Higgs as a Probe of New Physics

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Osaka University
This talk

Introduction

Fingerprinting Higgs sector at future colliders

Higgs potential and EW Phase Transition

Gravitational waves as a probe of Higgs sector

Synergy (LHC, ILC, LISA, …)

Summary
Introduction
Standard Model

Gauge principle: Interaction
\[ SU(3)_C \times SU(2)_I \times U(1)_Y \]

<table>
<thead>
<tr>
<th>Color</th>
<th>Isospin</th>
<th>Hypercharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_\mu )</td>
<td>( W^a_\mu )</td>
<td>( B_\mu )</td>
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</table>

Spontaneous Symmetry Breaking: Mass
\[ SU(2)_I \times U(1)_Y \rightarrow U(1)_{em} \]

Quarks and leptons 3-generations

<table>
<thead>
<tr>
<th>SU(2) _L</th>
<th>U(1) _Y</th>
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<tr>
<td>( q_L = \begin{pmatrix} u_L \ d_L \end{pmatrix} )</td>
<td>2</td>
</tr>
<tr>
<td>( u_R )</td>
<td>1</td>
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<tr>
<td>( d_R )</td>
<td>1</td>
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<tr>
<td>( l_L = \begin{pmatrix} \nu_{eL} \ e_L \end{pmatrix} )</td>
<td>2</td>
</tr>
<tr>
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Massless
\[ A_\mu \]
Photon

Massive
\[ W^\pm_\mu \]
Weak bosons
\[ Z^0_\mu \]
**Standard Model**

**Gauge principle: Interaction**

\[ SU(3)_C \times SU(2)_I \times U(1)_Y \]

- **Color**
- **Isospin**
- **Hypercharge**

\[ g^\alpha_\mu \text{ Gluon} \quad W^a_\mu \quad B_\mu \]

**Spontaneous Symmetry Breaking: Mass**

\[ SU(2)_I \times U(1)_Y \rightarrow U(1)_{\text{em}} \]

**Tentatively introducing a scalar doublet (Higgs field)**

\[ \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

\[ V(\Phi) = +\mu^2 |\Phi|^2 + \lambda |\Phi|^4 \]

\[ \phi^0 = \frac{1}{\sqrt{2}}(v + h + iz) \]

\[ \mu^2 < 0 \]

**Quarks and leptons 3-generations**

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<td>2</td>
<td>1/3</td>
</tr>
<tr>
<td>(u_R, d_R)</td>
<td>1</td>
<td>4/3</td>
</tr>
<tr>
<td>(l_L = (\nu_{eL}, e_L))</td>
<td>2</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Massless**

- \(A_\mu\) Photon

**Massive**

- \(W^\pm_\mu\) and \(Z^0_\mu\) Weak bosons

\[ \downarrow \text{VEV 246 GeV} \]

\[ \uparrow \text{Higgs boson} \]
LHC experiment

Discovery of a scalar particle
Mass 125 GeV, ...
Spin, Pality $0^+$
Coupling with many particles
$h\gamma\gamma, hgg, hZZ, hWW, h\tau\tau, htt, hbb, \ldots$
Identified as a Higgs boson

Measured couplings turned out to be consistent with the SM Higgs
Tentative SM Higgs sector works well!

No BSM particle has been found

Standard Model is enough?

ATLAS/CMS
July 2012
Higgs problems

Higgs boson was found, but Higgs sector is unknown

- Nature of Higgs boson
  \[ \delta m_H^2 = \frac{\Lambda^2_{\text{cutoff}}}{16\pi^2} \]
- Structure
  Only one Higgs?
- Higgs Potential
  \[ \mu^2 < 0 \]

Hierarchy Problem
New paradigm of New Physics

Multiplet structure, Symmetry, …
Relation to new paradigms and BSM phenomena

EW Symmetry Breaking
Dynamics of EWSB
EW Phase Transition

By the discovery of \( h(125) \), these problems became frontier
Beyond the Standard Model

Many reasons to consider New Physics beyond SM

Unification of Law
  – Paradigm of Grand Unification
  – Yukawa structure (flavor physics)

Problem in the SM Higgs
  – Hierarchy Problem, Shape of Higgs sector, Nature, ...

BSM Phenomena
  – Dark Matter
  – Neutrino mass and mixing
  – Baryon Asymmetry of Universe
  – Inflation, Dark Energy, Gravity,...

New Physics is necessary

At which scale?

If TeV scale, they should have connection with Higgs physics
Higgs physics is a key to new physics

• It is the weakest part in the SM (dirty)
• Its structure remains unknown
• It relates to the physics beyond the SM
• It can be tested by current and future experiments

We can access to the new physics empirically via the Higgs physics!
Nature of Higgs

Higgs Nature ⇔ BSM Paradigm

- Elementary Scalar
- Composite of fermions
- A vector field in extra D
- Pseudo NG Boson
- ......
Nature of Higgs

Higgs Nature \iff BSM Paradigm

- Elementary Scalar \quad SUSY
- Composite of fermions \quad Dynamical Symmetry Breaking
- A vector field in extra D \quad Gauge Higgs Unification
- Pseudo NG Boson \quad Minimal Composite Models
- ...... ...... 

