



SMR.1832-1

***SPRING SCHOOL ON SUPERSTRING THEORY
AND RELATED TOPICS***

22 - 30 March 2007

Physics beyond the Standard Model and the LHC

PART 1

**M. SCHMALTZ
Department of Physics
Boston University
509 Commonwealth Ave.
Boston, MA 02215
U.S.A.**

Physics Beyond the Standard Model (and the LHe)

Martin Schmaltz

Boston University

Preview =

Lecture 1: motivation, the Standard Model
electroweak symmetry breaking,
SM success and failure

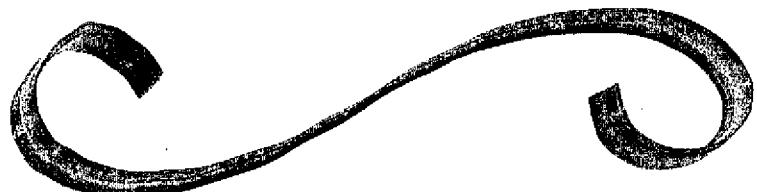
Lecture 2: SUSY , why it's great and
why it stinks !

Lecture 3: little higgs , what it does
well and what not

Lecture 4: to be announced

Lecture 1:

- the LHC
 - effective Standard Model
 - Naturalness problems
 - indirect constraints on
New Physics
- Model requirements



the LHC :-

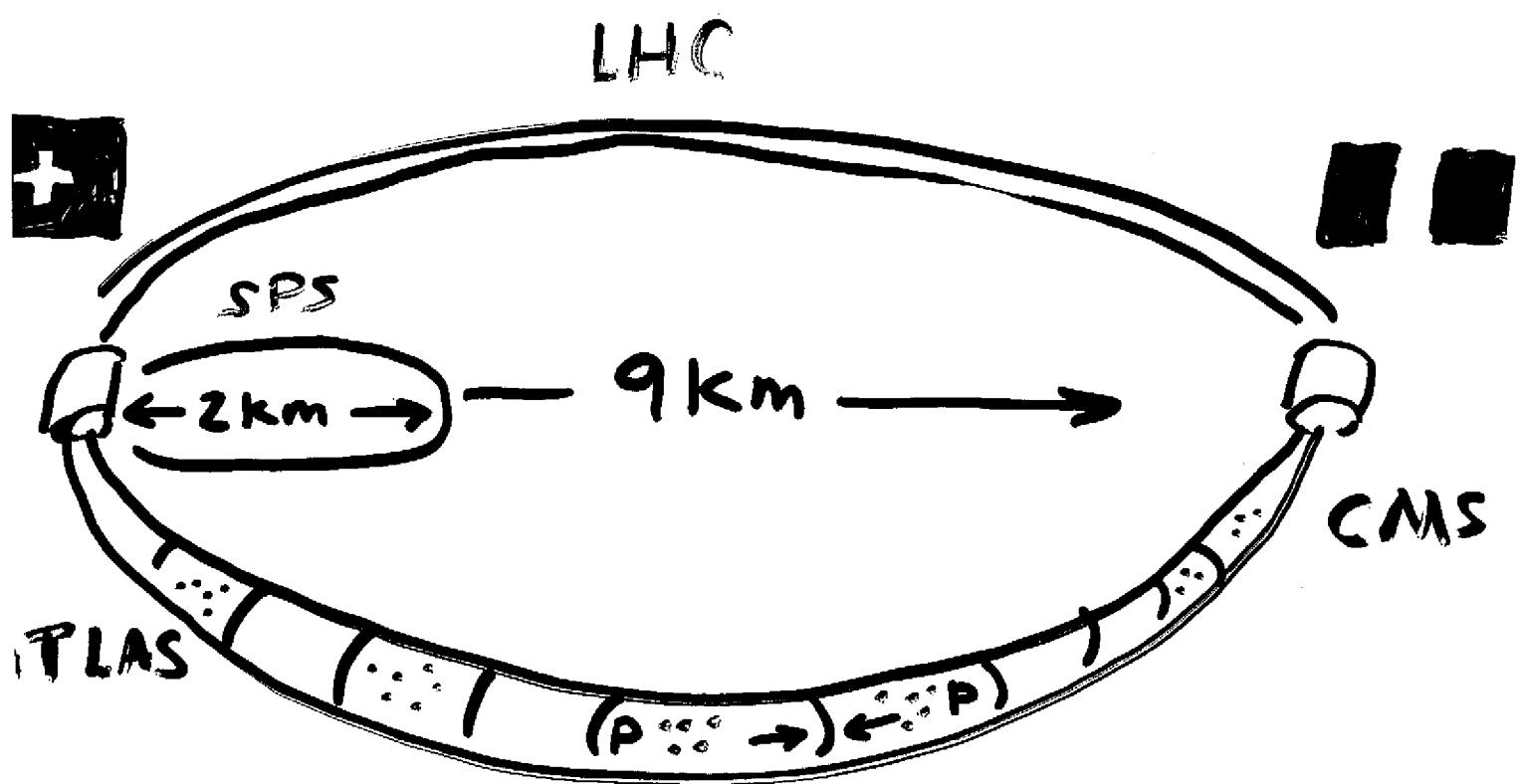
- 14 TeV in Aug 2008.
- 900 GeV in Nov 2007
- Approved in 1994
- SSC canceled (40 TeV) 1993
- Schmitz starts PhD 1992

