Electroweak Symmetry Breaking and Triple Gauge Coupling Measurements

NCTS, Theory Division

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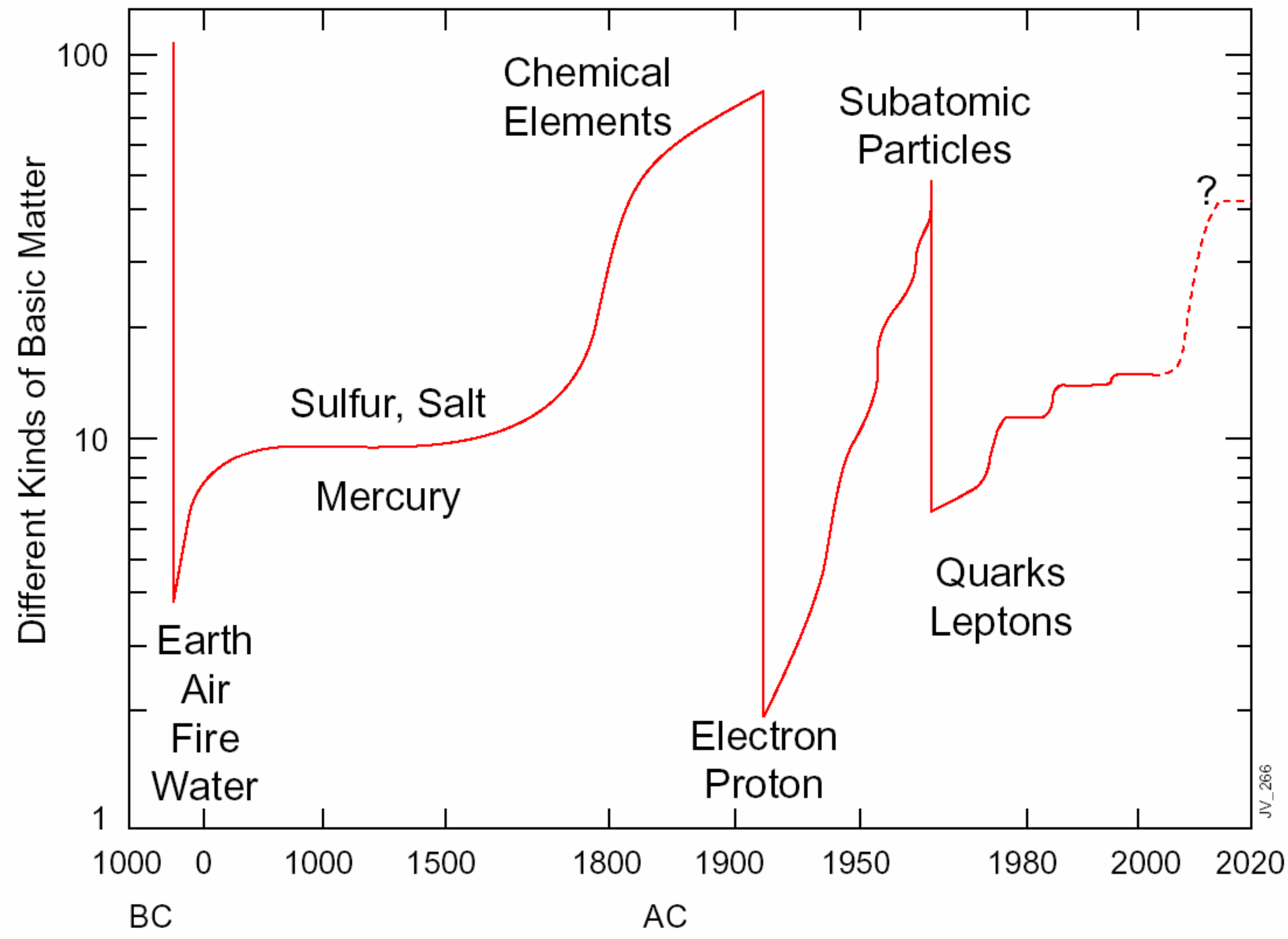
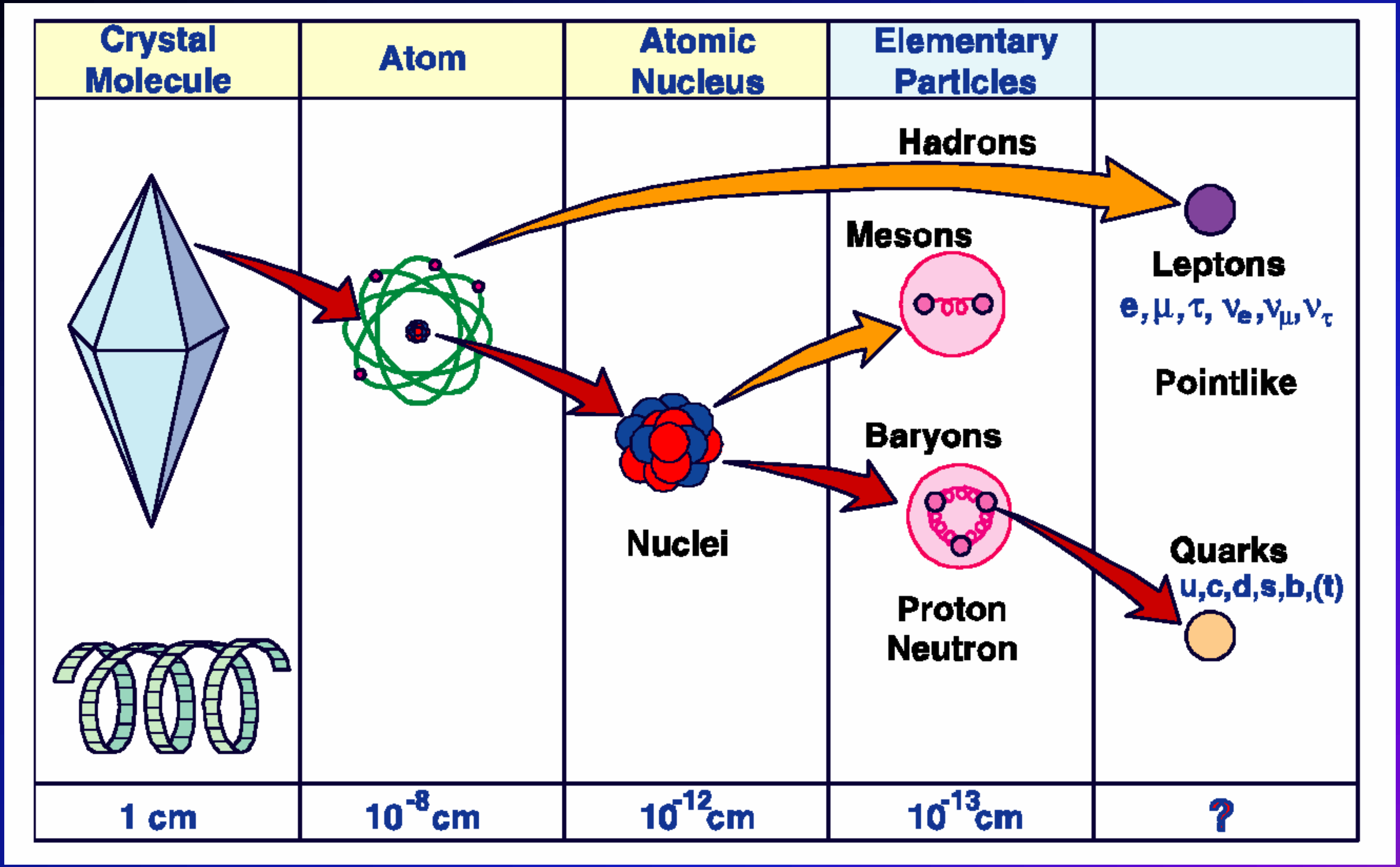
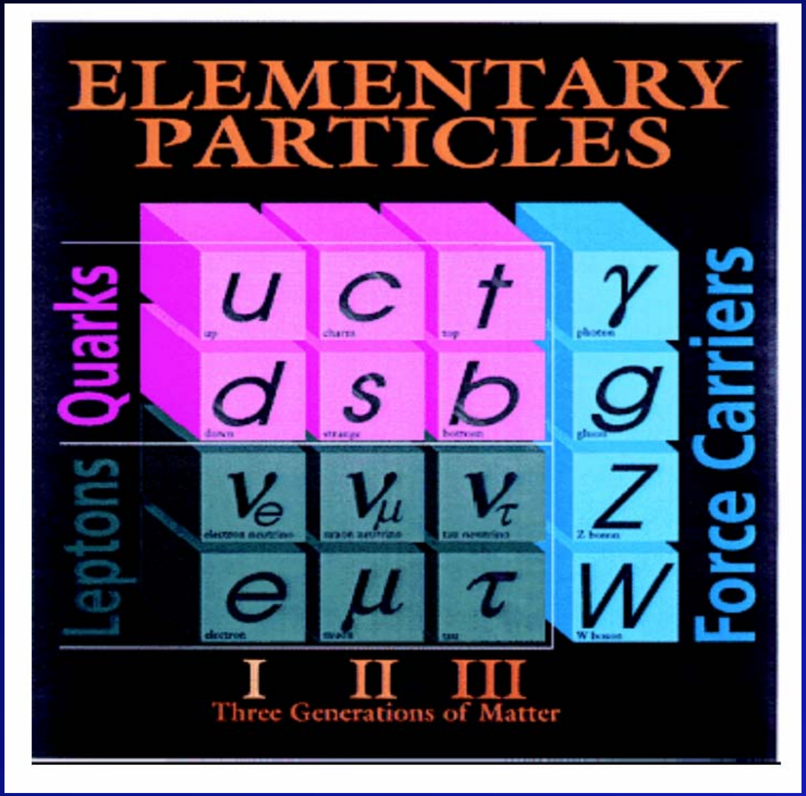
NTHU, 14:00-15:00, 22, March, 2007


