Higgs as a Probe of New Physics

Shinya KANEMURA
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

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

Color — Isospin — Hypercharge

$\boxed{g_\mu^\alpha}$ Gluon $\quad W_\mu^a \quad B_\mu$

Spontaneous Symmetry Breaking: Mass

$$SU(2)_I \times U(1)_Y \to U(1)_{\mathrm{em}}$$

Quarks and leptons 3-generations

Massive

	$SU(2)_L$	$U(1)_Y$
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	2	1/3
u_R	1	4/3
d_R	1	−2/3
$l_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	2	−1
e_R	1	−2

Massless — Massive

$\boxed{A_\mu}$ Photon

$\boxed{W_\mu^\pm \quad Z_\mu^0}$ Weak bosons

Standard Model

Quarks and leptons
3-generations

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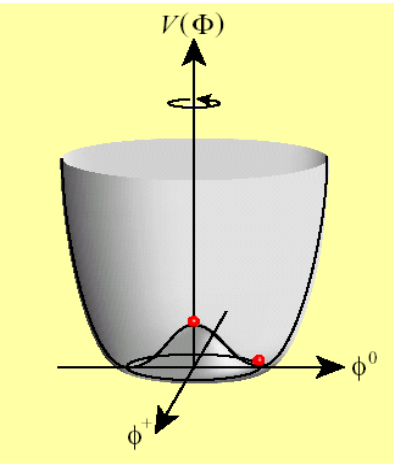


Tentatively introducing a scalar doublet (Higgs field)

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

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

$\mu^2 < 0$

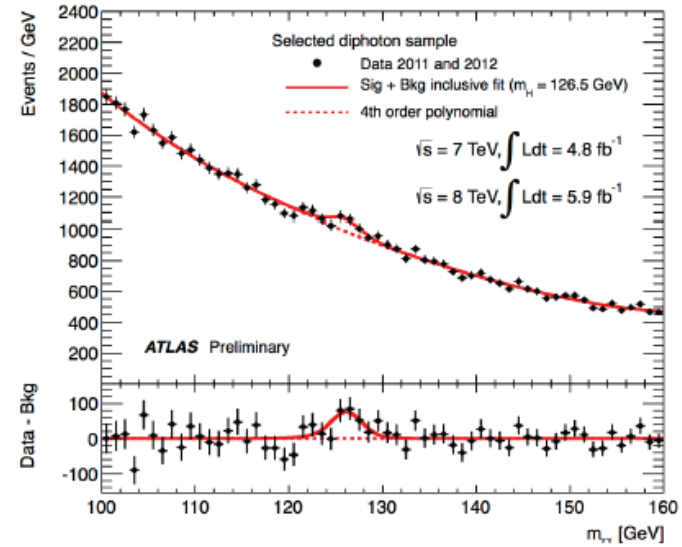
↓VEV 246GeV

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

Higgs boson

LHC experiment

ATLAS/CMS
July 2012



Discovery of a scalar particle

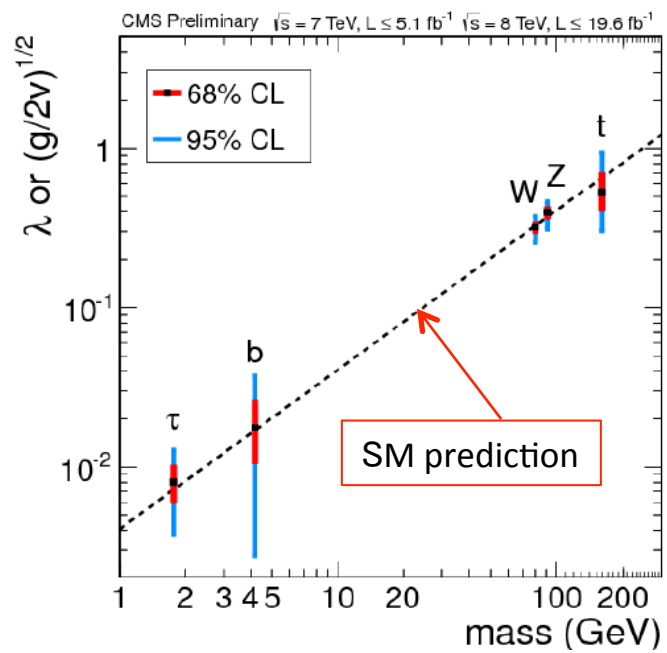
Mass 125 GeV, . . .

Spin, Pality 0^+

Coupling with many particles

hγγ, hgg, hZZ, hWW, hττ, htt, hbb, . . .

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?

Higgs problems

Higgs boson was found, but Higgs sector is unknown

- **Nature of Higgs boson**

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

Hierarchy Problem

New paradigm of New Physics

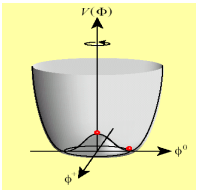
- **Structure**

Only one Higgs?

Multiplet structure, Symmetry, …

Relation to new paradigms and BSM phenomena

- **Higgs Potential**



$\mu^2 < 0$

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	SUSY
– Composite of fermions	Dynamical Symmetry Breaking
– A vector field in extra D	Gauge Higgs Unification
– Pseudo NG Boson	Minimal Composite Models
– ……	……

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Each new paradigm predicts a specific Higgs sector

(eg. MSSM: two Higgs doublets,

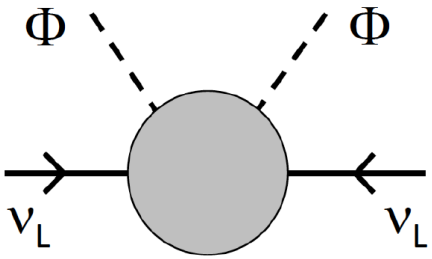
GHU: all Higgs couplings are weaker)

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass (< eV)

Majorana mass

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

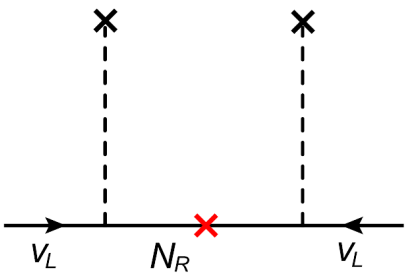


Seesaw Mechanism

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

Tiny mass

← Large mass of Right-handed Neutrinos



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Mediated by RH neutirnos N_R

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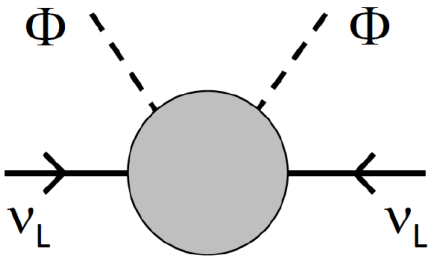

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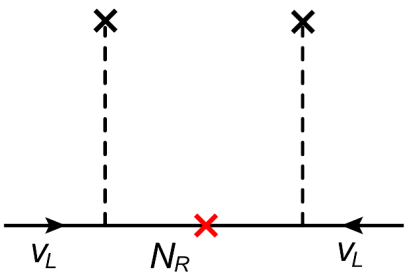


Seesaw

Mediated by RH neutirnos N_R

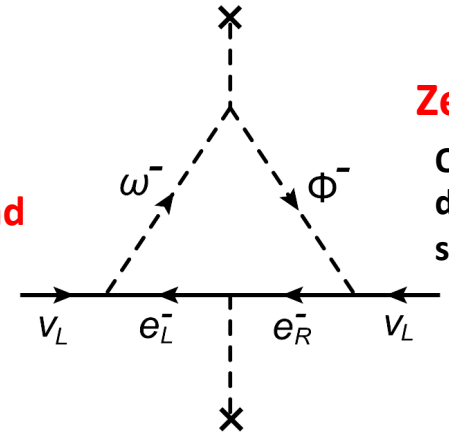
Alternative Scenario by quantum effects

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

Tiny mass

Quantum suppression

Mass around TeV scale



Zee model

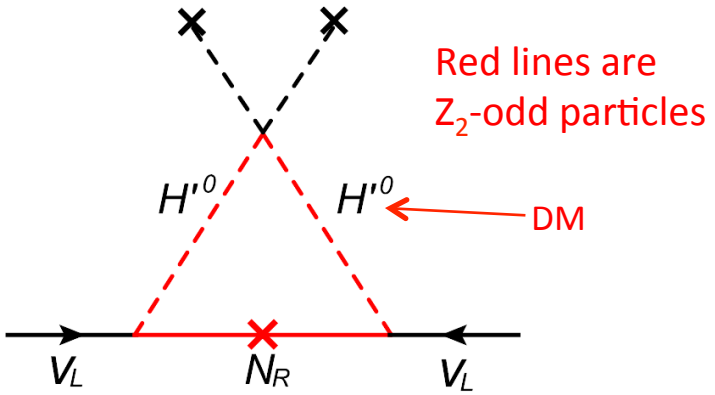
Quantum effect due to additional scalar fields

Physics of specific extended Higgs sectors

Models of neutrino mass with dark matter

Introducing a discrete Z_2

- **Stability of new particle（DM）**
- **Loop induced masses**

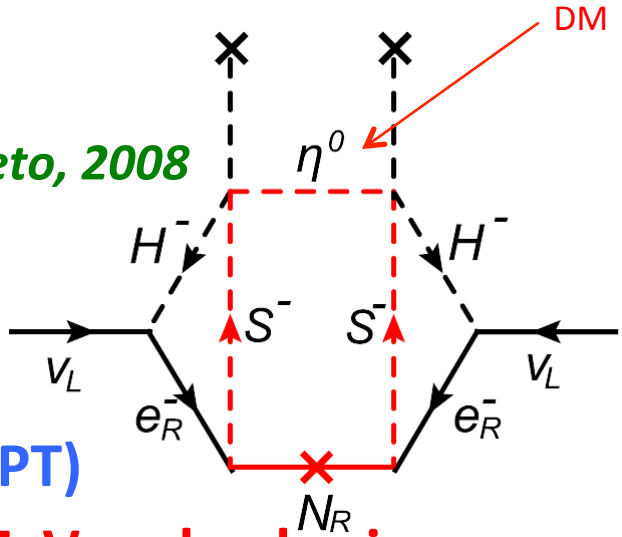


Ma model *Ma, 2006*

SM+ H' + N_R

1-loop induced ν-mass

Dark matter candidate [H']



Model with higher loop effects *Aoki, SK, Seto, 2008*

2HDM + η^0 + S^+ + N_R

ν-masses are 3-loop induced

DM candidate [η^0]

EW Baryogenesis possible (CPV, 1stOPT)

3 Problems can be explained by the TeV scale physics

Baryogenesis and Higgs

Baryon Number of the Universe

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

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

Sakharov's Condition

Sakharov 1967

1. **ΔB ≠ 0** — Sphaleron process
2. **C and CP violation** — Chiral gauge theory KM phase
3. **Departure from thermal equilibrium** — Strongly first order phase transition

SM could satisfy these conditions but excluded by the data

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Scenario of Baryogenesis

1. Electroweak Baryogenesis — **Physics of (extended) Higgs sector**

2. Leptogenesis — **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

Φ_{SM}+Singlet, Φ_{SM}+Doublet (2HDM),
Φ_{SM}+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)

$$\Phi_i = \begin{pmatrix} \omega_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + h_i + i z_i) \end{pmatrix} \quad (i = 1, 2)$$

Sharing the VEV $\quad v = 246\ \mathrm{GeV} = \sqrt{v_1^2 + v_2^2} \qquad \tan\beta = \dfrac{v_2}{v_1}$

Field Mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \qquad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} \omega_1^{\pm} \\ \omega_2^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \omega^{\pm} \\ H^{\pm} \end{pmatrix}$$

New Particles

CP-odd Charged

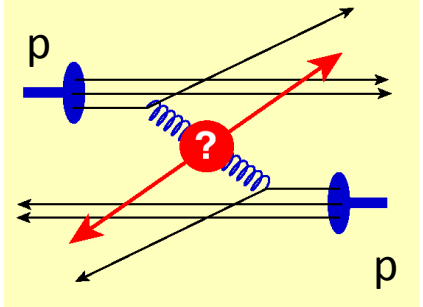
$$\underset{\substack{\uparrow \\ h(125)}}{h} \quad \underbrace{H \quad A \quad H^{\pm}}_{\text{Additional bosons}}$$

Other three are unphysical Nambu-Goldstone bosons

Deviation in the coupolings of *h*(125)

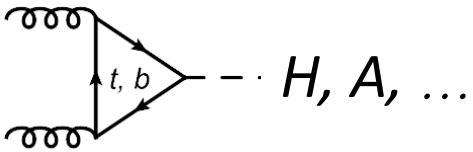
SM			2HDM
hVV	1	→ *hVV*	sin(β−α)

Direct search and indirect tests



- **Direct searches of additional Higgs bosons**

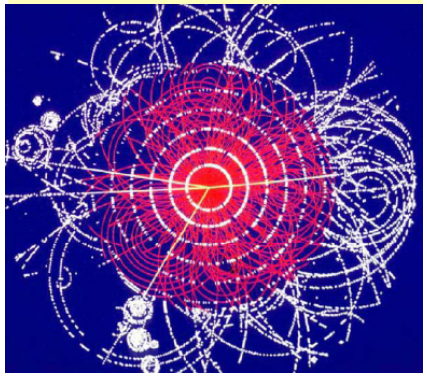
h*(125), *H, A, H⁺, H⁺⁺, …



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}**



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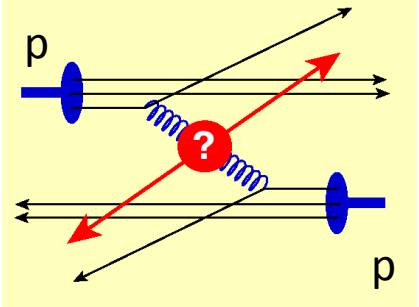

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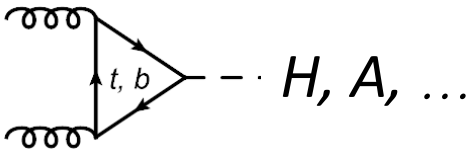

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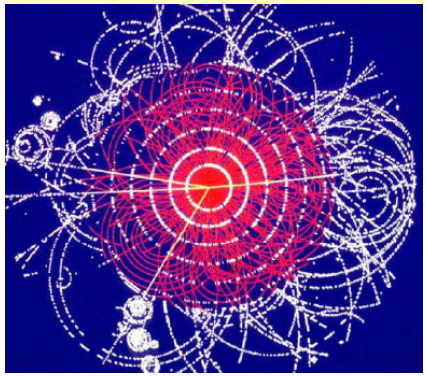
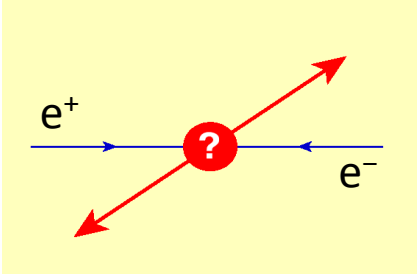


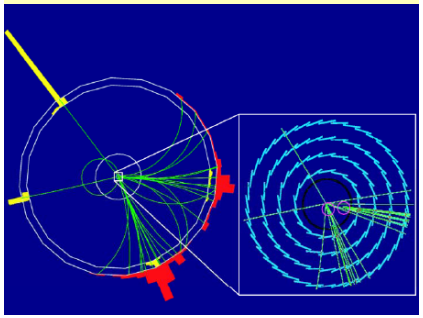
- **Indirect test by finding deviations from SM**

EW parameters *m_W, S, T, U, Zff, Wff', WWV, …*

Couplings of *h*(125) *hWW, hZZ, hγγ, hff, hhh, …*



Precision measurements!

