Higgs Boson: a Window to New Physics

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LHC New Discovery →
High Energy Physics at <u>Turning Point</u>

- **Run-1 Higgs Discovery h(125GeV) in 2012**
- **Run-2 New Particle Discovery in 2016 ??**

These will lead to

New Set of Key Physics Questions
for Future Colliders to answer!!

& Interface with Cosmology & Quantum Gravity

Making of the Standard Model

$$\mathcal{L} =$$
$$-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{\ell}_i i\not{D}\ell_i$$
$$+\left(Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i\ell_j H + c.c.\right)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

SM Structure seems complete, but ....

Recall: situation around 1900 –

Newton Mechanics was Complete → End of Physics !?

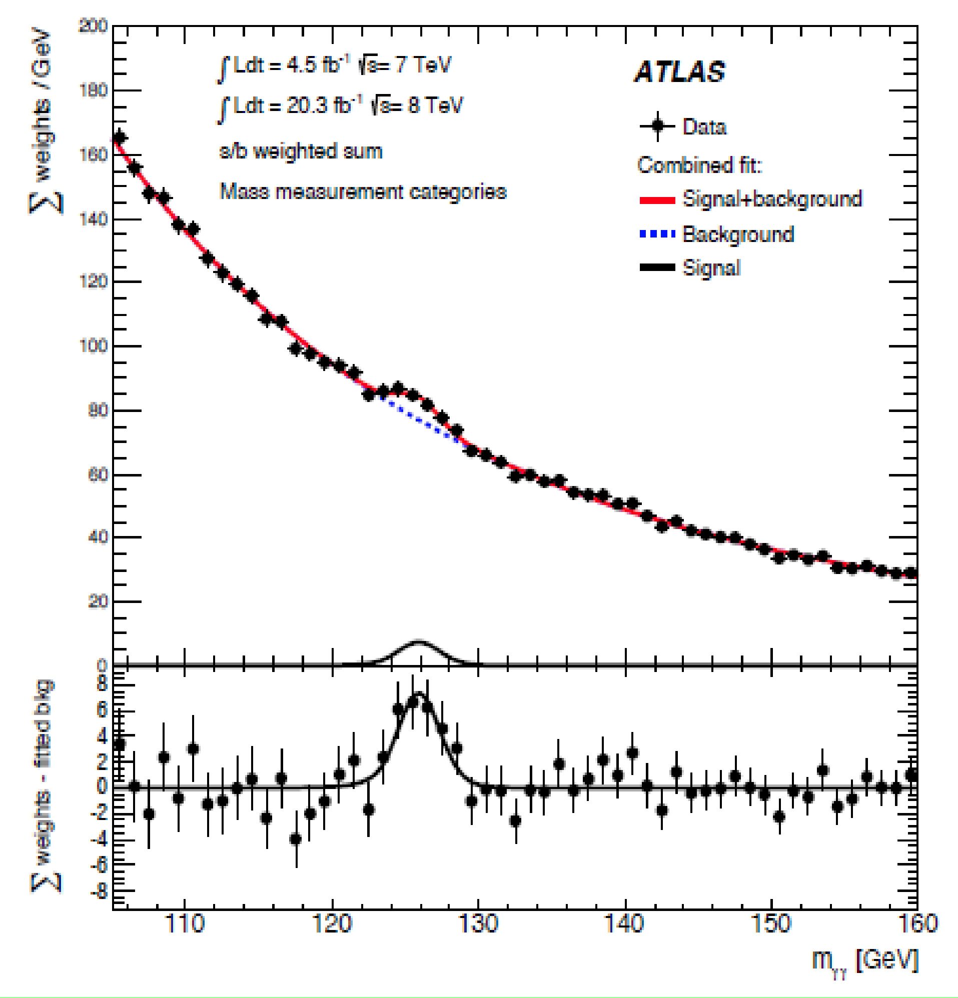
→ No !

Now, 4 Years after 2012:

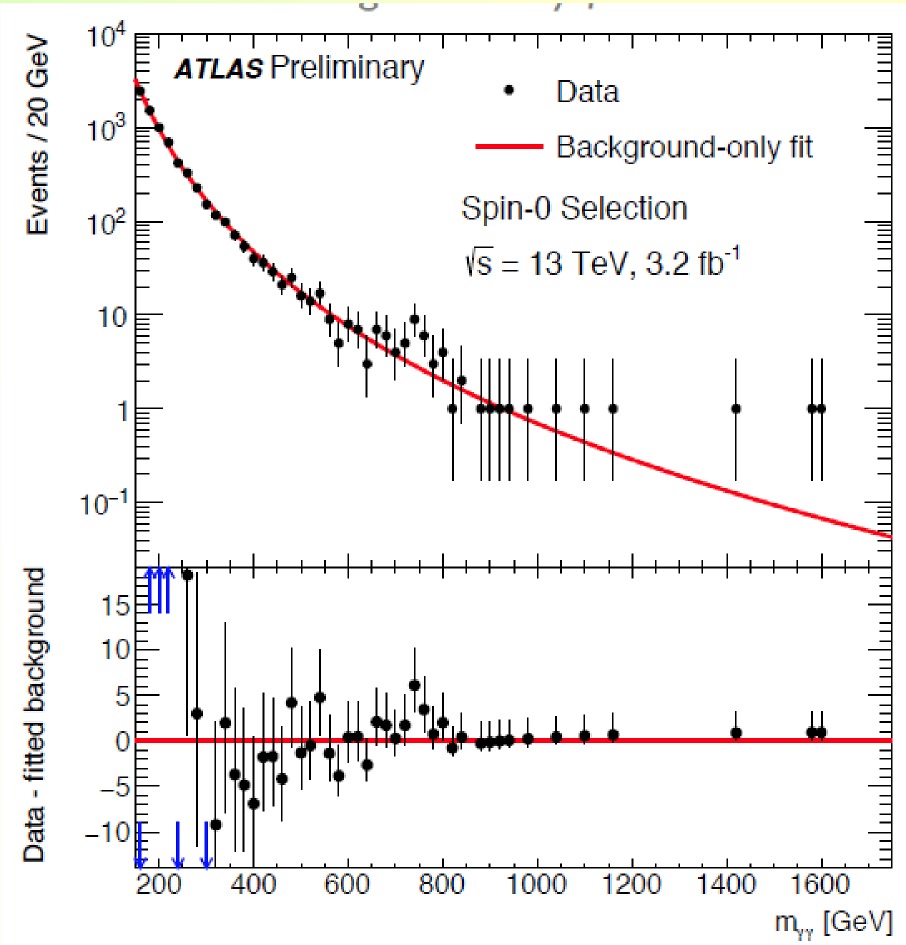
New Physics Beyond SM ???

- h(125GeV) Discovery at LHC Run-1.
- X(750GeV) or Any New State at LHC Run-2 ?!

✓ H (125GeV)



X(750GeV)?? or Any New State ?!



2878 events ($m_{\gamma\gamma}$ > 200 GeV) a Window to New Physics ??

Spin-0 Higgs Boson Itself

is

New Physics !!!

Representation of Lorentz Group

- **Isomorphic Lorentz Group:** $O(3,1) \cong SU(2) \otimes SU(2)$
- **Group Generators of** $SU(2) \otimes SU(2)$ **:**
- **Lorentz Algebra:**

$$\begin{cases} [A^i, A^j] = i\epsilon^{ijk} A^k \\ [B^i, B^j] = i\epsilon^{ijk} B^k \\ [A^i, B^j] = 0 \end{cases} \qquad \begin{cases} A^i = \frac{1}{2}(J^i + iK^i) \\ B^i = \frac{1}{2}(J^i - iK^i) \end{cases}$$

- **Irreducible Representation (j) of SU(2) (j=0, ½, 1, 3/2…)**
  → Representations of Lorentz Group: (j, j′).
  (½ , 0), (0, ½) → Fermions; (½ , ½) → Gauge Bosons.

- **The Simplest Lorentz representation is Scalar Representation:**

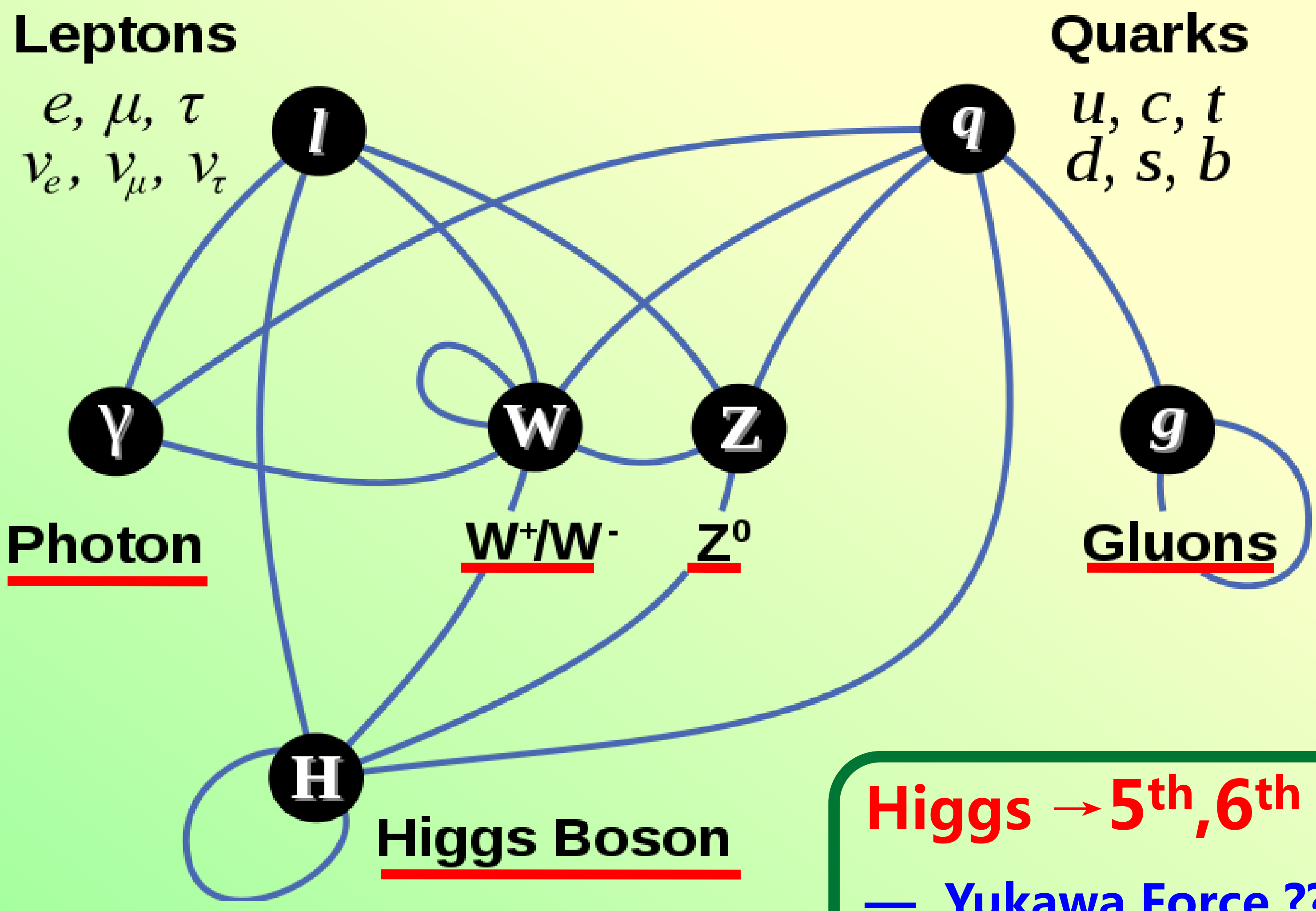
(0, 0)

Special Relativity predicted possible Scalar Particle (Higgs Boson) !!!

