Shinya KANEMURA
U. of TOYAMA

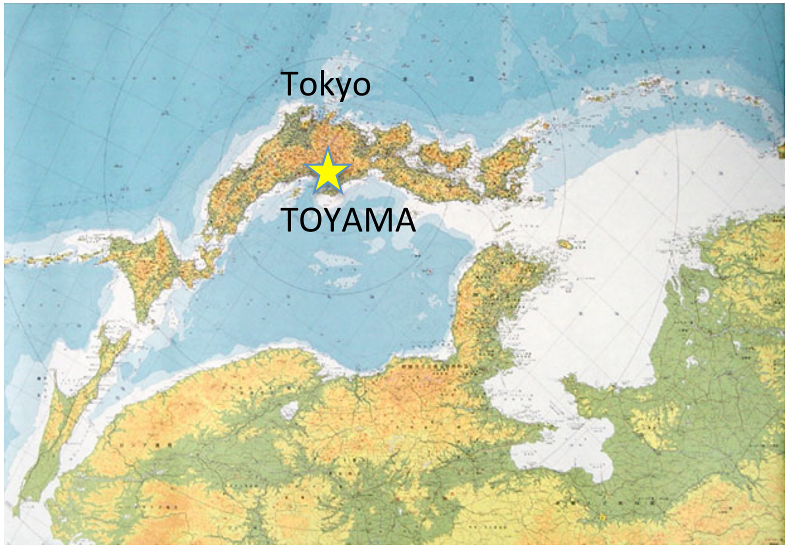
Higgs Physics at LCs

30 August 2016, 1st IBS-Honam Program on Particle Physics Phenomenology

Toyama?

- Toyama is at Centre of Japan!
- Toyama (富山Rich Mountains)
- High Mountains (Japan Alps)
- Much Snow
- Nice Fresh Fishes
- Univ. of Toyama

  Closest to Kamioka



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  Closest to Kamioka Facility

Mt. Tsurugi in Toyama

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End of April, Toyama

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Yellowfish

Toyama?

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SUSHI

Toyama?

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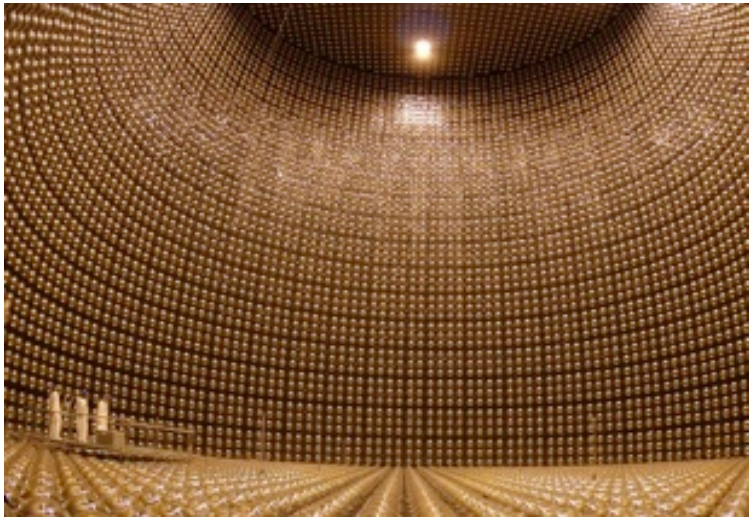


Super Kamiokande

Our group
is a member of KAGRA

This talk

- Introduction
- Lepton Colliders
- Why need precision?
- Higgs Portal New Physics
- Fingerprinting
- Higgs Potential and New Physics
- Summary

Introduction

Introduction

What is the Higgs?

It couples to all particles

It gets a VEV (*v*) by EWSB (scalar field)

Higgs mechanism $m_W = g\, v$

Yukawa interaction $m_{q,l} = Y_{q,l}\, v$

Dimension 5 operator (neutrino mass) $m_\nu = C_\nu v^2/M$

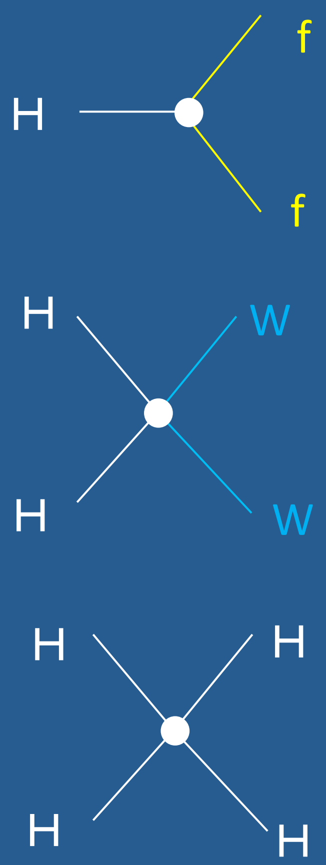
Higgs = Origin of Mass

Higgs is Origin of Mass

Yukawa Coupling

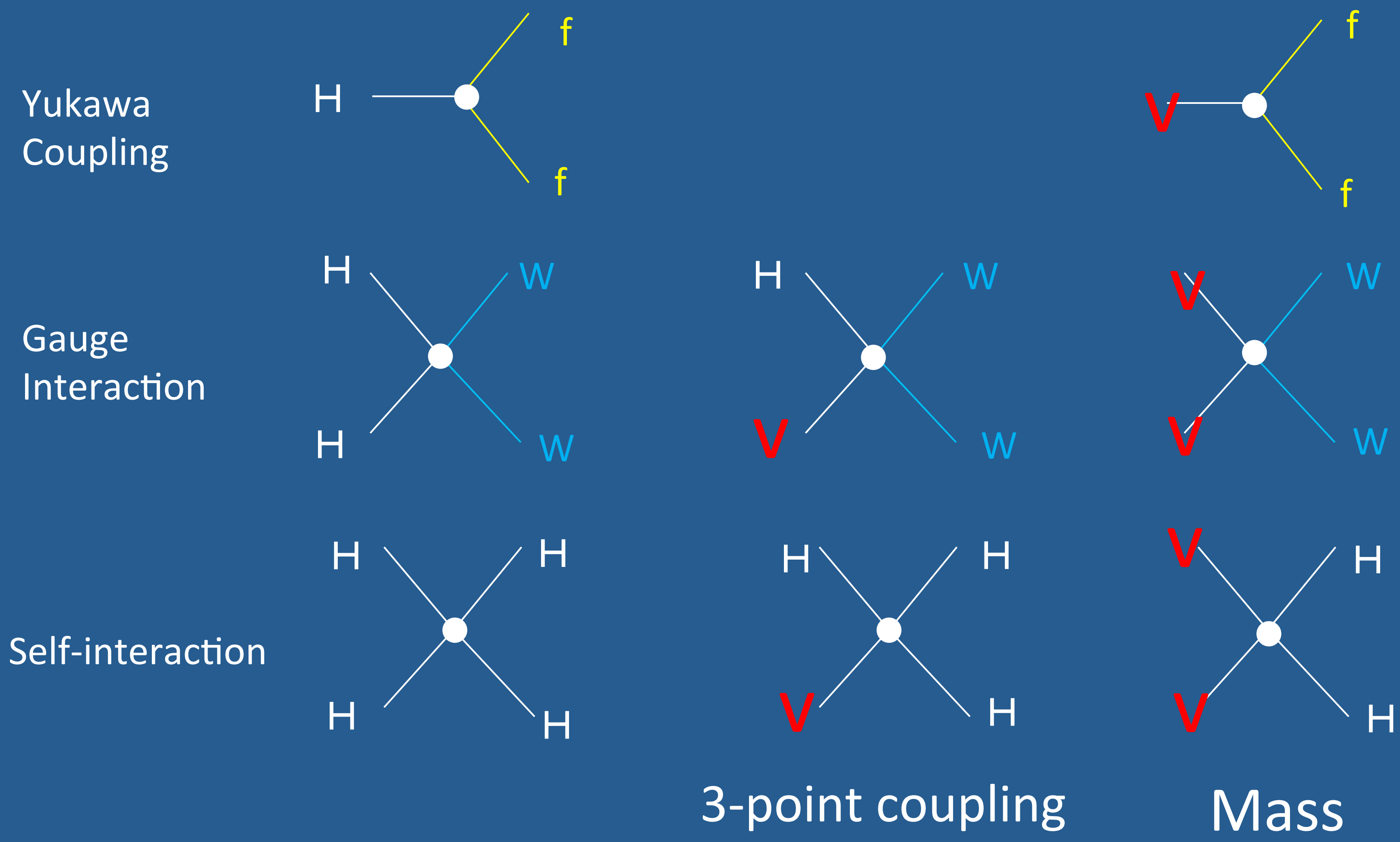
Gauge Interaction

Self-interaction



Higgs is Origin of Mass

Masses of all particles come from vacuum!



Introduction

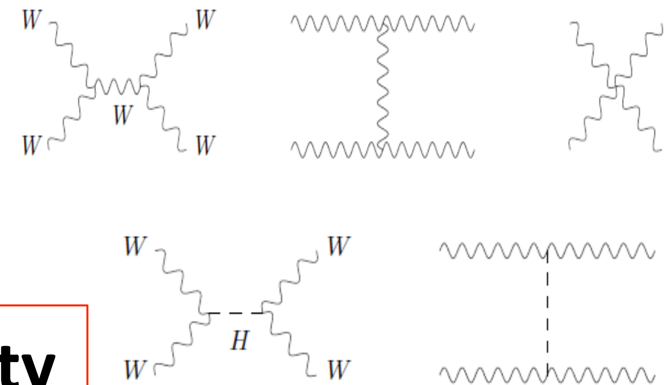
$W_L^+ W_L^-$ Elastic Scattering

$$a^0(W_L^+W_L^- \to W_L^+W_L^-) \approx A\,E^4 + B\,E^2 + C \quad (E \to \infty)$$

Unitarity Violation if $A, B \neq 0$

A=0 because of gauge symmetry

To make B=0, diagrams mediated by a scalar field h must be added



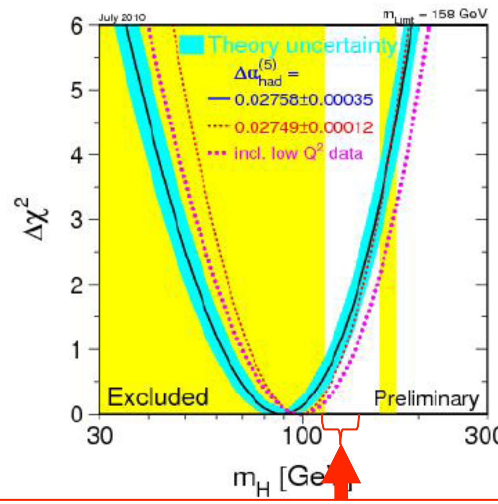
Higgs field is required to save unitarity

Perturbative Unitarity

$$|a^0(W_L^+W_L^- \to W_L^+W_L^-)| < 1 \quad \Rightarrow \quad m_h < 1\ \text{TeV}$$

Higgs discovery in 2012

The mass is 125 GeV

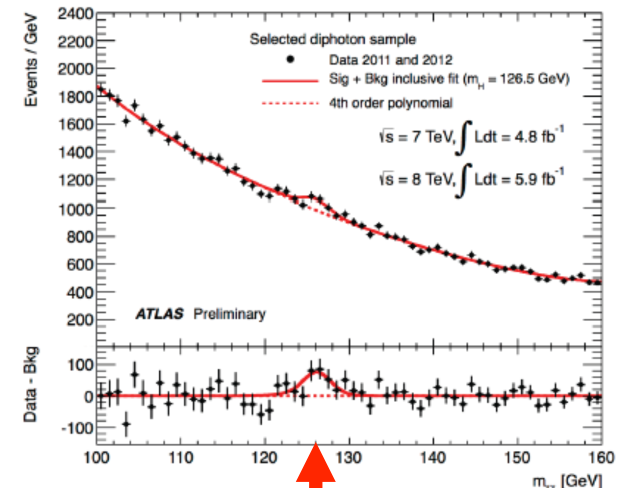


Spin/Parity 0^+

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!

ATLAS-CONF-2015-044

Run 1

Best fit values for combination of ATLAS and CMS

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

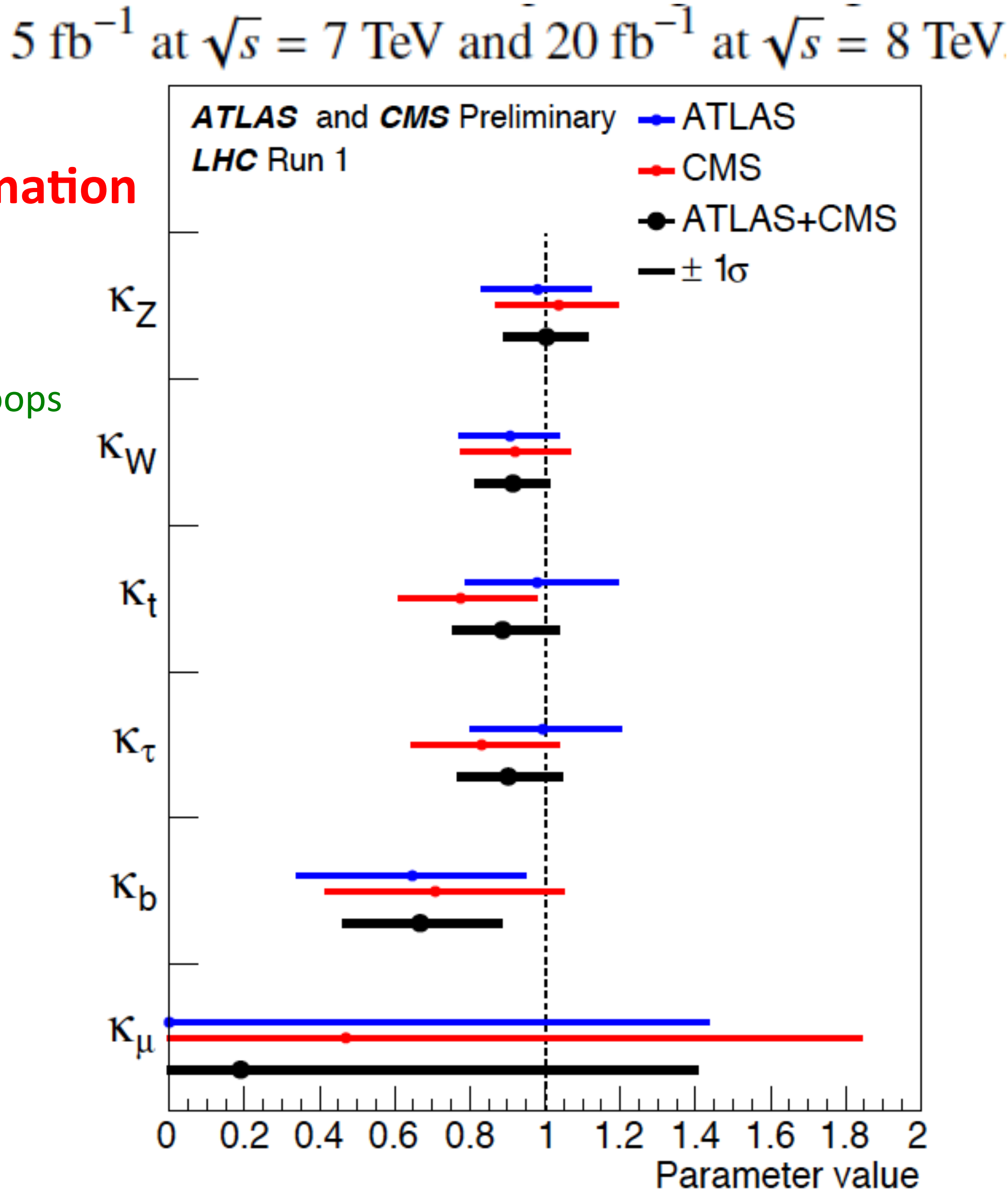
$$\kappa_Z = 1.00^{+0.10}_{-0.11}$$

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

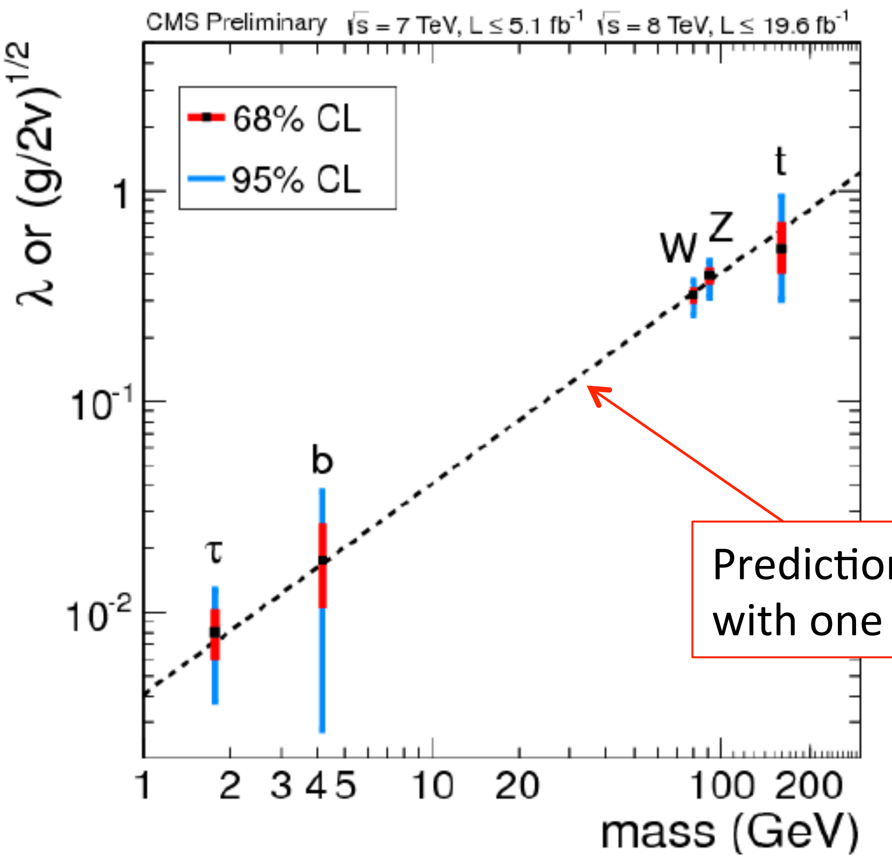
$$\kappa_t = 0.89^{+0.15}_{-0.13}$$

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

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



What a coincidence!



Prediction in the SM with one Higgs doublet

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW
hZZ

Yukawa Interaction

$h\tau\tau$, hbb
htt, …

Dim 6 Operators

hgg
$H\gamma\gamma$, $hZ\gamma$

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

Flavor Structure

New particle effect
in the loop

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

EW Symmetry Breaking

hhh, $hhhh$

Multiplet structure
Physics behind EWSB
Essence of Higgs boson

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
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EW Symmetry Breaking

hhh, hhhh

Multiplet structure
Physics behind EWSB
Essence of Higgs boson

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

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism	Yukawa Interaction	Dim 6 Operators
hWW	*hττ, hbb*	*hgg*
hZZ	*htt, …*	*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
Essence of Higgs boson

Little is known about the Higgs potential

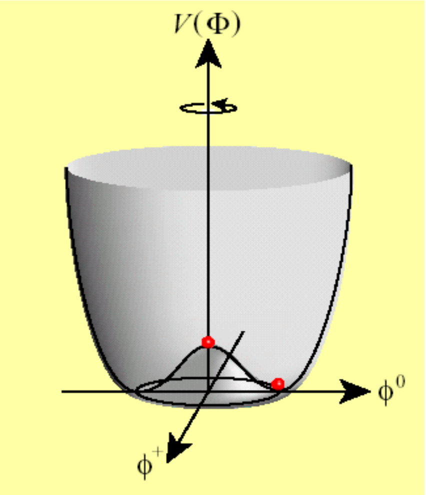
Introduction

Higgs Sector in the Standard Model :

One SU(2) doublet Φ

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

Assumption of $\mu^2 < 0$ $\Rightarrow$ EWSB



This is simple but …

Questions:

Why minimal? (no reason)

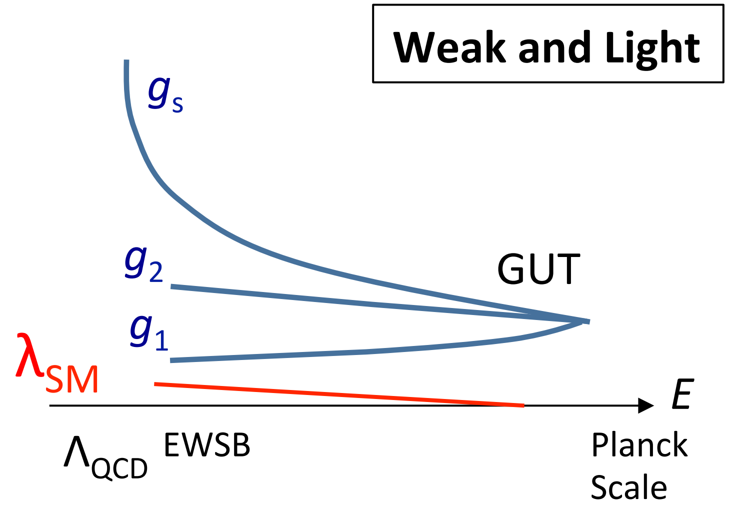
Why $\mu^2 < 0$

What is Origin of the Higgs force λ?

Dynamics behind the 125 GeV Higgs

- **Weak and Light Scenario**
  - Perturbative
  - Grand Desert
  - Traditional Grand Unification

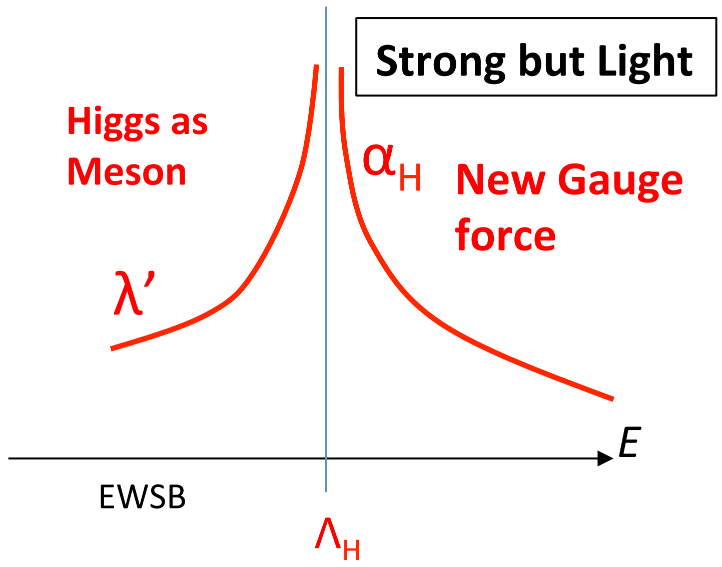
$$m_h^2 \propto \lambda v^2$$



- **Strong but Light Scenario**

$$m_h^2 \propto \frac{\lambda'^2}{(4\pi)^2} v^2$$

  - IR theory:
    Higgs as a composite field
    Landau pole at Λ_H
  - UV theory:
    A new gauge symmetry with confinement at Λ_H



Beyond the Standard Model

However, 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, Essence, …

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

Introduction

Second Higgs boson?

SM Higgs sector = just a guess!

No principle for the minimal Higgs sector of the SM

Many possibilities for non-minimal Higgs sectors

These extended Higgs sectors can provide sources for

- **Baryogenesis**
- **Dark Matter**
- **Neutrino Mass**
- **…**

Higgs sector = Window for new physics

Introduction

Scalar field causes quadratic divergences

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

Hierarchy problem

Ideas of new physics to solve the problem

- Supersymmetry
- Dynamical Symmetry Breaking (Technicolor)
- Extra Dimensions (such as gauge-Higgs unification)
- Higgs as a Pseudo-Nambu-Goldstone boson
- Scale invariance, ….

These ideas give different pictures for the essence of the Higgs boson

Higgs sector = Window for new physics

Introduction

Higgs is important not only for EWSB but also as a window to new physics beyond the SM

Discovery of a Higgs boson in 2012:

Great step to construct the Higgs sector and to understand the essence of the Higgs field

From the detailed study of the Higgs sector, we can determine direction of new physics beyond the SM

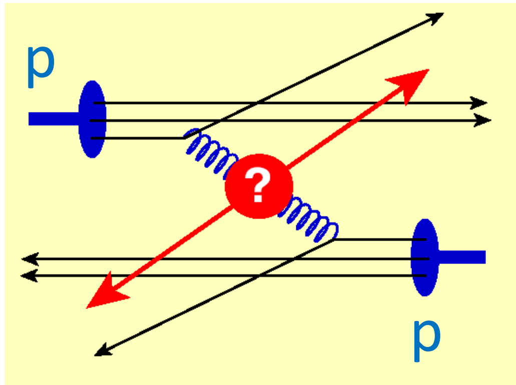
New era has started since 2012!

