

*Highlight and Vision*

*Physics*

*Shinya KANEMURA*



*ALCW2018, June 1, 2018, Fukuoka*

# *Thank all speakers for nice talks*

## Plenary:

*Higgs*

*H. Okawa*

*D. Jeans*

*G. Garillot*

*S. Kawada*

*S. Jung*

*K. Mawatari*

*T. Ogawa*

*K. Fujii*

*J. Tian*

*P.-Y. Tseng*

*M. Kakizaki*

*K. Hashino*

*K. Sakurai*

*T. Kono*

*M. Iwasaki*

*M. Peskin*

*S. Matsumoto*

*BSM*

*Y. Hosotani*

*M. Yamanaka*

*T. Suehara*

*G.-C. Cho*

*S. Shirai*

*A. Mustahid*

*T. Katayose*

*P.-Y Tseng*

*S. Heinemeier*

*K. Fujii*

*M. Borggren*

*K. Okumura*

*T. Shimomura*

*Top/QCD/Loopverein*

*M.P. Rosello*

*Y. Kurihara*

*P. Gomis*

*J. Reuter*

*P.R. Femonia*

*M. Nio*

*H. Takaura*

*Joint Higgs/Top/QCD*

*S. Pagnis*

*S. Heinemeier*

*Y. Fujitani*

*S. Heinemeier*

*Joint Higgs/BSM*

*S. Heinemeier*

*R. Nagai*

*Y. Uchida*

*K. Yagyu*

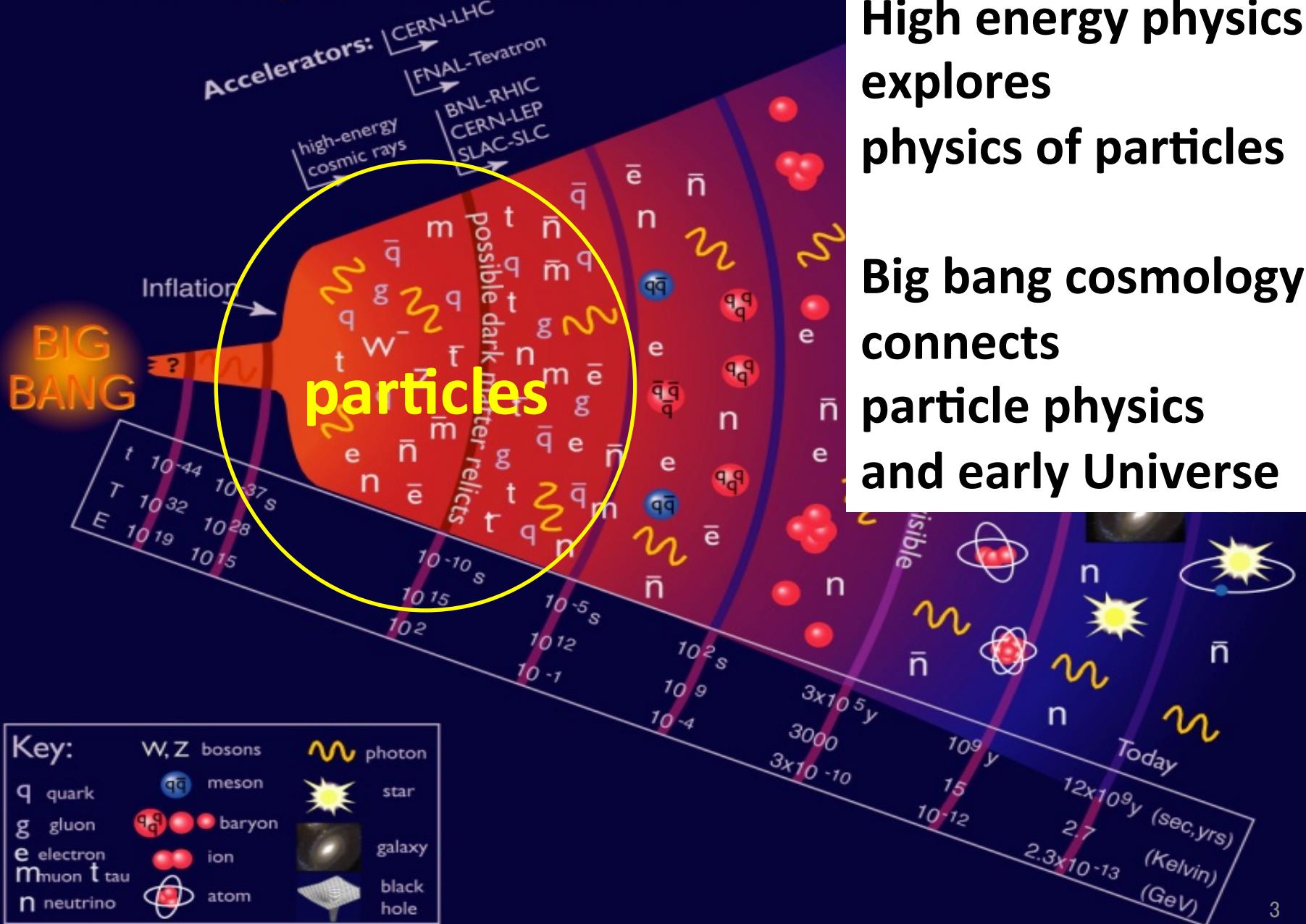
*S. Kawada*

*T. Liu*

47 talks... Too many to summarize in 30 minutes...

→ the usual apologies

# History of the Universe



High energy physics explores physics of particles

Big bang cosmology connects particle physics and early Universe

# Standard Model

Gauge principle: Interaction

Gauge symmetry

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

Color	Isospin	Hypercharge
$g_\mu^\alpha$	$W_\mu^a$	$B_\mu$
Gluon		

Spontaneous Symmetry Breaking: Mass

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

Quarks and leptons  
3-generations

Massive

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

Massless

Massive

$$A_\mu$$

Photon

$$W_\mu^\pm \quad Z_\mu^0$$

Weak bosons

# Standard Model

Gauge principle: Interaction

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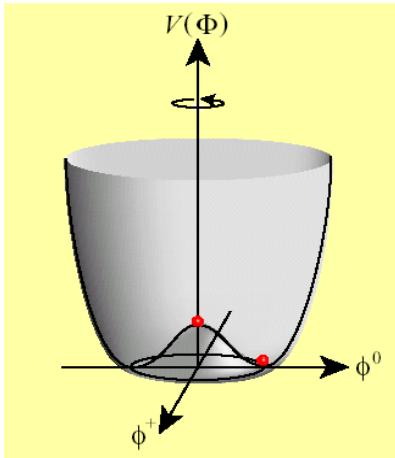
$A_\mu$
---------

Photon

Massive

$W_\mu^\pm$	$Z_\mu^0$
-------------	-----------

Weak bosons



Tentatively introducing a scalar doublet (Higgs field)

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

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

$\mu^2 < 0$

$\downarrow \text{VEV } 246\text{GeV}$

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

↑

Higgs boson

# Higgs discovery at LHC

ATLAS/CMS  
July 2012

Discovery of a scalar particle

Mass 125 GeV, ...

Spin, Parity  $0^+$

Coupling with many particles

$h\gamma\gamma$ ,  $hgg$ ,  $hZZ$ ,  $hWW$ ,  $h\tau\tau$ ,  $htt$ ,  $hbb$ , ...

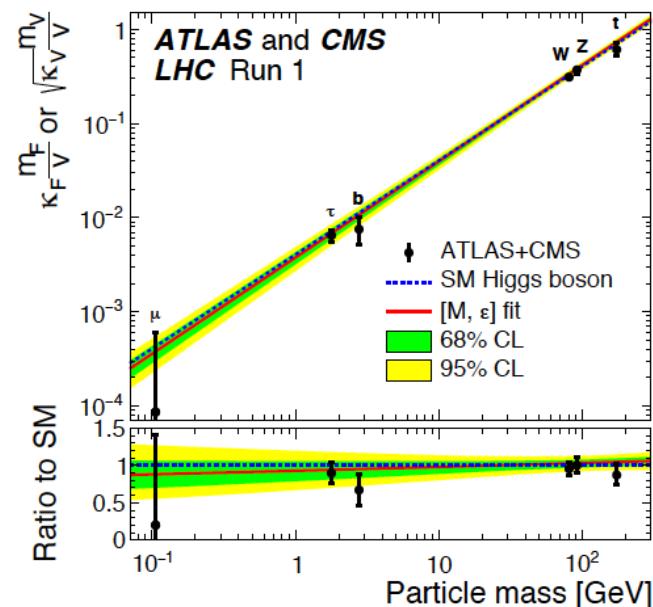
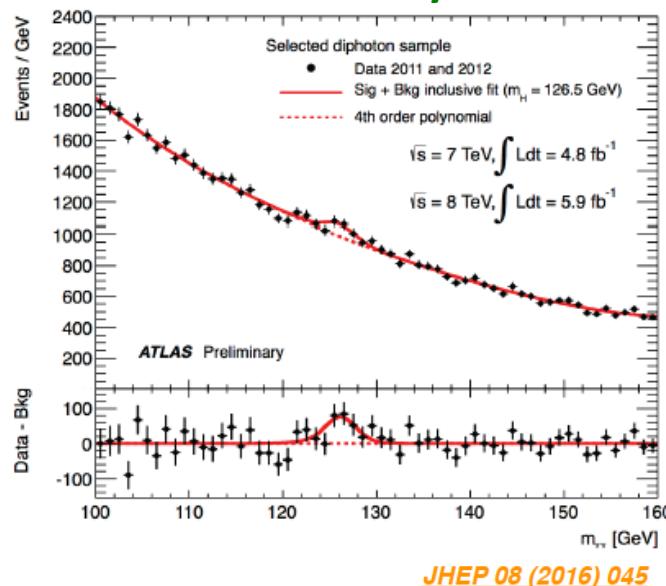
Identified as a Higgs boson

Measured couplings turned out to be consistent with the SM Higgs

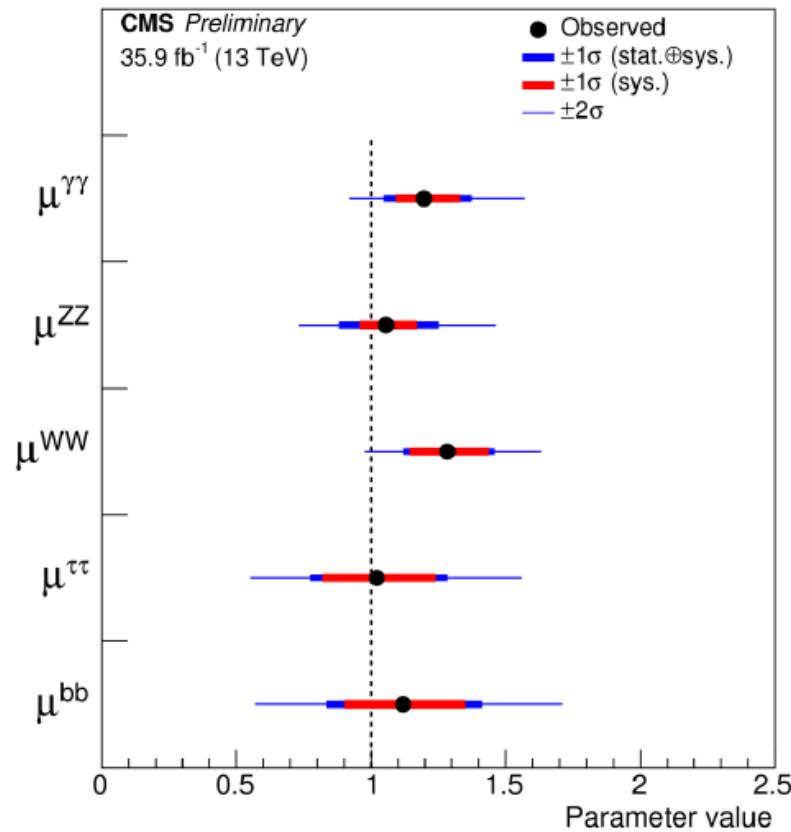
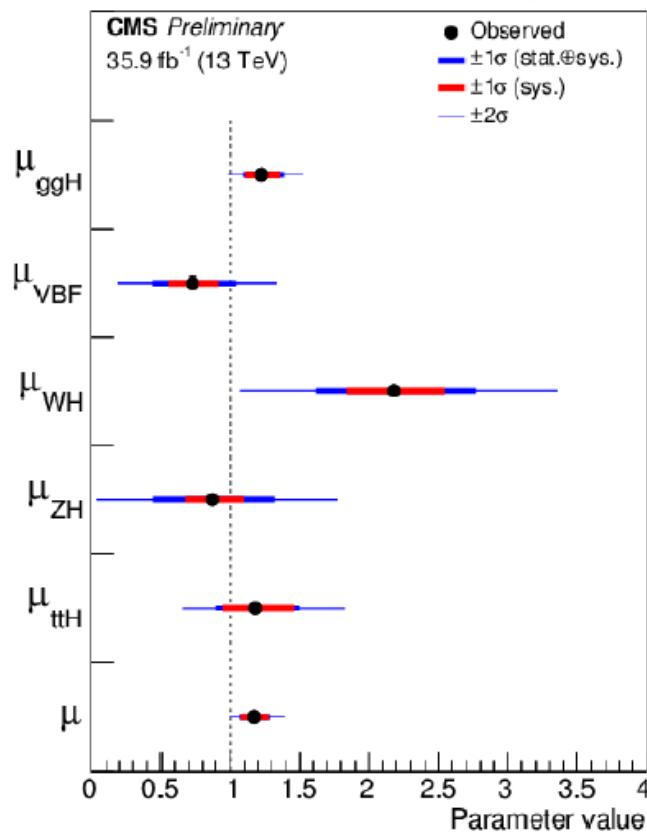
The “tentative” SM Higgs sector works well!

No BSM particle has been found

Standard Model is enough?



# Signal strengths at production and decay



- Limited by systematics in several channels
- Similar results are also available from ATLAS (ATLAS-CONF-2017-047)

[CMS-PAS-HIG-17-031](#)

The Standard Model is extremely successful in explaining the measured properties of elementary particles. But, it is manifestly incomplete.

The Standard Model:

- cannot explain electroweak symmetry breaking
- cannot explain the spectrum of quark and lepton masses
- cannot explain matter/antimatter asymmetry
- cannot explain the existence of dark matter

Many theories are proposed. How can we have a clue as to which is right ?

# Beyond the Standard Model

There are many reasons to consider New Physics beyond SM

## Unification of Law

- Paradigm of Grand Unification
- Yukawa structure (flavor physics)

## Problem in the SM Higgs

- Hierarchy Problem, Shape of Higgs sector, Nature, ...

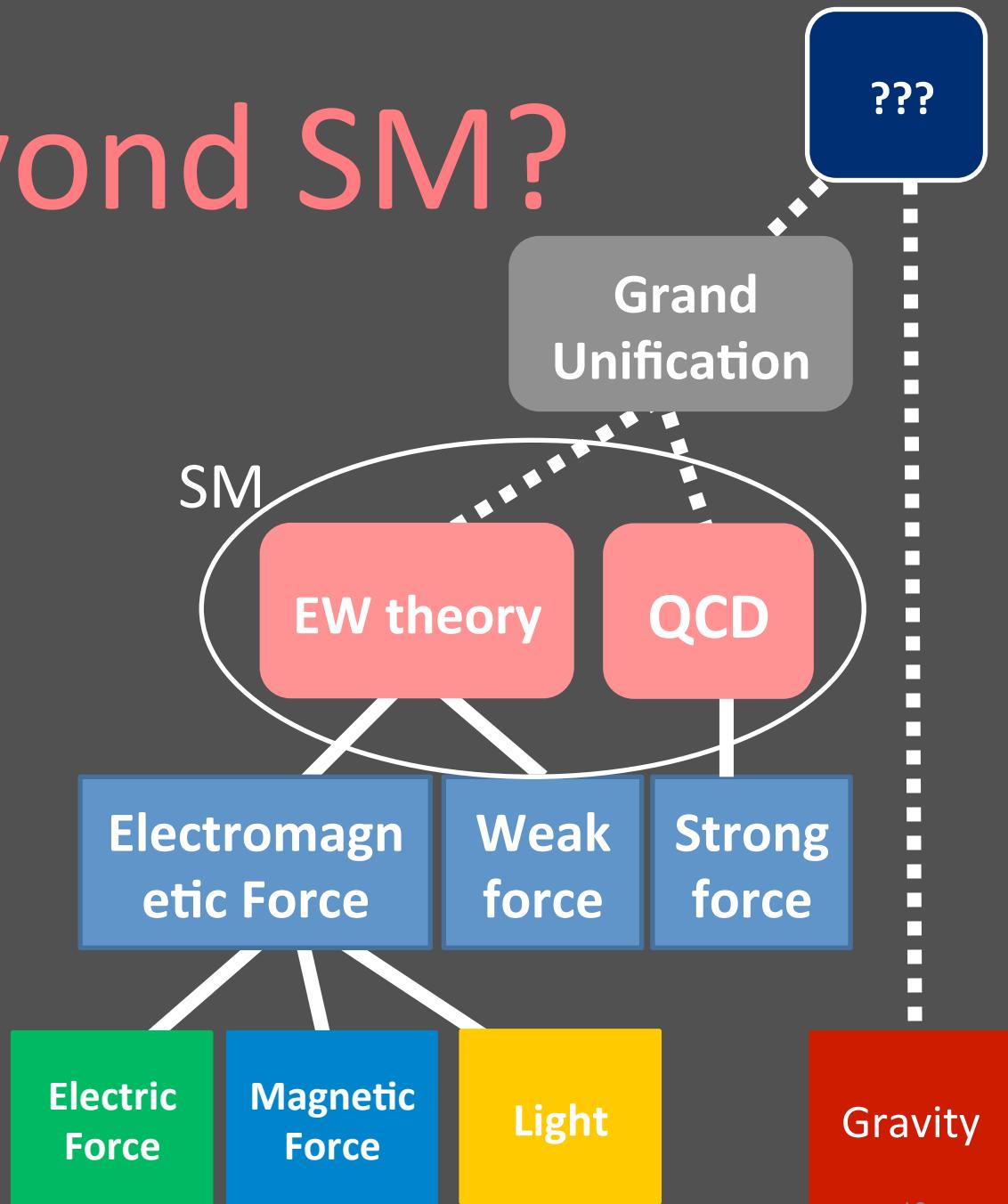
## BSM Phenomena

- Dark Matter
- Neutrino mass and mixing
- Baryon Asymmetry of Universe
- Inflation, Dark Energy, Gravity,...

New Physics must exist!

