New Physics at the LHC: maybe the little higgs?

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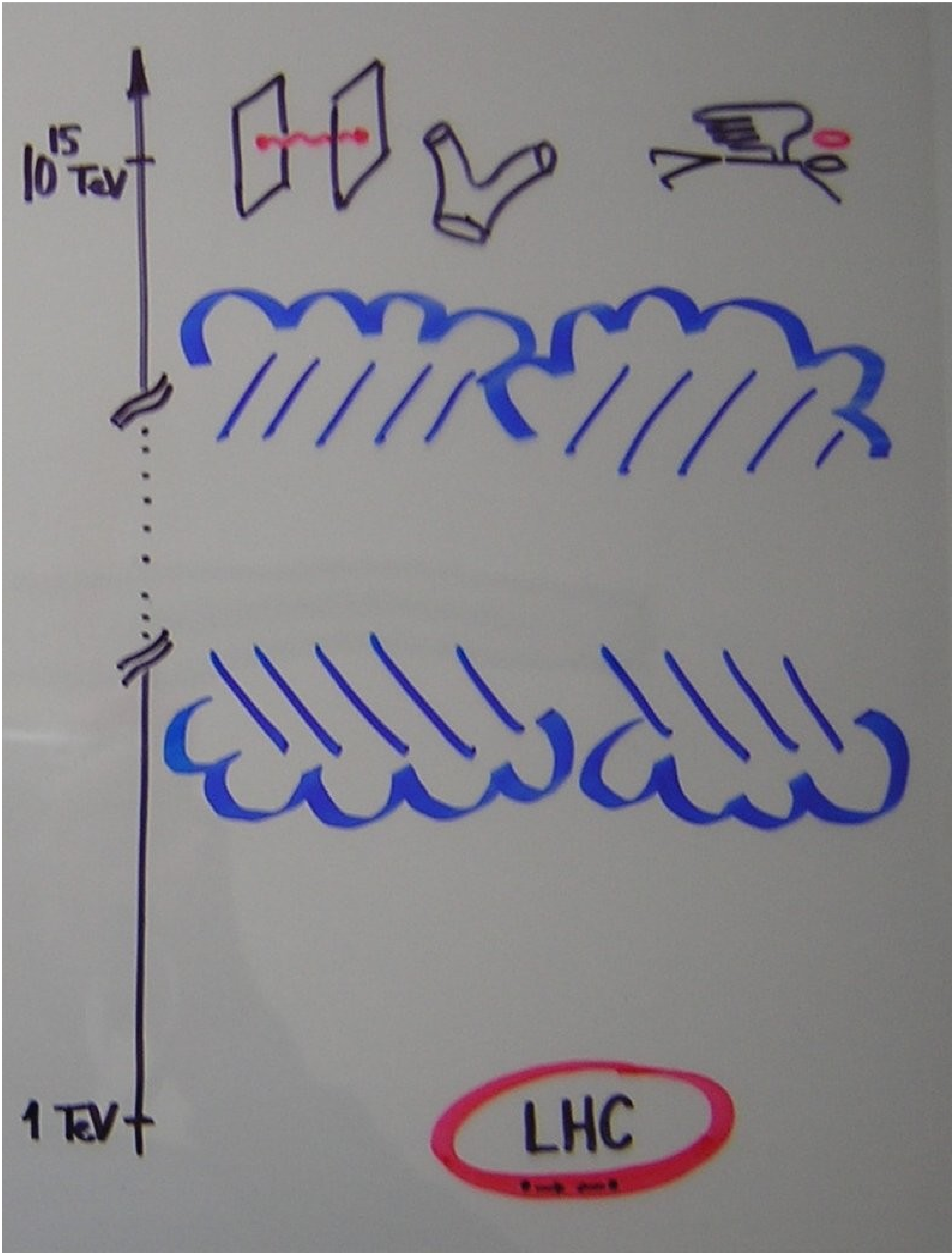
today's lecture

- why do we expect to find the Higgs at the LHC?
  - Unitarity
  - precision EW experiments
- why we expect more than the Higgs
  - naturalness

tomorrow

- physics beyond the SM
  - partners
  - little Higgs
  - T-parity

Why do we expect new Physics at the LHC ?



10 15 TeV
1 TeV
LHC

1. Why not ?!

1 order of magnitude in energy, there's got to be something there!

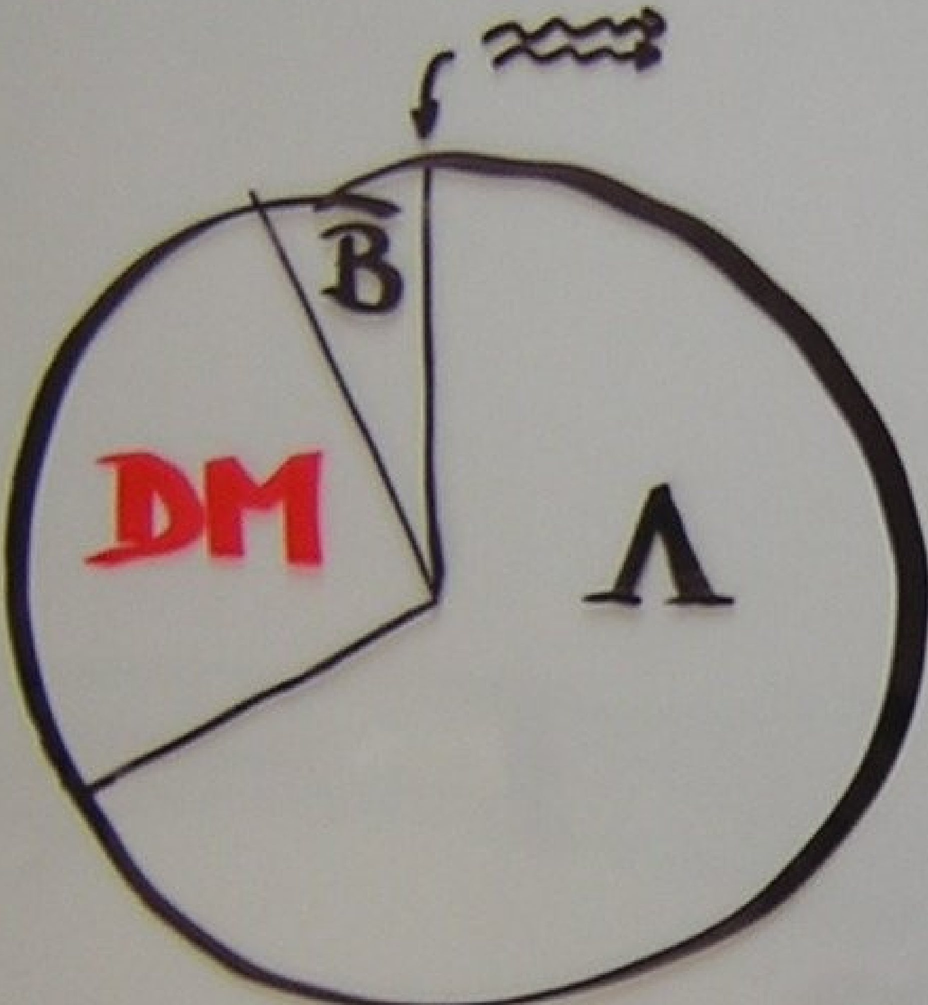
2 definitions for New physics :

Experimenter : anything we have not directly produced in the lab

Theorist : anything outside the Standard Model

the difference : Higgs

2. dark matter

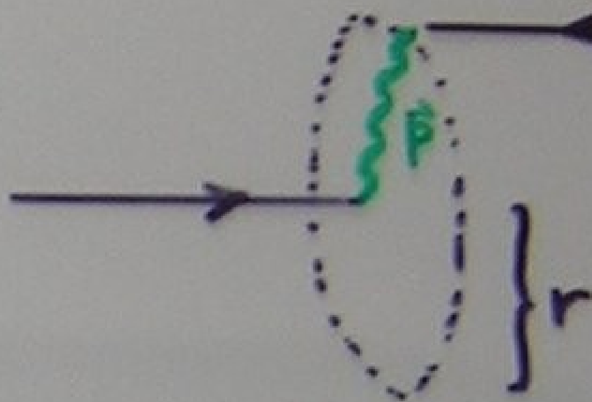


big bang + <u>weakly</u> <u>interacting</u> <u>stable</u> particle gives correct abundance

3. Unitarity

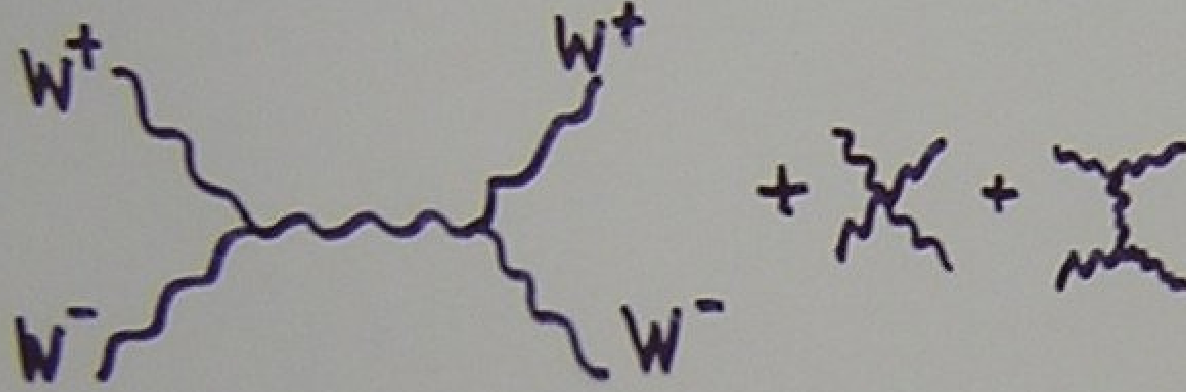
cross section σ bound

QM:



$$\sigma(E_{cm}^2) \approx r^2 \lesssim \left(\frac{\hbar}{p}\right)^2 \approx \frac{1}{E_{cm}^2}$$

$W_L W_L$ - scattering



$$\frac{1}{E_{CM}^2}\left(\frac{E_{CM}}{M_W}\right)^4$$

violates the bound for $E_{CM} \gtrsim M_W$!

1. QM wrong
2. Calculation wrong
3. Model wrong

1. QM wrong

we wish ...

what replaces QM ?

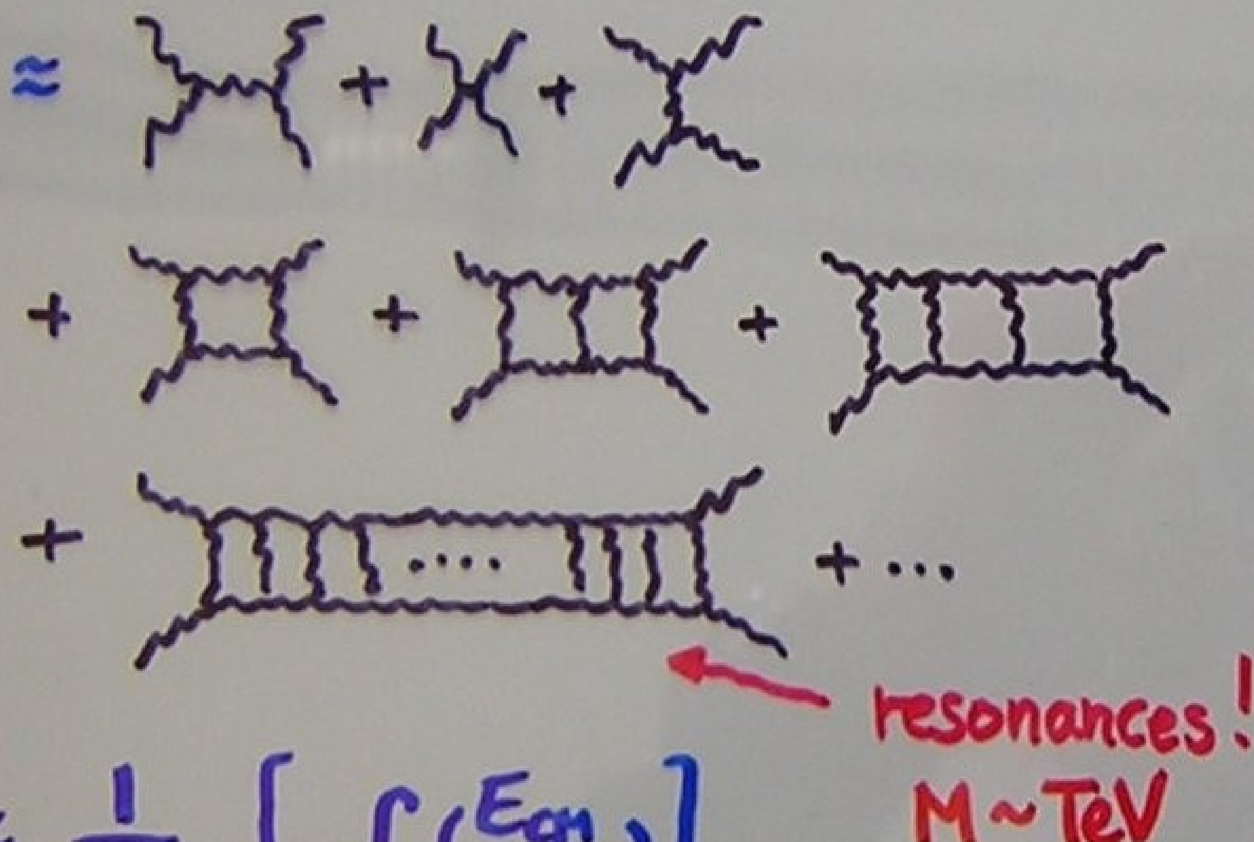
how do we predict ?

