Higgs potential, future colliders and future GW interferometers

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

K. Hashino, M. Kakizaki, SK, T. Matsui, Phys. Rev. D94 (2016) no.1, 015005

K. Hashino, M. Kakizaki, SK, P. Ko, T. Matsui, arXiv: 1609.00297

Multi-Higgs Workshop 2016, 6-9 September 2016, Lisbon

The 3rd Toyama Workshop
"Higgs as a Probe of New Physics (*HPNP2017*)" 1.-4. March 2017

Local Organizing Committee

Mayumi Aoki	(Kanazawa U.)	Mitsuru Kakizaki	(U. of Toyama)
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Hiroaki Sugiyama	(U. of Toyama)	Koji Tsumura	(Kyoto U.)

You are cordially invited !!

This talk

We know that the Higgs potential is important to understand the nature of EWSB

It can be tested by measuring the *hhh* coupling

We here discuss how the future precision measurement of Gravitational Waves is useful to explore the Higgs potential

Future Colliders

v.s.

Future GW interferometers

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW
hZZ

Yukawa Interaction

hττ, hbb
htt, …

Dim 6 Operators

hgg
Hγγ, hZγ

$$L_{eff} = |D_\mu \Phi|^2 - y\, L\Phi R\ - 1/v^2\ |\Phi|^2 GG$$

Flavor Structure

New particle effect
in the loop

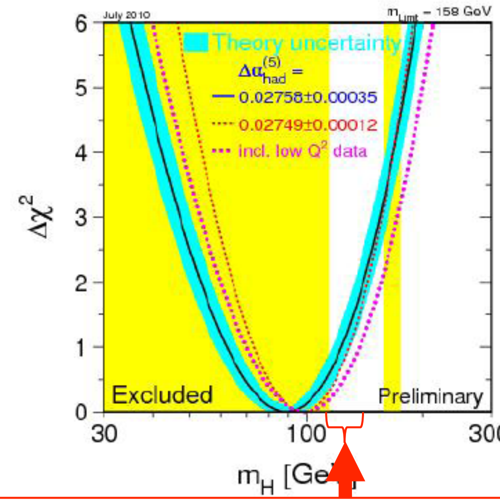
$$-\ V_{eff}(\Phi)$$

EW Symmetry Breaking

hhh, hhhh

Multiplet structure
Physics behind EWSB
Nature of Higgs boson

Higgs discovery in 2012



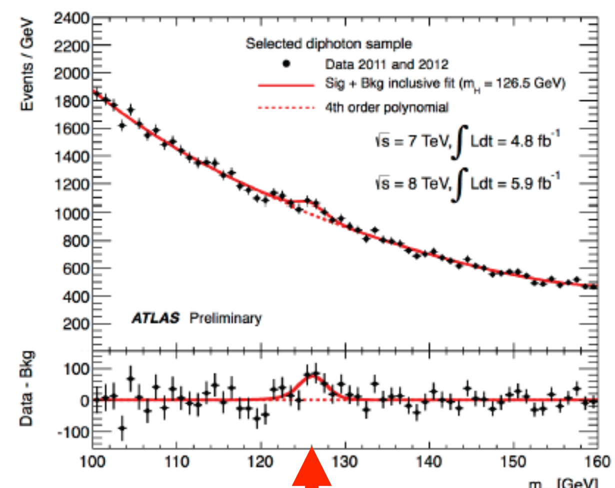
The mass is 125 GeV

Spin/Parity 0^+

It couples to ***γγ, ZZ, WW, bb, ττ, …***

Higgs Mass indicated by LEP/SLC

This is really a Higgs!

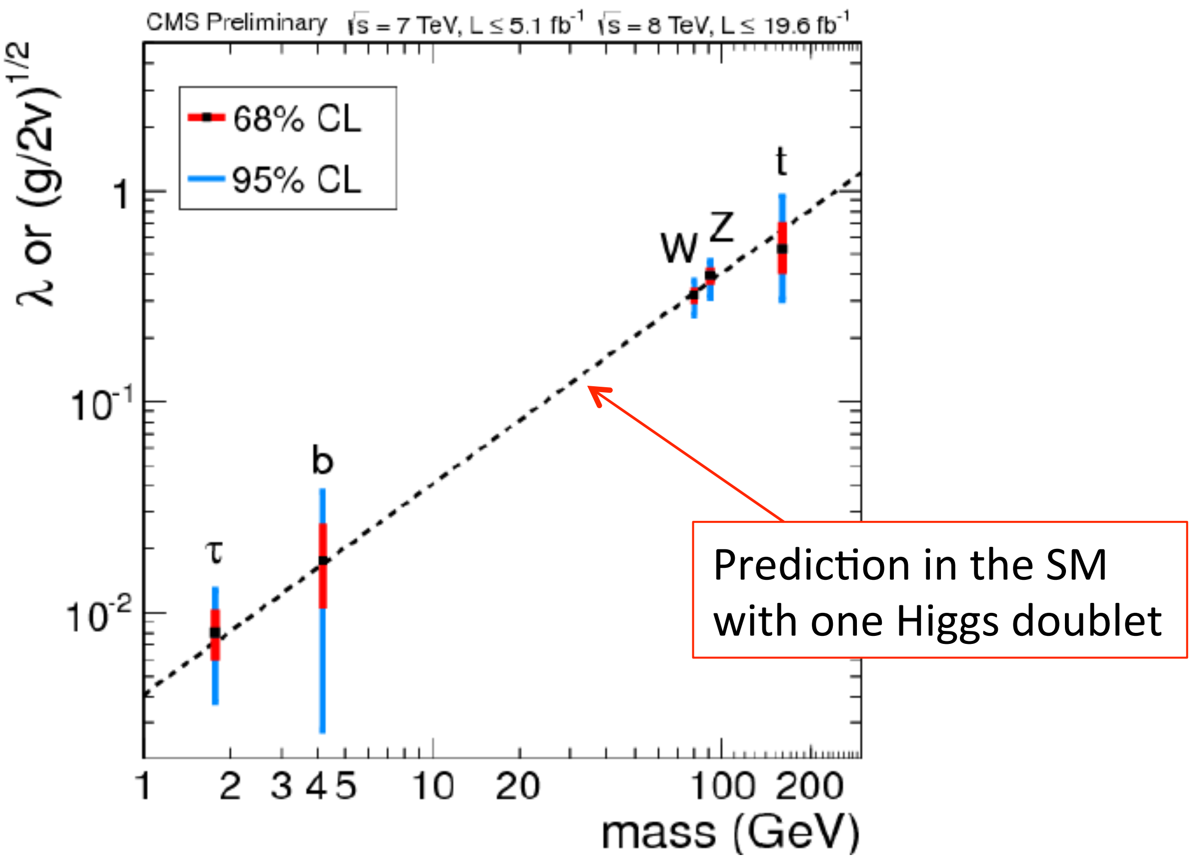


Measured couplings look consistent with the SM Higgs within the current errors

ATLAS/CMS July 2012

New Particle !

What a coincidence!



Higgs Sector

Mass Generation mechanisms

Higgs Mechanism	Yukawa Interaction	Dim 6 Operators
hWW	$h\tau\tau$, hbb	hgg
hZZ	htt, …	$H\gamma\gamma$, $hZ\gamma$

