One-loop Corrections to the *S* and *T* Parameters in ~~Higgs~~ Models

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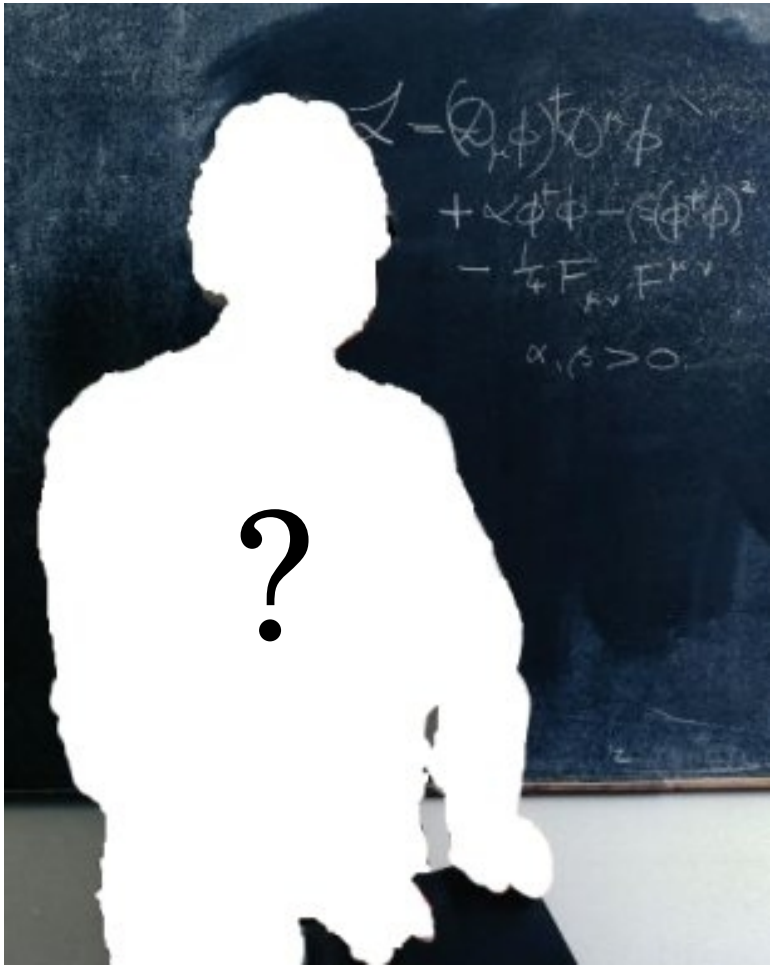
- The Model(s)
  - The "Three Site" Model
- Gauge-dependence of Two-point Functions
- The "Pinch" Technique
- "Generic" Results
- Application to Three Site Model



The Model(s)

- ~~Higgs~~ Models:
  - Extra-dimensional: gauge symmetries broken via non-trivial BCs on 5-d wavefunctions
  - Deconstructed: coupled non-linear sigma models with extended gauge symmetries of the form $SU(2) \times SU(2)^N \times U(1)$
- Related Features:
  - Spectrum: massless photon and towers W's and Z's

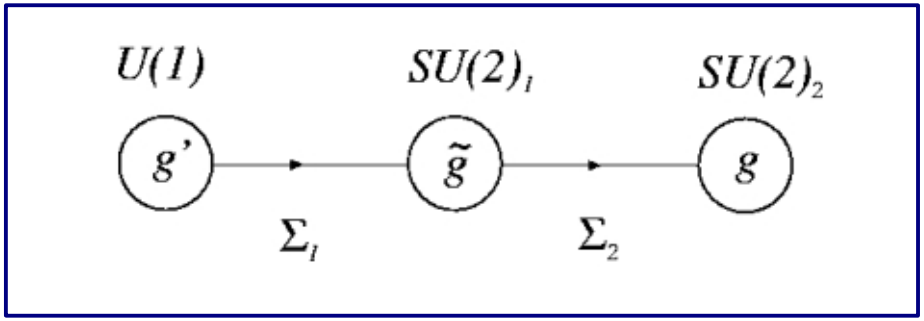
$$B^\mu = b_{00}\gamma^\mu + \sum_{n=1}^{N+1} b_{0n} Z^\mu_{(n)} \qquad W_{3,i} = b_{i0}\gamma^\mu + \sum_{n=1}^{N+1} b_{in} Z^\mu_{(n)} \qquad W_i^{\pm,\mu} = \sum_{n=1}^{N+1} a_{in} W^{\pm,\mu}_{(n)}$$

