Experimental Aspects of New Physics at TeV Scale & Precision Electroweak

Atul Gurtu
TIFR, Mumbai
Nature of LC measurements

**Stand-alone:**
Direct search for new & undiscovered particles with limited energy reach

Precision measurements of known processes to discover deviations from SM to reveal new physics even beyond direct energy reach

**Guided by LHC:**
Disentangle the LHC discoveries
Presentations in the five sessions on New physics at TeV scale and precision electroweak

New Vector Boson related:
- Use of polarized beams;
- EW measurement related (TGC)
- W-pair prod., 3-gauge boson;
- Loop calculations (ew mixing angle, 2-fermion, running $\alpha$);
- Special models (NCSM, Little Higgs);

ED/KK related (Higgsless model, UED, dark matter, graviton induced brems, Higgs pair prod, 5-D SM extn);

Experiment related:
- Precision luminosity measurement, results on muon g-2.

Interesting and varied topics.
- Cannot hope to present all. All talks are (will be) available on the WEB.

Hope to give you a flavor.
Plan of the talk

- Electroweak
- Contact interactions, Z’ etc
- Theory to match
- Examples of importance of Polarization
- Extra dimensions
- Recent models (Little Higgs, Warped Higgsless)
  Don’t know how far I will get!
Importance of Precision Electroweak studies

SM: $W,Z$ conceal Higgs field DOF

Thus:

- Precision study of $W, Z$ properties, & their production & decay characteristics will reveal nature of EWSB and test the internal consistencies within SM.

- Deviations from SM will imply NEW PHYSICS.

- Nature of deviations: which (or NEW) model.
Precision Electroweak - masses

$\rightarrow$ $M_z$ LEP: 2 MeV error

$\rightarrow$ $M_W$ current: 34 MeV (dominated by LEP),
Tevatron-Run2: ~20-25 MeV,
LHC: ~15 MeV ?  LC: ~5-10 MeV ?

$\rightarrow$ $M_{\text{top}}$ current: 4 GeV, Tevatron-Run2:
2-3 GeV, LHC: 1-2 GeV (?), LC: 100 MeV ?
Importance of precise mass determinations
New top mass and $M_{\text{higgs}}$

Precision electroweak data:
Constrain $M_H$ in the MSM

Old:

$$M_{\text{top}} = 174.3 \pm 5.1 \text{ GeV}$$

$$\log M_H = 1.98^{+0.21}_{-0.22}$$

$$M_H = 96^{+6C}_{-38} \text{ GeV}$$

or $< 219 \text{ GeV (95\% CL)}$

New:

$$M_{\text{top}} = 178.0 \pm 4.3 \text{ GeV}$$

$$\log M_H = 2.07^{+0.20}_{-0.21}$$

$$M_H = 117^{+67}_{-45} \text{ GeV}$$

or $< 251 \text{ GeV (95\% CL)}$

(Procedure as in hep-ex/0312023)
Specially sensitive to models of EWSB
At LC, will be measured with very high precision ($10^{-4}$)

Use $\sigma$, $d\sigma/d\cos\theta$. 
Precision Electroweak (contd)
Gauge Couplings at LEP

Common set: \([g^z_1, \kappa_z, \kappa_\chi, \lambda_z, \lambda_\chi]\),

SM: CP- conserving
\[g^z_1 = \kappa_z = \kappa_\chi = 1; \quad \lambda_z = \lambda_\chi = 0\]

SM: not C or P- conserving
\[g^z_5, g^z_4, \kappa^z_\sim, \kappa^\chi_\sim\]
Precision Electroweak (contd)  
Charged TGC’s at LEP

ALEPH  DELPHI  L3  OPAL  LEP

\[ \Delta \ln L \]

\[ g_T^2 \]

\[ \kappa_T \]

\[ \lambda_T \]

\[ \kappa_T \]

\[ \lambda_T \]

\[ \kappa_T \]

\[ \lambda_T \]