$$L_{eff} = |D_\mu \Phi|^2 - y\, L\Phi R \;\; - 1/v^2\, |\Phi|^2 GG$$

Flavor Structure

New particle effect in the loop

$$- V_{eff}(\Phi)$$

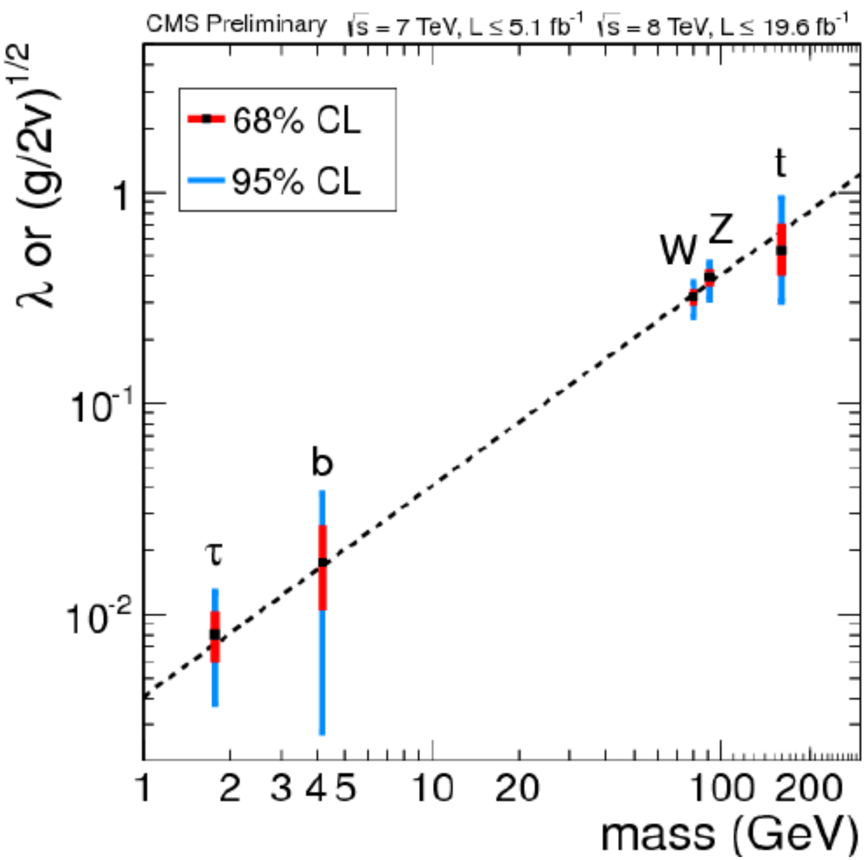
EW Symmetry Breaking

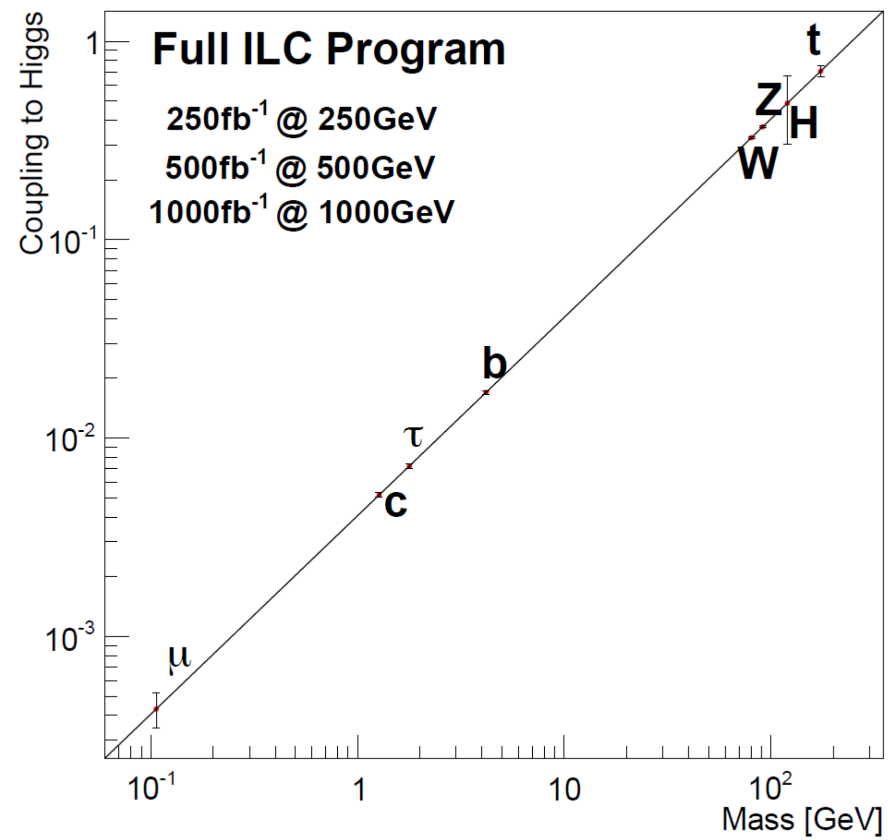
hhh, $hhhh$

Multiplet structure
Physics behind EWSB
Nature of Higgs boson

LHC Run I, II results, consistent with SM
But with more precision, They may differ from SM

Future precision measurements





The precision must be improved in future at HL-LHC and LC

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW
hZZ

Yukawa Interaction

hττ, hbb
htt, …

Dim 6 Operators

hgg
Hγγ, hZγ

$$L_{eff} = |D_\mu \Phi|^2 - y\, L\Phi R - 1/v^2 |\Phi|^2 GG$$

Flavor Structure

New particle effect
in the loop

$$- V_{eff}(\Phi)$$

EW Symmetry Breaking

hhh, hhhh

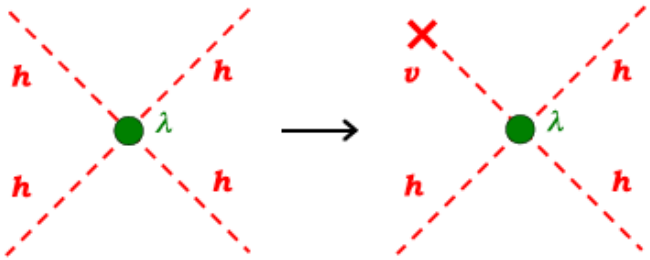
Multiplet structure
Physics behind EWSB
Nature of Higgs boson

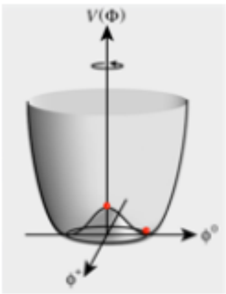
Little is known about the Higgs potential

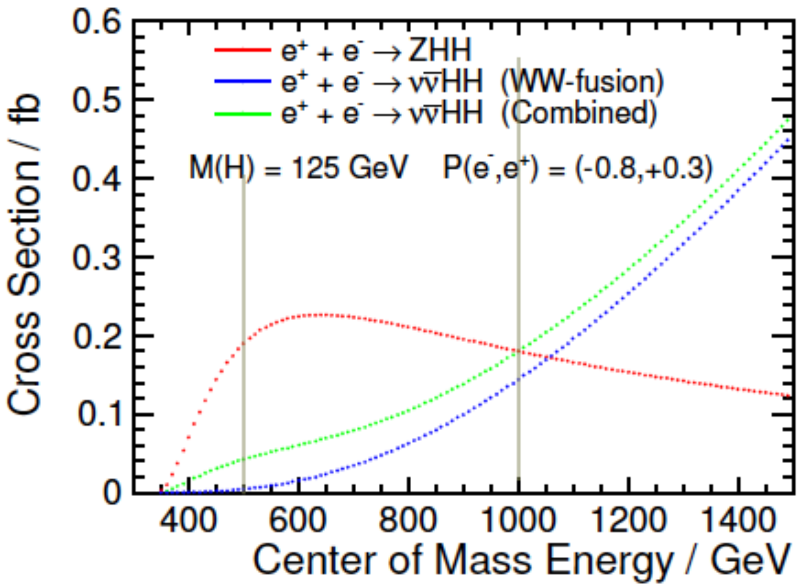
Higgs Self-Coupling

Slide by Keisuke Fujii

hhh coupling =
consequence of vacuum condensation



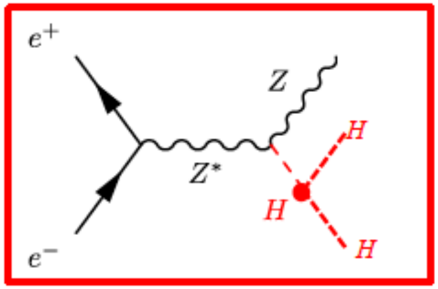


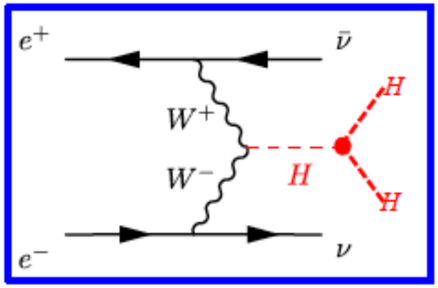


Challenging measurement because of:

- 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	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	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

Higgs potential

To understand the essence of EWSB, we must know the self-coupling in addition to the mass independently

$$V_{\text{Higgs}} = \frac{1}{2}\underline{m_h^2} h^2 + \frac{1}{3!}\underline{\lambda_{hhh}} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots$$

Effective potential $V_{\text{eff}}(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4 + \sum_f \frac{(-1)^{2s_f} N_{C_f} N_{S_f}}{64\pi^2} m_f(\varphi)^4 \left[\ln \frac{m_f(\varphi)^2}{Q^2} - \frac{3}{2}\right]$

Renormalization Conditions

$$\left.\frac{\partial V_{\text{eff}}}{\partial \varphi}\right|_{\varphi=v} = 0, \quad \left.\frac{\partial^2 V_{\text{eff}}}{\partial \varphi^2}\right|_{\varphi=v} = m_h^2, \quad \left.\frac{\partial^3 V_{\text{eff}}}{\partial \varphi^3}\right|_{\varphi=v} = \lambda_{hhh}$$

SM Case

$$\lambda_{hhh}^{\text{SMloop}} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