Lepton Colliders

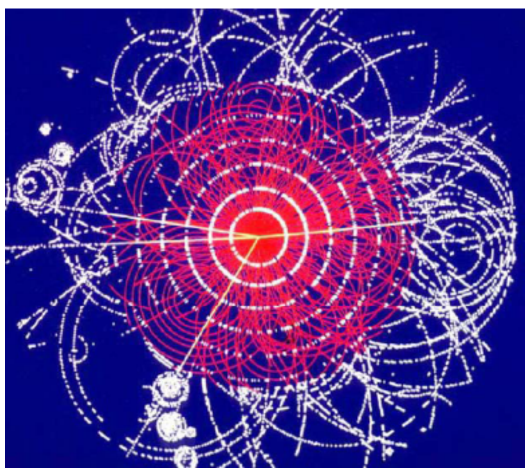
Hadron Collider

Complicated Kinematics

Lost information along beam line



Suffer from serious QCD backgrounds



$E =$ 13-14 TeV, $L =$10-300 fb^{-1}

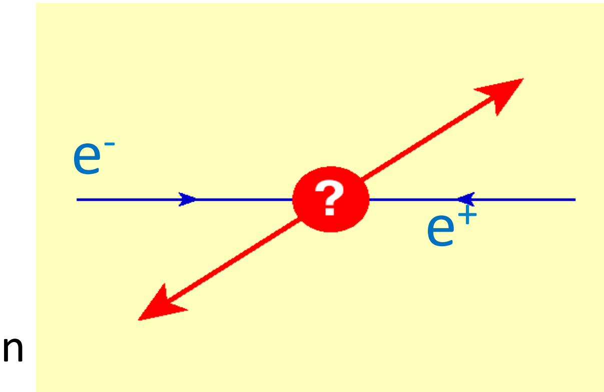
PDF gives high energy parton collisions

Machine for new particle discovery

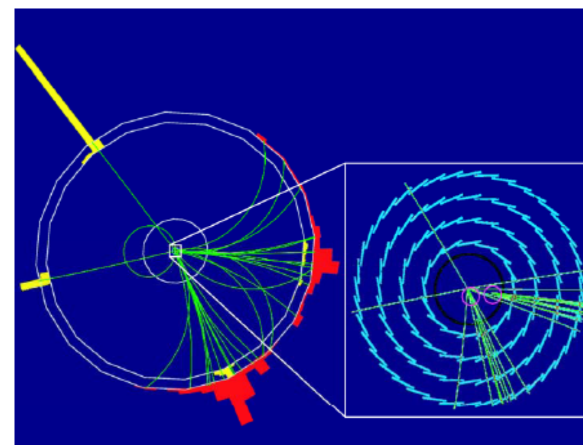
Lepton Collider

Simple Kinematics

Complete reconstruction



Less backgrounds



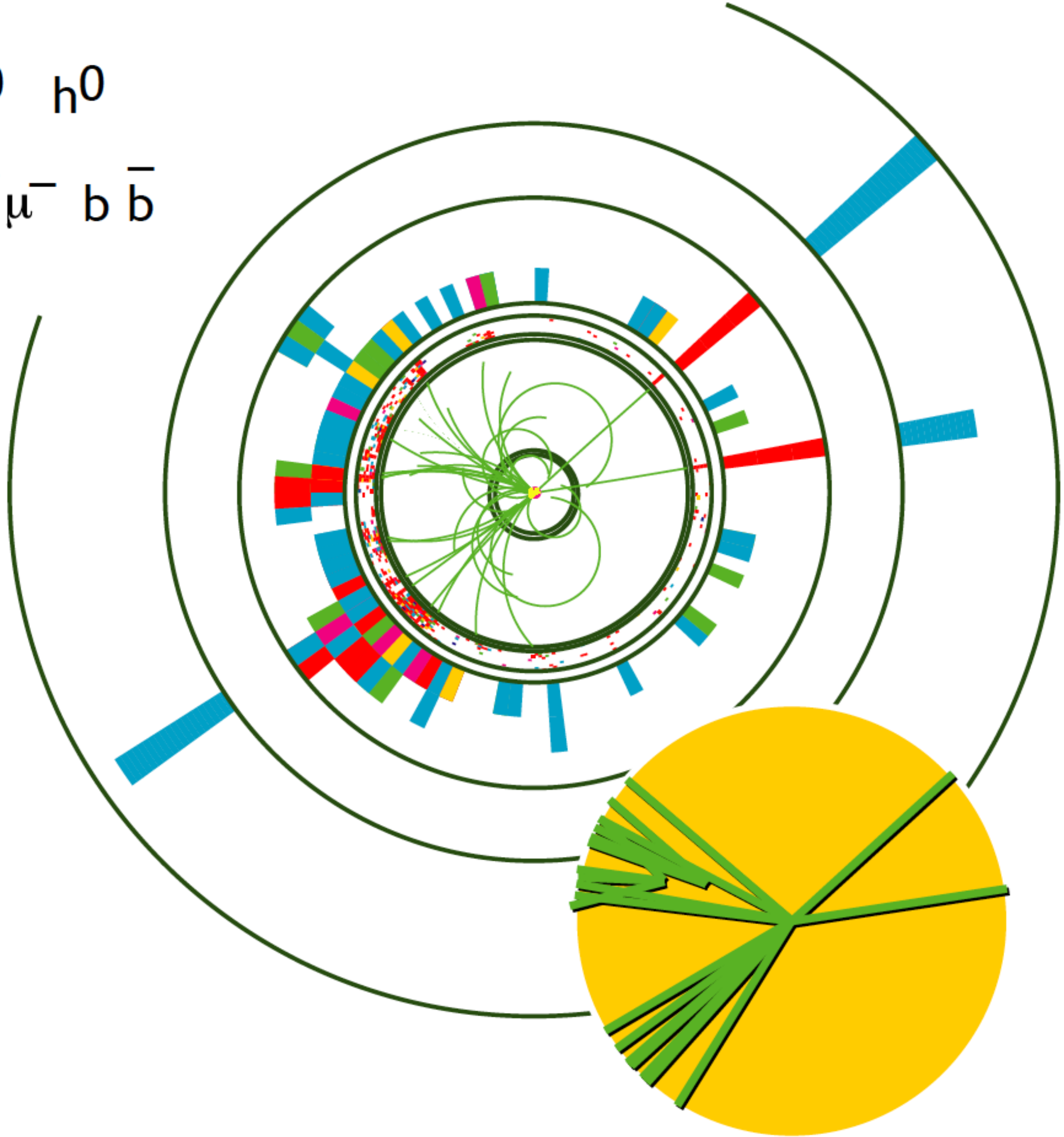
$E =$ 0.25 - 1TeV, $L =$0.5 to a few ab^{-1}

Excellent discovery ability if energy reaches.

Machine for precision study

$e^+e^- \rightarrow Z^0 \quad h^0$

$\rightarrow \mu^+\mu^- \; b\,\bar{b}$



Basic Role of LCs

- LHC discover new particles
  → Precision measurement at LCs
  (ex: SUSY Spectroscopy)
- No discovery at LHC
  → Try to detect deviations from SM by LCs

If deviation → Fingerprinting new physics
Model discrimination
If no deviation → SM holds up to high scales
Go to the Planck scale by SM!

Lepton Colliders

- Circular e^+e^- colliders (associated with future hadron colliders)
  - FCCee (350GeV, 1-40 ab^{-1}) CEPC (240 GeV 5 ab^{-1})
    - Energy relatively low (Z, h, top Factory) with high lumi
- Linear colliders
  - ILC (250GeV, 500GeV, 1TeV, a few ab^{-1})
  - CLIC (3-5TeV, a few ab^{-1})
    - Energy can be high (Top Yukawa, *hhh* measurement)

ILC is ready (waiting for the approvement)

Technical Design Report

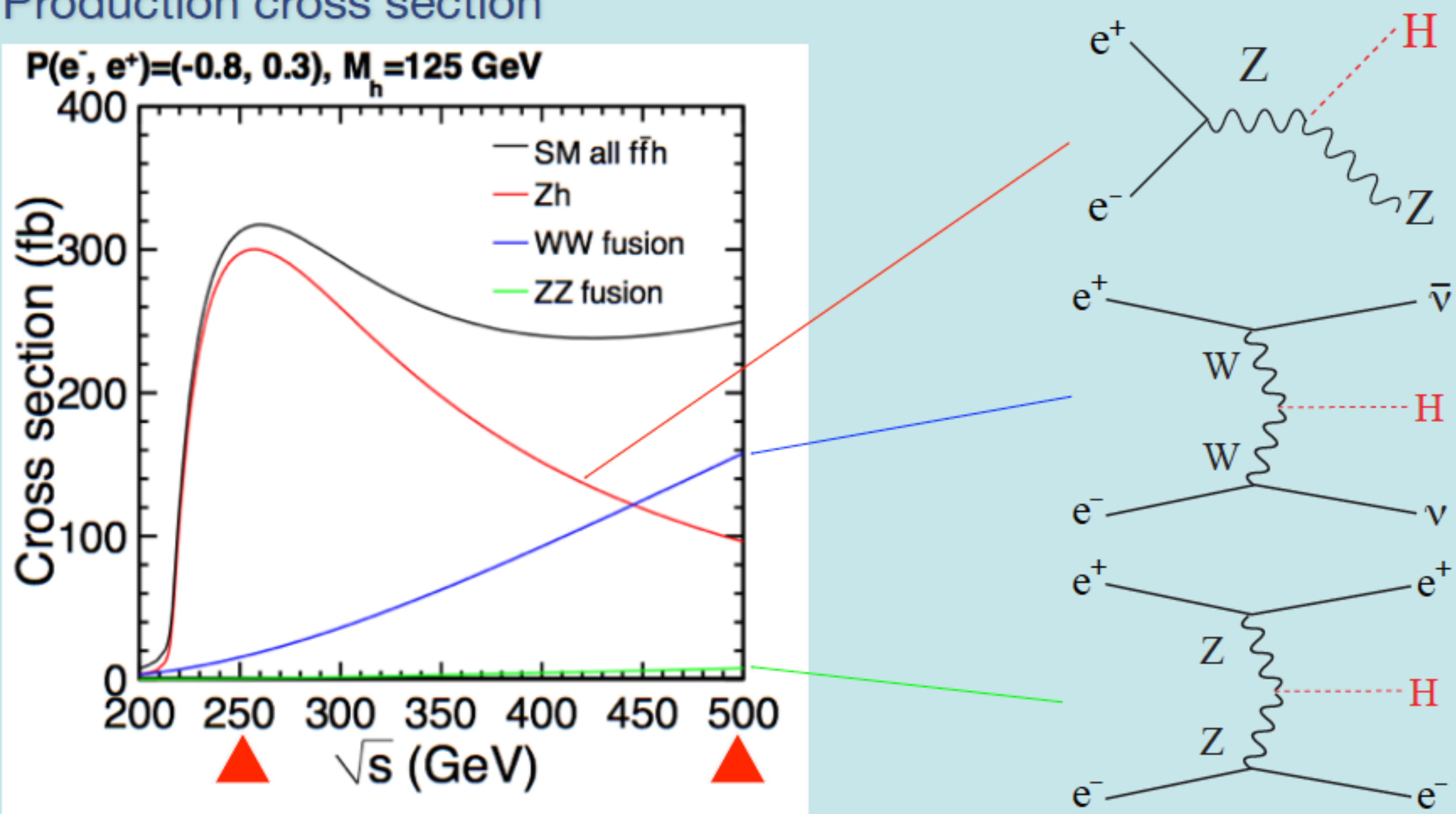
Government working groups/negotiation underway

Higgs Physics at ILC

Main Production Processes

Single Higgs Production

Production cross section

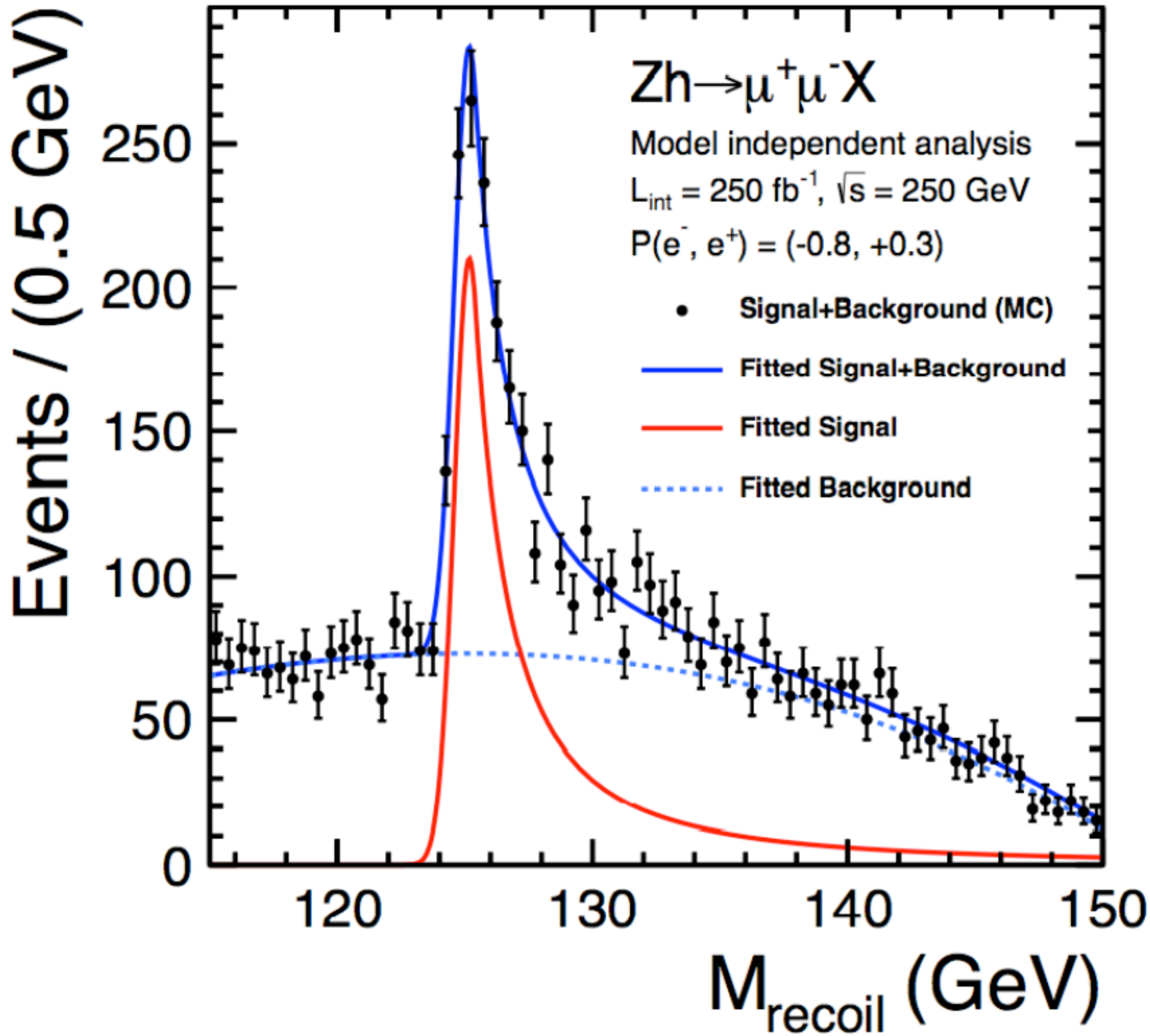


ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

ννH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

Possible to rediscover the Higgs in one day!

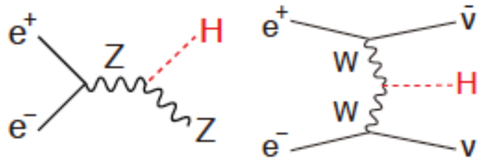
m_h to 30 MeV using a recoil technique



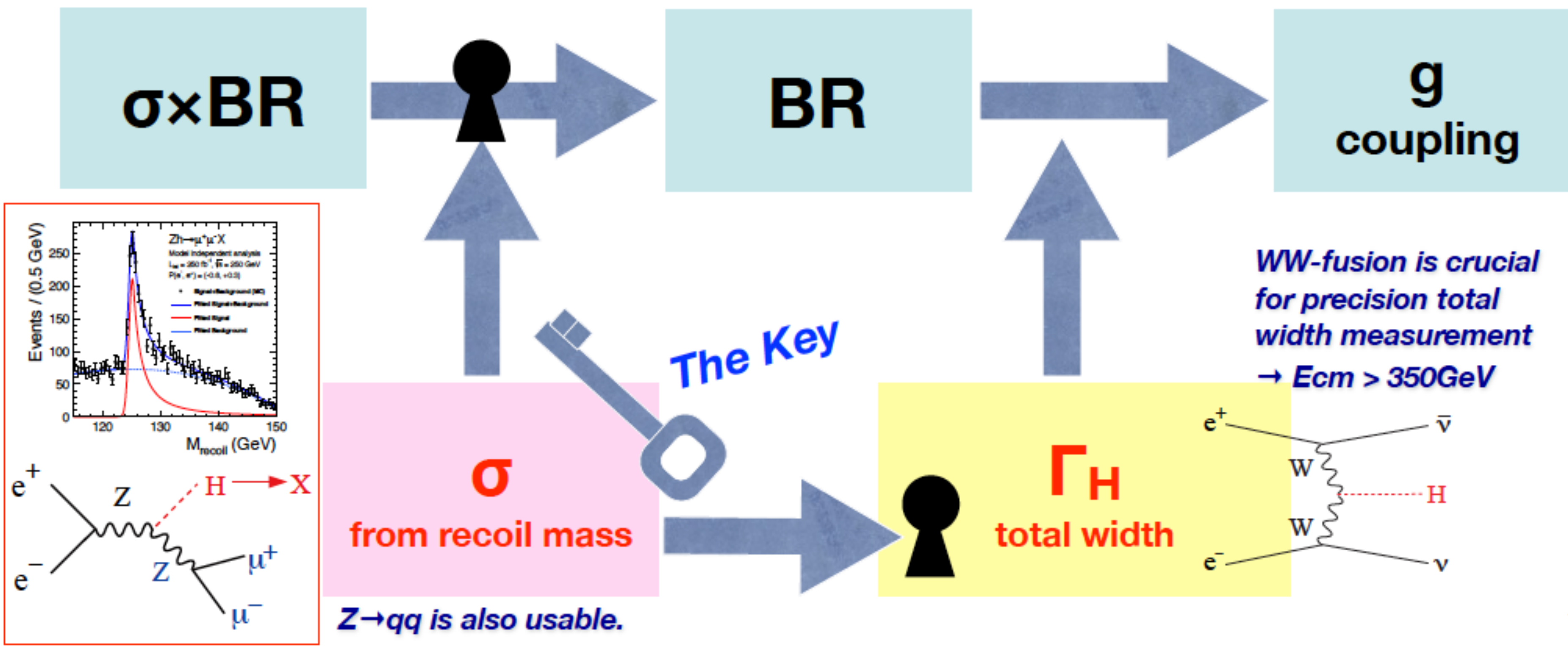
Key Point

At LHC all the measurements are σ×BR measurements.

At ILC all but *the σ measurement using recoil mass technique* is σ×BR measurements.



$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



Total Width and Coupling Extraction

One of the major advantages of the LC

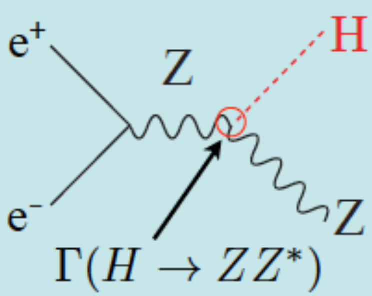
To extract couplings from BRs, we need the total width:

$$g_{HAA}^2 \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

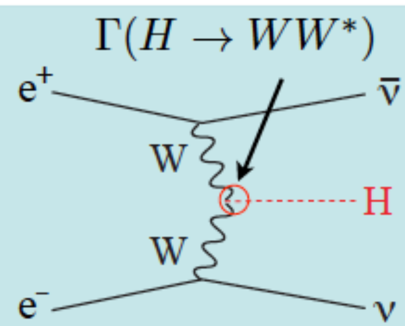
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 20\%$



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

Independent Higgs Measurements at LC

Baseline (=TDR) LC program

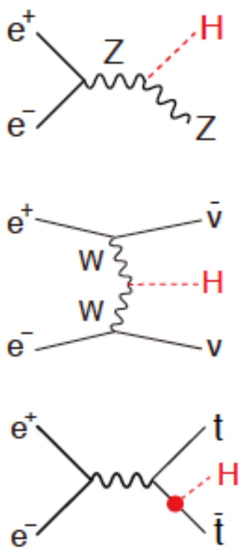
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

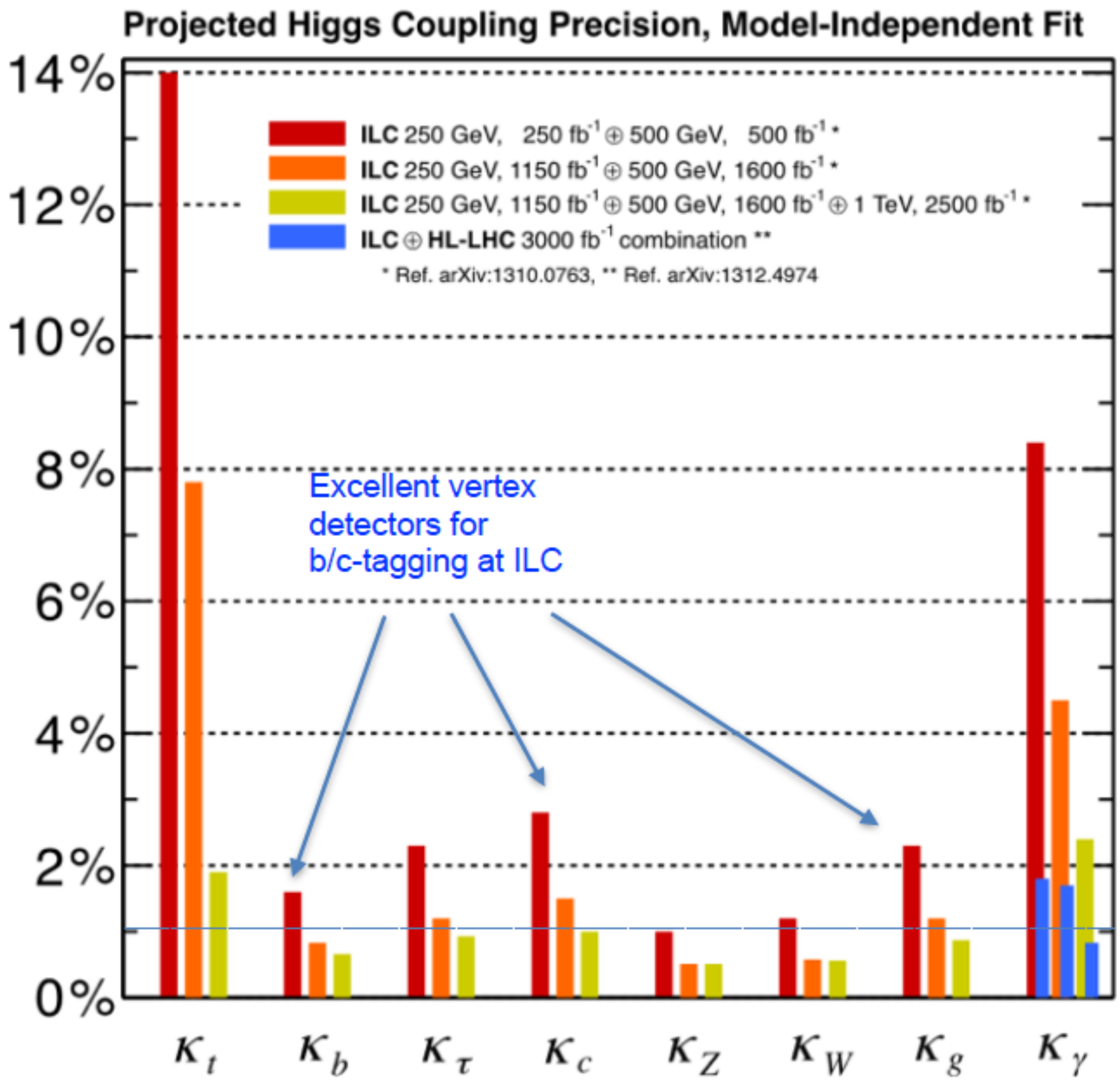
(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb^{-1}]	250		500		1000
polarization (e^-,e^+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	ννH(fusion)	ZH	ννH(fusion)	ννH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.32%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	4.2%		5.4%	9%	3.1%
H→ZZ*	18%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	100%	-	-	-	31%

Higgs Couplings

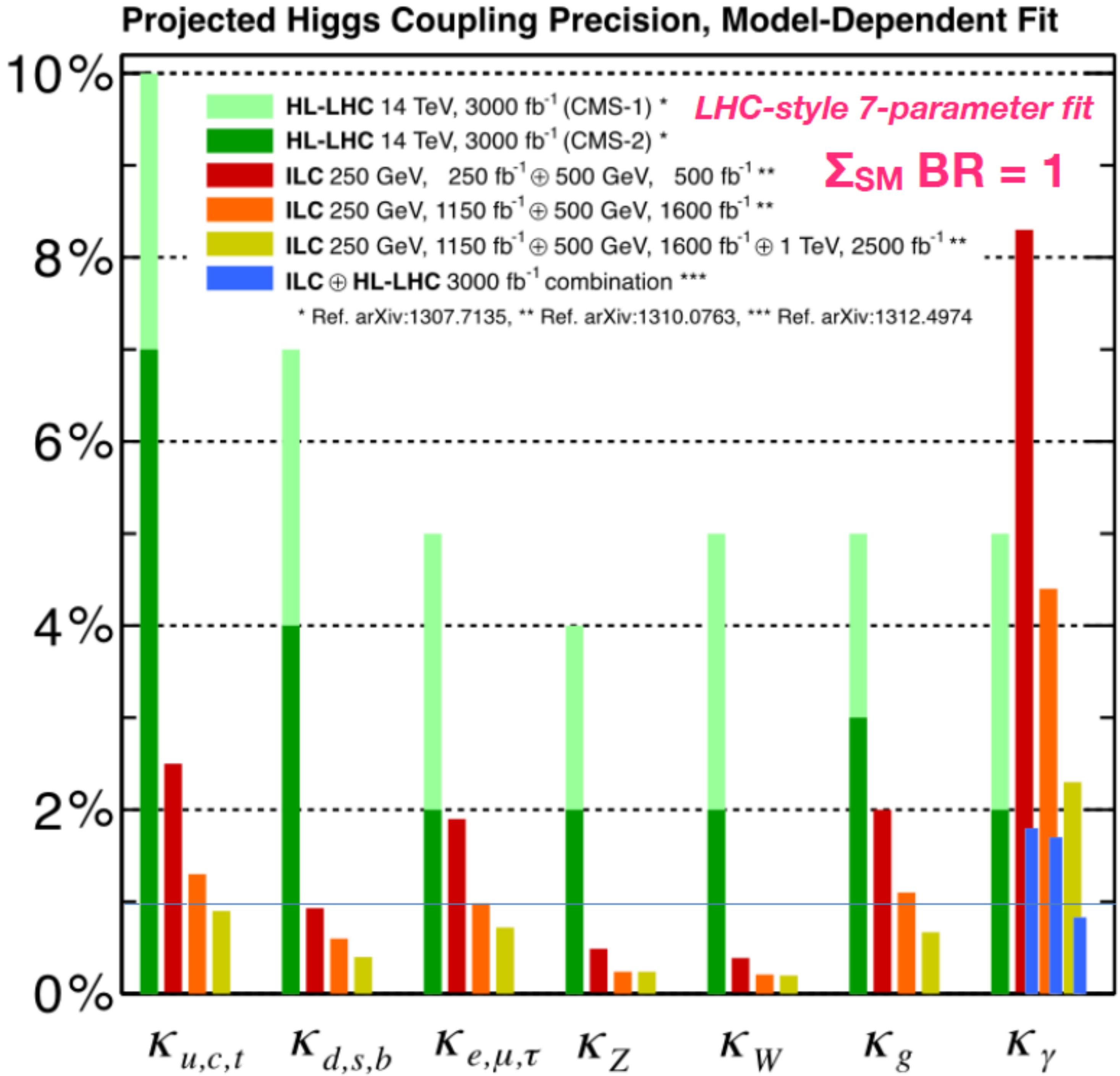
***Model-independent* coupling determination, impossible at LHC**





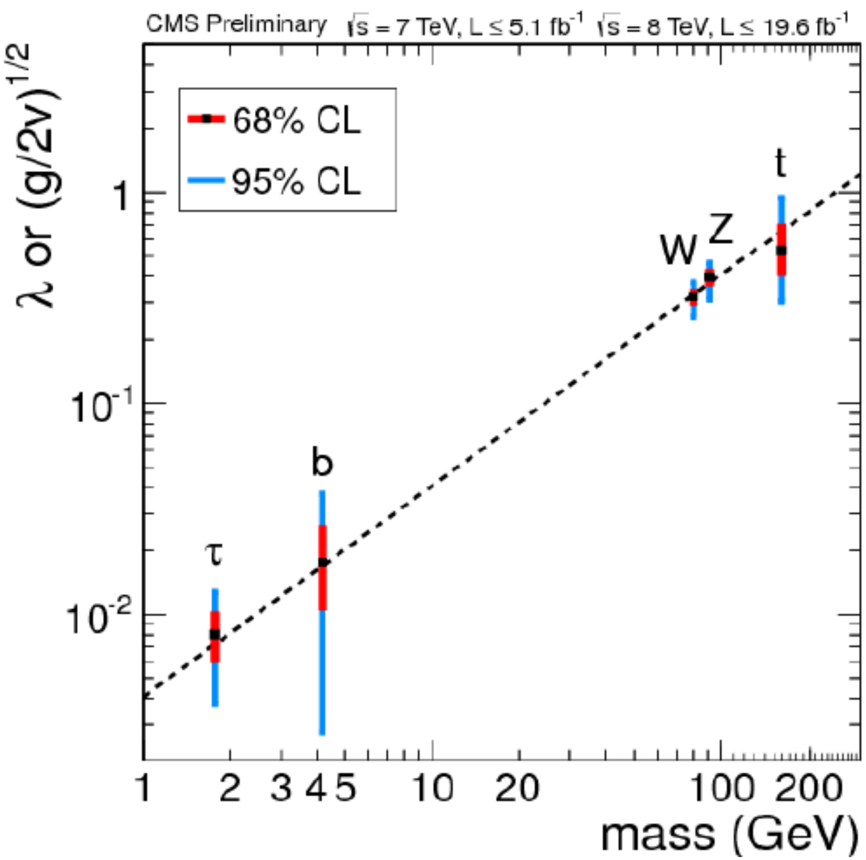
All of major Higgs decay modes accessible at ILC!

