The Niels Bohr Institute

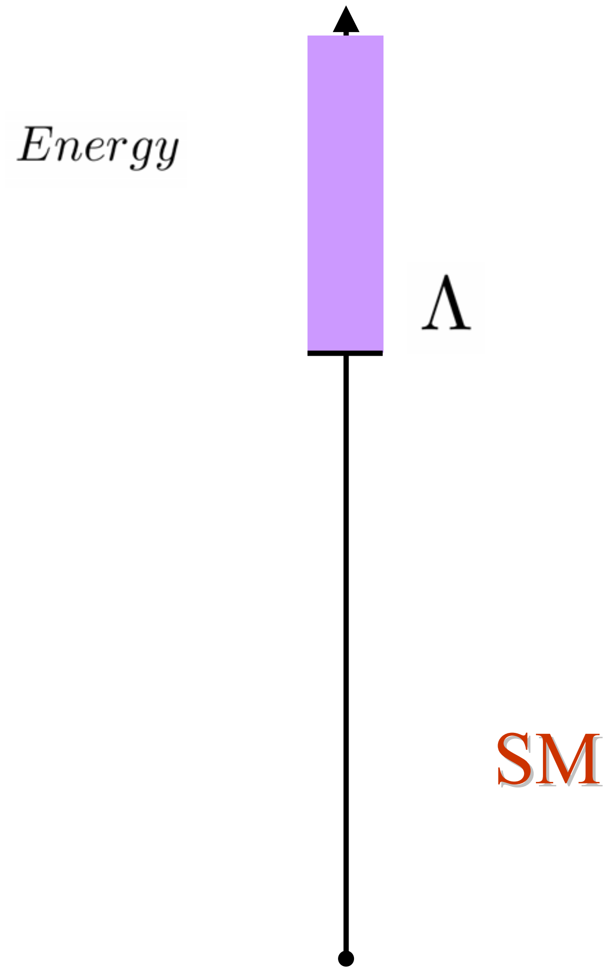
Dynamical EW Breaking:

A Classic

Francesco Sannino

MARIE CURIE ACTIONS

Low Energy Effective Theory



….is not so standard

- Origin of Mass of weak gauge bosons, quarks and leptons is unknown.
- Strong Interactions are not fully understood/explored.
- Strong CP problem:
  Unnaturally small Neutron Electric Dipole Moment

New Challenges from Cosmology.