Non-decoupling effect

Higgs potential in multi-Higgs models

Deviation from the SM value due to new effect

Some examples

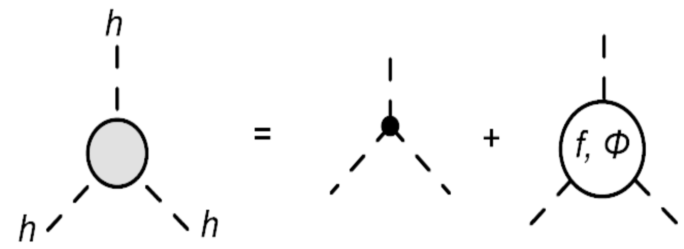
- 2HDM (mixing/quantum corrections)
- Models based on the CW mechanism
  (Classically scale invariant models)
- 1st Order Phase Transition (EW Baryogenesis)
  (2HDM, singlet models, …)

Case of Non-SUSY 2HDM

Case where the lightest *h* is SM-like [sin(β−α)=1]

At tree, the *hhh* coupling takes the same form as in the SM

At 1-loop, non-decoupling effect $m_\Phi{}^4$ (If *M* < *v*)



Φ = *H*, *A*, *H*±

$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

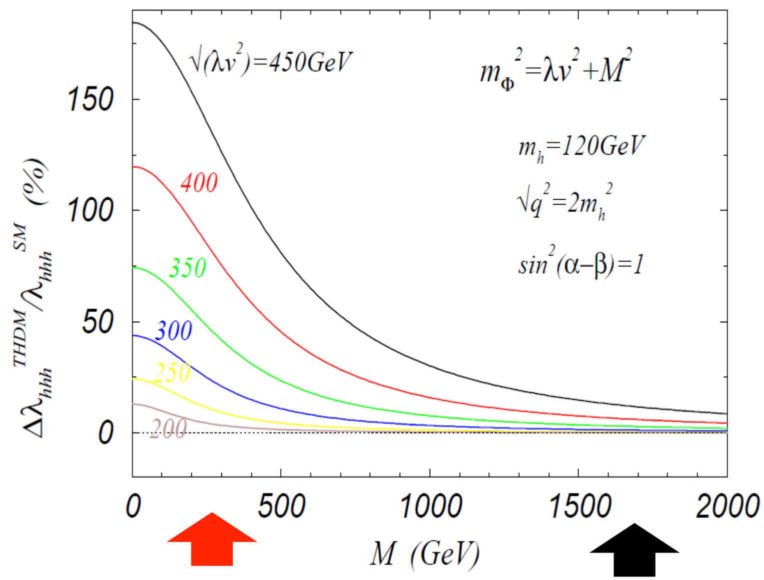
Extra scalar loop — Top loop

$$m_\Phi^2 = M^2 + \lambda_i v^2$$

(Φ = *H*, *A*, *H*±)

Deviation from SM can be 〜 100%

SK, Kiyoura, Okada, Senaha, 2003



Non-decoupling effect — Decoupling

Classically Scale Invariant models

EWSB can occur in CSI models (*m*=0 at tree)

Coleman, Weinberg '73
Gildener, Weinberg '76

$$V_{\rm eff}(\varphi) = A\varphi^4 + B\varphi^4 \ln\frac{\varphi^2}{Q^2}$$

$$A = \frac{1}{64\pi^2 v^4}\left[3{\rm Tr}\left(M_V^4 \ln\frac{M_V^2}{v^2}\right) - 4{\rm Tr}\left(M_f^4 \ln\frac{M_f^2}{v^2}\right) + {\rm Tr}\left(M_S^4 \ln\frac{M_S^2}{v^2}\right)\right]$$

$$B = \frac{1}{64\pi^2 v^4}\left[3{\rm Tr}\left(M_V^4\right) - 4{\rm Tr}\left(M_f^4\right) + {\rm Tr}\left(M_S^4\right)\right]$$

To satisfy m_h=125 GeV, *B* must contain additional scalar/vector field

$$m_h^2 \equiv \left.\frac{\partial^2 V_{\rm eff}}{\partial\varphi^2}\right|_{\varphi=v} = 8Bv^2 \simeq (125{\rm GeV})^2$$

$${\rm Tr}M_S^4 = 8\pi^2 v^2 m_h^2 - 3m_Z^4 - 6m_W^4 + 12m_t^4$$

$$\Gamma_{hhh}^{\rm CCI} \equiv \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v} = \frac{5m_h^2}{v}$$

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \sim \frac{2}{3}$$

Endo Sumino, 2015
Fuyuto Senaha, 2015
Hashino, SK, Orikasa, 2015

In CSI models, $\Delta\lambda_{hhh}$ is universally predicted to be about 67% larger than SM.

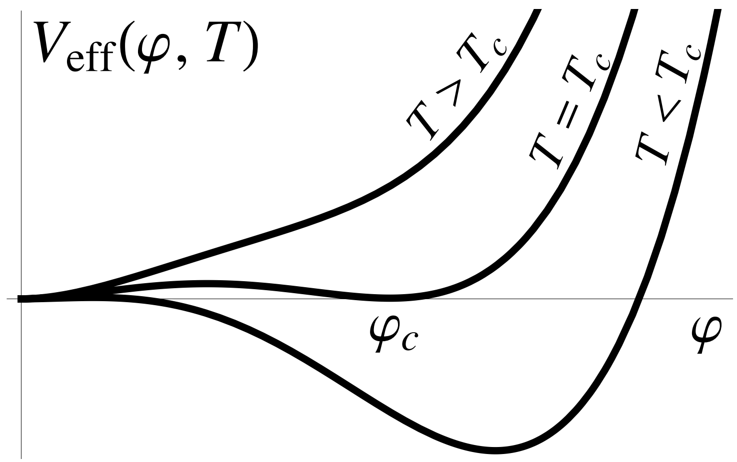
Strongly 1st OPT (EW Baryogenesis)

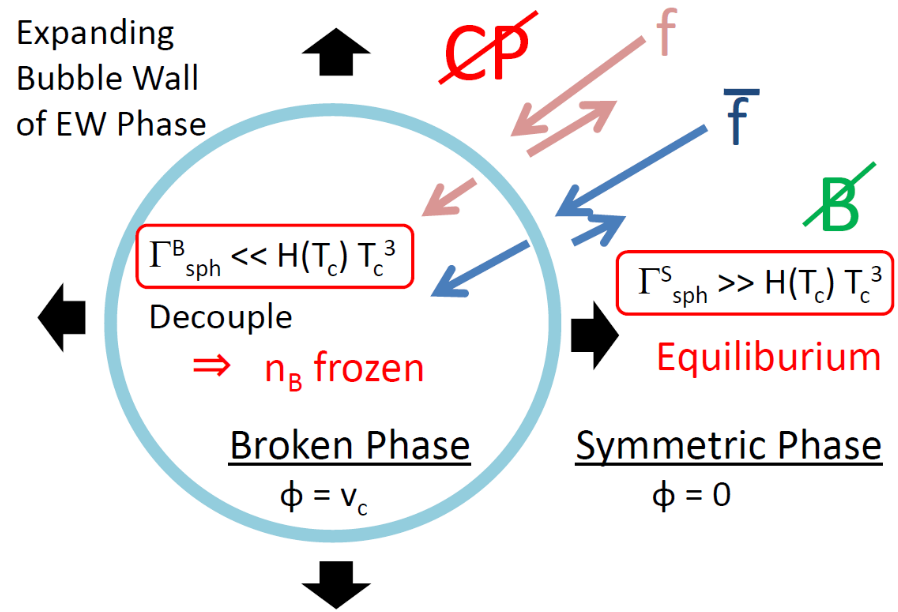
$\Gamma \sim e^{-E_{\rm sph}/T} \ (T < T_c)$

$\Gamma \sim \kappa(\alpha_W T)^4 \ (T_c < T)$

Sakharov conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1st Order EW Phase Transition





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

(Sphaleron Rate) < (Expansion Rate) ➡ $\varphi_c/T_c > 1$

The SM cannot satisfy the condition

High Temperature Expansion (just for sketch)

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

Condition of Strongly 1st OPT

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

However, the SM cannot realize the strongly 1st OPT

$$E \simeq \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3 + \cdots\right) \quad \lambda_{T_C} \sim \frac{m_h^2}{2v^2} + \cdots$$

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

For m_h = 125 GeV

We need a mechanism to enlarge φ_c/T_c to realize strongly 1st OPT

1^{st} OPT in extended Higgs sectors

High Temperature Expansion (just for sketch)

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

Condition of Strongly 1^{st} OPT

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

The condition can be satisfied by thermal loop effects of additional scalar bosons Φ (Φ = *H, A, H*⁺, …) $m_\Phi^2 \simeq M^2 + \lambda_i v^2$

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

1st OPT in extended Higgs sectors

High Temperature Expansion (just for sketch)

