Precision Measurements and New Physics

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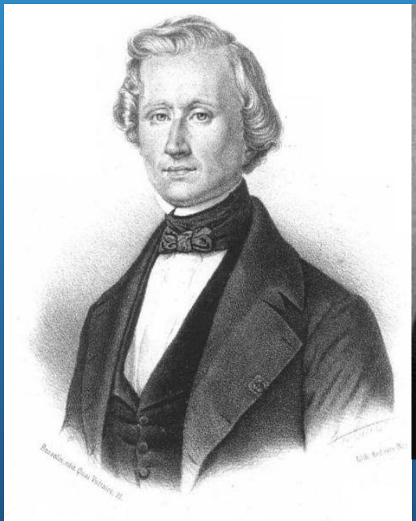
Part 1
温故知新
（論語）

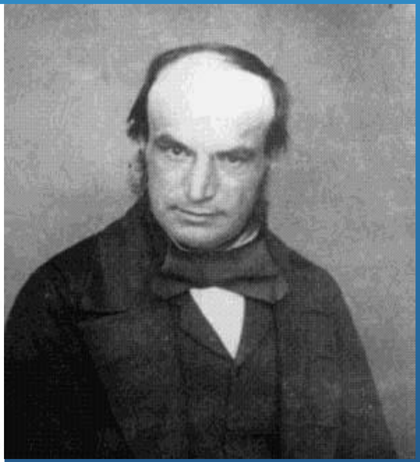
By scrutinizing existing Knowledge,
you can obtain New Knowledge

Example in Astronomy:

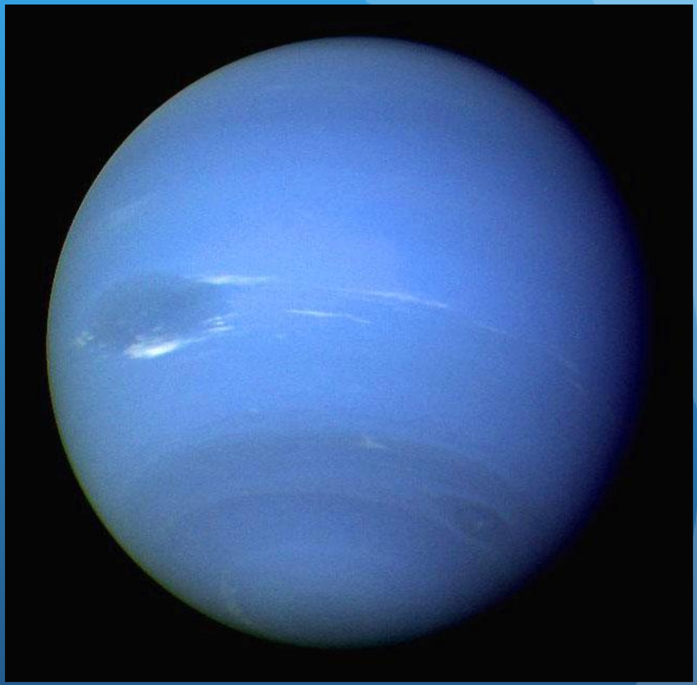
- Discovery of Neptune: (September 23, 1846)



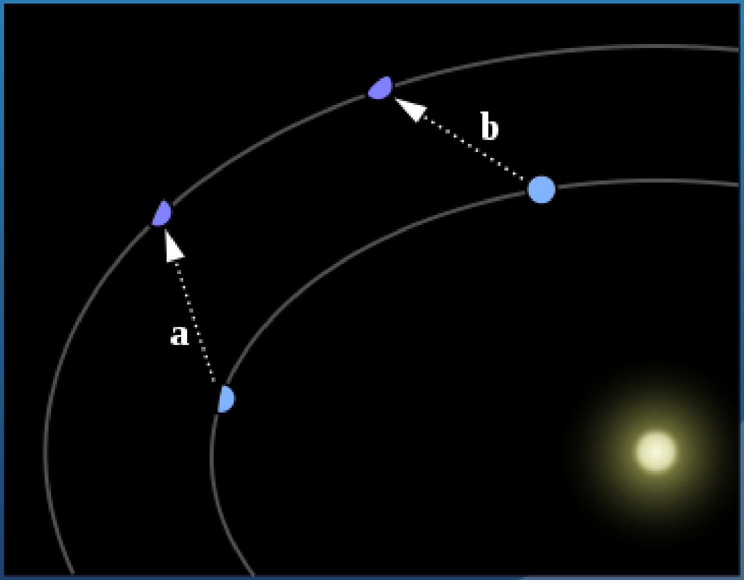
Le Verrier



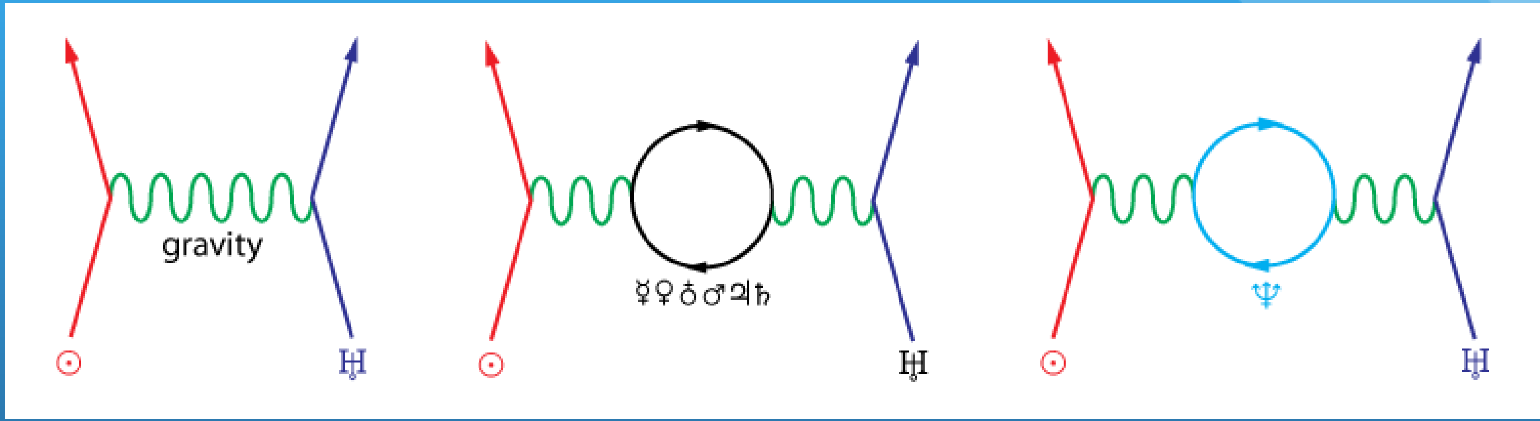
Adams



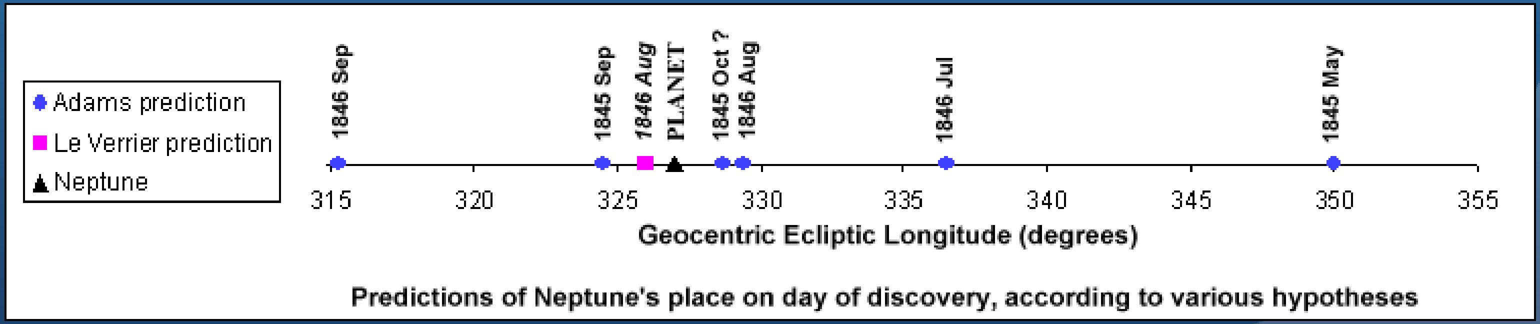
- Precise measurement of the orbit of Uranus (discovered March 13, 1781)
- Did not agree with the Standard 7 Planet Model of the solar system
- Assume deviation is due to perturbation from yet undiscovered 8th planet



- Calculate properties of 8th planet so that the theoretical orbit of Uranus agrees with observation



- Tell observers (experimentalists) to look for it!

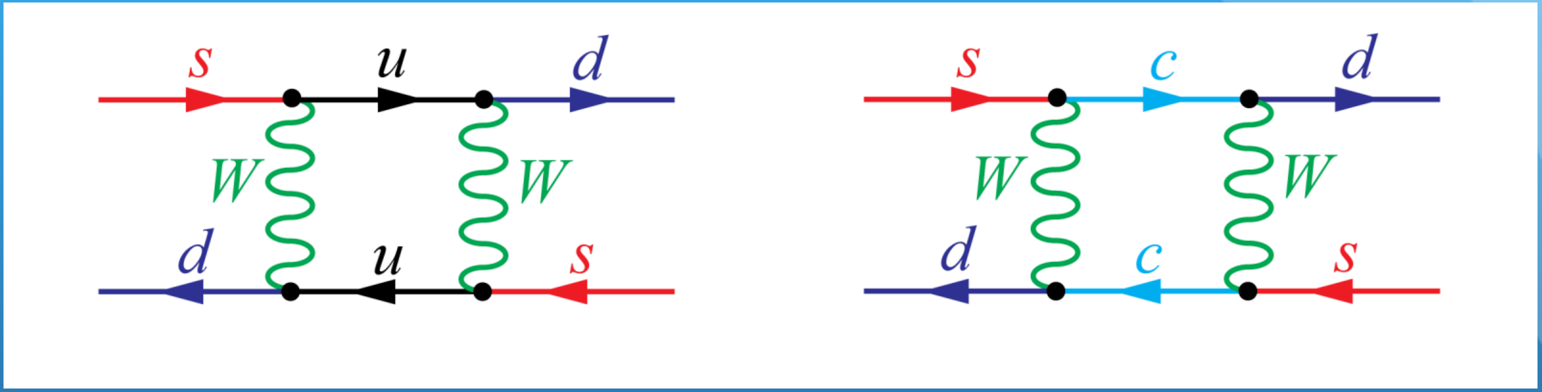


The “Neptune” strategy for Particle Physics:

- Measure the properties of known particles to extreme precision.
- Compare with Standard Model predictions and look for deviations.
- Calculate properties of New Physics that can explain the discrepancy.
- Tell experimentalists what to look for at the LHC, and other experiments.