Goal :-

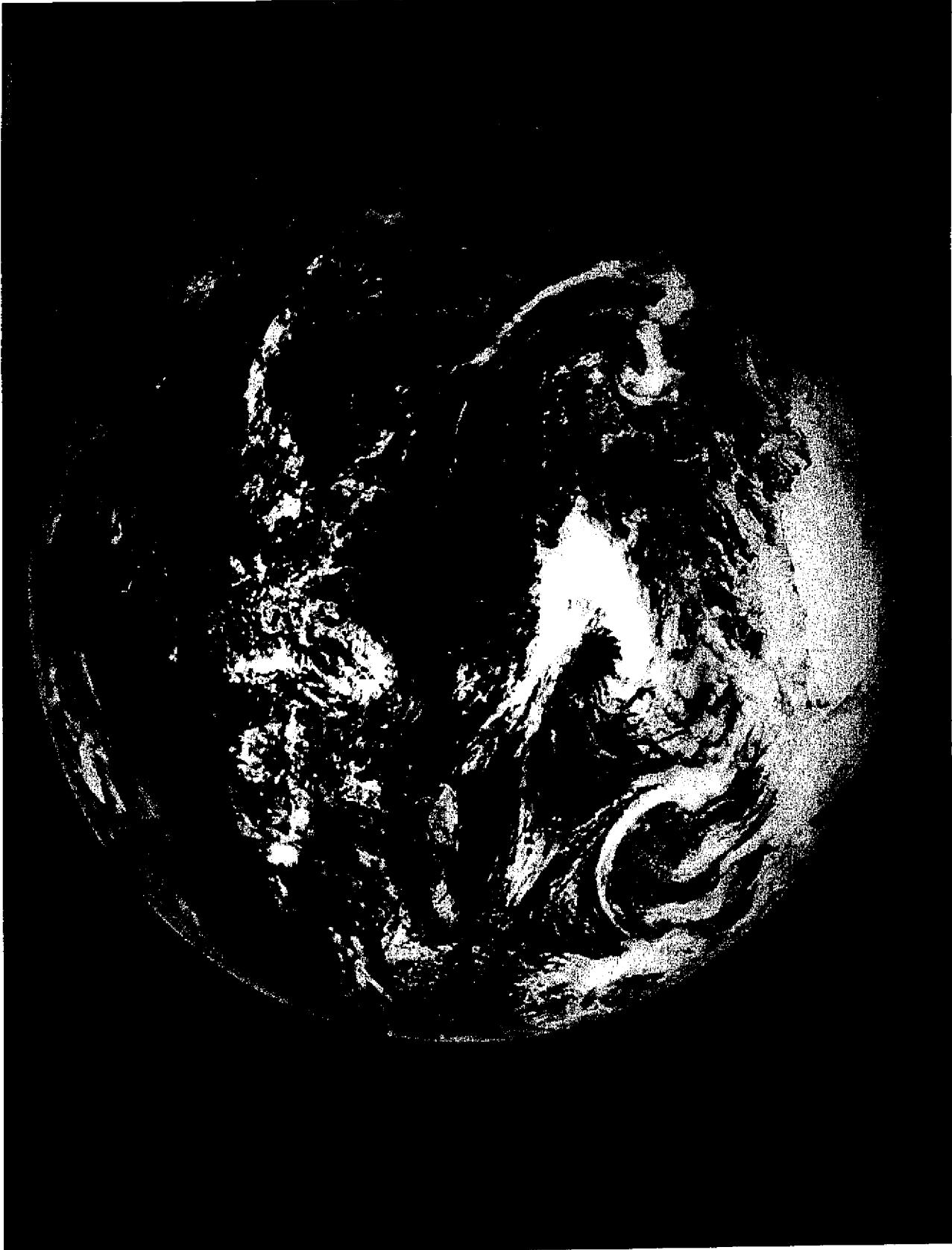
- explore TeV energy frontier
- electroweak symmetry breaking