# Beyond SM?

- History tells us... unification laws in the nature
- Unification is Goal
- We are still on the way



Thus **everyone** knows that SM must be replaced by a BSM model

**No one** knows where and how SM is broken...

1 TeV? 10TeV? 100TeV? or  $10^{16}$ GeV??

However, there is one method that is available to us but we have not yet begun to exploit:

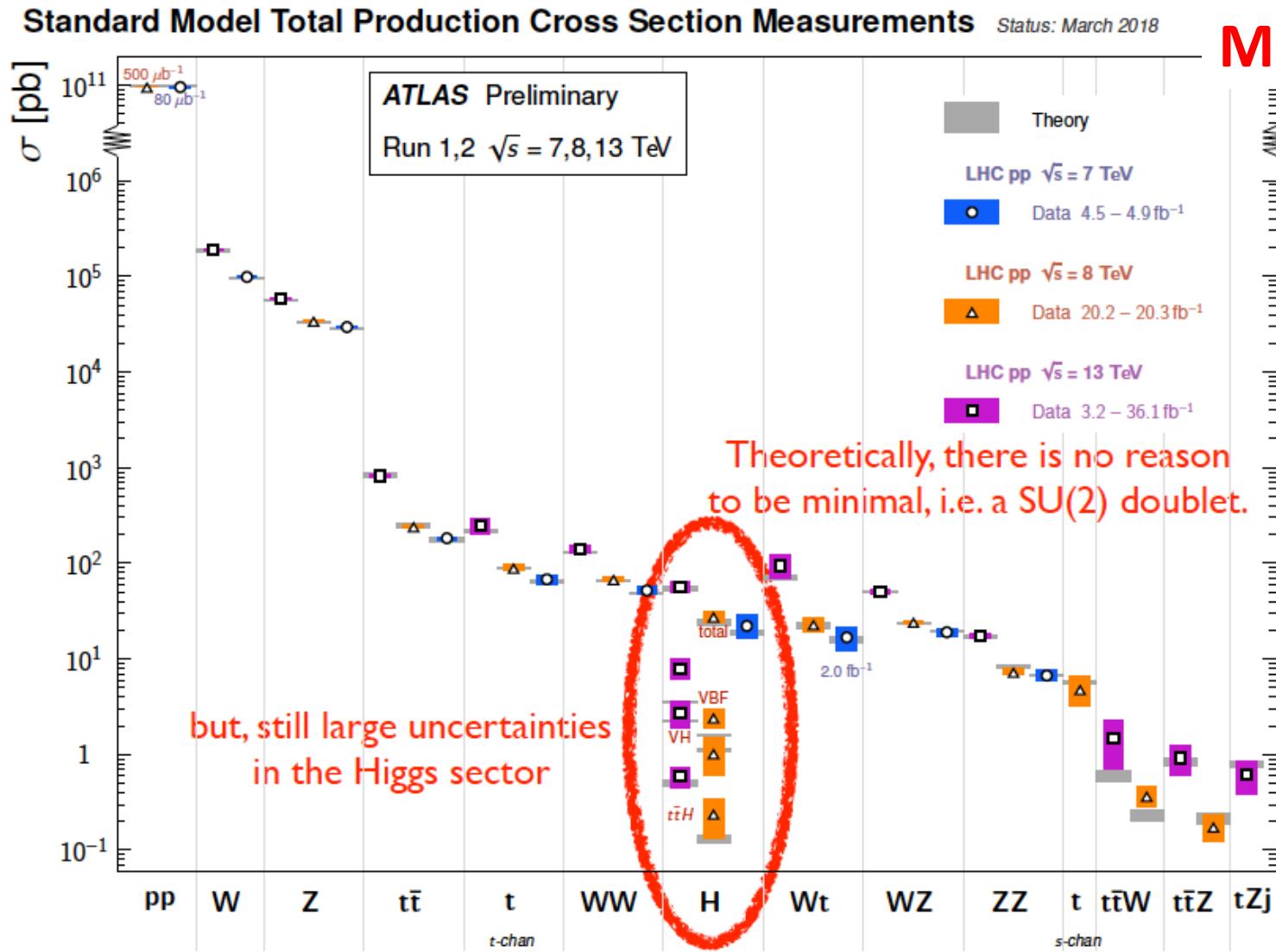
This is the study of the couplings of the Higgs boson.

# Higgs is a key to new physics

- Higgs sector is the weakest part (**No principle**)
  - Hierarchy problem, nature of a Higgs boson
  - Its structure (multiplet structure, interaction, symmetry, phase transition) remains unknown
  - It strongly depends on and relates to new phenomena
- It can be thoroughly tested by current and future experiments (find a new fundamental principle for Higgs)

We can access to the new physics via the Higgs physics!

# SM is consistent with the LHC data



Mawatari

There is still a room for non-standard Higgs sectors

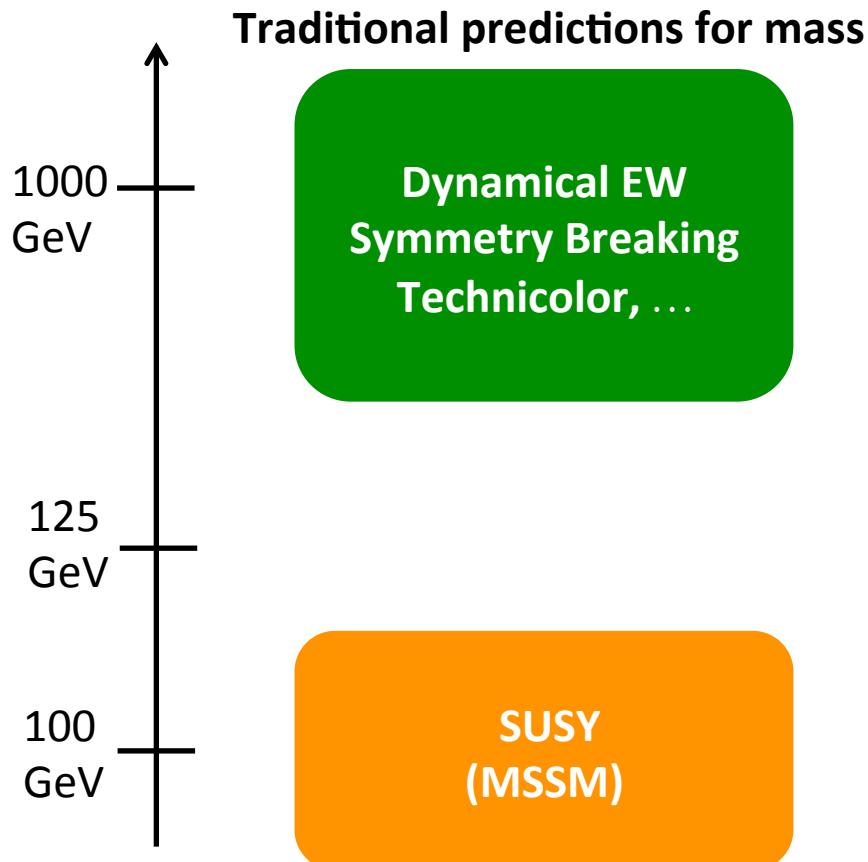
# Nature of Higgs

# Higgs Nature $\Leftrightarrow$ BSM Paradigm

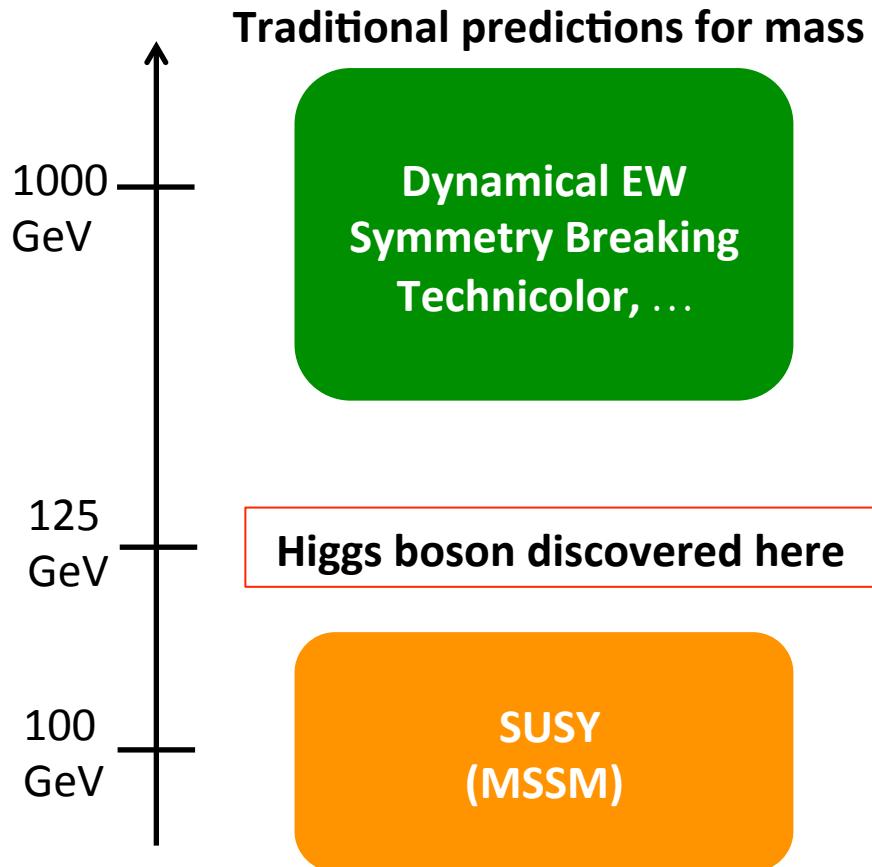
- Elementary Scalar SUSY, Scale Invariance
  - Composite of fermions Dynamical Symmetry Breaking
  - A vector field in extra D Gauge Higgs Unification
  - Pseudo NG Boson Minimal Composite Models
  - .....

## Each new paradigm predicts a specific Higgs sector

# How we can explain 125GeV?

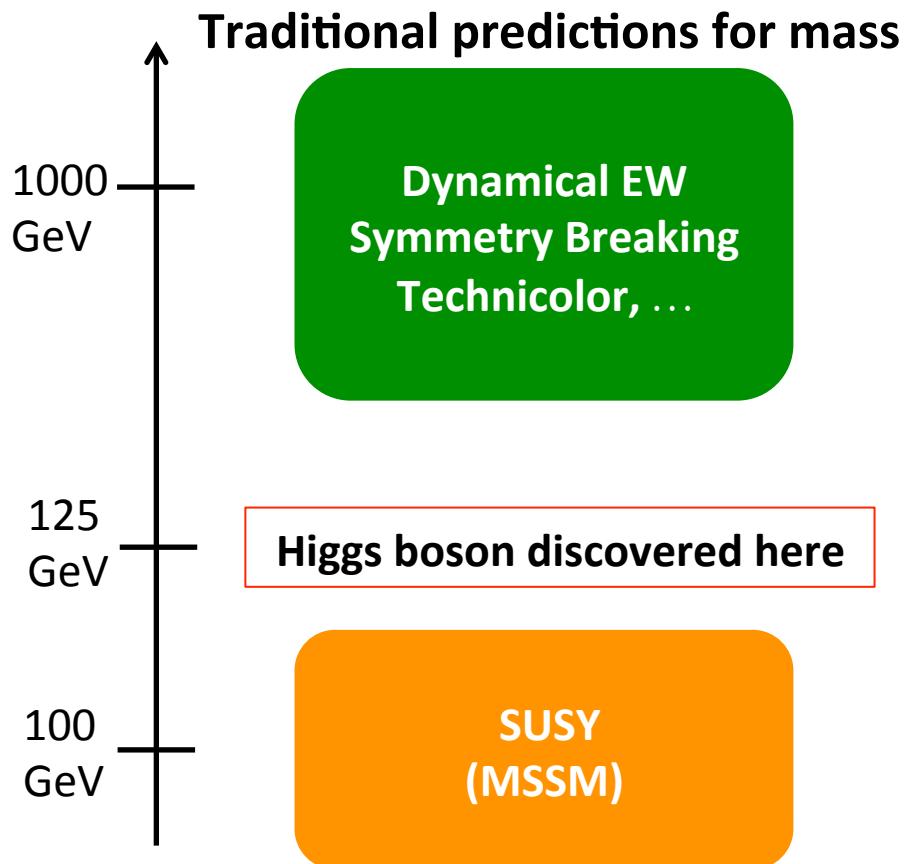


# How we can explain 125GeV?

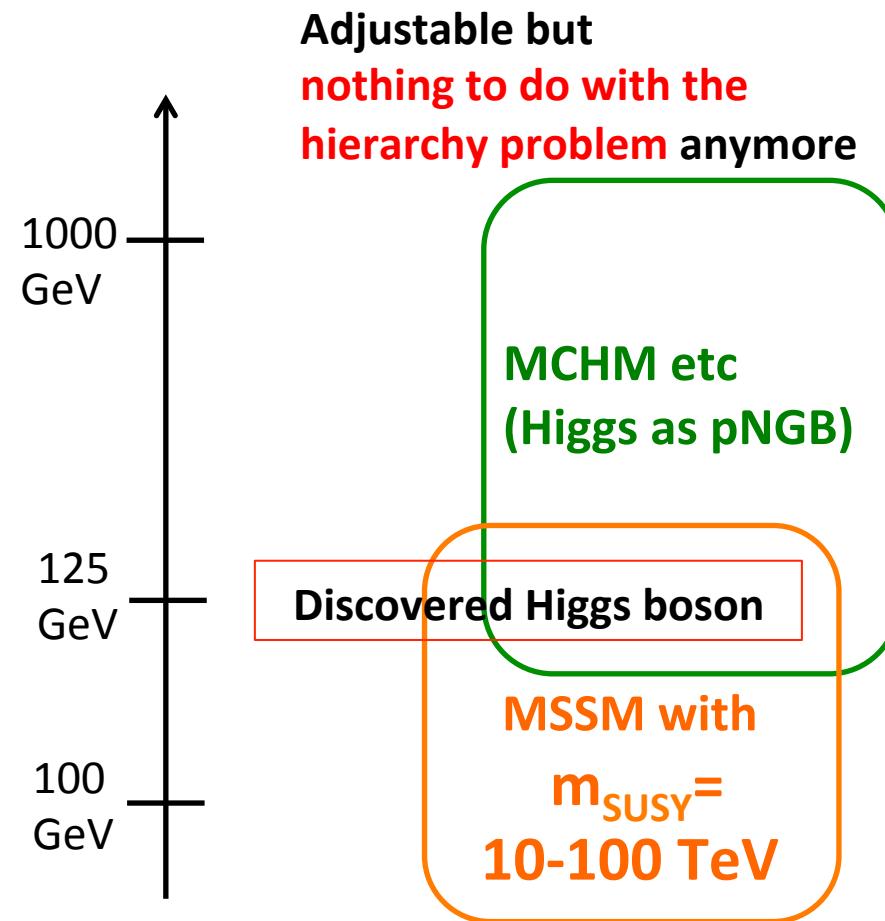


Both cannot explain 125 GeV  
in a natural way

# How we can explain 125GeV?



Both cannot explain 125 GeV  
in a natural way



Anything must be wrong ??  
Natural?

# Extended Higgs sectors

## Multiplet Structure (with additional scalars)

$\Phi_{\text{SM}}$ +Isospin **Singlet**,

$\Phi_{\text{SM}}$ +**Doublet** (2HDM),

$\Phi_{\text{SM}}$ +**Triplet**, ...

## Additional Symmetry

Discrete or Continuous?

Exact or Softly broken?

## Interaction

Weakly coupled or Strongly Coupled?

Hint for  
BSM  
models

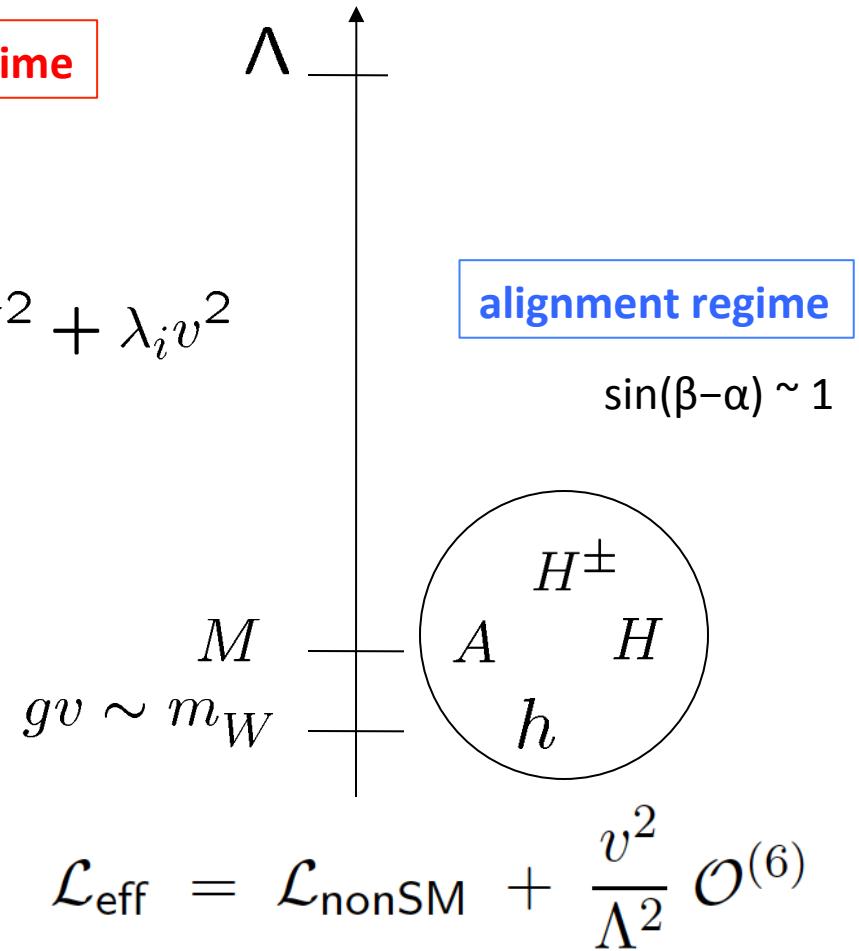
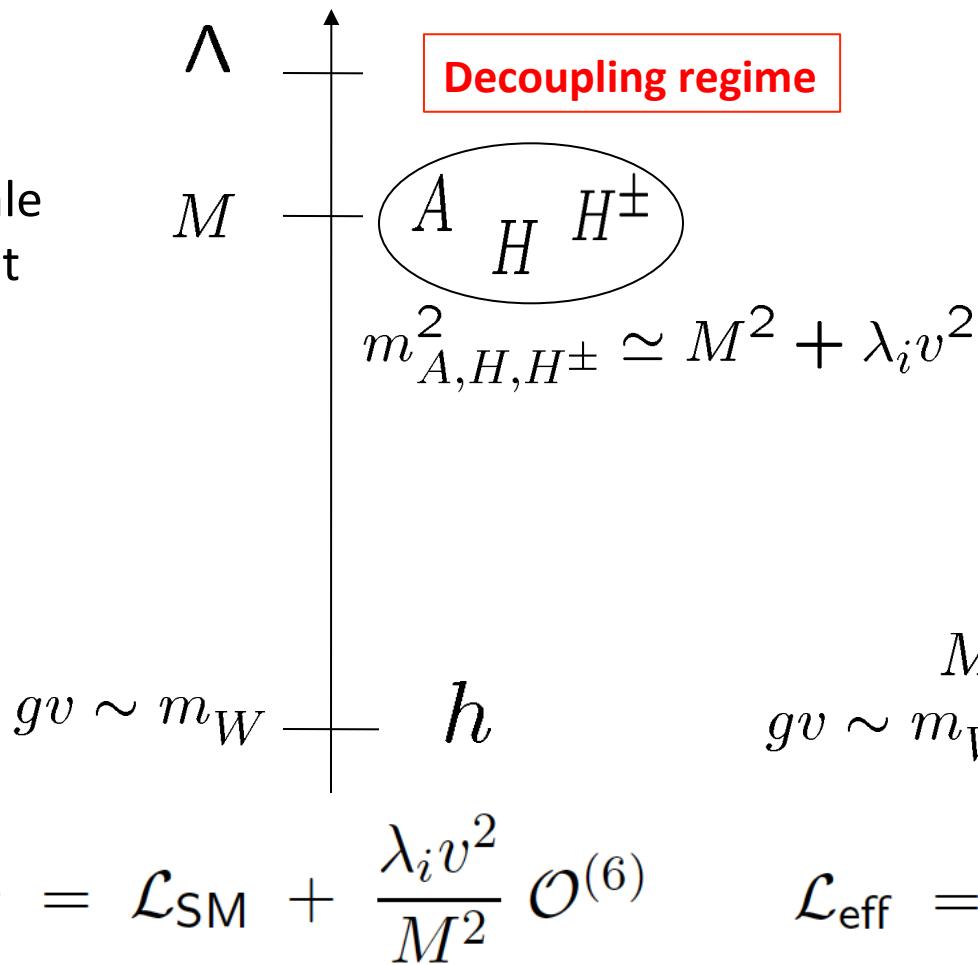
# Non-SM Higgs sectors