Spin-0 Higgs Boson Itself is New Physics:

- **Mass Puzzle:**
  - W,Z Masses (EWSB)
  - Fermion Masses (Quark/Lepton/Neutrino) ?
  - Higgs Boson Mass: Naturalness ?
    Higgs Self-interactions ?
- **Vacuum Puzzle:**
  - Vacuum Stability ?
  - Vacuum Energy (Dark Energy) ?
- **Inflation Puzzle:** – Higgs Boson as Inflaton ?
- **Dark Matter Puzzle:** – Higgs Portal ?
- **Missing Antimatter Puzzle:**
  - Baryogenesis, Leptogenesis, … ?

Fundamental Forces vs Higgs Boson



Higgs → 5th, 6th Forces:

— Yukawa Force ??

— Higgs Self-Interaction ??

3 Types of Fundamental Forces in SM Itself

- **1. Gauge Forces： mediated by Spin-1 Vector Boson.**
- **2. Yukawa Forces： mediated by Spin-0 Higgs Boson.**
- **3. Higgs Self-Interaction Force： h^3 & h^4 forces,（concerns spontaneous EWSB and generating Higgs mass itself）.**

- **Type-2 & Type-3 are two New Fundamental Forces, *Solely due to Spin-0 Higgs,* which were never directly probed before, despite they already exist in SM !!!**

3 Types of Fundamental Forces in SM Itself

- 1. Gauge Forces： mediated by Spin-1 Vector Boson.
- 2. Yukawa Forces： mediated by Spin-0 Higgs Boson.
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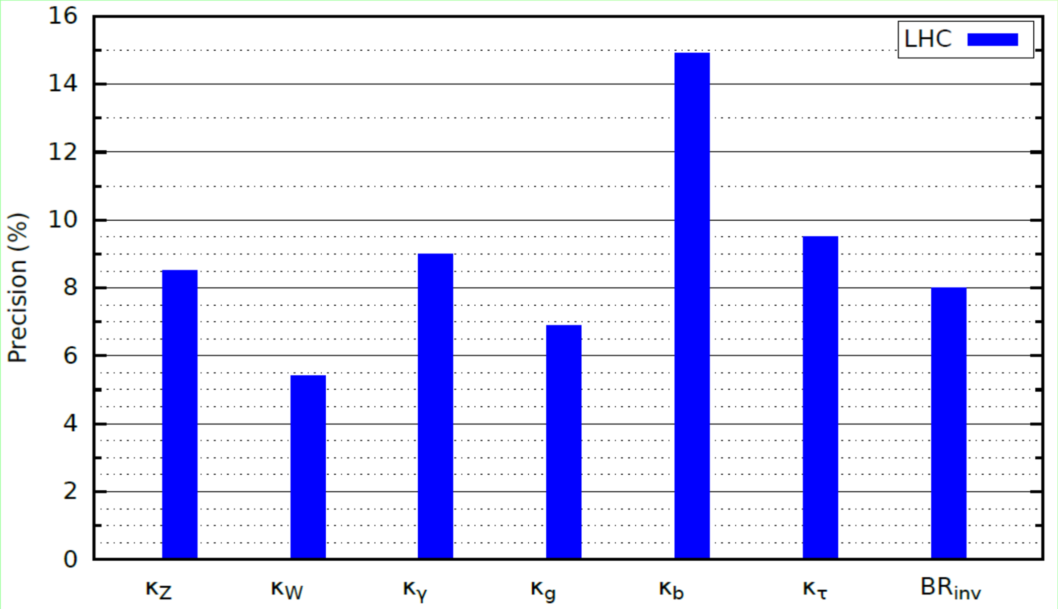
- In SM, Only Higgs can have Self-Interactions (involving exactly the same particle, h^3 & h^4), but not all other fundamental particles (as forbidden by their spin & charge).
- Spin-0 Higgs Boson is Unique in many ways, but all its associated forces are not yet directly tested, especially, the New Type-2 and Type-3 forces mediated by Higgs Itself .

3 Fundamental Forces inside SM Itself

Status:

- LEP/Tevatron/LHC only have good tests on Gauge Forces .
- LHC only has weak sensitivity to Yukawa couplings of
  h-τ-τ, h-b-b, h-t-t at order of 10-20% .
- LHC cannot probe Most Other Yukawa Couplings !
- LHC can hardly probe Higgs Self-Interaction !
- LHC cannot establish h(125GeV) as God Particle !



LHC(14TeV, 300/fb)
M. E. Peskin, Snowmass Study, arxiv:1312.4974

Higgs 125GeV and Beyond

Conclusion-1: **Higgs is not only a New Particle, but also New Forces !!!**

Even *within SM Forces*, strongly motivated to quantitatively test Type-2 & Type-3 New Forces (Higgs Yukawa Forces and Self-Interaction-Forces) mediated by Higgs Boson.

Conclusion-2: **Any New Discovery of Run-2 will require further Precision Tests.**

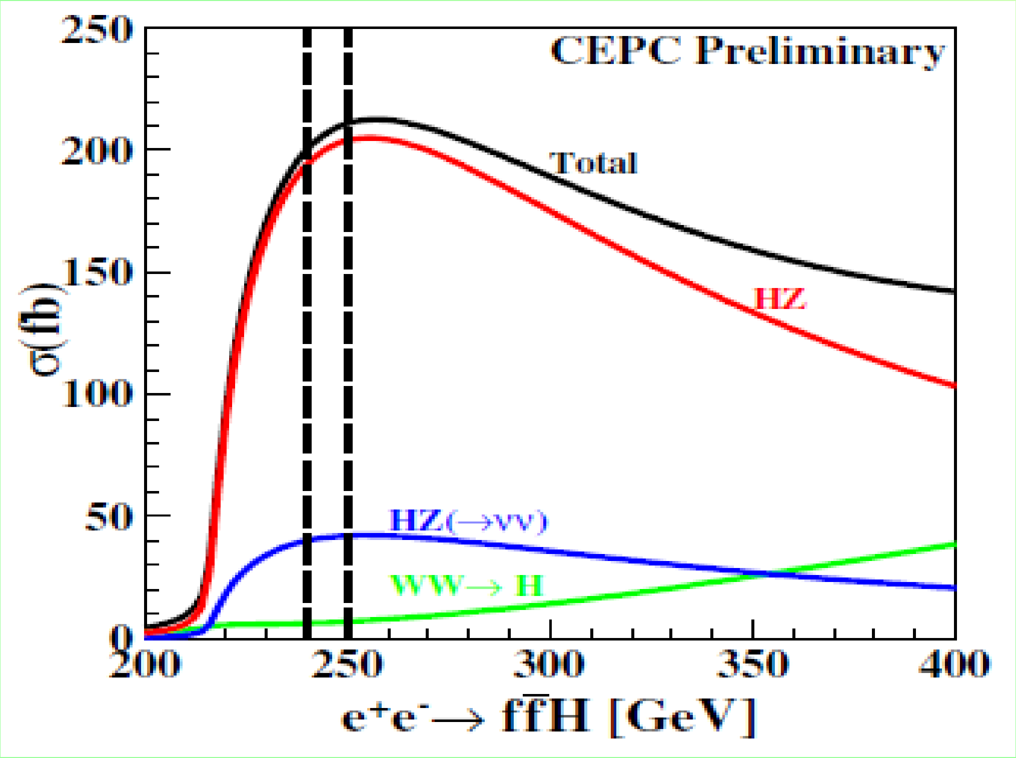
→ **This requires to Go Beyond the LHC !**

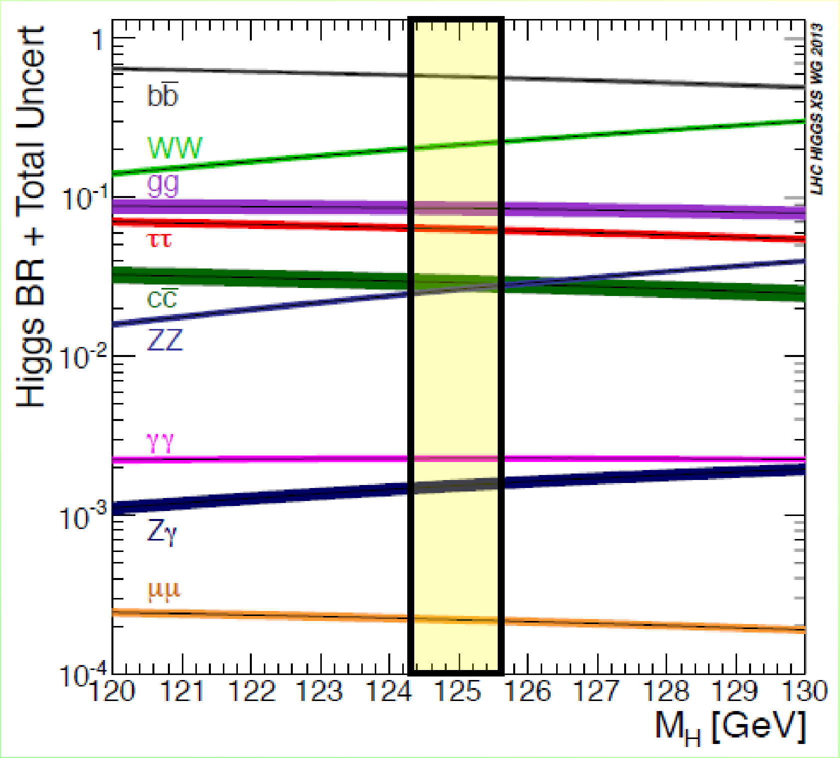
→ **High Energy Circular Colliders: CEPC/SPPC & FCC**
ee (90-250GeV, 350GeV)
pp(50-100TeV)

Higgs Factory: CEPC (240-250GeV)

- LHC-8 tells us: h(125) is SM-like. ⟶ *Precision Test is Crucial !*
- CEPC produces h(125) mainly via ee → hZ and ee → ννh .
- CEPC makes indirect probe to New Physics !

CEPC designed: 5/ab for 2 detectors in10y. ⟶ 10^6 Higgs Bosons !!





