WW scattering studies at a Future Linear Collider

A presentation given at the University of Edinburgh - High Energy Physics Group.

Andres F. Osorio-Oliveros
andres@hep.man.ac.uk

High Energy Physics Group
The University of Manchester
Outline

- Motivations
  - Physics (why $W W$ scattering?)
  - Why a FLC?
- Plans for a Future Linear Collider
- $W W$ Scattering Analysis
- $Z$ and $W$ reconstruction
- Results
- Sensitivities
- Conclusions
Motivations

- The mechanism describing how Nature gives mass to particles remains one of the open questions in particle physics today.

- The Higgs Mechanism is the answer in the Standard Model

- If there is no a Higgs, new physics is needed at the TeV scale to restore unitarity

- It is in this context, that the strong scattering of $W_L W_L$ bosons provides a window to look for information about the underlying symmetry.

![-diagram-diagram-83.png]
Motivations

- The mechanism describing how Nature gives mass to particles remains one of the open questions in particle physics today.
- The Higgs Mechanism is the answer in the Standard Model.
- If there is no a Higgs, new physics is needed at the TeV scale to restore unitarity.
- It is in this context, that the strong scattering of $W_LW_L$ bosons provides a window to look for information about the underlying symmetry.

The EW can be described by the EW Chiral Lagrangian.

This is an effective theory which:
- has operators of higher dimensions
- introduces anomalous couplings

In particular there are two 4D operators:

- $L_4 = \frac{\alpha_4}{16\pi^2} tr(V_{\mu}V_{\nu})tr(V^{\mu}V^{\nu})$
- $L_5 = \frac{\alpha_5}{16\pi^2} tr(V_{\mu}V^{\mu})tr(V_{\nu}V^{\nu})$

The coefficients $\alpha_4$ and $\alpha_5$ are related to the scale of the new physics (in the SM these parameters are 0).
Motivations

  - EW Chiral Lagrangian
  - Unitarisation protocols
  - Prediction of resonances depending on the values of the $\alpha_4$ and $\alpha_5$ parameters

As an example:

To sum up:

- What's the sensitivity to the $\alpha_4$ and $\alpha_5$ that can be reached at a Future Linear Collider? Can I improve previous analysis on the subject? (Ref: Chierici, et al - LC-PHSM-2001-038)

- Given that these parameters can be measured, what can we learn about new physics at higher energies? (LHC - LC complementarity)
Motivations

The LC scenario
Motivations

The LC scenario

The LHC scenario
A Future Linear Collider

A global collaboration and project (ILC home page http://www.linearcollider.org)

<table>
<thead>
<tr>
<th>SLC</th>
<th>NLC 0.5 - 1.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td></td>
</tr>
</tbody>
</table>

- Positron source
- Electron-positron collision
- High energy physics experiments
- Electron-positron collider
- Linear accelerator
- Damping ring
- Preaccelerator
- Electron source (HEP and x-ray laser)
- Positron source and 2nd electron source
- Electron-positron collider
- Linear accelerator
- Damping ring
- Preaccelerator
- Electron source (HEP and x-ray laser)

H. Weise 3/2000

33 km
Signal consists of the following processes:

\[ e^+ e^- \rightarrow \nu \bar{\nu} W^+ W^- \rightarrow \nu \bar{\nu} q\bar{q}q\bar{q} \]
\[ e^+ e^- \rightarrow \nu \bar{\nu} ZZ \rightarrow \nu \bar{\nu} q\bar{q}q\bar{q} \]

**Scenario:** \( \alpha_4 = \alpha_5 = 0.0 \) (SM) Higgs \( \rightarrow \infty \)

**Backgrounds:**
\[ e^+ e^- \rightarrow \nu \bar{\nu} q\bar{q}q\bar{q} \) (non-res.)
\[ e^+ e^- \rightarrow e^+ e^- W^+ W^- \]
\[ e^+ e^- \rightarrow e^+ \nu W^- Z \]
\[ e^+ e^- \rightarrow W^+ W^- (ZZ) \]
\[ e^+ e^- \rightarrow q\bar{q} \]
**WW Scattering Analysis**