?

2. Calculation wrong ...

theory becomes strongly coupled at $E \sim \text{TeV}$

$\sigma \approx$



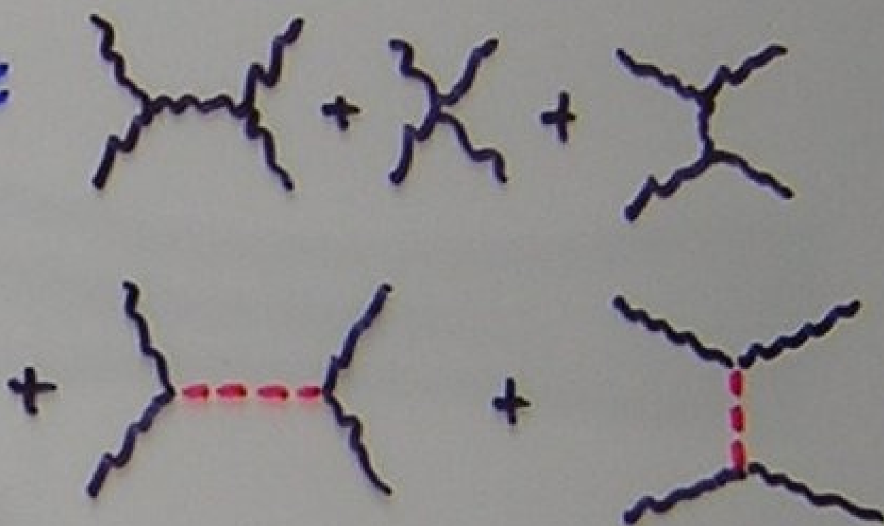
$$\approx \frac{1}{E_{cm}^2}\left[f\left(\frac{E_{cm}}{\text{TeV}}\right) \right]$$

not calculable

3. Model wrong...

new particles at $E_{cm} \gtrsim M_W$

$\sigma \approx$



$$\approx \frac{1}{E_{cm}^2}\left[\left(\frac{E_{cm}}{M_W}\right)^4 - \left(\frac{E_{cm}}{M_W}\right)^4 + \text{"finite"}\right]$$

delicate cancellation requires symmetry

spontaneously broken gauge symmetry

Higgs mechanism!

Most theorists believe option 3:

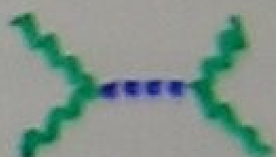
Higgs with

$114\ \text{GeV} < m_H \lesssim 500\ \text{GeV}$

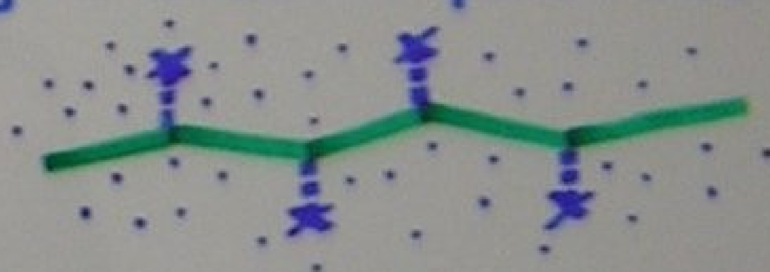
The case for the standard model Higgs

The standard model Higgs ...

... unitarizes WW scattering

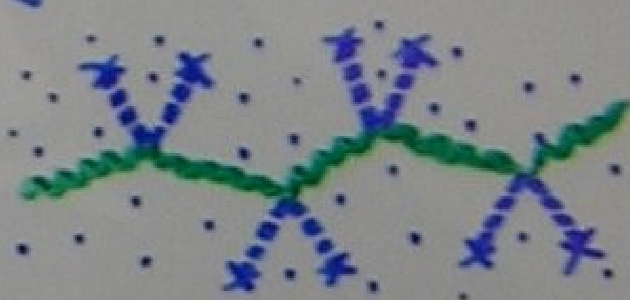


... gives masses to quarks and leptons



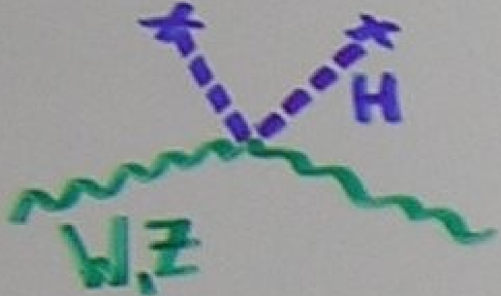
tested by
→ flavor physics

... gives masses to W and Z



→ precision electro-
weak physics

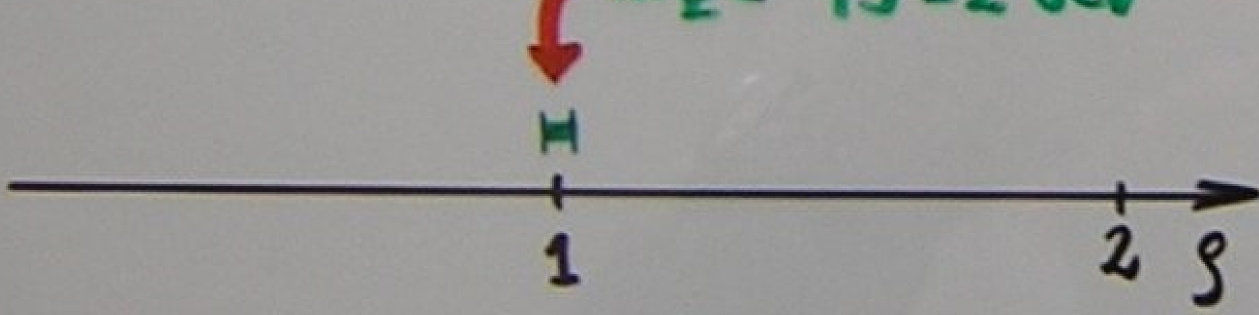
M_W and M_Z in the SM :



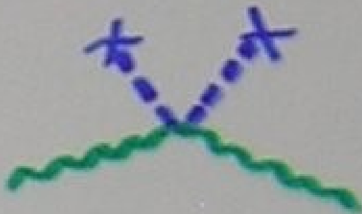
$$\Rightarrow M_W = M_Z \cos\theta_W$$

$$\Leftrightarrow \quad \rho_0 \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta} = 1$$

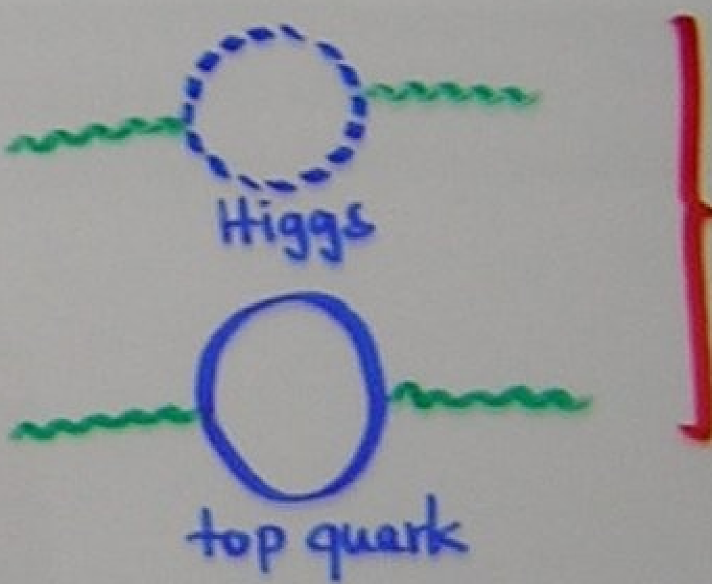
1983 UA1, UA2: $m_W = 82 \pm 2$ GeV
$m_Z = 93 \pm 2$ GeV



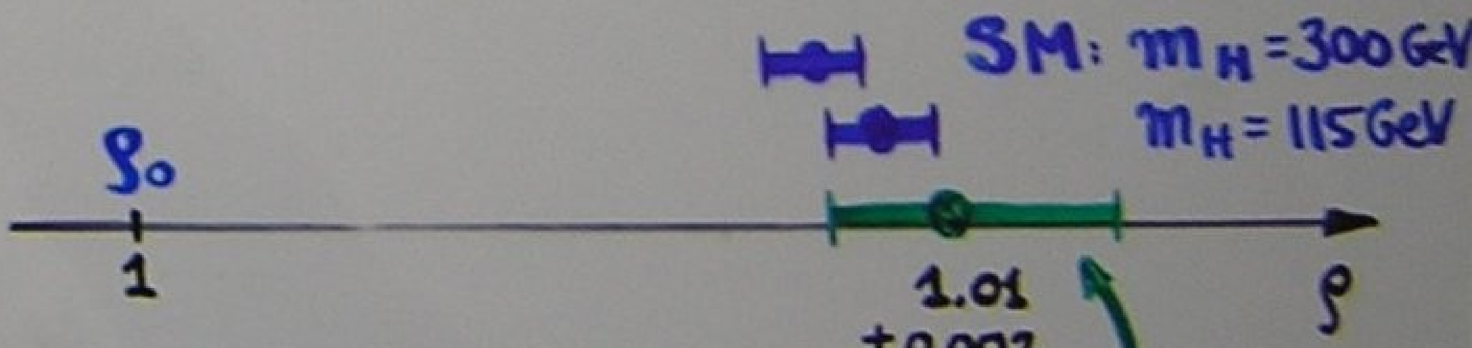
Quantum corrections and precision measurements M_W, M_Z



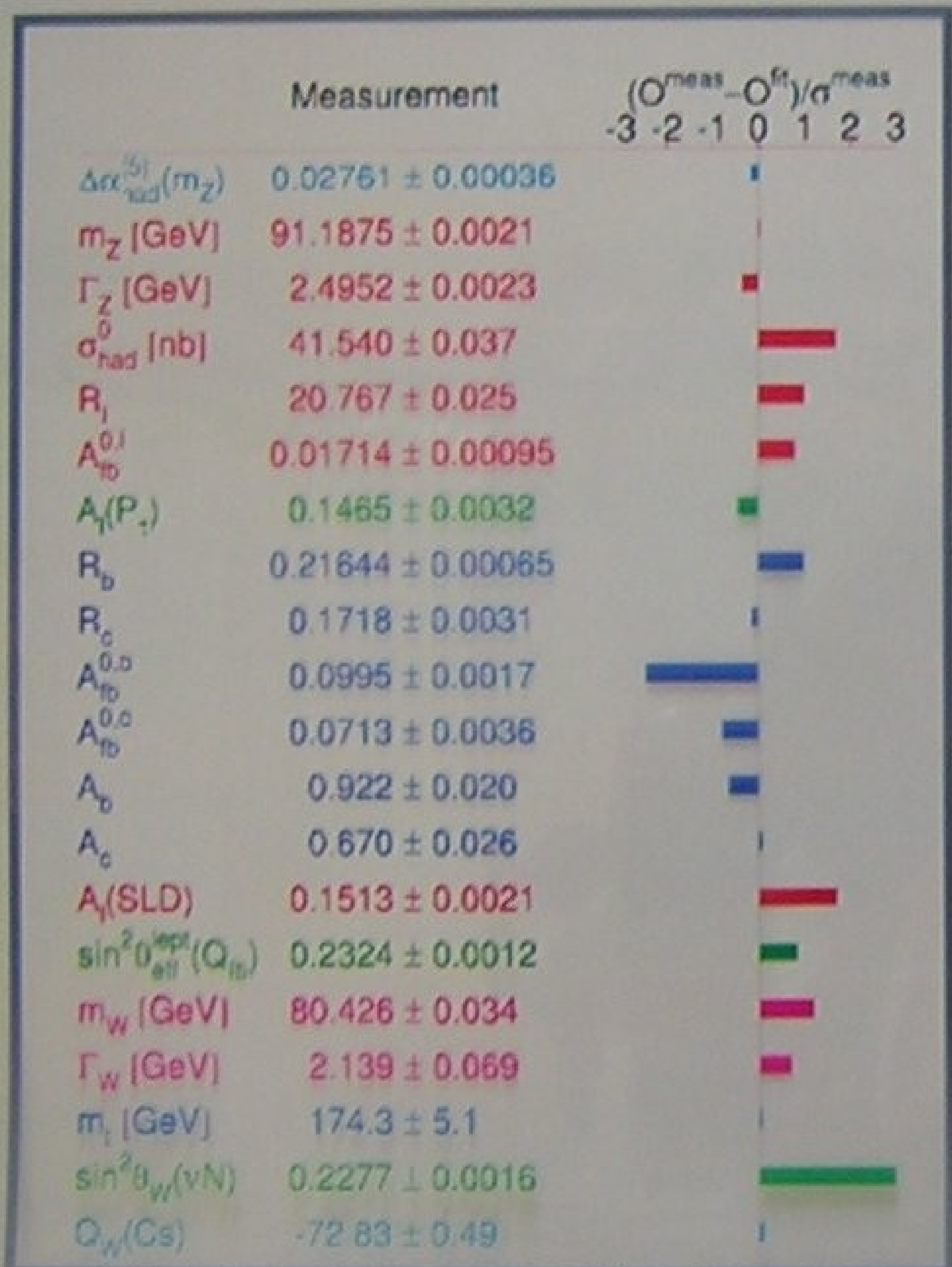
we must also include effects of virtual particles