Different Kinds of Basic Matter
100
10
1
Chemical
Elements
Subatomic
Particles
?
Sulfur, Salt
Mercury
Earth
Air
Fire
Water
Electron
Proton
Quarks
Leptons
1000
0
1000
1500
1800
1900
1950
1980
2000
2020
BC
AC
JV_266


Crystal Molecule
Atom
Atomic Nucleus
Elementary Particles
Hadrons
Mesons
Baryons
Leptons
$e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau$
Pointlike
Nuclei
Quarks
u,c,d,s,b,(t)
Proton
Neutron
1 cm
10^{-8}cm
10^{-12}cm
10^{-13}cm
?



- Mass Origin and the Elctroweak Symmetry Breaking Mechanism
- Three generations
- Too many free parameters
- No dark matter candidate
- …

The SM is an effective description of a fundamental theory!

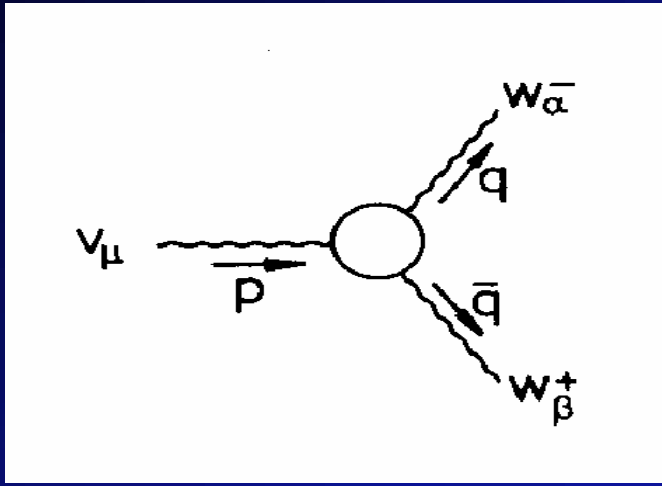
EWSB and S Parameter

1.a Candidates of electroweak symmetry breaking mechanism:
(Unitarity conditions $V_l V_l \to V_l V_l$, Quadratic divergences, Naturalness)

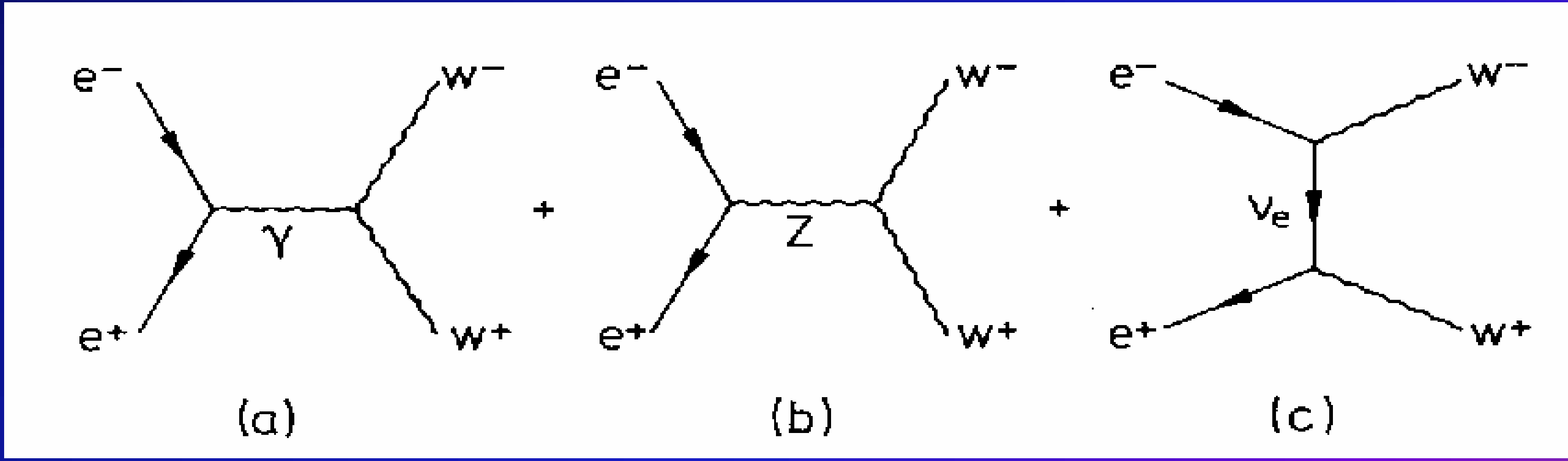
- a.1 SUSY models: MSSM, SUGRA, Superstring inpired models, splitted SUSY models, NMSSM, SUSY in warped RS space, etc ...
- a.2 Extra dimension models and relatives: KK, DGG, RSI, RSII, ADD, Higgsless model, dimension deconstruction models, little Higgs models, Higgs-Gauge(-Gravity) unification model, etc ...
- a.3 Higgs model(MSM), THDMs, Z', extra $W^{\pm}$, 4th generation, etc ...
- a.4 Strongly dynamics inspired models: technicolor models, topcolor condensate models, composite W/Z models, BESS models, etc ...

How conclusively precision data can rule out QCD-like dynamics for EWSB sector?

Triple Gauge Couplings



- Examining the non-Abelian structure of the SM
- Measuring the size of weak bosons
- Removing bkgd for new physics
- …



Outline

1. The S parameter problem
2. Introduction to the EWCL
3. RGEs
4. Precision data and bounds
5. Uncertainty in $S(\Lambda) - T(\Lambda)$
6. Discussions and Conclusions