Precedents:

- K-Kbar mixing:



- Predicted charm mass: 1.5 GeV (Gaillard and Lee, March 1974)
- J/ψ (c-cbar bound state) discovered at 3.1 GeV (November 1974)
- Top quark mass was also predicted from B-Bbar mixing.

Implimentation:

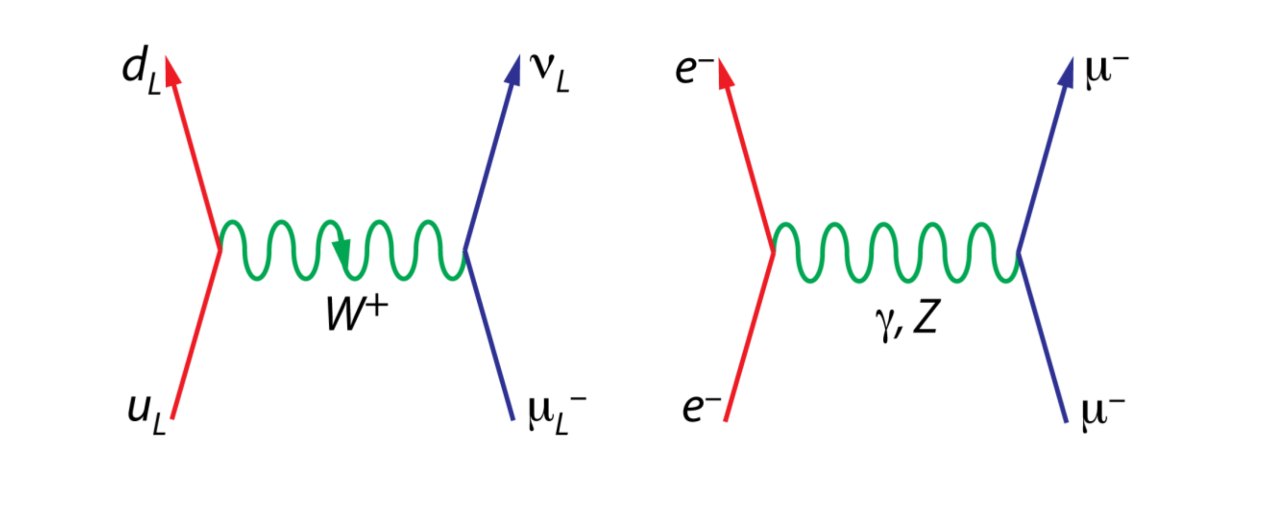
- Both precise experimental data and theoretical predictions are necessary. Forget QCD. Concentrate on electroweak observables.

- Make some reasonable assumptions about new physics (eg. 8^{th} planet hypothesis) :
  1. Electroweak Gauge Group is $SU(2)_L x U(1)_Y$
  2. New particles couple weakly to light fermions
  3. The scale of new physics is large compared to the electroweak scale

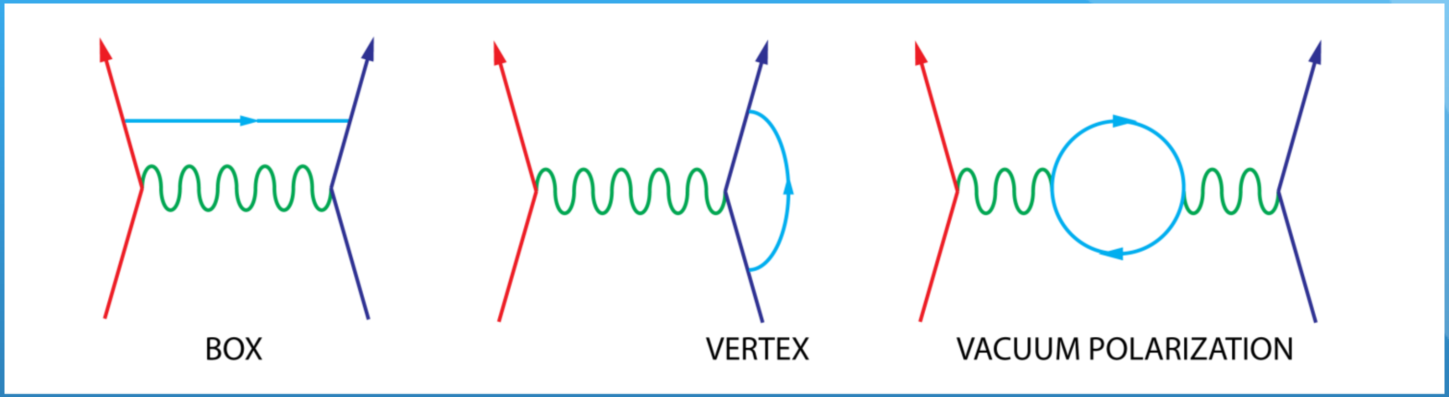
- These assumptions allow for a (relatively) model independent parametrization of radiative corrections from new physics

Consequences of the Assumptions:

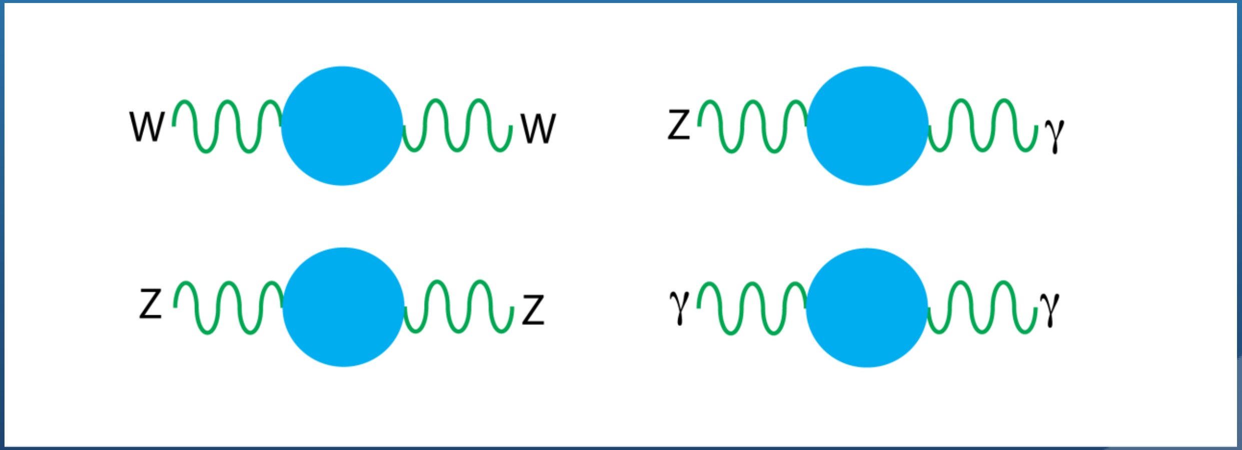
- Electroweak Gauge Group is $SU(2)_L x U(1)_Y$
  - No new electroweak gauge bosons
  - Only need to consider W, Z, and photon exchange diagrams



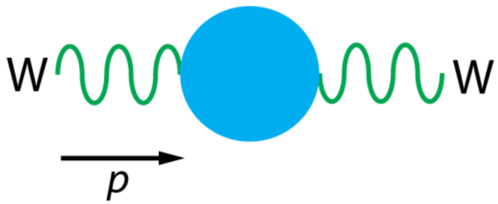
- New particles couple weakly to light fermions
  - Vertex corrections and box diagrams are suppressed



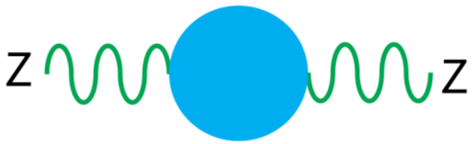
  - Only vacuum polarizations need to be considered.



