Little Higgs with T-parity @ILC

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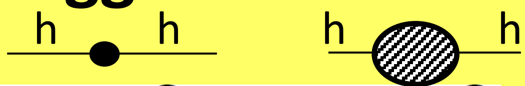
Little Hierarchy problem

There are 2 predictions on where the energy scale of new physics should emerge.

1. **Fine tuning of Higgs mass**



$$m_{Higgs}^2 = m_0^2 + \delta m^2$$

Measured Higgs mass **Bare mass** **Correction term**

Λ : Energy scale $\delta m^2 \approx (0.27\Lambda)^2$

Λ<1 TeV

2. **Electroweak precision measurement** **Λ>10TeV**

➡ Conflict between the 2 energy scales.

➡ **Little Higgs model was proposed!**

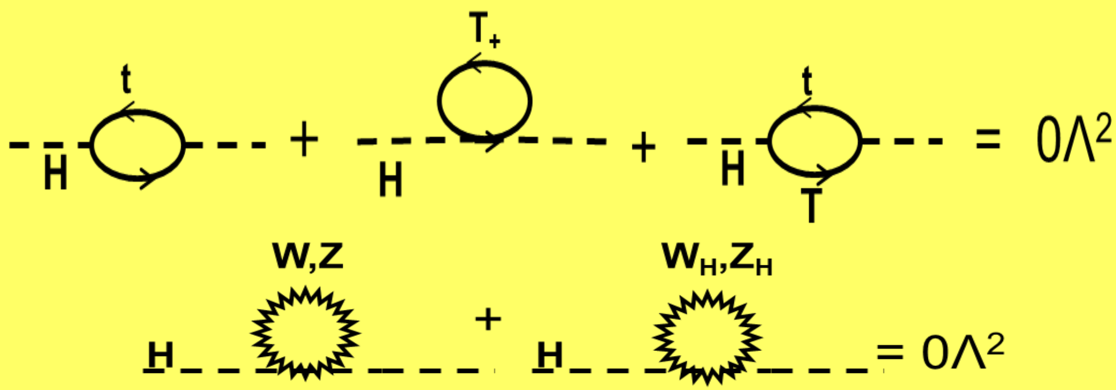
Little Higgs model

<Little Higgs mechanism>

Global Symmetry : SU(5) **f ~ 1 TeV** SO(5) **v ~ <h>**

subgroup : $[\,SU(2)_L \times U(1)_Y]^2$ ⇨ $SU(2)_L \times U(1)_Y$ ⇨ $U(1)_Y$

<Higgs mass contribution>



Quadratic divergent terms cancel at 1-loop order

Solves Little hierarchy problem

Selection of model parameters

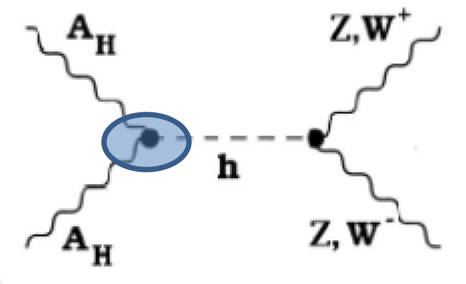
lepton and gauge sector are described with 2 model parameters

κ	f	m_H
0.5	580(GeV)	134(GeV)

*K small→l_H,ν_H mass too small
*K large→4 fermi interaction contribution increases and large discrepancy from SM.

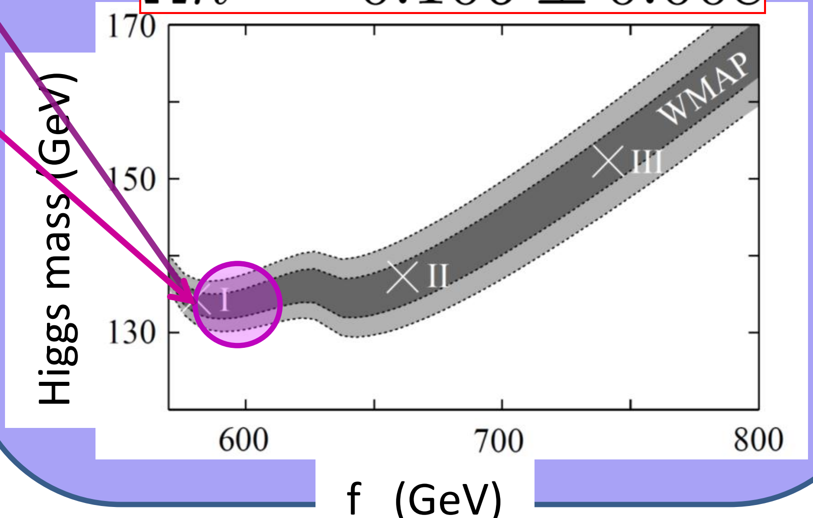
relic density measure from WMAP

Main annihilation mode

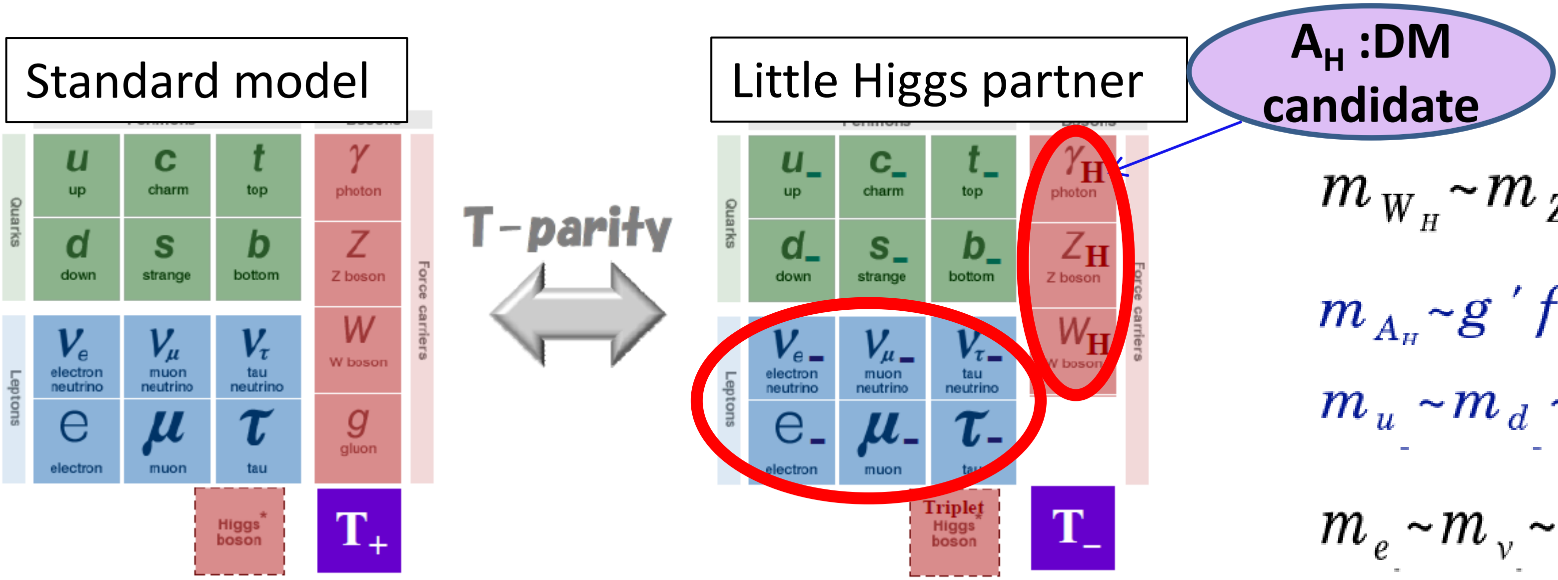


Cross section depends on m_{AH}&m_H

$$\Omega h^2 = 0.106 \pm 0.008$$



Littlest Higgs with T-Parity model



$$m_{W_H} \sim m_{Z_H} \sim g f$$

$$m_{A_H} \sim g' f / \sqrt{5}$$

$$m_{u_-} \sim m_{d_-} \sim \sqrt{2} k_q f$$

$$m_{e_-} \sim m_{\nu_-} \sim \sqrt{2} k_l f$$

LHT masses in gauge & lepton sector can be described with 2 parameters

- f(VEV): energy scale of global symmetry breaking
- K : lepton Yukawa coupling

Important parameters which describe how LHT particles obtain masses & solve little hierarchy problem.

