Little Higgs measurements at the ILC

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Little Higgs is one of the possibility for TeV new physics.
In this talk, we study the phenomenology of Littlest Higgs model with T-parity (LHT) at ILC.

SM	g	W	Z	A,	q	l,	H
Partner		W_H	Z_H	$A_{H,}$	q_H	$l_{H,}$	Φ_H

- SM particles & their partners have same spin.
- M_(New particles) ~ f ~ 1 TeV.

We estimate…

- Measurement accuracy of M_{WH}, M_{ZH}, M_{AH}, M_{lH}.
- Determination of VEV **f** & other model parameters
- Determination of couplings with new particles @ ILC.

Plan

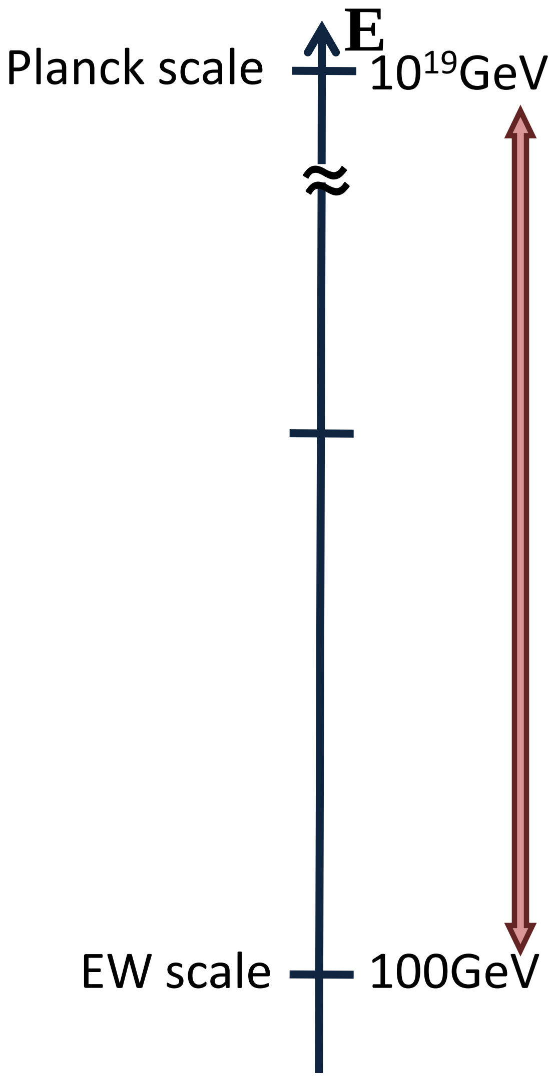
- Introduction
- What is the LHT?
- How to measure the LHT at ILC?
- Simulation results
- Summary and discussion

SM is the successful model
describing physics below ~ 100 GeV.

But…

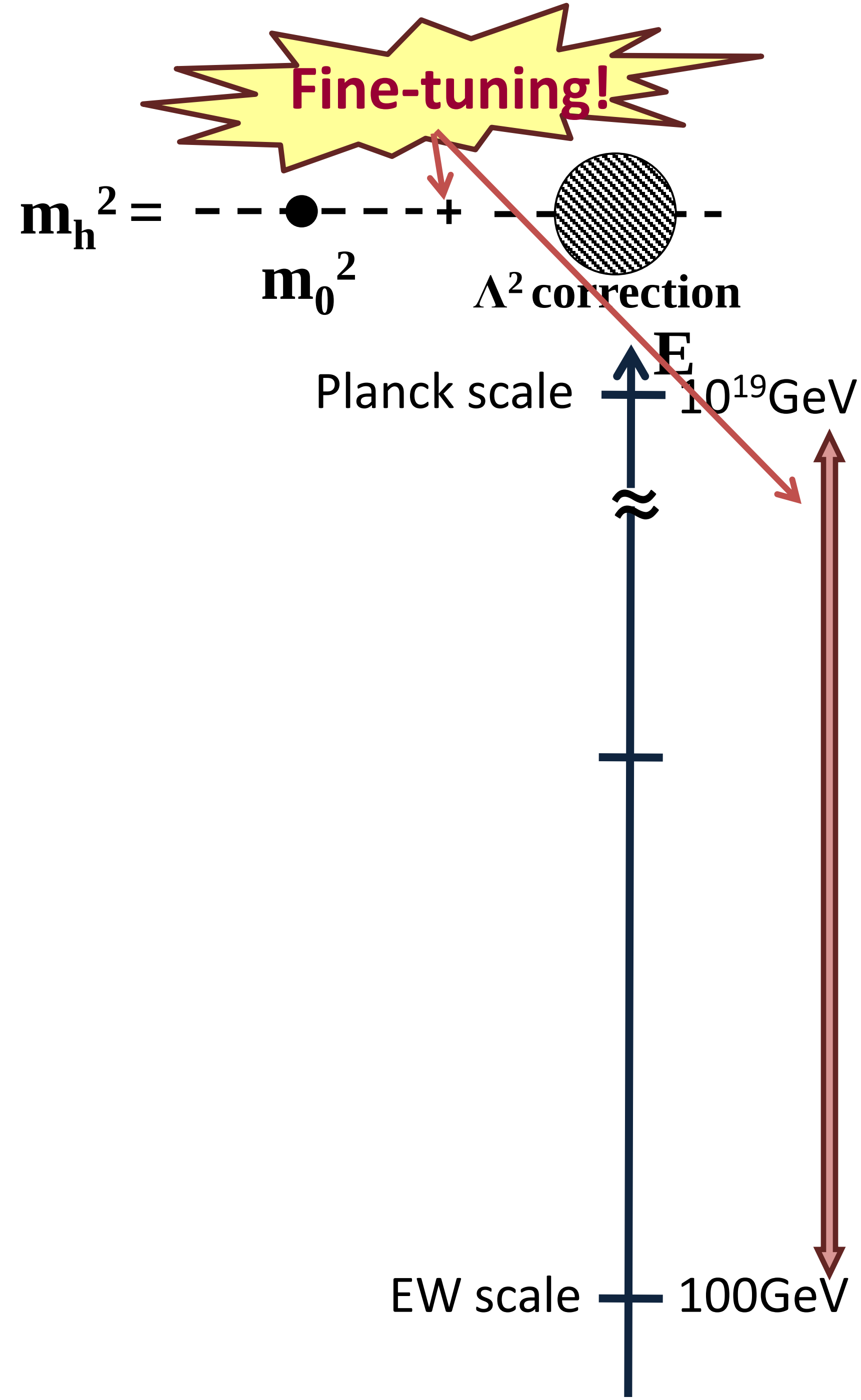
If we assume that SM is valid all the way up to the Planck scale, there is a hierarchy problem.

$$\Rightarrow \quad m_h^2 \sim m_0^2 + 3\ yt\hat{}2\ \Lambda^2/4\pi + \ldots$$



- **Hierarchy Problem**

  related to quadratic divergence to the Higgs boson mass term.



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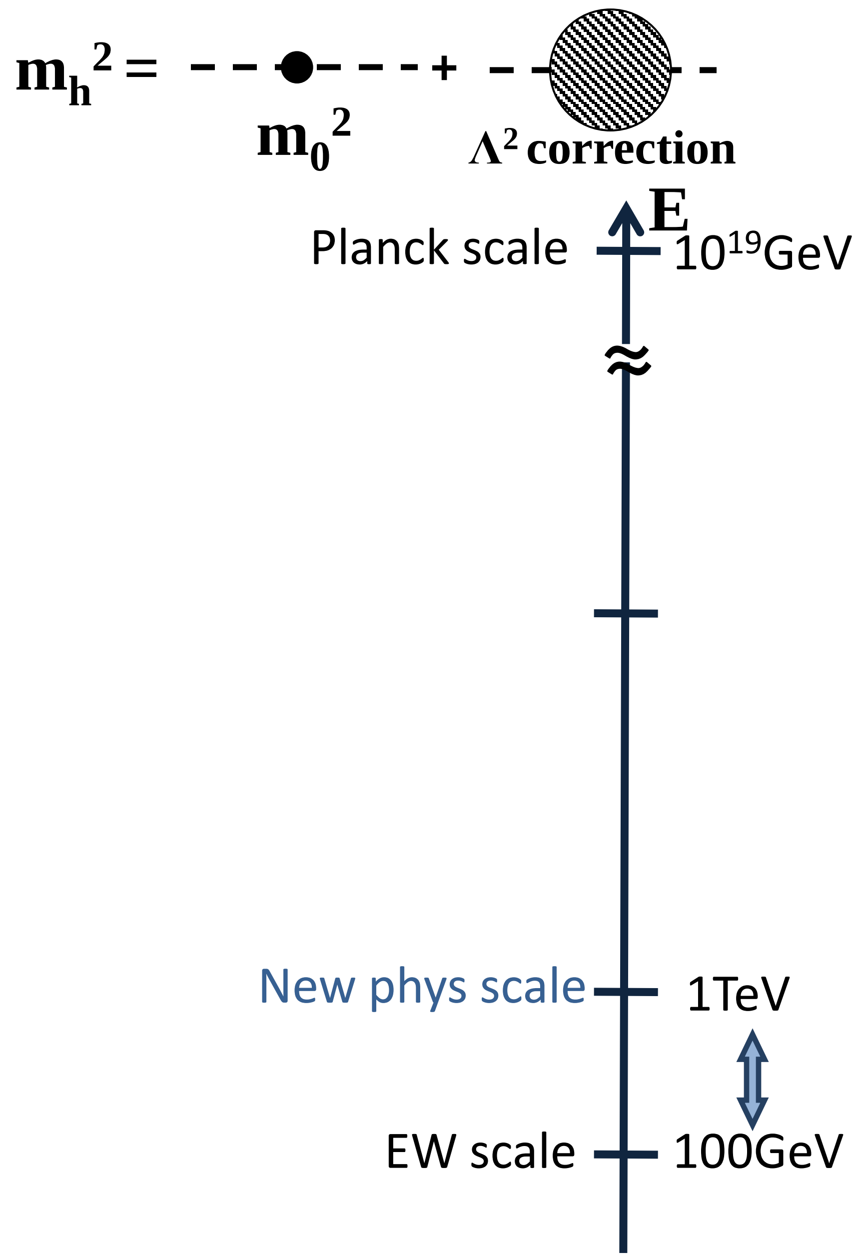
solution

- low energy cut off scenario

If $\Lambda \sim 1\ \text{TeV}$,

there are no fine-tuning!



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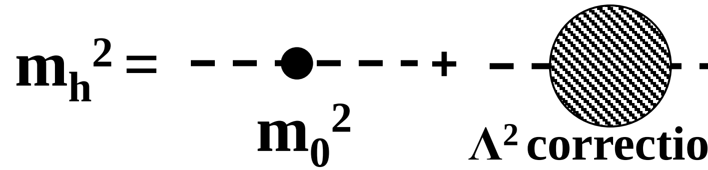

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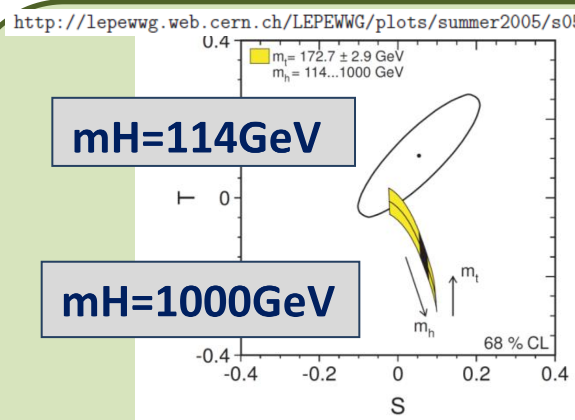
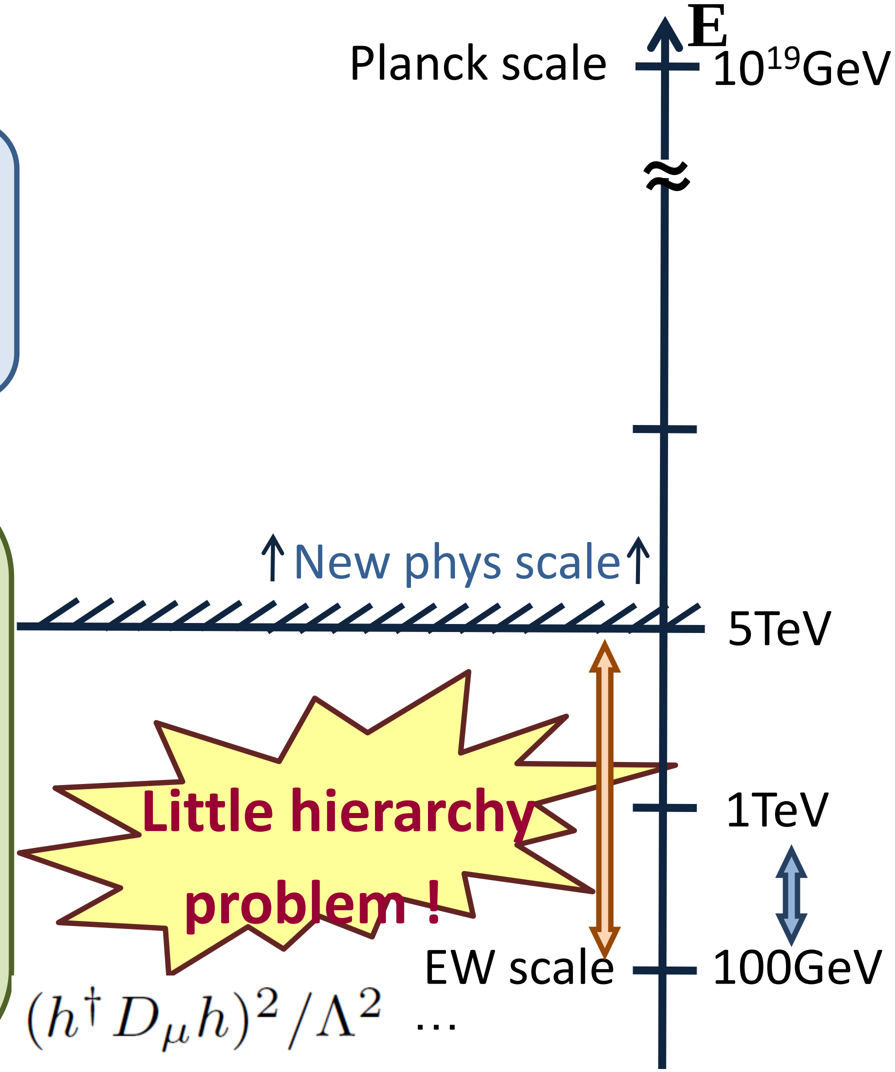
But… LEP experiments require



