Heavy neutrino production at colliders

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Heavy neutrinos at collider scale:

Theoretically challenging

Experimentally “easy”*

* “easy”: Easier than light neutrinos. But not as easy as one might think.

Theoretical challenges

Seesaw contributions $m_\nu \sim Y^2 v^2 / m_N$ to light neutrino masses

- either Y very small (N decoupled from the light sector)
- or cancellation with another term

Need to decouple mixing angles from mass ratios

Usual seesaw: $m_\nu \sim \dfrac{Y^2 v^2}{m_N}$, $V \sim \dfrac{Y v}{m_N} \quad \Rightarrow \quad V \sim \sqrt{\dfrac{m_\nu}{m_N}}$

Both difficulties can be solved but require symmetries

Then, why N at TeV scale?

Seesaw simple and beautiful, but... $m_N \sim 10^{14}$ GeV unobservable

☞ Attempts to construct models with N at a lower scale and observable

Examples:

- Little Higgs models [Aguila, Masip, Padilla, PLB '05]

  Pseudo-Dirac neutrinos with $m_N \sim 1$ TeV, mixing $\sim v/f$, with $f \sim 1$ TeV

- τ leptogenesis [Pilaftsis, Underwood, PRD '05]

  Pseudo-Dirac neutrino $m_N \sim 250$ GeV, mixing $V \sim 10^{-2}$,

- More examples welcome. . .

Summary

Overview of the model

We consider the possibility of Heavy Majorana or Dirac neutrinos

We introduce additional neutrino fields $\left[\begin{array}{ll} N'_{iL},\, \nu'_{iR},\, N'_{iR} & \text{Dirac} \\ N'_{iR} & \text{Majorana} \end{array}\right.$

We do not introduce extra interactions:

$$\begin{aligned} \mathcal{L}_W &= -\frac{g}{\sqrt{2}}\, \bar{l}'_L \gamma^\mu \nu'_L W_\mu + \text{H.c.} \\ \mathcal{L}_Z &= -\frac{g}{2c_W}\, \bar{\nu}'_L \gamma^\mu \nu'_L Z_\mu \\ \mathcal{L}_H &= -\frac{1}{\sqrt{2}}\, \left[\bar{\nu}'_L Y \nu'_R + \bar{\nu}'_L Y' N'_R\right] H + \text{H.c.} \end{aligned}$$

with $\nu'_{iR} \equiv (\nu'_{iL})^c$ in the Majorana case

These heavy N are not

- $\mathrm{SU}(2)_R$ doublet neutrinos
- "Excited neutrinos" ν^*

and their interactions are obtained by mixing $O(0.1)$ or smaller with light neutrinos

$$\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}} \left(\bar{\ell} \gamma^\mu V_{\ell N} P_L N \; W_\mu + \bar{N} \gamma^\mu V_{\ell N}^* P_L \ell \; W_\mu^\dagger \right) \\
\mathcal{L}_Z &= -\frac{g}{2c_W} \left(\bar{\nu}_\ell \gamma^\mu V_{\ell N} P_L N + \bar{N} \gamma^\mu V_{\ell N}^* P_L \nu_\ell \right) Z_\mu \\
\mathcal{L}_H &= -\frac{g \, m_N}{2M_W} \left(\bar{\nu}_\ell \, V_{\ell N} P_R N + \bar{N} \, V_{\ell N}^* P_L \nu_\ell \right) H
\end{aligned}$$

☞ With additional interactions, additional (larger) signals

N decays:

$N \to W^+ \ell^-$	plus $N \to W^- \ell^+$ (M)
$N \to Z \nu_\ell$	$\Gamma_M = 2\,\Gamma_D$
$N \to H \nu_\ell$	$\Gamma_M = 2\,\Gamma_D$

- For equal $|V_{\ell N}|$, the total width of a Majorana neutrino is two times larger than for a Dirac neutrino See why
- For $m_N \gg M_Z, M_W, M_H$

$$\Gamma(N \to W^\pm \ell^\mp) \ : \ \Gamma(N \to Z \nu_\ell) \ : \ \Gamma(N \to H \nu_\ell) \ = \ 2 \ : \ 1 \ : \ 1$$

Constraints on light-heavy mixing

Mixing angles $V_{\ell N}$ constrained by three kinds of processes:

- Tree-level processes measuring $\ell \nu_\ell W$, $\nu_\ell \nu_\ell Z$ couplings: $\pi \to \ell \nu_\ell$, $Z \to \nu \bar{\nu} \dots$
- LFV processes to which N can contribute at one loop: $\mu \to e\gamma$, $Z \to \ell \ell' \dots$
- Neutrinoless double beta decay ➜ Majorana only