Each new paradigm predicts a specific Higgs sector
(eg. MSSM: two Higgs doublets, GHU: all Higgs couplings are weaker)
Neutrino mass and Higgs

Neutrino Oscillation $\rightarrow$ Tiny mass ($< eV$)

Majorana mass

\[ \mathcal{L} = \frac{c}{\Lambda} (\phi \overline{\nu}_L) (\nu_L \phi) \]

Seesaw Mechanism

\[ m_{ij}^{\nu} = y_i y_j \langle \phi \rangle^2 \frac{\Lambda}{M_R} \]

Tiny mass $\rightarrow$ Large mass of Right-handed Neutrinos

Seesaw Mediated by RH neutrinos $N_R$
Neutrino mass and Higgs

Neutrino Oscillation $\rightarrow$ Tiny mass ($< \text{eV}$)

Majorana mass

$$\mathcal{L} = \frac{c}{\Lambda} (\phi \nu^c_L)(\nu_L \phi)$$

Seesaw Mechanism

$$m^{ij}_\nu = y_i y_j \frac{\langle \phi \rangle^2}{M_R}$$

Tiny mass

Large mass of Right-handed Neutrinos

Alternative Scenario by quantum effects

$$m^{ij}_\nu = c_{ij} \left( \frac{1}{16\pi^2} \right)^N \frac{\langle \phi \rangle^2}{M_{\phi^+}}$$

Tiny mass

Quantum suppression

Mass around TeV scale

Physics of specific extended Higgs sectors

Seesaw

Mediated by RH neutrinos $N_R$

Zee model

Quantum effect due to additional scalar fields
Models of neutrino mass with dark matter

Introducing a discrete $\mathbb{Z}_2$
- Stability of new particle (DM)
- Loop induced masses

Ma model \textit{Ma, 2006}

SM + $H'$ + $N_R$
1-loop induced $\nu$-mass
Dark matter candidate [$H'$]

Model with higher loop effects \textit{Aoki, SK, Seto, 2008}

2HDM + $\eta^0$ + $S^+$ + $N_R$
$\nu$-masses are 3-loop induced
DM candidate [$\eta^0$]
EW Baryogenesis possible (CPV, 1stOPT)
3 Problems can be explained by the TeV scale physics
Baryogenesis and Higgs

Baryon Number of the Universe

\[ \eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} \]  
\[ = (5 - 7) \times 10^{-10} \]

Sakharov’s Condition

1. \( \Delta B \neq 0 \)
2. \( C \) and CP violation
3. Departure from thermal equilibrium

Sakharov 1967

What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

SM could satisfy these conditions but excluded by the data
Baryogenesis and Higgs

Baryon Number of the Universe

\[ \eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (5 - 7) \times 10^{-10} \]

**Baryogenesis**

What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

**Sakharov’s Condition**

- 1. \( \Delta B \neq 0 \)
- 2. C and CP violation
- 3. Departure from thermal equilibrium

SM could satisfy these conditions but excluded by the data

Scenario of Baryogenesis

1. Electroweak Baryogenesis
2. Leptogenesis

Physics of (extended) Higgs sector

New physics at very high scales
Higgs is a window to new physics

Higgs portal new physics scenarios

SUSY
- Dynamical symmetry breaking
- Higgs as a pNGB
- Gauge Higgs Unification
- CW mechanism
- Higgs portal dark matter
- Inert scalar models
- Radiative neutrino mass models
- Electroweak baryogenesis
...

It is important to experimentally determine the Higgs sector to explore new physics beyond SM
Fingerprinting extended Higgs sector at colliders
Extended Higgs sectors

**Multiplet Structure**
- $\Phi_{\text{SM}} + \text{Singlet}$, $\Phi_{\text{SM}} + \text{Doublet}$ (2HDM),
- $\Phi_{\text{SM}} + \text{Triplet}$,
- ...

**Additional Symmetry**
- Discrete or Continuous?
- Exact or Softly broken?

**Interaction**
- Weakly coupled or Strongly Coupled?
- Decoupling or Non-decoupling?
Simplest extension
2 Higgs doublet model (2HDM)

\[ \Phi_i = \left( \frac{\omega^\pm_i}{\sqrt{2}} (v_i + h_i + i z_i) \right) \quad (i = 1, 2) \]

Sharing the VEV

\[ v = 246 \text{ GeV} = \sqrt{v_1^2 + v_2^2} \]

\[ \tan \beta = \frac{v_2}{v_1} \]

Field Mixing

\[ \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \]

\[ \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix} \]

\[ \begin{pmatrix} \omega^\pm_1 \\ \omega^\pm_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \omega^\pm \\ H^\pm \end{pmatrix} \]

New Particles

\[ h, H, A, H^\pm \]

Other three are unphysical Nambu-Goldstone bosons

Deviation in the couplings of \( h(125) \)

\[ \text{SM} \quad hVV \quad 1 \quad \rightarrow \quad \text{2HDM} \quad hVV \quad \sin(\beta-\alpha) \]
Direct search and indirect tests

• Direct searches of additional Higgs bosons

\[ h(125), \ H, \ A, \ H^+, \ H^{++}, \ldots \]

Machine for discovery!

Hadron Collider (LHC)
- Run 1 7-8 TeV 20fb\(^{-1}\)
- Run 2,3 13-14 TeV 300fb\(^{-1}\)
- HL-LHC 13-14 TeV 3000fb\(^{-1}\)
Direct search and indirect tests

• Direct searches of additional Higgs bosons
  $h(125), \ H, A, H^+, H^{++}, \ldots$
  Machine for discovery!
  Hadron Collider (LHC)
  Run1 7-8 TeV 20fb$^{-1}$
  Run 2,3 13-14 TeV 300fb$^{-1}$
  HL-LHC 13-14 TeV 3000fb$^{-1}$

• Indirect test by finding deviations from SM
  EW parameters $m_W, S, T, U, Zff, Wff', WWV, \ldots$
  Couplings of $h(125)$ $hWW, hZZ, hyy, hff, hhh, \ldots$
  Precision measurements!