LEP Preliminary

\[ \kappa_T = 0.984 \pm 0.042 \]

\[ \kappa_T = 0.984 \pm 0.047 \]

\[ \lambda_T = -0.016 \pm 0.021 \]

\[ \lambda_T = -0.016 \pm 0.023 \]

\[ g_T^2 = 0.991 \pm 0.022 \]

\[ g_T^2 = 0.991 \pm 0.021 \]

LEP Preliminary

\[ 95\% \text{ c.l.} \]

\[ 90\% \text{ c.l.} \]

\[ 2\sigma \text{ fit result} \]
Expectations at LC (TESLA-TDR), comparison of Colliders

Table 5.1: Results of the single parameter fits ($\Delta \sigma_1$) to the different triple gauge couplings. For $\sqrt{s} = 500$ GeV $C = 1000$ fb$^{-1}$ and for $\sqrt{s} = 800$ GeV $C = 1000$ fb$^{-1}$ has been assumed. For both energies $P_{tr} = 80\%$ and $P_{re} = 60\%$ has been used.

<table>
<thead>
<tr>
<th>$\Delta \sigma_1$</th>
<th>error $\times 10^{-3}$</th>
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<tr>
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<td>$\sqrt{s} = 500$ GeV</td>
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<td>$\sqrt{s} = 800$ GeV</td>
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<td>$\Delta \omega_1$</td>
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<td>$\Delta \omega_2$</td>
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<td>$\omega_3$</td>
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<tr>
<td>$\omega_4$</td>
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<tr>
<td>$\omega_5$</td>
<td>6.7</td>
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</table>

Figure 5.13: $1\sigma$ and $95\%$ c.l. (2D) contours for $\Delta \omega_1$, $\Delta \omega_2$, $\Delta \omega_3$, $\Delta \omega_4$, and $\omega_5$ in the 5-parameter fit ($\sqrt{s} = 800$ GeV; $C = 1000$ fb$^{-1}$; $P_{tr} = 0.6$). For the combinations not shown the correlations are small.

Figure 5.14: Comparison of $\Delta \omega_1$ and $\Delta \omega_5$ at different machines. For LHC and TESLA three years of running are assumed (LHC 500 fb$^{-1}$, TESLA $\sqrt{s} = 500$ GeV 900 fb$^{-1}$, TESLA $\sqrt{s} = 800$ GeV 1500 fb$^{-1}$).
e.g.

$W$ - couplings at an $e\gamma$ collider & comparison with $e^+e^-$ and $\gamma\gamma$ colliders

K. Mönig, J. Sekaric
DESY - Zeuthen
**Overview**

\[ e^-\gamma \rightarrow \nu_e W^- \quad \sqrt{S} = 450 GeV \]

- Deviations from SM TGC values → *test of EW theory, probe of some possible extensions* → *new physics beyond the SM*
- Precision measurements of deviations from its SM values (anomalous TGC)

Vector ‘\(\rho\)’-like resonance in \(e^+e^- \rightarrow W^+W^-\)

DCS for \(J_\gamma = \pm 1\) in SM
- \(J_\gamma = -1\) → left-handed \(e^-\), right-handed \(\gamma\)
- \(J_\gamma = +1\)
In order to estimate the precision of measurement of TGC:

- Signal ($\gamma e^-\rightarrow\nu W$) sample (background, pile-up) (WHIZARD – W. Kilian & CIRCE2 – T. Ohl, variable energy spectra, polarized beams)
- Response of a detector simulated with SIMDET V4
- $W$s are reconstructed from hadronic final states
- Estimated errors of measurement of $\kappa_\gamma$ and $\lambda_\gamma$ parameters, obtained by fit (binned $\chi^2$) for real ($e\gamma$-collider) and parasitic ($\gamma\gamma$-collider) $e\gamma$-mode
- Estimation of systematic errors
Comparison ...