Processes in first, second group constrain the quantities

$$\Omega_{\ell\ell'} \equiv \delta_{\ell\ell'} - \sum_{i=1}^{3} V_{\ell \nu_i} V_{\ell' \nu_i}^* = \sum_{i=1}^{3} V_{\ell N_i} V_{\ell' N_i}^*$$

Present limits

[Bergmann, Kagan NPB '99]
[Tommasini et al., NPB '95]

First group of processes

$$\sum_i |V_{eN_i}|^2 \leq 0.0054$$
$$\sum_i |V_{\mu N_i}|^2 \leq 0.0096$$
$$\sum_i |V_{\tau N_i}|^2 \leq 0.016$$

model-independent
cannot be evaded

Second group of processes

$$\sum_i V_{eN_i} V^*_{\mu N_i} \leq 0.0001$$
$$\sum_i V_{eN_i} V^*_{\tau N_i} \leq 0.01$$
$$\sum_i V_{\mu N_i} V^*_{\tau N_i} \leq 0.01$$

model-dependent
cancellations possible

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model-dependent
cancellations possible

Present limits

Neutrinoless double beta decay constrains $\sum_{i=1}^{3} \frac{V_{eN_i}^2}{m_{N_i}}$

- cancellations possible (e.g. pseudo-Dirac)
- For $V_{eN}^2 = 0.0054$ and no cancellations $m_N \gtrsim 1$ TeV (with theoretical uncertainties on nuclear matrix element)

Overview of N production at colliders

Heavy N can lead to three classes of signals:

- Lepton number violating (LNV): Requires Majorana N (can also violate flavour)
- Lepton flavour violating (LFV): Requires N (D / M) coupling with more than one charged lepton
- Lepton number and flavour conserving (LNC, LFC): always present

Backgrounds grow from top to bottom

Overview of N production at colliders

At LHC:

- $pp \to \ell N$ LNV [Aguila, JAAS, Pittau]

At e^+e^- colliders:

- $e^+e^- \to N\nu$ LNC, LFC [Gluza, Zrałek, PRD '97] [Aguila, JAAS, '05]
- $e^+e^- \to \ell N W$ LNV [Aguila, JAAS, Pittau, '06]
- $e^+e^- \to NN$ LNV ☞ suppressed by mixing and phase space

Other future heavy neutrino signals

Apart from LHC and e^+e^- colliders:

- $e^-\gamma \to NW^- \to \ell^+W^-W^-$ LNV [Bray, Lee, Pilaftsis '05]
- $e^-\gamma \to N\mu^-\nu \to W^+\mu^-\mu^-\nu$ LNV [Bray, Lee, Pilaftsis '05]
- $ep \to Nj$ LNV [Buchmuller, Greub '91]

Other future heavy neutrino signals

Indirect signals:

- $Z \to \ell^+ \ell'^-$ at ILC [Illana, Riemann PRD '01]
- $\mu \to e\gamma$, $\mu - e$ conversion...
- CP violation in neutrino oscillations [Bekman et al., PRD '02]

Single N production at e^+e^- colliders

We select the decay channel $N \to \ell W \to \ell jj$ [Aguila, JAAS '05]

Process: $e^+e^- \to \ell W \nu \to \ell jj\nu$ ☞ large branching ratio; final state reconstructed

at ILC ($E_{\mathrm{CM}} = 500$ GeV) and CLIC (3 TeV) with polarised beams
$P_{e^+} = 0.6$, $P_{e^-} = -0.8$

We sum coherently SM and heavy neutrino diagrams
(non-resonant contributions included)

See diagrams

Quadratic corrections to the $\ell\nu W$, $\nu\nu Z$ vertices can be ignored
Light neutrino masses can be neglected

Skip details

Single N production at e^+e^- colliders

ISR and beamstrahlung effects are included

We perform a parton-level analysis, with a Gaussian smearing of charged lepton and jet energies

$$\frac{\Delta E^e}{E^e} = \frac{10\%}{\sqrt{E^e}} \oplus 1\% \qquad \frac{\Delta E^j}{E^j} = \frac{50\%}{\sqrt{E^j}} \oplus 4\%$$

$$\frac{\Delta E^\mu}{E^\mu} = 0.02\%\, E^\mu \;(0.005\%\, E^\mu) \qquad \text{ILC} \quad (\text{CLIC})$$

Kinematical cuts $p_T \geq 10$ GeV, $|\eta| \leq 2.5$, $\Delta R \geq 0.4$

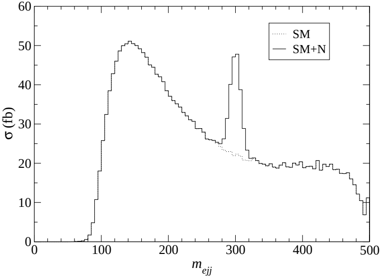
Light neutrino momentum determined from missing 3-momentum and requiring $p_\nu^2 = 0$

