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WHY THE WORLD DOESN'T FALL APART: THE MYSTERY OF THE ELECTROWEAK SYMMETRY BREAKING

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Outline:

1. Introduction
2. EWSB in the Standard Model
3. Supersymmetry
4. Strong EWSB
5. Extra Dimensions
6. Making Contact with Experiments

A World Without the Higgs...

- In a world with no Higgs doublet, the weak symmetry is *still* broken...
  - Non-perturbative QCD effects induce an quark condensate

$$< \overline{q}_L \, q_R > \sim \Lambda_{QCD} \sim 200 \, \mathrm{MeV}$$

  - We don't really understand exactly *how* this happens, but we see its effects in hadron interactions.
  - Since left-handed quarks are weak doublets, and right-handed ones are singlets, this combination carries the same quantum numbers as a Higgs.
  - The result is masses for the Weak Bosons of order Λ_{QCD}
  - This is the basic idea behind Technicolor...

$$< \overline{\Psi}_L \, \Psi_R > \sim \Lambda_{TC} \sim 246 \, \mathrm{GeV}$$

...Would Fall Apart!

- Quarks stay (approximately) massless, unless we add something more to the theory.
- With no quark masses, the proton is heavier than the neutron
- (The difference comes mostly from the fact that the proton is charged and thus gets electromagnetic corrections to its mass)

$$\Delta M \sim \frac{\alpha_{EM}}{4\,\pi} M \sim 0.5\,\mathrm{MeV}$$

- The electron and neutrino are massless...
- And the proton decays through an off-shell W into a neutron and leptons!
- More details in Stuart Samuel, [hep-ph/9910559]

- In the real world, this disaster is averted by EWSB
  - EWSB leads to up and down quark masses ($m_d > m_u$: but *why?*)
  - This in turn gives us a neutron heavier than the proton
  - So the decay goes “the other way”...
  - $n \to p\, e^-\, \bar{\nu}$

Introduction

- The EWSB is really what we are aiming to figure out
  - The gauge structure of the SM is “all in order”
  - Three (four?) coupling constants describe the gauge interactions
  - The SM Higgs mechanism parameterizes the symmetry breaking
  - Without having conclusively seen the Higgs we have no reason to prefer the SM to any other theory of EWSB...
  - After all, consider the lesson of chiral symmetry breaking from QCD, or superconductors in QED!

- Higgs and Flavor
  - Fifteen parameters are needed for Higgs interactions
  - (Even more for massive neutrinos)
  - It seems like we are missing some kind of organizing principle here...
  - Flavor may be intimately connected with the EWSB
- Right now colliders are finally probing the energies of order $v = 246$ GeV
- And understanding the EWSB may be the key to theories for *even* higher scales!

EWSB in the Standard Model

- (Complex) Higgs doublet with $Y = 1$

  $$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

- VEV: $< \Phi >= |v| = \sqrt{-\mu^2/\lambda}$

- Three of the real scalars are “eaten” to give masses to W and Z; one escapes to become the Higgs particle

- $M_W = e\, v/2\, s_W$ and $M_Z = M_W/c_W$ which fixes a combination of λ and μ^2

- Also note that $\rho = M_W/M_Z c_W = 1$, which follows entirely from the Higgs gauge assignment

- Higgs boson has mass $M_H = \sqrt{2\,\lambda}\, v$

Fermion Masses in the SM

- One of the remarkable things about the SM is that the Higgs that gives boson masses is exactly what is needed for fermion masses:

$$\sum_{n=1}^{3} \sum_{m=1}^{3} \left(y_e^{nm}\, \overline{e}_R^n\, \Phi^\dagger\, L_L^m \;+\; y_e^{nm\,*}\, \overline{L}_L^m\, \Phi\, e_R^n \right)$$
$$+ \left(y_d^{nm}\, \overline{d}_R^n\, \Phi^\dagger\, Q_L^m \;+\; y_d^{nm\,*}\, \overline{Q}_L^m\, \Phi\, d_R^n \right)$$
$$+ \left(y_u^{nm}\, \overline{u}_R^n\, \tilde{\Phi}^\dagger\, Q_L^m \;+\; y_u^{nm\,*}\, \overline{Q}_L^m\, \tilde{\Phi}\, u_R^n \right)$$

- After diagonalizing: 6 quark masses, 3 charged lepton masses, 3 CKM angles, and one CKM phase

- No FCNC's!

