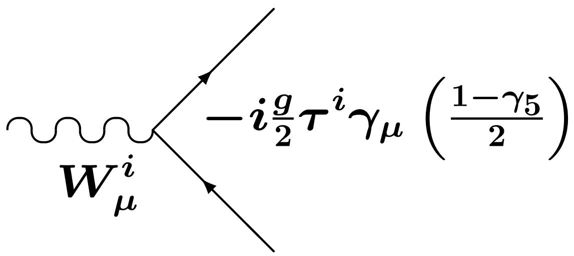
Why the Top Quark?

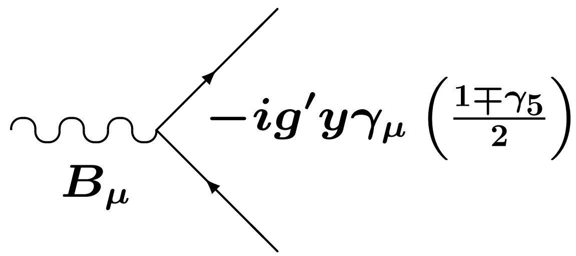
- **Did it have to be there?**
- **Did it have to be heavy?**
- **Why is is important?**
- **What is its role?**

A Model of Leptons (1967)

- **Group** $SU(2) \times U(1)$; **gauge bosons** $(W^{\pm}, W^{0}),\ B$
- **Gauge couplings** $g,\ g'$: $\tan\theta_W \equiv g'/g; \quad e = g\sin\theta_W$

$$\underbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{e_R^- \qquad \mu_R^-}_{\text{singlets}}$$





Extension to Quarks: Flavor Changing Neutral Currents

- Cabibbo mixing of $d_L - s_L$ needed by charged current

$$\begin{pmatrix} u \\ d' \equiv d\cos\theta_c + s\sin\theta_c \end{pmatrix}_L \qquad s'_L = -d_L \sin\theta_c + s_L \cos\theta_c$$

$$u_R \qquad d_R \qquad s_R$$

- Flavor changing neutral current transitions predicted, not observed

$$\begin{aligned} J_Z^\mu &= \bar{u}_L \gamma^\mu u_L - \bar{d}'_L \gamma^\mu d'_L - 2\sin^2\theta_W\, J_Q^\mu \\ &= \bar{u}_L \gamma^\mu u_L - \cos^2\theta_c\, \bar{d}_L \gamma^\mu d_L - \sin^2\theta_c\, \bar{s}_L \gamma^\mu s_L \\ &- \cos\theta_c \sin\theta_c \left(\bar{d}_L \gamma^\mu s_L + \bar{s}_L \gamma^\mu d_L\right) - 2\sin^2\theta_W\, J_Q^\mu \end{aligned}$$

The Charm Quark

- **GIM (1970): Introduce fourth (c) quark**
  - Quarks and leptons treated symmetrically (up to ν_R)
  - d_L and s_L both in doublets $\longrightarrow$ no tree-level FCNC
  - FCNC loops calculable: $m_{K_L} - m_{K_S} \longrightarrow m_c \sim$ few GeV
  - No triangle anomalies
  - *But*, strong resistance to introducing new particle (cf. Pauli)

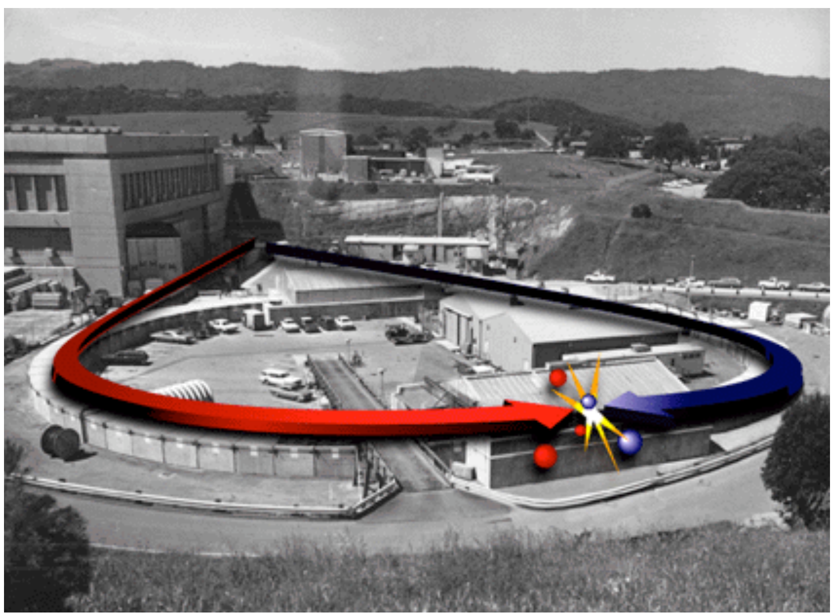
$$\underbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{e^-_R \qquad \mu^-_R}_{\text{singlets}}$$

