Higgs Precision Combination New Physics Scales via Dim-6 Operator and Differential Distributions @ CEPC

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

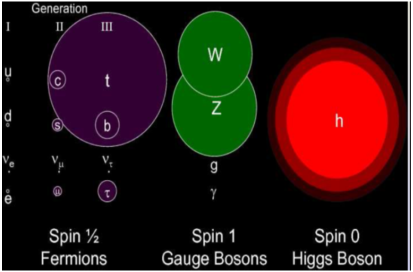
CEPC preCDR

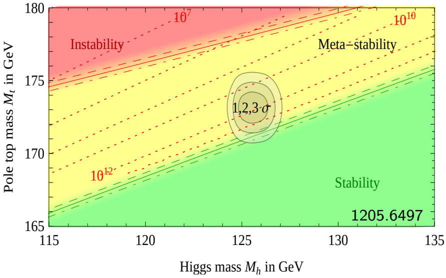
Higgs discovery is not just about *H* particle

- **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 [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!

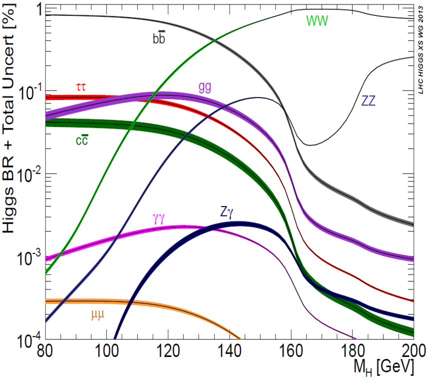
- Mass Generation
  - Yukawa force is **Flavor-Dependent** & **Hierarchically Unnatural**
  - Higgs mass itself is **Radiatively Unnatural**
- Neutrino Oscillation
- Dark Matter
- Matter-Antimatter Asymmetry
- Vacuum Stability
- Vacuum Energy & Inflation

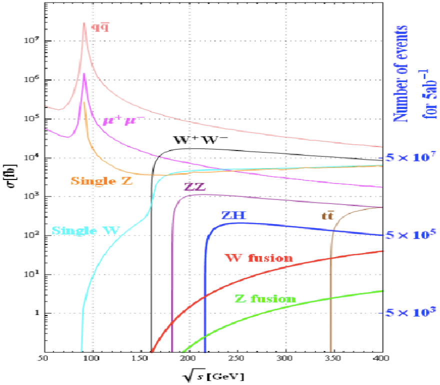




Higgs Factory @ 250 GeV

- **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 → Cross Section & BR

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

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

for details see other talks at this meeting

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

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

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})**.