$\delta\rho \approx 1\,\%$

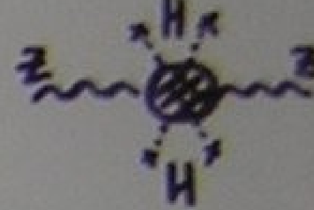


Precision electroweak measurements



~0.1%

S & T operators



$$S \sim \frac{B_{\mu\nu} H^{+} W^{\mu\nu} H}{\Lambda^2}$$

$$\Longrightarrow \frac{v^2}{\Lambda^2} B_{\mu\nu} W_3^{\mu\nu}$$

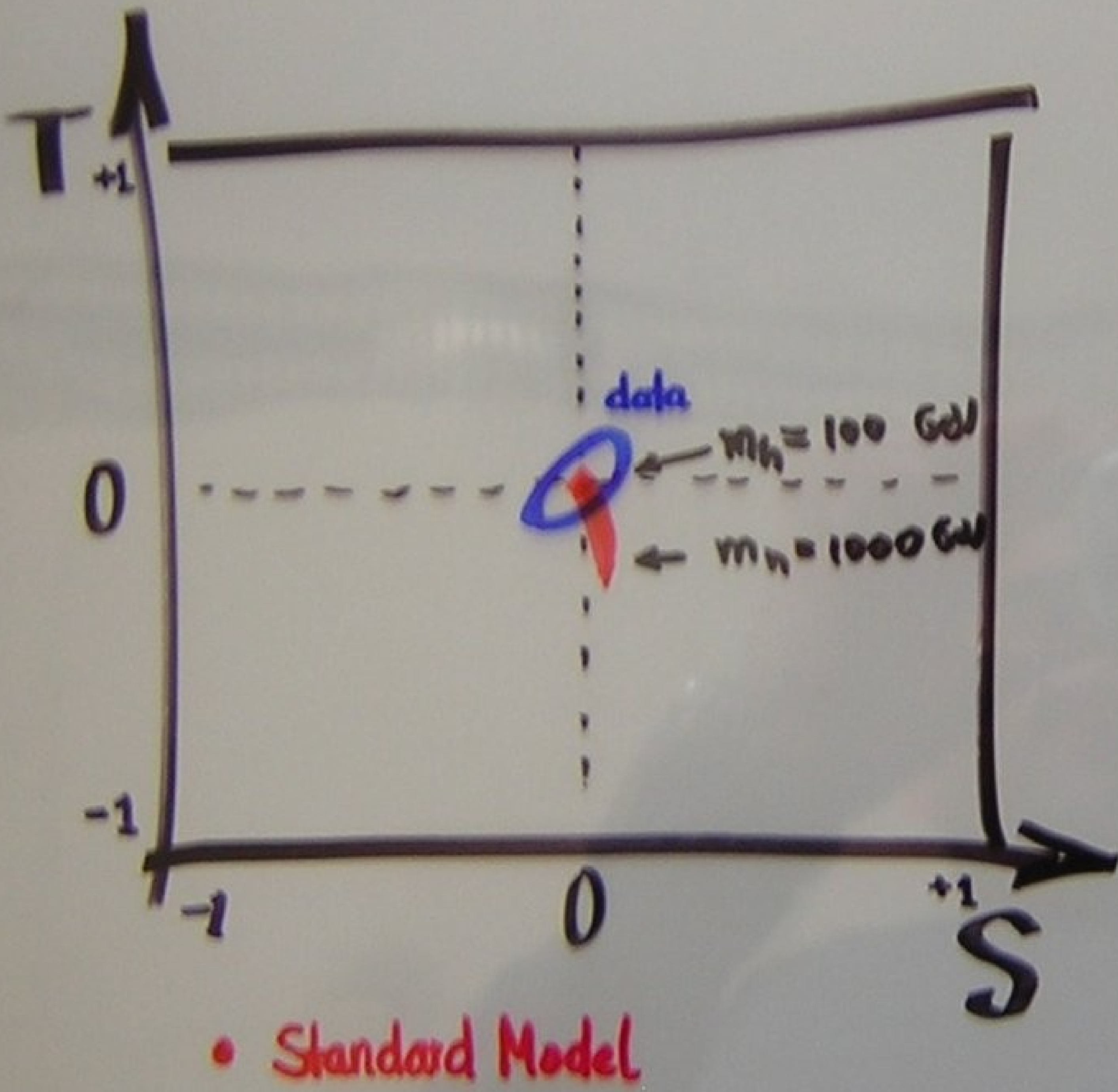
$$T \sim \frac{H^{+} D_{\mu} H \, H^{+} D^{\mu} H}{\Lambda^2}$$

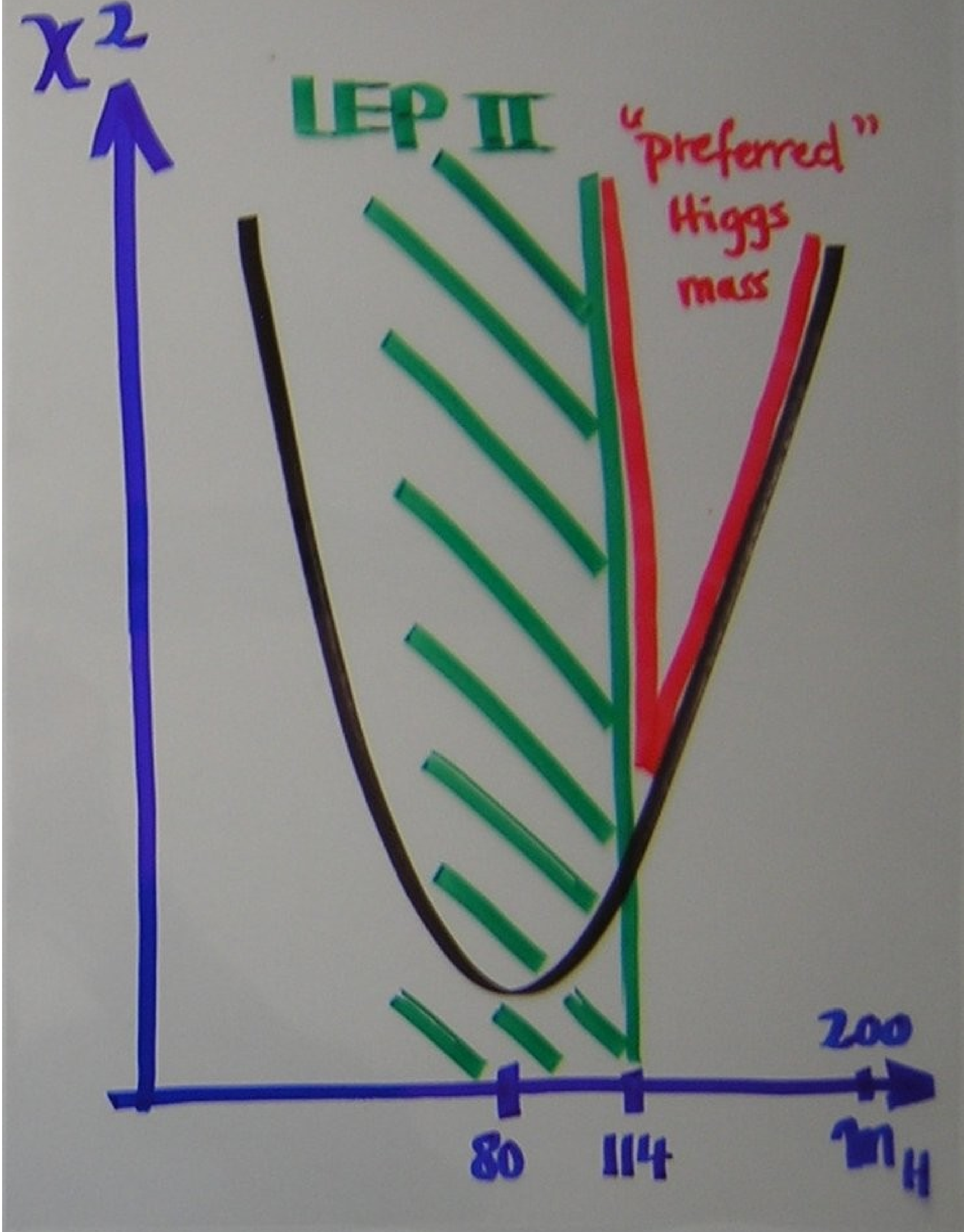
$$\Longrightarrow m_Z^2 \frac{v^2}{\Lambda^2} Z_{\mu} Z^{\mu}$$

PEW experiments: $\Lambda \gtrsim 5$ TeV

S & T ellipse

(LEP-EWWG, spring '02)





χ²
LEP II
"preferred" Higgs mass
200
80
114
m_H

Conclusion:

the SM + Higgs fits the data very well

⇒ assume that it is correct

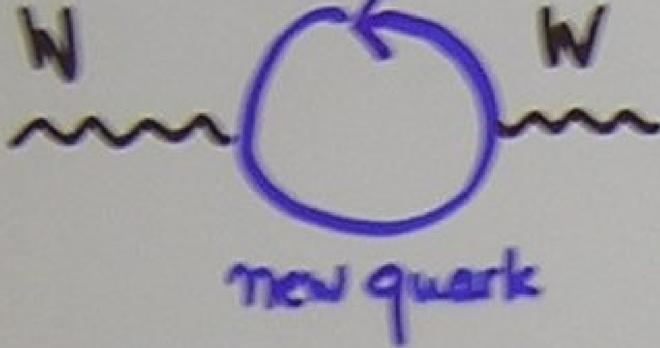
New Physics = Physics beyond the SM

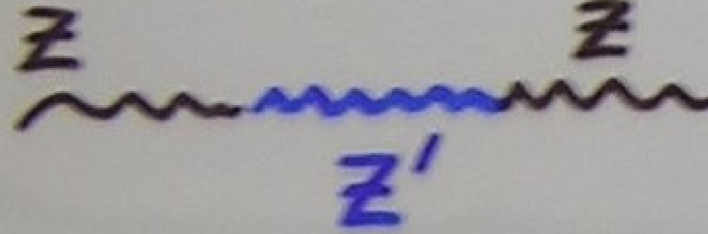
noHiggs - strong coupling

resonances at ~ TeV

$$\delta S, \delta T \sim \frac{\pi}{\alpha_W} N \left(\frac{M_W}{M_{res}}\right)^2 \approx \frac{N}{4} \approx 1$$

