Electroweak Precision Tests and Physics Beyond the Standard Model II

Topical Seminar on Frontier of Particle Physics 2006:

Beyond the Standard Model, Beijing

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Plan of this talk

§.0 Power of precision

§.1 Weinberg-Salam model at tree level

§.2 Decoupling theorem and its violation in EW physics

§.3 S-T fit

§.4 Higgs mass

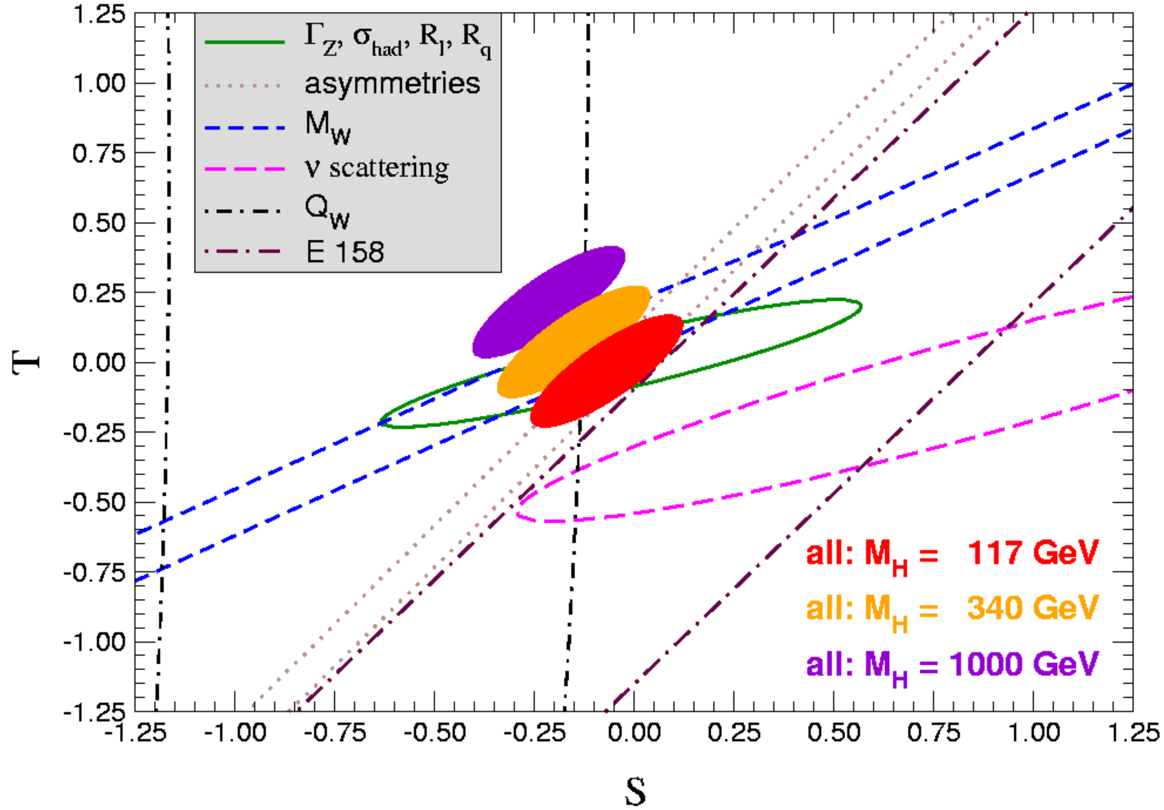
§.5 Estimate of S in technicolor models

§.6 Electroweak chiral perturbation theory

§.7 "Universal" non-oblique corrections

§.8 Summary

S-T plot of Erler-Langacker review in RPP2006



$$S = -0.13 \pm 0.10$$
$$T = -0.13 \pm 0.11$$
$$U = 0.20 \pm 0.12$$

for $M_H = 117\text{GeV}$

90%CL

Erler and Langacker, in RPP2006

$$S = -0.21 \pm 0.10$$
$$T = -0.04 \pm 0.11$$
$$U = 0.21 \pm 0.12$$

for $M_H = 300\text{GeV}$

§.5 Estimate of S in technicolor models

Dynamical chiral symmetry breaking in QCD

Chiral $SU(2)_L \times SU(2)_R$ symmetry in 2-flavor massless QCD:

$$q_L \to g_L q_L, \quad q_R \to g_R q_R \qquad g_{L,R} \in SU(2)_{L,R}, \qquad q_{L,R} \equiv \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}.$$

The $\bar{q}q$ condensate is caused by non-perturbative QCD dynamics and breaks the chiral symmetry into diagonal $SU(2)_V$:

$$\langle \bar{q}q \rangle \neq 0, \qquad SU(2)_L \times SU(2)_R \to SU(2)_V,$$

which looks similar to the EW symmetry breaking with custodial symmetry.

Technicolor models

Attempts applying this mechanism for the EW symmetry breaking.