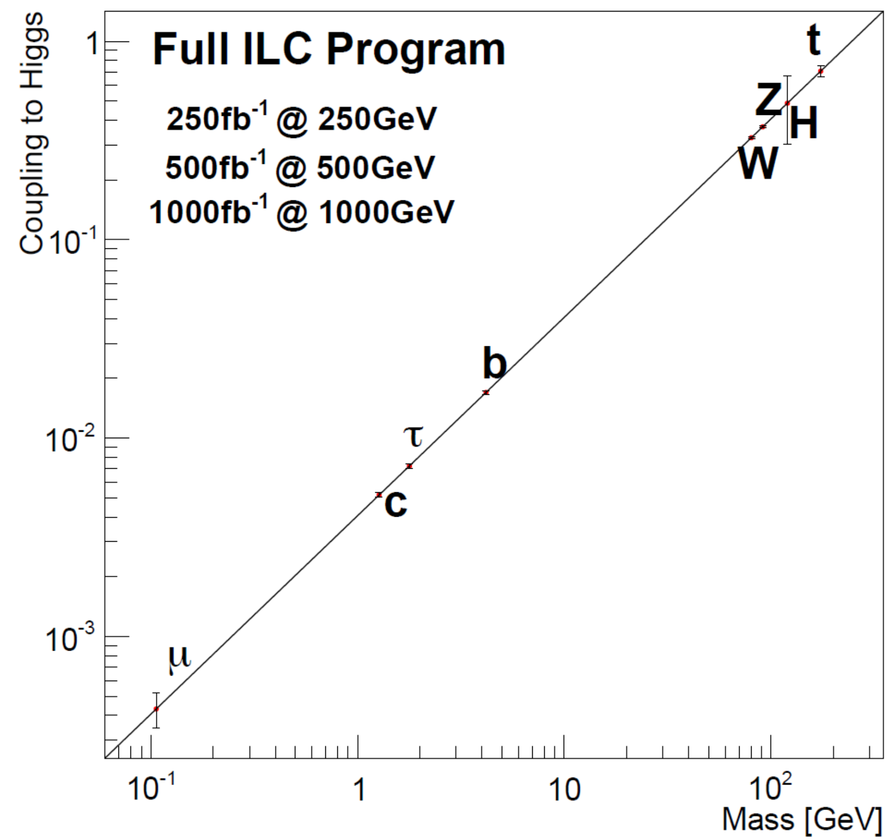
500 GeV already excellent except for K_t and K_γ



Projected Higgs Coupling Precision, Model-Dependent Fit
HL-LHC 14 TeV, 3000 fb^{-1} (CMS-1) *
HL-LHC 14 TeV, 3000 fb^{-1} (CMS-2) *
ILC 250 GeV, 250 fb^{-1} ⊕ 500 GeV, 500 fb^{-1} **
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} **
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} ⊕ 1 TeV, 2500 fb^{-1} **
ILC ⊕ HL-LHC 3000 fb^{-1} combination ***
* Ref. arXiv:1307.7135, ** Ref. arXiv:1310.0763, *** Ref. arXiv:1312.4974
LHC-style 7-parameter fit
Σ_{SM} BR = 1
10%
8%
6%
4%
2%
0%
$\kappa_{u,c,t}$
$\kappa_{d,s,b}$
$\kappa_{e,\mu,\tau}$
κ_Z
κ_W
κ_g
κ_γ

Current LHC data v.s. Full ILC





The precision must be improved in future at LHC 13-14 TeV and at the LC

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

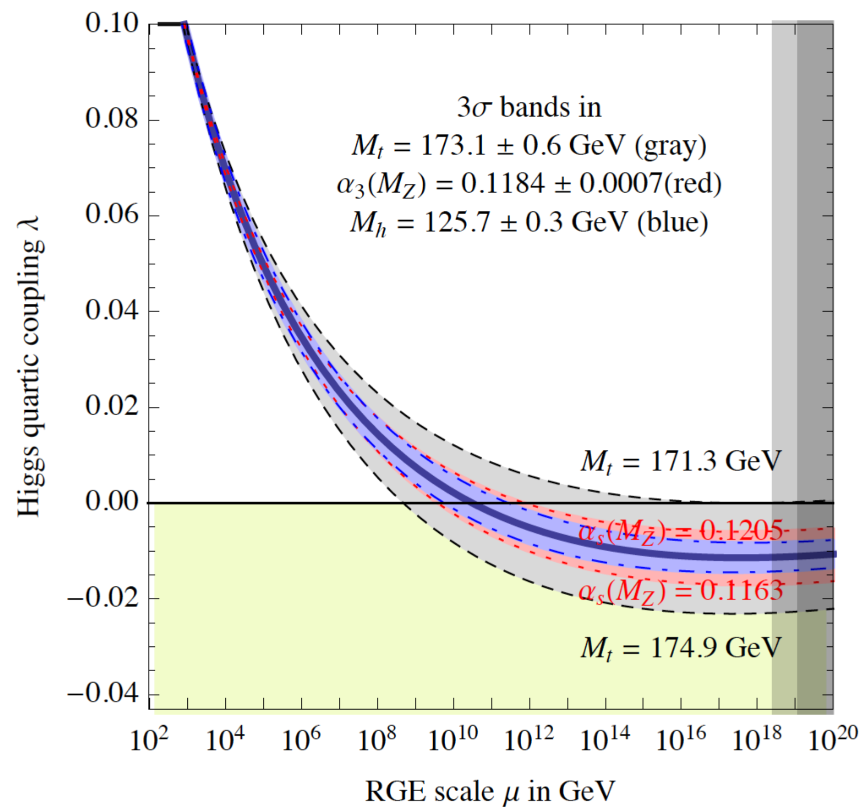
Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%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

Why Precision?

The absolute cut-off of the SM Λ

arXiv:1205.6497, Degrassi et al



With the discovered 125 GeV Higgs boson, λ becomes negative below Planck Scale (at central value of m_t)

Cut off $\Lambda = 10^7 - 10^{19}$ GeV
large uncertainty comes from large Δm_t

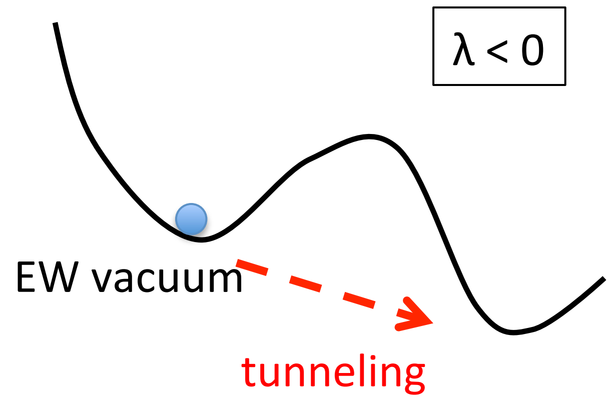
At ILC, $\Delta m_t \approx 30$ MeV is expected
Cutoff Λ can be determined

At Planck Scale, $\lambda(M_{pl}) < 0$, but the theory satisfies the condition of the meta-stable vacuum

Tunneling into the other vacuum

Decay Rate of EW vacuum
(Tunneling effect)

$$\Gamma \sim \varphi^4 e^{-S_4}$$

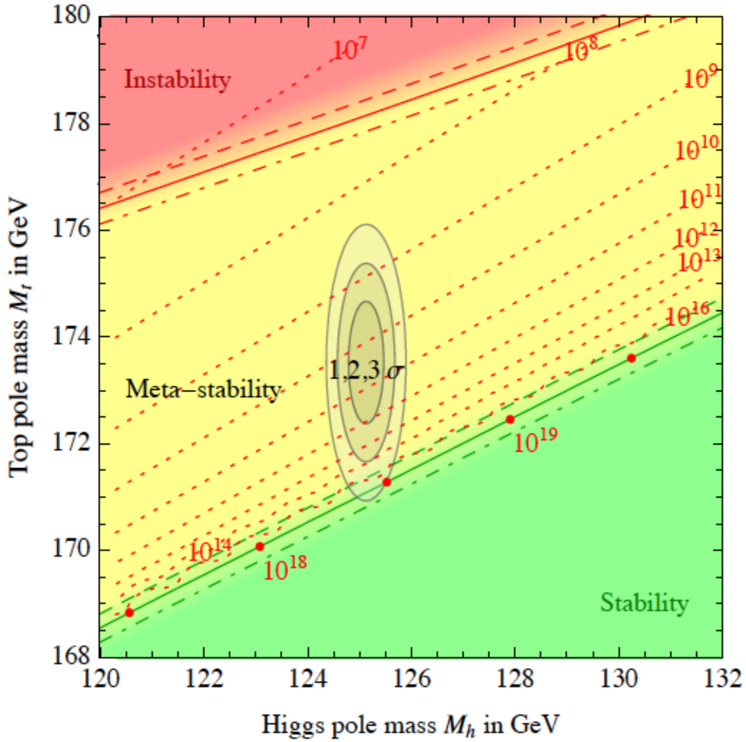


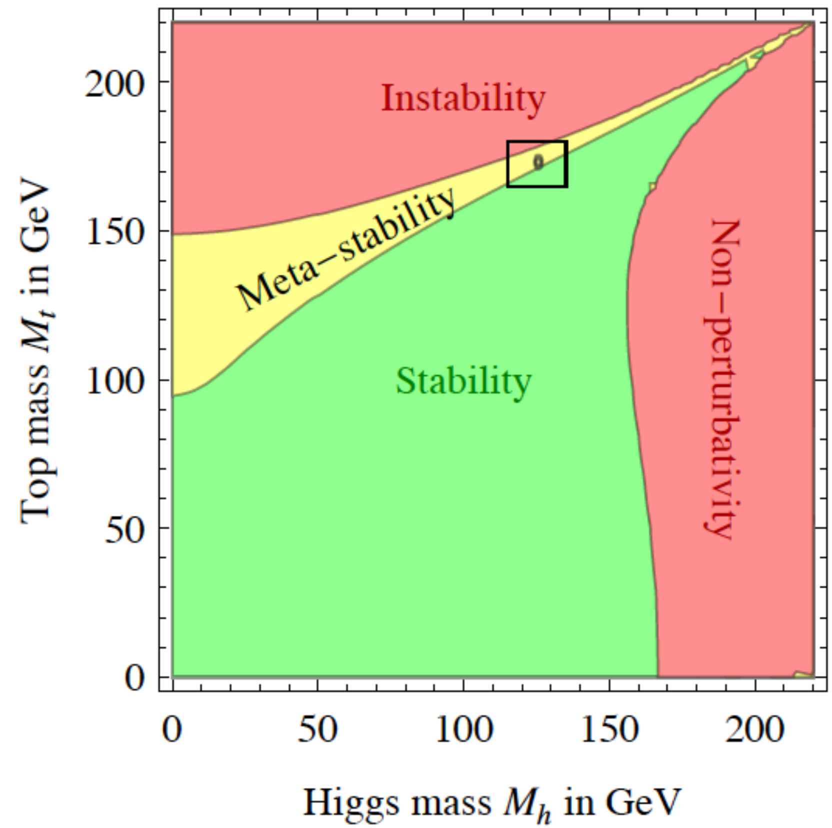
Destiny of the Universe is determined by the balance of
the age of the Universe (τ_U) and the life time (τ_{EW}) of the EW vacuum

If $\lambda(h_t) = -0.01$, $\tau_U << \tau_{EW}$. Meta-stable but not dangerous

If $\lambda(h_t) < -0.05$, $\tau_U > \tau_{EW}$. Instability and dangerous

Are we on the edge?





Condition of meta-stability
is satisfied. $\tau_{EW} >> \tau_U$

arXiv:1205.6497, Degrassi et al

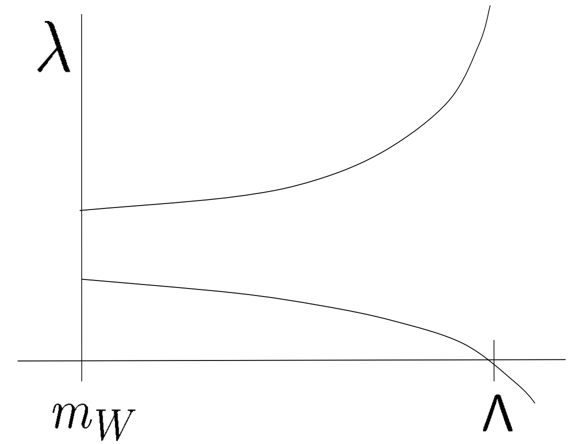
125GeV is an interesting value

- Vacuum is meta-stable
- Rather heavy if SUSY

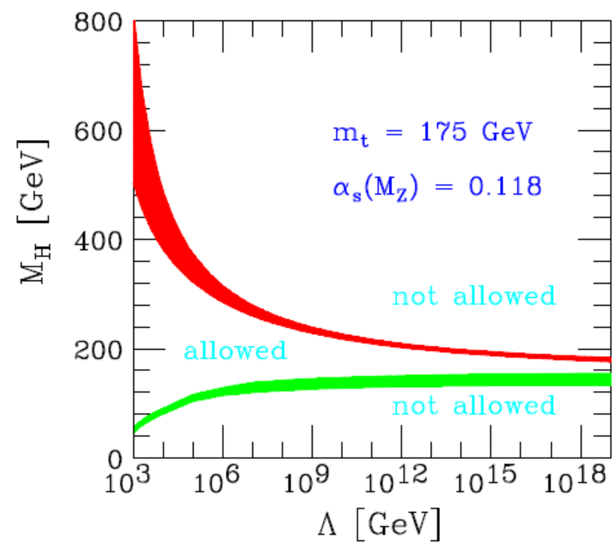
Triviality and Vacuum Stability

Require that the SM holds up to a scale Λ

- **No Landau Pole**
- **Stable Vacuum ($\lambda > 0$)**



$m_h^2 = 2\lambda v^2$



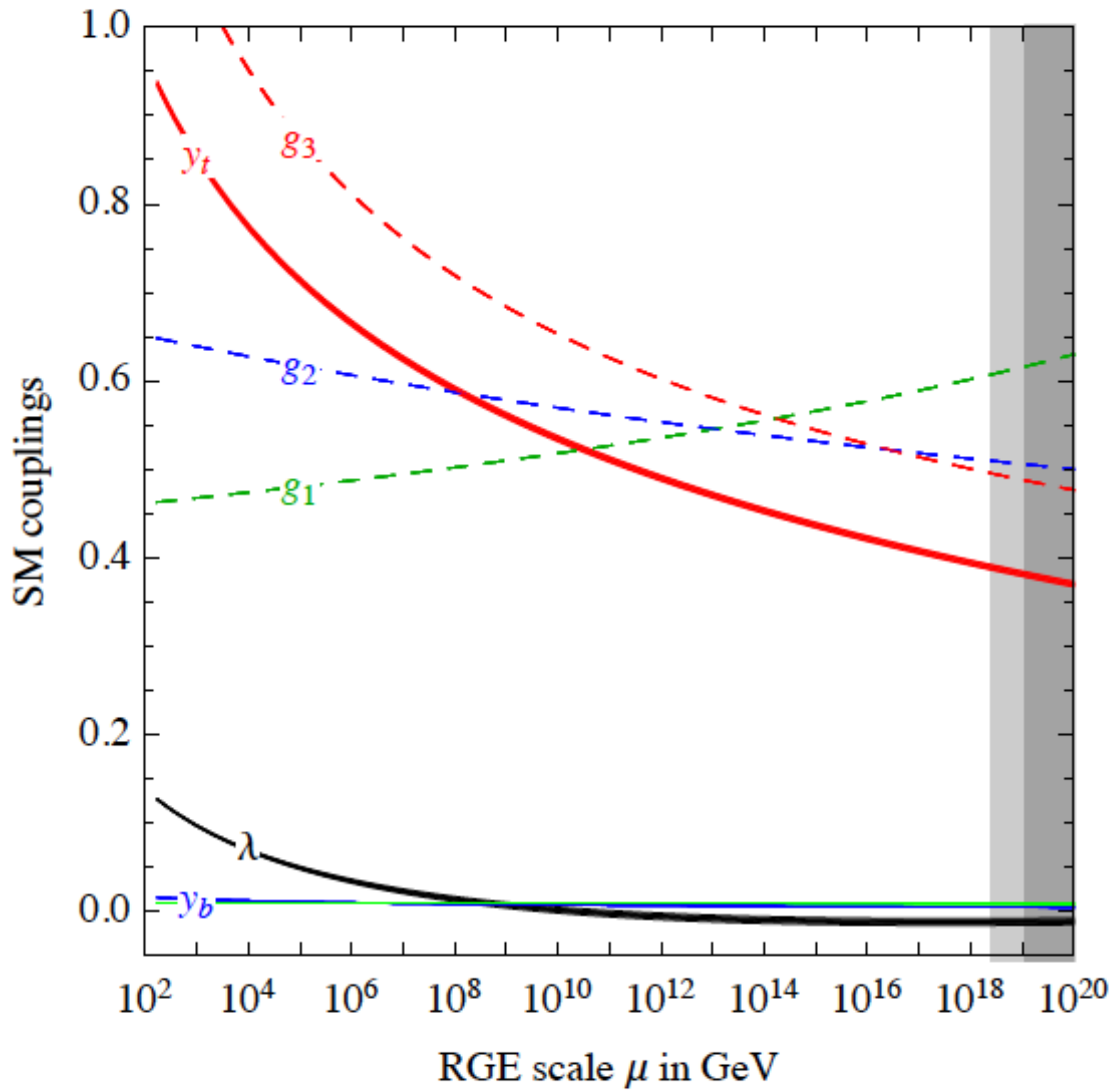
RGE of λ coupling

$y_t = O(1)$

$$16\pi^2 \mu \frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^4 + \ldots.$$

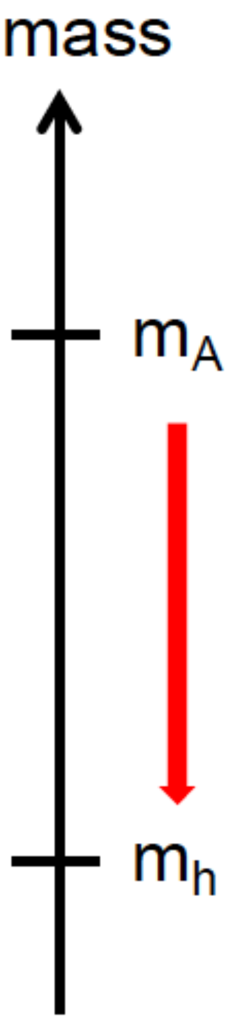
If initial value of λ is large, β-function is positive (blow up)

If the 2nd term is stronger, β-function is negative (fall down)



1.0
0.8
0.6
0.4
0.2
0.0
SM couplings
y_t
g_3
g_2
g_1
λ
y_b
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
RGE scale μ in GeV

Precision = Energy frontier



Decoupling theorem

Deciation in Couplings ⇆ New Physics Scale

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

Mass of heavy Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

composite scale

New Physics at 1TeV gives only a few % deviation
We need 1 % level precision to see such a deviation
→ *LC*

All SM parameters are found

Next target is new physics!

- **Importance of Radiative Correction calculation**
- **Future precision measurements**
  - ***S, T, U*** **(Giga Z, Mega W)**
  - **Top (e.g. ttZ) couplings**
  - **Many Couplings of the discovered Higgs**

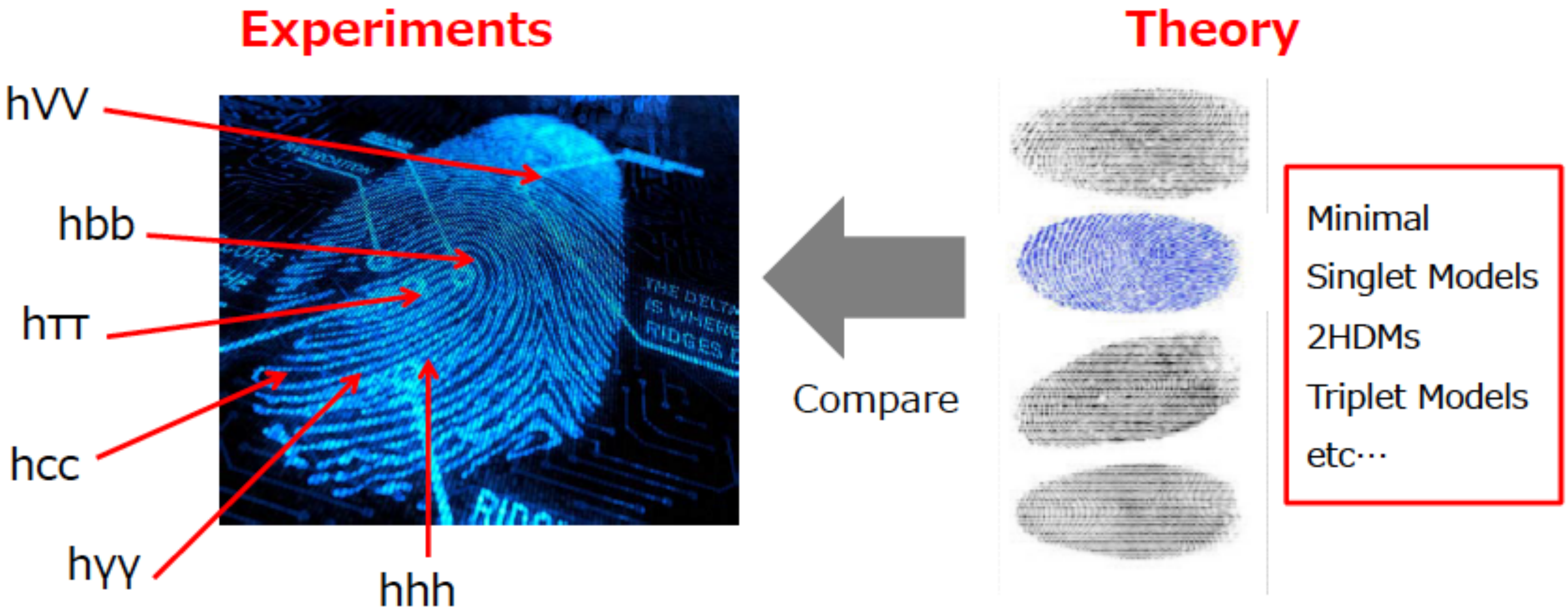
hgg, hγγ, hWW, hZZ, htt, hbb, hττ, hμμ, hcc, …, hhh

At ILC, we may be able to distinguish models by detecting a pattern of deviations in the *h* couplings from the SM values!

Fingerprinting new physics models

All SM parameters are found

Next target is new physics!



Fingerprinting new physics models

Higgs related new physics

Higgs Problems

→ **New Physics Paradigms**

SUSY
Dynamical EWSB
Scale Invariance
pNGB
Gauge-Higgs Unification
…

BSM Phenomena

Physics at High scales

Seesaw Mechasism
Leptogenesis
Axion (Peccei-Quinn at high scales)
…

Physics at TeV scales

Radiative neutrino mass models
Electroweak Baryogenesis
WIMP DM (Higgs portal DM, …)
…

Higgs is a Probe of New Physics

Higgs portal
new physics models

SUSY
Dynamical symmetry breaking
pNGB
CW mechanism
Higgs portal dark matter
Inert scalar models
Radiative neutrino mass models
Electroweak baryogenesis
…

Essence of Higgs

Higgs Nature	⇔	BSM Paradigm

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

Each new paradigm predicts a specific Higgs sector

Higgs sector in new paradigms

- SUSY
  - 2 Higgs doublets are required (type II 2HDM)
  - Quartic couplings are given by weak gauge couplings
  - Prediction on the mass of h ($< m_Z$) (MSSM)
  - Some extensions with a singlet (NMSSM etc)

- Higgs as a pseudo NG boson (pNGB)

  # of pNGB is determined by the group structure of dynamics at high energy

  - SO(5)/SO(4) # = 4 → 1 doublet (MCHM)
  - SU(4)/Sp(4) # = 5 → 1 doublet + 1 singlet
  - SO(9)/SO(8) # = 8 → 2 doublets

Multiplet structure of the Higgs sector is related to new physics

Phenomena beyond the SM

We already know BSM phenomena:

- **Neutrino oscillation**

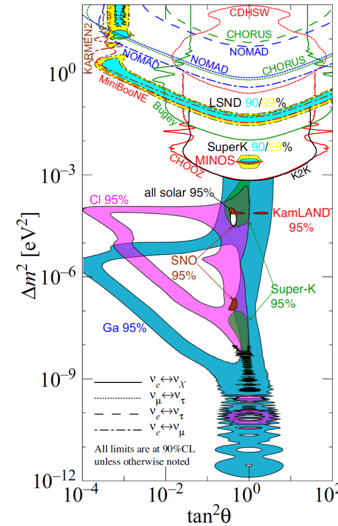
  $\Delta m^2 \sim 8\times10^{-5}\,\mathrm{eV}^2,\ \Delta m^2 \sim 2\times10^{-3}\ \mathrm{eV}^2$

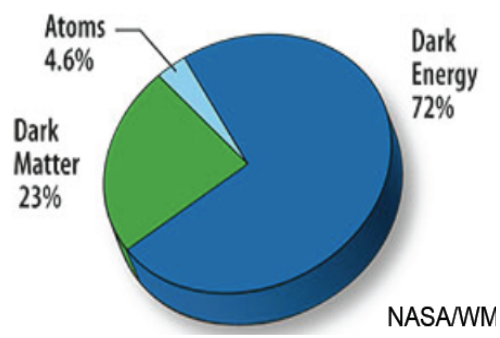
- **Dark Matter**

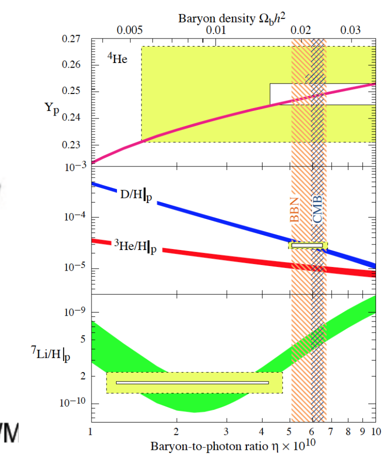
  $\Omega_{DM}h^2 \sim 0.12$

- **Baryon Asymmetry of the Universe**

  $n_B/n_\gamma \sim 6\times10^{-10}$







New physics is necessary!
Which scale?

