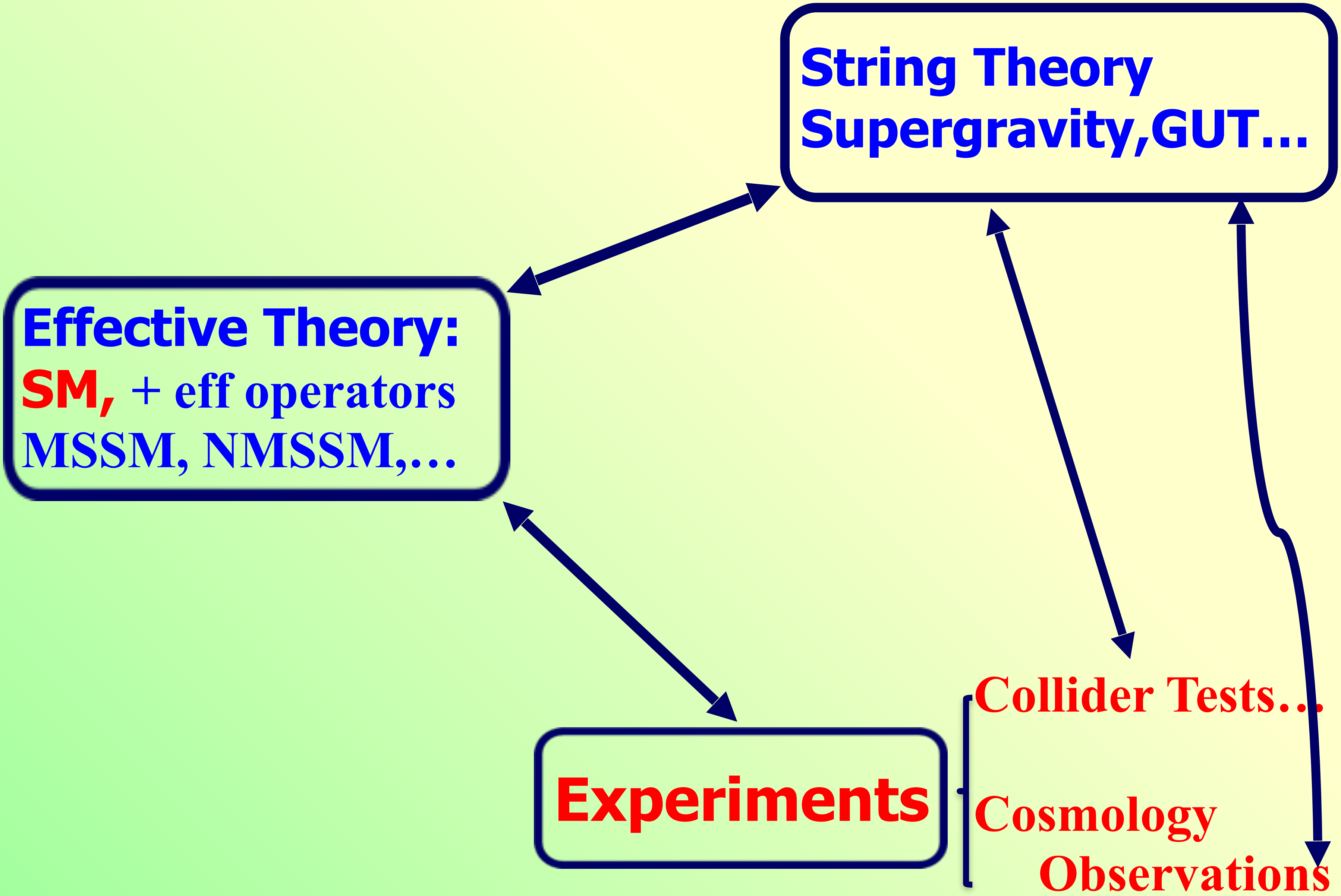
Higgs Boson: from Collider Test to SUSY GUT Inflation

Hong-Jian He
Tsinghua University

String-2016, Tsinghua, Beijing, August 5, 2016


String Theory
Supergravity,GUT…
Effective Theory:
SM, + eff operators
MSSM, NMSSM,…
Experiments
Collider Tests…
Cosmology
Observations

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

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- Run-2 New Particle Discovery in 2016 ??

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New Set of Key Physics Questions

for Next Colliders to answer !!

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Making of the Standard Model

$$
\begin{aligned}
\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) \\
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Key Role of Higgs Boson in SM:

Mass Generations for W/Z + Quarks/Leptons

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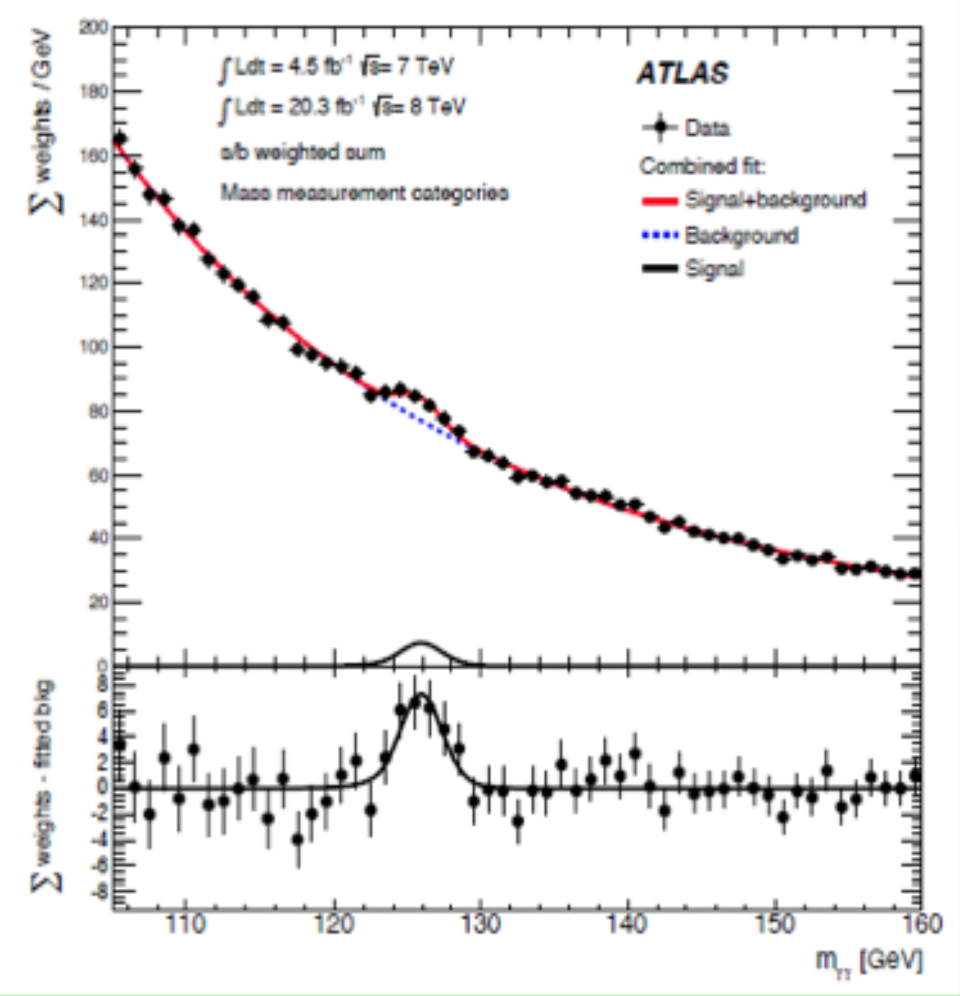
➢ h(125GeV) Discovery at LHC Run-1.

➢ X(750GeV) or Any New State at LHC Run-2 ?!

✓ H (125GeV) @ Run-1



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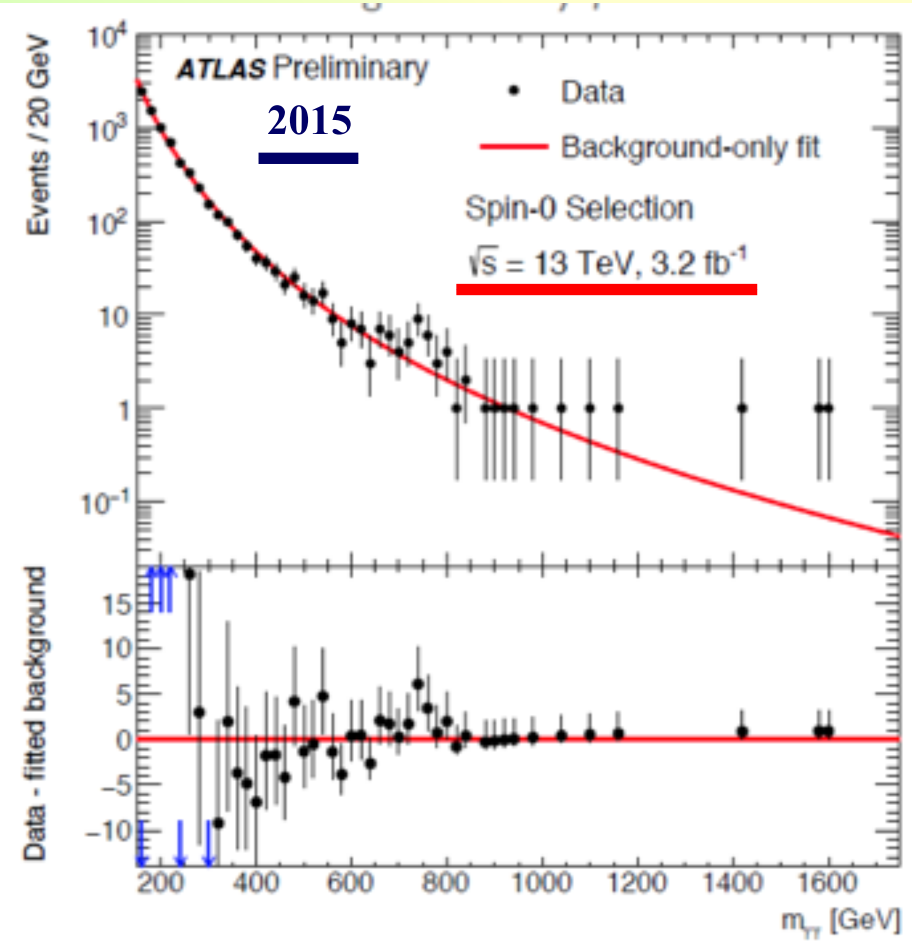

2878 events ($m_{\gamma\gamma}$ > 200 GeV)

a Window to New Physics ??

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Spin-0 Higgs Boson Itself

is

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Representation of Lorentz Group

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- **Missing Antimatter Puzzle:**
  - Baryogenesis, Leptogenesis, … ?

