Why M_{top} is Important: SM and Beyond

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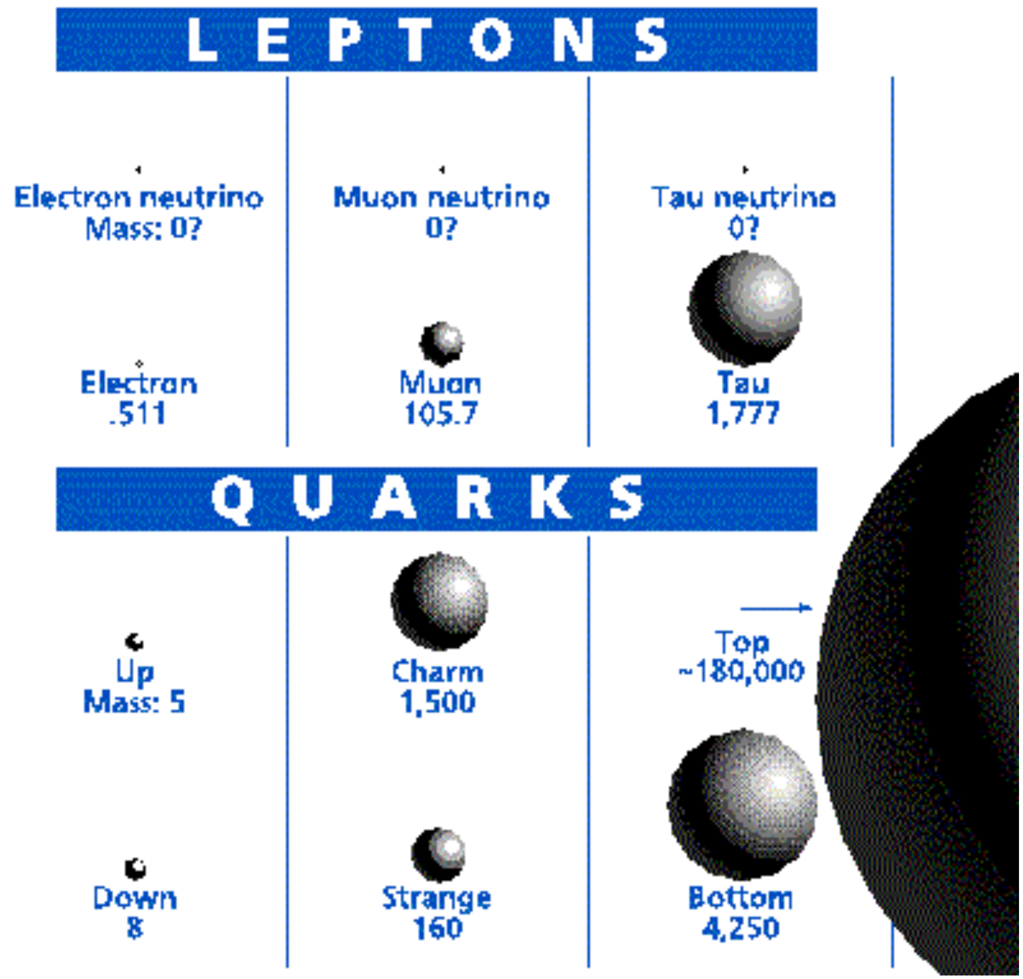
Outline

I. Introduction
II. The Top Mass in the Standard Model
III. The Top Mass Beyond the SM
IV. Is the Top only the Top?
V. Outlook

The King of Fermions!

- In the SM, top is superficially much like other fermions.
- What really distinguishes it is the huge mass, roughly 40x larger than the next lighter quark, bottom.
- This may be a strong clue that top is special in some way.
- It also implies a special role for top within the Standard model itself.
- Top is only fermion for which the coupling to the Higgs is important: it is a laboratory in which we can study EWSB.
- $M_t \sim M_W$. Is top the only special quark – or the only natural one?!

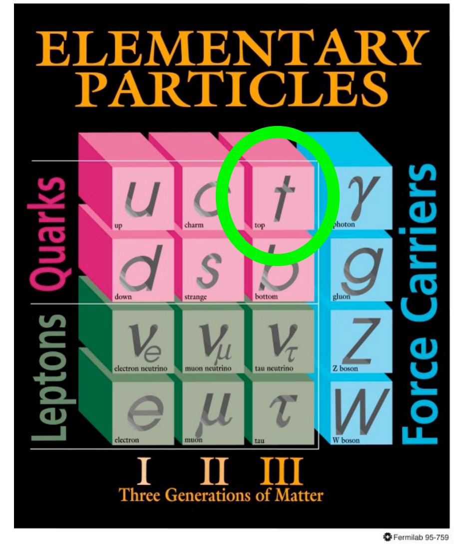
SM Fermions



From Practical to Sublime…

- The top mass is interesting for a large variety of reasons, ranging from the pure practical to the speculative to some of the deepest mysteries in particle physics.
  - The top mass is an important input in the Standard Model. Knowing its value precisely is very helpful in order to understand precision electroweak physics, b physics, Higgs physics, etc…
  - The top mass is an important input into speculative theories for physics beyond the Standard Model. It plays a key role in the minimal supersymmetric model, and inspires theories such as top color.
  - Finally, the pattern of fermion masses is something that ultimately should be explained by some larger organizing principle. The top is an important piece of the puzzle, because unlike the other fermions, its mass seems natural, on the scale of the EWSB itself. This means that whatever physics it was that chose the flavor structure we observe, it treated the top very differently from the other fermions, and thus top is likely to be a great place to learn about it.