New Physics @ TeV



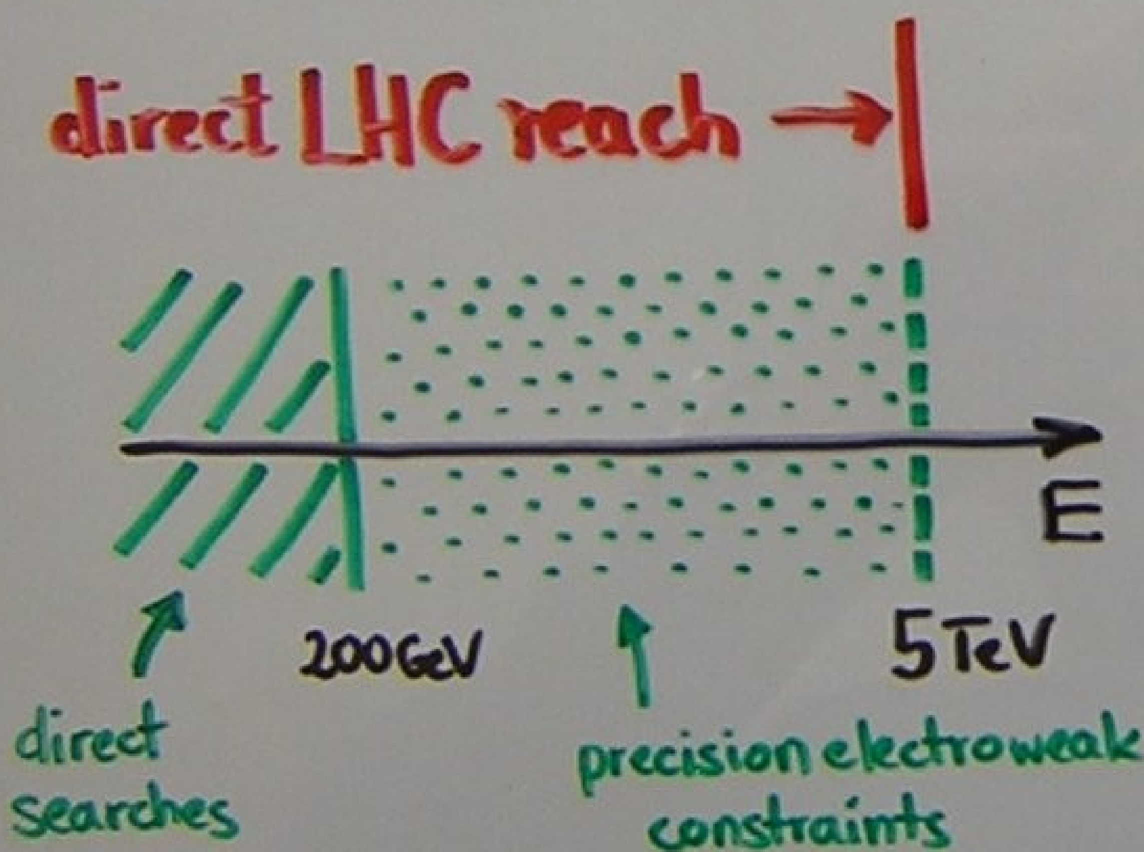


$$\delta S, \delta T \sim \left(\frac{M_W}{M_{NP}}\right)^2$$

constraints on new particles up to ~5 TeV

TeV scale New Physics

Does this imply that the LHC will "only" discover the Higgs ?



No!

- there is room for new physics in the indirect data

- the SM has a naturalness problem which motivates new physics $\lesssim 2$ TeV

Higgs (un)naturalness

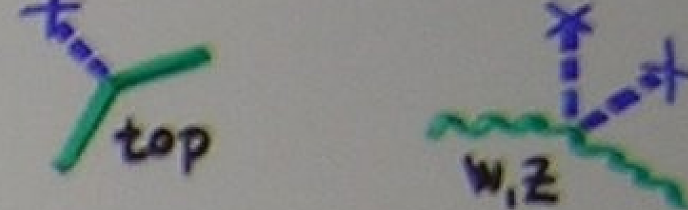
$$V_{Higgs} \approx -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$m \sim 200$ GeV $\lll M_{pl}$

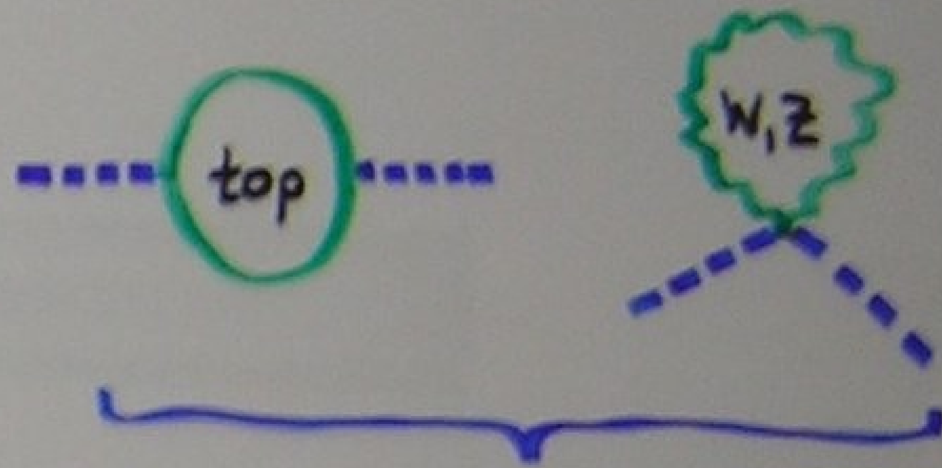
not the naturalness problem

Naturalness and the SM

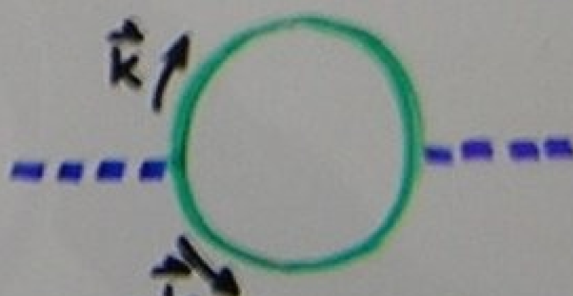
the couplings



imply



Contribute to Higgs mass

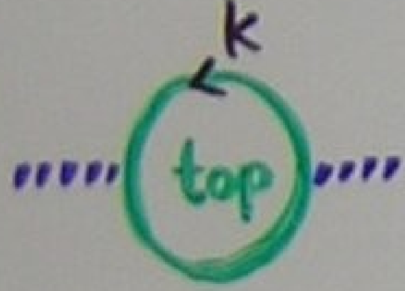


$\Rightarrow \quad \delta m^2_{Higgs} \propto k^2$

infinite as $k^2 \to \infty$!

Renormalize : $\infty - \infty = m^2_{Higgs}$

but, is the SM valid for $k \gg \mathrm{TeV}$?



$k < \mathrm{TeV}$

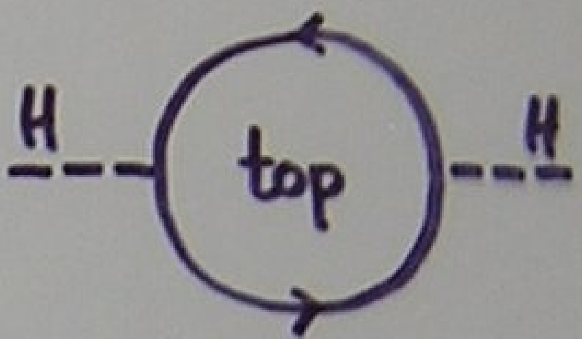
$k \gg \mathrm{TeV}$

<u>not</u> the SM Feynman rules

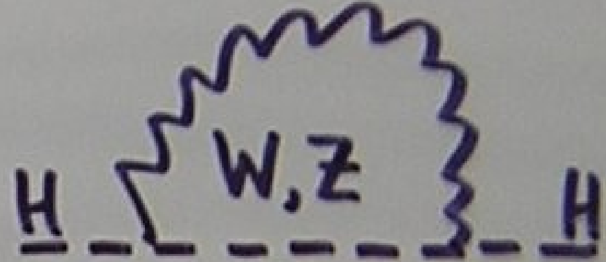
we should limit loop momenta $k < \Lambda$
to scales where we believe the SM

Quantum corrections

$\Lambda = 10\,\text{TeV}$



$$-\frac{\lambda_t^2}{16\pi^2}\Lambda^2 \sim 100\, m^2$$

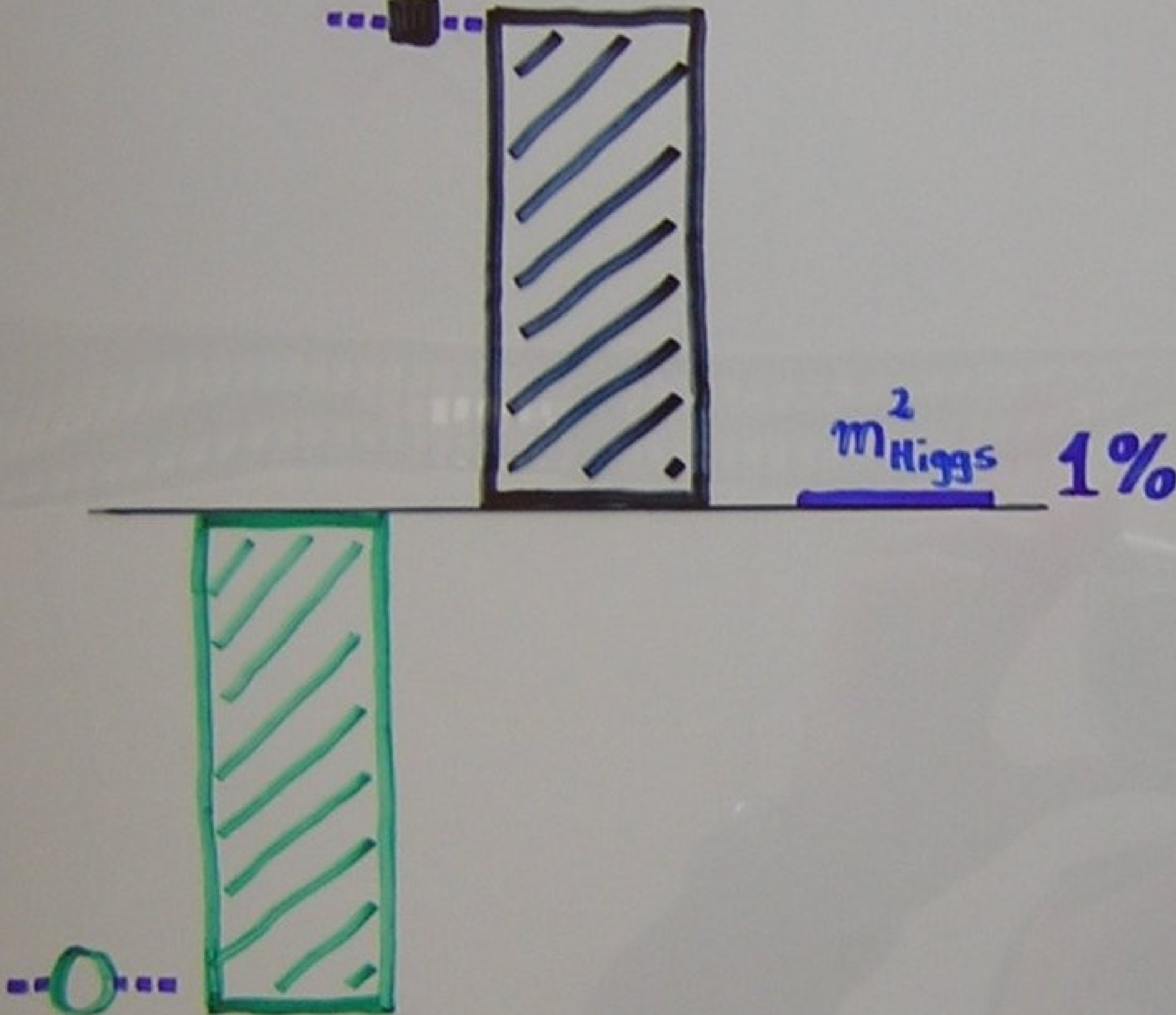


$$\frac{g^2}{16\pi^2}\Lambda^2 \sim 10\, m^2$$

quantum corrections with $\Lambda = 10\,\text{TeV}$
are 100x too big!

$\Longrightarrow$ New physics below ~TeV

"Fine - tuning"



not "natural" !

the Veltman condition ...

$$\Delta m_H^2 = \underbrace{\left\{ -\lambda_t^2 \quad + \quad g^2 \quad + \quad \lambda_H \right\}}_{=0} \frac{\Lambda^2}{16\pi^2}$$

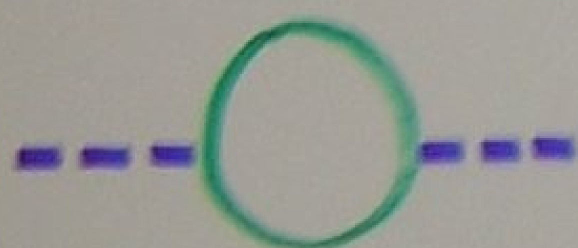
$= 0 \Rightarrow$ Higgs mass prediction!

$m_H^2 = \lambda_H v^2$

is crap !!!

Conclusion: new physics below 10 TeV must invalidate the calculation.

quantitatively: (demand $< 10\,\%$ fine tuning)



requires new physics $\lesssim 2$ TeV

" $\lesssim 5$ TeV

What is the

New

Physics?