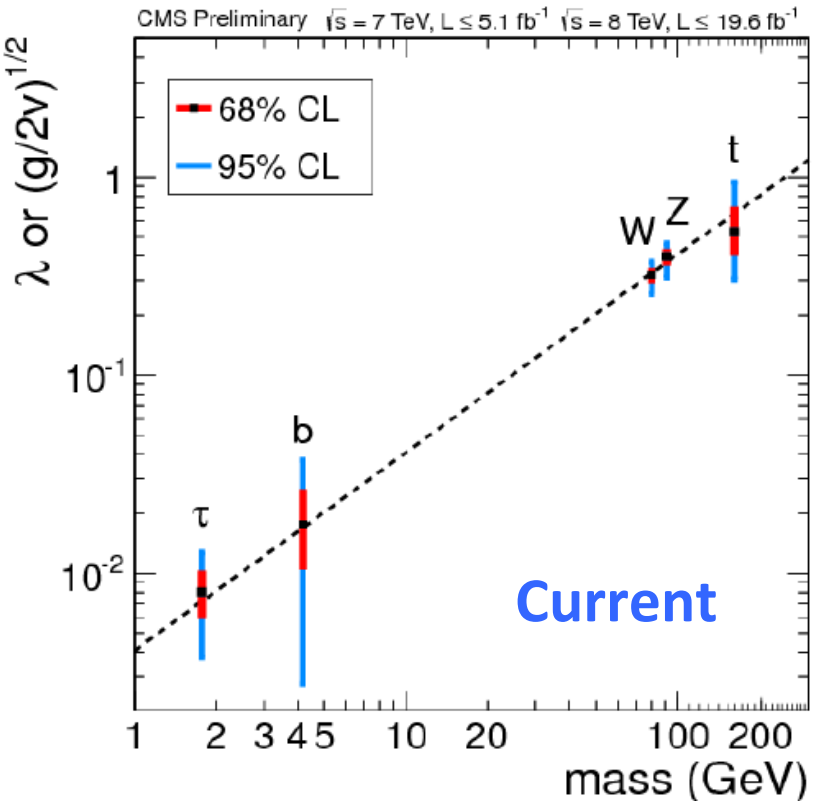


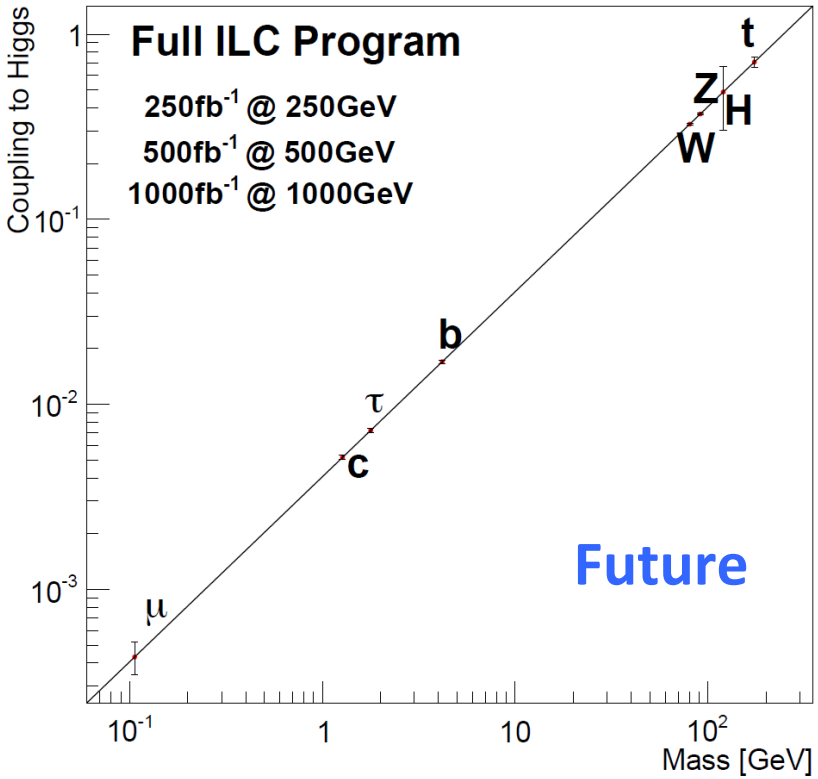
Advantage for lepton colliders

Future International Linear Collider (ILC)

***E* = 250GeV, 500GeV, 1TeV**

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

Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

Snowmass Higgs Working Group Report 1310.8361

Deviation = New Physics scale

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Scaling factor κ_i : factor of deviation from the SM value

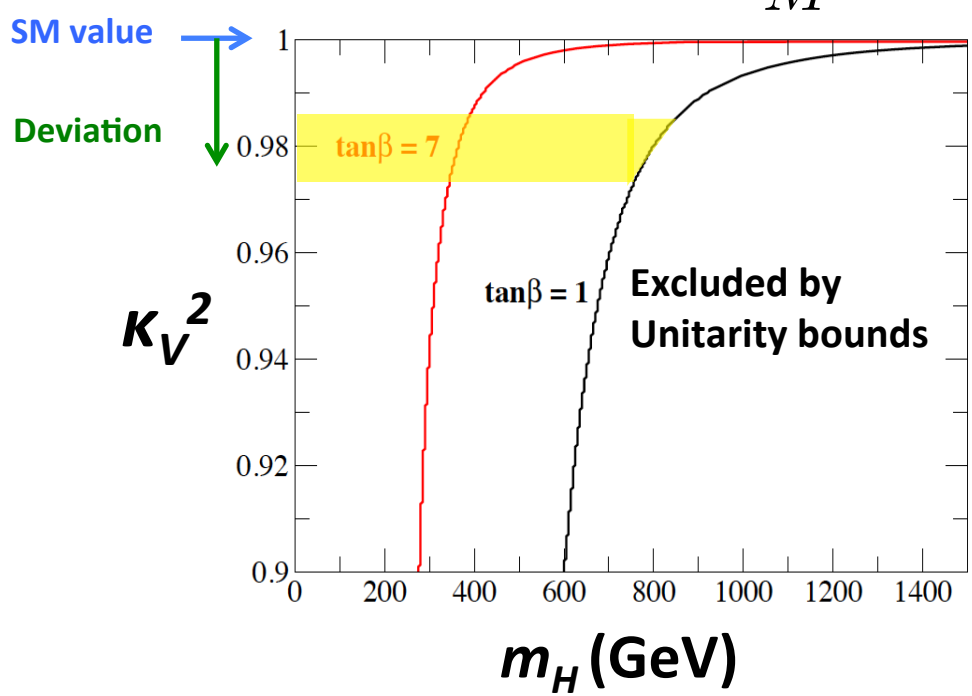
Coupling of *h*(125) and weak bosons *V* (=W, Z) ***hVV***

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

If a 2% deviation in κ_V^2

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

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



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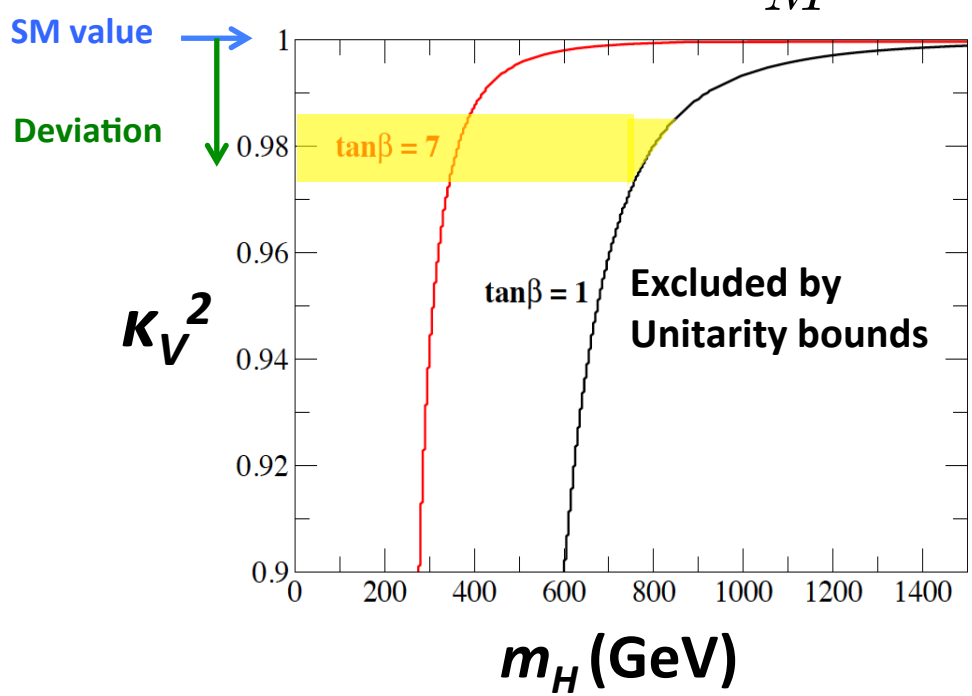
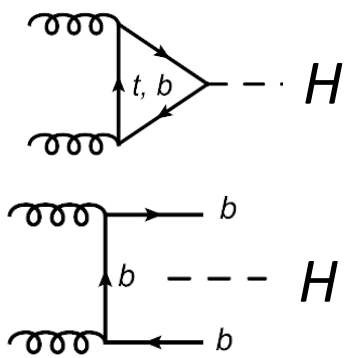
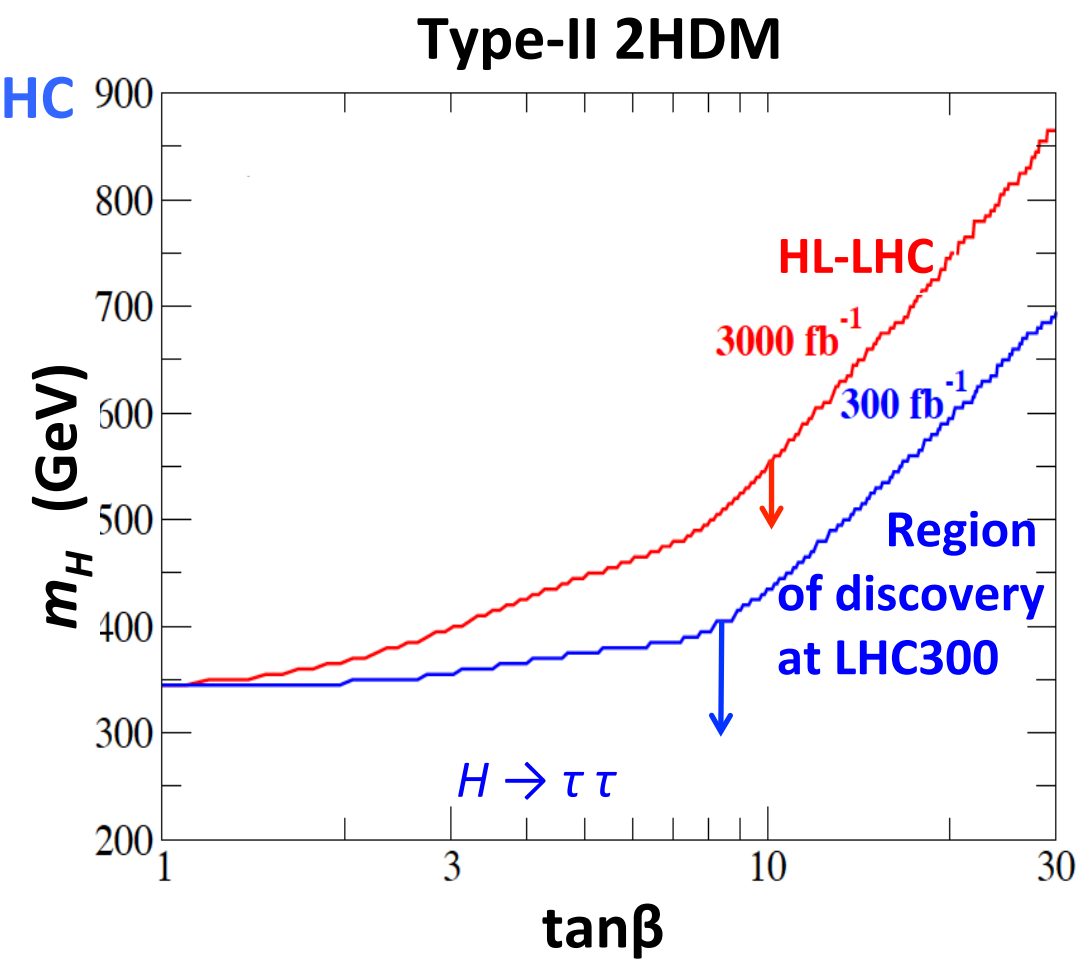


Precision test has the similar power to the direct search

Complementarity

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





SK, Tsumura, Yagyu, Yokoya, 2014

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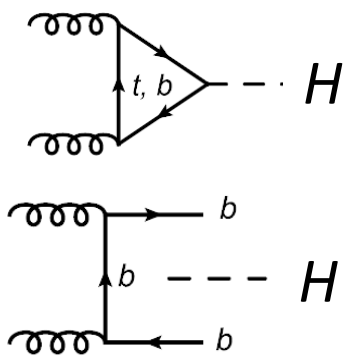

