



*The Abdus Salam  
International Centre for Theoretical Physics*



**SMR. 1832-2**

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

*22 - 30 March 2007*

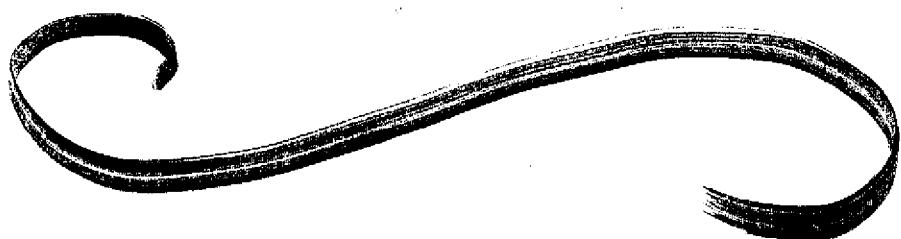
**Physics beyond the Standard Model and the LHC  
PART 2**

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# lecture 2.

- Precision Electro-Weak
- the MSSM  
R-parity  
Soft masses
- MSSM scorecard

N. Luty hep-ph/0509029



# Yesterday = SM EFT

$$\mathcal{L} \sim \Lambda_{cc}^4 + \Lambda_H^2 H^\dagger H + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \dots$$

Maybe we  
can't understand  
gravity at  
 $\approx 10^{-3}$  eV

need new  
physics at  
 $\sim 1$  TeV

the successes  
of the SM  
lie here,  
precisely  
tuned!

$\nu$ -mass

$$P_6 \rightarrow \cancel{\beta}, \cancel{\gamma}, \text{ flavor} + \frac{(f^+ f)^2}{\Lambda^2} + \frac{(H^\dagger D_\mu H)^2}{\Lambda^2} + \frac{H^\dagger W H B}{\Lambda^2}$$

easily suppressed by symmetries

$\Delta \gtrsim 5 \text{ TeV}$

+ ...

LEPII

T

S

Sg or T:

$$\frac{(\underline{H}^\dagger \underline{D}_\mu \underline{H})^2}{\Lambda^2} \xrightarrow{\langle H \rangle = (0)} \frac{y^4}{\Lambda^2} (Z_\mu)^2$$

a shift in  $m_Z$  relative to  $m_W$

$$f_0 = \frac{\delta m_Z^2}{m_Z^2} \approx \frac{v^2}{\Lambda^2} \stackrel{\text{expt.}}{<} \text{few} \cdot 10^{-3}$$

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

tension: need new physics coupling to Higgs  
at 1 TeV but it should not generate  
T.

"Custodial symmetry" can forbid T generation

# S parameter:

$$\frac{H^+ W_{\mu\nu} H B^{\mu\nu}}{\Lambda^2} \xrightarrow{\langle H \rangle} \frac{v^2}{\Lambda^2} Z_{\mu\nu} \gamma^{\mu\nu}$$

kinetic mixing of  $Z$  and  $\gamma$

expt:

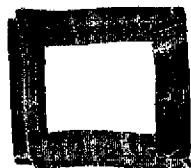
$$\boxed{\Lambda \geq 5 \text{ TeV}}$$

$S$  cannot be forbidden by a symmetry!

$S$  contained in  $D^2 H^+ D^2 H$  which has the same symmetry structure as  $D H^+ D H$

$\Rightarrow$  new physics at 1 TeV will have to "accidentally" not generate a large  $S$  param.

