Single heavy neutrino production at e^+e^- colliders

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ECFA ILC workshop
Vienna, Nov. 14th, 2005

Heavy neutrinos at collider scale:

Theoretical problems

and experimental advantages

Theoretical problems

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 source for light neutrino masses

Need to decouple mixing angles from mass ratios

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

Both difficulties can be solved but require symmetries

Example:

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

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

- More examples welcome …

Summary

Overview of the model

We consider the possibility of Majorana or Dirac neutrinos

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

In both cases the mass terms are written similarly

$$\mathcal{L}_{\text{mass}} = -\,(\bar{\nu}'_L\ \bar{N}'_L) \begin{pmatrix} \frac{v}{\sqrt{2}} Y' & \frac{v}{\sqrt{2}} Y \\ B' & B \end{pmatrix} \begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \text{H.c.} \qquad \text{(D)}$$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\,(\bar{\nu}'_L\ \bar{N}'_L) \begin{pmatrix} M_L & \frac{v}{\sqrt{2}} Y \\ \frac{v}{\sqrt{2}} Y^T & M_R \end{pmatrix} \begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \text{H.c.} \qquad \text{(M)}$$

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

We do not introduce extra interactions

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \bar{l}_L \gamma^\mu V \begin{pmatrix} \nu_L \\ N_L \end{pmatrix} W_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} (\bar{\nu}_L \; \bar{N}_L) \gamma^\mu X \begin{pmatrix} \nu_L \\ N_L \end{pmatrix} Z_\mu$$

with V of dimension 3×6 and $X = V^\dagger V$

$V_{\ell N}$ small $\longrightarrow$

$X_{\nu_\ell N} = V_{\ell N}$ also small

$X_{N_i N_j} = \sum_{\ell=e,\mu,\tau} V^*_{\ell N_i} V_{\ell N_j}$ even smaller

N produced singly through interactions $\propto V_{\ell N}$
N pairs produced through interactions $O(V^2)$

☞ Study single N production

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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 two kinds of processes:

- Tree-level processes measuring $\ell\nu_\ell W$, $\nu_\ell\nu_\ell Z$ couplings:
  $\pi \to \ell\nu_\ell$, $Z \to \nu\bar{\nu}$ ...
- LFV processes to which N can contribute at one loop:
  $\mu \to e\gamma$, $Z \to \ell\ell'$ ...

These processes 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

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

Second group of processes

$$\sum_i V_{eN_i} V^*_{\mu N_i} \leq 0.0001$$
$$\sum_i V_{eN_i} V^*_{\tau N_i} \leq 0.01$$
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model-independent
cannot be evaded

model-dependent
cancellations possible

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model-dependent
cancellations possible

Heavy neutrino direct signals

At e^+e^- colliders:

- Single N production: $e^+e^- \to N\nu$ [Gluza, Zrałek, PRD '97]
- N pair production $e^+e^- \to NN$ ☞ suppressed by mixing and phase space

At $e^-\gamma$ colliders:

- $e^-\gamma \to NW^-$ [Bray, Lee, Pilaftsis '05]

At LHC:

- $pp \to \ell^\pm \ell'^\pm W^\mp$ [Ali, Borisov, Zamorin EPJC '01]

Single N production at e^+e^- colliders

We select the decay channel $N \to \ell W \to \ell jj$ [Aguila, JAAS, JHEP '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 ▸ 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 $p_\nu^2 = 0$

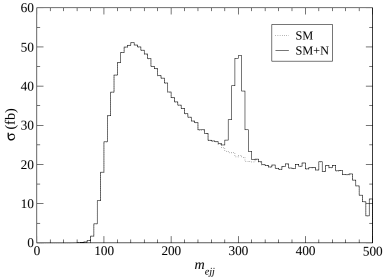
See τ

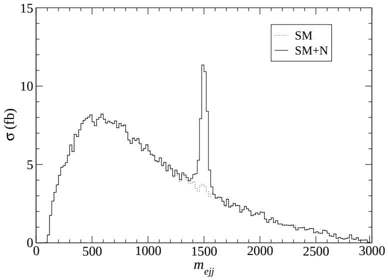
Main characteristics of the $\ell W \nu$ signal