Top in the SM



a=1: top; i: color index; a=2: bottom

$$Q_{i\alpha} = \begin{bmatrix} t_L^i \\ b_L^i \end{bmatrix} \qquad t_R^i$$

Top is two separate objects:
A left-handed quark doublet.
A right-handed quark singlet.

In 4 component notation: $t_i = \begin{bmatrix} t_R^i \\ t_L^i \end{bmatrix}$

H: Higgs (doublet)
G: gluons
B,W^n: $W^\pm$, Z, **g**

$$L = i\bar{Q}_{i\alpha}\gamma^\mu \left(D_\mu Q\right)_{i\alpha} + i\bar{t}_i\gamma^\mu \left(D_\mu t\right)_i + y_t \tilde{H}\bar{Q}t + H.c.$$

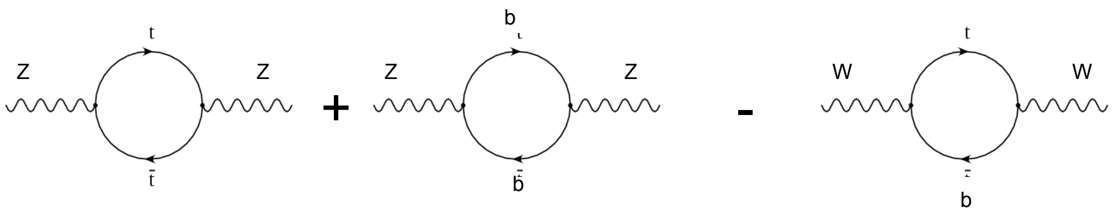
$$\left(D_\mu Q\right)_{i\alpha} \equiv \partial_\mu Q_{i\alpha} + i g_S T^a_{ij} G^a_\mu Q_{j\alpha} + i g_W \tau^n_{\alpha\beta} W^n_\mu Q_{i\beta} + i\frac{1}{6} g_Y B_\mu Q_{i\alpha}$$

$$\left(D_\mu t\right)_i \equiv \partial_\mu t_i + i g_S T^a_{ij} G^a_\mu t_j + i\frac{2}{3} g_Y B_\mu t_i$$

The Yukawa interaction is the origin of the large top mass, and the reason top is so interesting to study EWSB.

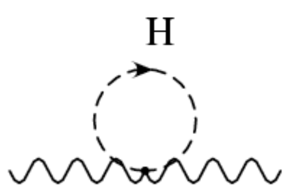
Top's Role in the SM

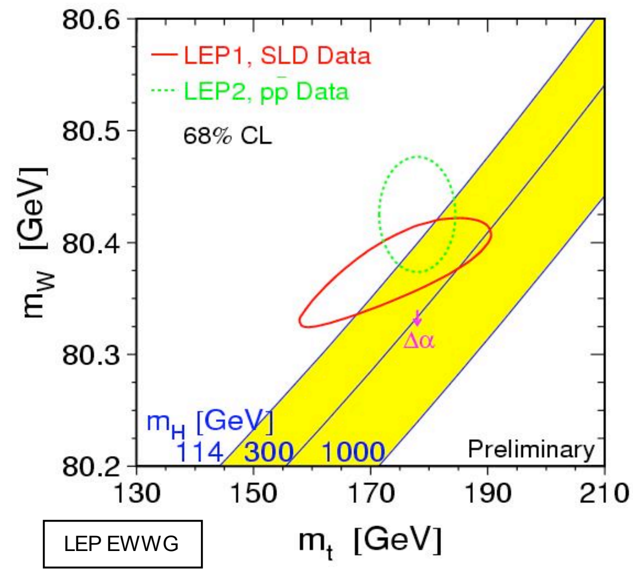
- Precision EW Physics:
  - The large top-bottom mass splitting is a strong violation of a custodial SU(2) symmetry (interchanging t_R and b_R)
  - This results in large corrections to Dr (DT).