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	–	–	–

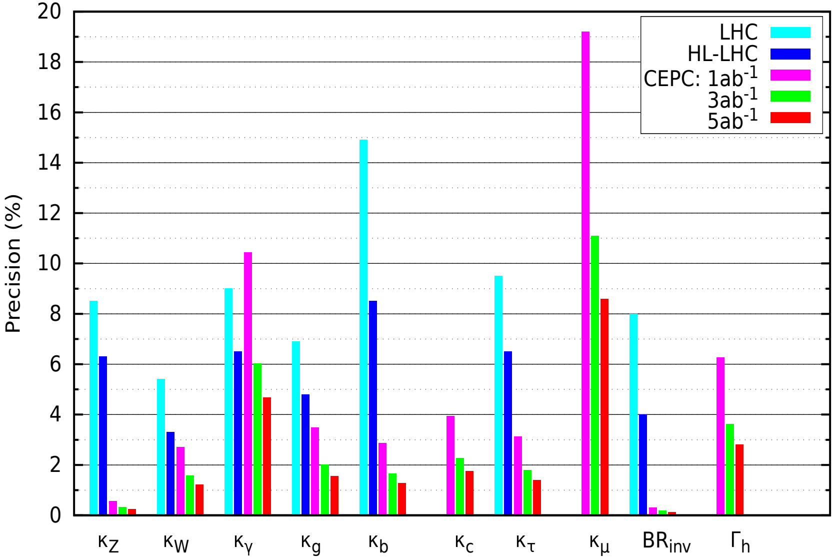
LHC & ILC from 1312.4974

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

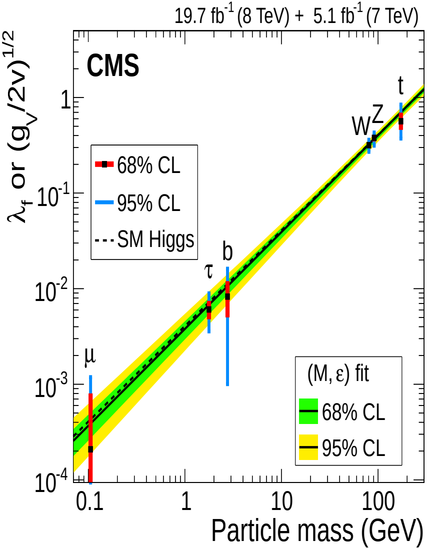
Combined Higgs Coupling Precision

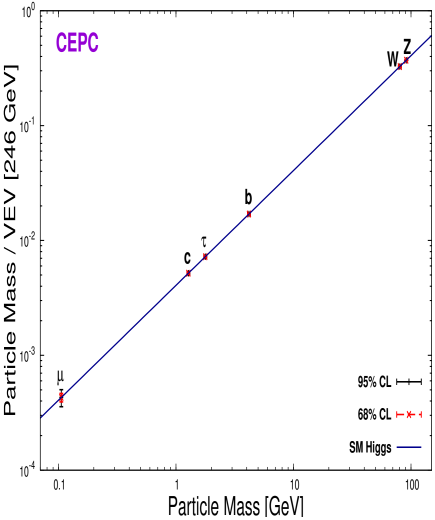
1603.03385, preCDR



Precision on Higgs Couplings

1603.03385, preCDR





New Physics Scales

1603.03385

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

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

- **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	$\mathcal{O}_{\mathbf{HW}} = ig(D^\mu \mathbf{H})^\dagger \sigma^a (D^\nu \mathbf{H}) W^a_{\mu\nu}$	$\mathcal{O}_{\mathbf{R}} = (i\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_{\mathbf{g}} = g_s^2 \lvert\mathbf{H}\rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{\mathbf{HB}} = ig'(D^\mu \mathbf{H})^\dagger (D^\nu \mathbf{H}) B_{\mu\nu}$	

Existing EWPO & Future HO

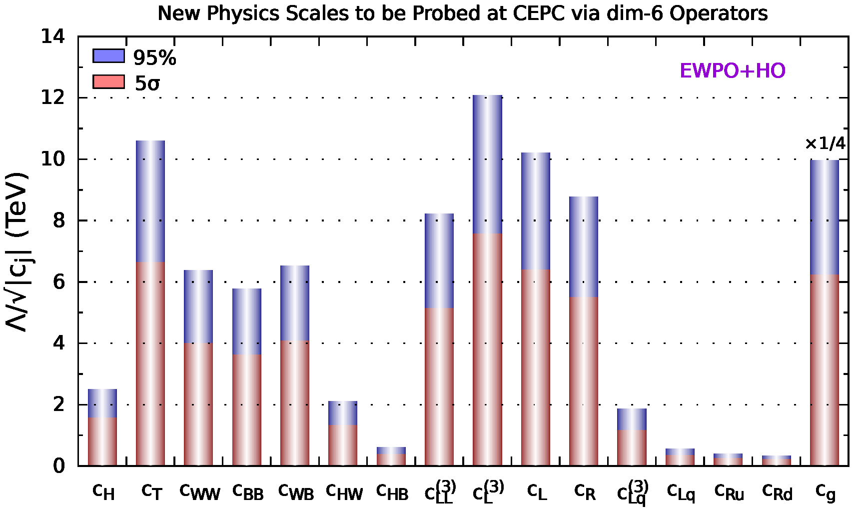
Observables: EWPO (PDG14) + HO (preCDR)