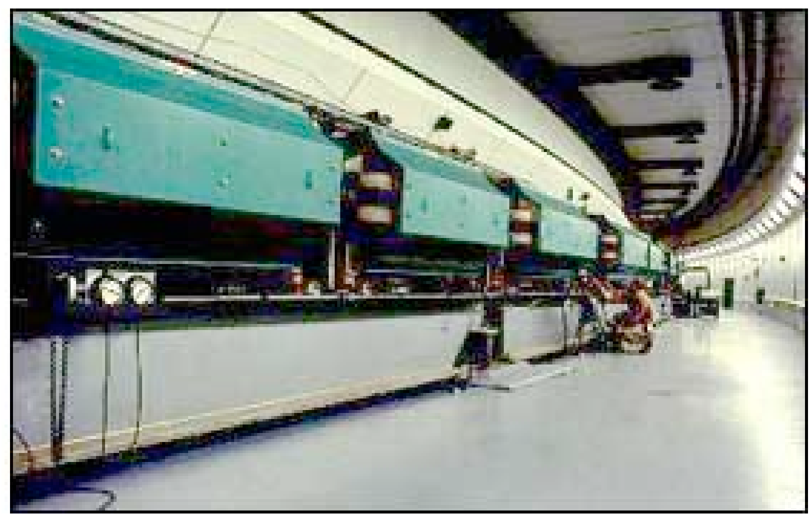
$$\underbrace{\begin{pmatrix} u \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{u_R \qquad d_R \qquad c_R \qquad s_R}_{\text{singlets}}$$

The J/ψ

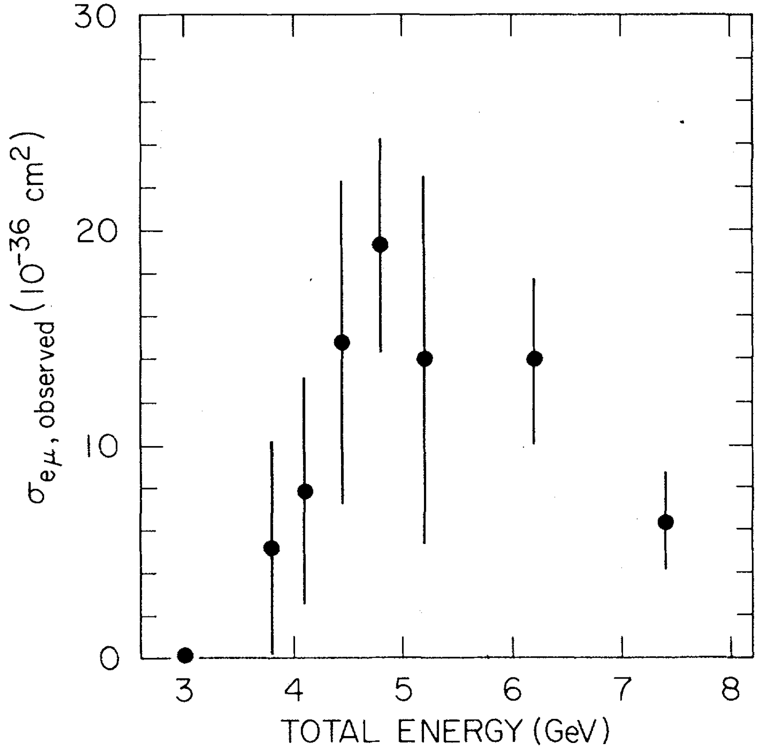
- J/ψ $(c\bar{c})$ discovered 1974 at Brookhaven and SLAC ($m_c \sim 1.5$ GeV)