Problems with EWSB in the SM

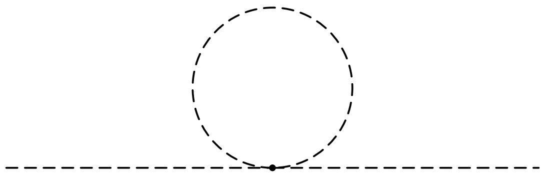
- Too many parameters and no idea where they came from
  - Three gauge couplings ($\alpha_S, \sin^2\theta_W, \alpha_{EM}$)
  - Two Higgs "Potential" couplings (M_Z, M_H)
  - Six quark masses, three charged lepton masses
  - Three quark mixing angles; one phase
  - Out of 18 parameters, 15 are Higgs couplings!
- Theories of Scalars are sick at high energies
  - Hierarchy
  - Triviality
- Most theories of new physics (connected to the EWSB anyway) are really trying to solve these problems

Hierarchy I

- The Hierarchy problem refers to the question as to why and how the weak scale we observe is so different from the Planck scale
- WHY
  - Why is the weak scale (TeV) SO much smaller than the Planck scale (10^{19} GeV) ?
  - A theory of quantum gravity (string theory?), has only one energy scale: M_P
  - However: Note the important lesson of QCD!
  - A theory with α_S set equal to some value at M_P, a small Λ_{QCD} appears because α_S runs!
  - This is called dimensional transmutation and is a natural consequence of any asymptotically free theory.

Hierarchy II

- HOW
  - How is the weak scale stabilized compared to the Planck scale?
  - The SM must break down as a good description of physics at some scale $\Lambda \leq M_P$



  - The problem is that the scalar mass is *very* sensitive to the physics at that cut-off scale

$$\delta M^2 \sim \lambda \, \Lambda^2$$

  - This tries to turn the Weak scale into the Planck scale, requiring $M^2 + \delta M^2$ to cancel to one part in 10^{17}!

An Aside on Radiative Corrections...

- Fermion masses are protected by a chiral symmetry

$$\mathcal{L} = i\,\overline{\Psi}_L\,\gamma^\mu\,D_\mu\,\Psi_L + i\,\overline{\Psi}_R\,\gamma^\mu\,D_\mu\,\Psi_R$$
$$-m_f\,\overline{\Psi}_L\,\Psi_R + H.c.$$

- When $m_f = 0$, I can rotate the left- and right-handed components independently

- For m_f non-zero, I have to rotate left and right together, so I have lost some of the symmetry of the zero mass theory.

- This symmetry implies that $m_f = 0$ in the Lagrangian means quantum corrections leave $m_f = 0$

- Thus, for non-zero m_f, corrections must still go like m_f so they vanish when $m_f \to 0$
- Since this takes care of the mass dimension of the answer, it can depend on Λ only through a $\log$

$$\delta m_f \sim \frac{g^2}{16\pi^2}\, m_f\, \log\left(\frac{\Lambda}{m_f}\right)$$

- The corrections to m_f are naturally of the same order as m_f itself
- There is a similar story to gauge boson masses, which are protected by the gauge symmetry
- Thus, a gauge theory of fermions does not suffer from the same kind of UV instability as a theory of scalars

Triviality

- Another scalar theory problem: they blow up at high energies: $\lambda(\mu) \to \infty$ as $\mu \to \mu_0$

$$\frac{d\lambda}{d\log\mu} = \frac{3\lambda^2}{(4\pi)^2}$$

- What this means is that the only way to have a theory which is valid to an arbitrarily high energy scale is to have it be "trivial" (non-interacting)

$$\lambda(\mu) = \frac{\lambda(\mu_0)}{1 - \lambda(\mu_0)\frac{3}{(4\pi)^2}\log\left[\frac{\mu}{\mu_0}\right]}$$

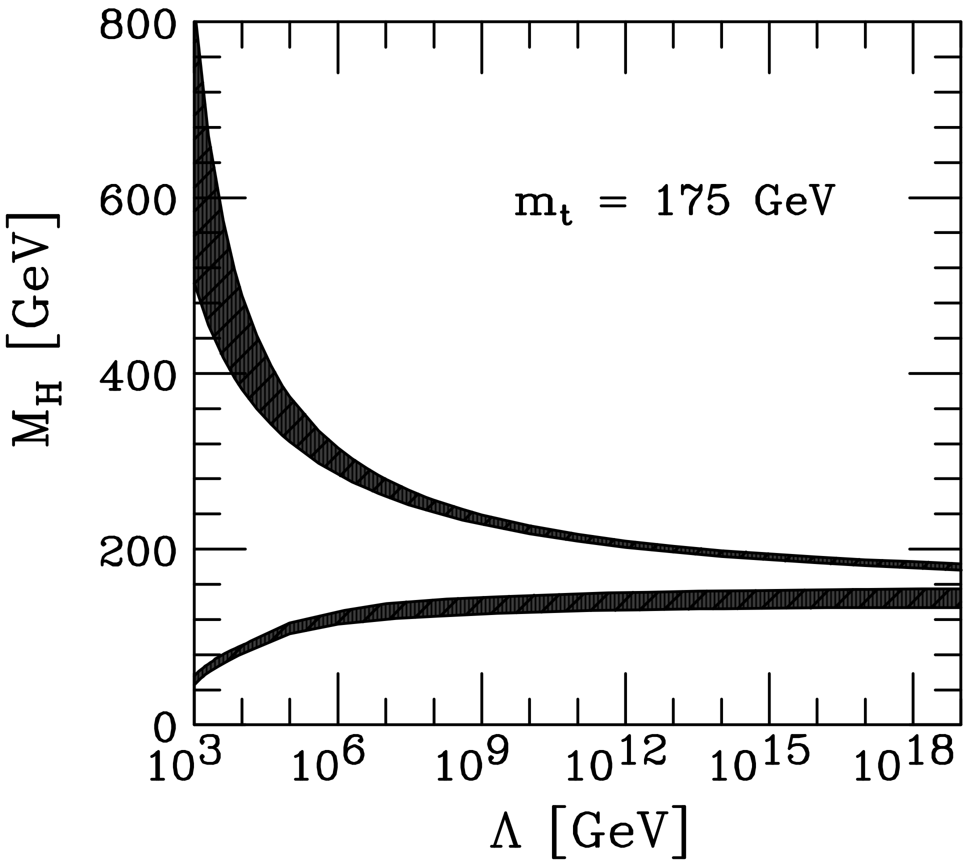
- This is different from (non-Abelian) gauge theories, which are asymptotically free

