Beam Polarisation and Triple Gauge Couplings in $e^+e^- \rightarrow W^+W^-$ at the ILC

J. List on behalf of the ILD & SiD detector concept groups

July 20, EPS-HEP 2013, Stockholm
Charged Triple Gauge Couplings

- most general lorentz-invariant $W^+W^-Z$ and $W^+W^-\gamma$ vertices: 14 complex couplings
- assume $C$ and $P$ conservation:
  6 real couplings: $g_1^\gamma, g_1^Z, k_\gamma, k_Z, \lambda_\gamma$ and $\lambda_Z$
- $g_1^\gamma$ fixed by em gauge invariance
- enforce $SU_L(2) \times U_Y(1)$ gauge relation:
  3 real couplings:
  $$\Delta k_Z = -\Delta k_\gamma \tan^2 \theta_W + \Delta g_1^Z$$
  $$\lambda_\gamma = \lambda_Z$$
- SM: $g_1^Z = k_\gamma = 1, \lambda_\gamma = 0$
- status: few percent precision from single parameter fits (LEP & LHC)
Charged Triple Gauge Couplings at the ILC

long established facts: [eg.: W. Menges, LC-PHSM-2001-022]

▶ expect significant improvement ($\sim$ 2 orders of magnitude)
▶ beam polarisation breaks correlation between $g_{1Z}$ and $\kappa_{\gamma}$
▶ ultimately allows to access all 28 coupling parameters without assuming $C$ and $P$ conservation (incl. running with transverse beam polarisation)
▶ but: knowledge of beam polarisation potentially limiting systematic uncertainty

wanted: luminosity weighted average of beam polarisation at $e^+e^-$ interaction point
Luminosity Weighted Average Polarisation – Strategy

1. Polarimeters:
   - instantaneous measurement for polarisation tuning
   - resolve time dependencies and correlations
   - aim for $\delta P/P = 0.25\%$, thereof $\sim 0.2\%$ scale uncertainty

2. spin tracking to/from IP, depolarisation in collision:
   $\rightarrow$ effects of the order of a few permille

3. long-term calibration of absolute scale at IP from $e^+e^-$ collisions: $e^+e^- \rightarrow W^+W^-$
   (or single $W$ / $Z$, esp. at $\sqrt{s} > 1$ TeV (CLIC!))
ILC Physics Simulations

- two detector concepts ILD and SiD, optimised for particle flow
- all studies presented here performed in full, Geant4-based detector simulation
- including beamspectrum and all relevant backgrounds
- results given as function of integrated luminosity
- one “Snowmass year” (10^7 s) of design accelerator operation
  - \( \sim 250 \text{ fb}^{-1} \) at \( \sqrt{s} = 500 \text{ GeV} \)
  - \( \sim 500 \text{ fb}^{-1} \) at \( \sqrt{s} = 1 \text{ TeV} \)
Methods to Extract the Beam Polarisation

Total Cross-Section (a.k.a. “modified Blondel scheme” [1])

\[ | P_{e^\pm} | = \sqrt{\frac{(\sigma_{--}+\sigma_{-+}-\sigma_{++}+\sigma_{+-})}{(\sigma_{++}-\sigma_{-+}+\sigma_{-+}+\sigma_{+-})}} \]

\[ (\pm\sigma_{--}\mp\sigma_{-+}\mp\sigma_{-+}+\sigma_{+-}) \]

\[ (\pm\sigma_{--}\mp\sigma_{-+}\mp\sigma_{-+}+\sigma_{+-}) \]

\[ \sigma_{+-} \text{ is total cross-section for } P(e^+, e^-) = (+x\%, -y\%), \text{ etc.} \]

\[ \text{assumes } P_+(e^-) = -P_-(e^-) \text{ and } P_+(e^+) = -P_-(e^+) \]

\[ \text{assumes no Beyond SM contributions with different polarisation dependence} \]
Differential Methods

Differential Cross-Section $d\sigma / d \cos \theta_W$

- $\cos \theta_W \simeq 1$: independent of TGCs
- more general: “new physics” expected to have different $\cos \theta_W$-dependence than SM

Double-Differential Cross-Section $d^2\sigma / d \cos \theta_W d \cos \theta_{\text{decay}}$

- $\cos \theta_{\text{decay}}$: decay angle in $W$ restframe ($W$ polarisation!)
- semi-leptonic: polar angle of charged lepton
- fully hadronic: average polar angle of jets
Results at $\sqrt{s} = 500$ GeV (ILD [2,3])

Total vs differential cross-section: semi-leptonic channel

- equal luminosity shares for $++$, $+-$, $-+$, $--$
- production angle adds significant information (but “unfair” comparison: total cross-section method could be extended beyond $W^+ W^-$…)
- high $|P(e^+)|$ increases precision (also for $|P(e^-)|$)
Luminosity Sharing

How much running time needed for ++ and −−?

► like-sign combinations less interesting for SM physics
► 10% to 20% like-sign lumi rather close to optimum (50%)
► even 2% halves already total lumi needed for 0.2% precision
Impact of Triple Gauge Couplings

Polarisation from simultaneous fit

- $g_1^Z$, $\kappa_\gamma$ and $\lambda_\gamma$ additional free parameters
- equal luminosity shares for $++$, $+-$, $-+$, $--$
- no loss in precision on polarisation due to free TGCs
Constraints on Triple Gauge Couplings

from same simultaneous fit

- reach a few $10^{-4}$ for all three couplings
- increasing $|P(e^+)|$ does not help significantly *here*
- with 500 fb$^{-1}$ or more, finer binning of data possible
  $\Rightarrow$ significant improvement for $\lambda_\gamma$

Beam Polarisation and TGCs in $e^+e^- \rightarrow W^+W^-$ at the ILC

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Impact of Polarimeter Precision

What if $P_+(e^-) \neq -P_-(e^-)$ and $P_+(e^+) \neq -P_-(e^+)$?