Advantage for lepton colliders
Future International Linear Collider (ILC)
$E = 250\text{GeV}, 500\text{GeV}, 1\text{TeV}$
**Higgs coupling measurements**

**Measurement accuracy at ILC (500-up)**
- $hVV$ coupling by about 0.4% (95% CL)
- Yukawa coupling by a few % (95% CL)

*Snowmass Higgs Working Group Report 2013*
Future $h(125)$-coupling measurements

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
</tr>
<tr>
<td>$\int Ldt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
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<tr>
<td>$\kappa_\gamma$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
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<tr>
<td>$\kappa_W$</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
<td>0.39%</td>
<td>0.21%</td>
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<tr>
<td>$\kappa_Z$</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
</tr>
<tr>
<td>$\kappa_\ell$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
</tr>
<tr>
<td>$\kappa_d = \kappa_b$</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
<td>0.93%</td>
<td>0.60%</td>
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<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
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Snowmass Higgs Working Group Report 1310.8361
Deviation = New Physics scale
Deviation = New Physics scale

Scaling factor $\kappa_i$: factor of deviation from the SM value

Coupling of $h(125)$ and weak bosons $V (=W, Z)$ $hVV$

$$\kappa_V^2 = \sin^2(\beta-\alpha)$$

If a 2% deviation in $\kappa_V^2$

The second Higgs $H$ must be lighter than 800 GeV

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2} \mathcal{O}^{(6)}$$
Deviation = New Physics scale

Scaling factor $\kappa_i$: factor of deviation from the SM value

Coupling of $h(125)$ and weak bosons $V (=W, Z)$ $hVV$

$$\kappa_V^2 = \sin^2(\beta-\alpha)$$

If a 2% deviation in $\kappa_V^2$

The second Higgs $H$ must be lighter than 800 GeV

Precision test has the similar power to the direct search
Direct detection of the heavier Higgs boson $H$ at LHC

$H \rightarrow \tau \tau$

$SK, Tsumura, Yagyu, Yokoya, 2014$
Complementarity

Direct detection of the heavier Higgs boson $H$ at LHC

Type-II 2HDM

Indirect limits allowed by tree unitarity when $\kappa_V^2 = 0.98$

HL-LHC

Region of discovery at LHC300

$H \rightarrow \tau \tau$

$SK, Tsumura, Yagyu, Yokoya, 2014$
Complementarity

Direct detection of the heavier Higgs boson $H$ at LHC

![Diagram of particle interactions]

Indirectly, new physics can be surveyed by detecting deviations even out of the direct search regions

Type-II 2HDM

Indirect limits allowed by tree unitarity when $\kappa_V^2 = 0.98$

Region of discovery at LHC300

$H \rightarrow \tau \tau$

$SK$, Tsumura, Yagyu, Yokoya, 2014
## Pattern of deviations

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<th>$K_b$</th>
<th>$K_c$</th>
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<td><strong>Type-I</strong></td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
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<tr>
<td><strong>Type-II</strong></td>
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<td>↑</td>
<td>↑</td>
<td>↓</td>
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<tr>
<td><strong>Type-X</strong></td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td><strong>Type-Y</strong></td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
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Gauge couplings: $hVV$

Yukawa couplings: $h\tau\tau$, $hbb$, $hcc$

$$\cos(\beta-\alpha) < 0$$

Direction of deviation in each coupling
We can fingerprint extended Higgs models from the pattern of deviation in Higgs couplings

<table>
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<tr>
<td>Type-I</td>
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Gauge couplings

Yukawa couplings

$\cos(\beta-\alpha) < 0$

Direction of deviation in each coupling

**Pattern of deviations**

We can fingerprint extended Higgs models from the pattern of deviation in Higgs couplings

*SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014*
Fingerprinting the 2HDM

\[ \kappa_V \equiv \frac{g_{hVV(2HDM)}}{g_{hVV(SM)}} = \sin(\beta - \alpha) \]

\[ x = \cos(\beta - \alpha) \quad \text{SM-like: } |x| \ll 1 \]

\[ \kappa_V = 1 - \frac{1}{2} x^2 + \ldots \]

When a Fermion couples to \( \Phi_1 \)

\[ \kappa_f = 1 + \cot \beta \ x + \ldots \]

and if it couples to \( \Phi_2 \)

\[ \kappa_f = 1 - \tan \beta \ x + \ldots \]

If deviation in \( \kappa^2_V \) can be large enough to be detected at future collider

4-models can be separated by looking at deviations in Yukawa couplings \( \kappa_{\tau}, \kappa_b, \kappa_c, \ldots \)

Ellipse = 68.27% CL

\[ K_\tau \]

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014

\[ hbb \text{ vs } h\tau\tau \]

SM point
Fingerprinting SUSY model and Composite Higgs models

Fingerprinting models by precision study at ILC
Radiative Corrections

Higgs couplings $h\gamma\gamma$, $hgg$, $hWW$, $hZZ$, $h\tau\tau$, $hbb$, $htt$, ... will be measured thoroughly in the future.

Clearly analyses with radiative correction is necessary.

Accurate Theory Predictions $\times$ Future Precision Measurements $\rightarrow$ New Physics!
Radiative Corrections

Higgs couplings $h_{\gamma\gamma}, h_{gg}, h_{WW}, h_{ZZ}, h_{\tau\tau}, h_{bb}, h_{tt}, \ldots$ will be measured thoroughly in the future. Clearly analyses with radiative correction is necessary.

Accurate Theory Predictions $\times$ Future Precision Measurements $\rightarrow$ New Physics!