  - Non-renormalizable $\rightarrow$ effective theories up to Λ (~ 5-10 TeV)
  - Three scales:

$$M_W^2 \ll M_{W'}^2 \ll \Lambda^2$$

The Three Site Model

- Non-linear sigma model based on global $SU(2)^3 \rightarrow SU(2)$ breaking
- Gauged sub-group is $SU(2) \times SU(2) \times U(1)$ which breaks to SM gauge group $SU(2)_L \times U(1)_Y$ via two Σ fields



- Kinetic terms for sigma fields (in unitary gauge) result in masses for gauge fields:

$$\mathscr{L}_\Sigma = \sum_{i=1}^{2} \frac{f_i^2}{4} Tr\, D^\mu \Sigma_i (D_\mu \Sigma_i)^\dagger$$

$$D^\mu \Sigma_1 = \partial^\mu \Sigma_1 - i g' T^3 B_\mu \Sigma_1 + i \tilde{g} \Sigma_1 T^a W_1^{\mu,a}$$
$$D^\mu \Sigma_2 = \partial^\mu \Sigma_2 - i \tilde{g} T^a W_1^{\mu,a} \Sigma_2 + i g \Sigma_2 T^a W_2^{\mu,a}$$

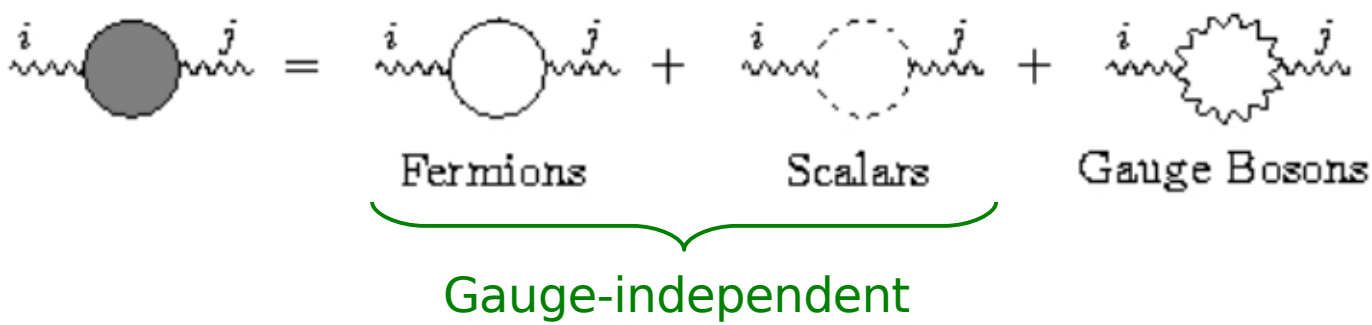
- Spectrum = SM plus one extra set (W', Z') with masses $\gg M_W$
- Low-energy symmetries (and operators) identical to those of EW Chiral Lagrangian with a heavy Higgs boson

Gauge-dependent Oblique Parameters?

- Oblique parameters defined in terms of SM gauge boson self-energies:

$$\frac{\alpha S}{4 s_W^2 c_W^2} = \Pi'_{ZZ}(0) - \Pi'_{\gamma\gamma}(0) - \frac{c_W^2 - s_W^2}{s_W c_W} \Pi'_{Z\gamma}(0) \qquad \alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

- Corrections to Π_{ij}'s can be separated into several sub-classes:

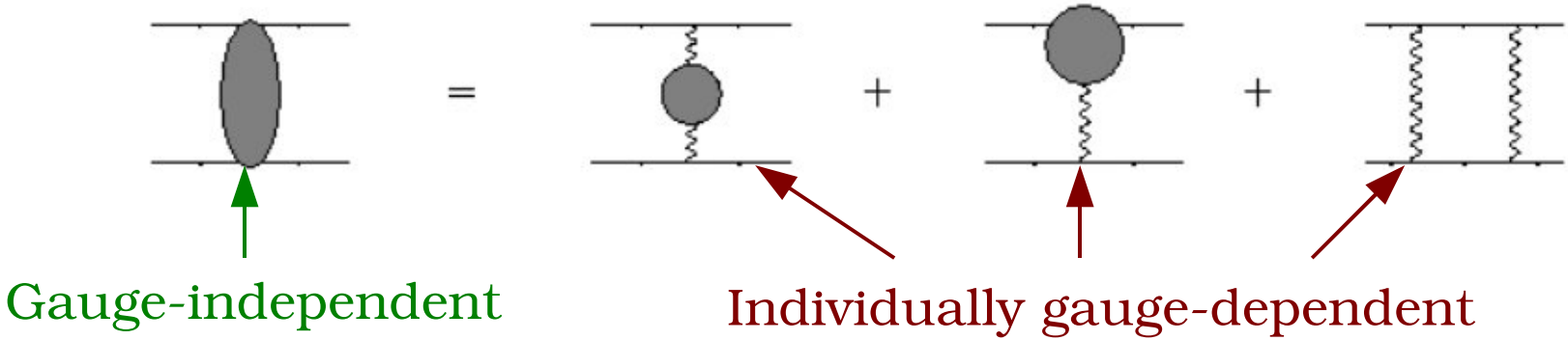


- Degrassi/Sirlin (c. 1992) showed that SM gauge boson corrections to Π_{ij}'s are non-trivially dependent on gauge-fixing parameter ξ_i ($i = \gamma$, W or Z):

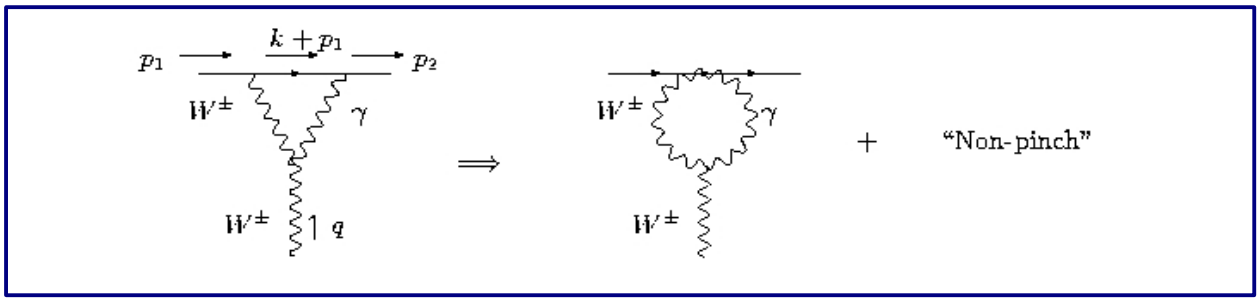
$$\Pi_{ij}(q^2) = \Pi_{ij}(q^2)\big|_{\xi=1} + f_{ij}(\xi_i, q^2, M_W, M_Z)$$

Gauge-dependent terms do not cancel in observables (e.g. S or T)

The Pinch Technique (PT)



- Pinch Technique: isolate "propagator-like" corrections from vertex/box diagrams and add to two-point functions



- The resulting expressions ($\Pi_{ii}^{PT} \equiv \Pi_{ij} + (q^2 - M_i^2)\{V_i\} + (q^2 - M_i^2)^2\{B_i\}$) are independent of the particular R_ξ gauge used in the calculation

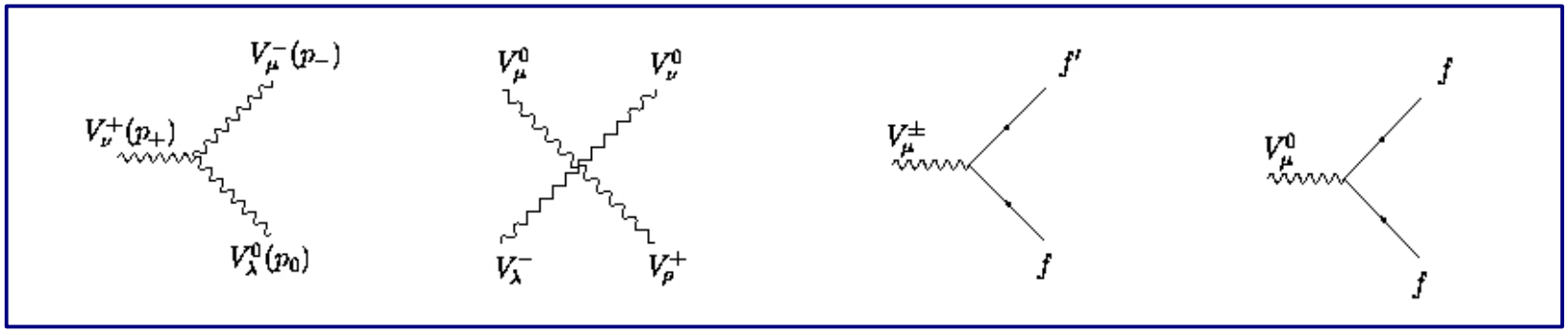
- Gauge-invariant expressions for oblique parameters are then constructed by replacing Π_{ij}'s by their PT counterparts Π_{ij}^{PT}'s