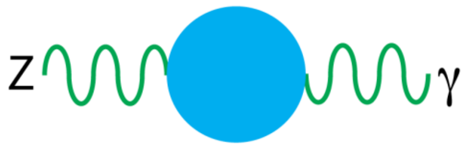
- The scale of new physics is large compared to the electroweak scale



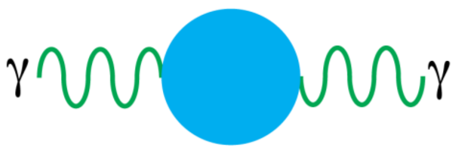
$$\Pi_{WW}(p^2) = \Pi_{WW}(0) + p^2\Pi'_{WW}(0) + \mathrm{L}$$



$$\Pi_{ZZ}(p^2) = \Pi_{ZZ}(0) + p^2\Pi'_{ZZ}(0) + \mathrm{L}$$



$$\Pi_{Z\gamma}(p^2) = p^2\Pi'_{Z\gamma}(0) + \mathrm{L}$$



$$\Pi_{\gamma\gamma}(p^2) = p^2\Pi'_{\gamma\gamma}(0) + \mathrm{L}$$

- Of the six (infinite) parameters, three linear combinations are absorbed into the three input parameters α, G_F, and M_Z and are unobservable.
- Three remaining (finite) parameters can be taken to be:

$$\alpha S = 4s^2c^2\left[\Pi'_{ZZ}(0) - \frac{c^2 - s^2}{sc}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

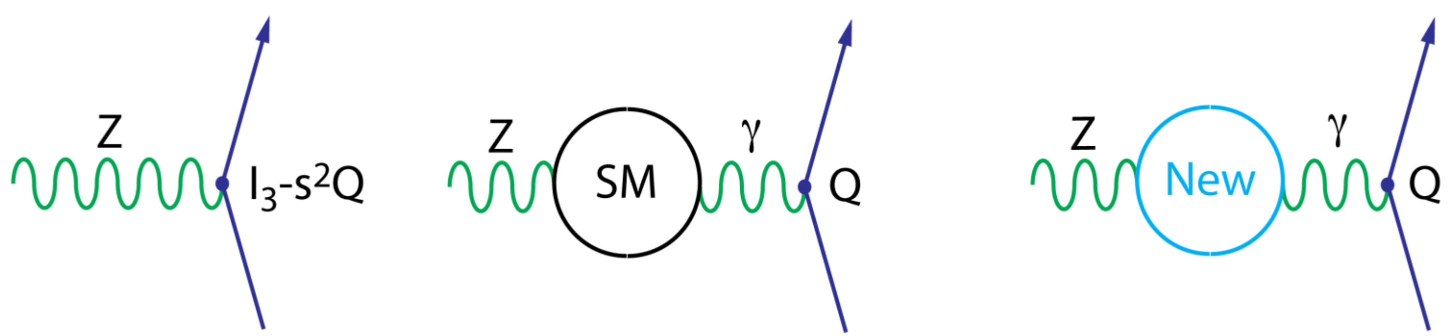
$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha U = 4s^2\left[\Pi'_{WW}(0) - c^2\Pi'_{ZZ}(0) - 2sc\Pi'_{Z\gamma}(0) - s^2\Pi'_{\gamma\gamma}(0)\right]$$

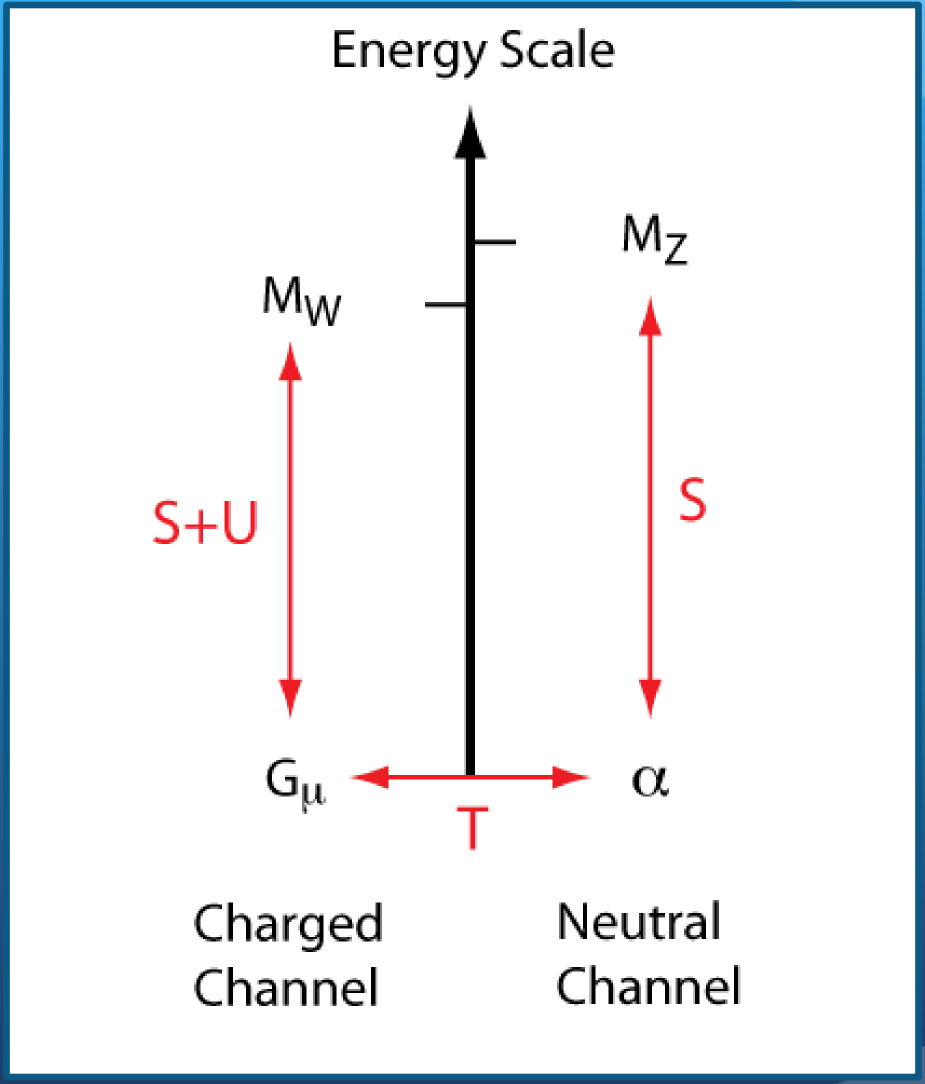
Examples:

$$\frac{M_W}{[M_W]_{SM}} = 1 - \frac{\alpha}{4(c^2 - s^2)}\left(S - 2c^2T - \frac{c^2 - s^2}{2s^2}U\right)$$

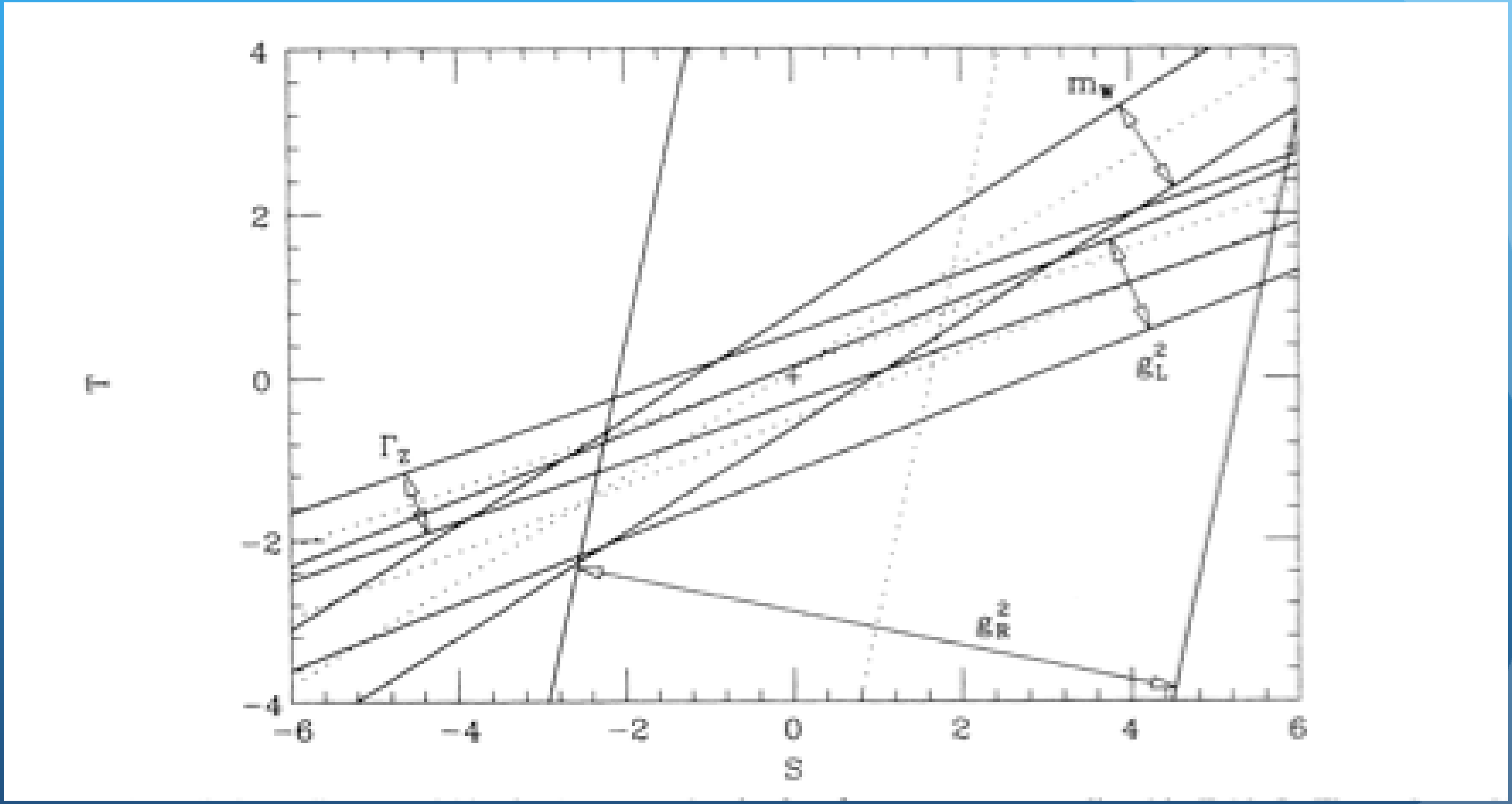
$$\frac{s_*^2}{\left[s_*^2\right]_{SM}} = 1 + \frac{\alpha}{4s^2(c^2 - s^2)}\left(S - 4s^2c^2T\right)$$