- Role of hadron, e^+e^-, precision, theory



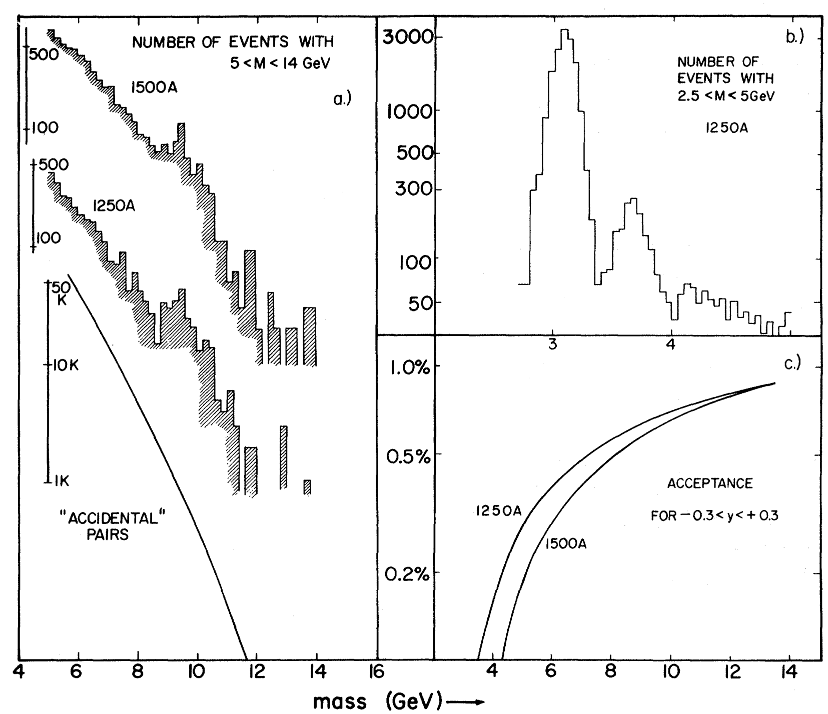


The Third Generation



τ lepton, SLAC (1975)

($m_\tau \sim 1.8$ GeV)



$\Upsilon(b\bar{b})$, Fermilab (1976)

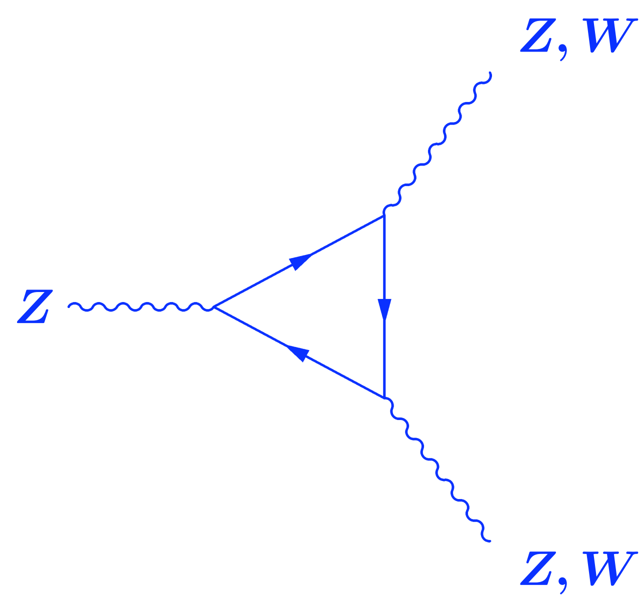
($m_b \sim 5$ GeV)

Sequential or Alternative?

- **Simplest interpretation: sequential family**

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \tau_R^- \qquad t_R \qquad b_R$$

  - This is the obvious generalization
  - Anomaly cancellation preserved
  - Allows CP violation



Other Possibilities

- **However, third family could be different** (e.g., string constructions)

- **Many other ways to cancel anomalies**

  – **Mirror family:** $\tau_L^- \quad t_L \quad b_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_R \quad \begin{pmatrix} t \\ b \end{pmatrix}_R$

  – **Singlet vector:** $\tau_L^- \quad b_L \quad \tau^-{}_R \quad b_R$ (topless)

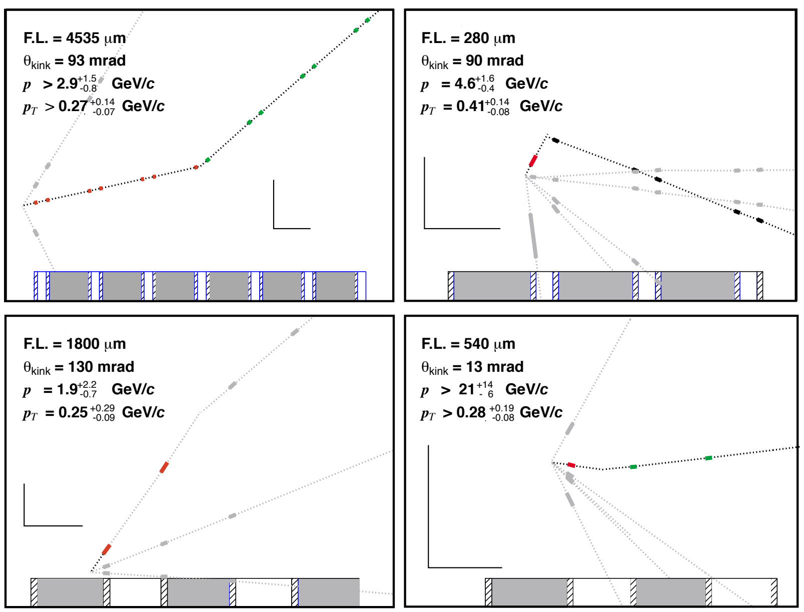
  – **Doublet vector:** $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_R \quad \begin{pmatrix} t \\ b \end{pmatrix}_R$

