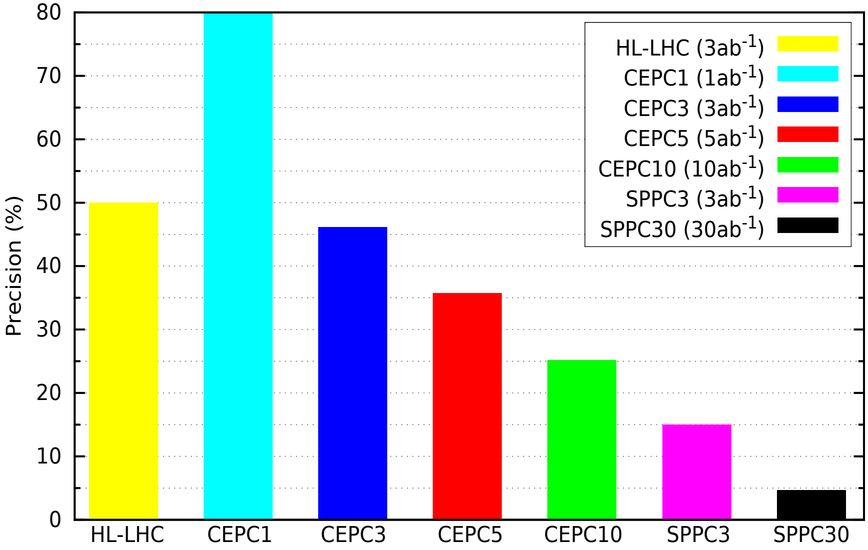


- Constrained by $\boldsymbol{\sigma}(\mathbf{Zh})$ meansurement

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

1312.3322

Higgs Self-Coupling



CEPC Test of Higgs CP Violation

1308.1094

- **LHC**: $\mathbf{h} \to \mathbf{ZZ}, \tau\tau$
- **CEPC**: $\mathbf{h} \to \tau\tau$

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

- Complex enough to retain info about the τ spin.

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

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°

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
  - Probe the scale of new physics to **10 TeV**
  - Higgs Self-Coupling $\sim$ **30%**
  - Precise measurement of CP $\sim 2.5^\circ$

Thank You!