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%

latest 1σ uncertainty
Software WS, March 26

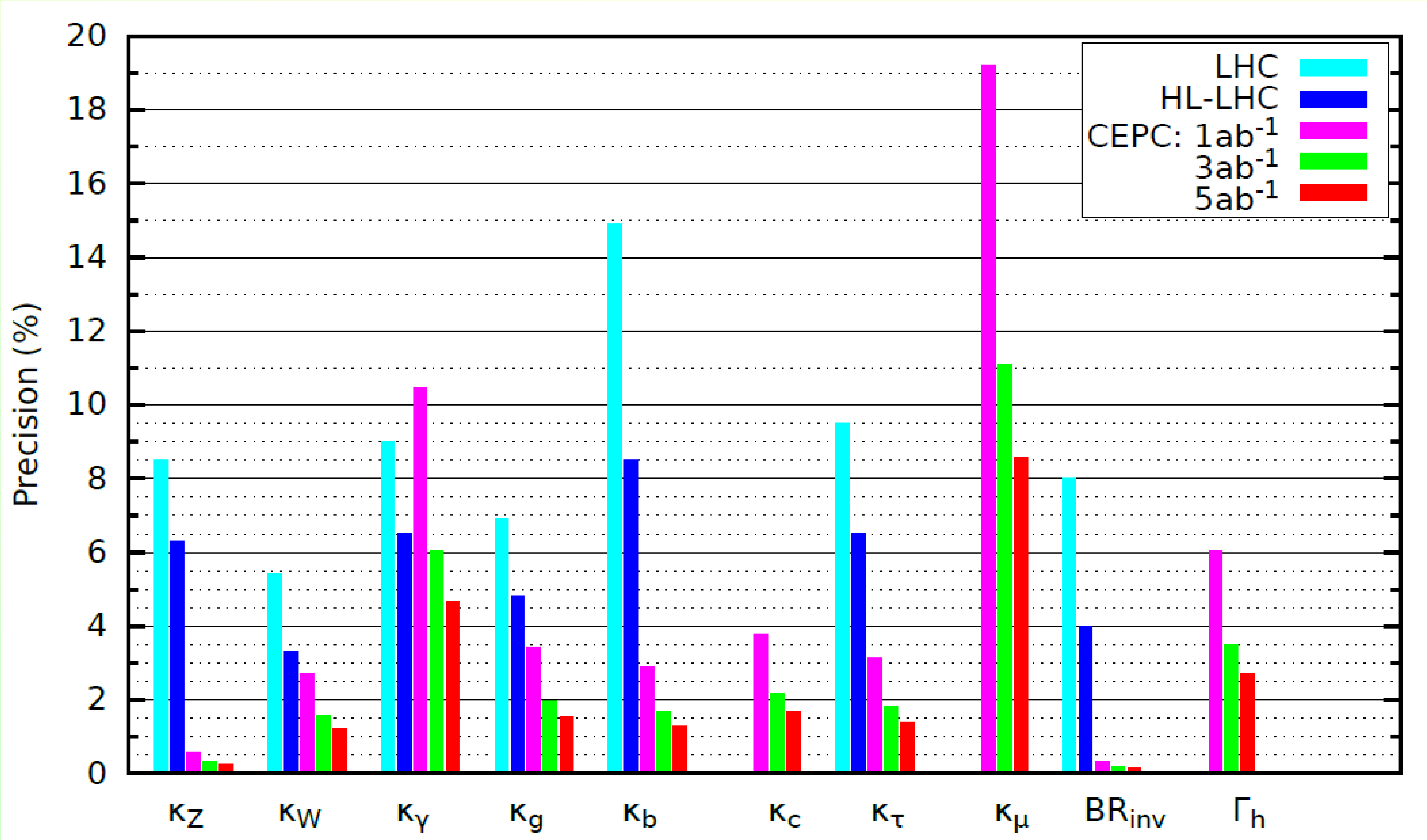
SM Predictions

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

Effective Higgs Couplings: Gauge & Yukawa

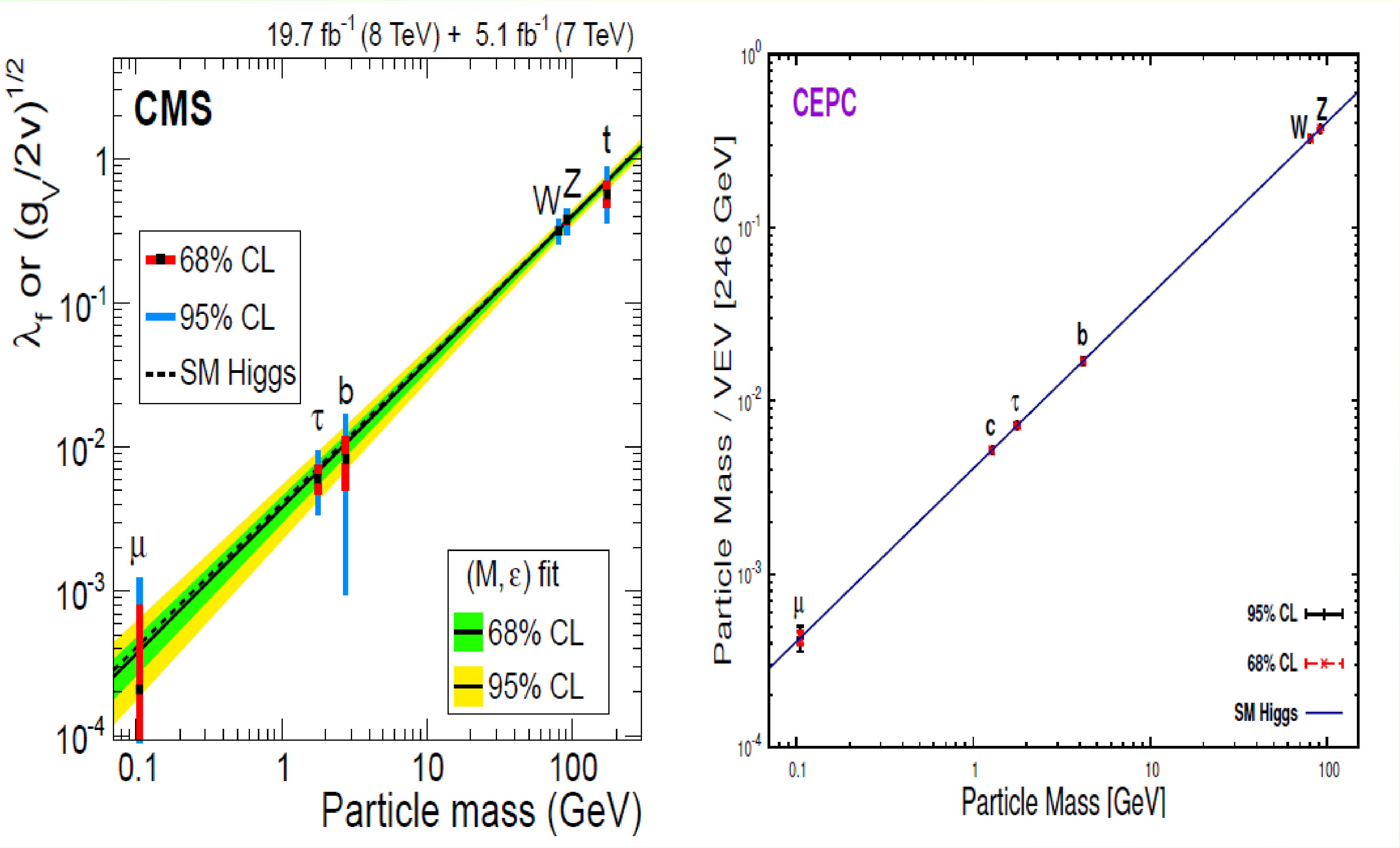
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H$$

Testing Higgs Coupling: CEPC vs LHC



Ge, He, Xiao, arXiv:1603.03385

Higgs Coupling Precision: LHC vs CEPC



arXiv:1603.03385

CEPC Sensitivity to Higgs Coupling

CEPC (250GeV, $5ab^{-1}$) vs LHC (14TeV, $300fb^{-1}$), HL-LHC ($3ab^{-1}$)

Precision (%)	Analytic	χ^2 fit	LHC	HL-LHC
κ_Z	0.254	0.254	8.5	6.3
κ_W	1.22	1.22	5.4	3.3
κ_γ	4.67	4.67	9.0	6.5
κ_g	1.52	1.52	6.9	4.8
κ_b	1.29	1.29	14.9	8.5
κ_c	1.69	1.69	–	–
κ_τ	1.40	1.40	9.5	6.5
κ_μ	–	8.59	–	–
Br(inv)	0.138	0.138	8.0	4.0
Γ_h	2.8	2.8	–	–

— CEPC Higgs WG Report, Ge and He

Indirect Probe of Higgs related New Physics

All can be formulated by:

Model-Independent Effective Operators

@ Dimension-6

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2} \mathcal{O}_{6,i}$$

(M = Λ)

Higgs	EW Gauge Bosons	Fermions
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H \rvert^2)^2$	$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{LL}^{(3)} = (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
	$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \Psi_L)$
Gluon	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_g = g_s^2 \lvert H \rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	

Effective Operators & Sizes of New Physics

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2} \mathcal{O}_{6,i}$$

(M = Λ)

Model	$\Delta\kappa_V$	$\Delta\kappa_t$	$\Delta\kappa_b(\Delta\kappa_\tau)$
MSSM	$\sim -0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4 \cot^2\beta$	$-\mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$	$\sim \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$
Composite	$-3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$	$-(3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$	$-(3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$

-- Higgs WG Report

Existing EWPO & Future HO

Observables: EWPO (PDG14) + HO (preCDR)

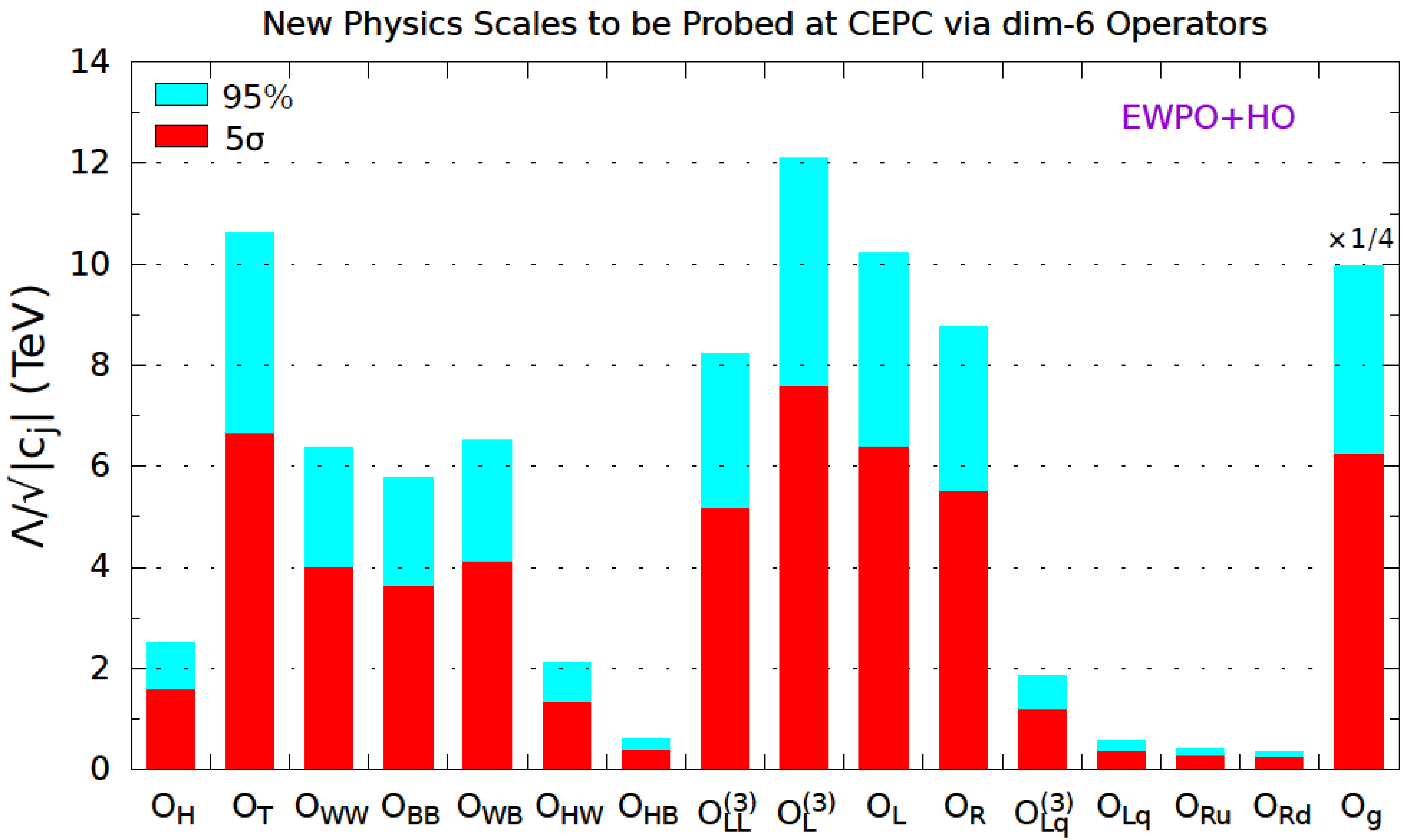
Observables	Central Value	Relative Error	SM Prediction
α	$7.2973525698 \times 10^{-3}$	3.29×10^{-10}	–
G_F	$1.1663787 \times 10^{-5}\text{GeV}^{-2}$	5.14×10^{-7}	–
M_Z	91.1876GeV	2.3×10^{-5}	–
M_W	80.385GeV	1.87×10^{-4}	–
$\sigma[Zh]$	–	0.51%	–
$\sigma[\nu\bar{\nu}h]$	–	2.86%	–
$\sigma[\nu\bar{\nu}h]_{350\text{GeV}}$	–	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

Ge, He, Xiao, 1603.03385

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



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

Ge, He, Xiao, arXiv:1603.03385

$\frac{\Lambda}{\sqrt{c_i}}$[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

- **Note: The CEPC Z-pole & W-pair simulation is preliminary. BUT, the detail does not really matter for above demonstrating the matter of principle for probing New Physics: including vs excluding CEPC measurements of M_Z, M_W .**

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].

