TOP PHYSICS

in

LITTLE HIGGS MODELS

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[loosely based on Peskin, Pierce, MP, hep-ph/0310039]

Introduction: Why Little Higgs?

- I will assume the Standard Model with a light Higgs

- The model describes electroweak symmetry breaking, but does not explain it:

$$V(H) = -\mu^2 H^+ H + \lambda (H^+ H)^2$$

- A more satisfactory theory of EWSB would predict the sign of the μ^2 term

- In SM, μ^2 receives large radiative corrections:

$$\mu^2(M_W) = \mu^2(\Lambda) + \frac{g^2}{16\pi^2}\left(c_1 \Lambda^2 + c_2 M^2 \log\Lambda + \ldots\right)$$

(Here Λ = strong coupling scale)

- To construct a predictive theory:
  - suppress the uncalculable contributions ($\mu^2(\Lambda)$, c_1) by symmetries
  - make sure that the calculable contributions have the correct sign ($c_2 < 0$) [top!]

The Role of the Top Quark

- Large top Yukawa coupling ⇒ top loops are the largest SM contribution

- In SM, dominant contribution is uncalculable (c_1)

- Calculability + naturalness require cancellations by new particles at $\lesssim 2$ TeV

$$\Delta\mu^2 = c_2 \frac{\lambda_t^2}{16\pi^2} M_X^2 \log\frac{\Lambda}{M_X}$$

c_2 is calculable! Typically $c_2 < 0$!

⇒ radiative EWSB is dominated by the top sector!

- Studying top + its partners at the Tevatron + LHC will test this idea.

The Littlest Higgs

[Arkani-Hamed, Cohen, Katz, Nelson 2002]

- Consider a model with SU(5) global symmetry spontaneously broken to SO(5) by

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

- Low-energy dynamics is described by 14 pion fields

$$\Sigma(x) = e^{2i\Pi/f}\,\Sigma_0$$

$$\Pi = \sum_{a=1}^{14} \pi^a(x)\, X^a$$

- Gauge on $[SU(2) \times U(1)]^2$ subgroup of SU(5):

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$$

$Y_1 = \mathrm{diag}\left(-\frac{3}{10}, -\frac{3}{10}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}\right)$; $Y_2 = \mathrm{diag}\left(-\frac{1}{5}, -\frac{1}{5}, -\frac{1}{5}, \frac{3}{10}, \frac{3}{10}\right)$

The Littlest Higgs - cont'd

- The gauge - Goldstone boson sector is described by

$$\mathcal{L}_{kin} = \frac{f^2}{8} \mathrm{Tr}\, (D_\mu \Sigma)(D^\mu \Sigma)^\dagger$$

with the covariant derivative

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} g_j W_j^a \left(Q_j^a \Sigma + \Sigma Q_j^{aT}\right)$$
$$- i \sum_{j=1}^{2} g'_j B_j^a \left(Y_j \Sigma + \Sigma Y_j\right)$$

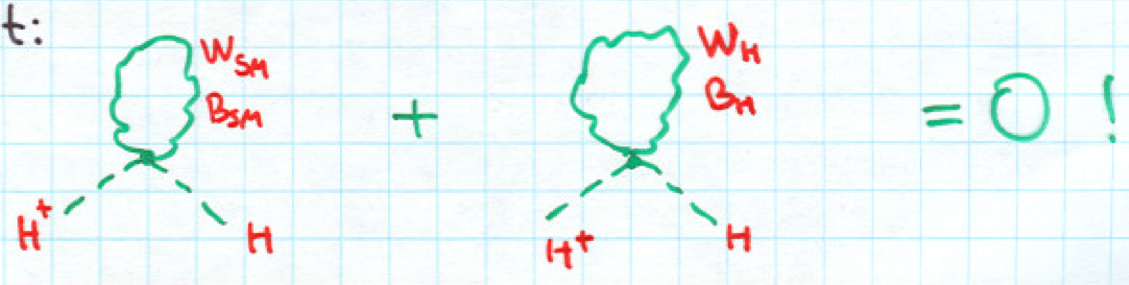
- The vev $\langle \Sigma \rangle = \Sigma_0$ breaks

$[SU(2) \times U(1)]^2 \rightarrow SU(2) \times U(1)$ - SM EW group!