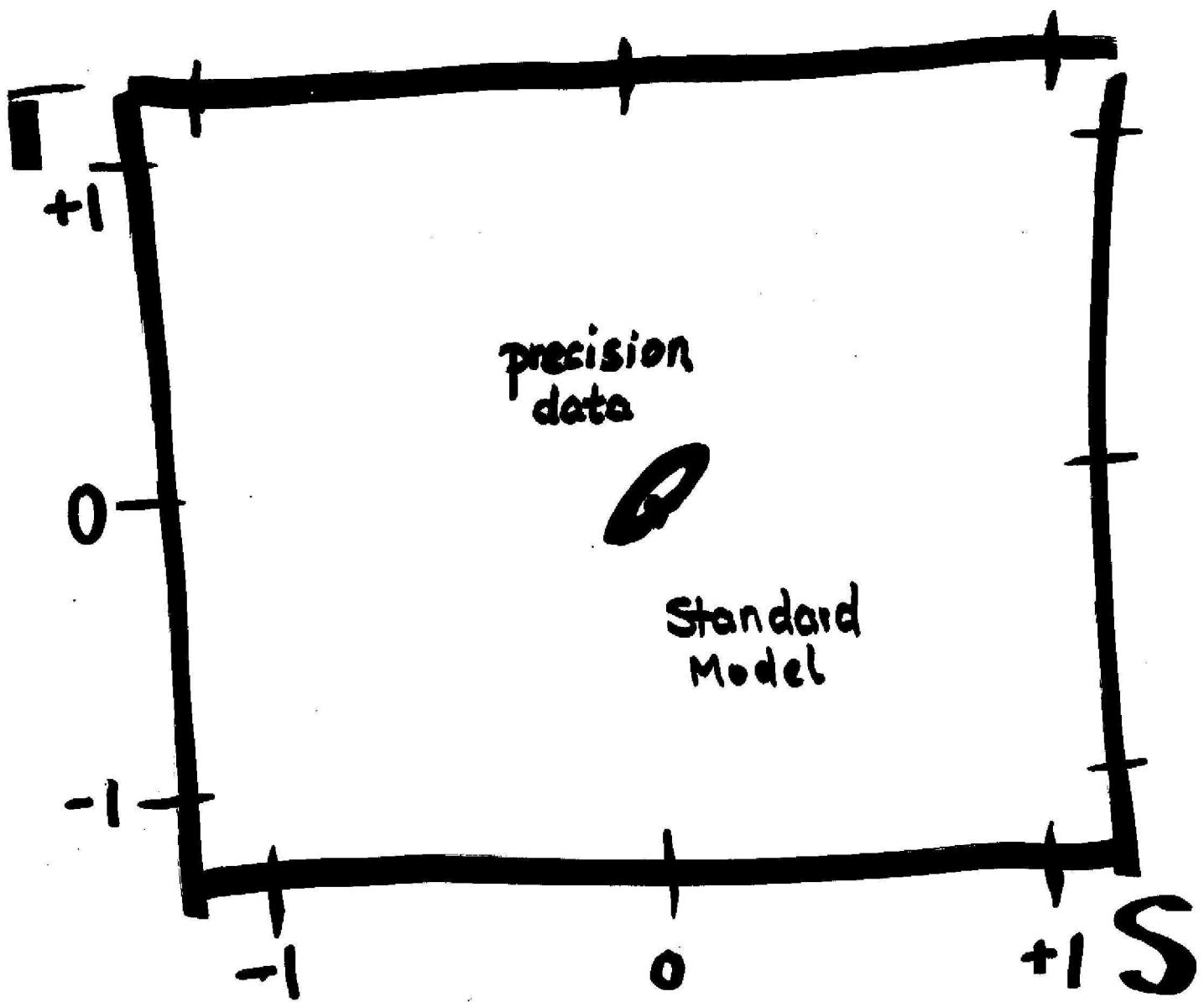
$\Lambda = 5 \text{ TeV}$



EFT

$\Lambda = 1 \text{ TeV}$

# S-T ellipse



# Summary

- the unnaturalness of the Higgs bi-linear motivates new physics at  $\approx 1 \text{ TeV}$
- the precision EW data severely constrain new physics up to 5 TeV, even if we impose symmetries like  $B, L, \text{flavor}$ .  
*little hierarchy problem*

“LEP paradox” is  
Italian R. Barbieri

# 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)

# Example : MSSM

we susyfy :

- chiral superfields

$Q U^c D^c L E^c \times 3$

- vector superfields

$SU(3) \times SU(2) \times U(1)$

- Higgs chiral superfields

$H_u \ H_d$

← needed for Yukawa  
and anomalies

# SUSY preserving interactions =

$$\mathcal{L} \sim \int d^4\theta K + \int d^2\theta W$$

Kähler terms:  $K = Q_i^+ e^\nu Q_i + \dots$

Superpotential:

$$W = \mu H_u H_D + \mu'_i L_i H_u$$

$$+ \lambda_{ij}^u Q_i H_u U_j^c + \lambda^d Q H_D D^c + \lambda^e L H_D E^c$$

$$+ L Q D^c + L L E^c + U^c D^c D^c$$

$$+ \frac{(L H_u)^2}{\Lambda} + \frac{\underline{Q Q Q L}}{\Lambda} + \dots$$

Immediate problem =

$\mu^* L H_u, L Q D^c, L L E^c, U^c D^c D^c$

violate L & B badly

$\Rightarrow$  proton decay,  $N \bar{N}$  oscillations,  
neutrino less double  $\beta$  decay, ...