H-COUP Project $SK, Kikuchi, Yagyu (2012–2016)$

Full set of Fortran codes to systematically calculate quantum corrections to Higgs couplings in various extended Higgs models. H-COUP ver. 1 is released in 2017.

- Additional Singlet Models
- 2HDM (I)
- 2HDM (II)
- 2HDM (X)
- 2HDM (Y)
- Inert doublet/singlet
- Triplet model
Example of $H$-COUP

1. 2HDM-I
2. Doublet-Singlet Model (HSM)
3. Inert Doublet Model (IDM)

Prediction on $hbb$, $h\tau\tau$, $h\gamma\gamma$
Scan of inner parameters (mass, mixing angles) under
- Perturbative unitarity
- Vacuum stability,
- Avoiding wrong vacua

We can fingerprint these models, if a deviation in $\kappa_Z$ is detected

Ellipse, $\pm 1\sigma$ at LHC3000 and ILC500

SK, M. Kikuchi, K. Yagyu, 2015
Most important part for EW symmetry breaking (Yet to be tested)

- Physics behind EWSB
  - Where come from $\mu^2 < 0$
  - Origin of $\lambda$

- Electroweak Phase Transition
  - 1\textsuperscript{st} OPT or not?
  - Relation to EW baryogenesis
  - Mechanism of Phase Transition

$$V(\Phi) = +\mu^2|\Phi|^2 + \lambda|\Phi|^4$$
Electroweak Baryogenesis

Sakharov 3rd condition
Departure from Thermal equilibrium

Sphaleron Decoupling
(Strong 1st OPT)

\[ \frac{\varphi_c}{T_c} \gtrsim 1 \]

Physics of the Higgs potential

\( V_{\text{eff}}(\varphi, T) \)

Expanding Bubble

\( T > T_c \)
\( T = T_c \)
\( T < T_c \)

\( \varphi_c \)
\( \varphi \)

Shpaleron Transition decouples

\( n_B \) is frozen

Broken Phase

CP

Symmetric Phase

\( \Delta B \neq 0 \)

Sphaleron transition

\( f \)
\( \overline{f} \)
Strongly 1st OPT

Potential at finite $T$
(high temp. approx.)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1$$

$E$: Thermal Loop Effects

$\lambda_{T_C}$: Self couplings $\sim m_h^2$
Strongly 1st OPT

Potential at finite T (high temp. approx.)

\[ V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots \]

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\( E: \) Thermal Loop Effects

\( \lambda_{T_C}: \) Self couplings \( \sim m_h^2 \)

SM no strong 1\textsuperscript{st} OPT

\[ \frac{\varphi_C}{T_C} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1 \]
Strongly 1st OPT

Potential at finite T
(high temp. approx.)

\[ V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots \]

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\[ E: \text{ Thermal Loop Effects} \]
\[ \lambda_{T_C}: \text{ Self couplings } \sim m_h^2 \]

SM no strong 1\textsuperscript{st} OPT

\[ \frac{\varphi_C}{T_C} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1 \]

Extended Higgs (2HDM): 1\textsuperscript{st} OPT possible

Quantum non-decoupling effect of \( \Phi \) ( = H, A, \( H^+ \), ...)

\[ \frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2} \left\{ 6m_W^3 + 3m_Z^3 + \sum_{\Phi} m_\Phi^3 \left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \left(1 + \frac{3M^2}{2m_\Phi^2}\right) \right\} > 1 \]
Strongly 1st OPT

Potential at finite $T$
(high temp. approx.)

$$V_{\text{eff}}(\varphi, T) \approx D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

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Extended Higgs (2HDM): 1$\text{st}$ OPT possible

Quantum non-decoupling effect of $\Phi$ ($= H, A, H^+, \ldots$)

$$\frac{\varphi_C}{T_C} \approx \frac{1}{3\pi v m_h^2} \left\{ 6m_W^3 + 3m_Z^3 + \sum_{\Phi} m_{\Phi}^3 \left( 1 - \frac{M^2}{m_{\Phi}^2} \right)^3 \left( 1 + \frac{3M^2}{2m_{\Phi}^2} \right) \right\} > 1$$

Prediction! Large deviation in the $hhh$ coupling as well

$$\lambda_{hhh} \approx \frac{3m_h^2}{v^2} \left\{ 1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \sum_{\Phi} \frac{m_{\Phi}^4}{12\pi^2 v^2 m_h^2} \left( 1 - \frac{M^2}{m_{\Phi}^2} \right)^3 \right\} > \lambda_{hhh}^{\text{SM}}$$
First Order Phase Transition

Effective potential at one-loop level:

\[ V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2} \varphi^2 + \frac{\lambda}{4} \varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left( \ln \frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2} \right) \]

Contribution at finite-temperatures:

\[ \Delta V_T(\varphi, T) = \frac{T^4}{2\pi^2} \left[ \sum_{i=\text{bosons}} n_i I_B(a^2) + \sum_{i=\text{fermions}} n_i I_F(a^2) \right] \]

High-temperature expansion:

\[ V_{\text{eff}}(\varphi, T) \approx D(T^2 - T_0^2) \varphi^2 - E T \varphi^3 + \frac{\lambda_T}{4} \varphi^4 + \ldots \]

\[ I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12} a^2 - \frac{\pi}{6} (a^2)^{3/2} - \frac{a^4}{32} \left( \ln \frac{a^2}{\alpha_B} - 3/2 \right) + \mathcal{O}(a^6) \]

\[ I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24} a^2 - \frac{a^4}{32} \left( \ln \frac{a^2}{\alpha_F} - 3/2 \right) + \mathcal{O}(a^6) \]

