Extra dimensions and Seesaw neutrino at ILC

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Outline

- Model
- Simulation condition
- Electron mode analysis
- Tau mode analysis
- Summary

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Seesaw Mechanism

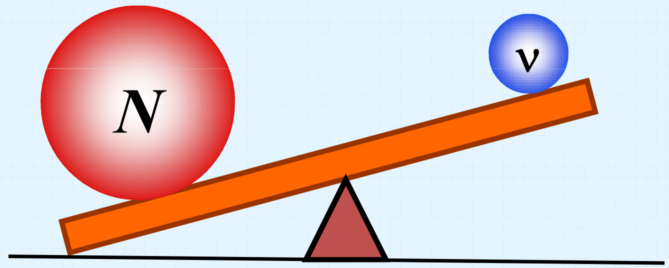
Seesaw mechanism : Origin of tiny neutrino mass is explained.

$$M_\nu = \frac{\upsilon^2 y^2}{2M_N}$$

y : Yukawa coupling

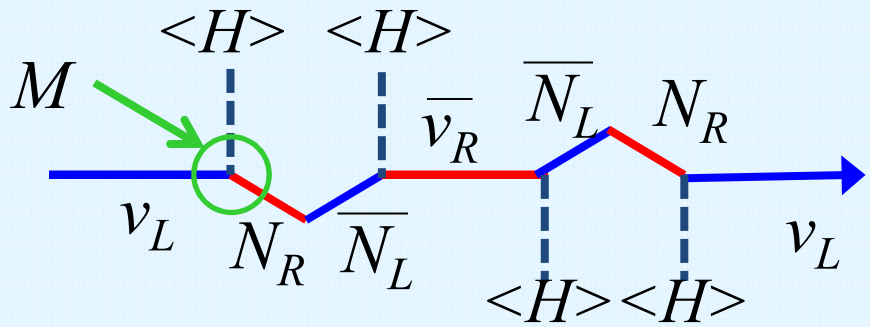
υ : VEV

Neutrino masses are realized by heavy Right-handed neutrino.



$M_\nu \sim 0.1$ eV

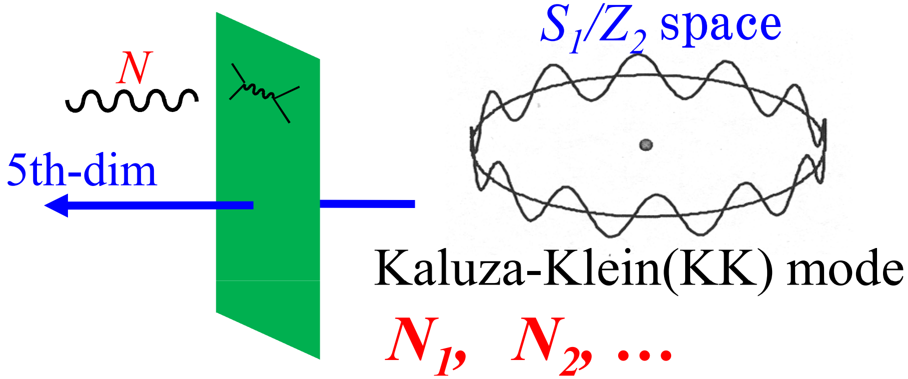
$\rightarrow$ $\boldsymbol{M_N = 10^{14}}$ **GeV**



***N* is too heavy to observe.**

Seesaw neutrino and Extra-dimension

Introducing the extra-dimension …



$$M_N = \frac{2n-1}{2R}(n = 1, 2, \cdots)$$

n : KK mode

R: Radius of 5th-dim

Each KK mode of N contributes to Seesaw.