Google!

#~~2~~1. Hit: "New Physics"

general relativity - Einstein

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

G gravity

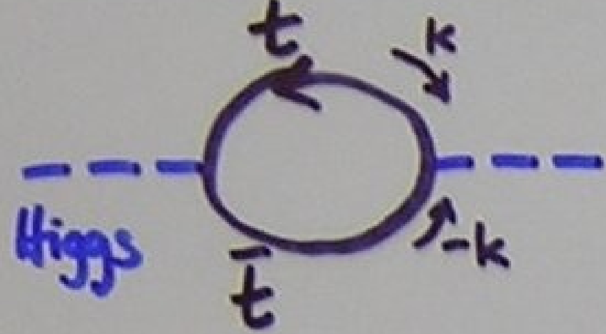
8 infinity

μ mass

ν velocity

T time

New physics must invalidate



for loop momenta of order $k \gtrsim$ TeV

Possible new physics

1. Technicolor : Higgs is composite at ~ TeV

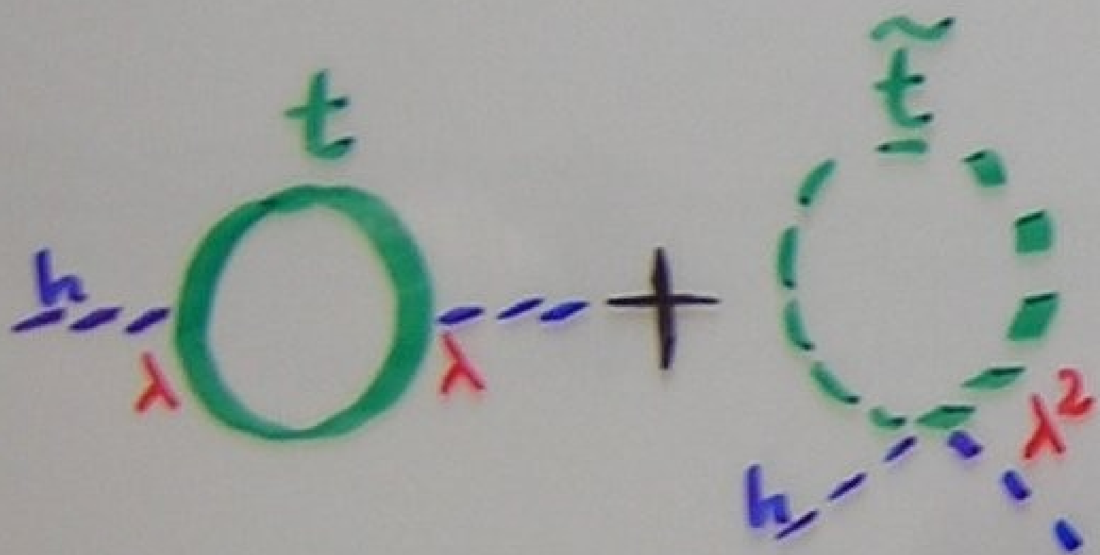
2. Large Extra Dimensions : Quantum gravity at ~ TeV

problem : expect large corrections to precision observables

e.g.  $\Rightarrow \delta\rho$

"partners"

partners for all fields which couple to the Higgs strongly (heavy) with masses ~ TeV



$$\approx \frac{\lambda^2}{16\pi^2} m_{\tilde{t}}^2$$

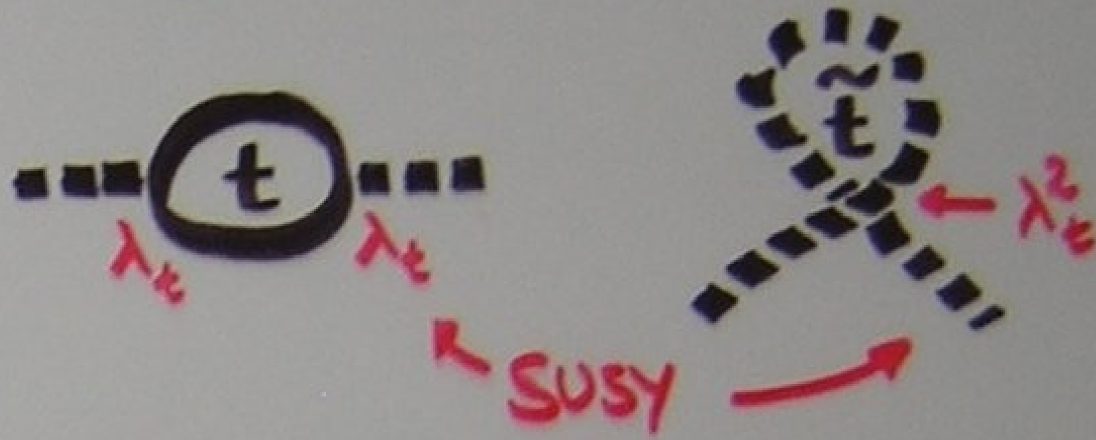
requires a symmetry $t \leftrightarrow \tilde{t}$

partner model examples:

SUSY

(MSSM)

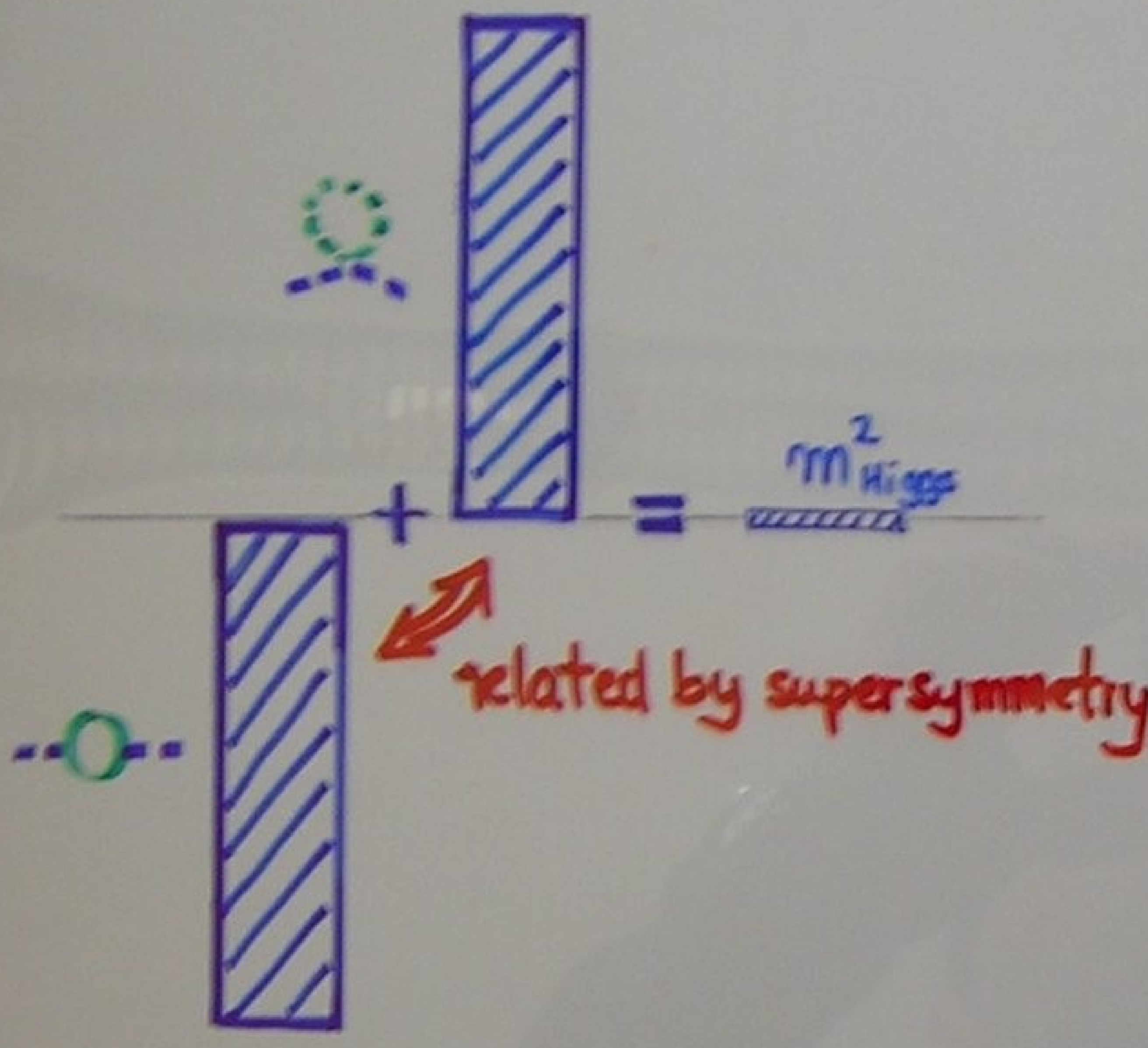
Susy top-stop cancel



$$\Delta m_H^2 = -\frac{\lambda_t^2}{16\pi^2}\Lambda_t^2 + \frac{\lambda_t^2}{16\pi^2}\Lambda_{\tilde{t}}^2$$

SUSY

Quantum corrections cancel naturally



Higgs mass and symmetry

scalar mass $m_H^2 H^\dagger H$ cannot be forbidden by symmetry

$$H \rightarrow e^{i\alpha} H$$

fermion mass $m_\psi \psi_L^\dagger \psi_R$ forbidden by chiral symm.

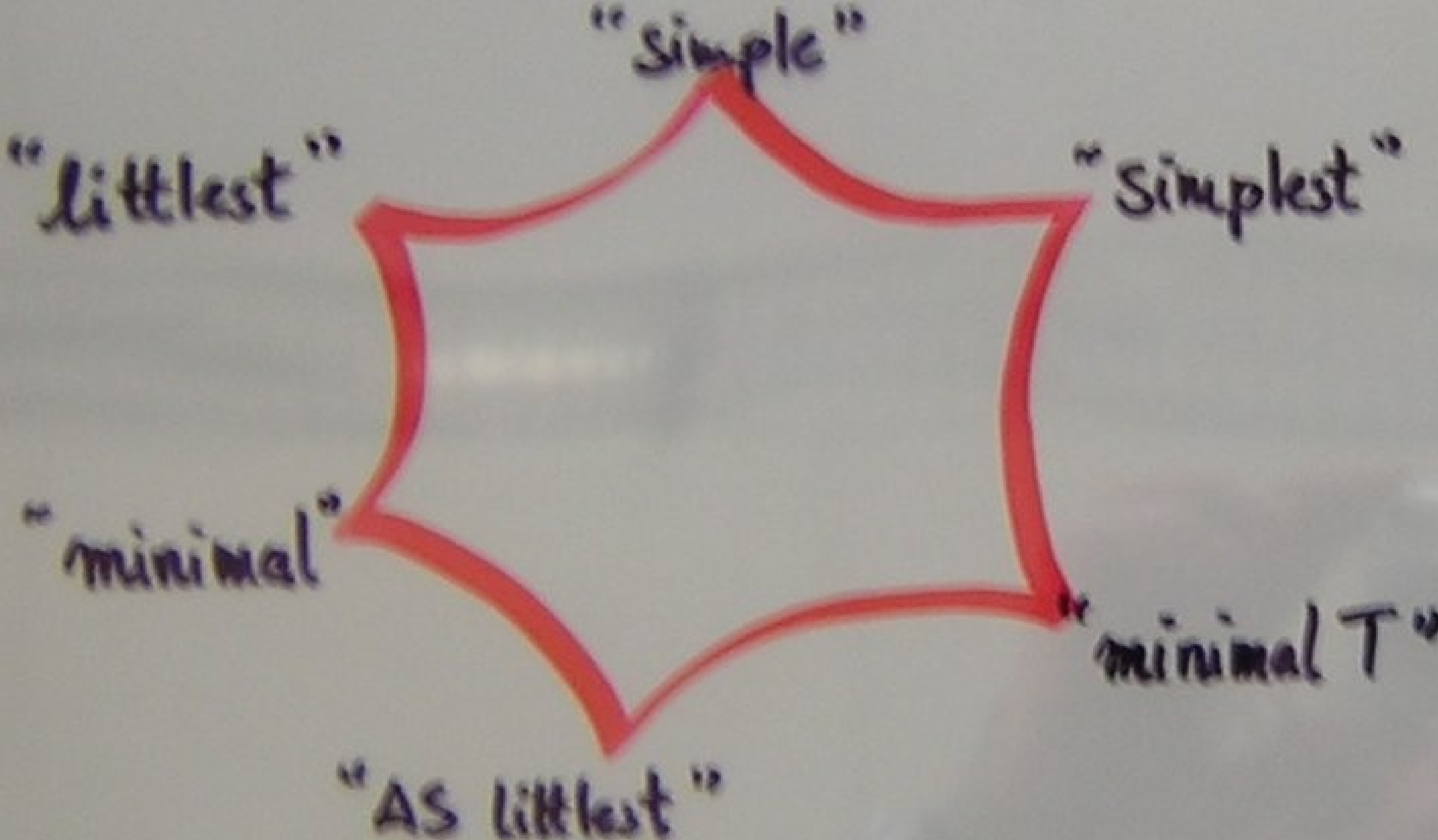
$$\psi_R \rightarrow e^{i\alpha} \psi_R$$
$$\psi_L \rightarrow \psi_L$$