- Dark Energy/Matter

Focus on two aspects of the SM

..and Beyond

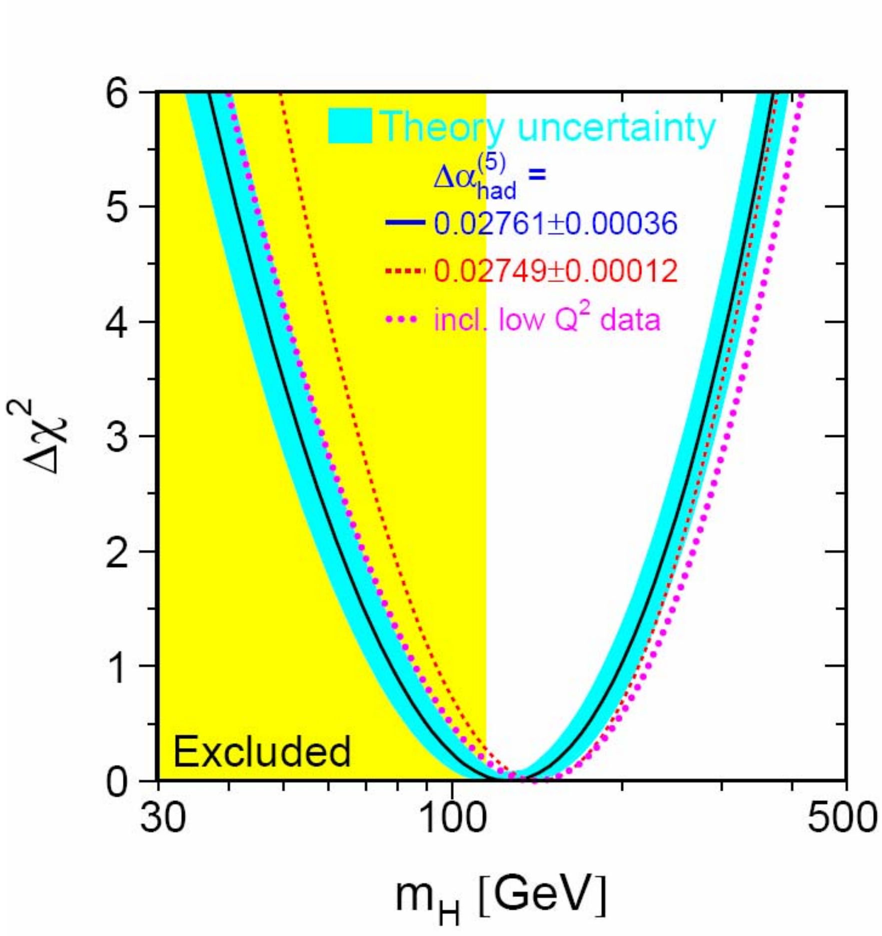
New as

Origin of Mass for the weak gauge bosons, quarks …

Understanding Strong Dynamics

Let there be Mass

SM Higgs: Current Status:

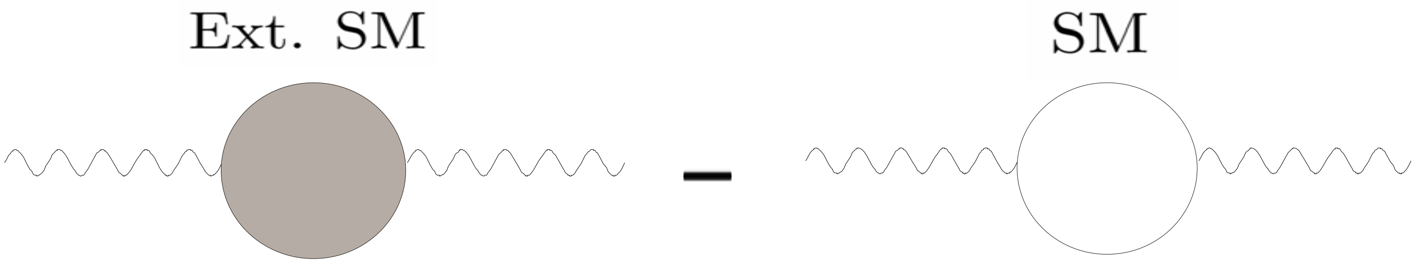


hep-ex/0509008

Electroweak Precision Measurements

We can already test New Physics!

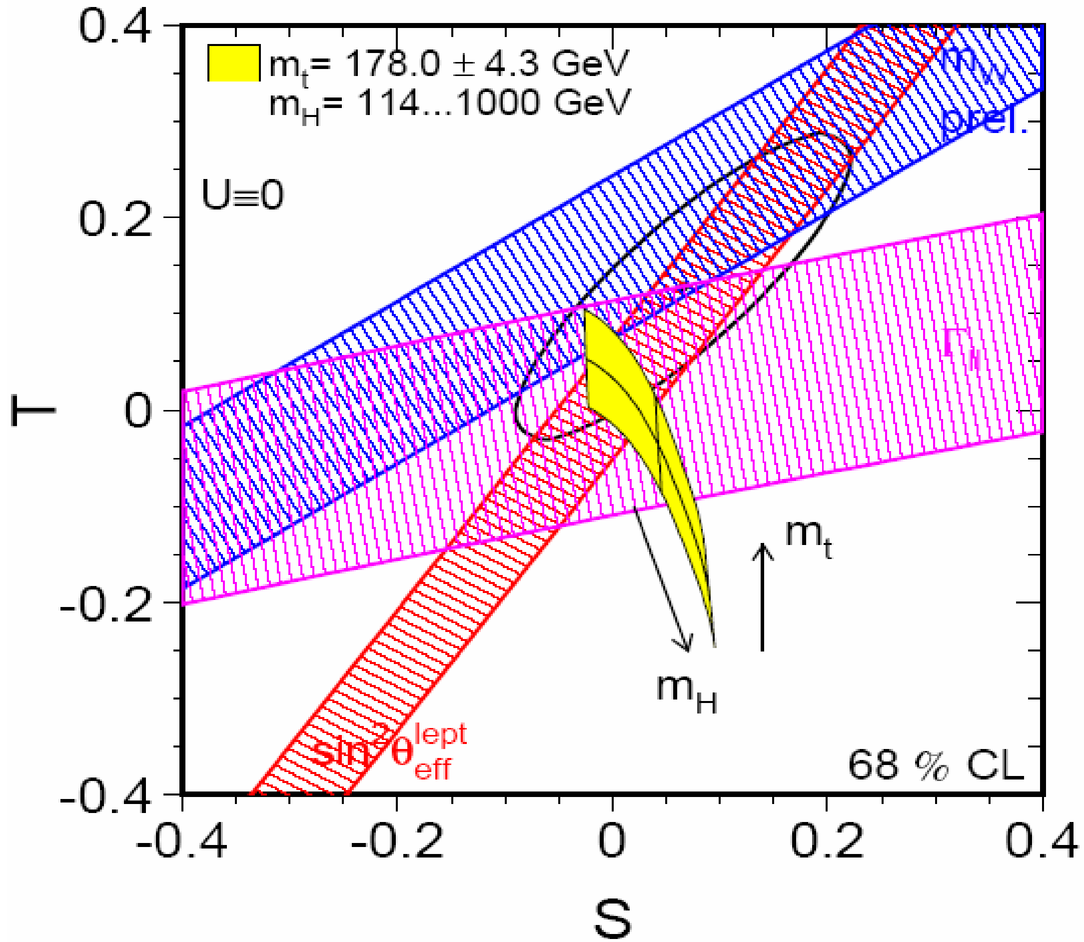
Kennedy,Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Marciano-Rosner,..:



$$\Pi^{\mu\nu}_{XY}(q^2) = \Pi_{XY}(q^2) g^{\mu\nu} + \cdots$$

$$\begin{aligned}
S &= -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2}\,, \\
T &= 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}\,, \\
U &= 16\pi \frac{[\Pi_{11}(m_Z^2) - \Pi_{11}(0)] - [\Pi_{33}(m_Z^2) - \Pi_{33}(0)]}{m_Z^2}
\end{aligned}$$

New Data



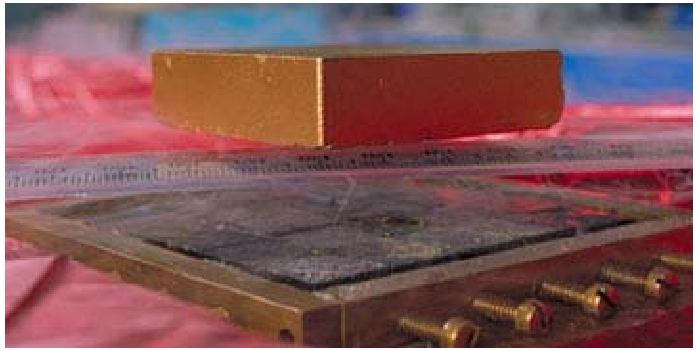
m_H=150 GeV

hep-ex/0509008

Now: S = 0.07±0.10

Before: S=-0.03±0.10

The Higgs Mechanism in Nature



Superconductivity

Macroscopic-Screening

Non-Relativistic

SM-Screening

Relativistic

$$T < T_c$$

$n_s = \text{Density SC electrons}$

$$|\psi|^2 = n_C = \frac{n_s}{2}$$

$$|\phi|^2 = \frac{v^2}{2}$$

Meissner-Mass
Static Vector Potential

$$M^2 = q^2 n_s/2m$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

$$\xi = 1/M \sim 10^{-6} cm$$

Hidden structure

Weak-GB-Mass

$$M_W^2 = g^2 v^2/4$$

$$M_W \sim 80\ GeV$$

$$\xi_W = 1/M_W \sim 10^{-15} cm$$

????

Elementary Higgs:

Trivial and Non-natural

Naturality

Small parameters stay small under radiative corrections.

<u>The electron Mass</u>

If set to zero the $U(1)_L \times U(1)_R$ forbids its regeneration

$$m_{e\,R} = R \times m_{e\,B}$$

Naturalness begs an explanation of the origin of mass.

No conflict with any small value of the electron mass

Is the Higgs Natural?

No *custodial* symmetry *protecting* a scalar mass.

$$M_{H}{}_R^2 = R \times M_{H}{}_B^2 + \Lambda^2$$

A mass appears even if *ab initio* is set to zero!

Hierarchy between the EW scale and the Planck Scale.

No!

Natural Scalars

Exact Super Symmetry:

Fermions $\leftrightarrow$ Bosons

Fermion’s *custodial symmetry* protects the Bosons

Observe: susy partners

Composite Scalars:

Recall Superconductivity

Substructure resolved at scale Λ_S

$$M_{H}{}_{R}^{2} = R \times M_{H}{}_{B}^{2} + \Lambda_S^2$$

Observe: New Bound States

Quasi Goldstone Boson:

Protected by spontaneously broken global symmetries.