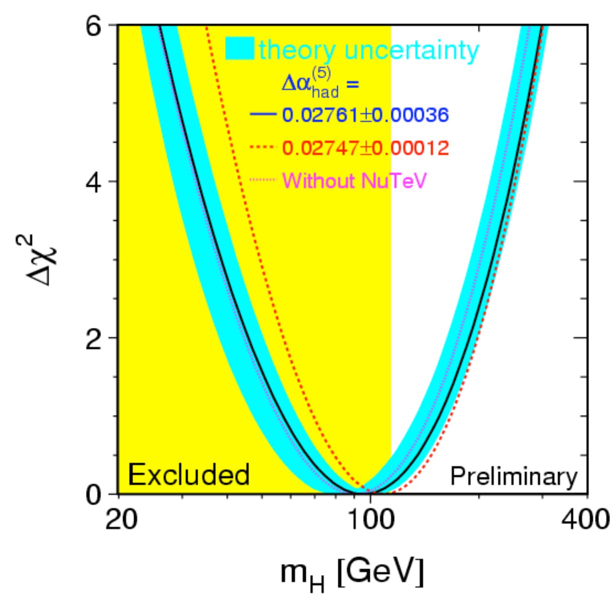


$$= \frac{N_c}{16\pi \sin^2\theta_W \cos^2\theta_W} \frac{m_t^2}{m_Z^2}$$

  - The one loop corrections are so sensitive to the top mass that precision measurements at LEP/SLD could infer something about m_t before top was observed at Tevatron.
  - Once m_t was directly measured, could look for subdominant effects like from the Higgs.



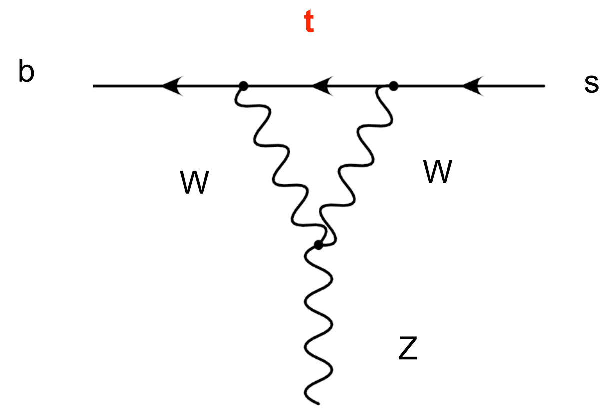




Top's Role in the SM

- Flavor Physics:

i.e.:



  - $B \to X_s \nu \bar{\nu}$

$$\mathrm{BR}(B \to X_s \nu \bar{\nu}) = 4.1 \times 10^{-5} \frac{|V_{ts}|^2}{|V_{cb}|^2} \left[\frac{m_t(m_t)}{170\ \mathrm{GeV}} \right]^{2.30}$$

  - $B_s \to \mu^+ \mu^-$

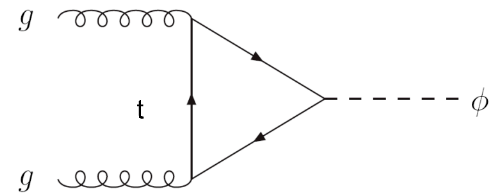
Buchalla, Buras, Lautenbacher RMP68,1125 (1996)

$$\mathrm{BR}(B_s \to \mu^+ \mu^-) = 4.18 \times 10^{-9} \left[\frac{|V_{ts}|}{0.04} \right]^2 \left[\frac{m_t(m_t)}{170\ \mathrm{GeV}} \right]^{3.12}$$

Precision inputs from the top sector for precision SM predictions.

Top's large mass disrupts the GIM mechanism!

