Beyond SM measurements at the ILC

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1 TeV

E

LHC √s = 14 TeV, L = 300 fb-1
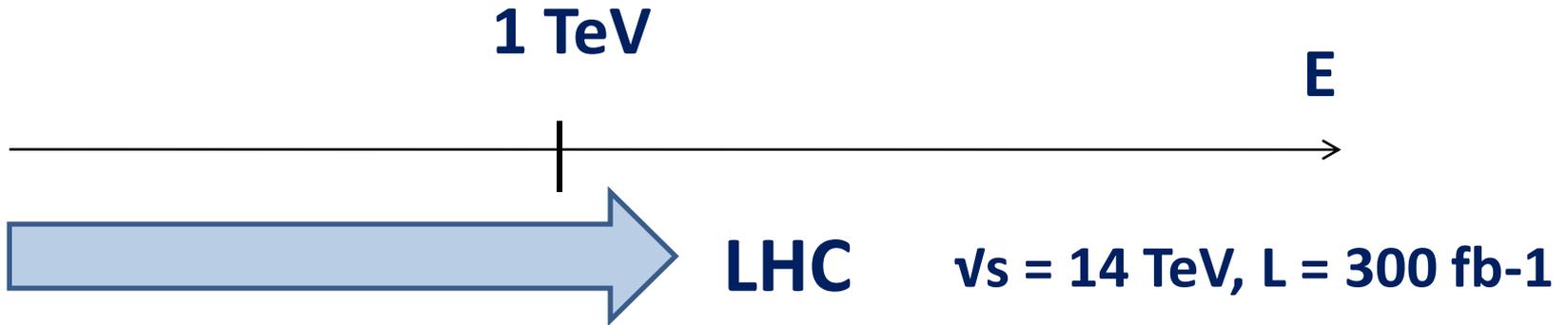
Discovery collider

LHC will determine the new particle mass scale by new particle production (directly).

1 TeV

E

LHC

500 GeV   ILC (new particle production)

(Ex. SUSY with R-parity)
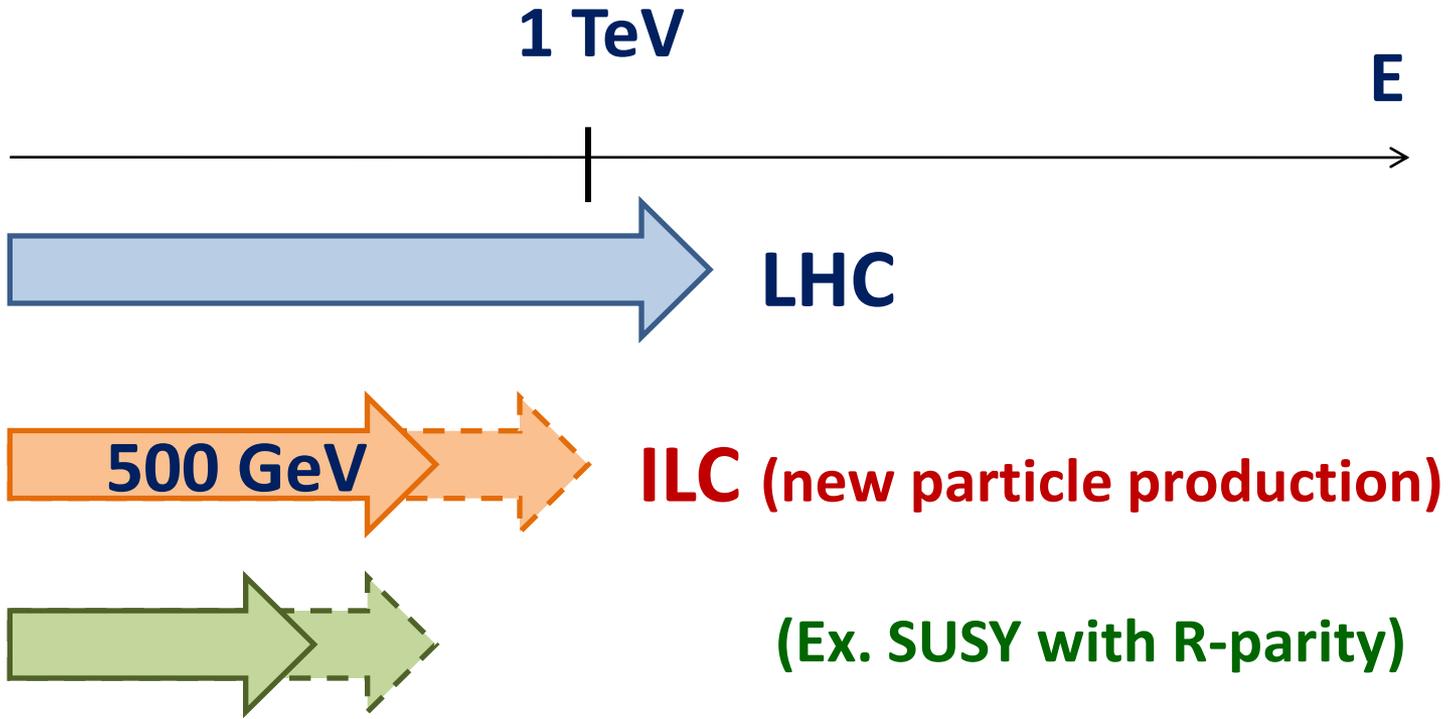
√s = 500 GeV (1 TeV), L = 500 fb-1 (1000 fb-1)

For example, in the SUSY case with R-parity,

New particles (>500 GeV) cannot be produced @ √s = 1TeV

1 TeV

E

LHC

500 GeV   ILC (new particle production)

(Ex. SUSY with R-parity)

ILC (direct + indirect measurements)
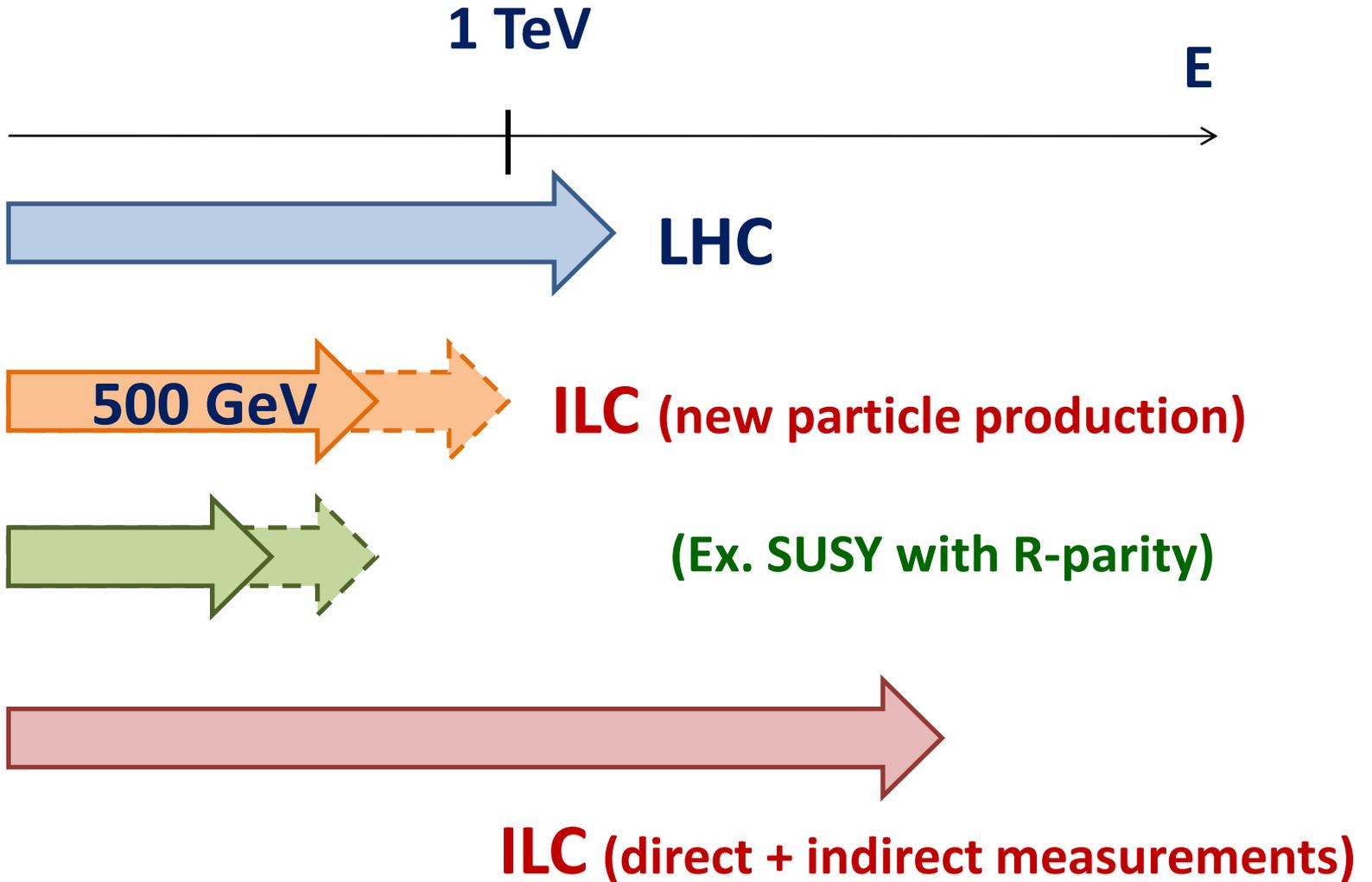
Including indirect measurements,

ILC will measure the TeV new physics model.

Introduction

E ↑

???