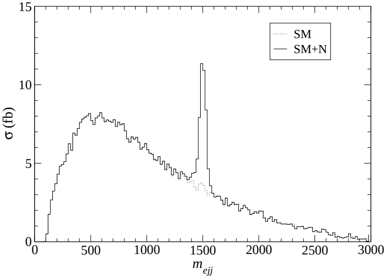
Main characteristics of the $\ell W \nu$ signal

- Dominated by on-shell $N\nu$ production
- Observable only if N couples to the electron
- For equal couplings, equal cross sections for Dirac and Majorana heavy neutrinos
- Large backgrounds (LNC, LFV) but large signal too
- At CLIC, smaller SM backgrounds in the μ and τ channels

Discovery of heavy neutrinos

Heavy neutrinos: peaks in the ℓjj invariant mass distribution





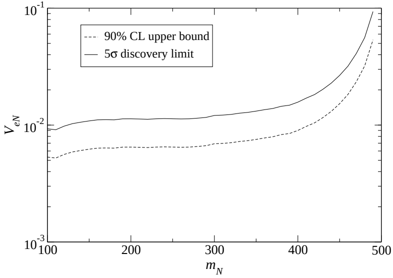
ILC

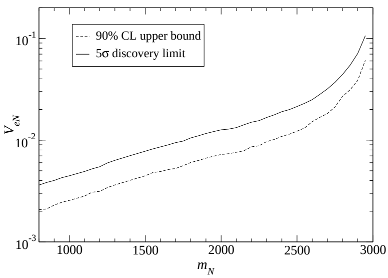
$m_N = 300$ GeV
$V_{eN} = 0.073$ $\quad V_{\mu N} = V_{\tau N} = 0$
Peak significance $\sim 200\ \sigma$

CLIC

$m_N = 1.5$ TeV
$V_{eN} = 0.05$ $\quad V_{\mu N} = V_{\tau N} = 0$
Peak significance $\sim 200\ \sigma$

Discovery limits / upper bounds on V_{eN}, m_N





ILC

$$V_{\mu N} = V_{\tau N} = 0$$

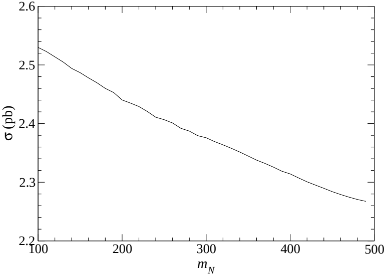
CLIC

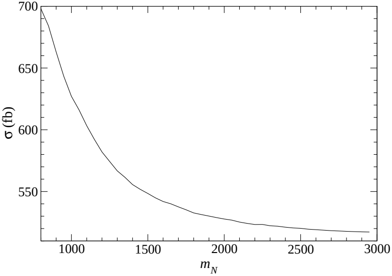
$$V_{\mu N} = V_{\tau N} = 0$$

Skip cross sections

Cross sections for $e^+e^- \to e^\pm jj\nu$

Cross sections decrease relatively slowly with m_N





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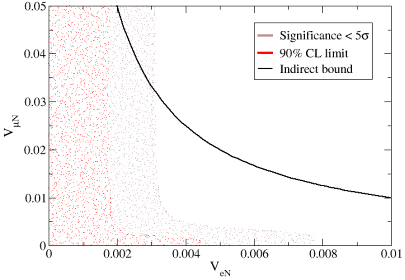
$V_{eN} = 0.073$ $\quad V_{\mu N} = V_{\tau N} = 0$

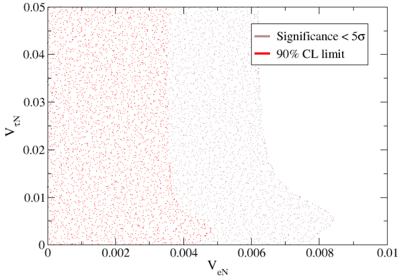
CLIC

$V_{eN} = 0.05$ $\quad V_{\mu N} = V_{\tau N} = 0$

Combined limits on V_{eN} and $V_{\mu N}$ or $V_{\tau N}$ (CLIC)

The statistical significances of the two channels are added





CLIC

$m_N = 1.5$ TeV $\quad V_{\tau N} = 0$

CLIC

$m_N = 1.5$ TeV $\quad V_{\mu N} = 0$

See diagrams

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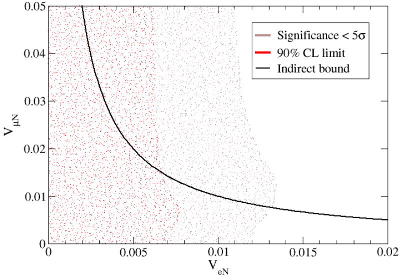