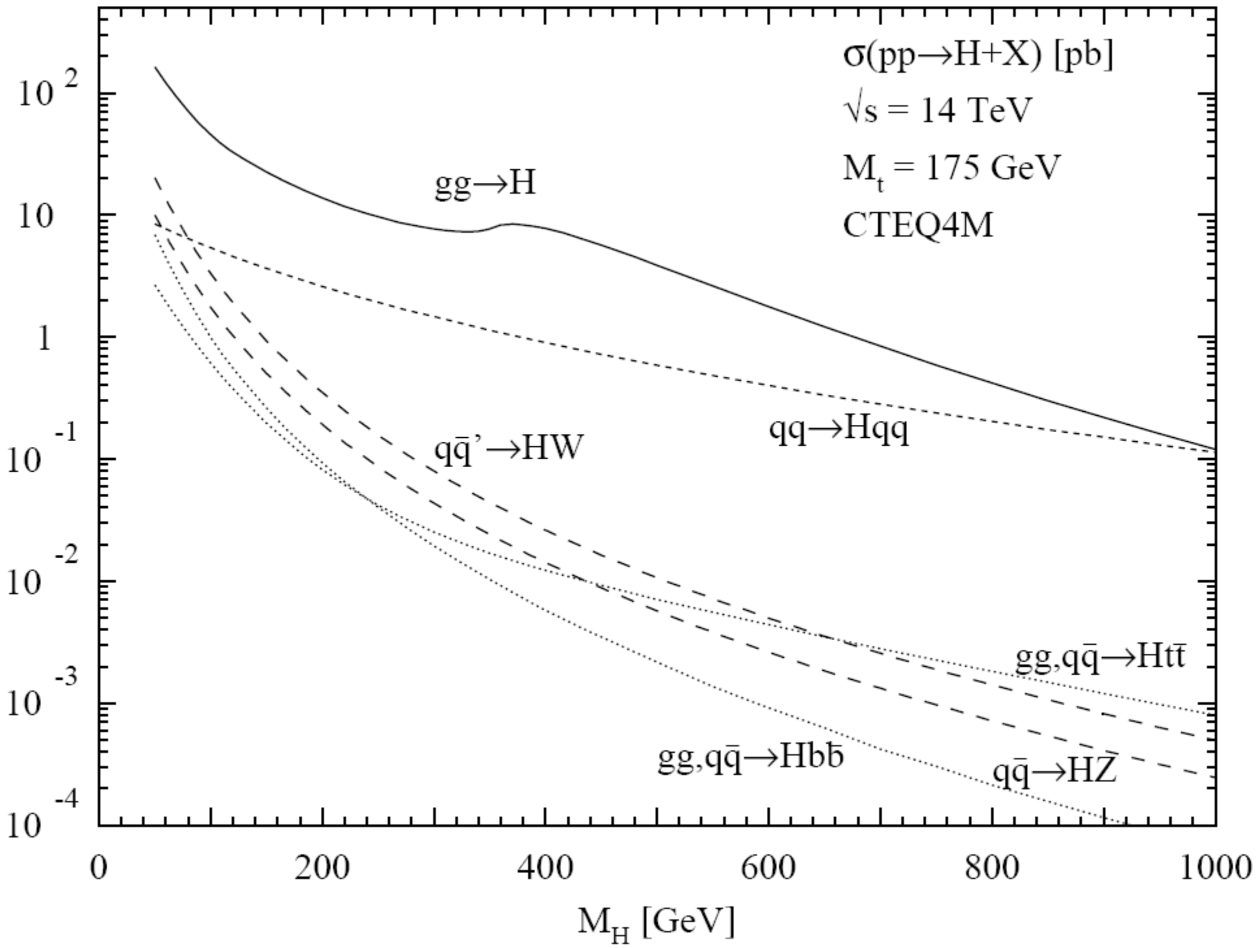
Higgs Physics



The large top mass means a strong coupling to the Higgs. Thus, several mechanisms of Higgs production rely on Top.

s (gg → h) ~ m_t^4

One in particular takes advantage of the fact that top is colored. Loops of top quarks mediate an interaction between Higgs and gluons. Despite being loop suppressed, this process *dominates* Higgs production at the LHC!



Top also contributes to the Higgs coupling to two photons.

W Polarization

- **W Polarization**
  - This is a direct test of the left-handed nature of the *W*-*t*-*b* vertex.
  - SM: Left-handed interaction implies that W's are all left-handed or longitudinal.
  - SM: Depends on $\mathbf{m_t}$ & $\mathbf{m_W}$:

$$f_0 = \frac{\text{\# longitudinal W's}}{\text{Total \# W's}} = \frac{m_t^2}{2M_W^2 + m_t^2} \sim 70\%$$

DØ: $f_0 = 0.56 \pm 0.31 \pm 0.04$

CDF: $f_0 = 0.91 \pm 0.37 \pm 0.13$

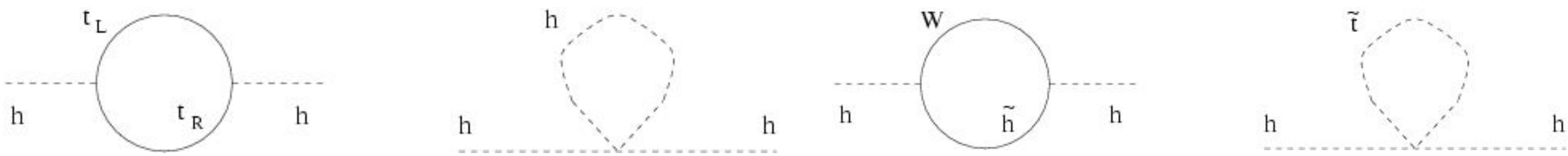
CDF PRL84, 216 (2000)
DØ hep-ex/0404040

  - The strong dependence on the top mass is a remnant of the fact that the longitudinal W boson is really part of the Higgs. It couples strongly to top because of its huge mass!
  - l_W correlated with the direction of p_e compared with the direction of p_b in the top rest frame.
  - The *W* polarization is independent of the parent top polarization. Thus, it is a good test of the *W*-*t*-*b* vertex structure and can be measured with large statistics from QCD production of top pairs.

Top Beyond the SM

Supersymmetry

- Supersymmetry is the best-motivated and best-studied solution to the hierarchy problem.
- The super-partners cancel exactly the big contributions to v^2.



- As an added bonus, most SUSY theories contain a lightest super-partner which is neutral and stable – a dark matter candidate!
- New sources of CP violation and extra DOF can lead to EW baryogenesis!
- SUSY has a lot of model parameters (all related to how we break it).
  - We have some theoretical guidance as to the rough features, but even those arguments aren't infallible.