Strongly 1\textsuperscript{st} OPT (\( \varphi_c/T_c \gtrsim 1 \)) can be achieved by adding bosons

Necessary for successful electroweak baryogenesis
Strong 1st OPT
⇔ Deviation in the $hhh$ coupling

EW Baryogenesis can be tested by detecting a large deviation in the $hhh$ coupling

Which collider?
LHC cannot do it
Only ILC (1 TeV) can measure it by $O(10)$%

K. Fujii et al., arXiv:1506.05992 [hep-ex]

Connection between Cosmological problem and Collider
Higgs Self-Coupling

hhh coupling = consequence of vacuum condensation

Challenging measurement because of:
- Small cross section (ZhH 0.2 fb at 500 GeV)
- Many jets in the final state
- Presence of irreducible BG diagrams

<table>
<thead>
<tr>
<th>arXiv:1310.0763</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
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<td>500/1000</td>
<td>500/1000</td>
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<td>1600‡</td>
<td>500+1000</td>
<td>1600+2500‡</td>
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<td>$P(e^-, e^+)$</td>
<td>$(-0.8, 0.3)$</td>
<td>$(-0.8, 0.3)$</td>
<td>$(-0.8, 0.3/0.2)$</td>
<td>$(-0.8, 0.3/0.2)$</td>
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<tr>
<td>$\sigma (ZH H)$</td>
<td>42.7%</td>
<td>42.7%</td>
<td>23.7%</td>
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<tr>
<td>$\sigma (\nu \bar{\nu} HH)$</td>
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<td>$\lambda$</td>
<td>83%</td>
<td>46%</td>
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Ongoing analysis improvements towards $O(10\%)$ measurement
Timeline

Original plan of ILC is like this...

LHC Run2, 3

Super KEKB

HL-LHC

ILC 250? ILC500?

Precision measurement of Higgs couplings

Far future !!

Measurement of $hhh$ coupling

ILC1TeV?

Today
Timeline

Super KEKB

LHC Run2, 3

HL-LHC

Far future !!

Measurement of \( hhh \) coupling

ILC might be realized, but as its minimum form ILC(250GeV) without extension

ILC250 with 1-2 ab\(^{-1}\) (?)

Precision measurement of Higgs couplings \( hVV, hff \)

2015  2020  2025  2030  2035  2040  2045

TODAY

ILC1TeV?
Good, but we CANNOT access the Higgs potential in the near future without ILC(1TeV)

ILC might be realized, but as its minimum form ILC(250GeV) without extension

**Super KEKB**

**LHC Run2, 3**

**HL-LHC**

**ILC250** with $1-2 \text{ ab}^{-1}$ (?)

Precision measurement of Higgs couplings $hVV, hff$

**Far future !!**

Measurement of $hhh$ coupling

ILC1TeV?
Fortunately, the situation has changed drastically

Direct detection of Gravitational Waves at LIGO

Space based GW interferometer LISA has been approved recently, which will start in 2028

We may be able to access the Higgs potential observing the Gravitational Waves from 1st Order Phase transition
Timeline

- **Super KEKB**
  - LHC Run2, 3
  - HL-LHC

- **ILC250** with 1-2 ab\(^{-1}\) (?)
  - Precision measurement of Higgs couplings \(hVV, hff\)

- **Far future !!**
  - Measurement of \(hhh\) coupling

TODAY
Timeline

Super KEKB

LHC Run2, 3
Direct searches

HL-LHC

ILC250 with 1-2 ab⁻¹ (?)
Precision measurement of Higgs couplings $hVV, hff$

LISA (approved!) 2028--
EW Phase Transition via Gravitational Waves

Far future !!
Measurement of $hhh$ coupling

ILC1TeV?

2015 2020 2025 2030 2035 2040 2045

2015 2020 2025 2030 2035 2040 2045

TODAY

Precision measurement of Higgs couplings $hVV, hff$

ILC250 with 1-2 ab⁻¹ (?)

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Far future !!
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2015 2020 2025 2030 2035 2040 2045

TODAY

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Far future !!
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2015 2020 2025 2030 2035 2040 2045

TODAY

Precision measurement of Higgs couplings $hVV, hff$

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EW Phase Transition via Gravitational Waves

Far future !!
Measurement of $hhh$ coupling

ILC1TeV?
Timeline

Super KEKB

LHC Run2, 3

2015 2020 2025 2030 2035 2040 2045

TODAY

Golden age 2030s !!

HL-LHC

ILC250 with 1-2 ab\(^{-1}\) (?)

Precision measurement of Higgs couplings \( hVV, hff \)

ILC1TeV?

Far future !!

Measurement of \( hhh \) coupling

Synergy!

SuperKEKB

Flavor Physics

HL-LHC

Energy Frontier (New Particle Searches)

ILC

Precision measurement of Higgs couplings

LISA

EW Phase Transition from GWs

TODAY
Gravitational Wave

a new tool for exploring physics BSM
Higgs potential via GWs

In 2016, aLIGO reported the first direct observation of GWs from merge of a BH Binary ($\sim 100$ Hz) → **Era of GW astronomy started**

*Ground based experiments* aLIGO, KAGRA, aVirgo…
Higgs potential via GWs

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Ground based experiments aLIGO, KAGRA, aVirgo…

GW Physics?