SUSY

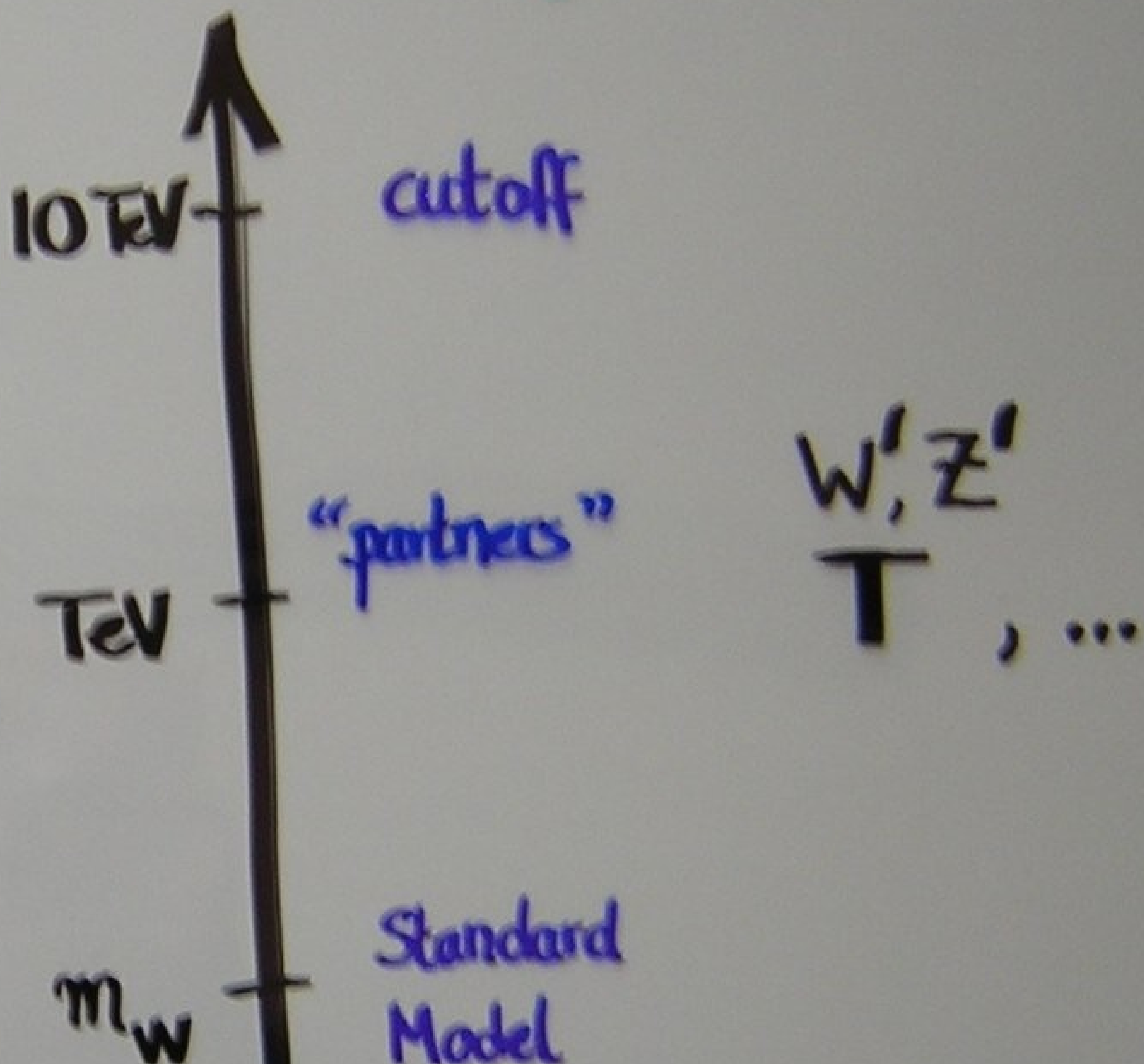
$$H \longleftrightarrow \tilde{H}$$
$$m_H^2 \longleftrightarrow m_{\tilde{H}}$$

Little Higgs

(Arkani-Hamed, Cohen, Georgi)



LH spectrum



Symmetry of LH ?

$m^2 H^\dagger H$

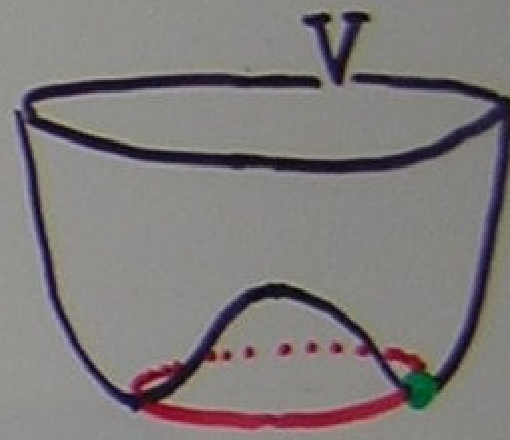
forbidden by $H \to H + \alpha$

Higgs = Nambu-Goldstone Boson

NGB

- complex scalar ϕ
- general $U(1)$-symmetric potential

$$V = \lambda(\phi^*\phi - f^2)^2$$



- spontaneous symmetry breaking

$$\phi(x) = (f + r(x))\, e^{i\theta(x)}$$

- $U(1)$ symmetry: $\phi \to e^{i\alpha}\phi$

$$\theta \to \theta + \alpha$$

SU(3)/SU(2)

$$V = \lambda\left(\Phi^\dagger \Phi - f^2\right)^2$$

Φ ← SU(3) triplet

f ← ~ 2TeV

$$\Phi = e^{i\Theta/f}\begin{pmatrix}0\\0\\f\end{pmatrix}$$

$$\Theta = \left(\begin{array}{cc|c} 0 & 0 & \multirow{2}{*}{H} \\ 0 & 0 & \\ \hline \multicolumn{2}{c|}{H^\dagger} & \rho \end{array}\right)$$

H ← massless SU(2) doublet

$H \to H + \alpha$ under SU(3) transformations

Let's make a TOY model for the top Yukawa using $SU(3)/SU(2)$

$$\phi = e^{i\theta} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

Shift symmetry

$$H \to H + \alpha$$

forbids all non-derivative interactions:

no $m^2 H^\dagger H$

no $\lambda (H^\dagger H)^2$

no $A_\mu H^\dagger A^\mu H$

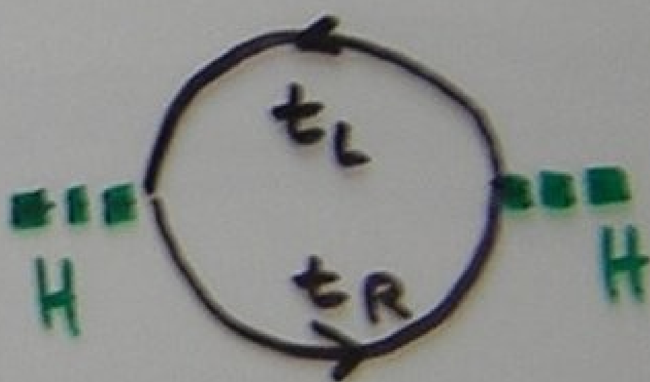
no $t_L^\dagger t_R H$

$\Rightarrow$ we need to break the symmetry explicitly!

Top Yukawa 1

$$\lambda_t \begin{pmatrix} \phi^\dagger \end{pmatrix} \begin{pmatrix} t_L \\ b_L \end{pmatrix} t_R^\dagger = \lambda_t H^\dagger \begin{pmatrix} t_L \\ b_L \end{pmatrix} t_R^\dagger$$

breaks SU(3) explicitly and reintroduces quadratic divergence



$$\approx \frac{\lambda_t^2}{16\pi^2} \Lambda^2$$

Top Yukawa 2

quark triplet to preserve SU(3)

$$\lambda_t \begin{pmatrix} \phi^\dagger \end{pmatrix} \cdot \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} t_R^\dagger$$

$$= \lambda_t \begin{pmatrix} \\ \\ f \end{pmatrix} \underbrace{e^{-i\Theta} \begin{pmatrix} t \\ b \\ T \end{pmatrix}_L}_{= \begin{pmatrix} t \\ b \\ T \end{pmatrix}_L} t_R^\dagger$$

by field redefinition

$$= \lambda_t f \, T_L t_R^\dagger$$

not a top Yukawa!

Top Yukawa 3

little Higgs trick — Arkani-Hamed, Cohen, Georgi

break SU(3) collectively!

$$\underbrace{\left(\phi\right)\cdot\begin{pmatrix} t \\ b \\ T \end{pmatrix}_L t_R^{+}}_{\text{SU(3) invariant}} + \underbrace{f' T_L T_R^{+}}_{\text{preserves SU(3) of } \phi}$$

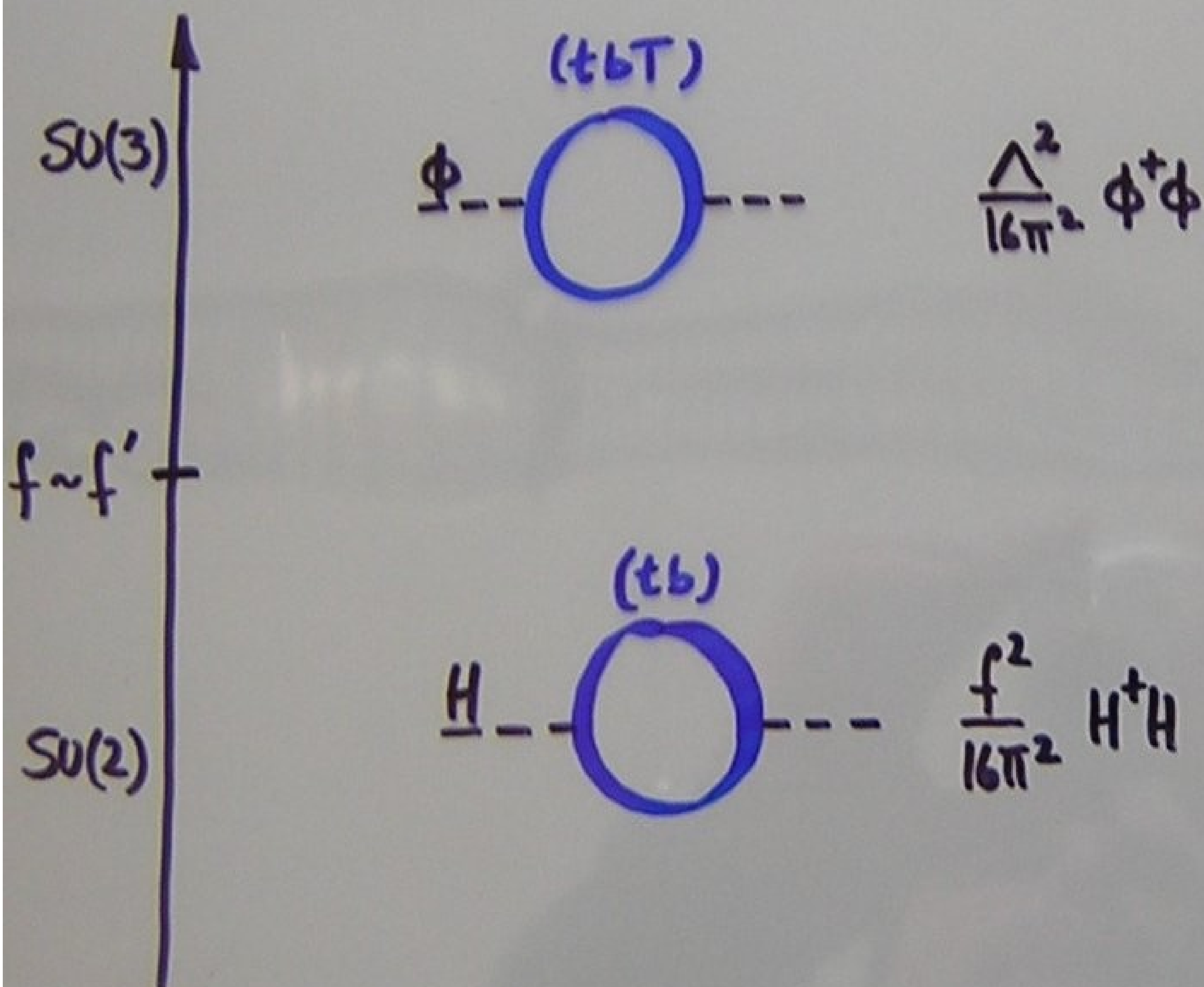
⇓

SU(3) broken

$$\underbrace{T_L\left(f\, t_R^{+} + f' T_R^{+}\right)}_{\text{mass} \sim f \text{ for } T} + \underbrace{H \begin{pmatrix} t \\ b \end{pmatrix}_L t_R^{+}}_{\text{top Yukawa}}$$