The model

We consider $SU(N_{\rm TC})$ technicolor with one-doublet techni-fermion:

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \qquad U_R, \quad D_R,$$

weak hypercharge:

$$Y_{Q_L} = 0, \quad Y_{U_R} = \frac{1}{2}, \quad Y_{D_R} = -\frac{1}{2}.$$

The $SU(N_{\rm TC})$ gauge coupling is assumed to become strong and causes TeV scale condensate:

$$\langle \bar{U}U \rangle = \langle \bar{D}D \rangle \sim ({\rm TeV})^3 \neq 0.$$

Nambu-Goldstone bosons are eaten by $W^{\pm}$ and Z. The mass of techni-ρ ($J^{PC} = 1^{--}$) can be estimated as

$$M_{T\rho} = \sqrt{\frac{3}{N_{\rm TC}}} \frac{v}{f_\pi} m_\rho \simeq \sqrt{\frac{3}{N_{\rm TC}}} \times 2 \ {\rm TeV}.$$

Estimate of S

Definition:

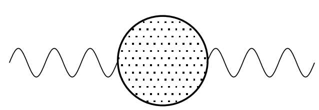
$$
\begin{aligned}
S &= 16\pi\left(\widetilde{\Pi}_{33}(0) - \widetilde{\Pi}_{3Q}(0)\right) = 16\pi\frac{d}{dk^2}\left(\Pi_{33}(k^2) - \Pi_{3Q}(k^2)\right)\Big|_{k^2=0} \\
&= -16\pi\frac{d}{dk^2}\Pi_{3Y}(k^2)\Big|_{k^2=0} = -16\pi\frac{d}{dk^2}\Pi_{L^3R^3}(k^2)\Big|_{k^2=0} \\
&= -4\pi\frac{d}{dk^2}\left(\Pi_{V^3V^3}(k^2) - \Pi_{A^3A^3}(k^2)\right)\Big|_{k^2=0},
\end{aligned}
$$

where

$$\Pi(k^2) = \Pi(0) + k^2\widetilde{\Pi}(k^2), \qquad \mathcal{Q} = I_3 + Y.$$

Challenge

How can we calculate

$\Pi(k^2) =$ 

reliably including *non-perturbative* technicolor correction?

Method working reasonably well in QCD hadron dynamics

Vector Meson Dominance (VMD)

$$\Pi^{\mu\nu}_{A^3 A^3}(k) = \left(g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2} \right) \Pi_{A^3 A^3}(k^2)$$

Nambu-Goldstone boson and the axial-vector ($J^{PC} = 1^{++}$) boson contribute to Π_{AA}:

$$\Pi_{A^3 A^3}(k^2) = v^2 + \frac{k^2}{M^2_{A1}} \frac{g^2_{A1}}{k^2 - M^2_{A1}}, \qquad v \simeq 246\text{GeV}.$$

The vector ($J^{PC} = 1^{--}$) boson contribution to Π_{VV}:

$$\Pi_{V^3 V^3}(k^2) = \frac{k^2}{M^2_{V1}} \frac{g^2_{V1}}{k^2 - M^2_{V1}}.$$

Weinberg Sum Rules

We know

$$\Pi_{V^3V^3}(k^2) - \Pi_{A^3A^3}(k^2) = 4\Pi_{L^3R^3}(k^2) \propto \frac{(\langle\bar{Q}Q\rangle)^2}{k^4},$$

which implies

$$v^2 + \frac{g_{A1}^2}{M_{A1}^2} = \frac{g_{V1}^2}{M_{V1}^2}, \qquad g_{A1}^2 = g_{V1}^2,$$

$$\Pi_{V^3V^3}(k^2) - \Pi_{A^3A^3}(k^2) = -\frac{v^2 M_{V1}^2 M_{A1}^2}{[M_{V1}^2 - k^2][M_{A1}^2 - k^2]},$$

under the VMD assumption.

$$S \simeq 4\pi \left(\frac{v^2}{M_{V1}^2} + \frac{v^2}{M_{A1}^2} \right) \simeq \frac{N_{\rm TC}}{3} \times 0.25.$$

We include chiral logarithm correction so as to make the prediction more precise:

$$S \simeq 4\pi \left(\frac{v^2}{M_{V1}^2} + \frac{v^2}{M_{A1}^2} \right) - \frac{1}{6\pi} \ln \frac{M_{H,\mathrm{ref}}}{M_{V1}}.$$

For $N_{\mathrm{TC}} = 3$, $M_{H,\mathrm{ref}} = 300\mathrm{GeV}$, we find

$$S \simeq 0.35,$$

which is ruled out by the present limit in the S-T plane.

Note:

- The VMD estimate $S \simeq 0.25$ is significantly larger than the one-loop free fermion estimate $S = 3/(6\pi) \simeq 0.16$. Non-perturbative technicolor correction is important.
- We don't have reliable way to estimate S in walking TC models. Naive conjecture: somewhere between 0.25 and 0.16?

Harada-Kurachi-Yamawaki
Kurachi-Shrock

§.6 Electroweak chiral perturbation theory

Catalogue of *non-decoupling* corrections

Use of the gauged non-linear σ model

T. Appelquist and C. Bernard, PRD22 (1980) 200.

Taking the $M_H \to \infty$ limit, the original linear σ model Higgs field Φ is replaced by the non-linear σ model field U:

$$\Phi = \sqrt{2} \begin{pmatrix} \varphi_0^* & \varphi_+ \\ -\varphi_+^* & \varphi_0 \end{pmatrix} \to vU = v \exp\left(\frac{i\tau^a w^a}{v} \right),$$

with w^a being the NG bosons eaten by $W^\pm$, Z.

