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:
\textbf{SM}, + eff operators
MSSM, NMSSM, ...

Experiments

Collider Tests...

Cosmology
Observations
LHC New Discovery →
High Energy Physics at Turning Point
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➢ Run-1 Higgs Discovery $h(125\text{GeV})$ in 2012
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LHC New Discovery →
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These will lead to

**New Set of Key Physics Questions**
for **Next Colliders** to answer !!
LHC New Discovery →
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+ Interface with Cosmology & Quantum Gravity
High Energy Physics at **Turning Point**

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Making of the Standard Model

\[ \mathcal{L} = -\frac{1}{4g'_{4}} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g_{2}} W_{\mu\nu}^{a} W^{\mu\nu a} - \frac{1}{4g_{s}^{2}} G_{\mu\nu}^{a} G^{\mu\nu a} \\
+ Q_{i} i \not{\partial} Q_{i} + \bar{u}_{i} i \not{\partial} u_{i} + \bar{d}_{i} i \not{\partial} d_{i} + \bar{L}_{i} i \not{\partial} L_{i} + \bar{\ell}_{i} i \not{\partial} \ell_{i} \\
+ \left( Y_{u}^{ij} \bar{Q}_{i} u_{j} \tilde{H} + Y_{d}^{ij} \bar{Q}_{i} d_{j} H + Y_{l}^{ij} \bar{L}_{i} \ell_{j} H + \text{c.c.} \right) \\
- \lambda (H^{\dagger} H)^{2} + \lambda v^{2} H^{\dagger} H - (D^{\mu} H)^{\dagger} D_{\mu} H \]
Making of the Standard Model

Key Role of Higgs Boson in SM: Mass Generations for W/Z + Quarks/Leptons

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New Physics Beyond SM ??
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➢ 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) @ Run-1

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

2015
a Window to New Physics ??
Spin-0 Higgs Boson Itself is a Window to New Physics?!?
Isomorphic Lorentz Group: \( \text{SO}(3,1) \cong \text{SU}(2) \times \text{SU}(2) \)
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→ Representations of Lorentz Group: $(j, j')$.

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- Mass Puzzle:
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➢ Missing Antimatter Puzzle:
  – Baryogenesis, Leptogenesis, … ?
3 Fundamental Forces in SM Itself
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➢ 2. Yukawa Forces: mediated by Spin-0 Higgs Boson.
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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 $h-\tau-\tau$, $h-b-b$, $h-t-t$ at order of $10-20\%$.
➢ LHC cannot probe Most Other Yukawa Couplings!
➢ LHC can hardly probe Higgs Self-Interaction!
➢ LHC cannot establish $h(125\text{GeV})$ as God Particle!

LHC(300/fb) + HL-LHC(3/ab)  
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.
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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 $ee \rightarrow hZ$ and $ee \rightarrow \nu\nu h$.

➢ 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

<table>
<thead>
<tr>
<th>$\Delta M_h$ (MeV)</th>
<th>$\Gamma_h$ (%)</th>
<th>$\sigma(Zh)$ (%)</th>
<th>$\sigma(\nu\bar{\nu}h) \times \text{Br}(h \rightarrow bb)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>2.6</td>
<td>0.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\sigma(Zh) \times \text{Br}$ (%)</th>
<th>Br (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow bb$</td>
<td>0.21</td>
<td>0.54</td>
</tr>
<tr>
<td>$h \rightarrow cc$</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$h \rightarrow gg$</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>$h \rightarrow \tau\tau$</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$h \rightarrow WW$</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>$h \rightarrow ZZ$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>$h \rightarrow \mu\mu$</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>$h \rightarrow \text{invisible}$</td>
<td>–</td>
<td>0.14</td>
</tr>
</tbody>
</table>

### SM Predictions

<table>
<thead>
<tr>
<th>BR($b\bar{b}$)</th>
<th>BR($c\bar{c}$)</th>
<th>BR($gg$)</th>
<th>BR($\tau\bar{\tau}$)</th>
<th>BR($WW$)</th>
<th>BR($ZZ$)</th>
<th>BR($\gamma\gamma$)</th>
<th>BR($\mu\bar{\mu}$)</th>
<th>BR($\text{inv}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.1%</td>
<td>2.10%</td>
<td>7.40%</td>
<td>6.64%</td>
<td>22.5%</td>
<td>2.77%</td>
<td>0.243%</td>
<td>0.023%</td>
<td>0</td>
</tr>
</tbody>
</table>