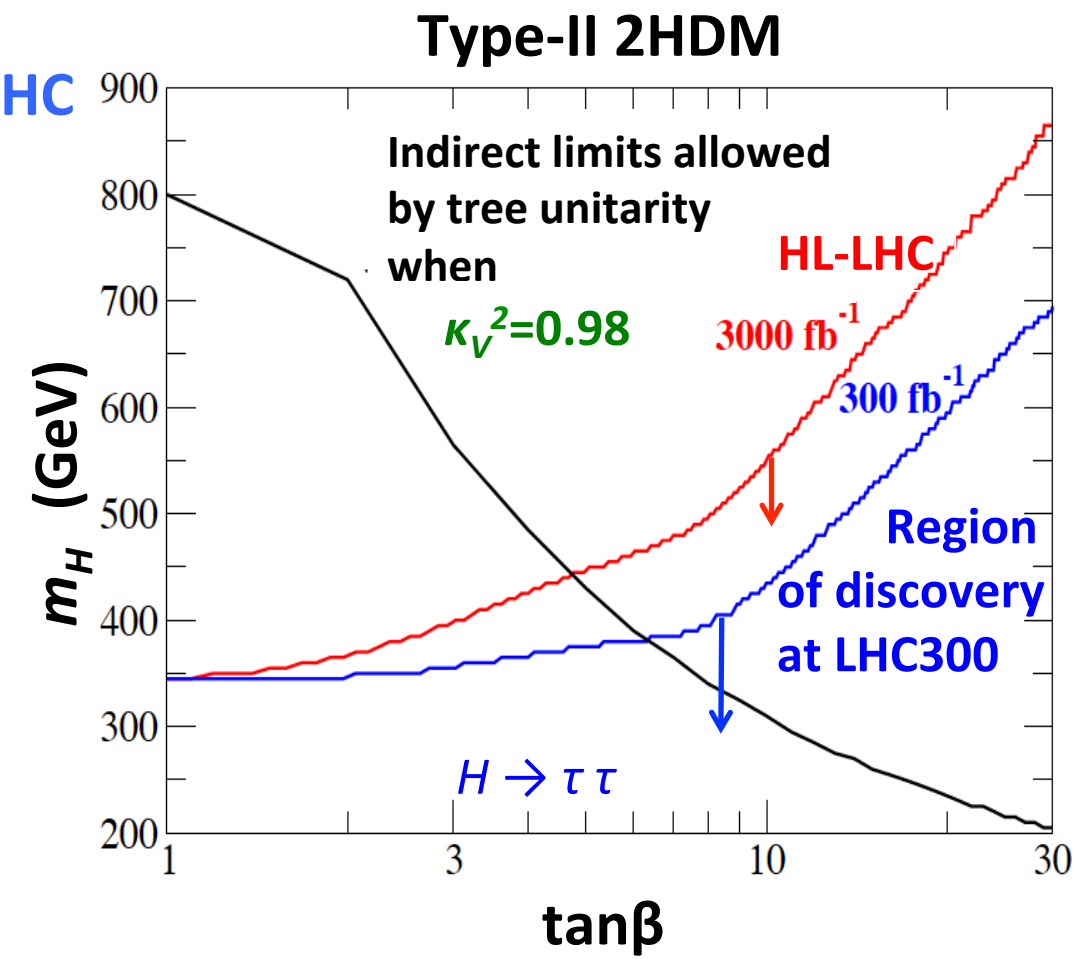

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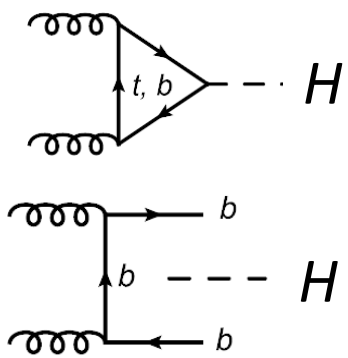
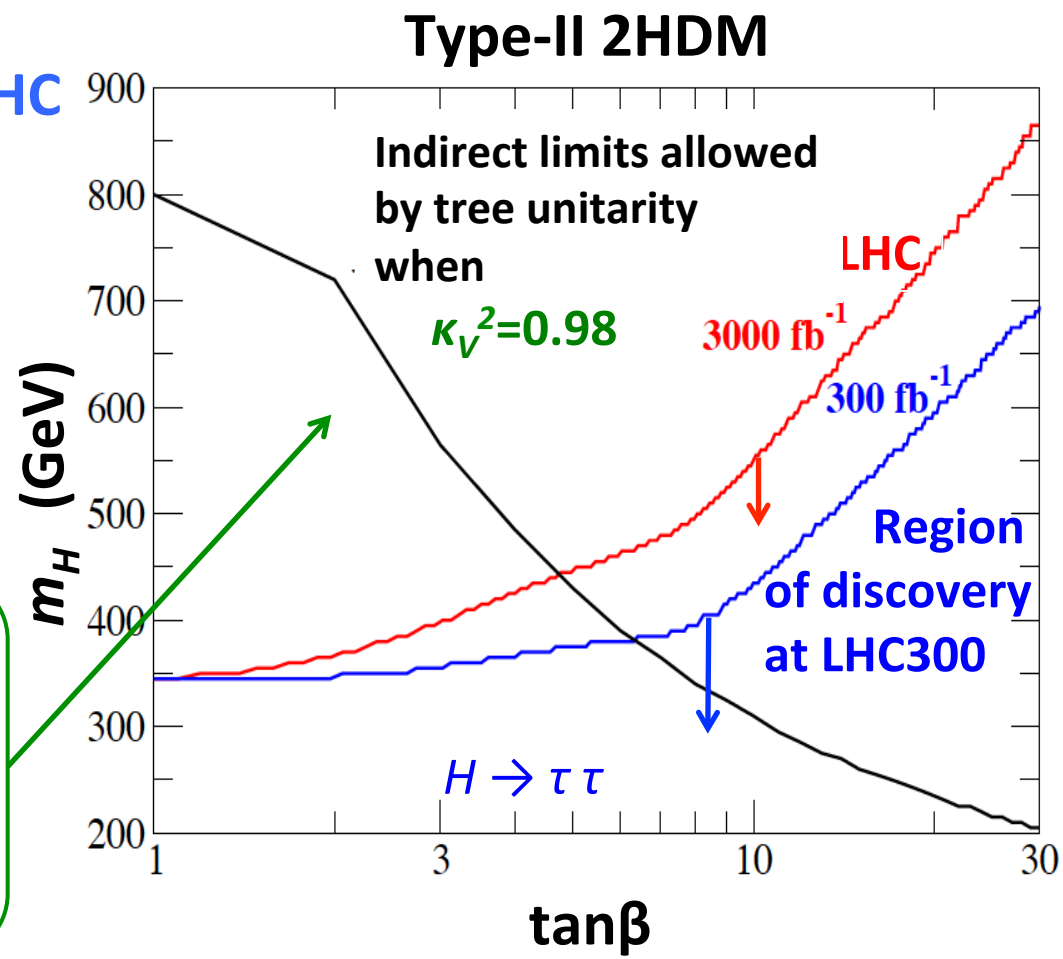


Indirectly, new physics can be surbeyed by detecting deviations even out of the direct search regions



SK, Tsumura, Yagyu, Yokoya, 2014

Pattern of deviations

Gauge couplings

Yukawa couplings

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

	hVV	$h\tau\tau$	hbb	hcc
	κ_V	κ_τ	κ_b	κ_c
Type-I	↓	↓	↓	↓
Type-II	↓	↑	↑	↓
Type-X	↓	↑	↓	↓
Type-Y	↓	↓	↑	↓

Direction of deviation in each coupling

Pattern of deviations

Gauge couplings — Yukawa couplings

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Direction of deviation in each coupling

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

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

$x = \cos(\beta-\alpha)$ **SM-like: $|x| \ll 1$**

$\kappa_V = 1 - (1/2)\, x^2 + \ldots$

When a Fermion couples to Φ_1

$\kappa_f = 1 + \cot\beta\, x + \ldots$

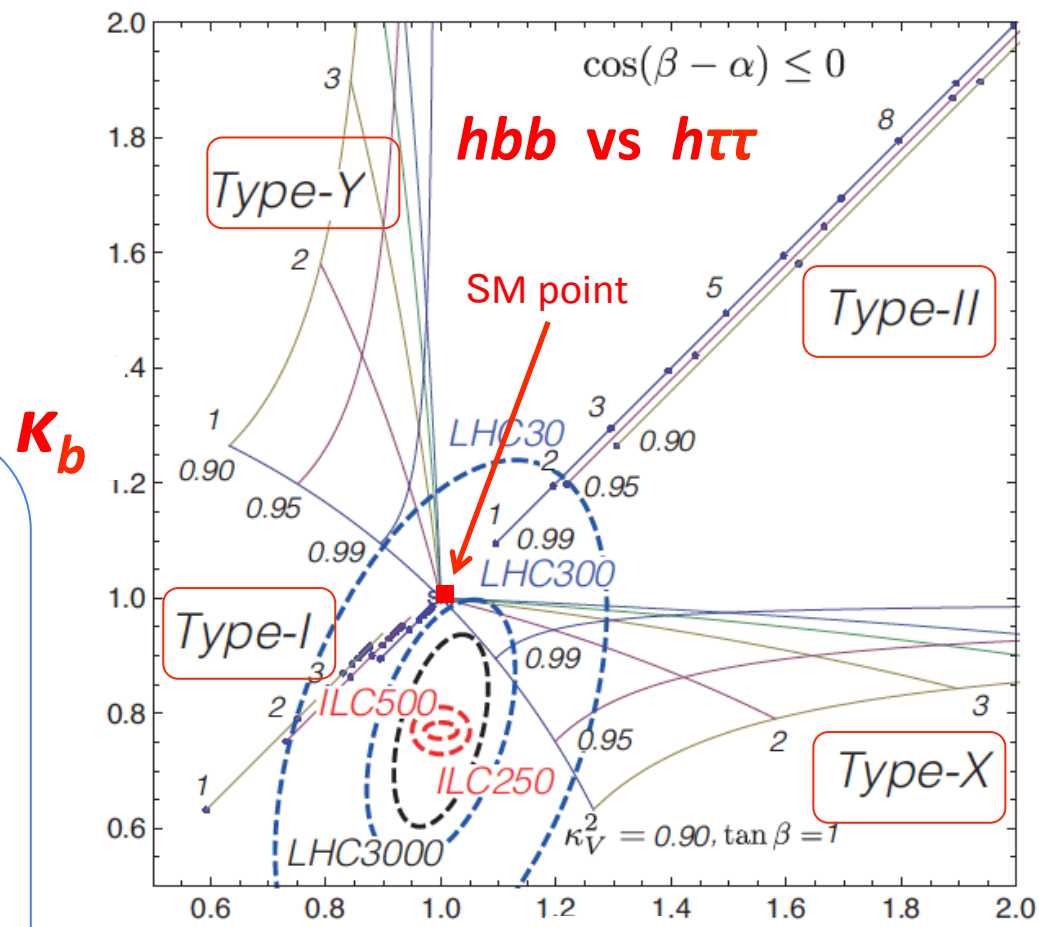
and if it couples to Φ_2

$\kappa_f = 1 - \tan\beta\, x + \ldots$

If deviation in κ^2_V can be large enough to be detected at future collider

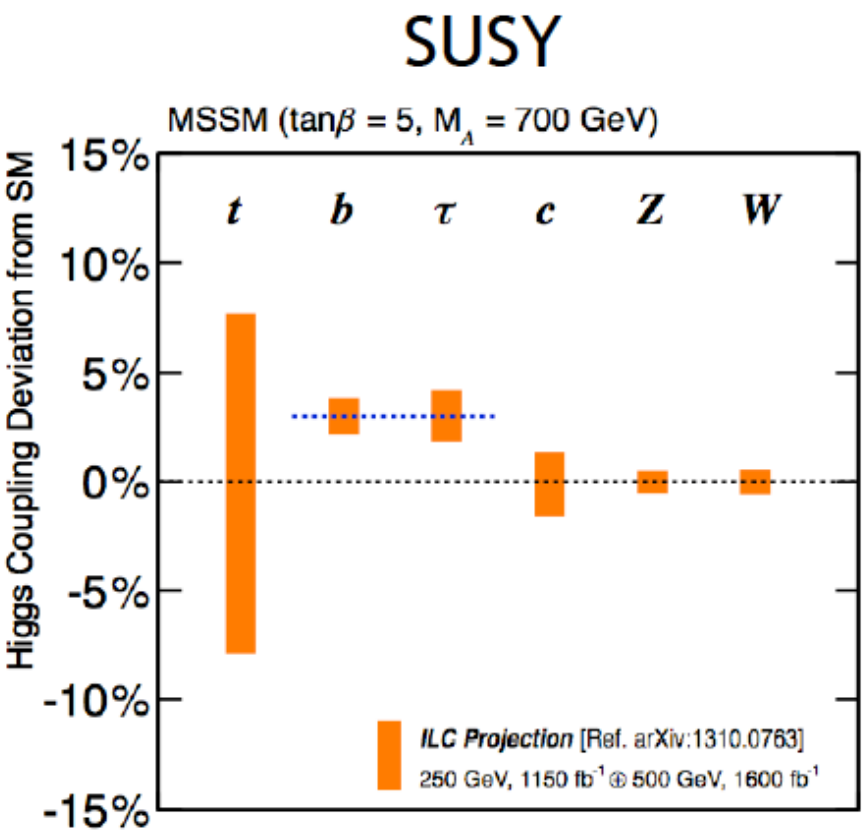
4-models can be separated by looking at deviations in Yukawa couplings κ_τ, κ_b, κ_c, …

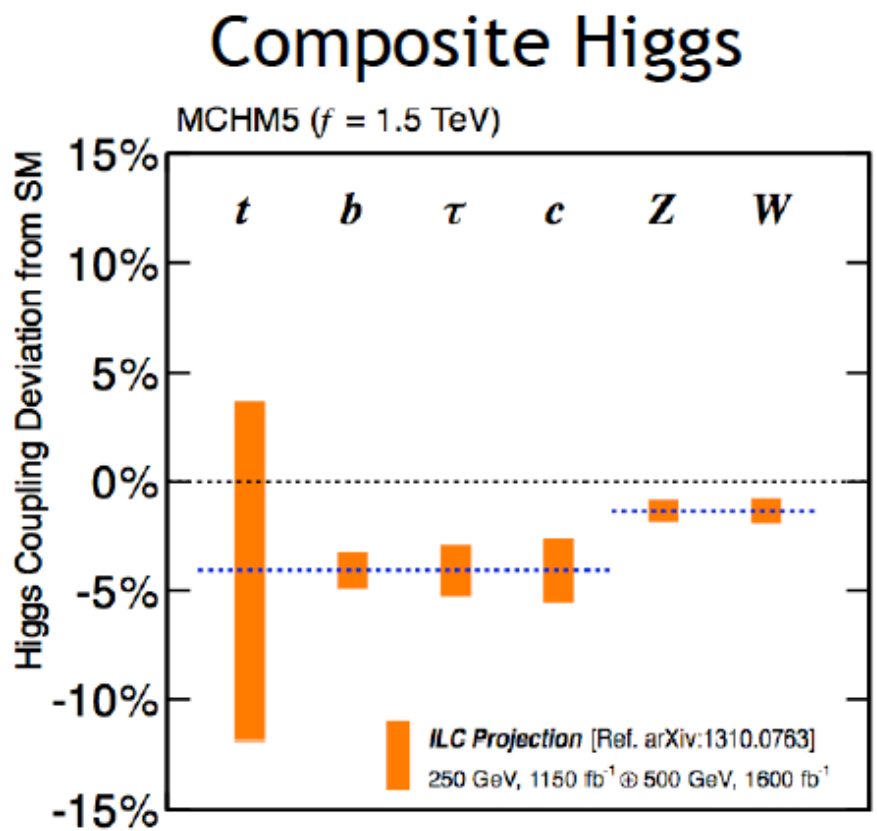
SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014



Ellipse = 68.27% CL

Fingerprinting SUSY model and Composite Higgs models

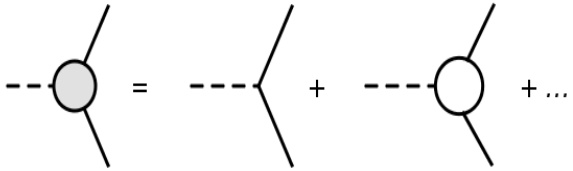




Fingerprinting models by precision study at ILC

Radiative Corrections

Higgs couplings *hγγ, hgg, hWW, hZZ, hττ, hbb, htt, …*
will be measured thoroughly in the future



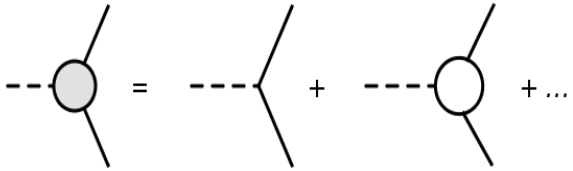
Clearly analyses with radiative correction is necessary

Accurate Theory Predictions × **Future Precision Measurements**

New Physics!

Radiative Corrections

Higgs couplings *hγγ, hgg, hWW, hZZ, hττ, hbb, htt, …*
will be measured thoroughly in the future



Clearly analyses with radiative correction
is necessary

Accurate Theory Predictions × **Future Precision Measurements**

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

Models
- Additional Singlet
- 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, hττ, hγγ

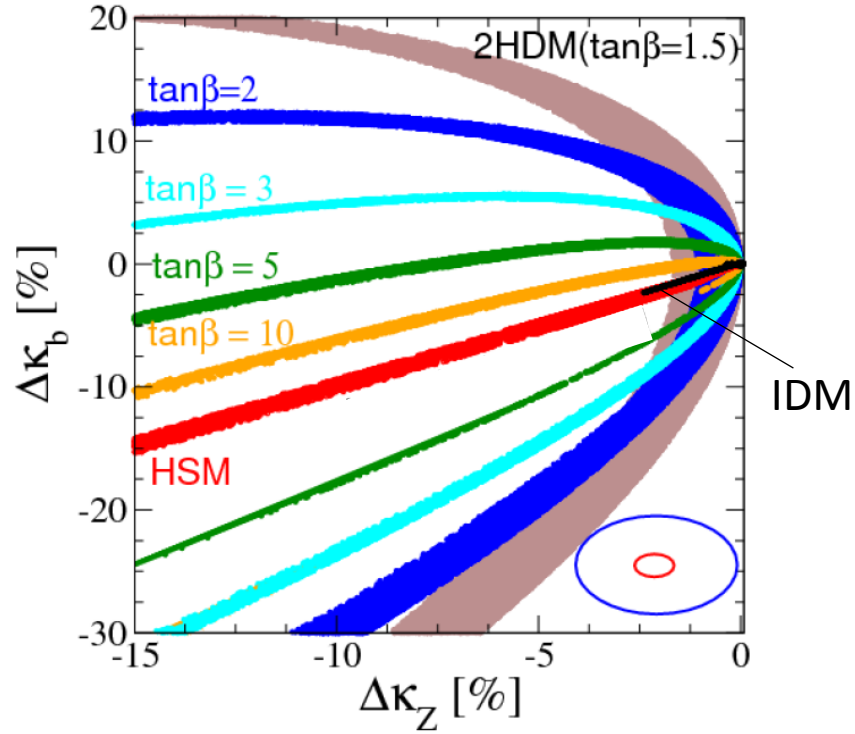
Scan of inner parameters (mass, mixing angles) under

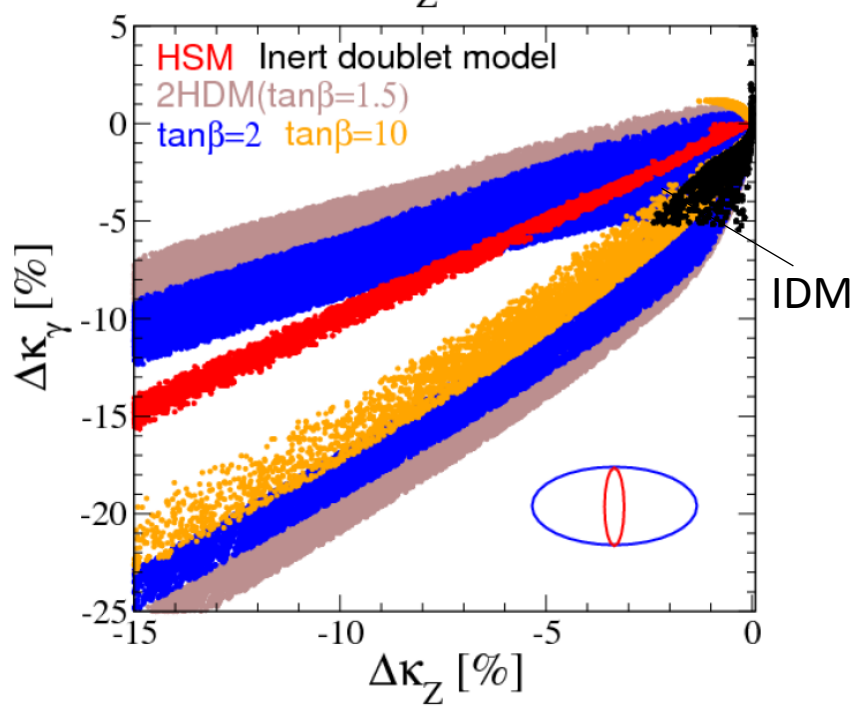
- Perturbative unitarity
- Vacuum stability,
- Avoiding wrong vacua