with $\gamma\gamma$ and $e^+e^-$ colliders

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<tr>
<th></th>
<th>$E_{\gamma\gamma} = 450$ GeV $\int L_{\Delta t}=110$ fb$^{-1}$</th>
<th>$E_{\gamma\gamma} = 400$ GeV $\int L_{\Delta t}=110$ fb$^{-1}$</th>
<th>$E_{ee} = 500$ GeV $\int L_{\Delta t}=500$ fb$^{-1}$</th>
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<tr>
<td>$\Delta L$</td>
<td>0.1%</td>
<td>0.1%</td>
<td>Acc *</td>
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<tr>
<td>$\Delta\kappa_\gamma \cdot 10^{-4}$</td>
<td>10.0/11.0</td>
<td>(6.7)</td>
<td>3.6</td>
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<tr>
<td>$\Delta\lambda_\gamma \cdot 10^{-4}$</td>
<td>4.9/6.7</td>
<td>(6.0)</td>
<td>11.0</td>
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() - fixed beam energy, 2D fit, generator level
• - generator level
• Demonstration of $10^{-4}$ to $10^{-3}$ capability of LC
Quartic gauge couplings in a strongly interacting heavy Higgs model

Michael Beyer:

\[ e^+ e^- \rightarrow WWZ, ZZZ \]

Carried out SIMDET simulation,
preliminary results on ability to obtain parameter values \((\alpha_4, \alpha_5)\).
Further studies in progress.
Precision Electroweak:
using di-fermion production

Cross section and asym. measurements:
- all agree with SM predictions

- Contact interaction scale can be used to place limits on
  mass of \( Z' \), scale of gravity or mass of lepto-quarks or other new physics.

Case of \( Z' \) is very important as additional \( Z \) bosons exist in many new physics scenarios (E6, Little Higgs and Higgsless models).

(Sabine Riemann, A. Freitas, W. Kilian, T. Rizzo, … – this conf.)
Contact Interactions

Contact interactions (C.I.) to describe interactions beyond the SM at $\sqrt{s} \ll \Lambda$

$$\mathcal{L}_{CI} = \sum_{L,R} \eta_{i,j} \frac{g^2}{\Lambda^2} \left( \bar{u}_{F,i} \gamma^\mu u_{F,i} \right) \left( \bar{u}_{F,j} \gamma\mu u_{F,j} \right)$$

$$\frac{d\sigma}{d\cos\Omega} \propto \sum_{i,j=L,R} \rho_{ij} |A_{ij}|^2 \text{ with } A_{ij} \sim A_{ij}^{SM} + \frac{\eta_{ij}\cdot s}{\Lambda^2}$$

$$\rho_{LL,RR} = (1 + \cos\theta)^2$$

$$\rho_{LR,RL} = (1 - \cos\theta)^2$$

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<th>model</th>
<th>LHC $\Lambda$ [TeV]</th>
<th>LC $\Lambda$ [TeV]</th>
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<th>(\Lambda_{-})</th>
<th>(\Lambda_{+})</th>
<th>(\Lambda_{-})</th>
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Gupta, Jain, Mondal, PRD62(2000)095003
SR, LC-TH-2001-007,
Babich et al., hep-ph/0107159
D. Bourikov, hep-ph/0305125
Pankov, Paver, hep-ph/0209058

LC: $\sqrt{s} = 500$ GeV
LEP – Z’ mass limit

Fits made to Z’ from E6 GUT & L-R symmetric Models and for Sequential SM (same couplings as SM).

Z’ model: chi psi eta L-R SSM
Mass limit: 673 481 434 804 1787 GeV
Z’ Limits at the LC

Most likely indirect Z’ search at LC

- derive Z’ couplings $\frac{g_{L,R}^f}{M_{Z'}}$
- observables: $\sigma_{tot}$, $A_{FB}$, $A_{LR}$, $A_{LF}^{EB}$
- search for contact terms:
  in case of Z’ one finds:

$$\frac{\eta_{LL}^{cf}}{\Lambda^2} \frac{\eta_{RR}^{cf}}{\Lambda^2} = \frac{\eta_{LR}^{cf}}{\Lambda^2} \frac{\eta_{RL}^{cf}}{\Lambda^2}$$

$$\sim \frac{g_L^f}{M_{Z'}} \frac{g_L^f}{M_{Z'}} \frac{g_R^f}{M_{Z'}} \frac{g_R^f}{M_{Z'}}$$