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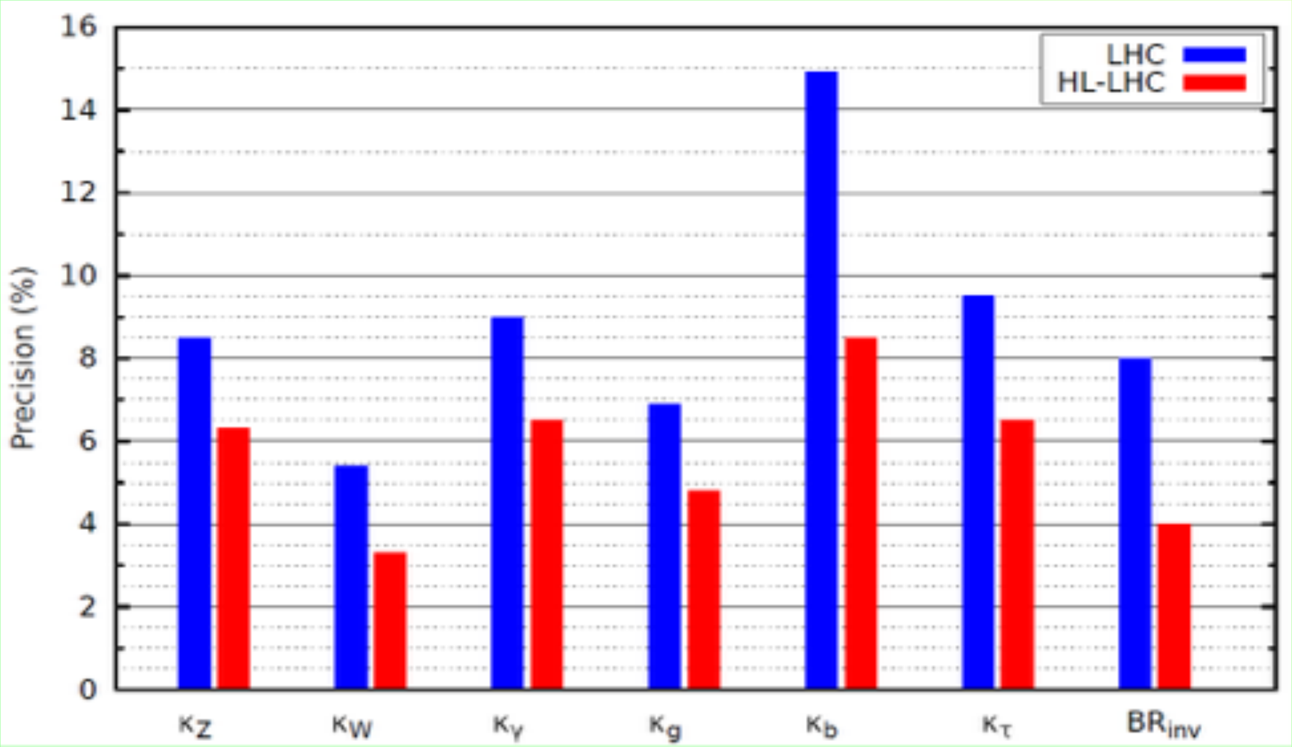
3 *Fundamental Forces* inside SM Itself

- 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(300/fb) + HL-LHC(3/ab)
M. E. Peskin, Snowmass Study,
arxiv:1312.4974

Higgs 125GeV and Beyond

→

→

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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

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mediated by Higgs Boson.

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

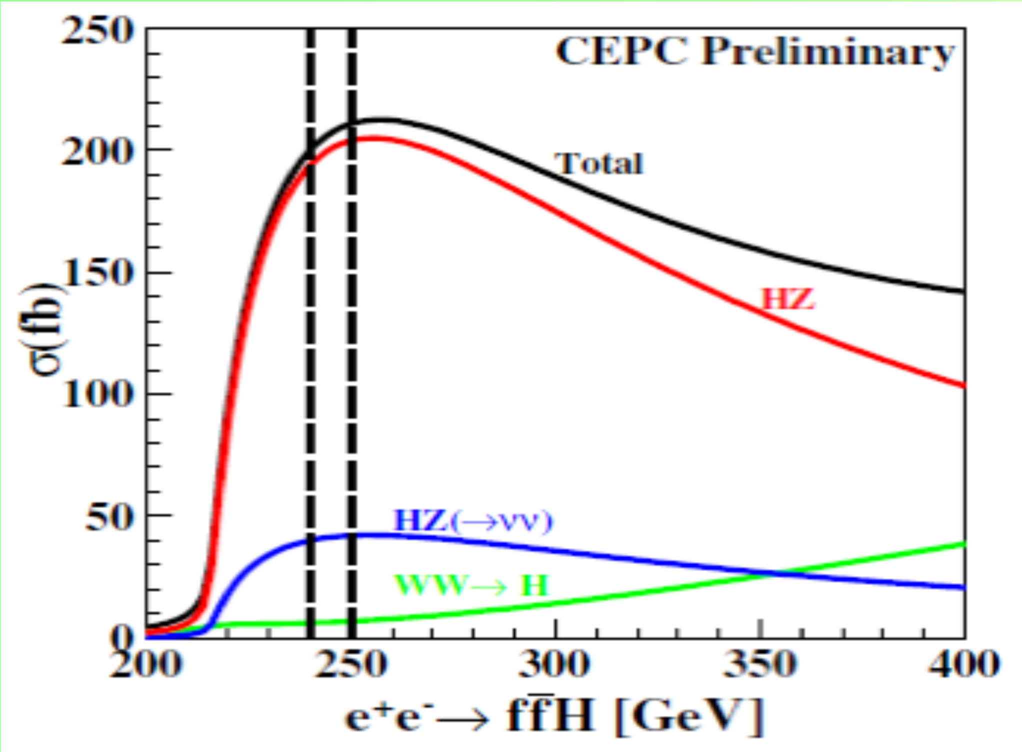
→ **This requires to Go Beyond the LHC!**

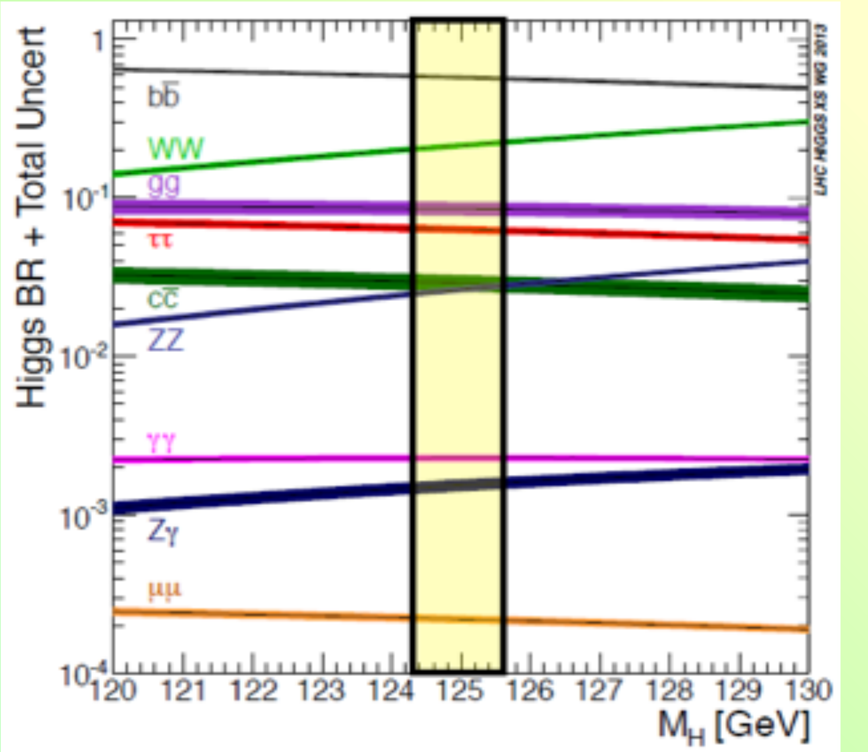
→ **High Energy Circular Colliders: CEPC/SPPC & FCC ee (90-250GeV, 350GeV) + pp(50-100TeV)**

Higgs Factory: CEPC (240-250GeV)

- **LHC-Run1+2: 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 in 10y. → **10^6 Higgs Bosons !!**





Inputs: Event Rate → Cross Section & BR

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

Decay Mode	$\sigma(Zh) \times Br$	Br
$h \to bb$	**0.21%**	0.54%
$h \to cc$	2.5%	2.5%
$h \to gg$	1.3%	1.4%
$h \to \tau\tau$	1.0%	1.1%
$h \to WW$	**1.1%**	1.2%
$h \to ZZ$	**4.3%**	4.3%
$h \to \gamma\gamma$	**9.0%**	9.0%
$h \to \mu\mu$	17%	17%
$h \to$ invisible	–	0.14%

latest 1σ uncertainty
KITPC WS, July 28

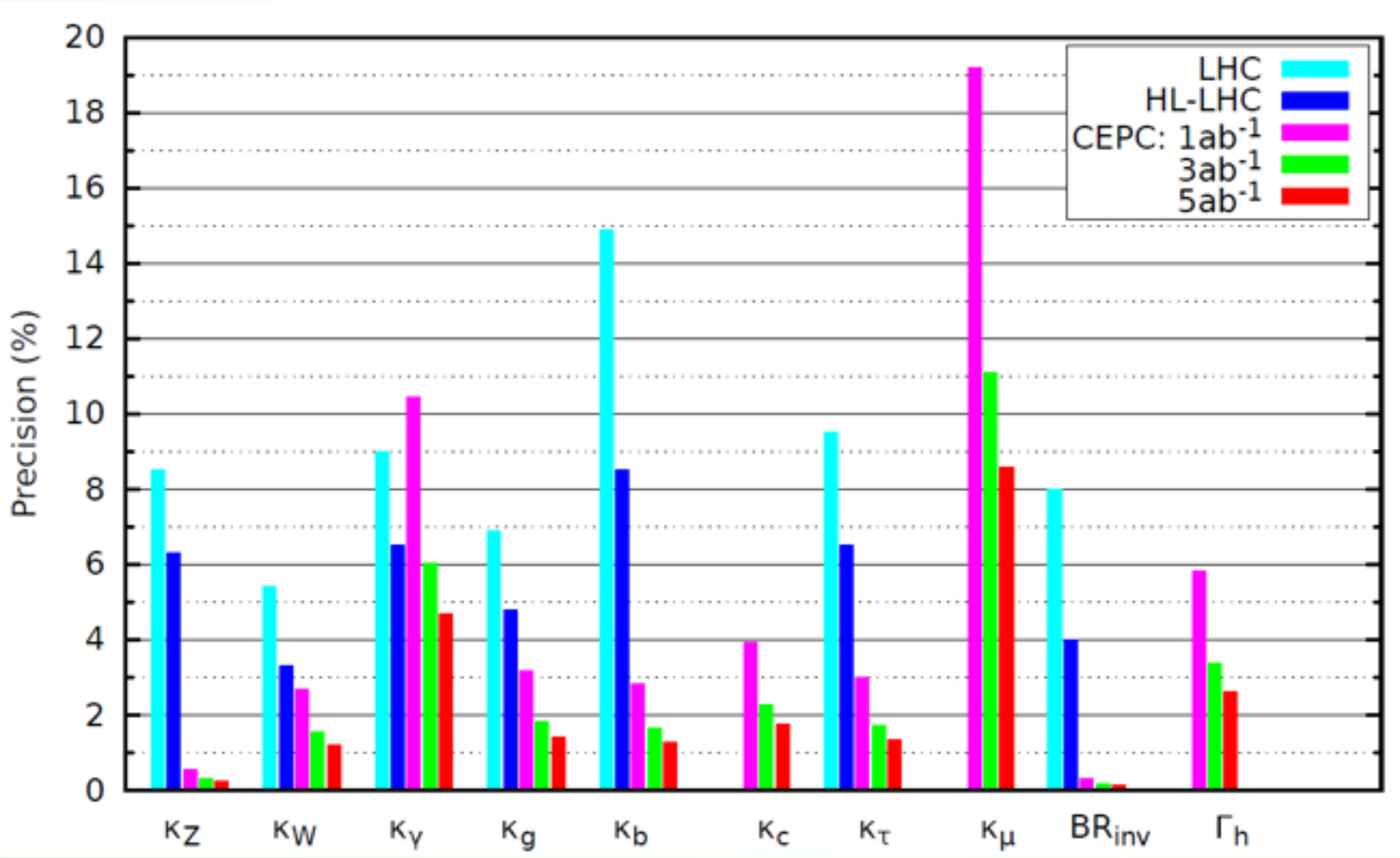
SM Predictions

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

Effective Higgs Couplings: Gauge & Yukawa

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

Testing Higgs Coupling: CEPC vs LHC



Ge, HJH, Xiao, arXiv:1603.03385

Indirect Probe of Higgs related New Physics

All can be formulated by:

Model-Independent Effective Operators

(Dimension-6)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_j \frac{c_j}{\Lambda^2}\mathcal{O}_j$$

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

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}	$3.7 \times 10^{-5} \sim 6.2 \times 10^{-5}$

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

Scheme-Independent Analysis

Ge, HJH, 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 demonstration of a 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

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_{L}^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
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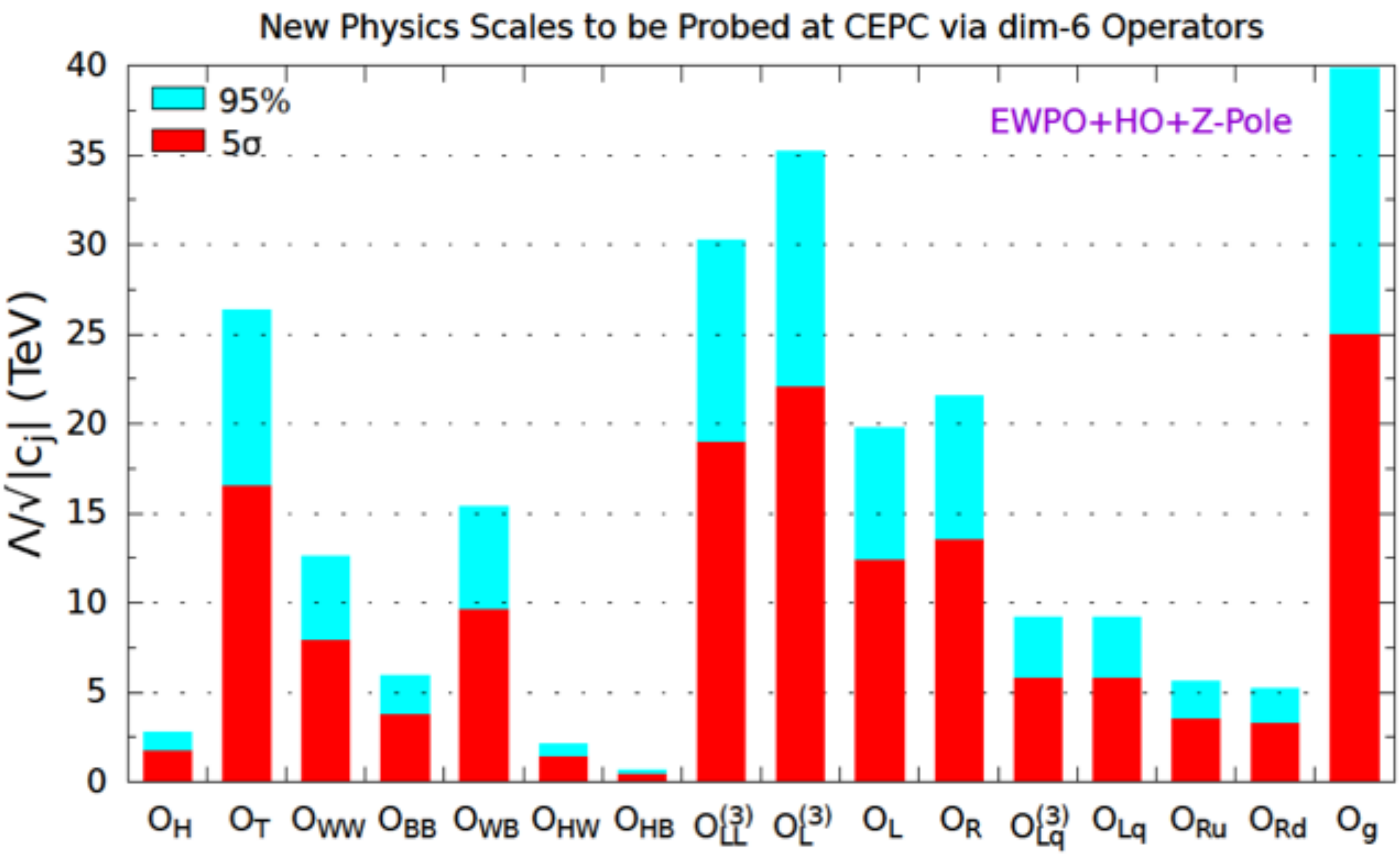
2.74	24.0	**8.32**	5.80	**12.2**	2.15	0.603	**20.7**	**23.0**	**12.5**	**13.0**	2.08	**1.62**	0.391	**3.97**	39.8
2.74	24.0	8.33	5.80	12.2	2.15	0.603	20.7	23.0	12.5	13.0	**7.90**	**7.89**	**3.55**	4.05	39.8
2.74	24.0	8.54	5.80	12.2	2.15	0.603	20.7	23.4	**14.4**	**14.0**	8.63	8.62	4.88	**4.71**	39.8
2.74	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