In this limit, the original Higgs Lagrangian is replaced by

$$\mathcal{L}_0 = \frac{1}{4} v^2 \mathrm{tr}[(D_\mu U)^\dagger (D^\mu U)] - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu},$$

where

$$D_\mu U = \partial_\mu U + i g_W \frac{\tau_a}{2} W^a_\mu U - i g_Y U \frac{\tau_3}{2} B_\mu .$$

Idea of Appelquist-Bernard paper

We can catalogue all possible non-decouplings effects as coefficients of operators upto dimension 4.

A. Longhitano, PRD22 (1980) 1166 ; NPB188 (1981) 118.
T. Appelquist and G.-H. Wu, PRD48 (1993) 3235.

List of CP even dimension 4 operators.

$$\mathcal{L}_1 \equiv \frac{1}{2}\alpha_1 g_W g_Y B_{\mu\nu}\mathrm{tr}(TW^{\mu\nu}),$$
$$\mathcal{L}_2 \equiv i\alpha_2 g_Y B_{\mu\nu}\mathrm{tr}(T[V^\mu, V^\nu]),$$
$$\mathcal{L}_3 \equiv i\alpha_3 g_W \mathrm{tr}(W_{\mu\nu}[V^\mu, V^\nu]),$$
$$\mathcal{L}_4 \equiv \alpha_4[\mathrm{tr}(V_\mu V_\nu)]^2,$$
$$\mathcal{L}_5 \equiv \alpha_5[\mathrm{tr}(V_\mu V^\mu)]^2,$$
$$\mathcal{L}_6 \equiv \alpha_6\mathrm{tr}(V_\mu V_\nu)\mathrm{tr}(TV^\mu)\mathrm{tr}(TV^\nu),$$
$$\mathcal{L}_7 \equiv \alpha_7\mathrm{tr}(V_\mu V^\mu)\mathrm{tr}(TV_\nu)\mathrm{tr}(TV^\nu),$$
$$\mathcal{L}_8 \equiv \frac{1}{4}\alpha_8 g_W^2[\mathrm{tr}(TW_{\mu\nu})]^2,$$
$$\mathcal{L}_9 \equiv \frac{1}{2}i\alpha_9 g_W \mathrm{tr}(TW_{\mu\nu})\mathrm{tr}(T[V^\mu, V^\nu]),$$
$$\mathcal{L}_{10} \equiv \frac{1}{2}\alpha_{10}[\mathrm{tr}(TV_\mu)\mathrm{tr}(TV_\nu)]^2,$$
$$\mathcal{L}_{11} \equiv \alpha_{11} g \epsilon^{\mu\nu\rho\lambda}\mathrm{tr}(TV_\mu)\mathrm{tr}(V_\nu W_{\rho\lambda}).$$

where

$$T \equiv U\tau_3 U^\dagger, \quad V_\mu \equiv (D_\mu U)U^\dagger, \qquad \dim(\alpha_i) = 0.$$

One additional dimension 2 operator

$$\mathcal{L}'_1 \equiv \frac{1}{4}\beta_1 v^2 \left[\mathrm{tr}(TV_\mu)\right]^2 ,$$

which violates custodial $SU(2)_C$ symmetry even in the $g_Y = 0$ limit.

	β_1	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}
$SU(2)_C$	×	○	○	○	○	○	×	×	×	×	×	×
#(gauge)	2	2	3	3	4	4	4	4	2	3	4	3

- From custodial symmetry, it is expected

$$\alpha_{1,2,3,4,5} \gg \alpha_{6,7,8,9,10,11} .$$

- β_1, α_1 and α_8 contribute to the electroweak oblique correction:

$$S = -16\pi\alpha_1, \qquad \alpha T = 2\beta_1, \qquad U = -16\pi\alpha_8 .$$

They are constrained severely from the electroweak precision tests.

- α_2, α_3, α_9 and α_{11} contribute to the triple-gauge-vertices:

$$
\begin{aligned}
\mathcal{L}_{\rm TGV} \quad = \quad & -ie\frac{c_{M_Z}}{s_{M_Z}}[1+\Delta\kappa_Z]W^+_\mu W^-_\nu Z^{\mu\nu} \\
& -ie[1+\Delta\kappa_\gamma]W^+_\mu W^-_\nu A^{\mu\nu} \\
& -ie\frac{c_{M_Z}}{s_{M_Z}}[1+\Delta g_1^Z](W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)Z_\nu \\
& -ie(W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)A_\nu \\
& -e\frac{c_{M_Z}}{s_{M_Z}}g_5^Z\epsilon^{\mu\nu\rho\lambda}[W^+_\mu(\partial_\rho W^-_\nu) - (\partial_\rho W^+_\mu)W^-_\nu]Z_\lambda
\end{aligned}
$$

Hagiwara-Peccei-Zeppenfeld-Hikasa, NPB282 (1987) 253.

