Strongly Interacting W Bosons:

The No-Higgs Case at the Linear Collider

Wolfgang Kilian (Karlsruhe)

Padova
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The Standard Model with a light Higgs boson fits EW data

But:

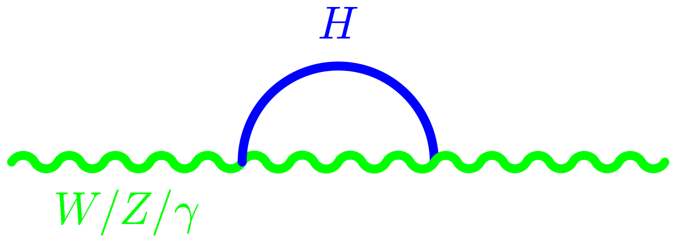
The Higgs has not (yet?) been found.

$\Rightarrow$ We have to consider the possibility:

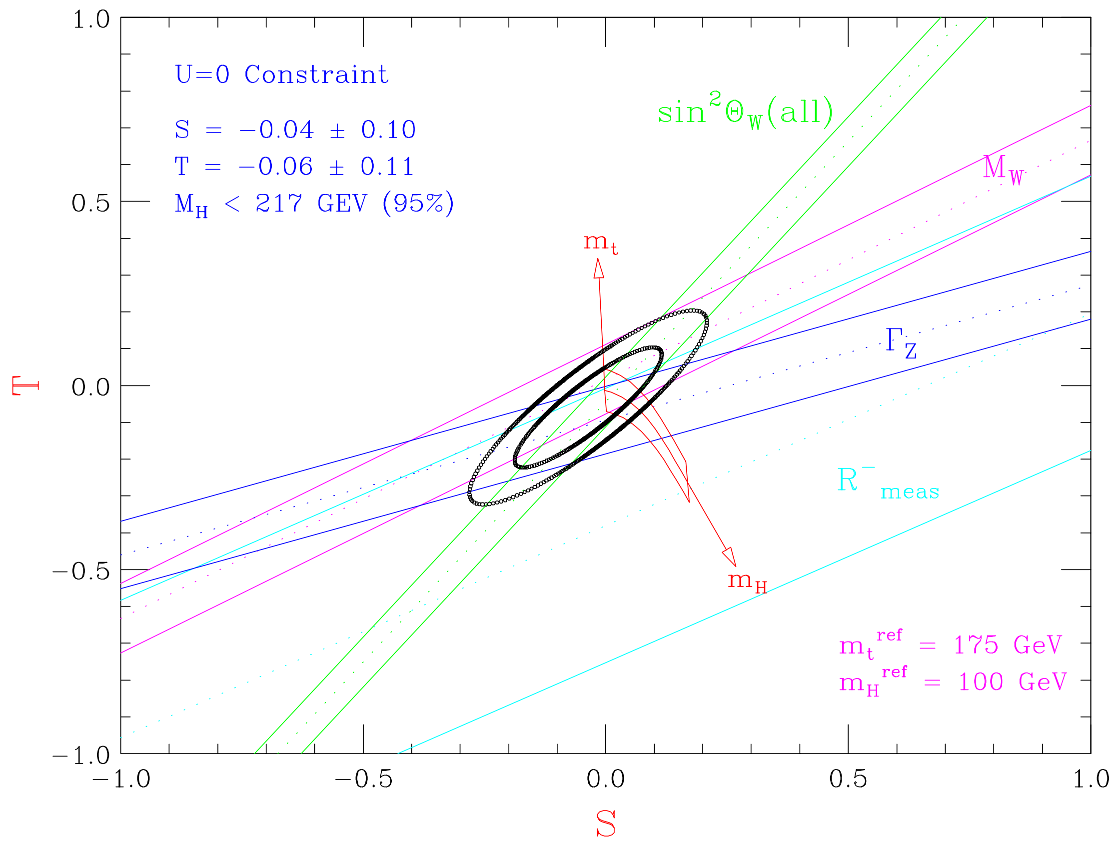
There is no (light) Higgs

- Compatible with data?
- Status of models?
- Implications for LC experiments?