Theorists view of the LHC



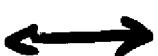
Fermi's dream machine



The short distance/high energy
frustration:



1 m



10^{-7} eV



$1 \text{ \AA} = 10^{-10} \text{ m} \leftrightarrow \text{KeV}$

LHC

10^{-20} m



14 TeV

What do we
expect to see
@ the

LHC

?

What do we know?

- particles with masses \leq TeV
- symmetries
- interactions

conveniently summarized
with an

Effective Field Theory,
the Standard Model

EFT:

- identify degrees of freedom and symmetries
- write most general action for d.o.f. respecting symmetries
- roughly $S = \int d^4x \Lambda^4 \mathcal{L}(\frac{\phi}{\Lambda}, \frac{\partial}{\Lambda})$
where $\Lambda = \Lambda_{UV}$ ultraviolet cut-off
(there can also be a Λ_{IR})
- naturalness, no coeffs in \mathcal{L} small without a "reason"

The Standard Model EFT(E):

Symmetries : 1 Poincaré

$$1 \text{ SU}(3) \times \text{SU}(2) \times \text{U}(1)$$

d.o.f. :

	SU(3)	SU(2)	U(1)	
Q	□	□	$\frac{1}{6}$	} x 3
U	□	-1	$-\frac{2}{3}$	
D ^c	□	-1	$\frac{1}{3}$	
L	1	□	$-\frac{1}{2}$	
E ^c	1	1	1	

spin $\frac{1}{2}$



2-component left-handed spinors

$$\text{Lorentz} \approx \text{SU}(2)_L \times \text{SU}(2)_R$$

$$\psi_L = (\psi_2, 0) \quad \psi_R = (0, \psi_2)$$

$$\psi^c = \sigma_2 \psi_R^* = (\psi_2, 0)$$

the SM EFT (II) :

Spin 1 fields : $SU(3) \times SU(2) \times U(1)$ gauge field

D fermion kinetic terms:

e.g. $Q_i^T i(\not{D} - i g_3 \not{A}_3 - i g_2 \not{A}_2 - i g_1 \frac{1}{c} \not{B}) Q_i$

$\begin{matrix} 1 \\ SU(3) \end{matrix}$
 $\begin{matrix} 1 \\ SU(2) \end{matrix}$
 $\begin{matrix} 1 \\ U(1) \end{matrix}$
 $\begin{matrix} \swarrow \\ 3 \text{ generations} \end{matrix}$

$$A = A_\mu^a \sigma^\mu T^a$$

\uparrow
 $\begin{matrix} \nearrow \\ \text{gauge generator} \end{matrix}$
 $\begin{matrix} \searrow \\ \text{Lorentz generator} \end{matrix}$

● gauge kinetic terms: $\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

■ no mass terms allowed!