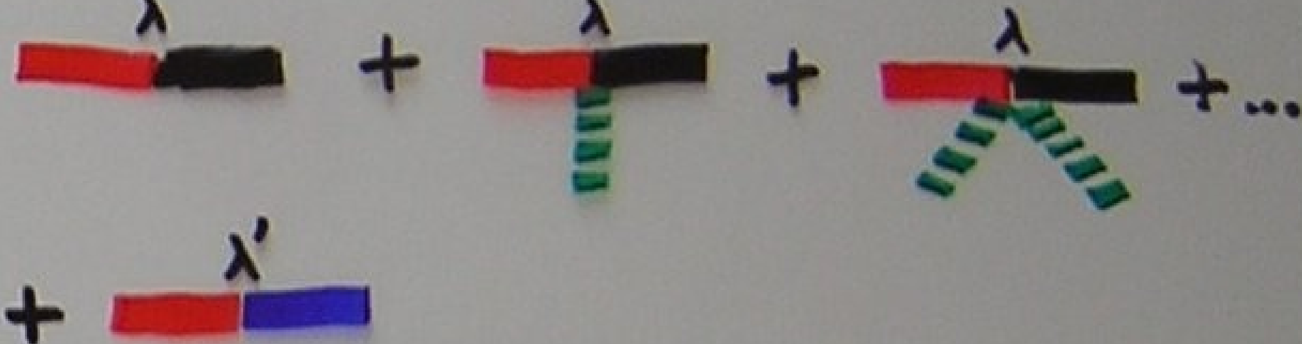
Higgs mass divergence ?

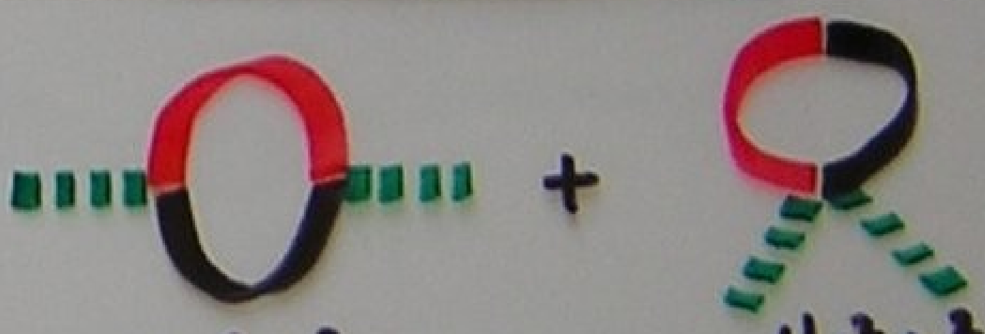
$$\Phi^\dagger \begin{pmatrix} t \\ b \\ T \end{pmatrix}_L t_R^\dagger + f\, T_L T_R^\dagger$$



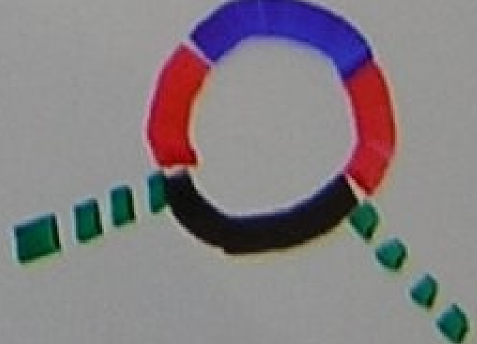
Diagramatically:

$$\lambda \underline{\Phi}^{\dagger} \underline{(t)}_L \underline{t_R^{\dagger}} + \lambda' f \underline{T_L} \, \underline{T_R^{\dagger}} =$$





$$|\lambda|^2 \Lambda^2 \qquad - |\lambda|^2 \Lambda^2 \qquad = 0$$



$$= \frac{|\lambda|^2 |\lambda'|^2 f^2}{16\pi^2}$$

$$\approx \frac{\lambda^2}{16\pi^2} m_T^2$$

Constructing a full little Higgs model

- extend SU(3) symmetry to full model
- introduce couplings λ_t, g, λ_4 with collective symmetry breaking

$\Rightarrow$ l.h. "partners" in each sector

$T, W', Z', \eta, \ldots$

SU(2) gauge sector

$$\left(\begin{array}{c|c} W^{\pm}, Z^{0} & W' \\ \hline W' & Z' \end{array}\right)$$

W, Z "partners" with
TeV scale masses

Scalars (h partners)

depend on Coset :

$SU(5)/SO(5)$, $SU(6)/SP(6)$,

$\left(SU(3)/SU(2)\right)^2$, ----

typical are : singlets, extra doublets
triplet (of $SU(2)$)

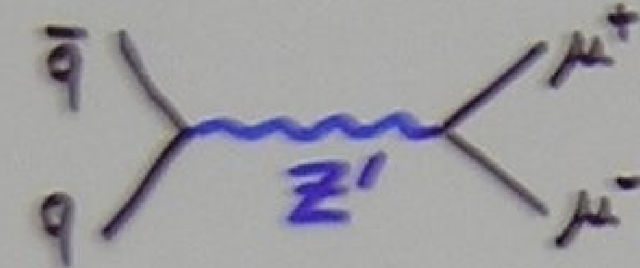
What is f ?

Higgs naturalness :

$$m_T \sim f \lesssim 2\,\text{TeV}$$

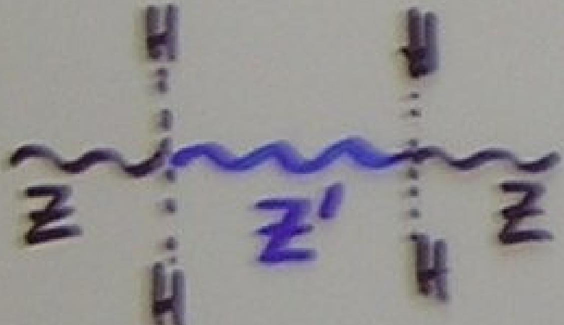
Lower bounds on f :

- Z' searches



$$m_{Z'} \sim f \gtrsim 900 \text{ GeV}$$

- precision electroweak (S&T)



$$\frac{(H^\dagger D_\mu H)^2}{m_{Z'}^2}$$

$$m_{Z'} \sim f \gtrsim 3 \text{ TeV}$$

Tension

naturalness : $f \lesssim$ couple TeV

precision EW : $f \gtrsim$ few TeV

a conundrum ...

in Little Higgs

$$m_{LH} \gtrsim \text{few TeV}$$

in SUSY

$$m_{SUSY} \gtrsim \text{few } 100 \text{ GeV}$$

... from Precision EW

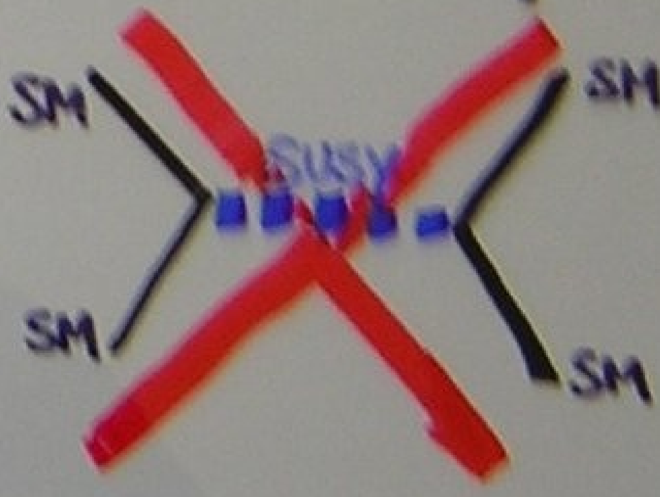
R-parity

all superpartners odd

LSP dark matter!

⇛ pair production

⇛ no tree level precision EW

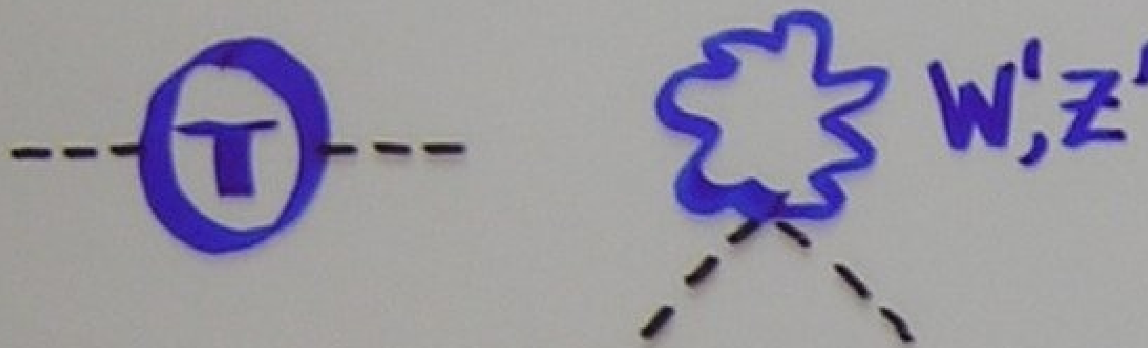


$$\delta_{PEW} \sim \frac{1}{16\pi^2} \frac{m_Z^2}{m_{SUSY}^2}$$

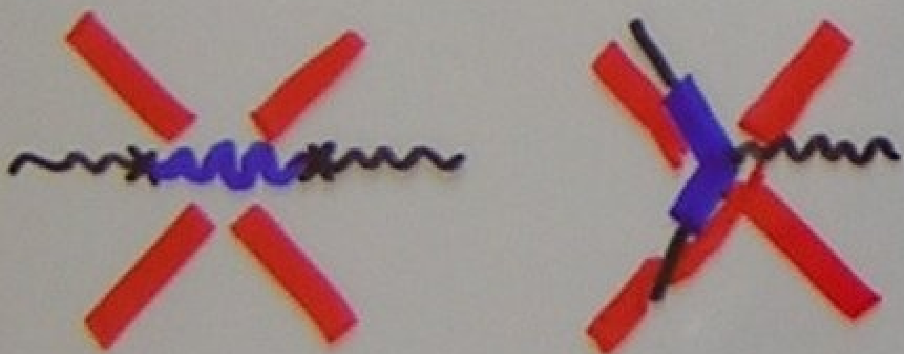
T-parity

H.C. Cheng, I. Low

- naturalness requires loops



- precision EW problems are trees

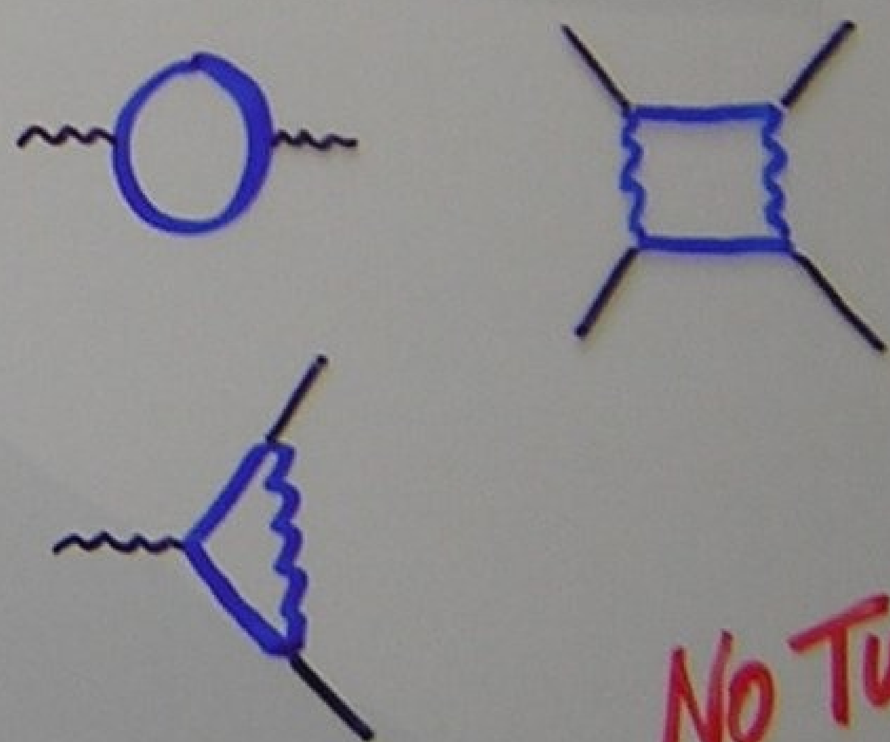


T-parity : all partners carry new Z_2 charge

T parity precision EW

Hubisz, Meade, Noble, Perelstein   Cheng, Low
in "Littlest Higgs"