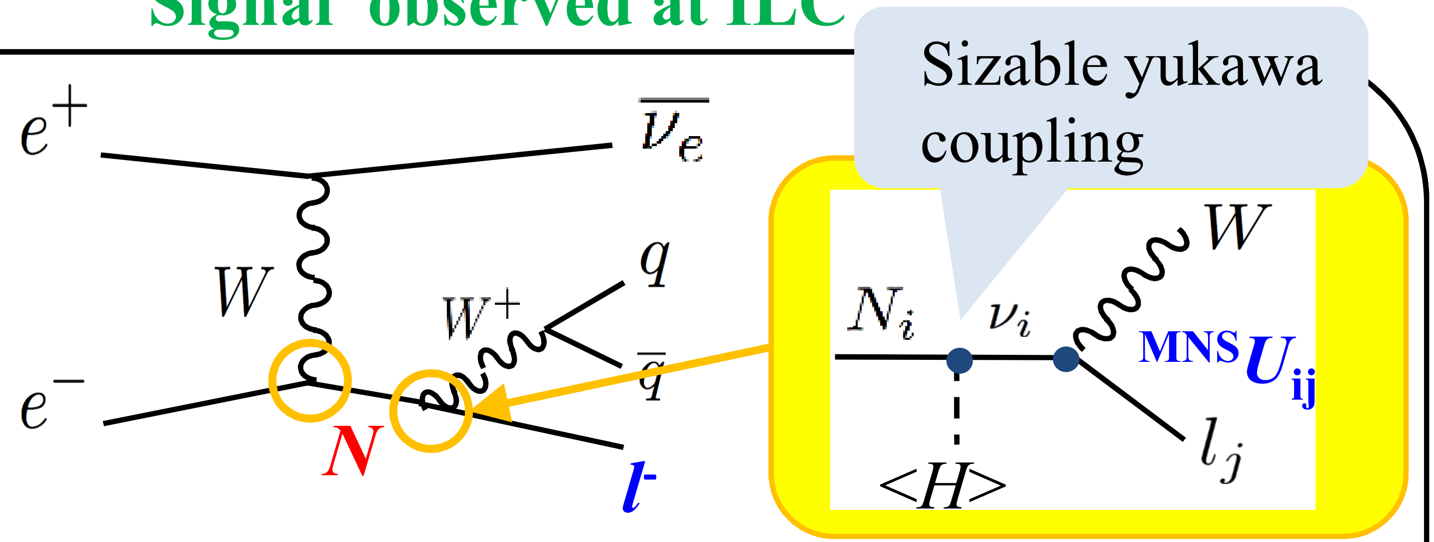
Characteristic of Model

- ☛ ν can be light with not so heavy N.
  - $\Rightarrow$ $1/R$~100GeV $\rightarrow$ M_N~100GeV
- ☛ Yukawa coupling can be large.
  - $\Rightarrow$ N has the sizable coupling to SM particles.

TeV-scale N can be observed at ILC.

Signal at ILC

Signal observed at ILC



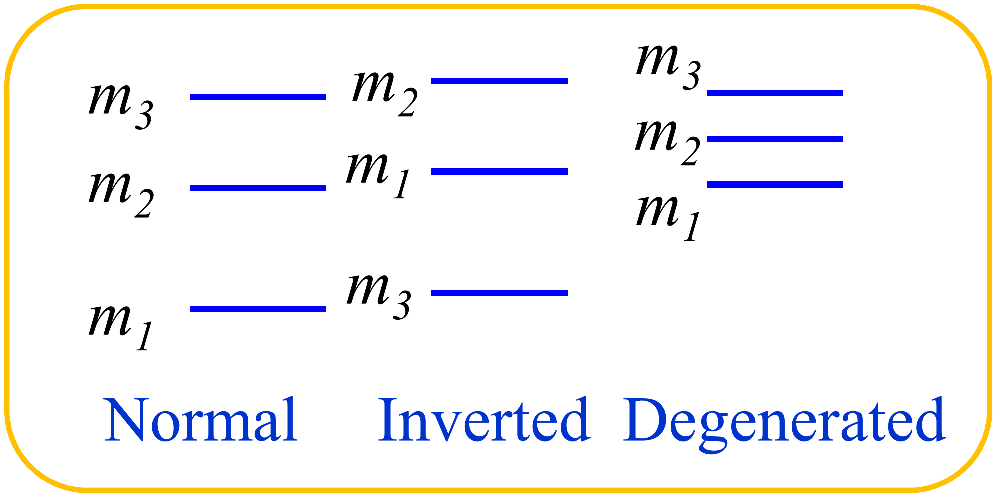
- N couples to W and l via ν
- W→qq
- Final state : lepton + 2jets + ν
- The lepton flarvors are mixed by the MNS matrix.

Electron-mode (l = e) and tau-mode (l = τ) were studied.

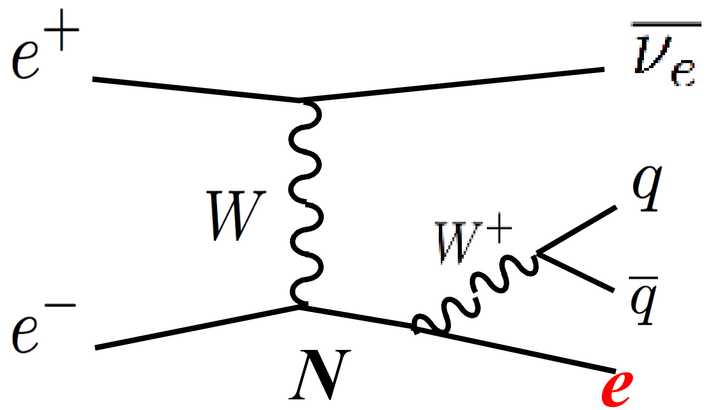
Simulation

- Event generator : Physsim (included ISR and beamstrahlung)
- GLD fast detector simulator
- C. M. energy : **500 GeV , 1 TeV**
- Integrated luminosity : **500 fb^{-1}**
- Neutrino mass hierarchy : Normal, Inverted, Degenerated
- Right-handed neutrino mass

  [KK mode]
  - N_1 : **150** GeV
  - N_2 : **450** GeV
  - N_3 : **750** GeV



Study of electron mode



Cross-section on Electron mode

The cross-sections of the signals and backgrounds are calculated by Physsim.

Signal	Ecm=500 GeV			Ecm=1TeV		
KK mode	Normal	Inverted	Degenerated	Normal	Inverted	Degenerated
1st KK	6.524	297.5	257.1	7.79	355	307
2nd KK	0.065	2.975	2.571	0.517	23.6	20.4
3rd KK	/	/	/	0.085	3.86	3.34

Background	Ecm=500 GeV	Ecm=1TeV
eνW	**4460**	**10300**
WW -> lνqq	**1320**	**560**
ZZ -> llqq+ννqq	108	42.8
tt	531	29.4