If NP appears at the TeV scale, it should have a strong connection with the physics behind the Higgs sector

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

Higgs sector and New Phenomena

DM（WIMP） ・Inert doublet, singlet, triplet models

Odd under a new unbroken symmetry

Baryogenesis ・EW Baryogenesis (Extended Higgs)

First Order Phase Transition
CP Violation

Neutrino mass ・Type-II Seesaw (Exotic Higgs (triplet))

Exotic representations

・Radiative neutrino mass models

New charged Higgs bosons

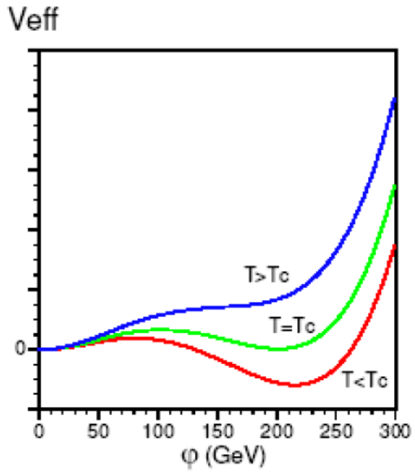
Multiplet structures, new symmetries, and the strength of couplings in the Higgs sector are closely related to new physics

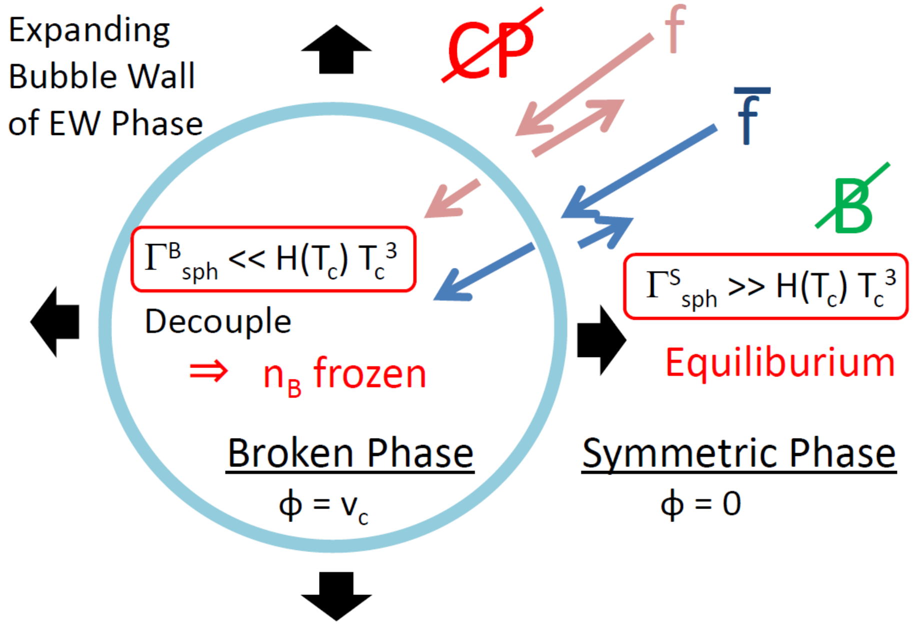
Electroweak Baryogenesis

$\Gamma \sim e^{-E_{\rm sph}/T} \ (T < T_c)$
$\Gamma \sim \kappa(\alpha_W T)^4 \ (T_c < T)$

Sakharov's 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

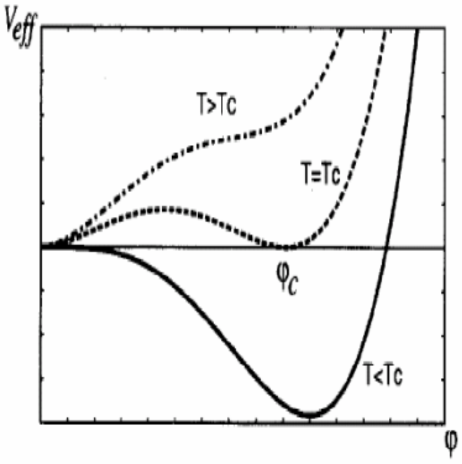
(Sphaleron Rate) < (Expansion Rate) ⇒ $\frac{\varphi_c}{T_c} \gtrsim 1$

Condition of Strong 1st OPT ($\varphi_c/T_c > 1$)

Finite Temperature Potential

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots\ldots$$

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$



EWBG was ruled out in the SM

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h << 125 \text{ GeV}$$

Contradiction with LHC results

Muti-Higgs models can satisfy the condition

$$E = \frac{1}{12\pi v^3}(2m_W^3 + m_Z^2 + m_H^3 + m_A^3 + 2m_{H^\pm}^3).$$

Thermal loop effect by additional Higgs boson

In order to satisfy $\phi_c/T_c > 1$ with $m_h = 125$GeV, Extension of the Higgs sector is necessary

Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

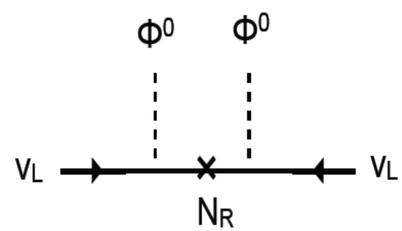
Mechanism for tiny masses:

$$m^{\nu}{}_{ij} = (c_{ij}/M)\, v^2 \quad < 0.1\ \text{eV}$$

Seesaw (tree level)

$$m^{\nu}{}_{ij} = y_i y_j\, v^2/M$$

Minkowski
Yanagida
Gell-Mann et al



(M>> 1TeV)

Quantum Effects (Radiative seesaw)

N-th order of perturbation

$$m^{\nu}{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

(M can be 1 TeV)

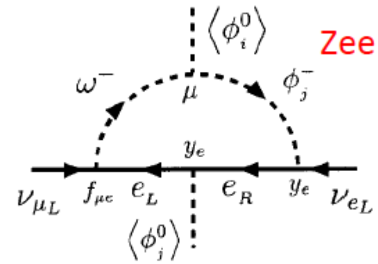
Explanations by the TeV scale physics

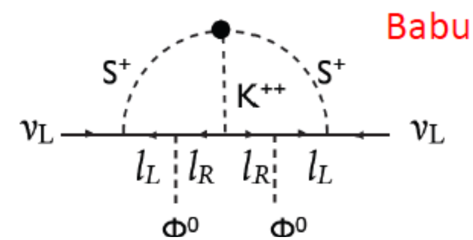
Radiative Seesaw Scenario

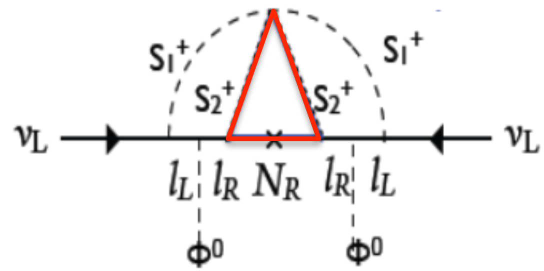
- Extended Higgs sector
- Z_2 parity
  - Neutrino mass generated at loop levels
  - WIMP Dark Matter
    - Lightest Z_2-odd particle
    - LSP (in SUSY extension)

Electroweak Baryogenesis

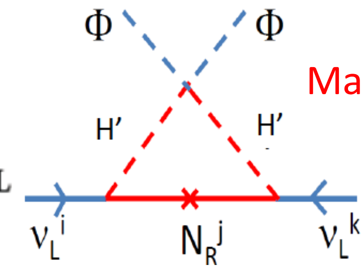
- Sphaleron
- Additional CP Phases
- Strong 1st Order Phase Transition

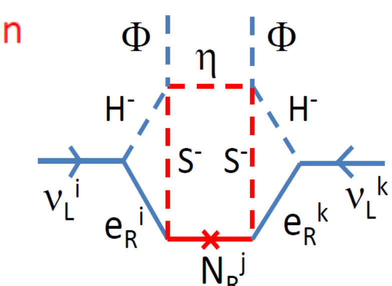






Krauss, Nasri, Trodden





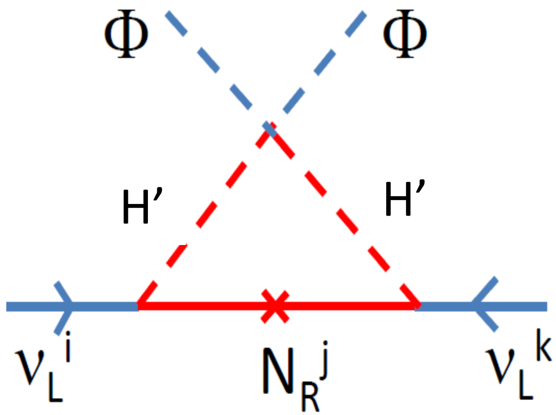
Aoki, SK, Seto

These scenarios are strongly related to the Higgs physics!

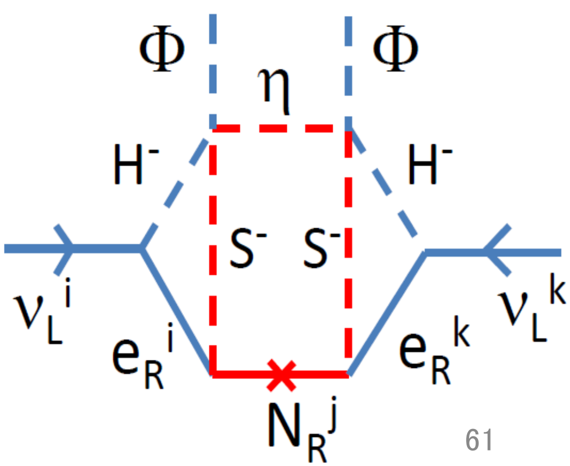
Radiative seesaw with Z_2

Z_2-parity plays roles:
1. No tree-level Yukawa (Radiative neutrino mass)
2. Stability of the lightest Z_2-odd particle (WIMP)

Ex1) 1-loop *Ma (2006)*
- Simplest model
- SM + Inert scalar doublet (H') + N_R
- DM candidate [H' or N_R]



Ex2) 3-loop *Aoki-Kanemura-Seto (2008)*
- Neutrino mass from O(1) coupling
- 2 Higgs doublets + η^0 + S^+ + N_R
- DM candidate [η^0 (or N_R)]
- Electroweak Baryogenesis



All 3 problems may be solved by TeV physics

A Strategy

- Many new physics scenarios predict special non-minimal Higgs sectors
- Comprehensive study of various extended Higgs sectors is very important
- Reconstruction of the Higgs sector by future experiments at LHC, HL-LHC and future lepton colliders
- From the Higgs sector to new physics BSM!

HPNP 2017 (1. - 4. March 2017, Univ. of Toyama)

Local Organizing Committee

Mayumi Aoki (Kanazawa U.)
Shinya Kanemura (U. of Toyama)
Hiroaki Sugiyama (U. of Toyama)
Mitsuru Kakizaki (U. of Toyama)
Tetsuo Shindou (Kogakuin U.)
Koji Tsumura (Kyoto U.)

Please participate to discuss Higgs and BSM physics!

Higgs is a Probe of New Physics

Higgs portal
new physics models

SUSY
Dynamical symmetry breaking
pNGB
CW mechanism
Higgs portal dark matter
Inert scalar models
Radiative neutrino mass models
Electroweak baryogenesis
…

Extended Higgs Sectors

The "SM-like" does not necessarily mean the SM.
Every extended Higgs sector can contain the SM-like Higgs boson $h(125)$ in its decoupling regime.

Properties of extended Higgs sectors

Multiplet Structure (2nd simplest Higgs models)

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?

Note: 2nd simplest Higgs models (HSM, 2HDMs, …) can be effective theories of more complicated Higgs sectors

Electroweak rho parameter

$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004}$

$Q = I_3 + Y/2$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i : $\mathrm{SU(2)_L}$ isospin
Y_i : hypercharge
v_i : v.e.v.
c_i : 1 for complex representation
1/2 for real representation

N=1 SM Higgs doublet Φ (T=1/2, Y=1) $\rho = 1$!

N=2 What kind of (2 field) extended Higgs sector $\Phi + X(T_X, Y_X)$ can satisfy $\rho = 1$?

We solve the equation

$$4\,T_X(T_X+1) = 3Y_X^{\,2}$$

$(T_X,$	$Y_X)$	X
(0,	0)	Singlet
(1/2,	1)	Doublet
(3,	4)	Septet
(25/2,	15)	26-plet
….		….

Larger T_x disfavored by unitarity (Logan et al,2014)

2 Higgs Doublet Model (soft-broken Z_2)

$$V_{\mathrm{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)}$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\mathrm{h.c.})\right]$$

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{bmatrix} \quad (i = 1, 2)$$

Φ_1 and $\Phi_2 \Rightarrow \underline{h, \; H,} \; A^0, H^\pm \oplus$ Goldstone bosons

↑ CPeven ↑ CPodd ↑charged

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

$$\frac{v_2}{v_1} = \tan\beta$$

Masses

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\mathrm{soft}}^2}\right),$$

$$m_H^2 = M_{\mathrm{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\mathrm{soft}}^2}\right),$$

$$m_{H^\pm}^2 = M_{\mathrm{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$

$$m_A^2 = M_{\mathrm{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

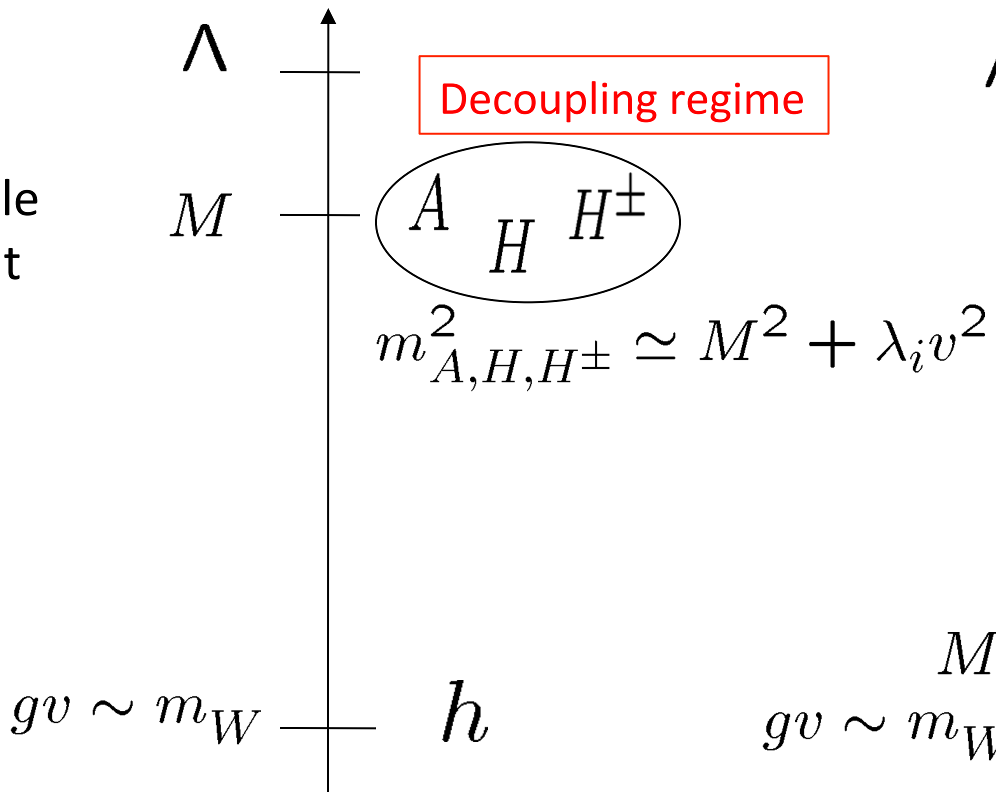
$M_{\mathrm{soft}} \; \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

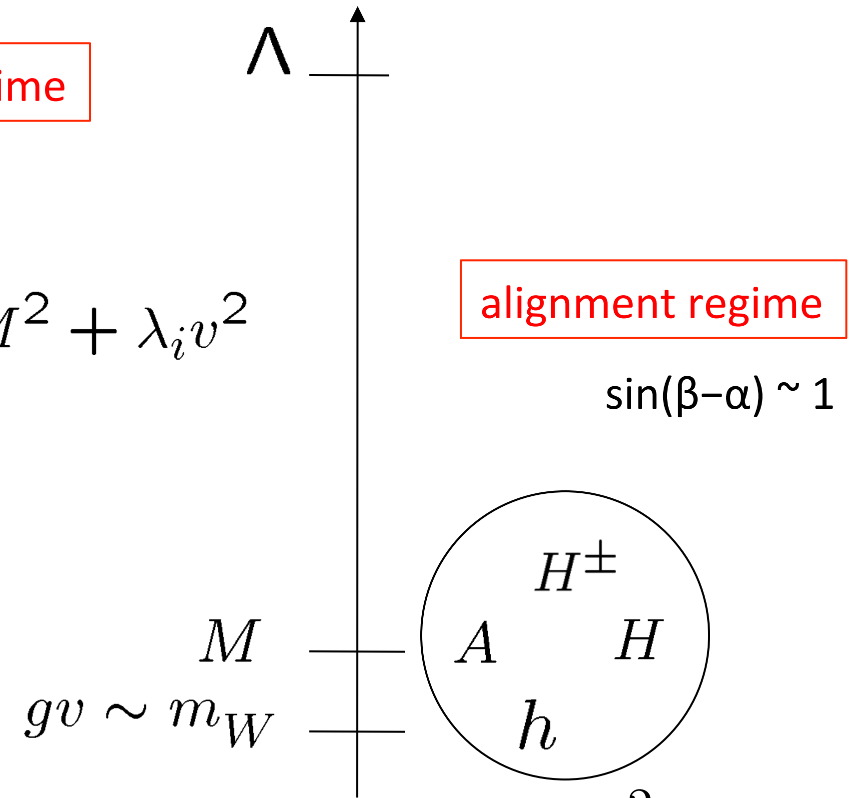
soft-breaking scale of the discrete symm.

Two Possibilities

Λ: Cutoff

M: Mass scale irrelevant to VEV





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

Effective Theory is the SM

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

Effective Theory is an extended Higgs sector

Non-decoupling effects

Unitarity in Non-SUSY 2HDM

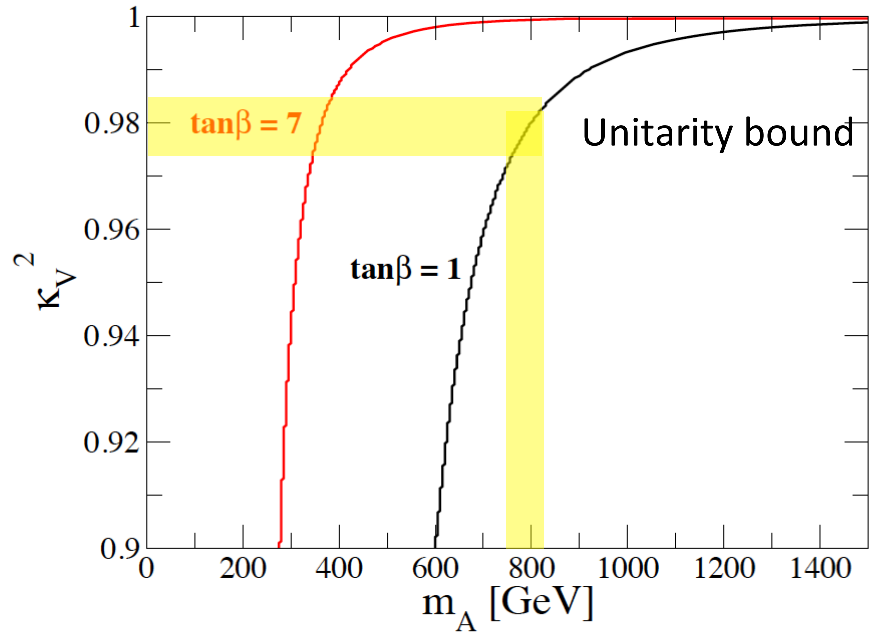
Φ₁ and Φ₂ **share v=246 GeV**

$v_1^2+v_2^2 = v^2$

m_h=125 GeV

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

If κ_V^2 is found to be less than 1, the upper bound on the mass of the second Higgs is obtained



$$\tan 2(\beta-\alpha) = \frac{2M_{12}^2}{M_{11}^2 - M_{22}^2} \sim -\frac{\lambda' v^2}{M^2}$$

$$M_{11}^2 = v^2(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta) + \frac{v^2}{2}\bar{\lambda}\sin^2 2\beta,$$

$$M_{22}^2 = \underline{M^2} + v^2\sin^2\beta\cos^2\beta(\lambda_1+\lambda_2-2\bar{\lambda}),$$

$$M_{12}^2 = \frac{v^2}{2}\sin 2\beta(-\lambda_1\cos^2\beta + \lambda_2\sin^2\beta) + \frac{v^2}{2}\sin 2\beta\cos 2\beta\bar{\lambda}.$$

FCNC Suppression

Multi-Higgs model: **FCNC appears via Higgs mediation**

2 Higgs doublet models:

to avoid FCNC, give different charges to Φ_1 and Φ_2

Discrete sym. $\Phi_1 \rightarrow +\Phi_{1,} \qquad \Phi_2 = -\Phi_2$

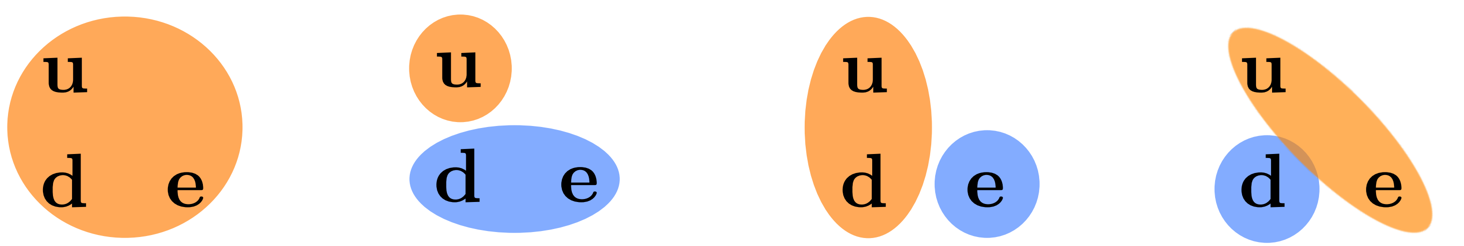
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

Barger, Hewett, Phillips

Classified by Z_2 charge assignment

Four Types of Yukawa coupling



Type-I
Fermiofobic
Neutrinophilic

Type-II
MSSM
NMSSM

Type-X
Lepton specific
Neutrino mass model
Muon g-2

Type-Y
Flipped
???