S in QCD-like Theories

By assuming custodial symmetry, the unsubtracted dispersion relations (also called Das-Mathur-Okubo sum rules, the 0-th Weinberg sum rule) can read as:

$$S = \frac{1}{3\pi} \int_0^{\infty} ds \frac{R_V(s) - R_A(s)}{s}$$

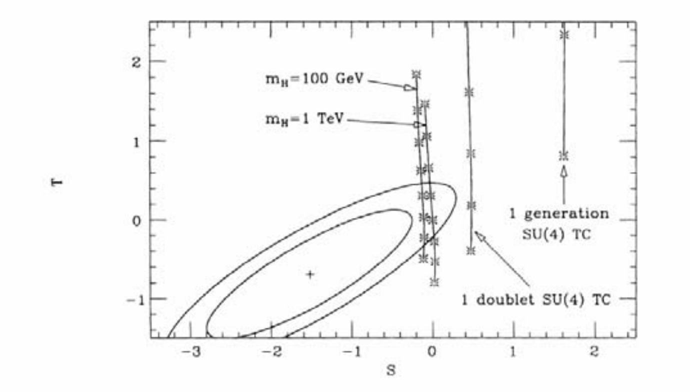
$$\begin{aligned} R_V(s) &= -12 \mathrm{Im}\Pi'_{VV} \\ R_A(s) &= -12 \mathrm{Im}\Pi'_{AA} \\ \frac{1}{3\pi}\int_0^{\infty} ds \; [R_V(s) - R_A(s)] &= 4\pi F_\pi^2 \\ \frac{1}{3\pi}\int_0^{\infty} ds\, s\, [R_V(s) - R_A(s)] &= 0 \end{aligned}$$

$$S \sim \frac{1}{6\pi} \frac{N_{TC} N_{TF}}{2}$$

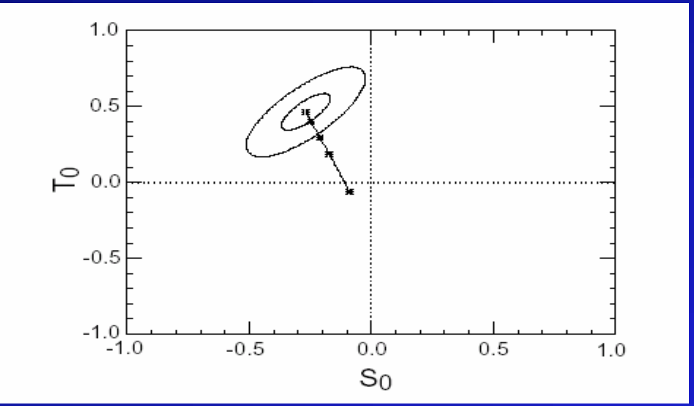
S parameter is postive!

Precision of S in Evolution

1990(2)

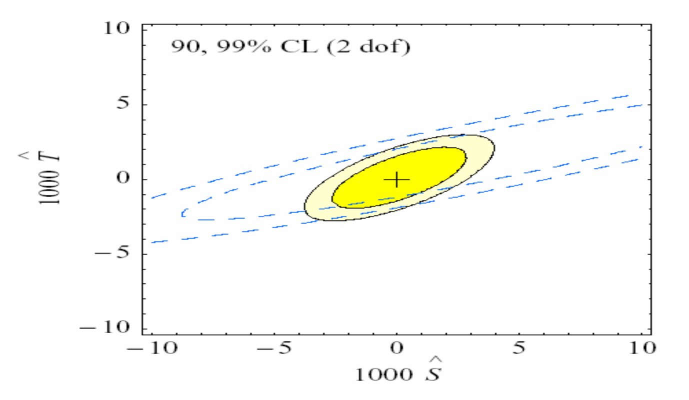


1999

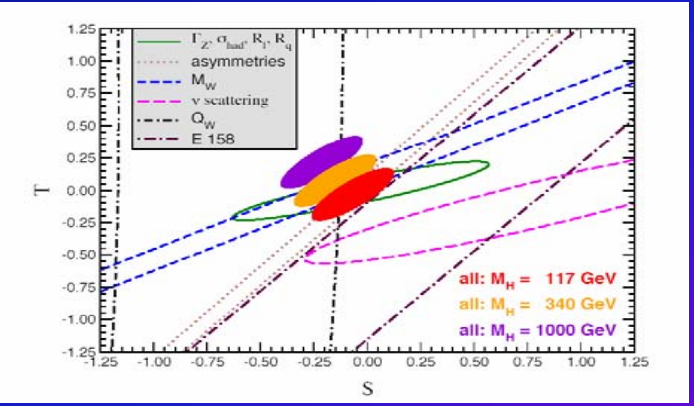


2004

$$S = 119\hat{S}$$
$$T = 129\hat{T}$$



2006 PDG



S parameter is negative!

This rules out simple Technicolor models with many techni-doublets and QCD-like dynamics.

Theoretical Effort for Solution

- Produce a negative S in TCs
- Include extra vector bosons
- Decrease T
- Extra Dimensions
- ADS/CFT
- …

Shortages in Experimental Uncertainty Analysis

– Higgs is the only next resonance in MSM.
– The next resonance might be 0^{--}, 1^{++}, 1^{--}, 2^{++}, 2^{--}, etc, with unknown mass.

Model independent analysis is favored!

– Only two point operators to describe new physics from $\mu = m_Z$ to Λ in previous works.
– New resonance can affect not only two-point but also three- and four-point functions.

It is necessary to have an integrated and general analysis with two-, three-, and four-point functions data.

What's New in this Talk?

- We extend 6 operator effective field theory analysis to 14 operator analysis
- Data of TGC measurement and unitarity bounds of QGC are incorperated
- Our findings:

inputs	value
PDG2004	$S(1\mathrm{TeV}) = -0.08 \pm 0.20$
PDG2006	$S(1\mathrm{TeV}) = -0.02 \pm 0.20$

S can be either positive or negative!

2 Introduction to the EWCL

- **Experimental Facts:**
  - γ is massless, and W/Z (SppS, 1983) are massive
  - The electroweak symmetry (local gauge symmetry) is broken
  - Higgs boson has not yet been found
- **Nambu-Goldstone theorem: No Fiction**
  - Symmetry and breaking pattern: $SU_L(2) \times U_Y(1) \to U_{EM}(1)$
  - Non-linear Goldstone boson: $U = exp(i2\xi^a T^a/v)$, (π^a and f_π)
  - Local Gauge fields: W, B

Operators :

$$\begin{aligned}
\mathcal{L}_{\mathrm{EW}} &= \mathcal{L}_{\mathrm{EW}}^{\mathrm{p}^2} + \mathcal{L}_{\mathrm{EW}}^{\mathrm{p}^2,\mathrm{p}^4} + \cdots \\
\mathcal{L}_{EW}^{p^2} &= -H_1 - H_2 + \mathcal{L}_{W/Z}\,, \\
\mathcal{L}_{EW}^{p^2,p^4} &= \alpha_0 \bar{\mathcal{L}}_0' + \sum_{i=1}^{10} \alpha_i \bar{\mathcal{L}}_i
\end{aligned}$$

where the auxiliary variables V_μ and $\mathcal{T}$ are defined as

$$\begin{aligned}
V_\mu &= (\partial_\mu U)\cdot U^\dagger + i W_\mu^a T_L^a - iU \cdot B_\mu T_R^3 \cdot U^\dagger\,, \\
\mathcal{T} &= 2U \cdot T_R^3 \cdot U^\dagger = U \cdot \tau_R^3 \cdot U^\dagger\,,
\end{aligned}$$

14 free parameters form the parameter space of the EWCL

Operators

Two Point Function

$$
\begin{aligned}
\mathcal{L}_{W/Z} &= \frac{v^2}{4} tr(V \cdot V)\,, \\
\bar{\mathcal{L}}'_0 &= \frac{v^2}{4}[tr(\mathcal{T} V_\mu)]^2\,, \\
H_1 &= \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu,\,a}\,, \\
H_2 &= \frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu}\,, \\
\bar{\mathcal{L}}_1 &= \frac{1}{2} B_{\mu\nu} tr(\mathcal{T} W^{\mu\nu})\,, \\
\bar{\mathcal{L}}_8 &= \frac{1}{4}[tr(\mathcal{T} W_{\mu\nu})]^2\,,
\end{aligned}
$$

Four Point function

$$
\begin{aligned}
\bar{\mathcal{L}}_4 &= [tr(V_\mu V_\nu)]^2\,, \\
\bar{\mathcal{L}}_5 &= [tr(V_\mu V^\mu)]^2\,, \\
\bar{\mathcal{L}}_6 &= tr(V_\mu V_\nu) tr(\mathcal{T} V^\mu) tr(\mathcal{T} V^\nu)\,, \\
\bar{\mathcal{L}}_7 &= tr(V_\mu V^\mu)[tr(\mathcal{T} V^\nu)]^2\,, \\
\bar{\mathcal{L}}_{10} &= \frac{1}{2}[tr(\mathcal{T} V_\mu) tr(\mathcal{T} V_\nu)]^2\,.
\end{aligned}
$$

Three Point Function

$$
\begin{aligned}
\bar{\mathcal{L}}_2 &= i\frac{1}{2} B_{\mu\nu} tr(\mathcal{T}[V^\mu, V^\nu])\,, \\
\bar{\mathcal{L}}_3 &= i tr(W_{\mu\nu}[V^\mu, V^\nu])\,, \\
\bar{\mathcal{L}}_9 &= i\frac{1}{2} tr(\mathcal{T} W_{\mu\nu}) tr(\mathcal{T}[V^\mu, V^\nu])\,,
\end{aligned}
$$