Higgs mass dependence (SM): S/T/U parameters



[M. Swartz, LP99]



⇒ Fit with Higgs mass $M_H = 100$ GeV: $S, T \approx 0$

S/T/U

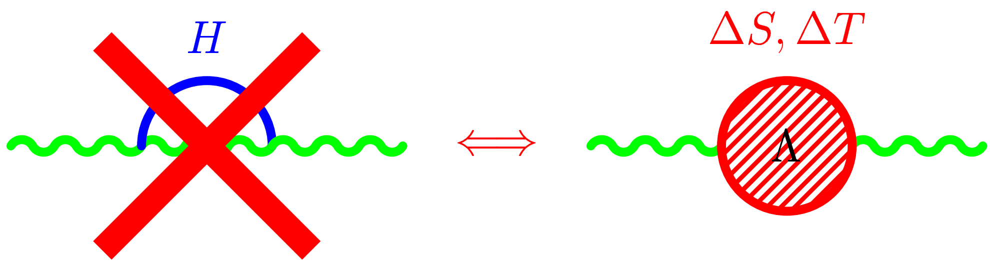
If there is no Higgs boson:
Theory (SM) predictions fail beyond $1 \ldots 3\ \mathrm{TeV}$

Fit with cutoff $\Lambda = 3\ \mathrm{TeV}$ [Bagger/Falk/Swartz 99]:

$$-0.37 < S < -0.17 \quad \text{and} \quad 0.34 < T < 0.58$$

$\Rightarrow$ S, T non-zero

But:
Unknown interactions beyond cutoff contribute to $S/T/U$



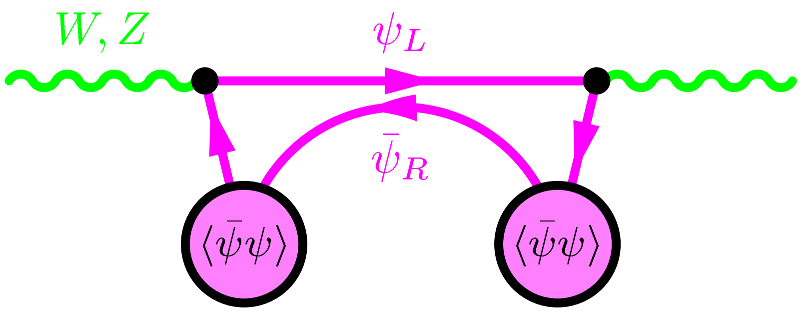
Estimate of shift in S, T: $(\Lambda = 3\ \mathrm{TeV})$

$$|\Delta S| \sim \frac{16\pi}{\sqrt{2}\, G_F\, \Lambda^2} \sim 0.3$$

$\Rightarrow$ Observed magnitude of S, T is natural without Higgs
$\Rightarrow$ TeV Physics may fake a "light-Higgs" signal

Higgs-less models of electroweak symmetry breaking:

- Without scalars, W and Z masses can be generated by a *fermion condensate*



- Need *new gauge interactions* and/or *new fermions*

Technicolor:

- Scaled-up QCD: new *techniquarks* and *technigluons*
- Additional *massive gauge bosons* responsible for fermion masses (ETC)
- Wrong sign of ΔS, quark masses/FCNC

Topcolor:

- Extended QCD: new *topgluons* generate $\bar{t}t$ *condensate*
- $m_{\text{top}} > 200$ GeV

Dynamical EWSB

Models of dynamical EWSB tend to be complicated:
they link electroweak with flavor physics

Walking technicolor:

- Interactions are strong over several orders of magnitude
- m_s, m_c; ΔS constraint avoided
- m_t still too large

Topcolor-assisted technicolor:

- $m_t = 175\ \mathrm{GeV}$ possible

See-saw topcolor:

- Top quark mixes with new heavy fermion(s)
- $m_t = 175\ \mathrm{GeV}$ possible, ΔS, ΔT acceptable