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

Condition of Strongly 1st OPT

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

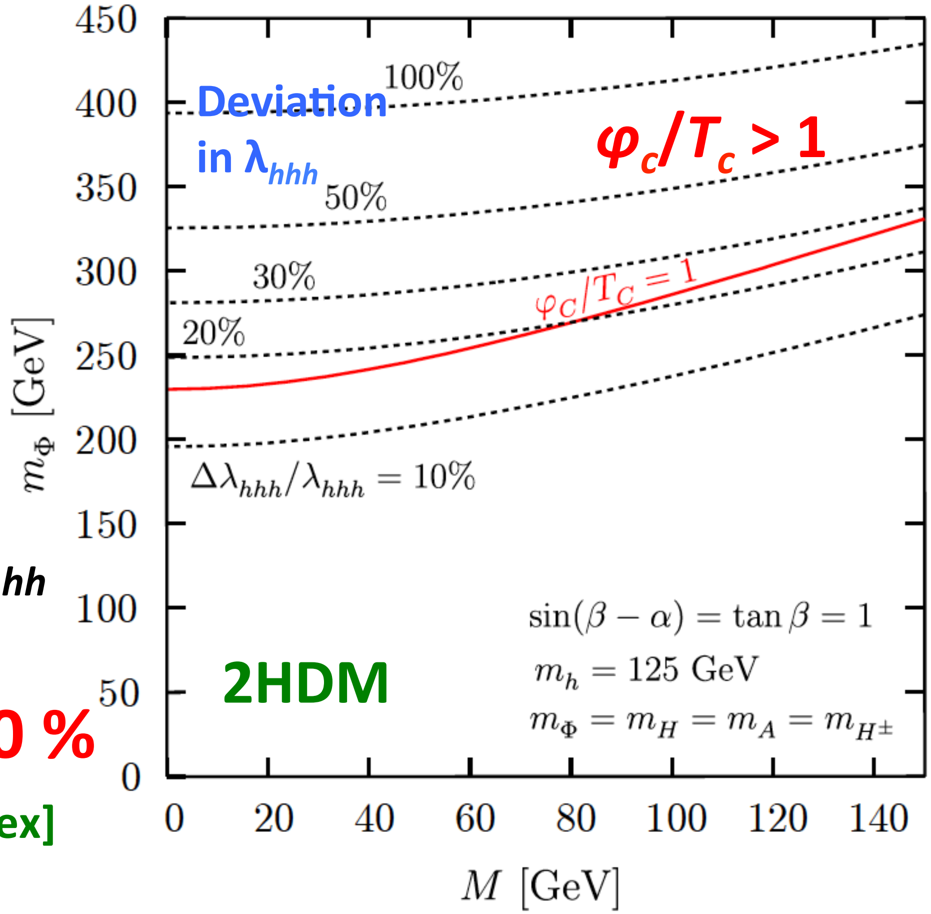
In this case, large quantum effects also appear in the *hhh* coupling

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

Strong 1st OPT and the *hhh* coupling

Strongly 1st OPT
⇔ Non-decoupling effect
⇔ large deviation in *hhh*

SK, Y Okada, E Senaha (2005)



At LHC, challenging to measure λ_{hhh}

ILC (1 TeV) can measure λ_{hhh} by 10 %

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

EW Baryogenesis can be tested at ILC!

Gravitational Waves

another probe of 1st OPT?

GW : another probe of 1st OPT?

Gravitational Waves (GWs)

- Propagating ripples in space-time curvature
- Produced by non-uniform motion of massive objects

Sources

Astronomical Origin Binary Stars (Black Holes, Neutron Stars, etc)
Supernova explosions, …

Targeted by ongoing ground-based experiments (aLIGO, aVirgo, KAGRA) aLIGO found it in 2015

Cosmological Origin First order phase transition (EW, GUT, …)
Cosmic inflation, …

Future space-based experiments (eLISA, DECIGO, BBO)

Previous studies of relic abundance of GWs from 1st OPT

1. Model Independent Analyses [1]

2.. Higher Oder Operators [2]

3. Non-decoupling effects of sparticles ...

   Stop search results tell that strong 1st OPT cannot be realized in MSSM [3]

4. Non-thermal effect at the tree level (NMSSM [3], real singlet model [4])

[1] C. Grojean and G. Servant, PRD75, 043507 (2007);

K. Kohri et al., arXiv:1405.4166.

[2] C. Delaunay et al., JHEP0804, 029 (2008).

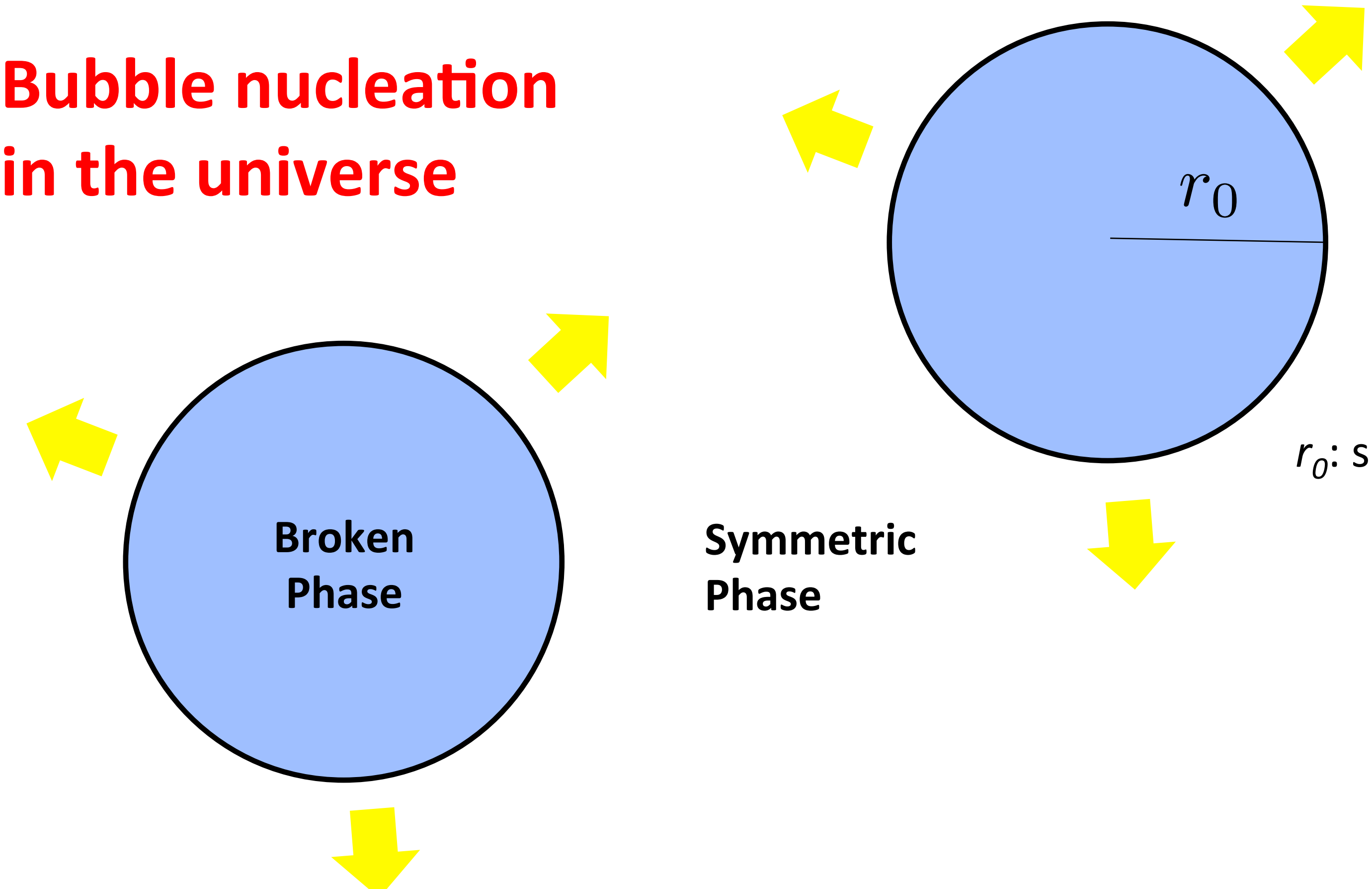
[3] R. Apreda et al., NPB631, 342 (2002).

[4] A. Ashoorioon and T. Konstandin, JCAP0809, 022 (2008).

Espinosa, et al (2010), No (2011), ...