- Unitarity, Oblique Corrections Nagai, Uchida
- Extended Higgs models (2HDM, Singlet) Sakurai  
Hashino
- MSSM, NMSSM Heinemeyer, K. Fujii,  
Okumura Kakizaki  
Mawatari
- Composite 2Higgs doublet model Yagyu
- Classically conformal invariant model Fujitani  
Kakizaki
- Flavor symmetry ( $U(1)_{L\mu-L\tau}$ ) Shimomura

# Decoupling or Alignment

$\Lambda$ : Cutoff

$M$ : Mass scale  
irrelevant  
to VEV



Low energy theory is the SM

Low energy theory is an extended Higgs sector

# Effective Field Theory

Tian, Peskin, Jung, Tseng, Liu, Ogawa

Data show NP effects nearly decouple so the deviations are small.

$$\Delta \mathcal{L} = \frac{c_H}{2v^2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) + \frac{c_T}{2v^2} (\Phi^\dagger \not{D}^\mu \Phi) (\Phi^\dagger \not{D}_\mu \Phi)$$

Higgs Z factor

$$- \frac{c_6 \lambda}{v^2} (\Phi^\dagger \Phi)^3$$

triple Higgs

$$+ \frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W_{\mu\nu}^a W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W_{\mu\nu}^a B^{\mu\nu}$$

h + W,Z,γ

$$+ \frac{g'^2 c_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2} \epsilon_{abc} W_{\mu\nu}^a W^{b\nu}{}_\rho W^{c\rho\mu}$$

Precision EW

$$+ i \frac{c_{HL}}{v^2} (\Phi^\dagger \not{D}^\mu \Phi) (\bar{L} \gamma_\mu L) + 4i \frac{c'_{HL}}{v^2} (\Phi^\dagger t^a \not{D}^\mu \Phi) (\bar{L} \gamma_\mu t^a L)$$

$$+ i \frac{c_{HE}}{v^2} (\Phi^\dagger \not{D}^\mu \Phi) (\bar{e} \gamma_\mu e)$$

h + q, l, g

$$- \sum_i \left\{ c_{\ell i \Phi} \frac{y_\tau \ell i}{v^2} (\Phi^\dagger \Phi) \bar{L}_i \cdot \Phi \ell_{iR} + c_{q i \Phi} \frac{y_\tau q i}{v^2} (\Phi^\dagger \Phi) \bar{Q}_i \cdot \Phi q_{iR} \right\}$$

$$+ \mathcal{A} \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

# Era of Precision Measurement again

Direct search reach 1-2TeV → 3 TeV (HL-LHC)  
at most a factor improvement

Indirect test 10-20% → 1% (Higgs factory)  
at least several 10s times better

Higgs factory: lepton collider  
ILC, CEPC, FCCee, CLIC

Coming months will be very important for ILC250

# ILC250

A  $e^+e^-$  linear collider with  $E = 250\text{GeV}$

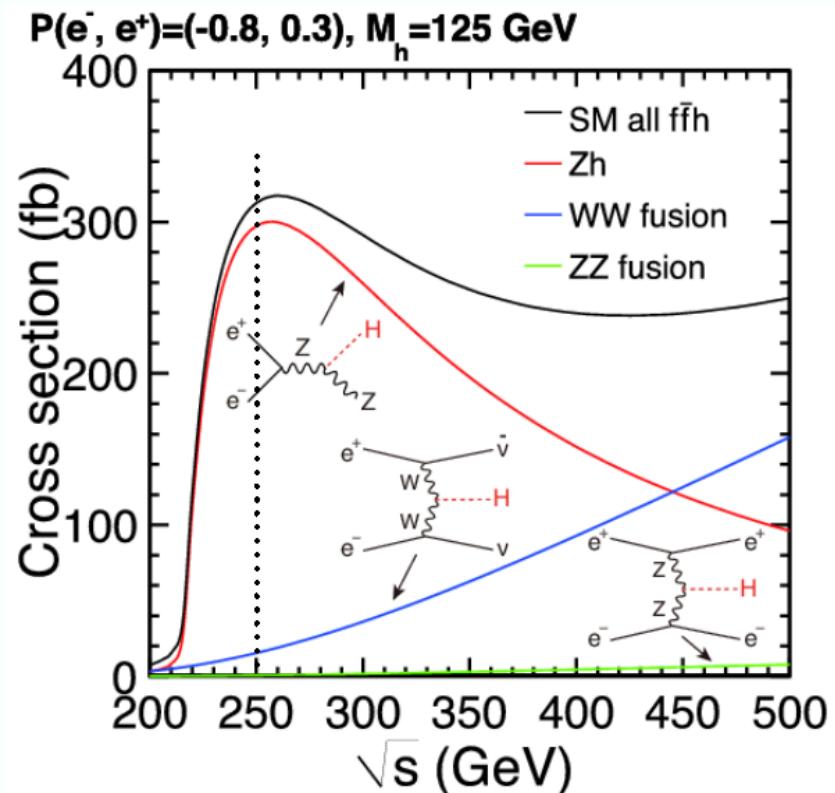
Integrated luminosity =  $2ab^{-1}$

Beam polarization ( $e^- 80\%$ ,  $e^+ 30\%$ )

Possibility of future  $E$  extensions

As compared to ILC500,  
the similar performance attained  
for the Higgs coupling determination  
by using synergy with LHC

The best energy for  
Higgs strahlung



Senergy is Key

## Slide by Peskin

The EFT approach leads to a more model-independent method than that used in previous analyses, and much more powerful use of the available data.

Here is an example:

In the general EFT treatment, the coupling of the Higgs boson to WW and ZZ is governed by two independent coupling constants.

$$\Delta L_{hWW} = 2(1 + \eta_W)m_h^2 \frac{h}{v} W_\mu^+ W^{-\mu} + \zeta_W \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu}$$

$$\Delta L_{hZZ} = (1 + \eta_Z)m_h^2 \frac{h}{v} Z_\mu Z^\mu + \frac{1}{2} \zeta_Z \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

This has been ignored in previous analyses.

# Slide by Junping Tian

recap 2: hWW is determined as precisely as hZZ @  $\sqrt{s} = 250$  GeV

- hWW/hZZ ratio can be determined to <0.1%: feature of a general  $SU(2) \times U(1)$  gauge theory

$$\Gamma(h \rightarrow ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) ,$$

$$\Gamma(h \rightarrow WW^*) = (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W)$$

$$\eta_W = -\frac{1}{2}c_H$$

SM-like hVV

custodial symmetry

$$\eta_Z = -\frac{1}{2}c_H - c_T .$$

$$c_i \sim O(10^{-4}-10^{-3})$$

$$\zeta_W = (8c_{WW})$$

anomalous hVV

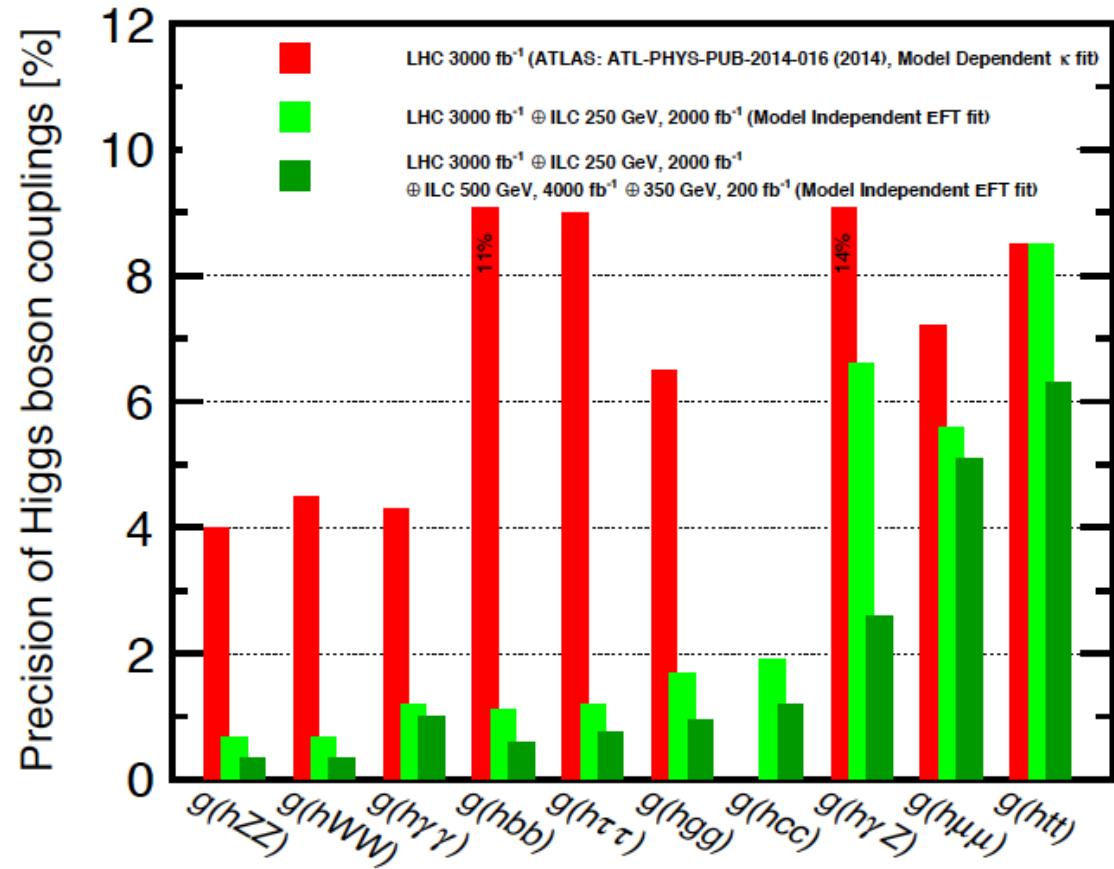
$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

# ILC250

Full use of  
beam polarization  
 $E^-$  80%,  $E^+$  30%

Synergy with LHC, EWPO  
custodial symmetry  
 $H\gamma\gamma$ ,  $H\gamma Z$ ,  $VWW$

Couplings precision of  
 $hWW$ ,  $hZZ$   $\sim 0.7 \%$   
 $hff$ ,  $hgg$   $\sim 1-2 \%$   
will be attained



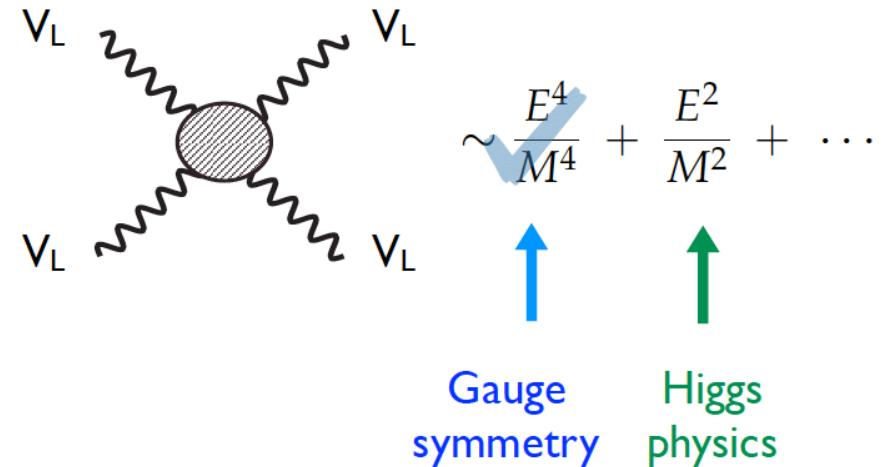
1710.07621

	ILC250		+ILC500	
	$\kappa$ fit	EFT fit	$\kappa$ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
$\Gamma_h$	3.9	2.5	1.7	1.6
$BR(h \rightarrow inv)$	0.32	0.32	0.29	0.29
$BR(h \rightarrow other)$	1.6	1.6	1.3	1.2

The longitudinal polarization vector grows as energy

# Perturbative Unitarity in extended scalar sectors

$\kappa_V \neq 1$  gives information  
of new physics



Talk by Nagai

$$\kappa_V^2 = \frac{\Gamma(V' \rightarrow Vh)}{\Gamma(V' \rightarrow VV)}$$

Deviation

BSM information

Talk by Uchida

tree level unitary  $\Rightarrow$  S,U parameter 1-loop finiteness  
In arbitral Higgs sector

# Deviation = New Physics Scale

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

Coupling of  $h(125)$  and weak bosons

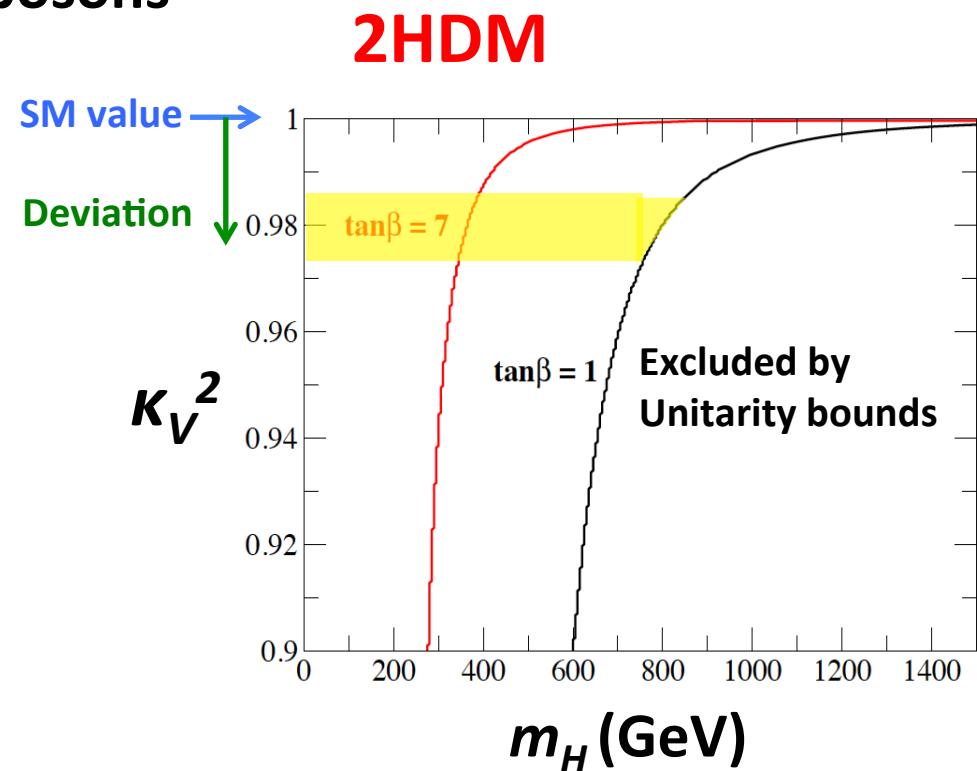
$V (=W, Z)$   $hVV$

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

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



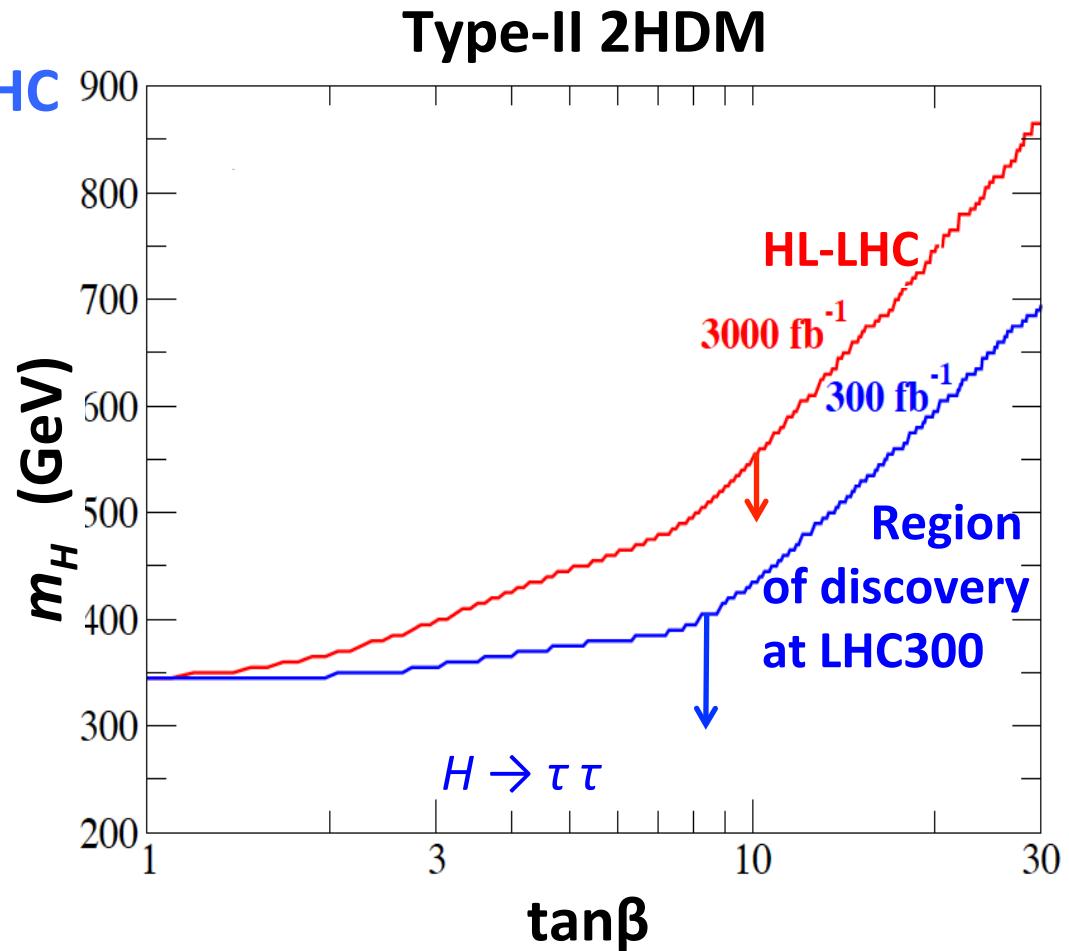
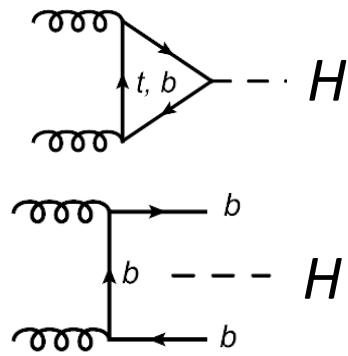
The second Higgs  $H$  must be lighter than 800 GeV