── 1TeV

$W, Z, \gamma,$
$u, c, t, d, s, b,$
$e, \mu, \tau,$
$\nu e, \nu \mu, \nu \tau$

"overview of physics beyond the <u>SM</u> at the ILC"

What we know so far is described by

Global : $\text{SU(2)}_L \times \text{SU(2)}_R \rightarrow \text{SU(2)}_C$

Gauge : $\text{SU(2)}_L \times \text{U(1)}_Y \rightarrow \text{U(1)}_{EM}$
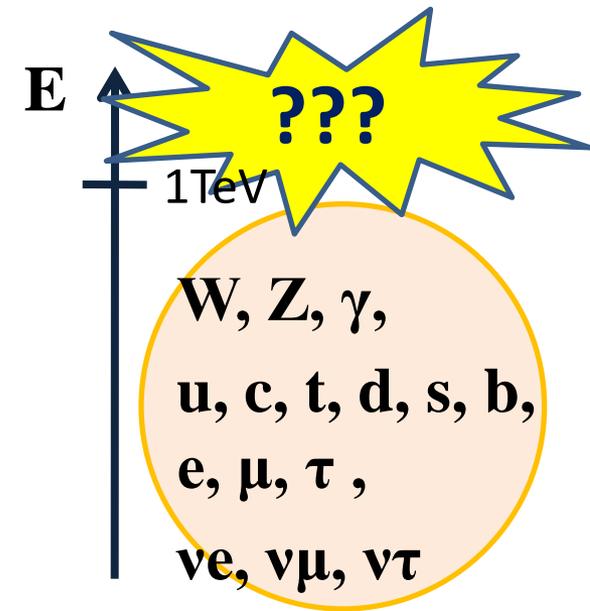
Non-linear σ model (low energy effective theory)
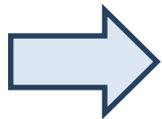
⟹ **Cut off scale exists**

ex) Unitarity violation ($\gtrsim$ **1 TeV**)

W_L ⟶ W_L

W_L ⟶ W_L
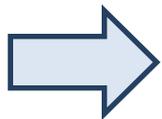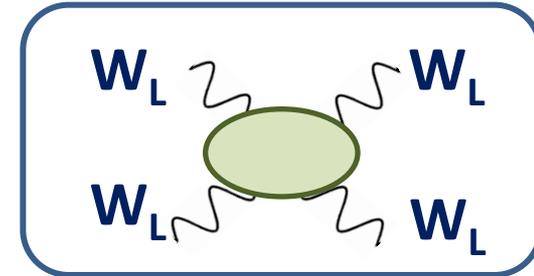
⟹ **At the LHC/ILC,**

an important discovery exists (we also already know)

- Higgs (SM)
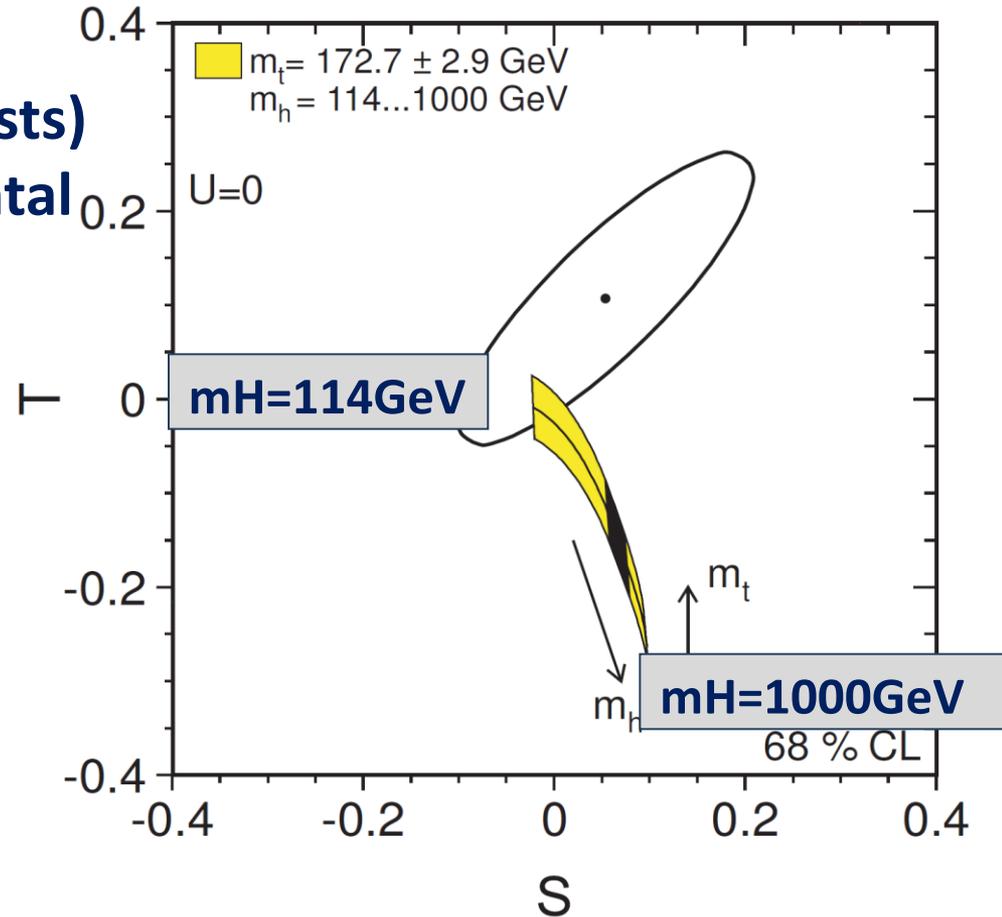- Strong dynamics (technicolor …)
- Higgs + … (SUSY)
- …

"overview of physics beyond the SM at the ILC"

Candidate of the scenario @ TeV

- Higgs (SM)
- Strong dynamics (technicolor …)
- Higgs + (SUSY)
- …

1. Standard model

■ **SM (in which light Higgs exsists) is consistent with experimental results.**

mH=114GeV

mH=1000GeV

http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2005/s05_stu_contours.eps

1. Standard model

SM Higgs potential:

$$V = m^2 |h|^2 + (\lambda/4) |h|^4$$

$$(\quad v^2 = -2 \, m^2 /\lambda \;, \quad m_h^2 = \lambda \, v^2 \quad)$$

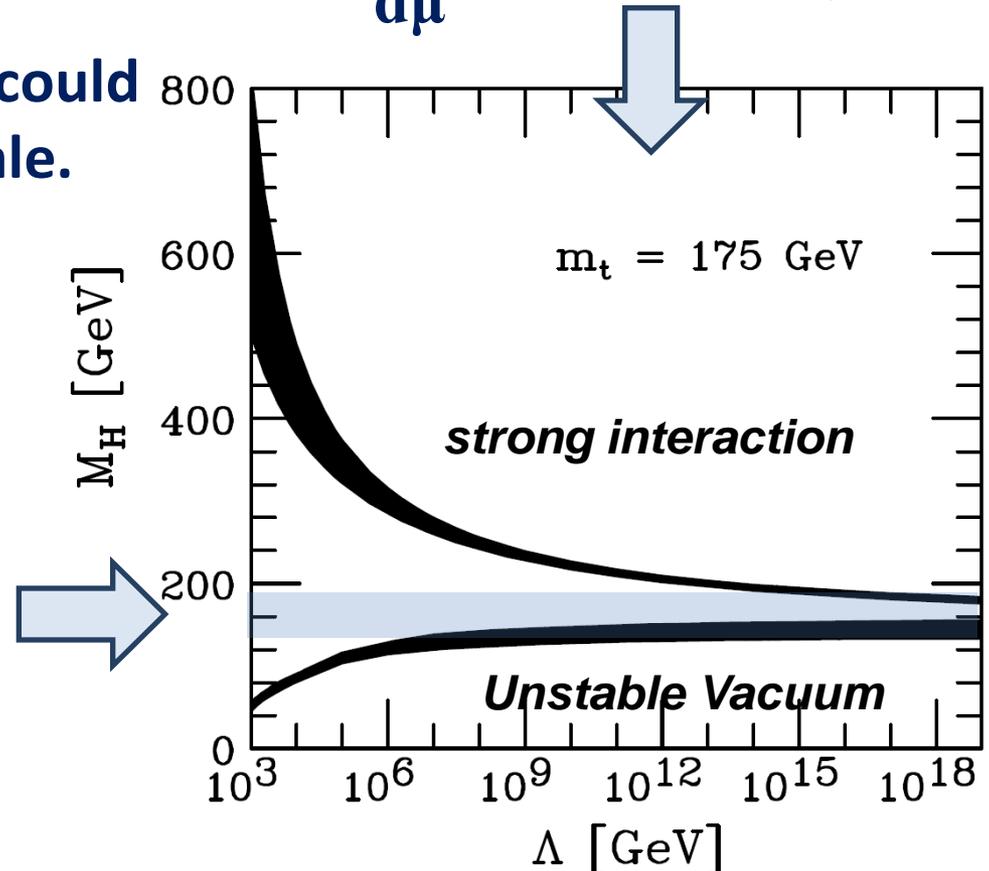$$16 \, \pi^2 \, \mu \frac{d}{d\mu} \lambda = 24 \, \lambda^2 - 6 \, y_t^4 + \dots$$

- **SM (in which light Higgs exsists) is consistent with experimental results.**

- **If mh is 130 ~ 160 GeV, SM could be extended to the GUT scale.**

Cabibbo, Maiani, et. al,(1979); Flores, Sher,(1983); Lindner,(1986); Sher,(1989); Casas, et. al.,(1995); Altarelli, G. Isidori, (1994); Espinosa, Quiros, (1995); Gomez-Bock, et. al. ,(2007).