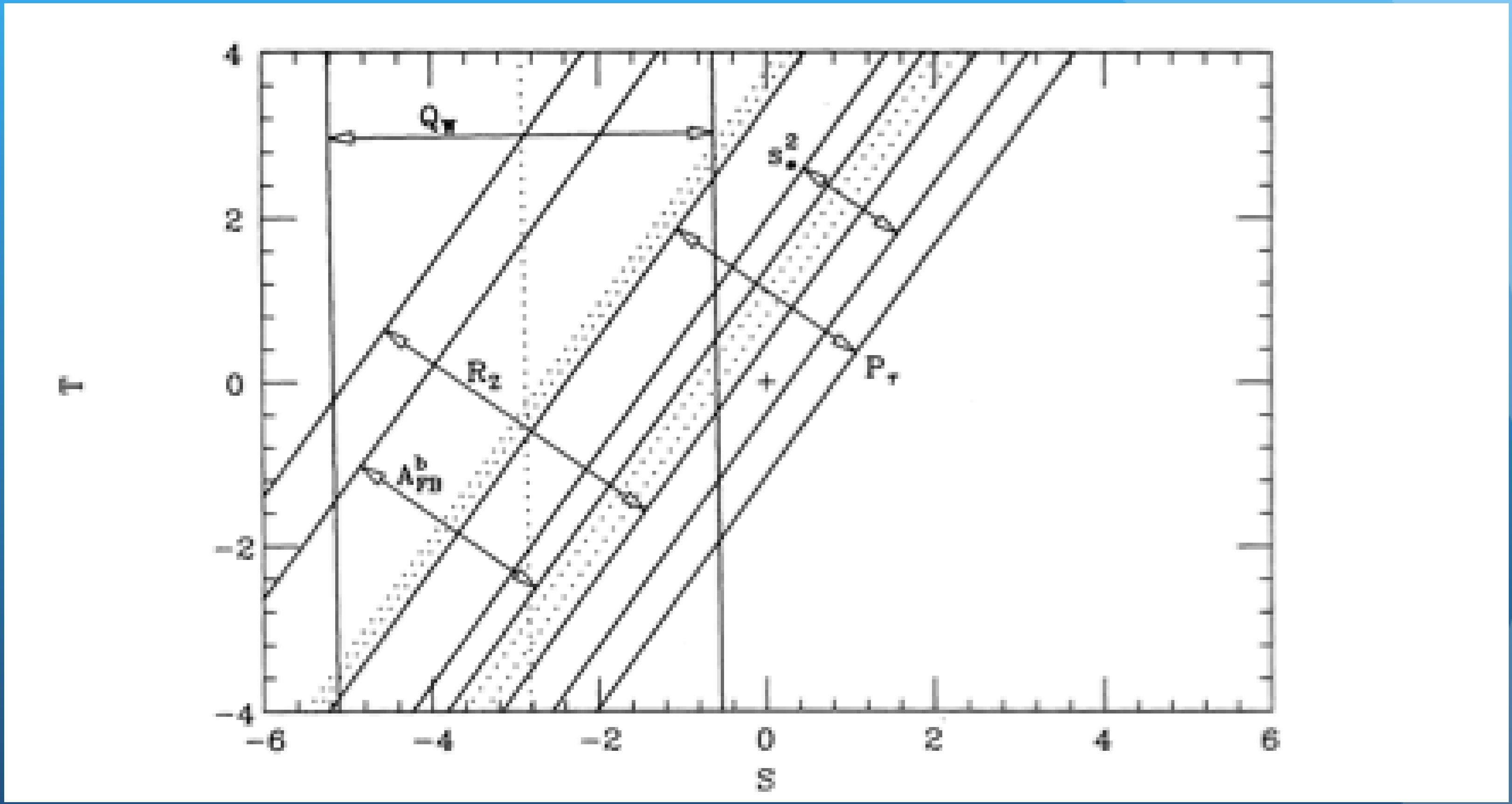
Only M_W depends on U:



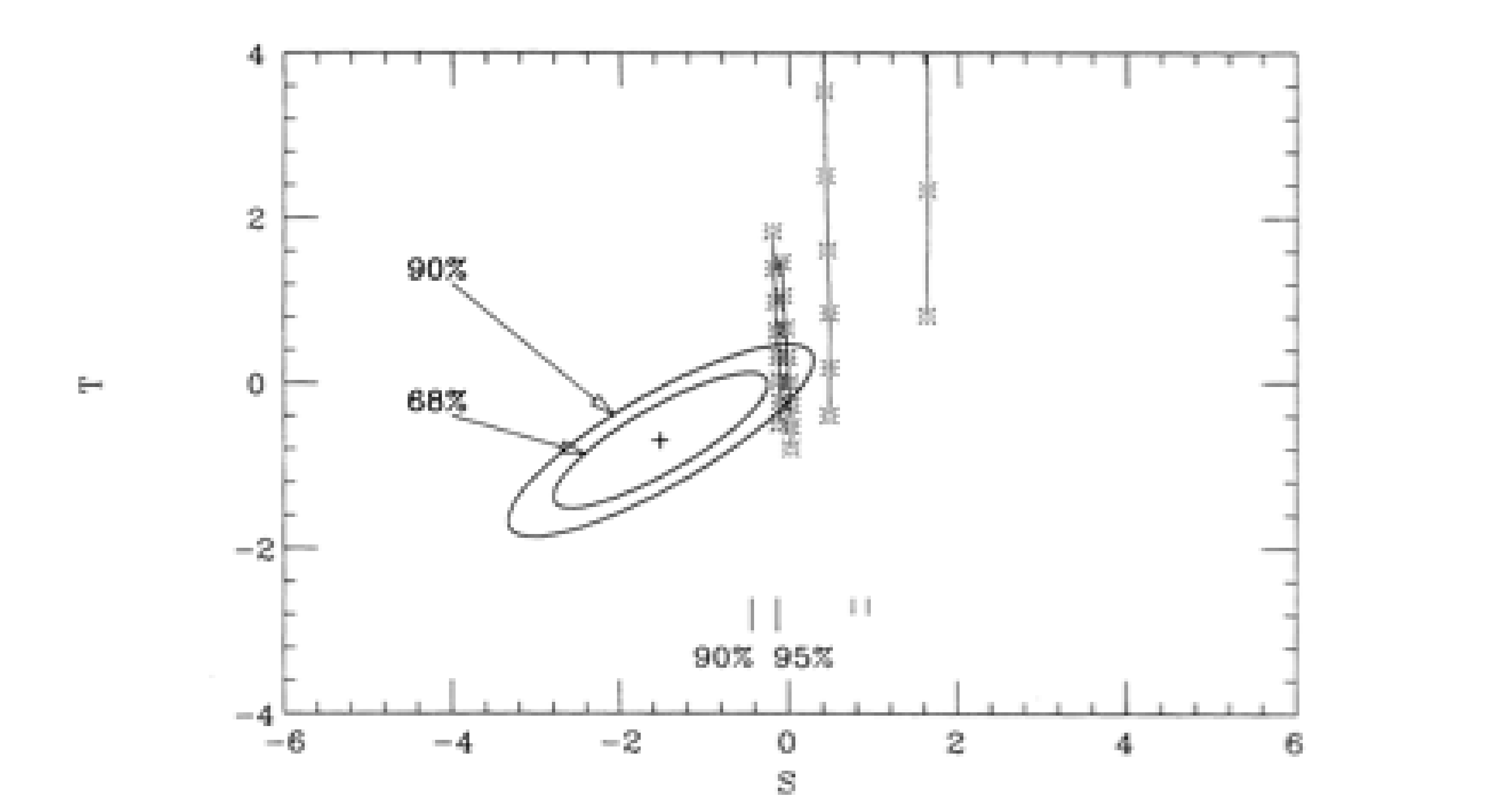
Circa 1991:



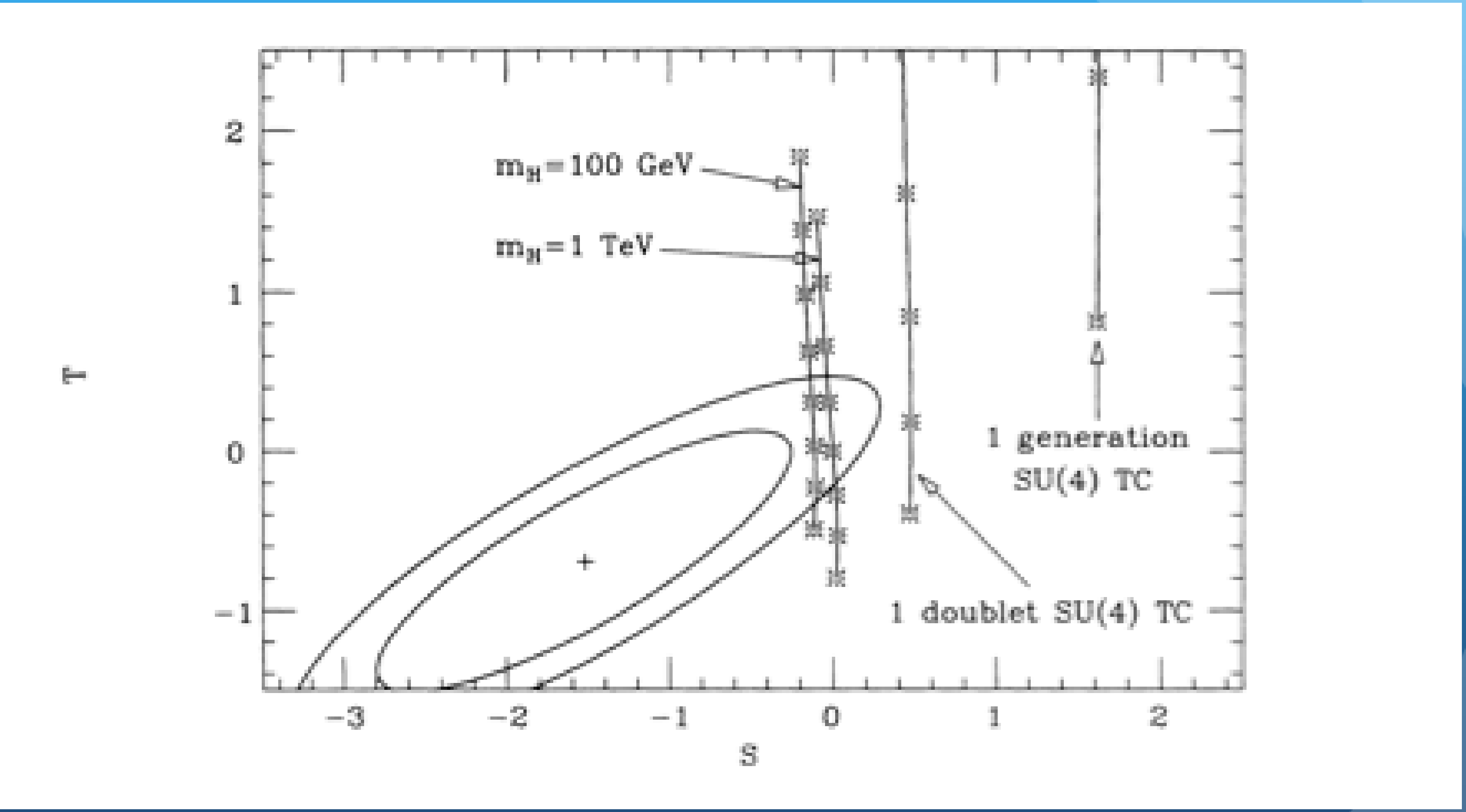
Circa 1991:



Circa 1991:

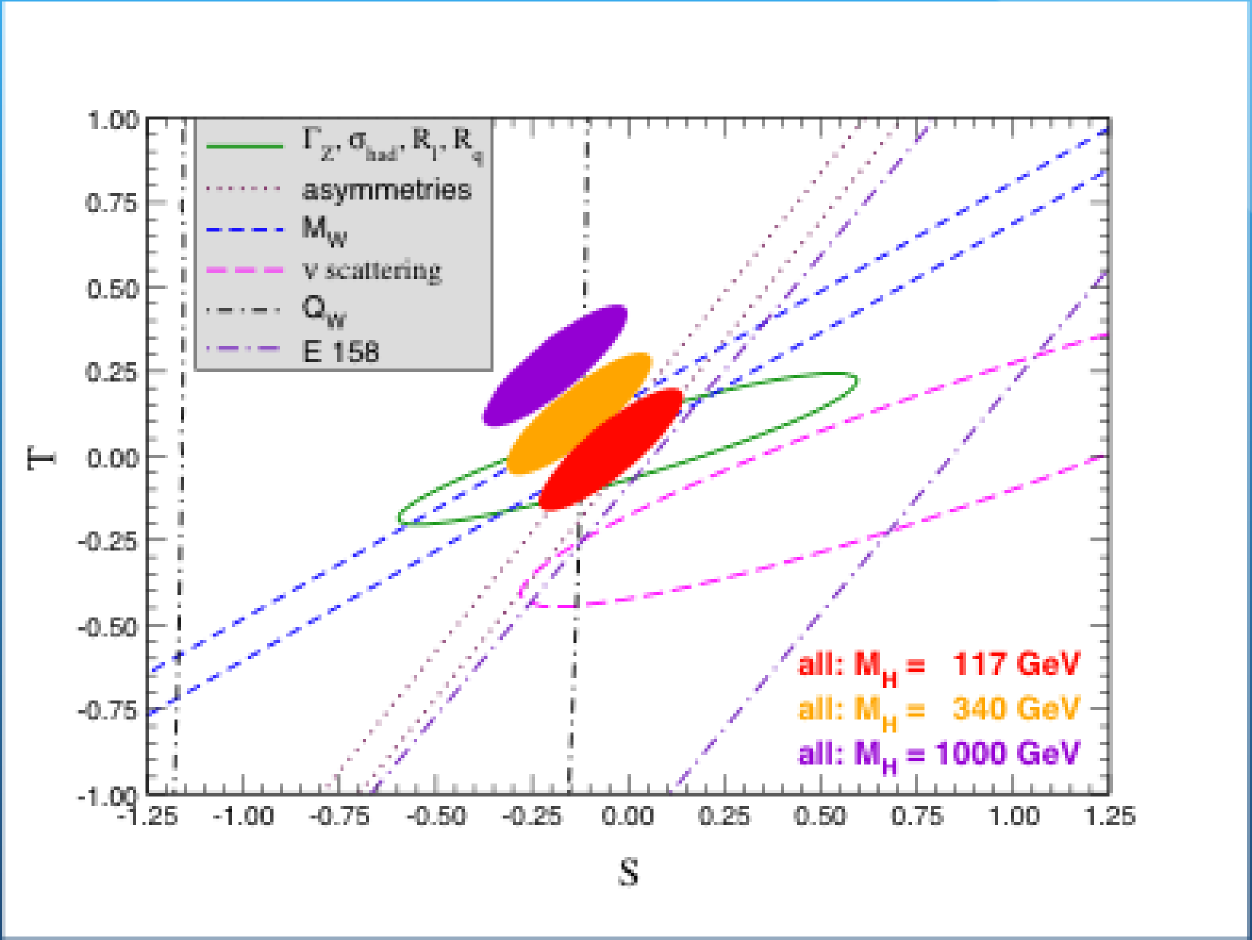


Circa 1991:



m_H=100 GeV
m_H=1 TeV
1 generation
SU(4) TC
1 doublet SU(4) TC
T
S
2
1
0
−1
−3
−2
−1
0
1
2

Current ST bounds:



From the 2008 PDB

Part 2
守株待兎
（韓非子）

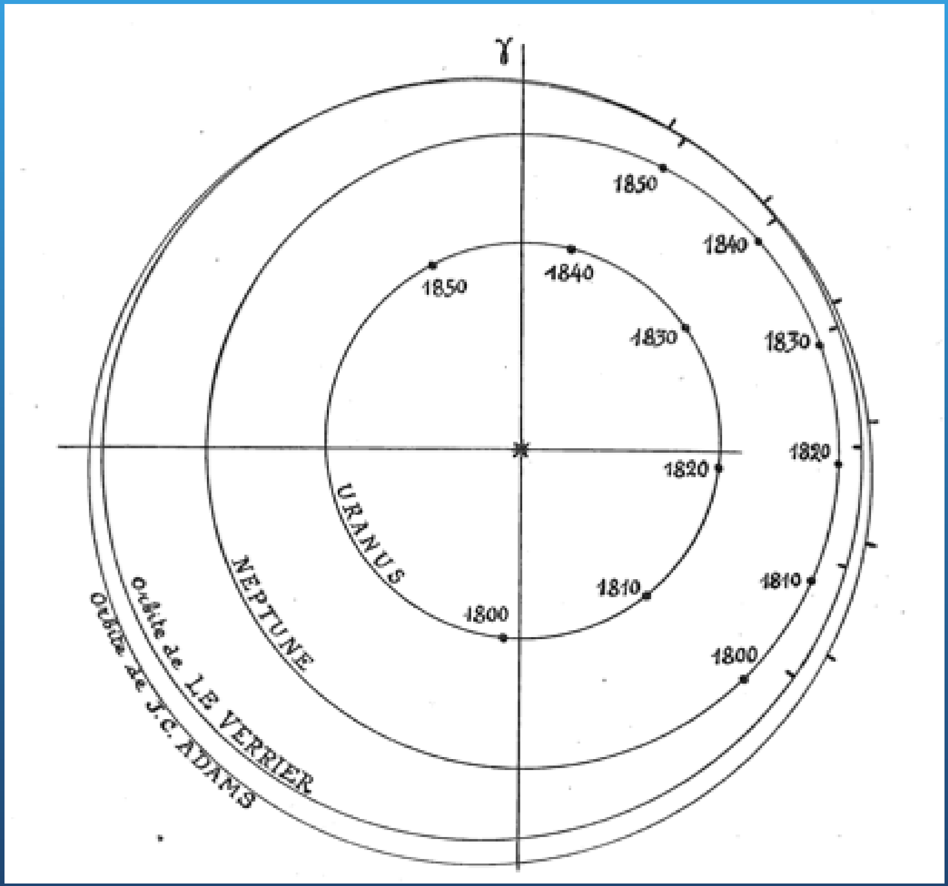
Just because it worked once does not necessarily mean it will ever work again

Search for the Planet Vulcan

- Precession of the perihelion of Mercury.
- Le Verrier hypothesized that it was due to a 0^{th} planet closer to the Sun than Mercury. (Named "Vulcan.")
- Prediction was made for its orbit.
- Was discovered many times. (Sun spots.)
- Correct explanation was Einstein's GR (1916).

Discovery of Neptune was a fluke:

- Both Le Verrier and Adams were mislead by Bode's Law.



$$a_n = 0.4 + 0.3 \times 2^n \ \text{AU}$$

$$\text{Mercury}: \quad n = -\infty$$
$$\text{Venus}: \quad n = 0$$
$$\text{Earth}: \quad n = 1$$
$$\text{Mars}: \quad n = 2$$
$$\text{Ceres}: \quad n = 3$$
$$\text{Jupiter}: \quad n = 4$$
$$\text{Saturn}: \quad n = 5$$
$$\text{Uranus}: \quad n = 6$$

Need to try different hypotheses/assumptions

- There exist several (minor) disagreements between the SM and experiments in the neutrino data which cannot be explained by the STU parameters:
  - The ratio of charged to neutral current neutrino-nucleon DIS cross sections disagrees with the SM by 3 sigma (NuTeV).
  - The invisible width of the Z is smaller than the SM prediction by 2 sigma.
  - The value of $\sin^2\theta_W$ determined from b-quark and lepton asymmetries on the Z-pole disagree by 3 sigma.
- NuTeV is often ignored as an “anomaly” and the Z-invisible width is considered a statistical fluctuation.
- What if they are not?