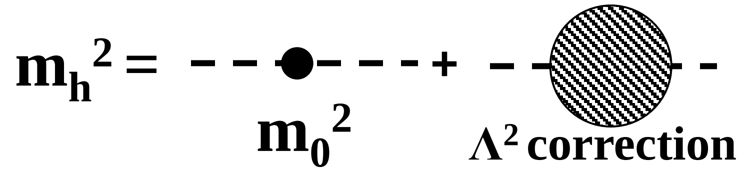
$$\Lambda \gtrsim 5 \text{ TeV}$$

R.Barbieri and A.Strumia ('00)



$(h^\dagger D_\mu h)^2/\Lambda^2$ …

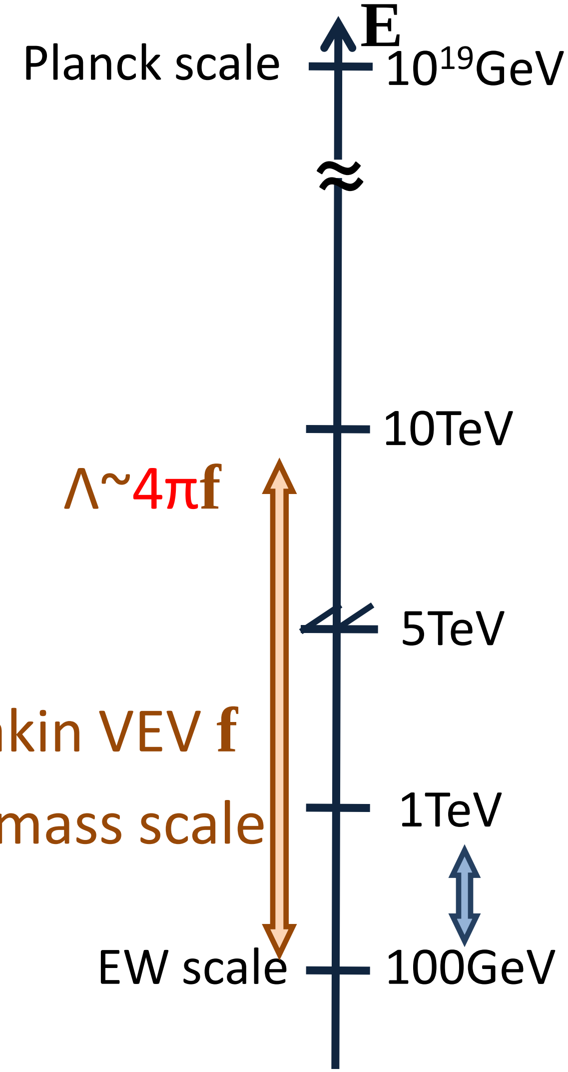
Little Hierarchy Problem



solution

Even if $\Lambda \sim 10$ TeV, no fine-tuning!

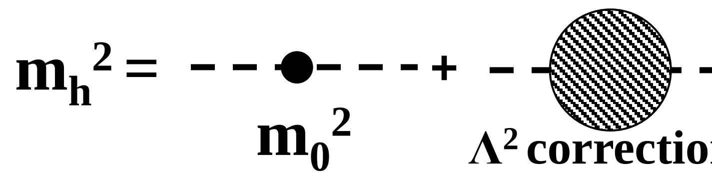
Because of



Global sym.breakin VEV **f**

& new particle mass scale

• Little Hierarchy Problem



solution

- Little Higgs model

  Even if $\Lambda \sim 10$ TeV, no fine-tuning!

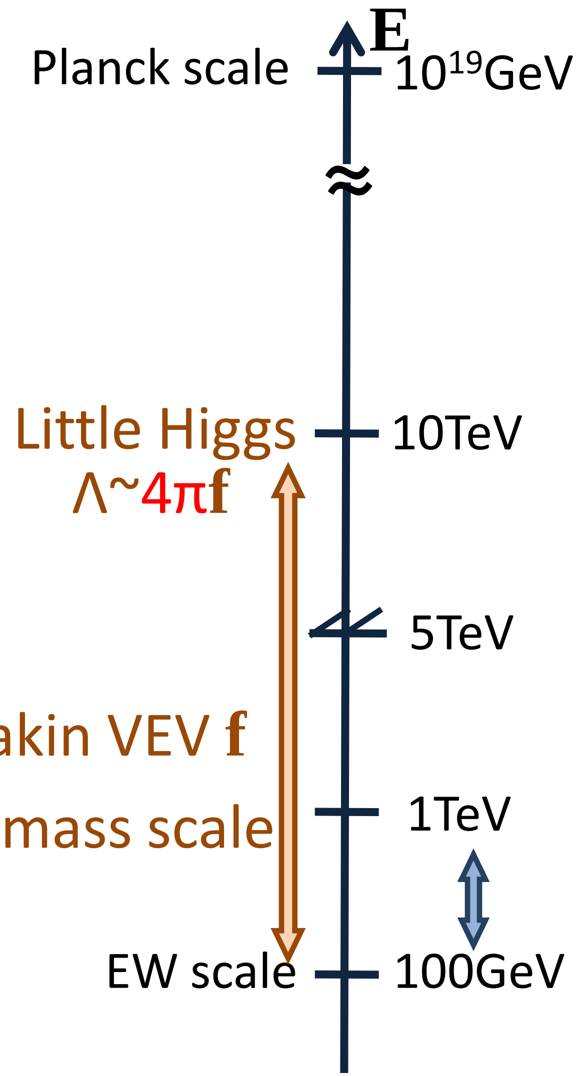
  Because of Little Higgs mechanism

  collective symmetry breaking (VEV **f**)

  induces cancelation

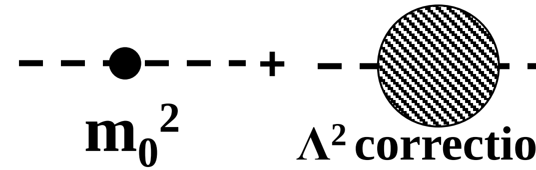
⇨ Global sym.breakin VEV **f**

& new particle mass scale



• Little Hierarchy Problem

$m_h^2 =$



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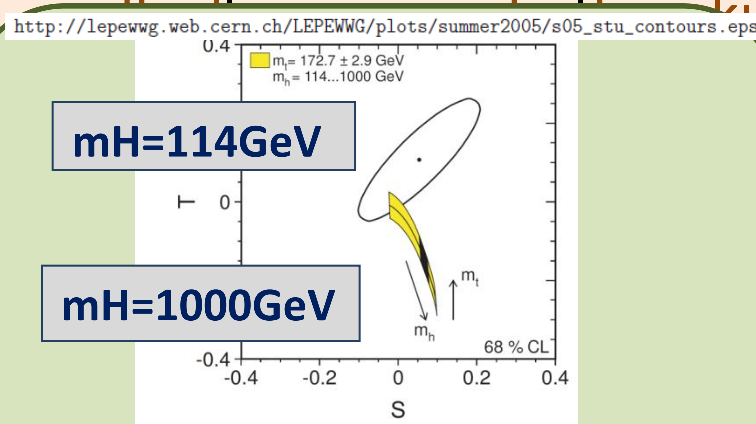

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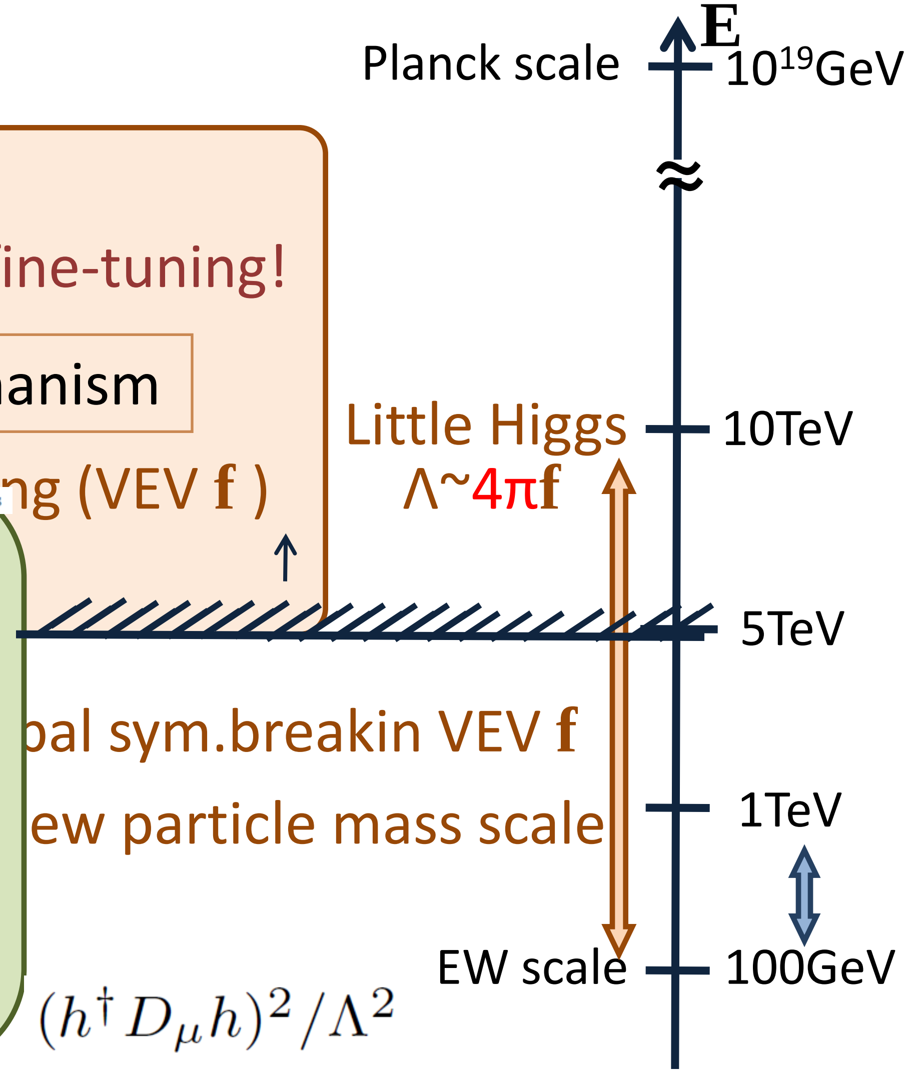
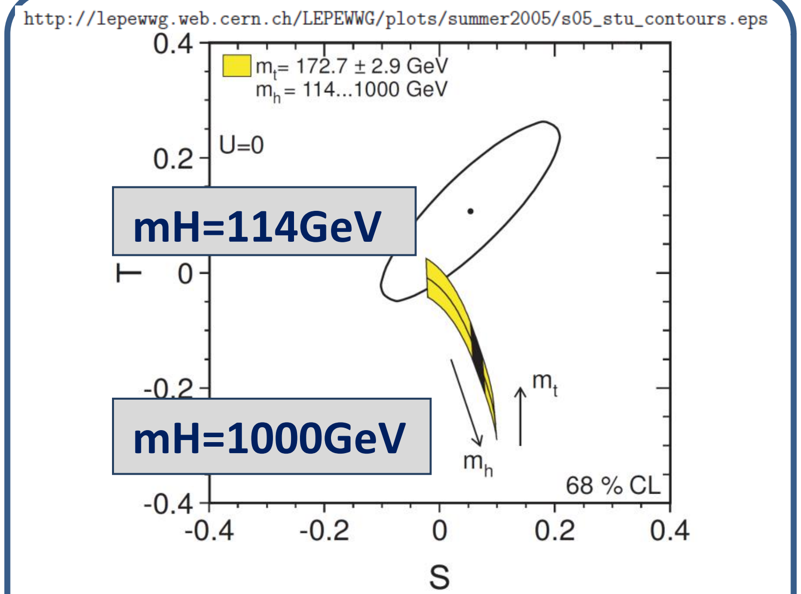