GW from 1\(^{st}\) OPT: homogeneous, isotropic, stationary, unpolarized
Relic GWs are characterized only by frequency

Transition temperature gives typical frequencies

\[ T = 100\text{GeV} \rightarrow f = 10^{-1} \text{--} 10^{-3}\text{ Hz} \]

Out of sensitivity at LIGO/KAGRA (10-10\(^3\)Hz)
Red-Shifted frequency

\[ f_0 = \frac{a_t}{a_0} f_t \]

\( f_t \): frequency at the transition

Conservation of the entropy per comoving volume

\[ s a^3 = \frac{2\pi^2}{45} g_s T^3 a^3 = \text{const} \]

\[ \frac{a_t}{a_0} = \left( \frac{g_{s0}}{g_s^t} \right)^{1/3} \frac{T_0}{T_t} \]

Radiation dominant Universe

\[ H = \sqrt{\frac{4\pi^3}{45} g_*^{1/2} \frac{T^2}{M_{Pl}}} \]

We obtain

\[ f_0 \simeq 1.7 \times 10^{-5} \left( \frac{g_*^t}{100} \right)^{1/6} \left( \frac{T_t}{100 \text{ GeV}} \right) \frac{f_t}{H_t} \text{ Hz} \]

\( f_t/H_t \) must be > 1, typically \( 10^2 \) (\( 10^2 \)-\( 10^4 \))

\[ f_0 = 10^{-3} - 10^{-1} \text{ Hz} \]
Higgs potential via GWs

In 2016, aLIGO reported the first direct observation of GWs from merge of a BH Binary ($\sim 100$ Hz) → Era of GW astronomy started
Ground based experiments
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Future space based GW experiments

LISA (USA/Europe) Sensitivity around mili Hz (2028–)
DECIGO (Japan) Sensitivity around deci Hz

We can explore GWs from the early Universe!
Properties of the representative eLISA configurations

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<th>C2</th>
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<td>Arm length [km]</td>
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<td>1M</td>
<td>2M</td>
<td>1M</td>
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<td>Duration [years]</td>
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<td>Noise level</td>
<td>N2</td>
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<td>N1</td>
</tr>
</tbody>
</table>

C. Caprini et al., arXiv:1512.06239

FP (Fabry-Perot)-DECIGO
1 cluster (arm length 1000km)
Correlation between 2 cluster

S. Kawamura et al, Class. Quant. Grav. 28, 094011 (2011)

Important background
Extragalactic WD binaries (isotropic)

\[ \Omega h^2 = 10^{-11} - 10^{-10} \]
\[ f_{\text{peak}} = 2 \times 10^{-2} \text{ Hz} \]

Schneider et al., 2005

LISA has been approved in 2016
It will start from 2028
Origin of GWs from 1st OPT

Bubble nucleation in the universe

Broken Phase

Symmetric Phase

$r_0$: size of critical bubble

Expanding babbles of the broken phase

Bubble is spherical $\Rightarrow$ No GW occurs
GWs from 1\textsuperscript{st} OPT

Bubble Collisions

“Turbulences in the plasma”

“Wall Collisions”
(Envelope approximation)

“Sound waves”
(Compressional plasma)

Spherical symmetry is violated by bubble collisions $\rightarrow$ GW occurs

\[ \Box \bar{h}_{\mu\nu} = \kappa T_{\mu\nu} \]

Source of GW
From bubble dynamics to GW spectrum

Bubble nucleation rate per unit volume and time

\[ \Gamma(T) = \Gamma_0 \exp(-S_3/T) \]

\[ S_3 = \int d^3r \left[ \frac{1}{2}(\nabla \varphi_b)^2 + V_{\text{eff}}(\varphi_b, T) \right] \]

\[ T_t \quad \text{Transition temperature} \]

\[ \left. \frac{\Gamma}{H^4} \right|_{T=T_t} \simeq 1 \rightarrow \frac{S_3(T_t)}{T_t} = 4 \ln(T_t/H_t) \simeq 140 \]

\[ \alpha \quad \text{Latent heat (released energy of false vacuum)} \]

\[ \alpha = \frac{\epsilon(T_t)}{\rho_{\text{rad}}(T_t)} \quad \epsilon(T) = -V_{\text{eff}}(\varphi_B(T), T) + T \frac{\partial V_{\text{eff}}(\varphi_B(T), T)}{\partial T} \]

\[ \beta \quad \text{Inverse of duration of phase transition} \]

\[ \beta = -\left. \frac{dS_E}{dt} \right|_{t=t_t} \simeq \frac{1}{\Gamma} \left. \frac{d\Gamma}{dt} \right|_{t=t_t} \quad \tilde{\beta} = \frac{\beta}{H_t} \]

GW spectrum is given as a function of \( T_t, \alpha, \beta \) (and \( v_b \))

Ex) Strength and peak frequency of GW (Fitting function)

\[ \tilde{\Omega}_{sw} h^2 \simeq 2.65 \times 10^{-6} \frac{v_b}{\tilde{\beta}} \left( \frac{\kappa(v_b, \alpha)\alpha}{1 + \alpha} \right)^2 \]

\[ \tilde{f}_{sw} \simeq 1.9 \times 10^{-5} \text{Hz} \frac{\tilde{\beta}}{v_b} \]

C.Caprini et al., arXiv:1512.06239
The spectrum of GWs from Bubble collision

Complicated numerical simulations are necessary

Approximate fitting formulae given by C.Caprini et al., arXiv:1512.06239

1. Sound waves (Compressional waves of thermal plasma)

\[
\tilde{\Omega}_{sw} h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left( \frac{\kappa_{\nu} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3} \tilde{f}_{sw} \simeq 1.9 \times 10^{-5} \text{Hz}\frac{1}{v_b} \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)
\]