Cut summary at 500 GeV

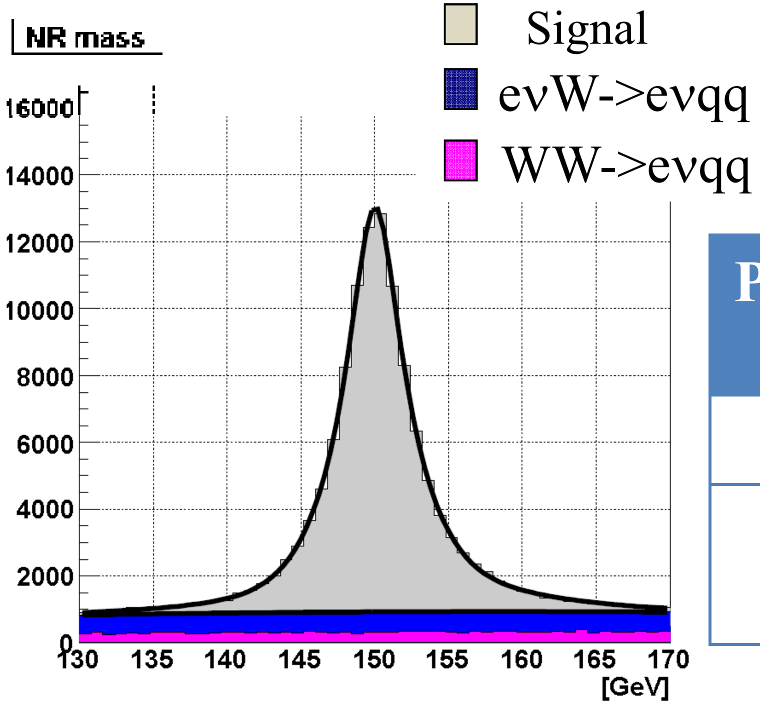
	Signal [Inverted]	evW	WW	ZZ	tt
before cut	177700	2231000	660000	54000	265500
10 < Electron Energy < 200	115728	188275	325990	2852	114198
60 < 2jet mass < 100	104679	126691	269700	129	2493
135 < *N* mass < 160	101057	22594	11324	1	568
Cut efficiency (%)	56.9%	1.00%	1.70%	0.00%	0.20%
Significance (S/N)	**274.5**				

Signal can be separated from the background.

Precision at 500GeV ILC

The measurement precision on *N* at 500GeV is estimated.

Reconstructed N mass[Inverted]



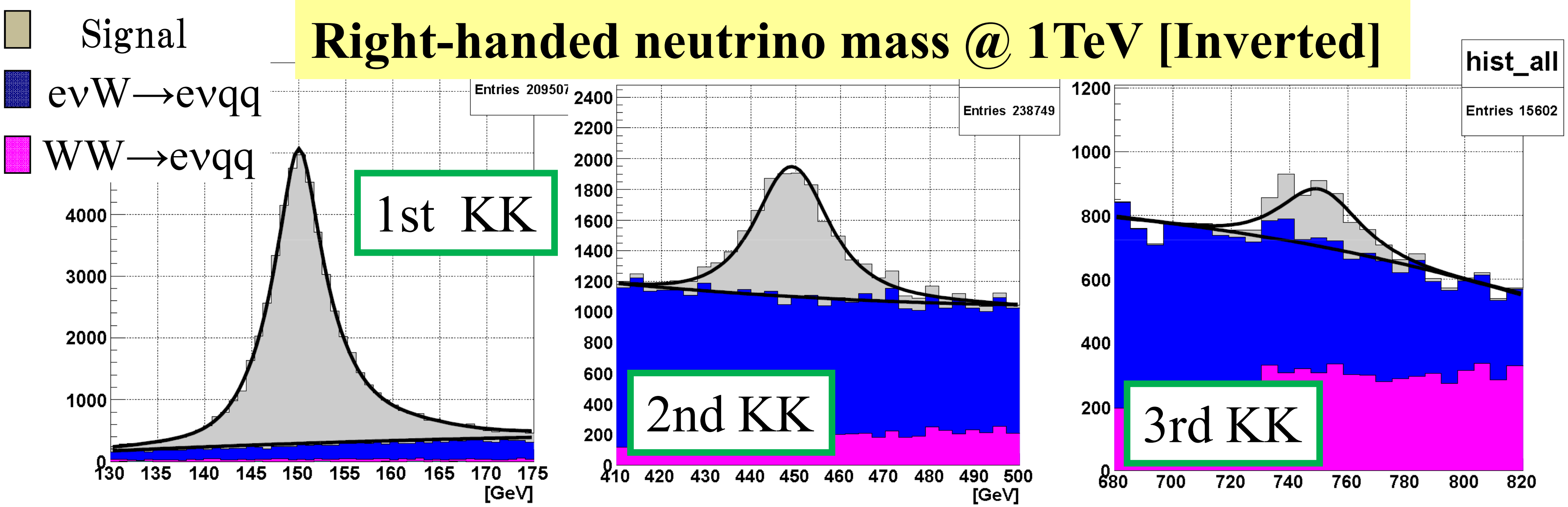
Precision at ILC (%)

Precision (%)	Normal	Inverted	Degenerated
M_N	0.14	0.008	0.009
Cross section	6.49	0.39	0.42

The 1st KK of *N* can be observed with high precision.

Precision at 1TeV ILC

The measurement precision on *N* at 1TeV is estimated.

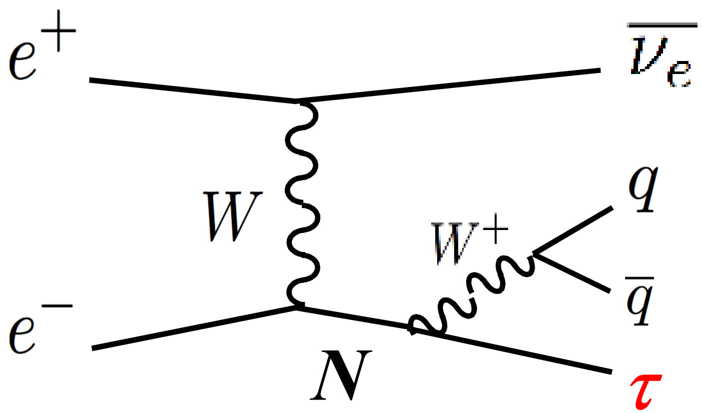


GeV

Precision at 1TeV ILC	1st KK	2nd KK	3rd KK
M_N (%)	0.02	0.05	0.2
Cross section (%)	0.58	2.8	9.9

Some KK mode of *N* can be observed at ILC with high precision.