Origin of GWs from 1st OPT

Bubble nucleation in the universe



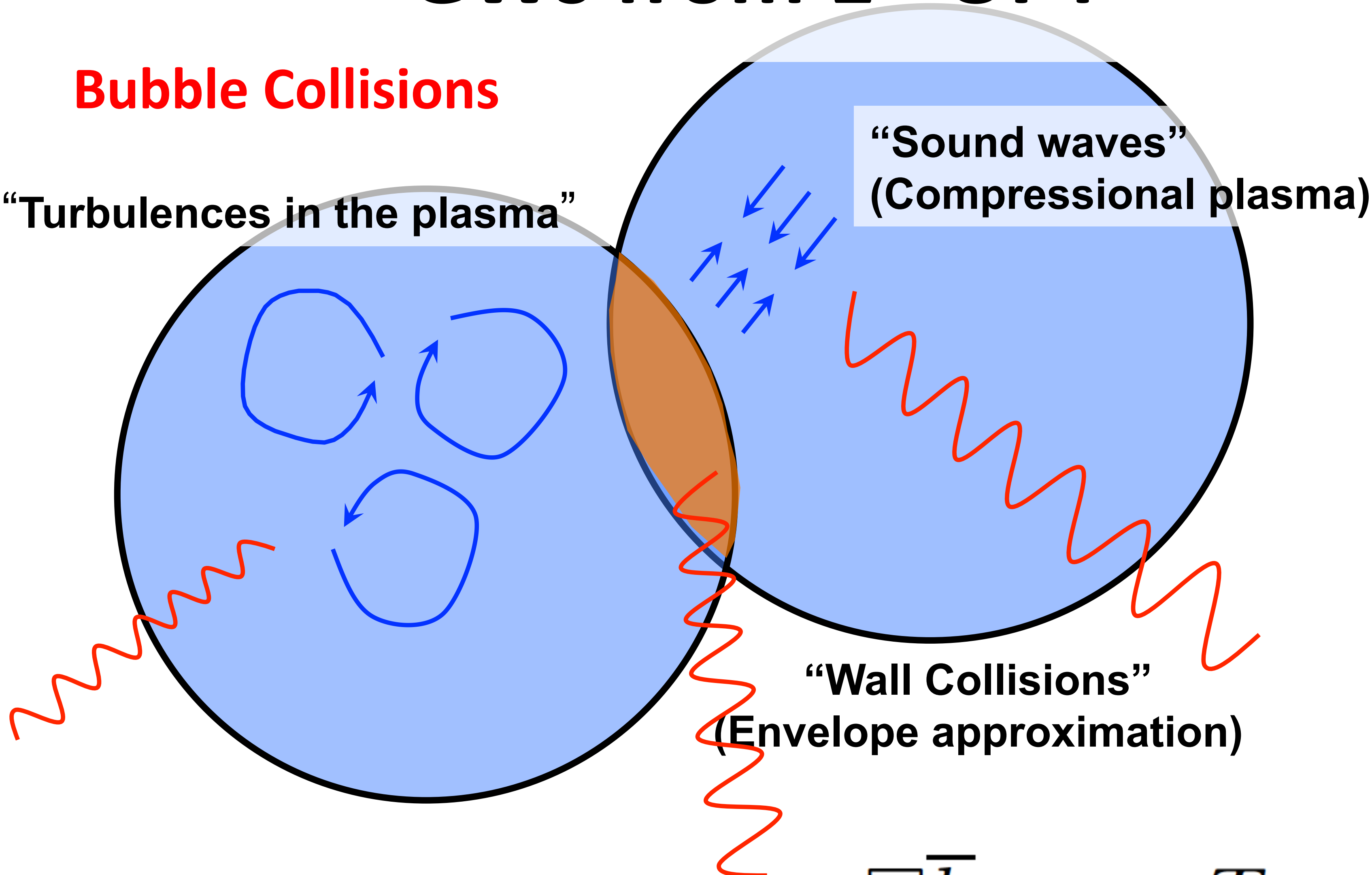
r_0: size of critical bubble

Expanding babbles of the broken phase

Bubble is spherical → No GW occurs

GWs from 1st OPT

Bubble Collisions



Spherical symmetry is violated by bubble collisions → GW occurs

$$\Box \bar{h}_{\mu\nu} = \kappa \underline{T_{\mu\nu}}$$

Souces of GW

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)

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

2. Collision of the bubbles (envelop approximation)

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

3. Magnetohydrodynamic (MHD) plasma turbulence in the bubbles

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

v_b : wall velocity κ_ϕ κ_v : efficiency factors $\epsilon = 0.05$

The spectrum are evaluated by inputting the lattent heat α, variation of the bubble nuclearation rate β and transition temperature T_t

GW spectrum is derived from the effective potential at finite temperatures $V_{\text{eff}}(\varphi, T)$

Bubble nucleation rate per unit volume per unit time:

$$\Gamma(t) = \Gamma_0(t)\exp[-S_E(t)] \qquad S_E(T) = S_3(T)/T \qquad S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\text{eff}}(\varphi_b, T)\right]$$

Transition temperature: T_t

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

Parameter α **Released false vacuum energy (Latent heat)**

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

Parameter β **Inverse of the duration of phase transition**

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

ILC v.s. LISA/DECIGO?

Question:

Can future GW observation be used to probe or distinguish models of particle physics like collider experiments? How precisely?

Higgs model with *N* singlet fields

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

Imposed O(*N*) for simplicity $S^{\mathrm{T}} = (S_1, \cdots, S_N)$

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

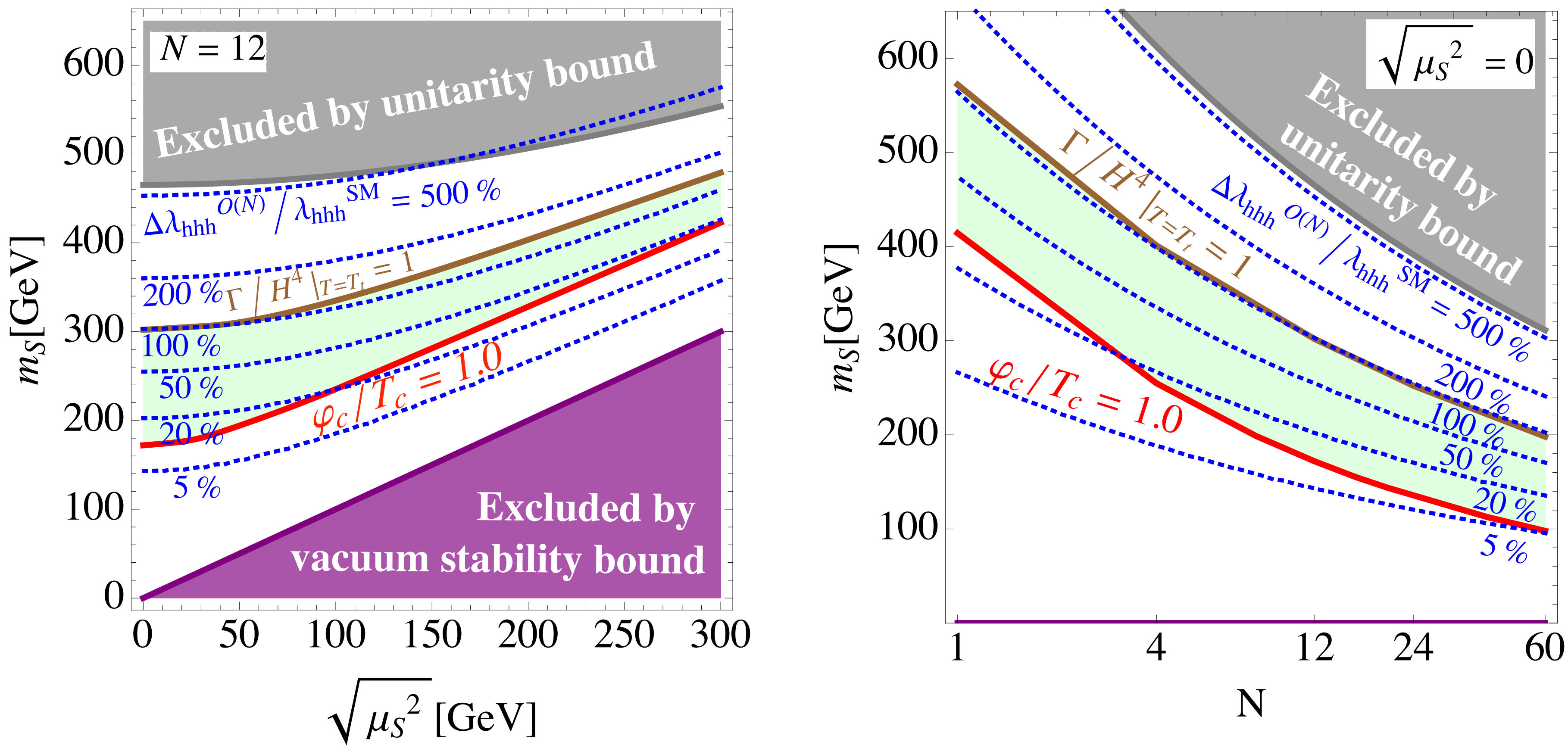
Mass of scalar fields: $m_S^2 = \mu_S^2 + \frac{c}{2}v^2$