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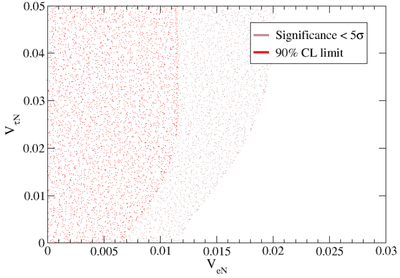
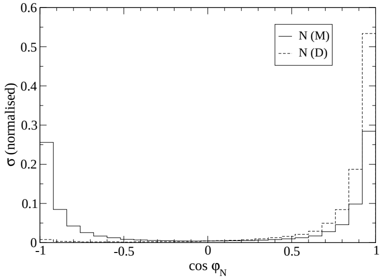


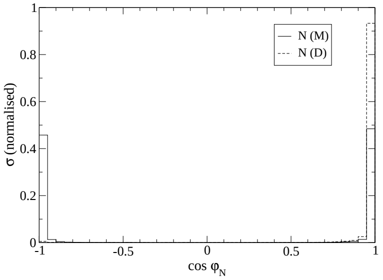
ILC

$m_N = 300$ GeV $\quad V_{\mu N} = 0$

Determination of heavy neutrino character

φ_N angle between N and incoming e^+/e^- for ℓ^+/ℓ^- final states ▸ See diagrams





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$V_{eN} = 0.073$ $\quad V_{\mu N} = V_{\tau N} = 0$
Peak cross section, SM subtracted

CLIC

$m_N = 1.5$ TeV
$V_{eN} = 0.05$ $\quad V_{\mu N} = V_{\tau N} = 0$
Peak cross section, SM subtracted

Single N production at LHC

Two processes:

- $u\bar{d} \to W^+ \to \ell^+ N$ (and $d\bar{u} \to W^- \to \ell^- N$)
- $q\bar{q} \to Z \to \nu N$

Huge backgrounds for LNC & LFC final states

☞ start with ℓN production and LNV decay

$$pp \to \ell^\pm \ell^\pm jj$$

($\ell = e, \mu$) and see what happens

Backgrounds

Final state $\ell^\pm \ell^\pm jj$ is LNV → Naively, this implies no or very small background

BUT in real world there IS background

Obvious ones: $WZjj$, with $W \to \ell\nu$, $Z \to \ell^+\ell^-$, lose one
$W^\pm W^\pm jj$, with both $W \to \ell\nu$

Not so obvious: $t\bar{t}$ semileptonic, with additional lepton from b, $\bar{b}$
(plus $Wb\bar{b}$, $Zb\bar{b}$)

Backgrounds

Bad news ☹

- Pile-up exists: *e.g.* not only $WZjj$, but also WZ, WZj contribute
- Higher orders exist: $WZ3j\ldots$ also contribute
  (cannot be removed due to pile-up on signal)

Further bad news ☹☹

- $t\bar{t}$, $Wb\bar{b}$, $Zb\bar{b}$ backgrounds large for $\ell = e$ $\quad (10\times$ than for $\ell = \mu)$
  Seen with fast simulation, must be confirmed with full simulation

Details of the simulation

Restrict ourselves to $\mu^\pm \mu^\pm jj$ signal

All processes (including N production) generated with ALPGEN

Backgrounds: $t\bar{t}nj$, $Wb\bar{b}nj$, $Zb\bar{b}nj$, $WWnj$, $WZnj$, $ZZnj$,
$WWWnj$, $WWZnj$, $WZZnj$, $ZZZnj$

generated with $n = 0 \dots 3$ ($0 \dots 5$ for $t\bar{t}$)

and matched with PYTHIA 6.4 using the MLM prescription

Fast detector simulation with ATLFAST

Events for 30 fb^{-1} — $m_N = 150$ GeV, $|V_{\mu N}|^2 = 0.0096$

$N\mu$	92.9	→	68.9
$t\bar{t}nj$	2294.4	→	163.5
$WZnj$	615.5	→	81.3
$Wb\bar{b}nj$	763.8	→	62.0
$WWnj$	316.4	→	12.2

$\not{p}_t \leq 25$ GeV
$\Delta R_{\mu j} \geq 0.5$
one $m_{\mu jj}$ $120 - 150$ GeV
m_{jj} $60 - 100$ GeV
[Han, Zhang '06]