Precision test has the similar power to the direct search

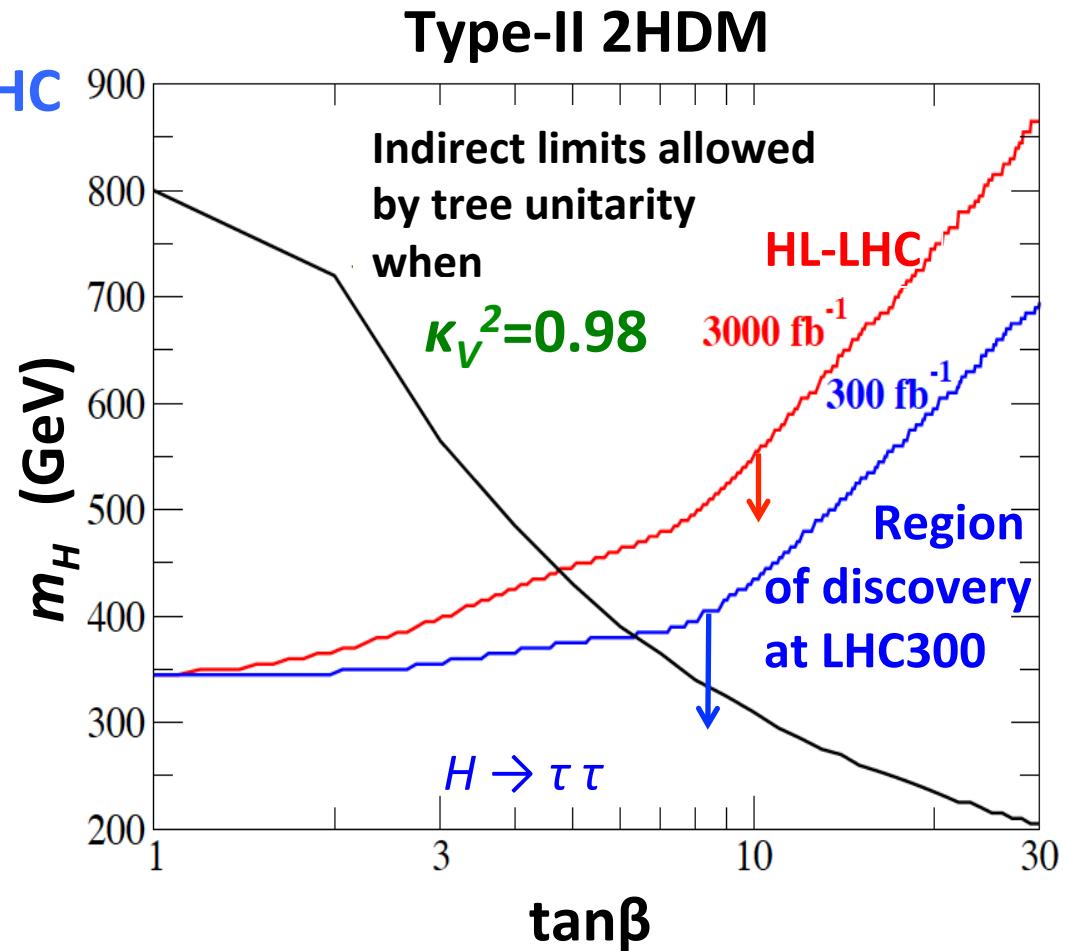
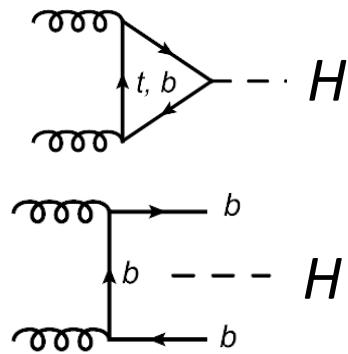
# Complementarity

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



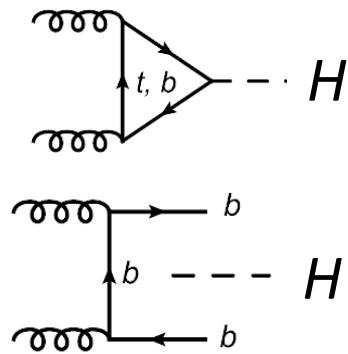
# Complementarity

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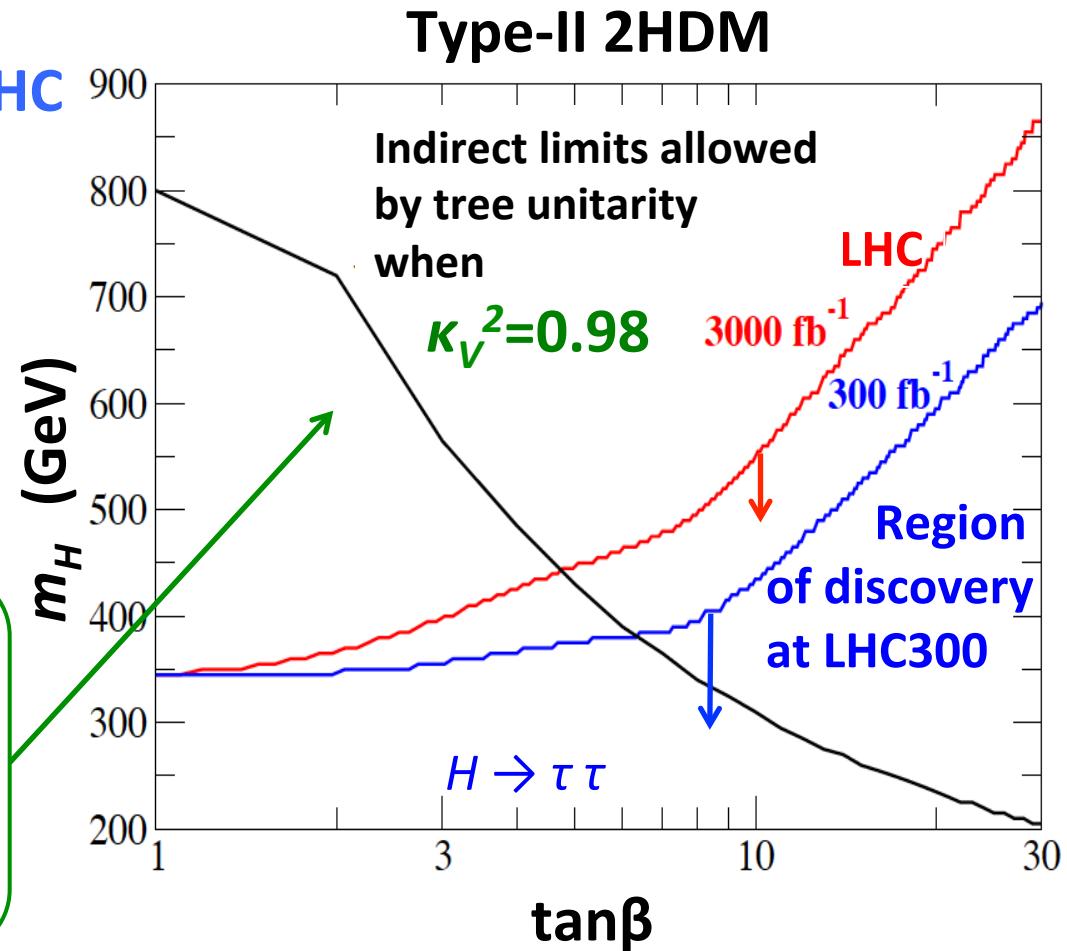


# Complementarity

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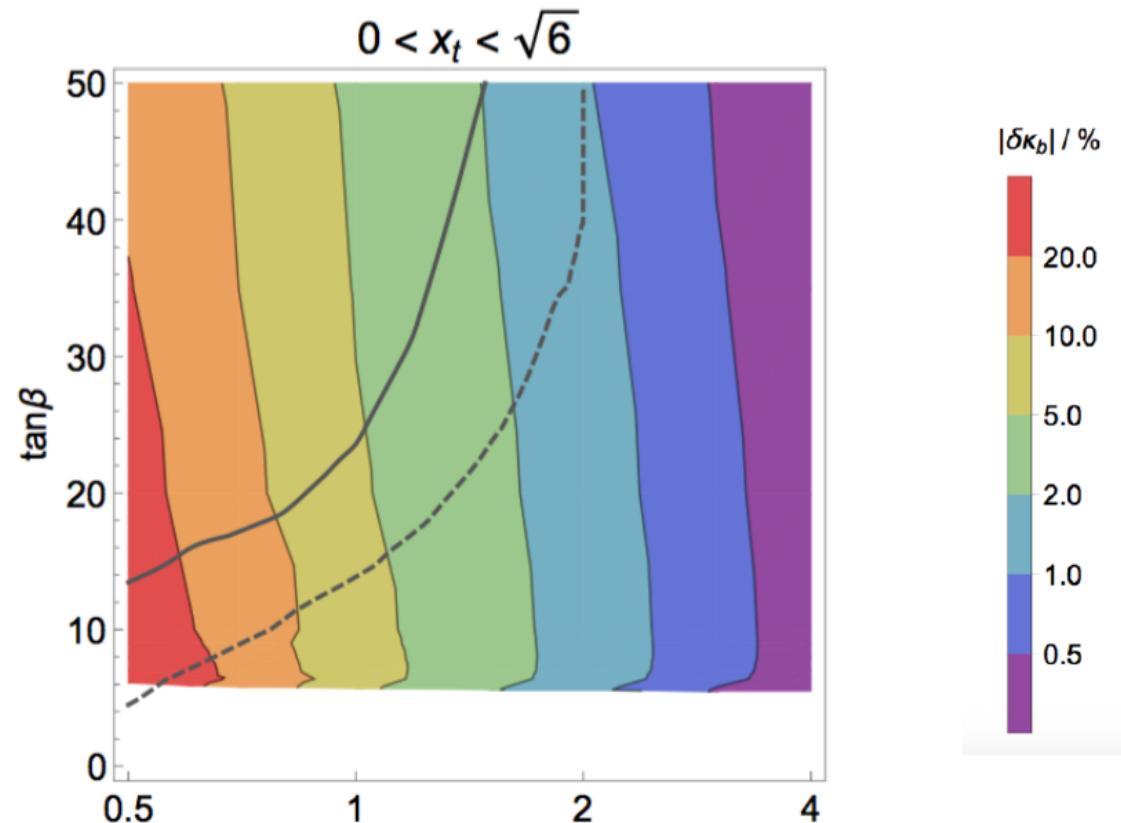


Indirectly, new physics can be surveyed by detecting deviations even out of the direct search regions



# Complementarity

Talk by  
M. Peskin



Wells and Zhang: (arXiv:1711:04774)

s with b-t unification

Our results show a nice complementarity between direct superpartner searches and precision Higgs measurements, as they probe the SUSY parameter space from different directions.

# Talk by K. Yagyu

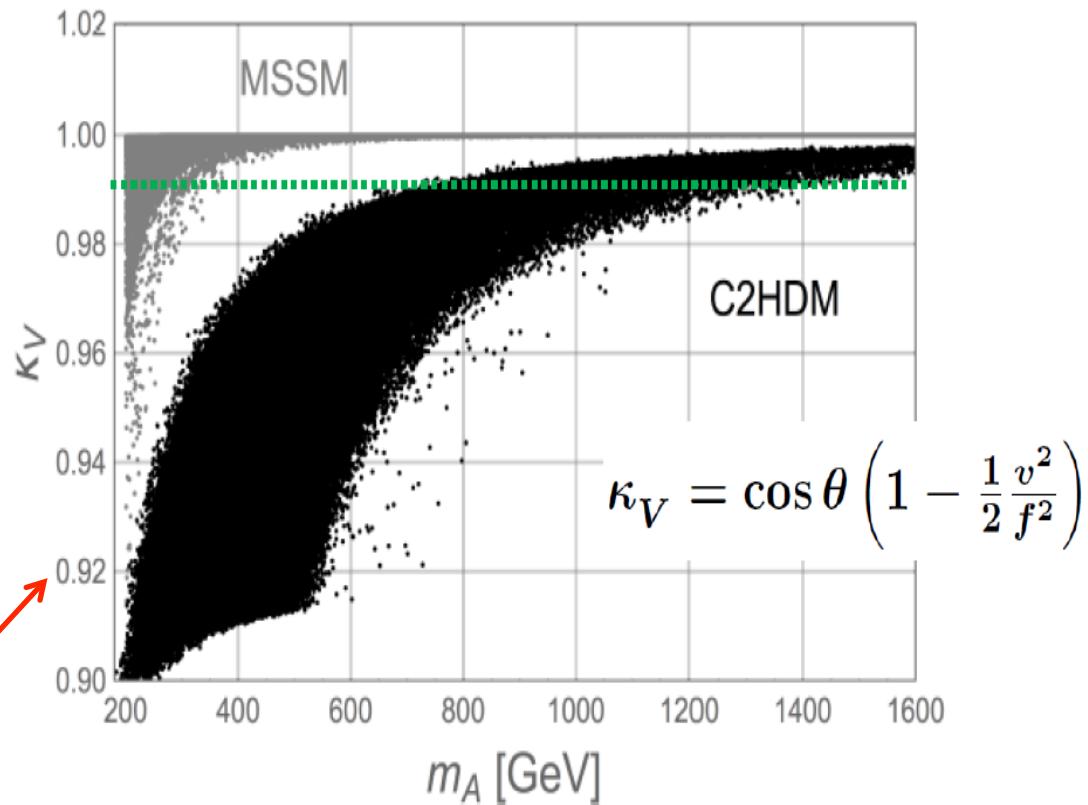
Two Higgs doublet model  
from MSSM  
from C2HDM