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	$1.1663787 \times 10^{-5}\text{GeV}^{-2}$	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%	–
$\text{Br}[WW]$	–	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 **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**	**6.52**	2.11	0.603	**8.21**	**12.1**	**10.2**	**8.78**	1.85	0.565	0.391	0.337	**39.8**
5σ	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



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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 and M_W @ CEPC [Z.Liang, "Z & W Physics @ CEPC"].

Scheme-Independent Analysis

$\frac{\Lambda}{\sqrt{c_i}}$ [TeV]	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}^{(3)}_{LL}$	$\mathcal{O}^{(3)}_{L}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}^{(3)}_{L,q}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
HO+EWPO	2.74	10.6	6.38	5.78	6.53	2.15	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.

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"].

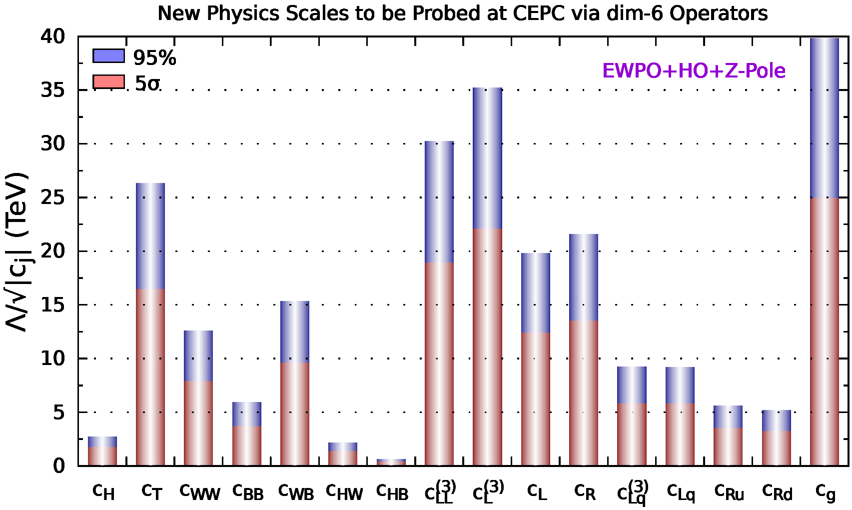
Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

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



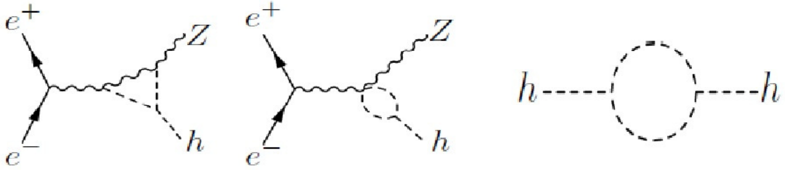
1603.03385

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**



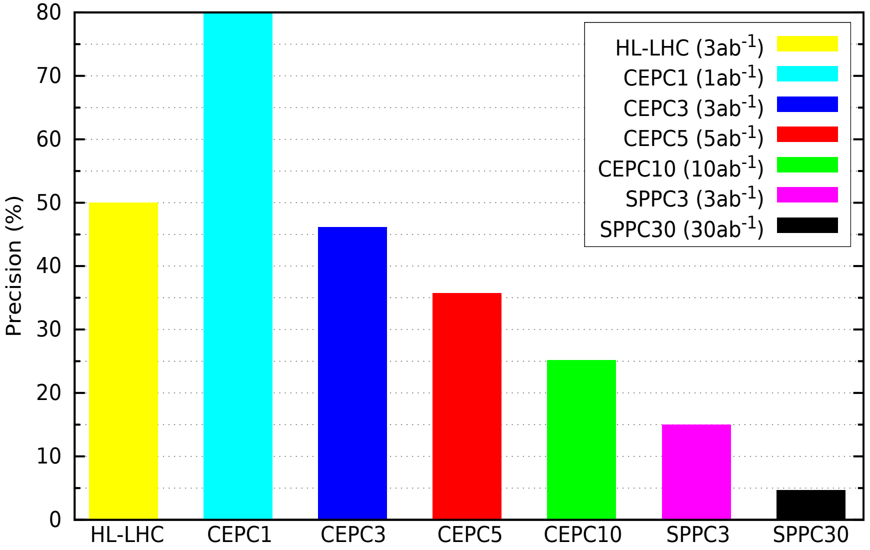
- Constrained by $\boldsymbol{\sigma}(\mathbf{Zh})$ meansurement