Signal consists of the following processes:

\[
e^+ e^- \rightarrow \nu \bar{\nu} W^+ W^- \rightarrow \nu \bar{\nu} q \bar{q} q \bar{q}
\]

\[
e^+ e^- \rightarrow \nu \bar{\nu} Z Z \rightarrow \nu \bar{\nu} q \bar{q} q \bar{q}
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- **Scenario:** \(\alpha_4 = \alpha_5 = 0.0\) (SM) Higgs \(\rightarrow \infty\)

- **Backgrounds:**
  
  \[
  e^+ e^- \rightarrow \nu \bar{\nu} q \bar{q} q \bar{q} \quad \text{(non-res.)}
  \]
  
  \[
  e^+ e^- \rightarrow e^+ e^- W^+ W^- \\
  e^+ e^- \rightarrow e^+ \nu W^- Z \\
  e^+ e^- \rightarrow W^+ W^- (Z Z) \\
  e^+ e^- \rightarrow q \bar{q}
  \]

**Framework:**

- **Event generation**
  
  WHiZard 1.29 is the main event generator:
  
  - 6 fermions final states
  - all possible quark final states were generated
  - need to apply cuts to separate signals from other processes
  - the anomalous \(\alpha_4\) and \(\alpha_5\) quartic couplings are included
  - beam polarisation

**Detector simulation**

**Reconstruction**

**Output**
We followed TESLA project specifications:
(TeV Energy Super-conducting
Linear Collider Accelerator)
- C.M.E.: $\sqrt{s} = 800$ GeV
- Polarised beams:
  $0.80 \, e^-, \, 0.40 \, e^+$ (PoWER Group)
- Luminosity: $L = 1000 \, fb^{-1}$
  $> L(10^{34} \, cm^{-2} \, s^{-1}) = 5.8$

Both ISR and FSR are turned On

Summary of the cross sections obtained from our study:

<table>
<thead>
<tr>
<th>Type</th>
<th>Generated process: $e^+e^- \rightarrow$</th>
<th>Cross Sect. [$\mu b$]</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 fermions</td>
<td>$W^+W^- \rightarrow q\bar{q}q\bar{q}$</td>
<td>9.21</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$ZZ\nu\nu \rightarrow q\bar{q}q\bar{q}$</td>
<td>4.02</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}q\bar{q}$ (backgrounds)</td>
<td>5.55</td>
<td>Whizard</td>
</tr>
<tr>
<td>4 fermions</td>
<td>$W^+W^- \rightarrow e^+e^- q\bar{q}q\bar{q}$</td>
<td>331.30</td>
<td>Pythia*</td>
</tr>
<tr>
<td></td>
<td>$W^+W^- \rightarrow q\bar{q}q\bar{q}$</td>
<td>1948.10</td>
<td>Pythia*</td>
</tr>
<tr>
<td></td>
<td>$ZZ \rightarrow q\bar{q}q\bar{q}$</td>
<td>142.00</td>
<td>Pythia*</td>
</tr>
<tr>
<td></td>
<td>$e^+e^- \rightarrow t\bar{t}$</td>
<td>1.30</td>
<td>Pythia*</td>
</tr>
<tr>
<td>2 fermions</td>
<td>$t\bar{t} \rightarrow X$</td>
<td>139.00</td>
<td>Pythia*</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}$</td>
<td>4404.00</td>
<td>Pythia*</td>
</tr>
</tbody>
</table>

* Pythia does not include a $e^+e^-$ polarized beams option during integration
**WW Scattering Analysis**