Composite 2HDM

$$G/H = SO(6)/SO(4) \times SO(2) \quad \#(G/H)=8$$

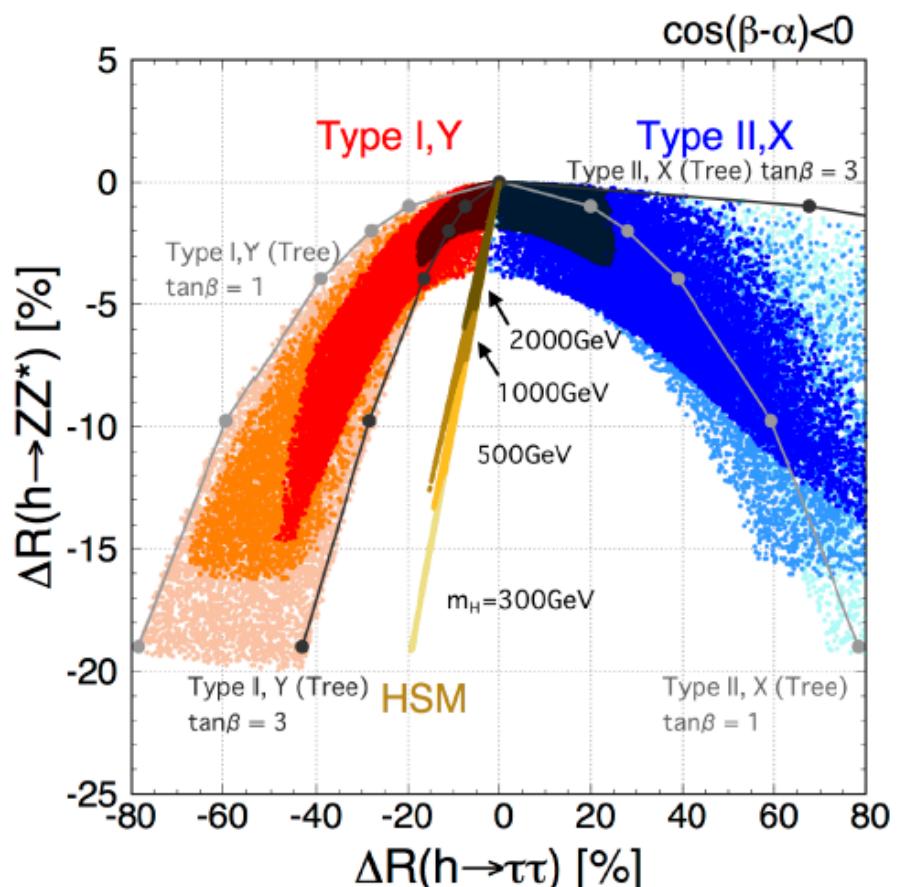
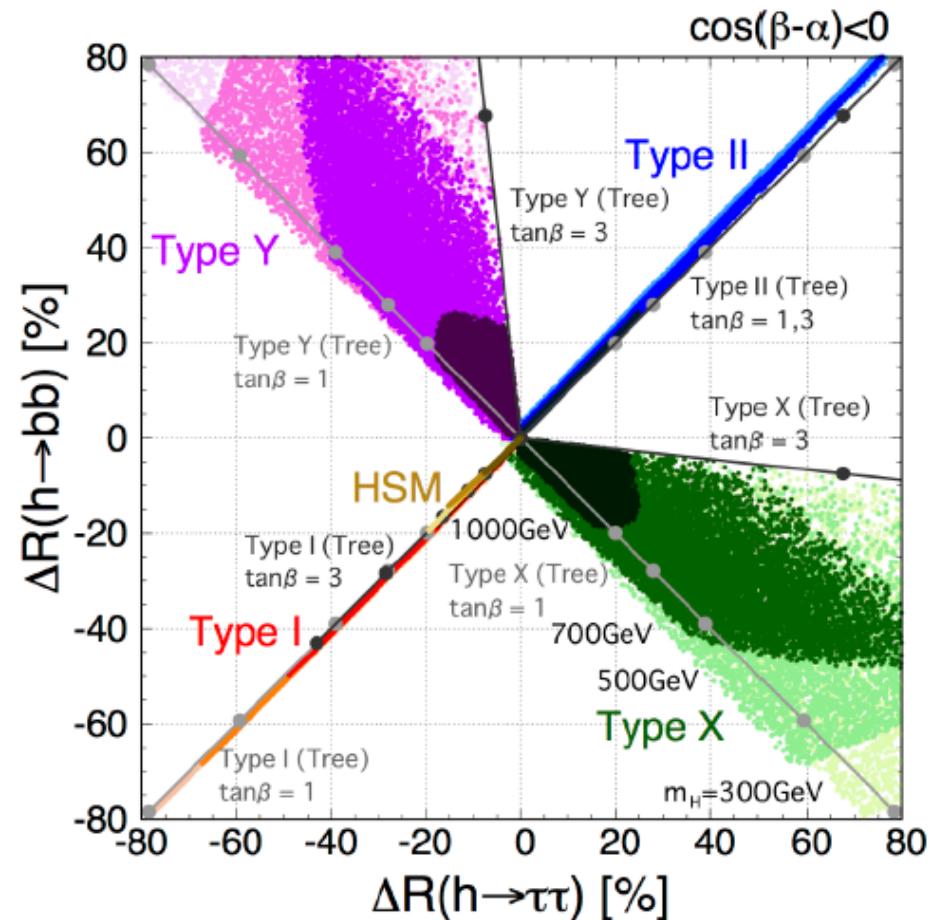
8NG boson  $\rightarrow$  2HDM

Different decoupling  
speed can separate  
MSSM and C2HDM



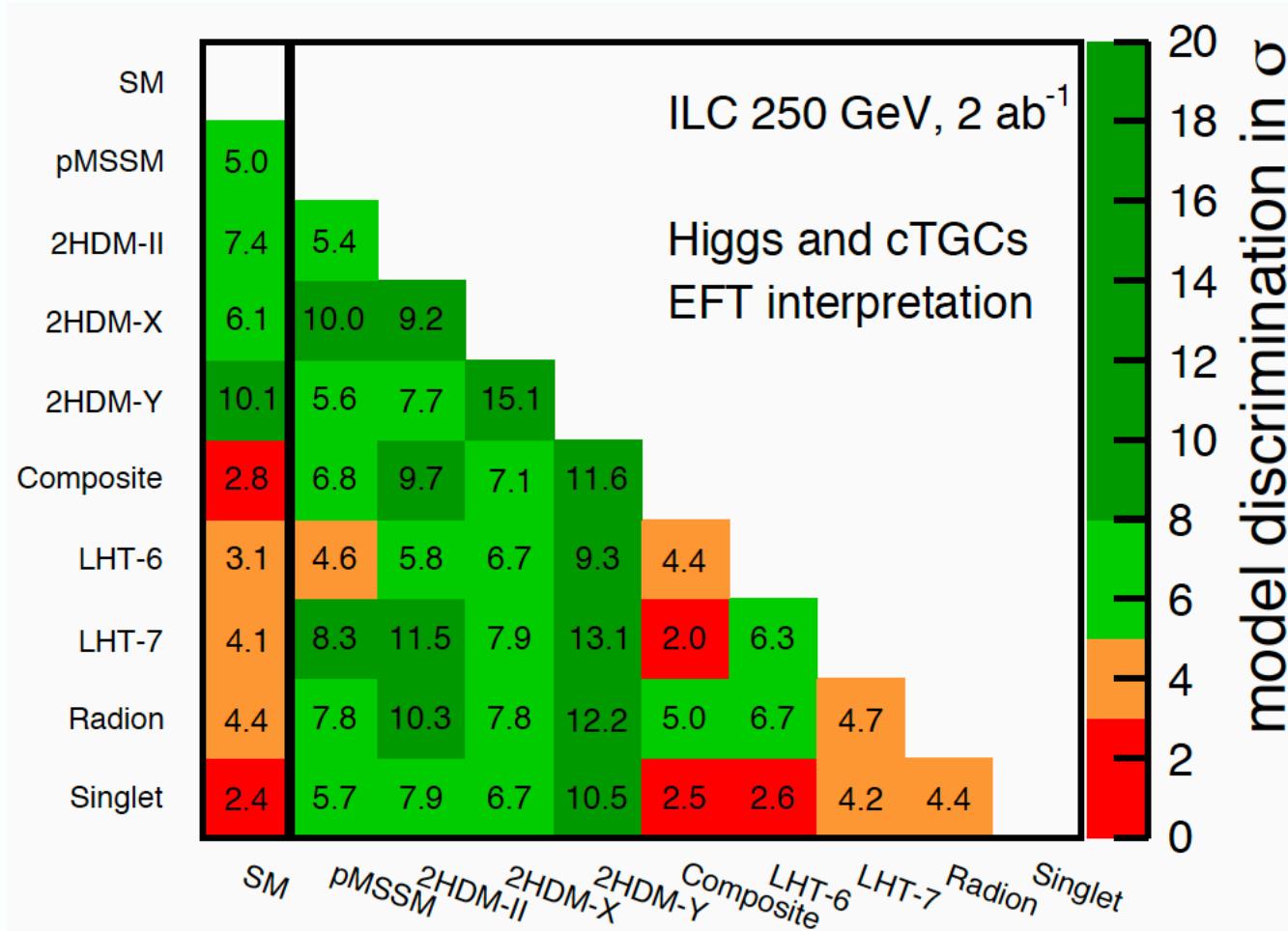
$$\Delta R(h \rightarrow XX) = \frac{\Gamma_{\text{NP}}(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

Sakurai

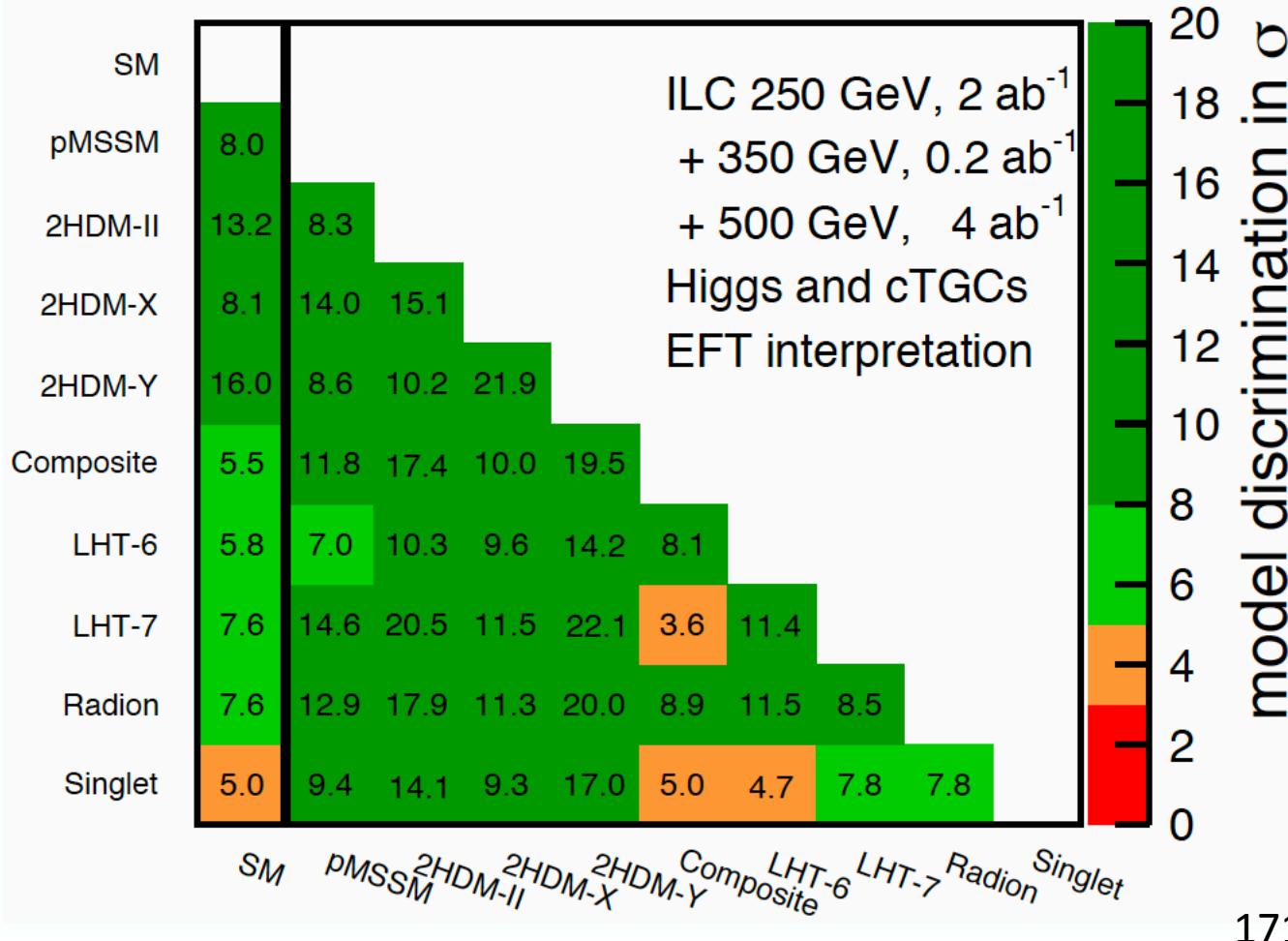


**Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements at ILC250 make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson**

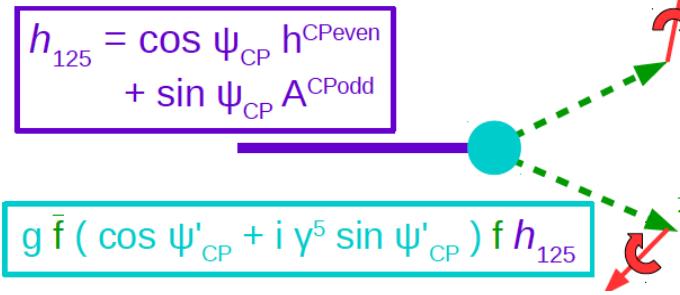
results: ILC 250 GeV 2 ab-1



results: ILC 250 GeV 2 ab<sup>-1</sup> + 500 GeV 4 ab<sup>-1</sup>

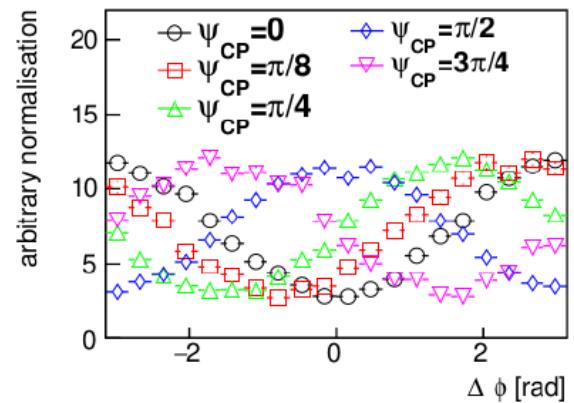
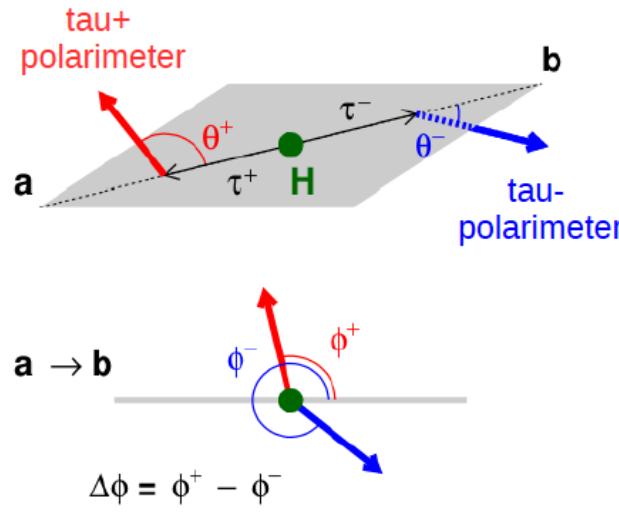


# Talk by Jeans



$h$  is a spin 0 state:  
 $|f \bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\Psi} |\downarrow\uparrow\rangle$   
 $[\Psi = \begin{matrix} 0 & \text{CP even}, \\ \pi/2 & \text{CP odd} \end{matrix}]$

The **correlation** between spins of Higgs decay products  
is sensitive to their CP state [in particular, the transverse correlation]

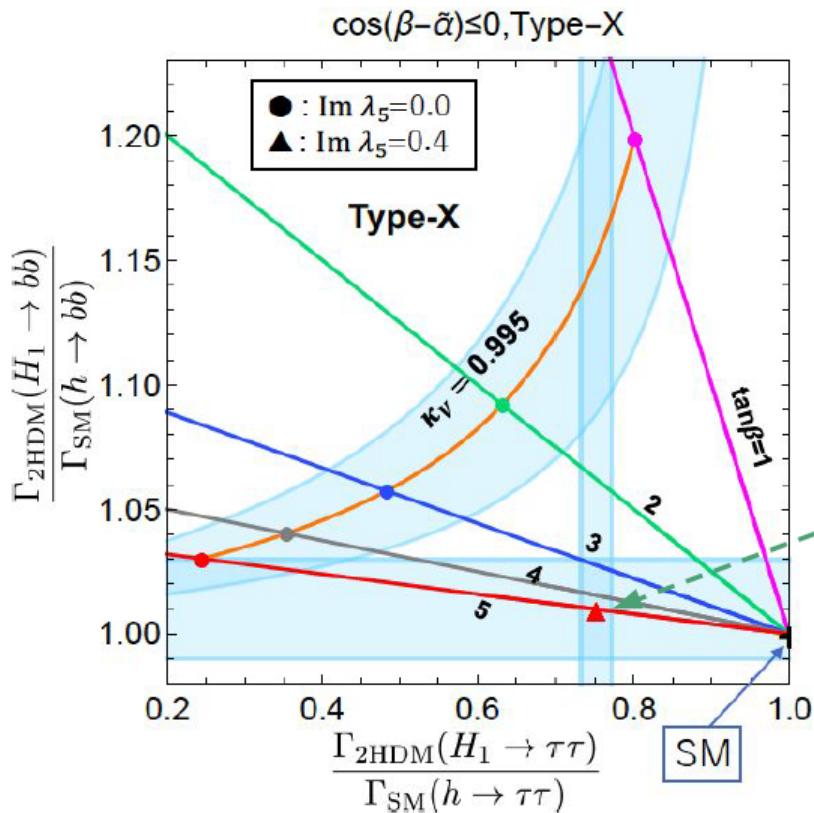


distribution of  $\Delta\phi$  is sensitive to  
CP mixing angle  $\Psi_{CP}$

demonstrated, using full detector simulation and backgrounds,  
that CP mixing in tau-pair from Higgs decays  
can be determined to 75 mrad  $\sim 4.3$  deg  
using 2 ab-1 of ILC250 data

# Testing CPV of the Higgs sector from precision Higgs couplings measurements

## Talk by Hashino



$$\begin{aligned}\kappa_V &: 0.2 \% \\ \kappa_\tau &: 1 \% \\ \kappa_b &: 1 \%\end{aligned}$$

The accuracy can be achieved with ILC250(8 $\text{ab}^{-1}$ ).

Red triangle mark isn't excluded by EDM experiment.

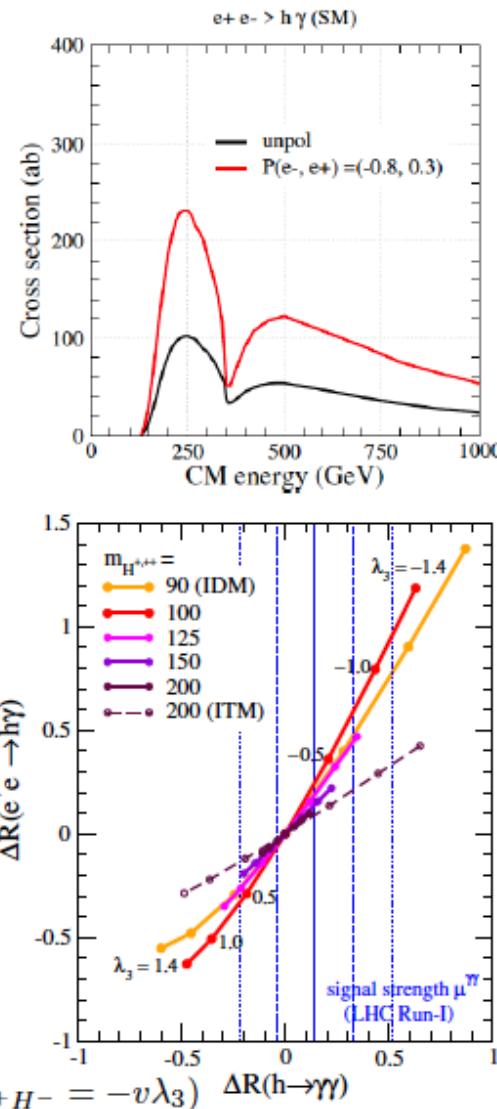
( $\tan\beta=5$ ,  $\kappa_V=0.995$  and  $\text{Im}\lambda_5=0.4$ )

- ❖ CP violating effects which aren't excluded by EDM can be tested by precision measurements of SM-like Higgs boson couplings. [ In preparation ] 17

It seems that we need sufficient Luminosity

## $h+\gamma$ production in extended Higgs

- $h+\gamma$  production at ILC250 is an interesting channel, although the cross section is rather small,  $\sigma \sim \mathcal{O}(0.1\text{fb})$ , due to the loop-induced process.
  - ▶ The cross section is peaked at  $E=250\text{GeV}$ .
  - ▶ Beam polarization can enhance the cross section.
  - ▶ The signal is clean and very sensitive to New Physics.
- By using the H-COUP program, we have been studying the process in various extended Higgs models, e.g. IDM/ITM (inert doublet/triplet model), systematically.
  - ▶ Light charged Higgs bosons can enhance the event rates by a factor of 2 at most under the theoretical (perturbative unitarity and vacuum stability) and experimental ( $h \rightarrow \gamma\gamma$ ) constraints.