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

1312.3322

Higgs Self-Coupling

CEPC preCDR



Higgs CP Phase in $h \to \tau^+\tau^-$ Decay

1308.1094

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

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

- **Complex enough to retrieve info about the τ spin & Higgs CP**

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

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

- Kinematic info of ν's **retrievable**
- Hadronic decay $\tau \to \rho\nu$ **fully reconstructable**
- BR($\tau \to \rho\nu$) $\approx$ **25%** & BR($\rho \to \pi\pi$) $\approx$ **100%**
- The ρ meson has narrow width $\Rightarrow$ **On-Shell**

Higgs CP Phase in $h \to \tau^+\tau^-$ Decay

1308.1094

- $h \to \tau^+\tau^-$: **Measure τ spin perpendicular to $\vec{p}_\tau$**

$$\mathcal{M}_{h\to\tau\tau} \propto |\vec{p}_{\tau^-}| \cos\Delta \frac{\chi_{1,1}+\chi_{-1,-1}}{\sqrt{2}} - iE_{\tau^-} \sin\Delta \frac{\chi_{1,1}-\chi_{-1,-1}}{\sqrt{2}}$$
$$\approx \frac{E_{\tau^-}}{\sqrt{2}} \left(e^{-i\Delta}\chi_{1,1} + e^{+i\Delta}\chi_{-1,-1} \right)$$

- $\tau^- \to \rho^-\nu_\tau$: $\vec{p}_\rho$ **follows τ spin**

$$\mathcal{M}_{\tau\to\rho\nu} \propto \epsilon^*_{\rho^-} \cdot \left(\varepsilon_{-1} \sin\frac{\theta}{2} - \varepsilon_0 \frac{m_\tau}{\sqrt{2}m_\rho} \cos\frac{\theta}{2} \right)$$

- $\rho^- \to \pi^-\pi^0$: **Momentum difference $\vec{p}_{\pi^-} - \vec{p}_{\pi^0}$ follows $\vec{p}_\rho$**

$$\mathcal{M}_{\rho\to\pi\pi} \propto \epsilon_{\rho^-} \cdot (p_{\pi^-} - p_{\pi^0})$$

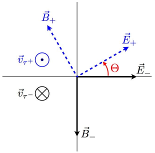
- **Neutrino momentum can be retrived** using
  - **Energy-momentum conservation**
  - **On-shell conditions**

Higgs CP Phase in $h \to \tau^+\tau^-$ Decay

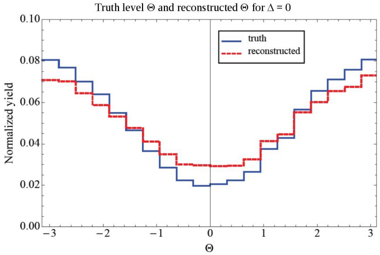
1308.1094

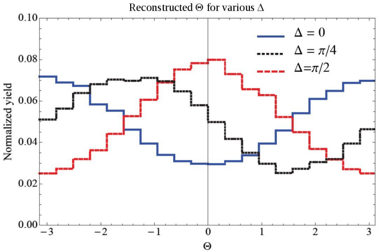
Θ Angle

$$\Theta \equiv \mathrm{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \arccos\left(\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|}\right)$$