  – **Other, more complicated, possibilities**

The ν_τ

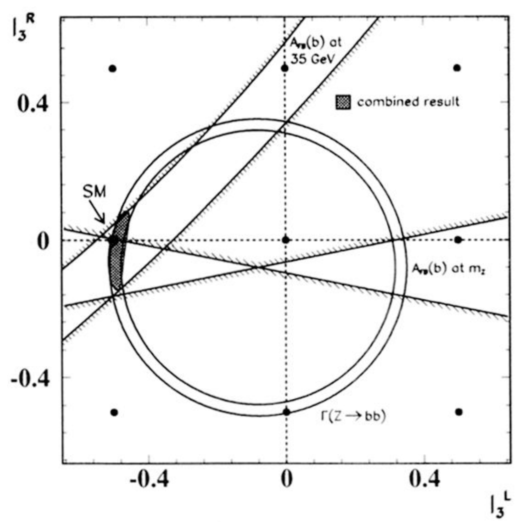
- **Weak interactions of τ** (lifetime, decay distribution, A^τ_{FB}, absence of FCNC $\tau \rightarrow l_1 l_2 \bar{l}_2$) **established sequential** $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \tau_R$

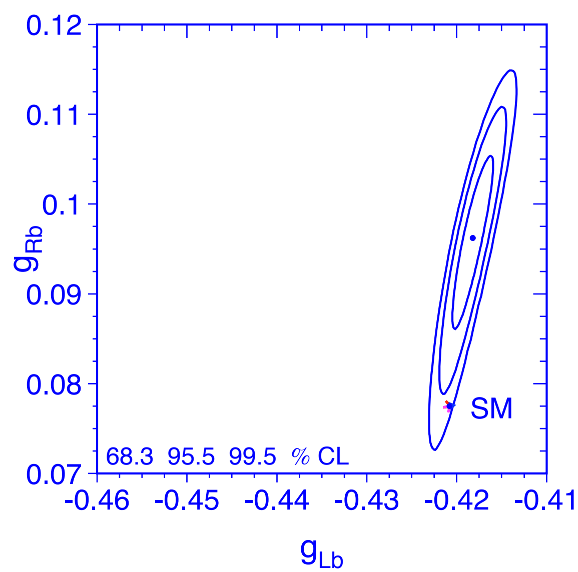
- **DONUT experiment (Fermilab, 2000) observed ν_τ directly**



The Weak Interactions of the b

- $e^+e^- \rightarrow b\,\bar{b}$ (full strength interaction)
  - Jade (DESY, 1988): A^b_{FB}(35 GeV) $\rightarrow t^b_{3L} - t^b_{3R} = -0.54 \pm 0.15$
    (sequental: $-\frac{1}{2}$; mirror: $+\frac{1}{2}$; singlet or doublet vector: 0)
  - LEP (1992): Γ_b/Γ_{had} and $A^b_{FB}(M_Z)$; LEP + SLC (2005)

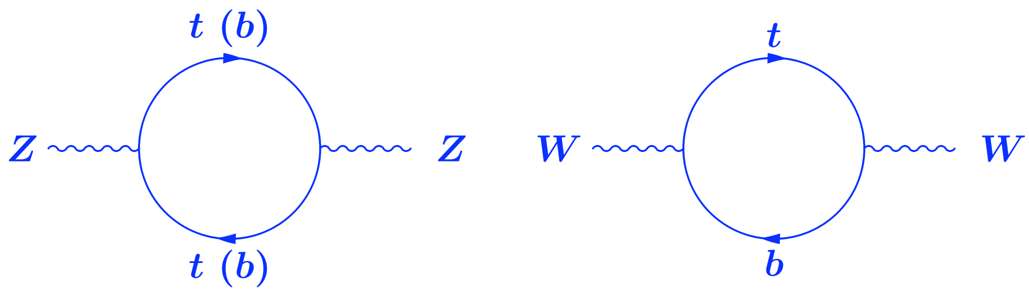




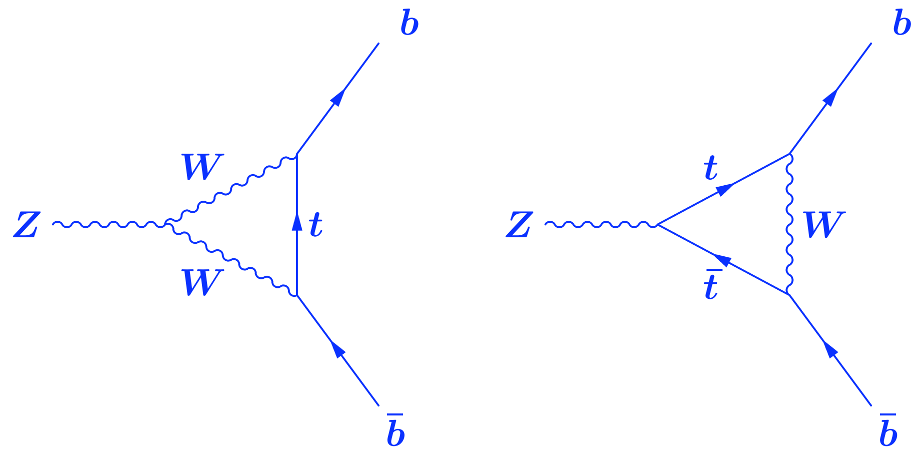
- CLEO (1987): absence of FCNC $B \rightarrow l^+ l^- X$ (but reduced strength)