$(h^\dagger D_\mu h)^2/\Lambda^2$

Little Hierarchy Problem

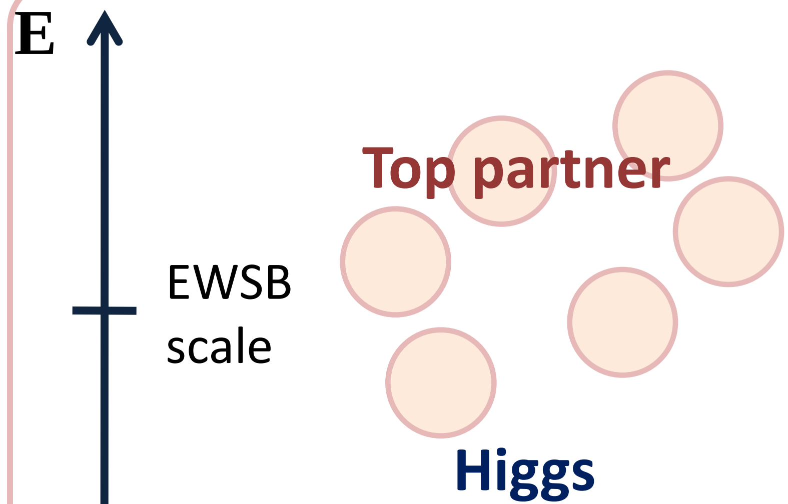
EWPM



Higgs is light (~100GeV) &

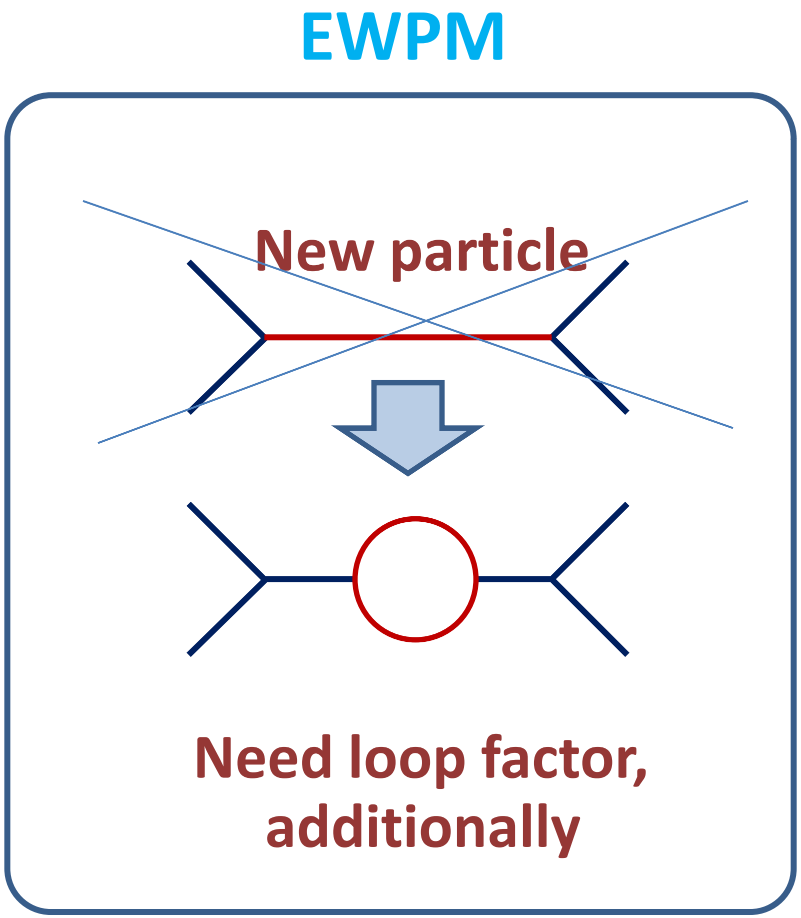
no new physics contribution

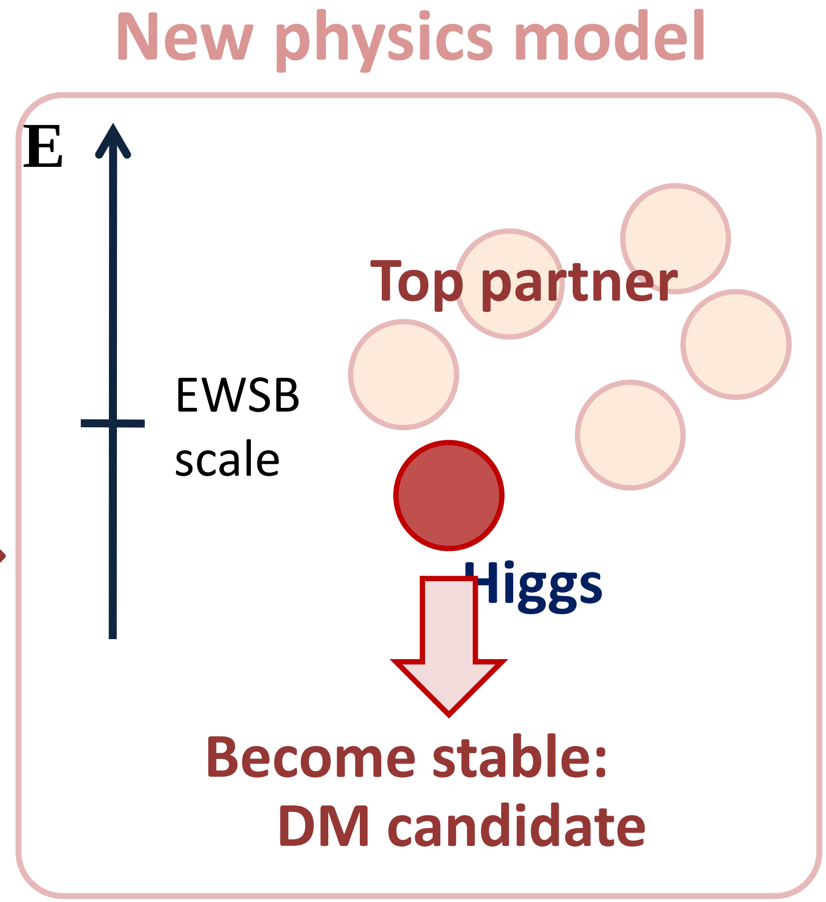
New physics model



Many particle should be ~ EWSB scale

• Little Hierarchy Problem





➡ Z_2 symmetry! (which guarantee "no tree level contribution to EWPM" & lightest Z_2-odd stable particle) Then,

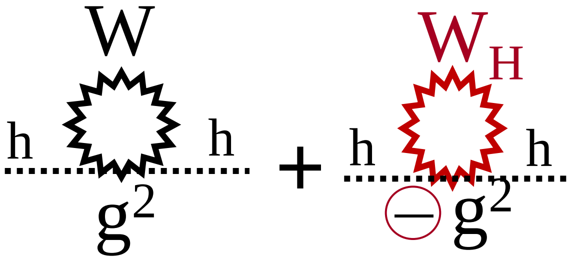
Z_2 symmetry would also be a key to solve little hierarchy (& DM).

Little Higgs model with T-parity

- **Little Higgs mechanism**

Collective symmetry breaking (VEV f) N. Arkani-Hamed, A. G. Cohen, H. Georgi ('01)

- Higgs boson is regarded as **Pseudo NG boson** of a global symmetry at some higher scale.
- Explicit breaking of the global symmetry is specially arranged to **cancel quadratic divergent corrections to m_h** at 1-loop level by new gauge bosons and fermions.



Λ can be ~10 TeV without fine-tuning!

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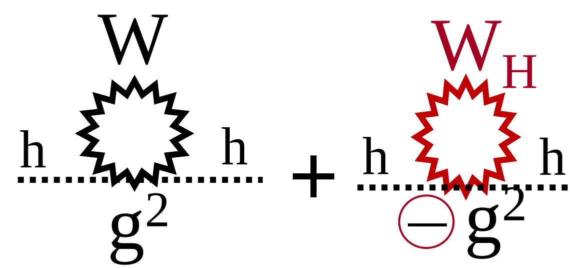
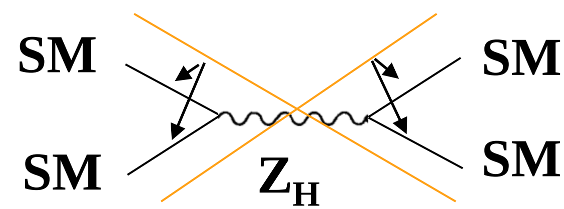


⇒ **Λ can be ~10 TeV without fine-tuning!**

- **T-parity** H. C. Cheng, I. Low ('03)

In order to avoid constraints from EWPM, Z_2 symmetry called T-parity are introduced.

SM ⇔ SM, New ⇔ - New



The model contains dark matter candidate! (Heavy photon A_H)

What is the LHT?

In order to Implement the Little Higgs Mechanism…

- Littlest Higgs model with T-parity is based on the non-linear sigma model breaking **SU(5)/SO(5)** symmetry breaking.
- The subgroup $[SU(2)\times U(1)]^2$ in SU(5) is gauged, which is broken down to the SM gauge group by vev **f**.

gauge group VEV

$$[SU(2)\times U(1)]^2$$

$\downarrow \longleftarrow$ $f \sim O(1)$ TeV

$$[SU(2)\times U(1)]_{SM}$$

$\downarrow \longleftarrow$ $\langle h \rangle$

$$U_{em}(1)$$

[Arkani-Hamed, Cohen, Katz and Nelson (2002)]

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Kinetic term of non-linear sigma model — gauge couplings (**SU(2)**)

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_j \left[g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + \dots, \right.$$

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$$

The global sym. is explicitly broken by gauge &Yukawa coupling but only collectively: Each gauged **[SU(2) × U(1)]i** commute with different subgroup of *G* that acts on the Higgs field non-linearly.

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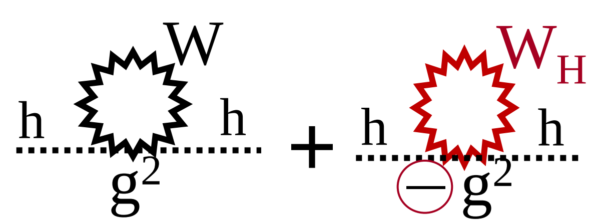
The global sym. is explicitly broken by gauge &Yukawa coupling but only collectively: Each gauged [**SU(2)×U(1)]i** commute with different subgroup of G that acts on the Higgs field non-linearly. Thus, if any one of gauge couplings is zero, the Higgs boson is an exact Nambu-Goldstone boson (due to the restoration of the global symmetry).

Since there are one gauge coupling in 1-loop diagram, the quadratic divergence is vanished in 1-loop level!



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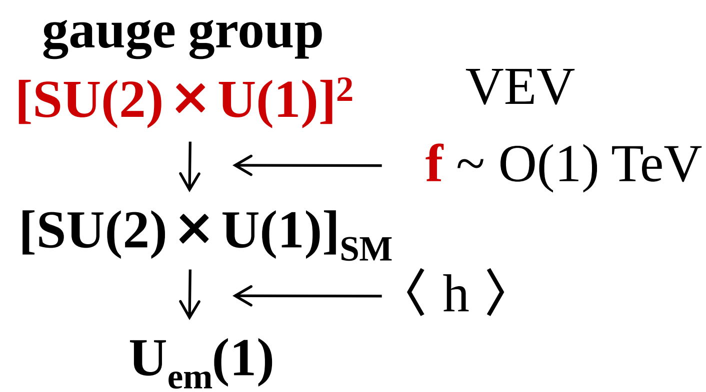
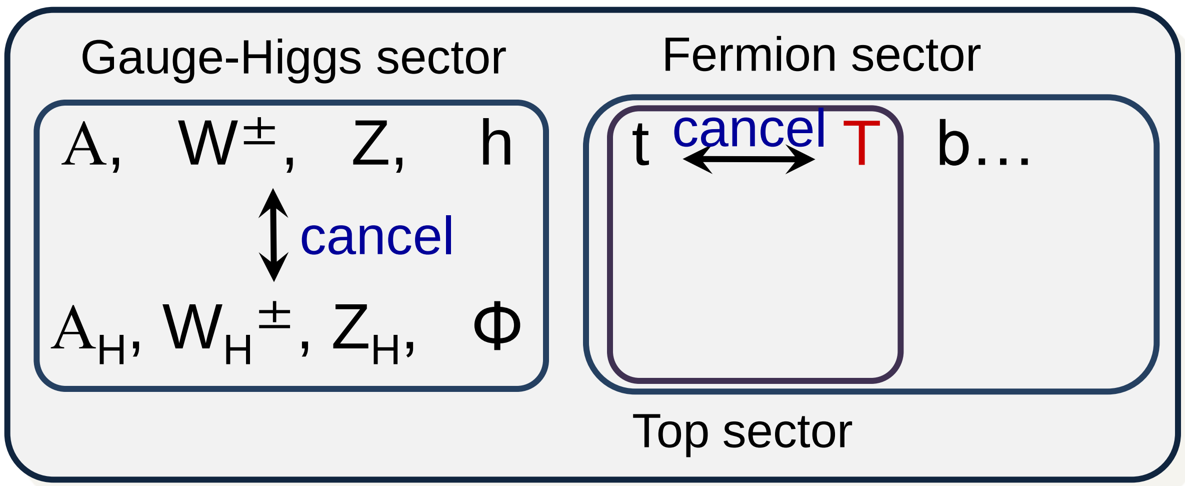
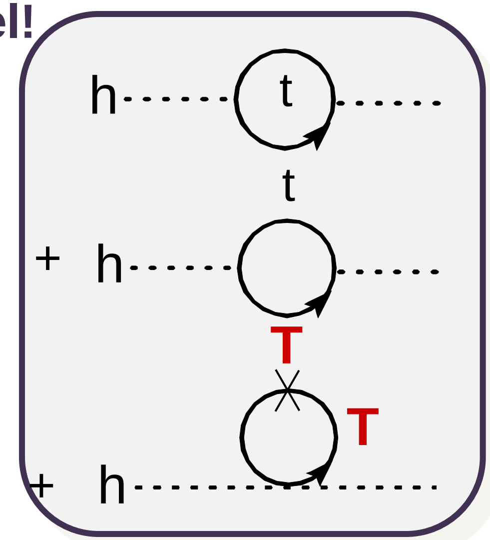


[Arkani-Hamed, Cohen, Katz and Nelson (2002)]

Particle contents



Cancel!



Due to the cancelation of quadratic divergences, partners are introduced. In the fermion sector, only top partner is required to cancel the quadratic divergences because other fermion Yukawa couplings are small.