Bosonic Vertices

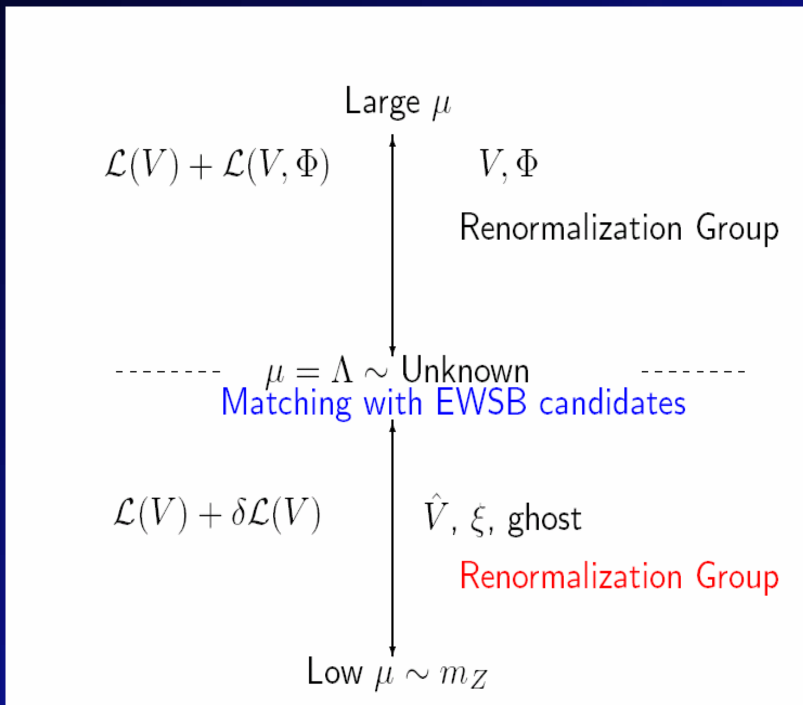
	2 point vertex	3 point vertex	4 point vertex
$v^2\bar{\mathcal{L}}'_0$	$\surd$		
$\bar{\mathcal{L}}_1$	$\surd$	$\surd$	
$\bar{\mathcal{L}}_2$		$\surd$	$\surd$
$\bar{\mathcal{L}}_3$		$\surd$	$\surd$
$\bar{\mathcal{L}}_4$			$\surd$
$\bar{\mathcal{L}}_5$			$\surd$
$\bar{\mathcal{L}}_6$			$\surd$
$\bar{\mathcal{L}}_7$			$\surd$
$\bar{\mathcal{L}}_8$	$\surd$	$\surd$	$\surd$
$\bar{\mathcal{L}}_9$		$\surd$	$\surd$
$\bar{\mathcal{L}}_{10}$			$\surd$

Hadronic QCD (80s')	$\pi-\rho$ system (90s')	EWCL (80s')
G	G $\times SU_V(N_f)$	$SU_L(2)\times U_Y(1)$
π	π & ρ	γ, $W^\pm$, Z
—	strong ($g\sim 6$)	weak ($g\sim 0.6$)
2+ 11	3+35	3+11 (2+12)
—	Gauge Fixing	Gauge Fixing

Tab. 2: $G = SU_L(N_f)\times SU_R(N_f)$

Comparison of Hadronic QCD, $\pi-\rho$ system, and EWCL up to $O(p^4)$

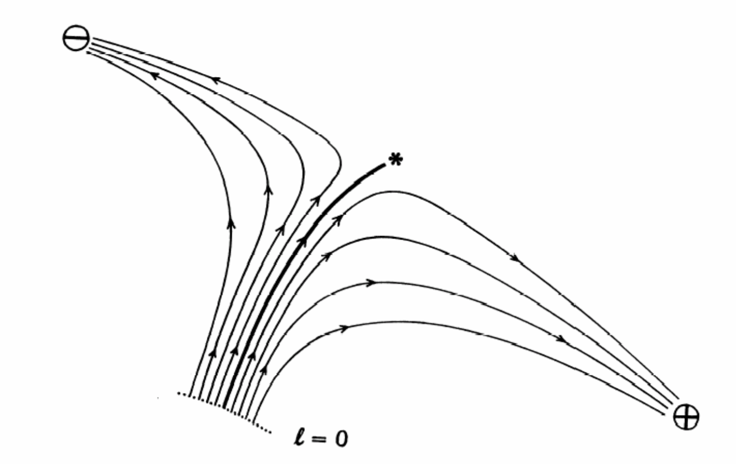
EWCL in Effective Field Theory



Relevant Operators (2)	Marginal Operators (12)
$\mathcal{L}_{W/Z}$, $\bar{\mathcal{L}}'_0$	H_1, H_2, $\bar{\mathcal{L}}_1$, $\bar{\mathcal{L}}_8$ $\bar{\mathcal{L}}_2$, $\bar{\mathcal{L}}_3$, $\bar{\mathcal{L}}_9$ $\bar{\mathcal{L}}_4$, $\bar{\mathcal{L}}_5$, $\bar{\mathcal{L}}_6$, $\bar{\mathcal{L}}_7$, $\bar{\mathcal{L}}_{10}$
v, α_0	g, g', α_1, α_8 α_2, α_3, α_9 α_4, α_5, α_6, α_7, α_{10}

We expect that S parameter should be a running parameter!

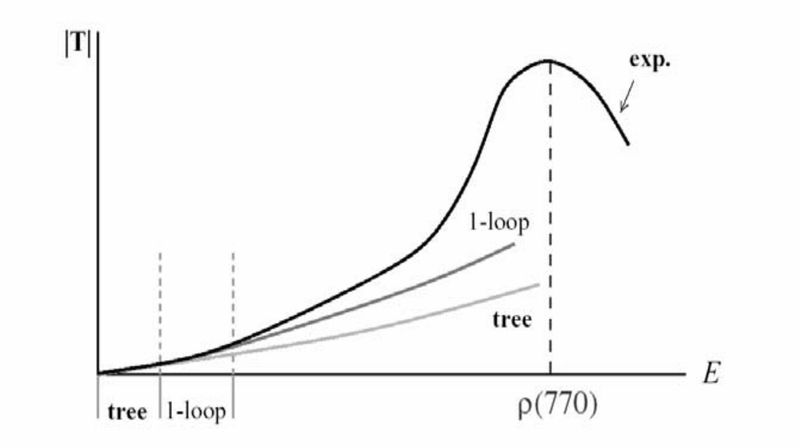
Running Allowed by QFT



Remarkable Points:

– Resonances near the UV cutoff (Non-perturbative effects) might change the RGE trajectories drastically

– Near UV cutoff, higher dimension operators ($O(p^6)$, $O(p^8)$, $\cdots$) dominate and the effective description breaks down



We assume that perturbation method could be valid from Mz to UV Cutoff with only dimension 2 and 4 operators.