- Spectrum: SM + 4 heavy gauge bosons
  + 10 physical Goldstones: H, ϕ

- At tree level, $m(H) = 0$ ✓

- At one-loop level, $m(H)$ is NOT quadratically divergent:



Collective Symmetry Breaking

- There is a symmetry reason for this cancellation!

  - recall the gauged SU(2) generators:

$$Q_1^a = \begin{pmatrix} \sigma^a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma_a^* \end{pmatrix}$$

  - imagine that $g_1 = 0, \quad g_2' \neq 0$

  - the "upper-left-corner" global SU(3) is not broken by gauging:

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

  - the vev Σ_0 breaks SU(3) → SU(2)

    the SM Higgs is the Goldstone in SU(3)/SU(2)

$$\Rightarrow \quad \delta M_H^2 \propto g_1^2$$

  - same argument with $1 \leftrightarrow 2 \quad \Rightarrow \delta M_H^2 \propto g_2^2$

$$\Rightarrow \quad \delta M_H^2 \propto g_1^2 g_2^2$$

- There is a quadratic divergence at two-loop level!

  BUT $c_1 \approx g^2/16\pi^2 \ll 1$.

The Littlest Higgs: the Top Sector

- Need to generate top Yukawa coupling without inducing one-loop quadratic divergences

- Again, make use of the collective symmetry breaking idea

- Add a pair of colored, SU(2) singlet, $Y = \pm 2/3$ fermions: $\tilde{t}$ and $\tilde{t}^c$

- Define $\chi = (t, b, \tilde{t})$

- Yukawa couplings arise from

$$\mathcal{L}_t = \frac{\lambda_1}{2} f \epsilon_{ijk} \epsilon_{xy} \chi_i \Sigma_{jx} \Sigma_{ky} u_3^c + \lambda_2 f \tilde{t} \tilde{t}^c$$

- 1st term preserves "upper-left-corner" SU(3)

  $\Rightarrow$ $m(H) = 0$ when $\lambda_2 = 0$

- 2nd term preserves the "lower-right-corner" SU(3)

  $\Rightarrow$ $m(H) = 0$ when $\lambda_1 = 0$

$\Rightarrow$ $\delta m^2(H) \propto \lambda_1^2 \lambda_2^2$

$\Rightarrow$ only two-loop quadratic divergence

LH Top Sector: Details

- Mass eigenstates:

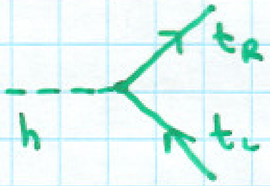
  - the SM top t

$$m_t = \frac{\lambda_t v}{\sqrt{2}} \quad , \quad \lambda_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}$$

  - the "heavy top" T

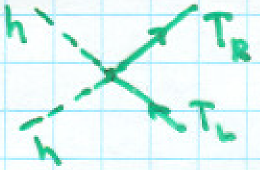
$$m_T = \sqrt{2(\lambda_1^2+\lambda_2^2)}\, f \geq \lambda_t f$$

- Feynman rules in the top-Higgs sector:



$$\frac{i\lambda_t}{\sqrt{2}}$$

$$\frac{i\lambda_T}{\sqrt{2}}$$



$$\frac{i\lambda_T}{2f}$$

$$\lambda_T = \frac{\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}}$$

- SUM RULE

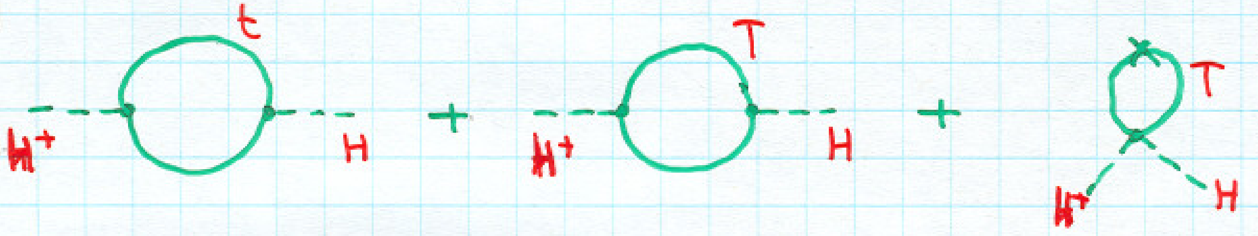
$$\frac{m_T}{f} = \frac{\lambda_t^2+\lambda_T^2}{\lambda_T}$$

ensures the cancellation of 1-loop quad. div. !