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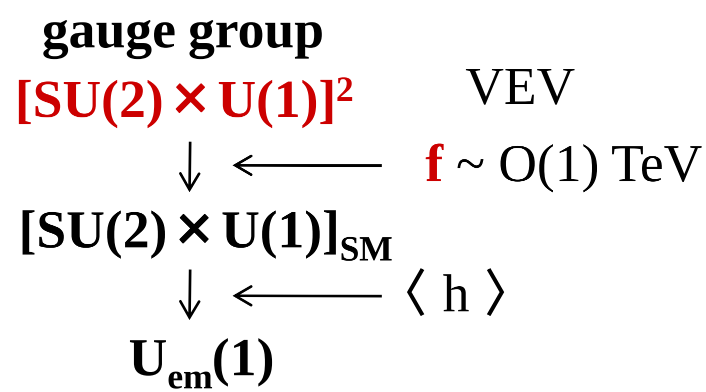

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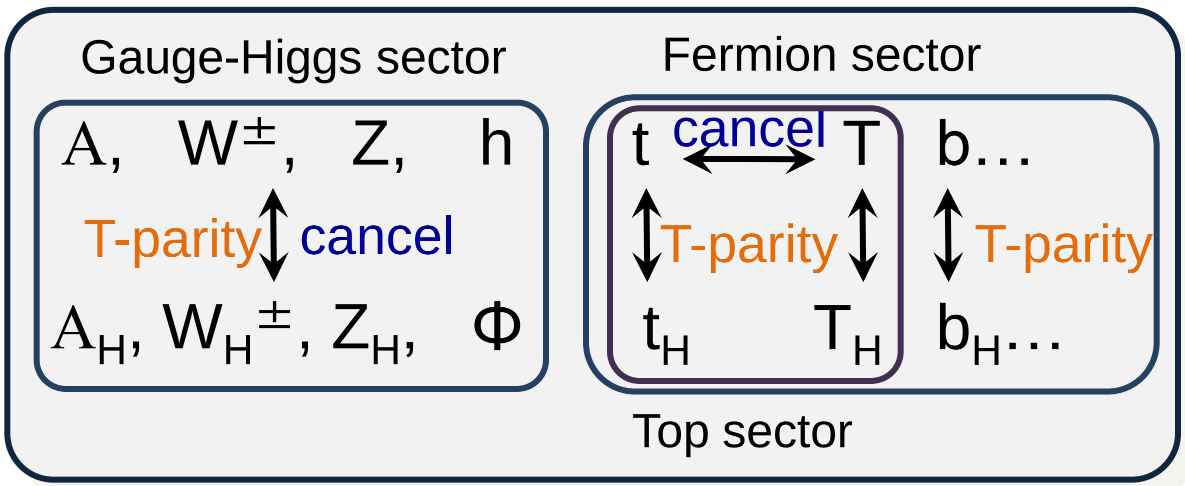
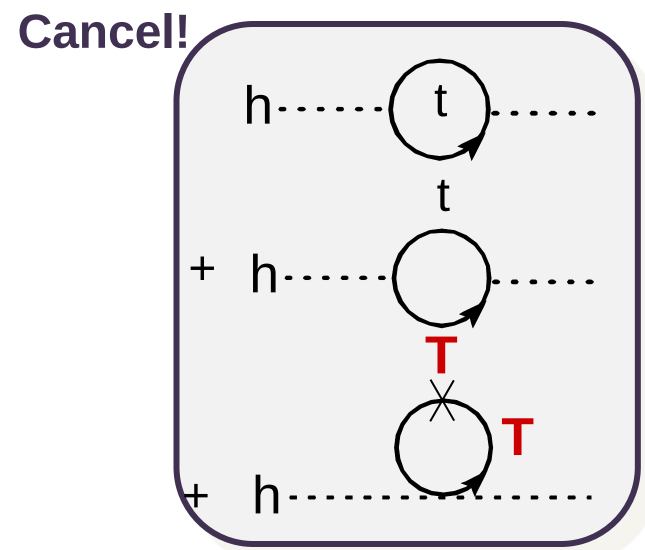




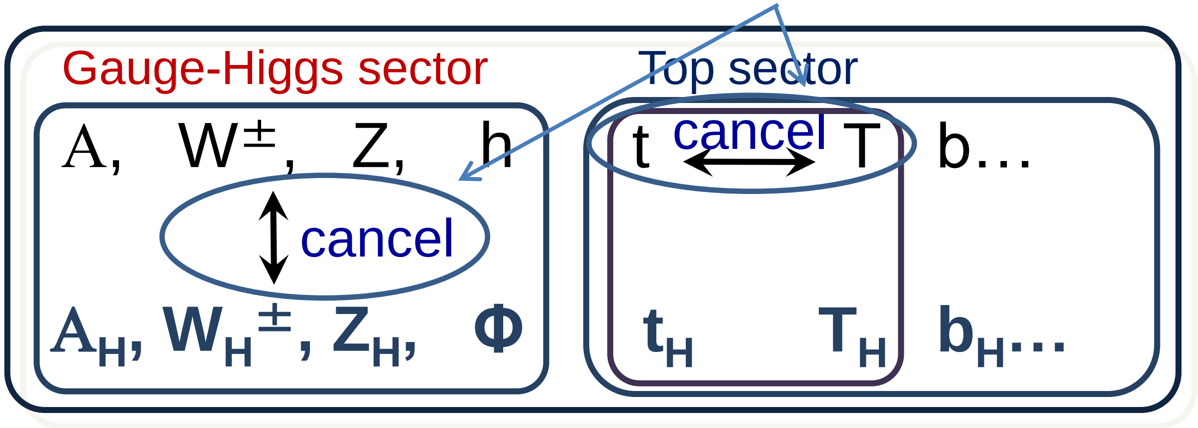
In order to implement the T-parity…

$$[SU(2)\times U(1)]_1 \longleftrightarrow [SU(2)\times U(1)]_2$$

T-odd partners are introduced for each fermions.

How to measure the LHT at ILC?

In order to verify the Little Higgs model,
we should measure the **Little Higgs mechanism!**



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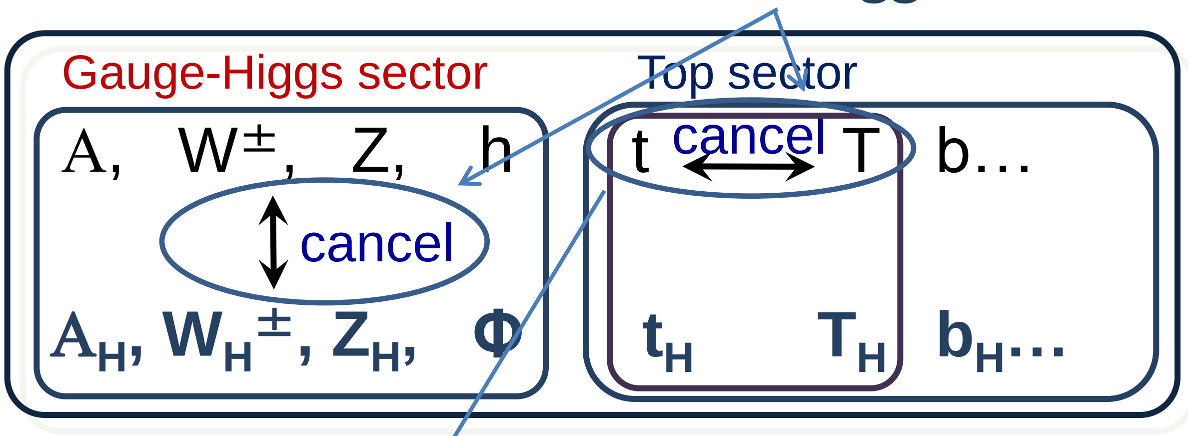

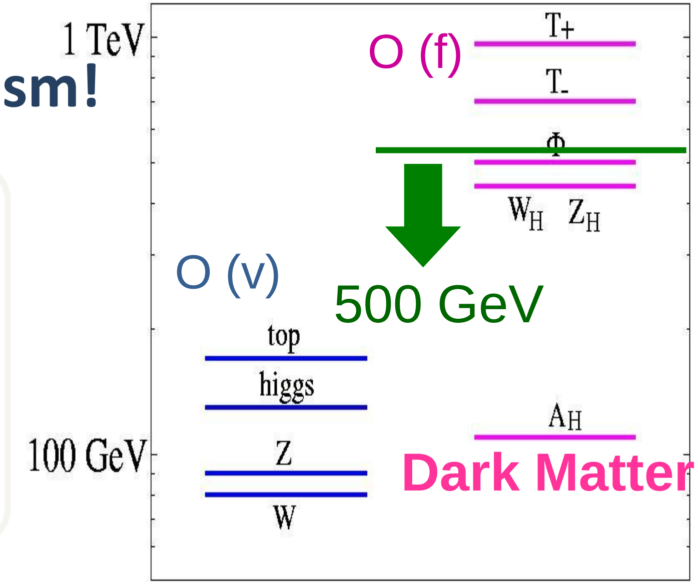

mass spectrum

1. Top sector

- can be measured at LHC.
- too heavy to produced at ILC.

S. Matsumoto, T. Moroi, K. Tobe (08) and recent papers …….

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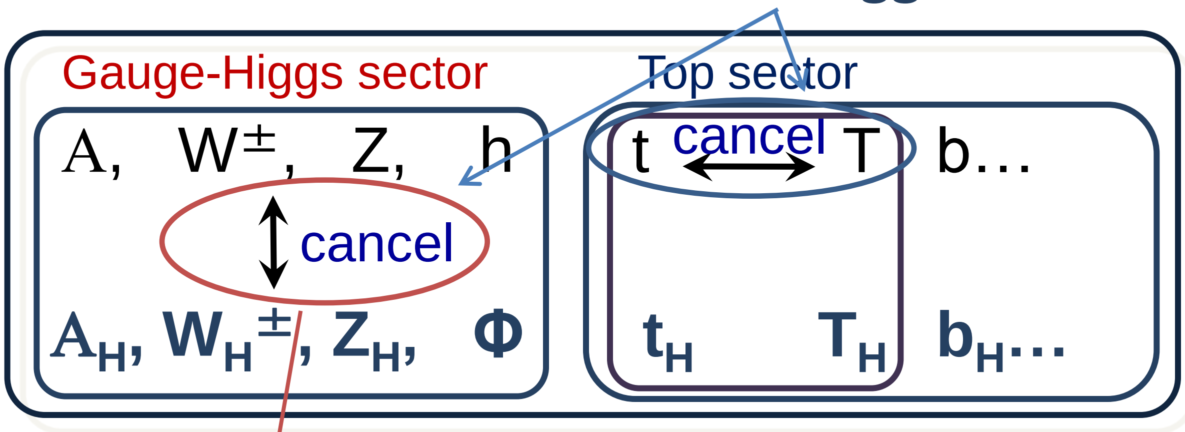

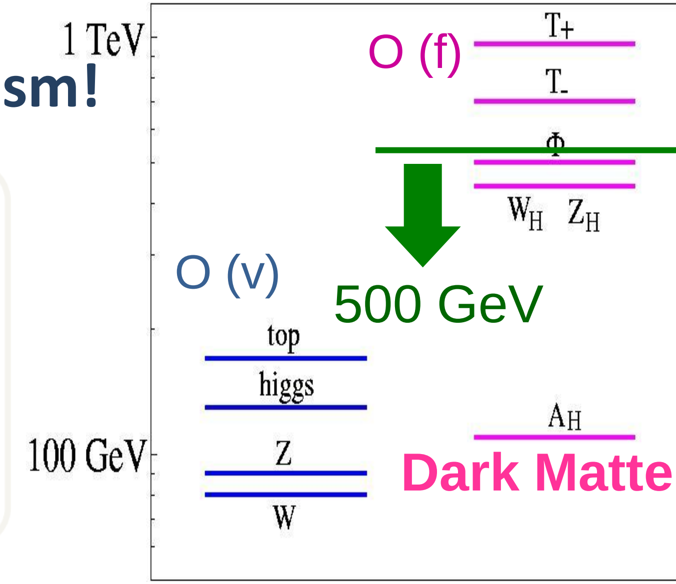

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2. Gauge sector

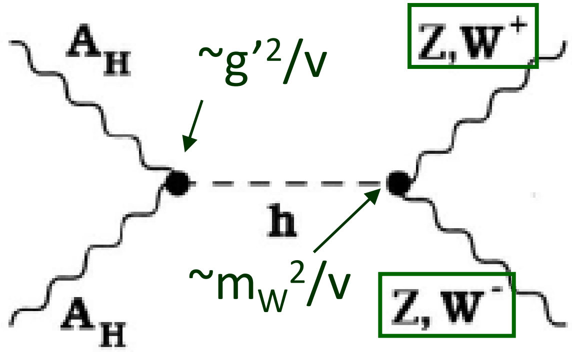
- can be produced at ILC!
- cannot precise measurement at LHC
- masses depend only on vev f!

Q. H. Cao, C. R. Chen (07); K. Cheung, et. al. (13)

We should measure the gauge sector in the LHT at ILC.

Representative point
of our simulation

Dark matter annihilation



- The relic density depends only on f & m_h!

$$m_{A_H} \simeq \frac{g'}{\sqrt{5}} f$$

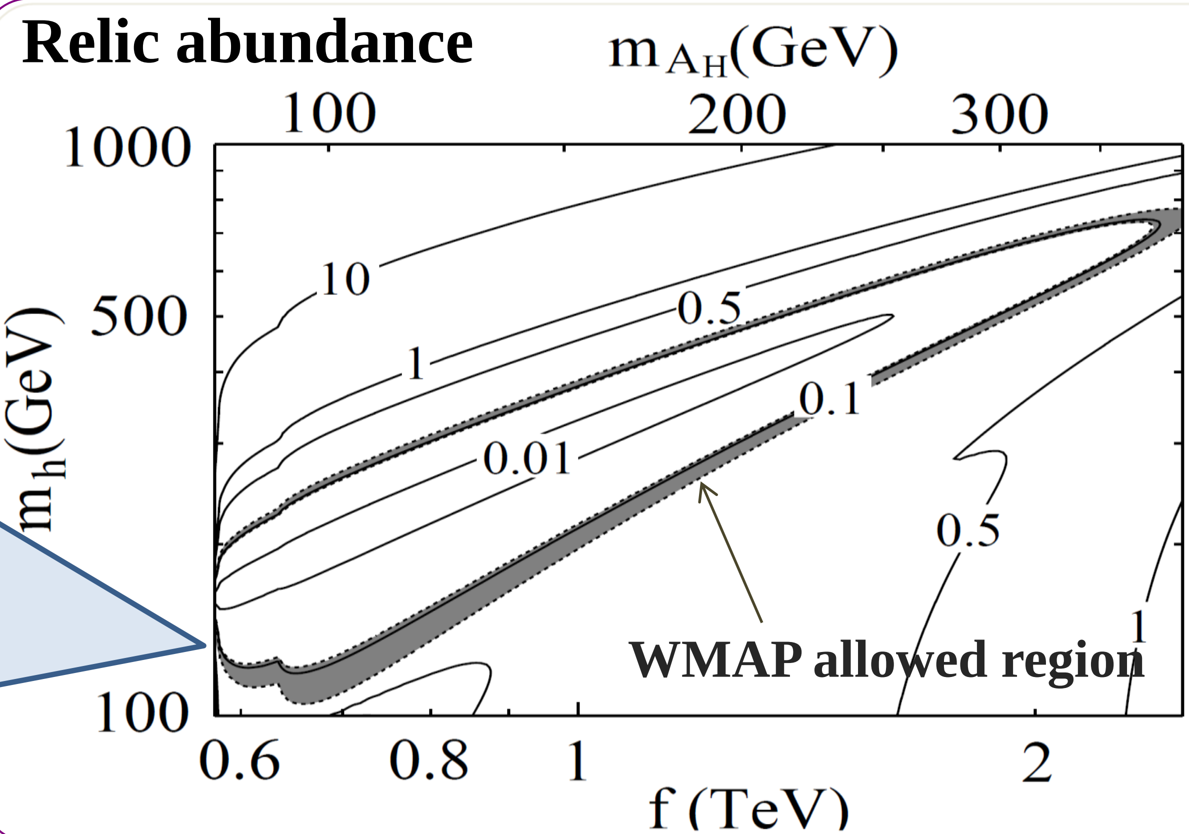
M. A, S. Matsumoto, N. Okada, Y. Okada PhysRevD.75.063506

Dark matter (A_H)

Shaded area is WMAP allowed region .