Study of tau mode



τ -mode study

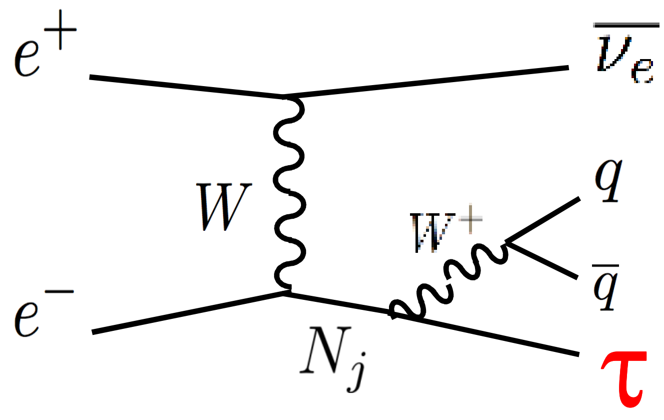
***N* itself can be observed by electron-mode**

However, it is necessary to study other modes to **prove the relation with the neutrino physics**.

τ-mode study ➤ Get $\frac{Br(N \to \tau W)}{Br(N \to eW)}$ ➤ Model ID

Analysis condition

- C.M. energy : 500GeV
- Integrated luminosity : 500 fb^{-1}
- Neutrino mass hierarchy : **Normal, Inverted**
- *N* mass (1stKK) : **150GeV**



Cross-section

Cross-sections of the signal and background are calculated.

Mode	Cross-section(fb)
Signal (Normal)	5.49
Signal (Inverted)	4.18
Electron mode	6.52
eνW	4460
WW → lνqq	3960

Bg (Electron mode, eνW, WW → lνqq)

Very large (eνW: 4460)

The powerful background rejection is necessary.

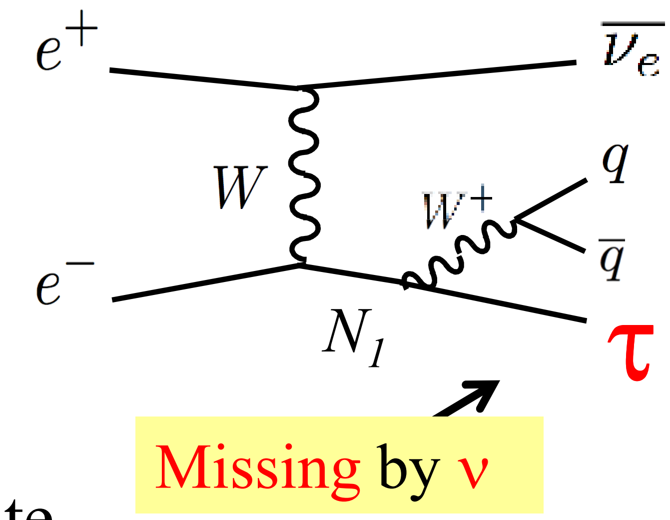
Event reconstruction

The event reconstruction is done by the following way.

1, Forced 3jet reconstruction

2, **τ jet ID**
⇒ A jet with the smallest number of track is selected.

3, **W reconstruction**
⇒ 2jets except for tau candidate



4, ***τ*** **jet reconstruction** with **the correction of *N* mass**

5, ***N*** **reconstruction** ⇒ 2jet + τ

Cut summary

	Signal [Inverted]	Electron mode	eνW	WW
No cut	2090	3260	2231000	1980000
$10 < E_{tau} < 150$	1880	2655	1574690	1155700
$60 < M_{2jet} < 100$	1525	2227	1206880	833895
Likelihood_eνw > 0.63	1077	1837	112158	683066
Likelihood_e > 0.11	999	996	81226	367250
$80 < M_N < 160$	993	939	53093	94225
$135 < M_N$ (corrected) < 165	821	554	12276	14861
Cut efficiency (%)	39.3%	17.0%	0.55%	0.75%
Significance	**4.86**			

Backgrounds are rejected effectively.