$10 - 100$ times larger than estimations in literature

Cannot be suppressed with naive cuts on $\not{p}_t$, ΔR, $m_{\mu jj}$

☞ Significance: 0.88σ
Previous estimate: 17σ

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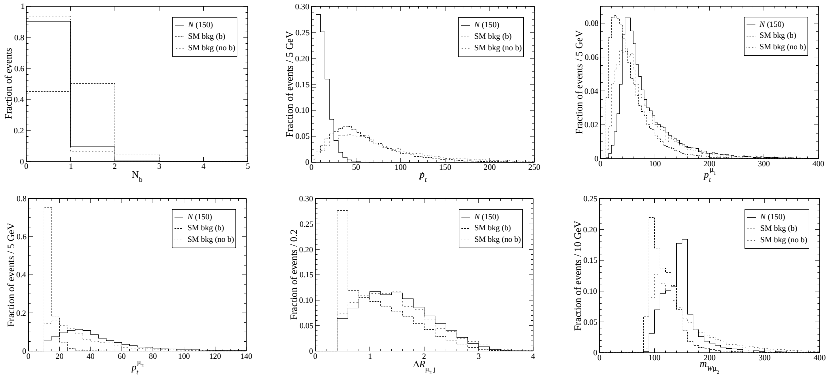
Variables I


Fraction of events
N (150)
SM bkg (b)
SM bkg (no b)
N_b
Fraction of events / 5 GeV
p̸_t
p_t^{μ1}
p_t^{μ2}
Fraction of events / 0.2
ΔR_{μ2 j}
Fraction of events / 10 GeV
m_{Wμ2}

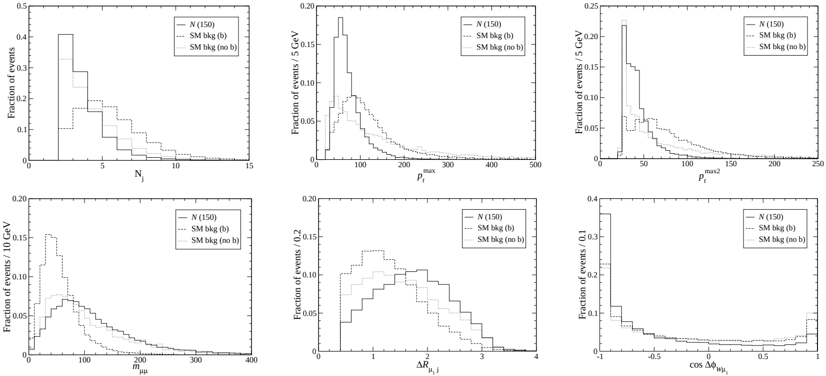
Events for 30 fb^{-1} $m_N = 150$ GeV, $|V_{\mu N}|^2 = 0.0096$

$N\mu$	92.9	→	30.6
$t\bar{t}nj$	2294.4	→	1.4
$WZnj$	615.5	→	12.4
$Wb\bar{b}nj$	763.8	→	0.1
$WWnj$	316.4	→	6.8

no extra μ
no b jets, ≤ 5 jets
$p_t^{\mu_1} \geq 40$ GeV
$p_t^{\mu_2} \geq 20$ GeV
$\not{p}_t \leq 20$ GeV
$\Delta R_{\mu_2 j} \geq 0.8$
$m_{\mu_2 jj} \geq 140$ GeV

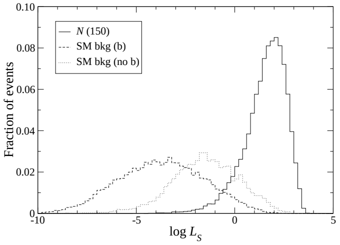
Background further reduced with improved variable selection ☞ Significance: 4.53σ

Variables II



Standard cuts on variables can reduce background… but signal too

☞ Build a signal likelihood function



$\log L_S/L_B \geq 1.75$

one $m_{\mu jj}$ 130 – 170 GeV

$N\mu$	92.9	→	38.3
$t\bar{t}nj$	2294.4	→	1.5
$WZnj$	615.5	→	4.8
$Wb\bar{b}nj$	763.8	→	0.4
$WWnj$	316.4	→	2.3

Significance: 9.9σ for 30 fb^{-1} – Discovery up to 175 GeV

(likely to be maintained with full simulation)

Conclusions I

- LHC is sensitive to Majorana N coupling to muon
- Analysis involved, background can be reduced but not wiped out
- Discovery up to 175 GeV – much lower than in previous (unrealistic) estimates due to backgrounds $\sim$ 100 times larger
- Full simulation must address μ charge misidentification
- Backgrounds larger for electrons due to detector effects. Full simulation possibly needed.
- τ: huge background (cannot see charge)
- LFV signals have larger (e) or huge (τ) backgrounds
- Needless to say about LNC & LFC signals…