We can fingerprint these models, if a deviation in κ_Z is detected

Ellipse, ±1σ at LHC3000 and ILC500

SK, M. Kikuchi, K. Yagyu, 2015



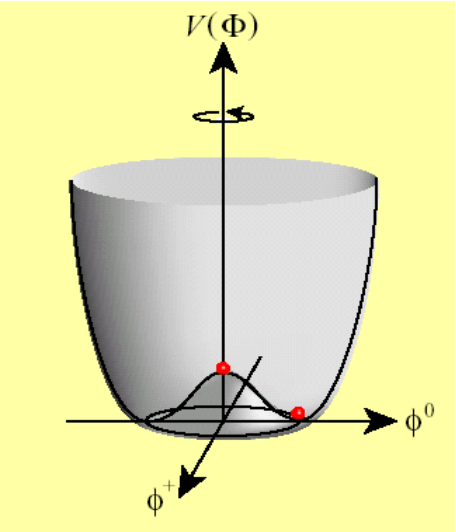


Higgs potential

Higgs potential

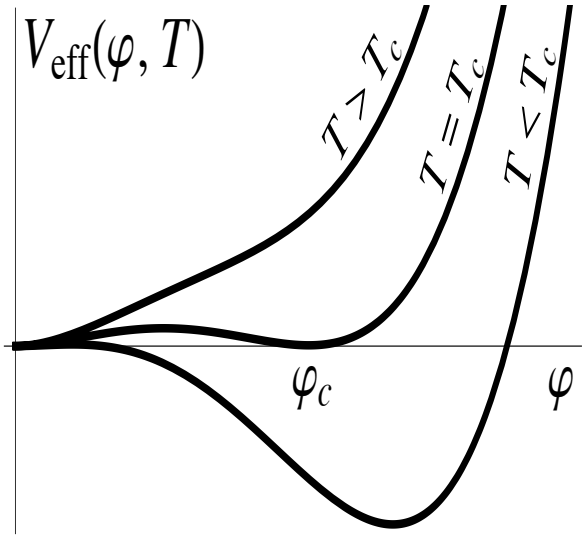
Most important part for EW symmetry breaking (Yet to be tested)

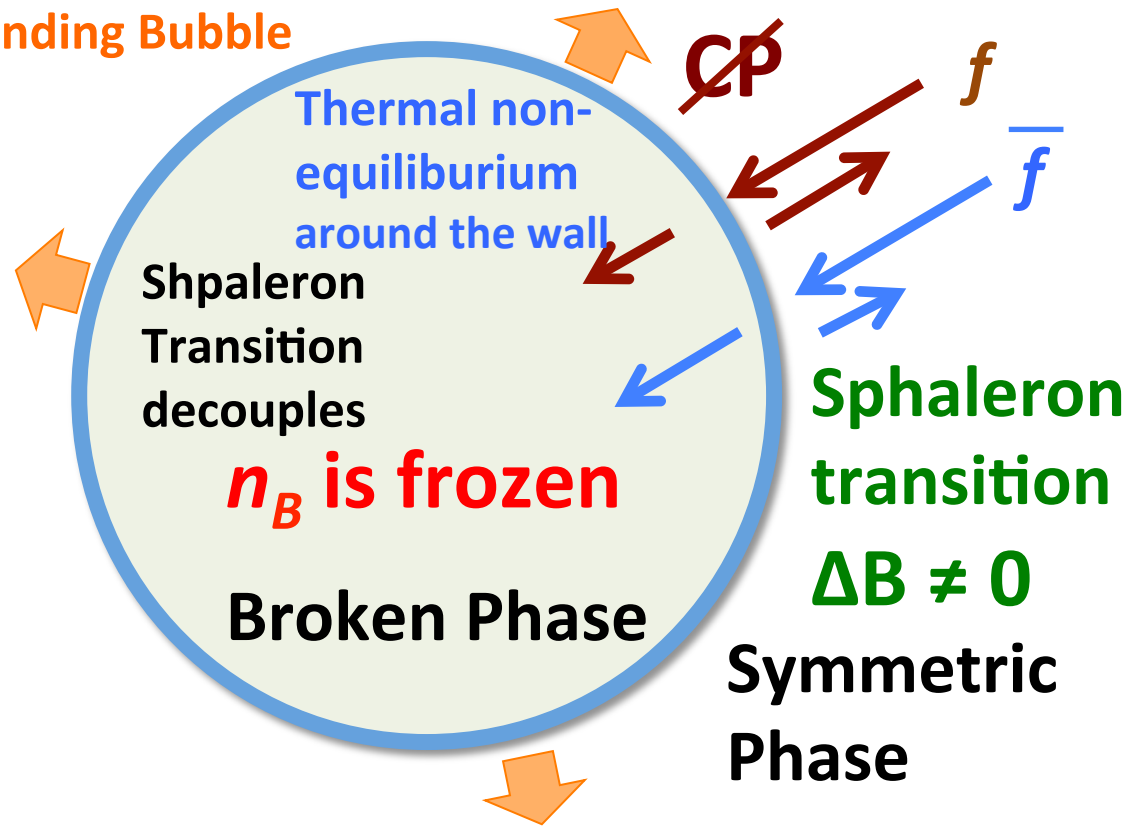
$$V(\Phi) = +\mu^2|\Phi|^2 + \lambda|\Phi|^4$$



- **Physics behind EWSB**
  - Where come from $\mu^2 < 0$
  - Origin of λ
- **Electroweak Phase Transition**
  - 1st OPT or not?
  - Relation to EW baryogenesis
  - Mechanism of Phase Transition

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

Strongly 1st OPT

Potential at finite T (high temp. approx.)

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

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

E: Thermal Loop Effects

λ_{T_C} : Self couplings ~ m_h^2

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SM **no strong 1st 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

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Extended Higgs (2HDM): 1st OPT possible

Quantum non-decoupling effect of Φ (= *H, A, H*⁺, …)

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

Strongly 1st OPT

Potential at finite T (high temp. approx.)

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Prediction! **Large deviation in the *hhh* couping as well**

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{\sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

First Order Phase Transition

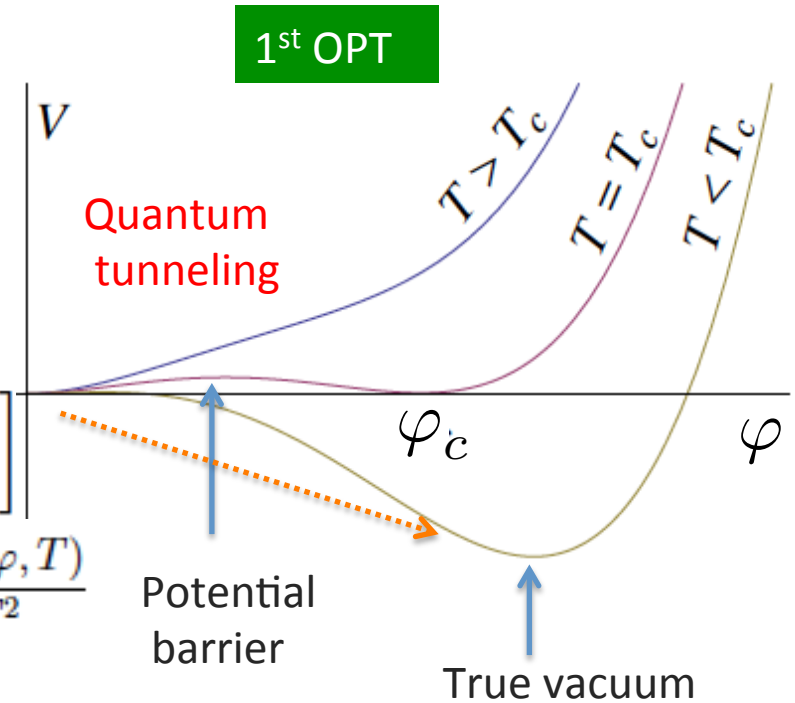
Effective potential at one-loop level:

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

Contribution at finite-temperatures:

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

$$I_{B/F}(a^2) = \int_0^\infty {\rm d}x x^2 \ln\left(1 \mp {\rm e}^{-\sqrt{x^2+a^2}}\right) \quad a^2 = \frac{M^2(\varphi, T)}{T^2}$$



High-temperature expansion:

$$V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - \underline{ET\varphi^3} + \frac{\lambda_T}{4}\varphi^4 + \cdots \qquad \varphi_c/T_c \propto E$$

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

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

Bosonic loop contribute to the cubic term

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

Necessary for successful electroweak baryogenesis

1st OPT and the *hhh* coupling

Strong 1st OPT
⇔ Deviation in the *hhh* coupling

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

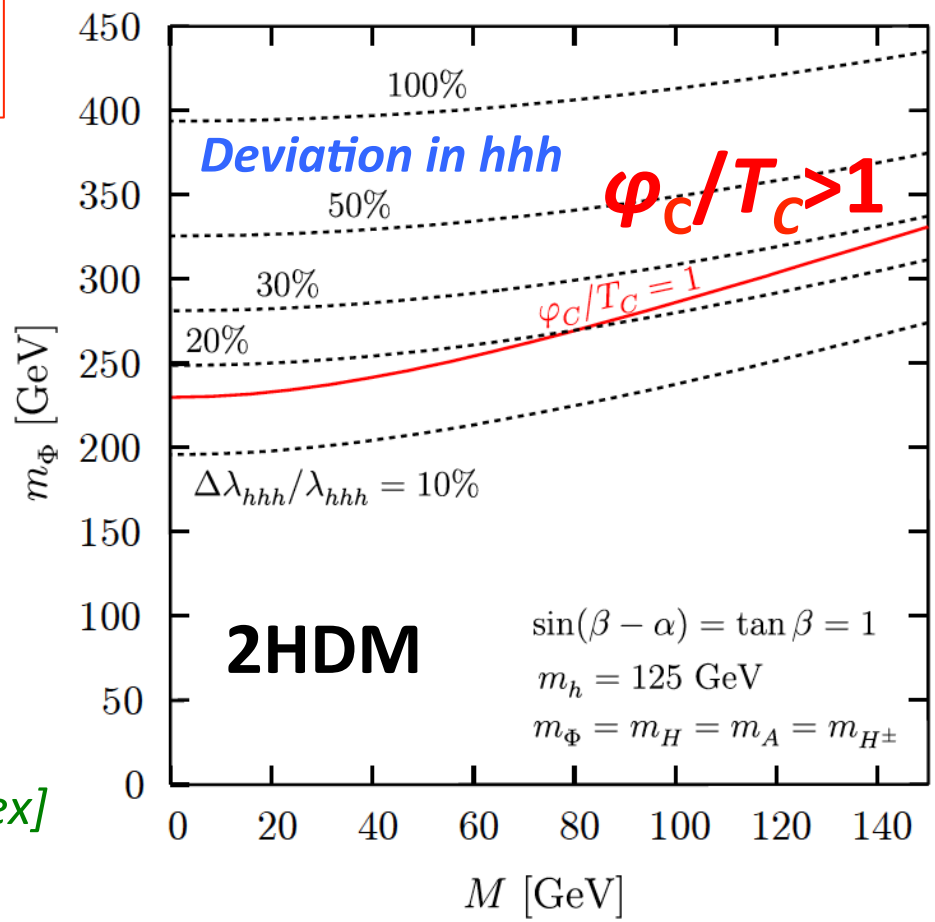
Which collider?

LHC cannot do it

Only ILC (1 TeV) can measure it by O(10) %

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

S.K., Y. Okada, E. Senaha (2005)

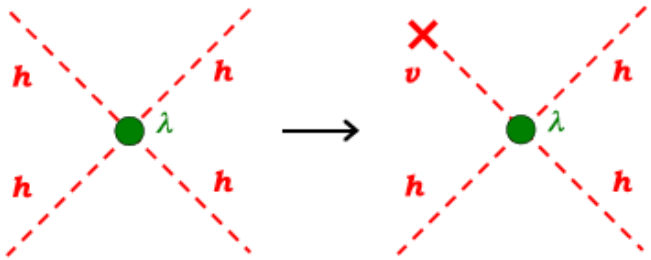


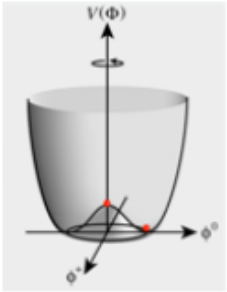
Connection between Cosmological problem and Collider

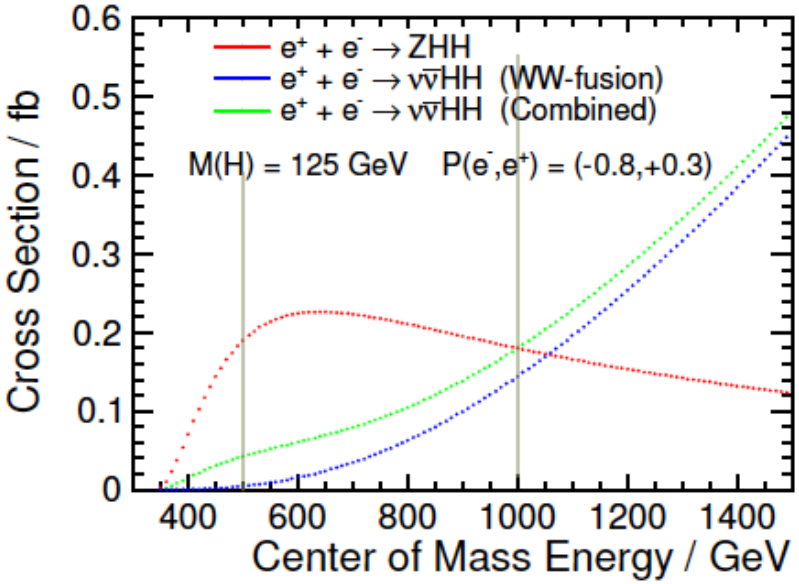
Higgs Self-Coupling

Slide by Keisuke Fujii

hhh coupling =
consequence of vacuum condensation

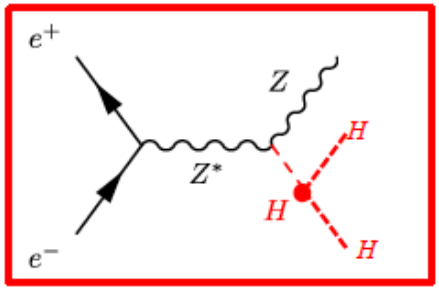


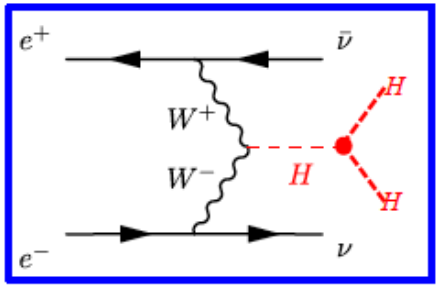




Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- ***Presence of irreducible BG diagrams***