Spin 1 : $m^2 A_\mu A^\mu$ not gauge invariant

Spin k_2 : $m \gamma_\alpha \gamma_\beta \epsilon^{\alpha\beta}$ not invariant for any γ, γ'

SM EFT (III):

	SU(3)	SU(2)	U(1)
Q u^c	1	0	- $\frac{1}{2}$
Q d^c	1	0	$\frac{1}{2}$
L e^c	1	0	$\frac{1}{2}$

introduce scalar: $\phi = (1, 0, +\frac{1}{2})$
 $\sigma_2 \phi^* = (1, 0, -\frac{1}{2})$

with VEV: $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} 0 \\ v \end{pmatrix} + \delta \phi$

fermion masses: $\lambda_u Q \phi u^c + \lambda_d Q \phi^* d^c$
 $+ \lambda_e L \phi^* e^c$

BONUS! W, Z masses from Higgs mechanism
 (Kibble, Englert, Brout, Guralnik, Hagen
 also Anderson in cond. matt.)

$$|D_\mu \phi|^2 \sim |(g_2 W_\mu + \frac{1}{2} g_1 B_\mu) \phi|^2$$

$$m_W = \frac{g_2 v}{2} \quad m_Z = \sqrt{\frac{g_1^2 + g_2^2}{2}} v$$

$$\sim 80 \text{ GeV}$$

$$\sim 91 \text{ GeV}$$

The SM EFT Lagrangian

$$\mathcal{L} \approx \Lambda^4 \mathbf{1} + \Lambda^2 H^\dagger H$$

$$+ \frac{\lambda}{4} (H^\dagger H)^2 + \mathcal{L}_{\text{kinetic}} + \mathcal{L}_{\text{Yukawa}} + \Theta F_3 \tilde{F}_3$$

$$+ \frac{(L H^*)^2}{\Lambda} + \frac{(H^\dagger D_\mu H)^2}{\Lambda^2} + \frac{H^\dagger F_2^{\mu\nu} H B_{\mu\nu}}{\Lambda^2}$$

$$+ \frac{QQQL}{\Lambda^2} + \frac{(D_i^c \gamma_\mu D_j^c)^2}{\Lambda^2} + \text{many more } D=6$$

$$+ \frac{(\quad)}{\Lambda^3} + \dots$$

$\Lambda = \Lambda_{uv} \sim$ largest scale for which EFT is valid

\leftrightarrow scale of UV physics which has been integrated out to produce this operator

2 Naturalness Disasters

$$\mathcal{L} \sim \Lambda_{\alpha}^4 \mathbf{1} \quad \text{cosmo const.}$$

$$\Lambda_H^2 H^+ H^- \quad \text{Higgs soft mass}$$

quantum corrections in the SM EFT:

$$\delta \Lambda_{cc}^4 \approx \frac{1}{16\pi^2} \Lambda_{uv}^4$$



$$\delta \Lambda_H^2 \approx \frac{\Lambda_{uv}^2}{16\pi^2} \left(2M_W^2 + \frac{M_Z^2 + M_H^2 - 4m_t^2}{\sqrt{2}} \right) \dots$$

experiment:

$$\Lambda_{cc} \sim 3 \cdot 10^{-3} \text{ eV} \implies \Lambda_{uv} \lesssim 10^{-2} \text{ eV}$$

$$\Lambda_H \sim 200 \text{ GeV} \implies \Lambda_{uv} \lesssim 1 \text{ TeV}$$

Naturalness disasters cont'd

- + we already explored physics in the regions $10^{-2} \text{ eV} \rightarrow \text{TeV}$
- + we have evidence for loop corrections:
 - running couplings
 - precision measurements ~~on~~

► Somehow quantum fluctuations at scales

$\gtrsim \Lambda_{\text{cc}}$ don't show up in $\delta \Lambda_{\text{cc}}$

$\gtrsim \Lambda_H$ " " " $\delta \Lambda_H$

// fine-tuning to cancel these contributions is //
inconsistent with naturalness!

an example for fine-tuning

Veltman condition:

$$2M_W^2 + M_Z^2 + M_H^2 - 4m_t^2 = 0$$

no symmetry! This is fine tuning.