3 RGEs

Dimensional regularization,
Background field method,
Feynman-'t Hooft gauge,
Modified MS,
Heat kernel method

The β function of α_0, $(T = \frac{2\alpha_0}{\alpha_{\rm em}})$

$$\begin{aligned}\beta_{\alpha_0} &= \frac{3g'^2}{8} + \frac{9\alpha_0 g^2}{4} - \frac{9\alpha_0 g'^2}{4} - \alpha_1 \frac{3g^2 g'^2}{4} + \alpha_8 \frac{3g^4}{8} \\ &+\alpha_2\left(\frac{3g^2g'^2}{2} - \frac{3g'^4}{4}\right) + \alpha_3\frac{3g^2g'^2}{2} + \alpha_9\left(-\frac{g^4}{2} + \frac{3g^2g'^2}{4}\right) \\ &+\alpha_4\left(\frac{15g^2g'^2}{4} + \frac{15g'^4}{8}\right) + \alpha_5\left(\frac{3g^2g'^2}{2} + \frac{3g'^4}{4}\right) \\ &+\alpha_6\left(\frac{3g^4}{4} + \frac{33g_z^4}{8}\right) + \alpha_7\left(3g^4 + 3g_z^4\right) + \alpha_{10}\left(\frac{9g_z^4}{2}\right). \qquad (26)\end{aligned}$$

The β function of α_1, $(S = -16\pi\alpha_1)$

$$\begin{aligned}\beta_{\alpha_1} &= \frac{1}{12} + 4\alpha_1 g^2 - \alpha_8 g^2 \\ &-\frac{5\alpha_2 g^2}{2} + \frac{5\alpha_3 g^2}{6} - \frac{\alpha_9 g^2}{2},\end{aligned}$$

The β function of α_8, $(U = -16\pi\alpha_8)$

$$\begin{aligned}\beta_{\alpha_8} &= \frac{\alpha_0}{2} + \alpha_1 g'^2 + 12\alpha_8 g^2 \\ &-\frac{5\alpha_2 g'^2}{6} + \frac{\alpha_3 g'^2}{2} - \frac{17\alpha_9 g^2}{6},\end{aligned}$$

Check Points

b.1 Gauge couplings' β functions without anomalous couplings.

b.2 The constant parts in β functions should agree with previous results.

b.3 The explicit $U_{em}(1)$ symmetry is carefully examined in each step.

b.4 Hermiticity of each operators is checked.[Only ghost sector violates it, but can be handled in quantum field theory]

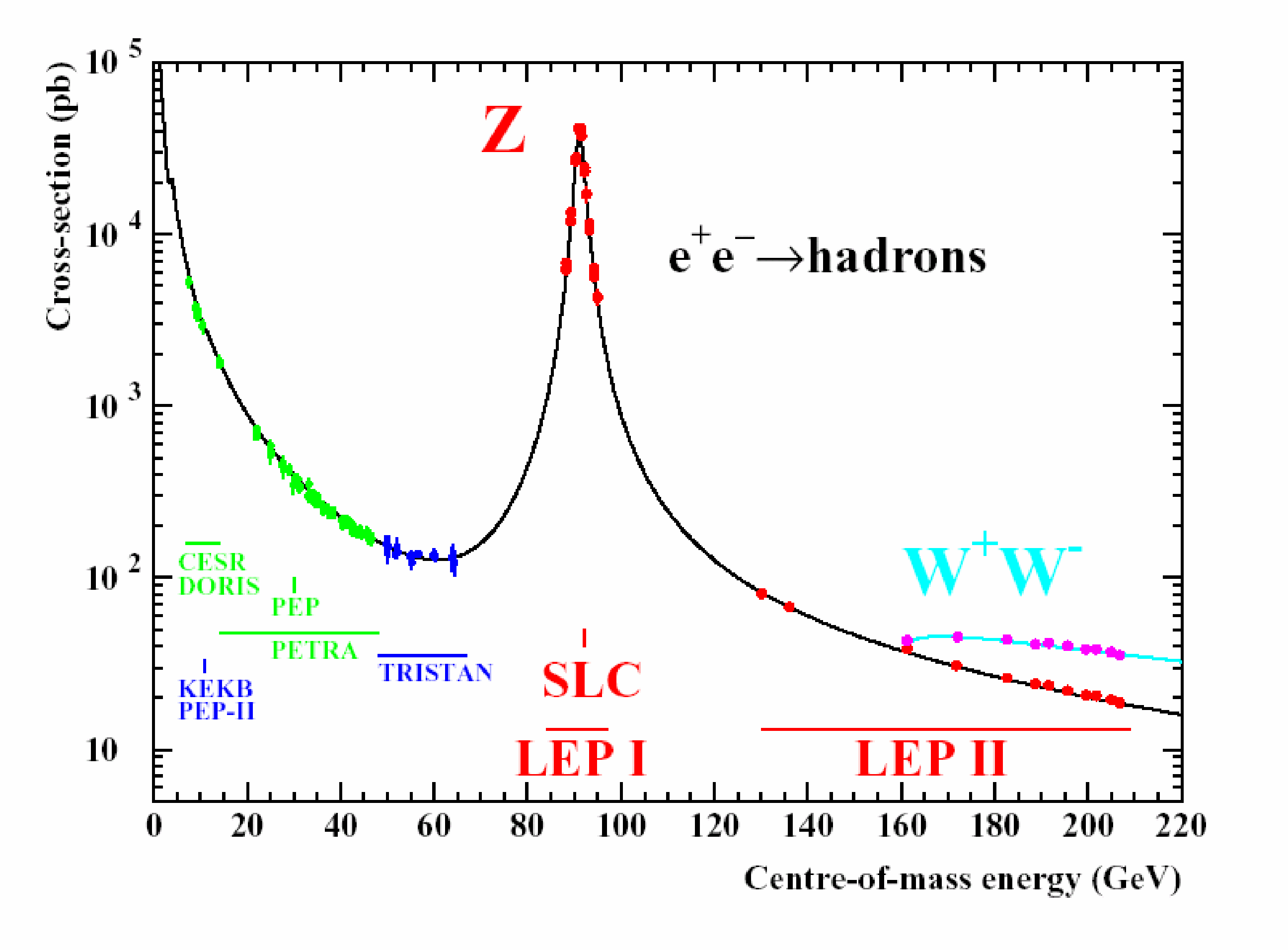
b.5 Calculate in unitary gauge and find differences.

- $*$ The β function of g and g' is not correct
- $*$ The constant term originating from the Goldstone's one-loop determinant is absent

b.6 $\hat{U} = \exp(\xi^3 T^3)\exp(\xi^+ T^+ + \xi^- T^-)$ or $\exp(\xi^3 T^3 + \xi^+ T^+ + \xi^- T^-)$, (EOMs of Goldstone guarantee Parameterization independence.)

b.7 Calculation in weak interaction eigenstate basis produces the same results.

4 Precision Data and Bounds



Precision Data of STU

parameter	current value
m_W (GeV)	80.425 ± 0.038
$sin\theta_w^{eff}$	0.23147 ± 0.00017
Γ_ℓ (MeV)	83.984 ± 0.086
m_t	175 GeV

$$\begin{aligned} m_W(\mathrm{GeV}) &= 80.377 - 0.288\Delta S + 0.418\Delta T + 0.337\Delta U \, . \\ \Gamma_\ell(\mathrm{GeV}) &= 0.08395 - 0.00018\Delta S + 0.00075\Delta T \, , \\ \sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} &= 0.23148 + 0.00359\Delta S - 0.00241\Delta T \, , \end{aligned}$$

$$\begin{aligned} \Delta S &= \Delta S_{\mathrm{SM}} - S_{\mathrm{Higgs}}^{ND} + S \, , \\ \Delta T &= \Delta T_{\mathrm{SM}} - T_{\mathrm{Higgs}}^{ND} + T \, , \\ \Delta U &= \Delta U_{\mathrm{SM}} - U_{\mathrm{Higgs}}^{ND} + U \, , \end{aligned}$$

inputs	value
$1/\alpha_e(m_Z)$	128.74
m_Z	91.18 GeV
G_F	1.16637×10^{-5} GeV^{-2}

$$\begin{aligned} S_{\mathrm{Higgs}}^{\mathrm{ND}} &= - \frac{1}{6\pi}\left[\frac{5}{12} - \ln\left(\frac{m_H}{m_Z}\right)\right] \, , \\ T_{\mathrm{Higgs}}^{\mathrm{ND}} &= \frac{1}{\cos^2\theta_W}\frac{3}{8\pi}\left[\frac{5}{12} - \ln\left(\frac{m_H}{m_Z}\right)\right] \, , \\ U_{\mathrm{Higgs}}^{\mathrm{ND}} &= 0 \, . \end{aligned}$$