- model-dependent search within various new gauge boson scenarios

Assumptions:

- $\mathcal{L}_{int} = 1ab^{-1}$, $\Delta \mathcal{L}_{int} = 0.2\%$
- $P_- = 0.8$, $P_+ = 0.6$, $\Delta P_- = \Delta P_+ = 0.5\%$
- $\Delta_{sys$(\text{lept}) = 0.2\%$, $\Delta_{sys$(\text{had}) = 0.1\%$

LHC: see Godfrey, hep-ph/0201093
What if Z’ has very weak couplings to fermions?

A. Freitas:

→ Very narrow, energy scan would miss it (washed out by Ecm spread due to ISR, beamstrahlung).

→ Use radiative return method (tag hard \( \gamma \)):
  reconstruct recoil jet-jet or \( \mu \mu \) system

→ Need very good mom./energy resolution
Results: Weakly coupled Narrow Z’

Comparison with hadron colliders

Combination of searches with radiative-return method for $M_{Z'} < \sqrt{s}$ and contact-interaction method for $M_{Z'} > \sqrt{s}$:

Sensitivity to high masses $M_{Z'}$, but only moderate coupling strength $g_{Z'ff}^2/(g_{Zff}^2)_{SM}$

Example for $\text{BR} = \text{BR}_{SM}$: $\sqrt{s} = 1000$ GeV, $\mathcal{L} = 1000$ fb$^{-1}$

![Graph showing the sensitivity of Z' coupling to its mass for different channels.](image)
Context of Higgsless model with Z’ like KK excitations (T. Rizzo et al)
Lepto-quark searches at a 500 GeV LC
ED - Estimate of $M_H$ limits using di-fermion data at 500 GeV LC

$M_D$, fundamental scale of higher dimensional theory

$[M^2(PI) = V_8 M_D^{2+8}]$, $V_8 =$ vol. of compactified dimensions.

(In general $M_H$, scale relevant to graviton exchange is not equal to $M_D$.)

Limit on $M_H$ (TeV) for $P(e^+) = 0.6$, 0.0

for $L_{int} =$ 1 ab$^{-1}$ at 500 GeV

$M_H$ limit ~8 TeV

$P=0.6$ at 800 GeV

<table>
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<th>Channel</th>
<th>4.1</th>
<th>3.8</th>
<th>4.4</th>
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<tr>
<td>$e^{+}e^{-} \rightarrow \mu \mu$</td>
<td>5.0</td>
<td>4.4</td>
<td></td>
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<tr>
<td>$e^{+}e^{-} \rightarrow bb$</td>
<td>5.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^{+}e^{-} \rightarrow cc$</td>
<td>4.4</td>
<td></td>
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Combined

| 5.6 | 5.0 |
Conclusion: Power of di-fermion study

“Fermion pair production is sensitive to most of new phenomena. The combination of different final states, angular distributions and helicity amplitudes can be exploited to disentangle the source of new physics up to a multiple of available c.m. energies.”
Precision Electroweak (contd)

Also solve left-over puzzle from LEP: disagreement in measured EW angle from different asyms.

‘Cleaner’ Measurements ➞ TOO LOW M_{higgs} value
Precision electroweak, Giga-Z, W-threshold runs

- Giga-Z: $10^9$ Z in 100 days run → partial widths, ew mixing angle, b, c- quark studies
- W-threshold → W-mass
Z’ searches: comparison of LHC with LC (GigaZ + high energy)

LHC and LC (GigaZ and 'high energy'):

\[
\begin{align*}
Z \text{ mass limit (GeV)} & \\
\text{FLC} & \text{LHC}
\end{align*}
\]
Theory to match

3 interesting talks:

T. Riemann: **automatized Calculation of 2f production** with aITALC for higher precision calculations

M. Awramik: **NNLO corrections to the effective weak mixing angle.** Need a precision of ~10^{-5} to match Giga-Z LC results.