Related with s-channel pole.

At this WMAP allowed region, the model also satisfys other experimental constraints!



Mode &Representative point

Which particle can produced at the ILC ? → It depends on VEV **f** .

Because heavy gauge boson massed depend only on vev f.

$e^+e^- \rightarrow A_H Z_H$

$e^+e^- \rightarrow W_H W_H$

If f is larger than ~800GeV, the hierarchy problem appears again.

M. A, S. Matsumoto, N. Okada, Y. Okada   PhysRevD.75.063506

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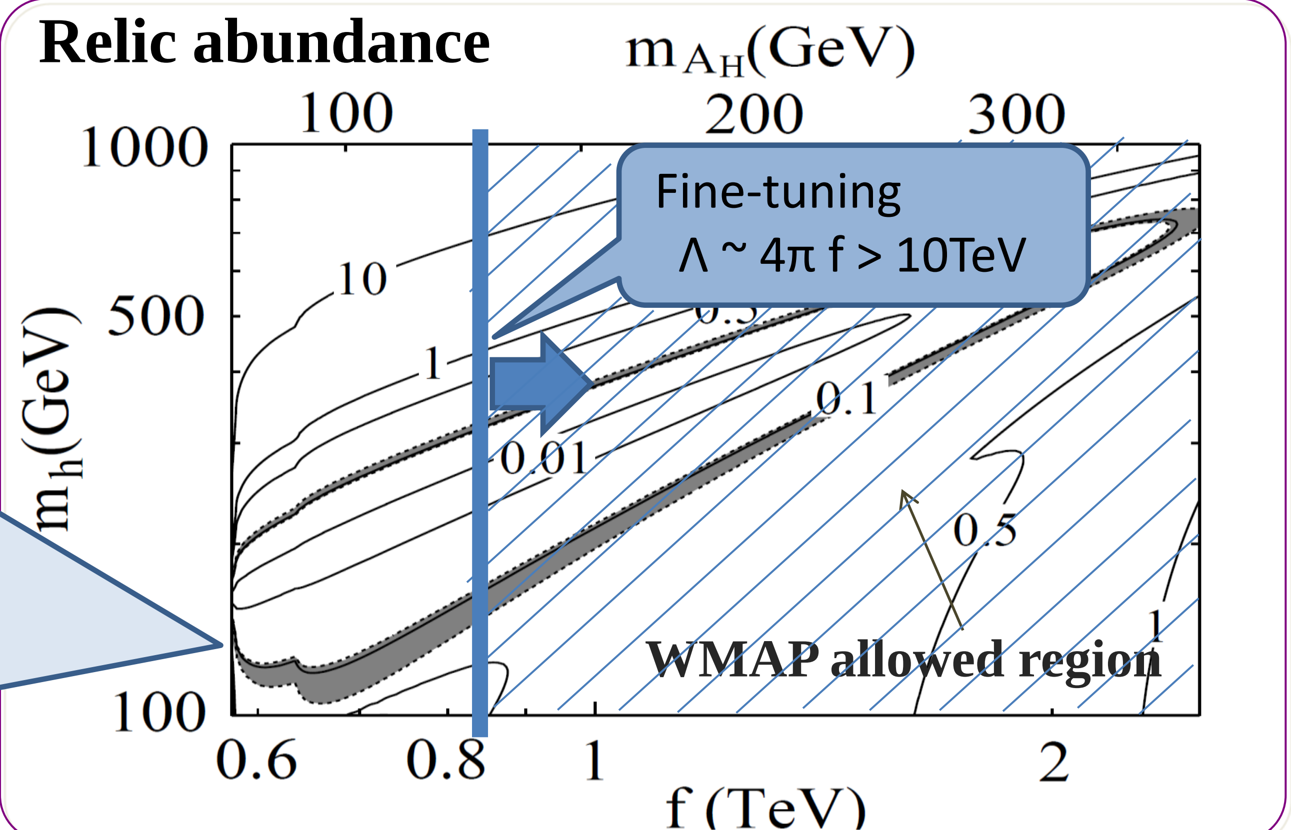

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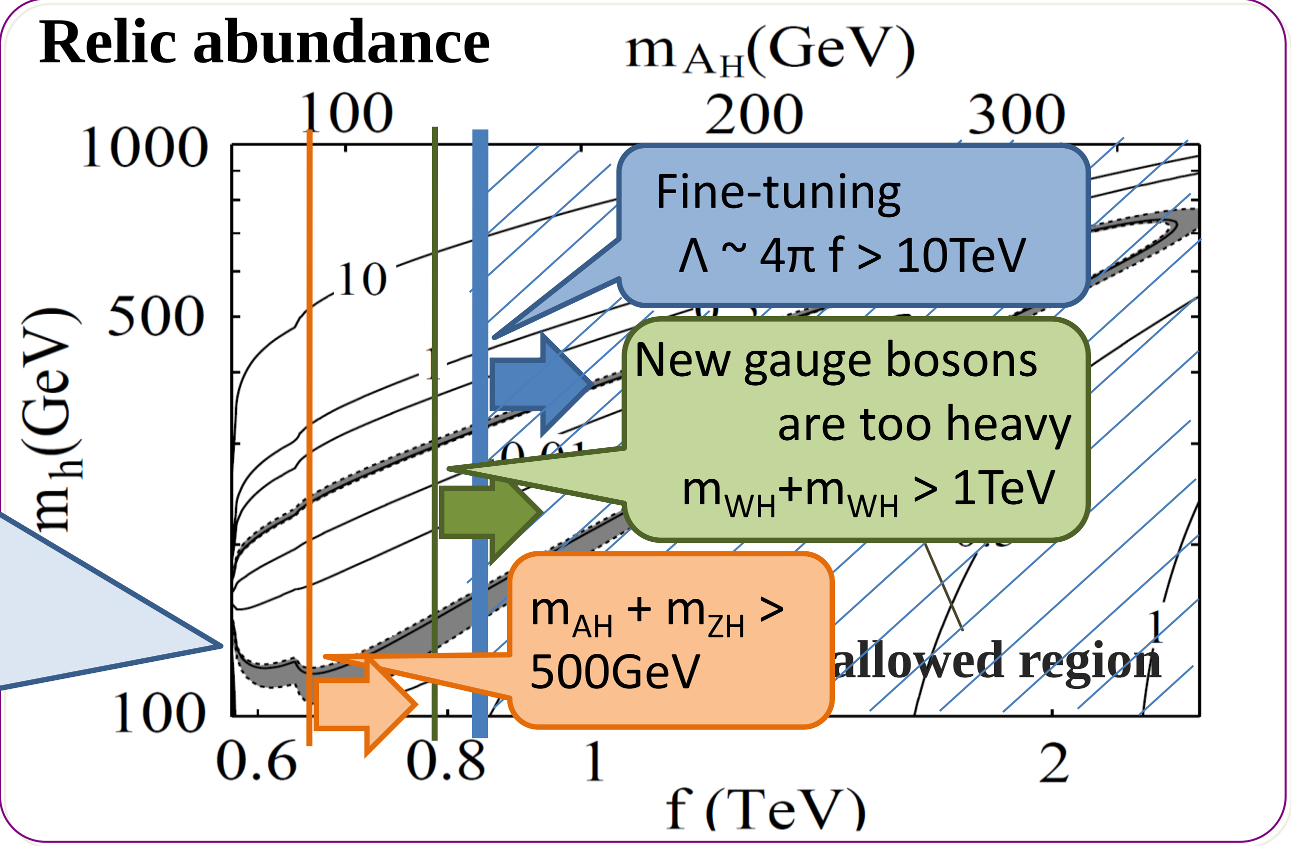

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If Higgs mass is changed as 126GeV, the result accuracy of this analysis would be better.

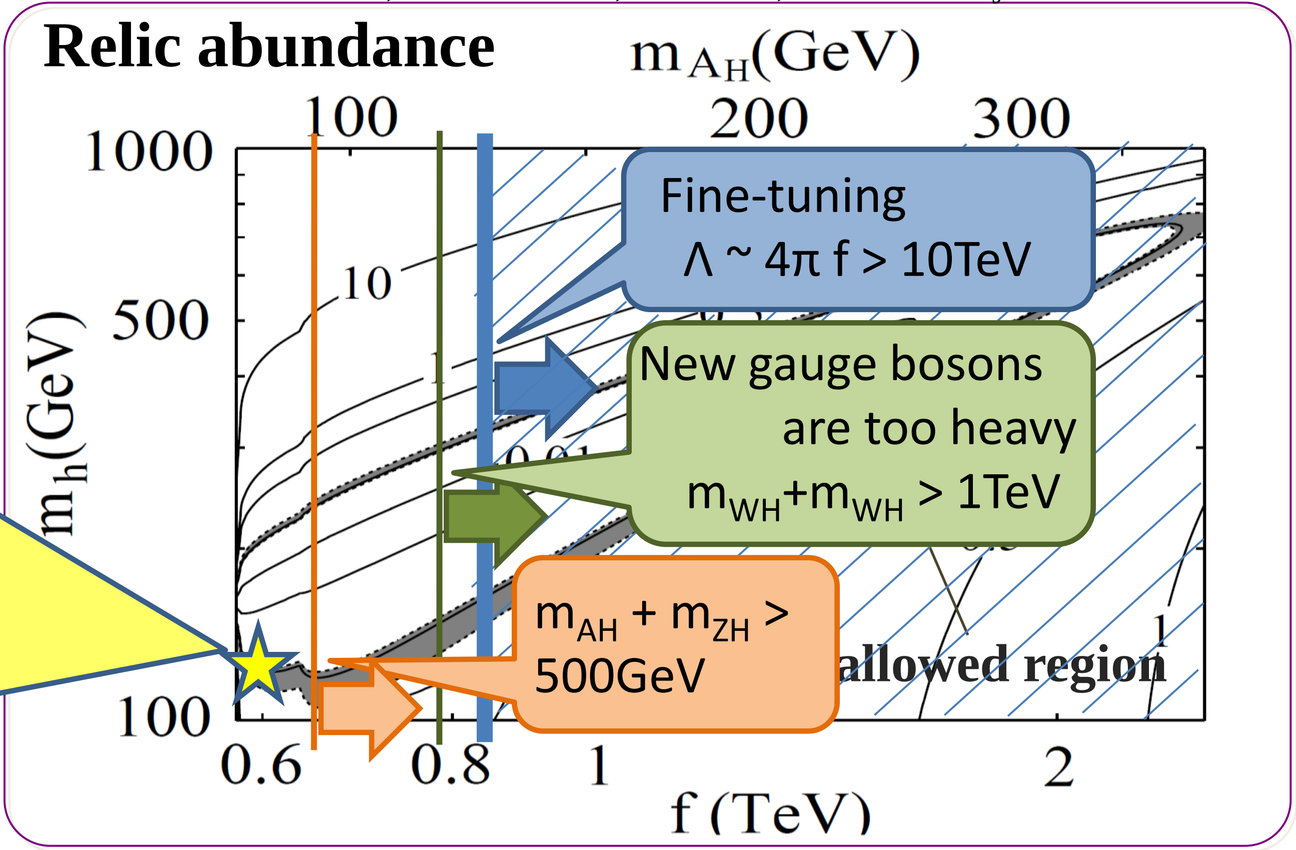
M. A, S. Matsumoto, N. Okada,Y. Okada PhysRevD.75.063506

Mass spectrum

f	580
e_H	410
Z_H	369
W_H	368
A_H	82
Higgs	134

Point I (GeV)

Sample points satisfy all experimental & cosmological constraints.



Simulation results

1.Event generation

Physsim : for **LHT** & **SM** process
- helicity amplitude calculation, gauge boson polarization effect
- phase space integration and generation of parton 4-momenta

2.Hadronization

PYTHIA - parton showering and hadronization

TAUOLA - for final state tau leptons

3.Detector simulation

JSFQuickSimulator - create vertex-detector hits
- smear charged-track parameters in central tracker
- simulate calorimeter signals as from individual segments

Simulations has been performed at $\sqrt{s}$ **= 1 TeV** with an Integrated luminosity of **500** $\mathbf{fb^{-1}}$

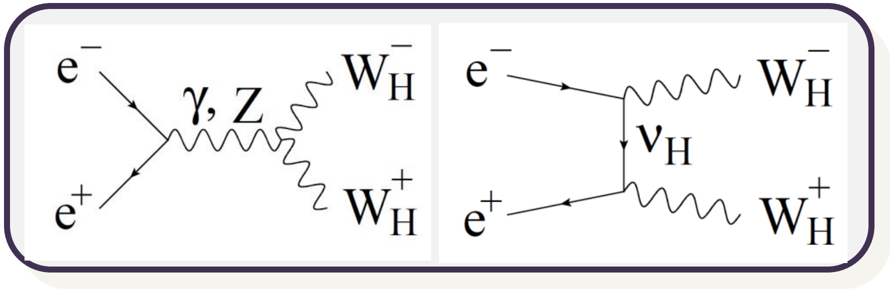
Heavy gauge boson masses

$e^+e^- \rightarrow W_H W_H$

$e^+e^- \rightarrow Z_H Z_H$

Event

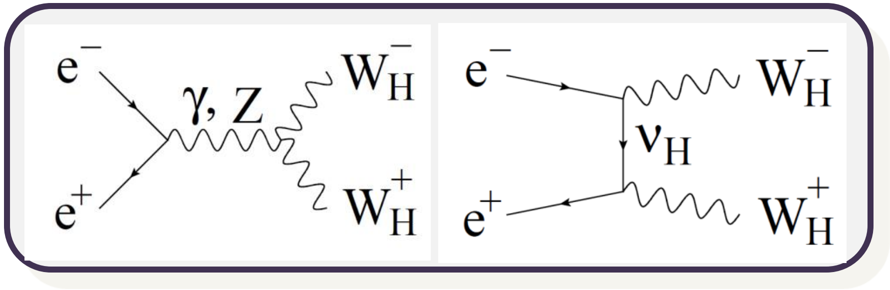
$e^+e^- \rightarrow W_H W_H$



Event

$e^+e^- \rightarrow W_H W_H \rightarrow A_H A_H WW$

$W \rightarrow q\bar{q}$ (BR = 67.6%)
$W \rightarrow l\nu$ (BR = 32.4%)