Aim of study

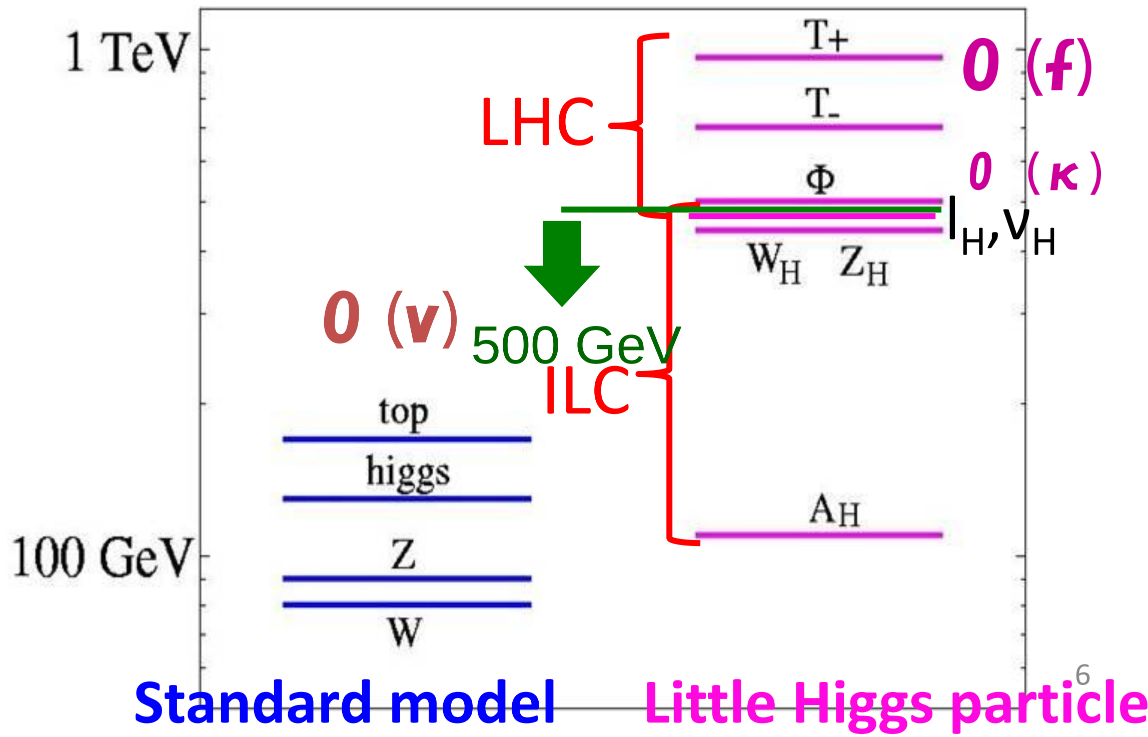
Evaluate ILC's sensitivity on …

- 1st aim : extracting model parameters
- 2nd aim: completing the mass spectrum and checking consistency with parameters

Strong proof that discovered particles are indeed LHT.

κ	f
0.5	580(GeV)

※Using Fast simulator



ILC ~ ILD ~

<ILC ~e^+e^- lepton collider~>

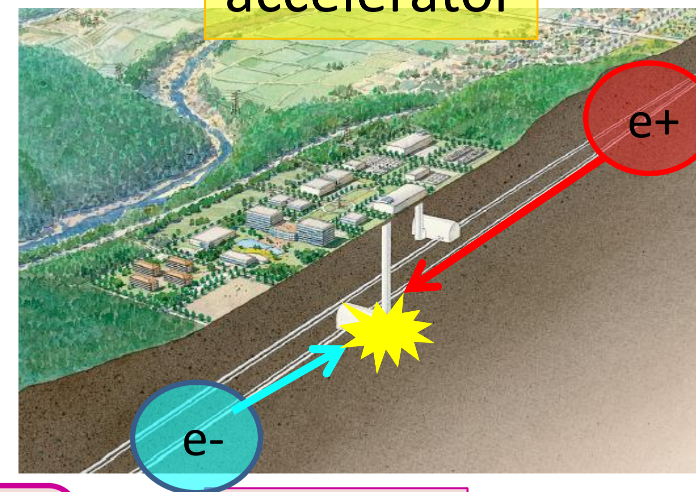
Total length ~31km

Center mass energy:$\sqrt{s}$=500GeV~1TeV

Integrated luminosity(4year)=500fb^{-1}

polarization: over 80%

accelerator

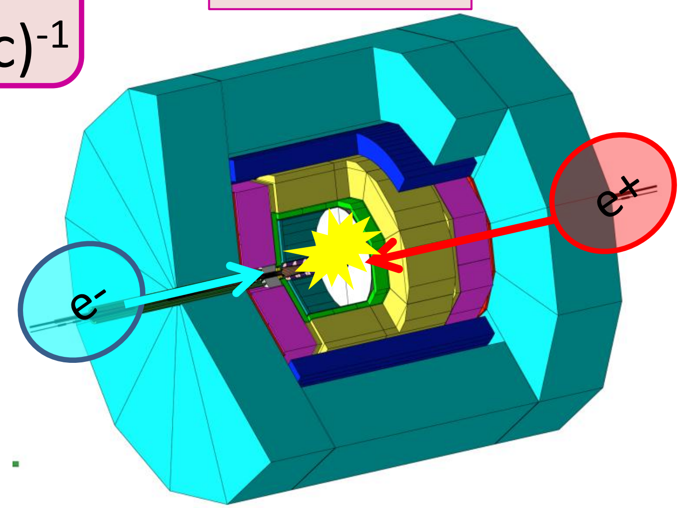


<ILD ~detector~> PFA

Energy resolution：$\Delta E/E = 30\%/\sqrt{E(GeV)}$

Momentum resolution: $\Delta P_t/P_t^2 = 5\times 10^{-5} (GeV/c)^{-1}$

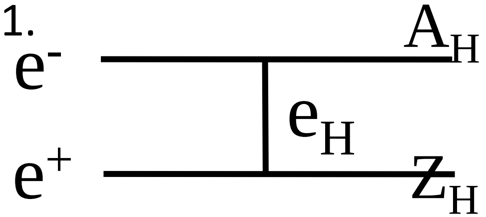
detector



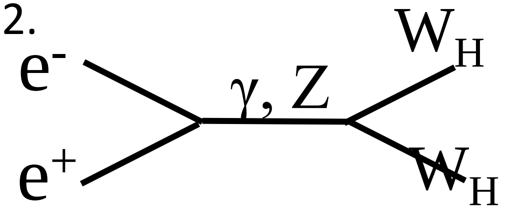
Clean environment
→ capable of jet reconstruction
Possible of doing precision
Measurements on Little Higgs particles

※study is done using Fast simulator

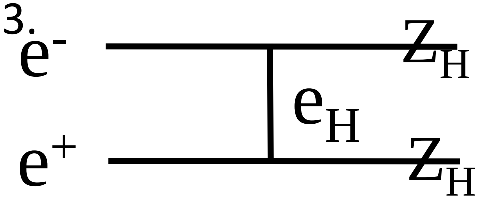
Analysis strategy

1.


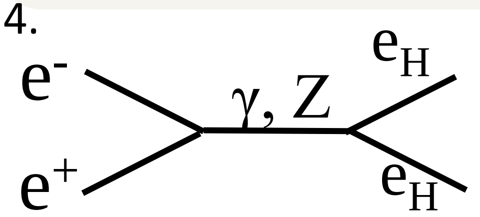
- $m_{AH} + m_{ZH} < 500$ GeV
- producable @ 500 GeV
- **First signal of LHT!**

2.


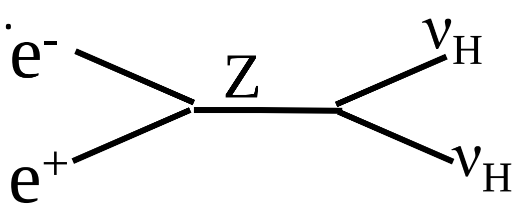
- Large cross section
- **Precision measurement on f.**

3.


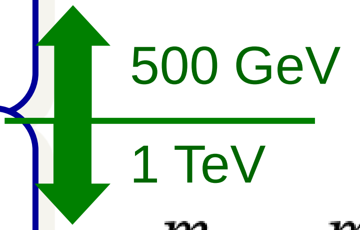
- Determine f.
- **complete mass spectrum in gauge sector**

4.


- **Precision measurement on κ**
- Determine l_H mass

5.


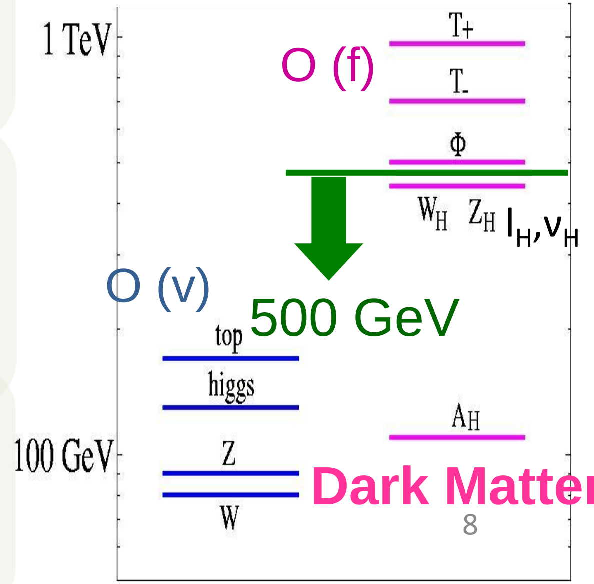
- **Complete mass spectrum in lepton sector**