Immediate fix =

impose B, L as global symmetries

more efficient: R-parity.

$$\Phi(\theta) \rightarrow \pm \bar{\Phi}(-\theta)$$

QUDLE

$H_u H_d$

$W_\alpha$

"-"  
"+"

SM particles even,  
superpartners odd

# An embarrassment =

$\mu$  Higgs is still not natural !  
(need  $\mu < \text{TeV} \ll \Lambda_{\text{uv}}$ )

\* it's "technically natural":

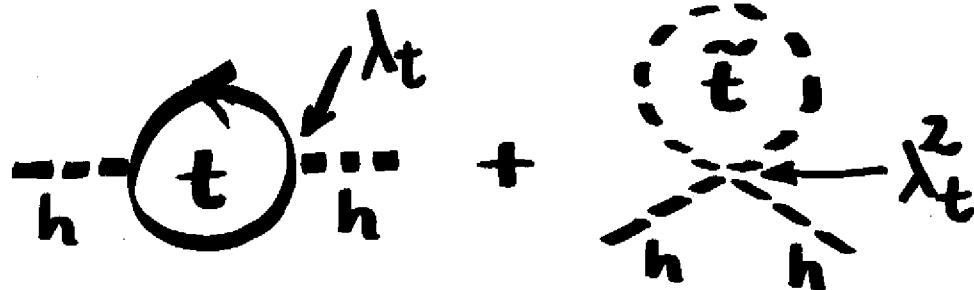
setting  $\mu=0$  gives a new symmetry

e.g. R-symmetry : QUDLE  $\leftrightarrow$  1  
 $H_u H_d \leftrightarrow 0$

$\Rightarrow$  quantum corrections cannot  
generate the  $\mu$ -term ■

(the Yukawa couplings in the SM  
are also technically natural, the  
symmetry: flavor)

# Quadratic divergence in Higgs mass is gone!



$$= -\frac{3}{8\pi^2} \lambda_t^2 \Lambda_t^2 + \frac{3}{8\pi^2} \lambda_{\tilde{t}}^2 \Lambda_{\tilde{t}}^2 = 0$$

SUSY relates:  $\lambda_t^2 = \lambda_{\tilde{t}}^2$

$\Lambda_t = \Lambda_{\tilde{t}}$  ← assuming  
supersymmetric  
UV cut-off

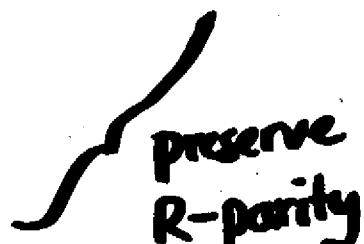
# Soft SUSY breaking

“Soft”: couplings which do not re-introduce quadratic divergences

gaugino masses:  $M_1 \lambda_1 \lambda_1 + M_2 \lambda_2 \lambda_2 + M_3 \lambda_3 \lambda_3$

scalar masses:  $m_{Q_{ij}}^2 \tilde{Q}_i^t \tilde{Q}_j + \dots$   
 $+ m_{H_u}^2 H_u^+ H_u + m_{H_d}^2 H_d^+ H_d$

A-terms :  $A_{ij} \tilde{Q}_i H_u \tilde{U}_j^c + \dots$

  
preserve  
R-parity

B-term :  $B_\mu H_u H_d$

the soft terms carry positive mass dimension

$$m^2$$

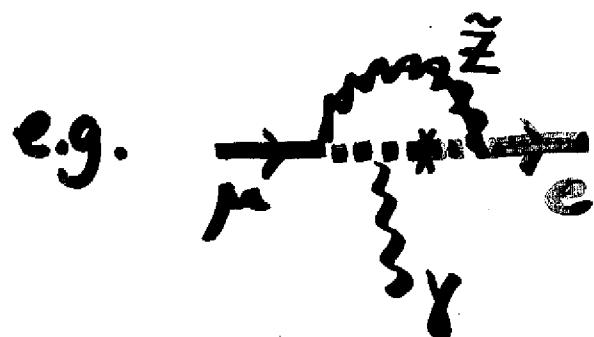


$$\sim \frac{\lambda_t^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{m_{\tilde{t}}^2}{\Lambda_{uv}^2}$$

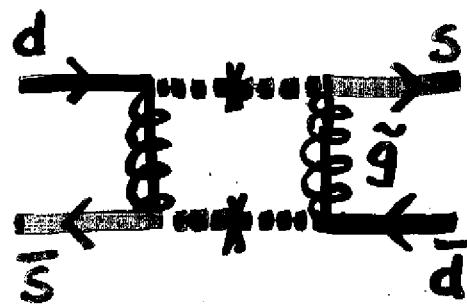
$$\sim \frac{1}{16\pi^2} A_t^2 \log \frac{m_{\tilde{E}}^2}{\Lambda_{uv}^2}$$

# flavor & CP problems

the soft terms can violate flavor and CP  
and easily violate bounds



$$\mu \rightarrow e\gamma$$



K- $\bar{K}$  mixing

generally requires

$$m_{ij}^2 = m_0^2 \delta_{ij} + \delta m_{ij}^2 \leftarrow \frac{\delta m_{12}^2}{m_0^2} \lesssim 10^{-3}$$

$$A_{ij} = A_0 \lambda_{ij} + \delta A_{ij}$$

$\Rightarrow$  separate flavor and susy breaking :

Hidden Sector SUSY breaking

**Do we have a good  
model for LHC  
physics here ?**



# Model Requirements

1. valid up to  $\Lambda_{uv} > 5\text{-}10\text{TeV}$  easy!  
😊

2. natural (except C.C.)