L. Trentadue: **Proposal to determine running of \( \alpha_{\text{QED}} \)** using small angle Bhabha scattering
Importance of both beams polarization, and transverse pol.

G. Moortgat-Pick & S.D. Rindani:
Apart from the general desirability of BOTH beams polarized, there are cases where TRANSVERSE polarization is essential to disentangle the physics or determine a coupling.

⇒ However sensitiv to one specific TGC only with trans. pol. via optimal observable method Diehl, Nachtmann, Nagel'03 reparametrisation and taking linear combinations → 'error minimisatio
⇒ one specific coupling \( \tilde{h}_\pm = \text{Im}(g_1^R \pm \kappa_R)/\sqrt{2} \) only sensitiv to \( P_T P_T \)

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<th>unpol</th>
<th>long (80%,0)</th>
<th>long (80%,60%)</th>
<th>trans (80%, 60%)</th>
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<tr>
<td>( \tilde{h}_- )</td>
<td>11</td>
<td>4.5</td>
<td>2.5</td>
<td>3.7</td>
</tr>
<tr>
<td>( \tilde{h}_+ )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
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⇒ other results comparable simulation results
Need of transverse polarization in LC studies

3 specific examples:

- CP violation in $e^+e^- \rightarrow t\bar{t}$ in the presence of chirality-violating scalar $S$ and tensor $T$ contact interactions
  (in collaboration with B. Ananthanarayan

- CP violation in $e^+e^- \rightarrow \gamma Z$ with chirality-preserving anomalous triple gauge couplings $\gamma\gamma Z$ and $\gamma ZZ$
  (in collaboration with B. Ananthanarayan, A. Bartl, R.K.Singh
  hep-ph/0404106)

- $e^+e^- \rightarrow t\bar{t}$ with scalar leptoquark intermediate states, both chirality preserving and chirality violating couplings
  (in preparation)
R. Rueckl: Non-universal 5D model.

Studied effects on SM processes. Determined Compactification scale by fitting EW data.

LEP data: 4-6 TeV (shifts higgs mass upward by 40-50 GeV)

TESLA: 15-25 TeV (syst errs incl.)
\[ \mathcal{O}^{5\text{DSM}} = \mathcal{O}^{\text{SM}} \left( 1 + \Delta_0^{5\text{DSM}} \right) \]

**\( \mathcal{O}^{\text{SM}} \):** standard model prediction including radiative corrections

**\( \Delta_0^{5\text{DSM}} \):** tree level effects in compactified 5D extensions (to \( O(m_Z^2/M^2) \), \( M = 1/R \))

- shifts in **couplings and masses** of the SM gauge bosons
- virtual exchange of heavy **KK modes**

\( \rightarrow \) modification of SM relations between **ew. parameters**

**input parameters** \( (\alpha, M_Z, G_F) \)
LEP1 (precision observables) and LEP2 (fermion-pair, W-pair production) data
Particle Data Group, Electroweak Working Group

one-parameter fit excluding (including) $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow W^+W^-$:

SU(2)×U(1) in bulk (brane Higgs): 6.4 (6.9) TeV
SU(2)×U(1) in bulk (bulk Higgs): 5.5 (6.0) TeV
U(1) in bulk: 5.0 (5.4) TeV
SU(1) in bulk: 4.5 (4.8) TeV

multi-parameter fit using ZFITTER (D. Bardin et al.):

SU(2)×U(1) in bulk (brane Higgs): 5.4 TeV
SU(2)×U(1) in bulk (bulk Higgs): 5.2 TeV
U(1) in bulk: 3.6 TeV
SU(2) in bulk: 4.3 TeV
Minimal Universal Extra dimensions – study at CLIC

A. De Roeck: Minimal UED model, d=4+1
(Cheng, Schmaltz, Matchev)

→ KK partners for all particles and LKP
   (Lightest KK Particle) dark matter candidate.
→ Signatures very much like SUSY; could be discovered at LHC. Would need LC for proper interpretation of the signal.
Comparison: angular distributions of muons