Application to a Generic ~~Higgs~~ Model

- Construct a "recipe" for calculating one-loop corrections to S and T in Higgsless models
- Starting points:
  - Spectrum consists of SM-like gauge bosons and one heavy set (W', Z')
  - Mass hierarchy: $M_W^2 \ll M_{W'}^2 \ll \Lambda^2$

$$\frac{1}{\epsilon} \rightarrow \log \frac{\Lambda^2}{M_i^2}$$

- Calculate diagrams in terms of "generic" couplings/Feynman rules:



- Identify "generic" couplings in terms of gauge couplings and mixing angles for a particular model

S and *T* in the Three Site Model

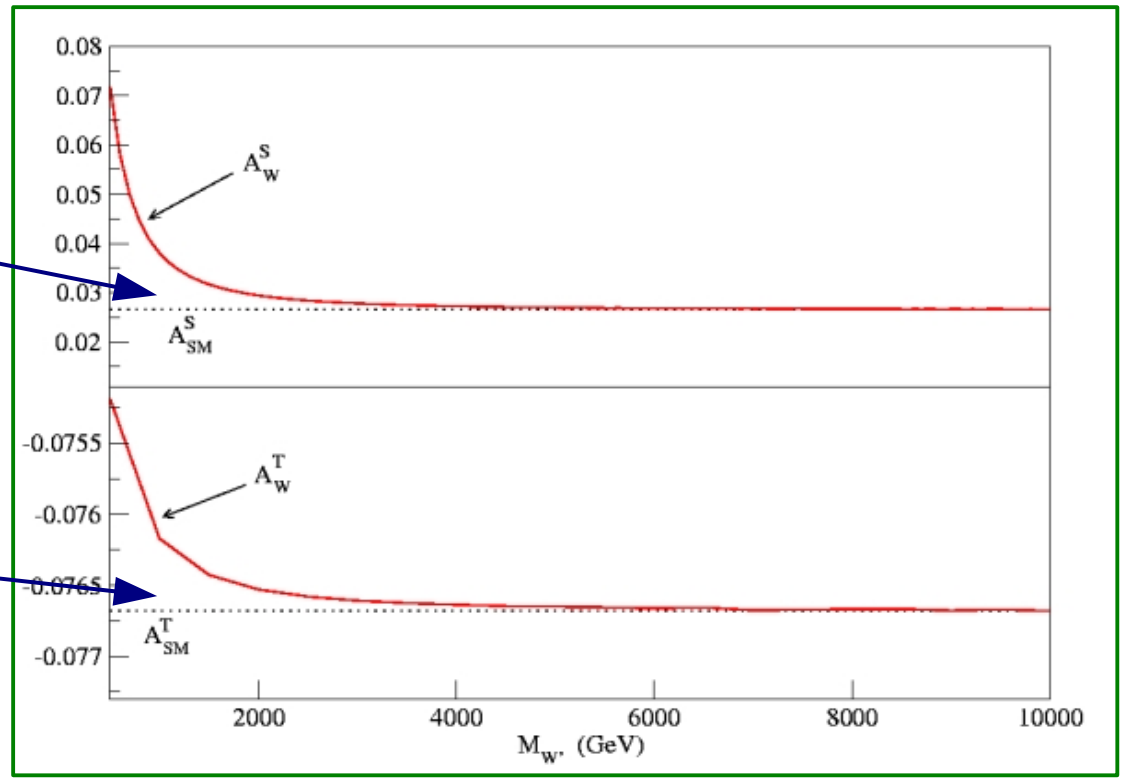
- One-loop corrections to X ($X = S$ or T) naturally separate into low- and high-energy contributions:

$$X = X_{tree} + A_W^X \log\frac{M_{W'}^2}{M_W^2} + (A_W^X + A_{W'}^X)\log\frac{\Lambda^2}{M_{W'}^2} + X_0$$