Differential Distribution





Precision Measurement @ CEPC

CEPC preCDR

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

Triple Gauge Coupling vs EFT

1507.02238

Mass Eigenstate Basis

$$\mathcal{L}_{TGC}/g_{WWV} \equiv i\mathbf{g}_{1,\mathbf{V}}\left(W^+_{\mu\nu}W^-_\mu V_\nu - W^-_{\mu\nu}W^+_\mu V_\nu\right) + i\boldsymbol{\kappa}_\mathbf{V} W^+_\mu W^-_\nu V_{\mu\nu} + \frac{i\boldsymbol{\lambda}_\mathbf{V}}{M_W^2} W^+_{\lambda\mu}W^-_{\mu\nu}V_{\nu\lambda}$$
$$+ \mathbf{g}_5^\mathbf{V}\varepsilon_{\mu\nu\rho\sigma}\left(W^+_\mu \overleftrightarrow{\partial}_\rho W_\nu\right)V_\sigma - \mathbf{g}_4^\mathbf{V} W^+_\mu W^-_\nu\left(\partial_\mu V_\nu + \partial_\nu V_\mu\right)$$
$$+ i\tilde{\boldsymbol{\kappa}}_\mathbf{V} W^+_\mu W^-_\nu \widetilde{V}_{\mu\nu} + \frac{i\tilde{\boldsymbol{\lambda}}_\mathbf{V}}{M_W^2} W^+_{\lambda\mu}W^-_{\mu\nu}\widetilde{V}_{\nu\lambda}\,.$$

EM gauge + Charge + Parity Invariances ⇒ 5 nonzero terms

$$\Delta\mathbf{g}_{1,\mathbf{Z}} \equiv \mathbf{g}_{1,\mathbf{Z}} - 1\,, \quad \Delta\boldsymbol{\kappa}_{\gamma,\mathbf{Z}} \equiv \boldsymbol{\kappa}_{\gamma,\mathbf{Z}} - 1\,, \quad \boldsymbol{\lambda}_\gamma\,, \quad \boldsymbol{\lambda}_\mathbf{Z}\,.$$

SILH Basis

$$\Delta\mathcal{L} = \frac{ig\,\mathbf{c_W}}{2M_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{\mathbf{c_{HW}}}{M_W^2}\mathcal{O}_{HW} + \frac{\mathbf{c_{HB}}}{M_W^2}\mathcal{O}_{HB} + \frac{g\,\mathbf{c_{3W}}}{6M_W^2}\epsilon^{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho\,.$$

$$\Delta\mathbf{g}_{1,\mathbf{Z}} = -\frac{\mathbf{c_{HW}}}{c_w^2}\,, \qquad \Delta\boldsymbol{\kappa}_\gamma = -(\mathbf{c_{HW}} + \mathbf{c_{HB}})\,,$$
$$\Delta\boldsymbol{\kappa}_\mathbf{Z} = \Delta g_{1,Z} - t_w^2\Delta\kappa_\gamma\,, \qquad \boldsymbol{\lambda}_\mathbf{Z} = \boldsymbol{\lambda}_\gamma = -\mathbf{c_{3W}}\,.$$

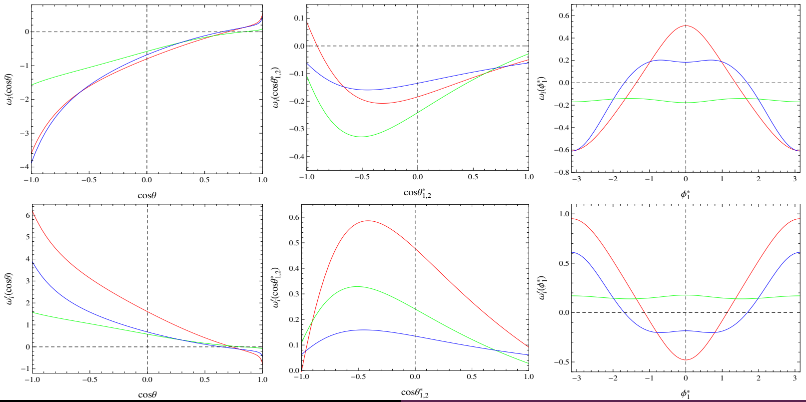
TGC – Five-fold Differential Distributions