$$
\begin{aligned}
\Delta g_1^Z &= \frac{1}{c^2 - s^2}\beta_1 + \frac{1}{c^2(c^2 - s^2)}e^2\alpha_1 + \frac{1}{s^2c^2}e^2\alpha_3 \\
\Delta\kappa_Z &= \frac{1}{c^2 - s^2}\beta_1 + \frac{1}{c^2(c^2 - s^2)}e^2\alpha_1 + \frac{1}{c^2}e^2(\alpha_1 - \alpha_2) + \frac{1}{s^2}e^2(\alpha_3 - \alpha_8 + \alpha_9), \\
\Delta\kappa_\gamma &= \frac{1}{s^2}e^2(-\alpha_1 + \alpha_2 + \alpha_3 - \alpha_8 + \alpha_9), \\
g_5^Z &= \frac{1}{s^2c^2}e^2\alpha_{11}
\end{aligned}
$$

If custodial symmetry violating term α_9 is negligible,

$$\Delta\kappa_Z = \Delta g_1^Z - \frac{s^2}{c^2}\Delta\kappa_\gamma.$$

Present experimental limits

$$\Delta g_1^Z = -0.016 + 0.022 - 0.019, \qquad \Delta\kappa_\gamma = -0.027 + 0.044 - 0.045,$$

lead to bounds on $\alpha_{2,3}$ at 10^{-2} level.

- $\alpha_{4,5,6,7,10}$ contribute to $WW \to WW$ process. Future colliders may be sensitive to these parameters:

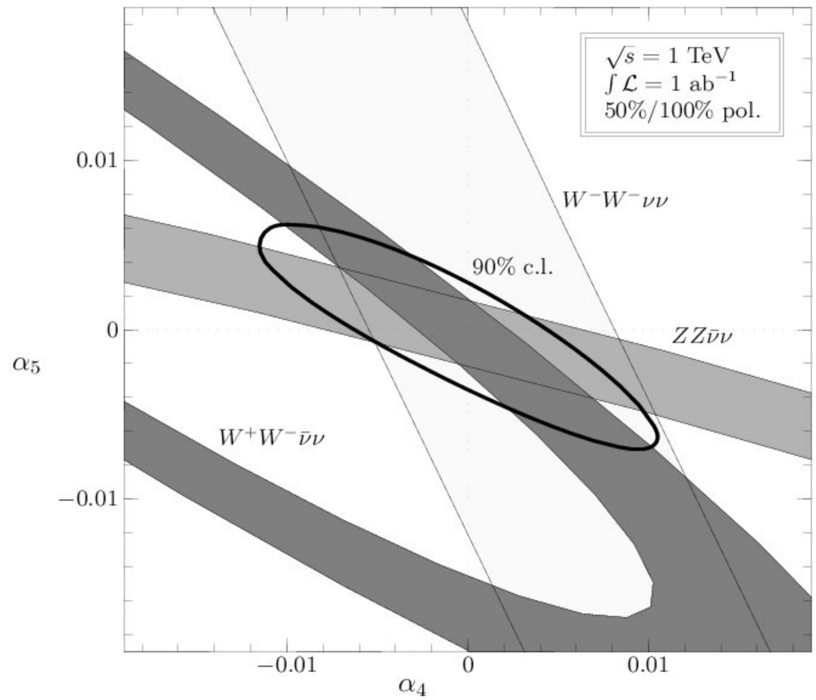


Figure 1: *Exclusion contours for the hypothesis $\alpha_{4,5} = 0$, assuming $\sqrt{s} = 1$ TeV and an integrated e^+e^- luminosity of $\int \mathcal{L} = 1$ ab^{-1} (50%/100% polarization). The 90% exclusion line has been obtained by combining the W^+W^- and ZZ channels (dark gray). The contour for the W^-W^- channel (light gray) corresponds to an integrated e^-e^- luminosity of $\int \mathcal{L} = 100$ fb^{-1} (100% polarization).*

E. Boos, H.-J. He et al., PRD61 (2000) 077901.

Effects of heavy fermion loop

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \qquad U_R, \quad D_R$$

Heavy U and D $\Rightarrow$ Large Yukawa coupling

violation of decoupling theorem

From S and U

$$\begin{aligned} \alpha_1 &= -\frac{N}{96\pi^2}\left[1 - 2Y_{Q_L}\ln\frac{m_U^2}{m_D^2}\right], \\ \alpha_8 &= -\frac{N}{96\pi^2}\left[-\frac{5m_U^4 - 22m_U^2 m_D^2 + 5m_D^4}{3(m_U^2 - m_D^2)^2}\right. \\ &\qquad \left. + \frac{m_U^6 - 3m_U^4 m_D^2 - 3m_U^2 m_D^4 + m_D^4}{(m_U^2 - m_D^2)^3}\ln\frac{m_U^2}{m_D^2}\right]. \end{aligned}$$