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

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

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

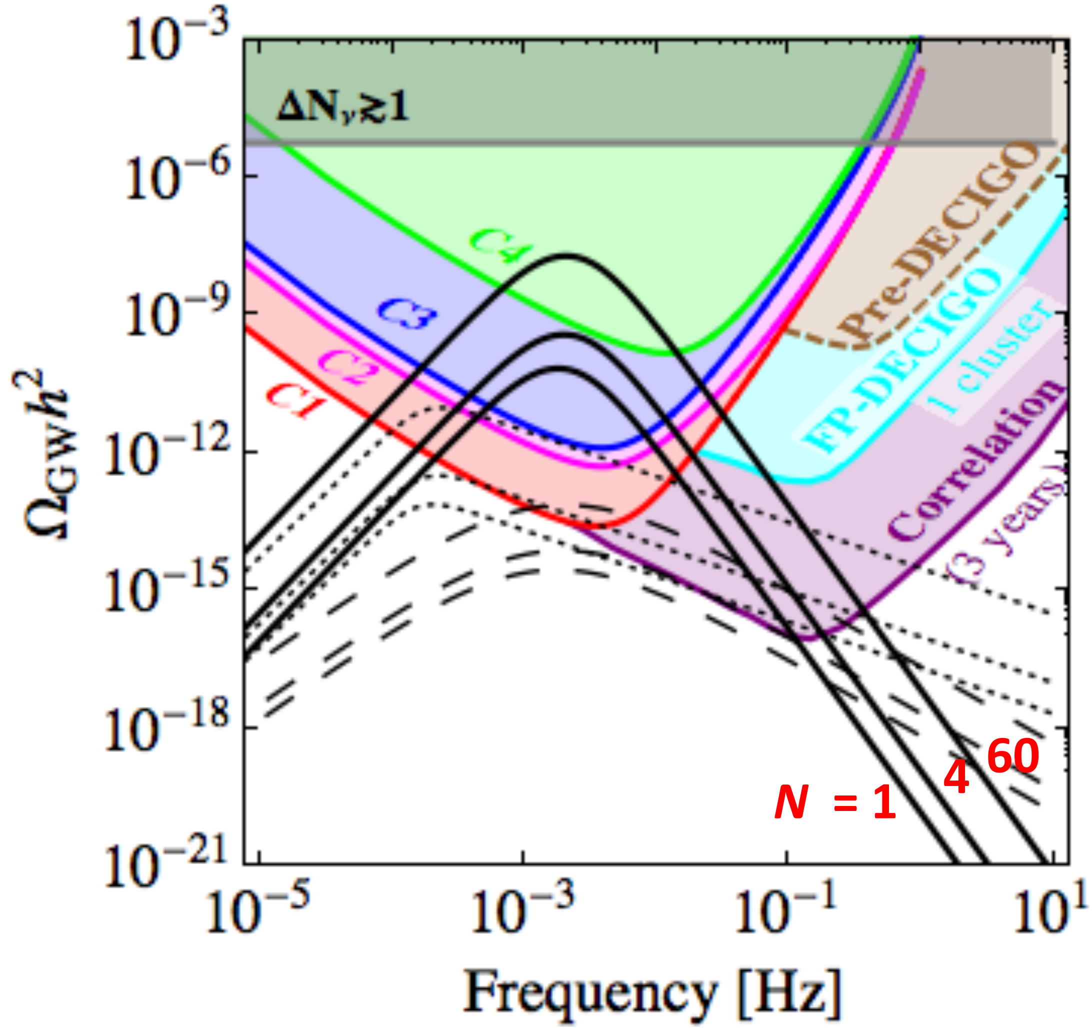
Predictions on the *hhh* coupling

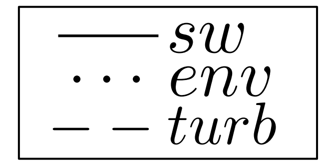


O(10)% deviations in *hhh* coupling

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

GW spectrum from 1st OPT





Sensitivities

eLISA
arXiv:1512.06239

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

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

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

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

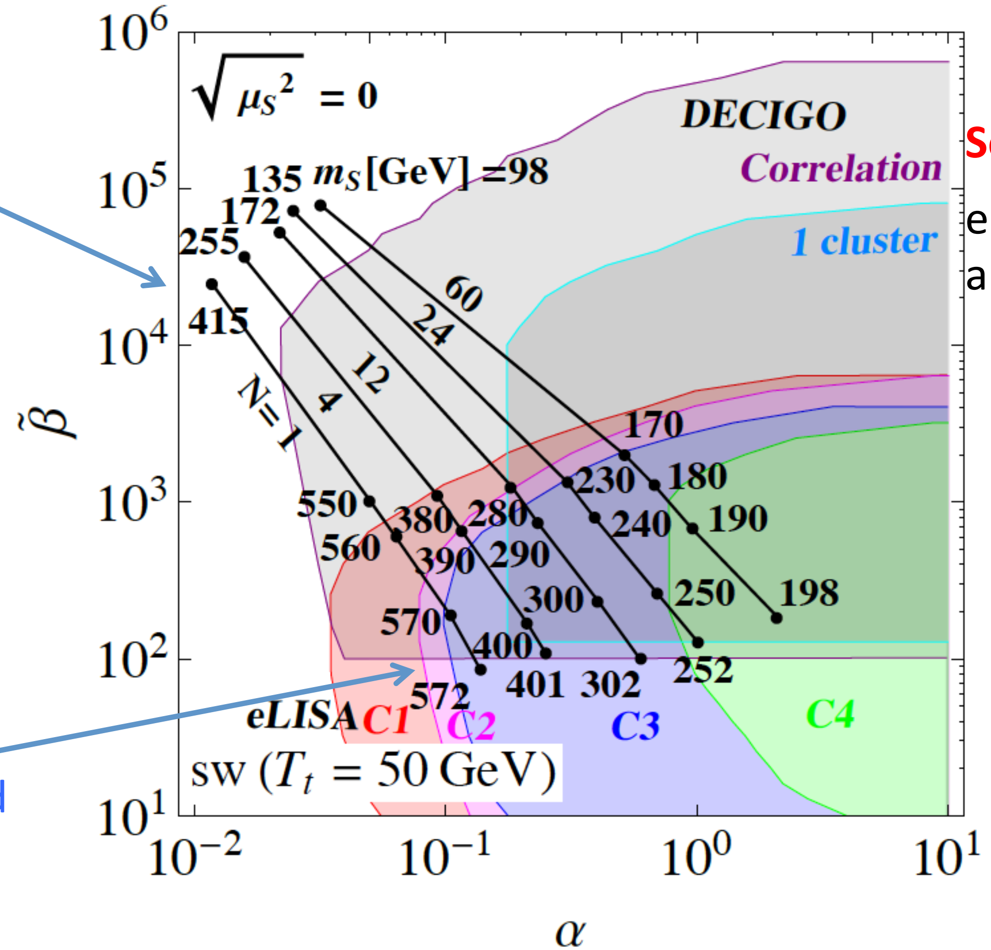
Extragalactic WD binaries (isotropic)

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

Schneider et al., 2005

Dependences on (N, m_s)

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



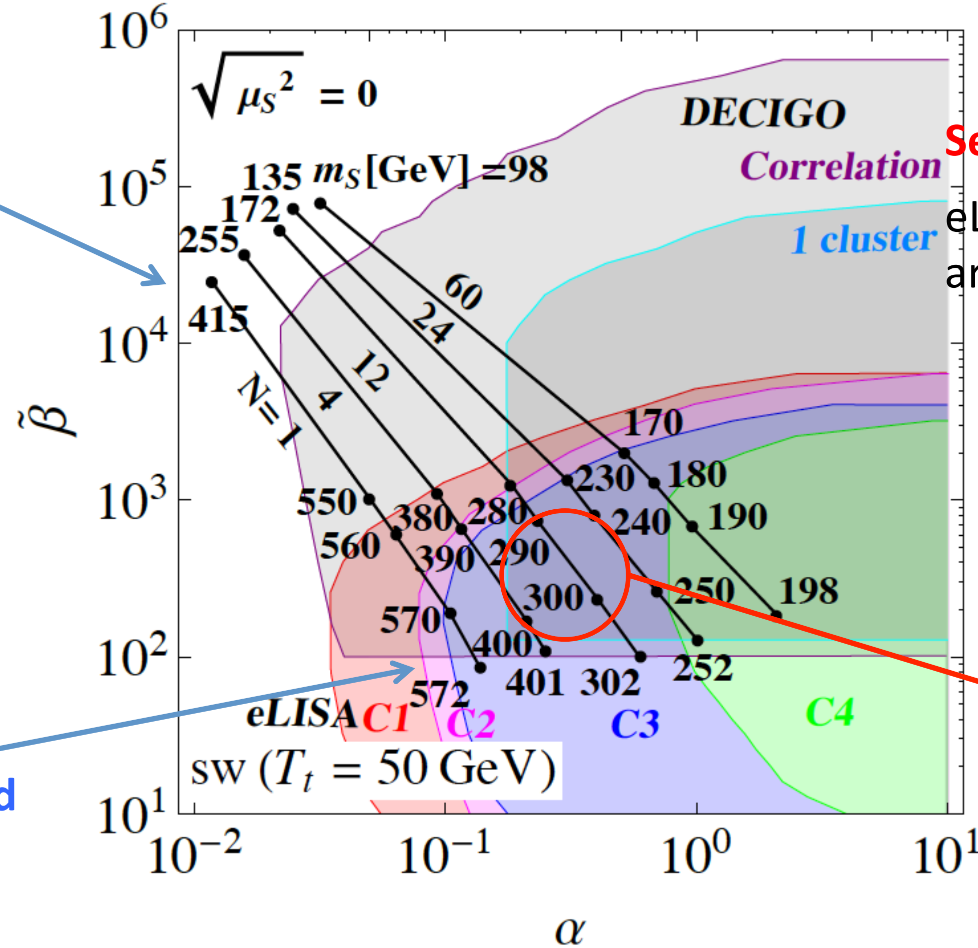
Sensitivities
eLISA
arXiv:1512.06239

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

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

Dependences on (N, m_s)