1507.02238

$$\frac{d\sigma(e^+e^- \to W^+W^- \to f_1\bar{f}_2\bar{f}_3 f_4)}{d\cos\theta\, d\cos\theta_1^*\, d\phi_1^*\, d\cos\theta_2^*\, d\phi_2^*} = \mathrm{BR}\frac{\beta}{32\pi s}\left(\frac{3}{8\pi}\right)^2 \sum_{\lambda\tau_1\tau_1'\tau_2\tau_2'} F^{(\lambda)}_{\tau_1\tau_2} F^{(\lambda)*}_{\tau_1'\tau_2'} \times D_{\tau_1\tau_1'}(\theta_1^*, \phi_1^*) D_{\tau_2\tau_2'}(\pi - \theta_2^*, \pi + \phi_2^*)$$

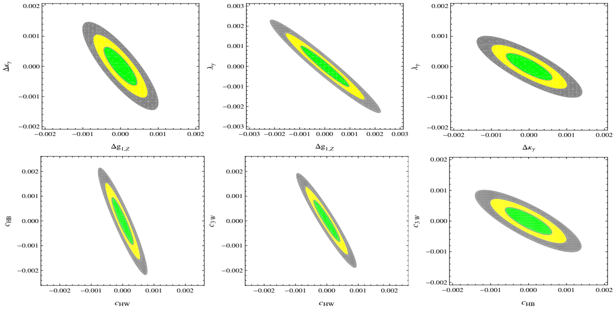
$$\frac{d\sigma}{d\Omega_k} = \frac{d\sigma_0}{d\Omega_k}\left[1 + \omega_i(\Omega_i)\alpha_i + \omega_{ij}(\Omega_k)\alpha_i\alpha_j\right] ,$$

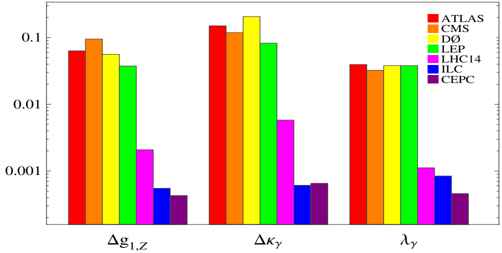
where $\Omega_k = \cos\theta, \cos\theta^*_{1,2}, \phi^*_{1,2}$, $\alpha_i = (\Delta g_{1,Z}, \Delta\kappa_\gamma, \lambda_\gamma)$ or $\alpha_i = (c_{HW}, c_{HB}, c_{3W})$



Triple Gauge Coupling

1507.02238





Angular Observable in Higgsstrahlung

1512.06877

CP violating dim-6 operators

$$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi) \qquad \mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$$

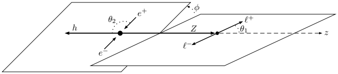
$$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi) \qquad \mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}^{(1)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell) \qquad \mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}^{(3)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell) \qquad \mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$$

$$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e) \qquad \mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}_{4L} = (\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell) \qquad \mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$$



$$\frac{d\sigma}{d\phi\, d\cos\theta_1\, d\cos\theta_2}$$

Observables

$$\sigma(s)$$

$$\mathcal{A}_{\theta_1} \equiv \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\, \mathrm{sgn}(\cos(2\theta_1))\,\frac{d\sigma}{d\cos\theta_1}$$