# Significance of ILC250

## (1) Higgs precision measurements (coupling % level)

There are more things ILC250 can do!

## (2) Precision test of the EW theory      SM observables      Heinemeyer

## (3) New gauge force (Z' searches) via $e^+e^- \rightarrow ff'$      Suehara, Hosotani(GHU)

## (4) WIMP Search mono-photon, exotic H decay, invisible H decay, ...

Matsumoto  
Shirai  
Katayose  
Tseng  
Mustahid

Suehara,  
Hosotani(GHU)  
Cho (LFV)

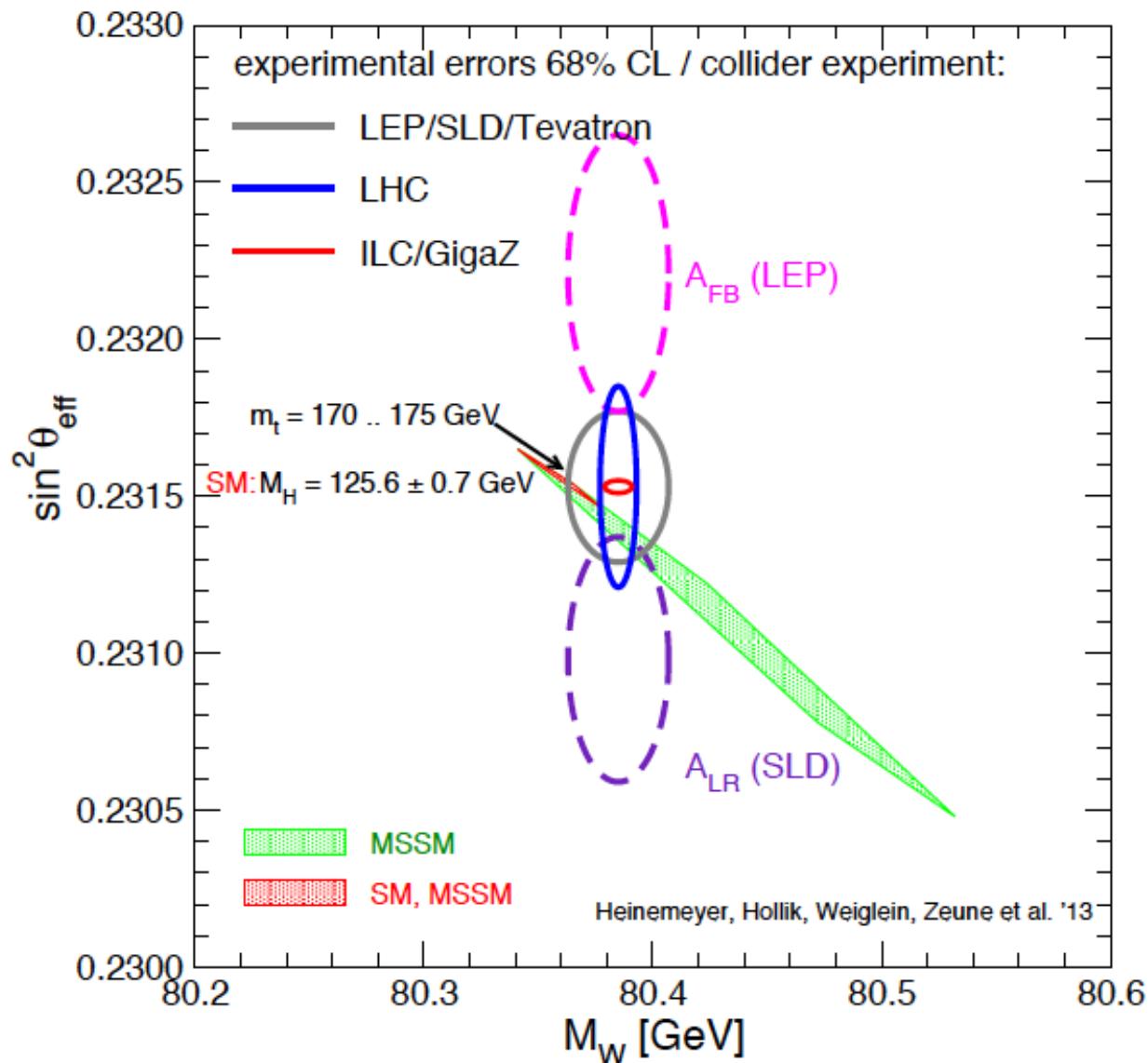
## (5) New particle search Light scalar boson from the Higgs exotic decay      Okumura

Kawada  
Shimomura

# What $M_W$ and $\sin^2 \theta_{\text{eff}}$ precision do we want?

[S.H., W. Hollik, G. Weiglein, L. Zeune et al. '13]

Talk by  
S. Heinemeyer

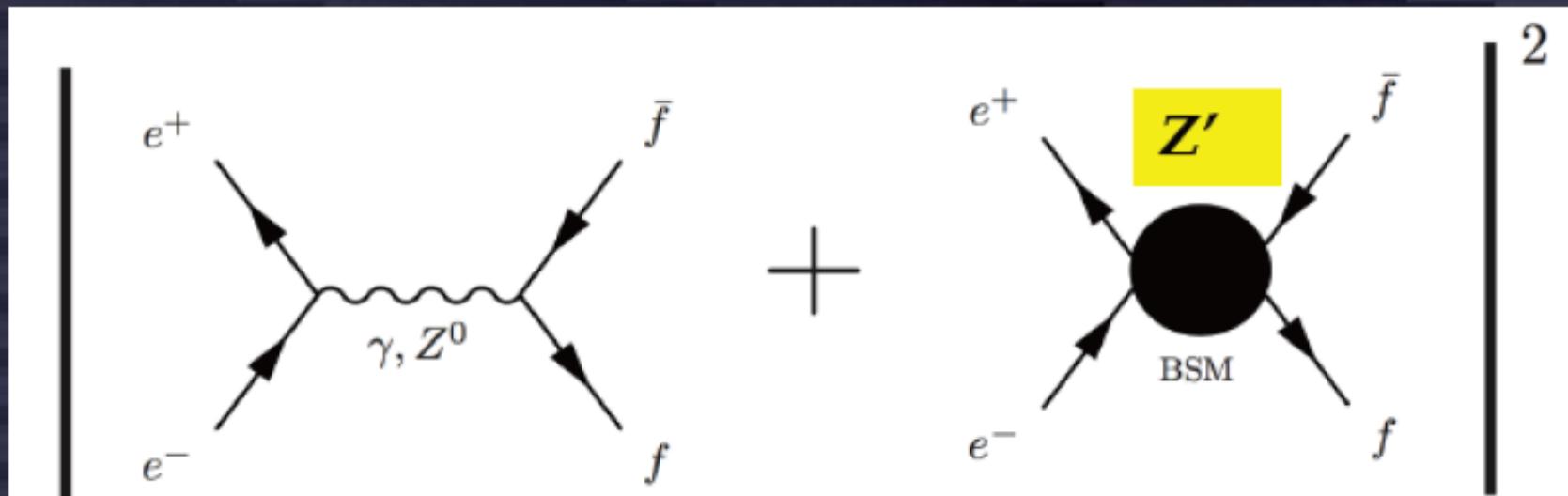


# 2-fermion final states in LC

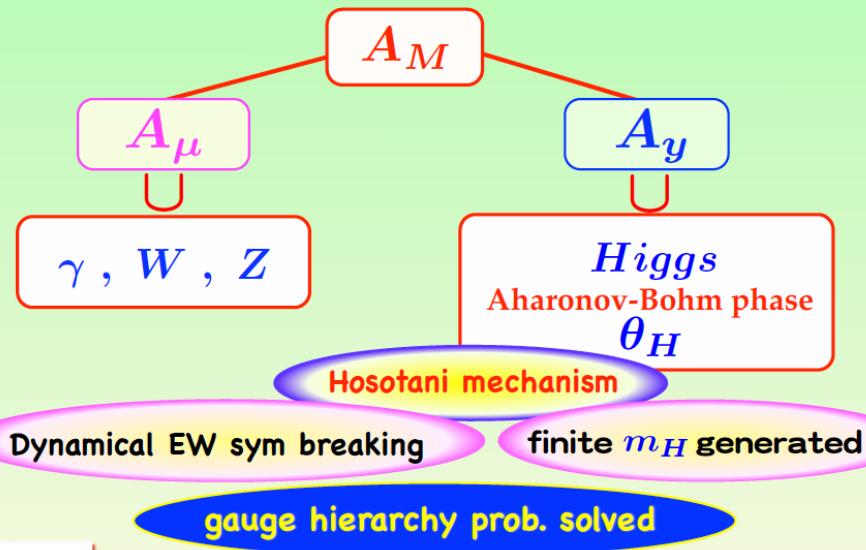
BSM models

Talk by Suehara

- Simple electroweak processes
  - Precise QED calculation
  - High cross section
- O(0.1%) cross section measurement possible
- Differential cross section (production angle)
- Sensitive to BSM models (and separation)



## Gauge-Higgs unification

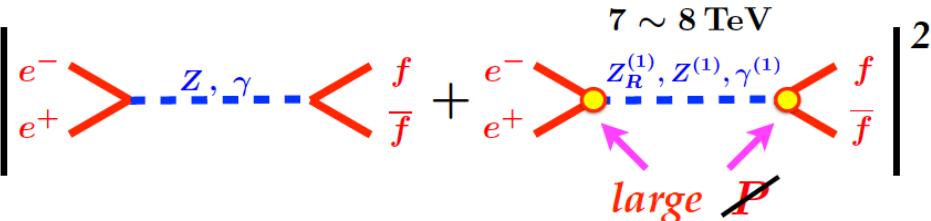


**Hosotani's GHU model can be well tested by 2 fermion final state processes**

**Using beam polarizations and interference effects mass of  $Z'$  to be 6-7TeV can be tested**

## ILC

## Hosotani

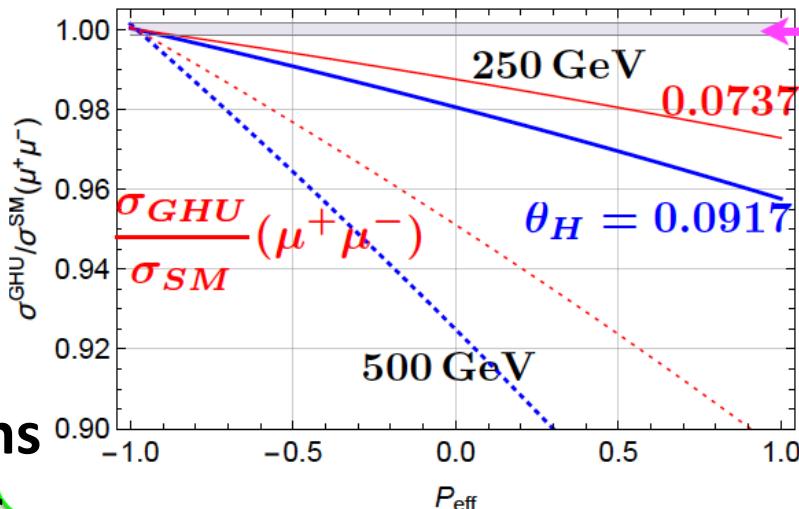


## interference effects

Funatsu, Hatanaka, YH, Orikasa, 1705.05282 (PLB 775, Nov 2017)

## Bhabha scattering, angular dep

F. Richard, 1804.02846 [hep-ex]



$$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} P_{e^+}}$$

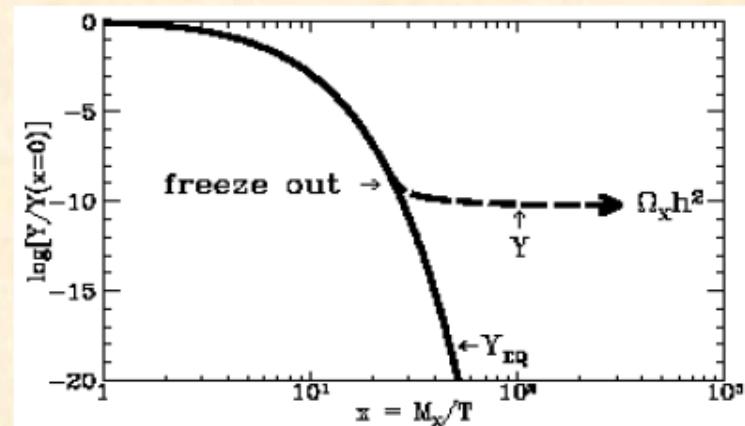
**Interference among  $\gamma, Z, Z'$**

4 % at  $P_{\text{eff}} = 0.877$  at 250 GeV

# WIMP (Thermal Dark Matter) hypothesis

Dark matter was in **equilibrium** with SM particles in the early universe, and it is eventually **decoupled** from the thermal bath. This process fixes the abundance of the dark matter at present universe.

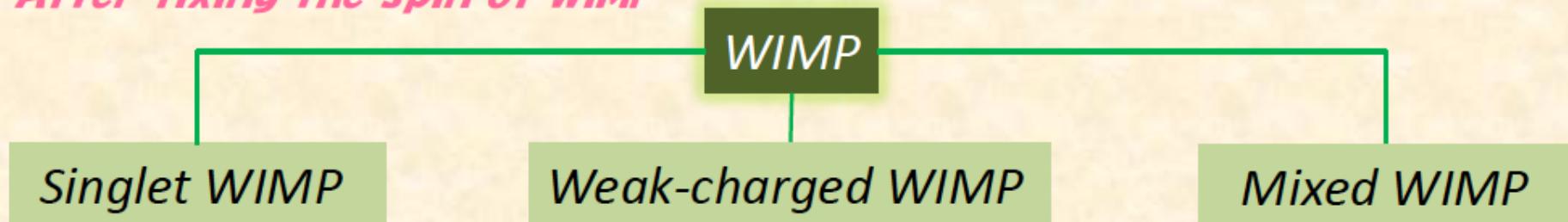
(The same mechanism as BBN/Recombination)



**Study of WIMP without depending on any specific new physics models.**

→ Classifying WIMP in terms of its quantum number (spin and weak charge) and construct a (minimal) simplified model for the WIMP.

After fixing the spin of WIMP



Since the mixed WIMP can be efficiently searched for at underground experiments, we will focus on singlet and weak-charged WIMP cases.

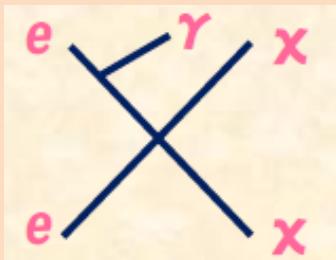
# Systematic investigation of the capability of ILC250 for WIMP search

Talk by S. Matsumoto

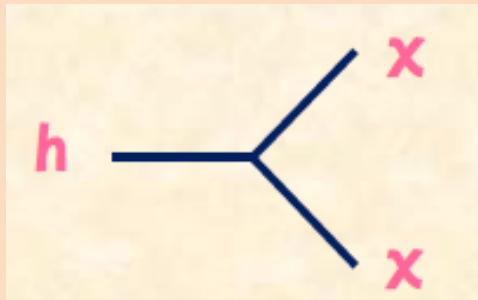
We systematically investigated the capability of 250GeV ILC to search for WIMP, based on a minimal model at each WIMP's quantum number.

250GeV lepton colliders play a crucial role for the following WIMPs.