1.   Standard model

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LHC

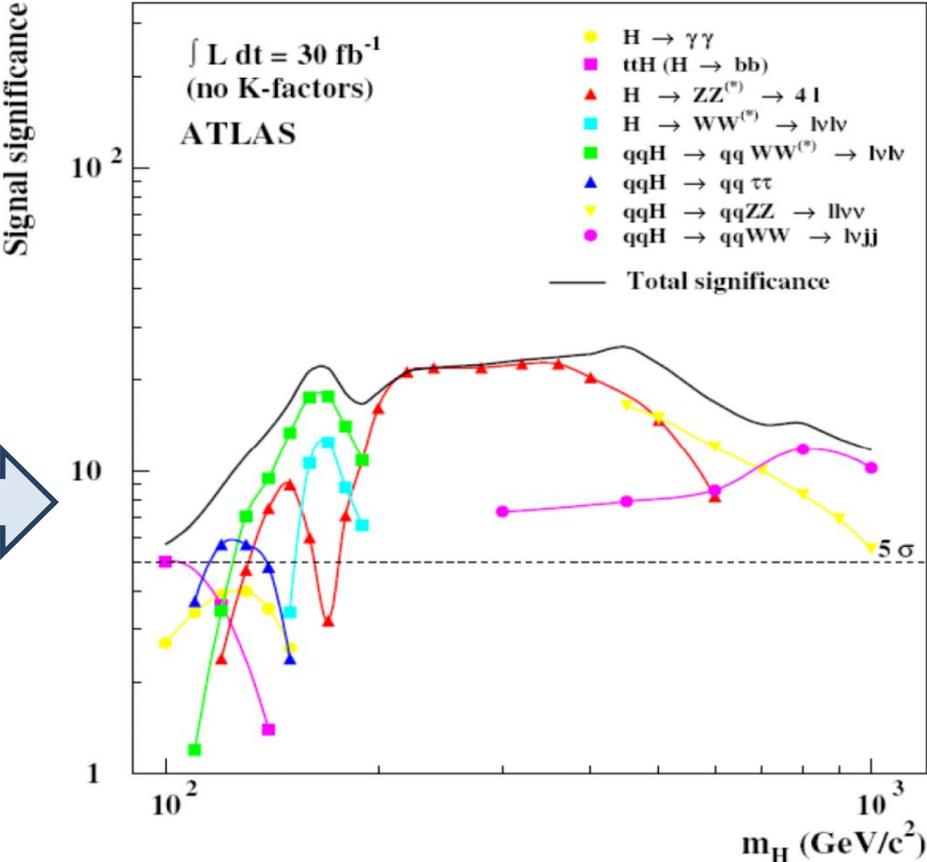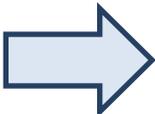- **SM Higgs could be discovered with L = 30 fb-1**

1. Standard model

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LHC

- **SM Higgs could be discovered with L = 30 fb-1**

ILC

We should check the SM

- **Higgs boson**
  - **Spin**
  - **Branching ratio**
  - **Yukawa coupling**
  - **Self coupling**

1. Standard model

For example, in some cases…

■ **Heavy new particle correction?**

H ---- T_{new} ⟩ **gg or γγ**

■ **Decay to WIMP DM?**

H ---- ⟨ DM DM

ILC

We should check the SM

■ **Higgs boson**

- ■ **Spin**
- ■ **Branching ratio**
- ■ **Yukawa coupling**
- ■ **Self coupling**

Even if the new particle will not discover directly, there maybe possibility of new physics discovery from Higgs precision measurement @ ILC.
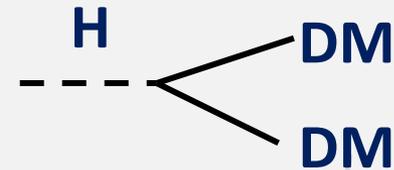
Candidate of the scenario @ TeV

- Higgs (SM)

- Strong dynamics (technicolor …)

- Higgs + (SUSY)

- …

2. $\quad$ (Naturalness) **Are there no problem in the SM at all?**

- **Higgs Potential**

$$V = m^2\,|h|^2 + (\lambda/4)\,|h|^4 \quad (\ v^2 = -2\,m^2/\lambda\,, \quad m_h^2 = \lambda\,v^2\ )$$
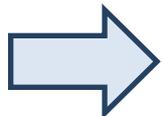
⬇

- **Higgs mass** $\quad m_h^2 = -m_0^2 + \delta m_h^2$

Quantum correction $\quad \delta m_h^2 \sim (y_t^2/16\pi^2)\,\Lambda^2$

$$\sim (y_t^2/16\pi^2)\,M_{Pl}^2$$

hierarchy problem

$$m_h^2\,/\,2 \iff (y_t^2/16\pi^2)\,M_{Pl}^2$$
$$\sim 10^4 \qquad\qquad \sim 10^{36}$$

➡ **Why $m^2 \ll M_{Pl}^2$?** $\quad$ In the SM, there are no symmetry or dynamics to explain the smallness.

2. Dynamical symmetry breaking
(One of the solution for naturalness)

Ex.
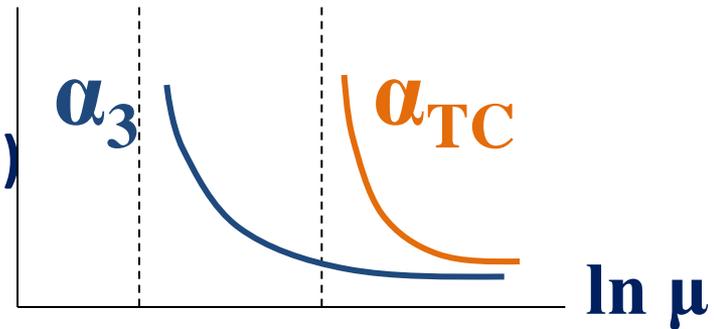
■ **Technicolor** Weinberg ('79); Susskind (''79)

Global : $SU(N)_L \times SU(N)_R$

Gauge : $SU(N)_{TC} \times SU(3) \times SU(2)_L \times U(1)_Y$

Techniquarks : $Q_{L,R}$ $\qquad$ $< \overline{Q}Q >_{TC} \neq 0$
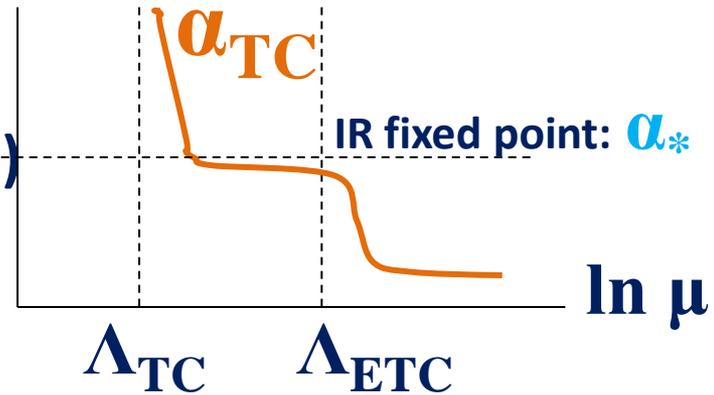
A scaled-up copy of QCD.

The EW scale appear dynamically.

2. Dynamical symmetry breaking

(One of the solution for naturalness)

Ex.

■ **Technicolor** Weinberg ('79); Susskind (''79)

In order to solve the flavor problem, (ex. top Yukawa)

■ **Walking Technicolor** B. Holdom; K. Yamawaki, M. Bando, and K. Matumoto; T.W. Appelquist, D. Karabali, and L.C.R. Wijewardhana; T. Appelquist and L.C.R. Wijewardhana

■ **Conformal Technicolor** M. Luty, T. Okui.

■

We don't know the complete model to avoid fine-tuning & constraint from S parameter yet. (not calculable)

But this scenario is one possibility.
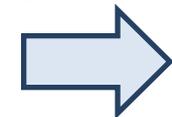
2. Dynamical symmetry breaking

(One of the solution for naturalness)

LHC

- **Ex.) ρ_techni production**
- **WW scattering behavior**

$$pp \rightarrow W^* \rightarrow \rho_T^\pm Z$$
$$pp \rightarrow \rho_T^\pm jj$$
$$\Rightarrow \rho_T^\pm \rightarrow W^\pm Z^0$$

ILC

We should

- **Precision measurements of weak gauge boson coupling**
- **Precision measurements of fermion (top) sector**

It is possible that there are correction from strong dynamics

3. **Extended EW nlσm like model in 4d. effective theory**

Another approach to naturalness

EW Non-linear σ model

Global : $SU(2)_L \times SU(2)_R \xrightarrow{} SU(2)_C$

Gauge : $SU(2)_L \times U(1)_Y \xrightarrow{f} U(1)_{EM}$

Extended EW Non-linear σ model

Global : $\xrightarrow{} SU(2)_C$

Gauge : $\xrightarrow{f} U(1)_{EM}$

Extended sym.

The f arising from the f' in extended non-linear σ model.