$\Rightarrow$ Dynamical EWSB compatible with low-energy data

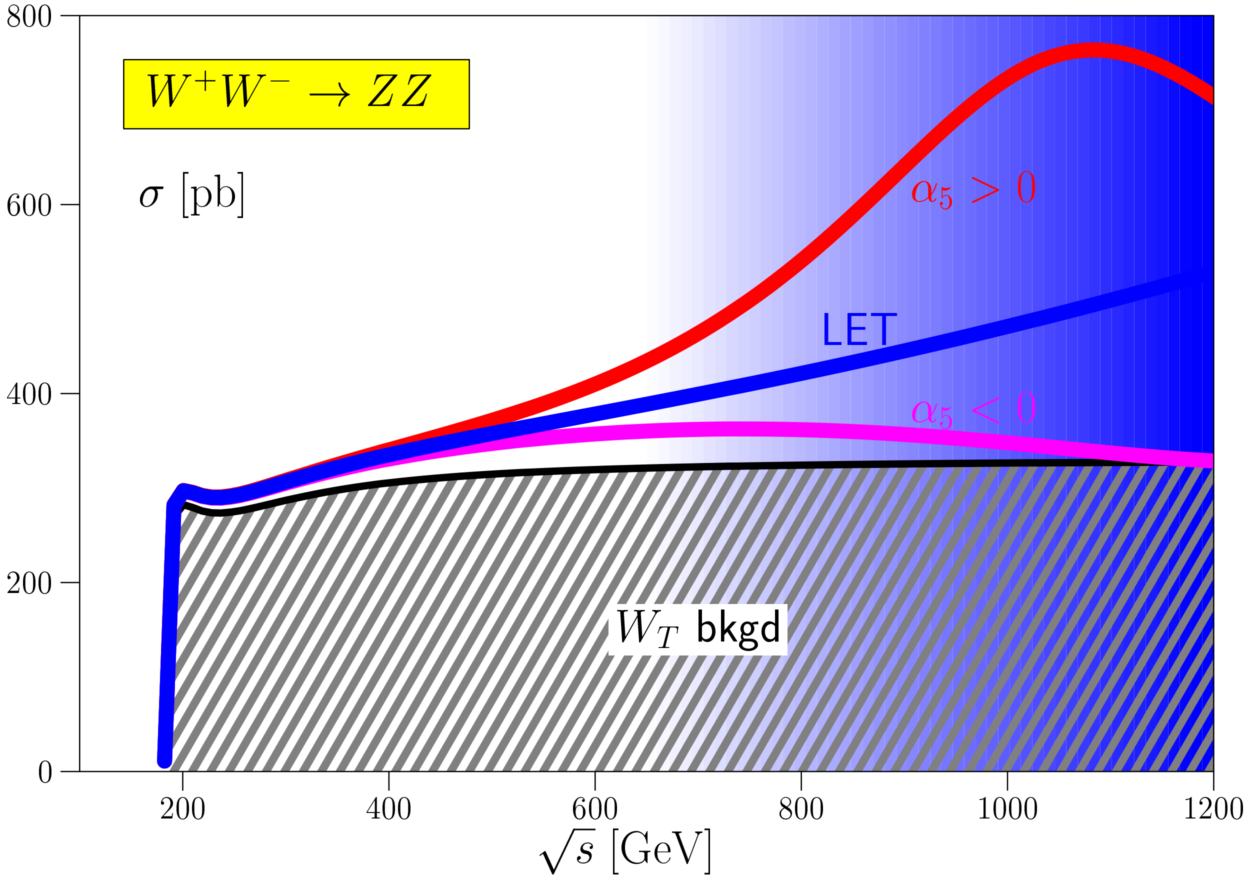
Effective theory

Below new-particle threshold Λ: Low-energy effective theory

$$\mathcal{L} = \underbrace{\mathcal{L}_{\mathsf{SM}}(\text{no Higgs})}_{\mathsf{LET}} + \underbrace{\sum \alpha_i \mathcal{O}_i}_{\mathsf{NLO:}\ s/\Lambda^2} + \ldots$$

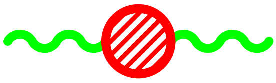
Information about high-energy structure is contained in α_i ("anomalous couplings")

Example:

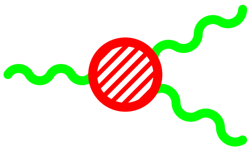


NLO couplings

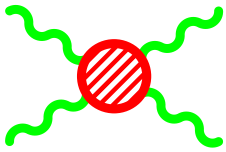
Expect observable effects in interactions of W, Z and t, b:



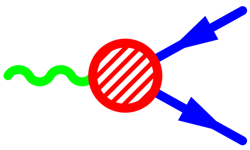
$\alpha_1, \beta_1, \alpha_8$ $\quad (S, T, U)$



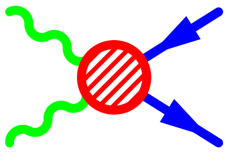
$\alpha_2, \alpha_3, \alpha_9, \alpha_{11}$ $\quad (g_1^Z, \kappa_\gamma, \kappa_Z, g_5^Z)$



$\alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_{10}$



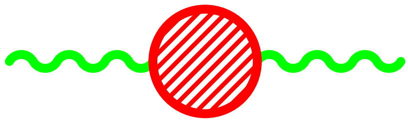
(4 parameters)



(19 parameters)

Size of anomalous couplings:

$$1 \gtrsim \alpha_i \gtrsim \frac{1}{16\pi^2} \quad \text{or} \quad 250 \text{ GeV} \lesssim \Lambda \lesssim 3 \text{ TeV}$$



Coefficients (from LEP1 etc.)

$$\alpha_1 = -\frac{1}{16\pi}\,\Delta S \qquad = 0.005 \pm 0.002$$

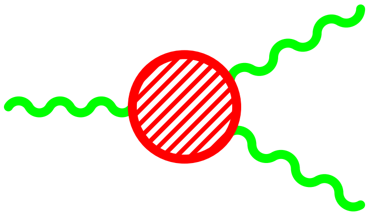
$$\beta_1 = \frac{\alpha_{\text{QED}}}{2}\,\Delta T \qquad = 0.0015 \pm 0.0005$$

This is of the order $1/16\pi^2 \Rightarrow \Lambda \approx 3\ \text{TeV}$ favored

LC: Accuracy can be improved by one order of magnitude $\rightarrow$ Giga$Z$

[Precisise calculation of $\Delta S, \Delta T$ difficult in strongly-interacting models . . .]

3-boson couplings



Coefficients (from LEP2 etc.)

$$|\alpha_2| = \frac{\sin^2\theta_W}{e^2}|\Delta\kappa_\gamma - \cos^2\theta_W\,\Delta g_1^Z| \qquad < 0.7$$

$$|\alpha_3| = \frac{\sin^2\theta_W\cos^2\theta_W}{e^2}|\Delta g_1^Z| \qquad < 0.2$$

This gives no significant constraints yet ...

LC: Expected limits $(500\ \mathrm{GeV}/500\ \mathrm{fb}^{-1})$ [C.Burgard, Sitges]

$$\Delta\kappa_\gamma < 0.0005 \quad \text{and} \quad \Delta g_1^Z < 0.0025 \quad (68\%)$$

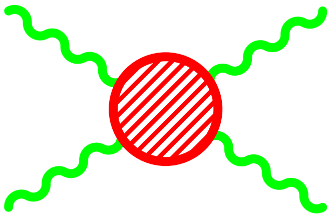
$\Rightarrow$ Strong-interaction region $\Lambda \approx 3\ \mathrm{TeV}$ can be tested

(Vector resonance would have strong effect)

LHC: Expected limits [LHC-WS 99]

$$\Delta\kappa_\gamma < 0.04 \quad \text{and} \quad \Delta g_1^Z < 0.008 \quad (95\%)$$

4-boson couplings



Interaction of longitudinal vector bosons
$\Rightarrow$ direct probe of the EWSB sector

Parameters: α_4, α_5 (and $\alpha_6, \alpha_7, \alpha_{10}$)

Low-energy data: *indirect constraints* only (naturalness assumption)