Conclusions II

- $e^+e^- \to N\nu$ sensitive to Dirac and Majorana N coupling to e
- Parton-level studies: ILC can discover $m_N = 400$ GeV with $V_{eN} \sim 0.01$, CLIC can discover $m_N = 1 - 2$ TeV with $V_{eN} = 0.004 - 0.01$
- More detailed simulations are required, but sensivity not likely to fall down. Signal large, and background suppression achieved with mass reconstruction
- If N is discovered, its Dirac or Majorana nature can easily be established looking at angular distributions

A closer look to heavy neutrino interactions

$\ell N W$ vertex:

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left(\bar{\ell} \gamma^\mu V_{\ell N} P_L N \; W_\mu + \bar{N} \gamma^\mu V_{\ell N}^* P_L \ell \; W_\mu^\dagger \right) \qquad (\mathrm{D}, \mathrm{M})$$

$\nu_\ell N Z$ vertex:

$$\mathcal{L}_Z = -\frac{g}{2 c_W} \left(\bar{\nu}_\ell \gamma^\mu V_{\ell N} P_L N + \bar{N} \gamma^\mu V_{\ell N}^* P_L \nu_\ell \right) Z_\mu \qquad (\mathrm{D}, \mathrm{M})$$

$$= -\frac{g}{2 c_W} \bar{\nu}_\ell \gamma^\mu \left(V_{\ell N} P_L - V_{\ell N}^* P_R \right) N \; Z_\mu \qquad (\mathrm{M})$$

$\nu_\ell N H$ vertex:

$$\mathcal{L}_H = -\frac{g \, m_N}{2 M_W} \left(\bar{\nu}_\ell \; V_{\ell N} P_R N + \bar{N} \; V_{\ell N}^* P_L \nu_\ell \right) H \qquad (\mathrm{D}, \mathrm{M})$$

$$= -\frac{g \, m_N}{2 M_W} \bar{\nu}_\ell \left(V_{\ell N} P_R + V_{\ell N}^* P_L \right) N \; H \qquad (\mathrm{M})$$

Back

A closer look to heavy neutrino interactions

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$$= -\frac{g \, m_N}{2 M_W} \, \bar{\nu}_\ell \left(V_{\ell N} P_R + V_{\ell N}^* P_L \right) N \; H \qquad (\mathrm{M})$$

Back

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$$\mathcal{L}_Z = -\frac{g}{2c_W} \left(\bar{\nu}_\ell \gamma^\mu V_{\ell N} P_L N + \bar{N} \gamma^\mu V_{\ell N}^* P_L \nu_\ell \right) Z_\mu \qquad (\mathrm{D}, \mathrm{M})$$

$$= -\frac{g}{2c_W} \bar{\nu}_\ell \gamma^\mu \left(V_{\ell N} P_L - V_{\ell N}^* P_R \right) N \; Z_\mu \qquad (\mathrm{M})$$

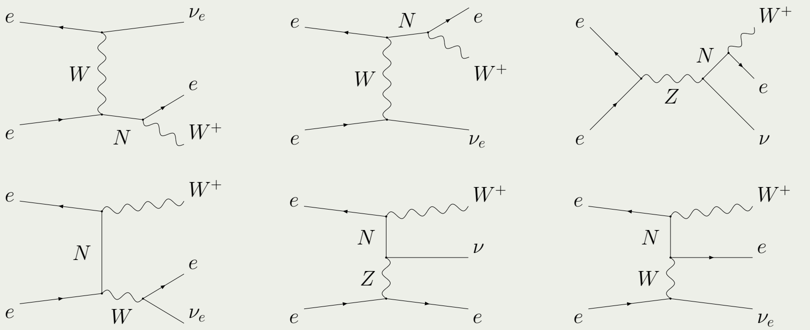
$\nu_\ell N H$ vertex:

$$\mathcal{L}_H = -\frac{g \, m_N}{2M_W} \left(\bar{\nu}_\ell \, V_{\ell N} P_R N + \bar{N} \, V_{\ell N}^* P_L \nu_\ell \right) H \qquad (\mathrm{D}, \mathrm{M})$$

$$= -\frac{g \, m_N}{2M_W} \bar{\nu}_\ell \left(V_{\ell N} P_R + V_{\ell N}^* P_L \right) N \; H \qquad (\mathrm{M})$$