$$\frac{dg_S}{d\log\mu} = -\frac{3g_S^3}{(4\pi)^2}\left[11 - \frac{2}{3}n_f\right]$$

Triviality II

- However, we need a Higgs potential which induces a VEV for Φ, so setting $\lambda = 0$ is not an option.
- The coupling going to infinity is a signal that we are trying to describe our theory using the wrong degrees of freedom
- For example, $\alpha_S \to \infty$ at Λ_{QCD} tells us that below this scale we shouldn't use quarks and gluons to describe the physics, but instead use baryons and mesons
- On the other hand, we know there is new physics at M_P so as long as our theory remains perturbative up to that scale, we can live with the situation.
- (This is why no one makes a big deal about the fact that QED suffers from the same sickness - QED blows up many orders of magnitude higher than M_P - so who cares?)

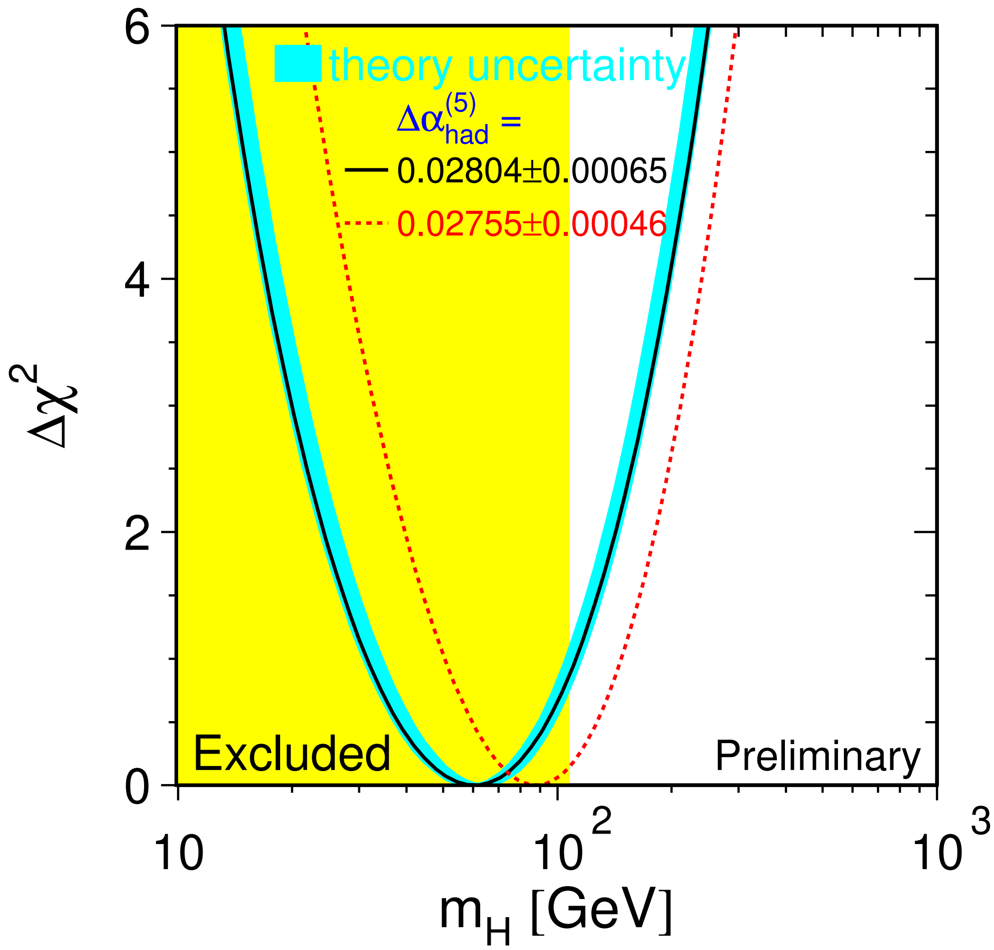
Triviality Bound



[“Run II Higgs Working Group”, hep-ph/0010338]

- Once I fix $\lambda \leftrightarrow M_H$ at low energies, I can calculate at which scale λ blows up, and new physics sets in
- Upper limits on M_H from triviality
- Lower limits from vacuum stability

Where is the Higgs?