2. Collision of the bubbles (envelop approximation)

\[
\tilde{\Omega}_{env} h^2 \simeq 1.67 \times 10^{-5} \times \left( \frac{0.11 v_b^3}{0.42 + v_b^2} \right) \tilde{\beta}^{-2} \left( \frac{\kappa_{\phi} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3} \tilde{f}_{env} \simeq 1.65 \times 10^{-5} \text{Hz} \times \left( \frac{0.62}{1.8 - 0.1 v_b + v_b^2} \right) \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)
\]

3. Magnethydrodynamic (MHD) plasma turbulence in the bubbles

\[
\tilde{\Omega}_{turb} h^2 \simeq 3.35 \times 10^{-4} v_b \tilde{\beta}^{-1} \left( \frac{\epsilon \kappa_{\nu} \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g_*^t} \right)^{1/3} \tilde{f}_{turb} \simeq 2.7 \times 10^{-5} \text{Hz}\frac{1}{v_b} \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)
\]

\( v_b \) : wall velocity \hspace{1cm} \( \kappa_{\phi} \kappa_{\nu} \) : efficiency factors \hspace{1cm} \( \epsilon = 0.05 \)

The spectrum are evaluated by inputting the latent heat \( \alpha \), variation of the bubble nucleartion rate \( \beta \) and transition temperature \( T_t \)
Higgs model with $N$ singlet fields

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007

Imposed $O(N)$ for simplicity

\[
S^T = (S_1, \cdots, S_N)
\]

\[
V_0 = -\mu^2|\Phi|^2 + \frac{\mu S^2}{2} |S|^2 + \frac{\lambda}{2} |\Phi|^4 + \frac{\lambda S}{4} |S|^4 + \frac{c}{2} |\Phi|^2 |S|^2
\]

Mass of scalar fields:

\[
m_S^2 = \mu_S^2 + \frac{c}{2} \nu^2
\]

$\varphi_c/T_c > 1$ is satisfied by the nondecoupling effect of the singlet fields (compatible with $m_h=125\,\text{GeV}$)

\[
\frac{\varphi_C}{T_C} \approx \frac{1}{3\pi \nu m_h^2} \left\{ 6m_W^3 + 3m_Z^3 + Nm_S^3 \left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 \left(1 + \frac{3\mu_S^2}{2m_S^2}\right) \right\} > 1
\]

\[
\lambda_{hhh}^{O(N)} \approx \frac{3m_h^2}{\nu^2} \left\{ 1 - \frac{m_t^4}{\pi^2 \nu^2 m_h^2} + N \frac{m_S^4}{12\pi^2 \nu^2 m_h^2} \left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 \right\} > \lambda_{hhh}^{\text{SM}}
\]
Large deviations in $hhh$ coupling

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007
GW spectrum from $1^{st}$ OPT

Mass $m_s$ is chosen such that the peak strength is maximal

$N = 1, 4, 60$

Bound from Non-observation of energy density of extra radiation

Sensitivities
- eLISA
- DECIGO

$\Omega_{GW} h^2$

$\Delta N, \geq 1$

$N$ scalar model

\[(N, m_s)\] \text{may be determined from GWs}

O(N) singlet model with the mass \(m_s\)

For smaller \(m_s\), \[\varphi/T_c > 1\] cannot be satisfied.

For larger \(m_s\), \[\Gamma/H^4 = 1\] cannot be satisfied.

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11, 115007
$(N, m_s)$ may be determined from GWs

O(N) singlet model with the mass $m_s$

If $\alpha$ and $\beta$ are determined with a resolution, We may be able to fingerprint the model with $(N, m_s)$

Sensitivities
- eLISA
- arXiv:1512.06239
- DECIGO,
  Class. Quant. Grav. 28, 094011 (2011)

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007
Timeline

Super KEKB

LHC Run2, 3

HL-LHC

ILC250 with 1-2 ab\(^{-1}\) (?)

Precision measurement of Higgs couplings \(hVV, hff\)

ILC1TeV?

Golden 2030s ???

Far future !!

Measurement of \(hhh\) coupling

Synergy!

SuperKEKB

HL-LHC

ILC

LISA

Flavor Physics

Energy Frontier (New Particle Searches)

Precision measurement of Higgs couplings

EW Phase Transition from GWs

TODAY
Final Example: Strongly 1\textsuperscript{st} OPT by non-thermal mixing effect

\[
V_{\text{eff}} = D(T^2 - T_0^2)\varphi^2 - (ET - e)\varphi^3 + \frac{\lambda(T)}{4} \varphi^4
\]

Thermal loop effect ↓

Non-thermal effect ↑

Higgs singlet model \hspace{1cm} K. Fuyuto and E. Senaha, 2014

\[
V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda\Phi|\Phi|^4 + \mu_\Phi S|\Phi|^2 S + \frac{\lambda_\Phi S}{2}|\Phi|^2 S^2 + \mu_3 S^3 + \frac{m_\Phi^2}{2} S^2 + \frac{\mu_3}{3} S^3 + \lambda S^4
\]

\[
\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{pmatrix}, \quad S = v_S + \phi_2 \quad (\phi_1, \phi_2) \rightarrow (h, H) \text{ with } \theta
\]

Multi-field analysis of EWPT is necessary

\[
(v_\Phi, v_S)
\]

Public tool "CosmoTransition" (Python code) is used.
LISA and DECIGO are capable of detecting GWs from 1\textsuperscript{st} OPT in the HSM.
$K = K_V = K_f = \cos \theta$

Precision measurement at ILC/LHC

Self-coupling $hhh$ measurement at ILC

Region of Strong 1st OPT

Direct searches of the second Higgs at LHC

$K = K_V = K_f = \cos \theta$

Precision measurement at ILC

$\kappa_V : 2\%$

$\kappa_Z : 0.37\%$

$\kappa_W : 0.51\%$

HL-LHC

ILC

$\varphi_c/T_c = 1.0$

$\Gamma/H^4 = 1$

$\Delta \lambda_{hhh}/\lambda_{hhh} = 10\%$

$\Delta \lambda_{H,h,h} : 10\%$

Measurement of Gravitational Waves at LISA/DECIGO

Direct searches of the second Higgs at LHC

Summary 1

- Structure of the Higgs sector is directly connected to new physics

- Extended Higgs sectors can be tested directly by discovering the 2nd Higgs bosons, or indirectly by measuring the couplings of $h(125)$.