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



Sensitivities

eLISA
arXiv:1512.06239

If α and β are determined with this kind of resolution, we may be able to fingerprint the model (N, m_S)

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$\Gamma/H^4 = 1$ cannot be realized

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

Synergy？

A simple example of the complementarity of

- measuring the *hhh* coupling at ILC
- measuring the GW spectrum at LISA/DECIGO.

K. Hashino, M. Kakizaki, SK, T. Matsui, Phys. Rev. D94 (2016)

We discuss discrimination between models with *N* singlets with/without classically scale invariance

Complementarity

If the deviation in *hhh* is found to be about 60-70% at the ILC, we can distinguish scale invariant models from usual models by the precision measurement of GWs at future GW interferometers

(Massive) O(N) singlet model

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} \simeq 1 + \frac{N m_S^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{\mu^2}{m_S^2}\right)^3$$

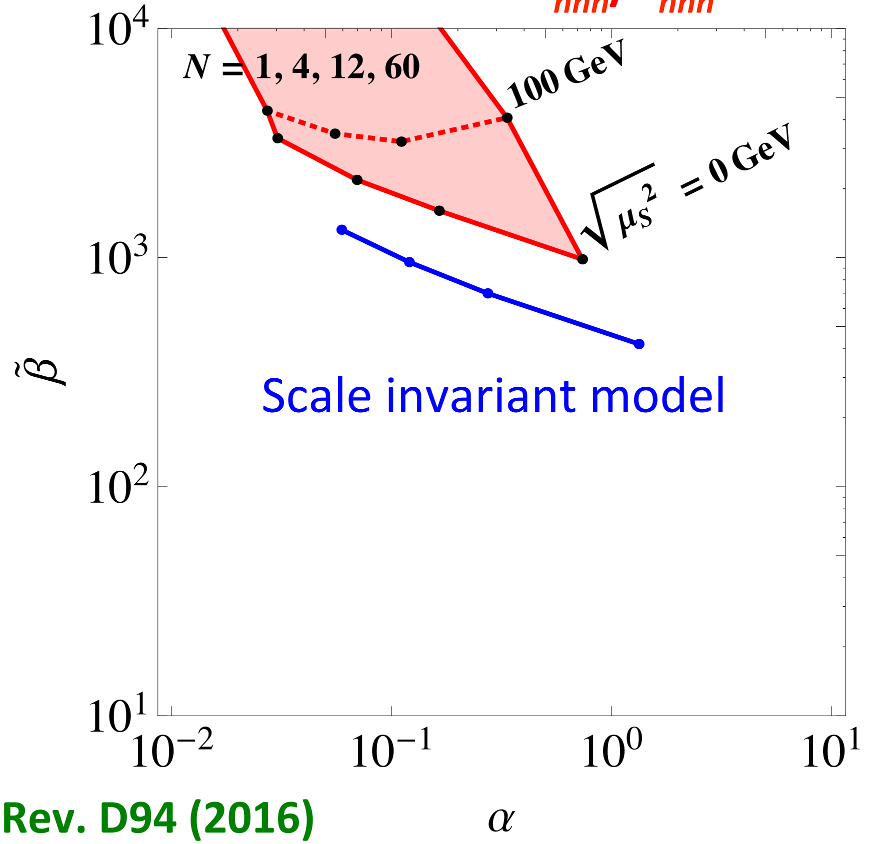
= 10 – 150 %

Scale Invariant O(N) singlet model

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} \simeq \frac{2}{3}$$

= 67 %

Massive model with $\Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$ = 67%



K. Hashino, M. Kakizaki, SK, T. Matsui, Phys. Rev. D94 (2016)

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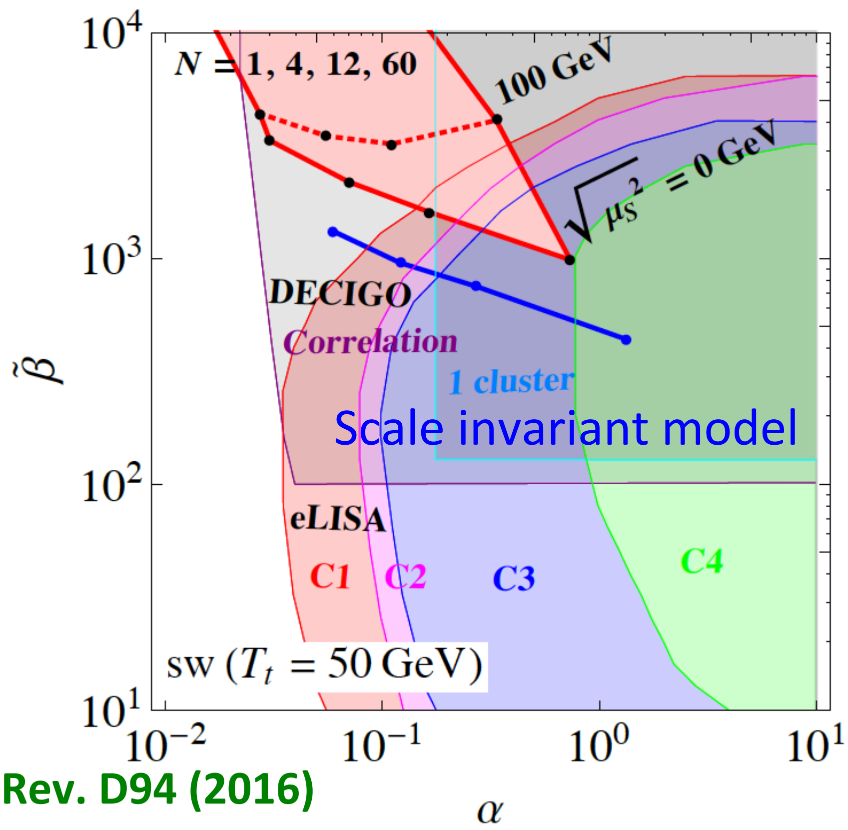