Inputs and formula to determine the two point chiral coefficients

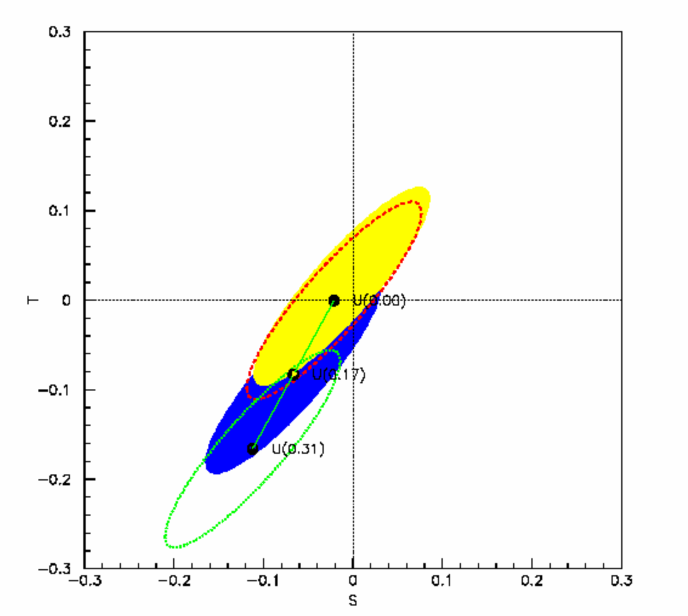
Precision Data of STU

– 3-parameter fit

$$\begin{aligned} S(m_Z) &= (-0.06 \pm 0.11) \\ T(m_Z) &= (-0.08 \pm 0.14) \\ U(m_Z) &= (+0.17 \pm 0.15) \end{aligned} \quad \rho_{co.} = \begin{pmatrix} 1 & +0.90 & -0.42 \\ +0.90 & 1 & -0.60 \\ -0.42 & -0.60 & 1 \end{pmatrix}$$

– 2-parameter fit $U = 0$:

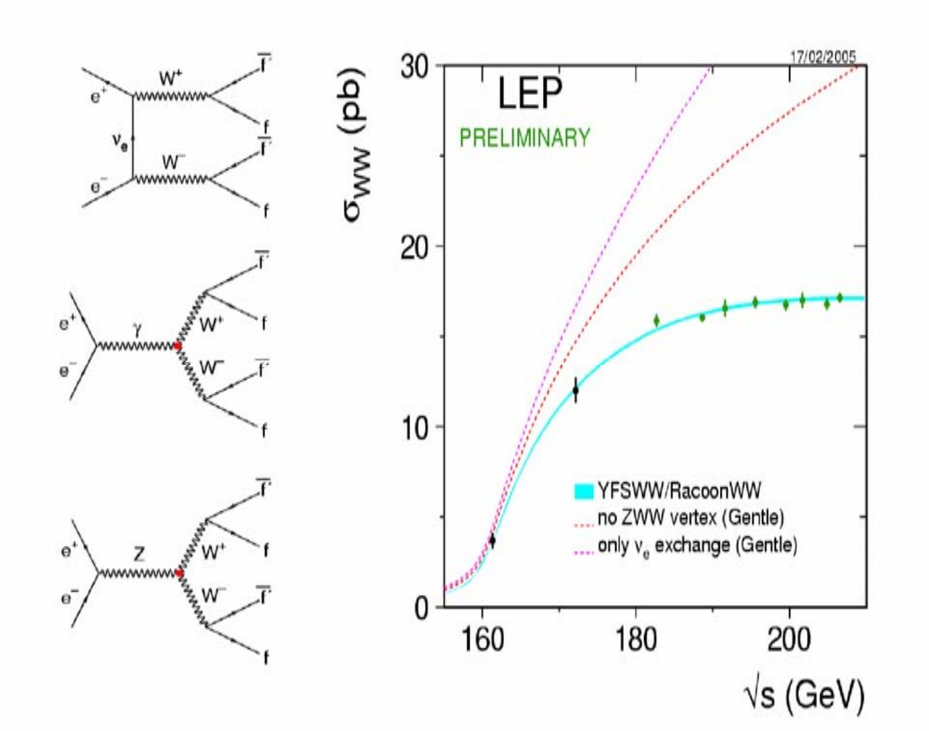
$$\begin{aligned} S(m_Z) &= (-0.01 \pm 0.10) \\ T(m_Z) &= (+0.02 \pm 0.11) \end{aligned} \quad \rho_{co.} = \begin{pmatrix} 1 & +0.89 \\ +0.89 & 1 \end{pmatrix} .$$



$$\begin{aligned} S(m_Z) &= -16\pi\alpha_1(m_Z) \,, \\ T(m_Z) &= \frac{2\alpha_0(m_Z)}{\alpha_{\rm em}(m_Z)} \,, \\ U(m_Z) &= -16\pi\alpha_8(m_Z) \,, \end{aligned}$$

$$\begin{aligned} \alpha_1(m_Z) &= (+0.13 \pm 0.21) \times 10^{-2} \,, \\ \alpha_0(m_Z) &= (-0.03 \pm 0.05) \times 10^{-2} \,, \\ \alpha_8(m_Z) &= (-0.35 \pm 0.29) \times 10^{-2} \,. \end{aligned}$$

Precision Data of TGC



$$
\begin{aligned}
\frac{\mathcal{L}_{WWN}}{g_{WWN}} &= i g^1{}_N (W^\dagger{}_{\mu\nu} W^\mu N^\nu - W_{\mu\nu} W^{\dagger\mu} N^\nu) \\
&+ i k_N W^\dagger{}_\mu W_\nu N^{\mu\nu} + i \frac{\lambda_N}{M_W^2} W^\dagger{}_{\lambda\mu} W^\mu{}_\nu N^{\nu\lambda} \\
&+ g_5^N \epsilon^{\mu\nu\rho\sigma} (W^\dagger{}_\mu \partial_\rho W_\nu - \partial_\rho W^\dagger{}_\mu W_\nu) N_\sigma
\end{aligned}
$$

K. Hagiwara, R. D. Peccei, D. Zeppenfeld and K. Hikasa, Nucl. Phys. B **282**, 253 (1987)

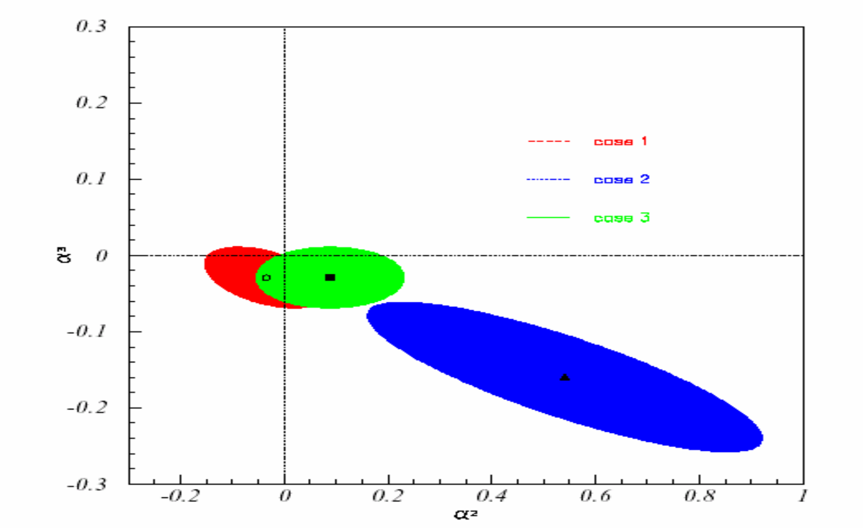
$$
\begin{aligned}
\delta k_\gamma &= -(\alpha_1 + \alpha_8 - \underline{\alpha_2} - \underline{\alpha_3} - \underline{\alpha_9}) g^2 \,, \\
\delta k_Z &= -\frac{g^2}{g^2 - g'^2} \alpha_0 + \frac{g'^2}{g^2 - g'^2} \alpha_1 g_z^2 - (\alpha_8 - \underline{\alpha_3} - \underline{\alpha_9}) g^2 \\
&\quad + (\alpha_1 - \underline{\alpha_2}) g'^2 \,, \\
\delta g_Z^1 &= -\frac{g^2}{g^2 - g'^2} \alpha_0 + \frac{g'^2}{g^2 - g'^2} \alpha_1 g_z^2 + \underline{\alpha_3} g_z^2 \,, \\
g_z^2 &= g^2 + g'^2
\end{aligned}
$$