$$m_{lh} \gtrsim 500 \text{ GeV}$$

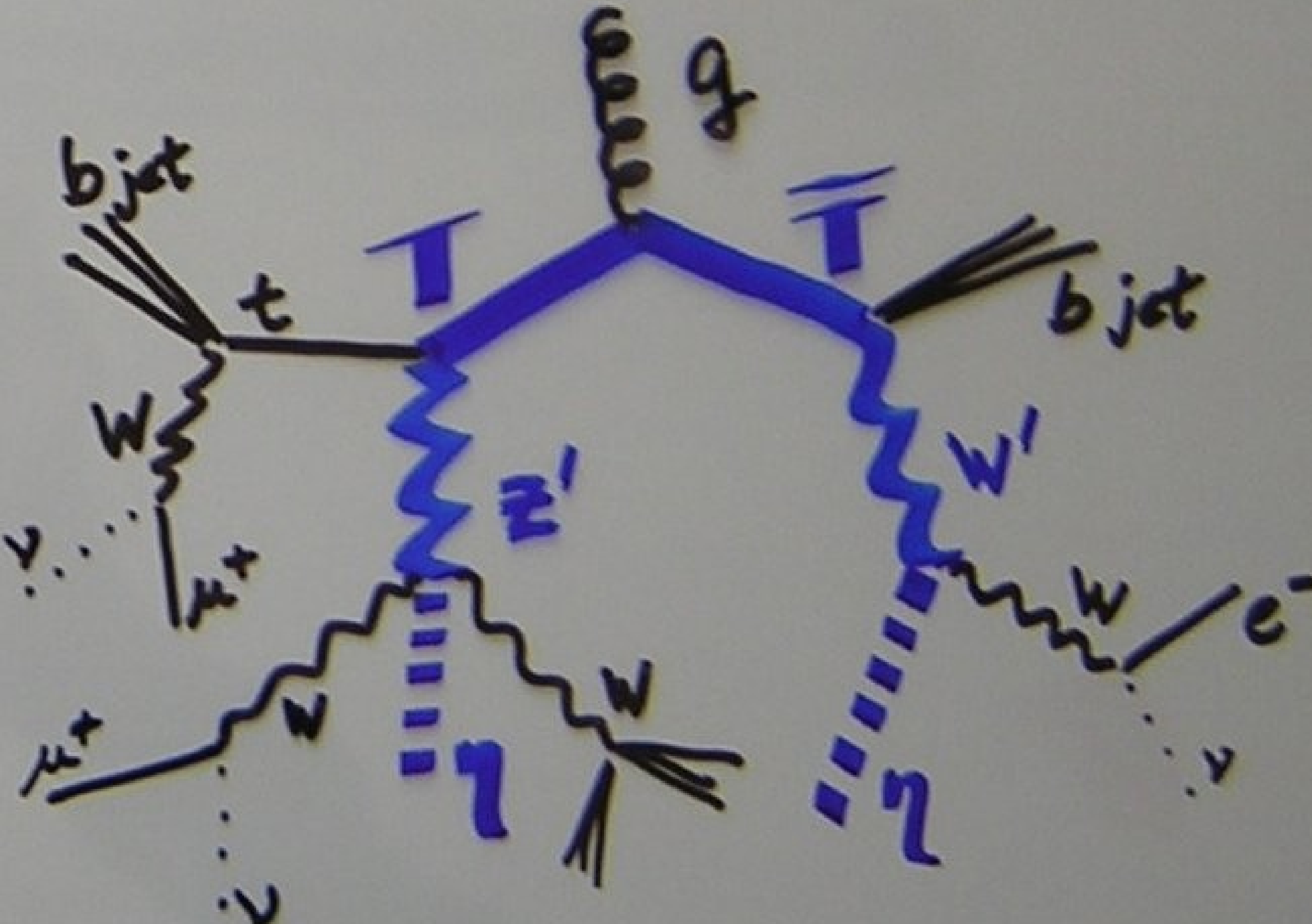


No Tuning! ☺

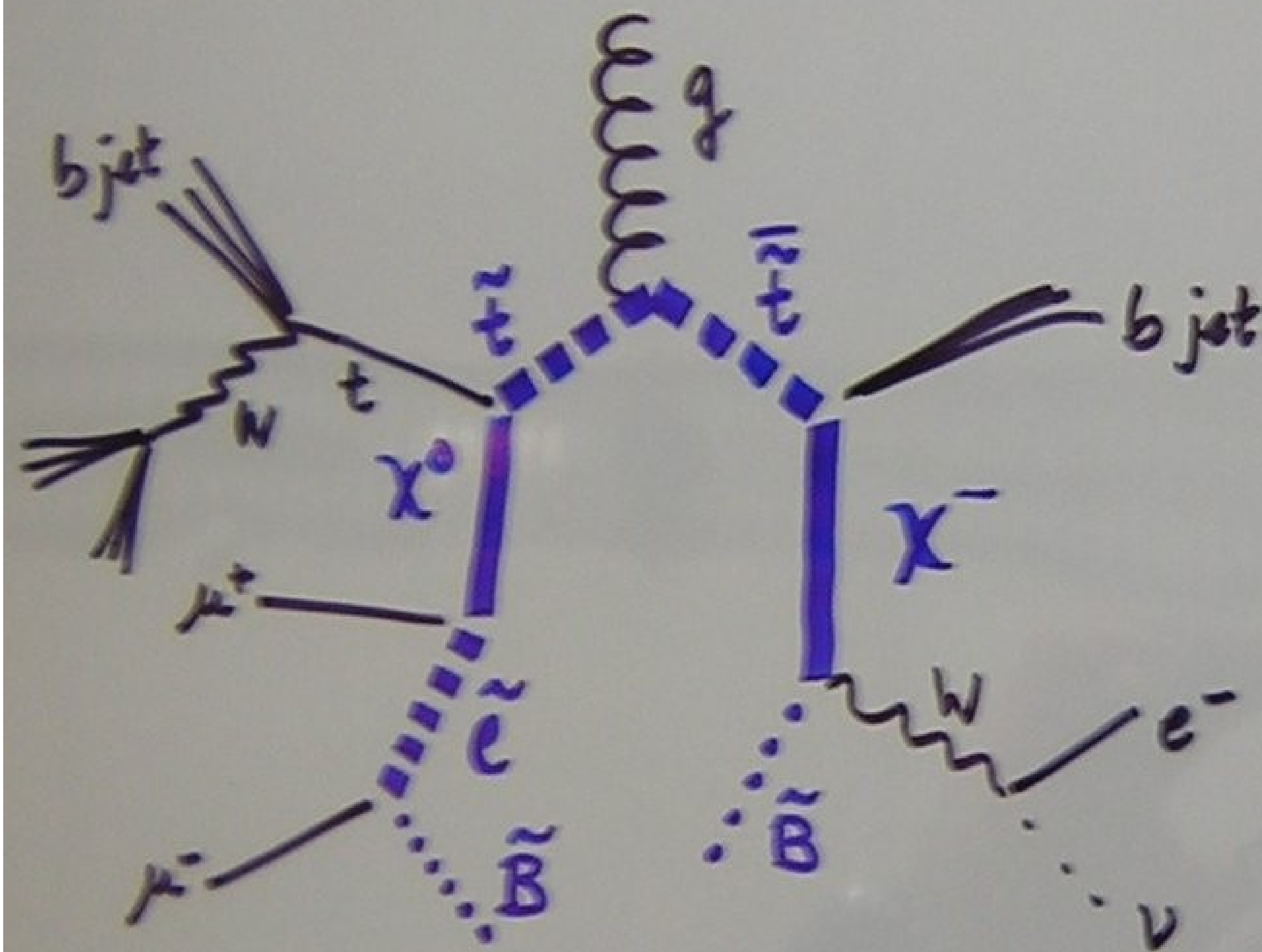

T-parity
DARK
MATTER

T-parity pheno

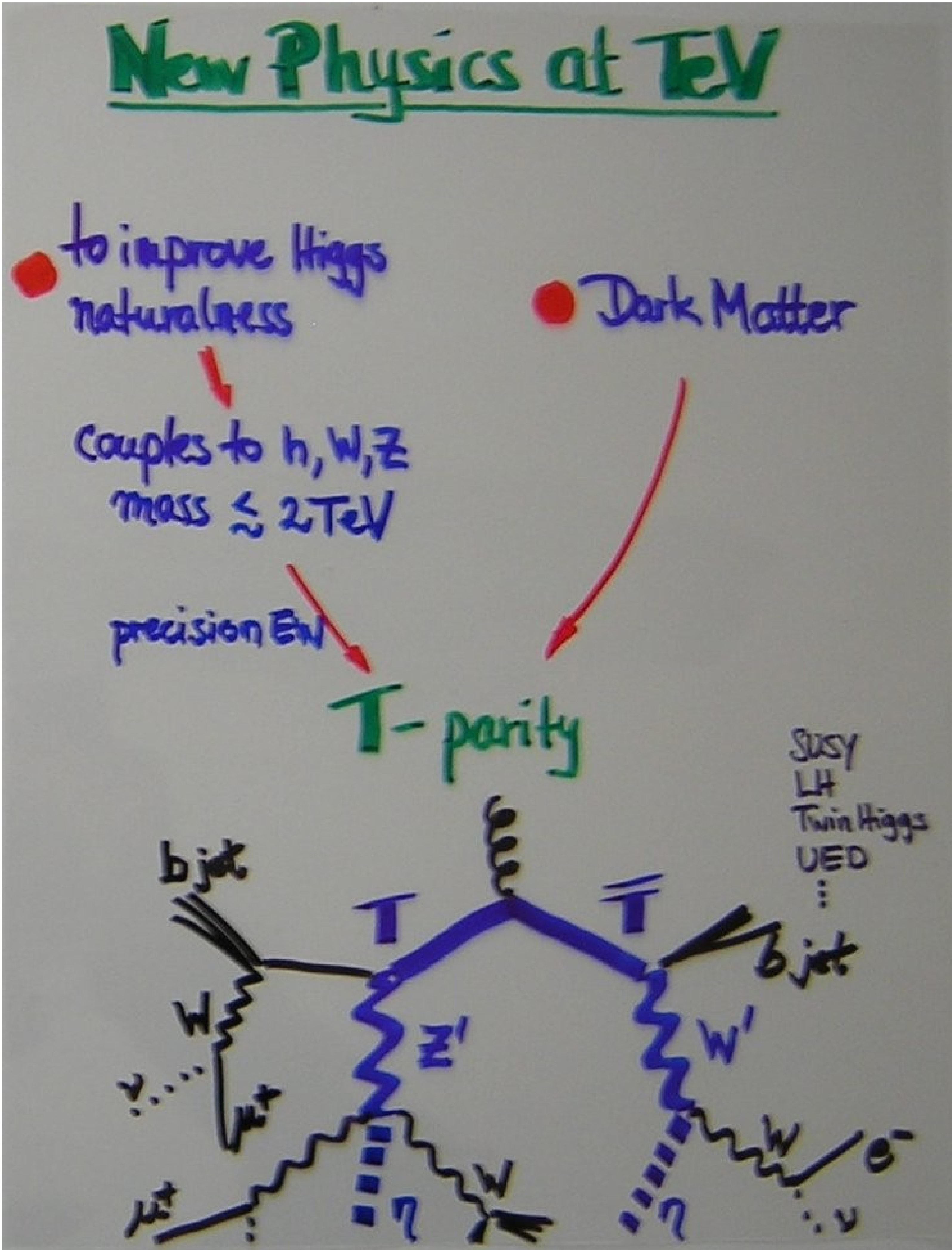
- pair production
- cascade decays
- missing E_t



_ just like SUSY !



can we tell them apart ?



New Physics at TeV
to improve Higgs naturalness
couples to h, W, Z
mass ≲ 2 TeV
precision EW
Dark Matter
T-parity
SUSY
LH
Twin Higgs
UED
b jet
T
T̄
b jet
W
Z'
W'
ν
μ+
μ+
W
W
e−
η
η
ν

SUMMARY

- Unitarity & precision EW predict the Higgs at the LHC

- Naturalness suggests TeV scale new physics

  - Technicolor / Etra dimensions ξ PEW
  - "Partners"
    - SUSY tuned
    - LH ξ PEW
    - LHT baroque

... nothing fully satisfactory !!!

What is going on ??

Little Higgs Collider

2008/9