$$m_{W_H} \sim m_{Z_H} \sim g f$$

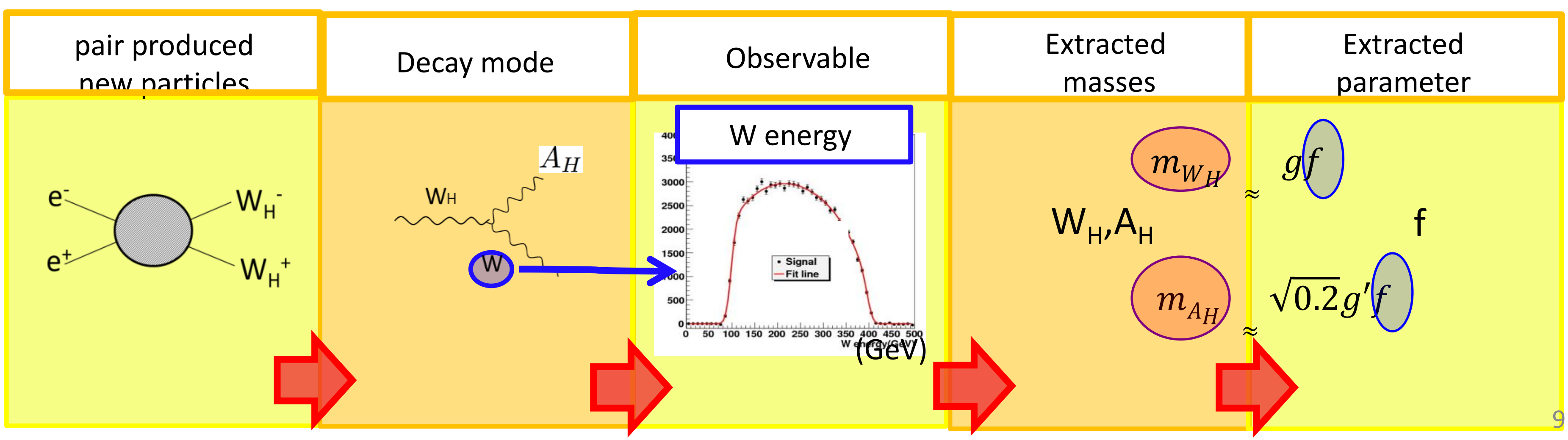
$$m_{A_H} \sim g' f / \sqrt{5}$$

$$m_{e_-} \sim m_{\nu_-} \sim \sqrt{2} k_l f$$



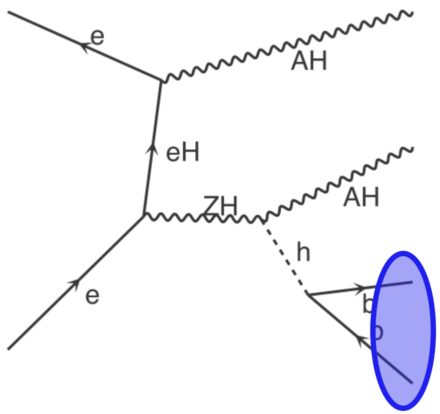
Analysis procedure

- T-Parity ➡ new particles are produced in pairs
- ➡ produced new particles decay into SM and LHT particles
- Extract LHT mass information by recognizing end point of SM energy.
- LHT masses are expressed with model parameters.



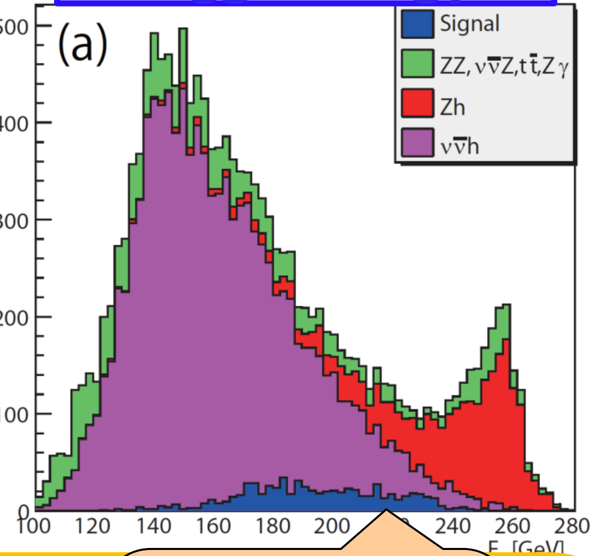
Heavy gauge boson sector

$Z_H A_H$ @500GeV

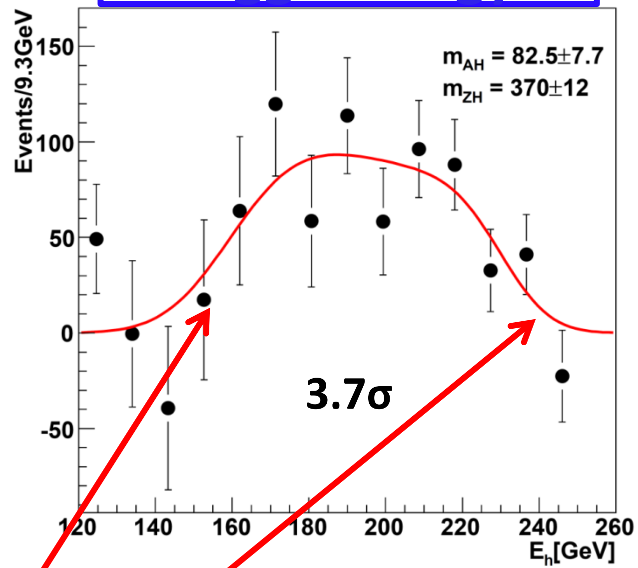


$e^+e^- \to A_H Z_H \to A_H A_H h$

Higgs energy



Higgs energy



（event selection）

- Higgs mass
- miss Pt cut
- b-tagging

Cross section small 1.05fb

Signal: $A_H A_H$**bb**

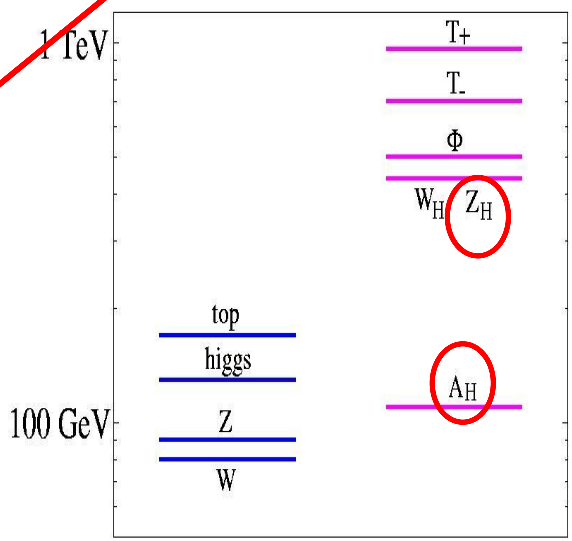
- Mass determination

  m_{AH} = 82.5 ± 7.7 GeV true(81.85)

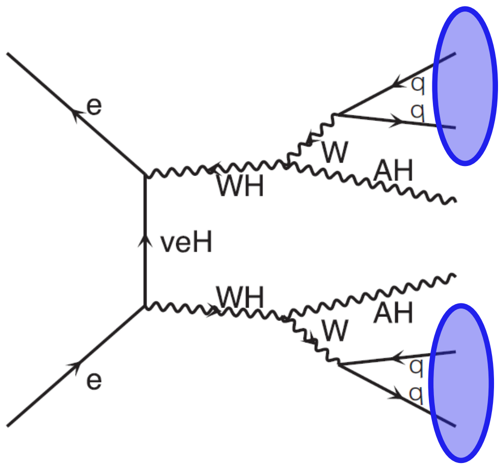
  m_{ZH} = 370. ± 12. GeV true(368.2)

- f determination: f = 581 ±17GeV true(580)

First signal of LHT

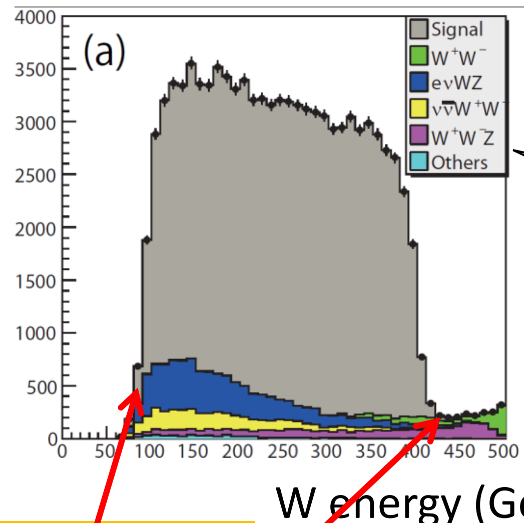


$W_H W_H$ @1TeV



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

$W^{\pm}$energy



（event selection）

- $W^{\pm}$energy
- $W^{\pm}$mass
- miss Pt

Large cross section :120fb

Signal: $A_H A_H$qqqq

This analysis produces 2 mass solutions.