Near Continuous Quantum Phase Transition cQPT:

$$M_H^2 = \Lambda^2 (t_c - t)^\nu$$

Zero-temperature Bose – Einstein Condensation
Lorentz symmetry is broken.

Chiral Phase Transition at zero temperature.
Lorentz symmetry is intact.

No Fundamental Scalars in Nature!

Electroweak Symmetry Breaking

@

LHC

Electroweak Symmetry Breaking

SUSY

Technicolor

Extra Dim.

Curved

Flat

Light Composite Higgs:

LCH @ LHC

Technicolor

New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 250\ GeV$$

Is it really Dead?

Problems with the Old Models

- S-parameter: too large
- Large Flavor Changing Neutral Currents (FCNC)
- Very heavy composite Higgs ~ 1 TeV.
- Limited knowledge of strong dynamics!

Fermion masses versus FCNC

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda_{ETC}^2} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \cdots$$

PNG Masses

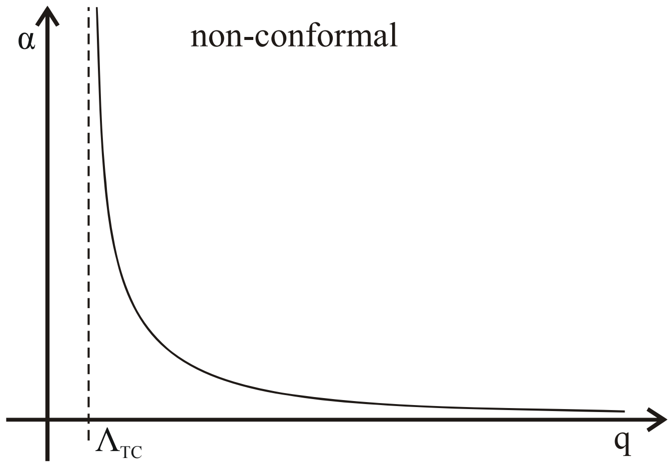
SM-Fermion Masses

FCNC Operators

Λ_{ETC} should be sufficiently larger than $\Lambda_{TC} \approx 250GeV$

to reduce FCNC.

Near Conformal Properties



Why the walking can help ?

$$\langle \bar{Q}Q_{ETC} \rangle = \exp \left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \langle \bar{Q}Q_{TC} \rangle$$

<u>QCD-Like</u>

$$\exp \left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \sim (\ln(\Lambda_{ETC}/\Lambda_{TC}))^{\gamma_m}$$

<u>Near the conformal window</u>

$$\exp \left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \sim (\Lambda_{ETC}/\Lambda_{TC})^{\gamma_m(\alpha^\star)}$$

Critical Number of techniflavors

For fermions in the fundamental representation near conformal means:

$$N_f^c \sim 4\,N$$

The number of techndoublets is

$$N_D = N_f/2$$

Still too large S-parameter

The S-parameter for fermions in the fundamental ③ is

$$S = \frac{N_f\, N}{12\pi} - \bullet$$

Appelquist - Sannino

Near conformal for N=2 means $N_f/2=4$ which yields:

$$S_{pert.} = 4/3\pi \sim 0.42$$

Experimentally S = 0.07±0.10

Progress in

Strong Interactions

`t Hooft - Large N

	$SU(N)$	$U_V(1)$	$U_A(1)$
ψ_c	$\square$	1	1
$\tilde{\psi}^c$	$\bar{\square}$	-1	1
G_μ	Adj	0	0

Corrigan and Ramond `79

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{[i,j]}$	$\genfrac{}{}{0pt}{}{\square}{\square}$	1	1
$\tilde{\psi}^{[i,j]}$	$\overline{\genfrac{}{}{0pt}{}{\square}{\square}}$	-1	1
G_μ	Adj	0	0

Relation with Super Yang-Mills

S-type

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{\{i,j\}}$	$\Box\!\Box$	1	1
$\widetilde{\psi}^{\{i,j\}}$	$\overline{\Box\!\Box}$	-1	1
G_μ	Adj	0	0

A-type

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{[i,j]}$	$\begin{smallmatrix}\Box\\ \Box\end{smallmatrix}$	1	1
$\widetilde{\psi}^{[i,j]}$	$\overline{\begin{smallmatrix}\Box\\ \Box\end{smallmatrix}}$	-1	1
G_μ	Adj	0	0

Armoni-Shifman-Veneziano

	$SU(N)$	$U_A(1)$
λ	Adj	1
G_μ	Adj	0

SYM

Physical world:

Towards small N

A-type:

QCD vacuum properties, spectrum and confinement

Sannino, Sannino-Shifman

N=1 Supersymmetric-Spectrum

Merlatti-Sannino

Feo-Merlatti-Sannino

S-type:

Composite Higgs from Higher Representations

Sannino

Not ruled out and LCH

Dietrich-Tuominen-Sannino,

Hong-Hsu-Sannino, Sannino-Tuominen

Evans-Sannino

The New Model

Near conformal for, N_f 🕔 2

No FCNC problem + Top mass

OK with precision data.