Likelihood analysis

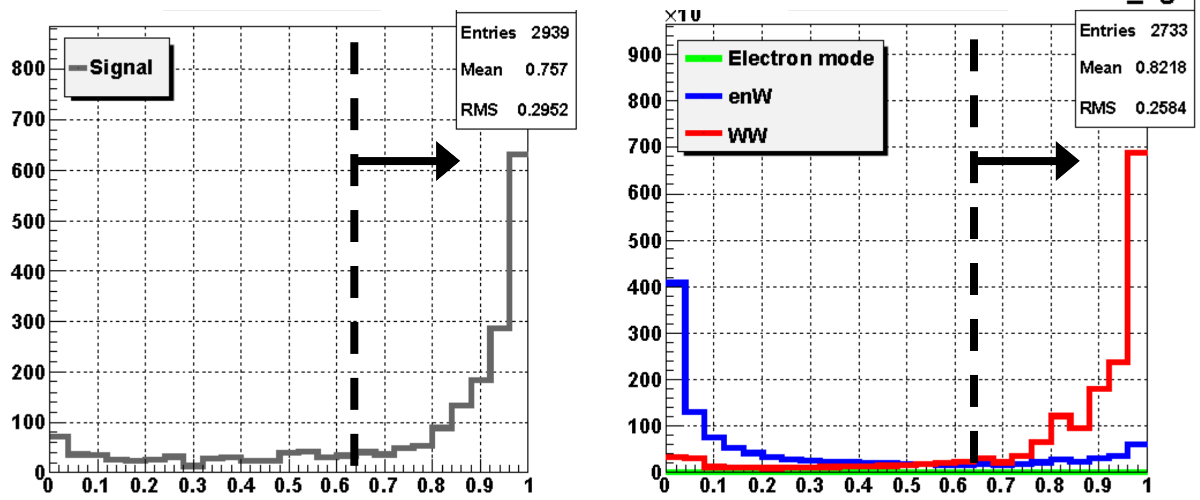
The likelihood analysis is applied to obtain better signal significance.

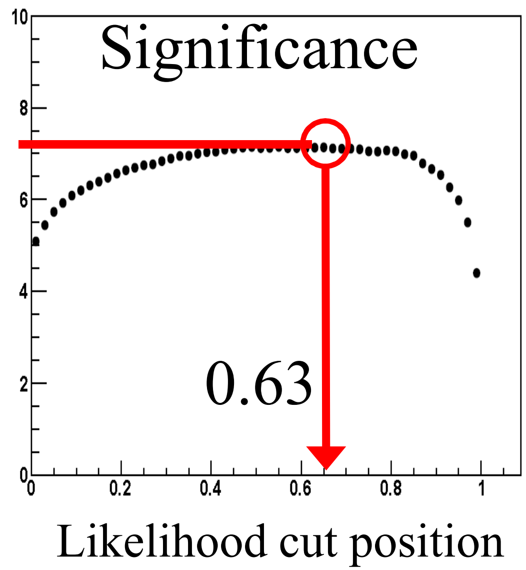
$$L = \frac{L_{sig}}{L_{sig} + L_{bg}}$$

Likelihood variables

① Number of the track in tau jet
② Max track energy in a tau jet
③ Energy in tau jet without the maximum energetic track

Likelihood distributions (WW)

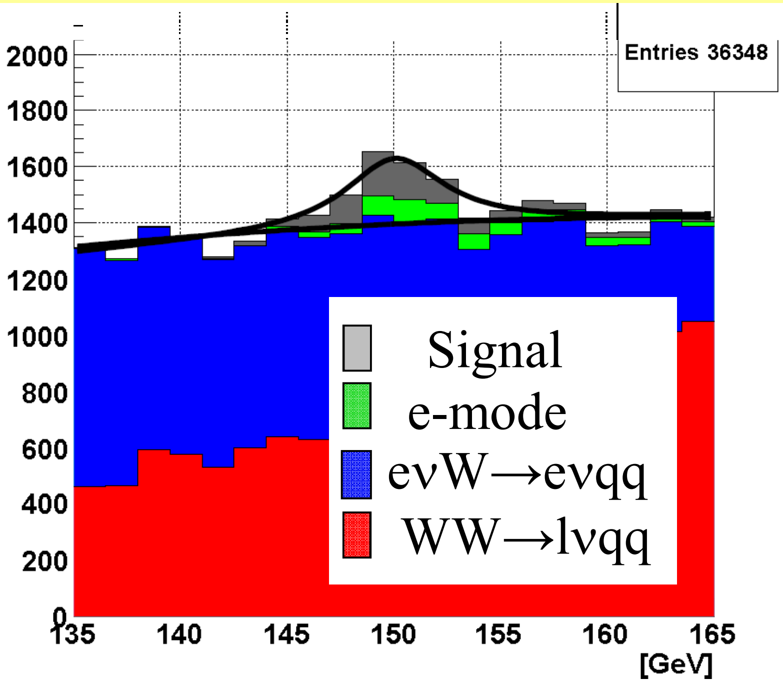




Right-handed neutrino mass

The precision on the cross section is evaluated with the reconstructed M_N distribution.

Right-handed neutrino mass [Inverted]



Precision at ILC (%)

Precision (%)	Normal	Inverted
M_N	0.18	0.21
Cross section	11.3	12.4
Br(τ)/Br(e)	13.1	12.4

Combined with the result from the study of the electron-mode

Br(τ)/Br(e) can be measured with about 10% precision.

Summary

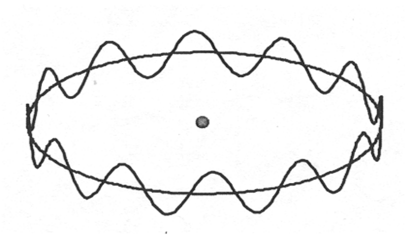
The measurement precision of TeV-scale N in the extra-dimension model was studied for ILC

- ☛ **Electron mode** : Able to observe some KK mode
- ☛ **Tau mode** : Able to observe the 1st KK modes

Precision	Normal	Inverted
$\Delta[Br(\tau\text{-}mode)/Br(e\text{-}mode)]$:	13.1 %	12.4 %

The physics model can be identified by the ratio of branching ratio

Seesaw mechanism and Extra-dimension



Kaluza-Klein(KK) mode

N_1, N_2, …

$$M_N = \frac{2n-1}{2R}(n = 1, 2, \cdots)$$

n : KK mode

R: Radius of 5th dimension

$$M_\nu = \underbrace{\frac{m_D^2}{M}}_{\text{0th KK}} + \underbrace{\left(\frac{m_D^2}{3M} - \frac{m_D^2}{M}\right)}_{\text{1st KK}} + \underbrace{\left(\frac{m_D^2}{5M} - \frac{m_D^2}{3M}\right)}_{\text{2nd KK}} \cdots$$

0th KK **1st KK** **2nd KK**

Neutrino become light by the sum of the contributions on each KK modes.

Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\rm int} \quad = \quad & -\frac{g}{\sqrt{2}}\bar{e}\not{W}U_{\rm MNS}P_L\nu + h.c. \\
& -\frac{g}{\sqrt{2}}\sum_{n=1}^{\infty}\frac{1}{\pi R m_n}\bar{e}\not{W}XP_LN^{(n)} + h.c. \\
& -\frac{g_Z}{2}\sum_{n=1}^{\infty}\frac{1}{\pi R m_n}\bar{\nu}\not{Z}\left(\frac{2m_\nu}{\mathcal{M}}\right)^{1/2}\mathcal{O}P_LN^{(n)} + h.c. \\
& -\frac{g_Z}{2}\sum_{n,m=1}^{\infty}\frac{1}{\pi^2R^2m_nm_m}\bar{N}^{(n)}\not{Z}\left(\frac{2m_\nu}{\mathcal{M}}\right)P_LN^{(m)} \\
& -\sum_{n=1}^{\infty}\frac{1}{\pi R v}h\bar{\nu}\left(\frac{2m_\nu}{\mathcal{M}}\right)^{1/2}\mathcal{O}P_RN^{(n)} + h.c. \\
& -\sum_{n,m=1}^{\infty}\frac{1}{\pi^2R^2vm_m}h\bar{N}^{(n)}\left(\frac{2m_\nu}{\mathcal{M}}\right)P_LN^{(m)} + h.c.
\end{aligned}
$$

Detector performance

Detector	Performance	Coverage
Vertex detector	$\sigma_b = 7.0 \oplus (20.0/p)/\sin^{3/2}\theta \mu m$	$\lvert\cos\theta\rvert \leq 0.90$
Central drift chamber	$\sigma_{P_T}/P_T = 1.1 \times 10^{-4} p_T \oplus 0.1\%$	$\lvert\cos\theta\rvert \leq 0.95$
EM calorimeter	$\sigma_E/E = 15\%/\sqrt{E} \oplus 1\%$	$\lvert\cos\theta\rvert \leq 0.90$
Hadron calorimeter	$\sigma_E/E = 40\%/\sqrt{E} \oplus 2\%$	$\lvert\cos\theta\rvert \leq 0.90$

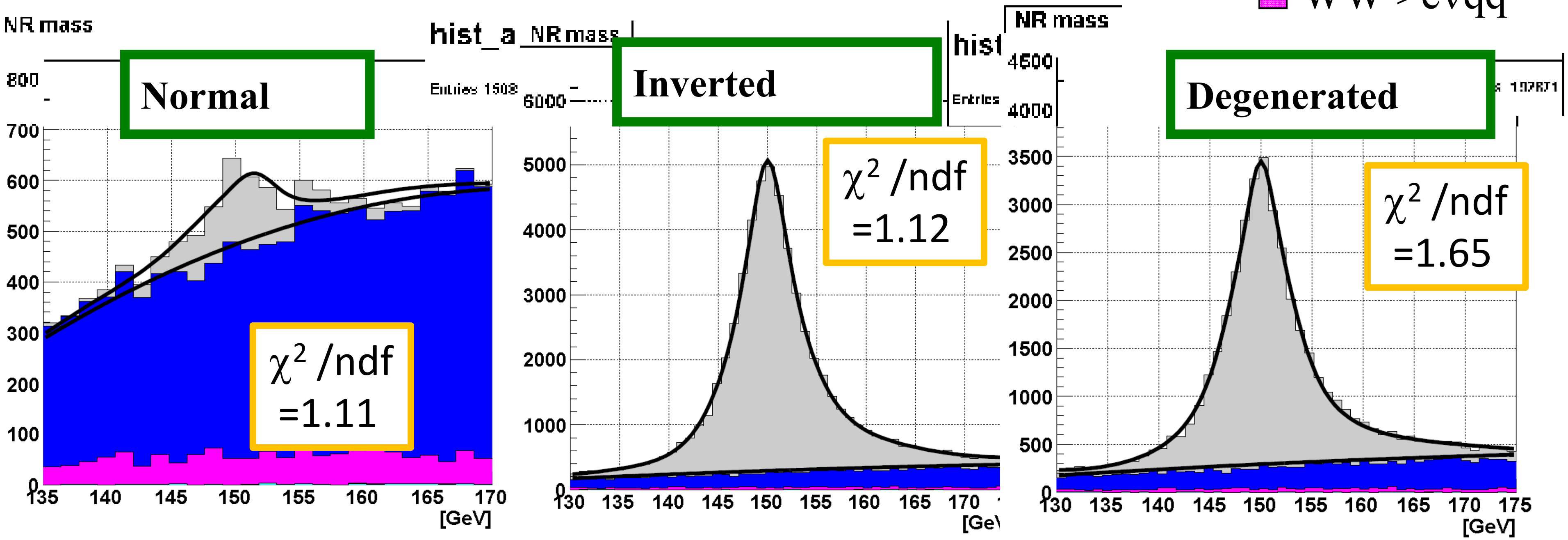
Cut summary at 1TeV

	Inverted	evW	WW	ZZ	tt
before cut	177700	5160000	280000	21400	14715
10 < Lepton Energy < 400	77419	253731	100860	2175	6546
60 < W mass < 100	51391	125755	58838	103	124
135 < N mass < 165	44021	9238	1234	5	23
efficiency (%)	**24.77%**	**0.18%**	**0.44%**	**0.02%**	**0.16%**
significance	188.5				