! what if we measure $M_H = 4m_t^2 - 2M_W^2 - M_Z^2$?

! it's still fine-tuning:

$$\begin{aligned} S\Lambda_H \approx & \frac{\Lambda_{uv}^2(\text{gauge})}{16\pi^2} \frac{2M_W^2 + M_Z^2}{v^2} + \frac{\Lambda_{uv}^2(\text{Higgs})}{16\pi^2} \frac{M_H^2}{v^2} \\ & - 4 \frac{\Lambda_{uv}^2(\text{top})}{16\pi^2} m_t^2 \end{aligned}$$

the different Λ_{uv} 's correspond to unbroken
UV physics!

Solutions to the fine-tuning problems

1. forbid the bad operator with a symmetry
2. cancel the quantum corrections with
New physics related by a symmetry

- * don't seem to work for C.G.!
- * SUSY, little Higgs do 2. }
technicolor does 1. } for Higgs

the desperate "solutions":

3. anthropics , ignore the problem

Let's proceed - we

- ignore the Cosmo. Const.
- anticipate solving the Higgs naturalness problem with new physics at $\sim \text{TeV}$

→ this new physics has already been integrated out in the SM EFT and is now indirectly seen in operators with $(\frac{1}{\Lambda_{NP}})^n$ coeffs.

example: $Z'_\mu l^+ \sigma^\mu l + m_{Z'}^2 (Z'_\mu)^2$

$$\begin{array}{c} \text{Feynman diagram: two fermion lines meeting at a vertex labeled } Z'_\mu, \text{ with a wavy line representing a gauge boson line attached to the same vertex.} \\ \Rightarrow \frac{1}{m_{Z'}^2} (l^+ \sigma^\mu l)^2 \end{array}$$

experiment

$$\theta_{\text{exo}} \lesssim 10^{-10}$$

O

solutions: - axion

- Nelson - Barr

- SUSY + ...

New physics

QQQL and Proton decay

$$\Gamma(p \rightarrow X) \sim \frac{m_p^5}{\Lambda^4}$$

dimensional analysis

$$\tau_p \gtrsim 10^{33} \text{ yrs}$$

SUPER-K
can you derive this limit?

↳ $\boxed{\Lambda \gtrsim 10^{13} \text{ TeV}}$

any new physics below 10^{13} TeV must have a symmetry to forbid this operator :
Baryon number or Lepton number

→ proton decay irrelevant for LHC, ignore QQQL.

$\frac{(LH^*)^2}{\Lambda}$ and ν masses

$$\left(\frac{LH^*}{\Lambda}\right)^2 \Rightarrow \frac{v^2}{\Lambda} \nu\nu \quad \text{neutrino mass}$$

Bonus: the SM EFT explains small ν masses if $\Lambda \gg v$

experiment: $m_\nu \sim 10^{-1} \text{ eV} \Rightarrow \boxed{\Lambda \sim 10^{11} \text{ TeV}}$

any physics below 10^{11} TeV should approx.
preserve lepton number.