In this case, we should consider the naturalness for f' ($> f$).

actual model →

3. Extended EW nlσm like model in 4d. Effective theory

C.Csaki et.al

Arkani-Hamed, Cohen, Georgi

■ Higgsless model

Global : $SU(2) \times SU(2)\ldots$

Gauge : $SU(2)\ldots \times U(1)\ldots$

NG boson : $\pi 0, \pi\pm, \pi 0', \pi\pm', \ldots$

■ Little Higgs model

ex. Littlest Higgs model

Global : $SU(5)$

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

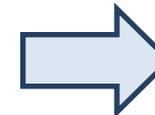NG boson : $\pi 0', \pi\pm', H, \Phi$

$\quad\quad\quad\quad\quad \pi 0, \pi\pm, h$

Collective symmetry breaking ($v_{EW} < f$)

$(1/v_{EW})^2 = \Sigma (1/f_i)^2$
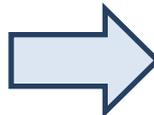
$\Longrightarrow$ ($v_{EW} < f$)

$\Delta m_h^2 \sim [\Pi(g_i^2/16\pi^2)] (4\pi f)^2$

$\Longrightarrow$ ($v_{EW} < f$)

3. Extended EW nlσm like model in 4d. Effective theory

■ **Higgsless model**

Global : $SU(2) \times SU(2)\dots$

Gauge : $SU(2)\dots \times U(1)\dots$

NG boson **:** $\pi 0, \pi\pm, \pi 0', \pi\pm', \dots$

■ **Little Higgs model**

ex. Littlest Higgs model

Global : $SU(5)$

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

NG boson **:** $\pi 0', \pi\pm', H, \Phi$

$\qquad\qquad\qquad \pi 0, \pi\pm, h$

Collective symmetry breaking ($v_{EW} < f$)

$$(1/v_{EW})^2 = \Sigma\, (1/f_i)^2$$

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New particles

W', Z',…
(will be responsible to restore the unitarity of $W_L W_L$ scattering instead of Higgs)
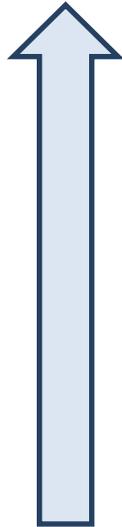
Higgs, W', Z', top partner,…
(Higgs is regarded as a pseudo NG boson)

3. Extended EW nlσm like model in 4d. Effective theory
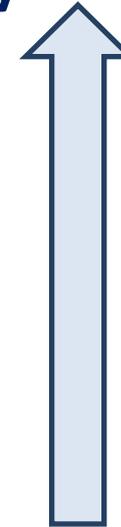
■ **Higgsless model**

■ **W', Z' discovery**

LHC

■ **Little Higgs model**

■ **Higgs, W', Z', top partner discovery**

New particles

W', Z',...
(will be responsible to restore the unitarity of $W_L W_L$ scattering instead of Higgs)

Higgs, W', Z', top partner,...
(Hiss is regarded as a pseudo NG boson)

3. **Extended EW nlσm like model in 4d. Effective theory** (recent attempt)

- **Higgsless model**

  - **W', Z' discovery**

  LHC

  - **Precision measurements of weak gauge boson coupling**
  - **Precision measurements of top sector**

- **Little Higgs model**

  - **Higgs, W', Z', top partner discovery**

  ILC

  Additionally,
  - **Higgs sector**
    - **Yukawa coupling**
    - **Self coupling**
    - **Higgs branching ratio**

Additionally, new particle can be measured @ILC.
From all of these, we will determine the TeV new physics.

4. Supersymmetry (SUSY)

- Λ^2 **terms are canceled**

$$m_h^2 / 2 \iff (y_t^2/16\pi^2) \, M_{Pl}^2$$

$$\iff (y_t^2/16\pi^2) \, m_{SUSY}^2 \, \ln\left(\frac{M_{mess}^2}{m_{SUSY}^2}\right)$$

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$$\iff (y_t^2/16\pi^2)\,m_{SUSY}^2 \ln\left(\frac{M_{mess}^2}{m_{SUSY}^2}\right)$$

- **light Higgs**

2. Higgs Potential in MSSM   gauge coupling !

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 + (m_3^2 H_1^0 H_2^0 + \text{h.c.}) + \frac{g^2 + g'^2}{8}(|H_1^0|^2 - |H_2^0|^2)^2$$

MSSM predicts light Higgs boson $m_h \sim m_Z$

4. Supersymmetry (SUSY)

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$$\iff (y_t^2/16\pi^2)\, m_{SUSY}^2 \ln(\frac{M_{mess}^2}{m_{SUSY}^2})$$
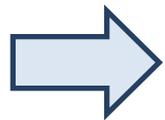
- **light Higgs**
- **R-parity** (SUSY correction cannot appear at tree level)

4. Supersymmetry (SUSY)

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$$m_h^2 / 2 \iff \cancel{(y_t^2/16\pi^2) M_{Pl}^2}$$

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- ■ light Higgs
- ■ R-parity (SUSY correction cannot appear at tree level)

⇨ **One of the solution for naturalness & EWPM.**

**If we consider the naturalness seriously,
stop & Higgsino is relatively light:**

Naturalness

$$m_h^2 \lessapprox 130 \text{ GeV}$$

$$V = m^2 |h|^2 + (\lambda/4) |h|^4 \qquad m_h^2 / 2 = -m^2$$

- **For a moderately large tanβ,**

$$\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle, \quad \text{e.g. } \tan\beta \gtrsim 2,$$

$$m^2 = \mu^2 + (m_{Hu}^2)_{tree} + (m_{Hu}^2)_{rad}$$

Naturalness

$$m_h{}^2 \lesssim 130 \text{ GeV}$$

$$V = m^2 |h|^2 + (\lambda/4) |h|^4 \qquad m_h{}^2 / 2 = - m^2$$

- **For a moderately large tanβ,**

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$$m^2 = \mu^2 + (m_{Hu}{}^2)_{tree} + (m_{Hu}{}^2)_{rad}$$

$$m_{\tilde{t}} \equiv (m_{\tilde{q}_3} m_{\tilde{u}_3})^{1/2}$$

$$m_{H_u}^2 |_{rad} \simeq -\frac{3y_t^2}{8\pi^2} \left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2 \right) \ln\left(\frac{M_{mess}}{m_{\tilde{t}}} \right)$$

A fine-tuning is required,

if there are contribution on |m|² which are

much larger than $m_h^2/2 \lesssim (130 \text{ GeV})^2/2$

For example

- **From μ term,**

$$|\mu| \lesssim 290 \text{ GeV} \quad \Rightarrow \quad \text{Light Higgsino}$$

- **From m_{H_u} term & Higgs mass bound**

$$500 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 500 \text{ GeV} \qquad \text{for } |A_t| \sim m_{\tilde{t}}$$
$$250 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 360 \text{ GeV} \qquad \text{for } |A_t| \sim 2m_{\tilde{t}}$$

$$m_{\tilde{t}_1} \lesssim 400 \text{ GeV} \quad (|A_t| \sim m_{\tilde{t}})$$
$$m_{\tilde{t}_1} \lesssim 200 \text{ GeV} \quad (|A_t| \sim 2m_{\tilde{t}})$$

$$\Rightarrow \quad \text{Light stop}$$

By assuming a small logarithm ($M_{\text{mess}} \sim 10 \text{ TeV}$)

$$\Rightarrow \quad \text{Massless gravitino}$$

$$\Rightarrow \quad \boxed{\text{Stop /Higgsino/gravitino system!}}$$

MA, H. D. Kim, R. Kitano, Y. Shimizu, 2010

4. Supersymmetry (SUSY)

LHC

- **Discovery of Light Higgs, stop, Higgsino, …**

ILC

- **Higgs physics**
  - **Yukawa coupling**
  - **Self coupling**   **(two Higgs doublet,**
  - **branching ratio**   **Light top partner   )**
- **New particle measurements**

ILC

Strong dynamics   Extended EW nlσm   SM (SUSY)

Higgsless or composite Higgs

- **weak gauge boson coupling**
- **Fermion(top) sector**
- **(new resonances measurement)**

- **Weak gauge boson coupling**
- **Fermion(Top) sector**
- **Higgs physics**
  - **Mass, Spin, CP**
  - **Branching ratio**
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  - **Self coupling**
- **(new particle measurement)**

Direct & indirect search for TeV physics

ILC

Strong dynamics   **Extended EW nlσm**   **SM (SUSY)**

Higgsless or composite Higgs

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- **(new particle measurement)**

Next, for example, we consider triple coupling especially.

Weak gauge boson coupling

■ **Triple coupling**

In the SM, $g_1^V = \kappa_V = 1$, all other couplings are equal to zero

$$\mathcal{L}_{WWV} = g_{WWV}\left[ig_1^V V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+\right) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda}\right.$$

$$+ g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + g_5^V \epsilon_{\mu\nu\lambda\rho} \left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+\right) V_\rho$$

$$\left.+ i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda}\right], \tag{(}$$

Among the different couplings g_1, κ and λ are C- and P-conserving, g_5 is C and P-violating but CP-conserving while g_4, $\tilde{\kappa}$, λ violate CP symmetry.

Weak gauge boson coupling

- **Triple coupling**

In the SM, $g_1^V = \kappa_V = 1$, all other couplings are equal to zero

$$
\begin{aligned}
\mathcal{L}_{WWV} = & \; g_{WWV} \Big[i g_1^V V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+ \right) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda} \\
& + g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu \right) + g_5^V \epsilon_{\mu\nu\lambda\rho} \left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+ \right) V_\rho \\
& + i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda} \Big] ,
\end{aligned}
$$

From $e^+ e^- \to W^+ W^-$

single parameter fits (1σ)

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500\,\text{GeV}$	$\sqrt{s} = 800\,\text{GeV}$
Δg_1^Z	15.5	12.6
$\Delta \kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta \kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

with $\mathcal{L} = 500\,\text{fb}^{-1}$ $1000\,\text{fb}^{-1}$
$\mathcal{P}_{e^-} = 80\%$ and $\mathcal{P}_{e^+} = 60\%$

Very sensitive

LHC: $300\,\text{fb}^{-1}$

ILC RDR(2007)

Weak gauge boson coupling

■ **Triple coupling**

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$$\mathcal{L}_{WWV} = g_{WWV}\left[ig_1^V V_\mu(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{\Lambda^2}W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda}\right.$$

From Δg1^z parameter, we can descriminate 5 dim. continuum model from deconstructed model in the Higgsless model.

(If a =1, the model is equal to three site Higgsless model.)