Light Composite Higgs.

Sannino-Tuominen, hep-ph/0405209 PRD (RC)
Hong, Hsu, Sannino, hep-ph/0406200 PLB
Dietrich, Sannino and Tuominen, hep-ph/0505059 PRD , hep-ph/0510217
Evans-Sannino, hep-ph/0512080

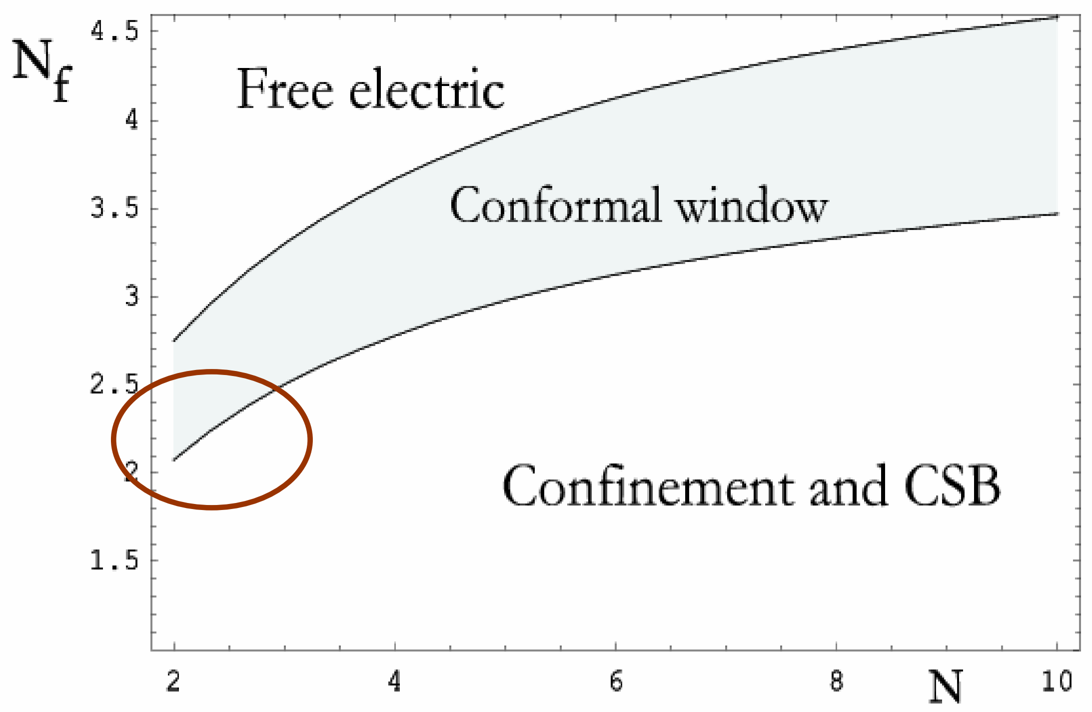
The Model: The generalized S-Theory

	$SU(N)$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	$U_A(1)$
$Q_{\{ij\}}$	$\square\square$	$\square$	1	1	1
$\widetilde{Q}^{\{ij\}}$	$\overline{\square\square}$	1	$\overline{\square}$	-1	1
G_μ	Adj	0	0	0	0

Here Q and $\widetilde{Q}$ are Weyl fermions.

The A-type is obtained by substituting $\square\square$ with $\begin{smallmatrix}\square\\ \square\end{smallmatrix}$.