*Latest 1σ uncertainty, KITPC WS, July 28*
Effective Higgs Couplings: Gauge & Yukawa

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

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{j} \frac{c_j}{\Lambda^2} \mathcal{O}_j \]

<table>
<thead>
<tr>
<th>Higgs</th>
<th>EW Gauge Bosons</th>
<th>Fermions</th>
</tr>
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<tbody>
<tr>
<td>( \mathcal{O}<em>H = \frac{1}{2} (\partial</em>{\mu}</td>
<td>H</td>
<td>^2)^2 )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>T = \frac{1}{2} (H^\dagger D</em>{\mu} H)^2 )</td>
<td>( \mathcal{O}_{BB} = g^2</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{WB} = gg' H^\dagger \sigma^a H W</em>{\mu \nu}^a B^{a\mu \nu} )</td>
<td>( \mathcal{O}<em>{HW} = ig(\overline{D}^\mu H)^{\dagger} \sigma^a (D^\nu H) W</em>{\mu \nu}^a )</td>
<td>( \mathcal{O}<em>{L} = (i H^\dagger D</em>{\mu} H)(\overline{\Psi}_L \gamma^\mu \Psi_L) )</td>
</tr>
<tr>
<td>Gluon</td>
<td>( \mathcal{O}<em>{HB} = ig'(D</em>{\mu} H)^{\dagger} (D^\nu H) B_{\mu \nu} )</td>
<td>( \mathcal{O}<em>{R} = (i H^\dagger D</em>{\mu} H)(\overline{\Psi}_R \gamma^\mu \psi_R) )</td>
</tr>
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</table>

\( \mathcal{O}_g = g_s^2 |H|^2 G_{\mu \nu}^a G^{a\mu \nu} \)
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 $M_Z$, $M_W$. 

Table: The $M_Z$ & $M_W$ @ CEPC [Z.Liang, “Z & W Physics @ CEPC” & preCDR].
Enhancement from Z-Pole Observables @ CEPC

<table>
<thead>
<tr>
<th>$N_{\nu}$</th>
<th>$A_{FB}(b)$</th>
<th>$R^b$</th>
<th>$R^\mu$</th>
<th>$R^\tau$</th>
<th>$\sin^2 \theta_w$</th>
</tr>
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<tbody>
<tr>
<td>$1.8 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$8 \times 10^{-4}$</td>
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Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

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<th>$O_H$</th>
<th>$O_T$</th>
<th>$O_{WW}$</th>
<th>$O_{BB}$</th>
<th>$O_{WB}$</th>
<th>$O_{HW}$</th>
<th>$O_{HB}$</th>
<th>$O^{(3)}_{LL}$</th>
<th>$O^{(3)}_{L}$</th>
<th>$O_L$</th>
<th>$O_R$</th>
<th>$O^{(3)}_{L,q}$</th>
<th>$O_{L,q}$</th>
<th>$O_{R,u}$</th>
<th>$O_{R,d}$</th>
<th>$O_g$</th>
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<td>2.74</td>
<td>23.7</td>
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➢ Extra Factor-2 Improvements from more Z-pole observables!
Sensitivity from EWPO+HO+Z-Pole

New Physics Scales to be Probed at CEPC via dim-6 Operators

\[ \frac{\mathcal{N}}{|\mathcal{C}_j|} \text{ (TeV)} \]

- 95% confidence level
- 5\( \sigma \) significance level

Operators:
- \( O_H \)
- \( O_T \)
- \( O_{WW} \)
- \( O_{BB} \)
- \( O_{WB} \)
- \( O_{HW} \)
- \( O_{HB} \)
- \( O_{L,L}^{(3)} \)
- \( O_{L,R}^{(3)} \)
- \( O_{L,q} \)
- \( O_{R,L} \)
- \( O_{R,q} \)
- \( O_{R,d} \)
- \( O_{g} \)