Conclusions

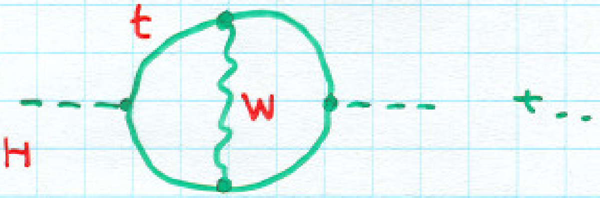
- "Little Higgs" models allow to stabilize a light Higgs with weakly-coupled TeV scale physics, without SUSY
- Special symmetry structure (collective breaking) ensures the cancellation of quadratic divergences in the Higgs mass at one loop
- EWSB is triggered radiatively by the top sector
- Heavy top partner is predicted in the 1-2 TeV mass range, should be seen at the LHC
- Determining T mass and couplings would allow for a non-trivial test of the model.

Electroweak Symmetry Breaking in the LH



$$= -\frac{3\lambda_t^2}{8\pi^2} M_T^2 \log\frac{\Lambda^2}{M_T^2}$$ ✓

- An uncalculable 2-loop contribution:



$$= c\,\frac{g^2}{16\pi^2}\,\frac{\lambda^2}{16\pi^2}\,\Lambda^2$$

- $\Lambda \approx 4\pi f \sim 4\pi M_T$

  ⇒ the calculable piece dominates by

$$\frac{\lambda^2}{g^2}\log\frac{\Lambda^2}{M_T^2} \sim 10$$

- Other (subdominant) contributions: gauge boson + Higgs loops

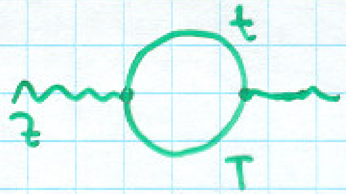
How Heavy is the Heavy Top?

- Upper bound: naturalness

$$M_T \lesssim 2\,\text{TeV} \cdot \left(\frac{M_H}{200\,\text{GeV}}\right)^2 \qquad [10\%]$$

- Lower bound: precision electroweak constraints

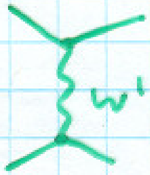
1. Top sector contribution [1-loop]



$$+ \ldots \Rightarrow T = \frac{3}{16\pi}\frac{1}{s_w^2 c_w^2}\frac{m_t^4}{M_Z^2 M_T^2}\left(\log\frac{M_T^2}{m_t^2} + \frac{1}{2}\right)$$