Production polar angle $\theta$ of the decay muons

If mass difference $M_{\mu 1} - M_{\gamma 1}$ small $\Rightarrow$ correlation between muons & pare

After detector simulation
$\chi^2$ fit: can distinguish UED from SUSY at 5$\sigma$ with 350 fb$^{-1}$ at $\sqrt{s}=3$ TeV
Higgs pair production in ED models

N. Okada: ADD scenario.
KK gravitons either direct observation or via indirect KK mediated process.

Studied higgs pair production. Both Higgs $\rightarrow$ bb; 4b final state.
Cross section & its angular distribution allows identification of spin-2 KK indirectly.
Virtual KK graviton mediated process

\[ e^- \rightarrow e^+ G^{(\vec{n})}_{\mu\nu} \rightarrow \bar{H} H \]

Sum over infinite tower of KK modes

\[ \sum_{\vec{n}} \frac{1}{s - (m_{KK}^{(\vec{n})})^2} \rightarrow \infty \quad \text{(for } \delta \geq 2) \]

Need regularization

Naïve: Cut Off by \( m_{KK}^{MAX} \sim M_{4+\delta} \)

\[
\frac{4\pi \lambda}{M_s^4} = -\frac{8\pi}{M_P^2} \sum_{\vec{n}} \frac{1}{s - (m_{KK}^{(\vec{n})})^2}, \quad \lambda = \pm 1
\]
Reconstruction of Angular Distribution (after selection)

Samples
- Signal
- ZH
- Predicted shape

integrated luminosity 500 $fb^{-1}$
Little Higgs Model
(Arkani-Hamed, Cohen, Georgi, 2001, …)

Higgs doublet part of pseudo-Goldstone bosons
multiplet associated with a global sym. at scale \( \Lambda \) in
multi-TeV range \( \rightarrow \) protects lightness of Higgs fields.

Characteristic scale of Goldstone multiplet \( F \), is given
by \( F \sim 4\pi \, v(\text{EW scale} \sim 250 \text{ GeV}) \sim \Lambda/4\pi \)

Addl particles introduced:
extra vector bosons, scalars, fermions whose properties
arranged to ensure at least one light higgs.
Others have masses of order \( F \) (many TeV), hence
unobserved so far.
Little Higgs: what signals?

W. Kilian (talk + hep-ph/0311095) and Gi-Chol Cho:
If new particles beyond LC reach
Check for indirect effects in precision measurement, e.g., Oblique correction variables S, T, U.
If discovered how to distinguish from other scenarios (e.g. E6 Z’).
Caveat: Direct and indirect effects of contact interactions

- Conventionally, $S, T, U$ are calculated using $G_F$ as reference scale

Shift in effective Fermi coupling:

$$G_F = \frac{1}{v^2} (1 - \alpha \Delta T + \delta) \quad \text{with} \quad \delta = \frac{c^4 \frac{\alpha^2}{F^2}}{

\Rightarrow \text{modified effective parameters}

$$S_{\text{eff}} = \Delta S$$

$$T_{\text{eff}} = \Delta T - \frac{1}{\alpha} \delta$$

$$U_{\text{eff}} = \frac{4 s_w^2}{\alpha} \delta$$

\Rightarrow \text{Partial cancellation in } T, \text{ positive } U \\
\text{due to nonvanishing } \delta \text{ (}SU(2)_c\text{-conserving)}
Identifying Little Higgs signals – need for precision measurement of all kinds of couplings

New observables: Linear Collider

- Triple gauge couplings:
  \[ \Delta g_\gamma = \Delta \kappa_\gamma = 0 \]
  \[ \Delta g_Z = \Delta \kappa_Z = 2M_Z^2 \frac{(c^2 - s^2)}{g^2 f^2} \]
  (equals \( \Delta S \) correction, but triplet part only)

- Higgs boson couplings:
  Anomalous \( ZZH, WWH \) vertices, sensitive to coefficient of \( \text{Tr} [V_\mu V^\mu] \)
  (nonvanishing if heavy vectors decouple, contains piece due to nonlinear representation)