From the TGV analysis,

$$\alpha_2 = -\frac{N}{96\pi^2}\left[1 - Y_{Q_L}\left((2+\frac{6m_U^2 m_D^2}{(m_U^2-m_D^2)^2})\ln\frac{m_U^2}{m_D^2} - 3\frac{m_U^2+m_D^2}{m_U^2-m_D^2}\right)\right],$$

$$\alpha_3 = -\frac{N}{64\pi^2}\left[\frac{m_U^2 m_D^2(m_U^2+m_D^2)}{(m_U^2-m_D^2)^3}\ln\frac{m_U^2}{m_D^2} + \frac{m_U^4-6m_U^2m_D^2+m_D^4}{2(m_U^2-m_D^2)^2}\right],$$

$$\alpha_9 = -\frac{N}{64\pi^2}\left[\frac{m_U^2 m_D^2(m_U^2+m_D^2)}{(m_U^2-m_D^2)^3}\ln\frac{m_U^2}{m_D^2} - \frac{m_U^4+10m_U^2m_D^2+m_D^4}{6(m_U^2-m_D^2)^2}\right] + \alpha_8,$$

$$\alpha_{11} = -\frac{N}{64\pi^2}\left[\frac{m_U^2 m_D^2}{(m_U^2-m_D^2)^2}\ln\frac{m_U^2}{m_D^2} - \frac{m_U^2+m_D^2}{2(m_U^2-m_D^2)}\right]$$

T. Appelquist and G.-H. Wu, PRD48 (1993) 3235.

If U and D are almost degenerated,

$$|\Delta m| \ll \hat{m}, \qquad \Delta m \equiv m_U - m_D, \qquad \hat{m} \equiv \frac{m_U + m_D}{2}$$

we find

$$\beta_1 \simeq \frac{N}{24\pi^2} \frac{(\Delta m)^2}{v^2}$$

$$\alpha_1 \simeq -\frac{N}{96\pi^2}, \quad \alpha_2 \simeq -\frac{N}{96\pi^2}, \quad \alpha_3 \simeq -\frac{N}{96\pi^2}\left[1 - \frac{(\Delta m)^2}{10\hat{m}^2}\right],$$

$$\alpha_8 \simeq -\frac{N}{96\pi^2}\frac{4(\Delta m)^2}{5\hat{m}^2}, \quad \alpha_9 \simeq -\frac{N}{96\pi^2}\frac{7(\Delta m)^2}{10\hat{m}^2}, \quad \alpha_{11} \simeq \frac{N}{96\pi^2}\frac{\Delta m}{2\hat{m}}$$

Note:

- Custodial $SU(2)_C$ symmetry in $\Delta m = 0$ limit.
- The sizes of $\alpha_{6,7,8,9,10,11}$ are extremely suppressed for $(\Delta m)^2 \ll \hat{m}^2$.
- Degenerated heavy 4th generation: $\alpha_1 = \alpha_2 = \alpha_3 \simeq 4.2 \times 10^{-3}$.

Renormalization Group

T. Appelquist and C. Bernard, PRD22 (1980) 200.

Even if we start with $\beta_1 = \alpha_i = 0$, the loop diagram of the lowest order Lagrangian $\mathcal{L}_0$ causes non-trivial running of β_1 and α_i:

$$\mu \frac{d}{d\mu} \beta_1^r(\mu) = \frac{\gamma_{\beta 1}}{(4\pi)^2}, \qquad \mu \frac{d}{d\mu} \alpha_i^r(\mu) = \frac{\gamma_{\alpha i}}{(4\pi)^2}.$$

$\gamma_{\beta 1}$	$\gamma_{\alpha 1}$	$\gamma_{\alpha 2}$	$\gamma_{\alpha 3}$	$\gamma_{\alpha 4}$	$\gamma_{\alpha 5}$
$\frac{3}{4} g_Y^2$	$\frac{1}{6}$	$\frac{1}{12}$	$\frac{1}{12}$	$-\frac{1}{6}$	$-\frac{1}{12}$

Tree level matching conditions with the Standard Model Higgs sector

$$\beta_1^r(\mu \simeq M_H) = 0, \qquad \alpha_1^r(\mu \simeq M_H) = 0$$

lead to

$$\beta^r(\mu) = -\frac{3g_Y^2}{4(4\pi)^2} \ln \frac{M_H}{\mu}, \qquad \alpha_1^r(\mu) = -\frac{1}{6(4\pi)^2} \ln \frac{M_H}{\mu},$$

$$T \simeq \frac{8\pi}{e^2} \beta_1^r(\mu) \simeq -\frac{3}{8\pi c^2} \ln M_H, \qquad S \simeq -16\pi \alpha_1^r(\mu) \simeq \frac{1}{6\pi} \ln M_H.$$

Alternative parametrization:
(motivated by the hadron chiral perturbation theory)

Gasser and Leutwyler

$$\begin{aligned}\mathcal{L}_{\rm GL} &= L_1 {\rm tr}(D_\mu U^\dagger D^\mu U){\rm tr}(D_\nu U^\dagger D^\nu U) + L_2 {\rm tr}(D_\mu U^\dagger D_\nu U){\rm tr}(D^\mu U^\dagger D^\nu U) \\ &\quad + i g_W L_{9L} {\rm tr}(D_\mu U D_\nu U^\dagger W^{\mu\nu}) + i g_Y L_{9R} {\rm tr}(D_\mu U^\dagger D_\nu U \frac{\tau_3}{2} B^{\mu\nu}) \\ &\quad + g_W g_Y L_{10} {\rm tr}(W^{\mu\nu} U \frac{\tau_3}{2} B_{\mu\nu} U^\dagger),\end{aligned}$$