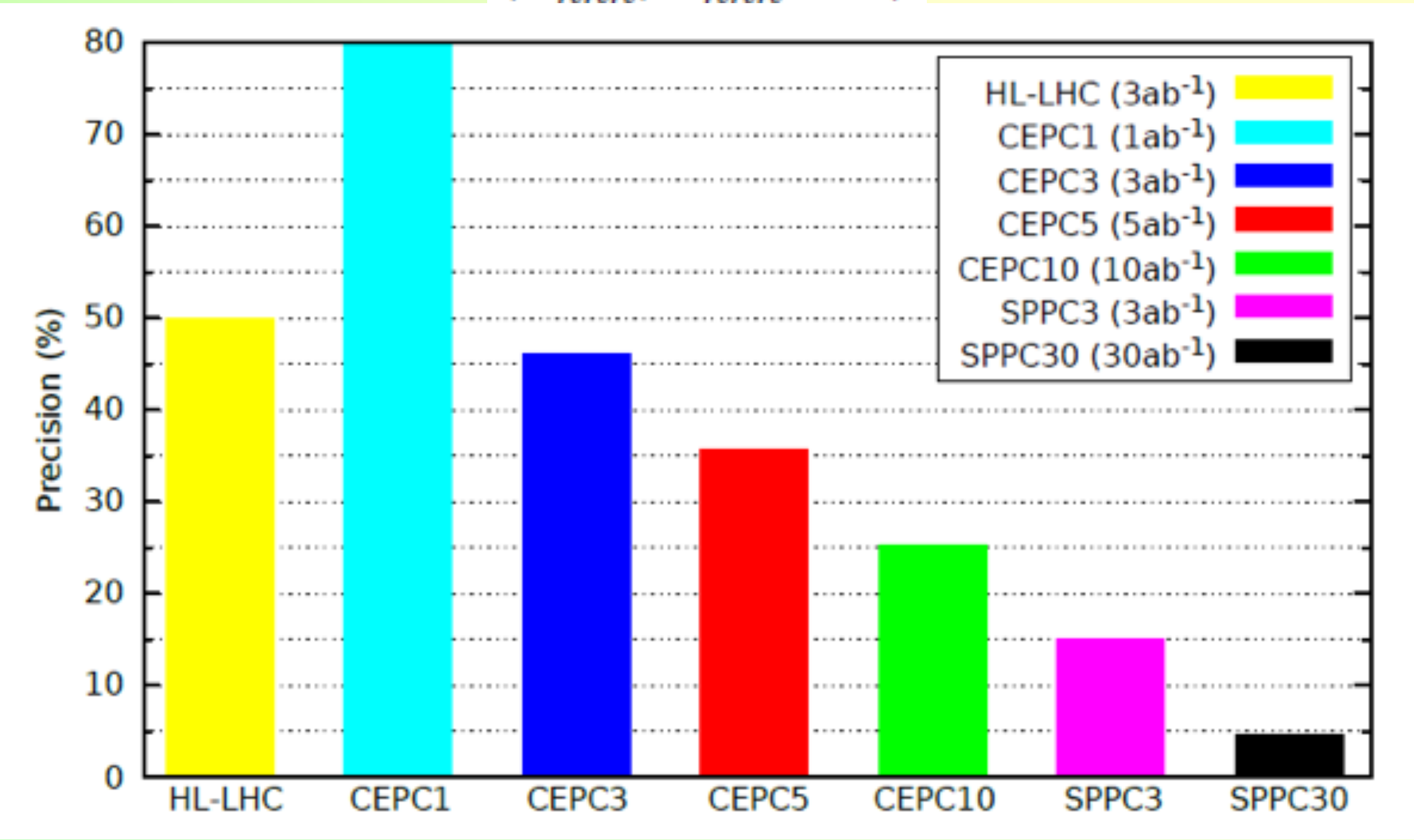


Ge, He, Xiao, 1603.03385

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):**

$$|\lambda_{hhh}/\lambda_{hhh}^{\rm sm} - 1|$$



-- Higgs WG Rept

Probe Higgs Self-Interaction h^3 at SPPC

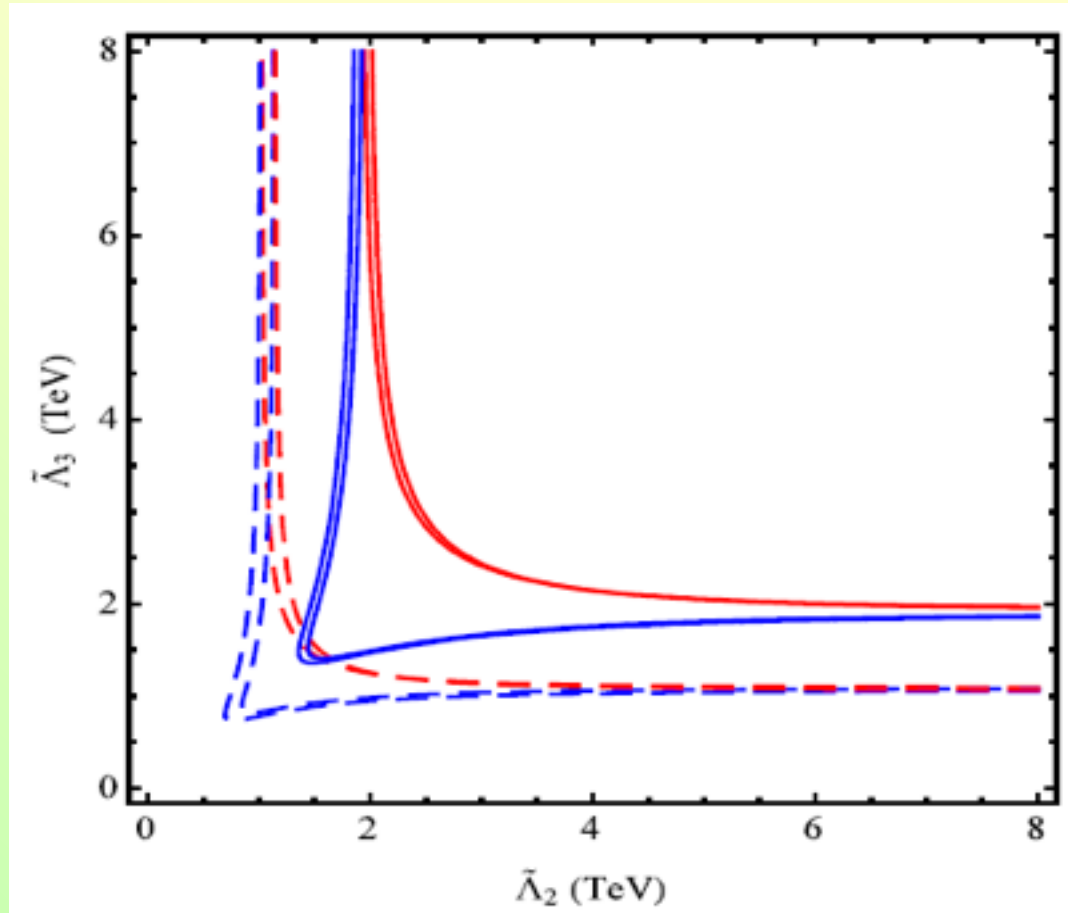
$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n, \qquad \tilde{\Lambda}_j \equiv \frac{\Lambda}{\sqrt{|f_{\Phi,j}|}}.$$

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

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

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

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



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

pp → hh → bbγγ

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

Probe Higgs Self-Interaction h^3

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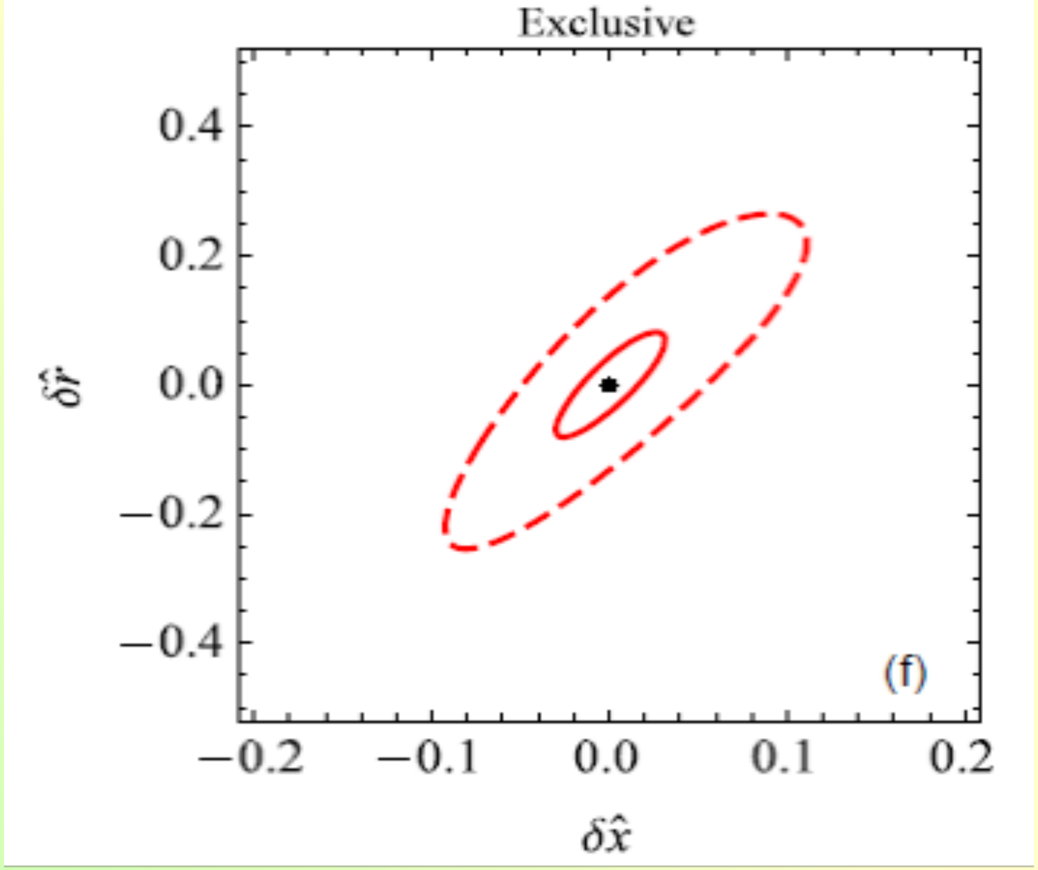


pp(100TeV) with (3, 30)/ab:

pp → hh → bbγγ

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)

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%

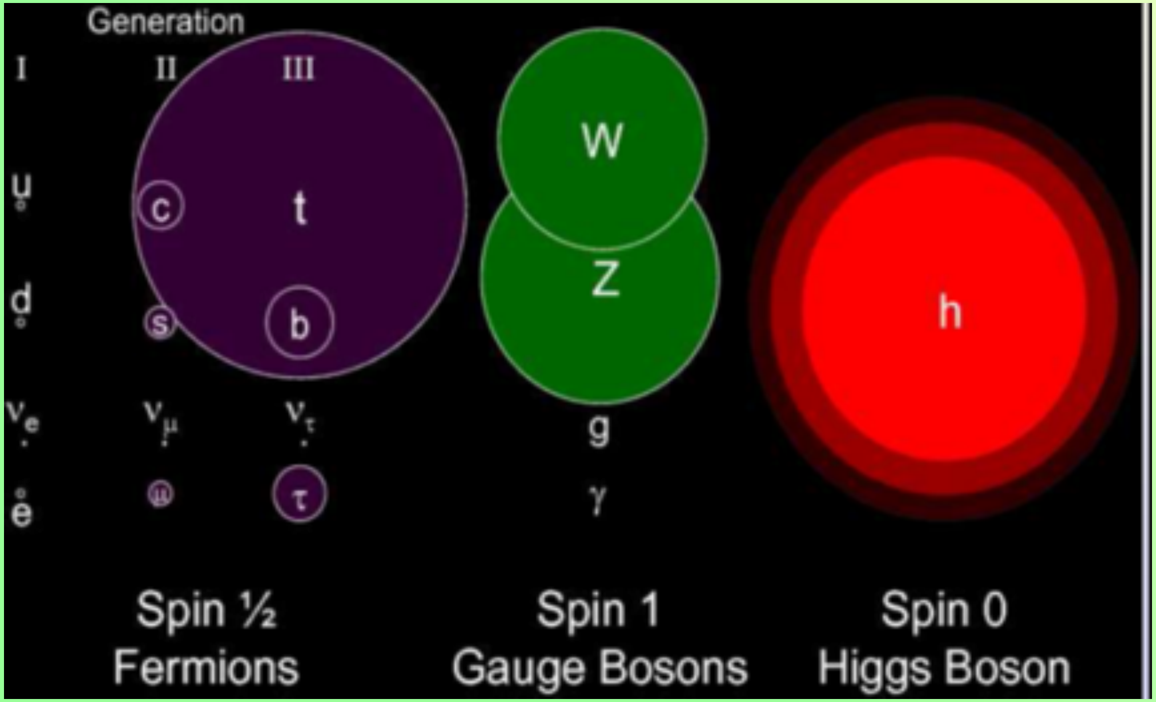
- ➢ CEPC Indirect Probe of New Physics Scales:
  up to ~10TeV (40TeV for O_g) from EWPO + HO.
  up to ~35TeV after including Z-pole, etc (CEPC).

- ➢ SPPC(100TeV) with 3/ab (30/ab) can sensitively probe
  h^3 Higgs Coupling ~ 5-13% (1.6-4.2%).

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?



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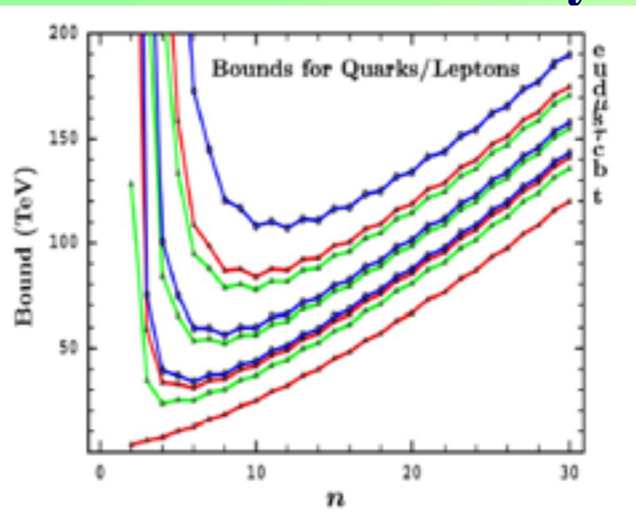
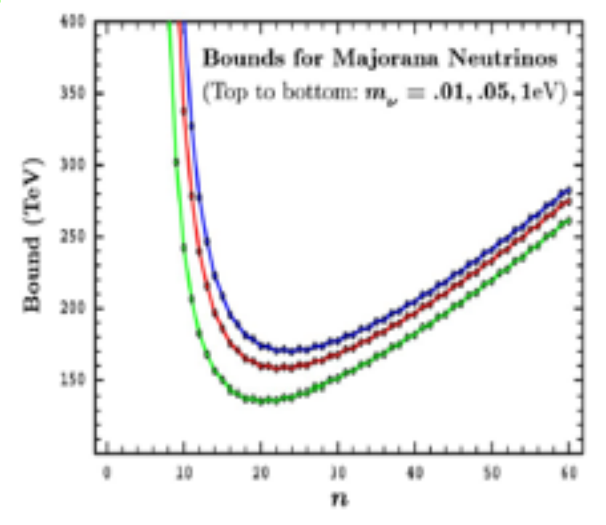




Upper Bounds on Scales of Fermion Mass Generations:

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

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

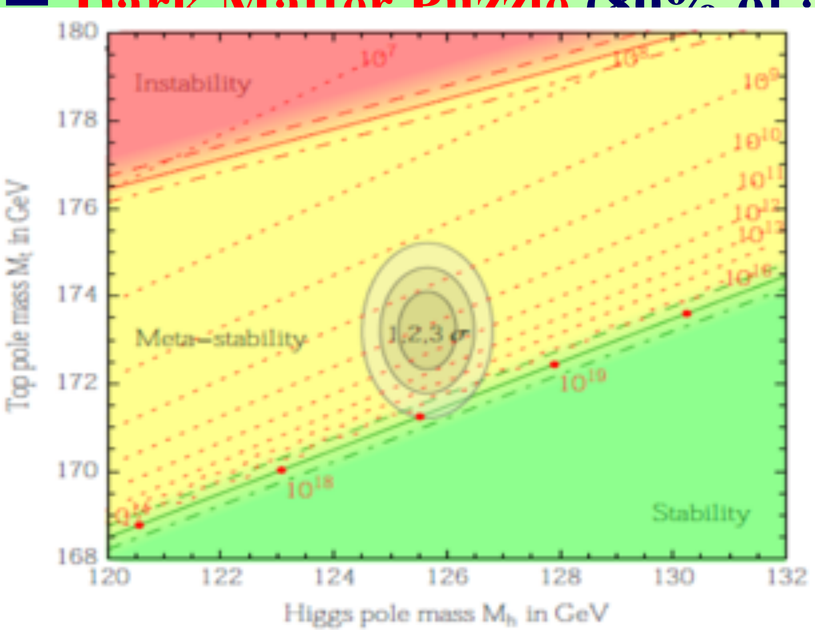
$\xi_1\xi_2$	V_LV_L	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$d\bar{d}$	$u\bar{u}$	$\tau^-\tau^+$	$\mu^-\mu^+$	e^-e^+	$\nu_L\nu_L$
Mass (GeV)	80.4	178	4.85	1.65	0.105	0.006	0.003	1.777	0.106	5.11×10^{-4}	5×10^{-11}
n_s	2	2	4	6	8	10	10	6	8	12	22
$E^{\star(\min)}_{2\to n}$ (TeV)	1.2	3.49	23.4	30.8	52.1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

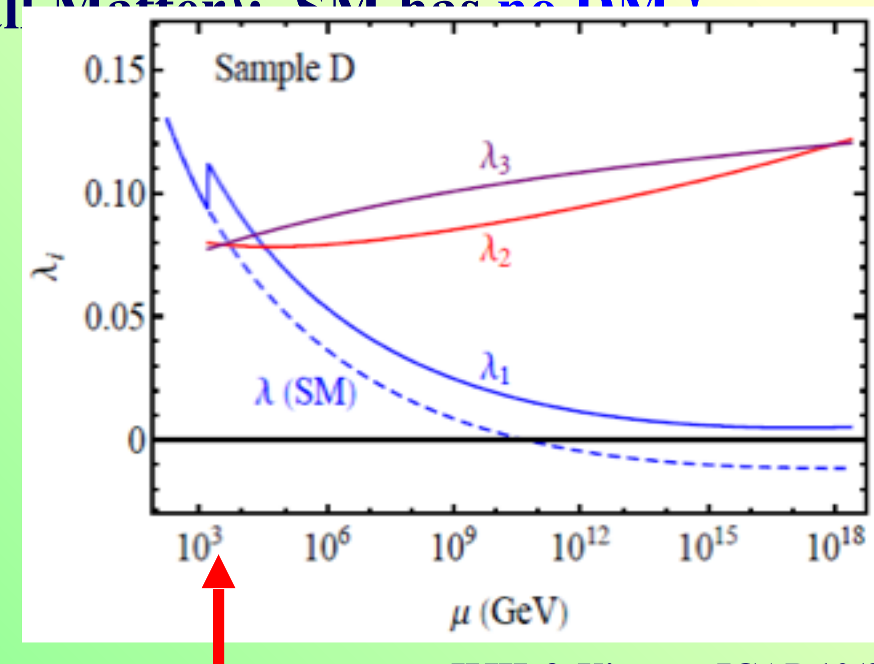
see: Nima's Overview in preCDR

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



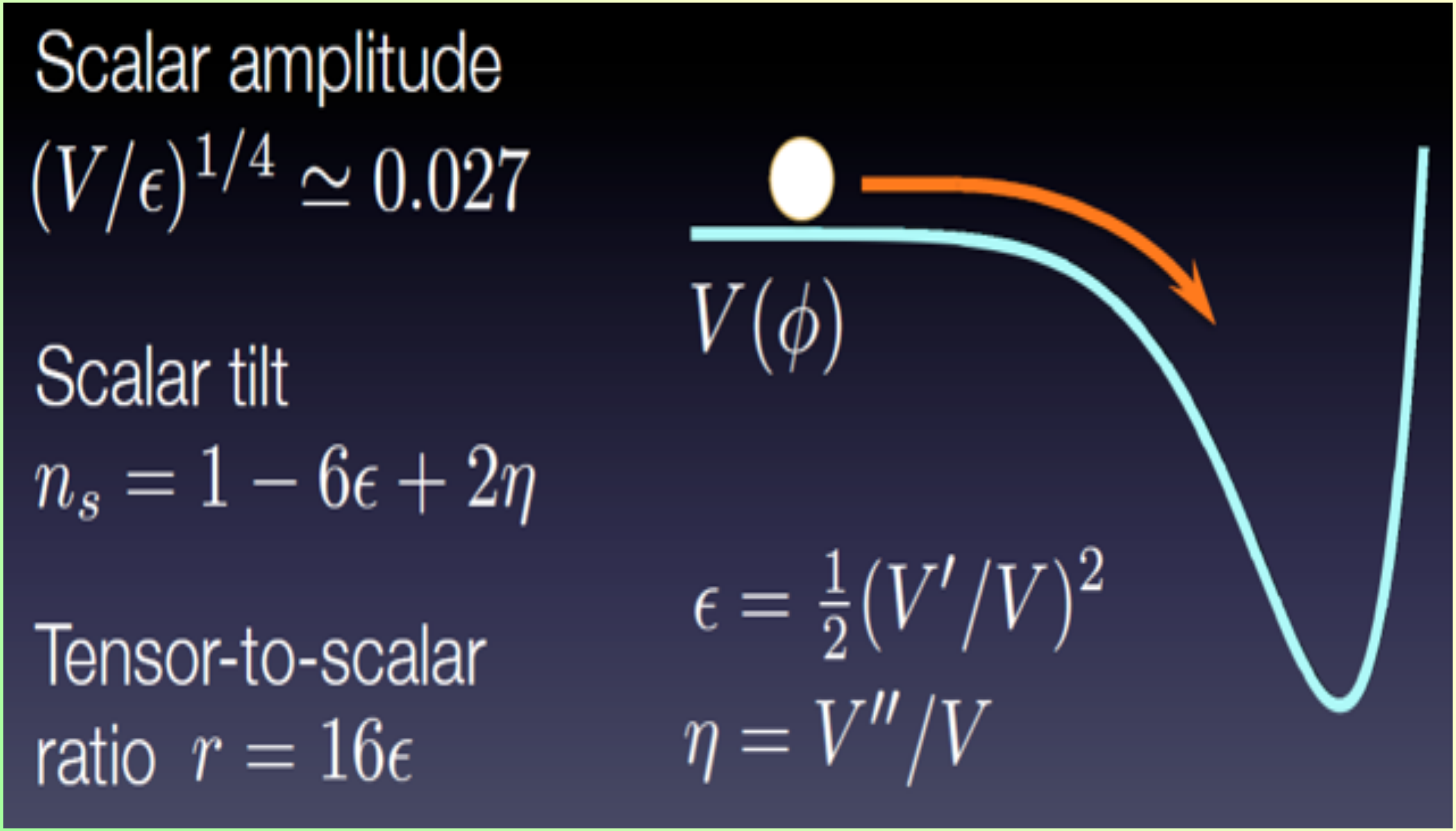
HJH & Xianyu, JCAP 10(2014) 019
also: arXiv:1602.01801

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

Higgs Boson as Inflaton ??

SM ⟵ Direct Link ⟶ Beginning of Universe

Picture of Inflation



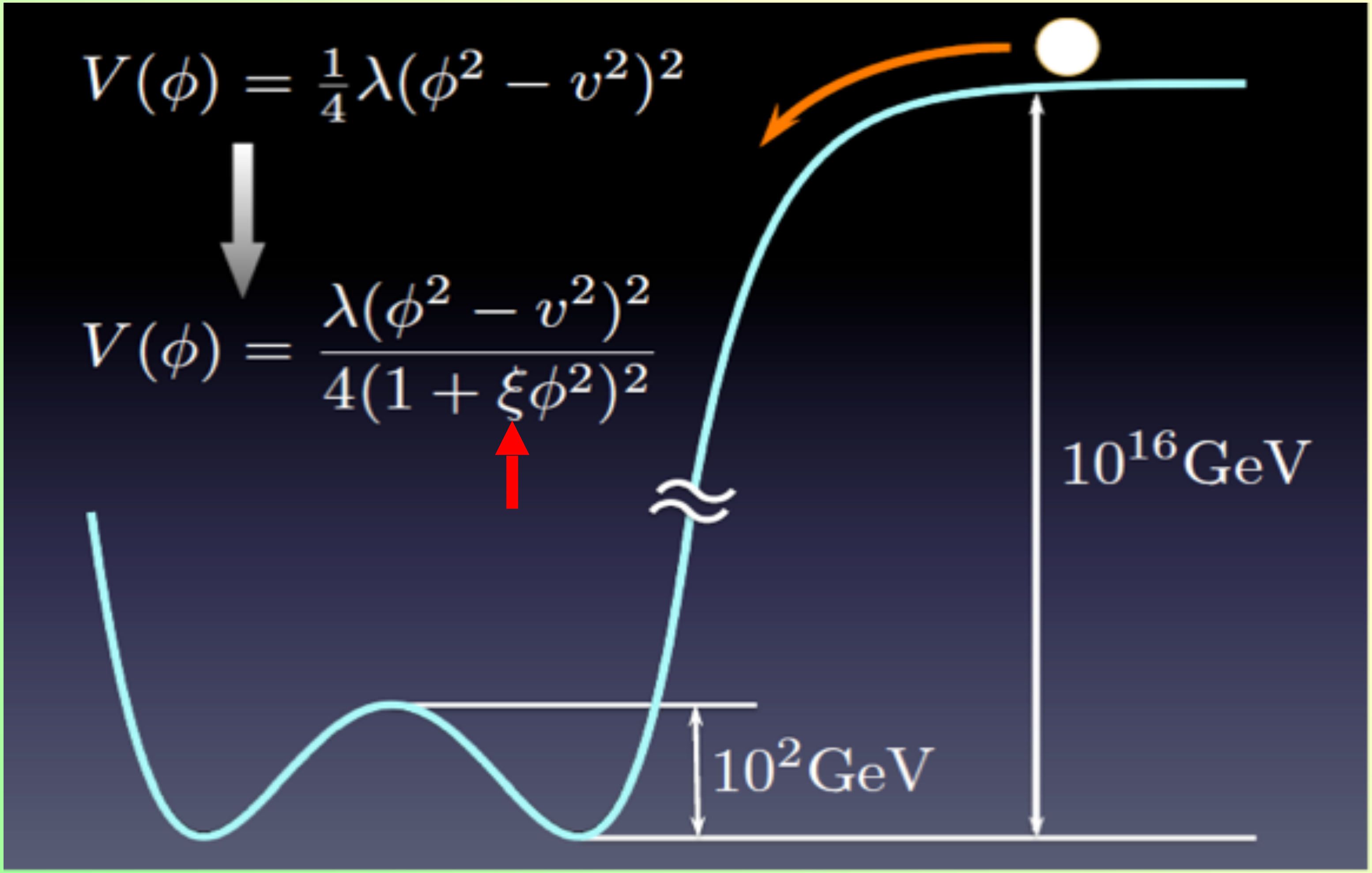
Conventional SM Higgs Inflation

$(M_{\mathrm{P}} = 1)$

$$\frac{\mathcal{L}_{\mathrm{J}}}{\sqrt{-g}} = \frac{1}{2}R + \frac{1}{2}\xi R\phi^2 + \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$$