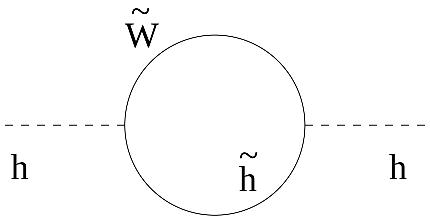
[LEP EW Working Group]

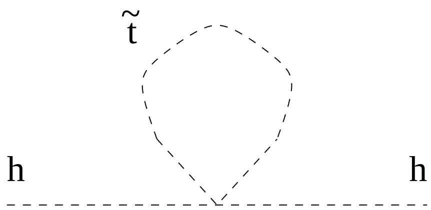
- So where is the Higgs anyway?
  - Either we've been unlucky finding it...
  - or the SM description is not quite correct...
  - or LEP really got gypped!

Solution I: Supersymmetry

- Supersymmetry is a new symmetry we add to the SM to cure its problems
  - $V^\mu \leftrightarrow \widetilde{\lambda}$
  - $\Psi \leftrightarrow \widetilde{S}$
  - $H \leftrightarrow \widetilde{\chi}$
- Solution to Triviality problem
  - in a gauge theory with SUSY, there are automatically interactions between scalars of the type $g^2|\Phi|^4$
  - But these couplings are gauge couplings, so they are asymptotically free (for a non-Abelian gauge group without too much matter)
  - So triviality is solved by replacing the badly-behaved λ with the better-behaved g

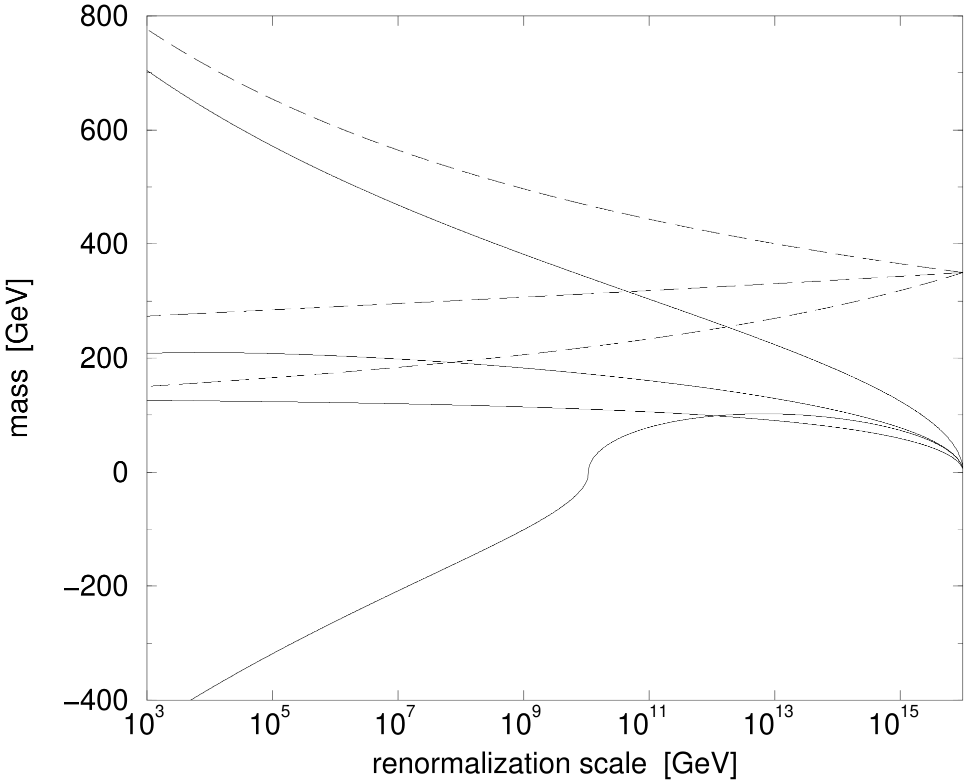
- Solution to the Hierarchy problem: How
  - Our new symmetry gives the Higgs a partner (higgsino) and forces their masses to be equal
  - But recall that there is a chiral symmetry which protects the fermion masses from large corrections
  - Thus, through the SUSY, the Higgs inherits the Higgsino's improved dependence on UV physics
  - In terms of Feynman diagrams, this appears as a cancellation between loops of particles and sparticles





  - So, once we set M_W to some value, this protects it from being driven to M_P

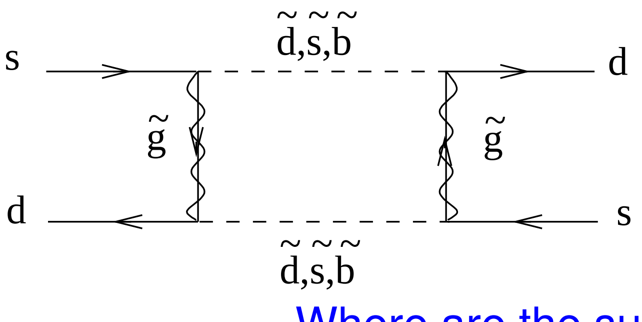
- Solution to the Hierarchy problem: Why
  - We just saw that SUSY stabilizes M_W compared to M_P, but can it explain the hierarchy?
  - Not really, but we can tie M_W to M_{SUSY}:

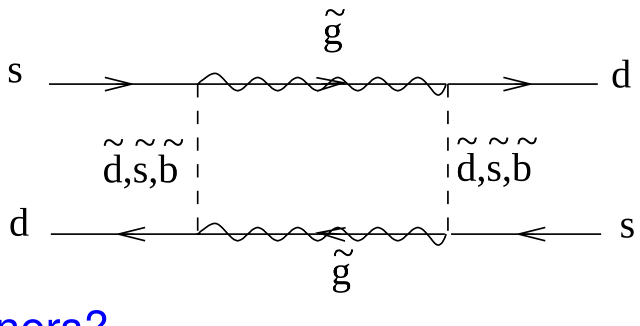


[D. Kaplan, G. Kribs, M. Schmaltz, hep-ph/9911293]

  - Progress: instead of two scales tiny compared to M_P, we only need to explain one of them

- SUSY Good Things
  - Gauge couplings unify at a higher scale
  - Some (tenuous!) contact with supergravity / superstring
  - We get to build more colliders to figure out how / why SUSY is broken
- SUSY Bad Things
  - Too many possible ways SUSY is broken
  - Flavor issue is much more complicated (and still not really explained..)





  - Where are the superpartners?

Solution II: Topcolor Top-seesaw

- I'll take topcolor as a (good) example of a theory with strong EWSB
- More details in papers by C.T. Hill and collaborateurs
- Basic philosophy: Scalar field theories have problems, so build a model without them
  - However, I need a scalar to get a VEV
  - So: the Higgs is a bound state of fermions
  - Analogy with QCD: pions (scalars) are bound quarks (fermions) stuck together with gluons
  - So I introduce some new (strong) force that sticks quarks together
- At high energies, the Higgs breaks apart into fermions, and there is no hierarchy / triviality issue

Topcolor

- One more observation: $m_t \sim M_W$
  - This suggests it would be a good idea to have top be one of the quarks that I will glue together into the Higgs
  - The Higgs and top will naturally have a strong coupling (as a residue of the strong dynamics that glues the Higgs together) which insures a big top mass
  - Other quarks don't feel this force and thus naturally have small masses
  - Added bonus: since the Higgs properties and top mass come from the topcolor force, described by its coupling g_{tc} and the coloron mass Λ_C, once I fix m_t and M_Z, M_H is predicted

Top Seesaw

- Unfortunately, the minimal model doesn't quite work
  - The problem is that to get reasonable EWSB, I end up with a top mass somewhat larger than 200 GeV
  - This can be cured by having a new quark (χ) pair up with top to be the Higgs
  - The top we observe is thus a mixture of the original t and χ fields:

$$- (\bar{t}_L \, \bar{\chi}_L) \begin{pmatrix} 0 & m_{t\chi} \\ \mu_{\chi t} & \mu_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + H.c.$$

  - Since χ_L is a singlet, this will mean top's weak interactions are somewhat unusual

Topcolor

- Good Topcolor stuff
  - Naturally explains large top mass
  - Predicts the Higgs mass (bad news : its heavy)
  - New particles/force(s) to discover at TeV scale
  - But I didn't have to *double* the number of particles to make things work!
- Bad Topcolor Stuff
  - Why does topcolor break at the weak scale?
  - How do I realize flavor?
  - Strong coupling: theoretically, our calculations are uncertain

Solution III: Extra Dimensions

- What if our four dimensional space is embedded in a five (or higher) one?
- Two basic formulations:
  - ADD (Arkani-Hamed, Dvali, Dimopoulos)
    * Diluted gravity in the extra dimension(s), while other forces are stuck in 4d
    * This makes M_P *seem* to be large (gravity seems to be weak) when it is really strong $M_P \sim M_W$
    * Hierarchy? What Hierarchy?
  - RS (Randall, Sundrum)
    * Gravity seems weak because it is *localized* far away from us in a warped space
    * The apparent M_W is really M_P, modified by the warp factor of the space
    * Again, presumably all physics is really at M_P

Extra Dimensions

- A new guise for the hierarchy problem: Instead of why is M_P so high, we can ask why is the extra dimension so big?
- Joanne Hewett gave a great (detailed) study of both models in December
- Good things about Extra Dimensions
  - Kaluza-Klein gravitons
  - KK other stuff?
  - Connection to string theory?
  - Lots of cute applications: Explain flavor, ν masses, SUSY breaking...
  - Having so many options is its own kind of drawback...