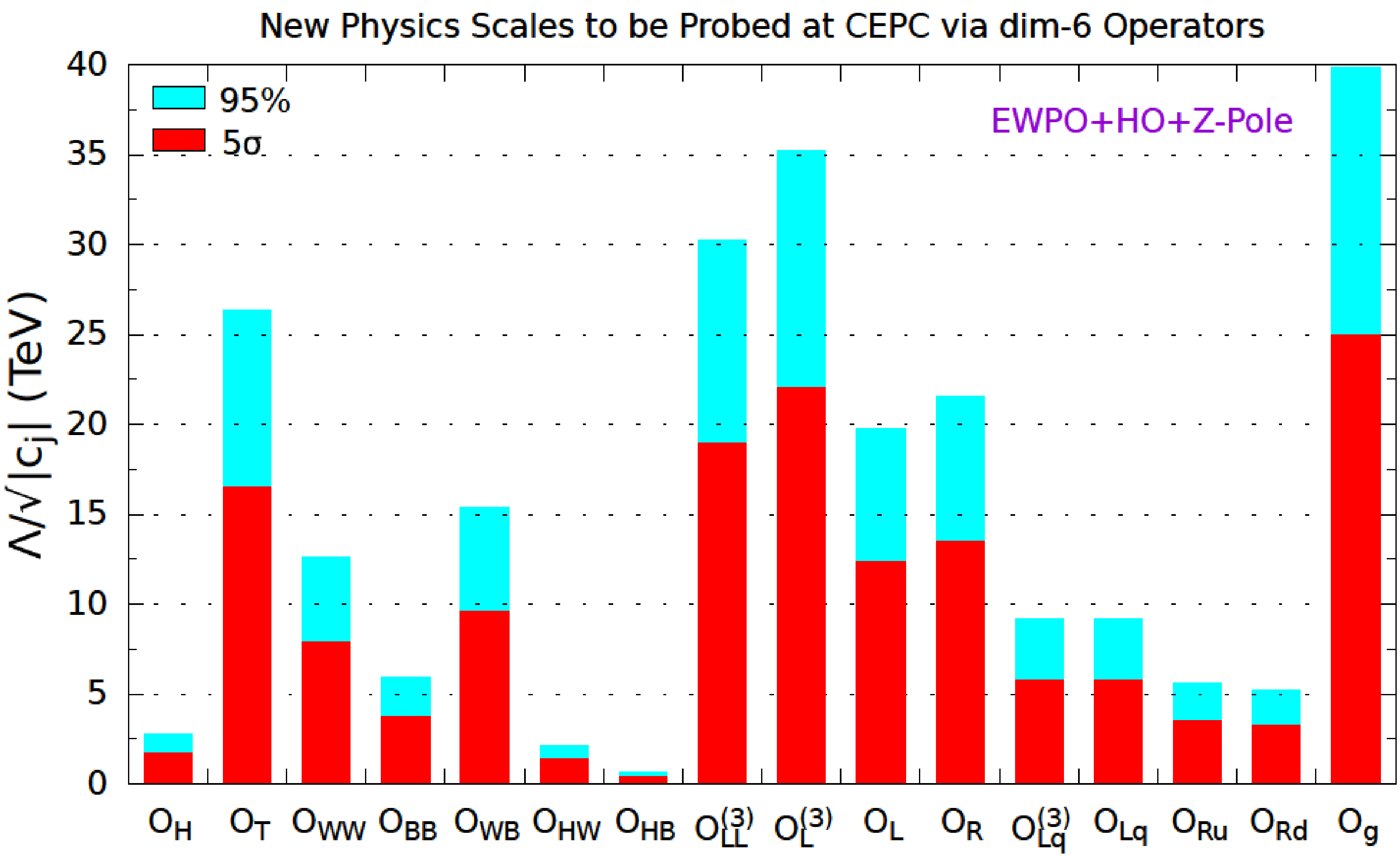
Ge, He, Xiao, 1603.03385

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

- **Extra Factor-2 Improvements from more Z-pole observales!**

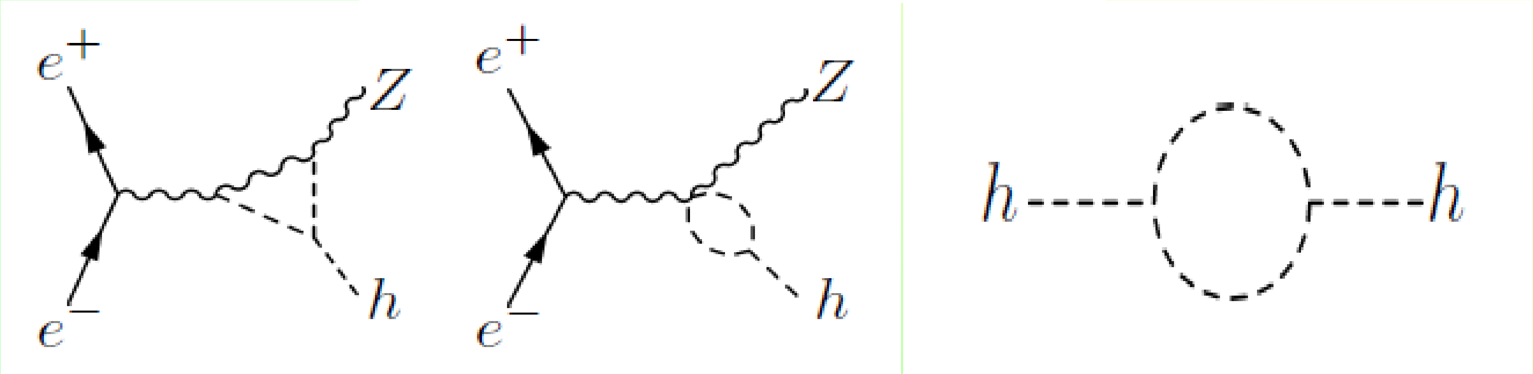
Sensitivity from EWPO+HO+Z-Pole



Ge, He, Xiao, 1603.03385

CEPC Probe of h^3 Coupling

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



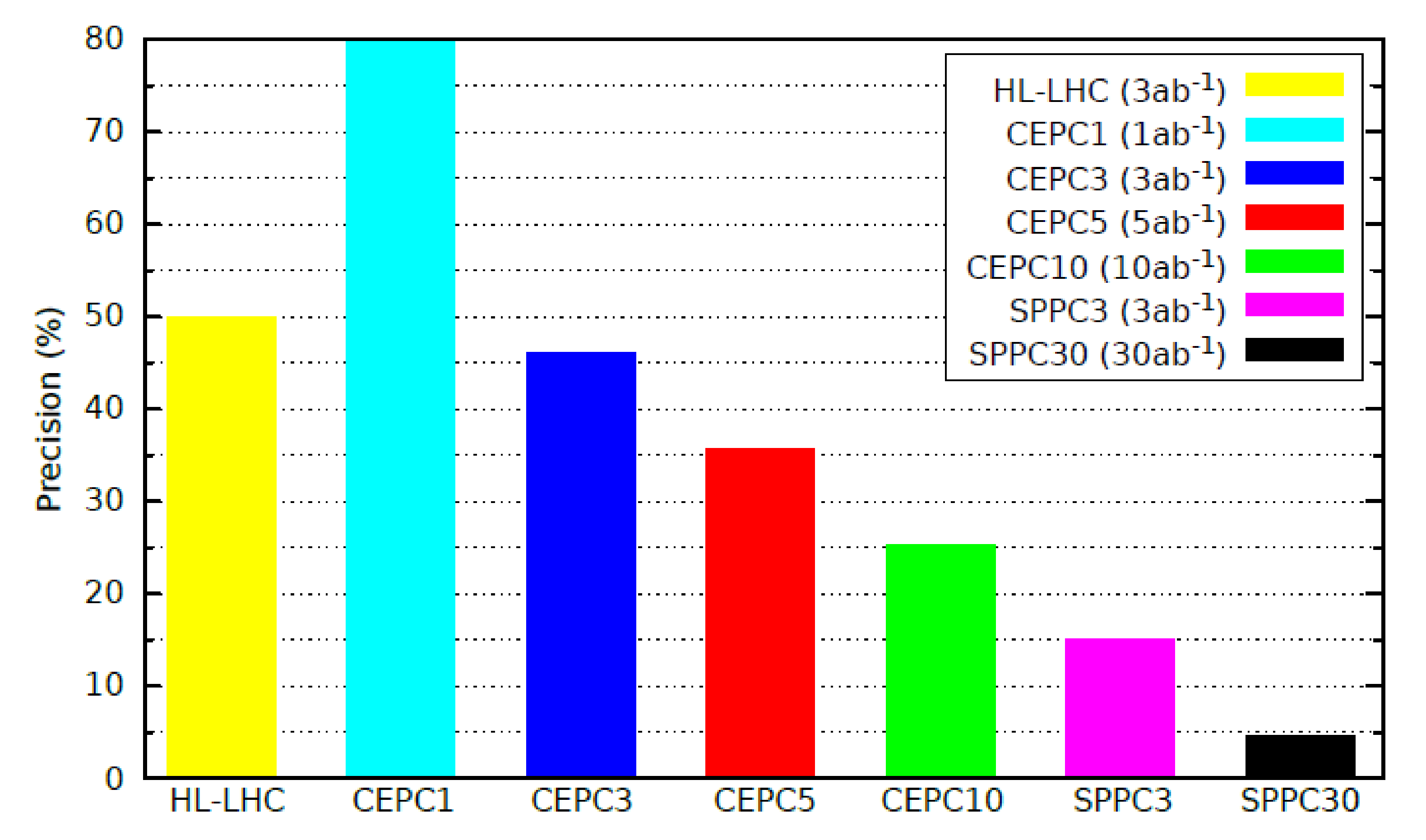
$$\delta_\sigma = \frac{\delta\sigma}{\sigma} = \frac{\sigma_{\delta_{h3}\neq 0}(e^+e^-\to hZ)}{\sigma_{\rm sm}(e^+e^-\to hZ)} - 1 = 2\,\delta\kappa_Z + 0.014\,\delta\kappa_{h3}$$

M. McCullough, arXiv:1312.3322

- **Recall:** **HL-LHC probes h^3 to 50%. ILC500 probes h^3 to 83%.**

Sensitivity to Higgs Self-Coupling h^3

- **Comparison: h^3 at CEPC(1, 3, 5/ab) and SPPC(3, 30/ab), vs HL-LHC (3/ab):** $|\lambda_{hhh}/\lambda_{hhh}^{sm} - 1|$



-- Higgs WG Rept

Summary of CEPC Precision Tests:

- **CEPC produces 10^6 Higgs Bosons at 250GeV (5/ab).**
  Higgs Gauge & Yukawa Couplings ~ O(1%)
  Higgs Self-coupling ~ 30%

- **CEPC Indirect Probe of New Physics Scales:**
  up to 10TeV (40TeV for O_g) from EWPO + HO.
  up to 35TeV after including Z-pole (CEPC).