Top Loops

- **Quadratic $G_F m_t^2$ dependence in gauge self-energies breaks $SU(2)$**
  ($M_{W,Z}$, widths, NC/CC)



- **Also $Z \rightarrow b\bar{b}$ vertex**
  (Γ_Z^b, A_{FB}^b)



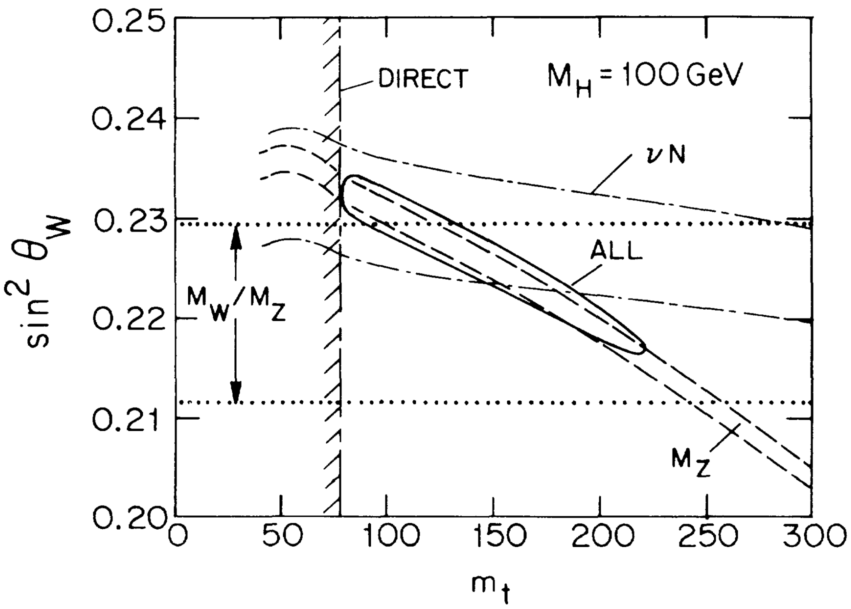
Precision Constraints on m_t

- **Theory, 1977**

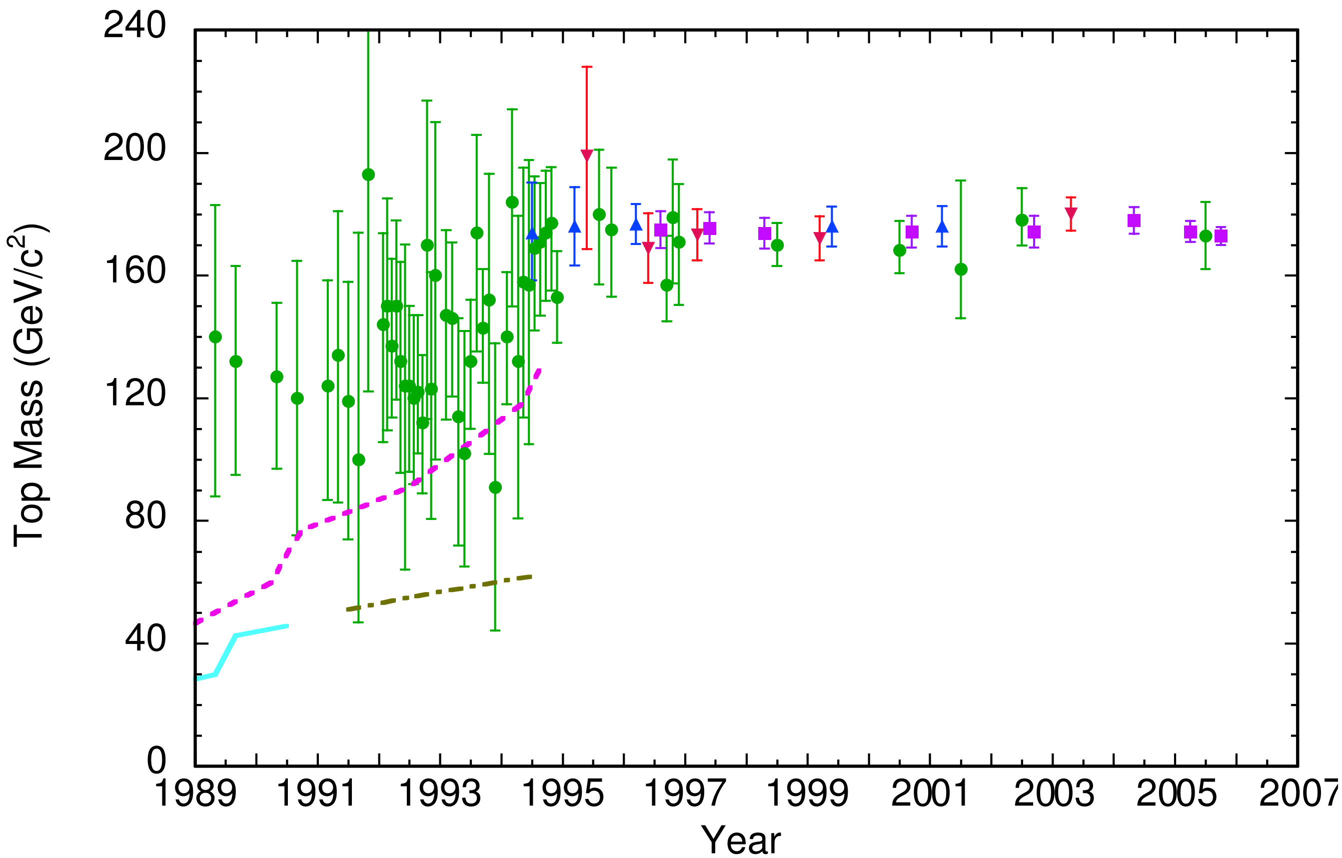
- **1980 global analysis: $m_L <$ 500 GeV** ($\rightarrow m_t < 290$ GeV)