- Corrections to Higgs Yukawa couplings, extra \( H H f \bar{f} \) terms (sensitive to scalar sector)

- Higgs contact terms: \( f f H W, f f H Z \)
  \( \Rightarrow \) include these in analysis of Higgs couplings

- Anomalous \( t \bar{t} Z \) and \( t \bar{b} W \) couplings (sensitive to heavy-top chirality)

- Modified quartic couplings \( H H W W, H H Z Z \)

- Modified Higgs self-coupling \( H H H H \)

W. Kilian, LCWS Paris 2004
Distinguishing between Little Higgs $Z'$ and E6 $Z'$

• LHC has a detectability of TeV $Z'$ boson in some class of models
• What can LC do if LHC find a $Z'$ boson ($<\ 1\text{TeV}$)?
  – If $Z'$ mass is smaller than the CM energy of LC, it can be produced in $s$-channel
• Can LC tell us that if discovered $Z'$ boson is in Littlest Higgs model or SUSY E6 models?
Signal cross section + FB asymmetry measurements

\[ A_{H} \]
\[ A_{\mu}^\nu \]
\[ A_{\psi}^{\eta} \]
\[ A_{\chi}^{\nu} \]
\[ A_{FB}^{\mu} \]

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<tr>
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<td>0.48</td>
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Try to do what Higgs does without it.

Randall-Sundrum framework:

Gravity localised in a 5-D non-factorizable geometry based on a slice of AdS$_5$. 
Goal is to have a model consistent with

1. existing precision EW data

2. Limits on Z’ from current data (compactification leads to KK tower of states which should show up as Z/W excitations)

3. Unitarity in high energy WW scattering

Doing all the above simultaneously is difficult.
TENSION HEADACHE:

Why? W/o a Higgs the SM violates unitarity in \(W_L W_R^*\) scattering at \(\sqrt{s} = 1.8\) TeV.

\(\therefore\) We need some KK's lighter than this to contribute to \(W_L W_R^*\) scattering to get P.O.

But: they can't have (yet) showed up at the Tevatron (or via LEP II contact int. searches, etc.)

And: light KK's usually imply a 'disruption' of good SM EWK results

Examples: The 3 \(\sin^2\theta\)'s... at tree level in the SM...

\[
\begin{align*}
\sin^2\theta_W & = 1 - M_W^2/M_Z^2 \\
\sin^2\theta_C & = \frac{G_F \langle \bar{\nu}_e \nu_e \rangle}{\sin^2\theta_W} \\
\sin^2\theta_Z & \text{ at the Z-pole}
\end{align*}
\]

\(\therefore\) Here they differ at tree level if \(M_W/M_Z\) are inputs
Context of Higgsless model with Z' like KK excitations (T. Rizzo et al)
Conclusions – Warped Higgsless Model

1. Higgsless models offer a potential method of EW symmetry breaking w/ a Higgs using extra dimensions.

2. The simplest models examined so far do not have all the required features and are not yet fully explored.

3. Many (All?) of the desired properties of a successful model have been identified: most likely signature

   - light Z/W-like KK states w/ small fermion couplings
   - Visible at LHC, LHC (or even TeV??)

4. A lot more work is needed to see if this idea can really work...
Final Remarks – New Physics, EW measurements sessions

- Many studies presented
- At LC most important will be PRECISION EW measurements (for Model Independent conclusions)
- High theoretical precision needed to match measurements – progress in this.
- Need for PRECISION detector to fully exploit the capabilities of the LC
- Status of models given – need more work
Universal Extra Dimensions

• The framework is all fields live in all dimensions:
  – Quarks & Gluons
  – Leptons
  – Photons and Gauge Bosons
  – Higgs
  – Gravity

• This is unlike the “brane world” scenario where everything except gravity is stuck to some point.

• This universality implies a translational invariance along the 5th dimension, and thus conservation of momentum in that direction.

• The result is a stable particle, necessary to have a dark matter candidate.
Universal ED’s in Cosmology (Dark Matter)

Tim Tait:
Lightest KK Particle as Dark matter candidate.