- **CEPC can sensitively probe Exotic Higgs Decays**

Probing Higgs Self-Interaction

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2,$$

$$\rightarrow \quad V_{\text{int}} = \frac{\lambda_3}{3!} h^3 + \frac{\lambda_4}{4!} h^4,$$

SM: $\lambda_3 = 6\lambda v = 3M_h^2/v$ and $\lambda_4 = 6\lambda = 3M_h^2/v^2$.

- **New Physics could modify h^3 & h^4 couplings only via dim-6 operators!**

$$\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H), \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H),$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3, \qquad \mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H).$$

$$\mathcal{O}_{\Phi,f} = (H^\dagger H)\overline{L} H f_R + \text{h.c.},$$

Under SU(2)c and using EOM, only 2 modify h^3/h^4 vertex:

$$\rightarrow \quad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H), \qquad \mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3.$$

Probing Higgs Self-Interaction h^3

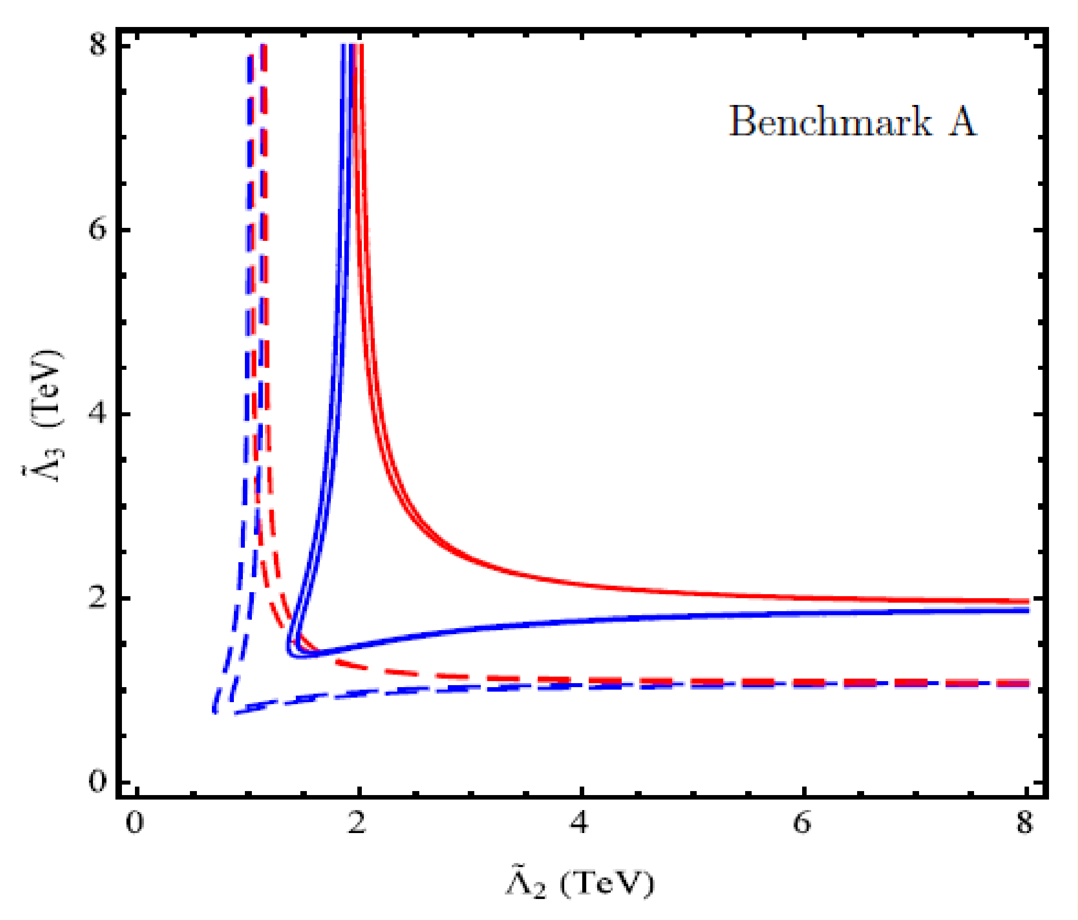
Benchmark A : $(\hat{r}, \hat{x})_{\rm sm} = (0, 0)$;

$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n, \qquad \tilde{\Lambda}_j \equiv \frac{\Lambda}{\sqrt{|f_{\Phi,j}|}}.$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H),$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3.$$

$$x_j \equiv \frac{f_{\Phi,j} v^2}{\Lambda^2} \qquad \hat{r} \equiv -x_3\zeta^2 \frac{2v^2}{3M_h^2}, \qquad \hat{x} \equiv x_2\zeta^2.$$

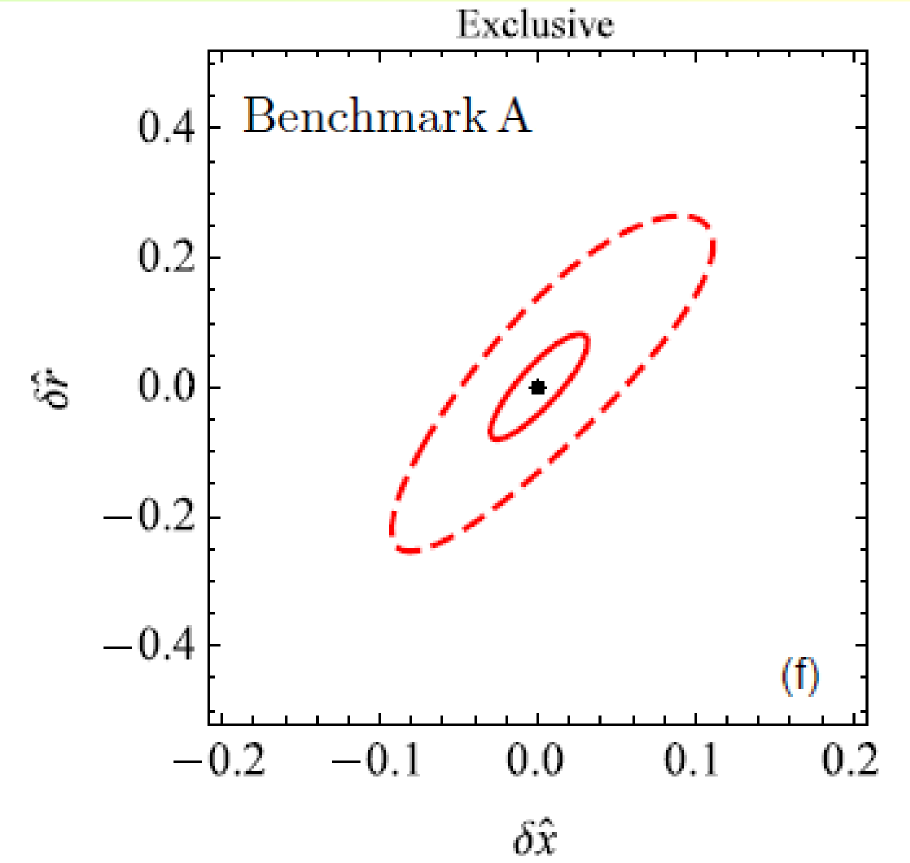


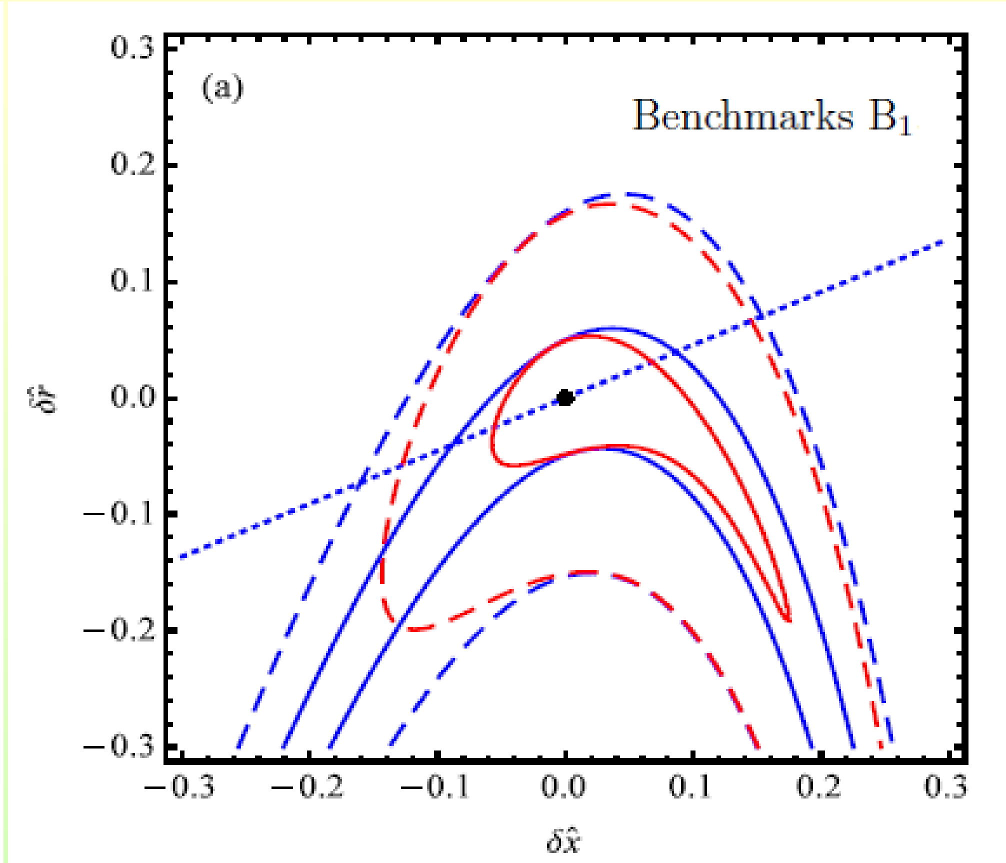
pp(100TeV) with (3, 30)/ab:

pp ⟶ hh ⟶ bbγγ

HJH, Ren, Yao, arXiv:1506.03302, PRD(2015)

Probing Higgs Self-Interaction h^3





$$gg \to hh \to b\bar{b}\gamma\gamma$$

$$\text{Benchmark A}: \quad (\widehat{r},\, \widehat{x})_{\rm sm} = (0,\, 0)\,;$$

$$\text{Benchmarks } B_1,\, B_2: \quad (\widehat{r},\, \widehat{x}) = (0,\, 0.2),\, (0,\, 0.5)\,;$$

With 3/ab (30/ab) Luminosity:
probe r to 13% (4.2%) precision .
probe x to 5% (1.6%) precision.