Phase Diagram for the S-Theory



Phase diagram as function of N_f and N. [Sannino-Tuominen]

For N=2,3,4,5 we have that $N_f = 2$

Nf=2 & N=2:

Minimal-Walking-Theory

$$\begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \quad U^a_R, \quad D^a_R \qquad a = 1, 2, 3$$

$$\begin{pmatrix} N \\ E \end{pmatrix}_L \qquad N_R \quad E_R$$

Universal critical number of flavors in the adjoint: Nf=2.075

S-parameter

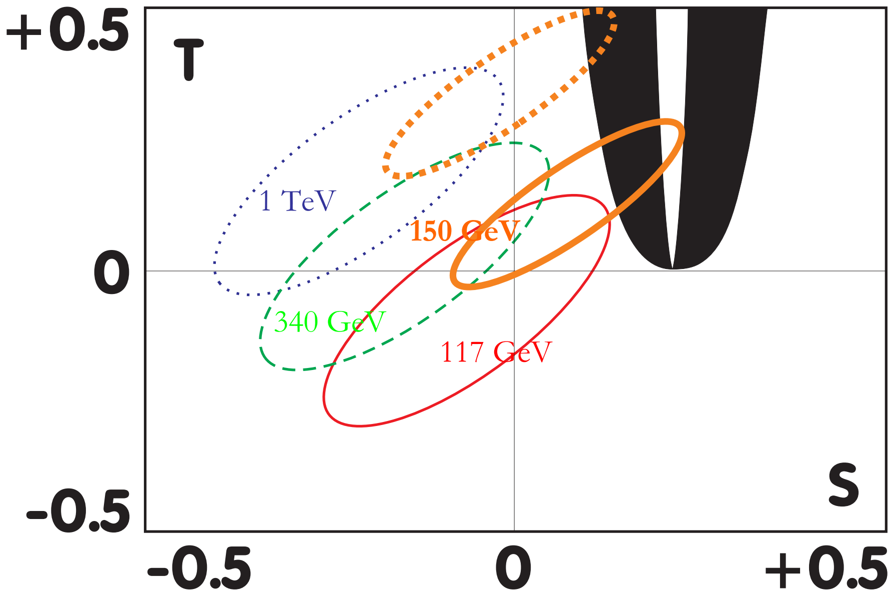
$$S = \left(\frac{1}{6\pi} - \delta\right) \frac{N(N+1)}{2} \cdot \frac{N_f}{2}$$

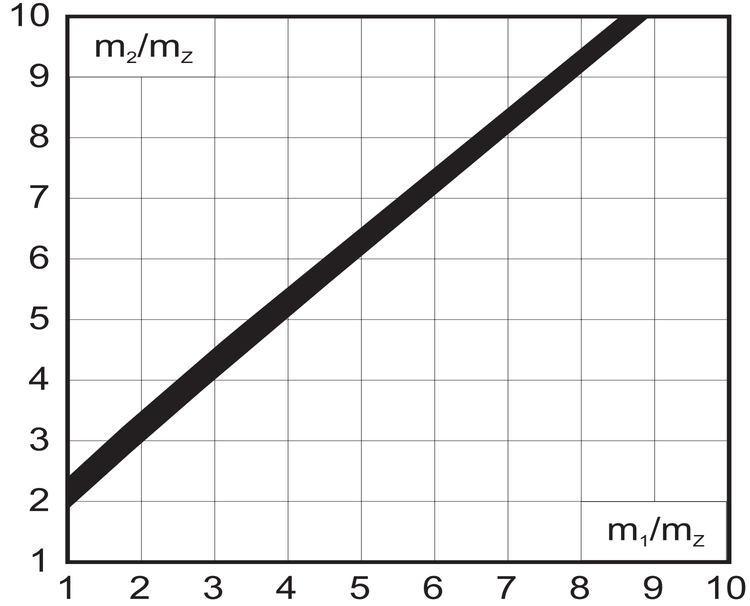
- $\delta \sim 0.013$ due to near conformal dynamics [Sundrum-Hsu, Appelquist-Sannino].

- The estimate for **S** in the S-type model is:

$$S(N=2, N_f=2) \simeq 0.1$$

Model versus EWPData





4th Lepton Family

68% contour

Electron (m2) and Neutrino (m1) Dirac masses.

Standard Hypercharge Assignment

A natural LCH

- Via trace anomaly and the behavior of the underlying beta function near the chiral/conformal phase transition we show:

$$M_H^2(N_f) \propto N_f^c - N_f$$

	QCD-like	WTC(3, 11)	WTC(2, 7)	S(3, 2)	S(2, 2)
$m_H(\text{GeV}) \approx$	1000	400	300	170 – 300	90 – 150

Some Predictions and Outlook

- $M_H \sim$ very light
- Fourth Family of Leptons around the Z mass.
- 6 light scalars will be observed.
- Electroweak baryogenesis.
  Possible Strongly First order phase transition.
- Lattice Simulations are starting
- Look at possible DM candidate
- Dynamically EW symmetry breaking is very much alive ☺