LC: Six-fermion final states

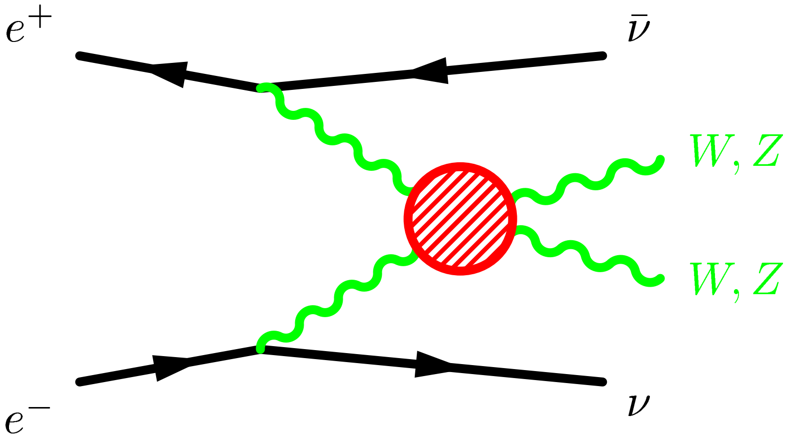
- Three-boson production

$$e^+e^- \to W^+W^-Z$$
$$e^+e^- \to ZZZ$$

- Vector boson scattering

$$e^+e^- \to \bar\nu\nu W^+W^-$$
$$e^+e^- \to \bar\nu\nu ZZ$$
$$e^-e^- \to \nu\nu W^-W^-$$

Detect/distinguish scalar, vector, tensor resonances



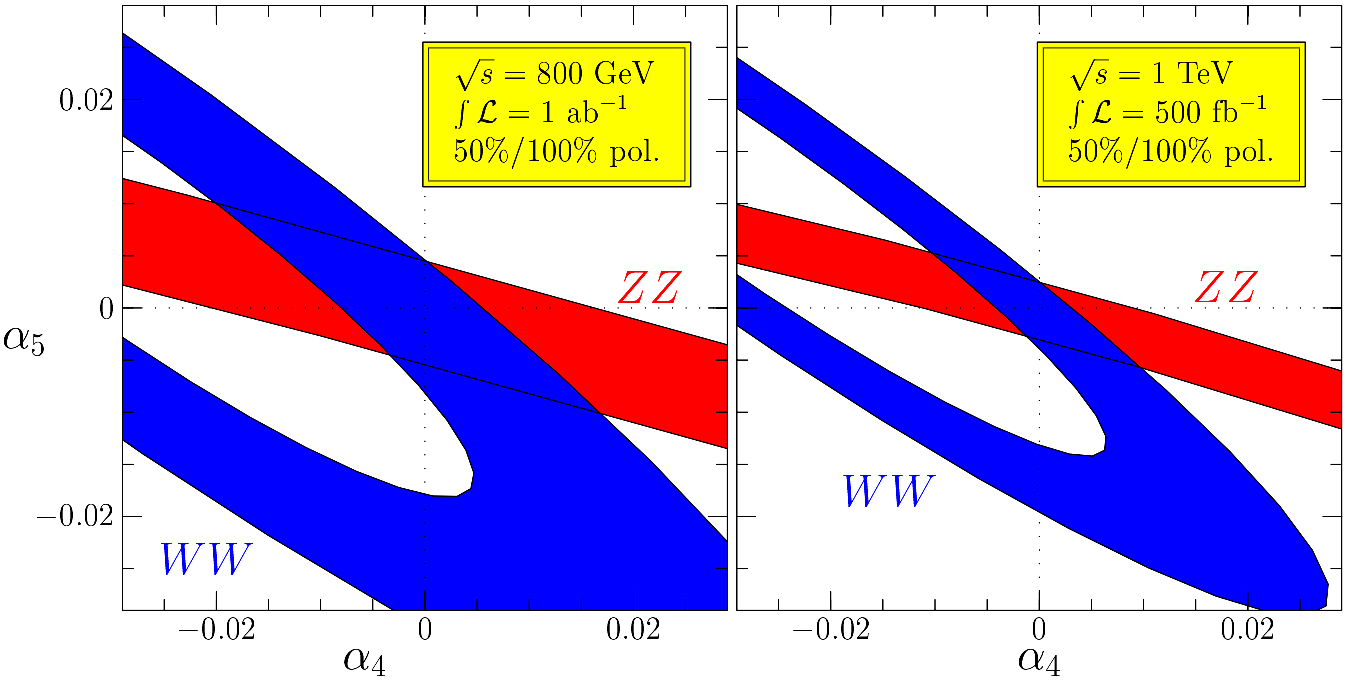
Signal:

- Large WW/ZZ invariant mass ($\alpha_{4/5}$ dependence)
- W/Z longitudinally polarized
- Central region
- Large missing invariant mass $M(\bar{\nu}\nu)$