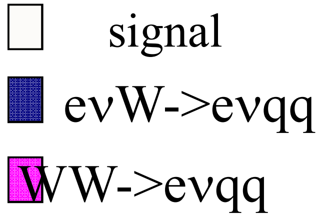
1stKK study on electron mode @ 500GeV

1st KK Right-handed neutrino mass

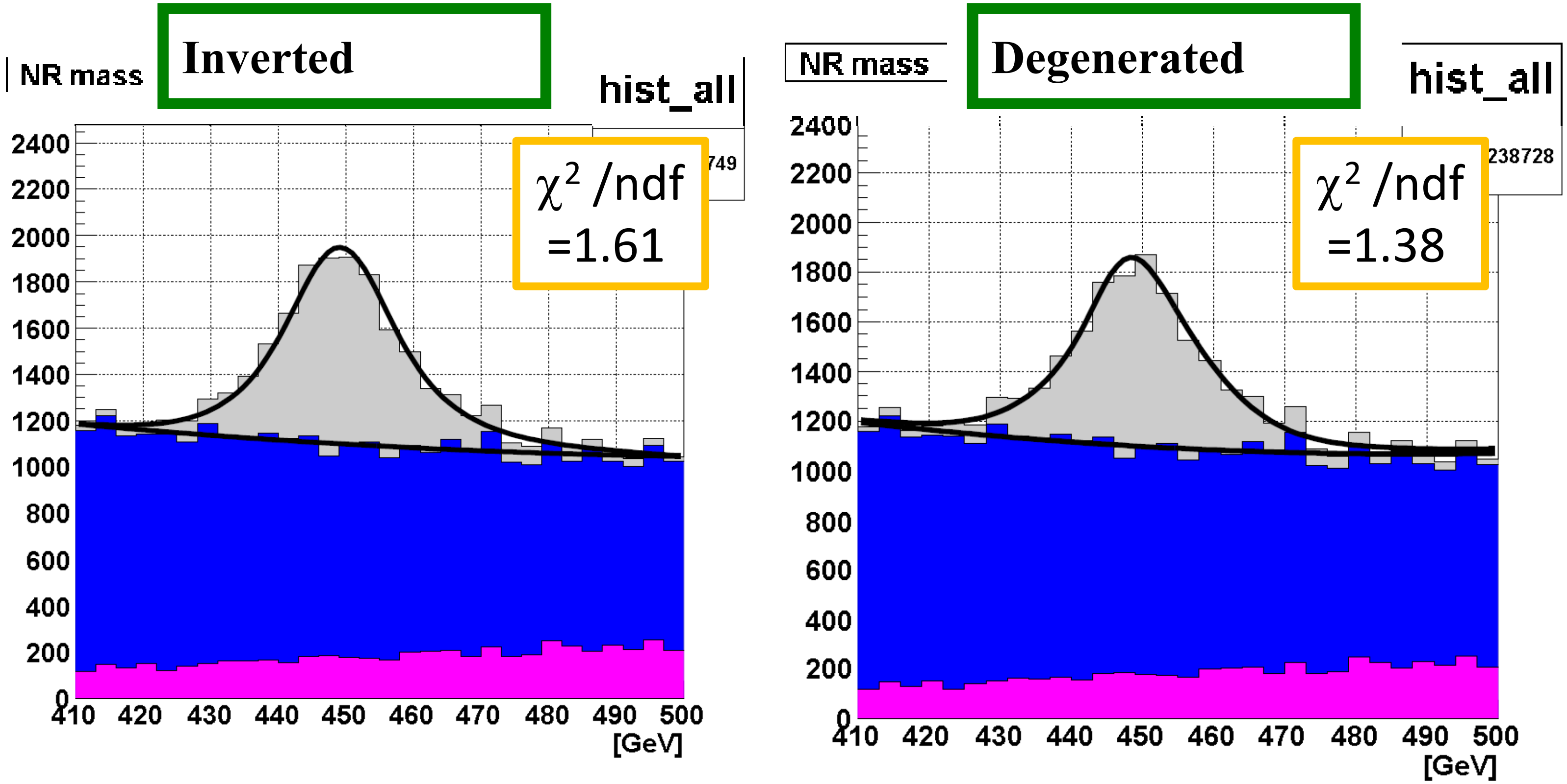
signal
eνW->eνqq
WW->eνqq



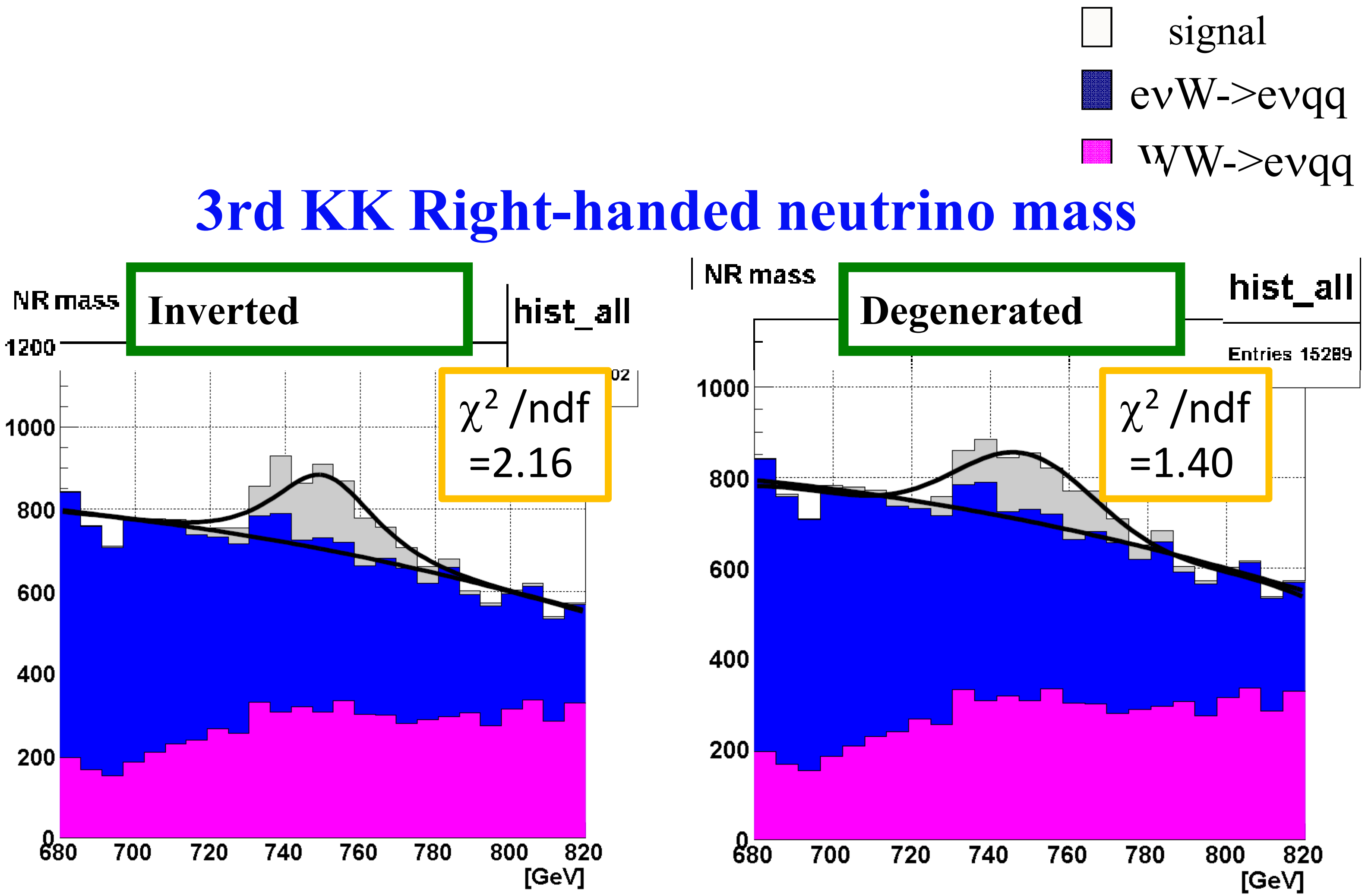
2nd KK study on electron mode @ 500GeV



2nd KK Right-handed neutrino mass



3rd KK study on electron mode @ 500GeV



Precision of cross-section @ 1TeV

		Normal	Inverted	Degenerated
1TeV	1st KK	13.6	0.58	0.74
	2nd KK	-	2.78	3.11
	3rd KK	-	9.92	10.0

Precision of cross-section @ 1TeV

	1st KK	2nd KK	3rd KK
Normal	0.409		