Proof of Non-Abelian Structure of the SM

Precision Data of TGC

$$
\begin{aligned}
\delta k_\gamma(m_Z) &= -0.03 \pm 0.05, \\
\delta g_1^Z(m_Z) &= -0.02 \pm 0.02,
\end{aligned}
$$

$$
\begin{aligned}
\alpha_2(m_Z) &= (-0.04 \pm 0.12) \\
\alpha_3(m_Z) &= (-0.03 \pm 0.04)
\end{aligned}
\quad \rho_{co.} = -0.46
$$



$$
\begin{aligned}
\delta k_Z &= -0.076 \pm 0.064, \\
\delta k_\gamma &= -0.027 \pm 0.045, \\
\delta g_Z^1 &= -0.016 \pm 0.022,
\end{aligned}
$$

$$
\begin{aligned}
\alpha_2(m_Z) &= (+0.09 \pm 0.14) \\
\alpha_3(m_Z) &= (-0.03 \pm 0.04) \\
\alpha_9(m_Z) &= (-0.12 \pm 0.12)
\end{aligned}
\quad \rho_{co.} = \begin{pmatrix} 1 & & \\ +0.01 & 1 & \\ -0.68 & -0.32 & 1 \end{pmatrix}
$$

$$
\begin{aligned}
\delta k_\gamma &= (+0.162 \pm 0.129) \\
\delta g_Z^1 &= (-0.088 \pm 0.054)
\end{aligned}
\quad \rho_{co.} = -0.710.
$$

$$
\begin{aligned}
\alpha_2(m_Z) &= (+0.54 \pm 0.36) \\
\alpha_3(m_Z) &= (-0.16 \pm 0.10)
\end{aligned}
\quad \rho_{co.} = -0.82
$$

Bounds of QGC

$$
\begin{aligned}
|4\alpha_4 + 2\alpha_5| &< 3\pi \frac{v^4}{\Lambda^4}, & W_L^+ W_L^+ &\to W_L^+ W_L^+, \\
|3\alpha_4 + 4\alpha_5| &< 3\pi \frac{v^4}{\Lambda^4}, & W_L^+ W_L^- &\to W_L^+ W_L^-, \\
|\alpha_4 + \alpha_6 + 3(\alpha_5 + \alpha_7)| &< 3\pi \frac{v^4}{\Lambda^4}, & W_L^+ W_L^- &\to Z_L Z_L, \\
|2(\alpha_4 + \alpha_6) + \alpha_5 + \alpha_7| &< 3\pi \frac{v^4}{\Lambda^4}, & W_L^+ Z_L &\to W_L^+ Z_L, \\
|\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})| &< \frac{6\pi}{5} \frac{v^4}{\Lambda^4}, & Z_L Z_L &\to Z_L Z_L.
\end{aligned}
$$

5 conditions (J=0 channel) to fix 5 free parameters

Chiral Coefficients in EWCL

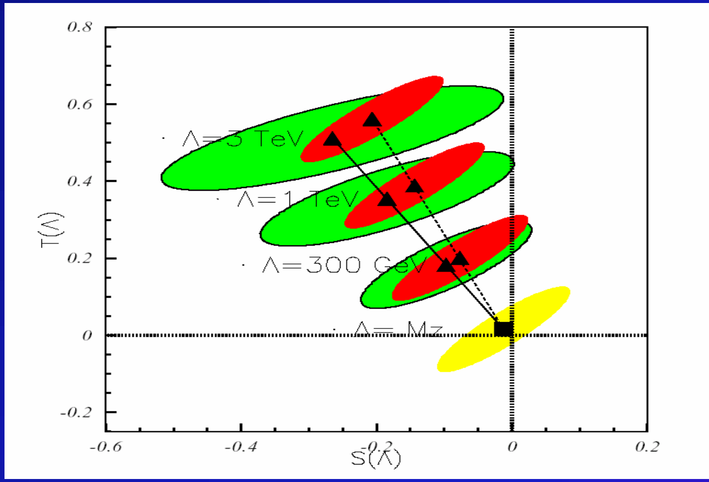
Chiral Coefficients	Central values	Error bars (±)
$\alpha_0(m_Z)$	$+0.0003$	0.0005
$\alpha_1(m_Z)$	$+0.0013$	0.0021
$\alpha_2(m_Z)$	-0.09	0.14
$\alpha_3(m_Z)$	$+0.03$	0.04
$\alpha_4(m_Z)$		$\sim \frac{v^4}{\Lambda^4}$
$\alpha_5(m_Z)$		$\sim \frac{v^4}{\Lambda^4}$
$\alpha_6(m_Z)$		$\sim \frac{v^4}{\Lambda^4}$
$\alpha_7(m_Z)$		$\sim \frac{v^4}{\Lambda^4}$
$\alpha_8(m_Z)$	-0.0035	0.0029
$\alpha_9(m_Z)$	$+0.13$	0.12
$\alpha_{10}(m_Z)$		$\sim \frac{v^4}{\Lambda^4}$

	$L_i^r(\mu=m_\eta)$ [80]	$L_i^r(\mu=m_\rho)$ [70]
$L_1^r(\mu)$	$(0.9 \pm 0.3)\times 10^{-3}$	$(0.7 \pm 0.3)\times 10^{-3}$
$L_2^r(\mu)$	$(1.7 \pm 0.7)\times 10^{-3}$	$(1.3 \pm 0.7)\times 10^{-3}$
$L_3^r(\mu)$	$(-4.4 \pm 2.5)\times 10^{-3}$	$(-4.4 \pm 2.5)\times 10^{-3}$
$L_4^r(\mu)$	$(0 \pm 0.5)\times 10^{-3}$	$(-0.3 \pm 0.5)\times 10^{-3}$
$L_5^r(\mu)$	$(2.2 \pm 0.5)\times 10^{-3}$	$(1.4 \pm 0.5)\times 10^{-3}$
$L_6^r(\mu)$	$(0 \pm 0.3)\times 10^{-3}$	$(-0.2 \pm 0.3)\times 10^{-3}$
$L_7^r(\mu)$	$(-0.4 \pm 0.15)\times 10^{-3}$	$(-0.4 \pm 0.15)\times 10^{-3}$
$L_8^r(\mu)$	$(1.1 \pm 0.3)\times 10^{-3}$	$(0.9 \pm 0.3)\times 10^{-3}$
$L_9^r(\mu)$	$(7.4 \pm 0.7)\times 10^{-3}$	$(6.9 \pm 0.7)\times 10^{-3}$
$L_{10}^r(\mu)$	$(-6.0 \pm 0.7)\times 10^{-3}$	$(-5.2 \pm 0.7)\times 10^{-3}$

TGC errors are two order larger than those of two-point chiral coefficients

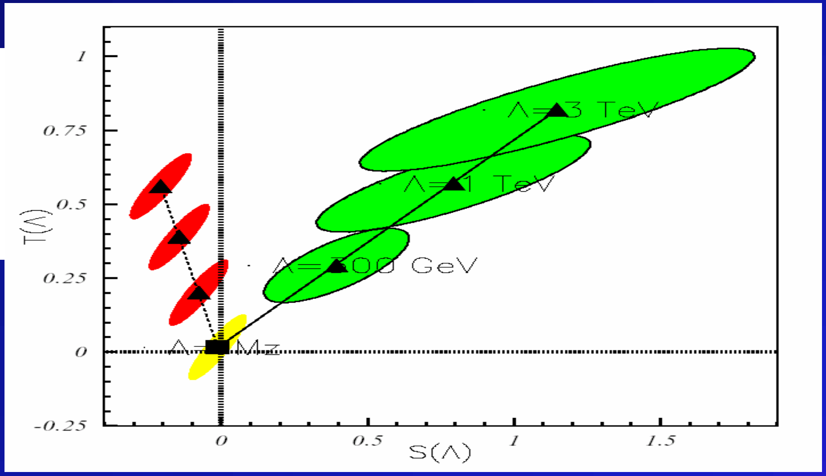
5 Uncertainty in S-T

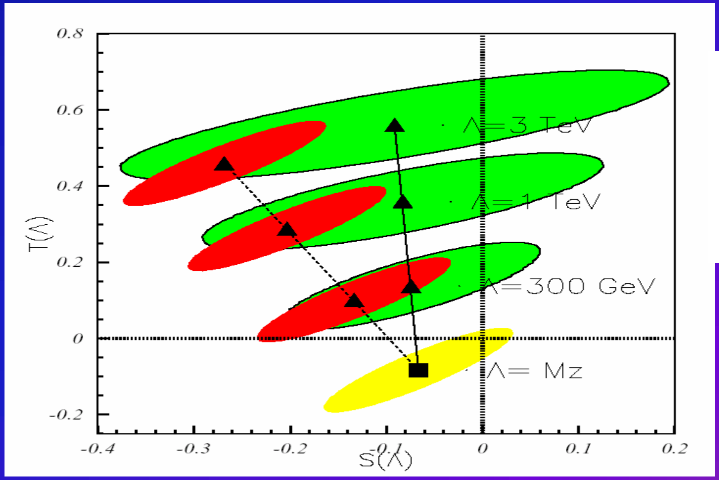
$$
\begin{aligned}
S(\Lambda) &= S(m_Z) - \frac{2}{\pi}\beta_{\alpha_1} \ln\frac{\Lambda}{m_Z}\,,\\
T(\Lambda) &= T(m_Z) + \frac{1}{4\pi^2\alpha\mathrm{em}}\beta_{\alpha_0} \ln\frac{\Lambda}{m_Z}\,,\\
U(\Lambda) &= U(m_Z) - \frac{2}{\pi}\beta_{\alpha_8} \ln\frac{\Lambda}{m_Z}\,,
\end{aligned}
$$