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):

\[
\left| \frac{\lambda_{hhh}}{\lambda_{hhh}^{\text{sm}}} - 1 \right|
\]
Probe Higgs Self-Interaction $h^3$ at SPPC

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} O_n, \quad \tilde{\Lambda}_j \equiv \frac{\Lambda}{\sqrt{|f_{\Phi,j}|}}. \]

\[ O_{\Phi,2} = \frac{1}{2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H), \]

\[ O_{\Phi,3} = \frac{1}{3} (H^\dagger H)^3. \]

\[ x_j \equiv \frac{f_{\Phi,j} v^2}{\Lambda^2}, \quad \hat{\tau} \equiv -x_3 \xi^2 \frac{2v^2}{3M_h^2}, \quad \hat{x} \equiv x_2 \xi^2. \]

Benchmark A: \quad (\hat{\tau}, \hat{x})_{\text{sm}} = (0, 0);

$pp(100\text{TeV})$ with $(3, 30)/\text{ab}$:

$pp \rightarrow hh \rightarrow bb\gamma\gamma$

Probe Higgs Self-Interaction $h^3$

\[ L_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} O_n, \quad \tilde{\Lambda}_j \equiv \frac{\Lambda}{\sqrt{|f_{\Phi,j}|}}. \]

\[ O_{\Phi,2} = \frac{1}{2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H), \]

\[ O_{\Phi,3} = \frac{1}{3} (H^\dagger H)^3. \]

\[ x_j \equiv \frac{f_{\Phi,j} v^2}{\Lambda^2}, \quad \hat{\rho} \equiv -x_3 \xi^2 \frac{2v^2}{3M_h^2}, \quad \hat{x} \equiv x_2 \xi^2. \]

$pp(100\text{TeV})$ with $(3, 30)/\text{ab}$:

$pp \rightarrow hh \rightarrow bb\gamma\gamma$

With $3/\text{ab}$ ($30/\text{ab}$) Luminosity:

probe $r$ to $13\%$ ($4.2\%$) precision.
probe $x$ to $5\%$ ($1.6\%$) precision.

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 $\sim 10\text{TeV}$ ($40\text{TeV}$ for $O_g$) from EWPO + HO. up to $\sim 35\text{TeV}$ 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?
**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:

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$V_{LL}$</th>
<th>$t\bar{t}$</th>
<th>$b\bar{b}$</th>
<th>$c\bar{c}$</th>
<th>$s\bar{s}$</th>
<th>$d\bar{d}$</th>
<th>$u\bar{u}$</th>
<th>$\tau^+\tau^-$</th>
<th>$\mu^-\mu^+$</th>
<th>$e^-e^+$</th>
<th>$\nu_{LL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.4</td>
<td>178</td>
<td>4.85</td>
<td>1.65</td>
<td>0.105</td>
<td>0.006</td>
<td>0.003</td>
<td>1.777</td>
<td>0.106</td>
<td>$5.11 \times 10^{-4}$</td>
<td>$5 \times 10^{-11}$</td>
<td></td>
</tr>
</tbody>
</table>

| $n_a$ | 2 | 2 | 4 | 6 | 8 | 10 | 10 | 6 | 8 | 12 | 22 |

| $E_{2 \rightarrow n}^{(\text{min})}$ (TeV) | 1.2 | 3.49 | 23.4 | 30.8 | 52.1 | 77.4 | 83.6 | 33.9 | 56.3 | 107 | 158 |

| $E_{2 \rightarrow 2}$ (TeV) | 1.2 | 3.49 | 128 | $6 \times 10^3$ | $10^5$ | $2 \times 10^6$ | 606 | $10^4$ | $2 \times 10^6$ | $1.1 \times 10^{13}$ |

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

— All these bounds Tied to $O(3-100\text{TeV})$ Scales!

see: Nima’s Overview in preCDR
SM is Incomplete: Vacuum, BA, DM, Inflation??

- **Vacuum Puzzle:** EW vacuum is **Unstable** at $10^{9-11}$ 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!