(a ~ 4/3 ~ 1.3 provide a better approximate description of continuum model.)

single parameter fits (1σ)

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500\,\text{GeV}$	$\sqrt{s} = 800\,\text{GeV}$
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λ_γ	5.9	3.3
$\Delta\kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

with $\mathcal{L} = 500\,\text{fb}^{-1}$ $\quad 1000\,\text{fb}^{-1}$
$\mathcal{P}_{e^-} = 80\%$ and $\mathcal{P}_{e^+} = 60\%$

$e_+^- e_-^+ \rightarrow W^+ W^-$

$\sqrt{s} = 500\,\text{GeV}$

$a = 1.3$

$a = 1$

ILC

A. S. Belyaev et. al.

$M_{W'}(\text{GeV})$

ILC

Strong dynamics   Extended EW nlσm   SM (SUSY)

Higgsless or composite Higgs

- **weak gauge boson coupling**
- **Fermion(top) sector**
- **(new resonances measurement)**

- **Weak gauge boson coupling**
- **Fermion(Top) sector**
- **Higgs physics**
    - **Mass, Spin, CP**
    - **Branching ratio**
    - **Yukawa coupling**
    - **Self coupling**
- **(new particle measurement)**

Higgs physics
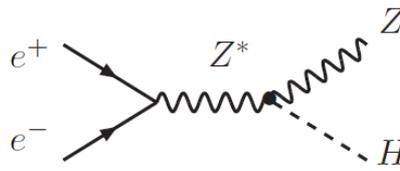
- **In Higgs–strahlung, the recoiling Z boson is mono–energetic and the Higgs mass can be derived from the Z energy at the ILC.**

- **A precision of ΔMH ~ 70 MeV can be reached for MH ~ 120 GeV.**

- **√s = 1 TeV collider can probe the entire Higgs mass range (MH < 700 GeV).**

- **Invisible Higgs decays can also be probed with a very good accuracy.**

- **Branching ratio**

Decay mode	Relative precision (%)	References
$b\bar{b}$	1.0–2.4	[8][93] [94][97]
$c\bar{c}$	8.1–12.3	[8][93] [94][97]
$\tau^+\tau^-$	4.6–7.1	[8] [93] [94]
gg	4.8–10	[8] [93] [94][97]
WW	3.6–5.3	[8][93] [94] [95]
$\gamma\gamma$	23–35	[94] [96]

$e^+e^- \rightarrow \mu^+\mu^- X$

√s=300GeV
500 fb⁻¹

ACFA Linear Collider Working Group, K. Abe et al., hep-ph/0109166.

No. of events/1GeV

Missing mass(GeV)
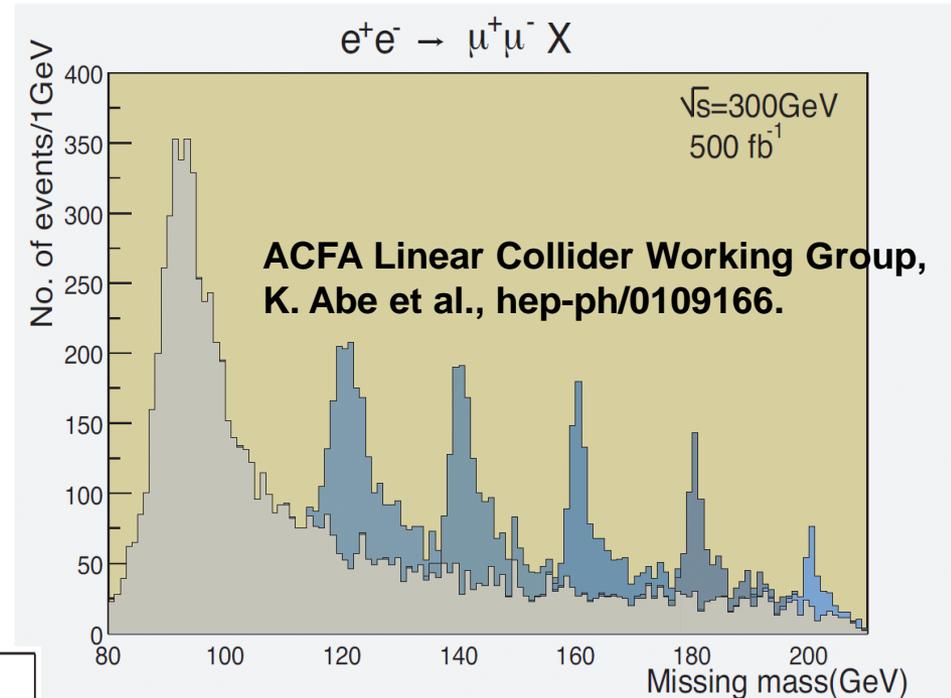
distribution of the µ+µ− recoil mass

ILC RDR(2007)

Higgs physics

For example, in some cases...

■ **Decay to WIMP DM?**

H ----< DM
           DM

■ **Heavy new particle correction?**

H ---- T_{new} → gg or γγ

ILC

We should check the SM

■ **Higgs boson**
   ■ **Spin**
   ■ **Branching ratio**
   ■ **Yukawa coupling**
   ■ **Self coupling**

■ **SUSY (two Higgs doublet model)**
→ **tan β effect**
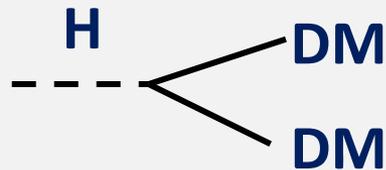
Higgs physics

Coupling Mass Relation

120 GeV SM Higgs

$m_i = v\kappa_i$
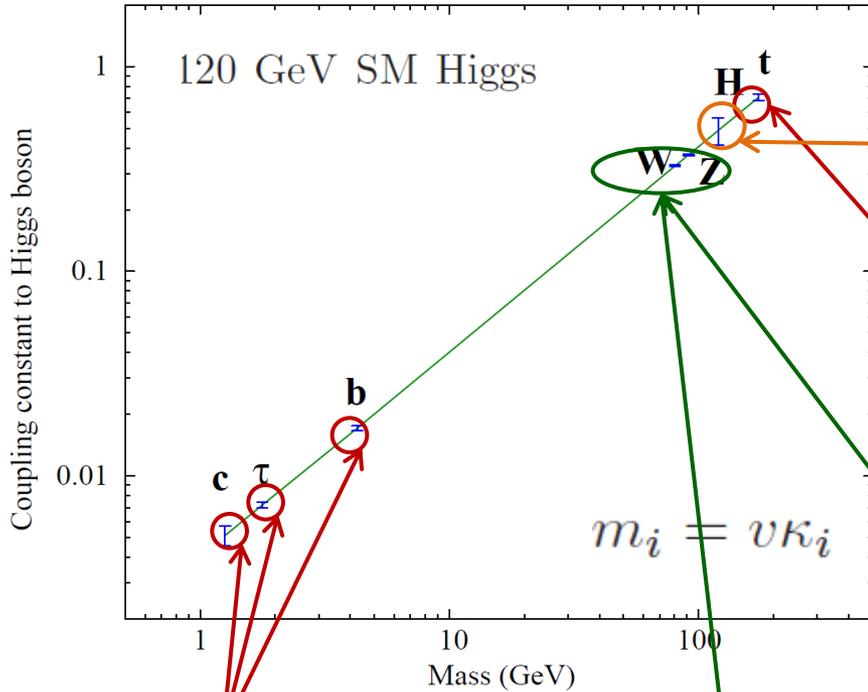
- **Self coupling**
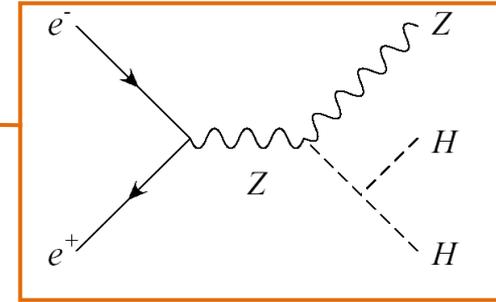
ZHH production

- **Yukawa coupling**
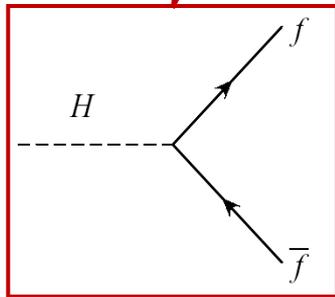
Branching ratios
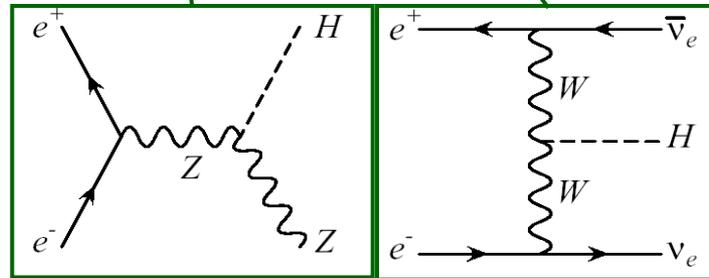
Production cross sections
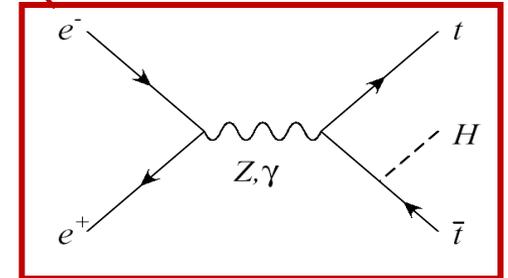
ttH production

ILC

Strong dynamics   Extended EW nlσm   SM (SUSY)

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- **Weak gauge boson coupling**
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    - **Mass, Spin, CP**
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    - **Yukawa coupling**
    - **Self coupling**
- **(new particle measurement)**

new particles measurements

If ILC reach new particle mass scale, we will also measure
the properties!

Ex.) in the case including **WIMP (Weakly Interacting Massive
Particle)** DM

TeV physics including **WIMP** is one of the plausible possibility:

- DM which has O(100 GeV) mass &

  interacts with SM particle weakly

  can consist with present DM relic abundance. →WIMP

- TeV physics relates with EWSB

  → Existence of WIMP in TeV physics is not a odd thing.

new particles measurements

If ILC reach new particle mass scale, we will also measure the properties!