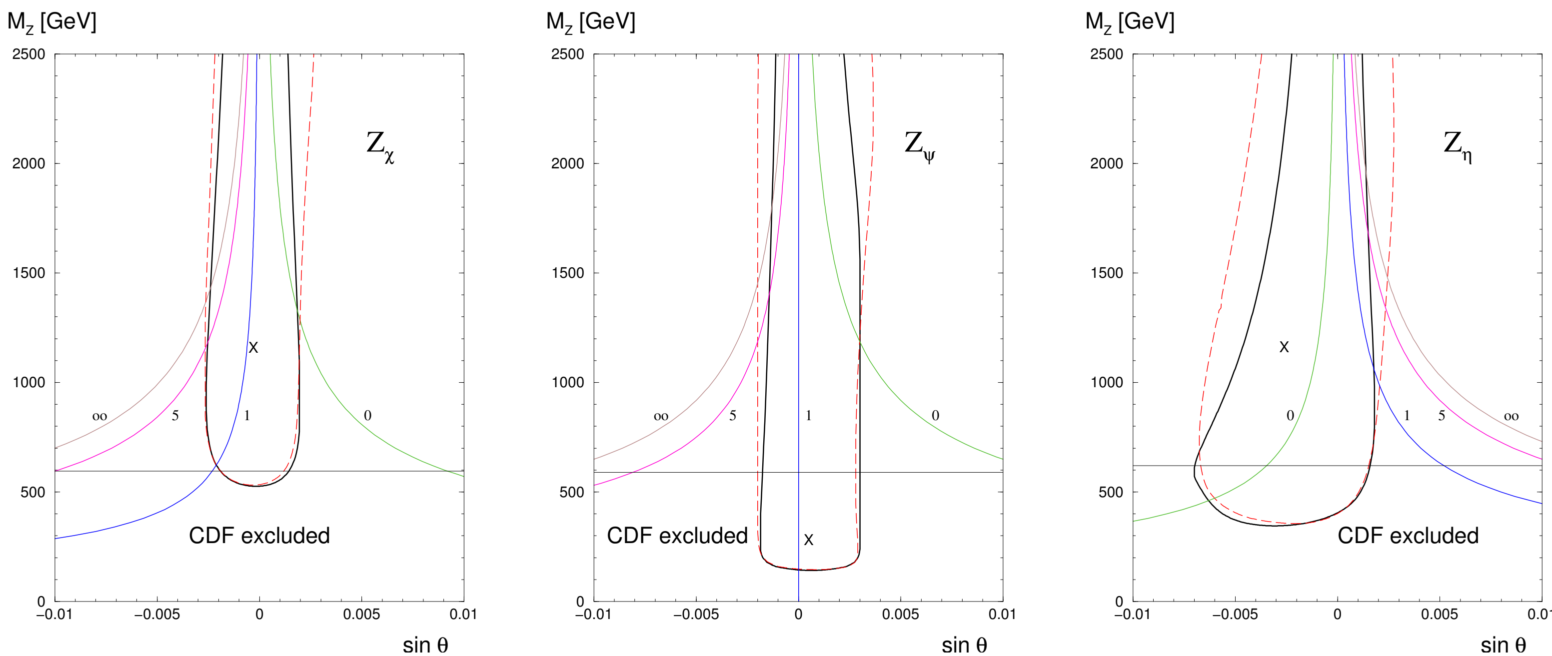
$$\begin{aligned}\alpha_1 &= L_{10}, \\ \alpha_2 &= -L_{9R}/2, \\ \alpha_3 &= -L_{9L}/2, \\ \alpha_4 &= L_2, \\ \alpha_5 &= L_1.\end{aligned}$$

§.7 "Universal" non-oblique corrections

R. Barbieri, A. Pomarol, R. Rattazzi, and A. Strumia, NPB703 (2004) 127.
R.S.Chivukula, E.H.Simmons, H.-J. He, M. Kurachi, and M.T., PLB603 (2004) 210.

Effects of heavy Z' cannot be fully parametrized in the S,T and U framework.

For E_6 models, dedicated study is required:



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Erler-Langacker, PLB456 (1999) 68.

Z' and W' couple with ordinary quarks/leptons only through $J_W^{a\mu}$, J_Y^{μ} in little-Higgs or Higgsless models. ("universal" models)

Fermion scattering amplitude in "universal" models: $(S, T, \alpha\delta, \Delta\rho)$

- Charged current process

$$-\mathcal{M}_{\rm CC} = \frac{(I_+ I'_- + I_- I'_+)/2}{-\left(\frac{s^2}{e^2} - \frac{S}{16\pi}\right)k^2 + \frac{1}{4\sqrt{2}G_F}\left(1 + \frac{\alpha\delta}{4s^2c^2}\right)} + \sqrt{2}G_F \frac{\alpha\delta}{s^2c^2}\frac{(I_+ I'_- + I_- I'_+)}{2}.$$

- Neutral current process

$$-\mathcal{M}_{\rm NC} = e^2 \frac{\mathcal{Q}\mathcal{Q}'}{-k^2} + \frac{(I_3 - s^2\mathcal{Q})(I'_3 - s^2\mathcal{Q}')}{-\left(\frac{s^2c^2}{e^2} - \frac{S}{16\pi}\right)k^2 + \frac{1}{4\sqrt{2}G_F}\left(1 - \alpha T + \frac{\alpha\delta}{4s^2c^2}\right)} + \sqrt{2}G_F \frac{\alpha\delta}{s^2c^2} I_3 I'_3 + 4\sqrt{2}G_F(\Delta\rho - \alpha T)(\mathcal{Q} - I_3)(\mathcal{Q}' - I'_3).$$

R.S.Chivukula, E.H.Simmons, H.-J. He, M. Kurachi, and M.T., PLB603 (2004) 210.