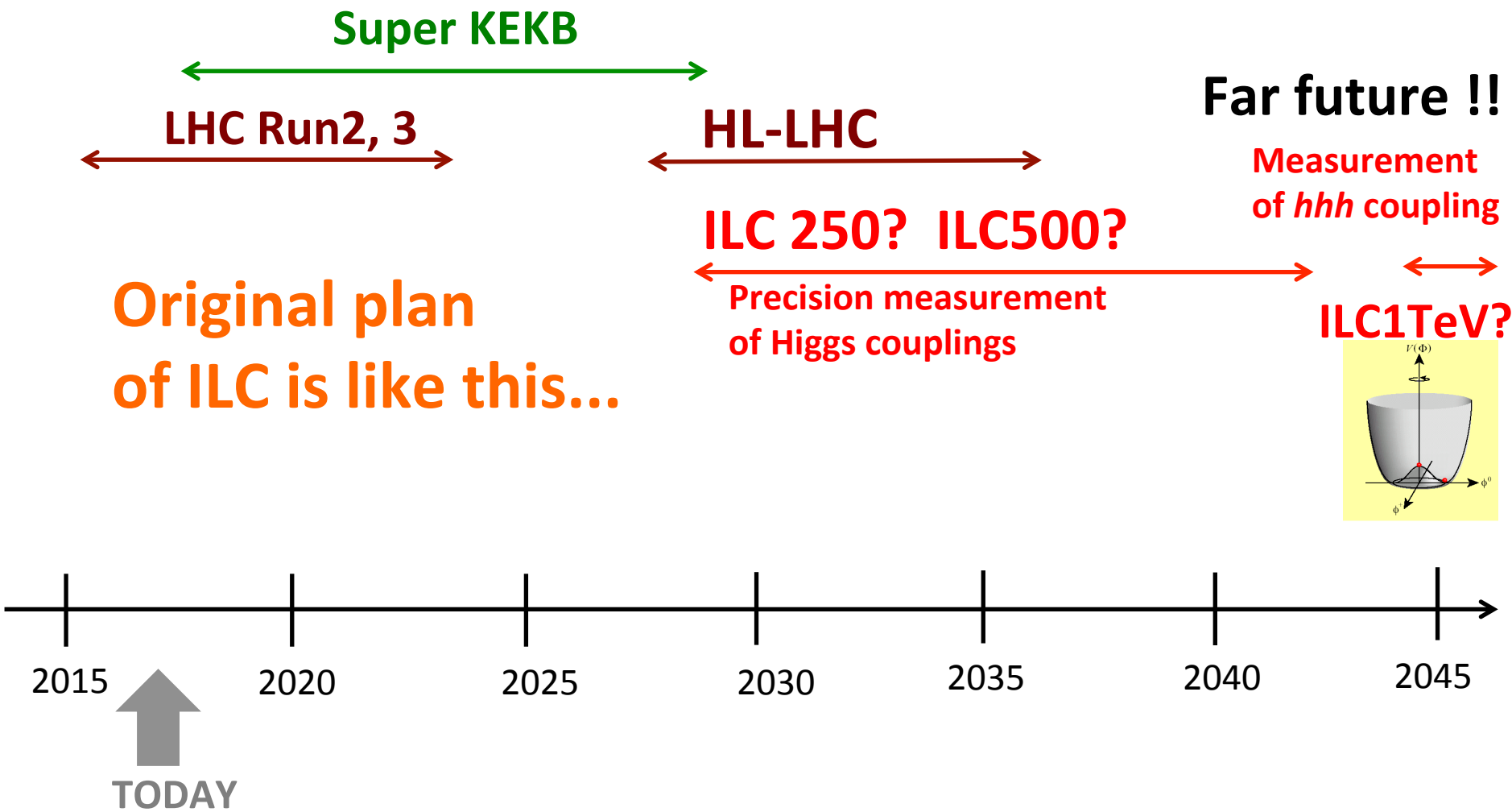


arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Ongoing analysis improvements ***towards O(10)% measurement***

See J.Tian's Poster

Timeline


Super KEKB
LHC Run2, 3
HL-LHC
Far future !!
Measurement of *hhh* coupling
ILC 250? ILC500?
Precision measurement of Higgs couplings
ILC1TeV?
Original plan of ILC is like this...
2015
2020
2025
2030
2035
2040
2045
TODAY

Timeline

Super KEKB

LHC Run2, 3

HL-LHC

Far future !!

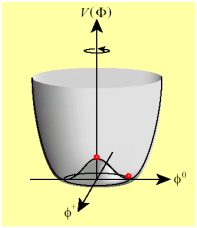
Measurement of *hhh* coupling

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*

ILC1TeV?



2015 2020 2025 2030 2035 2040 2045

TODAY

Timeline

Super KEKB

LHC Run2, 3

HL-LHC

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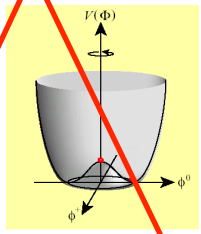


2015 2020 2025 2030 2035 2040 2045

TODAY

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

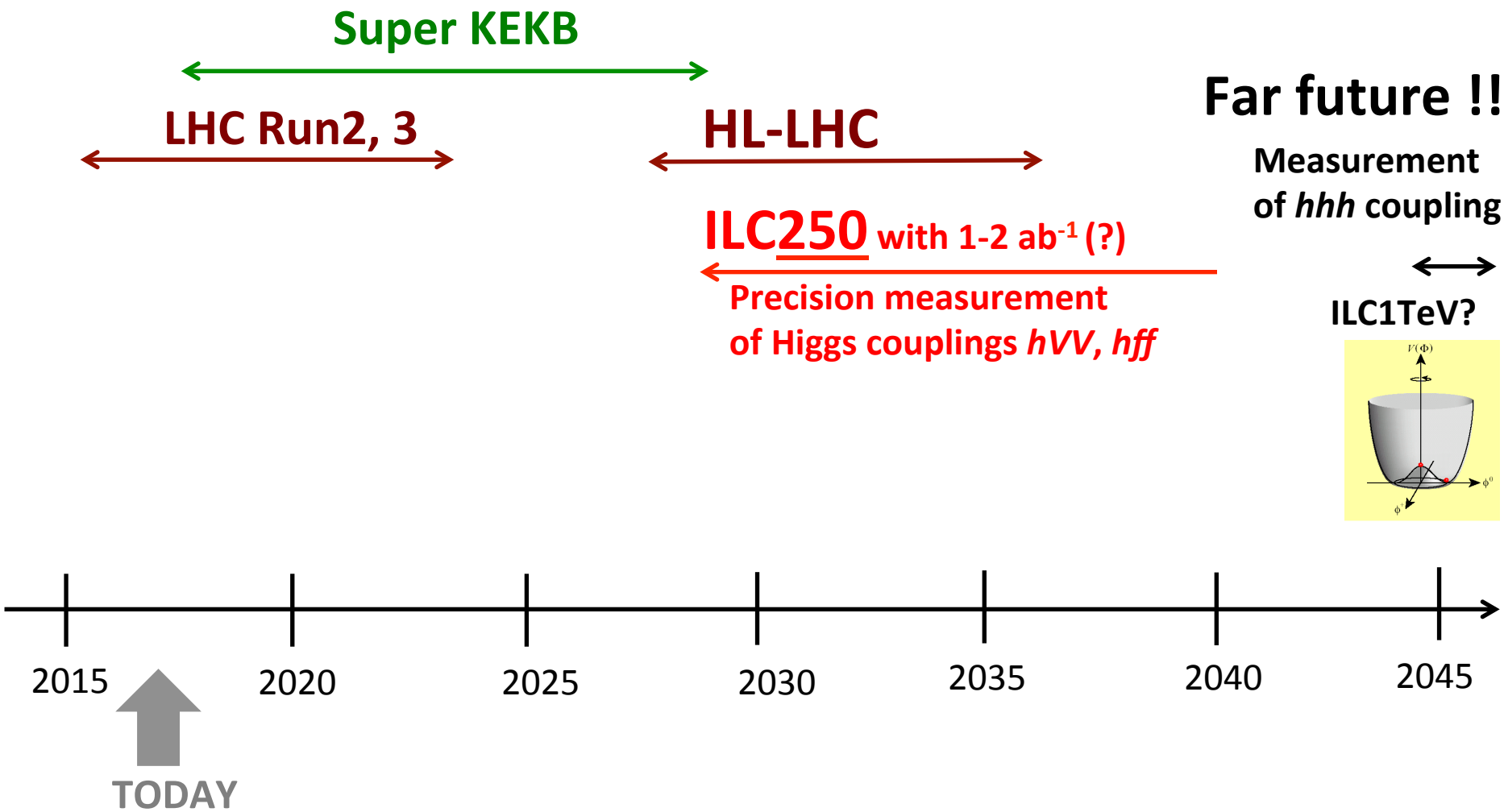
Fortunately, the situation has changed drastically

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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2015
2020
2025
2030
2035
2040
2045
TODAY

Timeline

Super KEKB

LHC Run2, 3

Direct searches

HL-LHC

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

Precision measurement of Higgs couplings *hVV*, *hff*

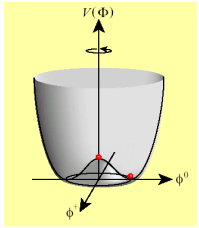
LISA (approved!) 2028--

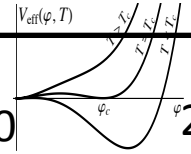
EW Phase Transition via Gravitational Waves

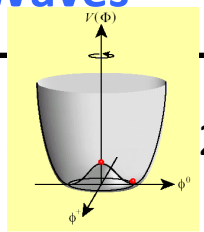
Far future !!

Measurement of *hhh* coupling

ILC1TeV?







2015 2020 2025 2030 2035 2040 2045

TODAY

Timeline

Golden age 2030s !!

Super KEKB

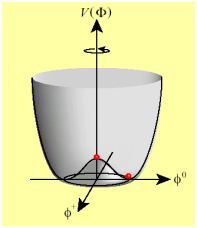
LHC Run2, 3

HL-LHC

Far future !!

Measurement of *hhh* coupling

ILC1TeV?

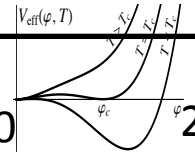


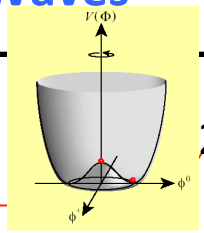
ILC250 with 1-2 ab^{-1} (?)

Precision measurement of Higgs couplings *hVV*, *hff*

LISA (approved!) 2028--

EW Phase Transition via Gravitational Waves





2015 2020 2025 2030 2035 2040 2045

TODAY

Synergy!

SuperKEKB	Flavor Physics
HL-LHC	Energy Frontier (New Particle Searches)
ILC	Precision measurement of Higgs couplings
LISA	EW Phase Transition from GWs

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 (～100 Hz) → Era of GW astronomy started

Ground based experimetns

aLIGO, KAGRA, aVirgo…

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GW Physics?

GW from 1st OPT: homogeneous, isotropic, stationary, unpolarized

Relic GWs are characterized only by frequency

Transition temperature gives typical frequencies

T = 100GeV → $f = 10^{-1} - 10^{-3}$ Hz

Out of sensitivity at LIGO/KAGRA (10-10^3Hz)

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

$$sa^3 = \frac{2\pi^2}{45} g_s T^3 a^3 = \text{const}$$

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

Radiation dominant Universe

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

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)

$$\boxed{f_0 = 10^{-3}\text{-}10^{-1}\ \text{Hz}}$$

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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

C.Caprini *et al.*, arXiv:1512.06239

Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1

LISA has been approved in 2016
It will start from 2028

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

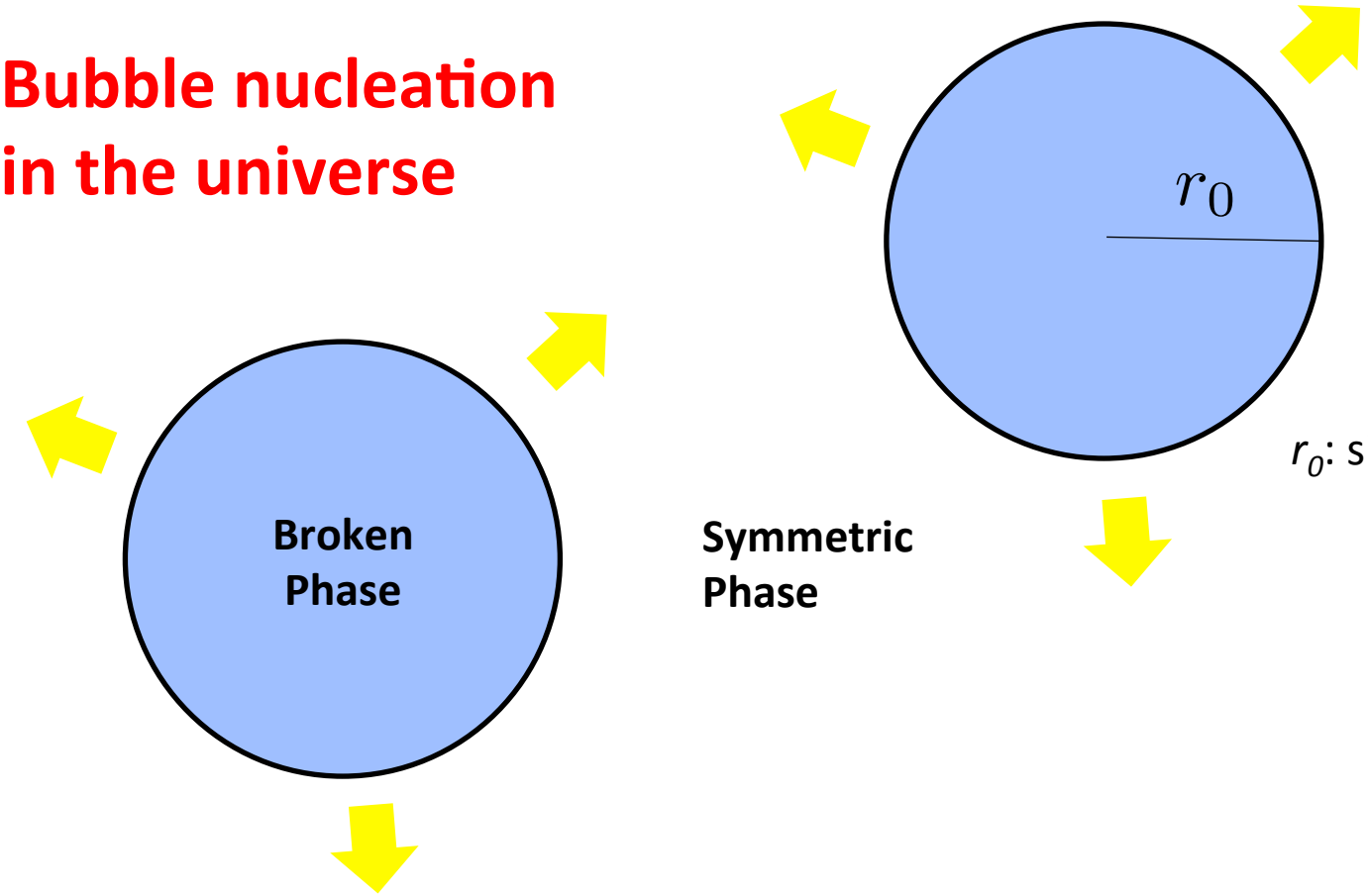
Extragalactic WD binaries (isotropic)