Ex.) in the case including WIMP (Weakly Interacting Massive Particle) DM

TeV physics including WIMP is one of the plausible possibility:

As an example, let's consider the new particle measurements in

■ **Littlest Higgs with T-parity**

A_H: Heavy Photon spin 1

W_H^+: Heavy W boson spin 1

DM

As an example

- **Littlest Higgs model with T-parity**

What is you get;

- **Mass**
- **Spin**
- **Interaction**

■ **Littlest Higgs with T-parity**

DM

A_H: Heavy Photon   spin 1

W_H^+: Heavy W boson   spin 1

As an example

- **Littlest Higgs model with T-parity**

What is you get;

- **Mass**
- **Spin**
- **Interaction**

<W energy distribution>
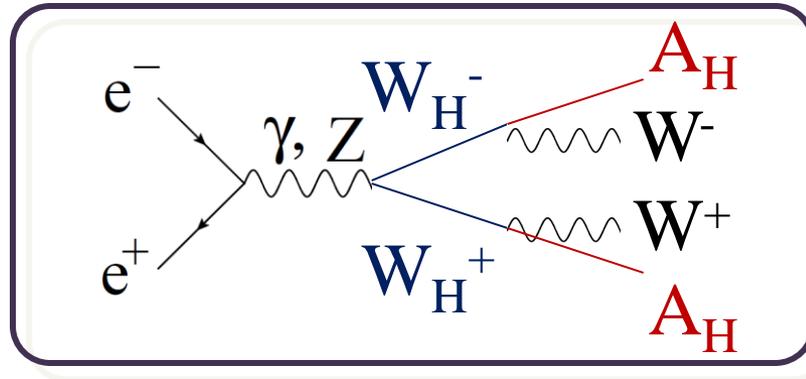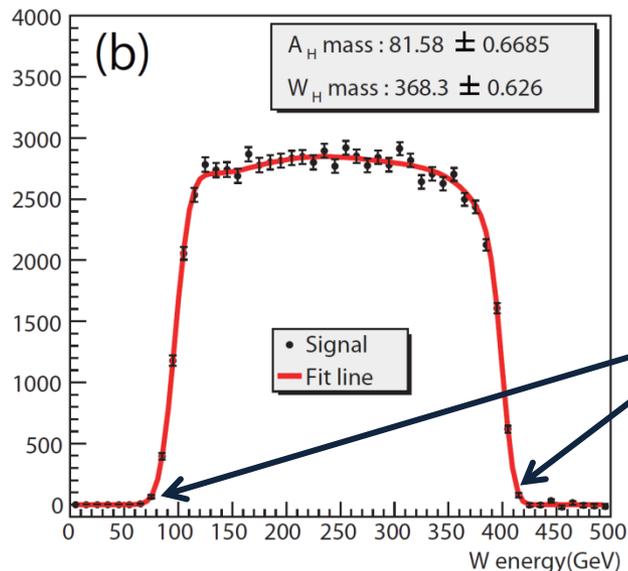
- ■ **depends on the new particles.**

- ■ **A_H & W_H masses can be measured from edges of the reconstructed W boson energy distribution.**

- ■ **Because the edges are very clear, the masses can be determined very accurately at the ILC.**

As an example

- **Littlest Higgs model with T-parity**

What is you get;

- **Mass**
- **Spin**
- **Interaction**

<distribution of $W_H^{\pm}$ production angle >
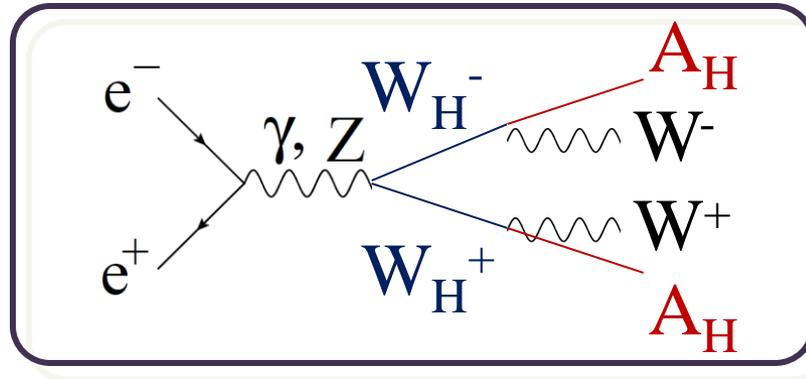
- **depends on the new particle spin.**

- **W_H momentum can be reconstructed although 2 missing in final state assuming back-to-back production of W_H^+ & W_H^-.**
  (with twofold ambiguity)

As an example

- **Littlest Higgs model with T-parity**

What is you get;

- **Mass**
- **Spin**
- **Interaction**

<distribution of $W_H^\pm$ production angle >
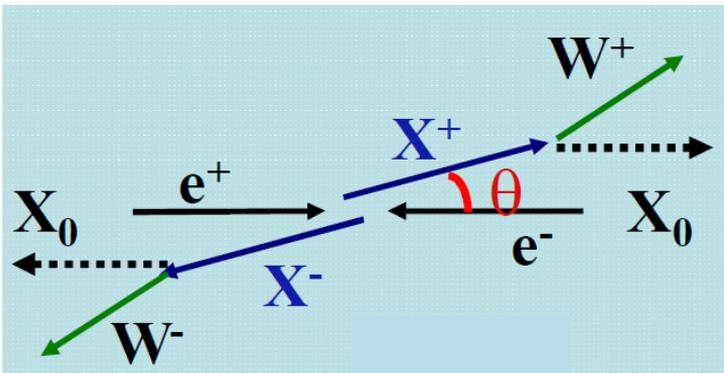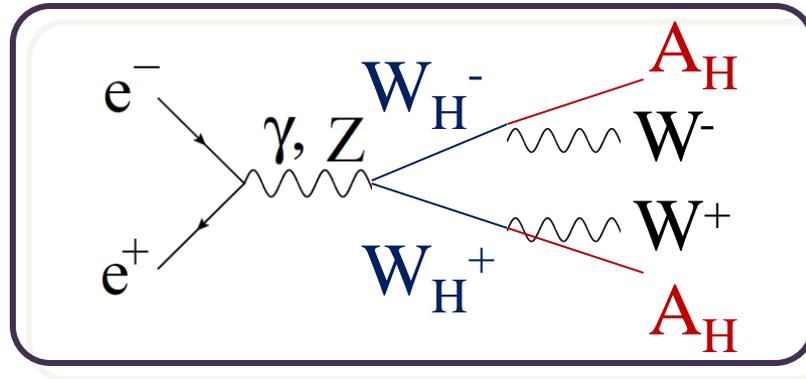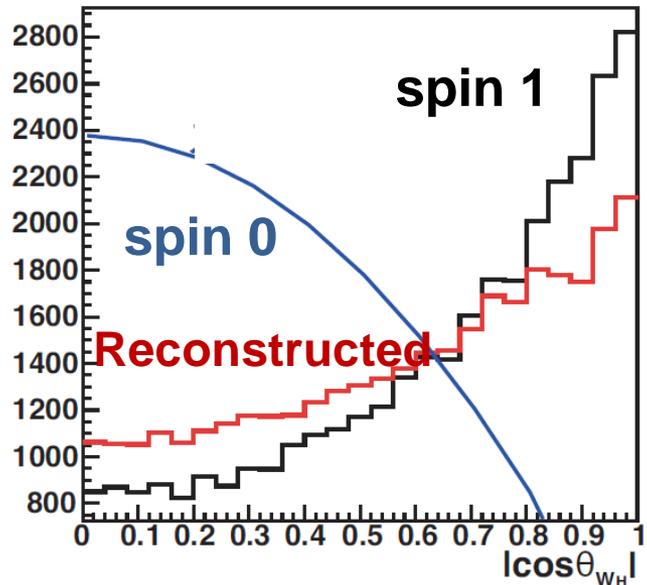
- depends on the new particle spin.

- W_H momentum can be reconstructed although 2 missing in final state assuming back-to-back production of W_H^+ & W_H^-.

(with twofold ambiguity)

The $W_H^\pm$ production angle shows that $W_H^\pm$ is spin 1.

As an example

- **Littlest Higgs model with T-parity**
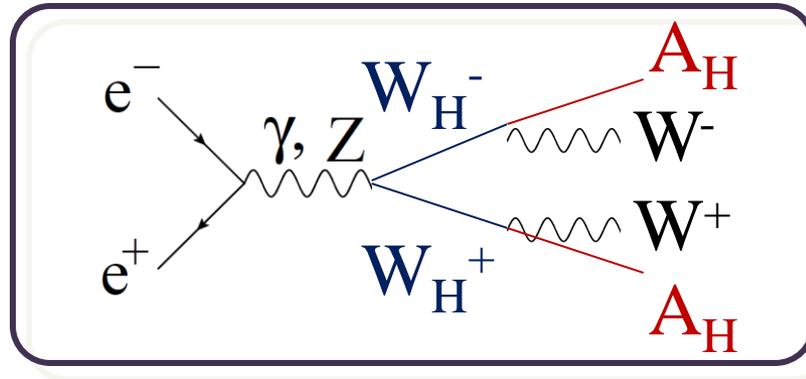
What is you get;