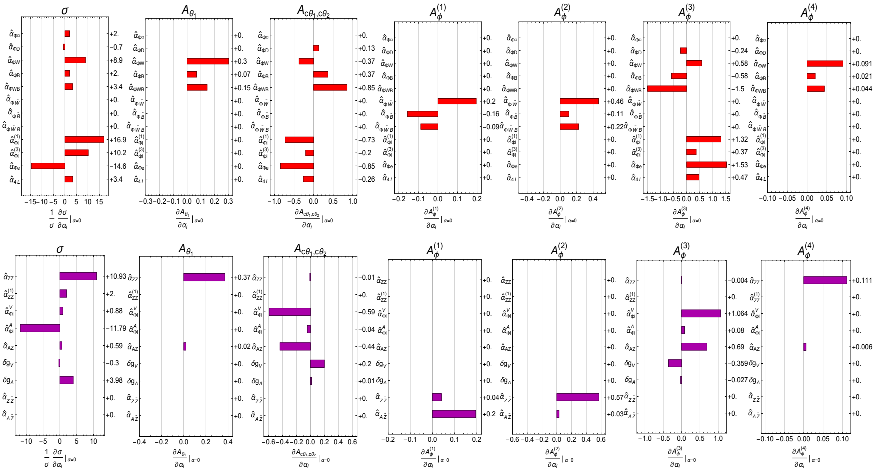
$$\mathcal{A}^{(1)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin\phi)\,\frac{d\sigma}{d\phi} \qquad \mathcal{A}^{(2)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin(2\phi))\,\frac{d\sigma}{d\phi}$$

$$\mathcal{A}^{(3)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos\phi) \qquad \mathcal{A}^{(4)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos(2\phi))\,\frac{d\sigma}{d\phi}$$

$$\mathcal{A}_{c\theta_1,c\theta_2} \equiv \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\,\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}$$

Angular Observable in Higgsstrahlung

1512.06877



	$\widehat{\alpha}_{ZZ}$	$\widehat{\alpha}_{ZZ}^{(1)}$	$\widehat{\alpha}_{\Phi\ell}^{V}$	$\widehat{\alpha}_{\Phi\ell}^{A}$	$\widehat{\alpha}_{AZ}$	δg_V	δg_A	$\widehat{\alpha}_{Z\widetilde{Z}}$	$\widehat{\alpha}_{A\widetilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	∞	∞
angles	0.016	∞	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	**0.0047**	0.00059	**0.0070**	**0.014**	0.0018	**0.012**	**0.036**

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** $\Rightarrow$ *Pave Road for SPPC*
    - Probe indirectly to **10 TeV** (**40 TeV** for $\mathcal{O}_g$) from **EWPO+HO**
    - **35 TeV @ Z-Pole**
  - **Differential Distributions**
    - **Θ Angle** in $h \to \tau^+\tau^- \to \rho^+\rho^-\nu\bar{\nu} \to \pi^+\pi^0\pi^-\pi^0\nu\bar{\nu} \Rightarrow$ CP $\sim$ **2.5°**
    - **Five-fold distributions** in TGC $\Rightarrow$ Error $\sim \mathbf{10^{-4}}$
    - **Angular observable** in Higgsstrahlung $\Rightarrow$ CP violating dim-6 $\mathcal{O}$

Thank You!

Scheme-Independent Analysis

1603.03385

EW Parameters:

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

which can be denoted as

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

Observables:

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

Analytical Fit:

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

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.

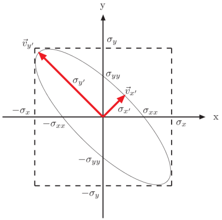
$$\mathbb{P}(\delta\kappa_1 \cdots \hat{\delta\kappa_k} \cdots \delta\kappa_n) = \int_{-\infty}^{+\infty} \mathbb{P}(\delta\kappa_1 \cdots \delta\kappa_k \cdots \delta\kappa_n)\, \mathbf{d}\boldsymbol{\delta\kappa_k}\,.$$

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.

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



Uncertainty

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

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%
```