- let all $P$ vary independently $\Rightarrow \delta P/P$ in percent regime, limits TGCs
- better: measure deviation to $\pm \delta P/P|_{pol} = 0.25\%$ with polarimeters
- limits ultimate precision on $P(e^-)$!
- with this level of polarimeter precision: negligible impact on TGCs
Results at $\sqrt{s} = 1$ TeV (ILD [4,5])

ILC Technical Design Report: from 500 GeV to 1 TeV

- is detector design / technologies still suitable?
- are accelerator backgrounds (beamstrahlung) tolerable?
- instantaneous luminosity twice as high (cross-sections dropping with $\sqrt{s}$!)
- what if positron polarisation is only 20%?

Polarisation from Total Cross-section

- Luminosity shared equally between $++, +−, −+, −−$
- $\delta P(e^-)/P(e^-)$ similar as at 500 GeV
- $\delta P(e^+)/P(e^+)$ worse if only 20%
Polarisation from Differential Cross-section $d\sigma/d\cos\theta_W$

How much running time needed for $++$ and $--$?

- 0% vs 20% for like-sign configurations
- 0% already better than total cross-section method with 50% like-sign luminosity
- $\delta P(e^+)/P(e^+)$ will profit from higher $|P(e^+)|$
Polarisation from $d^2\sigma/d\cos\theta_W d\cos\theta_{\text{decay}}$ (SiD [6])

\[ P(e^+, e^-) = (+1, -1) \]

\[ \cos\theta_{\text{decay}} \text{ vs } \cos\theta_W \]

\[ P(e^+, e^-) = (-1, +1) \]

\begin{table}
\begin{tabular}{cccccc}
1000 fb$^{-1}$, equal share $++, --, +-$ & $\cos \theta$ range & $P(e^+, e^-)$ & $\delta P(e^-)/P(e^-)$ & $\delta P(e^+)/P(e^+)$ \\
\hline
avoid TGC region & $0.8 < \cos \theta < 1$ & $(+0.2, -0.8)$ & 15\% & 38.5\% \\
avoid TGC region & $0.8 < \cos \theta < 1$ & $(-0.2, +0.8)$ & 0.58\% & 11.5\% \\
assume SM & $-1 < \cos \theta < 1$ & $(+0.2, -0.8)$ & 7.25\% & 19\% \\
assume SM & $-1 < \cos \theta < 1$ & $(-0.2, +0.8)$ & 0.51\% & 9\% \\
assume SM & $-1 < \cos \theta < 1$ & sum & 0.25\% & 1.45\%
\end{tabular}
\end{table}

complementary method, gives compatible result with ILD
Conclusions

- the ILC will be a great place for Triple Gauge Couplings
- $e^+e^- \rightarrow W^+W^-$ allows *simultaneous* determination of beam polarisations and charged TGCs
- Triple Gauge Couplings:
  - $g_1^Z$, $k_\gamma$, $\lambda_\gamma$: resolutions of few $10^{-4}$ in simultaneous fit
  - ultimately: access *all* couplings, incl. $C$, $P$, $CP$ violating ones
- luminosity weighted average beam polarisation:
  - three complementary methods all reach precisions of few $10^{-3}$
  - still to do: combine to optimal polarisation measurement
  - will provide important scale calibration for all physics channels
  - high $|P(e^+)|$ improves asymptotic resolution
  - 10 to 20% of data with like-sign helicities very beneficial
- all about the ILC: plenary talk by S. Komamiya this afternoon!
References


Experimental Conditions at 1 TeV
On average $\sim 4$ low-$p_t \gamma\gamma \rightarrow$ hadrons events per bunch crossing
Impact of Luminosity Uncertainty

- assume relative uncertainty of $10^{-3}$
- noticeable but not dramatic
- not an issue when fast (train-by-train) helicity flip for positrons available

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Blondel</th>
<th>Angular no TGCs</th>
<th>Angular with TGCs</th>
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<tbody>
<tr>
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<td>60% $e^+$ polarization</td>
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<tr>
<td>$\Delta P_{e^+}$</td>
<td>0.1%</td>
<td>0.08%</td>
<td>0.07%</td>
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<tr>
<td>$\Delta P_{e^-}$</td>
<td>0.04%</td>
<td>0.02%</td>
<td>0.02%</td>
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<tr>
<td>$\Delta g_{1Z} \cdot 10^{-04}$</td>
<td>-</td>
<td>-</td>
<td>0.0002</td>
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<tr>
<td>$\Delta \kappa_{\gamma} \cdot 10^{-04}$</td>
<td>-</td>
<td>-</td>
<td>0.0002</td>
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<tr>
<td>$\Delta \lambda_{\gamma} \cdot 10^{-04}$</td>
<td>-</td>
<td>-</td>
<td>0.0002</td>
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<td></td>
<td>30% $e^+$ polarization</td>
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<td>$\Delta P_{e^+}$</td>
<td>0.3%</td>
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