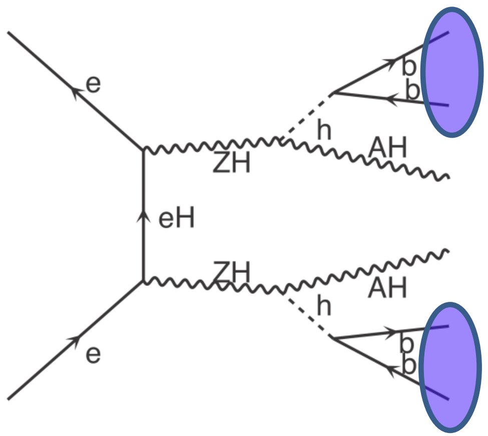
True solution

m_{AH} = 81.6 GeV , 81.0 GeV **1.3%**

m_{WH} = 368.3 GeV , 218.0 GeV **0.2%** (phys. Rev D79.075013)

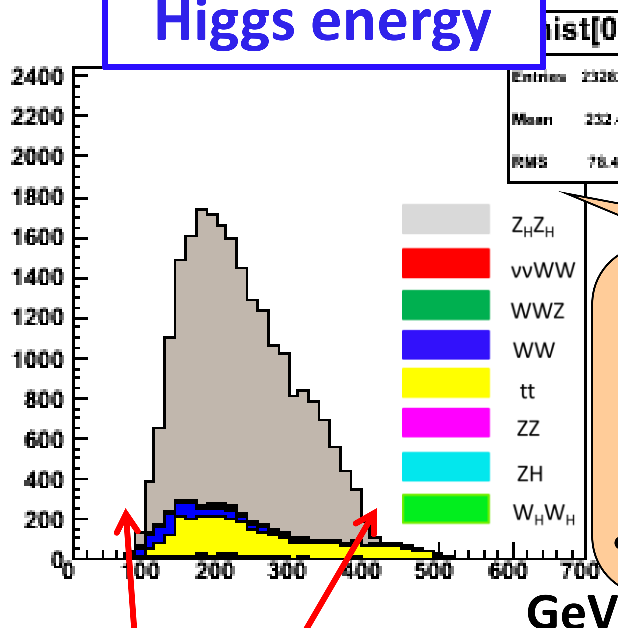
Highly accurate, however true solution needs to be selected

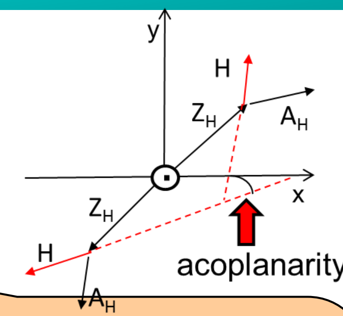
$Z_H Z_H$ @1TeV



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

Higgs energy





（event selection）
- Higgs mass
- isolated lepton rejection
- \# b-tag jets
- acoplanarity

Large cross section :99fb

Signal: $A_H A_H$qqqq

This analysis also produces 2 mass solutions.

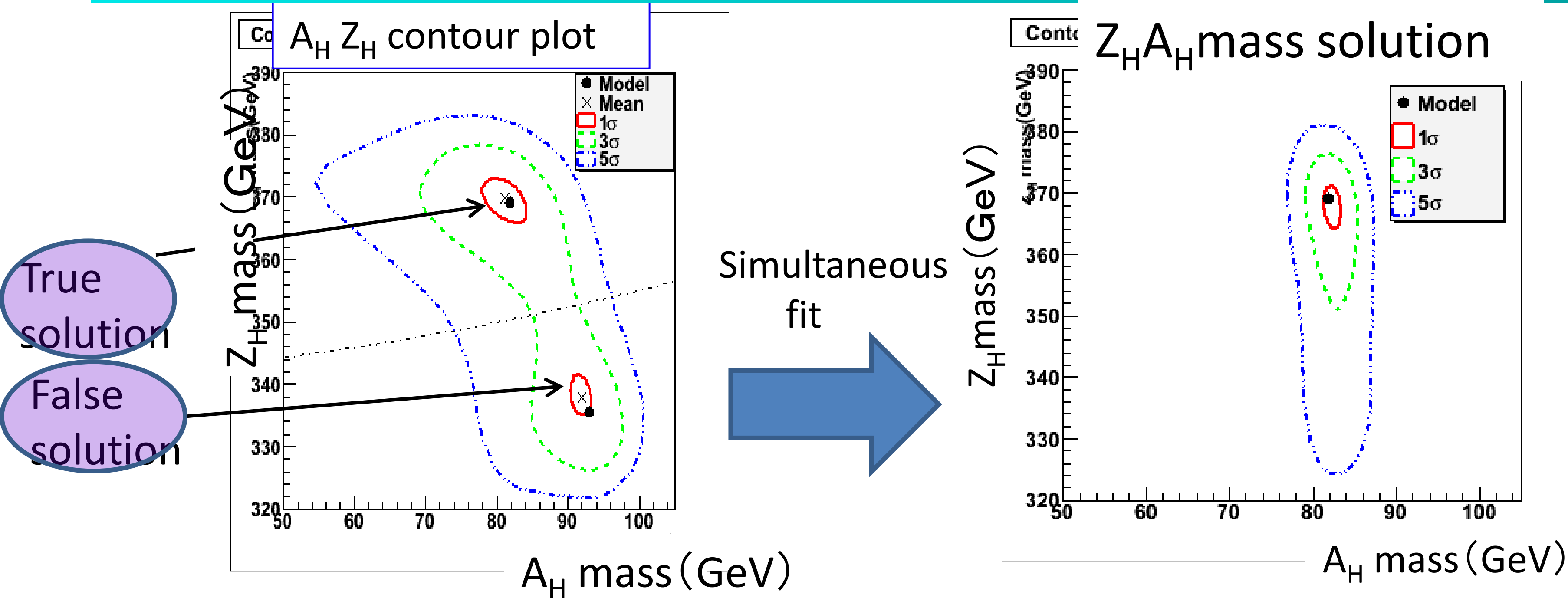
True solution

m_{AH} = 82.7 GeV , 93.1 GeV **4.2%**

m_{ZH} = 366.1 GeV , 335.4 GeV **1.3%**

Highly accurate, however true solution needs to be selected

Mass determination in gauge sector



Through simultaneous fitting $W_H W_H$ & $Z_H Z_H$ (both derive A_H mass), we were able to derive a single mass solution.

- Mass measurement accuracy: A_H 1.3%, Z_H 1.1% W_H 0.20%
- parameter measurement accuracy: f 0.16%

ILC is highly sensitive to f !

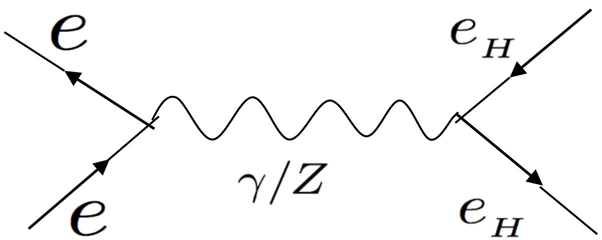
Heavy lepton sector

$e_H e_H$ @1TeV

Aim:

extract lepton Yukawa coupling κ by measuring e_H mass.

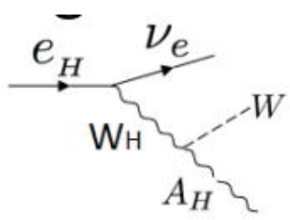
Extremely important in knowing mass generation mechanism.



$m_{eH}=\sqrt{2}\kappa f=410\text{GeV}$

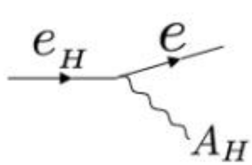
Signal(4.56fb)

$e_H e_H \rightarrow eZ_H eZ_H \rightarrow eeqqqq$



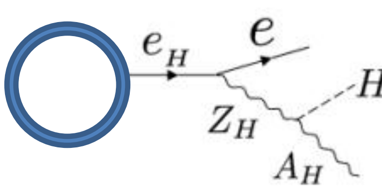
45%

Same signal as $W_H W_H$.
e_H access difficult



30%

Charge suppressed.
Large SM & LHT background.



25%

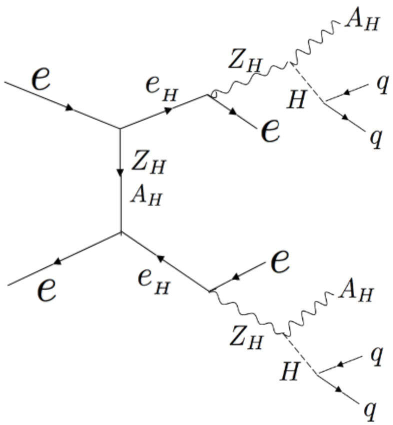
2 higgs characteristic final state
Small background.

Signal Electron selection

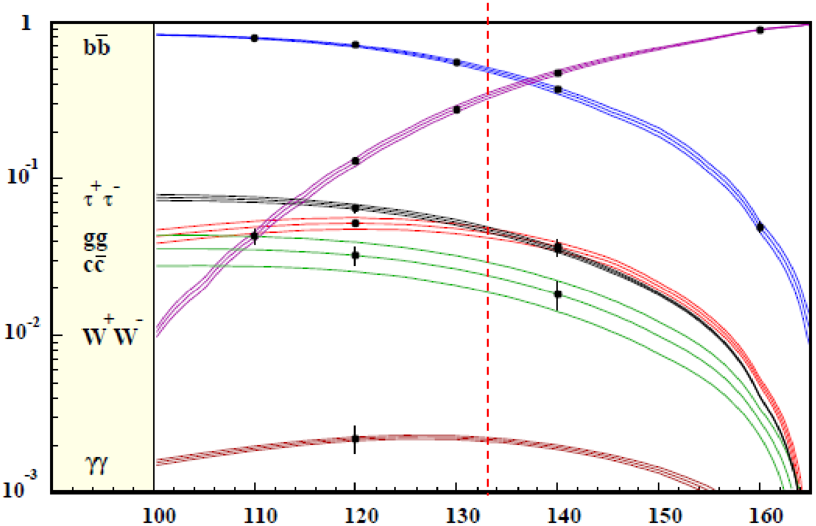
- $e_H e_H \to e Z_H e Z_H$ analysis: 2e + 4jet
- Higgs decay: ○save full hadronic events