$\Omega h^2 = 10^{-11} - 10^{-10}$ $f_{peak} = 2 \times 10^{-2}$ Hz

Schneider et al., 2005

Origin of GWs from 1st OPT

Bubble nucleation in the universe



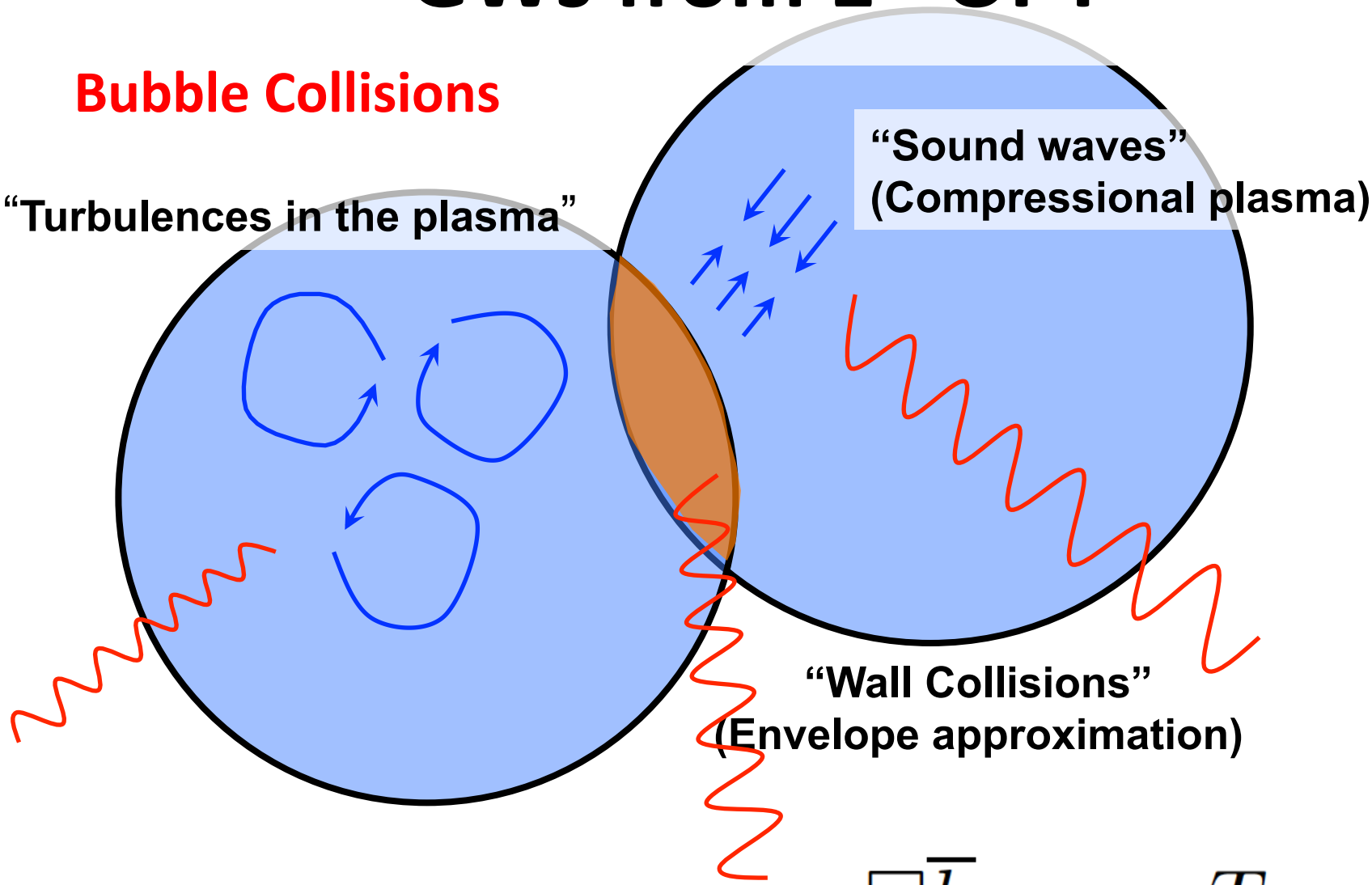
r_0: size of critical bubble

Expanding babbles of the broken phase

Bubble is spherical
→ No GW occurs

GWs from 1st OPT

Bubble Collisions



$$\Box \bar{h}_{\mu\nu} = \underbrace{\kappa T_{\mu\nu}}_{\text{Source of GW}}$$

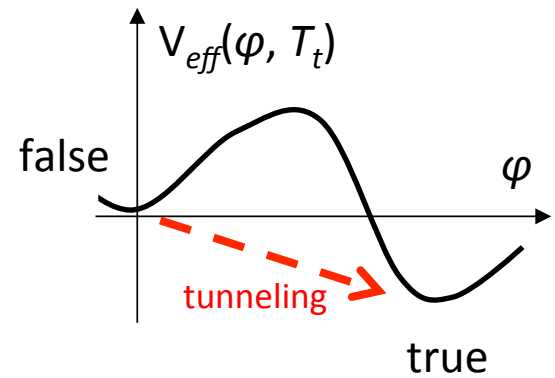
Spherical symmetry is violated by bubble collisions → GW occurs

From bubble dynamics to GW spectrum

Bubble nucleation rate per unit volume and time

$\Gamma(T) = \Gamma_0 \exp(-S_3/T)$

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



T_t **Transition temperature**

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

α **Latent heat (released energy of false vacuum)** **Depth of the potential**

$$\alpha = \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)} \qquad \epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$$

β **Inverse of duration of phase transition** **Speed of transition**

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

GW spectrum is given as a function of T_t, α, β (and v_b) v_b: wall velocity

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

$$\tilde{\Omega}_{\rm sw} h^2 \simeq 2.65 \times 10^{-6} \frac{v_b}{\tilde{\beta}} \left(\frac{\kappa(v_b, \alpha)\alpha}{1+\alpha}\right)^2 \qquad \tilde{f}_{\rm sw} \simeq 1.9 \times 10^{-5}{\rm Hz}\frac{\tilde{\beta}}{v_b}$$

C.Caprini et al., arXiv:1512.06239

Spectra 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)

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

2. Collision of the bubbles (envelop approximation)

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

3. Magnethydrodynamic (MHD) plasma turbulence in the bubbles

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

v_b : **wall velocity** $\qquad \kappa_\phi \quad \kappa_v$: **efficiency factors** $\qquad \epsilon = 0.05$

The spectrum are evaluated by inputting the latent heat α, variation of the bubble nuclearation rate β 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 $S^{\mathrm{T}} = (S_1, \cdots, S_N)$

$$V_0 = -\mu^2|\Phi|^2 + \frac{\mu_S{}^2}{2}|S|^2 + \frac{\lambda}{2}|\Phi|^4 + \frac{\lambda_S}{4}|S|^4 + \frac{c}{2}|\Phi|^2|S|^2$$

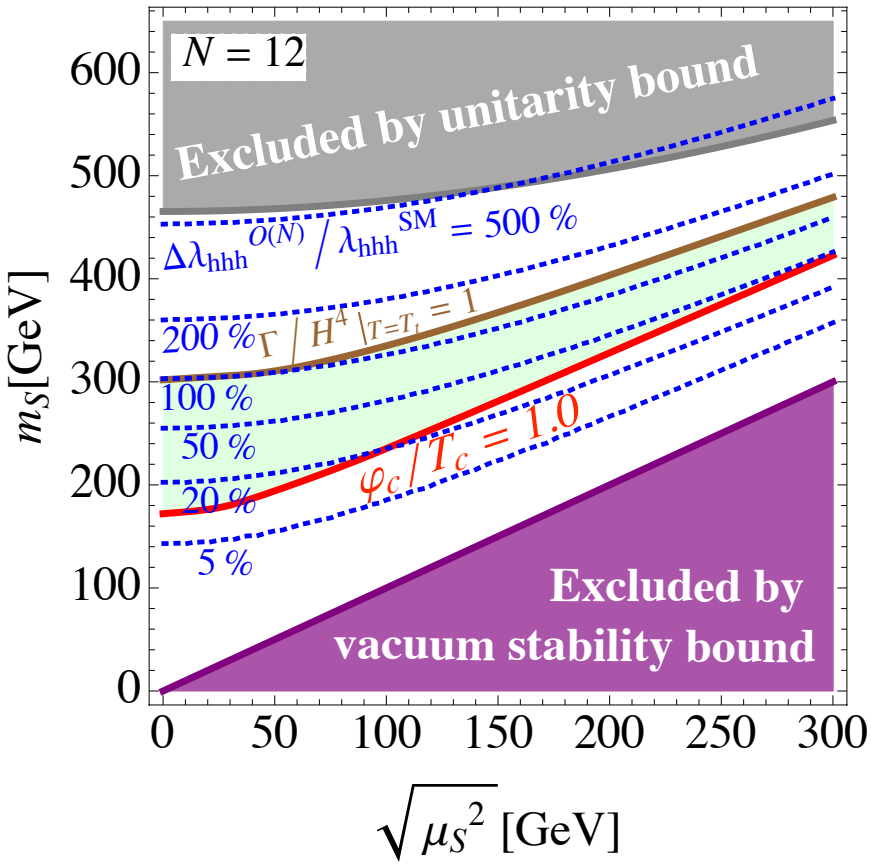
Mass of scalar fields: $\boxed{m_S^2 = \mu_S^2 + \frac{c}{2}v^2}$

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

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{N m_S^3\left(1-\frac{\mu_S^2}{m_S^2}\right)^3\left(1+\frac{3\mu_S^2}{2m_S^2}\right)}\right\} > 1$$

$$\lambda_{hhh}^{O(N)} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{N\frac{m_S^4}{12\pi^2 v^2 m_h^2}\left(1-\frac{\mu_S^2}{m_S^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

Predictions on the *hhh* coupling

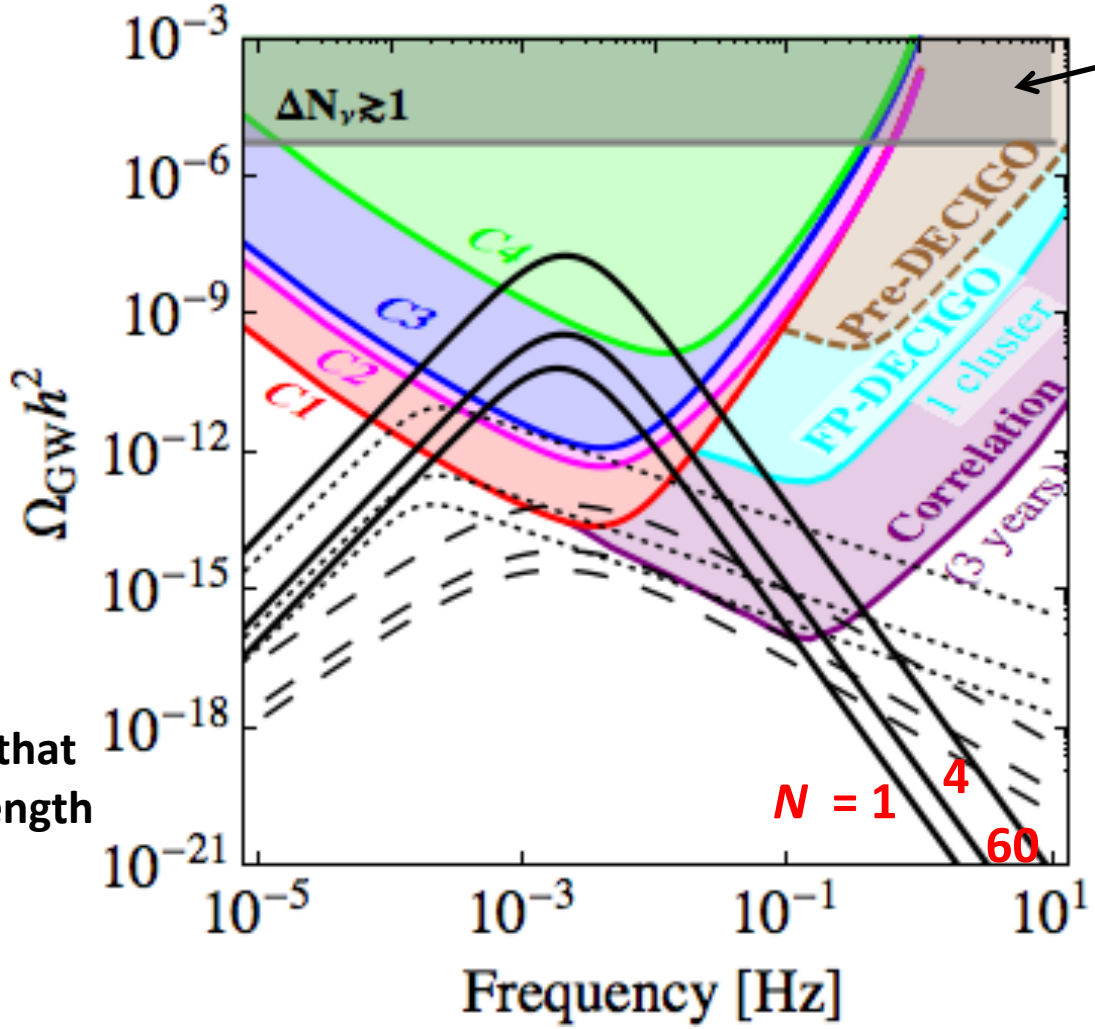


Large deviations in *hhh* coupling

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

GW spectrum from 1st OPT

***N* scalar model**



Bound from Non-observation of energy density of extra radiation

sw
env
$turb$

Sensitivities

eLISA
arXiv:1512.06239

DECIGO
Class. Quant. Grav. 28, 094011 (2011)

Mass m_s is chosen such that the peak strength is maximal

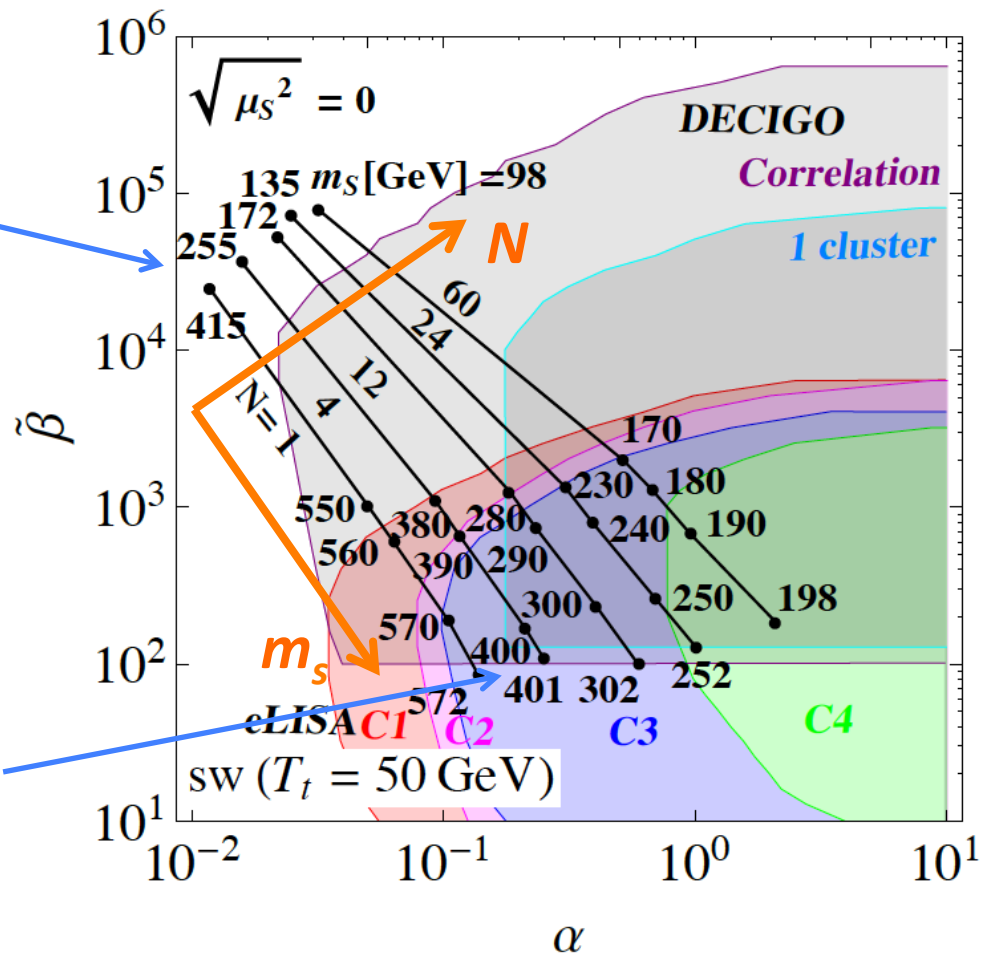
M. Kakizaki, S.K., T. Matsui, Phys. Rev. D92 (2015) no.11,115007

(N, m_s) may be determined from GWs

O(N) singlet model with the mass m_s

For smaller m_s
$\varphi_c/T_c>1$
cannot be satisfied

For larger m_s
$\Gamma/H^4 = 1$ cannot
be satisfied



Sensitivities

eLISA
arXiv:1512.06239

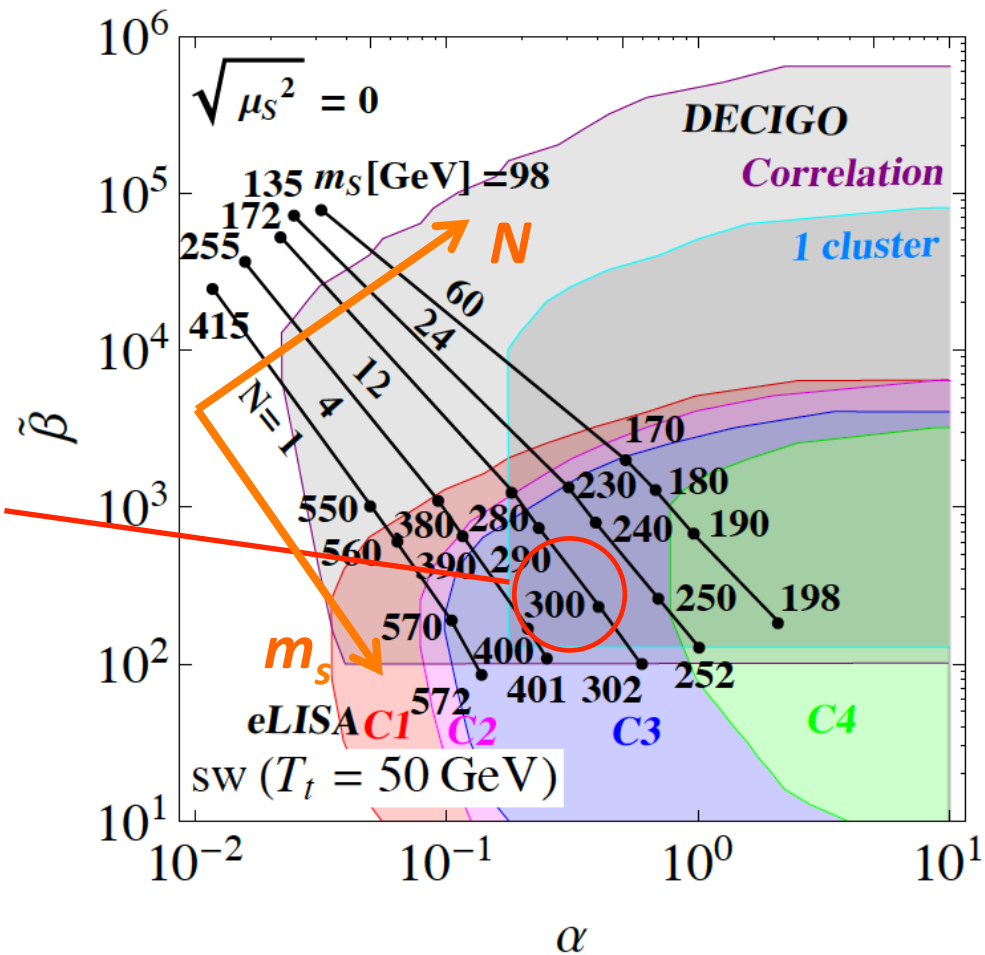
DECIGO,
Class. Quant. Grav.
28, 094011 (2011)

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 α and β 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

Golden 2030s ???