- 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
- 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
$V_{eN} = 0.073$
Peak significance $\sim 200\,\sigma$

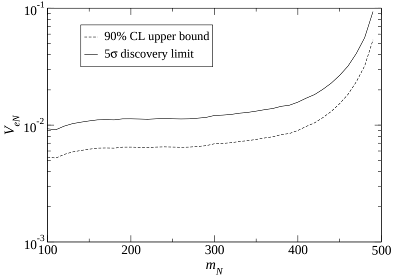
$V_{\mu N} = V_{\tau N} = 0$

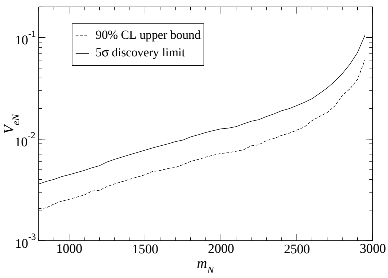
CLIC

$m_N = 1.5$ TeV
$V_{eN} = 0.05$
Peak significance $\sim 200\,\sigma$

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

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





ILC

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

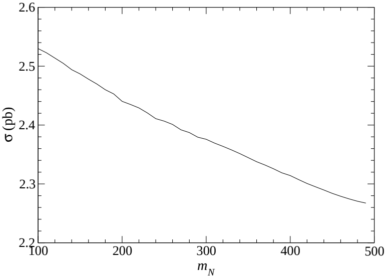
CLIC

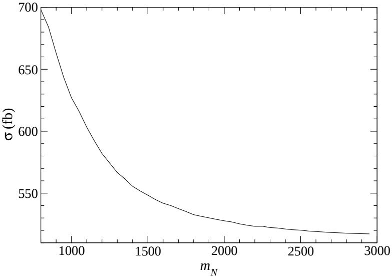
$$V_{\mu N} = V_{\tau N} = 0$$

Skip cross sections

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

Cross sections decrease relatively slowly with m_N





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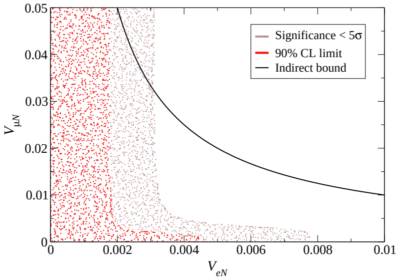
$V_{eN} = 0.073$ $V_{\mu N} = V_{\tau N} = 0$

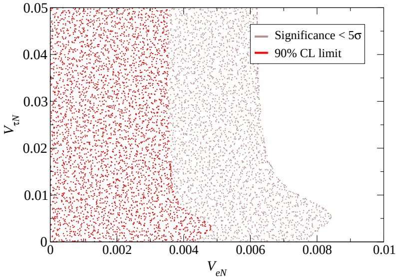
CLIC

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

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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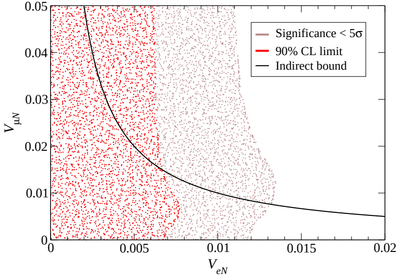
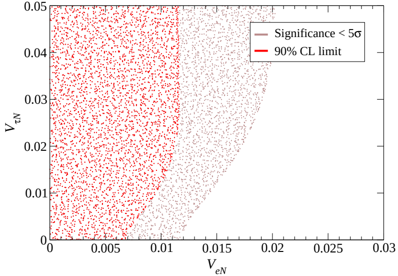