  ×lose isolated electron emitting events

⇒ optimize isolated electron selection



Higgs branching ratio



higgs mass = 134GeV

Br(h→bb) =42.35% ○

Br(h→WW)=39.57%

Br(h→ZZ) =5.50%

Br(h→ττ)= 5.21%

× **Isolated electron emitting decay**

○**non electron emitting Full hadronic decay**

Br(h→gg) =4.49% ○

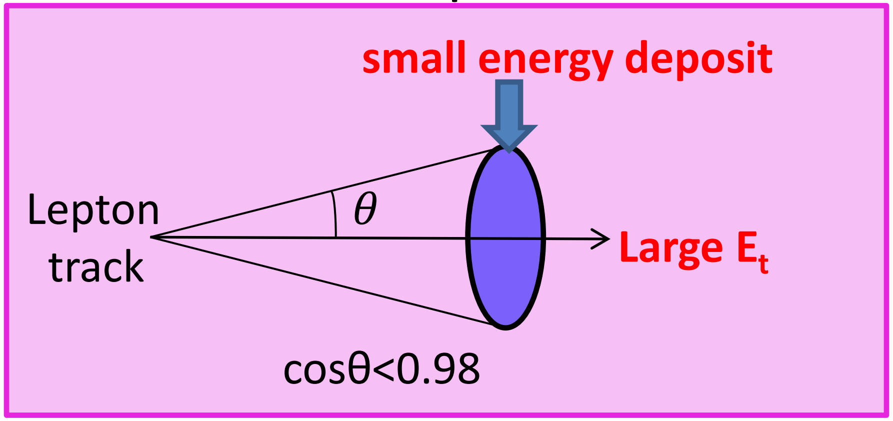
Br(h→cc)= 2.31% ○

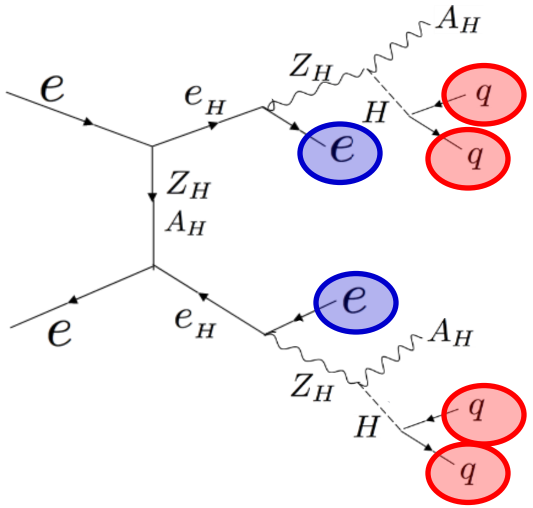
Event reconstruction

1. Select 2 Isolated lepton with maximum energy
2. Reconstruct and force the rest of the tracks as 4 jets.
3. Select reconstructed jet pair that minimizes χ^2 .

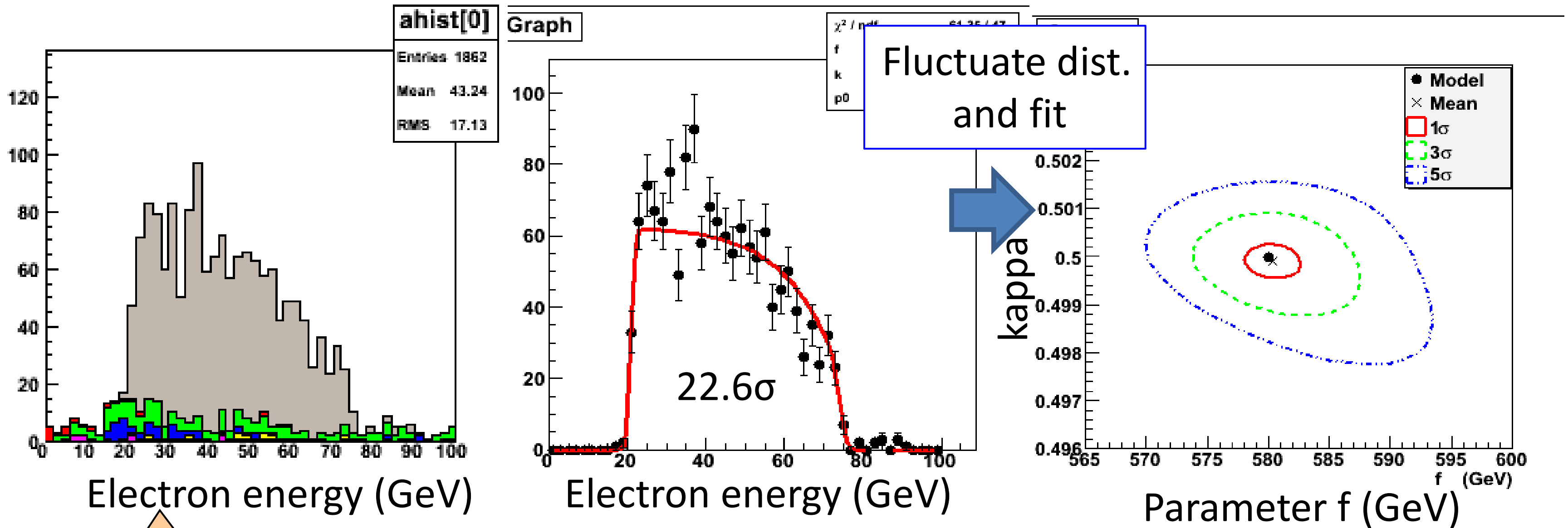
$$\chi^2_H = \left(\frac{M_{H1} - M_H}{\sigma_{M_H}}\right)^2 + \left(\frac{M_{H2} - M_H}{\sigma_{M_H}}\right)^2 \quad M_H = 134.0(GeV)$$

Isolated Lepton ID





e_H mass/parameter extraction



（event selection）

- #Isolated e =2
- h mass diff 30GeV
- miss Pt>50GeV

BG: $\tau_H \tau_H$,
tt,ttZ,tth
evWZ,eeWW,ZZZ

- No multiple solution.

extracted value: f=579.6±3.0(GeV) κ=0.5±4e-4

True value: f=580(GeV) , κ=0.5

mass accuracy: e_H:412.8 ±1.7(GeV) Z_H :371.2 ±1.5(GeV)

Successfully extract mass and parameters.

summary

- Results show that ILC is capable of doing highly accurate precision measurements on LHT masses and parameters.
- This is extremely important in studying LHT's mass generation mechanism.

particle	mass	sensitivity
A_H	81.9(GeV)	1.3%
W_H	369(GeV)	0.20%
Z_H	368(GeV)	0.56%
e_H	410(GeV)	0.46%
ν_H	400(GeV)	

parameter	True value	Measurement accuracy
f	580(GeV)	0.16%
K	0.5	0.0001%

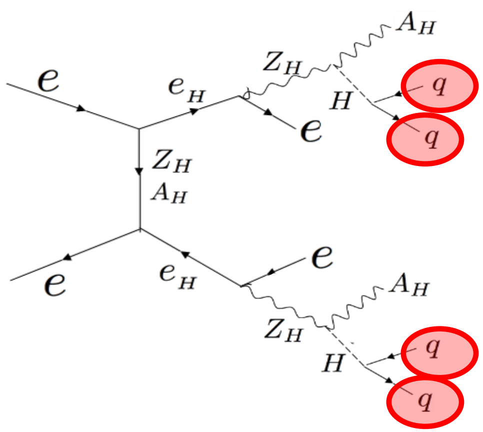
plan

- Analyze $\nu_H \nu_H$ and complete mass spectrum
- Production angle measurement
- Cross section measurement-> coupling measurement (see polarization dependence)

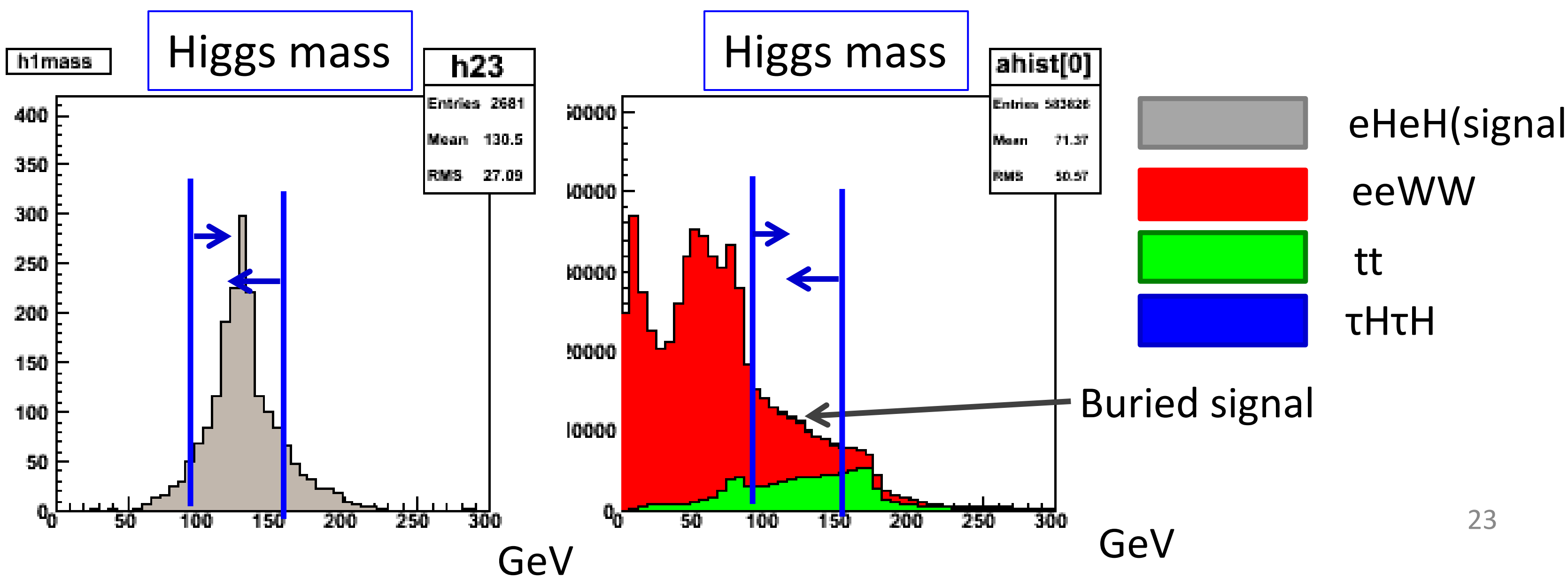
Thank you for listening!!