Super KEKB

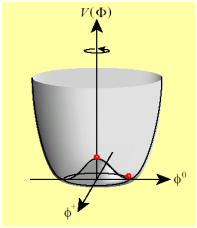
LHC Run2, 3

HL-LHC

Far future !!

Measurement of *hhh* coupling

ILC1TeV?

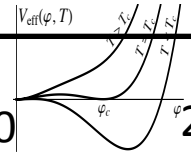


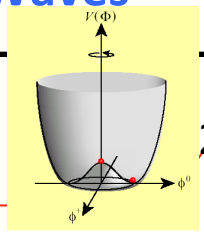
ILC250 with 1-2 ab^{-1} (?)

Precision measurement of Higgs couplings *hVV*, *hff*

LISA (approved!) 2028--

EW Phase Transition via Gravitational Waves





2015 2020 2025 2030 2035 2040 2045

TODAY

Synergy!

SuperKEKB	Flavor Physics
HL-LHC	Energy Frontier (New Particle Searches)
ILC	Precision measurement of Higgs couplings
LISA	EW Phase Transition from GWs

Final Example: Strongly 1st OPT by non-thermal mixing effect

Thermal loop effect ↓

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

Non-thermal effect ↑

Higgs singlet model

K. Fuyuto and E. Senaha, 2014

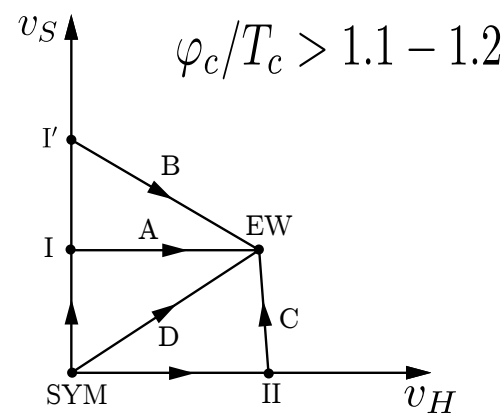
$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{pmatrix}, \quad S = v_S + \phi_2$$

$(\phi_1, \phi_2) \rightarrow$ (*h*, *H*) with θ

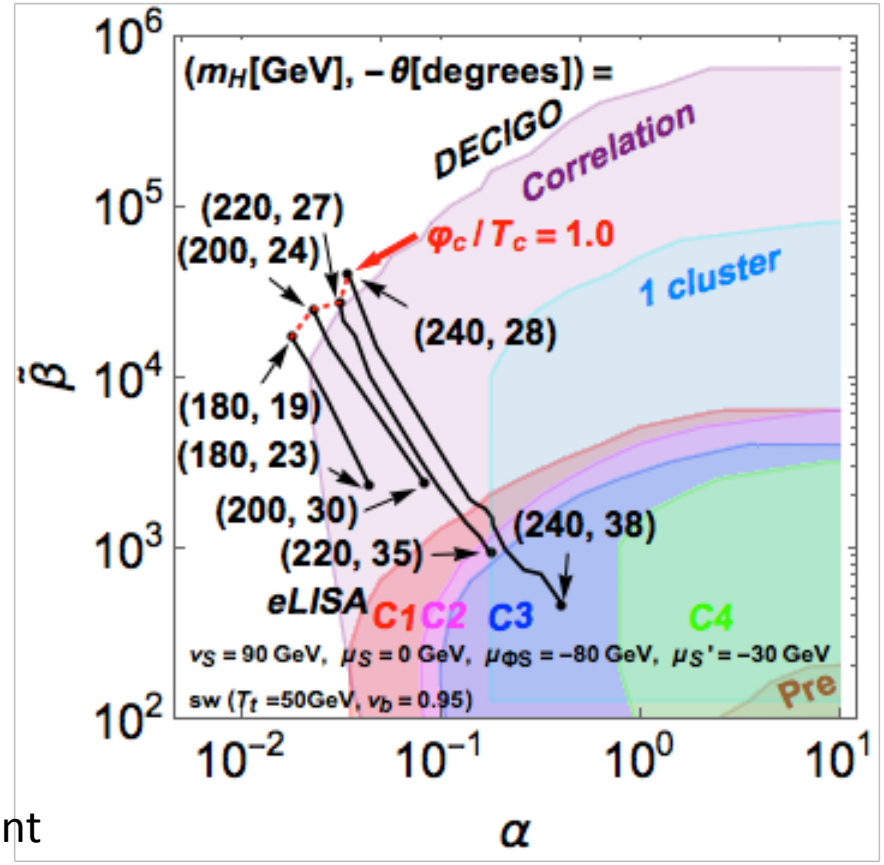
Multi-field analysis of EWPT is necessary

$$(v_\Phi, v_S)$$



Public tool "CosmoTransition" (Python code) is used.

K.Hashino, M.Kakizaki, S.K., T.Matsui, P.Ko, arXiv1608.00297



LISA (C1-C4):
[Caprini et al. (2015)]

DECIGO
(Pre, 1 cluster, Correlation)
[Kawamura et al. (2011)]

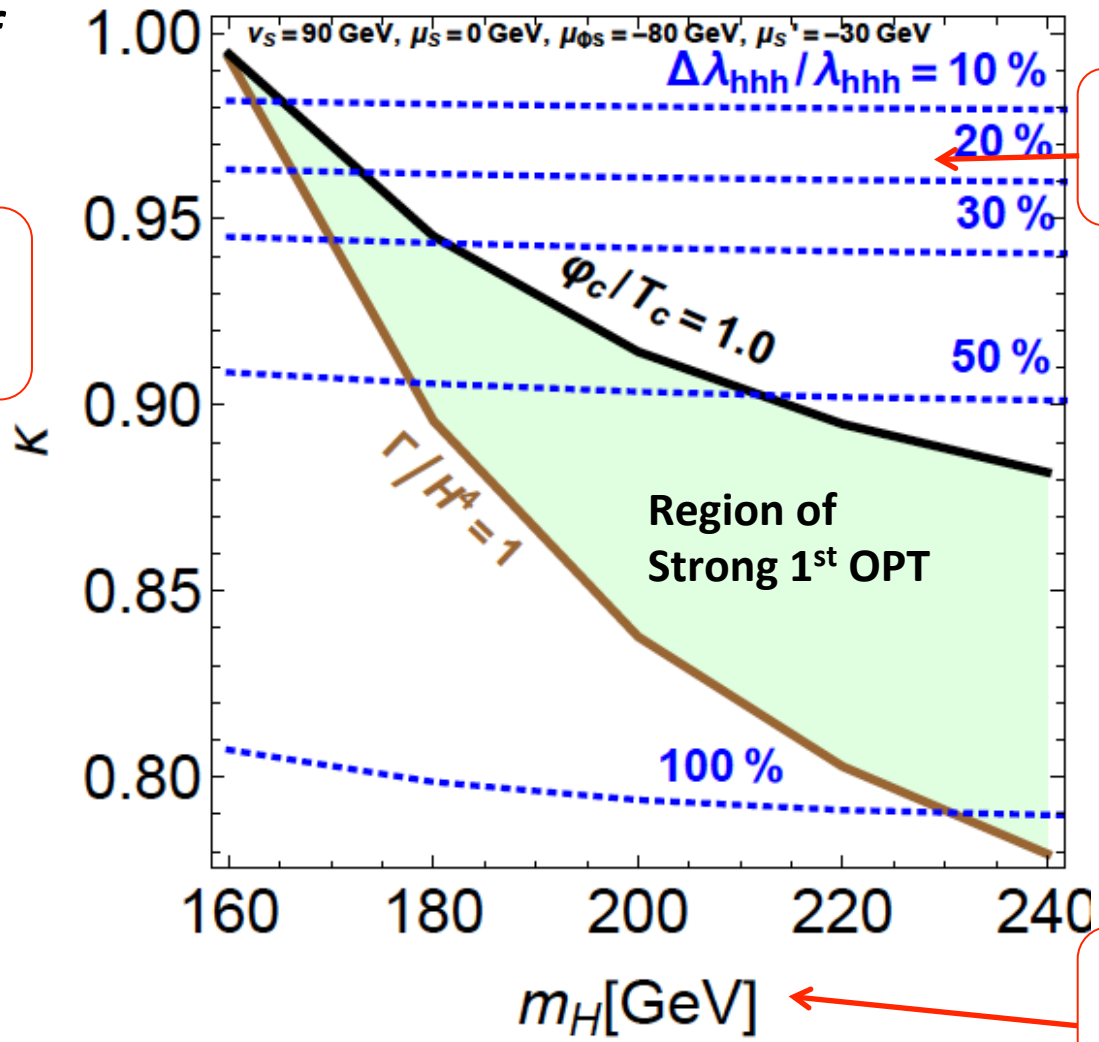
Benchmark point

v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	-80	-30	0	[160, 240]	[-45, 0]

LISA and DECIGO are capable of detecting GWs from 1st OPT in the HSM.

$\kappa = \kappa_V = \kappa_f$
$= \cos\theta$

Precision measurement at ILC/LHC



Self-coupling *hhh* measurement at ILC

Direct searches of the second Higgs at LHC

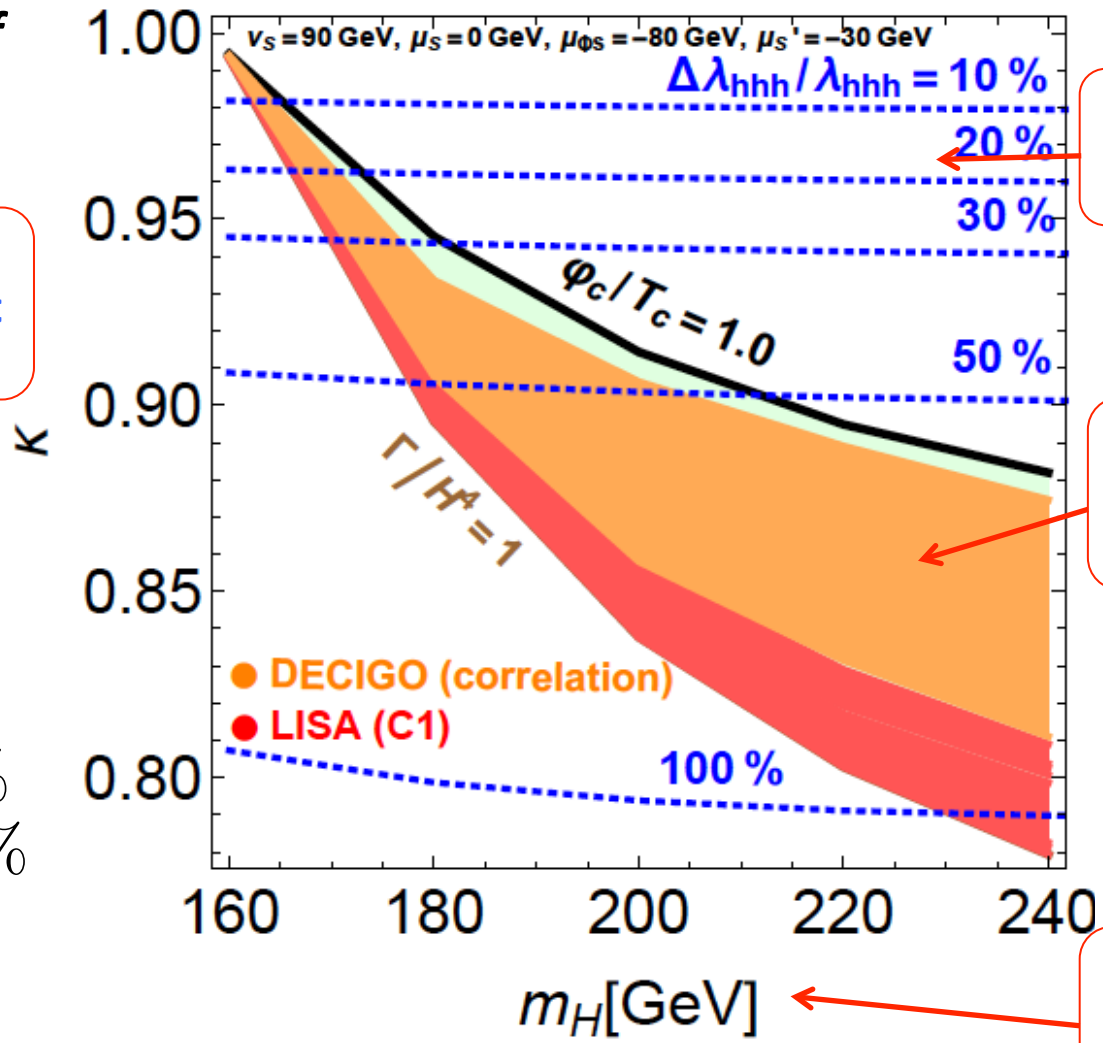
K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