→ neutrino masses irrelevant for LHC
we ignore them

$\frac{(d^+ s)^2}{\Lambda^2}$ and flavor

↳ $K \bar{K}$ mixing : $\boxed{\Lambda \gtrsim 10^3 \text{ TeV}}$

- ⇒ new physics below 10^3 TeV must preserve approximate flavor symmetry (and CP)
- ⇒ no (1st and 2nd generation) flavor physics at the LHC, we ignore

$\frac{(H^\dagger D_\mu H)^2}{\Lambda^2}$ and δ_F or T parameter

\hookrightarrow contains $\frac{v^4}{\Lambda^2} Z_{\mu\nu} Z^\mu$, a shift in the Z -mass
(and not the W -mass)

$$\delta_F \equiv \frac{S m_Z^2}{m_Z^2} \approx \frac{v^2}{\Lambda^2} < \text{few} \cdot 10^{-3}$$

$$\Rightarrow \boxed{\Lambda \gtrsim 5 \text{ TeV}}$$

this is potentially a disaster, we want new physics, coupling to the Higgs (for naturalness) with mass $\Lambda \lesssim 1 \text{ TeV}$.

Is there a symmetry which can forbid

$$\frac{(H^\dagger D_\mu H)^2}{\Lambda^2} ?$$

Custodial symmetry and T

define: $\Sigma = \begin{pmatrix} H^c & H \\ H & H^* \end{pmatrix}$ with $H^c = i\sigma_2 H^*$

$\uparrow \uparrow$
both transform like $SU(2)$ doublets

transform $\Sigma \rightarrow U_{\text{weak}} \sum U_{\text{cust.}}^+$

$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$ breaking

$SU(2)_{\text{weak}} \times SU(2)_{\text{cust.}} \rightarrow SU(2)_{\text{diag.}}$

unbroken $SU(2)_{\text{cust.}}$ implies unbroken $SU(2)_{\text{diag.}}$

$\Rightarrow W$ and Z form massive triplet and

$$m_W = m_Z$$

Hypercharge breaks custodial symmetry

$$D_\mu \Sigma = \partial_\mu \Sigma - ig_2 \vec{A}_2 \cdot \frac{\vec{\sigma}}{2} \Sigma - ig_1 B \Sigma \frac{\sigma_3}{2}$$

$$\text{tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) \approx |D_\mu H|^2$$

Custodial symmetry & T (II)

$$\frac{1}{\Lambda^2} (H^\dagger D_\mu H)^2 \Rightarrow \frac{1}{\Lambda^2} \text{Tr} (\Sigma^\dagger D_\mu \Sigma \sigma_3)^2$$

↑
not $SU(2)_{\text{cust.}}$
invariant

⇒ we probably want new physics at
 $\sim 1 \text{ TeV}$ to preserve custodial symmetry
but we may get away without and
some cancellations (fine tuning).

$H^+ \frac{W_{\mu\nu} H}{\Lambda^2} B^{\mu\nu}$, the S parameter

$\approx \text{tr}(\Sigma^\dagger W_{\mu\nu} \Sigma) B^{\mu\nu}$ custodial $\text{SU}(2)$ invariant