backup

Reconstructed Higgs mass

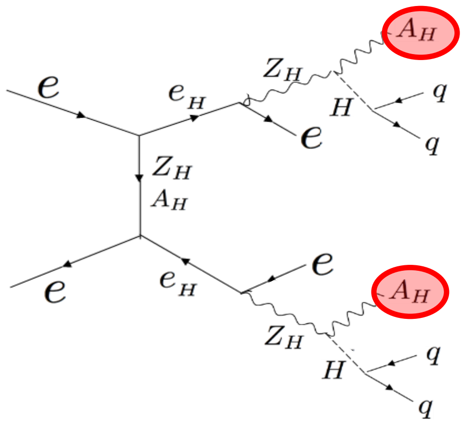


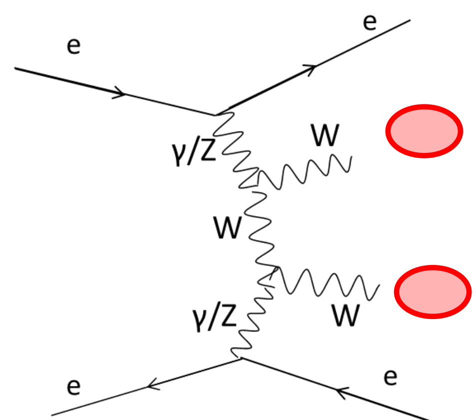
Decay mode	Reconstructed particle
$e_H e_H$	Higgs
eeWW	W boson
tt	B meson
$\tau_H \tau_H$	Higgs

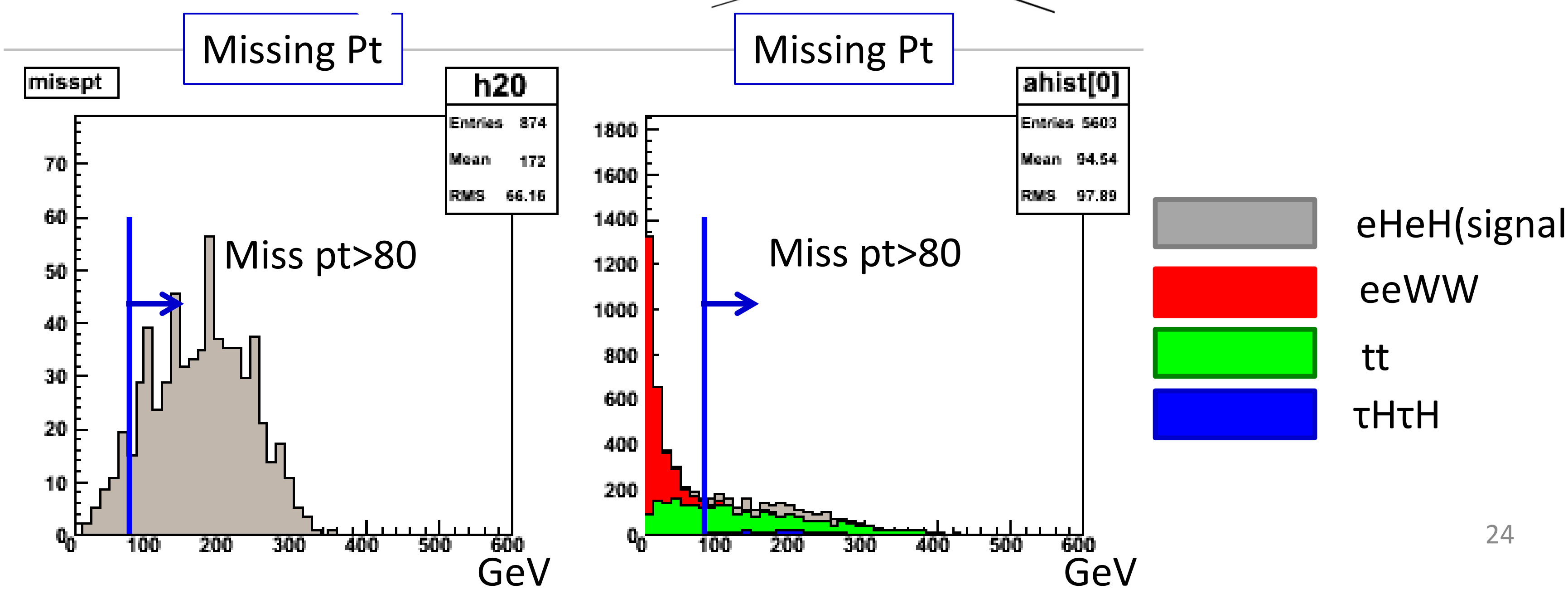


Missing transverse momentum

- Signal has large missing transverse momentum



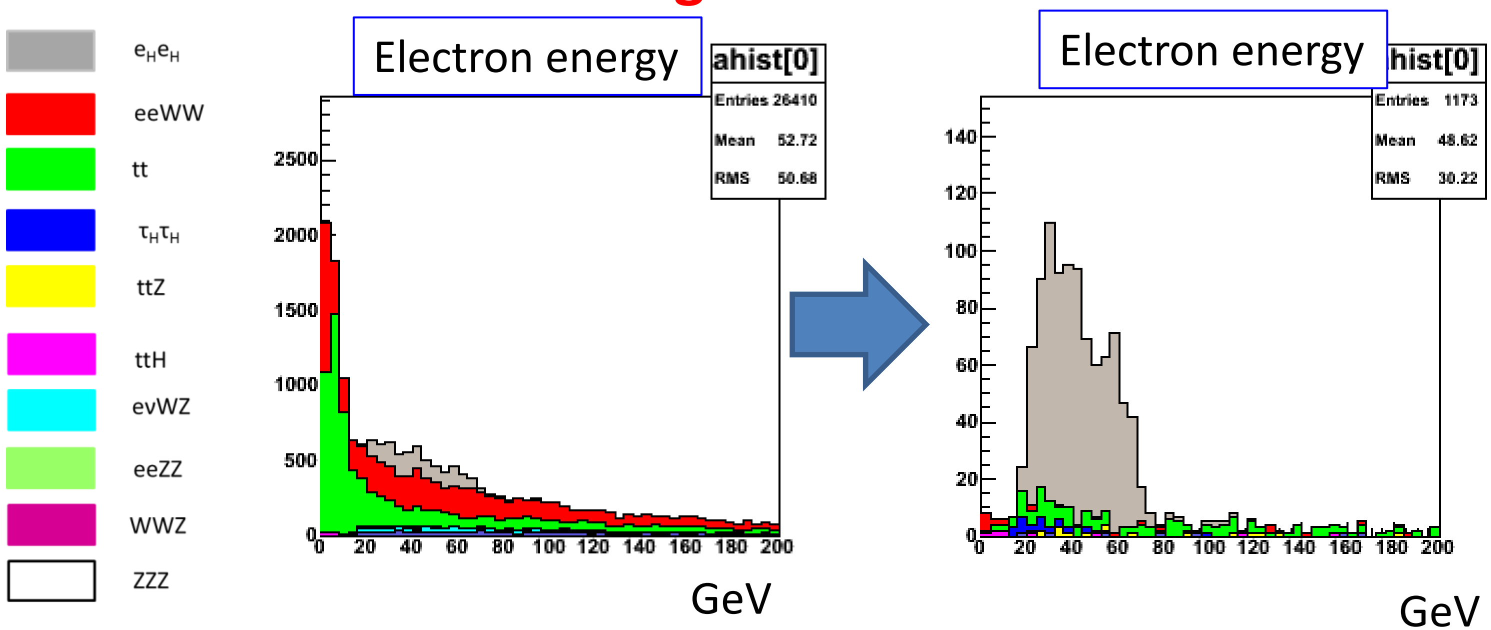




Selection criteria

Selection criteria	Signal ($e_H e_H \rightarrow e Z_H e Z_H$)	background
# isolated electron =2	1638	13221
m_H-30<H mass<m_H+30(GeV)	917	752
Miss P_t>50 (GeV)	849	333