$\kappa = \kappa_V = \kappa_f$
$= \cos\theta$

Precision measurement at ILC

HL-LHC
κ_V : 2%

ILC
κ_Z : 0.37%
κ_W : 0.51%



Self-coupling *hhh* measurement at ILC

$\Delta\lambda_{hhh}$: 10%

Measurement of Gravitational Waves at LISA/DECIGO

Direct searches of the second Higgs at LHC

K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

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**

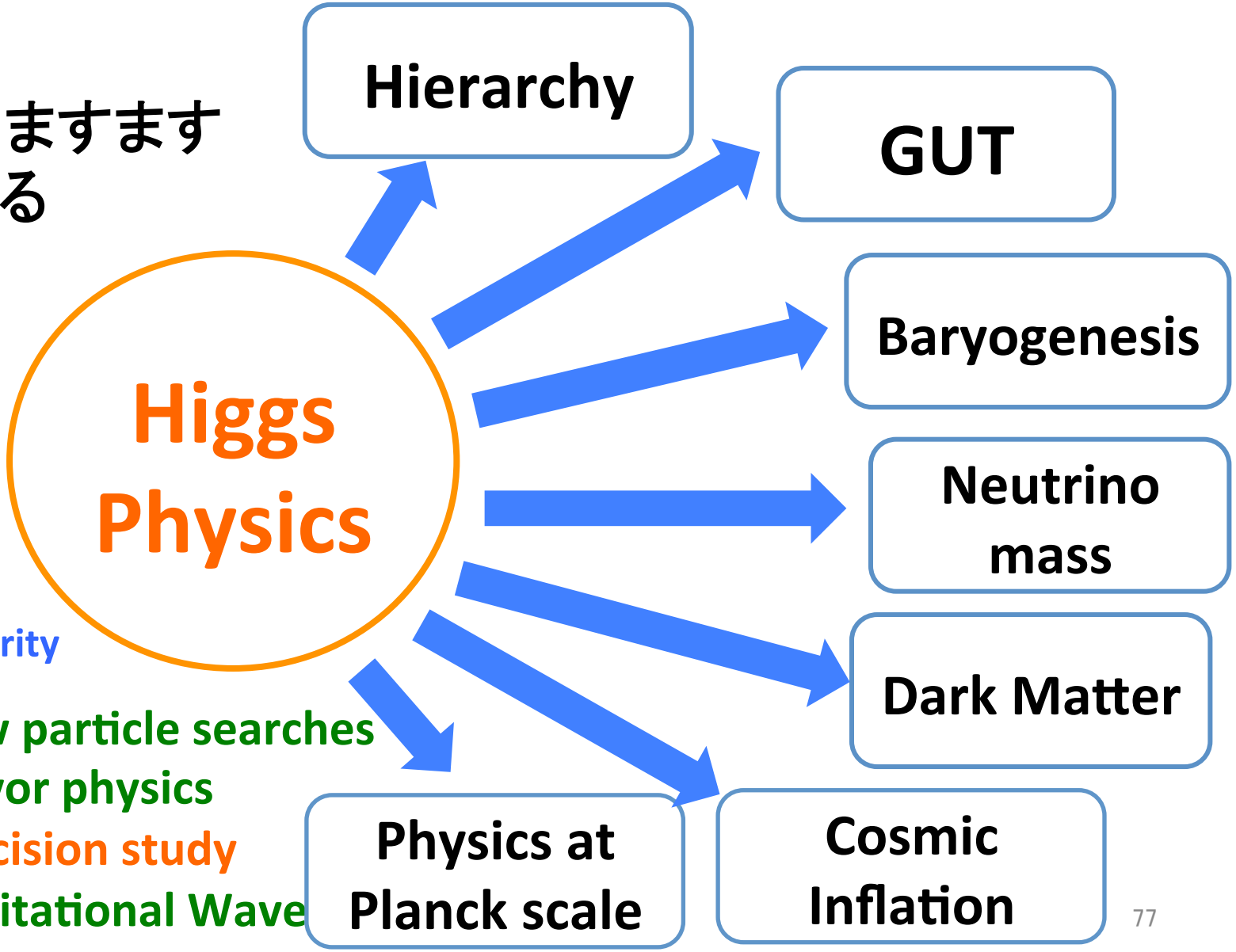
- **Extended Higgs models of 1st OPT predict always large deviations in the *hhh* coupling and also produce Gravitational Waves**

- **Future precision measurements of GWs may be able to fingerprint models of 1st OPT**

- **There can be a strong synergy in model identification among direct searches at HL-LHC, precision measurements of Higgs couplings (κ_i) at ILC and the GW spectrum at LISA in 2030s**

Higgs as a Probe of New Physics

これからますます
面白くなる



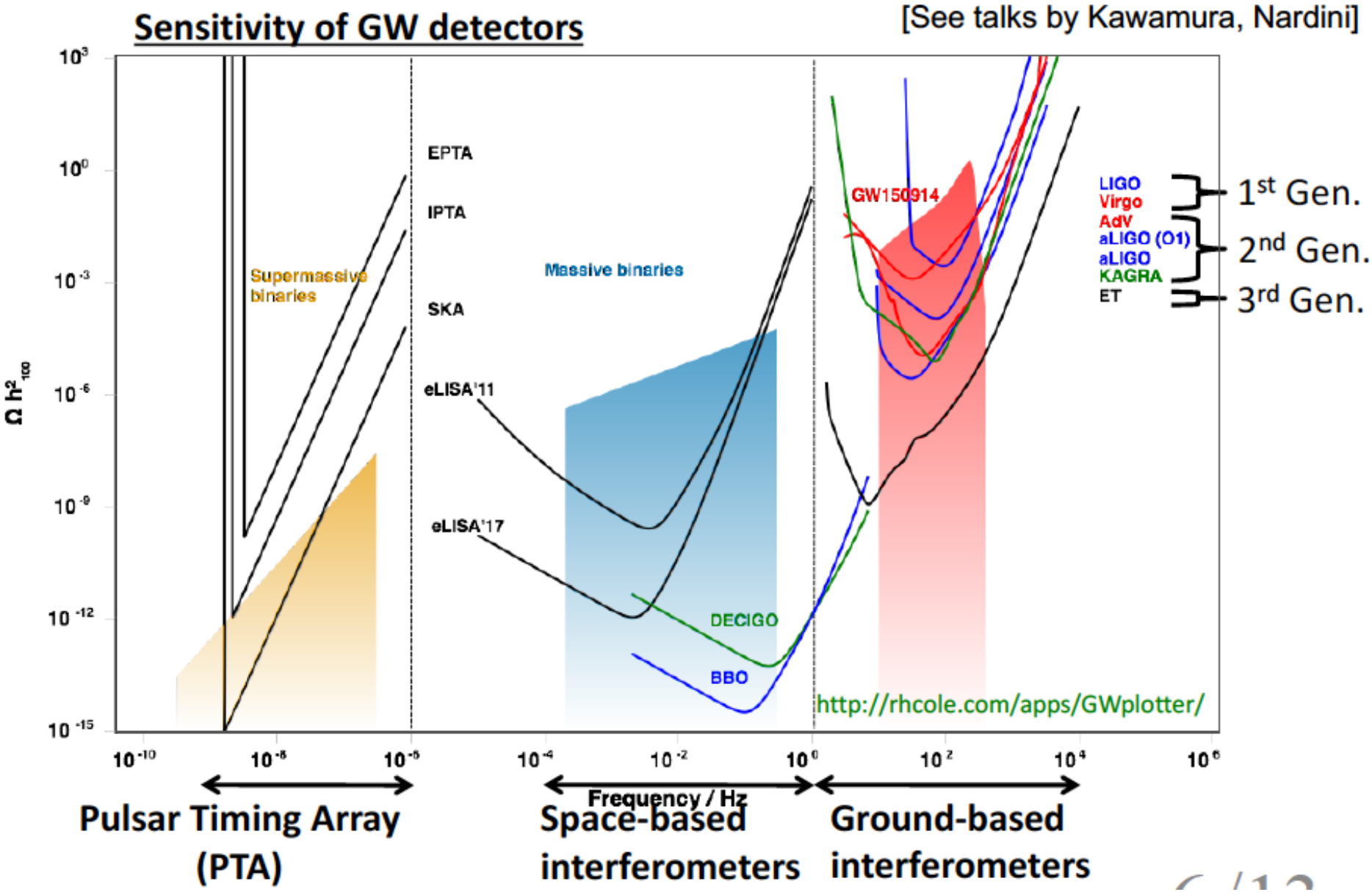
Synergy and
Complementarity

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

Thank you

~ Probing the Higgs potential by GW observations ~

[See talks by Kawamura, Nardini]



Landau pole

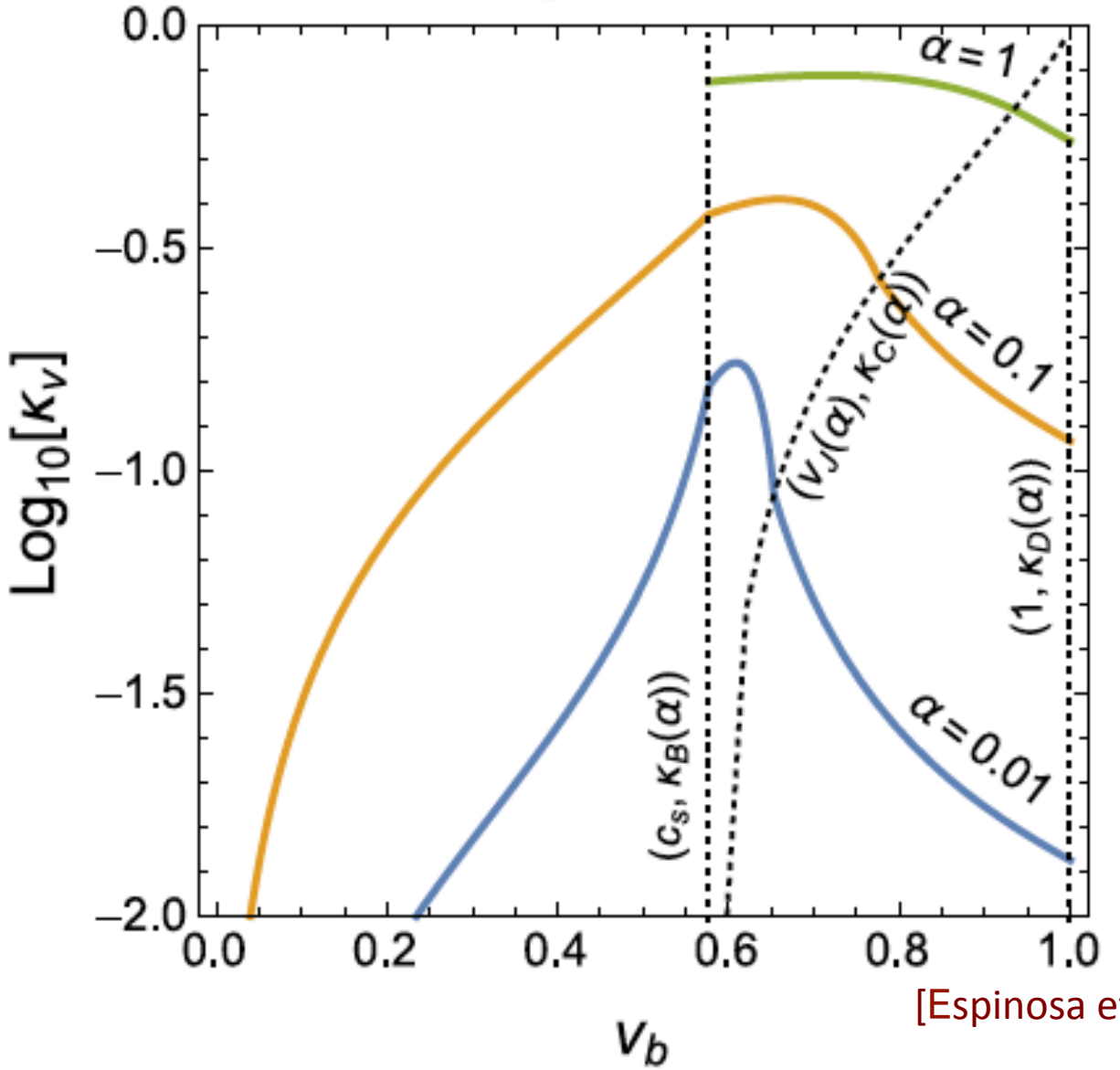
- Large scalar couplings at the EW scale

➡ Landau pole near the EW scale

N	1	4	12	60
Q	381 GeV	257 GeV	188 GeV	119 GeV
$\Lambda(\lambda_S = 0)$	5.4 TeV	17 TeV	28 TeV	33 TeV
$\Lambda(\lambda_S = 0.1)$	5.3 TeV	16 TeV	23 TeV	13 TeV
$\Lambda(\lambda_S = 0.2)$	5.2 TeV	15 TeV	19 TeV	5.4 TeV
$\Lambda(\lambda_S = 0.3)$	5.0 TeV	14 TeV	15 TeV	2.7 TeV

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

Efficiency factor



[Espinosa et al. (2010)]

ATLAS-CONF-2015-044

$5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV

Run 1

Best fit values for combination of ATLAS and CMS

Assumption,
absense of BSM particles in the loops
and $BR_{BSM} = 0$

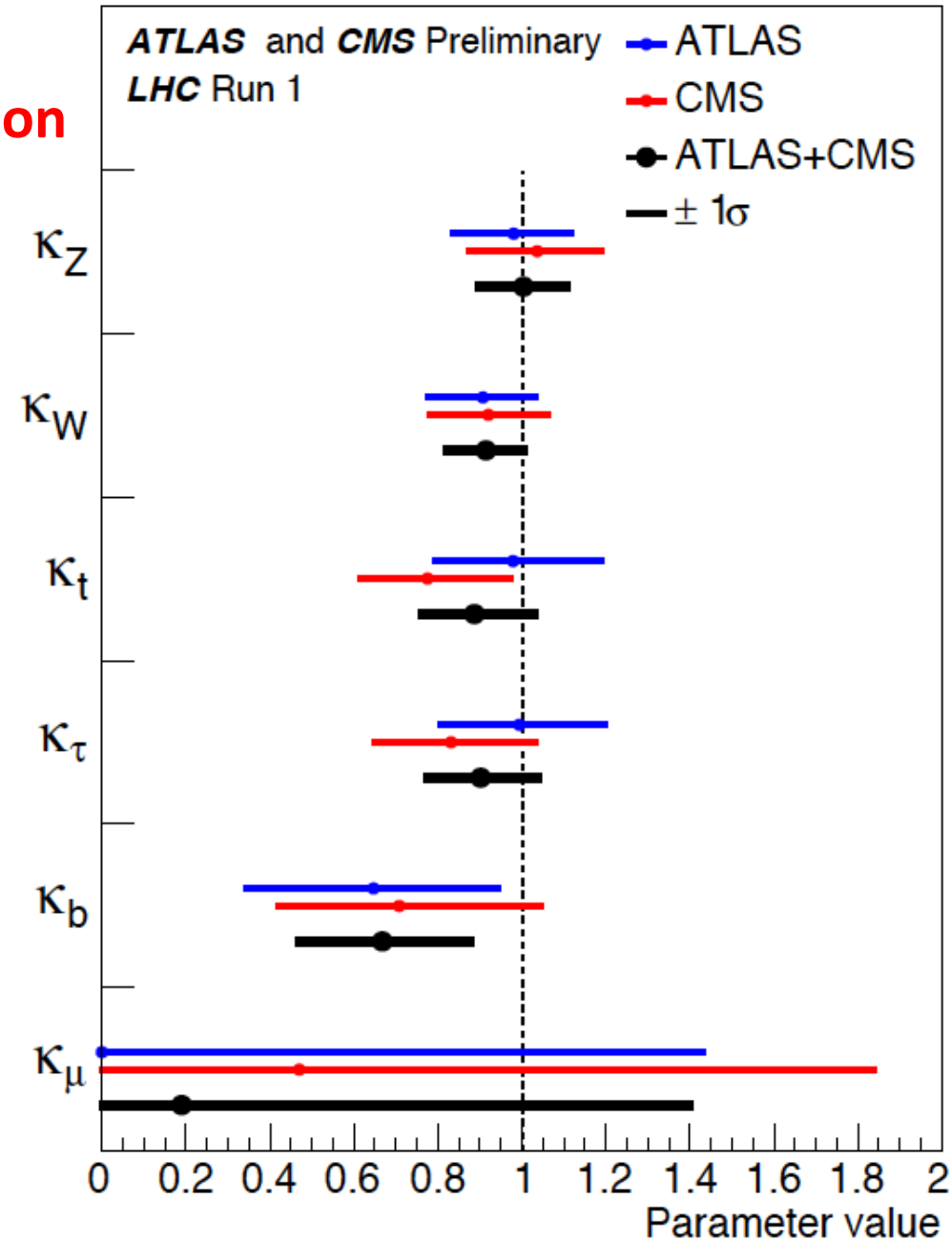
$$\kappa_Z = 1.00^{+0.10}_{-0.11}$$

$$\kappa_W = 0.91^{+0.09}_{-0.09}$$

$$\kappa_t = 0.89^{+0.15}_{-0.13}$$

$$\kappa_\tau = 0.90^{+0.14}_{-0.13}$$

$$\kappa_b = 0.67^{+0.22}_{-0.20}$$



Roughly Higgs couplings are determined by 20 %

Snowmass White Paper (Aug. 2013)

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_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.

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	17 %	8.3 %	3.8 %	2.3 %
gg	6.1 %	2.0 %	1.1 %	0.7 %
WW	4.7 %	0.4 %	0.3 %	0.2 %
ZZ	0.7 %	0.5 %	0.5 %	0.3 %
$t\bar{t}$	6.4 %	2.5 %	1.3 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	1.9 %	1.3 %	0.7 %
$\Gamma_T(h)$	9.0 %	1.7 %	1.1 %	0.8 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
hhh	–	83 %	21 %	13 %
BR(invis.)	$<$ 0.7 %	$<$ 0.7 %	$<$ 0.7 %	$<$ 0.3 %
$c\bar{c}$	6.8 %	2.9 %	2.0 %	1.1 %

Future *h*(125)-coupling measurements

Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

Snowmass Higgs Working Group Report 1310.8361