What did NuTeV measure?

$$R_{\nu} = \frac{\sigma(\nu_{\mu}N \to \nu_{\mu}X)}{\sigma(\nu_{\mu}N \to \mu^{-}X)} = g_L^2 + r g_R^2$$

$$R_{\overline{\nu}} = \frac{\sigma(\overline{\nu}_{\mu}N \to \overline{\nu}_{\mu}X)}{\sigma(\overline{\nu}_{\mu}N \to \mu^{+}X)} = g_L^2 + \frac{g_R^2}{r}$$

$$r = \frac{\sigma(\overline{\nu}_{\mu}N \to \mu^{+}X)}{\sigma(\nu_{\mu}N \to \mu^{-}X)} \approx \frac{1}{3}$$

The target must be an isoscalar for these relations to be valid.

The NuTeV Anomaly:

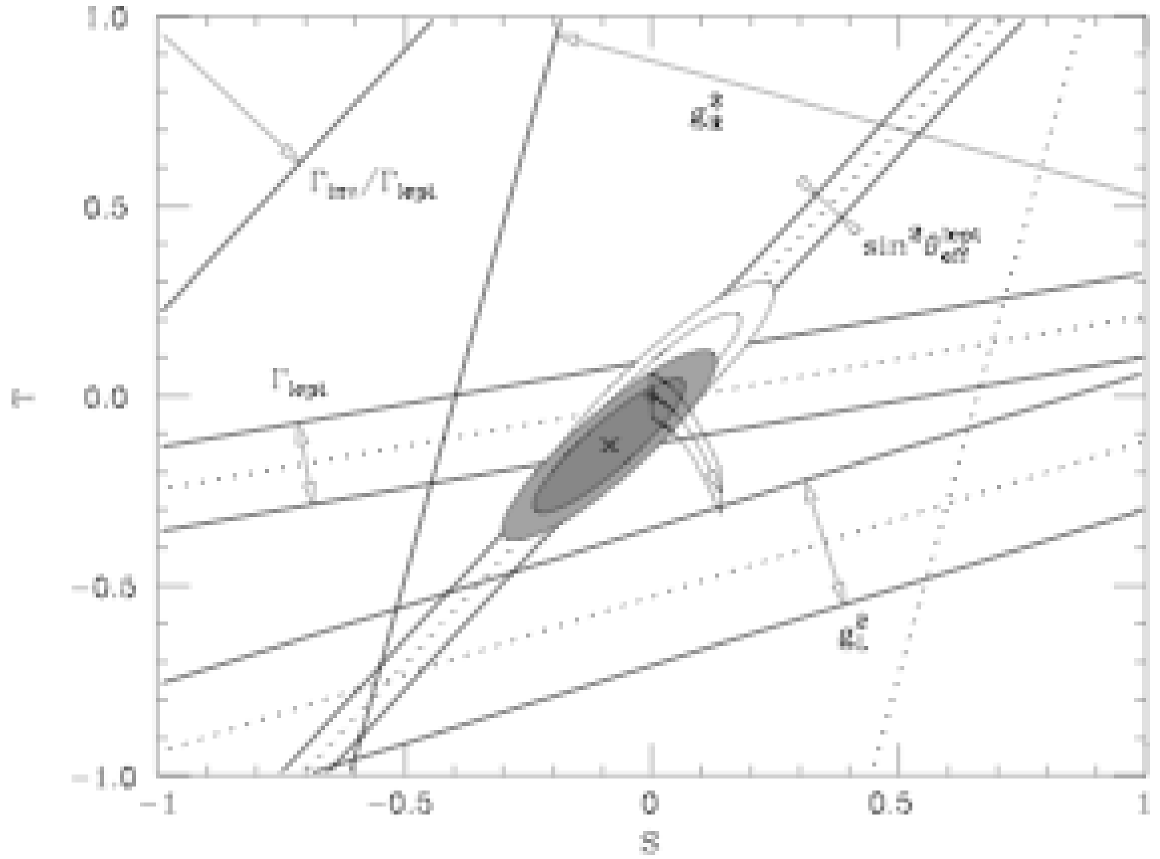
- NuTeV result:

$$g_L^2 = 0.3001 \pm 0.0014 \Leftrightarrow 0.3038$$

$$g_R^2 = 0.0308 \pm 0.0011 \Leftrightarrow 0.0301$$

- R{ was smaller than the SM prediction.
- This cannot be explained with new physics contributions through S and T.

Fit with S and T:



- Can be explained if the neutrino mixed with heavy (=heavier than Z) sterile states:

$$\nu = \nu_{light}\cos\theta + \nu_{heavy}\sin\theta$$
$$\chi = -\nu_{light}\sin\theta + \nu_{heavy}\cos\theta$$

- Effective couplings will be suppressed:

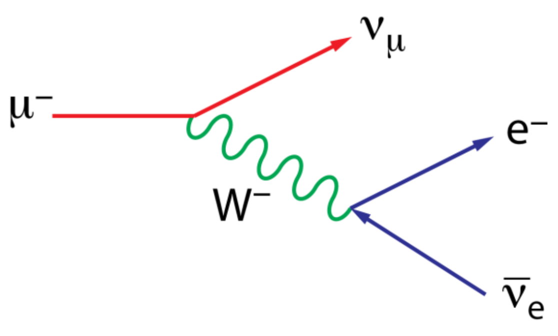
$$Z\nu\nu \rightarrow Z\nu_{light}\nu_{light}\cos^2\theta = Z\nu_{light}\nu_{light}(1-\varepsilon)$$
$$W\ell\,\nu \rightarrow W\ell\,\nu_{light}\cos\theta = W\ell\,\nu_{light}\left(1-\frac{\varepsilon}{2}\right)$$

- The suppression of the couplings will lead to:

$$R_\nu = [R_\nu]_{SM}(1-\varepsilon)$$
$$\Gamma_{inv} = [\Gamma_{inv}]_{SM}(1-2\varepsilon)$$

- However, the relation between the Fermi constant and the muon decay constant will also be modified:

$$G_F = G_\mu(1+\varepsilon)$$



- To maintain the agreement between the SM and all other electroweak observables, shift in G_F must be absorbed in the $\rho=1+\alpha T$ parameter:

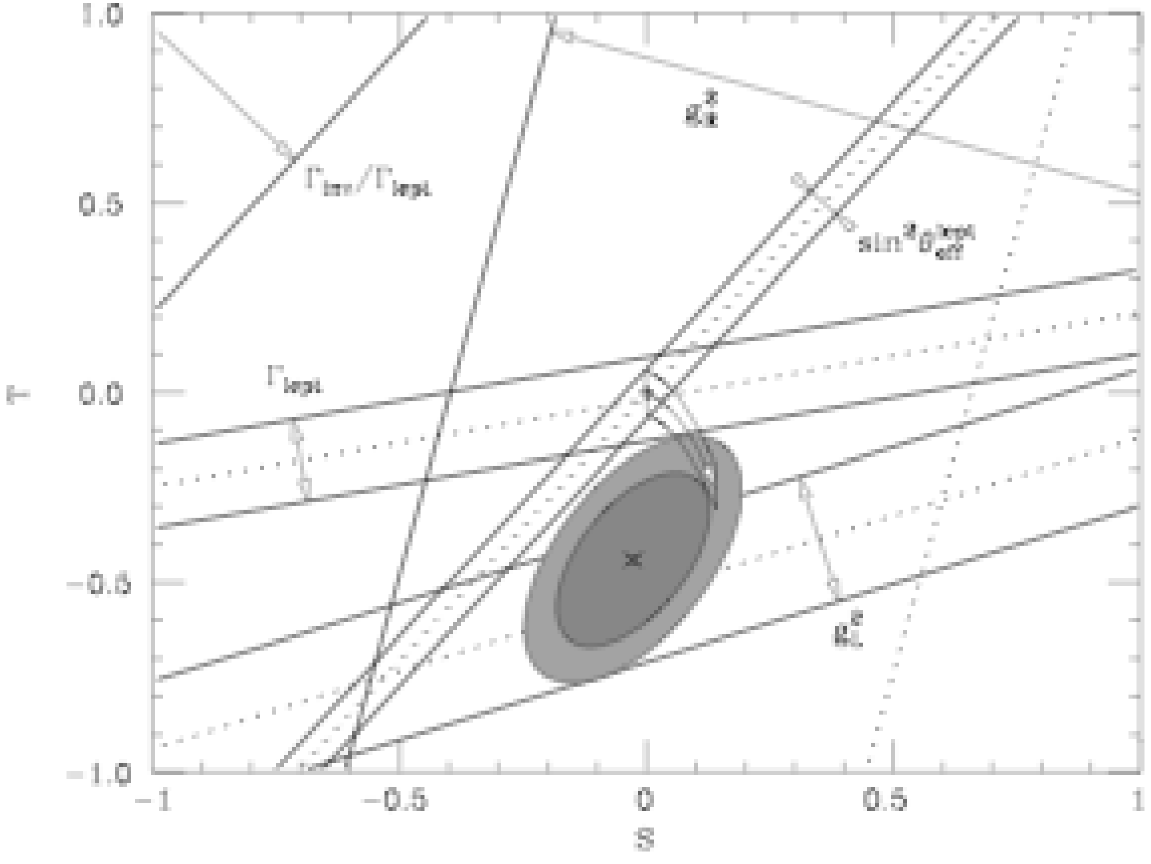
$$L=-\frac{G_F}{\sqrt{2}}\left[J^+J^-+\rho J^0J^0\right]$$

$$\rho G_F = G_\mu(1+\alpha T)(1+\varepsilon)$$

$$= G_\mu(1+\alpha T+\varepsilon)$$

- Must perform fit with S, T, and ε.