SUSY Light Higgs Mass

- The MSSM has two Higgs doublets.
- In the SM, the Higgs quartic l is a free parameter. The physical Higgs mass is m_h^2 = l v^2.
- Remarkably, in the MSSM l is not a free parameter:

$$\lambda^2 = \left(g_W^2 + g_Y^2\right)$$

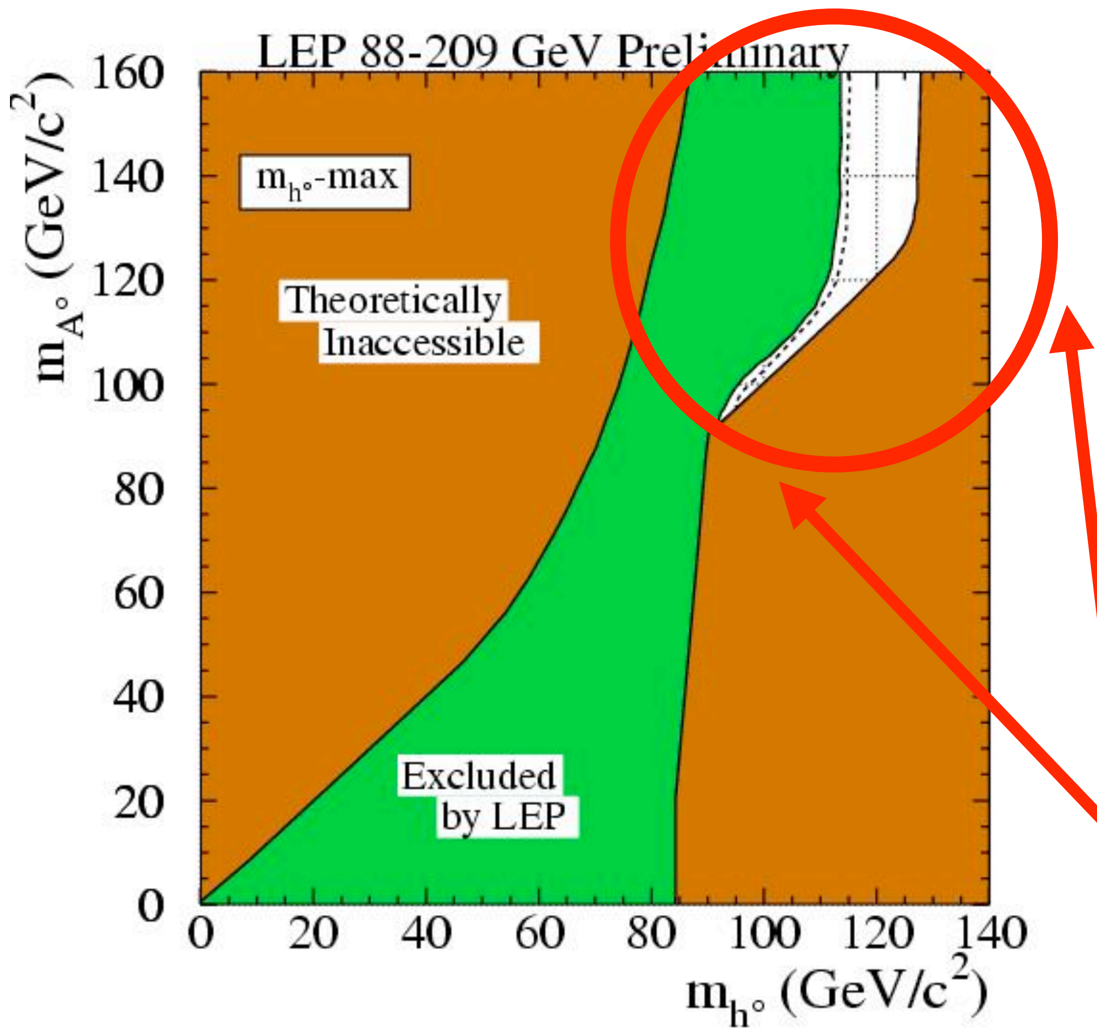
- This results in a tree-level prediction for m_h:

$$m_h^2 = \lambda v^2 \cos^2 2\beta \leq M_Z^2$$

- This is corrected at one-loop by top/stop:

$$\delta m_h^2 = \frac{3 m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

LEP II

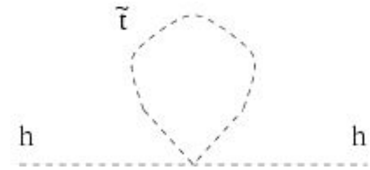


- LEP II rules out

$$m_h^{(SM)} \leq 115 \text{ GeV}$$

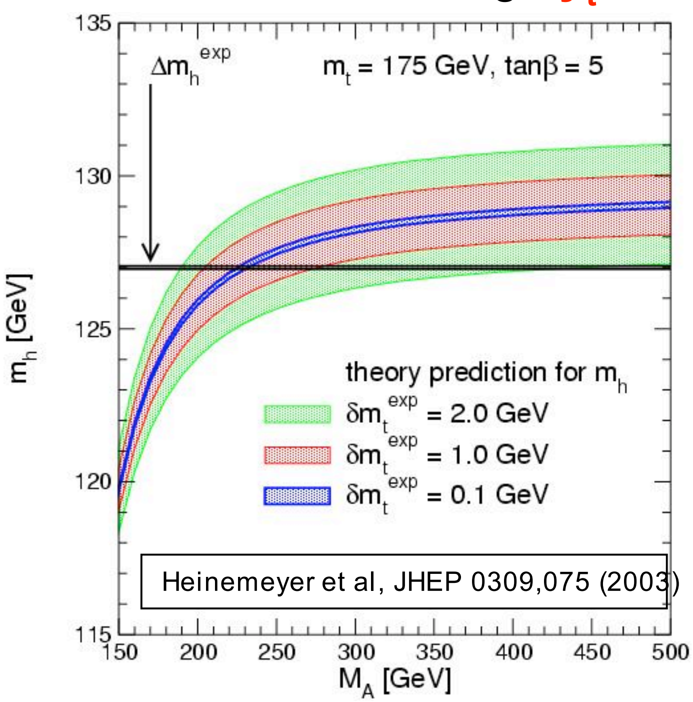
- The boundary on the right is the MSSM upper limit, assuming M~1 TeV and maximal stop mixing.
- The dashed curves are hypothetical exclusions assuming only SM backgrounds.
- The MSSM lives in the white sliver.

Top Sector and SUSY



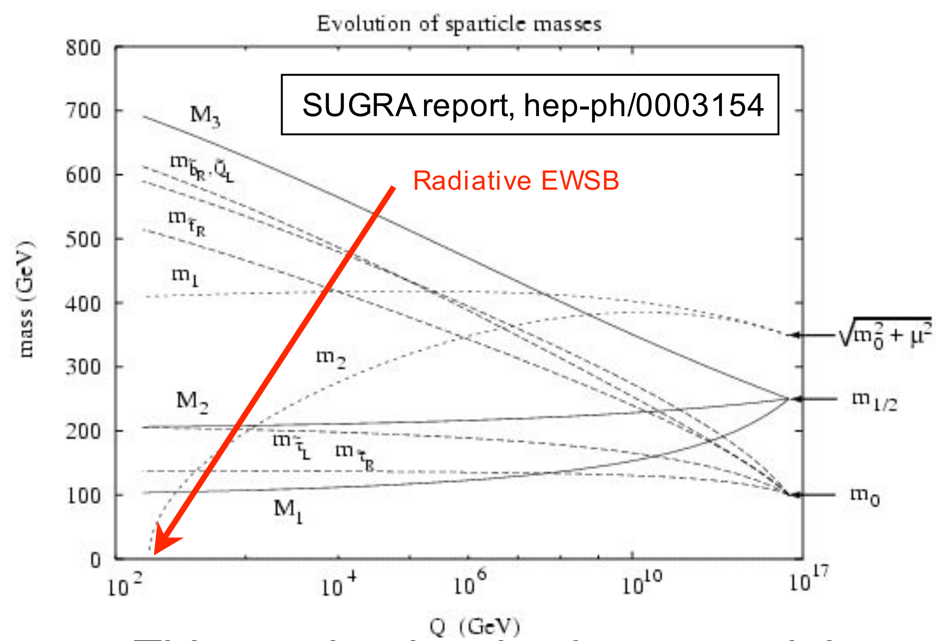
Top plays an important role in the minimal supersymmetric standard model.

- Most importantly, the MSSM only survives the LEP-II bound on m_h because of the large y_t:



- (m_t < 160 GeV rules out MSSM!)

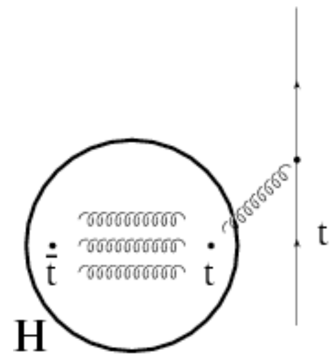
- The large top Yukawa leads to the attractive scenario of radiative electroweak symmetry-breaking:



- This mechanism is also essential in many little Higgs theories.

Top-color: Composite Higgs

- Why is the top so heavy? Top-color tries to answer this by proposing that the Higgs is actually a bound state of top quarks.
- It solves the hierarchy problem because there are no fundamental scalar particles.
- A new strong force (top-color) forms the Higgs (F) as a bound state of top.
- Top is heavy because the Higgs "remembers" that it is made out of top quarks – and couples strongly to them through the top-gluons (**g'**).
- If g_{TC} is large enough, one loop corrections drive the Higgs mass^2 negative, triggering EWSB.
- However, g_{TC} is also the top Yukawa coupling; to get the right Z mass, $y_t \sim 1.4$ and m_t~250 GeV. That is why TC needs to be supplemented with technicolor or a top seesaw to be viable.