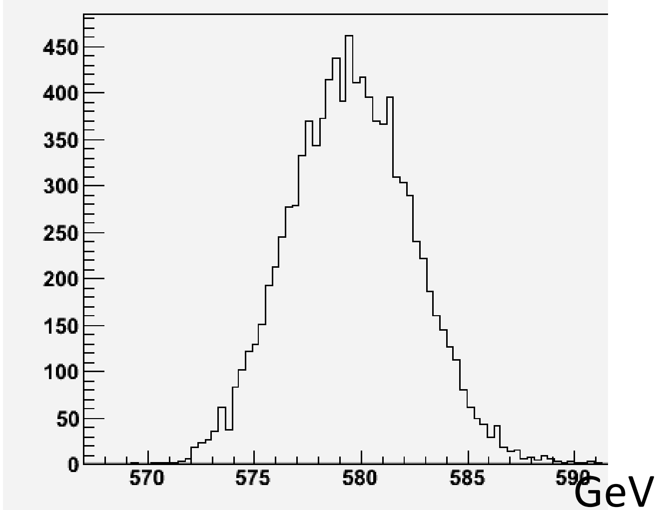
Significance 22.6σ



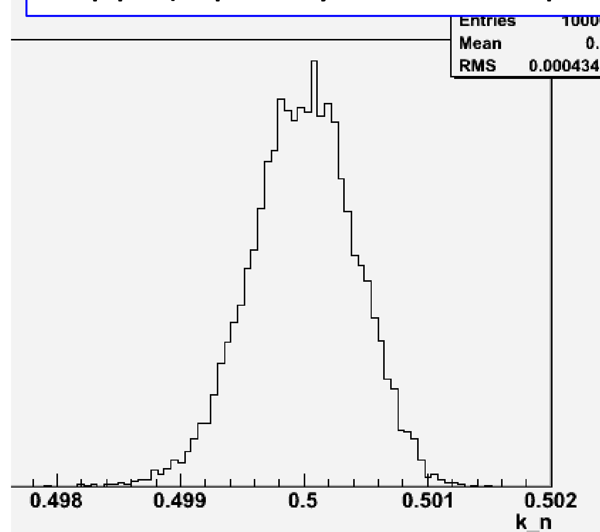
Parameter extraction

- Through Toy MC, Confirmed that fitting is valid.
  - extracted value: f=579.6±3.0(GeV) , κ=0.5±4e-4
  - True value: f=580(GeV) , κ=0.5
- Extracted parameters include true value

f (vacuum expectation value)



kappa(lepton yukawa coupling)



Signal Electron selection

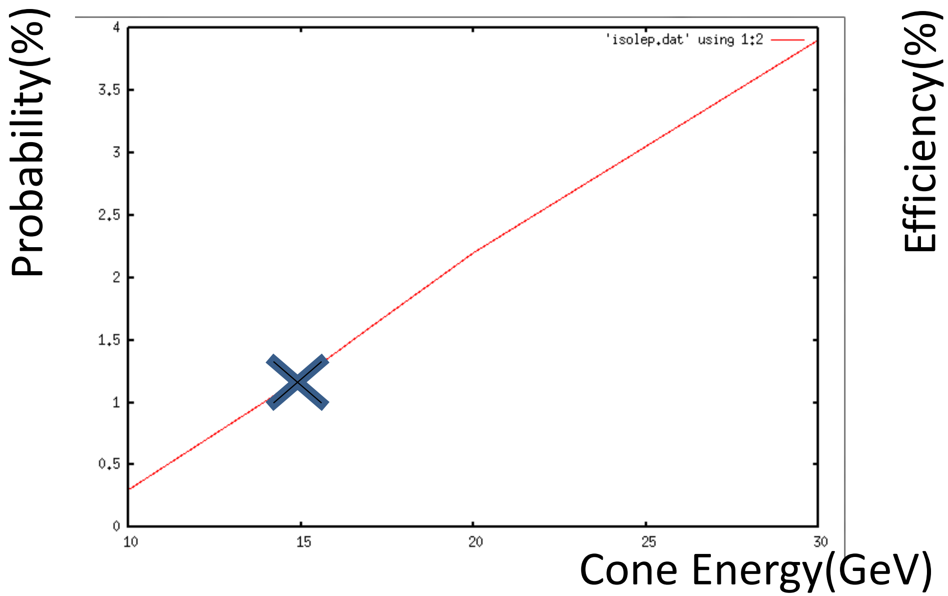
- Probability of missIDing e from b jet is small.(signal:H→bb)

  ⇒Optimize with selection efficiency of e from e_H.

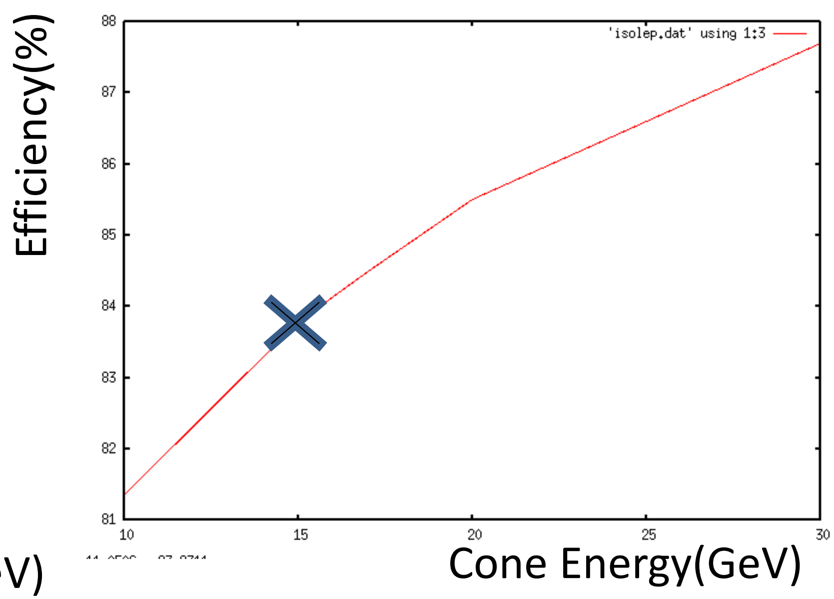
  — Select point right before slope becomes shallow.

- Cone Energy <15GeV :P(missID)=1.2%,signal efficiency=84%

Probability of miss IDing e from b jet



Selection efficiency of e from eH



e_H Branching ratio study

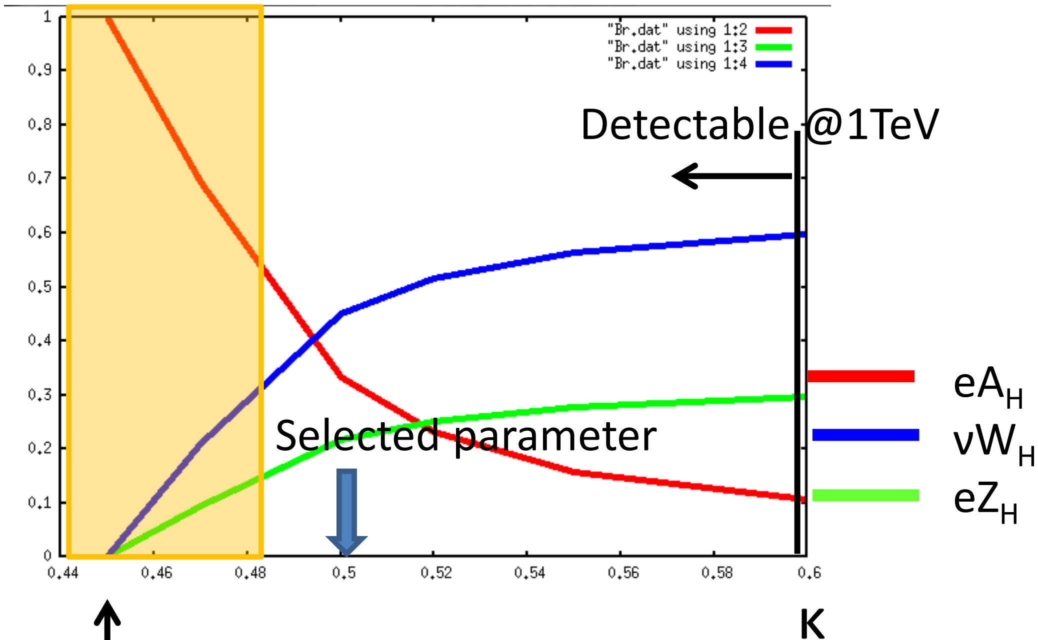
$$\mathcal{L}_{\mathrm{L}}^{(\mathrm{Gauge})} = \ldots + \frac{g}{\sqrt{2}} [\bar{e}_H \not{W}_H P_L \nu$$
$$- \frac{g}{2} \left[\bar{e}_H \not{Z}_H \left(c_H - \frac{s_W}{5 c_W} s_H \right) P_L e \right.$$
$$- \frac{g}{2} \left[\bar{e}_H \not{A}_H \left(s_H + \frac{s_W}{5 c_W} c_H \right) P_L e \right.$$

Charge suppressed

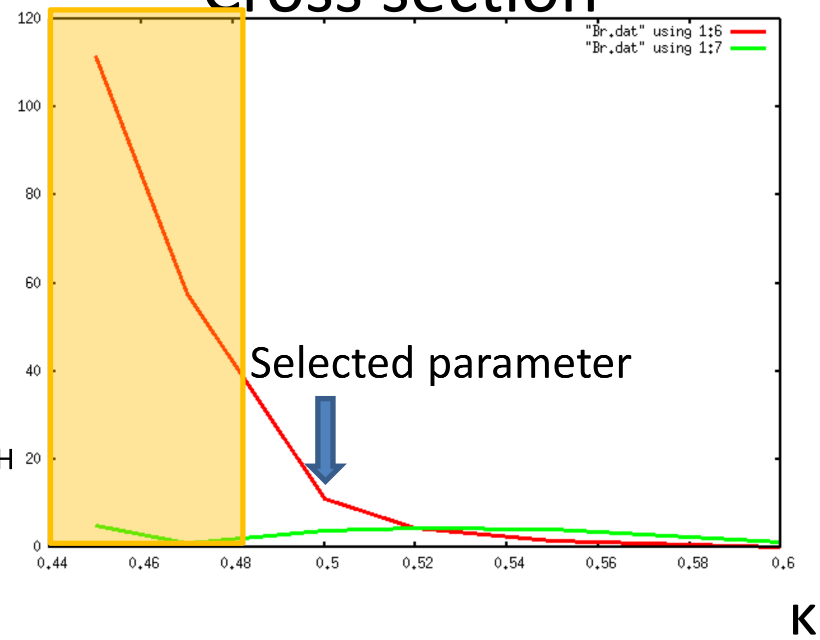
Extremely small mixing angle
s_H~0.1

e_H Branching ratio study

Branching ratio @f = 580[GeV]