Fit with S, T, and ε:



Fit result:

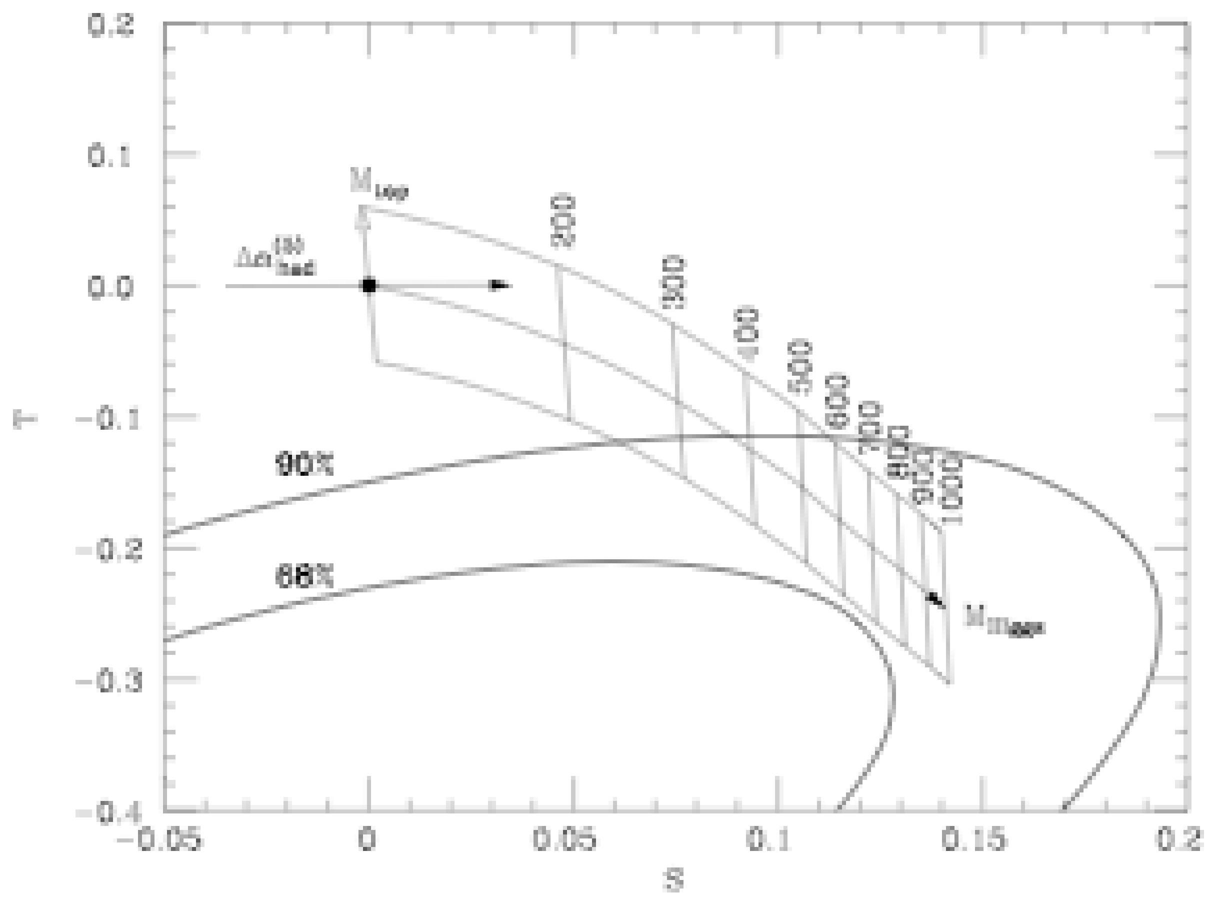
$$S = -0.03 \pm 0.10$$

$$T = -0.44 \pm 0.15$$

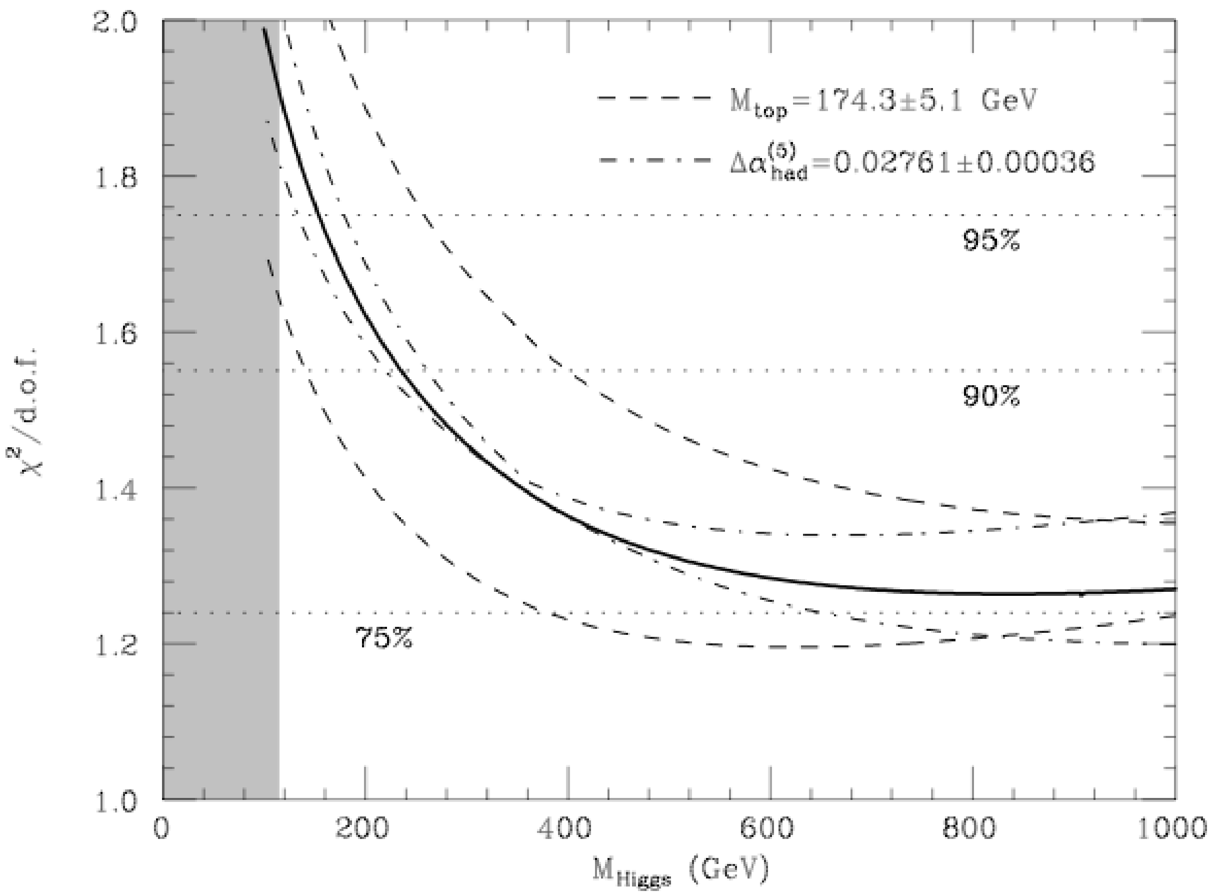
$$\varepsilon = 0.0030 \pm 0.0010$$

- What type of new physics will generate the required values of S and T?
  - Heavy Higgs!

Blowup of ST plot:

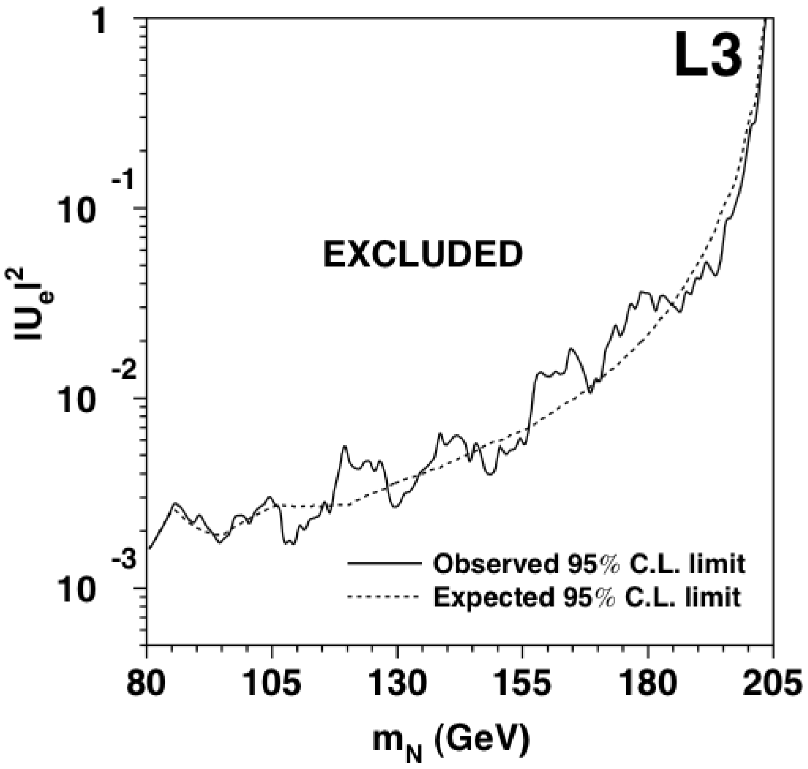


Dependence of χ^2 on the Higgs mass:



How heavy are the heavy states?