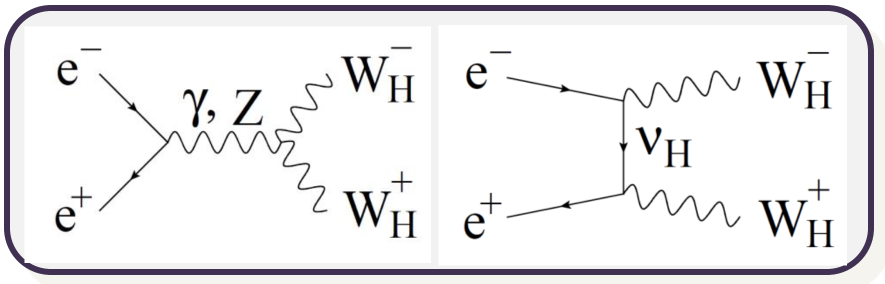


$A_H A_H$ qqqq as the signal event

Event

$e^+e^- \rightarrow W_H W_H \rightarrow A_H A_H WW$

- Large missing energy
- 4 jet in final state



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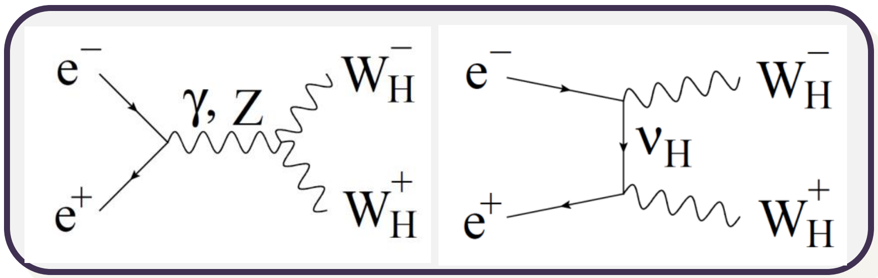
Signal

Background

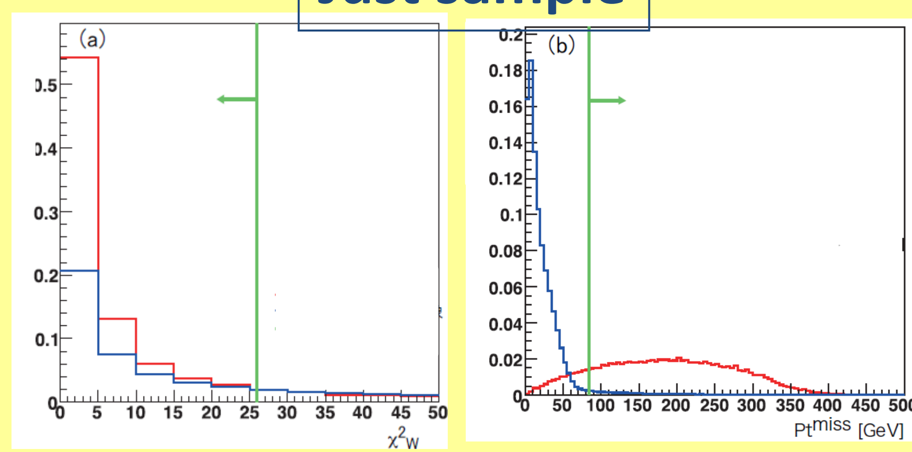
- Large missing energy
- 4 jet in final state

Process	cross section (fb)
$W_H W_H \to A_H A_H qqqq$	120.0
$WW \to qqqq$	1307
$eeWW \to eeqqqq$	490
$e\nu_e WZ \to e\nu_e qqqq$	24.5
$\nu\bar{\nu}WW \to \nu\bar{\nu}qqqq$	18.8
$ZWW \to \nu\bar{\nu}qqqq$	7.23
$Z_H Z_H \to A_H A_H qqqq$	5.61



Selection Cut

Just sample



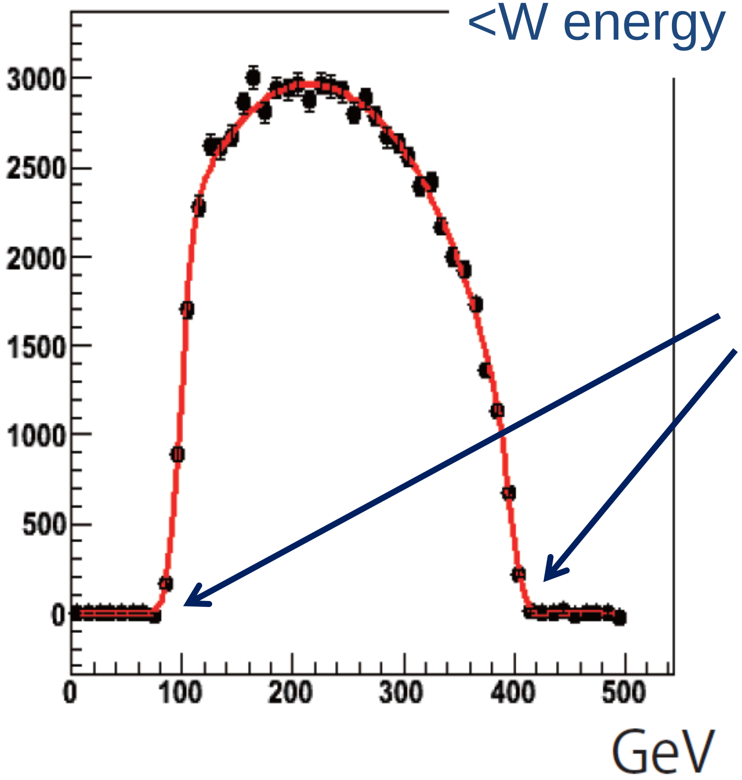
$\chi_W^2 < 26$ $\quad$ $P_t^{miss} > 84$(GeV)

E_W < 500GeV : energy of W

χ_W^2 < 26 : χ^2 for $W^\pm$ reconstruction from jets

P_T^{miss} > 84 GeV/c : Missing transverse momentum

<W energy distribution>



The Energy distribution of W from $W_H W_H$ after subtraction of the backgrounds, whose number of events was estimated by independent BG samples. The distribution is fitted by a polynomial function.

Results

Preliminary

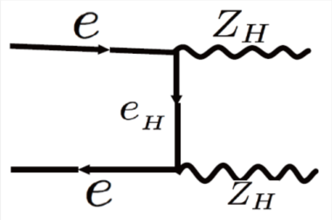
$$\mathbf{m_{AH}} = 81.9 \pm 0.6 \text{ GeV},$$
$$\mathbf{m_{WH}} = 368.2 \pm 0.6 \text{ GeV}$$

or

$$\mathbf{m_{AH}} = 81.0 \pm 0.6 \text{ GeV},$$
$$\mathbf{m_{WH}} = 218.0 \pm 0.7 \text{ GeV}$$

Event

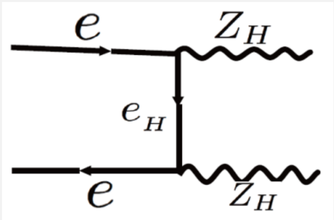
$e^+e^- \rightarrow Z_H Z_H$



Event

$e^+e^- \rightarrow Z_H Z_H \rightarrow A_H A_H hh$

- Large missing energy
- 4 jet in final state



Higgs boson mainly decays into bb (or WW)

$A_H A_H$ qqqq as the signal event

Event

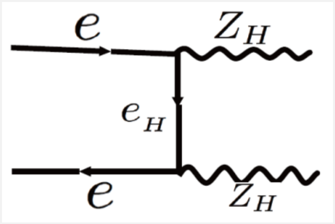
$e^+e^- \rightarrow Z_H Z_H \rightarrow A_H A_H hh$

Signal

Process	cross section (fb)
$Z_H Z_H \rightarrow A_H A_H HH$ $\rightarrow A_H A_H qqqq$	98.0
WWZ	63.86
$\nu\nu WW$	14.67
WW	3069
tt	192.9
ZZ	202.2
ZH	17.98
$W_H W_H$	108.6

Background

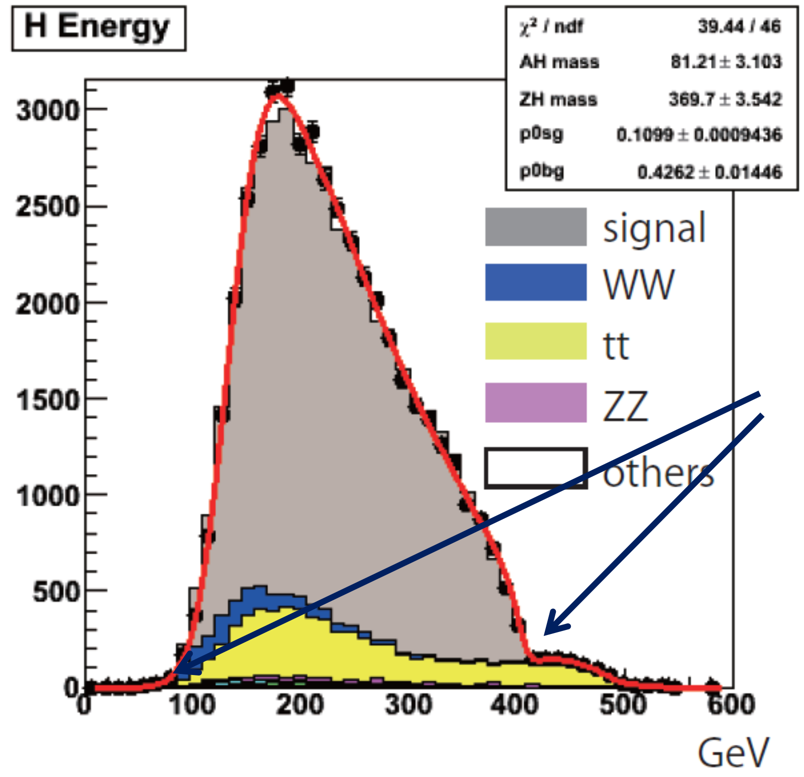
- Large missing energy
- 4 jet in final state



Selection Cut

No isolated leptons
♯of b-jet > 1
Acoplanarity > 20°

E_h < 500GeV : energy of higgs
χ_h^2 < 60 : χ^2 for higgs reconstruction from jets
P_T^{miss} > 84 GeV/c : Missing transverse momentum



<Higgs energy distribution>

The Energy distribution of reconstructed higgs boson. The distribution is fitted by a polynomial function.

Results

Preliminary

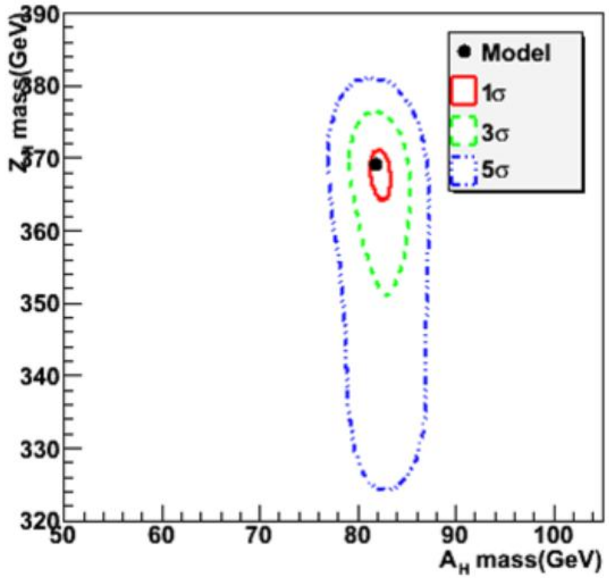
$$\mathbf{m_{AH}} = 82.7 \pm 3.5 \text{ GeV},$$
$$\mathbf{m_{ZH}} = 367.1 \pm 4.7 \text{ GeV}$$

or

$$\mathbf{m_{AH}} = 93.0 \pm 3.5 \text{ GeV},$$
$$\mathbf{m_{ZH}} = 335.4 \pm 4.7 \text{ GeV}$$

Process	obtained mass	solution 1 (GeV)	solution 2 (GeV)
$W_H W_H$	(A_H, W_H)	(81.9, 368.3)	(81.0, 218.0)
$Z_H Z_H$	(A_H, Z_H)	(82.7, 366.1)	(93.0 , 335.4)

Simultaneous fit using $W_H W_H$ & $Z_H Z_H$ signal



in order to obtain the true mass because true solution of mAH.

Preliminary

Results

A_H	81.9 GeV	1.3%
W_H	369 GeV	0.20%
Z_H	368 GeV	0.56%

High accuracy !

f = 580 GeV 0.16 %

Heavy lepton masses

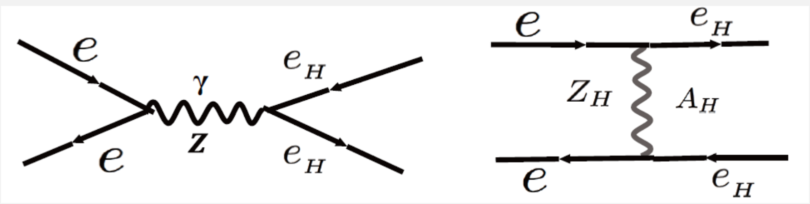
$e^+e^- \rightarrow e_H e_H$

$e^+e^- \rightarrow \nu_H \nu_H$

Event

$e^+e^- \rightarrow e_H e_H \rightarrow eeZ_H Z_H \rightarrow eeA_H A_H qqqq$

Particle	Branch	Br
	eA_H	30%
e_H	eZ_H	25%
	νW_H	45%



$eeA_H A_H$ qqqq as the signal event

Event

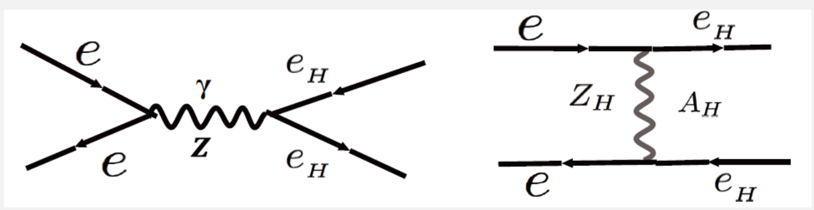
$e^+e^- \rightarrow e_H e_H \rightarrow eeZ_H Z_H \rightarrow eeA_H A_H qqqq$

Signal

Background

Process	cross section (fb)
$e_H e_H \rightarrow eeZ_H Z_H \rightarrow eeA_H A_H qqqq$	3.91
tt	200.7
$eeWW$	1020
$\tau_H \tau_H$	3.32
$ttZ, ttH,$	114.5