Inverted	0.015	0.053	0.206
Degenerated	**0.019**	**0.076**	0.226

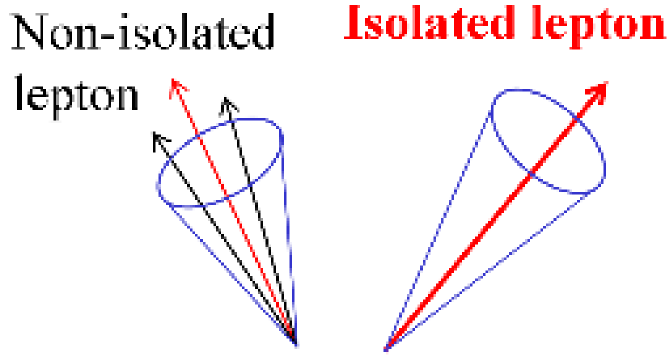
Event reconstruction

N mass is reconstructed by information of the decay products

1, Identification of an isolated lepton track

① **Energy sum of the track around 20 deg. < 5 GeV**

② **The most energetic track of ①**
⇒ **Lepton candidate**

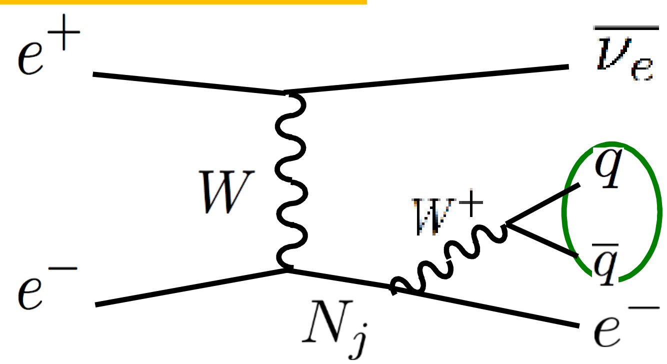


2, Forced 2jet reconstruction except for the lepton

⇒ **W is reconstructed**

3, Reconstruction of N mass

$$P_N = P_W + P_l$$



Likelihood_e