- Direct search limits are weak:



Seesaw Type Model:

- If the scale of the Dirac masses is m, and the scale of the Majorana masses is M, the suppression factor is:

$$\varepsilon \approx \frac{m^2}{M^2}$$

- I order to have ε=0.003 and m~100 GeV, we must have M~2 TeV.
  - ➢ The heavy states will be light enough to be produced at the LHC!
  - ➢ Unfortunately, the production cross section is too small.(Tao Han, et al.)
  - ➢ Is there any other way to detect the presence of these states?

The Electric Dipole Moment:

- Magnetic and Electric Dipole Moments:

$$\mu\vec{\sigma}\cdot\vec{B} \qquad d\vec{\sigma}\cdot\vec{E}$$

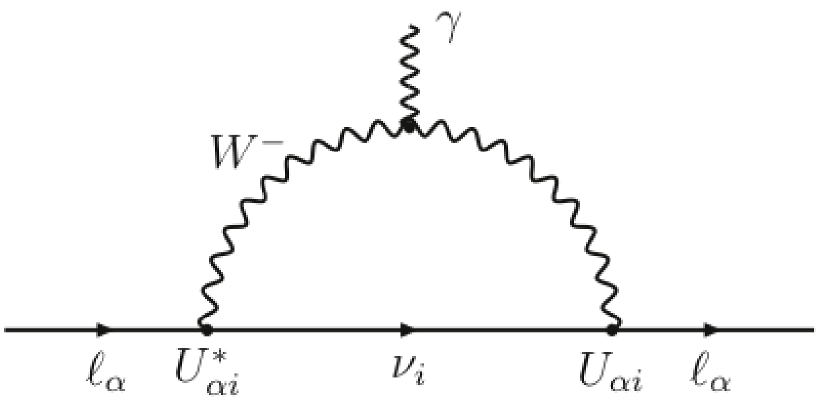
- Under CPT:

$$\vec{\sigma} \xrightarrow{P} +\vec{\sigma} \xrightarrow{C} -\vec{\sigma} \xrightarrow{T} +\vec{\sigma}$$

$$\vec{B} \xrightarrow{P} +\vec{B} \xrightarrow{C} -\vec{B} \xrightarrow{T} +\vec{B}$$

$$\vec{E} \xrightarrow{P} -\vec{E} \xrightarrow{C} +\vec{E} \xrightarrow{T} +\vec{E}$$

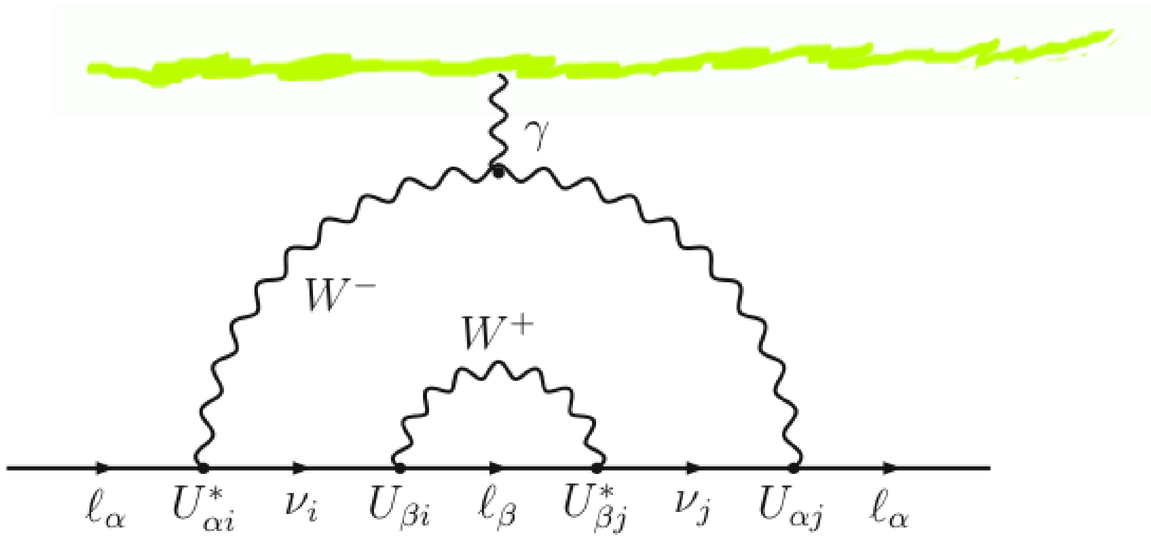
1-loop diagram



$$\propto |U_{\alpha i}|^2$$

Insensitive to complex phases

2-loop diagram



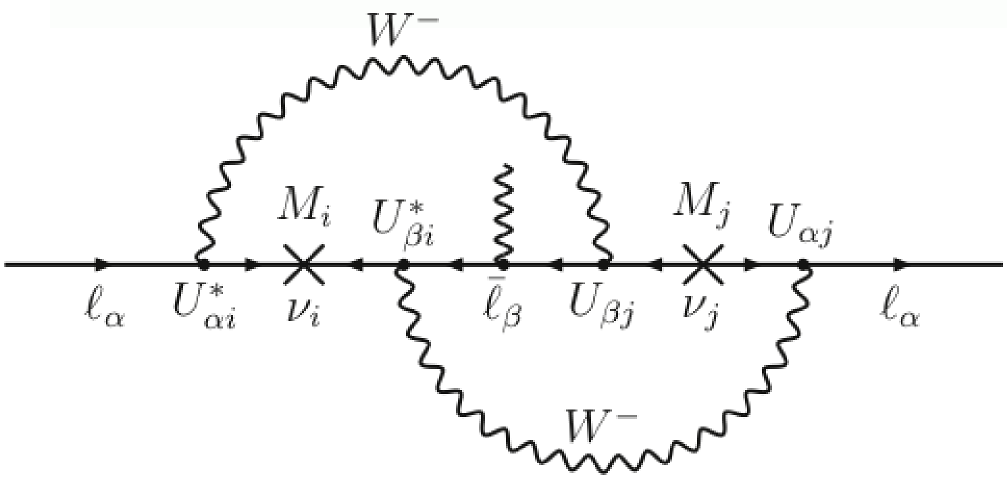
$$\propto (U^*_{\alpha i} U_{\beta i})(U_{\alpha j} U^*_{\beta j})$$

Diagram is symmetric under the interchange $i \leftrightarrow j$

$\Longrightarrow$ Imaginary parts of $(U^*_{\alpha i} U_{\beta i})(U_{\alpha j} U^*_{\beta j})$ cancel

Shabalin, Sov. J. Nucl. Phys. 28 (1978) 75

2-loop diagram unique to leptons

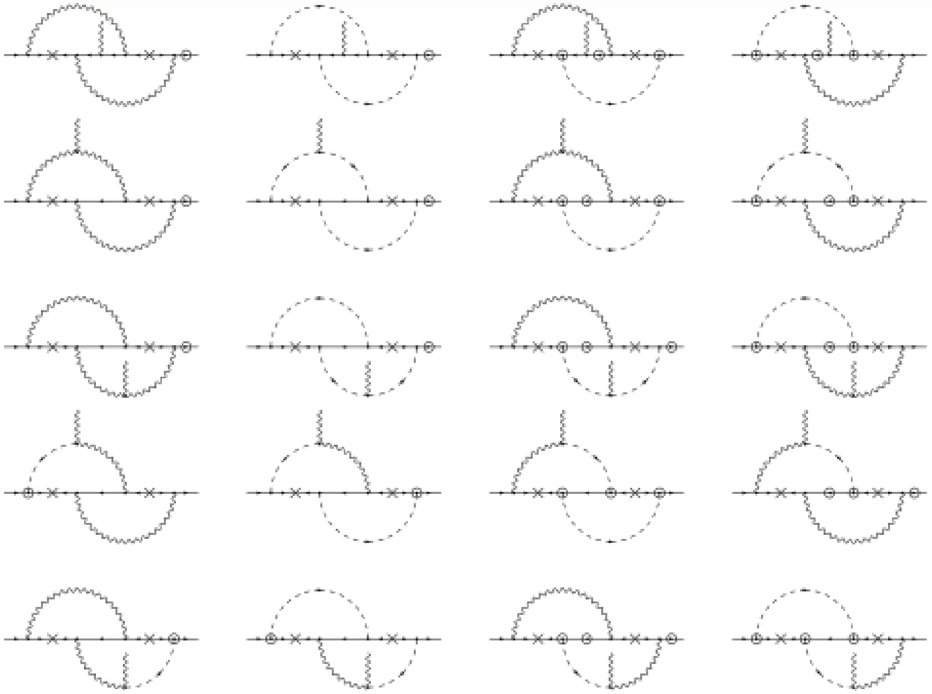


$$\propto (U^*_{\alpha i} U^*_{\beta i})(U_{\alpha j} U_{\beta j})$$

Diagram is anti-symmetric under the interchange $i \leftrightarrow j$

$\Longrightarrow$ Imaginary parts of $(U^*_{\alpha i} U^*_{\beta i})(U_{\alpha j} U_{\beta j})$ survive

20 Diagrams



Result of 2-loop Calculation:

- Seesaw type model:
  (calculation by Saifuddin Rayyan)

$$d_l = 10^{-31} \sim 10^{-32} e \cdot cm$$

- Current experimental constraint:

$$d_e = (6.9 \pm 7.4) \times 10^{-28} e \cdot cm$$

$$d_\mu = (3.7 \pm 3.4) \times 10^{-19} e \cdot cm$$

- Proposals exist to improve current bound by many orders of magnitude. (Whether they would work or not is still controvertial.)

Conclusions:

- Precision electroweak data from LEP and SLD place very strong constraints on what we can expect to see at the LHC.
- The STU parameters provide a simple way to visualize the compatibility of your model and the data.
- However, be mindful of the fact that the STU parameters do not necessarily encompass all possible new physics.
- You never really know what you will find until you get there. (Recall WMD's in Iraq.)