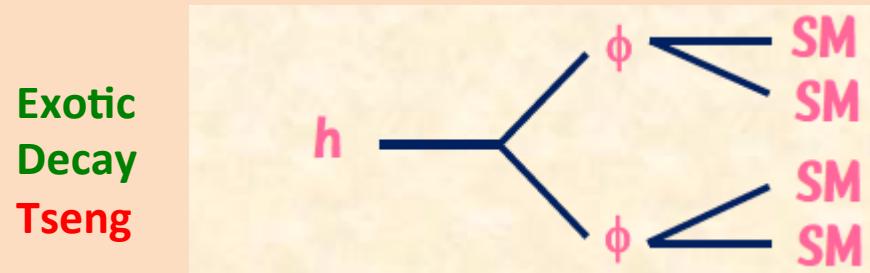
- ✓ Leptophilic WIMP (Muon anomalous magnetic moment, Mono- $\gamma$ )
- ✓ CP violating H-funnel WIMP ( $\gamma$ -ray anomaly from G.C.,  $\Gamma_h(\text{invisible})$ )
- ✓ Light WIMP (Small scale structure problem,  $\Gamma(h \rightarrow \phi\phi)$ )
- ✓ EW weak iso-doublet WIMP (Focus-point SUSY,  $e^-e^+ \rightarrow f\bar{f}$ )



Mono-photon  
process  
Mastahid  
Katayose

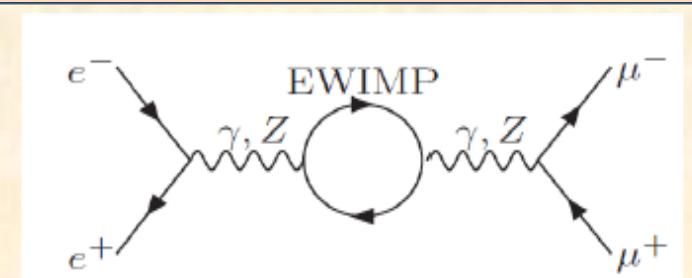


Invisible  
decay  
Tseng



Exotic  
Decay  
Tseng

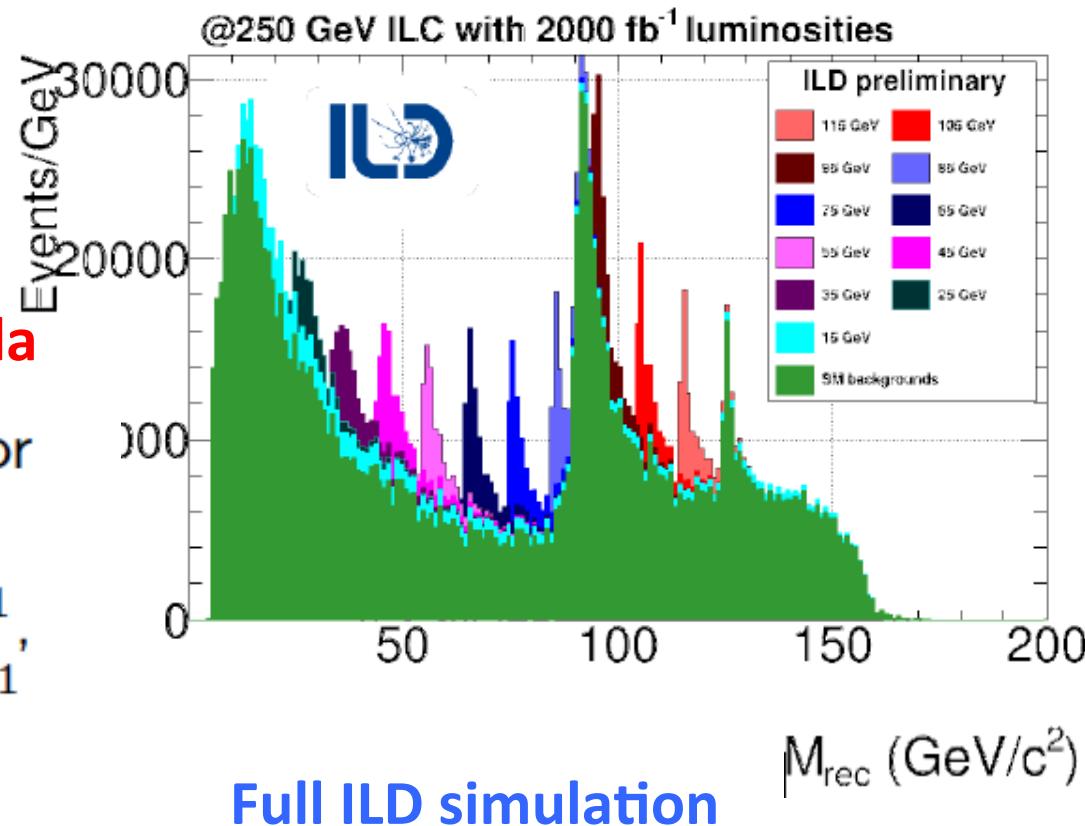
2 fermion  
process  
Shirai  
Suehara



# Searching for a new light scalar at ILC250

Wang, List, Berggren, Kawada

- recoil mass distribution for different  $M_{S^0}$ .
- $(-, +) / (+, -)$   $900 \text{ fb}^{-1}$ ,  
 $(-, -) / (+, +)$   $100 \text{ fb}^{-1}$   
polarization @ 250 GeV



Exclusion limits for  $\kappa_{hZZ}^{95}$  coupling factor

- $\kappa_{hZZ}^{95} \in (0.05-0.12)$ .
- 1 order better than LEP recoil results.

Such a light scalar was discussed in the context of the BSM model, the U(1)L $\mu$ -L $\tau$  model (**Talk by T. Shimomura**) and the NMSSM with the mirage mediation (**Talk by K. Okumura**)

# *comments*

**ILC500 → ILC250**

Higgs precision measurements

Similar performance possible!

Top physics

Energy not enough

HHH Self-Coupling (Higgs potential)

Energy not enough

How we consider these two issues?

# Physics of the top quark

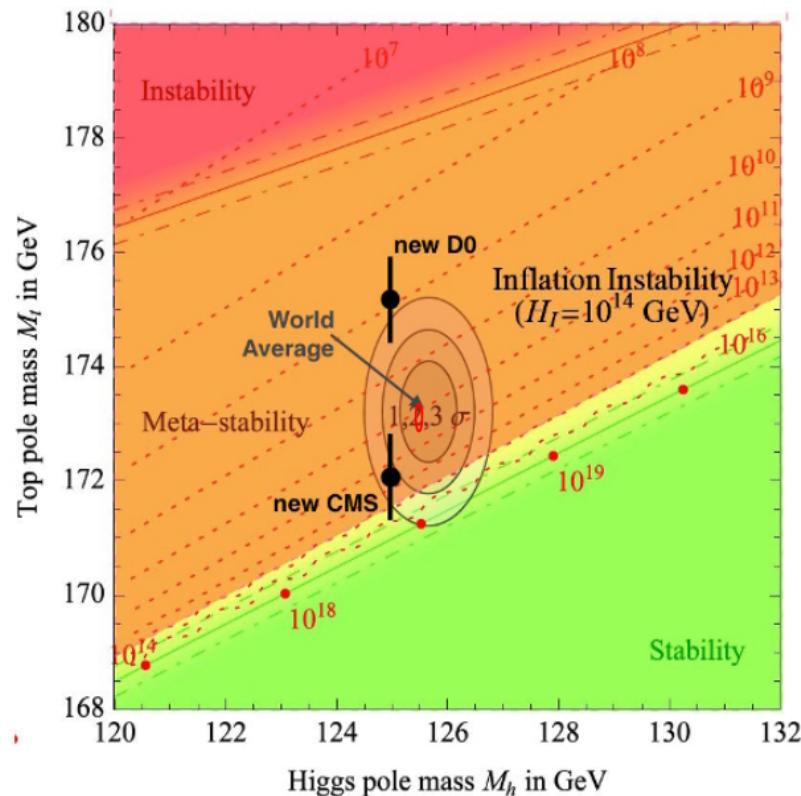
Although there are very nice expectation  
for the top physics at ILC350, ILC500

Perello, Kurihara, Gomis, Reuter,...

ILC250 is kinematically limited

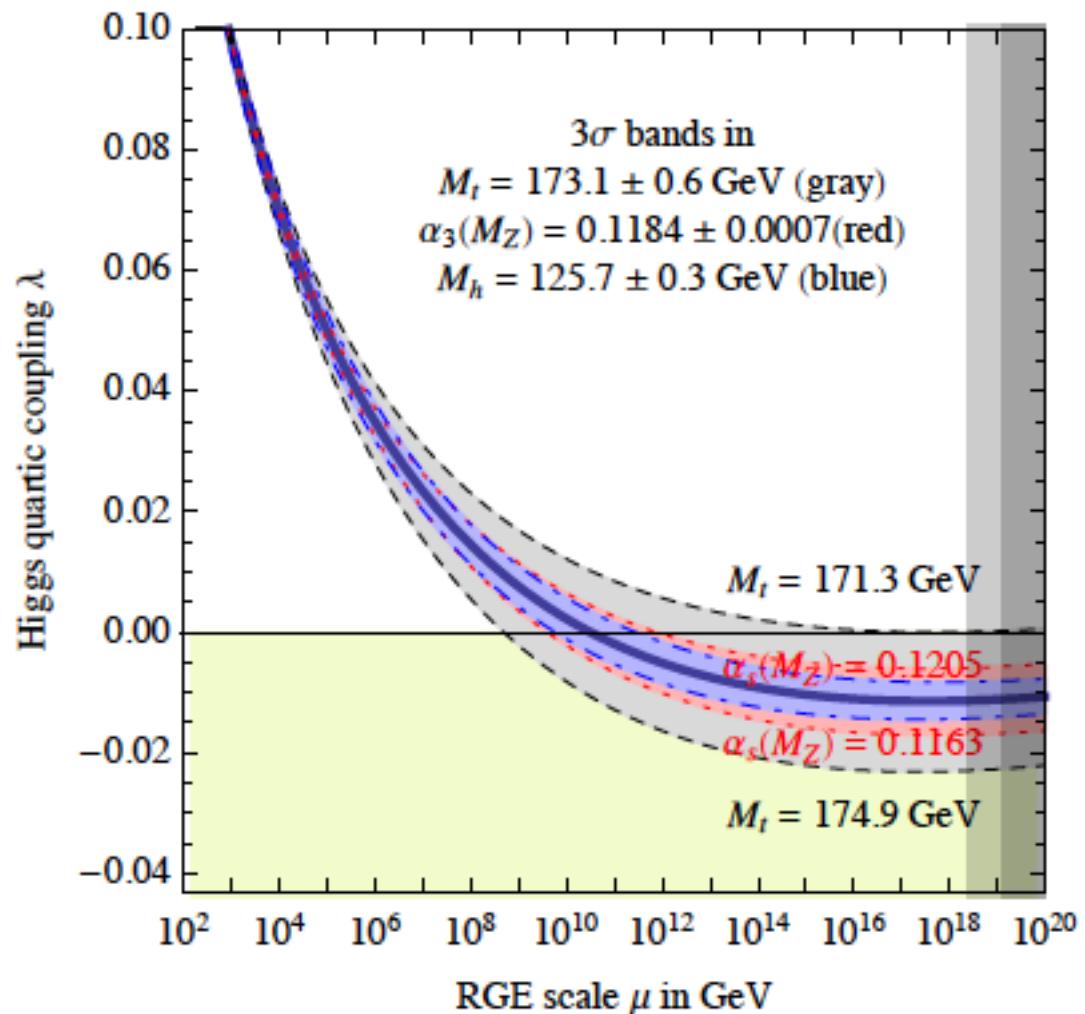
I may say one thing...

For the vacuum stability, we can  
conclude where  $\lambda$  goes down to be  
negative with the accuracy  
 $\Delta m_t = 0.3$  GeV at HL-LHC.



So, more precision at ILC350, ILC500 might not be urgent

Buttazzo et al, arxiv:1307.3536



# Measurement of the HHH coupling

Although HL-LHC will try to measure  
the hhh coupling to some extent, ... Talk by Paganis  
it is not enough

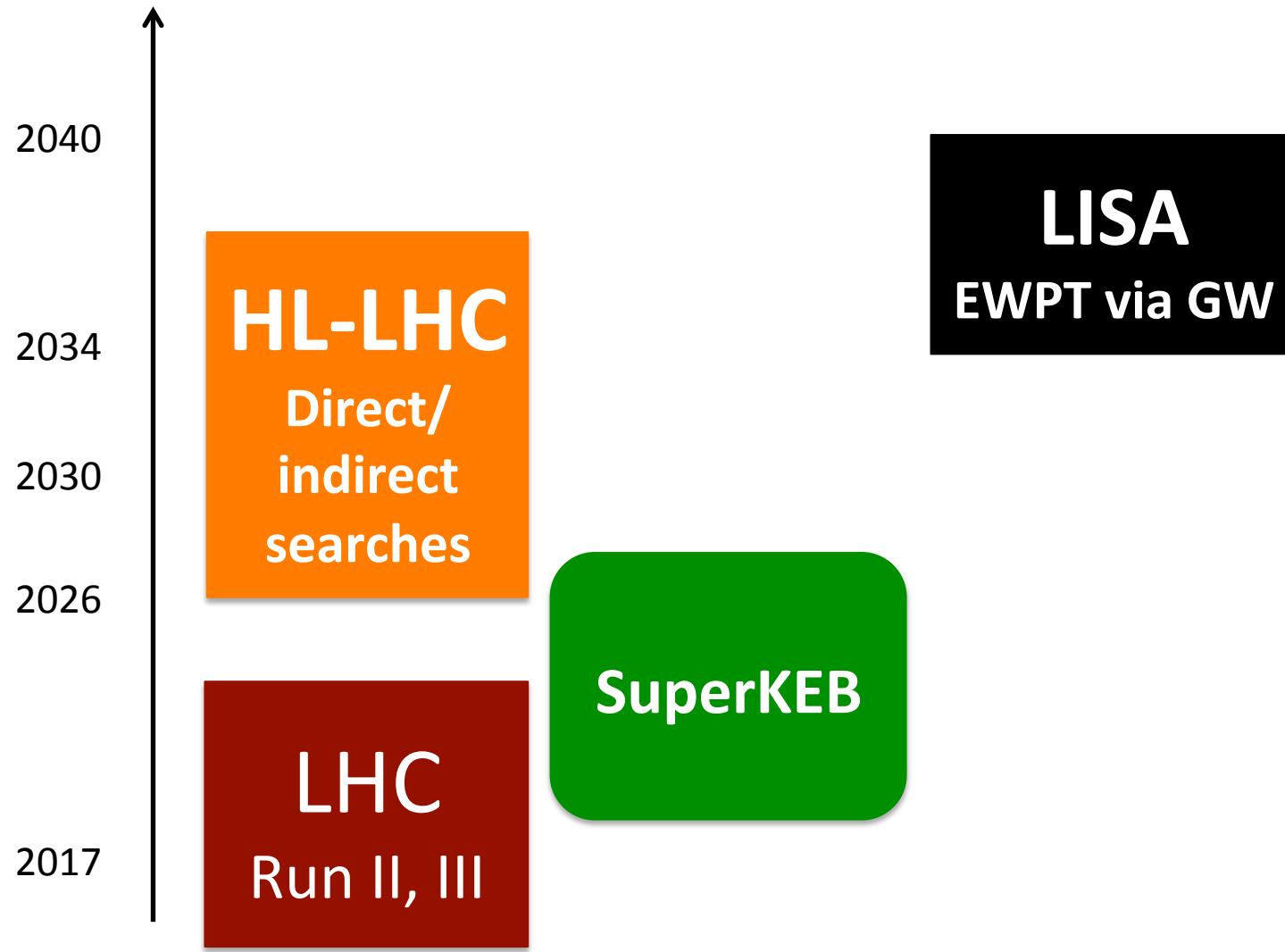
To test the 1<sup>st</sup> order phase transition of EW symmetry breaking,  
as required for a successful scenario of EW baryogenesis,  
the HHH coupling should be measured by O(10) % accuracy

Fortunately, in 2034 a new gravitational wave (GW) experiment  
“Laser Interferometer Space Antenna (LISA)” will start its operation,  
where we can detect GW from 1<sup>st</sup> order phase transition

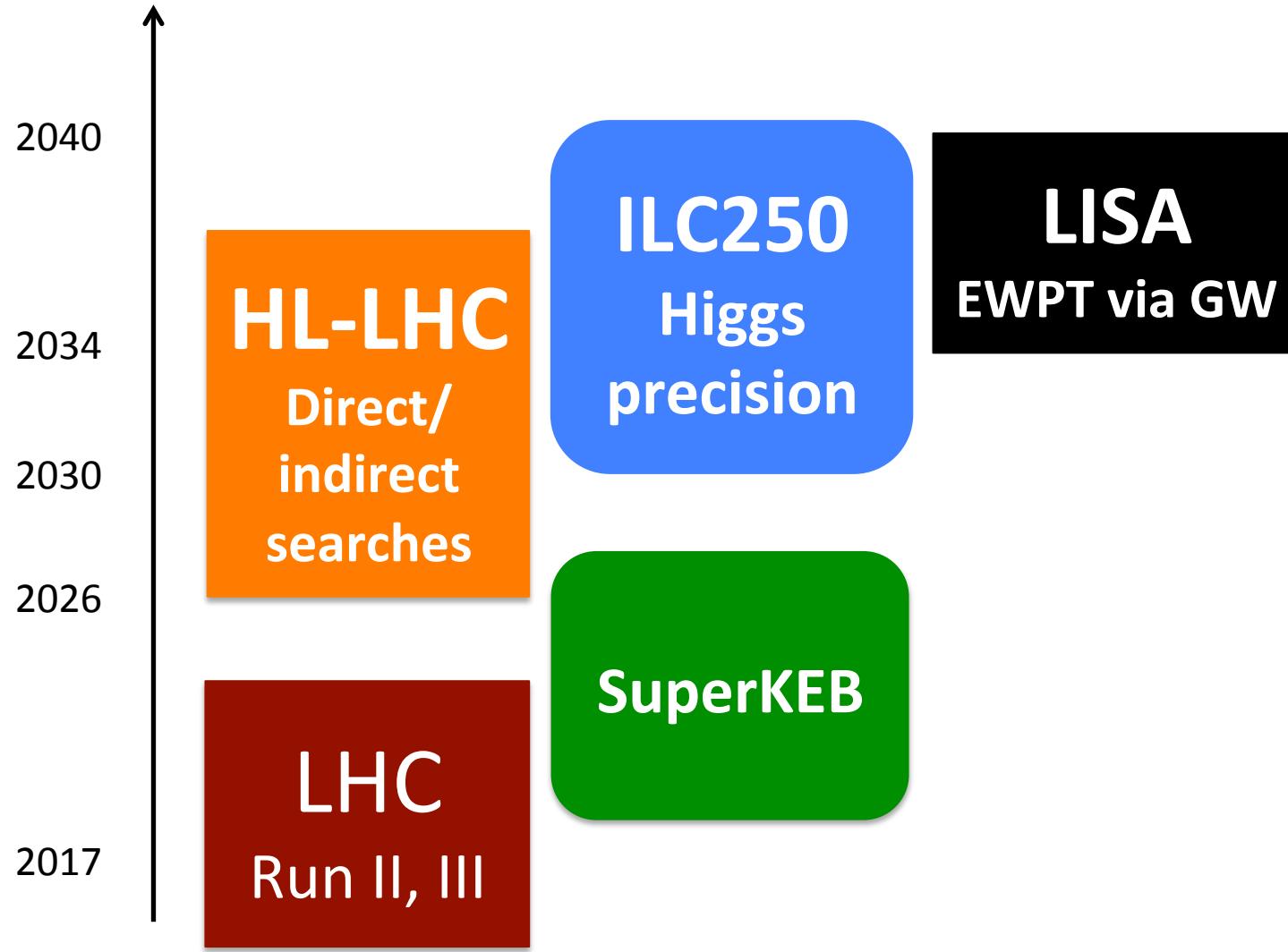
Talk by Kakizaki

If ILC250 is realized, the Higgs precision test at the ILC250 and  
the test of the phase transition at LISA can run in the same time