$\approx |D_{[\mu} D_{\nu]} H|^2$ invariant under everything

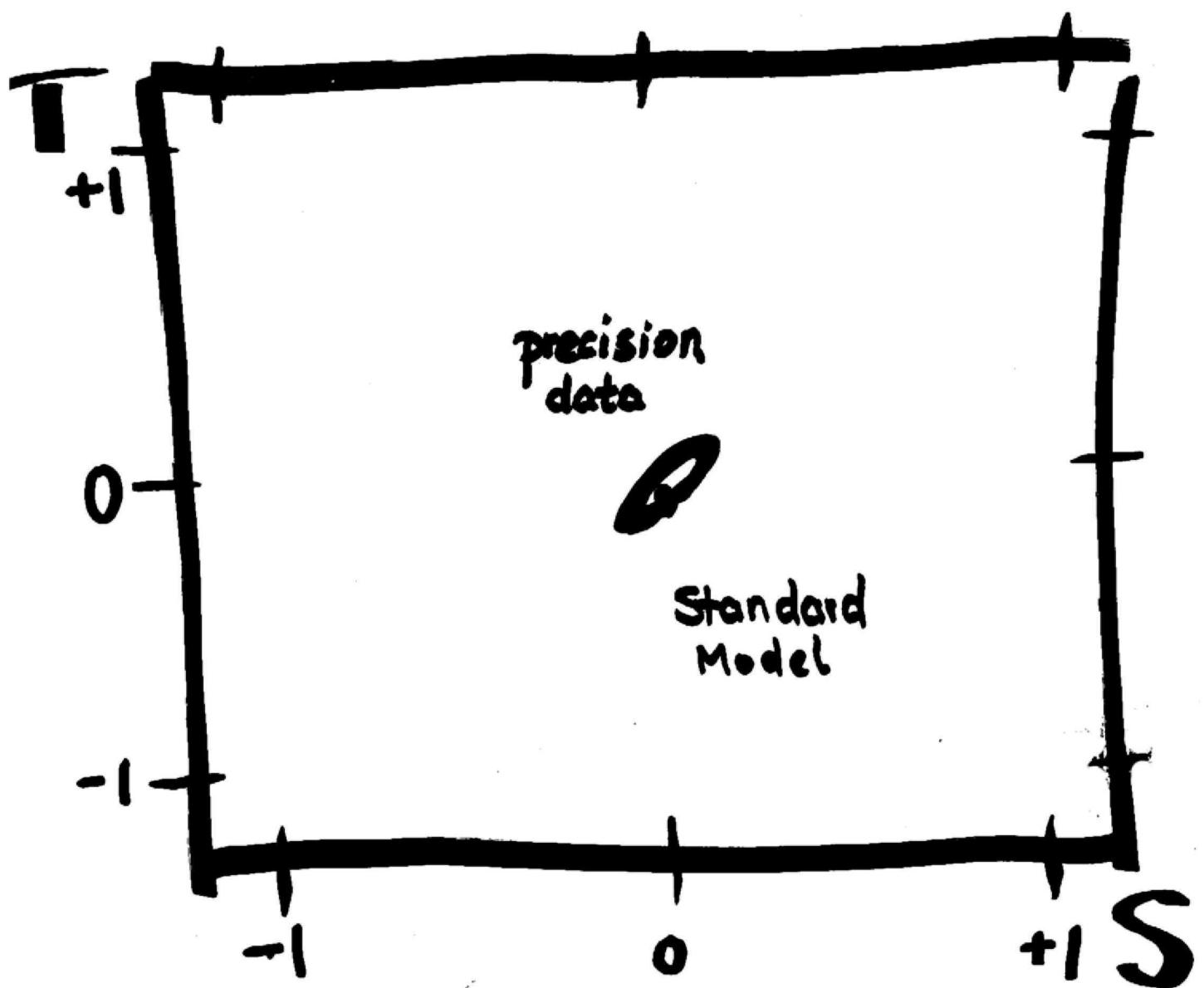
S cannot be forbidden by symmetry !