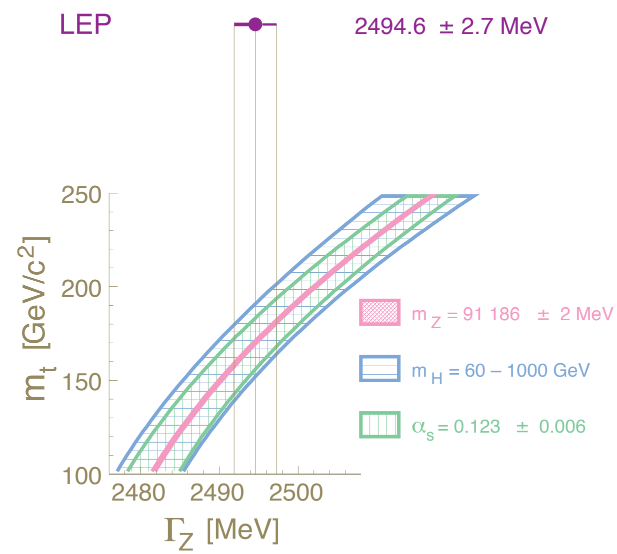
- **1987: $m_t < (175, 180, 200)$ GeV at 90% cl** (for $M_H = (10, 100, 1000)$ GeV)

- **1989: Precise M_Z (SLD) and $M_{W,Z}$ (CDF): $m_t = 140^{+43}_{-52}$ GeV for $M_H = 100$** ($\rightarrow$128 (165) for $M_H = 10(1000)$ GeV)



The LEP, SLD Era, and the Tevatron



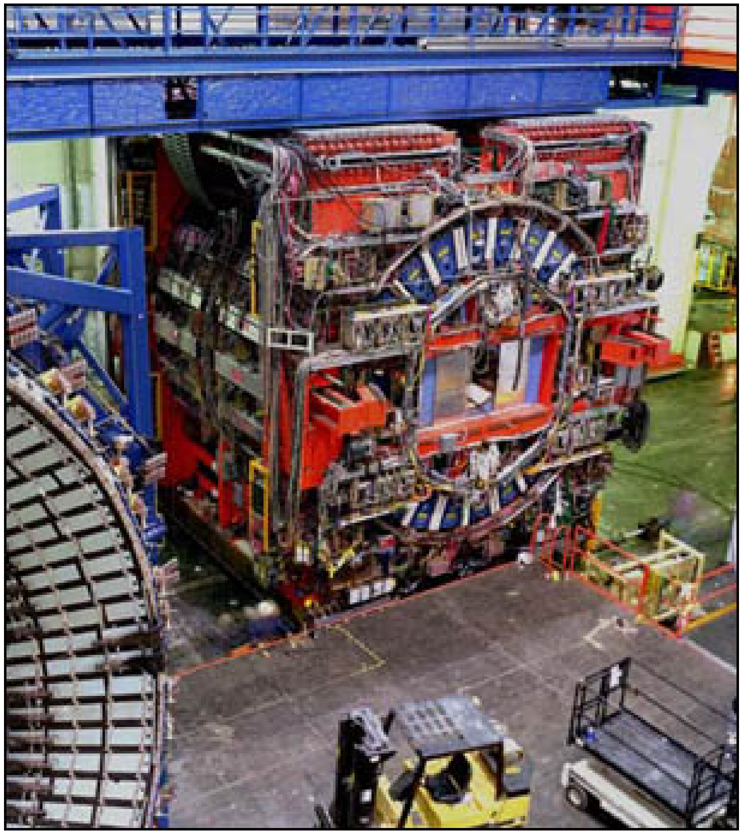


- **Two loop $m_t - M_H$ and $m_t - \alpha_s$ effects**

A House of Cards?