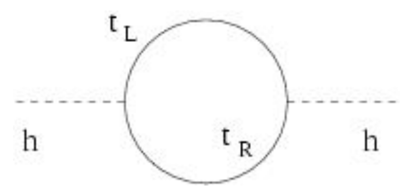


W Bardeen, C Hill, M Lindner PRD41,1647 (1990);

C Hill PLB345,483 (1995)

$$\frac{g_{TC}^2}{M_{TC}^2}\left[\bar{Q}\gamma^\mu Q\right]\left[\bar{t}\gamma_\mu t\right] = \frac{g_{TC}^2}{M_{TC}^2}\left[\bar{Q}t\right]\left[\bar{t}Q\right]$$

$$\to -M_{TC}^2|\Phi|^2 + g_{TC}\Phi\bar{Q}t + g_{TC}\Phi^*\bar{t}Q$$



$$m_\Phi^2 = M_{TC}^2 - \frac{N_c g_{TC}^2}{8\pi^2}M_{TC}^2 + \ldots$$

B Dobrescu, C Hill
PRL81, 2634 (1998)

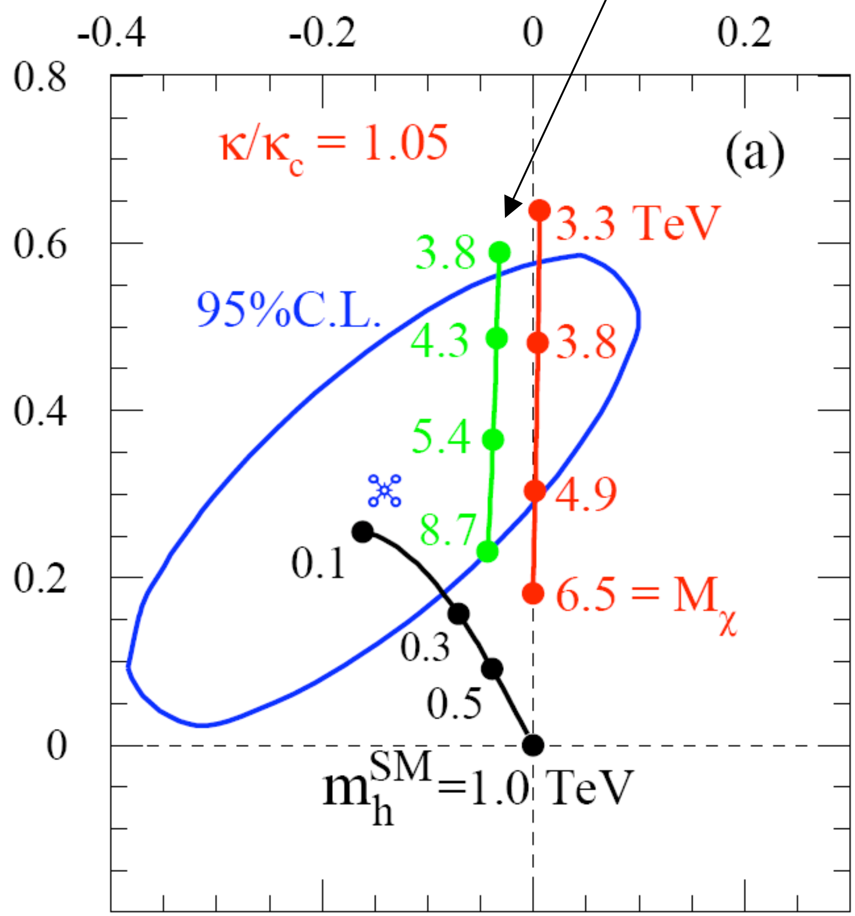
Top Seesaw

- The problem in top-color with the top mass arises because one single interaction must drive EWSB (and thus fit the Z mass) and also produce the top Yukawa coupling.
- A very interesting idea to relieve this tension is to have the Higgs be a bound state of tL and a vector-like right-handed top ($\mathbf{h}_R$).
- Now the large "mass" is just an off-diagonal entry in the mass matrix:

$$\begin{bmatrix} \bar{t}_L & \bar{\eta}_L \end{bmatrix} \begin{bmatrix} 0 & \sim 250\,\mathrm{GeV} \\ \mathrm{M}_{\eta t} & \mathrm{M}_{\eta\eta} \end{bmatrix} \begin{bmatrix} t_R \\ \eta_R \end{bmatrix}$$

- By tuning the new parameters $\mathbf{M_{hh}}$ and $\mathbf{M_{ht}}$, one fits the correct top mass, despite the much larger entry demanded by the Z mass.
- The EW fit then tells us what the mass of the new top-like quark should be!
- This depends highly on the value of m_t!

New Quark Masses



HJ He, C Hill, T Tait.
Phys.Rev.D65:055006,2002

Something hiding with top?