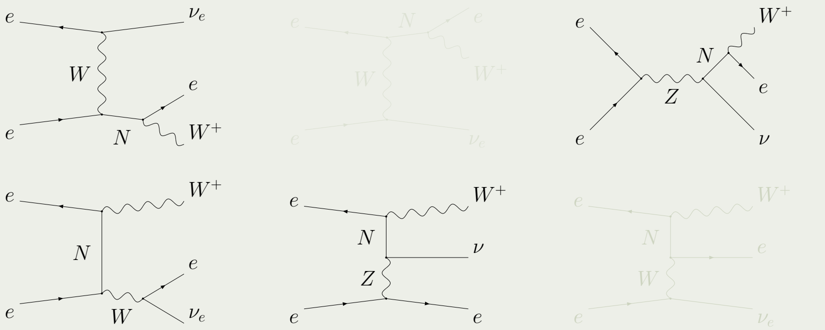
Back

Signal diagrams for $\ell = e$ (M)



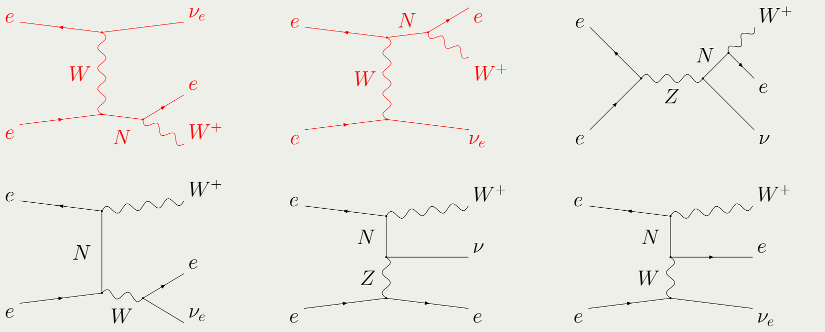
Back Skip

Signal diagrams for $\ell = e$ (D)



Back
Skip

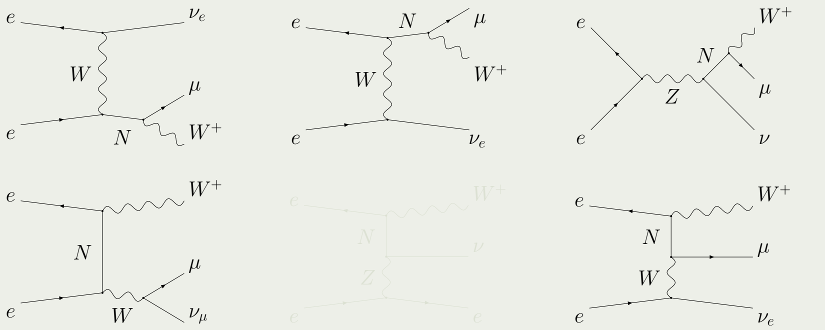
Dominant signal diagrams for $\ell = e$



Diagrams related by $t \leftrightarrow u$ interchange

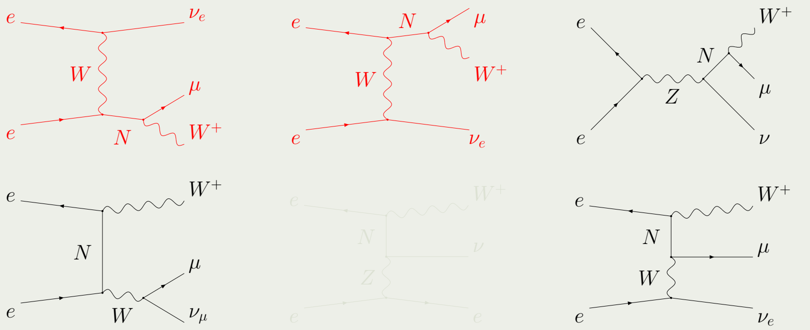
Back Results Skip

Signal diagrams for $\ell = \mu$ (M)



Back Skip

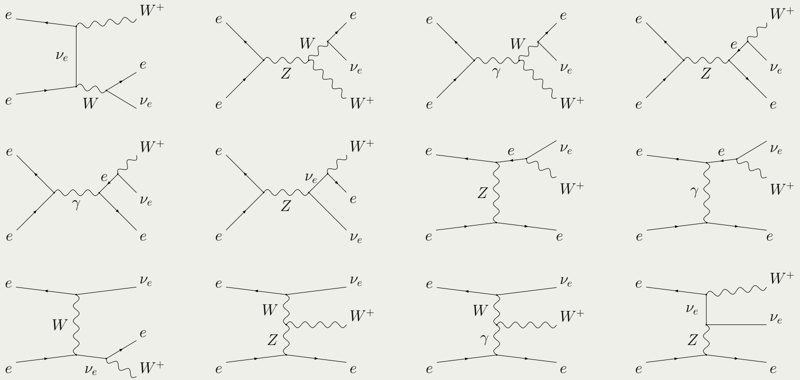
Dominant signal diagrams for $\ell = \mu$