Making contact with Experiments

- All of these theories are *theoretically* well-motivated
- What we really need is experimental data!
- The Tevatron can do new physics
  - Many super-particles and the topcolor extra quarks are strongly coupled - big production rates at a hadron collider!
  - KK gravitons couple to *everything*, so the higher Tevatron energies and luminosity means they are mass-produced!
  - While the SM Higgs prospects aren't *great* they aren't *hopeless* either - and at this point I think we would be surprised if the Higgs looked *exactly* SM-like - maybe we will do better than we hoped!
  - Tevatron is the first place we can study top directly...

Worst Case Scenario

- Maybe we model-building theorists don't have any idea what we're talking about
- Maybe there aren't any new particles to discover at the Tevatron
- In that case the best we can do is to scrutinize the particle interactions for the known particles, and look for a deviation
- We expect deviations from two sources
  - If there is underlying structure to the SM such that one or more of the SM particles is a mixture of more fundamental objects, this could appear as a deviation of the couplings of those particles (i.e., the top quark in topcolor)
  - Loops of particles that are too heavy for us to produce directly could cause small deviations in measurements (ie. the superpartners of SUSY)

Example: Weak Interactions of Top

- To parameterize new physics model-independently, we use the Electroweak Chiral Lagrangian
- EW symmetry realized nonlinearly: more appropriate for strongly coupled underlying theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_4 + \mathcal{L}_5 + \ldots + H.c.$$

$$\begin{aligned}
\mathcal{L}_4 &= \frac{e}{\sqrt{2}\,\sin\,\theta_W} W^{+}{}_{\mu} \left(\kappa^L_{Wtb}\,\bar{b}\,\gamma^\mu\,P_L\,t + \kappa^R_{Wtb}\,\bar{b}\,\gamma^\mu\,P_R\,t\right) \\
&+ \frac{e}{2\,\sin\theta_W\,\cos\theta_W} Z_\mu \left(\kappa^L_{Ztc}\,\bar{c}\,\gamma^\mu\,P_L\,t + \kappa^R_{Ztc}\,\bar{c}\,\gamma^\mu\,P_R\,t\right) \\
\mathcal{L}_5 &= \frac{g_S\,G^a_{\mu\nu}}{\Lambda_{gtc}} \left(\kappa^L_{gtc}\,\bar{c}\,T^a\,\sigma^{\mu\nu}\,P_L\,t + \kappa^R_{gtc}\,\bar{c}\,T^a\,\sigma^{\mu\nu}\,P_R\,t\right) \\
&+ \frac{2\,e\,F_{\mu\nu}}{3\,\Lambda_{\gamma tc}} \left(\kappa^L_{\gamma tc}\,\bar{c}\,\sigma^{\mu\nu}\,P_L\,t + \kappa^R_{\gamma tc}\,\bar{c}\,\sigma^{\mu\nu}\,P_R\,t\right)
\end{aligned}$$

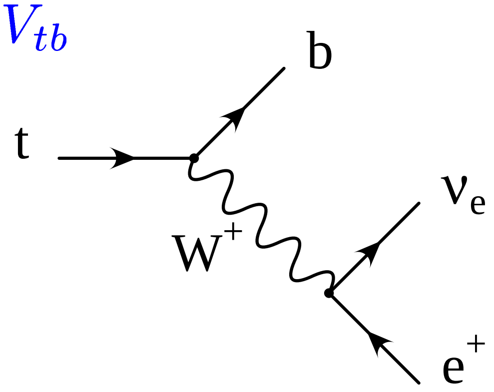
- A linear realization would suppress many of these coefficients by powers of v/Λ.

Linear versus Nonlinear Realizations

- If we want to parameterize what strange couplings we could find, we need to write down the *most general* Lagrangian consistent with the ingredients we know we have:
  - 8 gluons, 1 photon (all massless)
  - 3 Weak bosons
  - 6 quarks, 6 leptons (with masses)
  - 3 Goldstone Bosons (GB's) that act like masses for the 3 weak bosons
- The key point is that until we see it, we don't include the Higgs on this list
- This theory with the GB's but no Higgs is said to realize the EW symmetry nonlinearly
- This is how the pion Lagrangian can be "intuited" from QCD- pions are GB's from the broken chiral symmetry of QCD

Weakly Interacting Tops in the SM

- Z-t-$\bar{t}$ interaction
  - Difficult at a hadron collider
  - $Zt\bar{t}$ too small at Tevatron
  - Possible at LHC, easy at NLC
- Top decay: $t \to W^+ b$
- In the SM: V_{tb}