- Many theories such as supersymmetry or little Higgs predict that the top has partners, needed to cancel its quadratically divergent contributions to the Higgs mass.
- These states have the same gauge interactions as top, and thus may look like it experimentally.
  - The top's super-partner, stop may decay in a way similar to some top decays:

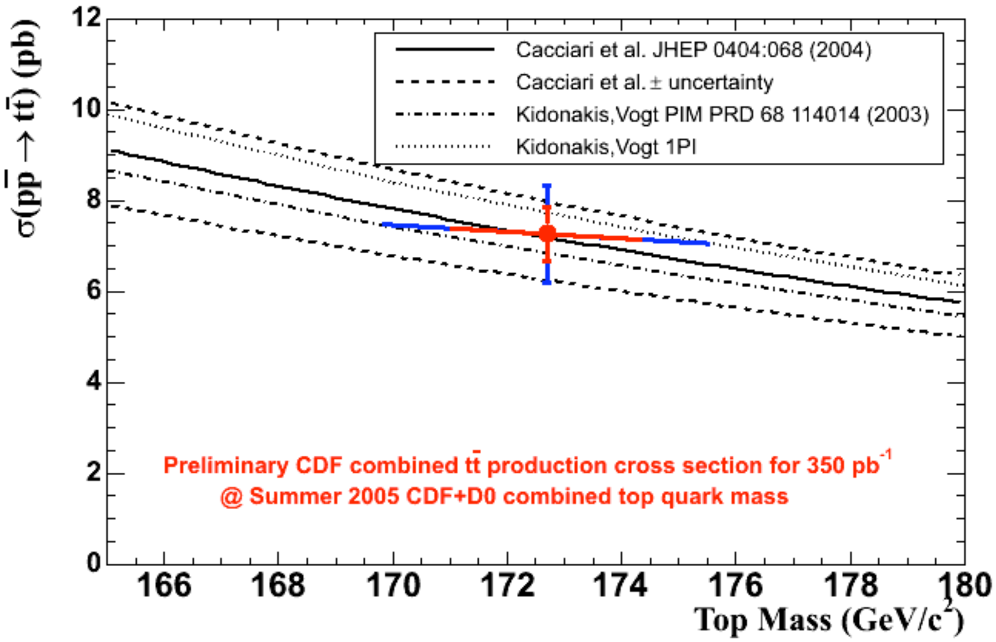
$$\tilde{t} \rightarrow \tilde{W}^{+} b, W^{+} \tilde{b} \rightarrow \ell^{+} \nu \tilde{\chi}^{0} b \quad : \mathrm{lepton} + \mathrm{b} + \not{E}_{\mathrm{T}}$$

  - The extra top-like quark from the top see-saw:

$$t' \rightarrow Wb \rightarrow \quad \text{any top final state}$$

  - Other theories of mirror quarks try to explain the A_{FB}^{b} discrepancy, or solve the hierarchy problem through the little Higgs mechanism.
- If the new state has a somewhat smaller production cross section than the top does, it may hide effectively in the top quark data sample.

$t\bar{t}$ Production Rates



- The top mass (and $\mathbf{a}_S$ at that scale) entirely determines tt the tt production rate.
- Precise measurements of both are necessary to use the rate to constrain or discover new physics hiding in the top sample.
- Of course, usually the new physics will have different kinematic properties as well.
- For a t', this could be just a small excess in the mt distribution tail.
- A precise value for the top mass is helpful in two ways: it implies a good understanding of the tails, and also allows one to tighten the selection to be more sensitive to new physics effects.

Outlook

- The top is unique among fermions. Its large mass means it is the place we can learn about fermion masses and electroweak symmetry breaking.
- All fermion masses are interesting because they are representation of
- The large top mass implies a special role for top already inside the Standard Model.
  - EW precision physics and the SM Higgs mass
  - Flavor physics
  - Higgs physics
- It also gives top a special role in physics beyond the Standard Model
  - Supersymmetric Higgs mass
  - Top color & top flavor
- As a concrete example, the MSSM lives or dies by what the top mass turns out to be!
- The question as to whether or not something new could be hiding along with top in the data requires extremely precise understanding of the top mass, the cross section, and kinematic distributions.

Supplementary Slides

Top in the Standard Model

- In the SM, top is the marriage between a left-handed quark doublet and a right-handed quark singlet.
- This marriage is consummated by EWSB, with the mass (m_t) determined by the coupling to the Higgs (y_t).
- This structure fixes all of the renormalizable interactions of top, and determines what is needed for a complete description of top in the SM.
- Mass: linked to the Yukawa coupling (at tree level) through: $m_t = y_t v$.
- Couplings: g_S and e are fixed by gauge invariance. The weak interaction has NC couplings, fixed in addition by s^2_W. CC couplings are described by V_{tb}, V_{ts}, and V_{td}.

Measurements

- How well are these quantities known?
- g_S, e, and s^2_W are well known (g_S at per cent level, EW couplings at per mil level) from other sectors.
- m_t is reconstructed kinematically at the Tevatron:
  - Run I: m_t = **178 ± 4.3 GeV**
  - Run IIb: prospects to a precision of **± 2 GeV** (systematic).
- V_{td}, V_{ts}, and V_{tb} are (currently) determined indirectly:
  - V_{td}: **0.004 – 0.014** (< 0.09)
  - V_{ts}: **0.037 – 0.044** (< 0.12)
  - V_{tb}: **0.9990 – 0.9993** (0.08 – 0.9993)
  - These limits assume the 3 (4^+?) generation SM, reconstructing the values using the unitarity of the CKM matrix.
- V_{tb} can be measured directly from single top production.

PDG: http://pdg.lbl.gov/pdg.html