- **Mass**
- **Spin**
- **Interaction**

<Angular distribution of jets>
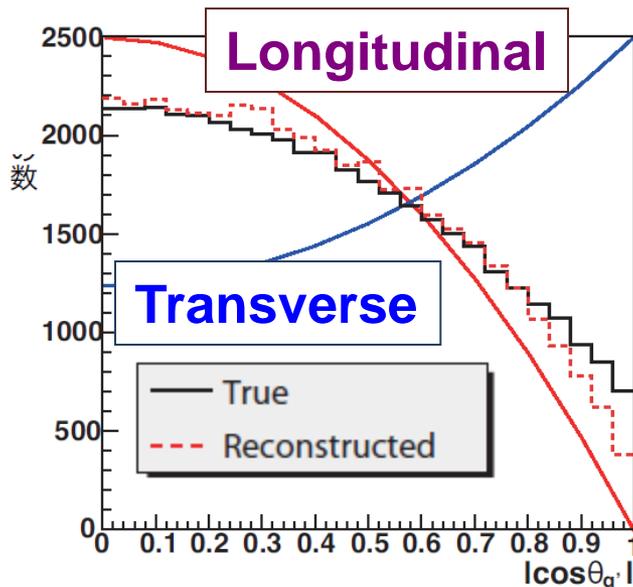
Angular distribution of jets in the helicity-frame of the $W^\pm$ carries information on the polarization of the $W^\pm$.

helicity
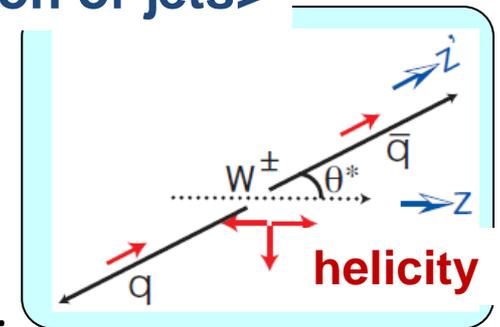
The dominance of the longitudinal mode

➡ **The coupling arises from EWSB**

46

As an example

- **Littlest Higgs model with T-parity**
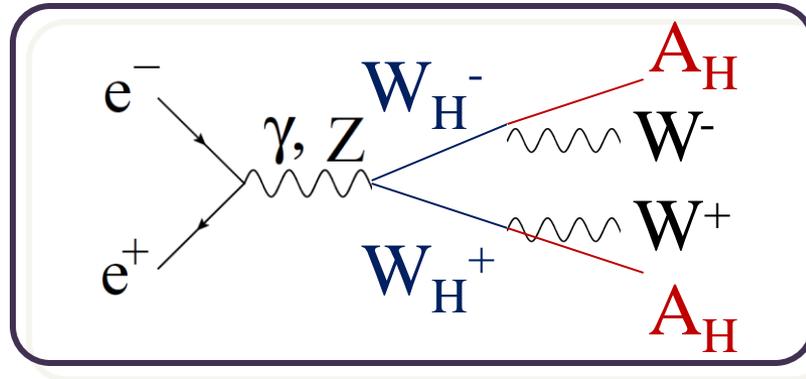
What is you get;

- **Mass**
- **Spin**
- **Interaction**

<Beam polarization>
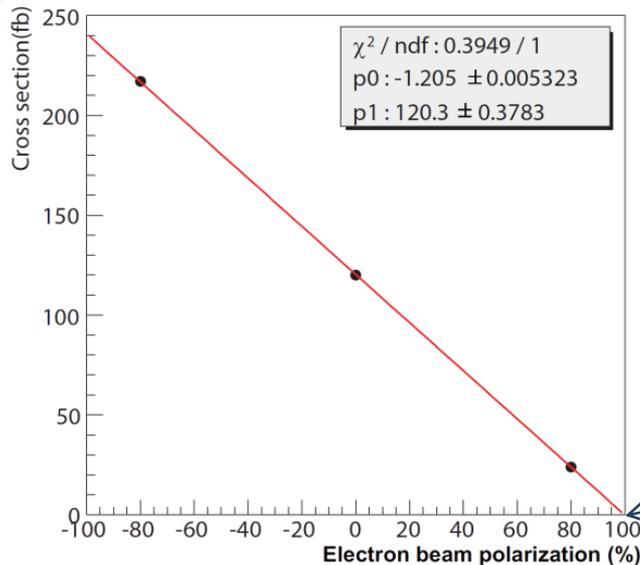
- shows the information of W_H.

- For the electron beam, polarization with a degree of larger than $\pm 80\ \%$ is possible at the ILC.

Measured cross sections extrapolate to zero for 100% RH polarization.

W_H **has** $SU(2)_L$ **charge, but no** $U(1)_Y$ **charge.**
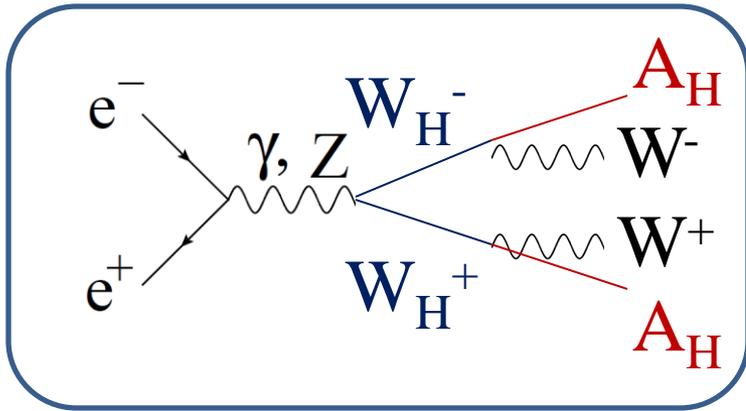
For example,

■ **Littlest Higgs with T-parity**

A_H: Heavy Photon spin 1

W_H^+: Heavy W boson spin 1

We shown that

we can determine several parameters using this process:

What is you get;

- **Mass**
- **Spin**
- **Interaction**

Furthermore, this mode is contained in many TeV new physics models with WIMPs scenario!

⇨ It is possible to **descriminate new physics model !**

For example,

- **Littlest Higgs with T-parity**

  A_H: Heavy Photon   spin 1

  W_H^+: Heavy W boson spin 1

Since WIMP DM is interact SM particle weakly, the DM will interact W+- gauge boson. To conserve the charge and Z2-symmetry, the interaction also includes Charged New Particles.
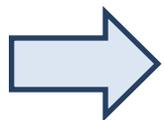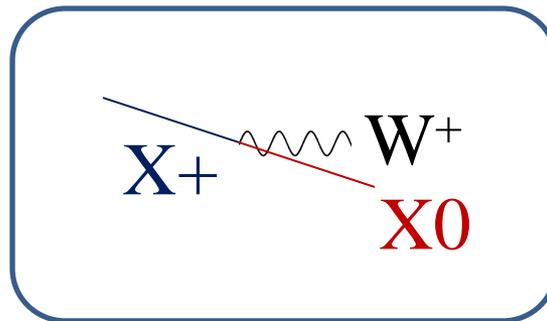
For example,

- **Littlest Higgs with T-parity**

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For example,

■ **Littlest Higgs with T-parity**

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Since WIMP DM is interact SM particle weakly, the DM will interact W+- gauge boson. To conserve the charge and Z2-symmetry, the interaction also includes Charged New Particles.

⇨ Other WIMP scenario will also have this mode!
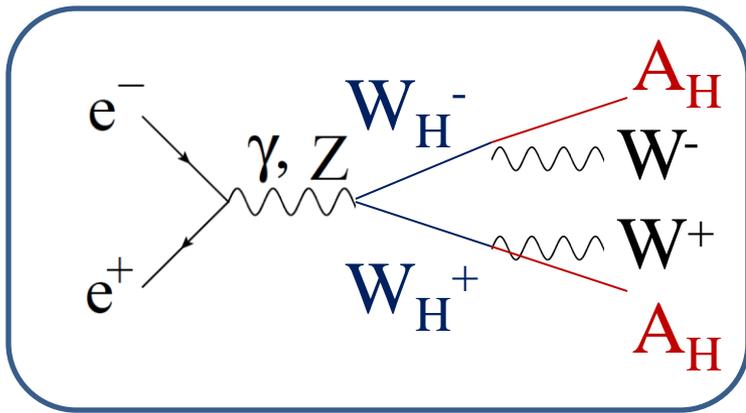
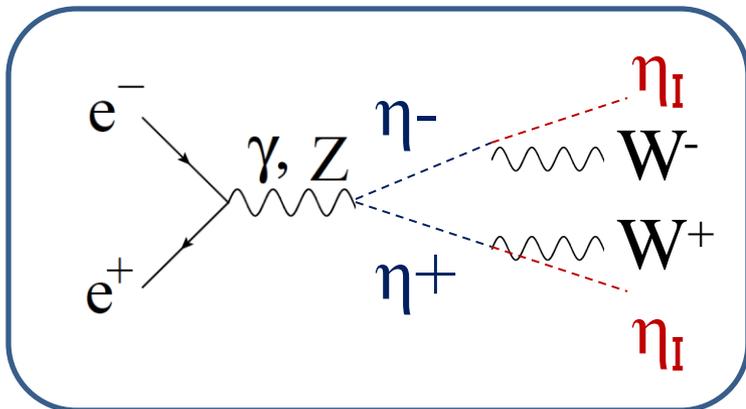■ **Littlest Higgs with T-parity**
A_H: Heavy Photon   spin 1
W_H^+: Heavy W boson spin 1
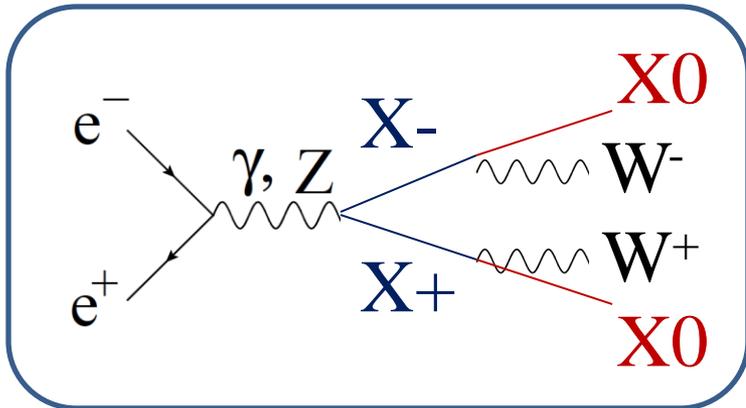
■ **SUSY**
X0: Neutralino   spin ½
X+: Chargino   spin ½