10% tuning (best case)



3. experimental constraints

- B&L violation      R-parity      😕
- flavor      Hidden sector SUSY breaking      😕
- Precision EW

# Natural?

$$V_H \sim \frac{t}{2} \tilde{O} - + \cancel{\frac{t}{2} \tilde{E}} = - \frac{3}{8\pi^2} m_t^2 \log \frac{M_{UV}^2}{m_t^2}$$

$t/2$        $M_{UV}/m_t^2$   
 $5-50$

$\Rightarrow$  need  $m_t \lesssim \text{few } 100 \text{ GeV}$  to avoid tuning

more precisely :

$$V_{\text{Higgs}} \sim \frac{m_H^2}{2} H^2 + \frac{g^2}{4} H^4$$

from D-terms  
 $(g_1^2 + g_2^2) / 8$

$$\Rightarrow m_H \sim g \langle H \rangle \sim m_Z$$

2 consequences :

- we need  $m_H \sim m_Z$  to avoid tuning
  - the higgs mass is too small !!!
- LEP II:  $m_H > 114 \text{ GeV}$

# bound on the Higgs mass

$$m_{H^0} = \sqrt{\lambda} \langle H \rangle$$

physical

quartic coupling  
in Higgs potential  
 $(g_1^2 + g_2^2)/8$  at tree level

$$\Rightarrow \underline{m_{H^0} \lesssim m_Z} \quad \text{at tree level, } \tan\beta \gg 1$$

(best case)

the top loop boosts the quartic

$$\delta\lambda_{\text{top}} \sim \text{loop diagram with } t + \text{loop diagram with } \tilde{t} \sim \underbrace{\frac{3\lambda_t^4}{4\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}}_{0.08}$$

$\Rightarrow$  want  $m_{\tilde{t}} \gg m_t$  to increase the log  
but that leads to fine tuning from  
the soft mass!

# Best case scenario =

$$m_{\tilde{t}} \approx 800 \text{ GeV} \rightarrow m_h \approx 115 \text{ GeV}$$

$$\begin{aligned} \text{fine tuning} &= \frac{\delta m_H^2}{m_H^2} \approx \frac{3/4\pi^2}{m_H^2} \frac{m_{\tilde{t}}^2}{m_{\tilde{t}}} \log \frac{\Lambda_{uv}}{m_{\tilde{t}}} \\ &= \begin{cases} 10\%^{-1} & \text{for } \Lambda_{uv} = 10 \text{ TeV} \\ 1\%^{-1} & \Lambda_{uv} = M_{\text{String}} \end{cases} \end{aligned}$$

or we can change the MSSM  
to try to increase the Higgs quartic

e.g: NMSSM       $W = N H_u H_d$

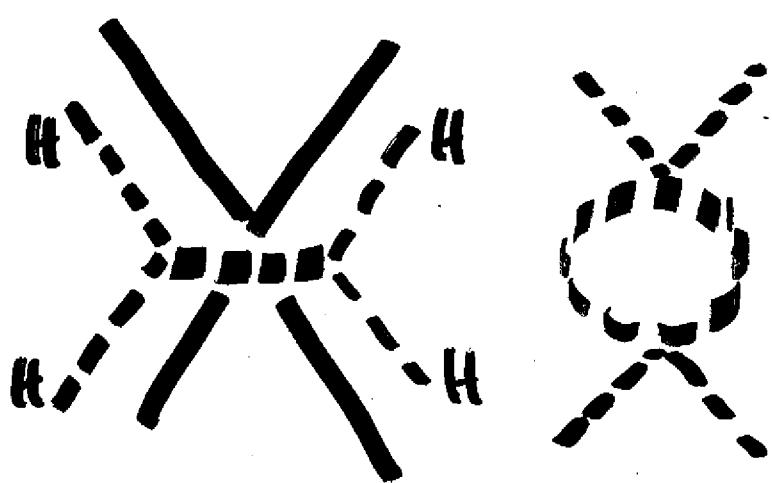
MSSM !

# Precision EW and R-parity

New physics (superpartners)  $\Theta < \text{TeV}$   
why don't we generate

$$\frac{(H^+ D_\mu H)^2}{(\text{TeV})^2} \quad (\Gamma)$$

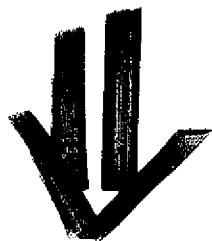
R-parity requires virtual superpartners to be in loops !



$$\approx \frac{1}{16\pi^2} \frac{1}{(\text{TeV})^2}$$



# R-parity



lightest superpartner  
is stable

DARK MATTER