We also consider
$e\nu WZ$, $eeZZ$, WWZ, ZZZ

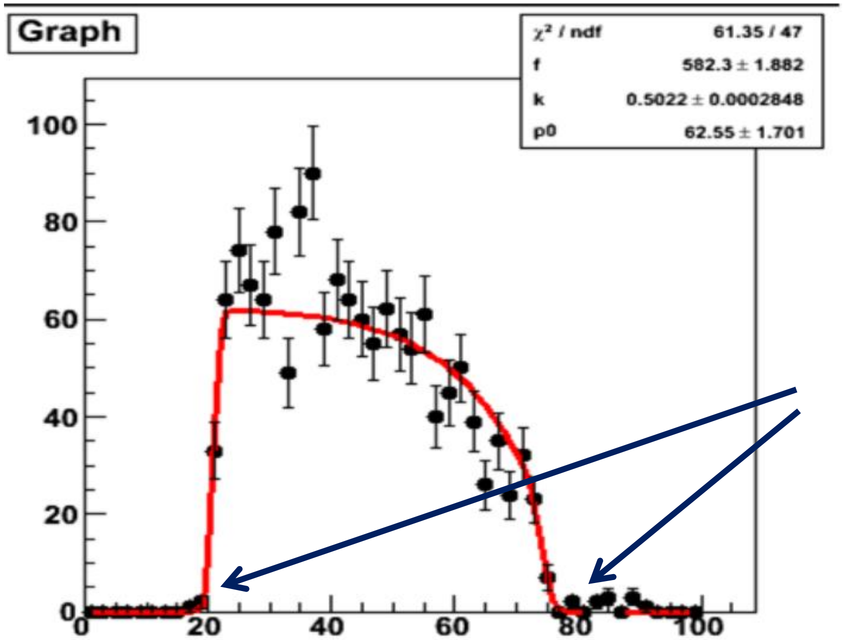


$eeA_H A_H$ qqqq as the signal event

Selection Cut

One isolated electrons & positron, and 4-jets
Two Higgs bosons (104 GeV < mh < 164 GeV)
P_T^{miss} > 50 GeV/c : Missing transverse momentum

<electron energy distribution>



The Energy distribution of reconstructed higgs boson. The distribution is fitted by a polynomial function.

Results

$$\mathbf{m_{eH}} = 412.8 \pm 1.7 \text{ GeV},$$
$$\mathbf{m_{ZH}} = 371.2 \pm 1.5 \text{ GeV}$$

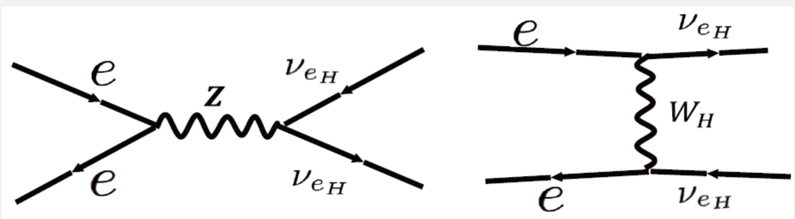
Preliminary

High accuracy !

Event

$e^+e^- \rightarrow \nu_H\nu_H \rightarrow eeW_HW_H \rightarrow eeA_HA_Hqqqq$

Particle	Branch	Br
	eW_H	65%
ν_H	νZ_H	11%
	νA_H	24%



eeA_HA_H qqqq as the signal event

parameter	True value	measurement accuracy
f	580 GeV	0.16 %
κ_ℓ	0.5	0.01 %

Event

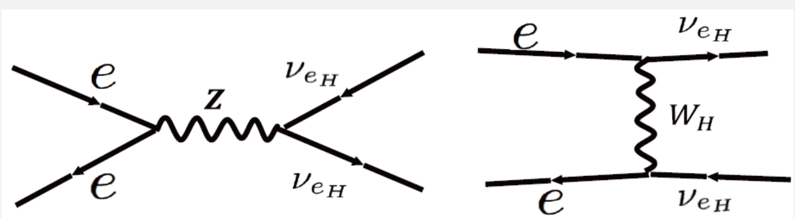
$e^+e^- \to \nu_H\nu_H \to eeW_HW_H \to eeA_HA_Hqqqq$

Signal

Background

Process	cross section (fb)
$\nu_H\nu_H \to eeW_HW_H$ $\to eeA_HA_Hqqqq$	26.0
$\nu_{\tau_H}\nu_{\tau_H}, e_He_H,$	3.3 + 3.9
$tt, ttZ, ttH,$	2482

We also consider
$e\nu WZ$, eeWW, WWZ, ZZZ

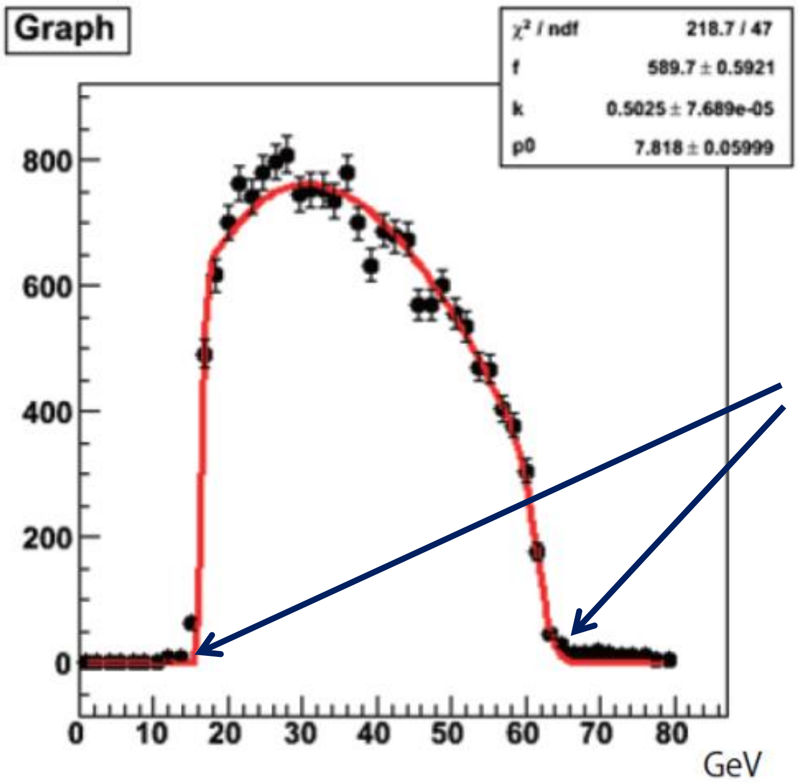


eeA_HA_H qqqq as the signal event

Selection Cut

One isolated electrons & positron, and 4-jets
Two W bosons (60 GeV < mW < 100 GeV)
P_T^{miss} > 50 GeV/c : Missing transverse momentum

<electron energy distribution>



The Energy distribution of reconstructed higgs boson. The distribution is fitted by a polynomial function.

Results

$\mathbf{m_{\nu H}} = 400.8 \pm 0.4$ GeV,

$\mathbf{m_{WH}} = 369.6 \pm 0.4$ GeV

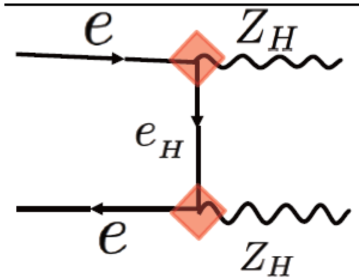
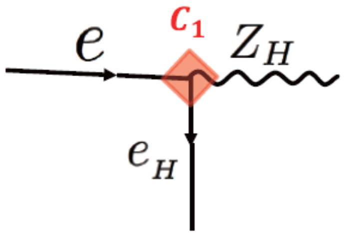
Preliminary

High accuracy !

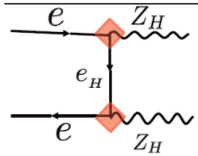
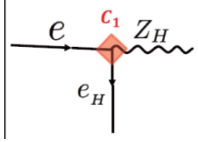
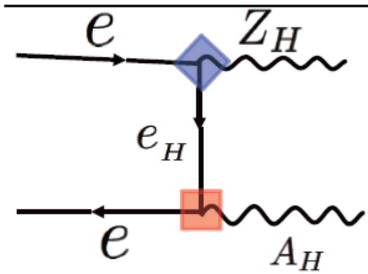
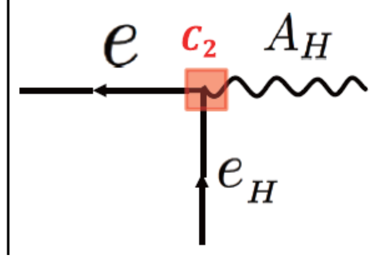
$$m_{eH} = \sqrt{2}\kappa_\ell f \ , \ m_{\nu H} = \left(\frac{\sqrt{2} + \sqrt{1+c_f}}{2}\right)\sqrt{2}\kappa_\ell f$$

κl= 0.5 GeV, 0.01 %

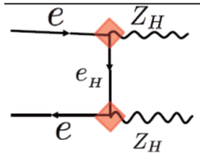
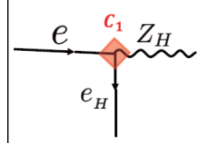
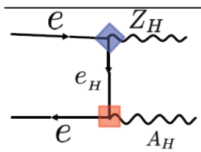
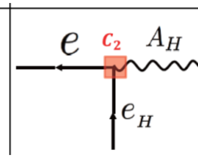
Coupling measurements

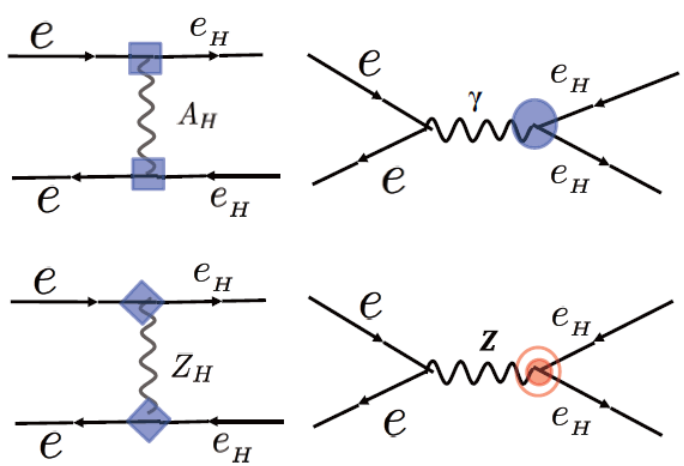
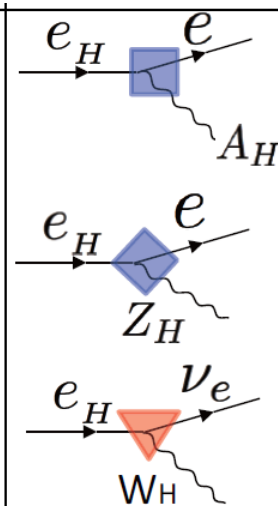
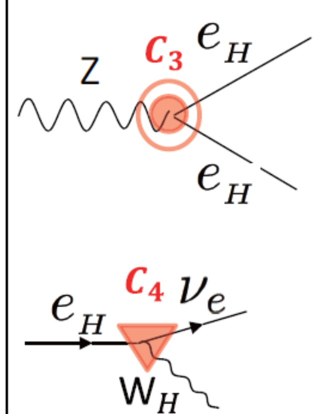
Process mode	Branch	derived vertex
		

- Cross section

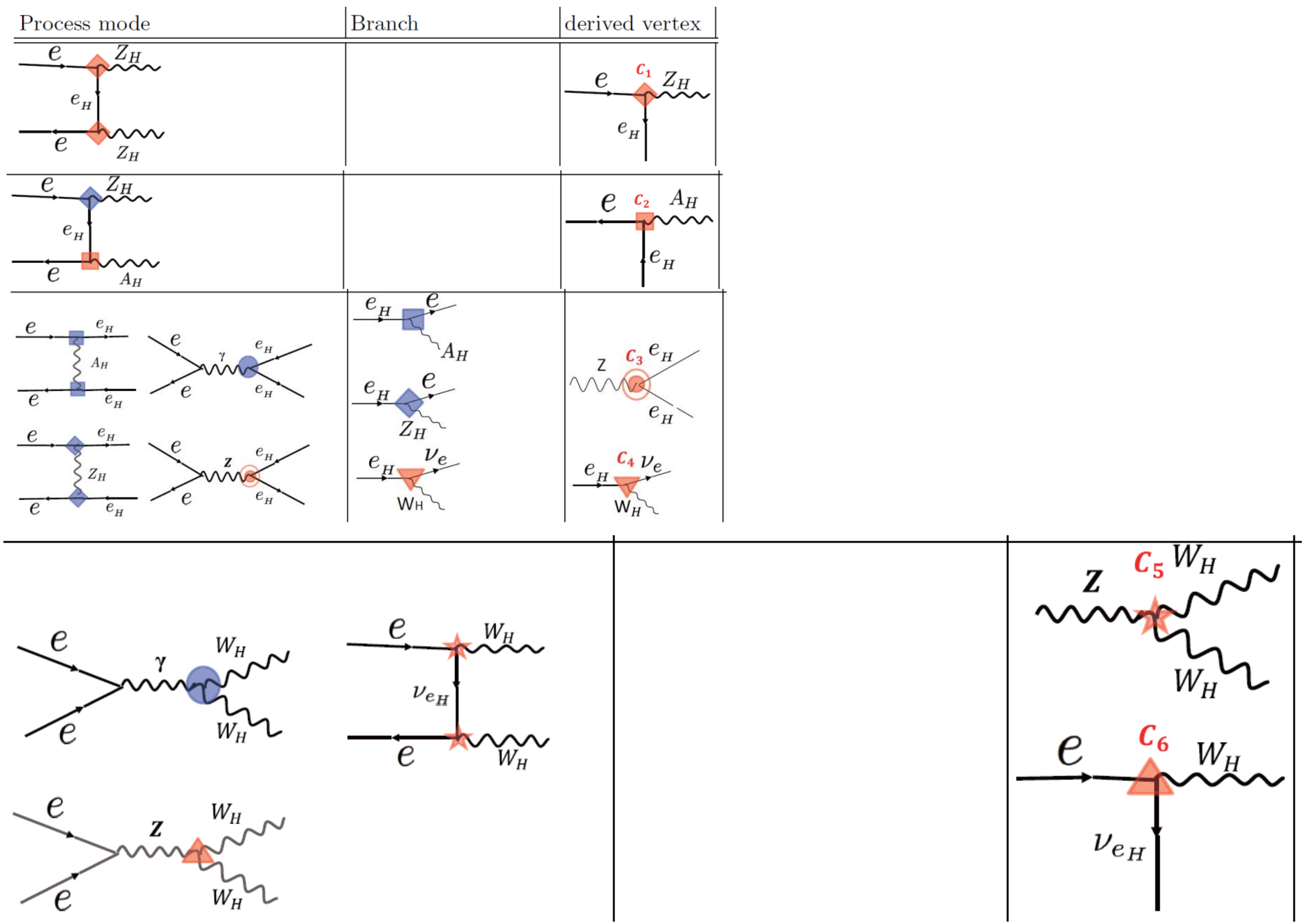
Process mode	Branch	derived vertex
		
		