- Possible weak links in indirect precision predictions
  - Global analysis; unexpected systematics/correlations
  - Gauge principle, group, representations
    (well tested by W, Z; fermion couplings)
  - Renormalization of spontaneously broken non-abelian gauge theories, including anomalies and mixed QCD-electroweak
    (μ, β decay)
  - A heavy Higgs (but $Z \to b\bar{b}$)
  - New $SU(2)$-breaking physics to compensate m_t
    ($Z - Z'$ mixing, Higgs triplets)
  - Physics beyond the standard model affecting observables

The Discovery by CDF and DØ

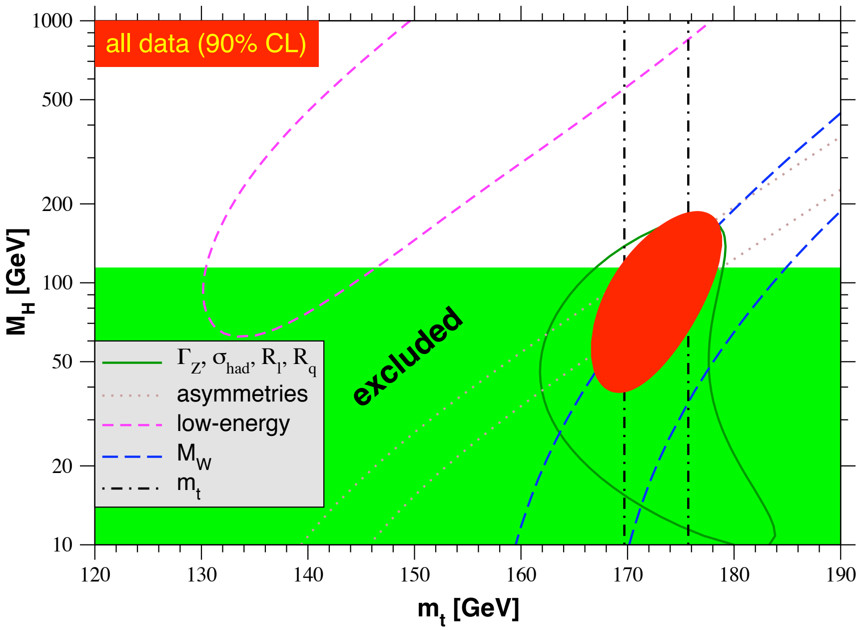


- **The lynchpin of the standard theory!**

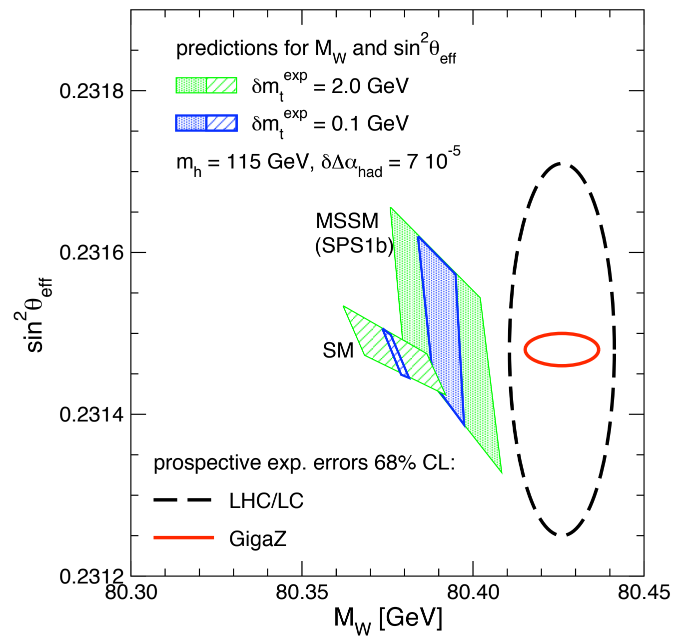
Why is the t Important?

- Established standard theory at loop level
- Signal and background for new physics
- Top properties, decays as probe of new physics
- Higgs machine (gg fusion, $t\bar{t}H$, etc.)
- Critical parameter (unitarity triangle, Higgs expectation in MSSM, precision constraint on Higgs mass)