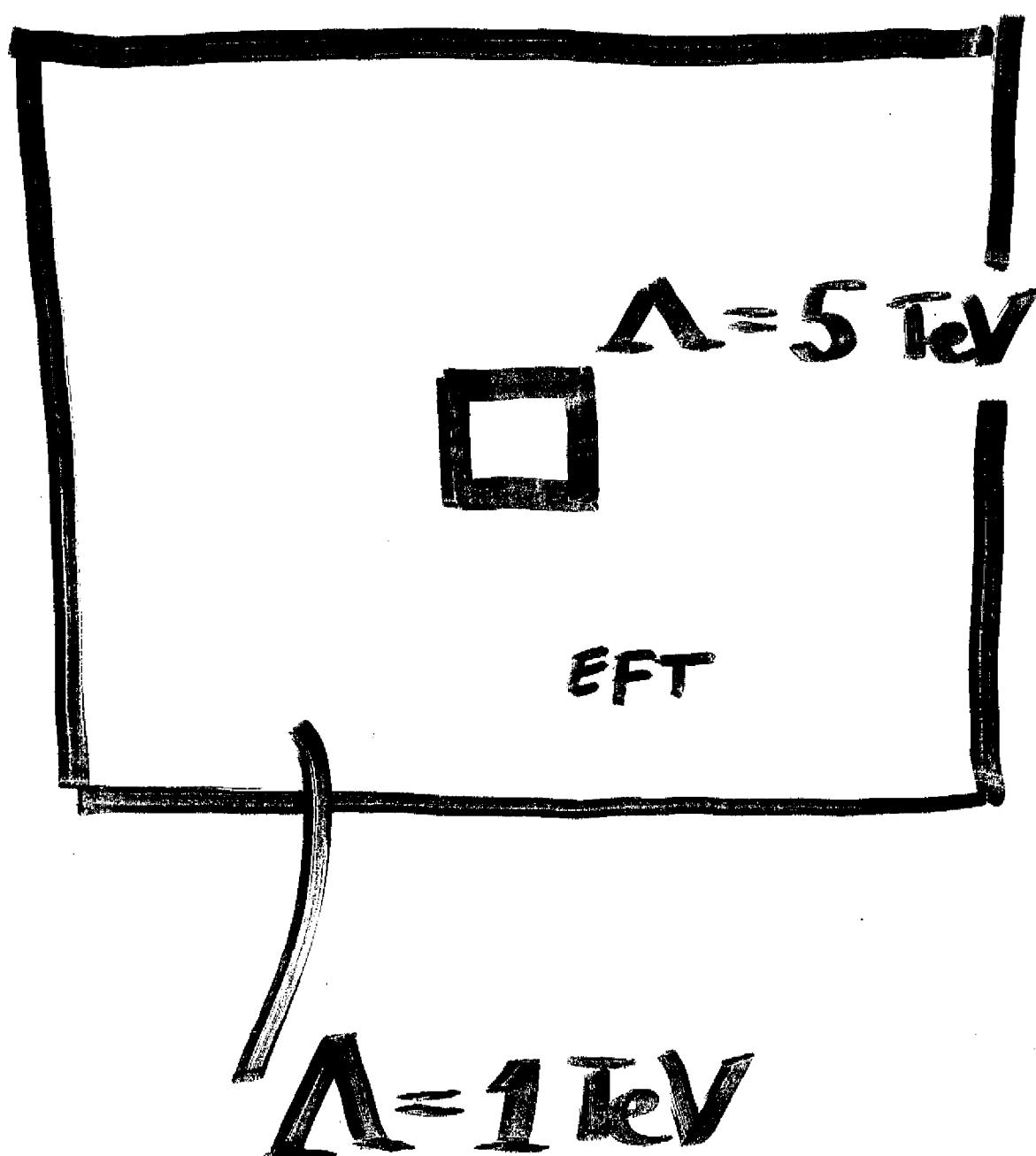
$H^+ \frac{W_{\mu\nu} H}{\Lambda^2} B^{\mu\nu} \rightarrow \frac{v^2}{\Lambda^2} W_{\mu\nu}^3 B^{\mu\nu}$ kinetic mixing
of Z, γ

experiment: $\boxed{\Lambda \gtrsim 5 \text{ TeV}}$

new physics at TeV will have to somehow
avoid this operator !

S-T ellipse





Precision EW constraints

- ★ 19 operators of dim. 6 which preserve
B,L , flavor
- ★ 10 are constrained at level $\Lambda \gtrsim \text{few TeV}$
(LEP 1+2, SLD)
- ★ S,T are often present in new physics
 \Rightarrow focused on these

Conclusion

whatever the new physics at $\sim 1 \text{ TeV}$ is,
it must be "clever" to avoid the
PEW constraints which probe up to
 5 TeV

Model Requirements =

- ★ Effective field theory valid up to $\Lambda \sim 5-10$ TeV (LHC energy)
- ★ Natural (except c.c.)
- ★ satisfy experimental constraints
 - Precision EW
 - flavor
 - $B\&L$ violation (proton decay)