Dominant diagrams involve eWN interaction

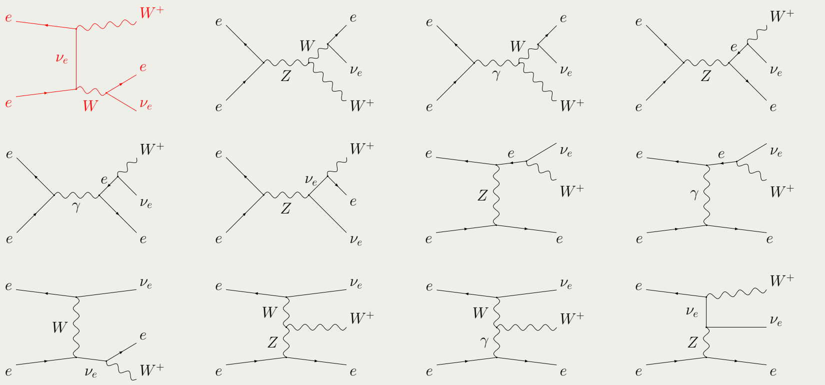
Back

SM diagrams for $\ell = e$



Back

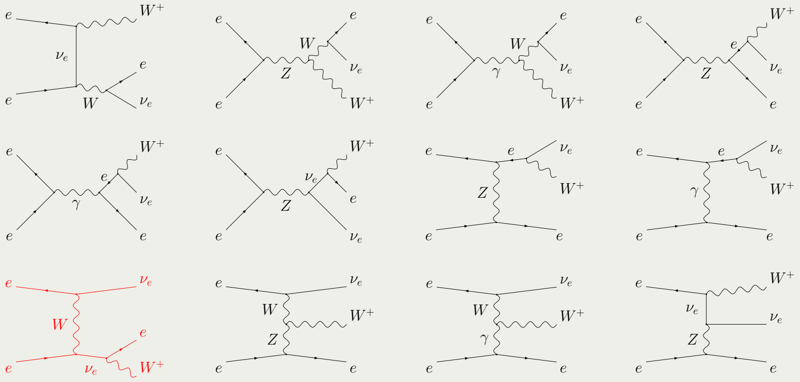
Dominant SM diagrams for $\ell = e$ (ILC)



Resonant W^+W^- production

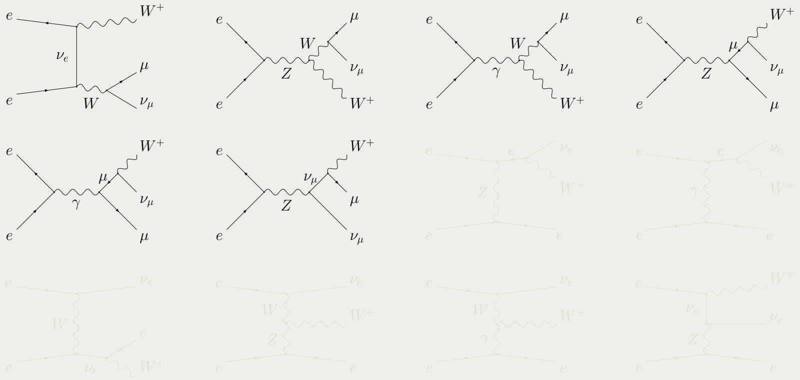
Back

Dominant SM diagrams for $\ell = e$ (CLIC)



Back

SM diagrams for $\ell = \mu$



Back
Results

Example I

$WZnj \to \mu^\pm \mu^\pm$ and ≥ 2 jets with $p_t \geq 20$ GeV

	Generated		Pre-selection			Selection	
WZ	6437×10	→	57.7	(0.90%)	→	0.2	(0.34%)
WZj	6088×10	→	156.1	(2.56%)	→	0.9	(0.57%)
$WZ2j$	5005×10	→	244.8	(4.89%)	→	2.9	(1.18%)
$WZ3j$	$3533^{(K)} \times 10$	→	156.9	(4.44%)	→	0.8	(0.51%)
Total			615.5		→	4.8	
$WZ2j$ without matching	5005×10	→	226.0	(4.51%)	→	2.0	(0.88%)

would-be $K = 2.7\ (2.4)$

Example II

$WWnj \to \mu^\pm \mu^\pm$ and ≥ 2 jets with $p_t \geq 20$ GeV

	Pre-selection		Selection	
WW	–		–	
WWj	–		–	
$WW2j$	116.2	→	1.5	(1.29%)
$WW3j$	200.2	→	0.8	(0.40%)
Total	316.4	→	2.3	
$WW2j$ without matching	135.7	→	0.9	(0.66%)

would-be $K = 2.3\ (2.5)$