HJH, Ren, Yao, arXiv:1506.03302, PRD(2015)

Probing Higgs Self-Interaction Hhh

$pp \to H \to hh \to WW^{*}\gamma\gamma$ ($WW^{*} \to \ell\bar{\nu}\bar{\ell}\nu$, $q\bar{q}'\ell\nu$)

$pp \to q\bar{q}'\ell\nu\gamma\gamma$	σ_{total}	Selection+Basic Cuts	$M_{\gamma\gamma}, M_{qq}, \not{E}_T$	Final Cuts
Signal (fb)	1.32	0.0891	0.0671	0.0533
BG[$qq\ell\nu\gamma\gamma$] (fb)	31.59	0.581	0.0291	0.00672
BG[$\ell\nu\gamma\gamma$] (fb)	143.3	0.0642	0.00454	0.000891
BG[Wh] (fb)	0.42	0.00509	0.00335	0.00139
BG[WWh] (fb)	0.0023	0.000210	0.000127	0.000057
BG[$t\bar{t}h$] (fb)	0.0148	0.00163	0.00111	0.000441
BG[hh] (fb)	0.00462	0.000291	0.000197	0.000155
BG[th] (fb)	0.0129	0.000479	0.000247	0.000104
BG[Total] (fb)	175.35	0.653	0.0386	0.0098
Significance(Z_0)	1.72	1.87	4.86	6.22

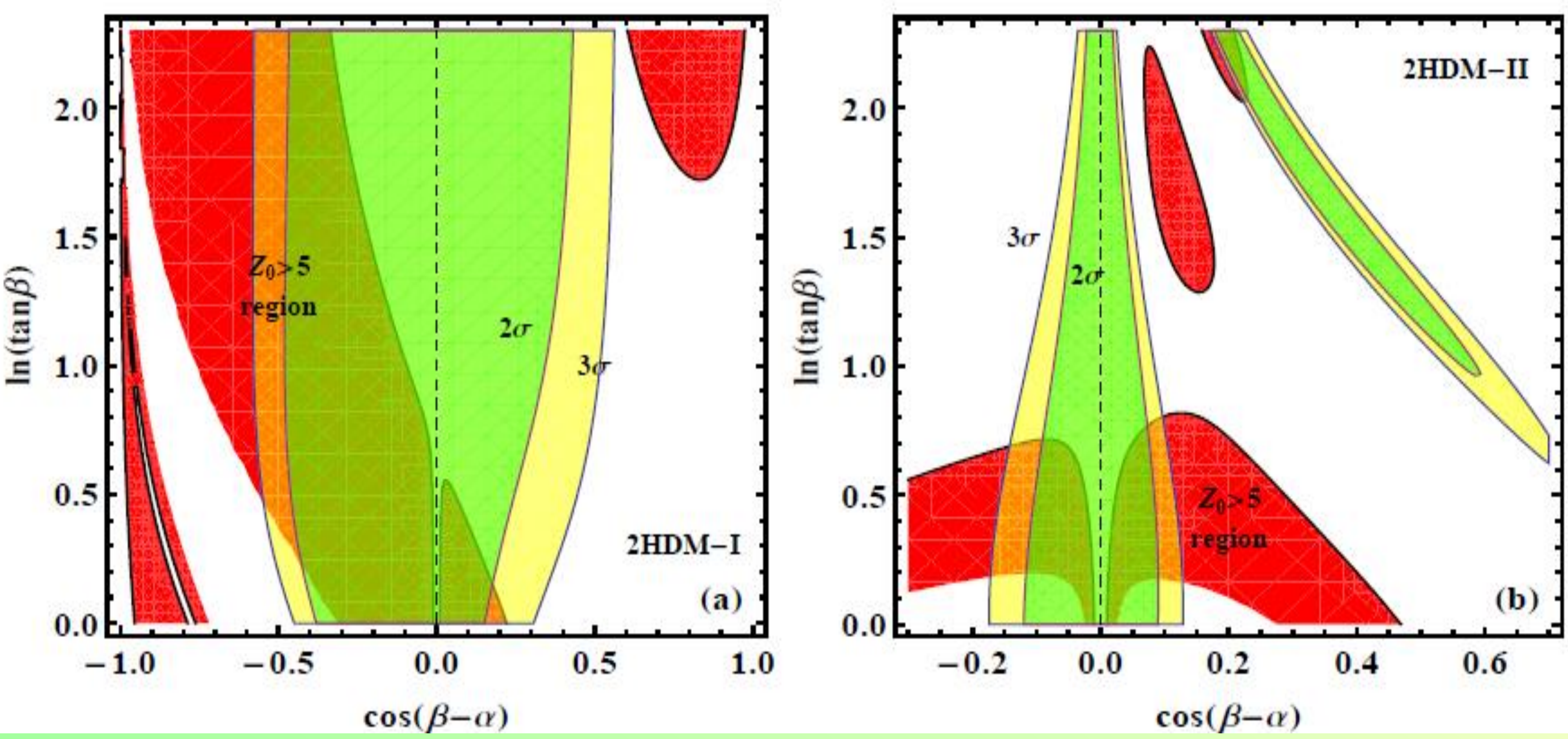
$M_H = (300,\ 400,\ 600)\,\text{GeV},$

$$\begin{aligned} Z_0(\text{combined}) &= \sqrt{Z_0^2(\ell\nu\ell\nu\gamma\gamma) + Z_0^2(q\bar{q}'\ell\nu\gamma\gamma)} \\ &\simeq (9.06,\ 7.41,\ 12.1)\,, \qquad \text{for } \mathcal{L} = (300,\ 300,\ 3000)\,\text{fb}^{-1}; \\ &\simeq (7.40,\ 6.05,\ 6.99)\,, \qquad \text{for } \mathcal{L} = (200,\ 200,\ 1000)\,\text{fb}^{-1}; \end{aligned}$$

Lv, Du, Fang, HJH, Zhang, arXiv:1507.02644, PLB(2015)

Probing Higgs Self-Interaction Hhh

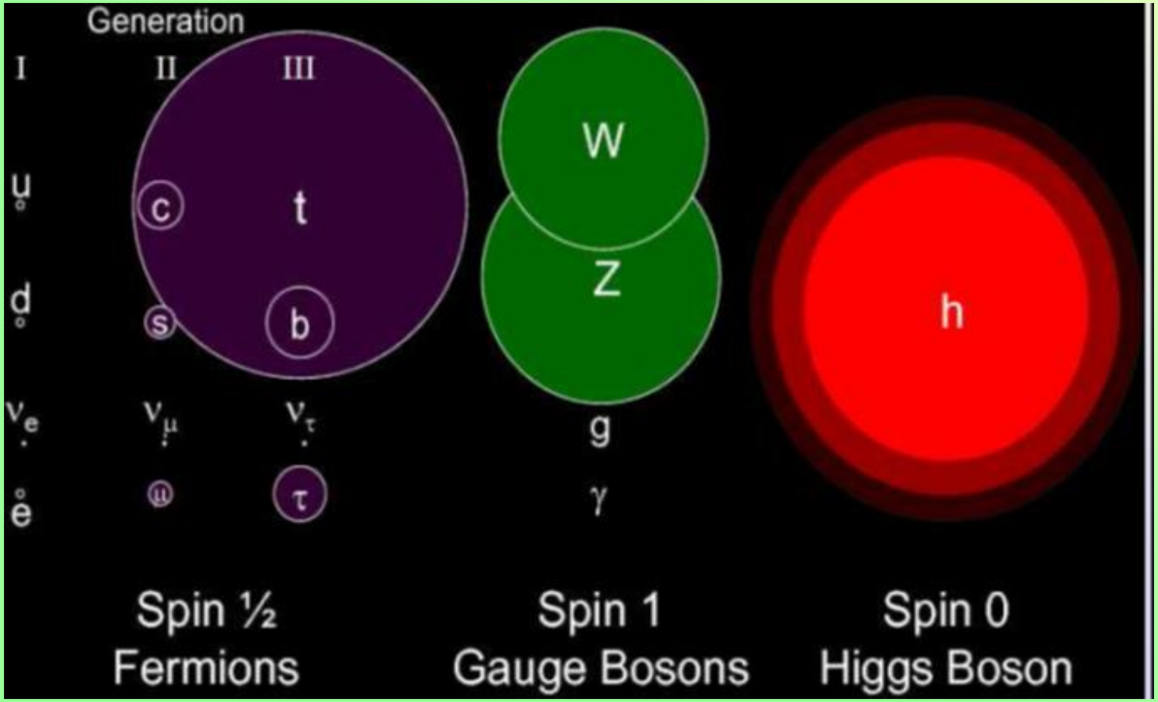
$pp \to H \to hh \to WW^*\gamma\gamma$ ($WW^* \to \ell\bar{\nu}\bar{\ell}\nu$, $q\bar{q}'\ell\nu$)



Lv, Du, Fang, HJH, Zhang, arXiv:1507.02644, PLB(2015)

SM *is* Incomplete: Mass Puzzle

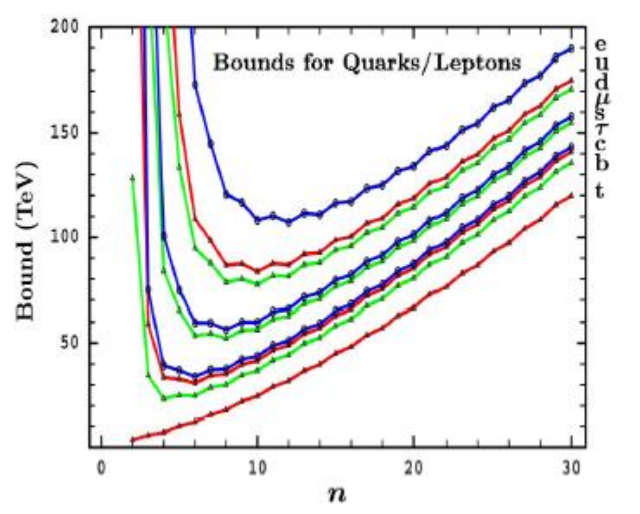
– Yukawa Force is Flavor-dependent & Unnatural !
  Why Quark/Lepton Masses differ so much at Tree Level?
– What are underlying Scales of Fermion Mass Generations ?
– Why is Higgs Mass itself Unnatural under Loop Corrections?

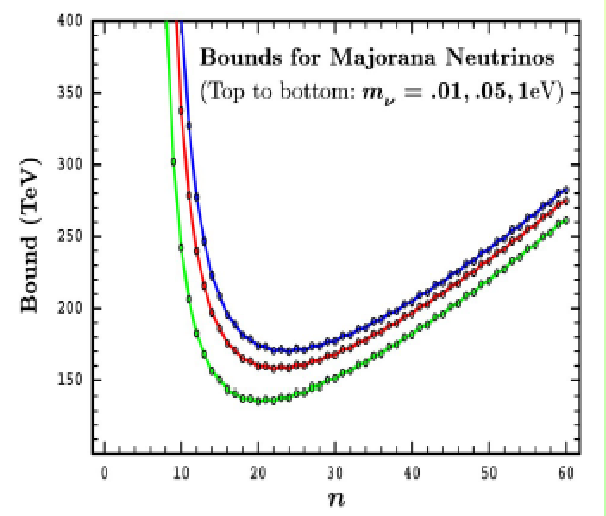


SM *is* Incomplete: Fermion Mass Puzzle

— **Yukawa Force is Flavor-dependent & Unnatural!**
Why Quark/Lepton Masses differ so much at Tree Level?

— **What are underlying Scales of Fermion Mass Generations?**





Upper Bounds on Scales of Fermion Mass Generations:

2nd+3rd Families: 3.5-56 TeV
1st Family: 77-107 TeV

— All these bounds Tied to O(3-100TeV) Scales !