The Standard Model (or decoupled MSSM) Higgs

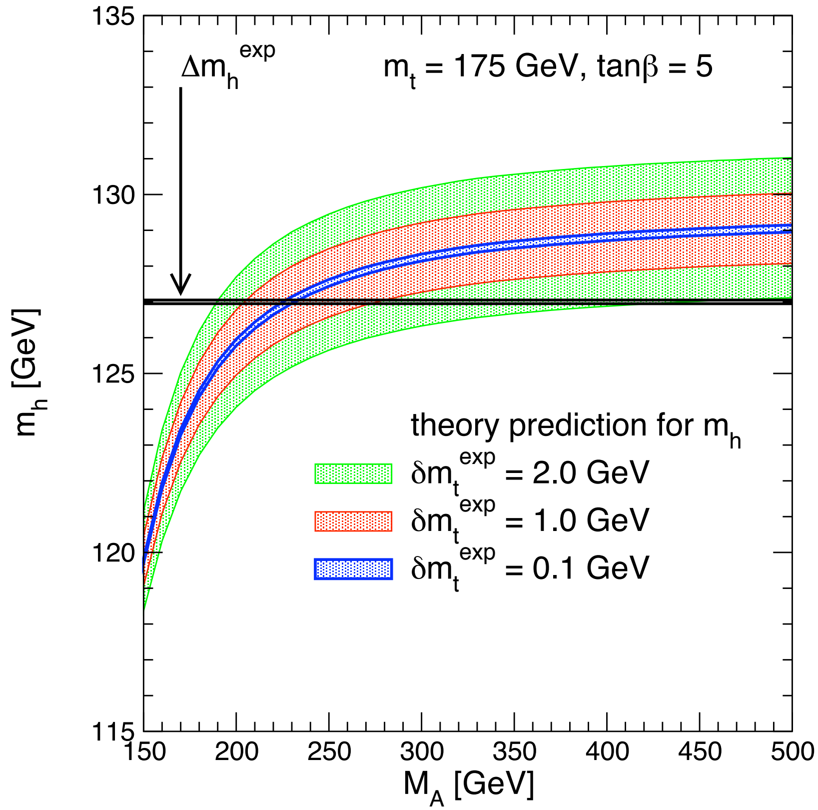


Present



Future

Expectation in MSSM



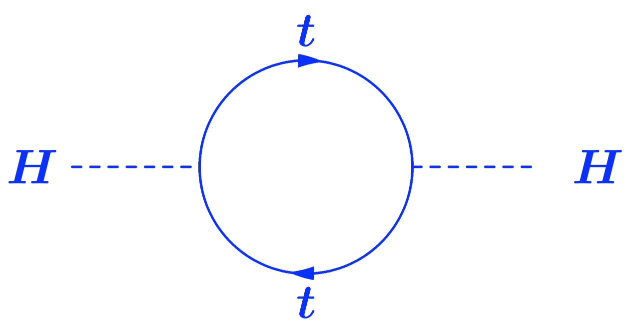
- **Bound weakened in extensions of MSSM**

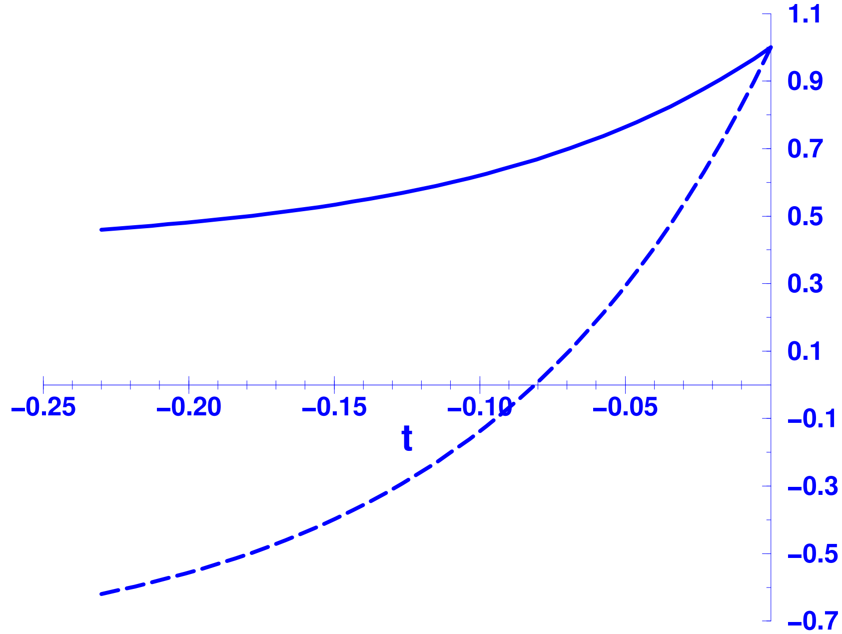
What is the Role of Top?

- **CP violation allowed in CKM matrix**
- **The top may be the only normal fermion**
- **The third family may be different** (e.g., strings, top-color)
- **May drive electroweak symmetry breaking** (e.g., radiative breaking in MSSM, top-color)

Radiative Electroweak Symmetry Breaking

- $m_H^2 > 0$ at Planck scale driven negative by large top Yukawa





Conclusions

- **Discovery was splendid achievement** **(experiments and accelerator)**
- **Critical for establishment of standard theory at quantum level**
- **Cooperation of discovery machines, precision, theory**
- **On to the Higgs (or alternative) and beyond**

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Congratulations!