ILC

$m_N = 300$ GeV $V_{\tau N} = 0$

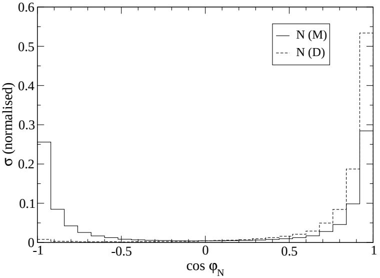
ILC

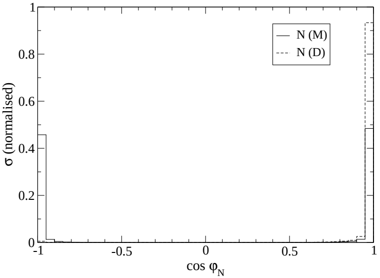
$m_N = 300$ GeV $V_{\mu N} = 0$

To conclusions

Determination of heavy neutrino character

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





ILC

$m_N = 300$ GeV
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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

To conclusions

Measurement of ℓNW couplings

S_e, S_μ, S_τ excess of events in the peak region

$$S_\ell = A_\ell \, V_{eN}^2 \, \frac{V_{\ell N}^2}{V_{eN}^2 + V_{\mu N}^2 + V_{\tau N}^2} \,, \quad A_\ell \text{ constants}$$

A_ℓ determined from MC simulation ☞

$$V_{eN}^2 = \frac{S_e}{A_e} + \frac{S_\mu}{A_\mu} + \frac{S_\tau}{A_\tau}$$

$$\frac{V_{\ell N}^2}{V_{eN}^2} = \frac{S_\ell}{A_\ell} \left(\frac{S_e}{A_e} \right)^{-1} \qquad \ell = \mu, \tau$$

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Measurement of ℓNW couplings

Example (CLIC)

Calculate A_ℓ for a “reference” set of couplings and assume a 10% common systematic uncertainty

Use as input the cross sections for $V_{eN} = V_{\mu N} = V_{\tau N} = 0.04$ (m_N = 1.5 TeV)

Values extracted:

$$\begin{aligned} V_{eN} &= 0.0388 \pm 0.00034\,(\text{stat}) \pm 0.0019\,(\text{sys}) \\ V_{\mu N}/V_{eN} &= 1.007 \pm 0.016\,(\text{stat}) \\ V_{\tau N}/V_{eN} &= 1.030 \pm 0.028\,(\text{stat}) \end{aligned}$$

Precision: 5% for V_{eN}, $2-3$% for the ratios

See chirality

Conclusions

- Heavy neutrinos in the $1-2$ TeV range can be produced at CLIC if they have a coupling to the electron of $0.004-0.01$ or larger
- Heavy neutrinos with masses of few hundreds of GeV can already be produced at ILC if they have a coupling $V_{eN} \sim 0.01$
- If produced, their Dirac or Majorana nature can easily be established
- If produced, their couplings to the charged leptons can be measured
- If they have masses of few hundreds of GeV, the chirality of these couplings might be determined

Other future heavy neutrino signals

Direct signals:

- $e^-\gamma \to NW^- \to \ell^+\nu W^-$ [Bray, Lee, Pilaftsis '05]
  Similar limits on V_{eN} as ILC
- $e^-\gamma \to N\mu^-\nu \to W^+\mu^-\mu^-\nu$ [Bray, Lee, Pilaftsis '05]
  Sensitive to $V_{\mu N} \sim 0.1$ even for $V_{eN} = 0$

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]

A closer look to heavy neutrino interactions

$\ell N W$ vertex:

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

$\nu_\ell N Z$ vertex:

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

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

$\nu_\ell N H$ vertex:

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

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

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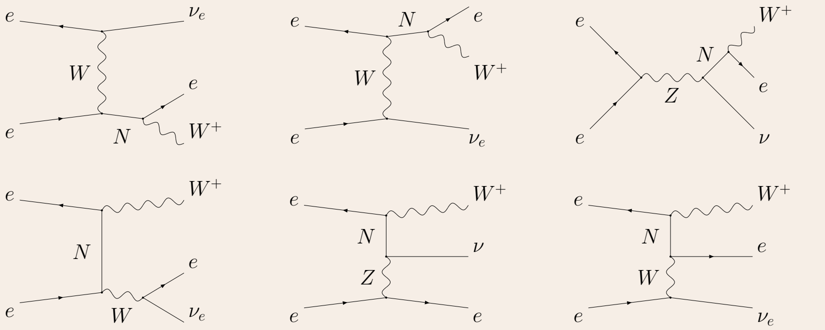
Signal diagrams for $\ell = e$ (M)



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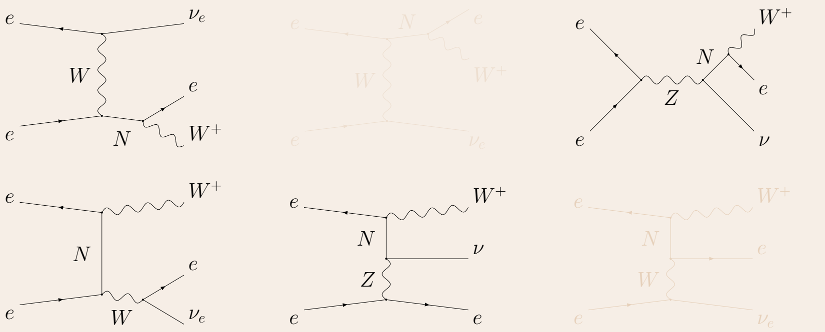
Signal diagrams for $\ell = e$ (D)



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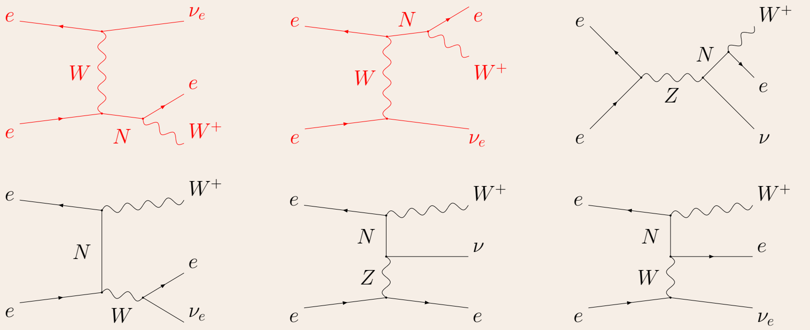
Dominant signal diagrams for $\ell = e$



Diagrams related by $t \leftrightarrow u$ interchange

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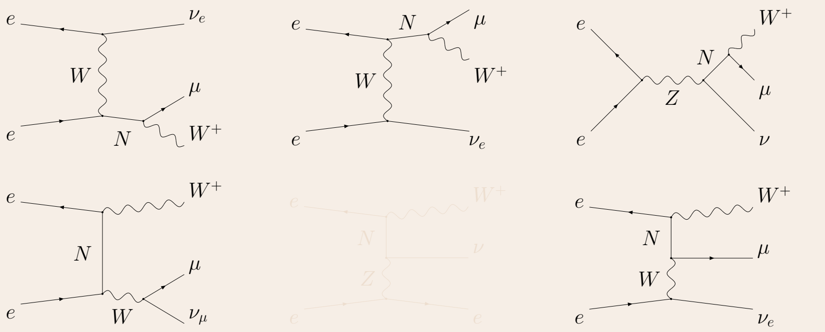
Signal diagrams for $\ell = \mu$ (M)