Cross section



$me_H \fallingdotseq mZ_H, mW_H$

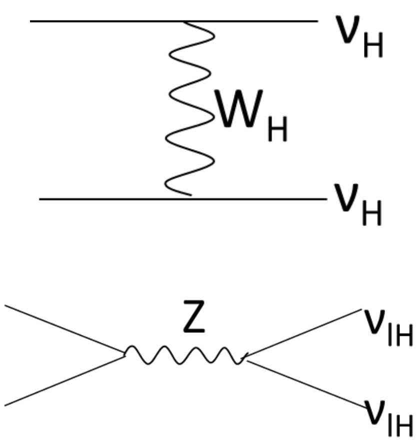
detectable@3fb^{-1} LHC. 2011-12ATLAS+CMS

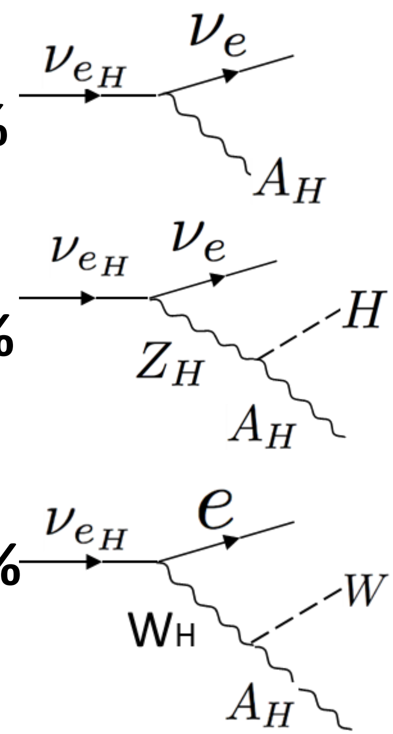
- Large K→ heavy l_H small cross section
  eA_H small branching ratio
- K>0.5 300fb^{-1} LHC 4.2σ(νW_H)
- eA_H: large SM & NP background
- eZ_H :2higgs(134GeV) characteristic final state small background

$\nu_H \nu_H$@1TeV

- **AIM: extract ν_H mass and complete LHT mass spectrum**
- **$\nu_H \nu_H (eW_H eW_H)$ (tot xsec :1320fb)**
  - Signal: eeqqqq(2W)$A_H A_H$ (55.74fb)

    $M_{\nu H} \fallingdotseq \sqrt{2}\kappa f$=400GeV





✗ **Br = 65.4%** — No signal!!

✗ **Br = 11.1%** — Same signal as $Z_H Z_H$ (smaller cross section)

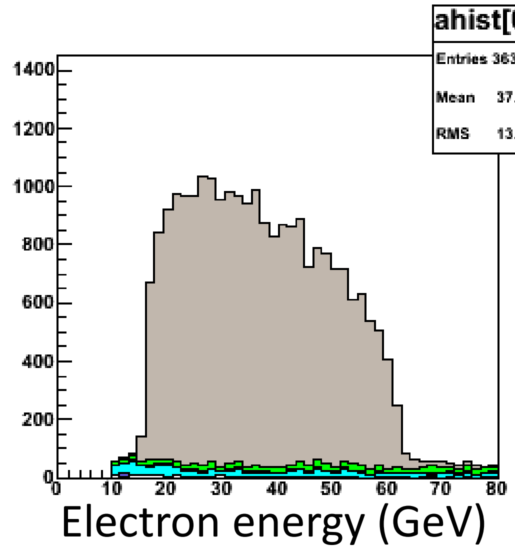
○ **Br = 23.5%** — **signal**

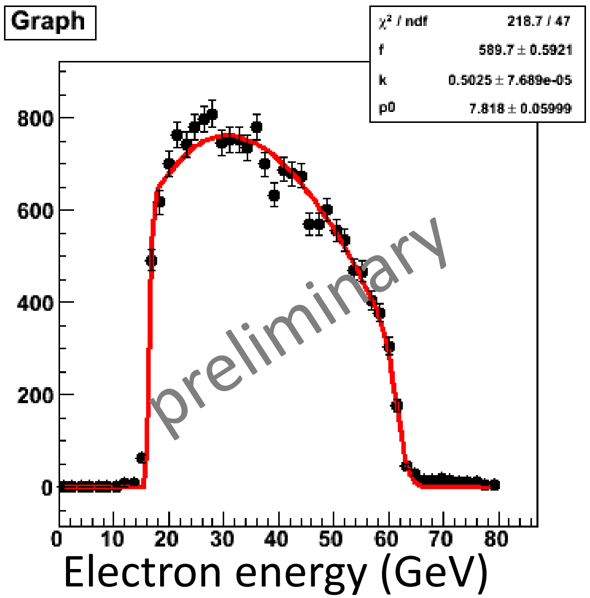
ν_H mass/parameter extraction

BG: $\nu_{\tau H}\ \nu_{\tau H}$, $e_H e_H$, $\tau_H \tau_H$,
tt, ttZ, tth
evWZ, eeWW, ZZZ

(event selection)

- #Isolated e =2
- W mass





- No multiple solution.

extracted value: f=582.0±0.6(GeV) κ=0.5±1e-4

True value: f=580(GeV) , κ=0.5

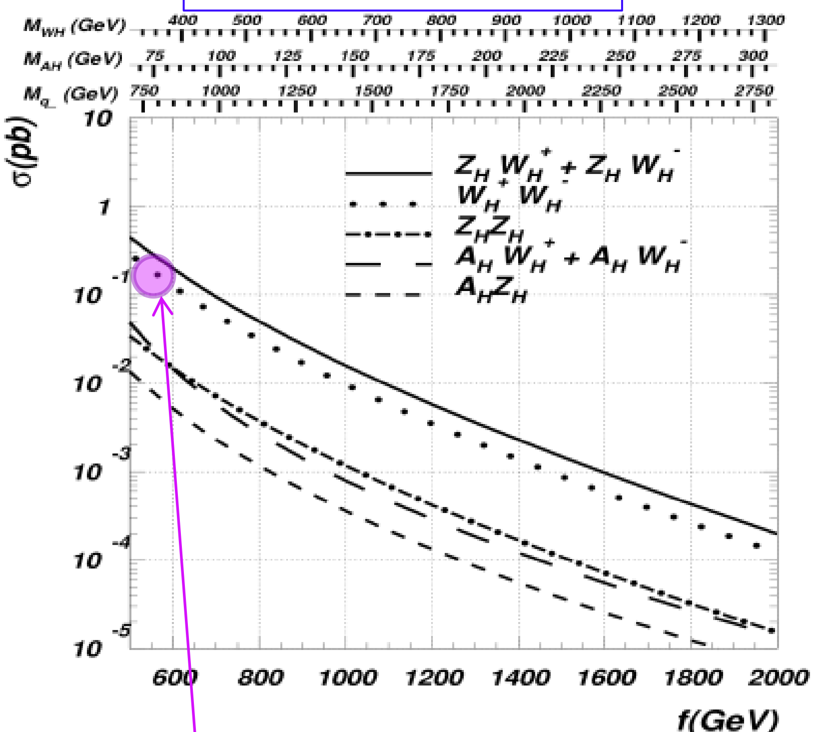
mass accuracy: ν_H:400.8 ±0.4(GeV) W_H :369.6 ±0.4(GeV)

Successfully extract mass and parameters.

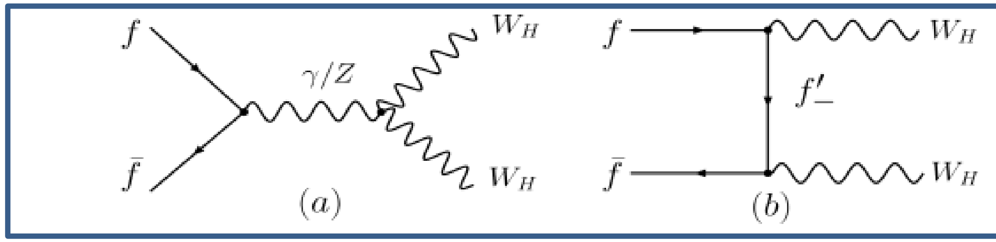
LHT heavy gauge bosons @LHC

Boson pair production cross section

VEV vs Cross section



Production of $W_H W_H$



Largest cross section: $W_H W_H$ ~100fb

Signal : $l\,l\,\not{E}$ (~5fb)

Large background: SM gauge boson

tt production

Cannot construct W energy

$W_H W_H$ total cross section a few 100fb @f=580 GeV

Reference: Alexander Belyaev, Chuan-ren Chen etal Phys Rev D74,115020