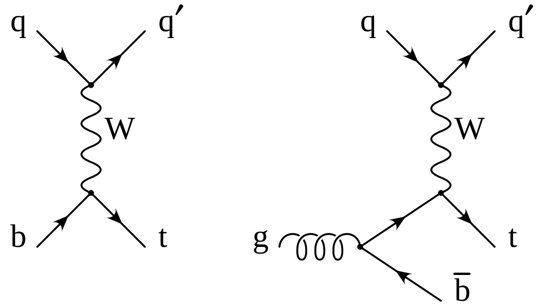


- Difficult to get the magnitude of the interaction from decays

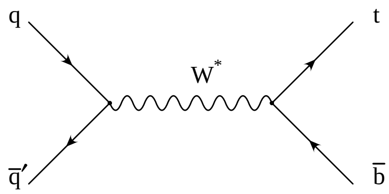
$$BR(t \to W^+ b) \quad \sim \quad 1$$

- However: decays provide a good test of the Dirac structure

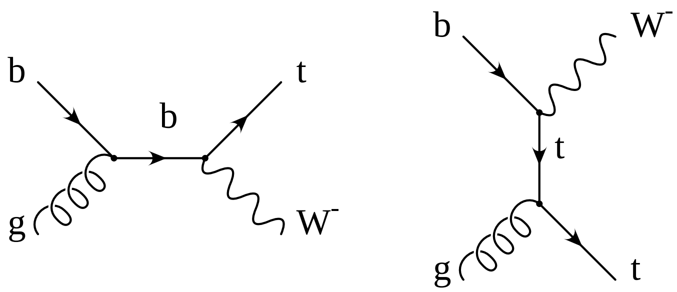
- Single top production
  - t-channel mode



  - s-channel mode



  - $t\,W^-$ mode (too small at the Tevatron)



- Excellent probe of the magnitude of the W-t-b interaction: rates directly proportional.
- They have *different* sensitivities to various new physics contributions!

Epilogue

- There are strong theoretical motivations to believe that the current generation of colliders will find something new, related to EWSB
- The possible signatures are many and diverse, and the dedicated searches for specific models are important
- However, even things we *think* we already understand can provide clues to new physics
- The weak (and strong, actually) interactions of top are something that have not been measured precisely before
- This is physics that the Tevatron will do first, and will do well