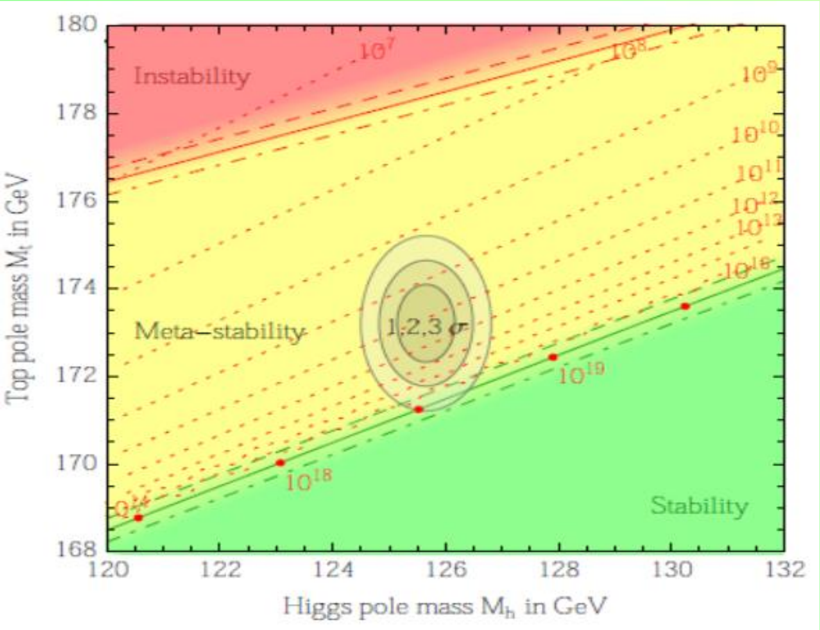
$\xi_1\xi_2$	V_LV_L	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$d\bar{d}$	$u\bar{u}$	$\tau^-\tau^+$	$\mu^-\mu^+$	e^-e^+	$\nu_L\nu_L$
Mass (GeV)	80.4	178	4.85	1.65	0.105	0.006	0.003	1.777	0.106	5.11×10^{-4}	5×10^{-11}
n_s	2	2	4	6	8	10	10	6	8	12	22
$E^{\star(\min)}_{2\to n}$ (TeV)	1.2	3.49	23.4	30.8	52.1	77.4	83.6	33.9	56.3	107	158
$E^{\star}_{2\to 2}$ (TeV)	1.2	3.49	128	377	6×10^3	10^5	2×10^5	606	10^4	2×10^6	1.1×10^{13}

Dicus and HJH,
PRL.94 (2005) 221802
PRD.71 (2005) 093009

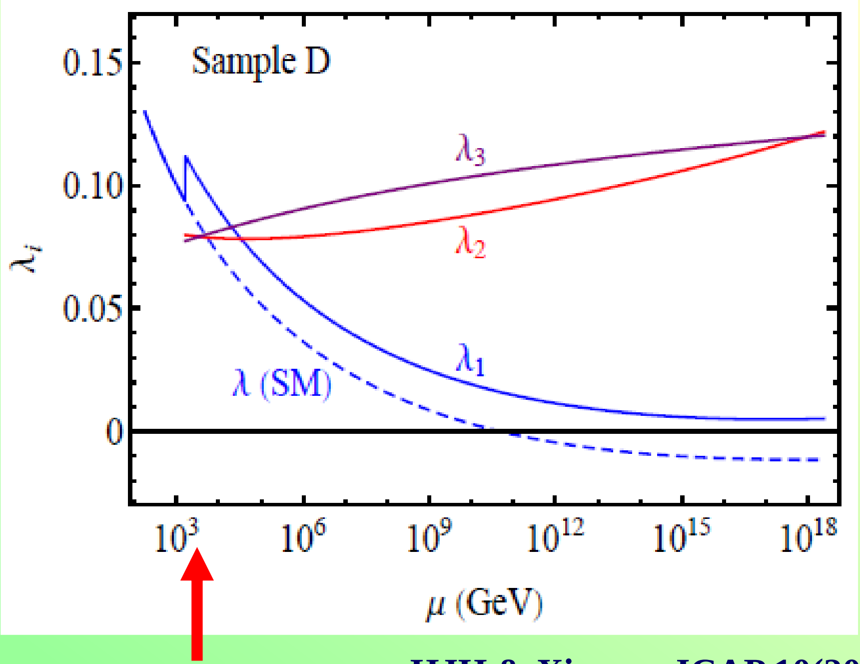
see: Nima's Overview in preCDR

SM *is* Incomplete: Vacuum, BA, DM, Inflation??

- **Vacuum Puzzle**: EW vacuum is **Unstable** at $10^{9\text{-}11}$ GeV !
- **Inflation Puzzle**: naive SM provides **no Inflaton** !
- **Puzzle of Missing Antimatter** (**Baryon Asymmetry**) ?
- **Dark Matter Puzzle** (80% of all Matter): SM has **no DM** !



Strumia et al, 1307.3536



HJH & Xianyu, JCAP 10(2014) 019.
arXiv:1602.01801

Eample: New Physics at TeV Scale:
New singlet scalar + New quarks of masses ~ O(TeV)

Higgs Inflation in No-Scale SUSY GUT

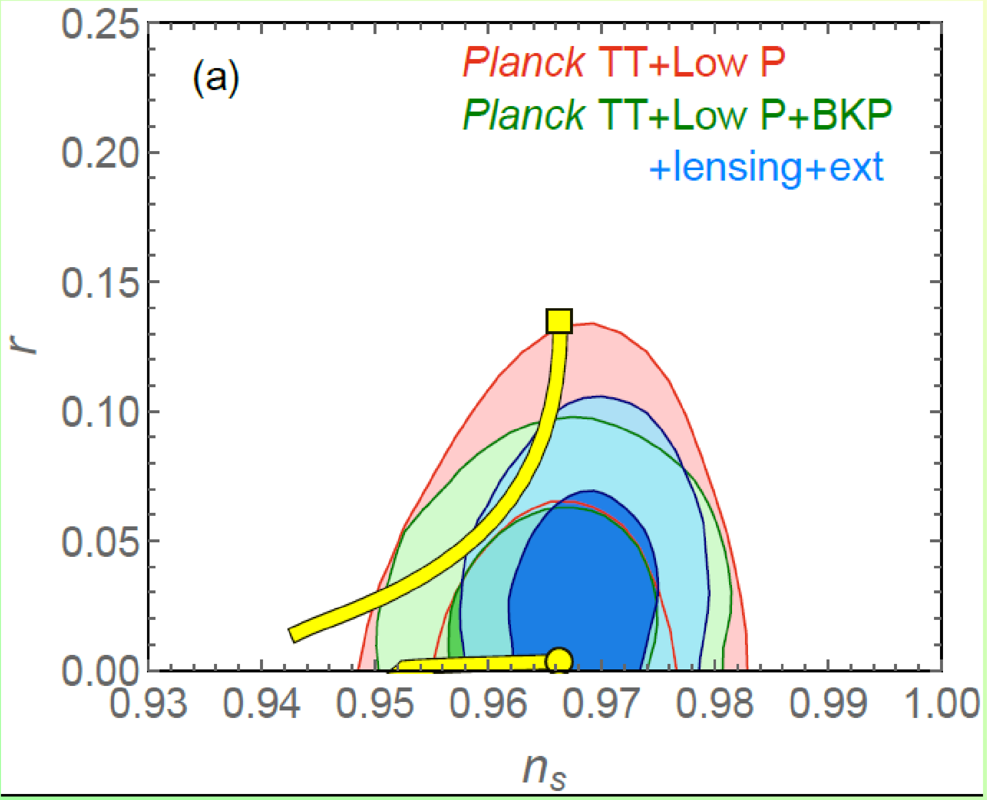
- **Predictions for inflation observables:**

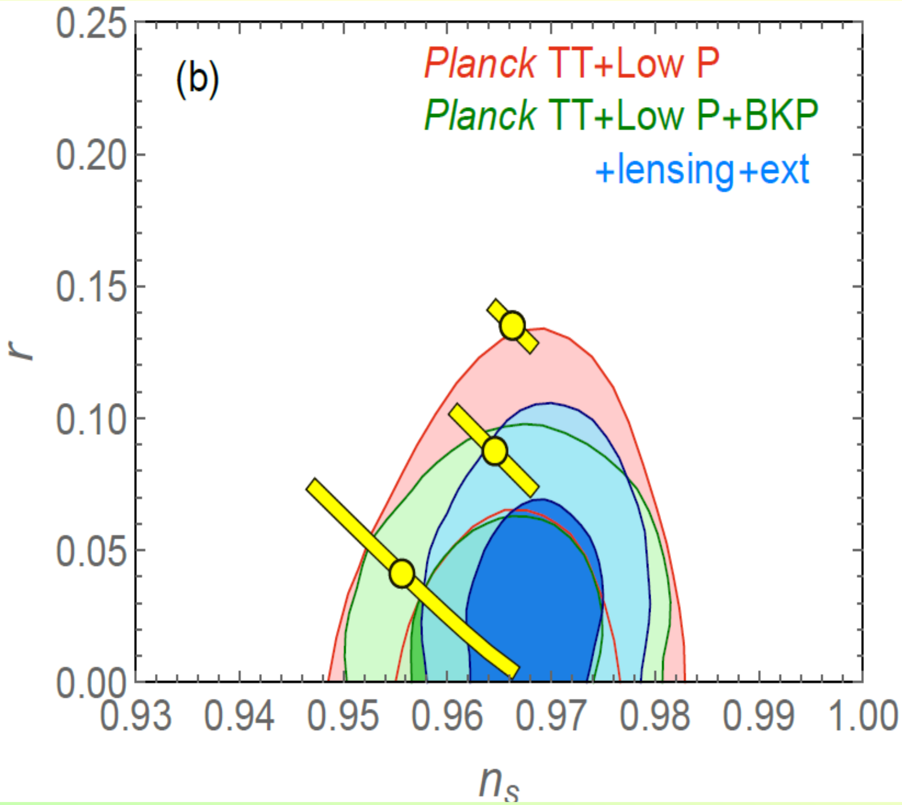
ζ =1: quadratical inflation.

ζ =0: Starobinsky-like inflation

With small deviation δ :