$$V(\phi) = \frac{1}{4}\lambda(\phi^2 - v^2)^2$$

$$V(\phi) = \frac{\lambda(\phi^2 - v^2)^2}{4(1 + \xi\phi^2)^2}$$



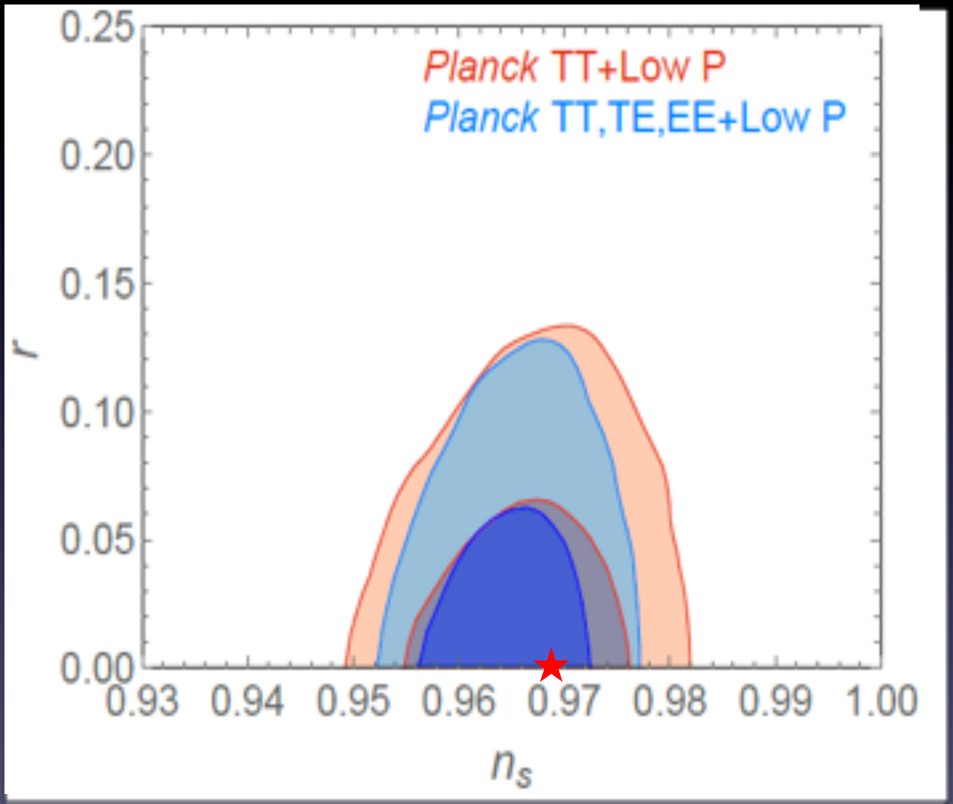
Bezrukov & Shaposhnikov, PLB(2008)

Conventional SM Higgs Inflation

$$(V/\epsilon)^{1/4} \simeq 0.027$$

$$\xi \simeq 10^4$$

$$n_s \simeq 0.967$$
$$r \simeq 0.003$$



Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, JCAP[arXiv:1606.02202], PRD[arXiv:1411.5537]

- **SUSY: a Natural Solution to Higgs Instability**
- **Inflation Scale ~ GUT Scale ⟶ SUSY GUT Inflation**
- **No-Scale SUGRA:** (Ellis, Kounnas, Nanopoulos, 1984)
  – **naturally from simple String Compactification** (Witten, 1984)
  – **provides Flat Directions useful for Inflation** (Ellis et al, 1985)
- **Flipped SU(5) GUT can naturally lift heavy mass of colored triplet Higgs H_C from weak scale doublet Higgs (H_u, H_d), and efficiently suppress dim-5 proton decays.**
- **Does not require Higgs in adjoint, good for embedding into string theory.**

Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, arXiv:1606.02202

- **No-Scale Kahler Potential of flipped SU(5):**

$$\mathcal{K} = -3\log\left[T + T^* - \frac{1}{3}|\Phi_j|^2 + \frac{\zeta}{3}(H\overline{H} + \text{h.c.})\right]$$

- **Superpotential up to dim-4:**

$$W = -MG\overline{G} - mH\overline{H} + \lambda GGH + \bar{\lambda}\overline{G}\overline{G}\overline{H} + \alpha(G\overline{G})^2 + \beta(H\overline{H})^2 + \gamma(G\overline{G})(H\overline{H})$$

where we set $M_p=1$, $\Phi_j = (G, \overline{G}, H, \overline{H}, \cdots)$, and

$$G = \begin{pmatrix} 0 & d^c_{G3} & -d^c_{G2} & d_{G1} & u_{G1} \\ & 0 & d^c_{G1} & d_{G2} & u_{G2} \\ & & 0 & d_{G3} & u_{G3} \\ & & & 0 & \nu^c_G \\ & & & & 0 \end{pmatrix}, \qquad H = \begin{pmatrix} H_c \\ H_u \end{pmatrix}, \qquad \overline{H} = \begin{pmatrix} \overline{H}_c \\ \widetilde{H}_d \end{pmatrix},$$

Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, arXiv:1606.02202

- **Inflation Potential:**

$$V = e^G\left(K_{ij^*}\frac{\partial G}{\partial\phi_i}\frac{\partial G}{\partial\phi_j^*} - 3\right)$$

$$V(G) = 2G\overline{G}(M - 2\alpha G\overline{G})^2$$

$$V \supset 4\lambda^2 v_G^2 |H_c|^2 + 4\bar{\lambda}^2 v_G^2 |\overline{H}_c|^2$$

- **GUT breaking:** $\langle G\overline{G}\rangle = M/(2\alpha)$

- **Doublet-Triplet Splitting:** $M_{H_c} = 2\lambda v_G$, $m = \gamma v_G^2$

Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, arXiv:1606.02202

- Potential Term (with $\beta = \frac{1}{3}(1-\zeta)m$):

$$V(h) = \frac{\left(1-\frac{\beta}{2m}\hat{h}^2\right)^2 m^2 \hat{h}^2}{2\left(1-\frac{1-\zeta}{6}\hat{h}^2\right)^2} \longrightarrow \frac{1}{2}m^2\hat{h}^2$$

Inflaton as EW Higgs Boson

$$\hat{h} = |H_u^0| + |H_d^0|$$

- Include kinetic term:

$$\mathscr{L}[\hat{h}] = \frac{1-\frac{\zeta(1-\zeta)}{6}\hat{h}^2}{2\left(1-\frac{1-\zeta}{6}\hat{h}^2\right)^2}(\partial_\mu\hat{h})^2 - \frac{1}{2}m^2\hat{h}^2$$

- Normalized field h:

$$h = \sqrt{6}\,\text{arctanh}\frac{(1-\zeta)\hat{h}}{\sqrt{6\left(1-\frac{1}{6}\zeta(1-\zeta)\hat{h}^2\right)}} - \sqrt{\frac{6\zeta}{1-\zeta}}\,\arcsin\left(\sqrt{\frac{\zeta(1-\zeta)}{6}}\,\hat{h}\right)$$

- 2 Important limits:

$\zeta = 0$ → V is exponentially flat.

$\zeta = 1$ → V is quadratic.

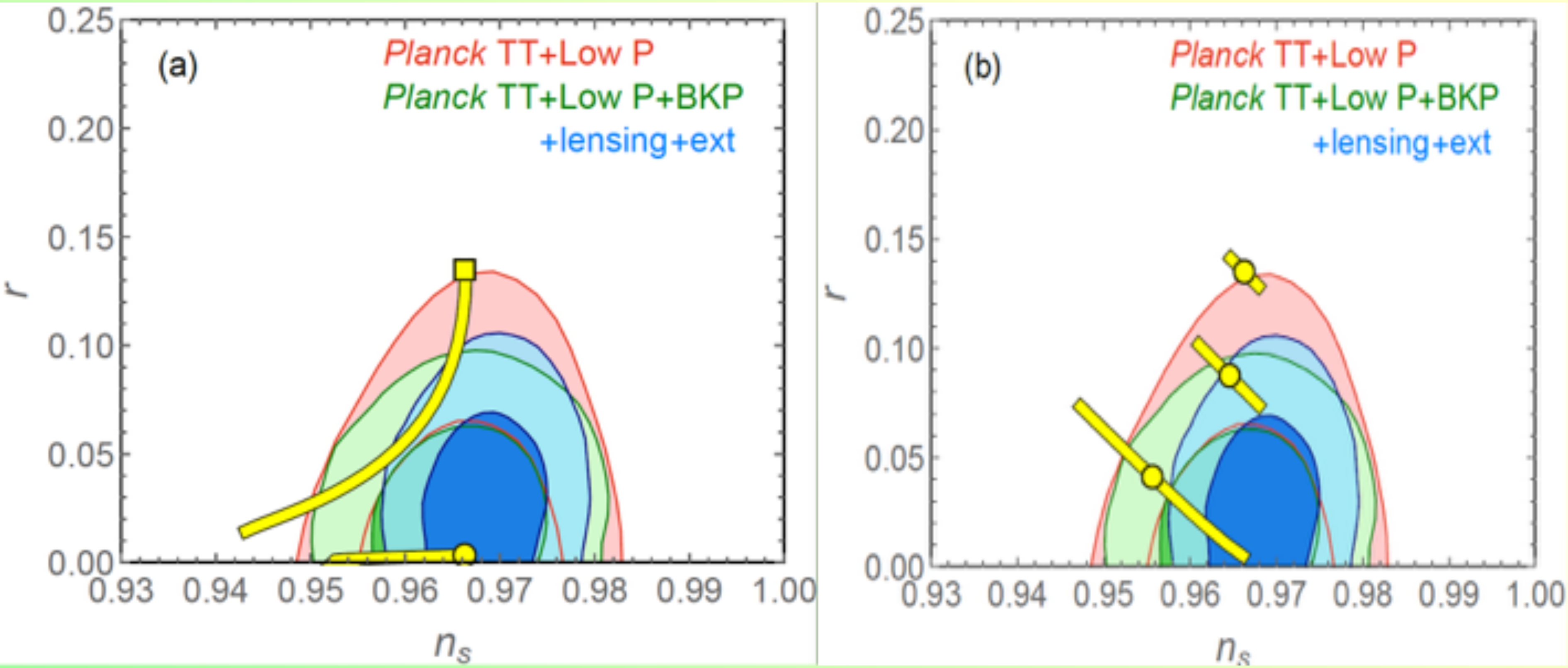
Higgs Inflation in No-Scale SUSY GUT

➢ **Predictions for inflation observables:** $N_e \simeq 59$

ζ = 1: quadratical inflation.
ζ = 0: Starobinsky-like inflation

With small deviation δ :