Example: New Physics at TeV Scale:
New singlet scalar + New quarks of masses $\sim O$(TeV)

Strumia et al, 1307.3536

HJH & Xianyu, JCAP 10(2014) 019
also: arXiv:1602.01801
Higgs Boson as Inflaton ??
Scalar amplitude
\[(V/\epsilon)^{1/4} \approx 0.027\]

Scalar tilt
\[n_s = 1 - 6\epsilon + 2\eta\]

Tensor-to-scalar ratio
\[r = 16\epsilon\]

\[\epsilon = \frac{1}{2}(V'/V)^2\]

\[\eta = V''/V\]
Conventional SM Higgs Inflation

\[ \frac{L_J}{\sqrt{-g}} = \frac{1}{2} R + \frac{1}{2} \xi R \phi^2 + \frac{1}{2} (\partial_\mu \phi)^2 - V(\phi) \]

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

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

Bezrukov & Shaposhnikov, PLB(2008)
Conventional SM Higgs Inflation

\[(V/\epsilon)^{1/4} \approx 0.027\]

\[\xi \approx 10^4\]

\[n_s \approx 0.967\]

\[r \approx 0.003\]
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.
No-Scale Kahler Potential of flipped SU(5):

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

Superpotential up to dim-4:

\[ W = -MG\bar{G} - mH\bar{H} + \lambda GGH + \bar{\chi}GG\bar{G} + \alpha (G\bar{G})^2 + \beta (H\bar{H})^2 + \gamma (G\bar{G})(H\bar{H}) \]

where we set \( M_p = 1 \), \( \Phi_j = (G, \bar{G}, H, \bar{H}, \cdots) \), and
Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, arXiv:1606.02202

➢ Inflation Potential:

\[
V = e^G \left( K_{i j} \frac{\partial G}{\partial \phi_i} \frac{\partial G}{\partial \phi_j^*} - 3 \right)
\]

\[
V(G) = 2G\bar{G}(M - 2\alpha G\bar{G})^2
\]

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

➢ GUT breaking:

\[
\langle G\bar{G} \rangle = M/(2\alpha)
\]

➢ Doublet-Triplet Splitting:

\[
M_{H_c} = 2\lambda v_G, \quad m = \gamma v_G^2
\]
Higgs Inflation in No-Scale SUSY GUT

Ellis, HJH, Xianyu, arXiv:1606.02202

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

\[
V(h) = \frac{(1 - \frac{\beta}{2m} \hat{h}^2)^2 m^2 \hat{h}^2}{2(1 - \frac{1-\zeta}{6} \hat{h}^2)^2}
\]

\[
\frac{1}{2} m^2 \hat{h}^2
\]

➢ Include kinetic term:

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

➢ Normalized field \( h \):

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

➢ 2 Important limits:

\( \zeta = 0 \) \( \Rightarrow \) V is exponentially flat.

\( \zeta = 1 \) \( \Rightarrow \) V is quadratic.
Higgs Inflation in No-Scale SUSY GUT

Predictions for inflation observables:

\( \zeta = 1 \): quadratical inflation.

\( \zeta = 0 \): Starobinsky-like inflation

\( N_e \approx 59 \)

With small deviation \( \delta \):

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

Ellis, HJH, Xianyu, JCAP, arXiv:1606.02202
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.
Higgs Boson: Window to New Physics!? 

Beyond Higgs Boson (125) ??!!
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?

Beyond Higgs Boson(125) ??!!
From Great Wall to Great Collider

see: book of Nadis and Yau won Prose Prize 2016

Shanhai Pass (山海关) vs CEPC-SPPC
More Excitements Ahead!