$$\beta = \frac{1}{3}(1 - \zeta + \delta)m$$





Ellis, HJH, Xianyu, arXiv:1606.02202

Higgs Inflation in No-Scale SUSY GUT

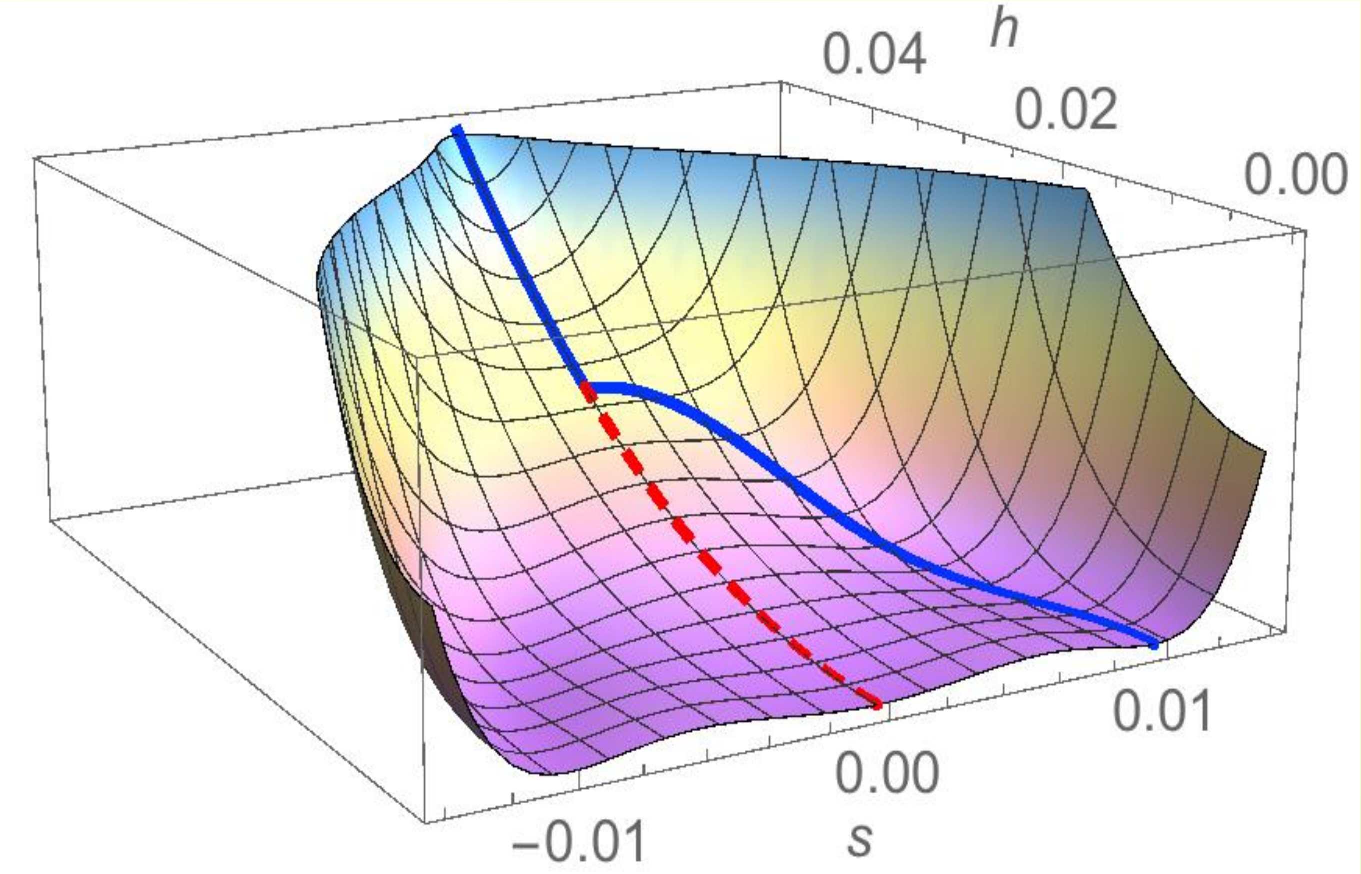


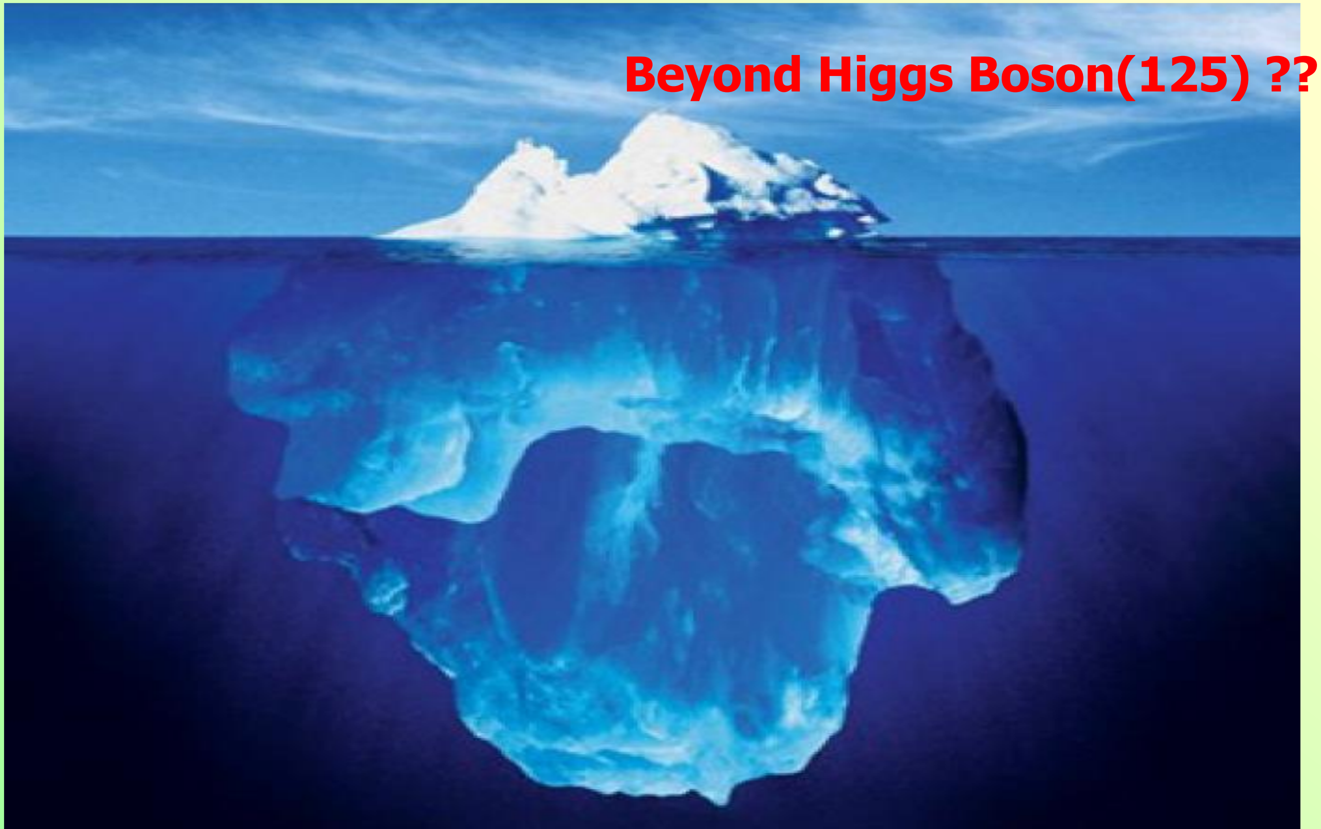
Figure 2. *Three-dimensional plot of the scalar potential $V(h,s)$ in the minimal SU(5) model as functions of the (h, s) fields. The blue curve depicts the trajectory of the inflaton after passing the branch point.*

Ellis, HJH, Xianyu, arXiv:1606.02202

Higgs Boson: Window to New Physics !?

- → All Particle Masses & Inflation of Universe ?! …..
  Connections to SUSY, DM, CPV, Baryogenesis? …..
- → h(125) is just the Tip of a giant Iceberg !

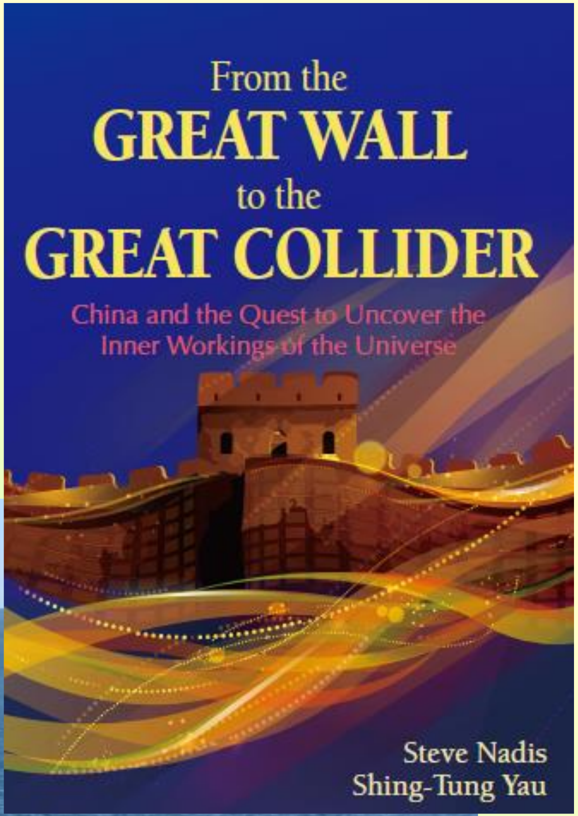
To open a Door to New Phys beneath water ?



Beyond Higgs Boson(125) ??!!

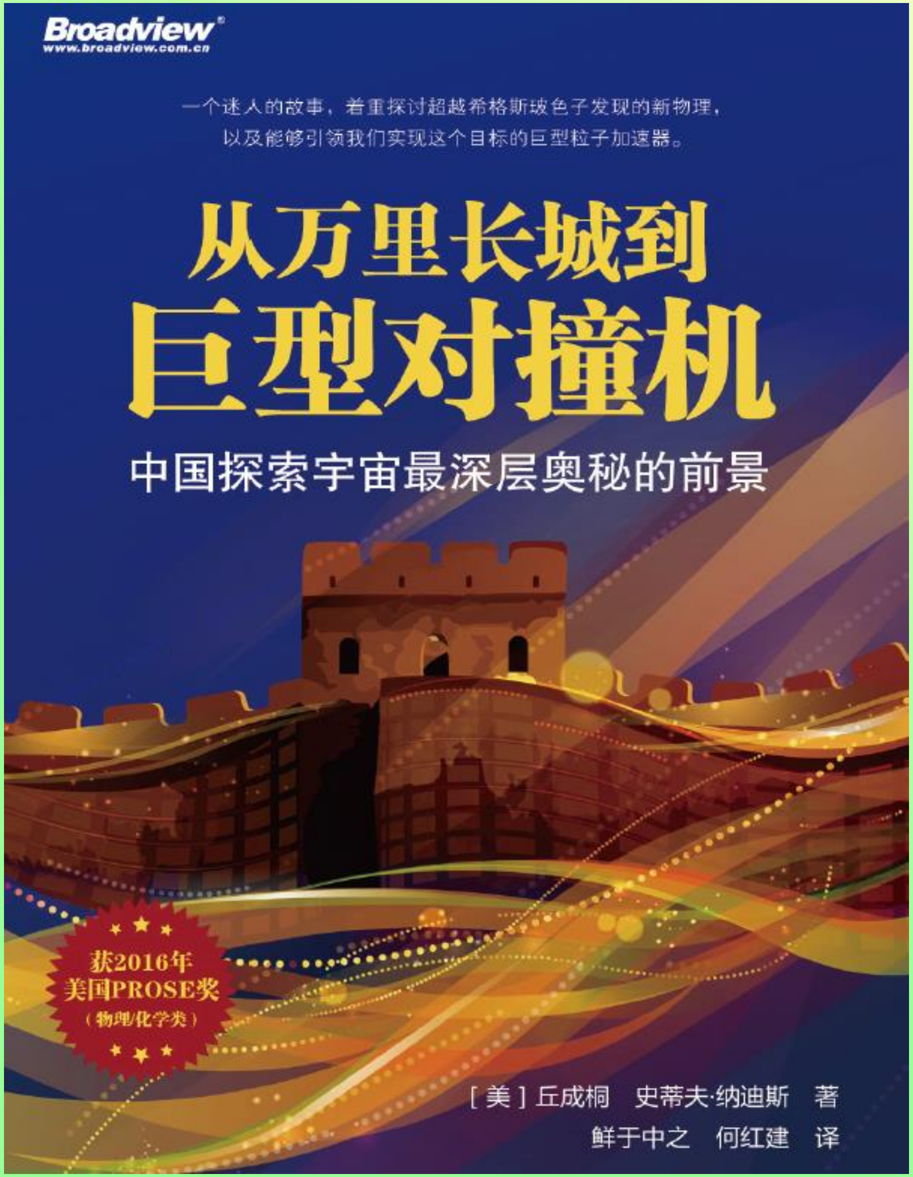
From Great Wall to Great Collider

see: book of Nadis and Yau



Shanhai Pass (山海关) vs CEPC-SPPC

Great Wall → Great Collider (CEPC-SPPC)



More Excitments Ahead！

Let us continue to work together and do good works !


Thank You !