K. Hashino, M. Kakizaki, SK, T. Matsui, Phys. Rev. D94 (2016)

Summary

- **Higgs potential is the last unknown part in SM**

- **Its property is tested by measuring the *hhh* coupling at colliders**

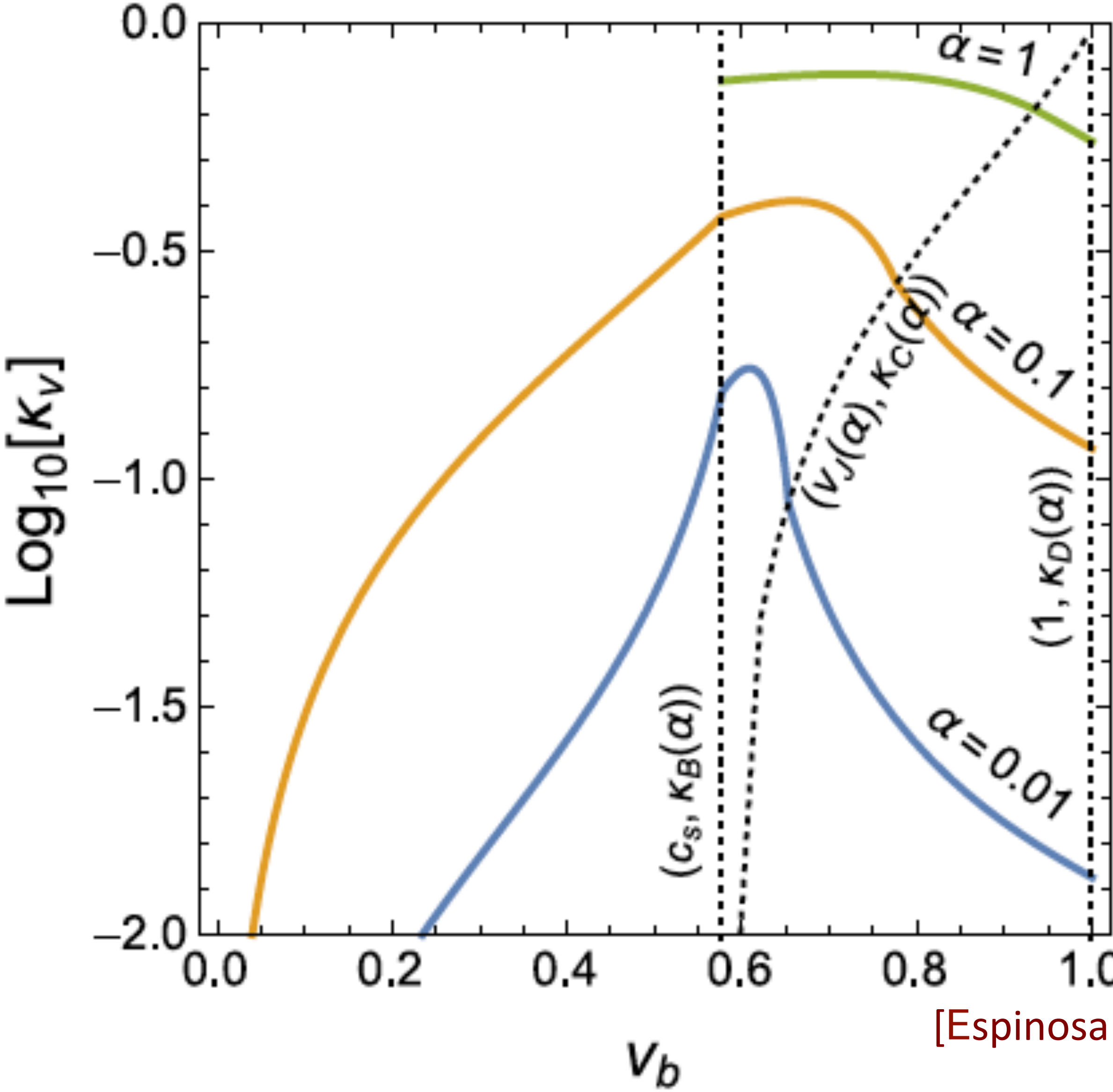
- **Extended Higgs models of 1st OPT predict large deviations in the *hhh* coupling and also produce Gravitational Waves**

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

- **There can be a synergy in model identification between precision measurements of the *hhh* coupling at LCs and the spectrum of GWs at LISA/DECIGO/BBO**

Thank you

Efficiency Factor



[Espinosa et al. (2010)]

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%

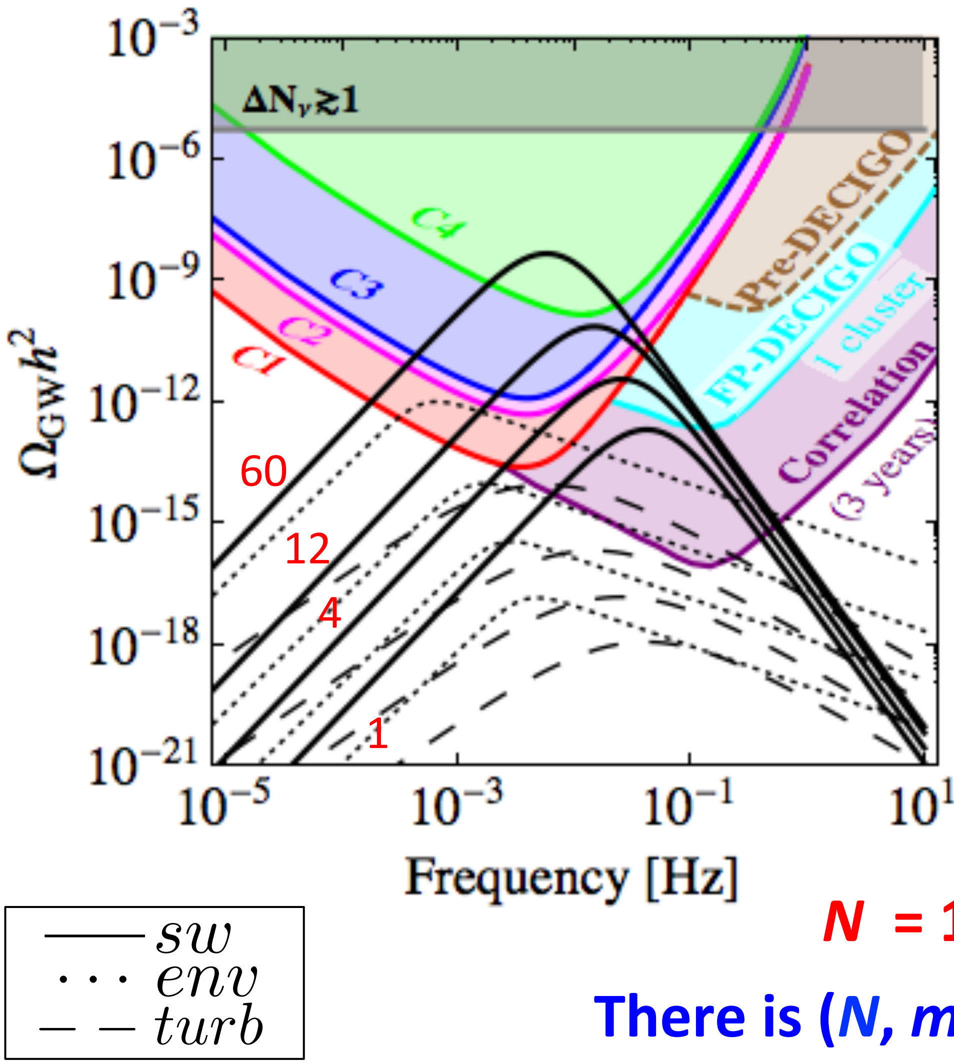
g(hxx)=κ$_x$ g(hxx)$_{SM}$

ILC Higgs White Paper

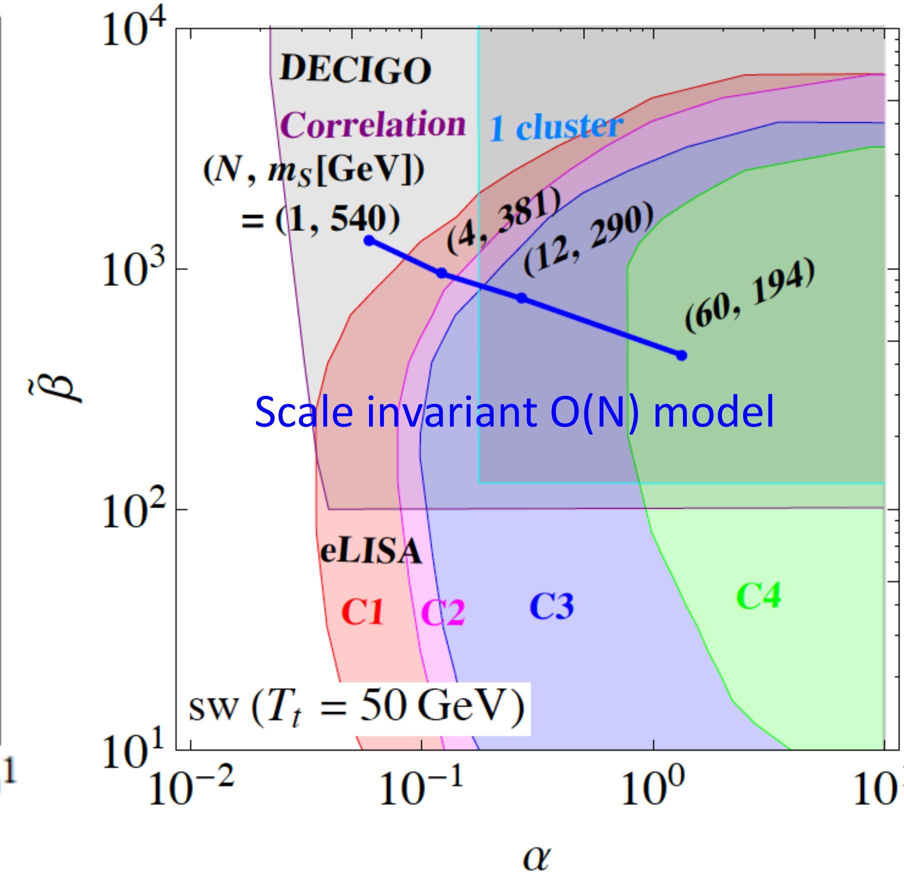
Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto, Weiglein, et al.

	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 %

Case of scale invariant models



$$\mathrm{Tr}M_S^4 = 8\pi^2 v^2 m_h^2 - 3m_Z^4 - 6m_W^4 + 12m_t^4$$



N = 1, 4, 12, 60

There is (N, m_S) dependence!