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



Ellis, HJH, Xianyu, JCAP, arXiv:1606.02202

Trajectory of Inflaton in No-Scale SUSY GUT

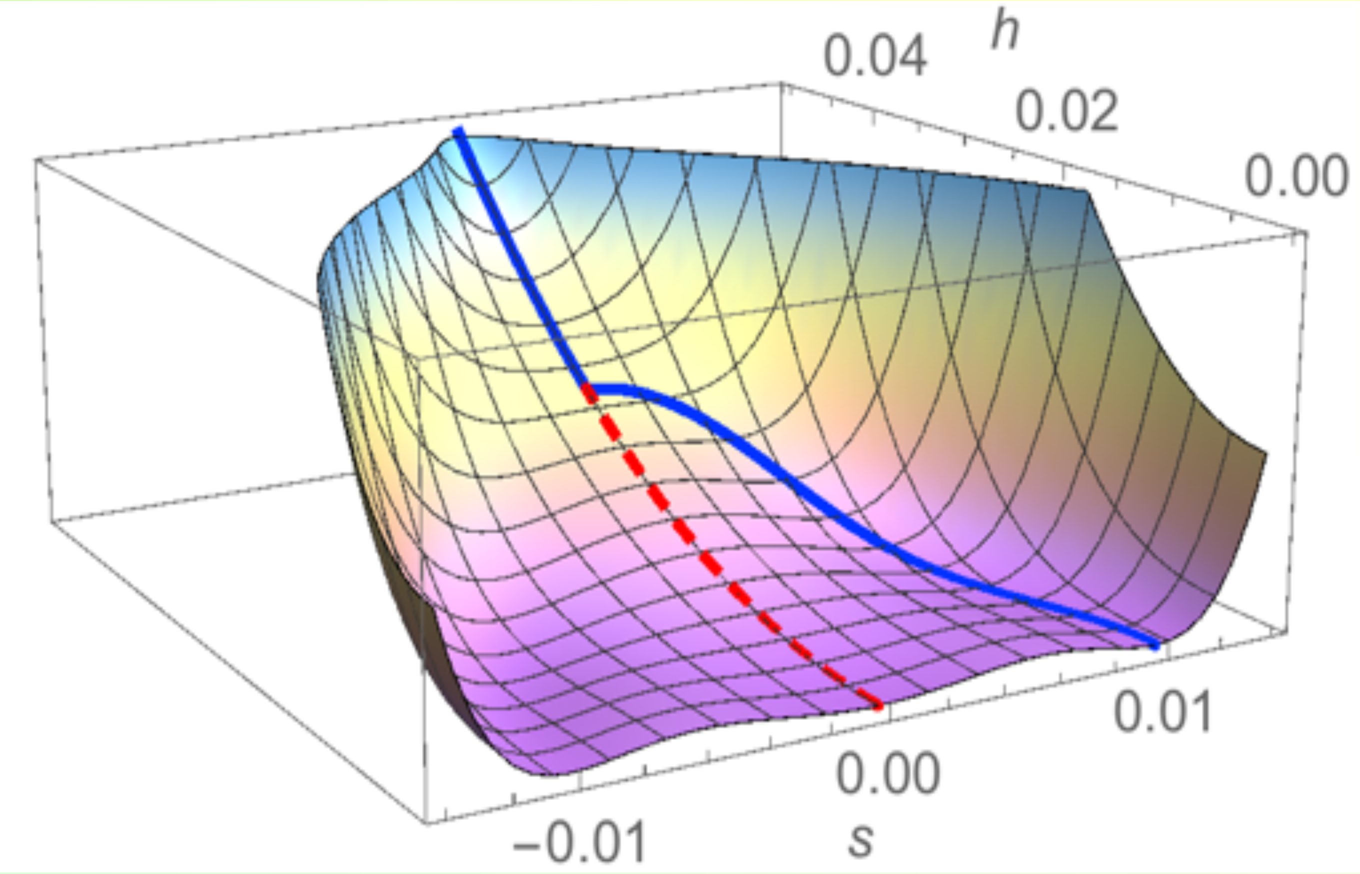


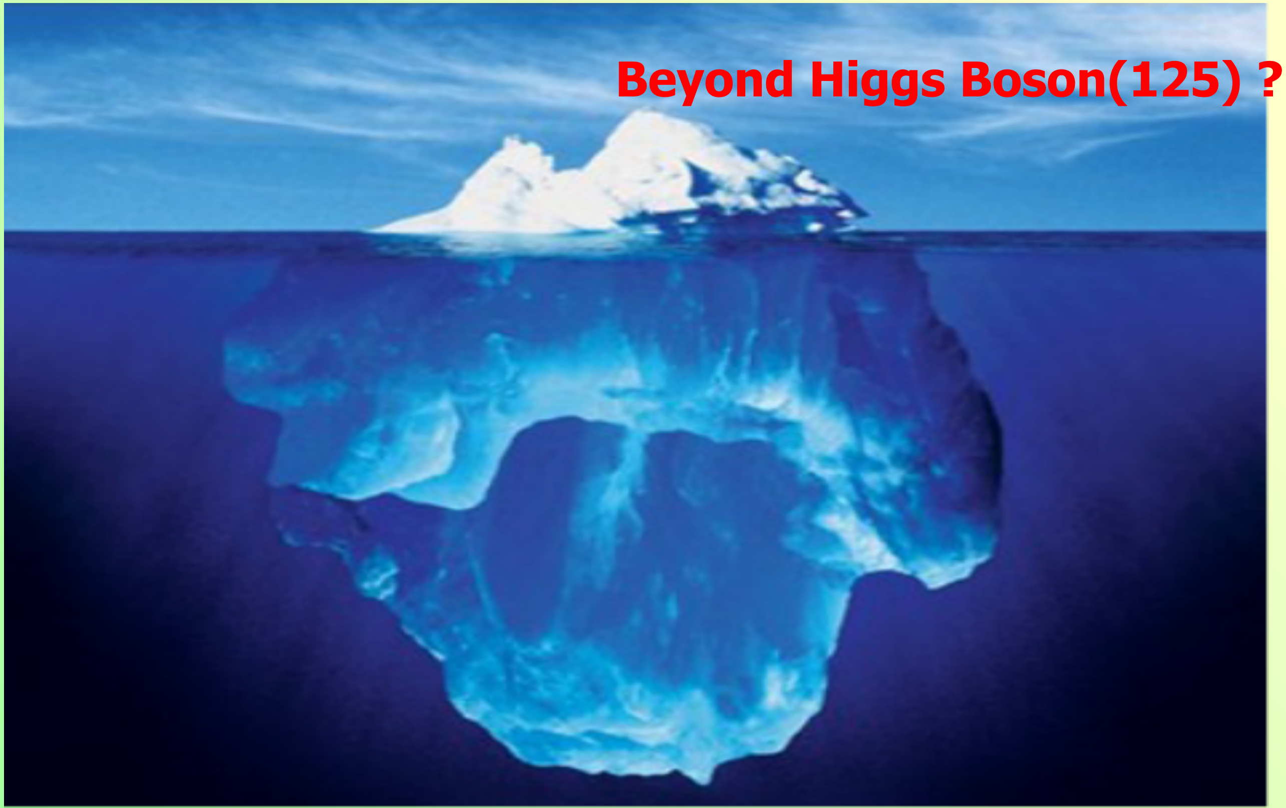
Figure 2. *Three-dimensional plot of the scalar potential $V(h,s)$ in the minimal SU(5) model as functions of the $(h,\ s)$ fields. The blue curve depicts the trajectory of the inflaton after passing the branch point.*

Ellis, HJH, Xianyu, JCAP, arXiv:1606.02202

Higgs Boson: Window to New Physics !?

→

→

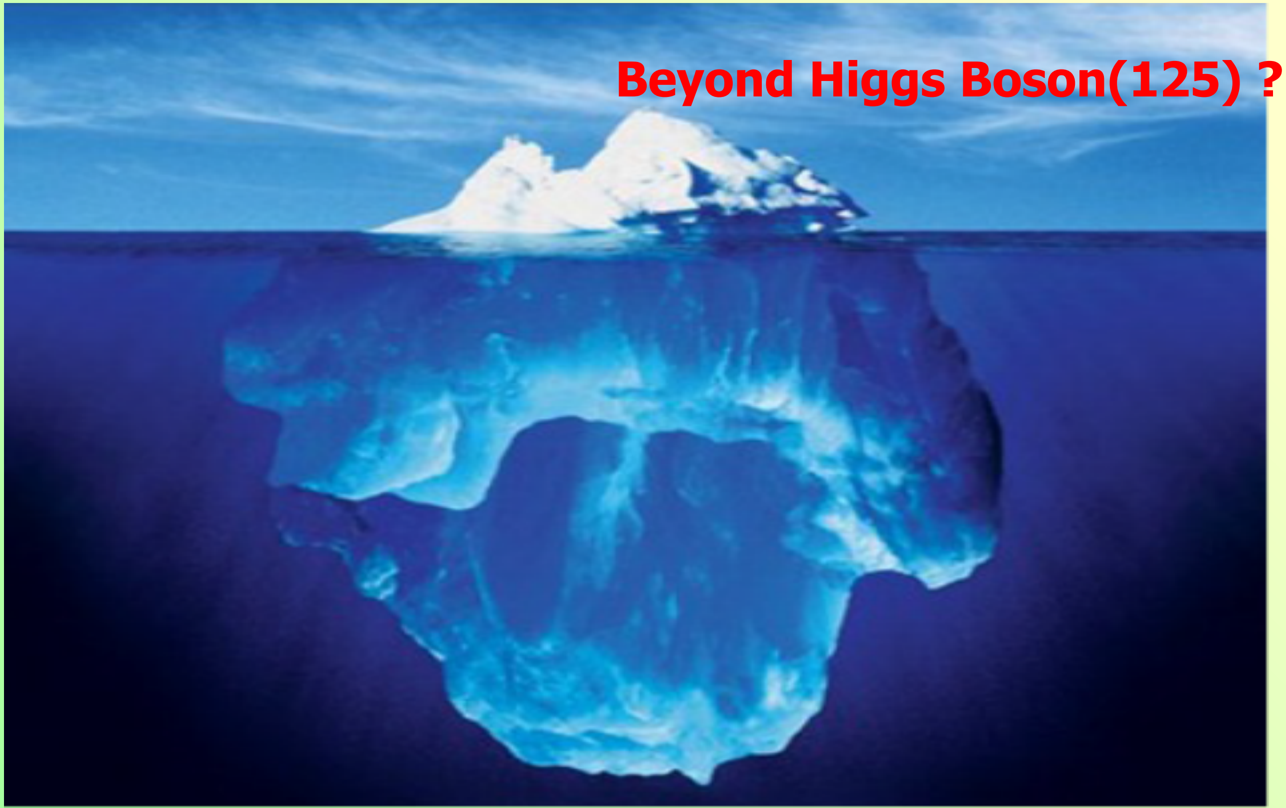


Higgs Boson: Window to New Physics !?

→ **All Particle Masses & Inflation of Universe ?! …..**
Connections to SUSY, DM, CPV, Baryogenesis? …..