- Since symmetries well below $M_{W'}$ are those of SM, the low-energy coefficient A_W should reduce to SM (w/ heavy Higgs) value:

$$A_{SM}^S = \frac{1}{12\pi}$$

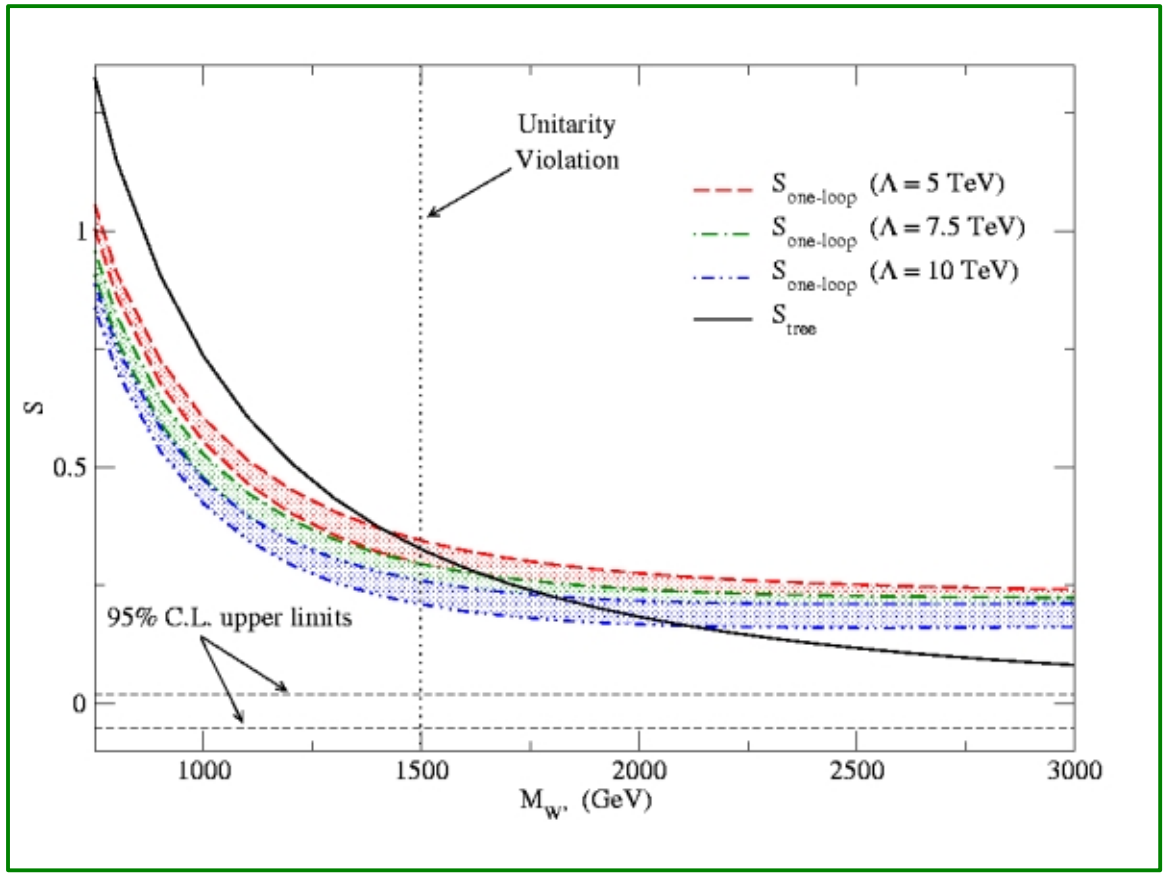
$$A_{SM}^T = -\frac{3}{16\pi c_W^2}$$



One-loop Corrections to *S* in the Three Site Model

- Subtracting the contribution from a heavy Higgs, the one-loop corrected *S* parameter in the three site model is:

$$S_{1-loop} = \frac{4 s_W^2 M_W^2}{M_{W'}^2} + \frac{1}{12\pi}\log\frac{M_{W'}^2}{M_{H,ref}^2} + \kappa_S \log\frac{M_{W'}^2}{M_W^2} + (A_{W'}^S + A_W^S)\log\frac{\Lambda^2}{M_{W'}^2}$$



- ☆ Large, positive tree-level contribution
- ☆ Chiral logs reduce total ...but probably not enough
- ☆ "Tension": Unitarity constraints vs. Constraints from *S*