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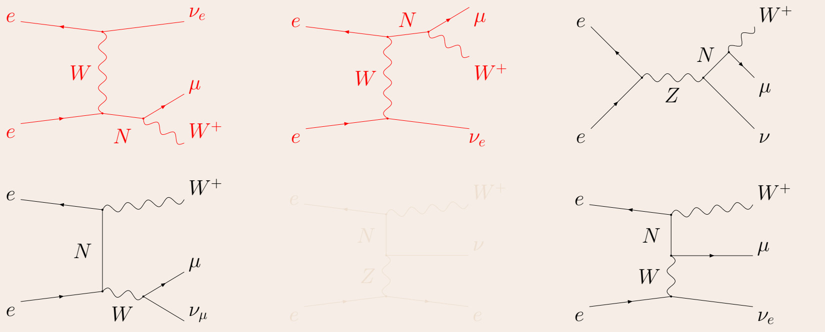
Dominant signal diagrams for $\ell = \mu$



Dominant diagrams involve *eWN* interaction

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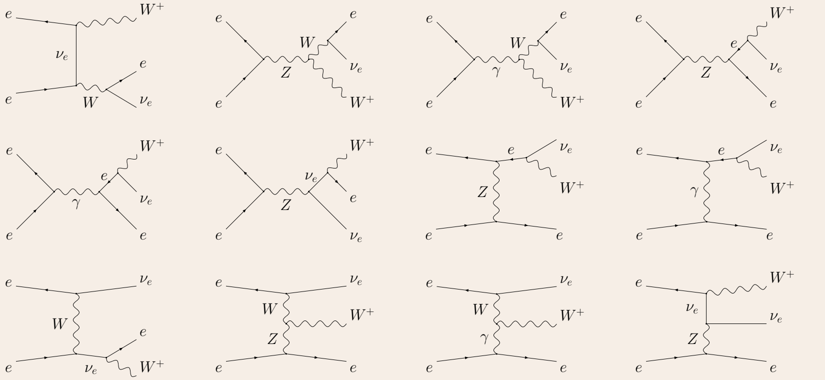
SM diagrams for $\ell = e$



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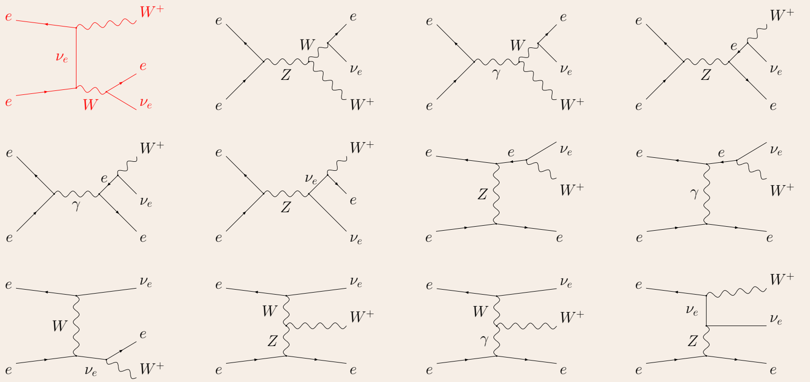
Dominant SM diagrams for $\ell = e$ (ILC)



Resonant W^+W^- production

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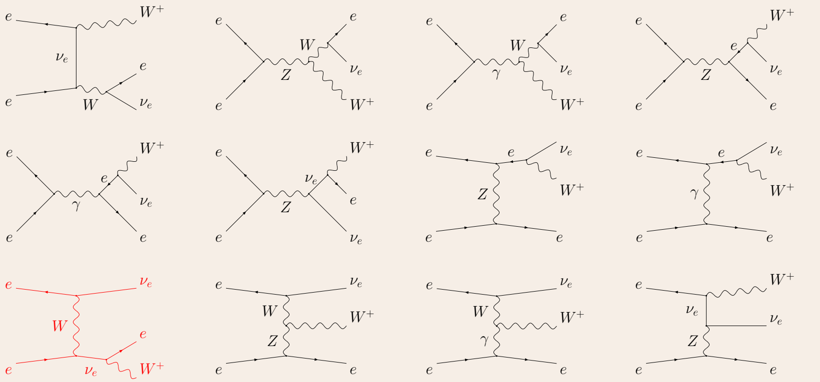
Dominant SM diagrams for $\ell = e$ (CLIC)