Z_2 assignment

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L	L_L
Type-I	$+$	$-$	$-$	$-$	$-$	$+$	$+$
Type-II	$+$	$-$	$-$	$+$	$+$	$+$	$+$
Type-X	$+$	$-$	$-$	$-$	$+$	$+$	$+$
Type-Y	$+$	$-$	$-$	$+$	$-$	$+$	$+$

Type II-2HDM (MSSM) Higgs couplings

VEV's: $v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$

Higgs mixing

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

SM

2HDM Type2

Gauge coupling:

$\phi VV \quad (V = Z, W)$ $\Rightarrow$

$$hVV \quad \sin(\beta - \alpha), \qquad HVV \quad \cos(\beta - \alpha)$$

Yukawa coupling:

$\phi b\bar{b}$ $\Rightarrow$

$$hb\bar{b} \quad \frac{\sin\alpha}{\cos\beta}, \qquad Hb\bar{b} \quad \frac{\cos\alpha}{\cos\beta}$$

$\phi t\bar{t}$ $\Rightarrow$

$$ht\bar{t} \quad \frac{\cos\alpha}{\sin\beta} \qquad Ht\bar{t} \quad \frac{\sin\alpha}{\sin\beta},$$

SM-like (alignment) regime

$$\sin(\beta-\alpha)\simeq 1$$

hVV	HVV
$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$

Only the lightest Higgs *h* couples to weak gauge bosons

h behaves like the SM Higgs

$$g_{hVV}\to g_{\phi VV}^{\text{SM}} \qquad g_{HVV}\to 0$$

$$y_{ht\bar{t}}\to y_{\phi t\bar{t}}^{\text{SM}} \qquad y_{Ht\bar{t}}\to y_{\phi t\bar{t}}^{\text{SM}}\cot\beta$$

$$y_{hb\bar{b}}\to y_{\phi b\bar{b}}^{\text{SM}} \qquad y_{Hb\bar{b}}\to y_{\phi b\bar{b}}^{\text{SM}}\tan\beta$$

$$y_{h\tau\tau}\to y_{\phi\tau\tau}^{\text{SM}} \qquad y_{H\tau\tau}\to y_{\phi\tau\tau}^{\text{SM}}\tan\beta$$

Type-II 2HDM

In difference type, the pattern is different

$$-\mathcal{L}_Y^{\rm int} = \sum_{f=u,d,e} \frac{m_f}{v}\left[\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - 2iI_f \xi_f \overline{f}\gamma_5 f A\right]$$
$$+\frac{\sqrt{2}}{v}\left[V_{ud}\overline{u}\,(m_d\xi_d P_R - m_u\xi_u P_L)\,d\,H^+ + m_e\xi_e\overline{\nu}P_R e H^+ + \text{h.c.}\right]$$

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

SM limit

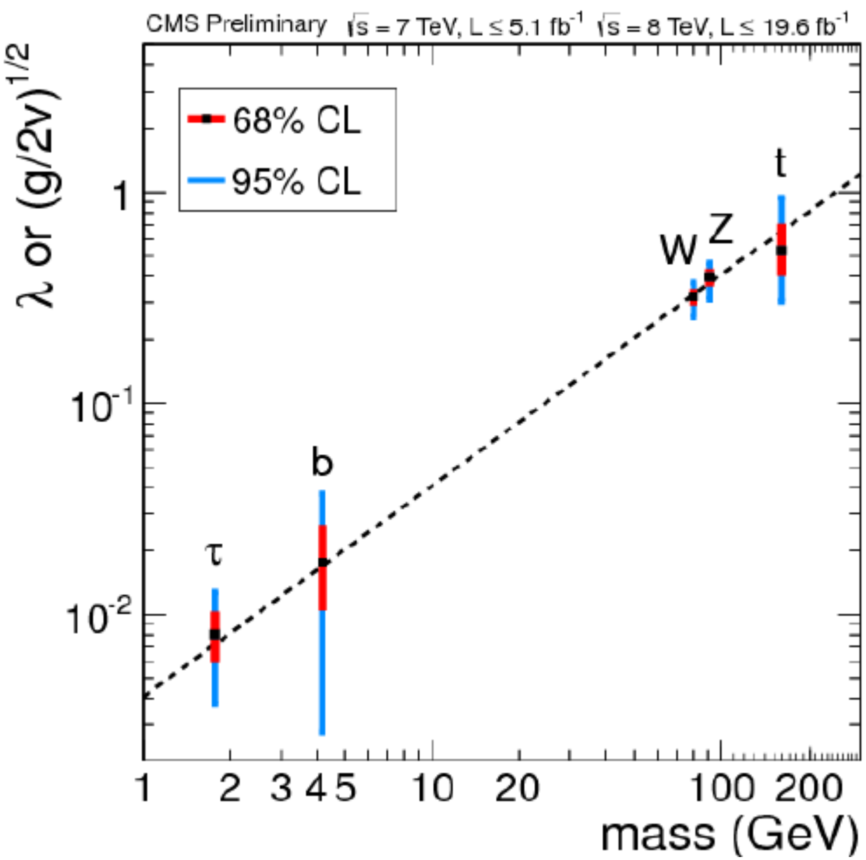
$$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cos(\beta-\alpha)\cot\beta$$
$$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta$$
→ 1

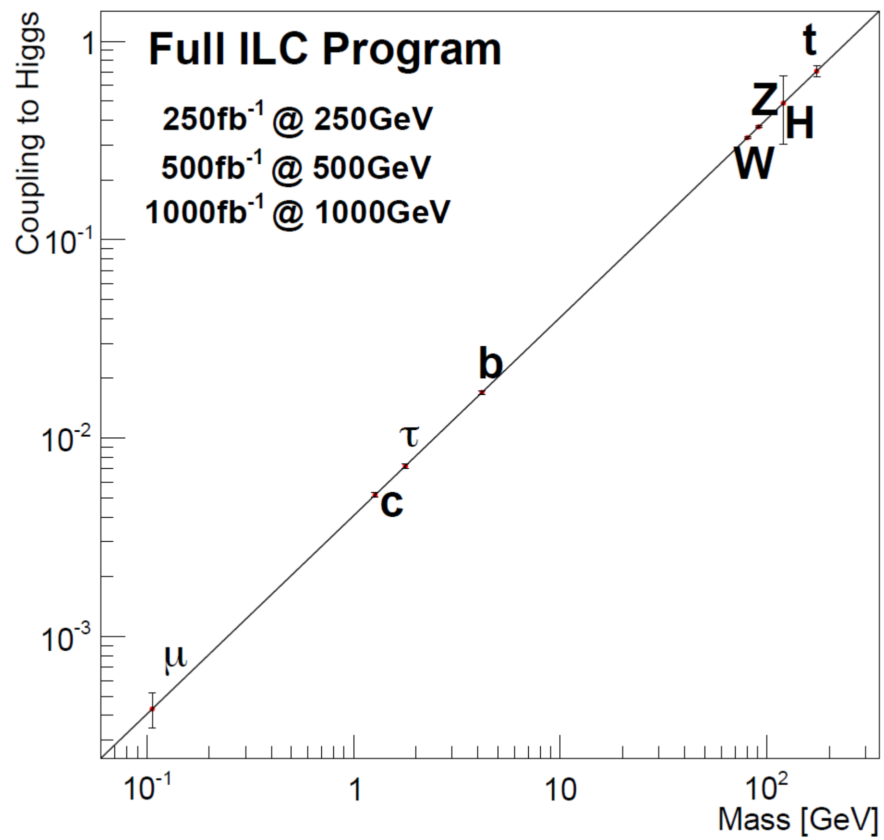
$$\sin\alpha/\sin\beta = \cos(\beta-\alpha) - \sin(\beta-\alpha)\cot\beta \;\rightarrow\; -\cot\beta$$
$$\cos\alpha/\cos\beta = \cos(\beta-\alpha) + \sin(\beta-\alpha)\tan\beta \;\rightarrow\; +\tan\beta$$

Fingerprinting Higgs sectors

by using future precision data for the couplings of *h*(125)

Current LHC data v.s. Full ILC





The precision must be improved in future at LHC 13-14 TeV and at the LC

All SM parameters are found

Next target is new physics!

- **Importance of Radiative Correction calculation**
- **Future precision measurements**
  - ***S, T, U*** **(Giga Z, Mega W)**
  - **Top (e.g. ttZ) couplings**
  - **Couplings of the discovered Higgs**

hgg, hγγ, hWW, hZZ, htt, hbb, hττ, hμμ, hcc, …, hhh

At ILC, we may be able to distinguish models by detecting a pattern of deviations in the *H* couplings from the SM values!

Fingerprinting new physics models

Pattern in deviations of g_{hVV} and Y_{hff}

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

cos(β-α) < 0

Singlet can be distinguished from the Type-I 2HDM

Y_{hff}/g_V=1 in the singlet model but Y_{hff}/g_V ≠1 in the 2HDM-I

In the triplet model, quark-Yukawa couplings are universally smaller, Lepton-Yukawa deviate universal. **κ_V can be greater than 1**

κ_V > 1 is a signature of exotic Higgs (with higher representations)

Extended Higgs models are distinguishable by precisely measuring *hVV* and *hff*

Fingerprinting the 2HDM (tree level)

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

x = cos(β−α) **SM-like: x <<1**

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

When a Fermion couples to Φ_1

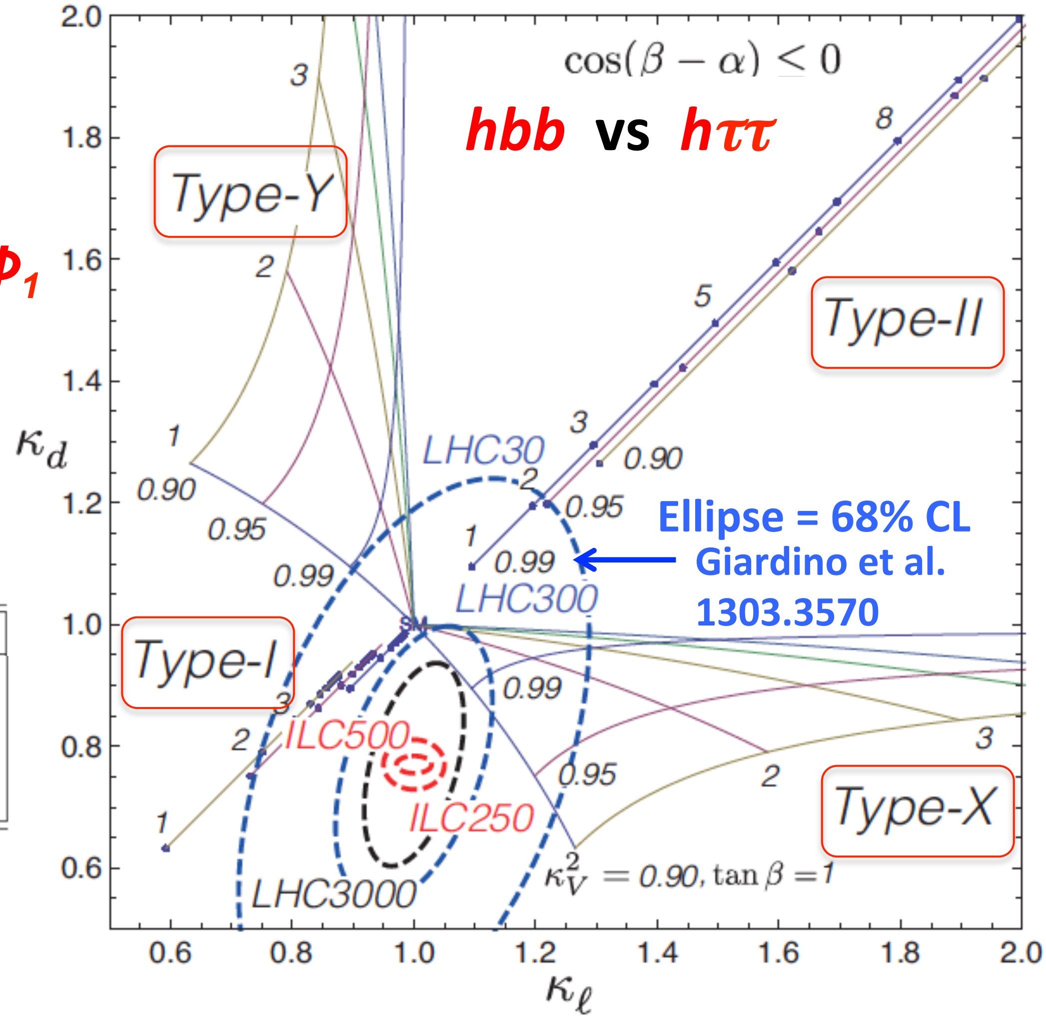
$$\kappa_f = 1 + \cot\beta\, x + \ldots$$

and if it couples to Φ_2

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

Model	μ	τ	b	c	t	g_V
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

SK, K. Tsumura, K. Yagyu, H. Yokoya 2014
ILC Higgs White Paper 2013



How do this result change with radiative corrections?

Fingerprinting the 2HDM (tree level)

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

x = cos(β−α)   **SM-like: |x| <<1**

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

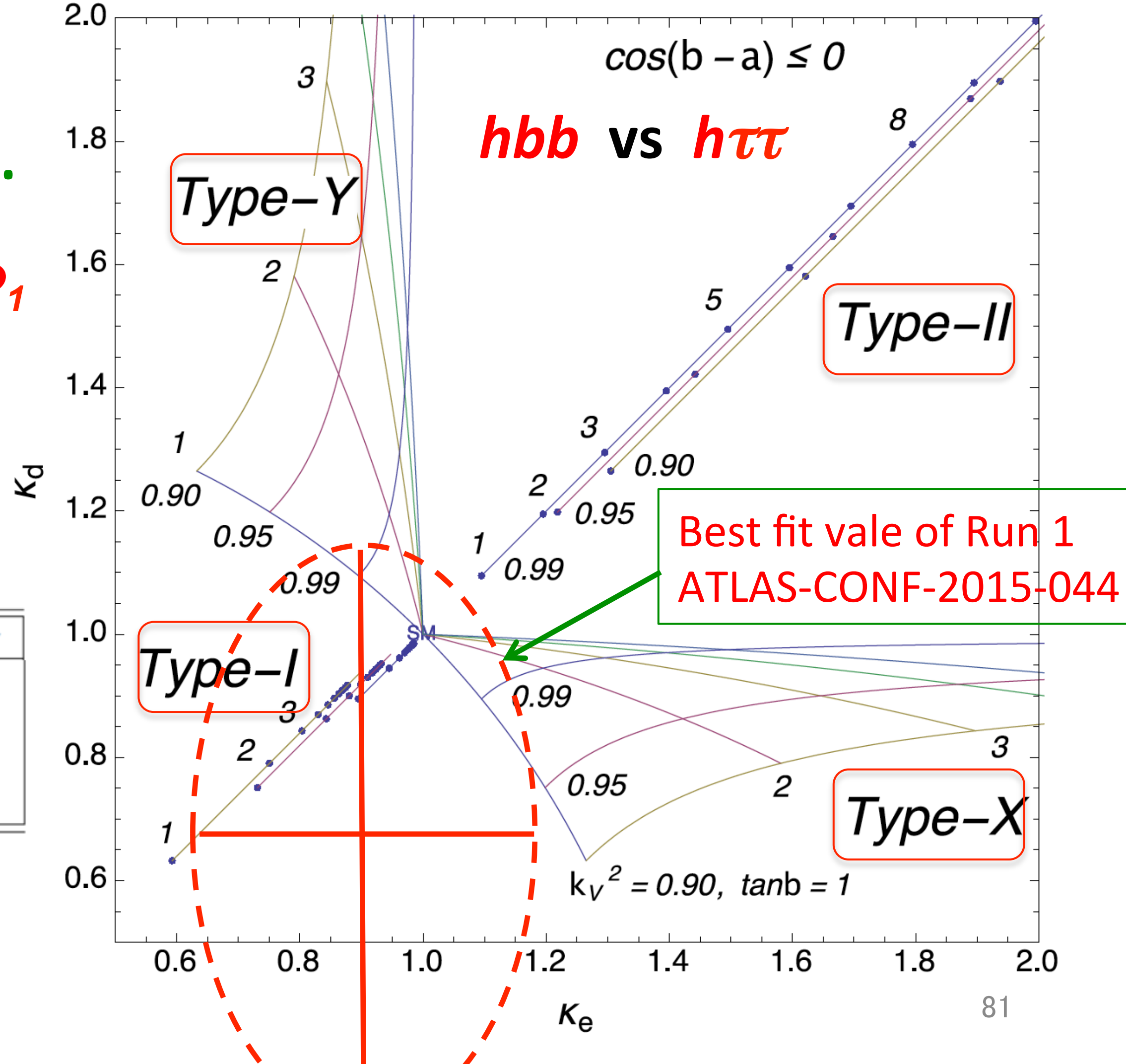
When a fermion couples to Φ_1

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

and if it couples to Φ_2

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

Model	μ	τ	b	c	t	g_V
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓



How do this result change with radiative corrections?

Radiative Corrections

In future, the Higgs couplings will be measured with much better accuracies at LCs

Clearly, tree level analyses are not enough

Analysis with Radiative Corrections (including quantum effect of the 2nd Higgs/BSM particles) is necessary

Theoretical predictions at loop levels × **Precision measurements at future colliders**

⇓

New Physics !

Scale Factors (1-loop level) in 2HDM

Mixing parameter x = cos(β−α) $\left[\sin(\beta-\alpha) = 1 - \frac{x^2}{2}\right]$ **SM-like x << 1**

Scale Factor of the *hVV* Couplings

$\Delta\kappa_X = \kappa_X - 1$

$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - \underline{A(m_\Phi^2, M^2)}$$

mixing   loop

Loop Effect

$$A(m_\Phi, M) = \frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2$$

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

$(\Phi = H^\pm, A, H)$

where

$$m_\Phi^2\left(1 - \frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \propto \frac{1}{m_\Phi^2} & (M >> v) \\ \propto m_\Phi^2 & (M \sim v) \end{cases}$$

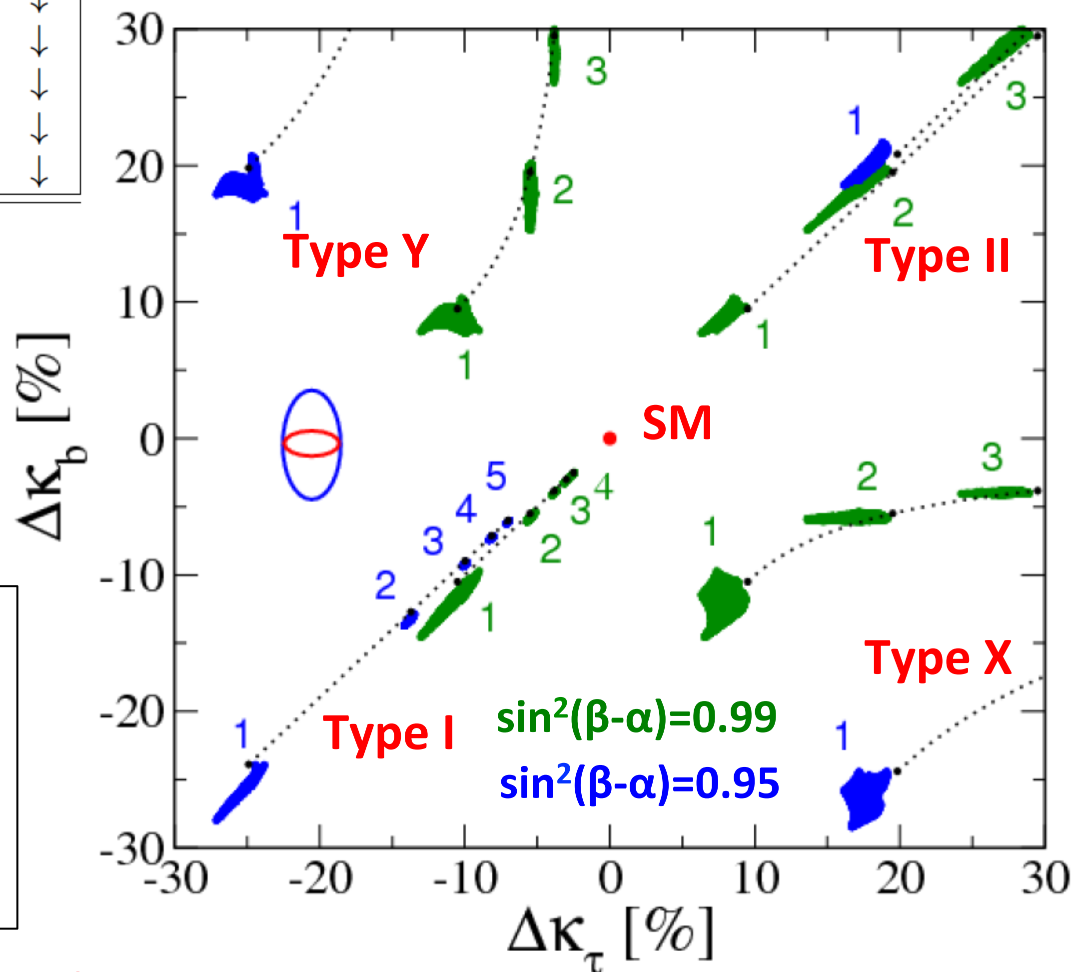
Decoupling! ($M >> v$)

Non-decoupling! ($M \sim v$)

Scaling factors at one-loop level

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Ellipse, ±1σ at LHC3000 and ILC500



Evaluation at one-loop

Scan of inner parameters (for each sin(β-α) and tanβ) under theoretical constraints

Even if only κ_V slightly differ from 1, the type of Yukawa interactions can be separated by precision measurements at the LHC3000 and LCs.

tanβ, sin(β-α) can also be determined

Kanemura, Kikuchi, Yagyu, PLB731 (2014) 27.

hVV coupling in the ϕ-X model (X: second scalar)

- Mixing angle α (ϕ and X)
- tanβ: Ratio of VEV between ϕ and X

Doublet-Singlet Model (1/2,1) + (0,0)

$$\kappa_V = \cos\alpha$$

$\kappa_V < 1$

2HDM (1/2,1) + (1/2,1)

$$\kappa_V = \sin\beta\cos\alpha - \cos\beta\sin\alpha = \sin(\beta - \alpha)$$

Doublet-Triplet Model (Georgi-Machasek Model) (1/2,1) + (1,2) + (1,0)

$$\kappa_V = \sin\beta\cos\alpha - 2\sqrt{2}\cos\beta\sin\alpha$$

Doublet-Septet Model (1/2,1) + (3, 4)

$$\kappa_V = \sin\beta\cos\alpha - 4\cos\beta\sin\alpha$$

$\kappa_V > 1$ is possible

Fingerptinting the model (Exotics)

SK, K. Tsumura, K. Yagyu, H. Yokoya 2013

Universal Fermion Coupling (κ_F)

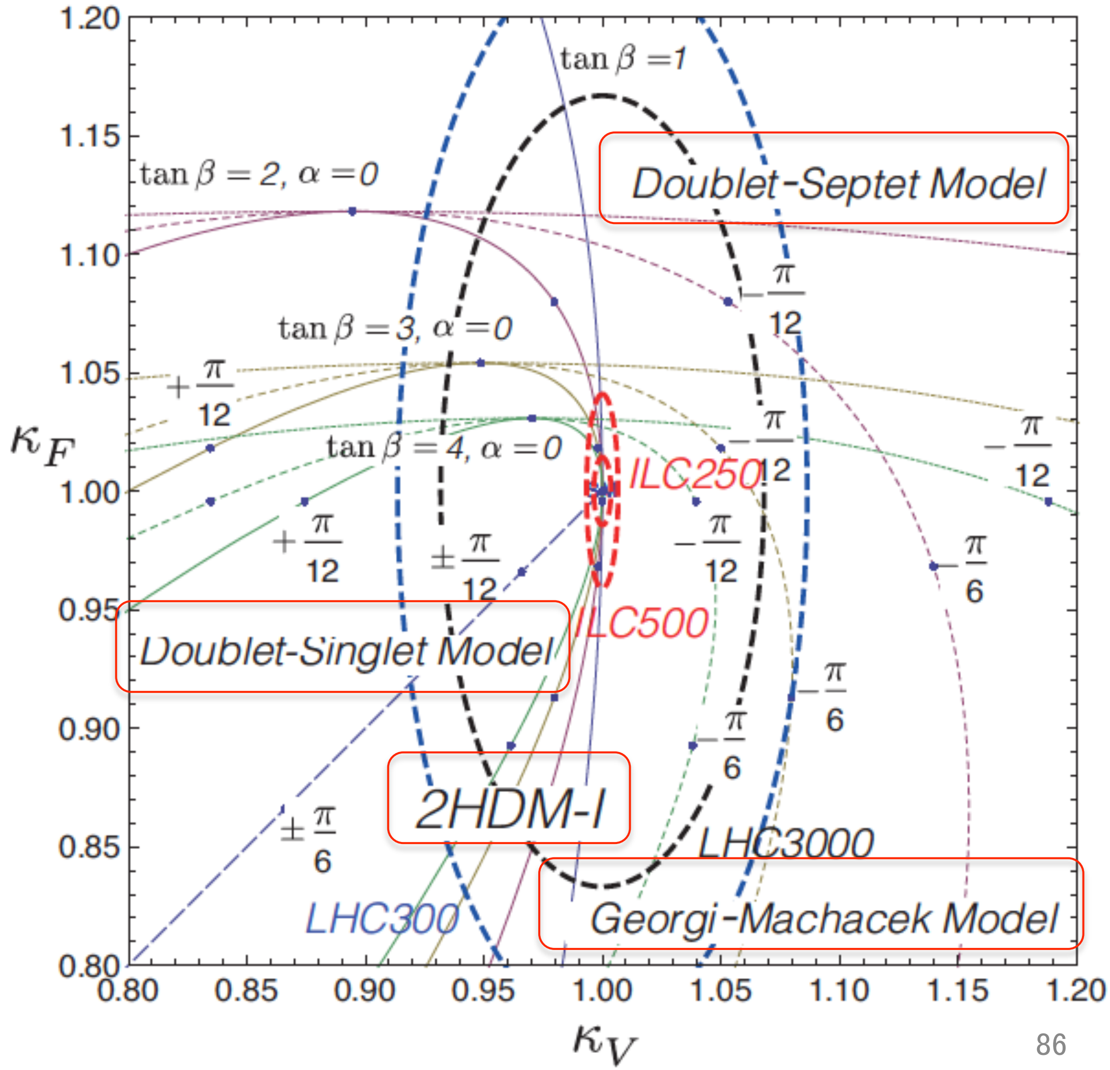
VS

***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models

Ellipse = 68% CL



Comparison of

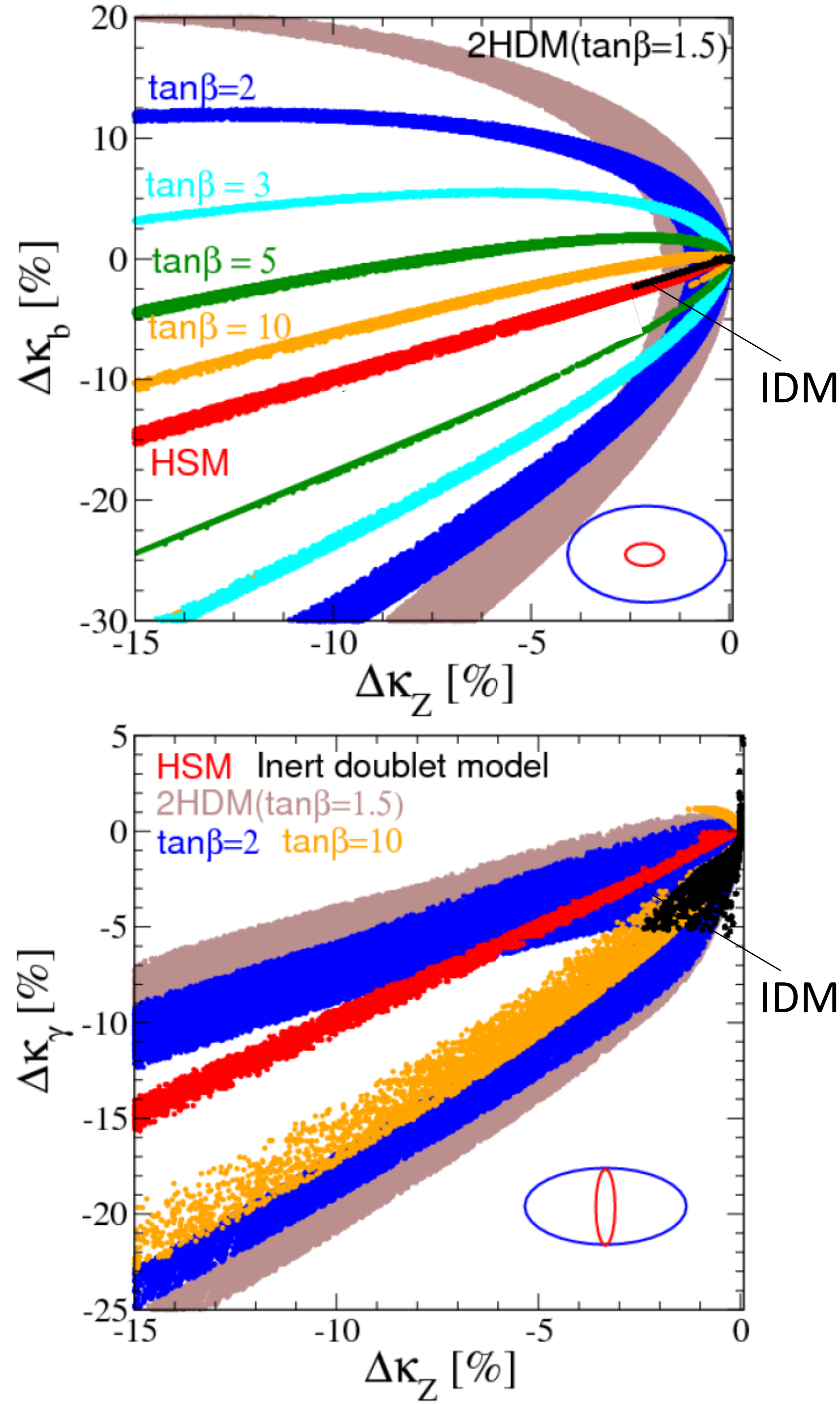
1. 2HDM-I

2. Doublet-Singlet Model (HSM)

3. Inert Doublet Model (IDM)

Scan of inner parameters (mass, mixing angles) under the theoretical conditions of
Perturbative unitarity
Vacuum stability
Condition for avoiding wrong vacuum (HSM)

These models may be distinguished, as long as a deviation in κ_Z is detected



Ellipse, ±1σ at LHC3000 and ILC500

H-COUP

S. K.
Mariko Kikuchi
Kei Yagyu

A full set of *Fortran Code* for evaluating one-loop corrected *h*(125) couplings in various 2nd simplest Higgs models

Doublet-Singlet model
SK, Kikuchi, Yagyu, 1511.06211, NPB to appear

Two Higgs doublet models (I, II, X, Y)
SK, Kikuchi, Yagyu, NPB896, 80 (2015)
SK, Kikuchi, Yagyu, PLB731, 27 (2014)

Doublet-Triplet model
Aoki, SK, Kikuchi, Yagyu, PRD87,015012(2013)

Inert Doublet/Singlet model
SK, Kikuchi, Sakurai, in preparation

All couplings of *h*(125)

hγγ, hγZ, hZZ, hWW, htt, hbb, hττ, hhh

Renormalization done in the *modified* on-shell scheme

***H-COUP* (ver.1) is to be in public in end of 2016**

Extraction of parameters

Slide by
Mariko Kikuchi

In the future,
how much precise can we extract values of inner parameters by using LHC3000 and ILC500 data ?