Background:

- Small WW/ZZ invariant mass (LET)
- W/Z transversally polarized
- Forward region: t-channel exchange
- Small missing invariant mass: $WW + (Z \to \bar{\nu}\nu)$
- Electron(s) near the beampipe: $\gamma\gamma \to WW$
- WZ events: undetected electron

Sensitivity estimate from simulation of $e^+e^- \to \bar{\nu}\nu W^+W^-$ and ZZ (including backgrounds), two-parameter fit:



800 GeV,	$1000\ \text{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.015$	$\to \Lambda > 2$ TeV
1 TeV,	$500\ \text{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.009$	$\to \Lambda > 2.5$ TeV
LHC,	$100\ \text{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.025$	$\to \Lambda > 1.5$ TeV

LC at 500 GeV, $100\ \text{fb}^{-1}$: [S. Rosati → EW Session]

$$-0.43 < \alpha_4 < 0.43 \qquad -0.40 < \alpha_5 < 0.24 \quad (95\%)$$

WWZ/ZZZ: [Han/He/Yuan]

$$500\ \text{GeV}, \quad 50\ \text{fb}^{-1}: \quad |\Delta\alpha_5| < 0.2$$

WW scattering

For a more reliable sensitivity estimate, we need a detailed simulation of the 6-fermion final states (including hadronization, detector):

$$e^+e^- \to \bar{\nu}\nu + 4 \text{ jets}$$
$$e^+e^- \to e^{\pm}\nu + 4 \text{ jets}$$
$$e^+e^- \to e^+e^- + 4 \text{ jets}$$

To be done/updated:

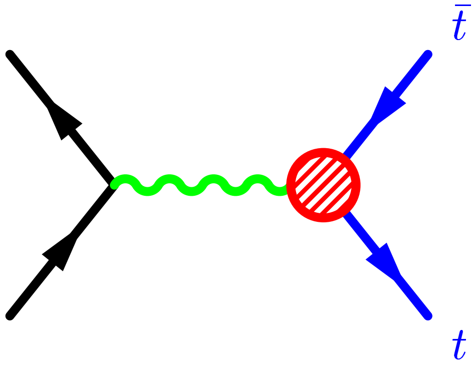
- WW and ZZ detection efficiency
- $WW/WZ/ZZ$ discrimination
- angular correlations $\Rightarrow$ projection on W_L, Z_L
- electron veto close to beampipe
- leptonic W decays

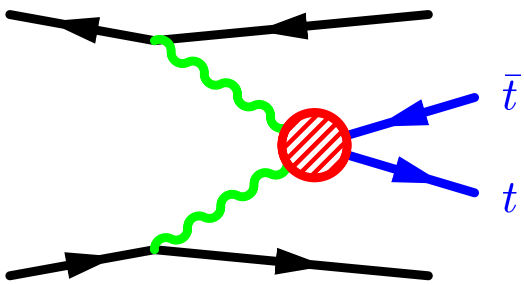
Polarization is important, but:

- $e^-(L)/e^+(R)$ enhances WW scattering signal
- $e^-(R)/e^+(L)$ enhances WWZ production signal

Dynamical symmetry breaking likely involves the top quark (topcolor, topcolor-assisted TC)

$\Rightarrow$ investigate top-quark interactions with W and Z:





for $M(\bar{t}t) \gg 2m_t$ (if possible)

Conclusions

- Models of dynamical symmetry breaking (no light Higgs) are compatible with electroweak precision data
- If scale of strong interactions is of the order $3\ \mathrm{TeV}$:
  $\Rightarrow$ can be probed only indirectly at the LC
- At lower energies: effective theory description
  $\Rightarrow$ finite set of "anomalous couplings"
- Anomalous couplings can be measured at the LC with accuracy comparable to or better than LHC
- Realistic simulation of WW scattering (and $WW \to \bar{t}t$, etc.) needed

Generic feature of dynamical EWSB: more global symmetries

$\Rightarrow$ Pseudo-Goldstone bosons may appear
($SU(2)$ multiplets: $H^{\pm}/A$; colored scalars, ...)

But: Most important test of dynamical EWSB:

Find or exclude a light Higgs!