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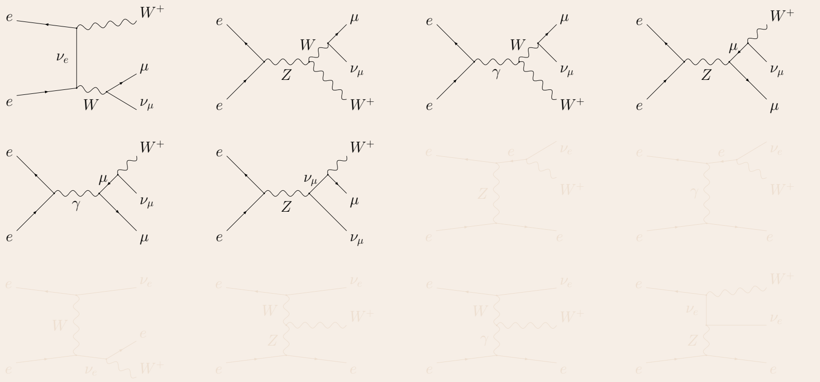
SM diagrams for $\ell = \mu$



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Special treatment of the $\tau W \nu$ signal

We select τ hadronic decays to π, ρ, a_1 mesons (Br $= 55\%$) and use τ tagging (efficiency 50%)

We assume that the jet 3-momentum direction is the one of the parent τ and its energy a fraction x of the τ energy

We solve for the primary neutrino momentum and x using the constraints

$$E_W + E_\nu + \frac{1}{x} E_j = \sqrt{s}$$

$$\vec{p}_W + \vec{p}_\nu + \frac{1}{x} \vec{p}_j = 0$$

$$p_\nu^2 = 0$$

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Chirality of $\ell N W$ couplings

Restrict to decays $W^+ \to c\bar{s}$ ($W^- \to \bar{c}s$) and use c tagging to distinguish among the two jets ☞ Signal 4 times smaller

Define $\theta_{\ell s}$ as the angle between the charged lepton ℓ and the s jet in the W rest frame

Define the FB asymmetry

$$A_{\mathrm{FB}} = \frac{N(\cos\theta_{\ell s} > 0) - N(\cos\theta_{\ell s} < 0)}{N(\cos\theta_{\ell s} > 0) + N(\cos\theta_{\ell s} < 0)}$$

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Chirality of ℓNW couplings

For a general ℓNW vertex

$$\mathcal{L}_{\ell WN} = -\frac{g}{\sqrt{2}} \bar{\ell} \gamma^\mu \left(g_L P_L + g_R P_R \right) N \; W_\mu + \text{H.c.}$$

the FB asymmetry is

$$A_{\text{FB}} = \frac{3M_W^2}{4M_W^2 + 2m_N^2} \, \frac{|g_L|^2 - |g_R|^2}{|g_L|^2 + |g_R|^2}$$

But ... for $m_N \gg M_W$, A_{FB} very small ☹

$m_N = 1.5$ TeV $\longrightarrow$ $A_{\text{FB}} = 4.3 \times 10^{-3}$

Chirality of ℓNW couplings

Example (ILC)

Use $m_N = 300$ GeV $V_{eN} = 0.073$, $V_{\mu N} = V_{\tau N} = 0$

Theoretical value: $A_{\rm FB} = 0.094$

After subtracting the expected background at the peak, the extracted value is $A_{\rm FB} = 0.083 \pm 0.016$ (stat)

Measurability difficult to assess in general

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