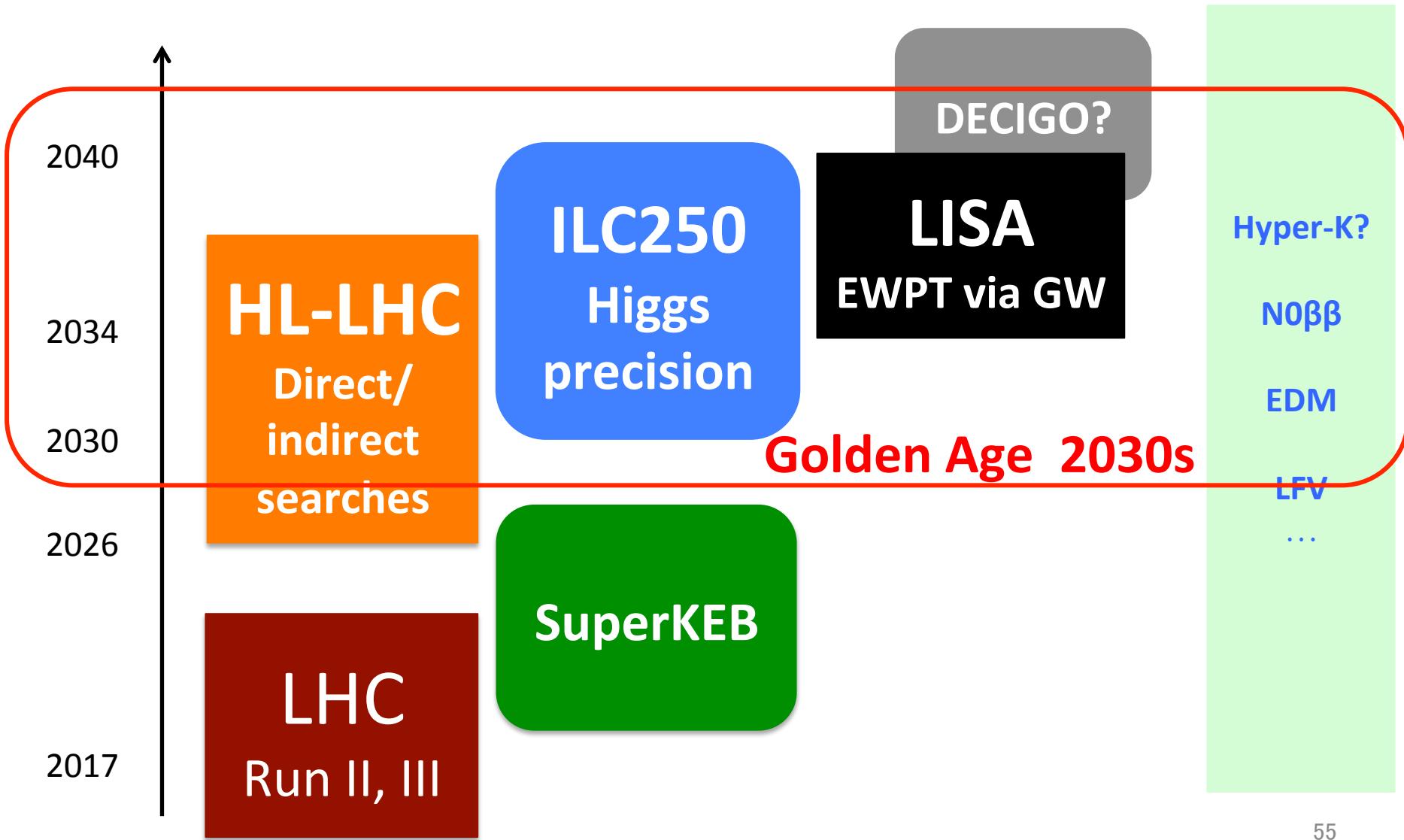
# Future experiments



# Future experiments



# Future experiments



# Synergy between Collider and GW

## Talk by Kakizaki

Models with 1<sup>st</sup> order phase transition

- GWs observable at future exps.

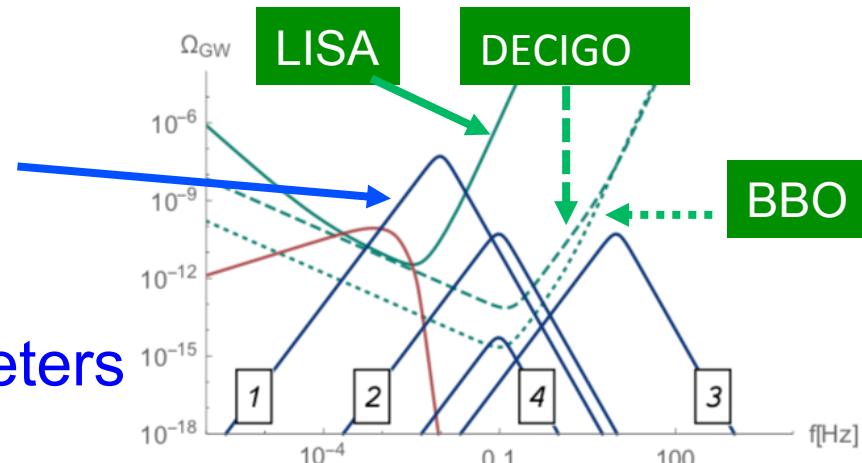
Idea: Fisher analysis

→ Constraints on model parameters

- e.g. Higgs singlet model

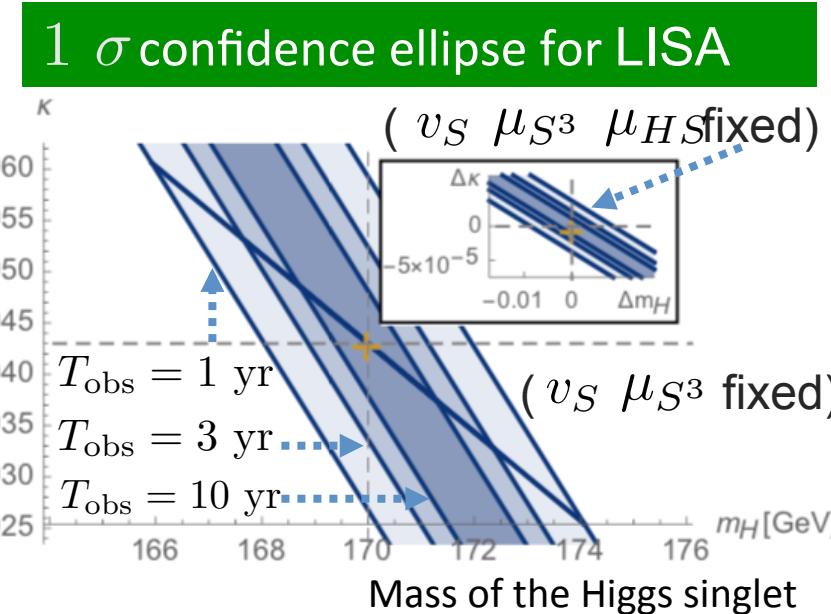
$$V_0 = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu'_S}{3} S^3 + \frac{\lambda_S}{4} S^4$$

Universal Scale factor



Synergy with future colliders

- ILC w/  $\sqrt{s} = 250$  GeV  $L = 2 \text{ ab}^{-1}$   
 $\Delta\kappa_V : 0.6\%$  [Durieux et al. (2017)]

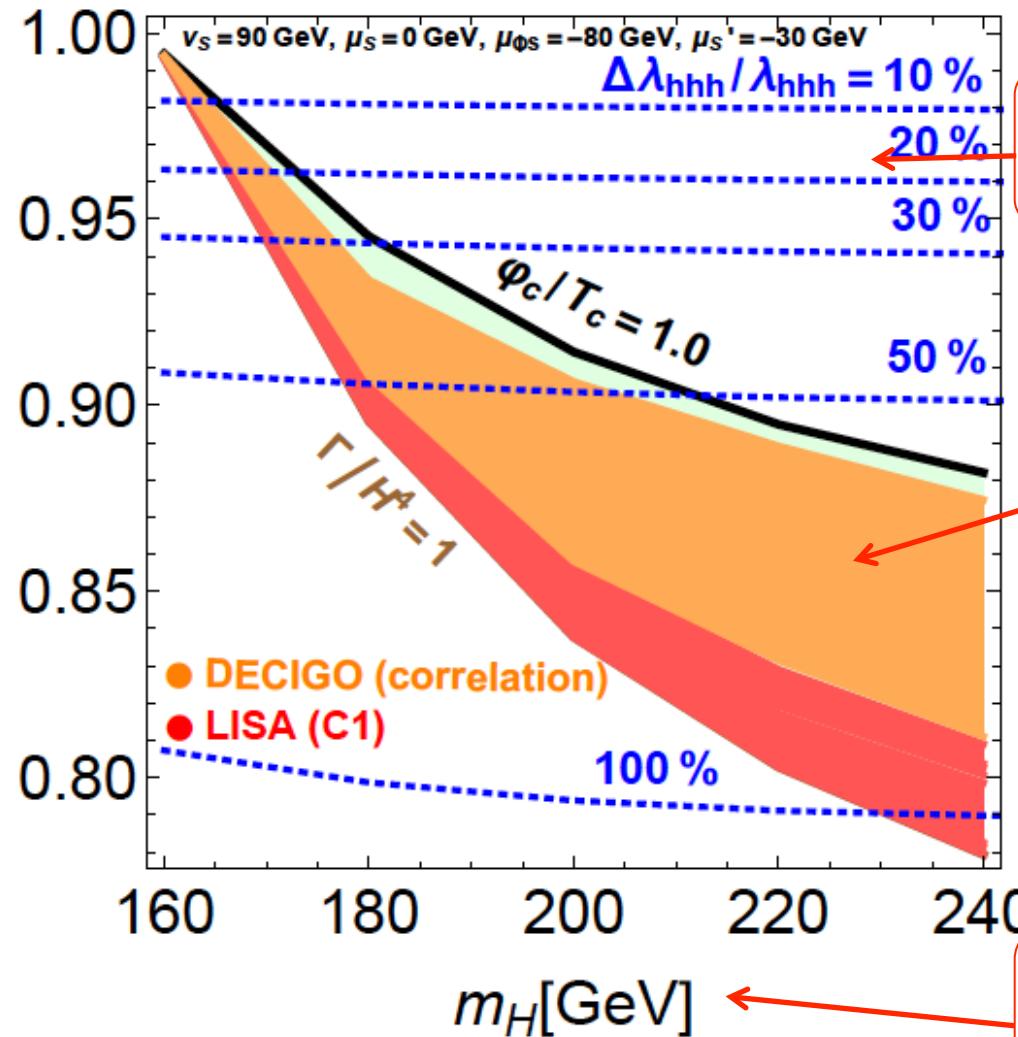


# Model of EW Baryogenesis will be well tested by the synergy of HL-LHC, ILC250, LISA/DECIGO, ....

$$K = K_V = K_f$$

$$= \cos \theta$$

Precision measurement at ILC250

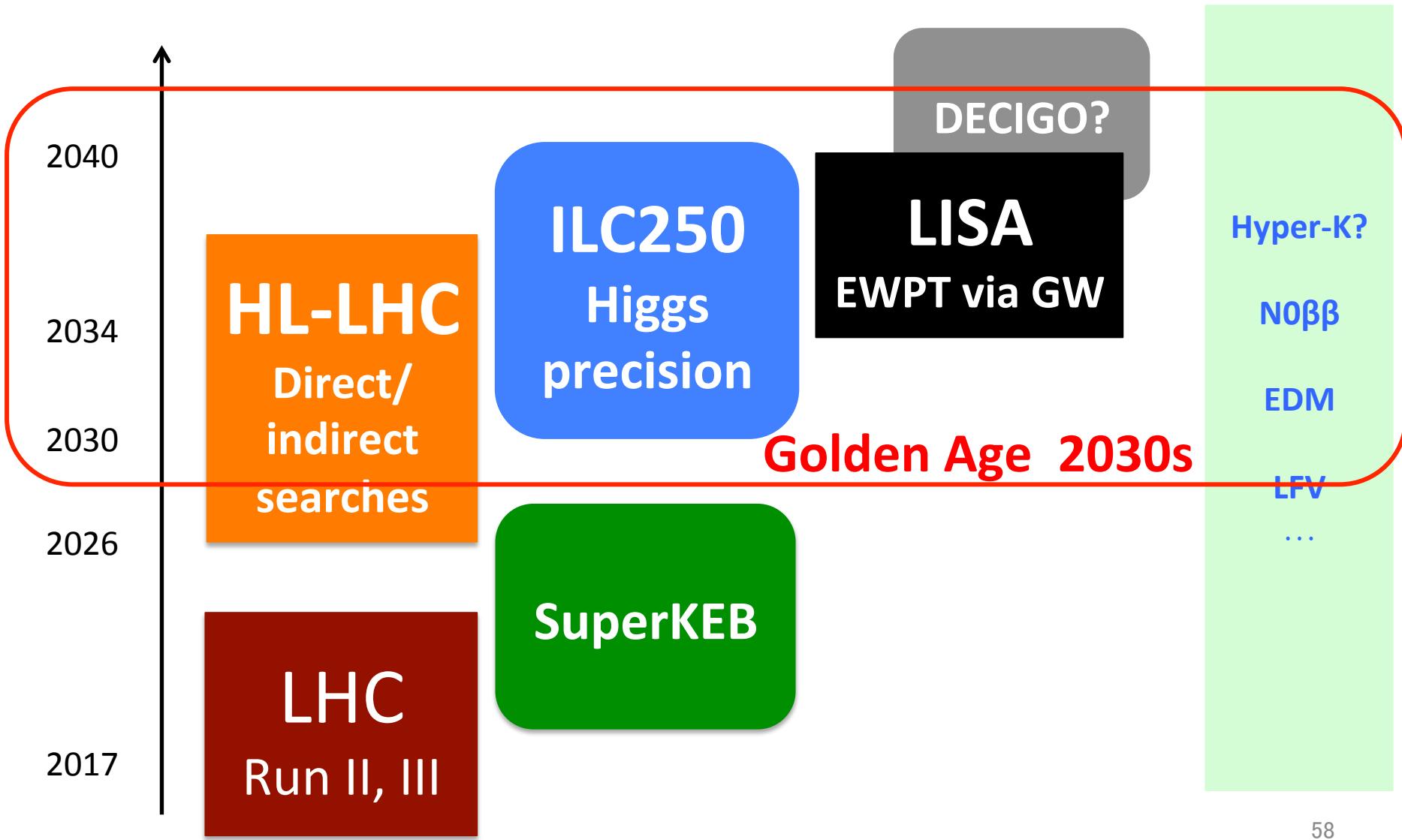


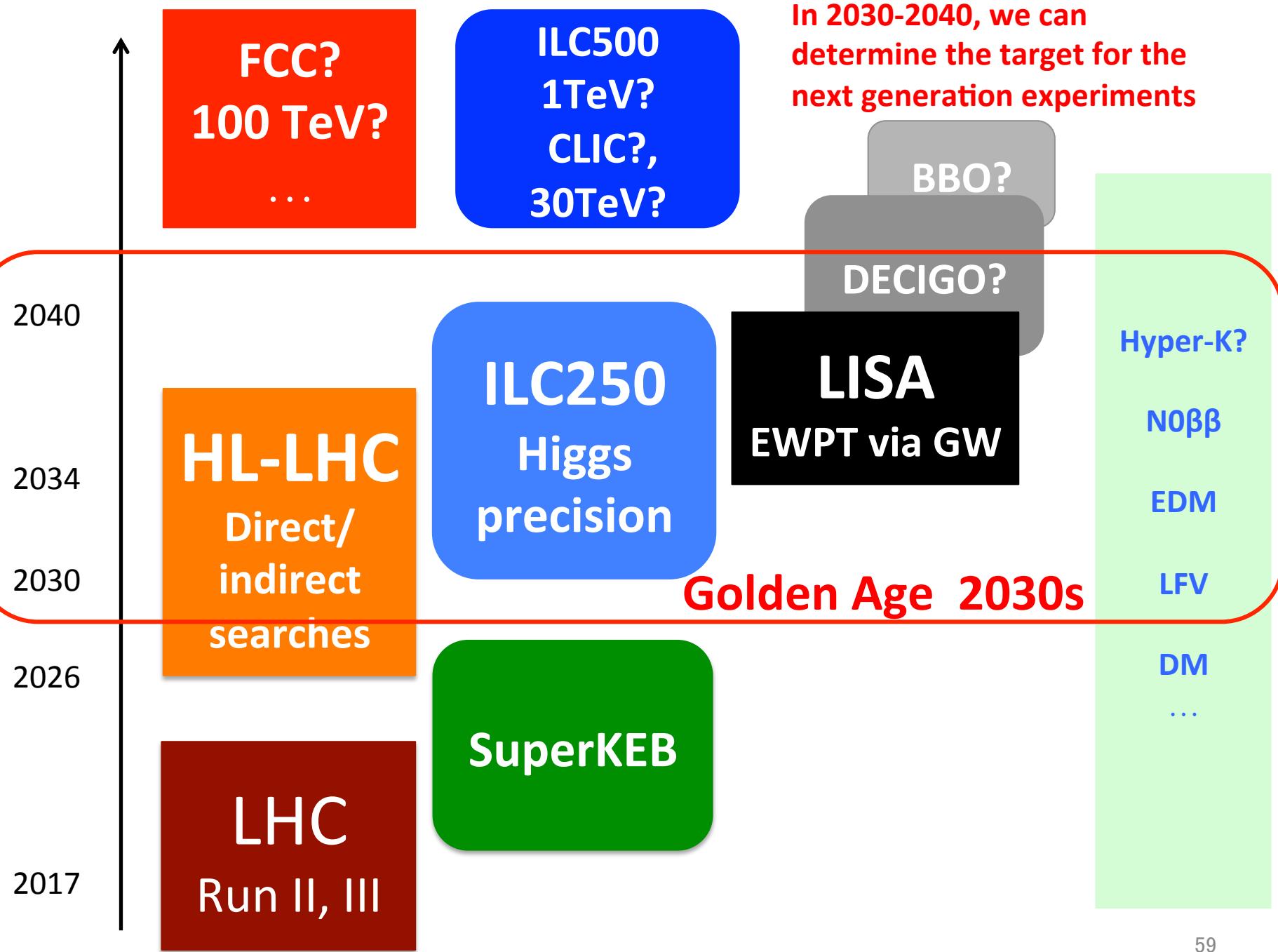
Self-coupling  $hhh$  measurement at ILC

Measurement of Gravitational Waves at LISA/DECIGO

Direct searches of the second Higgs at LHC

# Future experiments





# ILC250!

# ILC250!

# ILC250!

## 1) Higgs Precision is most important

ILC is absolutely necessary as a Higgs factory at this VERY timing  
for the good synergy with other ongoing and preparing future experiments

ILC250 is the best machine! Precise (% level or better) measurements possible.  
With the synergy with HL-LHC and LISA which will run in the same time,  
Higgs sector will be thoroughly explored (The golden age for the Higgs sector )

From the Higgs sector we can get the hint of BSM, and most possibly we will  
know the next energy target of next energy frontier experiment

At ILC250, the followings can also be tested

2) Dark Matter: thorough test of WIMP dark matter scenario possible  
Mono-photon search, Higgs invisible decay, Higgs exotic decay

3) New gauge Force: Z' boson effect on  $e^+e^- \rightarrow ff'$

4) New particle search: Discovery of a new light scalar via Higgs exotic decay

*Got ILC ?*

Thanks you very much