TGC Case 1

TGC Case 2





TGC Case 3

Uncertainty in T

Λ	$T(\Lambda) \pm 1\sigma$	$\delta T(m_Z)$	δT^{TGC}	δT^{QGC}
0.3 TeV	0.25 ± 8.91	± 0.14	± 0.06	± 8.91
0.5 TeV	0.29 ± 1.16	± 0.14	± 0.08	± 1.15
1 TeV	0.40 ± 0.22	± 0.14	± 0.12	± 0.10
3 TeV	0.60 ± 0.25	± 0.14	± 0.17	± 0.04

Summary

$$S_\Lambda = -0.08\ (-0.02) \pm 0.20$$
$$T_\Lambda = +0.40\ (+0.52) \pm 0.22$$

When TGC & QGC uncertainty is taken into account

$$S_\Lambda = -0.17\ (-0.11) \pm 0.10$$
$$T_\Lambda = +0.38\ (+0.50) \pm 0.14$$

When TGC & QGC uncertainty isn't taken into account

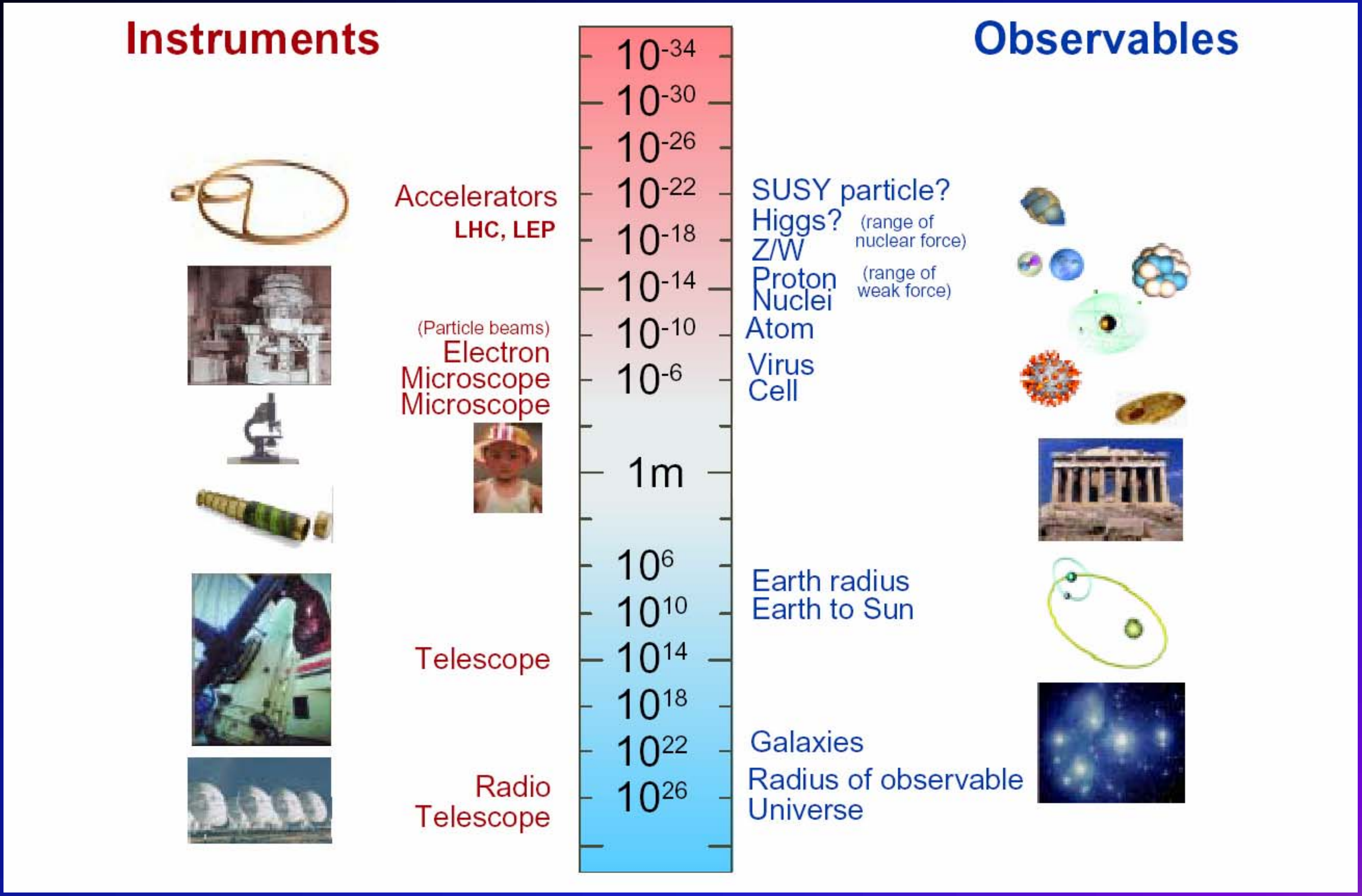
6 Conclusions

d.1 LEP1 measurements have significantly bounded two point function paramters.

d.2 LEP2 TGC measurements have further considerably shrunk the parameter space of EWCL.

d.3 The sign of $S(\Lambda)$ can not be fixed by current precision data due to the large uncertainty in TGC measurements.

d.4 EWSB mechanism is still an open question. LHC will reveal it soon.



Instruments
Observables
10^{-34}
10^{-30}
10^{-26}
10^{-22}
10^{-18}
10^{-14}
10^{-10}
10^{-6}
1m
10^{6}
10^{10}
10^{14}
10^{18}
10^{22}
10^{26}
Accelerators
LHC, LEP
(Particle beams)
Electron
Microscope
Microscope
Telescope
Radio
Telescope
SUSY particle?
Higgs?
Z/W
Proton
Nuclei
(range of
nuclear force)
(range of
weak force)
Atom
Virus
Cell
Earth radius
Earth to Sun
Galaxies
Radius of observable
Universe

Backup

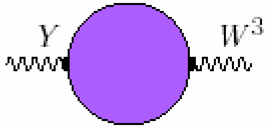
Discussions

Should S parameter run?

$$S(\Lambda) = S(m_Z) + \beta_S \ln \frac{\Lambda}{m_Z} \,,$$

Subtracted dispersion relation without custodial symmetry

$$S(q^2) = S(0) - \frac{q^2}{3\pi} \int_{s>m_z^2}^{\infty} ds \frac{R_{3Y}(s)}{s(s-q^2)}$$



$$\Longrightarrow \quad R_{3Y}(s) = -12\pi \mathrm{Im}\Pi'_{3Y}(s)$$

Necessity for this modification:

$\mathbf{Im}\Pi'_{33}(s)$, $\mathbf{Im}\Pi'_{YY}(s)$, $\mathbf{Im}\Pi'_{3Y}(s)$, counts the number of active degree of freedoms which belong, to $SU(2)_L$, to $U(1)_Y$, and to **both**, respectively.

Power counting problem

∗ If the derivative power counting rule holds, uncertainty from the TGC measurements is the biggest uncertainty to S.

- Two loop effects of $O(p^2)$ do not introduce large uncertainty
- $O(p^6)$ operators affect tree level 2-, 3-, and 4-point function fits and bounds, but do not contribute to RGEs

If the derivative power counting rule doesn't hold, our results are the most conservative perturbation calculation.

- **High order operators can affect STU and TGC fitting and QGC bounds significantly. Effective description might break down.**
- **High order operators can affect the RGEs running dramatically, especially near the UV region.**