- Cross section

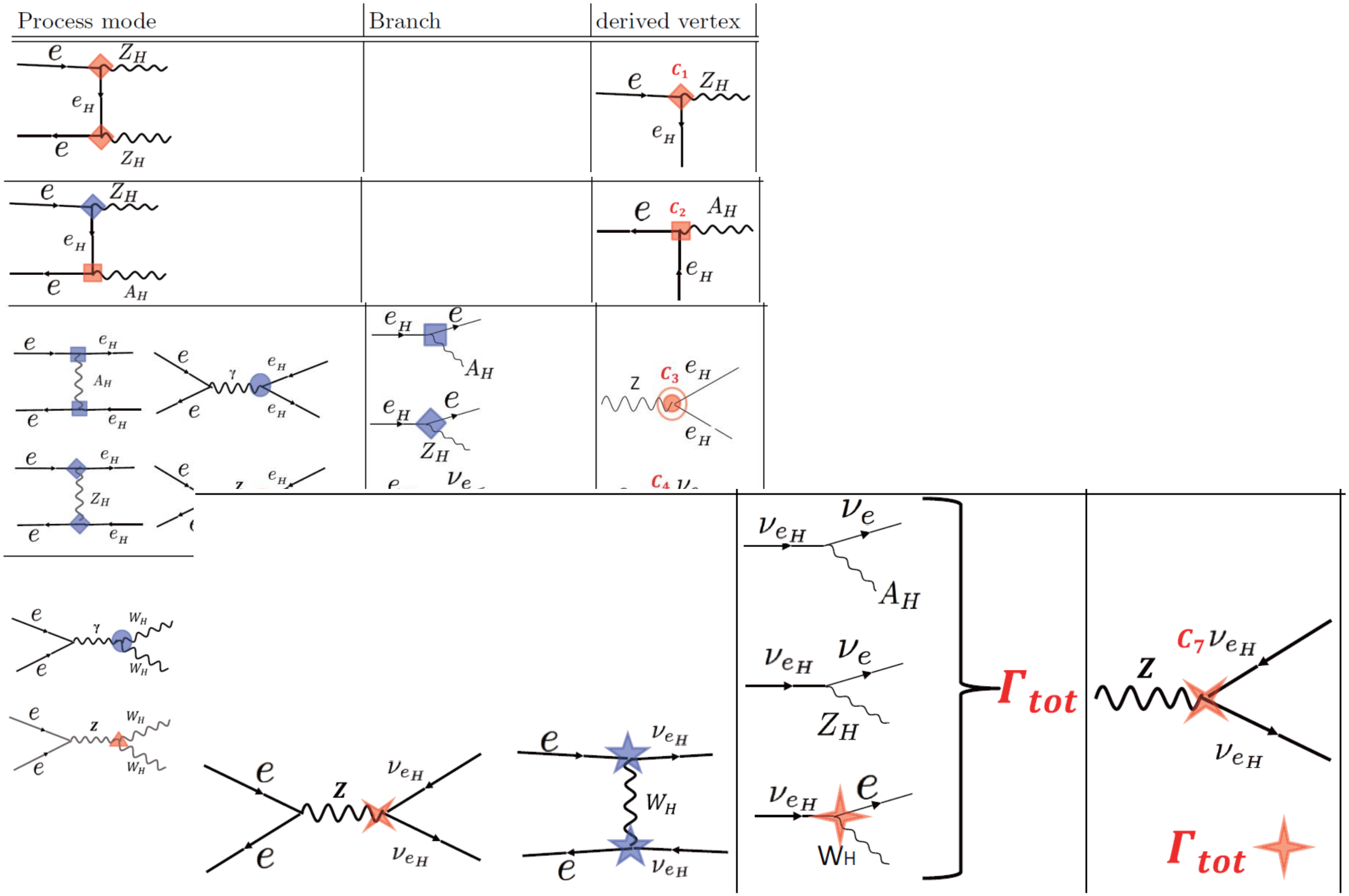
Process mode	Branch	derived vertex
		
		

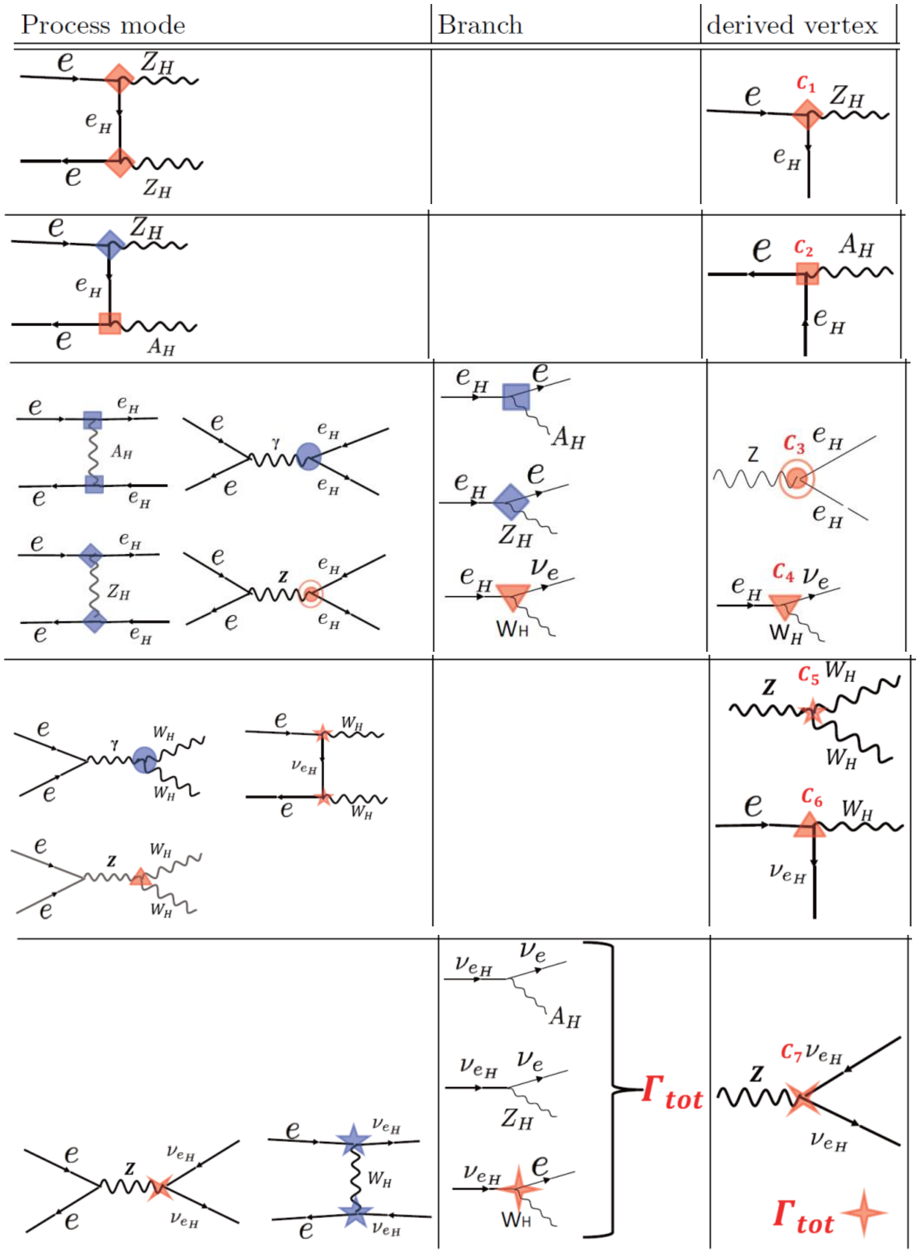
- Cross section
- polarization



- Cross section
- polarization



- Cross section
- polarization



0.21%

3.9%

15%

11%

0.87%

0.21%

0.28%

0.21%

Preliminary

Summary & Discussion

Summary

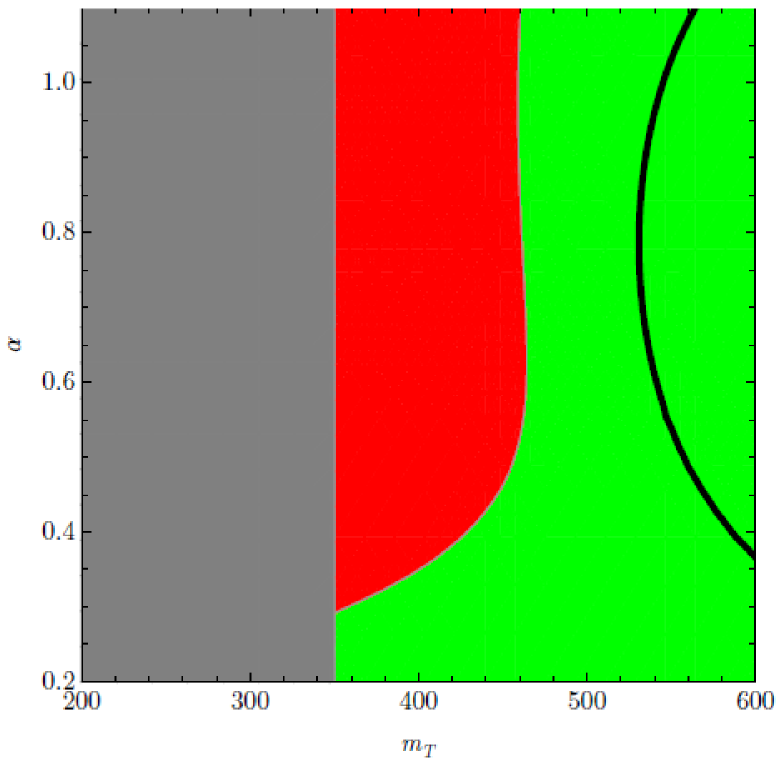
- **Little Higgs** is one of the attractive models for physics beyond the SM.
- We study the phenomenology of non-colored new particles in **Littest Higgs model with T-parity (LHT)** at the ILC.
- Heavy gauge boson and heavy lepton masses are determined with good accuracy

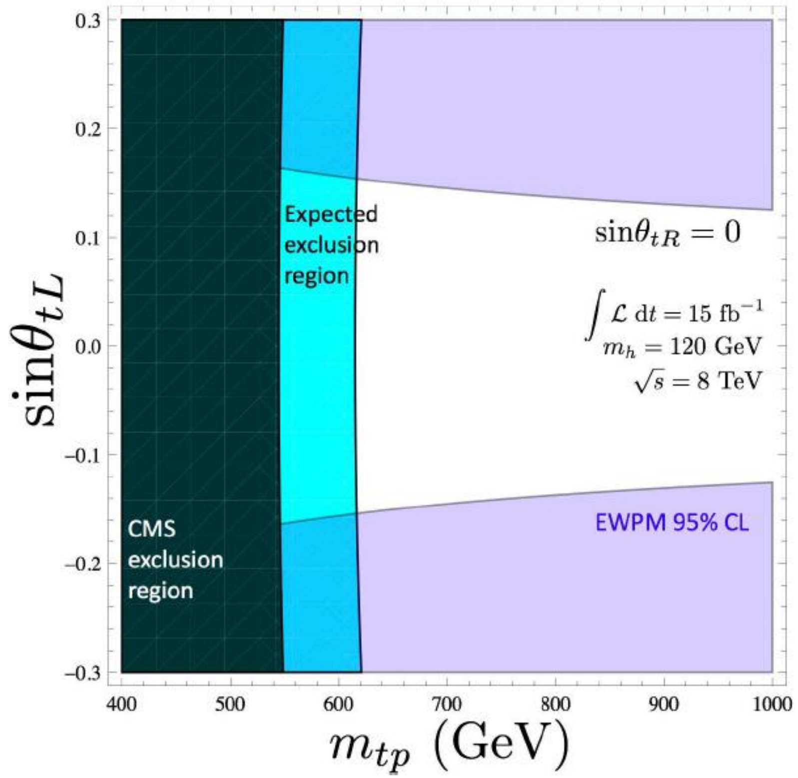
  & from these, we also obtain the VEV f & other model parameters.
- Furthermore, coupling of new particles can also be measured and it would help to confirm the TeV physics model.

Back up

Process	cross section (fb)	♯ of events	♯ of events after all cuts
$W_H W_H \to A_H A_H qqqq$	120.0	60,000	41,190
$WW \to qqqq$	1307	653,500	678
$eeWW \to eeqqqq$	490	245,000	46
$e\nu_e WZ \to e\nu_e qqqq$	24.5	12,250	3,797
$\nu\bar{\nu}WW \to \nu\bar{\nu}qqqq$	18.8	9,400	213
$ZWW \to \nu\bar{\nu}qqqq$	7.23	3,615	1,597
$Z_H Z_H \to A_H A_H qqqq$	5.61	2,805	1,533

Process	cross section (fb)	♯ of events	♯ of events after all cuts
$Z_H Z_H \to A_H A_H HH \to A_H A_H qqqq$	98.0	49760	18989
WWZ	63.86	31933	227
$\nu\nu WW$	14.67	7336	86
WW	3069	1947408	994
tt	192.9	96472	1749
ZZ	202.2	101094	114
ZH	17.98	8989	47
$W_H W_H$	108.6	54343	87





Berger, Hubisz, Perelstein (1205.0013) **Harigaya, Matsumoto, Nojiri, Tobioka (1204.2317)**

$$\chi^2 = \frac{({}^{rec}M_{SM1} - {}^{tr}M_{SM})^2}{\sigma^2_{M_{SM}}} + \frac{({}^{rec}M_{SM2} - {}^{tr}M_{SM})^2}{\sigma^2_{M_{SM}}} \quad (25)$$