Let us continue to work together and do good works!
Thank You !
Effective Operators & Sizes of New Physics

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_j \frac{c_j}{\Lambda^2} \mathcal{O}_j \]

<table>
<thead>
<tr>
<th>Model</th>
<th>(\Delta\kappa_V)</th>
<th>(\Delta\kappa_t)</th>
<th>(\Delta\kappa_b, (\Delta\kappa_T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>(\sim -0.5% \left(\frac{400 \text{ GeV}}{M_A}\right)^4 \cot^2 \beta)</td>
<td>(-O(10%) \left(\frac{400 \text{ GeV}}{M_A}\right)^2 \cot^2 \beta)</td>
<td>(\sim O(10%) \left(\frac{400 \text{ GeV}}{M_A}\right)^2)</td>
</tr>
<tr>
<td>Composite</td>
<td>(-3% \left(\frac{1 \text{ TeV}}{f}\right)^2)</td>
<td>(-(3-9)% \left(\frac{1 \text{ TeV}}{f}\right)^2)</td>
<td>(-(3-9)% \left(\frac{1 \text{ TeV}}{f}\right)^2)</td>
</tr>
</tbody>
</table>
### Existing EWPO & Future HO

**Observables:** EWPO (PDG14) + HO (preCDR)

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

### Exclusion (95%) & Discovery (5\sigma) Reach

<table>
<thead>
<tr>
<th>$O_H$</th>
<th>$O_T$</th>
<th>$O_{WW}$</th>
<th>$O_{BB}$</th>
<th>$O_{WB}$</th>
<th>$O_{HW}$</th>
<th>$O_{HB}$</th>
<th>$O_{LL}$</th>
<th>$O_{L}$</th>
<th>$O_{R}$</th>
<th>$O_{L,q}$</th>
<th>$O_{R,u}$</th>
<th>$O_{R,d}$</th>
<th>$O_{g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>2.50</td>
<td>10.6</td>
<td>6.38</td>
<td>5.78</td>
<td>6.52</td>
<td>2.11</td>
<td>0.603</td>
<td>8.21</td>
<td>12.1</td>
<td>10.2</td>
<td>8.78</td>
<td>1.85</td>
<td>0.565</td>
</tr>
<tr>
<td>5\sigma</td>
<td>1.57</td>
<td>6.64</td>
<td>3.99</td>
<td>3.62</td>
<td>4.08</td>
<td>1.32</td>
<td>0.378</td>
<td>5.14</td>
<td>7.57</td>
<td>6.39</td>
<td>5.49</td>
<td>1.16</td>
<td>0.354</td>
</tr>
</tbody>
</table>
CEPC Probe of $h^3$ Coupling

Recall: HL-LHC probes $h^3$ to 50%. ILC500 probes $h^3$ to 27%.

M. McCullough, arXiv:1312.3322
Probing Higgs Self-Interactions

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

\[ V_{\text{int}} = \frac{\lambda_3}{3!} h^3 + \frac{\lambda_4}{4!} h^4 , \]

**SM:**
\[ \lambda_3 = 6\lambda v = 3M_h^2/v \text{ and } \lambda_4 = 6\lambda = 3M_h^2/v^2 . \]

➢ New Physics could modify \( h^3 \) & \( h^4 \) couplings only via dim-6 operators!

\[ O_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H) , \quad O_{\Phi,2} = \frac{1}{2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) , \]
\[ O_{\Phi,3} = \frac{1}{3} (H^\dagger H)^3 , \quad O_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H) . \]
\[ O_{\Phi,f} = (H^\dagger H) \overline{L} H f_R + \text{h.c.} , \]

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

\[ O_{\Phi,2} = \frac{1}{2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) , \quad O_{\Phi,3} = \frac{1}{3} (H^\dagger H)^3 . \]
Probing Higgs Self-Interaction $Hhh$

$$pp \rightarrow H \rightarrow hh \rightarrow WW^*\gamma\gamma$$

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

$M_H = (300, 400, 600)$ GeV,

$$Z_0(\text{combined}) = \sqrt{Z_0^2(\ell\nu\nu\gamma\gamma) + Z_0^2(q\bar{q}'\ell\nu\gamma\gamma)}$$

$\simeq (9.06, 7.41, 12.1)$, for $L = (300, 300, 3000)$ fb$^{-1}$;

$\simeq (7.40, 6.05, 6.99)$, for $L = (200, 200, 1000)$ fb$^{-1}$;

Probing Higgs Self-Interaction $Hhh$

$pp \to H \to hh \to WW^*\gamma\gamma$

$WW^* \to \ell\bar{\nu}\ell\nu$

$q\bar{q}'\ell\nu$