Summary : Tevatron

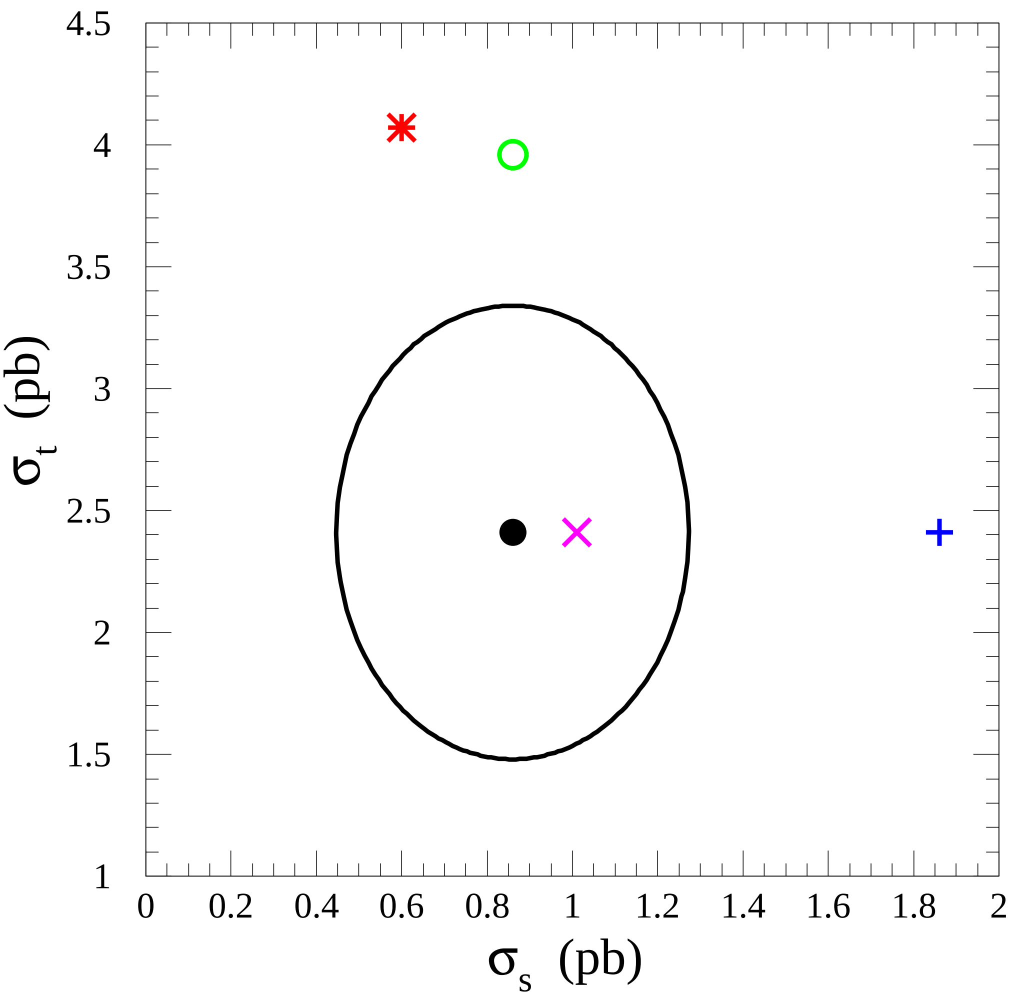


Figure 1: The location of the Tevatron SM point (the solid circle) in the σ_s-σ_t plane, and the 3σ theoretical deviation curve. Also shown are the points for the top-flavor model (with $M'_Z = 1$ TeV and $\sin^2\phi = 0.05$) as the X, the FCNC Z-t-c vertex ($|\kappa_{Ztc}| = 1$) as the open circle, a model with a charged top-pion ($m_{\pi^\pm}$ = 250 GeV and t_R-c_R mixing of $\sim 20\%$) as the cross, and a four quark generation scenario with $|V_{ts}| = 0.55$ and $|V_{tb}| = 0.835$ as the asterisk. All cross sections sum the t and $\bar{t}$ rates.

Summary : LHC

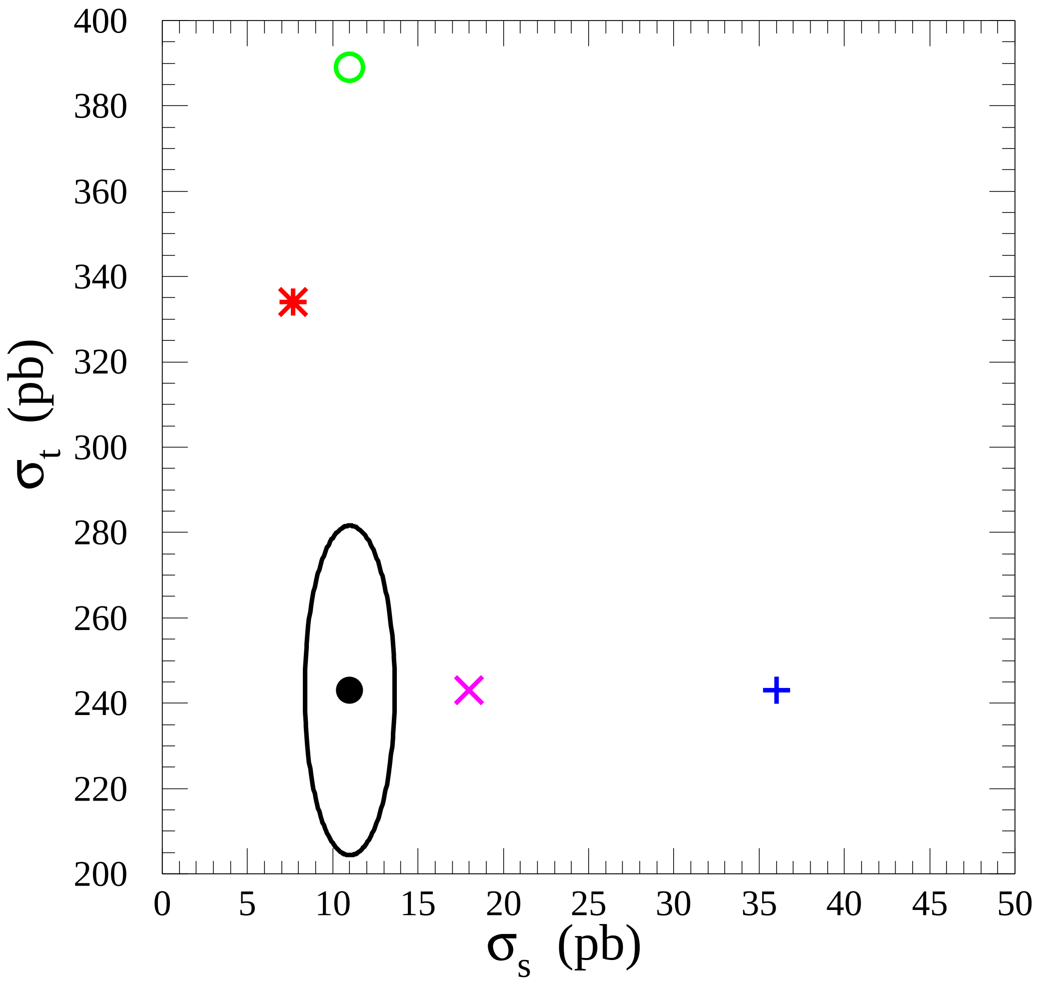


Figure 2: The location of the LHC SM point (the solid circle) in the σ_s-σ_t plane, and the 3σ theoretical deviation curve. Also shown are the points for the top-flavor model (with $M'_Z = 1$ TeV and $\sin^2\phi = 0.05$) as the X, the FCNC Z-t-c vertex ($|\kappa_{Ztc}| = 1$) as the open circle, a model with a charged top-pion ($m_{\pi^\pm} =$ 450 GeV and t_R-c_R mixing of $\sim 20\%$) as the cross, and a four quark generation scenario with $|V_{ts}| = 0.55$ and $|V_{tb}| = 0.835$ as the asterisk. All cross sections sum the t and $\bar{t}$ rates.