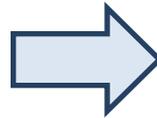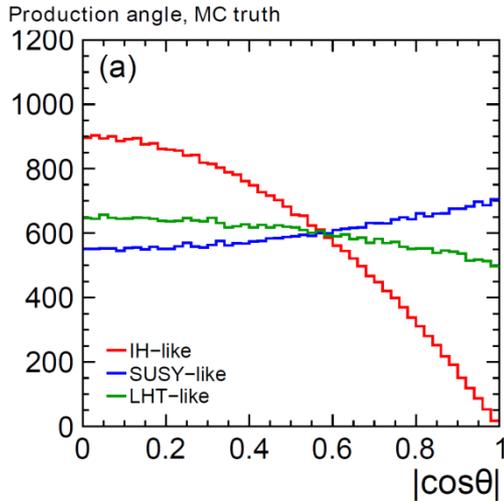■ **Inert Higgs model**
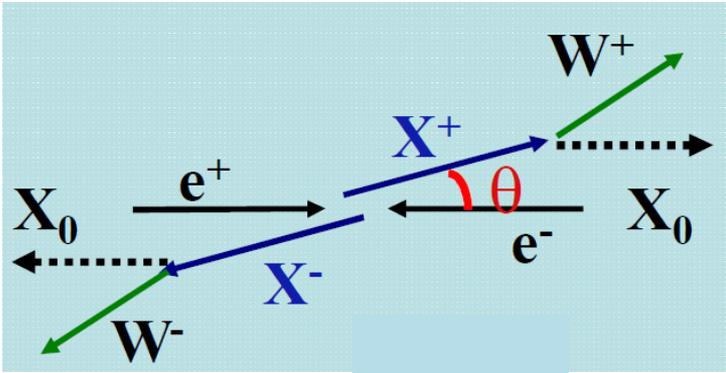η_I: Neutral Inert Higgs   spin 0
η^+: Charged Inert Higgs spin 0

Model identification

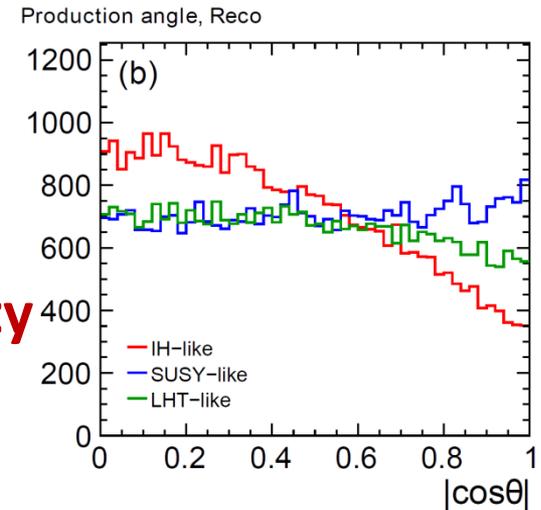**<distribution of X$^\pm$ production angle >**

- W_H momentum can be reconstructed although 2 missing in final state assuming back-to-back production of W_H^+ & W_H^- (**with twofold ambiguity**).

worse
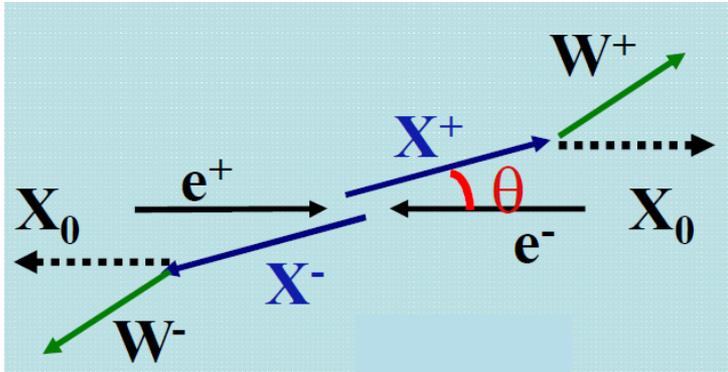
due to twofold ambiguity

Model identification
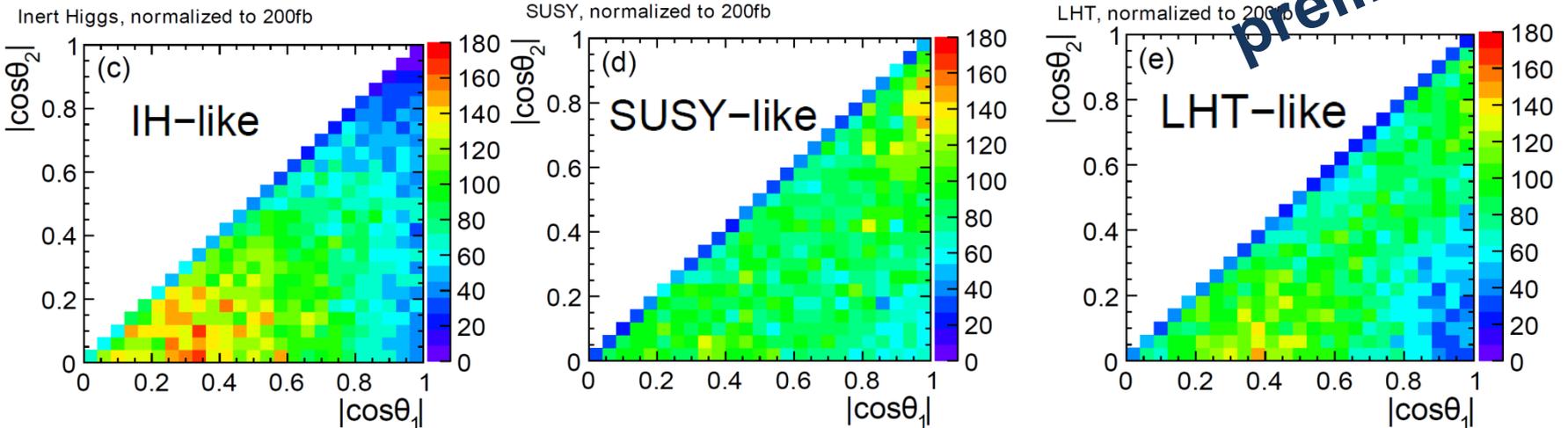
<distribution of $X^{\pm}$ production angle >

- W_H momentum can be reconstructed although 2 missing in final state assuming back-to-back production of W_H^+ & W_H^- (**with twofold ambiguity**).

We plot both values of Θ in 2d plot (with $cos\theta_1 > cos\theta_2$)

preliminary

to increase the statistics.

Model identification
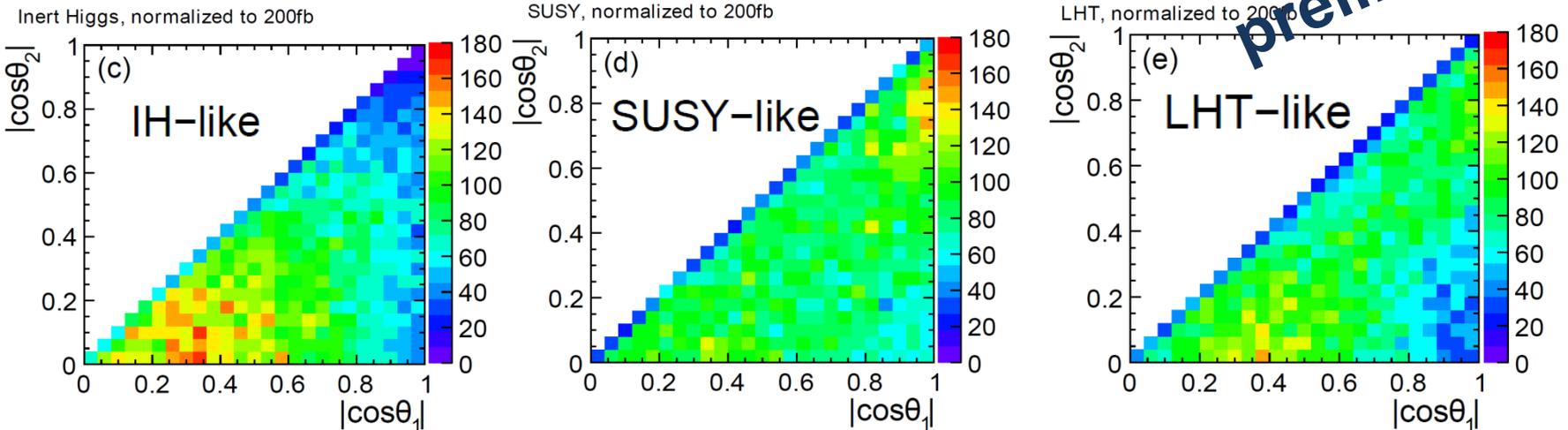
<distribution of X$^\pm$ production angle >

To quantify the difference, we compare the production angle distribution for one model (dubbed as "data") against another model ("template").

As the result of χ^2 analys, **Each model can be identified.**

**We plot both values of Θ in 2d plot (with** $cos\theta_1 > cos\theta_2$ **)** *preliminary*

Inert Higgs, normalized to 200fb — (c) IH–like

SUSY, normalized to 200fb — (d) SUSY–like

LHT, normalized to 200fb — (e) LHT–like

to increase the statistics.

summary

ILC

determine accurately

- **Weak gauge boson coupling**
- **Fermion(Top) sector**
- **Higgs physics**
    - **Mass, Spin, CP**
    - **Branching ratio**
    - **Yukawa coupling**
    - **Self coupling**
- **(new particle measurement)**
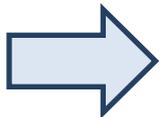
➡ **verify the EWSB physics**

After we determine origin of yukawa coupling, we will understand the flavor physics.