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<td>$W^+W^- \rightarrow q\bar{q}q\bar{q}$</td>
<td>9.21</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$ZZ \rightarrow q\bar{q}q\bar{q}$</td>
<td>4.92</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}q\bar{q}$ (backgrounds)</td>
<td>5.55</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow q\bar{q}$</td>
<td>38.50</td>
<td>Whizard</td>
</tr>
<tr>
<td></td>
<td>$e^{+}e^{-}W^{+}W^{-} \rightarrow e^{+}e^{-}q\bar{q}q\bar{q}$</td>
<td>334.30</td>
<td>Pythia*</td>
</tr>
<tr>
<td>4 fermions</td>
<td>$W^{+}W^{-} \rightarrow q\bar{q}$</td>
<td>2048.10</td>
<td>Pythia*</td>
</tr>
<tr>
<td></td>
<td>$ZZ \rightarrow q\bar{q}q\bar{q}$</td>
<td>142.00</td>
<td>Pythia*</td>
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<tr>
<td></td>
<td>$e^{+}e^{-}t\bar{t}$</td>
<td>1.30</td>
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<tr>
<td></td>
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<td>4404.00</td>
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- We used the fast Detector Simulation SIMDET (v.4.01):
  - Tracking system: CCD vertex detector (1.5cm) + Forward Tracker
  - Magnetic field: 4 T

- Calorimetry:
  - ECal resolution: $\Delta E/E = 0.2/\sqrt{E}$
  - HCal resolution: $\Delta E/E = 0.5/\sqrt{E}$

- 3D cells - good granularity $\rightarrow$ Energy Flow concept.
Z and W reconstruction

Main problem is to reconstruct Z and W pairs

- Objects from the detector simulation are forced into 4 jets using the $K_T$ jet algorithm
  - exclusive mode, E recomb. scheme

- If succeed, we then have 3 possible combinations

- Use a 1C Kinematic Fit to find the best pair option
  \[ Q(\vec{x}, \vec{\lambda}) = (\vec{x} - \vec{x}_0)V^{-1}(\vec{x} - \vec{x}_0) + 2\vec{\lambda}f(\vec{x}) \]

  Where:
  - $\vec{f}(\vec{x})$: constraints
  - $\vec{x}$: jet parameters ($P_{tot}, \theta, \phi$)
  - $\vec{\lambda}$: Lagrange multipliers
  - $V$: error matrix

  Error matrix: resolution functions
  - $\sigma_{P_{tot}}(p_q)$, $\sigma_{\theta}(p_q)$, $\sigma_{\phi}(p_q, \theta_q)$

- $1c: M_{jet_1jet_2} = M_{jet_3jet_4}$
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$V$ : error matrix 
Error matrix: resolution functions 
$\sigma_{P_{tot}}(p_q), \sigma_\theta(p_q), \sigma_\phi(p_q, \theta_q)$

1c : $M_{jet1jet2} = M_{jet3jet4}$
Z and W reconstruction

Recoil Mass distribution

General selection cuts
- Recoil mass: $M_{recoil} \geq 200\,\text{GeV}$
- $P_T \geq 20\,\text{GeV}$
- $E_{trans} \geq 150\,\text{GeV}$
- Scaled $y_{cut}$ parameter
  \[ 4.0 \leq \ln \sqrt{y_{cut1,2} \times s} \leq 7.2 \]
- Total missing momentum
  \[ |\cos \theta_{P_{miss}}| < 0.99 \]
- Most energetic track
  \[ |\cos \theta_{P_{E_{max}}}| < 0.99 \]
- Charged tracks in each jet
  \[ n_{Tracks} \geq 2 \]
- Probability ($\chi^2$) > 0.005
- Ask for energy around highest track
  \[ \geq 2\,\text{GeV} \, 5\,\text{deg cone} \]

ZZ selection
\[ 85 < M_{1C} < 100\,\text{GeV} \]

WW selection
\[ 75 < M_{1C} < 85\,\text{GeV} \]