- Detecting a pattern of deviations in the $h(125)$ couplings, we can fingerprint the Higgs sector and further direction of new physics
Summary 2

• Higgs potential is the last unknown part in SM. Its property is tested by measuring the $hhh$ coupling at colliders.

• Extended Higgs models of 1$^{\text{st}}$ OPT predict always large deviations in the $hhh$ coupling and also produce Gravitational Waves.

• Future precision measurements of GWs may be able to fingerprint models of 1$^{\text{st}}$ OPT.

• There can be a strong synergy in model identification among direct searches at HL-LHC, precision measurements of Higgs couplings ($\kappa_i$) at ILC and the GW spectrum at LISA in 2030s.
Higgs as a Probe of New Physics

Hierarchy

GUT

Baryogenesis

Neutrino mass

Dark Matter

Cosmic Inflation

Physics at Planck scale

Synergy and Complementarity

LHC New particle searches
SKEKB Flavor physics
ILC Precision study
LISA Gravitational Waves

これからますます面白くなる
Thank you
Probing the Higgs potential by GW observations

Sensitivity of GW detectors

[See talks by Kawamura, Nardini]

http://rhcole.com/apps/GWplotter/
Landau pole

- Large scalar couplings at the EW scale

Landau pole near the EW scale

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<td>$\Lambda(\lambda_s = 0.2)$</td>
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<td>14 TeV</td>
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<td>2.7 TeV</td>
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</table>

[Hashino, MK, Kanemura, Matsui (2016)]
Efficiency factor

[Image of a graph showing efficiency factor as a function of $V_b$]

$\alpha = 1$
$\alpha = 0.1$
$\alpha = 0.01$

$V_f(\alpha), k_c(\alpha)$
$(c, k_B(\alpha))$
$(1, k_D(\alpha))$

$\log_{10}[K_v]$

$0.0$
$0.5$
$1.0$
$1.5$
$2.0$

$0.0$
$0.2$
$0.4$
$0.6$
$0.8$
$1.0$

[Espinosa et al. (2010)]
Run 1
Best fit values for combination of ATLAS and CMS

Assumption, absence of BSM particles in the loops and $\text{BR}_{\text{BSM}} = 0$

$$\kappa_Z = 1.00^{+0.10}_{-0.11}$$
$$\kappa_W = 0.91^{+0.09}_{-0.09}$$
$$\kappa_t = 0.89^{+0.15}_{-0.13}$$
$$\kappa_\tau = 0.90^{+0.14}_{-0.13}$$
$$\kappa_b = 0.67^{+0.22}_{-0.20}$$

Roughly Higgs couplings are determined by 20%
### Snowmass White Paper (Aug. 2013)

<table>
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<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
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</tr>
<tr>
<td>$\int L dt$ (fb^{-1})</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
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</table>

| $\kappa_\gamma$  | 5 – 7%  | 2 – 5%  | 8.3%    | 4.4%      | 3.8%      | 2.3%       | $\pm 5.5/5.5\%$ | 1.45%        |
| $\kappa_g$       | 6 – 8%  | 3 – 5%  | 2.0%    | 1.1%      | 1.1%      | 0.67%      | 3.6/0.79/0.56%  | 0.79%        |
| $\kappa_W$       | 4 – 6%  | 2 – 5%  | 0.39%   | 0.21%     | 0.21%     | 0.13%      | 1.5/0.15/0.11%  | 0.10%        |
| $\kappa_Z$       | 4 – 6%  | 2 – 4%  | 0.49%   | 0.24%     | 0.44%     | 0.22%      | 0.49/0.33/0.24%  | 0.05%        |
| $\kappa_t$       | 6 – 8%  | 2 – 5%  | 1.9%    | 0.98%     | 1.3%      | 0.72%      | 3.5/1.4/\textless 1.3% | 0.51%        |
| $\kappa_\ell$    | 10 – 13%| 4 – 7%  | 0.93%   | 0.51%     | 0.51%     | 0.31%      | 1.7/0.32/0.19%  | 0.39%        |
| $\kappa_u$       | 14 – 15%| 7 – 10% | 2.5%    | 1.3%      | 1.3%      | 0.76%      | 3.1/1.0/0.7%    | 0.69%        |

\[
g(hxx) = \kappa_x \ g(hxx)_{SM}
\]

**ILC Higgs White Paper**

*Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto, Weiglein, et al.*
# Future $h(125)$-coupling measurements

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
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<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
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<tr>
<td>$\int d\beta (\text{fb}^{-1})$</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
</tr>
<tr>
<td>$\kappa_{\gamma}$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
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<td>$\kappa_{\ell}$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
</tr>
<tr>
<td>$\kappa_{d} = \kappa_{b}$</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
<td>0.93%</td>
<td>0.60%</td>
</tr>
<tr>
<td>$\kappa_{u} = \kappa_{t}$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Snowmass Higgs Working Group Report 1310.8361