→

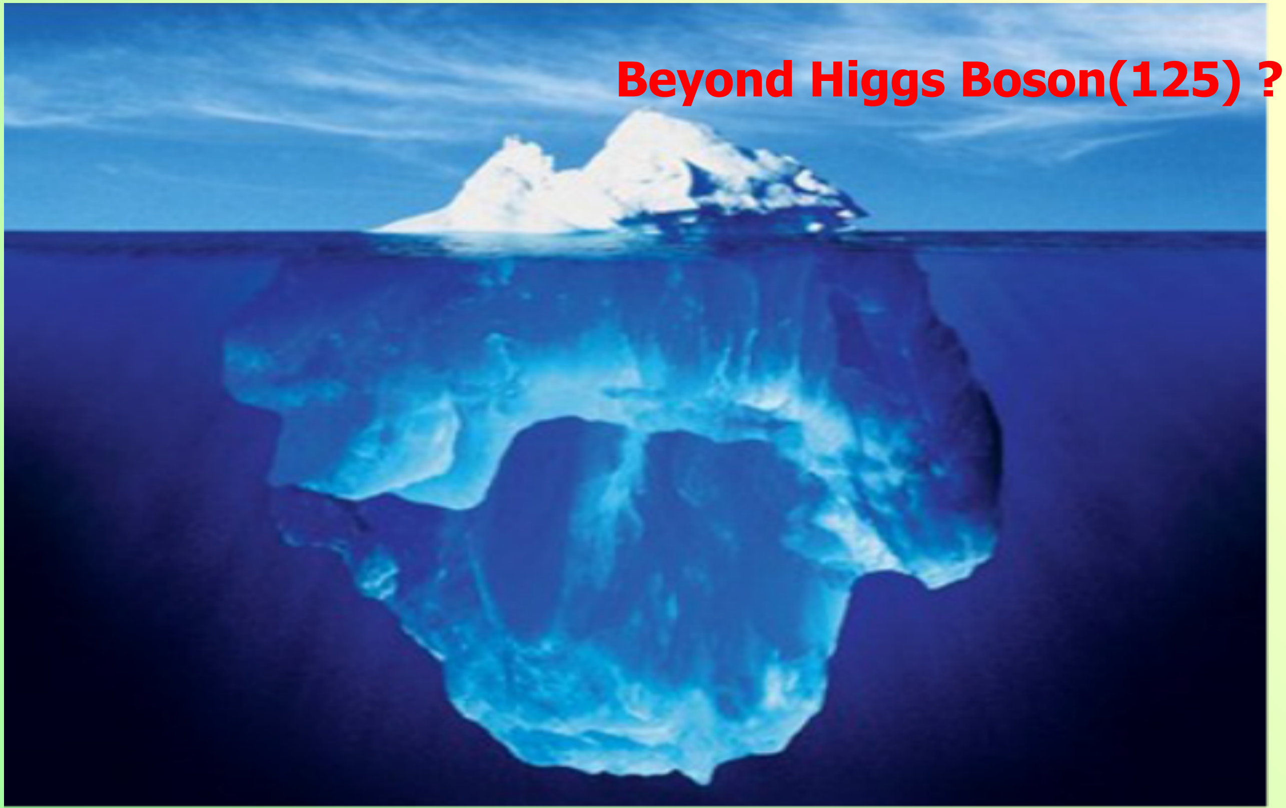
Beyond Higgs Boson(125) ??!!



Higgs Boson: Window to New Physics !?

→ All Particle Masses & Inflation of Universe ?! …..
Connections to SUSY, DM, CPV, Baryogenesis? …..

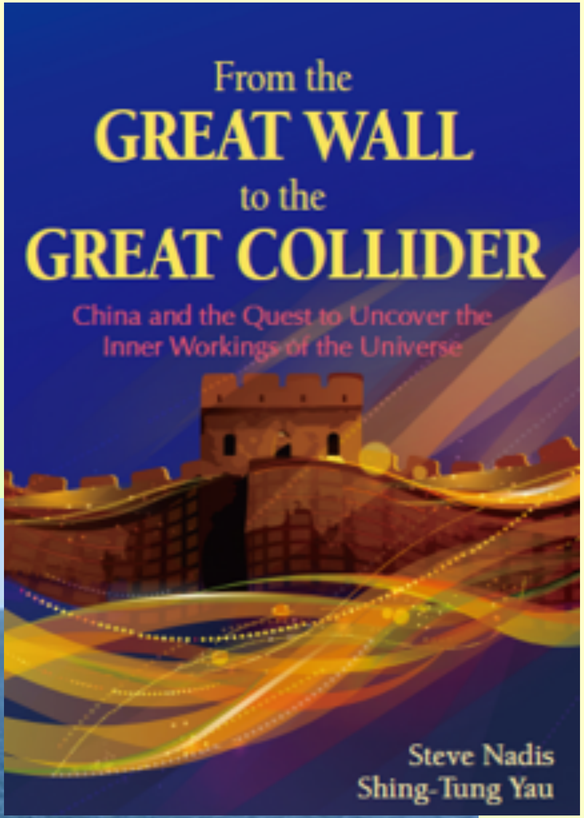
→ h(125) is just the Tip of a giant Iceberg !
To open a Door to New Phys beneath water ?



From Great Wall to Great Collider

see: book of Nadis and Yau
won Prose Prize 2016

Shanhai Pass (山海关) vs CEPC-SPPC



Great Wall → Great Collider (CEPC-SPPC)

Chinese Edition, 4-2016

More Excitements Ahead ！

Let us continue to work together and do good works !


Thank You !

Effective Operators & Sizes of New Physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_j \frac{c_j}{\Lambda^2}\mathcal{O}_j$$

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)

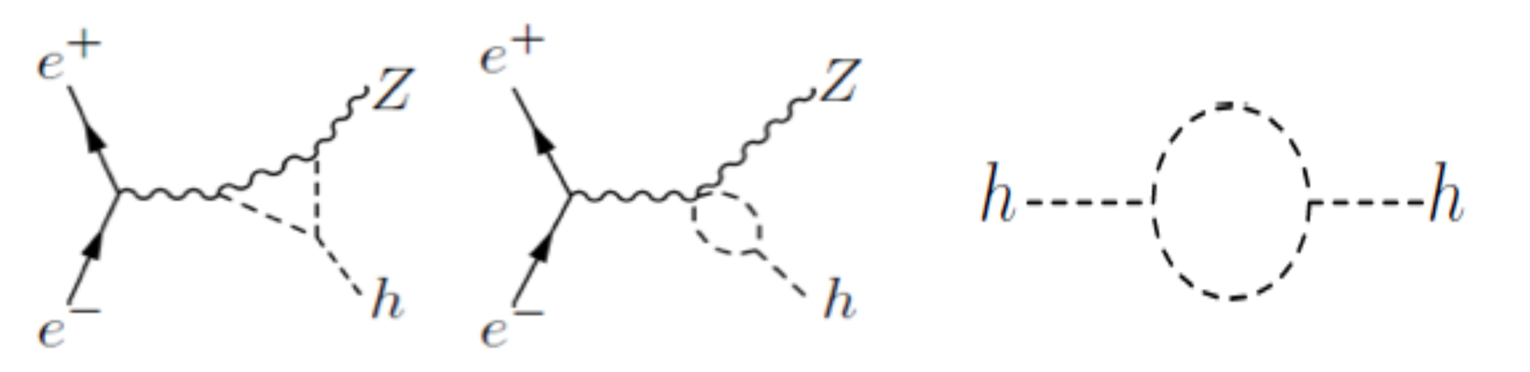
Observables	Central Value	Relative Error	SM Prediction
α	$7.2973525698 \times 10^{-3}$	3.29×10^{-10}	–
G_F	$1.1663787 \times 10^{-5}\mathrm{GeV}^{-2}$	5.14×10^{-7}	–
M_Z	91.1876GeV	2.3×10^{-5}	–
M_W	80.385GeV	1.87×10^{-4}	–
$\sigma[Zh]$	–	0.51%	–
$\sigma[\nu\bar{\nu}h]$	–	2.86%	–
$\sigma[\nu\bar{\nu}h]_{350\mathrm{GeV}}$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

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 27%.**

Probing Higgs Self-Interactions

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

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

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:

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

Probing Higgs Self-Interaction 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

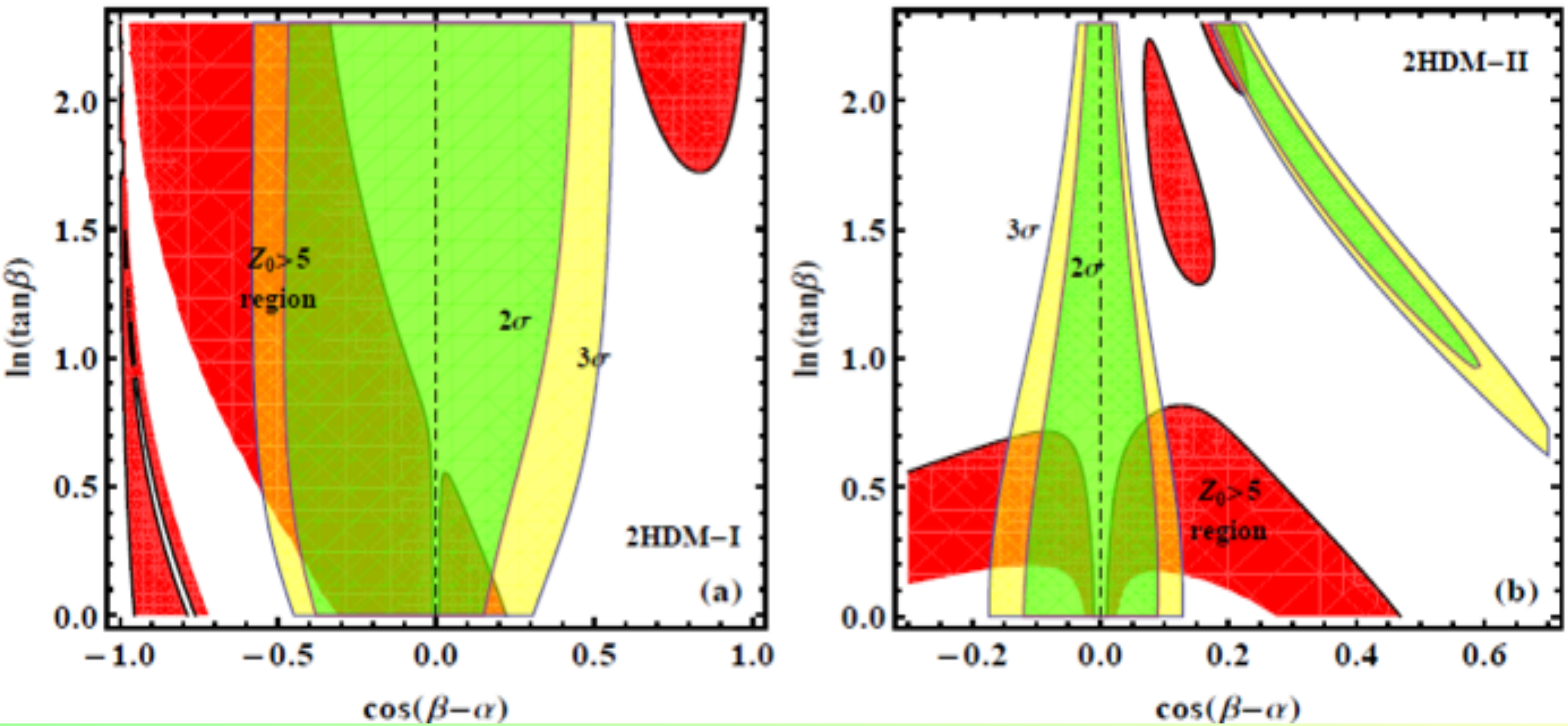
$M_H = (300,\ 400,\ 600)\ \mathrm{GeV},$

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

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)