Note:

- In the absence of W' and Z' induced four-fermion couplings, S and T agree with the Peskin-Takeuchi definitions of S and T.

- $\Delta\rho$ agrees with the original ρ parameter definition:

$$\rho = 1 + \Delta\rho = \frac{G_{\rm NC}}{G_{\rm CC}},$$

  which has been measured through the low energy NC experiments.

- In the absence of $\alpha\delta$, even if $\Delta\rho \neq \alpha T$, limits on S-T is identical to the exisiting S-T limit derived from the Z-pole precision data.

An example of "universal" model

$$SU(2)_W \times U(1)_{Y1} \times U(1)_{Y2}$$

Mass matrix of neutral gauge boson

$$\frac{1}{4}(W^3_\mu \; B_{1\mu} \; B_{2\mu}) \begin{pmatrix} g_W^2 v^2 & -g_W g_{Y1} v^2 & 0 \\ -g_W g_{Y1} v^2 & g_{Y1}^2 (v^2 + v_B^2) & -g_{Y1} g_{Y2} v_B^2 \\ 0 & -g_{Y1} g_{Y2} v_B^2 & g_{Y2}^2 v_B^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B_1^\mu \\ B_2^\mu \end{pmatrix}$$

Interaction with quarks and leptons:

$$\mathcal{L}_{\text{int}} = g_W J_W^{a\mu} W_\mu^a + g_{Y1} J_Y^\mu B_{1\mu}.$$

For $g_W, g_{Y1} \ll g_{Y2}$, we find

$$\alpha S = -4 s^2 c^2 \frac{M_W^2}{M_{Z'}^2} \frac{g_{Y1}^2}{g_{Y2}^2}, \quad \alpha T = -s^2 \frac{M_W^2}{M_{Z'}^2} \frac{g_{Y1}^2}{g_{Y2}^2}, \quad \alpha\delta = 0, \quad \Delta\rho = 0.$$

Negative S ! Negative T !

Technicolor plus $SU(2)_W \times U(1)_{Y1} \times U(1)_{Y2}$

- Technicolor large positive S may be canceled by the negative S from Z'.
- Negative T from extra Z' may be canceled by custodial symmetry breaking in the TC sector.

Sounds very nice!

This model predicts

$$\Delta\rho - \alpha T \sim 0.3 \times 10^{-2}.$$

Alternative parametrization

R. Barbieri, A. Pomarol, R. Rattazzi, and A. Strumia, NPB703 (2004) 127.

Dimension 6 operators

$$\mathcal{L} = c_{WB}\mathcal{O}_{WB} + c_H\mathcal{O}_H + c_{WW}\mathcal{O}_{WW} + c_{BB}\mathcal{O}_{BB},$$

with

$$\mathcal{O}_{WB} = \frac{1}{g_W g_Y}(\phi^\dagger \tau^a \phi) W^a_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_H = |\phi^\dagger D_\mu \phi|^2,$$

$$\mathcal{O}_{WW} = \frac{1}{2g_W^2}(D_\rho W^a_{\mu\nu})^2, \qquad \mathcal{O}_{BB} = \frac{1}{2g_Y^2}(\partial_\rho B_{\mu\nu})^2.$$

$$\hat{S} = \frac{c}{s} v^2 c_{WB}, \quad \hat{T} = -\frac{v^2}{2} c_H, \quad W = -\frac{g_W^2 v^2}{2} c_{WW}, \quad Y = -\frac{g_Y^2 v^2}{2} c_{BB}.$$

Dictionary between $(S, T, \alpha\delta, \Delta\rho)$ and $(\hat{S}, \hat{T}, W, Y)$

$$\begin{aligned}
\alpha S &= 4s^2(\hat{S} - Y - W), \\
\alpha T &= \hat{T} - \frac{s^2}{c^2}Y, \\
\alpha\delta &= 4s^2c^2W, \\
\Delta\rho &= \hat{T}.
\end{aligned}$$