Transverse momentum distribution

more...
Results

Cut flow summary

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signals</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu\bar{\nu} W$</td>
<td>$\nu\bar{\nu} ZZ$</td>
</tr>
<tr>
<td>$m_{\text{cut}}$</td>
<td>5019</td>
<td>4350</td>
</tr>
<tr>
<td>$M_{\text{endpoint}}$</td>
<td>7128</td>
<td>3825</td>
</tr>
<tr>
<td>$P_T$</td>
<td>6863</td>
<td>3664</td>
</tr>
<tr>
<td>$E_T$</td>
<td>6347</td>
<td>3562</td>
</tr>
<tr>
<td>$y_{\text{cut}}$</td>
<td>6141</td>
<td>3497</td>
</tr>
<tr>
<td>$\cos \theta_{P_{\text{miss}}}$</td>
<td>6133</td>
<td>3493</td>
</tr>
<tr>
<td>$\cos \theta_{P_{\text{miss}}}$</td>
<td>6086</td>
<td>3470</td>
</tr>
<tr>
<td>Charged tracks</td>
<td>6086</td>
<td>3228</td>
</tr>
<tr>
<td>$E_{\text{cone}}$</td>
<td>5911</td>
<td>2981</td>
</tr>
<tr>
<td>$P(\chi^2)$</td>
<td>5871</td>
<td>2295</td>
</tr>
</tbody>
</table>

$\nu\bar{\nu} ZZ$ selection

![Graph showing $ZZ$ events distribution with various cuts applied]
Results

Cut flow summary

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signals</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu\bar{\nu}WW$</td>
<td>$\nu\bar{\nu}ZZ$</td>
</tr>
<tr>
<td>$n\text{jet}$</td>
<td>9219</td>
<td>4459</td>
</tr>
<tr>
<td>$M_{\text{encl}}$</td>
<td>7128</td>
<td>3825</td>
</tr>
<tr>
<td>$P_T^{Z}$</td>
<td>6683</td>
<td>3064</td>
</tr>
<tr>
<td>$E_T^{\text{T}}$</td>
<td>6347</td>
<td>3562</td>
</tr>
<tr>
<td>$y_{\text{rel}}$</td>
<td>6141</td>
<td>3447</td>
</tr>
<tr>
<td>$\cos \theta_{P_{\text{miss}}}$</td>
<td>6133</td>
<td>3443</td>
</tr>
<tr>
<td>$\cos \theta_{P_{\text{cone}}}$</td>
<td>6886</td>
<td>3470</td>
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<tr>
<td>Charged tracks</td>
<td>6886</td>
<td>3284</td>
</tr>
<tr>
<td>$E_{\text{cone}}$</td>
<td>5971</td>
<td>2295</td>
</tr>
</tbody>
</table>

$\nu\bar{\nu}ZZ$ selection

$\nu\bar{\nu}WW$ selection

Armentero-Podolanski plot
Sensitivity study

Now I have Z and W candidates and a working analysis system. I combined the pairs of Z and W and make some distributions:

$M_{WW}$ and $|\cos \theta^*|$ distribution for $\alpha_4 = \alpha_5 = 0.0$

What happens when $\alpha_4$ and $\alpha_5$ are different from zero?

Expected rate change in the end results and therefore deviations from SM predictions.
I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)
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Looked at the cross section for each and compare it to SM
Sensitivity study

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Sensitivity study

- I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)

- Looked at the cross section for each and compare it to SM

- We expect better sensitivity to $\alpha_5$ than $\alpha_4$ in particular when looking at the $\nu\bar{\nu}WW$ channel
Generated 12 extra scenarios with both $\alpha_5$ and $\alpha_4$ diff. from zero (each scenario had 400,000 events, enough statistics)
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Rerun the whole analysis
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Rerun the whole analysis

Examples of the new $M_{WW}$ distributions:
Sensitivity study

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Rerun the whole analysis

Examples of the new $M_{WW}$ distributions:

In order to study the sensitivity I used a Binned Maximum Log Likelihood applied to both $M_{WW}$ and $|\cos \theta^*|$ distributions for each scenario
Sensitivity study

- Generated 12 extra scenarios with both $\alpha_5$ and $\alpha_4$ diff. from zero (each scenario had 400,000 events, enough statistics)

- Rerun the whole analysis

- Examples of the new $M_{WW}$ distributions:

<table>
<thead>
<tr>
<th>$m_{WW}$ [GeV]</th>
<th>Events</th>
<th>Signal+Backgrounds</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>-0.0950</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>-0.0633</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>-0.0317</td>
</tr>
</tbody>
</table>

- In order to study the sensitivity I used a Binned Maximum Log Likelihood applied to both $M_{WW}$ and $|\cos \theta^*|$ distributions for each scenario

- BLLH takes as input: SM predicted signal, "observed" events, expected BKG and uncertainties in selection efficiencies, backgrounds and luminosity (not really needed ; $= 0.001$)
I end up with 32 LLH values for every scenario and each distribution
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These are the results for those 20 scenarios mentioned before:
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These are the results for those 20 scenarios mentioned before:
Sensitivity study

- I end up with 32 LLH values for every scenario and each distribution
- These are the results for those 20 scenarios mentioned before:

- Observation: no symmetric behaviour of those LLH points with respect to the minimum (SM scenario)
The combined results for those two distributions are
Under construction!

The fit of those LLH values has been more complicated than expected

At the moment, I'm using S-plines to get a nice fit to those points and extract the limits that I want (and desperately need :) )

What are the estimated \textit{values}?
Conclusions

The hadronic decays of processes

\[ e^+ e^- \rightarrow \nu \bar{\nu} W^+ W^- \]
\[ e^+ e^- \rightarrow \nu \bar{\nu} ZZ \]

can be exploited to find new physics provided LHC does not find a Higgs boson.

If our ignorance about new physics is parametrised in term of the \( \alpha_4 \) and \( \alpha_5 \) anomalous couplings, they could be measure at the ILC.

I achieved to write an analysis framework to study hadronic and leptonic decays.

It is OO and it would be interesting to see what can do with semi-leptonic decays.

I applied very useful analysis techniques (jet reconstruction, kinematic fit, binned log likelihoods).

There is progress done on extracting the sensitivity to those anomalous couplings and therefore provide 68/90 percent Confidence Levels.
Conclusions

If you can look into the seeds of time,
And say which grain will grow and which will not
Speak to me.

Macbeth, William Shakespeare
Signal preparation using the following cuts in phase space:

\[
147.0 \text{ GeV} \leq m_{q\bar{q}}^1 + m_{q\bar{q}}^2 \leq 171.0 \text{ GeV} : W \\
171.0 \text{ GeV} \leq m_{q\bar{q}}^1 + m_{q\bar{q}}^2 \leq 195.0 \text{ GeV} : Z \\
|m_{q\bar{q}}^1 + m_{q\bar{q}}^2| \leq 20.0 \text{ GeV} \\
m_{\nu\bar{\nu}} \geq 100.0 \text{ GeV}
\]

Multiplicity: 3  
Resonances: 3  
Log-enhanced: 2  
t-channel: 2
More distributions:
Chierici et al results

Previous results:

Confidence Levels contours

Sensitivities (1 dimensional limits)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_4$</td>
<td>$-1.1$</td>
<td>$0.8$</td>
</tr>
<tr>
<td>$\alpha_5$</td>
<td>$-0.4$</td>
<td>$0.3$</td>
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My preliminary results

- using a polynomial fit

Sensitivities (2 dimensional limits)

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</thead>
<tbody>
<tr>
<td>$\alpha_4$</td>
<td>$-1.18$</td>
<td>$1.24$</td>
</tr>
<tr>
<td>$\alpha_5$</td>
<td>$-0.95$</td>
<td>$0.96$</td>
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