Case A LHC3000 ILC500 1σ

$\Delta\hat{\kappa}_V = -2.0 \;\; \pm 2.0 \;\; \pm 0.4\%$

$\Delta\hat{\kappa}_\tau = +5 \;\; \pm 2.0 \;\; \pm 1.9\%$

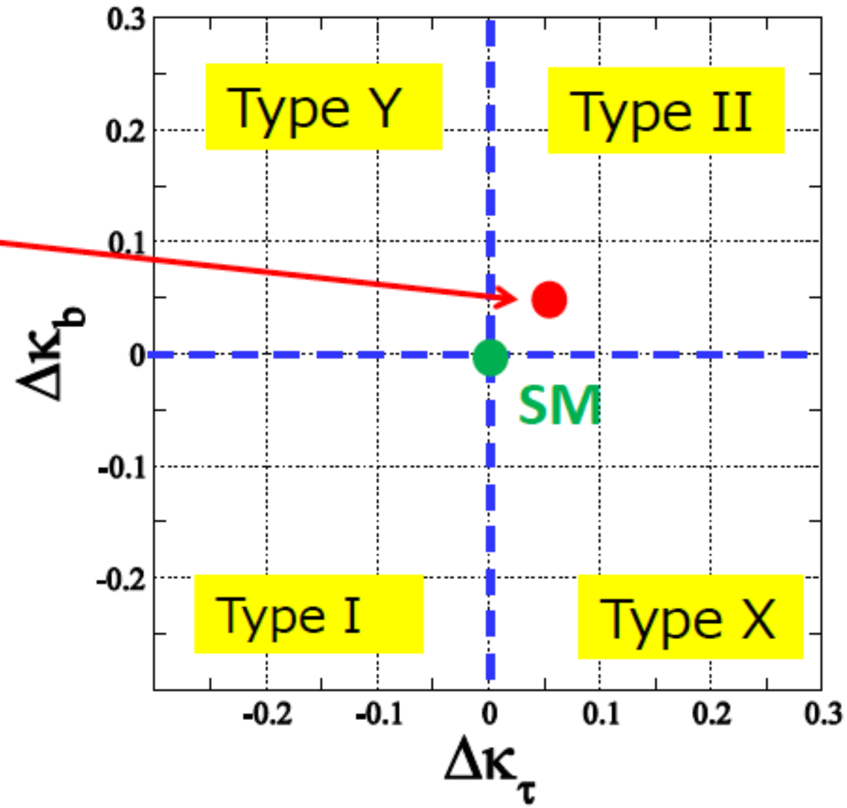
$\Delta\hat{\kappa}_b = +5 \;\; \pm 4.0 \;\; \pm 0.9\%$

Errors are from ILC(500) *in Snowmass 2014 Rep.*

Type-II

We survey parameter regions by scanning inner parameters

x*, tanβ, *m*$_\Phi$, *M



Φ = H⁺, H, A

Extraction of parameters

$$x = \cos(\beta - \alpha)$$

$$\Delta\hat{\kappa}_\tau - \Delta\hat{\kappa}_V \simeq -\tan\beta\, x$$

Input

Errors are from
Snowmass 2014 Rep.

Case A

	LHC3000	ILC500
$\Delta\hat{\kappa}_V = -2.0$	± 2.0	$\pm 0.4\%$
$\Delta\hat{\kappa}_\tau = +5$	± 2.0	$\pm 1.9\%$
$\Delta\hat{\kappa}_b = +5$	± 4.0	$\pm 0.9\%$

Errors are from ILC(500)
in Snowmass 2014 Rep.

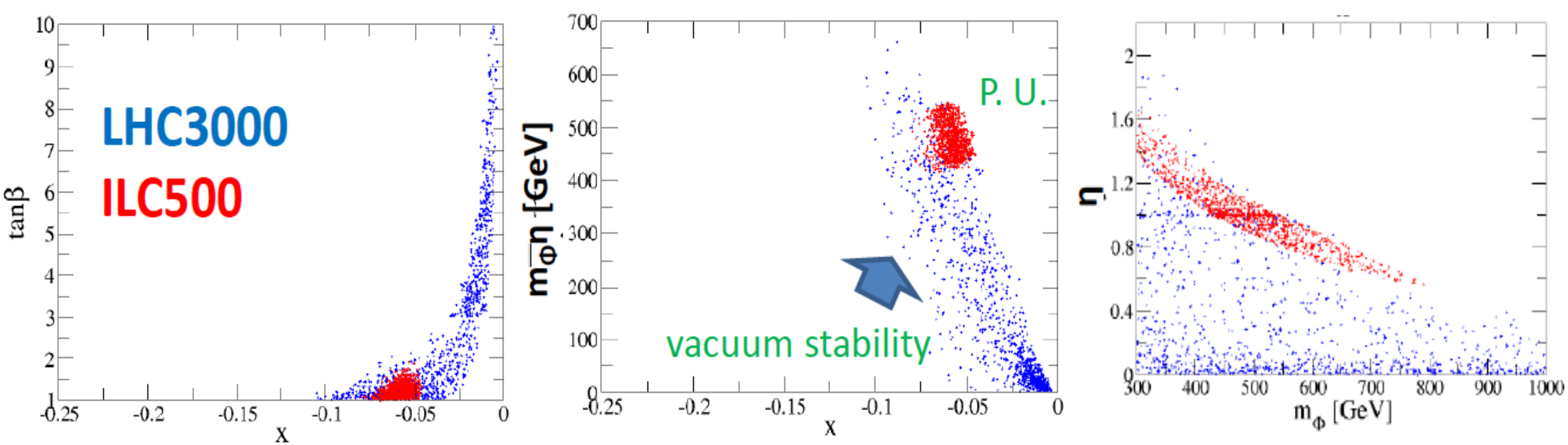
Type-II

$$\eta = 1 - \frac{M^2}{m_\Phi^2}$$

$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - A(m_\Phi^2, M^2)$$

$$A(m_\Phi, M) = \frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{1}{v^2}\left\{m_\Phi\left(1 - \frac{M^2}{m_\Phi^2}\right)\right\}^2$$

$$(\Phi = H^\pm, A, H)$$



New mass scale can be extracted! $m_\Phi < 800$ GeV

In addition to the type, parameters x and tanβ can be extracted !!

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

Deviation in *hff*

If $\Delta\kappa_V = -1\,\%$

Singlet

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ — O(1) %

Type I 2HDM

$\Delta\kappa_u = +\cot\beta\,x$, $\Delta\kappa_d = +\cot\beta\,x$, $\Delta\kappa_\tau = +\cot\beta\,x$ — O(10) %

Type X (Lepton Specific) 2HDM

$\Delta\kappa_u = +\cot\beta\,x$, $\Delta\kappa_d = +\cot\beta\,x$, $\Delta\kappa_\tau = -\tan\beta\,x$ — O(10) %

MSSM (Type II 2HDM)

$\Delta\kappa_u = +\cot\beta\,x$, $\Delta\kappa_d = -\tan\beta\,x$, $\Delta\kappa_\tau = -\tan\beta\,x$ — O(10) %

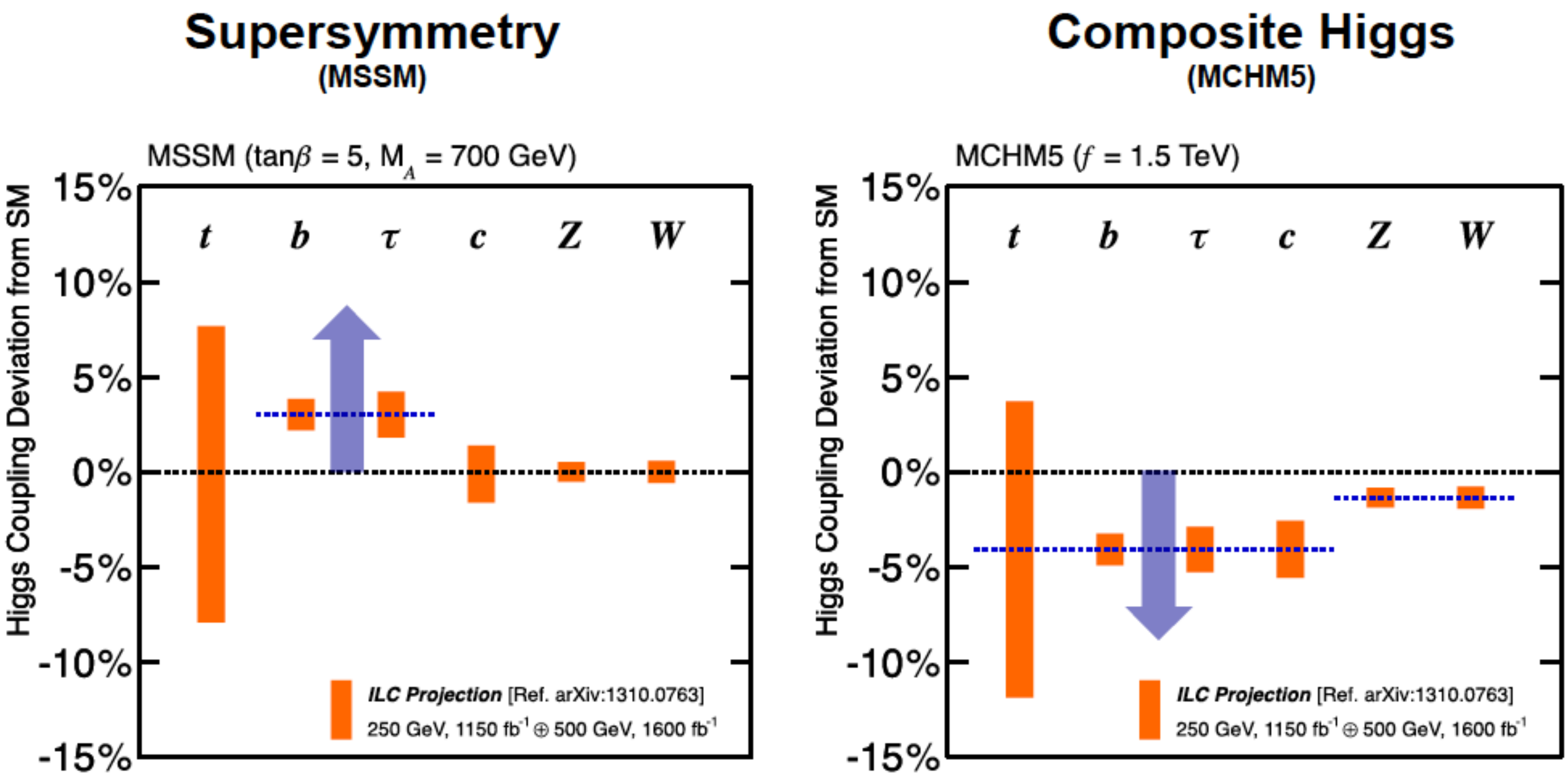
MCHM4

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ — O(1) %

MCHM5

$\Delta\kappa_u = -(3/2)\,x^2$, $\Delta\kappa_d = -(3/2)\,x^2$, $\Delta\kappa_\tau = -(3/2)\,x^2$ — O(1) %

Finger Printing



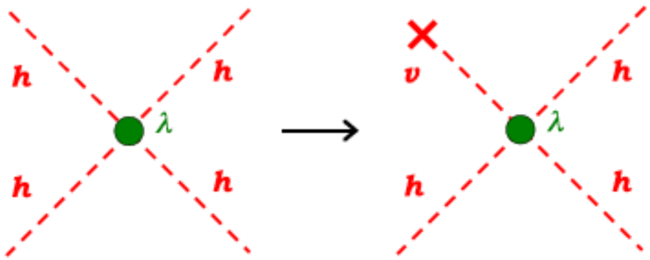
ILC 250+500 LumiUP

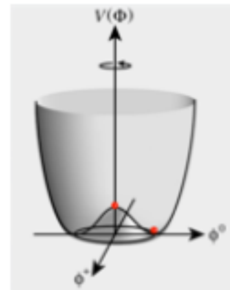
Higgs potential and new physics

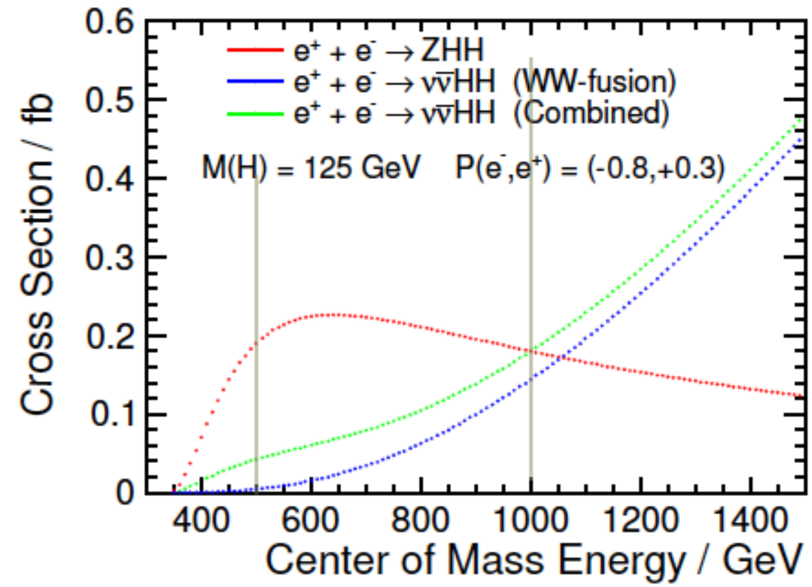
Although *h*(125) was found, we know nothing about the structure of the Higgs potential yet

Higgs Self-Coupling

hhh coupling =
consequence of vacuum condensation

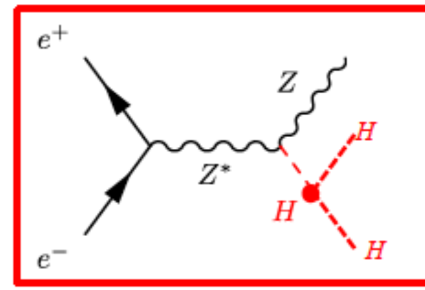




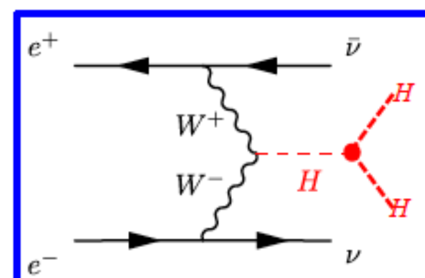


Challenging measurement because of:

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



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%



See J.Tian's Poster

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

Higgs potential

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

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

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

Renormalization Conditions

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

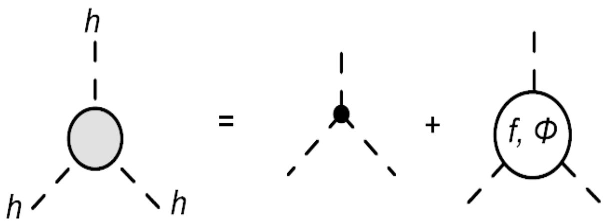
SM Case

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

Non-decoupling effect

Case of Non-SUSY 2HDM

- Consider when 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*±

SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

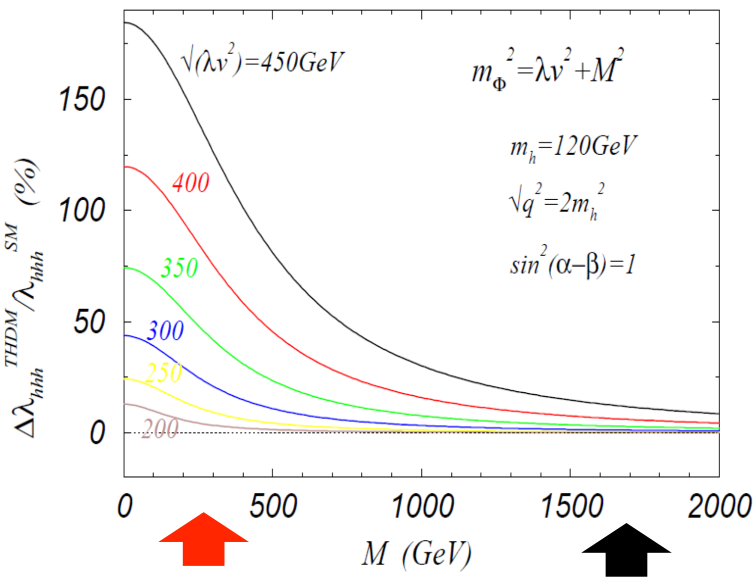
$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 - \frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

Extra scalar loop — Top loop

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

(Φ = *H, A, H*±)

Correction can be huge 〜 100%



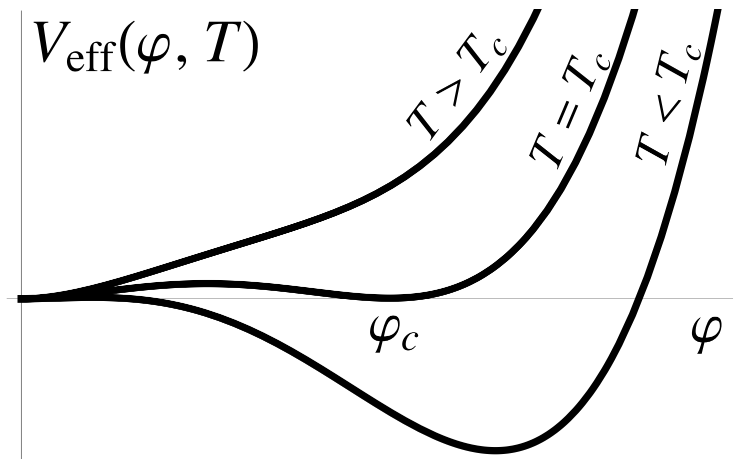
Non-decoupling effect — Decoupling

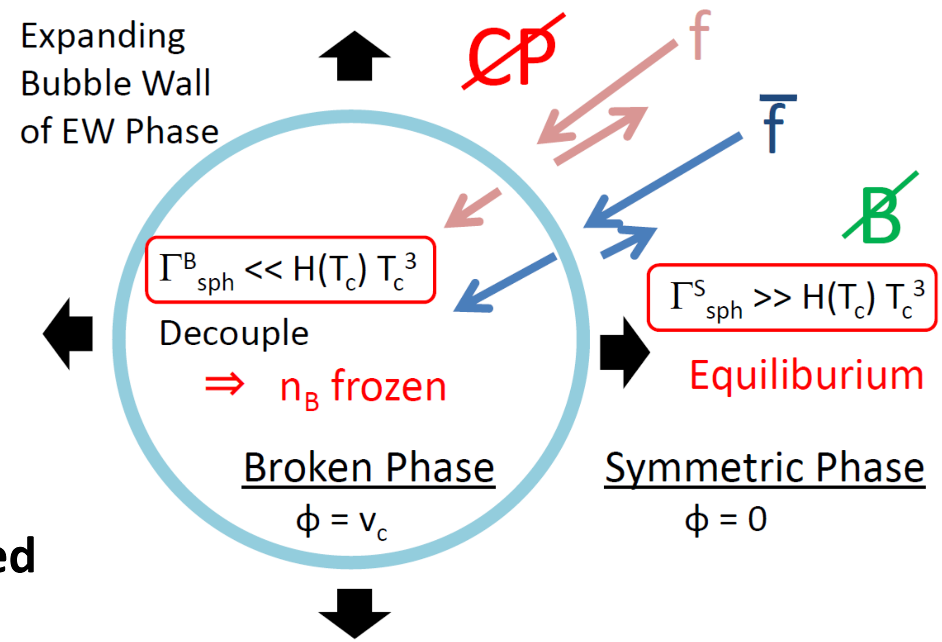
An example: EW Baryogenesis

$$\Gamma \sim e^{-E_{\rm sph}/T} \;\; (T < T_c)$$
$$\Gamma \sim \kappa(\alpha_W T)^4 \;\; (T_c < T)$$

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

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

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

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

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

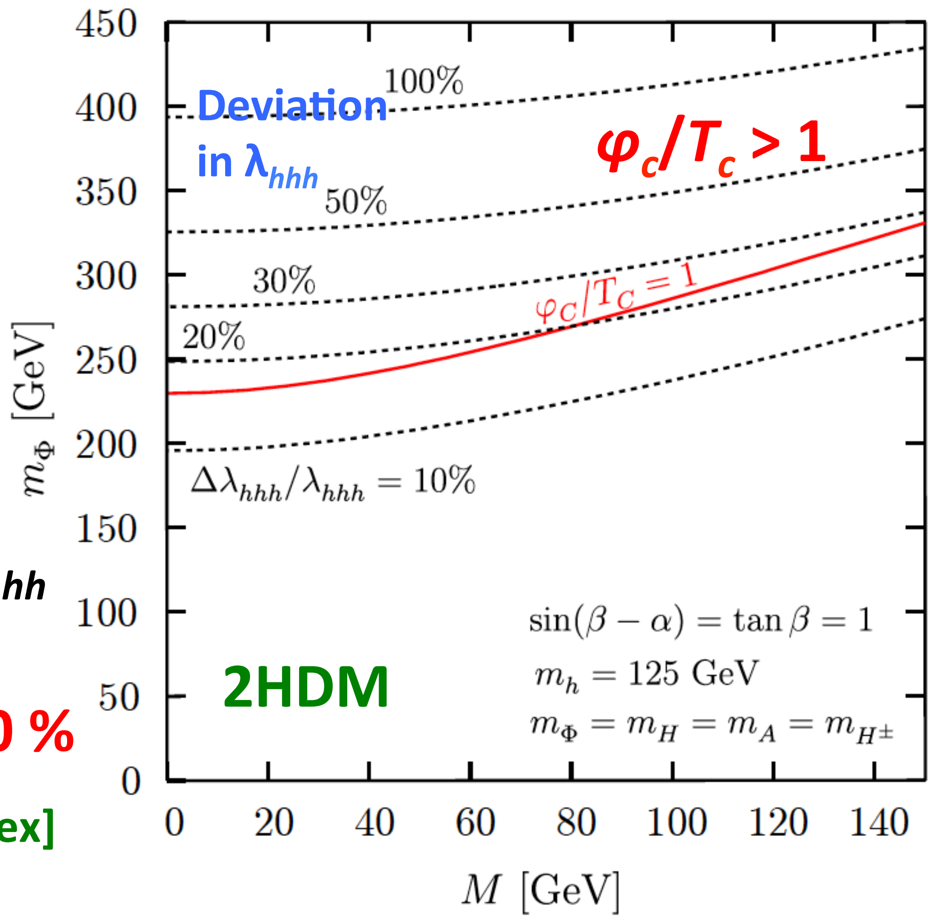
In this case, large quantum effects also appear in the *hhh* coupling

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

Strong 1st OPT and the *hhh* coupling

SK, Y Okada, E Senaha (2005)

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



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!

GW : another probe of 1st OPT?

Gravitational Wave Experiments

aLIGO (USA), KAGRA (JPN), aVIRGO (ITA), …

- **Trial for first discovery of GWs (Recently LIGO did make it!)**
- **GWs from astronomical phenomena (binary of NSs, BHs, …)**

New era of GW astronomy has come ture!

Future exp: eLISA [EUR], DECIGO [JPN], …

- **GWs from early Universe (Inflation, 1st OPT, …)**

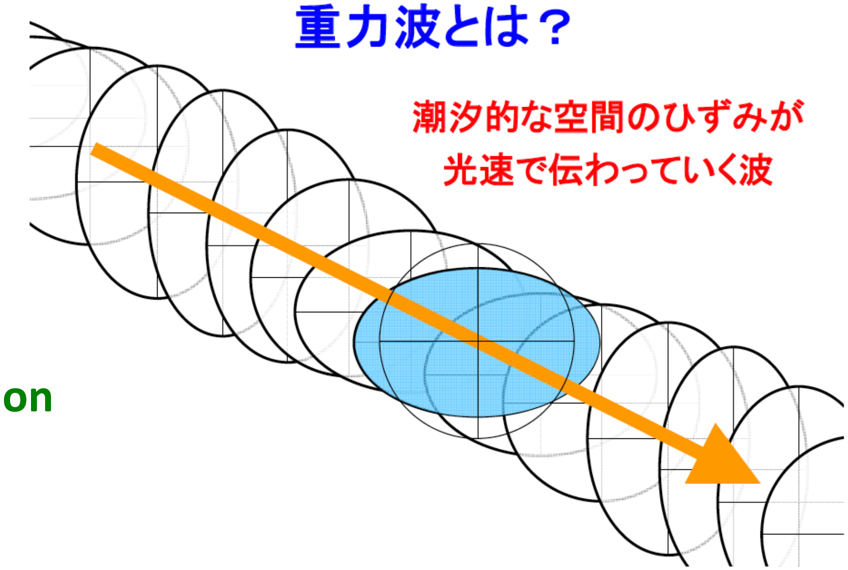
GWs may be used for exploration of the Higgs potential, as a complementary mean with collider experiments.