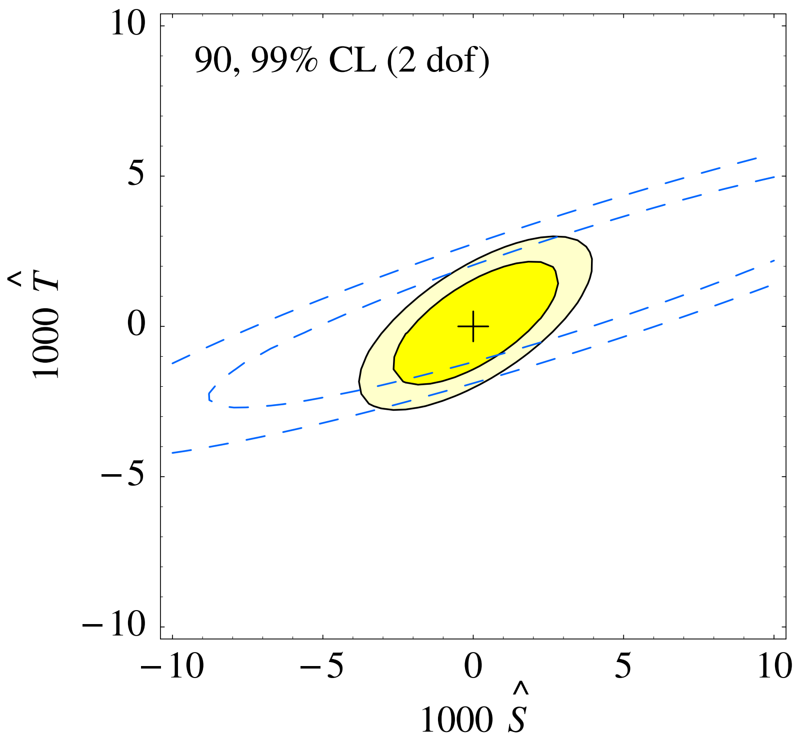
$$\begin{aligned}
\hat{S} &= \frac{1}{4s^2}\left(\alpha S + 4c^2(\Delta\rho - \alpha T) + \frac{\alpha\delta}{c^2}\right), \\
\hat{T} &= \Delta\rho, \\
W &= \frac{\alpha\delta}{4s^2c^2}, \\
Y &= \frac{c^2}{s^2}(\Delta\rho - \alpha T).
\end{aligned}$$

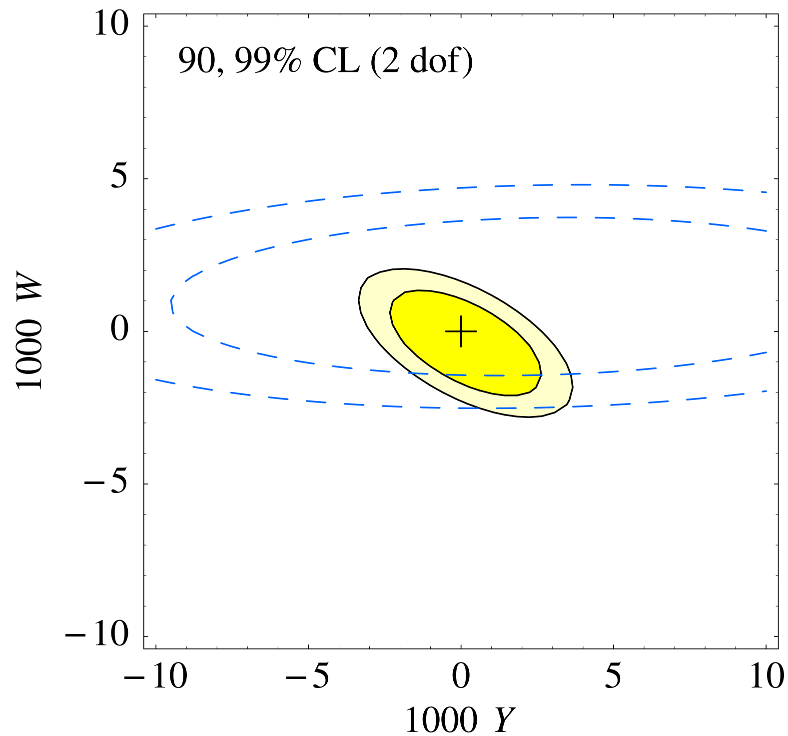
- In the absence of "universal" non-oblique corrections, $W = Y = 0$ and

$$\alpha S = 4s^2\hat{S}, \qquad \alpha T = \hat{T}.$$

- Technicolor plus $SU(2)_W \times U(1)_{Y1} \times U(1)_{Y2}$ model predicts $\hat{S} \simeq 0$, $\hat{T} \simeq 0$, $W \simeq 0$, but $Y \simeq 10^{-2}$.

$(\hat{S}, \hat{T}, W, Y)$-fit with and without LEP2 data of $\sigma(e^+e^- \to f\bar{f})$





$(\hat{S}, \hat{T})$ for generic (W, Y)

(W, Y) for generic $(\hat{S}, \hat{T})$

Barbieri et al. hep-ph/0405042

§.8 Summary

- New physics scenarios which affect EW physics through *non-decoupling* radiative corrections are severely constrained by the precision data:
  - Heavy 4th generation
  - Technicolor models
- The precision data suggest that, in the standard model framework, Higgs should be light $M_H \leq 199\text{GeV}$. Heavier Higgs thus indicates BSM.
- Electroweak chiral perturbation theory provides a powerful tool to catalogue all possible *non-decoupling* corrections:
  S-T-U, TGV, $WW \to WW$
- In the "universal" models (little-Higgs, Higgsless, etc.), S-T fit is not enough. We can do better by using $(S, T, \alpha\delta, \Delta\rho)$ or $(\hat{S}, \hat{T}, W, Y)$.
  $\Rightarrow$ Prof. Chivukula's lecture for Higgsless models.

謝謝！

Thank you very much !