$$\Rightarrow \quad M_T \gtrsim 1\,\text{TeV} \qquad [95\%\ \text{c.l.}]$$

2. Gauge sector contribution [tree]



$+ \ldots$

3. Scalar contribution (incl. triplet vev)

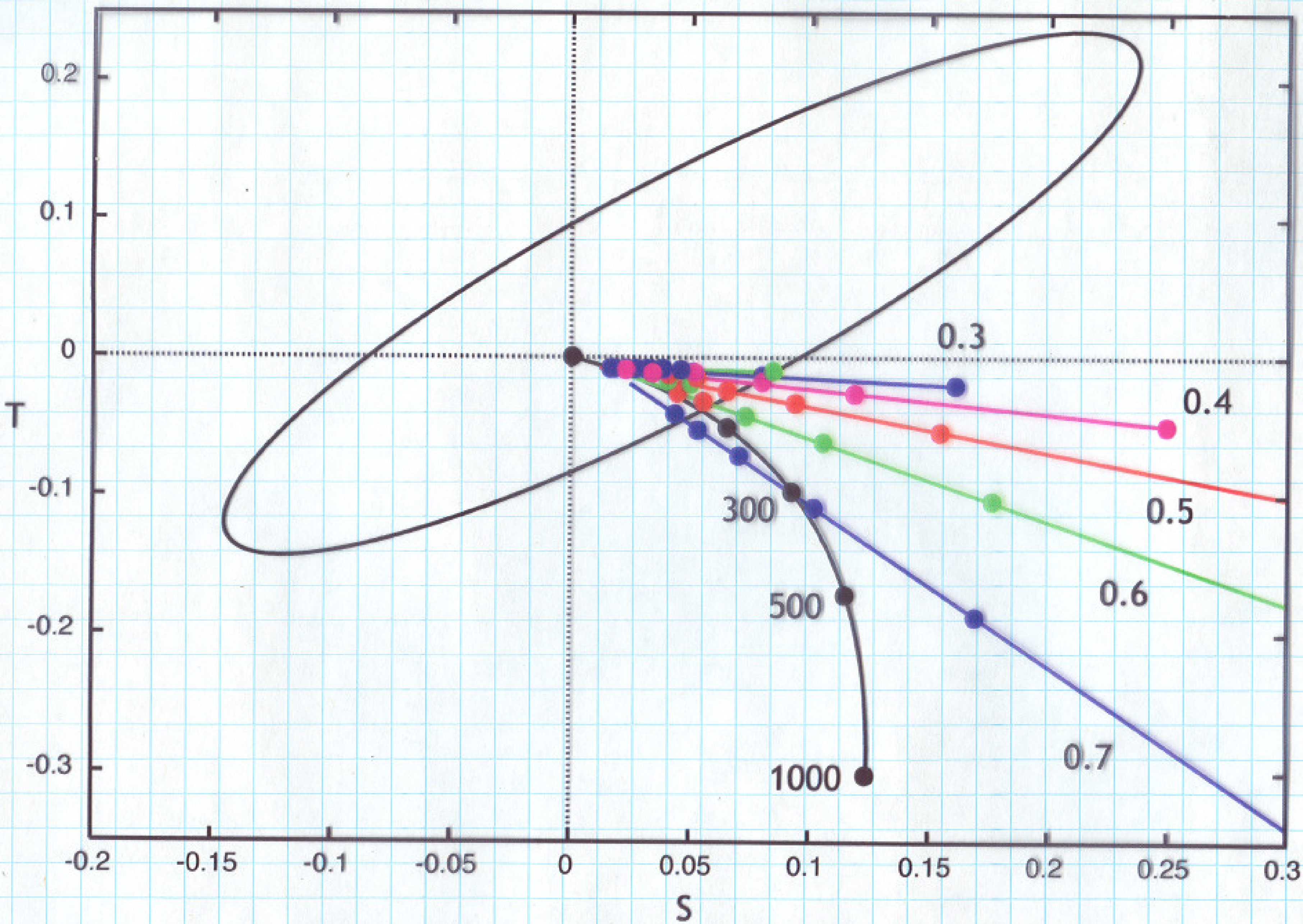
[Csàki et al. ; Han et al ; Chen+Dawson ; . . .]

- Precise PEC bound very model-dependent:

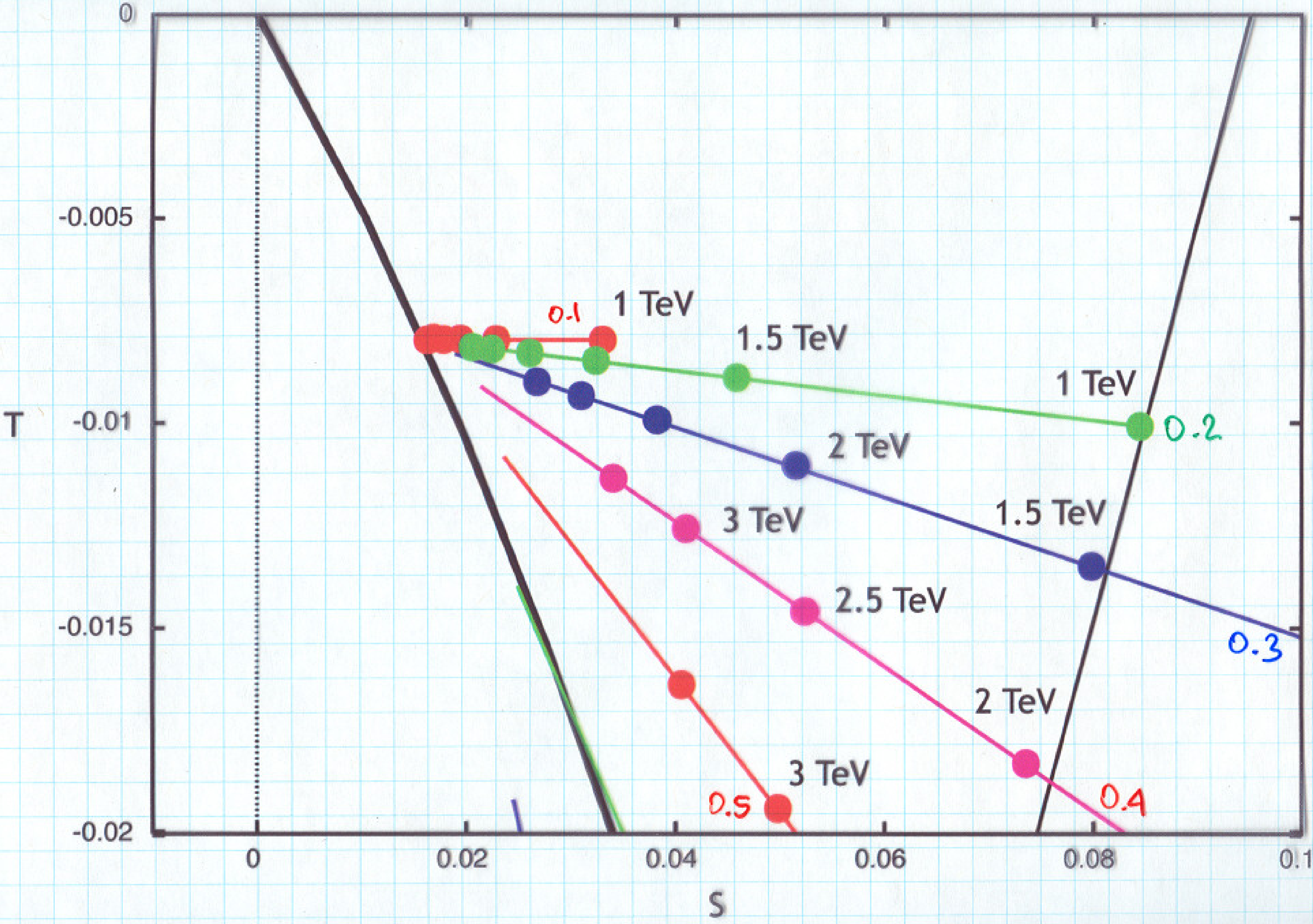
e.g. in $SU(2) \times SU(2) \times U(1)$ $\quad f \gtrsim 1$ TeV

$M_T \gtrsim 2f$

SU(2)×SU(2)×U(1) model @ tree level



SU(2) x SU(2) x U(1) model @ tree level



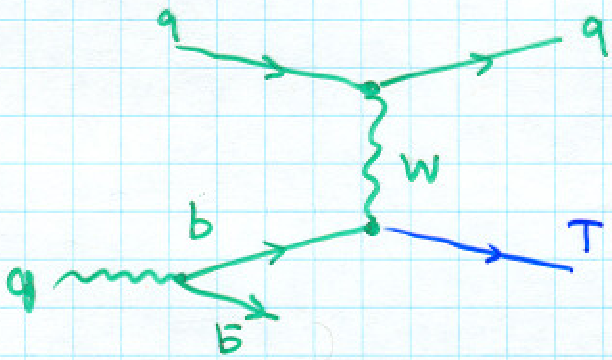
for $\sin\theta = 0.2$, $f \geq 1$ TeV are allowed!

Finding the Heavy Top

- Production mechanisms @ the LHC:

  - pair production $q\bar{q} \to T\bar{T}$, $gg \to T\bar{T}$

  - single T production



[cross section plot]

  - single production dominant for $M_T \gtrsim 1$ TeV

- Decay channels:

$$Br(T \to th) = Br(T \to tZ_0) = 25\%$$

$$Br(T \to bW) = 50\%$$

[G. B. Eq. Th.]

$$\Gamma(T) = \frac{\lambda_T^2}{16\pi} M_T$$

- Example: $T \to bW$ [ATLAS, hep-ph/0405156]

$\ell + \not{E}_T + 2$ b-jets (1 tagged)

Backgrounds: $t\bar{t}$, $W + b\bar{b}$

$\boxed{\text{Ok for 1 TeV } T}$

Testing the Cancellation?

- Recall that the LH cancellation hinges on the sum rule:

$$\frac{m_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}$$

- In principle, all 4 quantities are measurable
  - f can be found from gauge boson studies

$$pp \to Z_H + X, \qquad Z_H \to \ell^+ \ell^-$$

$$\Rightarrow M(Z_H), \quad \Gamma(Z_H) \qquad \Rightarrow f, \quad \psi$$

  - how well can we reconstruct M_T?
  - how to measure λ_T?

$$\sigma_{prod} \propto \lambda_T^2$$

p.d.f. uncertainties?