Gravitational Waves

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x) \quad |h_{\mu\nu}| \ll 1$$

Linearized Einstein Equation $\Box h_{\mu\nu} = 0$

Wave equation



Sources of Gravitational Waves

Astrophysical Origins

- Binary Star system (Neutron stars, Black holes, etc)
- Supernovae explosion, …

Target of ongoing ground-based experiments (*aLIGO, KAGRA, aVirgo*)

Cosmological Origins

- Cosmic Inflation
- First order phase transition (Electroweak, GUT, …)

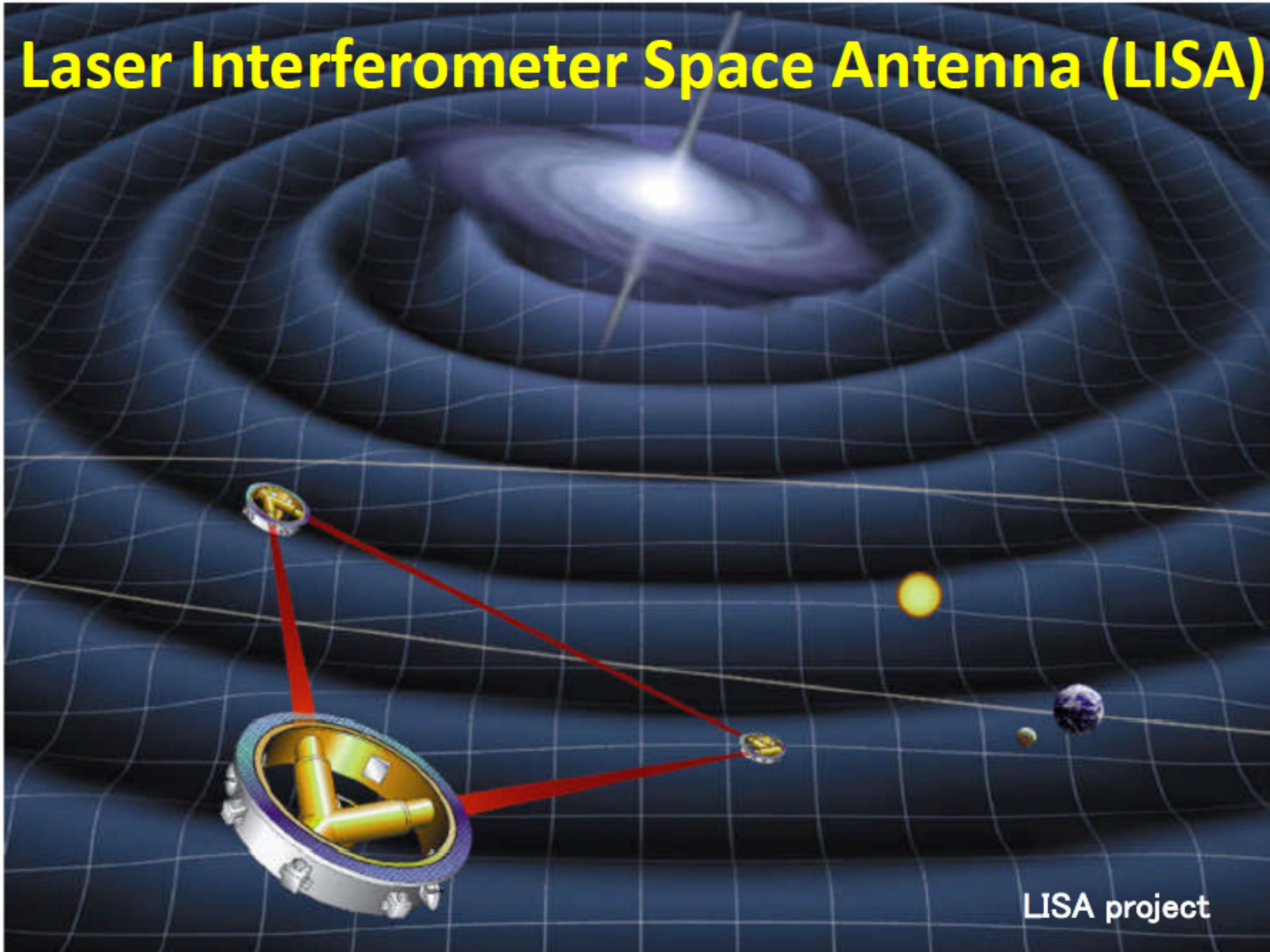
Proved by future space-based experiments (*eLISA, DECIGO, BBO*)

Abundance of relic GW

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f}$$

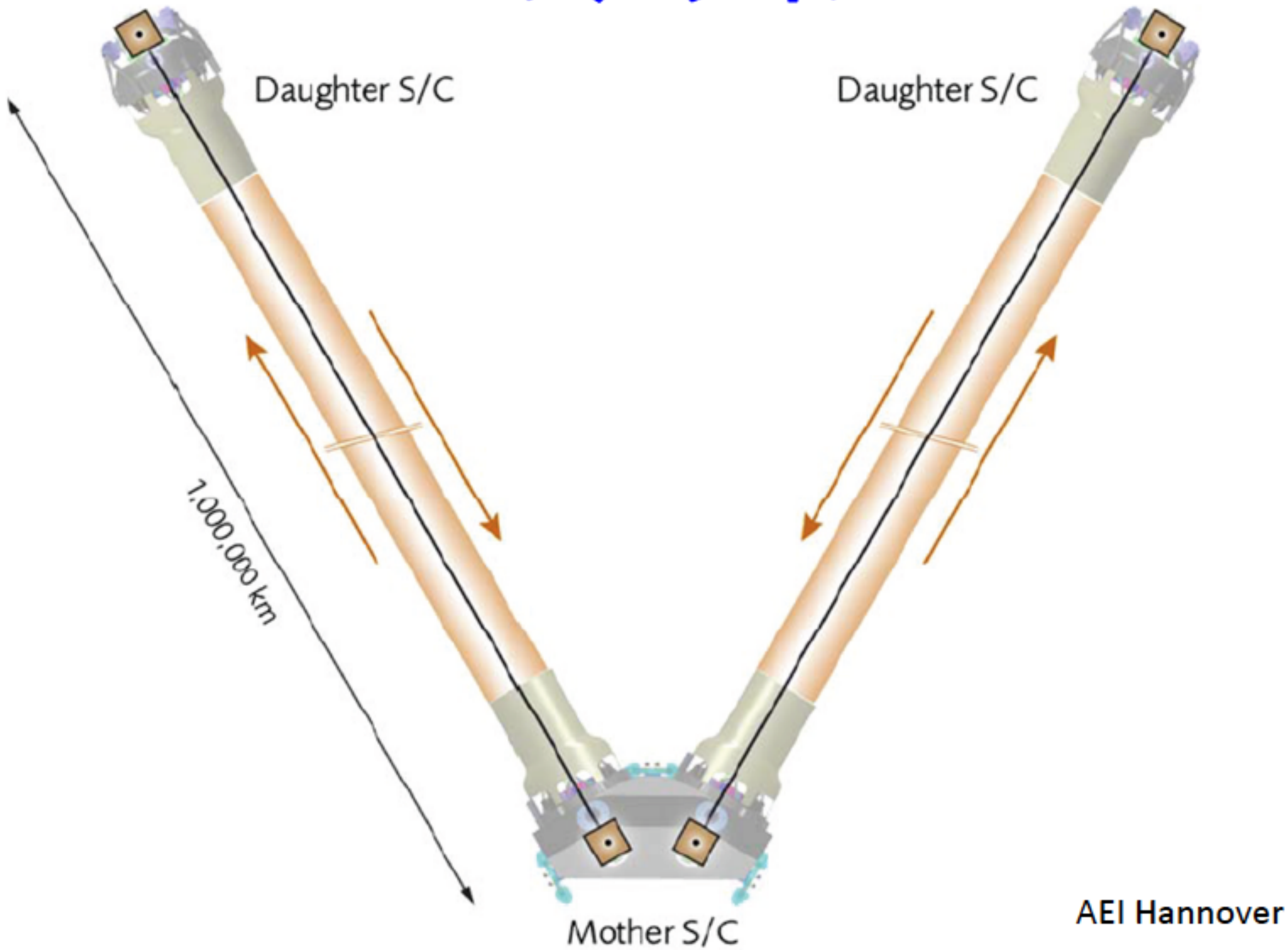
Energy density $\rho_{\rm GW} = \dfrac{1}{32\pi G}\langle \dot{h}_{ab}\dot{h}^{ab}\rangle$

Critical density $\rho_c = \dfrac{3H_0^2}{8\pi G}$



川村静児氏のスライド

eLISAのデザイン



川村静児氏のスライド

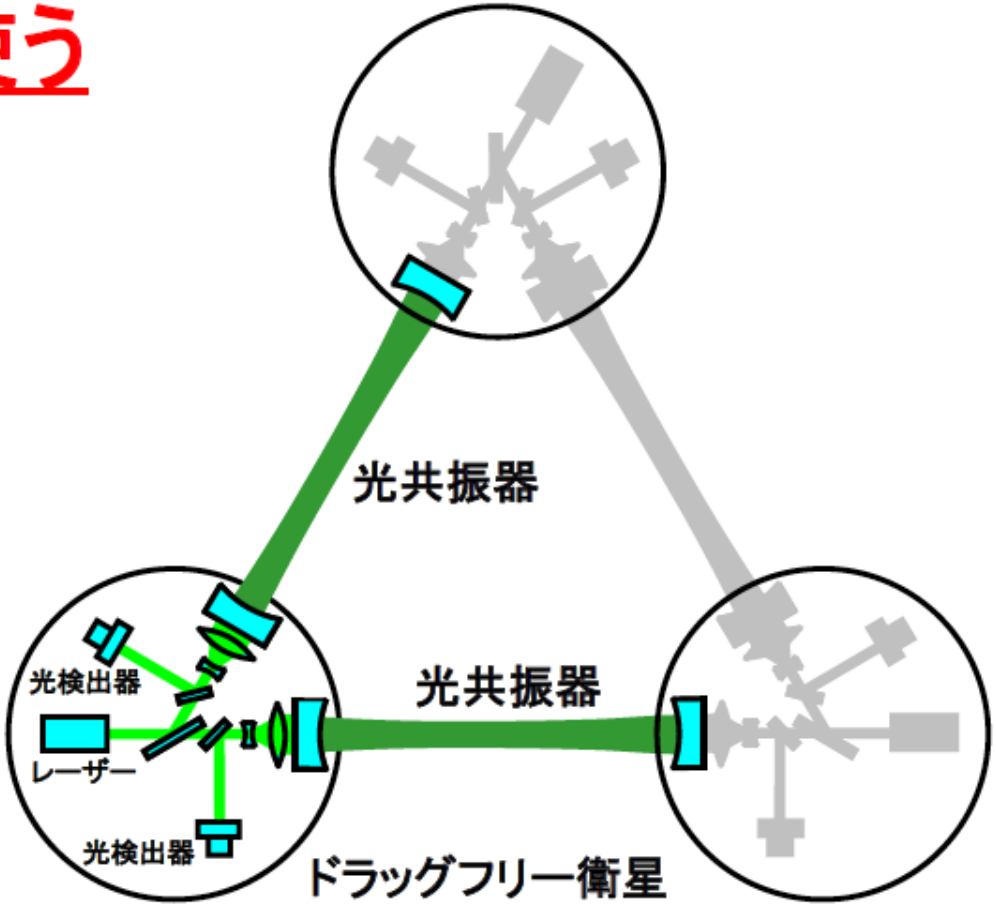
DECIGO

予備概念設計

光共振器を使う

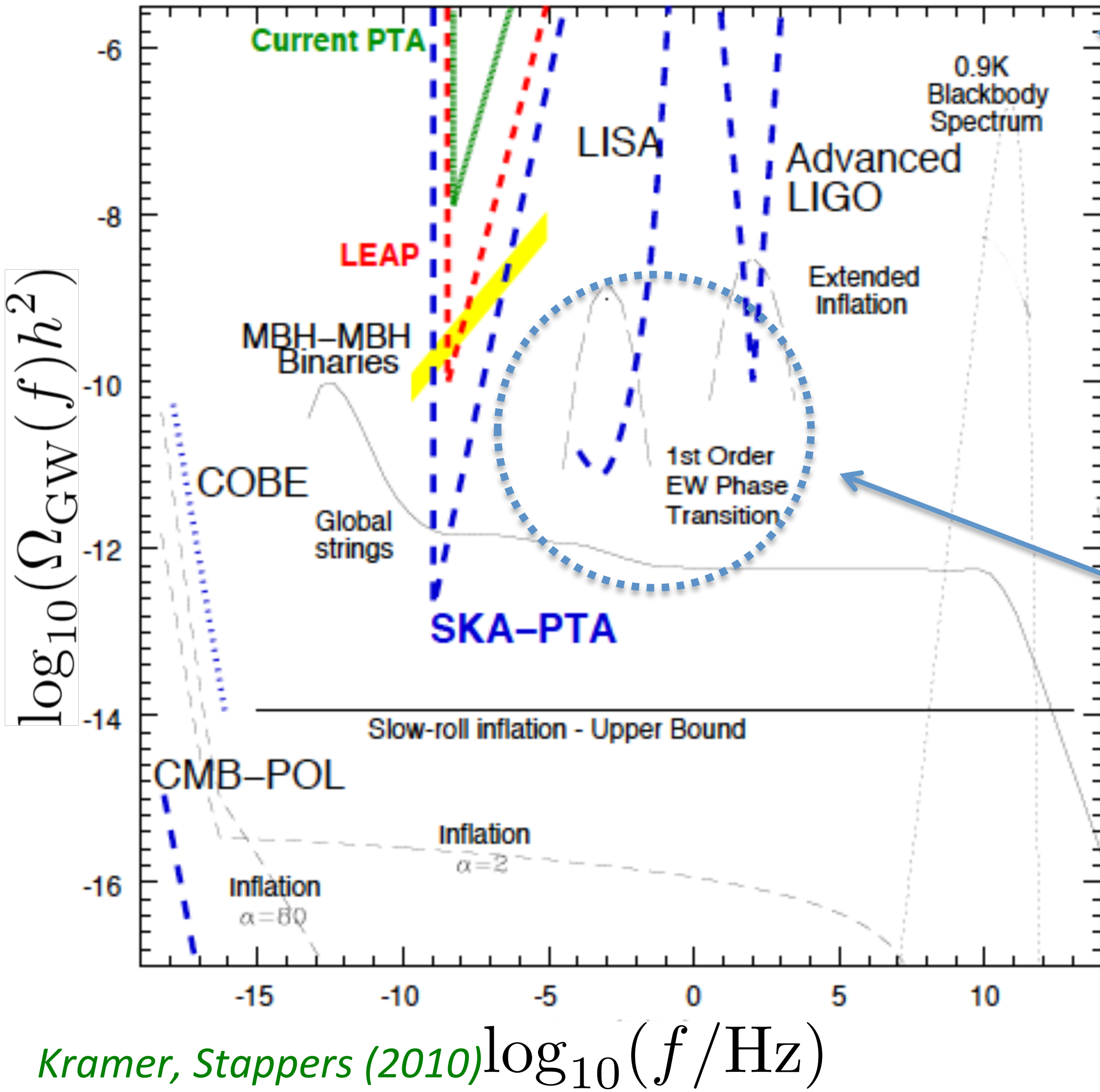
アーム長：1000 km
ミラー直径：1 m
レーザー波長：532 nm
フィネス：10
レーザーパワー：10 W
ミラー質量：100 kg

干渉計3台で
1クラスター



川村静児氏のスライド

Landscape of relic GWs



Kramer, Stappers (2010)

Current cosmological constraints from CMB and BBN:

Constraints on extra radiation:

$$\Delta N_\nu \lesssim 1$$

$$\Omega_{\rm extra}h^2 = 5.6 \times 10^{-6}\Delta N_\nu$$

Future GW observation at space-based interferometers:

Timeline

2025/26: **Pre-DECIGO**

Afterwards: **DECIGO**

2034: **eLISA**

Ando (2016 JPS Annual Meeting)

ILC vs LISA/DECIGO

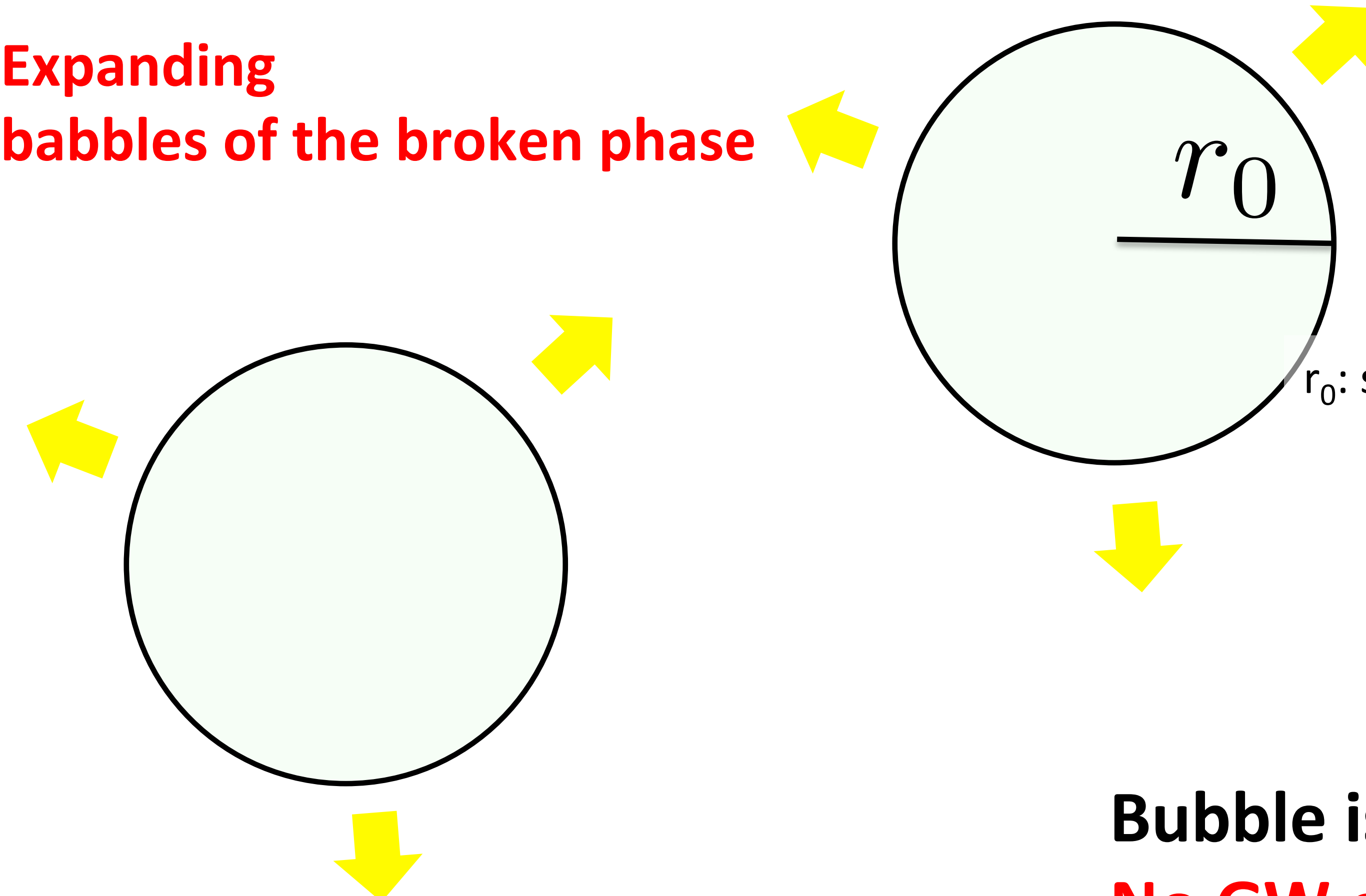
Question:

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

We here discuss how future GW experiments can distinguish models of the 1st order EW phase transition

Origin of GWs from 1st OPT

Expanding
babbles of the broken phase

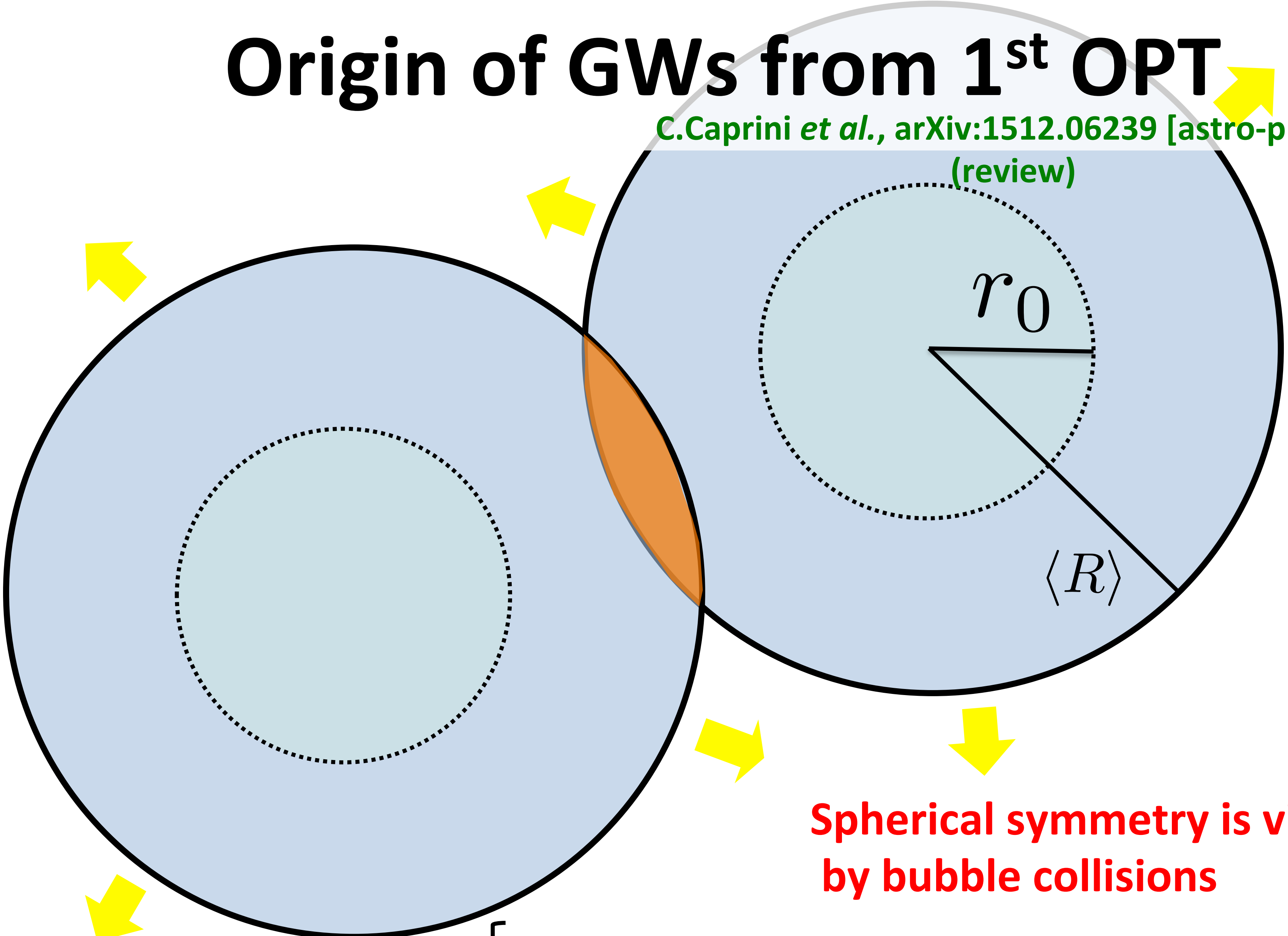


r_0: size of critical bubble

Bubble is spherical
No GW occurs

Origin of GWs from 1st OPT

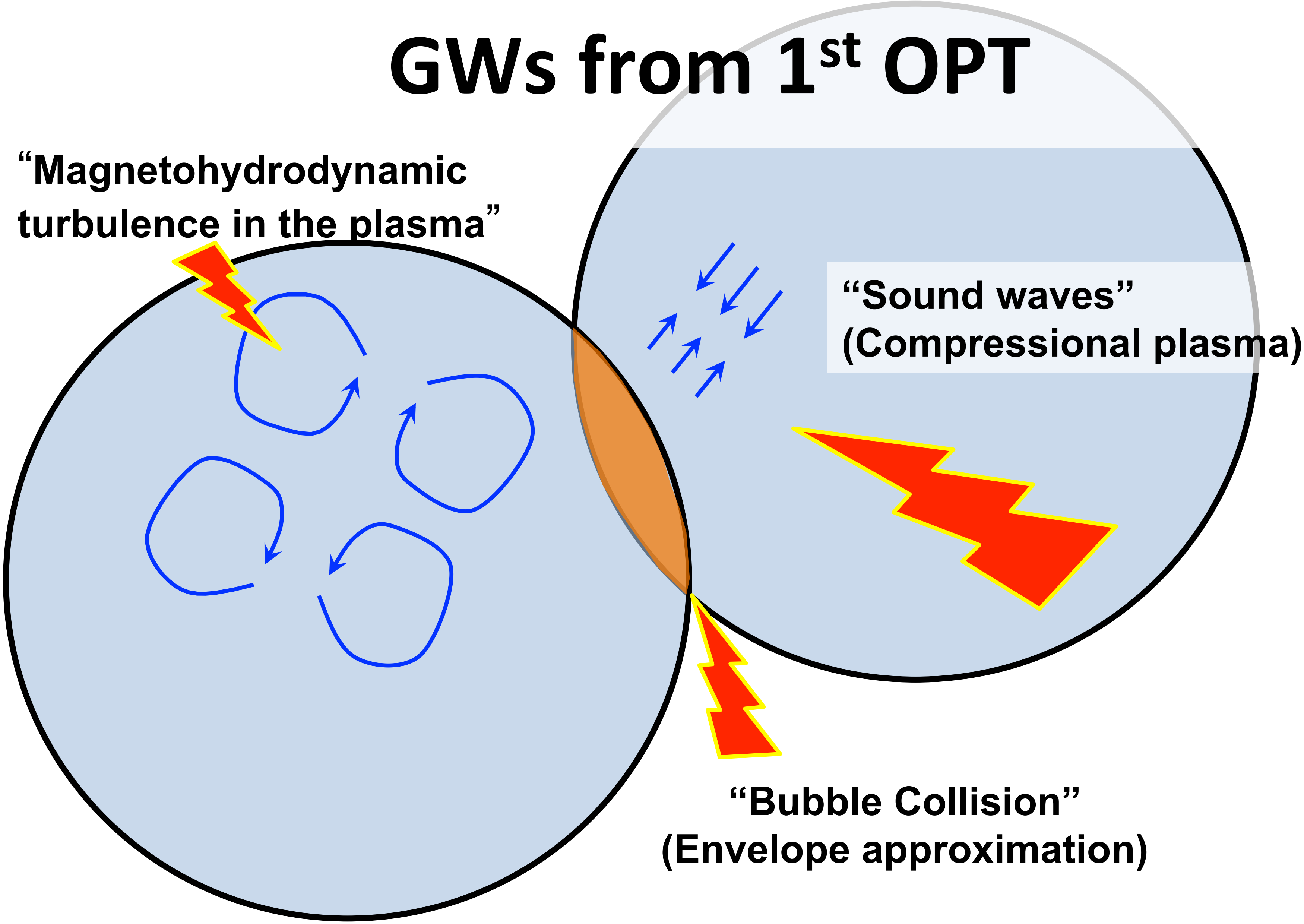
C.Caprini *et al.*, arXiv:1512.06239 [astro-ph.CO] (review)



Spherical symmetry is violated by bubble collisions

- Typical radius of colliding bubbles: $\langle R \rangle \propto v_b \tau$
- Transition time: $\tau \simeq \beta^{-1}$

GWs from 1^{st} OPT



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

Spectra of GWs from Bubble collision

C.Caprini et al., arXiv:1512.06239

1. Sound wave (Compressional Plasma)

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

2. Collision of the bubbles (envelop approximation)

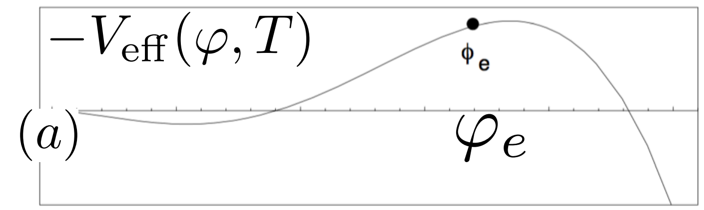
$$\widetilde{\Omega}_{\rm env}h^2 \simeq \frac{1.84\times 10^{-6}v_b^3}{(0.42+v_b^2)\tilde{\beta}^2}\left(\frac{\kappa(v_b,\alpha)\alpha}{1+\alpha}\right)^2 \qquad \tilde{f}_{\rm env}\simeq 1.0\times 10^{-5}{\rm Hz}\frac{\tilde{\beta}}{1.8-0.1v_b+v_b^2}$$