One-loop Corrections to *T* in the Three Site Model

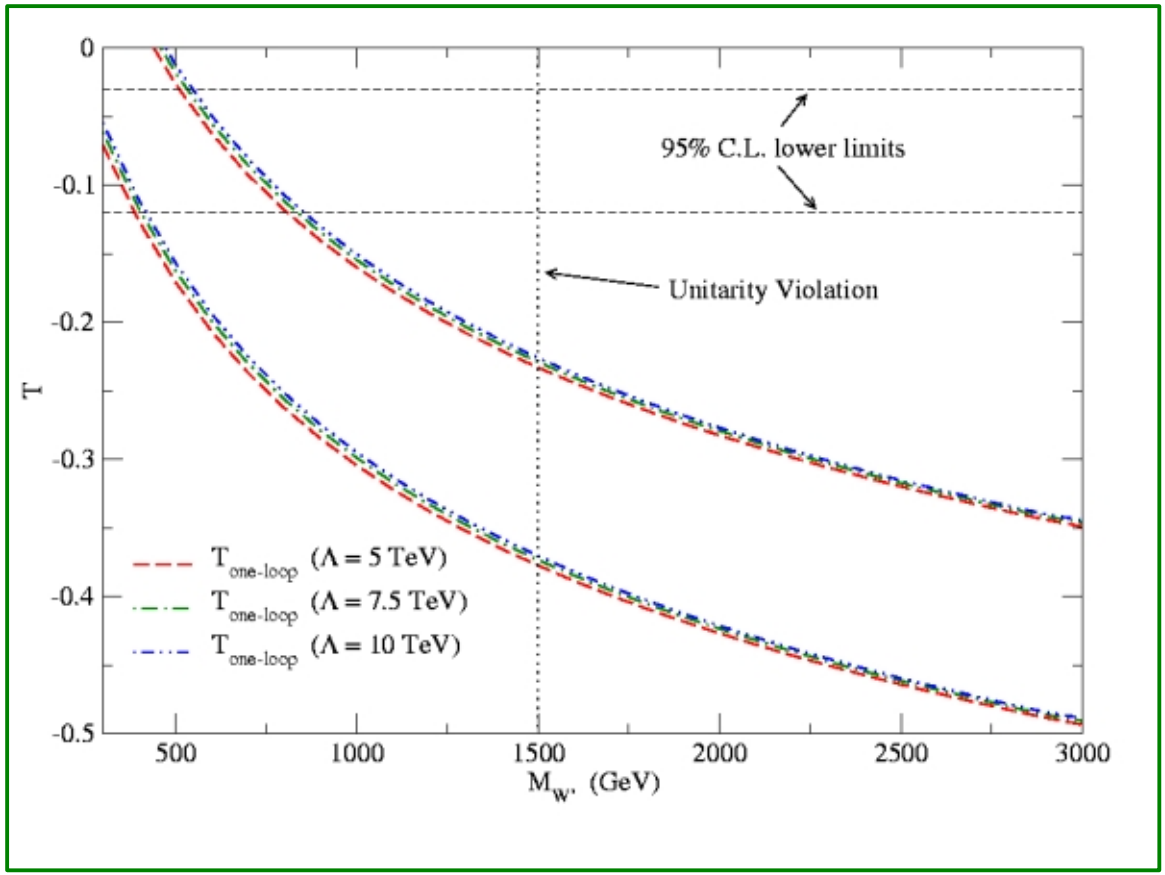
- Subtracting the contribution from a heavy Higgs, the value of *T* in the three site model is:

$$T_{1-loop} = -\frac{3}{16\pi c_W^2}\log\frac{M_{W'}^2}{M_{H,ref}^2} + \kappa_T \log\frac{M_{W'}^2}{M_W^2} + \left(A_{W'}^T + A_W^T\right)\log\frac{\Lambda^2}{M_{W'}^2}$$

- Values of *T* consistent with constraints from Unitary
- One-loop corrections to *T* are **independent of cutoff scale** Λ

$$A_{W'}^T + A_W^T \simeq 0$$

Custodial Symmetry at Work!



Conclusions and Outlook

- ~~Higgs~~ models provide viable alternatives to explain EWSB
- General features:
  - Spectrum = SM gauge boson *plus* "towers" of heavy *W*'s and *Z*'s
  - Mass hierarchy: $M_W^2 \ll M_{W'}^2 \ll \Lambda^2$
- "Recipe" for calculating corrections to *S* and *T* in ~~Higgs~~ models
  - Novel application of "Pinch" Technique
- Application to Three Site Model
  - Corrections to *S* not enough to overcome large tree-level piece
  - "High-energy" corrections to *T* vanish (custodial symmetry)
- Outlook: apply "recipe" to models with fundamental (or composite) Higgs bosons to calculate gauge sector contribution to *S* and *T*