3. Magnetohydrodynamic Plasma turbulence in the bubbles

$$\widetilde{\Omega}_{\rm turb}h^2 \simeq \frac{9.35\times 10^{-8}v_b^2}{0.00354v_b\tilde{\beta}+\tilde{\beta}^2}\left(\frac{\epsilon\kappa(v_b,\alpha)\alpha}{1+\alpha}\right)^{3/2} \qquad \tilde{f}_{\rm turn}\simeq 2.7\times 10^{-5}{\rm Hz}\frac{\tilde{\beta}}{v_b}$$

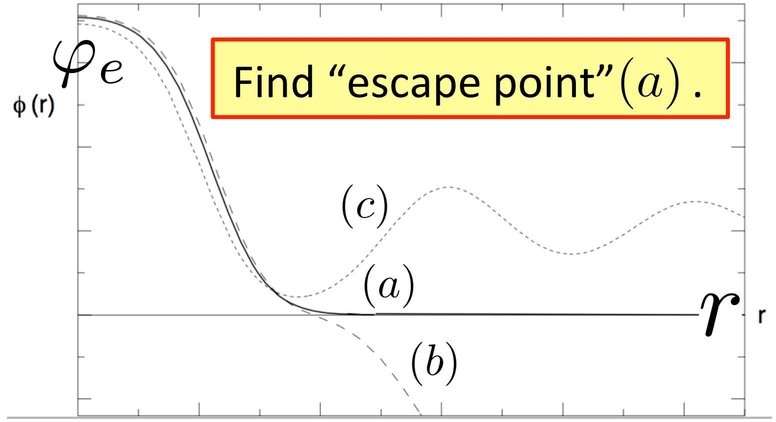
The spectrum are evaluated by inputting the lattent heat α, variation of the bubble nuclearation rate β and transition temperature T_t

$V_{\rm eff}(\varphi, T)$ → $\alpha,\ \tilde{\beta}$ @$T=T_t$



Profile of critical babbles

$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \frac{dV_{\rm eff}}{d\varphi} = 0 \quad \rightarrow \quad \varphi(r)$$



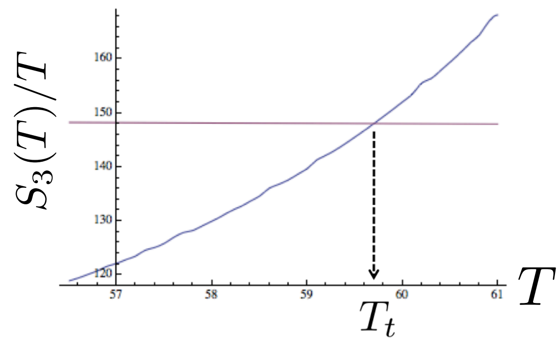
Transition Temperature

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$$

$$S_3(T) = \int dr^3 \left\{ \frac{1}{2}\left(\vec{\nabla}\varphi\right)^2 + V_{\rm eff}(\varphi, T) \right\}$$

Condition of Transition Completion

$$\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1 \quad \rightarrow \quad T_t$$



$$\alpha \equiv \left.\frac{\epsilon}{\rho_{\rm rad}}\right|_{T=T_t} \qquad \epsilon(T) \equiv -\Delta V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial \Delta V_{\rm eff}(\varphi_B(T))}{\partial T}$$

cf. $U=-F+T(dF/dT)$

$$\beta \equiv \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t} \qquad \tilde{\beta}\left(\equiv \frac{\beta}{H_t}\right) = T_t \left.\frac{d(S_3(T)/T)}{dT}\right|_{T=T_t}$$

Higgs model with O(*N*) singlet fields

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

***N*-scalar singlets** $S^{\mathrm{T}} = (S_1, \cdots, S_N)$

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

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

Higgs model with O(*N*) singlet fields

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

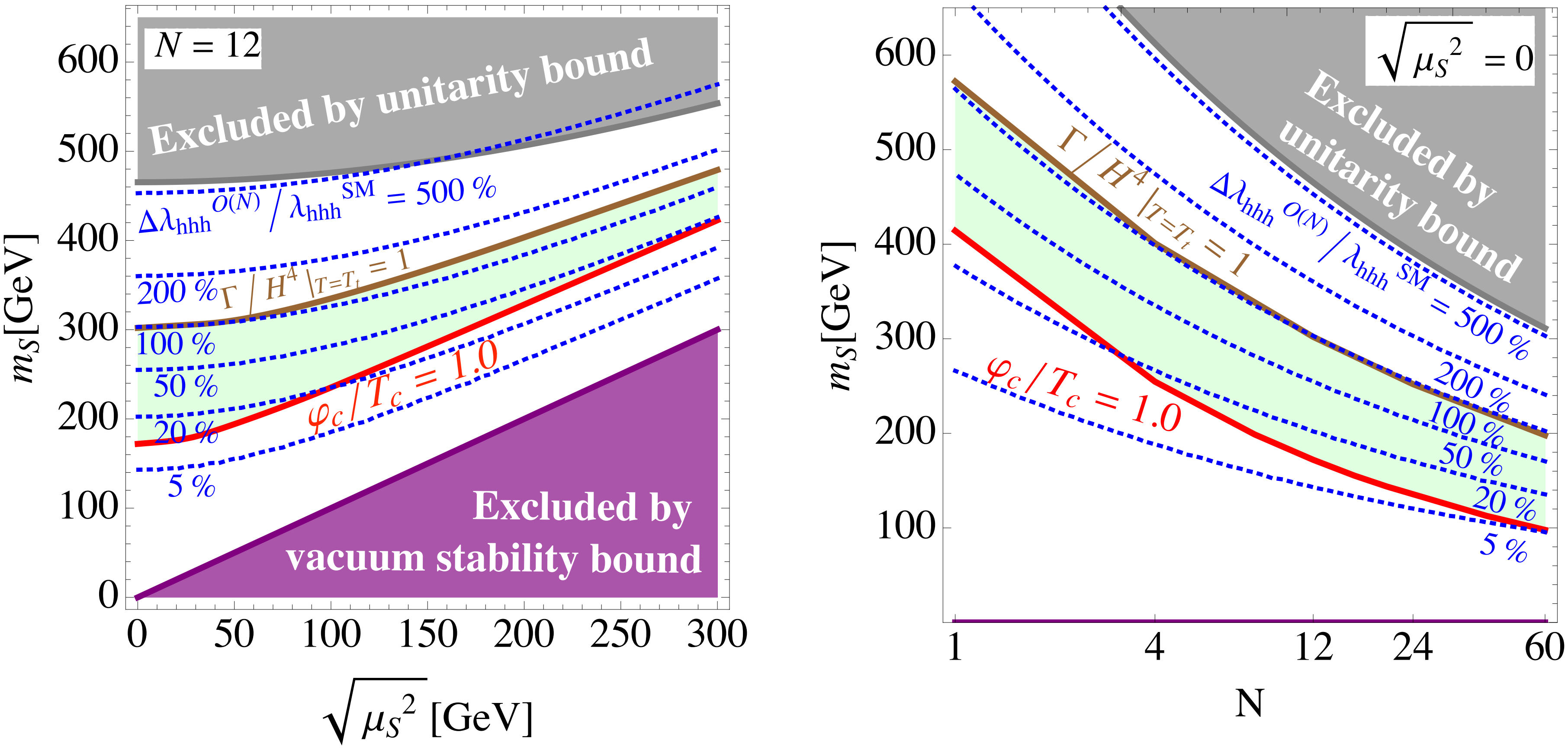
$\varphi_c/T_c > 1$ is satisfied by the nondecoupling effect of the singlet fields（compatible with m_h=125GeV）

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

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

Predictions on the *hhh* coupling

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]



O(10)% deviations in *hhh* coupling

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)

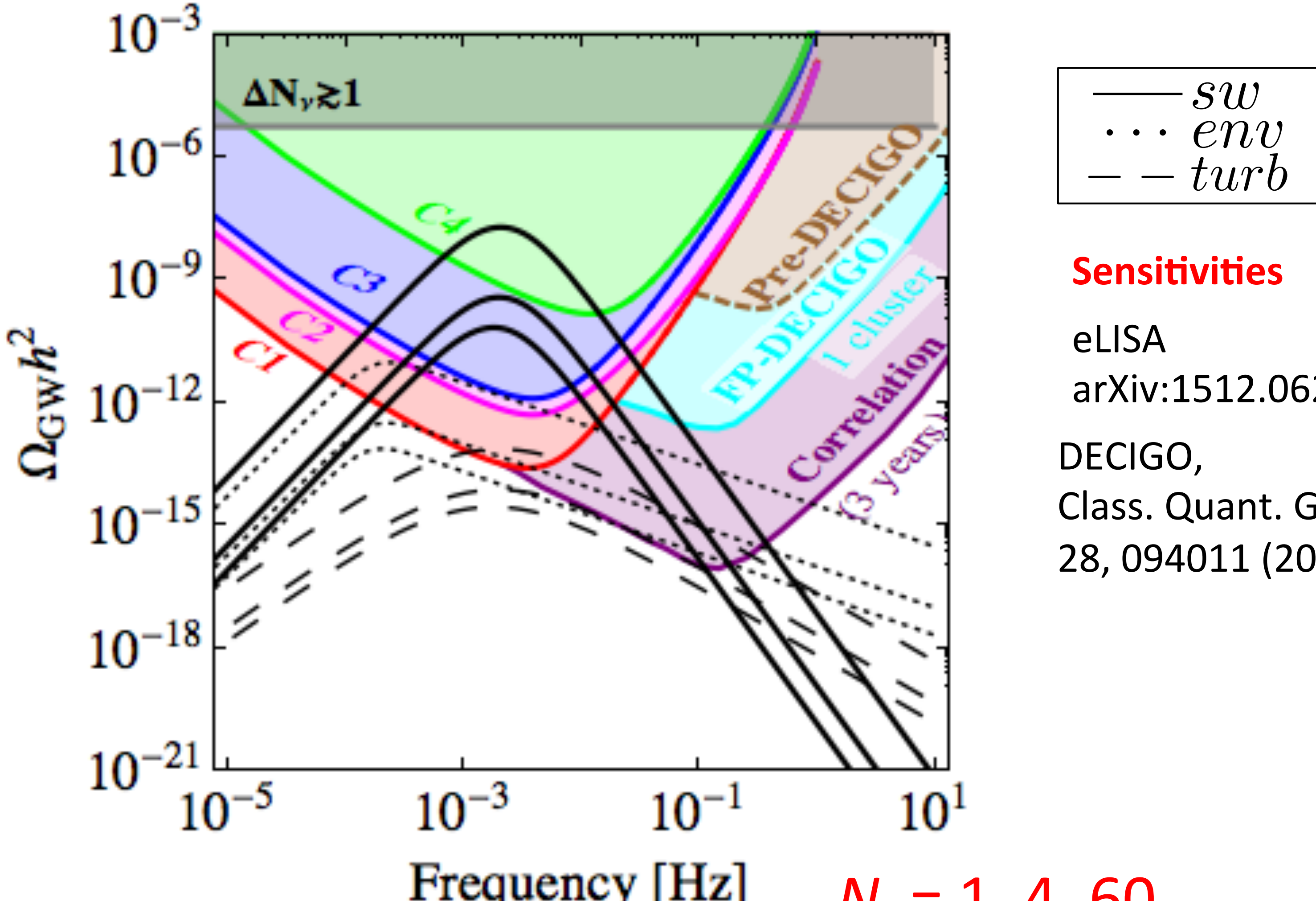
Important background

Extragalactic WD binaries (isotropic)

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

Schneider et al., 2005

GW spectrum from 1st OPT



Sensitivities

eLISA
arXiv:1512.06239

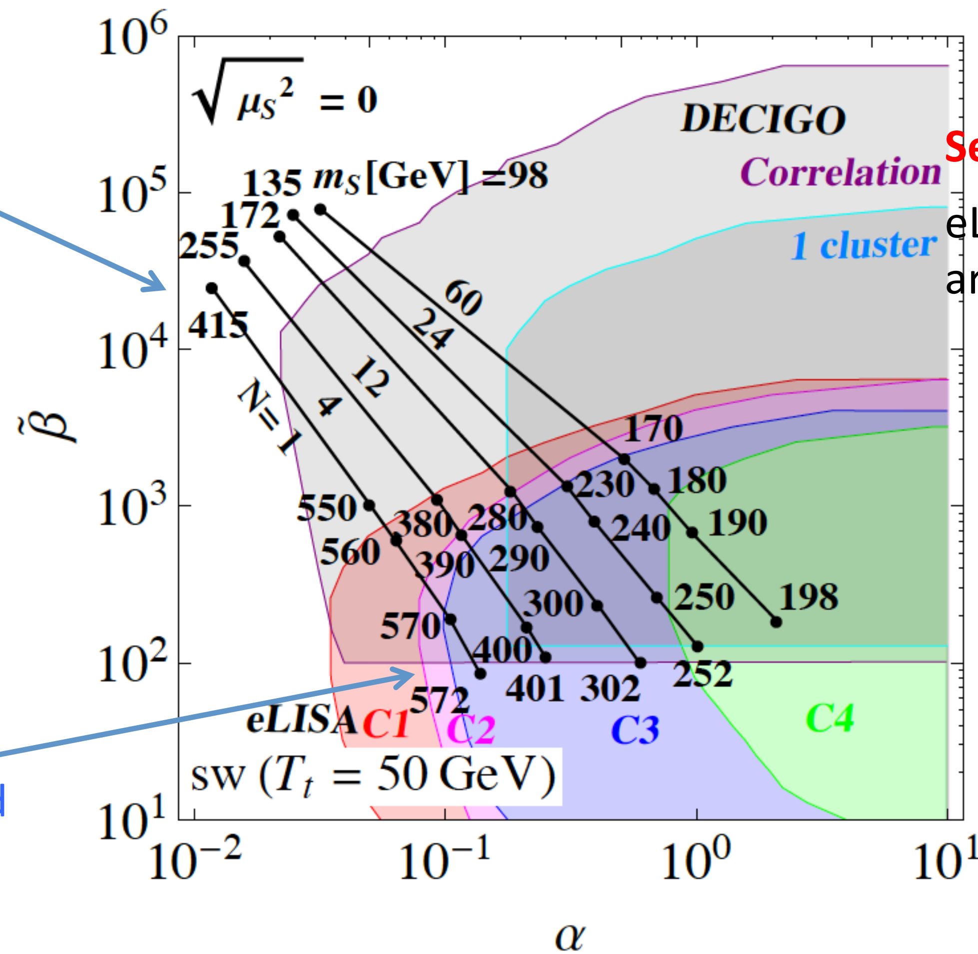
DECIGO,
Class. Quant. Grav. 28, 094011 (2011)

$N = 1, 4, 60$

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

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, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

Fingerprinting models of 1st OPT

If spectrum of GW is measured precisely by future GW interferometers (LISA, DECIGO, …), details of the model of 1st OPT may be tested

(Ex.) Peak power and frequency → (N, m_S)

A simple example of the complementarity of

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

Scale invariant *N*-scalar model

Coleman, Weinberg '73
Gildener, Weinberg '76

EWSB can occur in CSI models

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

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

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

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

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

We consider the model with *N* scalars with the common mass m_S

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

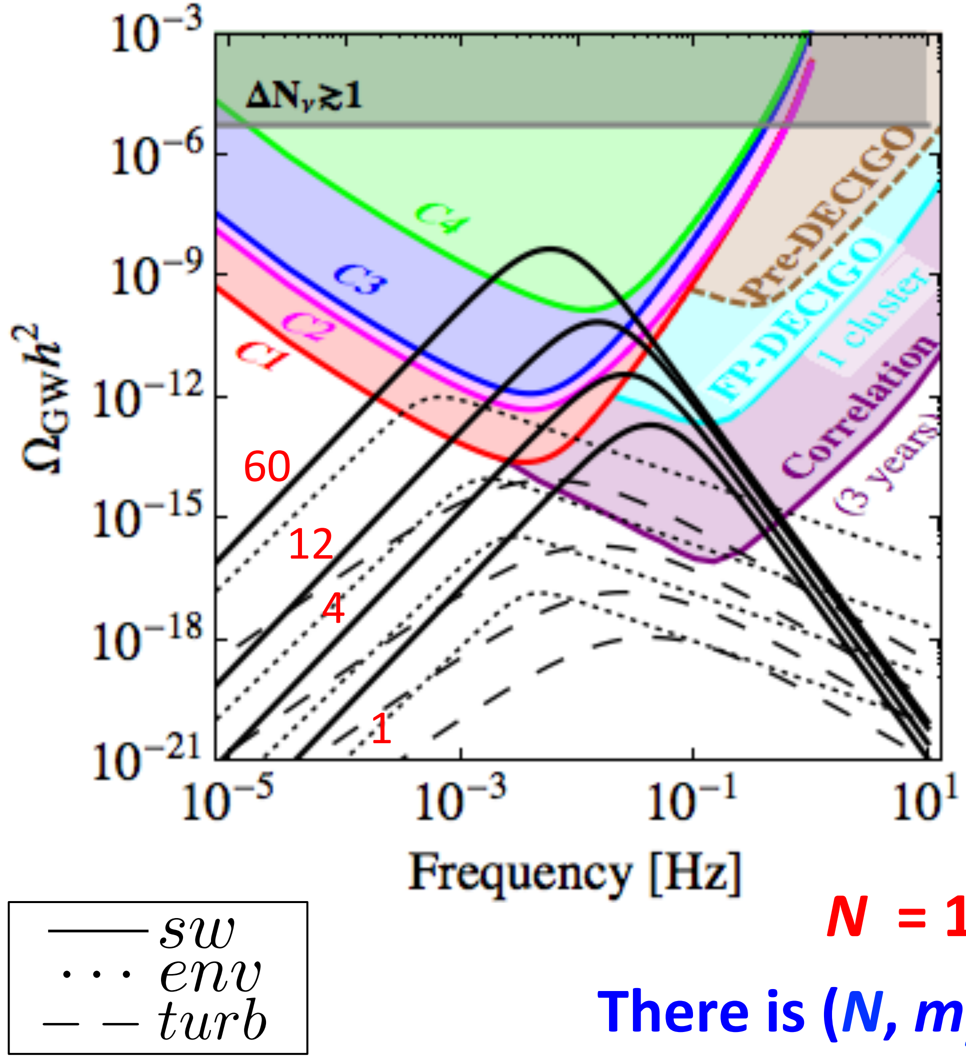
$$\Gamma_{hhh}^{\rm CCI} \equiv \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v} = \frac{5m_h^2}{v}$$

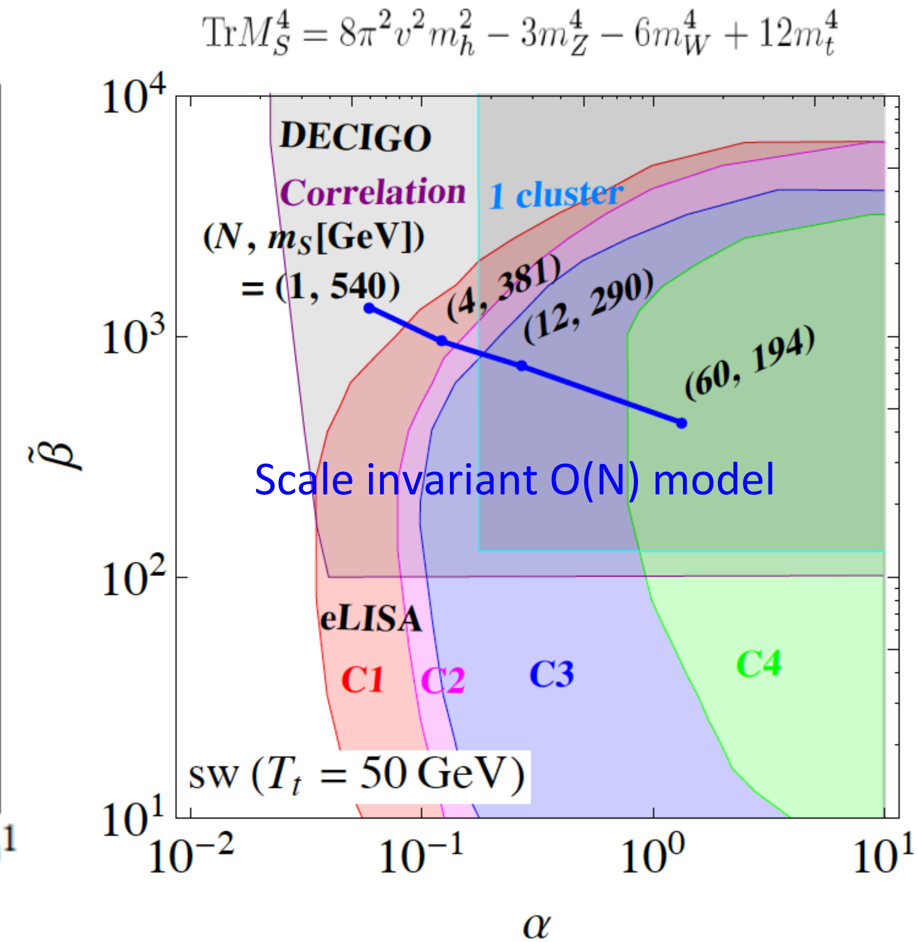
$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \sim \frac{2}{3}$$

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

In scale invariant Higgs models, the *hhh* coupling is universally predicted to be about 67% larger than the SM. (No (*N*, m_S) depencence!)

Case of scale invariant models





***N* = 1, 4, 12, 60**

There is (*N*, m_S) dependence!

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

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

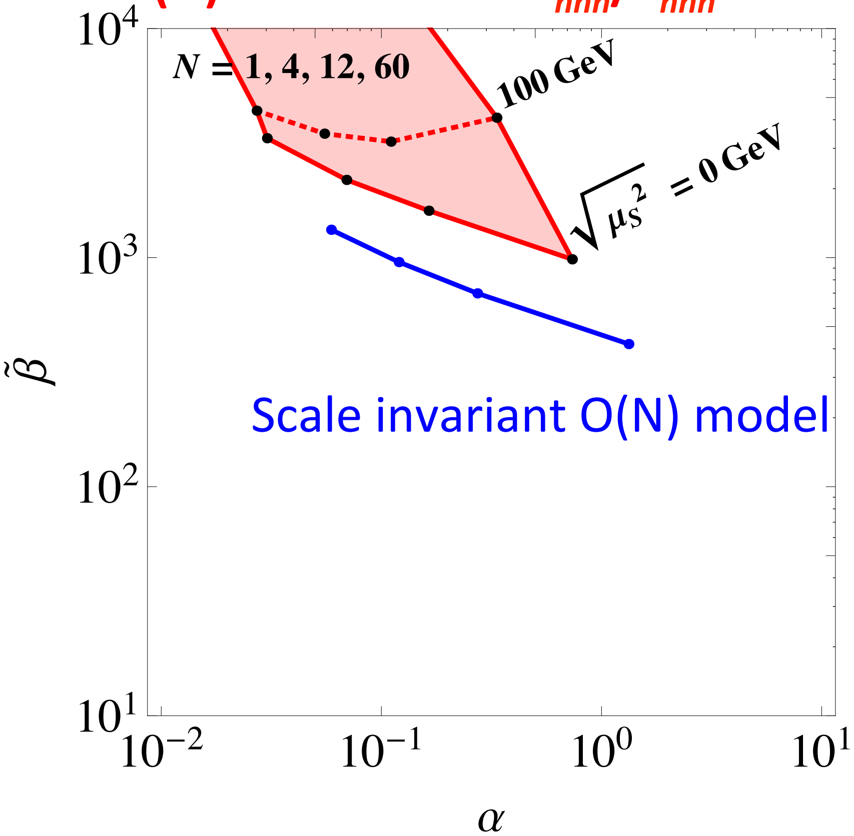
= 10 – 150 %

Scale Invariant O(N) singlet model

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

= 67 %

O(N) model with $\Delta\lambda_{hhh}/\lambda_{hhh}^{SM}$ = 67%



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= 67 %

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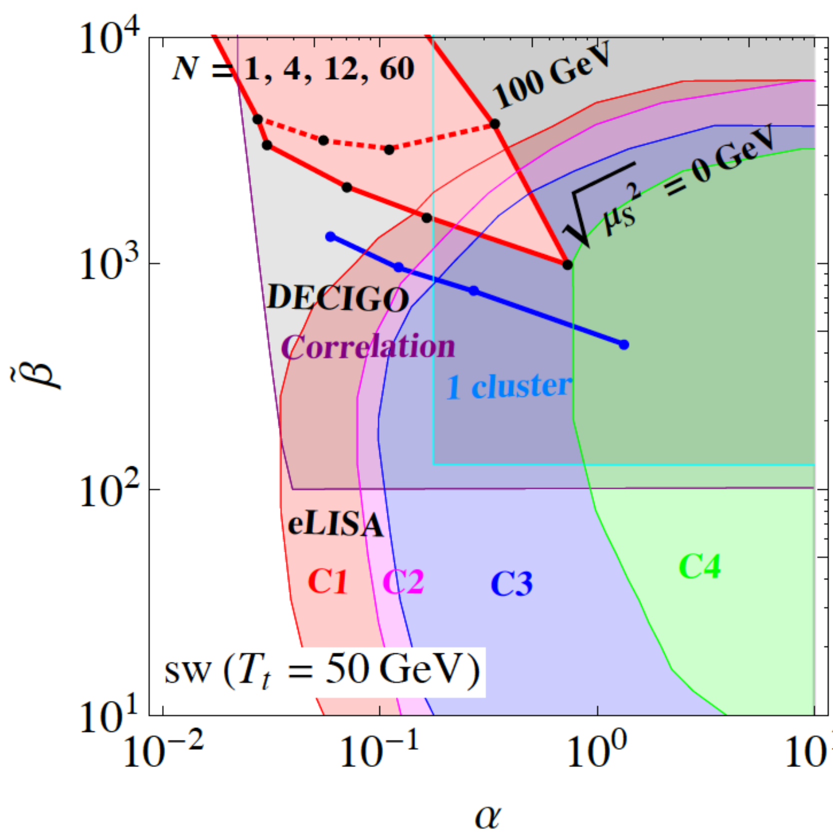

Summary

- Structure of the Higgs sector is directly connected to new physics
- Extended Higgs sectors can be tested 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 a Higgs sector and further the direction of new physics
- The *hhh* coupling is a window for Higgs potential
  Precision measurement of the *hhh* coupling can test 1^{st} OPT, which is required for successful electroweak baryogenesis

These things can only be done at lepton colliders

The precision study of the Higgs boson will be one of the next great adventures in particle physics.

The Higgs boson has many secrets that are still hidden. But it is within our power to find them out.

Michael Peskin

We need LC

Thank you very much!